Looking forward to new physics with the FASER experiment

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

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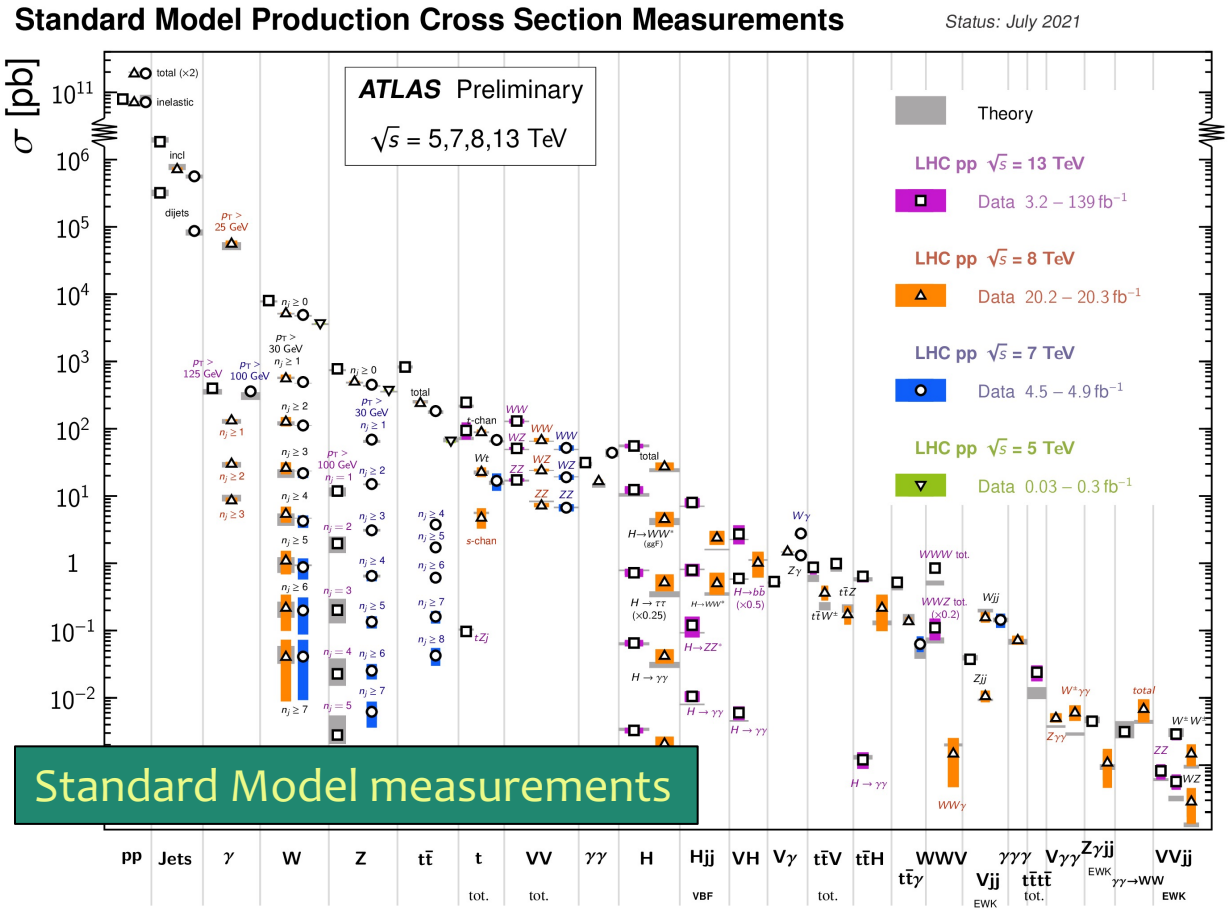
FACULTY OF SCIENCE

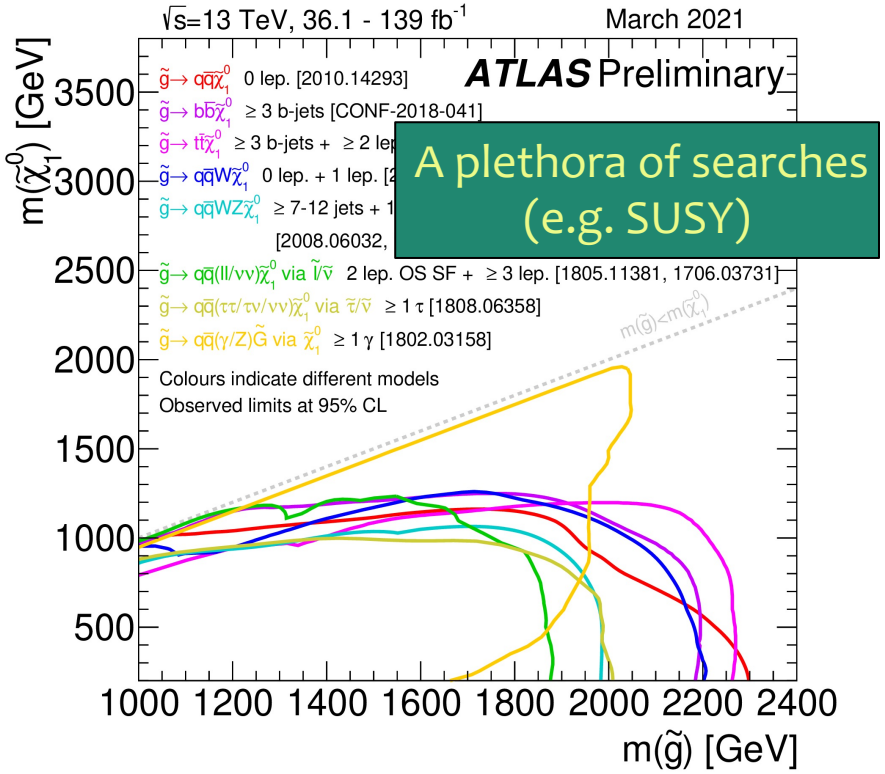
The landscape of new particles @ colliders

The landscape of LHC physics

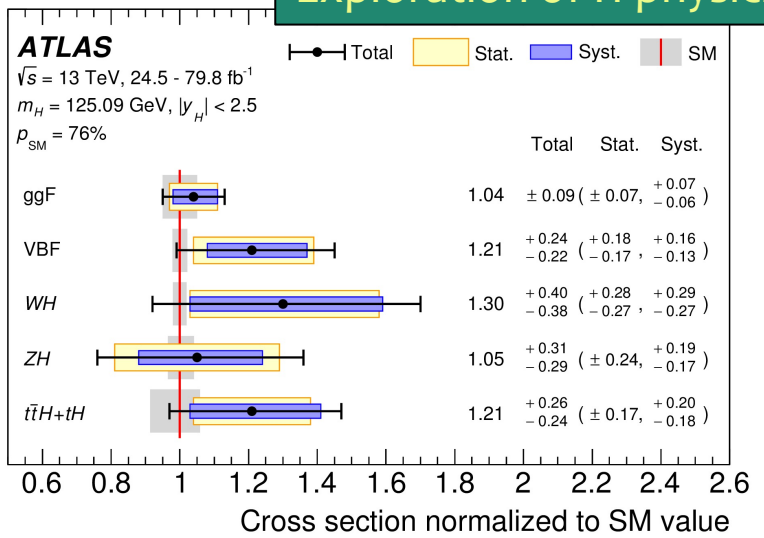
Consistent among all experiments, here using ATLAS as an example



Standard Model measurements



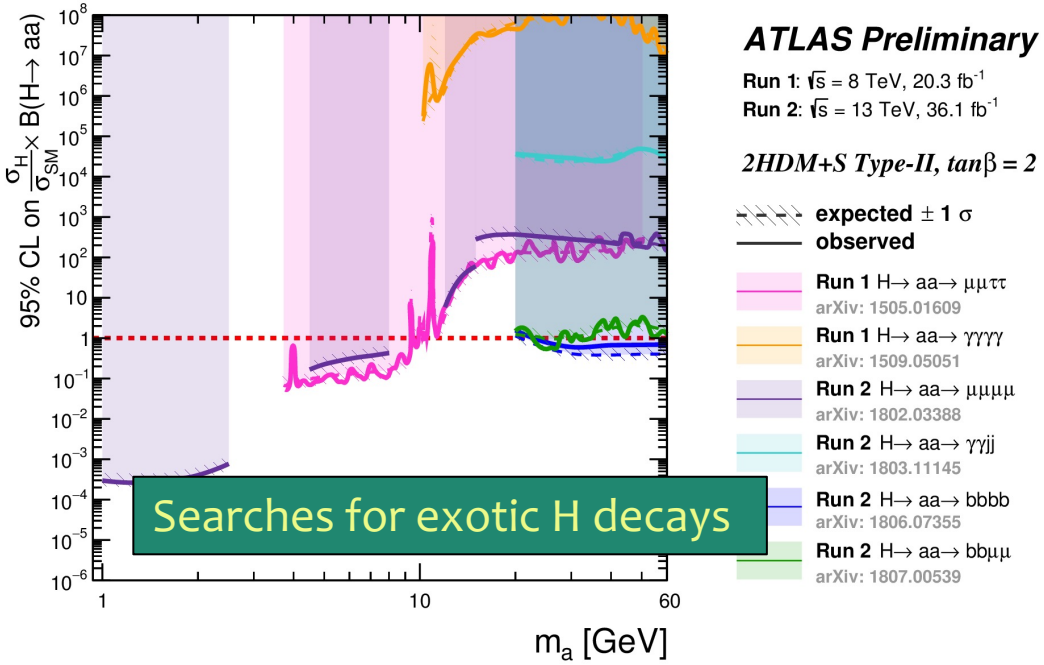
A plethora of searches (e.g. SUSY)



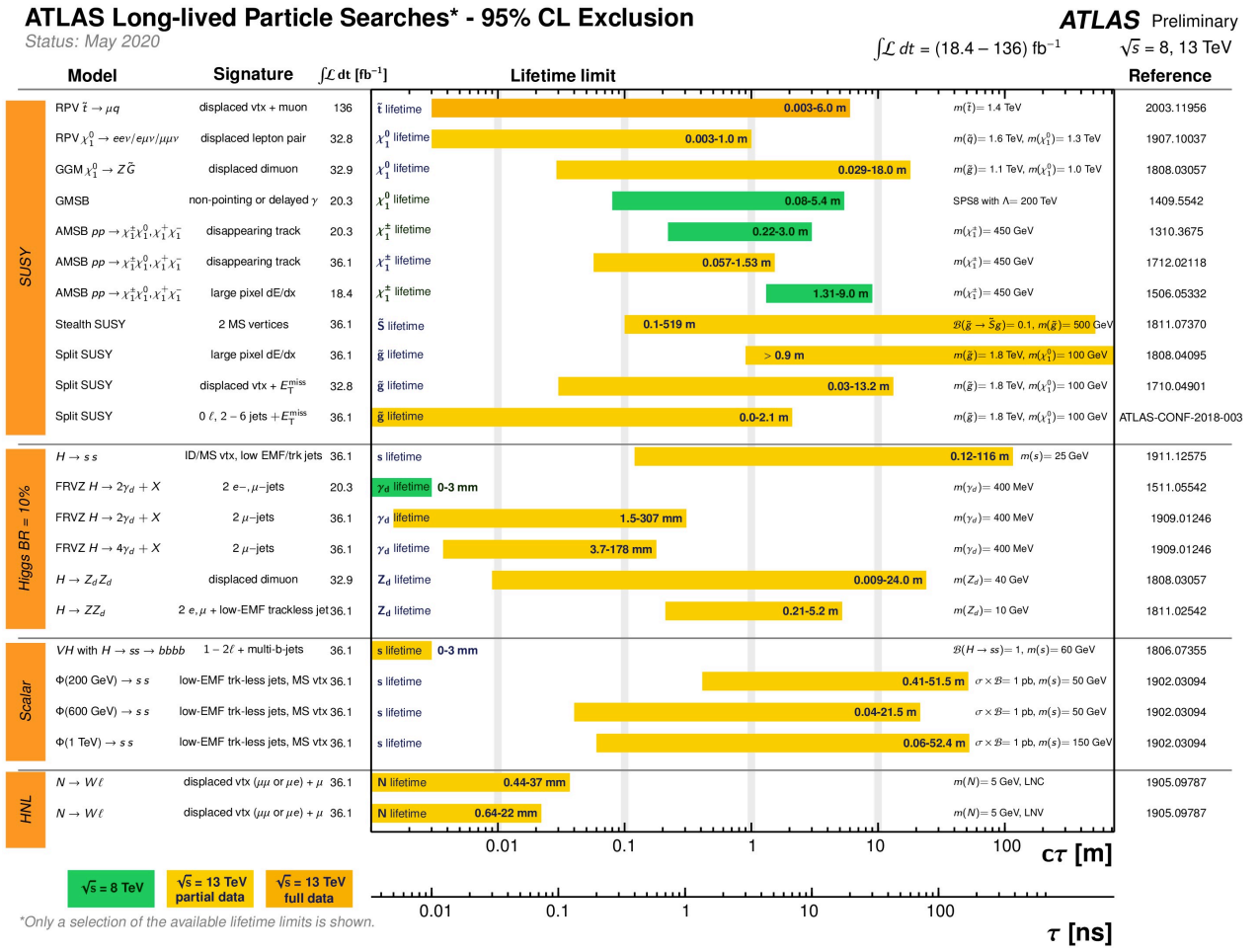
Exploration of H physics

The landscape of LHC physics

Consistent among all experiments, here using ATLAS as an example

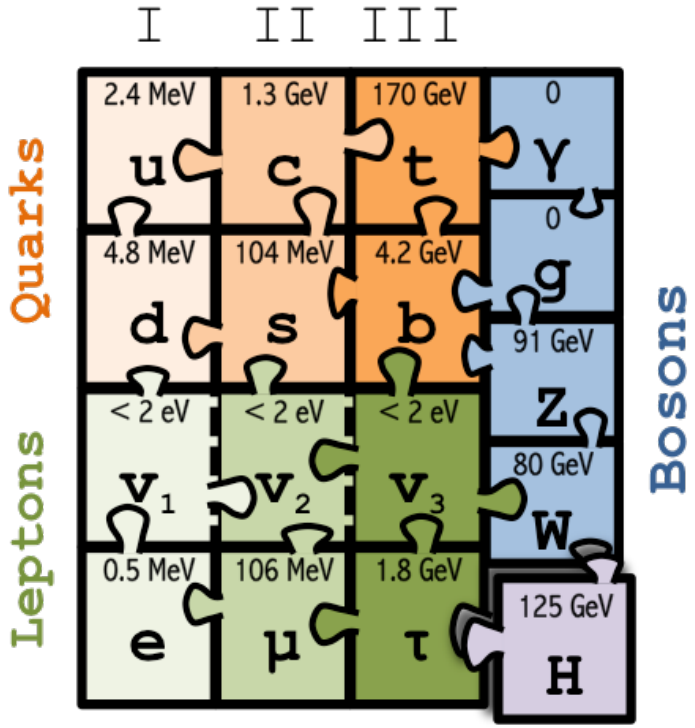


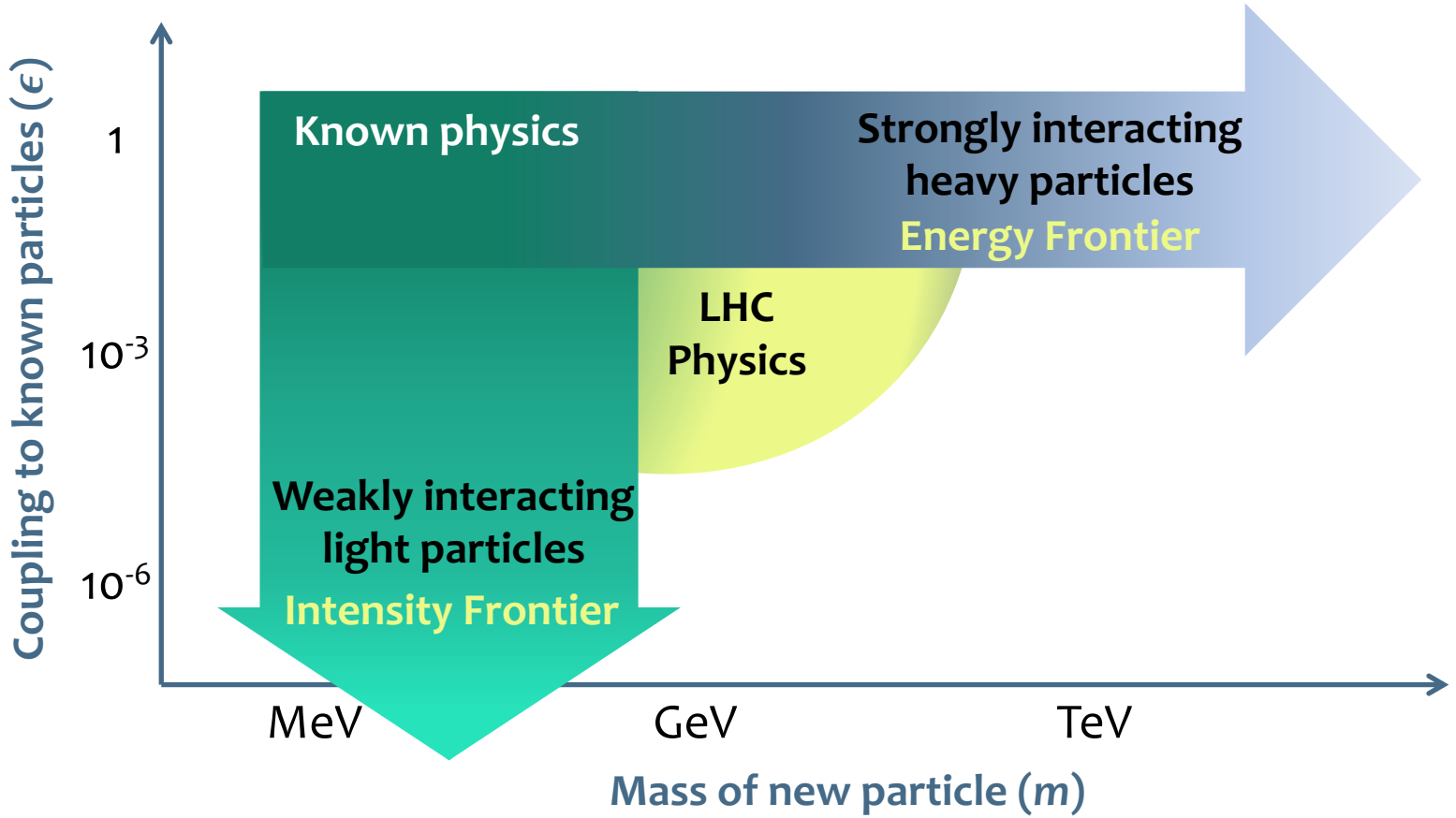
Searches for Long-Lived Particles



The landscape of new particles @ colliders

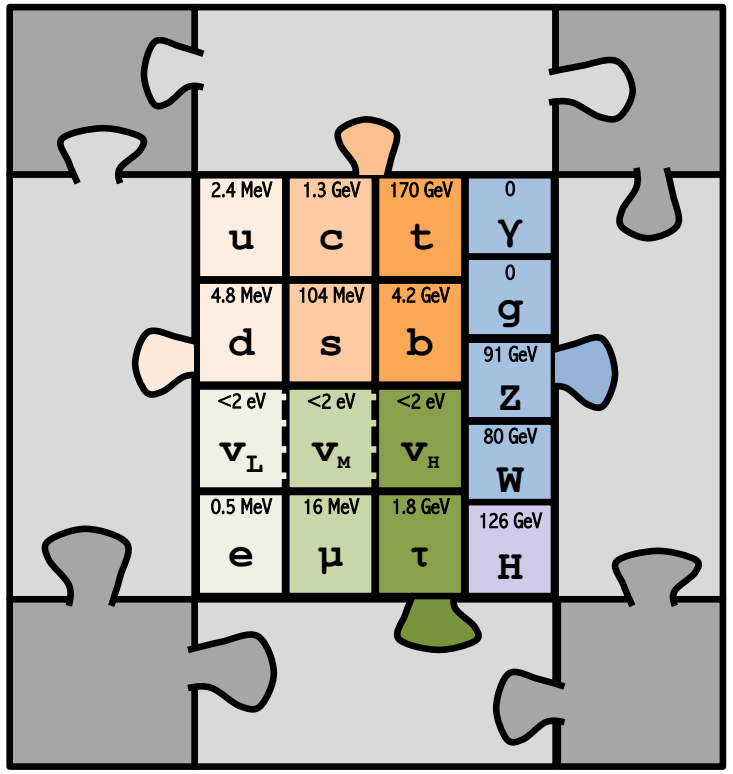
- Collider physics: a plethora of measurements and searches
- The Standard Model is complete and confirmed

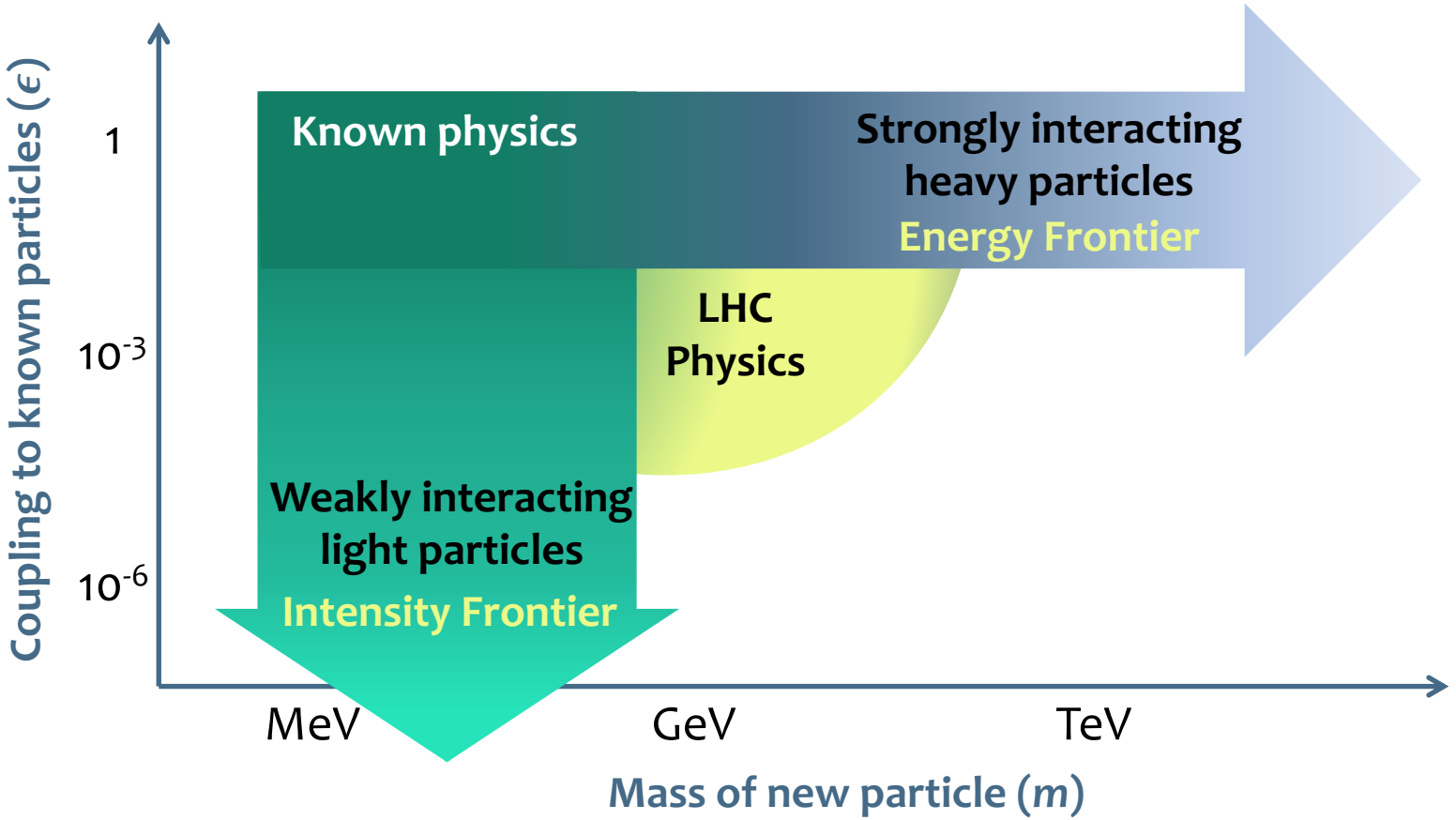




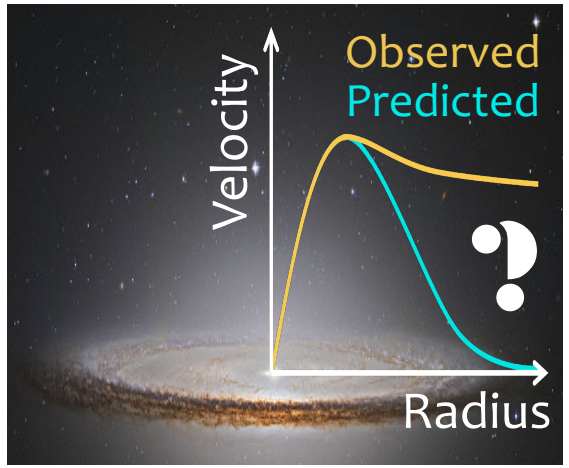
The landscape of new particles @ colliders

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

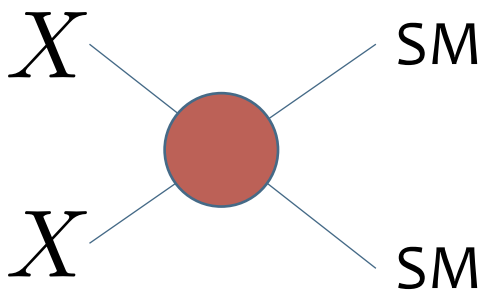




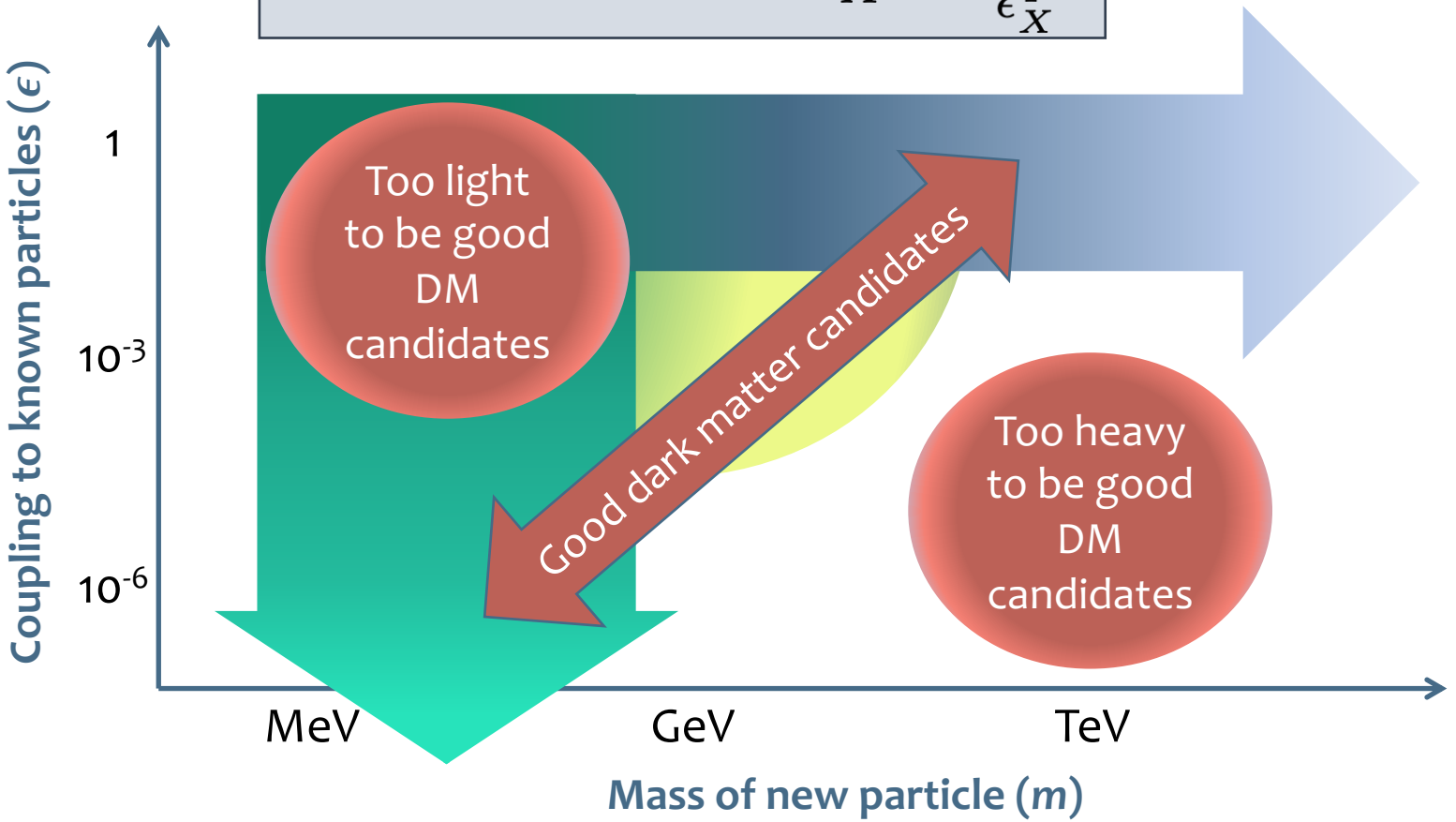
The landscape of new particles @ colliders



- Simple mechanism for DM generation: "freeze out"



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



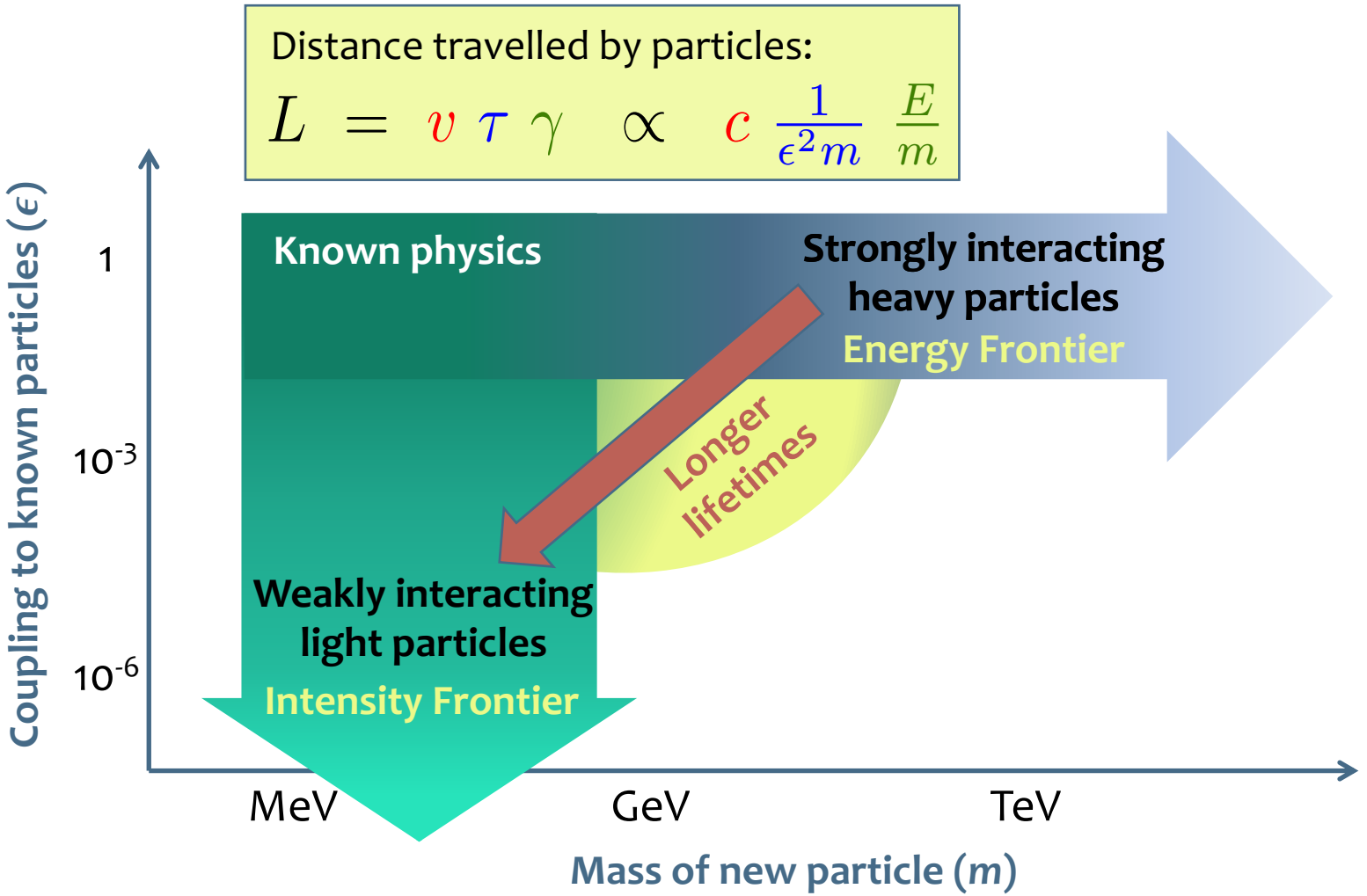
Feng, Kumar - PRL 101, 231301 (2008)

The landscape of new particles @ colliders

Lifetime
a characteristic of weakly interacting light particles

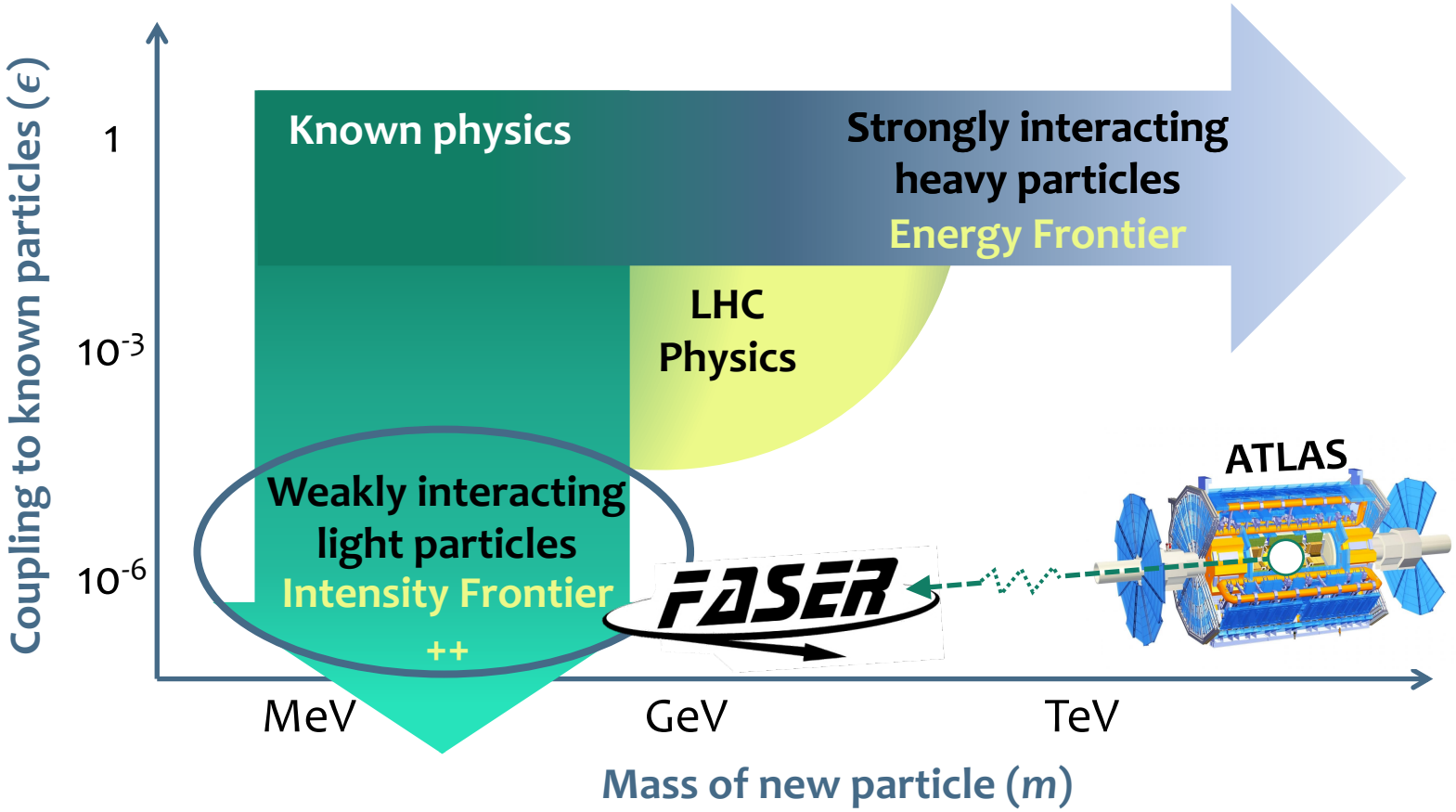
Distinct signatures

Opportunity for exploration!



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

ForwArd Search ExpeRiment at the LHC



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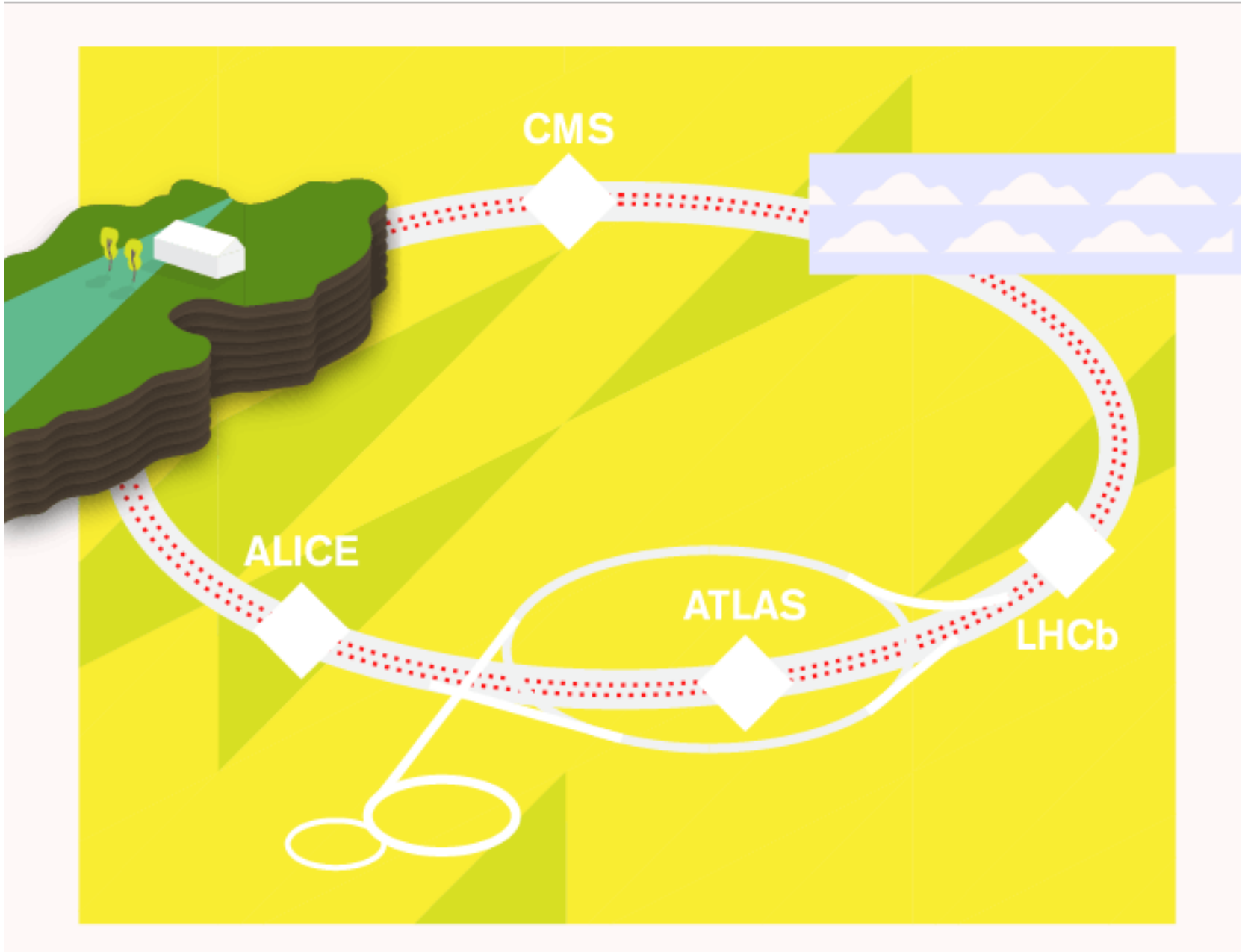
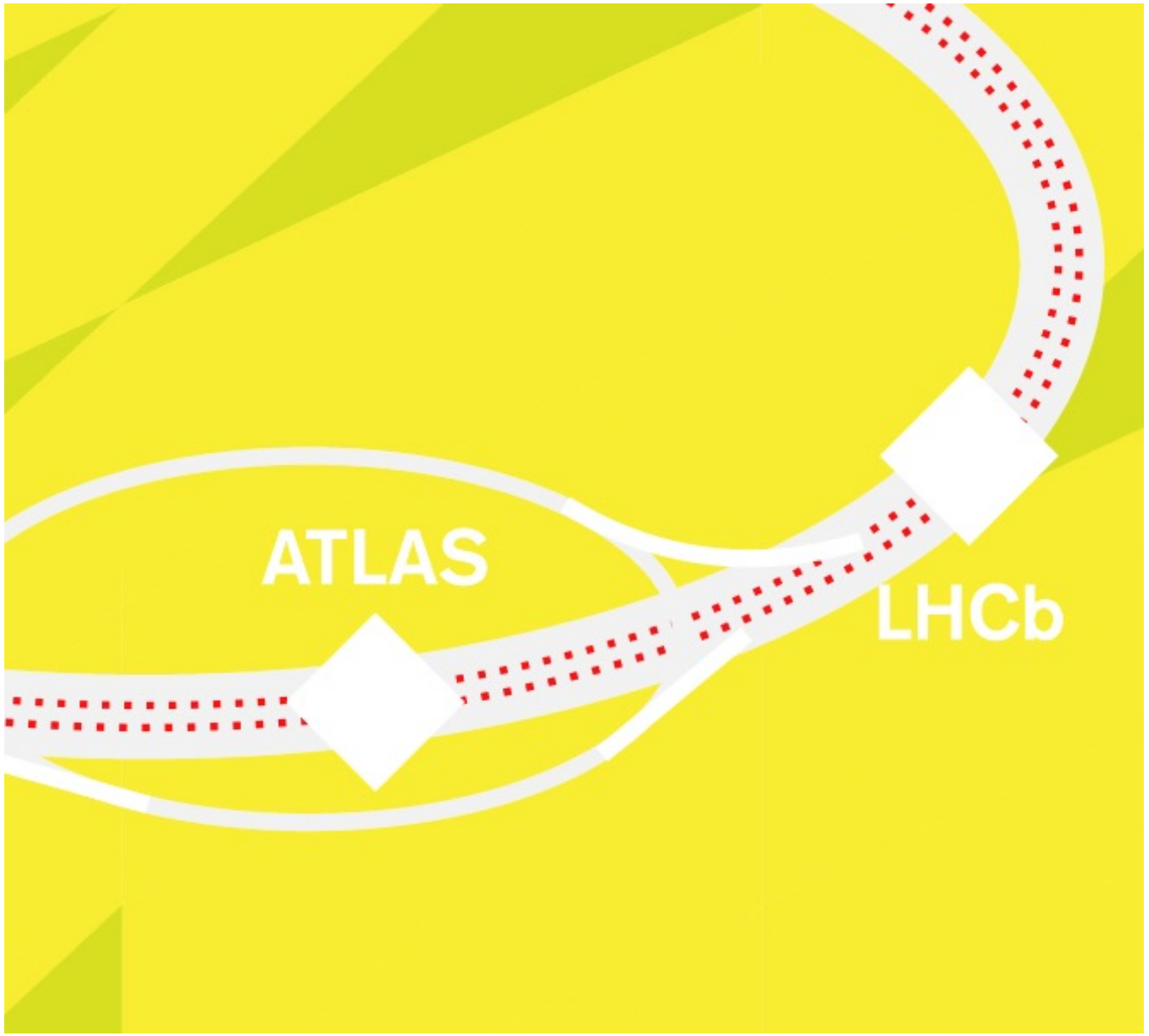


https://www.symmetrymagazine.org/article/a-tiny-new-experiment-at-the-lhc



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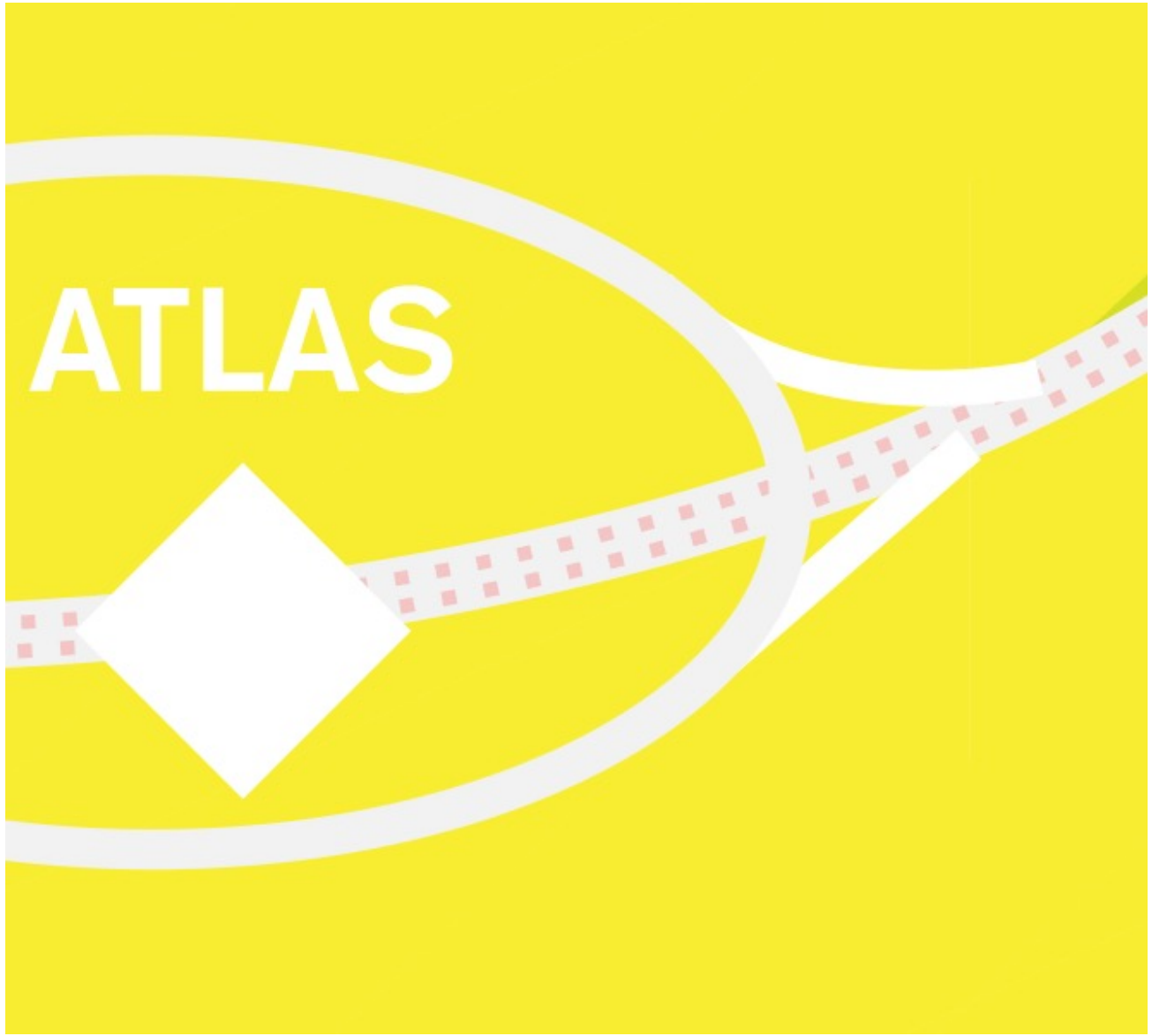

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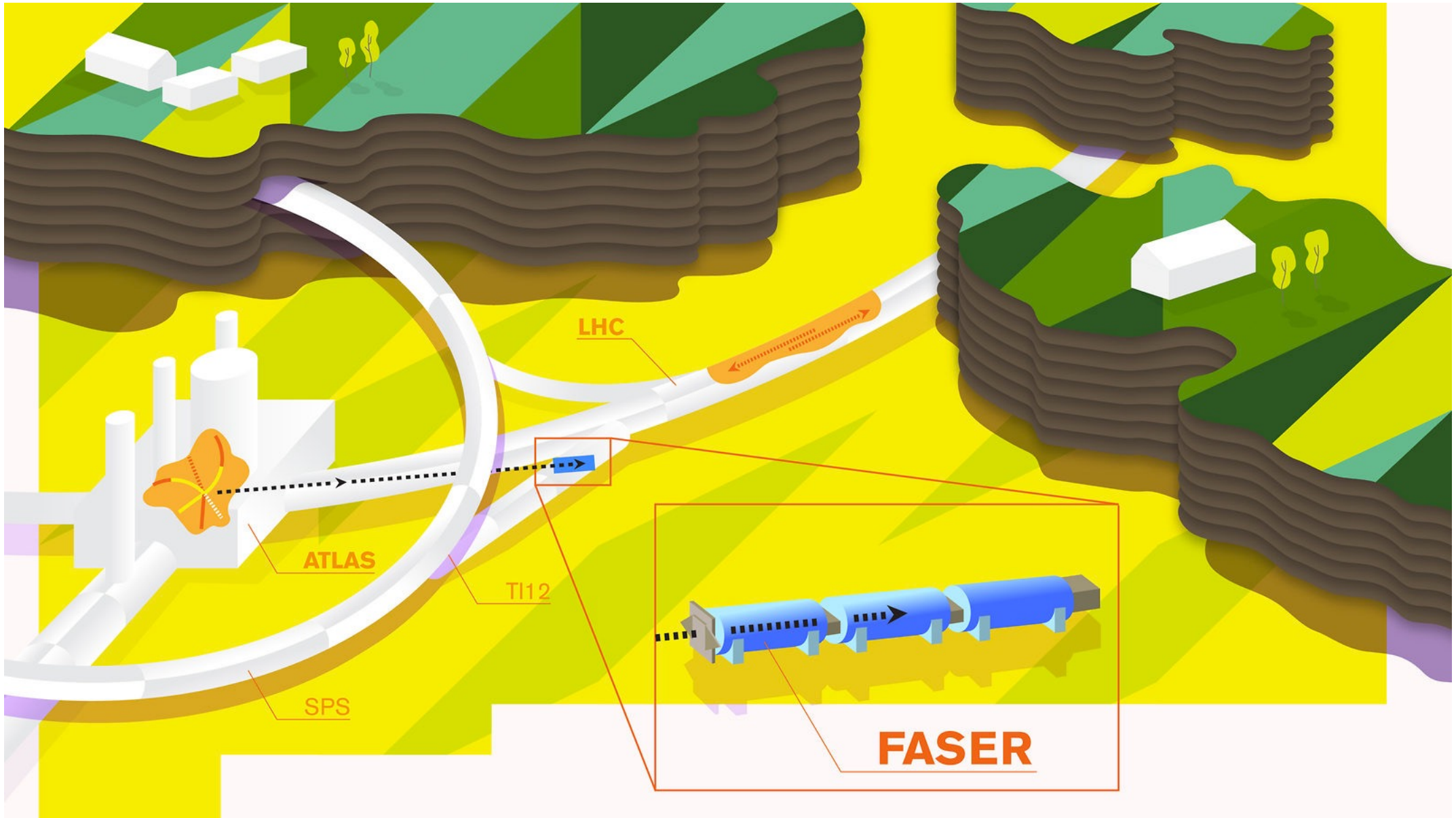

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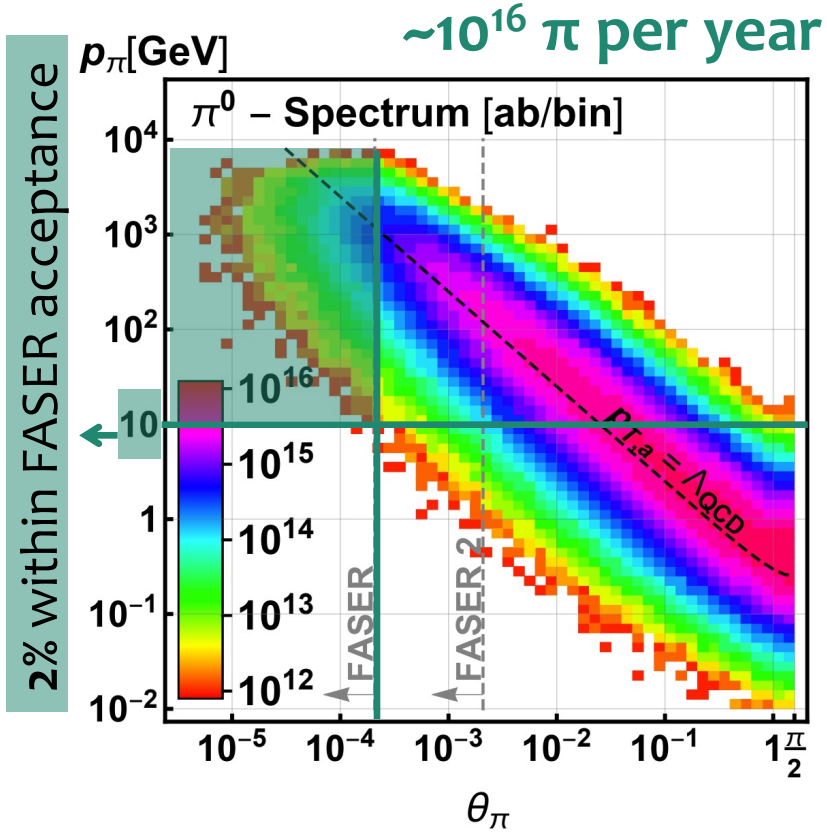
ForwArd Search ExpeRiment at the LHC

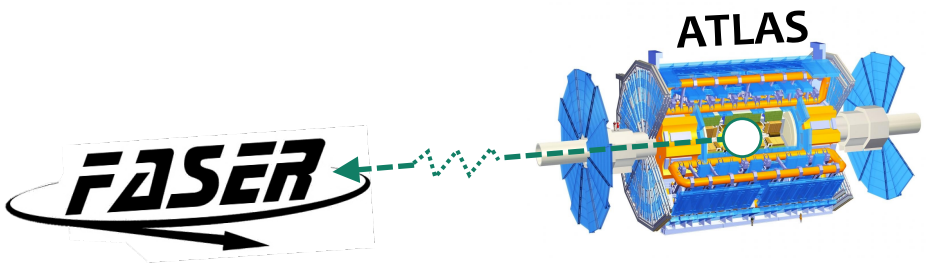
Searches for new weakly interacting light particles, coupling to SM via mixing with SM "portal" operator



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

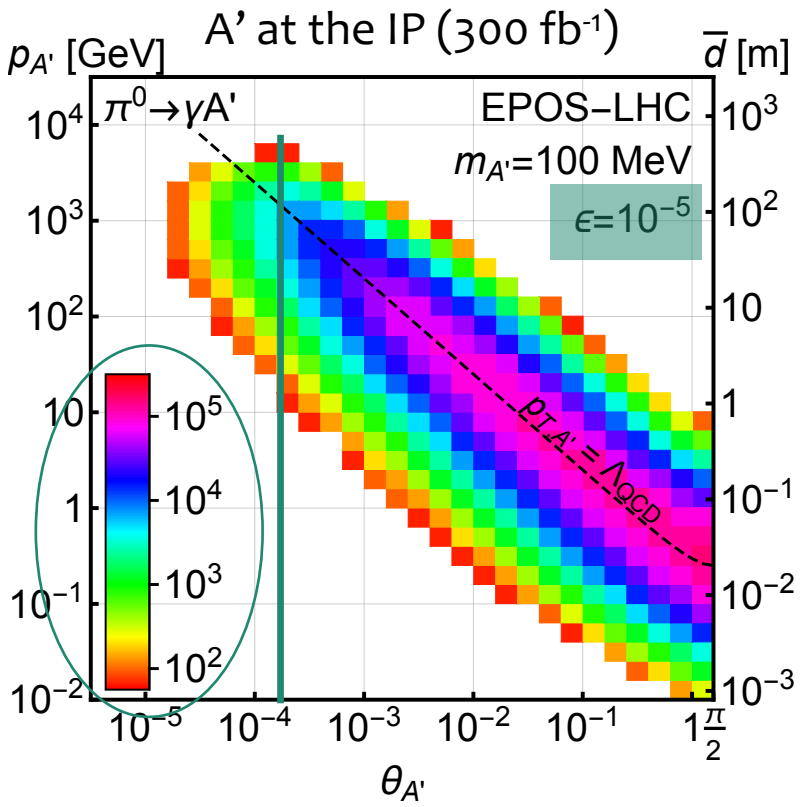
  20 cm diameter, 480 m from ATLAS IP

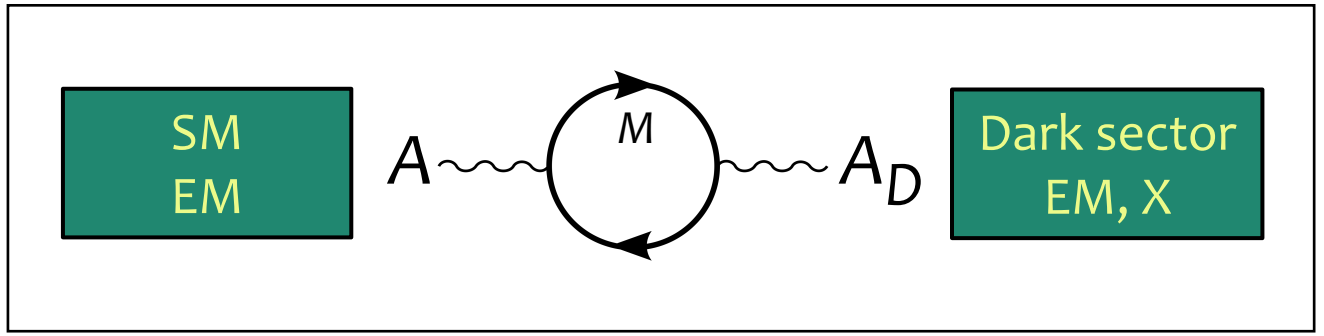
  (ONLY **2x10^{-6}% solid angle**)

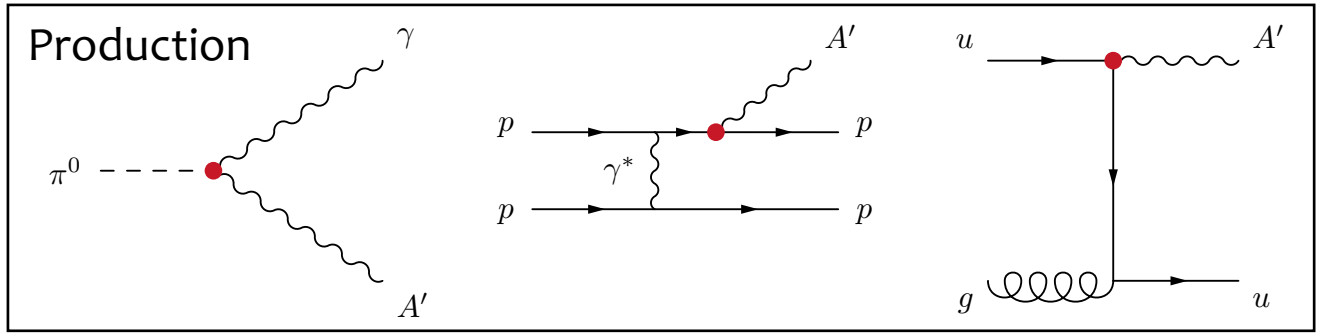


An example physics case: Dark Photon A'

- 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



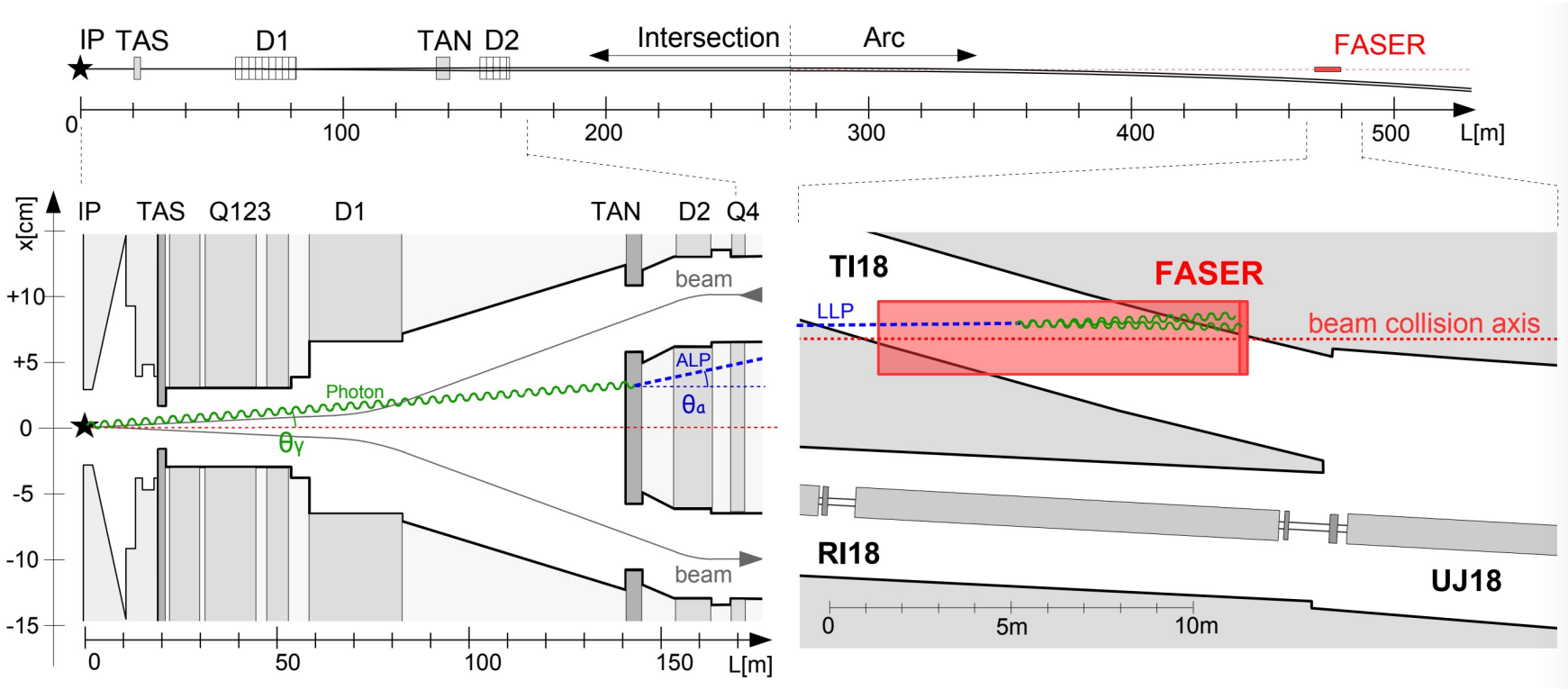


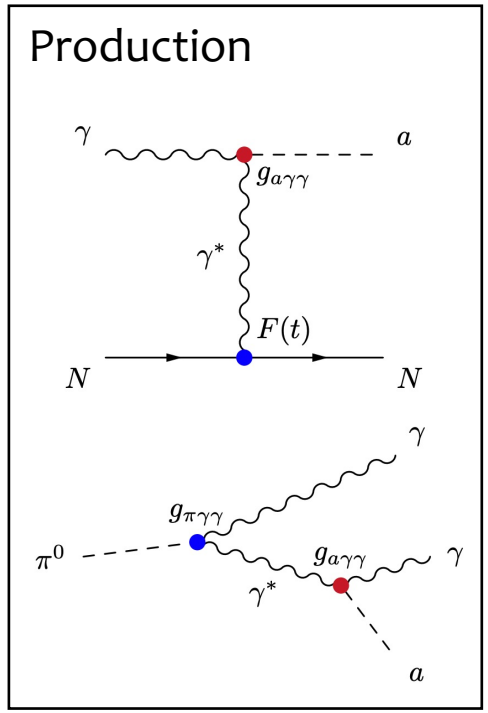


Another example: Axion-like particles (ALPs)

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**

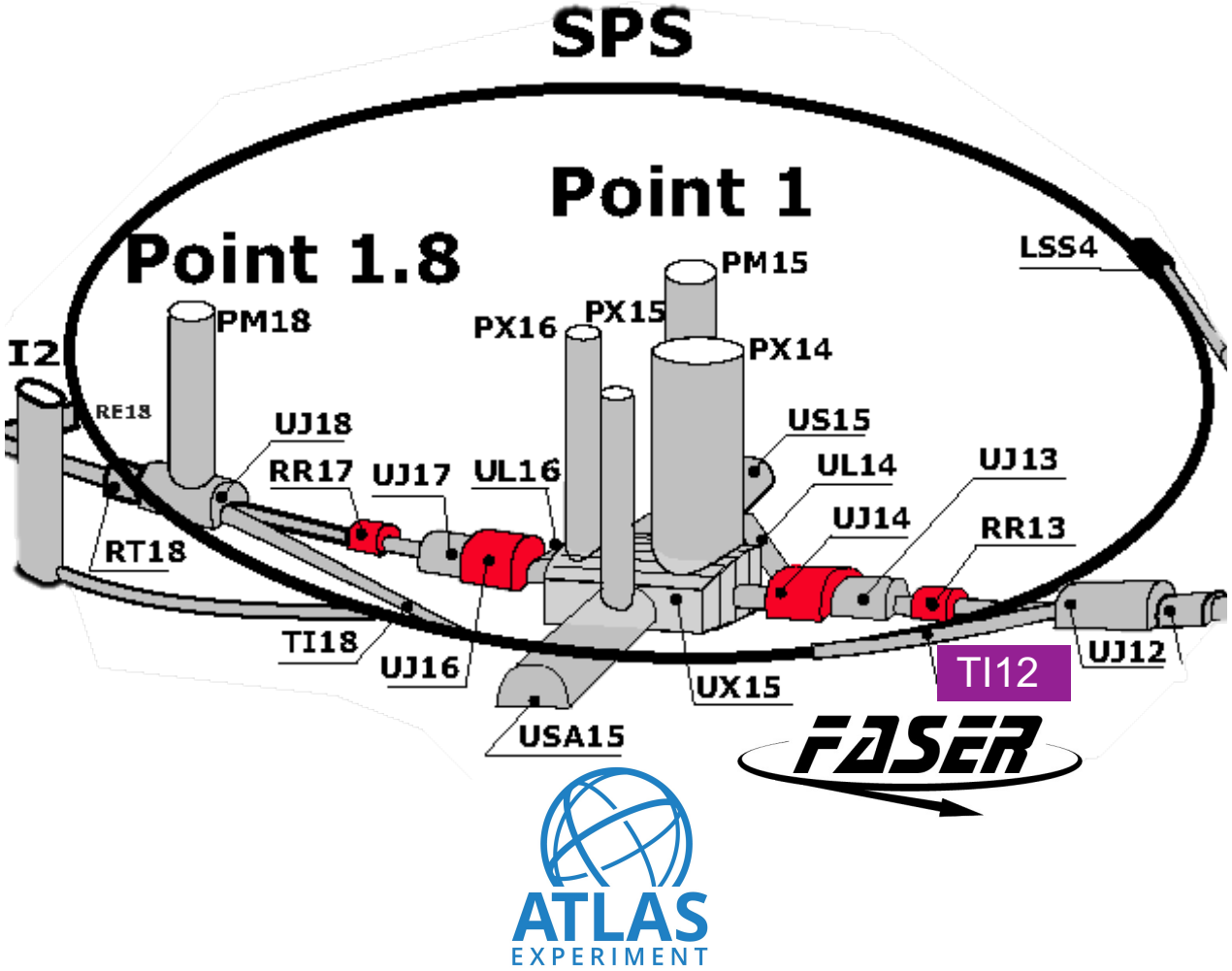


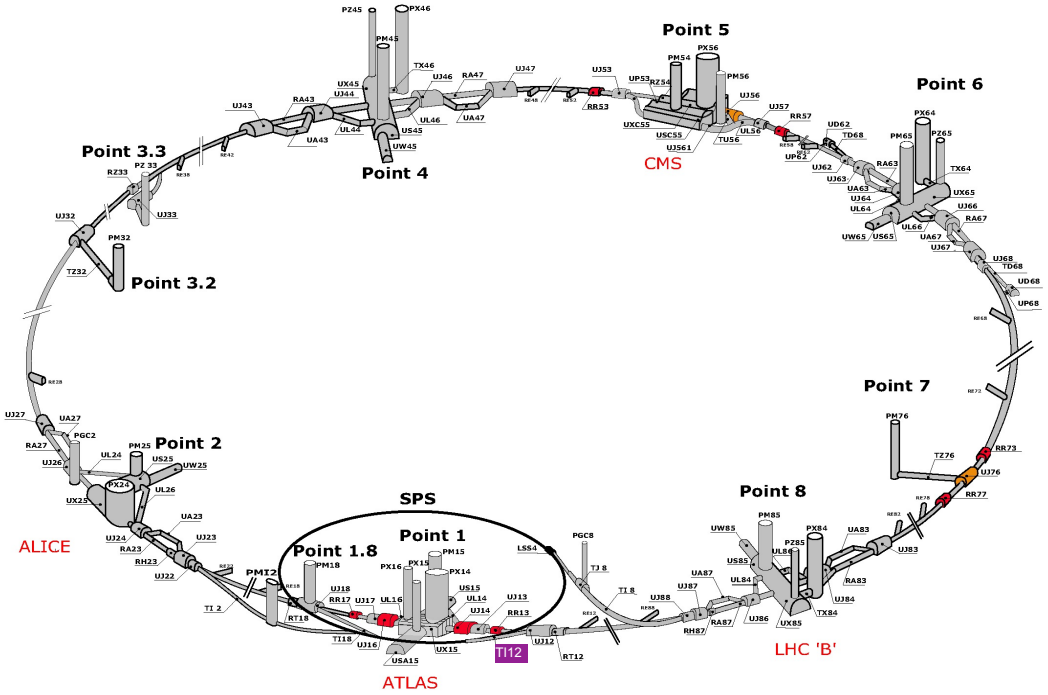


Feng, Galon, Kling, Trojanowski – Phys. Rev. D 98, 055021 (2018)

The  experiment

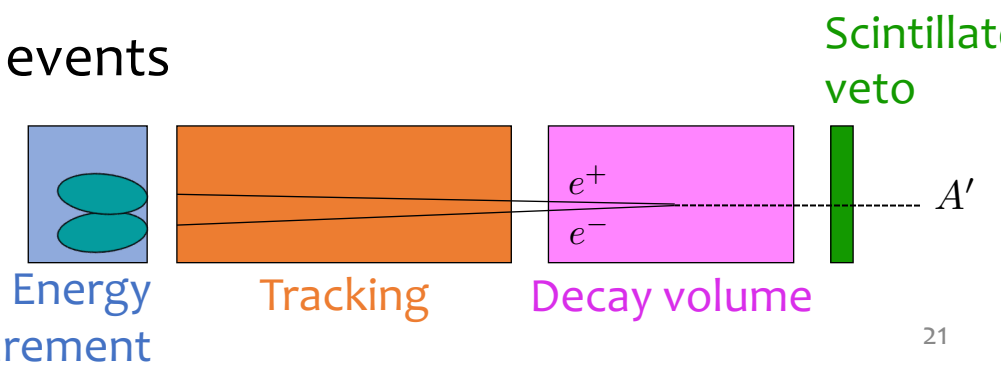
FASER Location



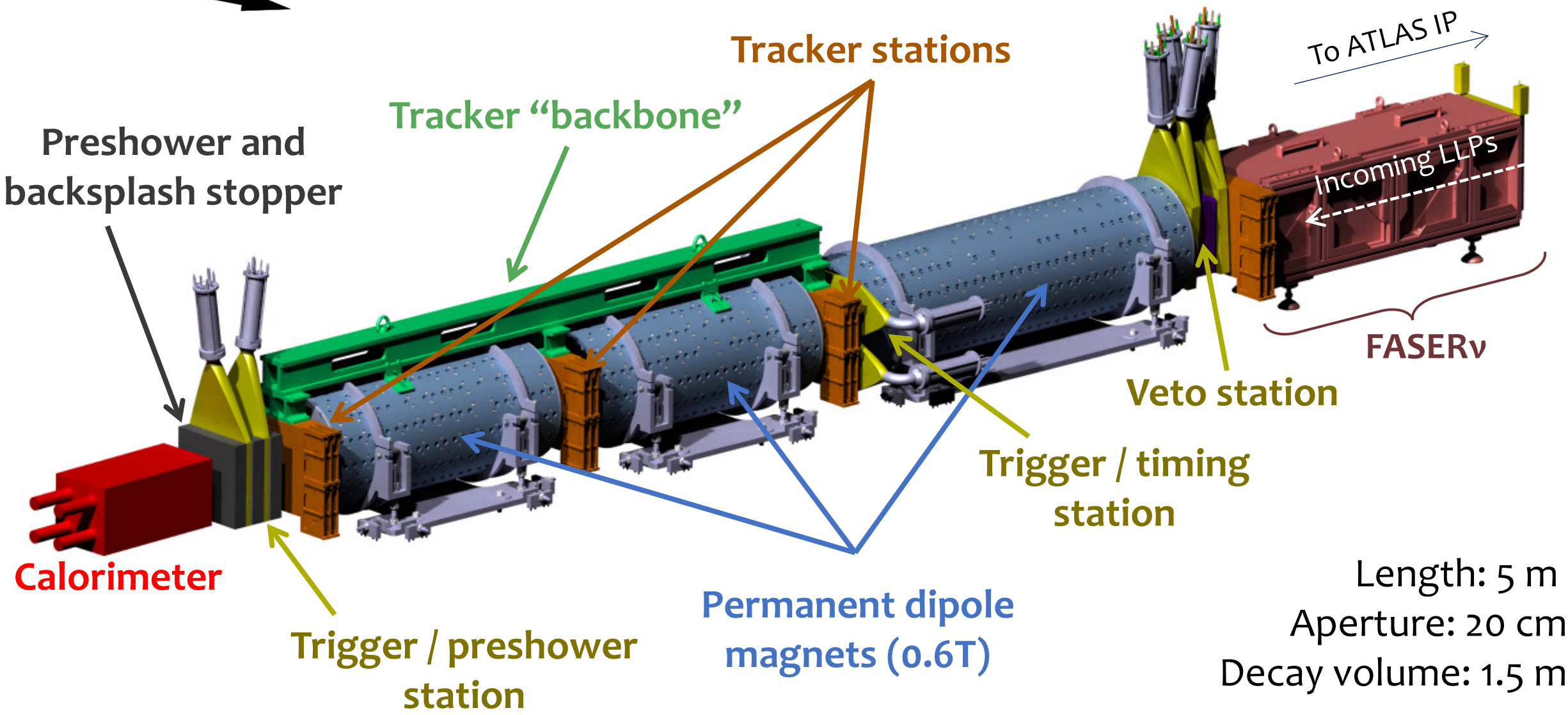


Detector concept

- **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



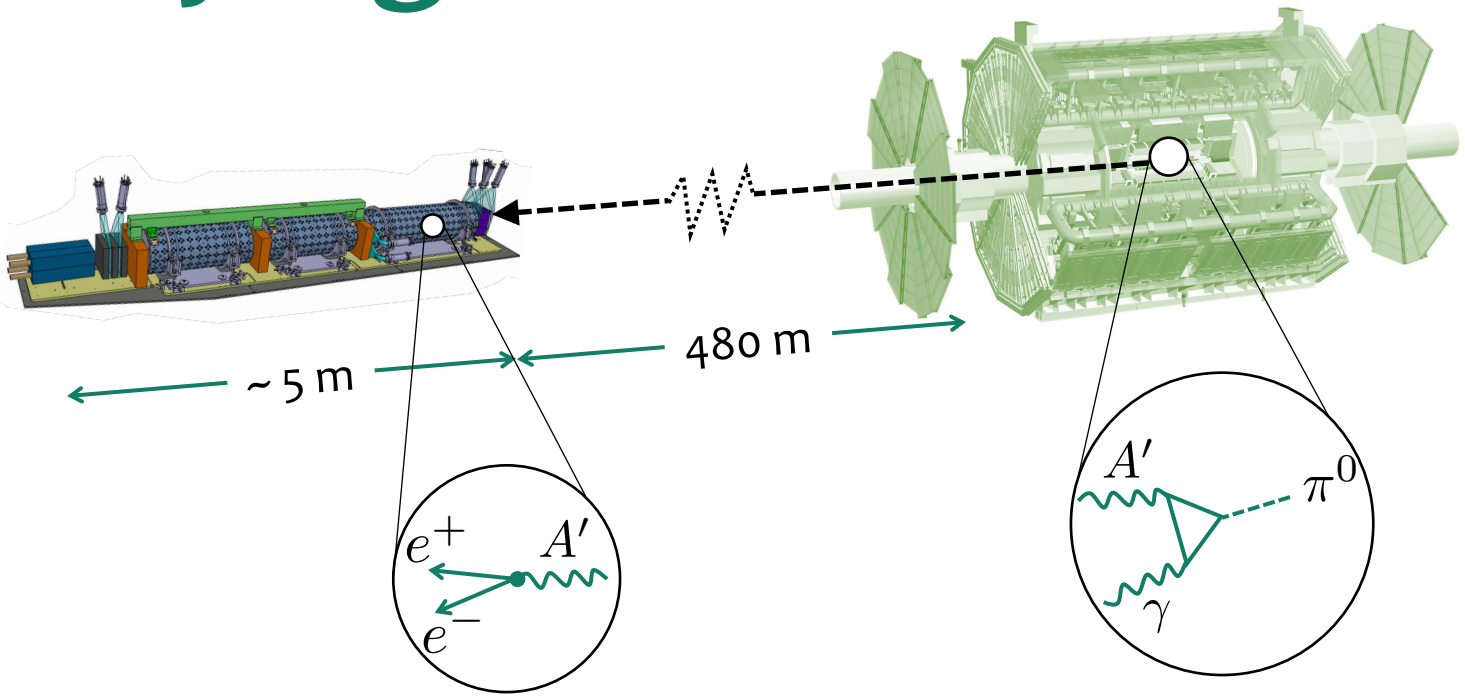
FASER Detector

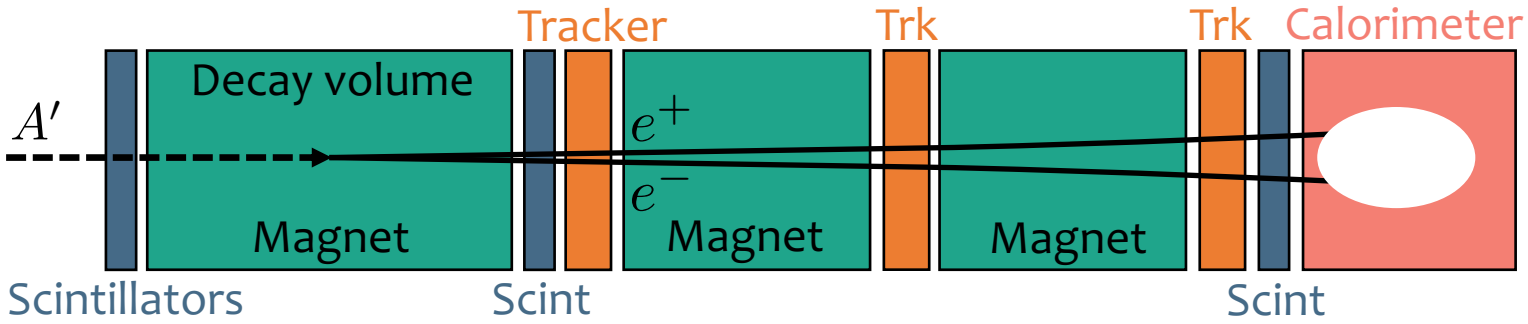


Length: 5 m
Aperture: 20 cm
Decay volume: 1.5 m

Key signatures

Dark photon (A')



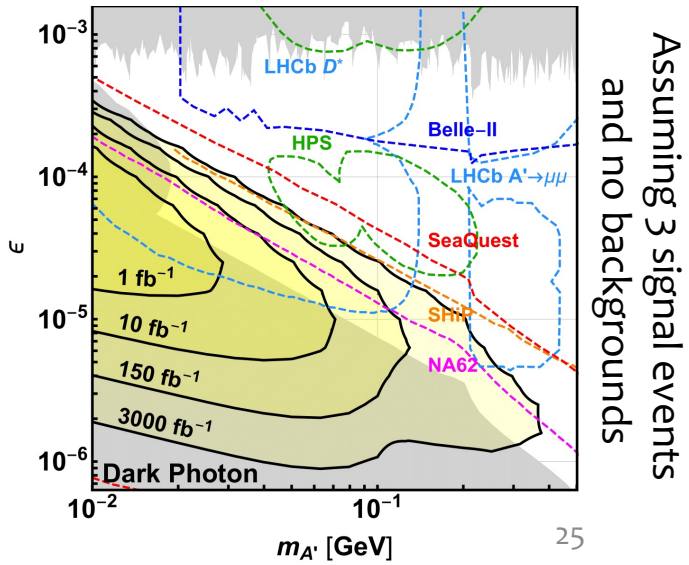


Ballpark numbers for *A'*:

- Momentum of 1 TeV
- Mass of 100 MeV

Decay products collimated

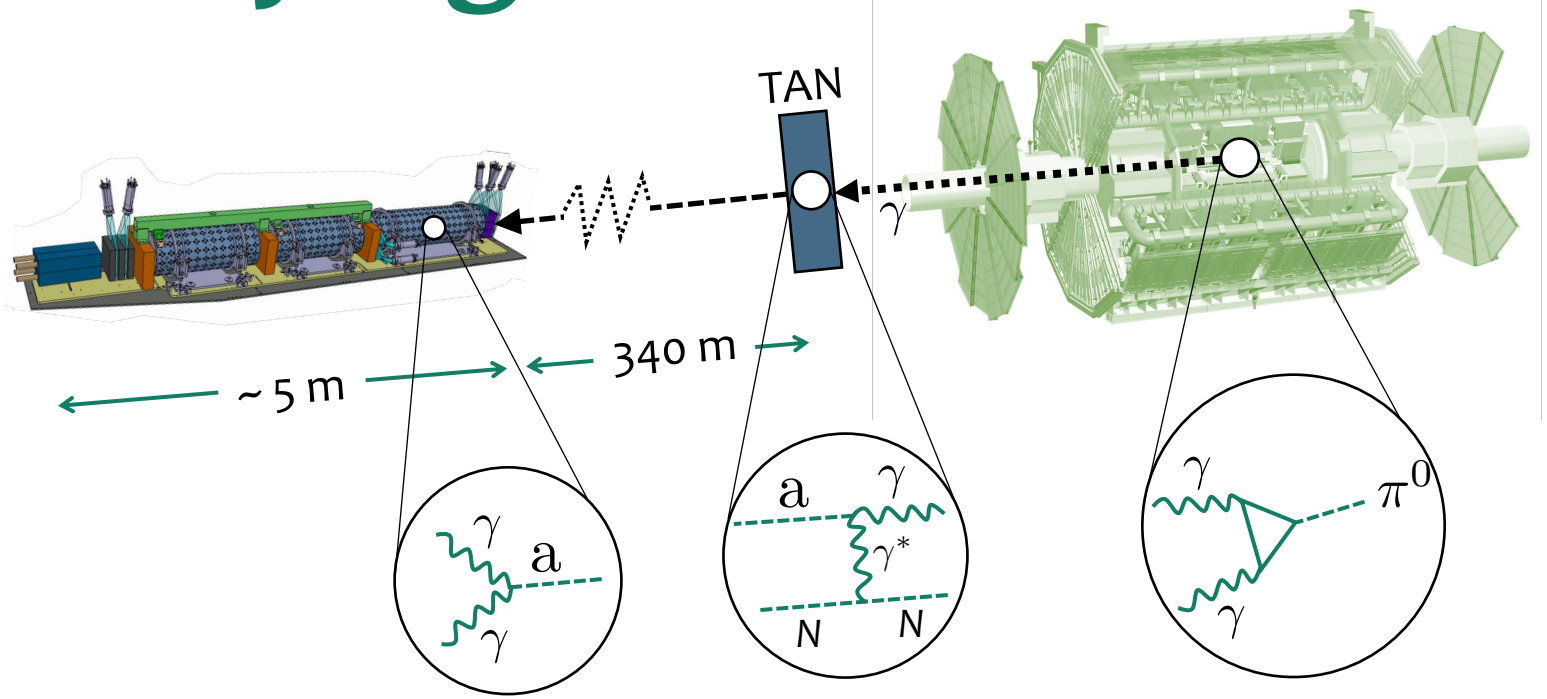
requirements for magnetic field & high resolution tracker

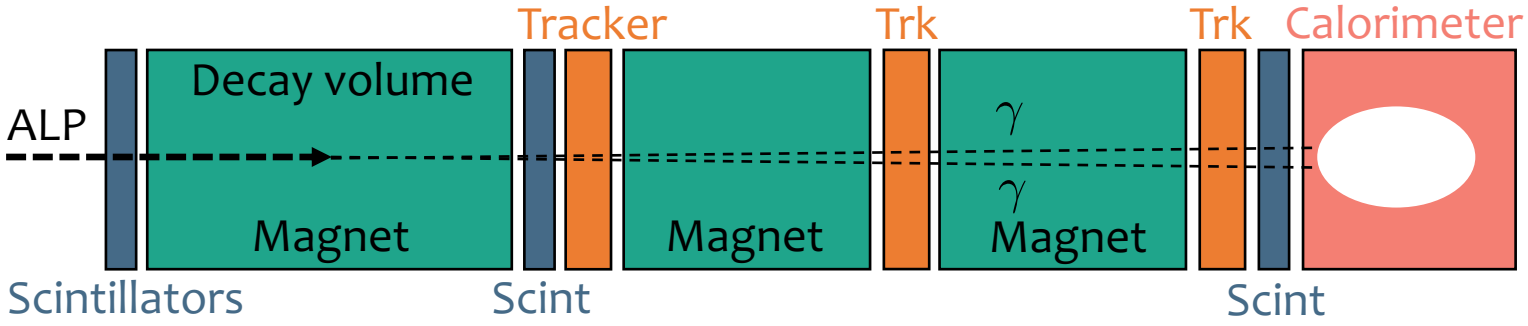


Assuming 3 signal events and no backgrounds

Key signatures

Axion-like particle (ALP, a)



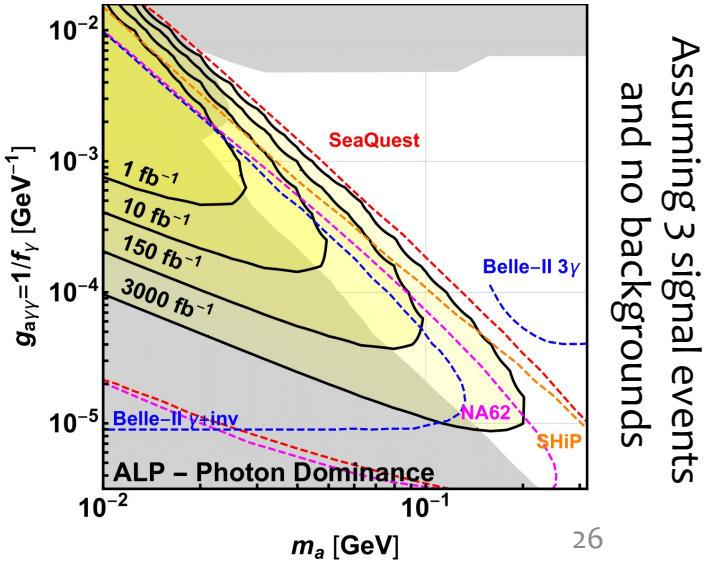


Ballpark numbers for ALPs:

- Momentum of 1 TeV
- Mass of 100 MeV

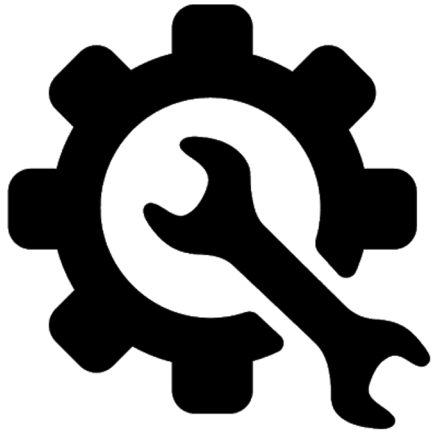
Decay products collimated

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

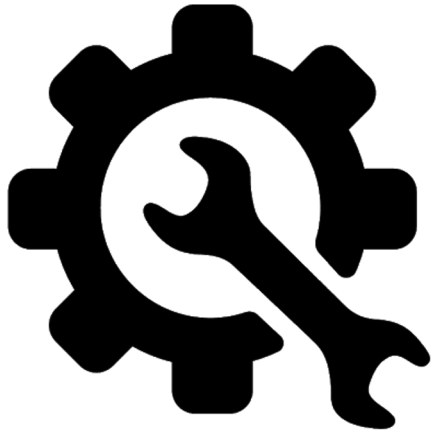


Assuming 3 signal events and no backgrounds

FASER experiment construction and commissioning



FASER experiment **construction** and commissioning

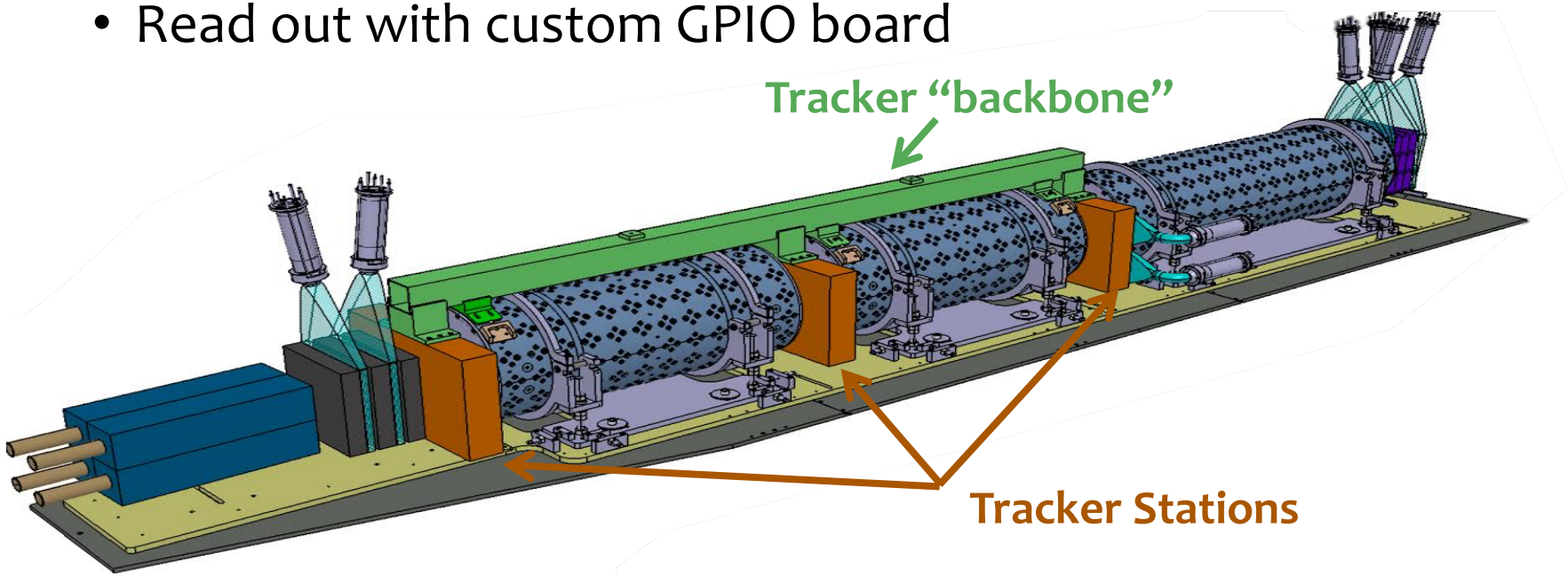


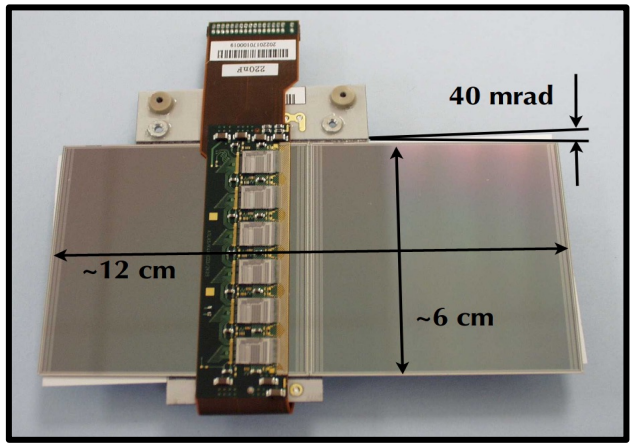
FASER Location

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

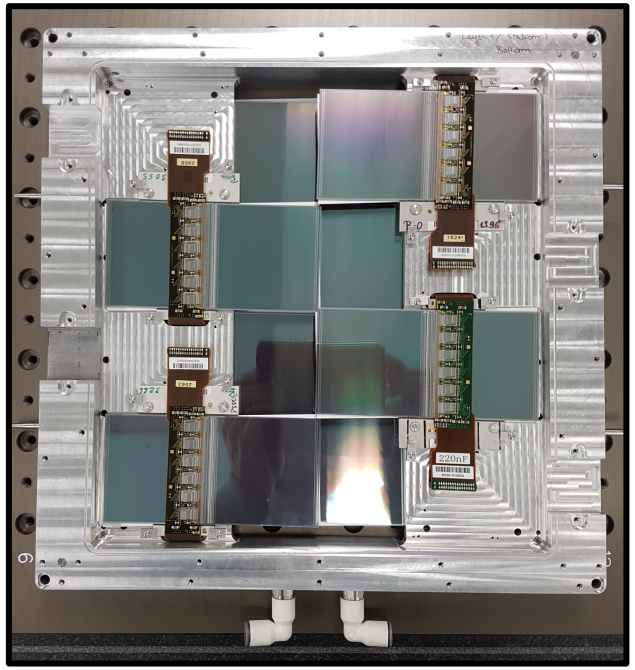




SCT module

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

Tracker layer

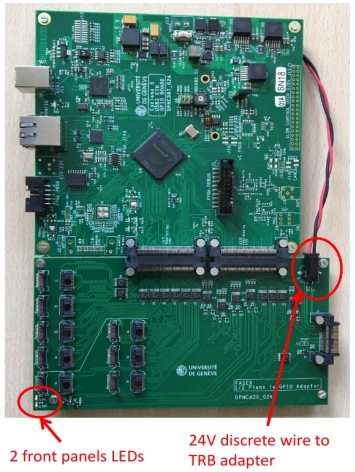


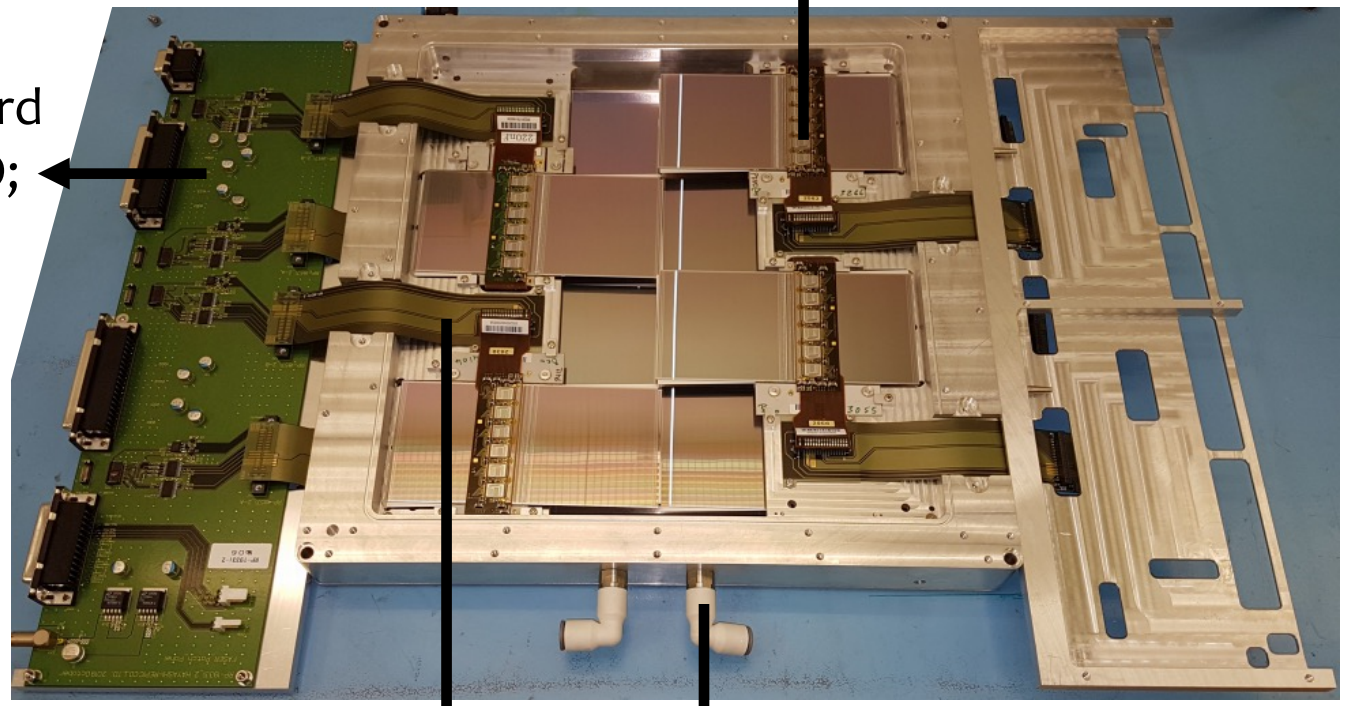
FASER Tracker

SCT module ASICs, require ~ 5 W / module

Low radiation in TI12 and much lower rates than ATLAS allow for simplifications in services and readout.

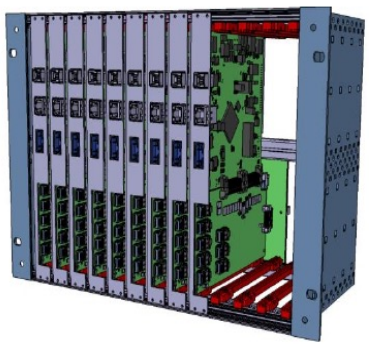
Patch panel to custom board based on home-made GPIO; Power (HV/LV), monitoring and readout lines.





FLEX cables

Into custom-made mini-crate



Detector cooling via water chiller operating at 10-15°C

FASER Tracker

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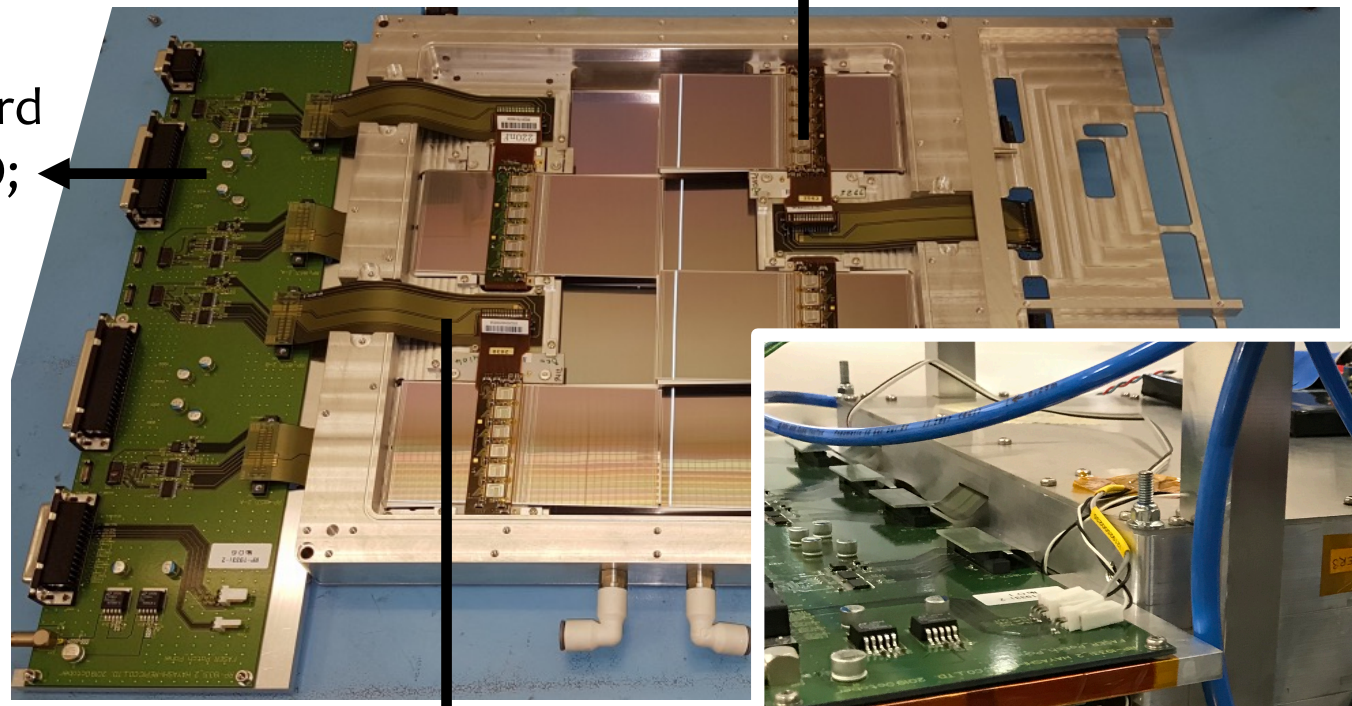
Patch panel to custom board based on home-made GPIO; Power (HV/LV), monitoring and readout lines.



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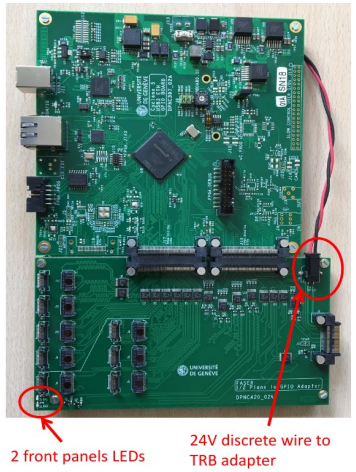

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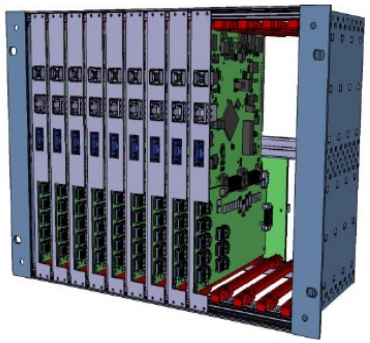
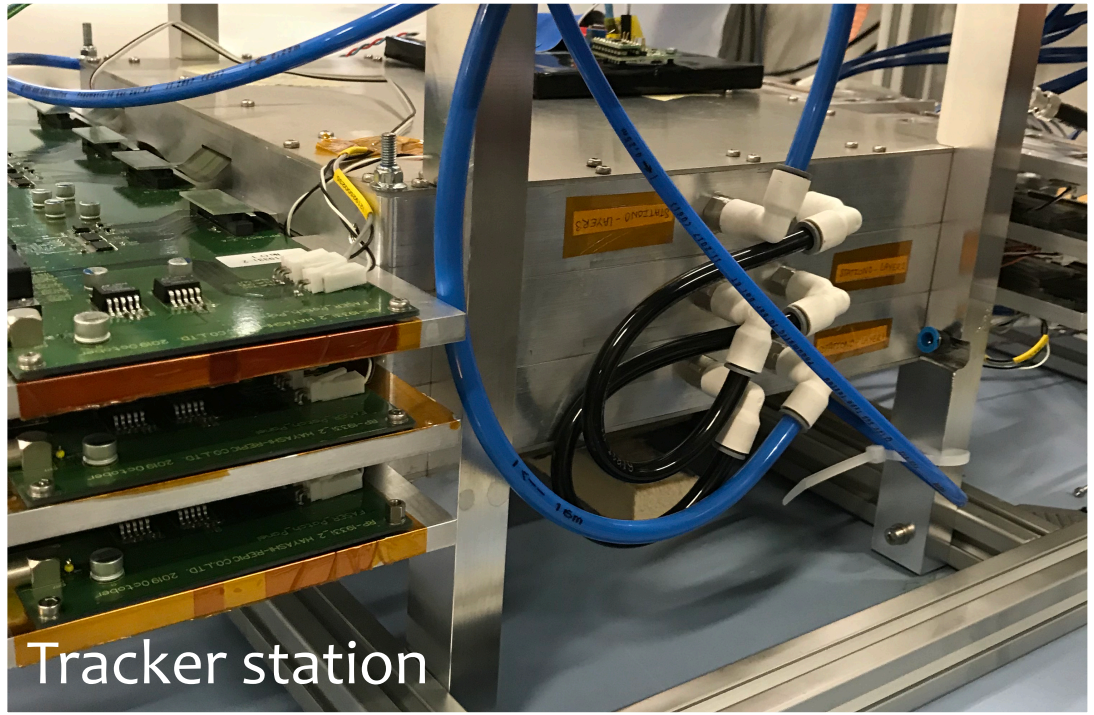
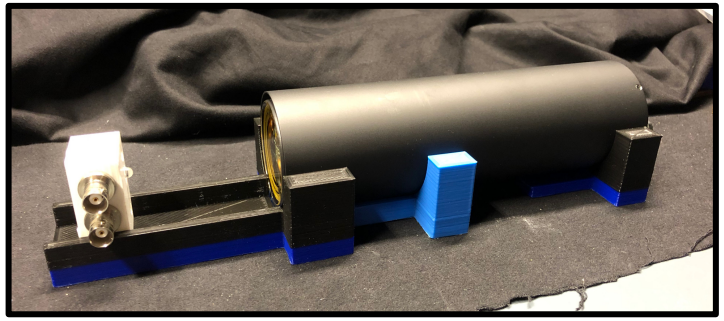


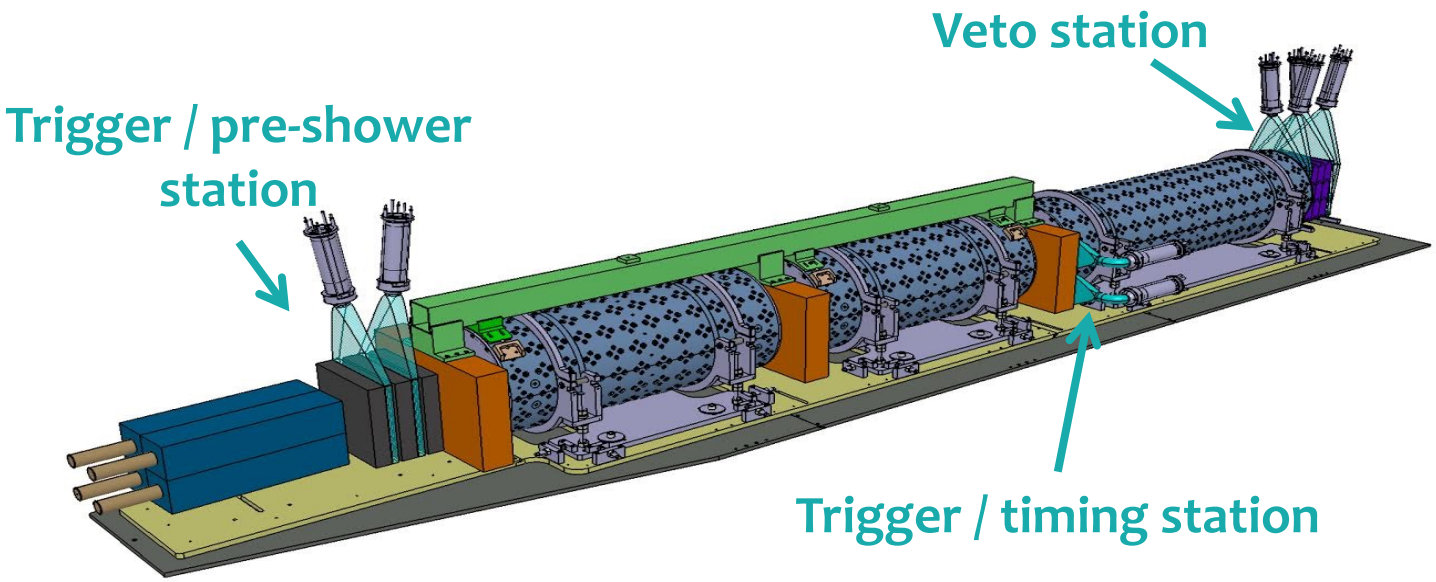


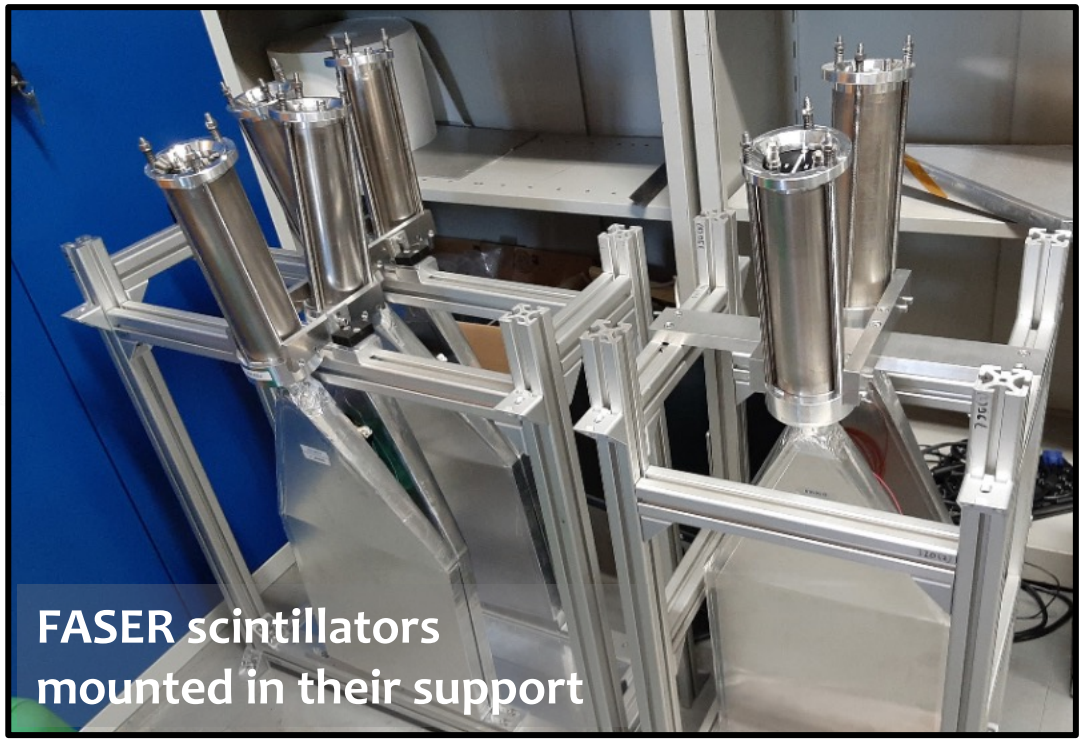
FASER Scintillators



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

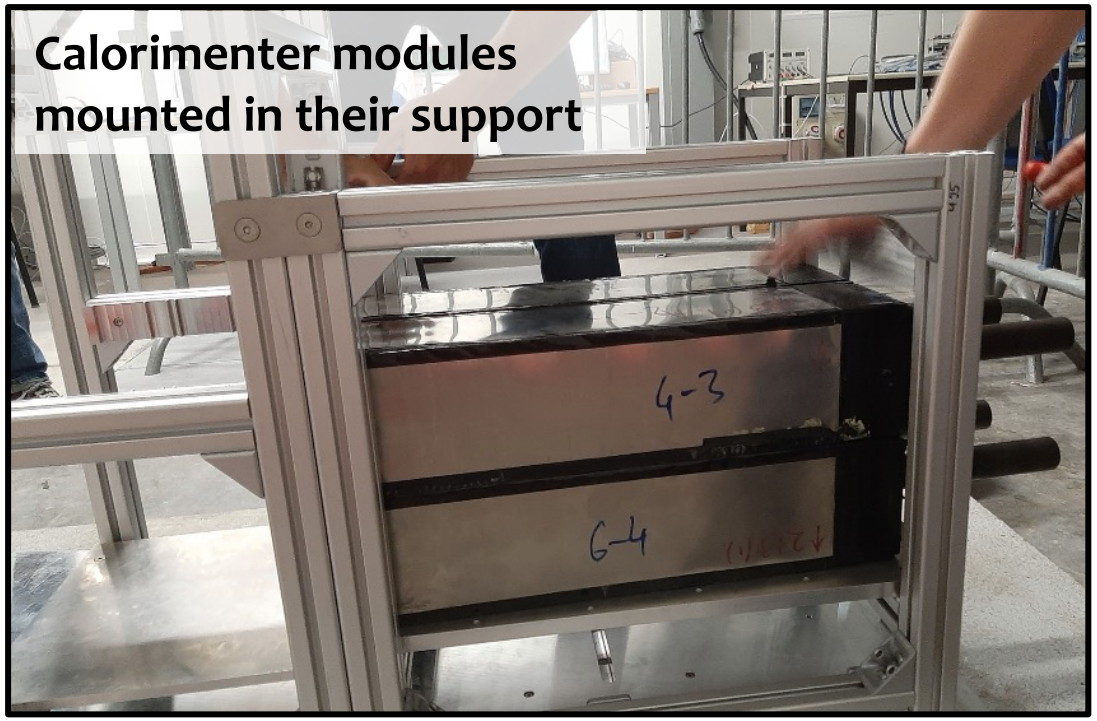


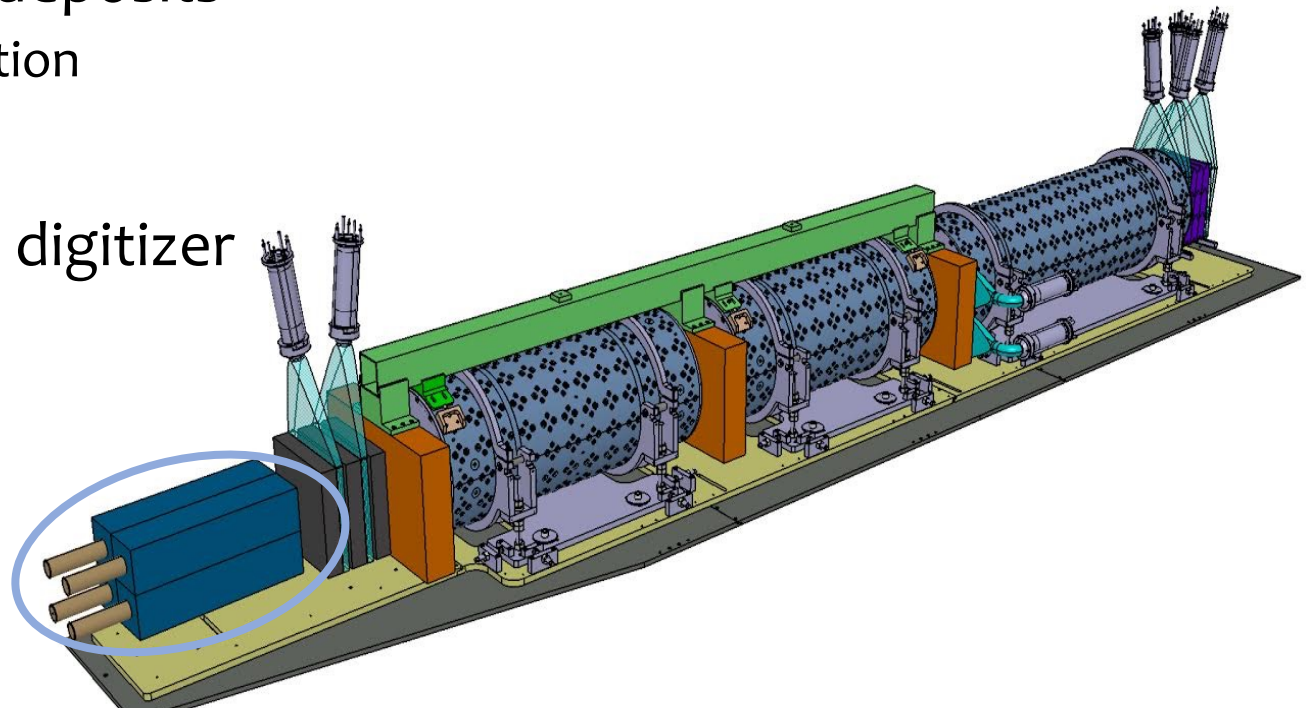


FASER Calorimeter

THANKS!

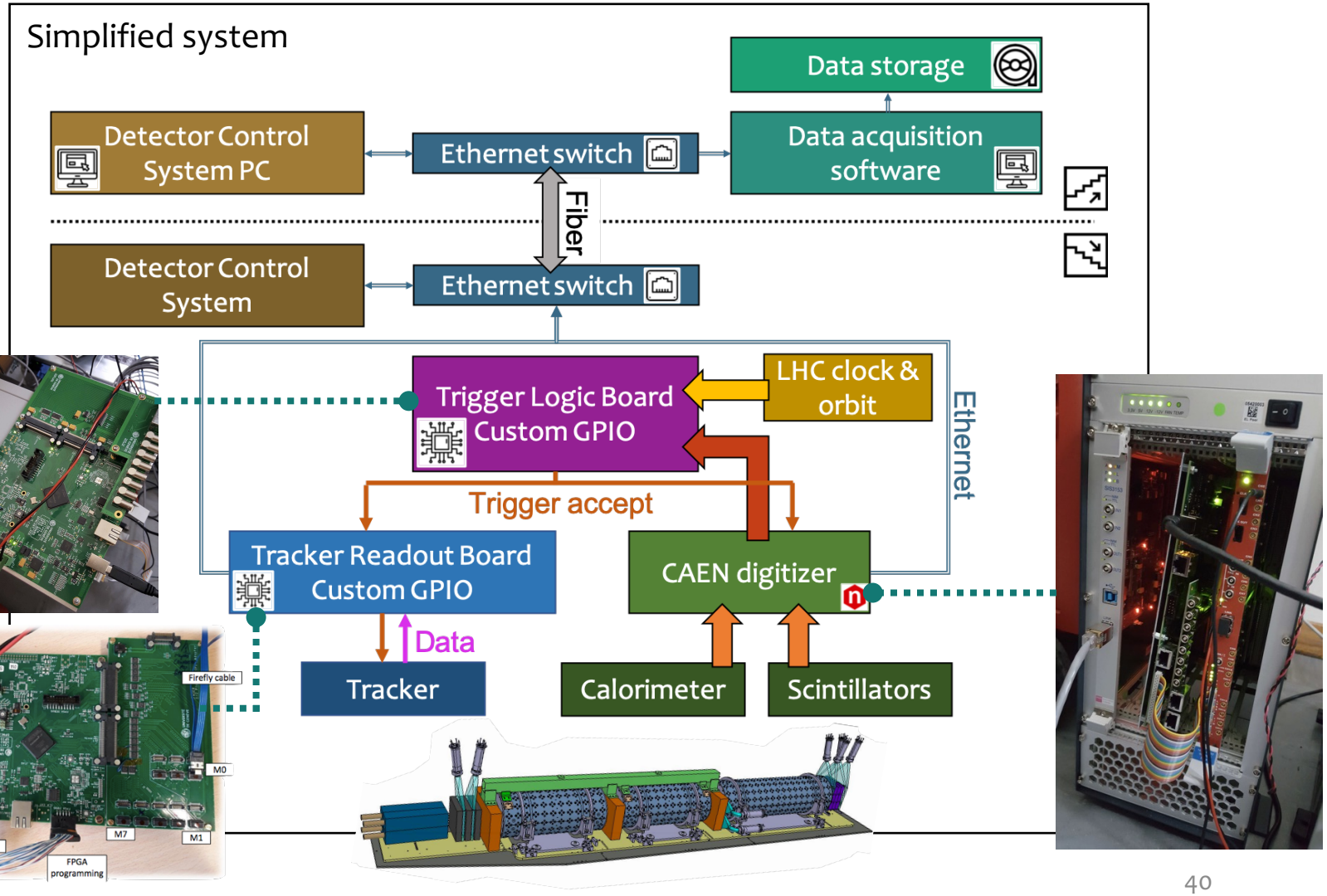
- FASER uses 4 LHCb spare outer ECAL modules
  - 25 radiation lengths long
  - Lead/scintillator calorimeter
- Energy resolution ~ 1% for TeV deposits
  - No longitudinal shower information
- Provides triggering capability
- Read out with PMTs and CAEN digitizer





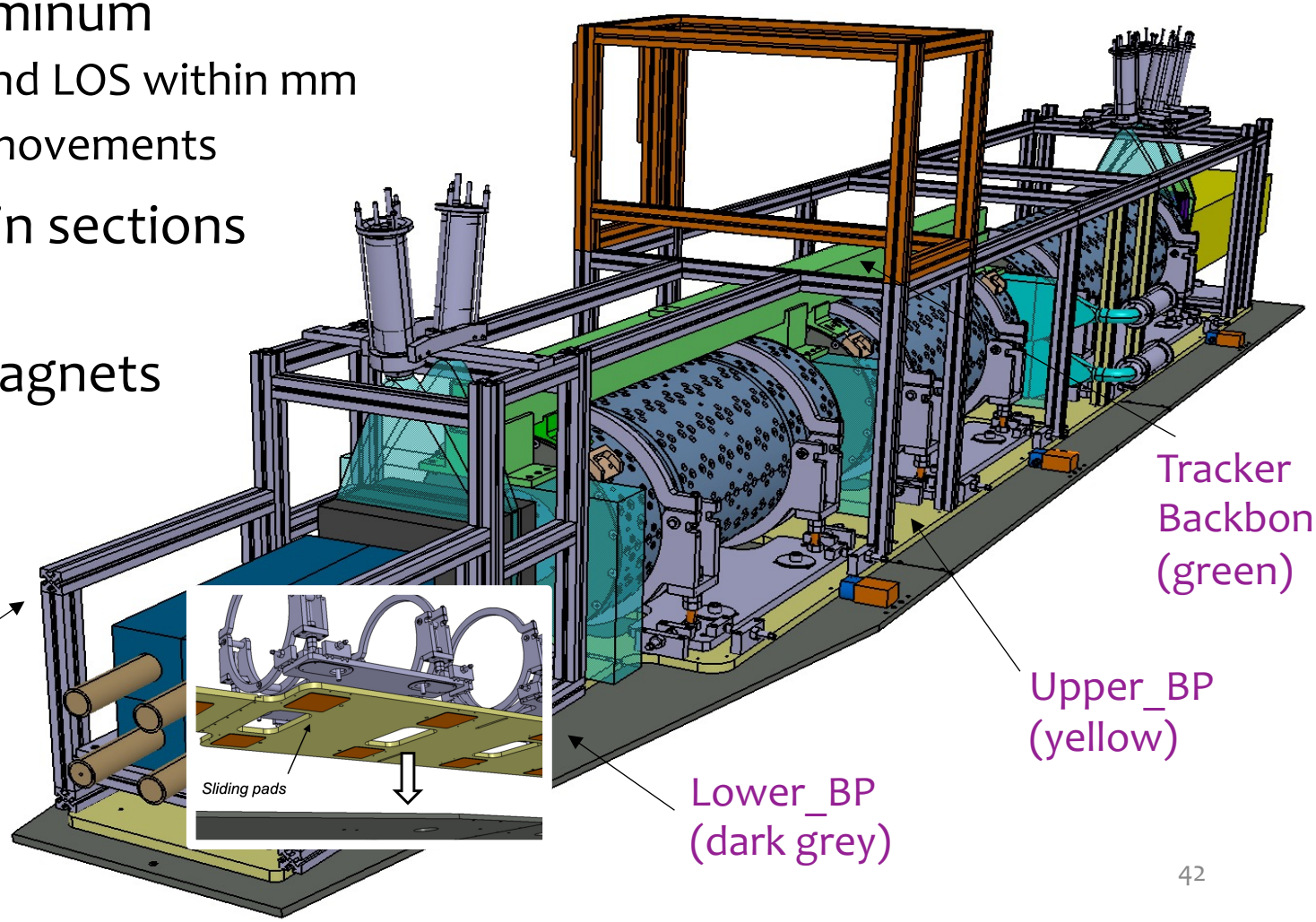
Trigger & Data acquisition

- 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

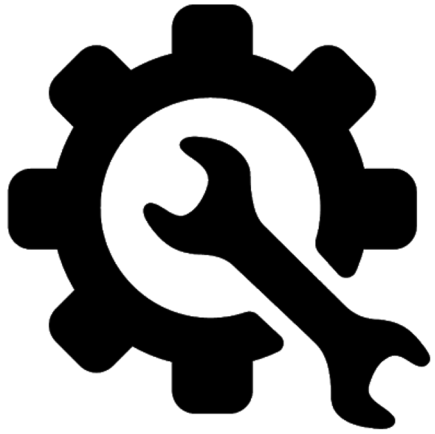


Detector support structure

- 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)



FASER experiment



construction and **commissioning**

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

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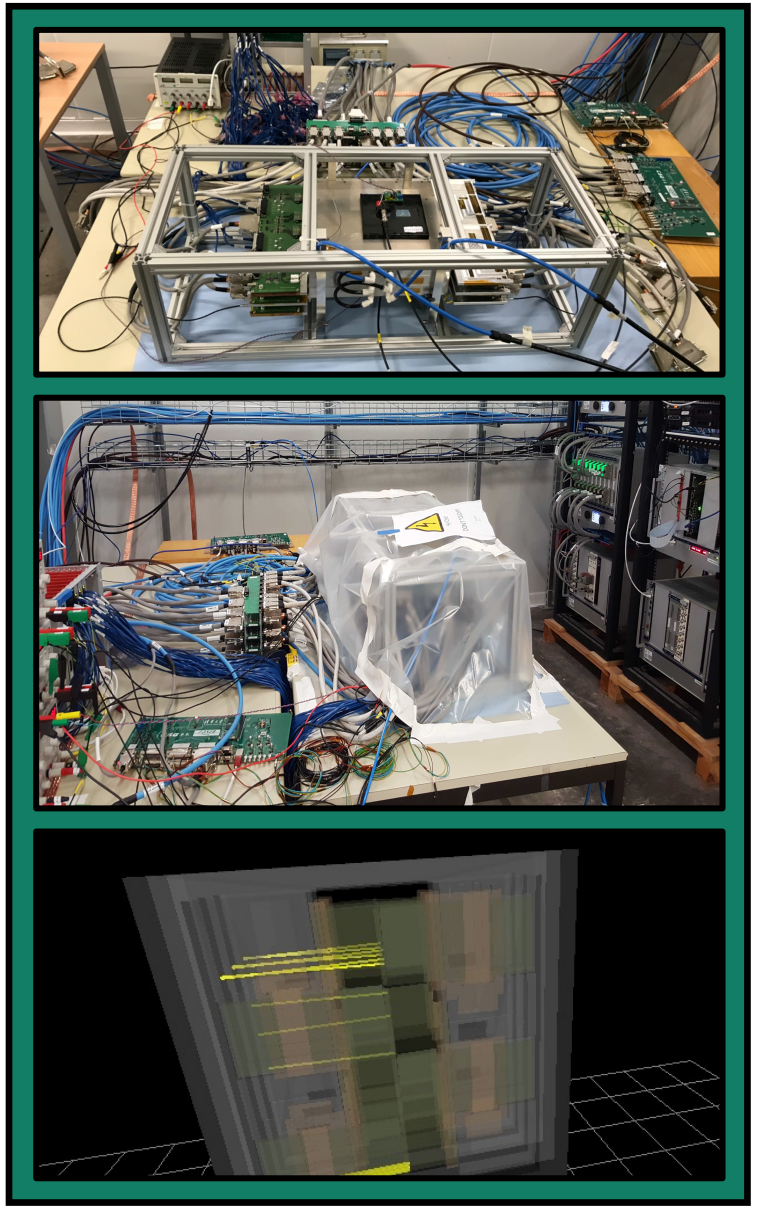
In-situ commissioning	TI12	During 2021

Cosmic data taking



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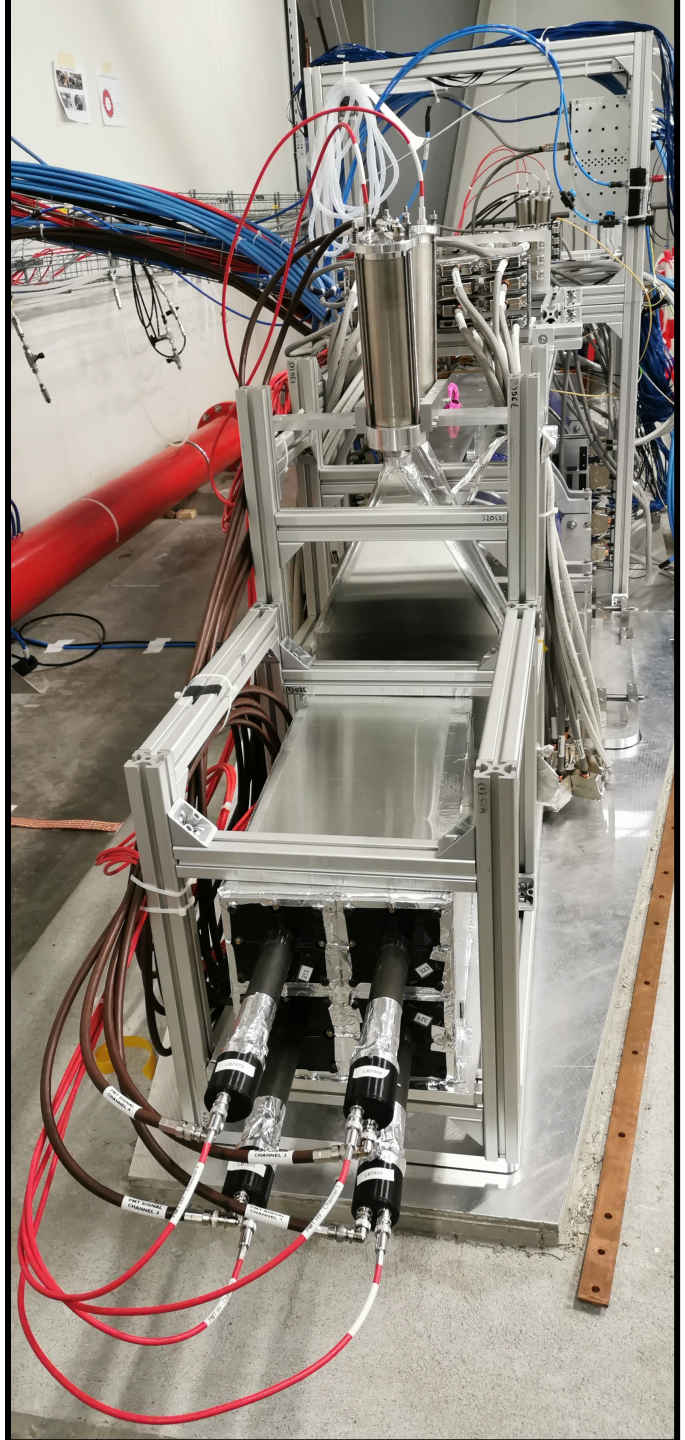
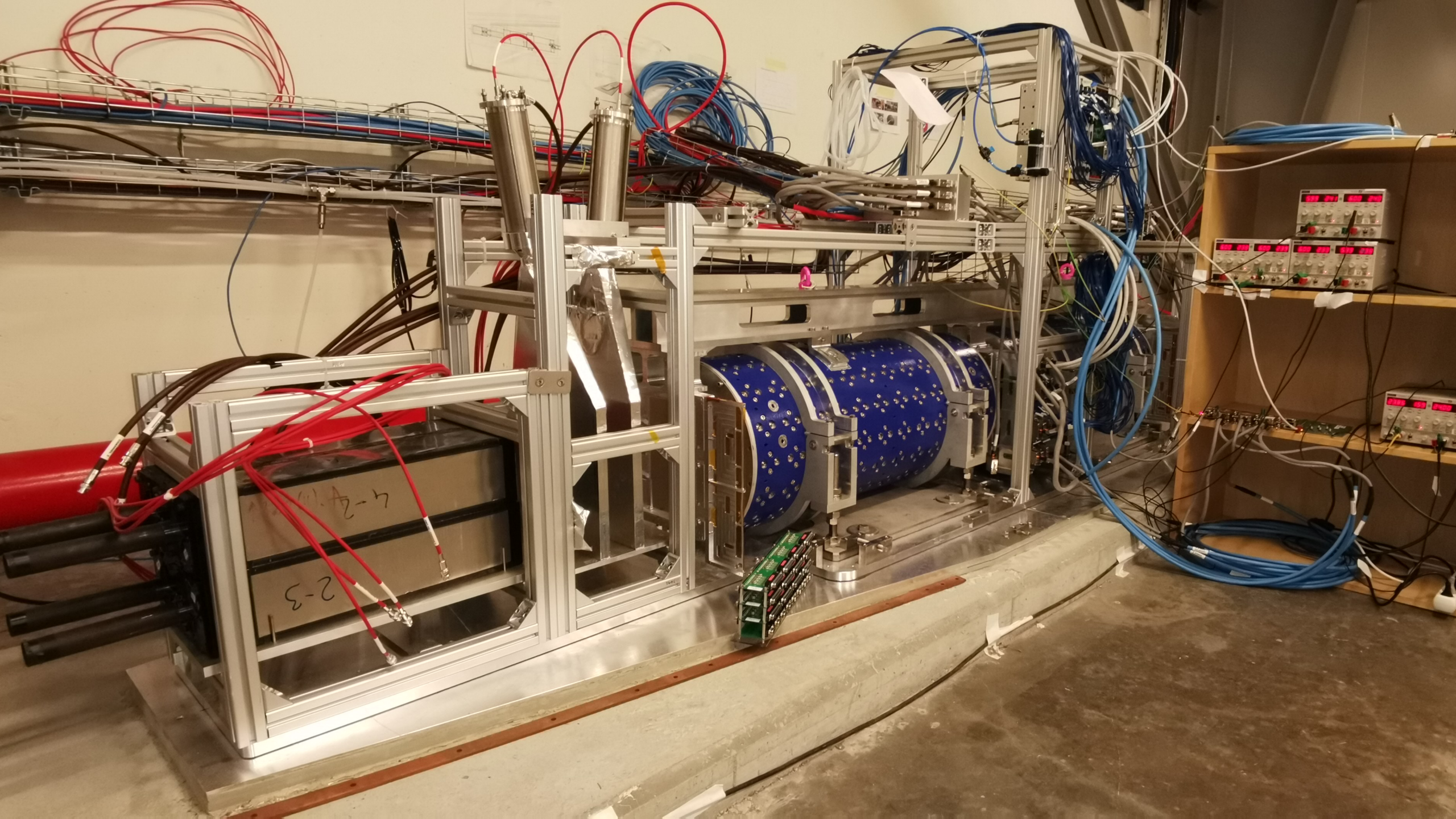



FASER
FRAGILE
DO NOT TOUCH



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In-situ commissioning	TI12	During 2021

Installation to TI12

End 2020

Installation to TI12

Second phase in

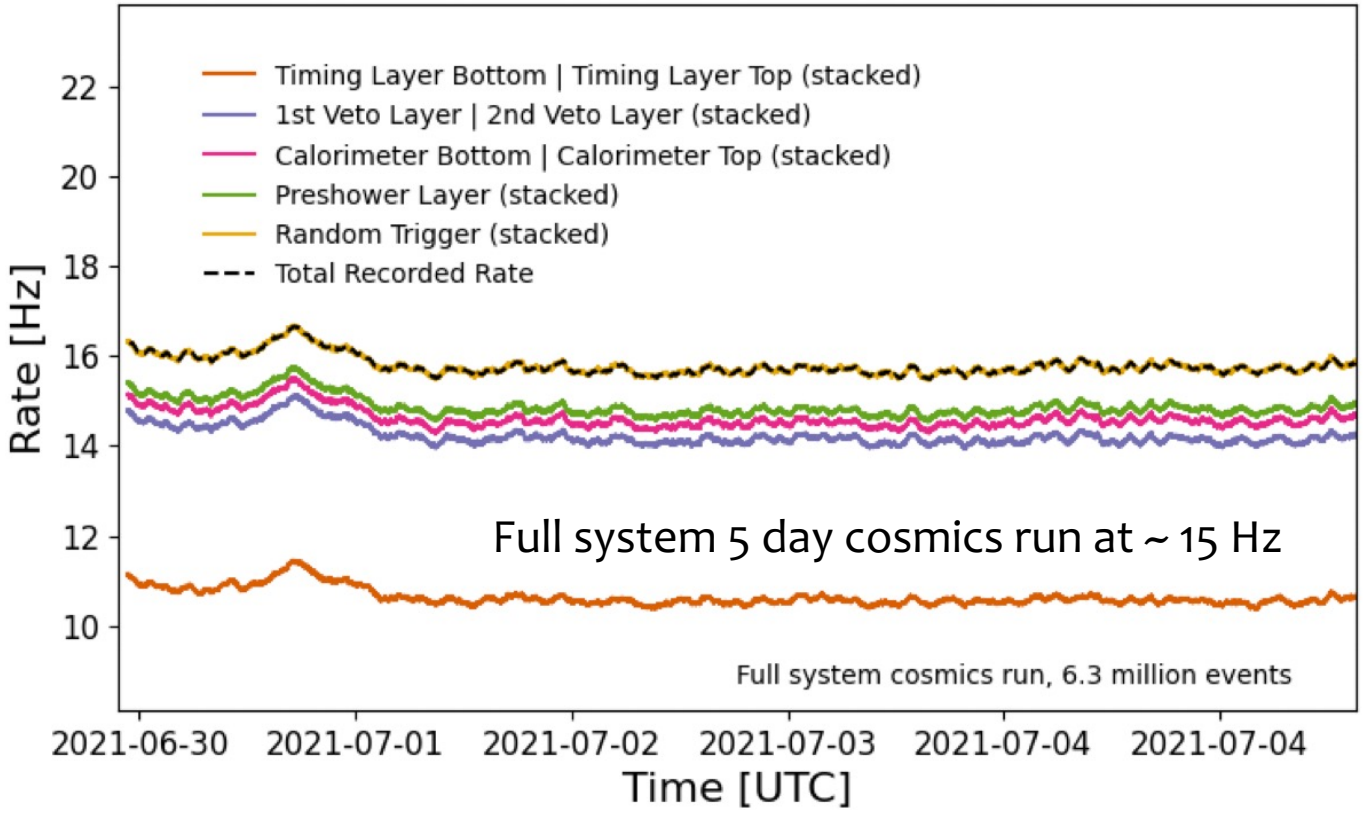
Time-lapse: https://videos.cern.ch/record/2759548

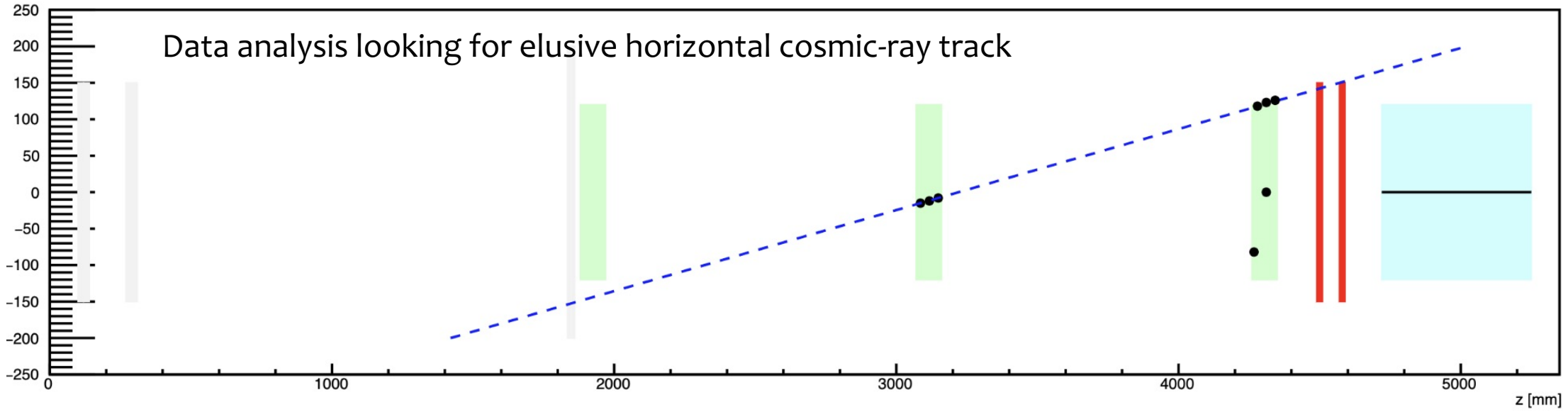

CMU 2t
CMU 2t
2t
ATTENTION
HAUTE TENSION
HIGH DANGER


ATTENTION
HAUTE
HIGH
TENSION
DANGER

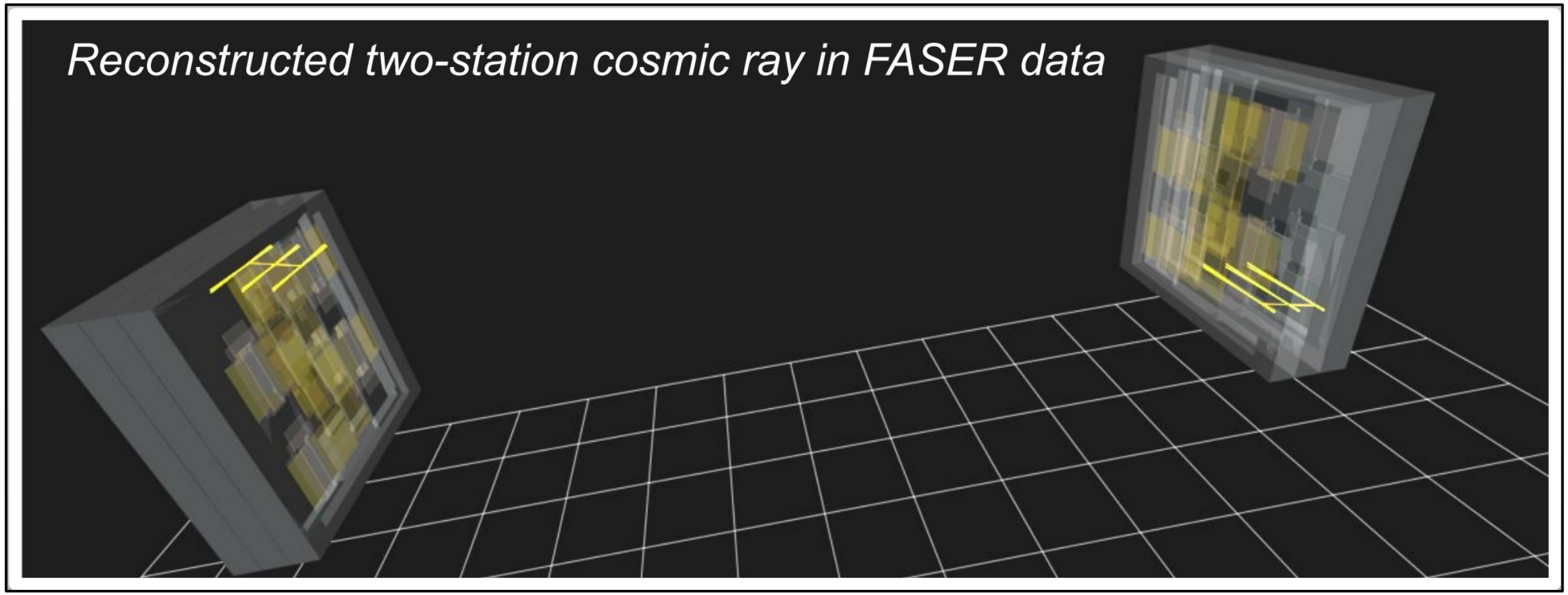
Cosmic data taking

Since installation FASER has been mostly taking cosmic data in TI12

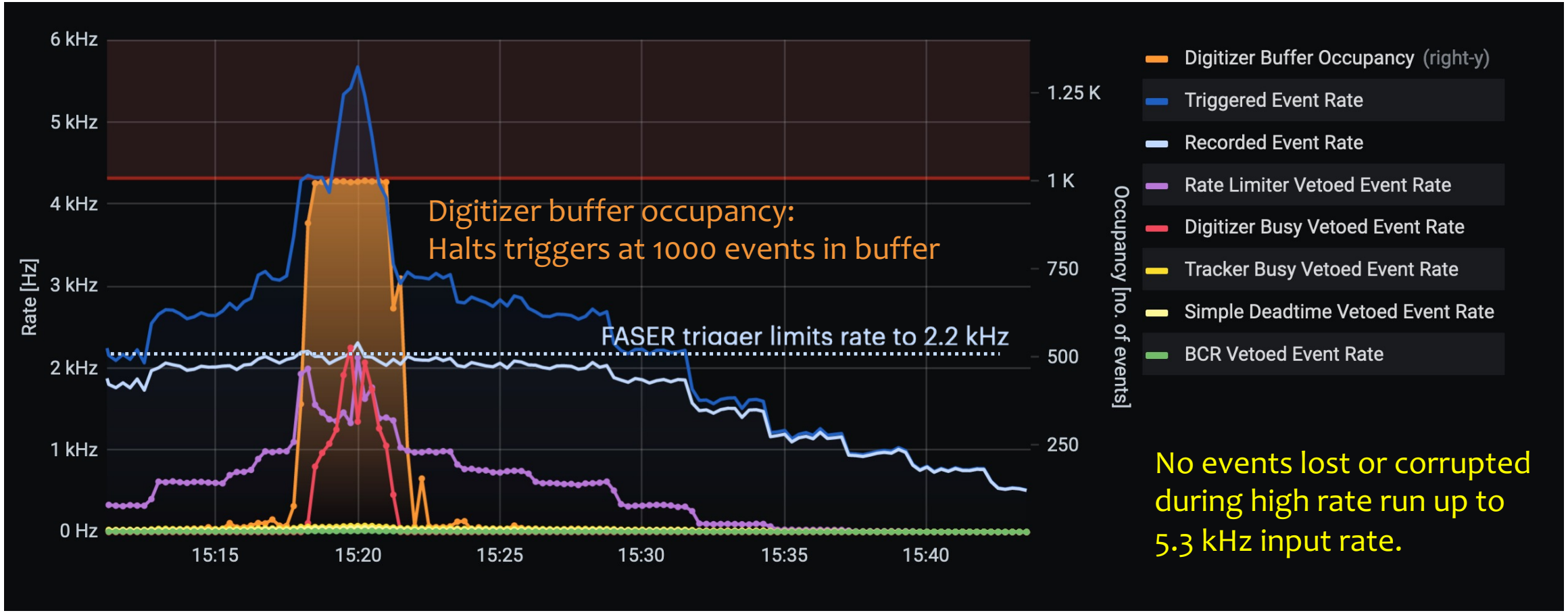




Cosmic data taking



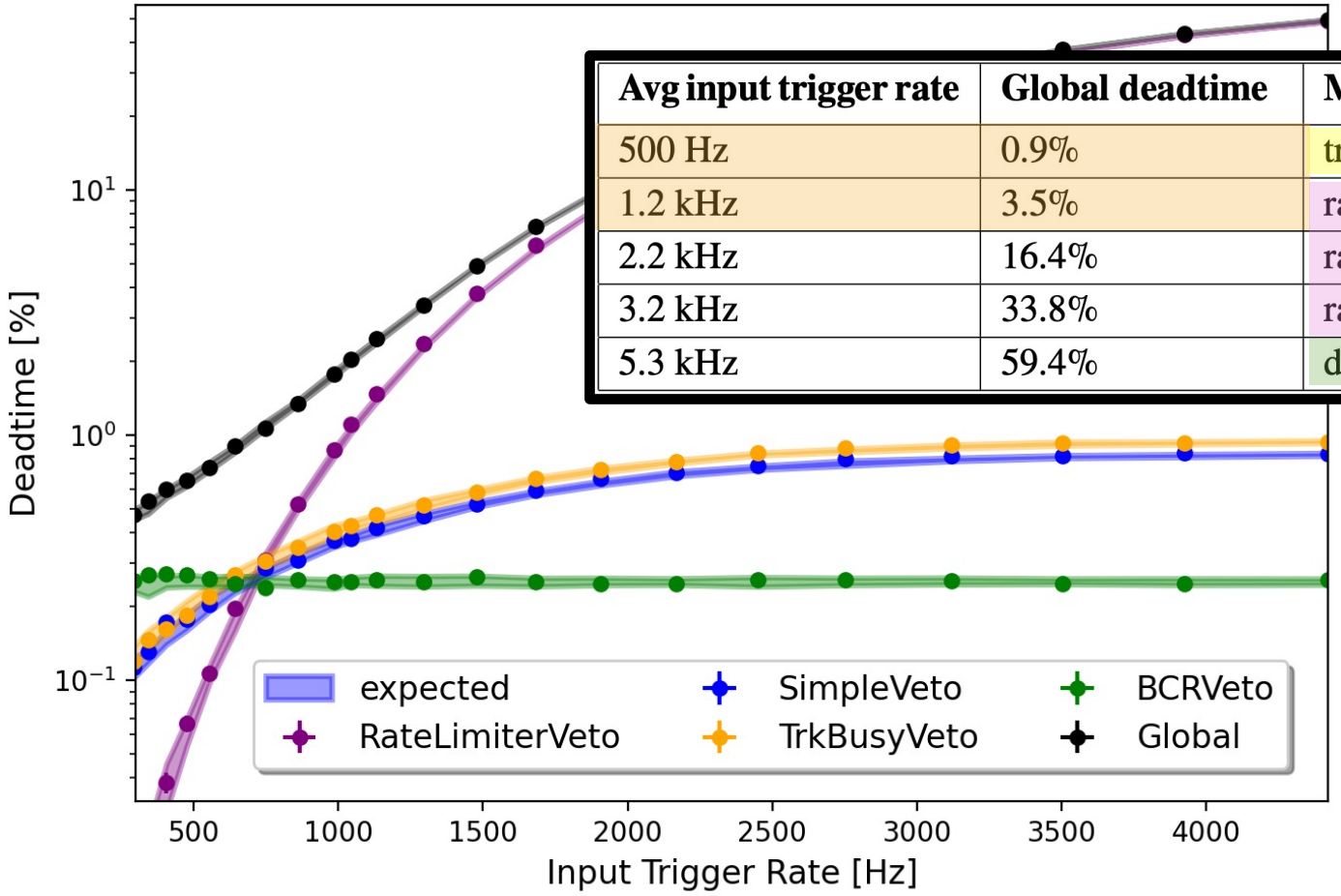
High rate tests



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 %

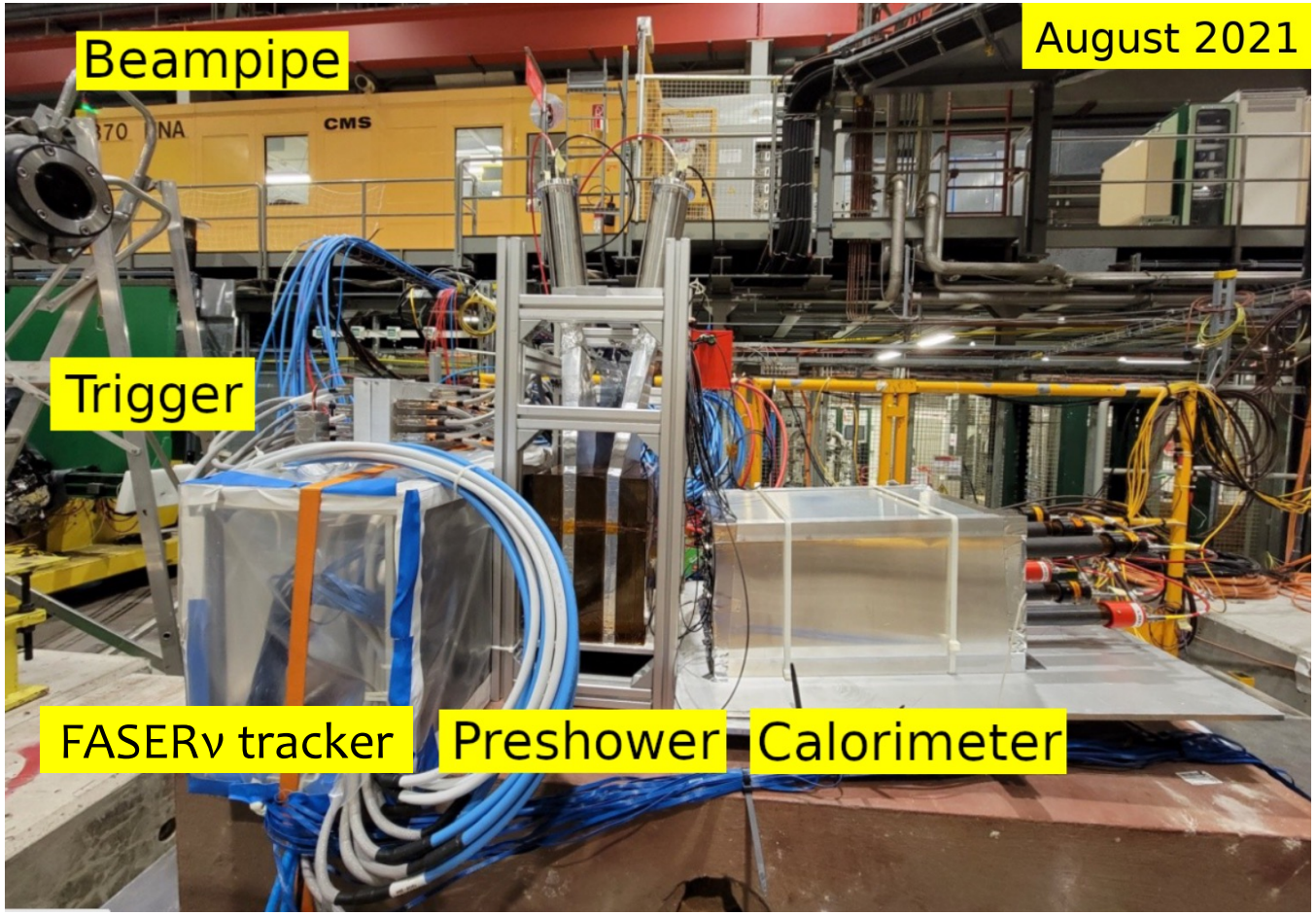
NEW! arXiv: 2110.15186

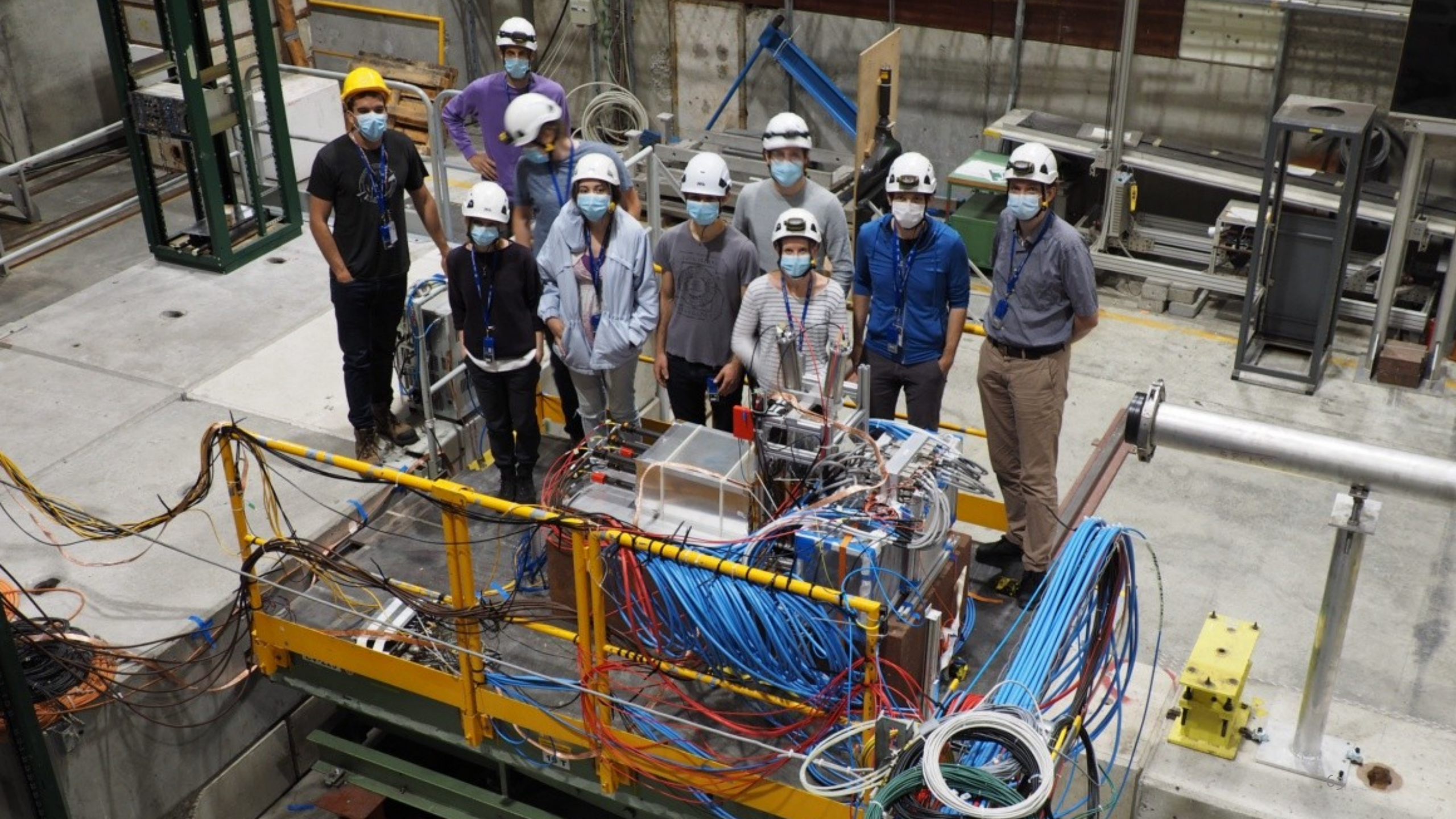
experiment

commissioning with beams!

FASER Testbeam

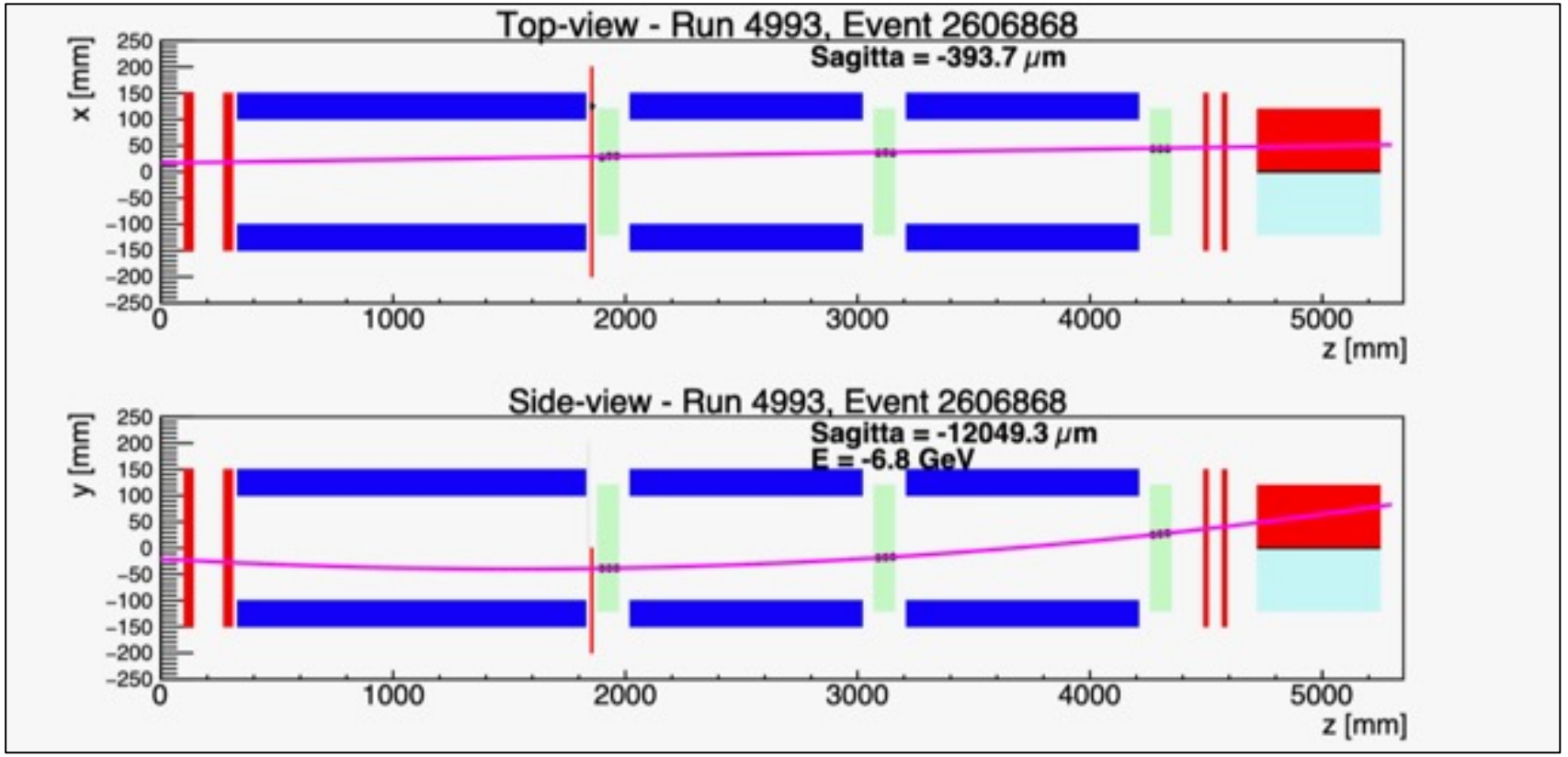
- July 28 – Aug 4th – carried out test beam in SPS North area
- Primary goal to calibrate the calorimeter with high energy electron beam
- 150M events collected using electron, muon and pion beams
- Analysis ongoing…





October 2021: First LHC beams since 2018!

- LHC pilot beams "splash" in front of ATLAS
- First collisions at 900 GeV CM energy
- **First time we see particles traversing the full detector!**



FASER experiment

And now, waiting for Run3 to start! ?


FASER

Huge flux of high-energy neutrinos

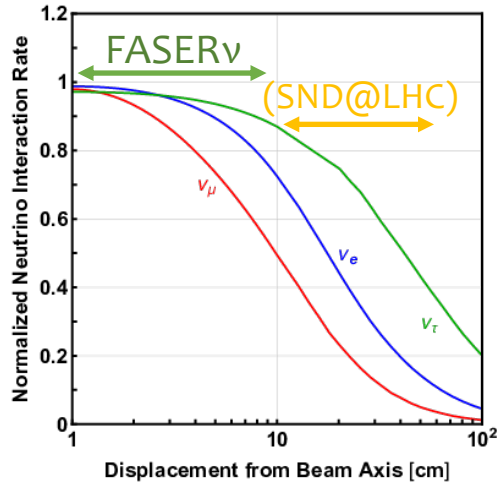
- Why not exploit FASER to also measure properties of neutrinos at the highest man-made energies ever recorded!

A bit of history

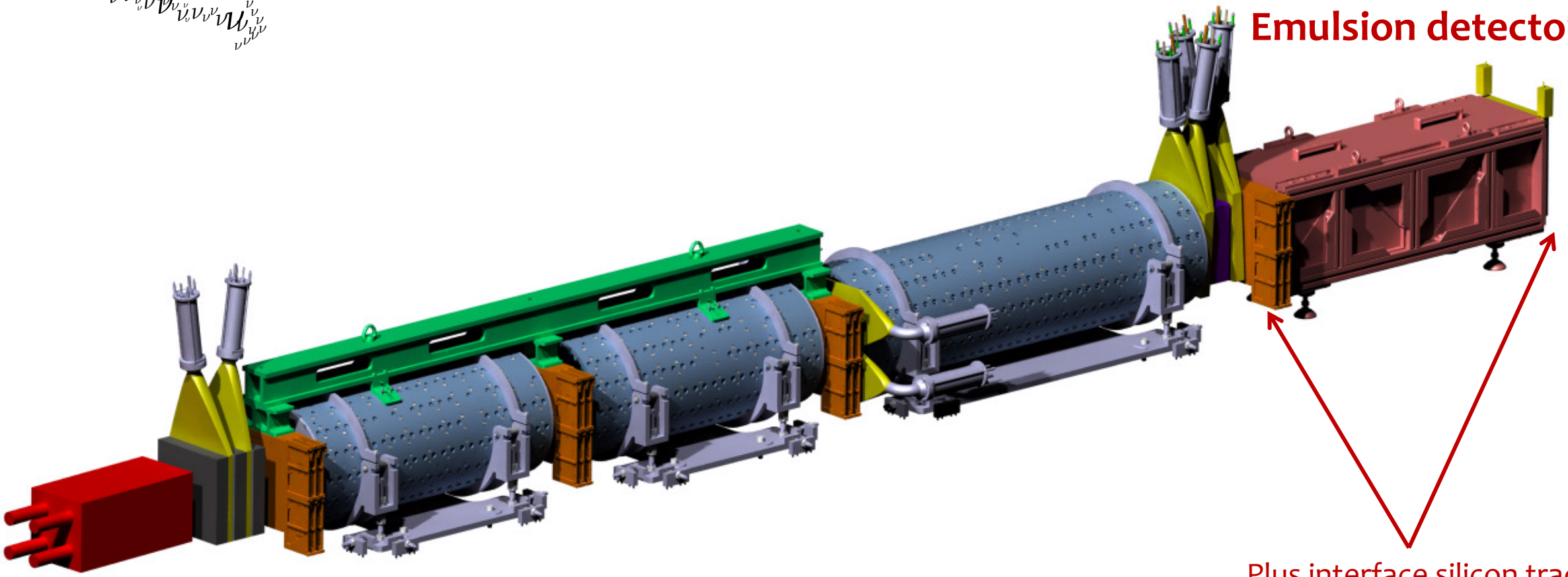
Experiments to study collider neutrinos have been proposed since the 80s, e.g.:

- 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.



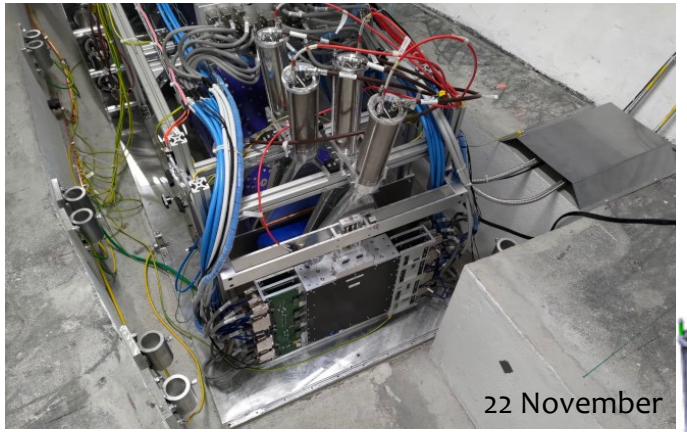
FASER Detector



FASERν
Emulsion detector

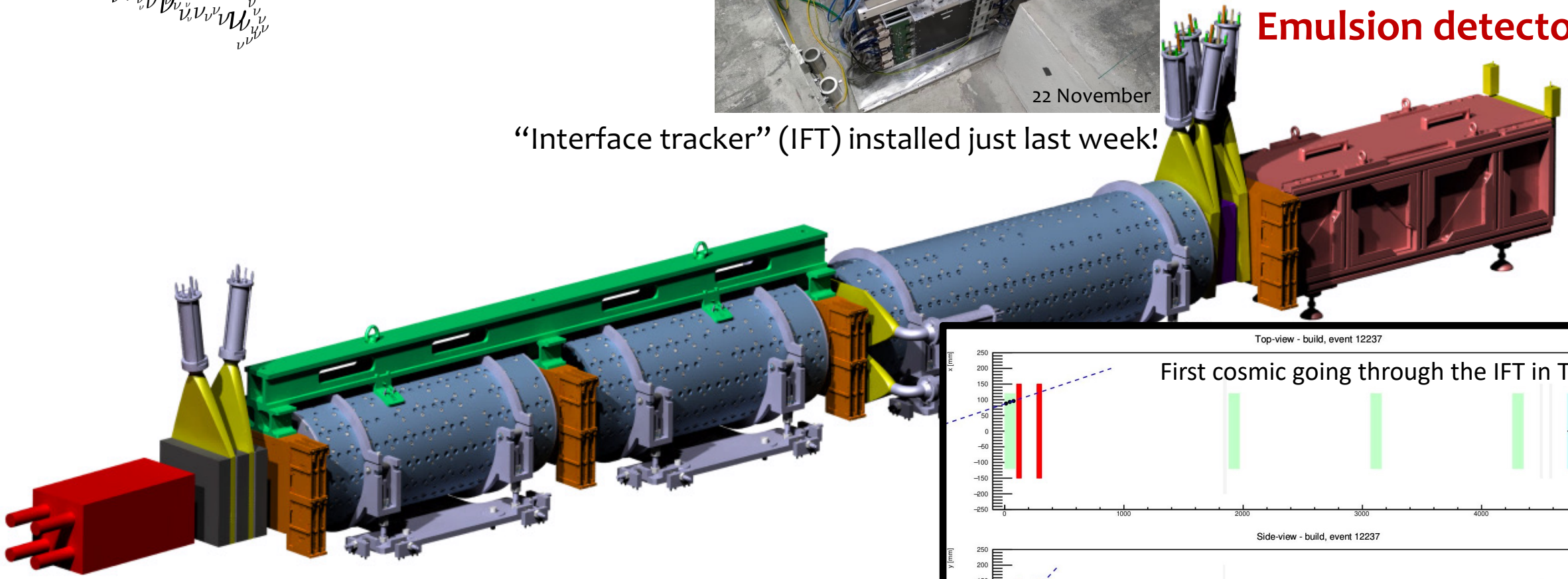
Plus interface silicon tracker
and a veto station

FASER Detector



FASERν
Emulsion detector

"Interface tracker" (IFT) installed just last week!

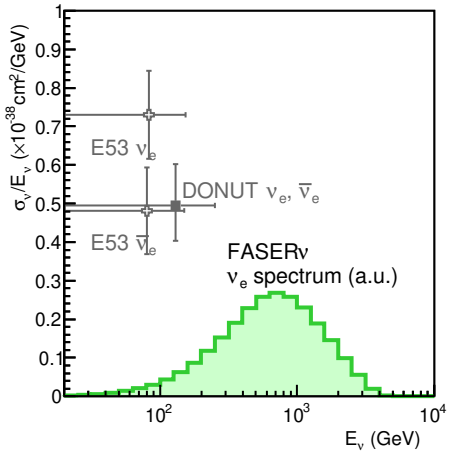


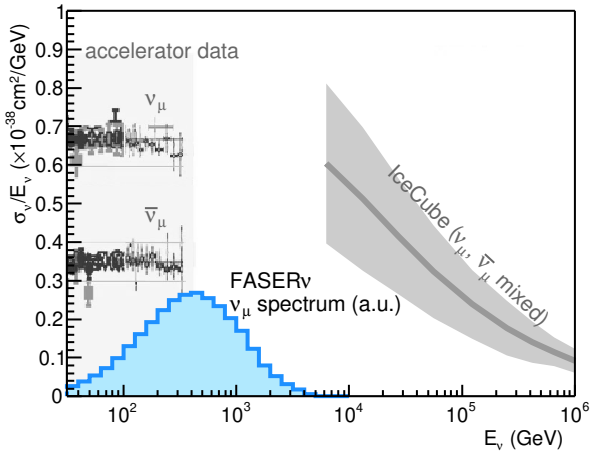
Huge flux of high-energy neutrinos

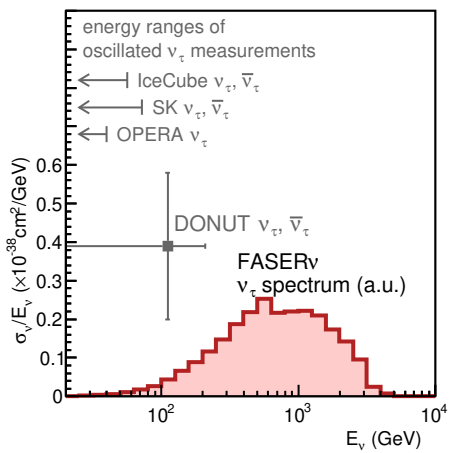
- Why not exploit FASER to also measure properties of neutrinos at the highest man-made energies ever recorded!

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

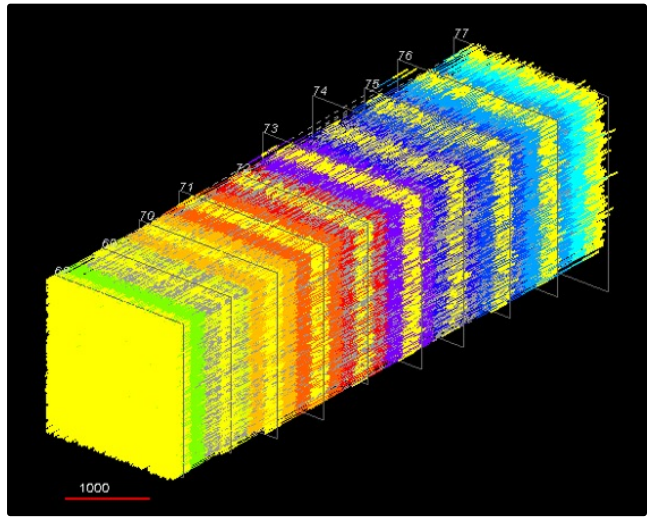
150/fb @14TeV	ν_e	ν_μ	ν_τ
Main production source	kaon decay	pion decay	charm decay
# traversing FASERnu 25cm x 25cm	$O(10^{11})$	$O(10^{12})$	$O(10^{9})$
# interacting in FASERnu (1.2tn Tungsten)	~1300	~20000	~20







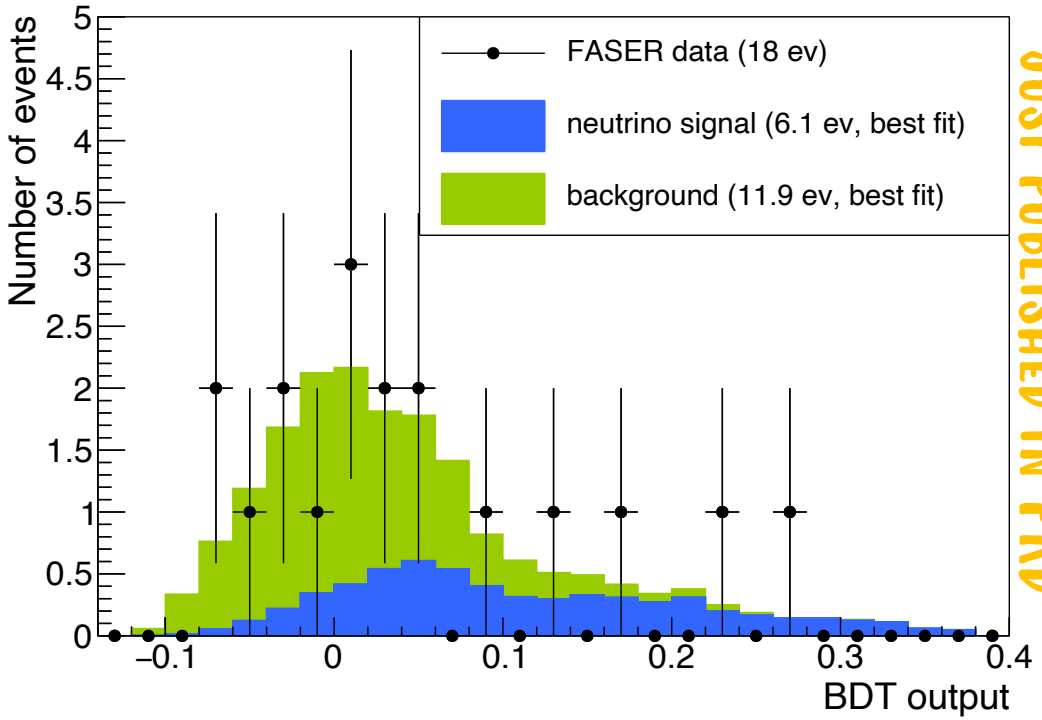
Pilot run in 2018



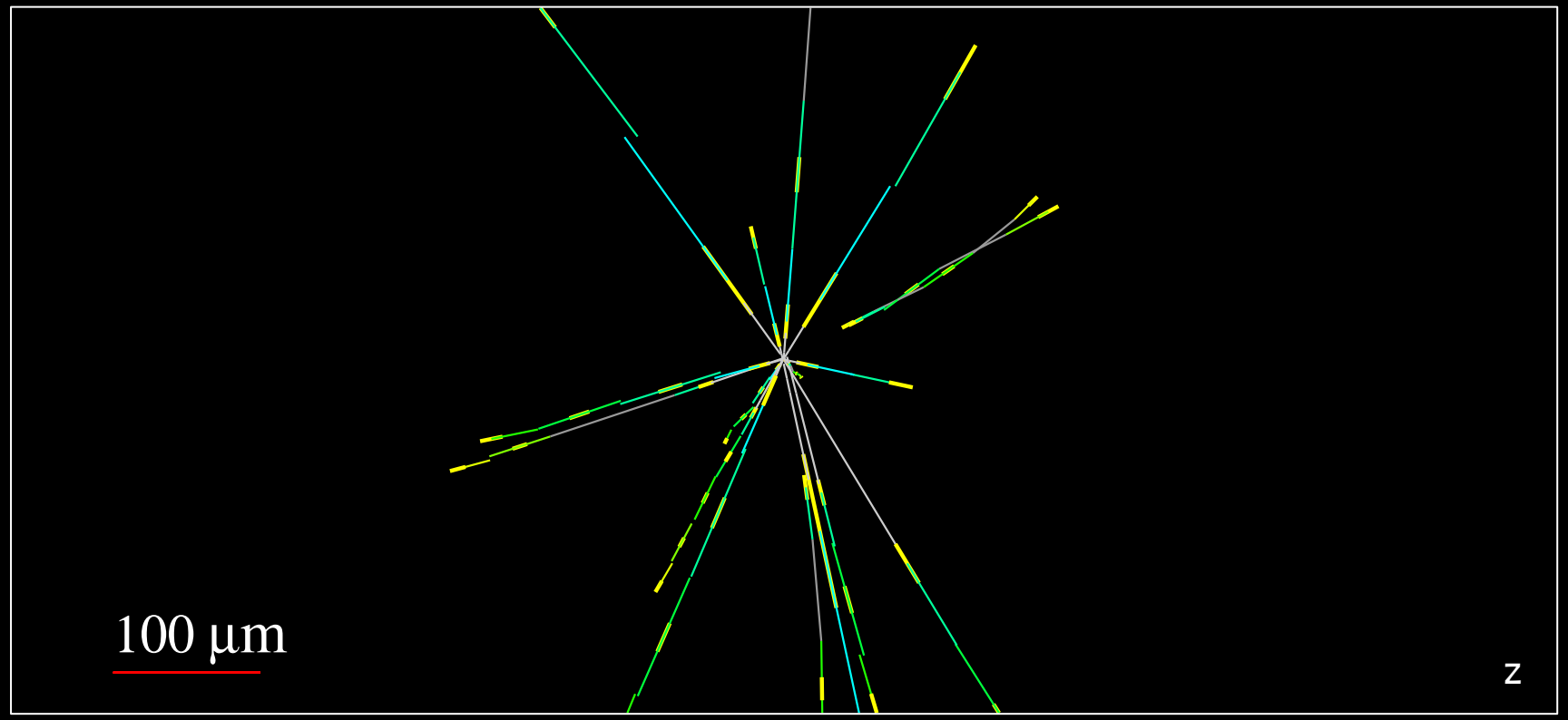
- A 30 kg detector at TI18
- Collected ~ 13/fb

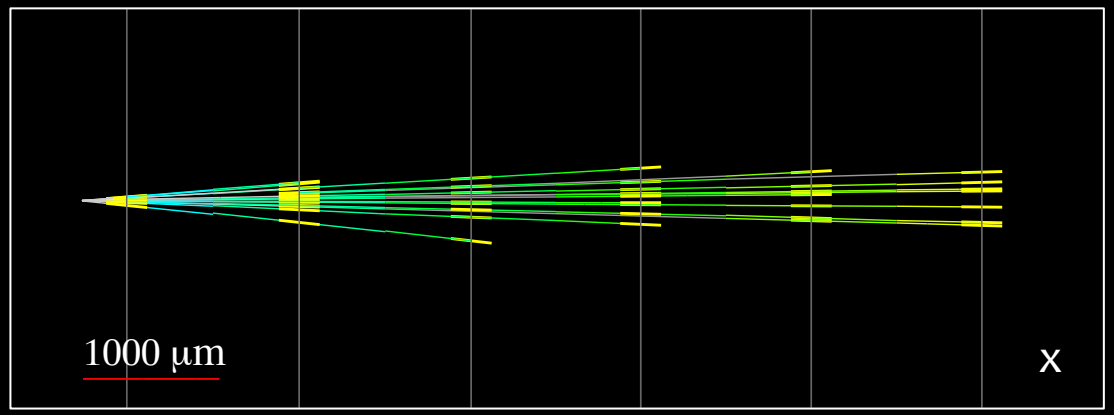
- About 3.3 neutrino interactions expected to have occurred after selections
- BDT developed to distinguish neutrino signal from neutral hadron background
  - The background-only hypothesis is rejected with significance of 2.7σ

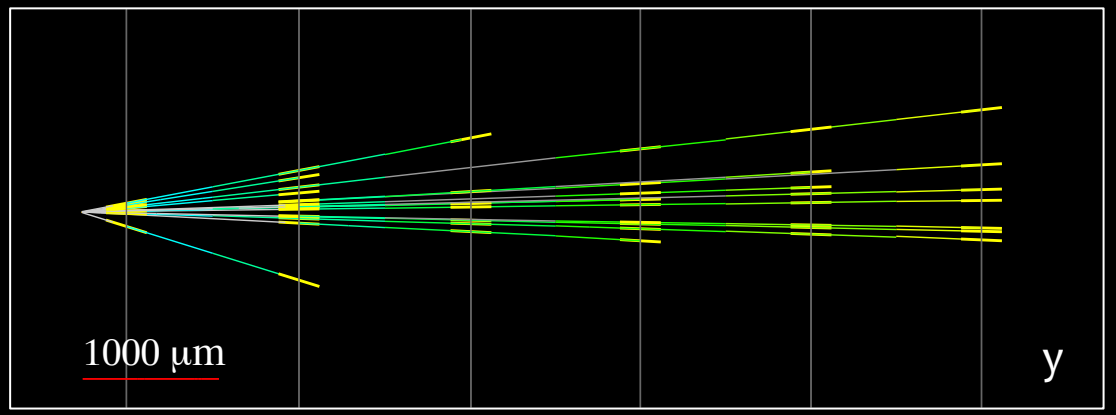
- Excellent testbed for future data analysis



NEW! JUST PUBLISHED IN PRD arXiv: 2105.06197

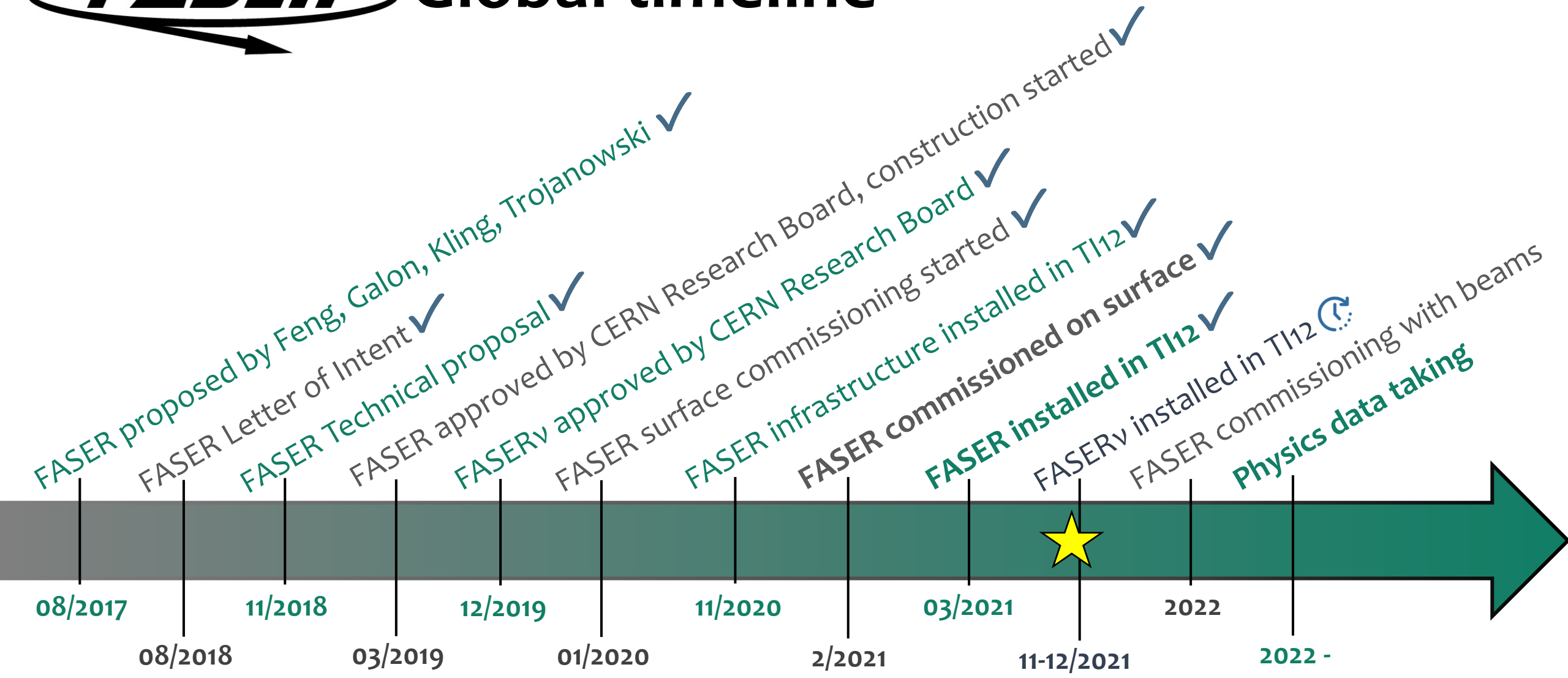

100 μm
z


1000 μm
x


1000 μm
y

FASER Timeline

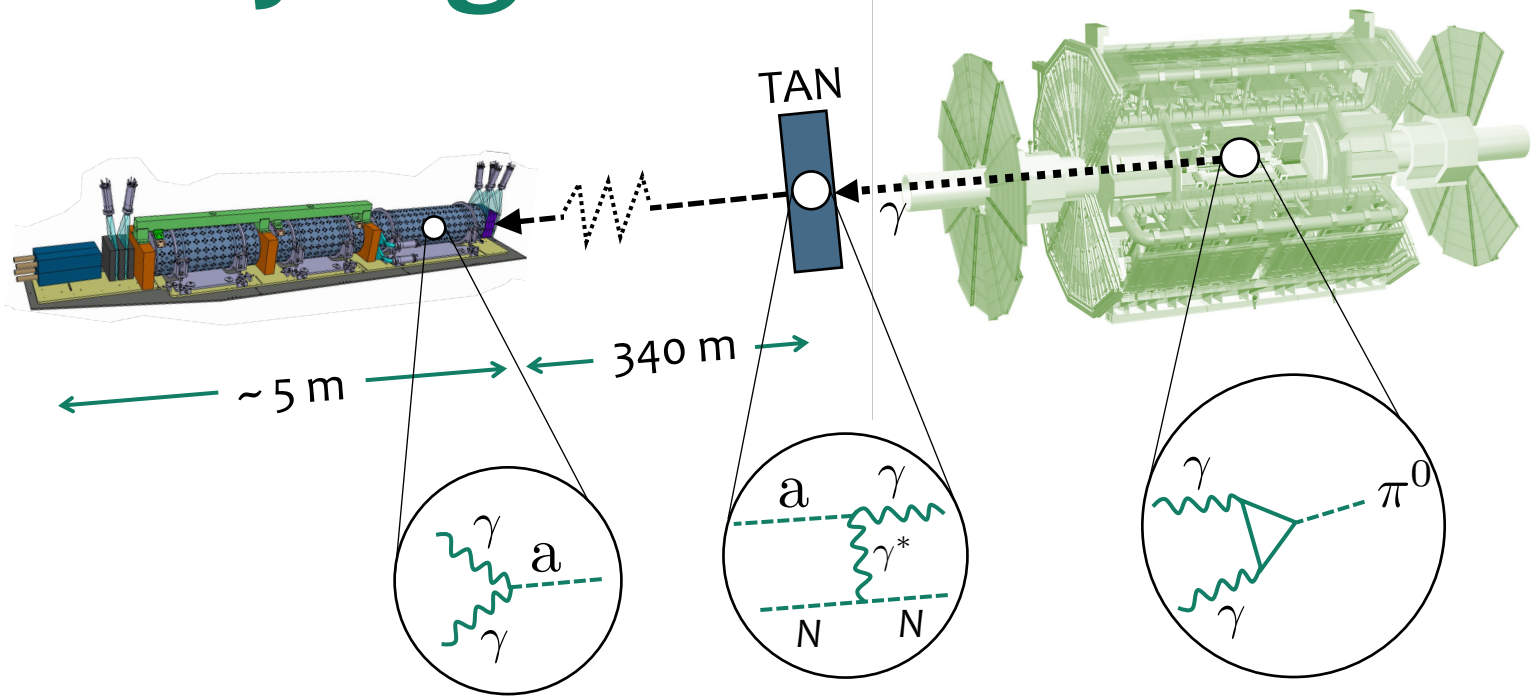
Global timeline

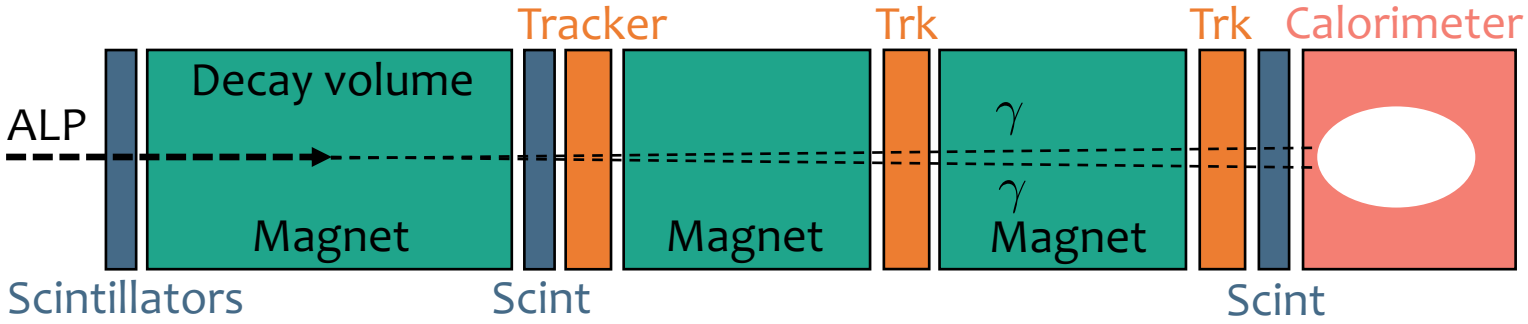


What’s beyond 2022?

Key signatures

Axion-like particle (ALP, a)



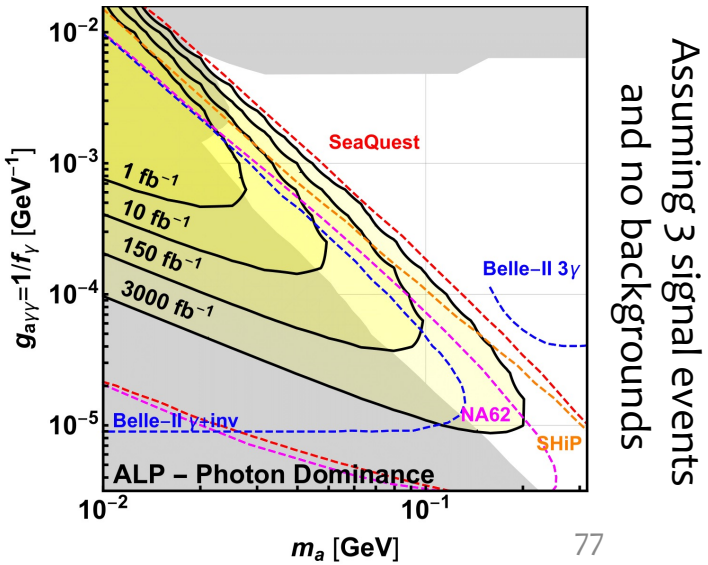


Ballpark numbers for ALPs:

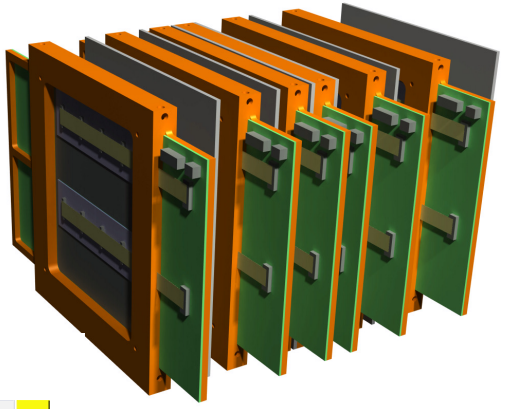
- Momentum of 1 TeV
- Mass of 100 MeV

Decay products collimated

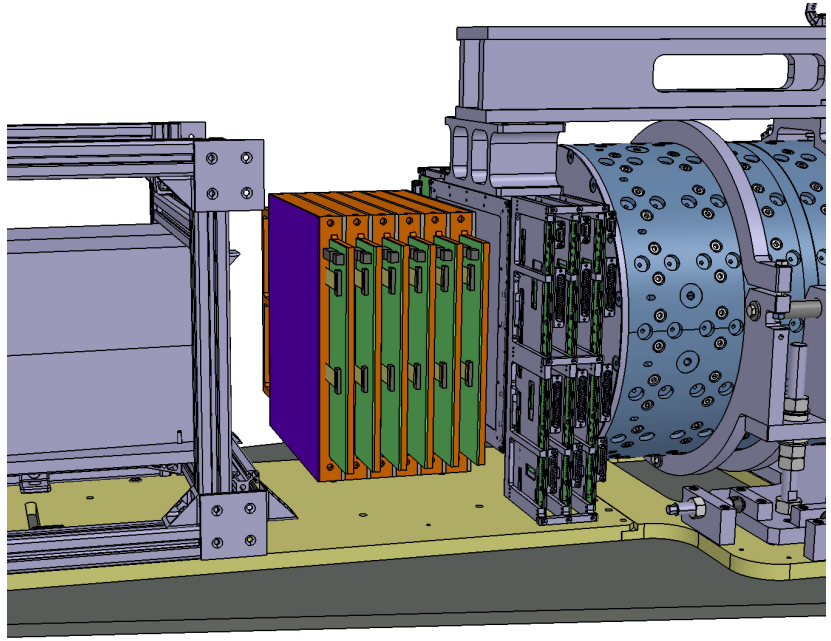
2-γ signature can't be resolved with present detector: upgrade

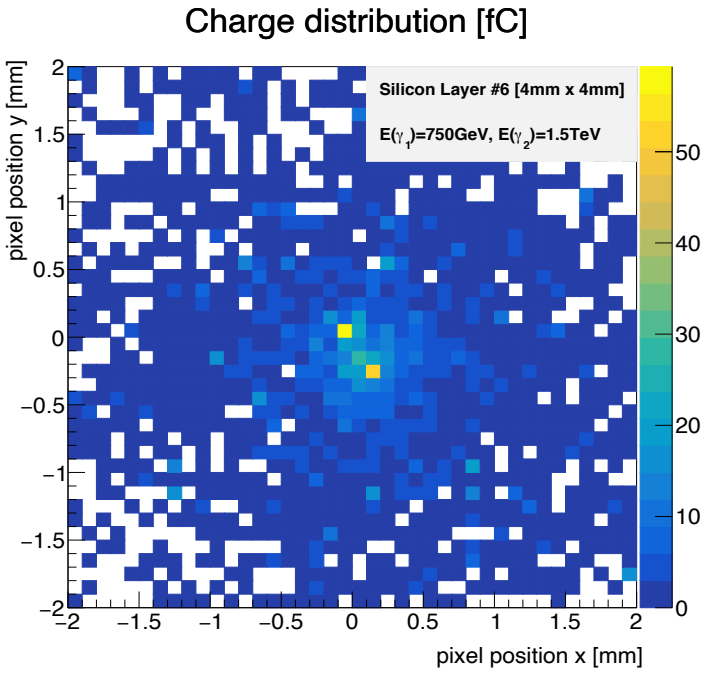


Upgrade to enable 2-γ physics



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



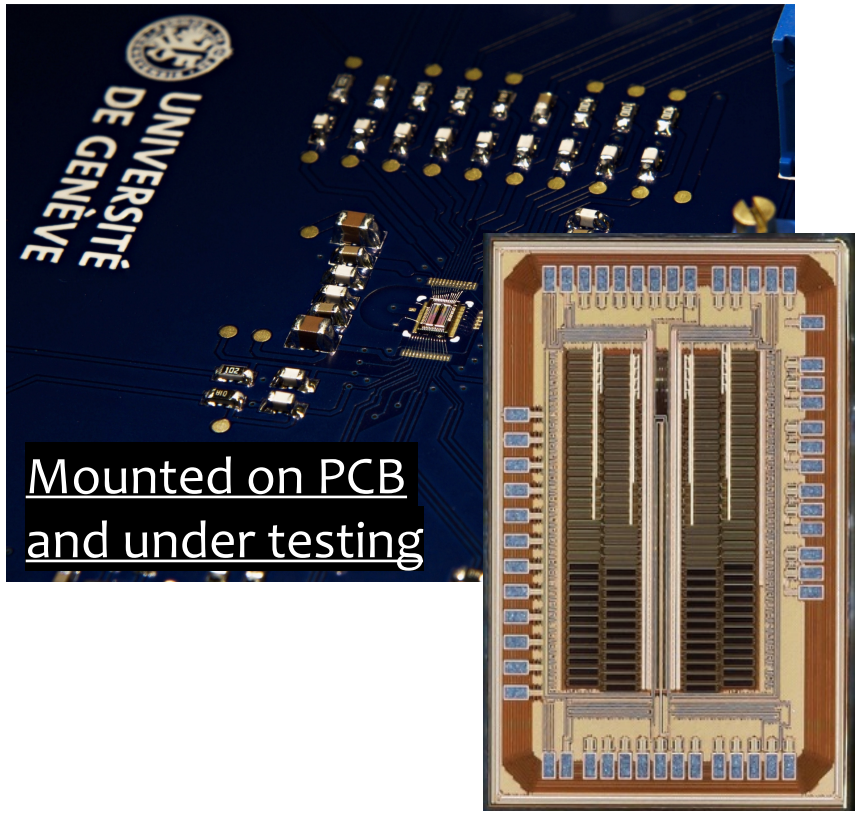


- Distance between two photons: 200 μm
- Distinguishable!

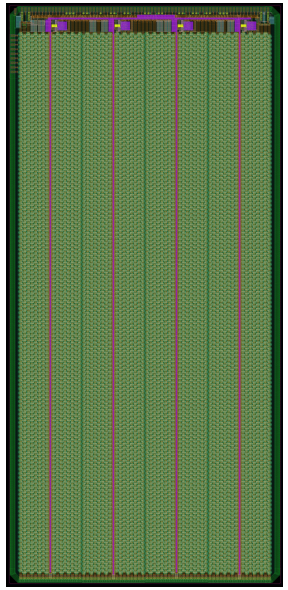
Detector to be used for 2024 data taking (60% of Run3 data)

From pixels to layers of modules

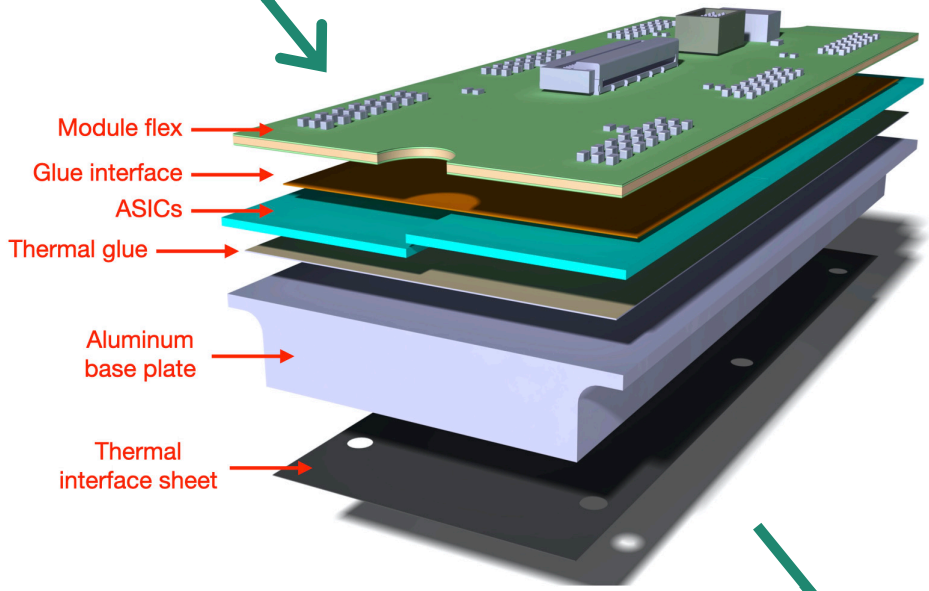
Prototype ASIC available end 2020



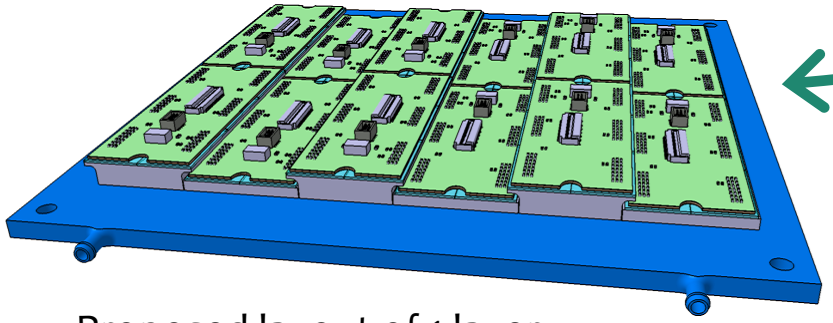
Pixel chips into sensor wafers



… into modules of pixels

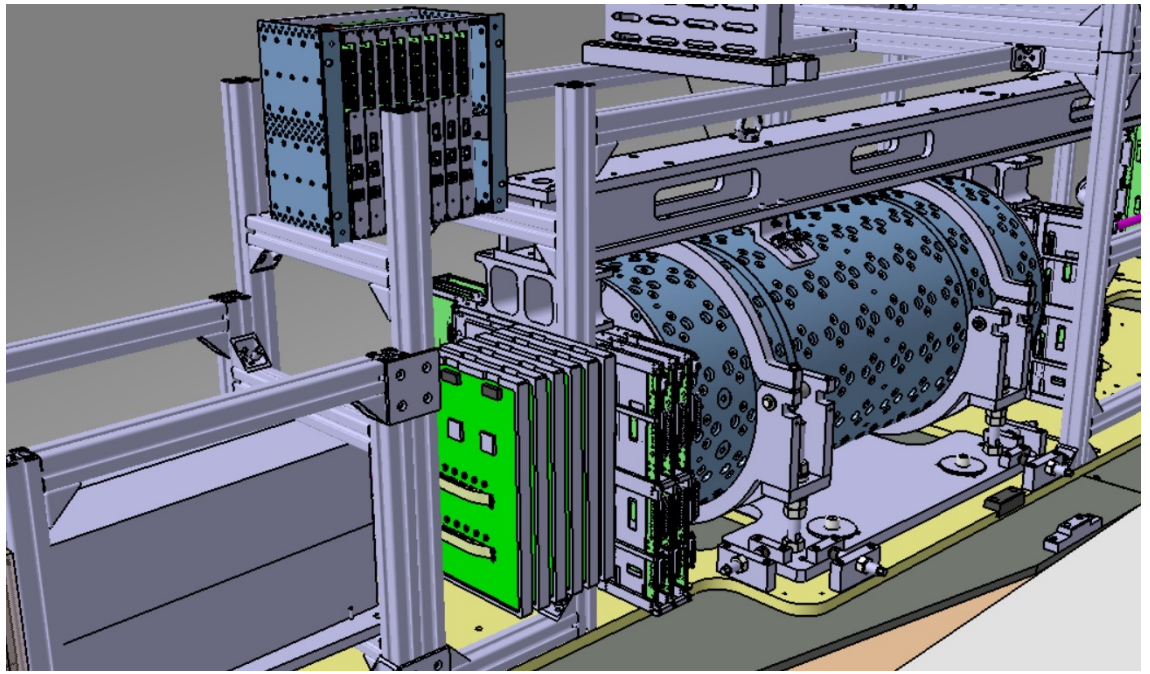


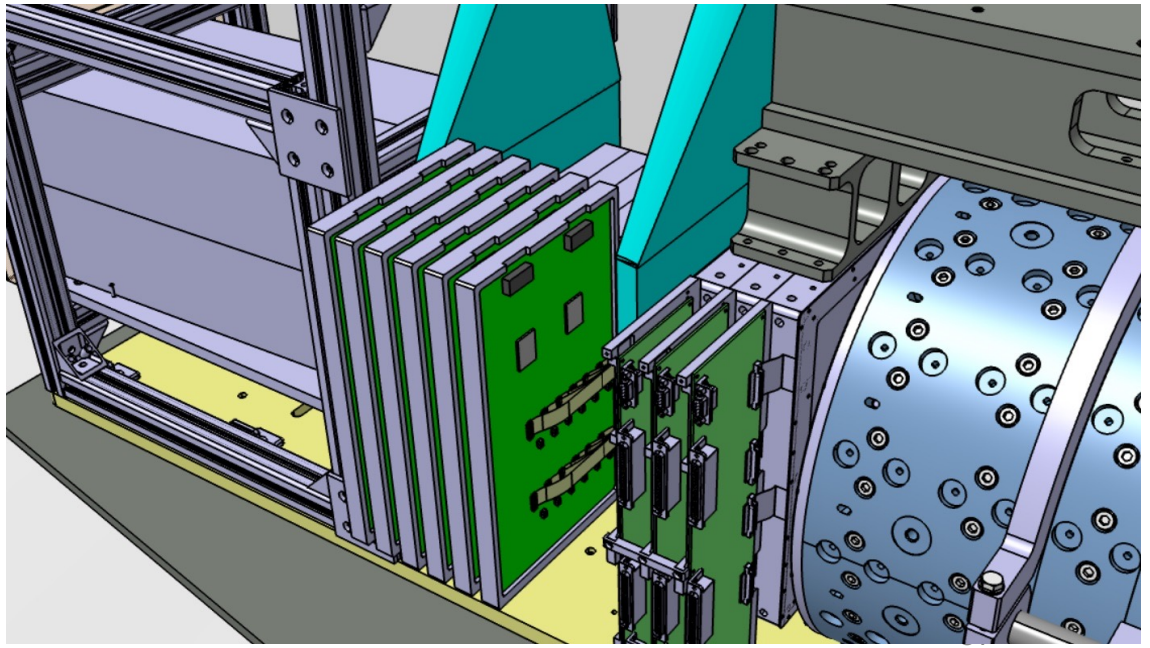
… into layers of modules



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

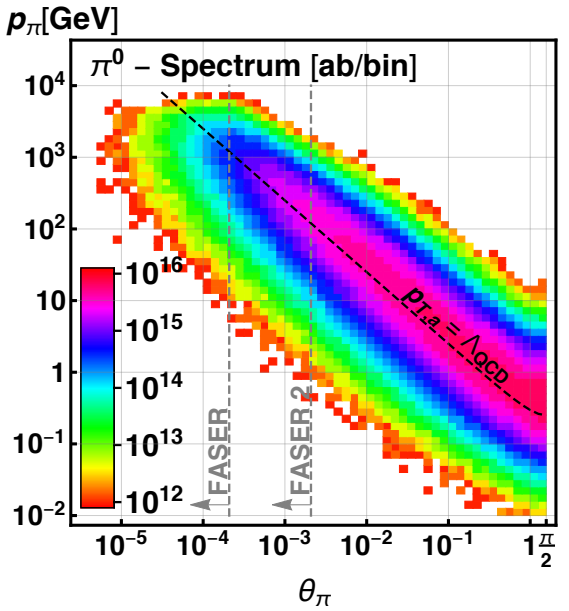
What’s beyond Run3?

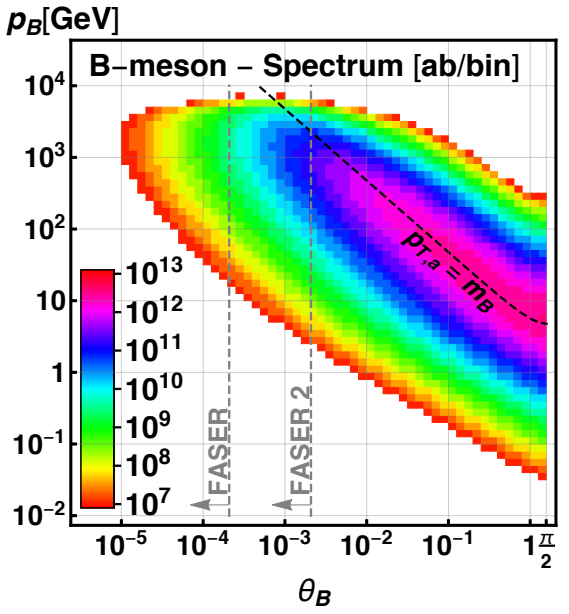
Beyond FASER?

FASER2

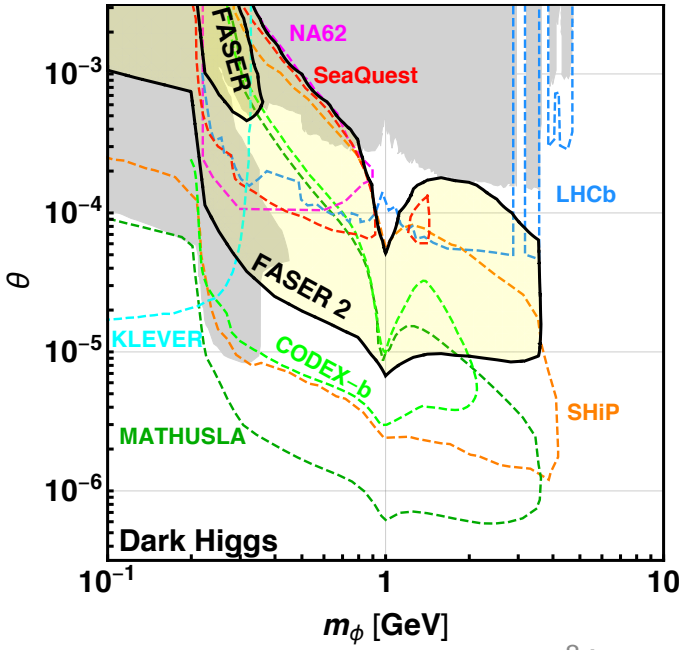
Benchmark model	FASER	FASER 2
Dark photons	✓	✓
$B-L$ gauge bosons	✓	✓
$L_i - L_j$ gauge bosons	...	...
Dark Higgs bosons	...	✓
Dark Higgs bosons with hSS	...	✓
HNLs with e	...	✓
HNLs with μ	...	✓
HNLs with τ	✓	✓
ALPs with photon	✓	✓
ALPs with fermion	...	✓
ALPs with gluon	✓	✓
Dark pseudoscalars	...	✓

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



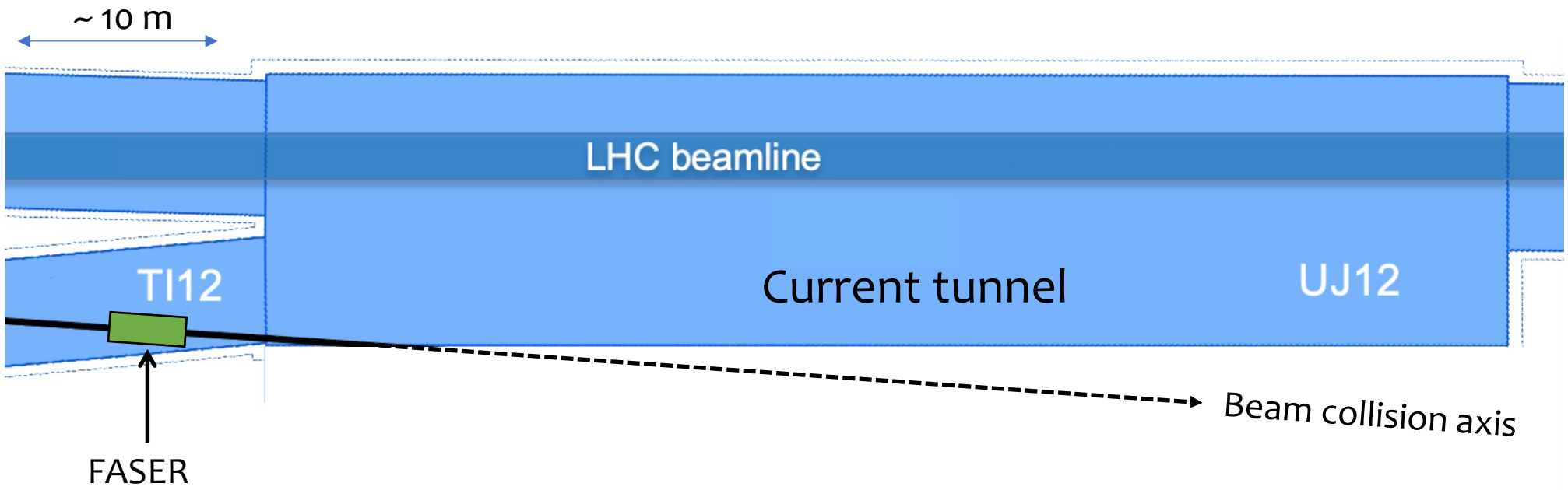


Increased detector radius to 1 m allows sensitivity to particles produced in heavy meson (B, D) decays increasing physics case beyond just increased luminosity



Beyond FASER?

A teaser for the proposed
Forward Physics Facility



More: [LoI for SNOWMASS-2021]
[FPF – Kickoff workshop]

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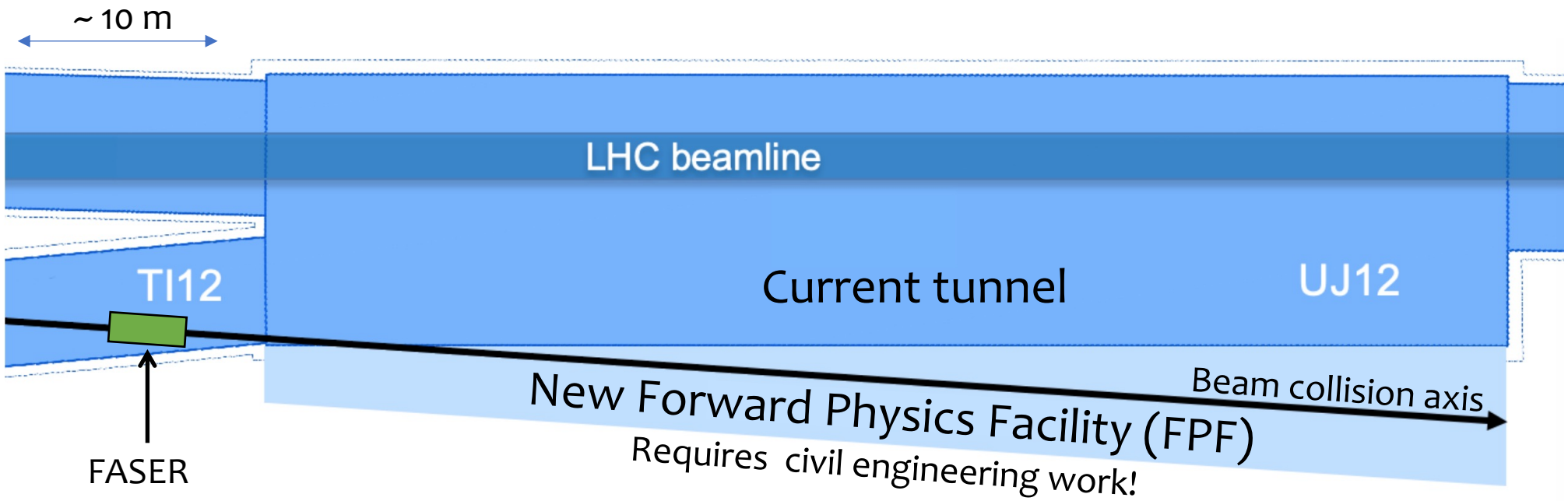

More: LoI for SNOWMASS-2021
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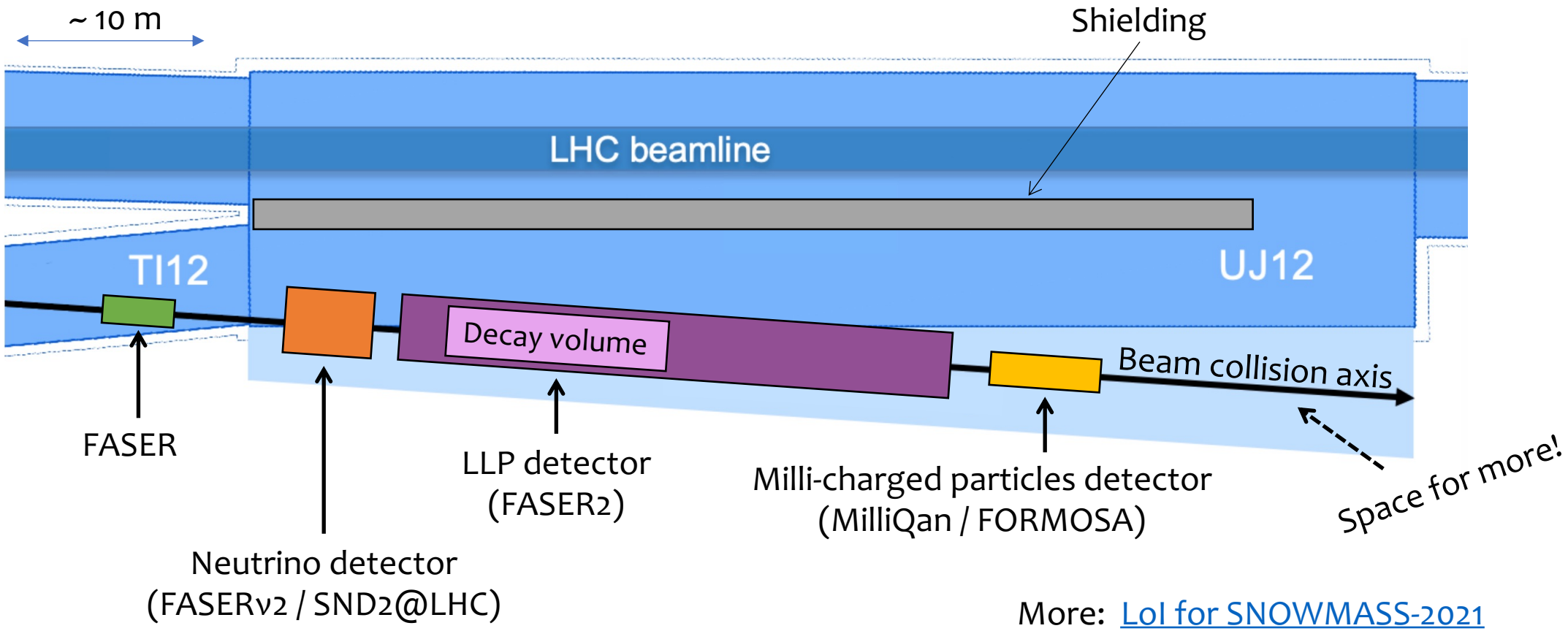
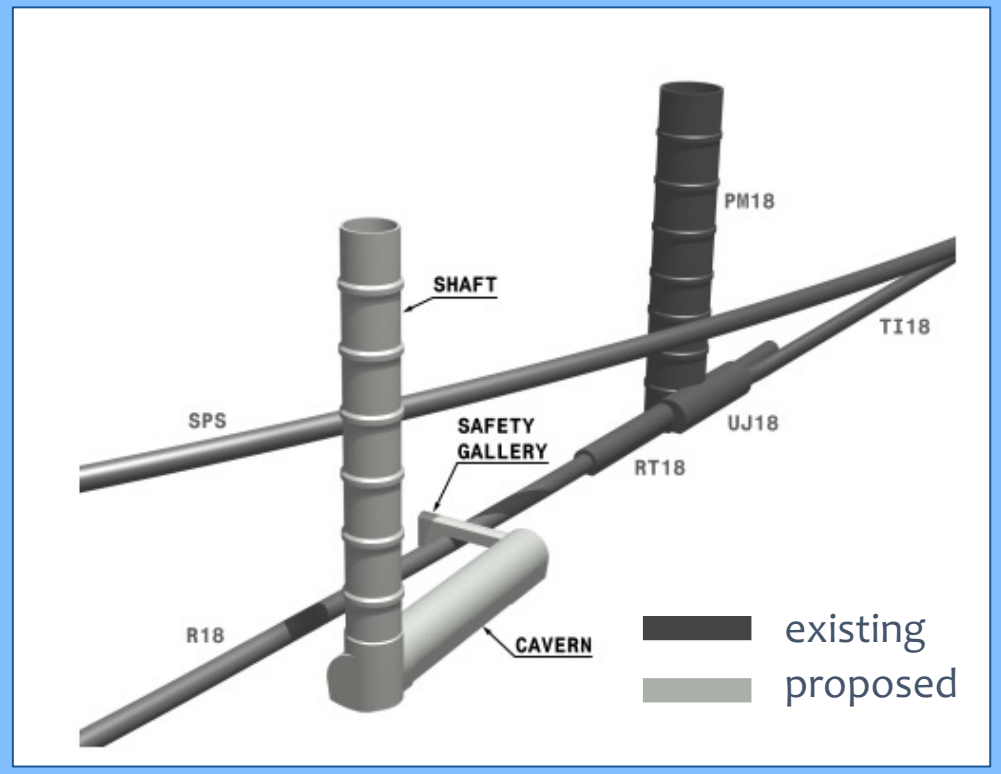
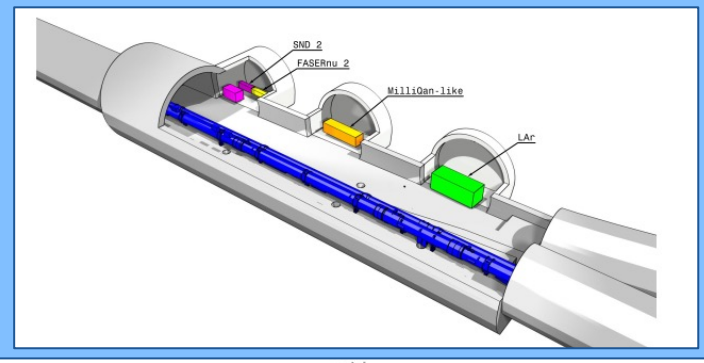
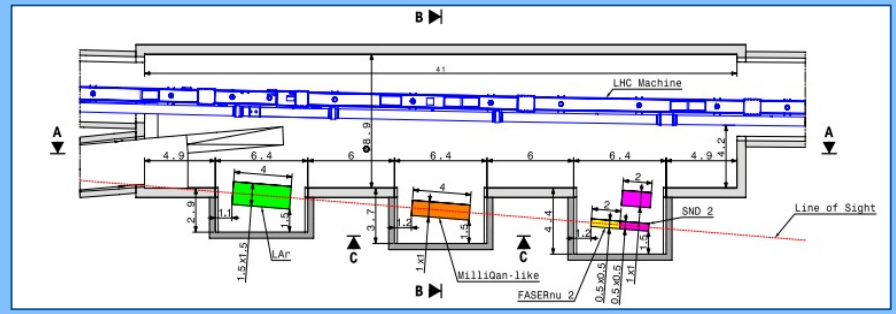


More: LoI for SNOWMASS-2021
FPF – Kickoff workshop

Possibilities for the Forward Physics Facility







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) are working 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

Thanks!

- 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

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

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