Taking physics forward with FASER

30 May 2023

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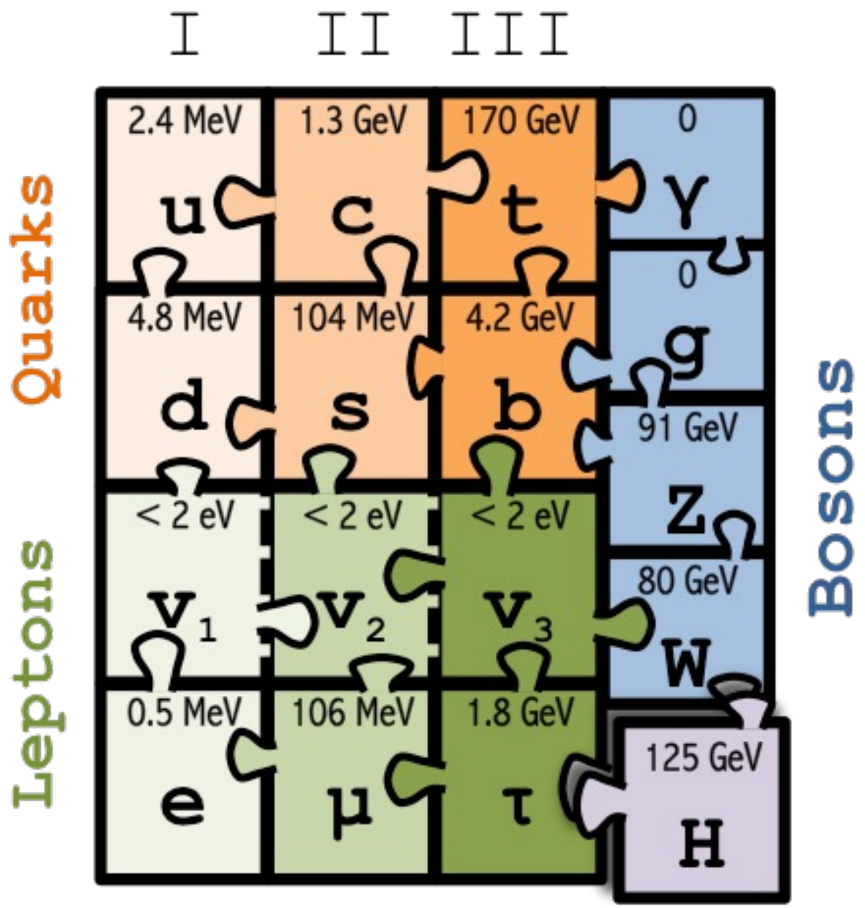
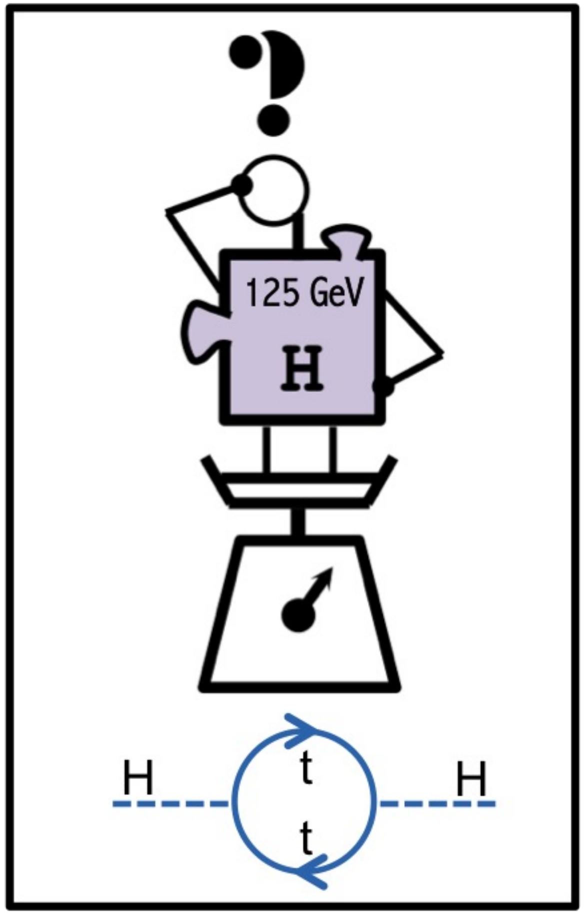
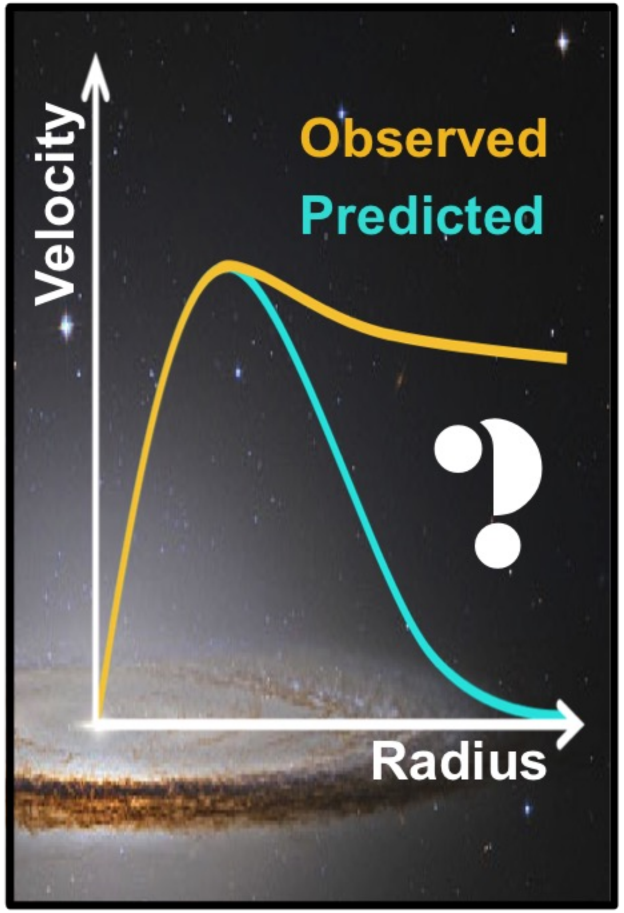
FACULTY OF SCIENCE

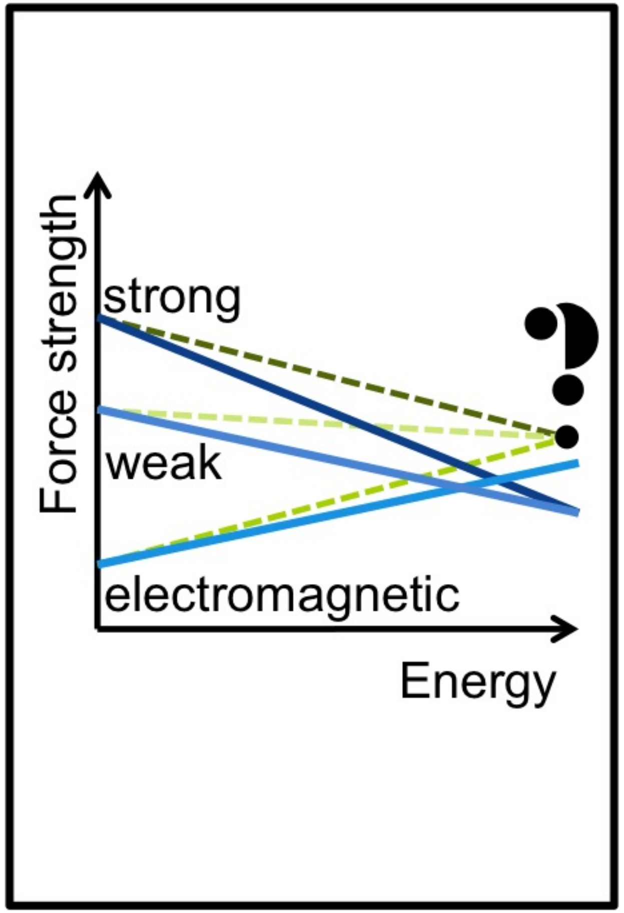
THE STANDARD MODEL



...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:

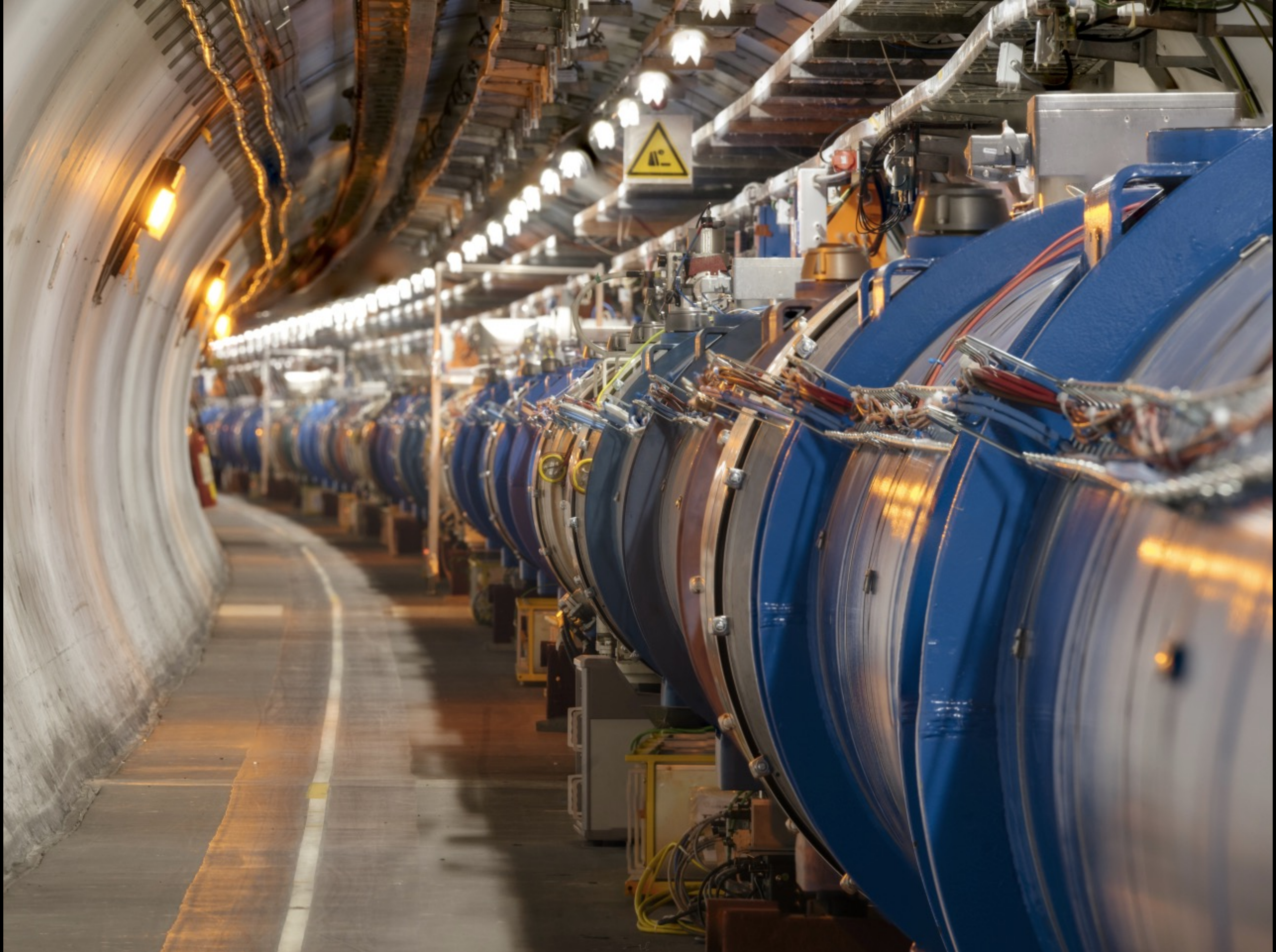
$$L_\theta = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

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

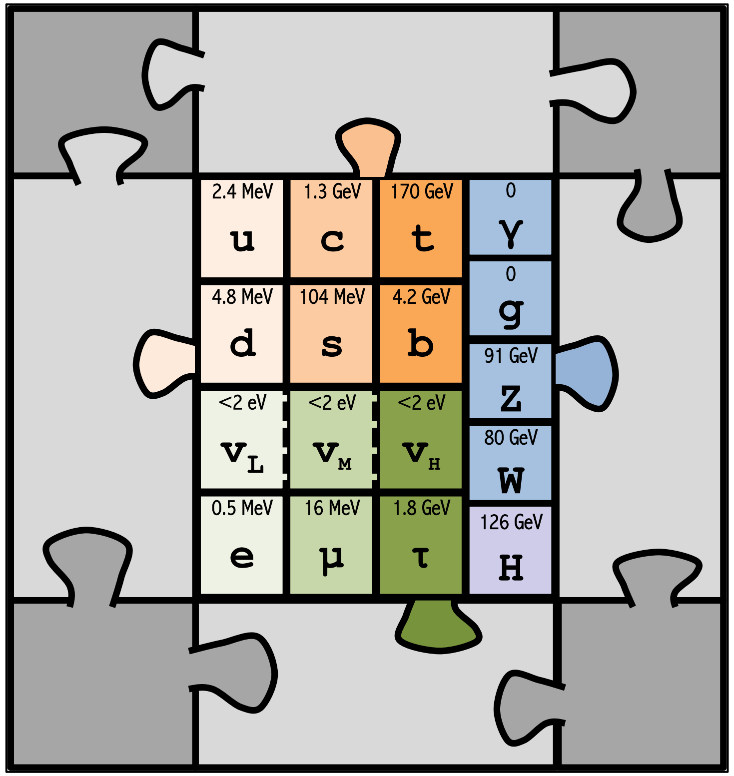
Most sensitive measurement on the neutron EDM to date achieved by the **PSI** experiment **nEDM**:

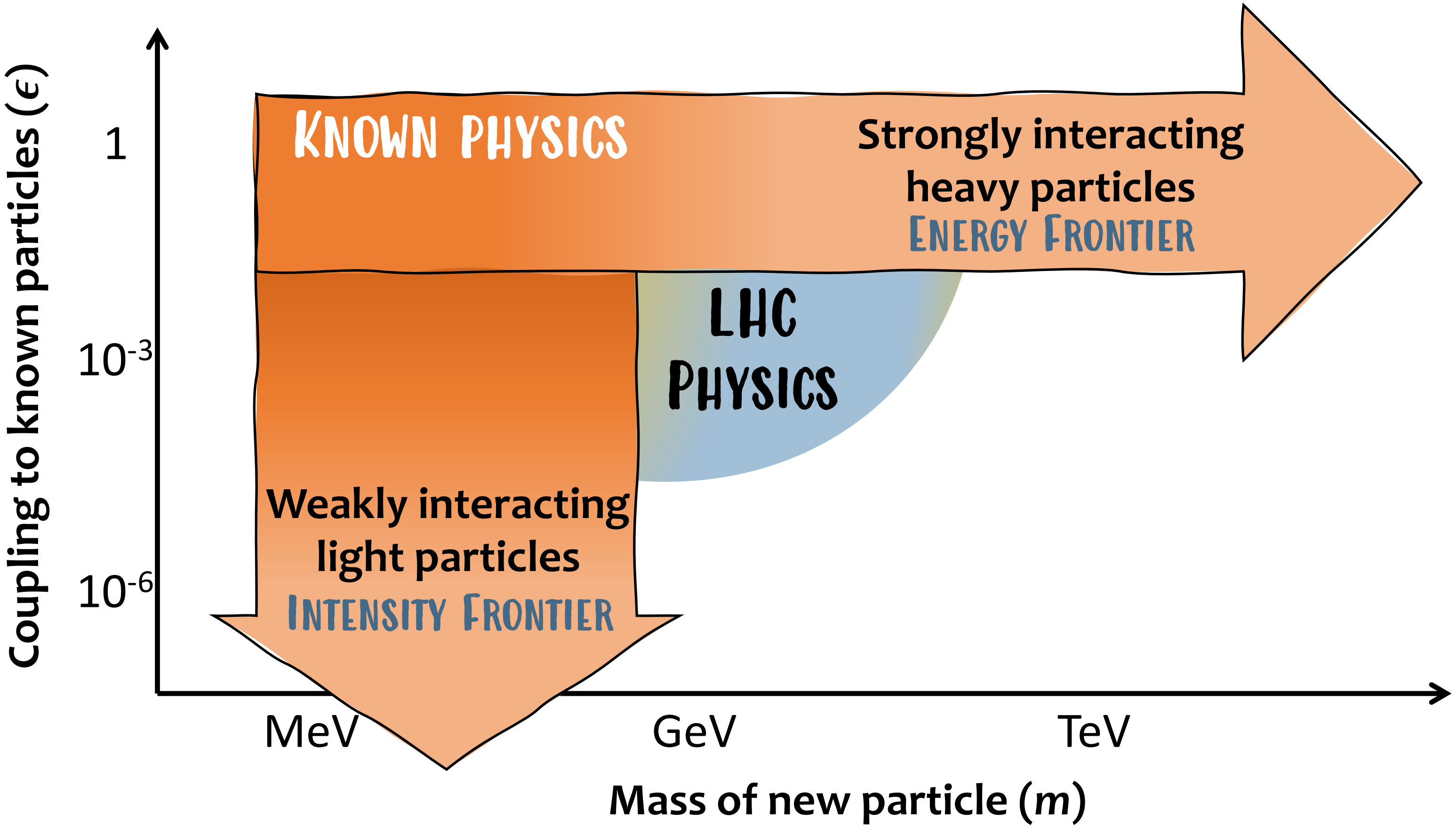
$d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{sys}) \times 10^{-26}$ e·cm.



The landscape of new particles @ colliders

- Collider physics: a plethora of measurements and searches
- The Standard Model is complete and confirmed; Burning questions still remain!





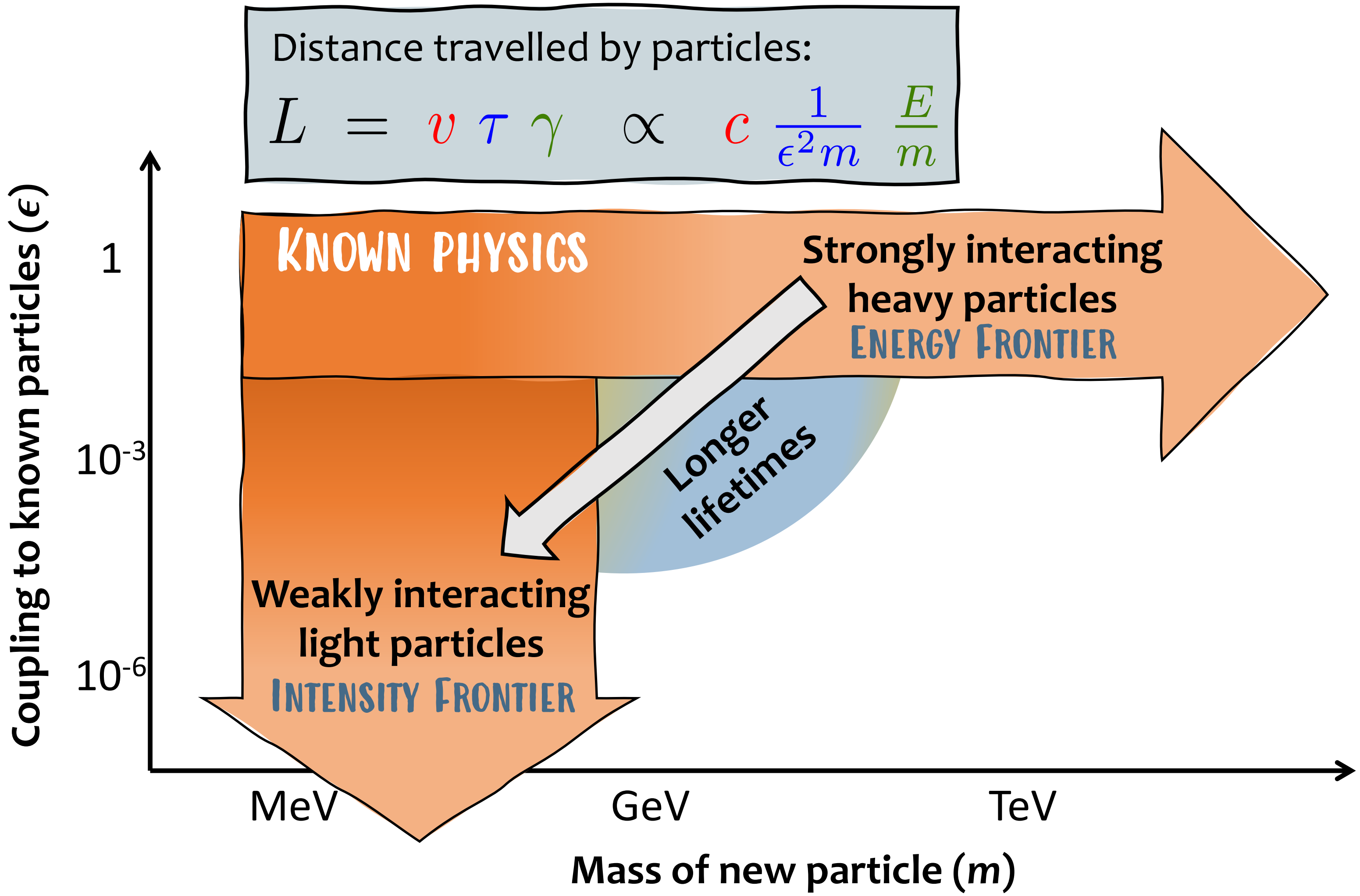
The landscape of new particles @ colliders

Lifetime

a characteristic of weakly interacting light particles

Distinct signatures

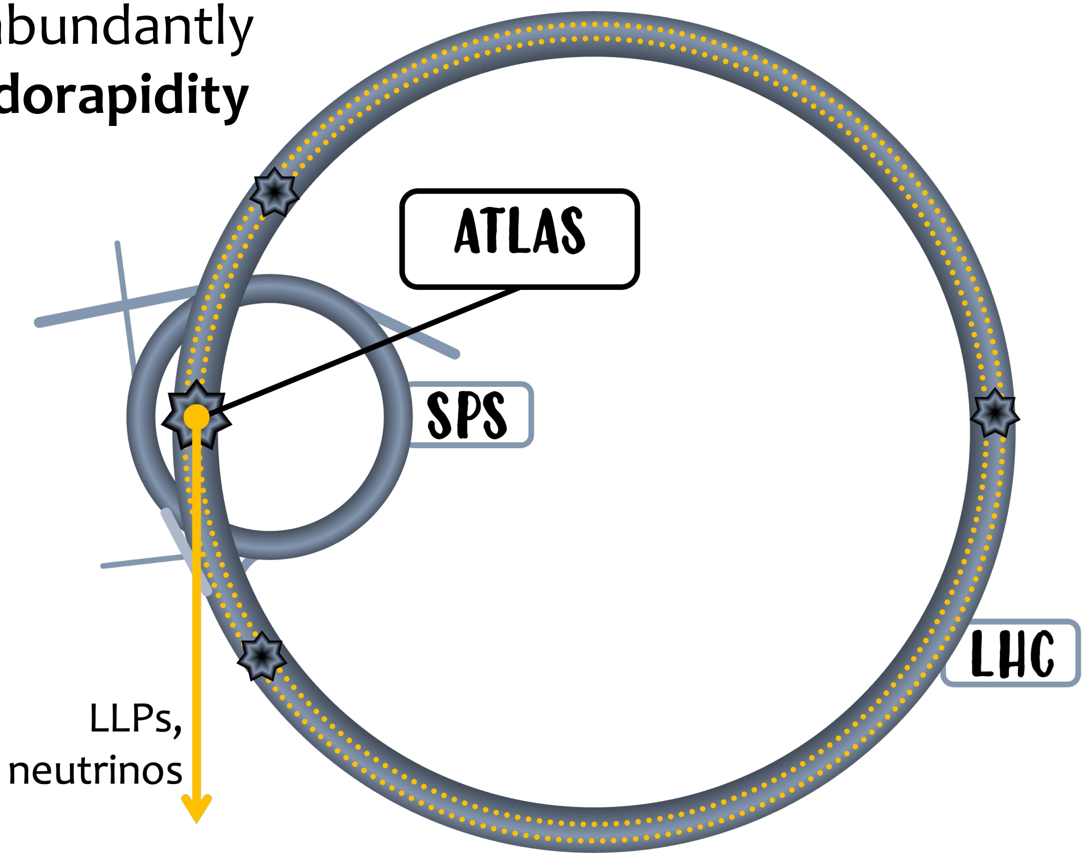
Opportunity for exploration!



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**



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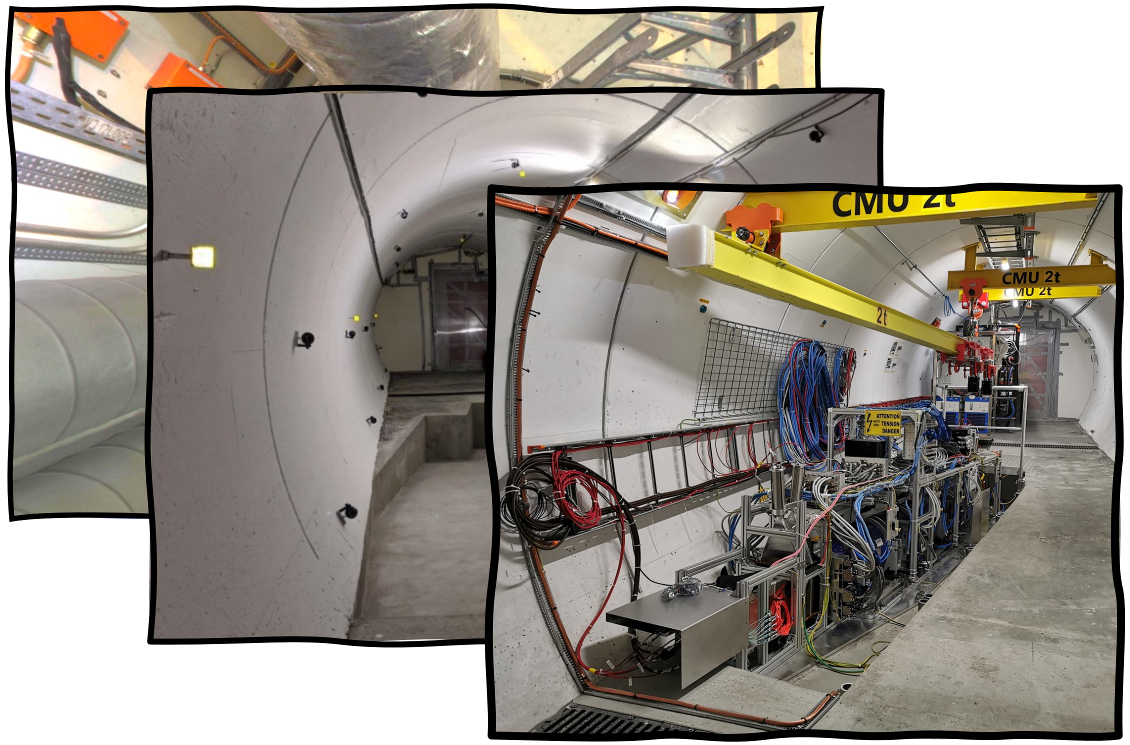

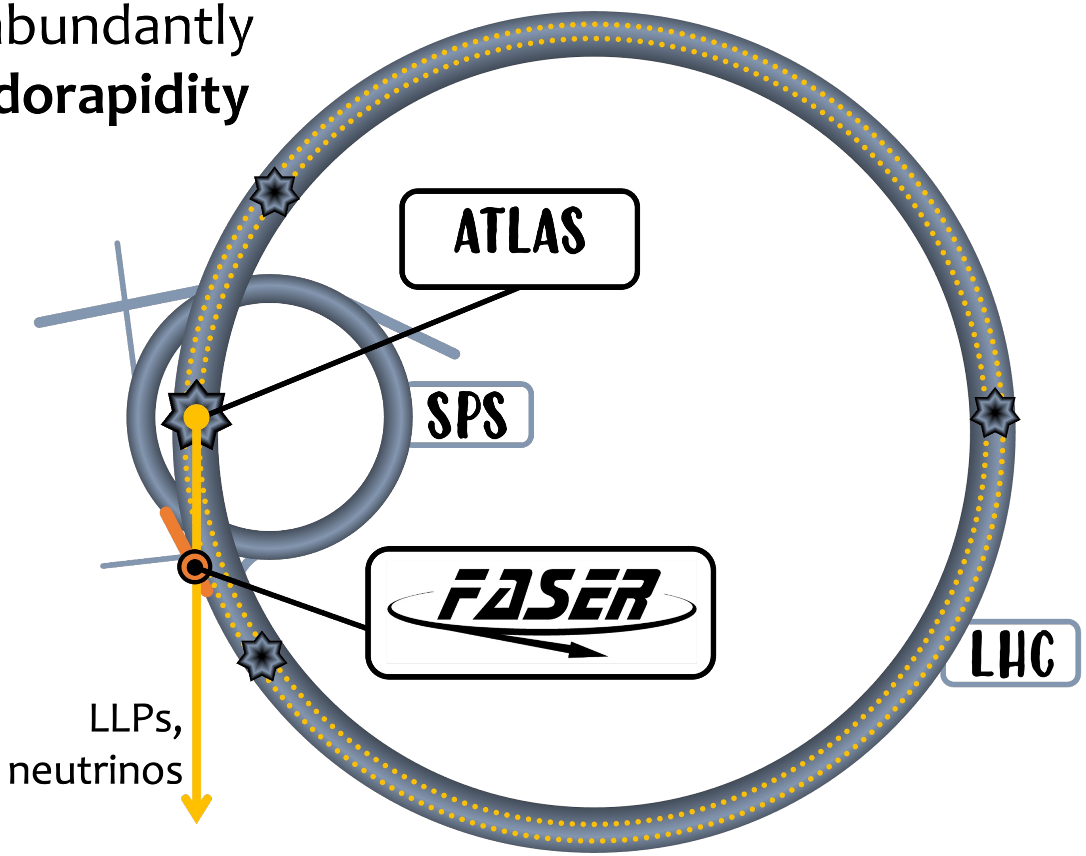

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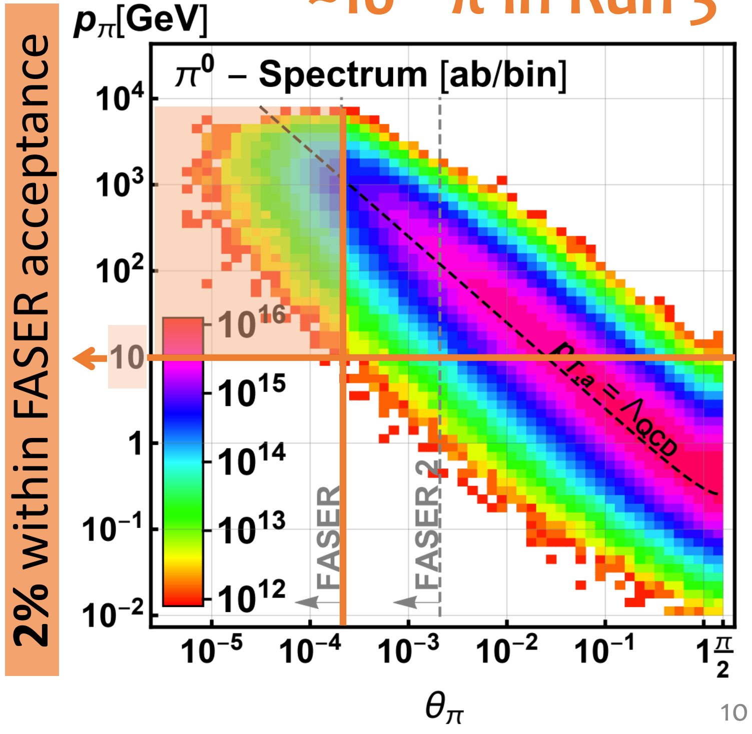
- **FASER acceptance:**
  20 cm diameter, 480 m from ATLAS IP
  (ONLY **10^{-6}% solid angle**)
  but still $O(10^{16})$ π in Run 3!

~10^{16} π in Run 3



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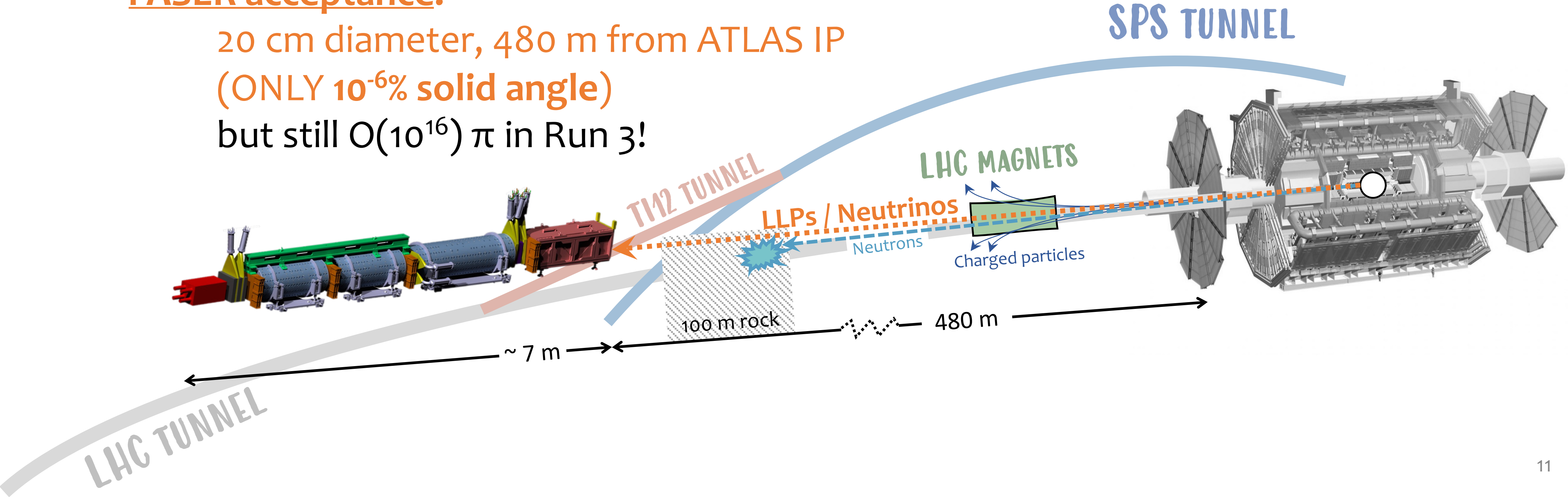
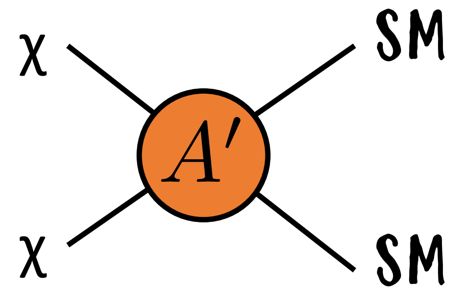
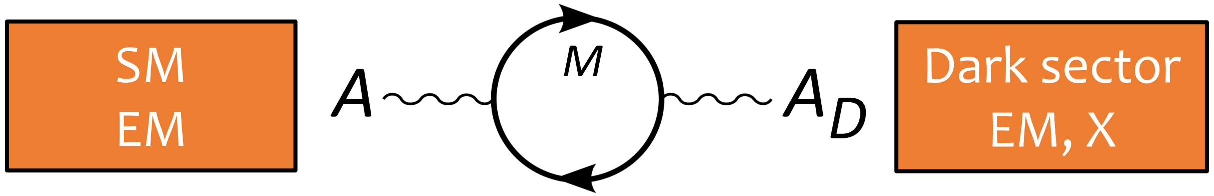
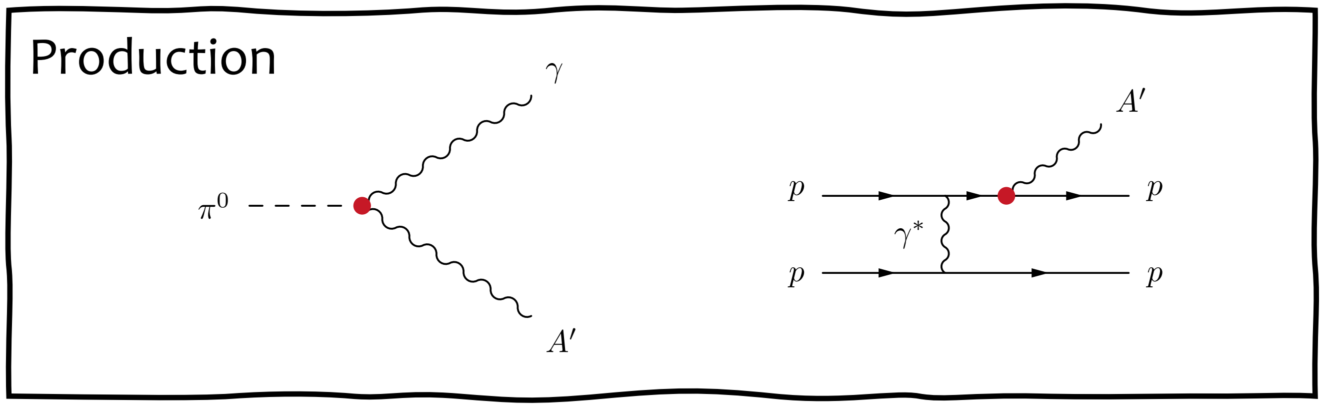


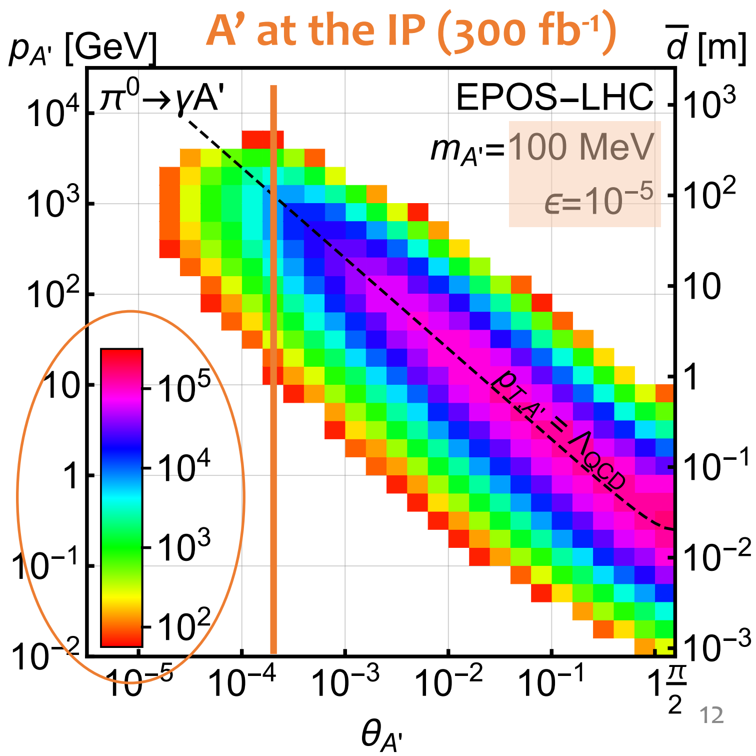
An example physics case: Dark Photon



- 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, ε ~ 10^{-5} and E~TeV, can travel long distance before decay





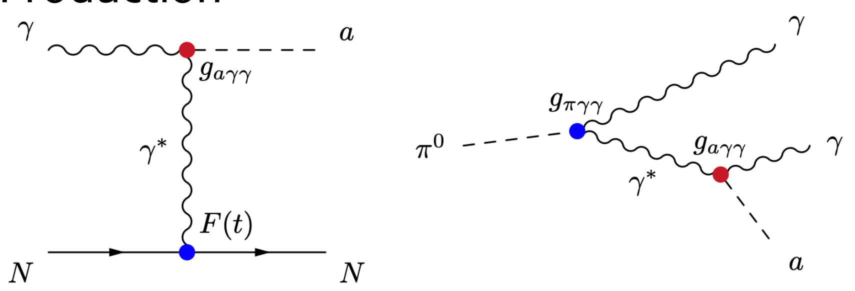


Another example: Axion-like particles (ALPs)

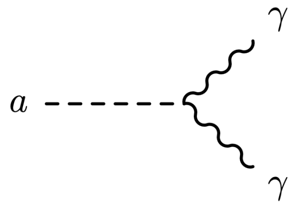
Qualitatively different: "High-energy photon beam dump experiment"

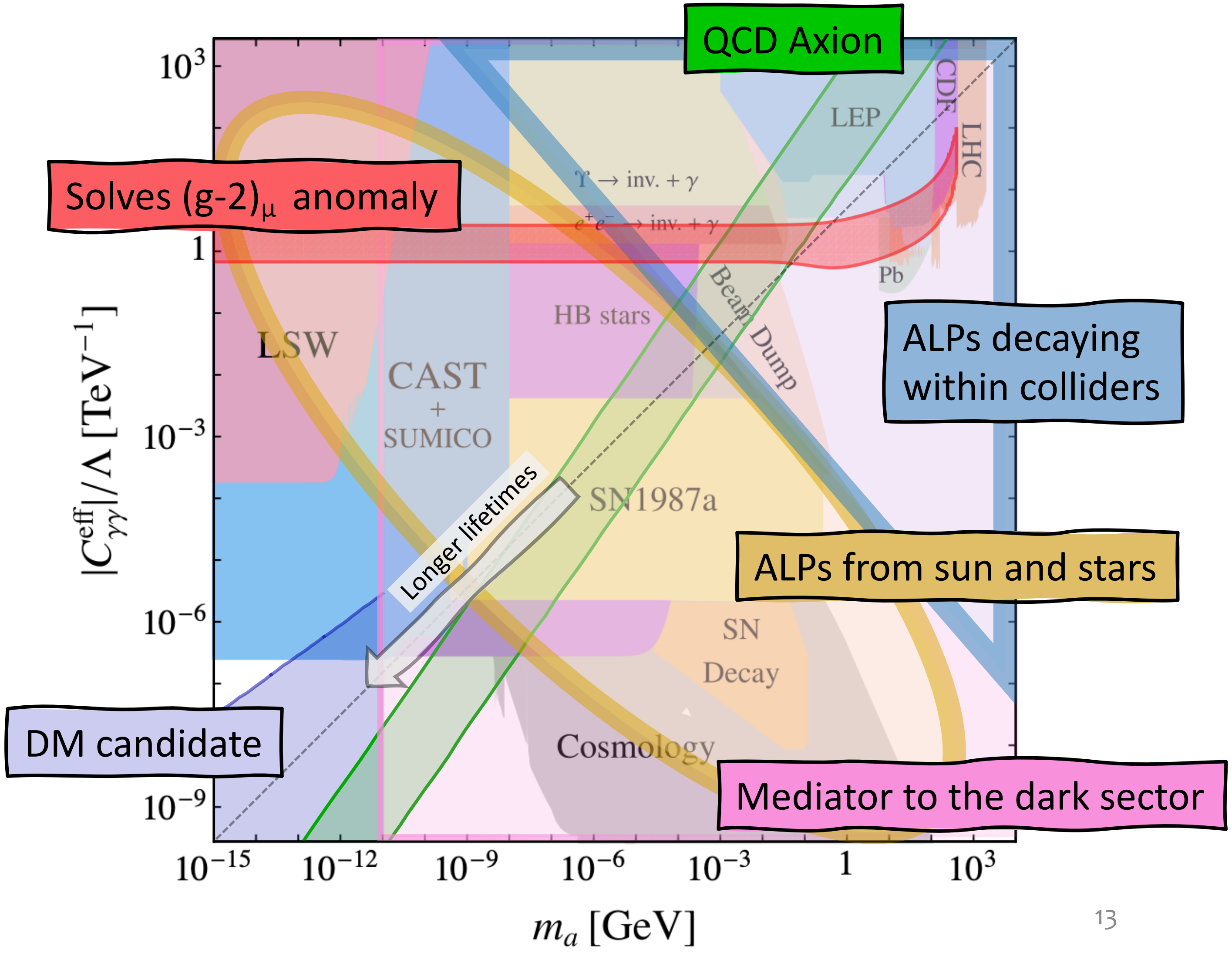
- Pseudoscalar SM-singlets; can appear in theories with broken global symmetries
- Low mass particles with suppressed couplings to SM

Production



Decay depends on mass





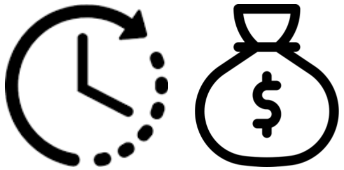
Thanks to Andrea Thamm for the figure!

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

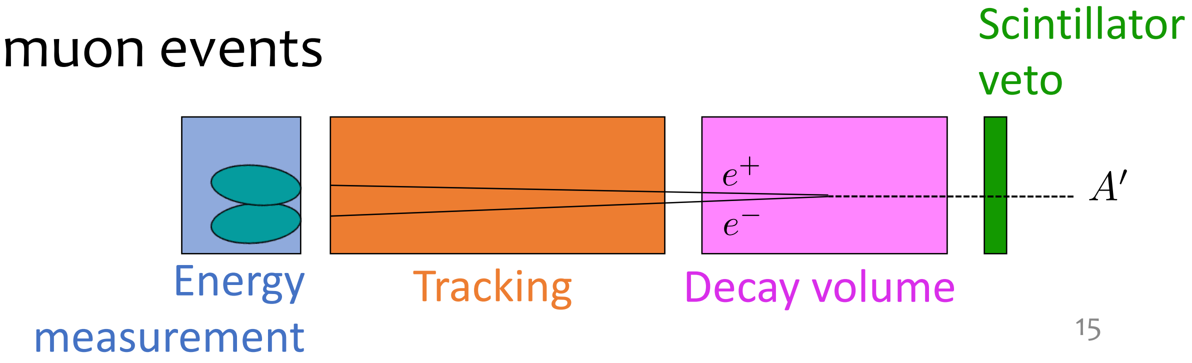
The FASER experiment

Detector concept

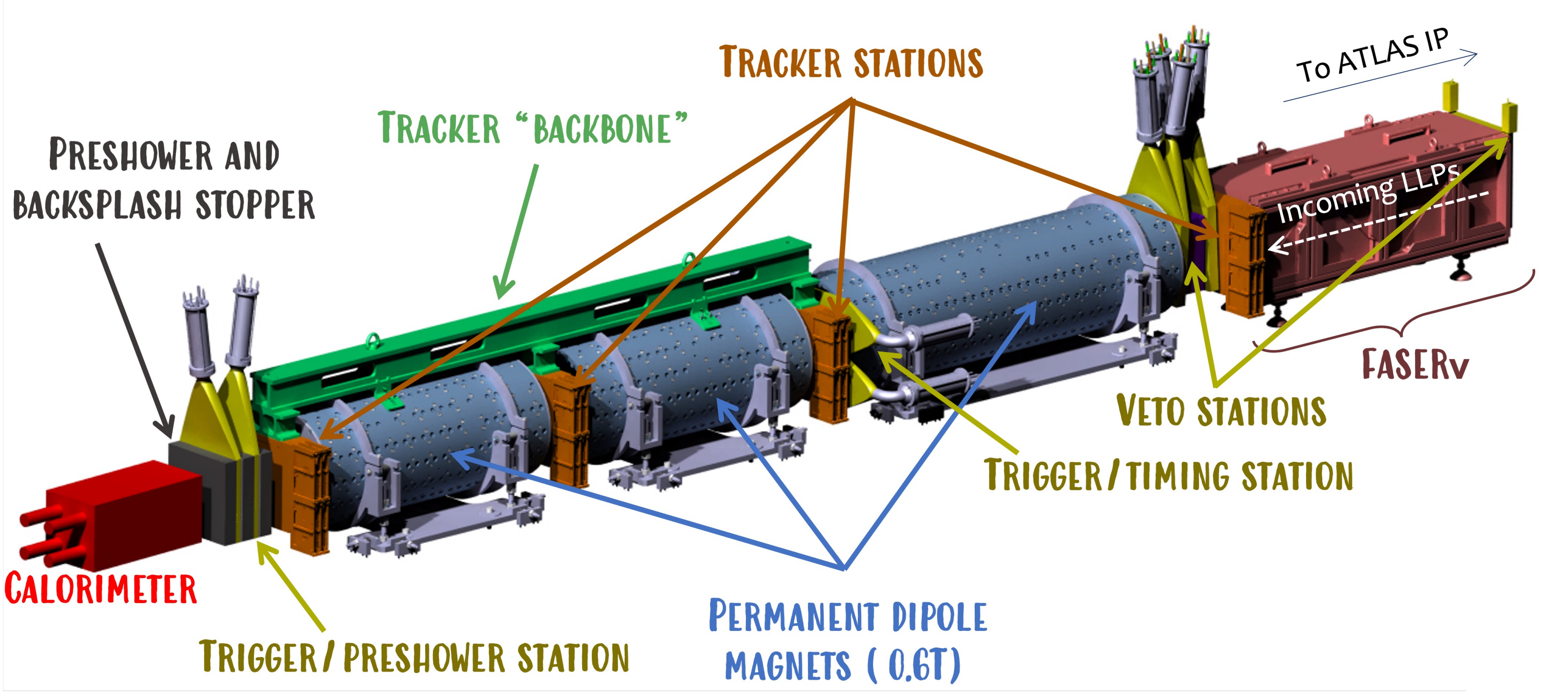
- **Drivers for choices:** Tight timeline between experiment approval and installation & the limited budget.
  - Detector that can be constructed and installed ***quickly & cheaply***
  - Have tried to re-use existing detector components where possible
  - Aimed for a simple, robust detector (access 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
Length of decay volume: 1.5 m

arXiv:2207.11427

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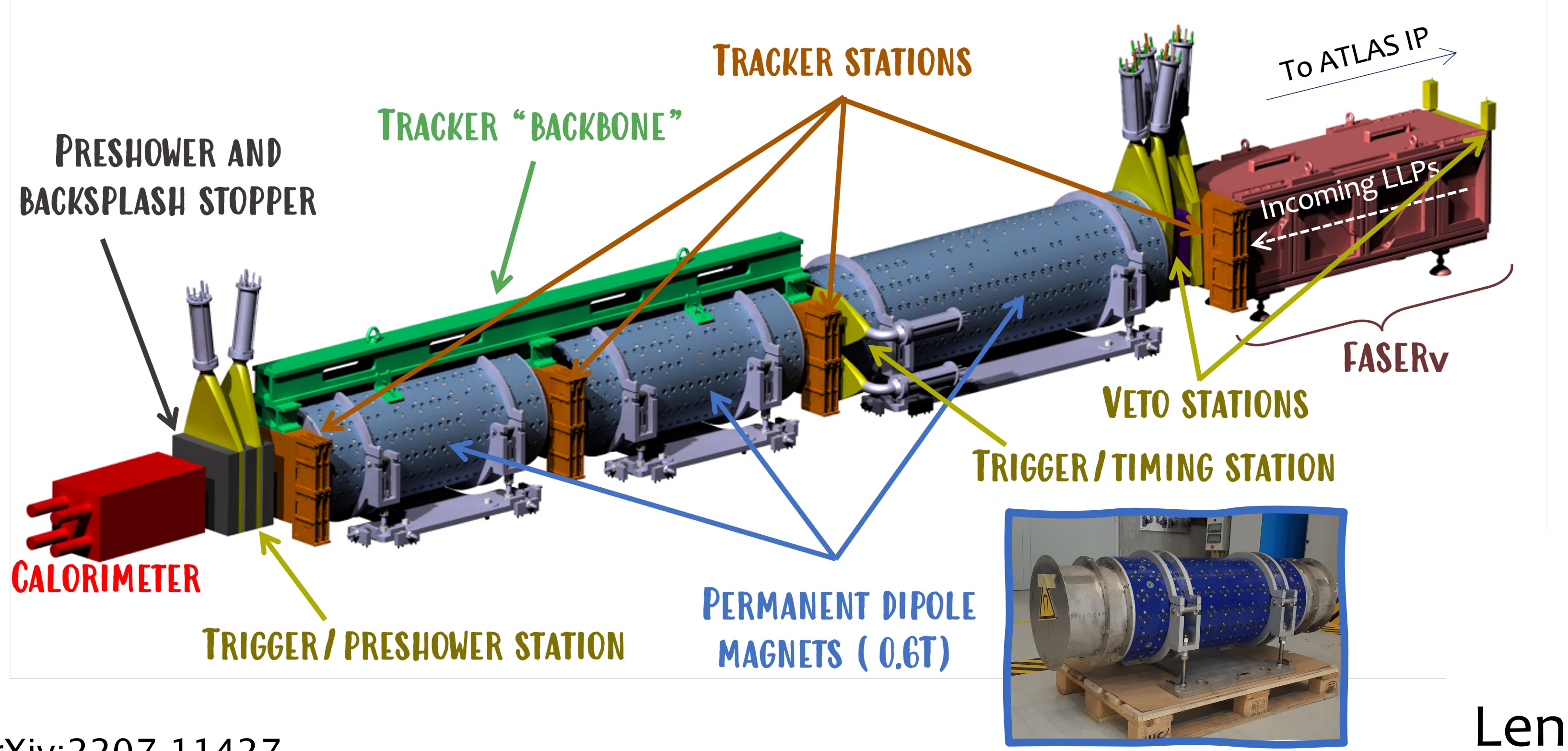

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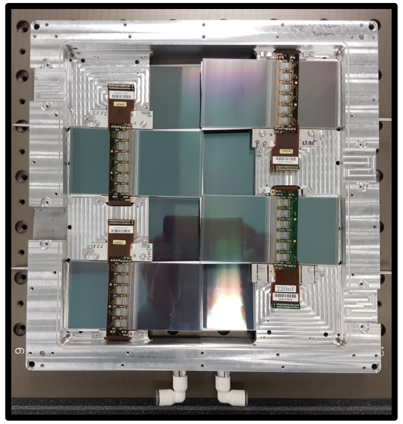
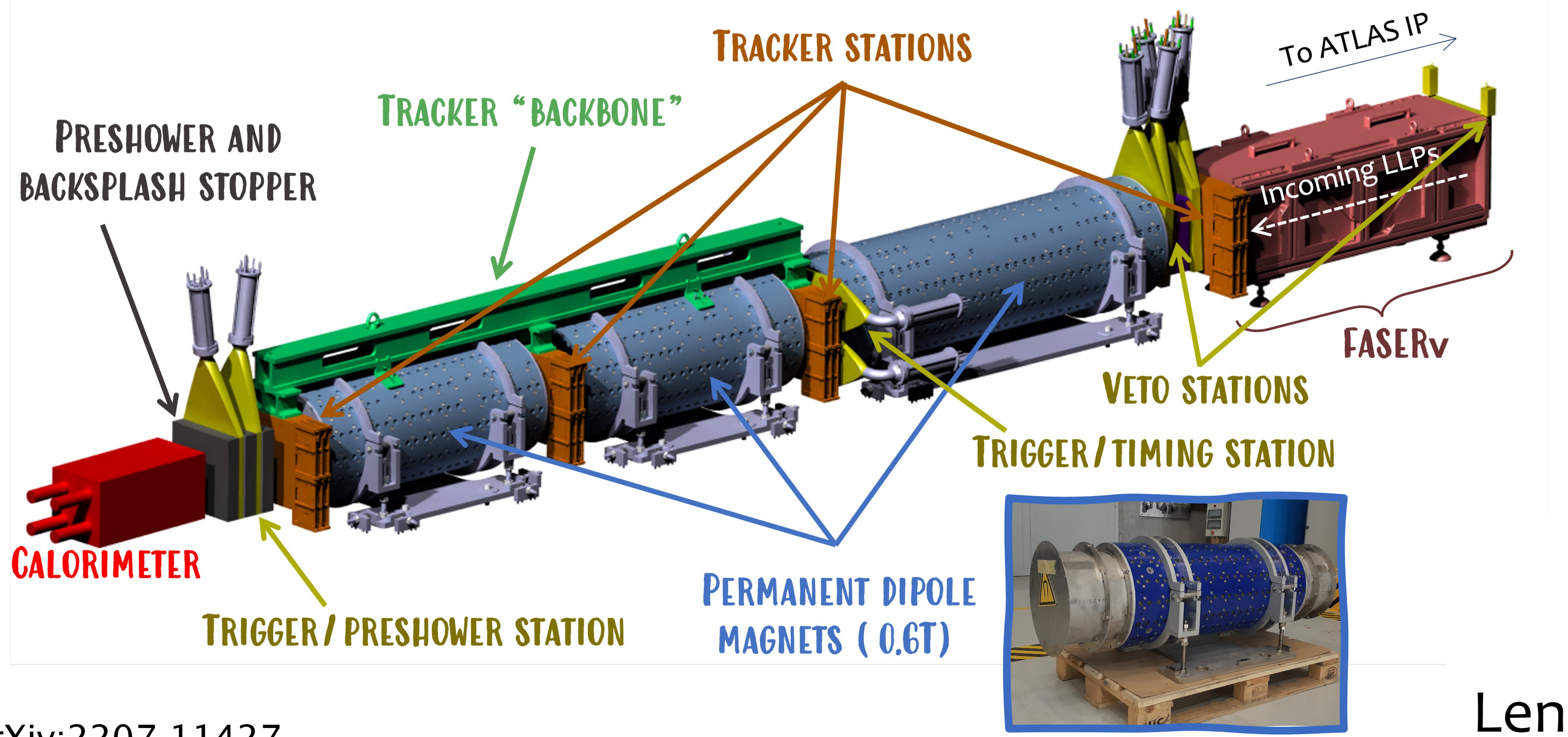


A tracker layer made of ATLAS SCT modules



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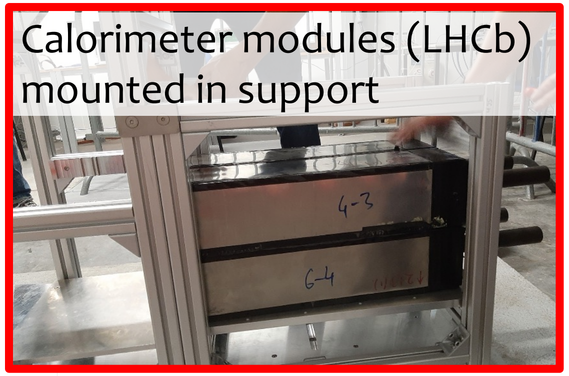
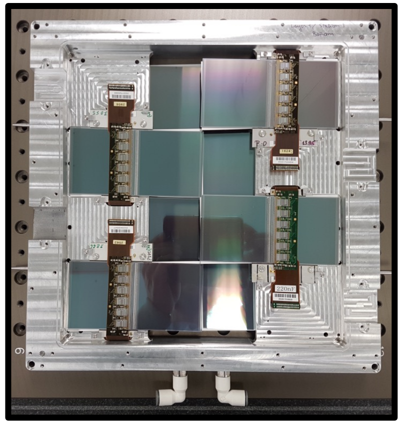


Calorimeter modules (LHCb) mounted in support



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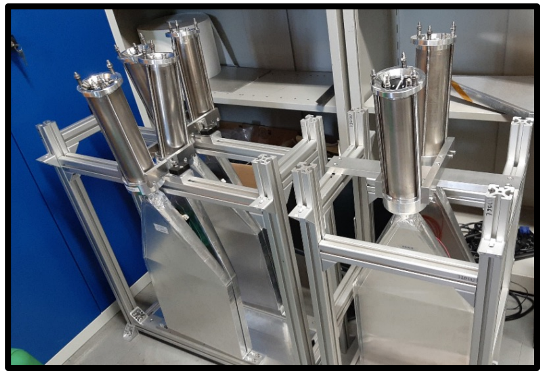
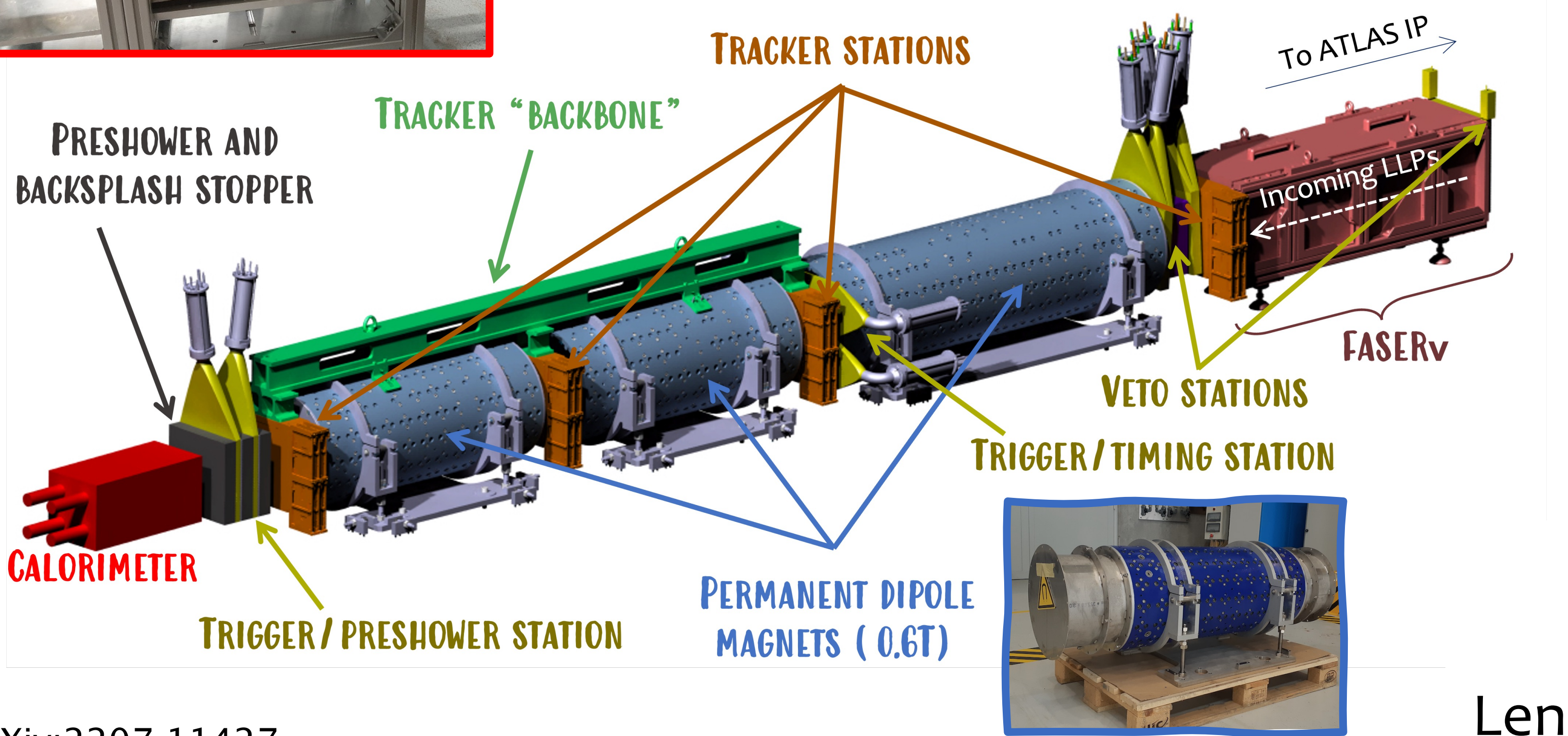


Two stations to veto O(10^9) muons
A timing station, resolution < 1 ns
A preshower station



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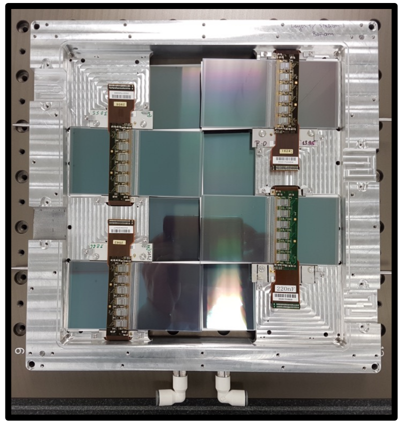
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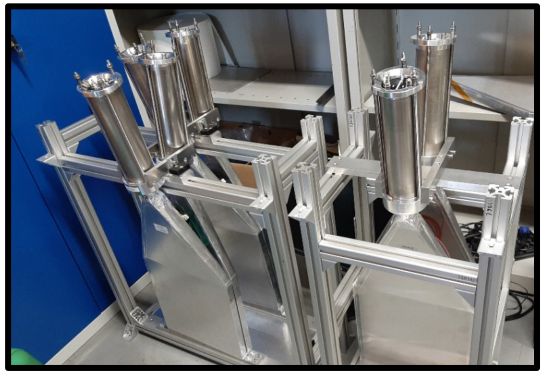
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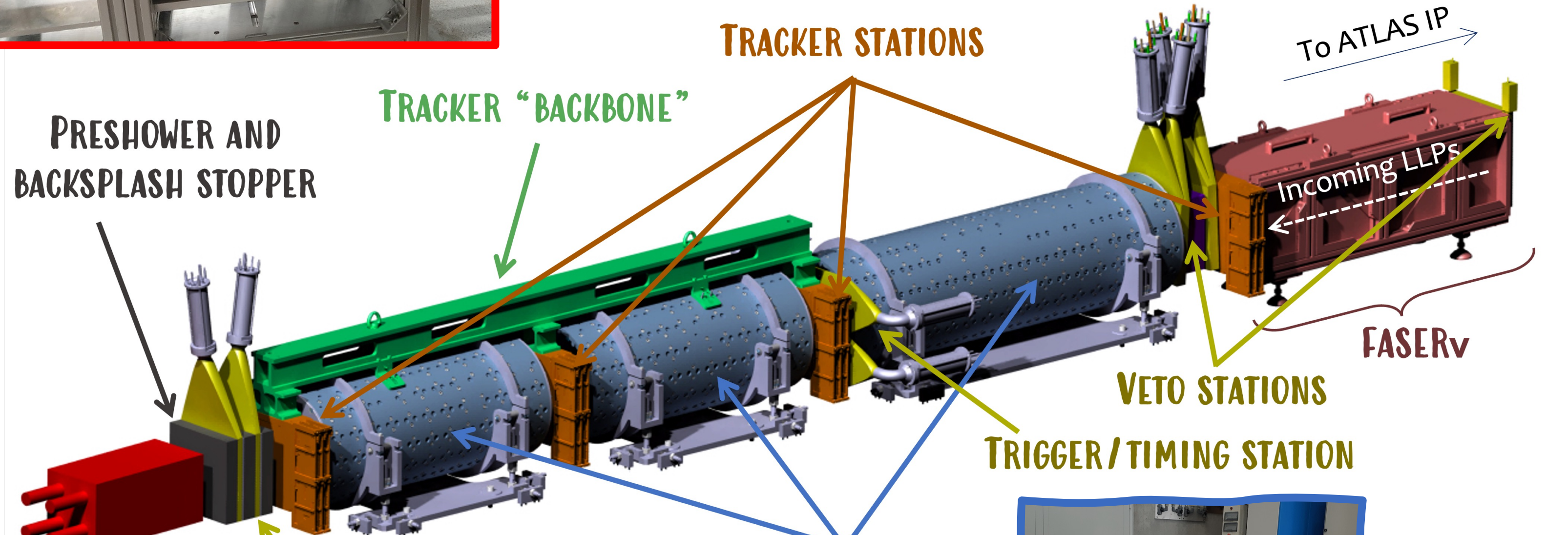

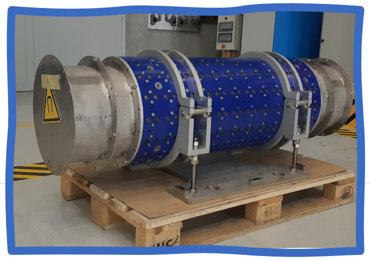


Triggers from scintillators and calorimeter
Expected trigger rate < 1 kHz, dominated by muons from the IP

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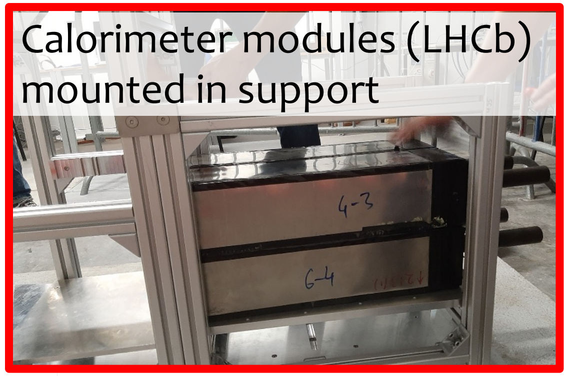
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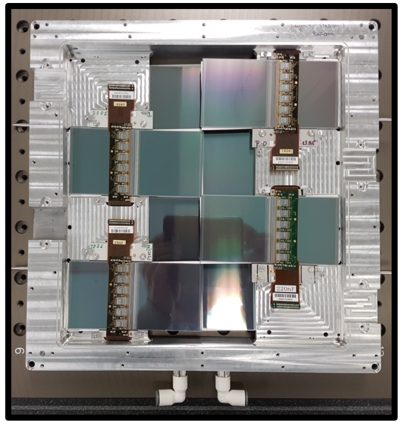
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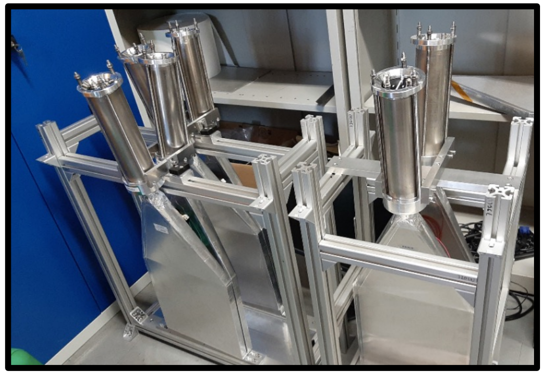
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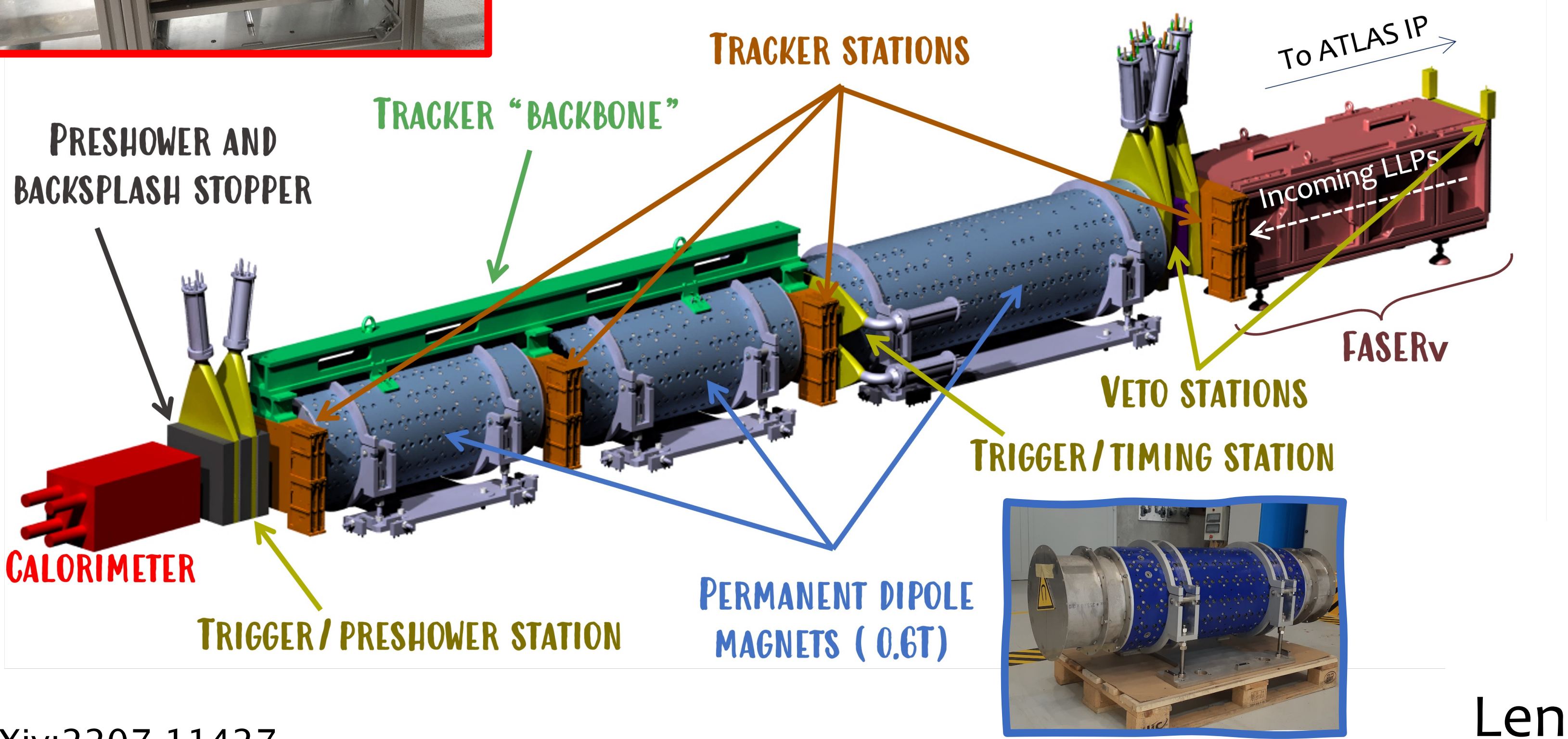


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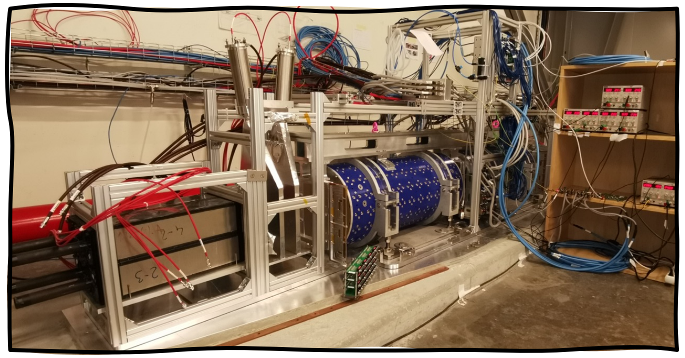
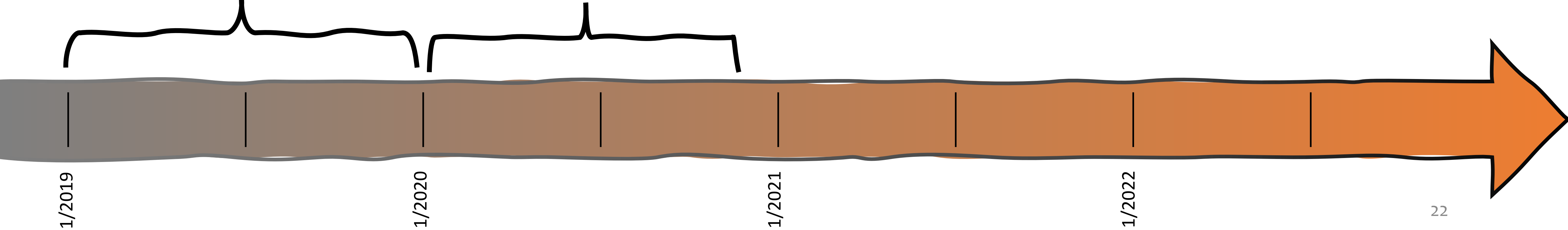
Commissioning

Timeline

Dedicated labs at CERN and UniGe for individual component testing



Dedicated area at CERN's Prevessin site ("EHN1") for full-detector commissioning



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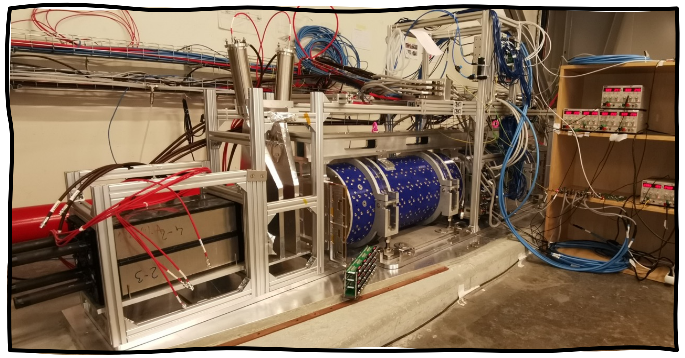

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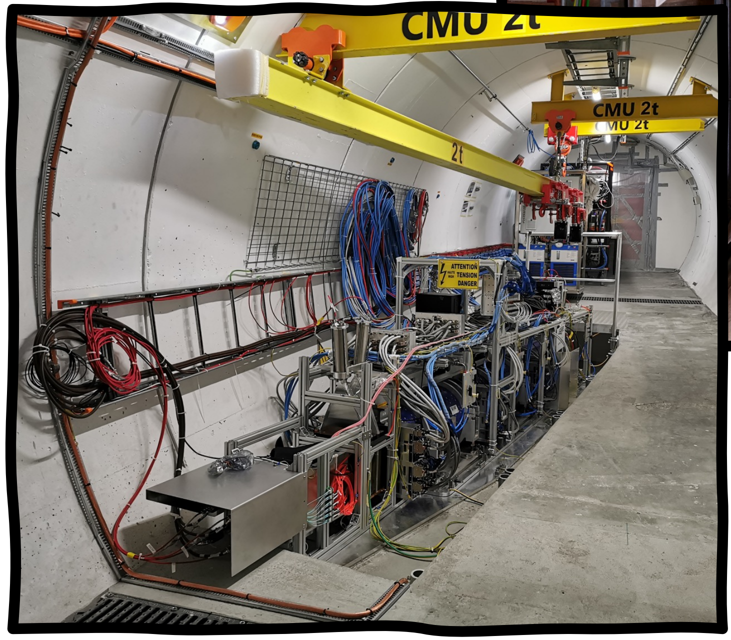
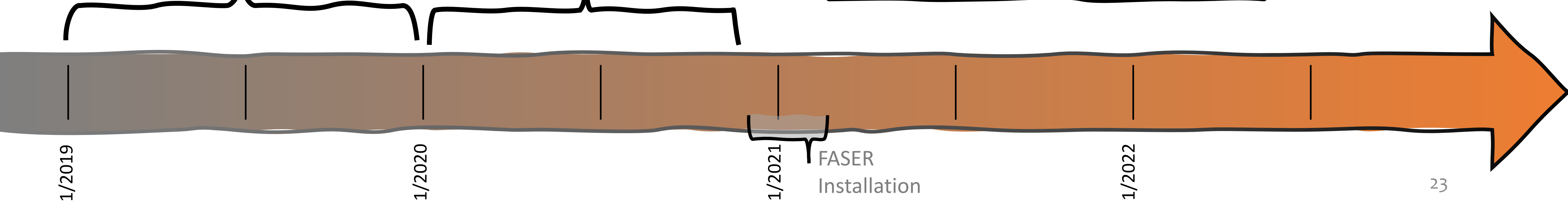
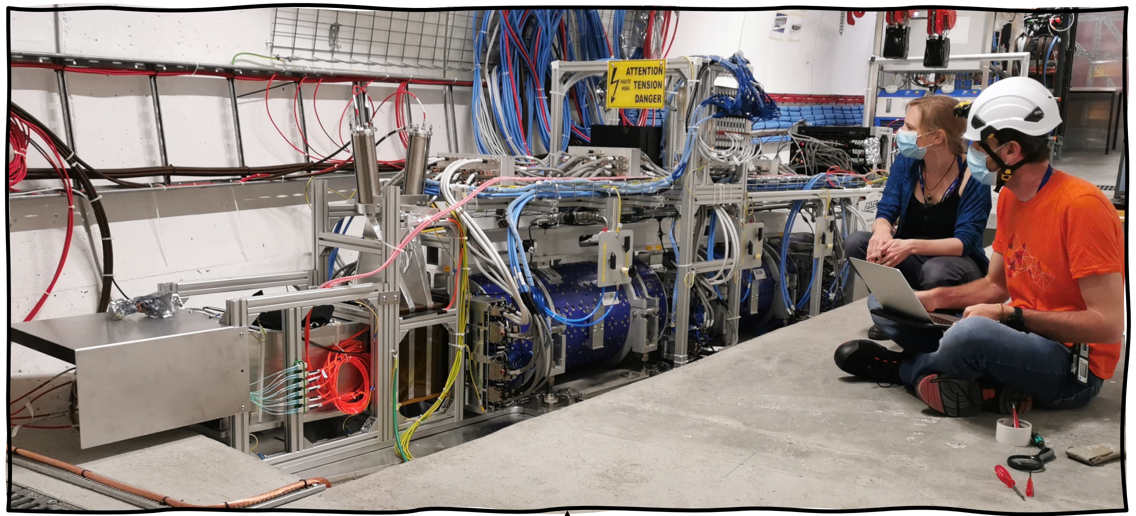





CMU 2t
CMU 2t
ATTENTION
TENSION
DANGER
FASER
FASER

Commissioning

Timeline



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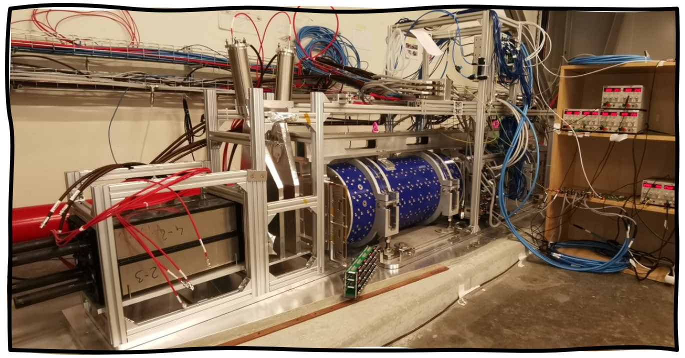

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Extensive in-situ commissioning

1/2019

1/2020

1/2021

FASER Installation

1/2022

Commissioning

Timeline

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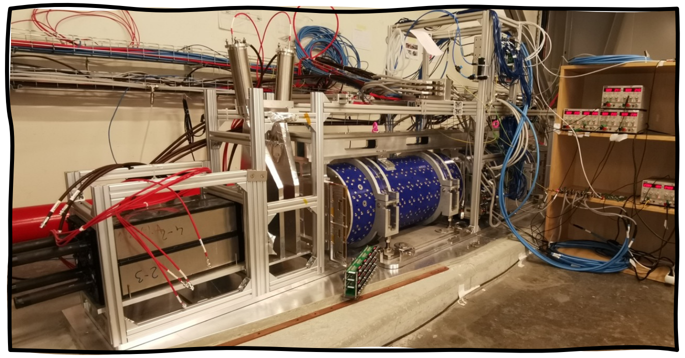

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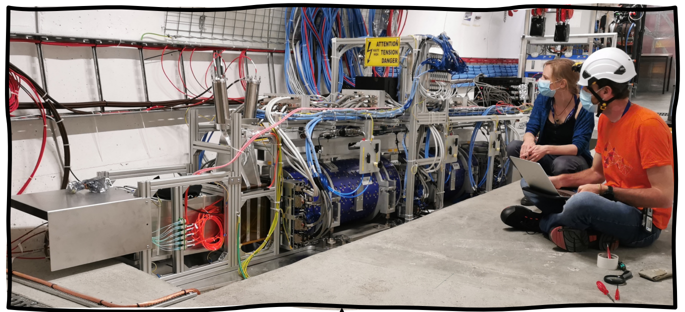

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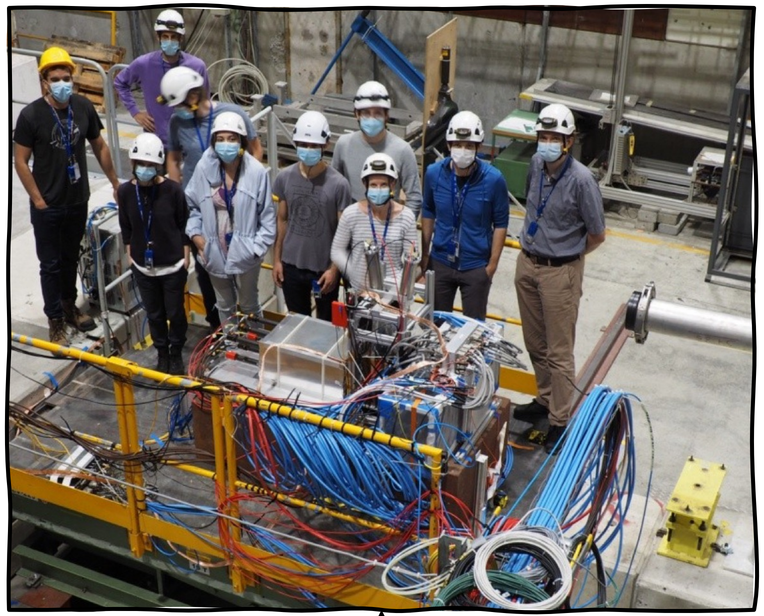
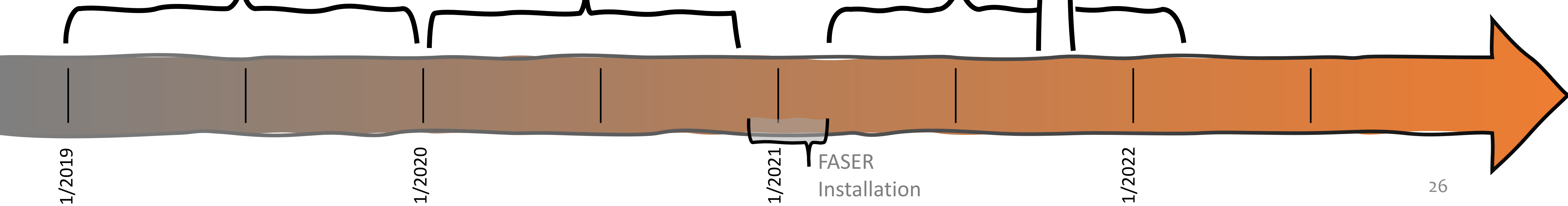


Testbeam



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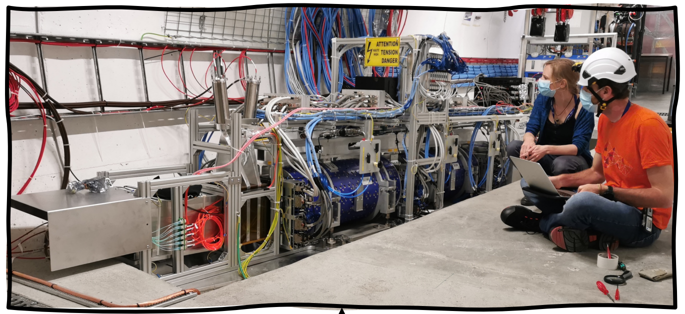

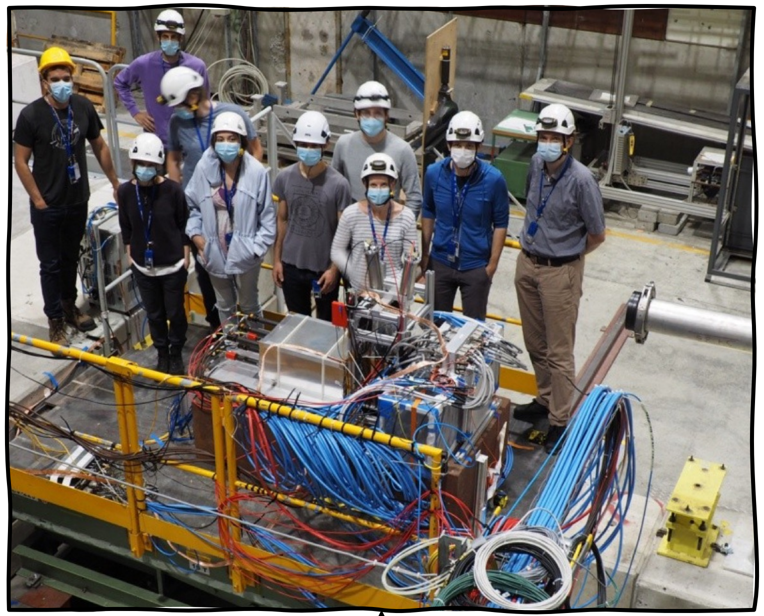

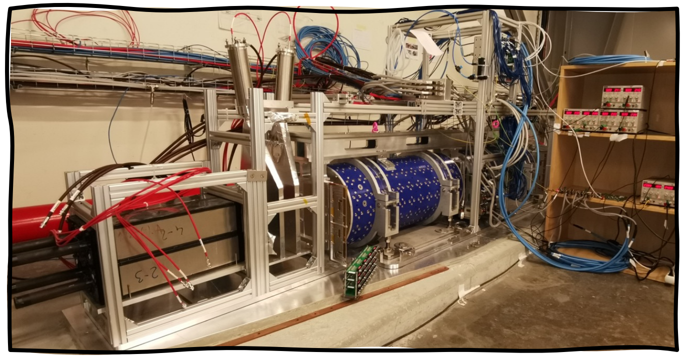

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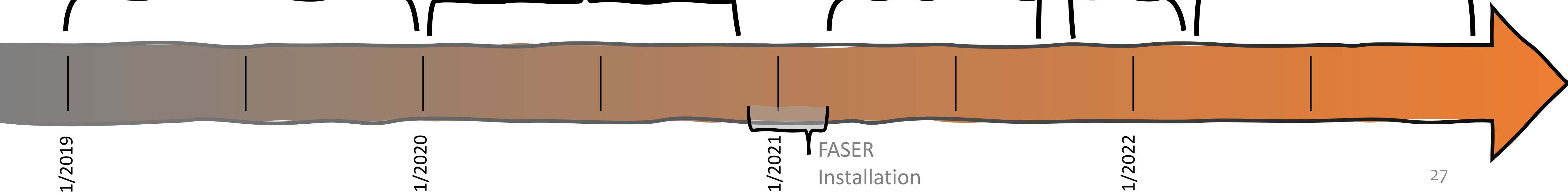
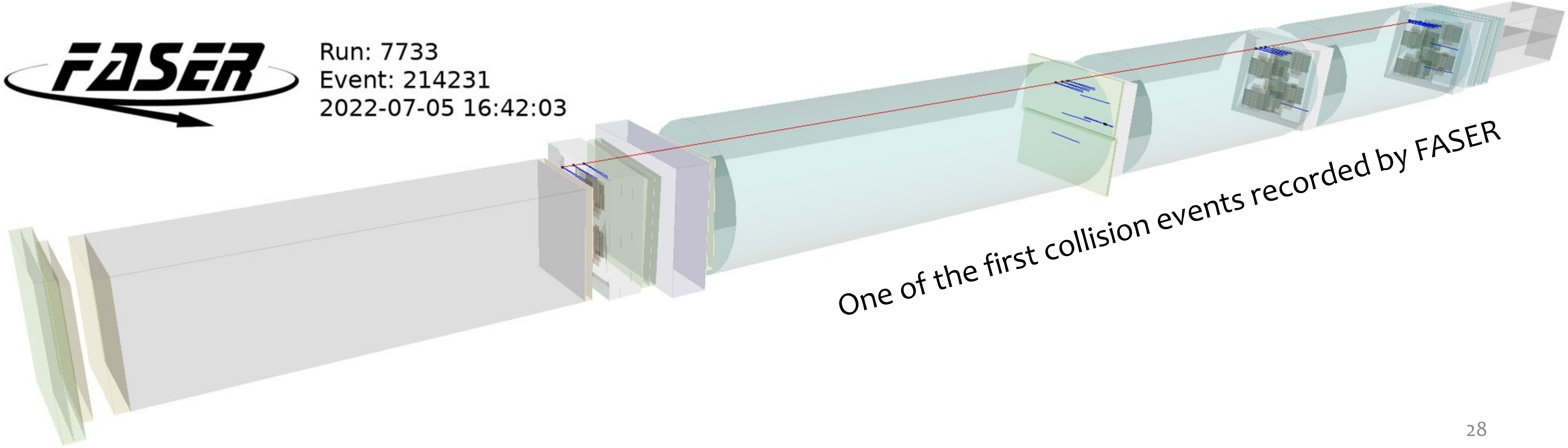
Collisions!



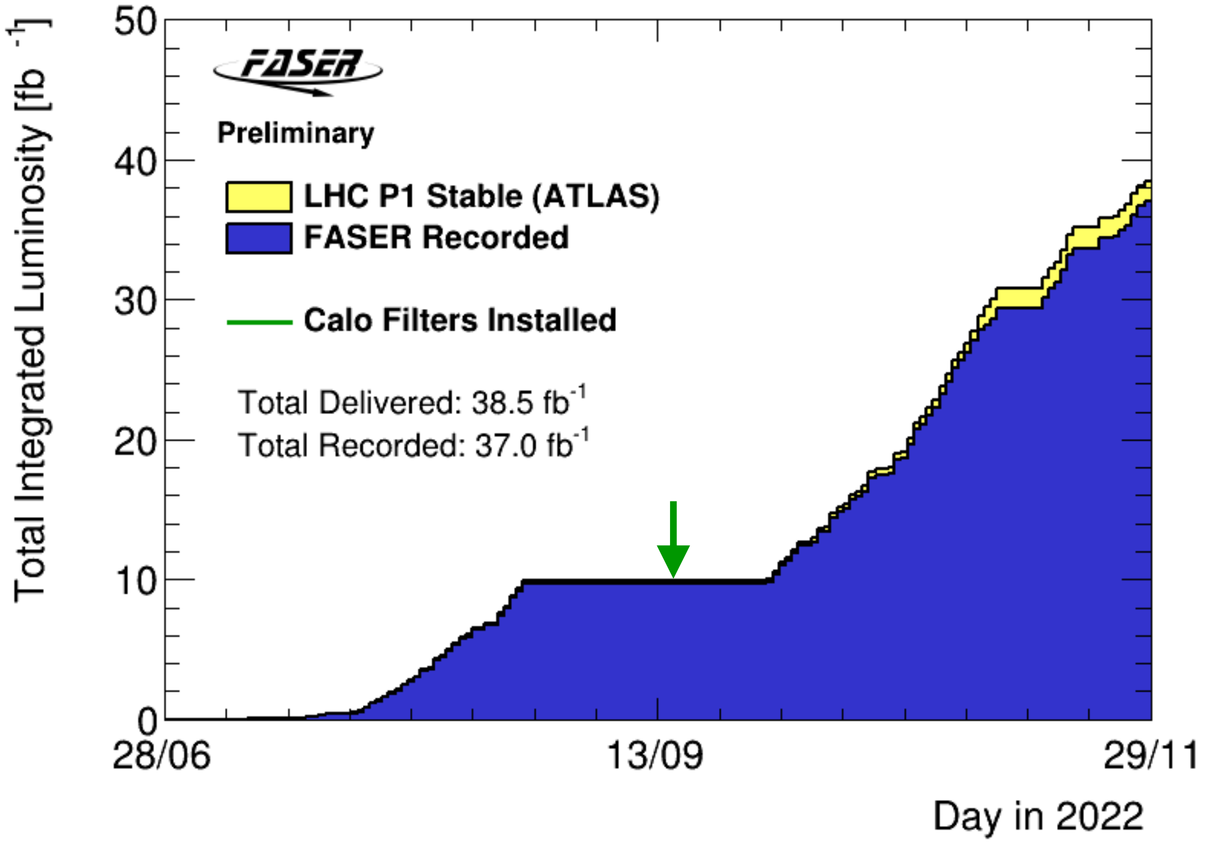
Run3 Data Taking

- Have successfully collected 13.6 TeV data
- Initial detector performance (being) assessed
- Offline and analysis software up and running
- **First analysis results produced for spring 2023 conferences**



FASER operations

- Recorded 96.1% of delivered lumi
- Dead-time of < 2 %
- About 2% data loss due to two specific operational issues
- Calorimeter gain optimised for
  - low E (< 300 GeV) initially
  - high E later in the run



Analyses produced use 27/fb or 35.4/fb

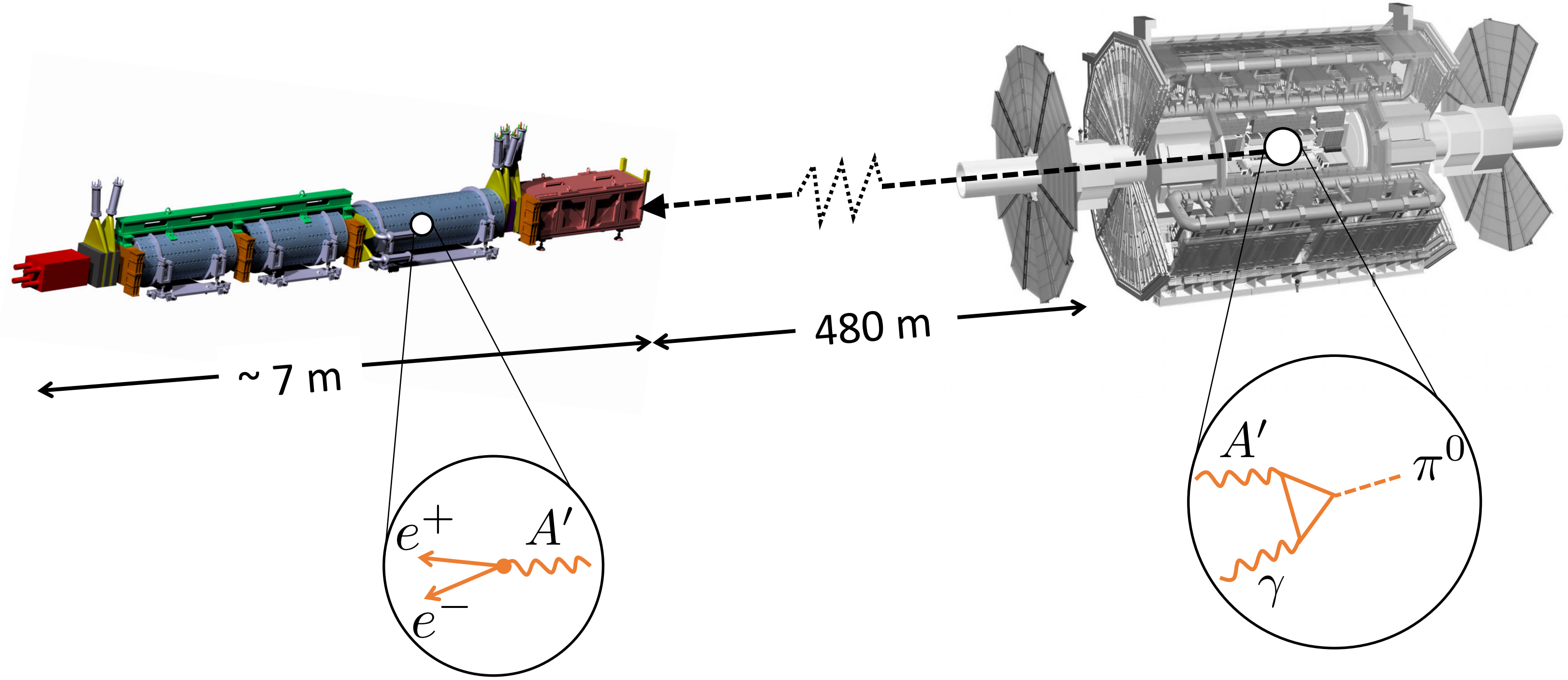
First Dark Photon Search with FASER

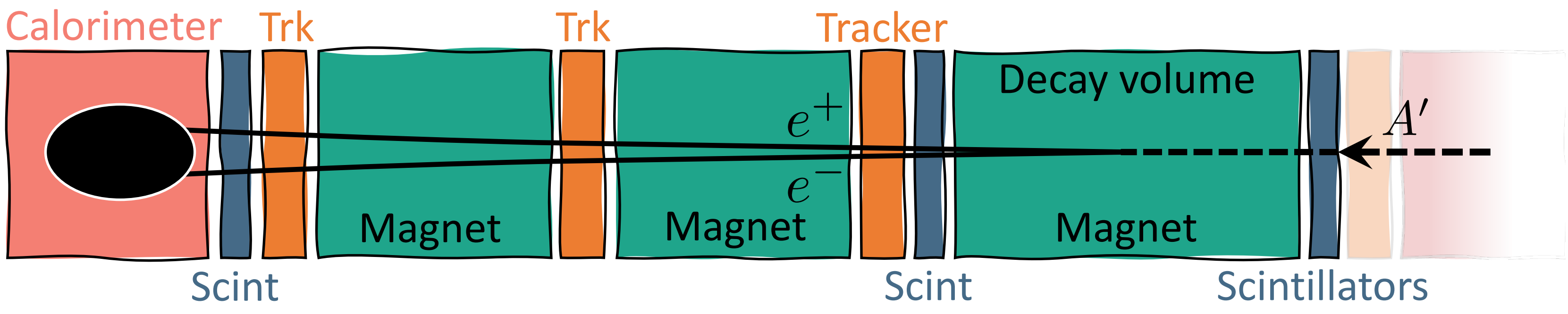
https://cds.cern.ch/record/2853210/files/CERN-FASER-CONF-2023-001.pdf

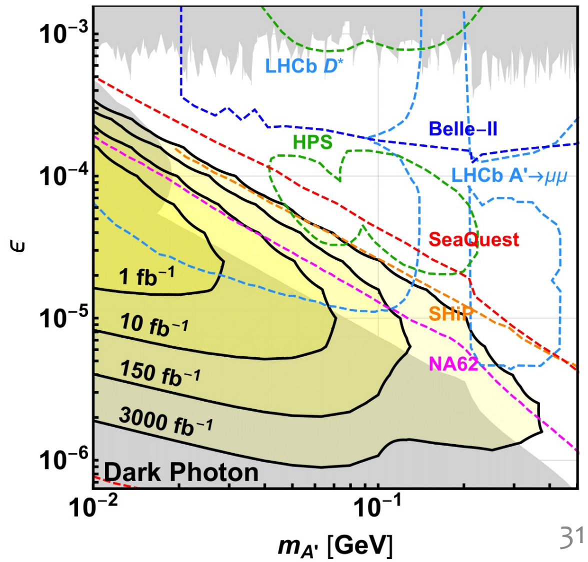
A Key Signature

Dark photon (A')

Decay products collimated
requirements for magnetic field & high-resolution tracker



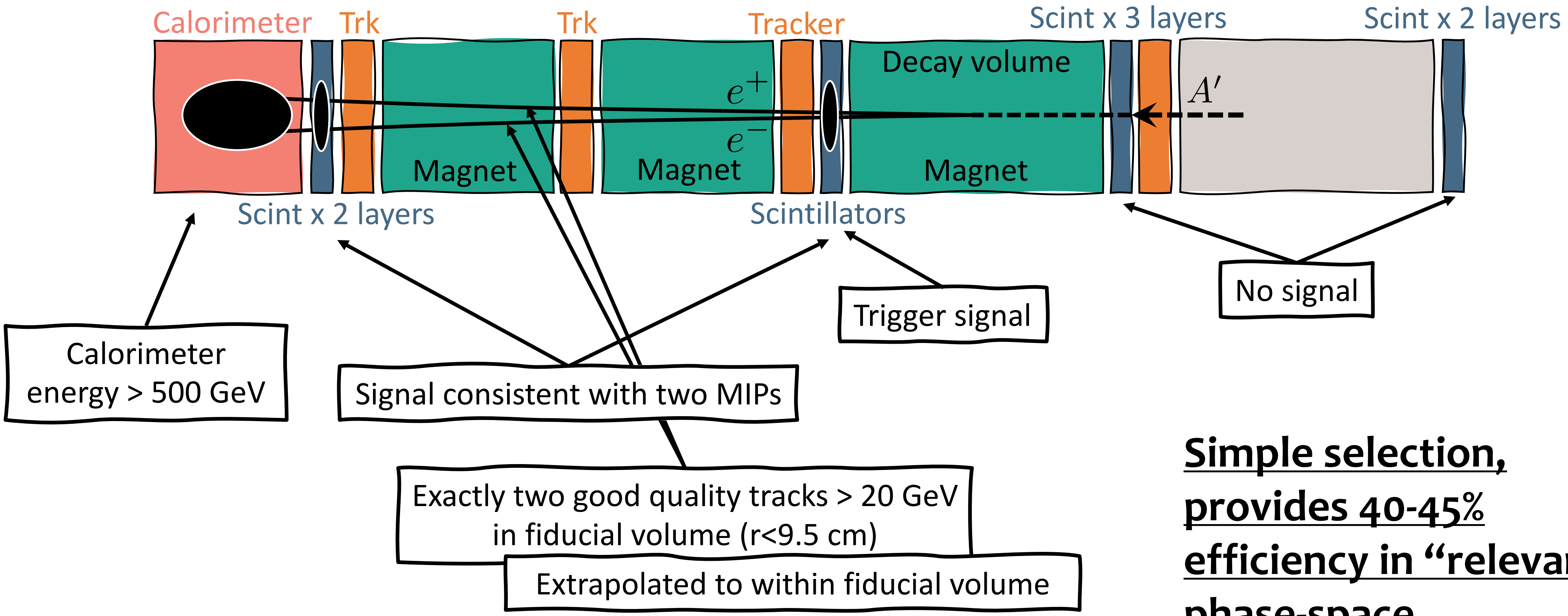




Assuming 3 signal events and no backgrounds

Signal Selection

Dark photon (A')

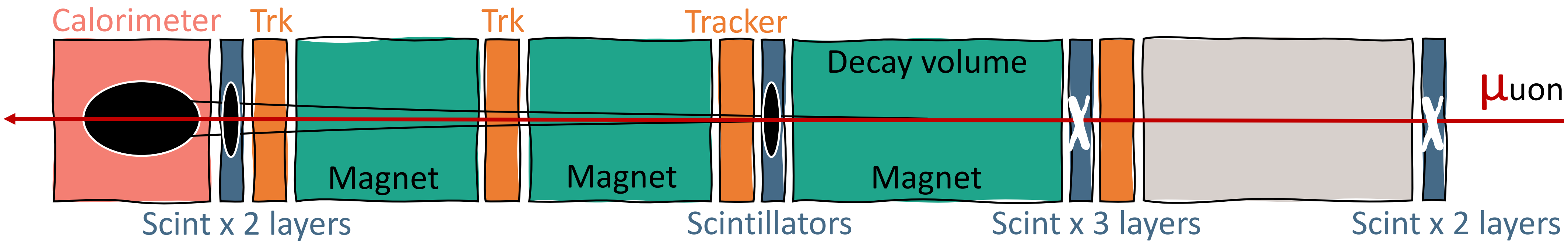


Simple selection, provides 40-45% efficiency in "relevant" phase-space

BACKGROUNDS

Dark photon (A')

1. Muons that are not vetoed by any of the 5 scintillator layers



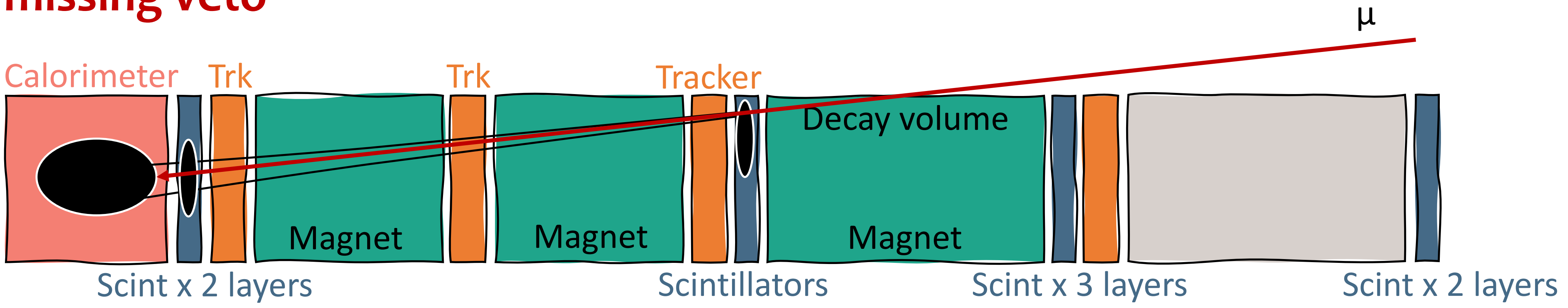
Scintillator	Efficiency
NuVeto-0	0.9999805(5)
NuVet0-1	0.9999810(5)
Veto-0	0.9999985(1)
Veto-1	0.9999984(1)
Veto-2	0.9999986(1)

- Total scintillator inefficiency < 10^{20}
- Even with O(10^8) muons (2022):
  - **zero** probability that one won't be vetoed

BACKGROUNDS

Dark photon (A')

2. Muons missing veto

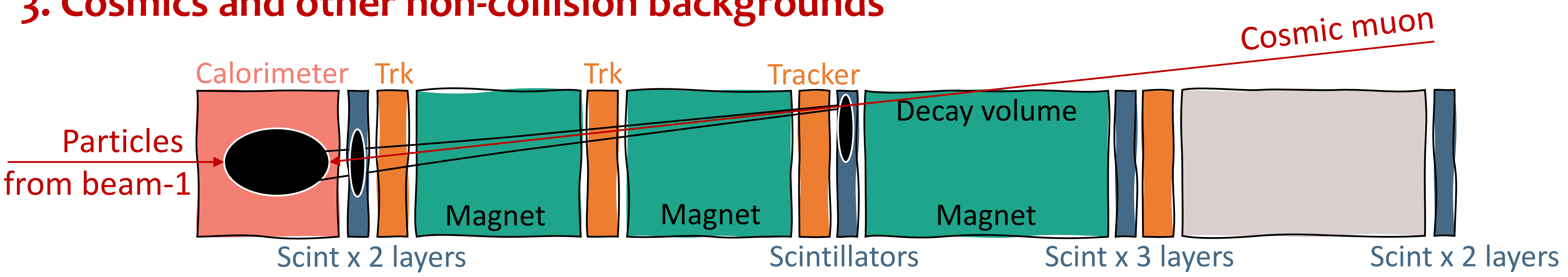


- Evaluated using MC
- **Zero** background

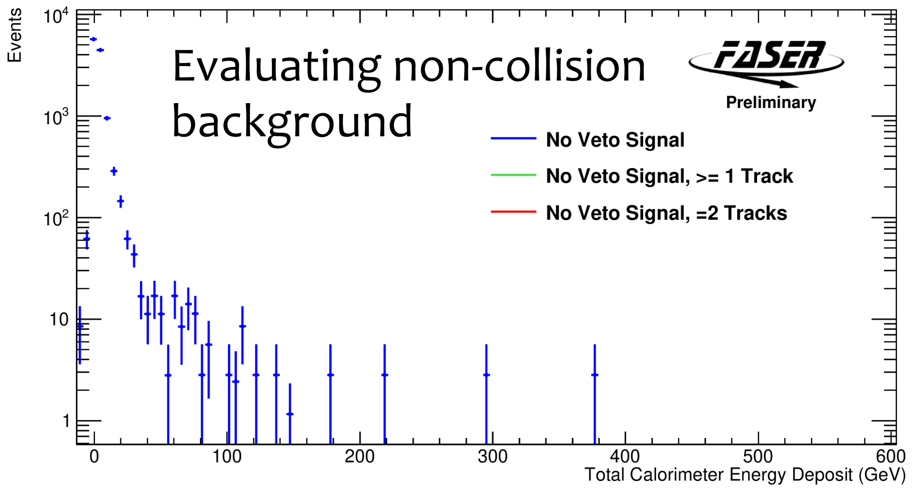
Backgrounds

Dark photon (A')

3. Cosmics and other non-collision backgrounds



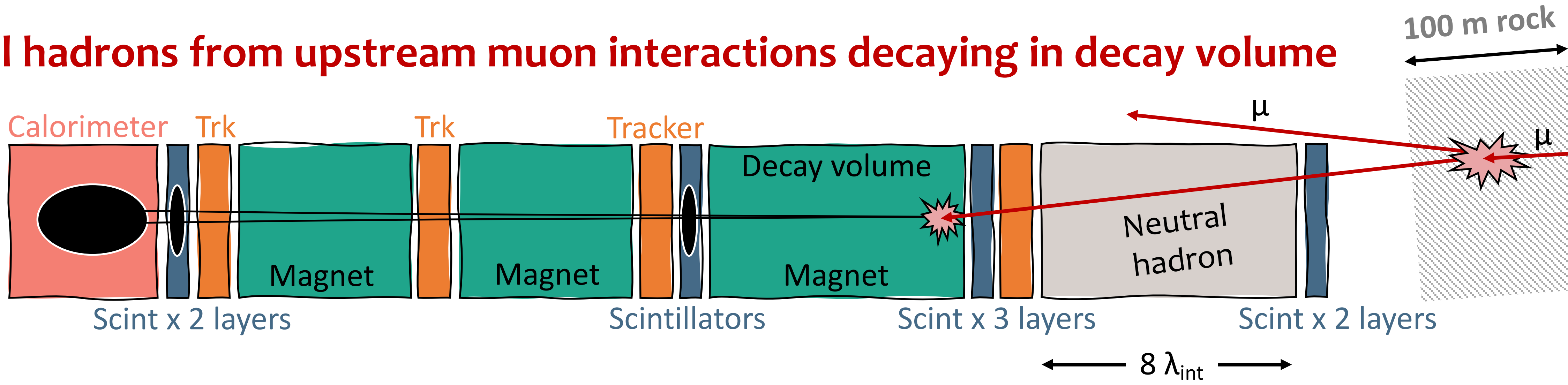
- Evaluated in non-colliding bunches and runs without beam
- **Zero** background



BACKGROUNDS

Dark photon (A')

4. Neutral hadrons from upstream muon interactions decaying in decay volume

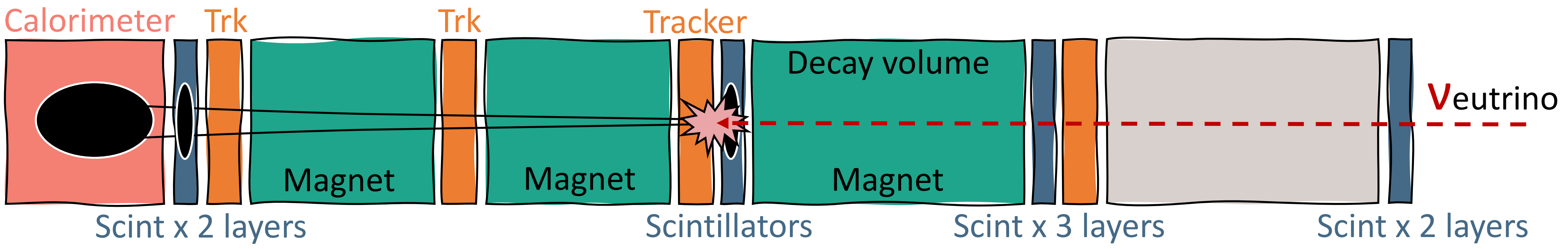


- Evaluated using three-track events, extrapolating from low energy to high energy and from loose to nominal veto requirements
- Estimated background: $\mathbf{(2.2 \pm 3.1)10^{-4}}$ **events**

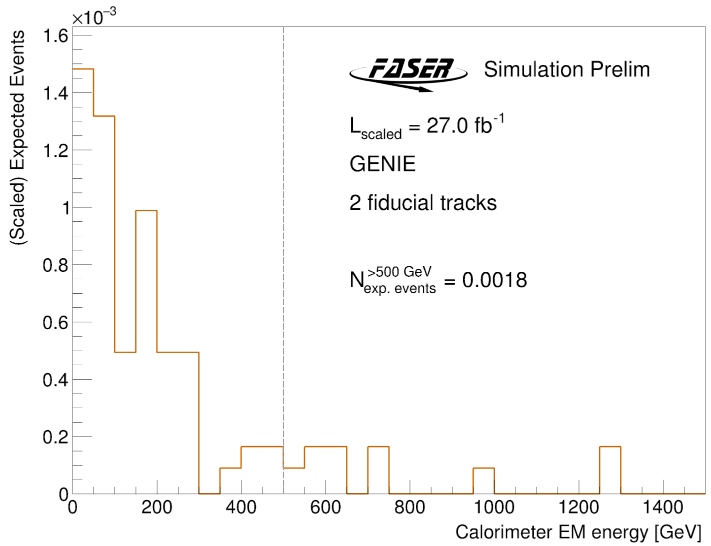
Backgrounds

Dark photon (A')

5. Neutrino interactions



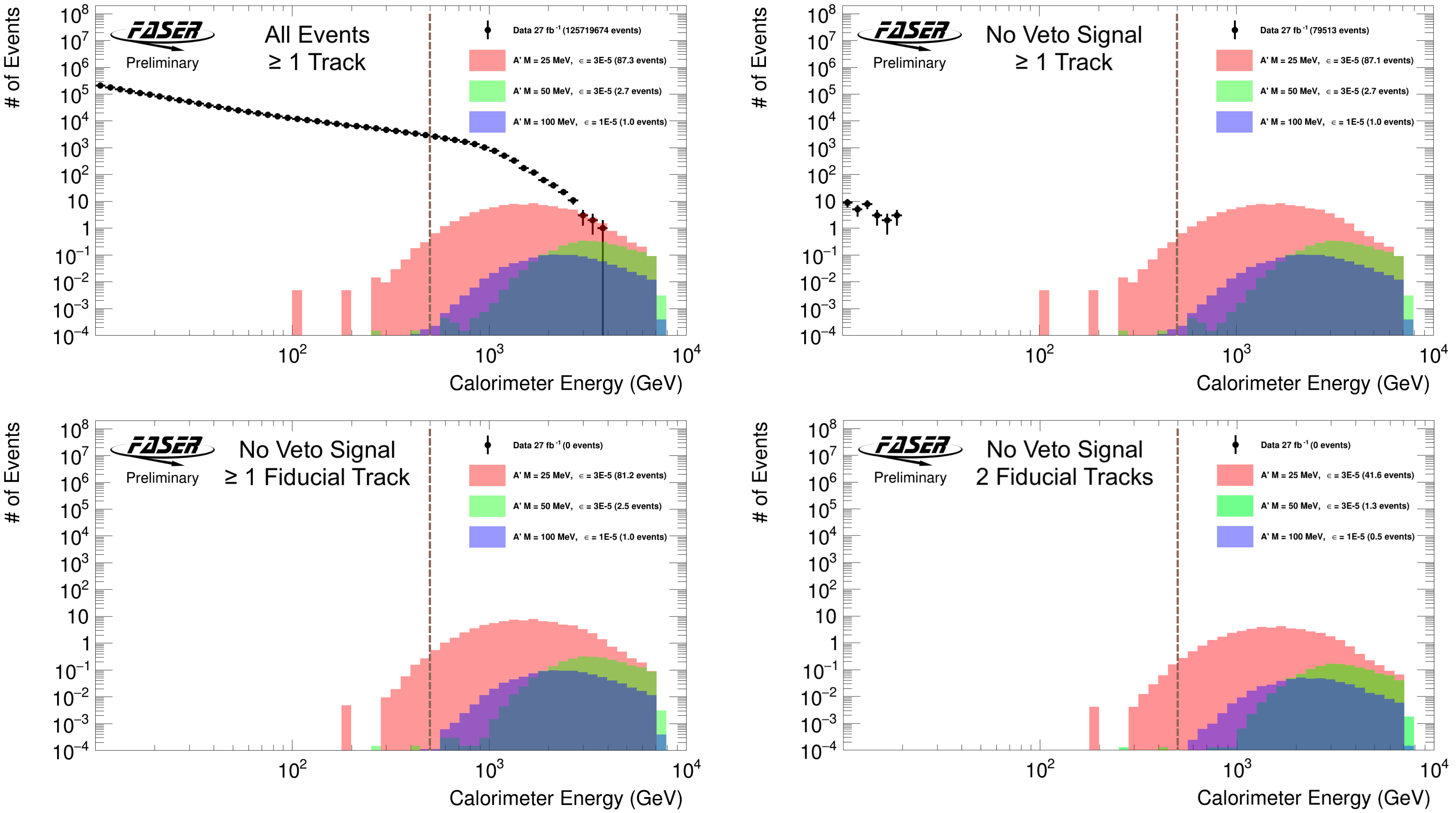
- Evaluated using MC
  - GENIE generator
  - 300/ab
- Estimated background: $(1.8 \pm 2.4)10^{-3}$ **events**



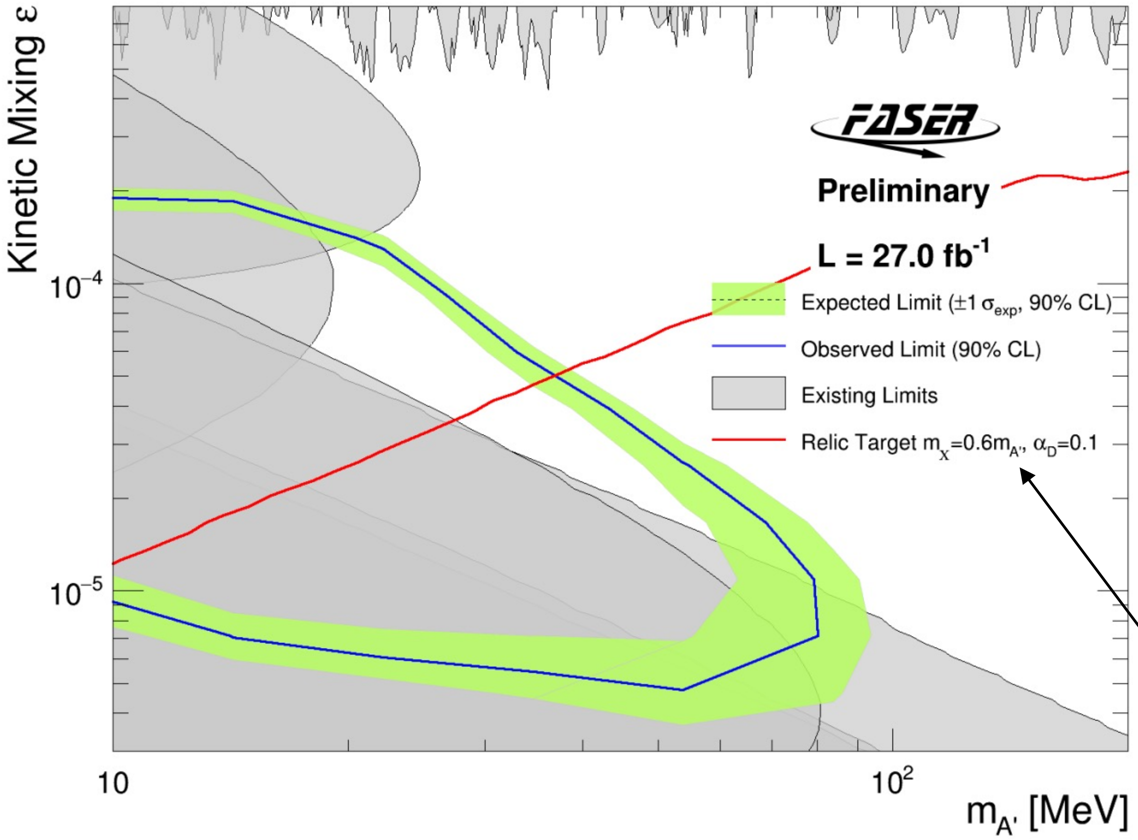
Looking in Data

Total background: (0.0020 ± 0.0024) **events**

No events seen in unblinded signal region

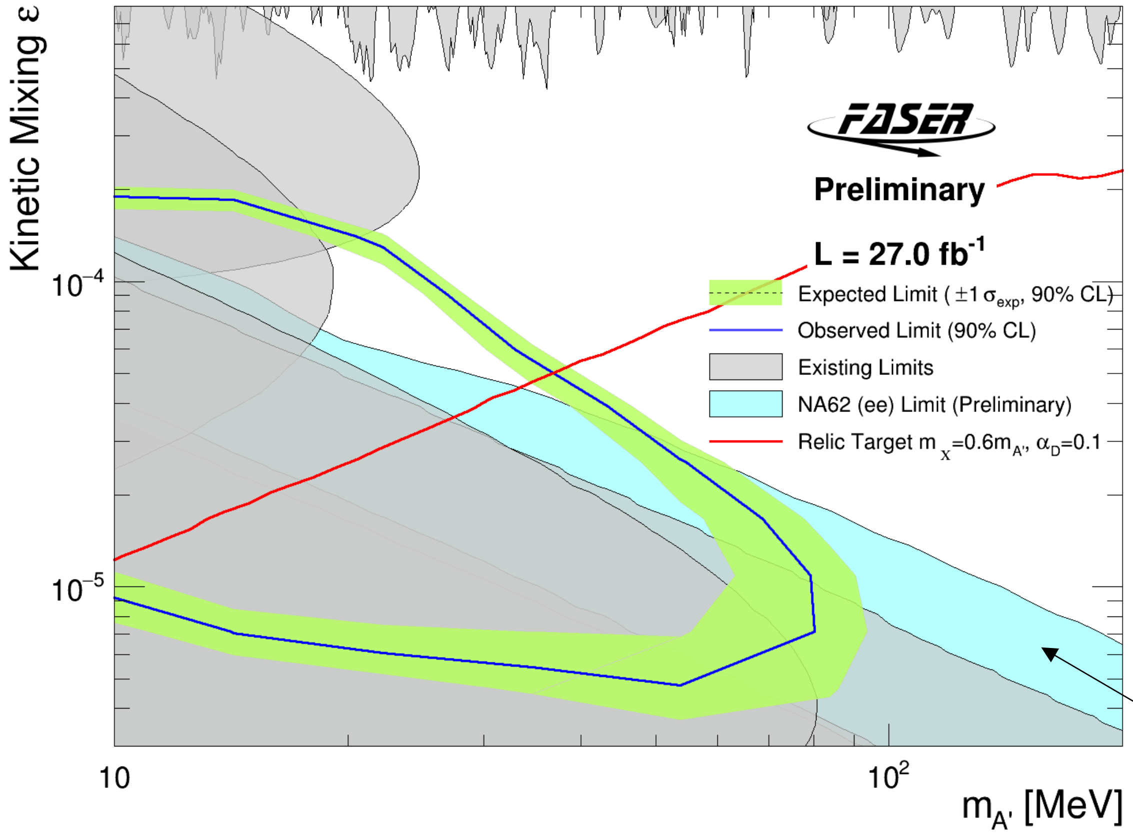


Exclusion reach On previously unexplored phase-space



- Parameters for which DM χ annihilates via $\chi\chi \rightarrow A' \rightarrow ff$
- *Model dependent line, but region favoured by DM relic density*

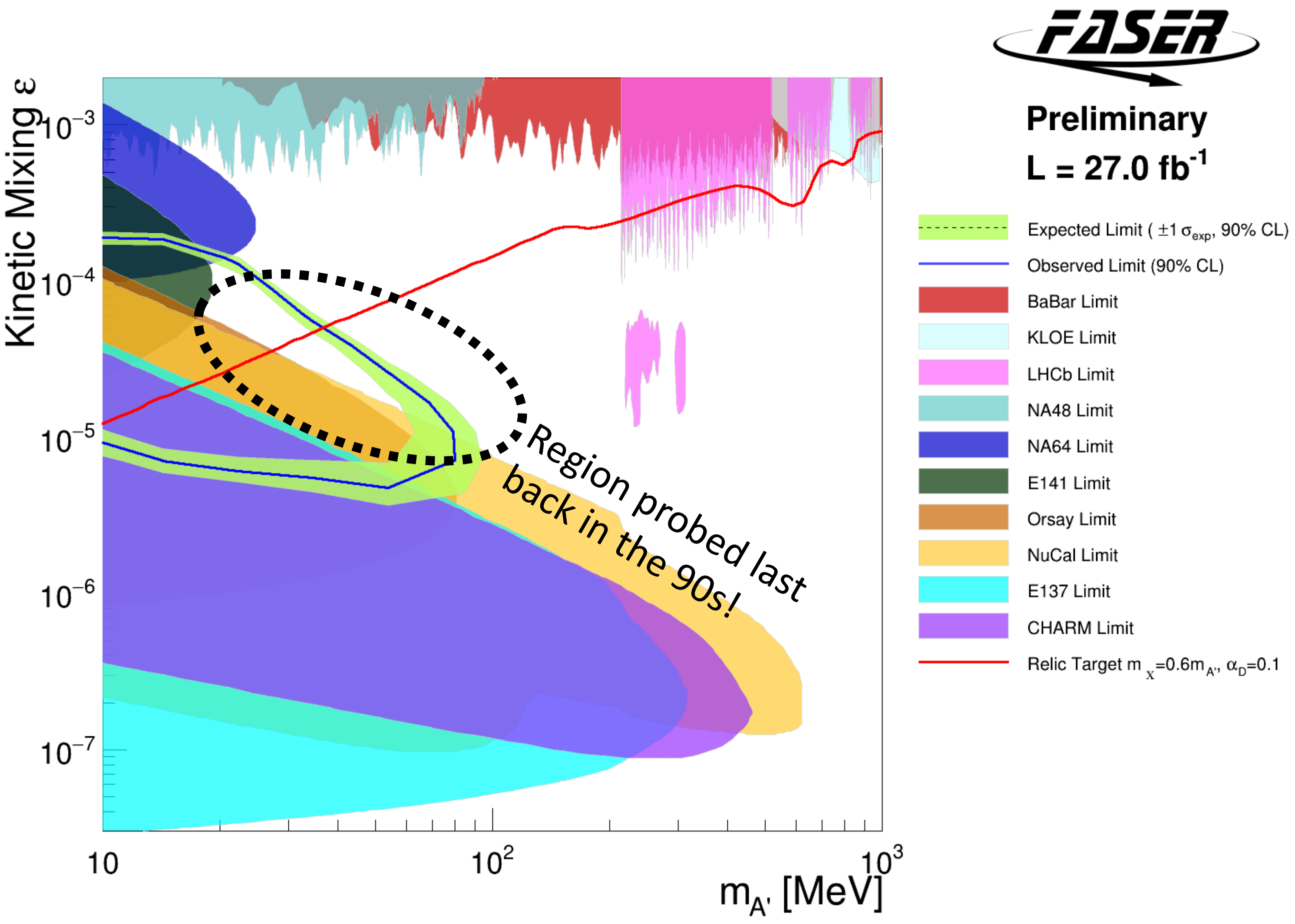
Exclusion reach On previously unexplored phase-space



For La Thuile 23, NA62 too announced a preliminary result, complementary to the FASER one

Exclusion reach

On previously unexplored phase-space



FASER

HUGE FLUX OF HIGH-ENERGY NEUTRINOS

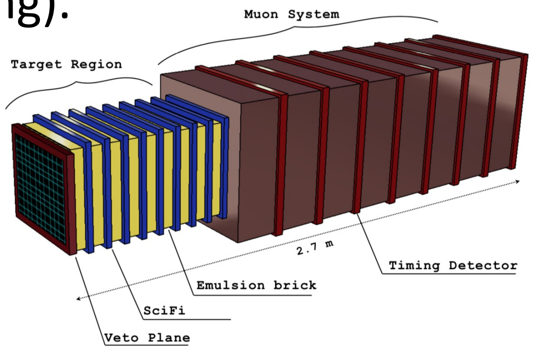
- Why not exploit FASER to also measure properties of neutrinos at the highest man-made energies ever recorded!

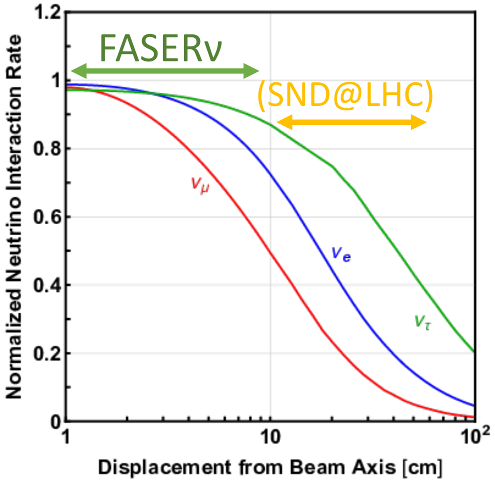
A bit of history

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 approved for Run 3 data taking (and is running).
FASERν was the first such experiment to be approved!
More on FASERν in what follows…



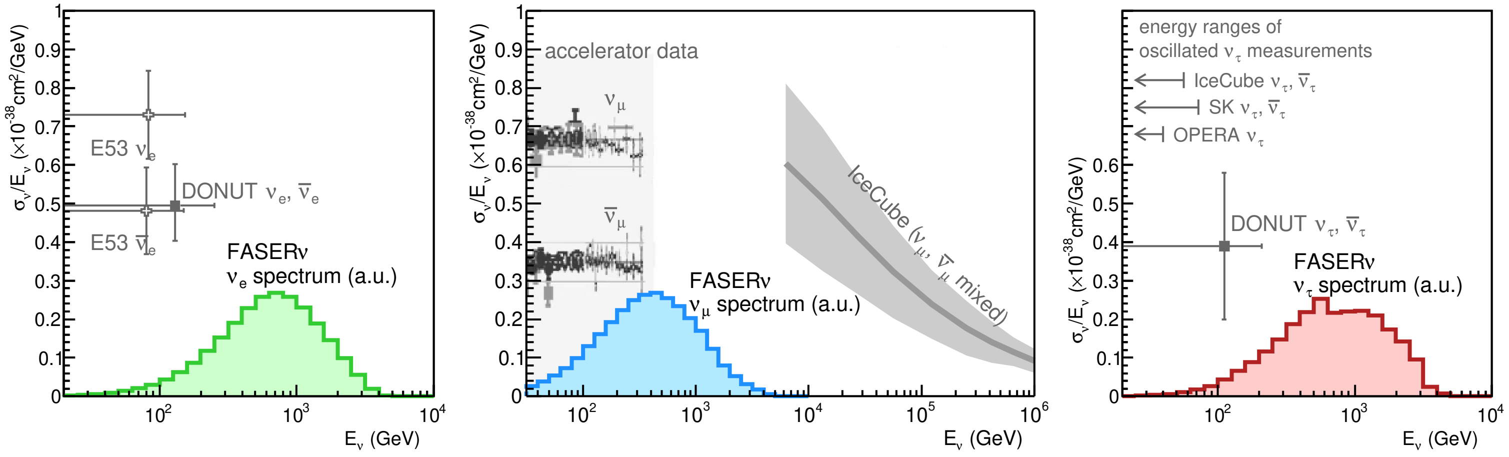


Huge flux of high-energy neutrinos

- 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, …)

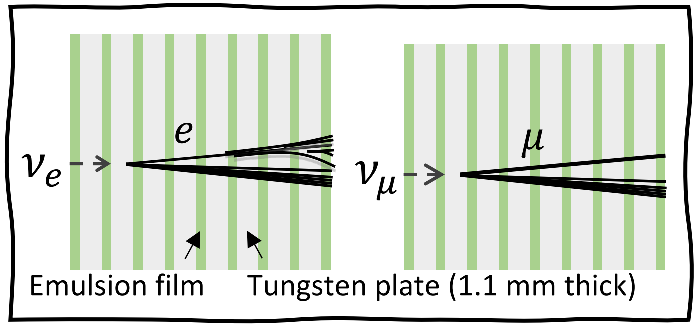
150/fb @14TeV	ν_e	ν_μ	ν_τ
Main production source	kaon decay	pion decay	charm decay
# traversing FASERnu 25cm x 25cm	$O(10^{11})$	$O(10^{12})$	$O(10^{9})$
# interacting in FASERnu (1 tn Tungsten)	~1000	~20000	~10

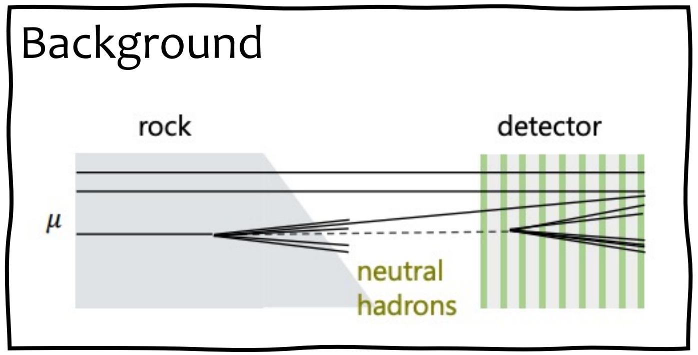


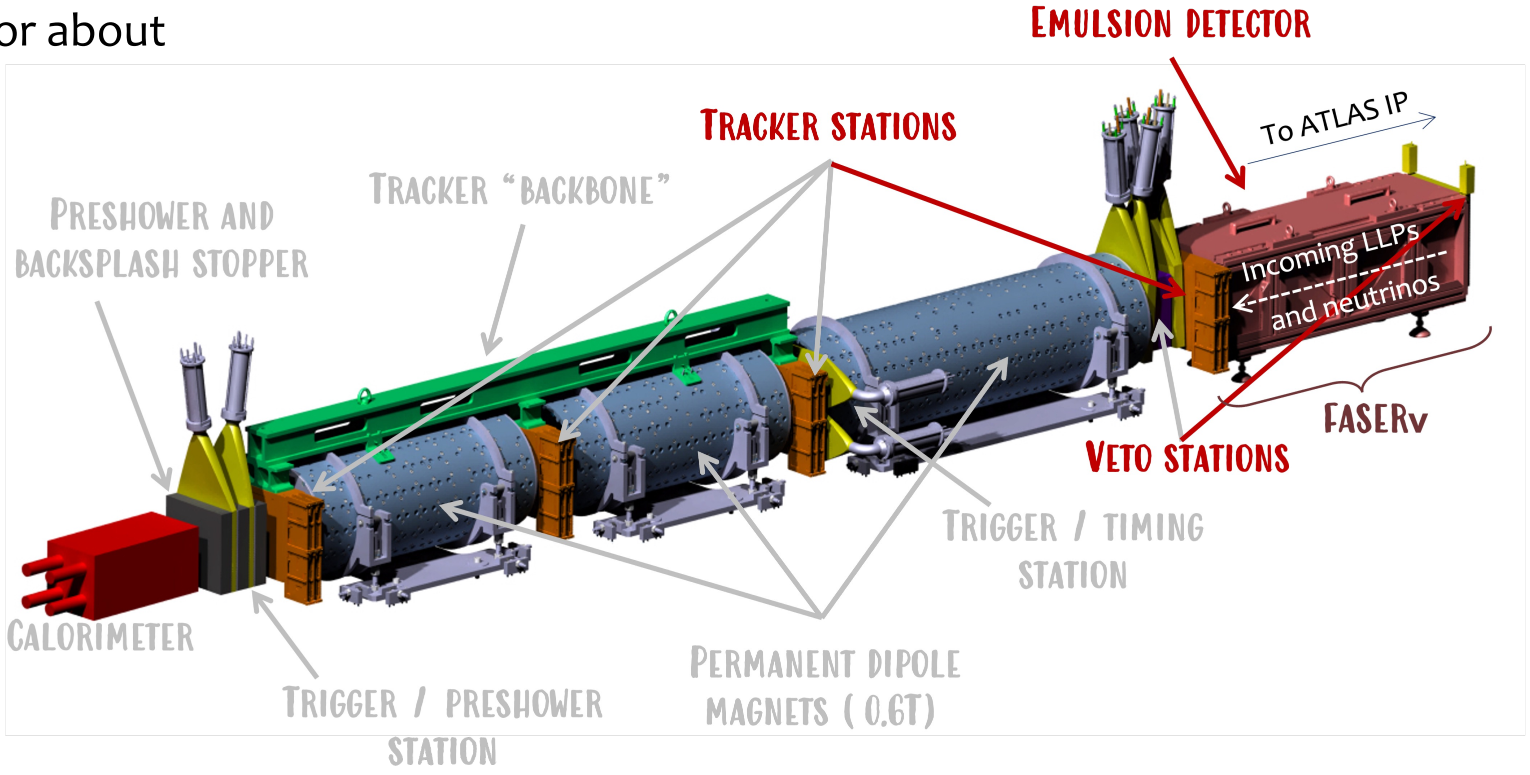
FASER Detector

Emulsion detector:
- Excellent track resolution
- No timing resolution
- Challenges: replace the 1-ton-scale detector about 3 times/year & develop the emulsion films

Total 730 emulsion films interleaved with 1.1-mm-thick tungsten plates







FASER Detector

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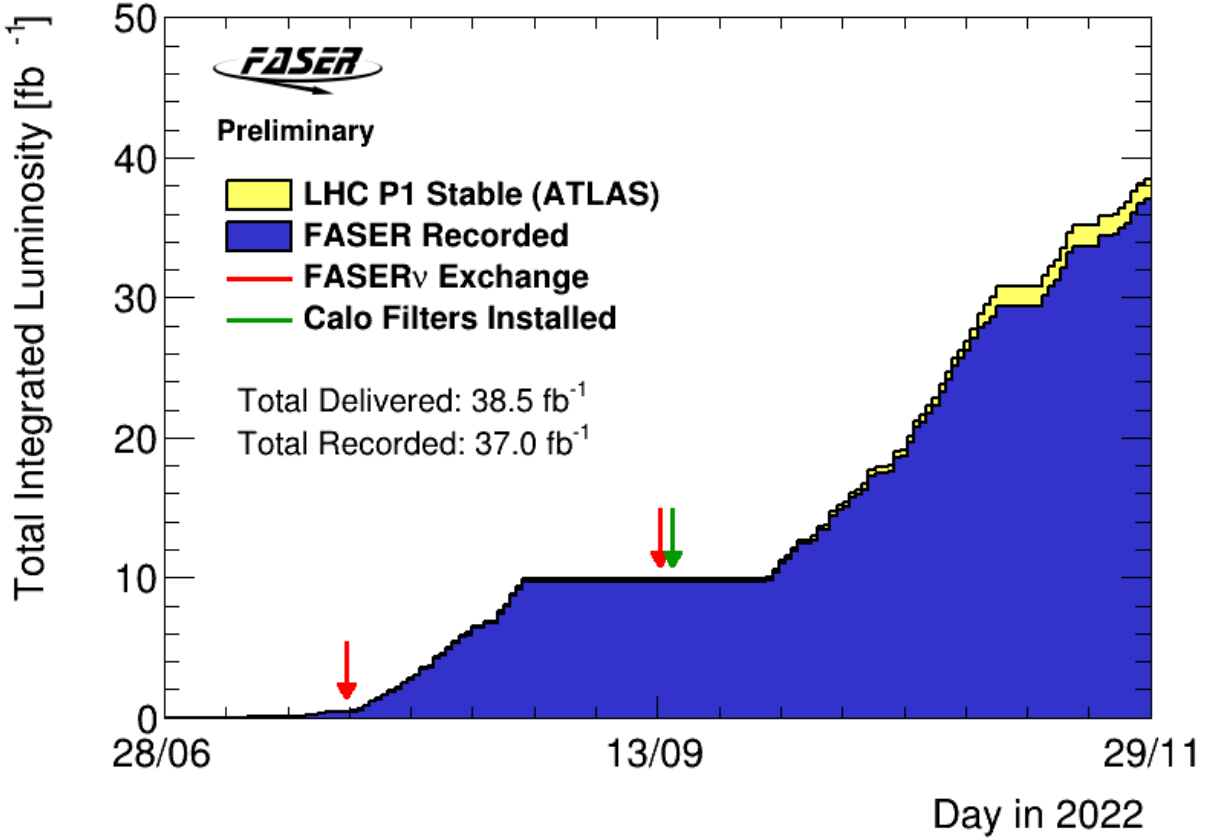
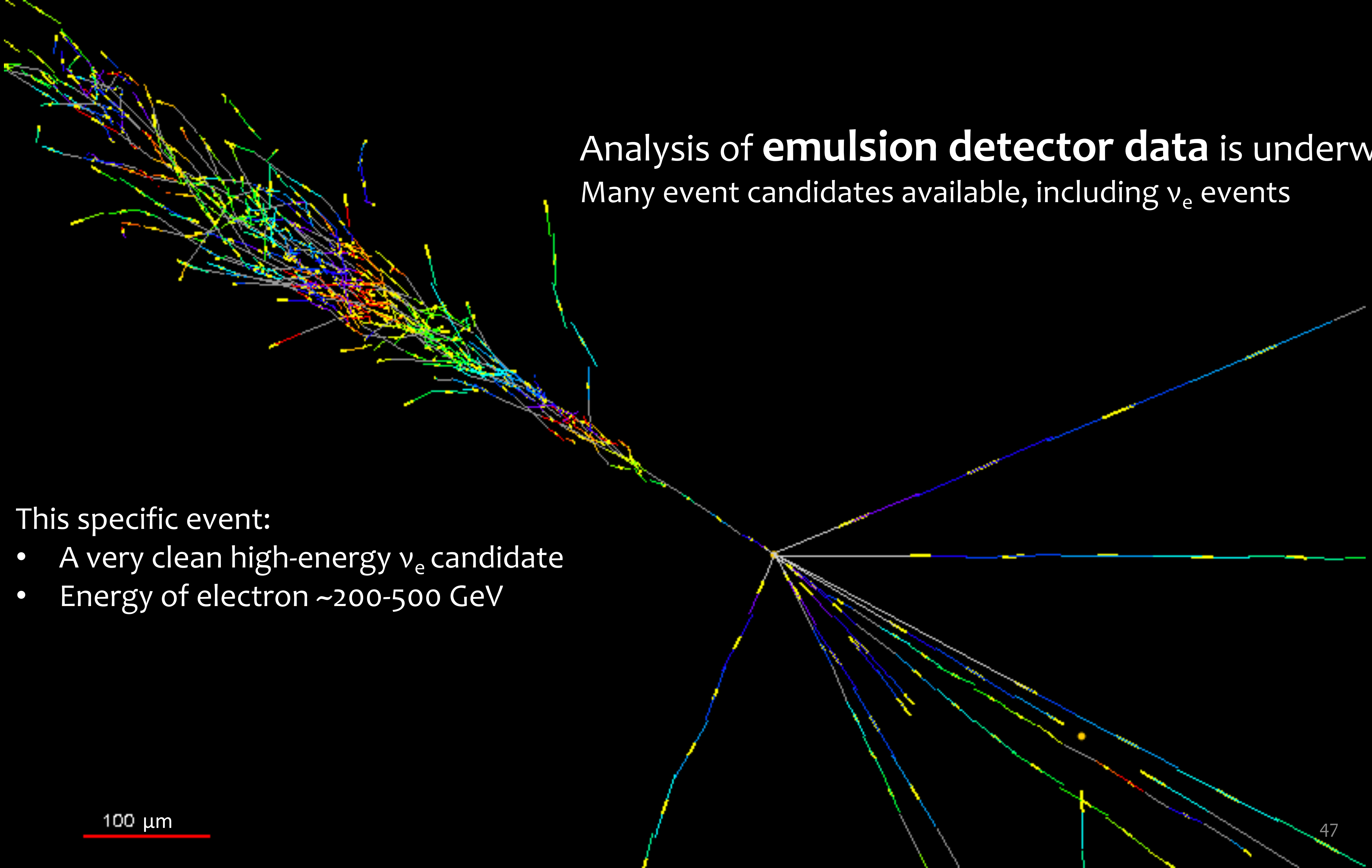


➔ The first FASER neutrino detection is based the "electronic" part of the detector.

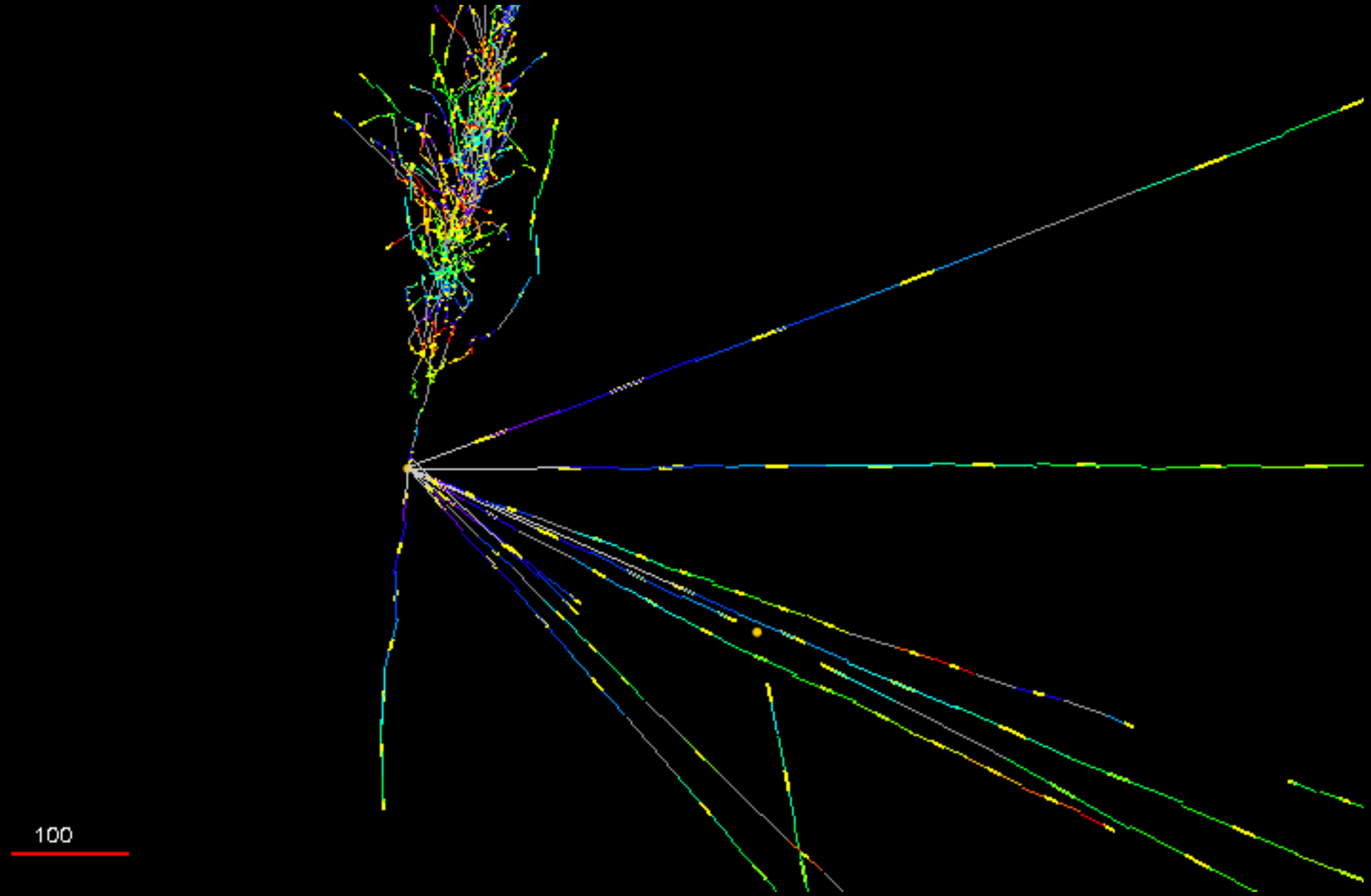
Analysis of **emulsion detector data** is underway

Many event candidates available, including ν_e events



This specific event:

- A very clean high-energy ν_e candidate
- Energy of electron ~200-500 GeV

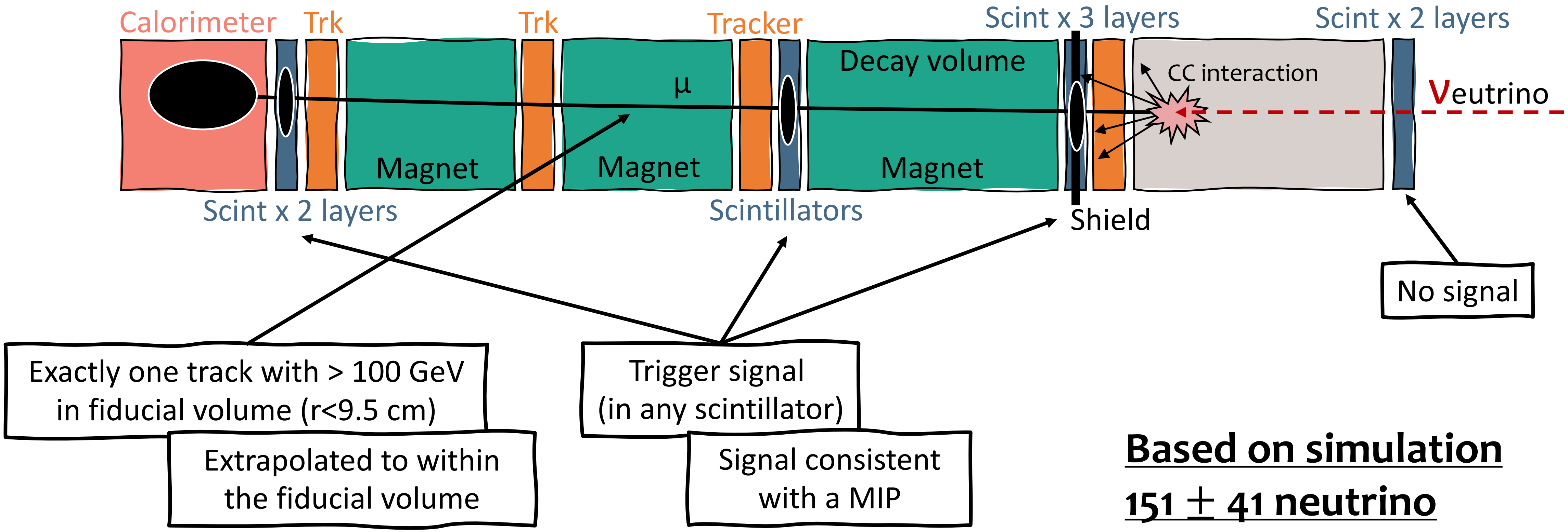

100

First Direct Neutrino Detection in a Hadron Collider with FASER

arXiv:2303.14185

Signal Selection

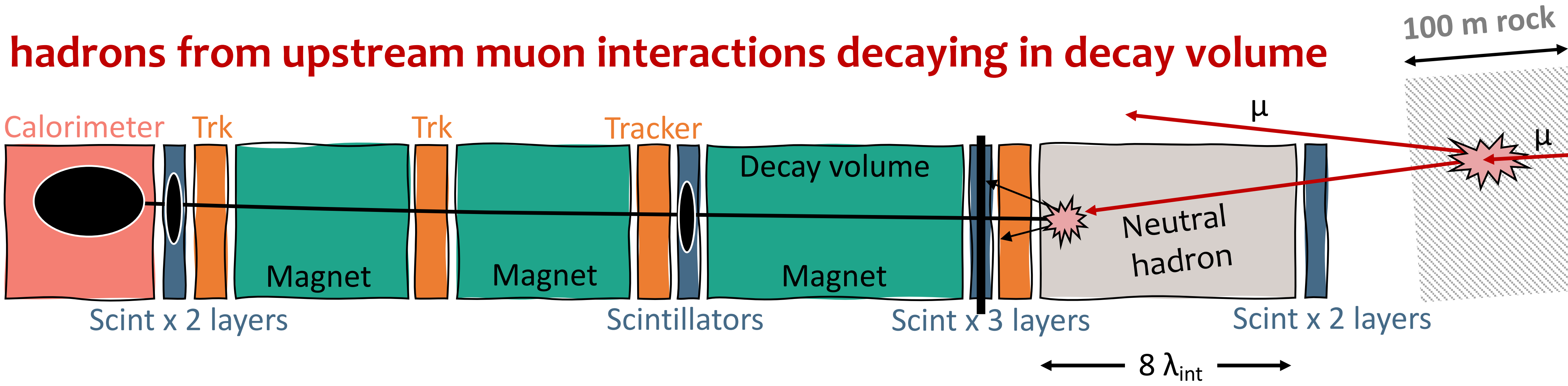
Neutrinos in FASER



Based on simulation 151 ± 41 neutrino events are expected

Backgrounds

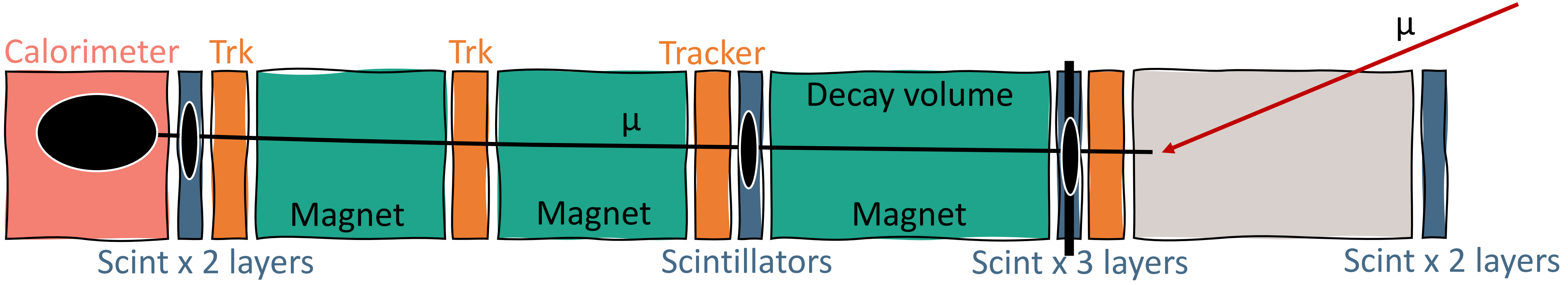
1. Neutral hadrons from upstream muon interactions decaying in decay volume



- Evaluated using two-step simulation
  - O(300) neutral hadrons with E>100 GeV would reach FASER
  - Most of them absorbed in tungsten
- Estimated background: $\mathbf{(0.11 \pm 0.06)}$ **events**

BACKGROUNDS

2. Scattered muons

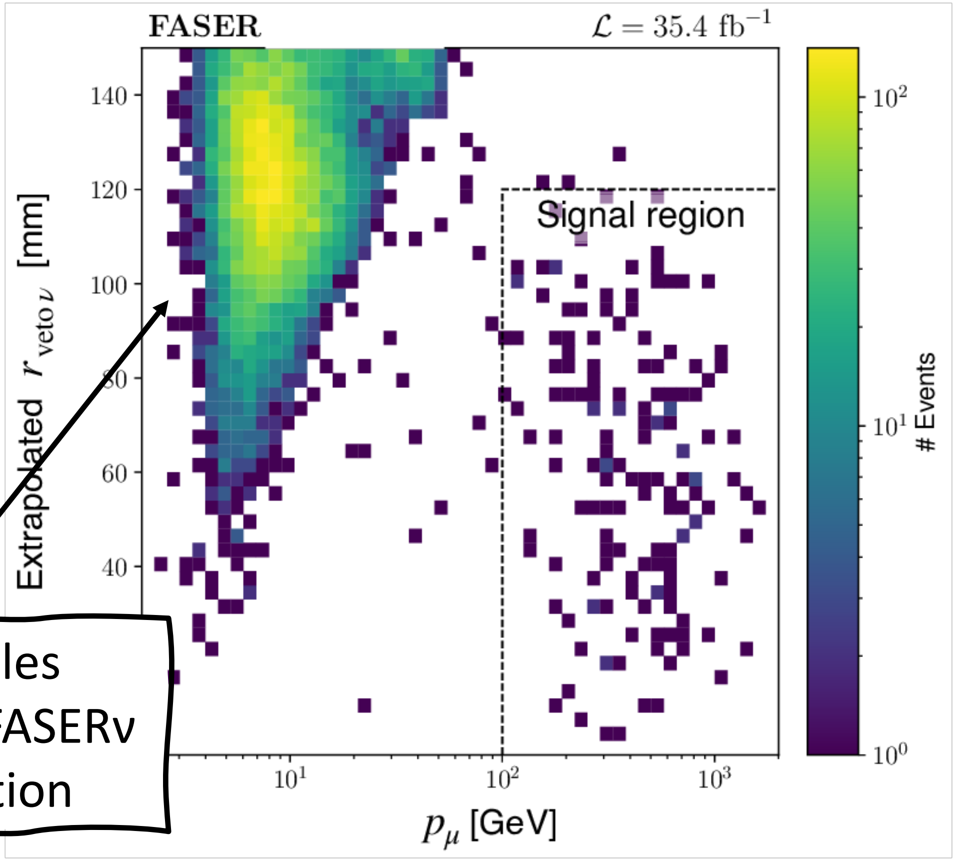


- Estimated from events with single track just outside the fiducial region
- Estimated background: $(\mathbf{0.08 \pm 1.83})$ **events**

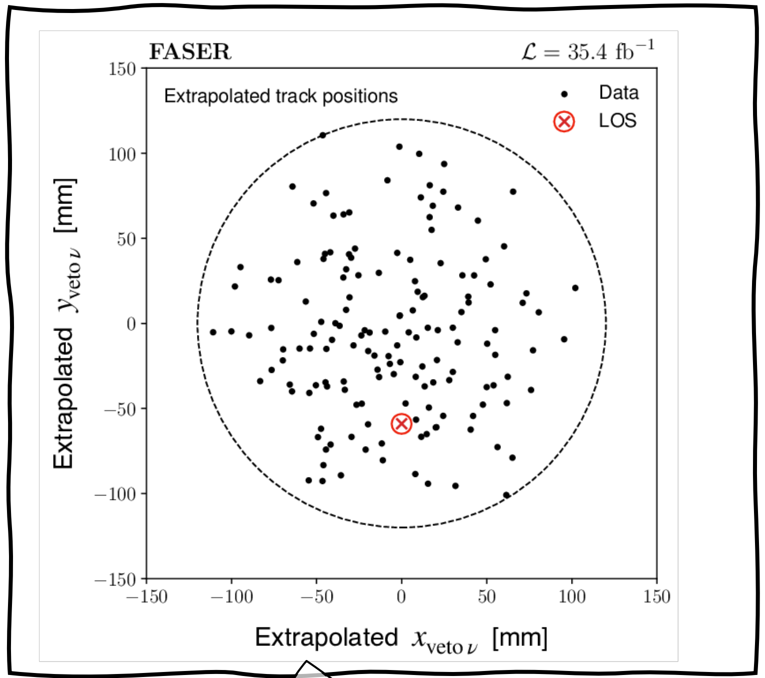
Looking in Data

153^{+12}_{-13} events $\Longrightarrow \gg 5\sigma$ significance

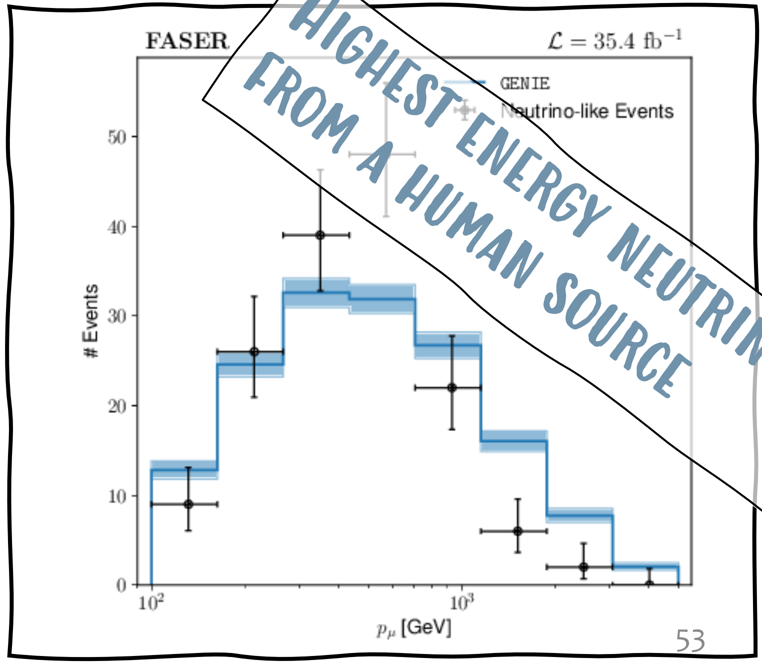
First direct observation of collider neutrinos!



Charged particles that miss the FASERv scintillator station

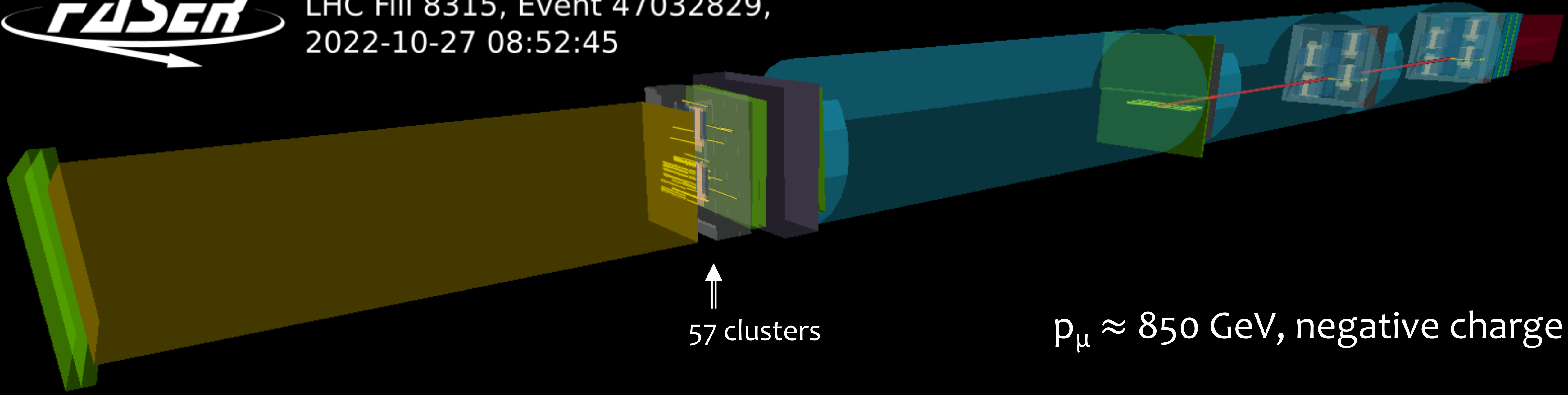


First assessment of properties



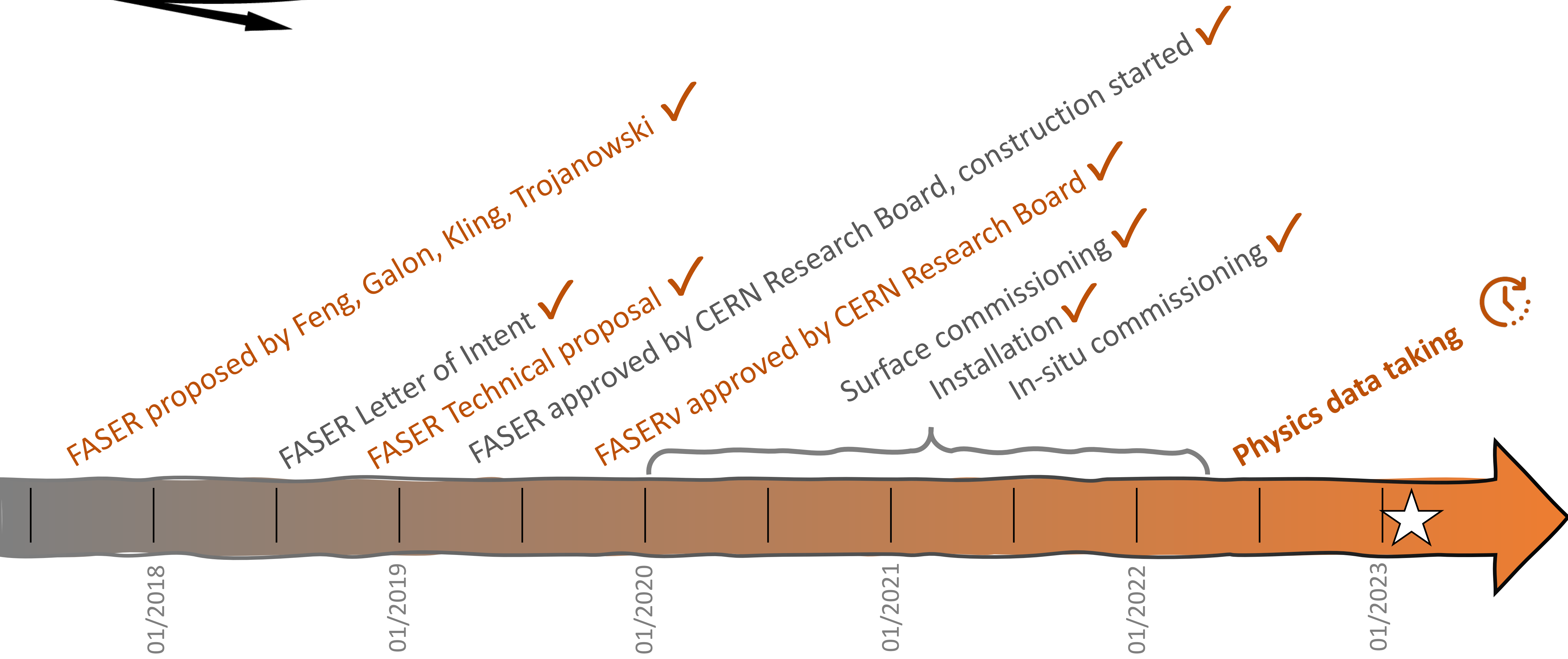
Highest energy neutrinos from a human source

N.B.: SND@LHC also had a collider neutrino observation with 8 signal events and ~ 0.1 background events (arXiv:2305.09383)

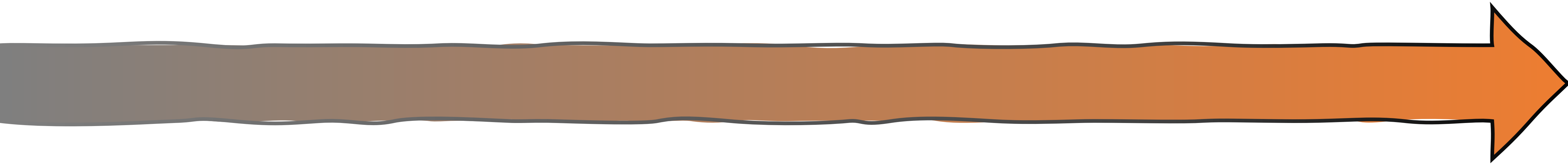


$p_{\mu} \approx 850$ GeV, negative charge

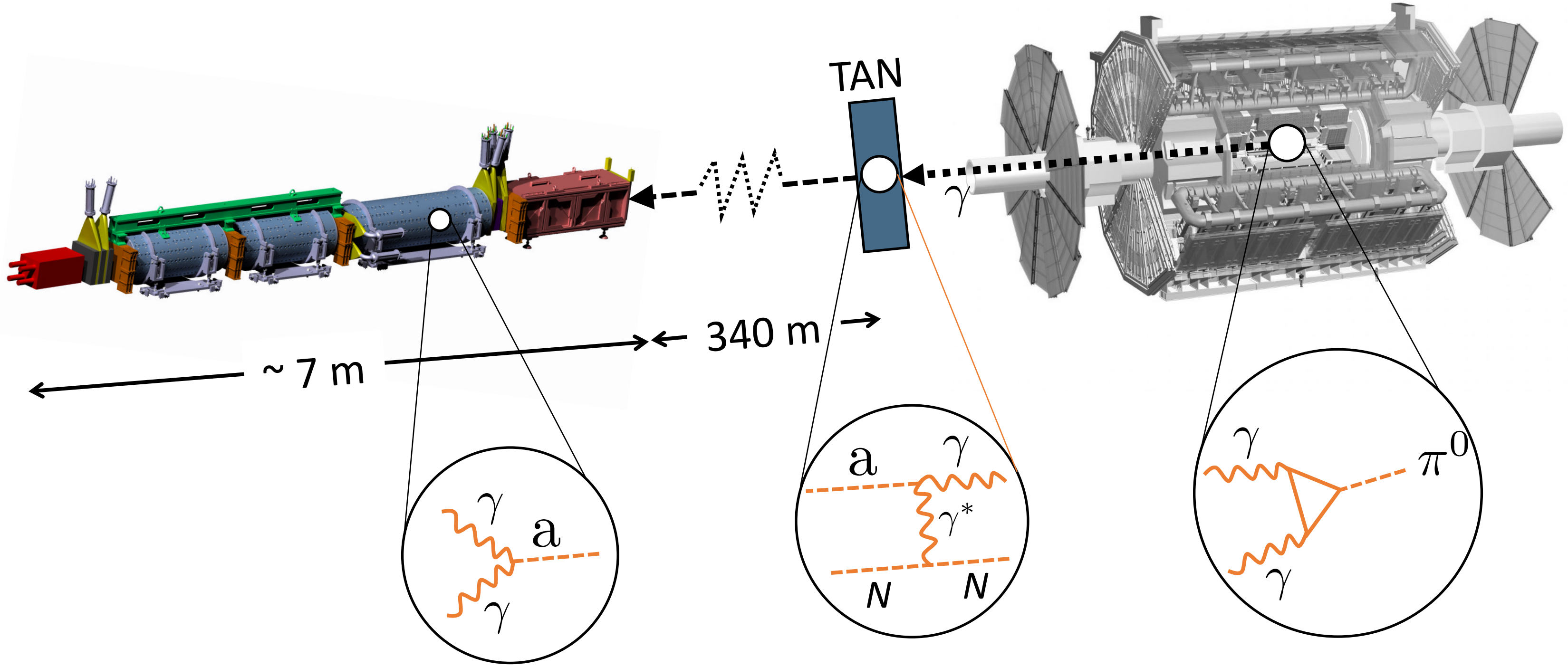
FASER Global timeline



WHAT'S BEYOND 2023 ?

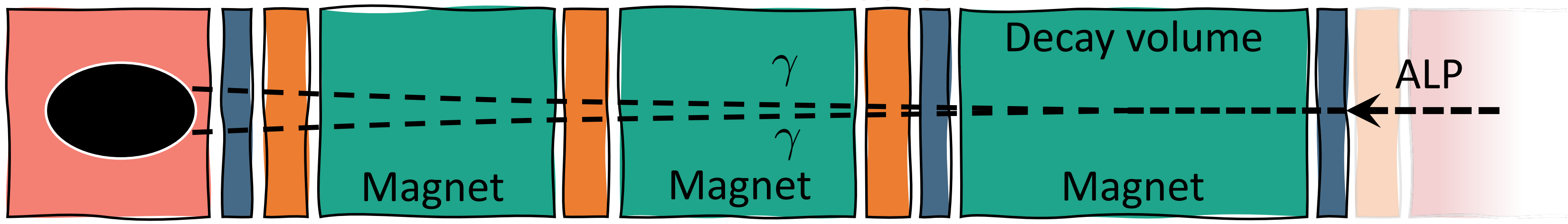


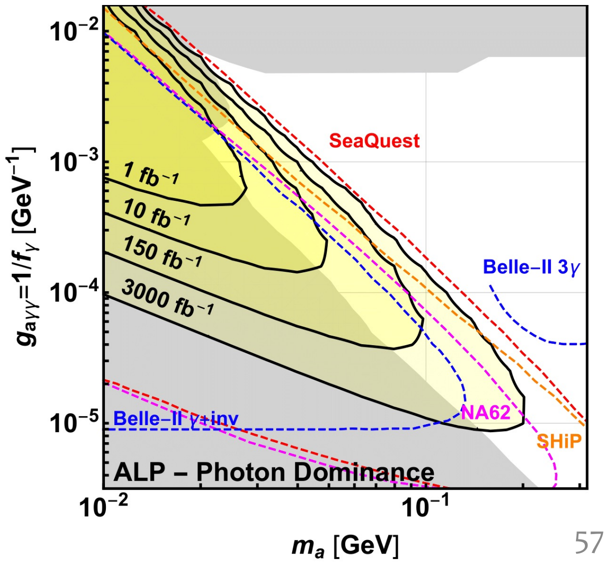
Another Physics example Axion-like particle (ALP, a)



Decay products collimated

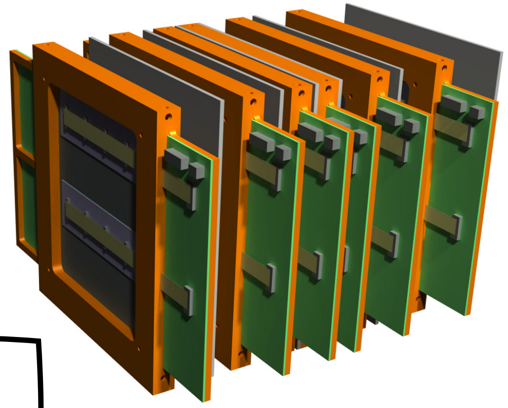
2-γ signature can't be resolved with present detector: **upgrade**





Assuming 3 signal events and no backgrounds

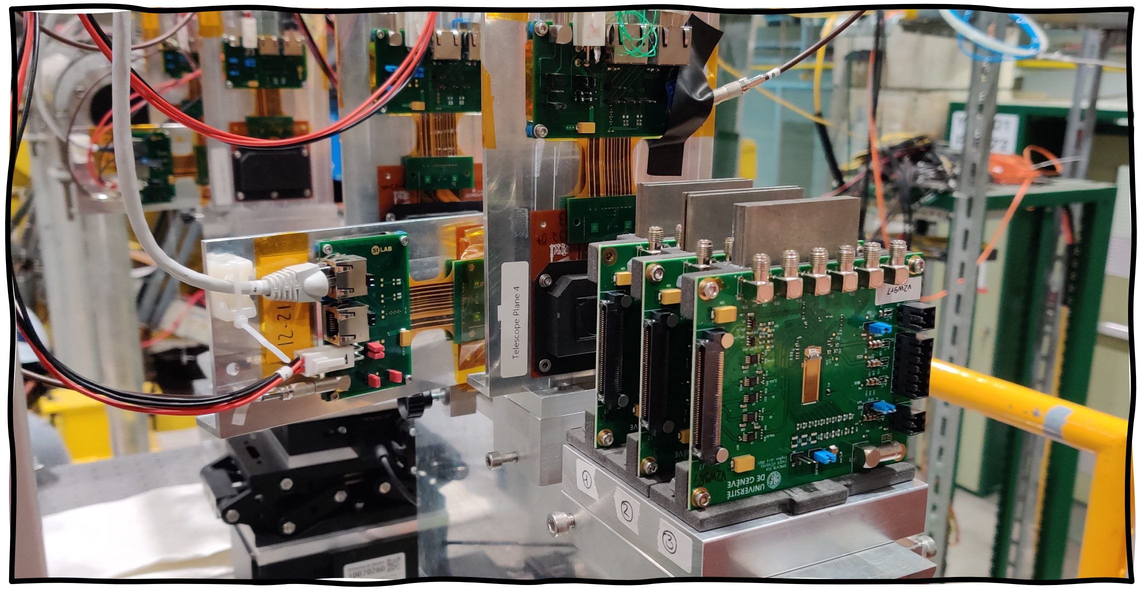
Preshower Upgrade

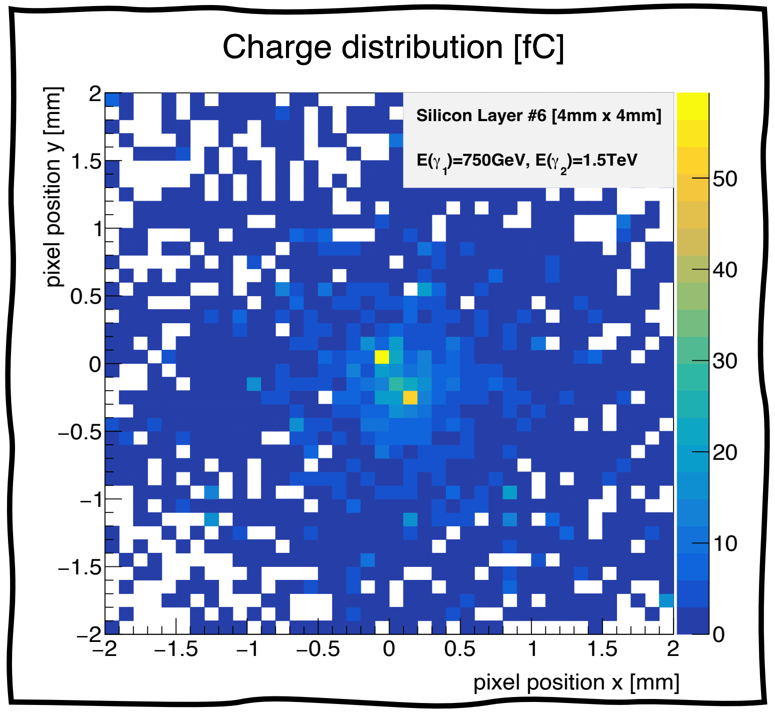


to enable 2-γ physics

- Existing pre-shower to be replaced with a high-resolution silicon pre-shower detector using monolithic pixel ASICs

Preproduction ASICs in testbeam, Sept 2022





- Distance between two photons: 200 µm
- Distinguishable!

Detector to be used for 2025 data taking

https://cds.cern.ch/record/2803084

What's beyond Run 3 ?

Beyond FASER? A teaser for the proposed Forward Physics Facility

The rich physics program in the far-forward region strongly motivates creating a dedicated Forward Physics Facility to house far-forward experiments for the HL-LHC era from 2028-2040s

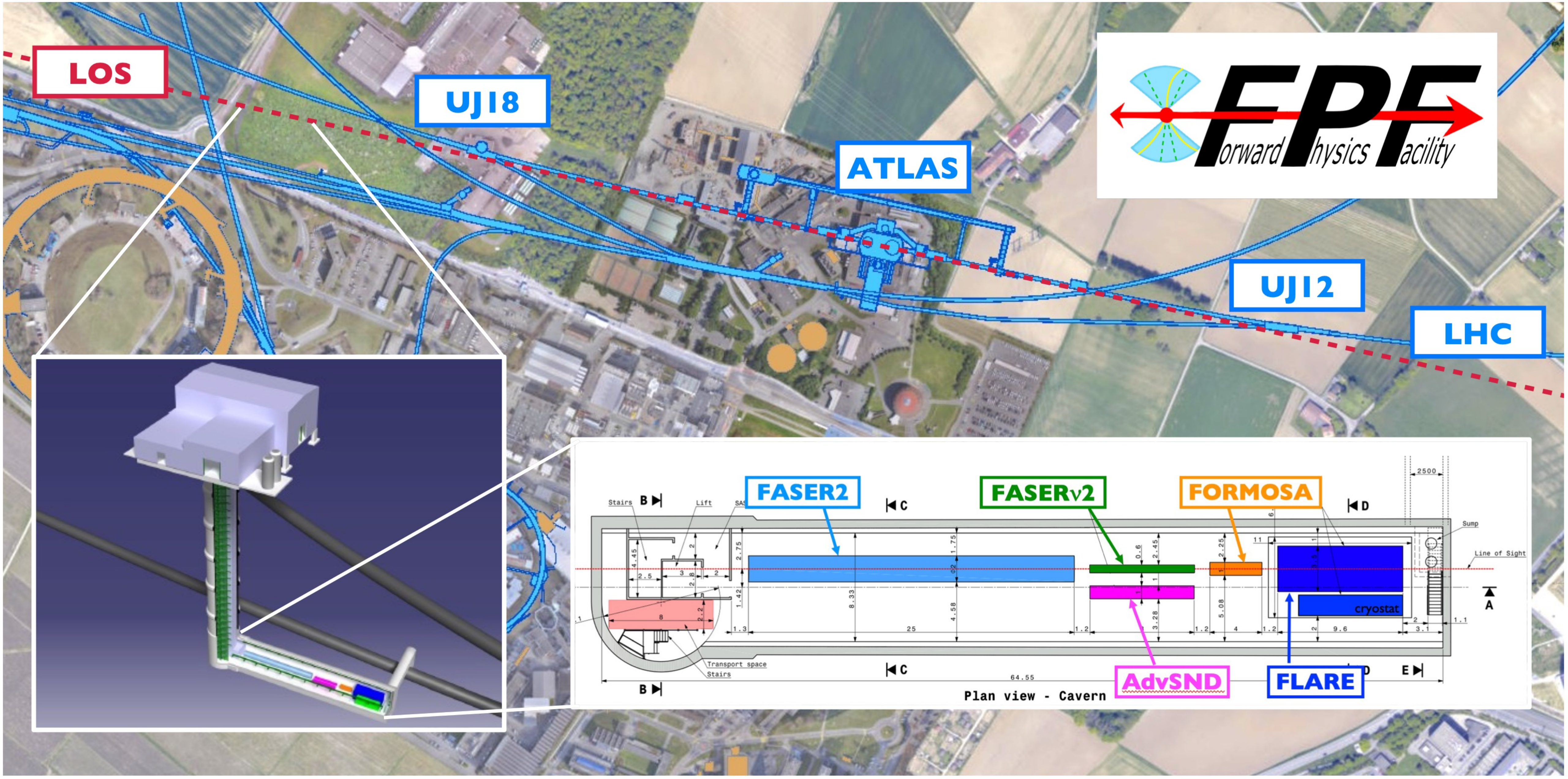
Well aligned with the recommendations of recent community studies

The full physics potential of the LHC and the HL- LHC [...] should be exploited.
1st recommendation of the 2020 European Strategy Update

Our highest immediate priority accelerator and project is the HL-LHC, [...] including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades.
Snowmass 2021 Energy Frontier Report

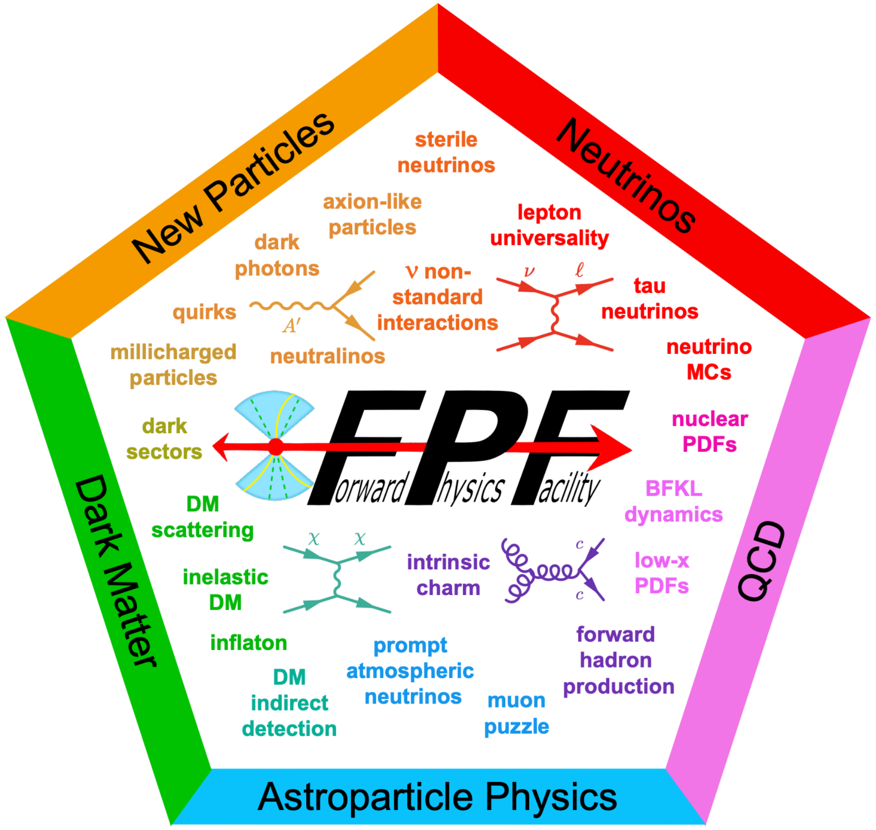
More: Submitted to P5 just in April 2023
LoI for SNOWMASS-2021
arXiv:2203.05090
FPF – Kickoff workshop
FPF – 5th (latest) workshop
FPF – 6th workshop coming up next week!

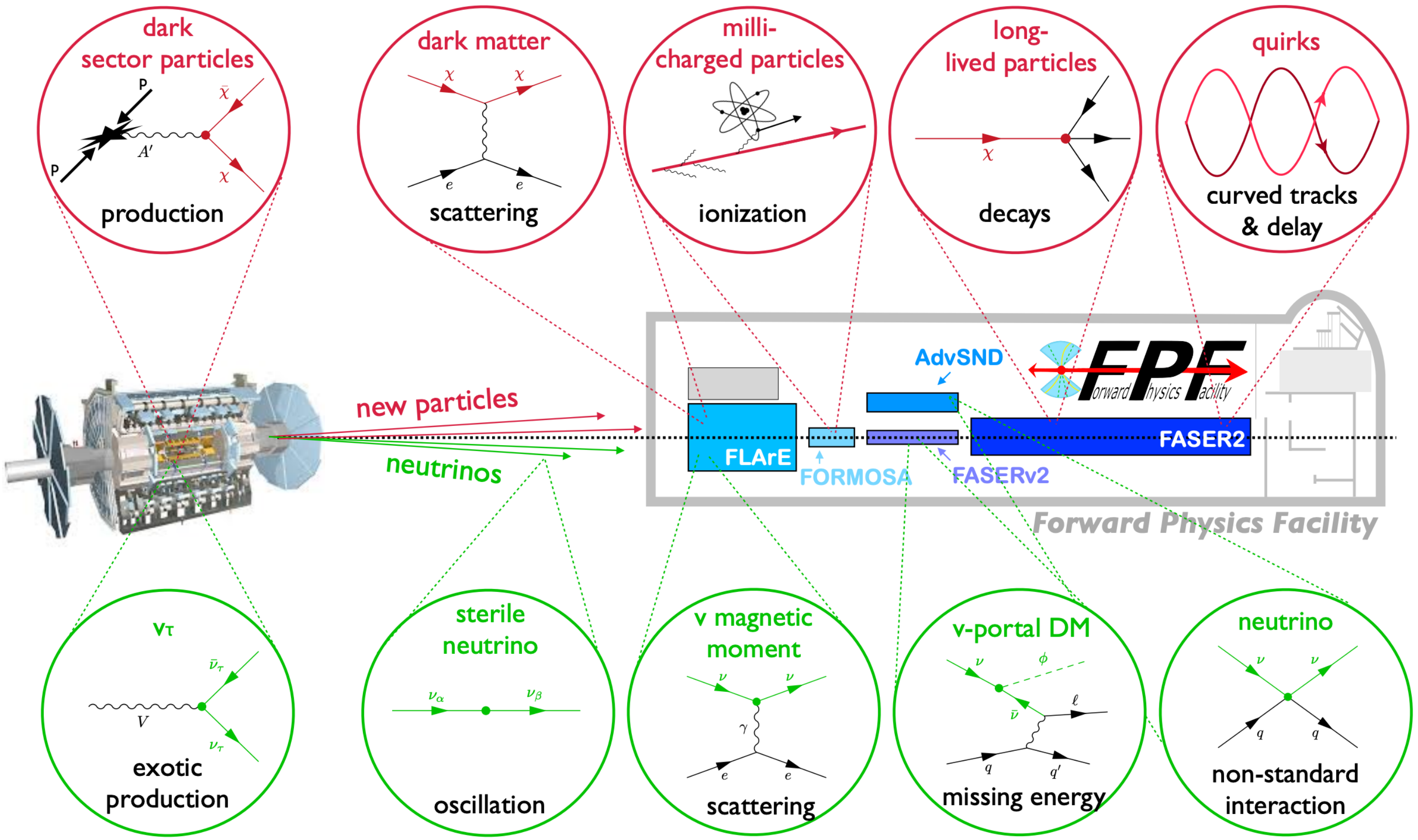
Please join if interested!



arXiv:2203.05090

The physics programme of FPF



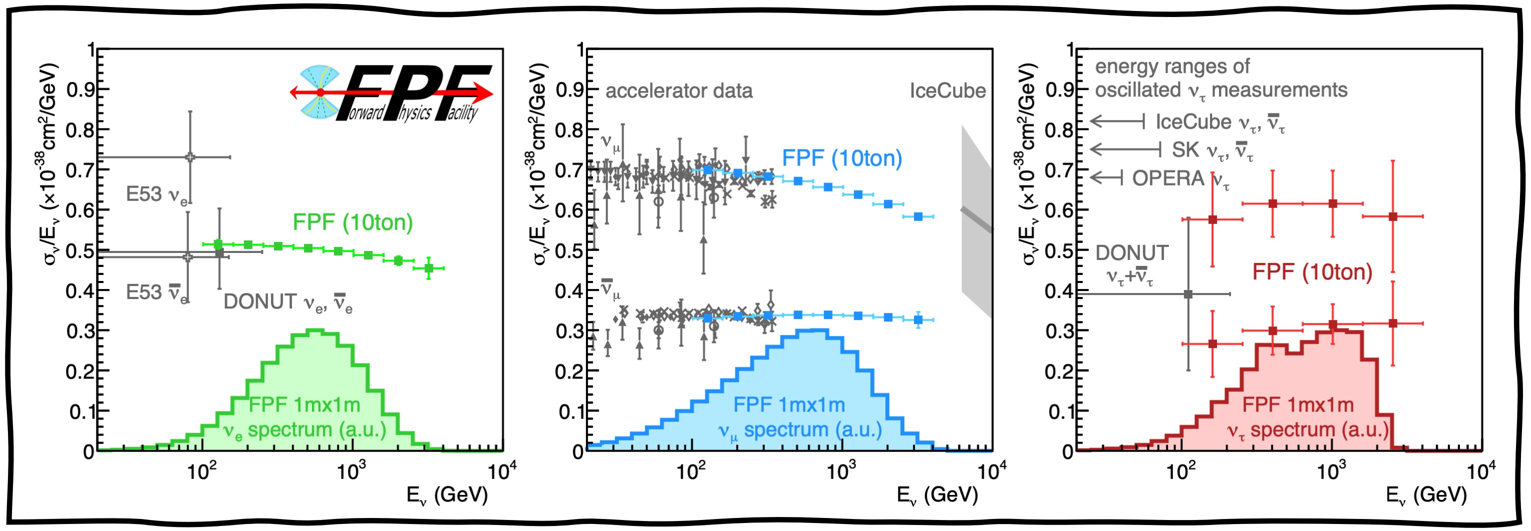


From https://pbc.web.cern.ch/sites/default/files/2023-04/FPFSummary_final.pdf

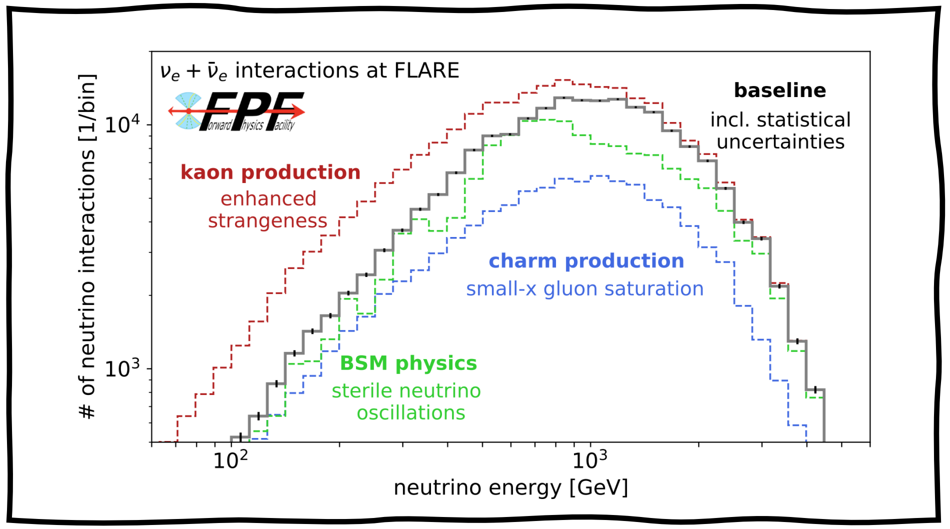
A rich neutrino programme

	Available lumi	Mass of *ν* detector	ν_e	ν_μ	ν_τ
Main production source			kaon decay	pion decay	charm decay
# interacting in FASER*ν*	150 / fb	1 tn Tungsten	~1000	~20000	~10
# interacting in FASER*ν*2	3000 / fb	10 tn Tungsten	~10^5	~10^6	~10^4

Unprecedented numbers of detectable neutrinos, at energy ranges where there is currently no available data!



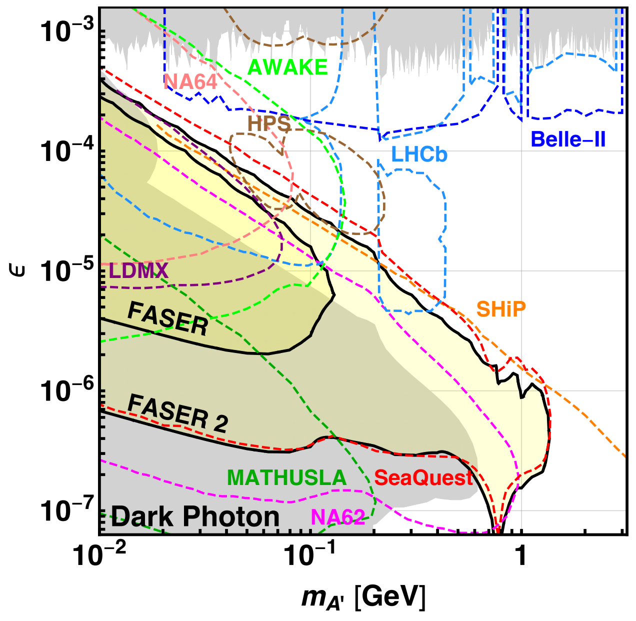
Expected precision of FPF measurements of the neutrino interaction cross section with nucleons

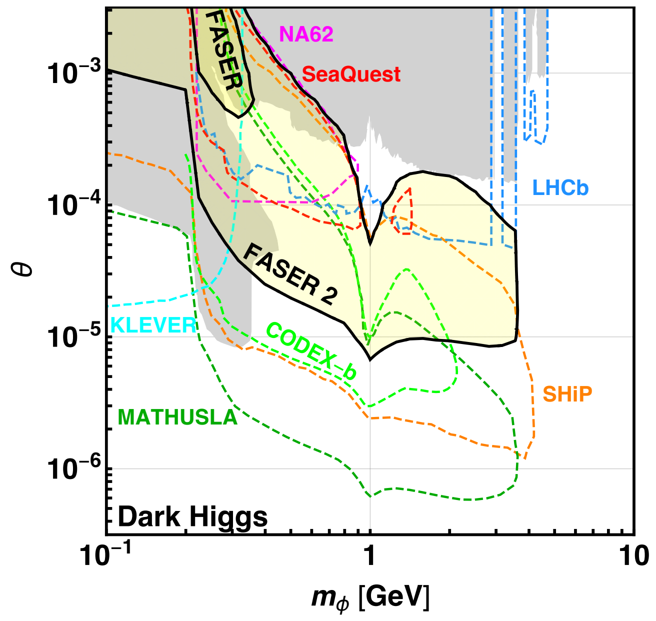


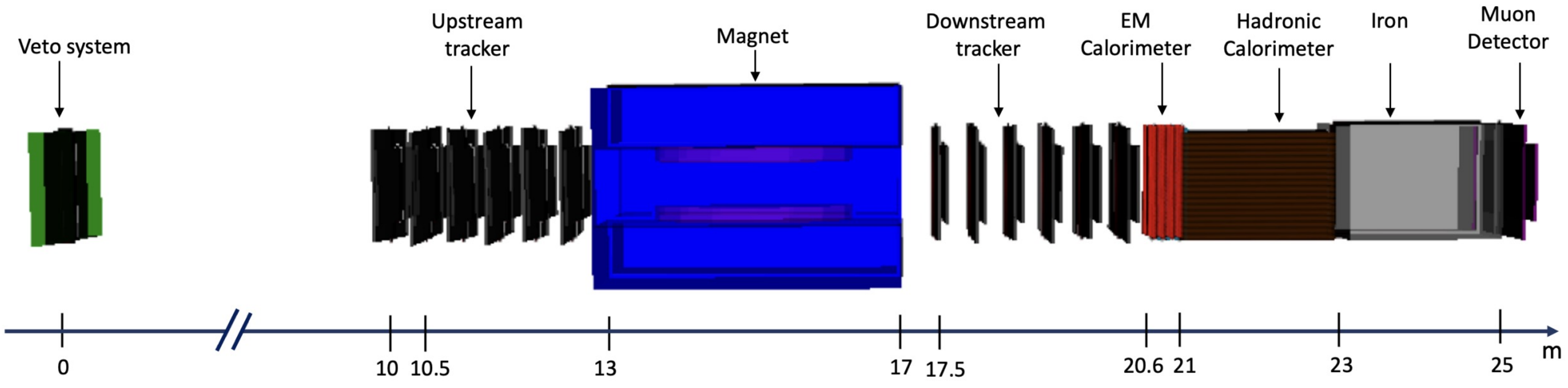
Coloured lines: three examples of physics that can change the expected flux, all probed at FPF

BSM & FASER2

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







Possible FASER2 layout

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) worked feverishly to construct, install & commission the detector over the Long Shutdown, & successfully collect Run 3 data
- **First FASER results available !**
  - **Dark photon exclusion in interesting thermal relic region**
  - **First collider neutrino direct detection**
- Have started 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!

For financial support:

HEISING-SIMONS FOUNDATION
SIMONS FOUNDATION
Swiss National Science Foundation
erc
科研費 KAKENHI

FASER Collaboration: 24 institutes, about 87 members

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Technion Israel Institute of Technology
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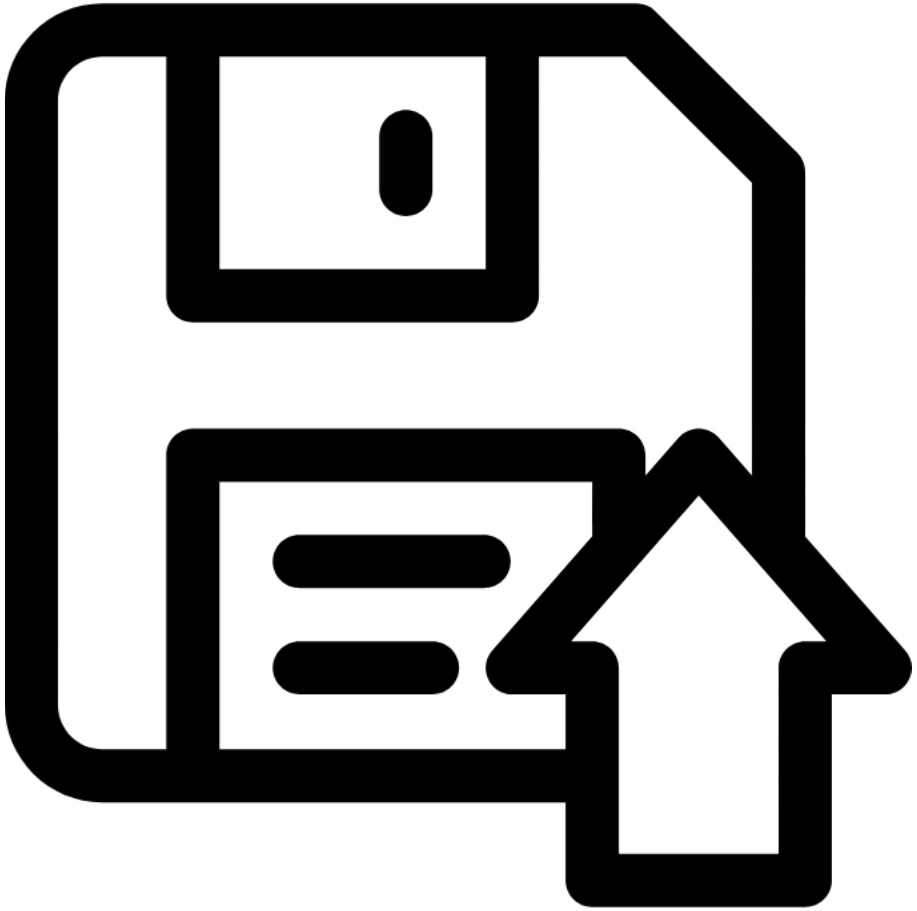
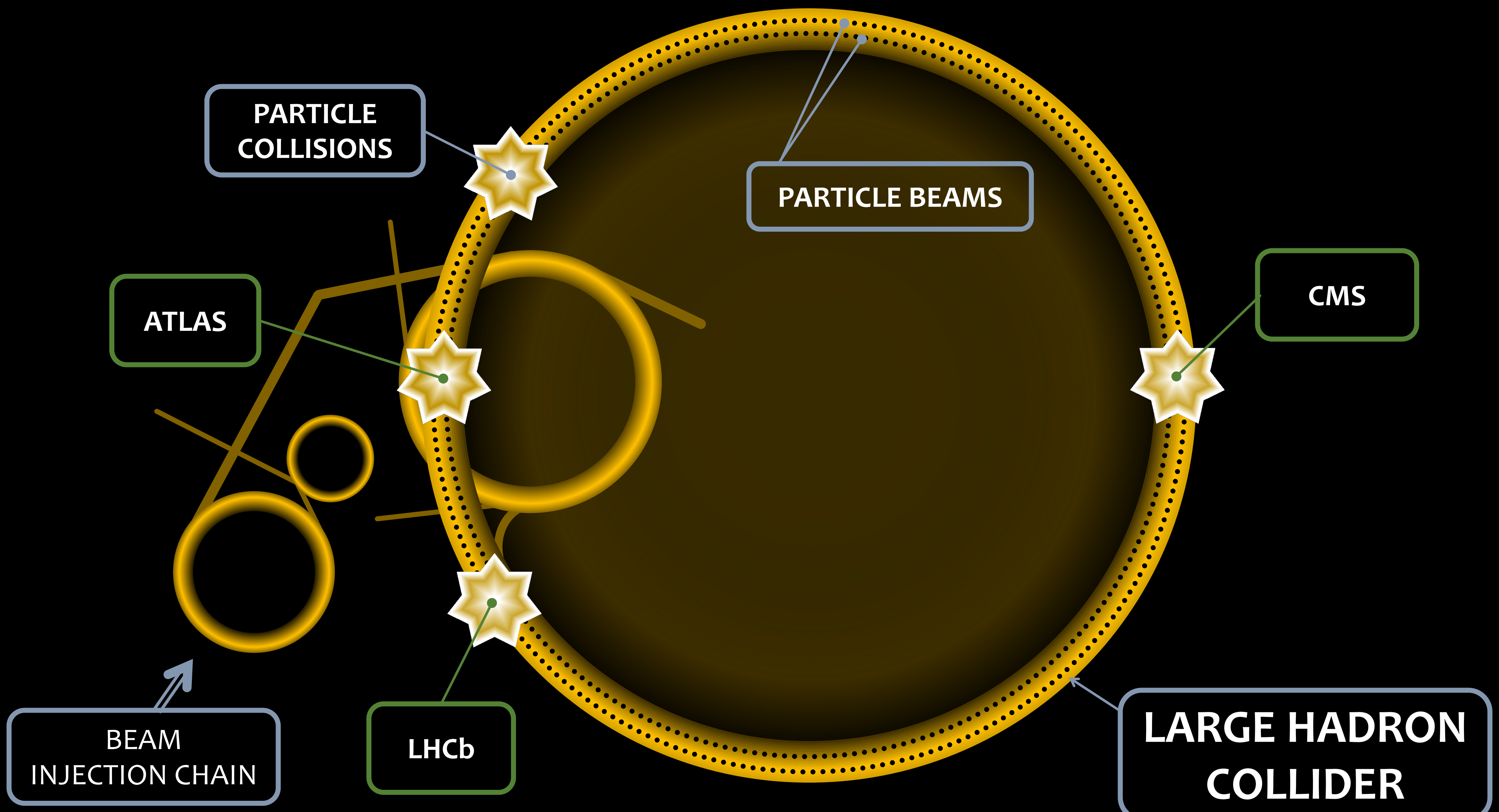
International laboratory covered by a cooperation agreement with CERN
UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

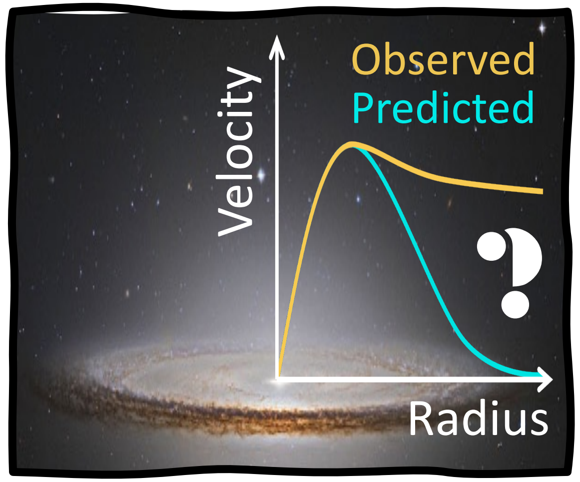
UNIVERSITÉ DE GENÈVE
FACULTY OF SCIENCE

CERN

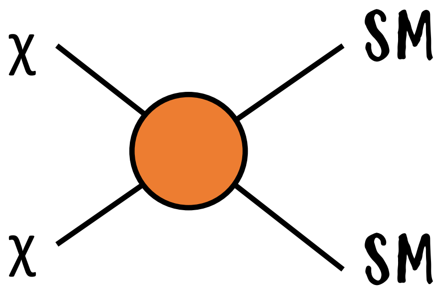


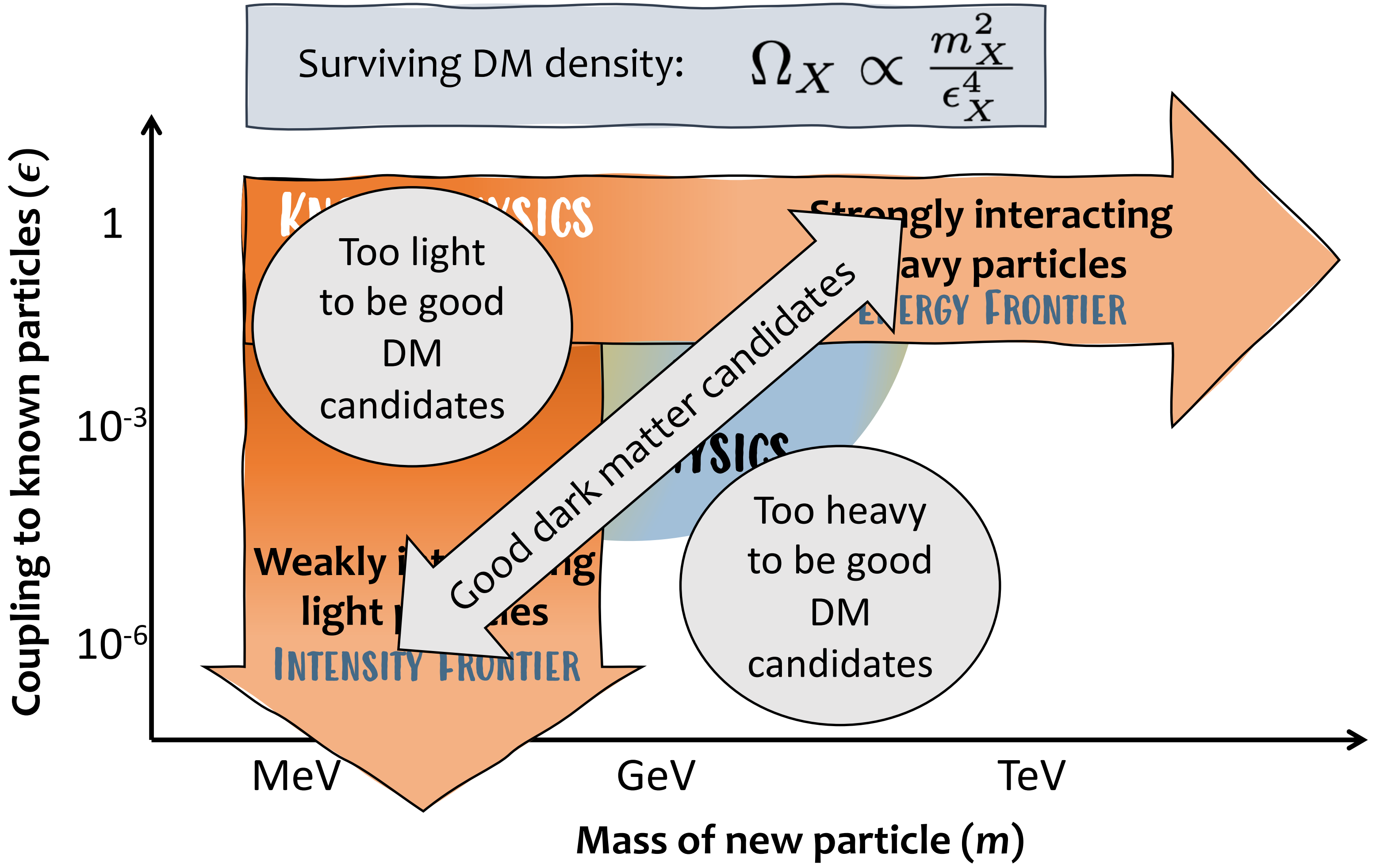

PARTICLE COLLISIONS
PARTICLE BEAMS
ATLAS
CMS
BEAM INJECTION CHAIN
LHCb
LARGE HADRON COLLIDER

The landscape of new particles @ colliders



- Simple mechanism for DM evolution: "freeze out"





Feebly Interacting Particles (FIPs)

- Due to interacting feebly, they are linked to a "hidden sector"
- Couplings between SM and hidden sector result from "portal" operators
- Large number of specific models; can be simplified to the following:

SM Higgs h — h ----- $(\mu S + \lambda S^2) H^\dagger H$ ----- S — Dark Higgs S

New scalar: **Dark Higgs**; couplings to SM μ, λ

SM EM A — A 〰 $-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} F_Y^{\mu\nu}$ 〰 A_D — Dark EM A_D

New vector: **Dark photon**; coupling to SM $\propto \epsilon Q$

SM 2γ or $2f$ — 2γ --- $\frac{\alpha}{f_\alpha} F_{\mu\nu} \tilde{F}^{\mu\nu}$; $2f$ --- $\frac{\partial_\mu \alpha}{f_\alpha} \bar{\psi} \gamma^\mu \gamma^5 \psi$ ----- α — ALP α

New pseudo-scalar: **ALP**; coupling to SM suppressed

(Axion Like Particle)

SM LH ν — ν —— $y_N h L \psi_D$ —— N — HNL N

New fermion: **HNL**; coupling to LH SM and h $\propto y_N$

(Heavy Neutral Lepton)

- The masses of the new particles can span several orders of magnitude

Dark Photon Physics

Dark photon's properties defined through the Lagrangian terms :

$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon\, e \sum_f q_f A'_\mu \bar{f} \gamma^\mu f \ ,$$

For dark photon masses $2m_e < m_{A'} < 2m_\mu \simeq 211$ MeV, dark photons decay to electrons with $B(A' \longrightarrow e{+}e{-}) \approx 100\%$:

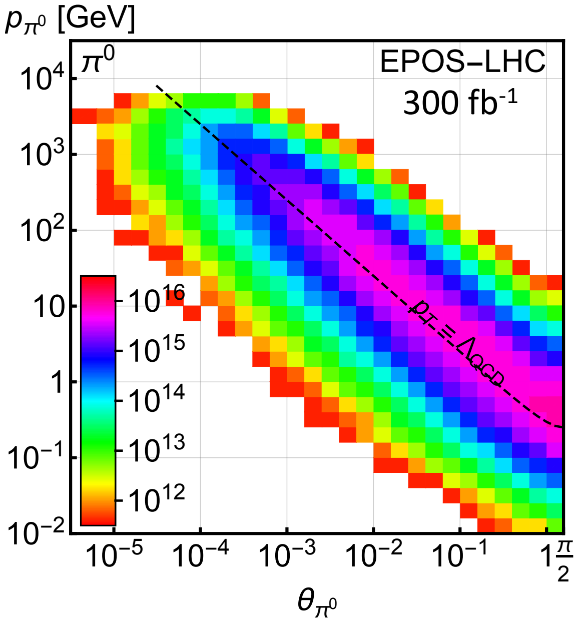
$$\Gamma_e \equiv \Gamma(A' \to e^+ e^-) = \frac{\epsilon^2 e^2 m_{A'}}{12\pi} \left[1 - \left(\frac{2m_e}{m_{A'}}\right)^2\right]^{1/2} \left[1 + \frac{2m_e^2}{m_{A'}^2}\right] \ .$$

For $E_{A'} \gg m_{A'} \gg m_e$, the dark photon decay length :

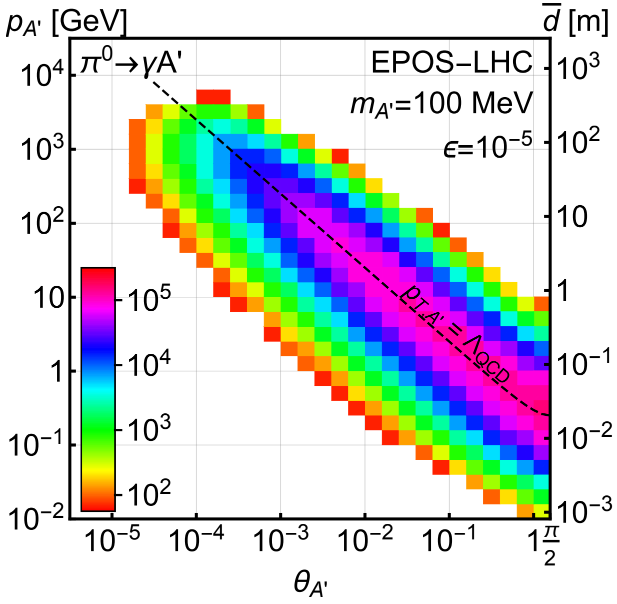
$$L = c\beta\tau\gamma \approx (80 \text{ m}) \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{\text{TeV}}\right] \left[\frac{100 \text{ MeV}}{m_{A'}}\right]^2$$

SIGNALS: DARK PHOTONS

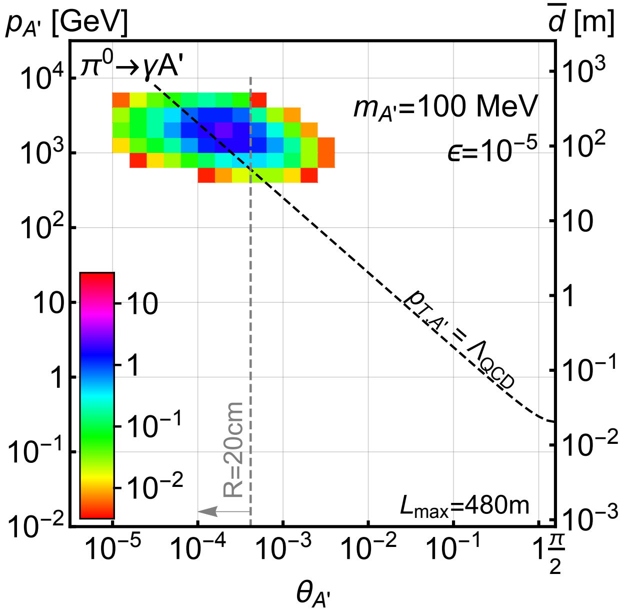
Pions at the IP



A's at the IP



A's decay in FASER



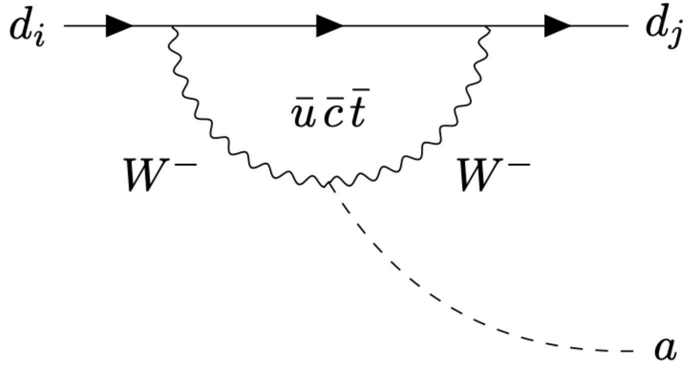
- Enormous event rates: $N_\pi \sim 10^{15}$ per bin
- Production is peaked at low transverse momentum ~250 MeV

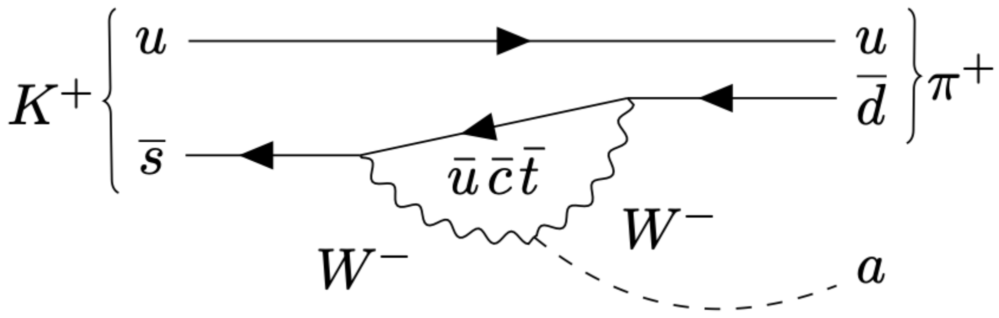
- Rates highly suppressed by $\varepsilon^2 \sim 10^{-10}$
- But still $N_{A'} \sim 10^5$ per bin; LHC is a dark photon factory!

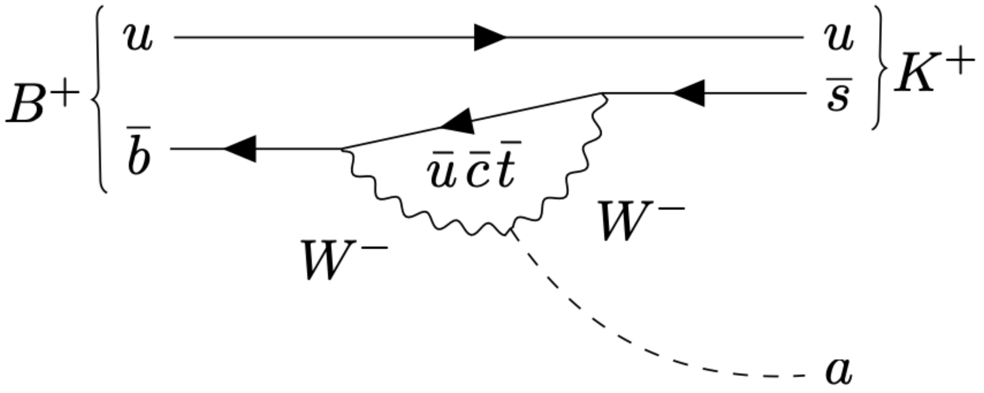
- Rates suppressed again, but still $N_{A'} \sim 100$ signal events
- Signal is E~TeV A's within 20 cm of the line of sight

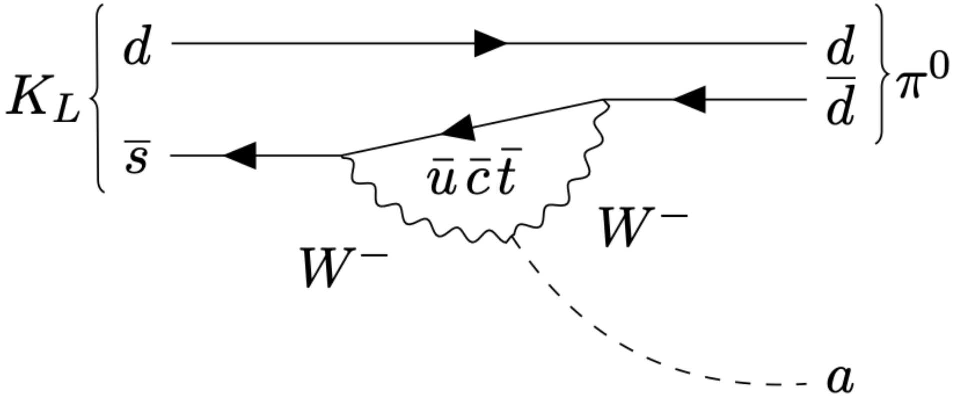
Slide from J. Feng

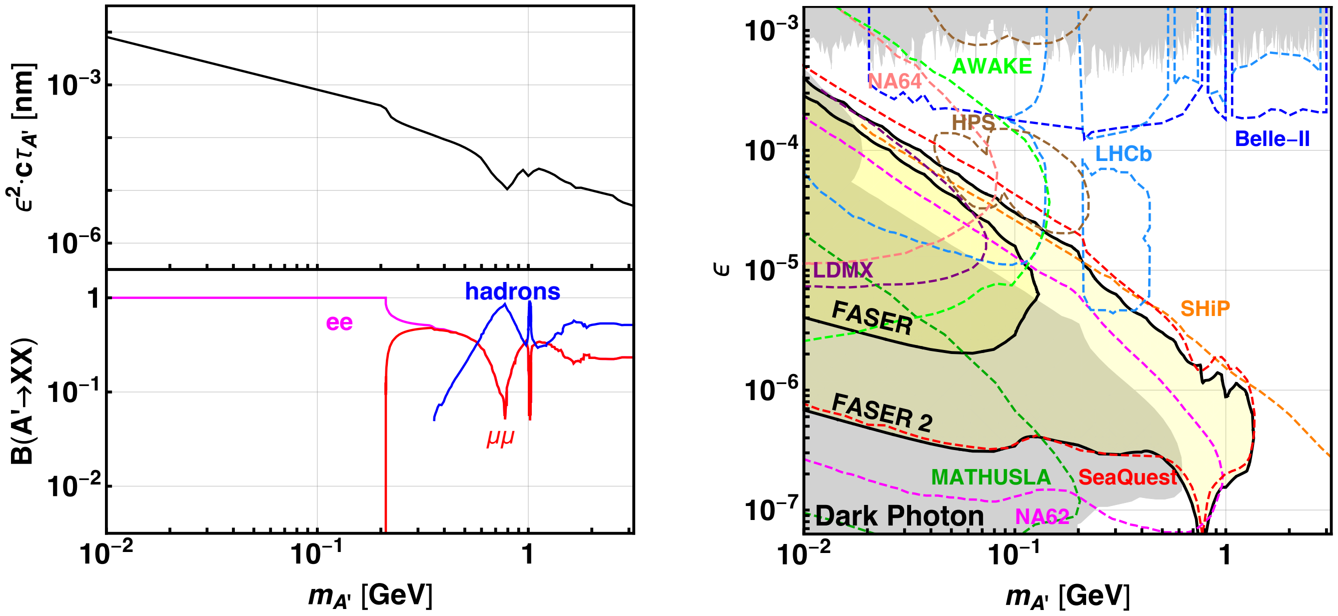
ALP production beyond primakoff



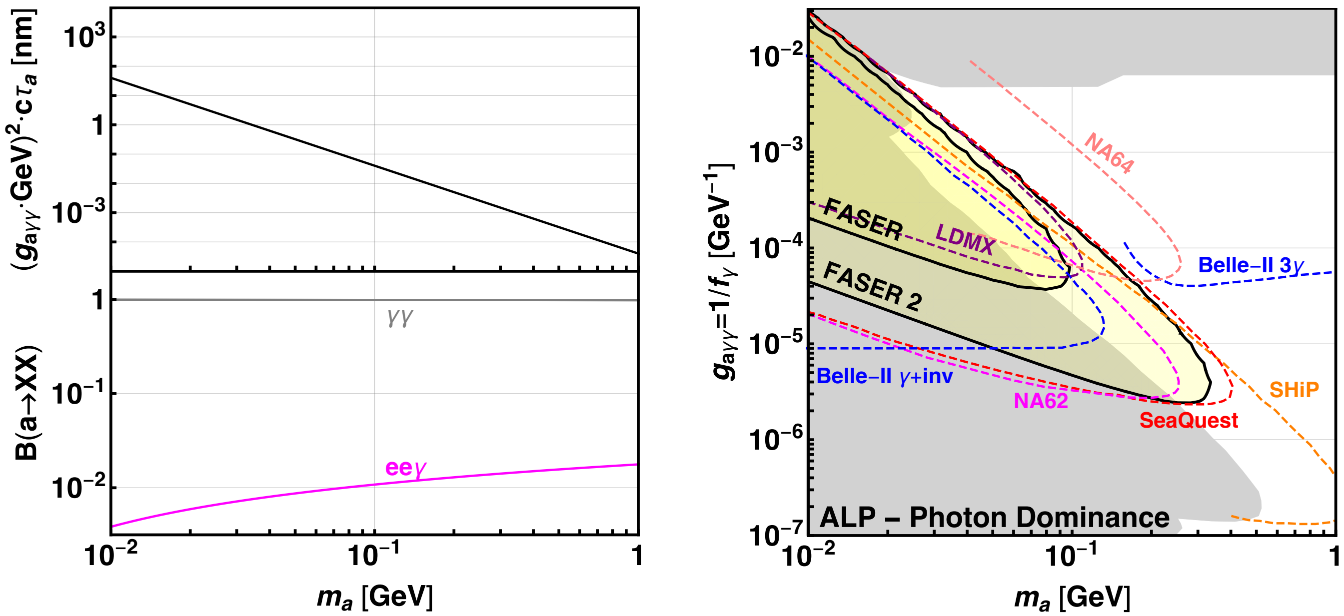








$\epsilon^2 \cdot c\tau_{A'}$ [nm]
B(A'→XX)
ee
hadrons
μμ
$m_{A'}$ [GeV]
AWAKE
NA64
HPS
LHCb
Belle–II
LDMX
SHiP
FASER
FASER 2
MATHUSLA
SeaQuest
NA62
Dark Photon
ϵ



$(g_{a\gamma\gamma} \cdot \mathrm{GeV})^2 \cdot c\tau_a$ [nm]
B(a→XX)
γγ
eeγ
m_a [GeV]
NA64
FASER
FASER 2
LDMX
Belle–II 3γ
Belle–II γ+inv
NA62
SeaQuest
SHiP
ALP – Photon Dominance
$g_{a\gamma\gamma}=1/f_\gamma$ [GeV^{-1}]

Reach for Heavy Neutral Leptons

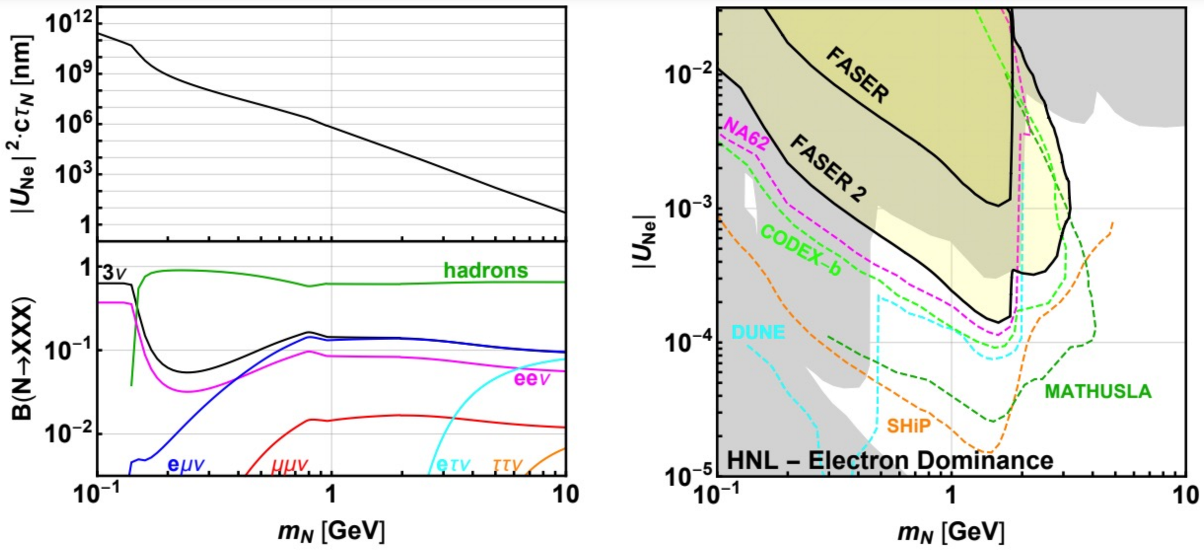


FIG. 12. **Benchmark Model F1.** The decay length (top left panel), decay branching fractions (bottom left panel), and FASER's reach (right panel) for the HNL that mixes only with the electron neutrino ν_e. The gray shaded regions are excluded by current limits, and the colored contours are the projected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

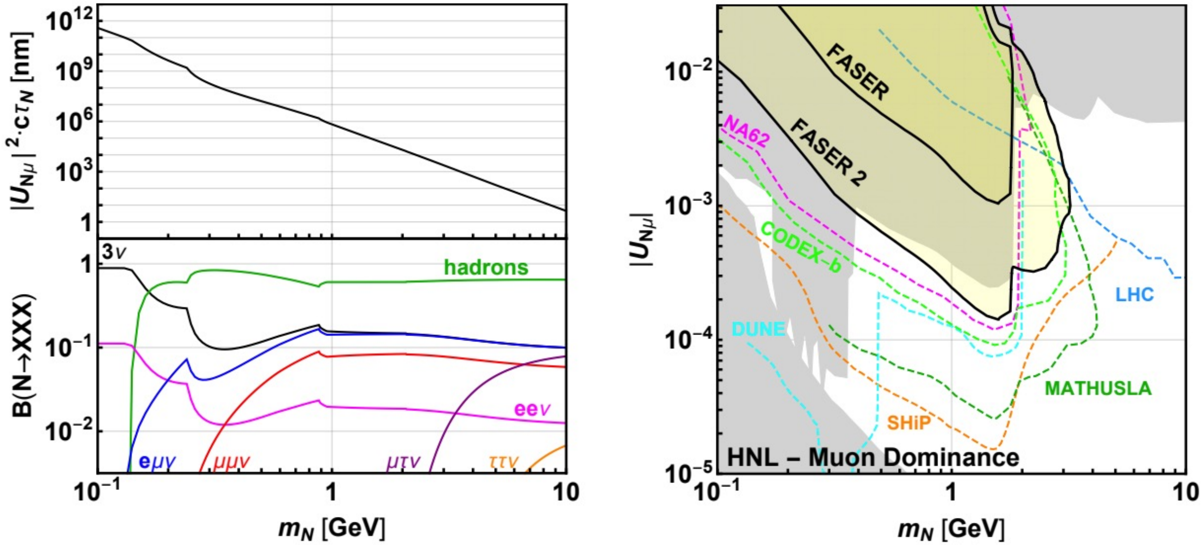


FIG. 13. **Benchmark Model F2.** As in Fig. 12, but for an HNL that only mixes with ν_μ.

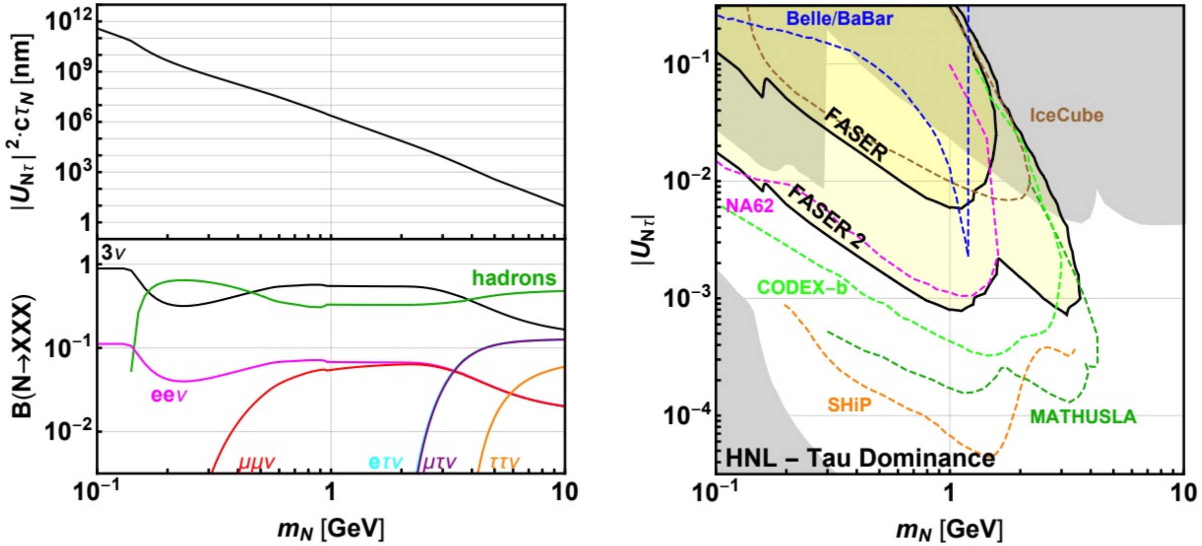
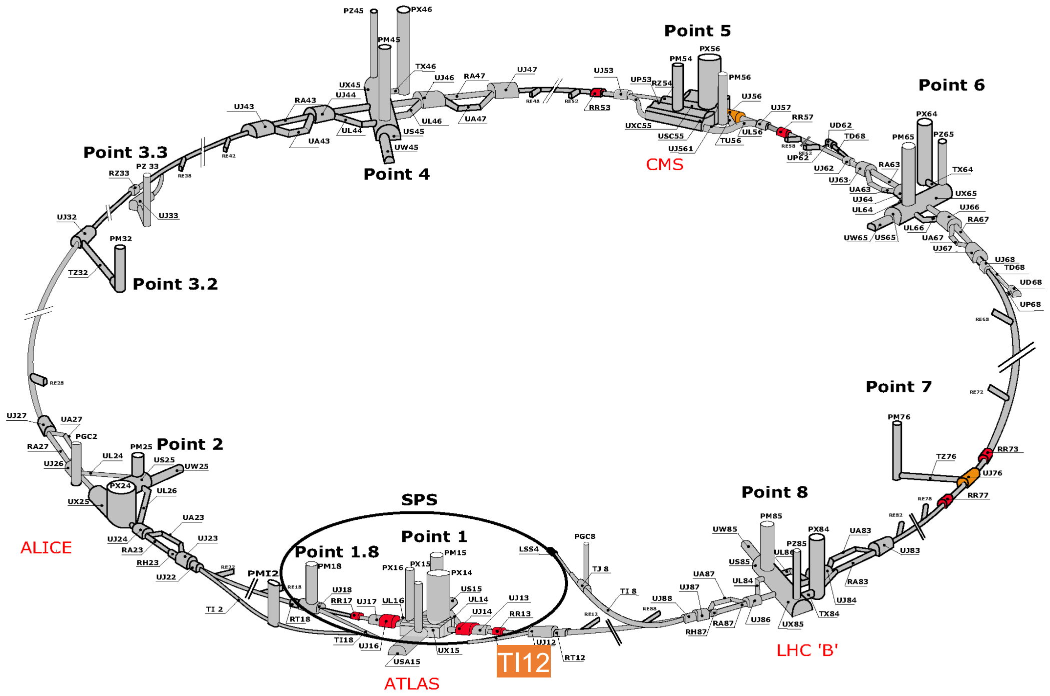
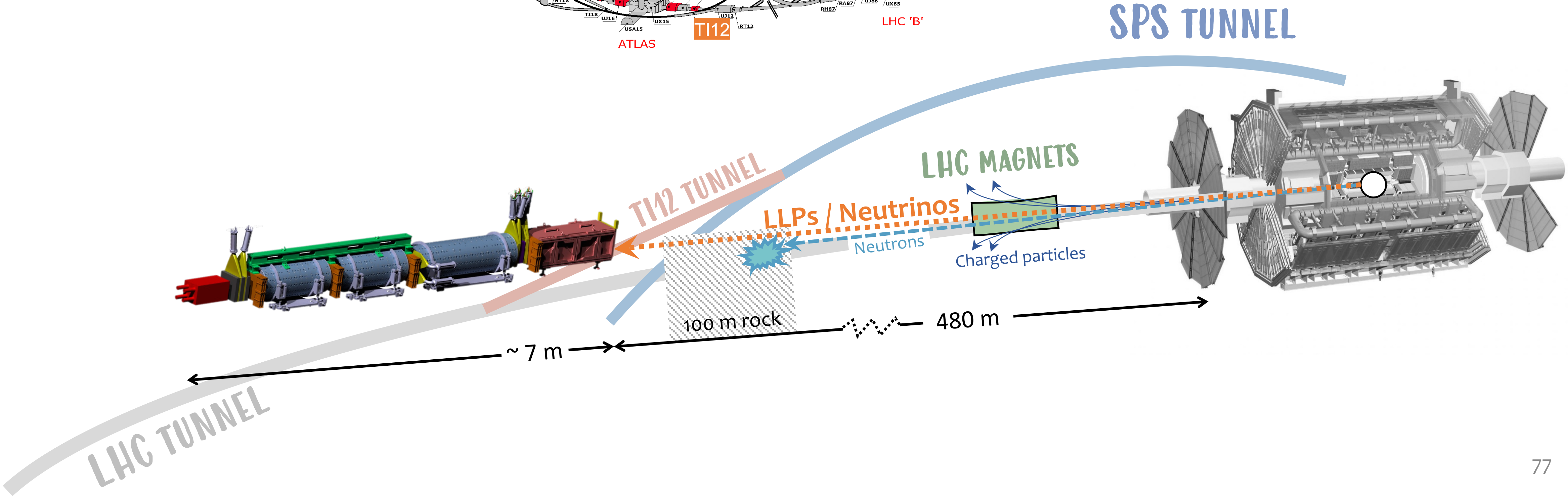


FIG. 14. **Benchmark Model F3.** As in Fig. 12, but for an HNL that only mixes with ν_τ.

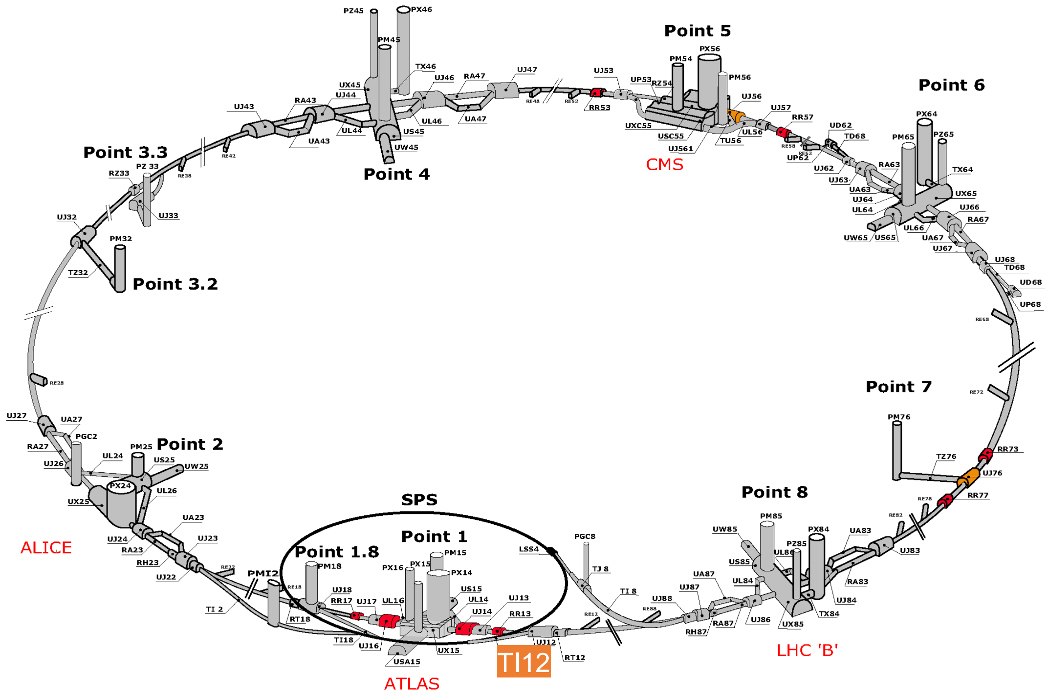
The FASER Detector

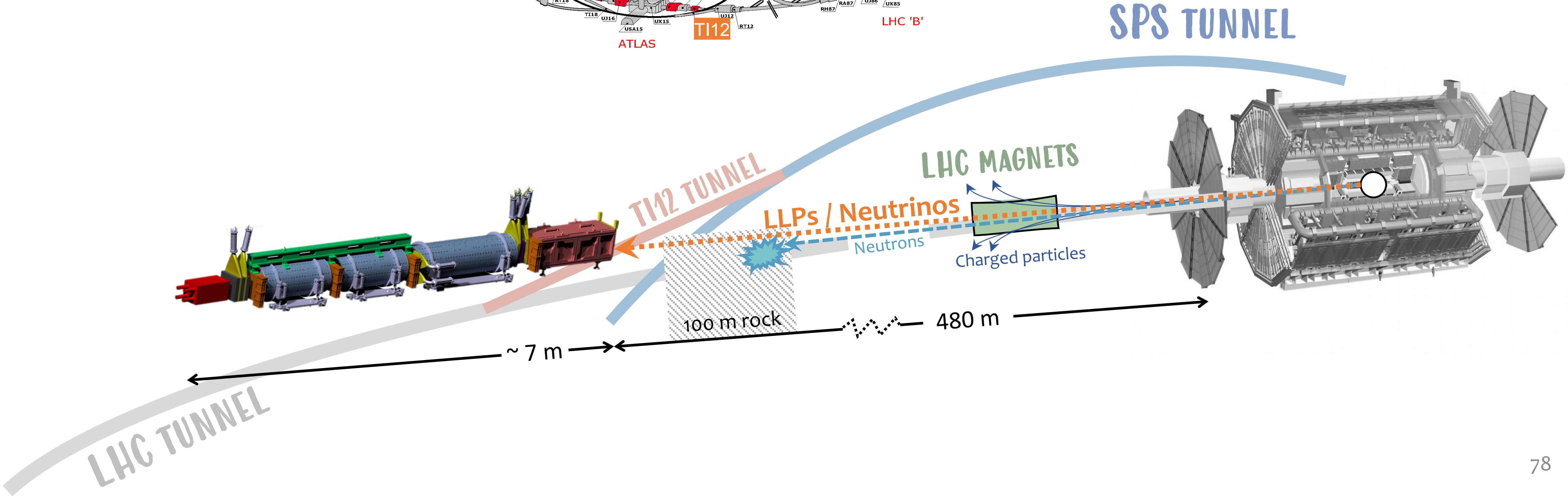
Location


Point 5
Point 6
CMS
Point 4
Point 3.3
Point 3.2
Point 7
Point 2
ALICE
SPS
Point 1
Point 1.8
Point 8
LHC 'B'
ATLAS
TI12

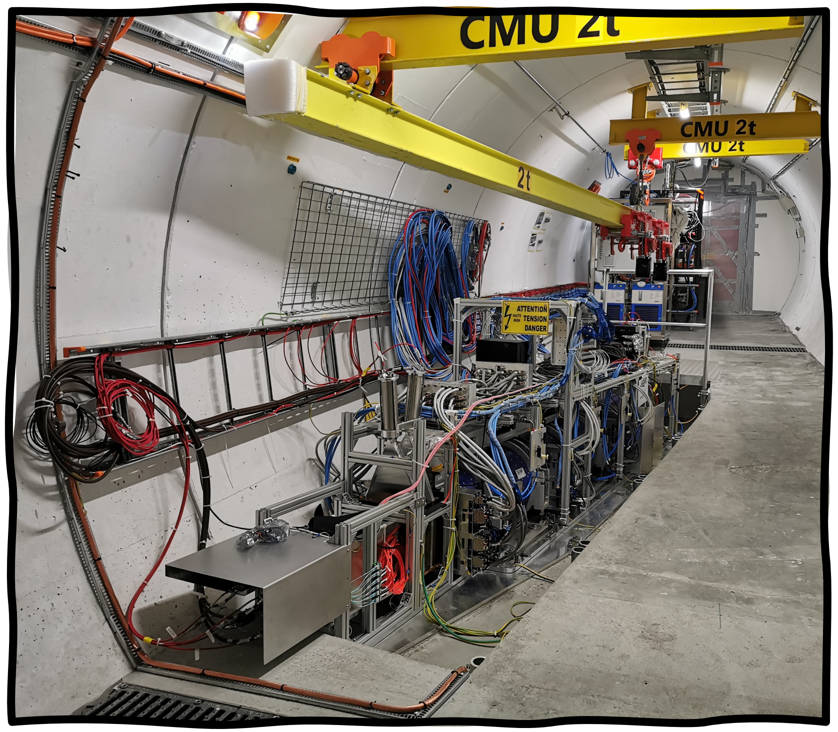

SPS TUNNEL
LHC MAGNETS
TI12 TUNNEL
LLPs / Neutrinos
Neutrons
Charged particles
100 m rock
480 m
~ 7 m
LHC TUNNEL

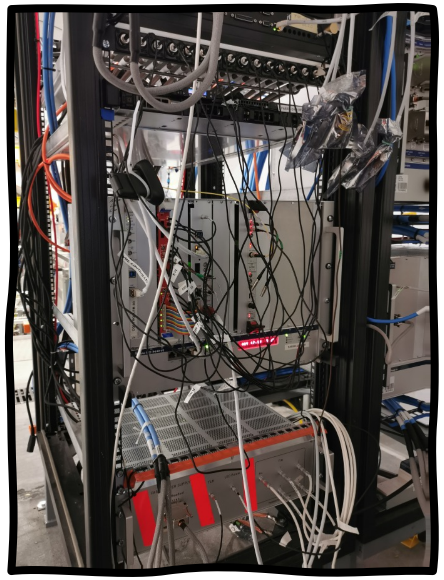
Location

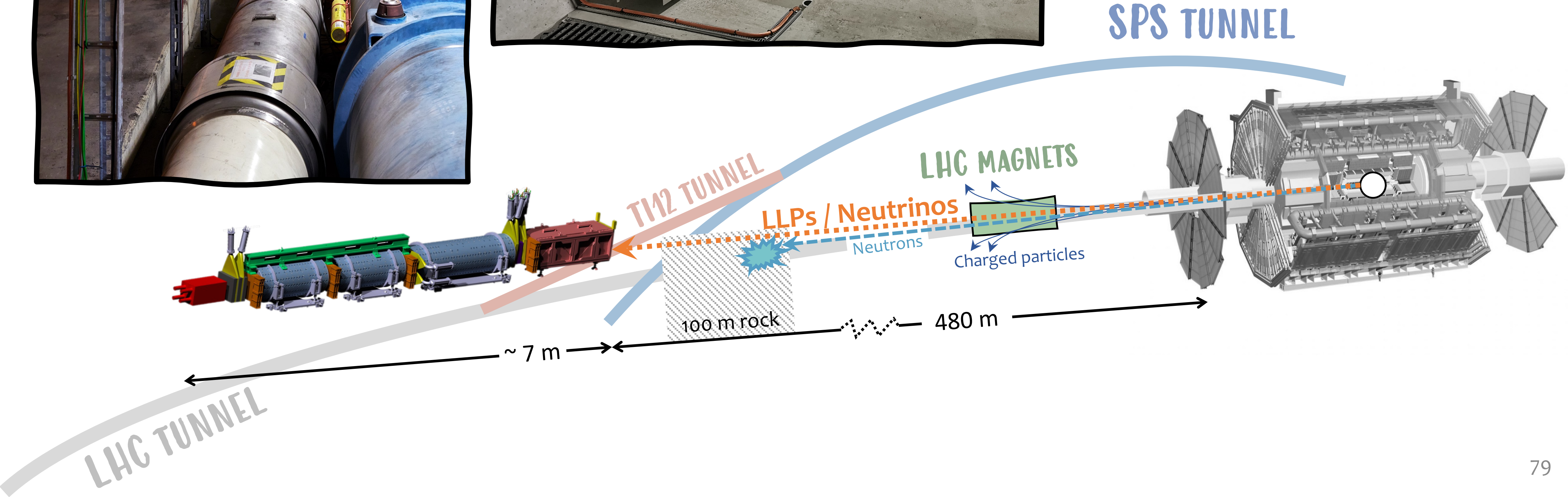

Point 5
Point 6
Point 3.3
Point 4
CMS
Point 3.2
Point 7
Point 2
Point 8
SPS
ALICE
Point 1
Point 1.8
TI12
ATLAS
LHC 'B'


SPS tunnel
LHC magnets
TI12 tunnel
LLPs / Neutrinos
Neutrons
Charged particles
100 m rock
480 m
~ 7 m
LHC tunnel

Location

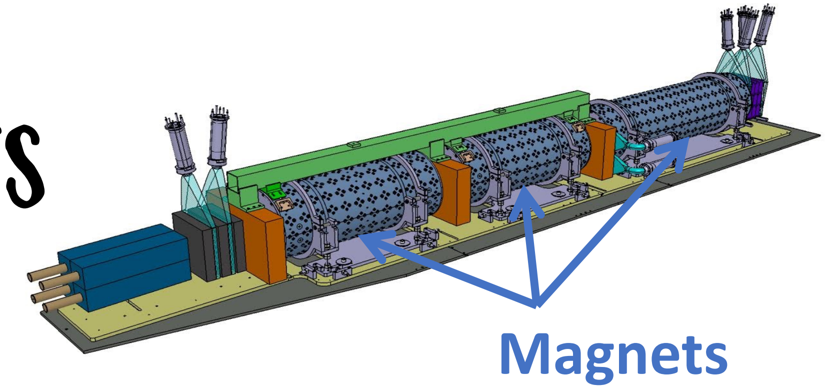


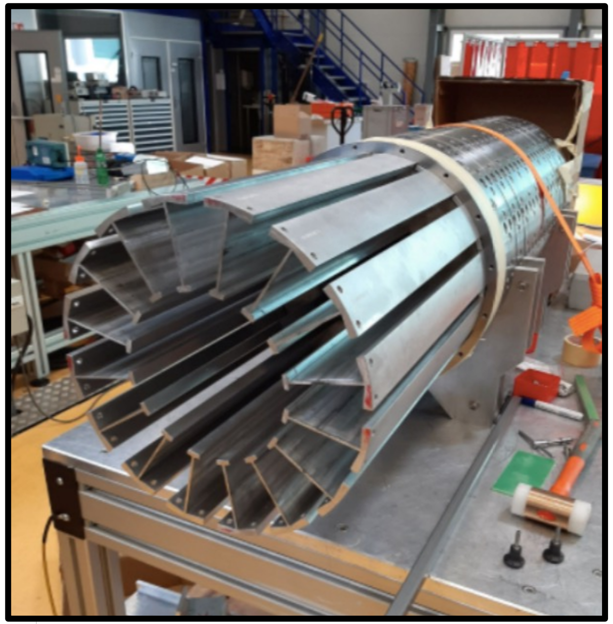




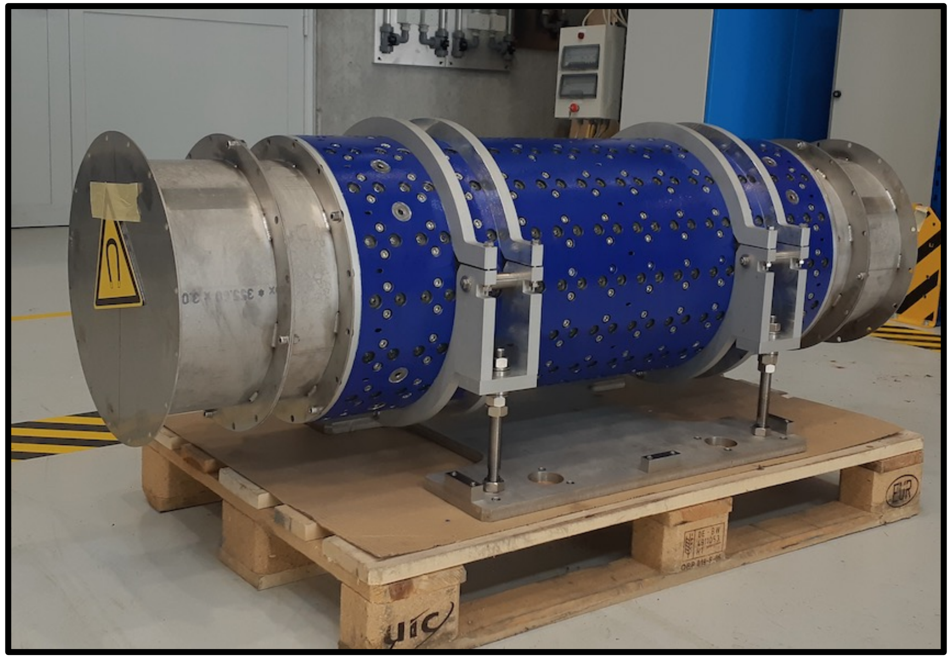
SPS tunnel
LHC magnets
T112 tunnel
LLPs / Neutrinos
Neutrons
Charged particles
100 m rock
480 m
~ 7 m
LHC tunnel

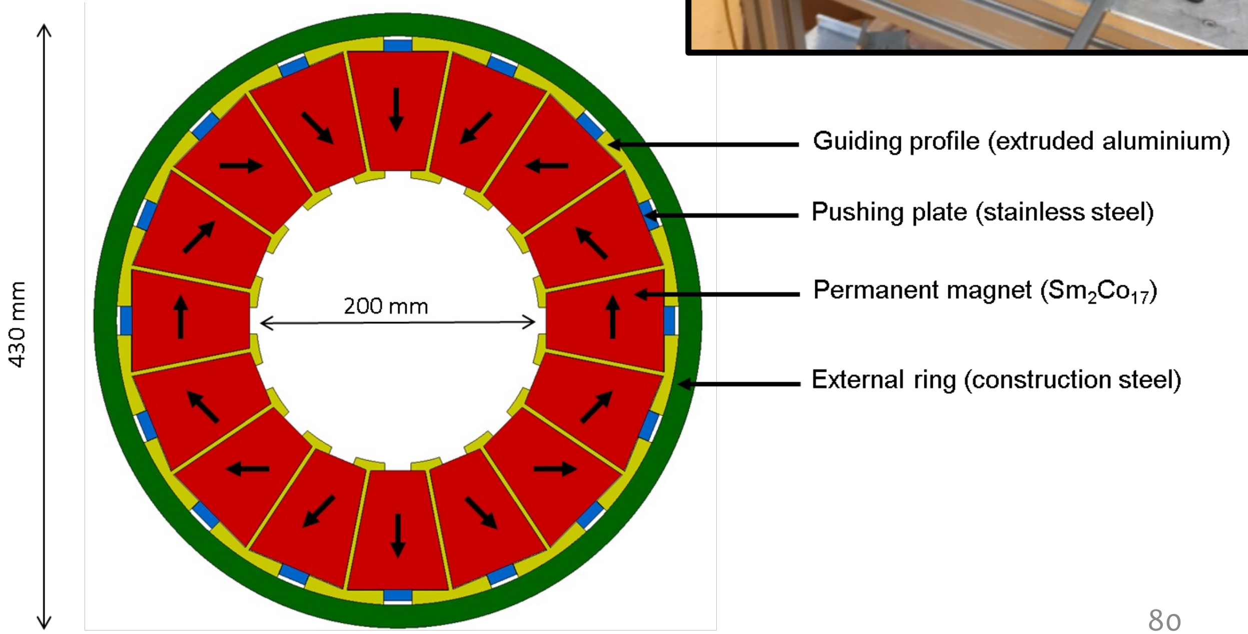
FASER Magnets



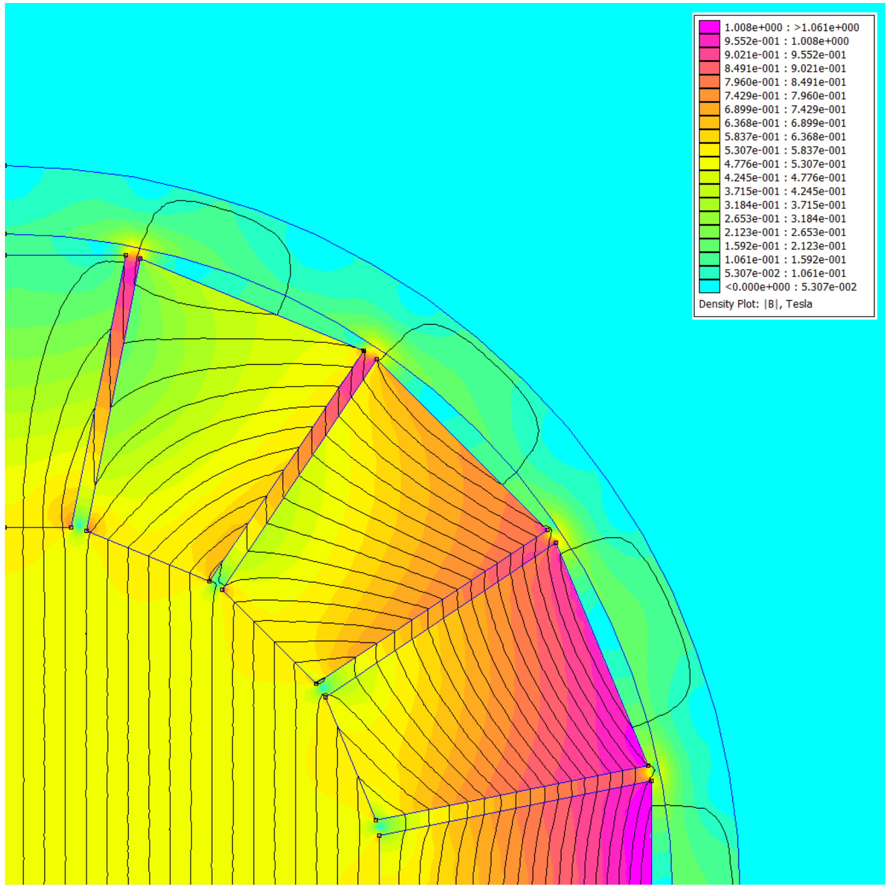


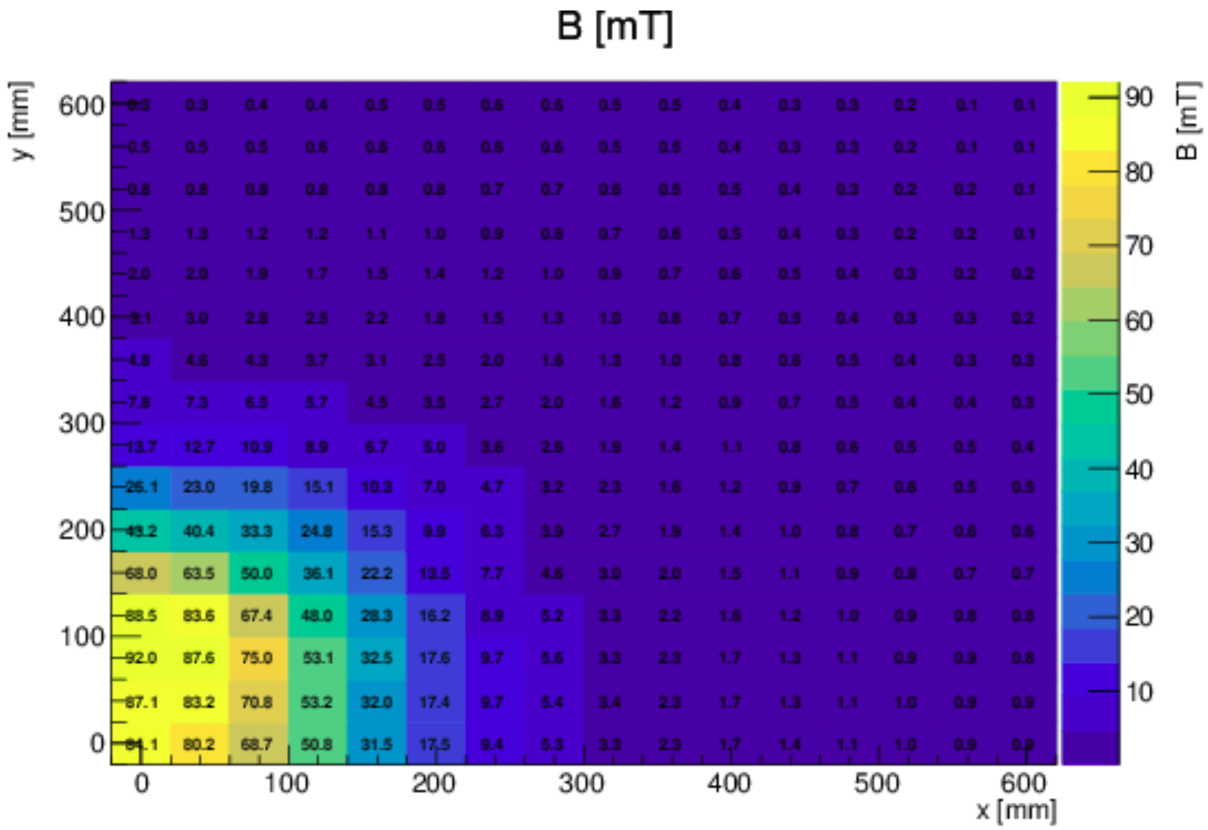
- Field of 0.55 T; permanent dipole
- Halbach array design with fixed-field magnets
  - Maximizes field without need for too much support infrastructure
  - Allows for a compact design, reducing amount of digging





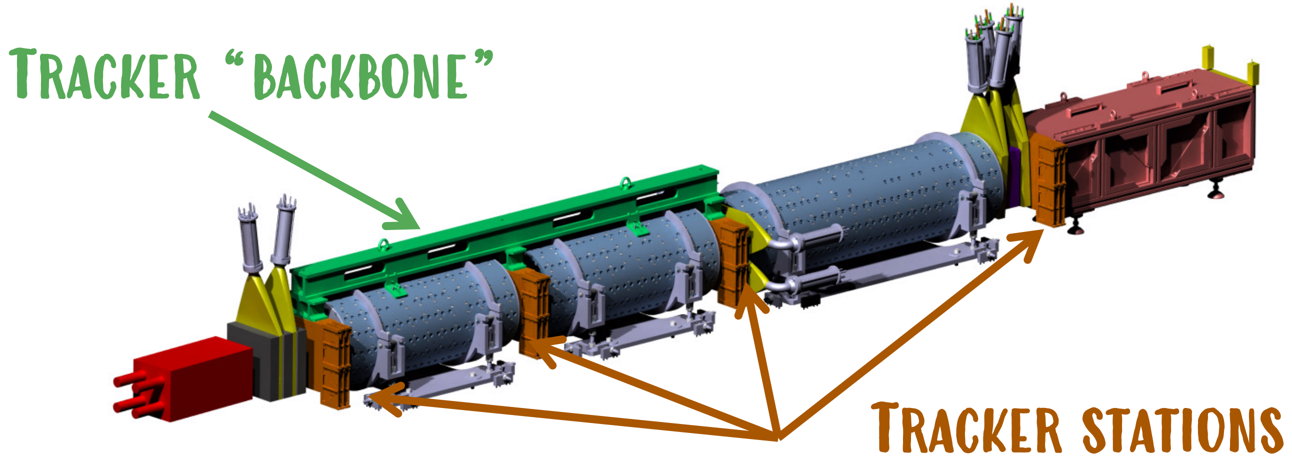
Magnets

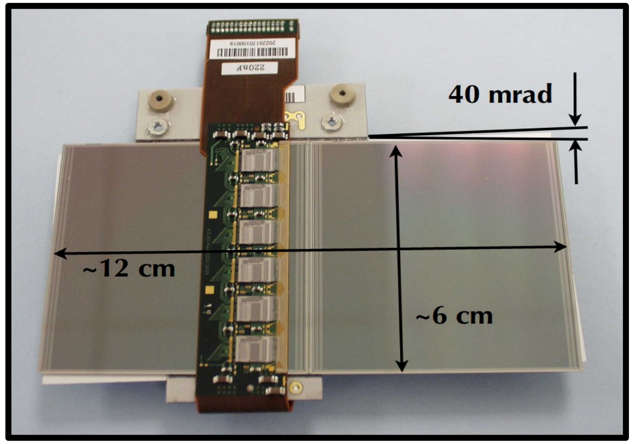

1.008e+000 : >1.061e+000
9.552e-001 : 1.008e+000
9.021e-001 : 9.552e-001
8.491e-001 : 9.021e-001
7.960e-001 : 8.491e-001
7.429e-001 : 7.960e-001
6.899e-001 : 7.429e-001
6.368e-001 : 6.899e-001
5.837e-001 : 6.368e-001
5.307e-001 : 5.837e-001
4.776e-001 : 5.307e-001
4.245e-001 : 4.776e-001
3.715e-001 : 4.245e-001
3.184e-001 : 3.715e-001
2.653e-001 : 3.184e-001
2.123e-001 : 2.653e-001
1.592e-001 : 2.123e-001
1.061e-001 : 1.592e-001
5.307e-002 : 1.061e-001
<0.000e+000 : 5.307e-002
Density Plot: |B|, Tesla


B [mT]
y [mm]
x [mm]
B [mT]
0
100
200
300
400
500
600
10
20
30
40
50
60
70
80
90

TRACKER

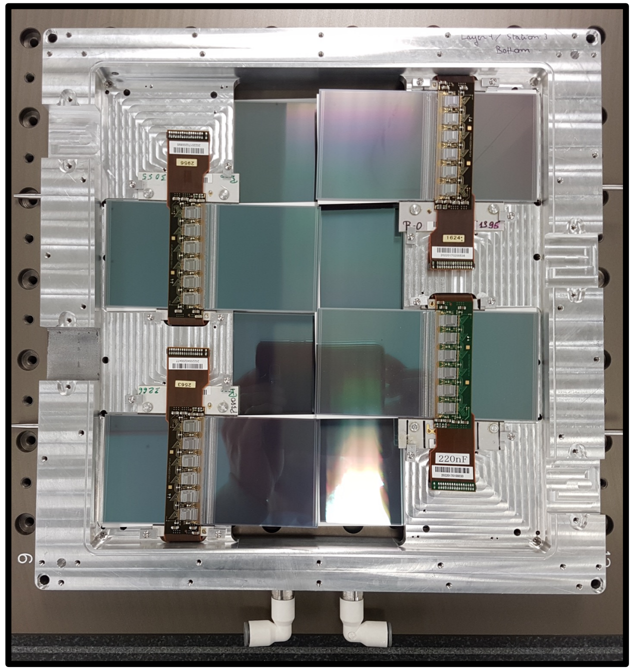
- FASER uses ATLAS SCT spare modules
- 4 tracker stations x 3 tracker layers x 8 modules
  - 96 modules and O(10⁵) channels in total
- Mechanical stability by "backbone" fixed on magnets
- Read out with custom GPIO board





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

Tracker layer



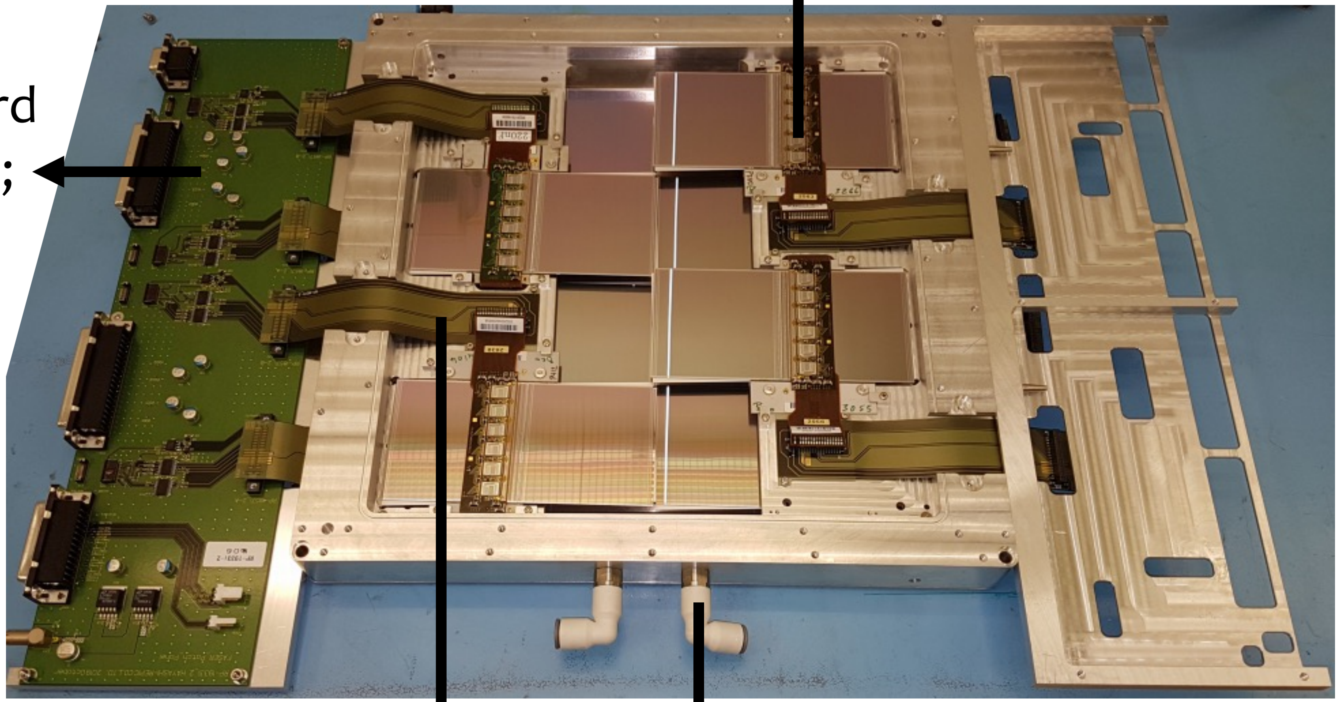
arXiv: 2112.01116

Tracker

SCT module ASICs,
require ~ 5 W / module

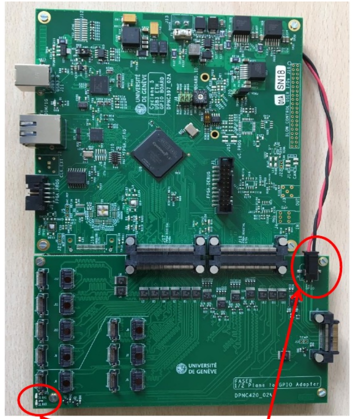
Low radiation in TI12 and much lower rates than ATLAS allow for simplifications in services and readout.

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

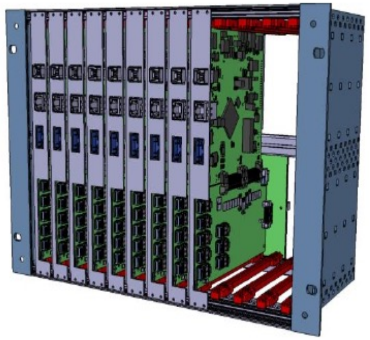


FLEX cables

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



Into custom-made mini-crate

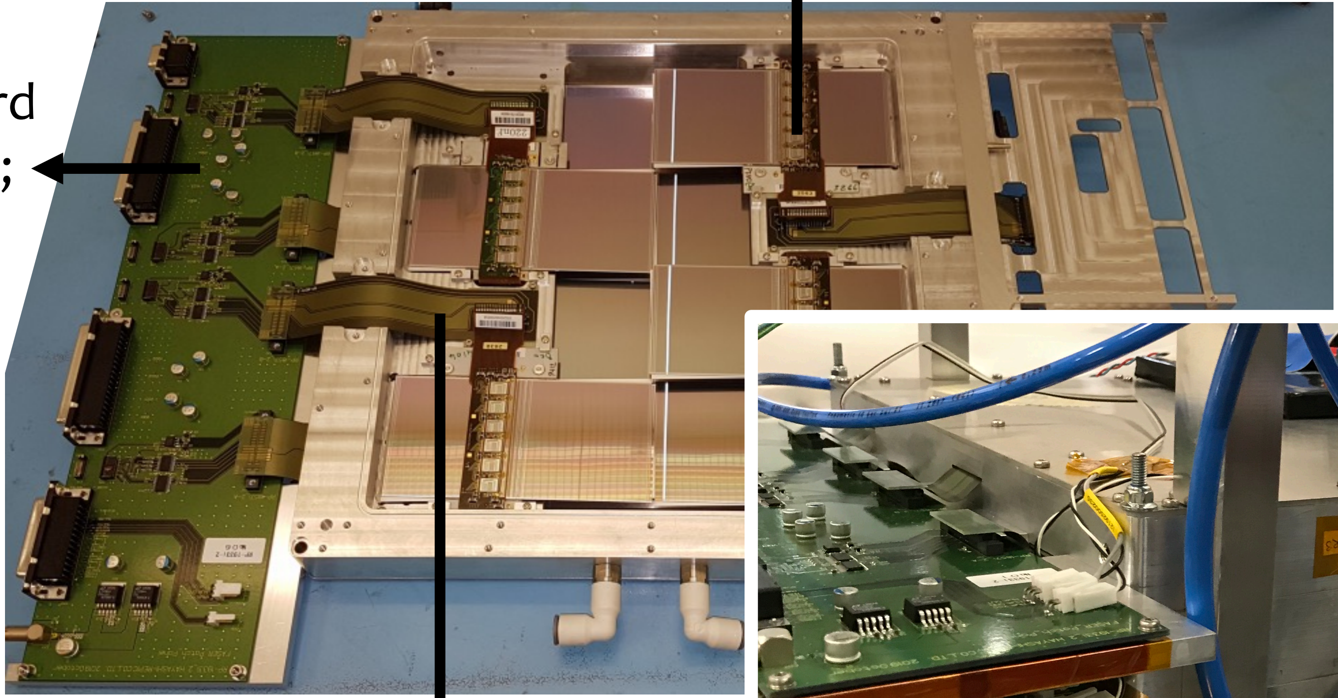


arXiv: 2112.01116

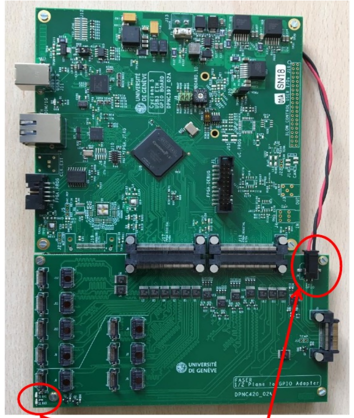
Tracker

SCT module ASICs, require ~ 5 W / module

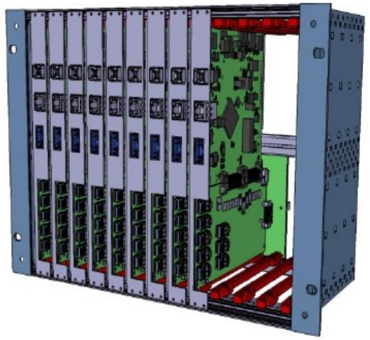
Patch panel to custom board based on home-made GPIO; Power (HV/LV), monitoring and readout lines.

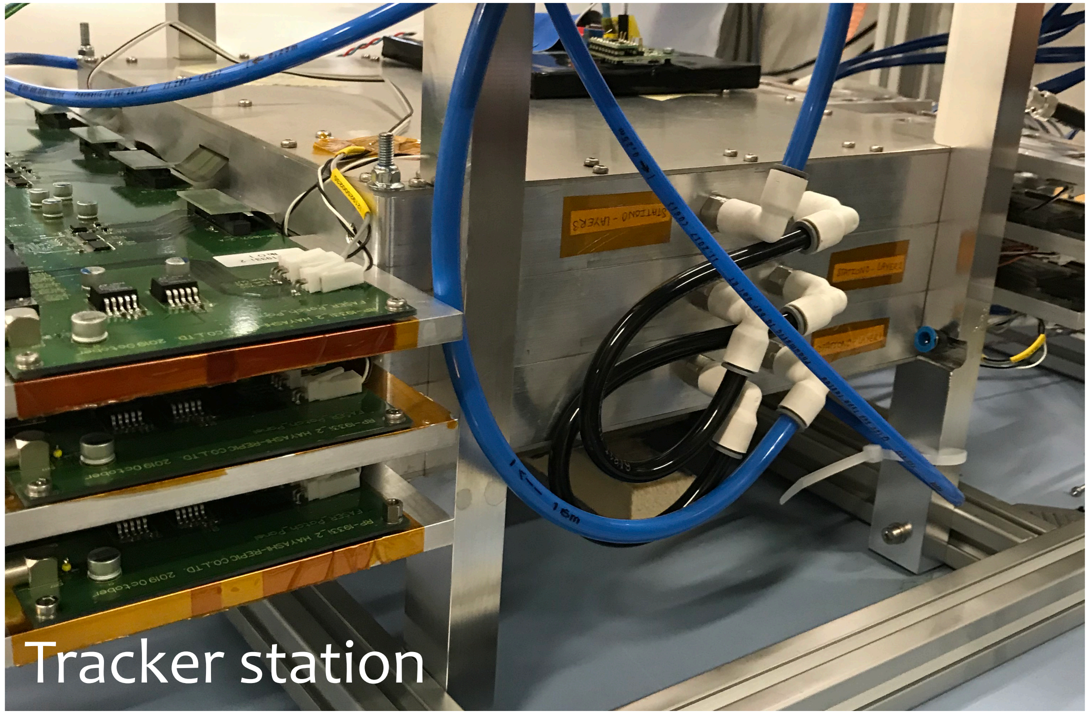


FLEX cables



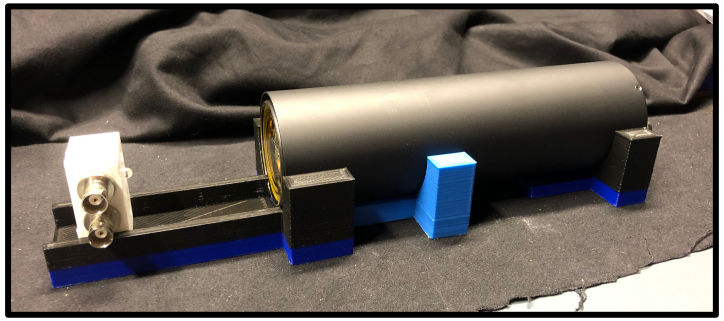
Into custom-made mini-crate





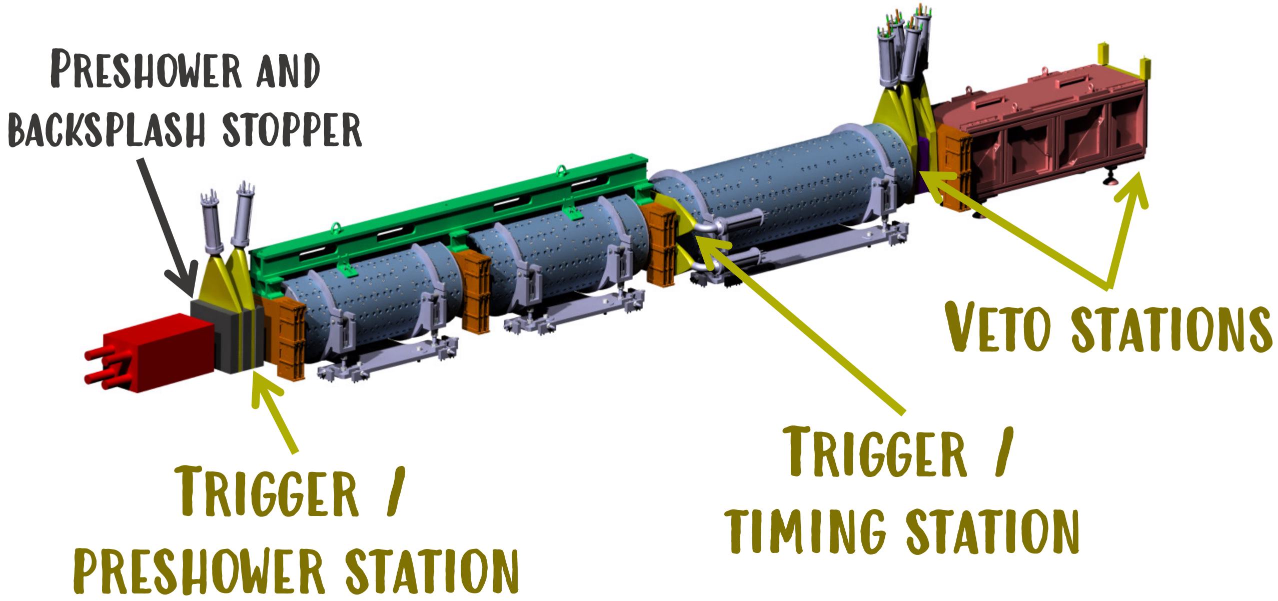
arXiv: 2112.01116

Scintillators



Scintillator PMTs

- Three stations all providing triggering capability:
  - Very high efficiency veto station for incoming charged particles (x6 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

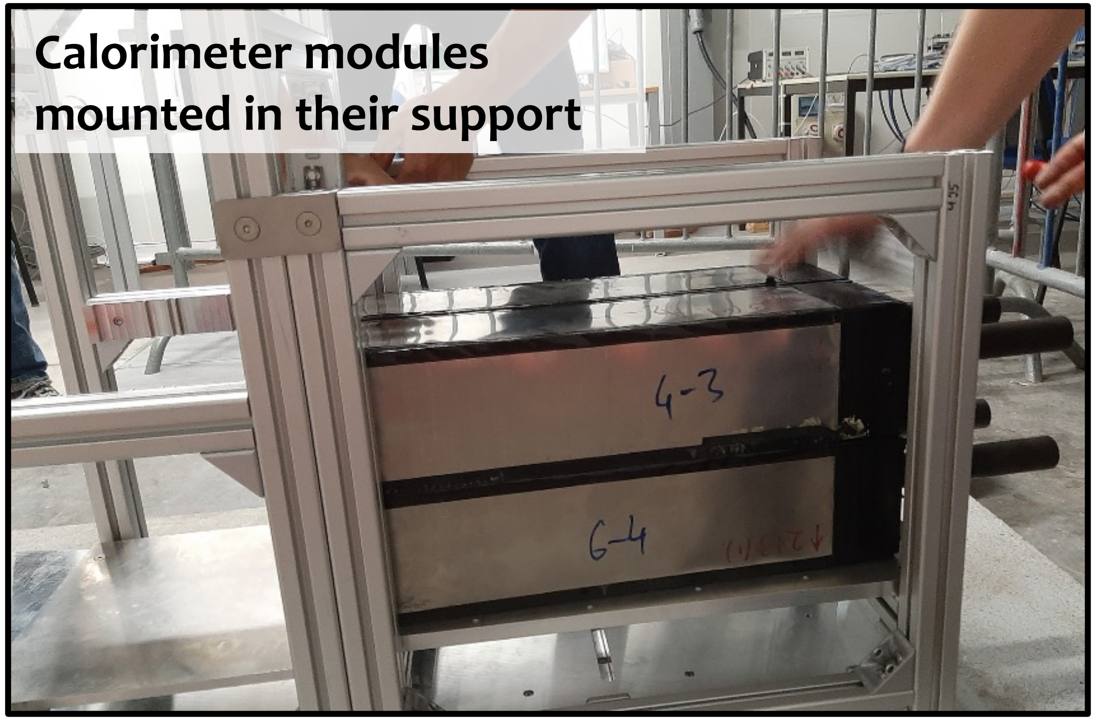


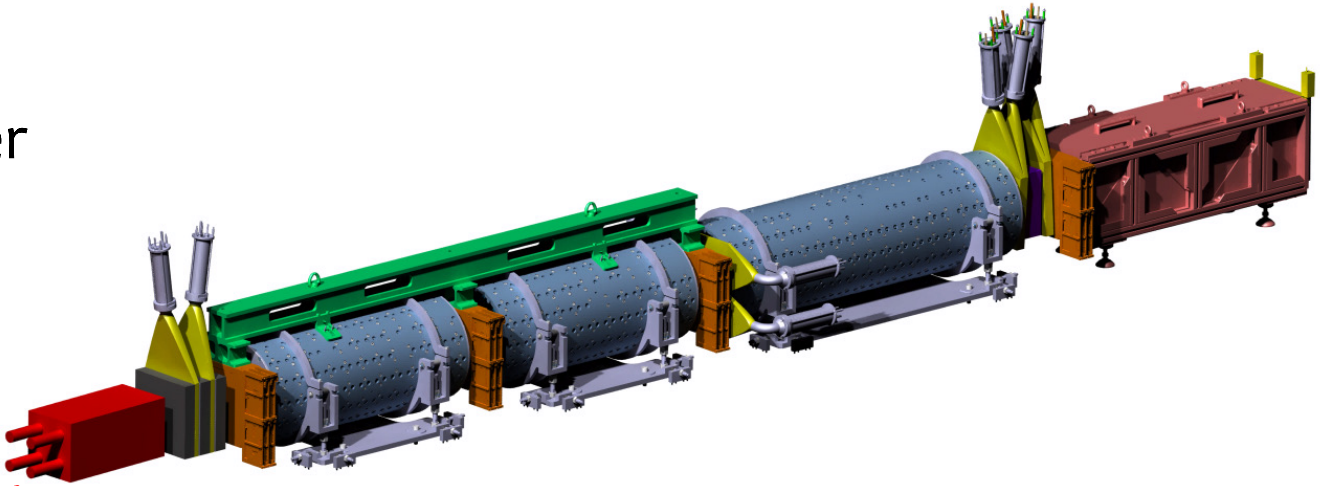
FASER scintillators mounted in their support

Calorimeter

THANKS!

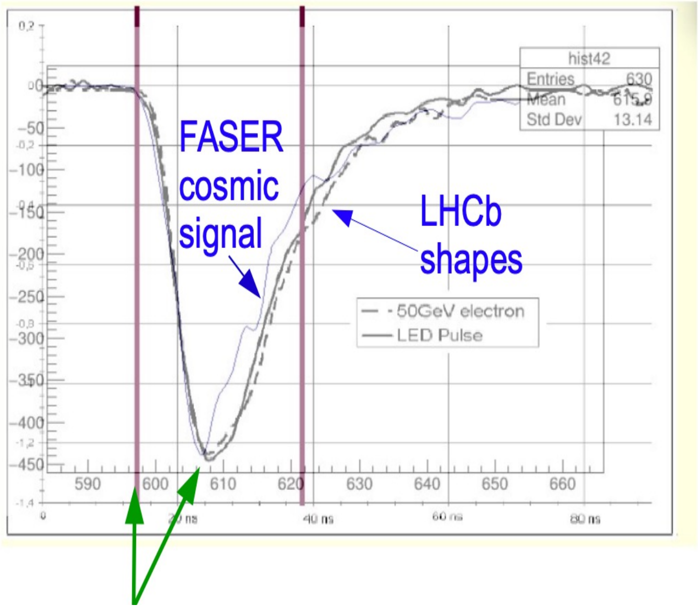
- FASER uses 4 LHCb spare outer ECAL modules
  - 25 radiation lengths long
  - Lead/scintillator calorimeter
- Energy resolution ~ 1% for TeV deposits
  - No longitudinal shower information
- Provides triggering capability
- Read out with PMTs and CAEN digitizer



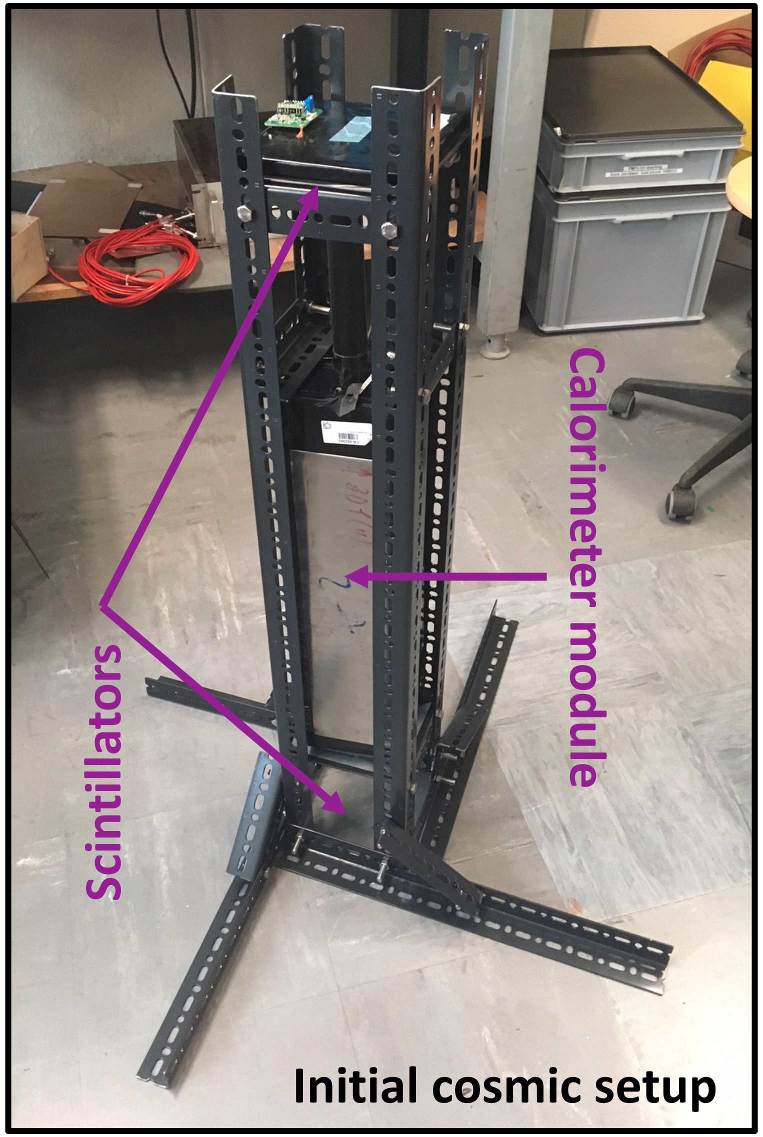


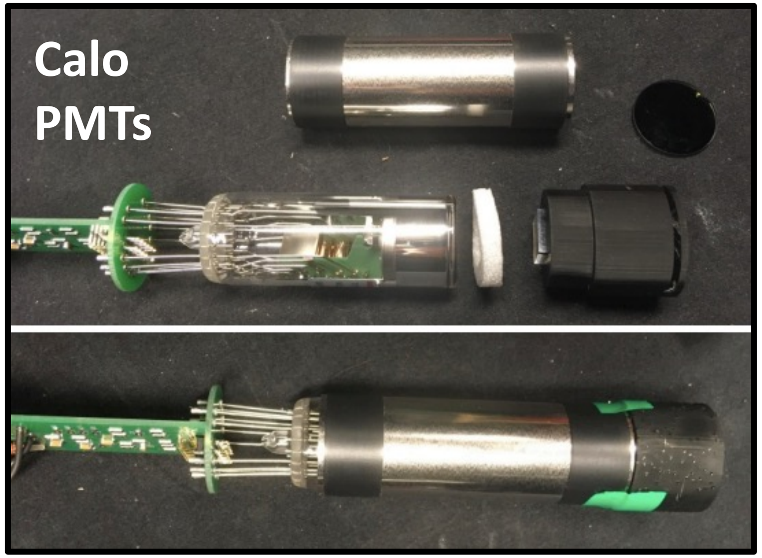
Calorimeter

Calorimeter



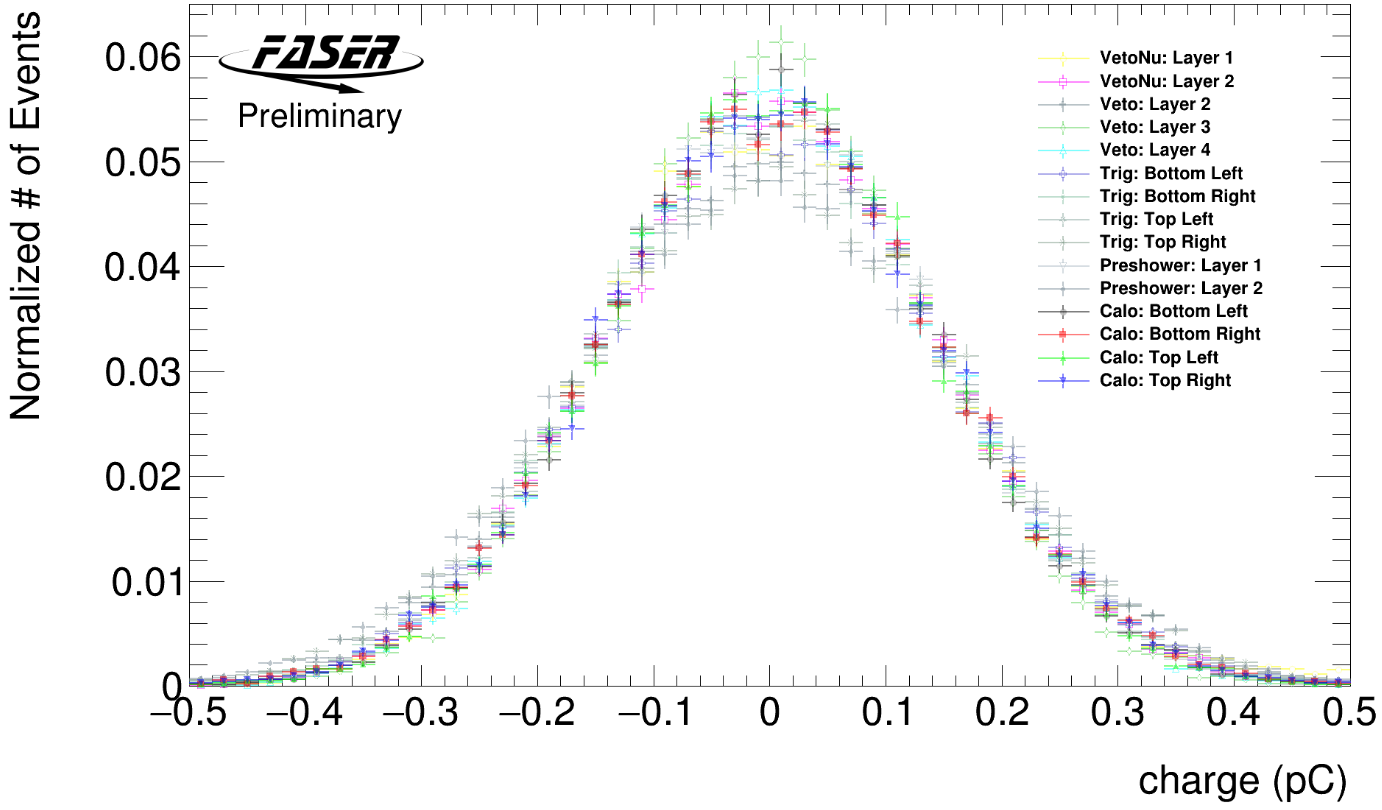
~10 ns rise time





Noise distributions for all scintillator and calo channels

- The pedestal subtracted charge distributions of randomly triggered events are shown for all scintillators and calorimeter modules. The charge is derived from the integration of the waveform over the standard 120 ns reconstruction window. Normalization of the distributions are done by dividing by the total number of events. The plot shows that the noise levels are similar across all scintillators and calorimeter channels, regardless of different PMT types and HV settings. Dominated by the digitizer noise, the total noise of each sub detector falls within the range of 0.15 ± 0.02 pC.

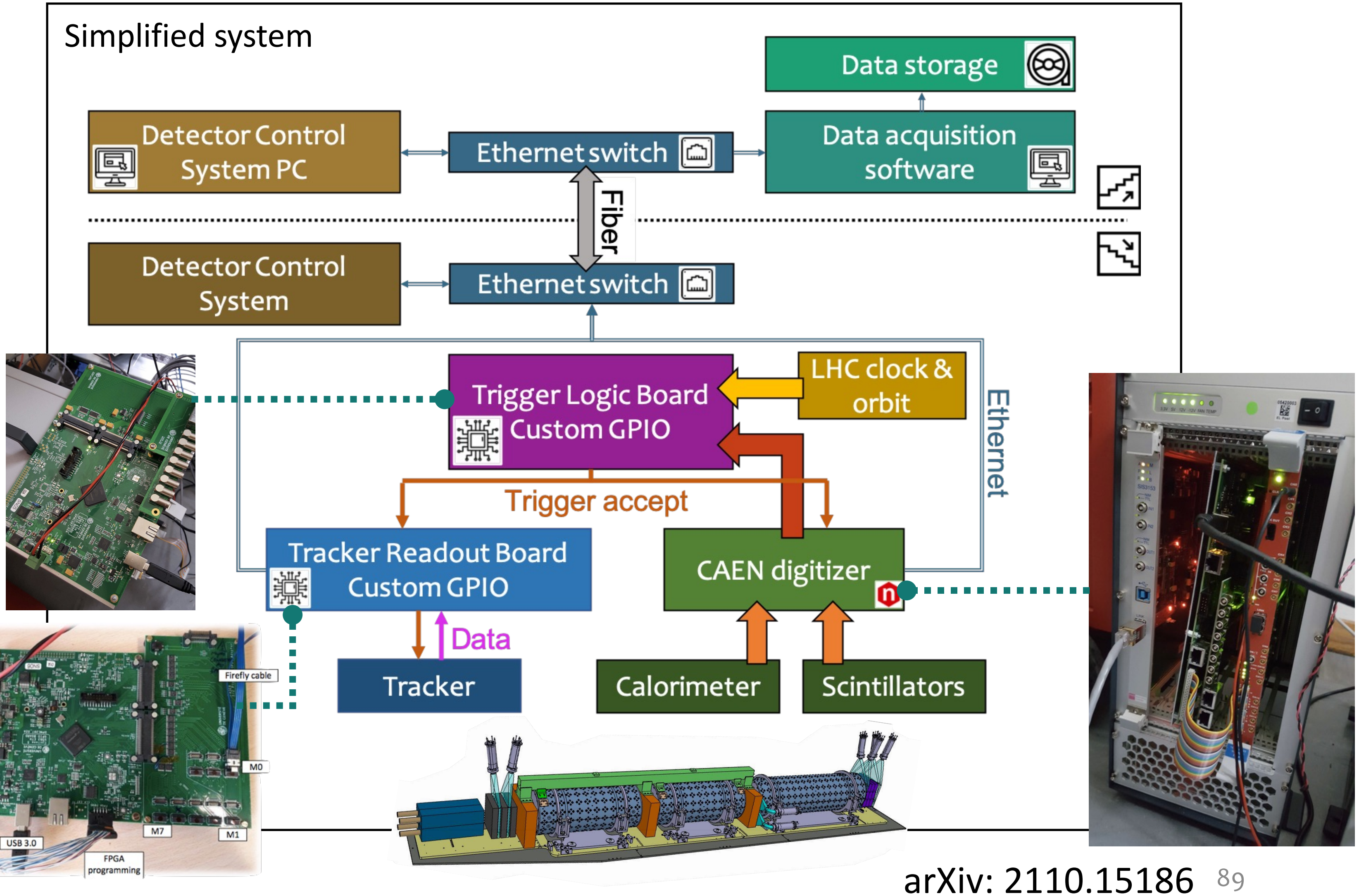


Trigger & Data acquisition

- 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

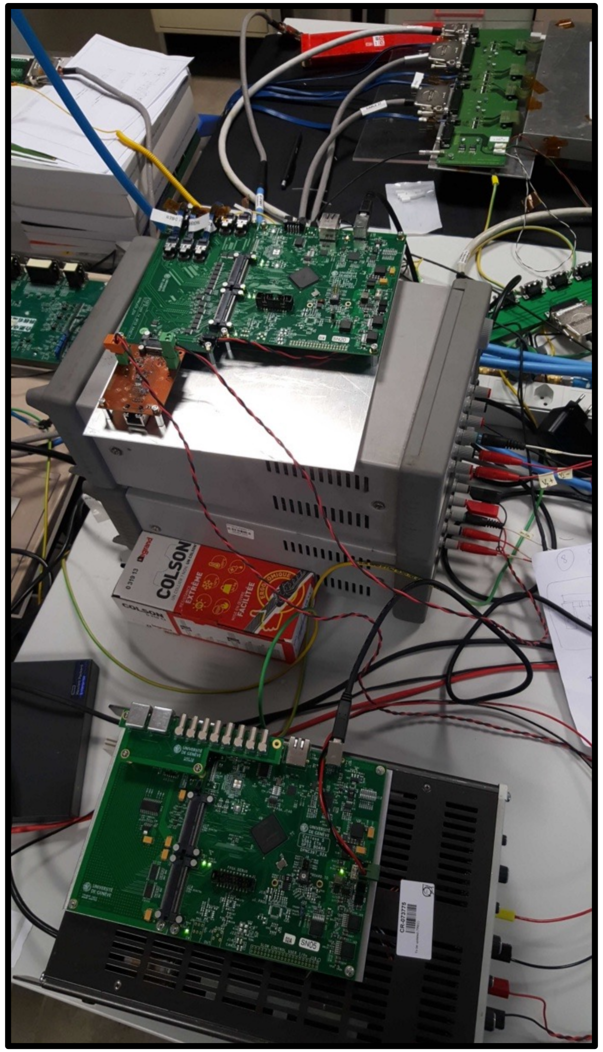


arXiv: 2110.15186

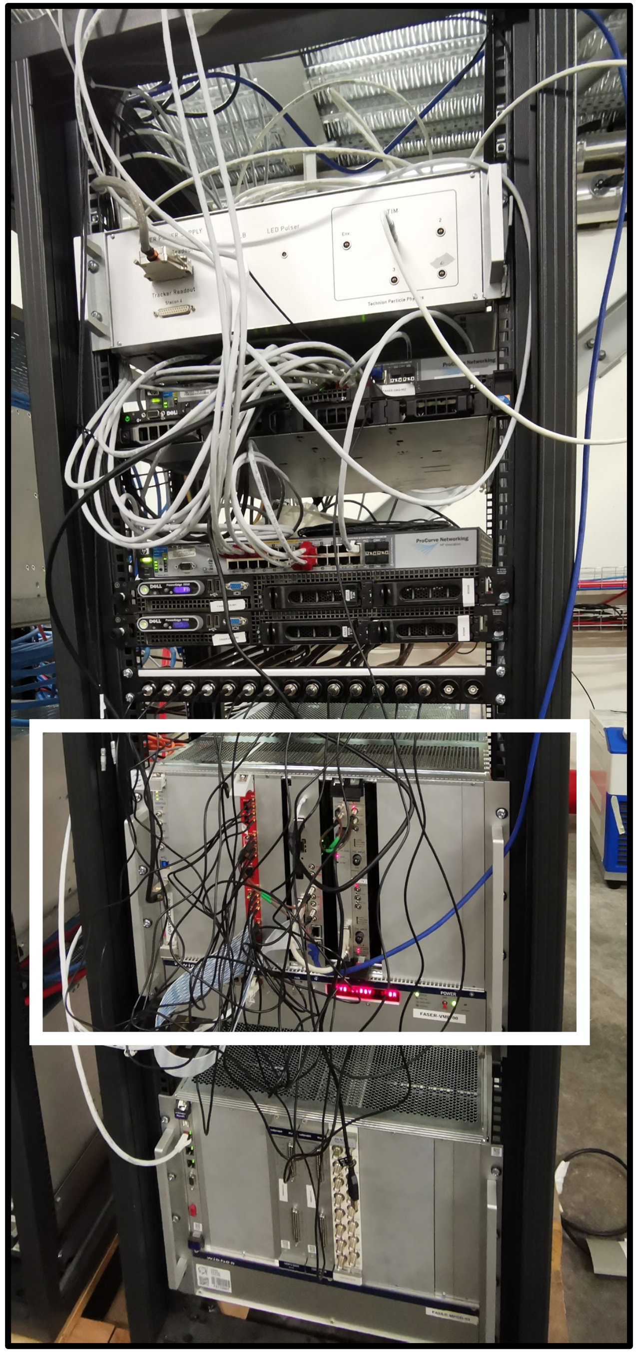
FASER Trigger & Data acquisition

Initial Run Control application, produced by summer intern

- L1A includes random and software triggers
- Expected **bandwidth** about **15 MB / s**, dominated by PMTs' wide signal (~ 1 μs)
- All TDAQ electronics will be placed in TI12

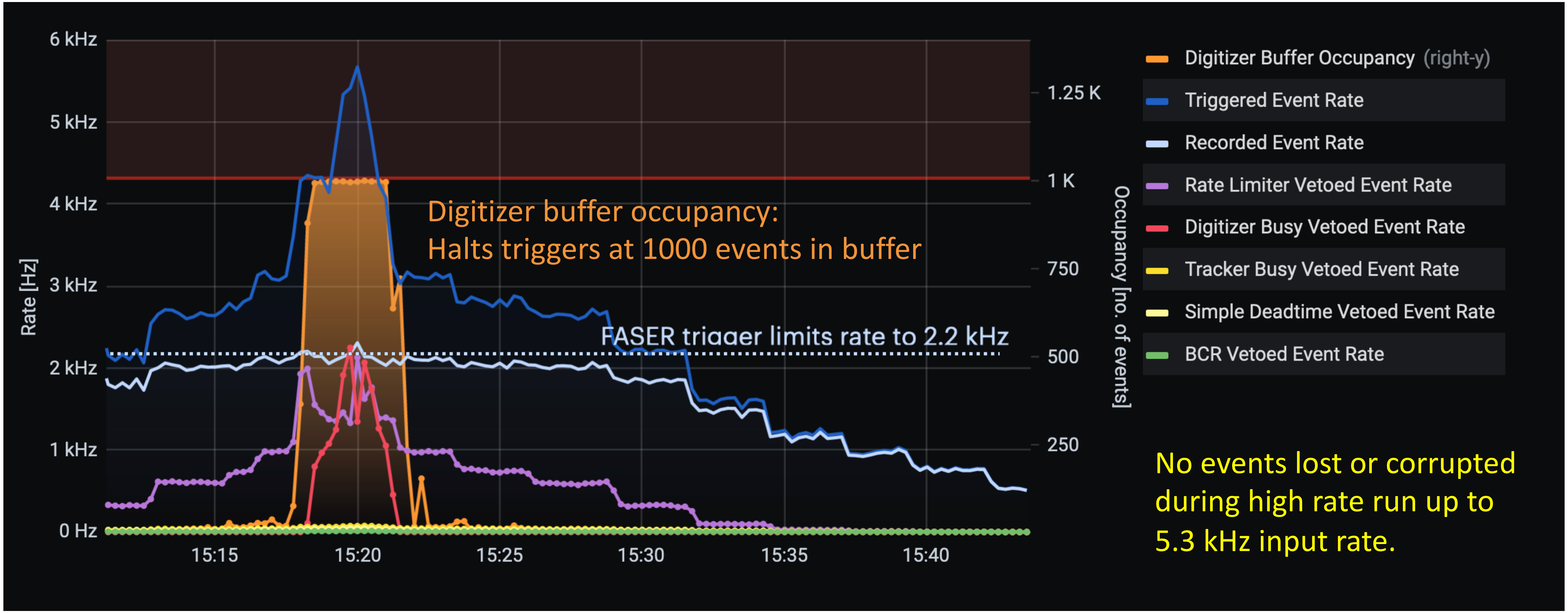


All boards connected together for tests



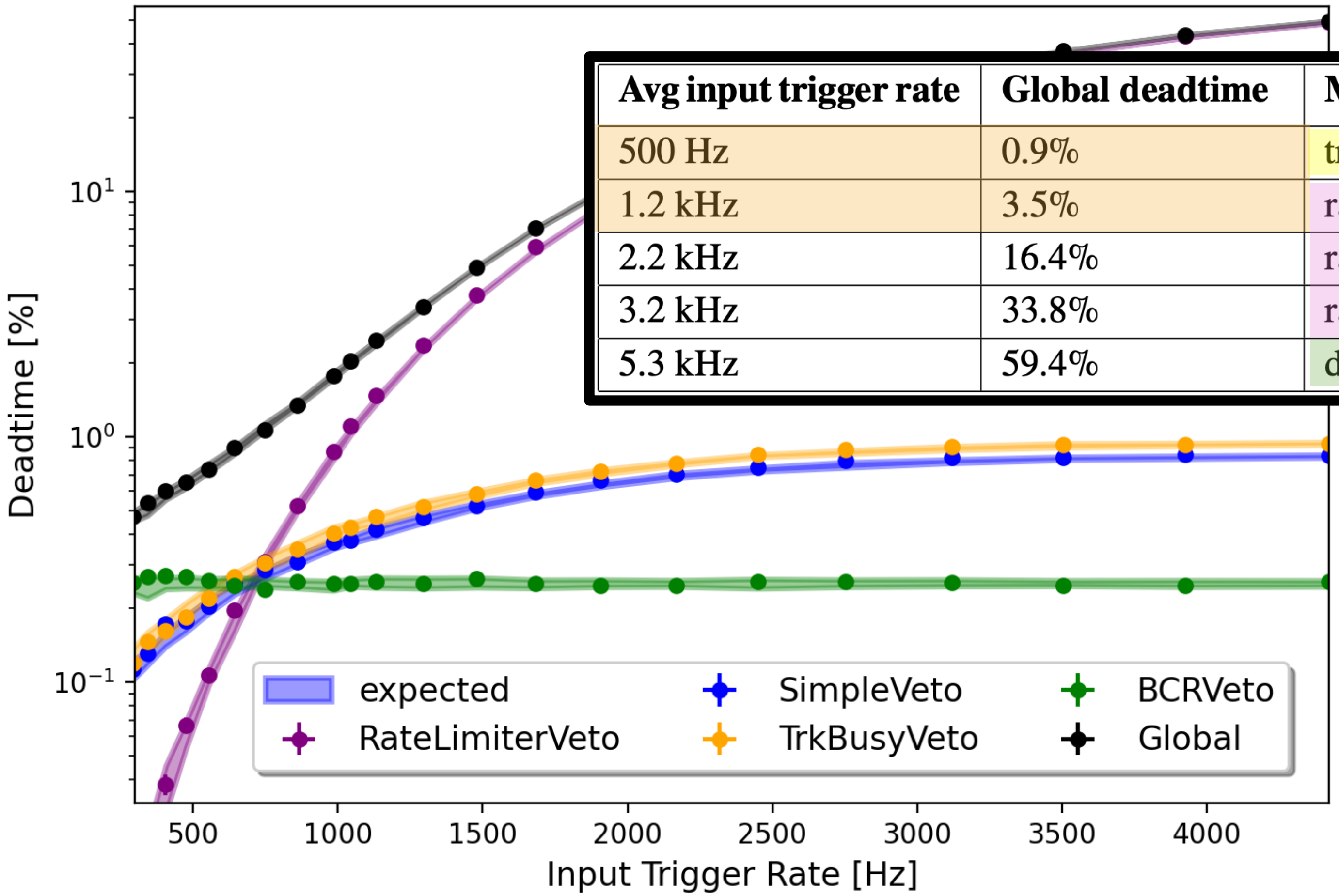
TDAQ boards in the final VME crate

High rate tests



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

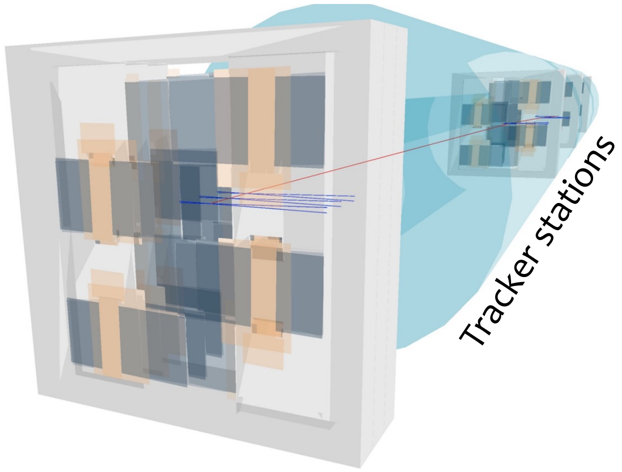
Rate is limited to 2.2 kHz

Digitizer read-out limitations

At 500 Hz,
deadtime expected to be < 1 %

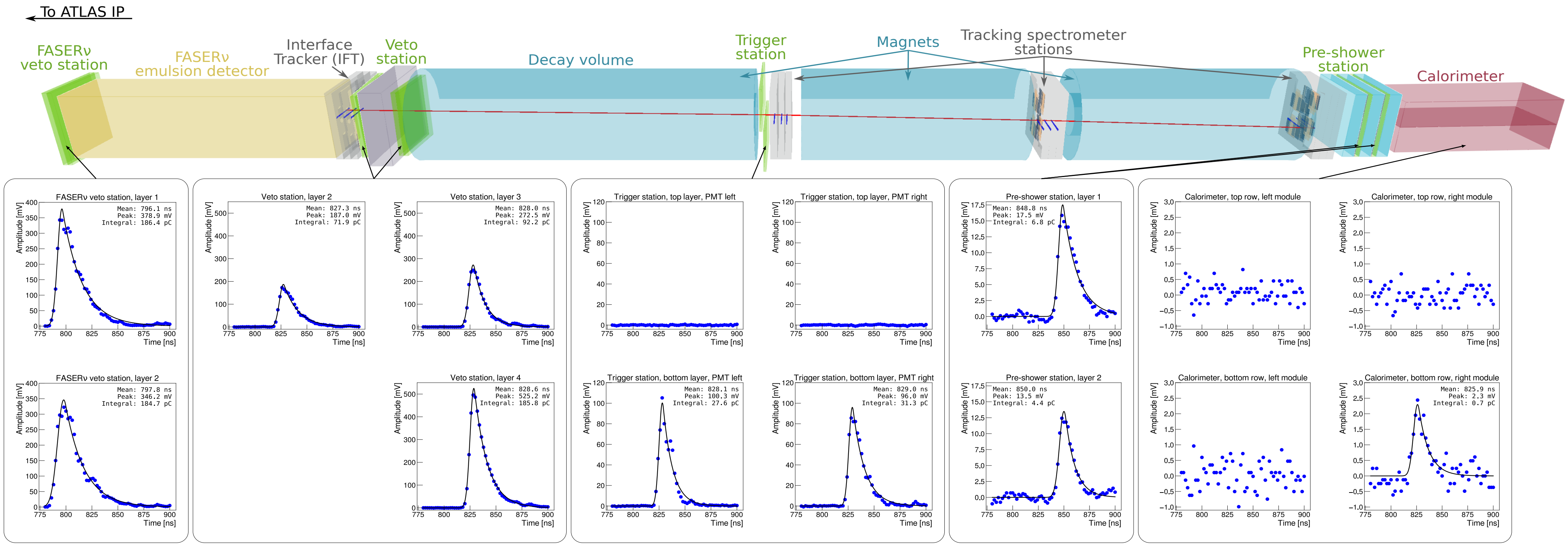
NEW! arXiv: 2110.15186

Example Typical event: muon

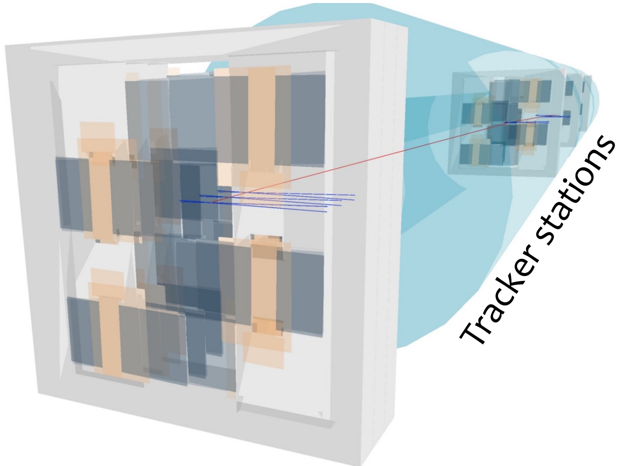


Run 8336
Event 1477982
2022-08-23 01:46:15

Collision event with muon traversing FASER



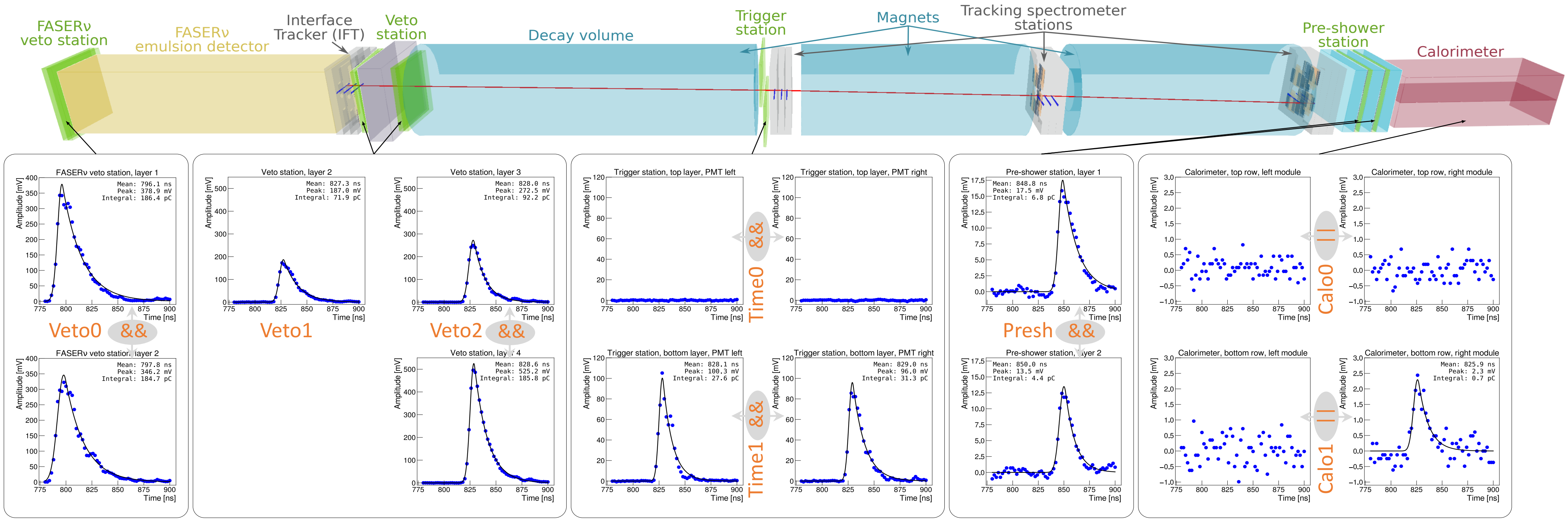
Example Typical event: muon



Run 8336
Event 1477982
2022-08-23 01:46:15

To ATLAS IP

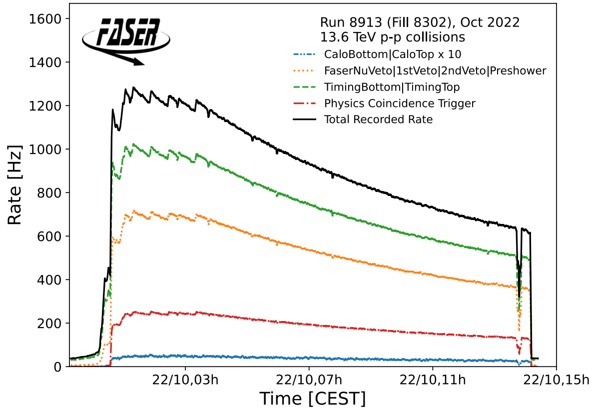
Collision event with muon traversing FASER

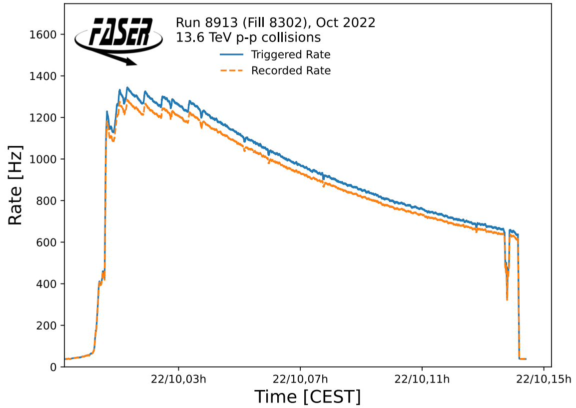


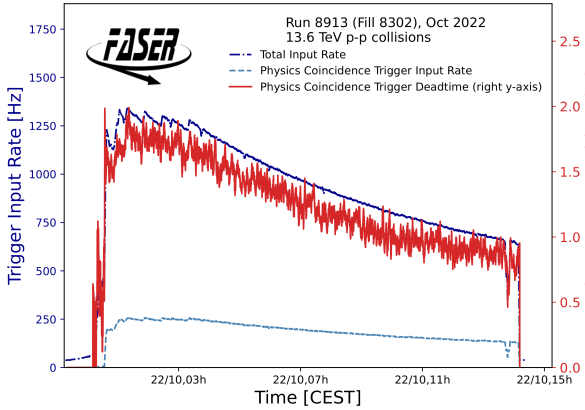
Trigger bits combined to trigger items -- e.g. "coincidence trigger" (incoming muons): (Veto0 || Veto2) && Presh

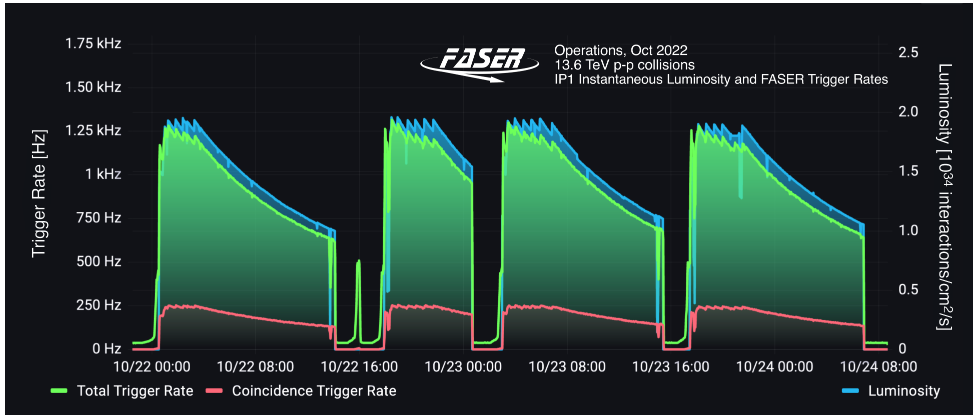
TDAQ Ops

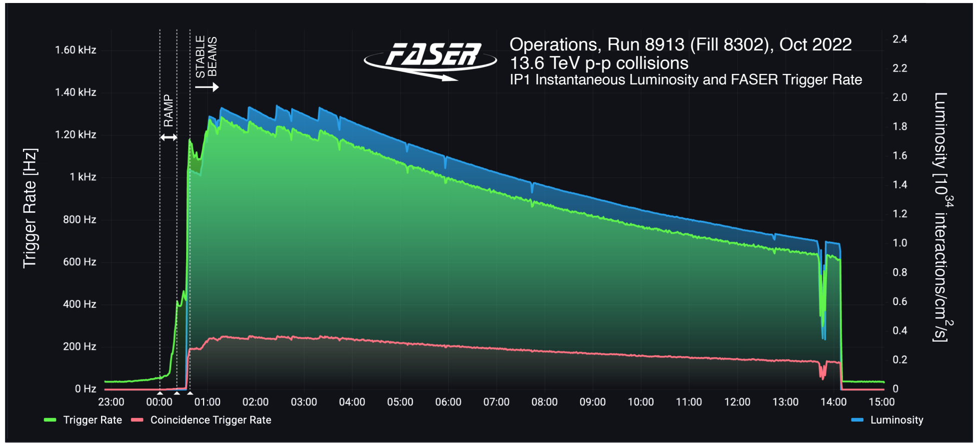
The rate of a coincidence trigger (requiring a signal in the veto scintillators at the front and the preshower scintillator layer at the back of FASER, likely signifying the passage of an energetic muon from the direction of IP1) is shown in red. The trigger rate trend generally follows the luminosity trend but it is evident that the trigger rate falls off more strongly at the beginning of fills than the luminosity. This is due to higher beam-induced backgrounds at the beginning of the fill. The dip in rate towards the end of the fill is due to an emittance scan at IP1.

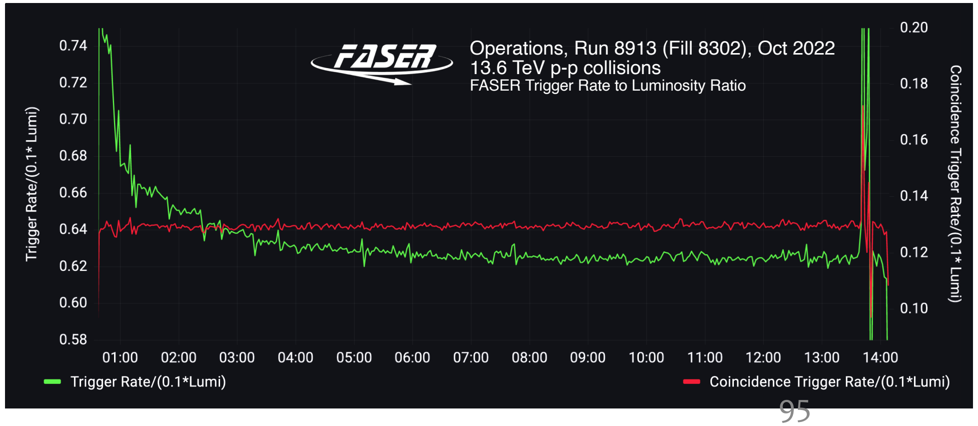






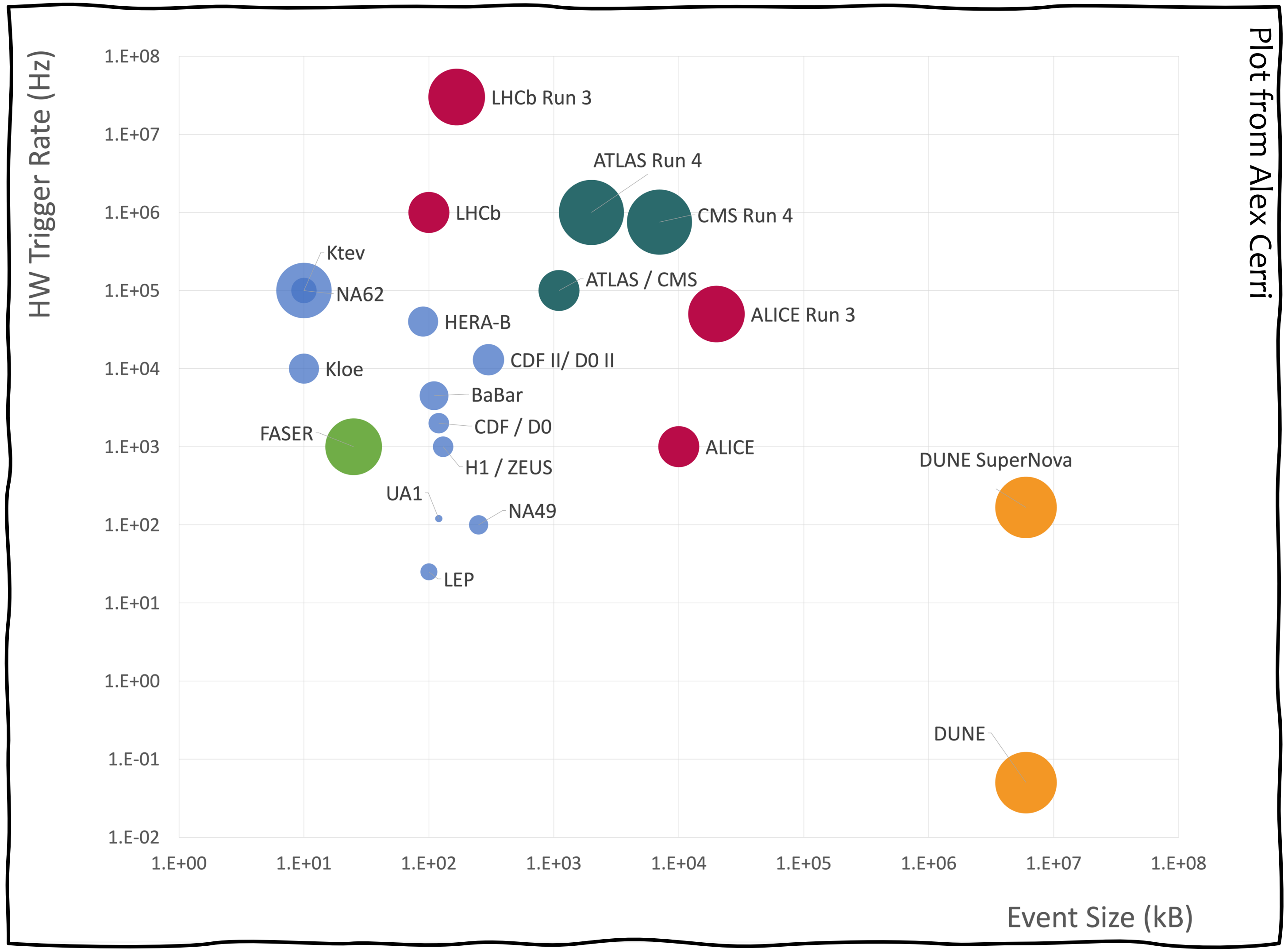






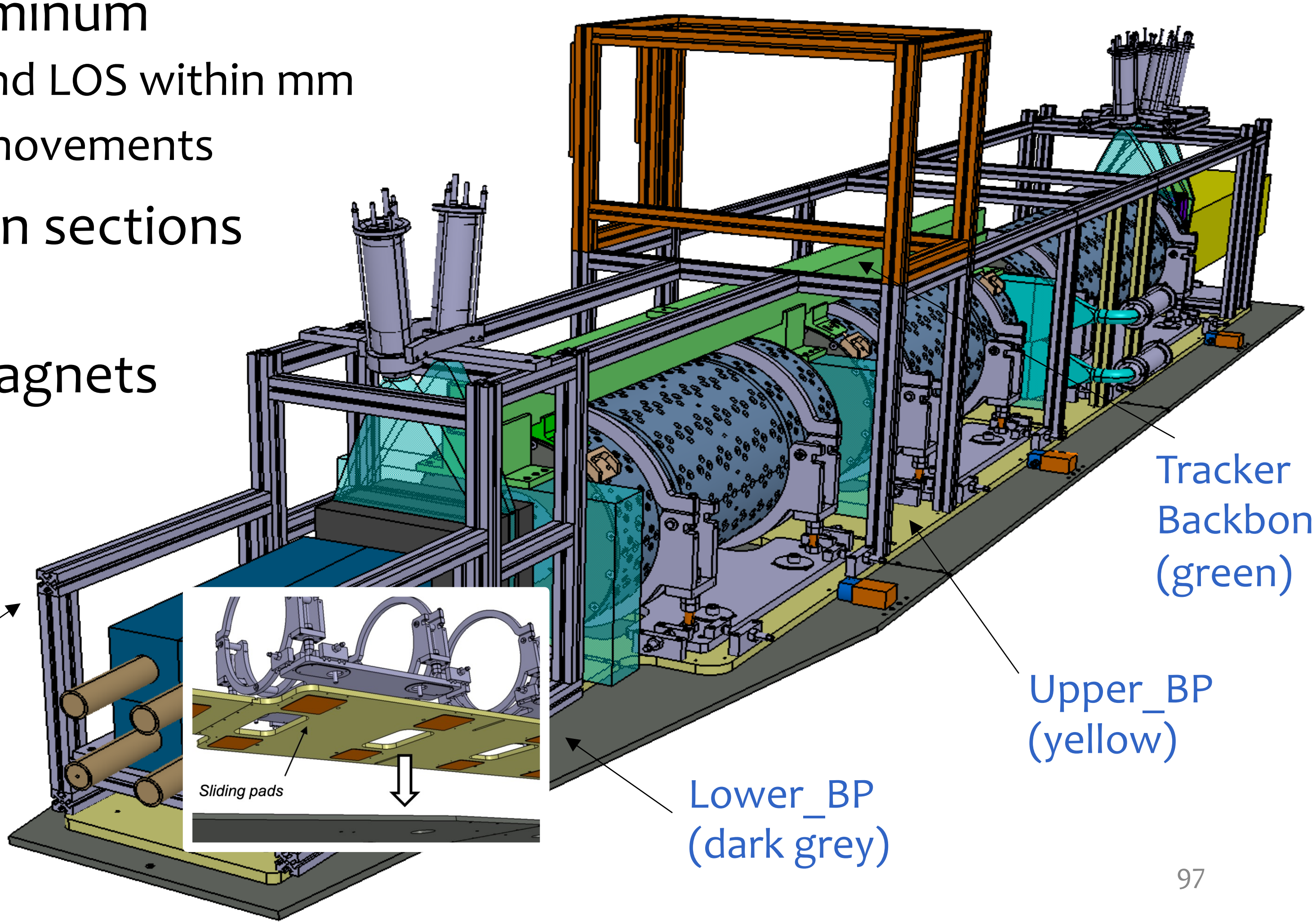
...WHY THIS ARCHITECTURE?

- Compare trigger rate and event size to other LHC experiments!



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)

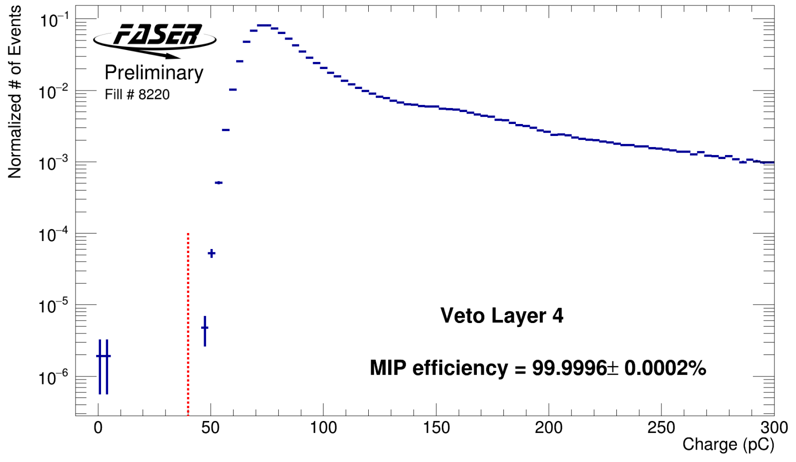


Performance Assessment

Veto scintillators

Veto layer charge distribution

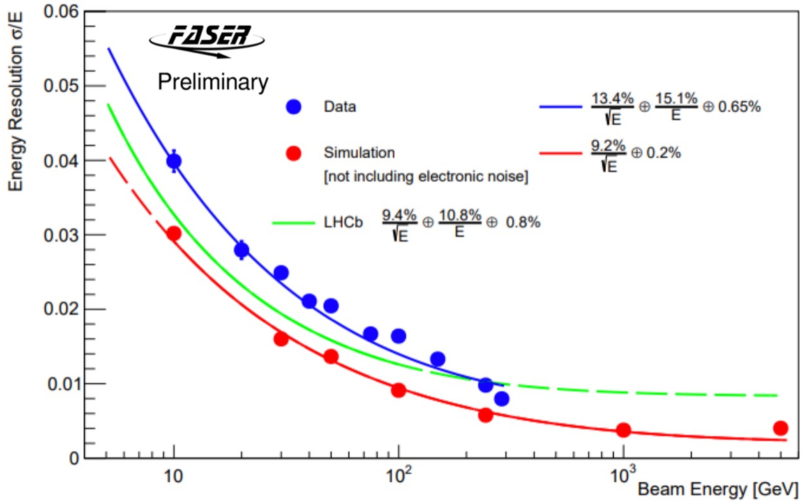
Efficiency > 99.99% per layer



Calorimeter

Calorimeter calibration at testbeam

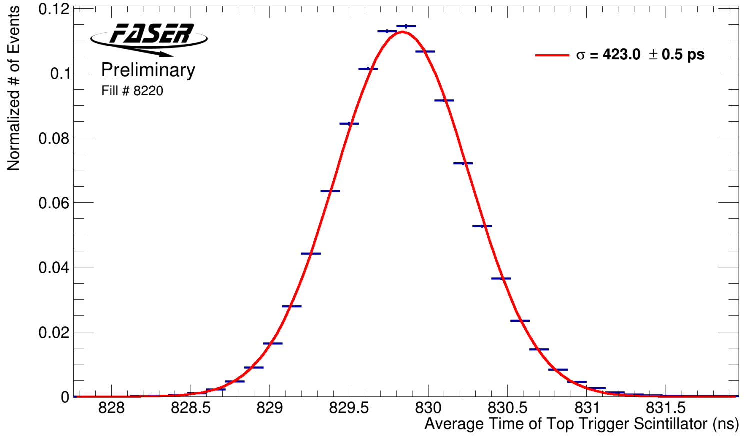
Resolution confirmed ~1% for high energy electrons



Timing scintillators

Timing distribution of top trigger scintillator

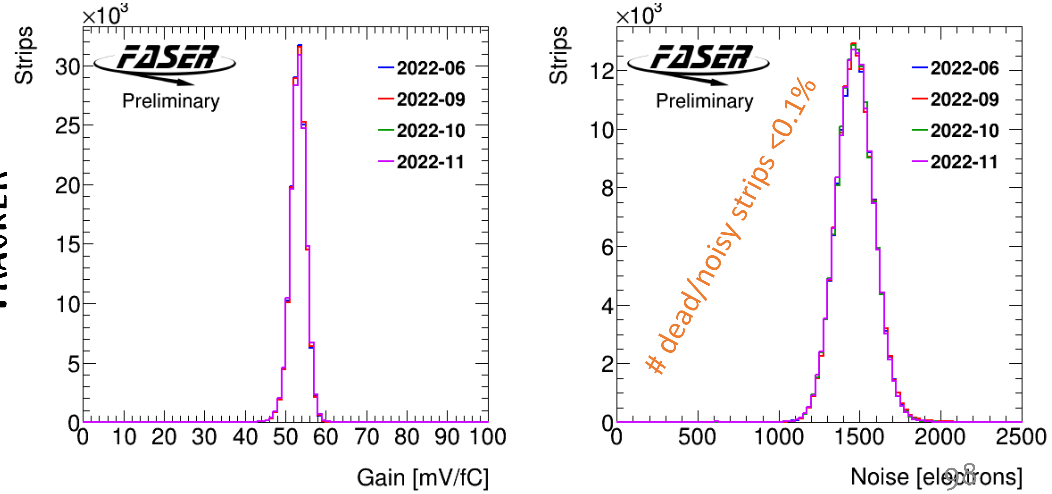
Resolution < 0.5 ns



Tracker

Gain and noise distributions of four tracking stations

Confirm stable data taking conditions



Studying backgrounds

- Before data taking, expected dominant background source:
  - high energy muons from IP
- With first data we see two extra background sources

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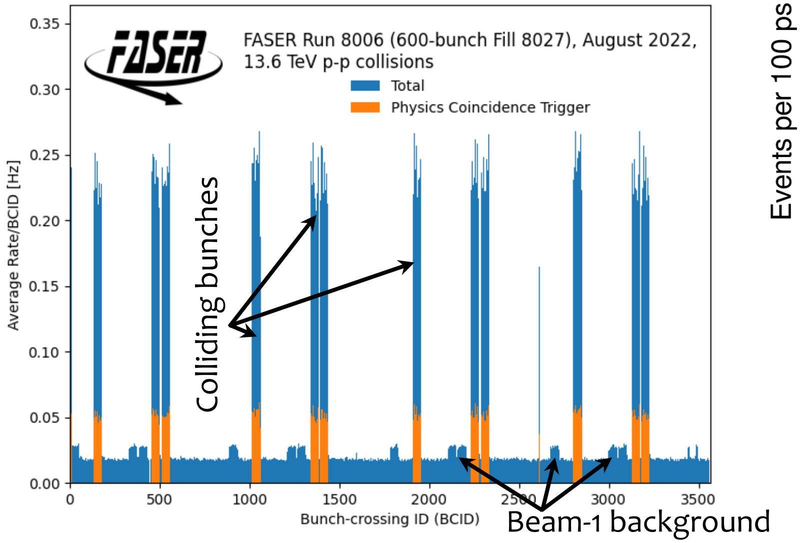
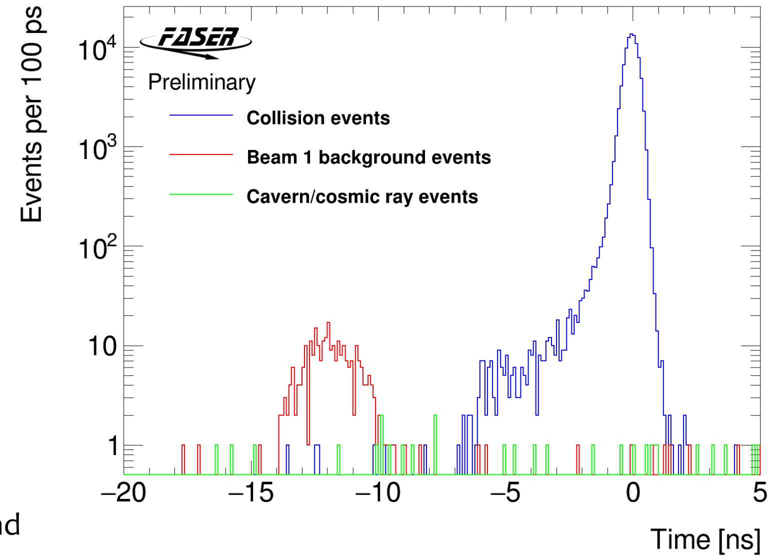
Source A

- Caused by beam-1 on the way to ATLAS passing from the back of FASER
- Early by about 3.2 μs compared to particles from IP
- First observed with pilot beams in Nov 2021
- Concrete shielding installed to reduce it

Average rate per bunch-crossing ID



Calorimeter time separation of collision events and Beam-1 background



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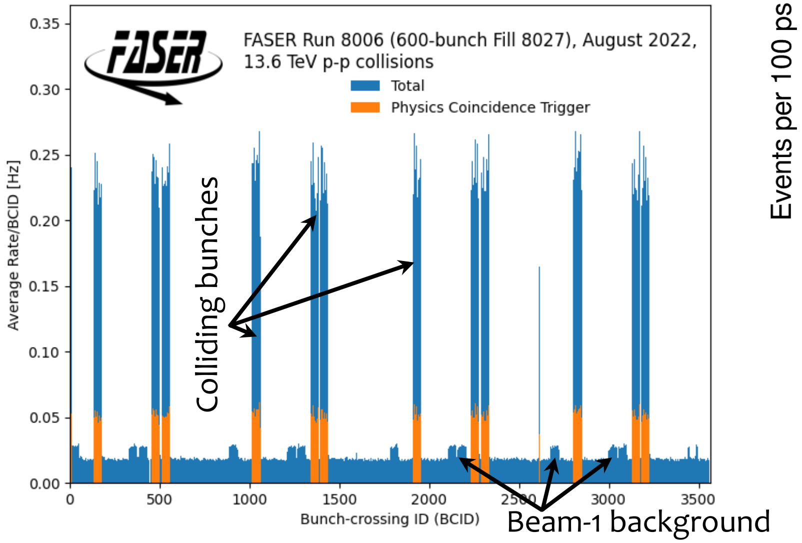

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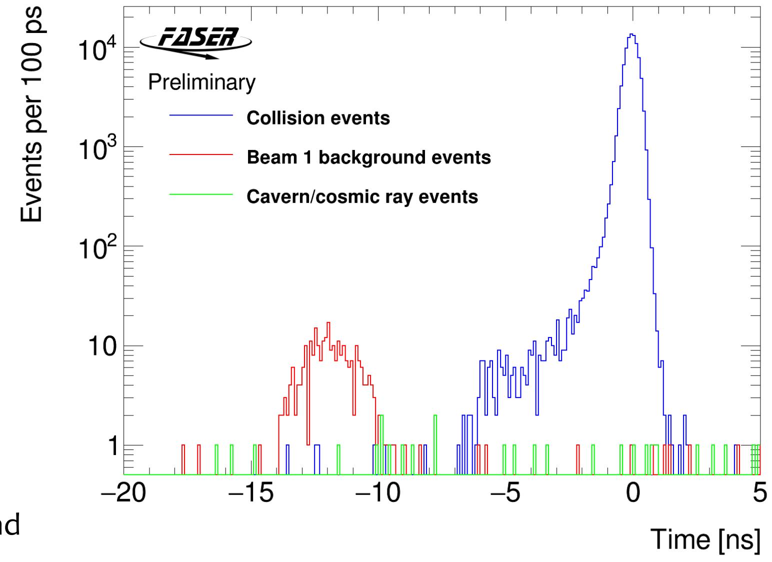

Source B

- Correlated to beam
- Only fires single scintillators
- Likely low energy neutrons

Studying backgrounds

- Before data taking, expected dominant background source:
  - high energy muons from IP
- With first data we see two extra background sources

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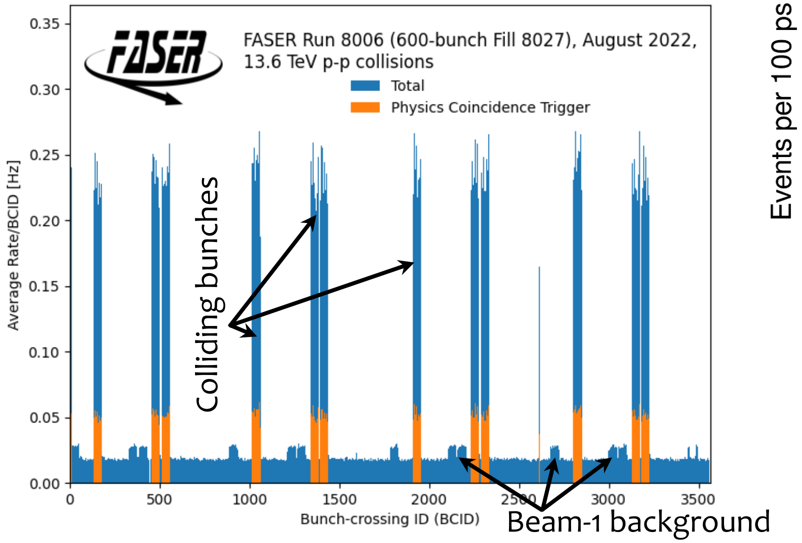
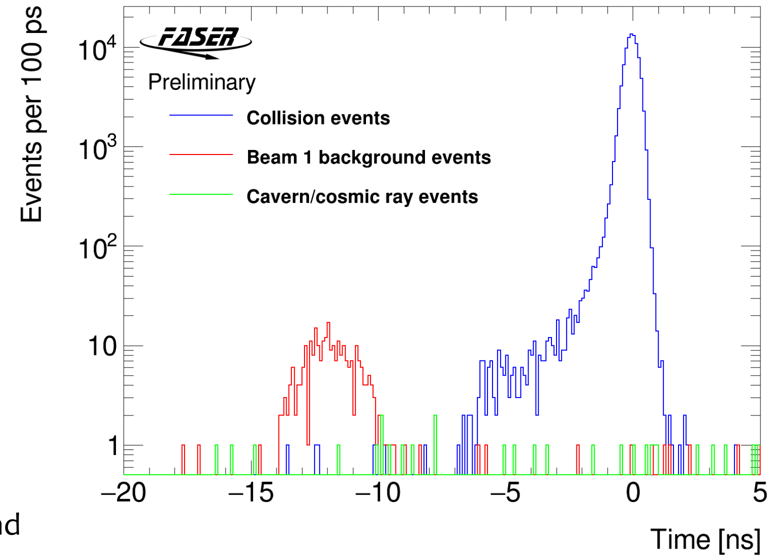


Calorimeter time separation of collision events and Beam-1 background

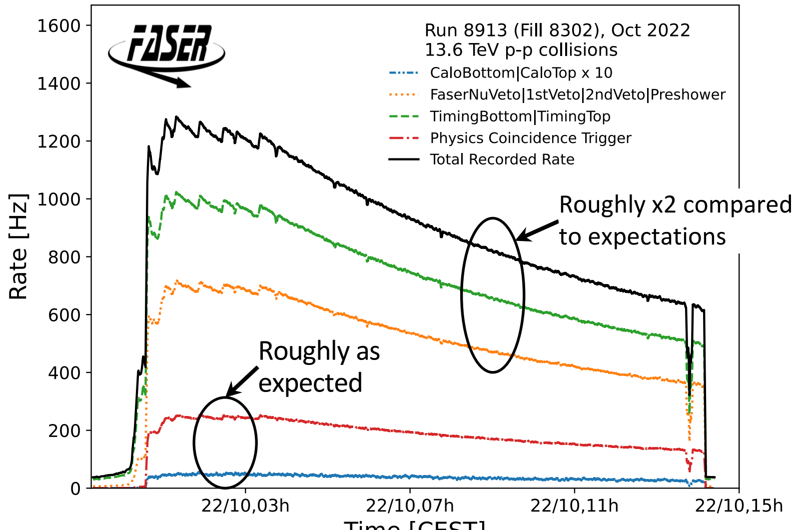


Source B

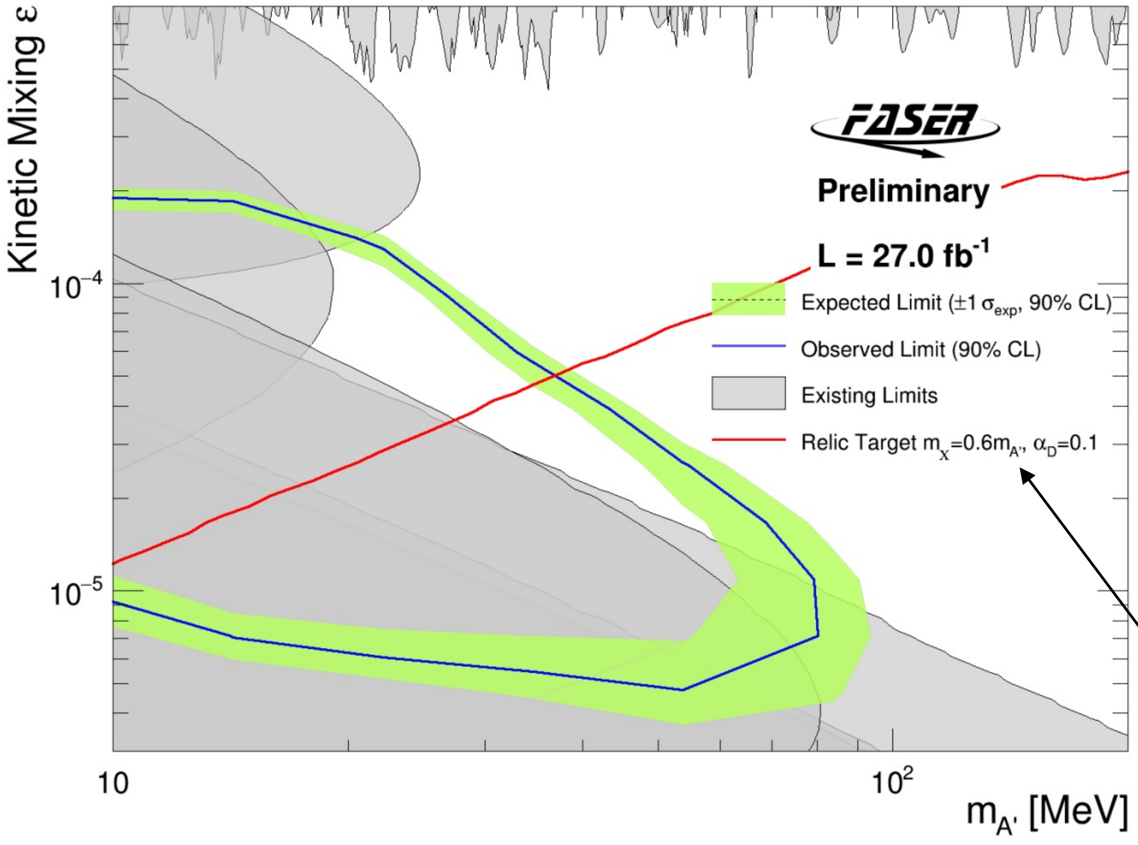
- Correlated to beam
- Only fires single scintillators
- Likely low energy neutrons

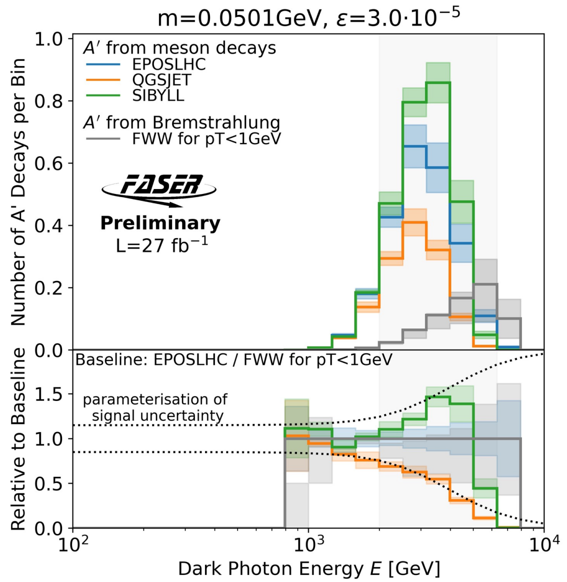
- Additional backgrounds give total trigger rate x2 than expected
- Rate of muons from IP roughly consistent with expectation
- Extra rate not problematic

FASER recorded rate per trigger item



Exclusion reach On previously unexplored phase-space





- Parameters for which DM χ annihilates via $\chi\chi \rightarrow A' \rightarrow ff$
- *Model dependent line, but region favoured by DM relic density*

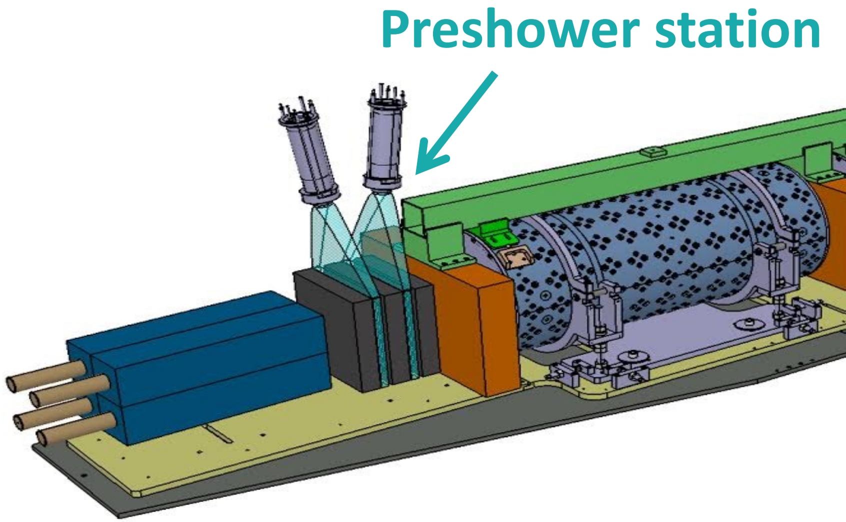
The FASER Detector

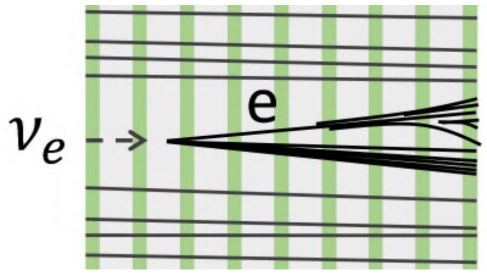
Preshower upgrade

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.

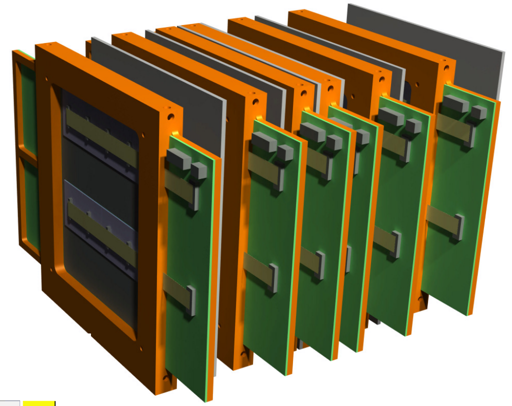
- **Limitations:**
  - **no information about the multiplicity of the photons or the topology of the event**
  - **neutrino DIS events produced in the 2 X0 lead of the present pre-shower will be undistinguishable from a photon (LLP) signature**
    - About 10 such events expected in 150/fb



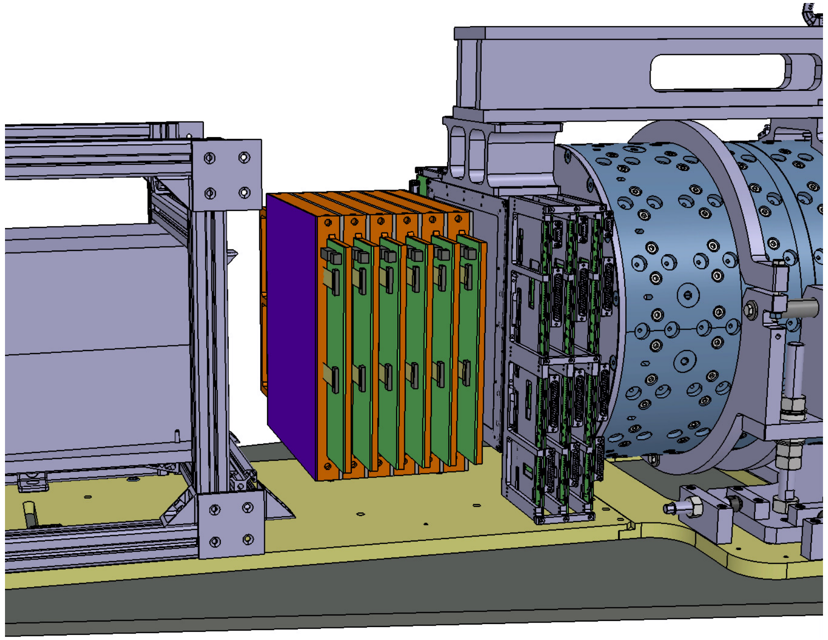


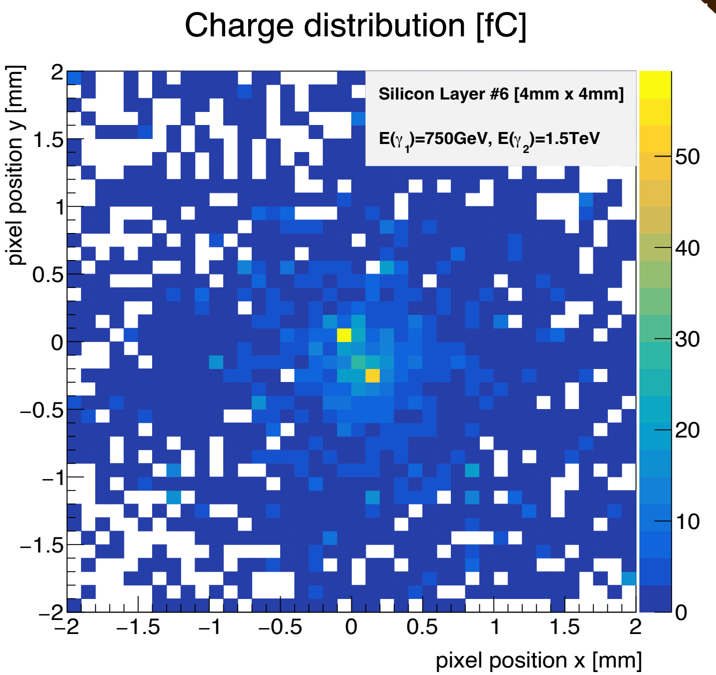
Cartoon of ν_e DIS in FASERν

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



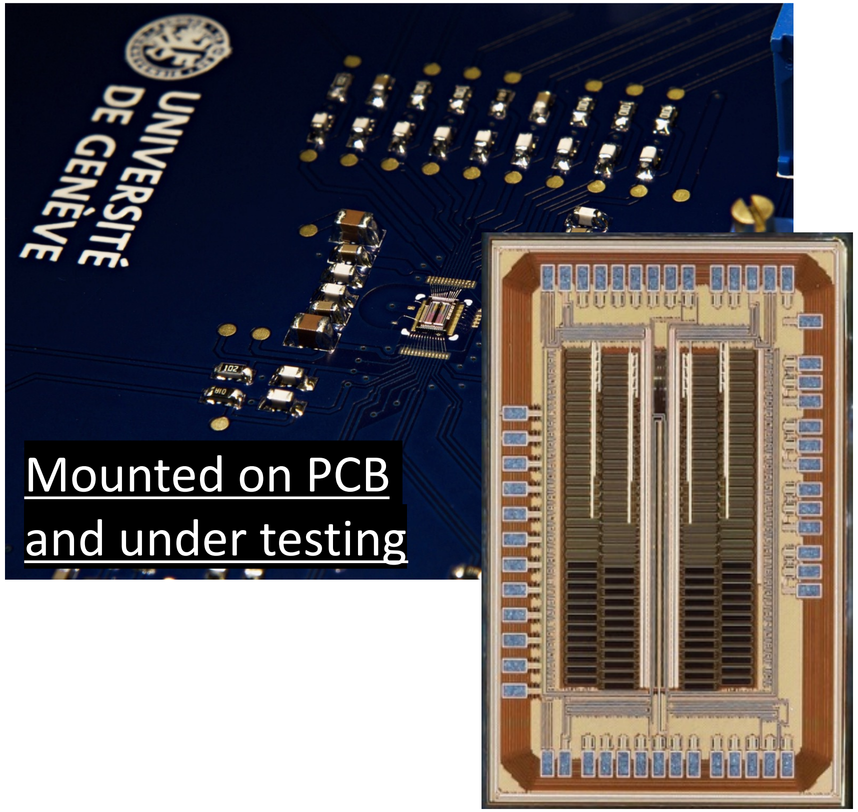


- Distance between two photons: 200 µm
- Distinguishable!

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

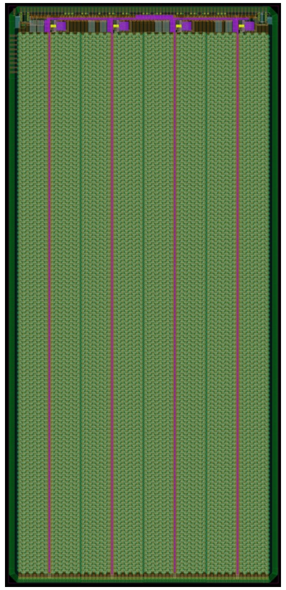
From pixels to layers of modules

Prototype ASIC available end 2020

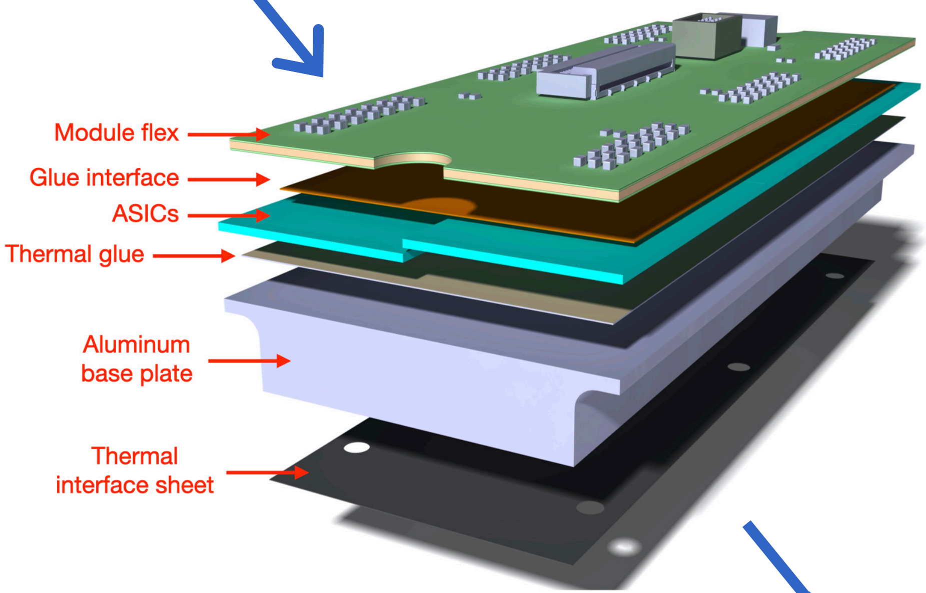


Mounted on PCB
and under testing

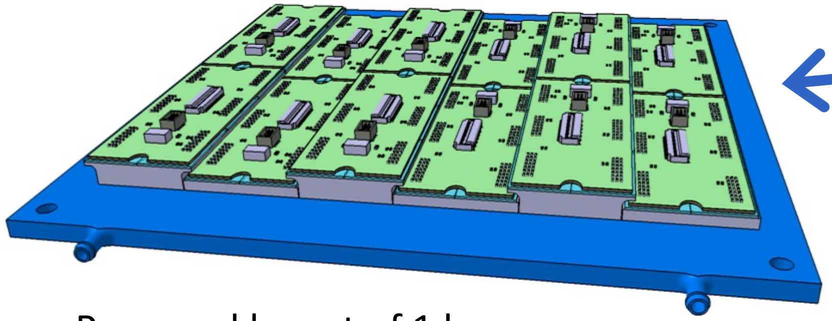
Pixel chips into
sensor wafers



...into modules
of pixels



...into layers
of modules



Proposed layout of 1 layer
with 12 modules.

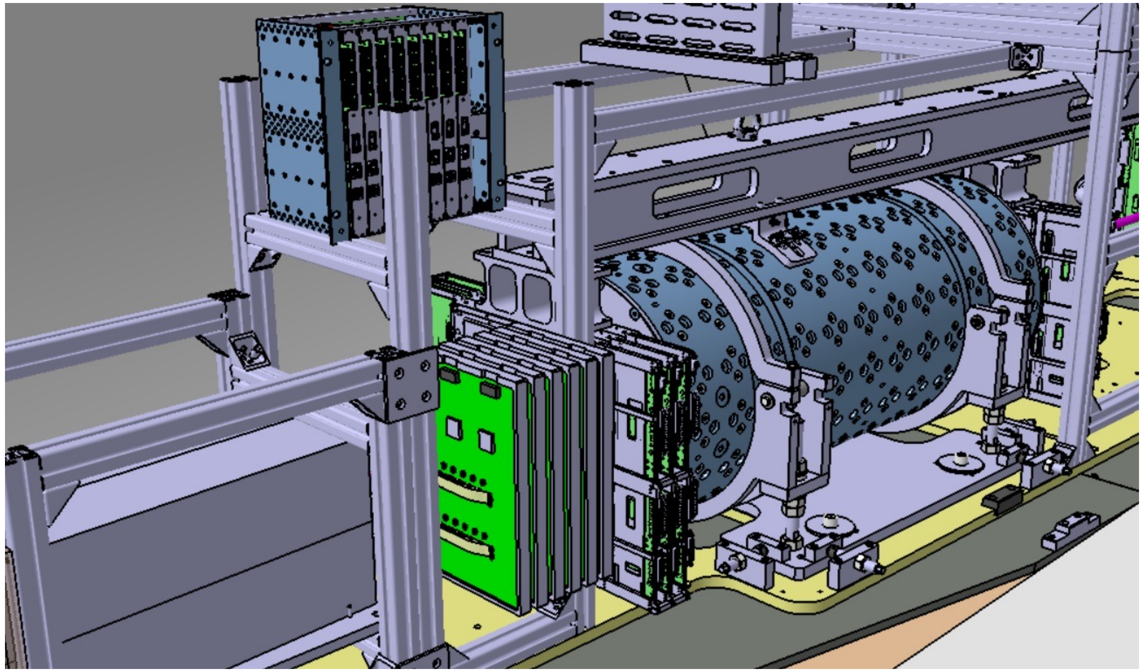
Upgraded pre-shower

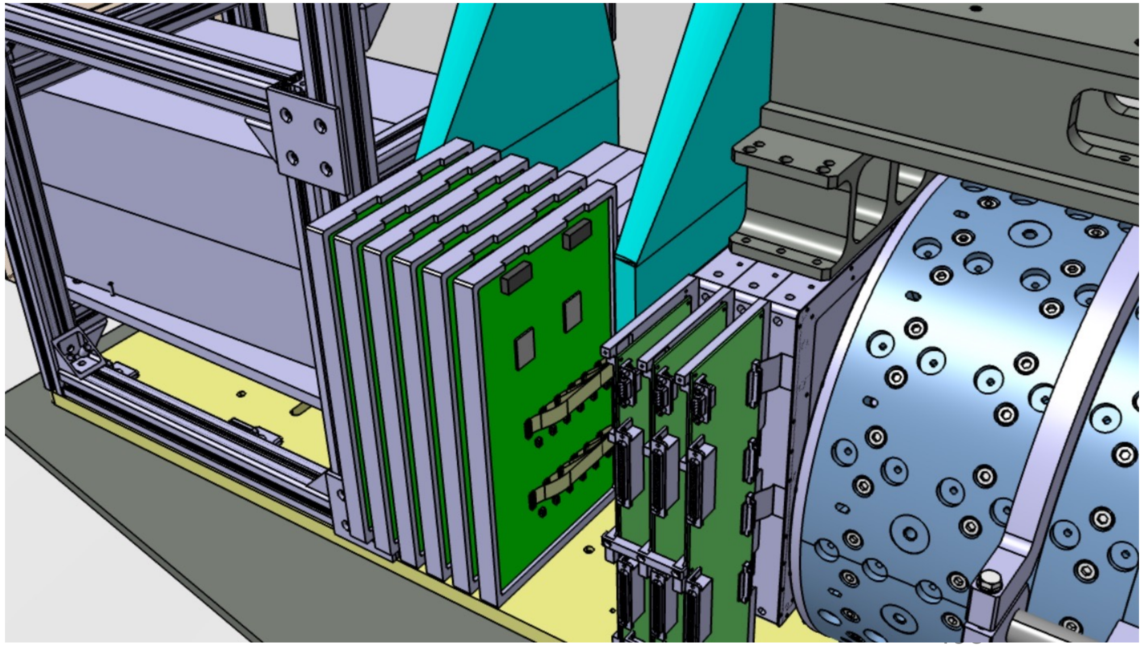
Status:

- 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

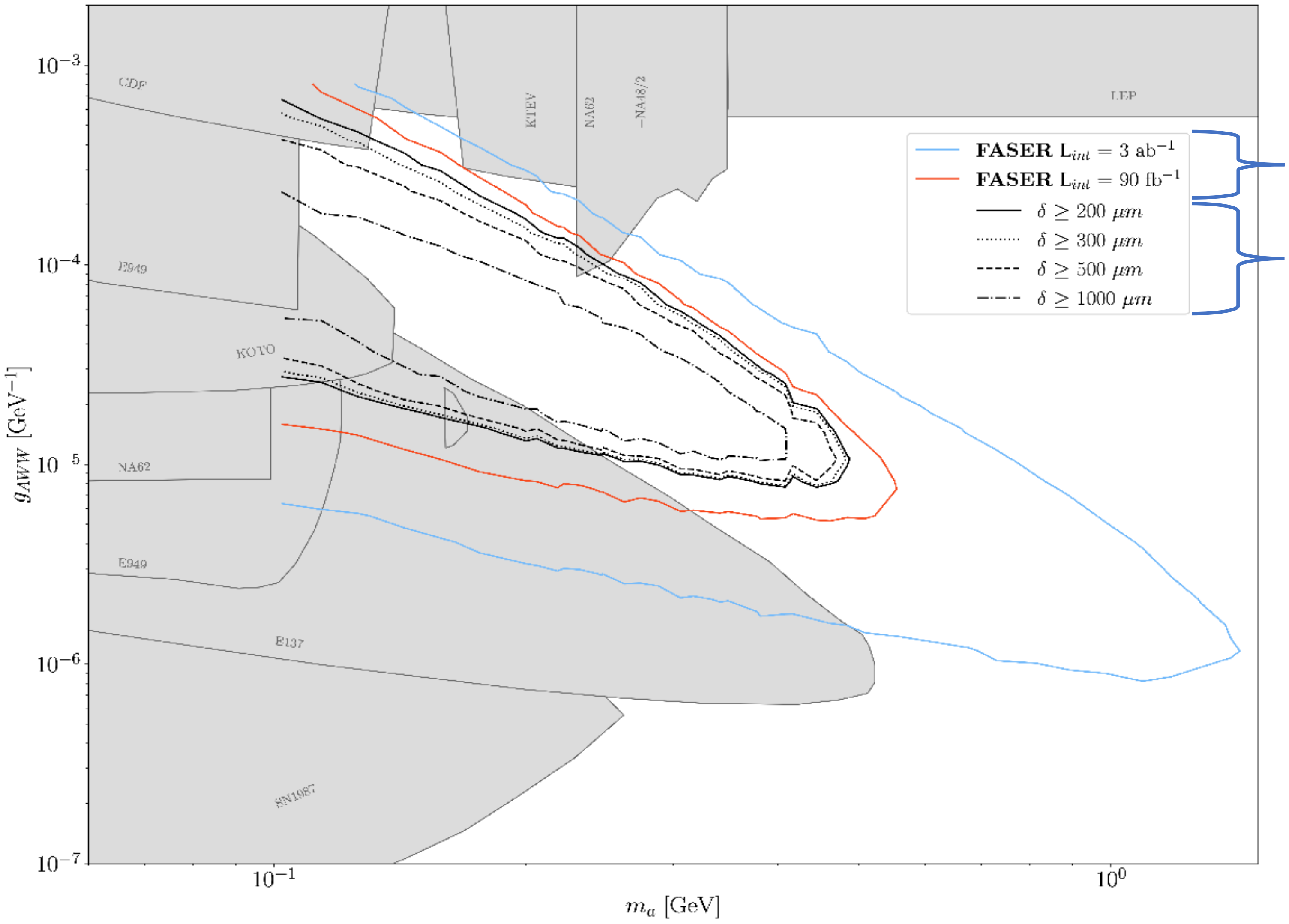
Plan:

- 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)

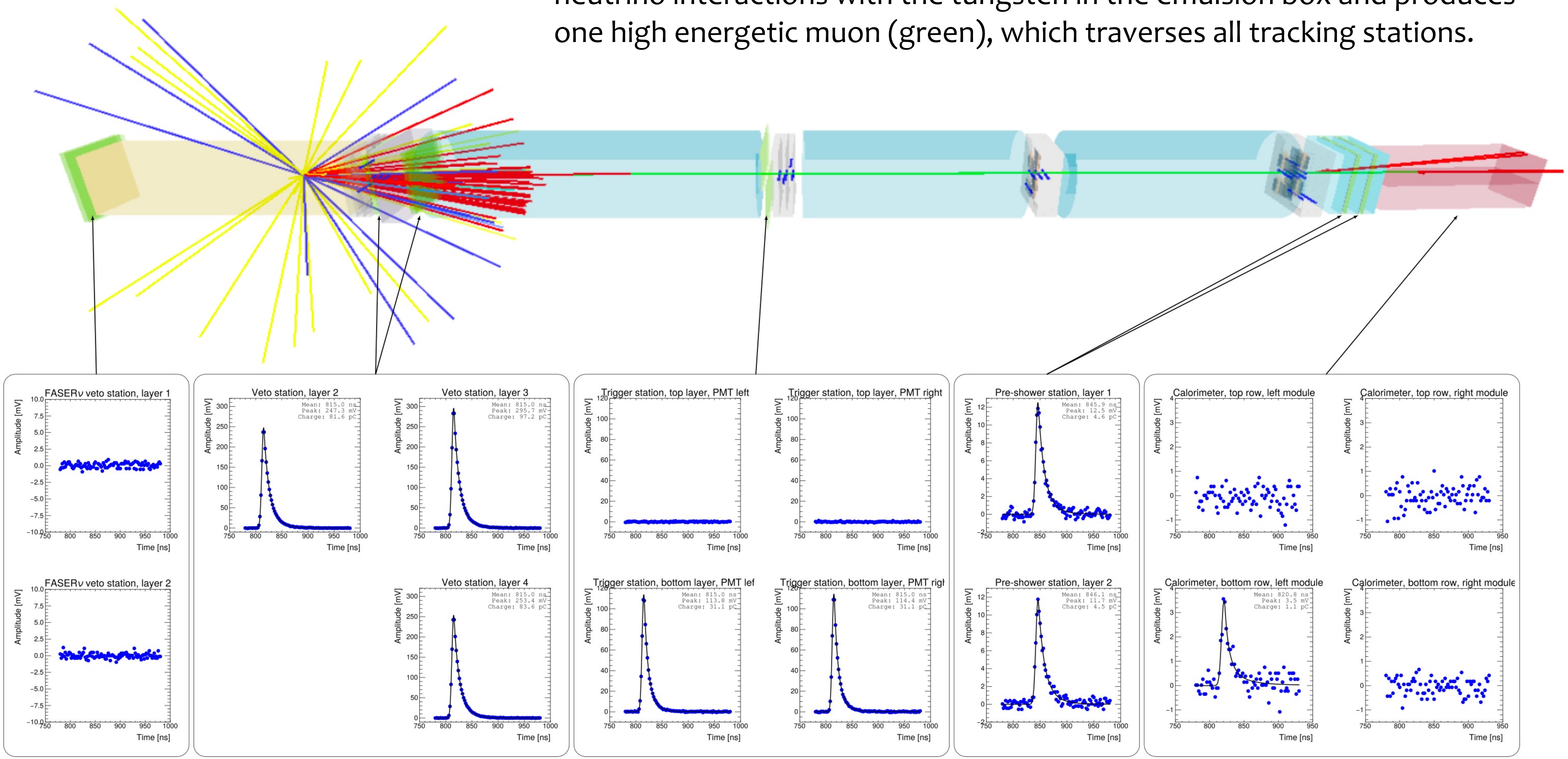
→ 2-photon pairs can be resolved and studied!

Otherwise: Indistinguishable from background

FASER

FASERnu

Event display for a typical charged current interaction where a muon neutrino interactions with the tungsten in the emulsion box and produces one high energetic muon (green), which traverses all tracking stations.

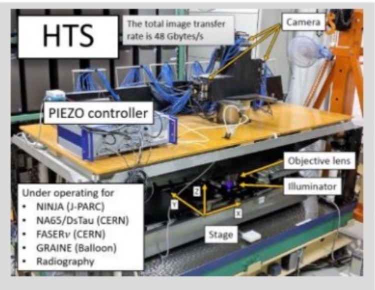


FASERν

Workflow







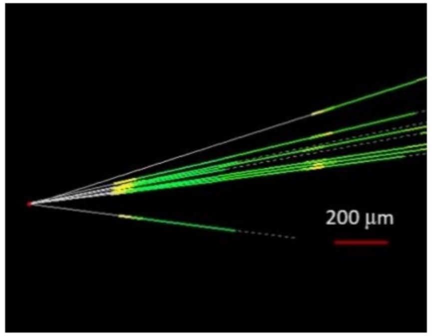
In Japan: **Emulsion film production** → **At CERN**: **Detector assembling** → **Exposure** → **Disassembling** → **Development** → **In Japan**: **Full area readout**

↓

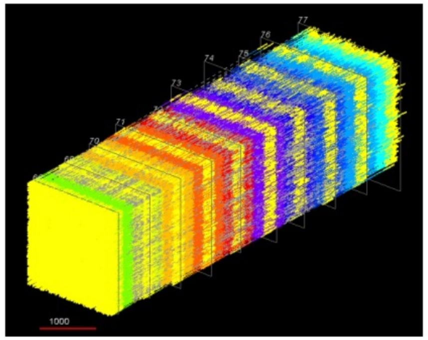
Off-line analysis: Alignment → Track reconstruction → Vertex reconstruction → μ / e ID → Search for tau/charm decays → Kinematical analysis

Interface tracker data

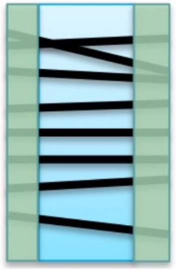
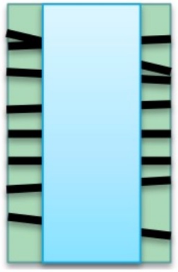
Spectrometer data



500-1000 TB/Run3



~500 TB/Run3

Emulsion

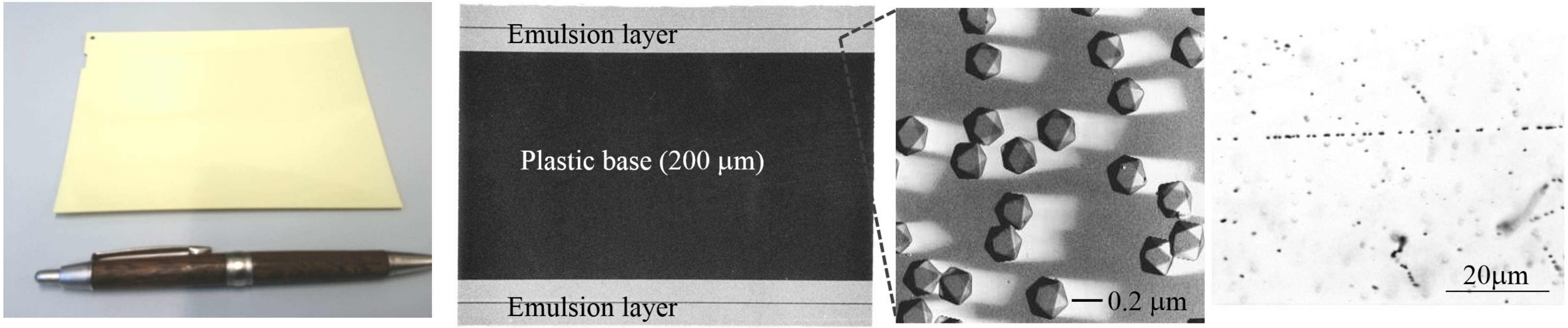


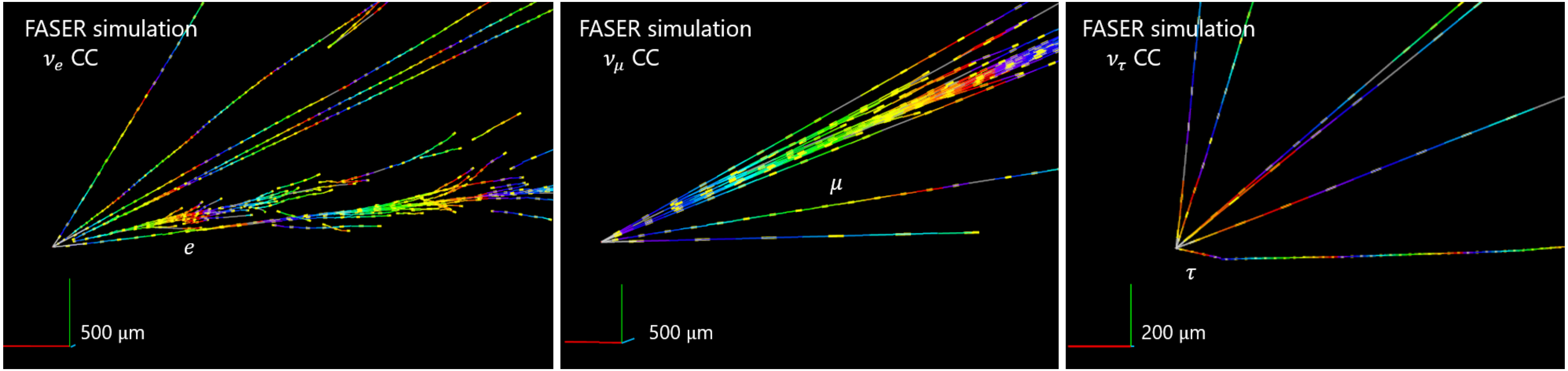
Photo of an emulsion film (left), its cross-sectional view (left center), electron microscope image of the silver halide crystals (right center), and a minimum ionising particle track from a 10 GeV/c π beam (right).

Neutrino production

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

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].

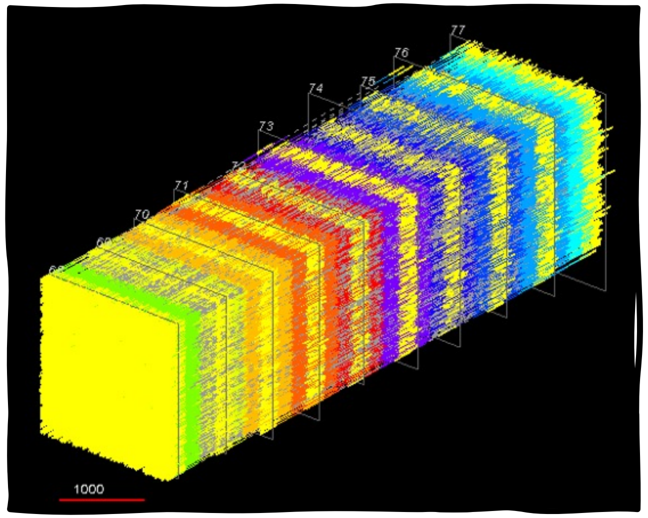
Event displays of simulated neutrino interaction vertices

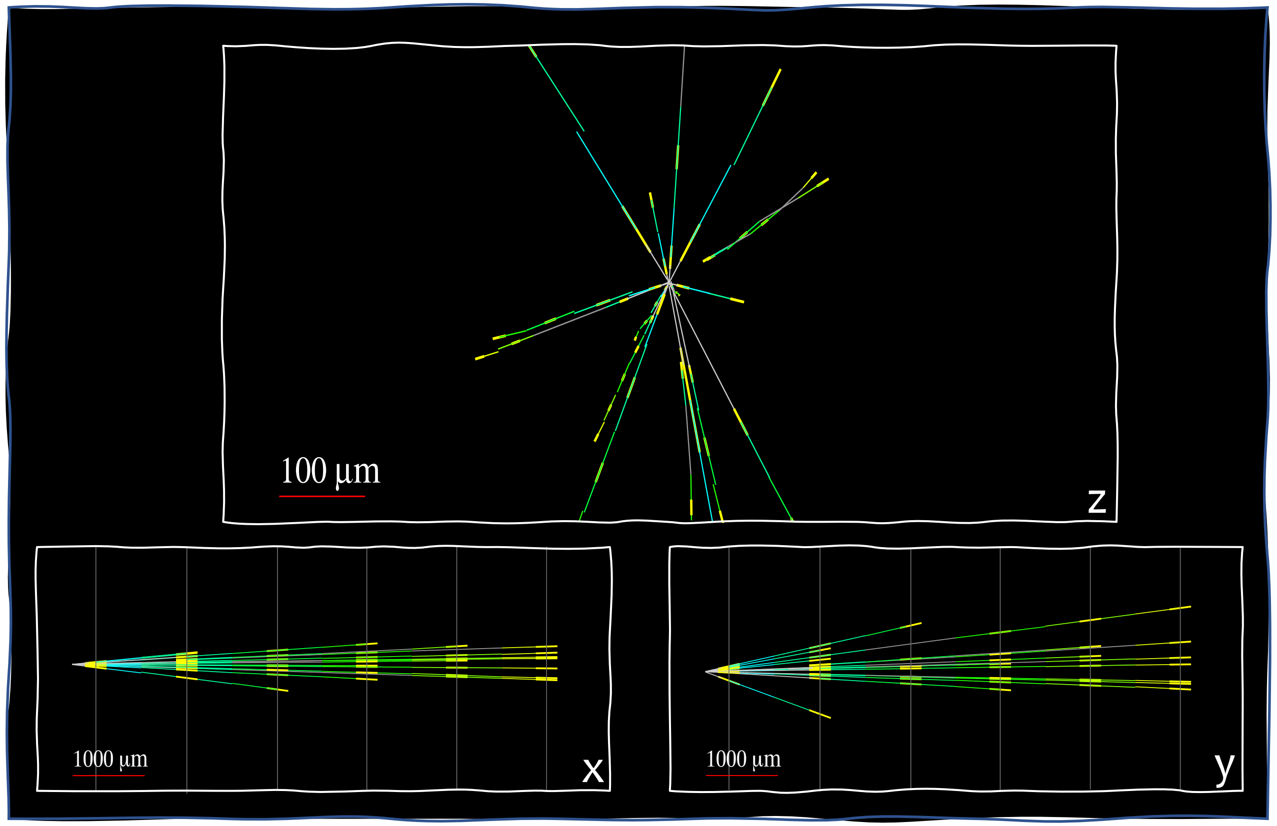


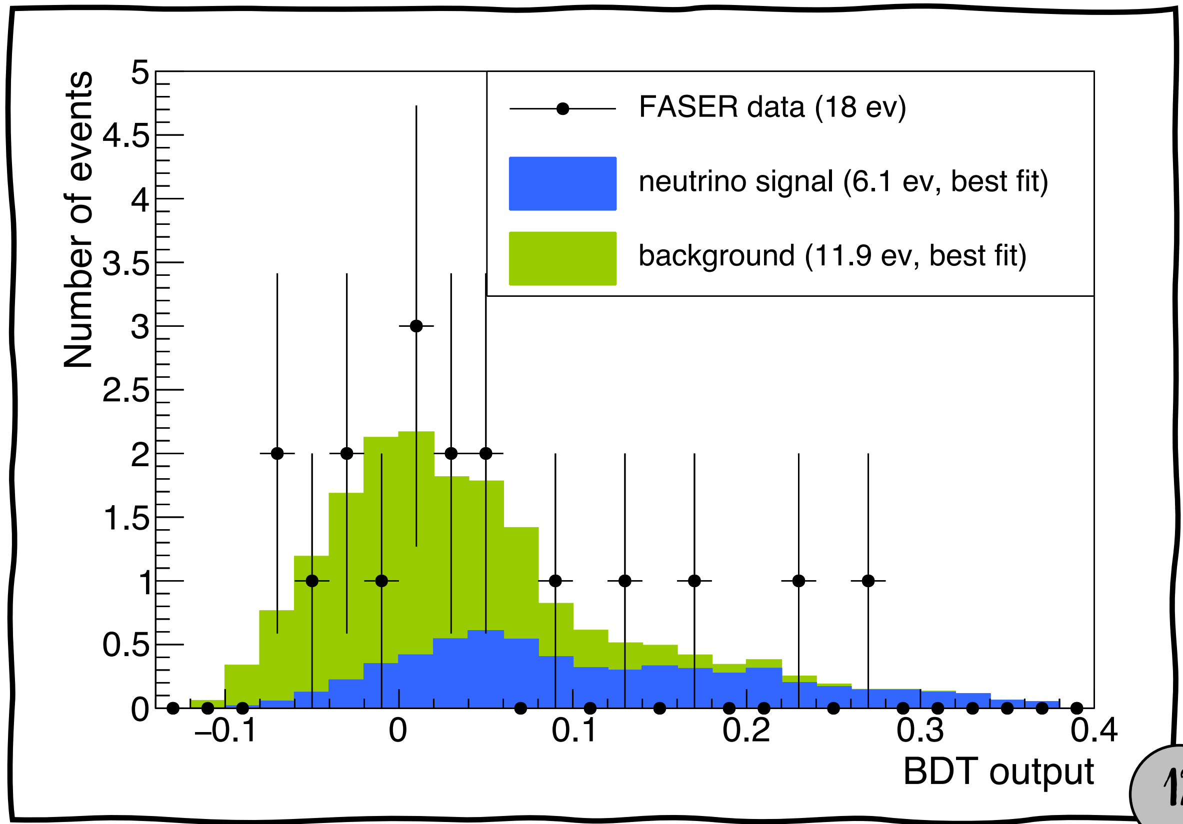
Event displays of simulated neutrino interaction vertices for 433 GeV nue CC, 664 GeV numu CC, and 831 GeV nutau CC. Yellow line segments show the trajectories of charged particles in the emulsion films. The other colored lines are extrapolations of the track hits to the neighboring tungsten plates, and the colors change depending on the depth in the detector.

Pilot run in 2018

First candidate **collider neutrino** interactions!

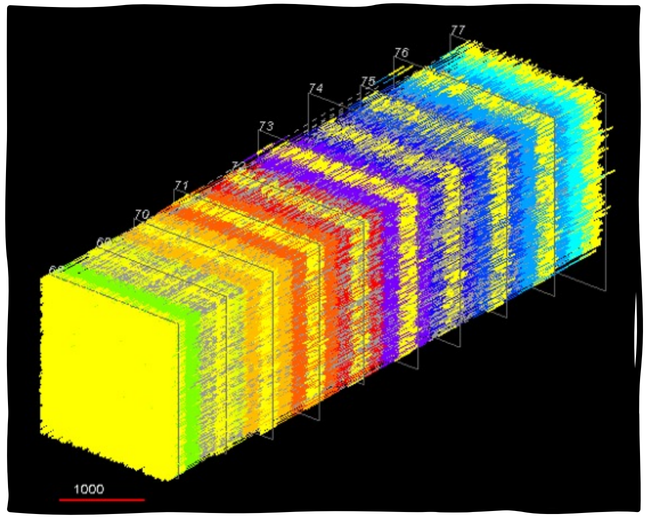






arXiv: 2105.06197

FASER Pilot run in 2018

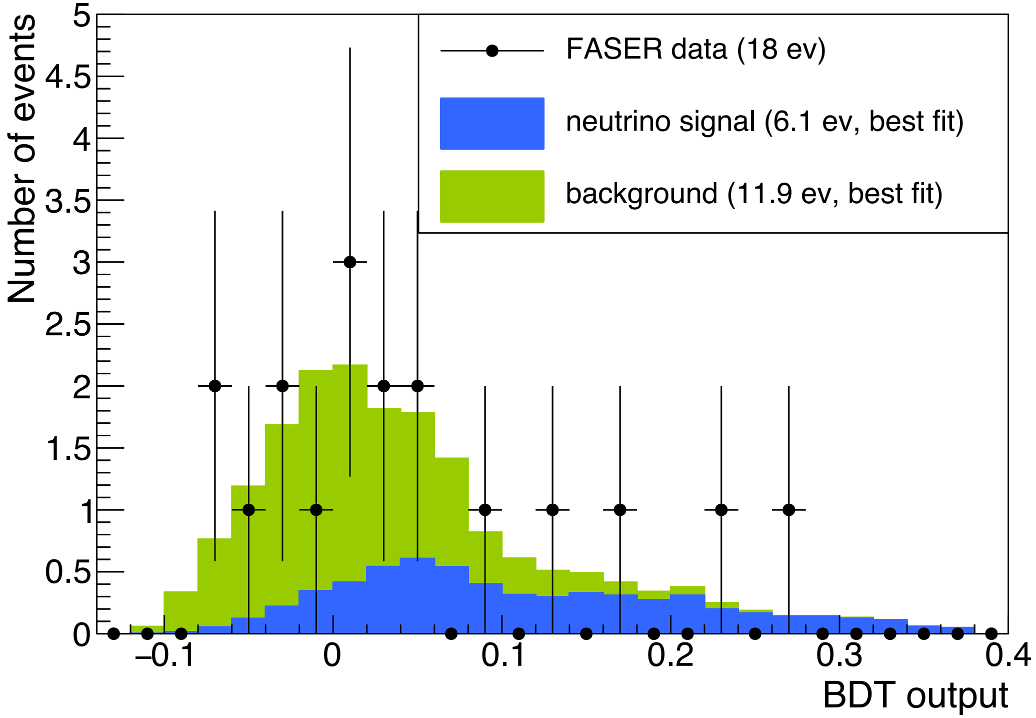


First candidate **collider neutrino** interactions!

- A 11 kg detector collected ~ 12/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



arXiv: 2105.06197

FASER Results

Neutrinos

Statistical analysis for significance estimation

Besides the signal category, we select:

n_{10}: Events for which the first layer of the FASERν scintillator produces a charge of >40 pC in the PMT, but no signal with sufficient charge is seen in the second layer.

n_{01}: Analogous events for which more than 40 pC in the PMT was observed in the second layer, but not in the first layer.

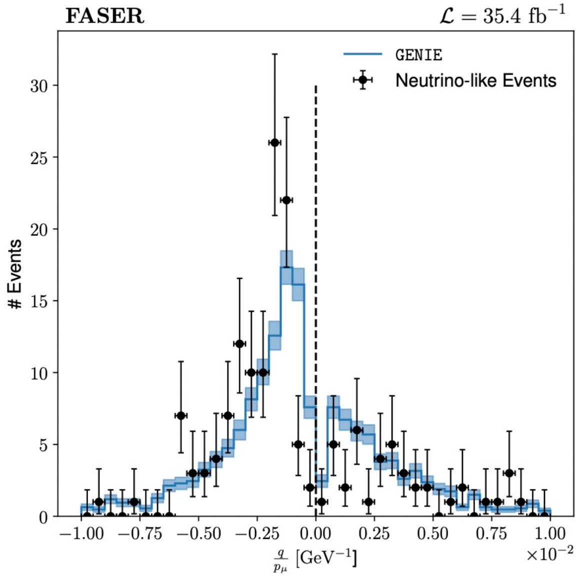
n_2: Events for which both layers observe more than 40 pC of charge.

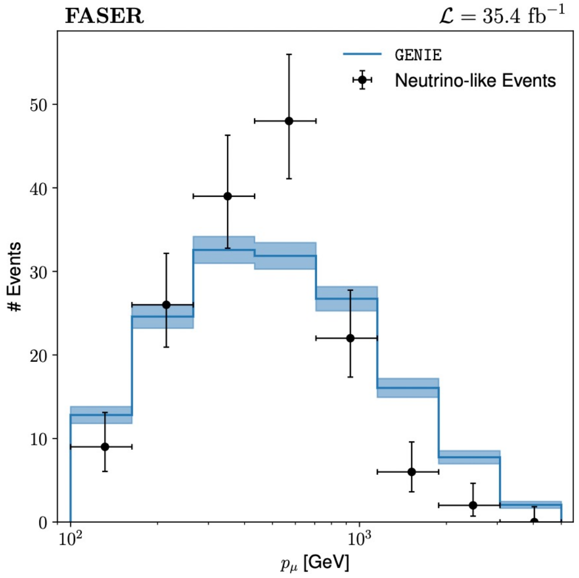
tor response and selection. The determined inefficiencies of the two FASERν scintillators are $p_1 = (6^{+4}_{-3}) \times 10^{-8}$ and $p_2 = (9^{+4}_{-3}) \times 10^{-8}$, showing values close to the expected performance [25].

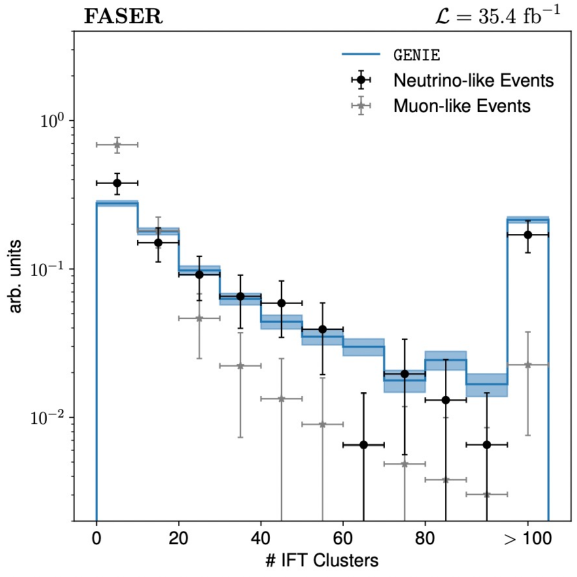
Category	Events	Expectation
Signal	153	$n_\nu + n_b \cdot p_1 \cdot p_2 + n_{\text{had}} + n_{\text{geo}} \cdot f_{\text{geo}}$
n_{10}	4	$n_b \cdot (1 - p_1) \cdot p_2$
n_{01}	6	$n_b \cdot p_1 \cdot (1 - p_2)$
n_2	64014695	$n_b \cdot (1 - p_1) \cdot (1 - p_2)$

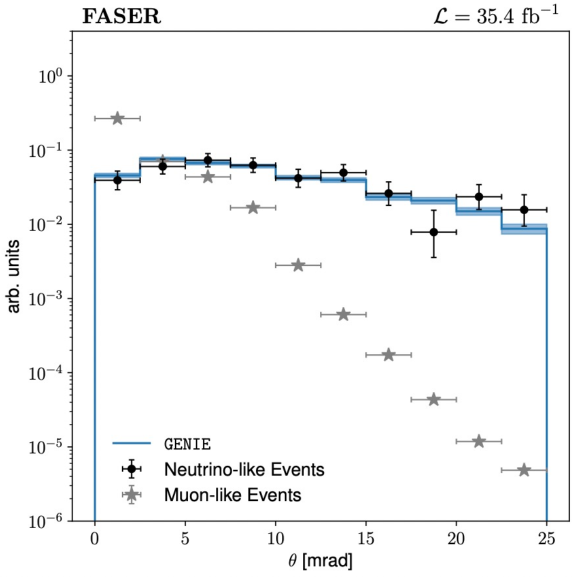
TABLE I. Observed event yields in 35.4 fb^{-1} of collision data and their relation to neutrino and background events.

Properties of observed events









FASER Results

Dark Photon

Expected dark photon phase-space

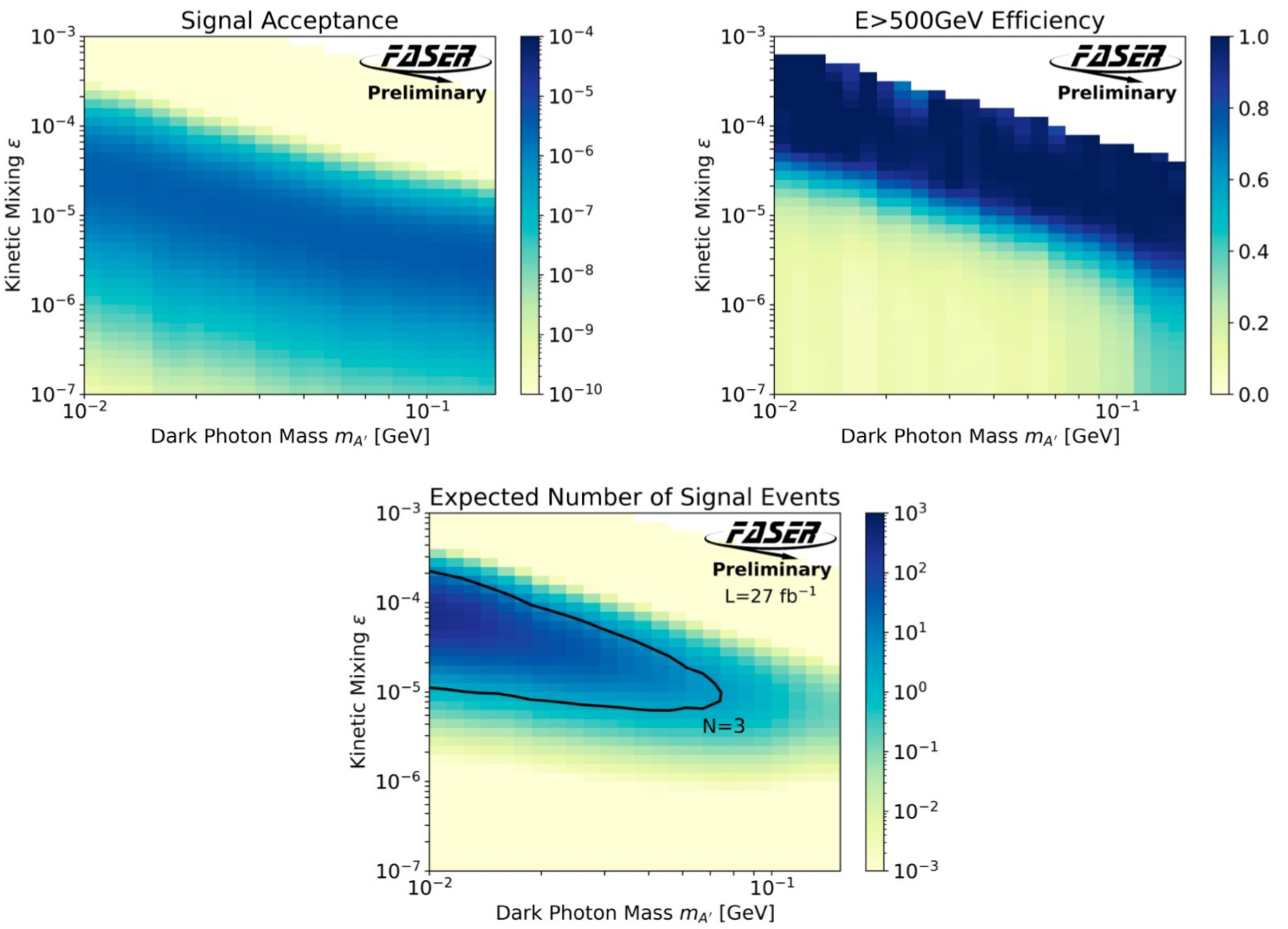
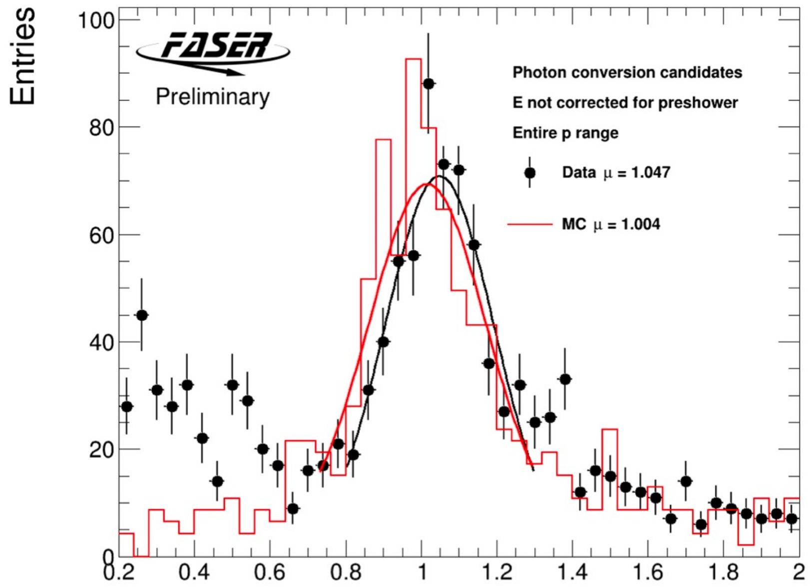
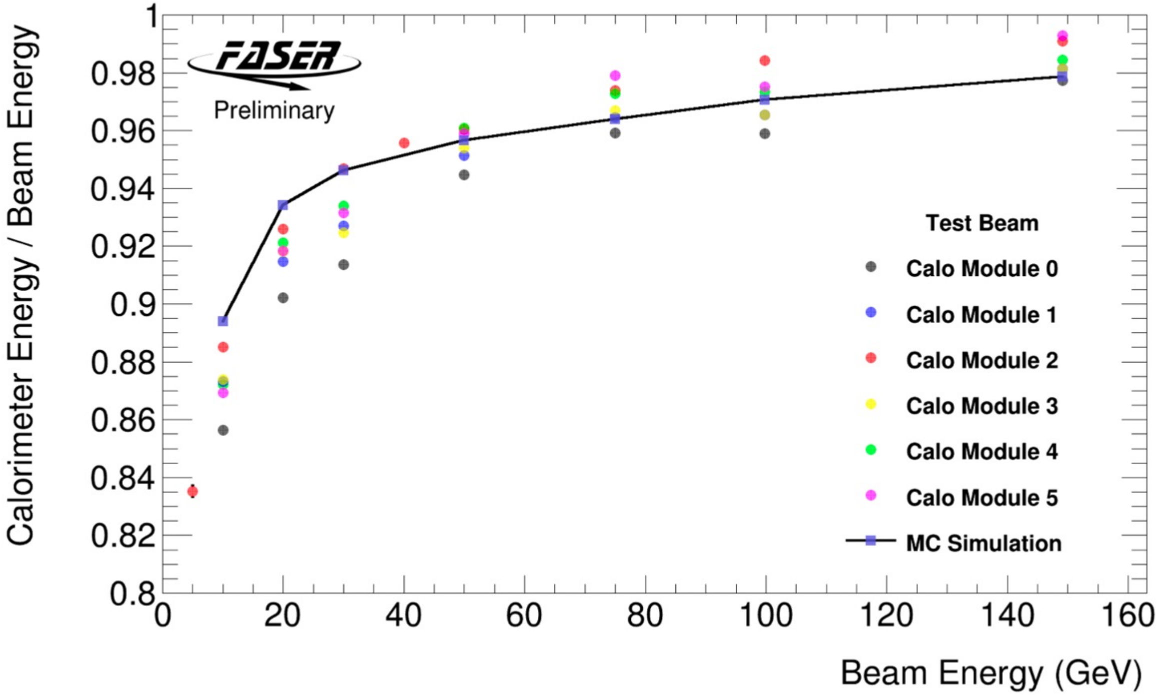


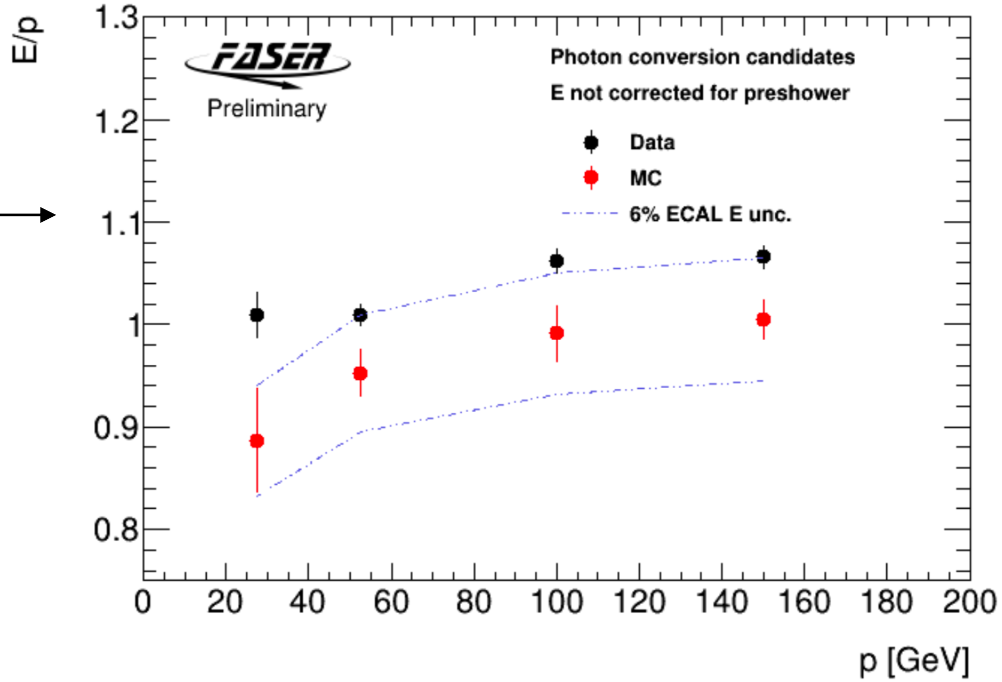
FIG. 1. Top left: The acceptance for dark photons to decay inside the FASER decay volume. Top right: The fraction of dark photons decaying inside the FASER decay volume that have energy greater than 500 GeV. Bottom: The expected number of dark photon events in FASER for 27.0 fb^{-1} of data, assuming a 50% signal efficiency, on top of the requirement that the A' energy is greater than 500 GeV.

CALO-RELATED PERFORMANCE ASSESSMENT

- Calorimeter energy scale and uncertainty estimated based on test beam data and in situ MIP calibration
- Validated using conversion events (μ with e+e- pair)
- E/p in data/MC agrees within 6%

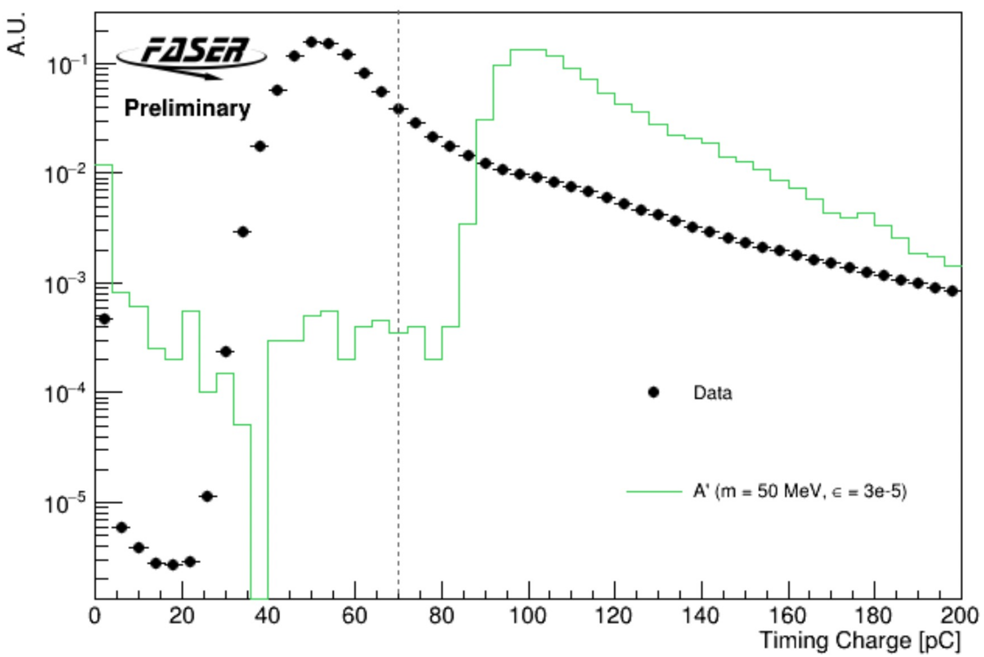






Selection in timing layer

Selecting events with more than 70pC in timing layer is ~100% efficient for signal, while also suppressing a large fraction of single track events



Systematics

Source	Value	Effect on signal yield
Theory, Statistics and Luminosity		
Dark photon cross-section	$\frac{0.15+(E_{A'}/4\text{TeV})^3}{1+(E_{A'}/4\text{TeV})^3}$	15-65% (15-45%)
Luminosity	2.2%	2.2%
MC Statistics	$\sqrt{\sum W^2}$	1-3% (1-2%)
Tracking		
Momentum Scale	5%	$< 0.5\%$
Momentum Resolution	5%	$< 0.5\%$
Single Track Efficiency	3%	3%
Two-track Efficiency	15%	15%
Calorimetry		
Calo E scale	6%	0-8% ($< 1\%$)

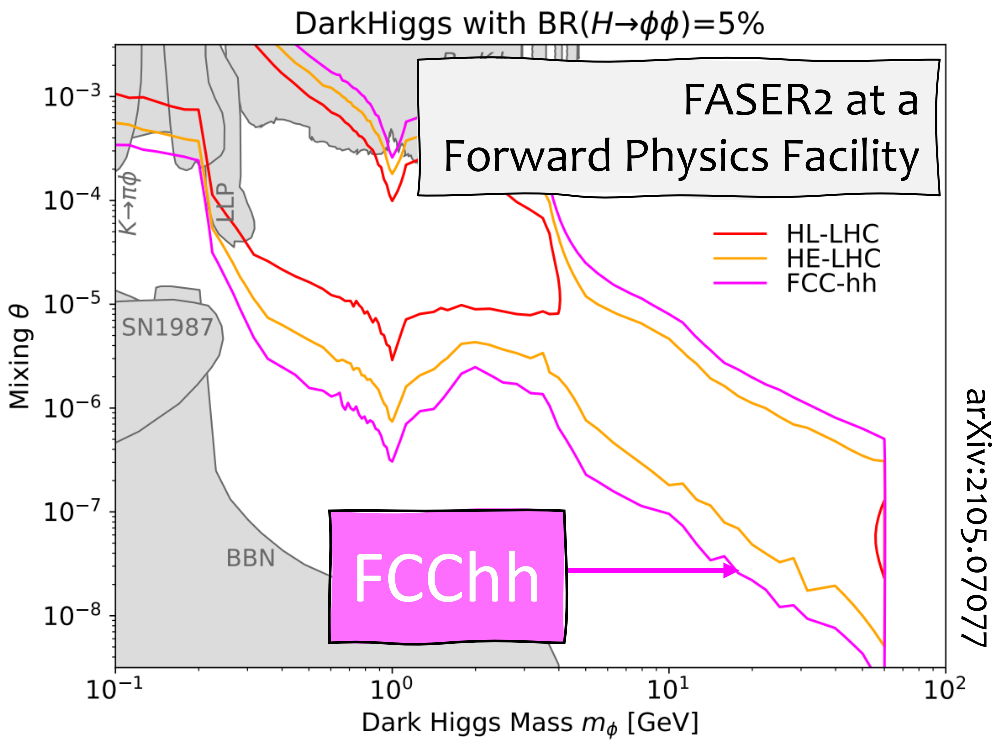
Yields

Cut	Data	
	Events	Efficiency
Good collision event	151750788	—
No Veto Signal	1235830	0.814%
Timing/Preshower Signal	313988	0.207%
≥ 1 good track	21329	0.014%
$= 2$ good tracks	0	0.000%
Track radius < 95 mm	0	0.000%
Calo energy > 500 GeV	0	0.000%

Beyond FASER

Opportunities for FIPs at FCC

At FCChh



Significant opportunities open up, beyond what can be done with conventional collider detectors! Essential to account for them since the beginning, to minimize overheads later on.