Looking forward to new physics with the FASER experiment

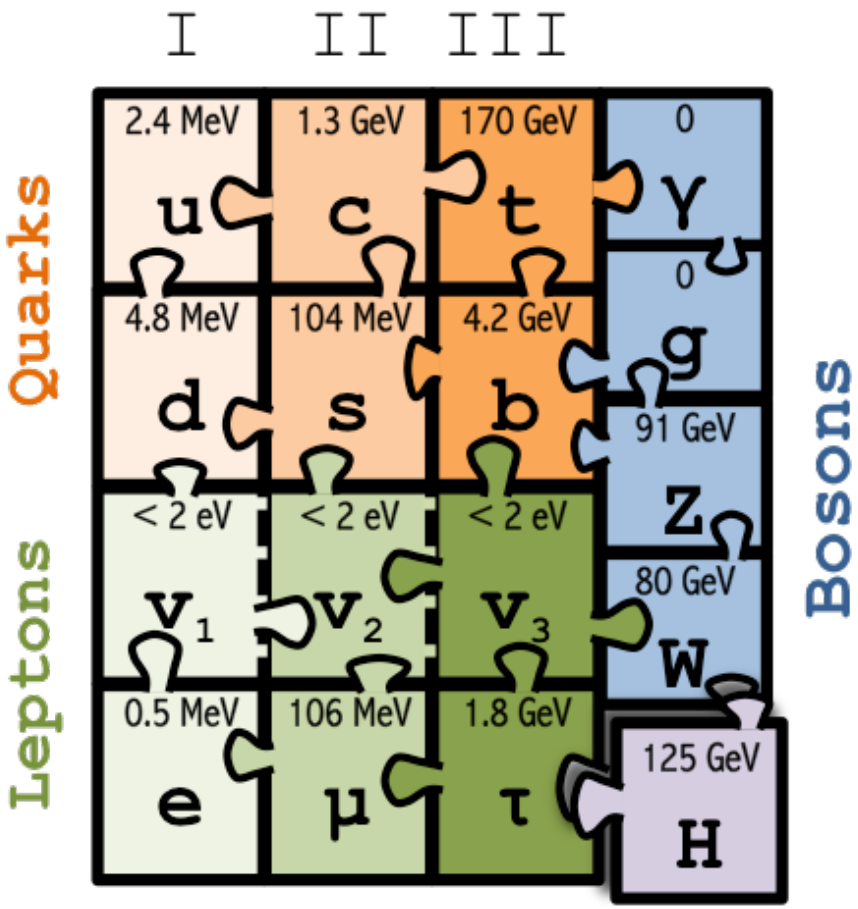
From searches for weakly interacting particles to first measurements of collider neutrinos

Seminar
16 May 2022

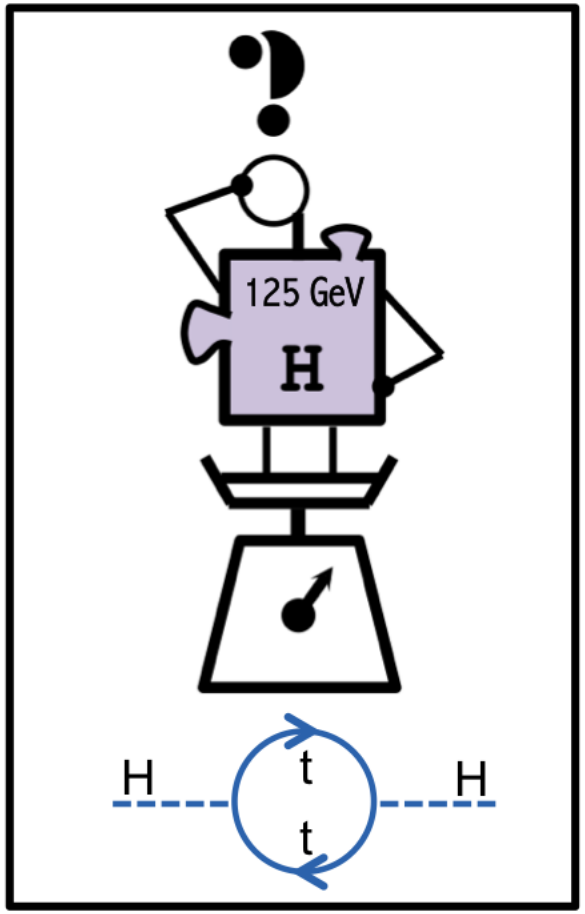
ARISTOTLE UNIVERSITY OF THESSALONIKI

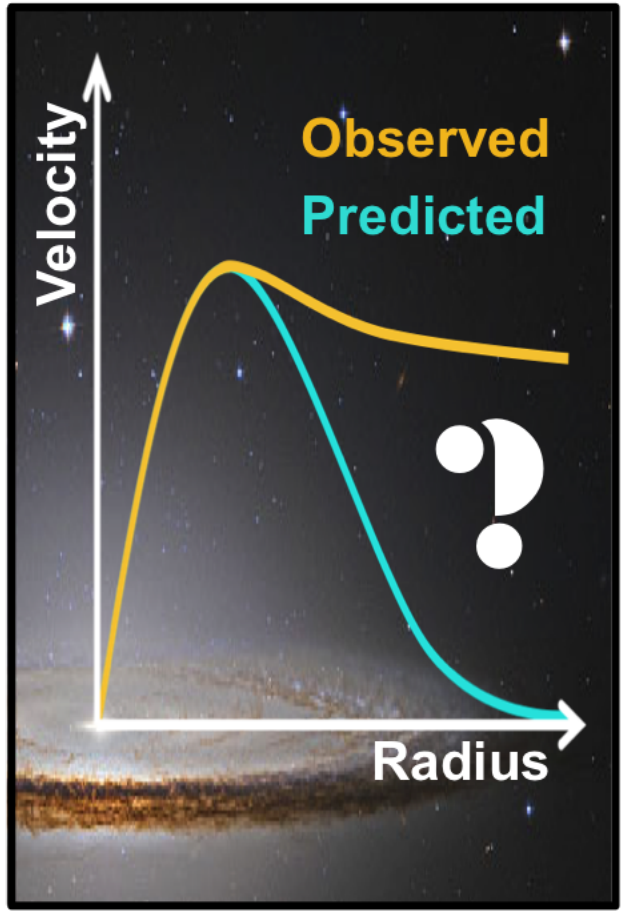
Άννα Σφύρλα
UNIVERSITÉ DE GENÈVE
FACULTY OF SCIENCE

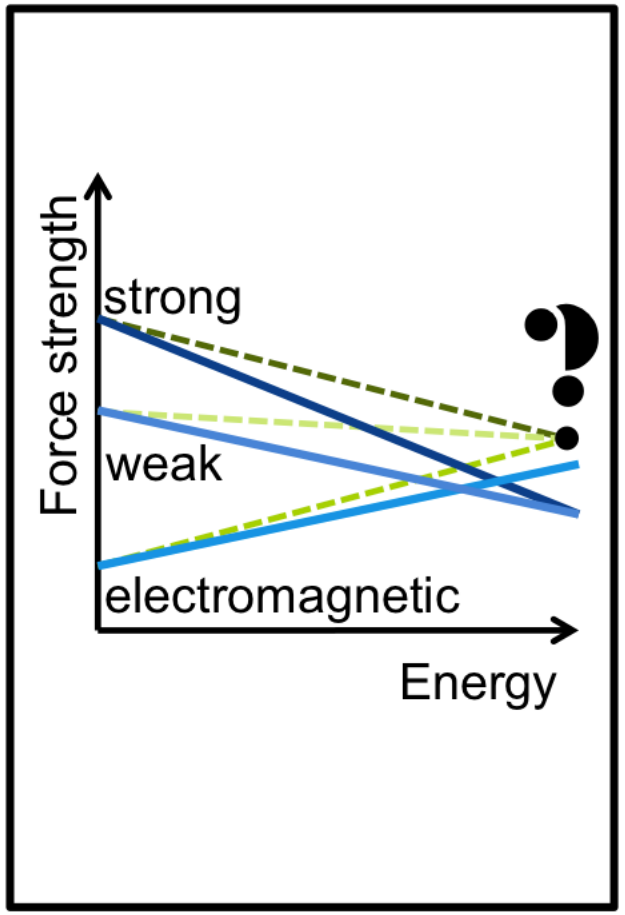
The STANDARD model



… its biggest open questions …







…and its more subtle ones!

The "strong CP problem": Why does QCD preserve CP symmetry?

Within the SM, the QCD vacuum structure introduces a CP violating term in the Lagrangian:

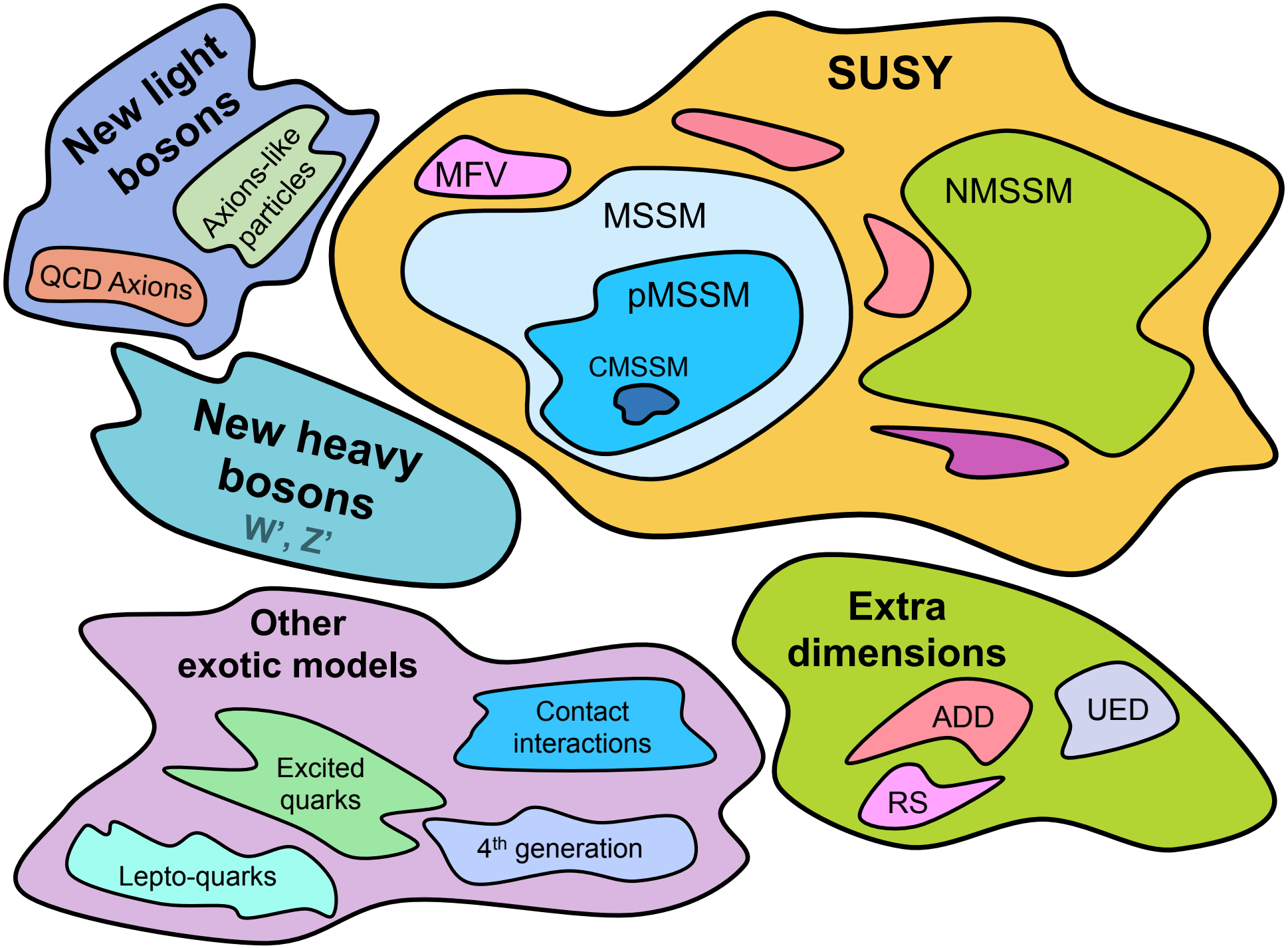
$$L_\theta = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

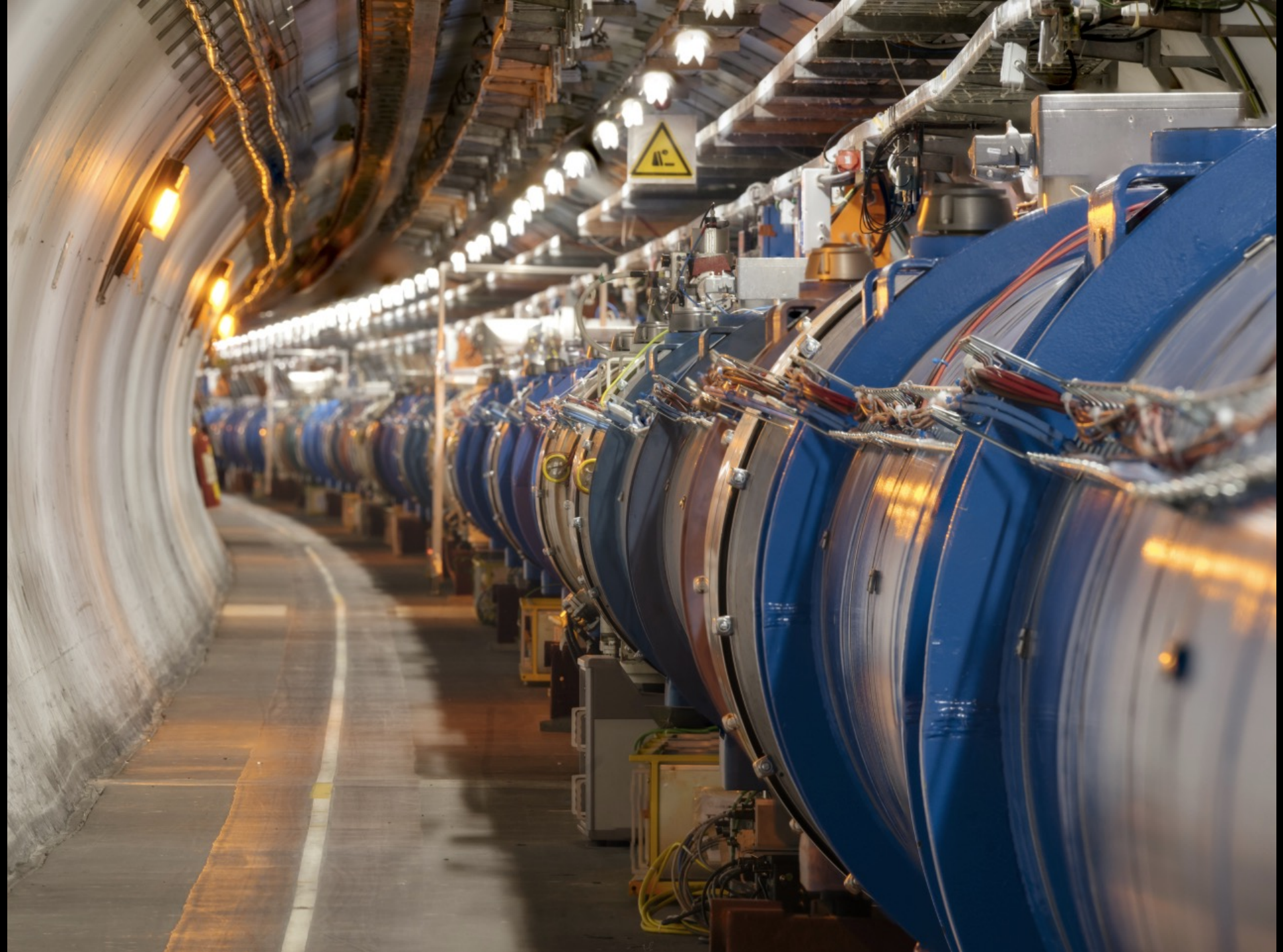
while measurements require that the vacuum angle θ is tiny!

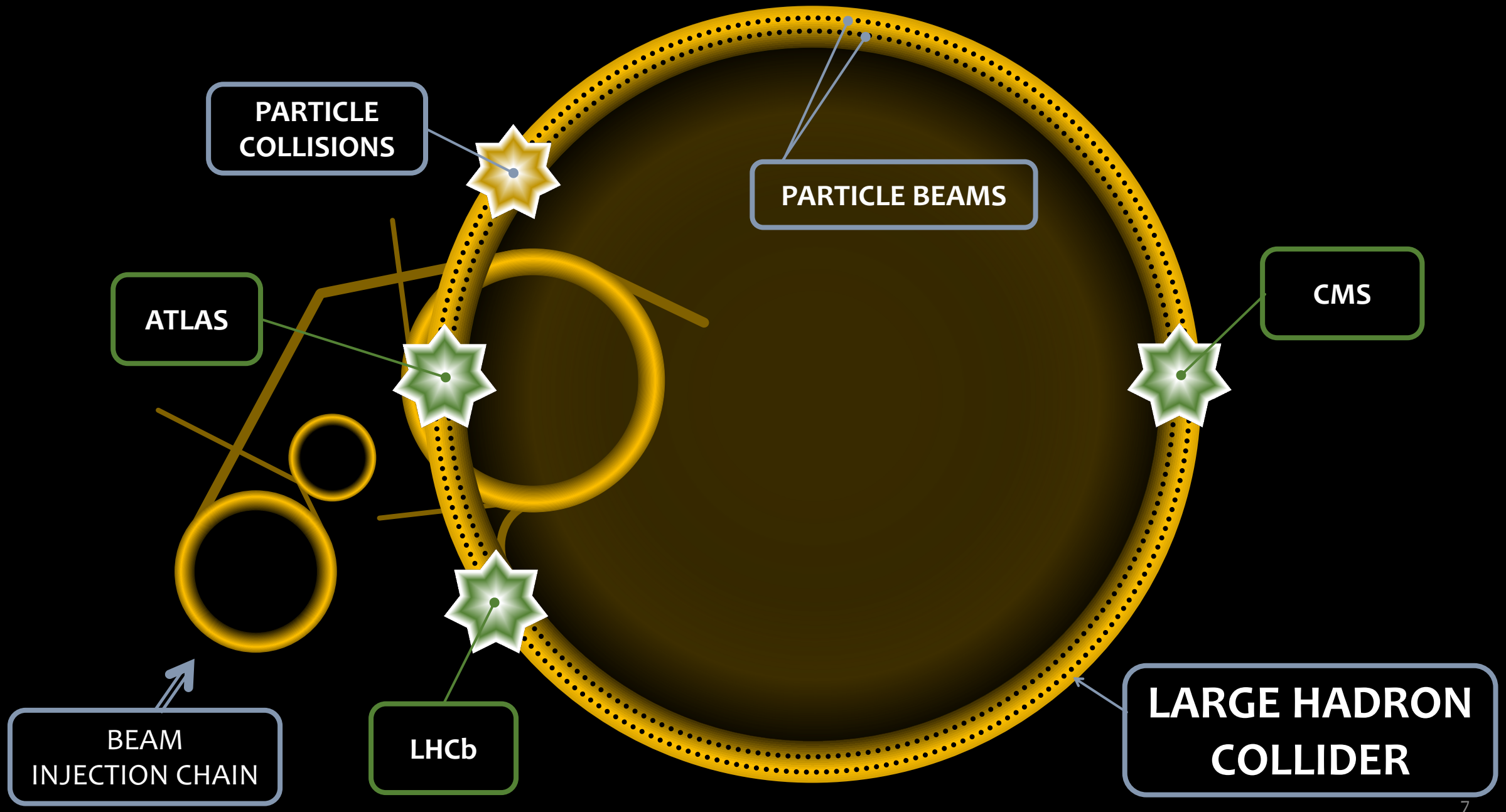
The non-zero angle θ implies non-zero neutron electric dipole moment (EDM)
The angle is stringently constrained by neutron EDM measurements

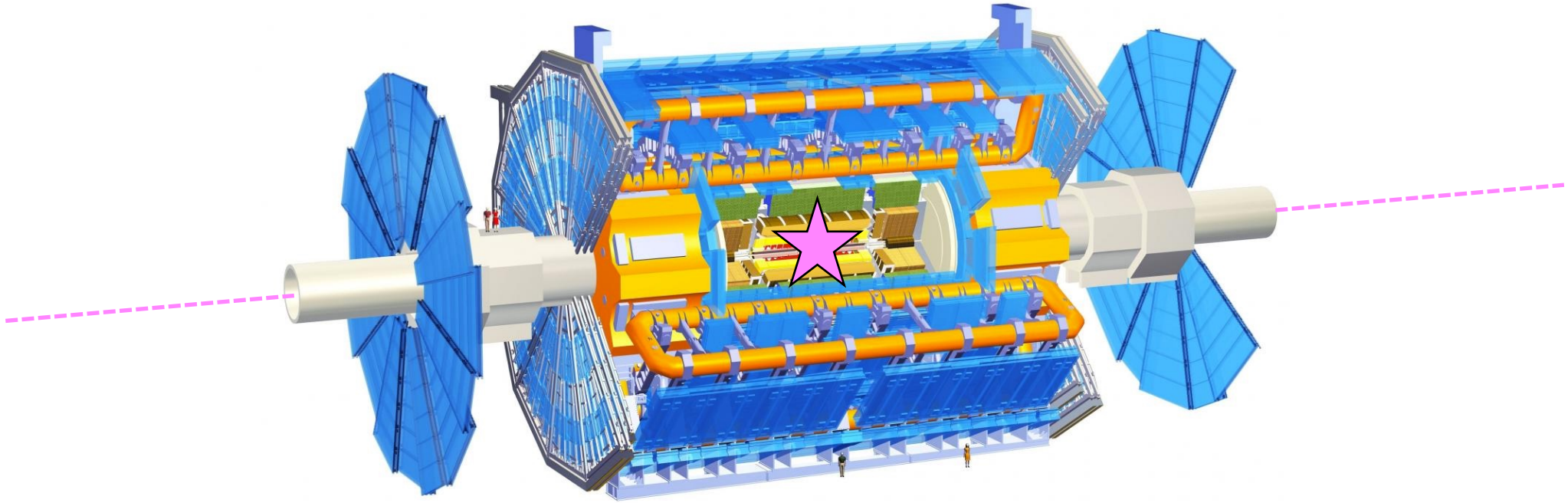
Most sensitive measurement on the neutron EDM to date achieved by the **PSI** experiment **nEDM:**

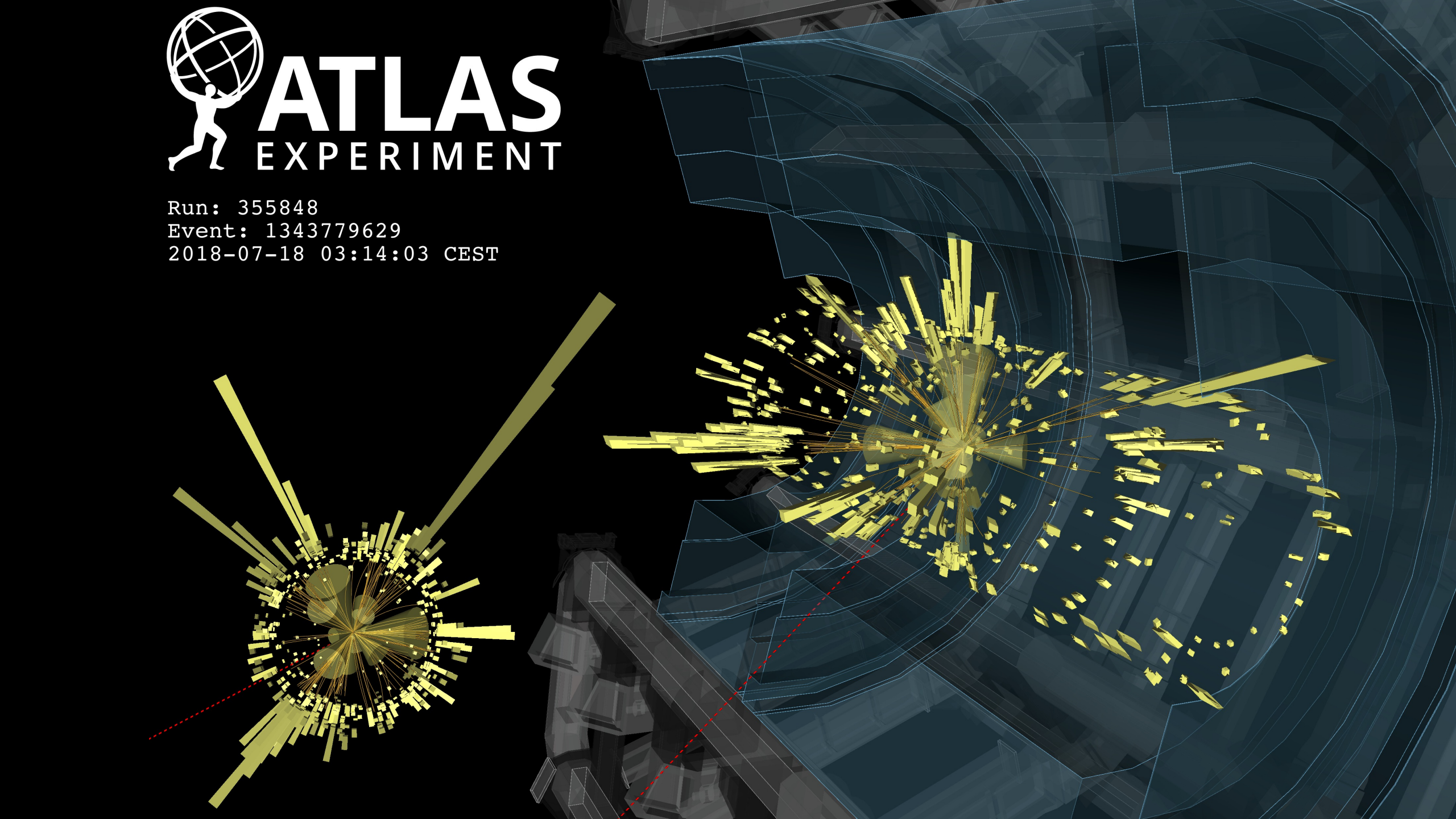
$d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{sys}) \times 10^{-26}$ e·cm.

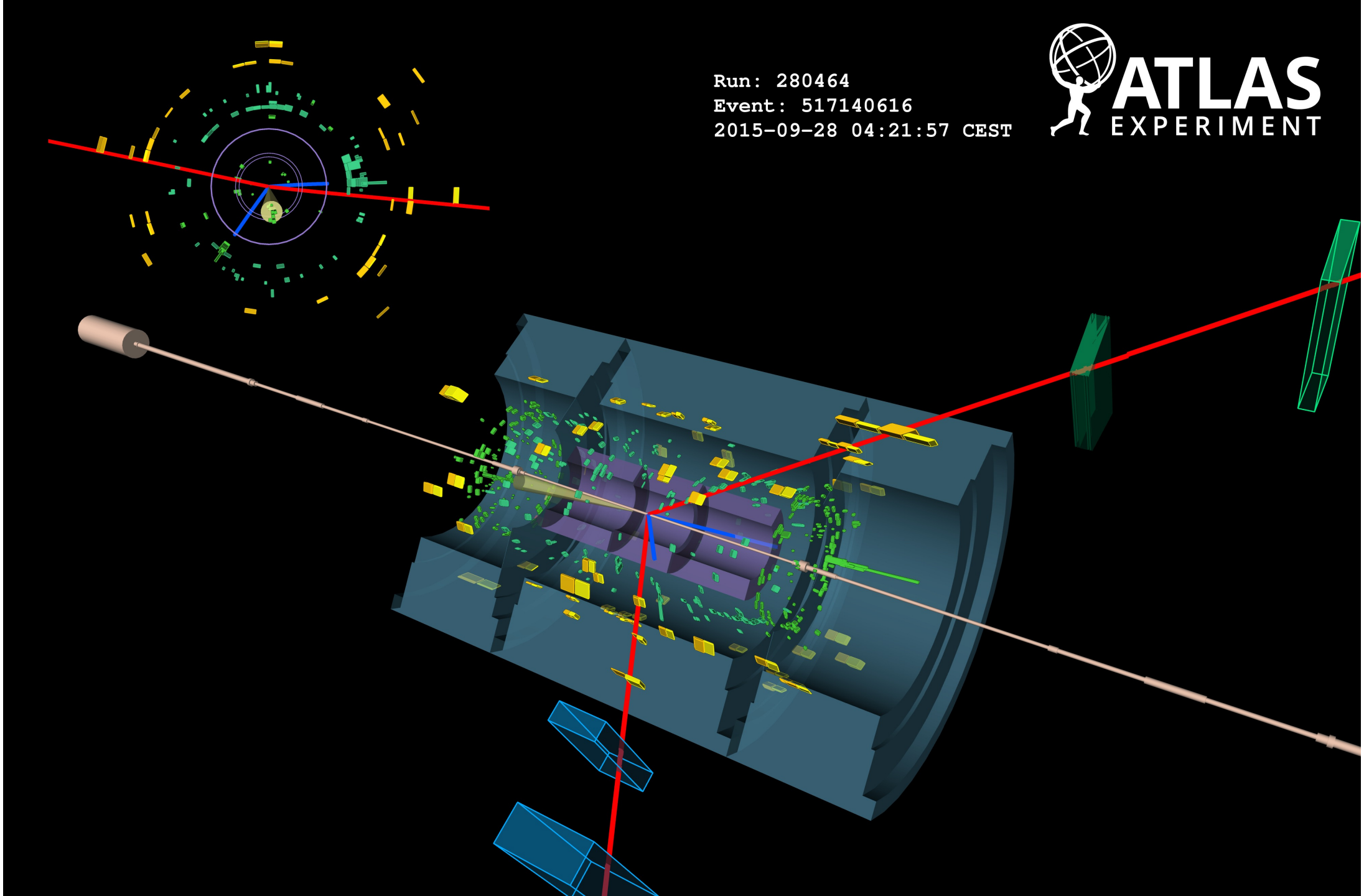

New light bosons
Axions-like particles
QCD Axions
SUSY
MFV
MSSM
pMSSM
CMSSM
NMSSM
New heavy bosons
W', Z'
Other exotic models
Contact interactions
Excited quarks
4th generation
Lepto-quarks
Extra dimensions
ADD
UED
RS




PARTICLE COLLISIONS
PARTICLE BEAMS
ATLAS
CMS
BEAM INJECTION CHAIN
LHCb
LARGE HADRON COLLIDER



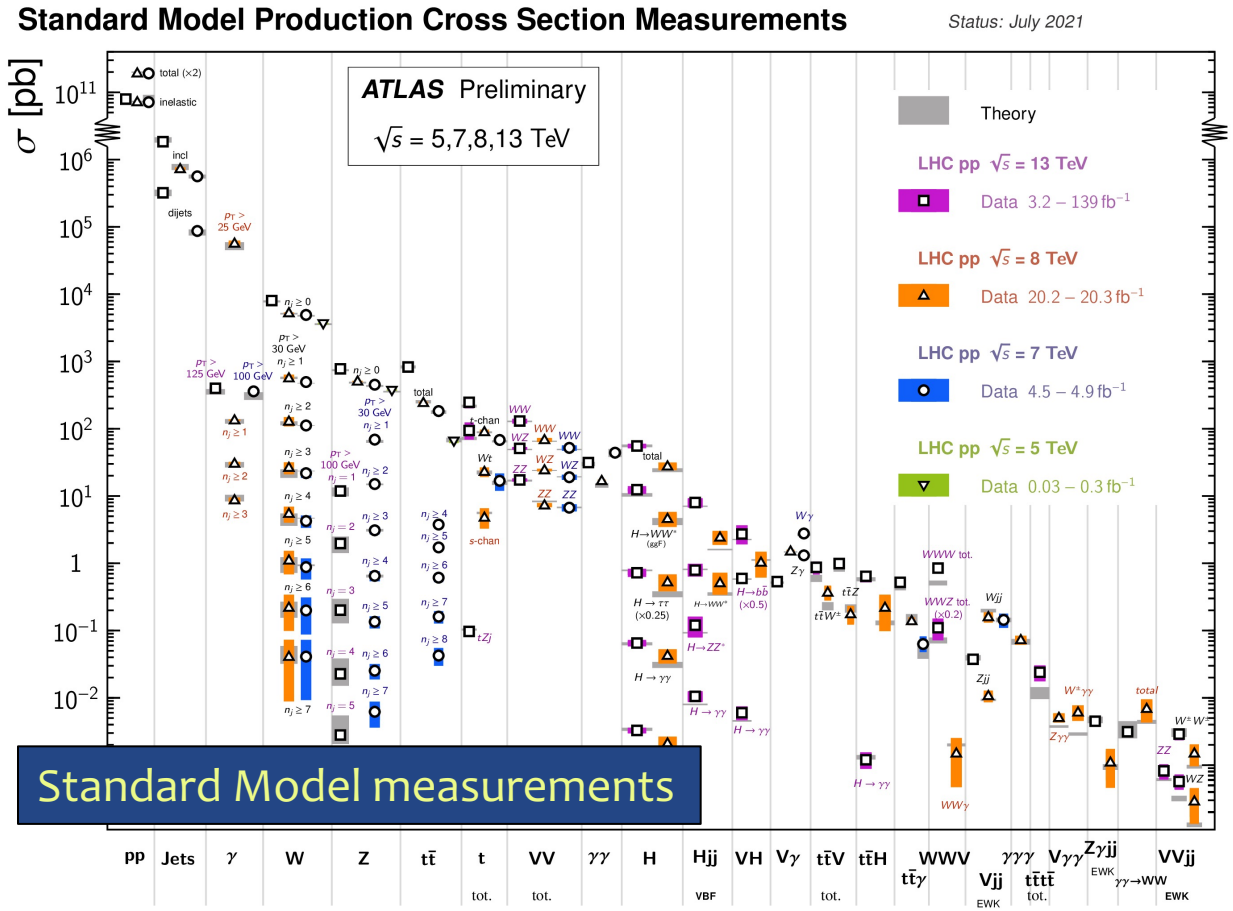

ATLAS
EXPERIMENT
Run: 355848
Event: 1343779629
2018-07-18 03:14:03 CEST


Run: 280464
Event: 517140616
2015-09-28 04:21:57 CEST
ATLAS
EXPERIMENT

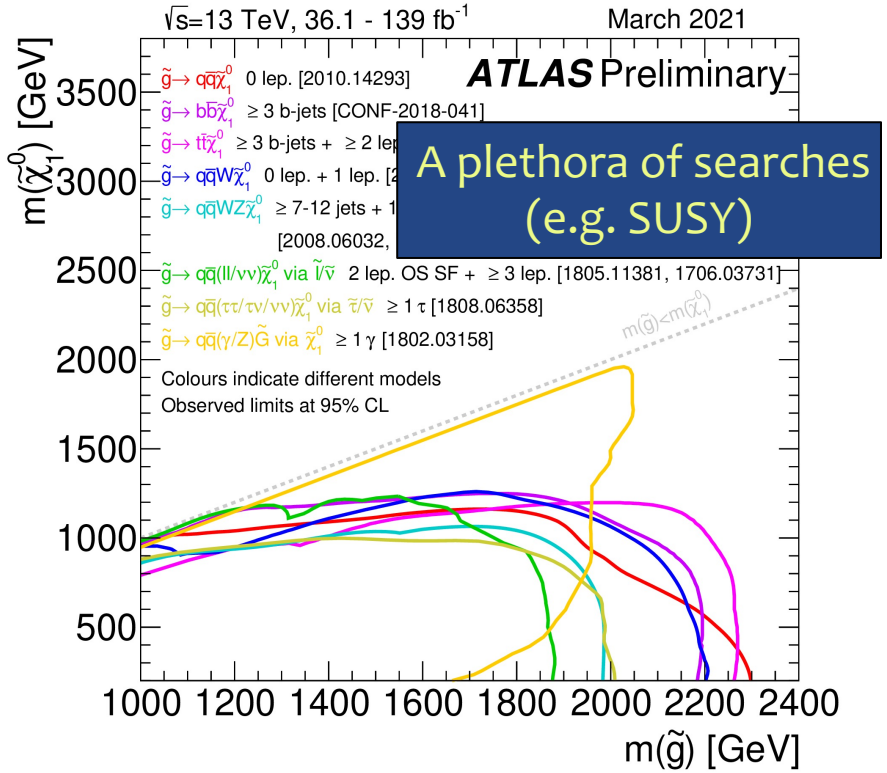
The landscape of new particles @ colliders

The landscape of LHC physics

Consistent among all experiments,
here using ATLAS as an example

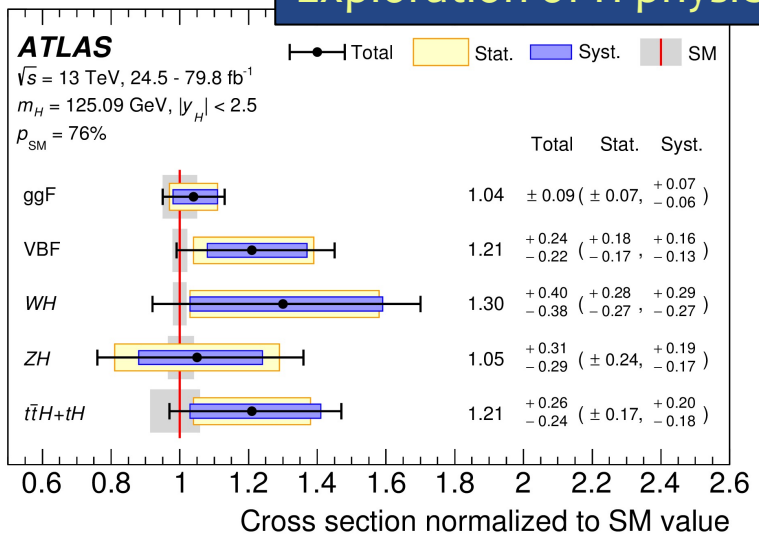


Standard Model measurements



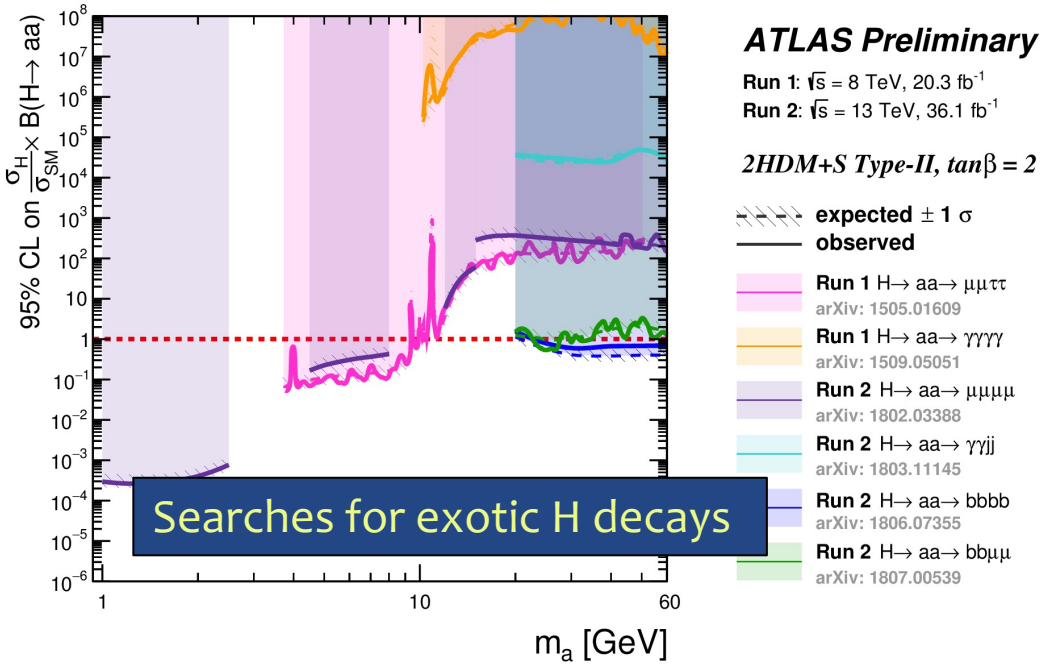
A plethora of searches
(e.g. SUSY)

Exploration of H physics



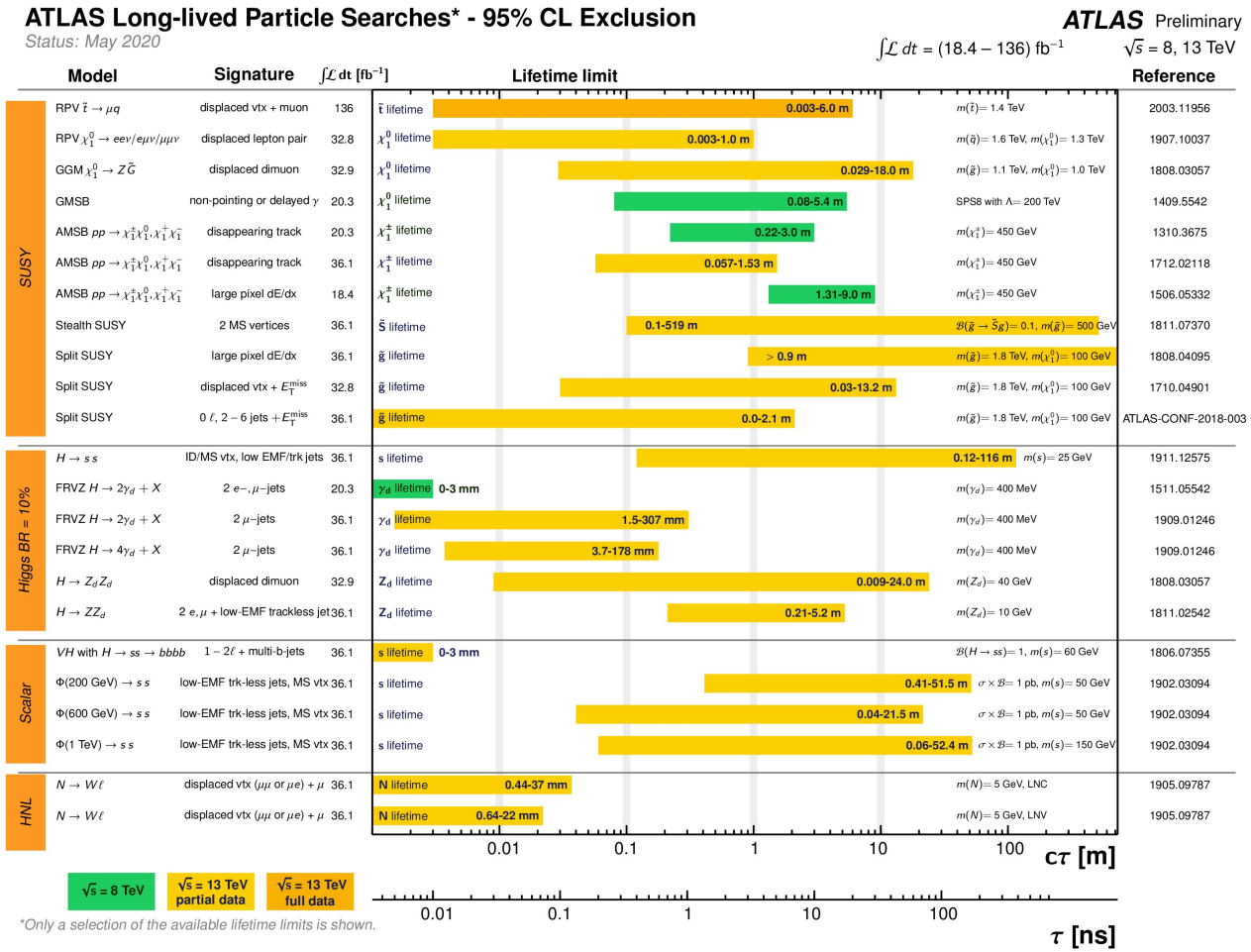
The landscape of LHC physics

Consistent among all experiments, here using ATLAS as an example



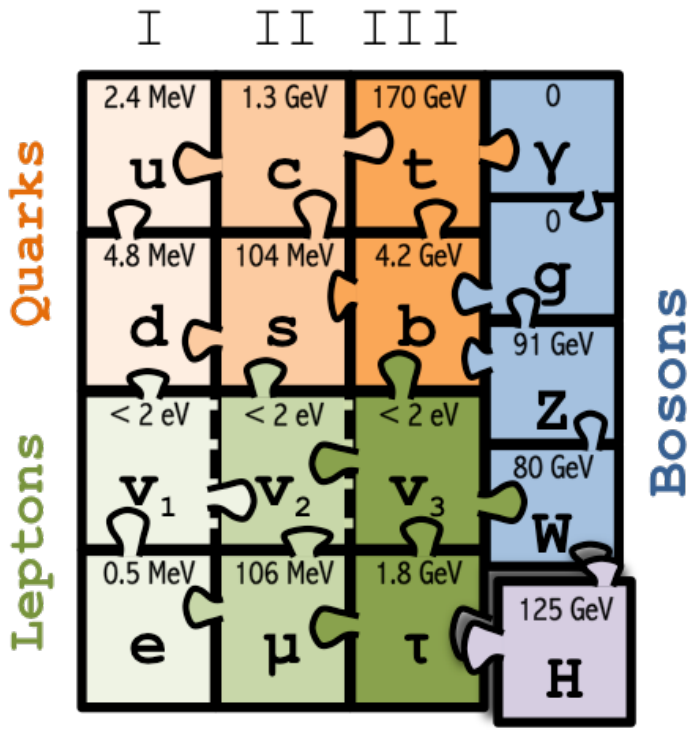
Searches for exotic H decays

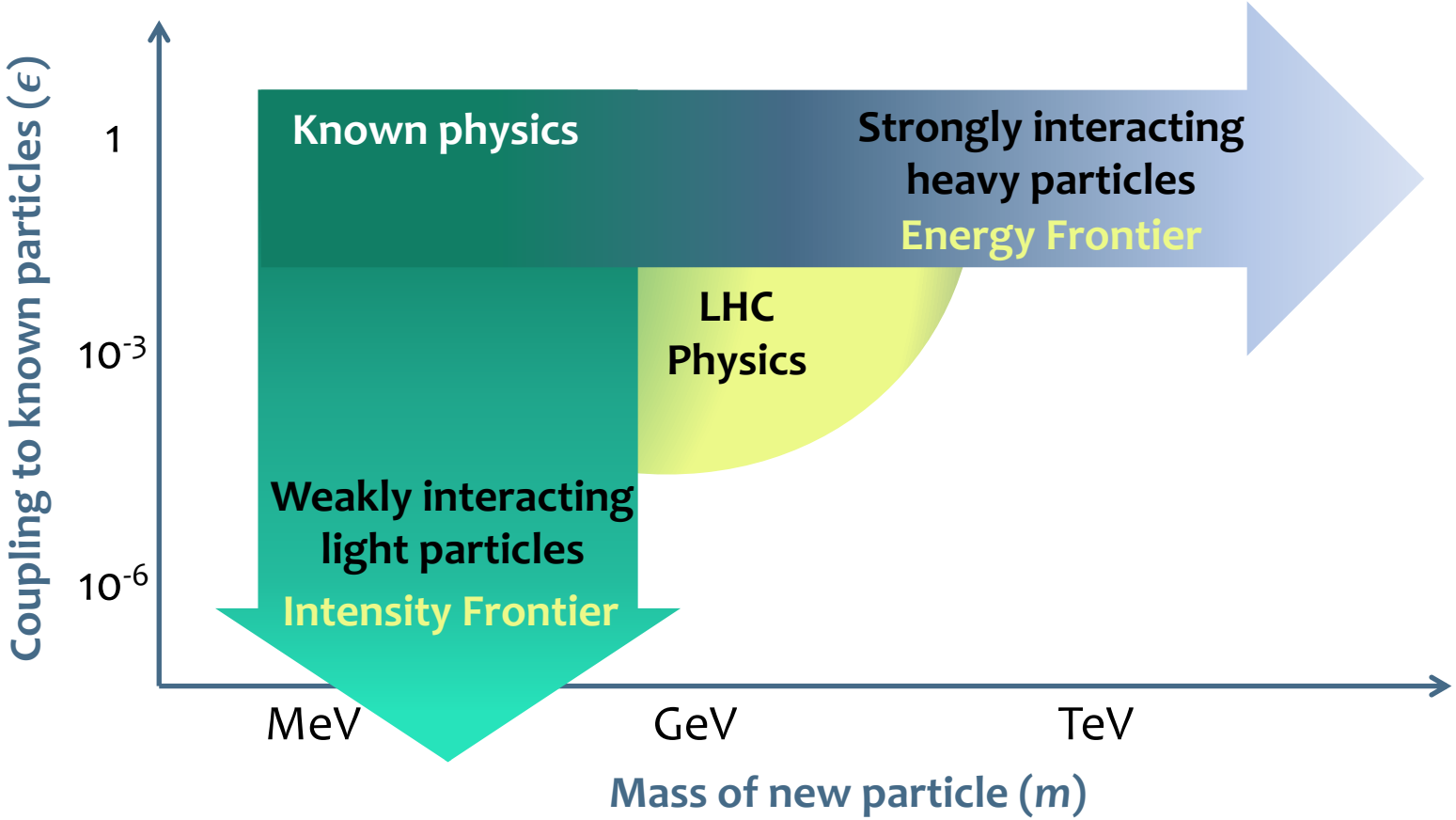
Searches for Long-Lived Particles



The landscape of new particles @ colliders

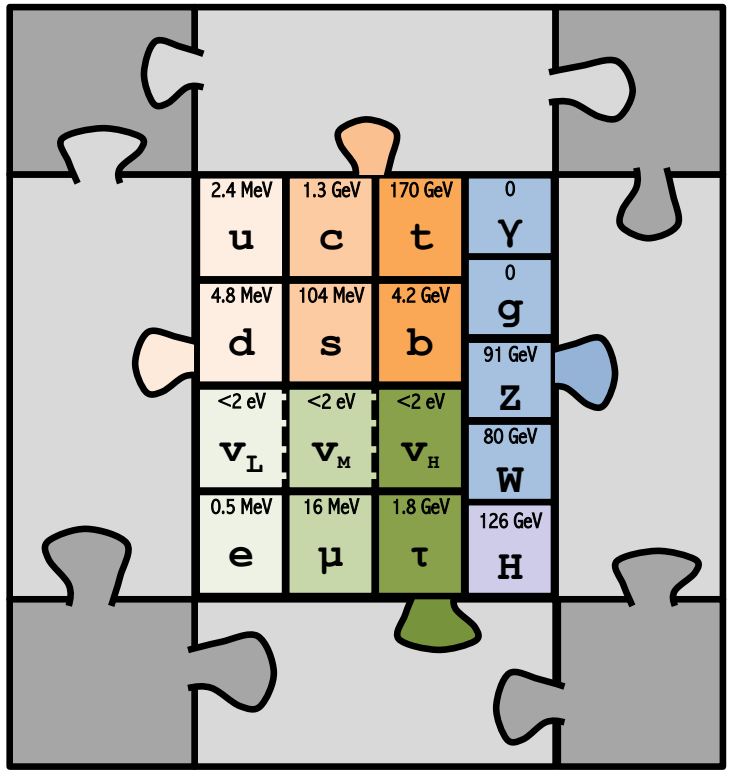
- Collider physics: a plethora of measurements and searches
- The Standard Model is complete and confirmed

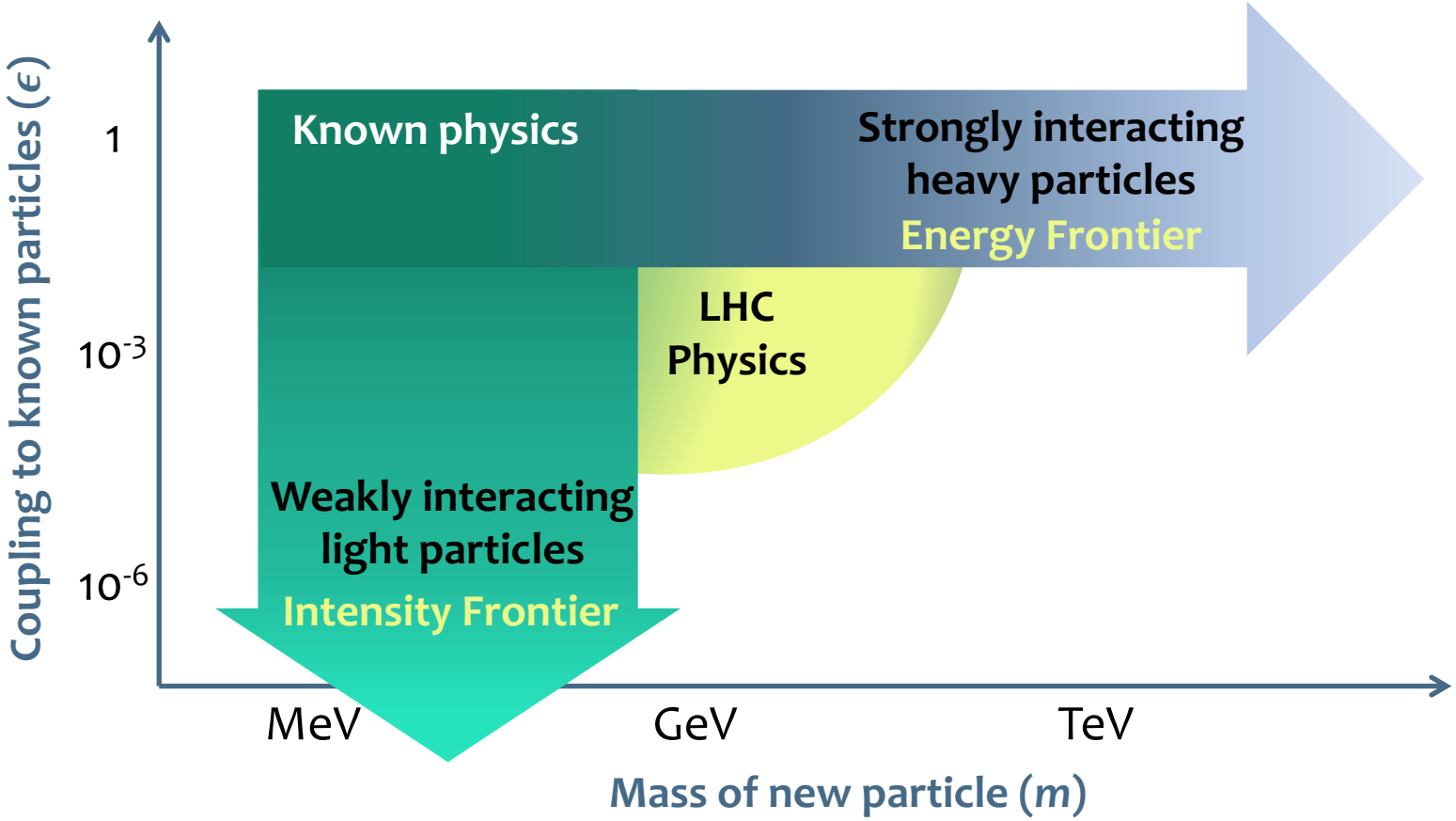




The landscape of new particles @ colliders

- Collider physics: a plethora of measurements and searches
- Burning questions still remain!





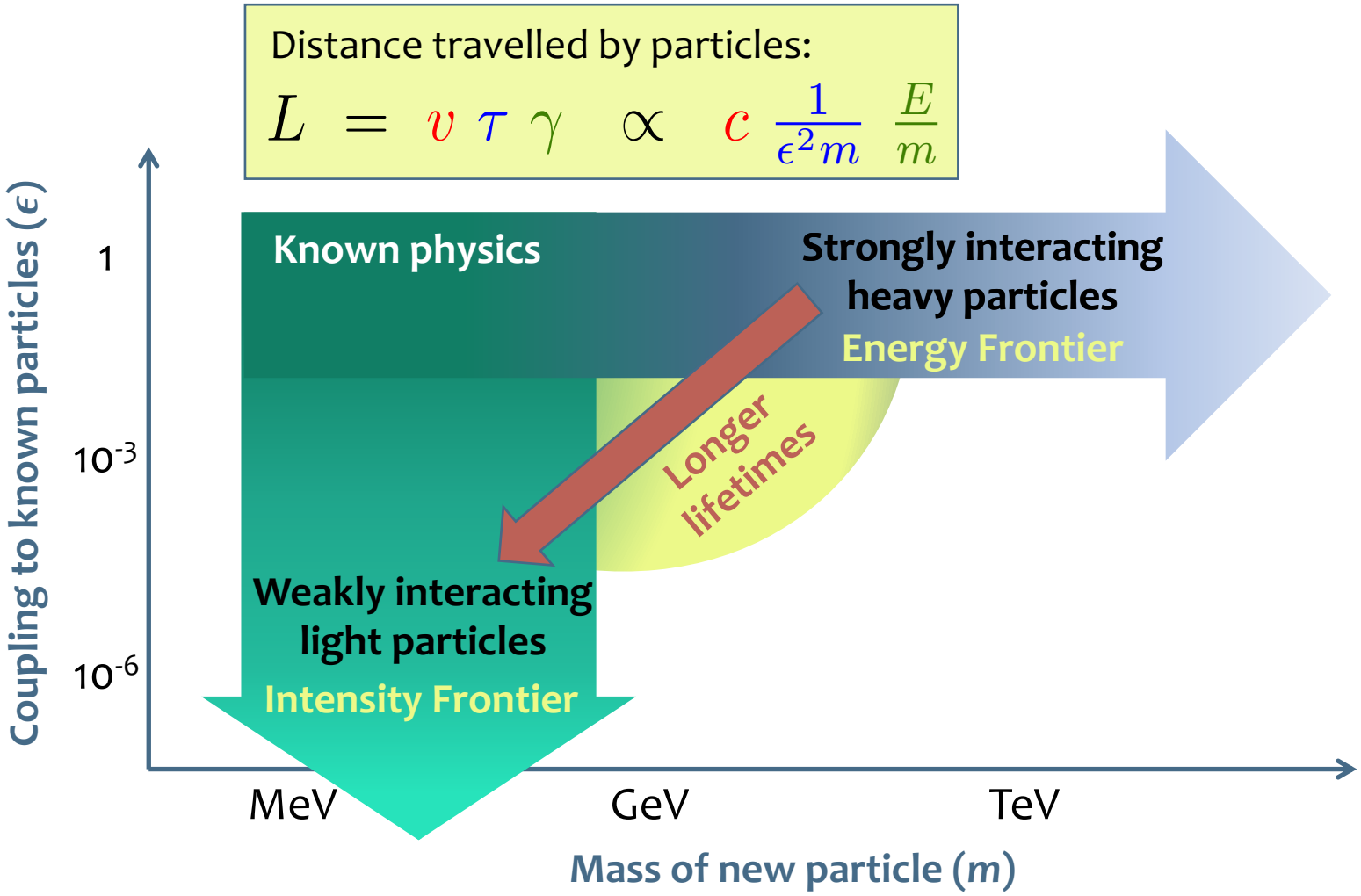
The landscape of new particles @ colliders

Lifetime

a characteristic of weakly interacting light particles

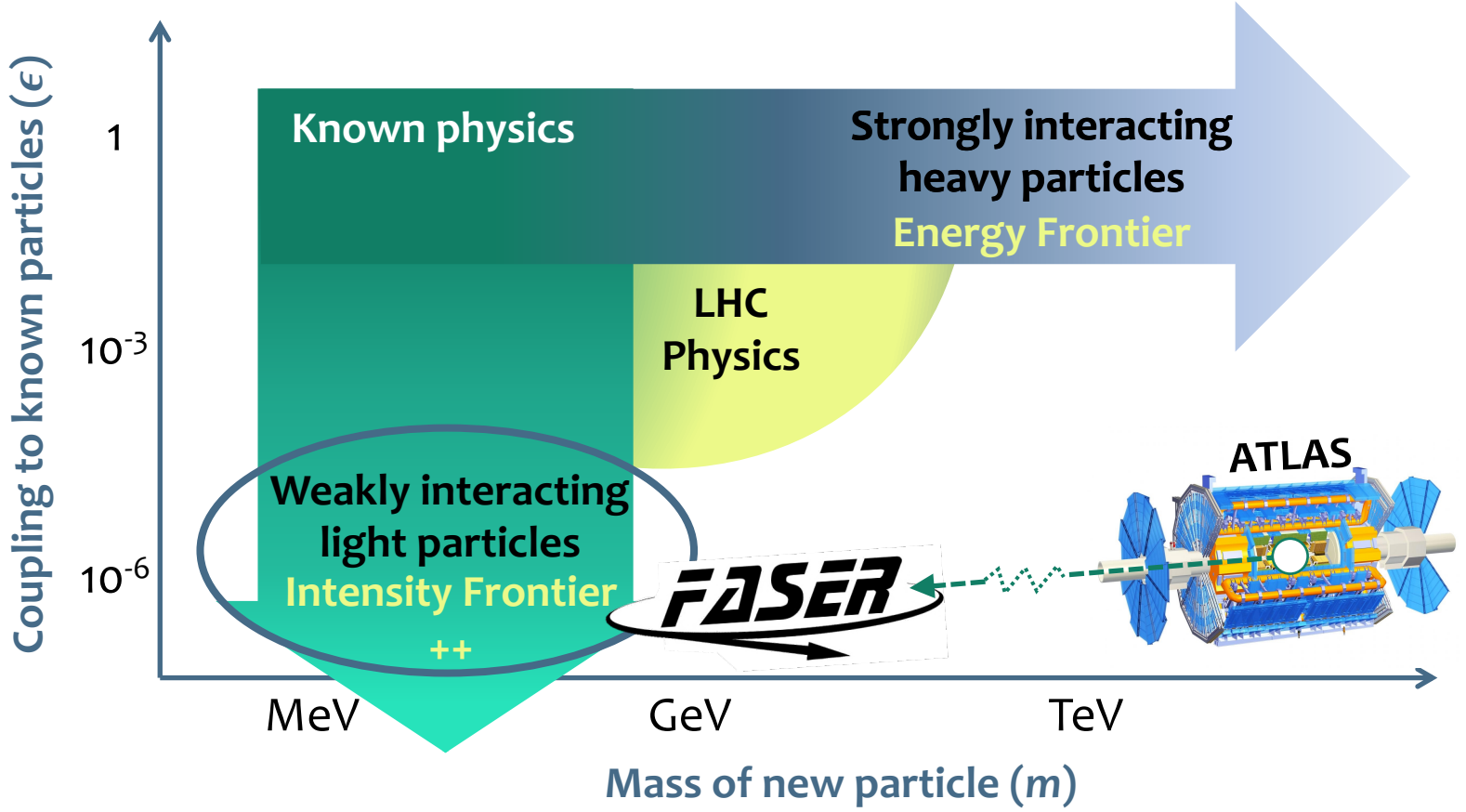
Distinct signatures

Opportunity for exploration!

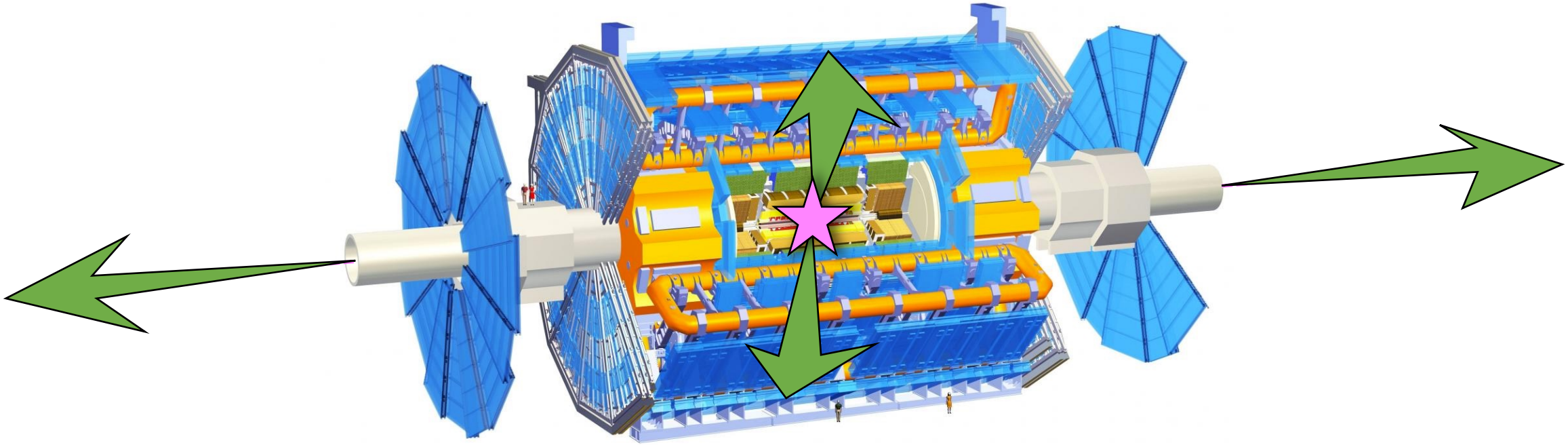


Feng, Galon, Kling, Trojanowski - Phys. Rev. D 97, 035001 (2018)

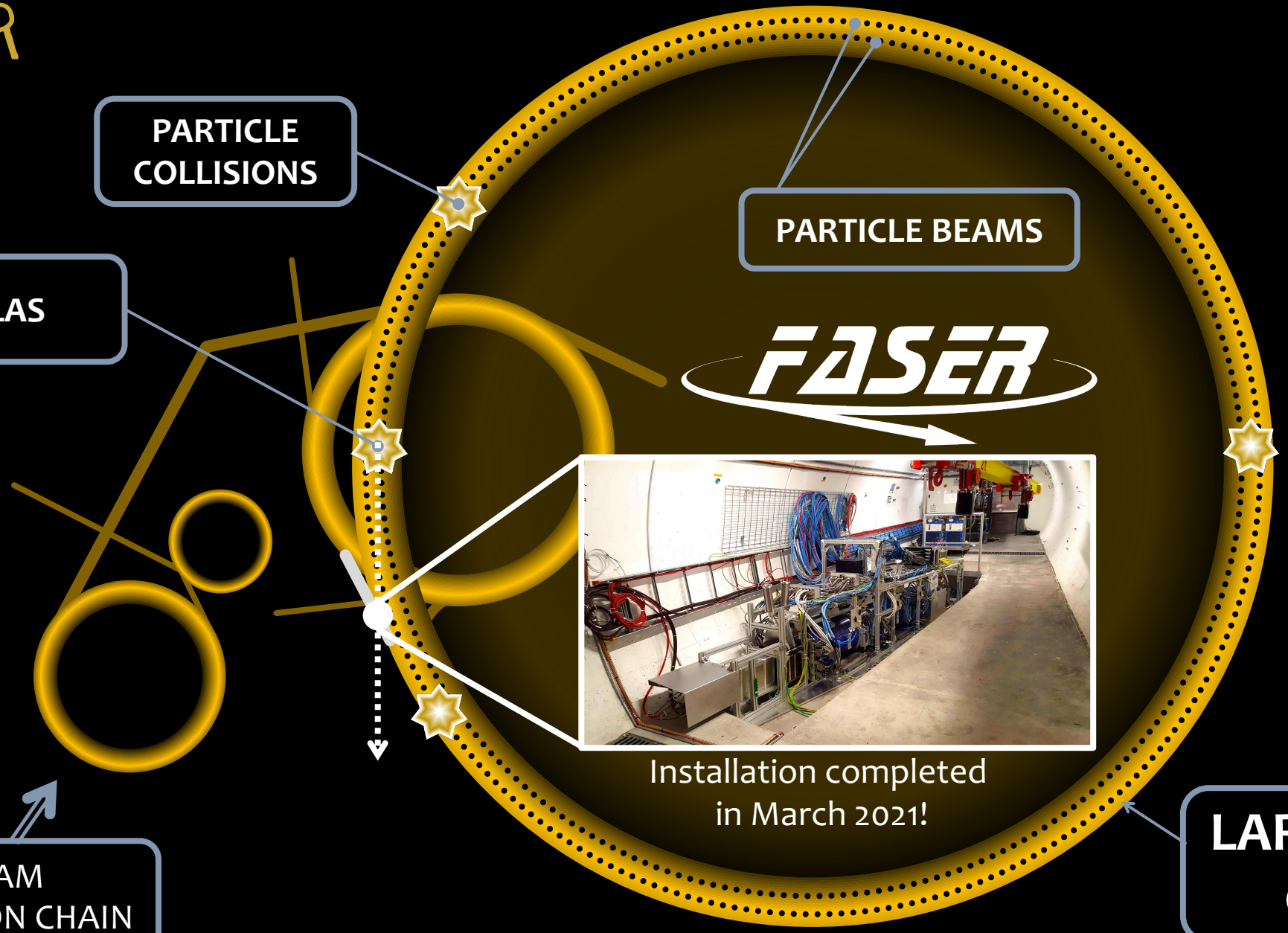
ForwArd Search ExpeRiment at the LHC

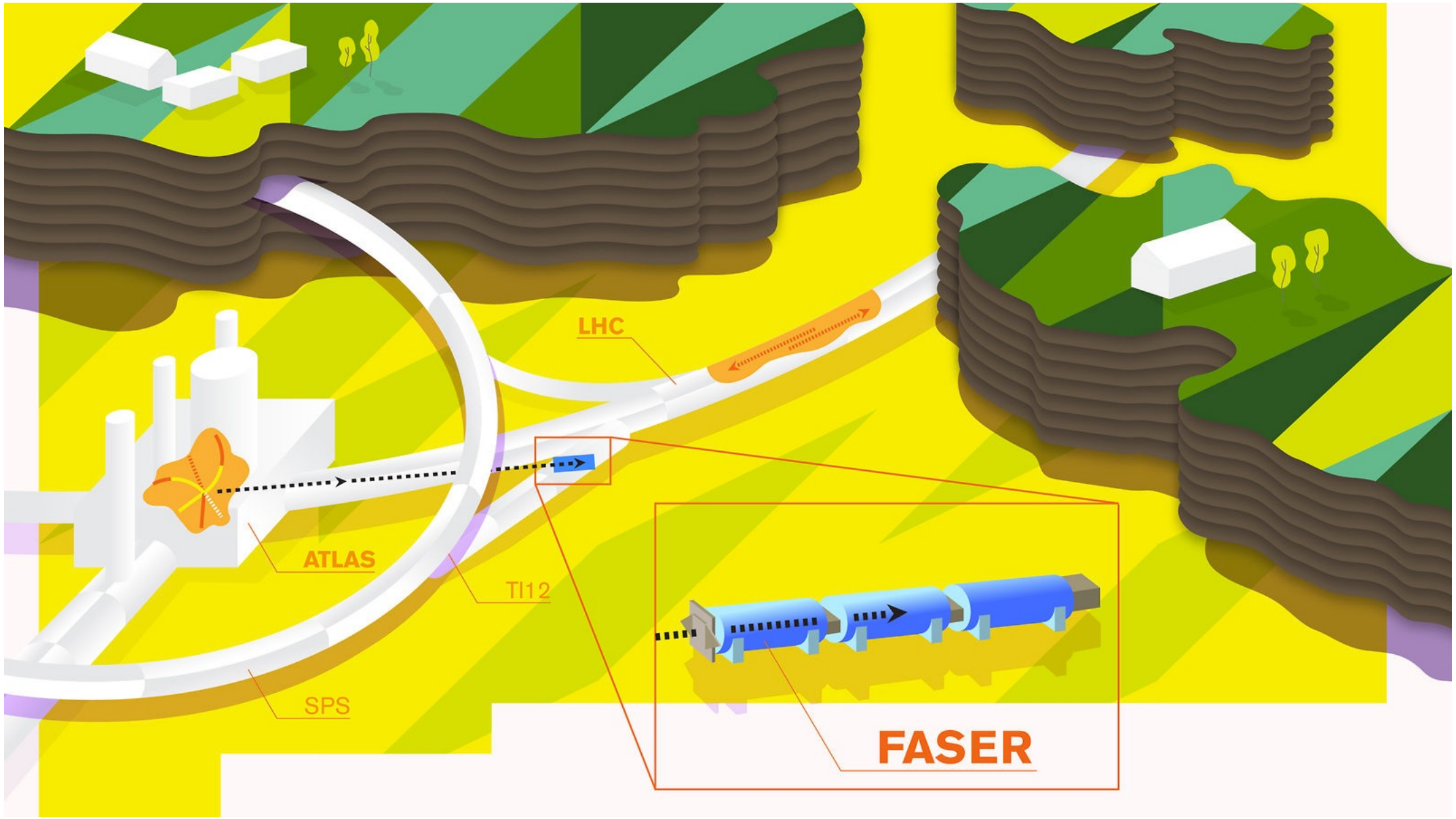


Feng, Galon, Kling, Trojanowski - Phys. Rev. D 97, 035001 (2018)



FASER

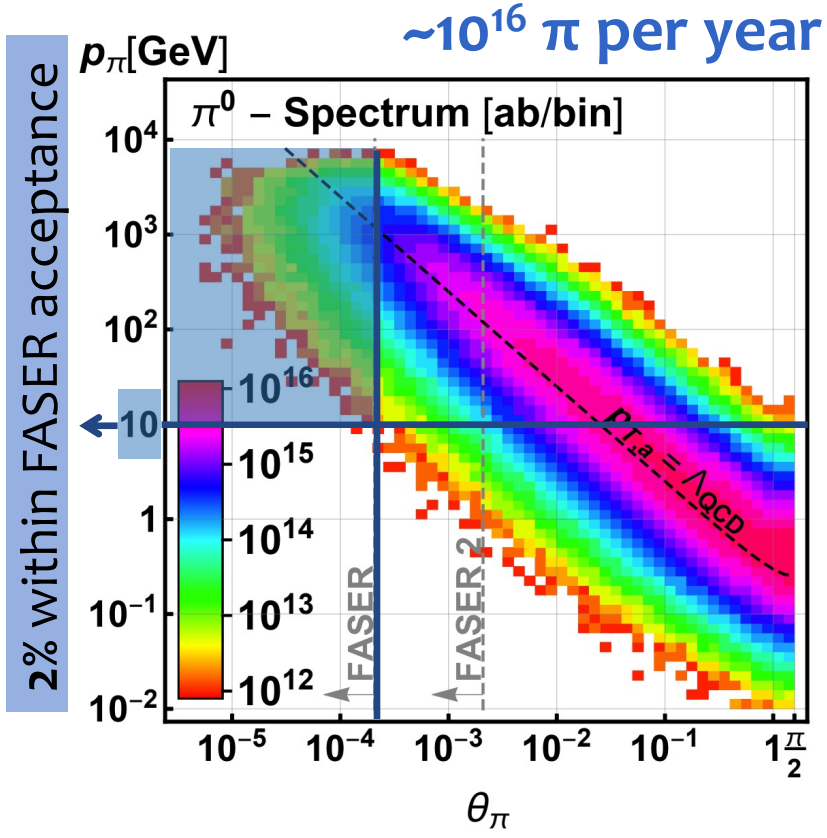

PARTICLE COLLISIONS
PARTICLE BEAMS
ATLAS
FASER
Installation completed in March 2021!
BEAM INJECTION CHAIN
LARGE HADRON COLLIDER



https://www.symmetrymagazine.org/article/a-tiny-new-experiment-at-the-lhc

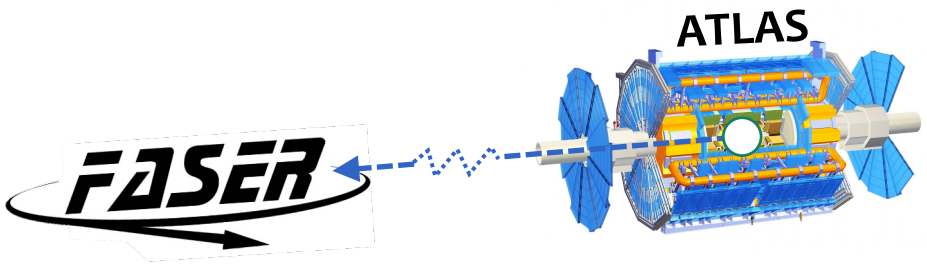
ForwArd Search ExpeRiment at the LHC

Searches for new weakly interacting light particles, coupling to SM via mixing with SM "portal" operator



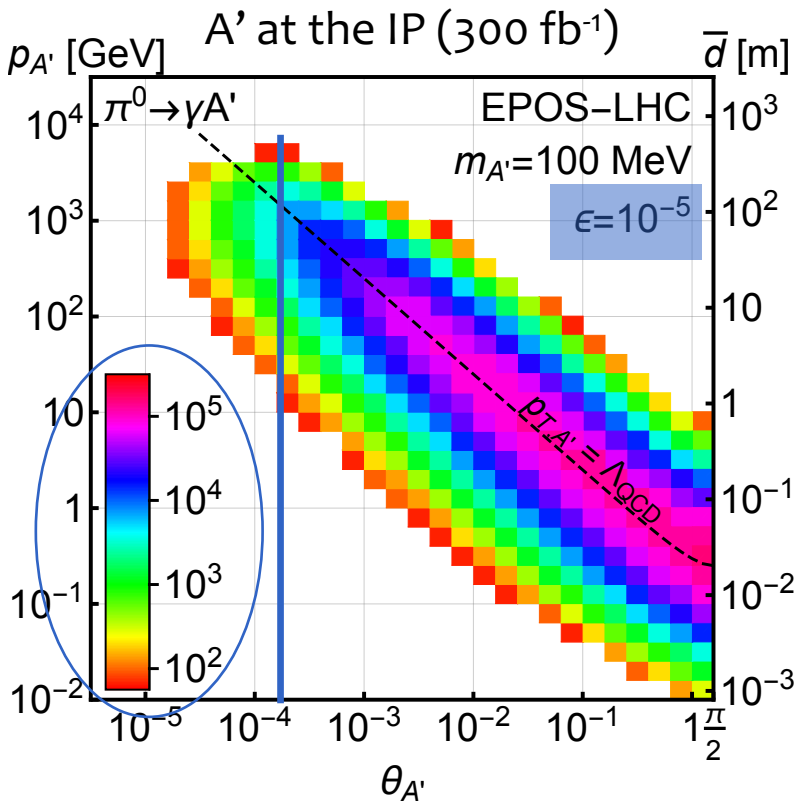
- Produced in decays of light mesons (e.g. π, K), abundantly present in p-p collisions, primarily in large pseudorapidity
- FASER acceptance:

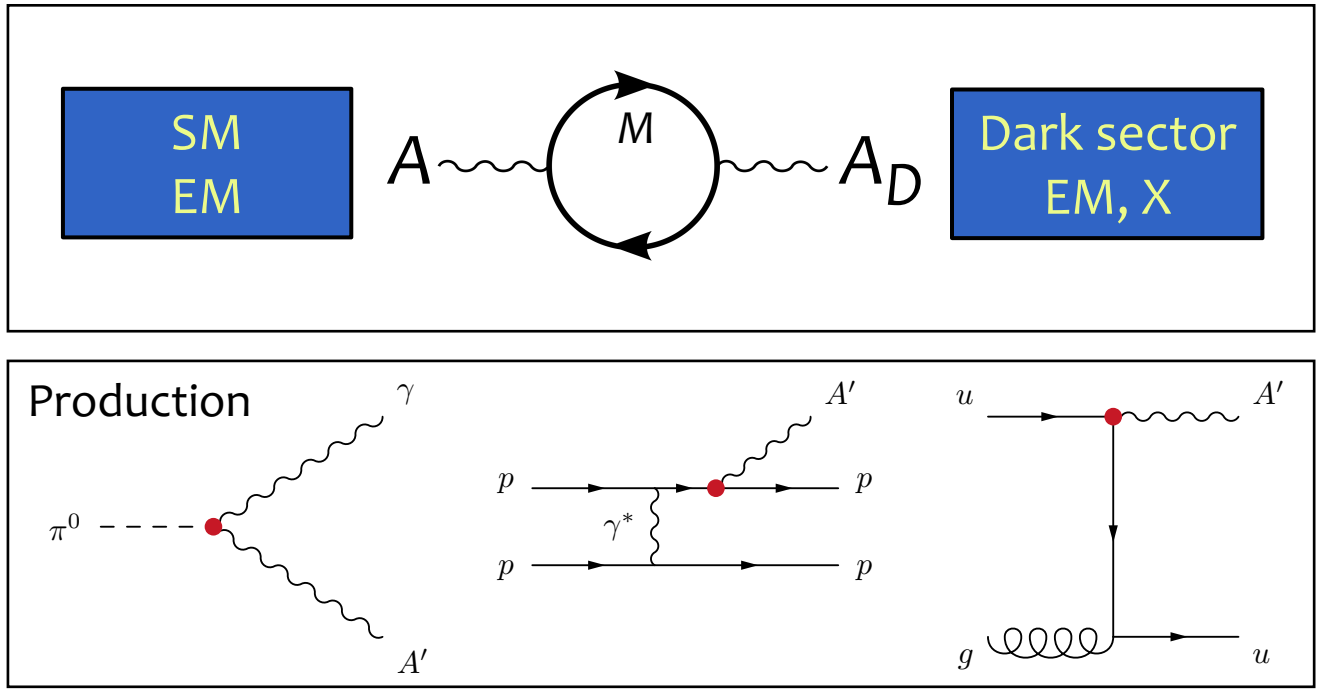
  20 cm diameter, 480 m from ATLAS IP (ONLY **10^{-6}% solid angle**)



An example physics case: Dark Photon A'

- New **massive** gauge boson in a dark sector with dark matter candidate X
- Spin 1, couples weakly to SM fermions (εQ_f coupling, small ε) through mixing with the photon
  - Will be searched for via its **decay to an electron-positron pair**
- For $m_{A'}$=100 MeV, $\varepsilon \sim 10^{-5}$ and E~TeV, can travel long distance before decay

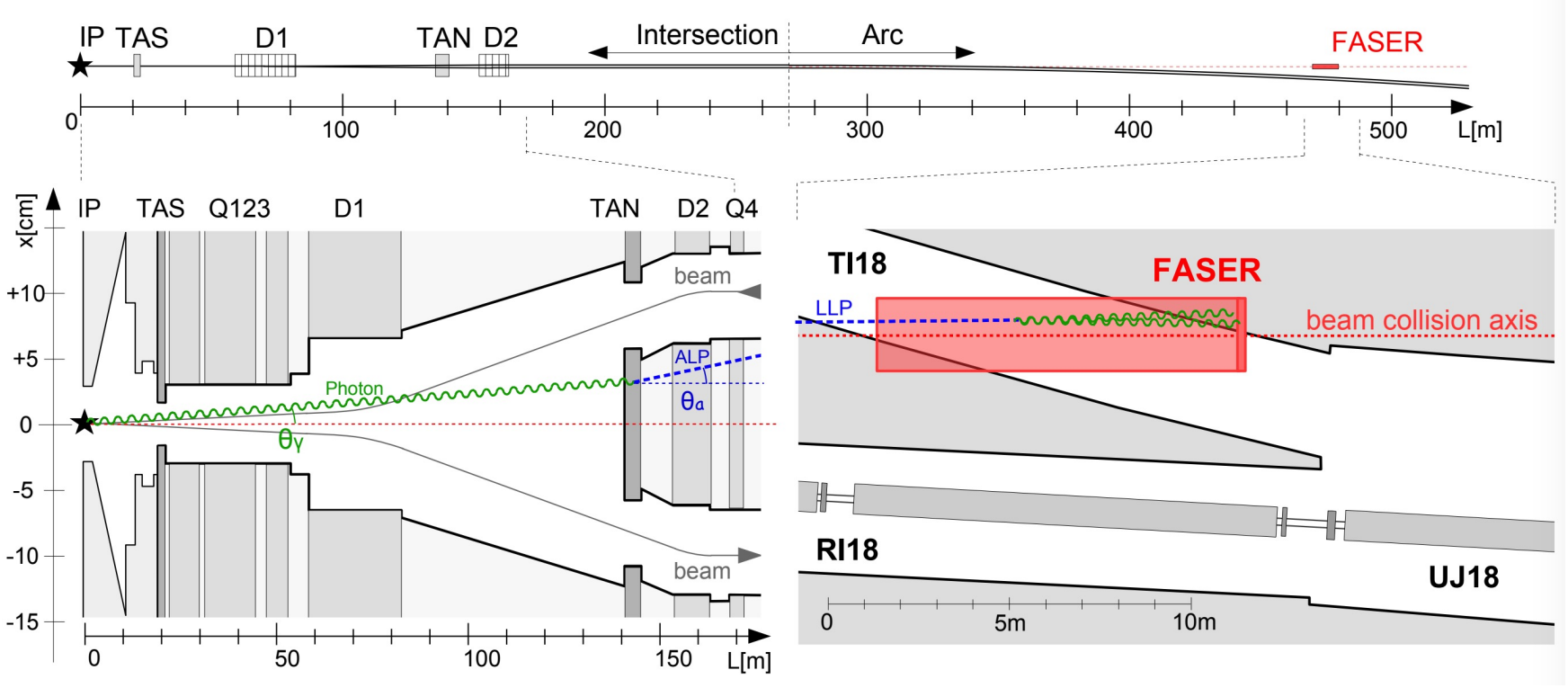


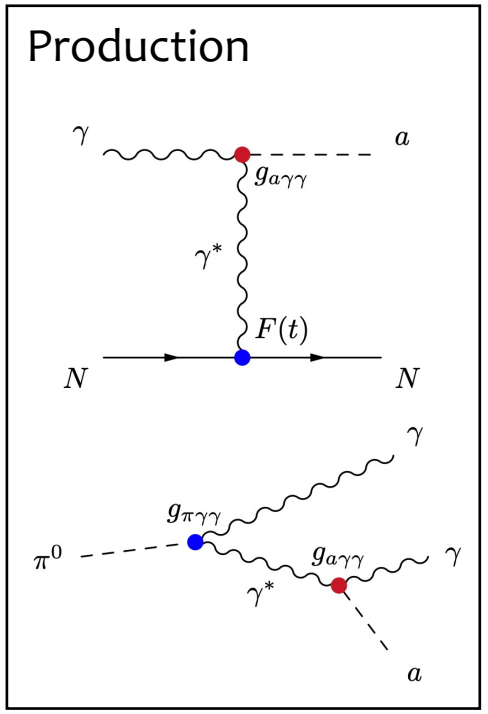


Another example: Axion-like particles (ALPs)

Qualitatively different: "High-energy photon beam dump experiment"

- Pseudoscalar SM-singlets; can appear in theories with broken global symmetries
- Photons from IP travel 140 m, collide with neutral particle absorber (TAN) and create ALPs
- Low mass particles with suppressed couplings to SM, predominantly **decaying to photons**



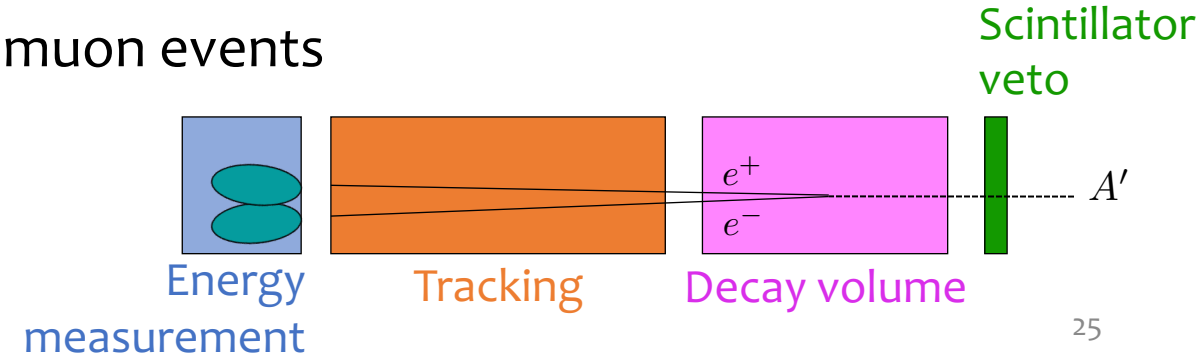


Feng, Galon, Kling, Trojanowski – Phys. Rev. D 98, 055021 (2018)

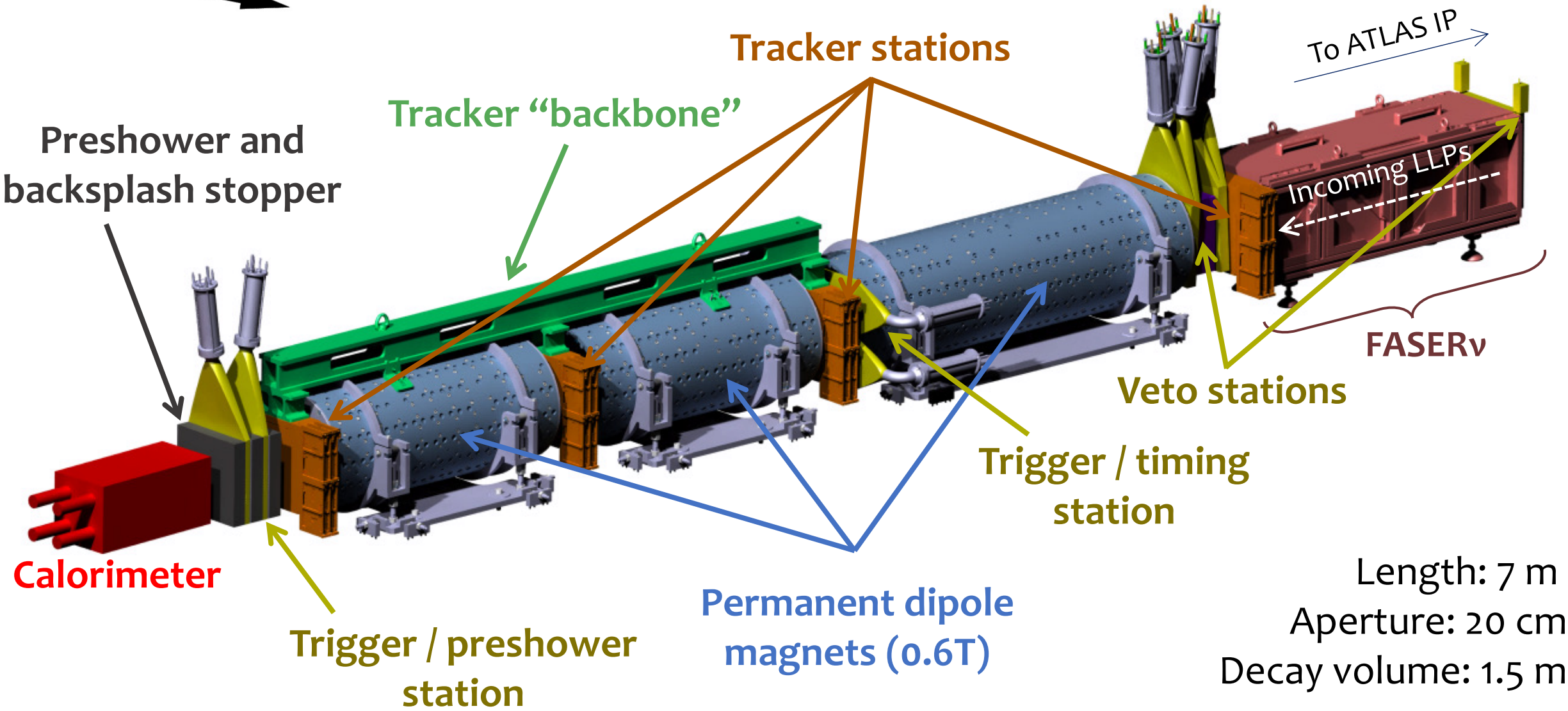
The FASER experiment

Detector concept

- **Drivers for choices:** Tight timeline between experiment approval and installation & the limited budget.
  - Detector that can be constructed and installed ***quickly & cheaply***
  - Have tried to re-use existing detector components where possible
  - Aimed for a simple, robust detector (access difficult)
  - Tried to minimize the services to simplify the installation and operations
- **Many challenges of the large LHC experiments not there for FASER:**
  - trigger rate O(500Hz) – mostly single muon events
  - low radiation
  - low occupancy / event size

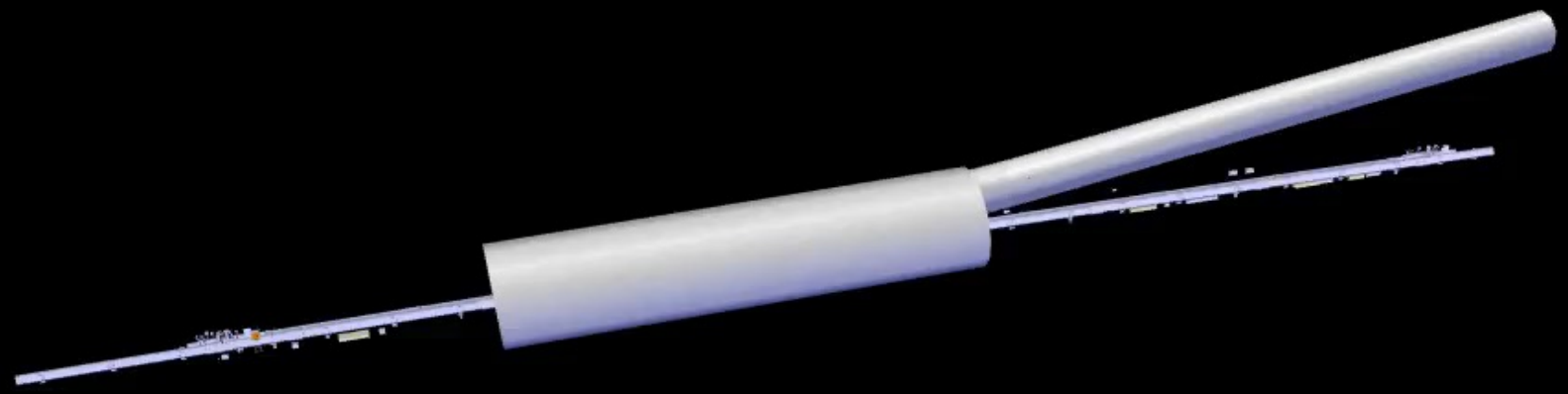


FASER Detector



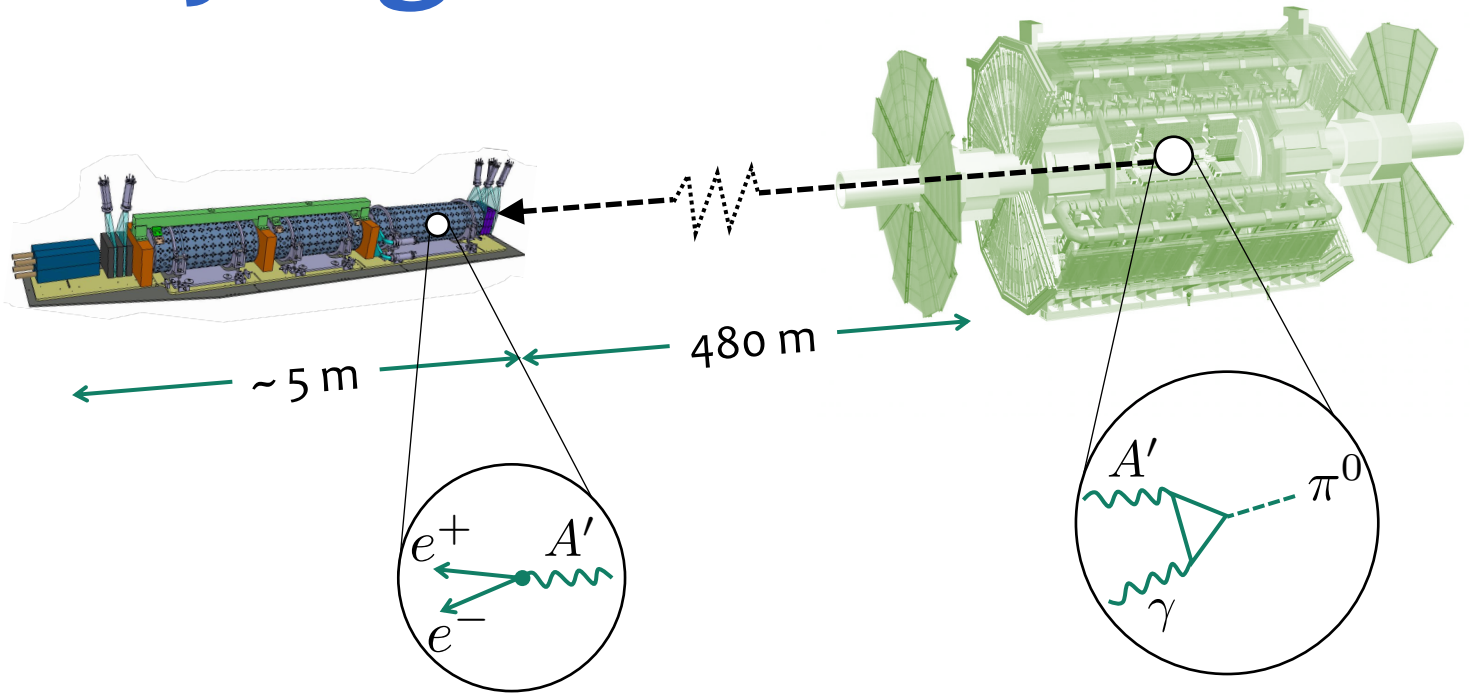
Length: 7 m
Aperture: 20 cm
Decay volume: 1.5 m

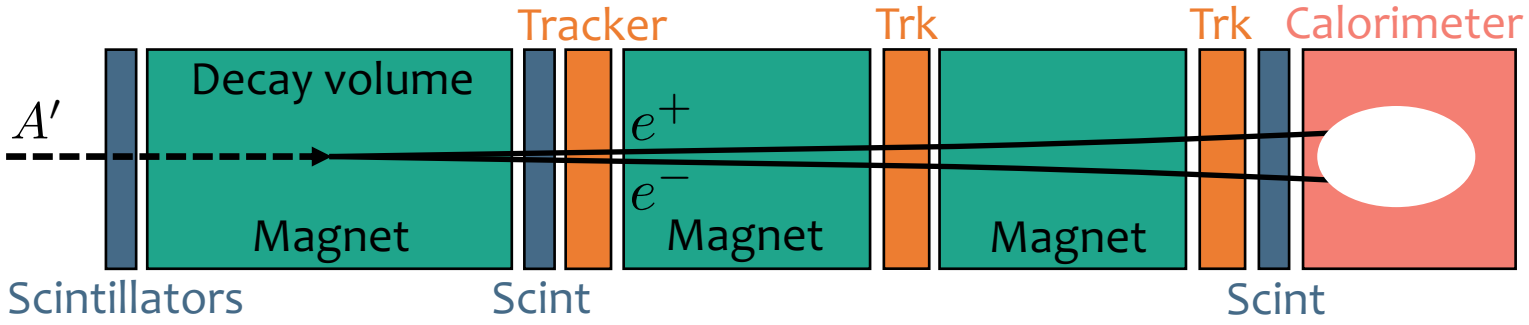
Dougherty, CERN Integration (2019)



Key signatures

Dark photon (A')



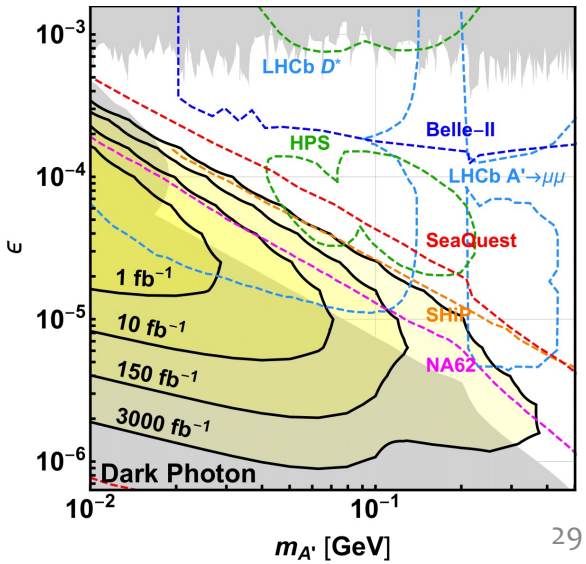


Ballpark numbers for *A'*:

- Momentum of 1 TeV
- Mass of 100 MeV

Decay products collimated

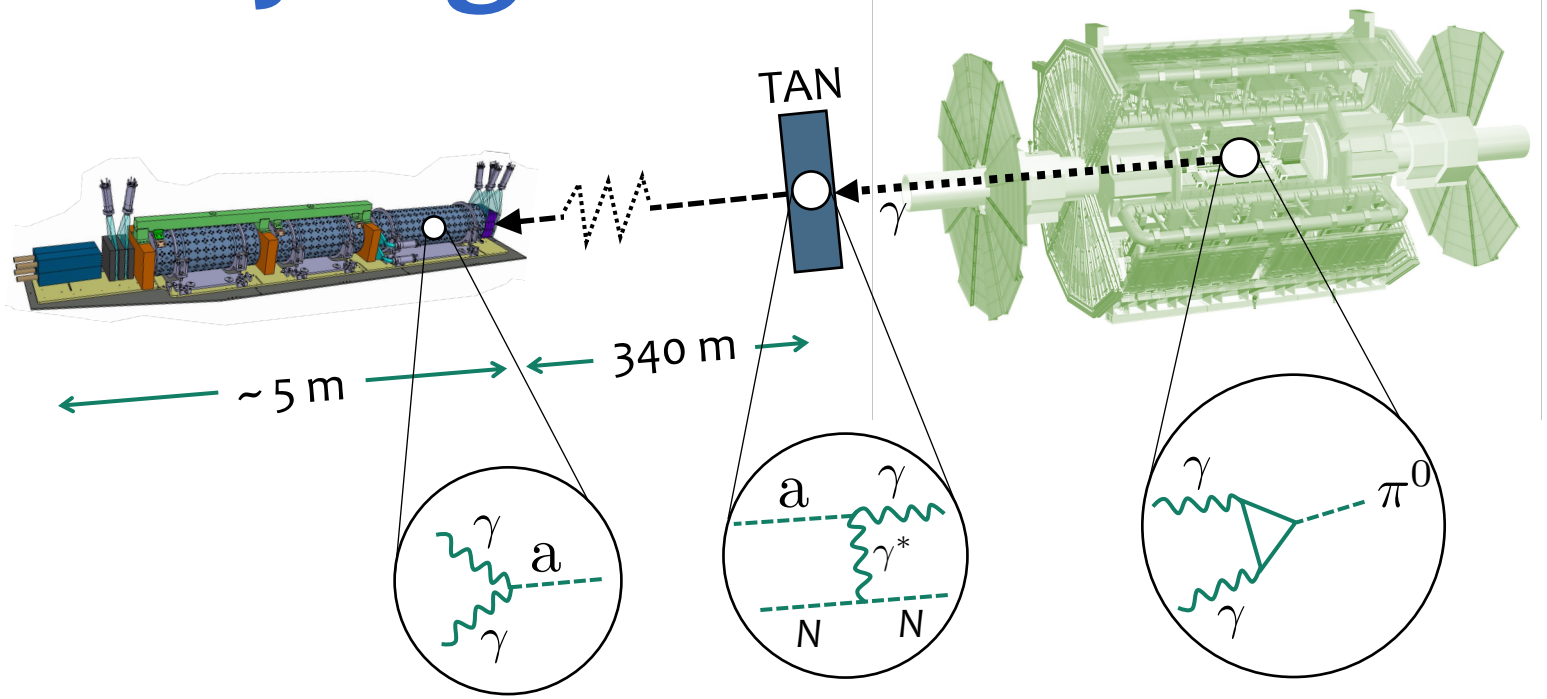
requirements for magnetic field & high resolution tracker

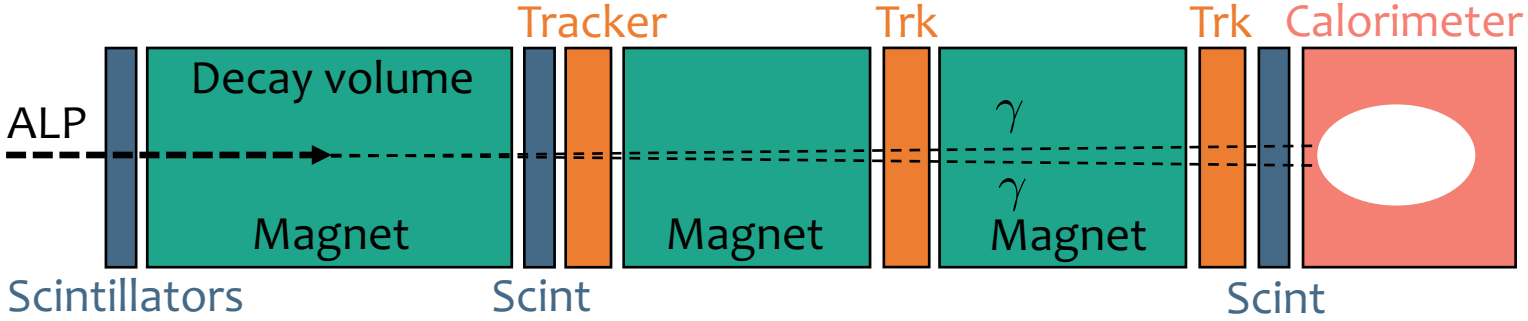


Assuming 3 signal events and no backgrounds

Key signatures

Axion-like particle (ALP, a)



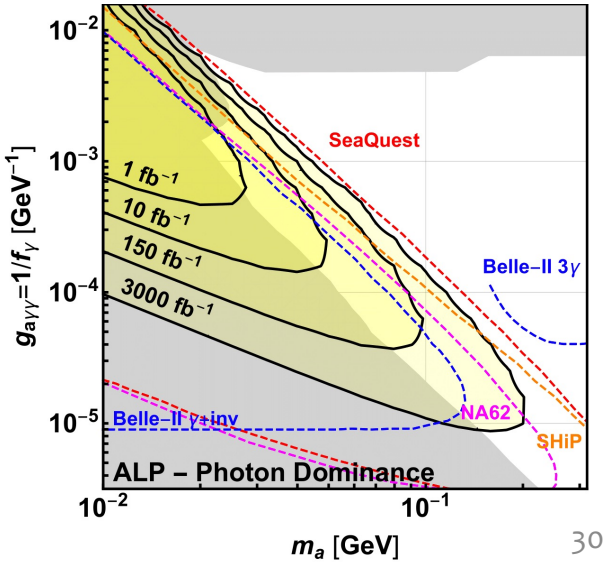


Ballpark numbers for ALPs:

- Momentum of 1 TeV
- Mass of 100 MeV

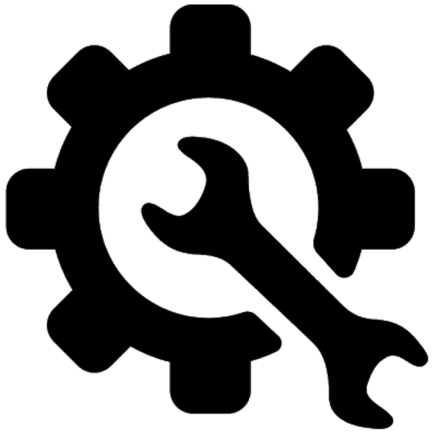
Decay products collimated

2-γ signature can't be resolved with present detector: **upgrade**

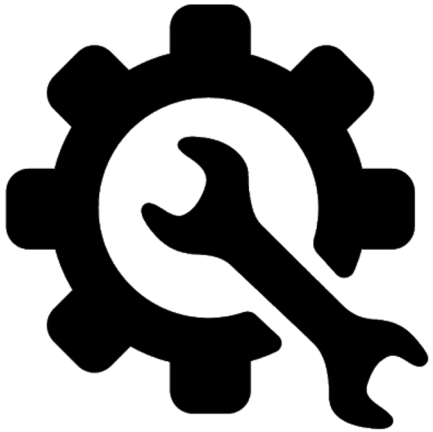


Assuming 3 signal events and no backgrounds

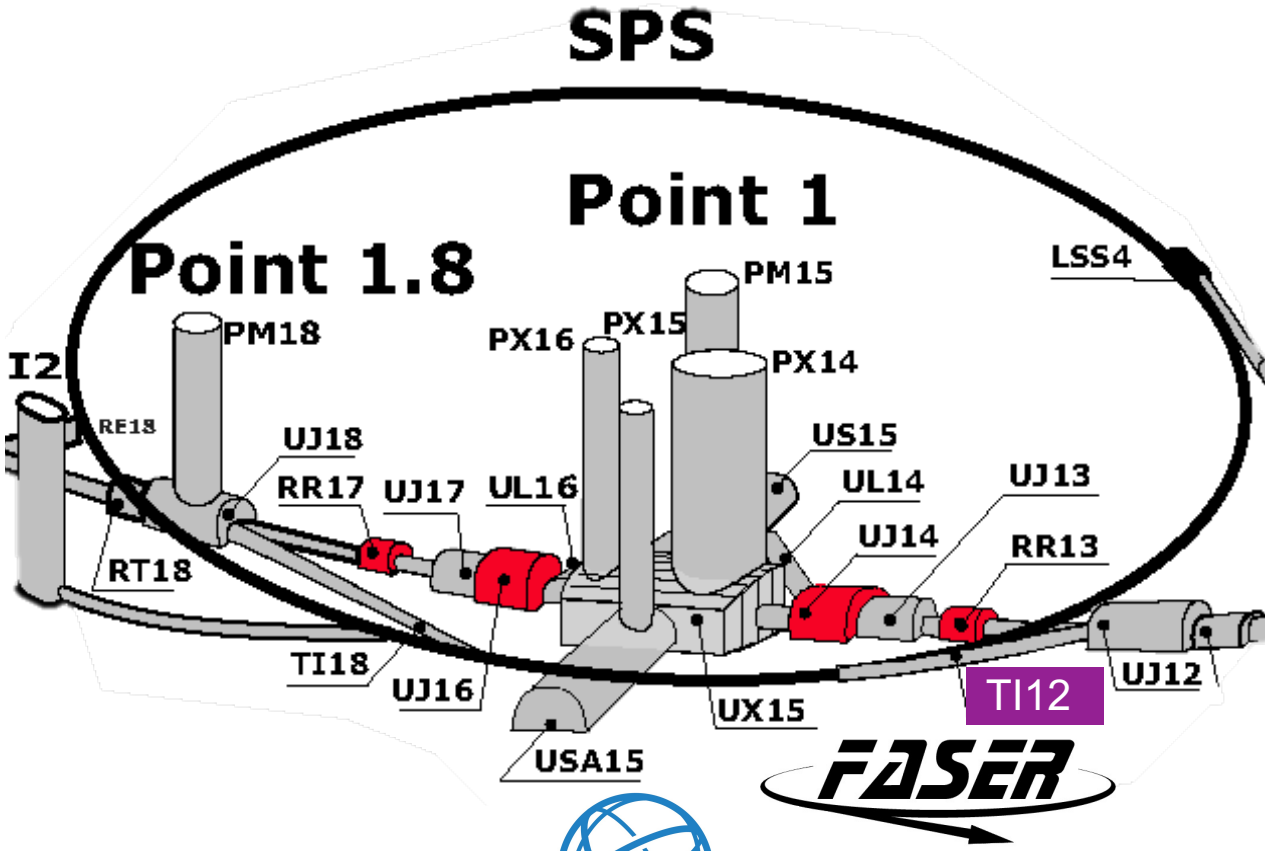
FASER detector construction and commissioning

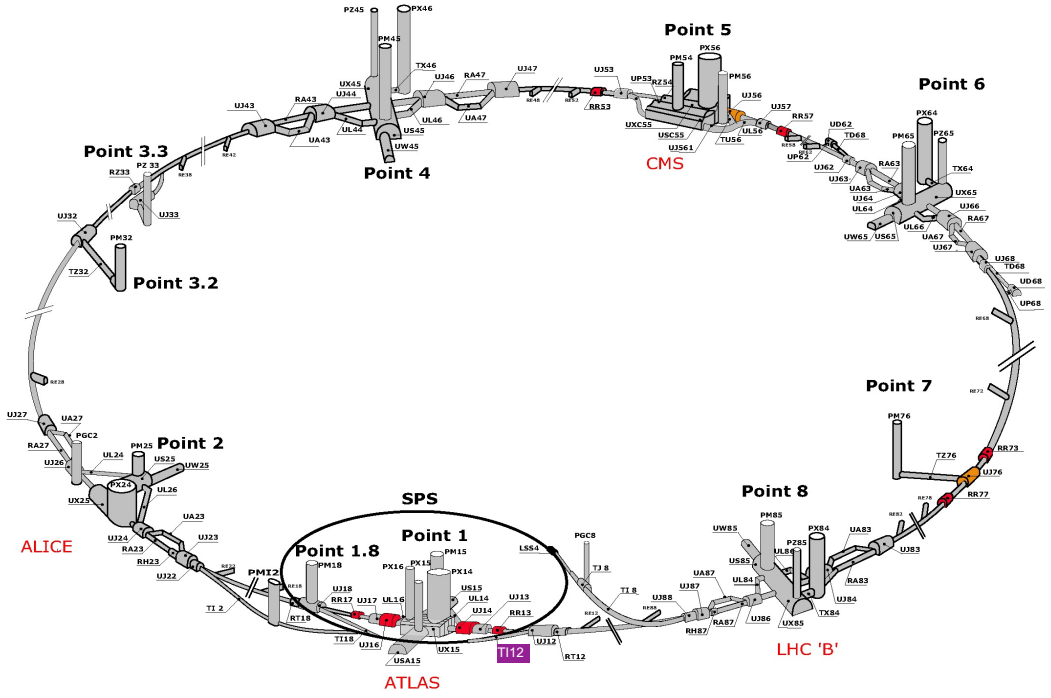


FASER detector
construction and commissioning



FASER Location





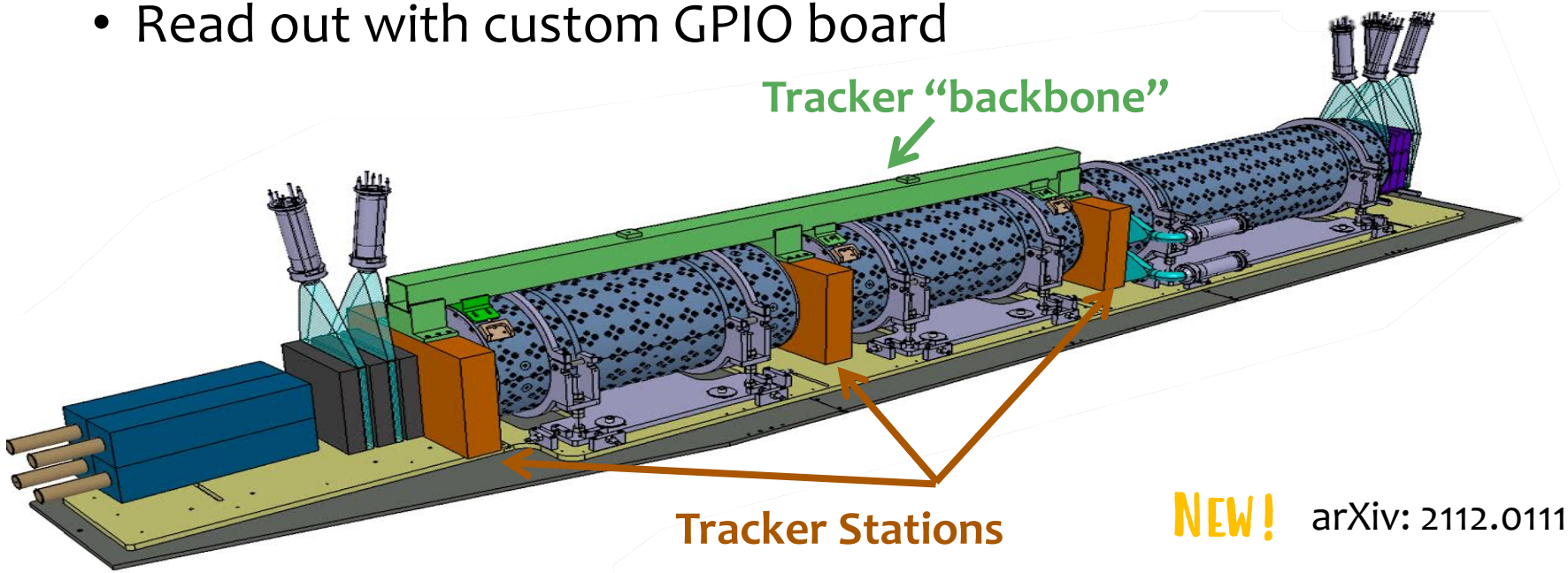
ATLAS EXPERIMENT

FASER Location

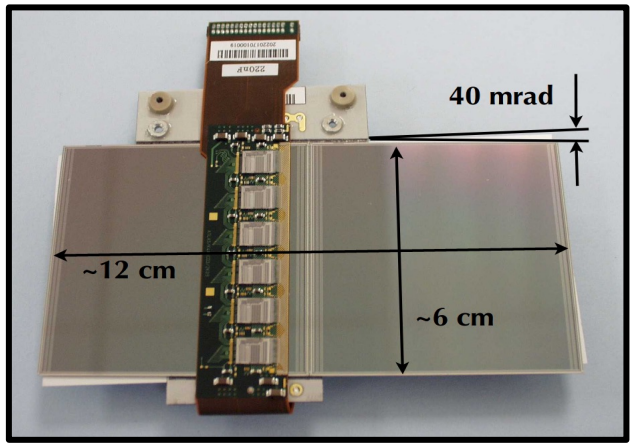
Significant and challenging civil engineering work done by CERN SMB & contractors

FASER Tracker

- FASER uses ATLAS SCT spare modules THANKS!
- 3 tracker stations x 3 tracker layers x 8 modules
  - 72 modules and O(10^5) channels in total
- Mechanical stability by "backbone" fixed on magnets
- Read out with custom GPIO board



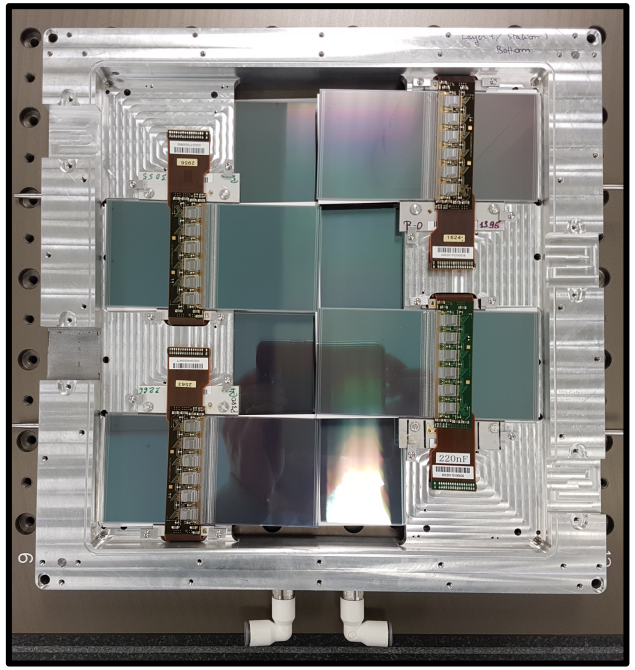
NEW! arXiv: 2112.01116



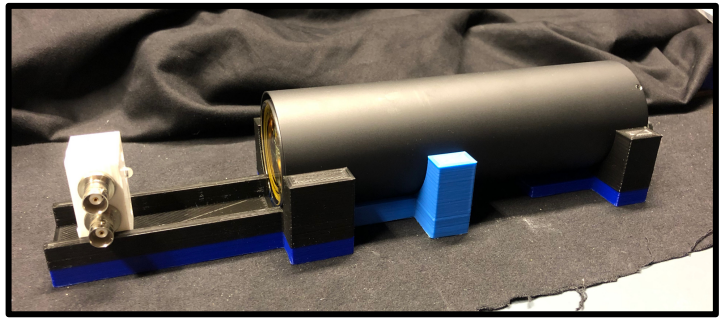
SCT module

80 μm strip pitch / 40 mrad angle
17 μm / 580 μm track resolution

Tracker layer

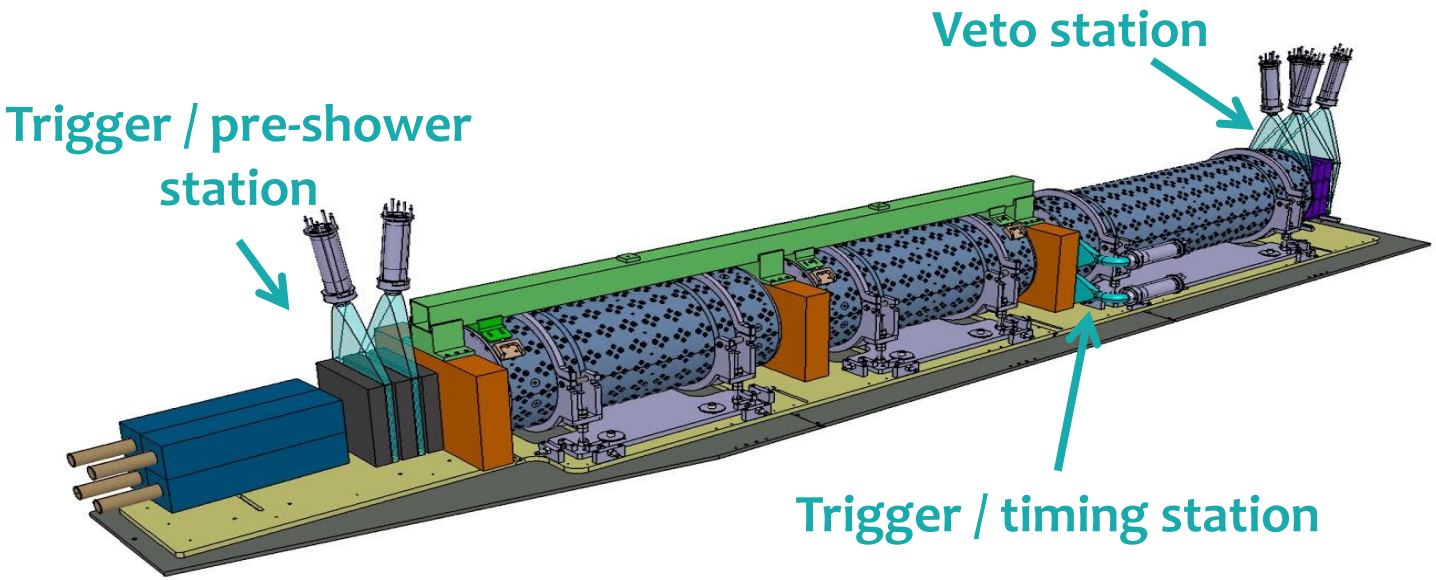


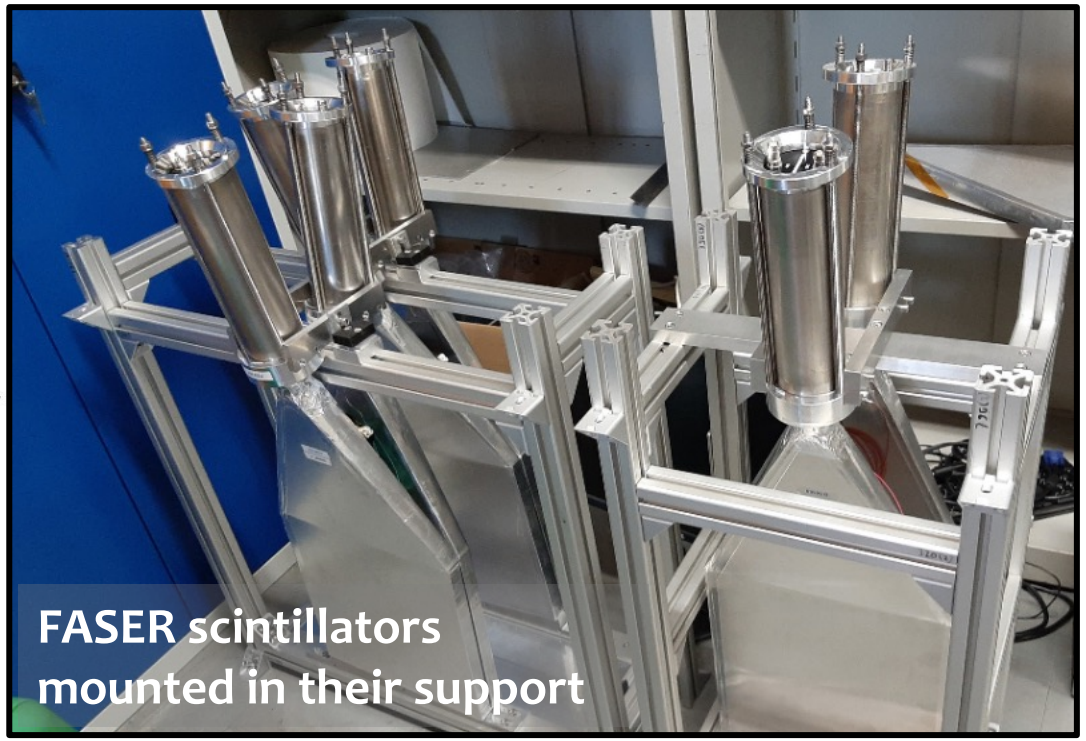
FASER Scintillators



Scintillator PMTs

- Three stations all providing triggering capability:
  - Very high efficiency veto station for incoming charged particles (x4 planes)
  - Timing station; precise timing (~ ns) wrt IP (x1 plane)
  - Pre-shower station; coincidence with timing station (x2 planes)
- Read out with PMTs and CAEN digitizer



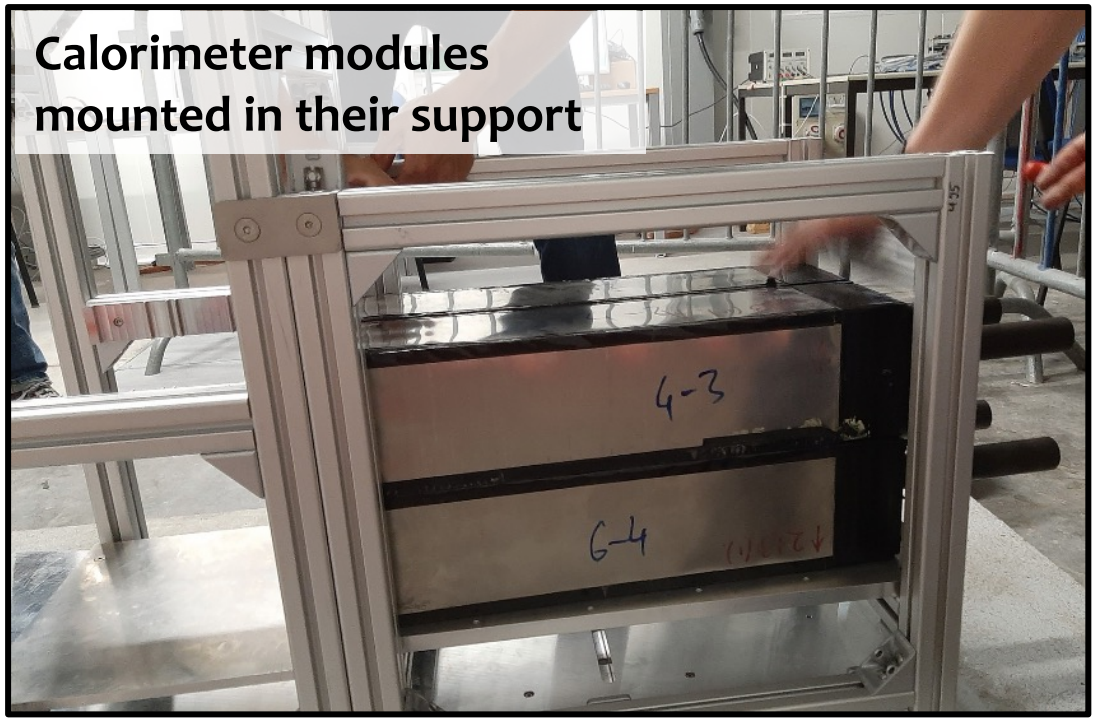


FASER scintillators mounted in their support

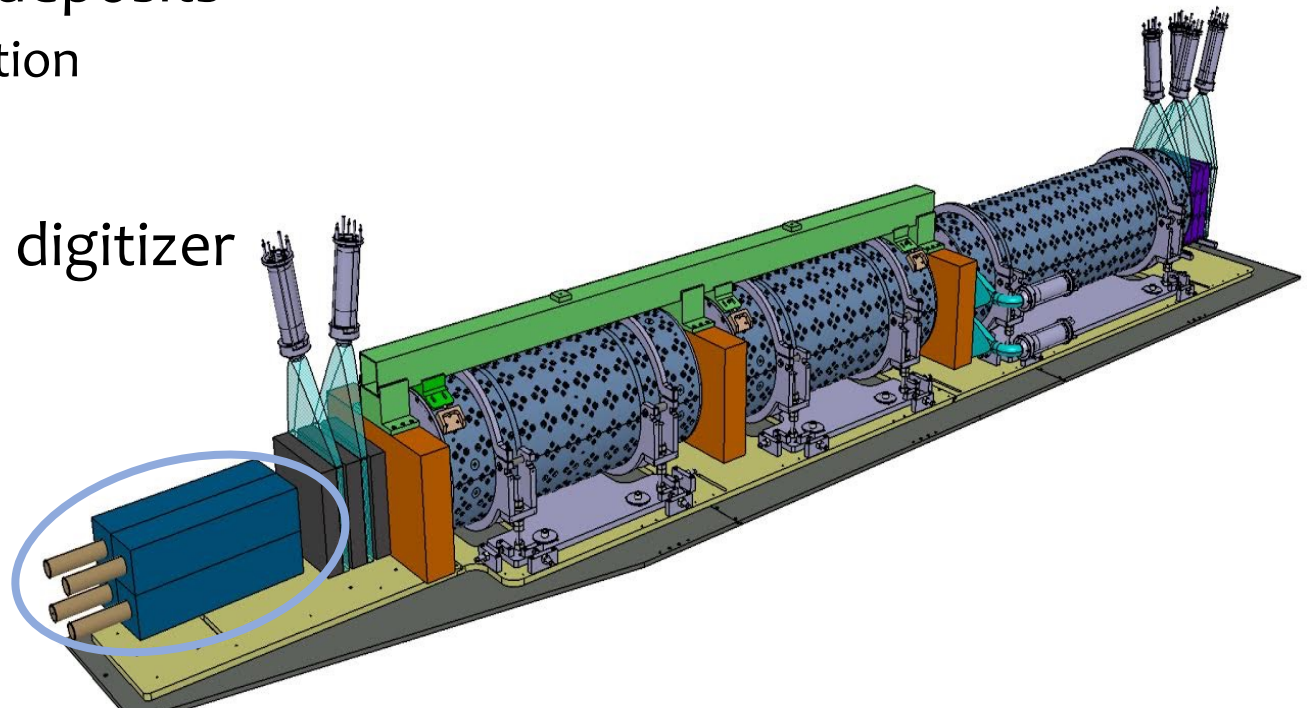
FASER Calorimeter

THANKS!

- FASER uses 4 LHCb spare outer ECAL modules
  - 25 radiation lengths long
  - Lead/scintillator calorimeter
- Energy resolution ~ 1% for TeV deposits
  - No longitudinal shower information
- Provides triggering capability
- Read out with PMTs and CAEN digitizer

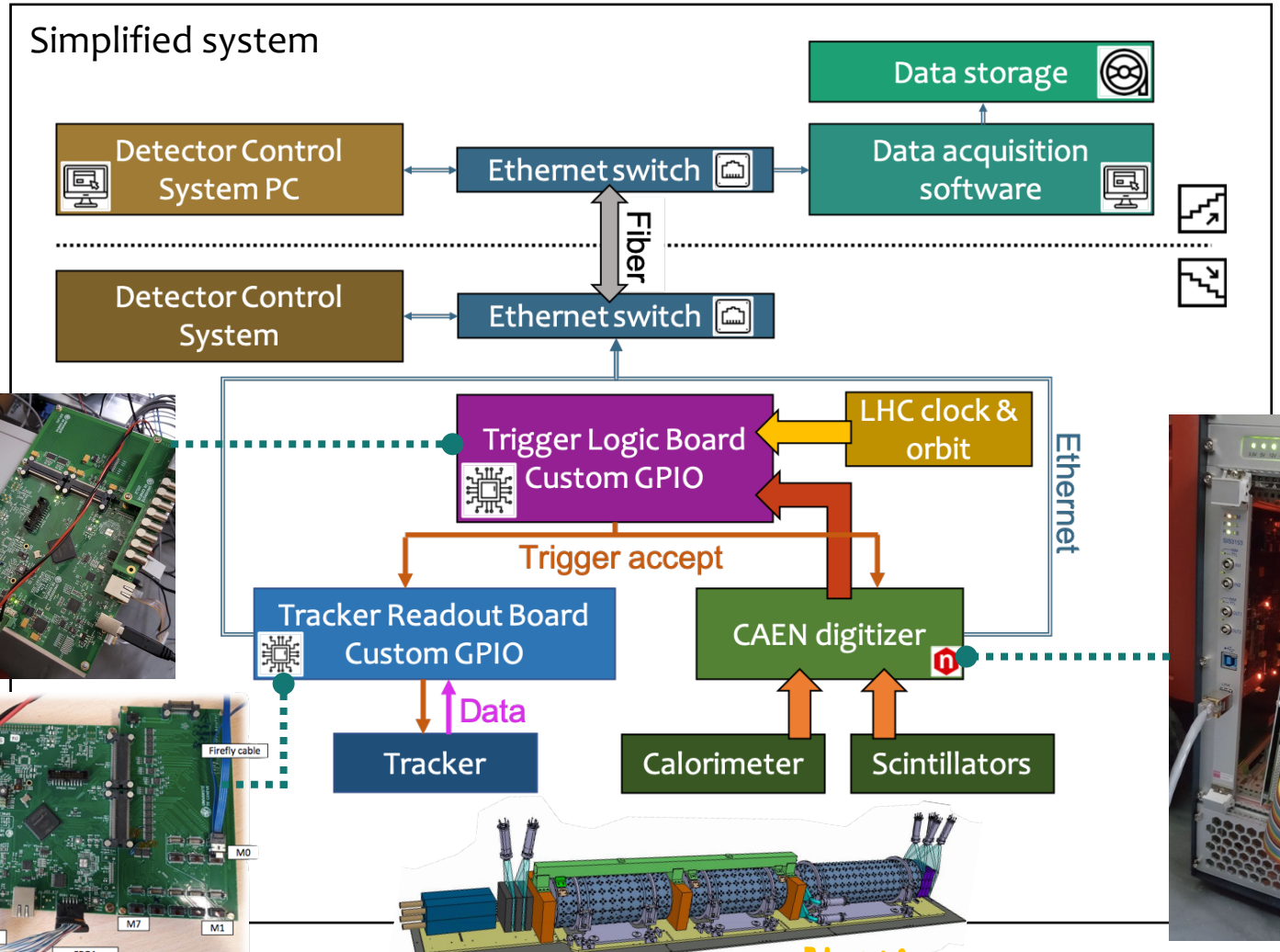


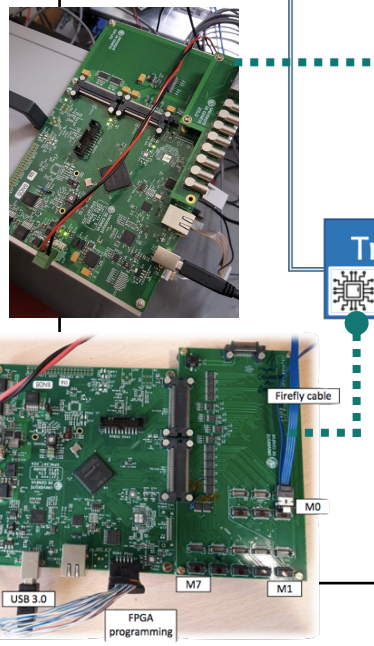
Calorimeter modules mounted in their support



Trigger & Data acquisition

- Expected **trigger rate** about **500 Hz,** dominated by muons from the IP
  - L1A includes random and software triggers
- Expected **bandwidth** about **15 MB / s,** dominated by PMTs' wide signal (~ 1 μs)
- All TDAQ electronics are placed in TI12

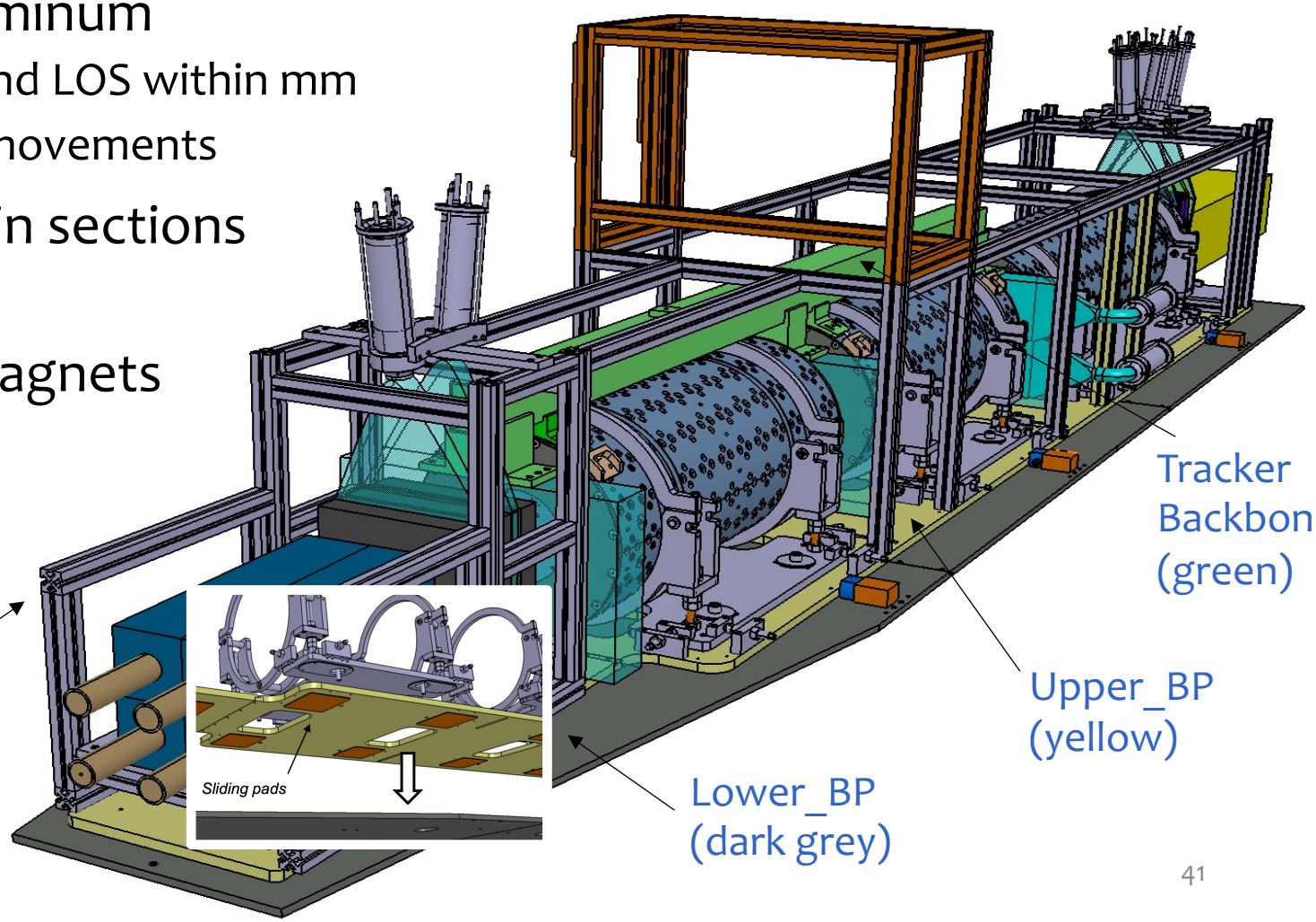




NEW! arXiv: 2110.15186

Detector support structure

- Two base-plates made of aluminum
  - Align magnets to each other and LOS within mm
  - Allow detector to follow LOS movements
- An upper frame, segmented in sections
  - Align detectors within mm
- Tracker backbone fixed on magnets
  - ensures tracker alignment (<100 μm wrt frame)



Upper Frame (Bosch profiles)

FASER experiment construction and **commissioning**

FASER Commissioning

- Dedicated labs available at CERN and the UniGe for individual component testing
- Dedicated area at CERN's Prevessin site ("EHN1") for full-detector commissioning

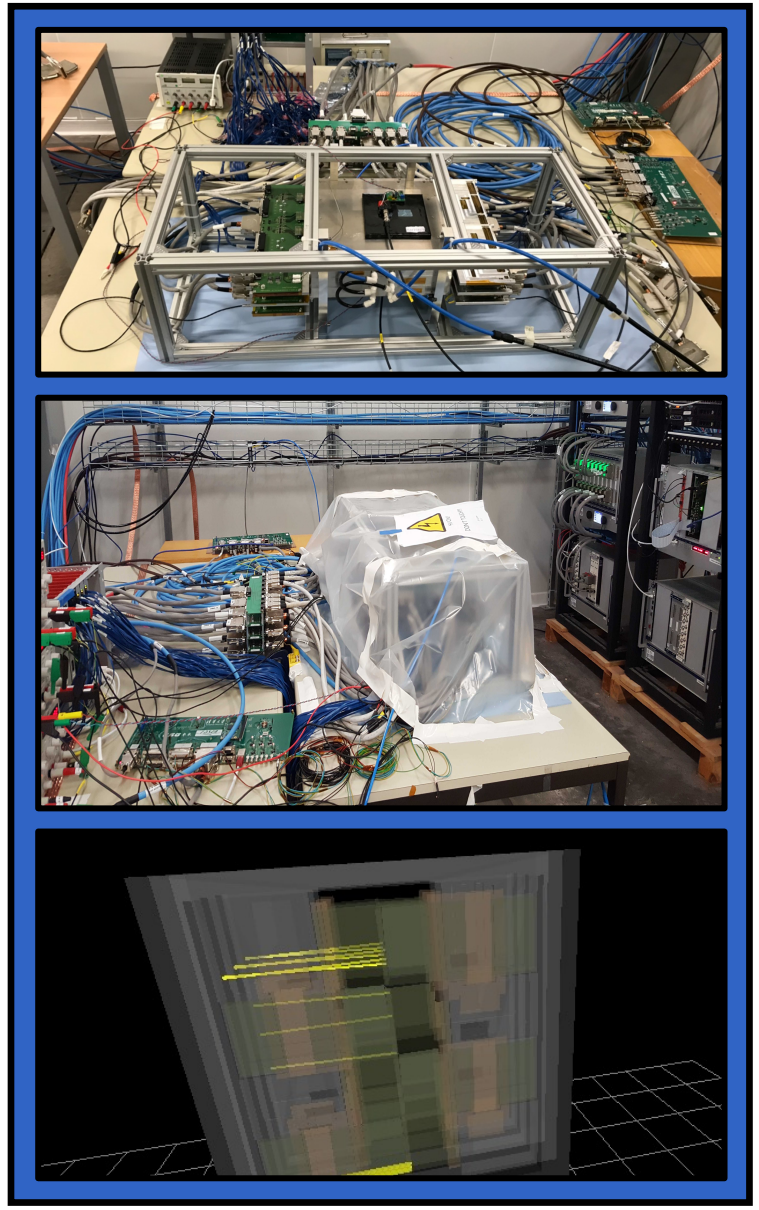
Milestone	Where	When
Individual component commissioning	labs	July 2020
Detector commissioning	EHN1	Sept 2020
Installation of magnets	EHN1	Sept 2020
Surface commissioning – part 1	EHN1	Oct 2020
Detector installation – part 1	TI12	Nov 2020
Surface commissioning – part 2	EHN1	Feb 2021
Detector installation – part 2	TI12	March 2021
In-situ commissioning	TI12	2021/2022

FASER Commissioning

- Dedicated labs available at CERN and the UniGe for individual component testing
- Dedicated area at CERN's Prevessin site ("EHN1") for full-detector commissioning

Milestone	Where	When
Individual component commissioning	labs	July 2020
Detector commissioning	EHN1	Sept 2020
Installation of magnets	EHN1	Sept 2020
Surface commissioning – part 1	EHN1	Oct 2020
Detector installation – part 1	TI12	Nov 2020
Surface commissioning – part 2	EHN1	Feb 2021
Detector installation – part 2	TI12	March 2021
In-situ commissioning	TI12	2021/2022

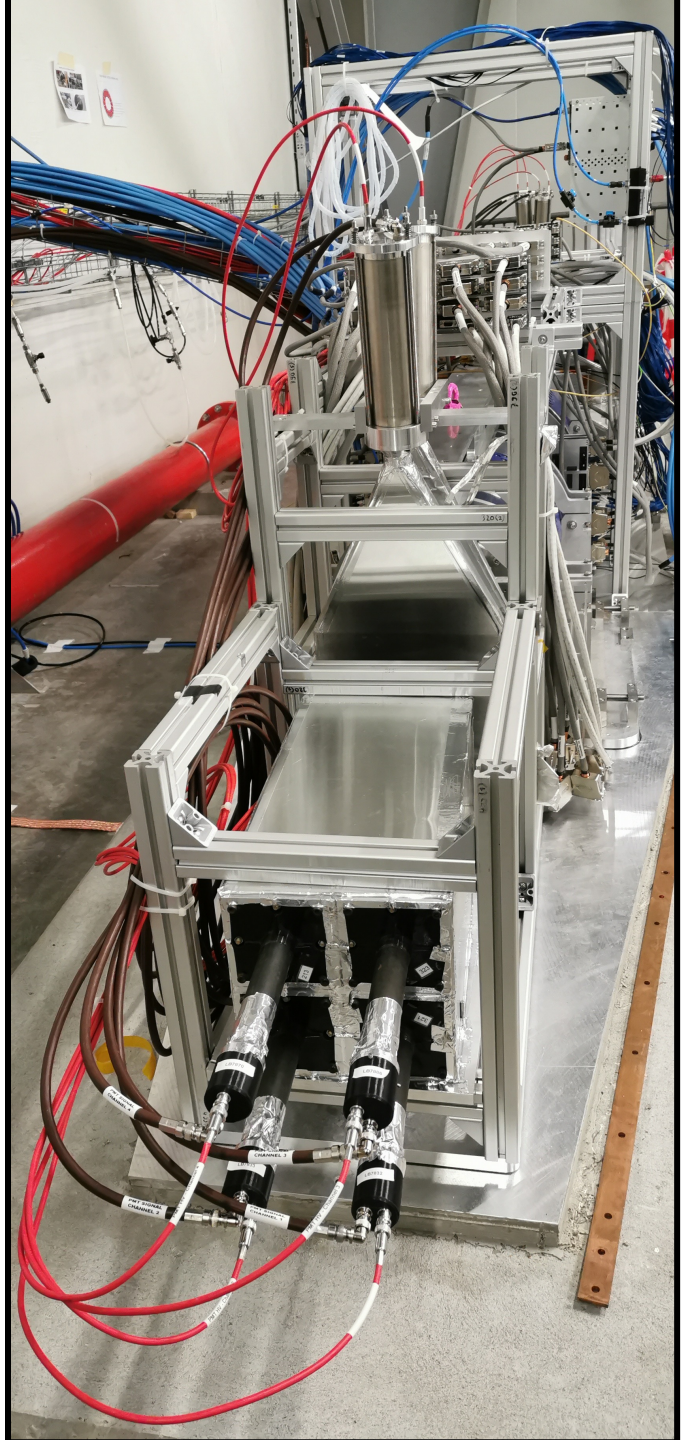
Cosmic data taking

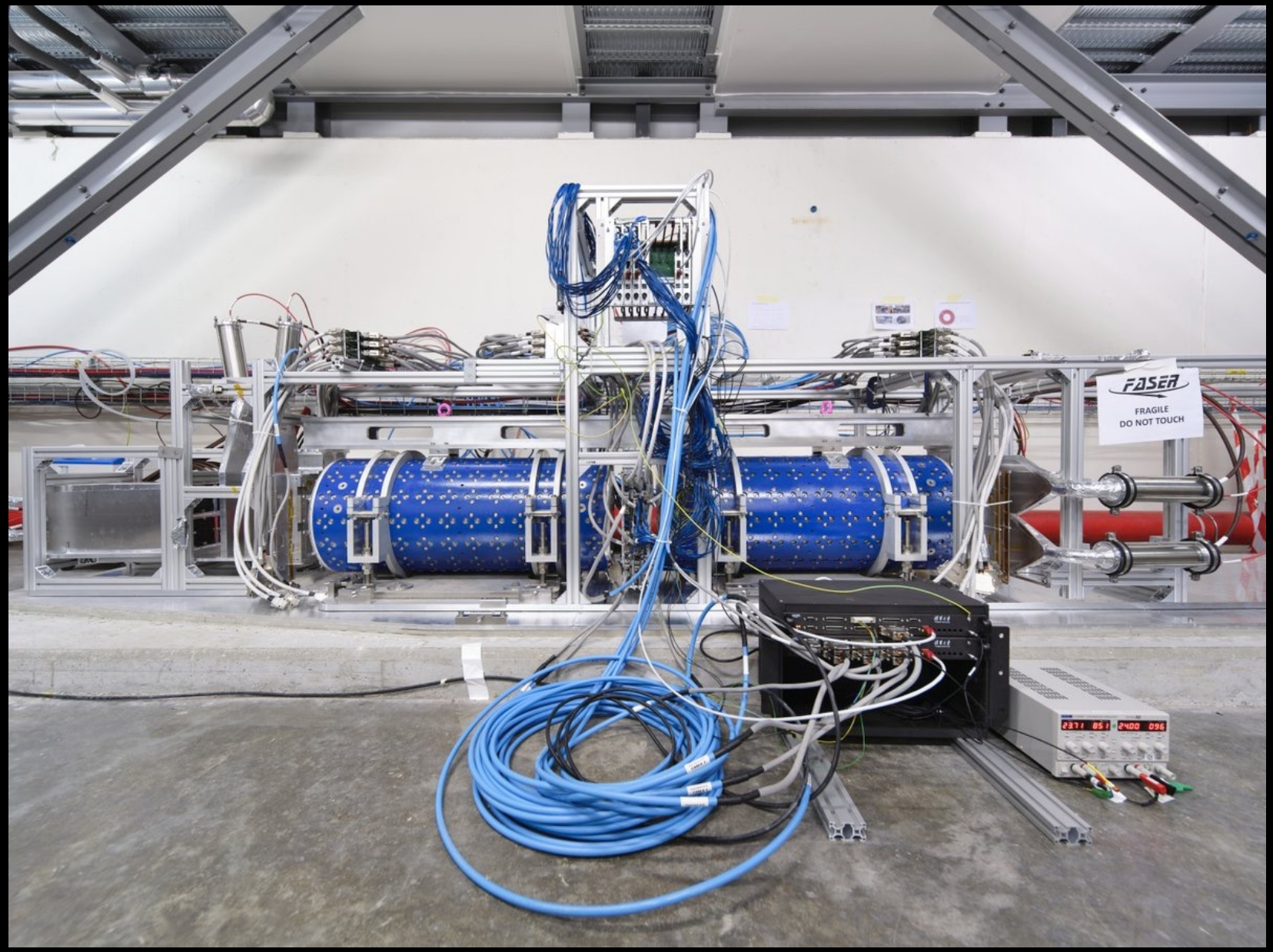


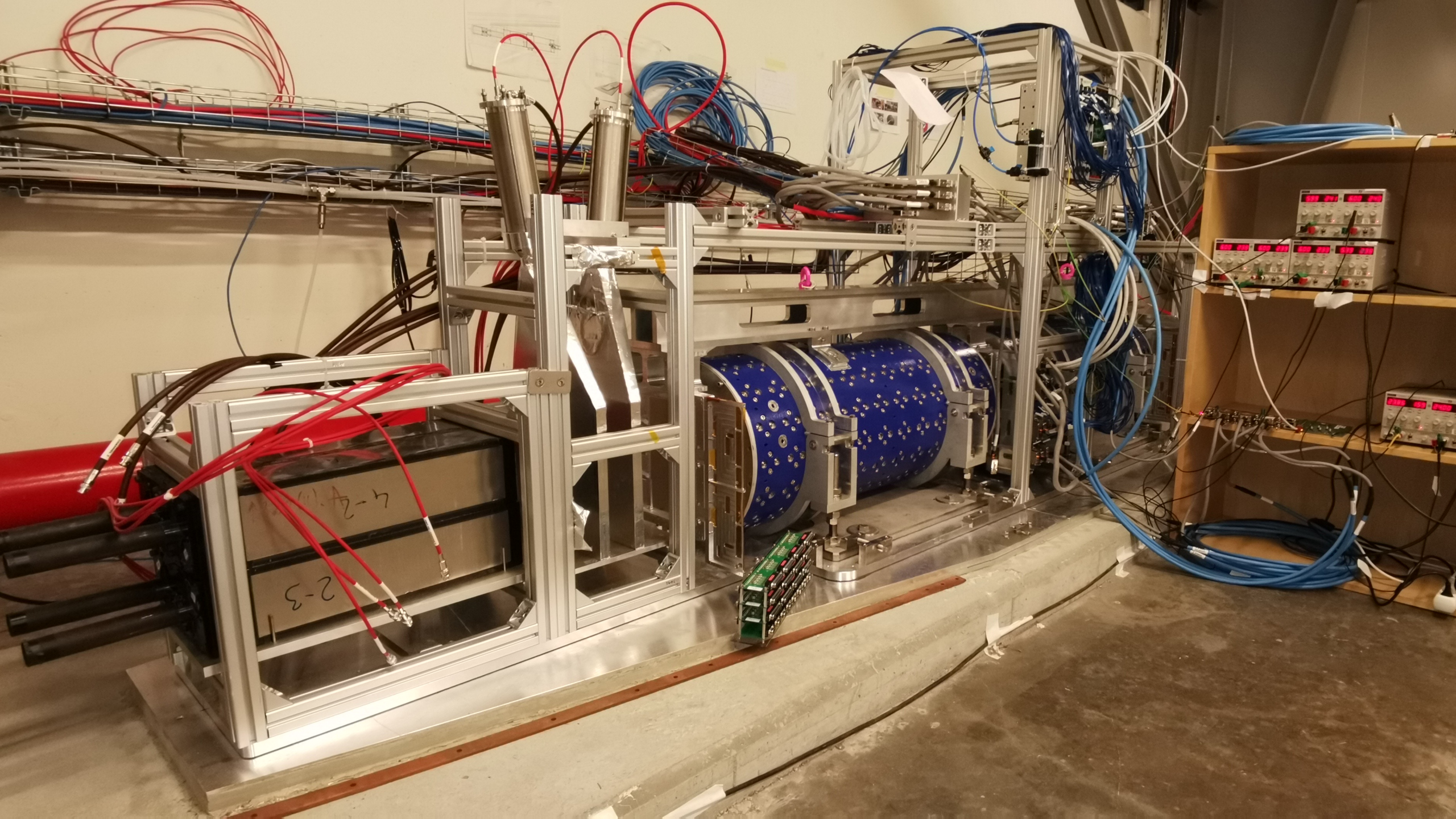
FASER Commissioning

- Dedicated labs available at CERN and the UniGe for individual component testing
- Dedicated area at CERN's Prevessin site ("EHN1") for full-detector commissioning

Milestone	Where	When
Individual component commissioning	labs	July 2020
Detector commissioning	EHN1	Sept 2020
Installation of magnets	EHN1	Sept 2020
Surface commissioning – part 1	EHN1	Oct 2020
Detector installation – part 1	TI12	Nov 2020
Surface commissioning – part 2	EHN1	Feb 2021
Detector installation – part 2	TI12	March 2021
In-situ commissioning	TI12	2021/2022




FASER
FRAGILE
DO NOT TOUCH



FASER Commissioning

- Dedicated labs available at CERN and the UniGe for individual component testing
- Dedicated area at CERN's Prevessin site ("EHN1") for full-detector commissioning

Milestone	Where	When
Individual component commissioning	labs	July 2020
Detector commissioning	EHN1	Sept 2020
Installation of magnets	EHN1	Sept 2020
Surface commissioning – part 1	EHN1	Oct 2020
Detector installation – part 1	TI12	Nov 2020
Surface commissioning – part 2	EHN1	Feb 2021
Detector installation – part 2	TI12	March 2021
In-situ commissioning	TI12	2021/2022

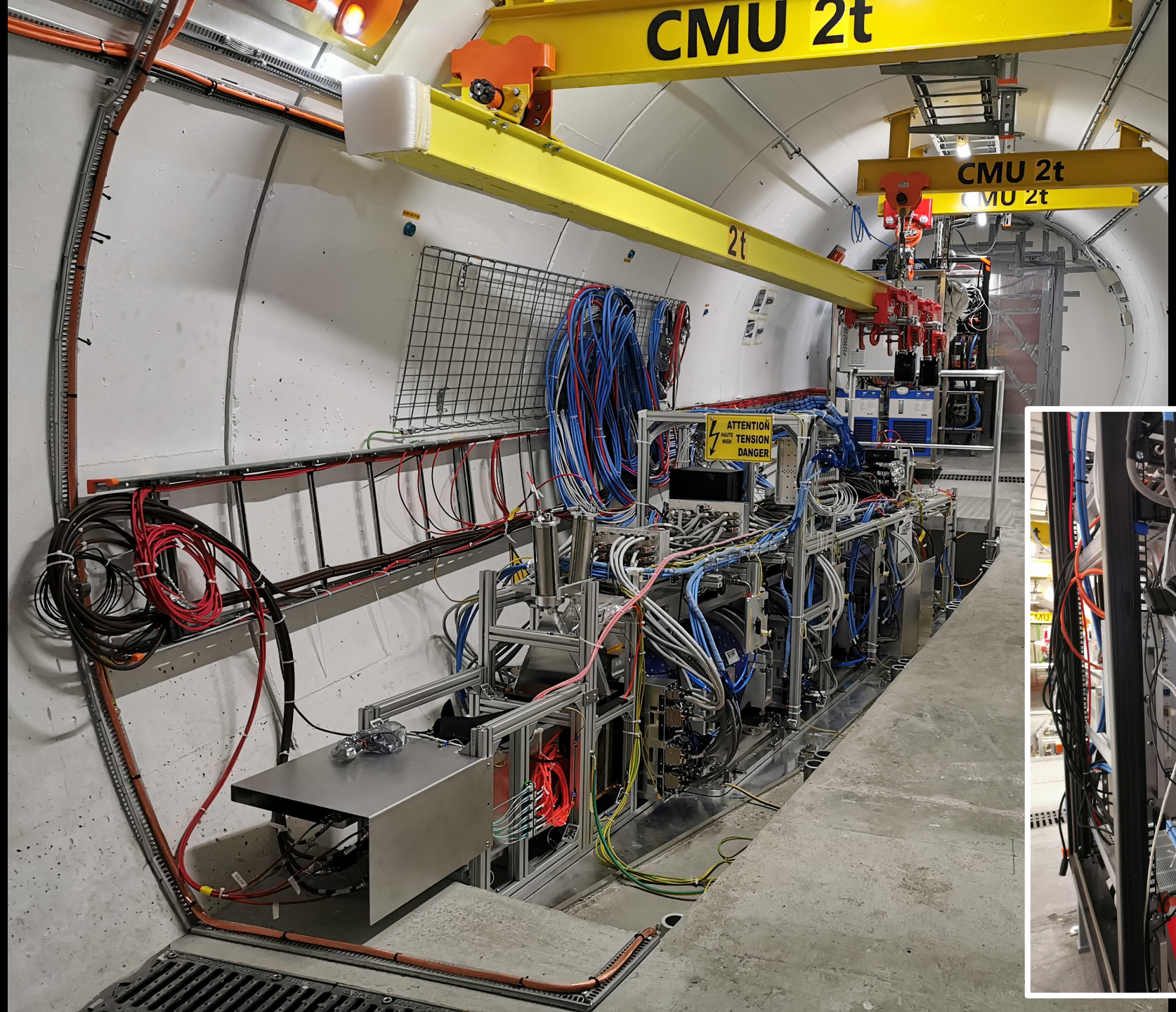
Installation to TI12

End 2020

Installation to TI12

Second phase in

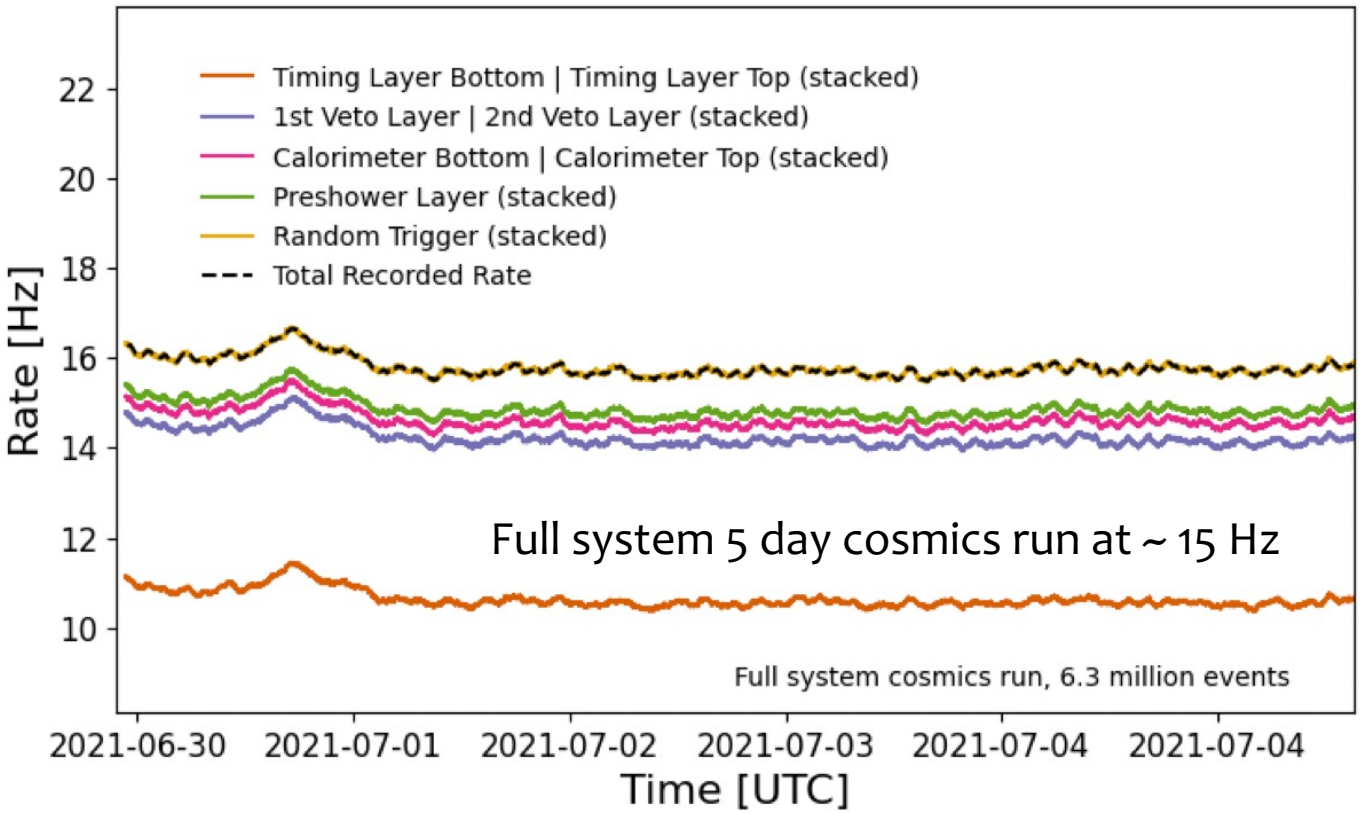
Time-lapse: https://videos.cern.ch/record/2759548

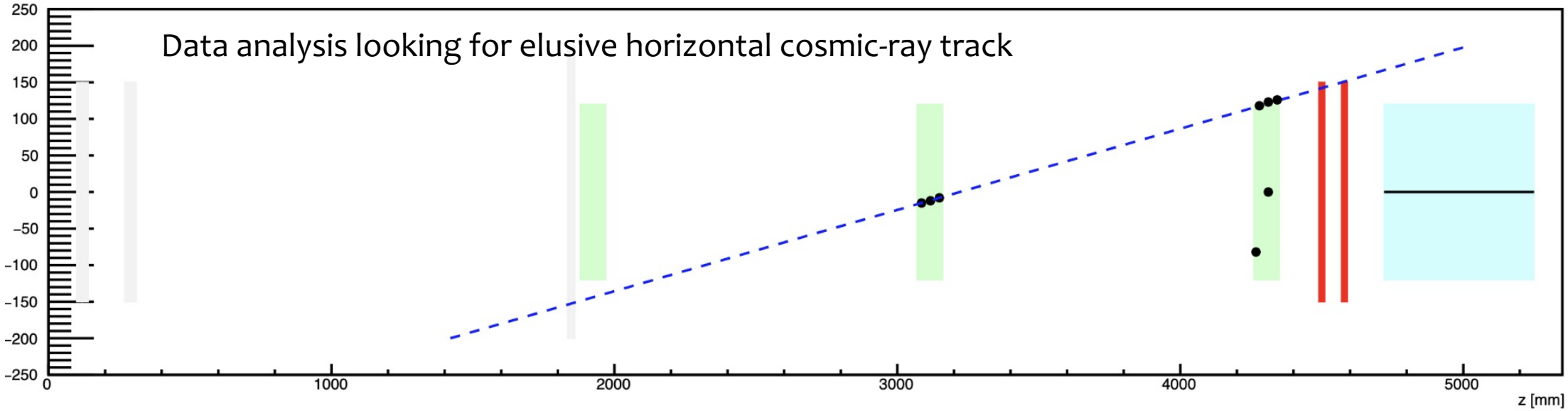

CMU 2t
CMU 2t
2t
ATTENTION
HAUTE TENSION
HIGH
DANGER

ATTENTION
HAUTE TENSION
HIGH DANGER

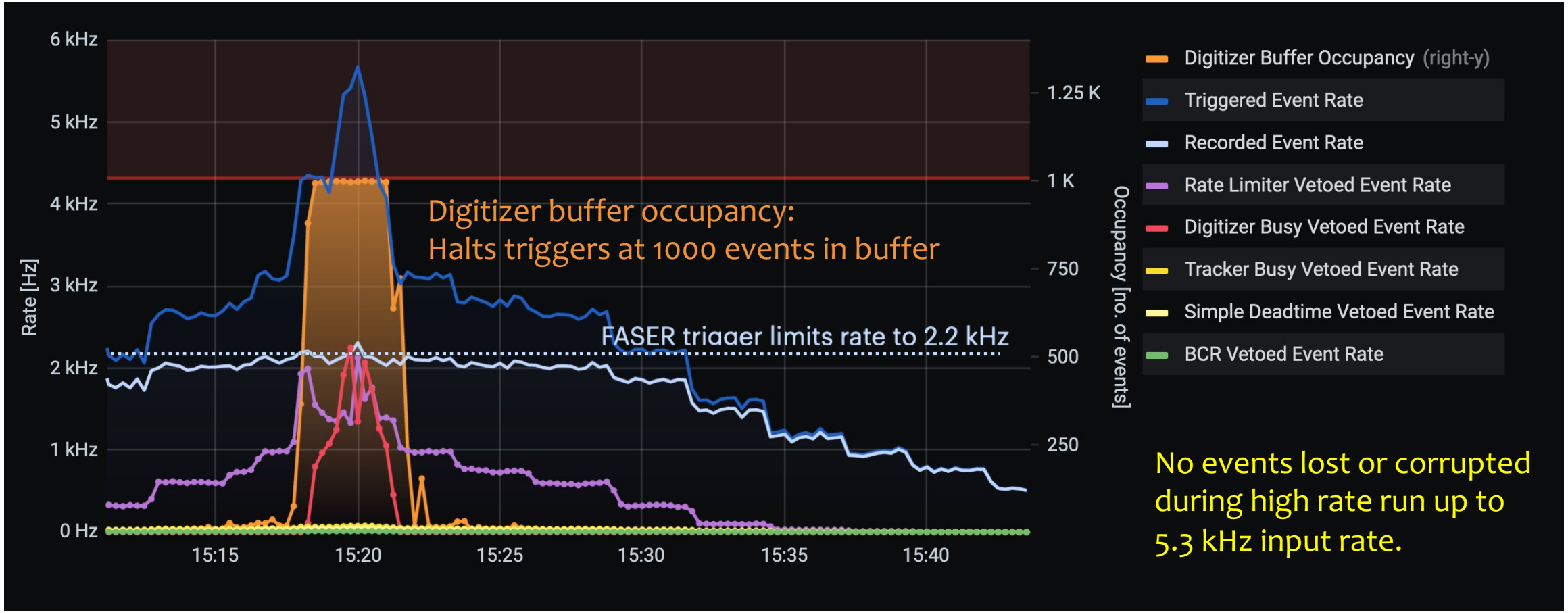
Cosmic data taking

Since installation FASER has been mostly taking cosmic data in TI12





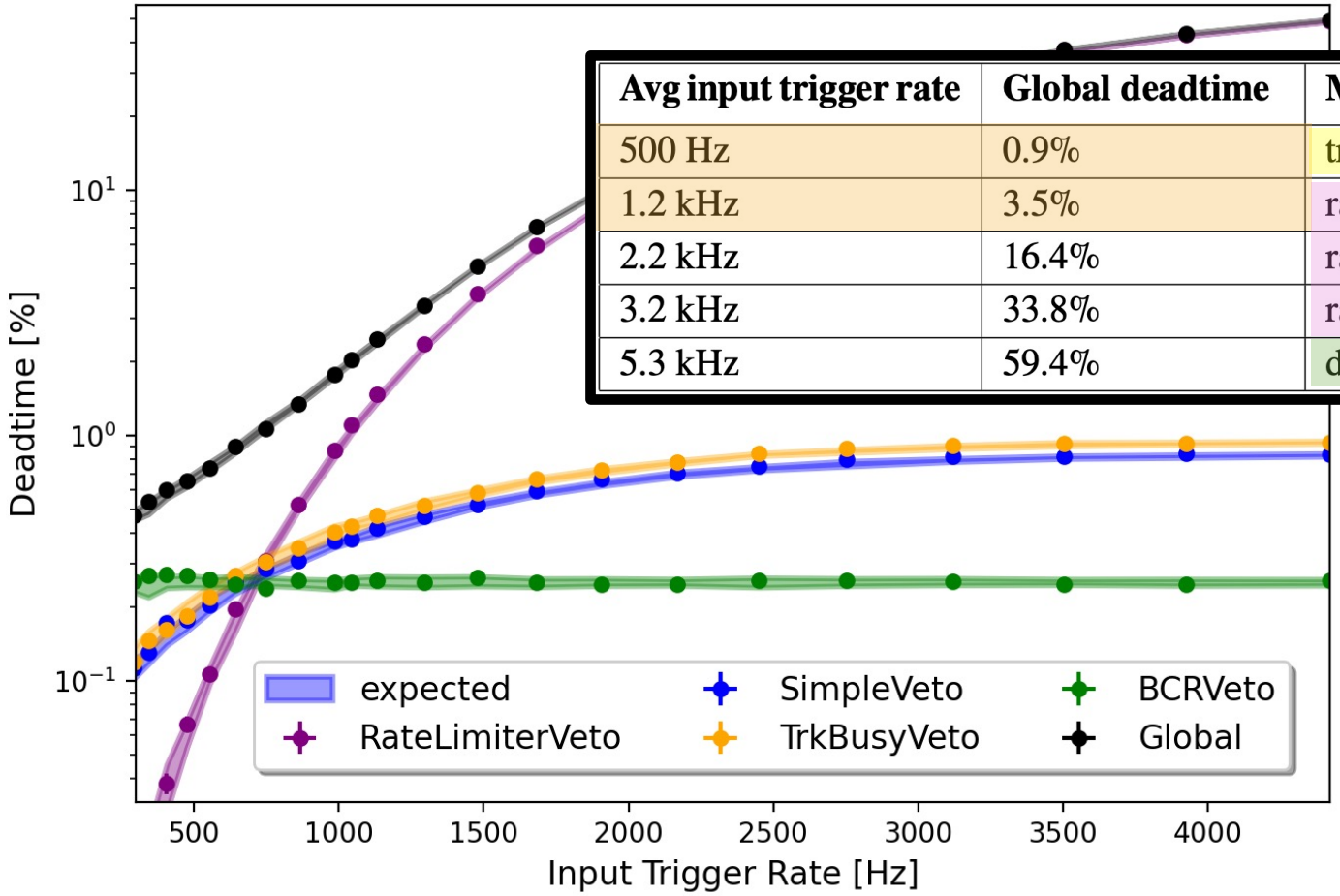
High rate tests



No events lost or corrupted during high rate run up to 5.3 kHz input rate.

NEW! arXiv: 2110.15186

Precise deadtime measurements



Avg input trigger rate	Global deadtime	Max deadtime source	Data throughput
500 Hz	0.9%	tracker	10 MBytes/s
1.2 kHz	3.5%	rate limiter	26 MBytes/s
2.2 kHz	16.4%	rate limiter	47 MBytes/s
3.2 kHz	33.8%	rate limiter	47 MBytes/s
5.3 kHz	59.4%	digitizer	47 MBytes/s

Expected Run3 rates

Tracker only reads out one event at a time

Rate is limited to 2.2 kHz

Digitizer read-out limitations

At 500 Hz,
deadtime expected to be < 1 %

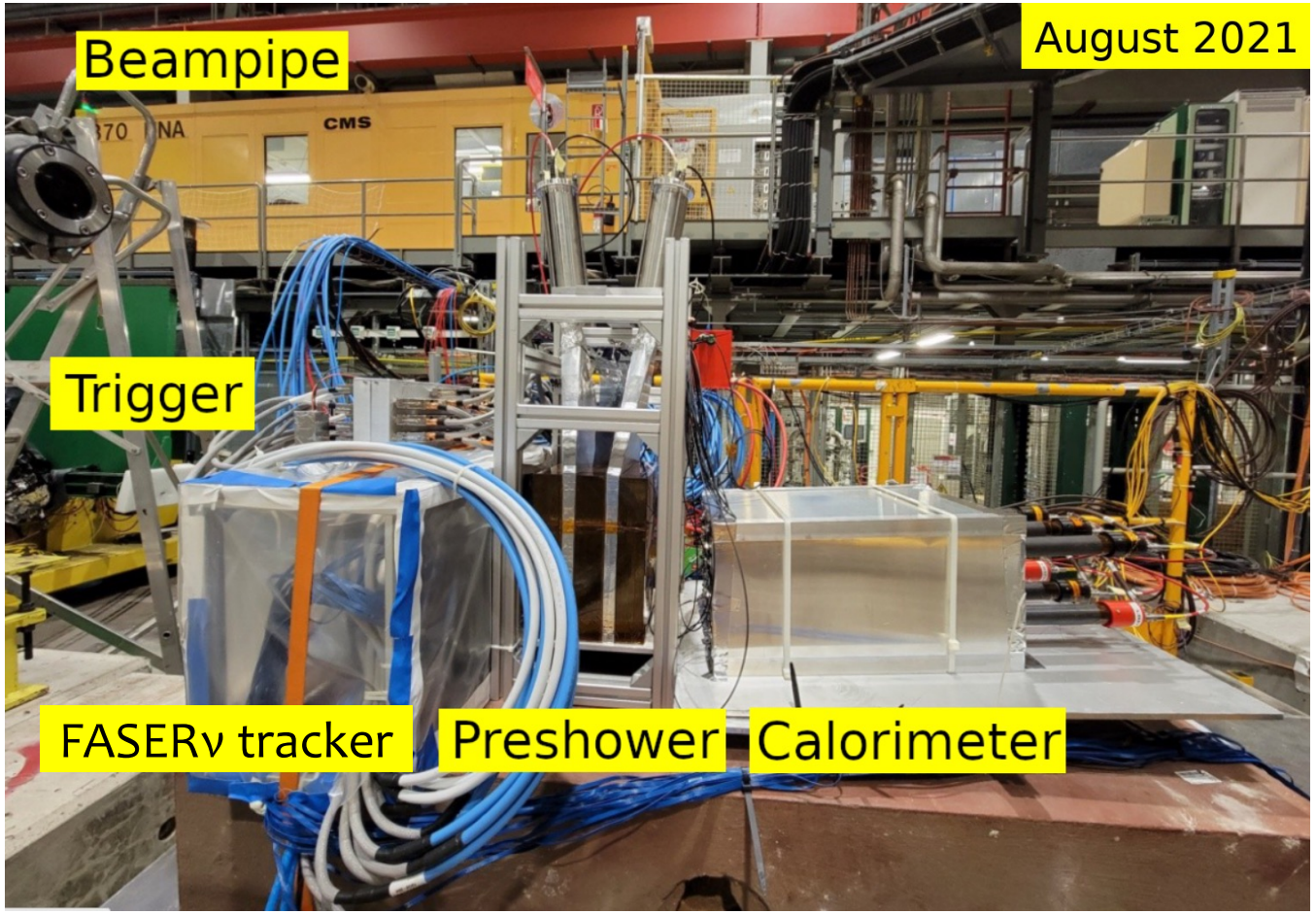
NEW! arXiv: 2110.15186

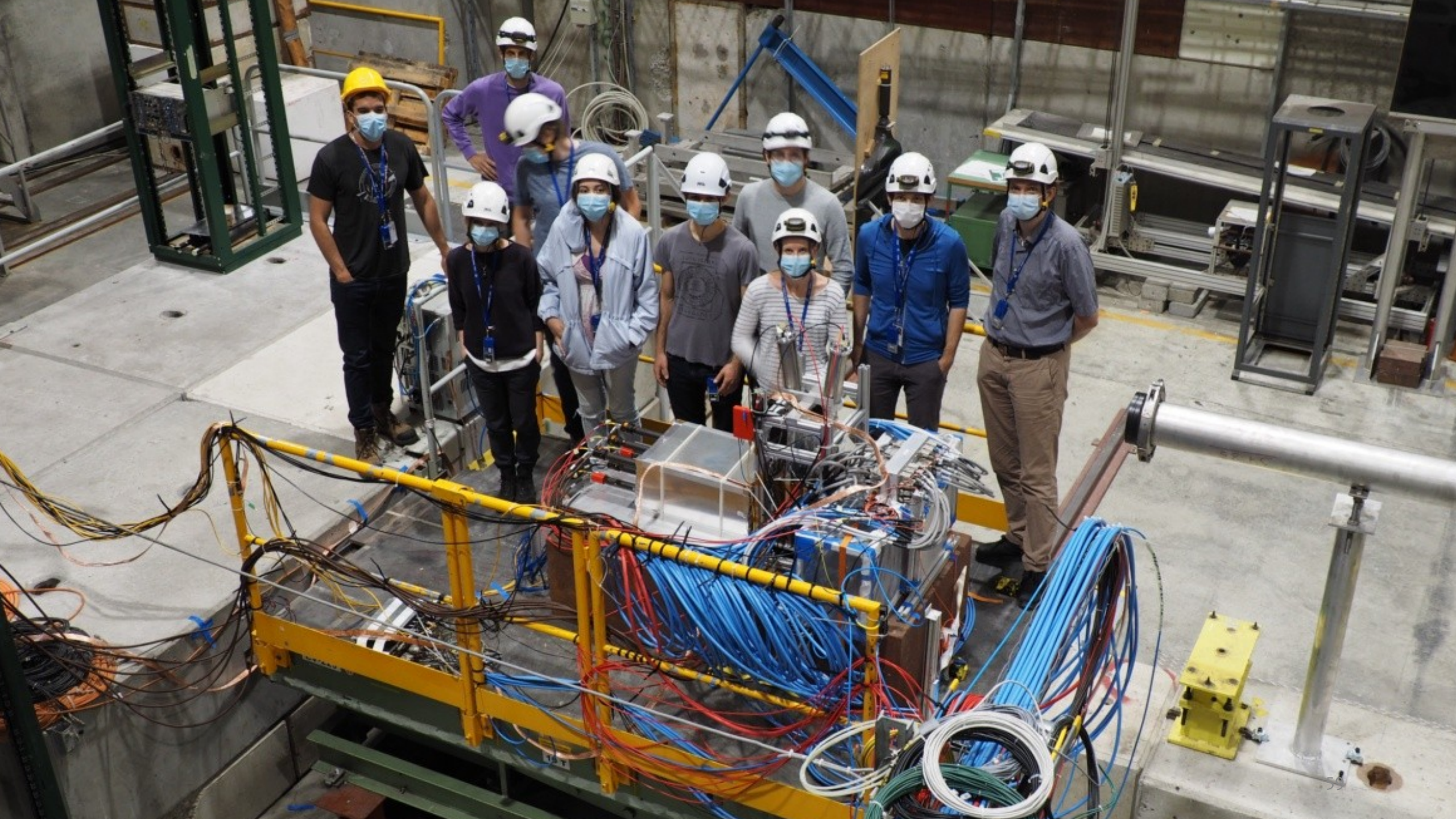
FASER experiment

commissioning with beams!

FASER Testbeam

- July 28 – Aug 4th : carried out test beam in SPS North area
- Primary goal to calibrate the calorimeter with high energy electron beam
- 150M events collected using electron, muon and pion beams
- Analysis ongoing…

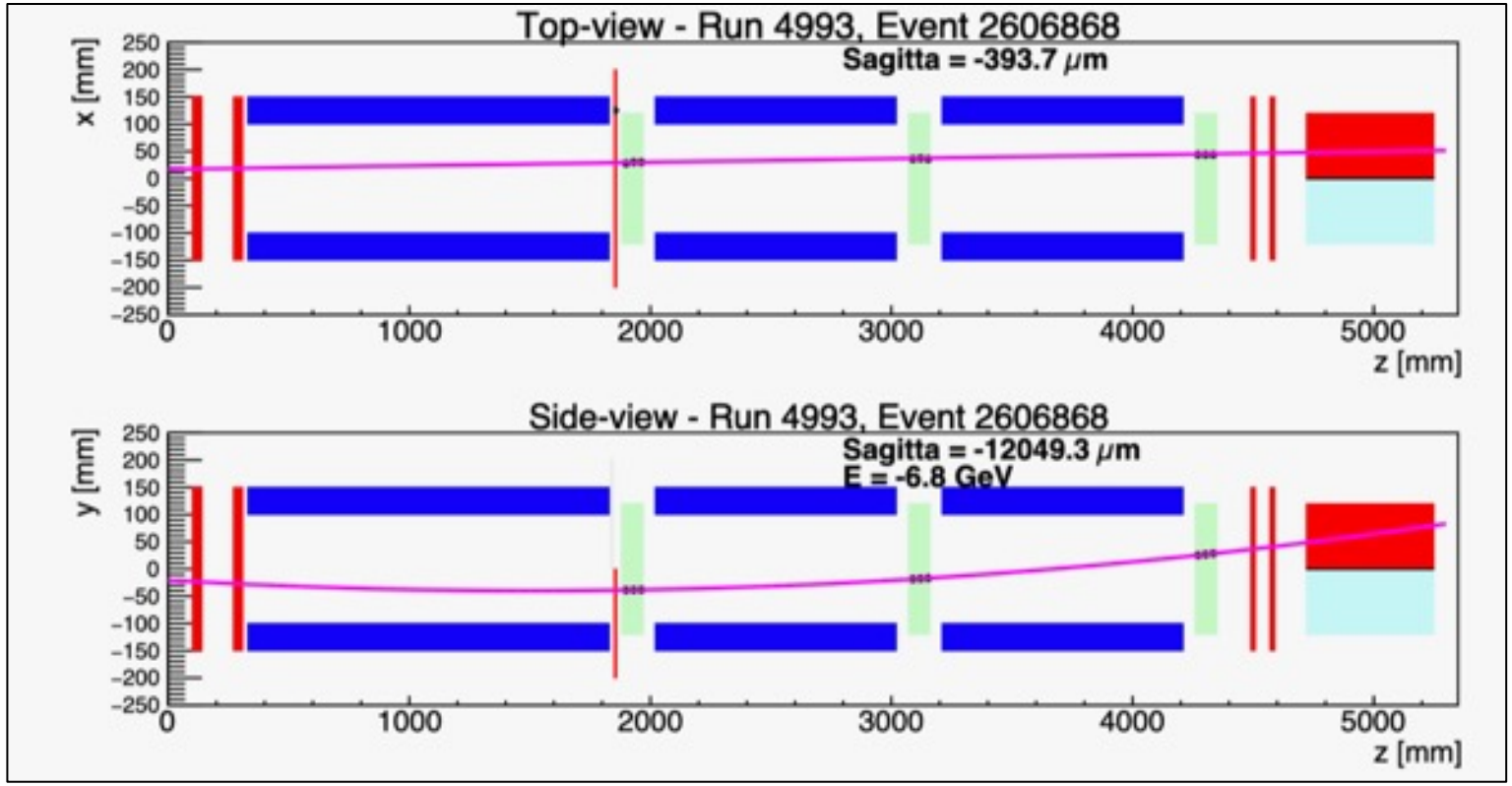




October 2021:
First LHC beams since 2018!

2 week pilot beam test, with 450 GeV beams circulated and collided

- FASER saw beam-related activity during various operations (beam splash, collimator alignment, single beam and colliding beams)
- Data used to time in the trigger, and for performance and background studies
- **First time we saw particles traversing the full detector!**



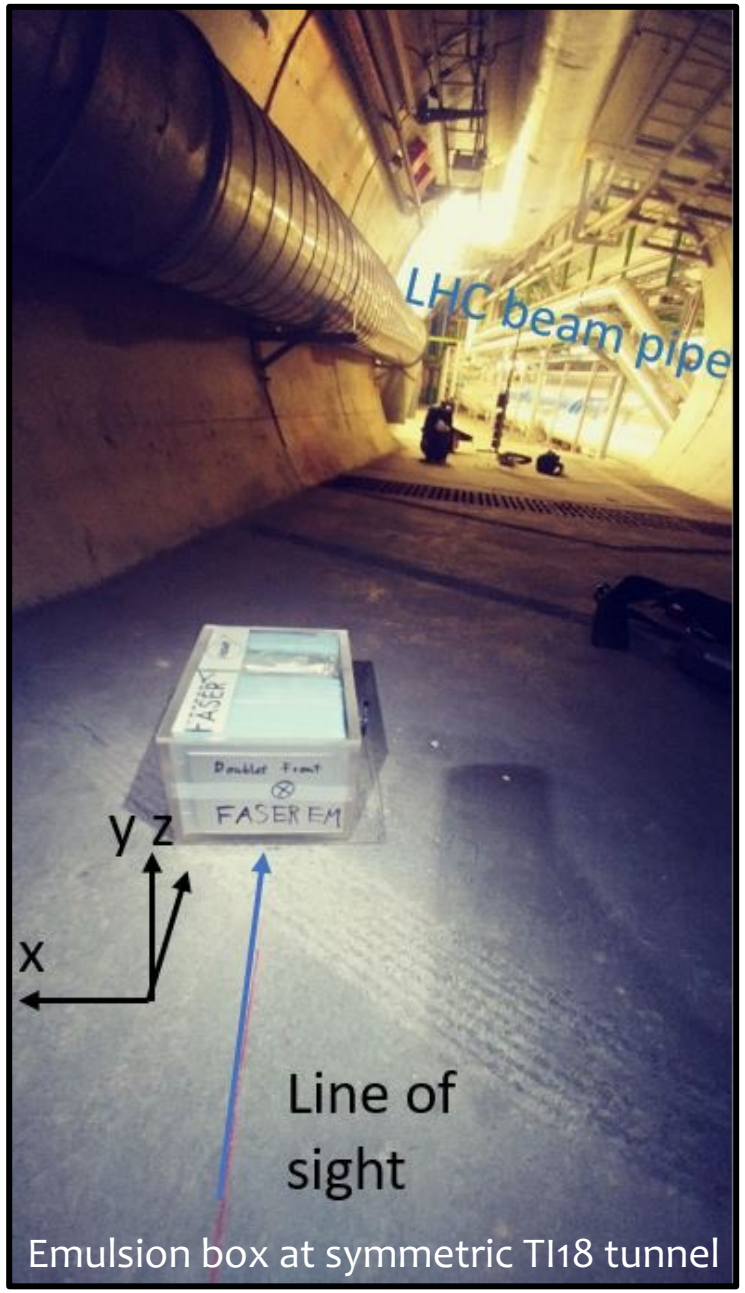
FASER experiment

And now, looking forward for collisions to come!

FASER Backgrounds

- **Major background from IP:**
  - Muons and **neutrinos** directly from IP; muons that brem off another particle
  - Veto in scintillators (4 uncorrelated layers) renders muon background negligible; DIS from neutrinos challenging
- **Background from beam:**
  - Beam-gas or diffractive proton losses are found to both be negligible
- Simulation, validated by emulsion-based measurement (recorded ~ **13/fb of data**). CERN beam monitoring also installed
- The radiation level is low ($<10^{-2}$ Gy/year)

⇢ **TI12 very quiet location!**



Emulsion box at symmetric TI18 tunnel

FASER

Huge flux of high-energy neutrinos

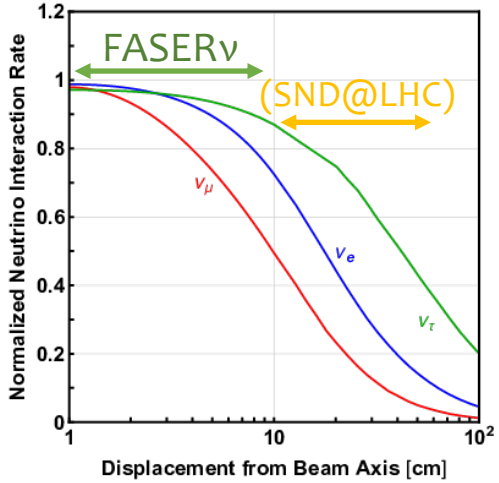
- Why not exploit FASER to also measure properties of neutrinos at the highest man-made energies ever recorded!

A bit of history

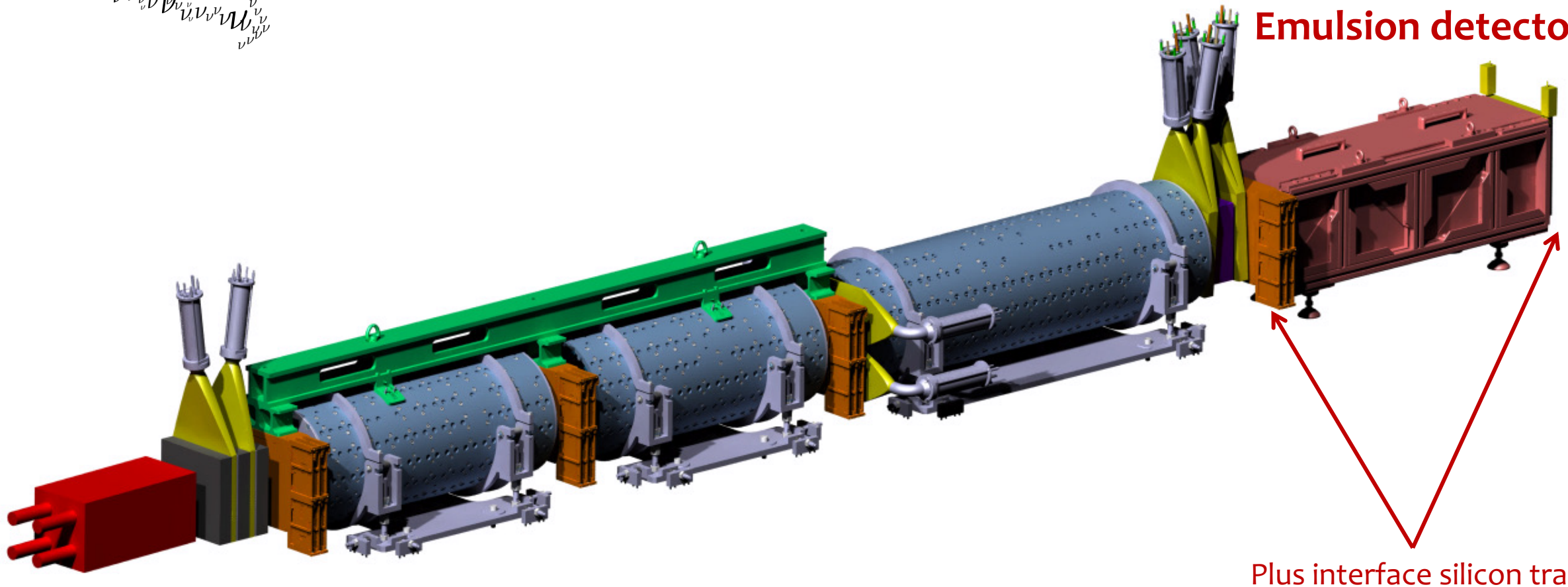
Experiments to study collider neutrinos have been proposed since the 80s, e.g.:

- A. De Rujula and R. Ruckl, "**Neutrino and muon physics in the collider mode of future accelerators**" ECFA-CERN Workshop on large hadron collider in the LEP tunnel, pp. 571–596, **1984**.
- Klaus Winter, **"Observing tau neutrinos at the LHC"**, LHC workshop, **1990**.

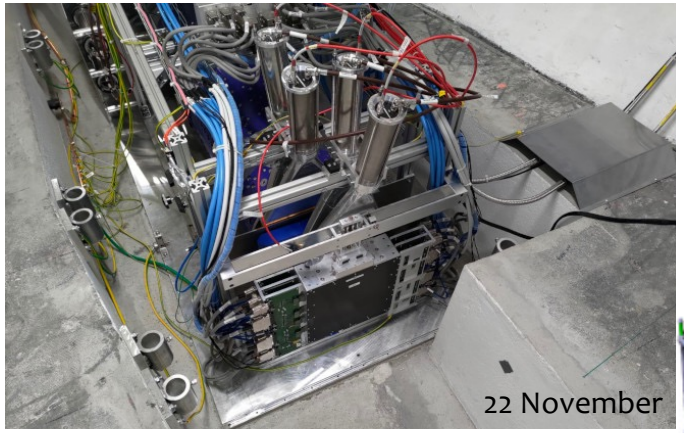
Other recent concrete experiment proposals include XSEN and SND@LHC.
SND@LHC recently approved.



FASER Detector

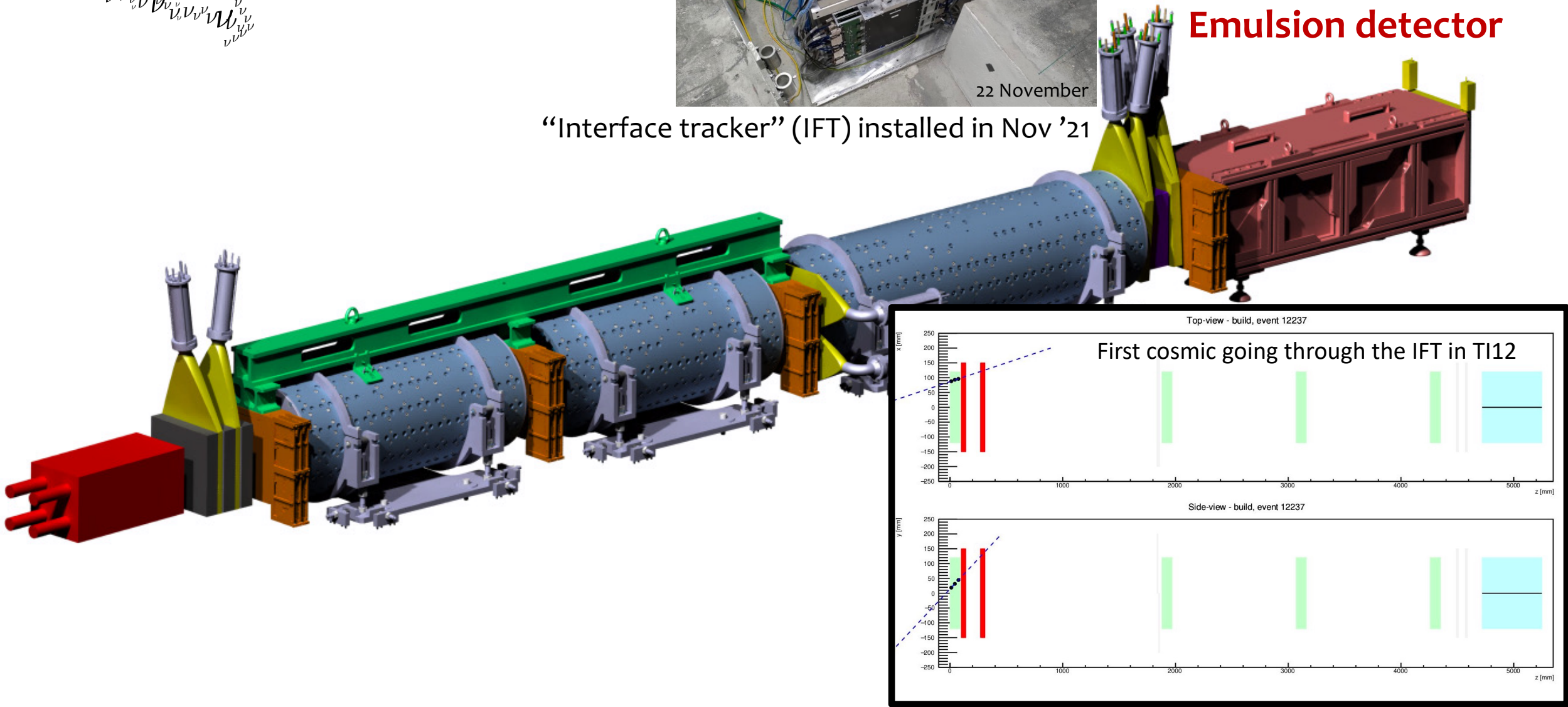


FASER Detector



"Interface tracker" (IFT) installed in Nov '21

FASERν
Emulsion detector

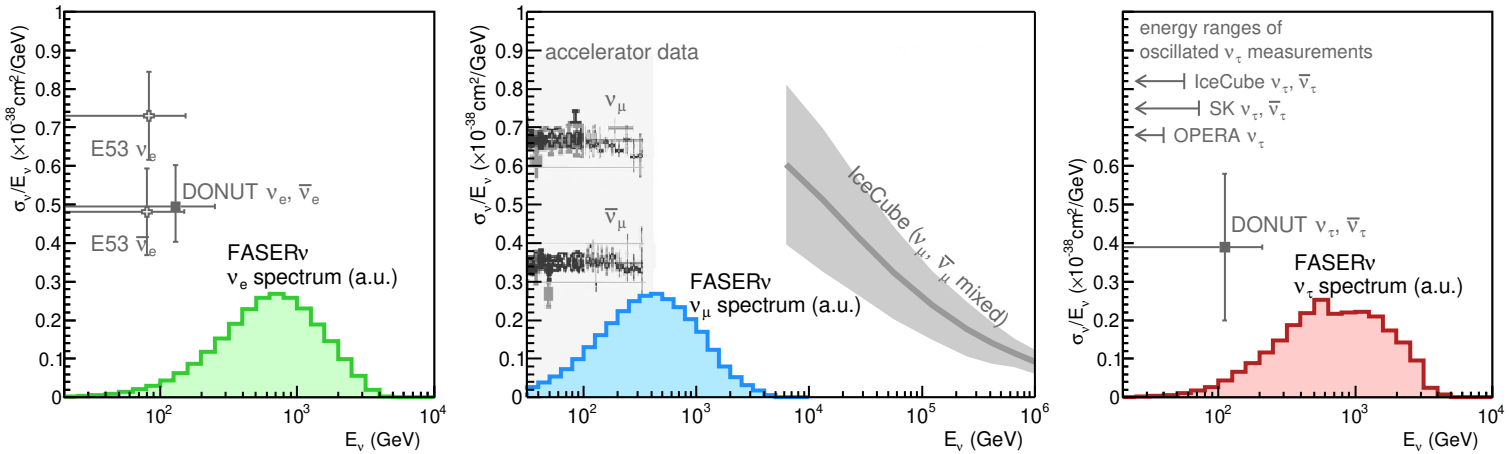


Huge flux of high-energy neutrinos

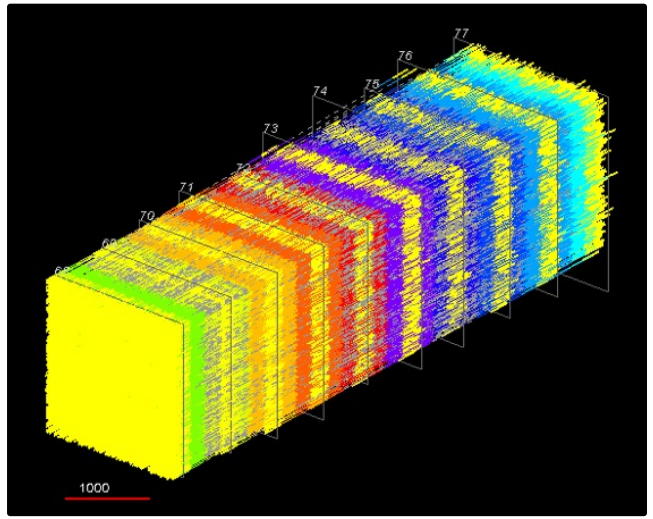
- Why not exploit FASER to also measure properties of neutrinos at the highest man-made energies ever recorded!

- **Expected spectra:** complementary to existing experiments
- **Expected cross section reach:** extends current measurements already with 150/fb
- **Rich QCD physics explorations**
- **Refine simulations that currently vary greatly** (EPOS-LHC, QGSJET, DPMJET, SIBYLL, PYTHIA, …)

150/fb @14TeV	ν_e	ν_μ	ν_τ
Main production source	kaon decay	pion decay	charm decay
# traversing FASERnu 25cm x 25cm	$O(10^{11})$	$O(10^{12})$	$O(10^{9})$
# interacting in FASERnu (1.2tn Tungsten)	~1300	~20000	~20



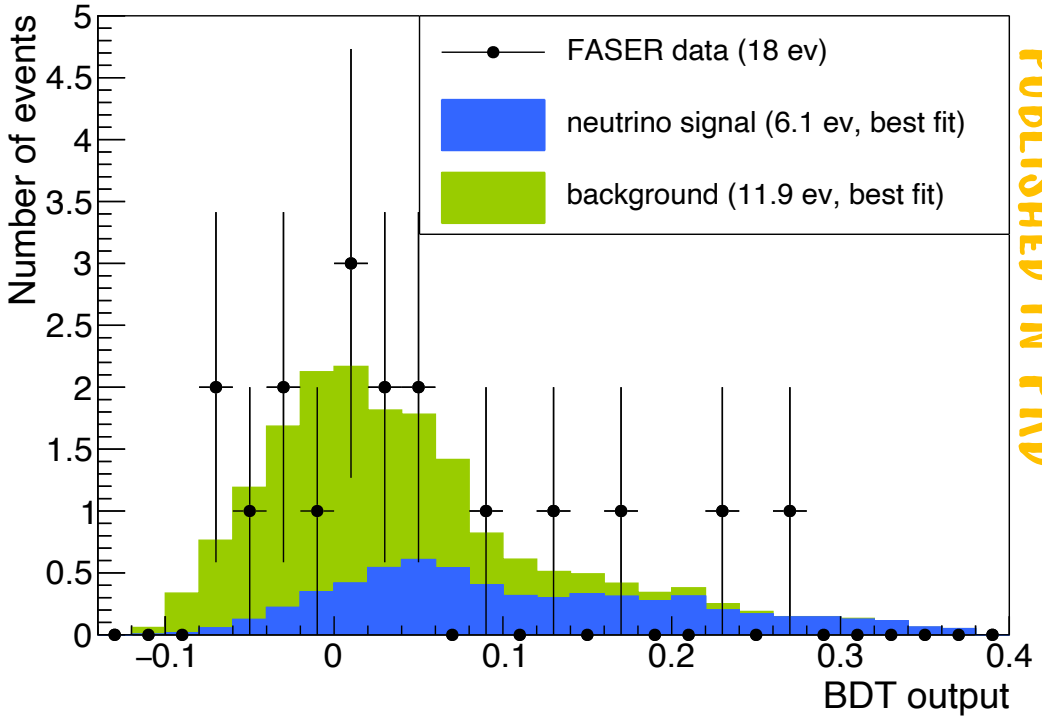
Pilot run in 2018



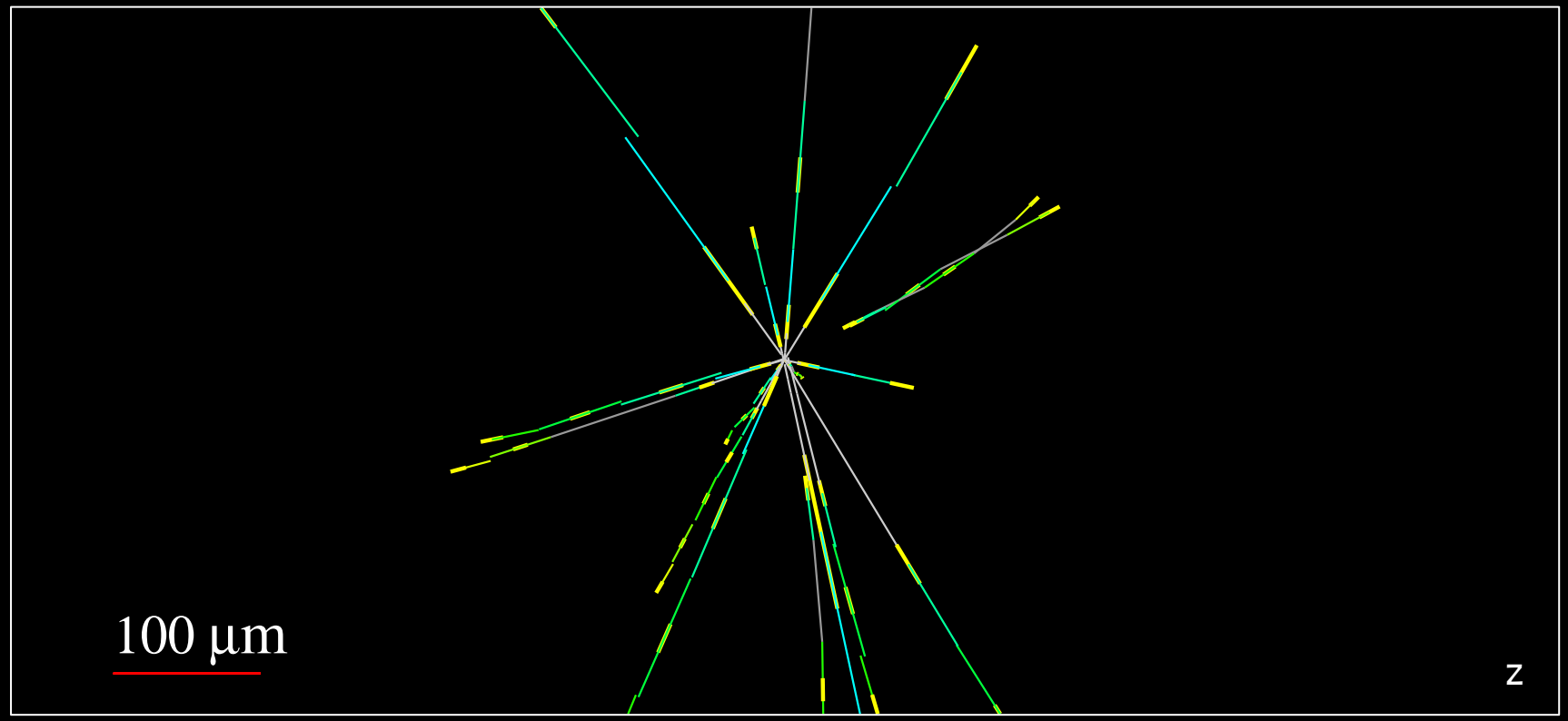
- A 30 kg detector at TI18
- Collected ~ 13/fb

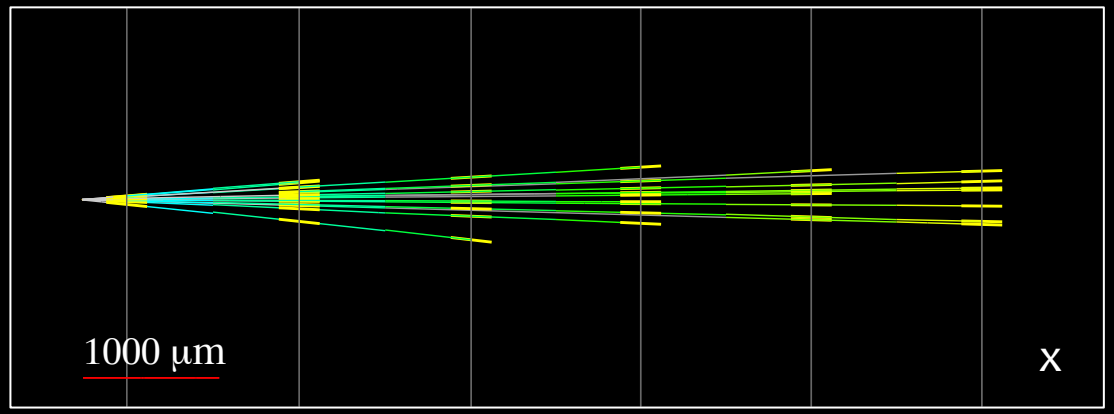
- About 3.3 neutrino interactions expected to have occurred after selections
- BDT developed to distinguish neutrino signal from neutral hadron background
  - The background-only hypothesis is rejected with significance of 2.7σ

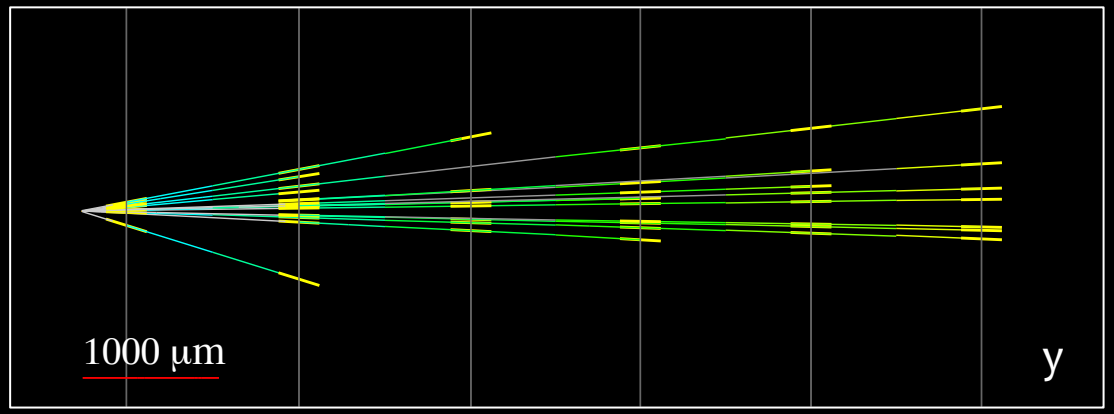
- Excellent testbed for future data analysis



NEW! arXiv: 2105.06197
PUBLISHED IN PRD

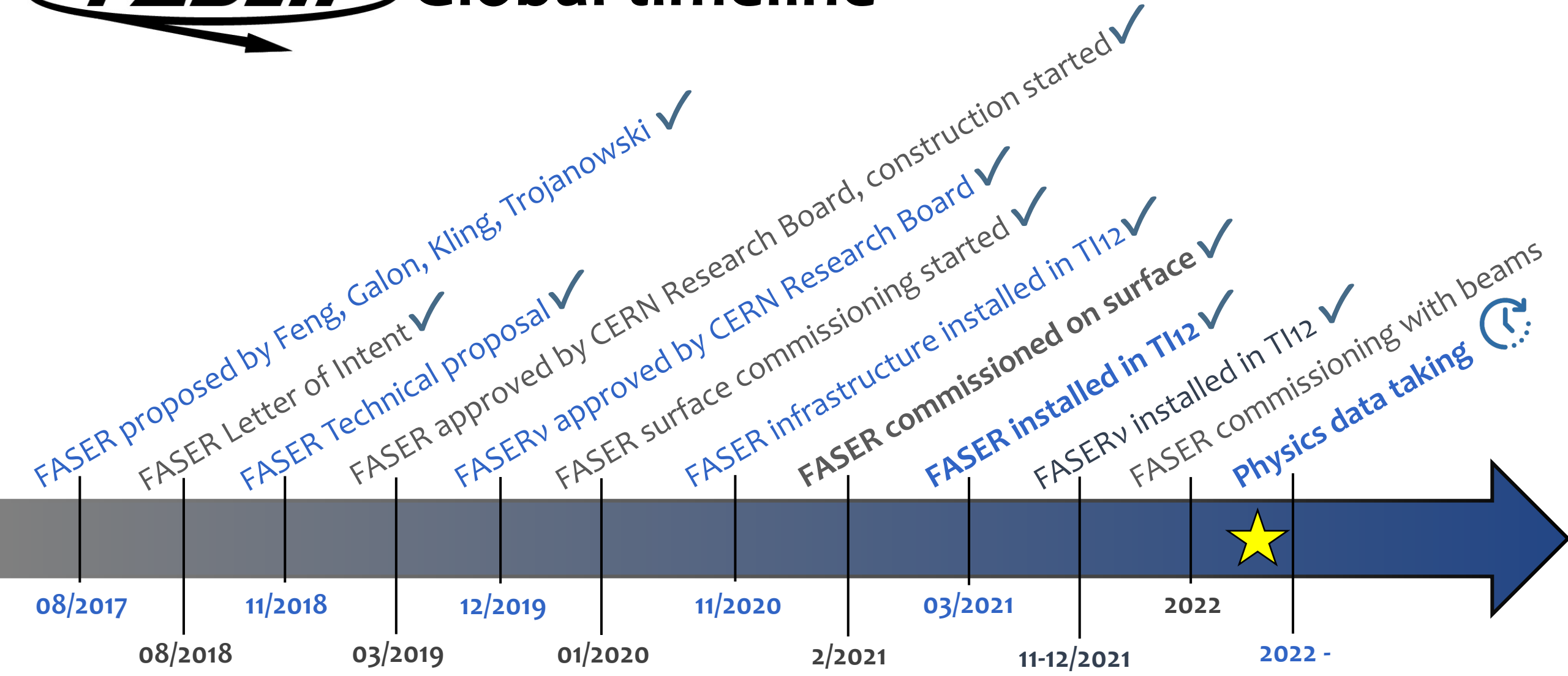

100 μm
z


1000 μm
x


1000 μm
y

FASER Timeline

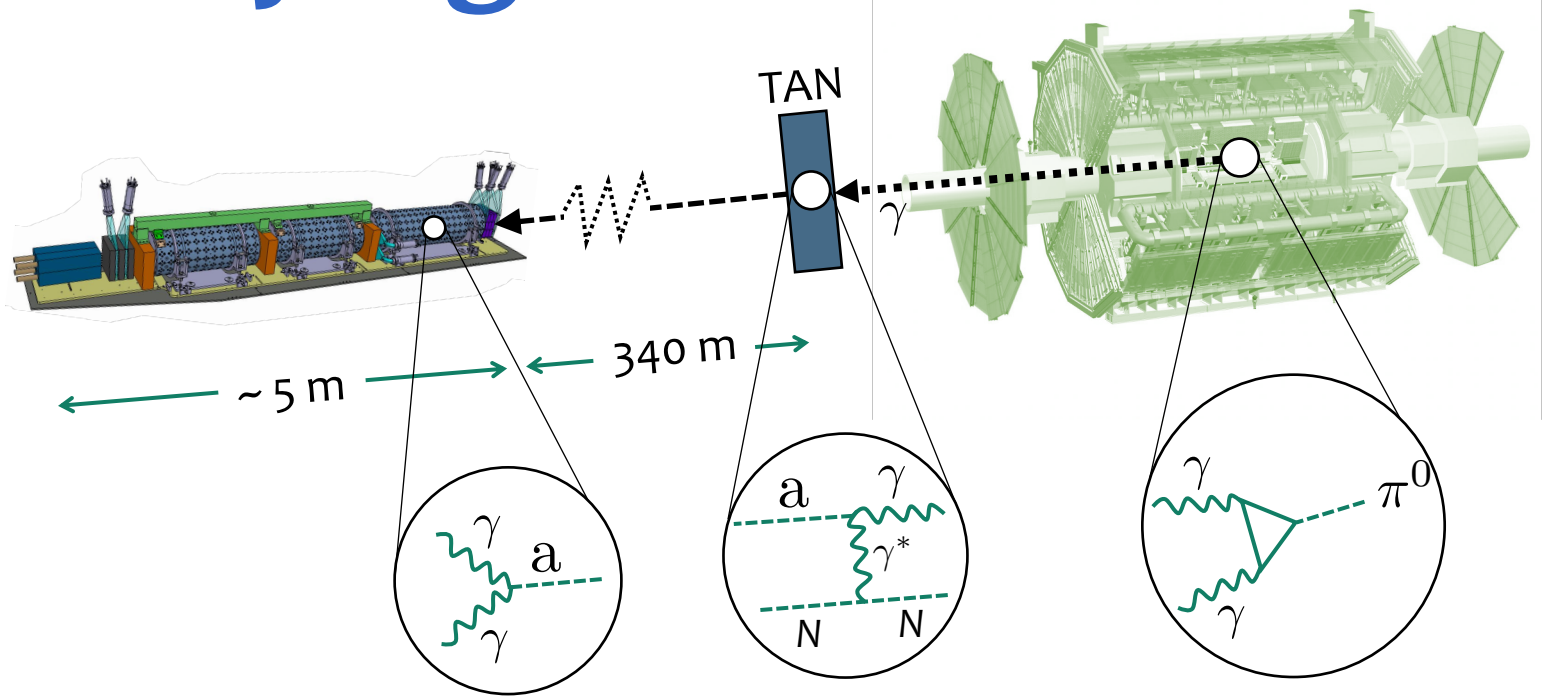
Global timeline



What’s beyond 2022?

Key signatures

Axion-like particle (ALP, a)

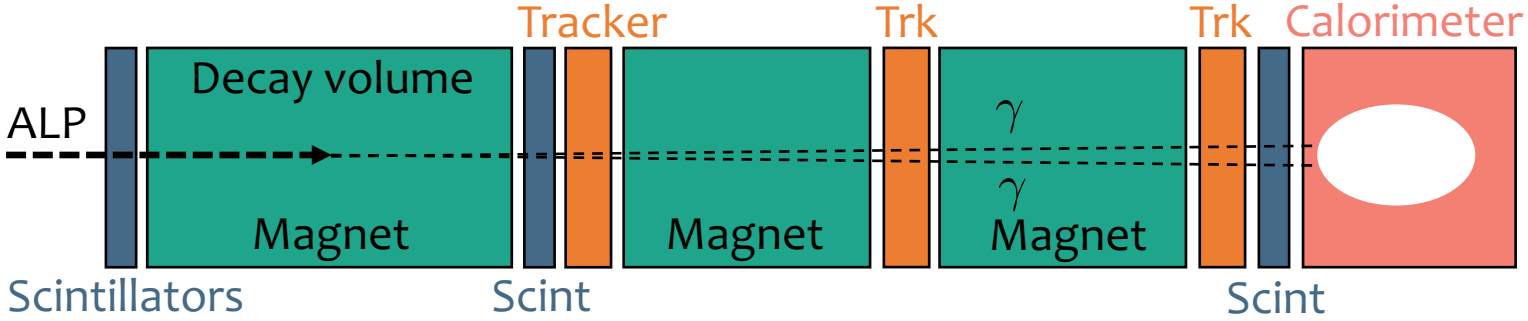


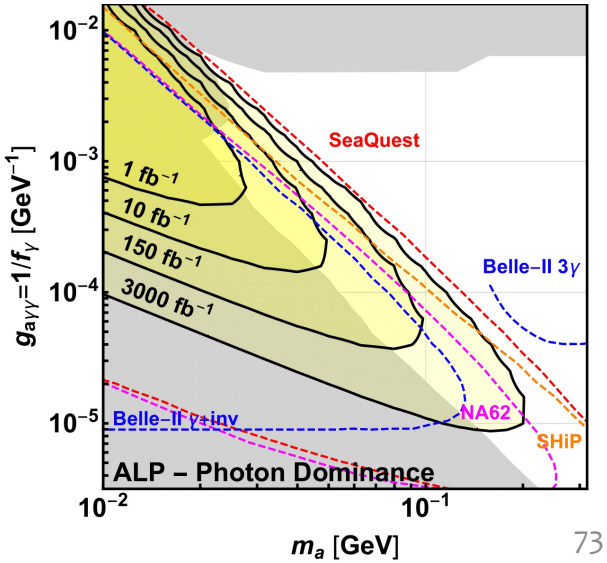
Ballpark numbers for ALPs:

- Momentum of 1 TeV
- Mass of 100 MeV

Decay products collimated

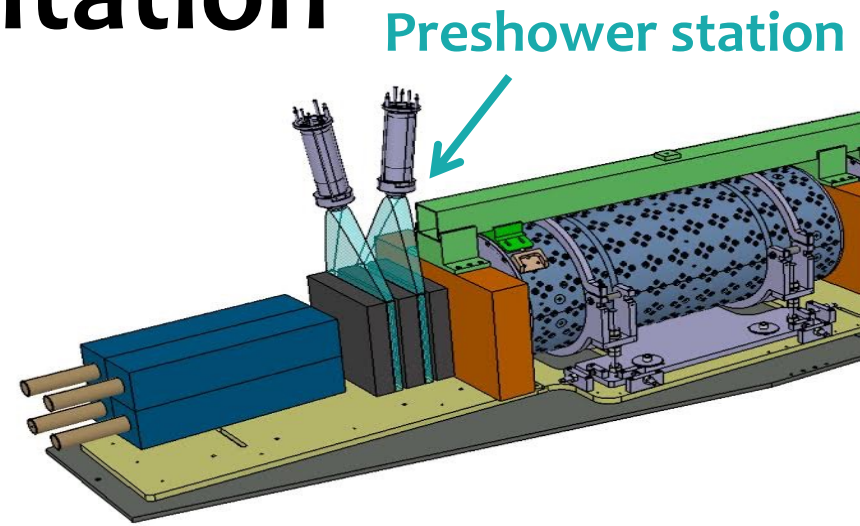
2-γ signature can't be resolved with present detector: upgrade





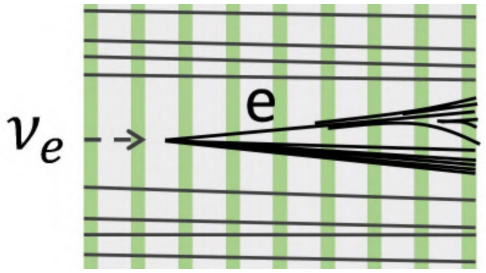
Assuming 3 signal events and no backgrounds

Current detector limitation



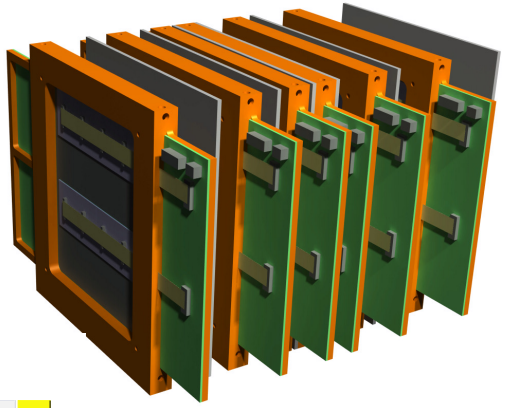
- **Current FASER pre-shower**
  - two layers of scintillators, each preceded by a 1X0 lead-radiator plane
  - will create a photon shower to help distinguish photons from electrons coming from deep inelastic scattering (DIS) of very energetic neutrinos in the calorimeter.

- **Limitations:**
  - **no information about the multiplicity of the photons or the topology of the event**
  - **neutrino DIS events produced in the 2 X0 lead of the present pre-shower will be undistinguishable from a photon (LLP) signature**
    - About 10 such events expected in 150/fb

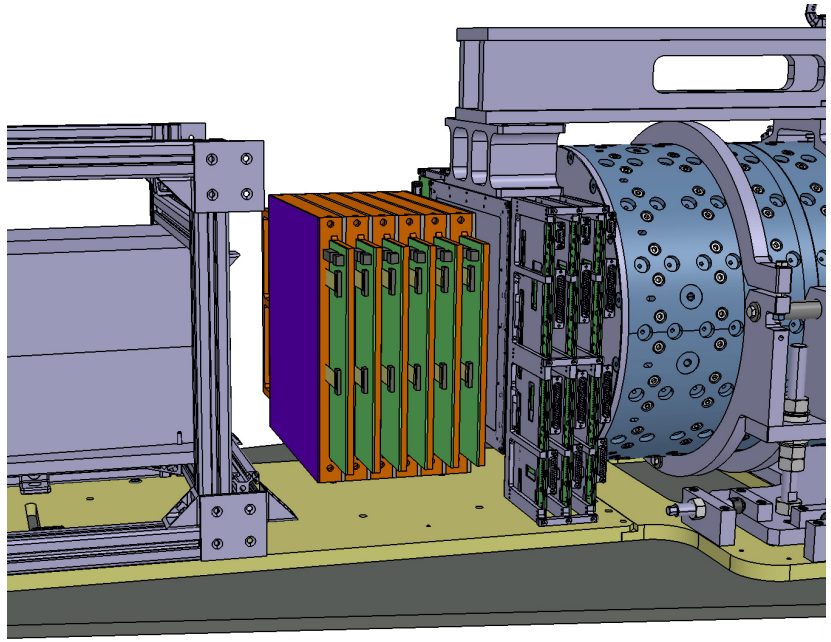


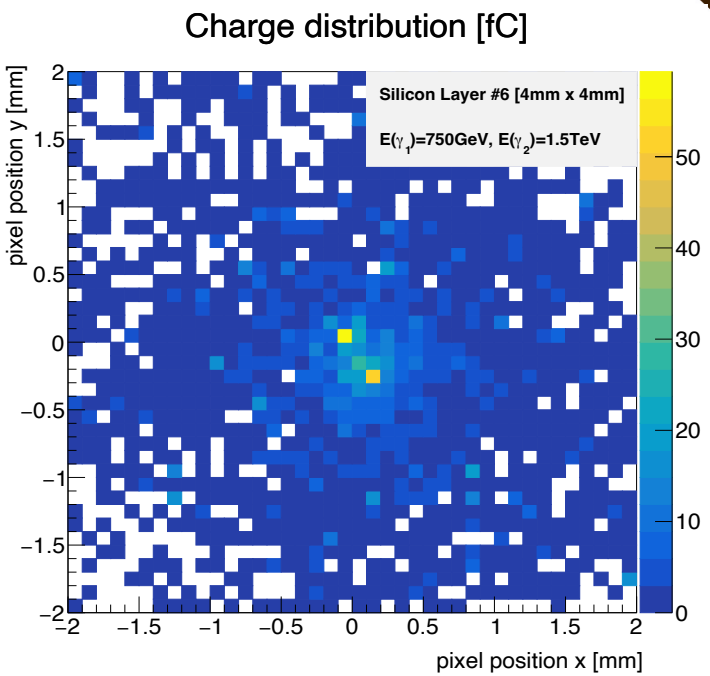
Cartoon of ν_e DIS in FASERν

Upgrade to enable 2-γ physics



- Existing pre-shower to be replaced with a high-resolution silicon pre-shower detector using monolithic pixel ASICs
  - hexagonal pixels of 65 μm side



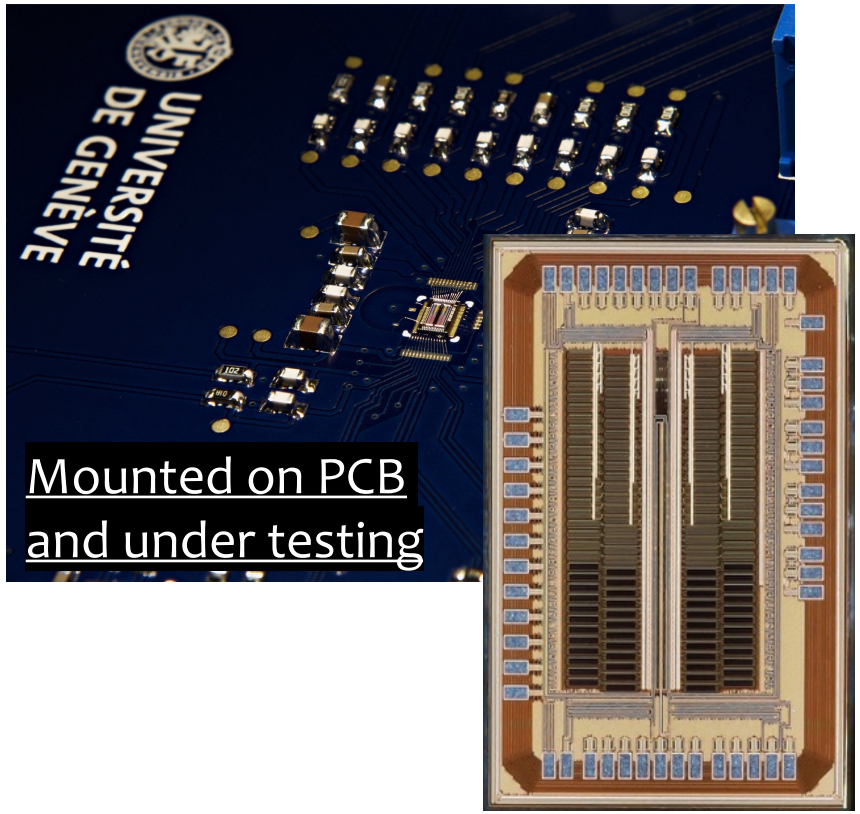


- Distance between two photons: 200 μm
- Distinguishable!

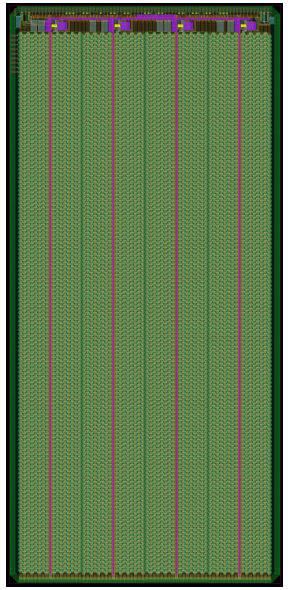
Detector to be used for 2024 & 2025 data taking (70% of Run3 data)

From pixels to layers of modules

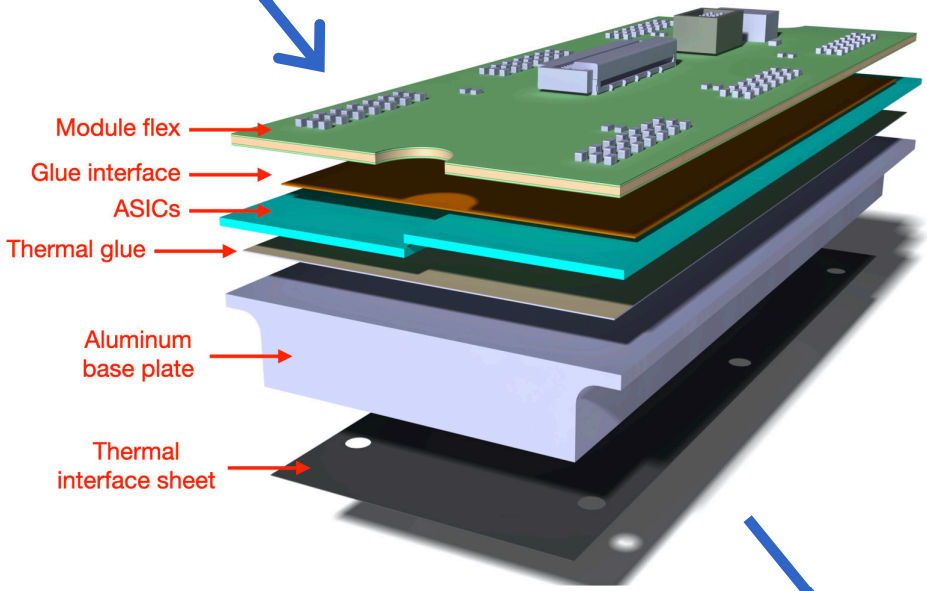
Prototype ASIC available end 2020



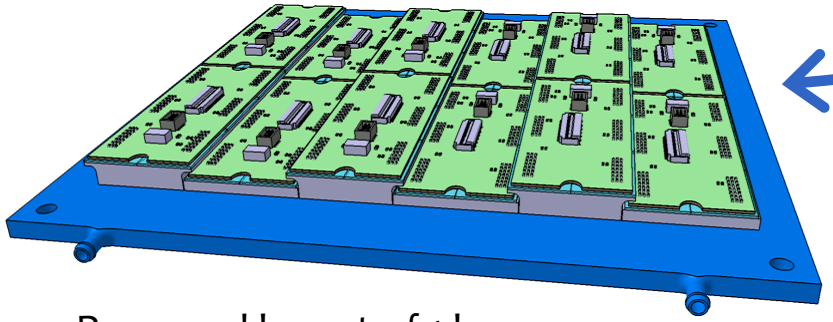
Pixel chips into sensor wafers



…into modules of pixels



…into layers of modules



Proposed layout of 1 layer with 12 modules.

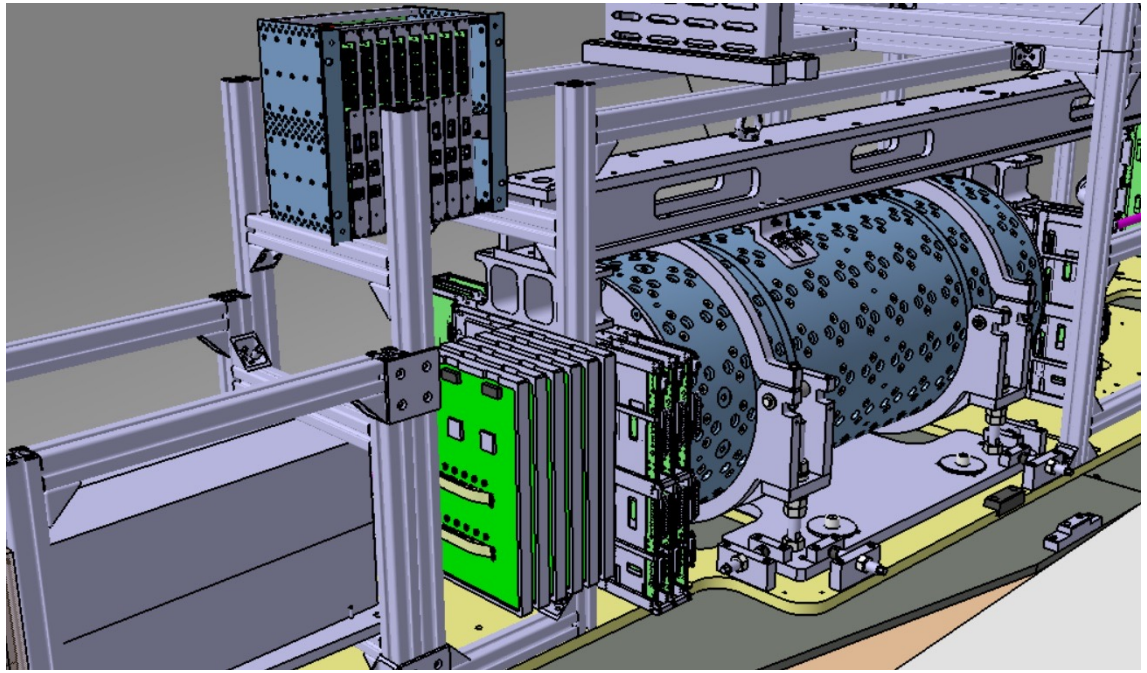
Upgraded pre-shower

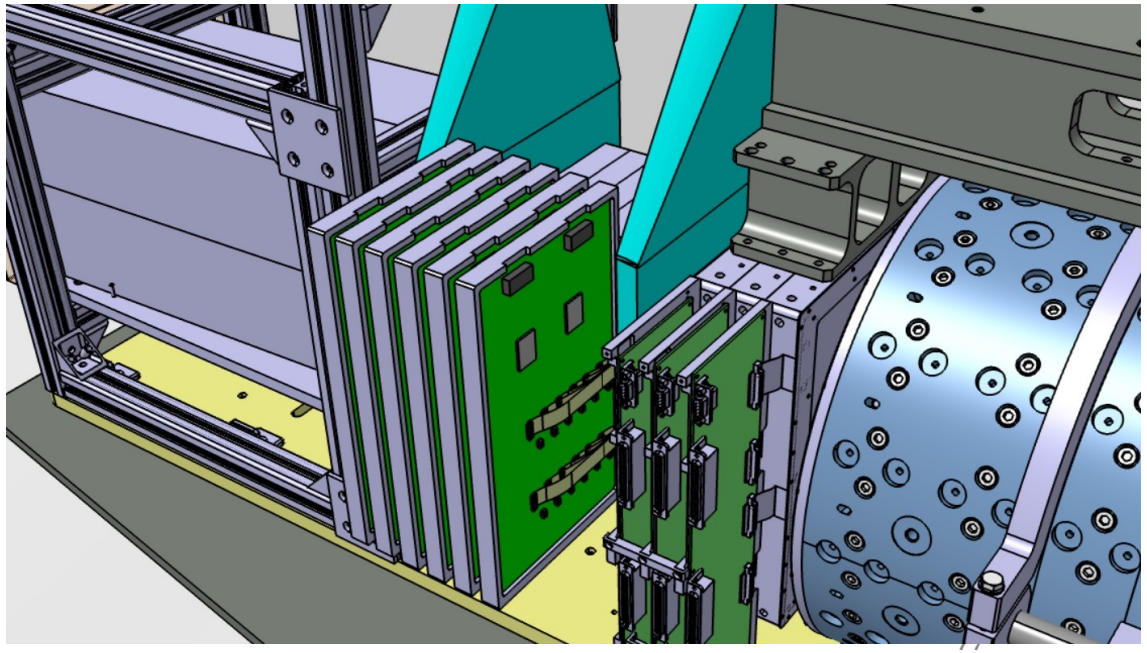
Status:

- Preparing the detailed technical proposal
- Pre-production ASICs in foundry, expected ~ March
- Design of modules, planes, mechanics, read-out in progress
- Simulation and reconstruction in progress

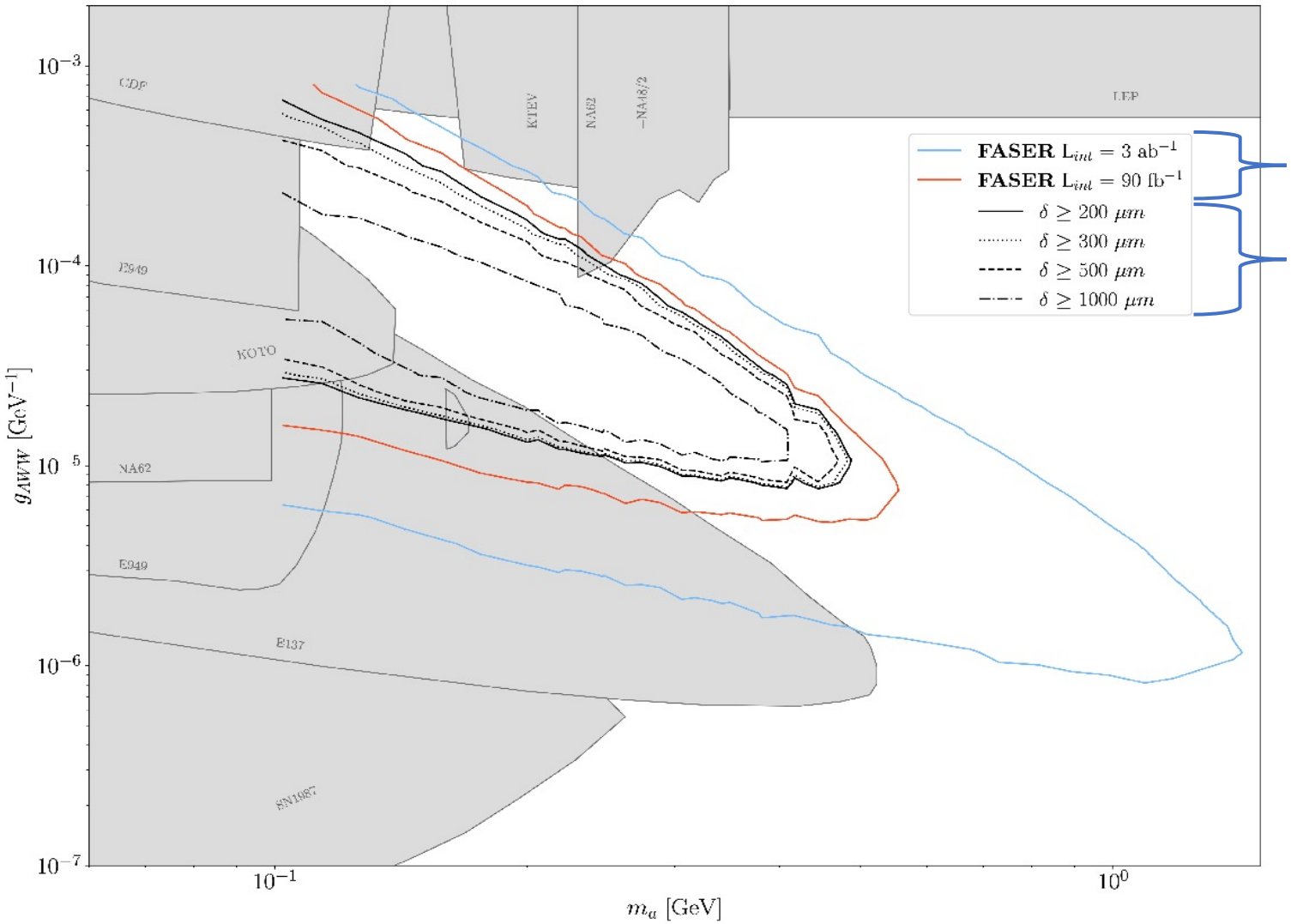
Plan:

- Install the detector end of 2023 for data taking in 2024 and the rest of Run3





Reach for ALPs



2-photon pairs with
E>250 GeV and $\delta_{\gamma\gamma}$ > 0.2mm
Zero background events assumed

Ideal detector (100% efficiency)

Realistic detector
(65-75% efficiency for a $\delta_{\gamma\gamma}$ = 0.2 mm,
85-90% efficiency for $\delta_{\gamma\gamma} \geq$ 0.3 mm)

→ 2-photon pairs can be resolved and studied!

Otherwise: Indistinguishable from background

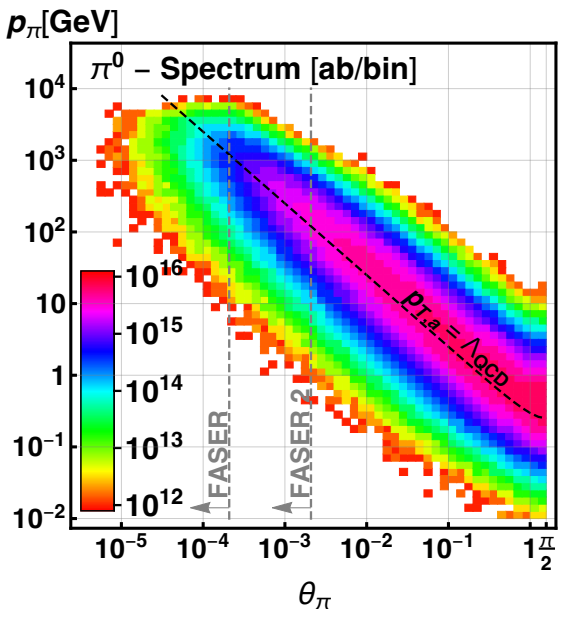
What’s beyond Run3?

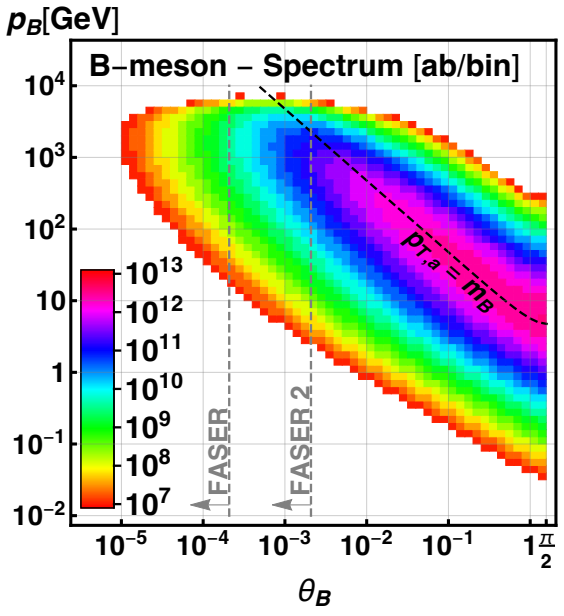
Beyond FASER?

FASER2

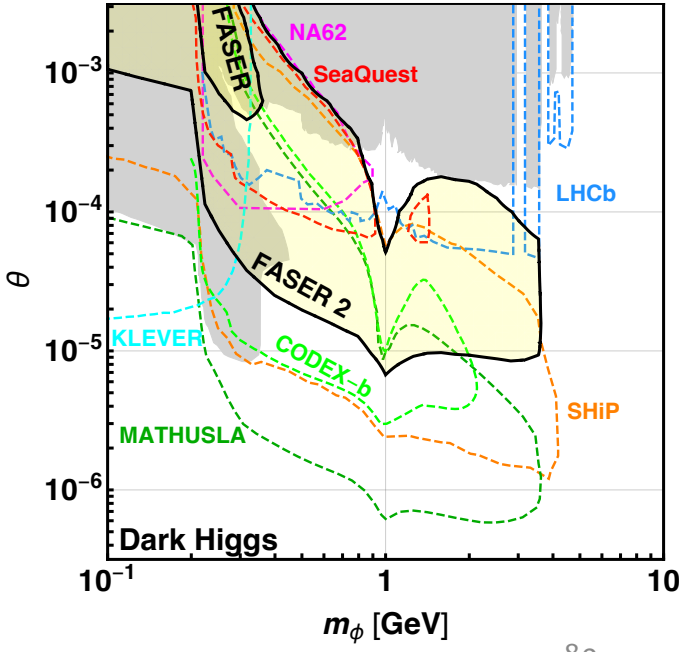
Benchmark model	FASER	FASER 2
Dark photons	✓	✓
$B-L$ gauge bosons	✓	✓
$L_i - L_j$ gauge bosons	...	...
Dark Higgs bosons	...	✓
Dark Higgs bosons with hSS	...	✓
HNLs with e	...	✓
HNLs with μ	...	✓
HNLs with τ	✓	✓
ALPs with photon	✓	✓
ALPs with fermion	...	✓
ALPs with gluon	✓	✓
Dark pseudoscalars	...	✓

More: https://arxiv.org/abs/1811.12522





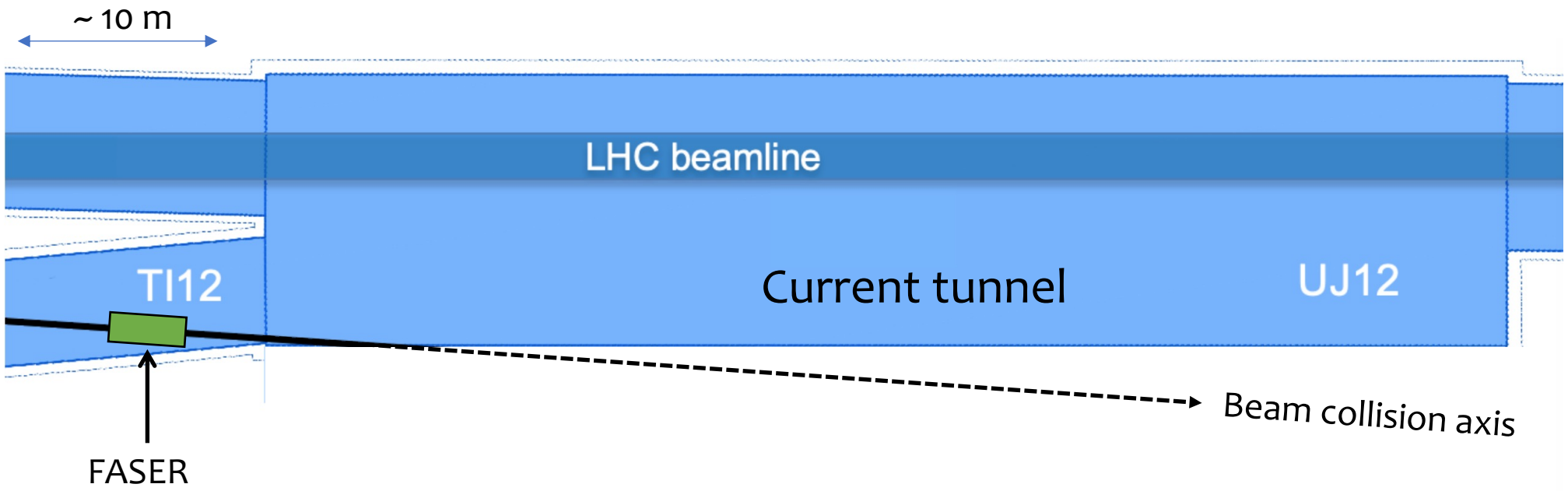
Increased detector radius to 1 m allows sensitivity to particles produced in heavy meson (B, D) decays increasing physics case beyond just increased luminosity



Beyond FASER?

A teaser for the proposed

Forward Physics Facility

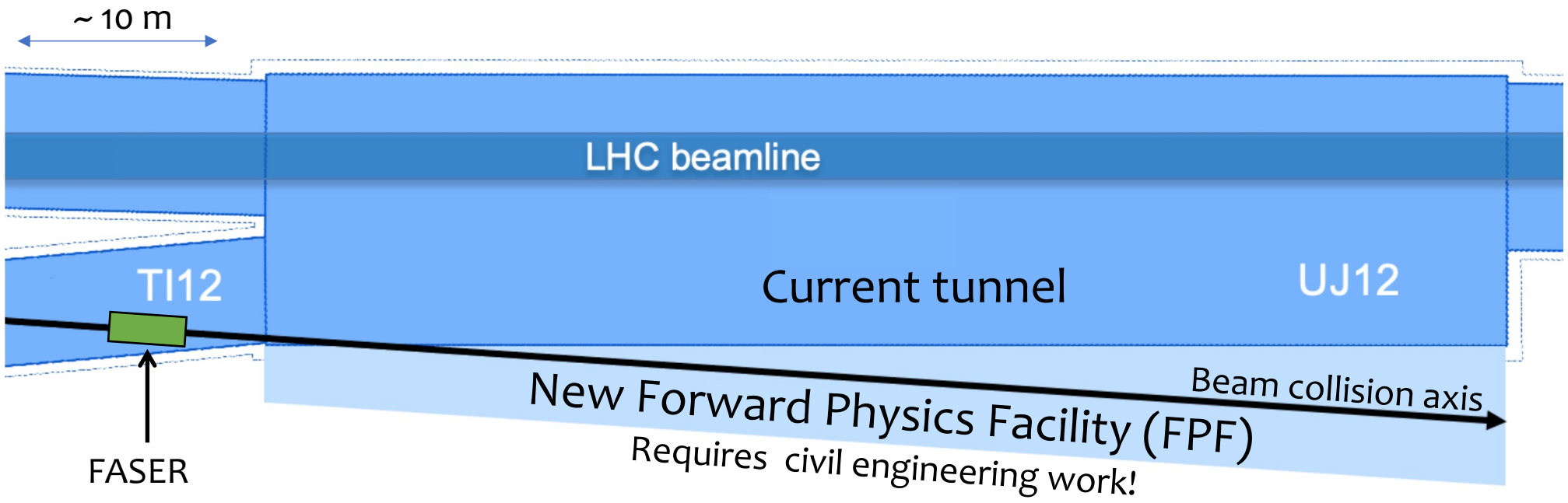


More: LoI for SNOWMASS-2021
FPF – Kickoff workshop
FPF – 4th (latest) workshop

Beyond FASER?

A teaser for the proposed

Forward Physics Facility

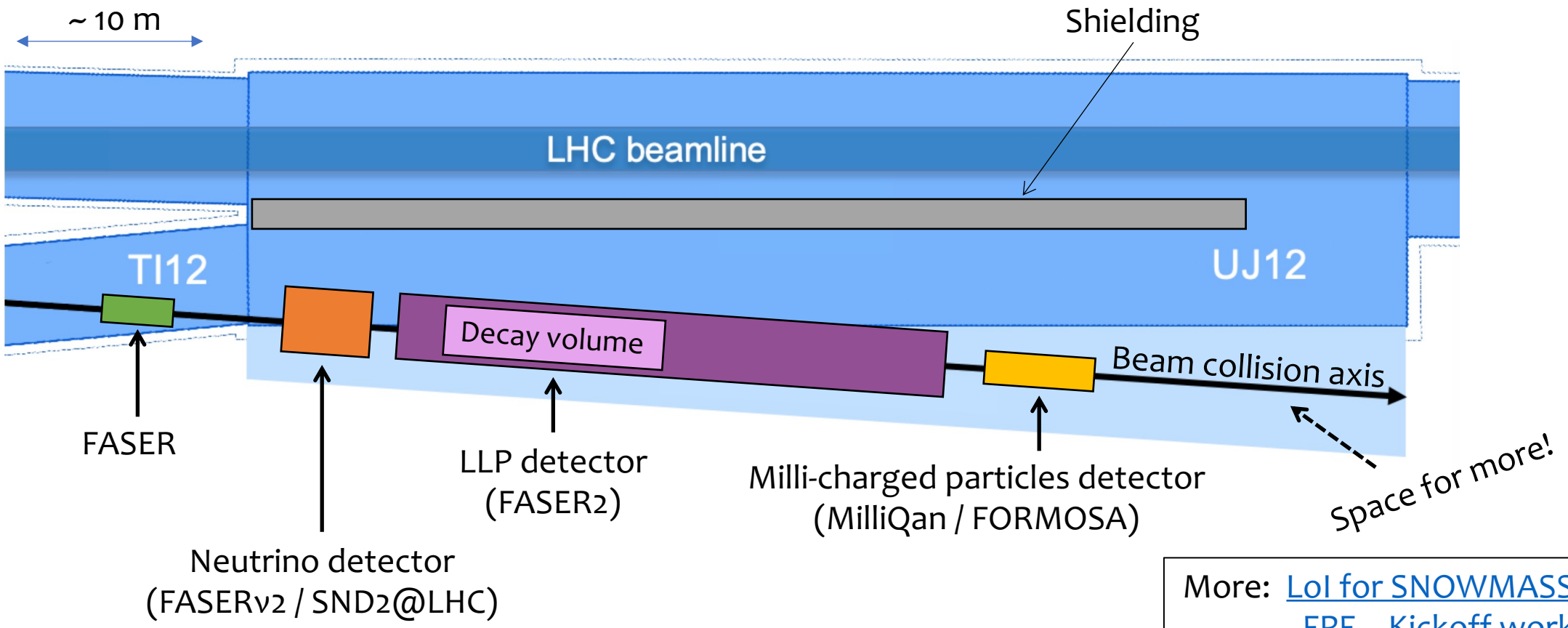


More: LoI for SNOWMASS-2021
FPF – Kickoff workshop
FPF – 4th (latest) workshop

Beyond FASER?

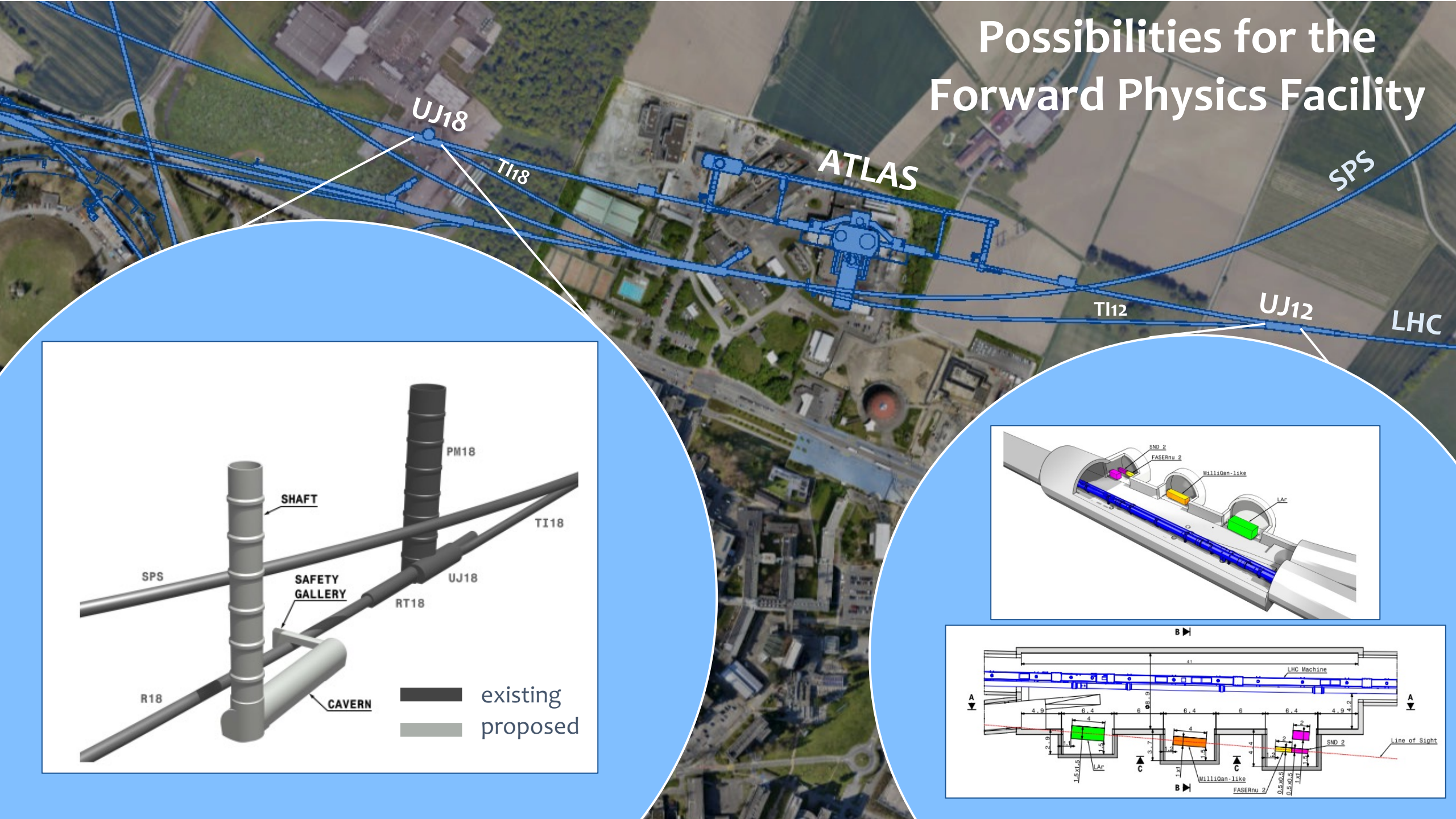
A teaser for the proposed

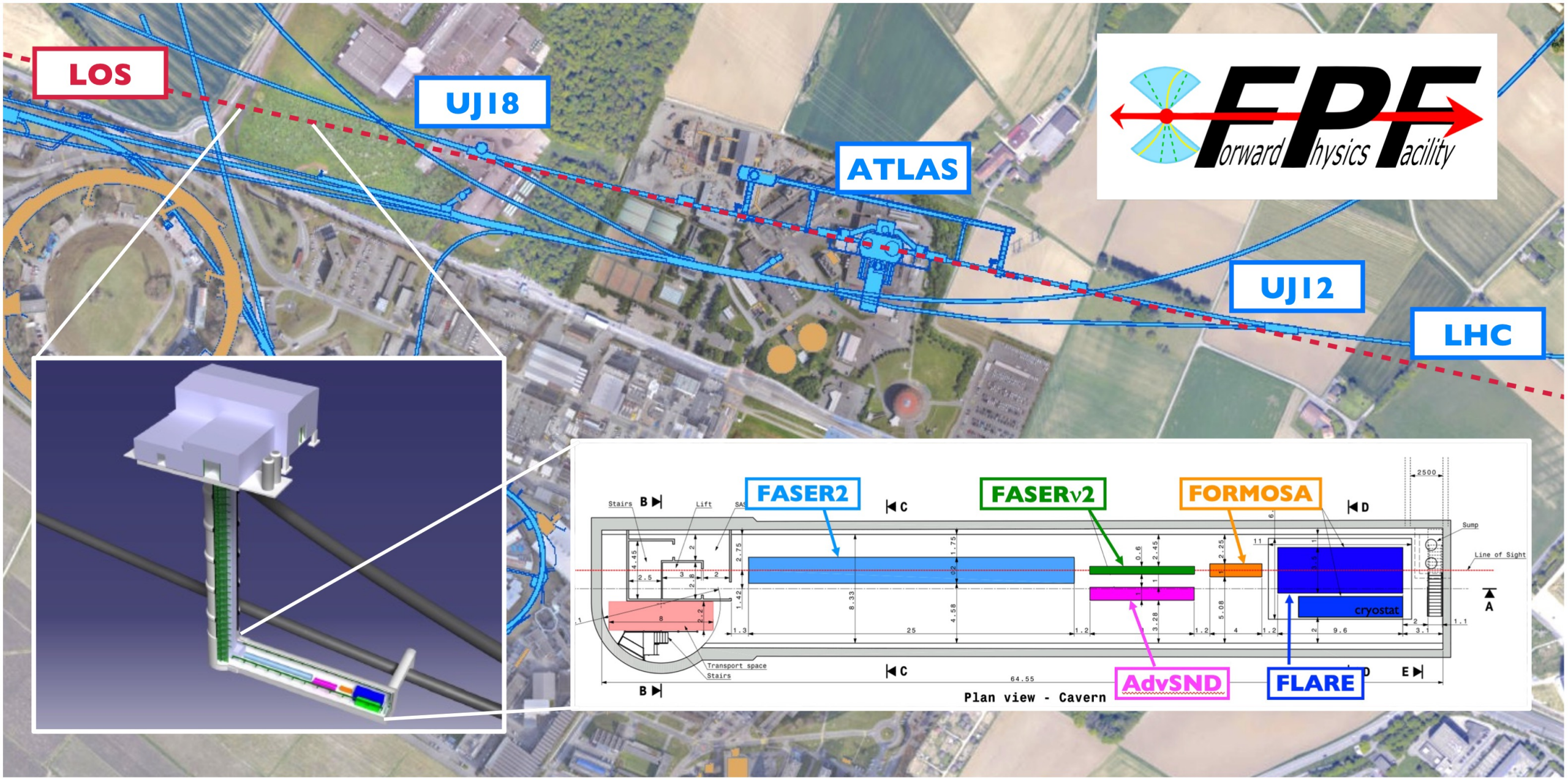
Forward Physics Facility



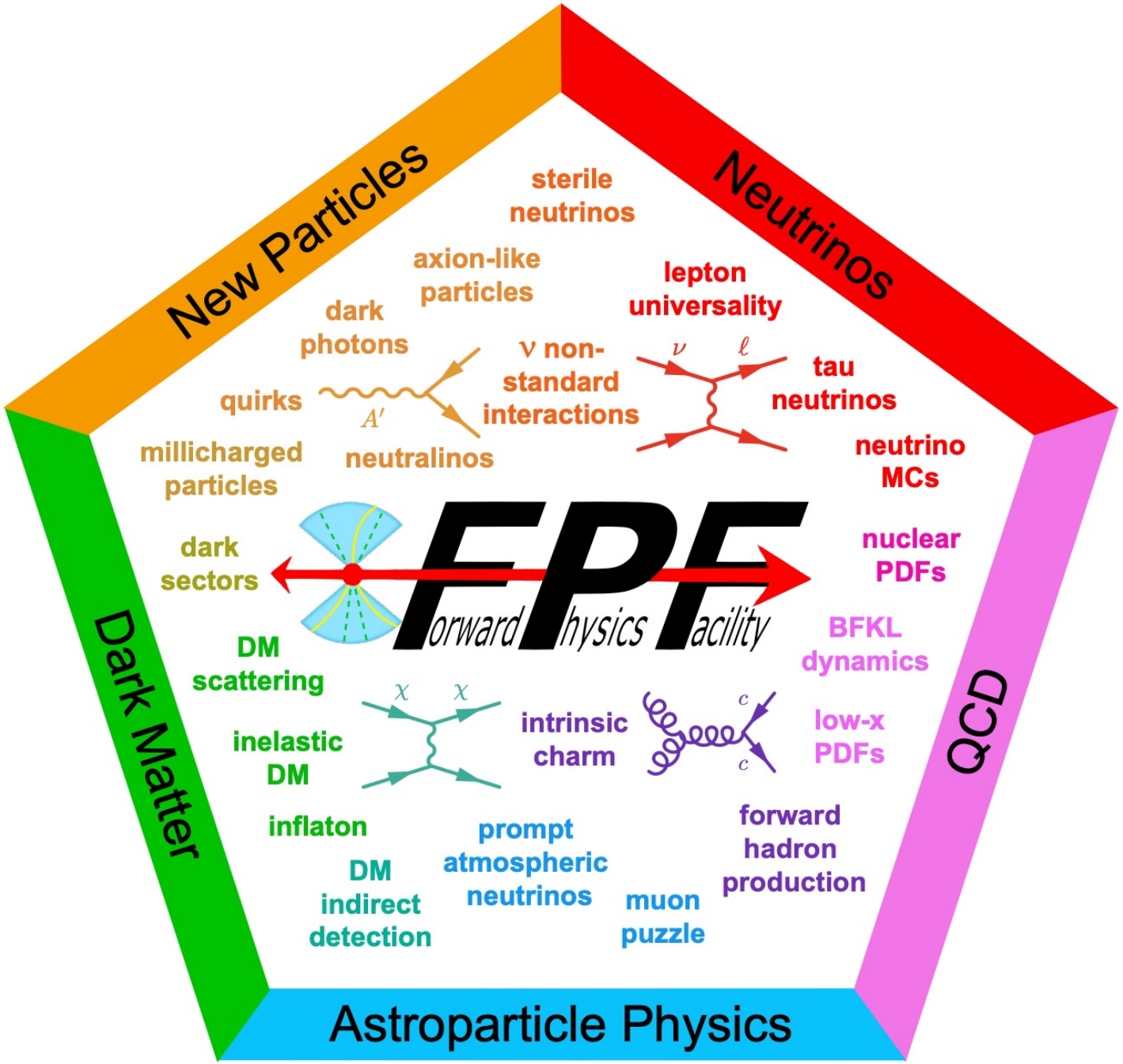
More: LoI for SNOWMASS-2021
FPF – Kickoff workshop
FPF – 4th (latest) workshop

Possibilities for the Forward Physics Facility





arXiv:2203.05090



arXiv:2203.05090

FASER Outlook

- The FASER experiment introduces **a novel approach** to exploit LHC collisions, to:
  - either make **a new discovery** or **constrain parts of phase-space which no current experiment has access to**; and
  - make the first **collider-originated neutrino measurements**
- Collaboration (& CERN technical teams) have worked feverishly to construct, commission and install the detector over the current Long Shutdown
- **Goal: get ready for data taking with the start of Run3!**
- Have started planning upgrades, and thinking about FASER2 & a future facility to further exploit forward production in LHC collisions!
- **Lots of exciting physics ahead!**

Stay in touch:
https://faser.web.cern.ch/
@FASERexperiment

FASER Thanks!

FASER Collaboration: 8 countries, 19 institutes, about 70 members

- Many thanks to my collaborators for providing material & great pictures from testing & installation, in particular Claire Antel (UniGe), Jamie Boyd (CERN) and Brian Petersen (CERN)
- And to the Heising-Simons foundation, Simons foundation, SNSF and CERN for their financial support

FNSNF Swiss National Science Foundation

Université de Genève Faculty of Science

Heising-Simons Foundation

Simons Foundation

CERN

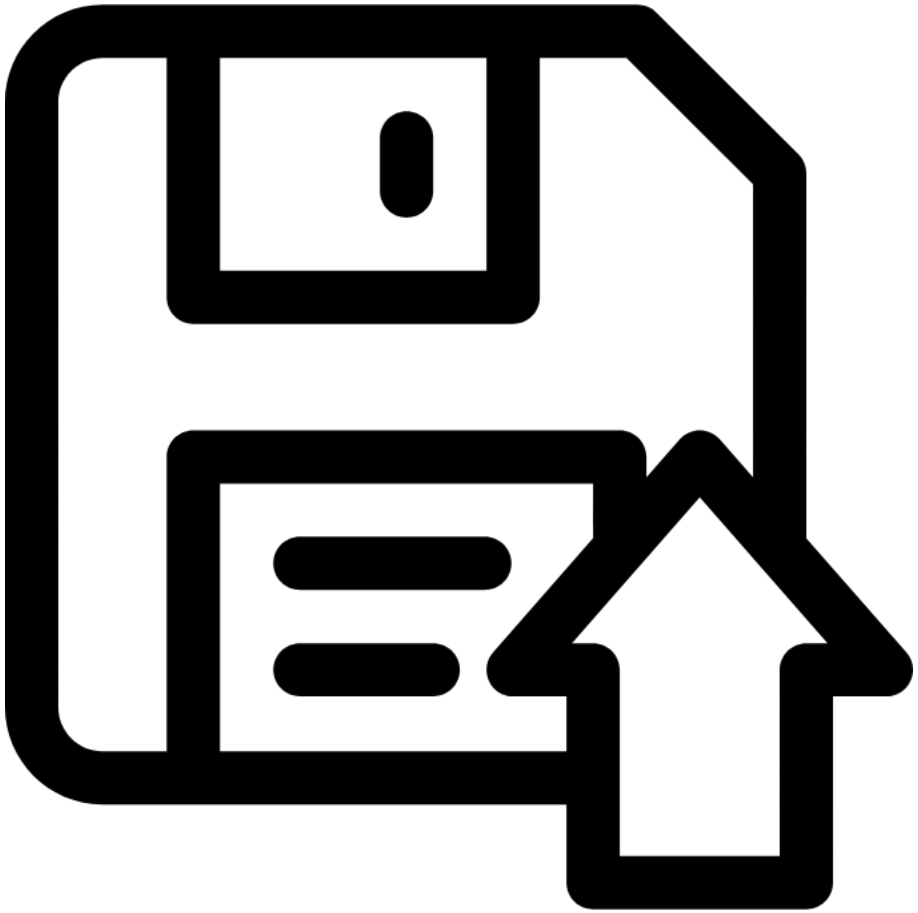
References

FASER collaboration:

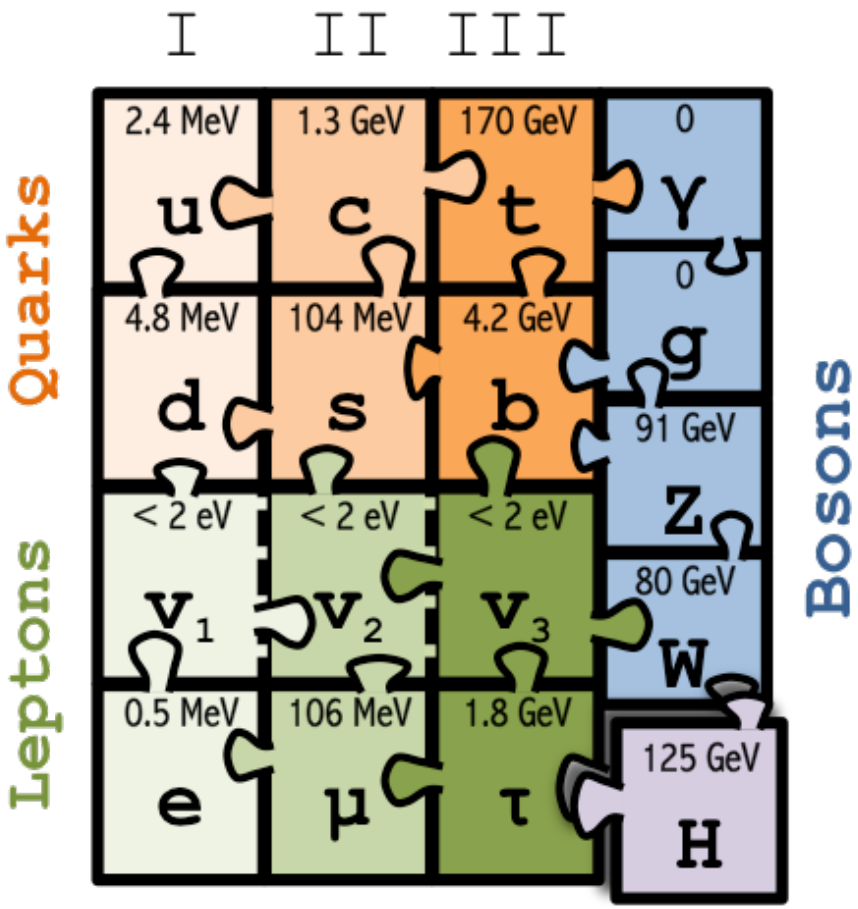
- Letter of Intent arXiv:1811.10243
- Technical Proposal arXiv:1812.09139
- FASER's Physics Reach for Long-Lived arXiv:1811.12522
- Input to the European Strategy for Particle Physics Update arXiv:1901.04468
- Detecting and Studying High-Energy Collider Neutrinos with FASER at the LHC arXiv:1908.02310
- Technical Proposal of FASERν neutrino detector arXiv: 2001.03073
- Forward Physics Facility Snowmass LoI
- First neutrino interaction candidates at the LHC arXiv:2105.06197
- The trigger and data acquisition system of the FASER experiment arXiv:2110.15186

Plus several theory papers

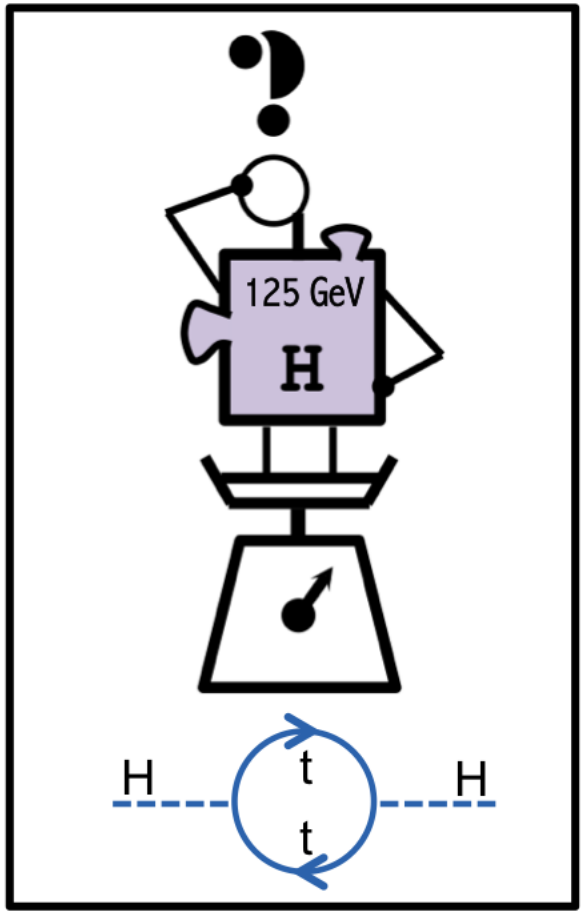
More information: https://faser.web.cern.ch/physics/publications

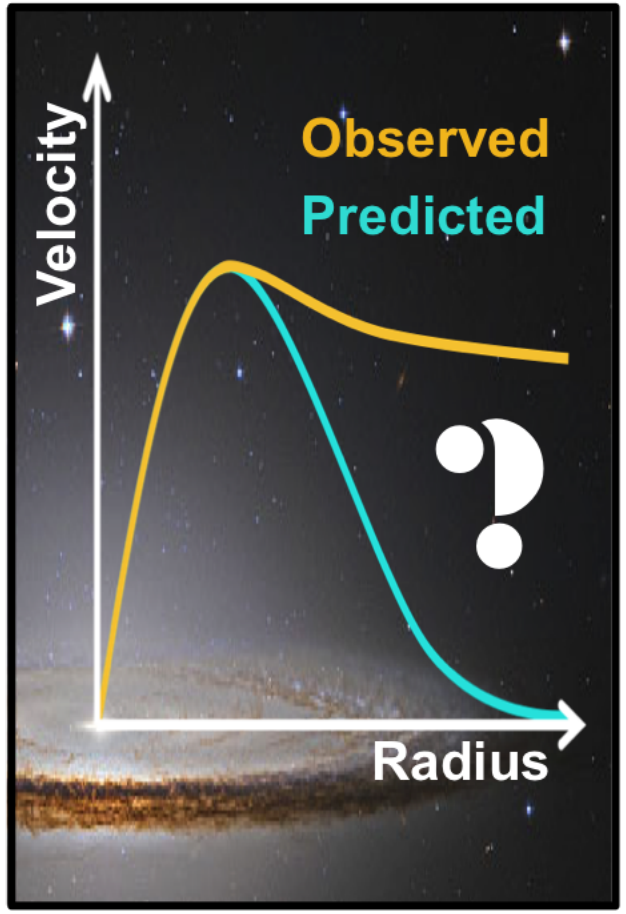


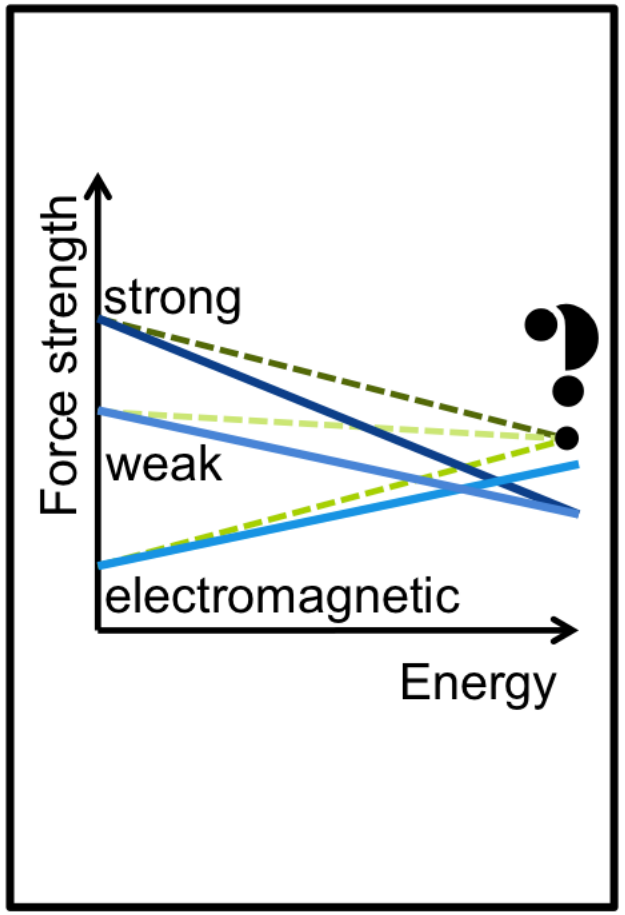
The STANDARD model



… its biggest open questions …







…and its more subtle ones!

The "strong CP problem": Why does QCD preserve CP symmetry?

Within the SM, the QCD vacuum structure introduces a CP violating term in the Lagrangian:

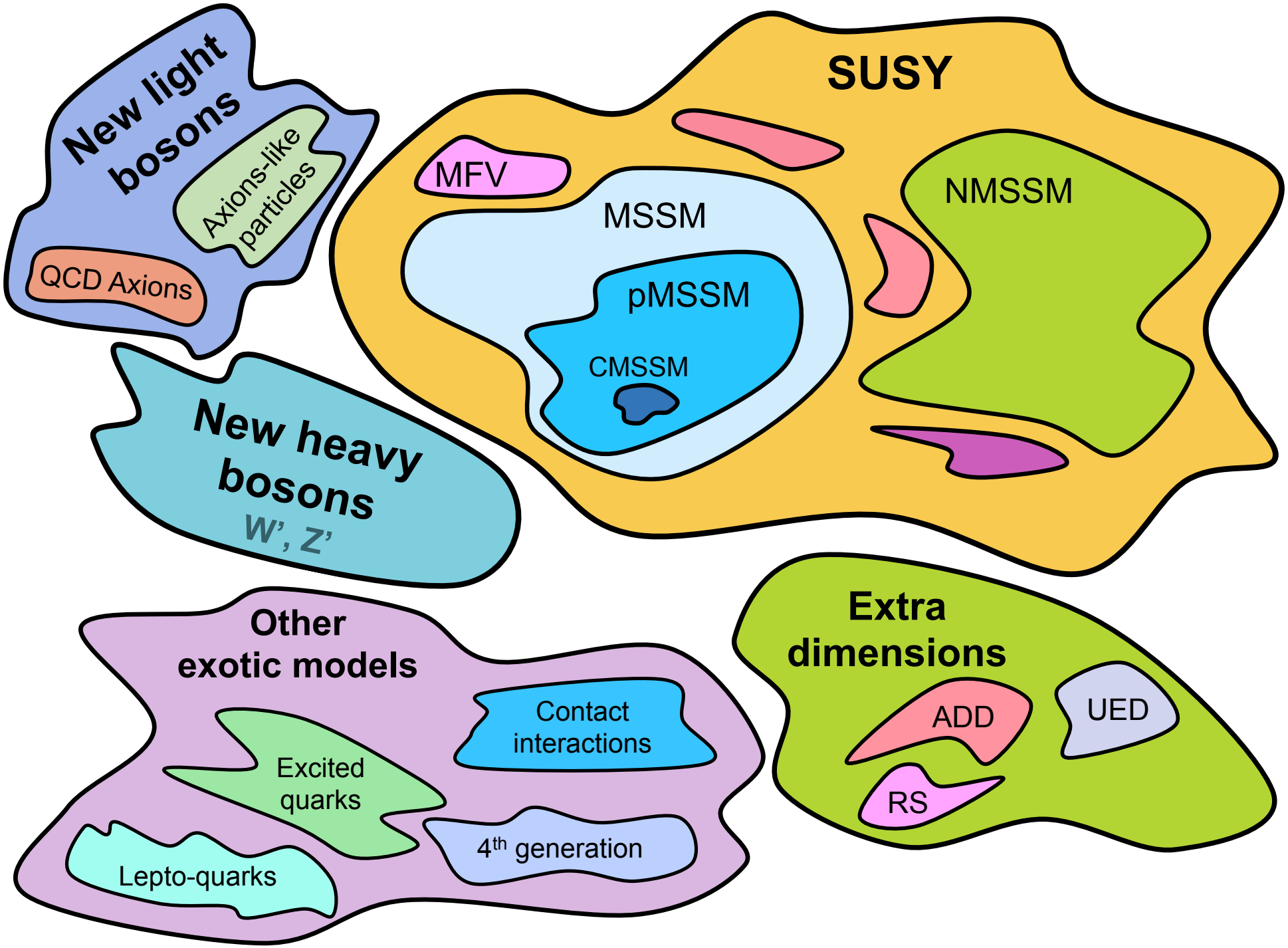
$$L_\theta = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

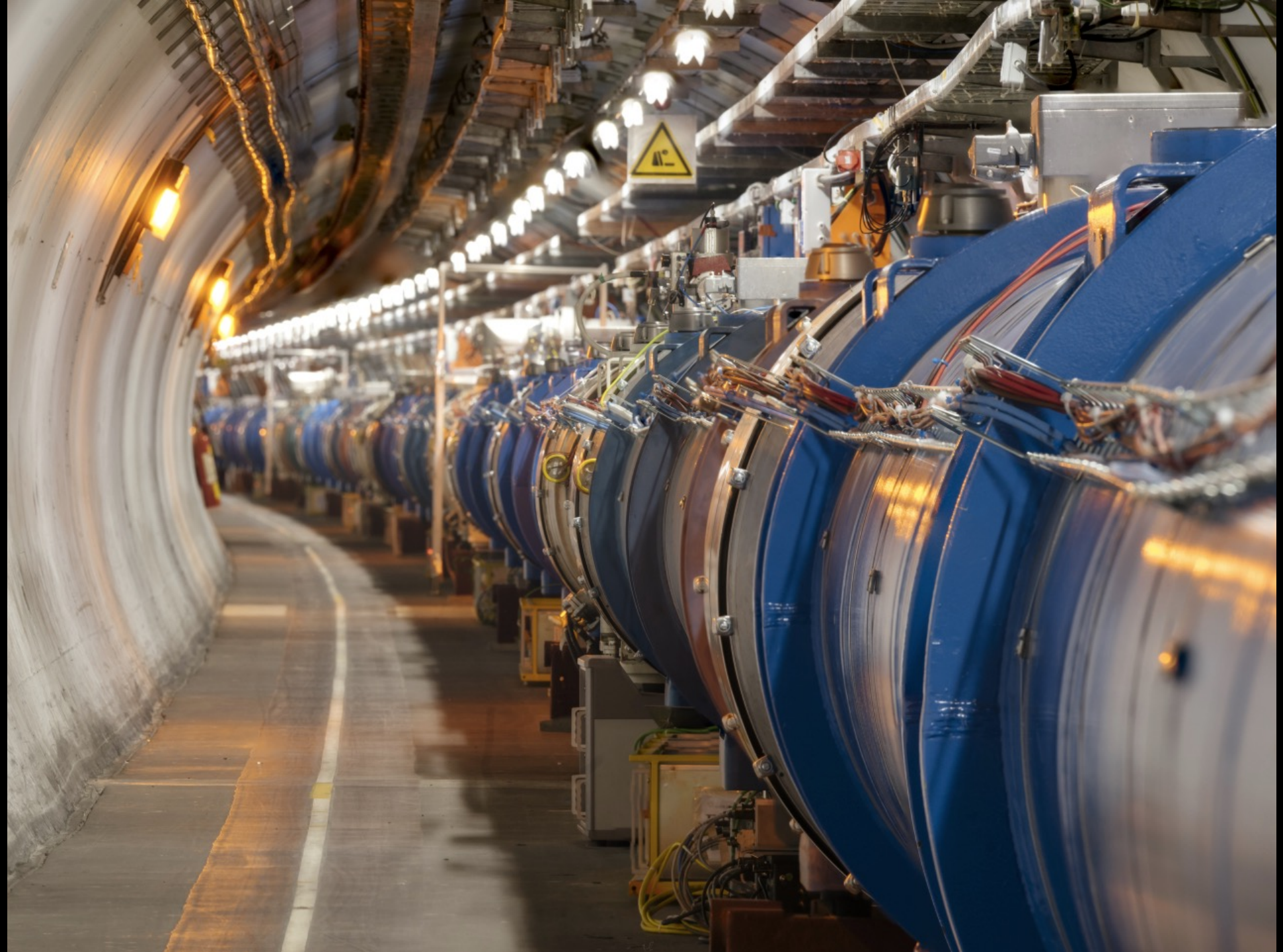
while measurements require that the vacuum angle θ is tiny!

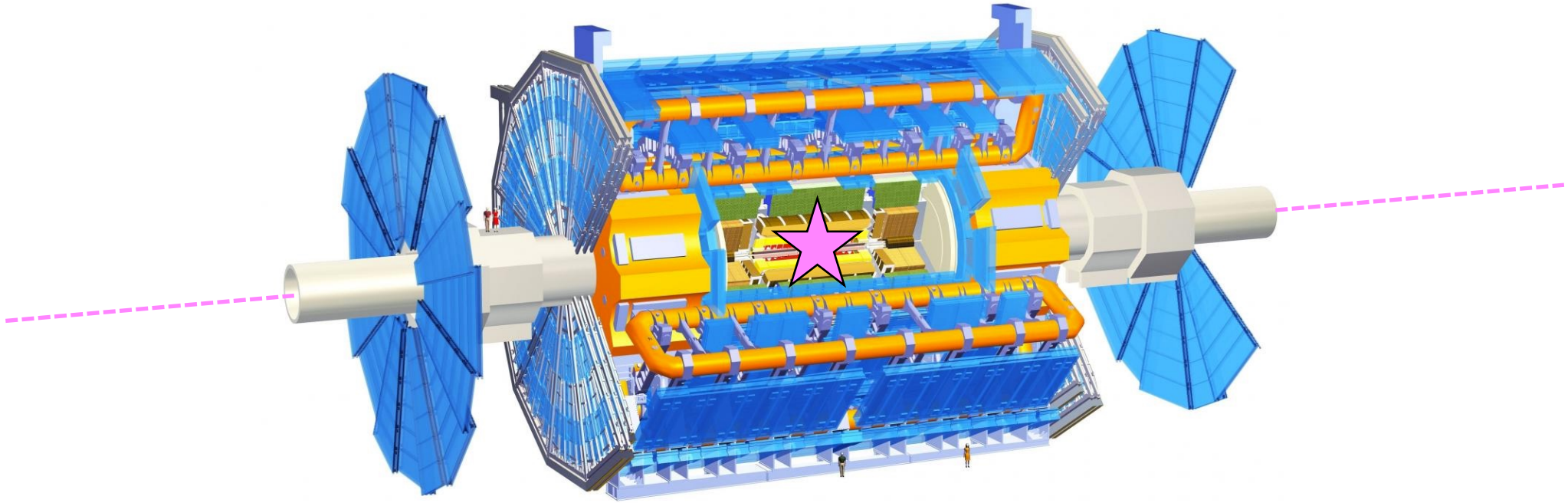
The non-zero angle θ implies non-zero neutron electric dipole moment (EDM)
The angle is stringently constrained by neutron EDM measurements

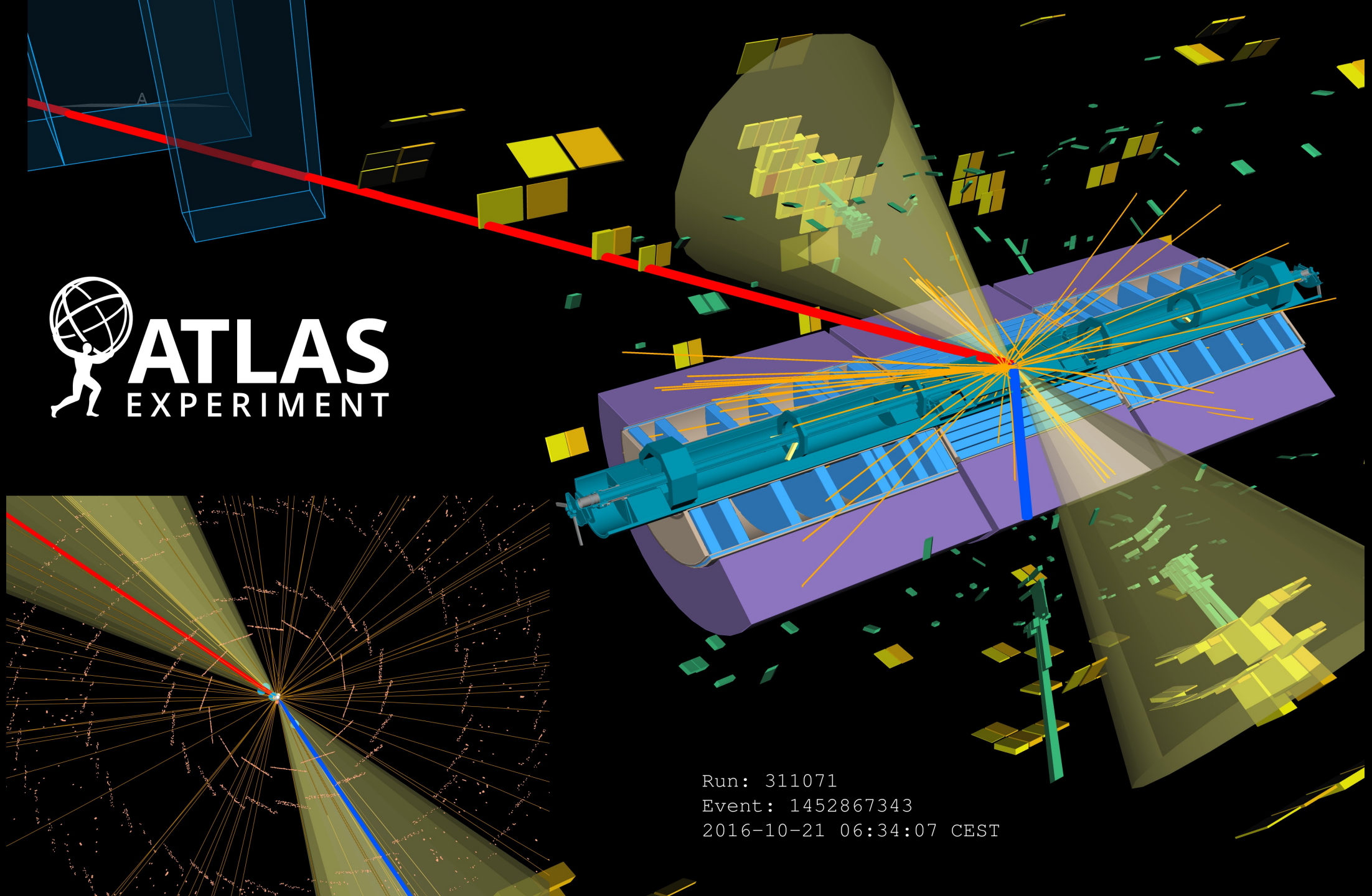
Most sensitive measurement on the neutron EDM to date achieved by the **PSI** experiment **nEDM:**

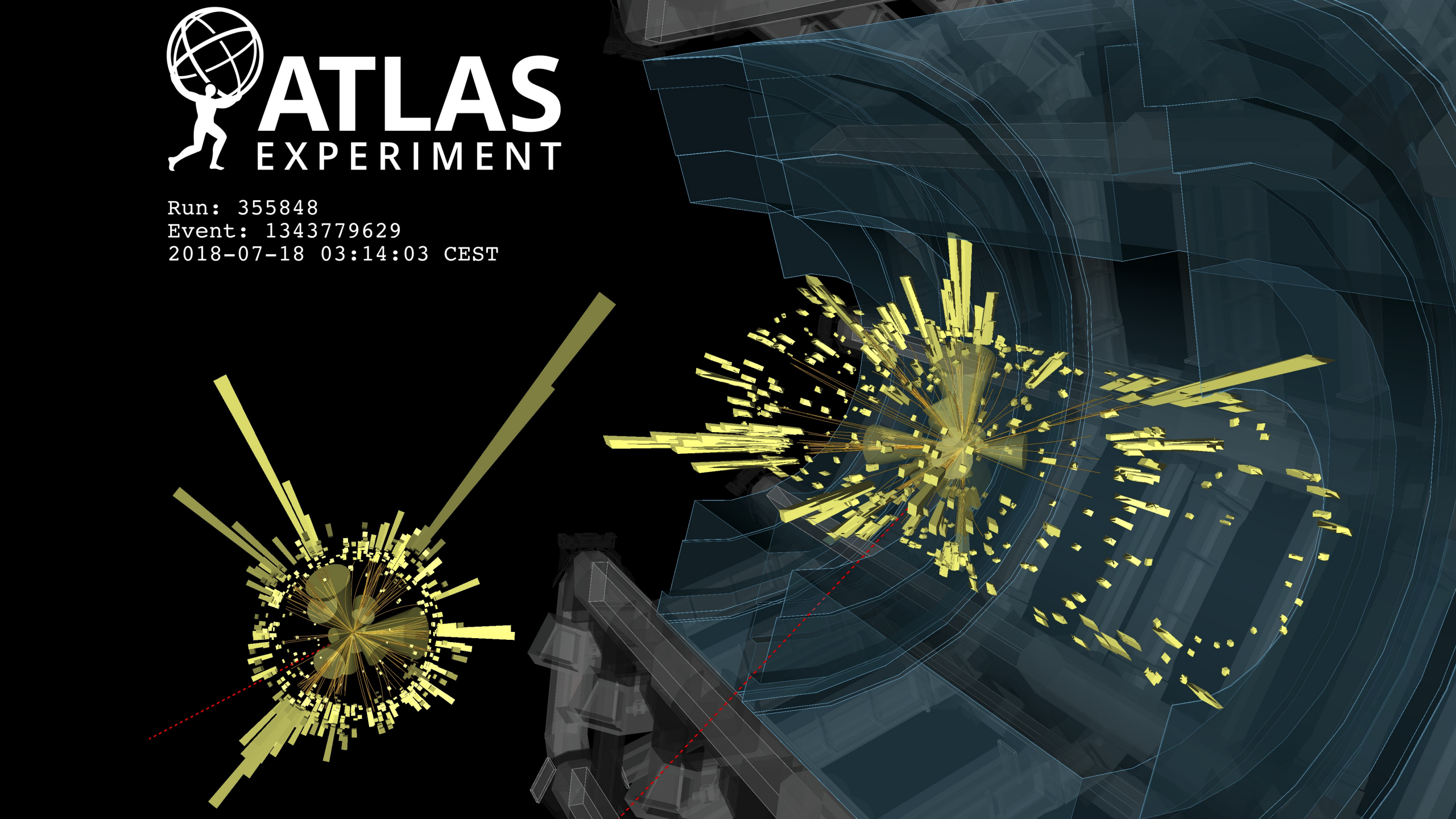
$d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{sys}) \times 10^{-26}$ e·cm.

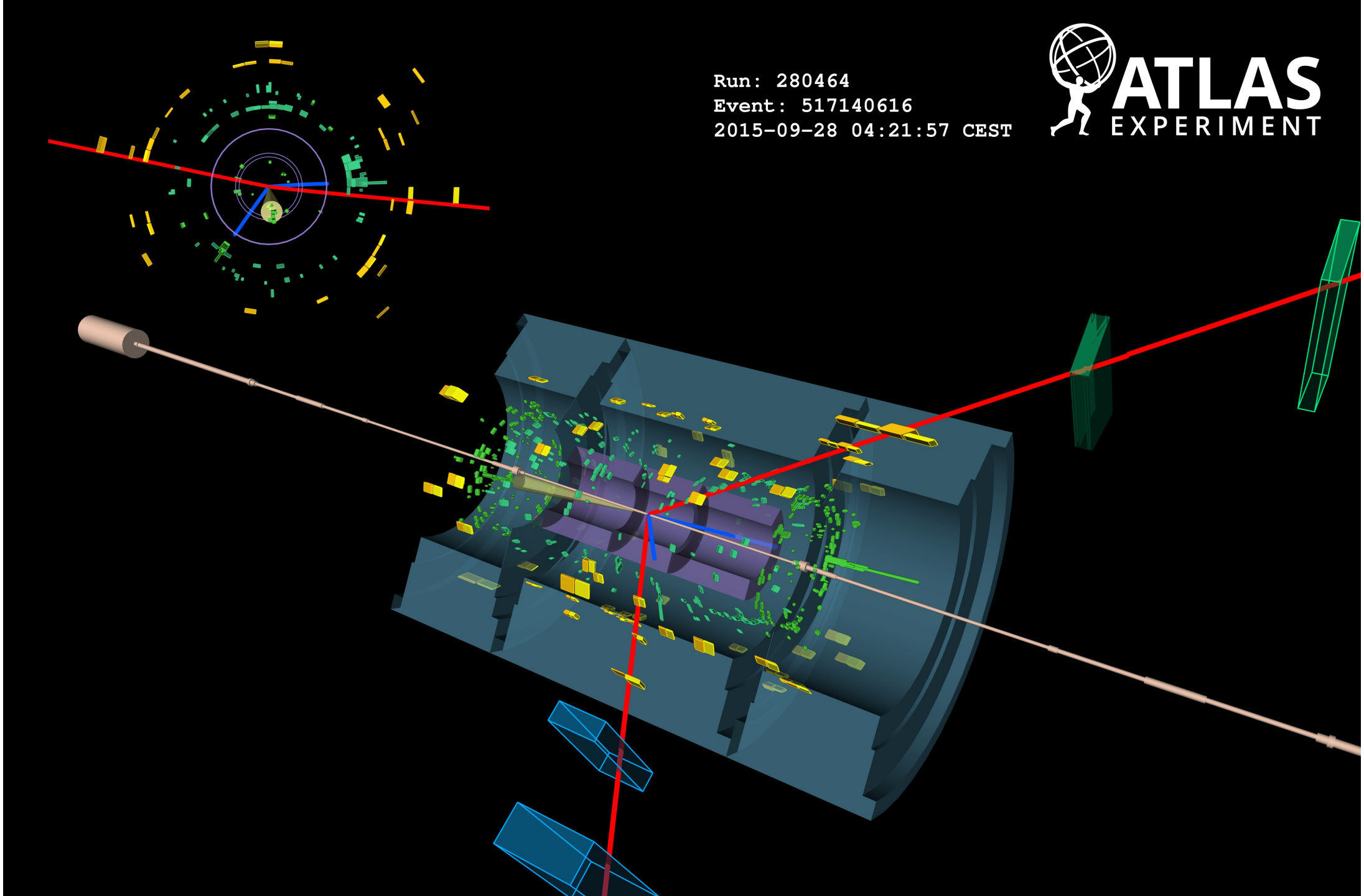

New light bosons
Axions-like particles
QCD Axions
SUSY
MFV
MSSM
pMSSM
CMSSM
NMSSM
New heavy bosons
W', Z'
Other exotic models
Contact interactions
Excited quarks
4th generation
Lepto-quarks
Extra dimensions
ADD
UED
RS



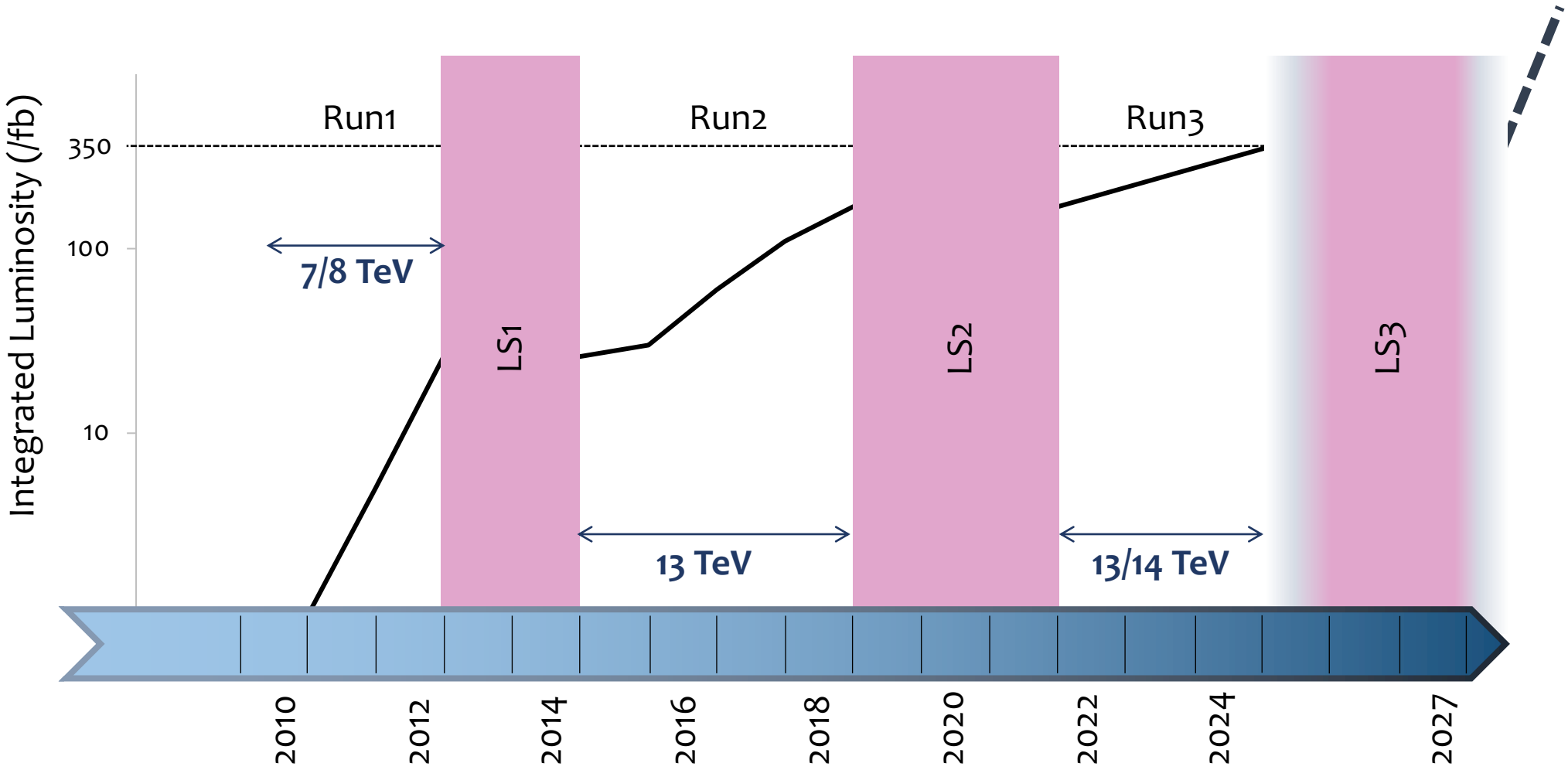



ATLAS
EXPERIMENT
Run: 311071
Event: 1452867343
2016-10-21 06:34:07 CEST


ATLAS
EXPERIMENT
Run: 355848
Event: 1343779629
2018-07-18 03:14:03 CEST


Run: 280464
Event: 517140616
2015-09-28 04:21:57 CEST
ATLAS
EXPERIMENT

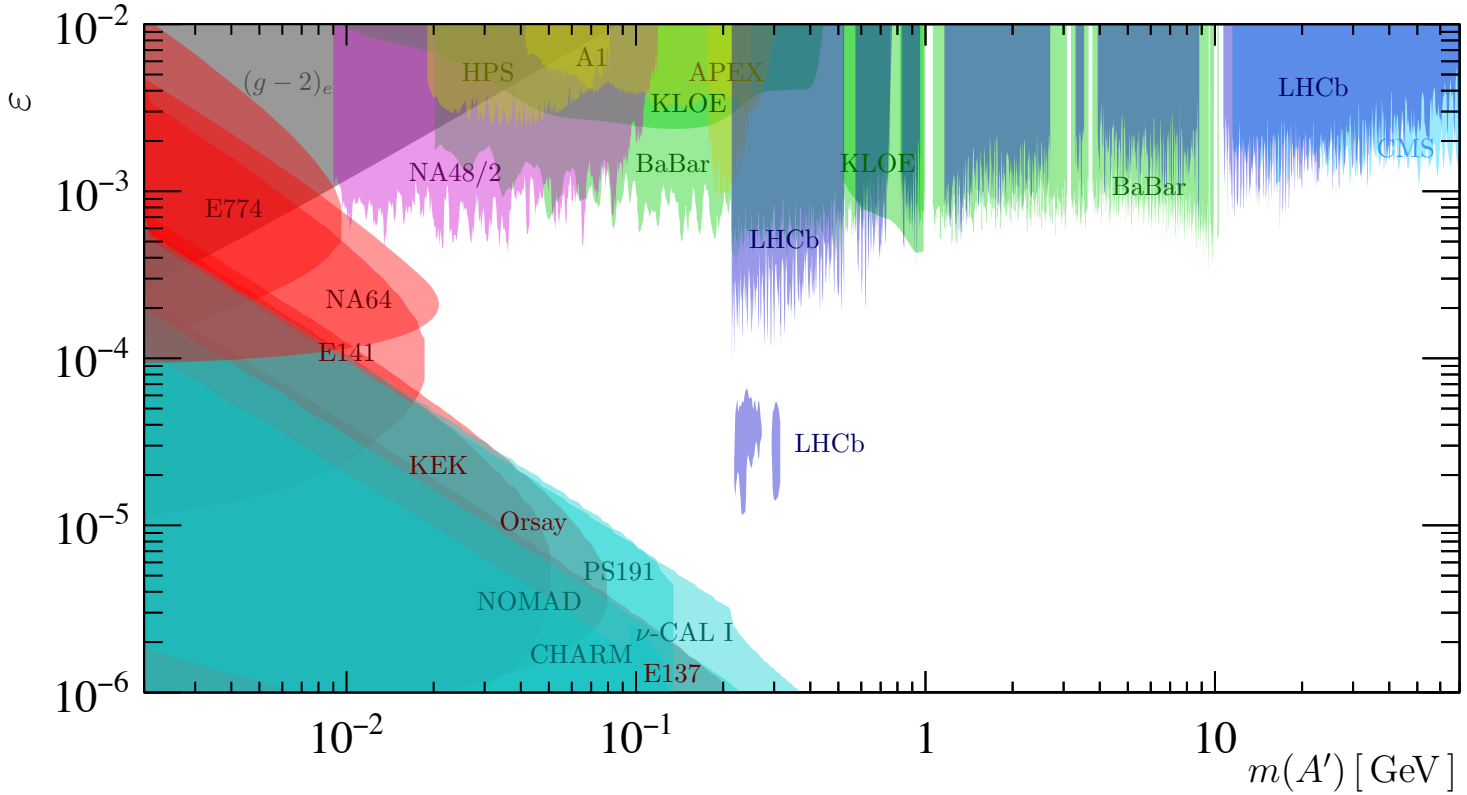
Run1, Run2 and beyond



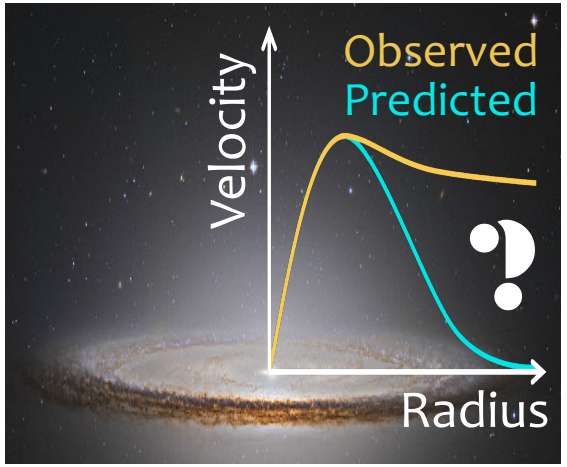
The landscape of LHC physics

Consistent among all experiments,
here using LHCb as an example

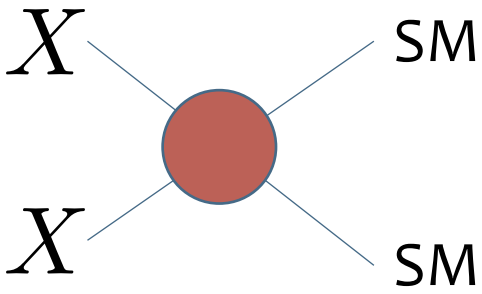
Searches for weakly coupled particles



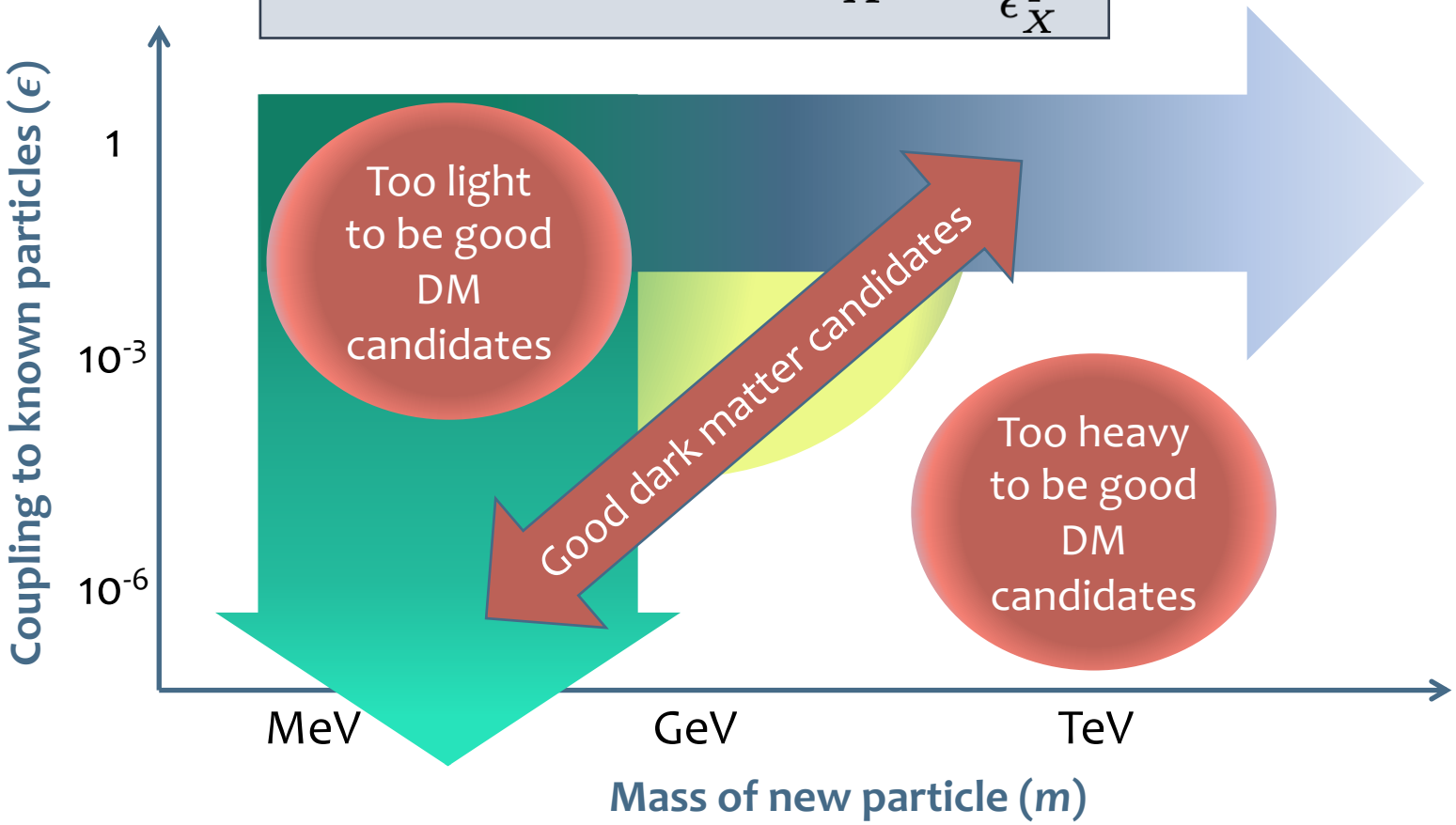
The landscape of new particles @ colliders



- Simple mechanism for DM generation: "freeze out"



Surviving DM density: $\Omega_X \propto \frac{m_X^2}{\epsilon_X^4}$



Feng, Kumar - PRL 101, 231301 (2008)

The landscape of new particles @ colliders

Lifetime

a characteristic of weakly interacting light particles

Distance travelled by particles:

$$L = v\,\tau\,\gamma \propto c\,\frac{1}{\epsilon^2 m}\,\frac{E}{m}$$

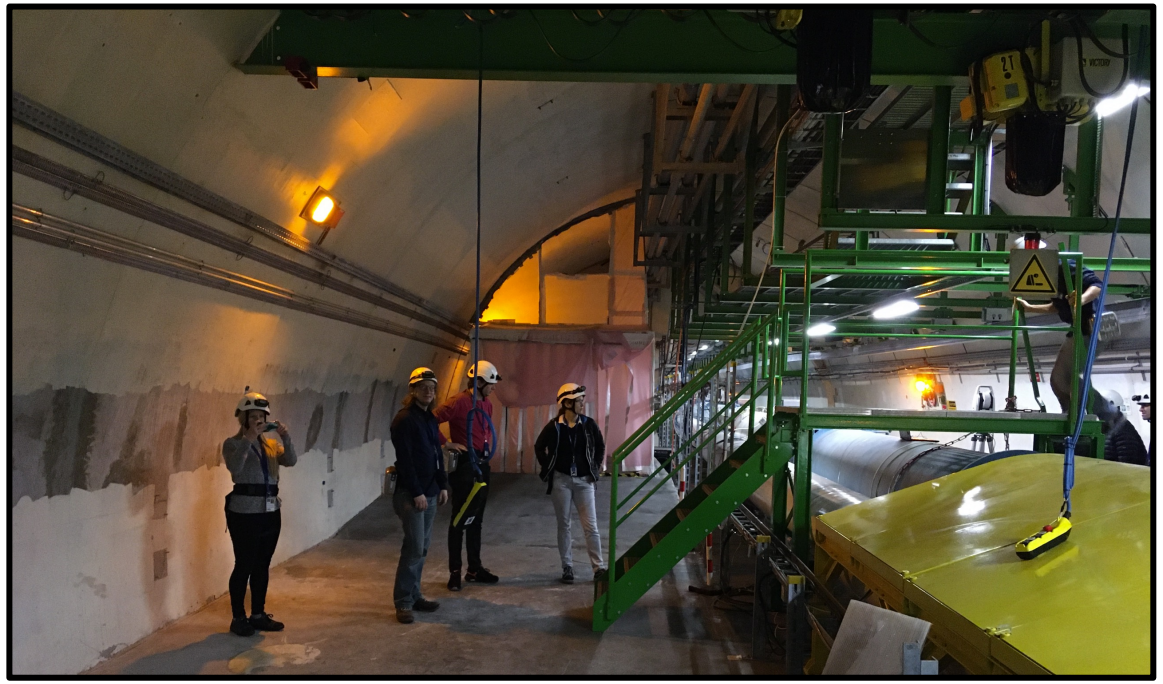
Distinct signatures, exploited in both general purpose and dedicated experiments

Most general purpose searches still do **target particles that decay promptly**

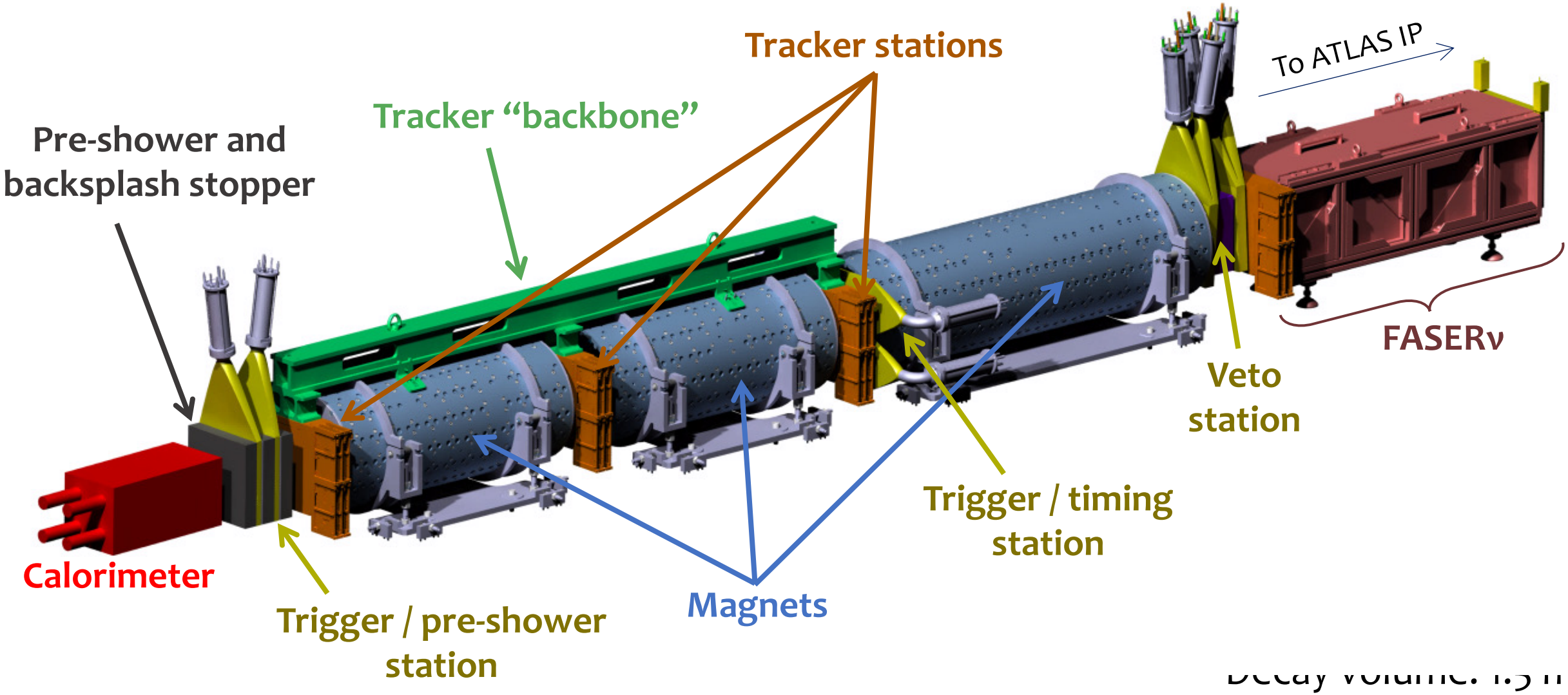
Opportunity for exploration!

Experiments under evaluation: MATHUSLA, milliQan, SHiP, LDMX, …

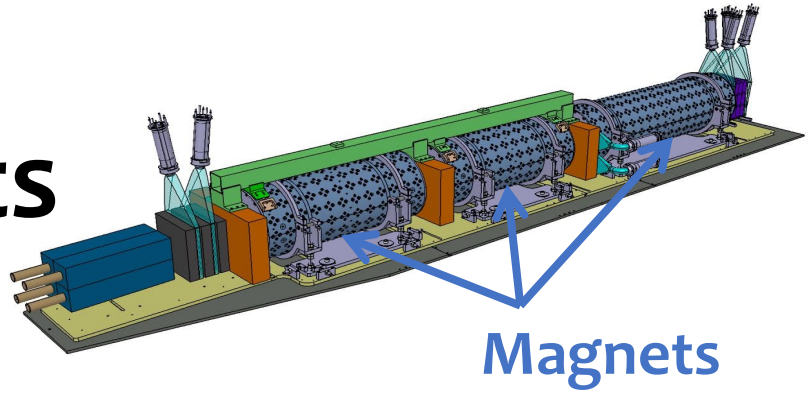
Approved: FASER

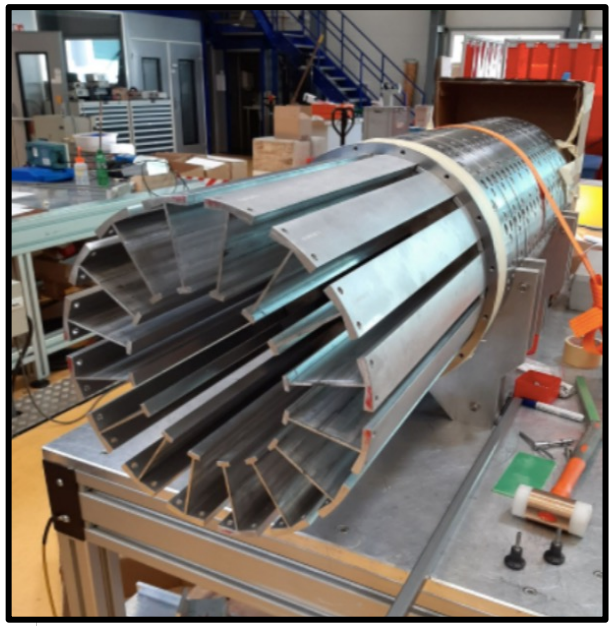


FASER Detector

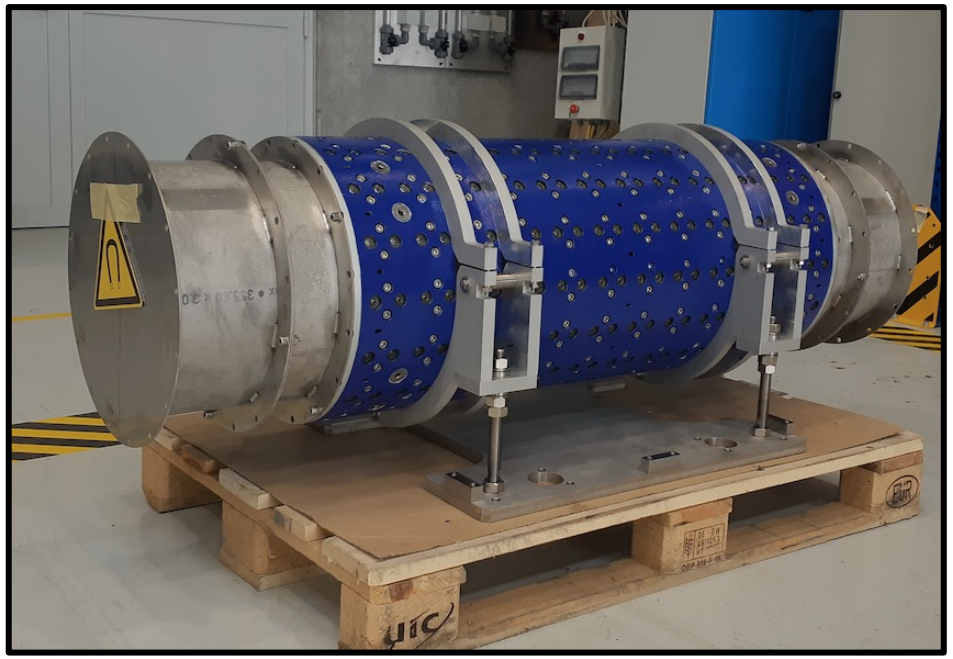


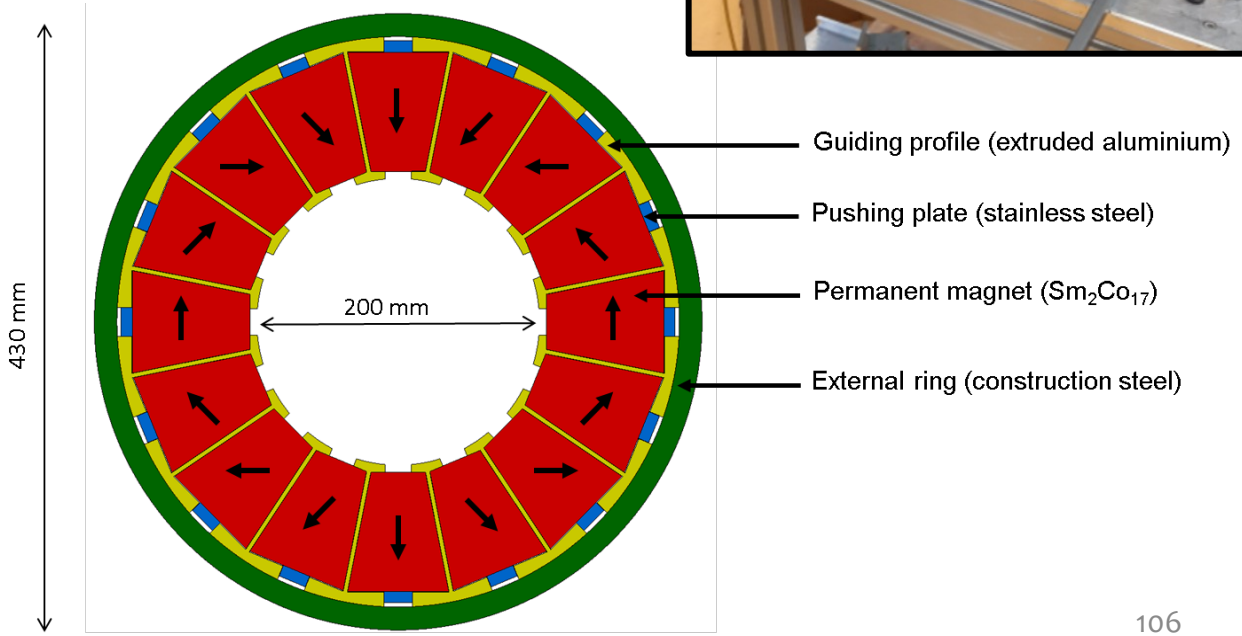
FASER Magnets





- Field of 0.55 T; permanent dipole
- Halbach array design with fixed-field magnets
  - Maximizes field without need for too much support infrastructure
  - Allows for a compact design, reducing amount of digging

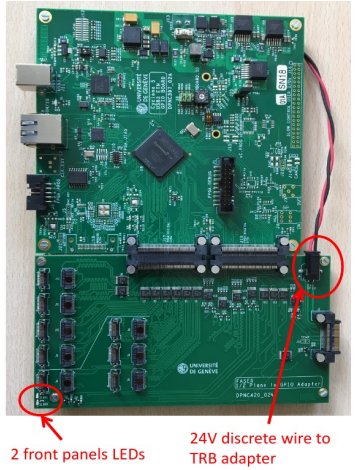


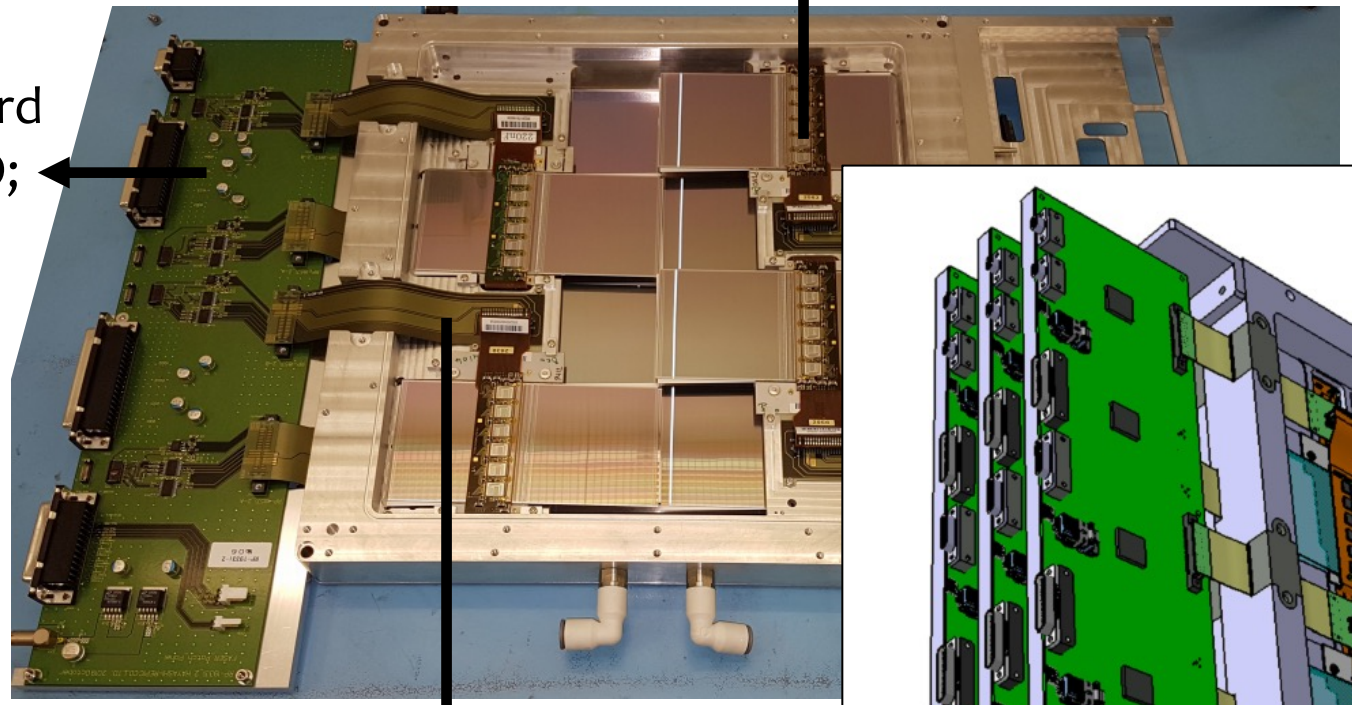


FASER Tracker

SCT module ASICs, require ~ 5 W / module

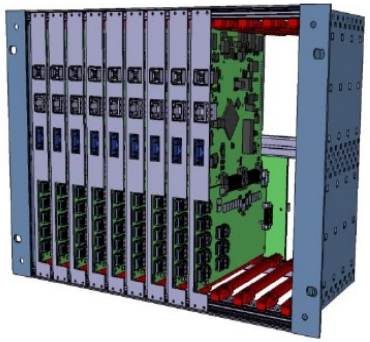
Patch panel to custom board based on home-made GPIO; Power (HV/LV), monitoring and readout lines.

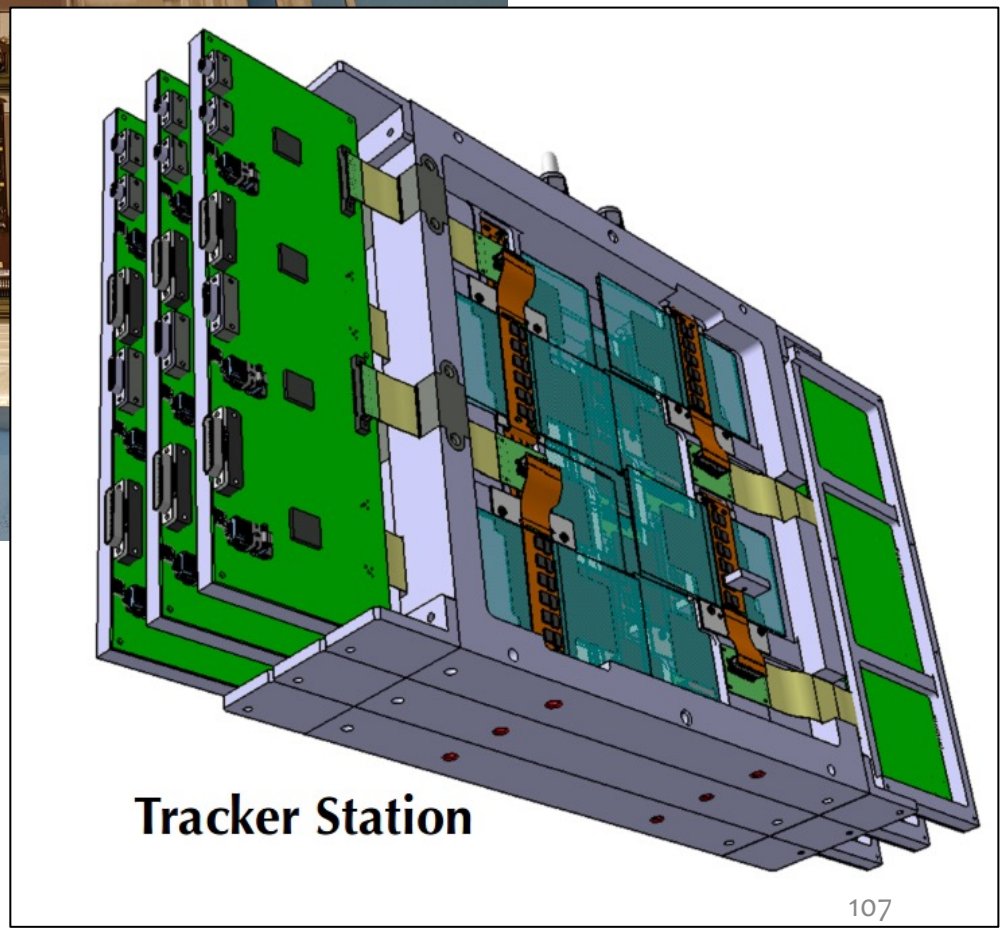




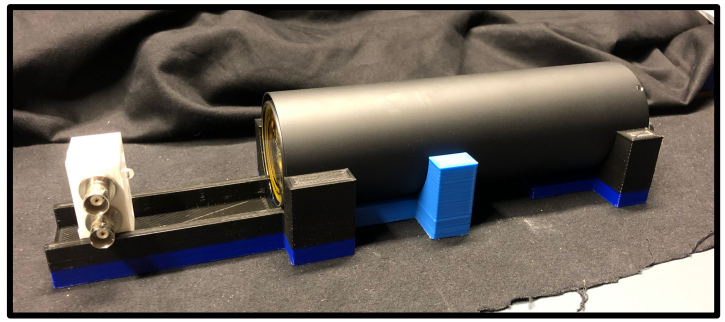
FLEX cables

Into custom-made mini-crate



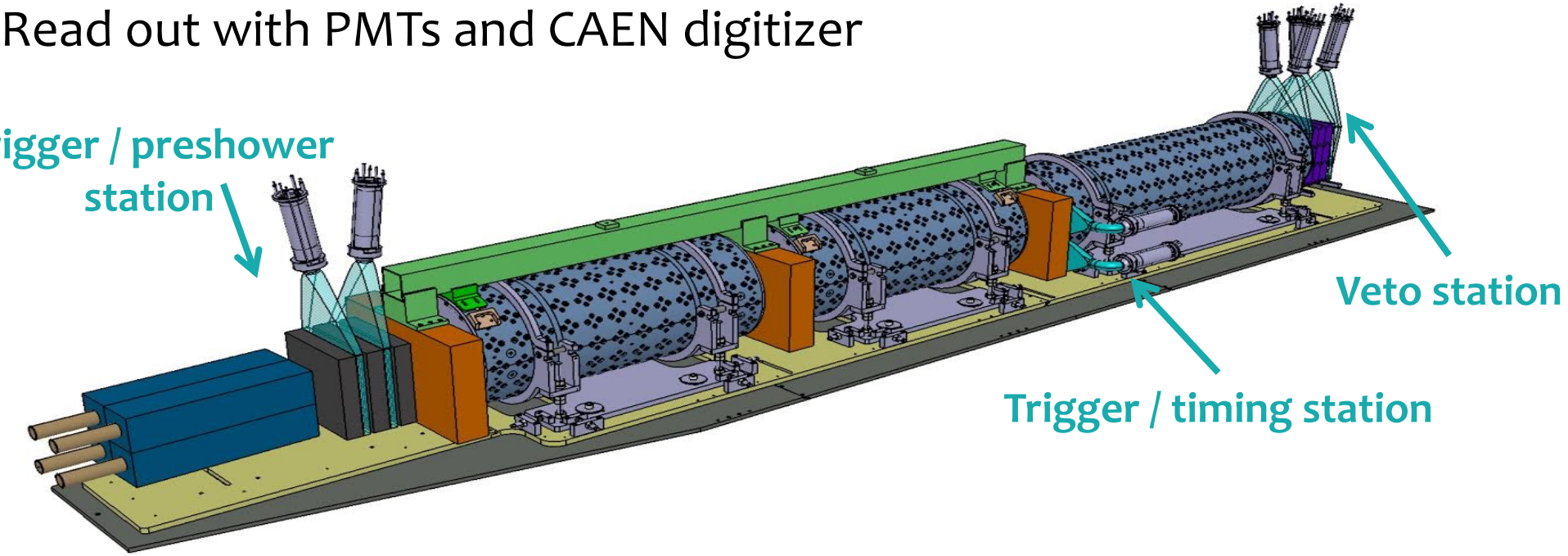


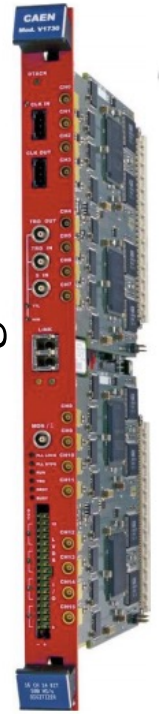
FASER Scintillators



Scintillator PMTs

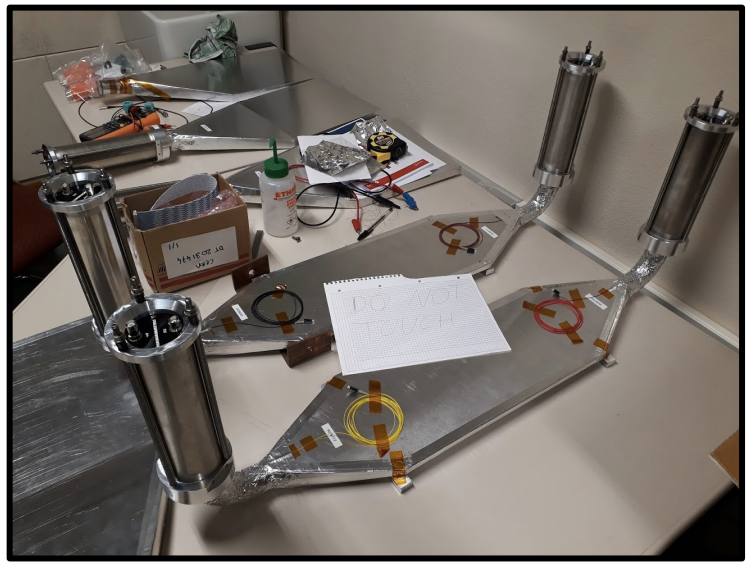
- Three stations all providing triggering capability:
  - Very high efficiency veto station for incoming charged particles (x4 planes)
  - Timing station; precise timing (~ ns) wrt IP (x1 plane)
  - Preshower station; coincidence with timing station (x2 planes)
- Read out with PMTs and CAEN digitizer



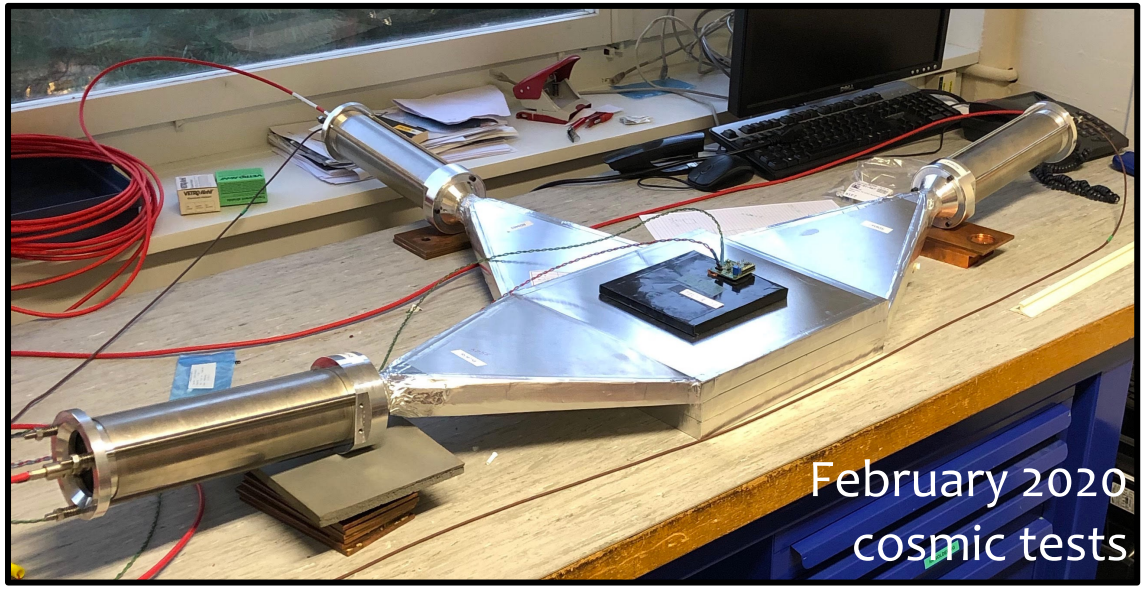


CAEN Digitizer

FASER Scintillators



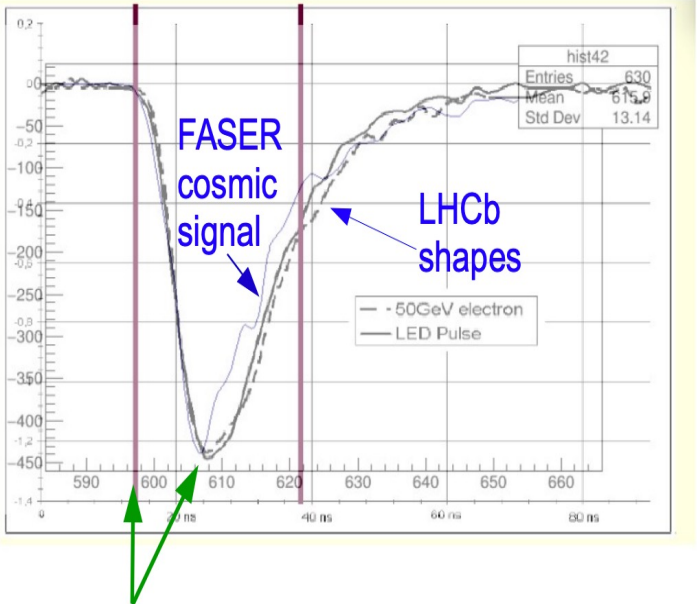
FASER scintillators produced at CERN



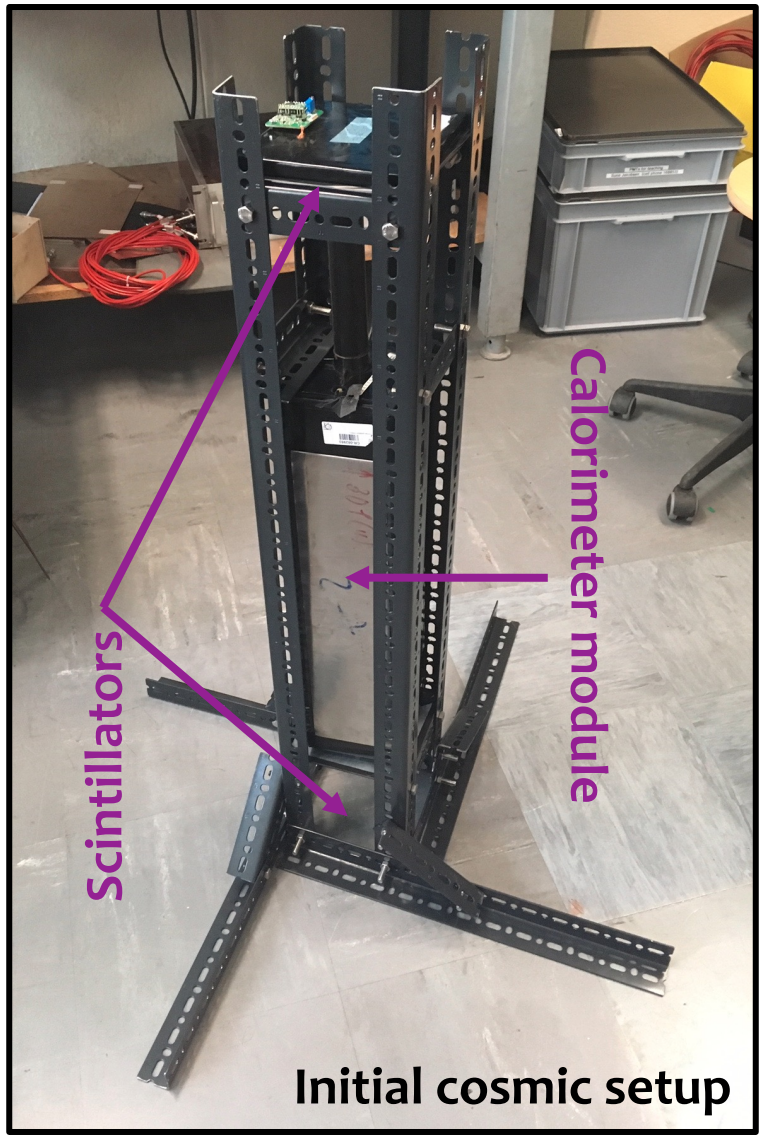
February 2020
cosmic tests

FASER scintillators mounted in their support

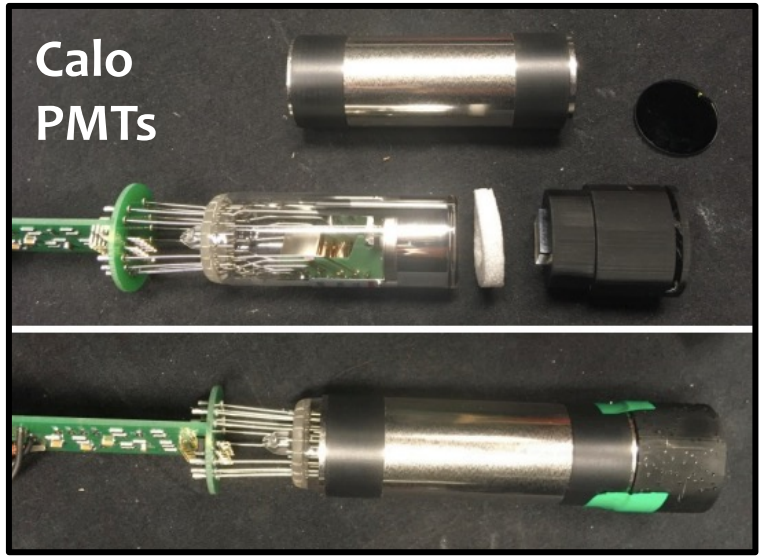
FASER Calorimeter

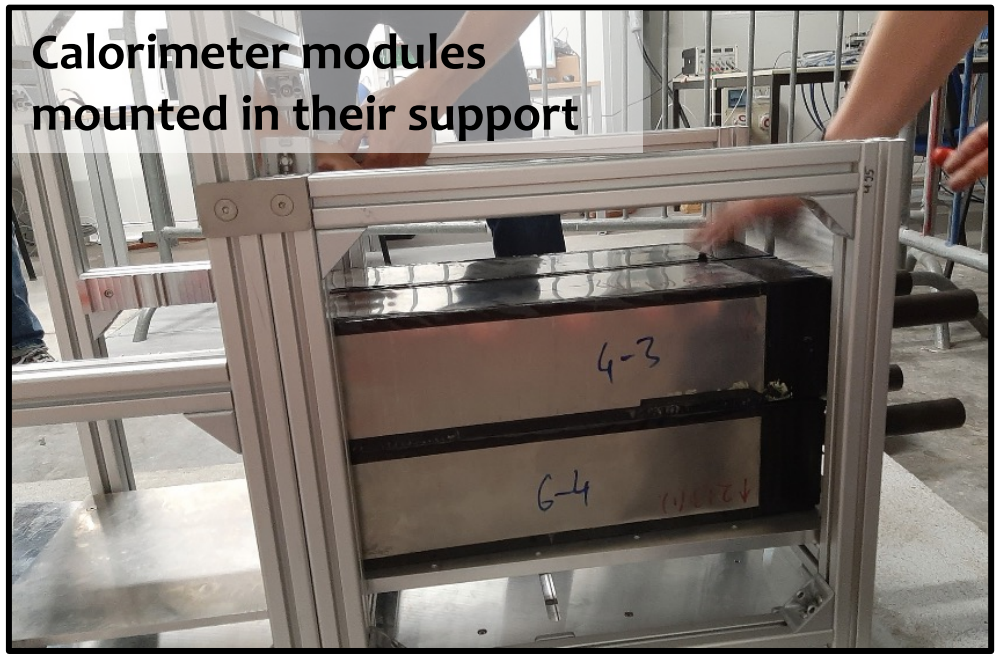


~10 ns rise time

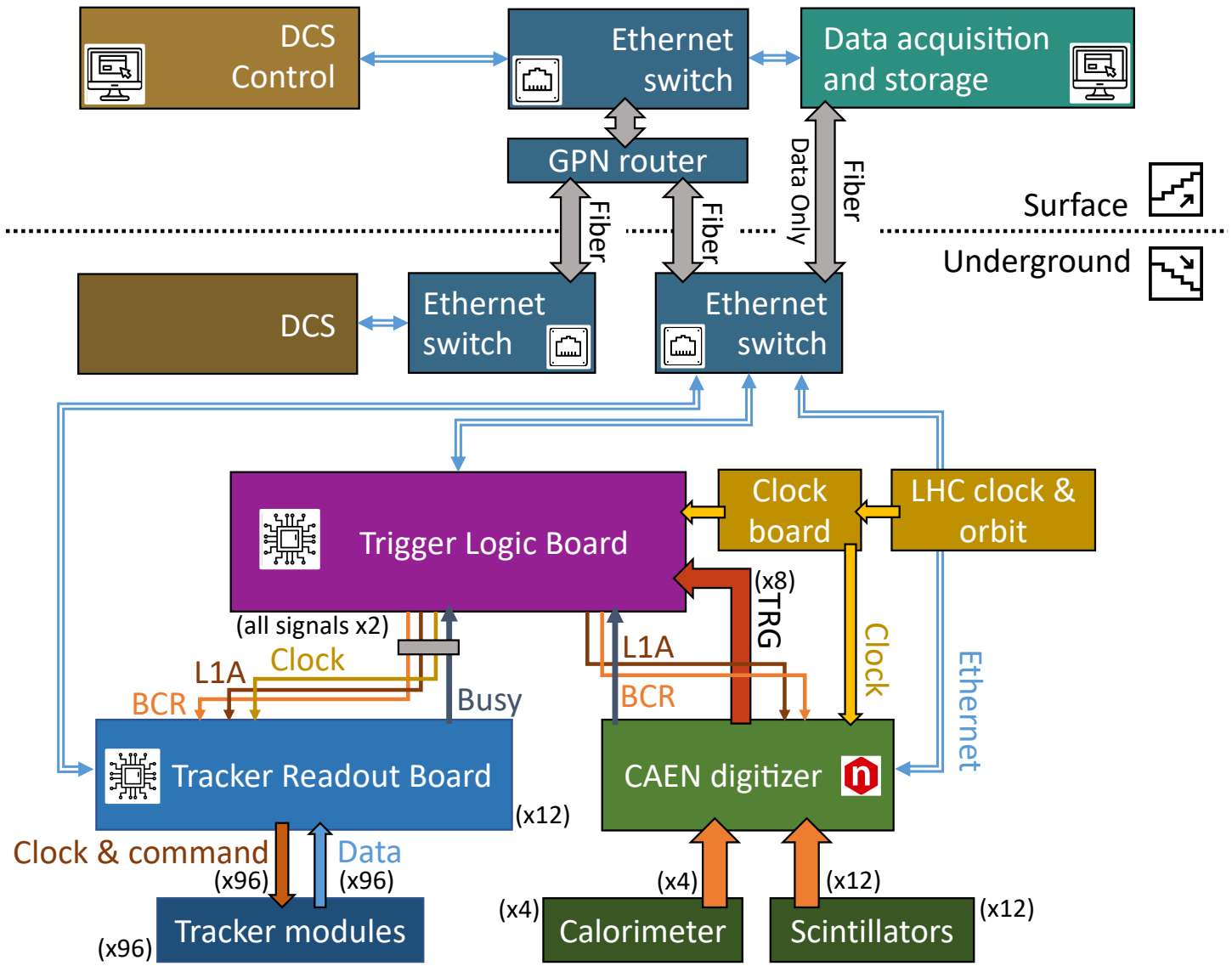


Initial cosmic setup



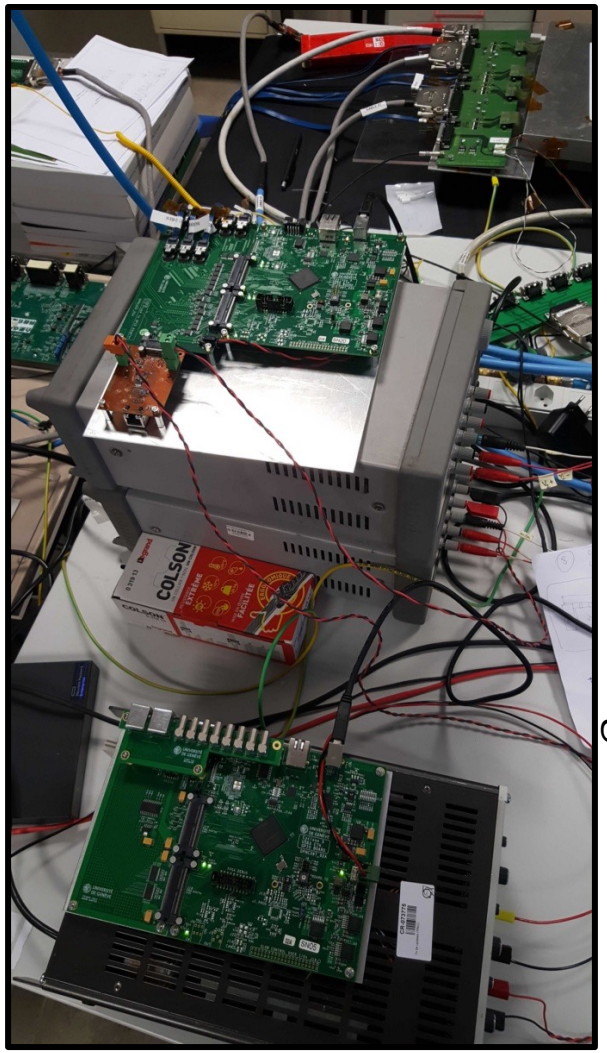


Calorimeter modules mounted in their support

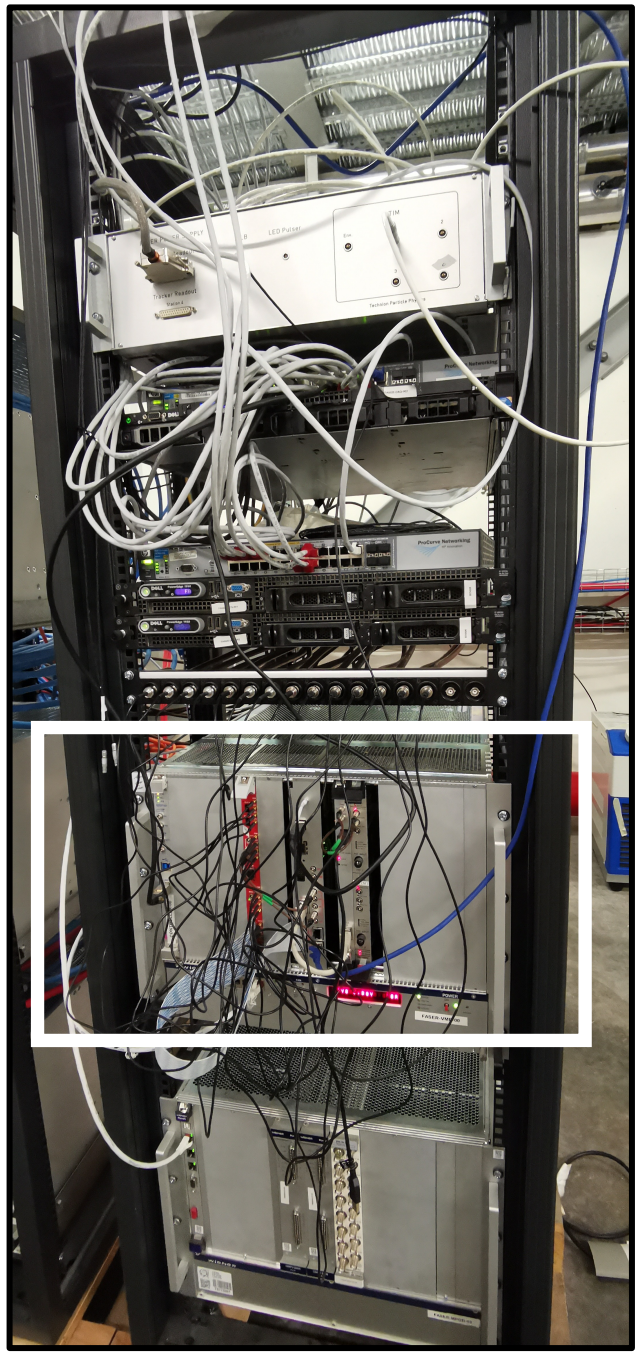

DCS Control
Ethernet switch
Data acquisition and storage
GPN router
Fiber
Fiber
Data Only
Fiber
Surface
Underground
DCS
Ethernet switch
Ethernet switch
Trigger Logic Board
Clock board
LHC clock & orbit
(x8)
TRG
(all signals x2)
L1A
Clock
BCR
Busy
L1A
BCR
Clock
Ethernet
Tracker Readout Board
CAEN digitizer
(x12)
Clock & command
(x96)
Data
(x96)
Tracker modules
(x96)
(x4)
Calorimeter
(x4)
(x12)
Scintillators
(x12)

Trigger & Data acquisition

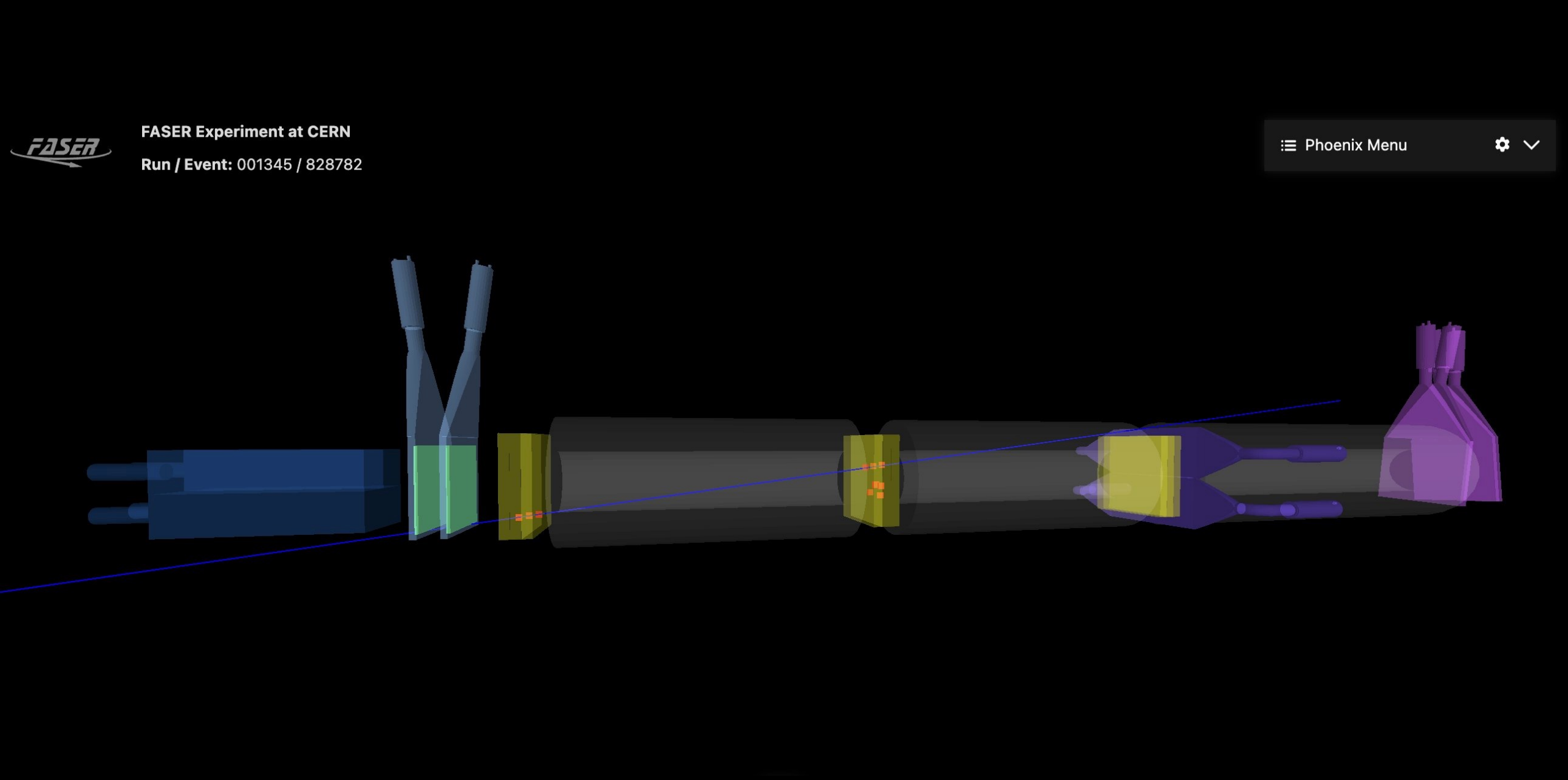
Initial Run Control application, produced by summer intern



All boards connected together for tests



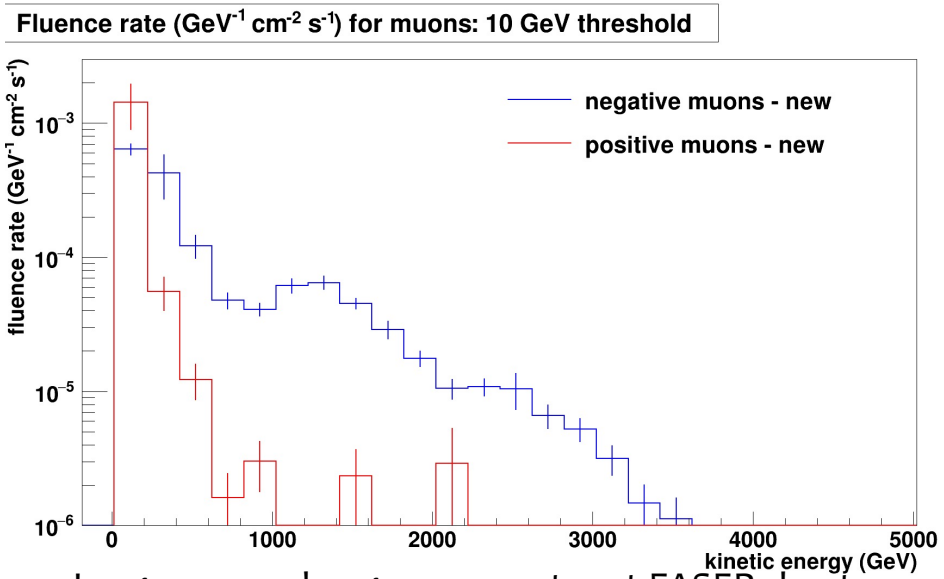
TDAQ boards in the final VME crate


FASER Experiment at CERN
Run / Event: 001345 / 828782
Phoenix Menu

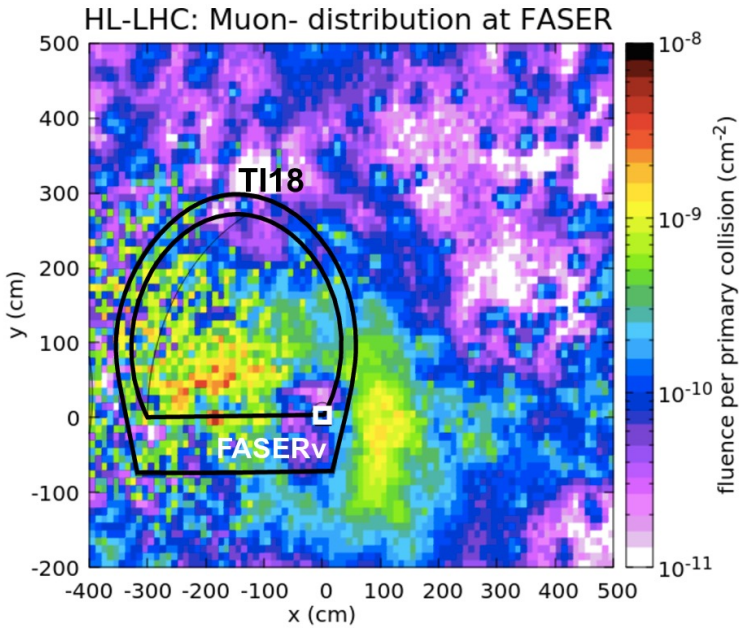
BEAM BACKGROUNDS

Slide from J. Boyd

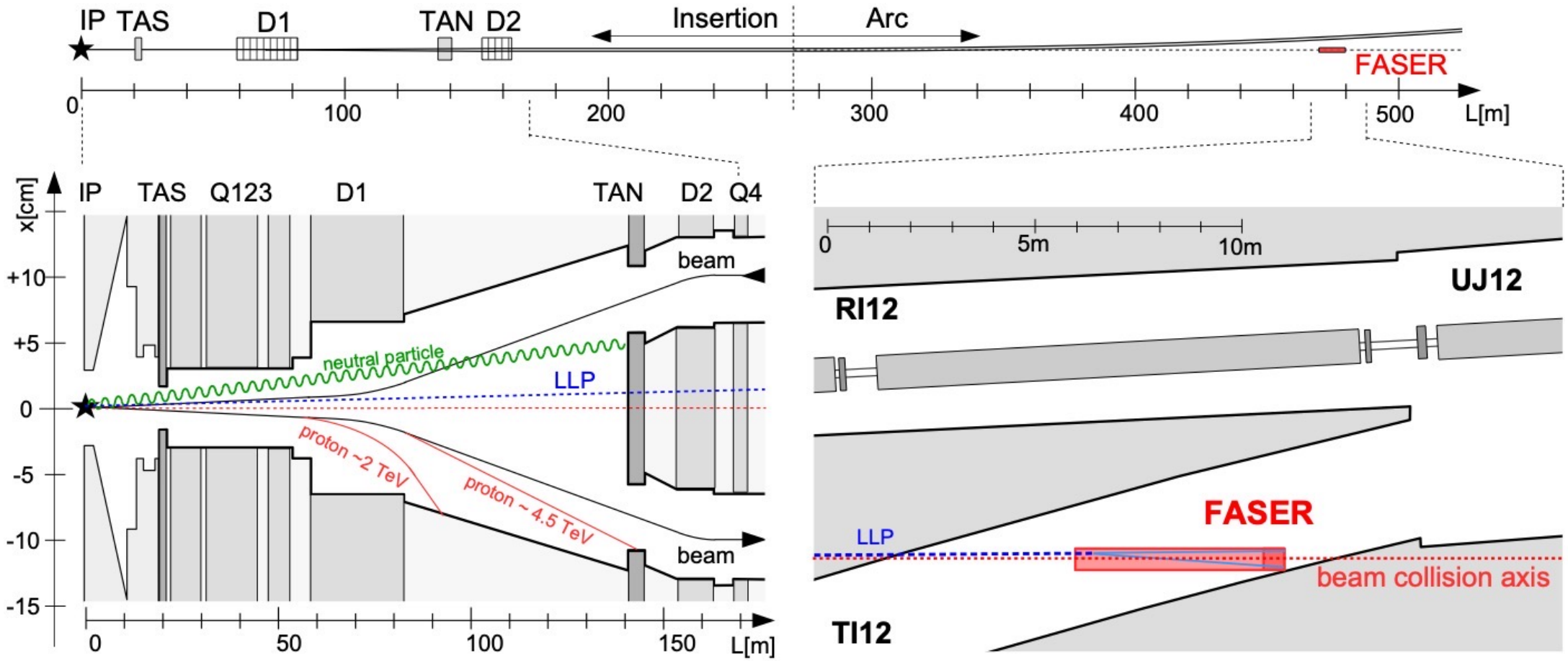
- FLUKA simulations and *in situ* measurements have been used to assess the backgrounds expected in FASER
- FLUKA simulations studied particles entering FASER from:
  - IP1 collisions (shielded by 100m of rock)
  - off-orbit protons hitting beam pipe aperture in dispersion suppressor (close to FASER) (following diffractive interactions in IP1)
  - beam-gas interactions
- Expect a flux of high energy muons (E>10 GeV) of 0.4cm^{-2}s^{-1} at FASER for 2e34cm^{-2}s^{-1} luminosity from IP1 collisions
  - Confirmed by *in situ* measurements in 2018 running (emulsion detector and TimePix BLM)



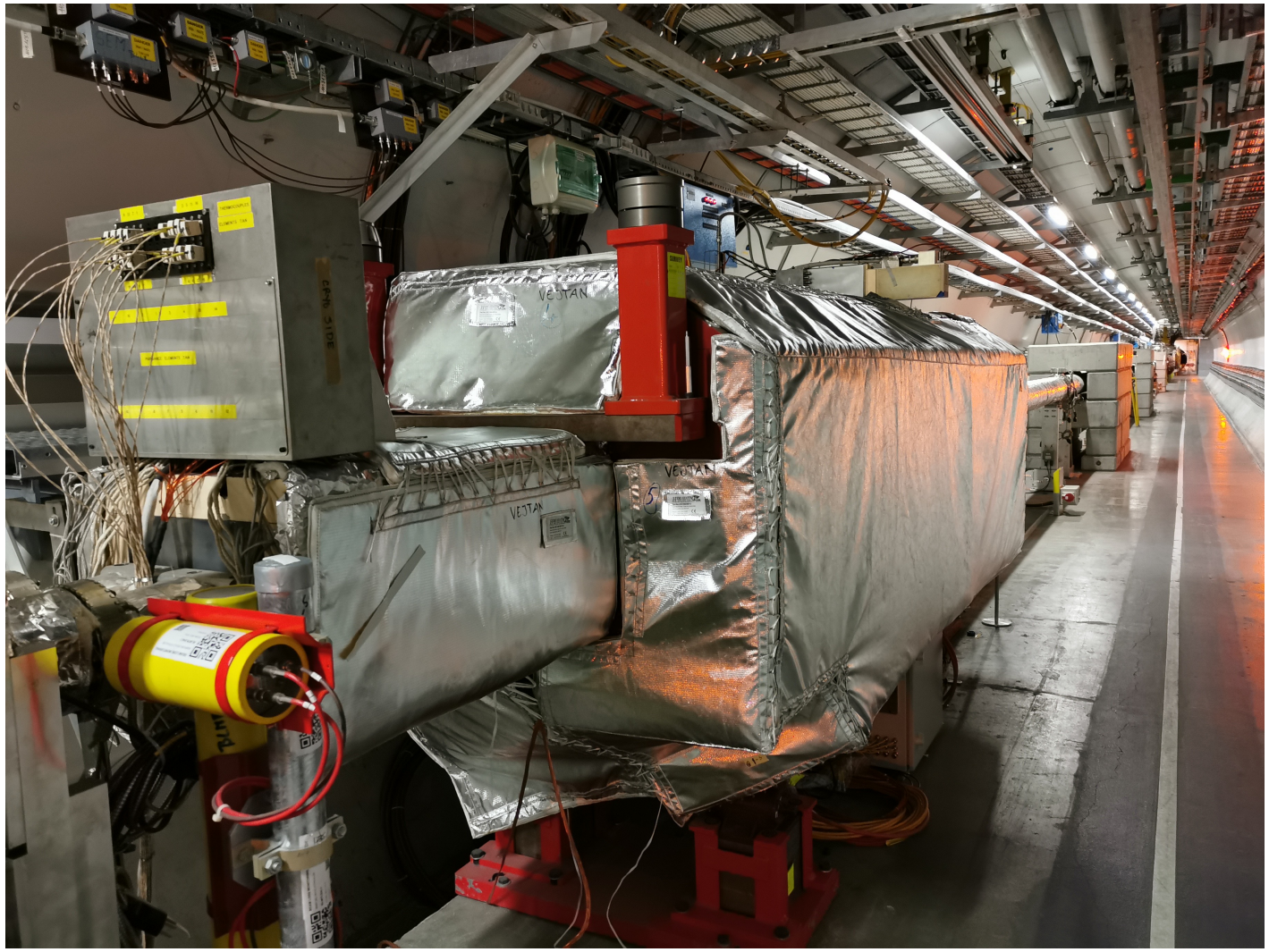
Large muon charge asymmetry at FASER due to LHC bending magnets



LLP production at ATLAS IP

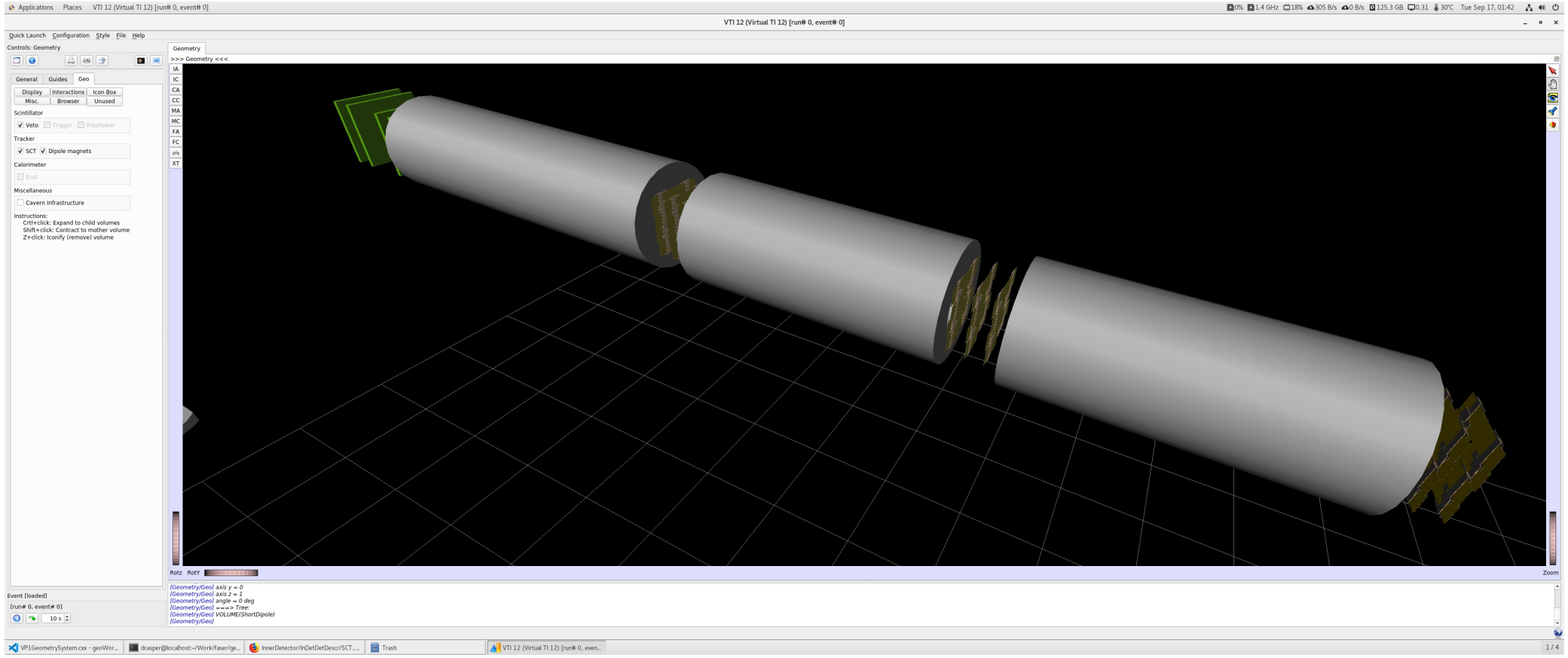


FASER TAN

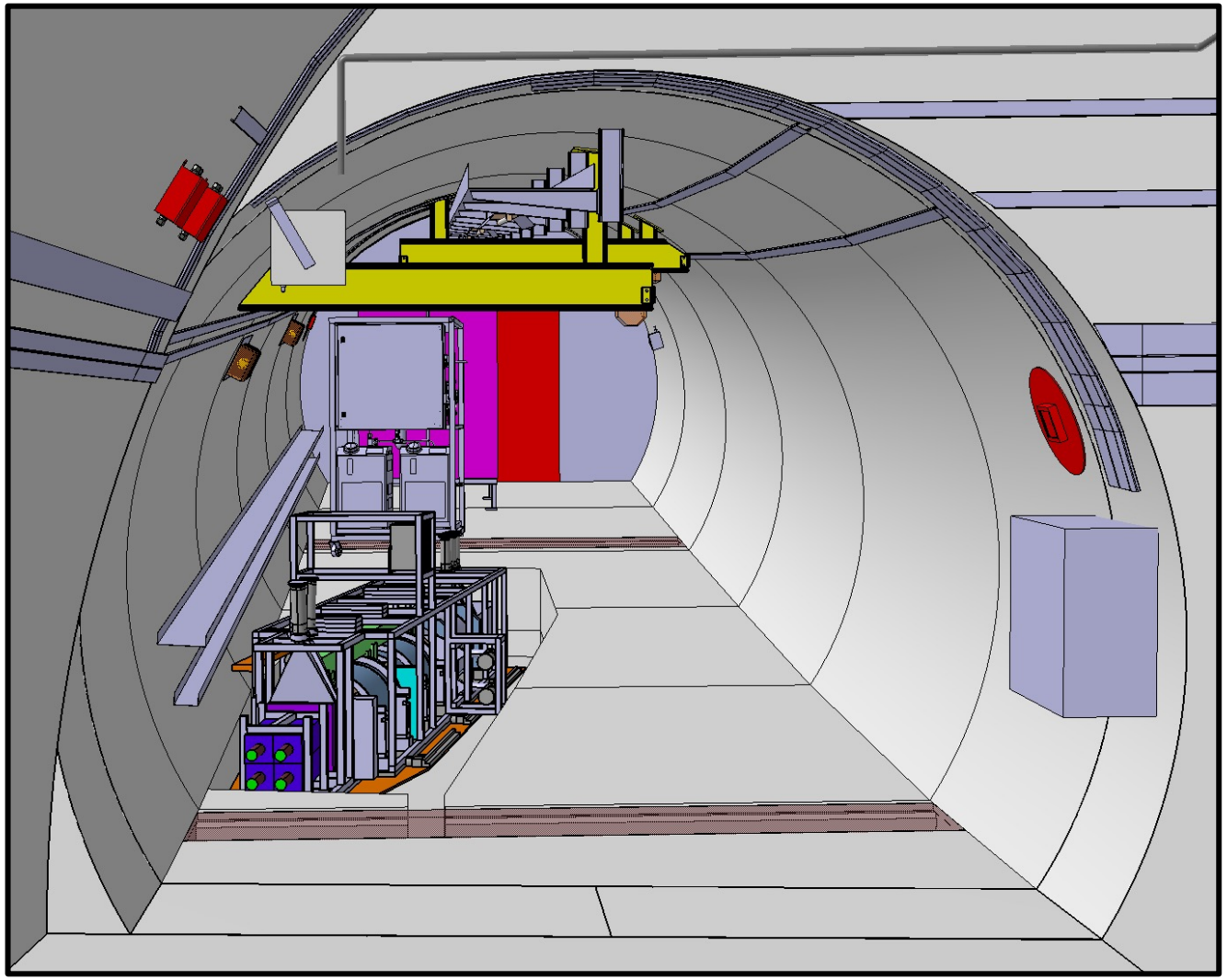


Offline

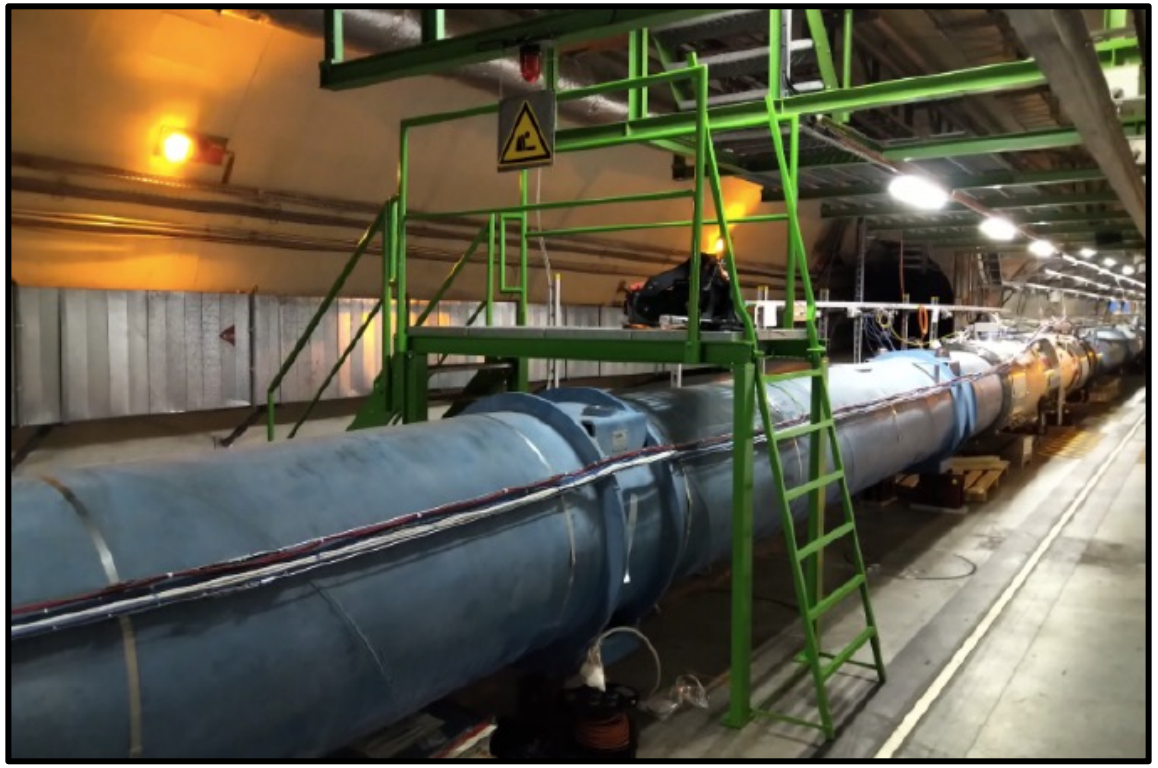
- Adapt open source ATLAS Athena ("Calypso")
- First versions of detector description, Geant4 simulation and event display working
- Track reconstruction with “ACTS” under development



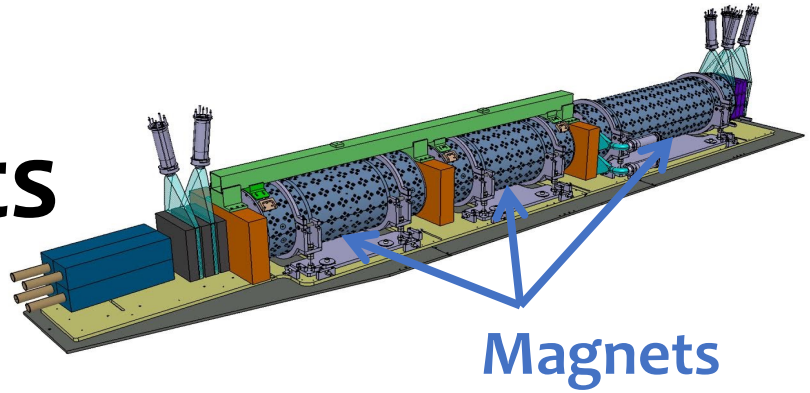
Access tunnel and Infrastructure

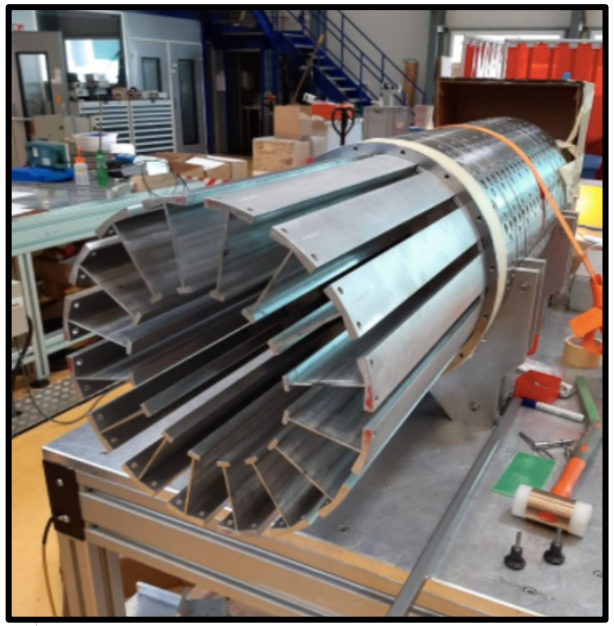


Access to TI12 is over the LHC machine complicates the transport & safety

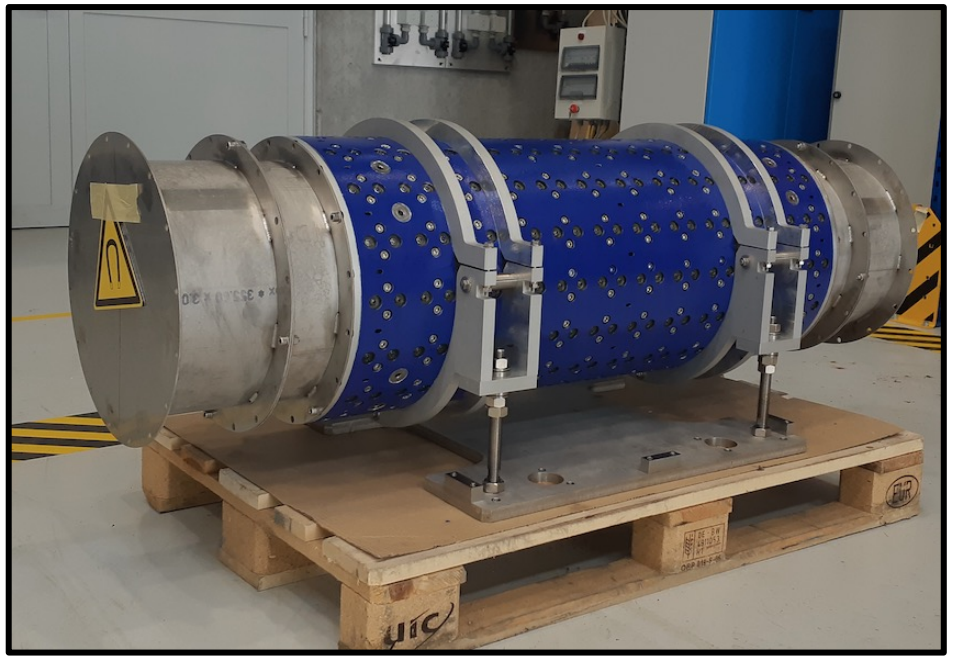


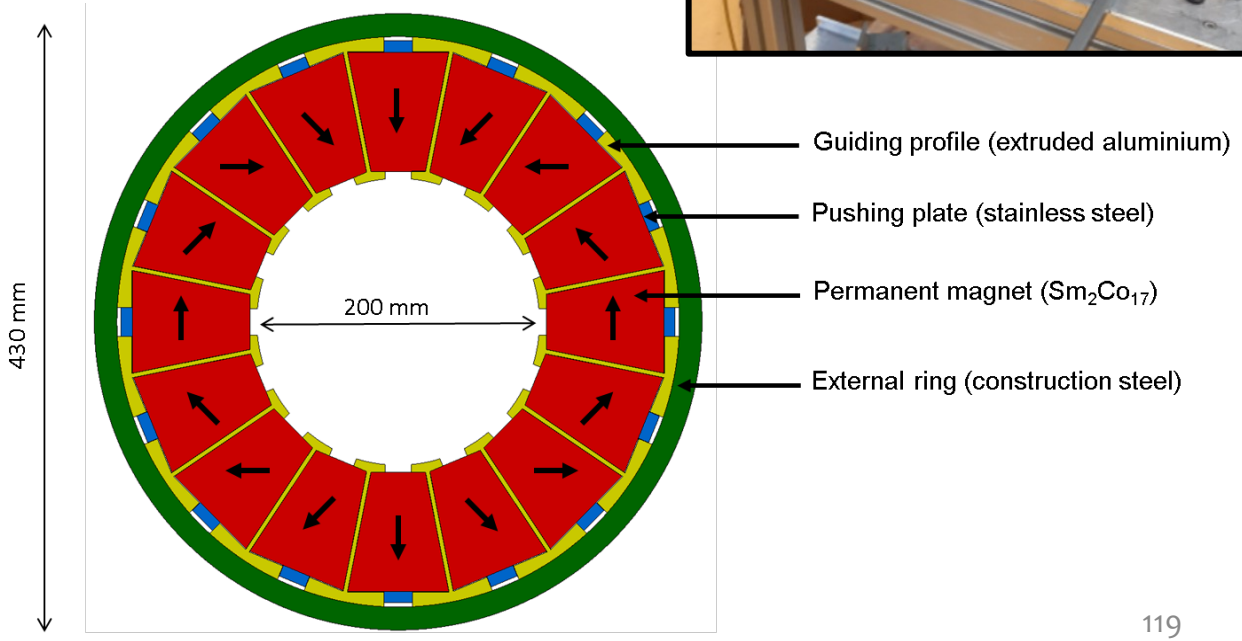
FASER Magnets



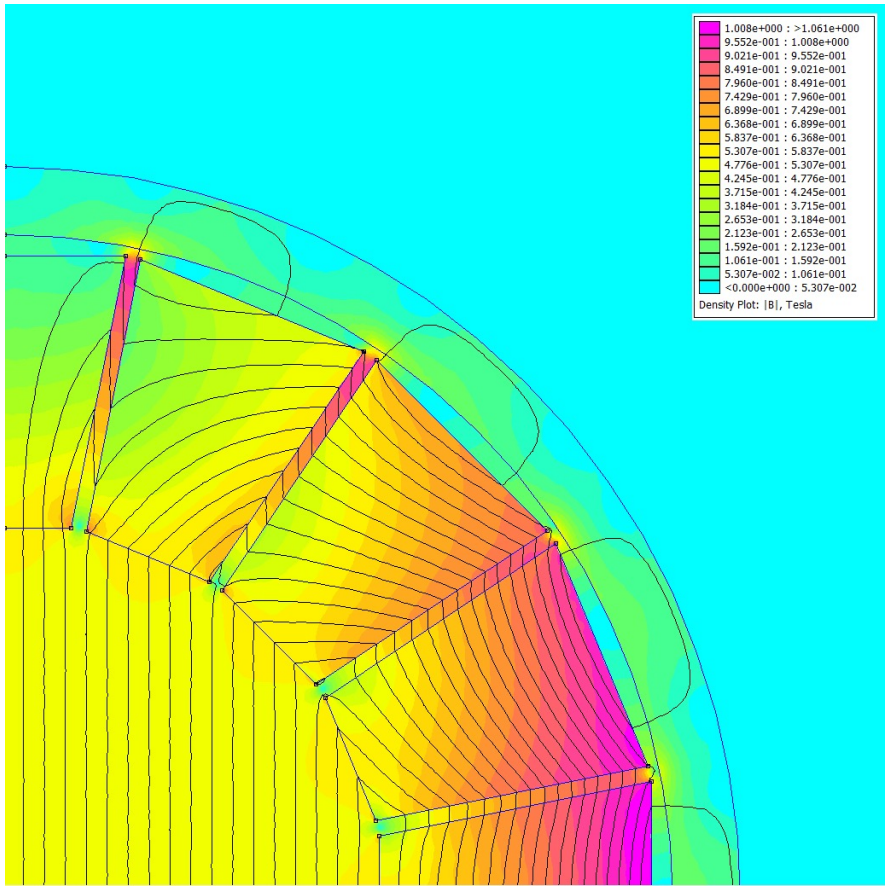


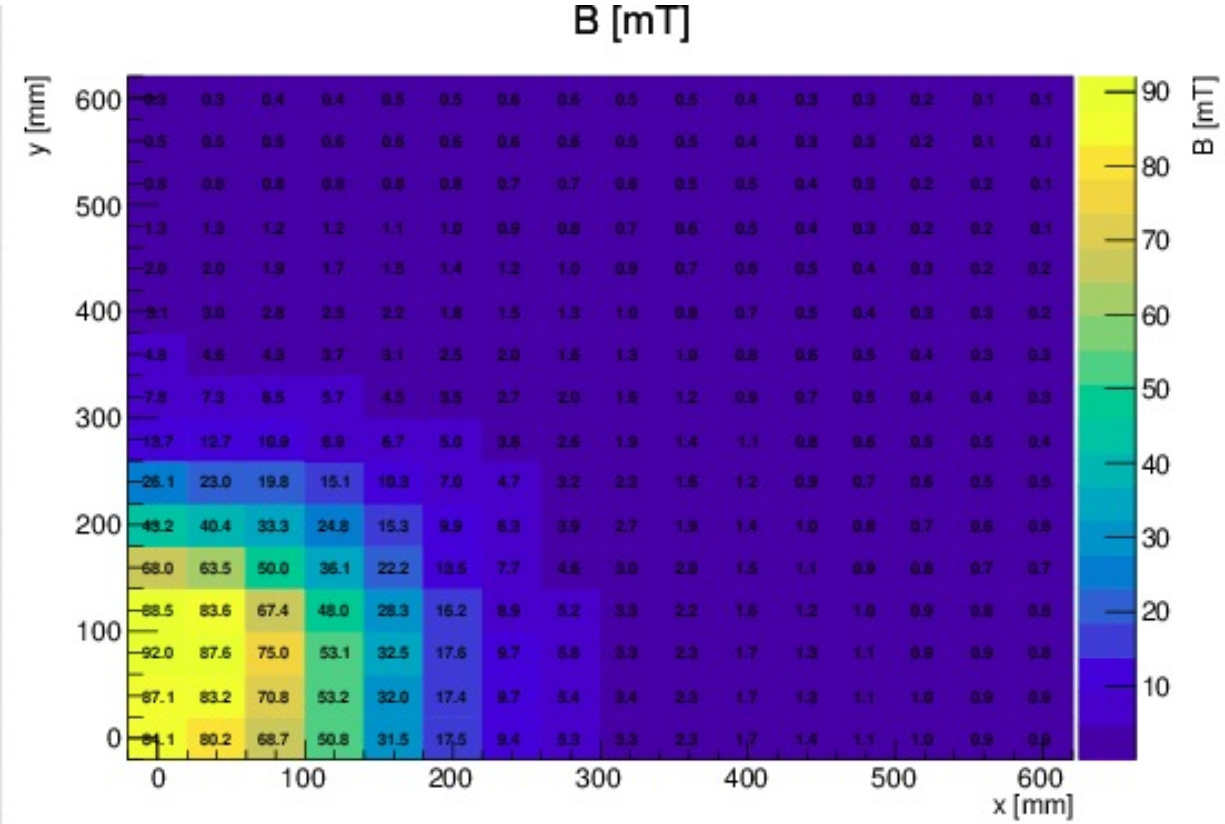
- Field of 0.55 T; permanent dipole
- Halbach array design with fixed-field magnets
  - Maximizes field without need for too much support infrastructure
  - Allows for a compact design, reducing amount of digging



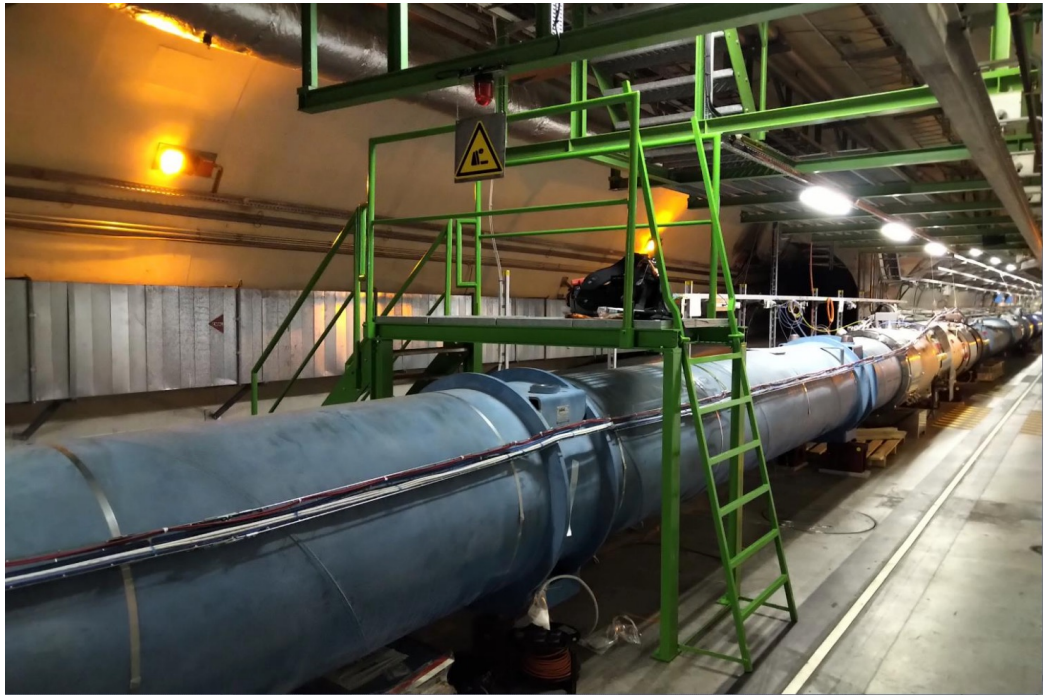


FASER Magnets



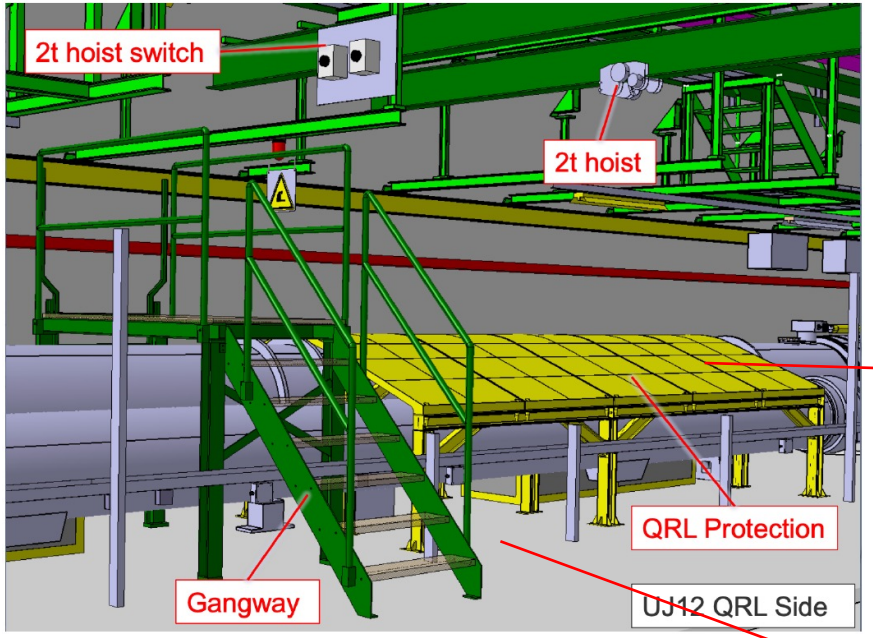


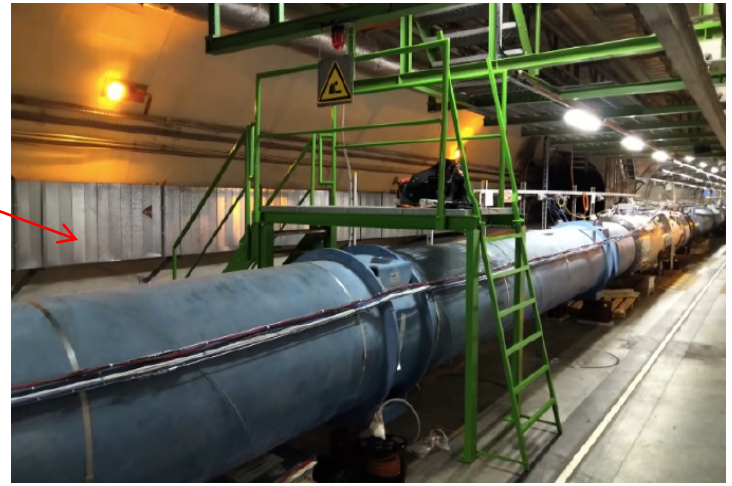
Accessing TI12



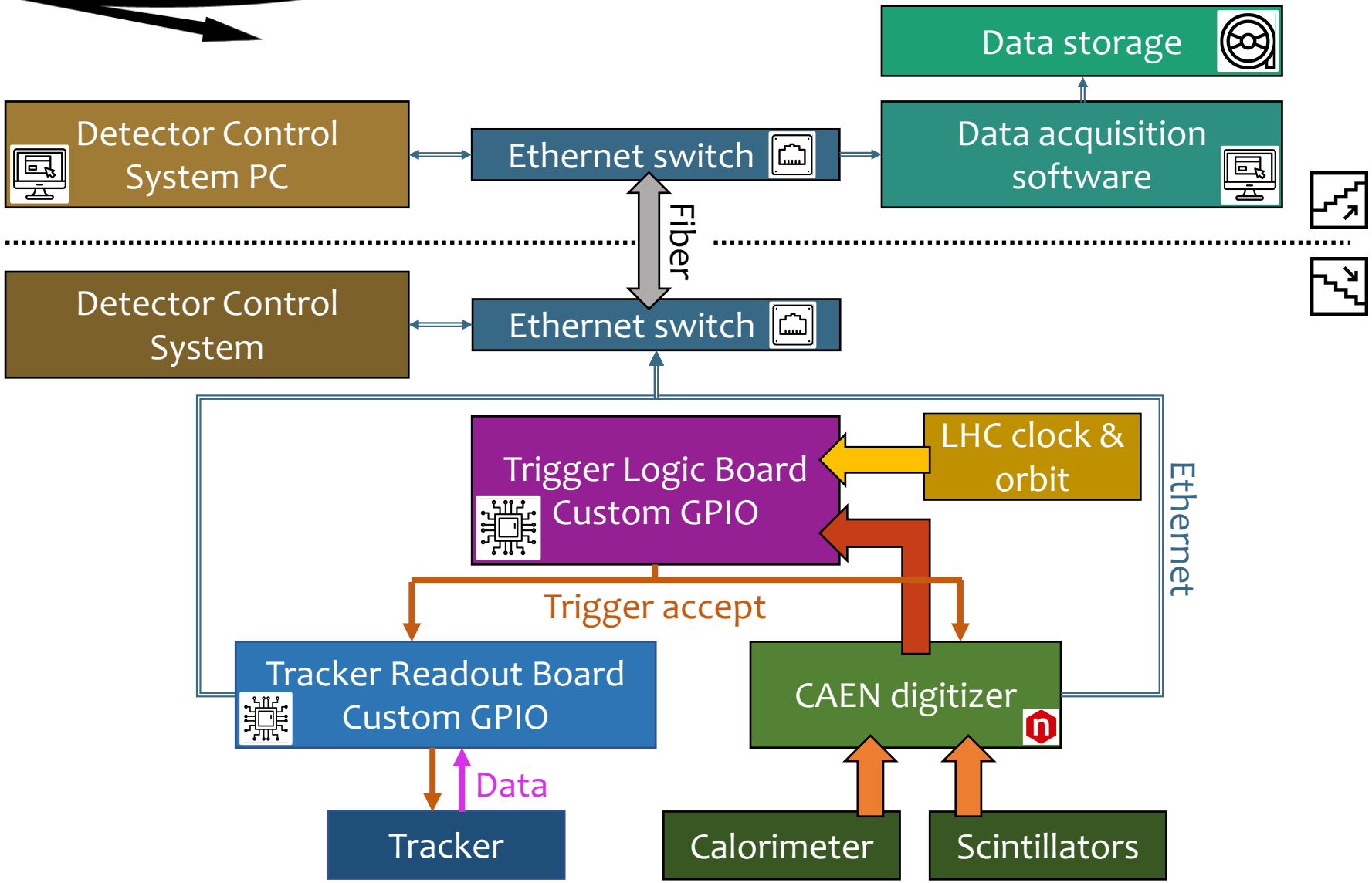
Preparation of TI12

Accessing TI12



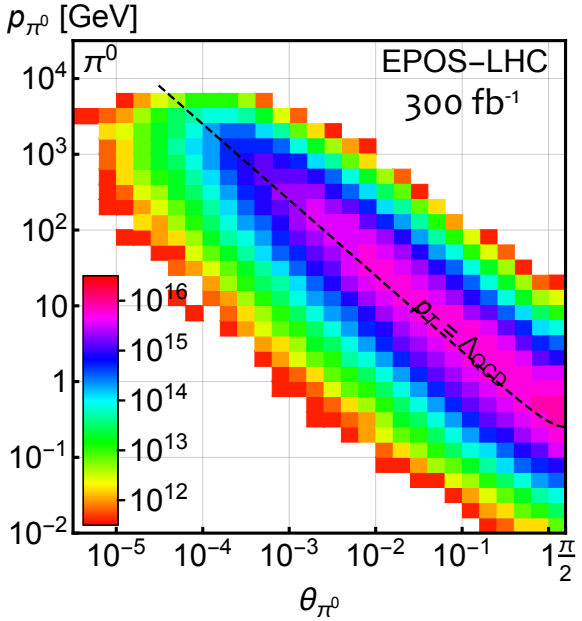


Extremely simplified TDAQ system

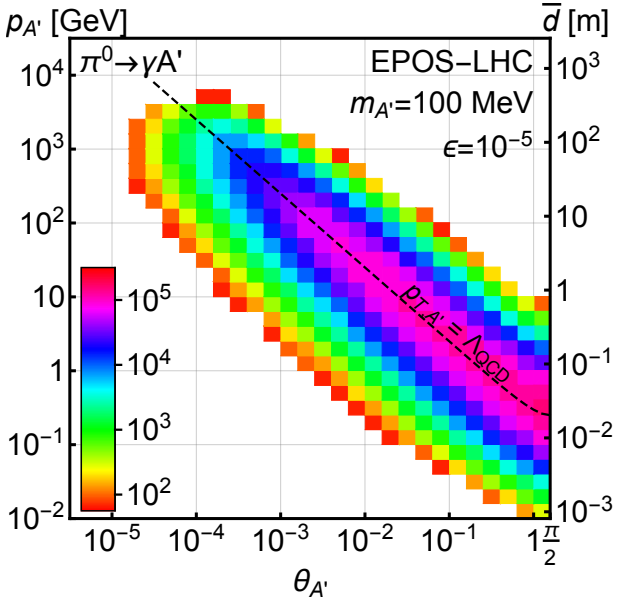


SIGNALS: DARK PHOTONS

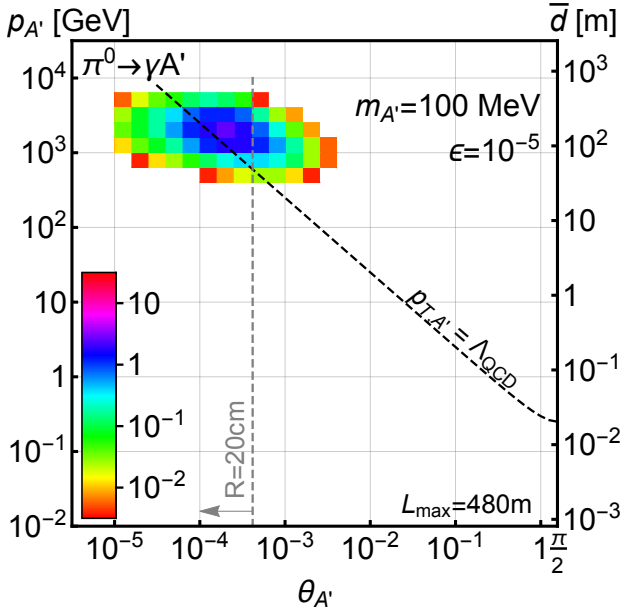
Pions at the IP



A's at the IP



A's decay in FASER



- Enormous event rates: $N_\pi \sim 10^{15}$ per bin
- Production is peaked at low transverse momentum ~250 MeV

- Rates highly suppressed by $\varepsilon^2 \sim 10^{-10}$
- But still $N_{A'} \sim 10^5$ per bin; LHC is a dark photon factory!

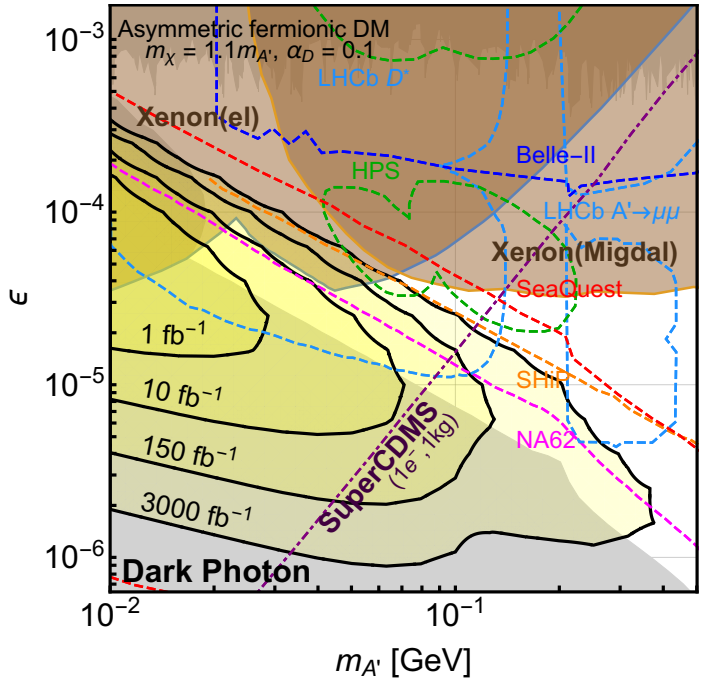
- Rates suppressed again, but still $N_{A'} \sim 100$ signal events
- Signal is E~TeV A's within 20 cm of the line of sight

Slide from J. Feng

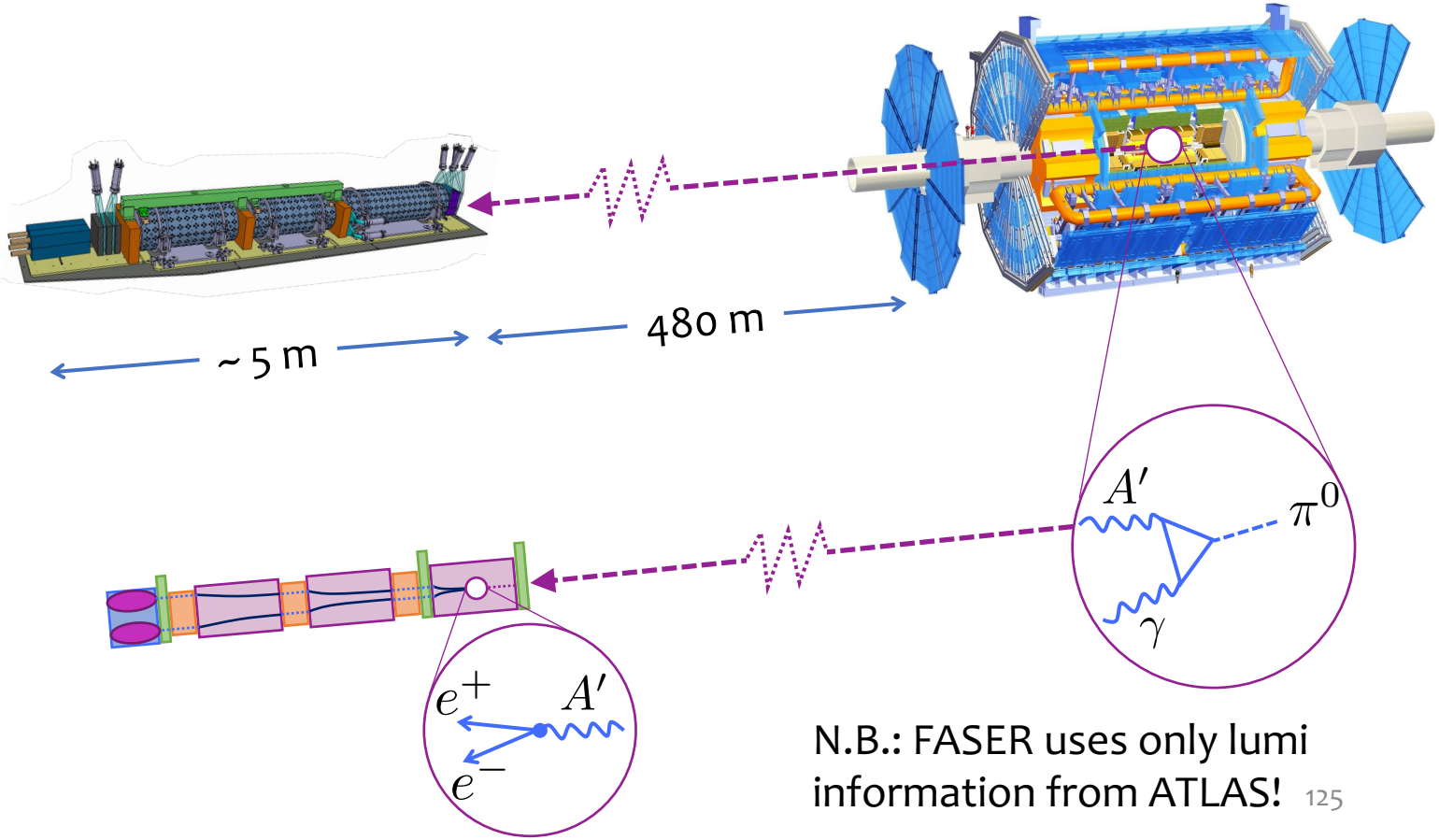
An example physics case: Dark Photon A'

- New massive gauge boson in a dark sector with dark matter candidate X
- Spin 1, couples weakly to SM particles through mixing with the photon
- For $m_{A'}$=100 MeV, $\epsilon \sim 10^{-5}$ and E~TeV, can travel long distance before decay

Plot produced in March 2020

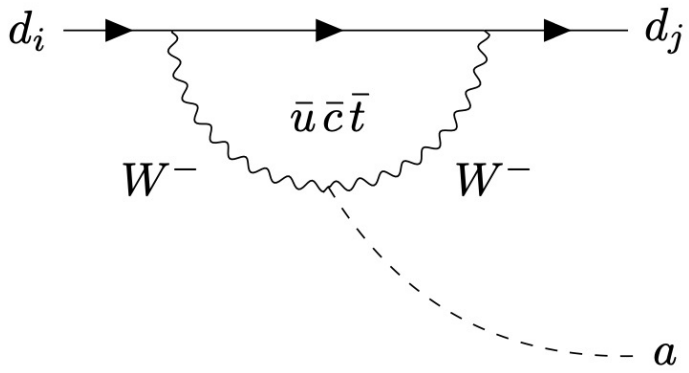


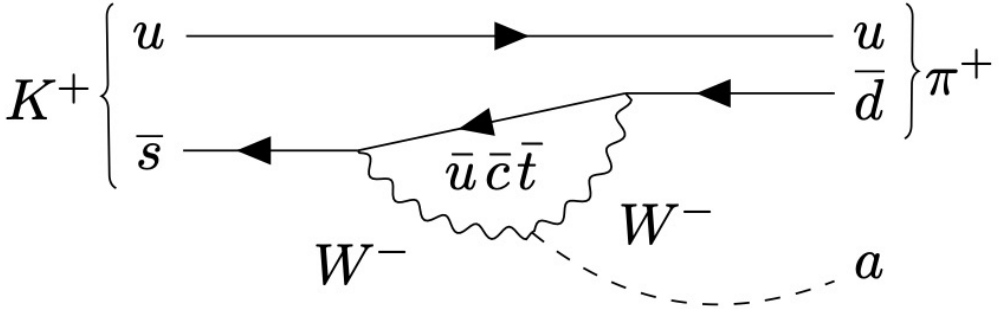
- Discovery contours assume at least 3 signal events, no background.

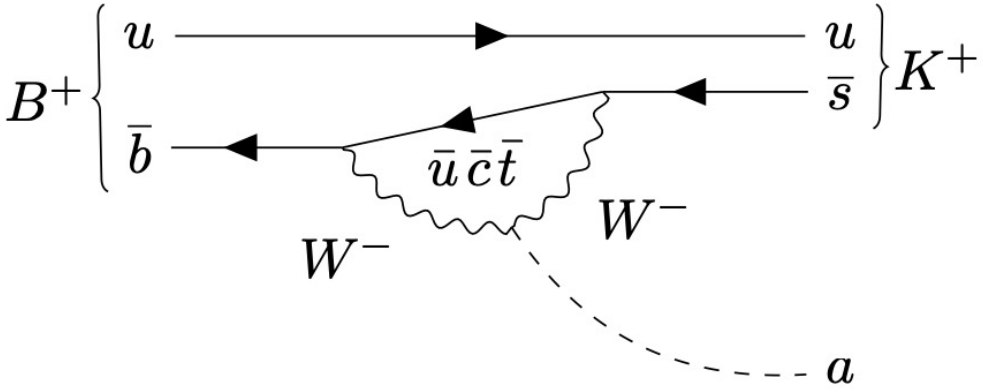


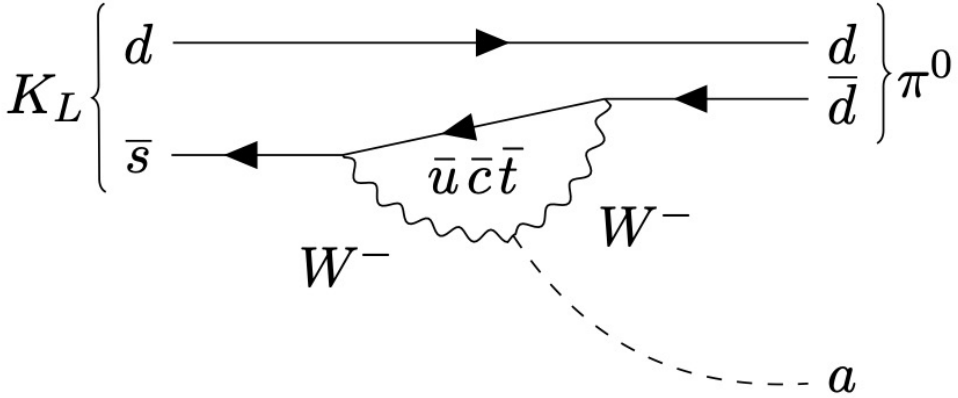
N.B.: FASER uses only lumi information from ATLAS!

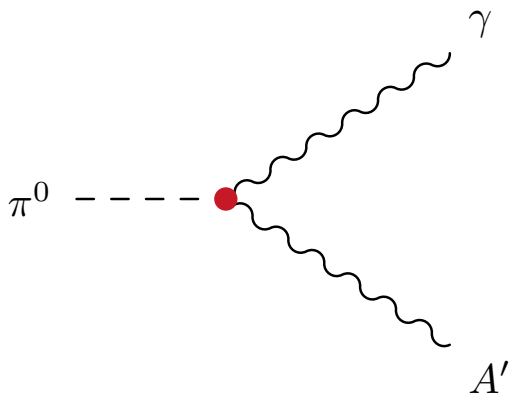
ALP production beyond primakoff

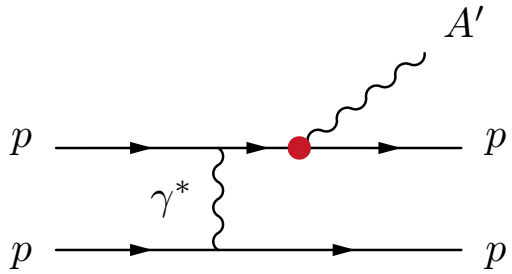


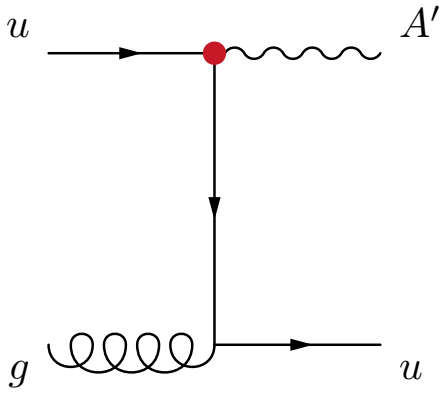


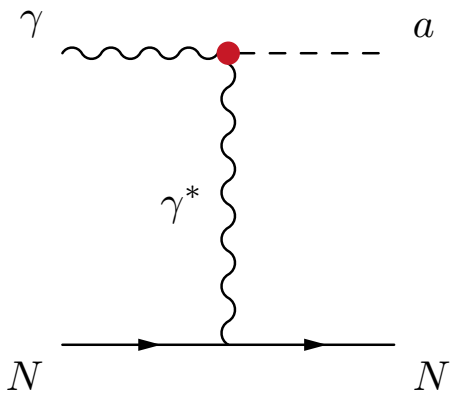


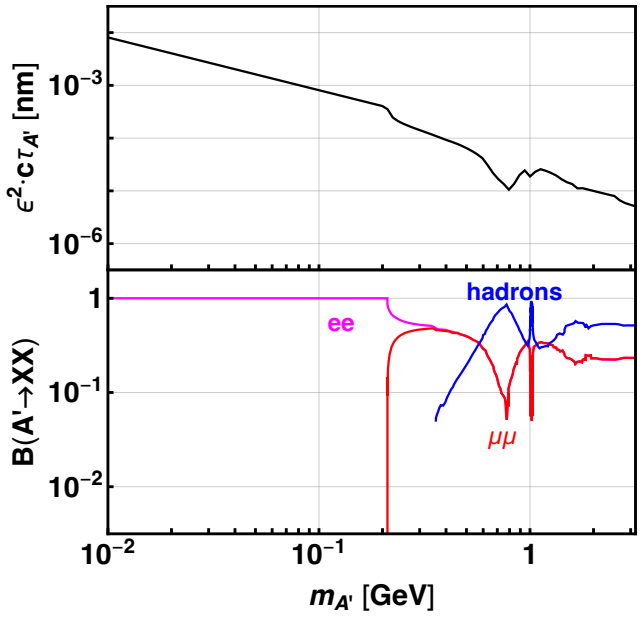


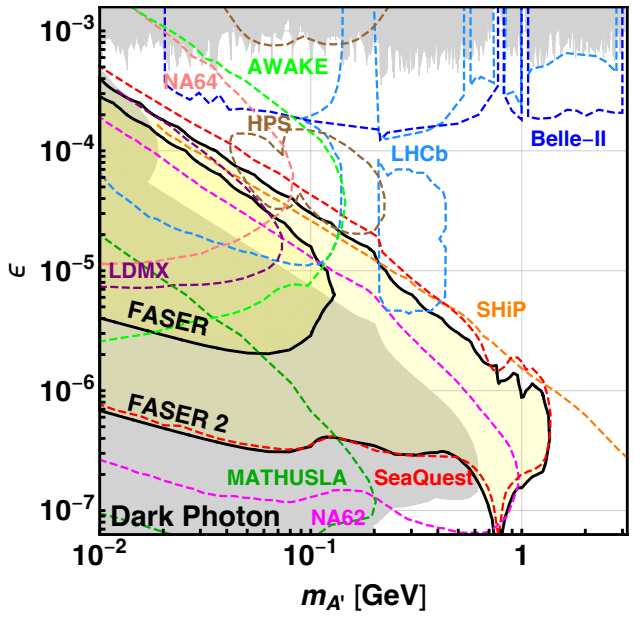

γ
π^0
A'

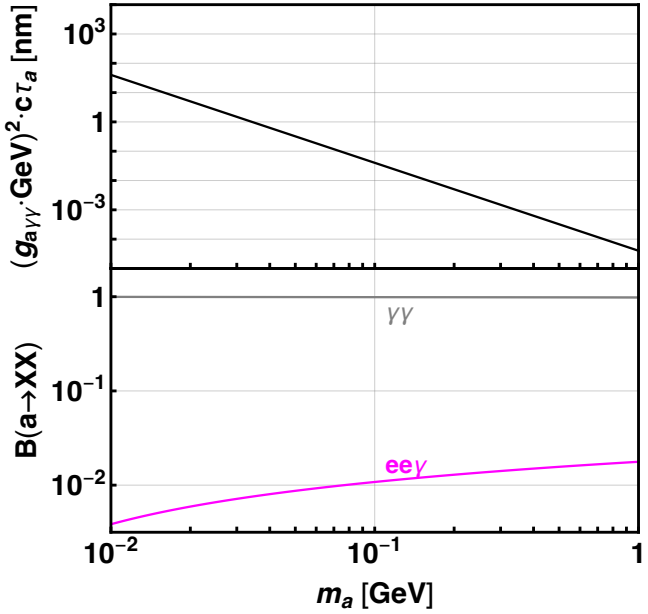

A'
p
p
γ^*
p
p

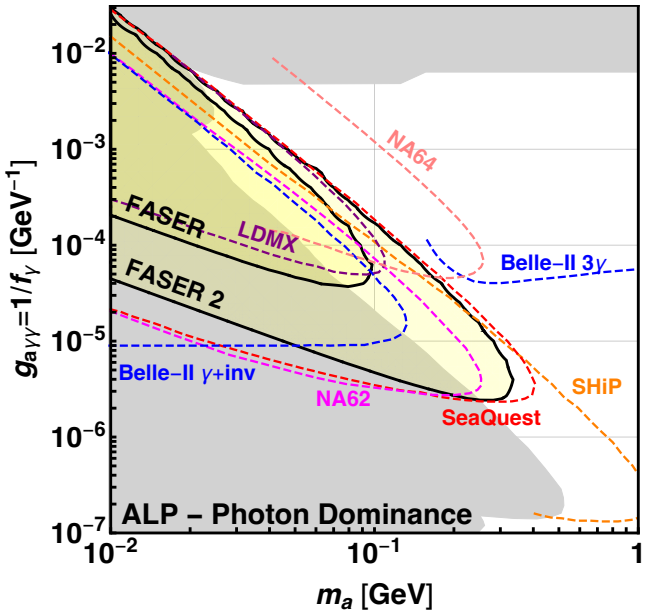

u
A'
g
u


γ
a
γ^*
N
N


$\epsilon^2 \cdot c\tau_{A'}$ [nm]
10^{-3}
10^{-6}
B(A'→XX)
1
10^{-1}
10^{-2}
ee
hadrons
μμ
10^{-2}
10^{-1}
1
$m_{A'}$ [GeV]


10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
ε
NA64
AWAKE
HPS
LHCb
Belle–II
LDMX
FASER
SHiP
FASER 2
MATHUSLA
SeaQuest
Dark Photon
NA62
10^{-2}
10^{-1}
1
$m_{A'}$ [GeV]


$(g_{a\gamma\gamma} \cdot \mathrm{GeV})^2 \cdot c\tau_a$ [nm]
10^3
1
10^{-3}
B(a→XX)
1
10^{-1}
10^{-2}
γγ
eeγ
10^{-2}
10^{-1}
1
m_a [GeV]


$g_{a\gamma\gamma}=1/f_\gamma$ [GeV^{-1}]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
NA64
FASER
LDMX
FASER 2
Belle–II 3γ
Belle–II γ+inv
NA62
SeaQuest
SHiP
ALP – Photon Dominance
10^{-2}
10^{-1}
1
m_a [GeV]

Reach for Heavy Neutral Leptons

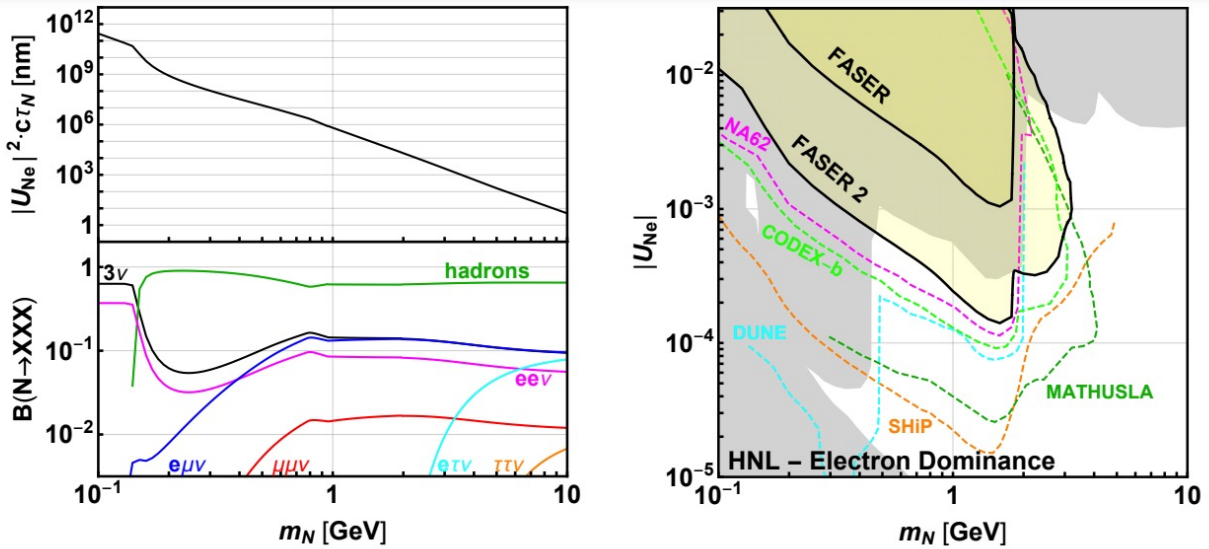


FIG. 12. **Benchmark Model F1.** The decay length (top left panel), decay branching fractions (bottom left panel), and FASER's reach (right panel) for the HNL that mixes only with the electron neutrino ν_e. The gray shaded regions are excluded by current limits, and the colored contours are the projected sensitivities for other proposed experiments. See the text for details.

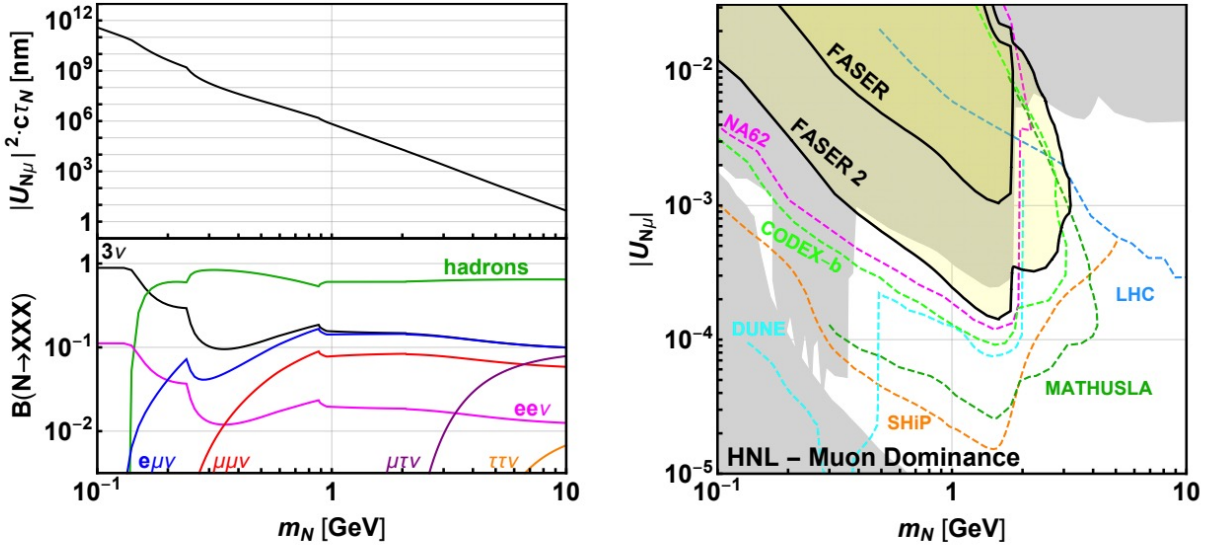


FIG. 13. **Benchmark Model F2.** As in Fig. 12, but for an HNL that only mixes with ν_μ.

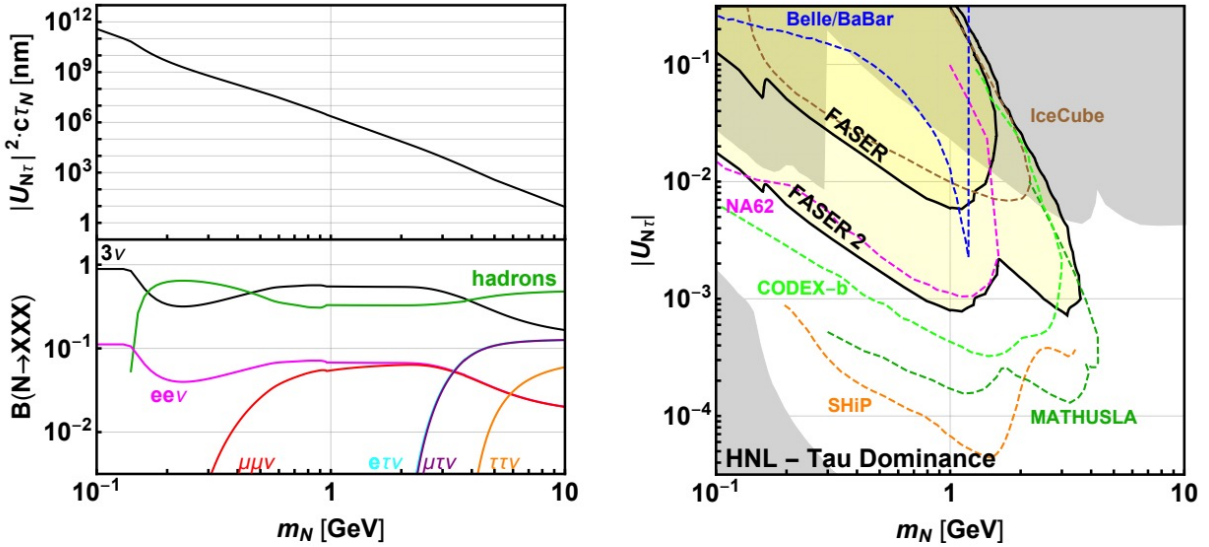
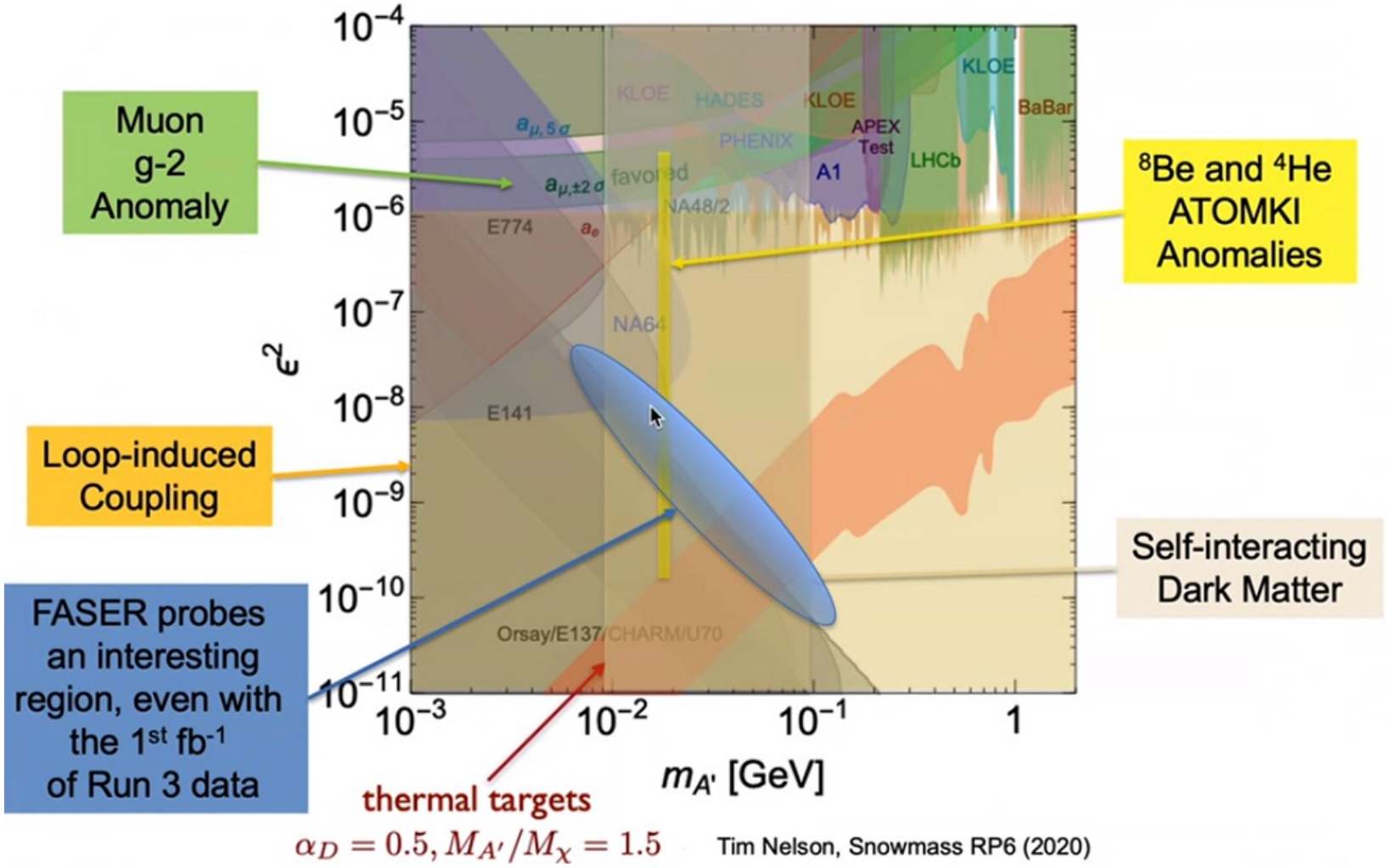
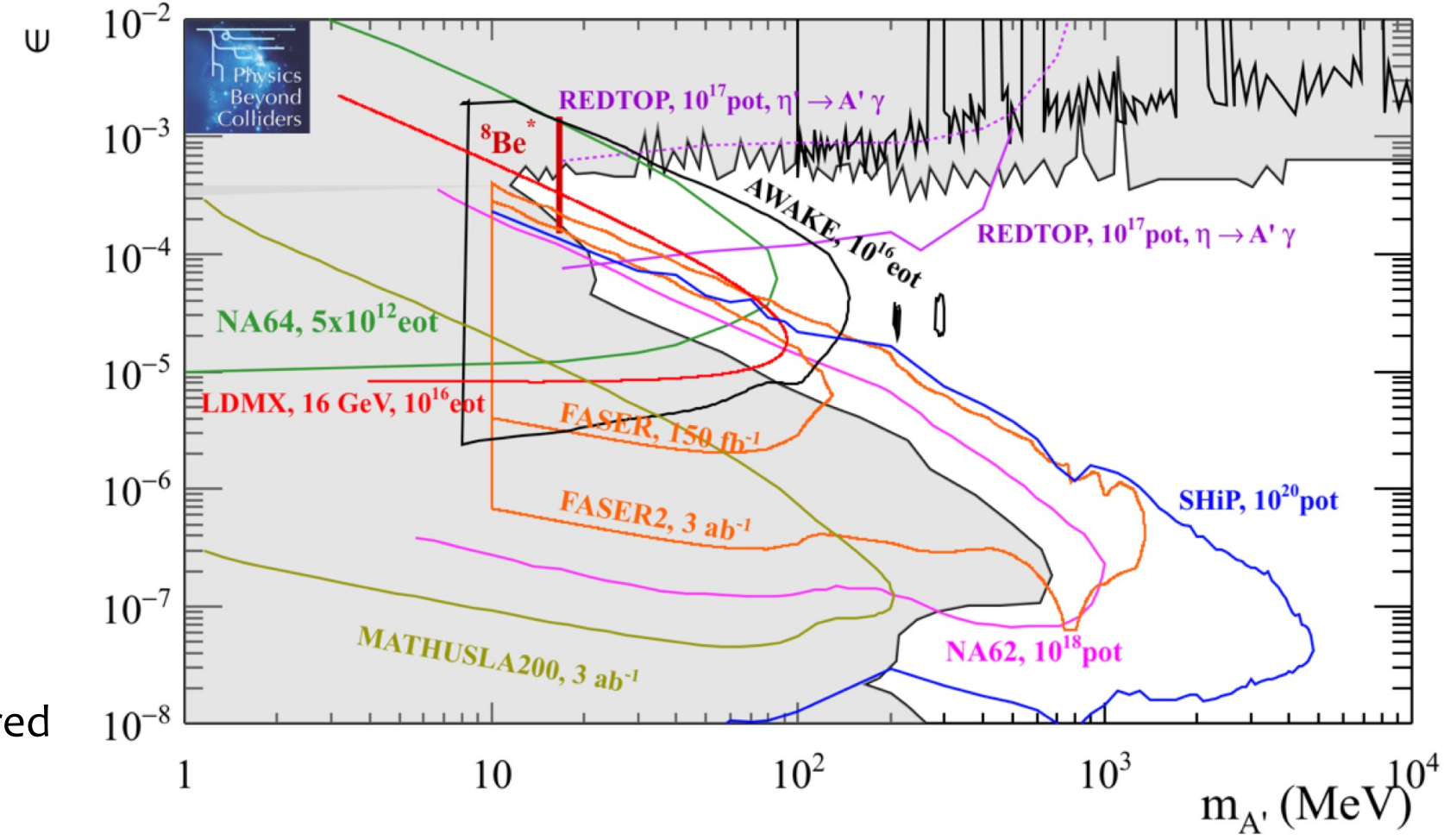


FIG. 14. **Benchmark Model F3.** As in Fig. 12, but for an HNL that only mixes with ν_τ.


Muon g-2 Anomaly
Loop-induced Coupling
FASER probes an interesting region, even with the 1st fb-1 of Run 3 data
8Be and 4He ATOMKI Anomalies
Self-interacting Dark Matter
thermal targets
$\alpha_D = 0.5, M_{A'}/M_\chi = 1.5$
Tim Nelson, Snowmass RP6 (2020)
ε^2
$m_{A'}$ [GeV]
KLOE
HADES
PHENIX
APEX Test
A1
LHCb
BaBar
E774
NA48/2
NA64
E141
Orsay/E137
CHARM/U70

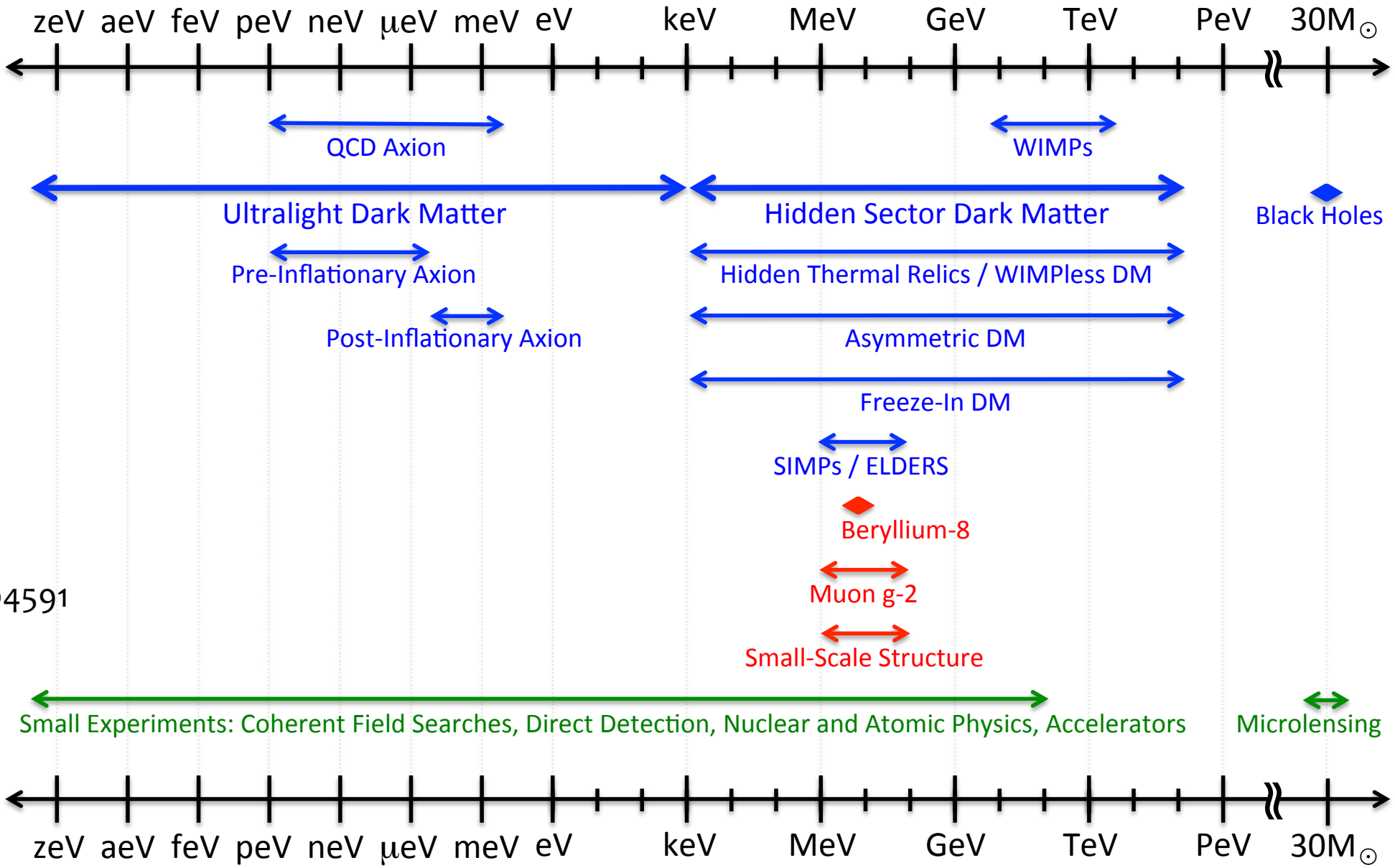
Physics Beyond Colliders BSM WG (2019)



Existing bounds are gray

Future searches are colored

Dark Sector Candidates, Anomalies, and Search Techniques



arXiv:1707.04591

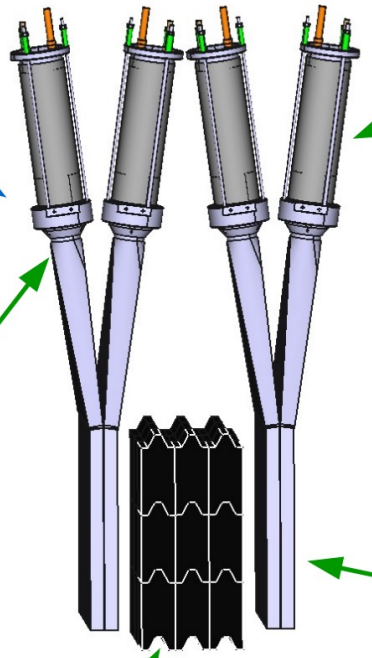
Assumptions in sensitivity plots

Results: The projected dark photon sensitivity reaches for FASER at LHC Run 3 with 150 fb^{-1} and FASER 2 at HL-LHC with 3 ab^{-1} are shown in the right panel of Fig. 6. The gray-shaded regions are excluded by current bounds; see Refs. [30, 37] and references therein. For comparison we also show the projected sensitivities of other experiments: NA62 assumes 10^{18} protons on target (POT) while running in a beam dump mode that is being considered for LHC Run 3 [17]; SeaQuest assumes 1.44×10^{18} POT, which could be obtained in two years of parasitic data taking and requires additionally the installation of a calorimeter [19]; the proposed beam dump experiment SHiP assumes $\sim 2 \times 10^{20}$ POT collected in 5 years of operation [20]; the proposed electron fixed-target experiment LDMX during Phase II with a beam energy of 8 GeV and 10^{16} electrons on target (EOT) [25]; Belle-II and LHCb assume the full expected integrated luminosity of 50 ab^{-1} [14] and 15 fb^{-1} [15, 16], respectively; HPS assumes 4 weeks of data at JLab at each of several different beam energies [1, 55]; NA64 [56] corresponds to 5×10^{12} EOT with 100 GeV energy; and AWAKE [57] is assumed to be working as a fixed-target experiment with a 10-m-long decay volume and 10^{16} EOT accelerated in a $50 - 100$ m long plasma cell to the energy $\mathcal{O}(50\ \text{GeV})$.

Scintillators – Veto stations

Final design could be more vertical PMT position

Will have port for LED signal



Light-guides, PMT-holders and assembly to be done at CERN

Interlocking lead bricks
- ~150x300x300mm^3
- exact bricks TBD
- shower/stops photons from upstream muons

Hamamatsu H6410 PMTs
- large diameter (46mm)
- large gain 10^6-10^8

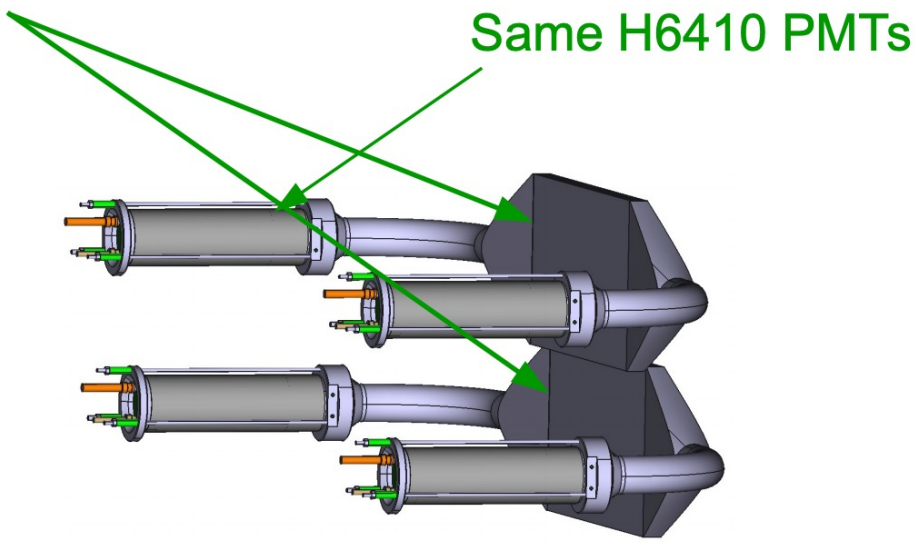
Two independent scintillator layers per station
- 20x300x300mm^3
- EJ-200 from Eljen Tech.

PROPERTIES	EJ-200
Light Output (% Anthracene)	64
Scintillation Efficiency (photons/1 MeV e$^-$)	10,000
Wavelength of Maximum Emission (nm)	425
Light Attenuation Length (cm)	380
Rise Time (ns)	0.9
Decay Time (ns)	2.1
Pulse Width, FWHM (ns)	2.5

- expect ~200 photo-electrons per MIP

Scintillators – Trigger / Timing

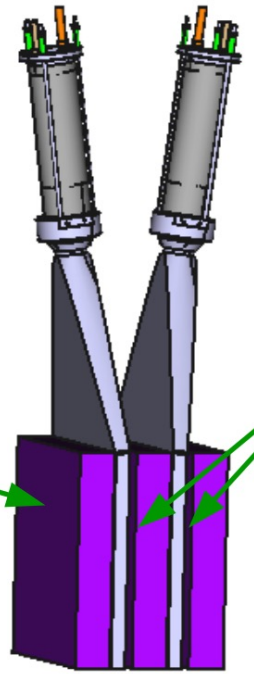
Scintillator layer split in two
- 10X200x400mm^3
- split reduces vertical time-walk and eases construction
- will have small offset and overlap to avoid gap
- again EJ-200 scintillator
- double sided readout:
  1. allows correction for horizontal time-walk
  2. can reduce noise triggers by requiring coincidence
- expect ~80 photo-electrons per MIP
- timing resolution still to be determined (~ns)



Large area to catch muons coming at angle generating showers only seen in last layer/calorimeter, a dominant(?) background for photons-only signal

Scintillators – Trigger / Preshower

Trigger/Preshower station has same scintillator design as veto stations



Carbon fiber (low-Z) blocks between tracker and calorimeter to reduce backsplash from calorimeter

- exact thickness will depend available space after support is designed should be three ~5cm thick blocks

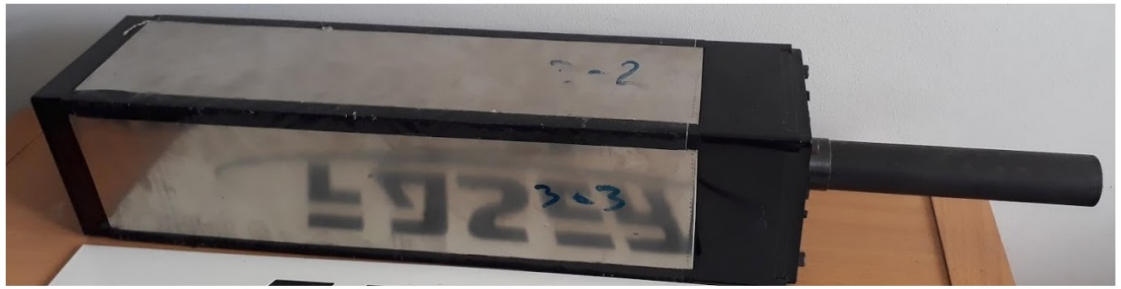
Embed/glue in two 1 radiation length (~5mm) lead plates in front of scintillator layers to start EM shower

- allows to discriminate between incoming di-photon signal and neutrino interactions in calorimeter

FASER Calorimeter

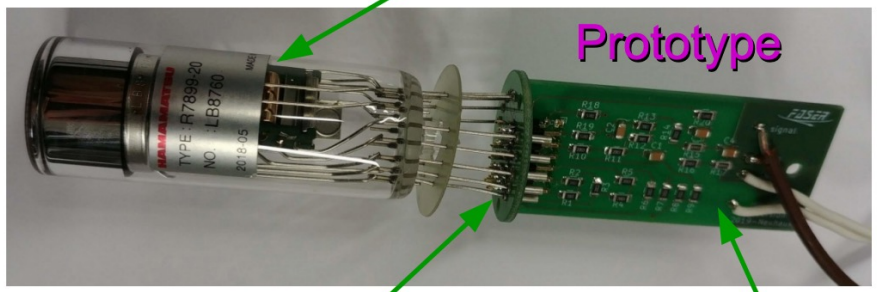
Using 4 LHCb spare outer ECAL modules for calorimeter (have 8)

Theoretical energy resolution ~1%, but we will be limited by how well we can calibrate and by punch-through



7 R7899-20 Hamamatsu PMT provided by LHCb

- tubes are almost new (from 2018)



Had to make our own HV base

- done by Friedemann

Have new base with non-solder connection

Divider to be shortened to fit in calorimeter tube – waiting for final tests of proto-type

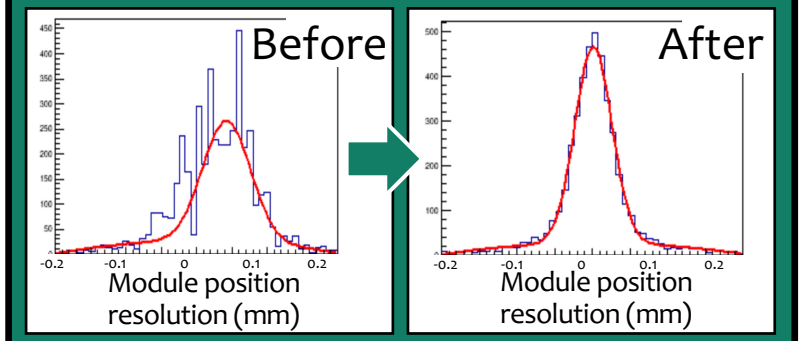
FASER Commissioning

- Dedicated labs available at CERN for individual component testing
- Dedicated area at CERN's Prevessin site ("EHN1") for full-detector commissioning

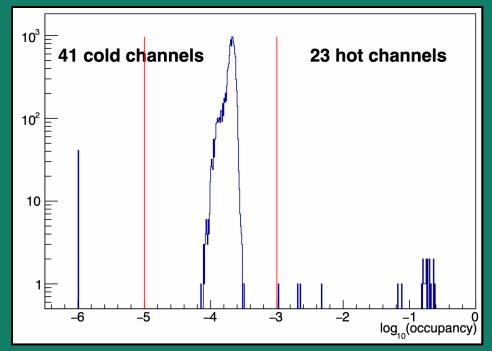
Milestone	Where	When
Individual component commissioning	CERN labs	July 2020
Detector commissioning	EHN1	Sept 2020
Installation of magnets	EHN1	Sept 2020
Surface commissioning – part 1	EHN1	Oct 2020
Detector installation – part 1	TI12	Nov 2020
Surface commissioning – part 2	EHN1	Feb 2021
Detector installation – part 2	TI12	March 2021
In-situ commissioning	TI12	During 2021

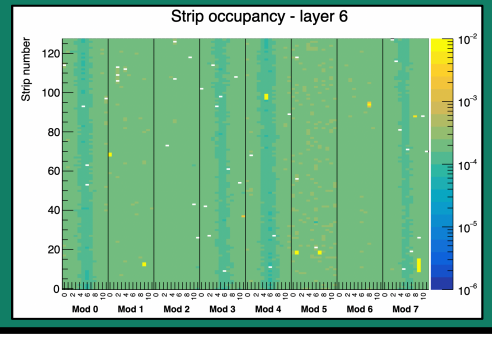
Cosmic data taking

First alignment efforts

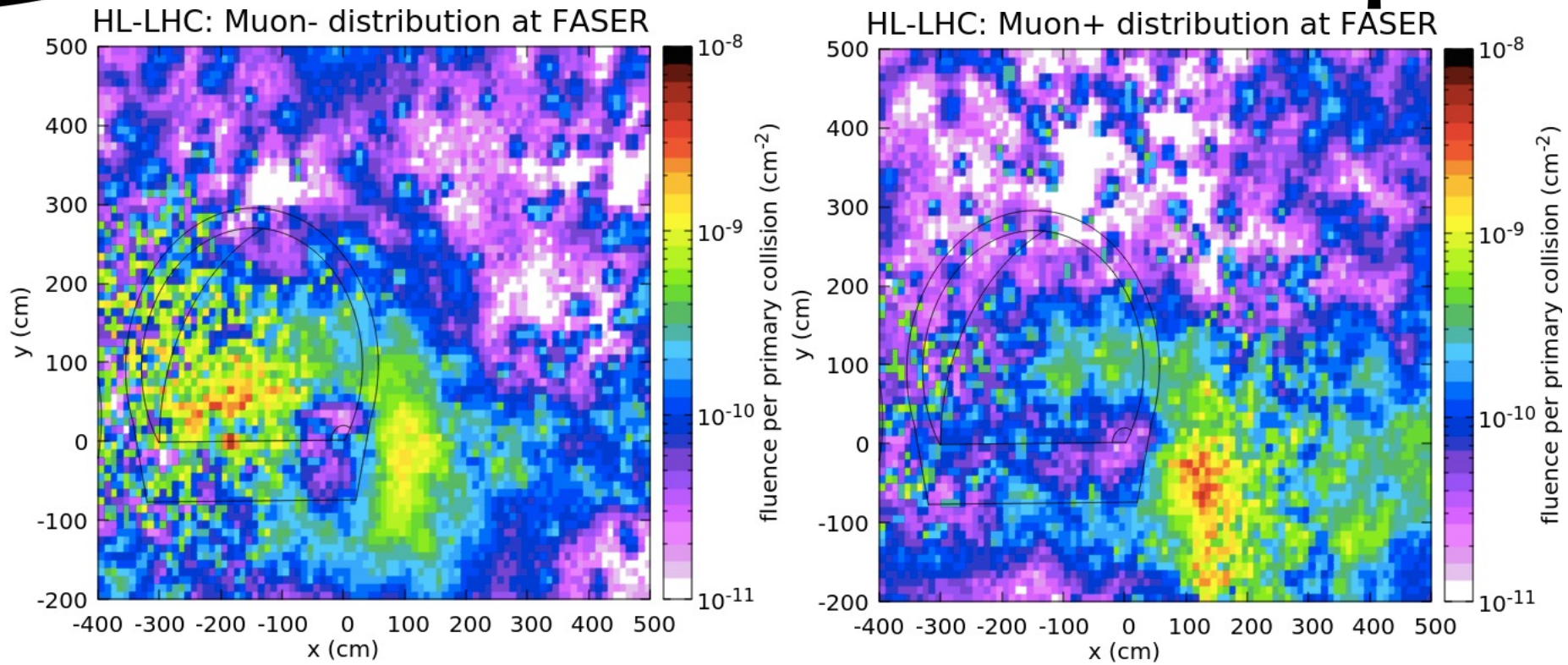


Noisy/dead strips in modules





FLUKA simulations: muon map

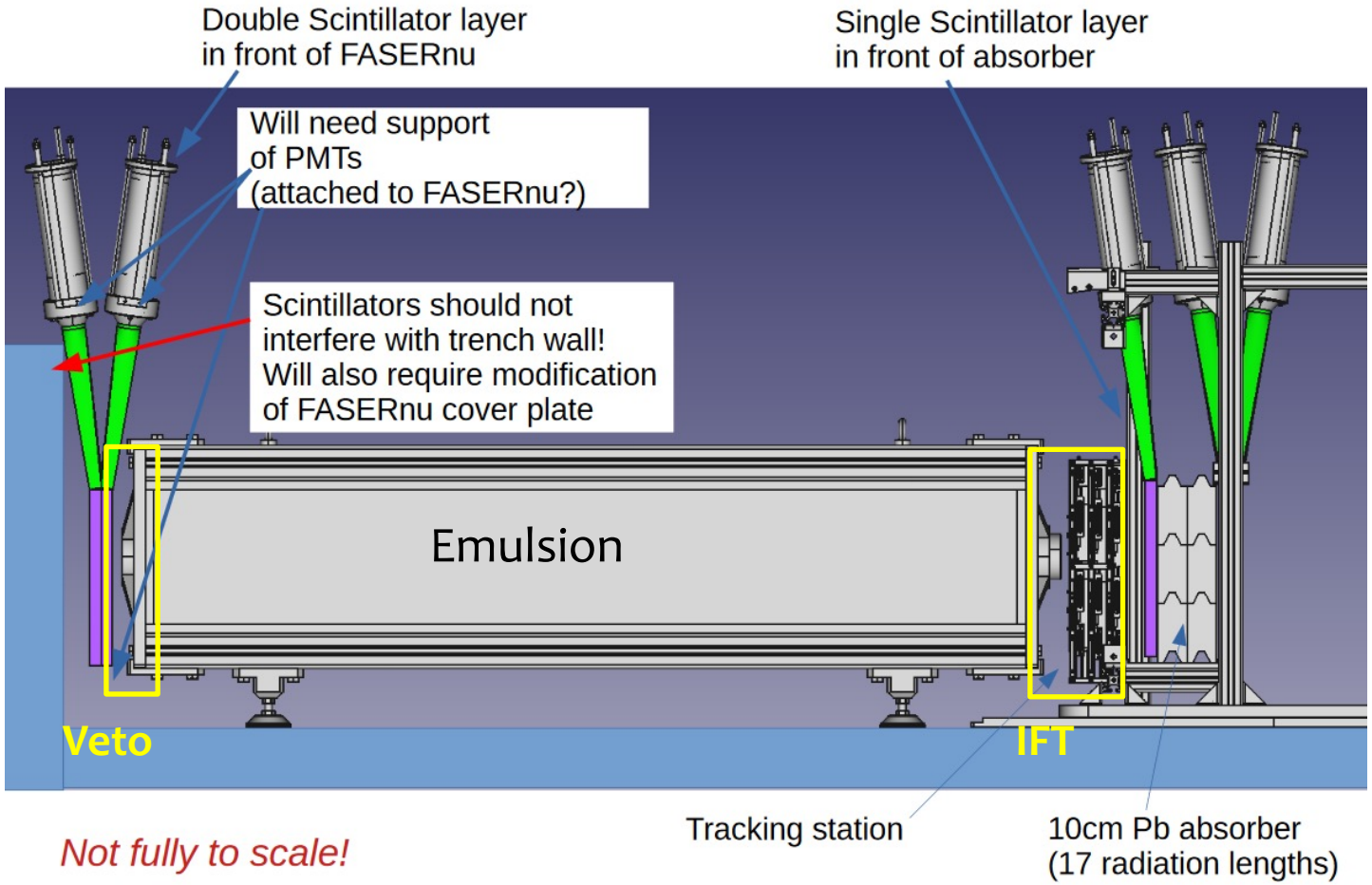


Due to bending from LHC magnets, muon flux on LOS is reduced:
μ^- tend to be bent to the left, μ^+ to the right of FASER.

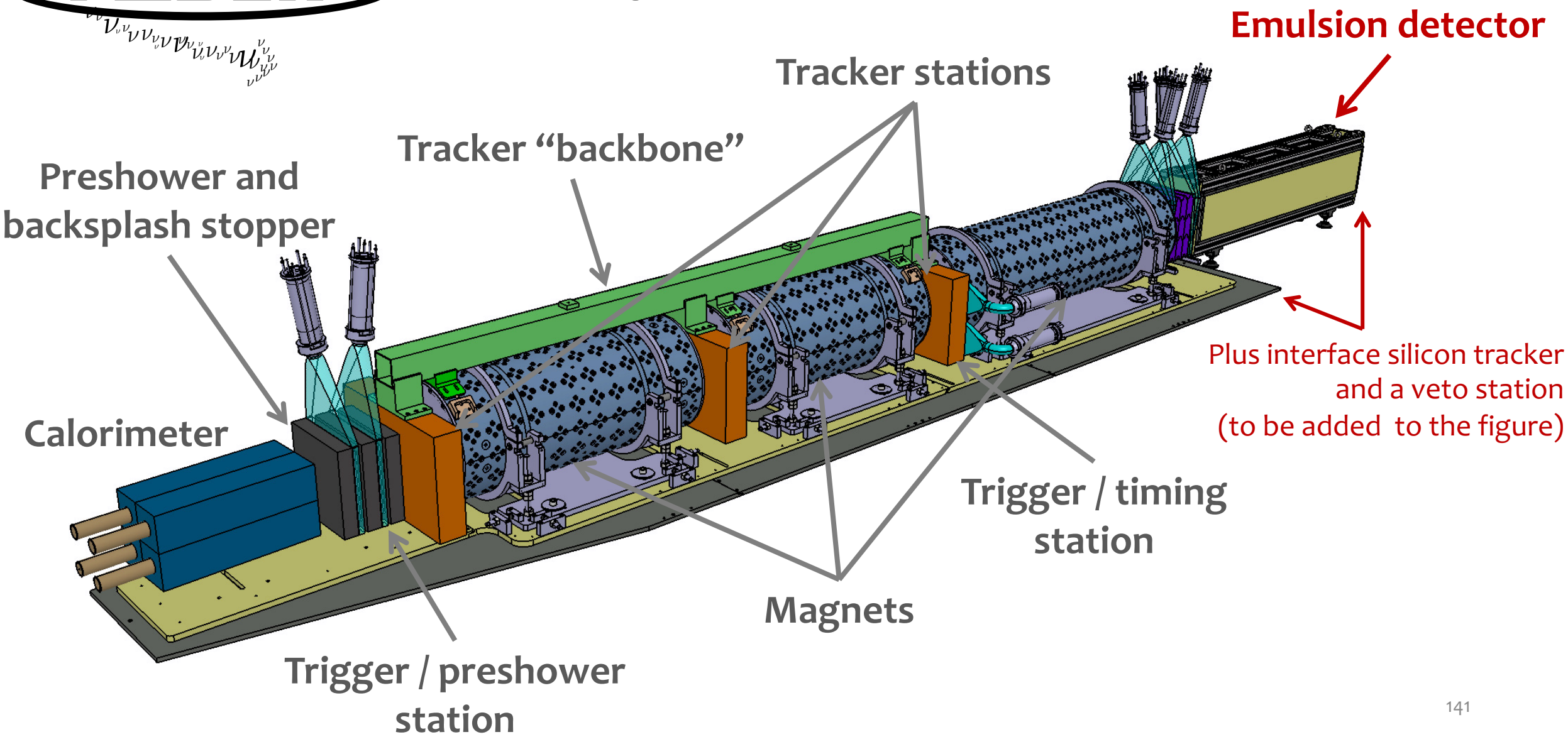
Energy threshold [GeV]	Charged particle flux [cm^{-2} s^{-1}]
10	0.40
100	0.20
1000	0.06

Expected charged particle rate for different energy thresholds (2e34$cm^{-2}s^{-1}$)

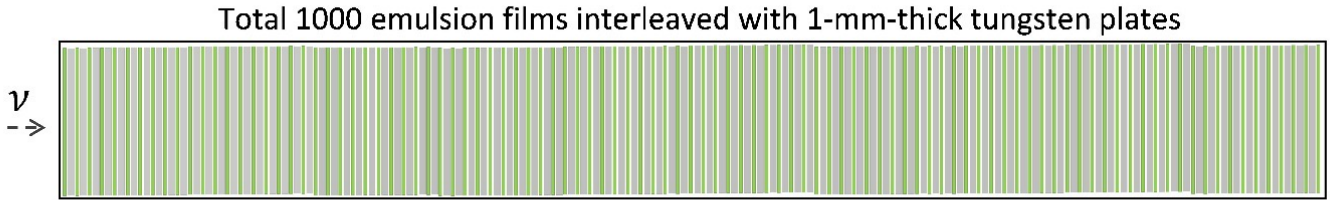
FASERν plus interface detector



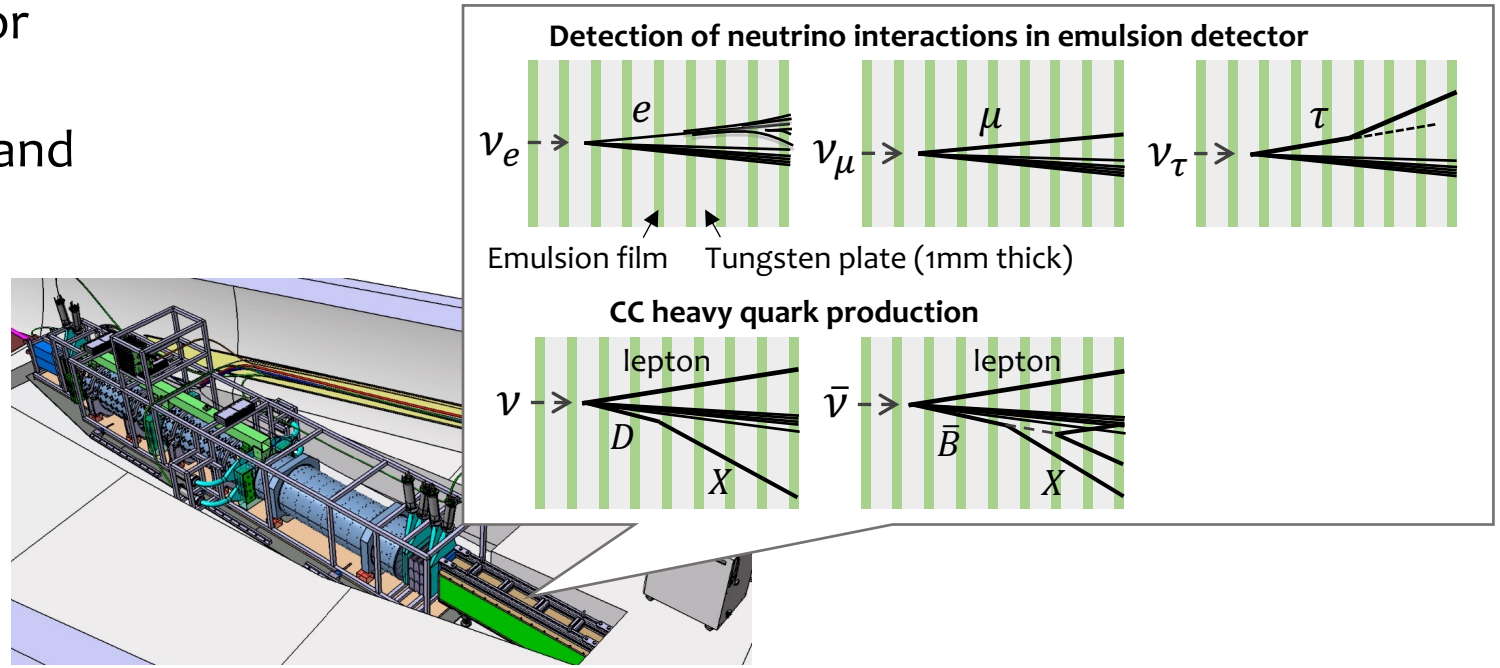
FASER Detector

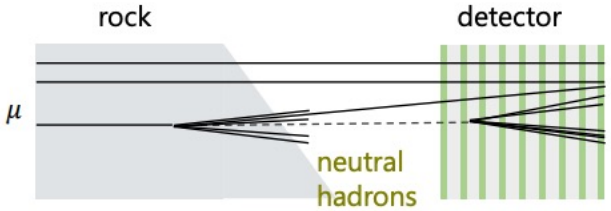


Detector - emulsion



- Emulsion film detector with tungsten plates; well known neutrino detector technology
- Track position resolution O(50nm), and angular resolution O(0.35mrad). No timing resolution
- Replace every 20-50/fb to maintain manageable track density
- Challenge: replace the 1-ton-scale detector about 3 times/year



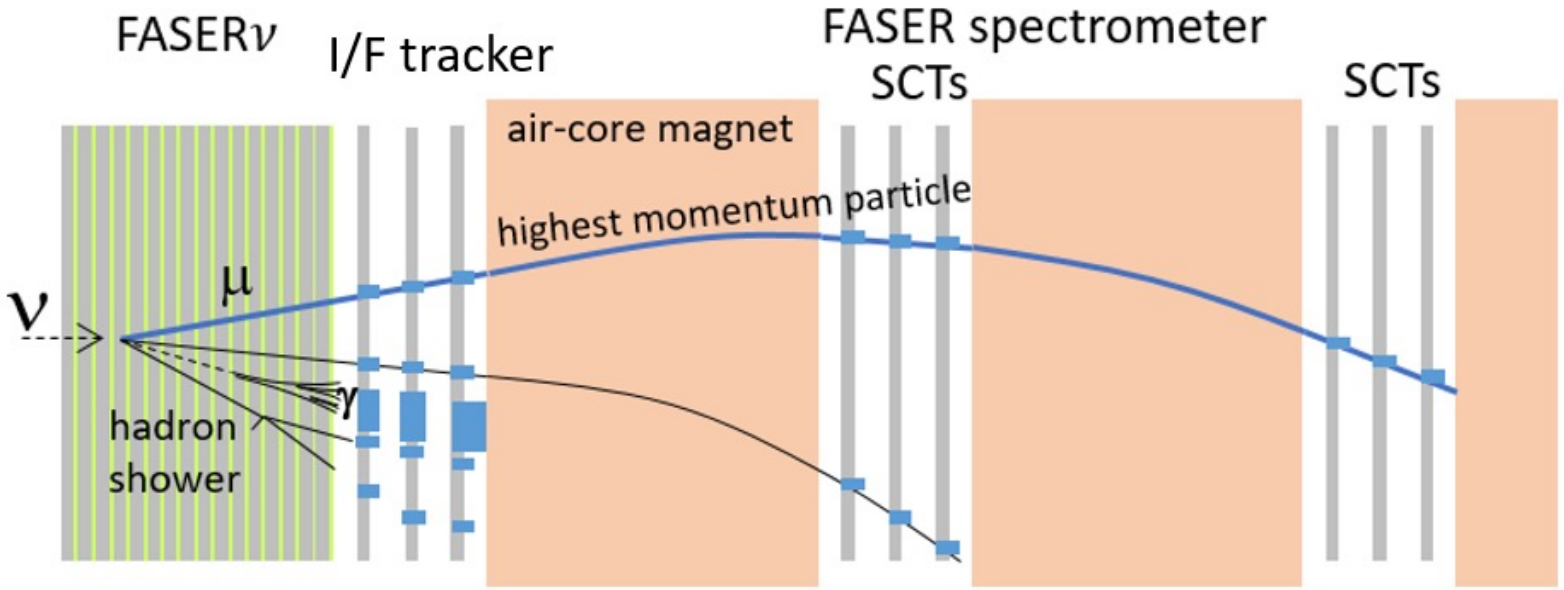


Background

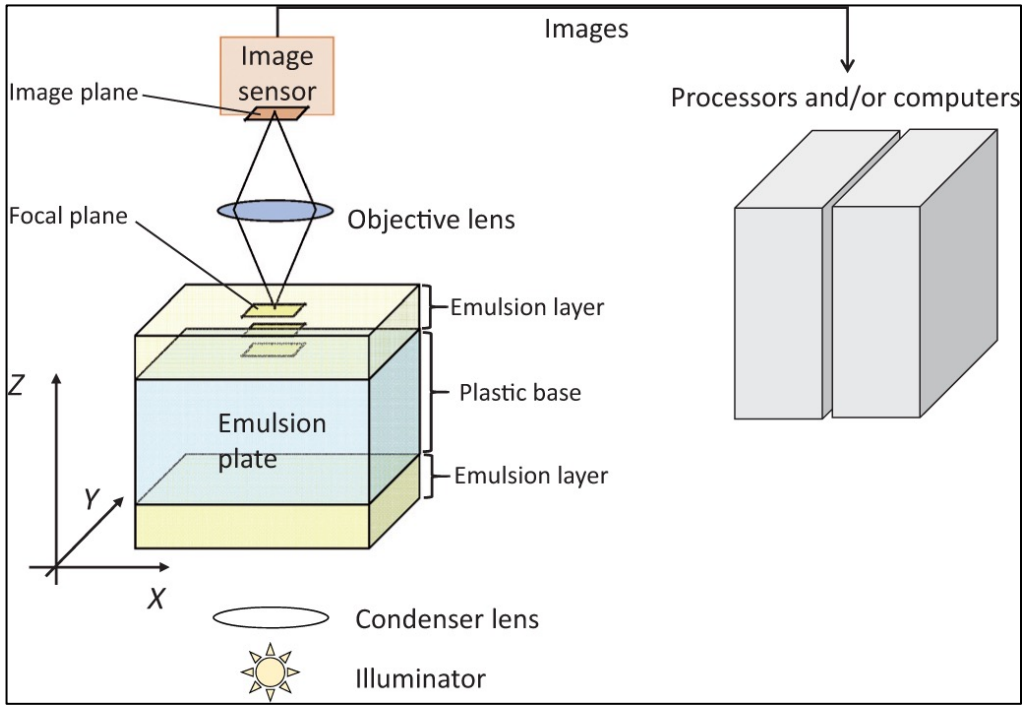
N.B.: Interface tracker for charge ID and improved measurements to be added!

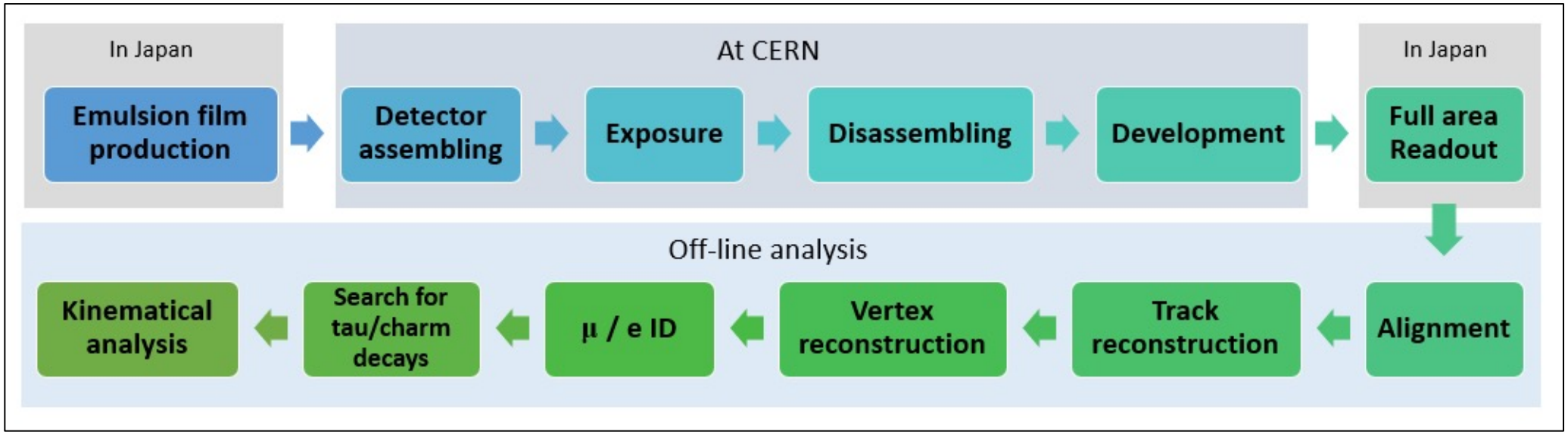
Interface detector

- Possibility to connect FASERν with rest of FASER for:
  - Charge identification, Improved energy resolution, Better background rejection
- Would require interface detector in front of FASER
  - Precision tracker to link FASERν and FASER tracks
  - Most likely a fourth station of spare ATLAS SCT modules
- To not jeopardize FASER schedule, this would be installed in 2021/22 YETS
  - Most data anyway expected after that

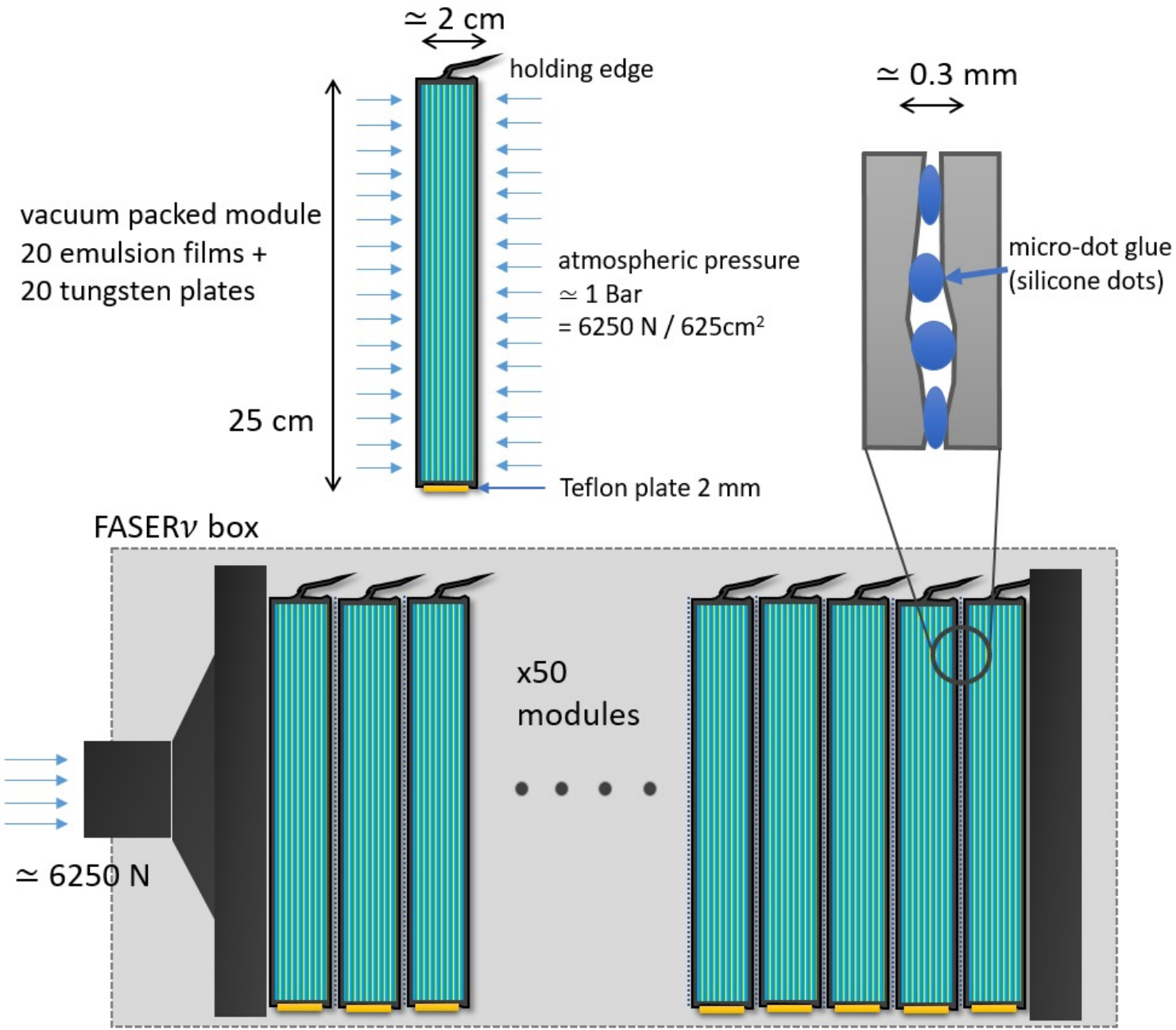


Read-out & Analysis





Module structure



Emulsion

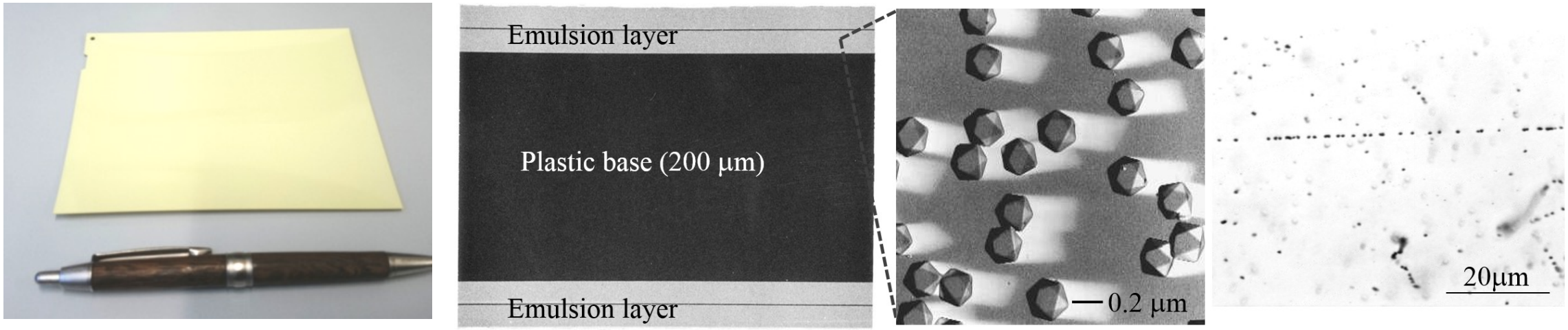


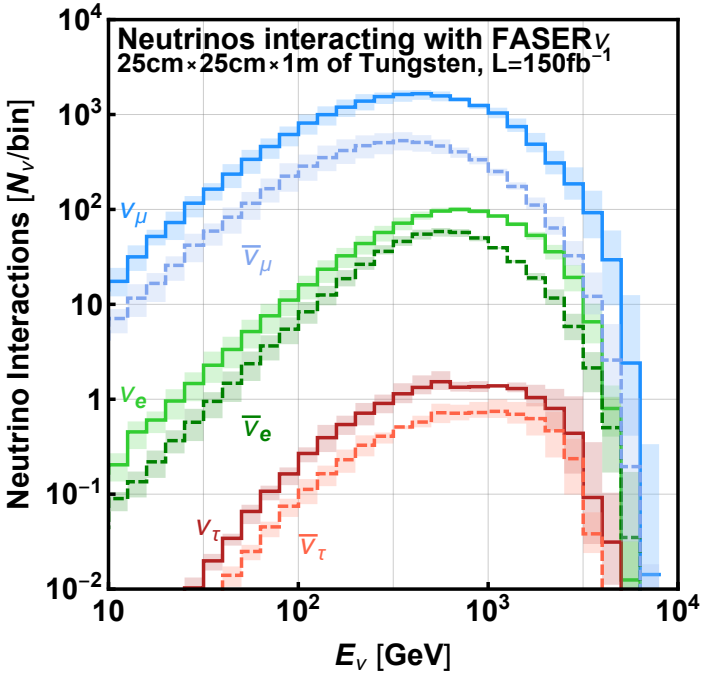
Photo of an emulsion film (left), its cross-sectional view (left center), electron microscope image of the silver halide crystals (right center), and a minimum ionising particle track from a 10 GeV/c π beam (right).

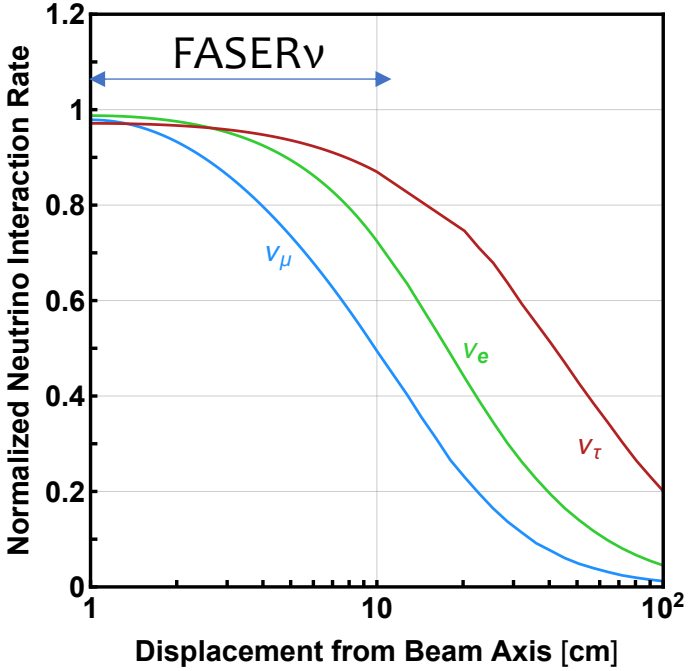
Neutrino production

Type	Particles	Main Decays	E	Q	S	P
Pions	π^+	$\pi^+ \to \mu\nu$	$\surd$	$\surd$	$\surd$	—
Kaons	K^+, K_S, K_L	$K^+ \to \mu\nu$, $K \to \pi\ell\nu$	$\surd$	$\surd$	$\surd$	—
Hyperons	Λ, Σ^+, Σ^-, Ξ^0, Ξ^-, Ω^-	$\Lambda \to p\ell\nu$	$\surd$	$\surd$	$\surd$	—
Charm	D^+, D^0, D_s, Λ_c, Ξ_c^0, Ξ_c^+	$D \to K\ell\nu$, $D_s \to \tau\nu$, $\Lambda_c \to \Lambda\ell\nu$	—	—	$\surd$	$\surd$
Bottom	B^+, B^0, B_s, Λ_b, ...	$B \to D\ell\nu$, $\Lambda_b \to \Lambda_c\ell\nu$	—	—	—	$\surd$

TABLE I. Decays considered for the estimate of forward neutrino production. For each type in the first column, we list the considered particles in the second column and the main decay modes contributing to neutrino production in the third column. In the last four columns we show which generators were used to obtain the meson spectra: EPOS-LHC (E) [59], QGSJET-II-04 (Q) [60], SIBYLL 2.3C (S) [61–64], and PYTHIA 8 (P) [66, 67], using both the MONASH-tune [68] and the minimum bias A2-tune [69].

Neutrino fluxes





The energy spectrum of neutrinos with CC interactions in a 1-ton tungsten detector with dimensions 25 cm × 25 cm × 1 m centered on the beam collision axis at the FASER location at the 14 TeV LHC with 150 fb−1

The neutrino interaction rate per unit area normalized to the prediction at the beam collision axis for a detector with large radius.

Possibility of probing tau neutrino production from the decay of light gauge bosons

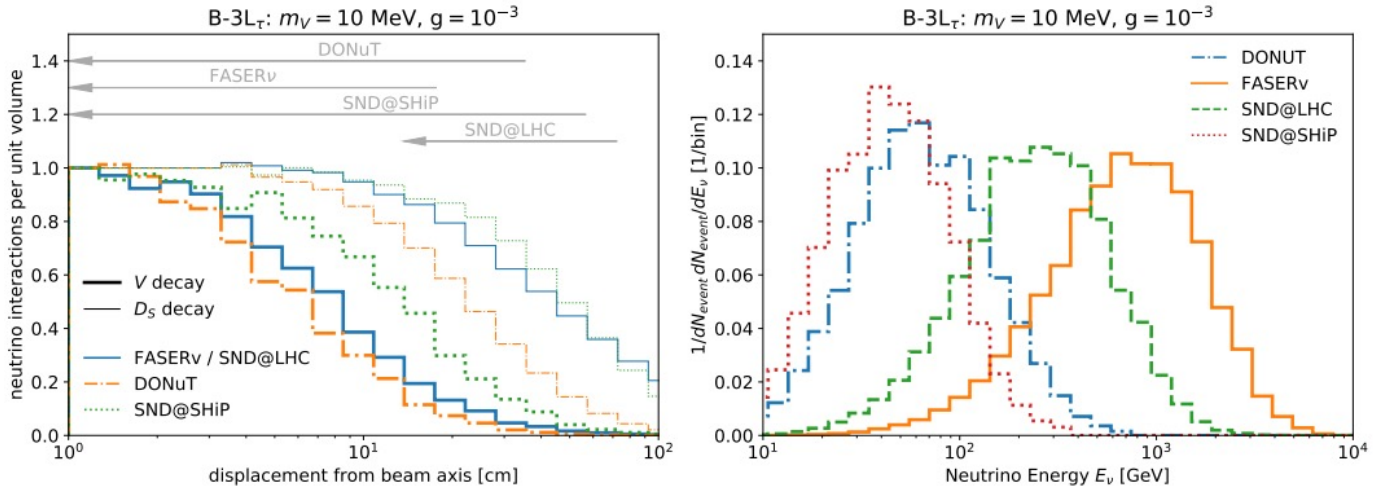
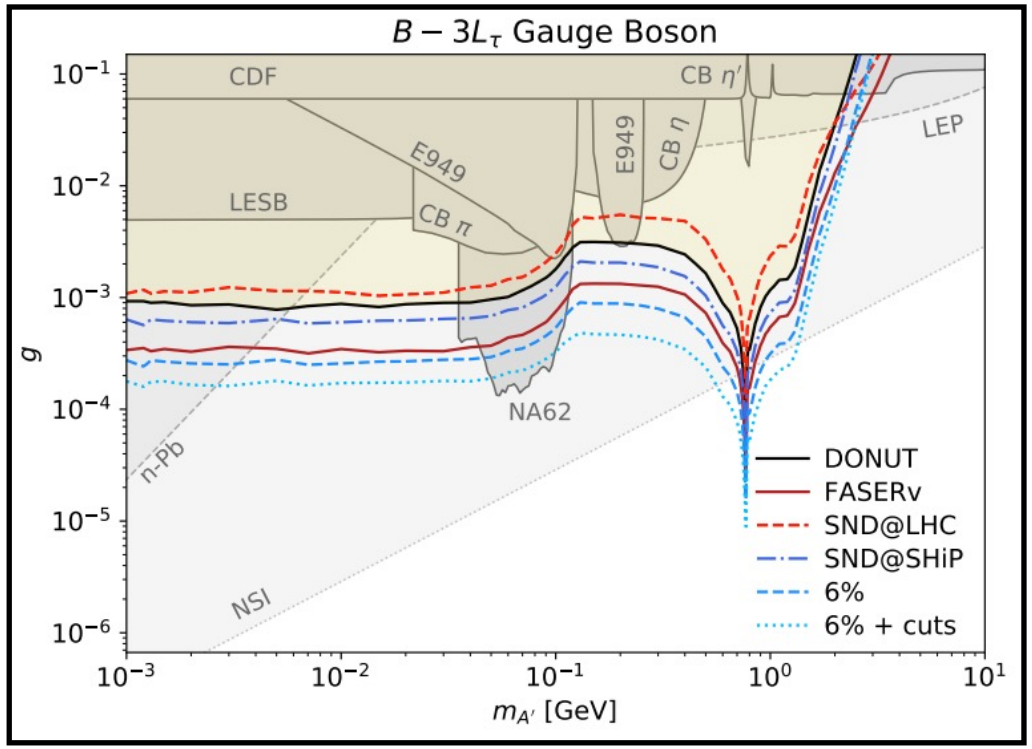


FIG. 1. Kinematic distributions of tau neutrinos produced in the decay of a $U(1)_{B-3L_\tau}$ vector boson with mass $m_V = 10$ MeV and coupling $g = 10^{-3}$ at the considered experiments. The left panel shows the possible rate of neutrino interactions per unit volume, normalized to its value at the beam axis, as a function of the displacement from the beam axis. For comparison, we also show the radial distribution for tau neutrinos from D_s decay. The gray arrows indicate the radial coverage of the considered experiments. The right panel shows the normalized energy distribution for ν_τ's from V decay interacting in the detector.



arXiv:2005.03594

TABLE I. Types of anomaly free gauge groups and corresponding fermion charges q_f.

Gauge Group	q_q	q_e	q_μ	q_τ
$x_e L_e + x_\mu L_\mu - (x_e + x_\mu) L_\tau$	0	x_e	x_μ	$-x_e - x_\mu$
$B + x_e L_e + x_\mu L_\mu - (3 + x_e + x_\mu) L_\tau$	1/3	x_e	x_μ	$-3 - x_e - x_\mu$
$B - L$	1/3	−1	−1	−1
$B - L_\mu - 2L_\tau$	1/3	0	−1	−2
$B - L_e - 2L_\tau$	1/3	−1	0	−2
$B - 3L_\tau$	1/3	0	0	−3

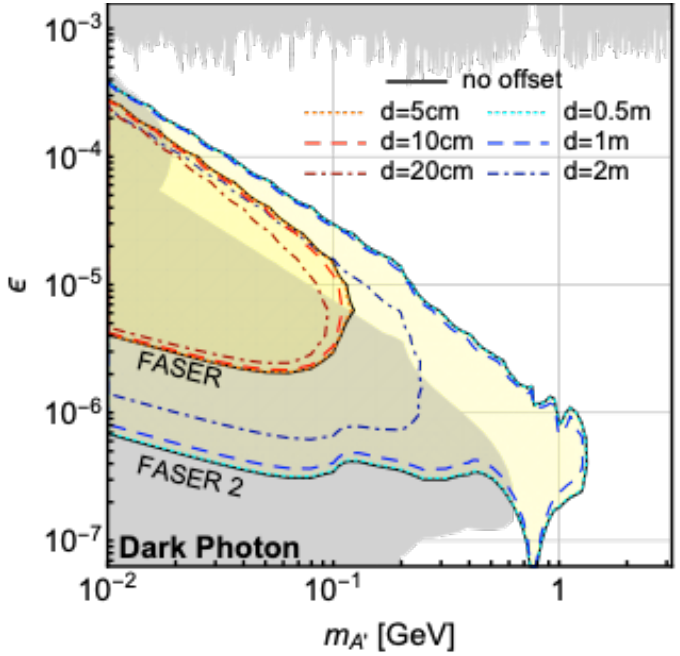
Experimental Setup							SM		$B-3L_\tau$		
Experiment	Status	$\mathcal{L}/N_{\rm POT}$	$m_{\rm det}$	$A_{\rm det}$	$\epsilon_{\rm det}$	Ref.	$N_{\rm event}$	$\langle E_\nu \rangle$	$N_{\rm event}$	$\langle E_\nu \rangle$	$N_{2\sigma}$
DONuT	completed	$3 \cdot 10^{17}$	0.26 t	50×50 cm^2	0.2	[3]	10 ± 4.6	112 GeV	12	84 GeV	9.1
FASERν	approved	150 fb^{-1}	1.2 t	25×25 cm^2	0.52	[7]	11.6 ± 5.1	965 GeV	96	928 GeV	10
SND@LHC	proposed	150 fb^{-1}	0.85 t	40×40 cm^2	0.5	[9]	4.3 ± 2.5	720 GeV	3.5	382 GeV	5
SND@SHiP	proposed	$2 \cdot 10^{20}$	8 t	80×80 cm^2	0.22	[5]	$(10.9 \pm 3.6) \cdot 10^3$	52 GeV	$2 \cdot 10^4$	54 GeV	7200

Extending the trench for FASERν

Effect of LHC crossing angle

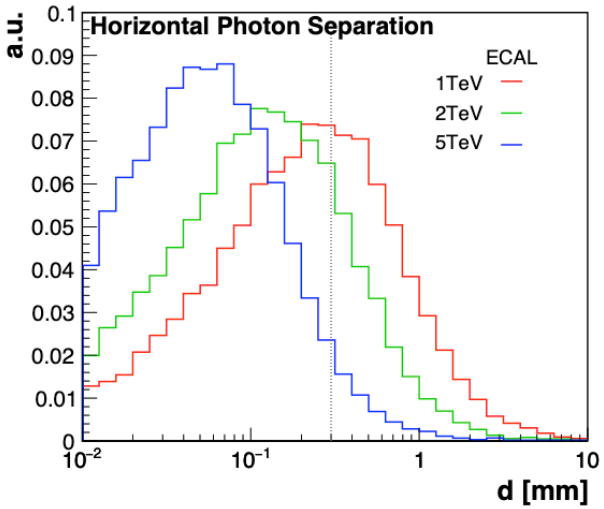
To avoid parasitic collisions and beam-beam effects in the common beampipe close to the IP, the LHC runs with a crossing-angle

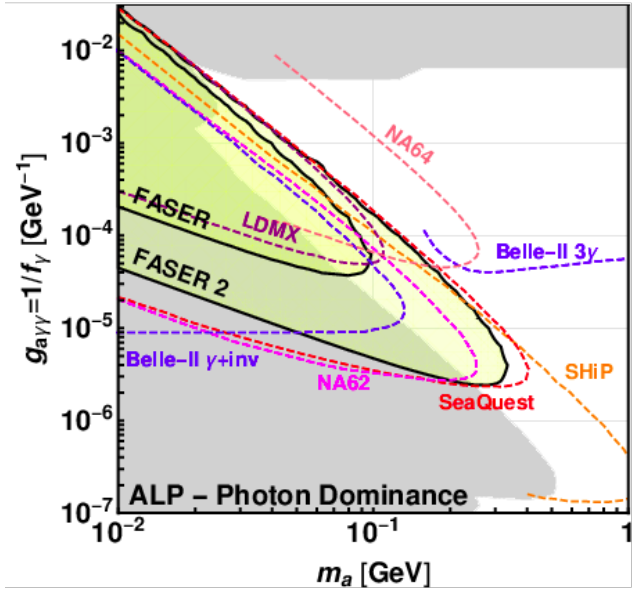
- The half crossing angle is ~150 μrad, which moves the collision axis by ~7.5 cm at the FASER location
- Such a change reduces the signal acceptance in FASER by ~25%
- Leads to very small changes in physics sensitivity



ALP->γγ performance

- For ALP->γγ decay, magnetic field does not help separate closely spaced decay products
- We investigated calorimeter / pre-shower to allow to be able to resolve closely spaced (~1mm) high energy photons (>500 GeV) - seems very challenging
- Preliminary studies suggest that events with no tracks and a large amount of EM energy in the calorimeter would be ~background free => an ALP signal would be detectable without the need to resolve the 2 photons.
- Further studies show an interesting background would be high energy neutrino's interacting in the calorimeter to give large EM showers
- In longer term investigating installing a fine granularity silicon pre-shower to be able to separate close-by photons.





Cost (estimates from TP)

FASER

Detector component	Cost [kCHF]	Detailed Table
Magnet	420	Table V
Tracker Mechanics	66	Table VI
Tracker Services	105	Table VII
Scintillator Trigger & Veto	52	Table VIII
Calorimeter	13	Table IX
Support structure	60	Table X
Trigger & Data Acquisition	52	Table XIV
Total	**768**	-
Spares	56	-

Biggest single costs:
Magnet
Power Supplies (~100kCHF)

FASERν

Item	Cost [kCHF]
Emulsion gel for 440 m^2	315
Emulsion film production cost for 440 m^2	32
Tungsten plates, 1200 kg (first set)	173
Tungsten plates, 1200 kg (second set)	173
Packing materials	5
Support structure	12
Chemicals for emulsion development	20
Tools for emulsion development	5
Racks for emulsion film storage	5
Computing server	10
Total	**750**
[Emulsion gel for 2024 running]	[135]
[Additional consumables for 2024 running]	[23]
[Total including 2024 running]	**[908]**

Biggest single costs:
Tungsten plates (~350kCHF)
Emulsion Gel (~300kCHF)

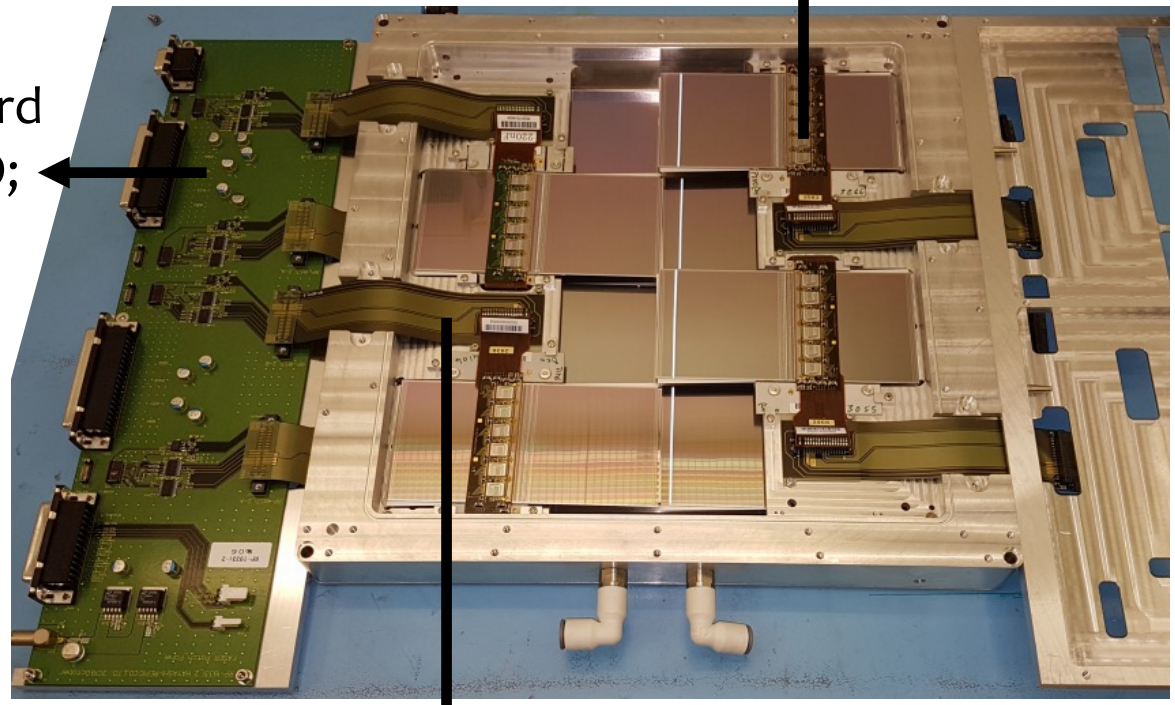
Infrastructure

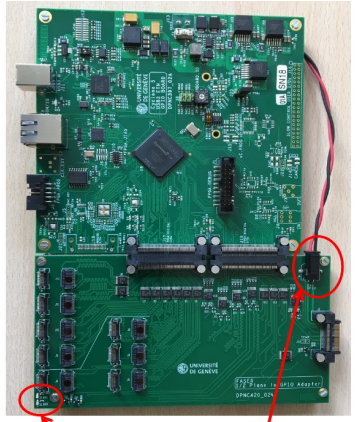
Work	Cost [kCHF]
Civil Engineering	160**
Transport	95**
Optical Fiber & Network Connection	10*
Power Connection	10
Compressed Air Connection	6
Preparation of TI12	10*
Total	291

FASER Tracker

SCT module ASICs, require ~ 5 W / module

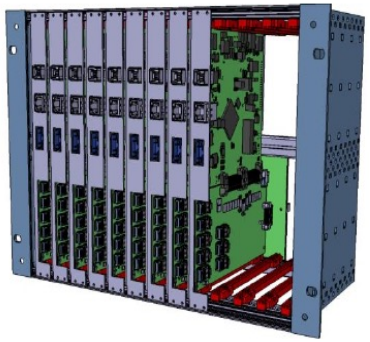
Patch panel to custom board based on home-made GPIO; Power (HV/LV), monitoring and readout lines.





FLEX cables

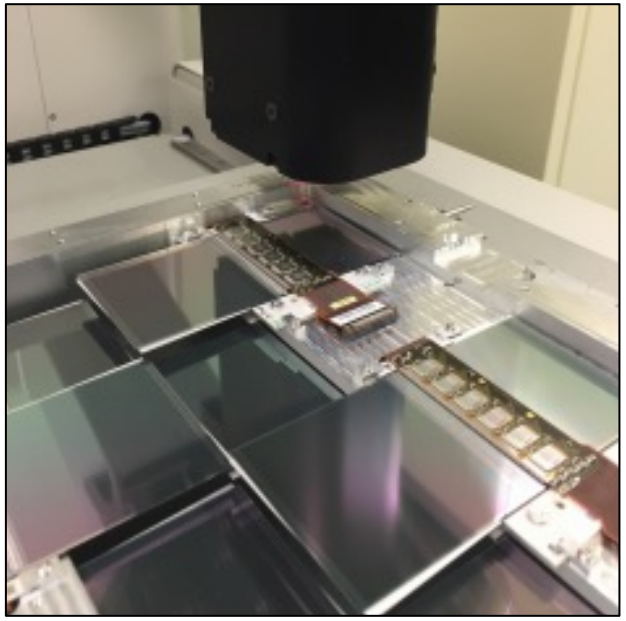
Into custom-made mini-crate



Provides LV and HV

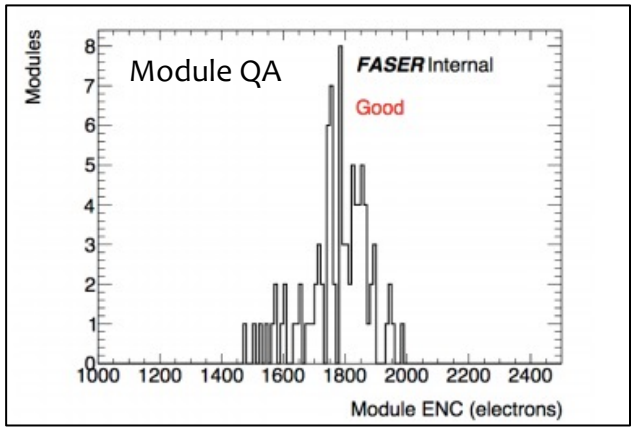
FASER Tracker Status

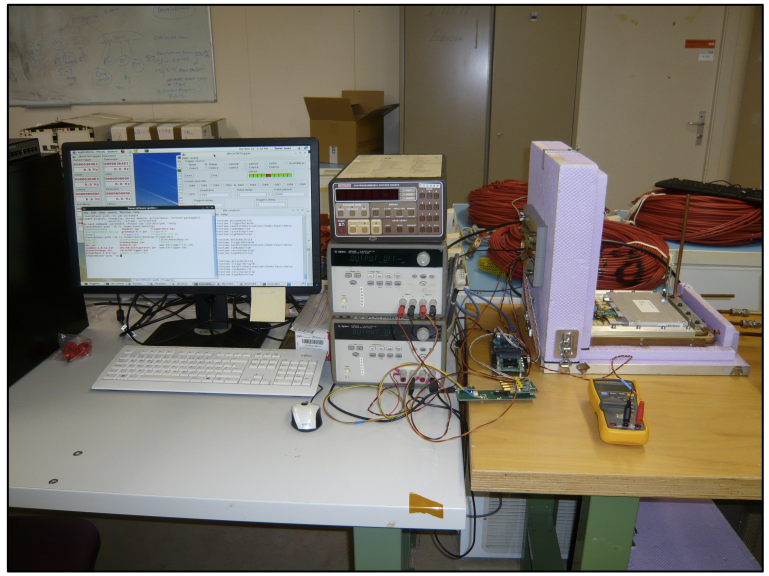
- Prototype layers produced and used for extensive testing (electrical, mechanical and thermal)
- Production planes in progress
- Commissioning started at CERN; well-defined procedure
- Gaining operational experience!



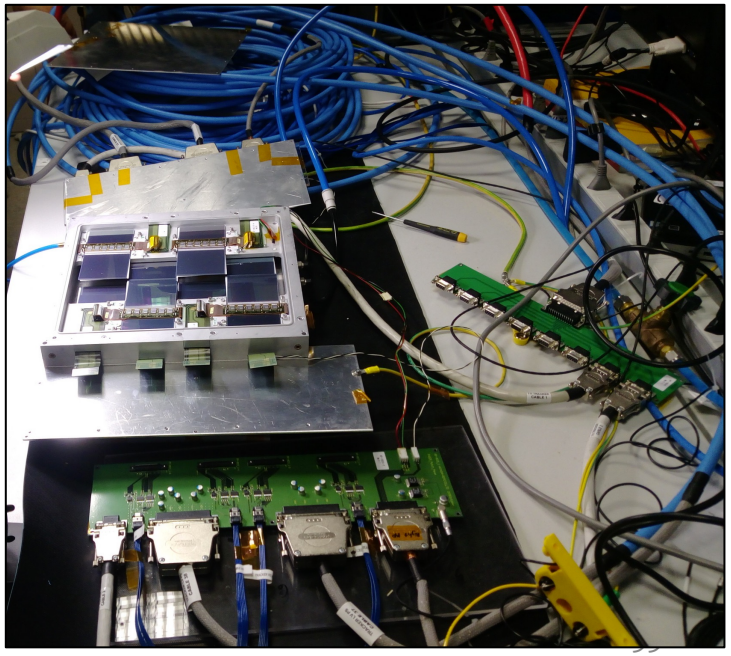
Metrology at the UniGe

- Module QA





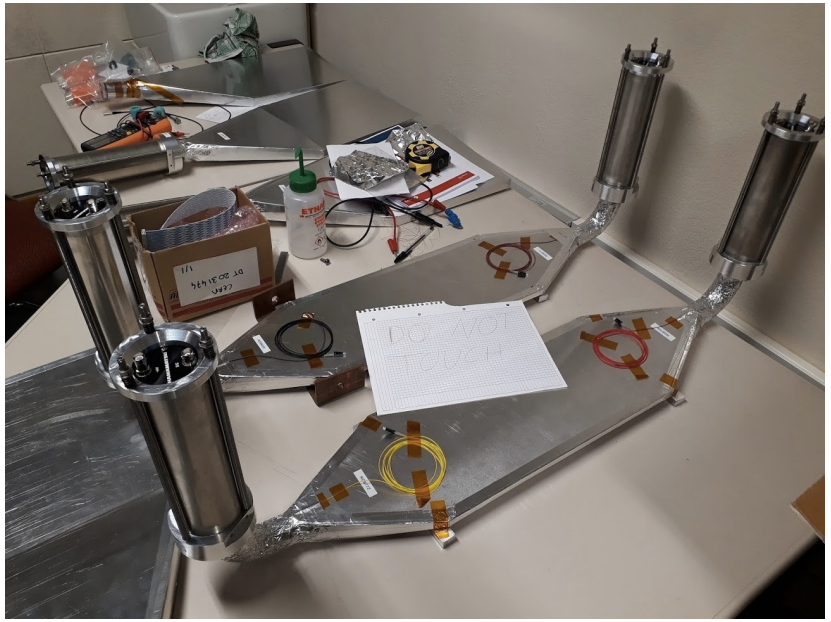
Module QA set up at CERN



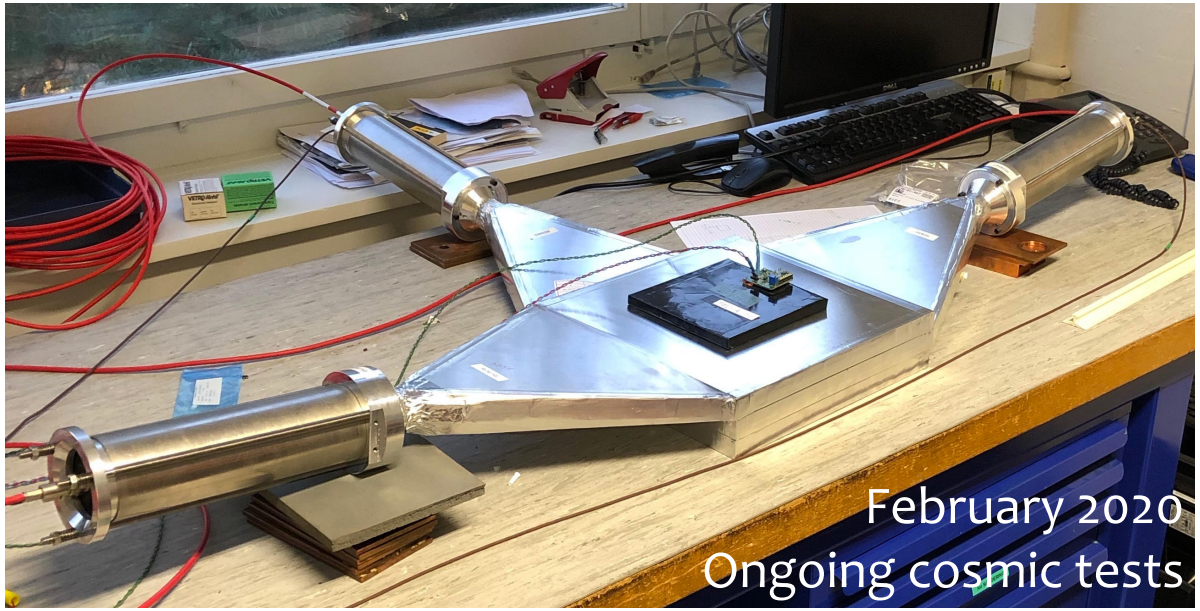
Tracker plane initial testing set up at CERN

FASER Scintillators Status

- Scintillator planes produced at CERN
- PMTs purchased and studied
- Characterization with cosmics and LEDs
  - First results indicate good light yields (~ 400 photo-electrons/MIP) and high efficiency (> 99.8%)



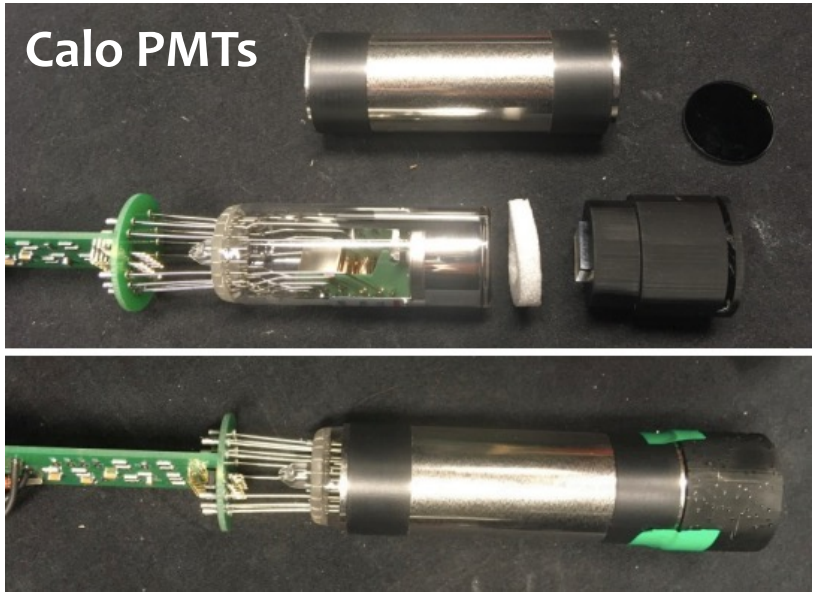
FASER scintillators produced at CERN

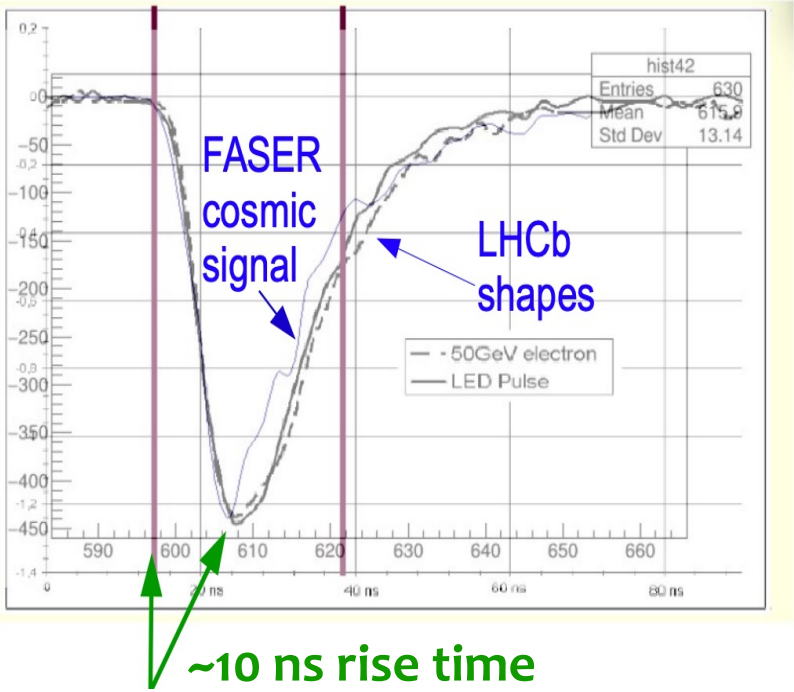


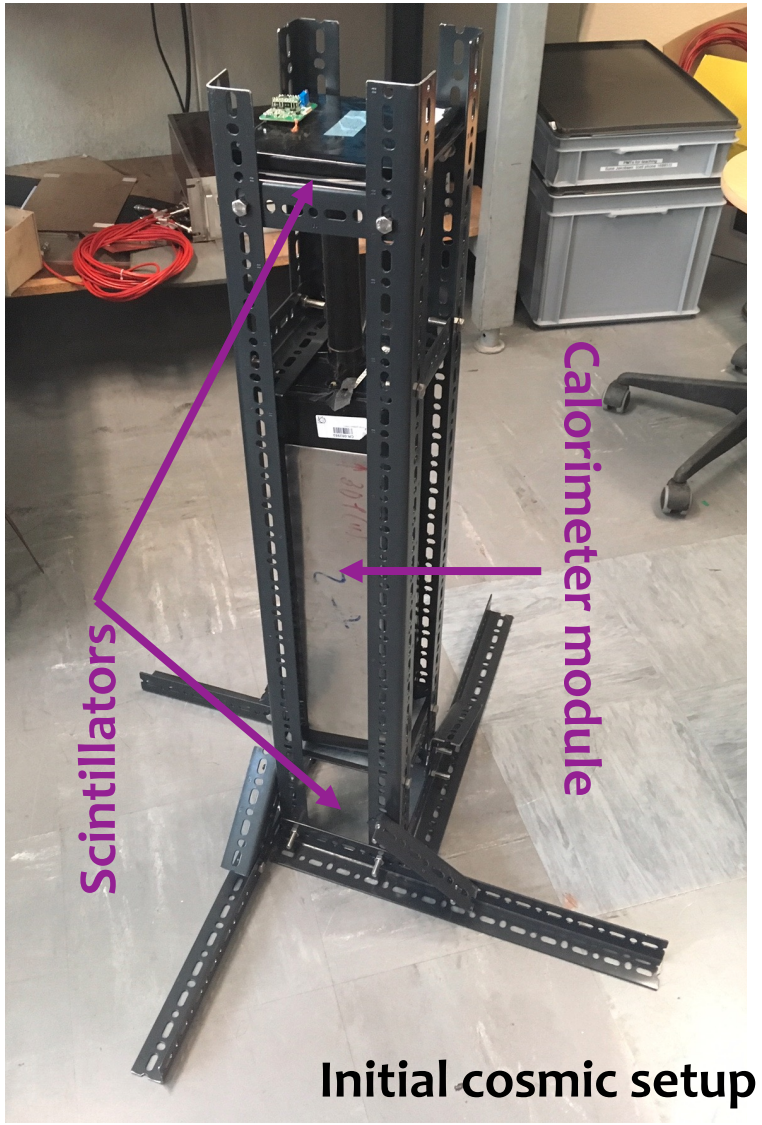
February 2020
Ongoing cosmic tests

FASER Calorimeter Status

- Calorimeter modules tested; characterization ongoing
- First calibration and linearity measurements with cosmics
  - good agreement with LHCb pulses



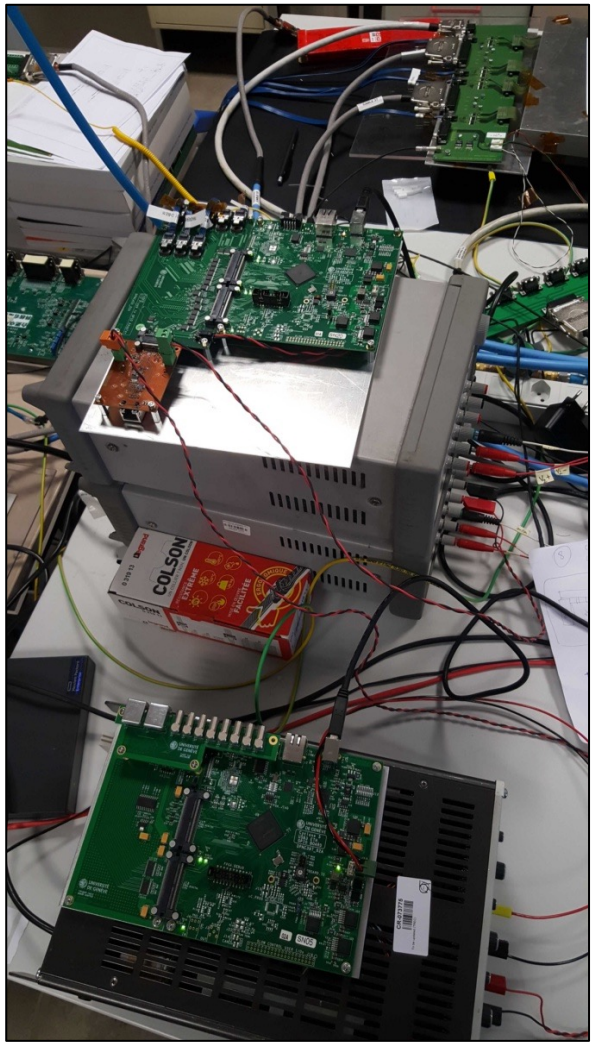




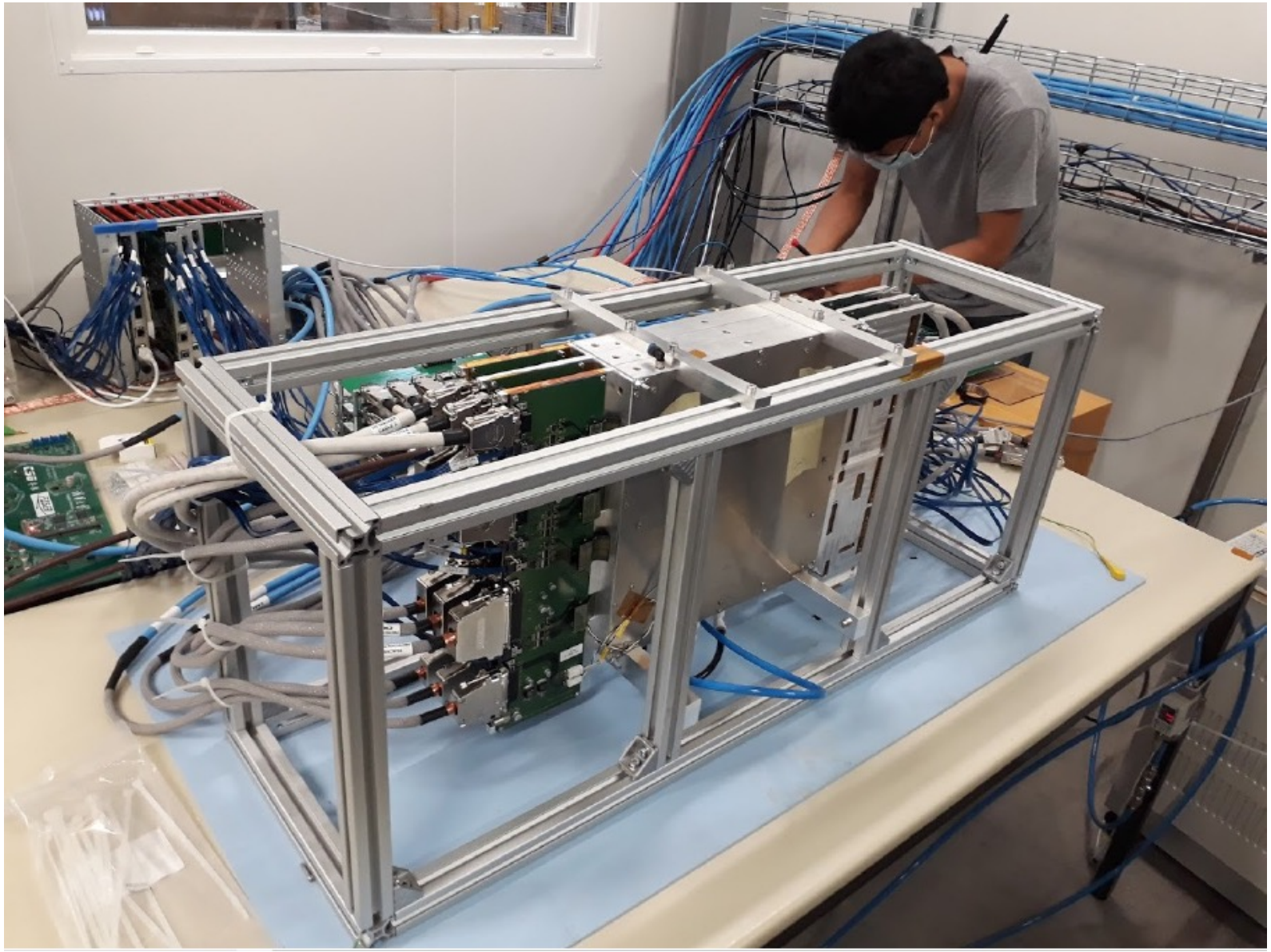
Trigger & Data acquisition Status

- **Electronics available and tested**
  - Connected to rack & available online during CERN lockdown for continuing testing
  - Communication tests resumed last week!
- **DAQ SW based on CERN's "DAQling", adapted for FASER**
  - Initial implementations for all detectors in place
  - Includes online monitoring
- **DCS follows CERN practices**

Initial Run Control application, produced by summer intern



All boards connected together for tests



DAQ Status

Trigger rate

Current Physics Event Rate	602 Hz

Event Builder Status

STATUS	0
BCID mismatches	0
corrupted fragments	0
timeouts	0
duplicate source IDs	0

Run Info

Run Number	1899
Total events	4301191
Run Start	05/04/2021, 18:06:39 PM

Byte rate to file

Data recording rate to physics stream	11.9 MB/s

FileWriter Status

STATUS	0

Digitizer & Trigger

Digitizer Status

STATUS	0
bad fragments	0
empty fragments	6

Trigger Board Status

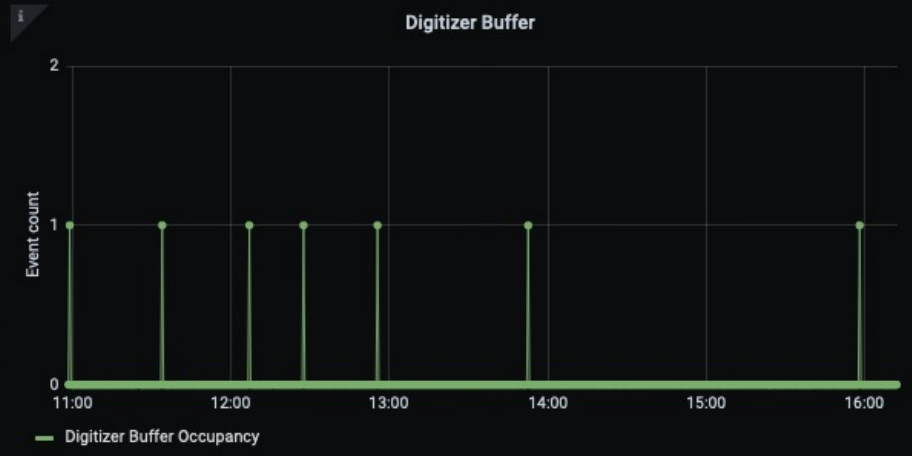
average payload size [bytes]	24
STATUS	1
bad fragments	0
missing event ID	6

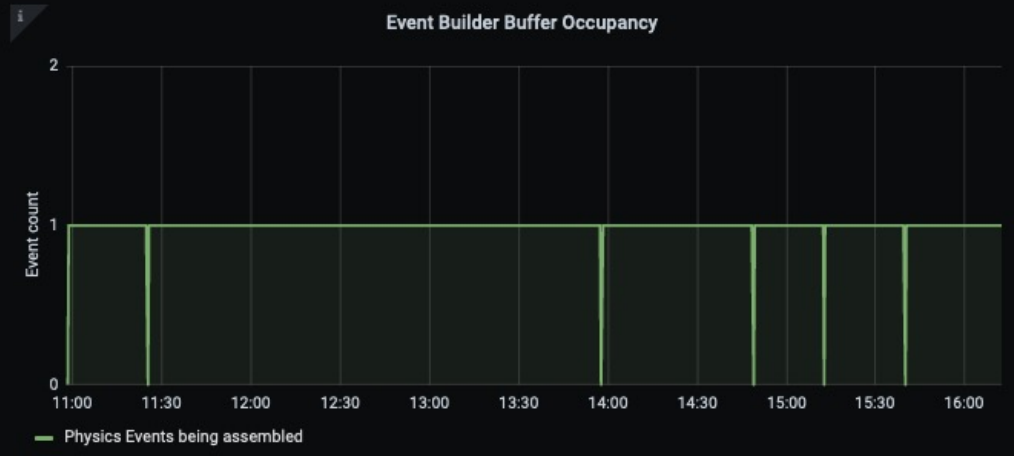
FASER Dashboards (scroll to see all)

- DAQ File Transfers
- DAQ Status Overview
- DAQling Online Data Flow
- Digitizer

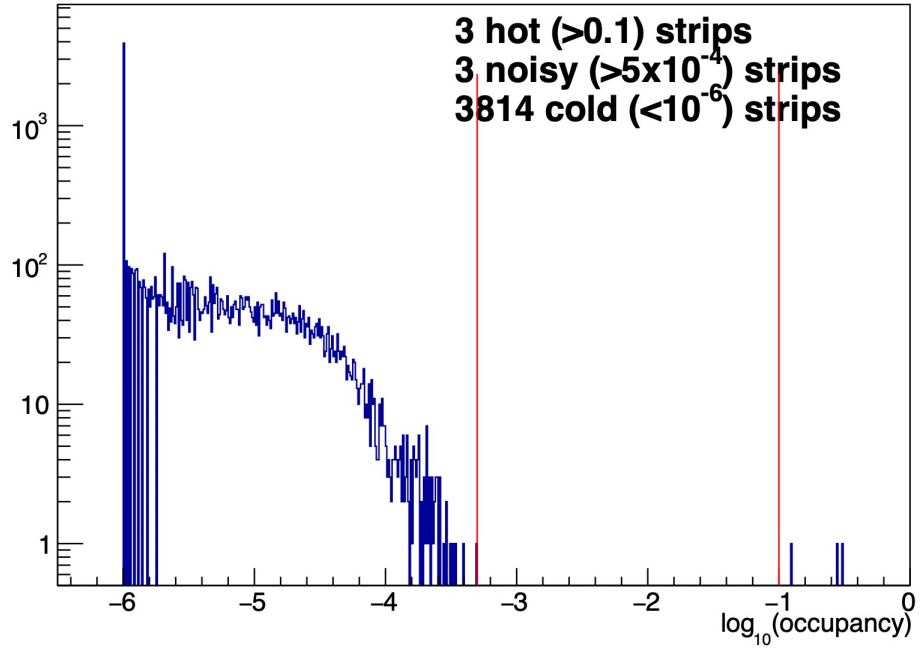
Veto counts

Metric	Current
BCRVeto	4
TrackerVeto	0
SimpleVeto	0
DigitizerVeto	0
RateLimiter	0
Physics Events	1780
Incomplete Events	0
Corrupted Events	0



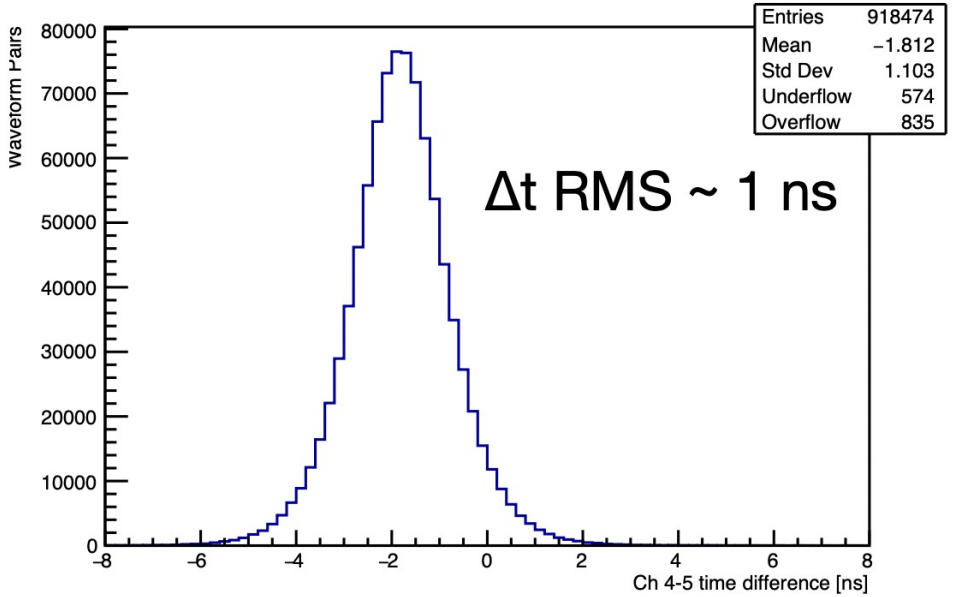


Detector studies



Strip Occupancy

- Strip occupancy in tunnel matches measurements on surface
- Worst layer has 19 hot (>10% occ.) strips out of 3820
- Setting up automated hot strip finding and DQ/monitoring



Scintillator time resolution

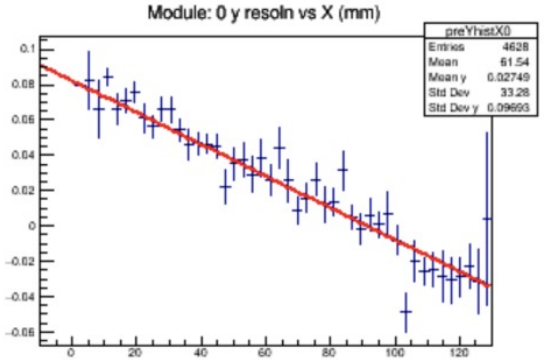
- As expected from surface studies, O(1ns)

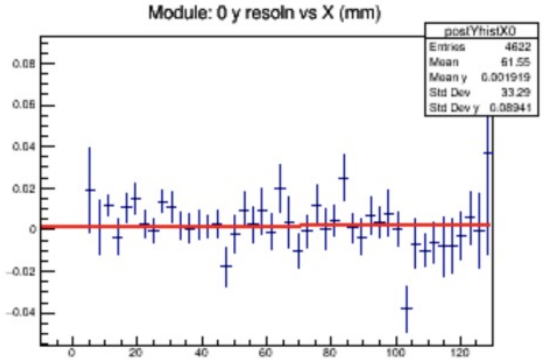
First offline analysis efforts!

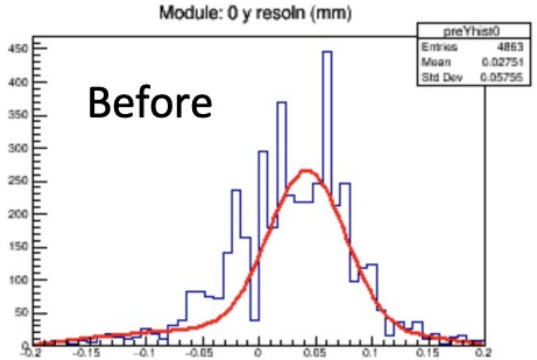
- Including with cosmic rays

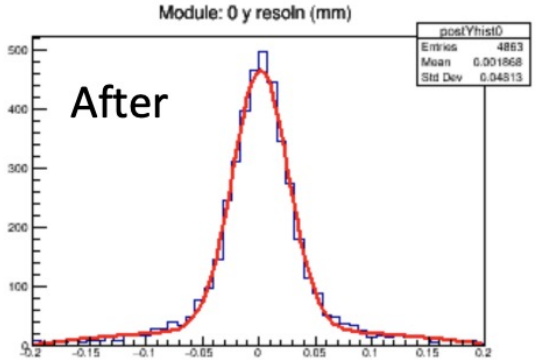
Tracker cosmic results: ‘In station’ alignment

Not proper alignment, but looking at residual distribution in middle tracking layer, and correcting for bias as function position along module.
(Fudges alignment by assuming all mis-alignment is in middle module).







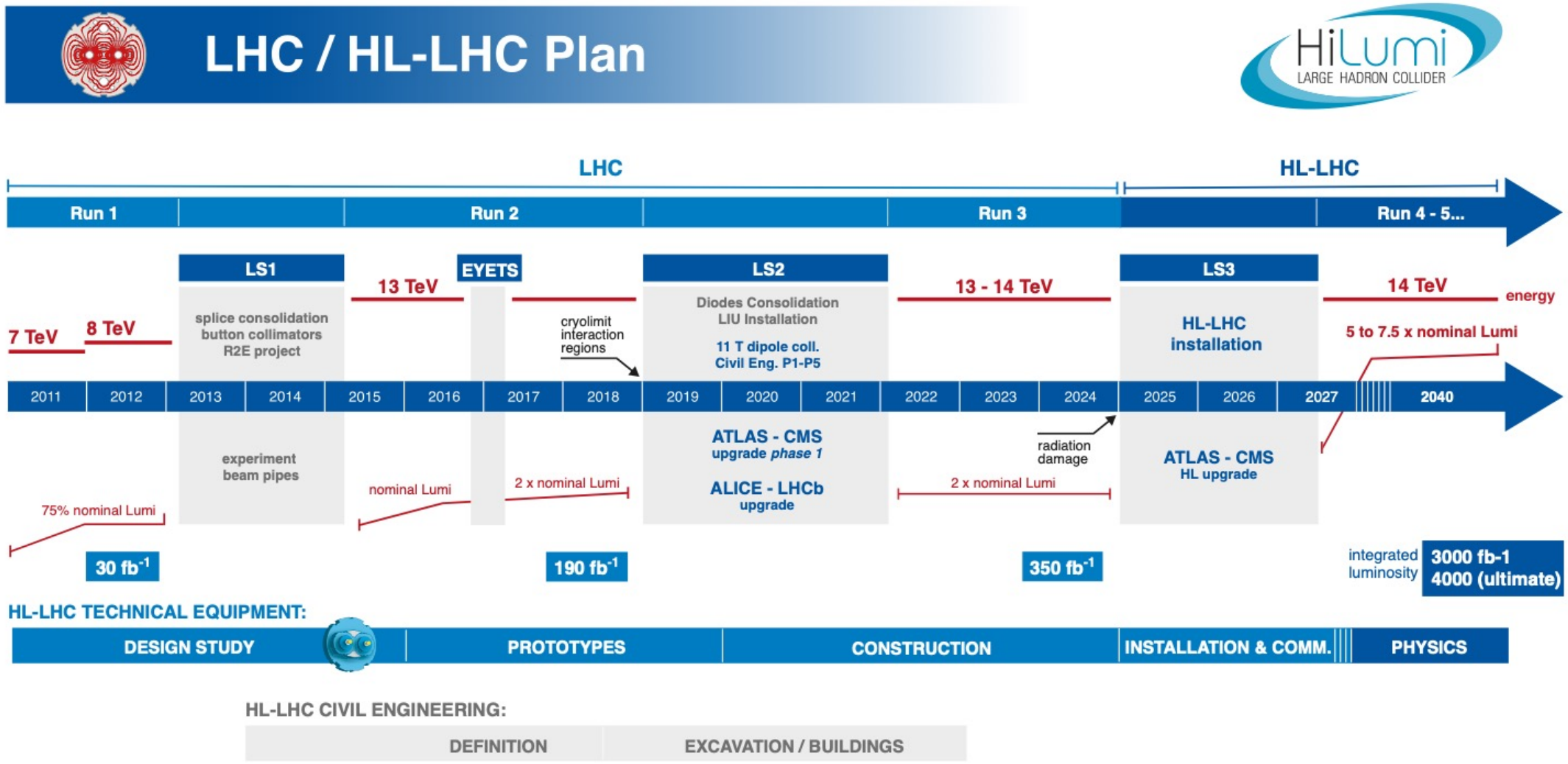


	PRE ALIGNMENT		POST ALIGNMENT	
	Mean (um)	Sigma (um)	Mean (um)	Sigma (um)
Mod: 0	42.6 +- 1.0	34.0 +- 1.0	1.7 +- 0.5	24.7 +- 0.5
Mod: 1	6.3 +- 0.7	36.5 +- 0.7	1.2 +- 0.4	24.3 +- 0.4
Mod: 2	-5.9 +- 0.5	28.4 +- 0.5	1.4 +- 0.4	24.7 +- 0.4
Mod: 3	5.7 +- 0.7	31.1 +- 0.7	0.5 +- 0.5	24.5 +- 0.5
Mod: 4	-4.9 +- 0.7	35.7 +- 0.6	0.3 +- 0.4	25.3 +- 0.4
Mod: 5	1.4 +- 0.9	69.4 +- 2.2	-3.0 +- 0.4	27.2 +- 0.4
Mod: 6	20.0 +- 0.9	43.7 +- 0.9	1.2 +- 0.5	27.2 +- 0.5
Mod: 7	-19.9 +- 0.8	34.5 +- 0.7	-0.6 +- 0.4	25.3 +- 0.4

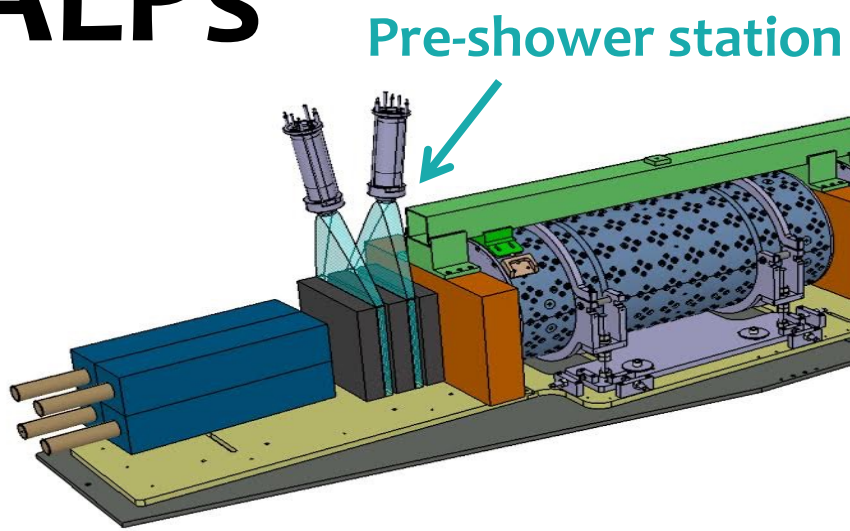
With this simple correction see residual distribution widths of ~25um, close to perfect alignment expectation of ~23um.

Starting to look at this data in offline s/w for more thorough alignment studies, and to test the offline reconstruction.

Run1, Run2 and beyond



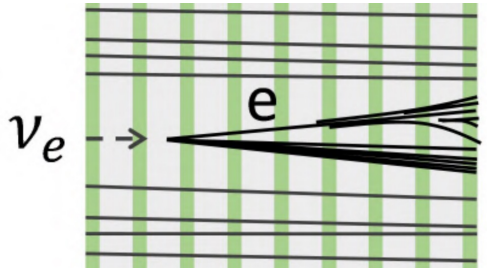
Backgrounds to ALPs



Current FASER pre-shower has major limitations

1. **no information** about the **multiplicity** of the photons or the topology of the event

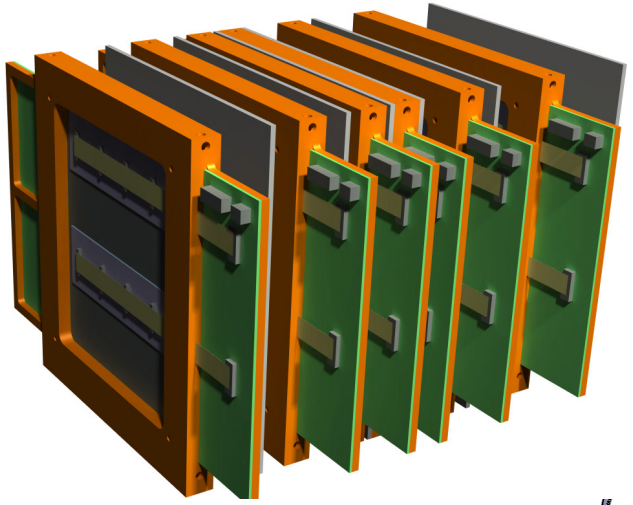
2. **neutrino DIS events** produced in the present pre-shower will be **undistinguishable** from a di-photon (LLP) signature
   - About 10 such events expected in Run3 (150/fb)



Cartoon of ν_e DIS in FASERν

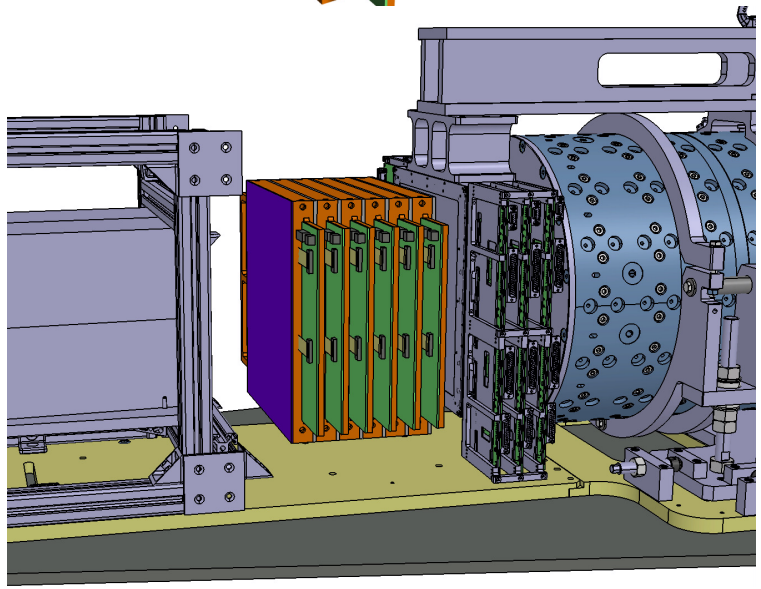
Pre-shower upgrade

Aim:
Introduce the capability to do physics with photons

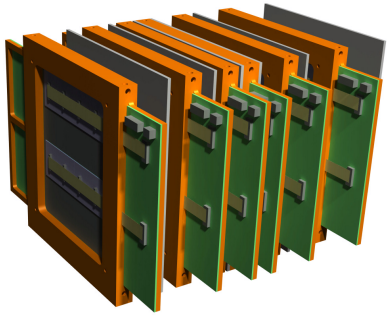


- Existing pre-shower to be replaced by a **high-resolution silicon detector using monolithic pixel ASICs**
  - **technology developed at the UniGe** (group of G. Iacobucci) in the context of other projects funded by SNSF (e.g. FLARE & SINERGIA) and ERC

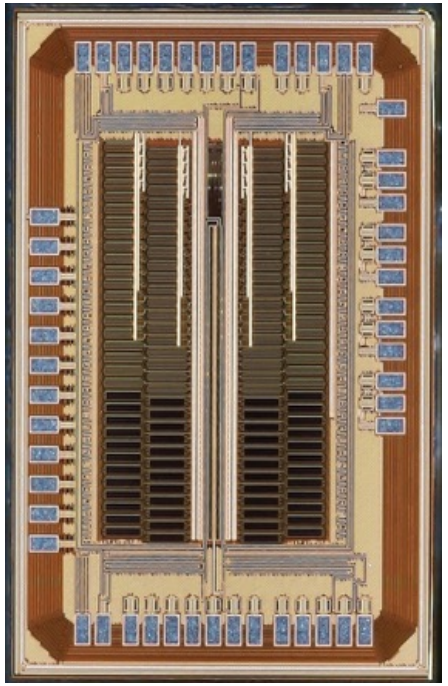
- Composed of six $1X_0$ tungsten layers, each followed by a plane of pixel detectors

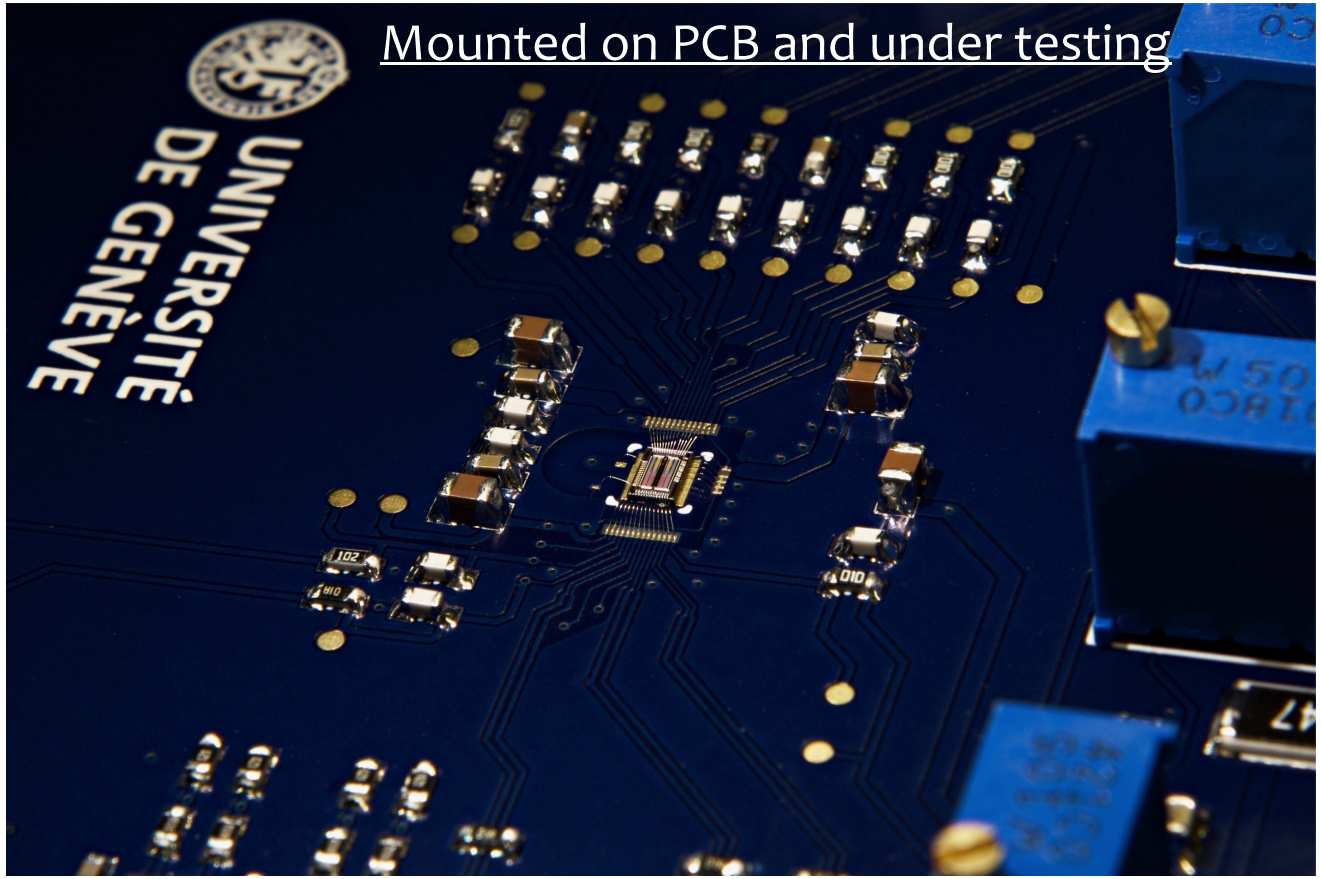


FASER Pixel ASIC



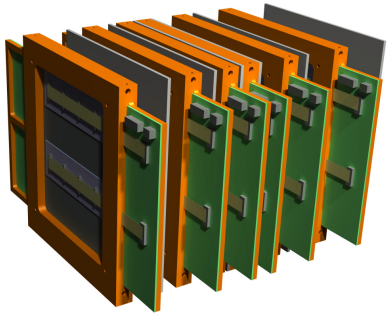
Prototype ASIC
available end 2020



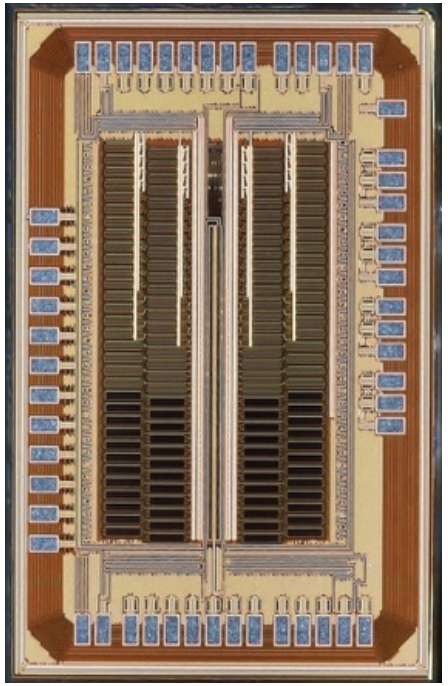


Mounted on PCB and under testing

FASER Pixel ASIC



Prototype ASIC
available end 2020



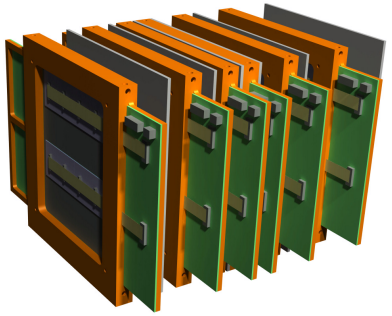
Prototype contains basic building blocks of final chip

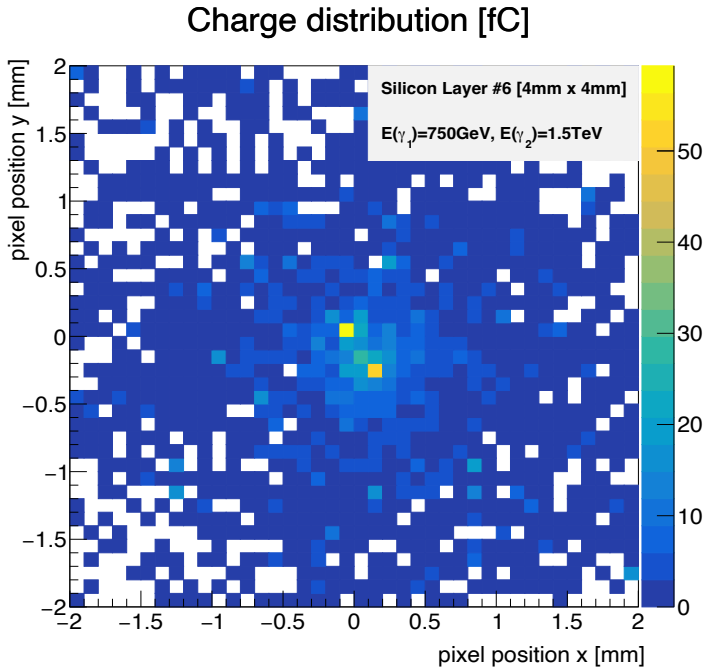
- Lab tests ongoing

Pre-production chip will scale from prototype

- Design in progress

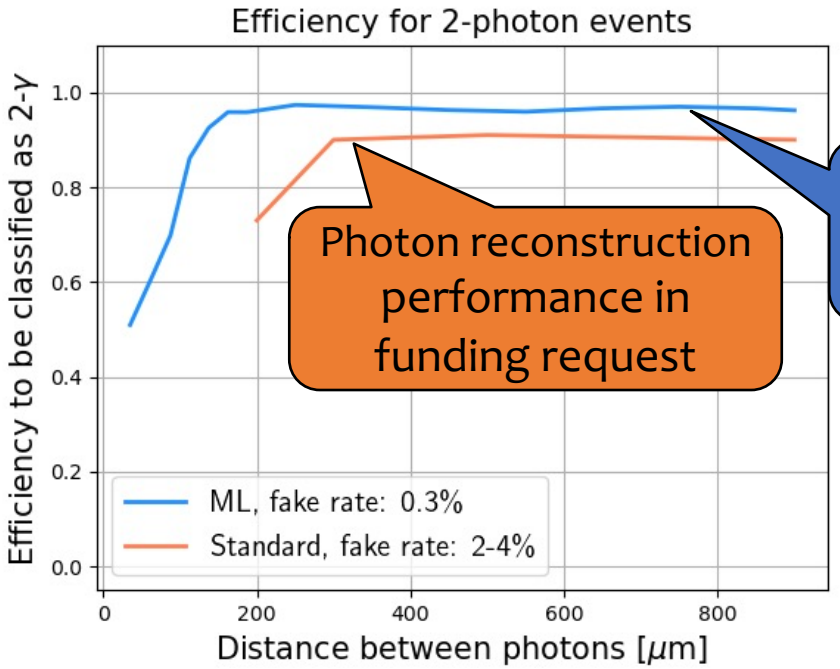
Expected performance





- Distance(2γ): 200 μm
- Distinguishable – because of the 100 μm pixel pitch

- Trained CNN to improve di-γ identification



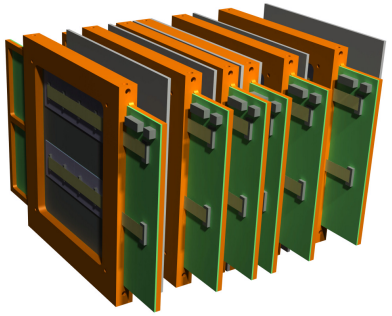
Photon reconstruction performance in funding request

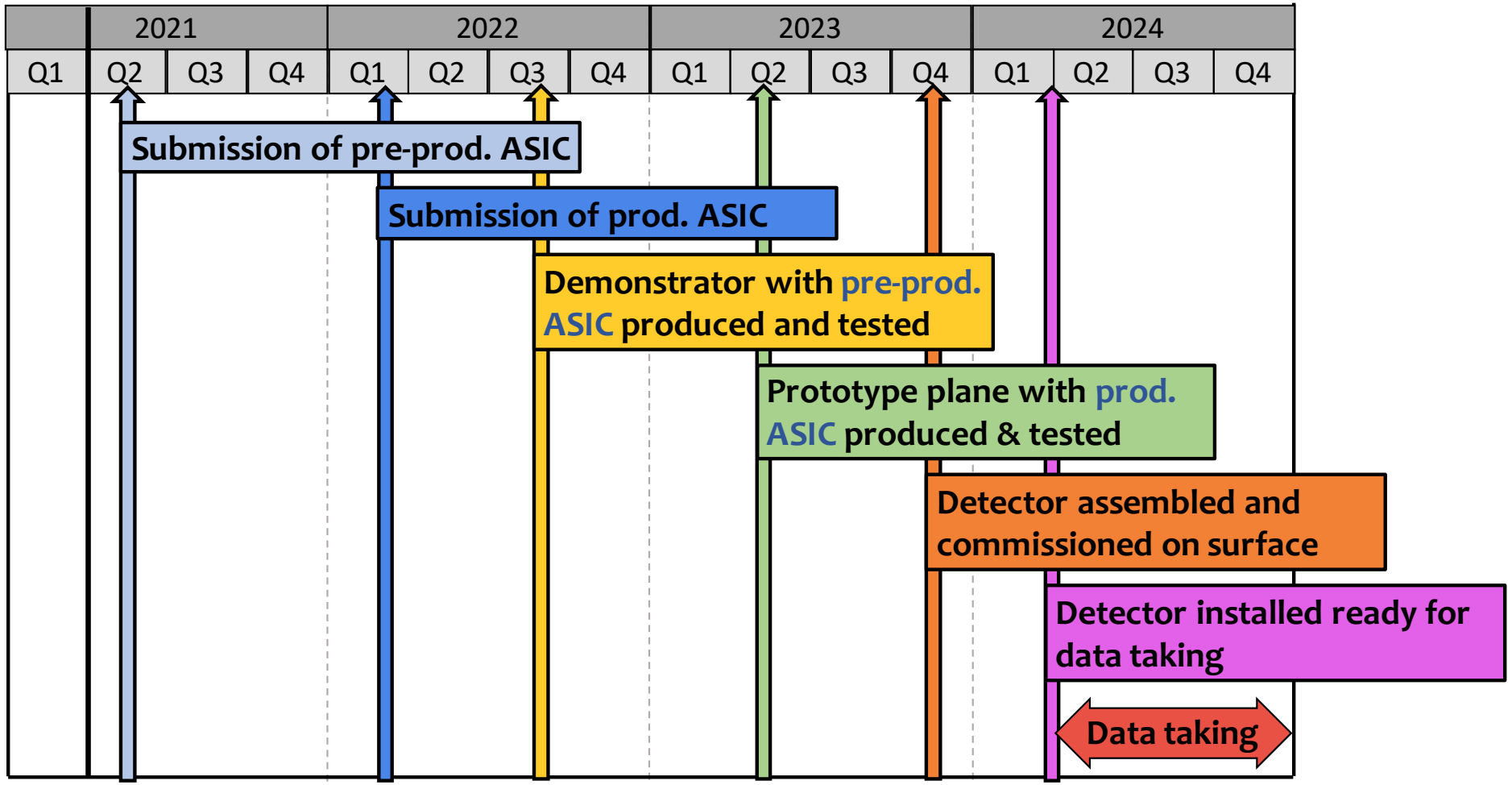
New!

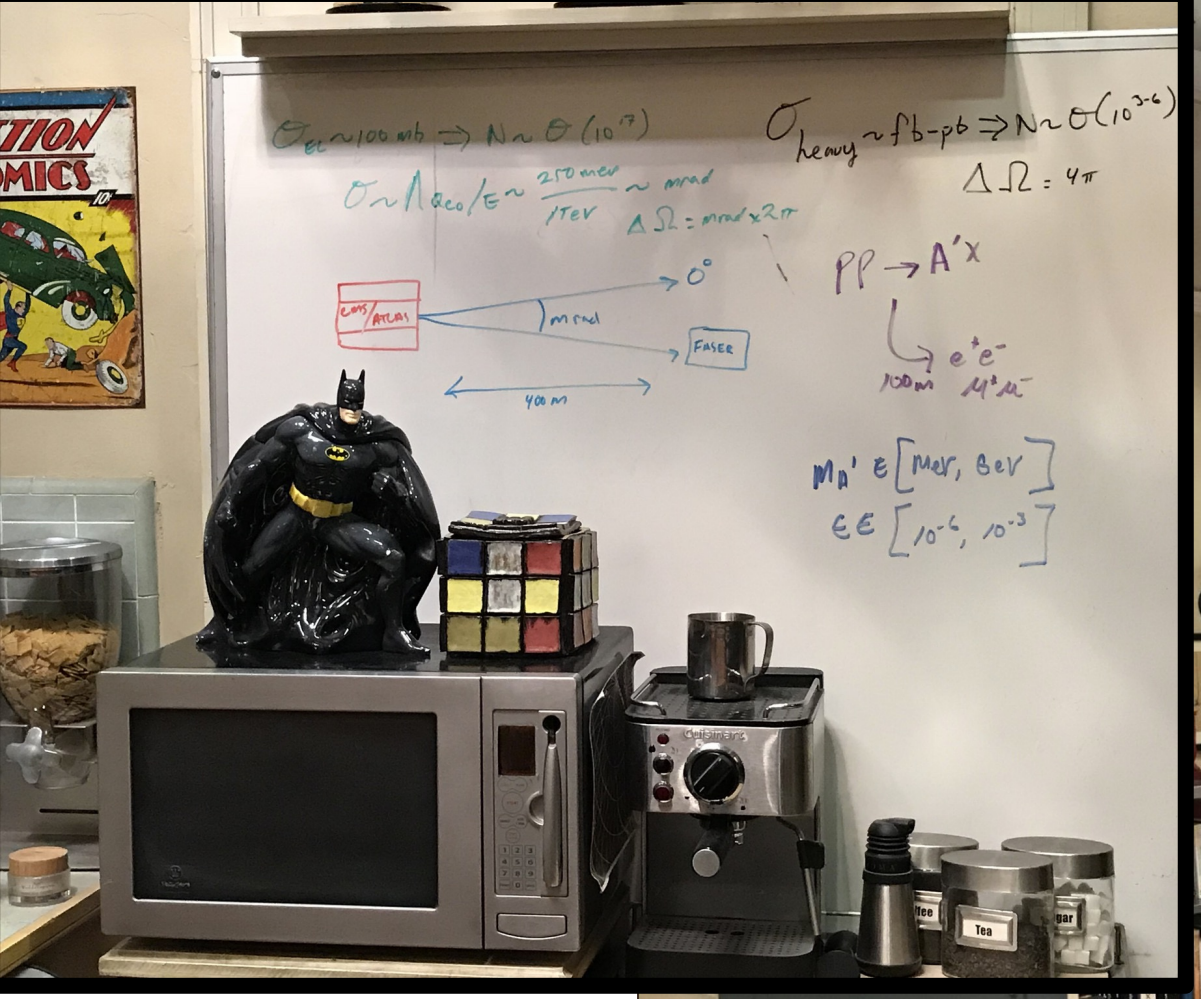
WORK IN PROGRESS

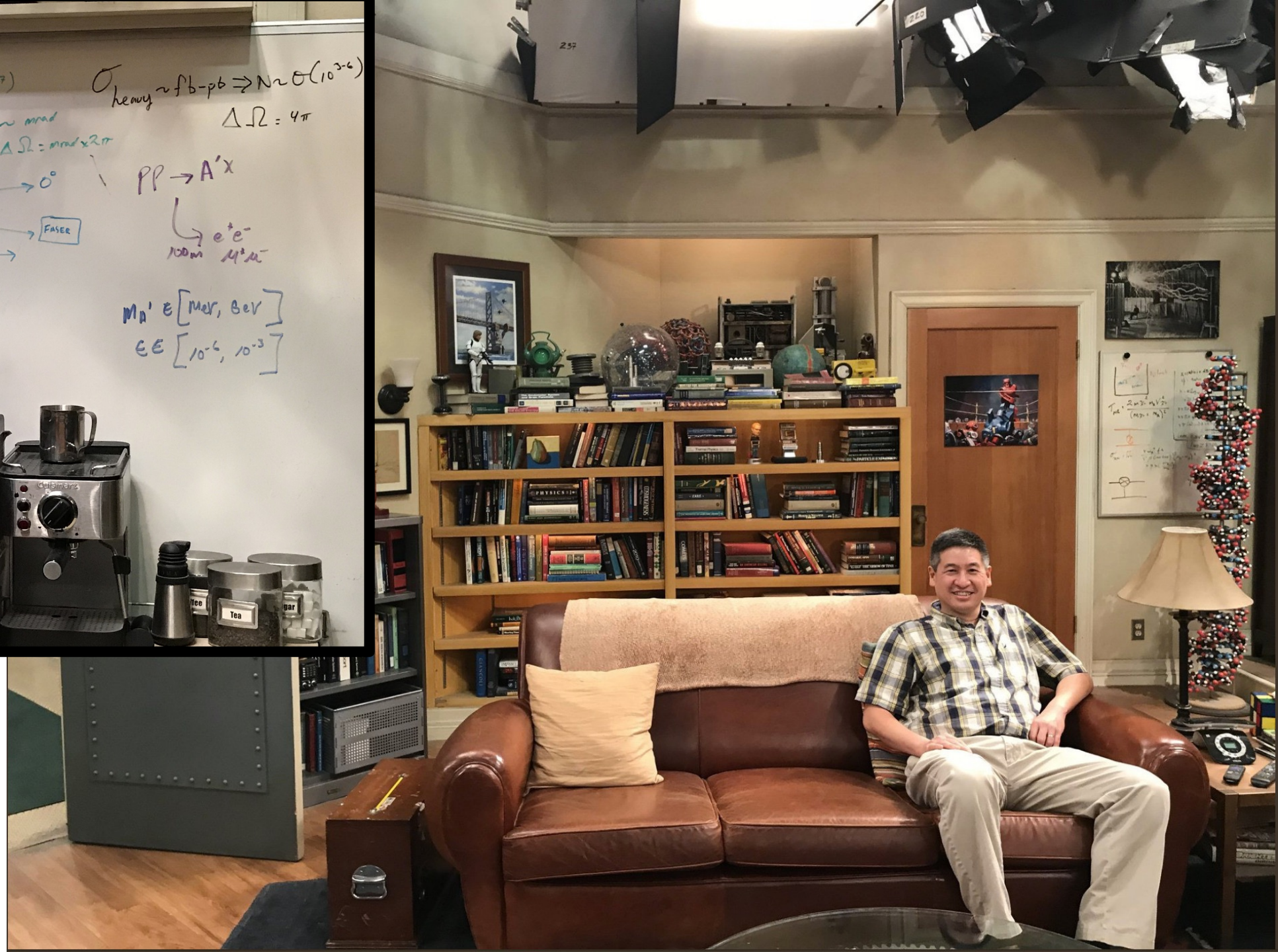
Already achieved 95% di-γ identification efficiency and < 0.5% fake rate

Project milestones



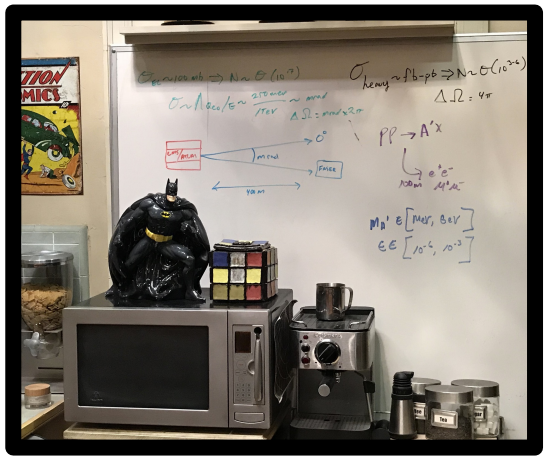



σel ~ 100 mb ⇒ N ~ O(10^17)
σheavy ~ fb-pb ⇒ N ~ O(10^3-6)
θ ~ Λqcd/E ~ 250 MeV / 1TeV ~ mrad
ΔΩ = mrad × 2π
ΔΩ = 4π
0°
CMS/ATLAS
mrad
FASER
400 m
pp → A'X
e+e-
100m μ+μ-
mA' ∈ [MeV, GeV]
ε ∈ [10^-6, 10^-3]
Tea



FASER Global timeline

(*)

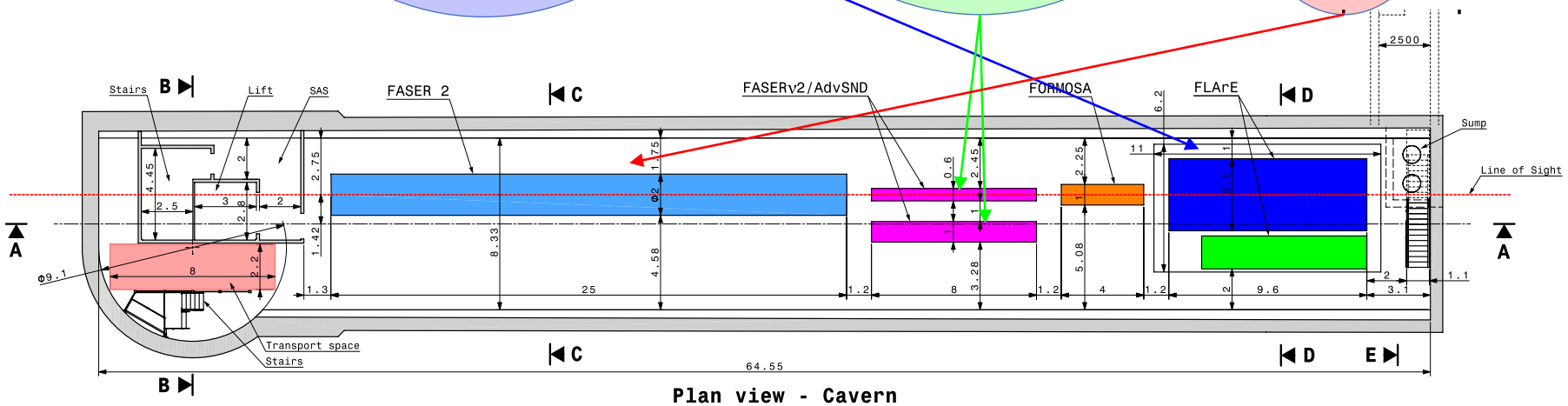


- 08/2017 — FASER proposed by Feng, Galon, Kling, Trojanowski ✓
- 08/2018 — (*) FASER Letter of Intent ✓
- 11/2018 — FASER Technical proposal ✓
- 03/2019 — FASER approved by CERN Research Board ✓
- 12/2019 — FASERν approved by CERN Research Board ✓
- 01/2020 — FASER surface commissioning started ✓
- 11/2020 — FASER infrastructure installed in TI12 ✓
- today
- 12/2020 — **FASER commissioned on surface**
- 02/2021 — **FASER installed in TI12**
- 01/2021 — **FASER commissioned in TI12**
- 06/2021 — FASERν installed in TI12
- 2022 — FASER commissioning with beams
- 2022 - **Physics data taking**

SIGNATURES FOR OTHER FPF EXPERIMENTS

Slide from J. Feng

Signature	DM DIS	DM Elastic	ν NC DIS	ν_τ CC DIS	LLP decays
Models	$U(1)_B$, $U(1)_{B-3\tau}$	$U(1)_B$, $U(1)_{B-3\tau}$	$U(1)_{B-3\tau}$	$U(1)_{B-3\tau}$	$U(1)_B$, $U(1)_{B-3\tau}$
Production	$pp \to V \to \chi\chi$	$pp \to V \to \chi\chi$	$pp \to D_s \to \nu_\tau$	$pp \to V \to \nu_\tau\bar{\nu}_\tau$	$pp \to V$
Detection	$\chi N \to \chi X$	$\chi p \to \chi p$	$\nu_\tau N \to \nu_\tau X$	$\nu_\tau N \to \tau X$	$V \to$ hadrons



Batell, Feng, Fieg, Ismail, Kling, Abraham, Trojanowski, 2111.10343

BSM SIGNALS

Slide from J. Feng

- FASER and FASER2 have discovery prospects for many PBC Benchmarks. For FASER, the dominant signatures considered have been $A' \rightarrow e^+e^-$, and $a \rightarrow \gamma\gamma$.

Benchmark Model	Underway	FPF	References
BC1: Dark Photon	FASER	FASER 2	Feng, Galon, Kling, Trojanowski, 1708.09389
BC1': $U(1)_{B-L}$ Gauge Boson	FASER	FASER 2	Bauer, Foldenauer, Jaeckel, 1803.05466 FASER Collaboration, 1811.12522
BC2: Dark Matter	–	FLArE	Batell, Feng, Trojanowski, 2101.10338 Batell et al., 2107.00666
BC3: Milli-Charged Particle	–	FORMOSA	Foroughi-Bari, Kling, Tsai, 2010.07941
BC4: Dark Higgs Boson	–	FASER 2	Feng, Galon, Kling, Trojanowski, 1710.09387 Batell, Freitas, Ismail, McKeen, 1712.10022
BC5: Dark Higgs with hSS	–	FASER 2	Feng, Galon, Kling, Trojanowski, 1710.09387
BC6: HNL with e	–	FASER 2	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
BC7: HNL with μ	–	FASER 2	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
BC8: HNL with τ	–	FASER 2	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
BC9: ALP with photon	FASER	FASER 2	Feng, Galon, Kling, Trojanowski, 1806.02348
BC10: ALP with fermion	–	FASER 2	FASER Collaboration, 1811.12522
BC11: ALP with gluon	FASER	FASER 2	FASER Collaboration, 1811.12522