First Data with FASER

A new LHC experiment for long lived particle searches

on behalf of the FASER collaboration

at Kruger Conference 2022: Discovery Physics at the LHC

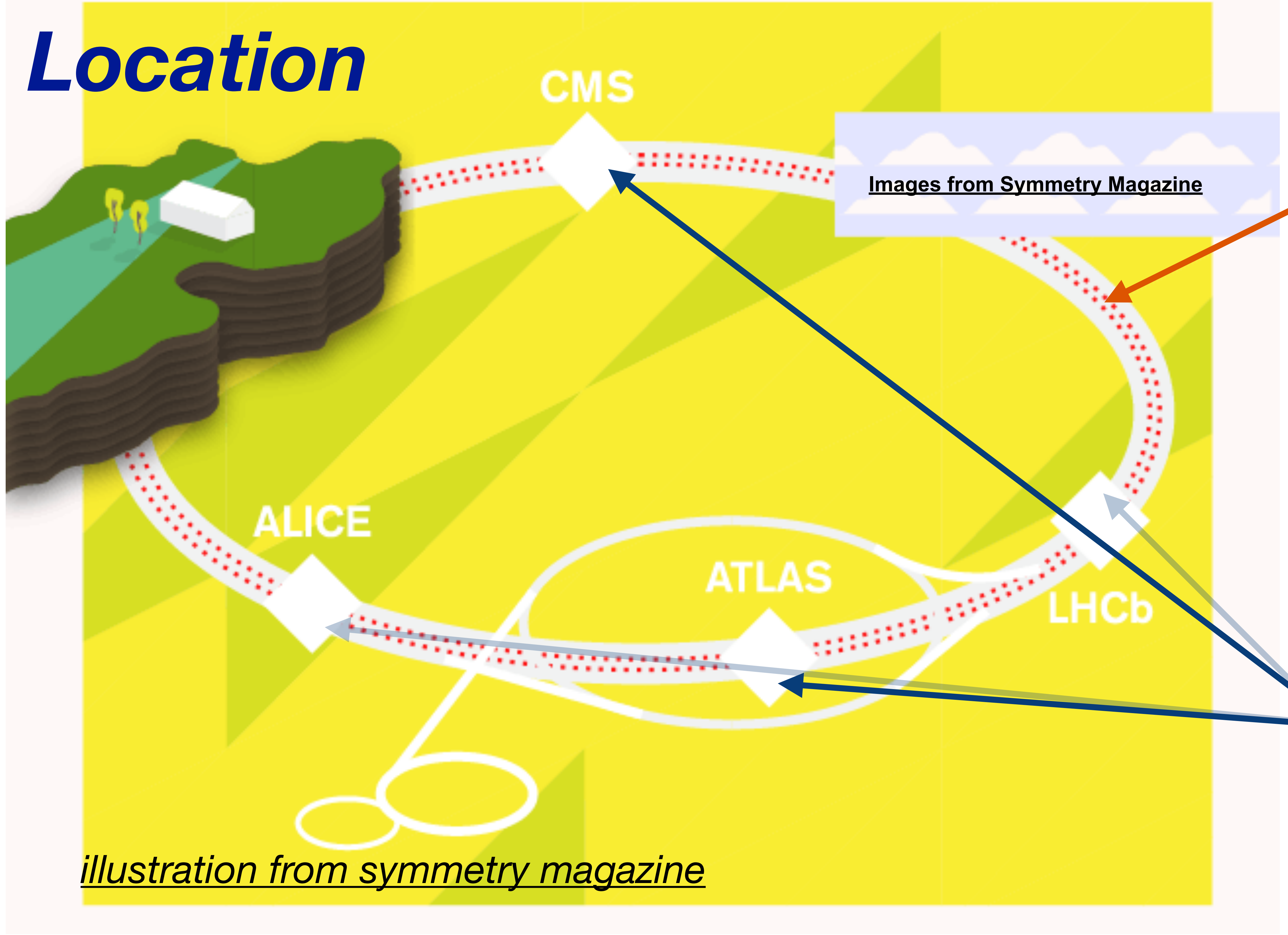
UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département de physique nucléaire et corpusculaire

Claire Antel, Geneva University, 6th Dec 2022.

Swiss National Science Foundation

FASER Overview

Location

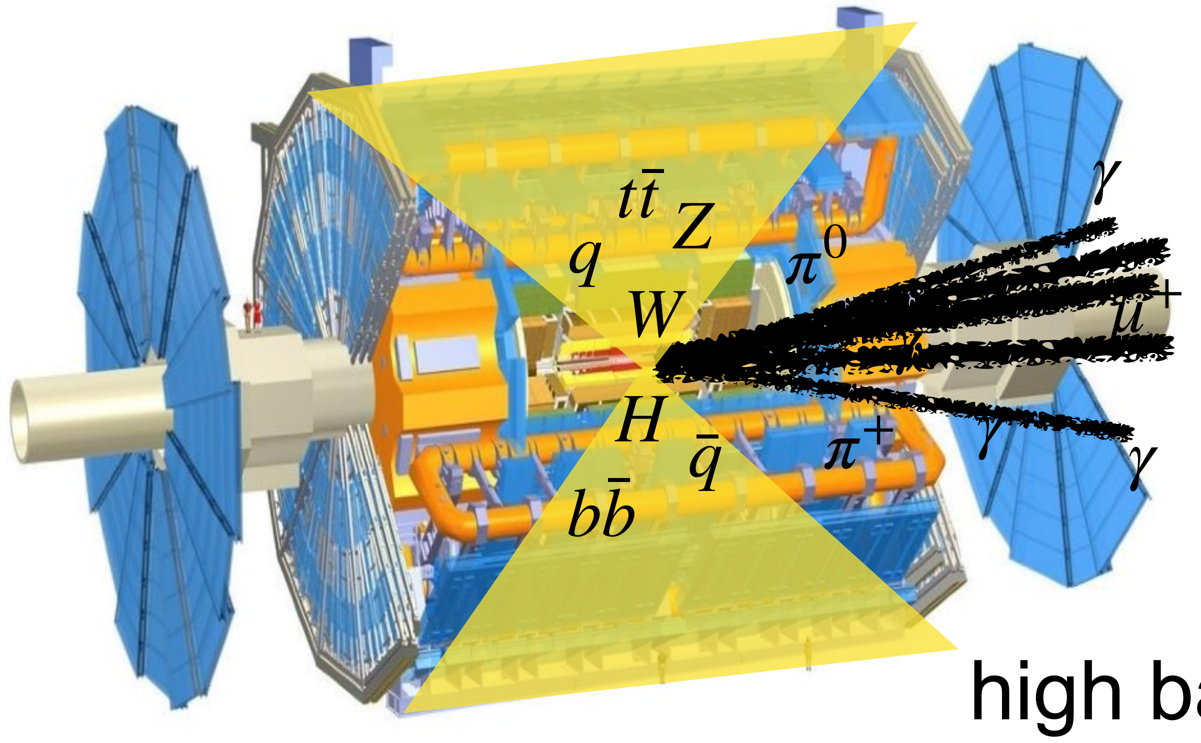


Large Hadron Collider, at HEP energy & intensity frontier.

"The Big 4" titan detectors on ring;

The biggest, CMS & ATLAS, ~$\mathcal{O}$(10s) meters in diameter & length, have wide physics agenda including searches for new particles

ATLAS & CMS



Focus on central/high pT,
EW-scale coupling, since
high background + no instrumentation
in very forward region

FASER Overview

Location

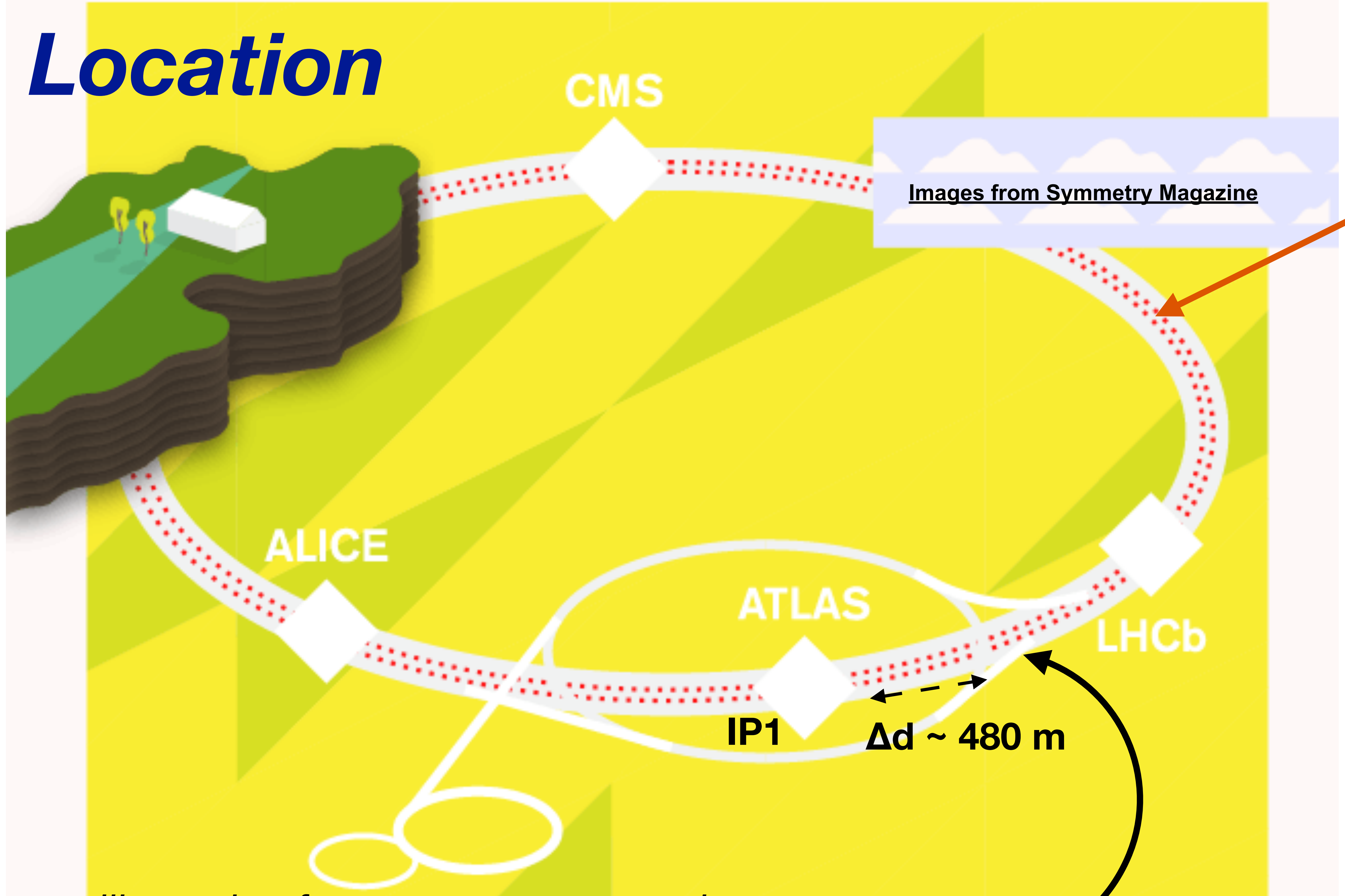


illustration from symmetry magazine

Large Hadron Collider, at HEP energy & intensity frontier.

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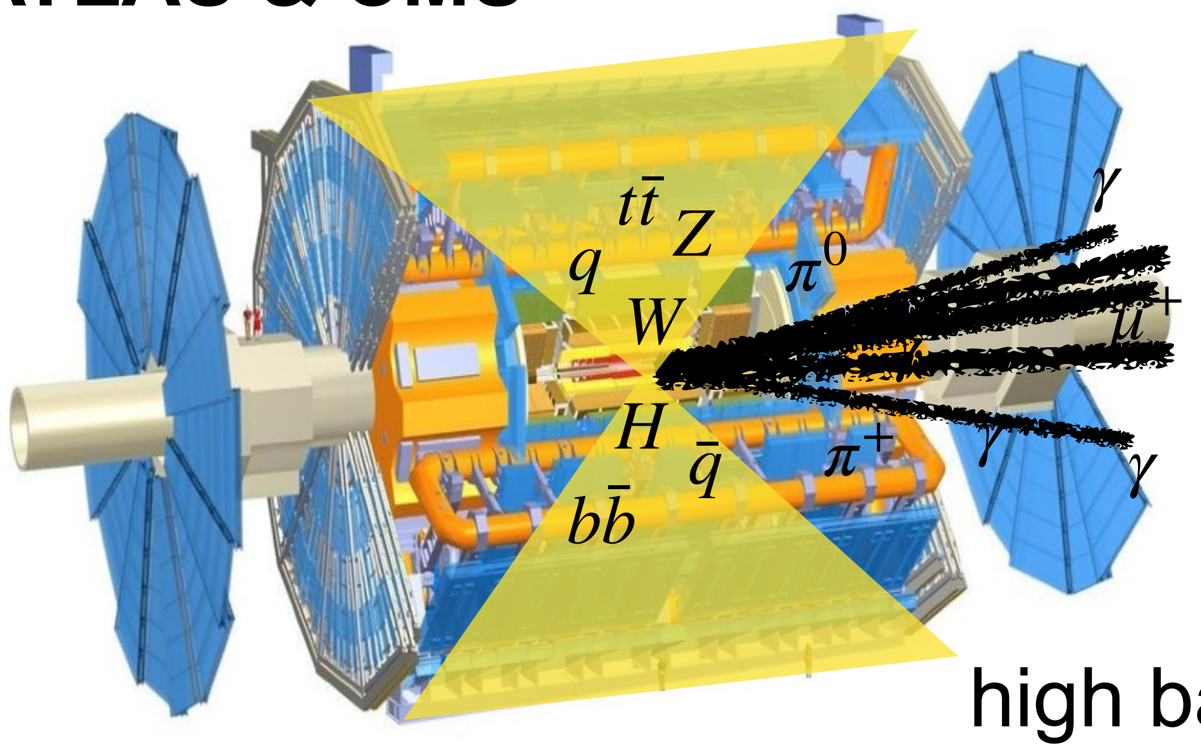
ATLAS & CMS



Focus on central/high pT, EW-scale coupling, since high background + no instrumentation in very forward region

FASER

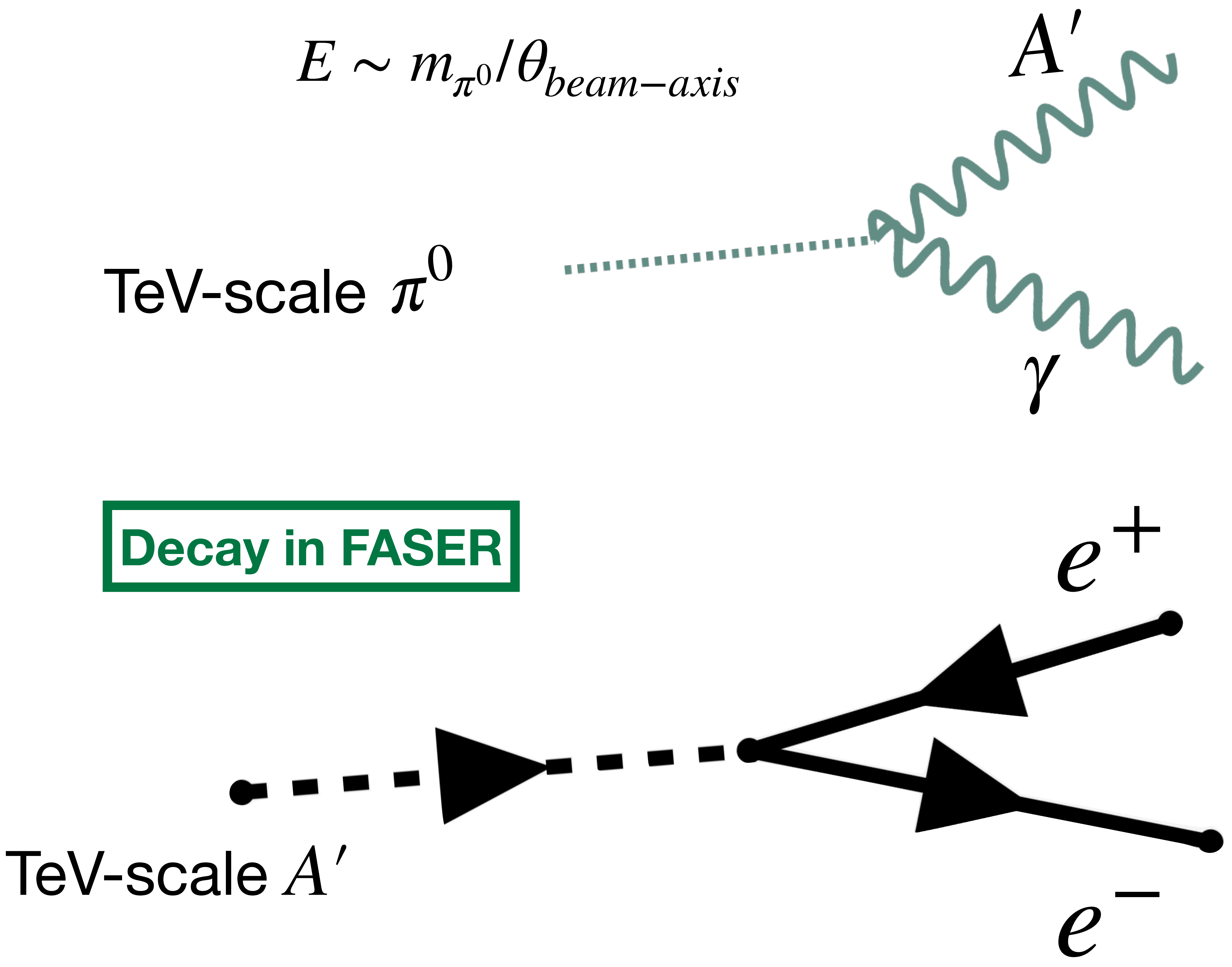
(**F**orw**A**rd **S**earch **E**xpe**R**iment)

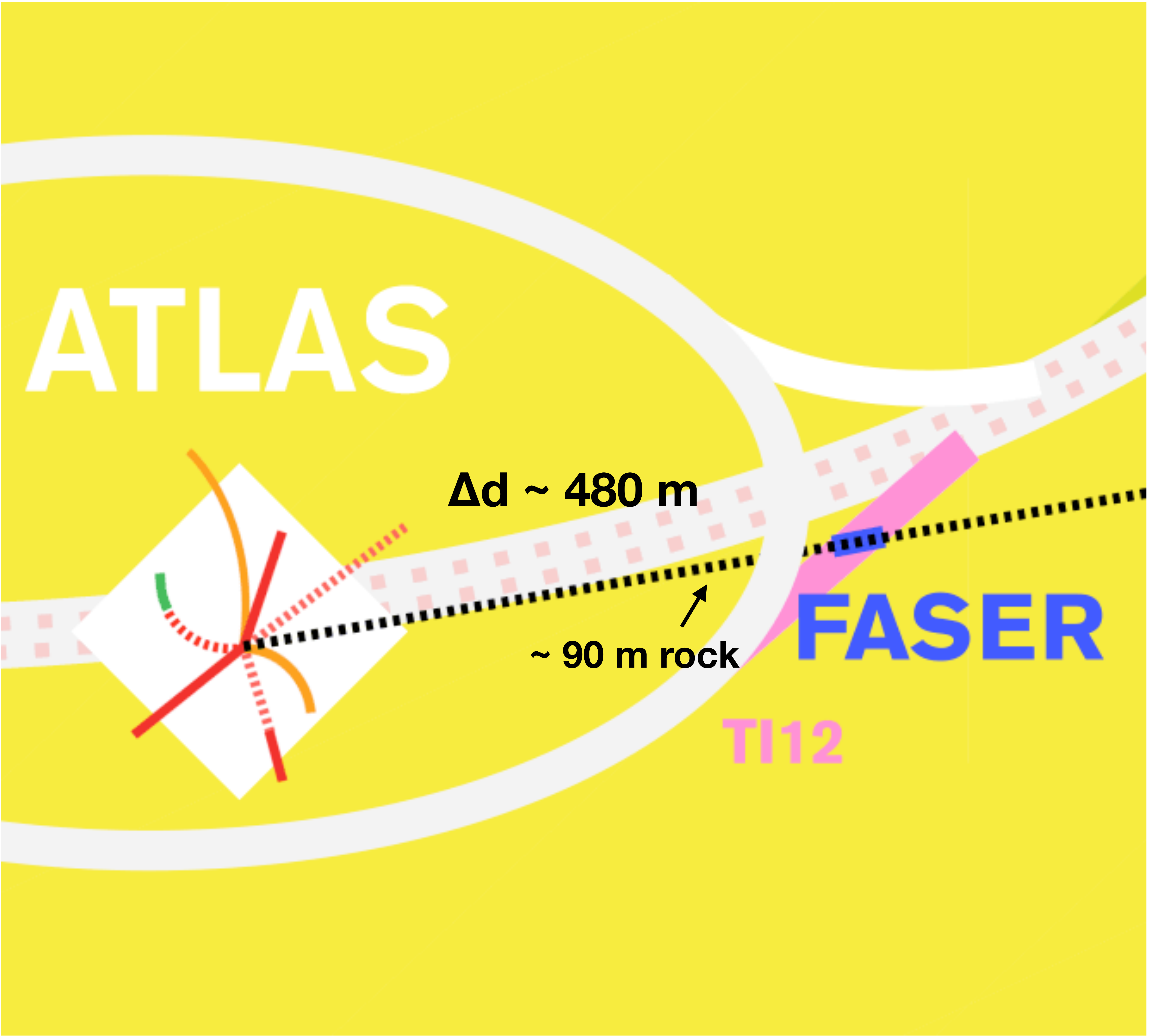
A new Run 3 small (20 cm diameter, ~ 7 m long) detector far from proton-proton collision point, but directly in line with beam pipe to ATLAS/IP1.

FASER Overview

Location

Production at IP1



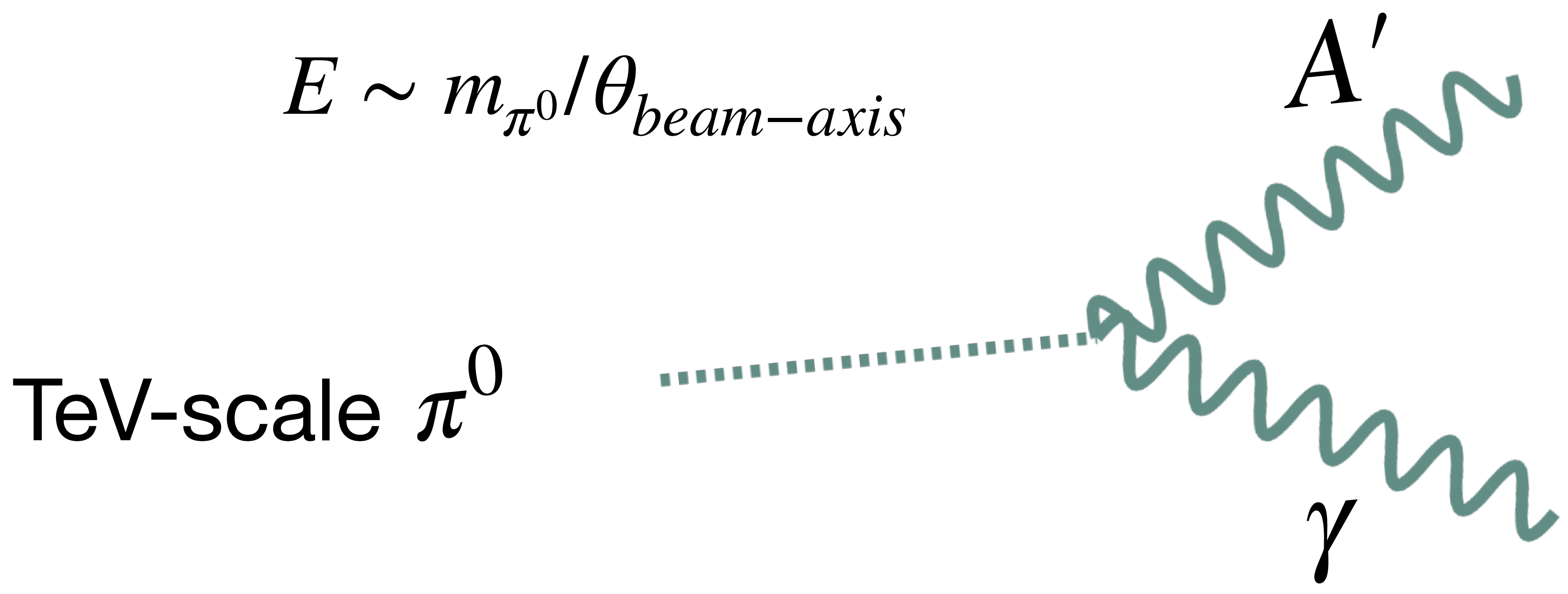


FASER Overview

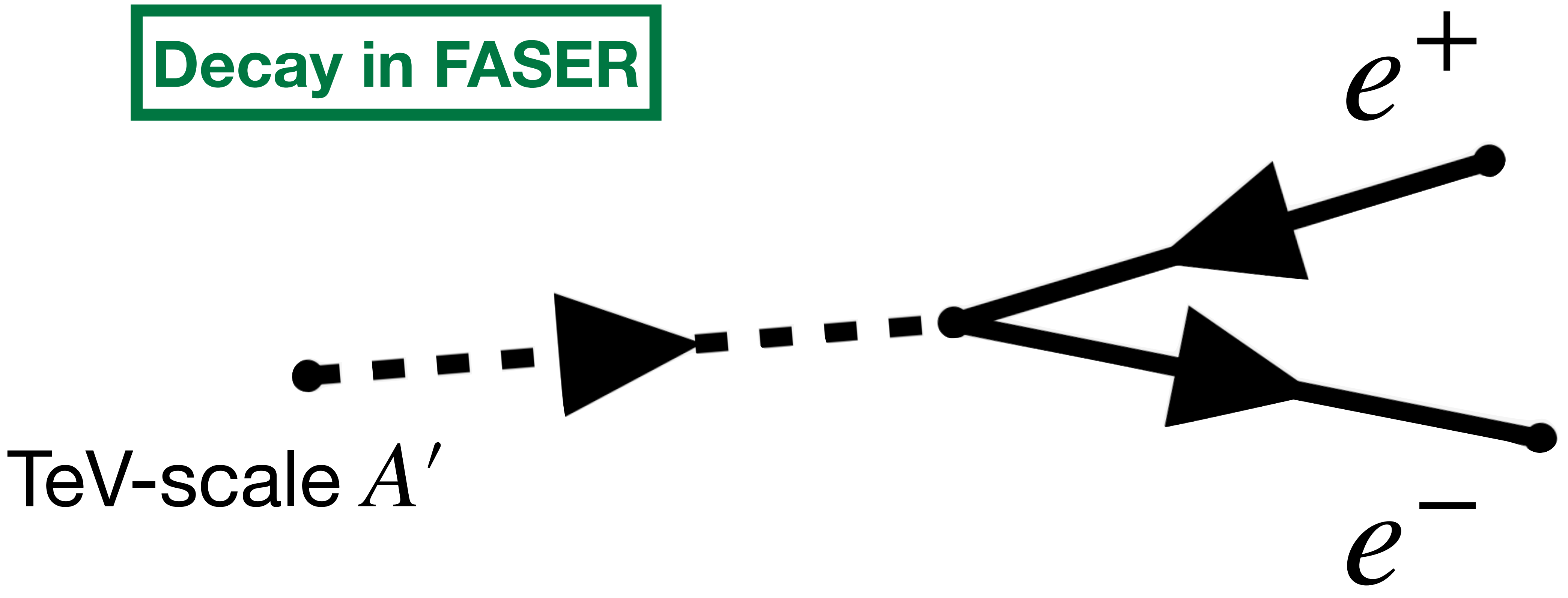
Location

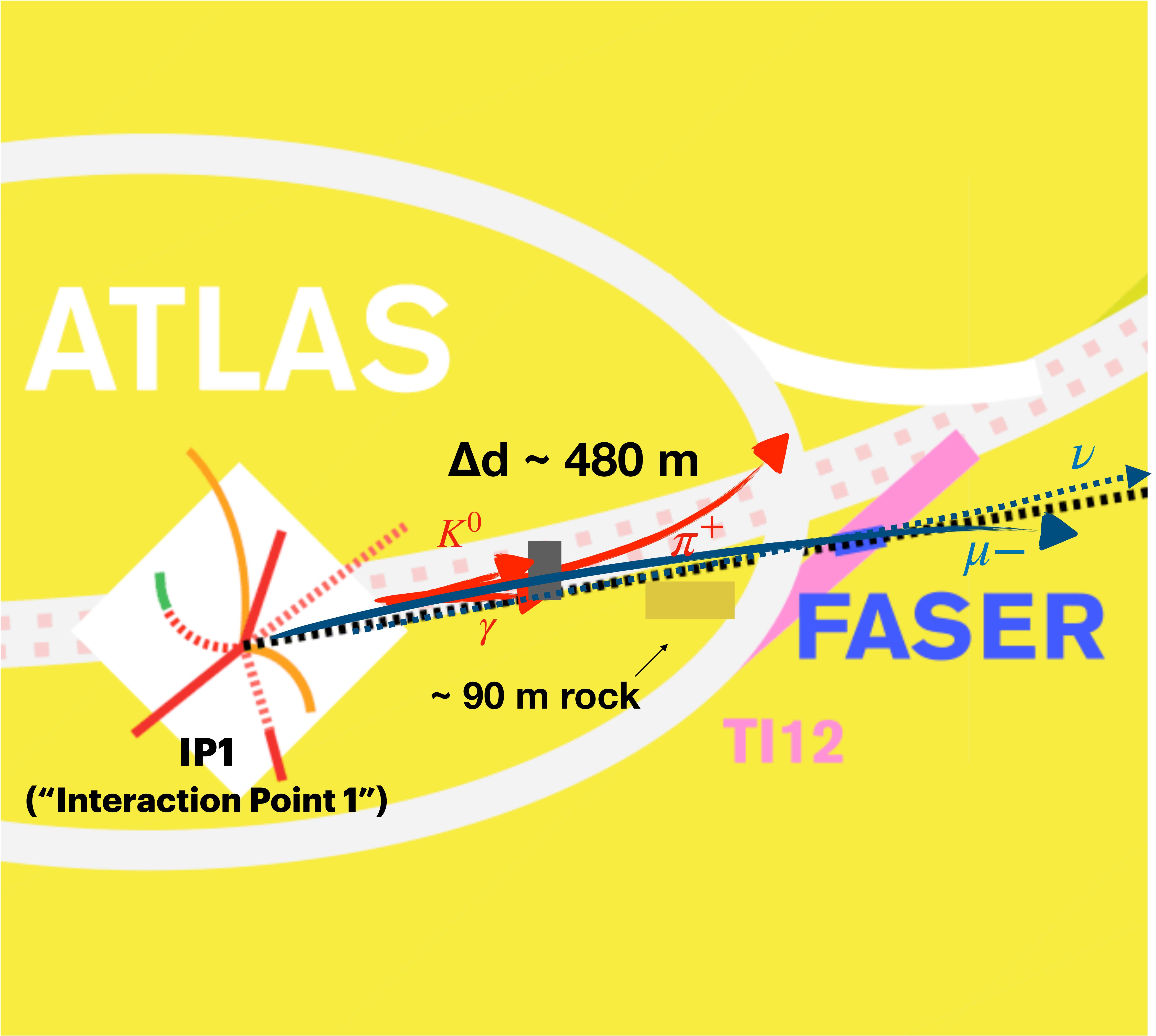
Production at IP1

$E \sim m_{\pi^0}/\theta_{beam-axis}$



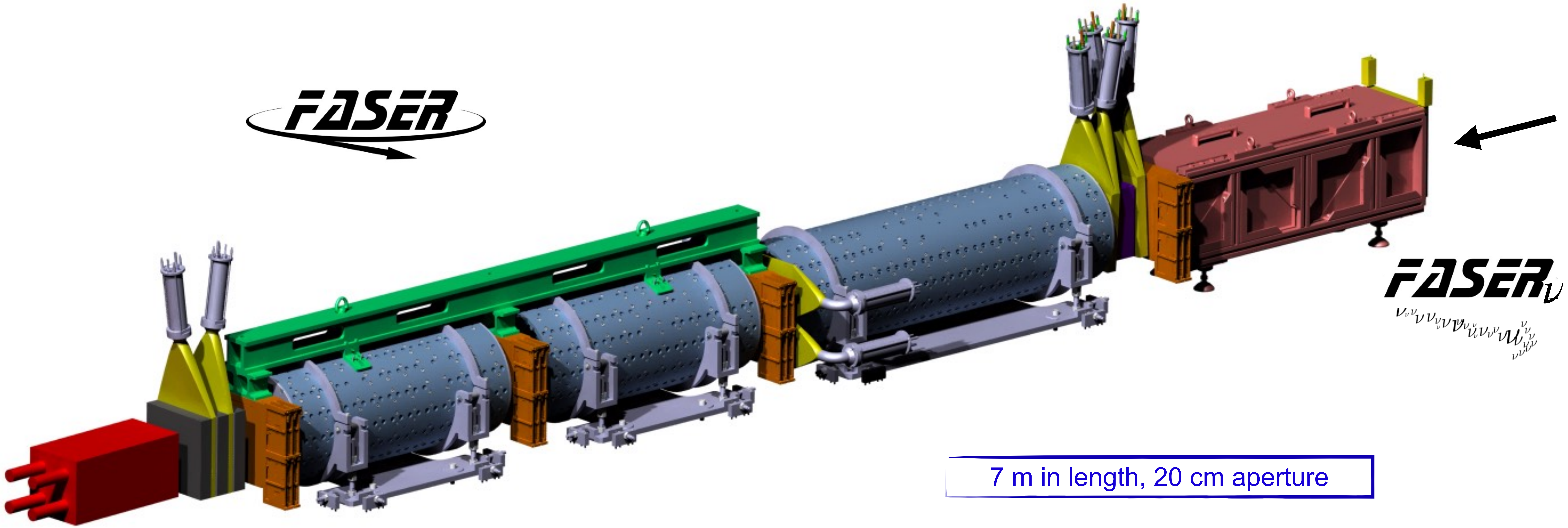
Decay in FASER





FASER Detector Design

- Cylindric, long in shape, to track/capture highly collimated Standard Model particles from energetic neutral vertex decays.

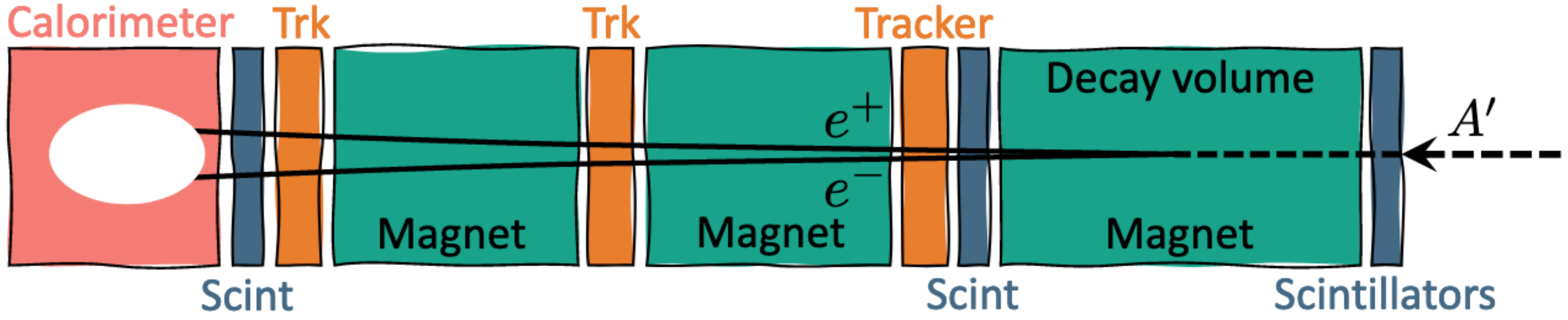


7 m in length, 20 cm aperture

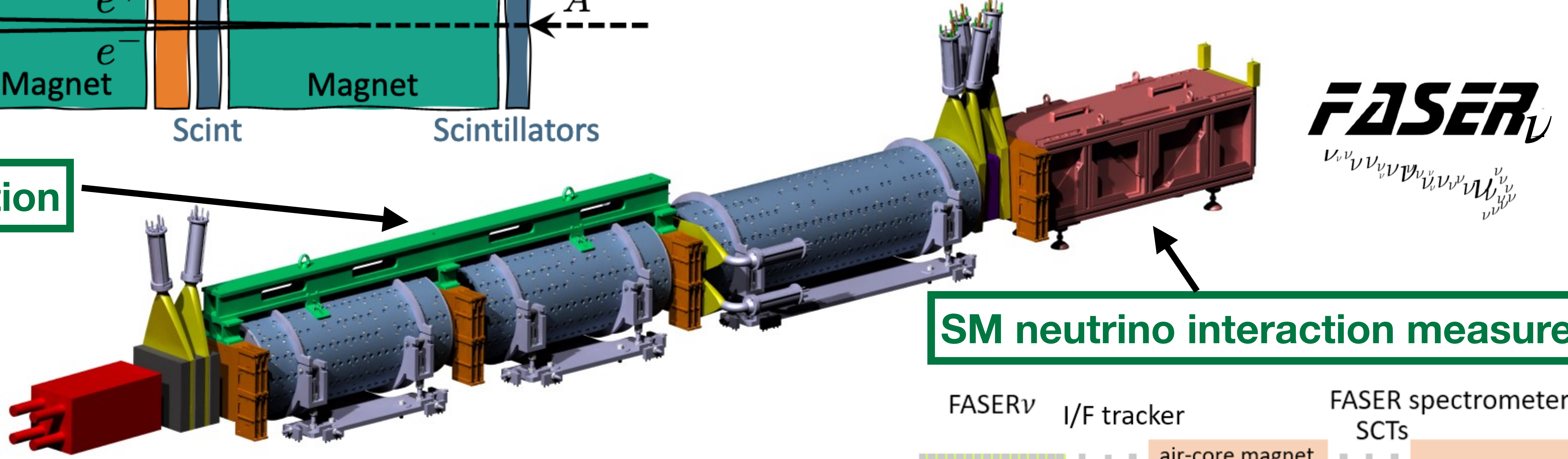
Publications:

[FASER Detector: arxiv: 2207.11427](#) [FASER TDAQ: JINST 16 (2021) 12, P12028](#) [FASER Tracker: NIMA 166825 (2022)](#)

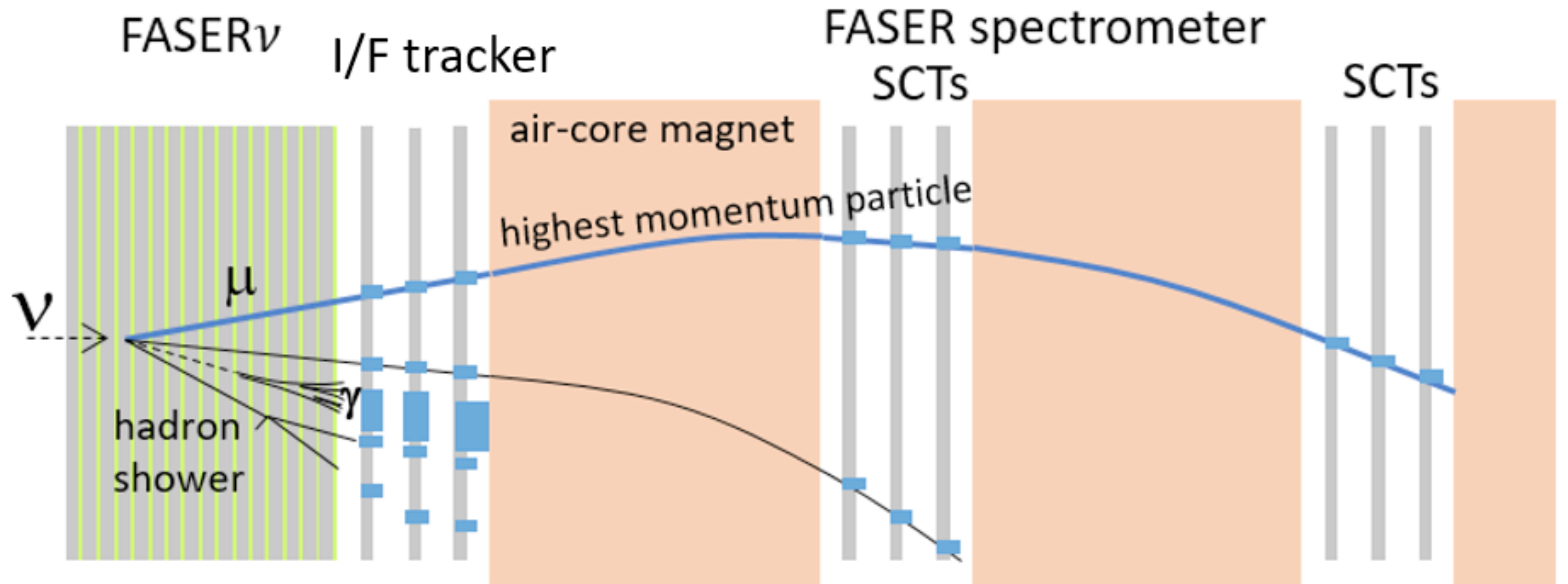
FASER Detector Design



Long-lived Particle Detection



SM neutrino interaction measurement



Recycled parts (ATLAS SCTs for tracker, LHCb modules for calorimeter) —> low cost experiment.

Emulsion box exchanged every 10-50 fb^{-1}.

Publications:

FASER Detector: arxiv: 2207.11427 FASER TDAQ: JINST 16 (2021) 12, P12028 FASER Tracker: NIMA 166825 (2022)

FASER Construction & Commissioning

A snapshot

The challenge: Short time scale!

2017
Concept born

ForwArd Search ExpeRiment at the LHC

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[2]*National Centre for Nuclear Research, Hoża 69, 00-681 Warsaw, Poland*

(Received 13 October 2017; published 5 February 2018)

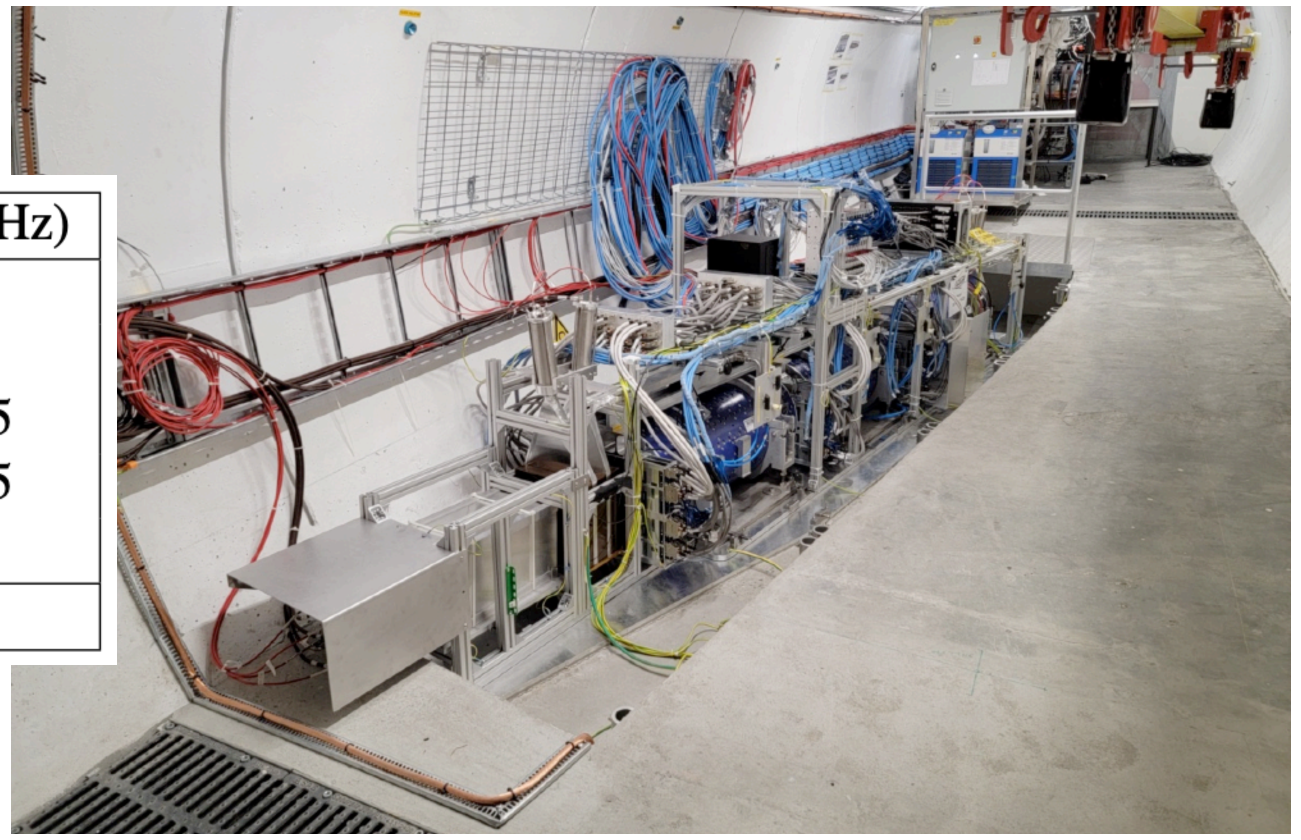
Dry assembly above surface (end 2020)

2019 March
FASER approved

~~2020~~ 2021 March
FASER installed

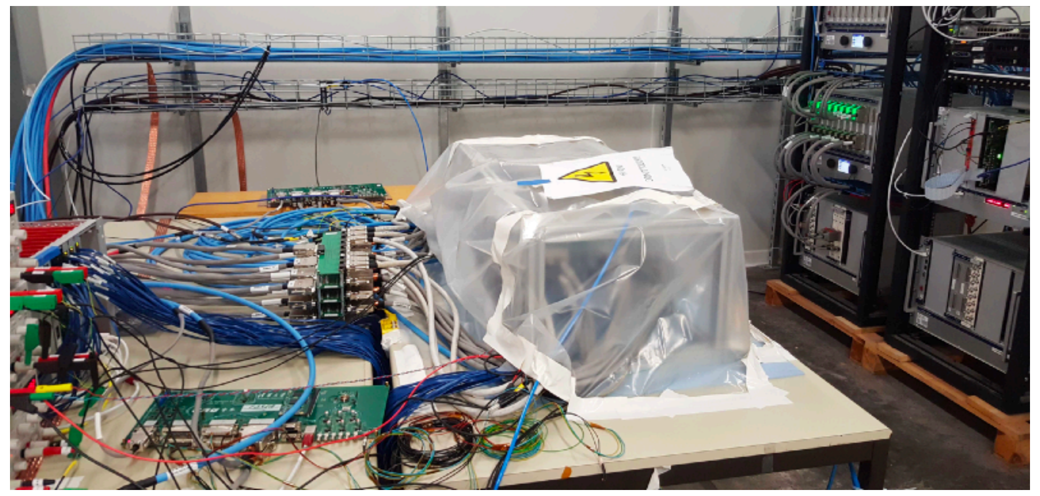
Delay due to COVID-19 pandemic

Installation in tunnel (March 2021)



Trigger	Rate (Hz)
Veto scintillator station	3.5
Timing scintillator station	10
Pre-shower scintillator station	0.25
Calorimeter	0.25
Random	1
Total rate	15

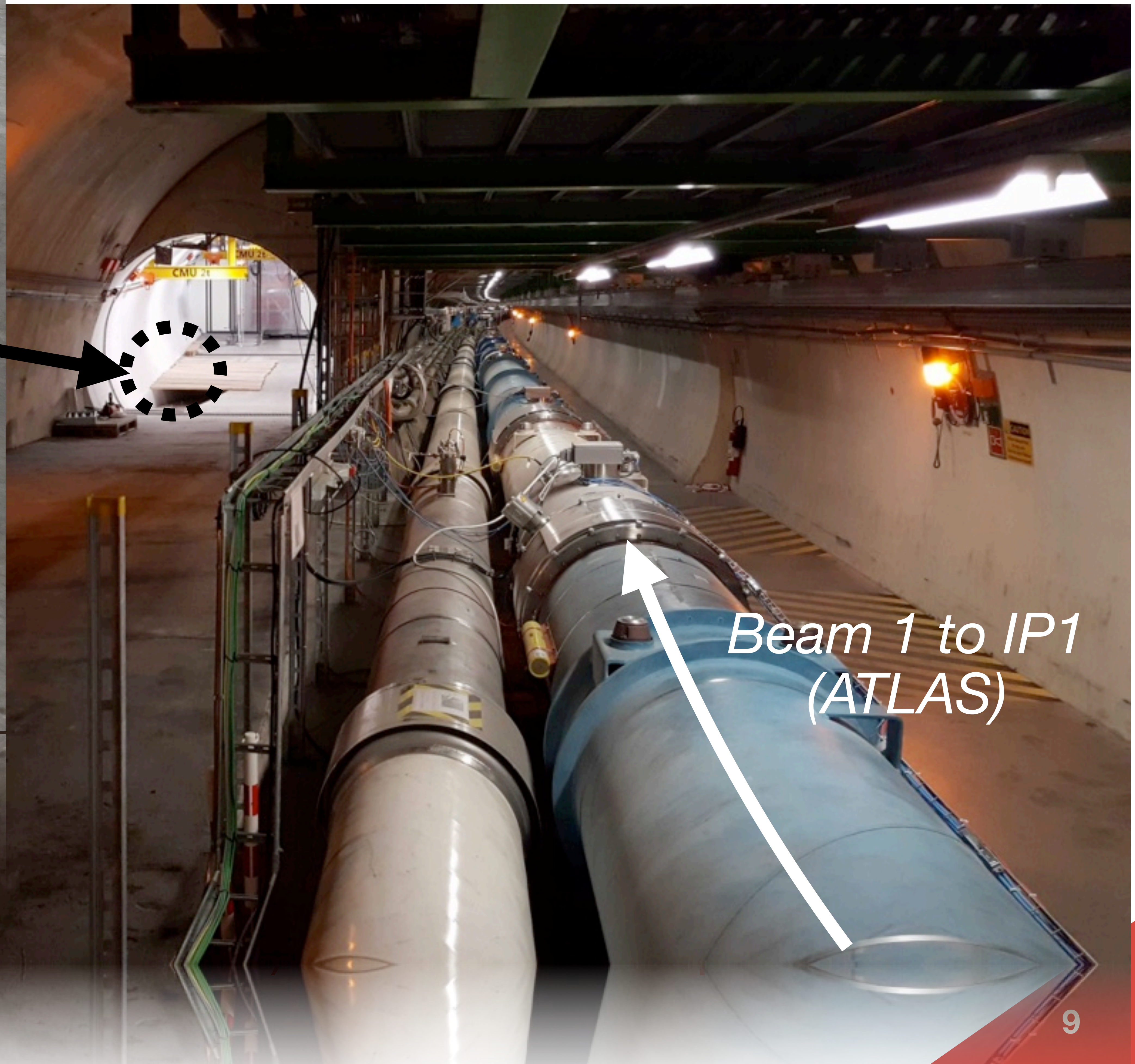
Cosmic-Ray stand:
FASER Scintillators + tracker planes (Summer 2020)



~~2021~~ 2022 July
Start of Run 3

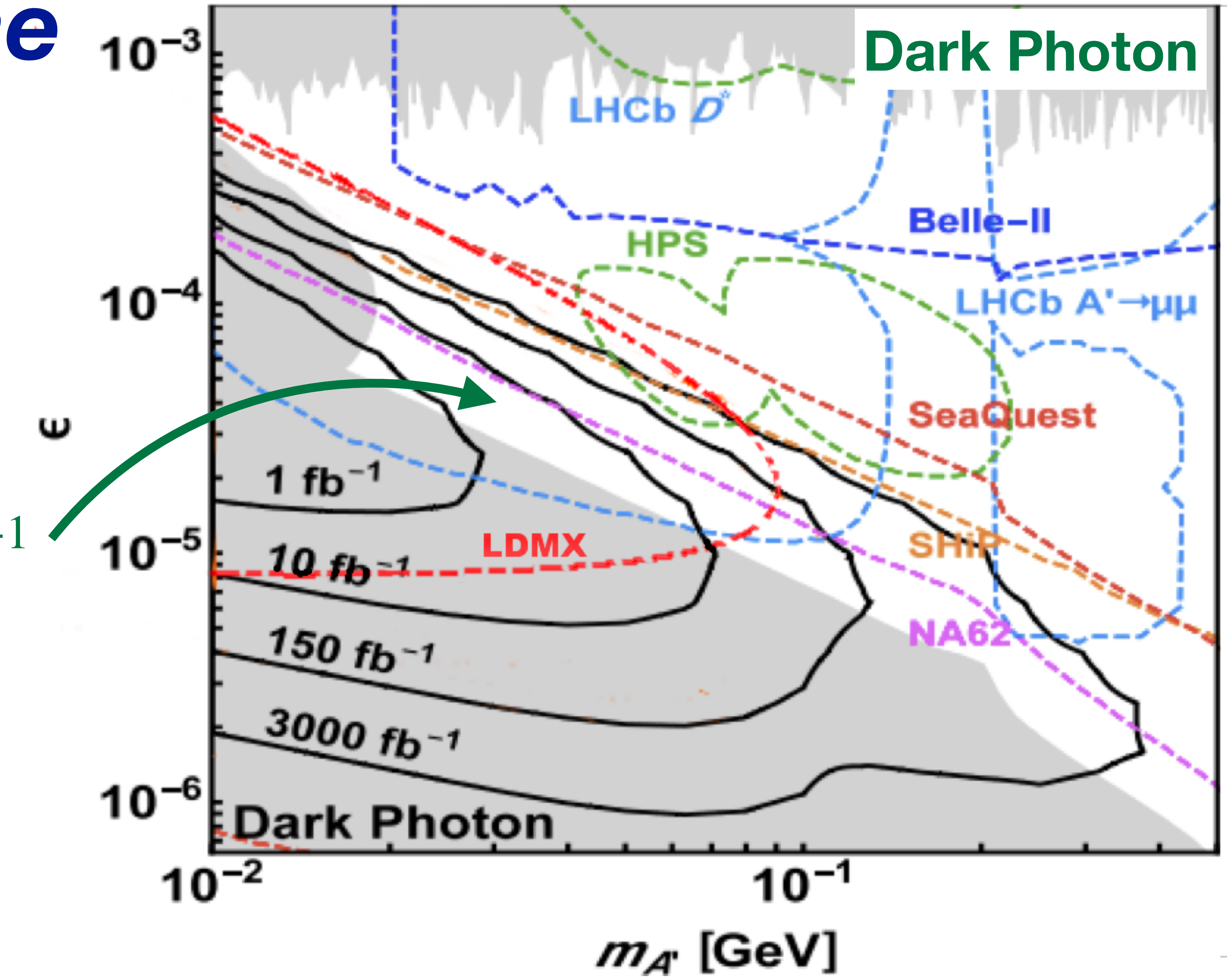
2021 in tunnel: 125 Million cosmic ray/noise induced events collected

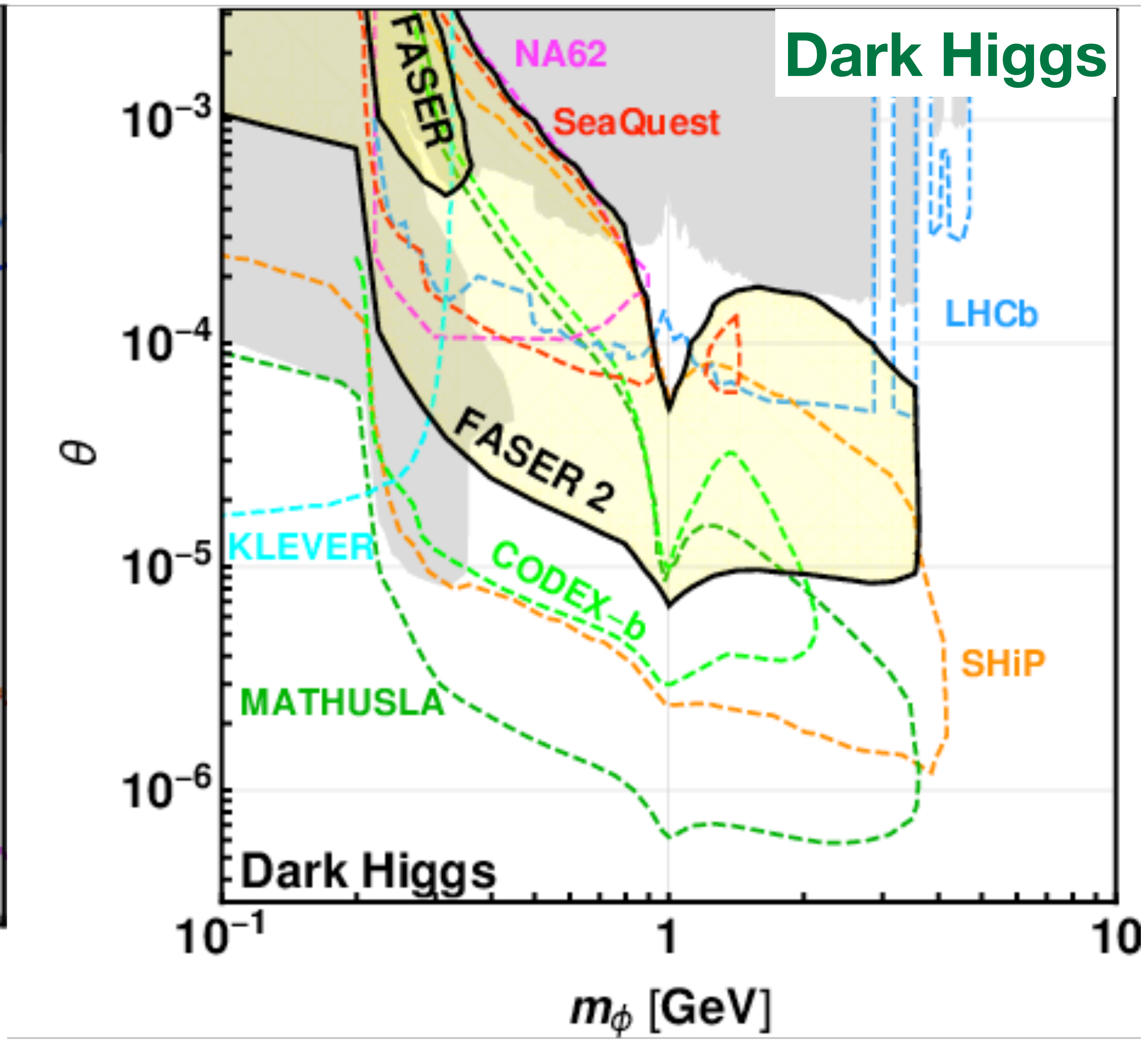
Actual FASER detector in actual tunnel.



FASER Overview

Physics Programme





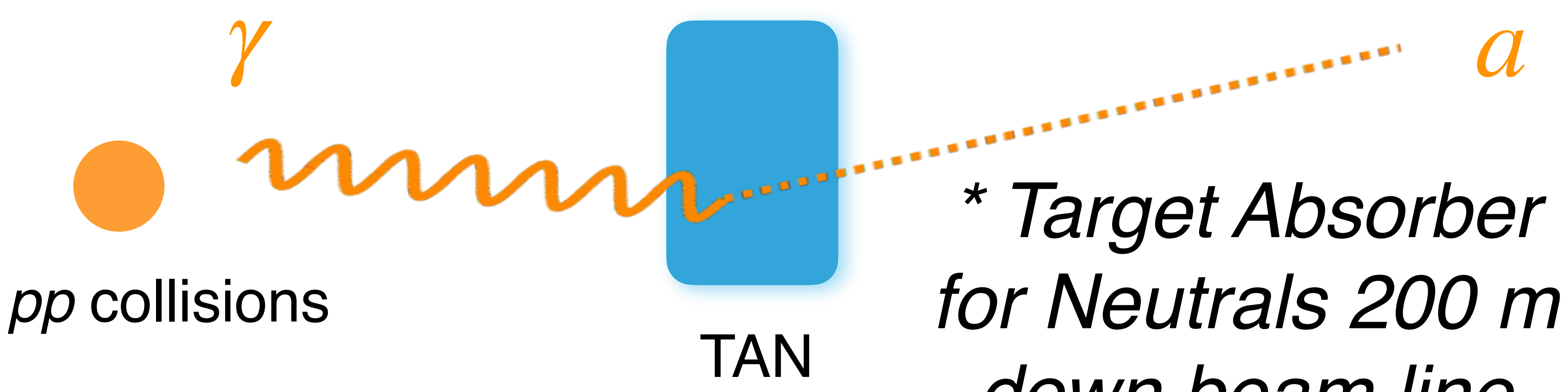
Already new ground with 10 fb^{-1} expected…

- **FASER (Run 3)** sensitive to unprobed phase space for dark photons, ALPs & Neutral Heavy Leptons.
- **Future FASER 2 (HL-LHC)** (assumed 10x bigger) could probe further.
  - Sensitivity to New Physics via heavy meson production (e.g. dark Higgs); Larger angle to beam axis.

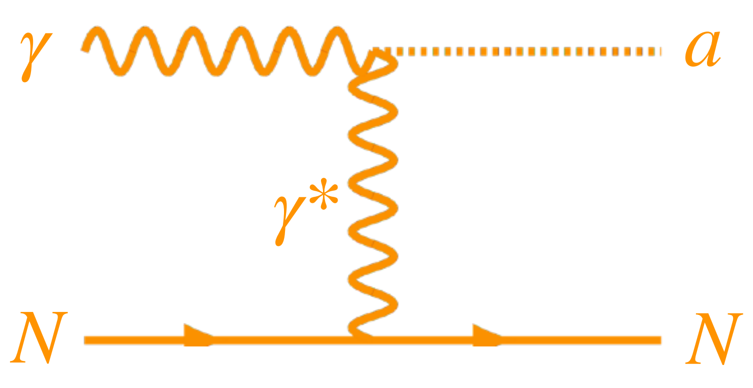
FASER Overview

Physics Programme

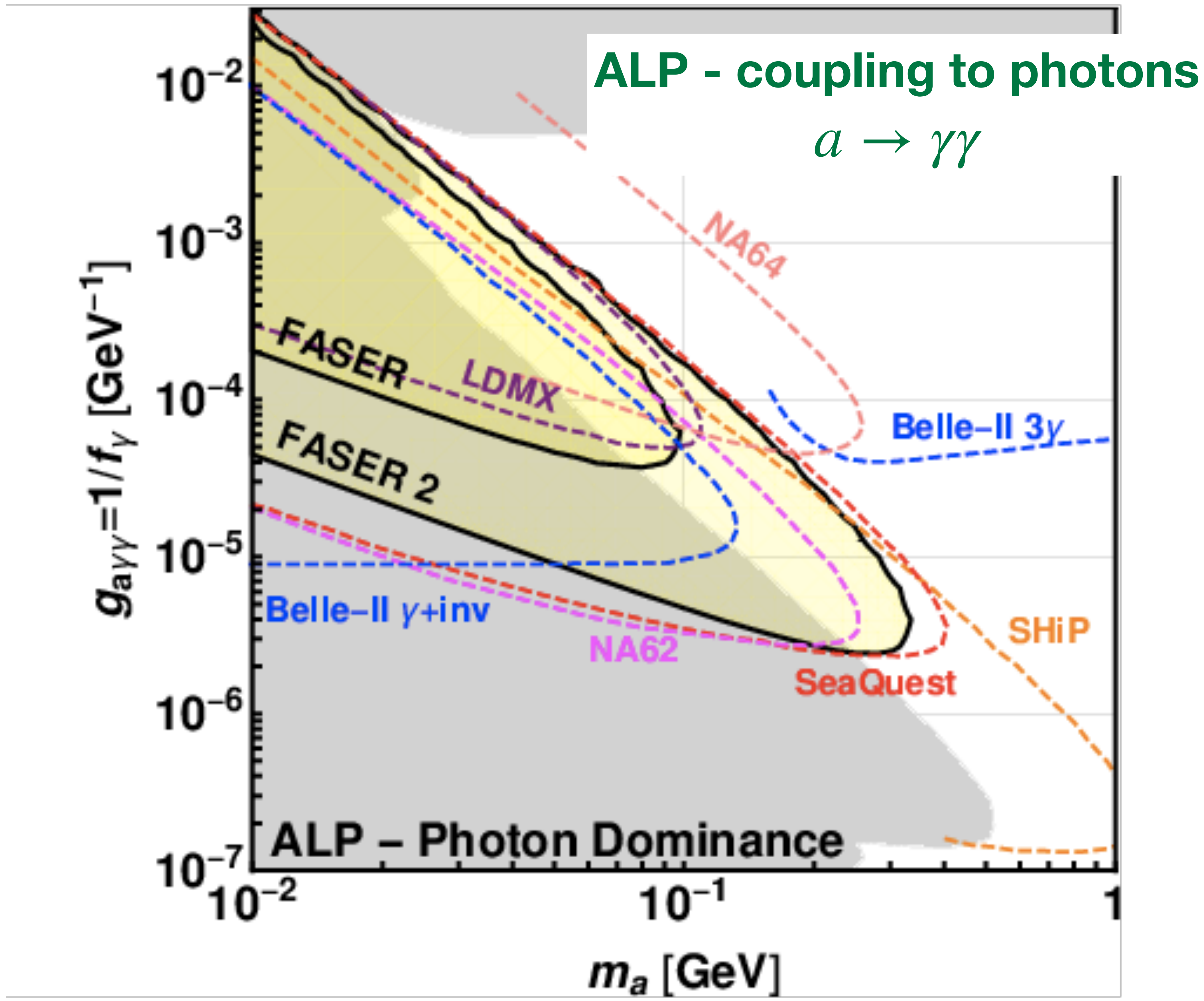
Primakoff process



** Target Absorber for Neutrals 200 m down beam line*
(largely copper)



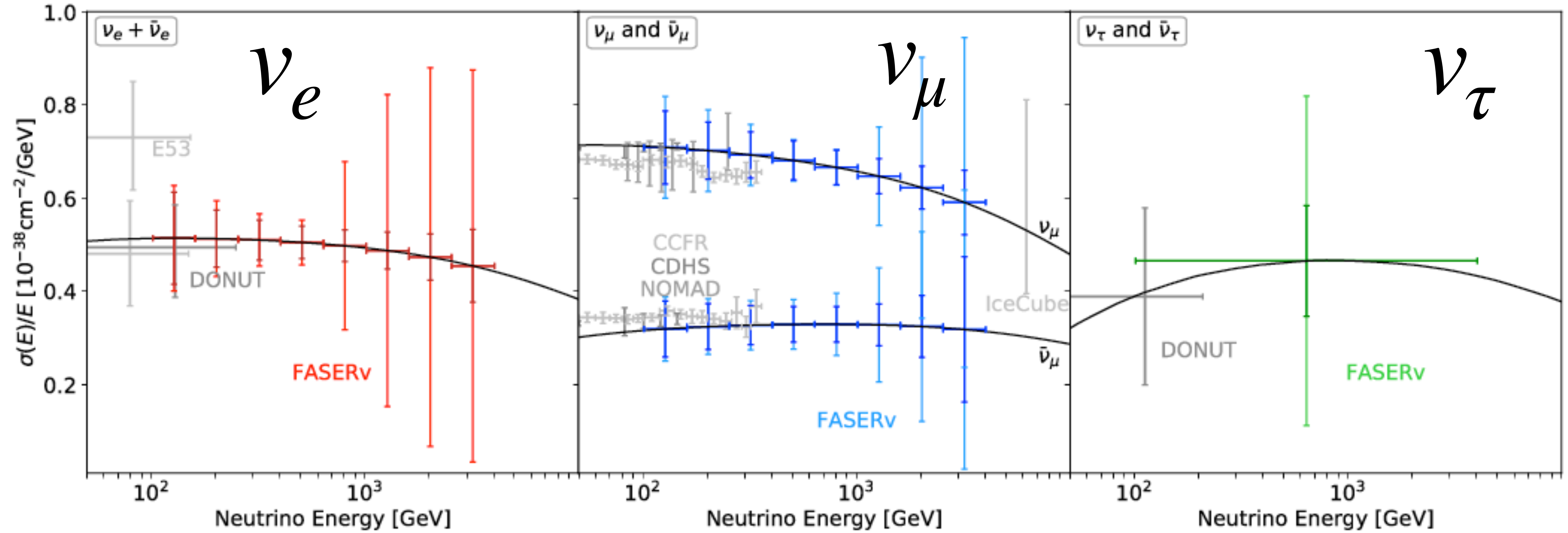
FASER: 10 cm radius, 150 fb^{-1} ,
"Future" FASER 2: 1 m radius, 3 ab^{-1}



- **FASER Run 3** interesting sensitivity boost to Axion-like particles with coupling to photons from downstream LHC components
  - Calorimeter important for detection of (trackless) TeV-scale in-time di-photon signal.

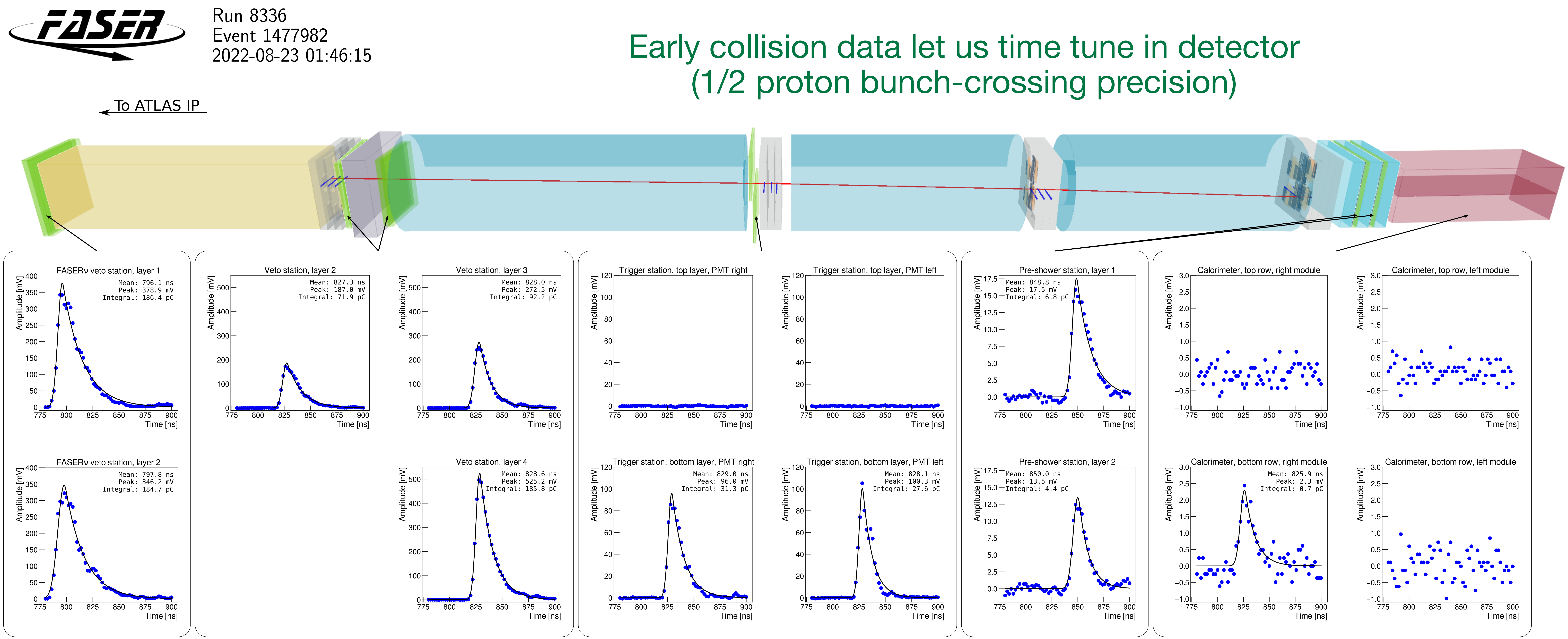
FASER Overview

Physics Programme



- **FASERν (Run 3)** to measure ~1000s ν_e, ~10 000s ν_μ and ~10s ν_τ neutrinos in 250 fb^{-1} data.
- To provide: Inclusive charged current neutrino cross-section measurements, constraints on neutrino production in (forward) hadronic interaction models, valuable input to simulation tools related to neutrino event shape and kinematic.

First data from 13.6 TeV proton collisions

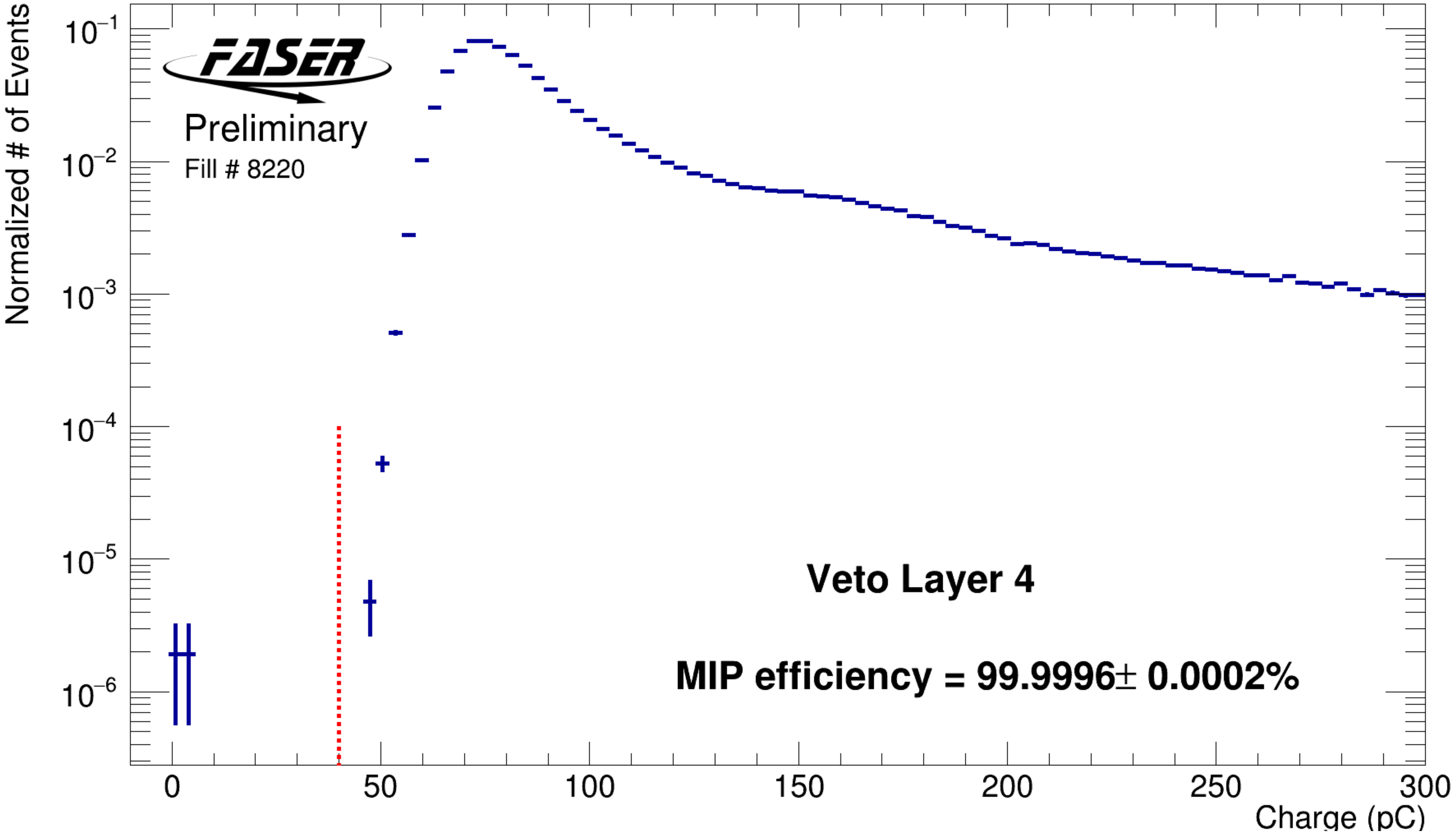


Early collision data let us time tune in detector
(1/2 proton bunch-crossing precision)

Now well timed in for triggering on charged particles passing through front to back of FASER.

First Data: Scintillator Performance

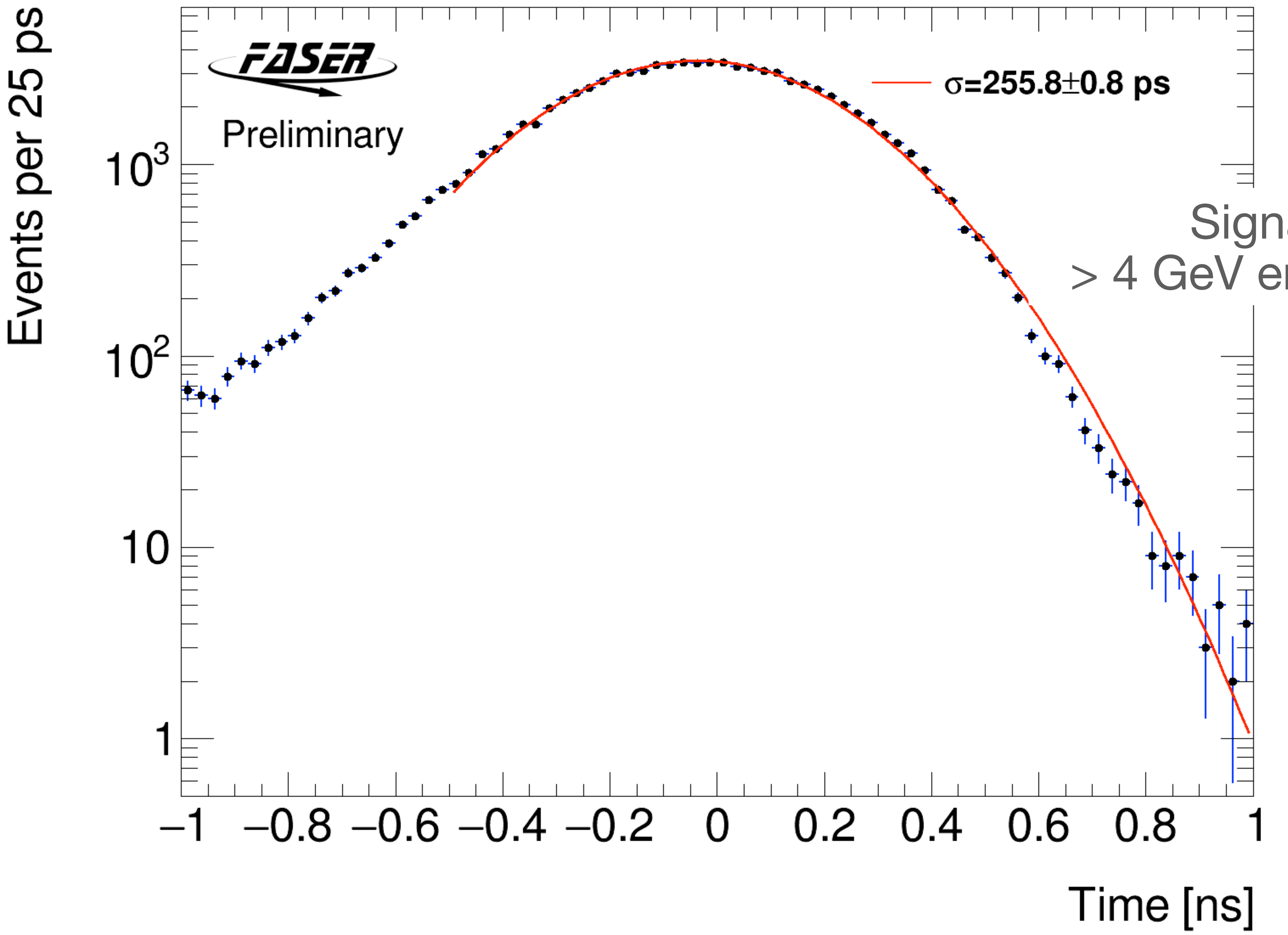
FASER aims to be background free: Need to reject all muons



> 99.995% veto efficiency/layer means negligible muon background after veto:
At 1 kHz rate, undetected muons in 4 veto layers
$\mathcal{O}(1\ \mathrm{kHz} * 0.00005^4 \sim 10^{-18})$ Hz

First Data: Calorimeter Performance

Good timing measurement in calorimeter important in particular to identify calorimeter-only signals in sync with proton collisions (ALPs->di-photon decay).

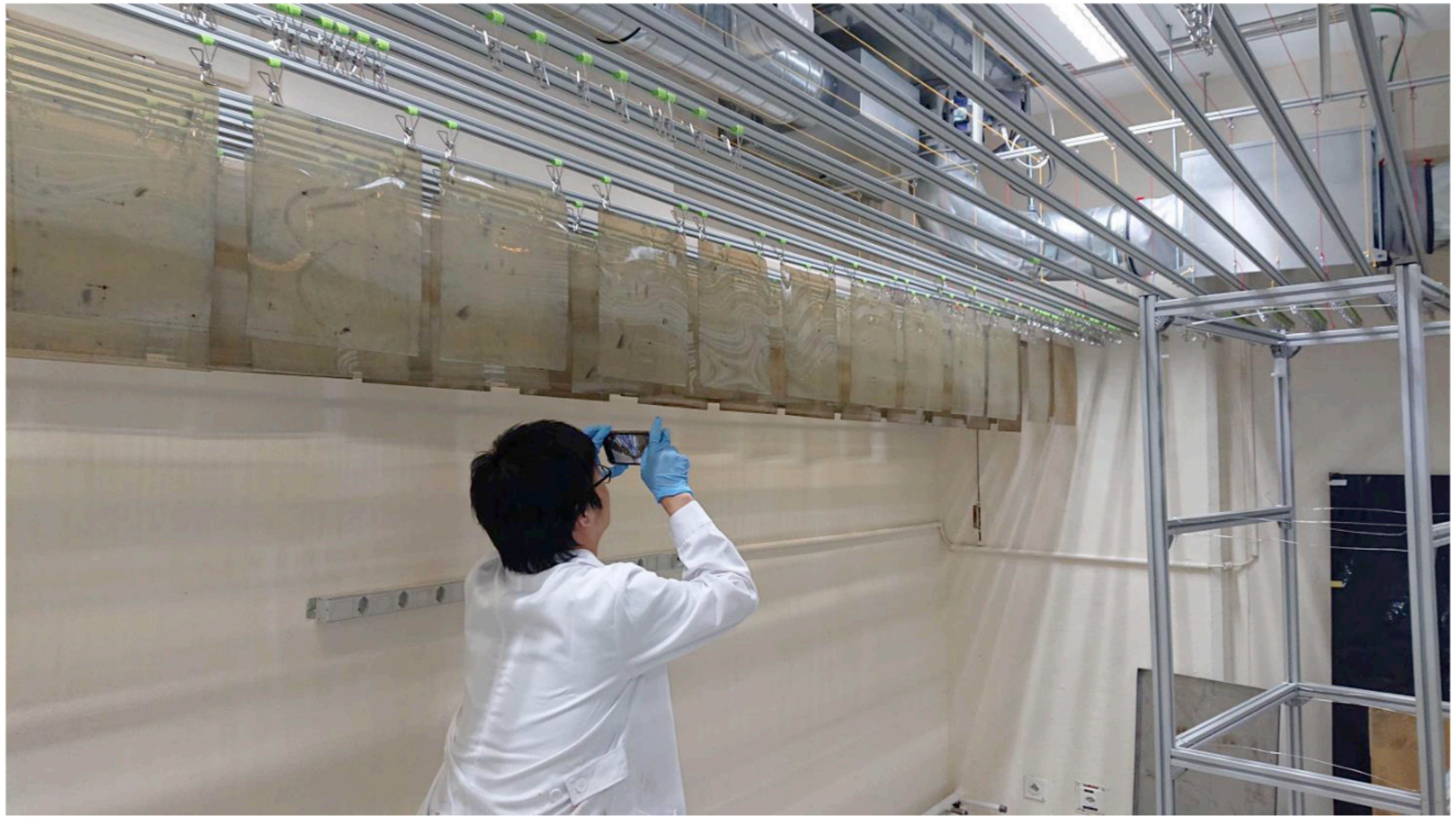


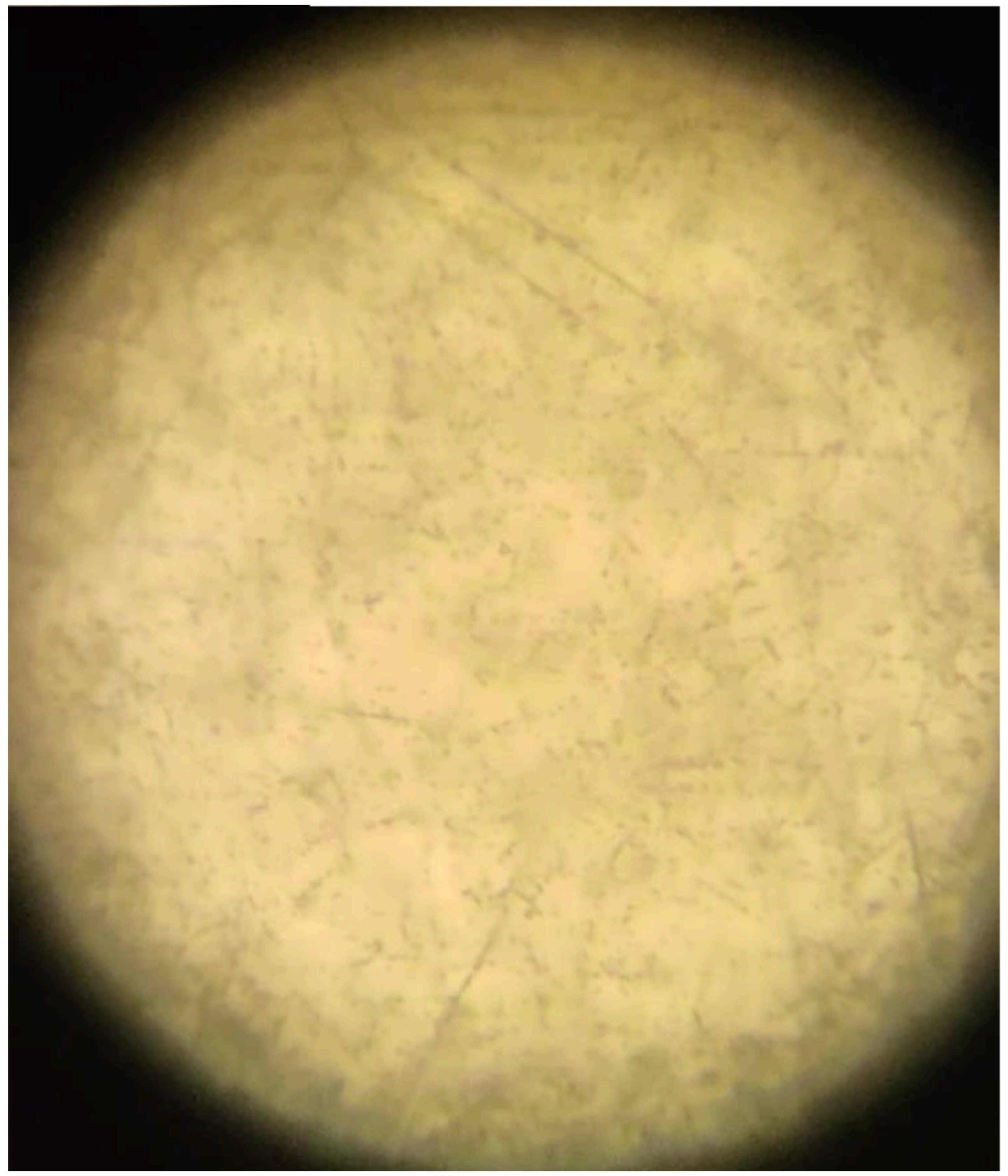
Signal timing distribution for
> 4 GeV energy deposits in calorimeter.

Measured < 1 ns timing resolution for calorimeter signals
(ultimately limited by
LHC collision time spread of 239 ps)

First Data: FASERν track reconstruction

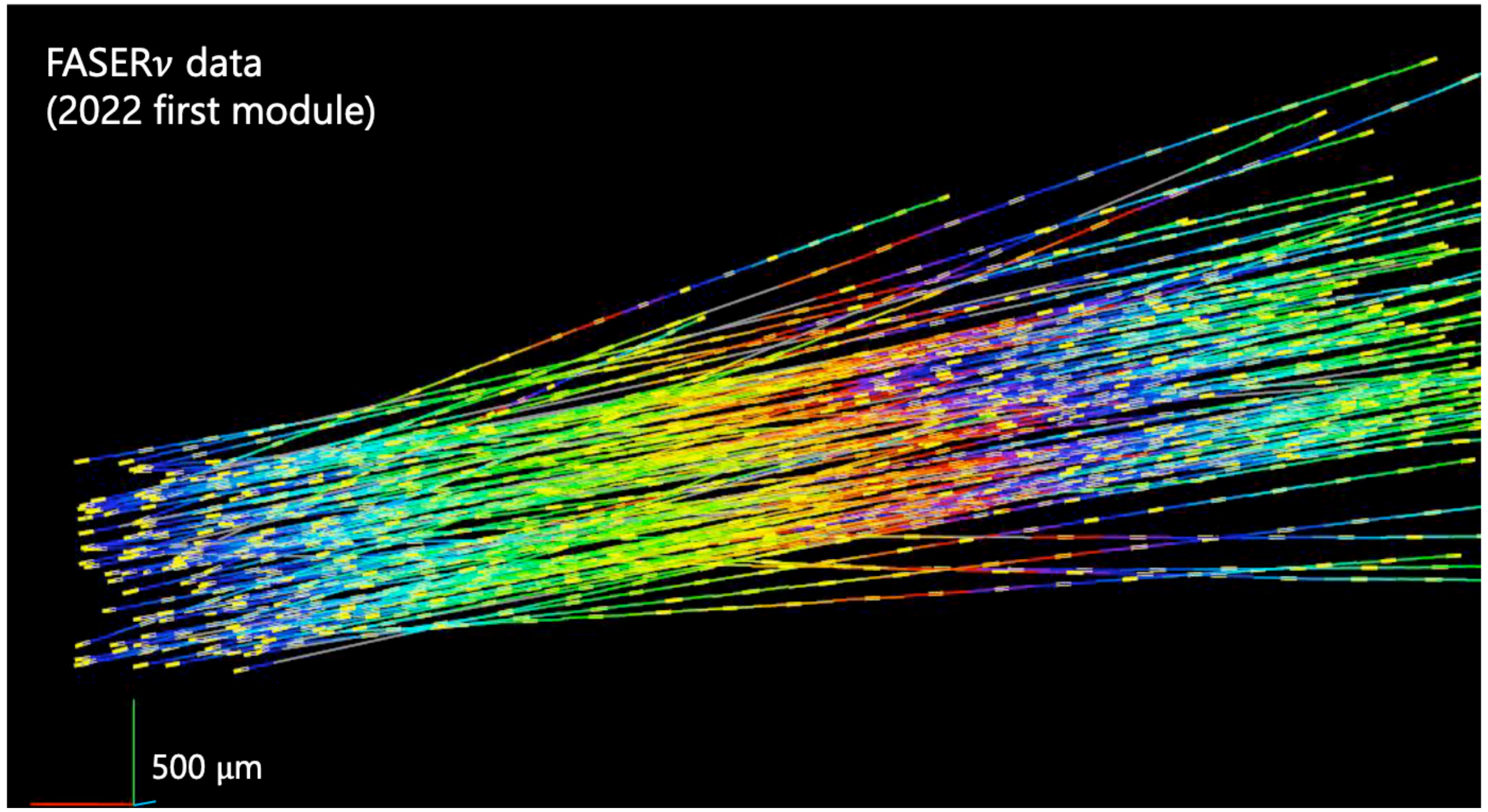
- 3 FASERν emulsion installations so far: 1st box of 0.5 fb^{-1}, 2nd box of 10 fb^{-1} and 3rd box of 30 fb^{-1} exposure.



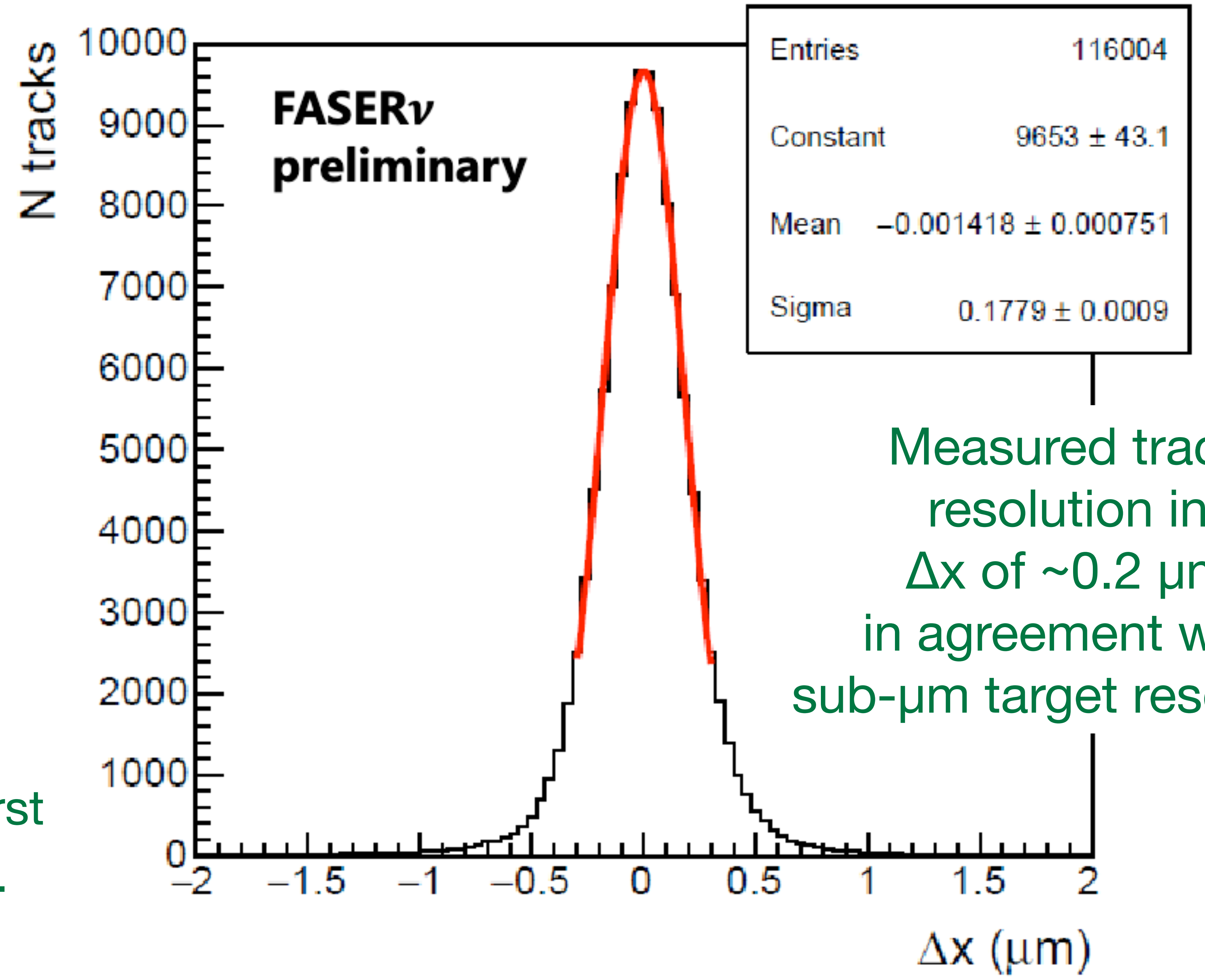


First Data: FASERν track reconstruction

- 3 FASERν emulsion installations so far: 1st box of 0.5 fb^{-1}, 2nd box of 10 fb^{-1} and 3rd box of 30 fb^{-1} exposure.
- Track measurements of first module of 0.5 fb^{-1} showed excellent track resolution.



Reconstructed > 1 GeV tracks in 1mm x 1 mm of 20 emulsion layers of first installed module (0.5 fb^{-1}). Measured track density of $1.2 \times 10^4/cm^2$.



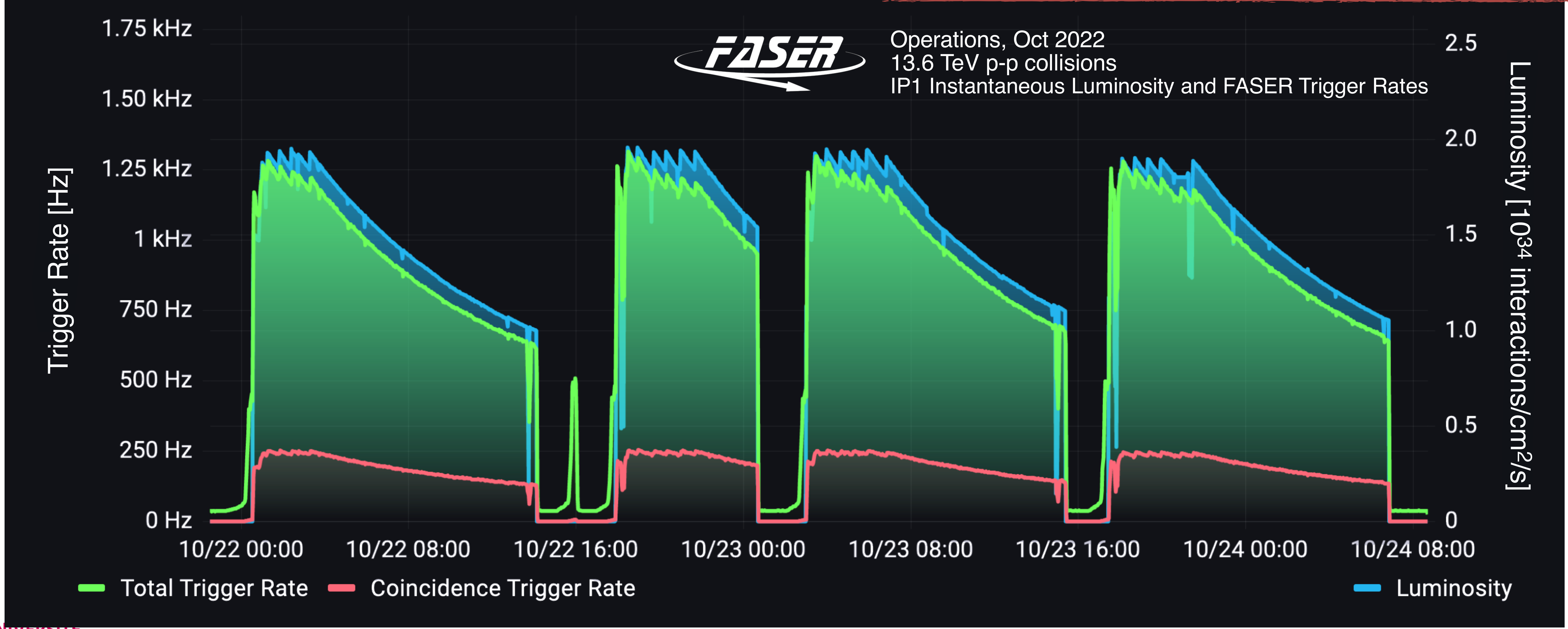
Measured track resolution in Δx of ~0.2 µm in agreement with sub-µm target resolution

- But higher expected track density in future modules with longer exposure: Maximum track density of $10^6/cm^2$.

First data from 13.6 TeV proton collisions

Reaching top FASER physics rates

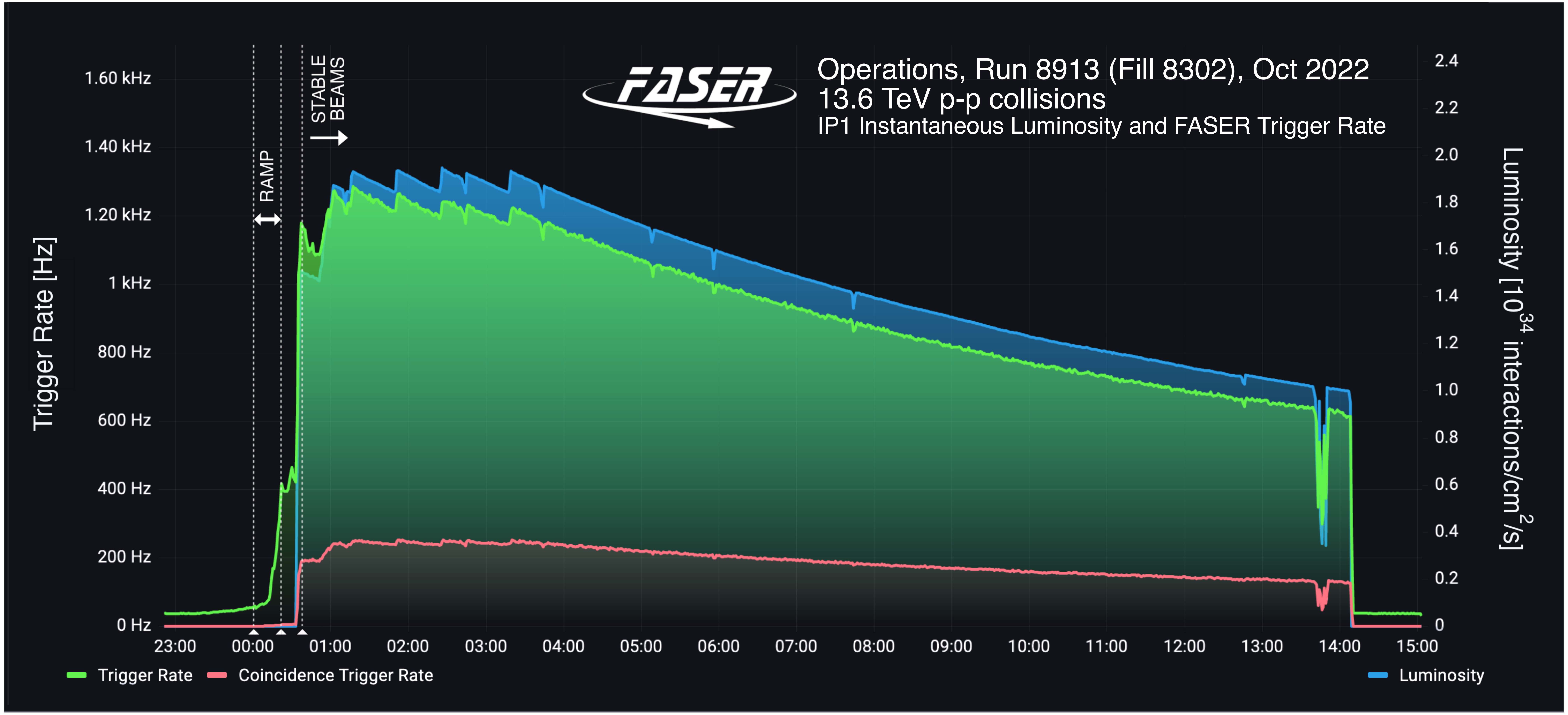
$40\ fb^{-1}$ integrated luminosity collected in 2022



First data from 13.6 TeV proton collisions

Reaching top FASER physics rates

- With some unexpected observations….

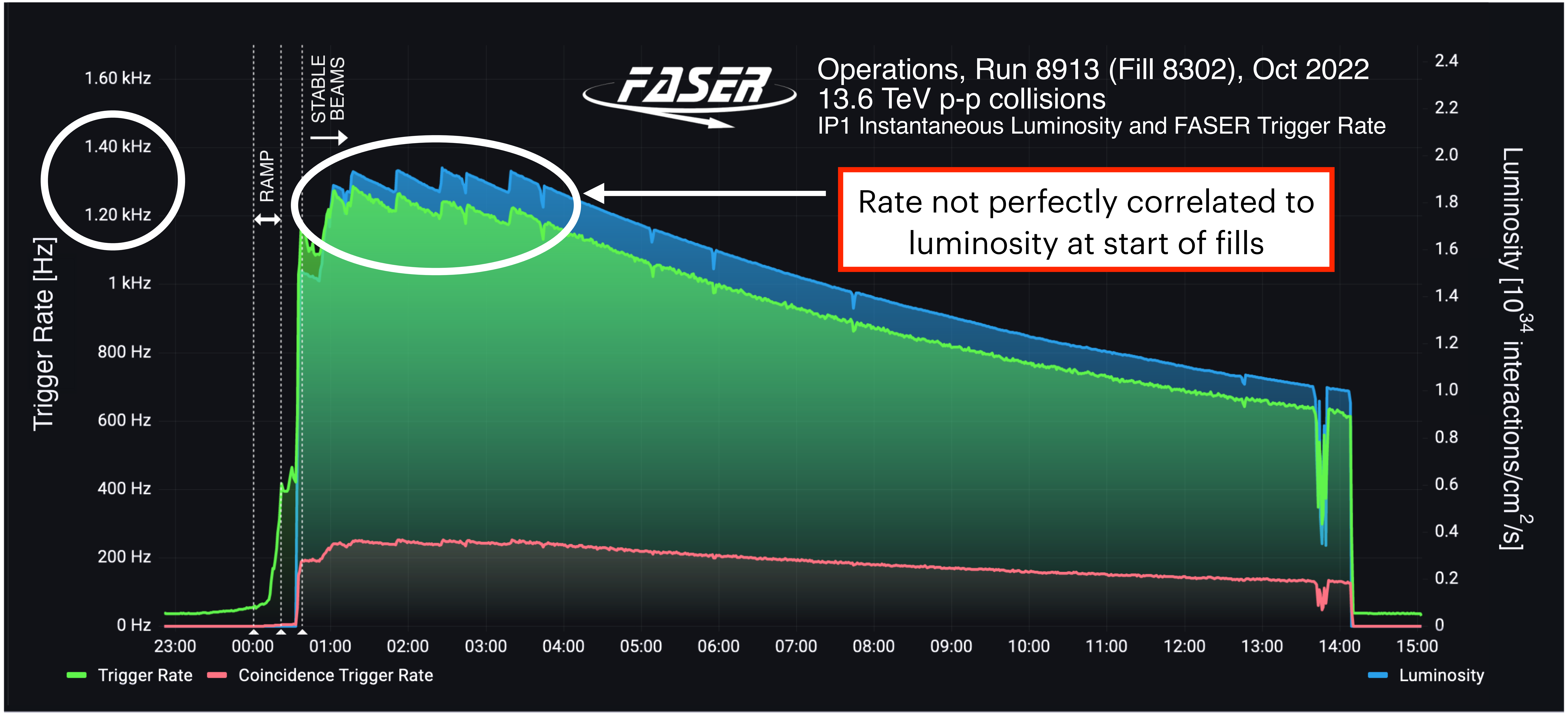


First data from 13.6 TeV proton collisions

Reaching top FASER physics rates

- With some unexpected observations….

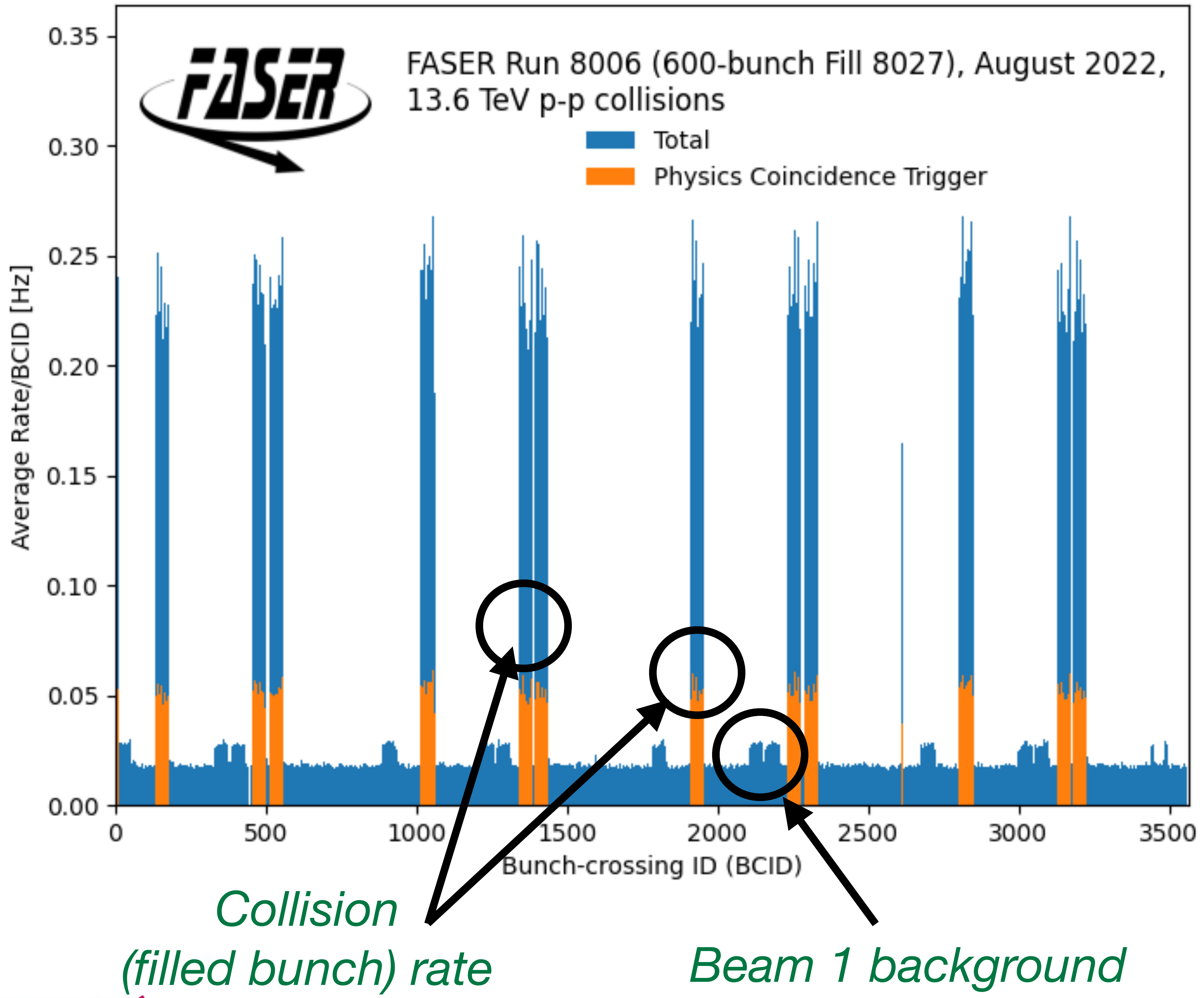
2x higher than predicted rates



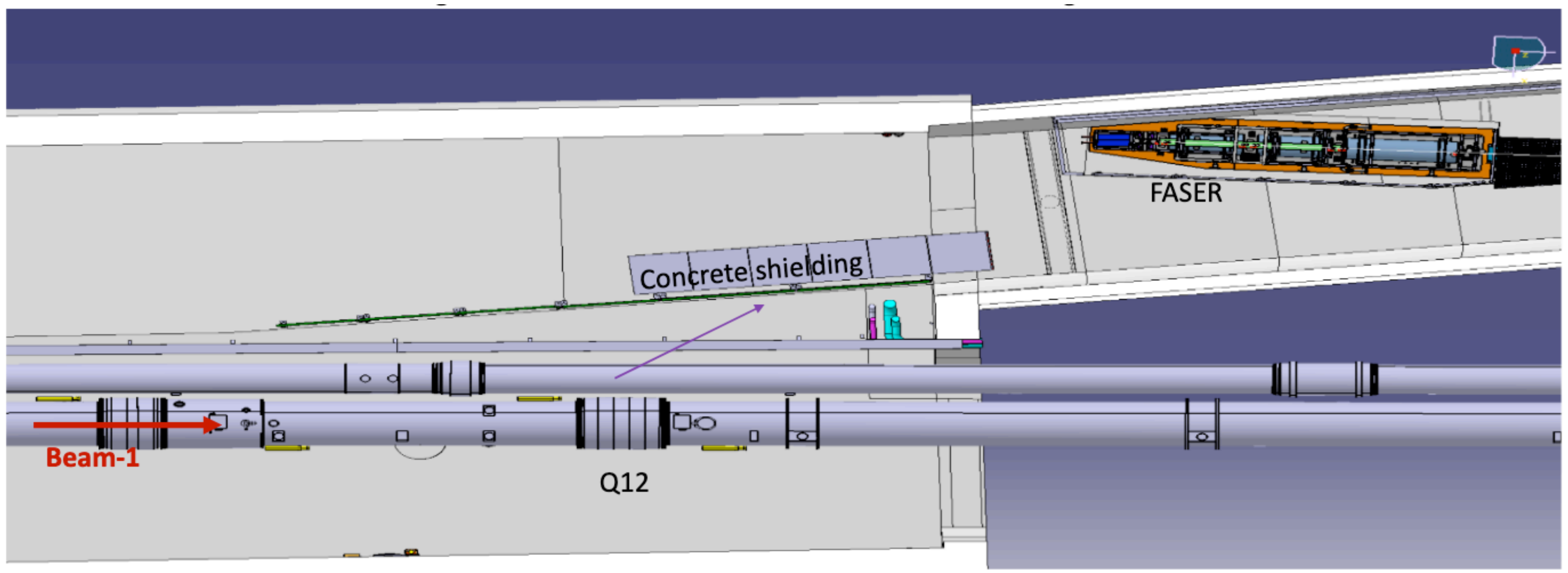
First data from 13.6 TeV proton collisions

Understanding trigger rates

Rate to proton bunch-crossing dependence paints a picture…



- ~80% rate correlated with filled bunches (energetic muons)
  - 1/5 leading to coincidence trigger (straight-through muons)
- ~3% beam 1 background
  (beam interaction with Q12 leads to background particles, not completely stopped by concrete shielding)
- ~1% cosmics/noise-induced rate



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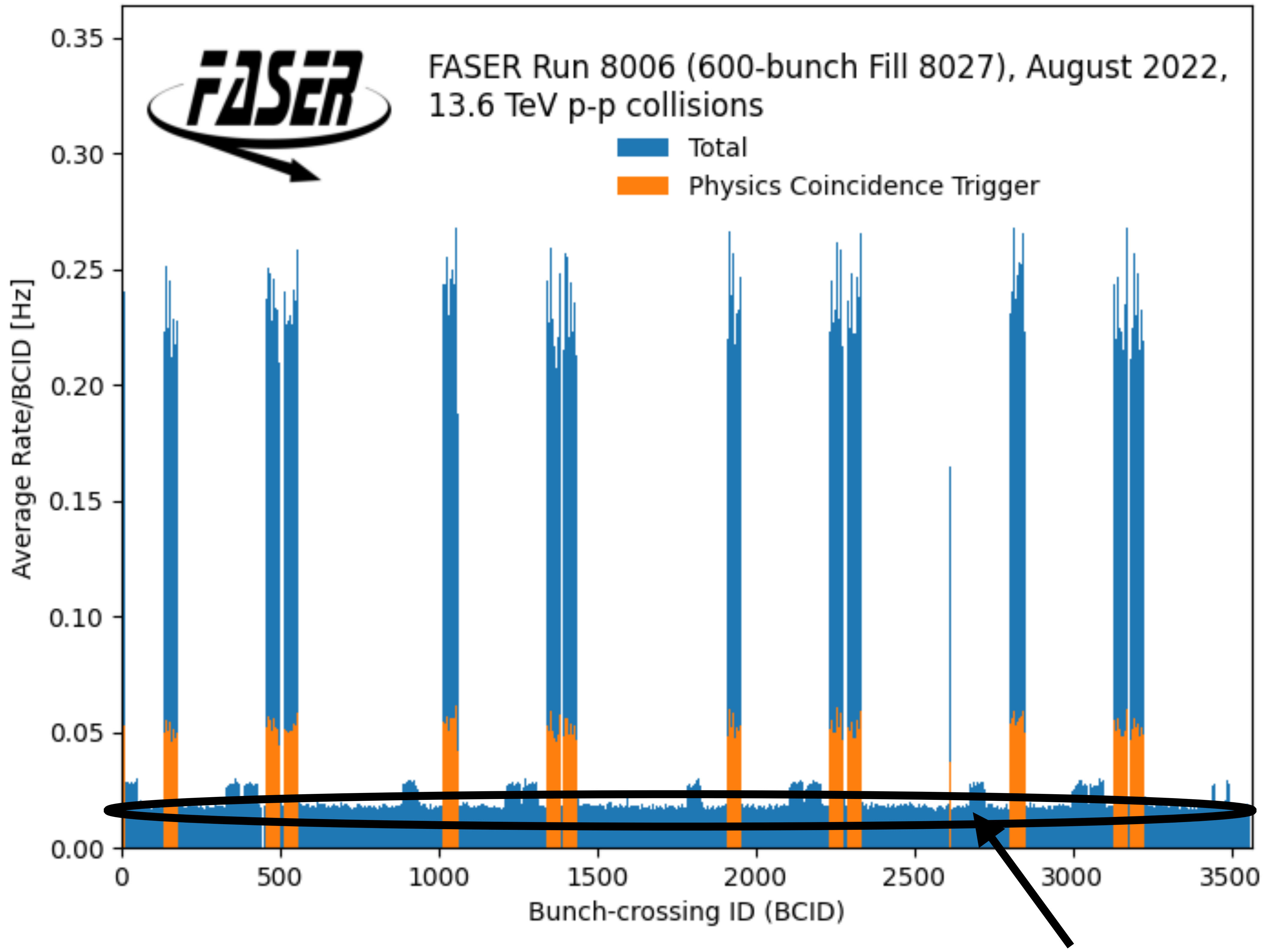
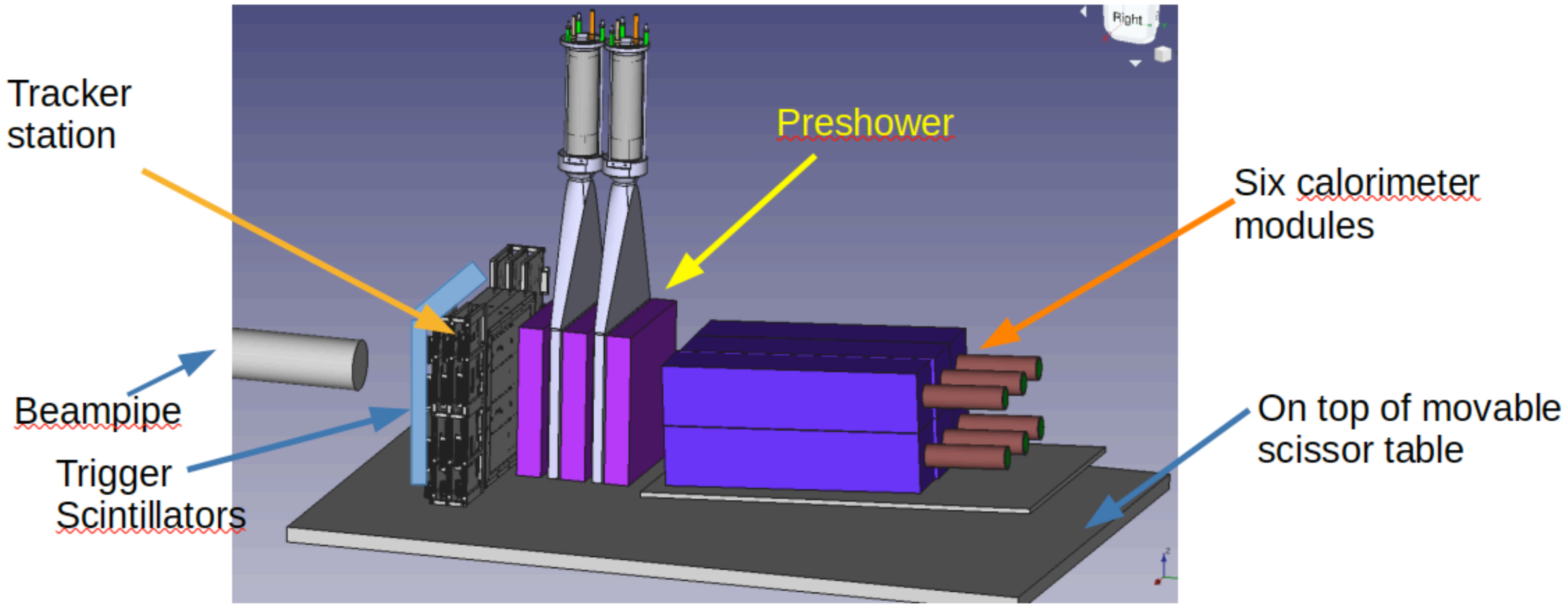


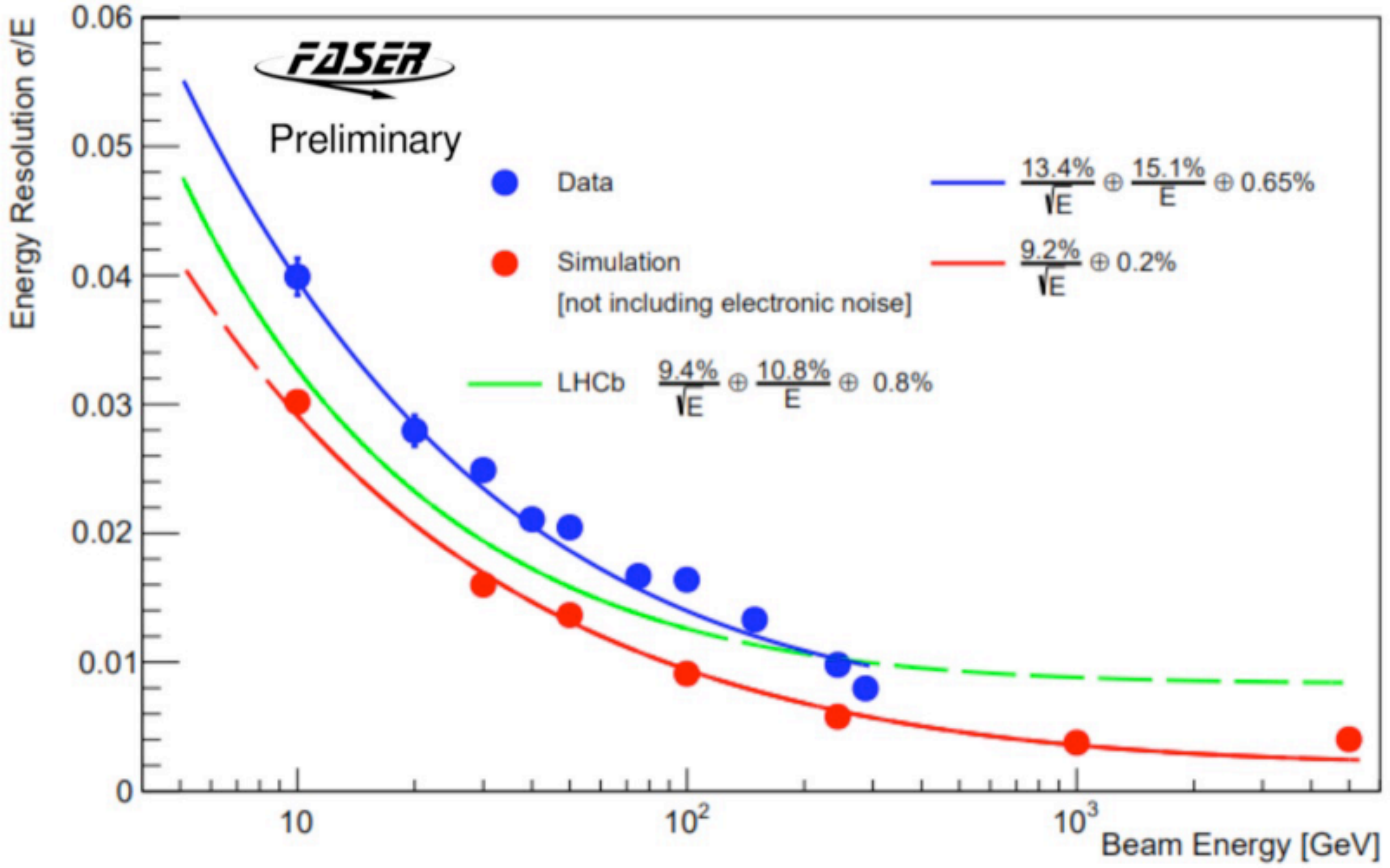
"ambient" rate with burn off during fill

- ~80% rate correlated with filled bunches (energetic muons)
  - 1/5 leading to coincidence trigger (straight-through muons)
- ~3% beam 1 background
  (beam interaction with Q12 leads to background particles, not completely stopped by concrete shielding)
- ~1% cosmics/noise-induced rate
- + ~20% "ambient" rate with no bunch correlation.
  - Suspect related to beam losses (greater at beginning of fill) causing slow moving particle background (neutrons).
- Increased rates not problem for FASER Physics.
  - Trigger system handles extra rate, < 2% deadtime.
  - Beam background can be effectively removed offline with timing cuts.

FASER Data Analysis

Towards calibrating data for physics analyses

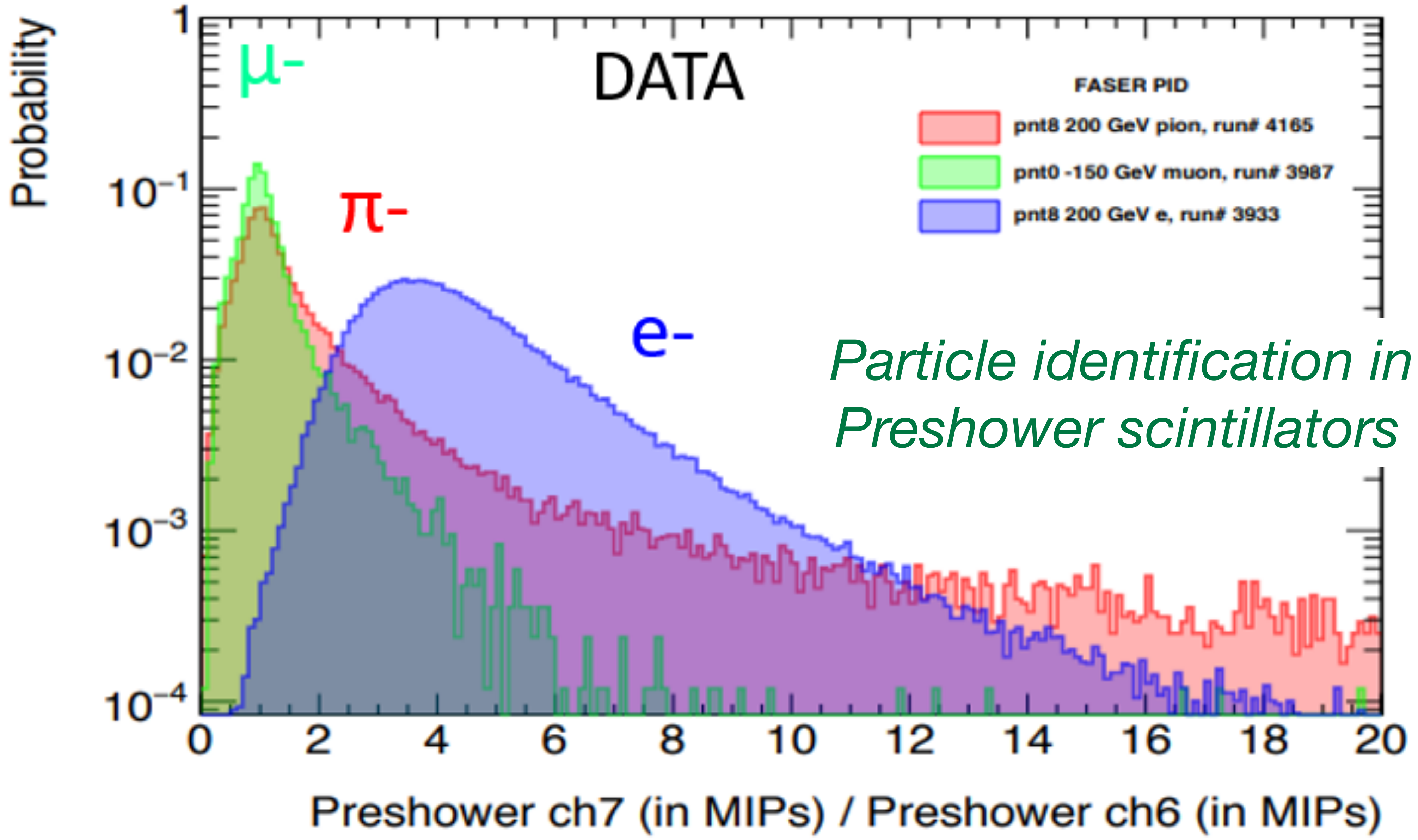




Good (~1% at TeV energies) calorimeter resolution achieved. Ongoing studies to understand and improve simulation vs data resolution difference.

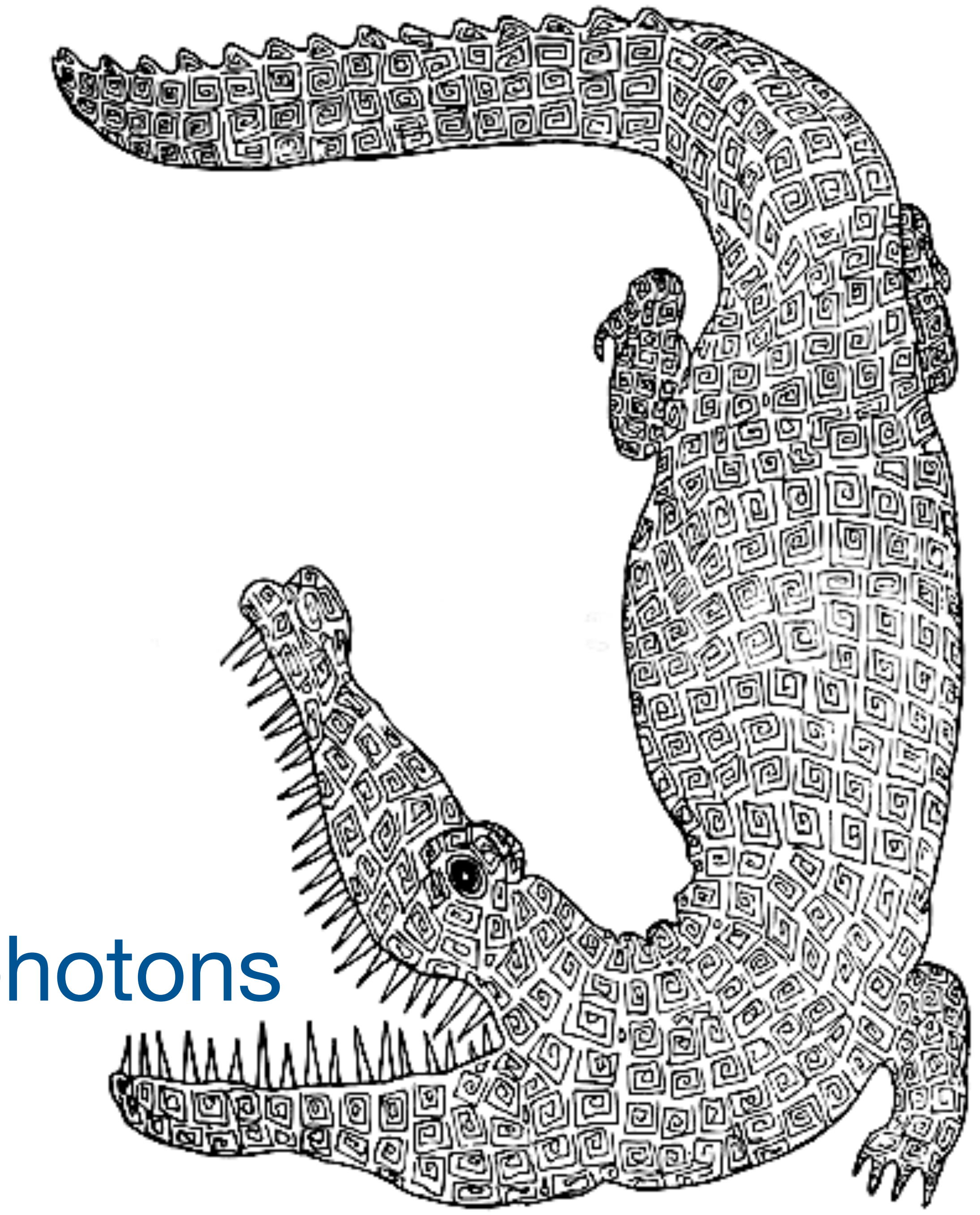
Summer 2021 Test Beam Data Analysis

- Dedicated Test Beam at CERN SPS last year to obtain calibration data for calorimeter modules.
- Test Beam data also used to study tracker alignment, data vs simulation, particle identification capabilities.



Particle identification in data using Preshower scintillators + tungsten

Summary



FASER is a new Run 3 experiment exploiting full LHC lumi at ~500 m down beamline of ATLAS interaction point, in wait for long lived particles such as dark photons & axions + studying high energy neutrinos.

Around 40 fb^{-1} of data collected in 2022, with sensitivity to dark photons in unconstrained regions of parameter space.

Interesting things learned about our environment in the tunnel since start of data taking (in particular, unexpected background rates).

Looking ahead ….

Lots of development for calibration and data vs sim studies ongoing for physics analysis.

Getting ready to provide first physics analysis results for next year's winter conferences.

Thanks for listening!

The FASER Collaboration

https://faser.web.cern.ch

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DESY.
JINR

We owe many thanks to: HEISING-SIMONS FOUNDATION, SIMONS FOUNDATION, CERN

for financial and technical support.

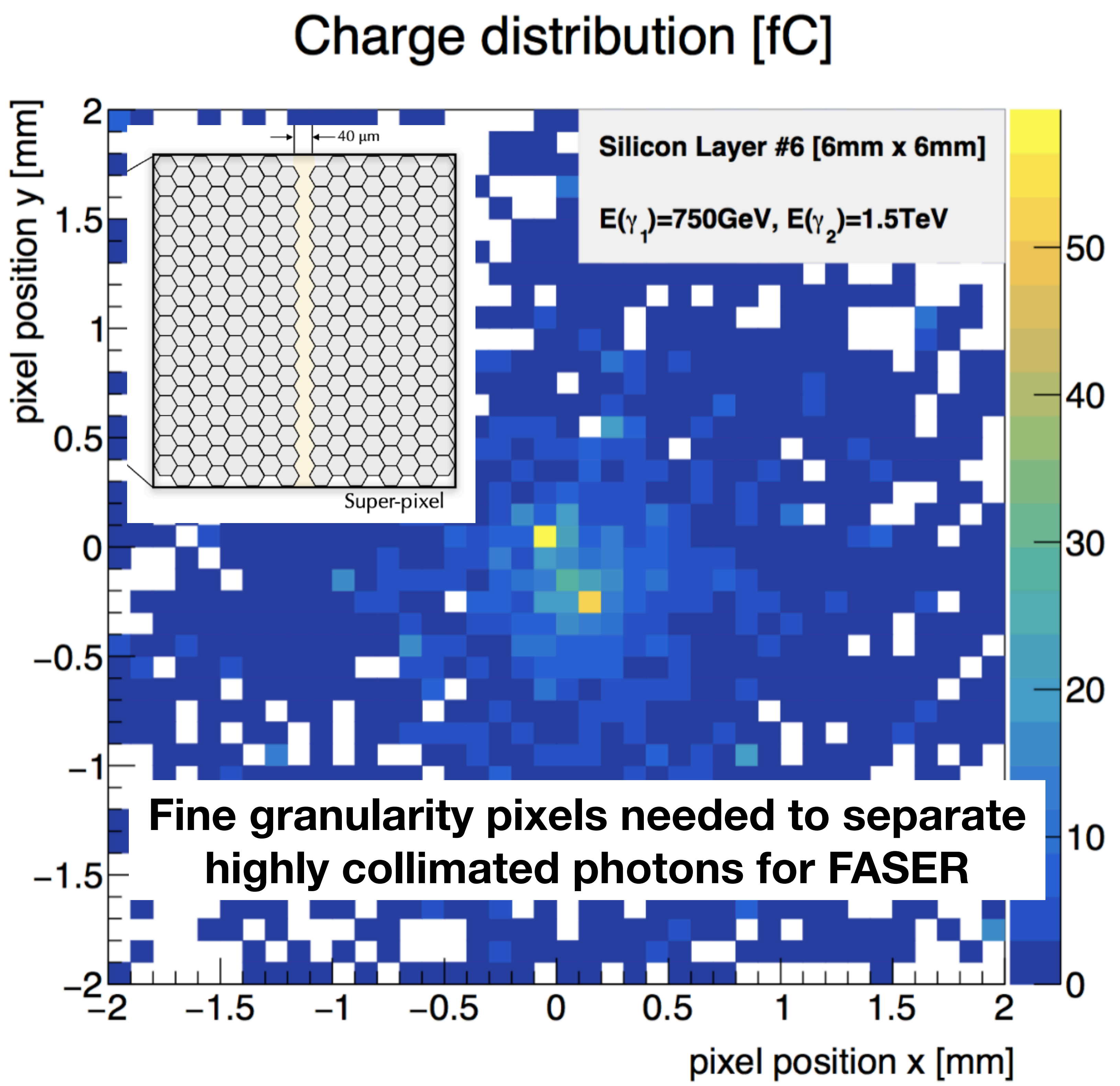
Back Up

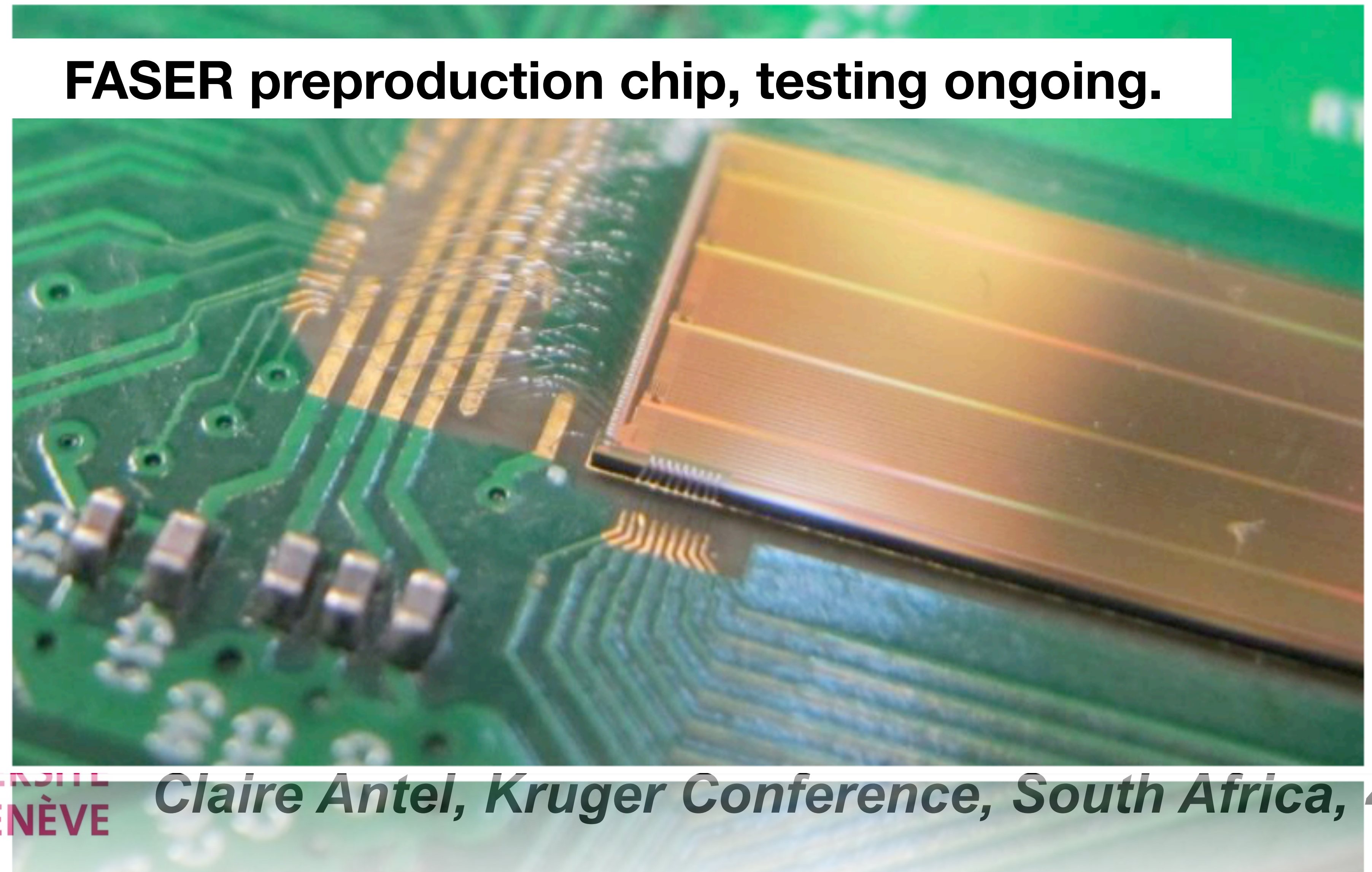
FASER Preshower Upgrade

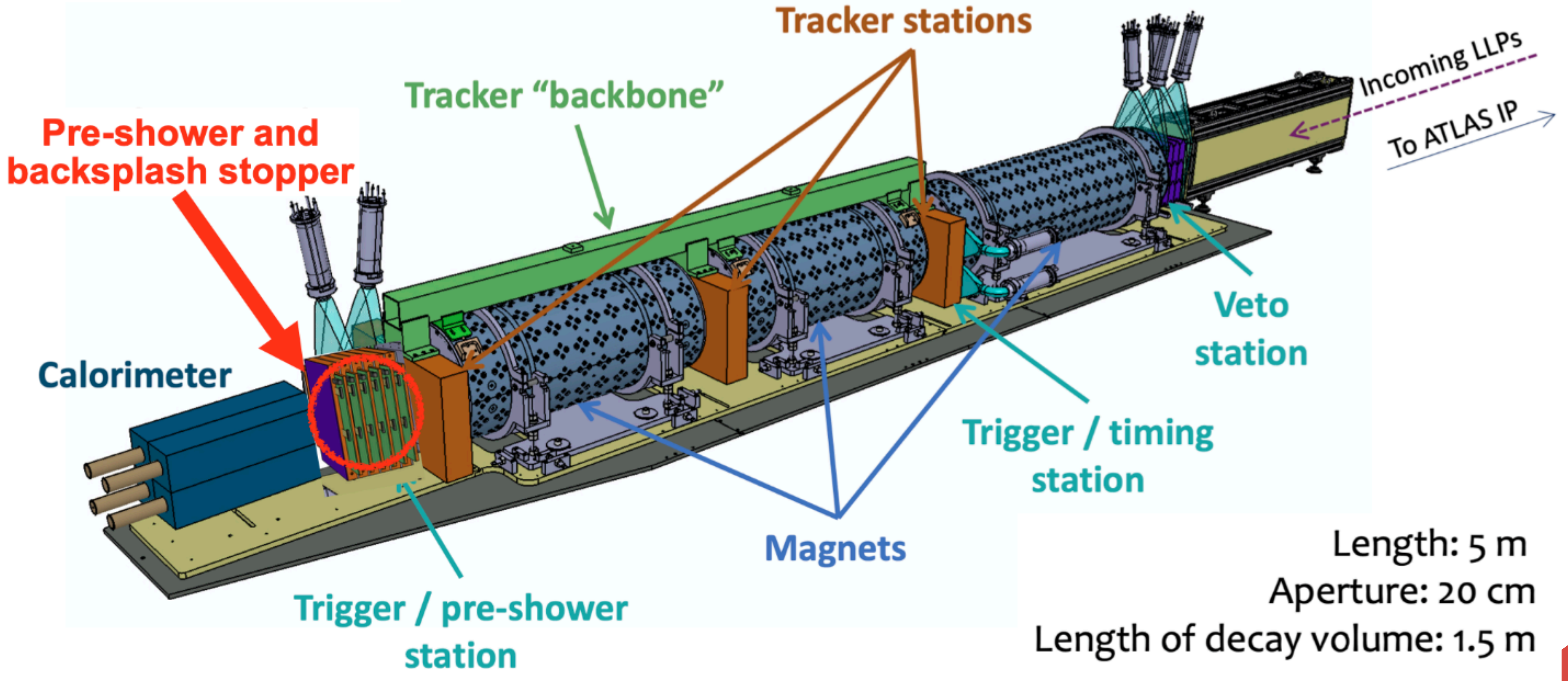
For ALPS->γγ

CERN-LHCC-2022-006

- FASER not capable of separating highly boosted ALP $\rightarrow \gamma\gamma$ decay with current calorimeter: For E ~ 1 TeV, < 1 mm photon separations.
- FASER Run 3 upgrade to replace current preshower with high precision monolithic pixel sensors (pixel pitch 100 μm) + tungsten absorber plates (up to 6 radiation lengths).
  - High dynamic range, readout of large number of pixels.
- Lab testing following Test Beam for preproduction ASICs ongoing.







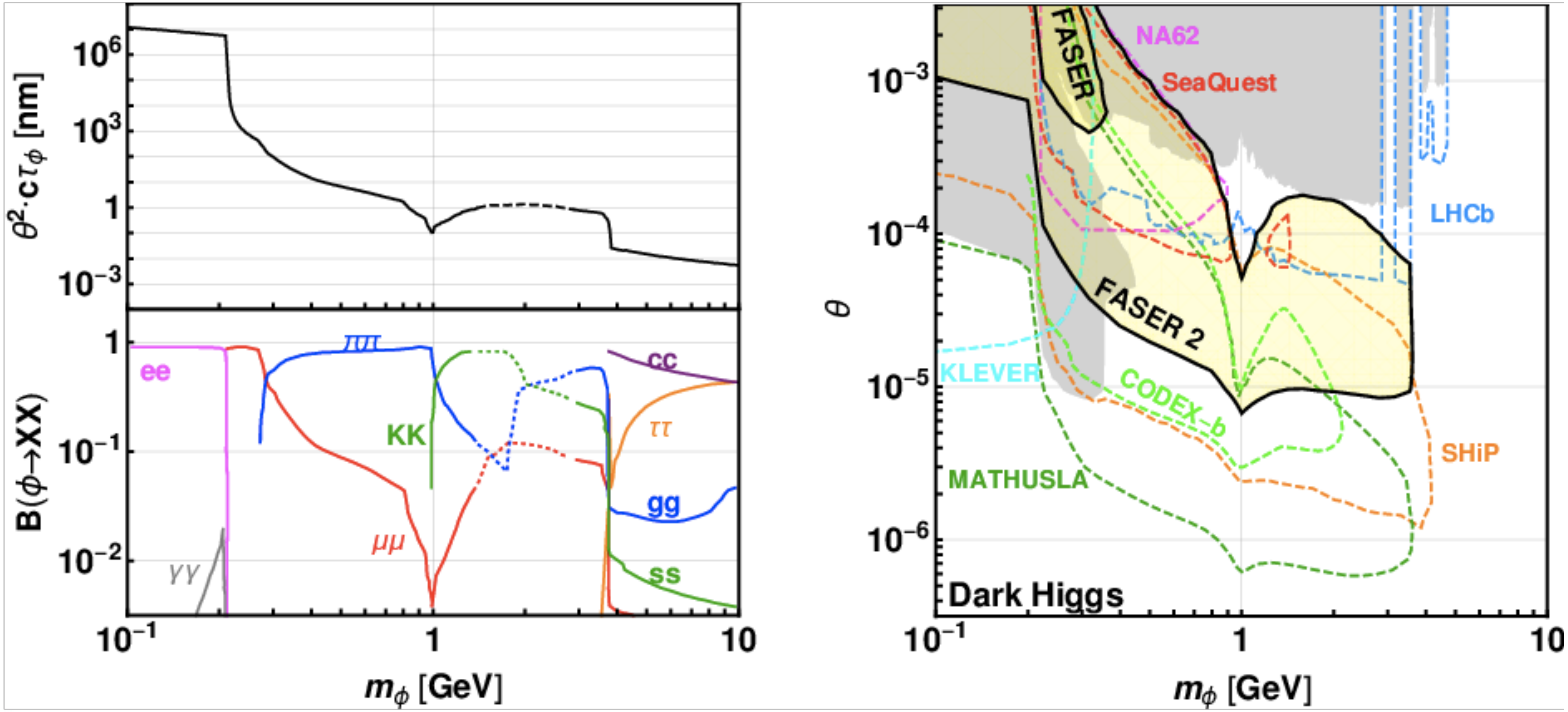
Assumptions in Sensitivity

Assumptions by other experiments in sensitivity plots:

NA62 assumes 10^{18} protons on target (POT) while running in a beam dump mode that is being considered for LHC Run 3; SeaQuest assumes 1.44×10^{18} POT, which could be obtained in two years of parasitic data taking and requires additionally the installation of a calorimeter; the proposed beam dump experiment SHiP assumes $\sim 2 \times 10^{20}$ POT collected in 5 years of operation; the proposed electron fixed-target experiment LDMX during Phase II with a beam energy of 8 GeV and 10^{16} electrons on target (EOT); Belle-II and LHCb assume the full expected integrated luminosity of 50 ab^{-1} and 15 fb^{-1}, respectively; HPS assumes 4 weeks of data at JLab at each of several different beam energies; NA64 corresponds to 5×10^{12} EOT with 100 GeV energy; and AWAKE is assumed to be working as a fixed-target experiment with a 10-m-long decay volume and 10^{16} EOT accelerated in a 50 – 100 m long plasma cell to the energy O(50 GeV).

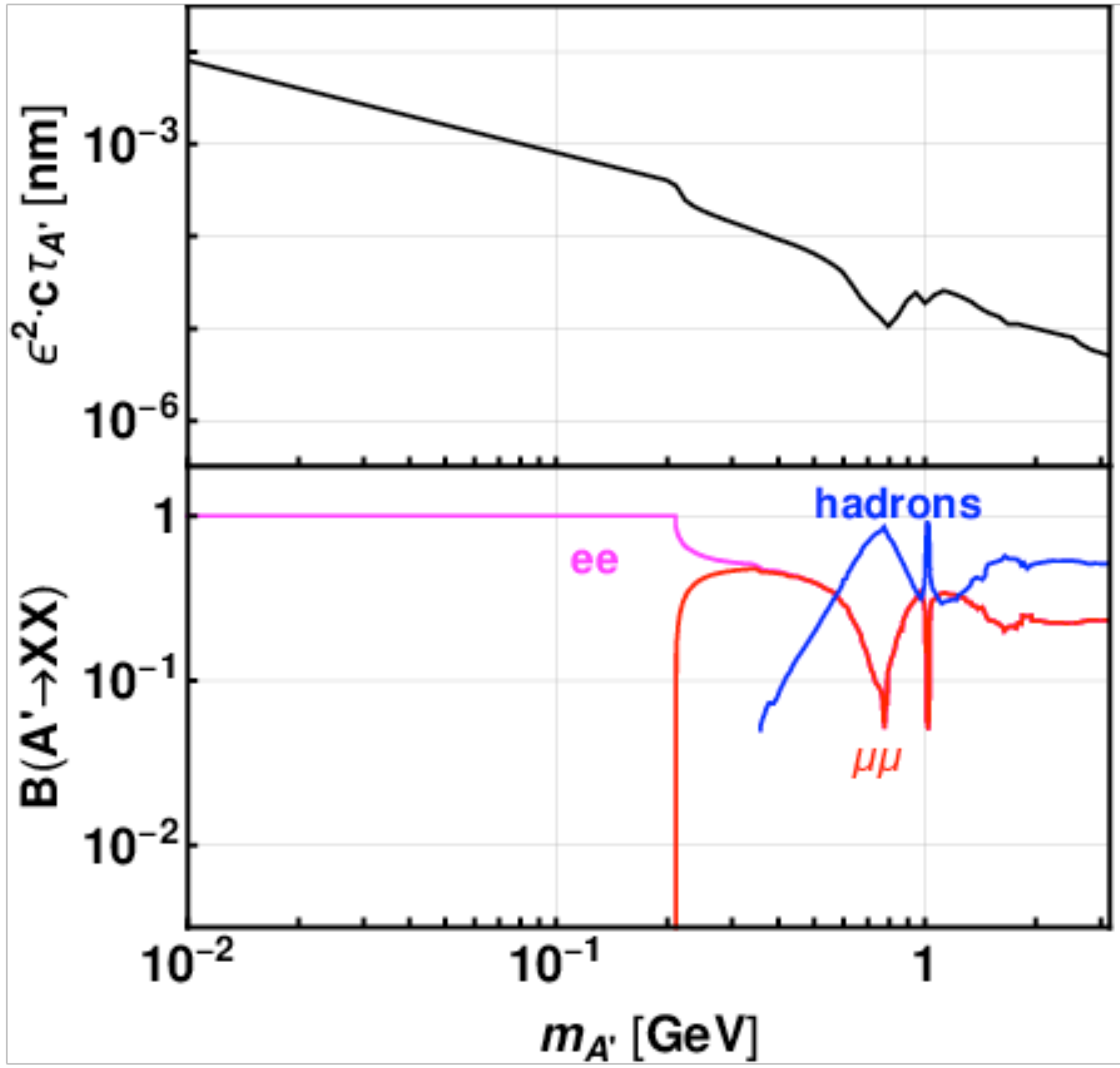
Dark Higgs sensitivity

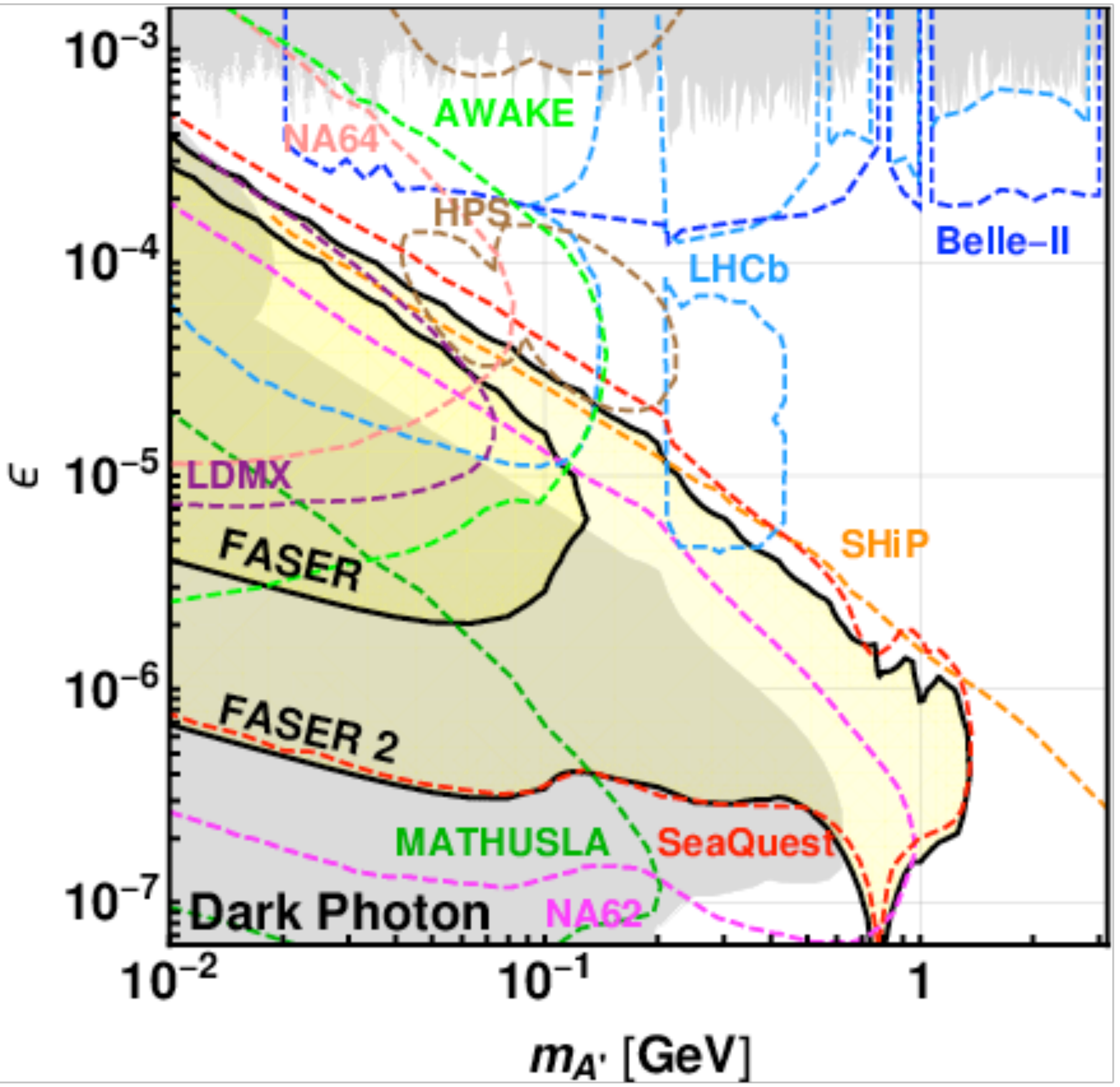
Without trilinear coupling



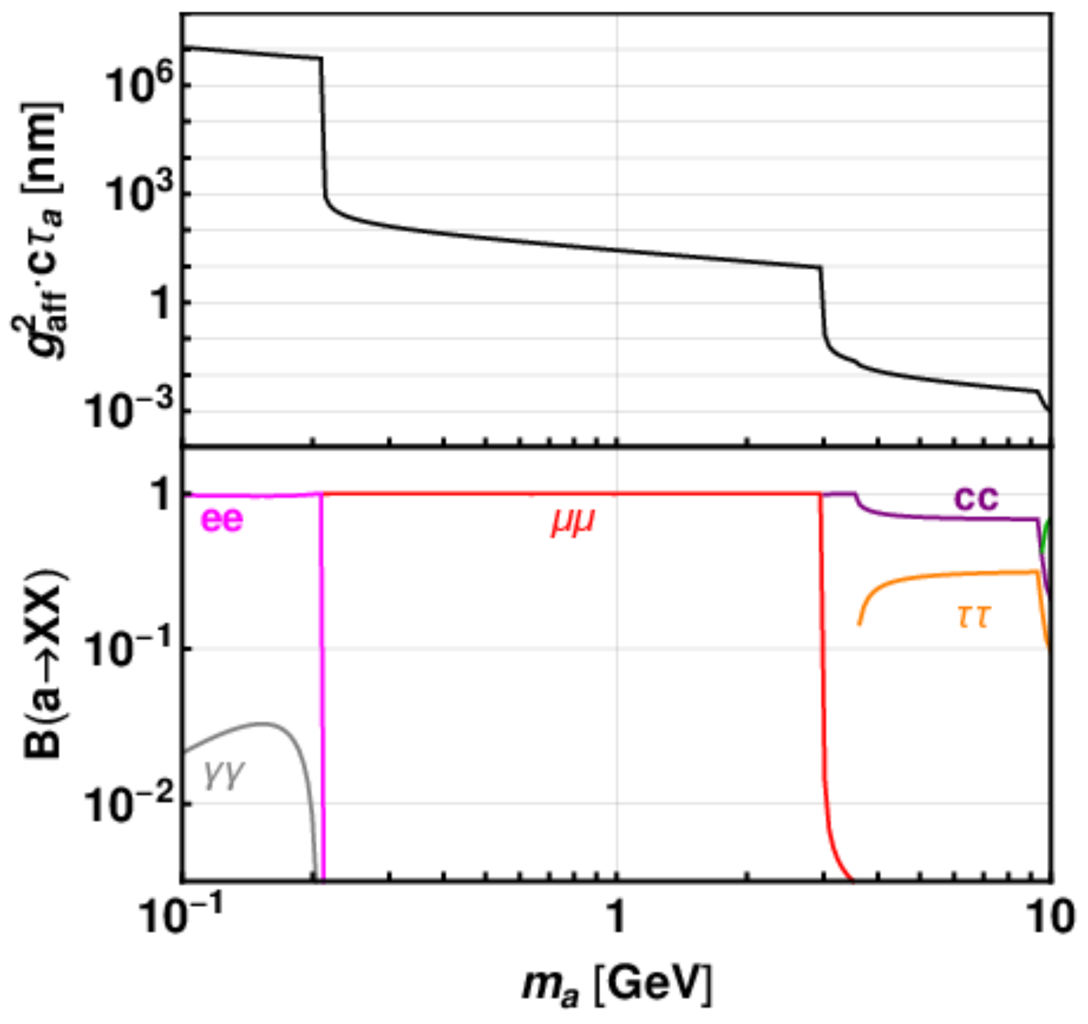
Dark Photon to visible decays

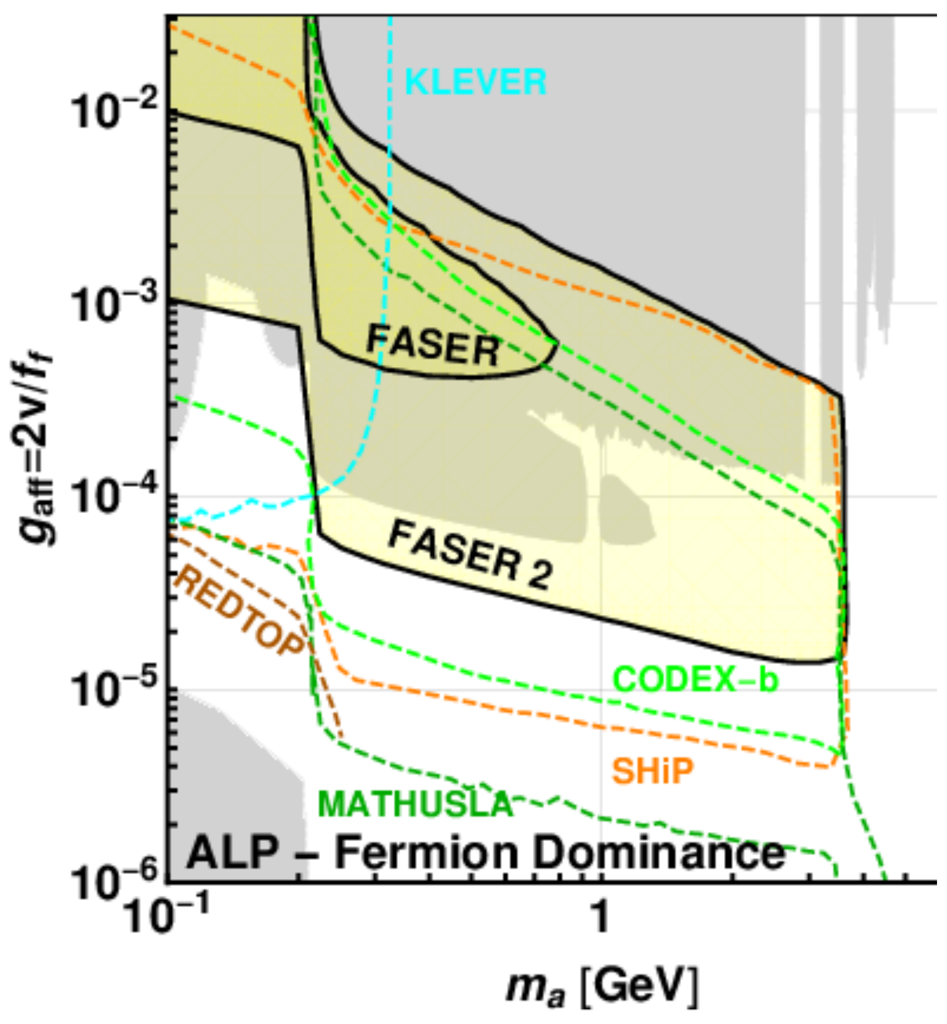
Sensitivity

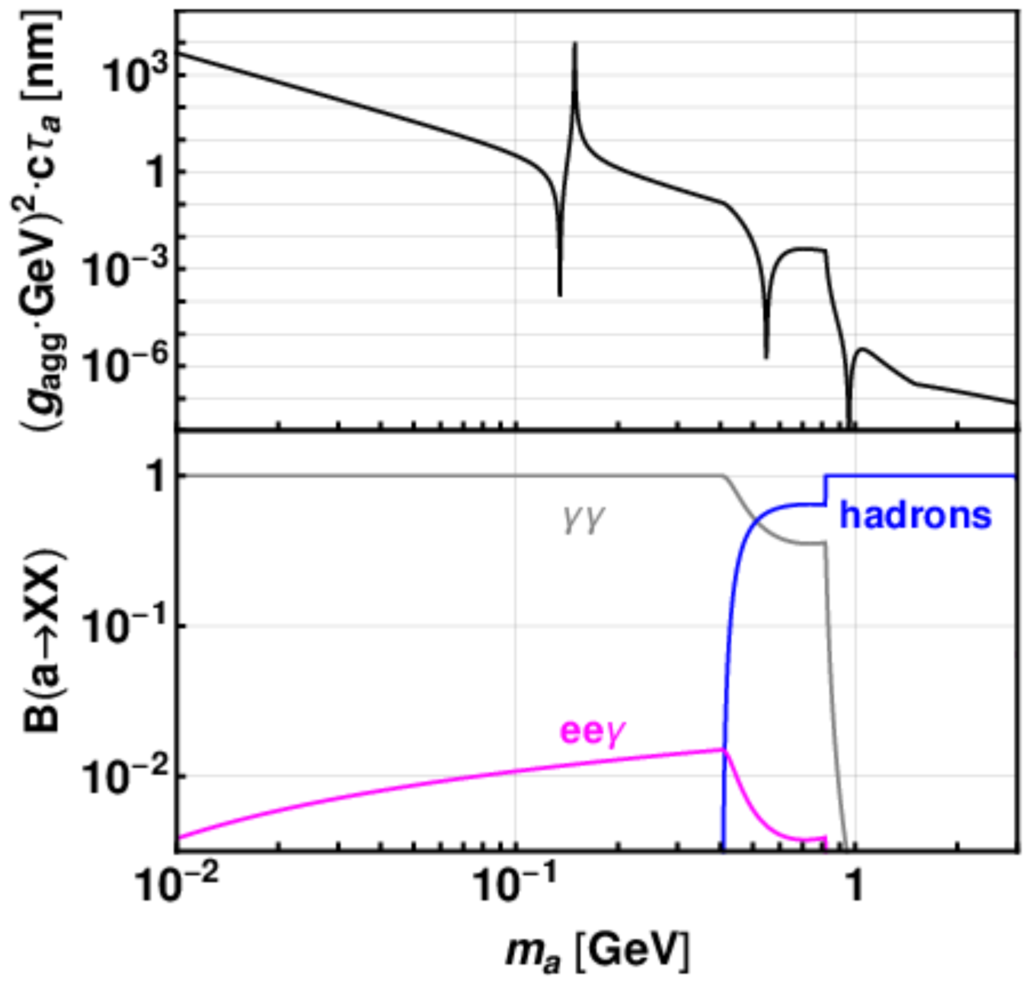


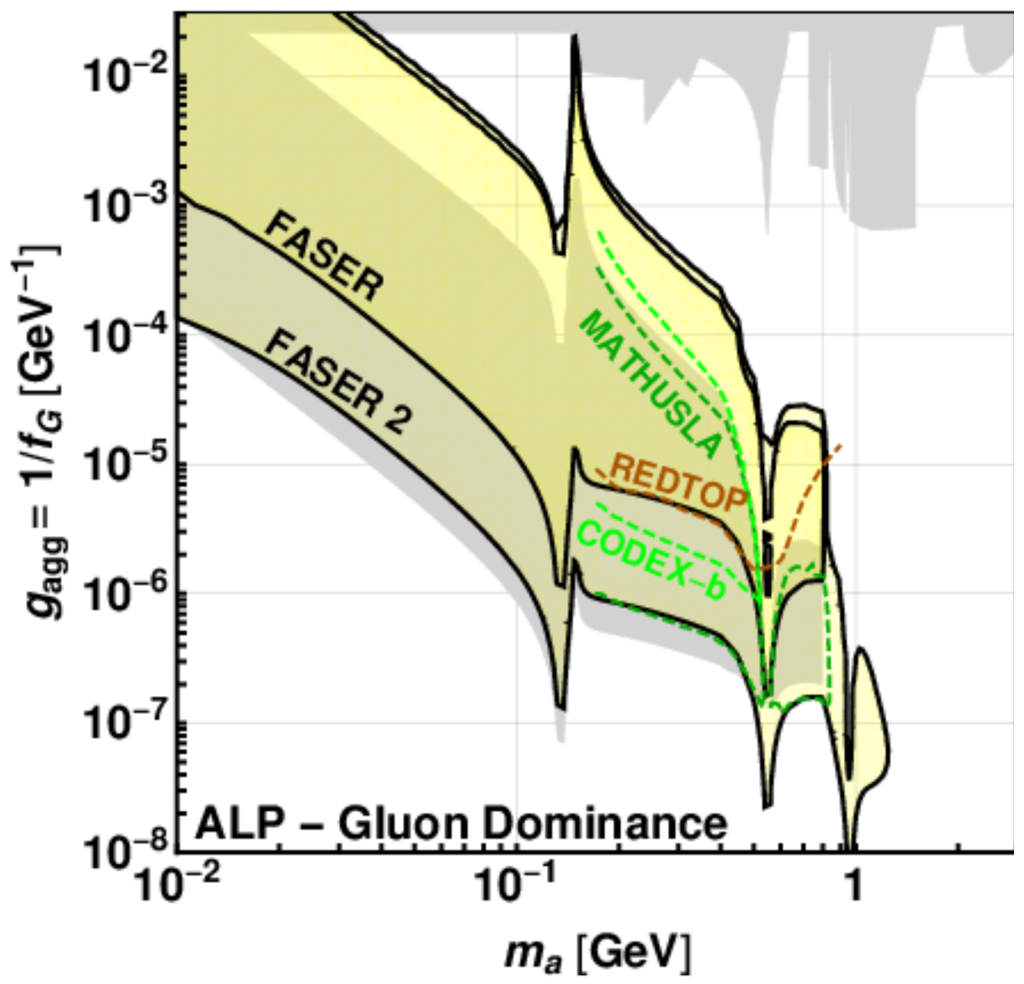


Sensitivity to ALPs









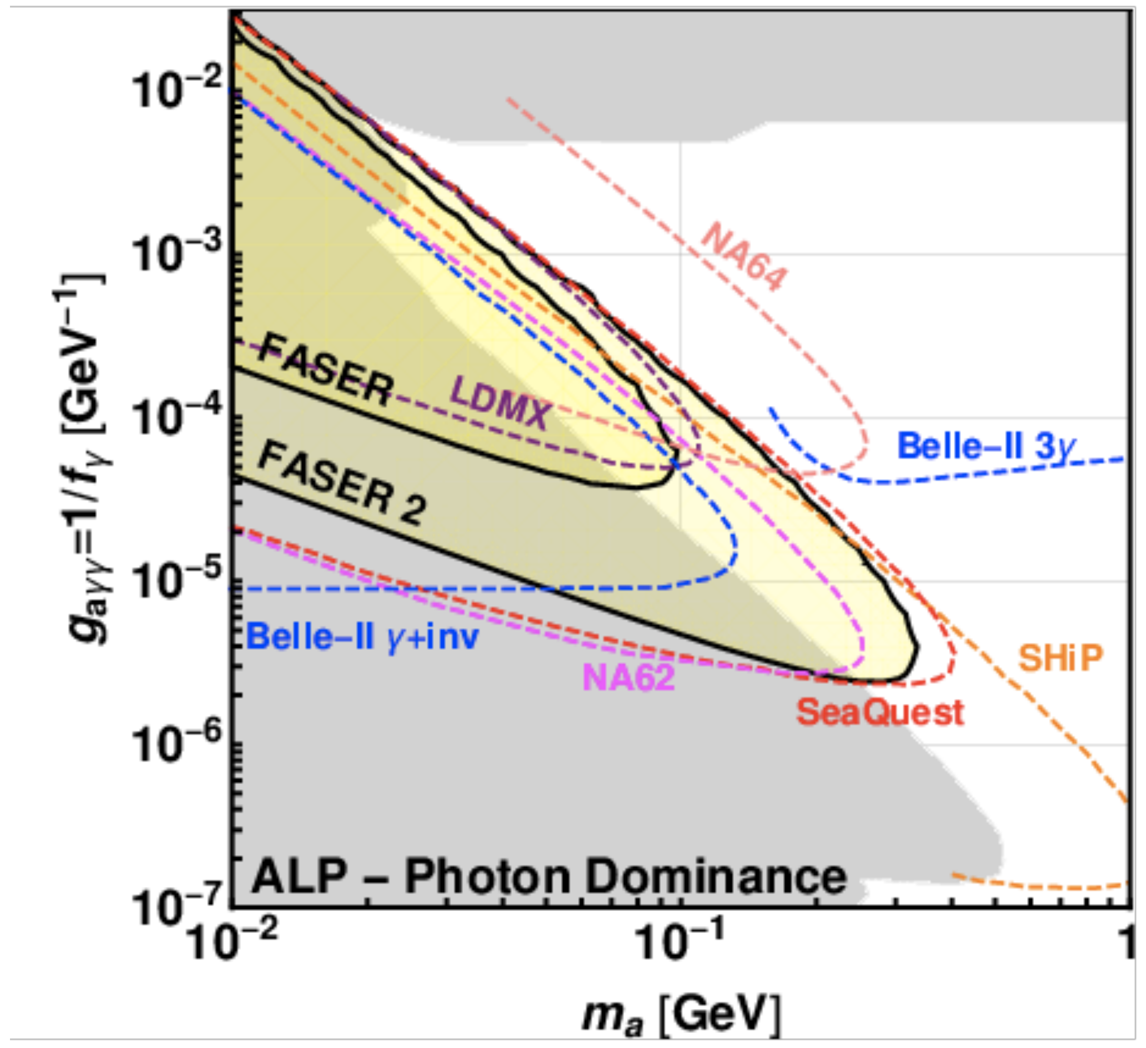
Effective Lagrangian

$$\mathscr{L} = \mathscr{L}_{SM} + \mathscr{L}_{DS} - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{g_s^2}{8}g_{agg}aG^A_{\mu\nu}\tilde{G}^{A\mu\nu} - i\Sigma_f g_{aff}\frac{m_f}{v}a\bar{f}\gamma_5 f$$

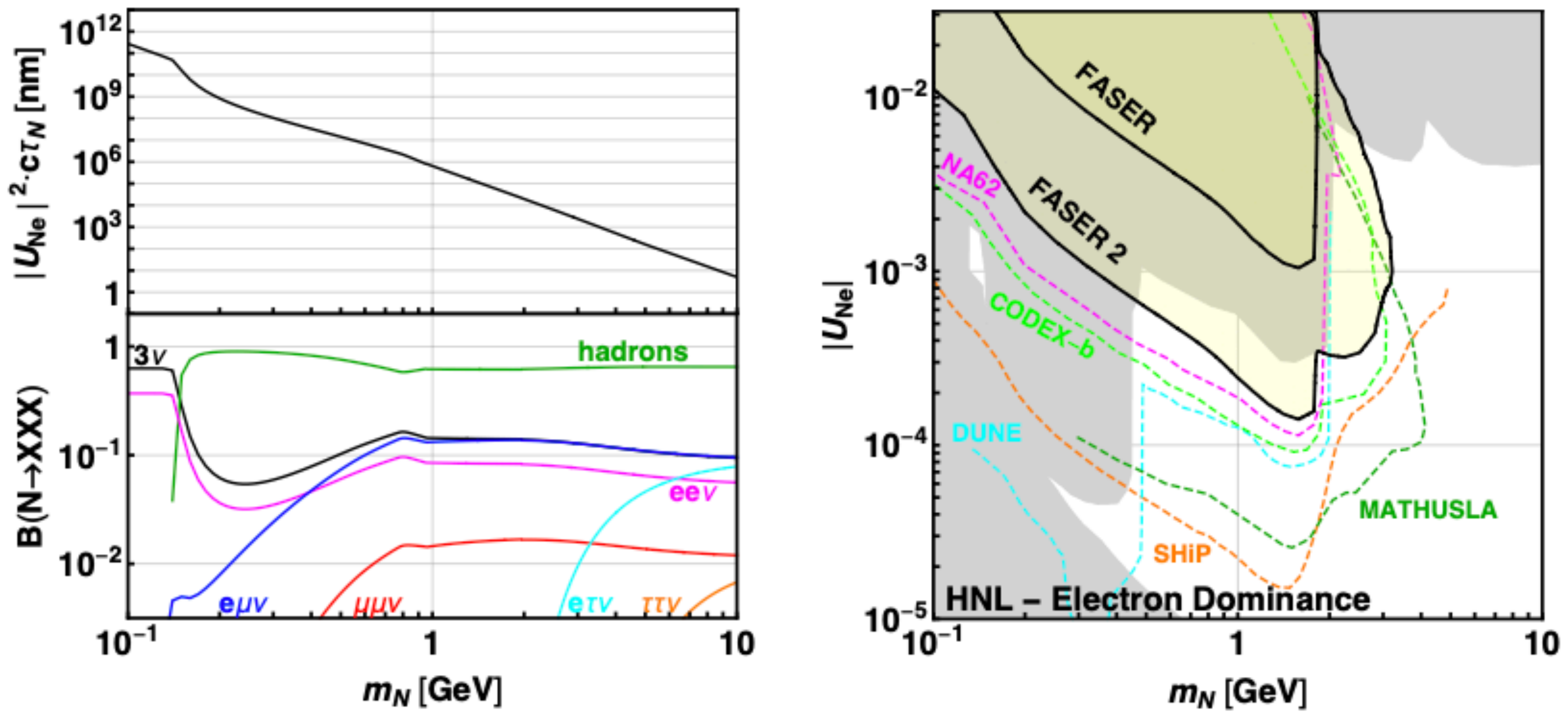
largest B.R.: $a \to \gamma\gamma$

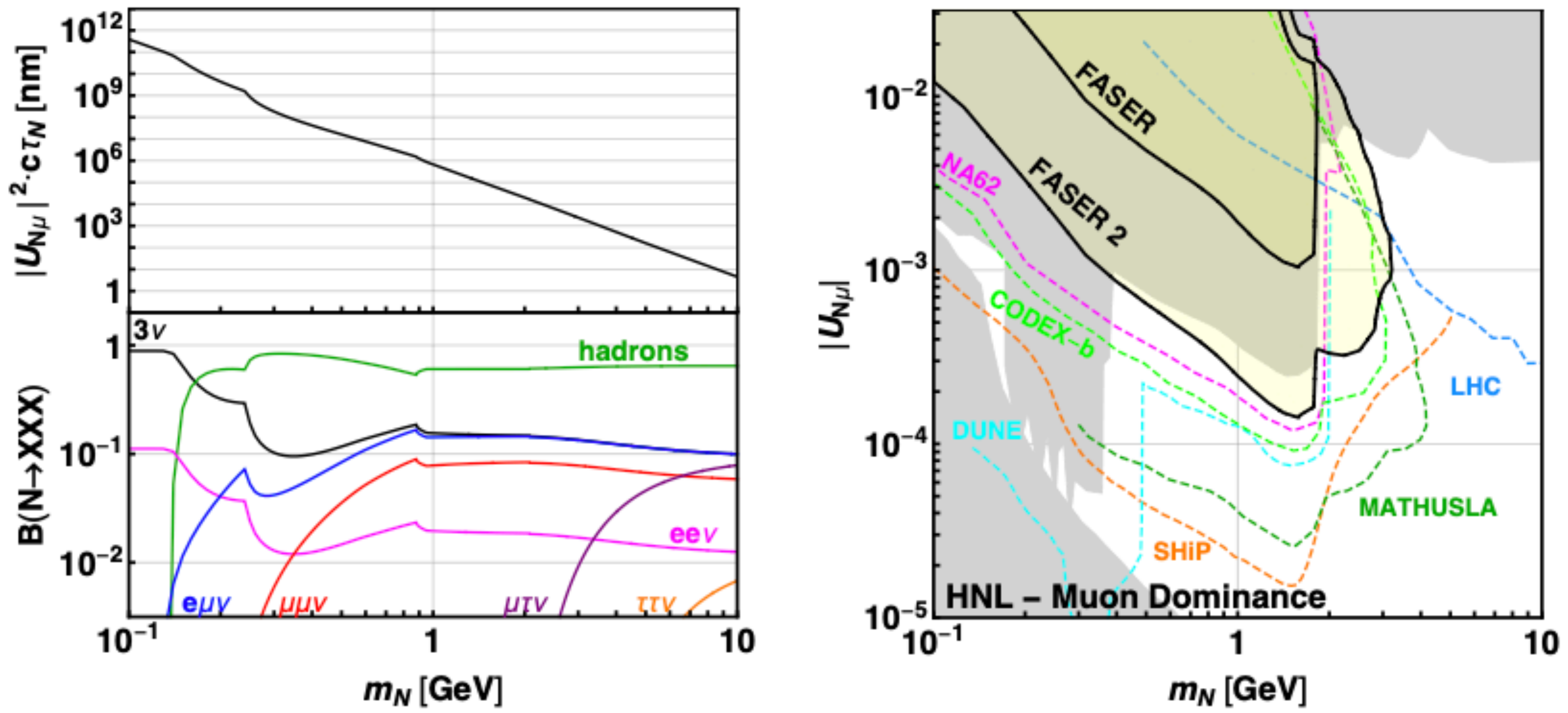
largest B.R.: $a \to \gamma\gamma$, $a \to hadrons$

yukawa—like coupling largest B.R.: $a \to f\bar{f}$

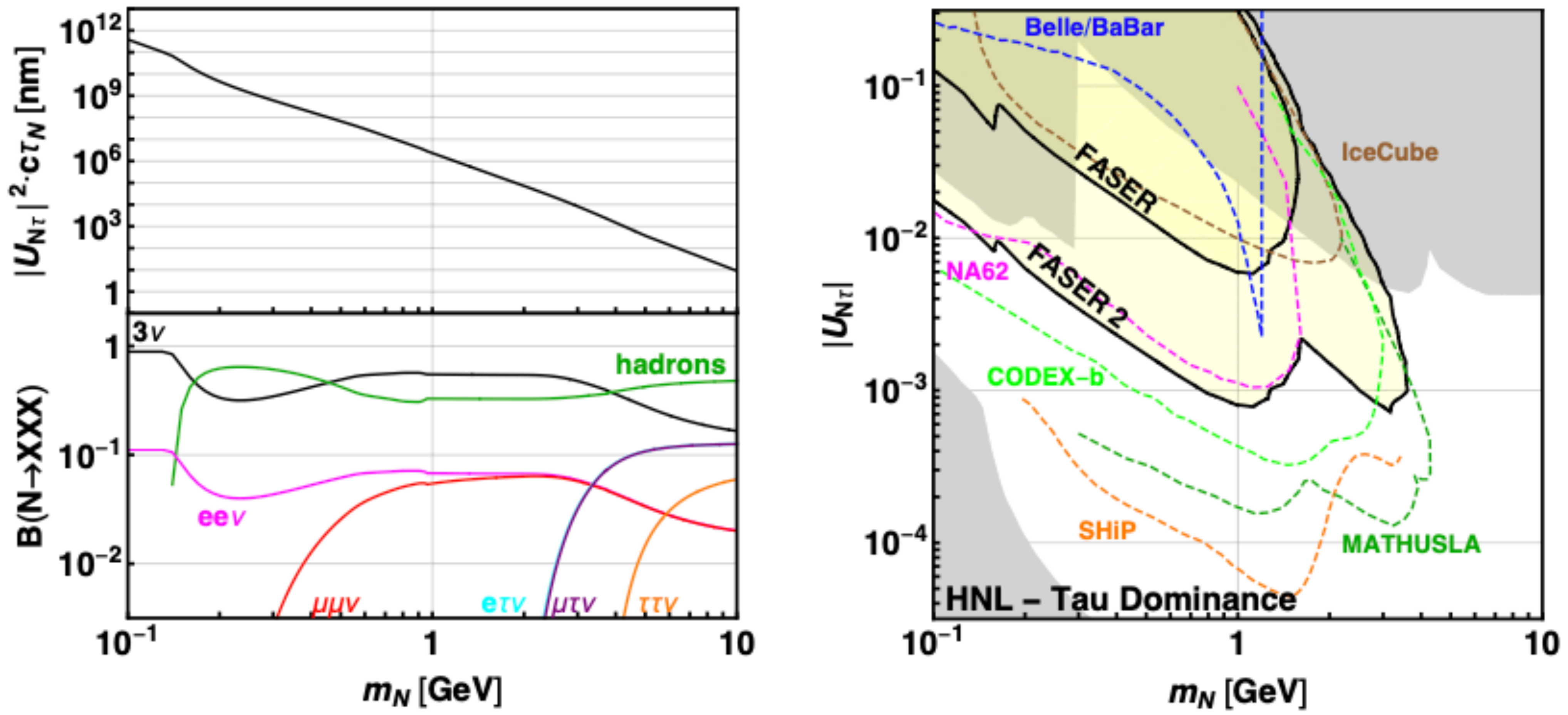


Sensitivity to Heavy Neutral Leptons





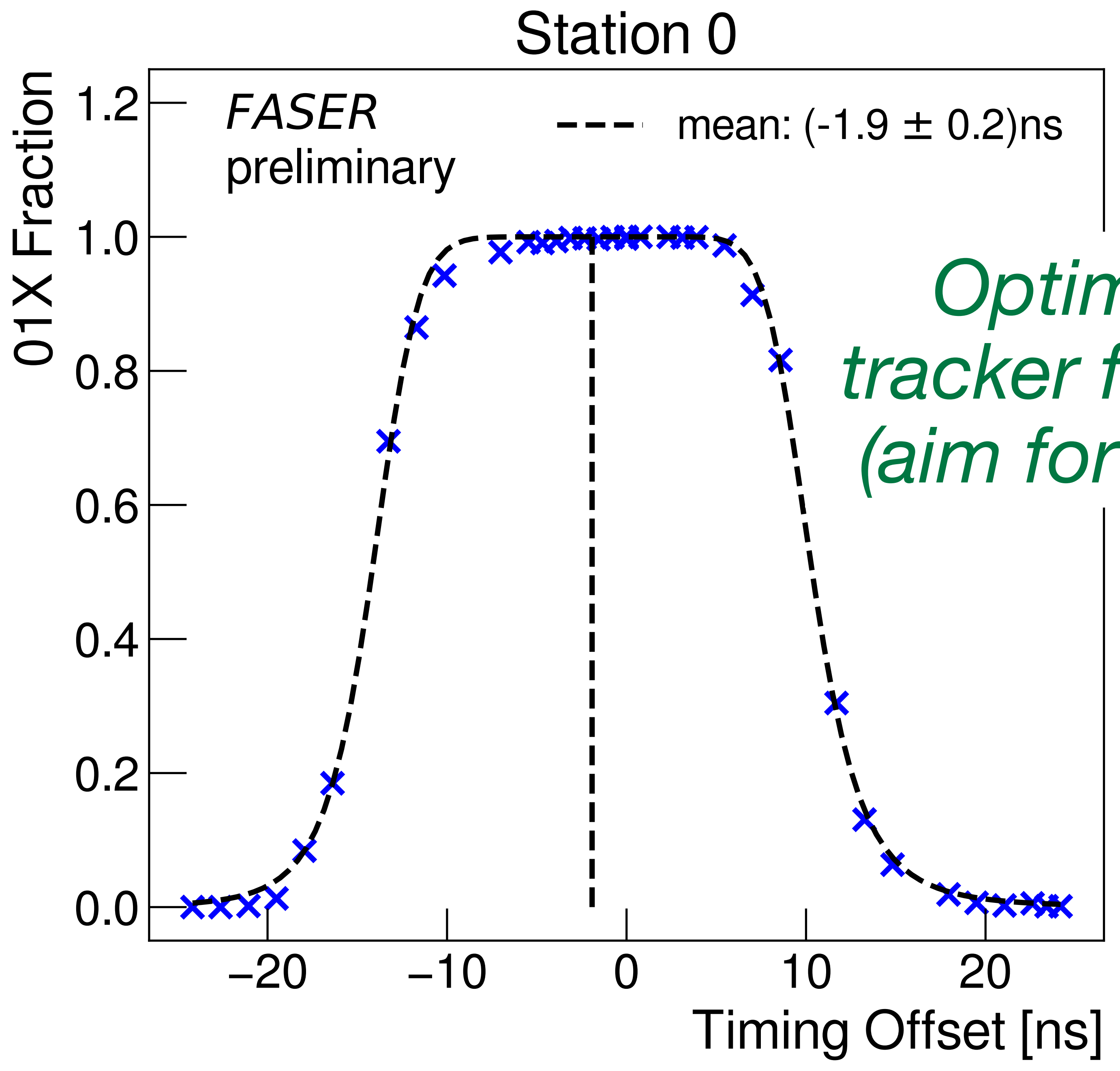
HNL production mainly through heavy meson and tau lepton decay.



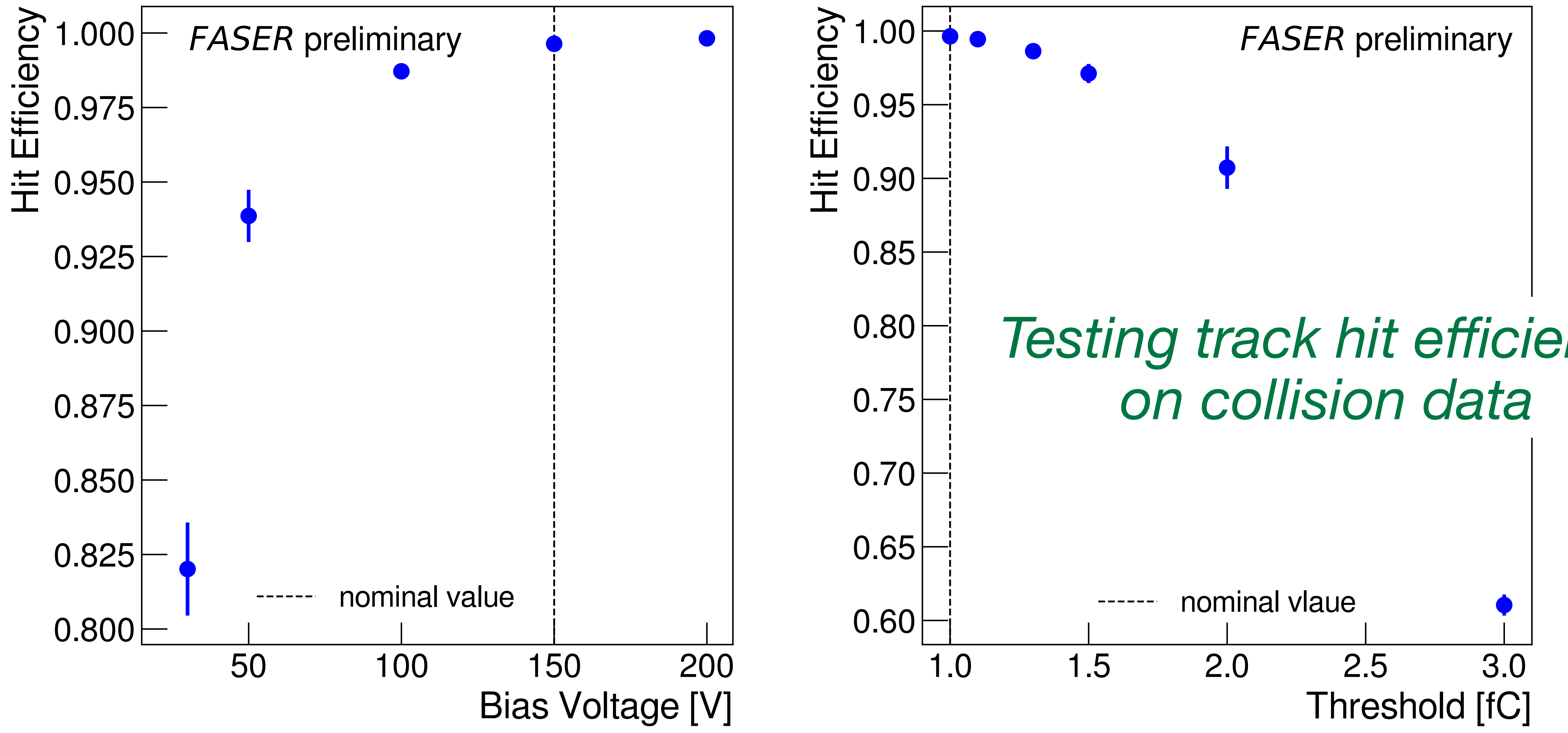
First data from 13.6 TeV proton collisions

Early physics runs dedicated to tracker performance

- Special runs during early collisions used for tracker fine time tuning + hit efficiency scans.



Optimising tracker fine time (aim for center)



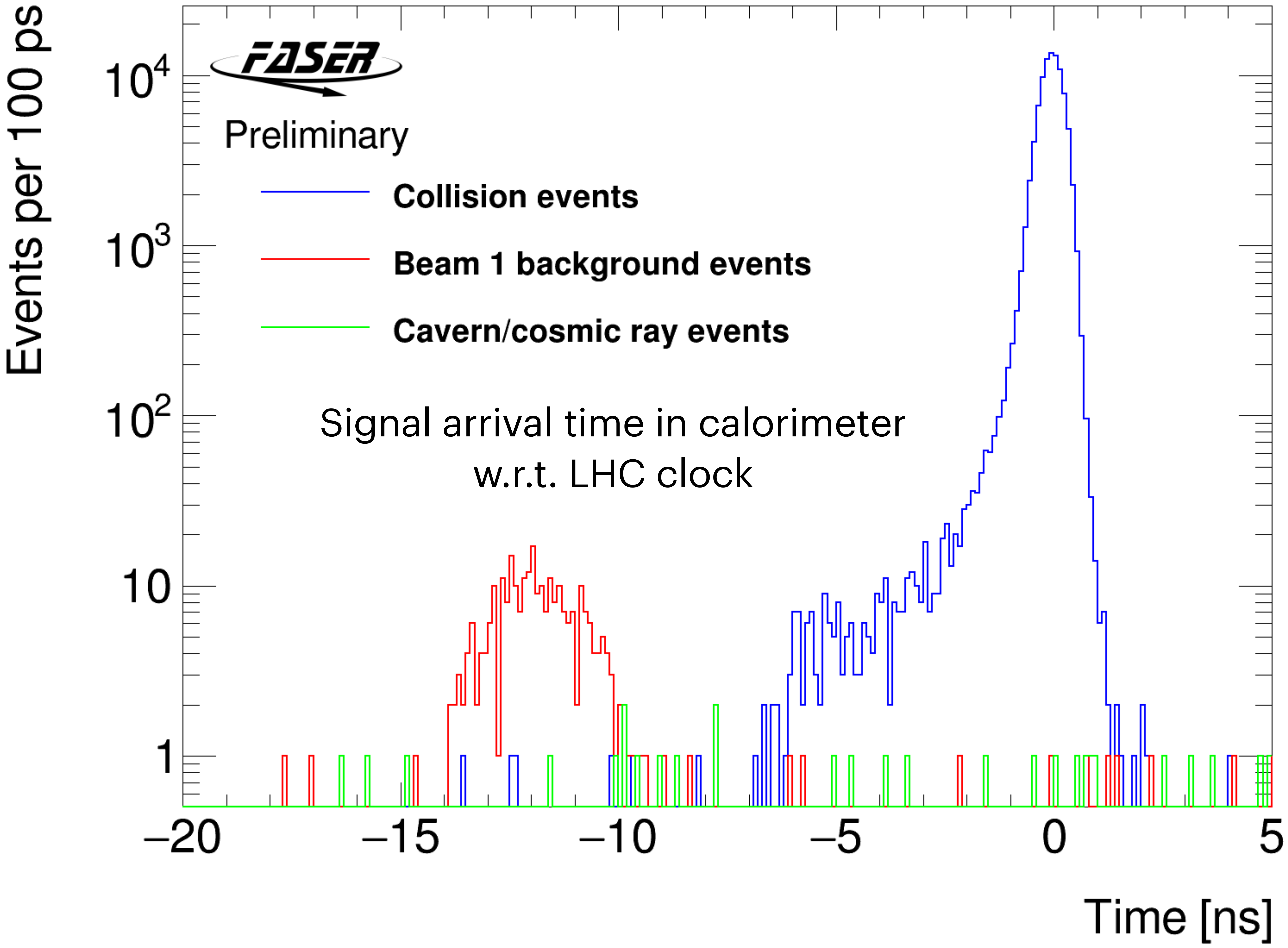
Testing track hit efficiency on collision data

Tracker SCT modules fine time tuned with 390 ps precision. Fine Timing of all stations updated in August.

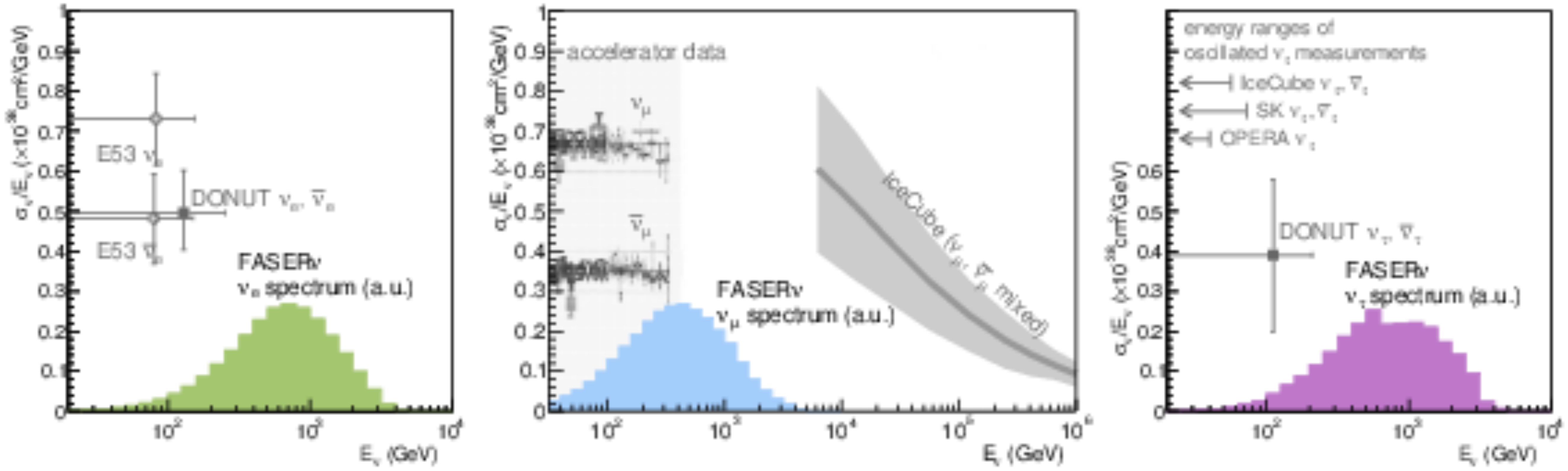
Hit efficiency dependent on hit threshold and bias voltage: Expected rise to ~100%, where our nominal values set.

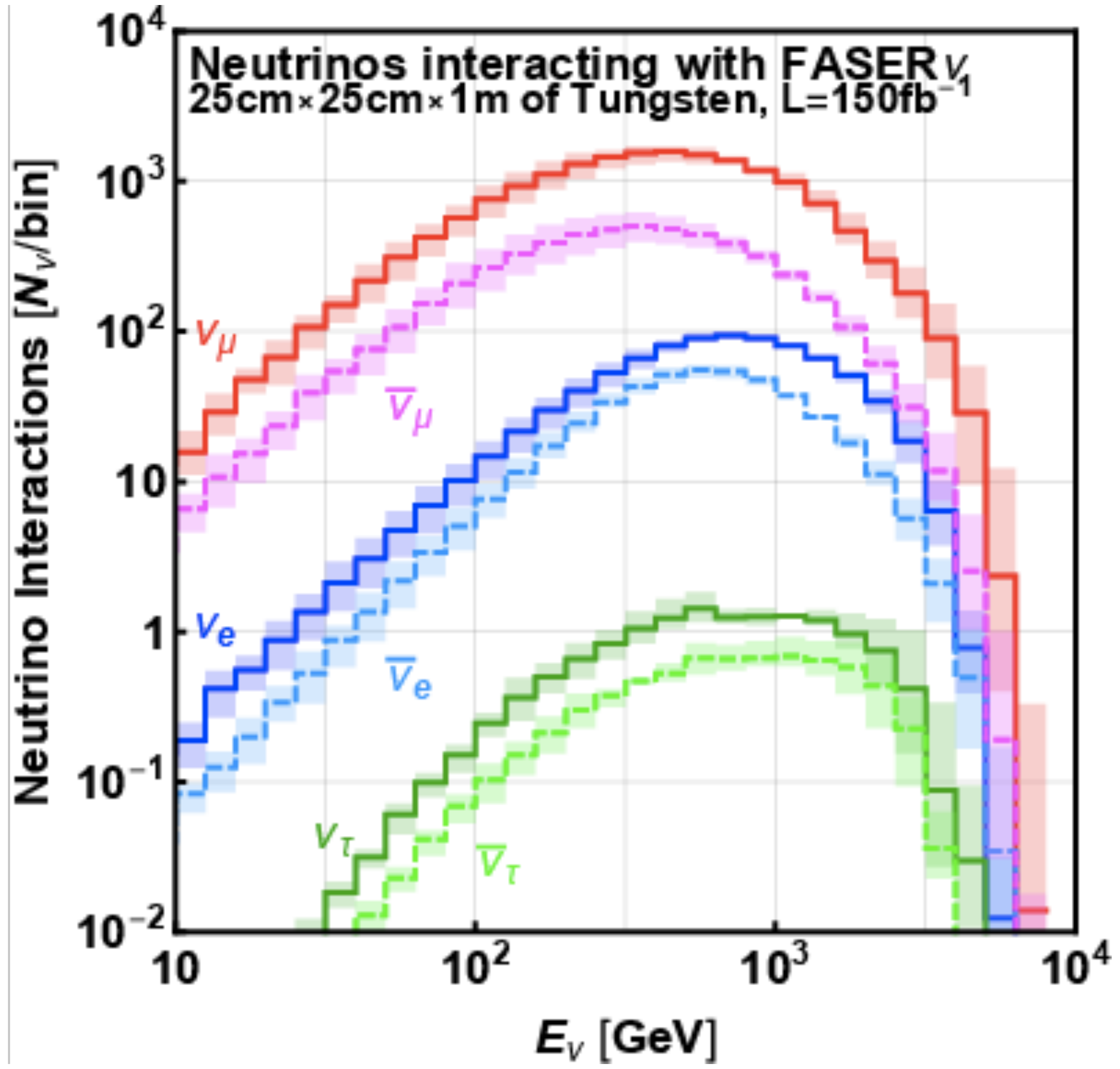
Calorimeter timing for different signals

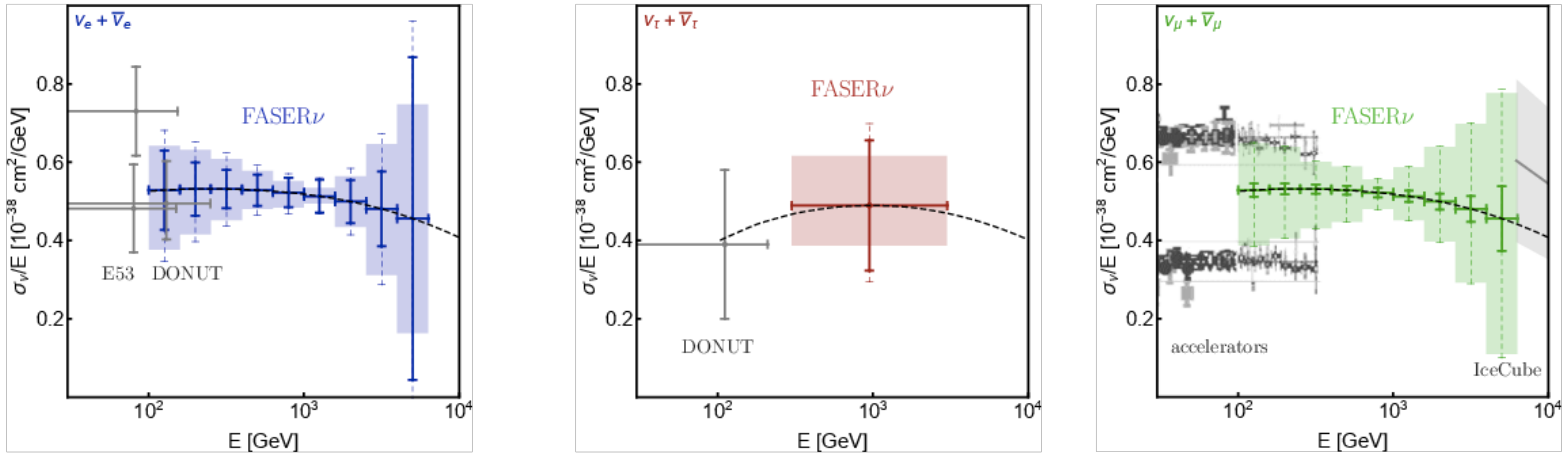
- Time of arrival of Beam 1 background happens to be perfectly separated from the arrival time of particles from IP1.
- Therefore, Beam 1 background easily reducible even with just calorimeter timing information.

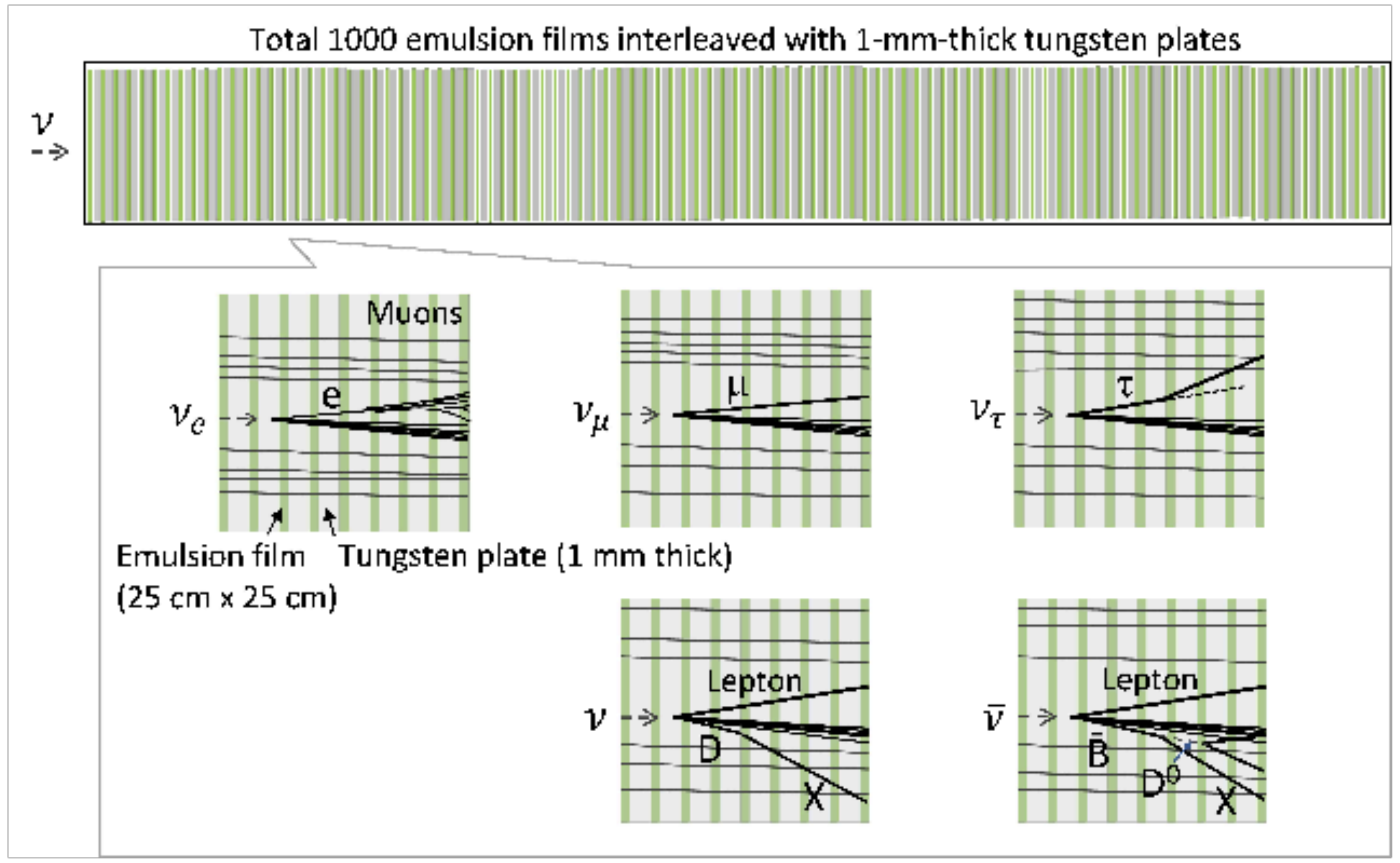


FASERν

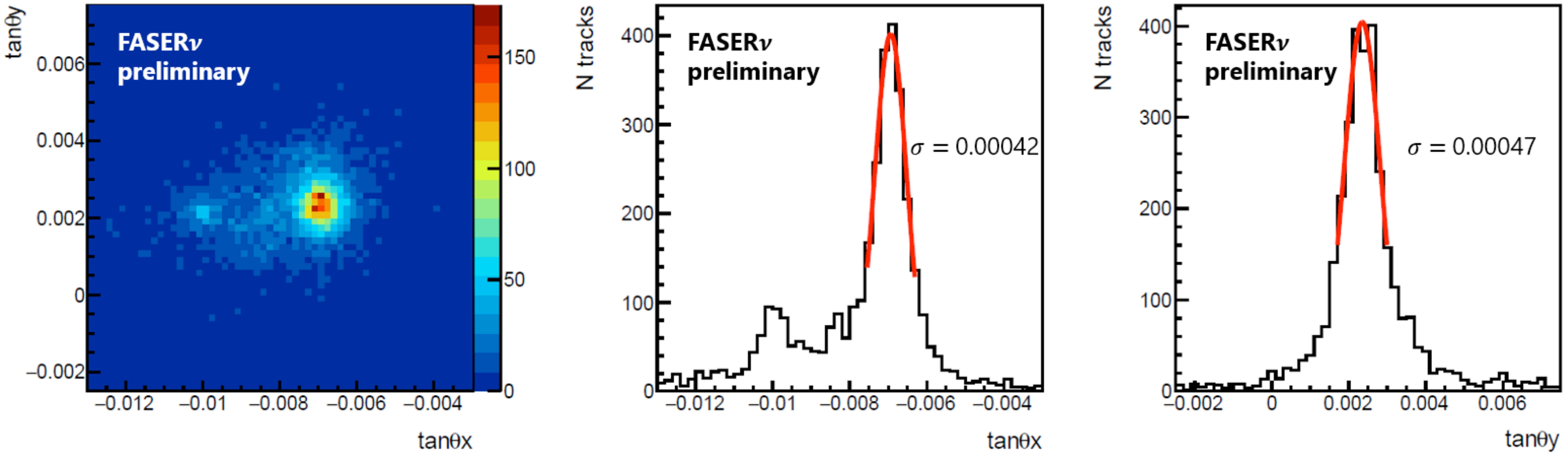

accelerator data
IceCube
energy ranges of oscillated ντ measurements
DONUT
FASERν
νe spectrum (a.u.)
νμ spectrum (a.u.)
ντ spectrum (a.u.)
Eν (GeV)


Neutrinos interacting with FASERν
25cm×25cm×1m of Tungsten, L=150fb⁻¹
Neutrino Interactions [Nν/bin]
Eν [GeV]


FASERν
E53
DONUT
accelerators
IceCube
σν/E [10⁻³⁸ cm²/GeV]
E [GeV]

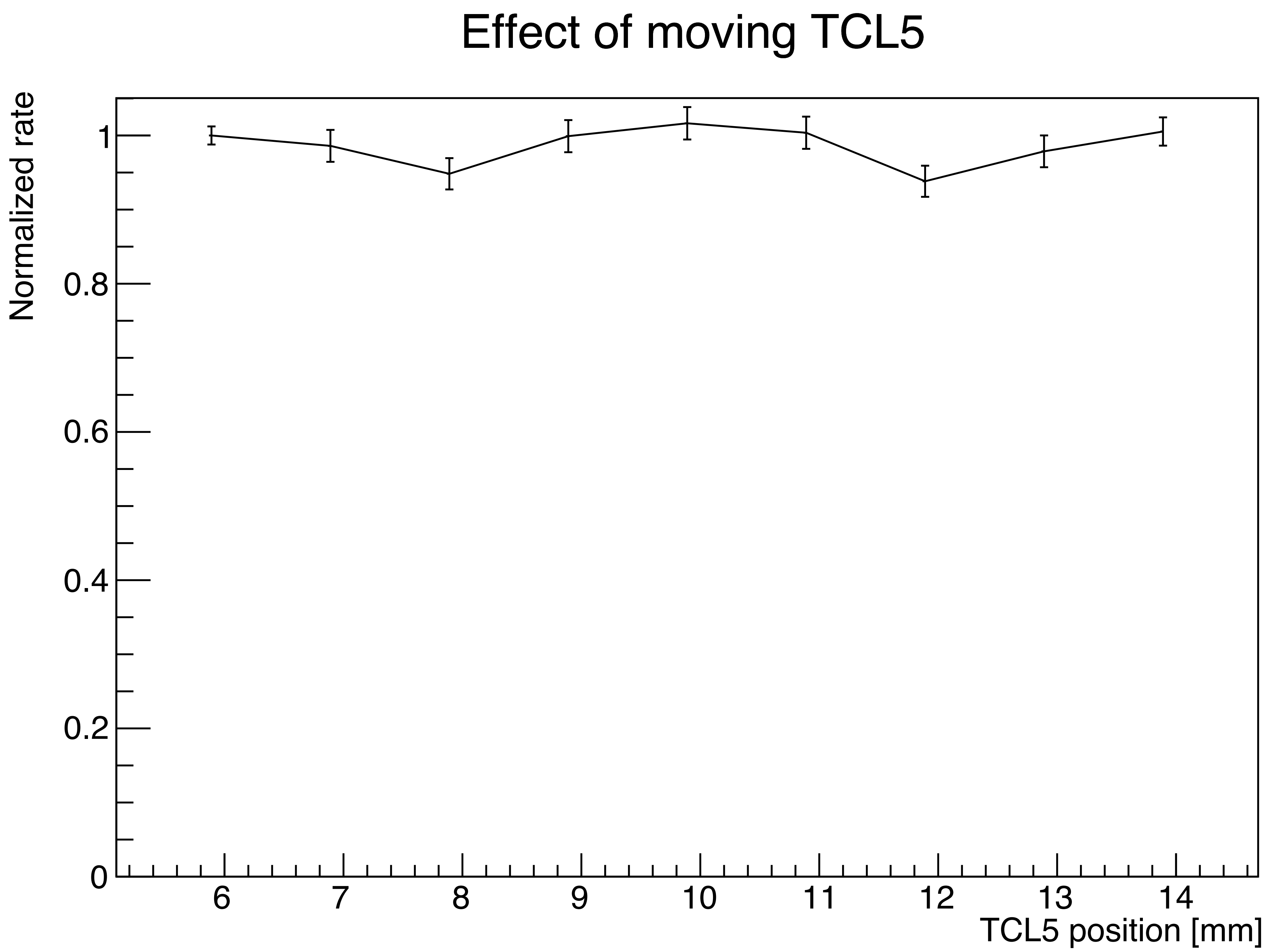

Total 1000 emulsion films interleaved with 1-mm-thick tungsten plates
Muons
Lepton
Emulsion film
(25 cm x 25 cm)
Tungsten plate (1 mm thick)

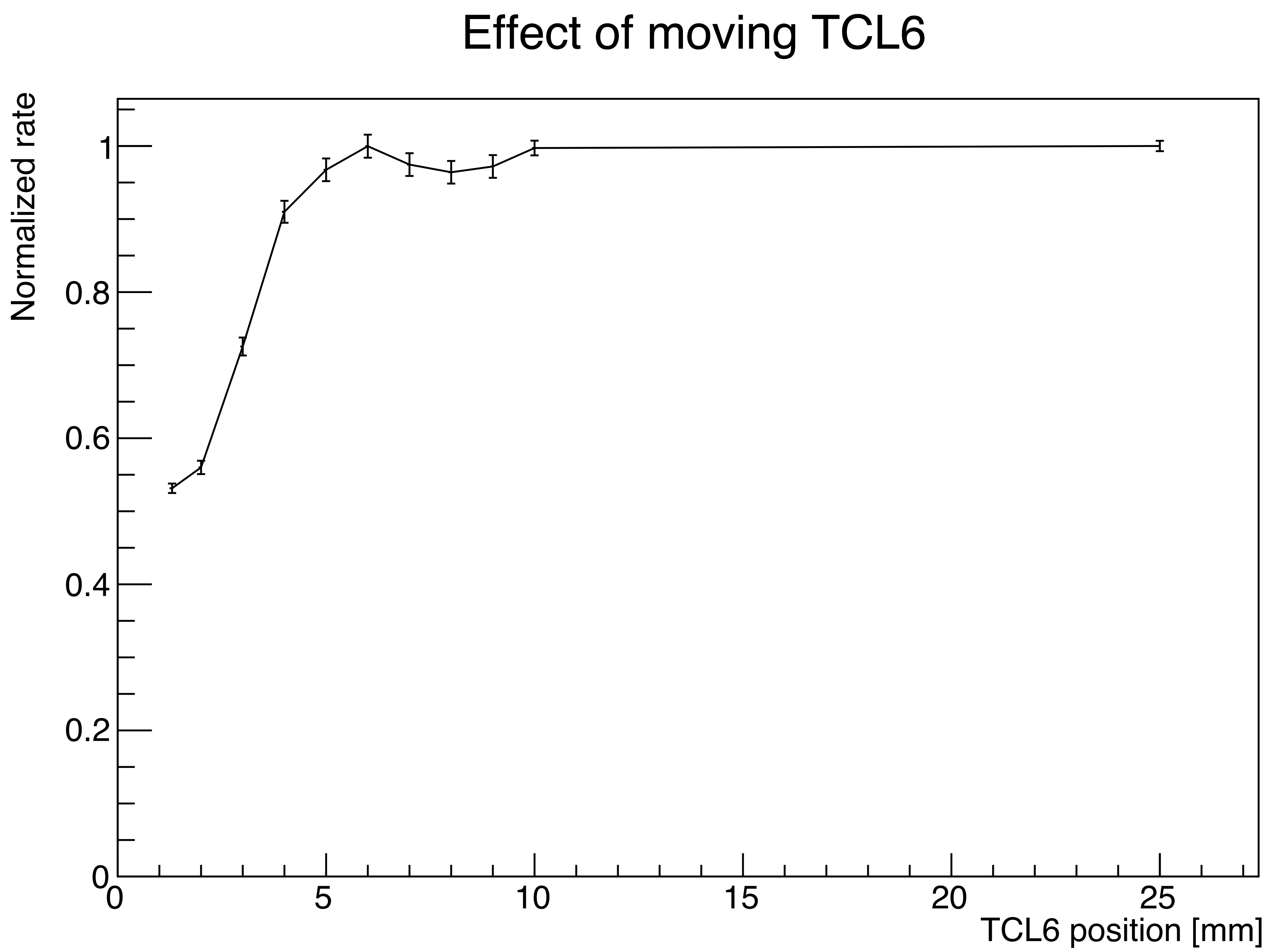
First Data: FASERν track reconstruction



- Angular distributions of reconstructed tracks in 1st emulsion box:
  - Distribution peaks consistent with particles from the beam line.
  - Angular spread of ~0.5 mrad consistent with multiple Coulomb scattering of ~100s GeV muons through 100 m of rock.

FASER Rate vs Collimator Position





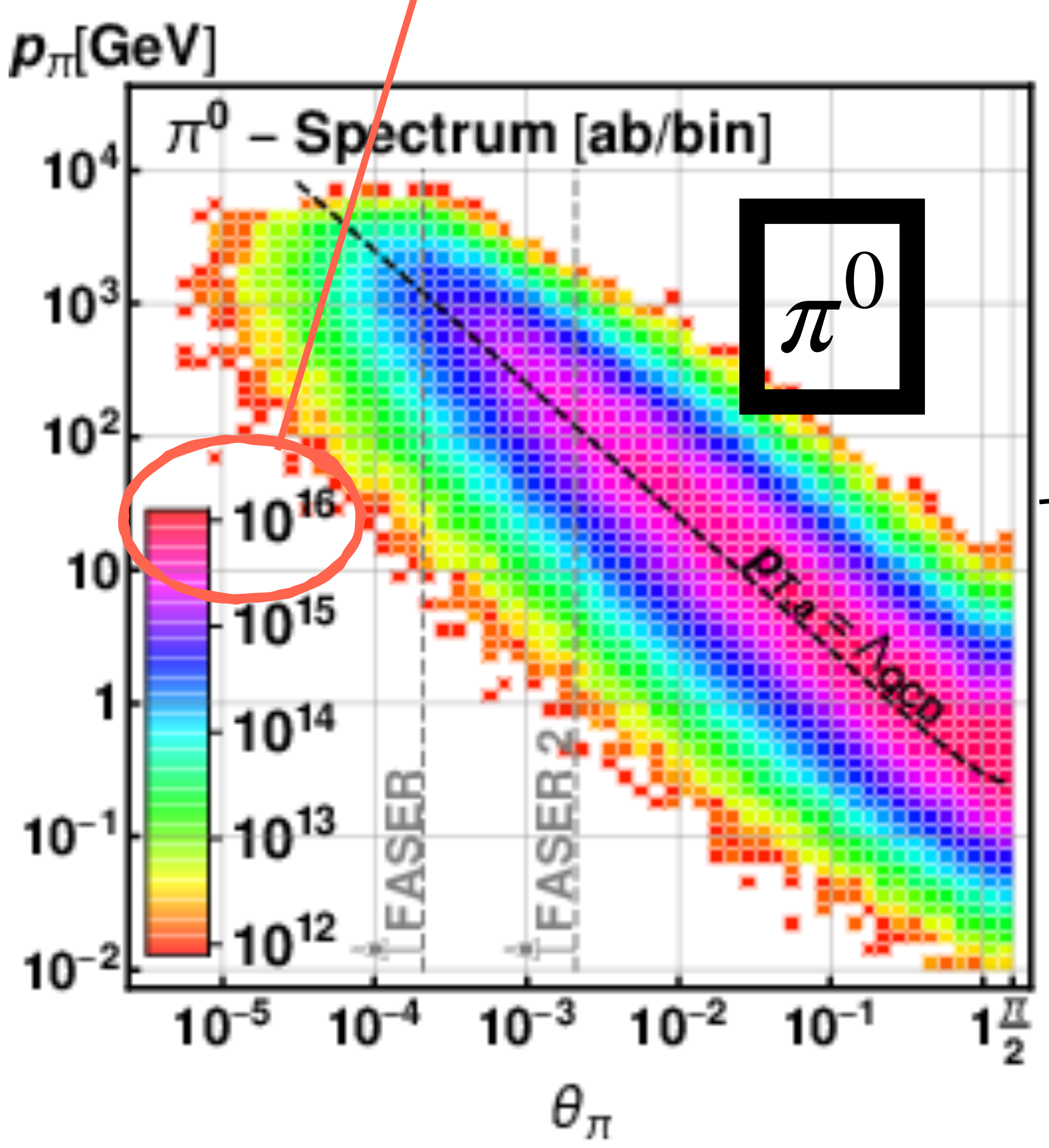
FASER Overview

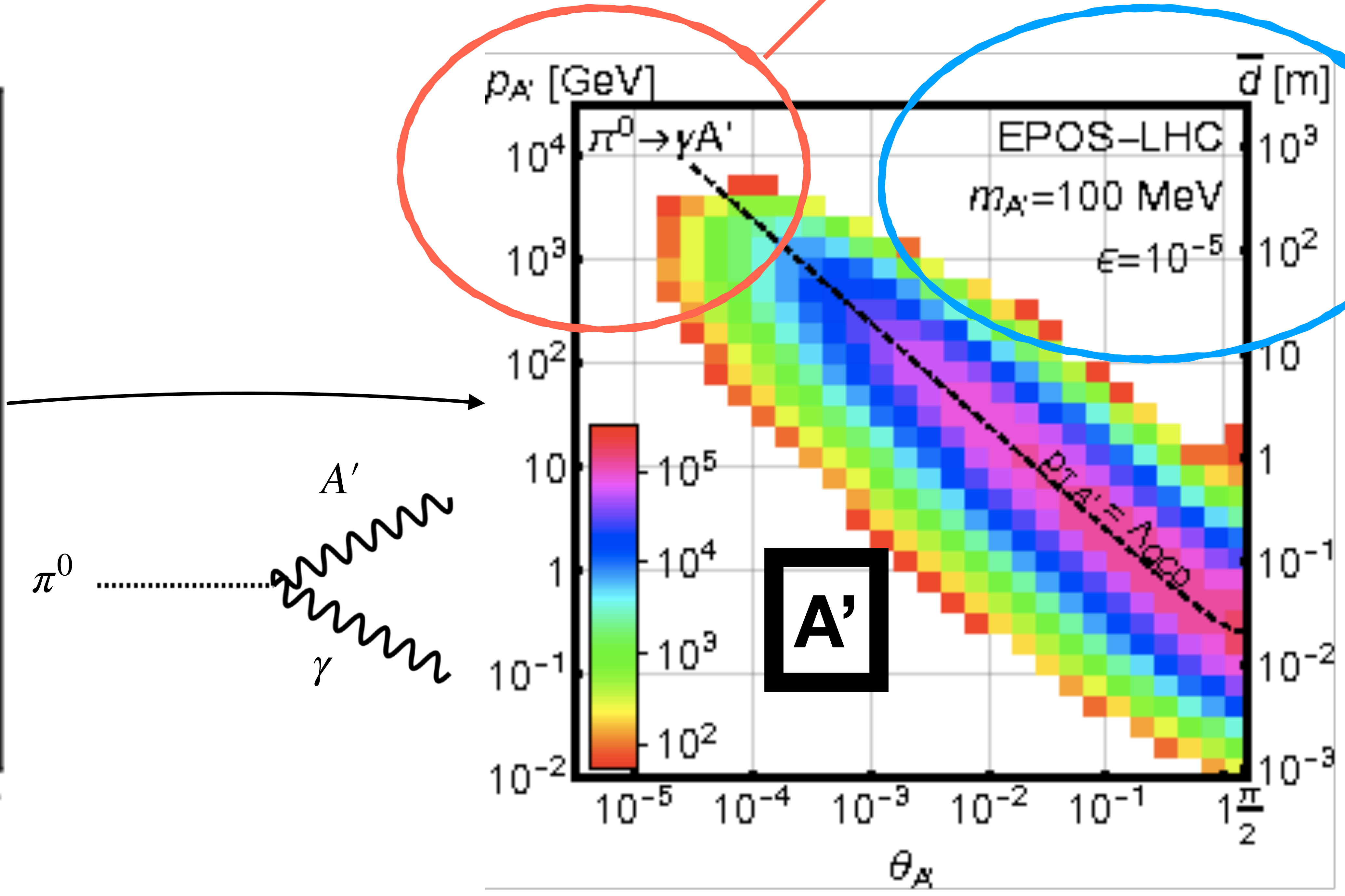
Physics

Large luminosity of highly energetic neutral pions:
Source of new boosted physics down beam pipe

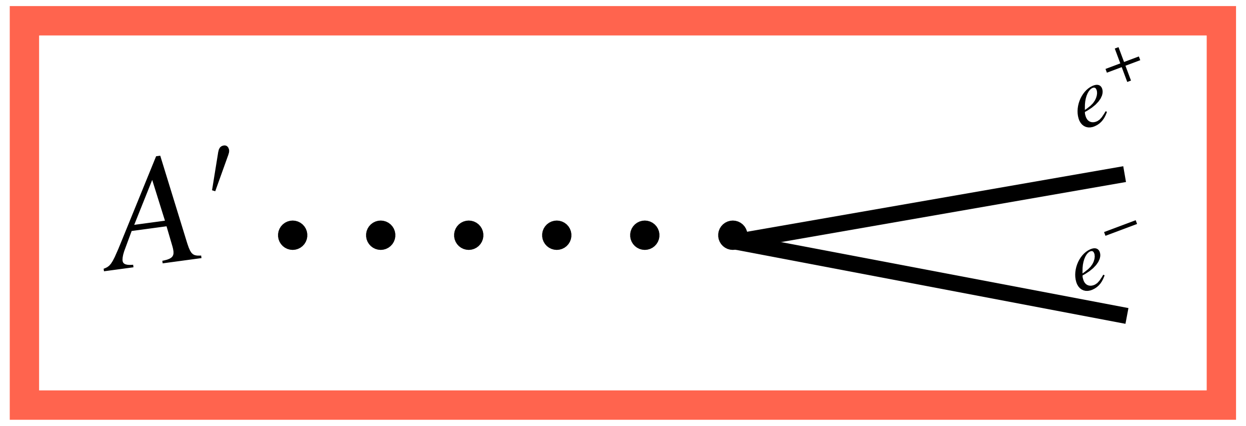
10^{16} inelastic events in 150 ifb

Highly energetic & boosted (TeV energies) if produced close to beam line.



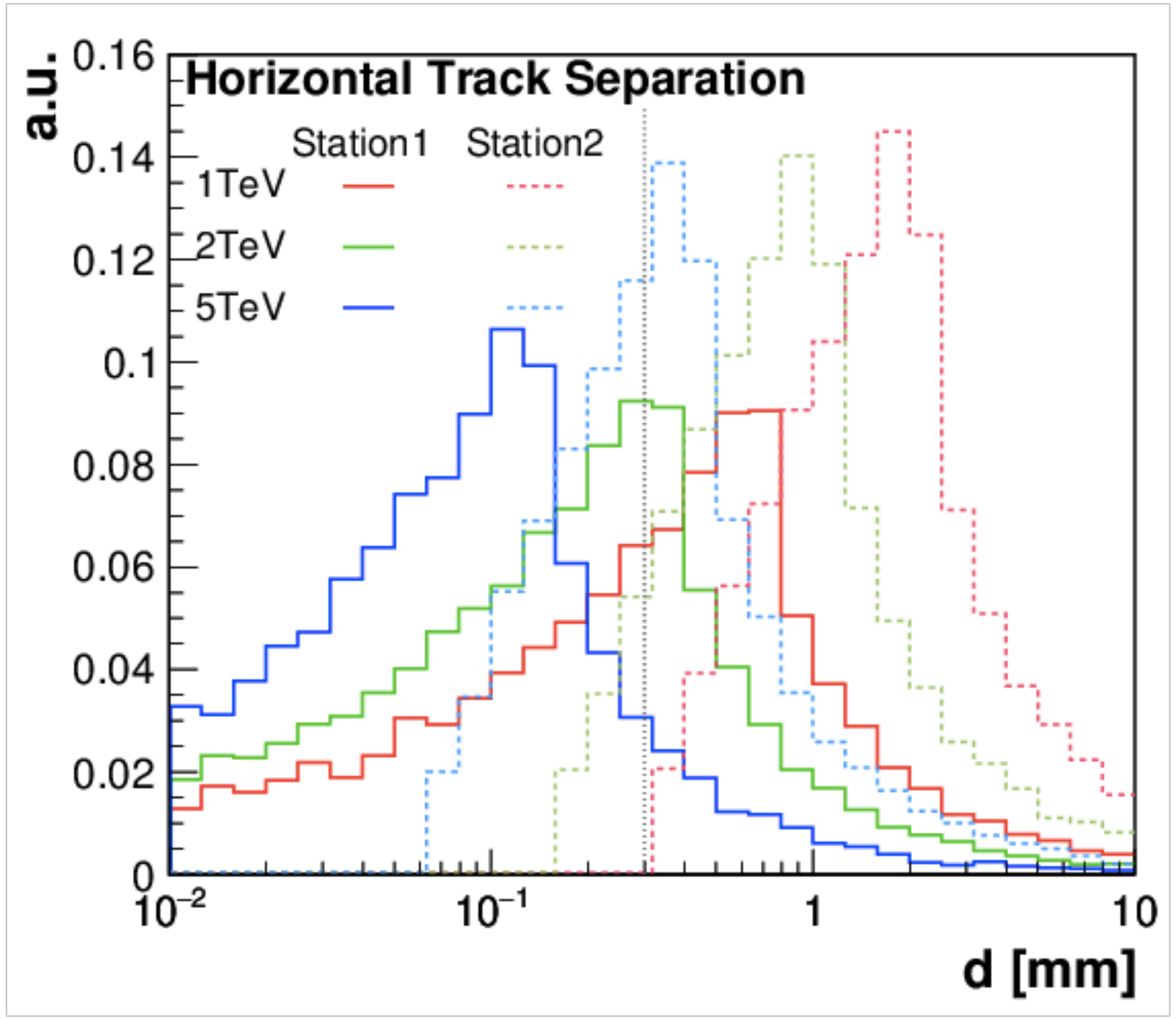


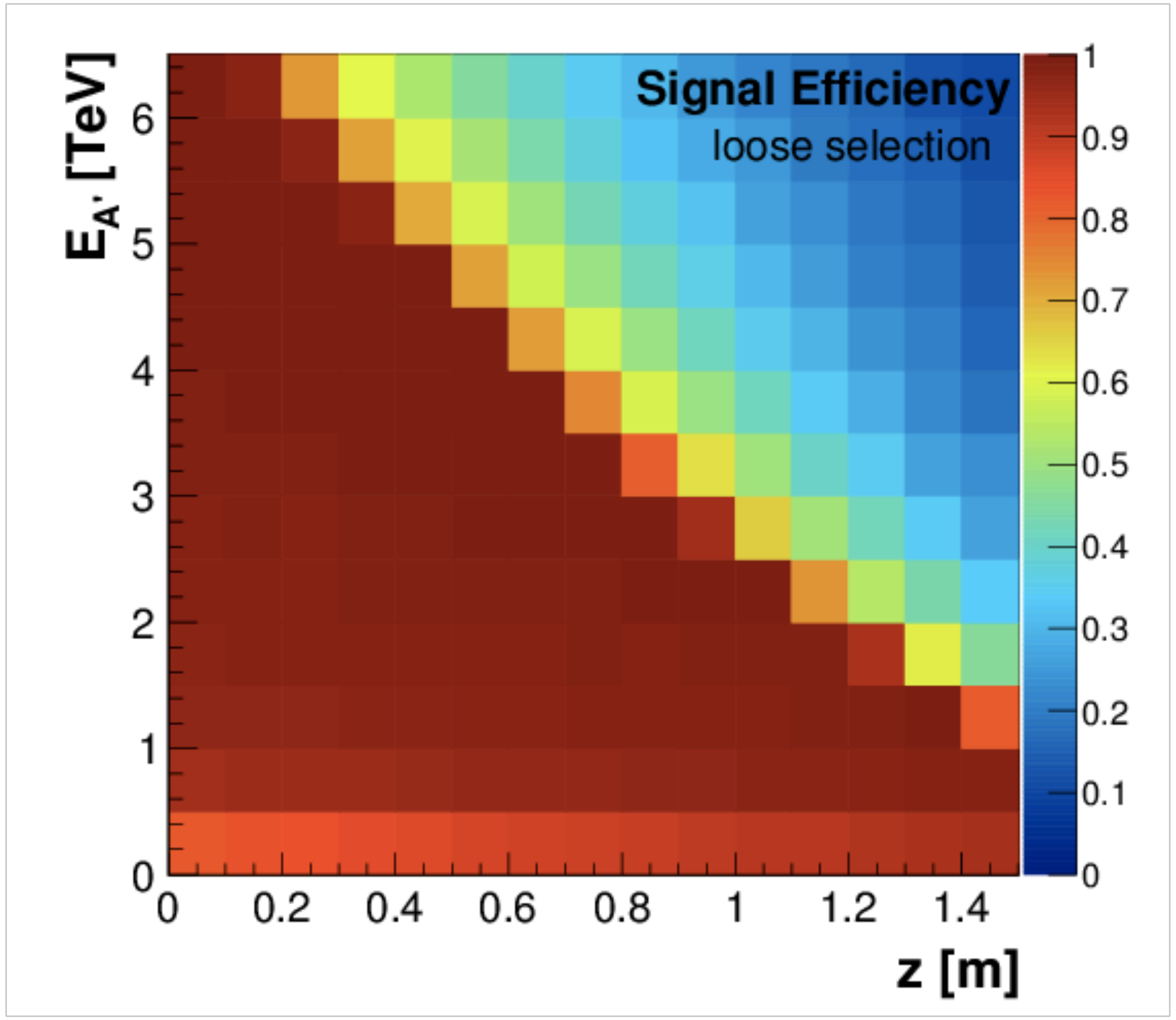
Small SM couplings + boost
-> Long-lived, can decay far
from collision to highly
collimated SM particle pair.



FASER Simulated Signal Efficiency

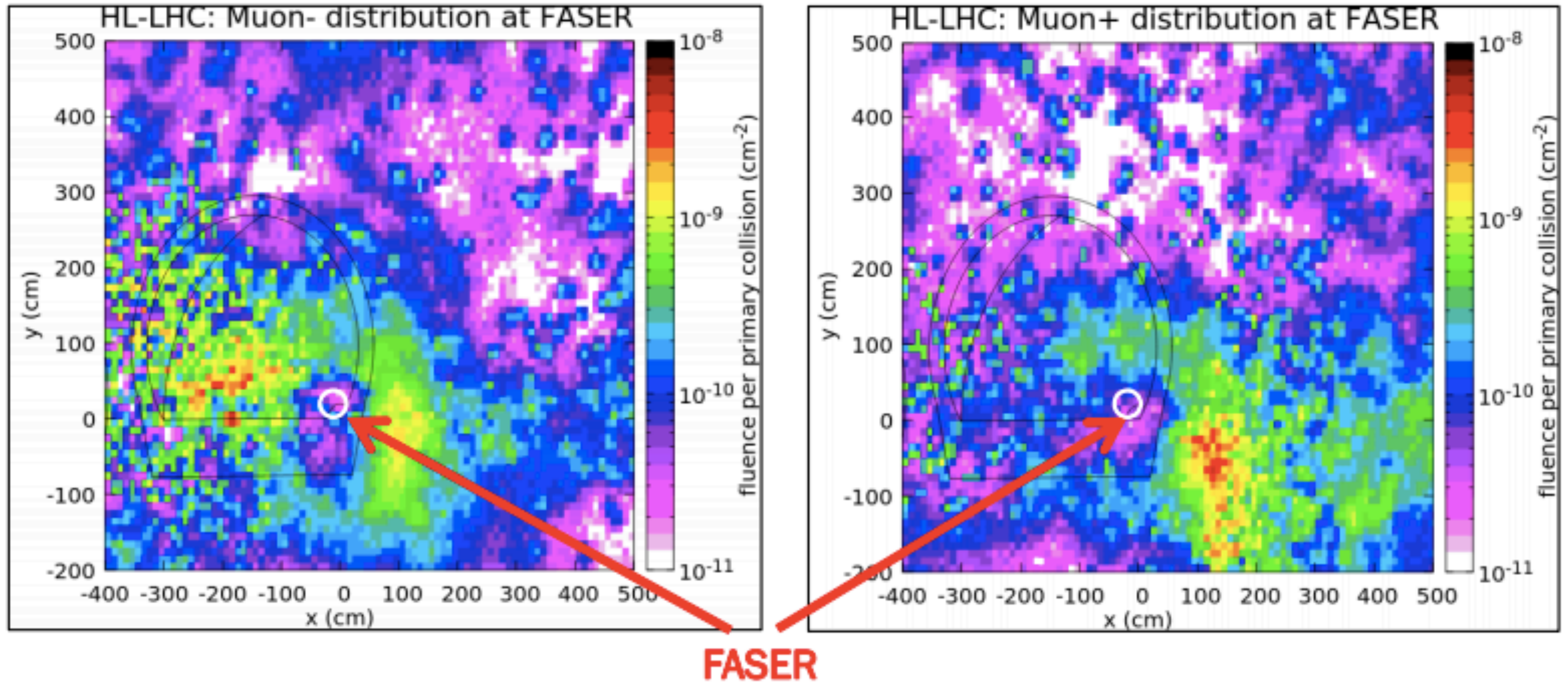
mA'=100 MeV, ε = 10^{-5}

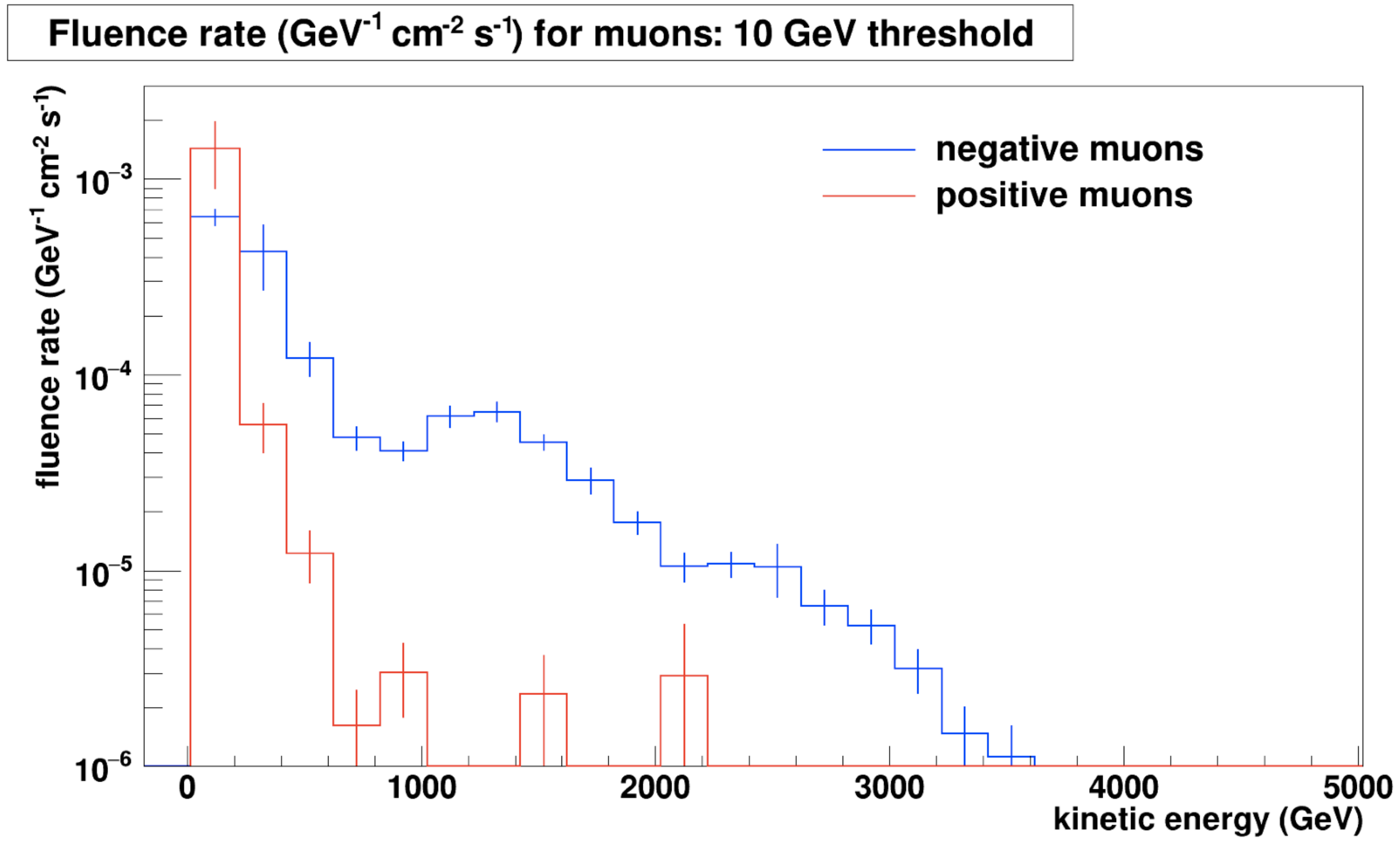




FASER Background

FLUKA simulation: Magnets very helpfully deflect muons away from beam axis.

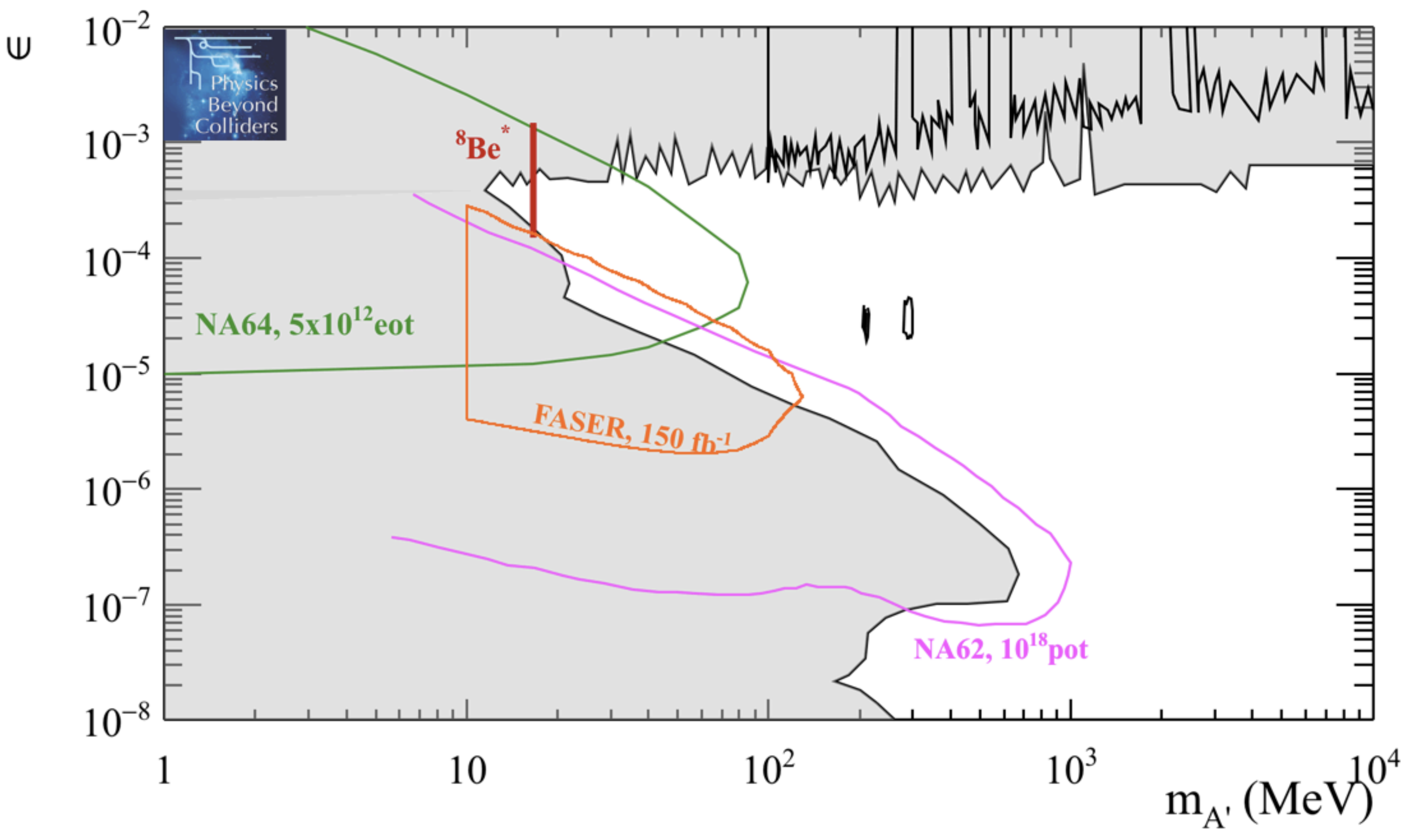


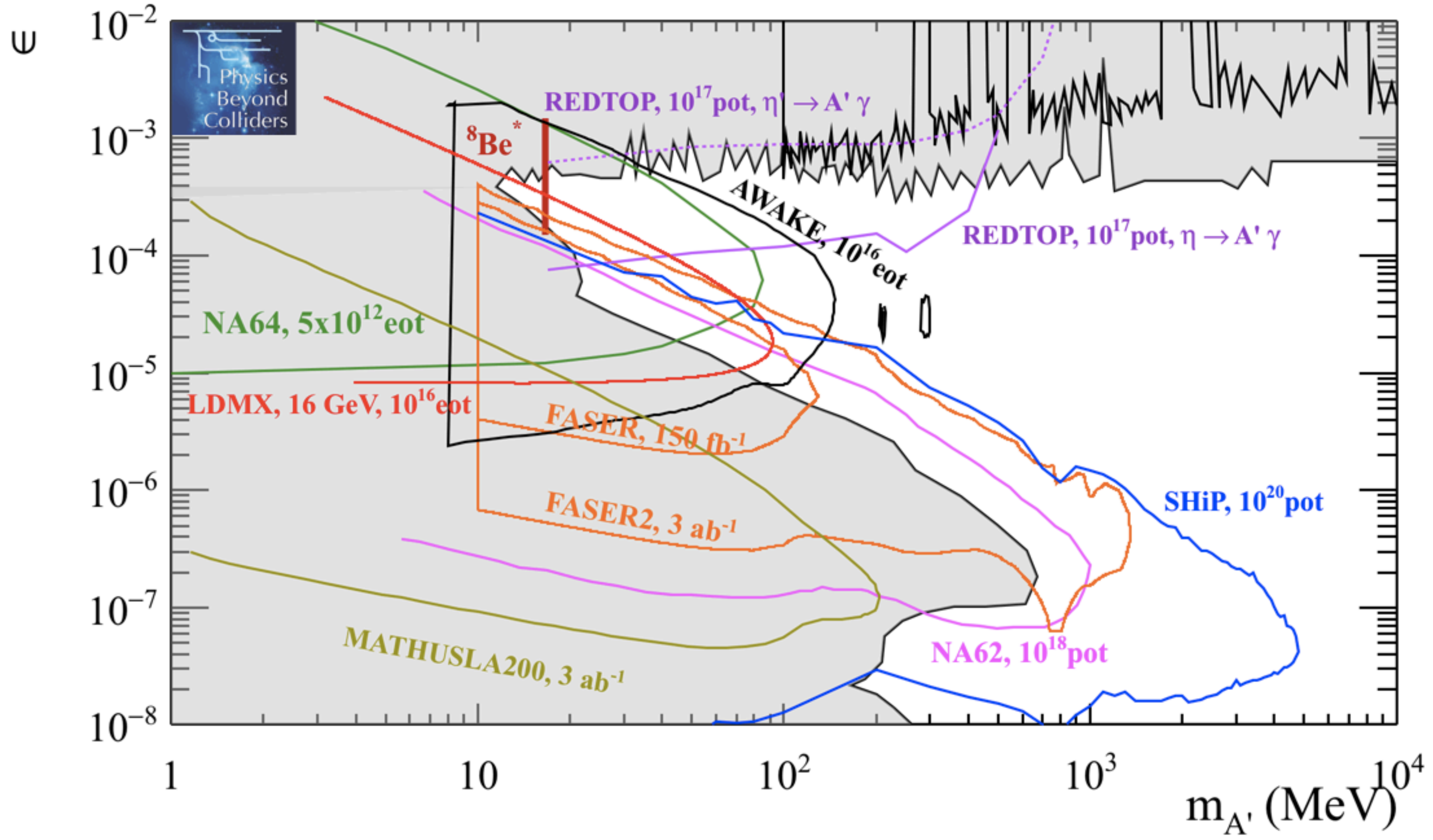


Dark photon to visible decay

Projections

- 5 year timescale





- 10-15 year timescale

Ref: Physics Beyond Colliders Working Group Report