# FASER: First Results

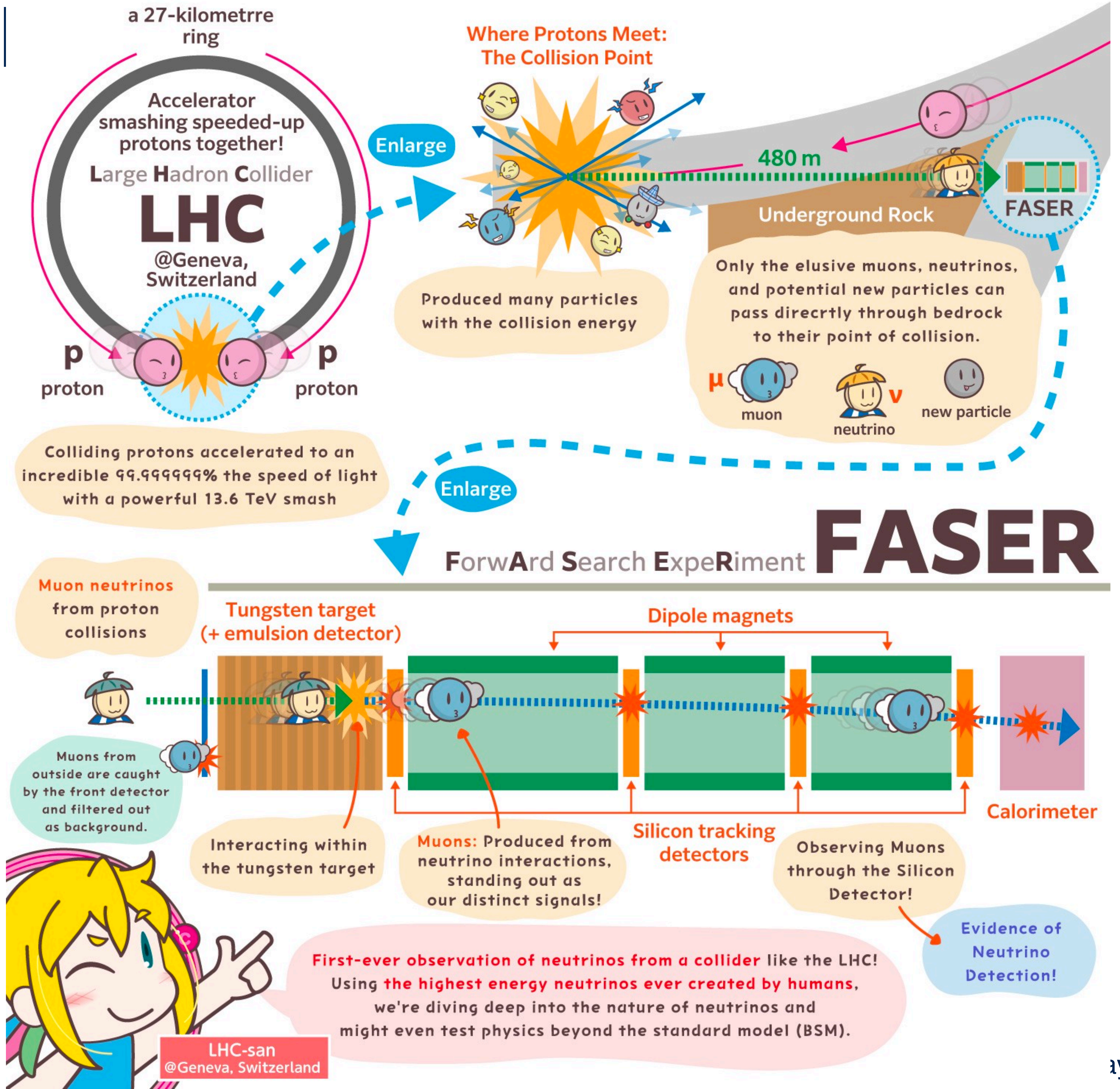
**Birmingham Seminar**

18/10/2023


**Josh McFayden** (University of Sussex)

@JoshMcFayden

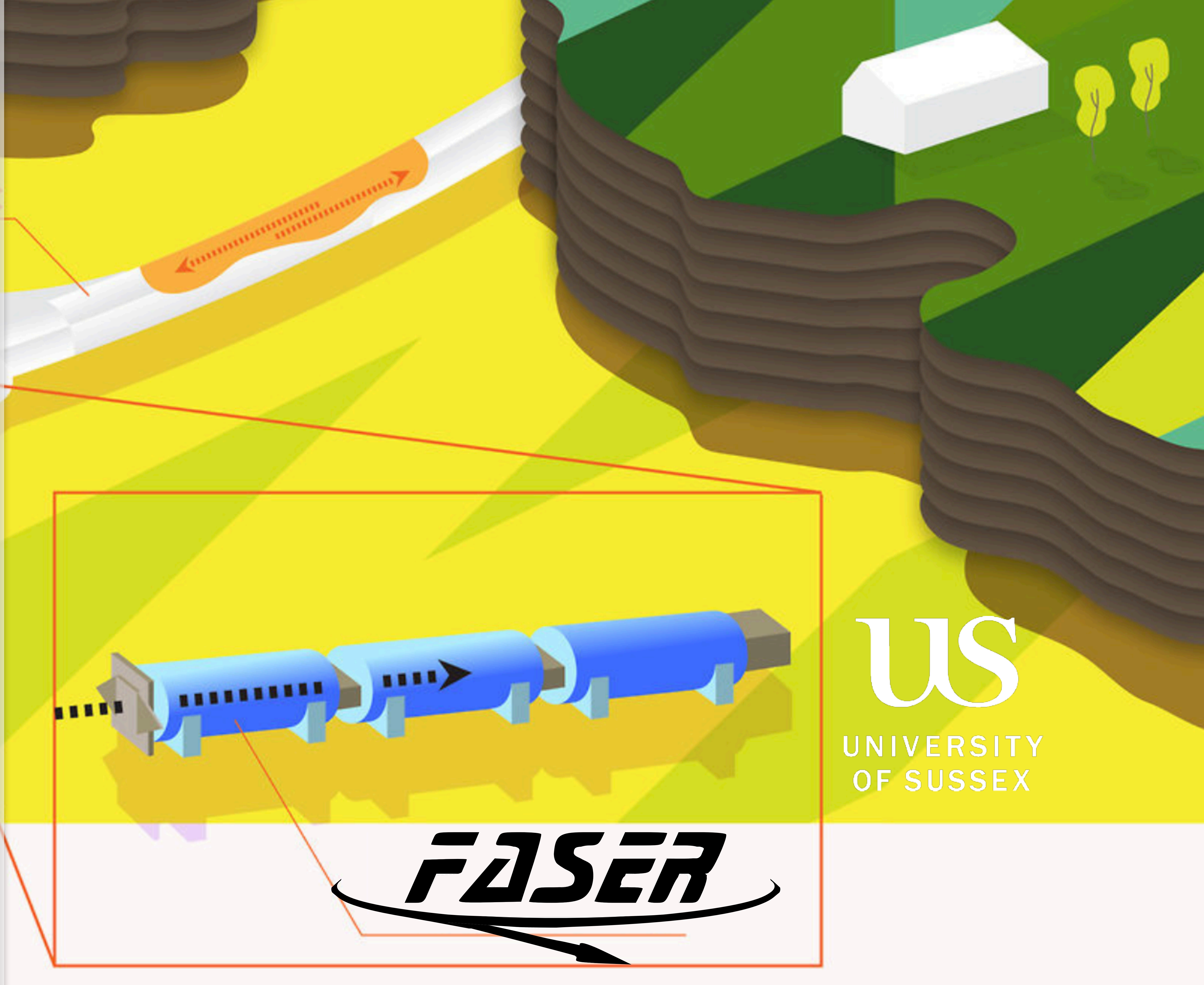

faser.web.cern.ch



a 27-kilometrre ring
Accelerator smashing speeded-up protons together!
Large Hadron Collider
LHC
@Geneva, Switzerland
p
proton
p
proton
Colliding protons accelerated to an incredible 99.999999% the speed of light with a powerful 13.6 TeV smash
Enlarge
Where Protons Meet: The Collision Point
Produced many particles with the collision energy
480 m
Underground Rock
FASER
Only the elusive muons, neutrinos, and potential new particles can pass direcrtly through bedrock to their point of collision.
μ
muon
ν
neutrino
new particle
Enlarge
ForwArd Search ExpeRiment FASER
Muon neutrinos from proton collisions
Tungsten target (+ emulsion detector)
Dipole magnets
Muons from outside are caught by the front detector and filtered out as background.
Interacting within the tungsten target
Muons: Produced from neutrino interactions, standing out as our distinct signals!
Silicon tracking detectors
Observing Muons through the Silicon Detector!
Calorimeter
Evidence of Neutrino Detection!
First-ever observation of neutrinos from a collider like the LHC! Using the highest energy neutrinos ever created by humans, we're diving deep into the nature of neutrinos and might even test physics beyond the standard model (BSM).
LHC-san
@Geneva, Switzerland

# Outline

- Background & Motivation
- FASER construction & operation
- First direct observation of collider neutrinos
- First observation of $\nu_e$ at collider
- First FASER Dark Photon search
- Looking ahead to HL-LHC




# Background and Motivation

# FASER Philosophy

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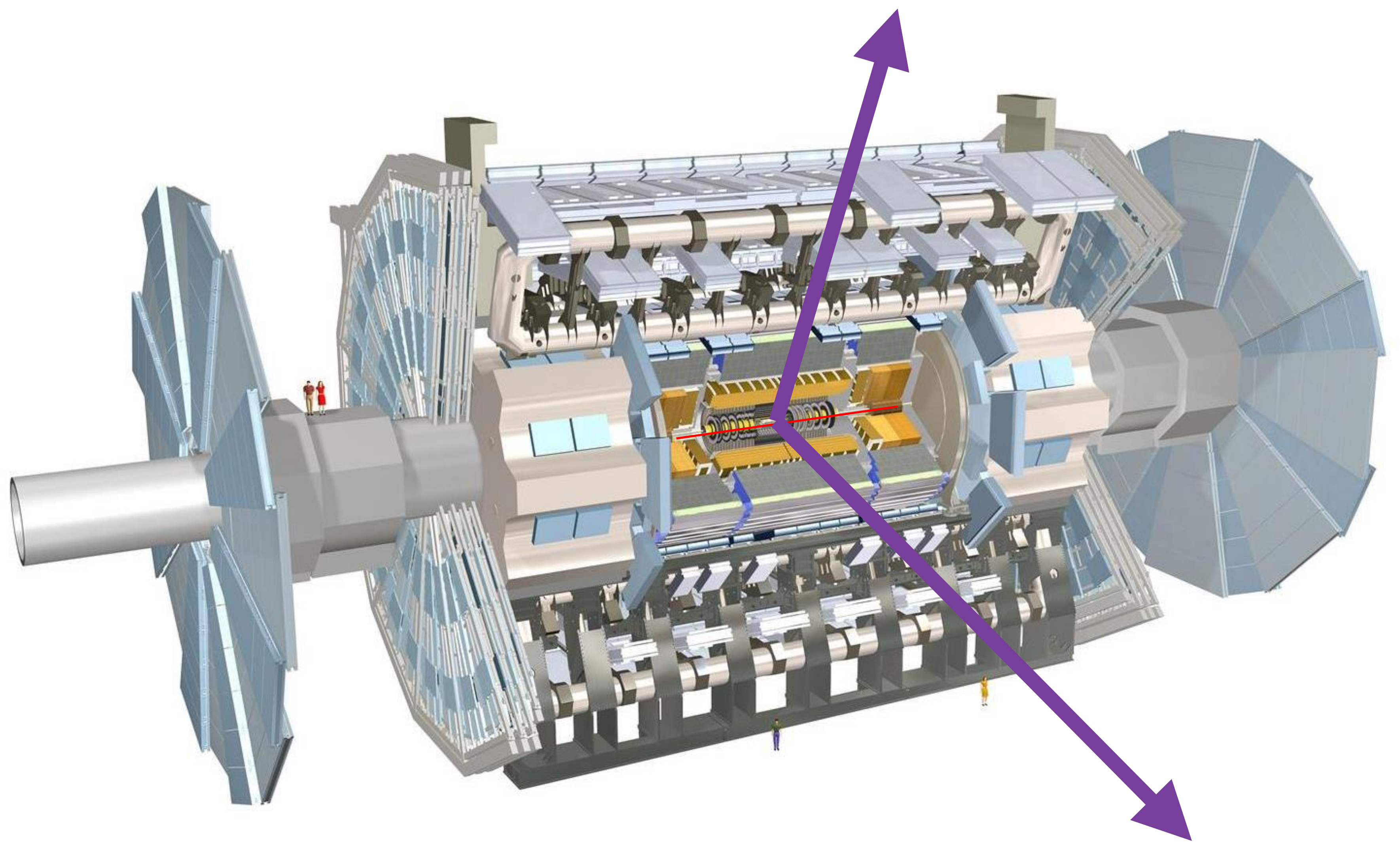
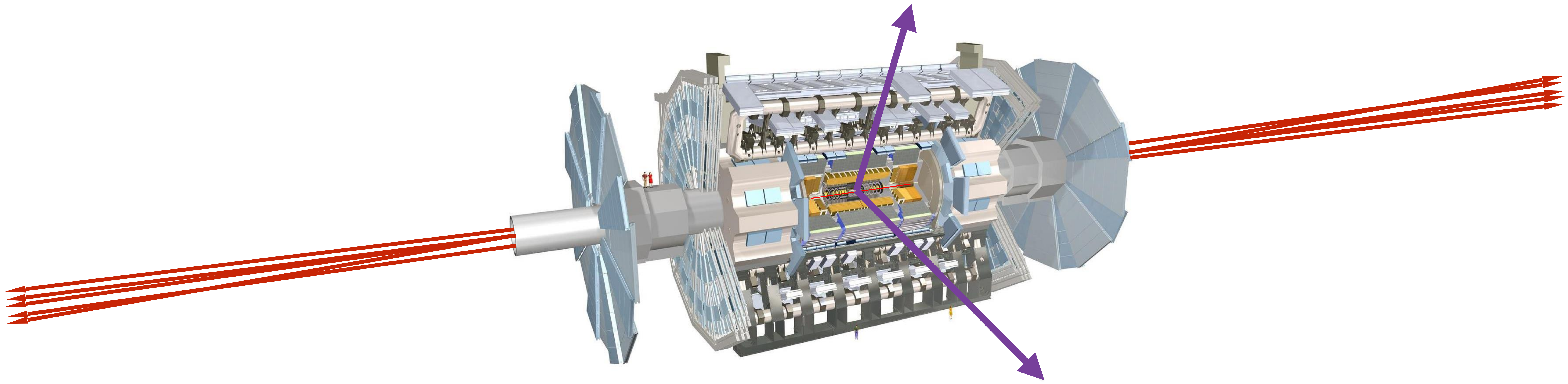
- LHC searches/experiments focus on **heavy, strongly interacting particles**
  - Produced ~isotropically and at relatively low rates, especially in high $p_T$ regions
    - $\sigma$ ~ fb to pb → In Run-3 N ~ $10^2 - 10^5$



# FASER Philosophy

- Could be misguided - Need to target light and weakly interacting particles
  - Lack of new physics in “traditional” searches.
  - Scenarios that e.g. satisfy Dark Matter relic density.
  - Exploit huge inelastic pp cross section → $10^{16}$ collisions in Run 3 → $10^{17}$ π, $10^{13}$ B
  - **Light meson**: low $p_T \sim \Lambda_{QCD}$ → particles are collimated:
    - $\theta \sim \Lambda_{QCD}/E$ ~mrad



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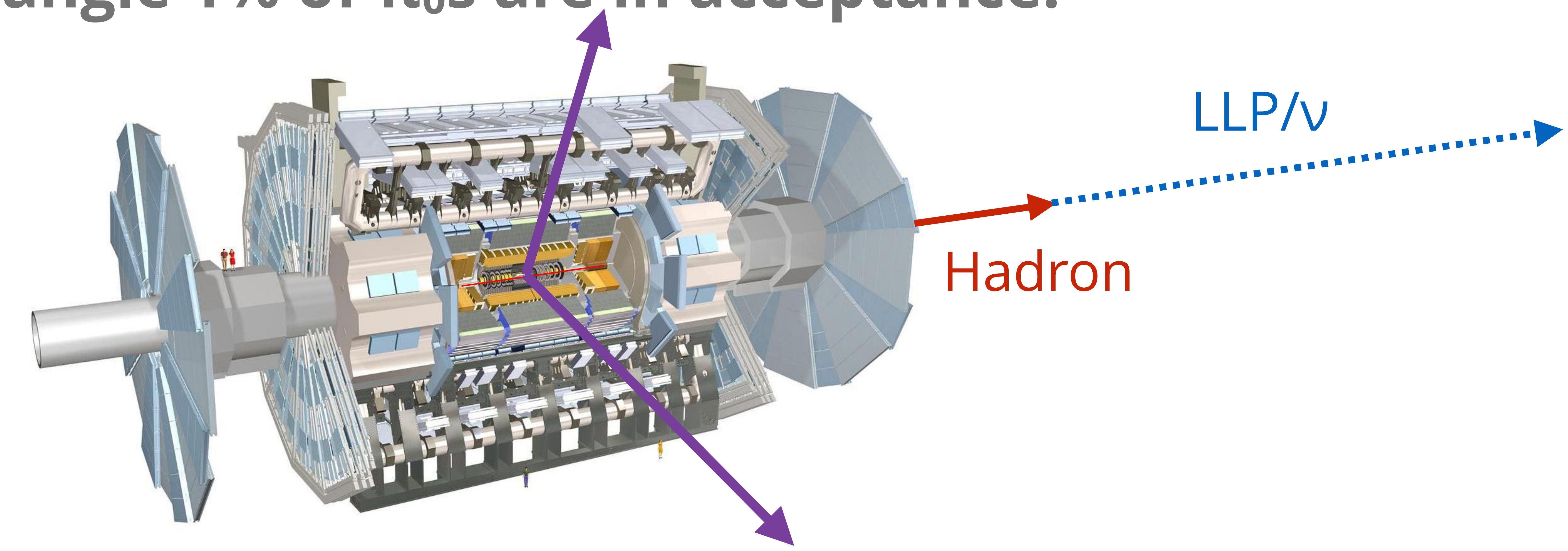
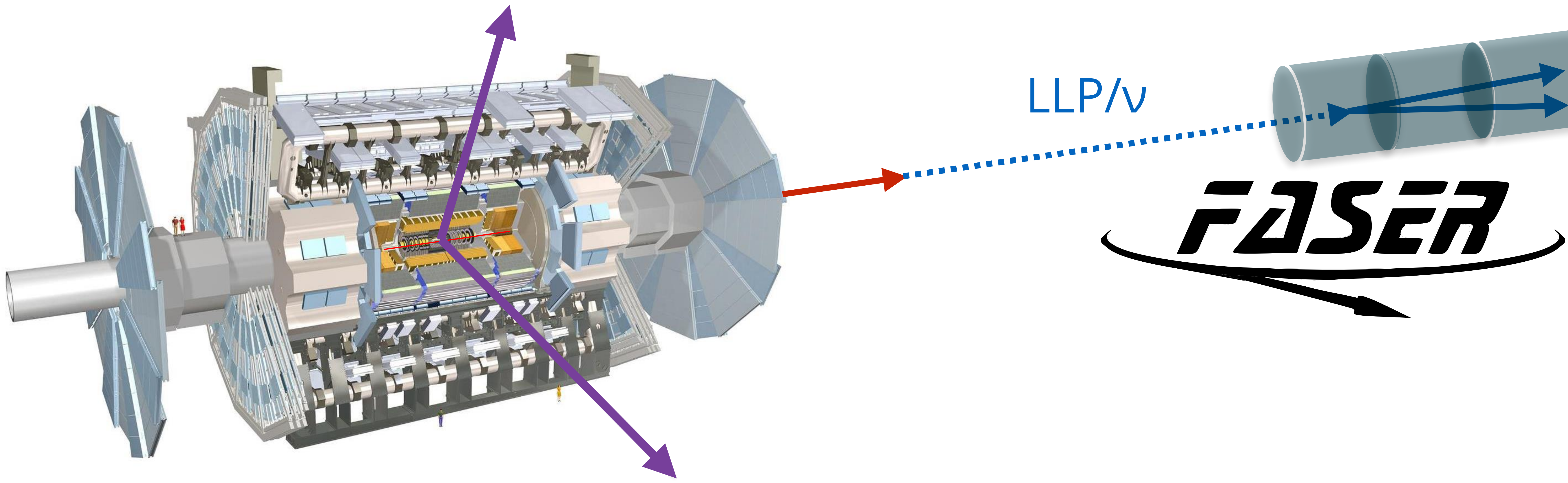
  - **From only $10^{-8}$ of solid angle 1% of $\pi_0$s are in acceptance.**



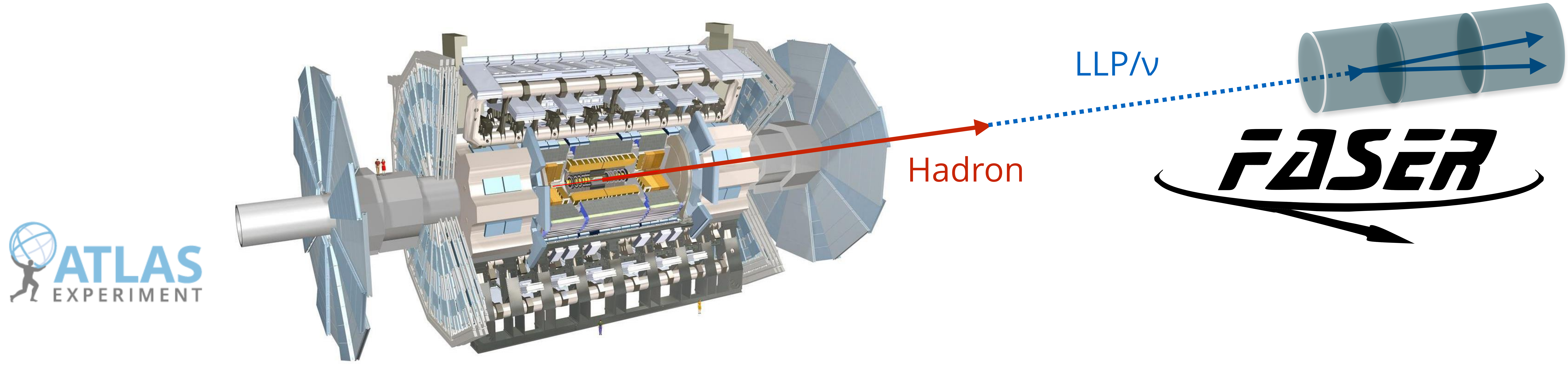

- **Gain sensitivity to long-lived particles with very weak couplings and neutrinos**

# FASER Philosophy

- **FASER** is a new experiment designed to cover this scenario at the LHC.



# FASER Overview




- Detector is 480m from ATLAS IP1
  - In line with beam collision axis. Transverse size of 10cm → mrad regime ($\eta$>9.1)

- **Neutrinos produced copiously in decays of forward hadrons**
- **Very weakly interacting LLPs could be produced in significant numbers**

# Concept and Location

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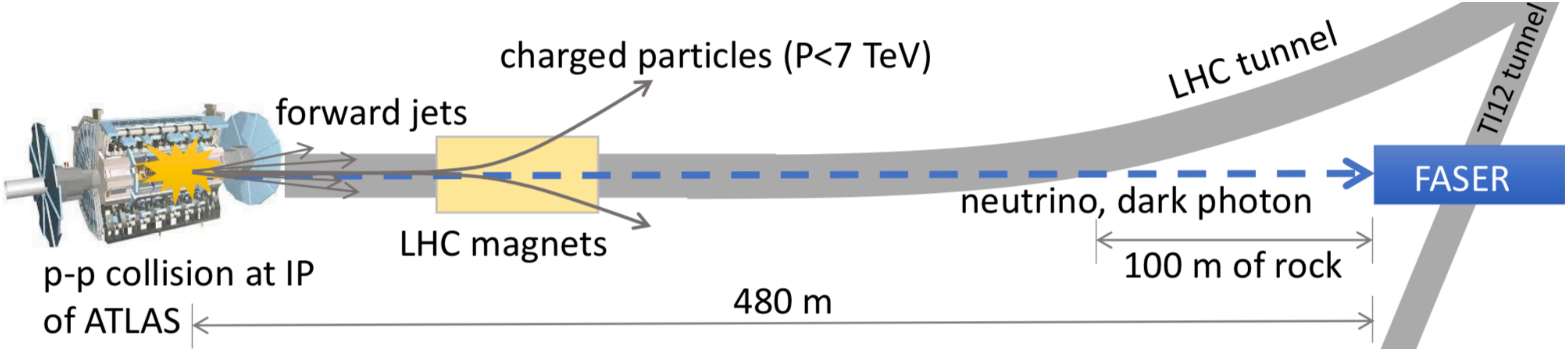
- First concept in 2017 (Feng, Galon, Kling, Trojanowski)
  - Approved by CERN in March 2019 (limited budget ~ $2M)
  - The TI12 service tunnel happens to be in just the right place for FASER:




- Old SPS → LEP tunnel
  - On line-of-sight (with some digging)
  - Shielded by ~100m rock/concrete
  - Low beam backgrounds - Charged particles bent by LHC magnets

# FASER Location

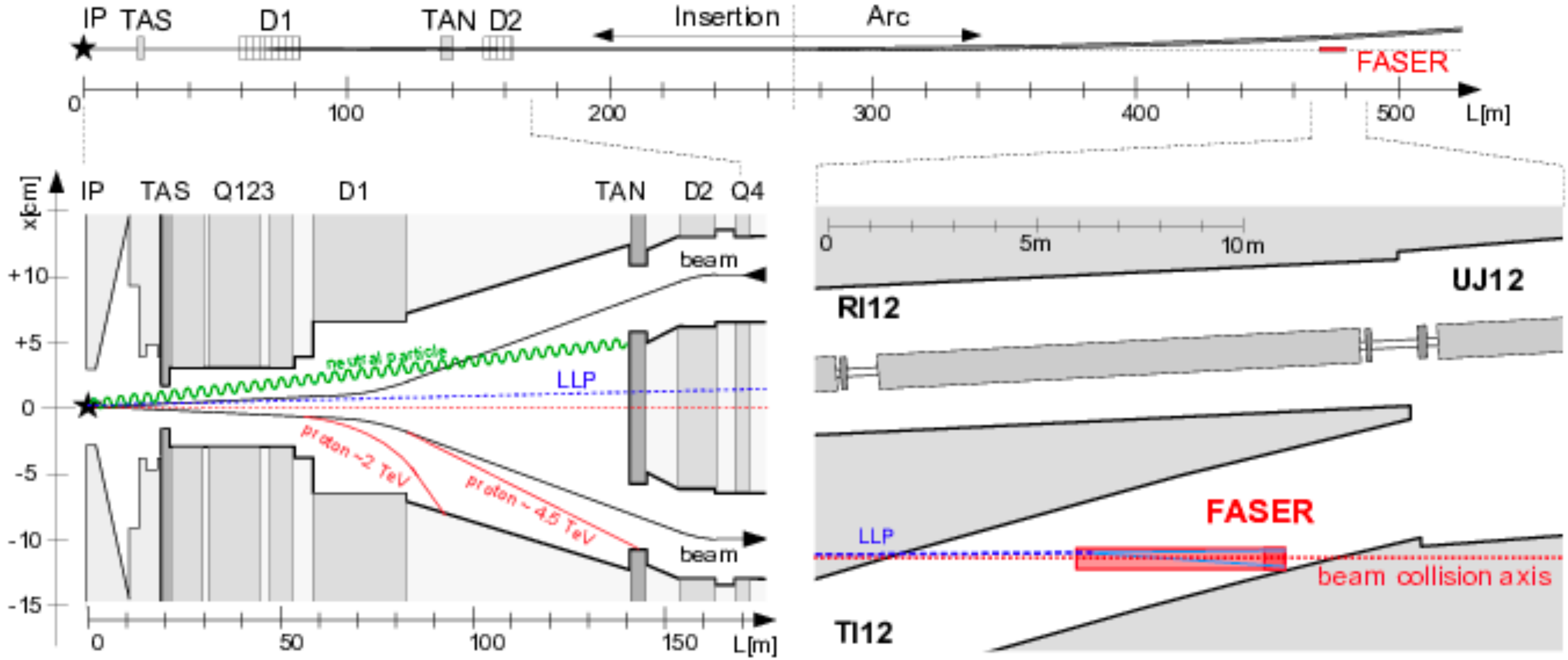
- Wider setting at the LHC

# FASER Location

- In relation to ATLAS at Point 1

# FASER Location

- A closer look at the LHC infrastructure on the line-of-sight:



# Making the case

FASER: ForwArd Search ExpeRiment at the LHC

Jonathan L. Feng,[1,*] Iftah Galon,[1,†] Felix Kling,[1,‡] and Sebastian Trojanowski[1,2,§]

[1]*Department of Physics and Astronomy, University of California, Irvine, CA 92697-4575 USA*

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

Abstract

New physics has traditionally been expected in the high-$p_T$ region at high-energy collider experiments. If new particles are light and weakly-coupled, however, this focus may be completely misguided: light particles are typically highly concentrated within a few mrad of the beam line, allowing sensitive searches with small detectors, and even extremely weakly-coupled particles may be produced in large numbers there. We propose a new experiment, **F**orw**A**rd **S**earch **E**xpe**R**iment, or FASER, which would be placed downstream of the ATLAS or CMS interaction point (IP) in the very forward region and operated concurrently there. Two representative on-axis locations are studied: a far location, 400 m from the IP and just off the beam tunnel, and a near location, just 150 m from the IP and right behind the TAN neutral particle absorber. For each location, we examine leading neutrino- and beam-induced backgrounds. As a concrete example of light,

**14th June 2017**

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**18th July 2018**


Submitted to the LHCC, 18 July 2018

CERN-LHCC-2018-030, LHCC-I-032
UCI-TR-2018-18, KYUSHU-RCAPP-2018-05


LETTER OF INTENT

FASER
FORWARD SEARCH EXPERIMENT AT THE LHC


Akitaka Ariga,[1] Tomoko Ariga,[1,2] Jamie Boyd,[3,*] David W. Casper,[4] Jonathan L. Feng,[4,†] Iftah Galon,[5] Shih-Chieh Hsu,[6] Felix Kling,[4] Hidetoshi Otono,[2] Brian Petersen,[3] Osamu Sato,[7] Aaron M. Soffa,[4] Jeffrey R. Swaney,[4] and Sebastian Trojanowski[8]

[1]Universität Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland
[2]Kyushu University, Nishi-ku, 819-0395 Fukuoka, Japan
[3]CERN, CH-1211 Geneva 23, Switzerland
[4]Department of Physics and Astronomy, University of California, Irvine, CA 92697-4575, USA
[5]New High Energy Theory Center, Rutgers, The State University of New Jersey, Piscataway, New Jersey 08854-8019, USA
[6]University of Washington, PO Box 351560, Seattle, WA 98195-1560, USA
[7]Nagoya University, Furo-cho, Chikusa-ku, Nagoya-shi 464-8602, Japan
[8]National Centre for Nuclear Research, Hoża 69, 00-681 Warsaw, Poland

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TECHNICAL PROPOSAL

FASER

FORWARD SEARCH EXPERIMENT AT THE LHC


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[2]Kyushu University, Nishi-ku, 819-0395 Fukuoka, Japan
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**7th Nov 2018**

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**14th June 2017**

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[arXiv:1708.09389]

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[arXiv:1811.10243]

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[1]Universität Bern, Sidlerstrasse 5,
[2]Kyushu University, Nishi-ku,
[3]CERN, CH-1211 Gene


[arXiv:1812.09139]

**29th Nov 2018**


UCI-TR-2018-19, KYUSHU-RCAPP-2018-06


FASER

FASER's Physics Reach for Long-Lived Particles


FASER Collaboration

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[3]CERN, CH-1211 Geneva 23, Switzerland
[4]Département de Physique Nucléaire et Corpusculaire, University of Geneva, CH-1211 Geneva 4, Switzerland
[5]Department of Physics and Astronomy,


[arXiv:1811.12522]

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**Approved by CERN in March 2019**

~18 months from theory paper to start of construction!

# Making the case

23rd July 2022

**Ready to take data for start of LHC Run3**

Detector Paper last year



**The FASER Detector**

**FASER Collaboration**

Henso Abreu[1], Elham Amin Mansour[2], Claire Antel[2], Akitaka Ariga[3,4], Tomoko Ariga[5], Florian Bernlochner[6], Tobias Boeckh[6], Jamie Boyd[7], Lydia Brenner[8], Franck Cadoux[2], David W. Casper[9], Charlotte Cavanagh[10], Xin Chen[11], Andrea Coccaro[12], Olivier Crespo-Lopez[7], Stéphane Débieux[2], Monica D'Onofrio[10], Liam Dougherty[7], Candan Dozen[13], Abdallah Ezzat[14], Yannick Favre[2], Deion Fellers[15], Jonathan L. Feng[9], Didier Ferrere[2], Edward Karl Galantay[2], Jonathan Gall[16], Enrico Gamberini[7], Stephen Gibson[17], Sergio Gonzalez-Sevilla[2], Carl Gwilliam[10], Daiki Hayakawa[4], Shih-Chieh Hsu[18], Zhen Hu[11], Giuseppe Iacobucci[2], Tomohiro Inada[11], Sune Jakobsen[7], Eliott Johnson[2], Enrique Kajomovitz[1], Hiroaki Kawahara[5], Felix Kling[19], Umut Kose[7], Rafaella Kotitsa[7], Jesse Krusse[20,21], Susanne Kuehn[7], Helena Lefebvre[17], Lorne Levinson[22], Ke Li[18], Jinfeng Liu[11], Chiara Magliocca[2], Fulvio Martinelli[2], Josh McFayden[23], Sam Meehan[7,24], Matteo Milanesio[2], Manato Miura[4], Dimitar Mladenov[7], Théo Moretti[2], Magdalena Munker[2],

**Approved by CERN in March 2019**

~18 months from theory paper to start of construction!

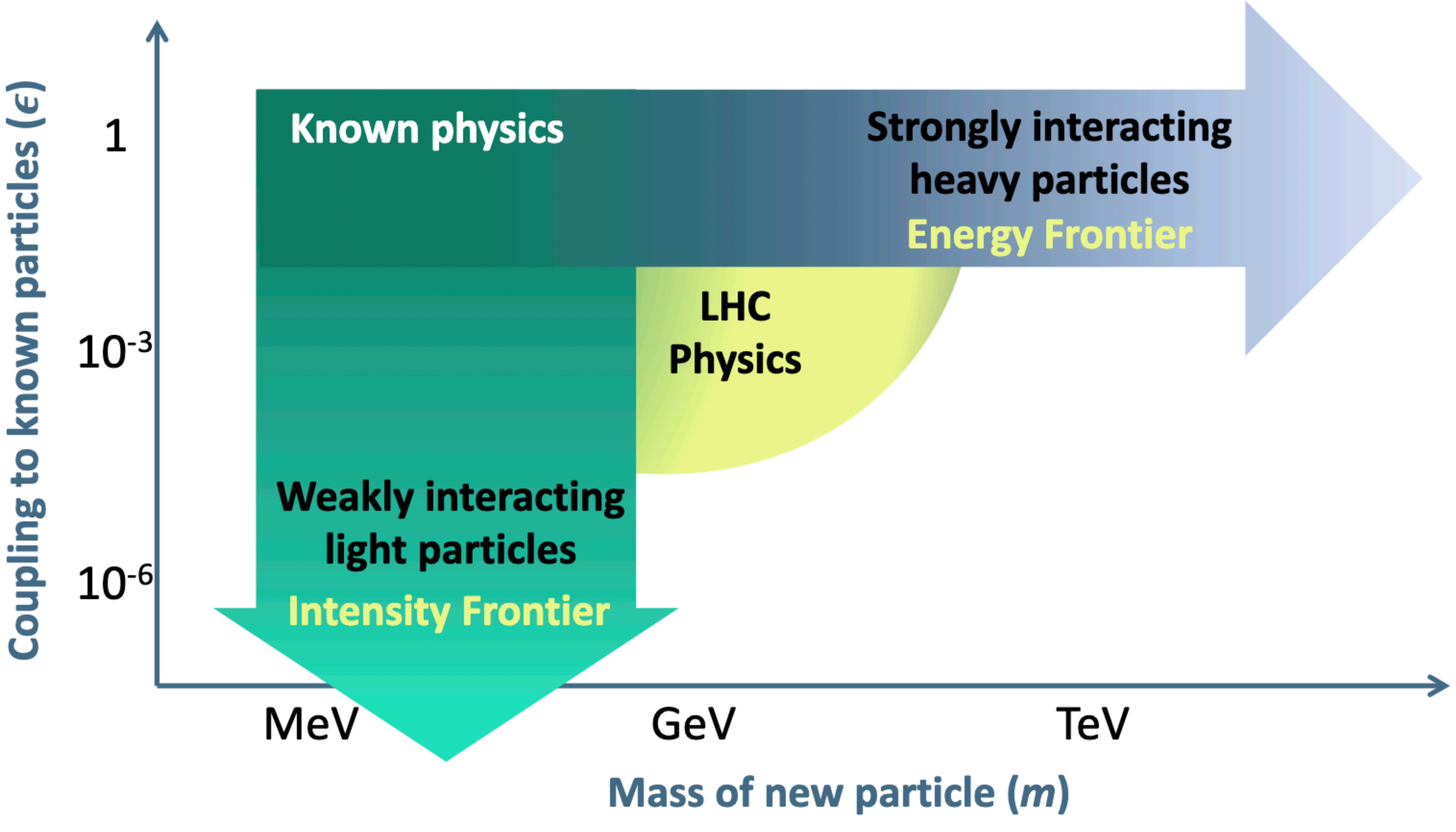
# F-A-S-E-R

- FASER: **F**orw**A**rd **S**earch **E**xpe**R**iment
  - “The acronym recalls another marvelous instrument that harnessed highly collimated particles and was used to explore strange new worlds.”

# Physics Motivation

- The **LHC experiments** are producing incredible results, searching in previously unexplored phase spaces and performing increasingly precise measurements.

- But the lack of any observation of BSM physics motivates **looking elsewhere** too.



# Physics Motivation

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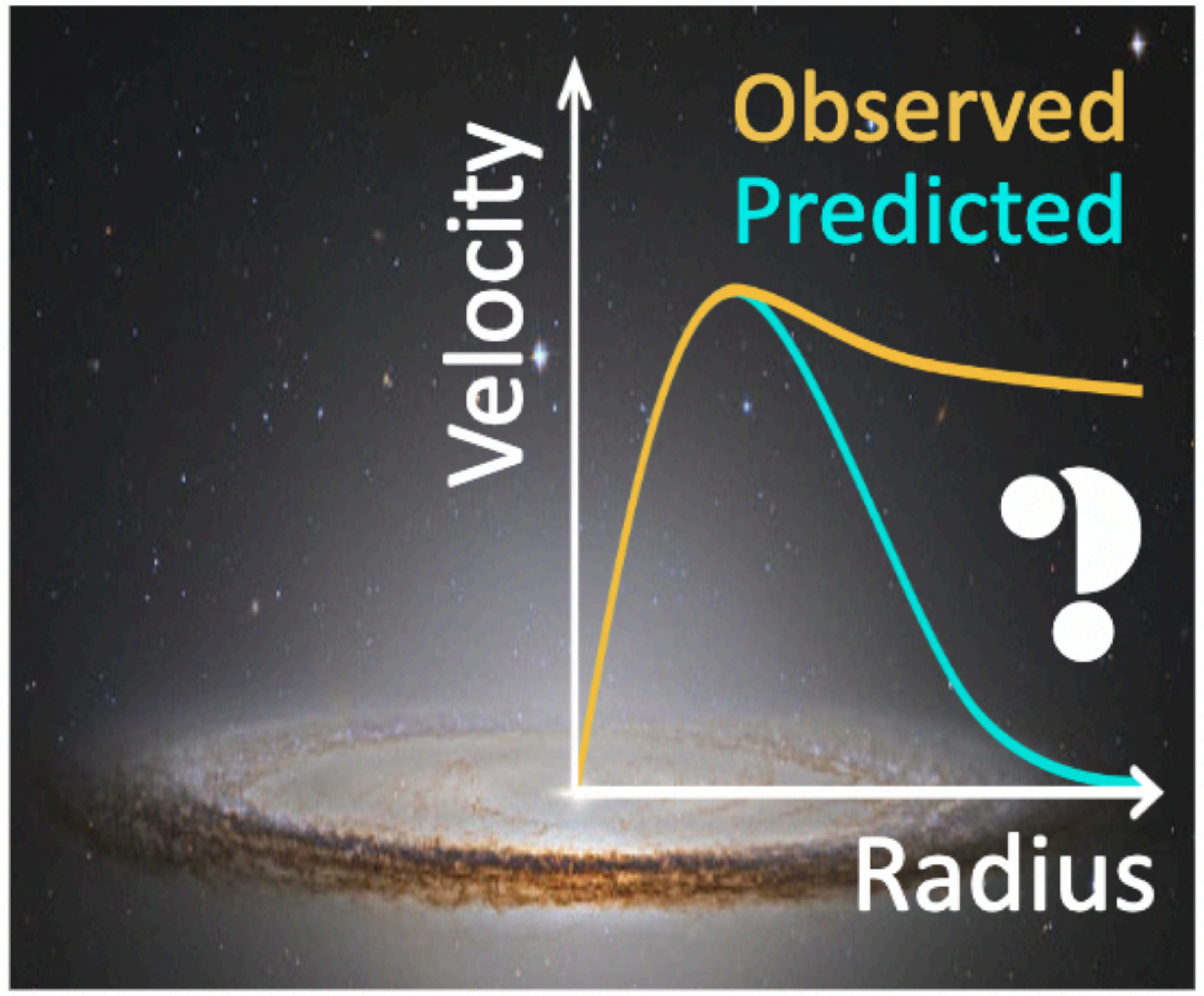
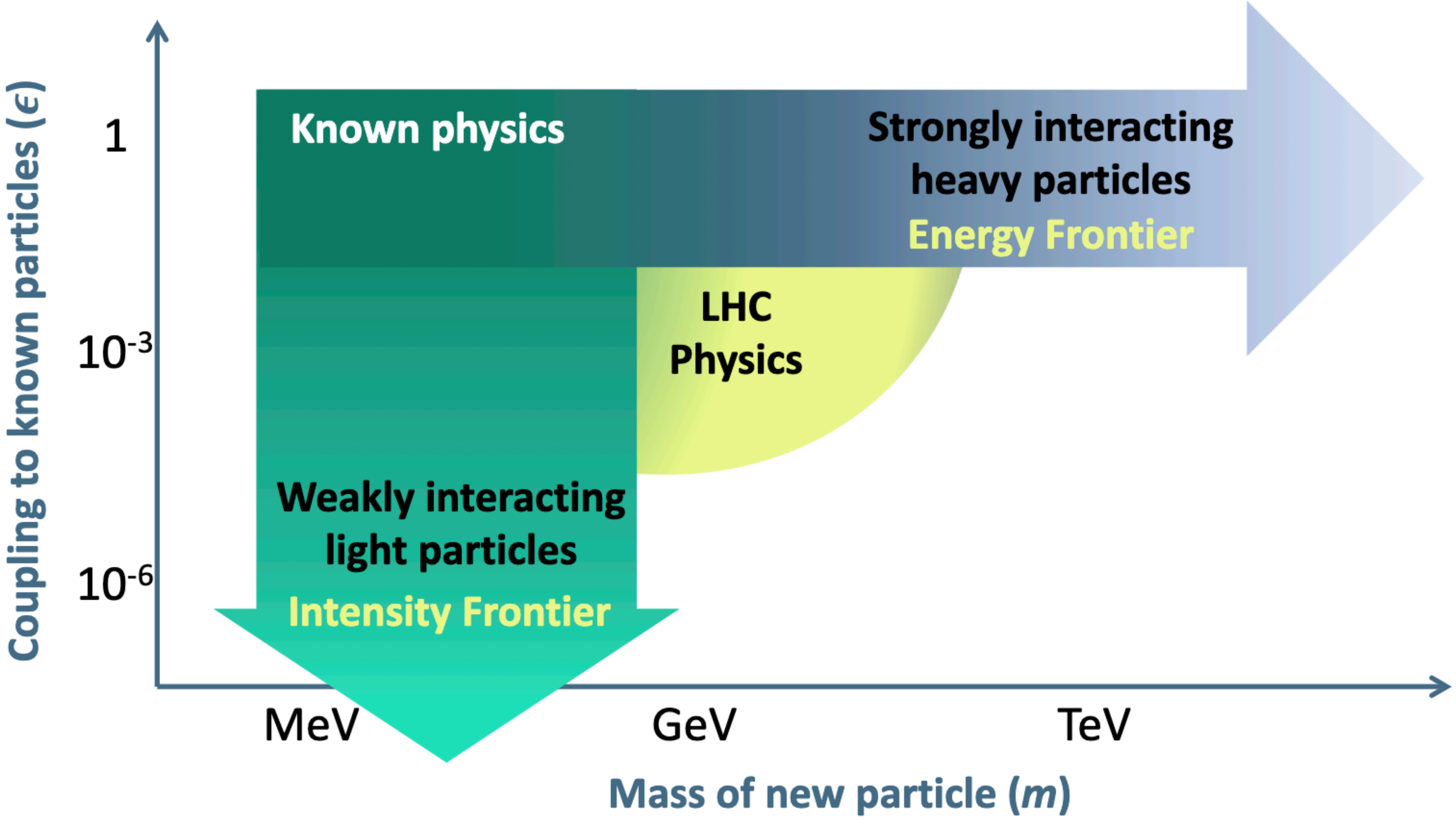
- The indirect observations of **dark matter** offers one of the most tangible indictions of BSM physics and strongly motivates closer attention.

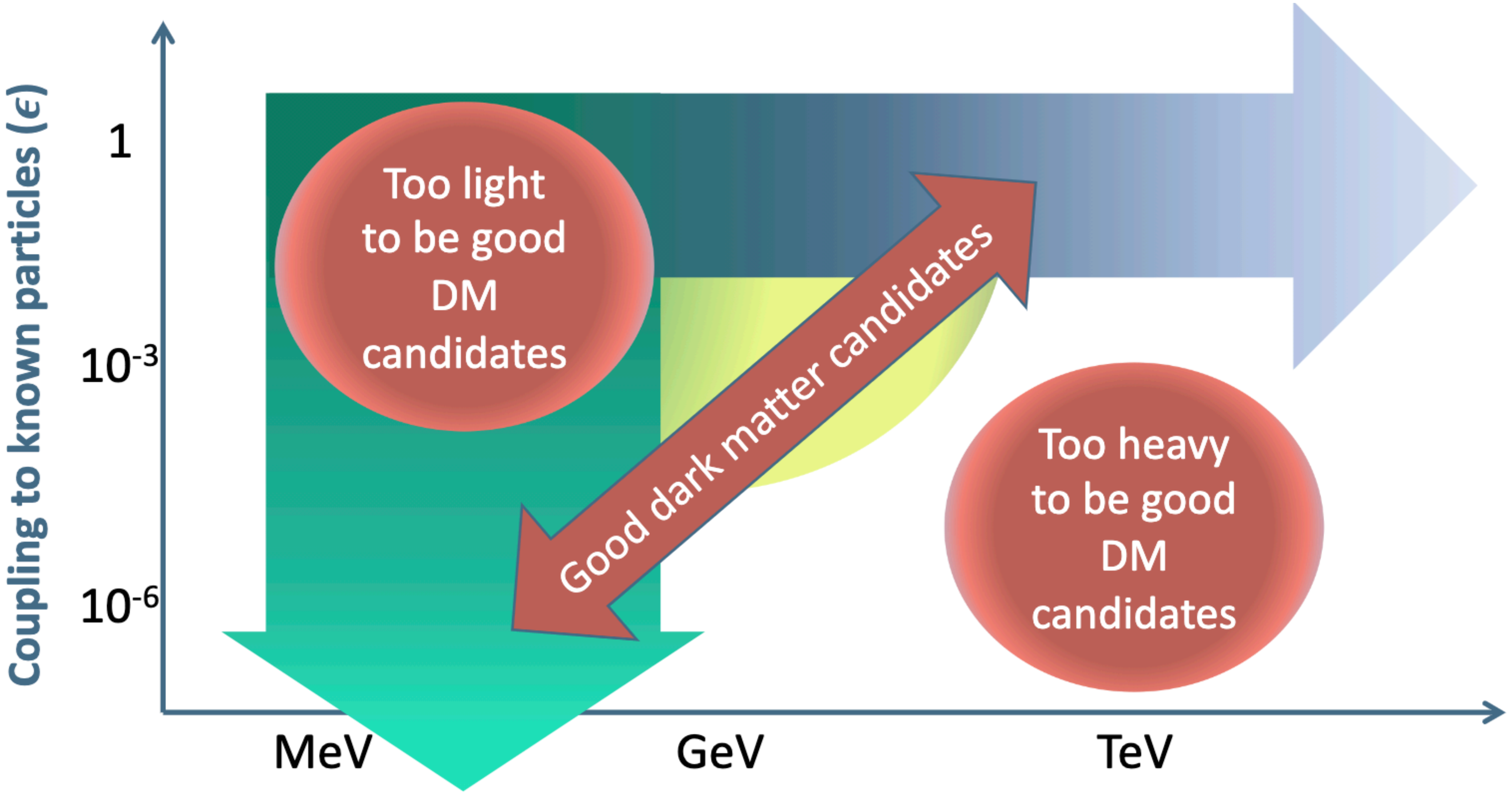


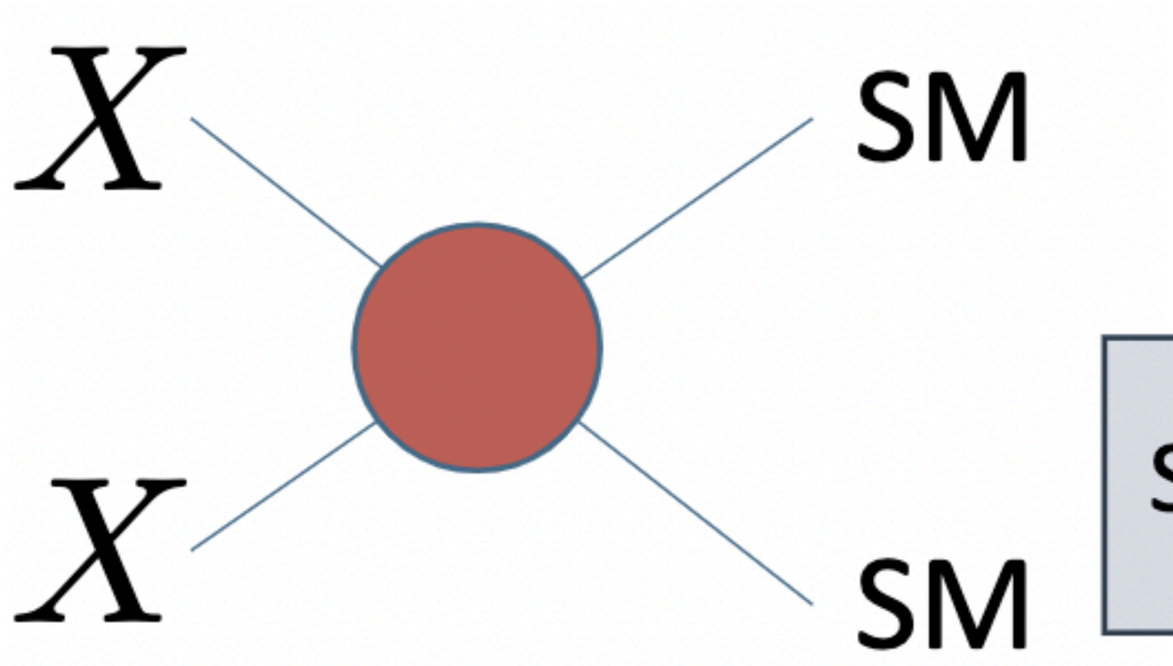



# Physics Motivation

- The indirect observations of **dark matter** offers one of the most tangible indictions of BSM physics and strongly motivates closer attention.

- Main region of interest is for new particles that satisfy DM relic density requirements.



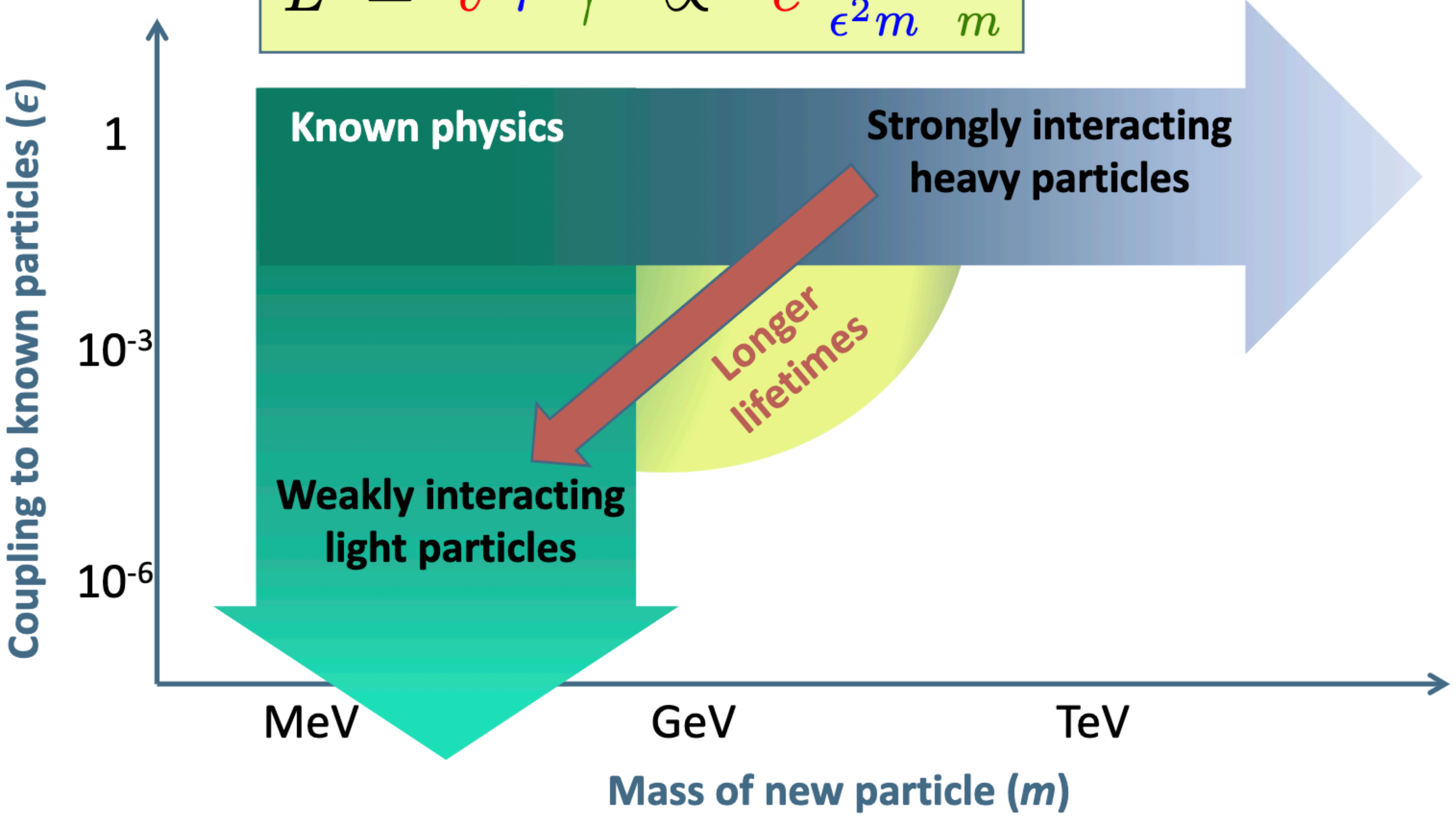

Surviving DM density: $\Omega_X \propto \frac{m_X^2}{\epsilon_X^4}$

# Physics Motivation

- One of the defining characteristics of weakly interacting light particles is their **long lifetime**.
- Distinct signatures
- Opportunity for exploration!

Distance travelled by particles:

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



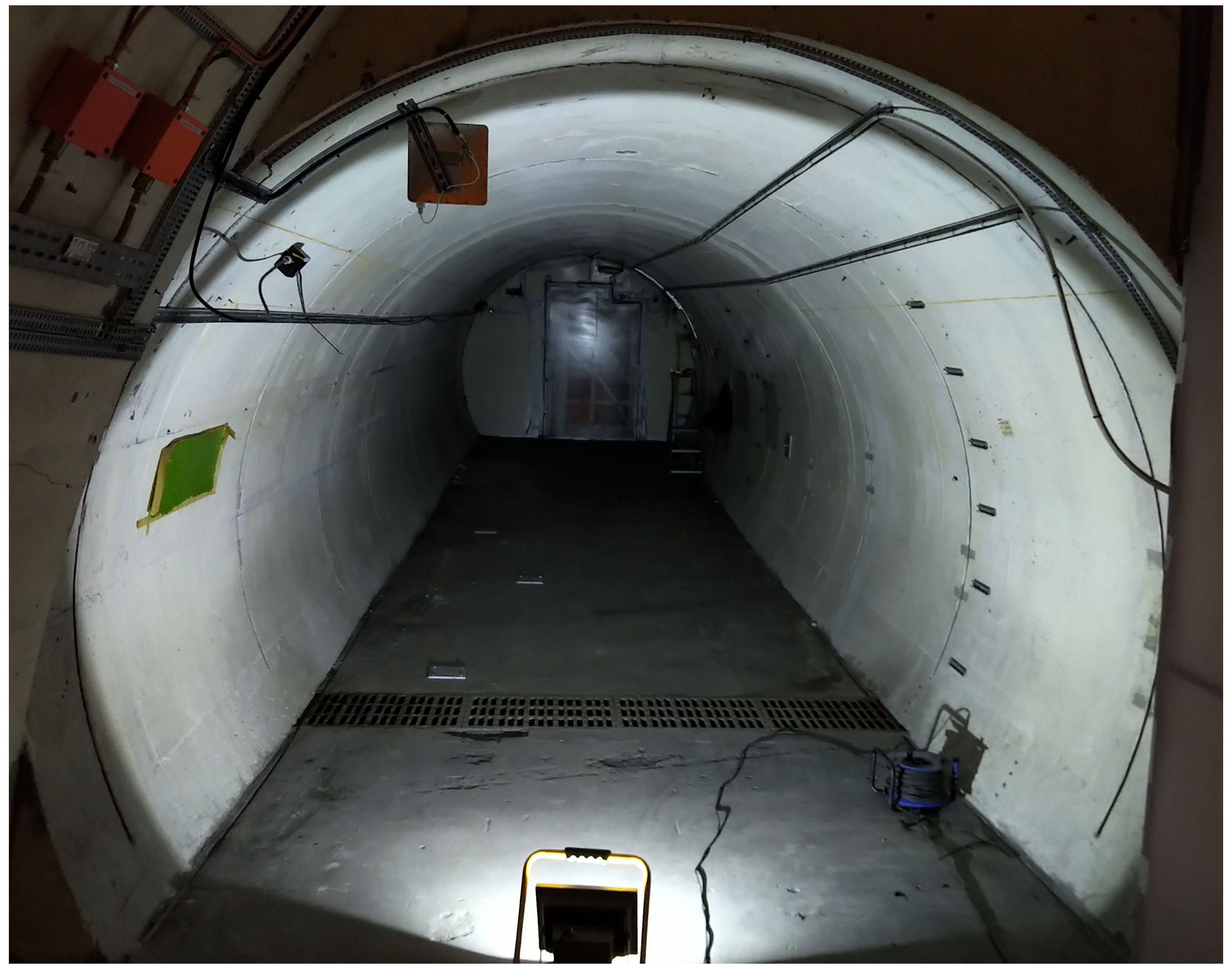

# Detector Construction and Operation

# Philosophy

- Given the very tight timeline between experiment approval and installation & the limited budget we have focused on:
  - 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
- Rough dimensions
  - 10 cm radius, 1.5 m decay volume, ~7 m total length
- Many challenges of the large LHC experiments not there for FASER:
  - trigger rate ~500Hz (mostly single muon events)
  - low radiation
  - low occupancy / event size

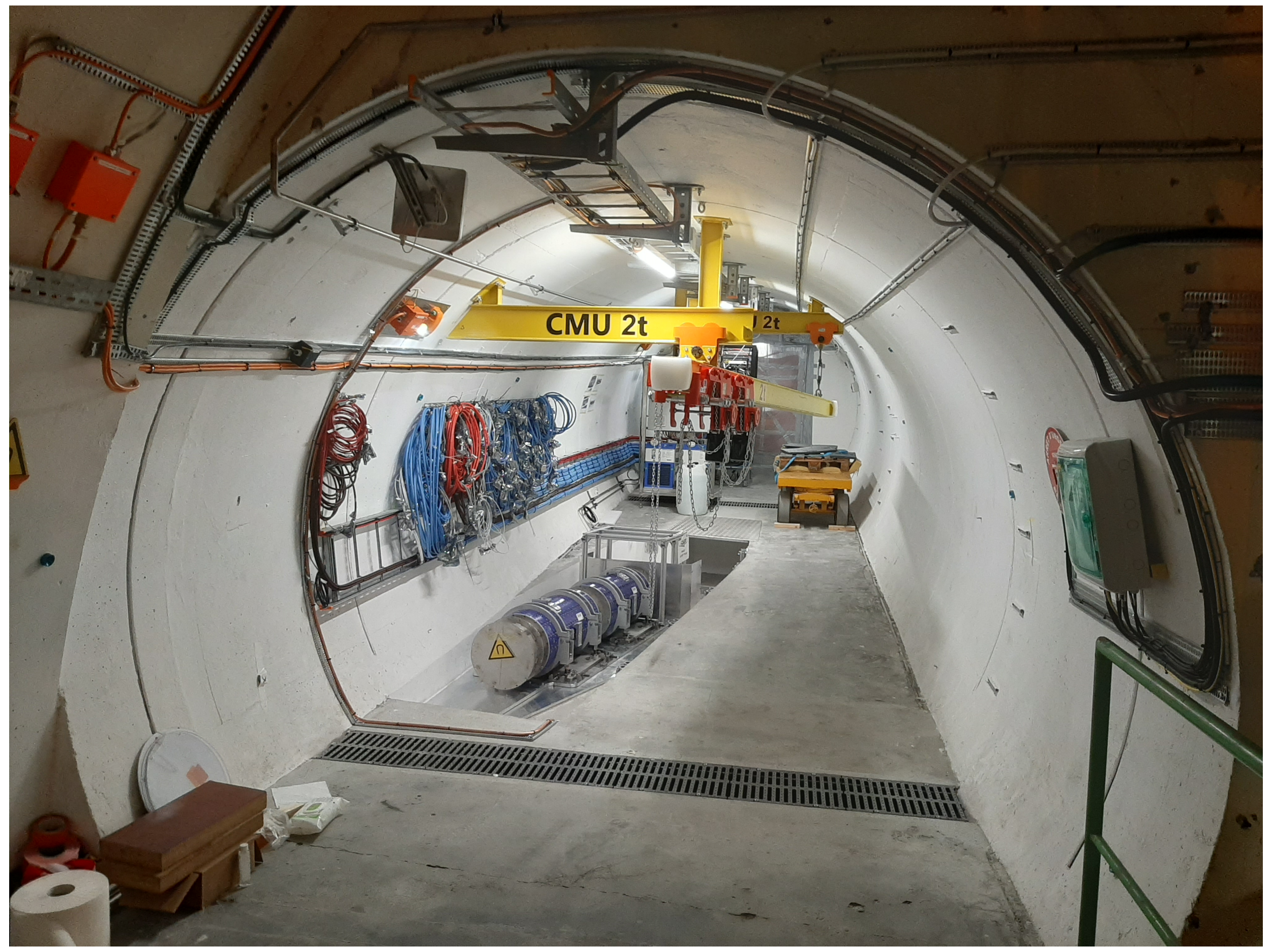
# Installation

8/2018



8/2019

4/2020




11/2020


3/2021

# Installation

8/201

11/2020

3/2021

# Detector design

- Small inexpensive design [2207.11427]

# Installation

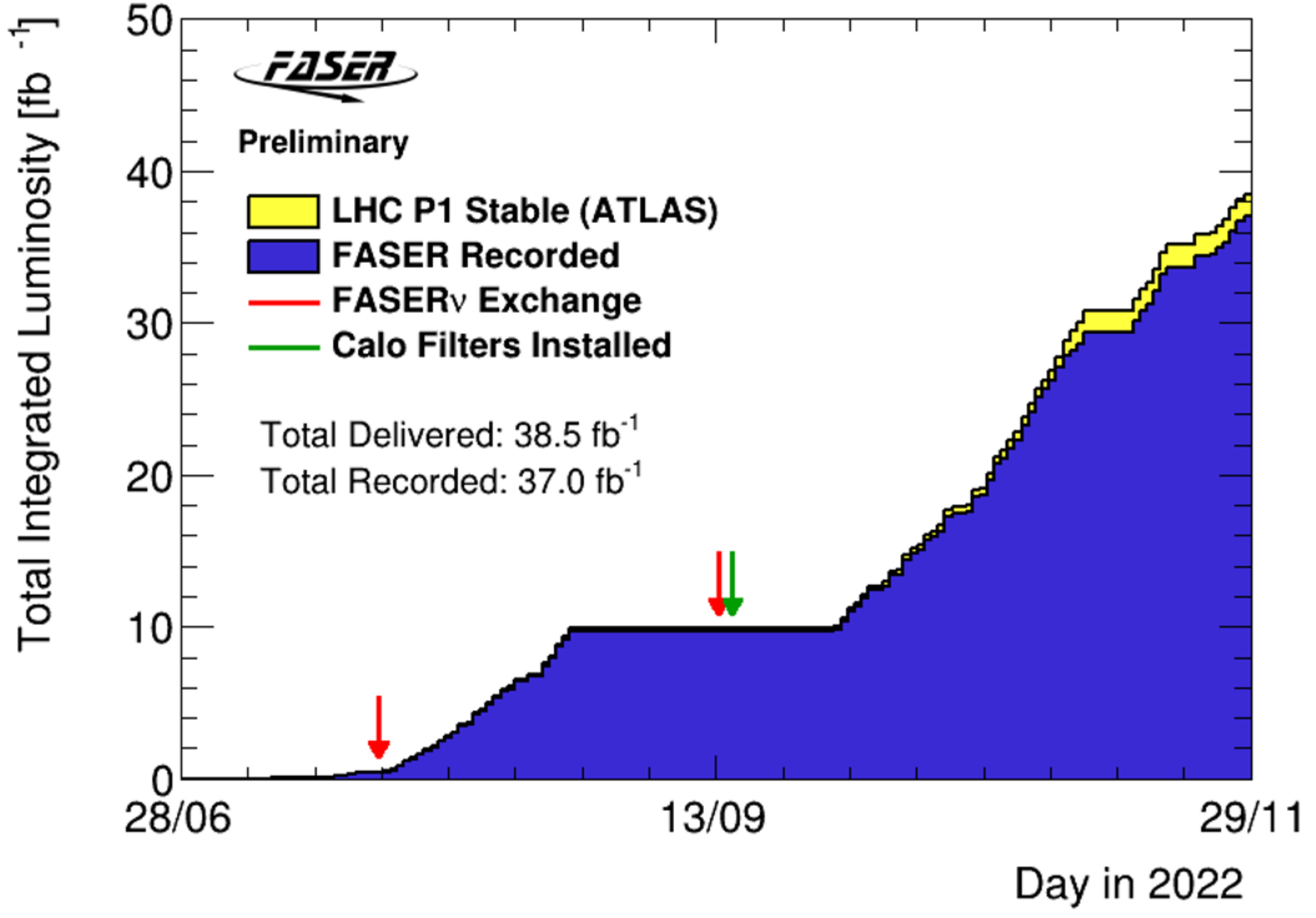

CMU 2t


CMU 2t
ATLAS


LHC collision
ATLAS
Long-lived particle
Decay
FASER

# Operations

- Successfully operated throughout 2022
  - Continuous data taking
  - Largely automated
  - Up to 1.3 kHz
- Recorded 96.1% of delivered lumi.
  - DAQ dead-time of 1.3%
  - couple of DAQ crashes
- Emulsion detector exchanged twice
  - Needed to manage occupancy
  - First box only partially filled
- Calorimeter gain optimised for:
  - Low E (<300 GeV) before 2nd exchange
  - High E (up to 3 TeV) after this exchange




**Analyses presented use 27.0 $fb^{-1}$ or 35.4 $fb^{-1}$**

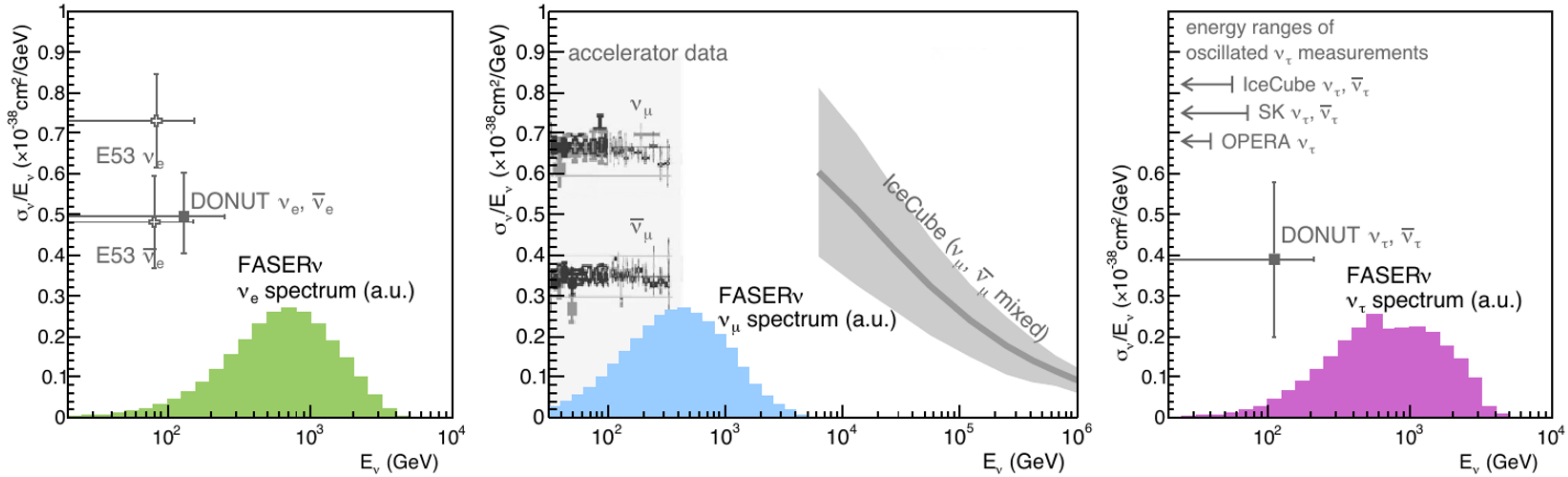
# Operations

- All detector components performing excellently
  - More than 350M single-muon events recorded
  - Example: muon leaving track passing through full detector - consistent with MIP


# First observation of collider neutrinos

# Neutrino analysis

- Neutrinos produced copiously in decays of forward hadrons
  - Highly energetic (TeV scale) → high interaction cross section
- Extends FASER physics program into SM measurements
  - Targets measurement of highest energy human-made neutrinos
  - Energy range complementary to existing neutrino experiments



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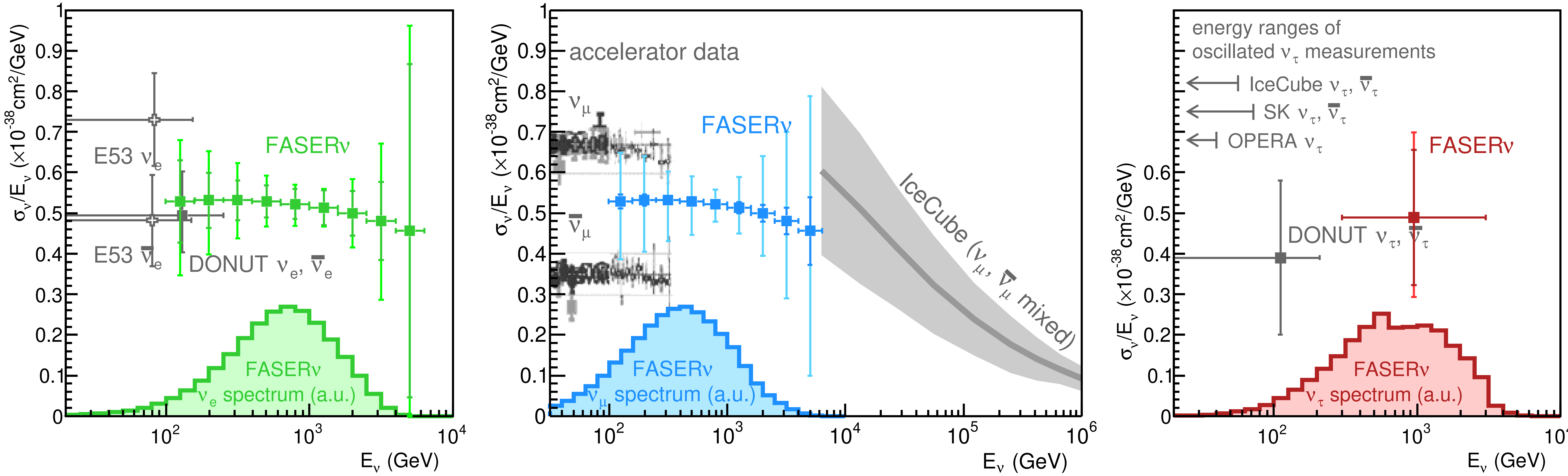

# Neutrino analysis

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| For 35 $fb^{-1}$ | $\nu_e$ | $\nu_\mu$ | $\nu_\tau$ |
|---|---|---|---|
| **Main source** | **Kaons** | **Pions** | **Charm** |
| # traversing FASERν | ~$10^{10}$ | ~$10^{11}$ | ~$10^{8}$ |
| # interacting in FASERν | ≈200 | ≈1200 | ≈4 |

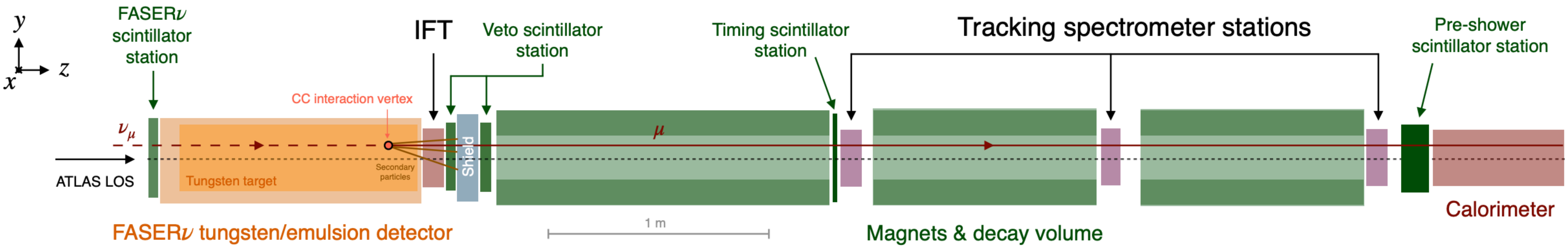
[PRD 104, 113008]

- Study at colliders originally proposed by Rújula and Rückl in 1984!

# Neutrino analysis | Selection

[2303.14185]

- 1. Collision event with good data quality
- 2. No signal (<40 pc) in 2 front vetos
- 3. Signal (>40 pC) in other 3 vetos
- 4. Timing and preshower consistent with ≥1 MIP
- 5. Exactly 1 good fiducial (r < 95 mm) track
  - p > 100 GeV and θ < 25 mrad
  - Extrapolating to r < 120 mm in front veto



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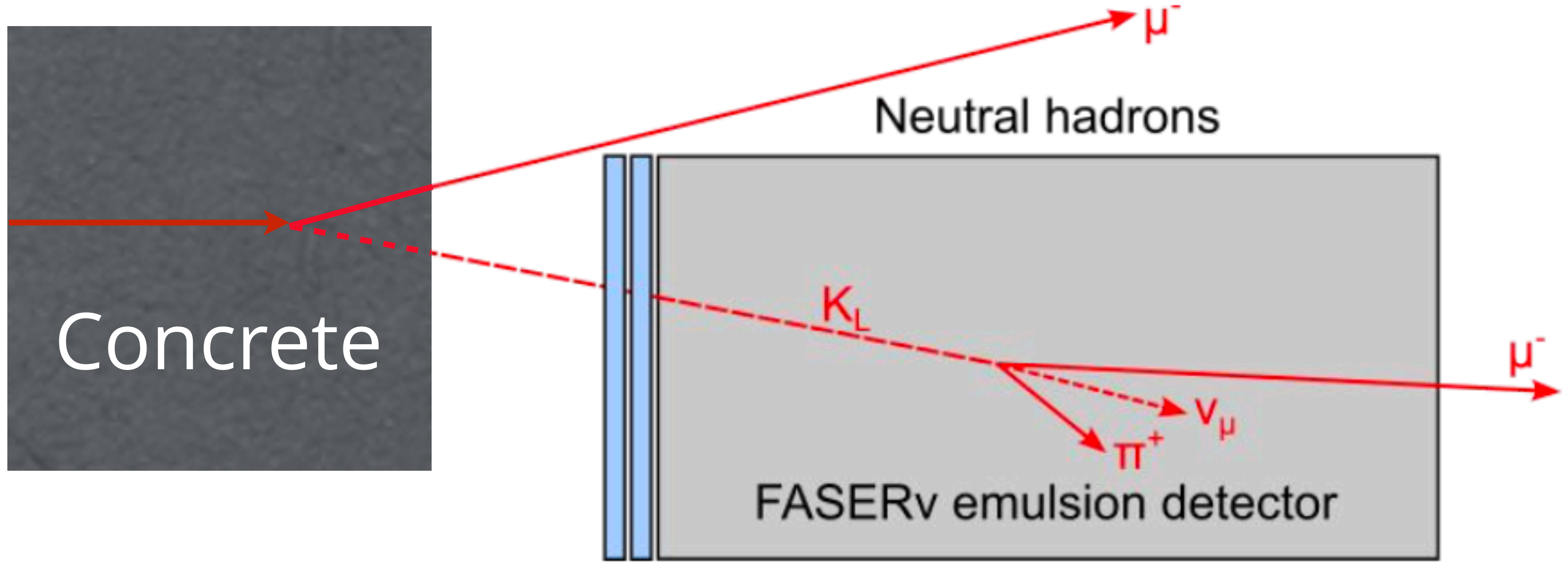
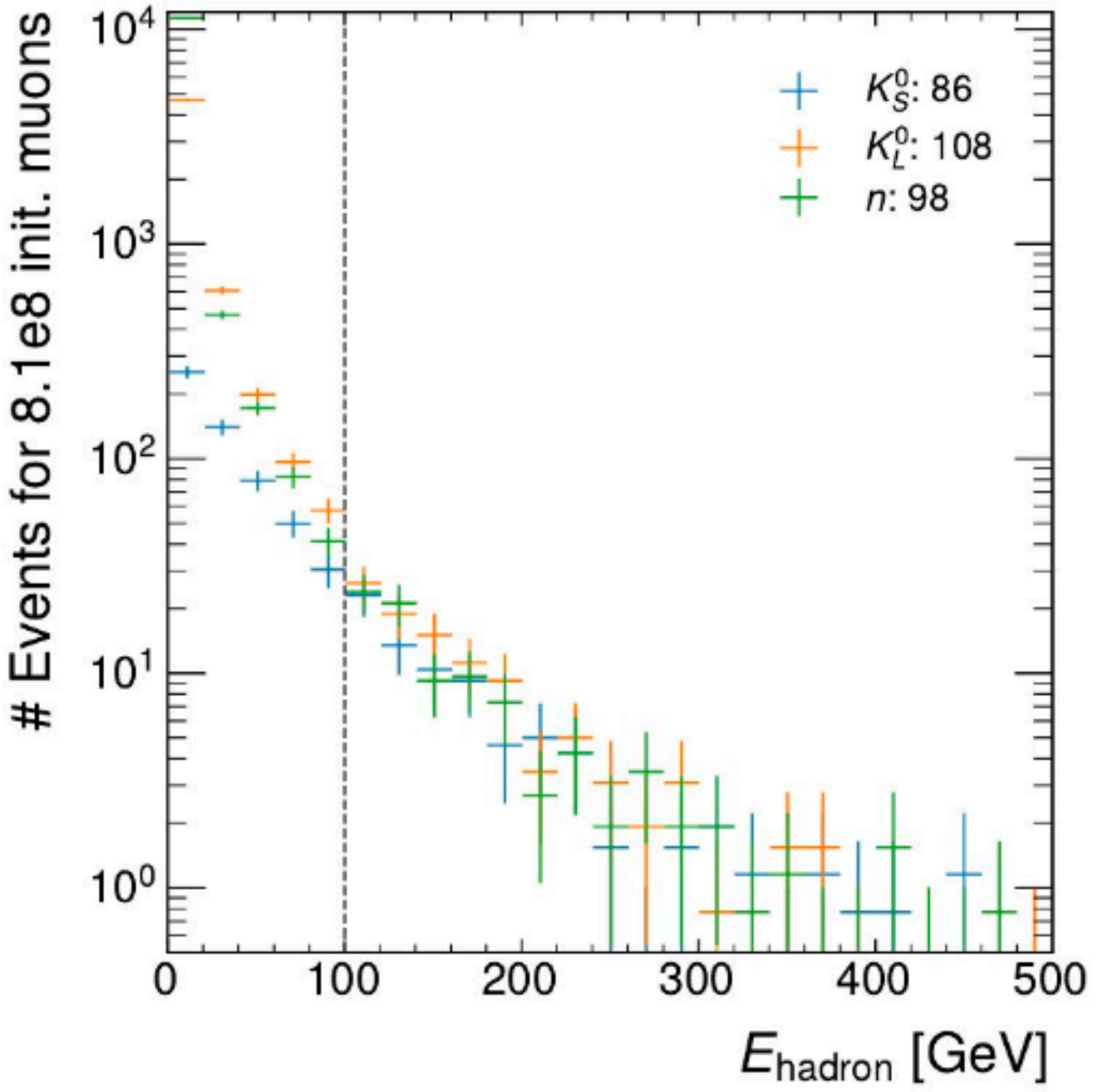
# Neutrino analysis | Backgrounds

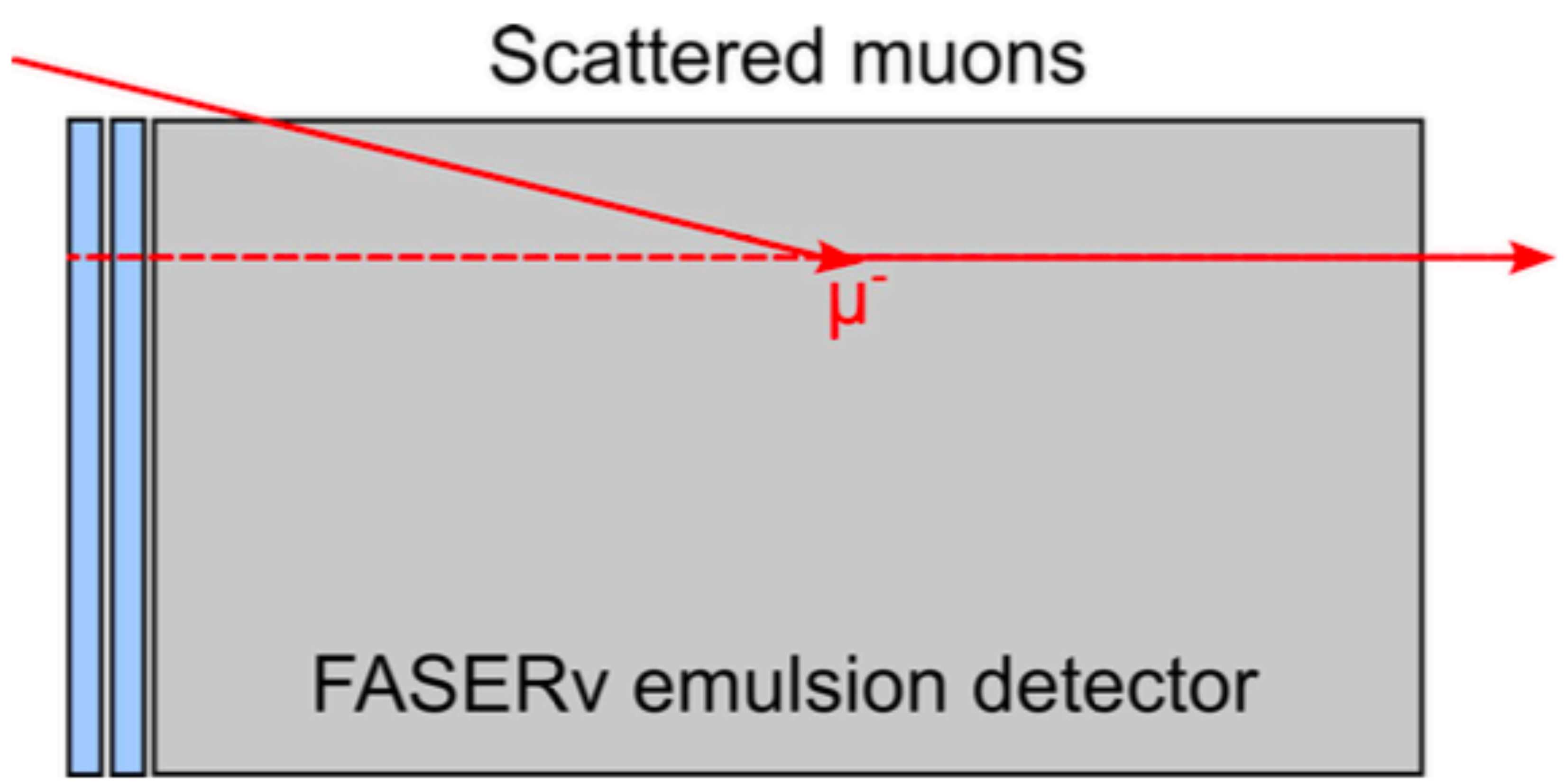
[2303.14185]

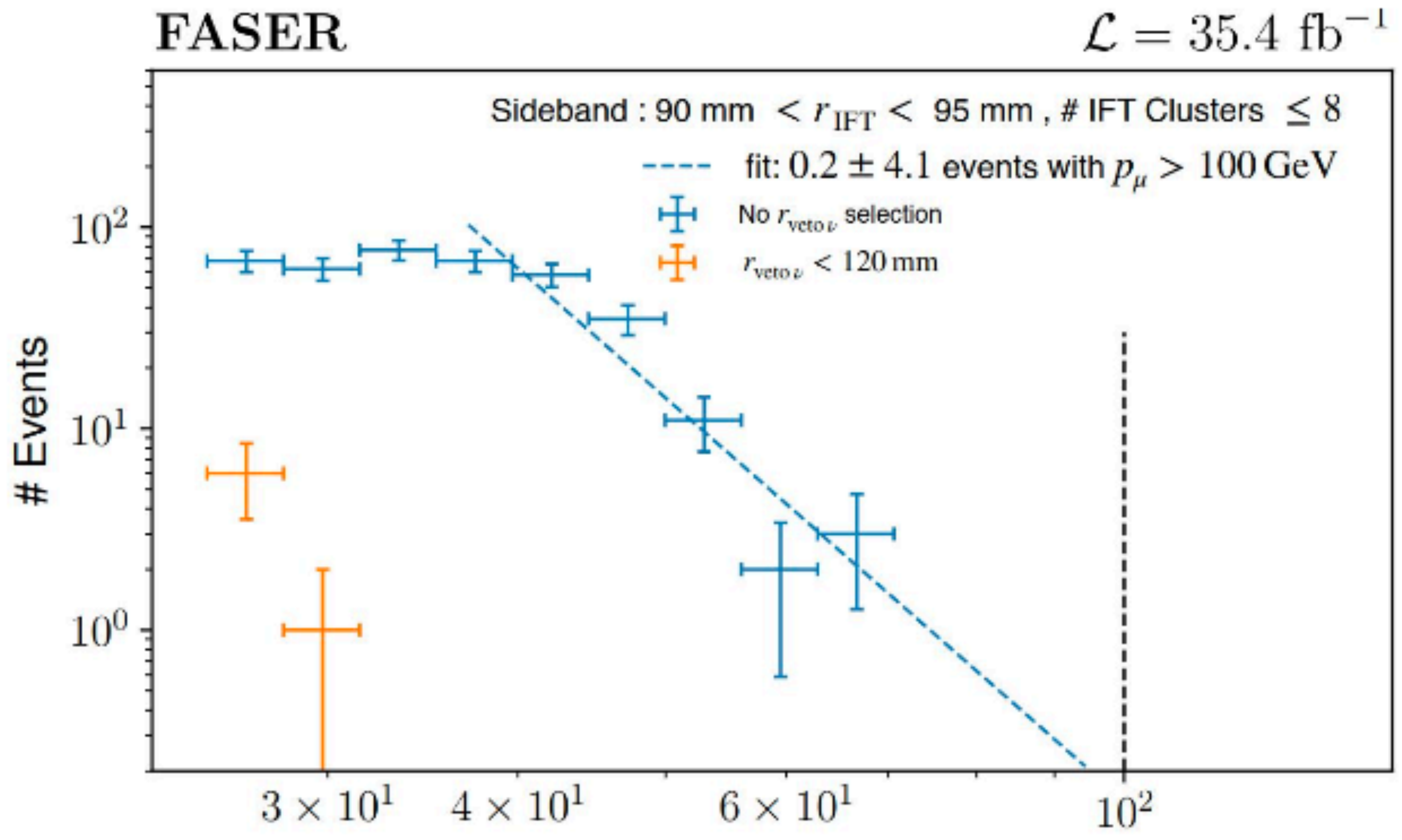
- Neutral hadrons
  - Estimated from 2-step simulation
  - Expect ~300 neutral hadrons with E>100 GeV reaching FASERν
  - Most accompanied by μ but conservatively assume missed
  - Estimate fraction of these passing event selection
  - Most are absorbed in tungsten with no high-momentum track
  - Predict N = 0.11 ± 0.06 events



- Scattered muons
  - Estimated from data sideband
  - Take events w/o front veto radius requirement and single track segment in first tracker station with 90 < r < 95 mm
    - Fit to extrapolate to higher momentum
  - Scale by # events with front veto cut
    - Use MC to extrapolate to signal region
  - Predict N = 0.08 ± 1.83 events
  - Uncertainty from varying selection

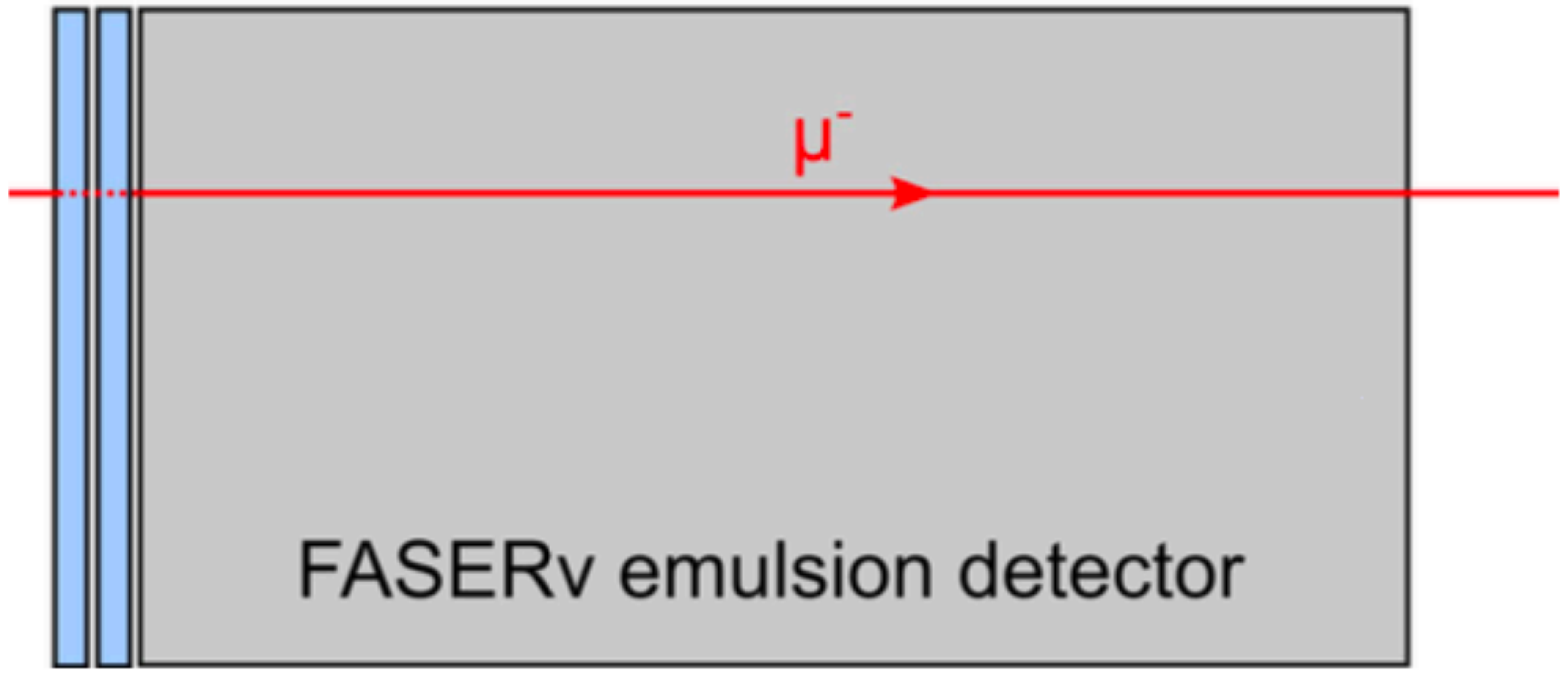


# Neutrino analysis | Backgrounds

[2303.14185]

- Veto inefficiency
  - Estimated from final fit
  - Fit events with 0 (SR) and also 1 (1st or 2nd) or 2 front veto layers firing
  - Final negligible background due to very high veto efficiency




| Category | Events | Expectation |
|---|---|---|
| Signal | | $n_\nu + n_b \cdot p_1 \cdot p_2 + n_{\text{had}} + n_{\text{geo}} \cdot f_{\text{geo}}$ |
| $n_{10}$ | 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 | $n_b \cdot (1 - p_1) \cdot (1 - p_2)$ |

# Neutrino analysis | Results

[2303.14185]

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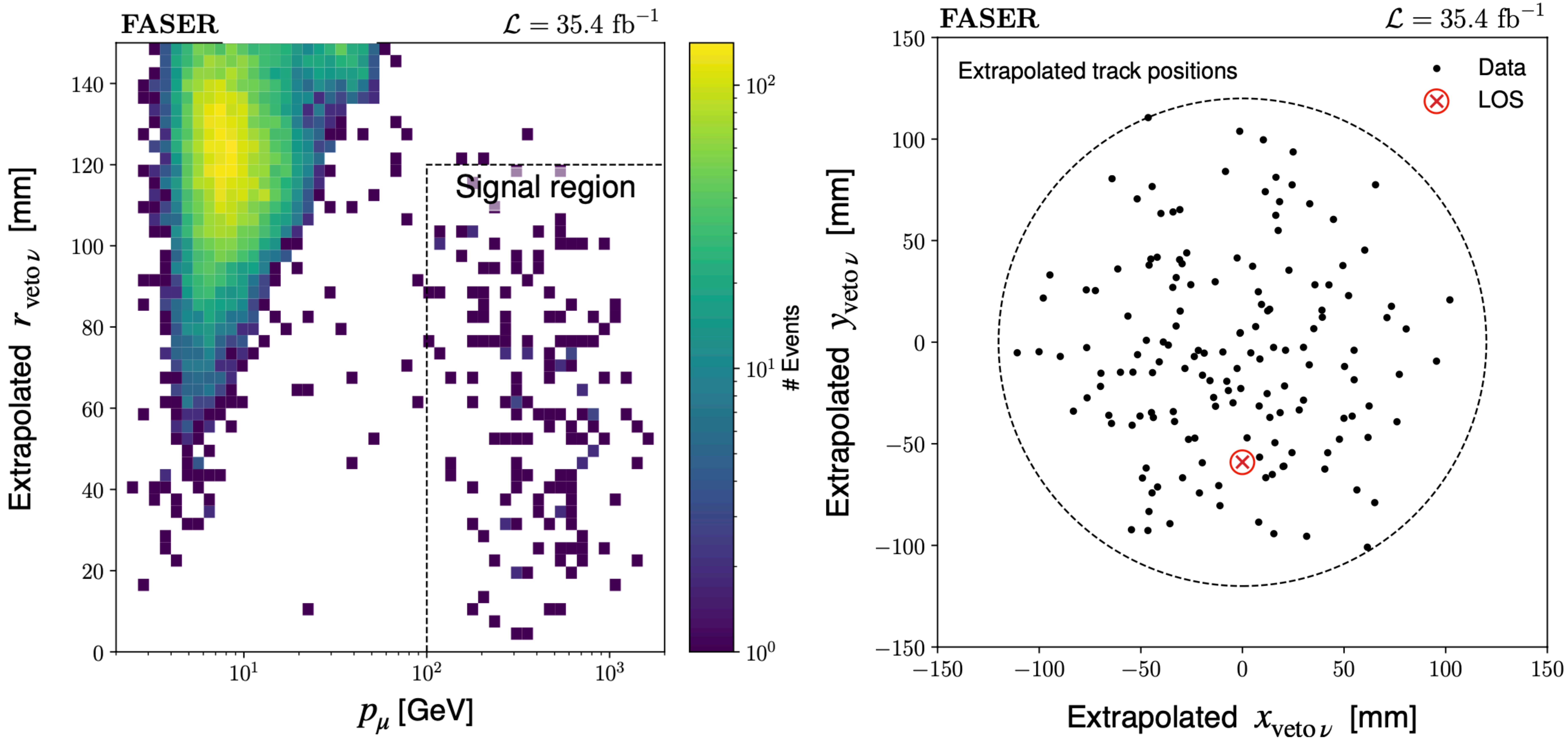
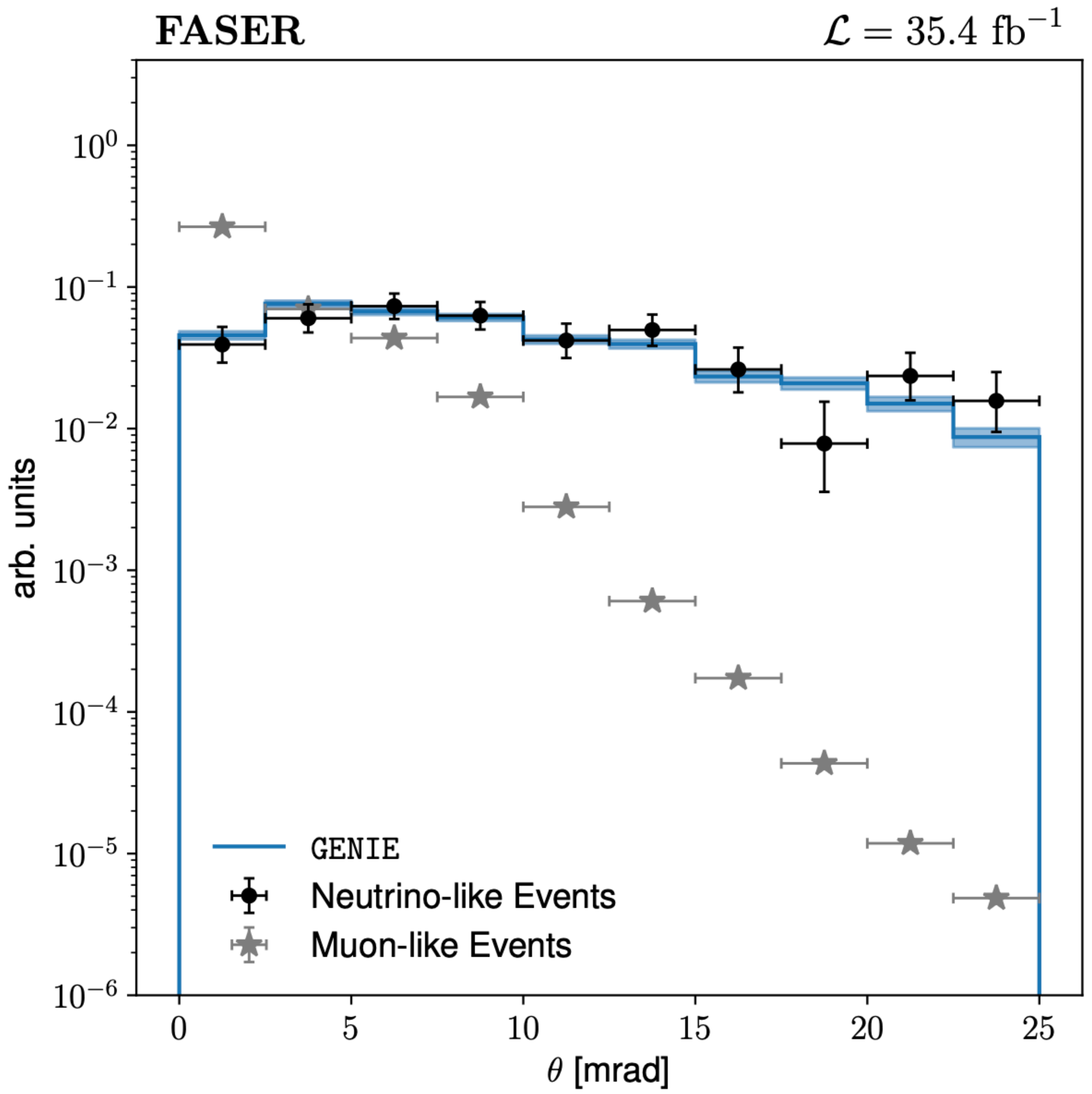
- Unblinded to find 153 events with no veto signal
  - Just 10 events with one veto signal
- **First direct detection of collider neutrinos!**
  - With signal significance of 16σ
  - Expected 151 ± 41 events from GENIE simulation

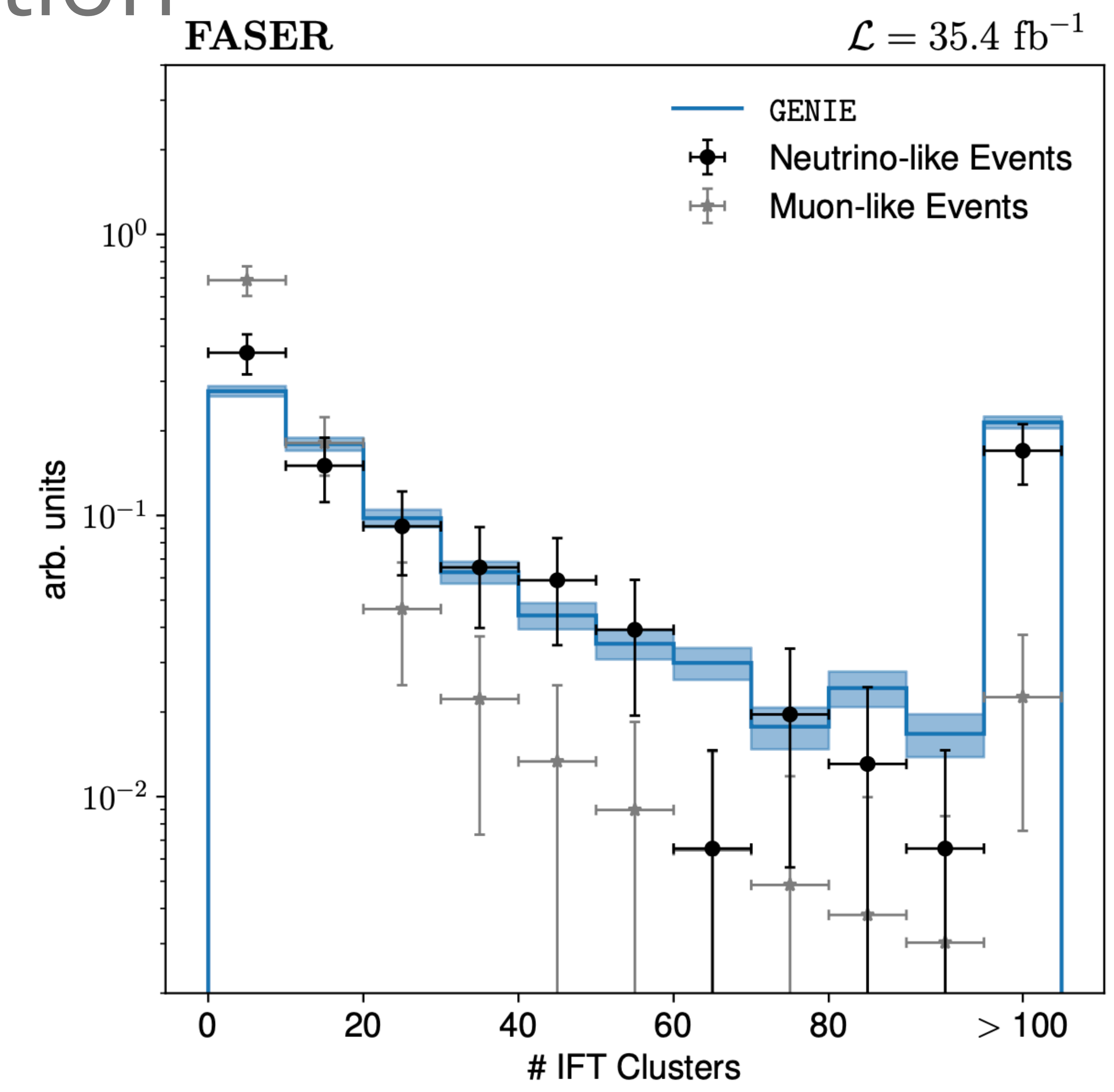


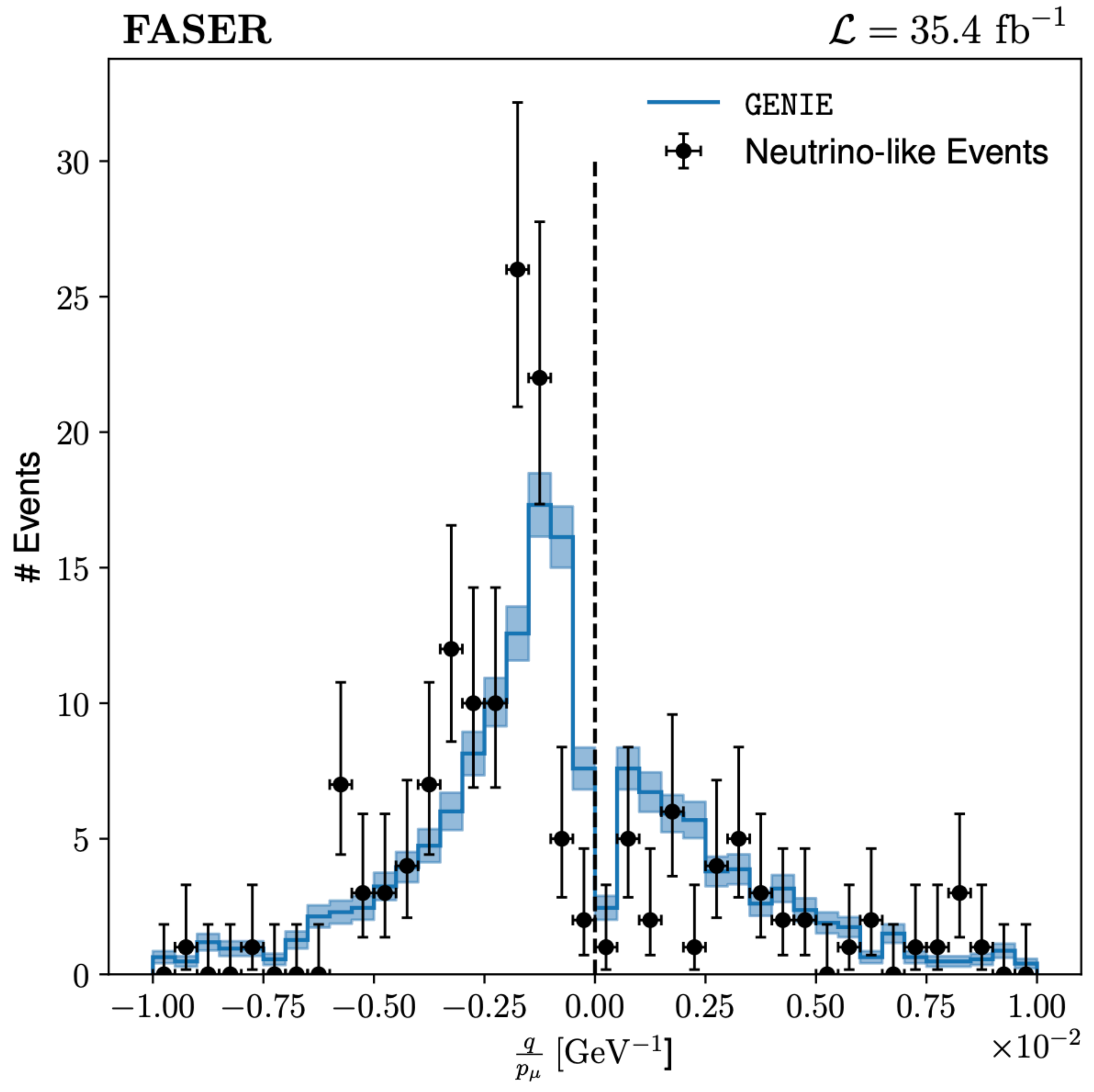
# Neutrino analysis | Results

- Candidate neutrino events match expectation from signal
  - High occupancy in front tracker station
  - Most events have high μ momentum
  - More $\nu_\mu$ than anti- $\nu_\mu$
  - High occupancy in front tracker station
  - Large angle θ with respect to LOS

- NB: no acceptance corrections nor any systematic uncertainties in these plots

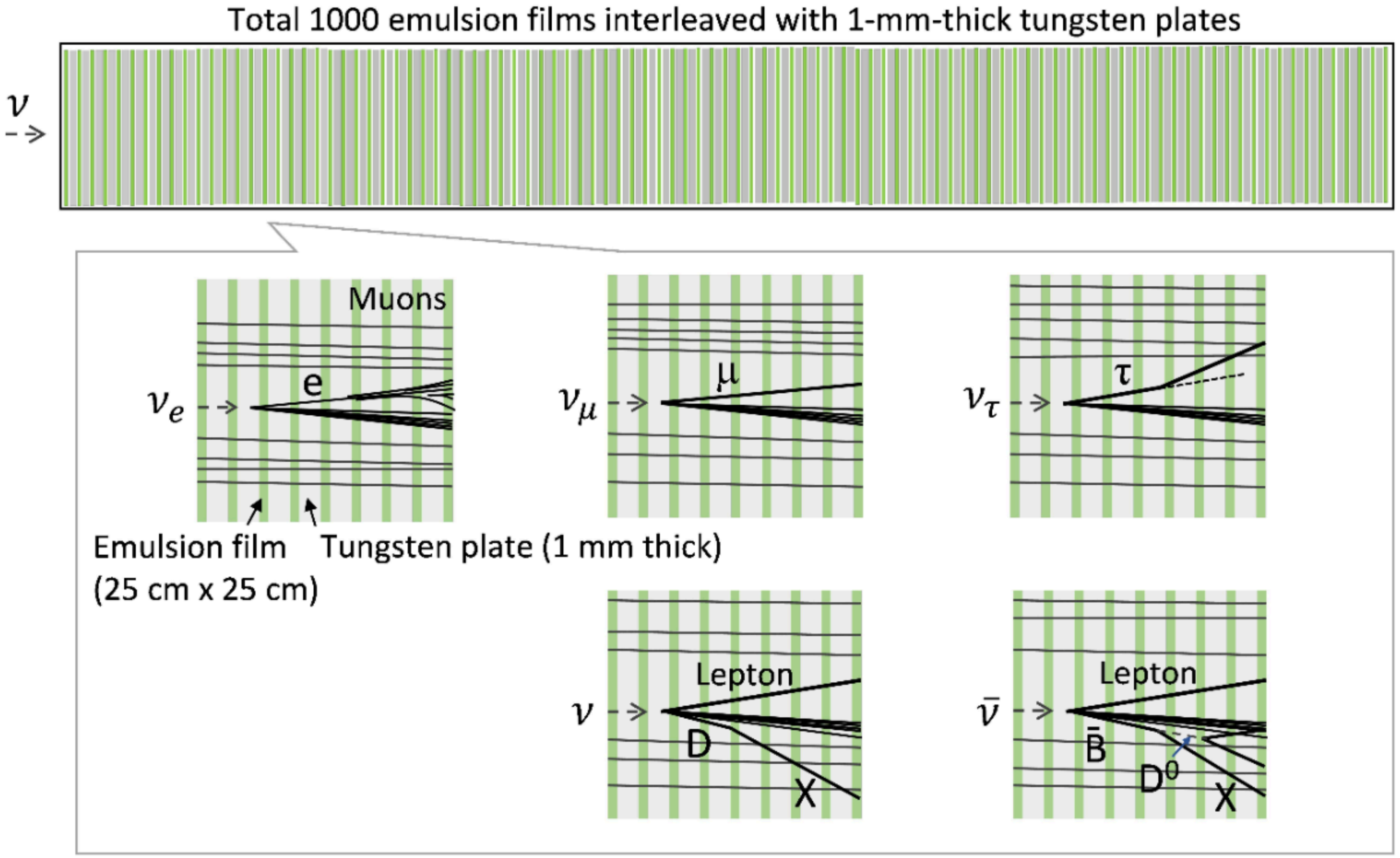


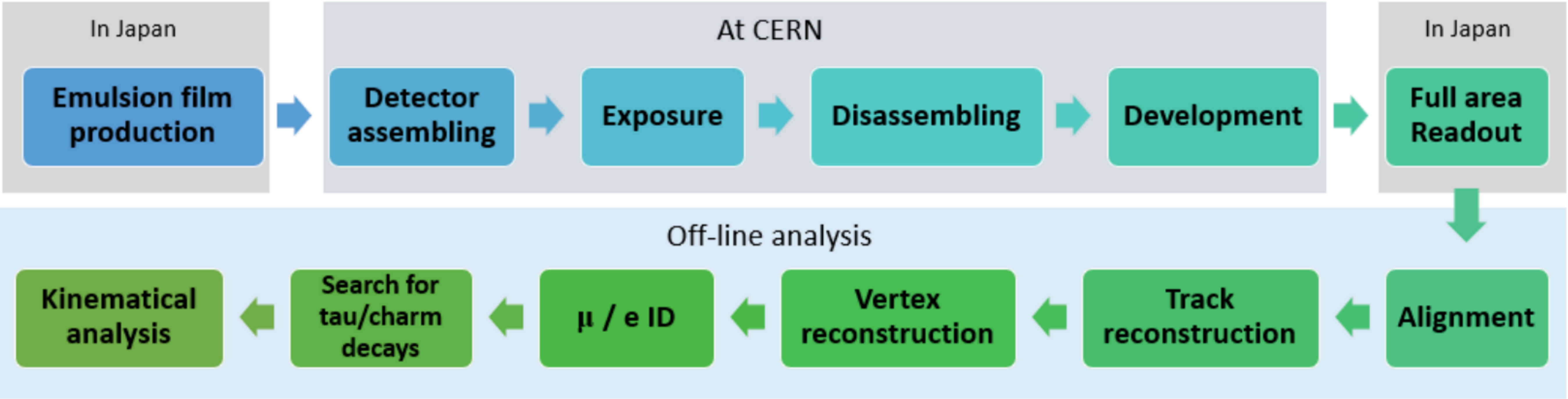



# Emulsion analysis | Detector

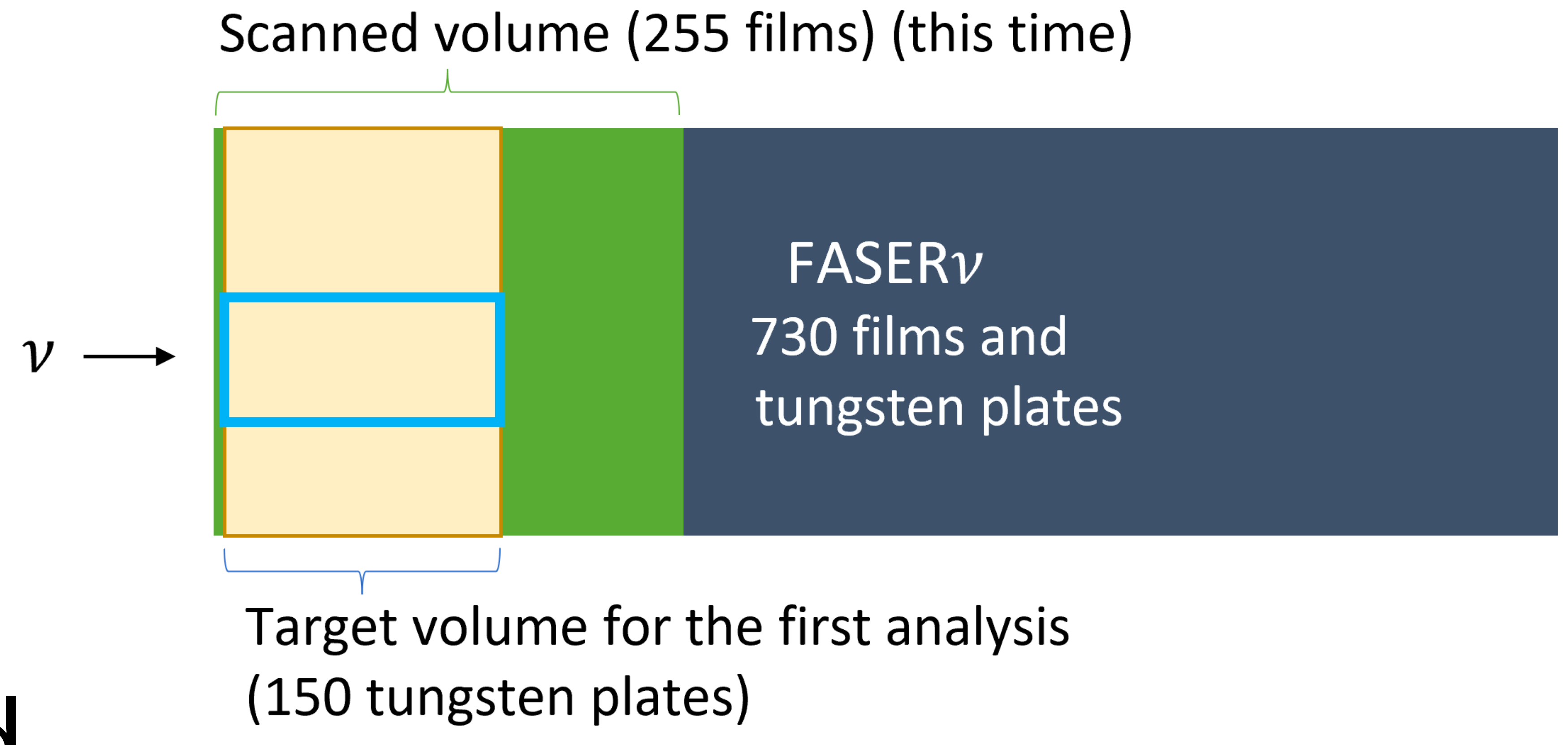
- Emulsion detector with 1.1T tungsten target
  - 730 1.1mm thick tungsten plates interleaved with emulsion film
    - Well understood neutrino detector technology
  - Replace every 20-50 $fb^{-1}$ to maintain track density low
- Challenges:
  - Logistics to transport and replace the 1-ton-scale detector every technical stop (3 times/year)
  - Procedure well developed for production and offline analysis
- New analysis!

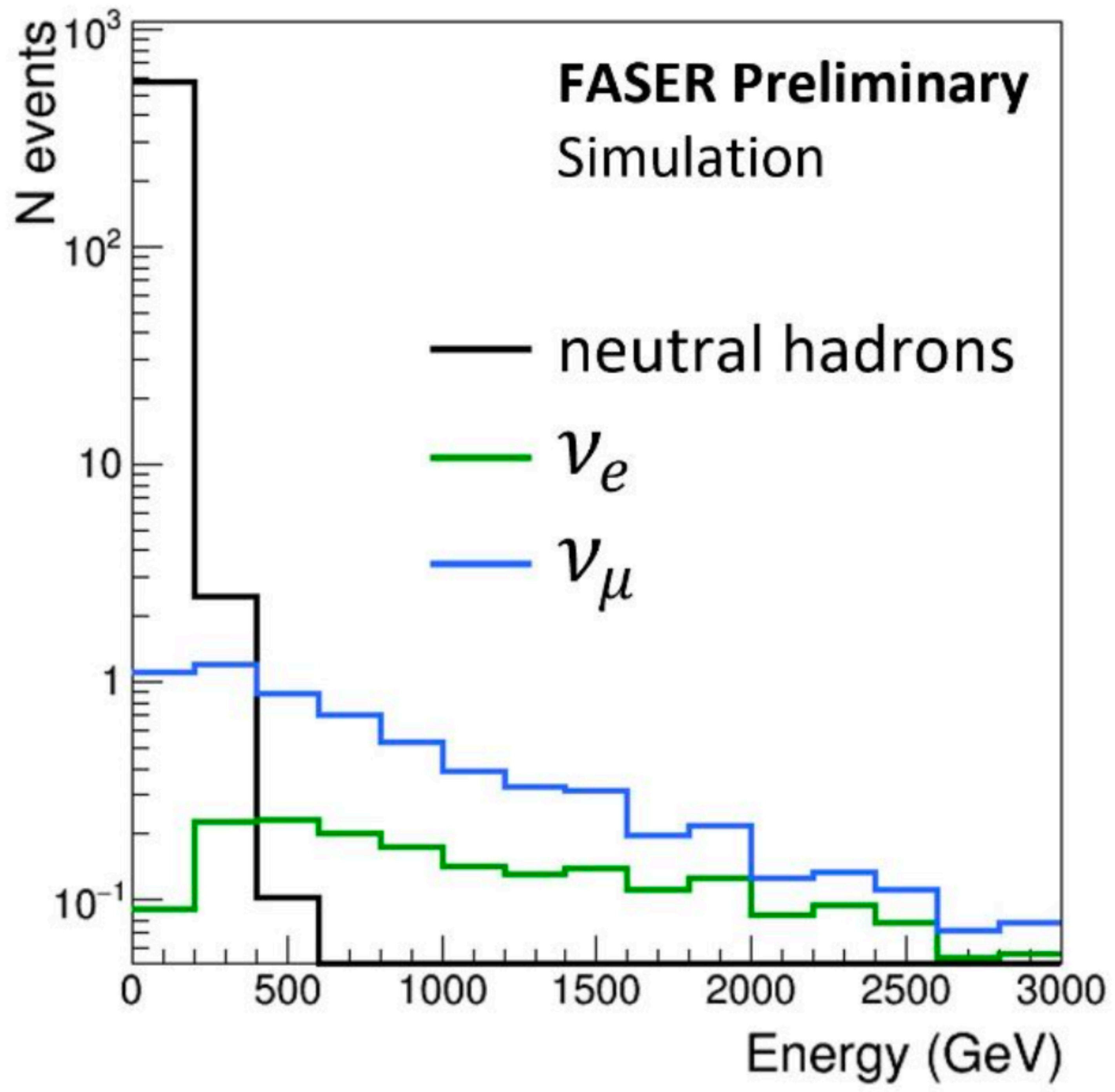


# Emulsion analysis | Dataset & Bkgds

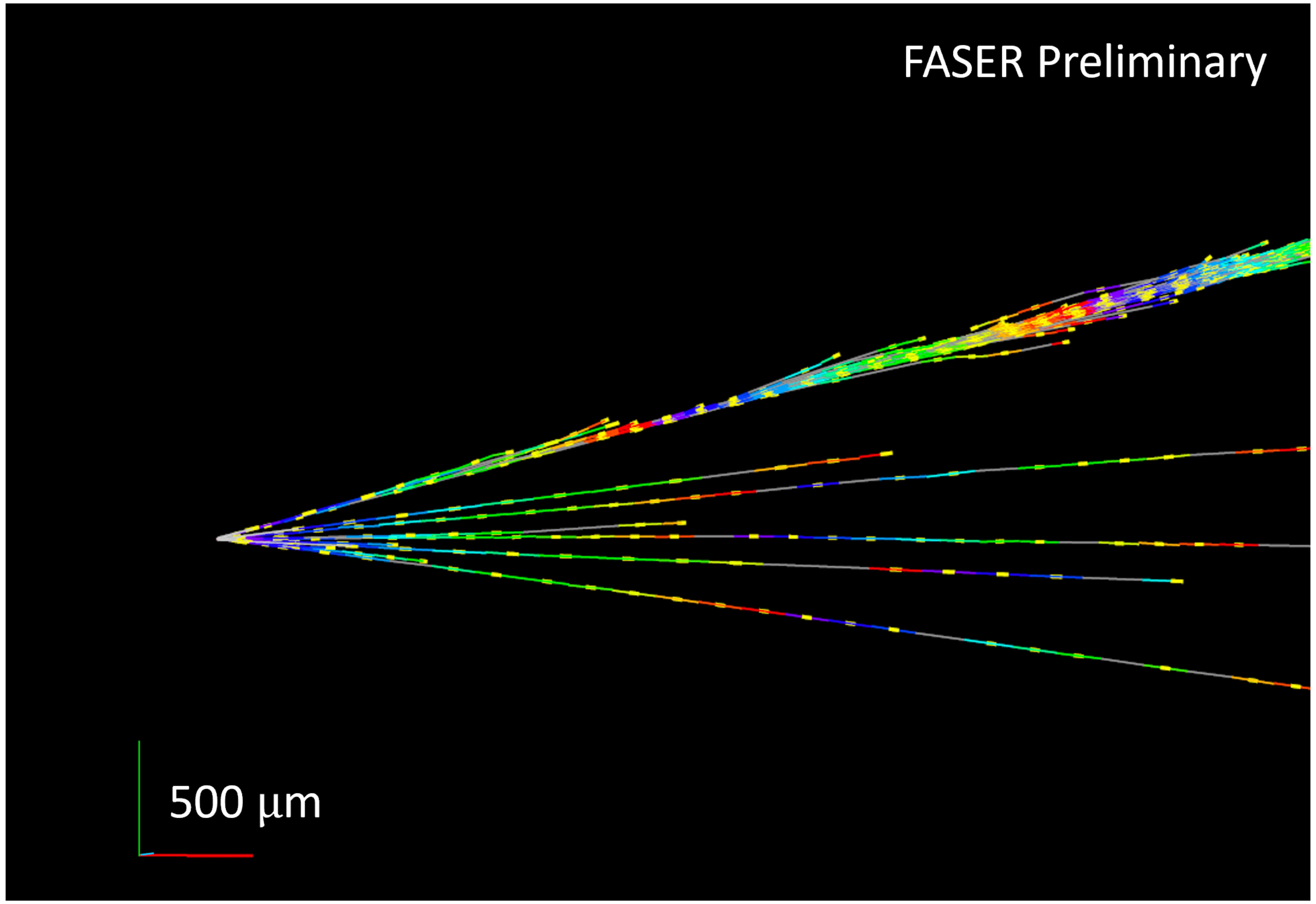
- First analysis includes 150 of 730 plates
  - 68kg target mass for this analysis (24 x 9 x 16.5 cm)
  - **9.5 $fb^{-1}$** of LHC proton collision data
- Expect 29.4 ± 5.0 ($\nu_\mu$) and 11.8 ± 7.5 ($\nu_e$) charged current (CC) neutrino interactions before selection
  - Select vertices with associated lepton candidate (e or μ) and E>200 GeV
- Backgrounds
  - Neutral hadron background; low-momentum signal
  - Neutral-current neutrino interactions

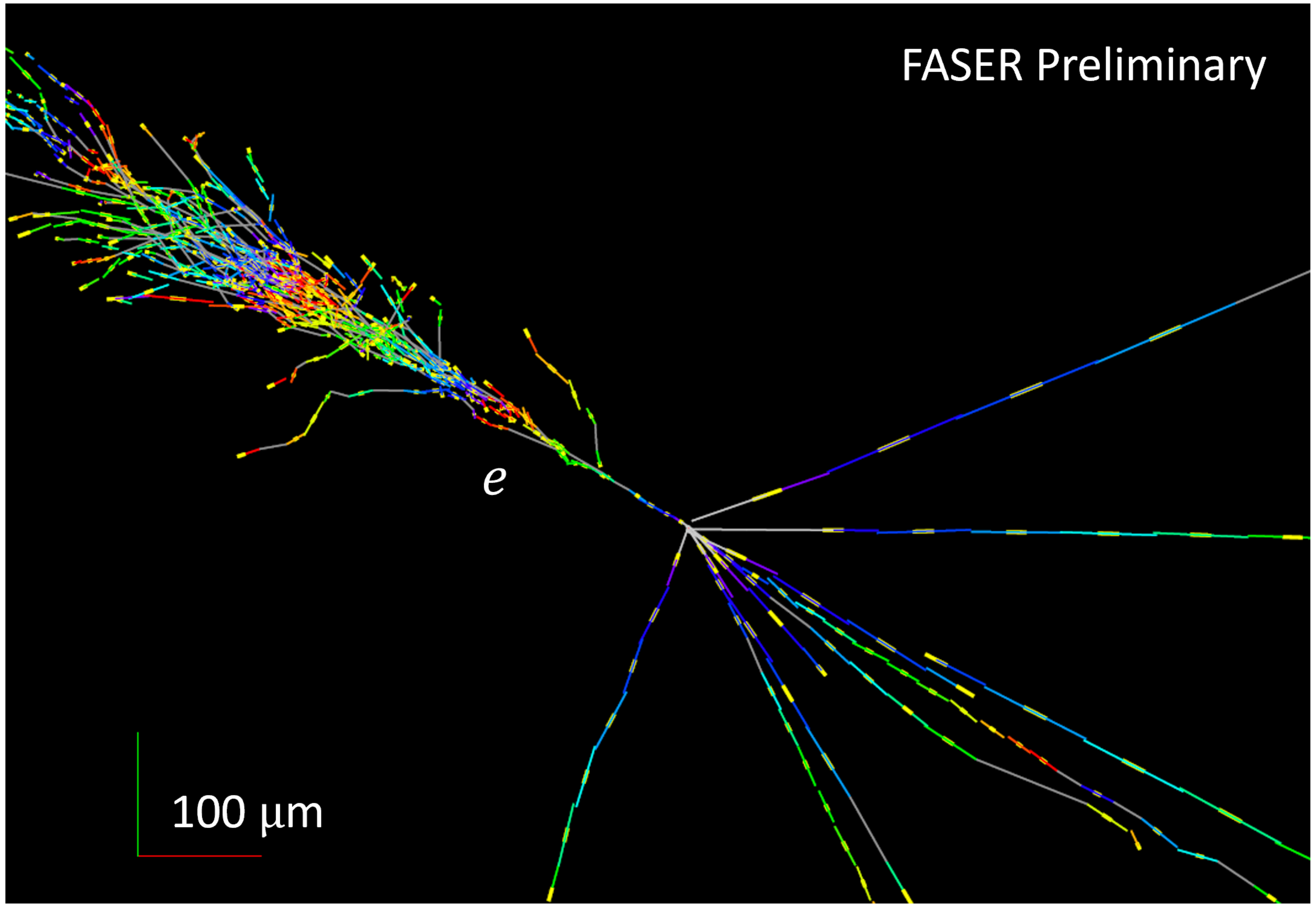


# Emulsion analysis | Results

- Preliminary results: CERN-FASER-CONF-2023-002
  - Expected 0.6–5.2 ($\nu_e$ CC) and 3.0–8.6 ($\nu_\mu$ CC) passing selection
  - Observed 3 $\nu_e$ vertices (5σ), and 4 $\nu_\mu$ vertices (2.5σ) - **Candidates with E ~ 1TeV!**




- **First direct observation of collider electron neutrinos!**

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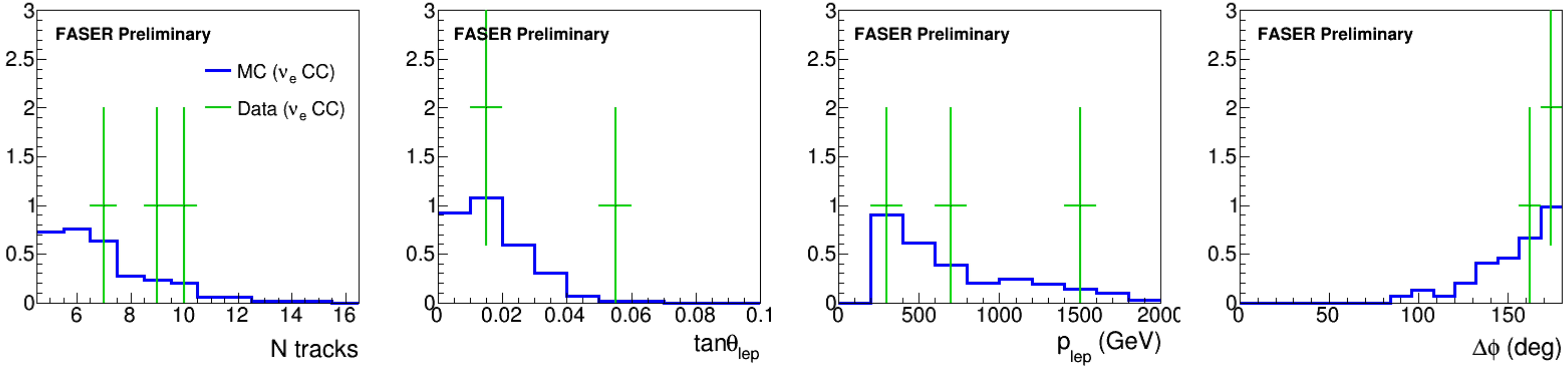


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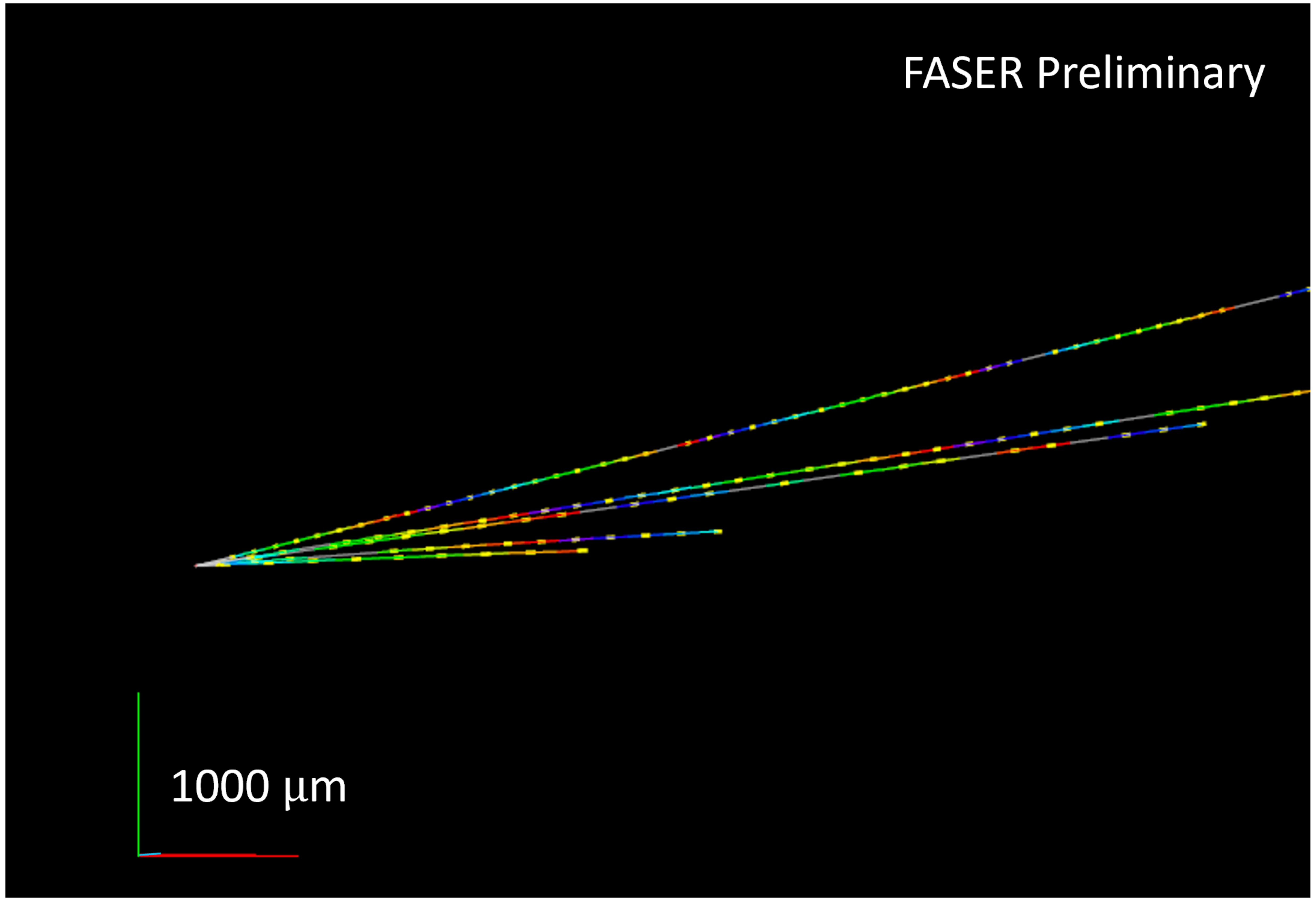


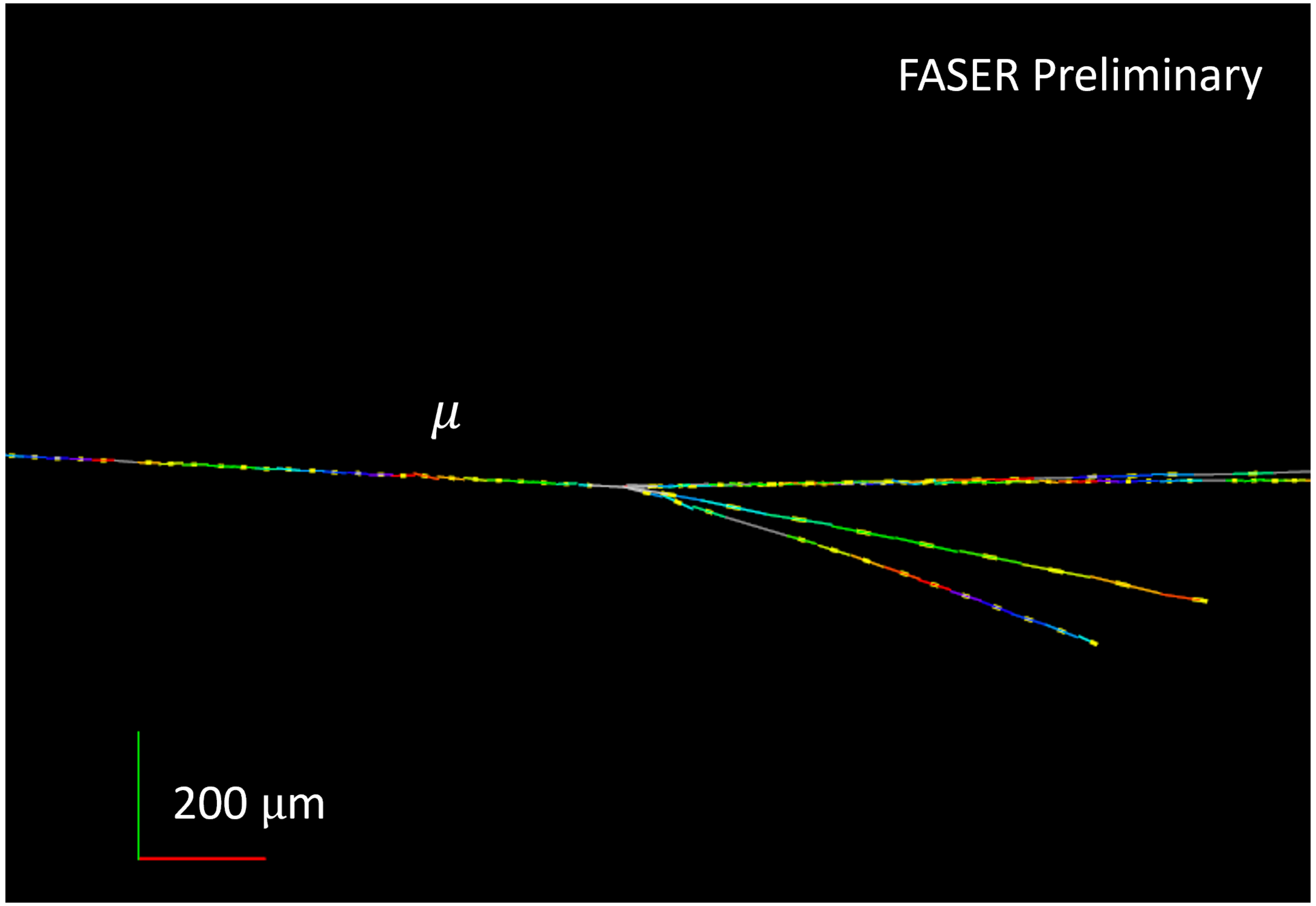


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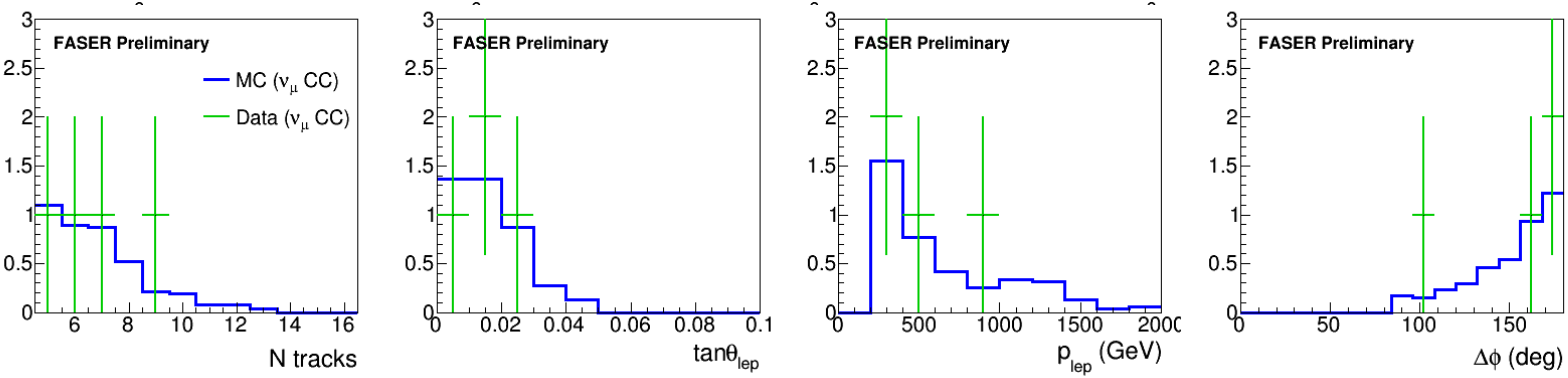


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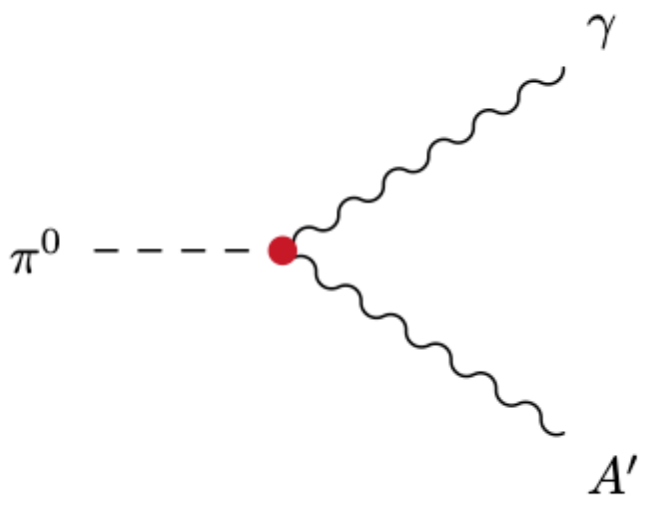
# Dark Photon Search

# Dark Photon Search

- Dark photon a common feature of hidden sector models
  - Weakly coupling to SM via kinetic mixing (ε) with SM photon

$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon\, e \sum_f q_f \bar{f} \not{A}' f$$

- MeV A's produced mainly in meson decays at LHC

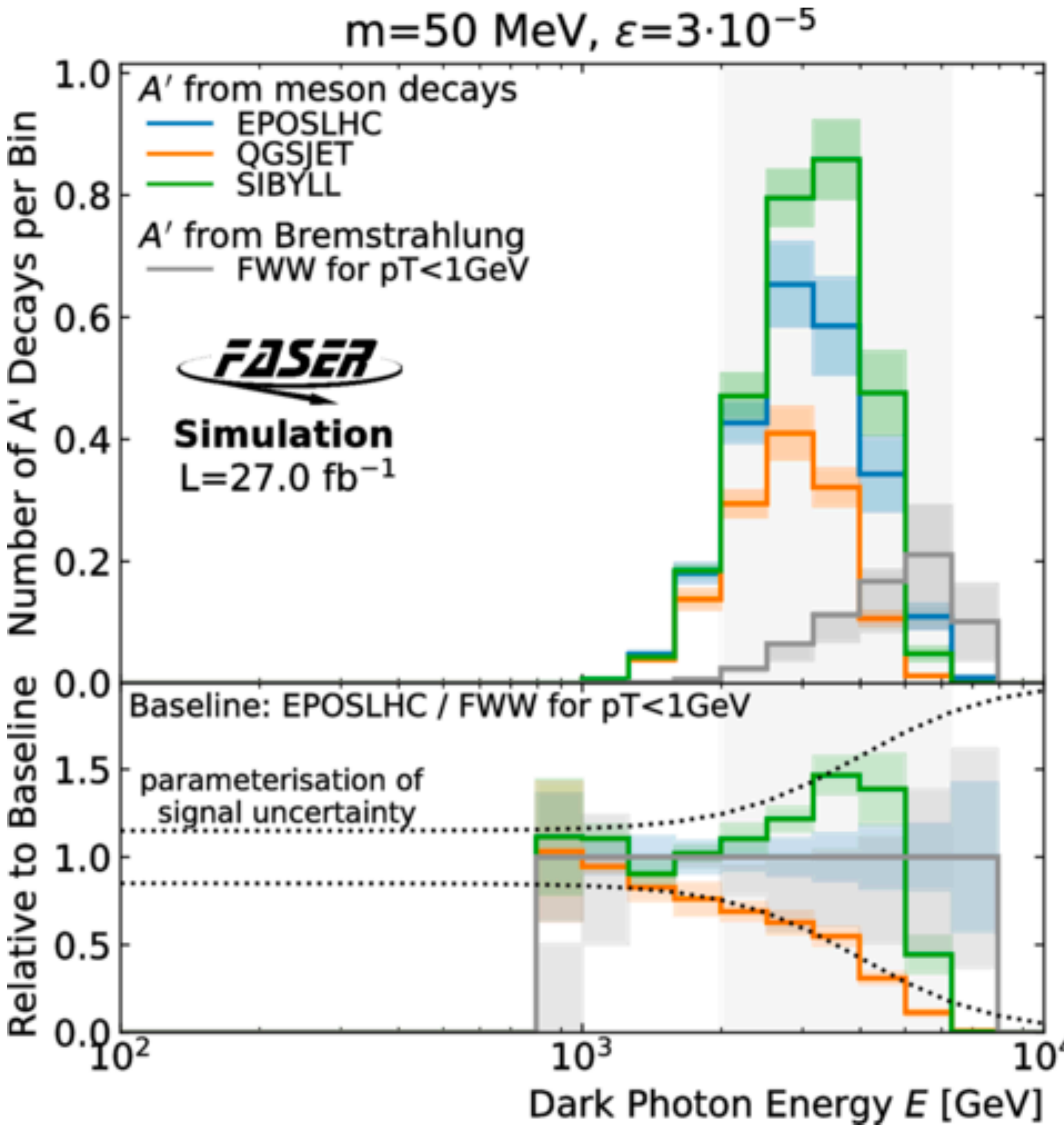



$$B(\pi^0 \to A'\gamma) = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 B(\pi^0 \to \gamma\gamma)$$

- FASER targets small ε, where A' has long decay length

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

  - Below $2m_\mu$, A' has 100% decay to $e^+e^-$ pair

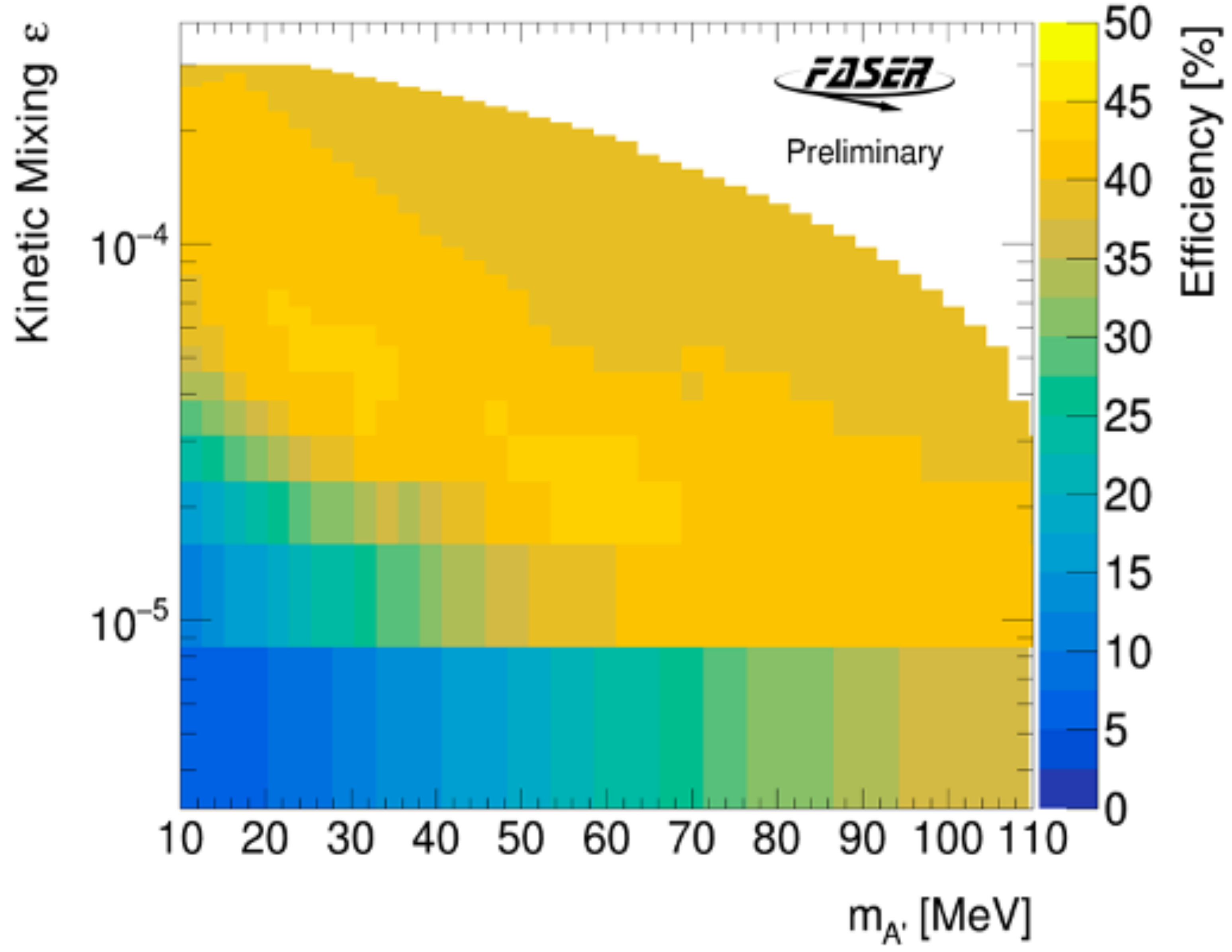



- A' → e+e- simulated with FORESEE*
  - $\pi_0$ and η via EPOS-LHC generator
  - Subdominant dark brem. via FWW
- Generator uncertainty dominates
  - Difference to QGSJET/SIBYLL
  - Parameterised based on A' energy

* arXiv:2105.07077

# Dark Photon Search | Selection

- Simple and robust $A' \rightarrow e^+e^-$ selection
  - Blind events with no veto signal and E(calo) > 100 GeV
- Selection
  - 1. Collision event with good data quality
  - 2. No signal (< 40 pc) in any veto scintillator
  - 3. Timing and preshower consistent with ≥2 MIPs
  - 4. Exactly 2 good fiducial tracks
    - p > 20 GeV and r < 95 mm && Extrapolating to r < 95 mm at vetos
  - 5. Calo E > 500 GeV




- Efficiency of ~40% across sensitive region


[arXiv:2308.05587]

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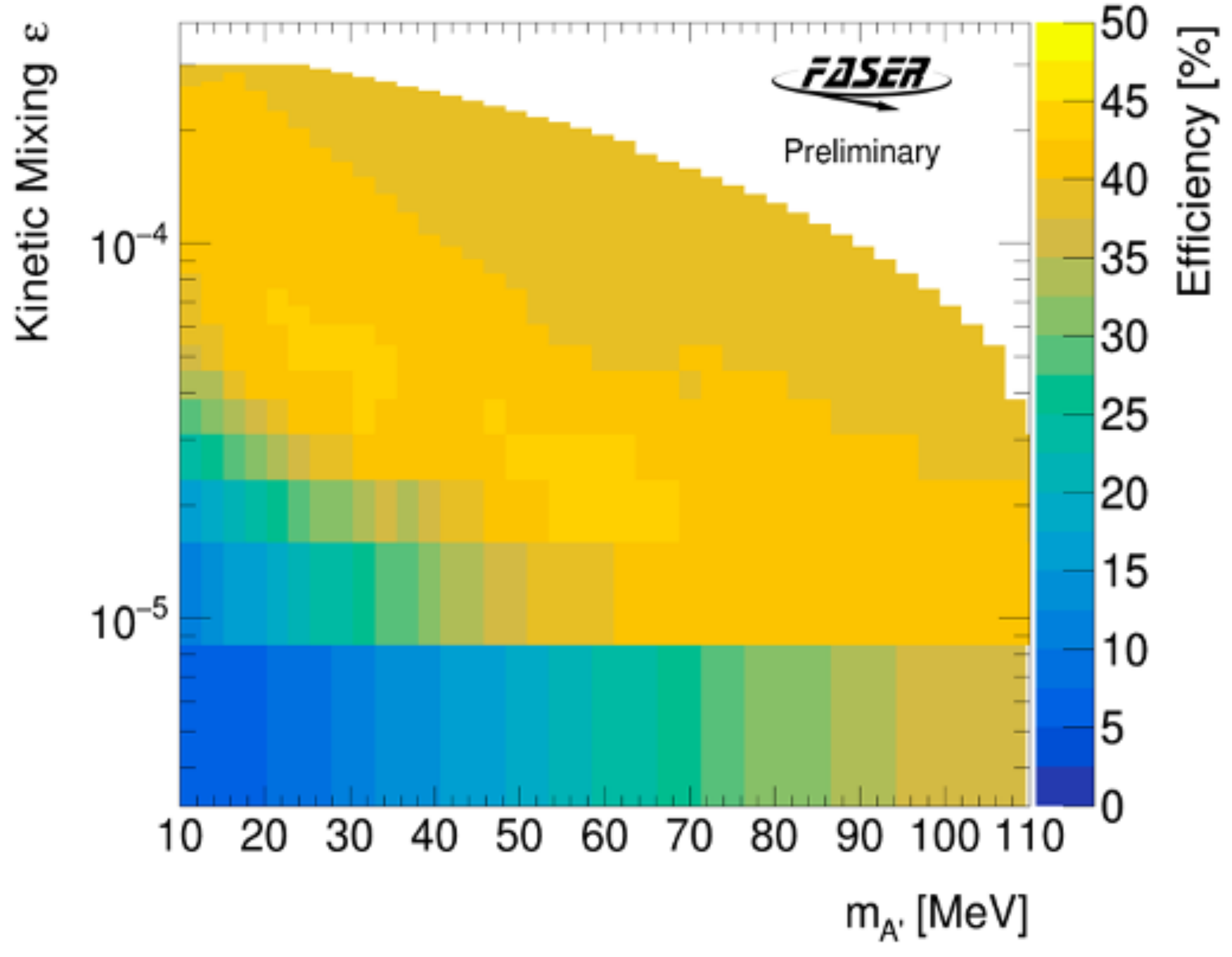


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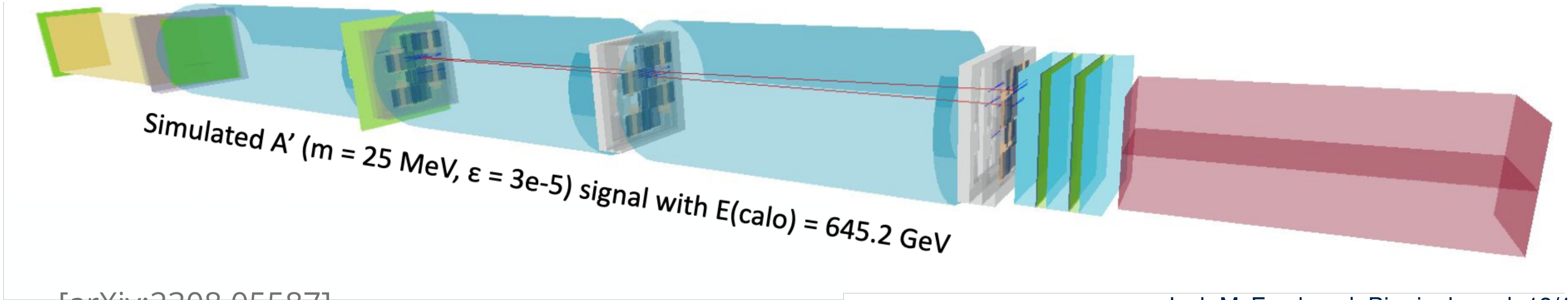
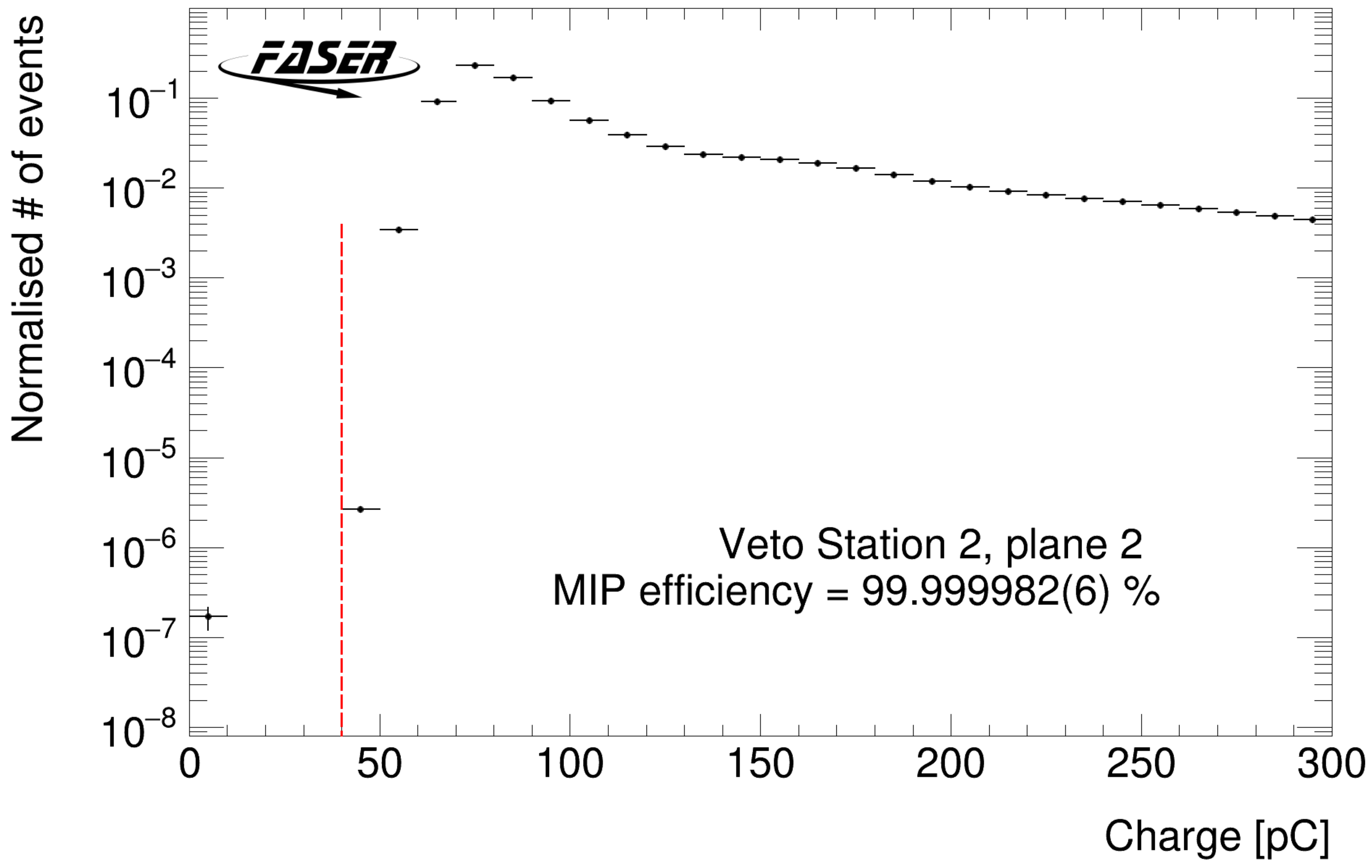


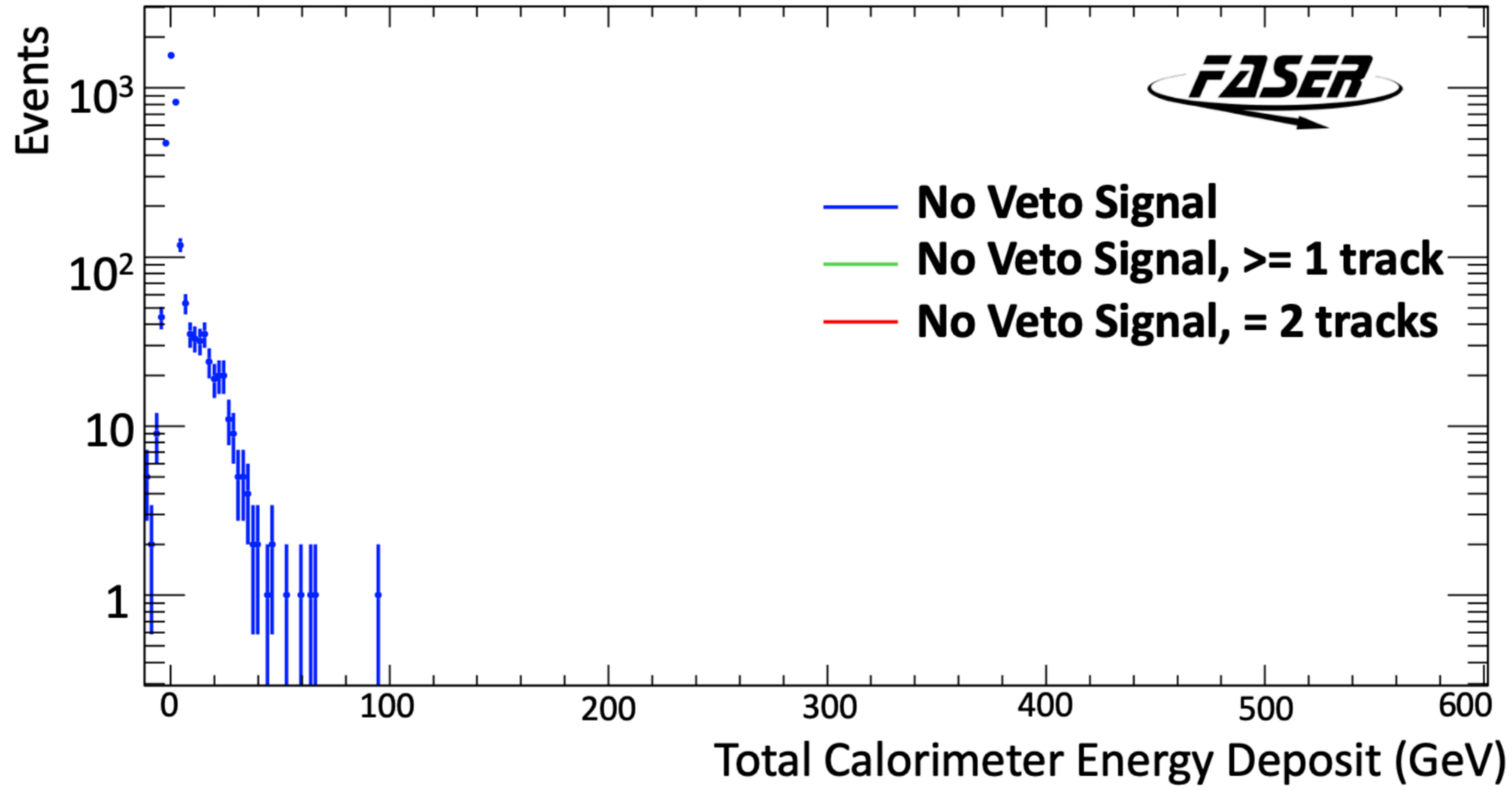

[arXiv:2308.05587]

# Dark Photon | Backgrounds

- Veto inefficiency
  - Measured layer-by-layer via muons with tracks pointing back to vetos
  - Layer efficiency > 99.998%
  - 5 layers reduce exp. $10^8$ muons to negligible level (even before cuts) ($<10^{-20}$ inefficiency)




- Non-collision backgrounds
  - Cosmics measured in runs with no beam
  - Near-by beam debris measured in non-colliding bunches
  - No events observed with ≥1 track or E(calo) > 500 GeV individually




[arXiv:2308.05587]

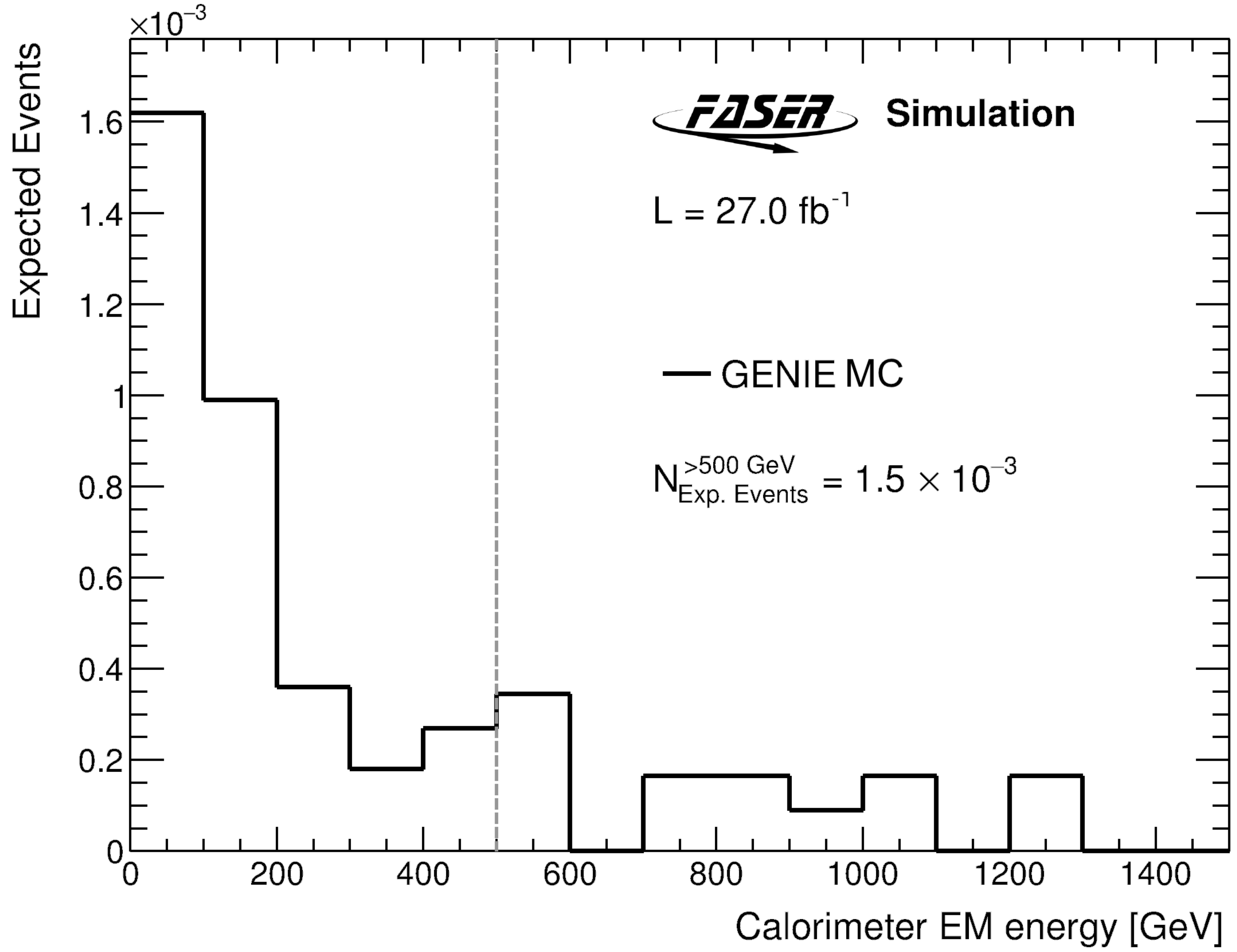
# Dark Photon | Backgrounds

- Main background is from Neutrino interactions
  - Primarily coming from vicinity of timing detector
  - Estimated from GENIE simulation (300 ab-1)
  - Uncertainties from neutrino flux & mismodelling
  - Predicted events with E(calo) > 500 GeV

**N = (1.5 ± 2.0) x $10^{-3}$**

- Neutral hadrons (e.g. Ks) from upstream muons interacting in rock in front of FASER
  - Heavily suppressed since:
    - muon nearly always continues after interaction
    - has to pass through 8 interaction lengths (FASERν)
    - decay products have to leave E(calo) > 500 GeV
  - Estimated from lower energy events with 2/3 tracks and different veto conditions

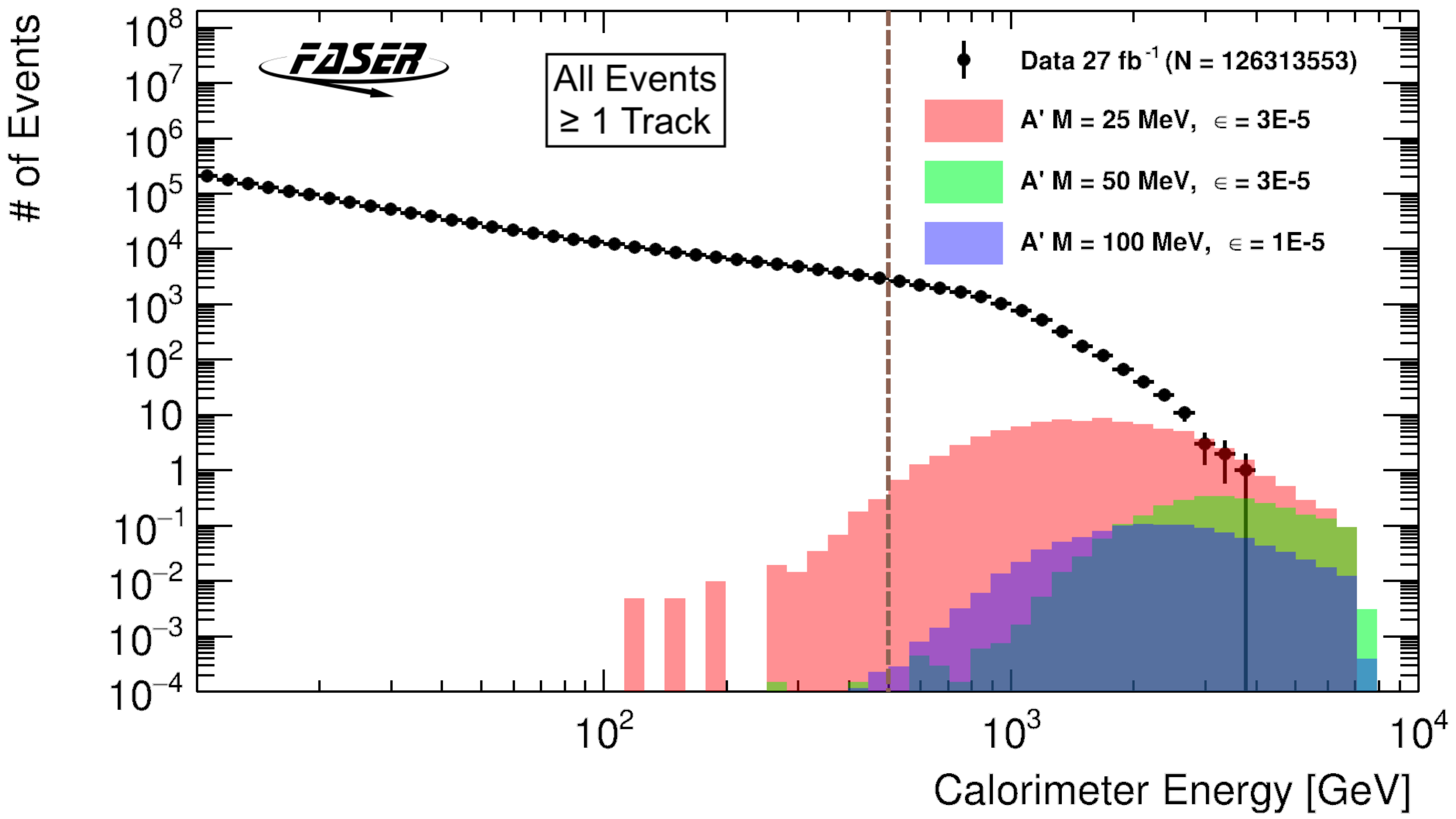
**N = (0.8 ± 1.2) x $10^{-3}$**

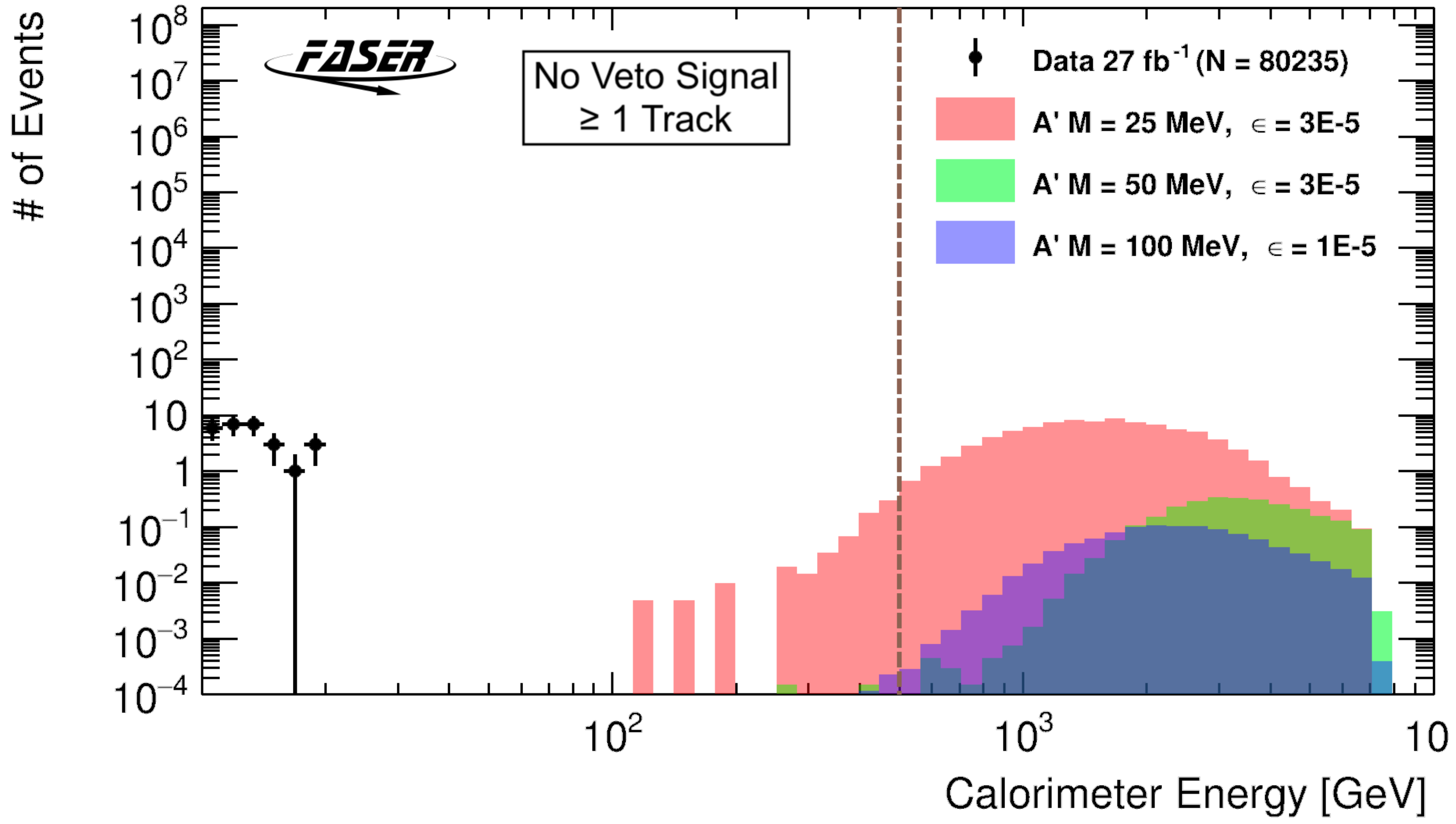


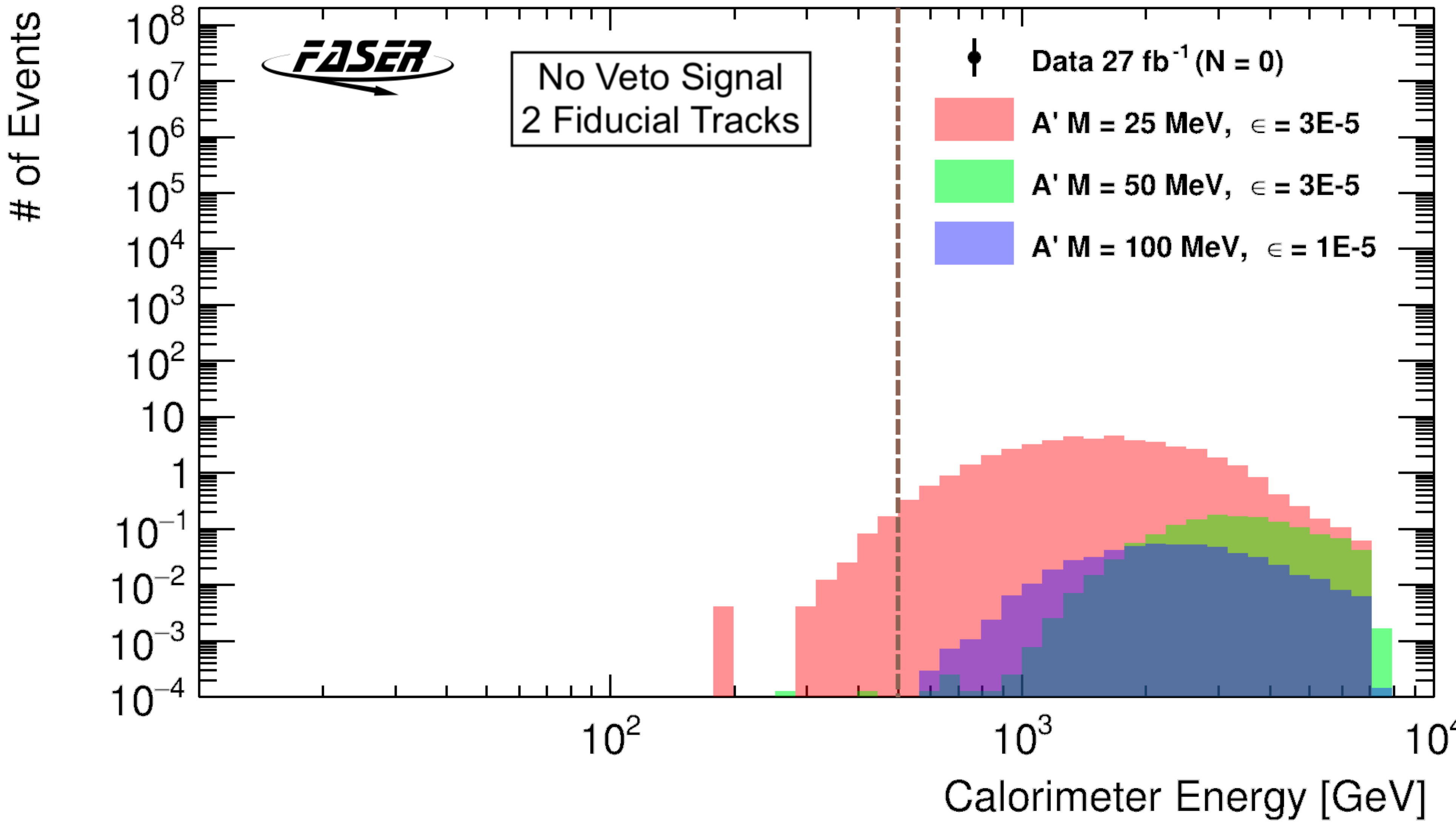

[arXiv:2308.05587]

# Dark Photon Search | Results

- No events in unblinded signal region
  - Not even any with ≥1 fiducial track
- Expected background
  - 0.0023±0.0023



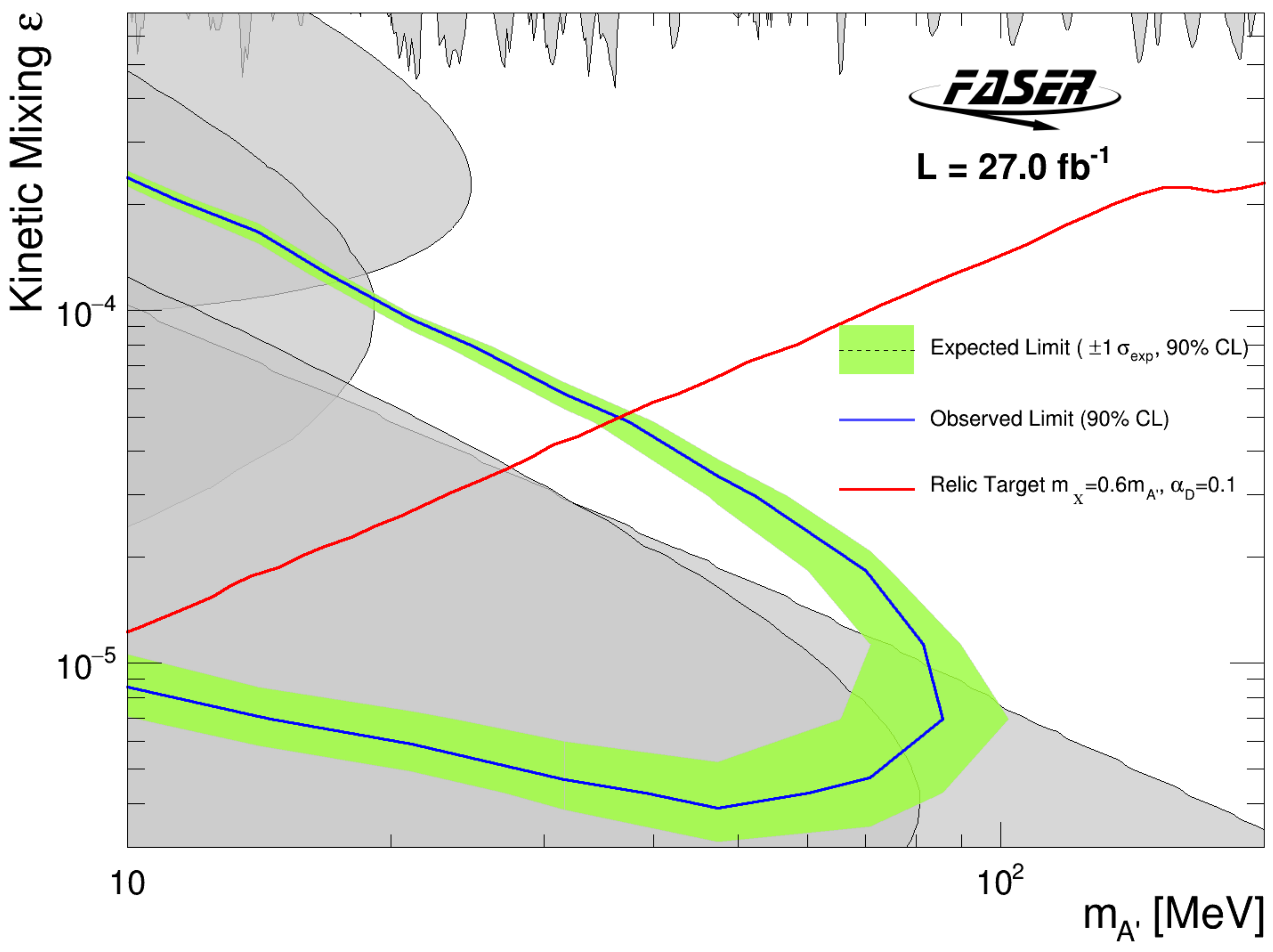



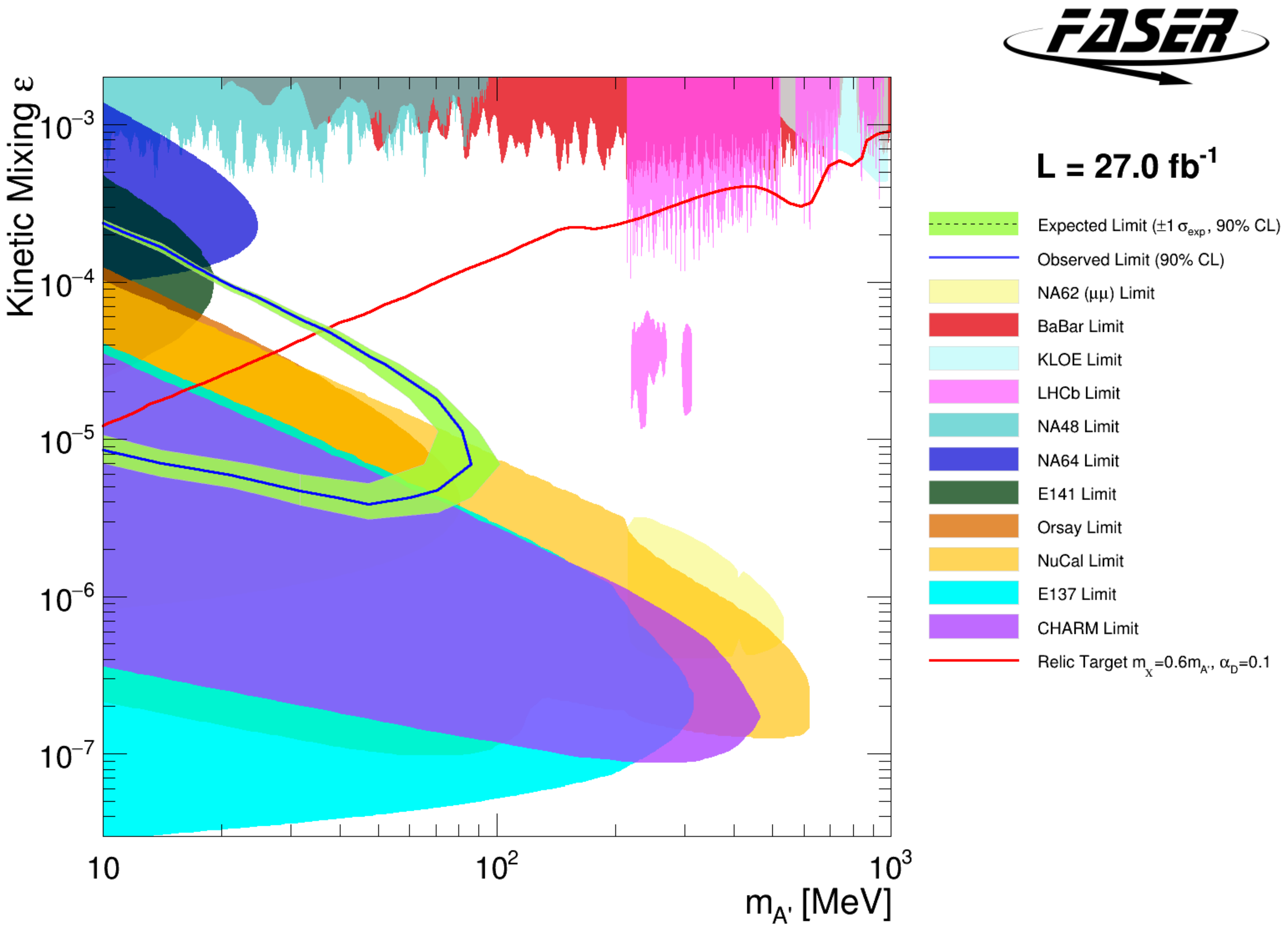




[arXiv:2308.05587]

# Dark Photon Search | Limits

- After unblinding, no events seen in signal region, FASER sets limits on previously unexplored parameter space.
- First incursion (with NA62) into thermal relic region from low ε since 1990's.
- Background-free analysis bodes well for future sensitivity.
  - Expect ~10fb$^{-1}$ luminosity in Run 3 from 2023-25.

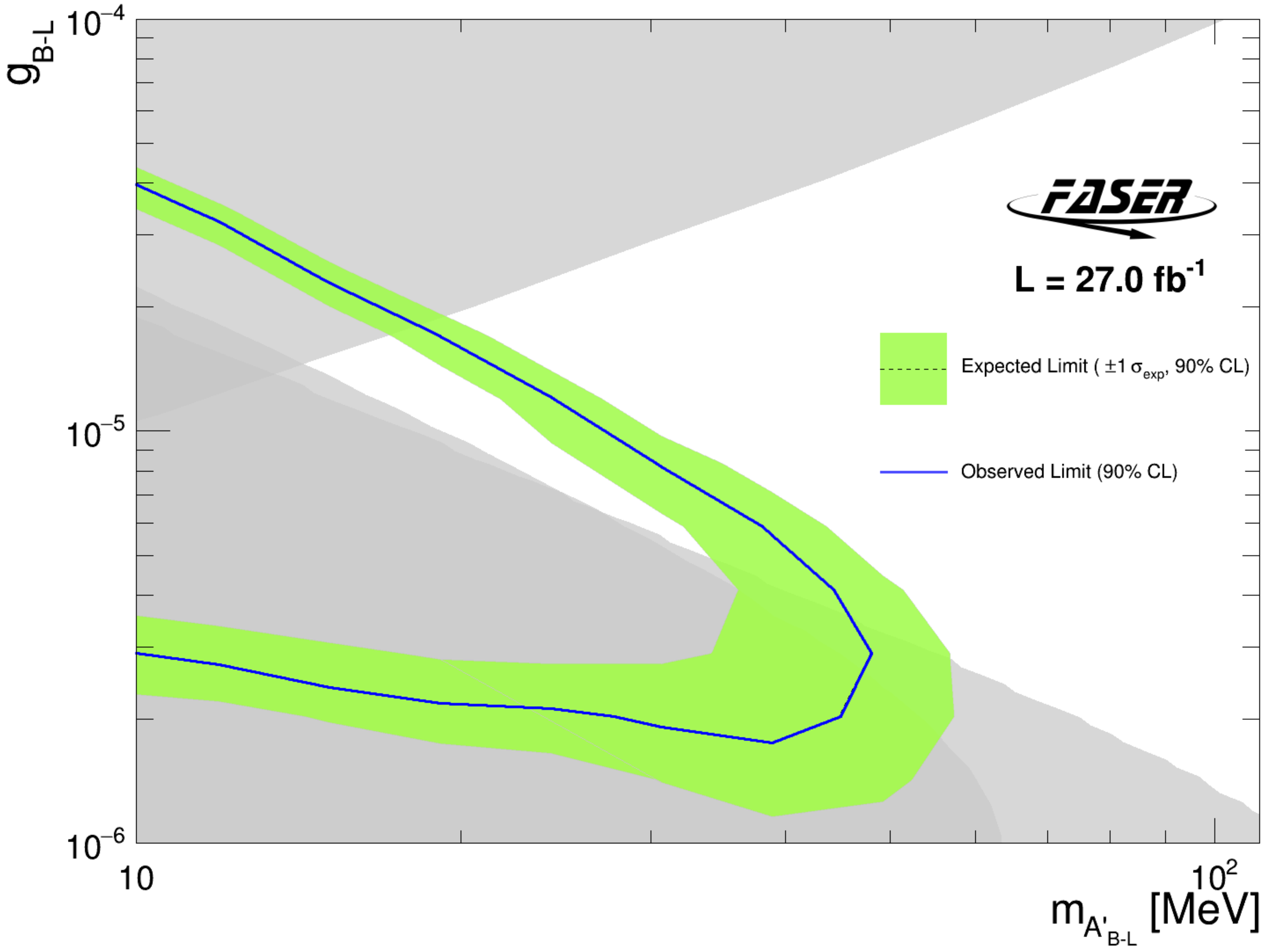


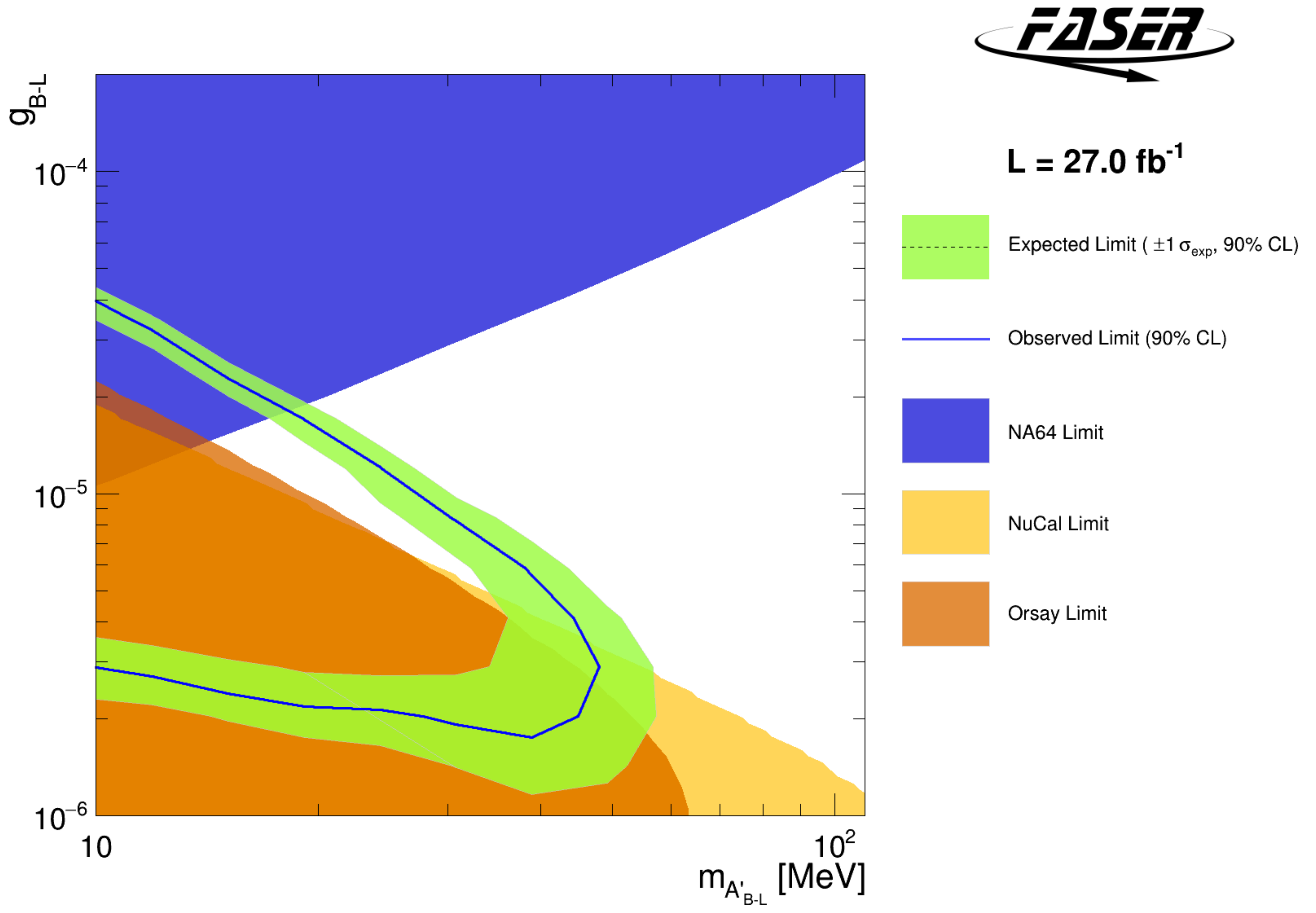




[arXiv:2308.05587]

# B-L Gauge Boson Search | Limits

- The region probed is cosmologically relevant
  - Assuming a dark matter particle with mass ½m(A'$_{B-L}$)—m(A'$_{B-L}$) & very large Q(B−L), limit includes region favoured by thermal freeze-out
  - As B−L model includes 3 sterile neutrinos, that could be produced through freeze-in mechanism, resulting relic density may be significant in excluded region.



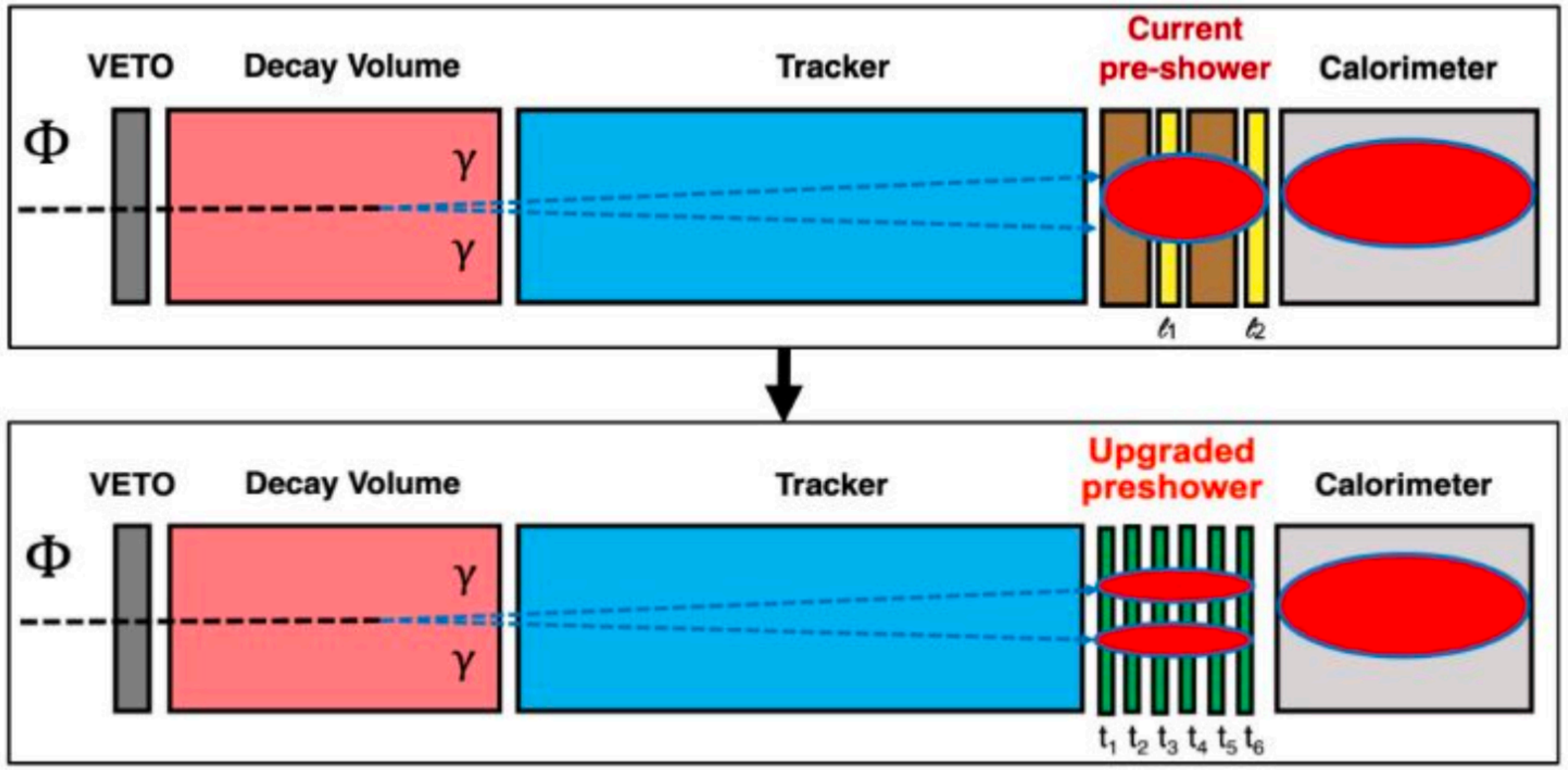




[arXiv:2308.05587]


# Next for FASER

# Dark Photon Search | Limits

- Preshower Upgrade
  - More transverse information
  - Beneficial for 2-photon signals, such as ALP searches
  - Installation planned for YETS 24/25
    - Technical proposal




- Run 3 and Beyond
  - Expect to collect 10x more data in Run 3
  - Excellent performance so far therefore…
  - Begun request process to continue operations after LS3
  - Potentially succeeded by FASER2/FASERν2 in the planned Forward Physics Facility (FPF) during the HL-LHC era


# Forward Physics Facility

# Forward Physics Facility

- FASER, FASERν, and other proposed detectors are currently highly **constrained by tunnels and infrastructure** that was never designed to support experiments.

- At the same time, it is becoming clear that there is a **rich physics program in the far-forward region**, spanning long-lived particle searches, neutrinos, QCD, dark matter, dark sector, cosmic rays, and cosmic neutrinos.

- Strongly **motivates to create a dedicated facility** to house several far-forward experiments

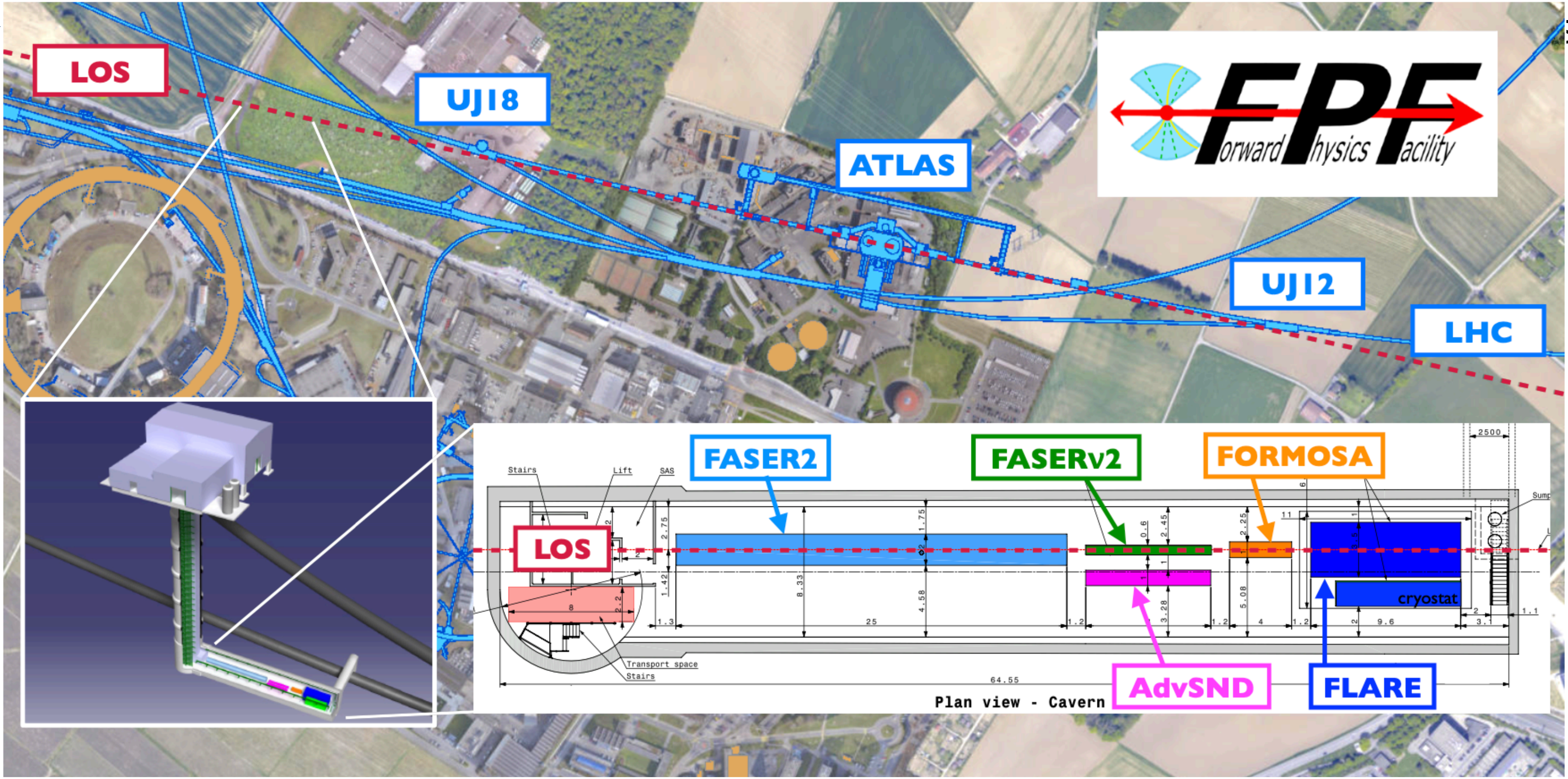
# Forward Physics Facility

- The FPF is well aligned with the recommendations of recent community studies in Europe and abroad:

  - 2020 European Strategy Update:
    - *"The full physics potential of the LHC and the HL- LHC…should be exploited"*
    - *"The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics. This search can be done in many ways, for example through … searches for axions, dark sector candidates and feebly interacting particles. …A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy. Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported"*

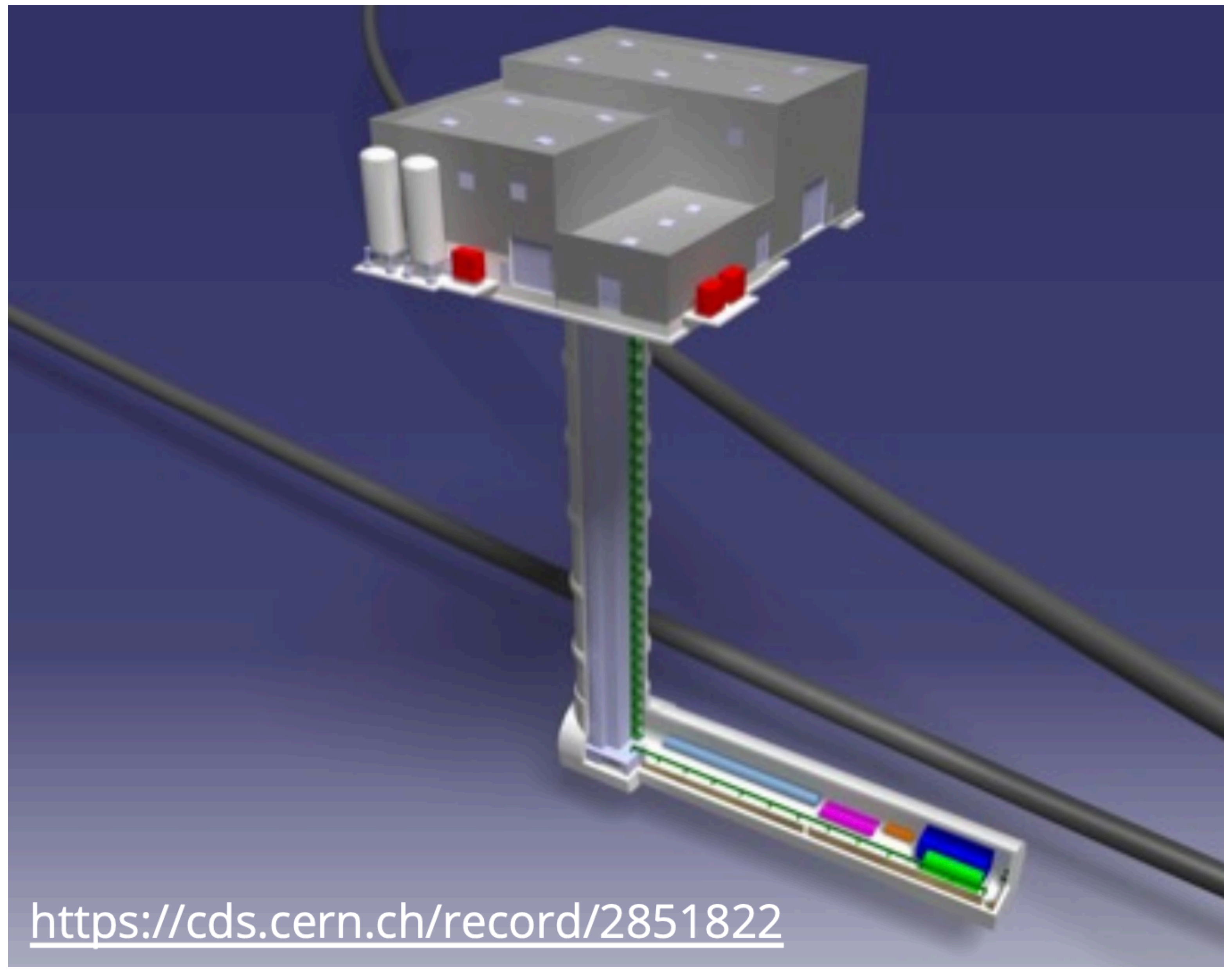
  - Snowmass 2021 Energy Frontier Report:
    - *"Our highest immediate priority accelerator and project is the HL-LHC,…including the construc- tion of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades"*

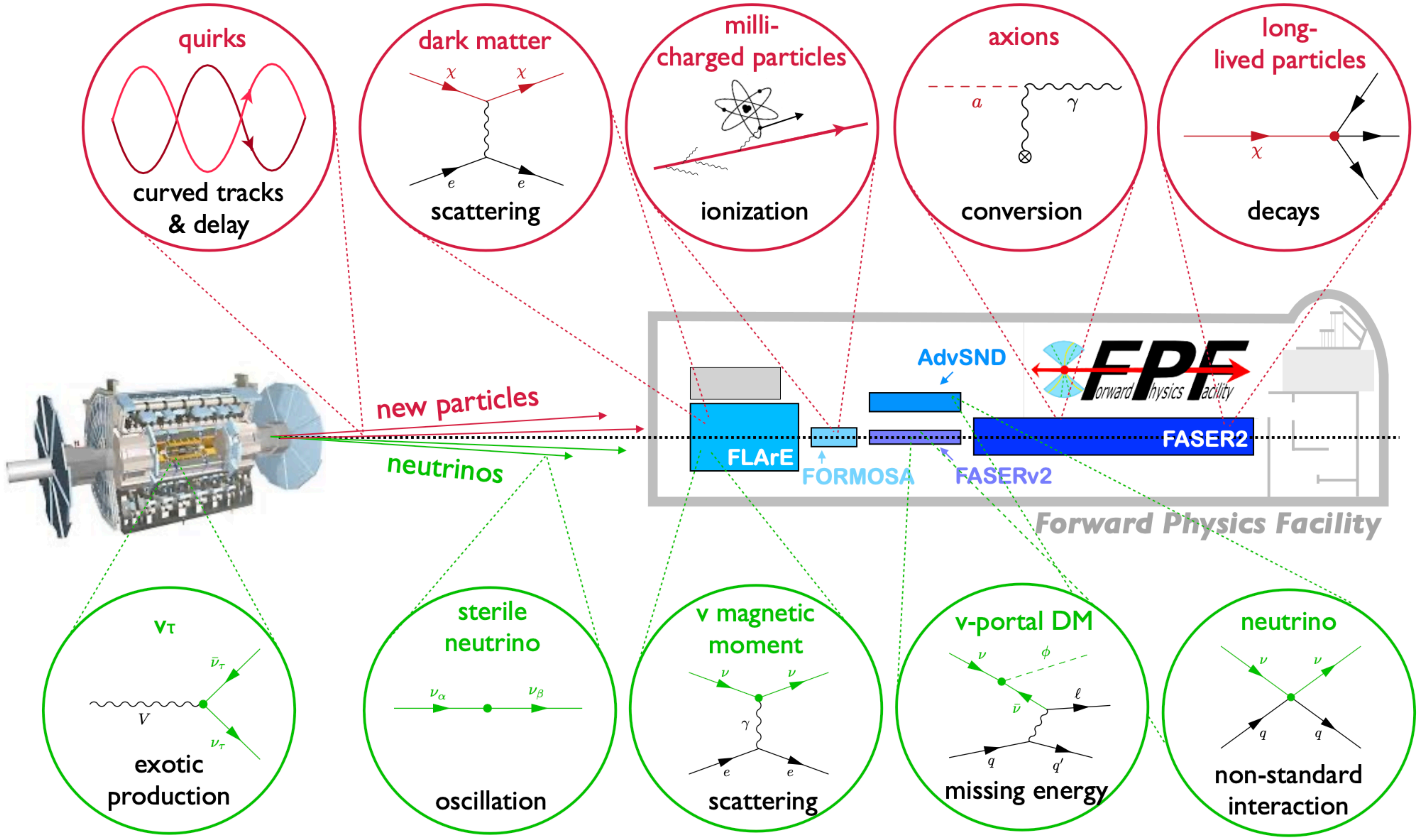
# Forward Physics Facility

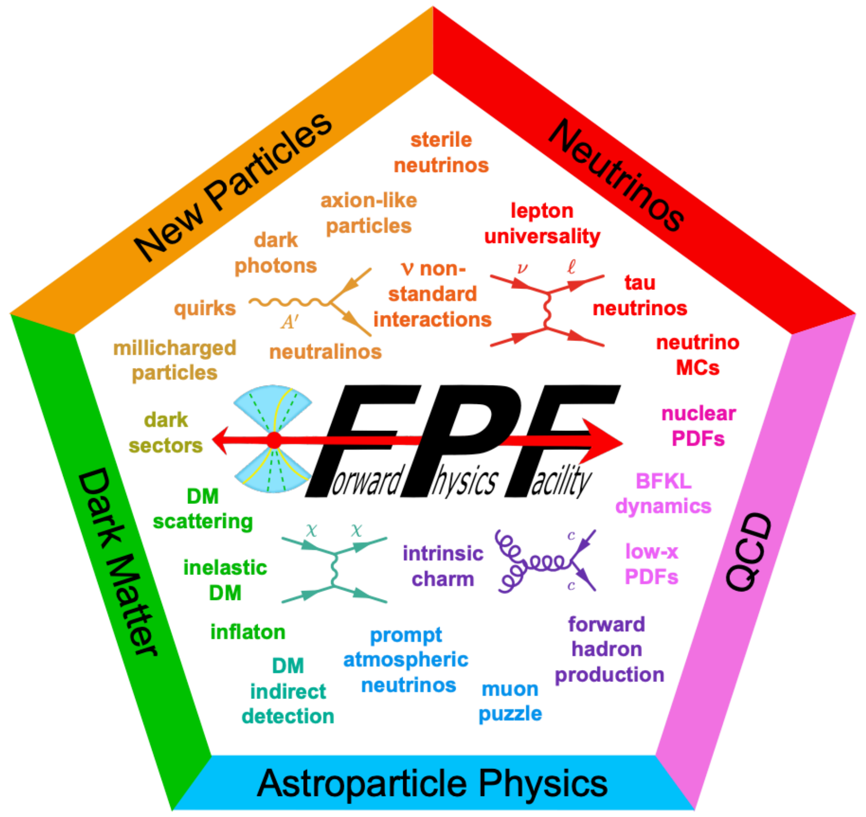


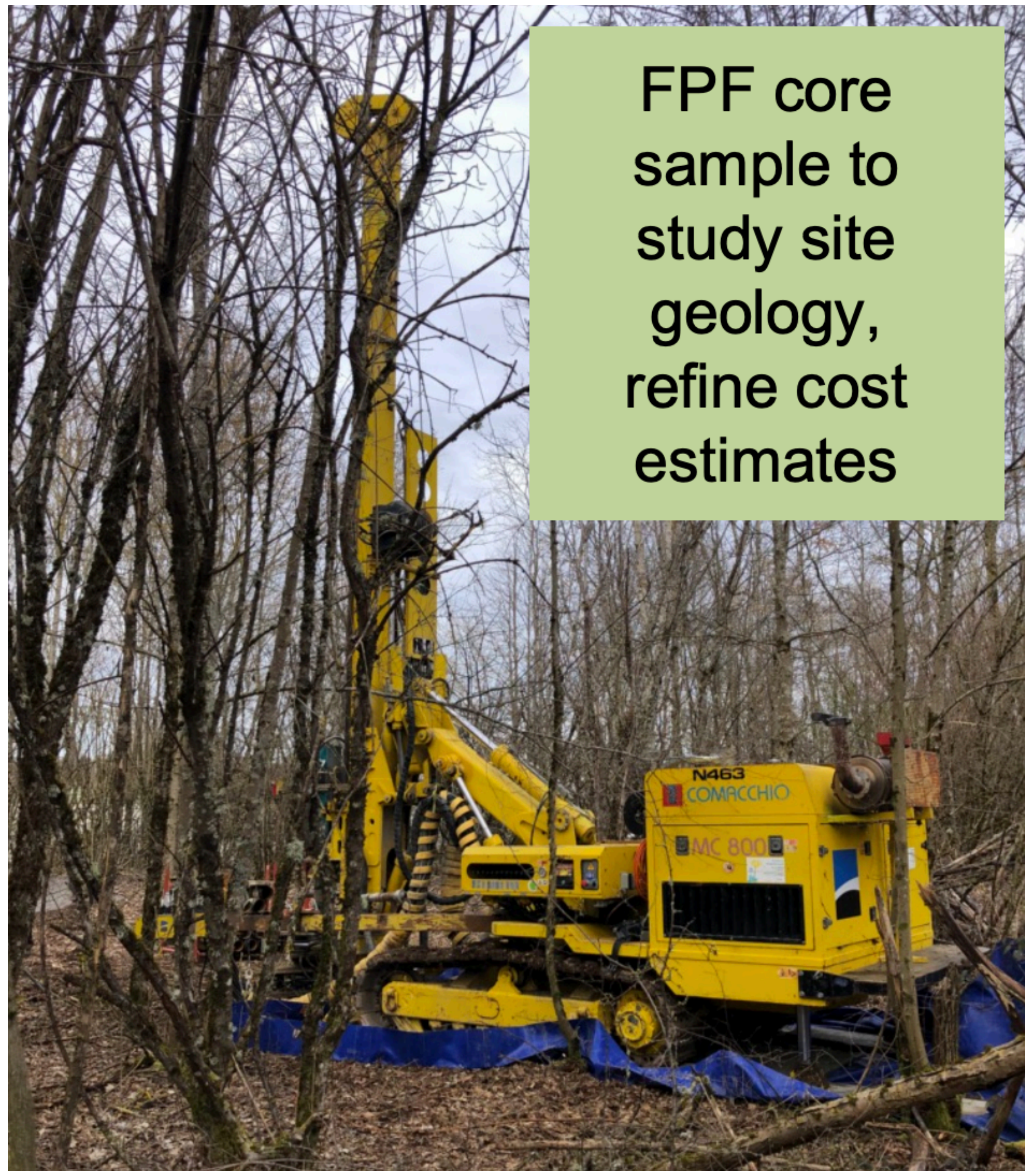
# Forward Physics Facility

- FPF Papers:
  - FPF "Short" Paper: Phys. Rept. 968, 1 (2022)
  - FPF White Paper: J. Phys. G (2022)



# FASER2


- Proof of principle now exists from FASER
- Slightly different design philosophy limited by large aperture magnet technologies
- Program for BSM and SM physics (main spectrometer to neutrino exps.)
- Currently considering, SciFi tracker and dual-readout calorimetry.

# FASER2


**Veto**

- Plastic scintillator-based veto system
- Expected to reject muon rates of ~ 20kHz

**Tracker**

- Silicon photomultiplier and scintillating fiber tracker technology
- Based on LHCb's SciFi[4] tracker
- Spatial resolution of ~ 100 μm
- Each station consists of vertical and horizontal SciFi modules

**Magnet**

- Rectangular aperture: 1 m in height, 3 m in width, 4 m depth
- Superconducting magnet technology
- Based on SAMURAI[5] experiment magnet
- BField 4 Tm bending power for particle separation, momentum resolution, and charge ID

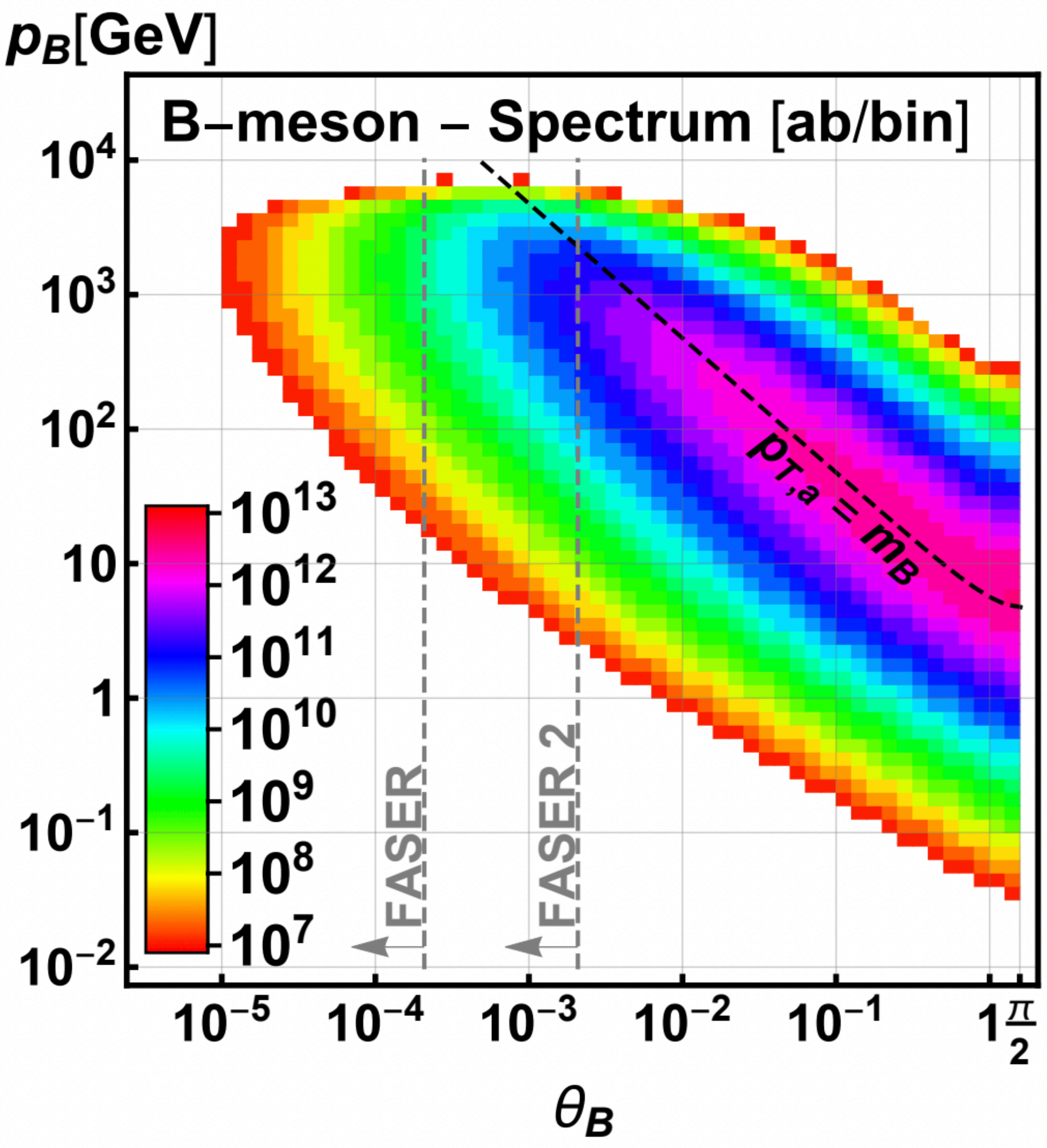
**EM Calorimeter**

**Hadronic Calorimeter**

- Dual-readout calorimetry[6] technology
- Spatial resolution for particle identification at ~ 1-10 mm separation
- Particle identification capabilities

# FASER2

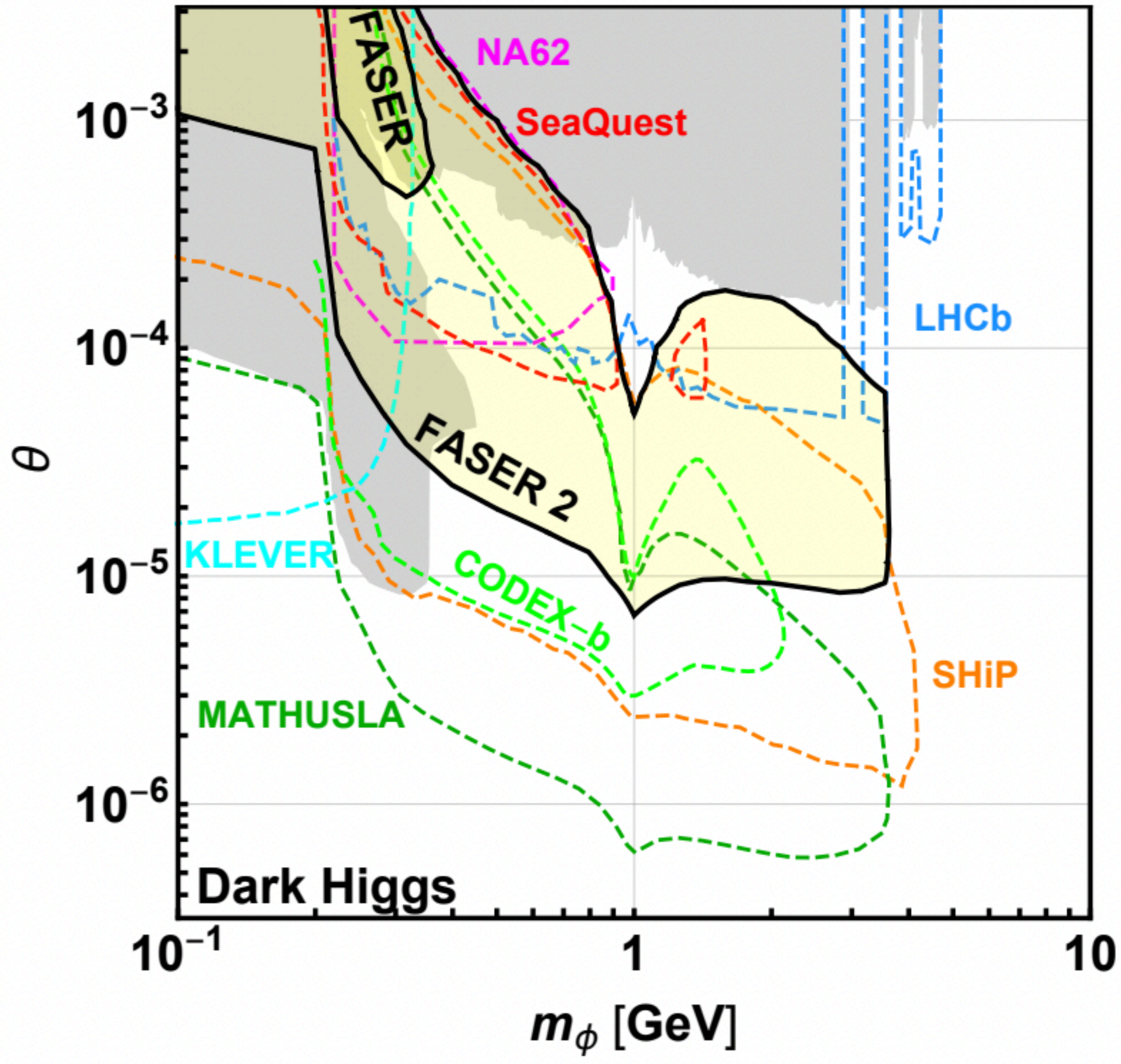
- Increasing detector radius to 1m would allow sensitivity to new physics produced in heavy meson (B, D) decays increasing the physics case beyond just the increased luminosity.



# FASER2

- Increasing detector radius to 1m would allow sensitivity to new physics produced in heavy meson (B, D) decays increasing the physics case beyond just the increased luminosity.

- FASER2 therefore becomes very strong compared to low energy experiments for certain models (dark Higgs), due to large B/D production rates at LHC:
  - $N_B/N_\pi \sim 10^{-2}$ ($\sim 10^{-7}$ at beam dump expts)



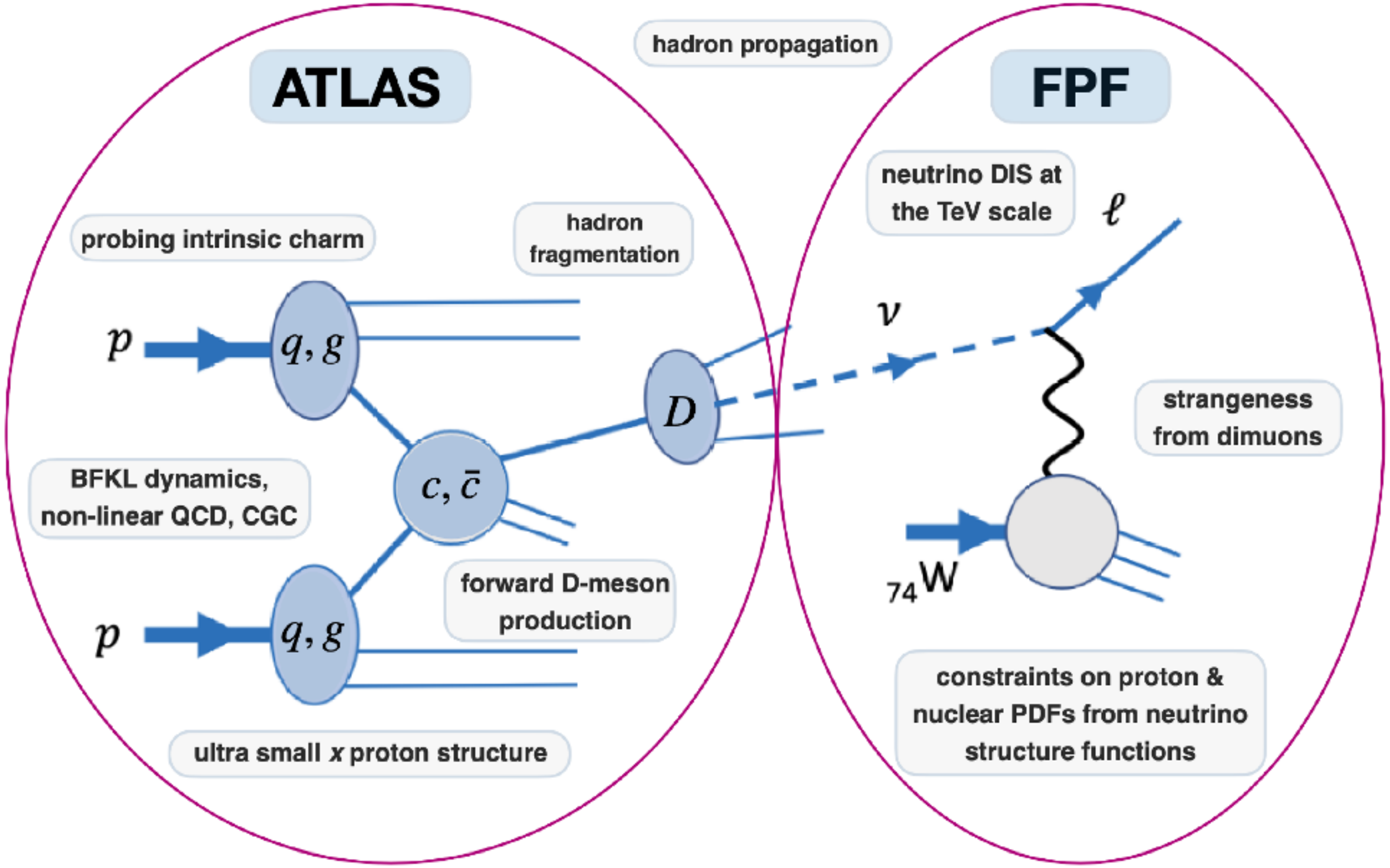
# FASER2

- FASER2 (R = 1 m, L = 5-20 m) can discover
  - All candidates with renormalizable couplings (dark photon, dark Higgs, HNL)
  - ALPs with all types of couplings (ɣ, f, g)
  - and many other particles.
- Among the PBC benchmark scenarios, FASER2's discovery potential extends to all benchmark scenarios
  - Except BC2 and BC3.

| Benchmark Model | FASER | FASER 2 |
|---|---|---|
| BC1: Dark Photon | √ | √ |
| BC1': $U(1)_{B-L}$ Gauge Boson | √ | √ |
| BC2: Invisible Dark Photon | – | – |
| BC3: Milli-Charged Particle | – | – |
| BC4: Dark Higgs Boson | – | √ |
| BC5: Dark Higgs with hSS | – | √ |
| BC6: HNL with e | – | √ |
| BC7: HNL with $\mu$ | – | √ |
| BC8: HNL with $\tau$ | √ | √ |
| BC9: ALP with photon | √ | √ |
| BC10: ALP with fermion | √ | √ |
| BC11: ALP with gluon | √ | √ |

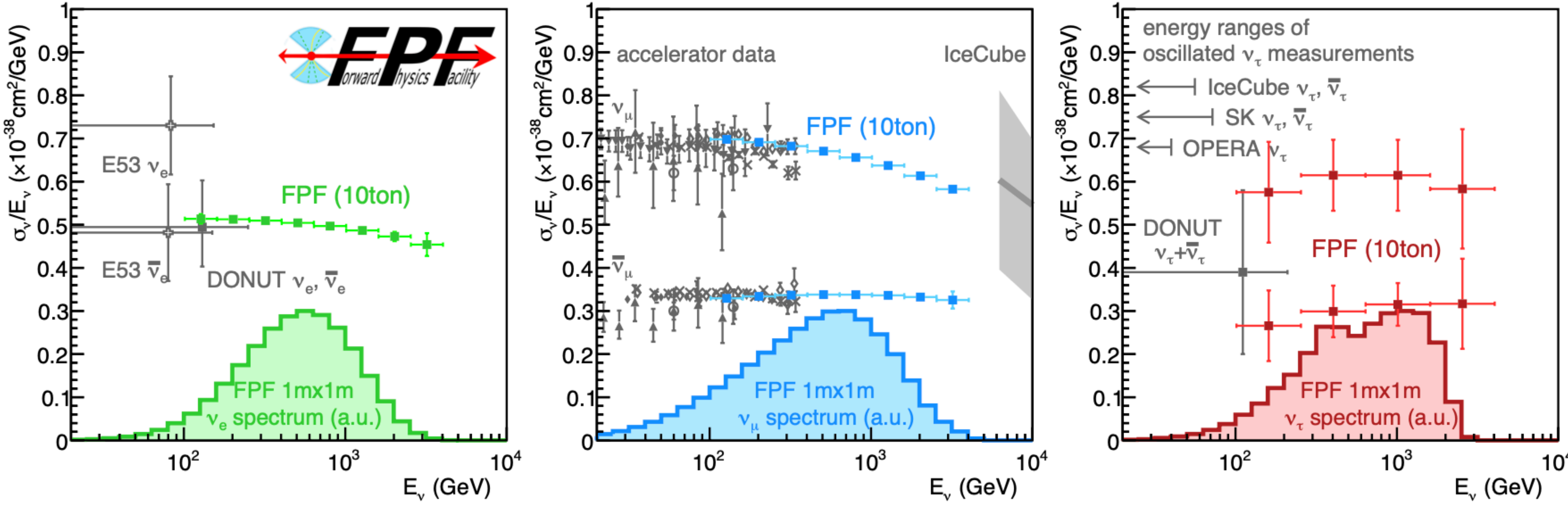
# Neutrino physics

- Study neutrino interactions at high energy
  - Search for BSM physics in neutrino production, propagation and interaction
  - Study PDFs by DIS of neutrino in the target (fixed target 75 GeV CoM E)
  - Study forward hadron production via neutrino flux measurements



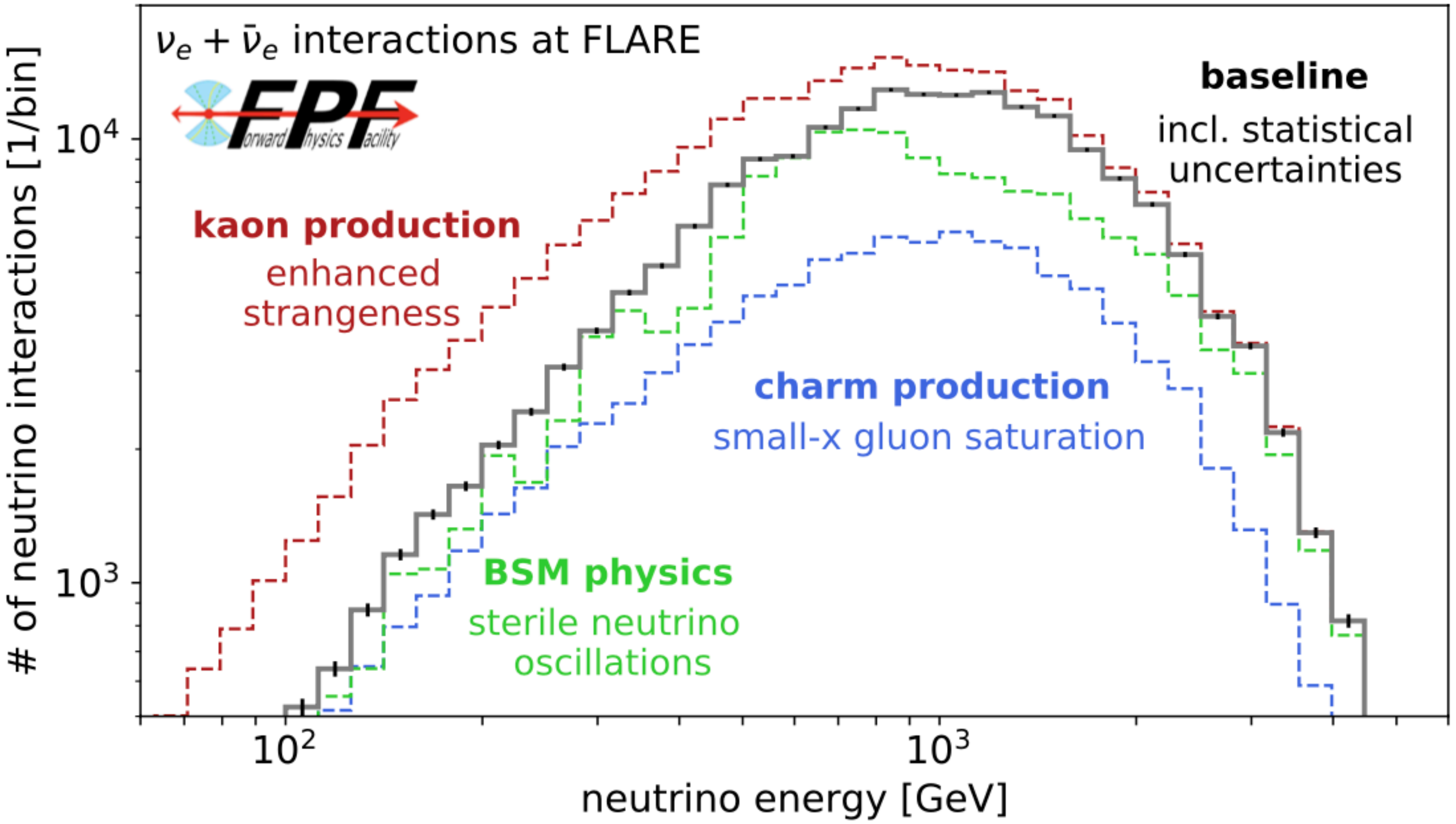
# Forward Physics Facility | Neutrinos

- The FPF experiments will see $10^5$ $\nu_e$, $10^6$ $\nu_\mu$ and $10^4$ $\nu_\tau$ interactions at E~TeV where there is currently no data



# Forward Physics Facility | Neutrinos

- Neutrinos are produced by forward hadron production: π, K , D…. Energy spectra will inform:
  - Astroparticle physics: muon puzzle, …
  - QCD: pdfs at x ~ $10^{-1}$, x ~ $10^{-7}$ , intrinsic charm, small-x gluon saturation, …
  - Neutrino properties: short-baseline neutrino experiment. Sensitive to sterile neutrinos



# Forward Physics Facility | Neutrinos

- Neutrinos are produced by forward hadron production: π, K , D…. Energy spectra will inform:
  - Astroparticle physics: muon puzzle, …
  - QCD: pdfs at $x \sim 10^{-1}$, $x \sim 10^{-7}$ , intrinsic charm, small-x gluon saturation, …
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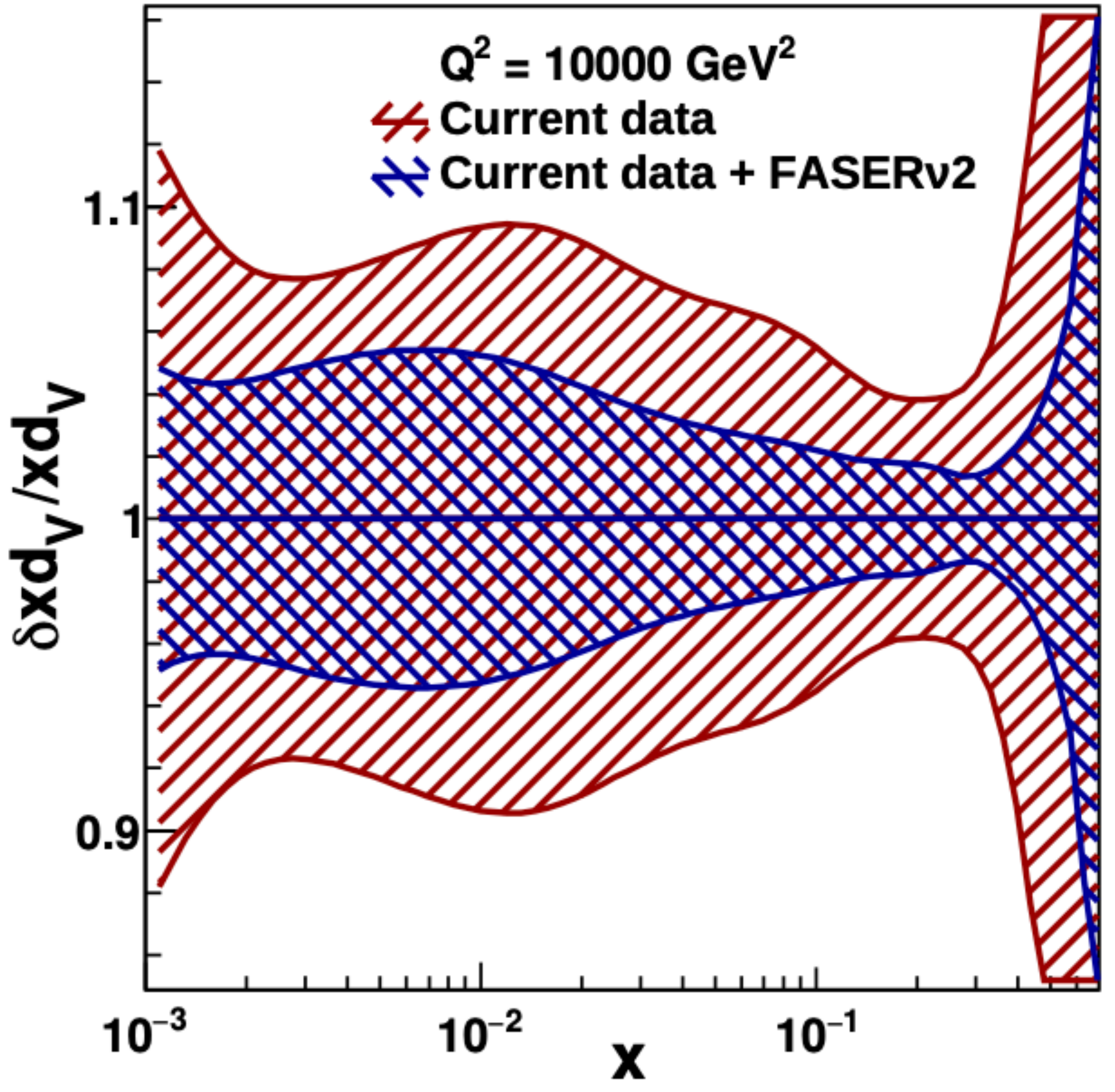
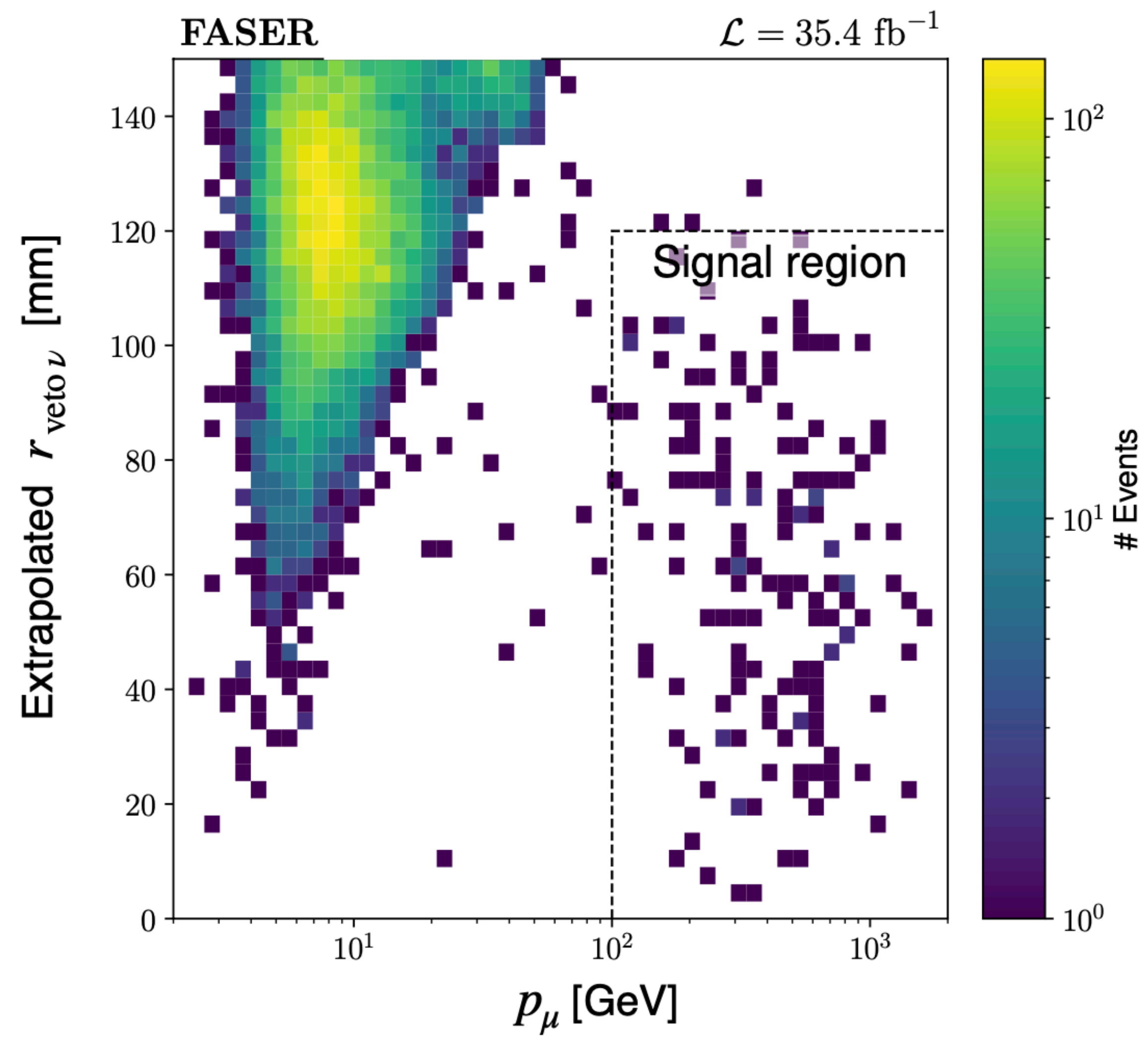


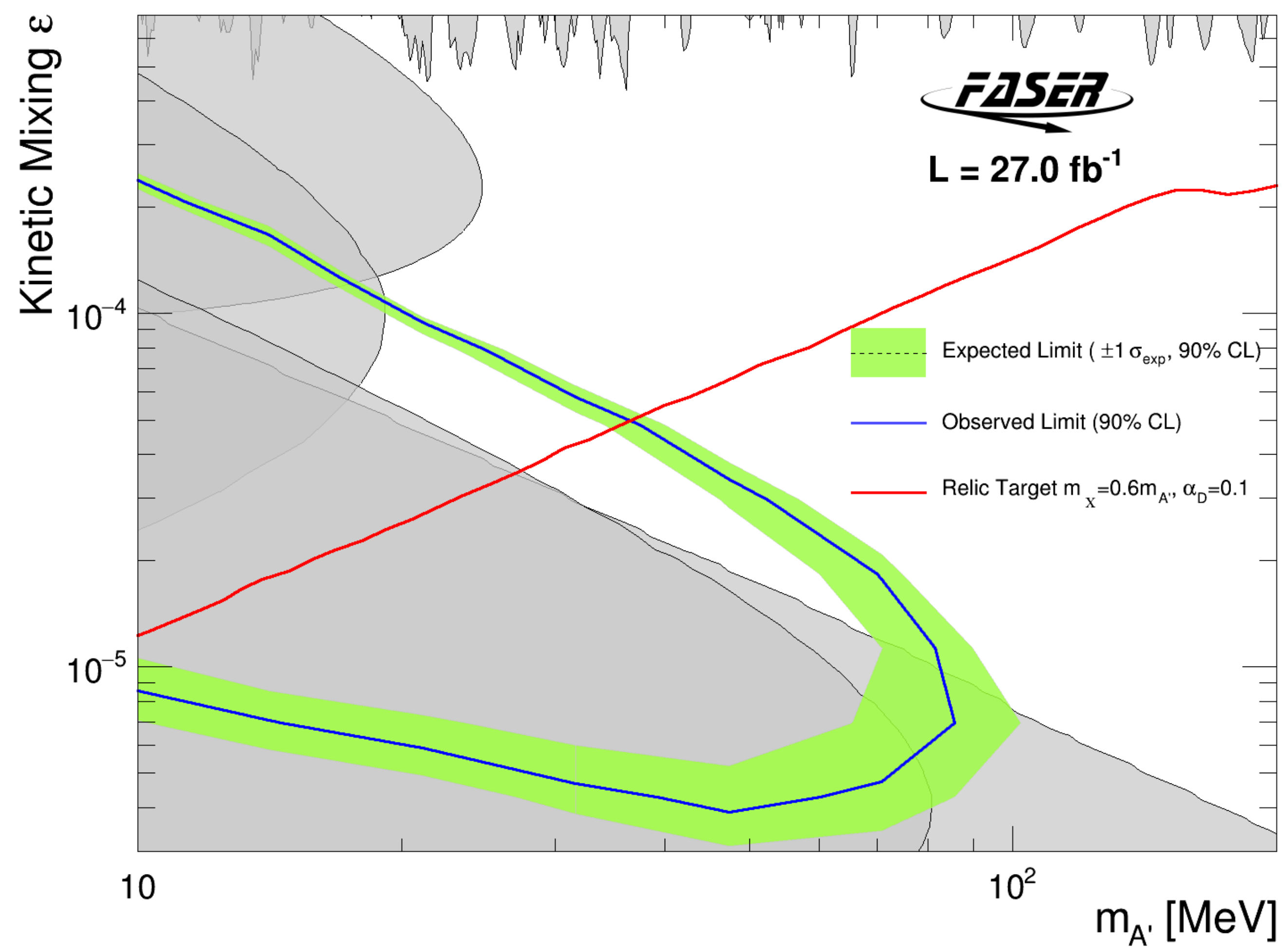

- Fully differential neutrino DIS scattering XS will improve constraints on pdfs by up to ~2x

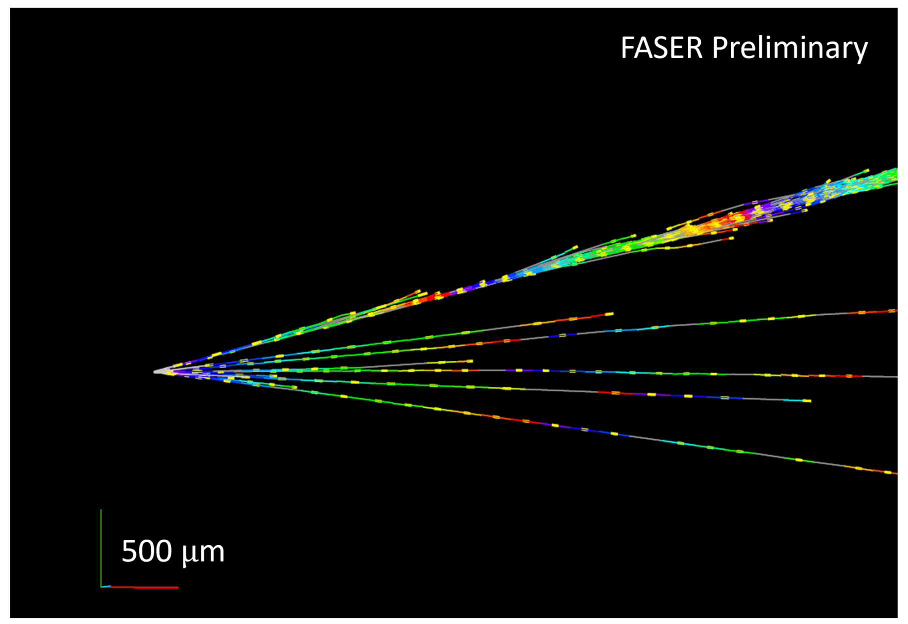

# Summary

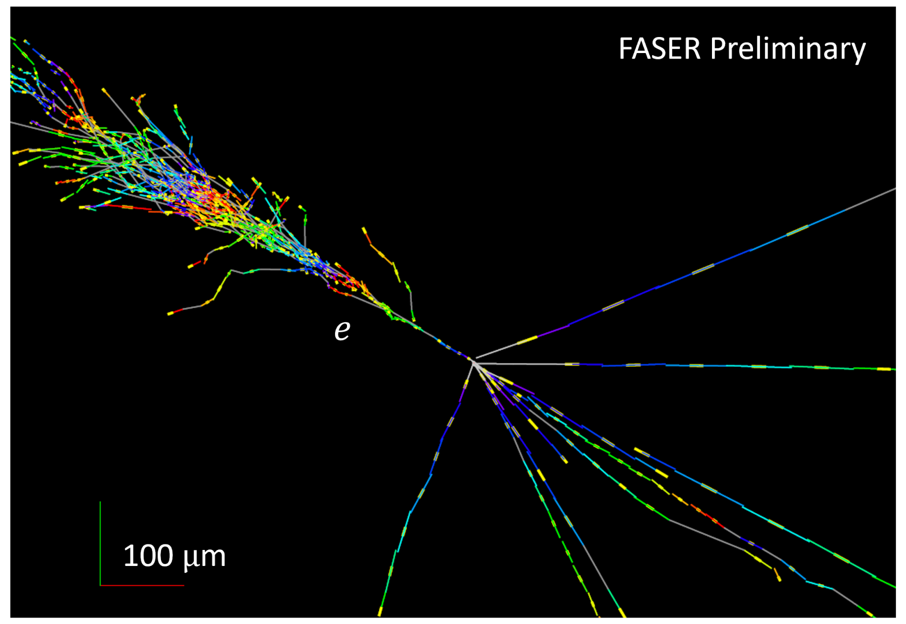
# Summary

- First direct observation of collider neutrinos
  - Opens a new field: neutrino physics at the LHC
  - Published in PRL [2303.14185]
- First Dark Photon search
  - First limit in thermal relic region from low coupling for 30 yrs
  - Submitted to [arXiv:2308.05587]
- High-energy $\nu_e$ interactions in emulsion detector
  - [CERN-FASER-CONF-2023-002]
- More neutrino studies and BSM searches to come
  - Including searches for ALPs, light gauge bosons, …
- Strongly motivates FPF & FASER2 for HL-LHC era



# Summary

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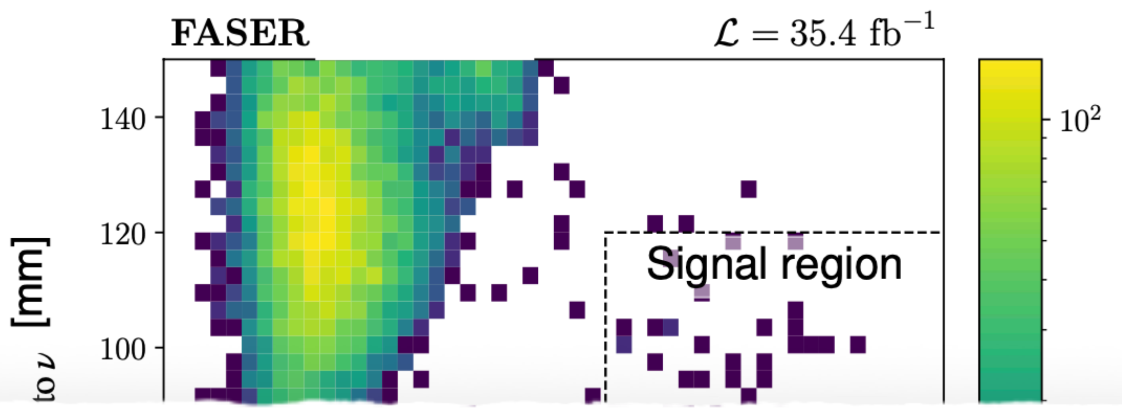


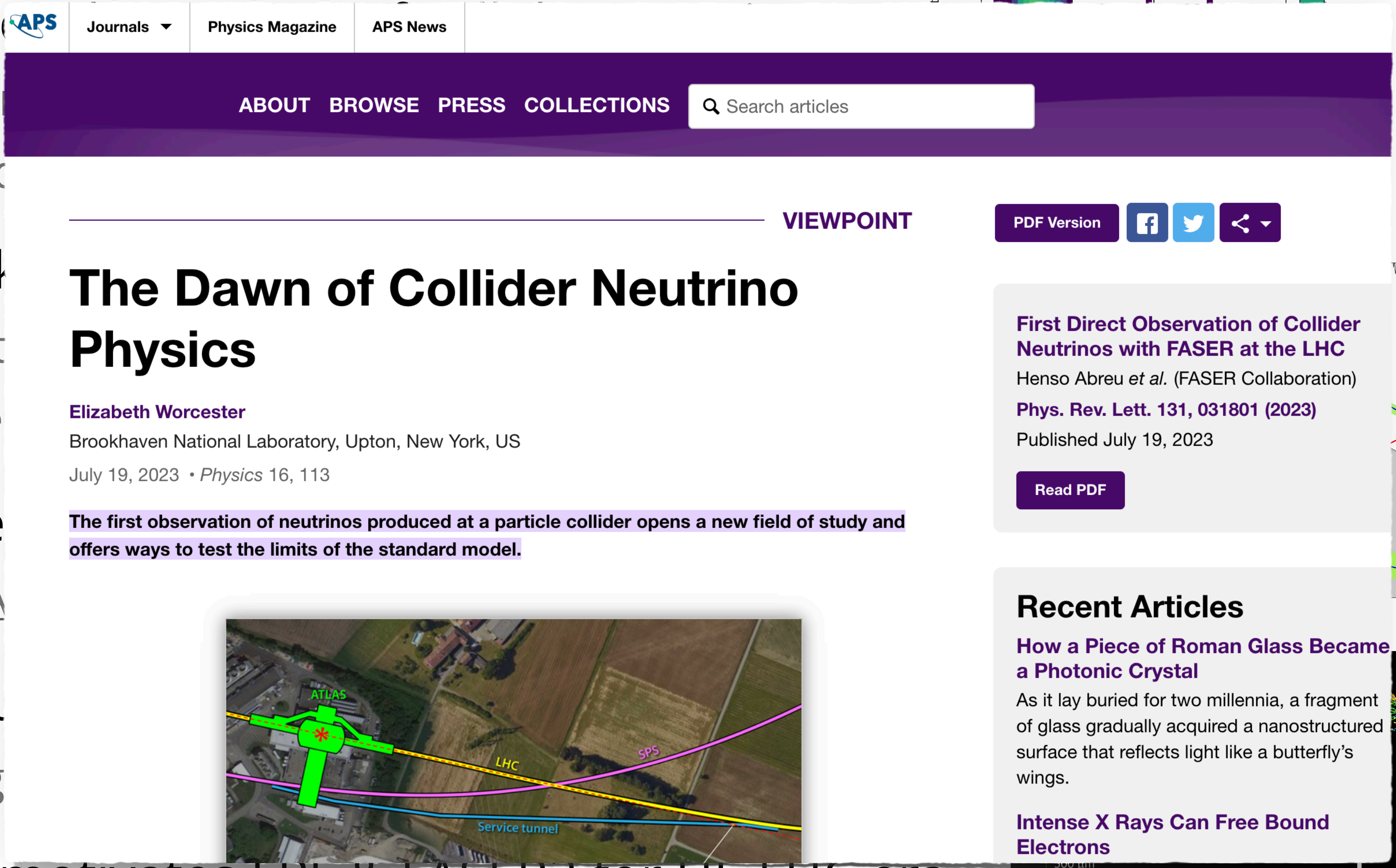
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VIEWPOINT

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## The Dawn of Collider Neutrino Physics

**Elizabeth Worcester**
Brookhaven National Laboratory, Upton, New York, US
July 19, 2023 • *Physics* 16, 113

**The first observation of neutrinos produced at a particle collider opens a new field of study and offers ways to test the limits of the standard model.**



**First Direct Observation of Collider Neutrinos with FASER at the LHC**
Henso Abreu *et al.* (FASER Collaboration)
**Phys. Rev. Lett. 131, 031801 (2023)**
Published July 19, 2023

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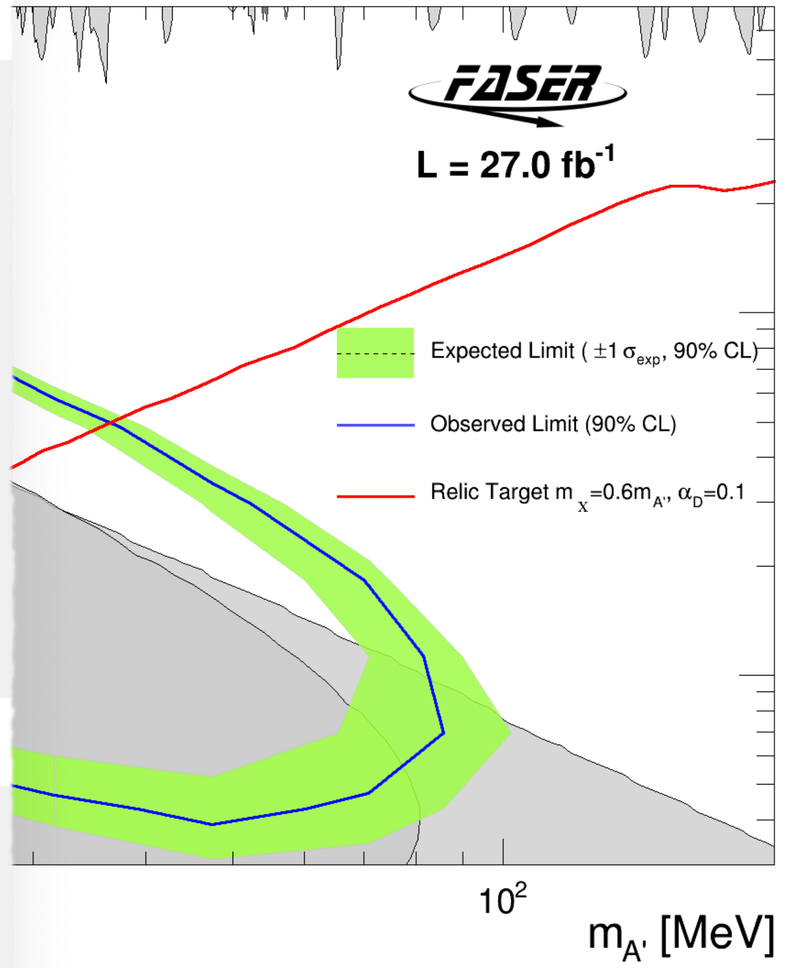
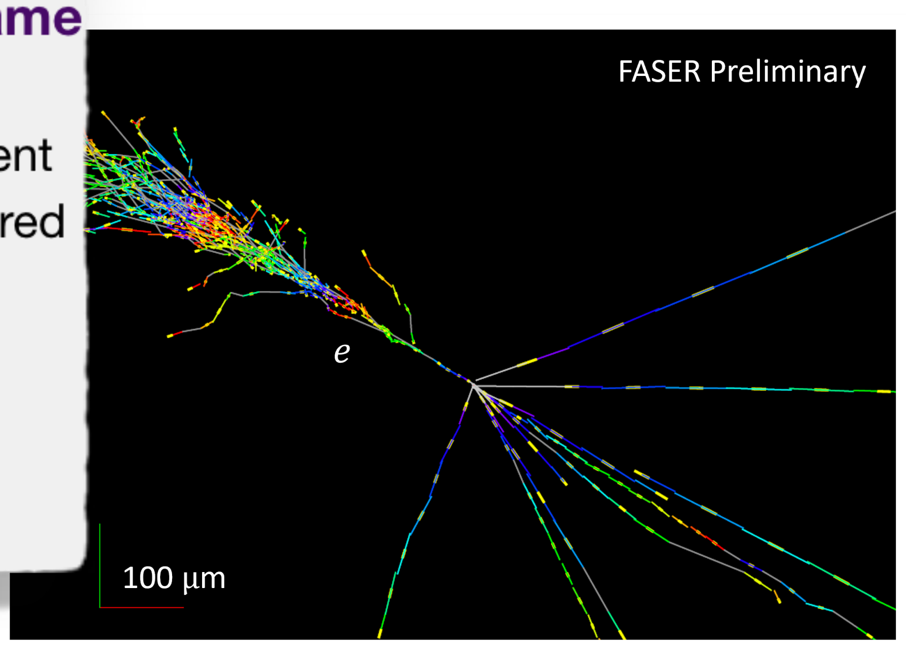
## Recent Articles

**How a Piece of Roman Glass Became a Photonic Crystal**
As it lay buried for two millennia, a fragment of glass gradually acquired a nanostructured surface that reflects light like a butterfly's wings.

**Intense X Rays Can Free Bound Electrons**




- Strongly motivates FPF & FASER2 for HL-LHC era

# Acknowledgements

UNIVERSITY OF SUSSEX


- FASER is supported by:

SIMONS FOUNDATION
HEISING-SIMONS FOUNDATION
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CERN
Swiss National Science Foundation
erc
科研費 KAKENHI
国家自然科学基金委员会 National Natural Science Foundation of China


- And would additionally like to thank
  - LHC for the excellent performance in 2022
  - ATLAS for providing luminosity information
  - ATLAS for use of ATHENA s/w framework
  - ATLAS SCT for spare tracker modules
  - LHCb for spare ECAL modules
  - CERN FLUKA team for background sim
  - CERN PBC and technical infrastructure groups for excellent support during design construction and installation

# Collaboration

- 87 members
- 24 institutions
- 10 countries

International laboratory covered by a cooperation agreement with CERN


# Back-ups

# Detector Performance: Trigger + DAQ

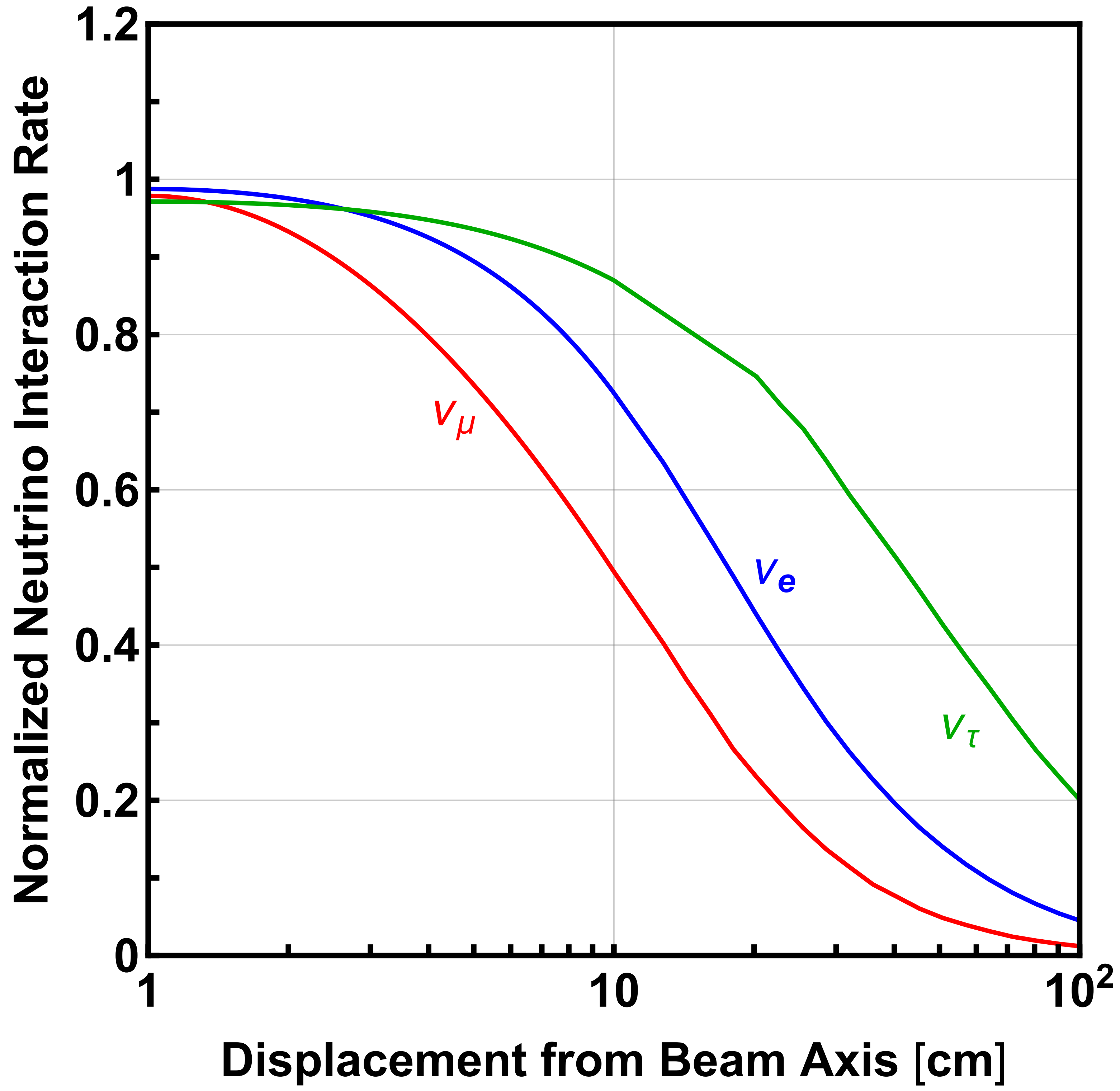
- DAQ running smoothly up to 1.3 kHz with deadtime only 1.3%
- Total trigger rate falls off faster than luminosity during run (higher beam-induced backgrounds) but coincidence trigger rate flat with respect to luminosity

# FASERν | Physics case

- The energy spectrum expected at FASERν is rather complementary to existing neutrino experiments

- Expected cross section sensitivity significantly extends current measurements during Run 3 (150 $fb^{-1}$)

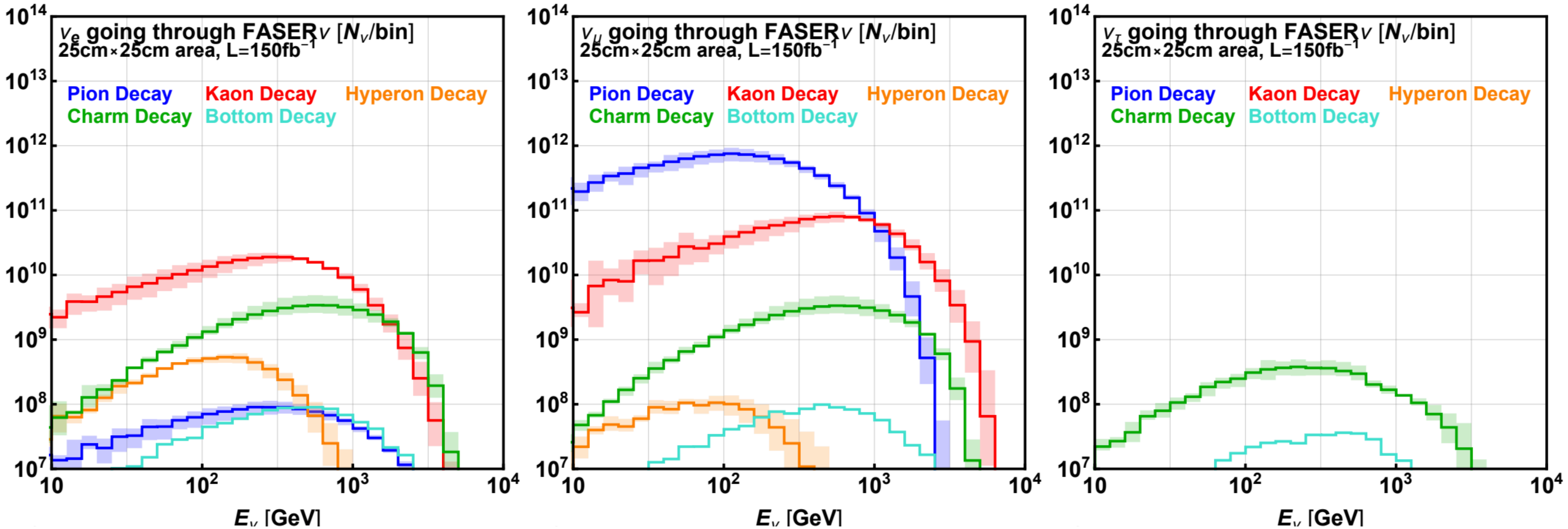
- Being located on line-of-sight FASERν is able to observe a maximum rate of all neutrino flavours:



# Neutrino analysis

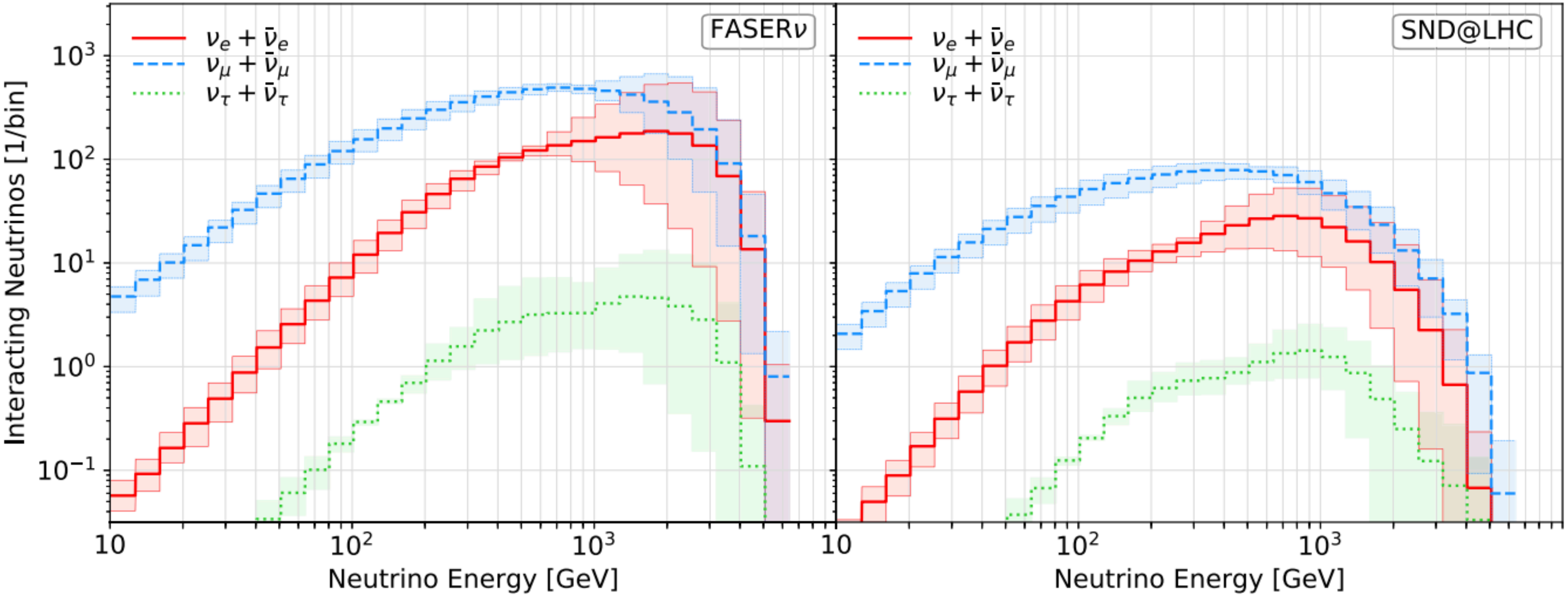
| Type | Particles | Main Decays | E | Q | S | P |
|---|---|---|---|---|---|---|
| Pions | $\pi^+$ | $\pi^+ \to \mu\nu$ | √ | √ | √ | — |
| Kaons | $K^+, K_S, K_L$ | $K^+ \to \mu\nu$, $K \to \pi\ell\nu$ | √ | √ | √ | — |
| Hyperons | $\Lambda, \Sigma^+, \Sigma^-, \Xi^0, \Xi^-, \Omega^-$ | $\Lambda \to p\ell\nu$ | √ | √ | √ | — |
| Charm | $D^+, D^0, D_s, \Lambda_c, \Xi_c^0, \Xi_c^+$ | $D \to K\ell\nu$, $D_s \to \tau\nu$, $\Lambda_c \to \Lambda\ell\nu$ | — | — | √ | √ |
| Bottom | $B^+, B^0, B_s, \Lambda_b, \ldots$ | $B \to D\ell\nu$, $\Lambda_b \to \Lambda_c\ell\nu$ | — | — | — | √ |

[arXiv:1908.02310]

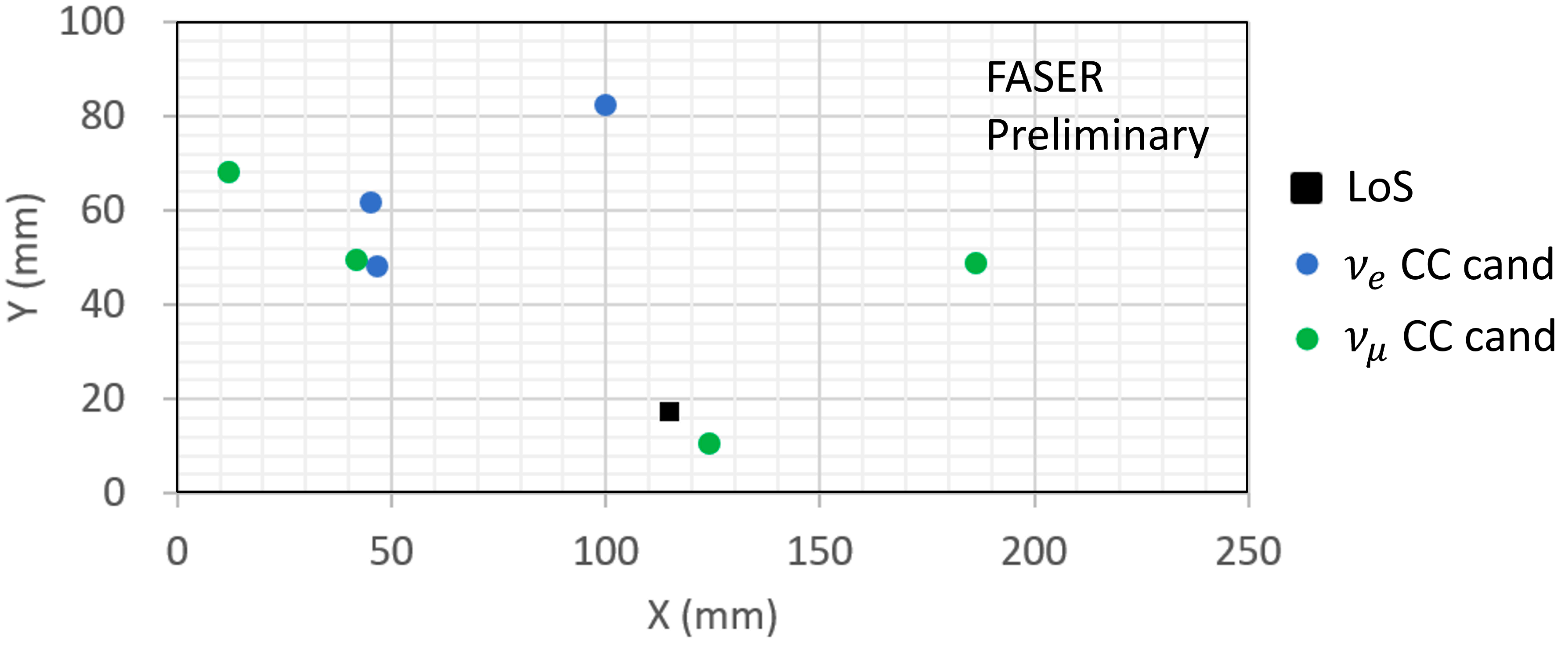


# Neutrino analysis

[PRD 104, 113008]



# Emulsion analysis | Results

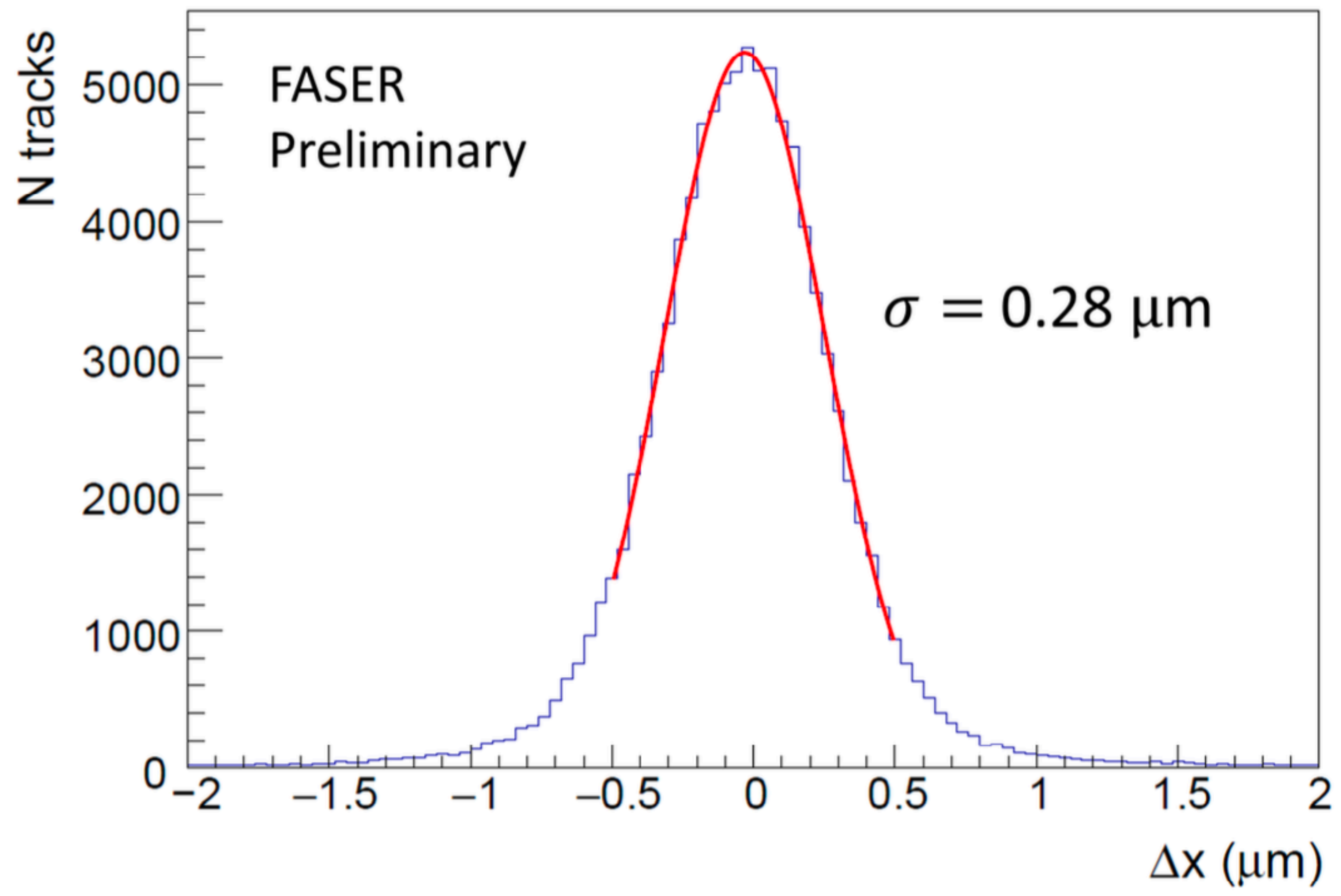


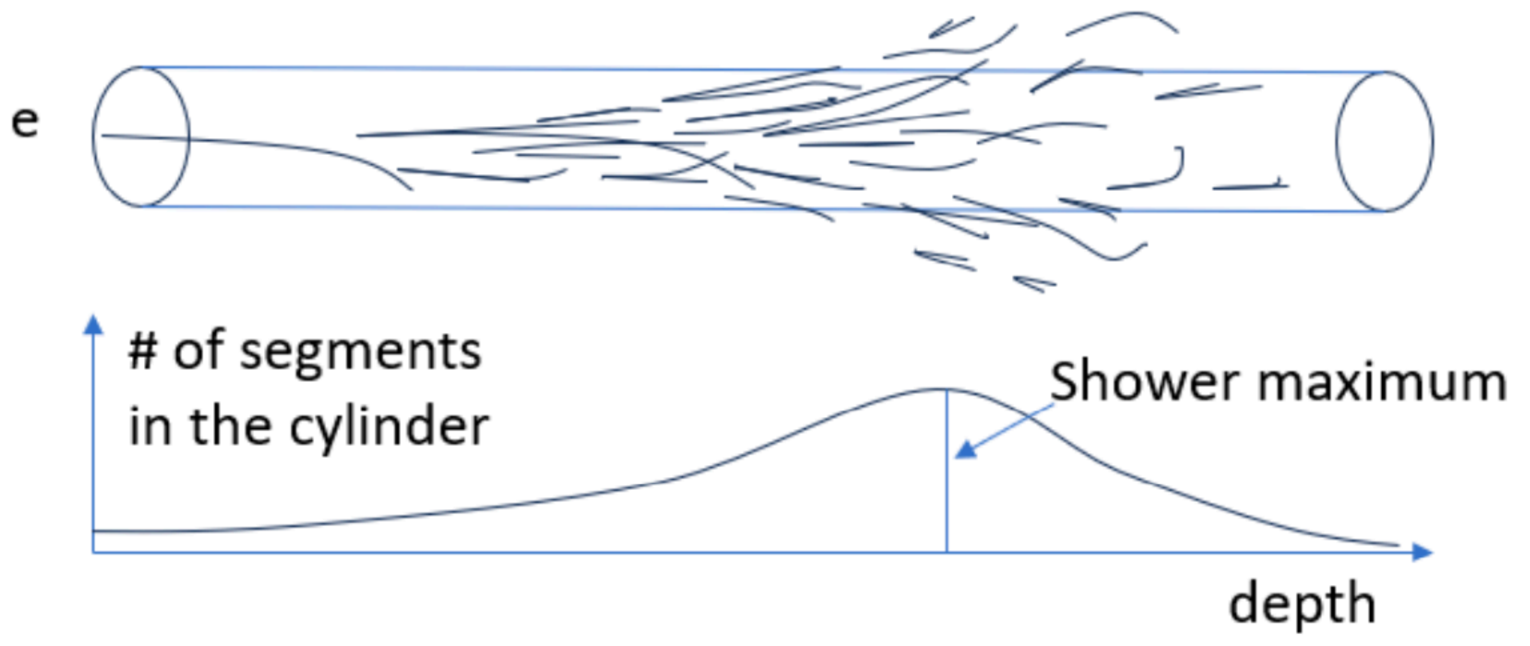
# Emulsion analysis | Results

| Selection | Quantity | $K_L$ | $n$ | $\Lambda$ | Total |
|---|---|---|---|---|---|
| $\nu_\mu$ selection $E > 50$ GeV | Raw MC events | 77 | 71 | 70 | - |
| $\nu_\mu$ selection $E > 200$ GeV | Raw MC events | 1 | 3 | 2 | - |
| | Scaled to analysis dataset | 0.07 | 0.16 | 0.10 | 0.32 |
| $\nu_e$ selection $E > 50$ GeV | Raw MC events | 0 | 1 | 0 | - |
| $\nu_e$ selection $E > 200$ GeV | Raw MC events | 0 | 0 | 0 | - |
| | Scaled to analysis dataset | 0 | 0 | 0 | 0 |

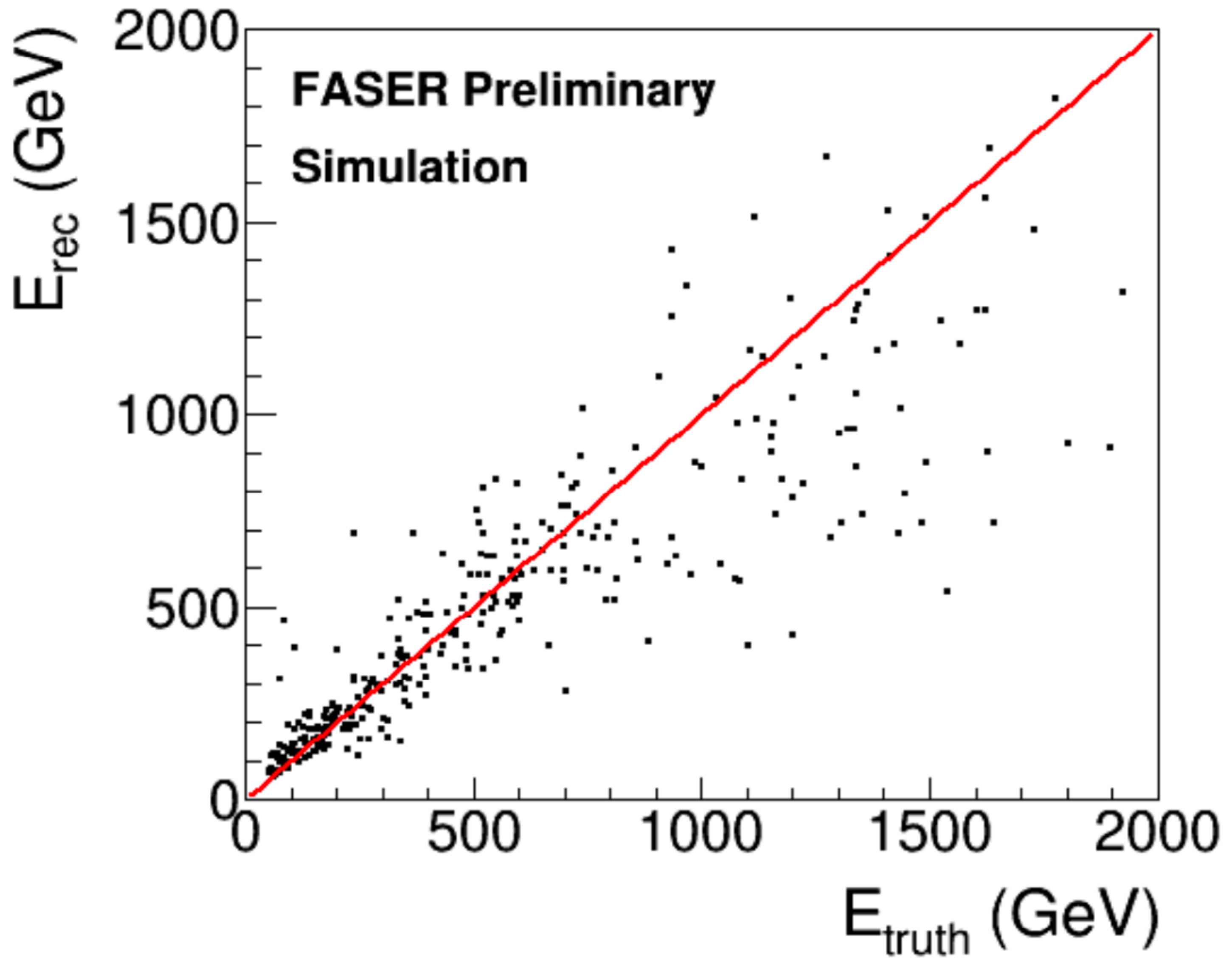
| Background | $\nu_\mu$ CC | $\nu_e$ CC |
|---|---|---|
| Neutral-hadron interactions | $0.32 \pm 0.15$ (stat.) $\pm 0.16$ (syst.) | $0.002 \pm 0.002$ (stat.) $\pm 0.002$ (syst.) |
| NC neutrino interactions | $0.19 \pm 0.15$ | - |
| Total | $0.51 \pm 0.27$ | $0.002 \pm 0.003$ |

# Emulsion analysis | Performance

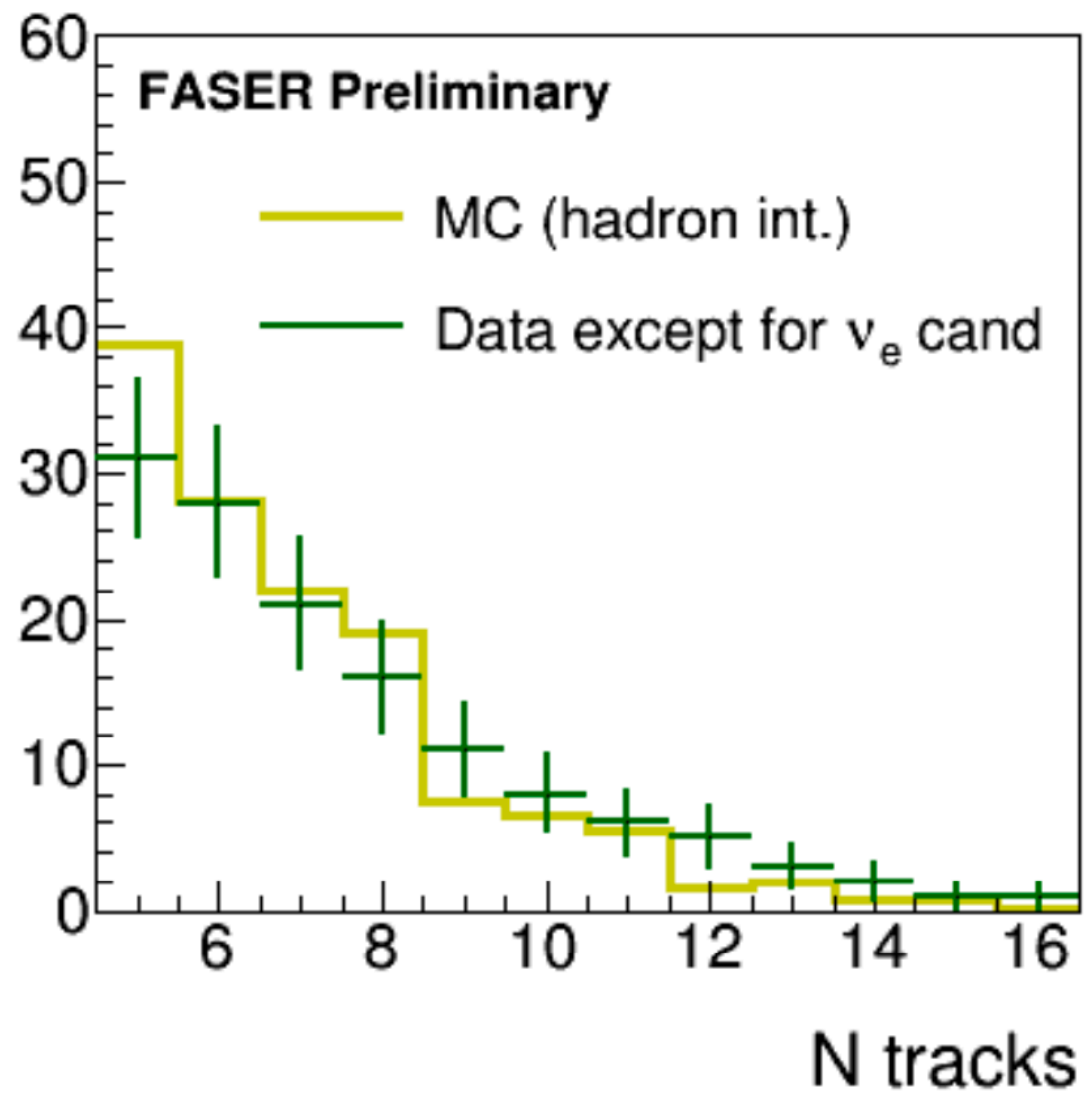


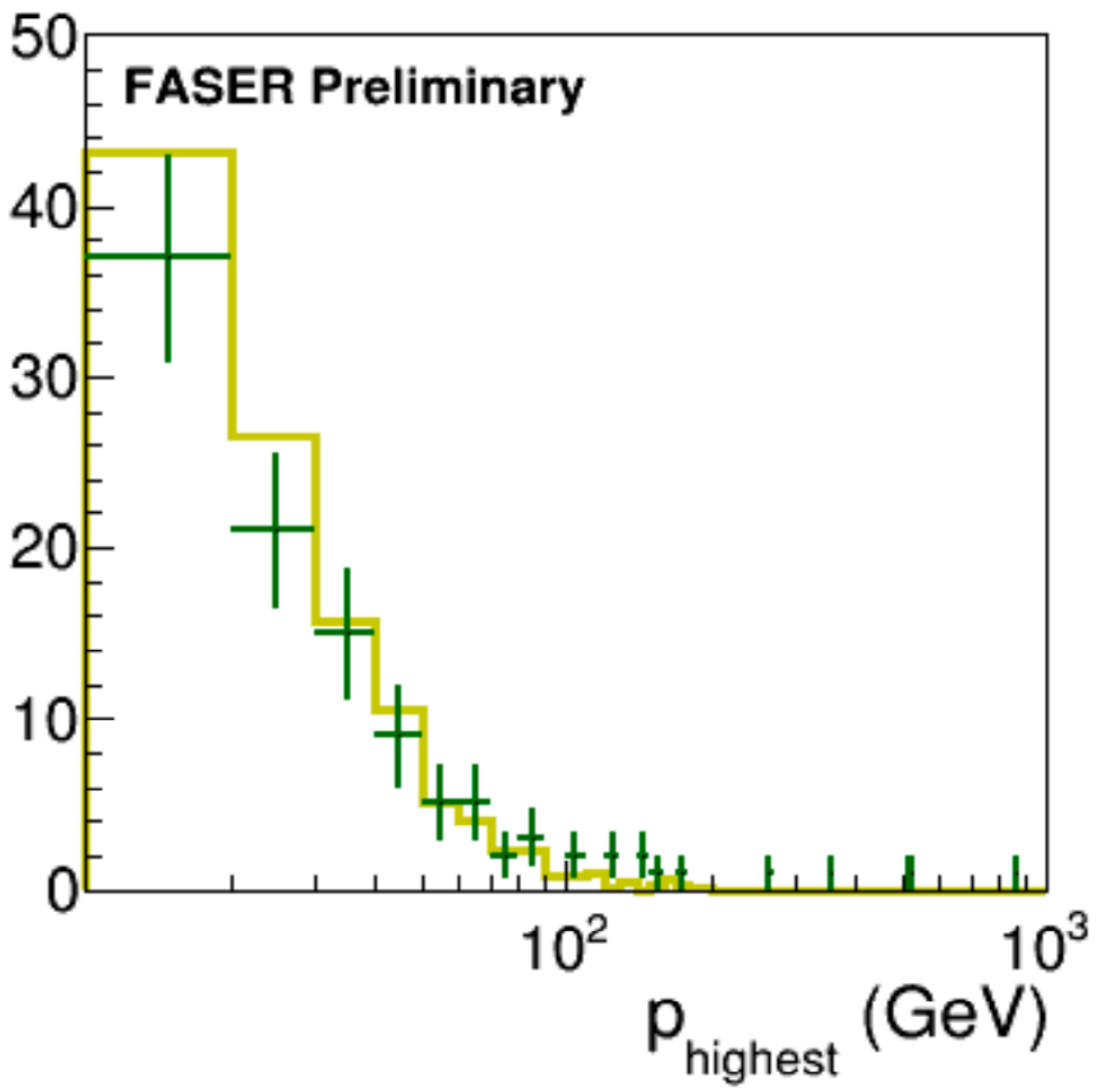



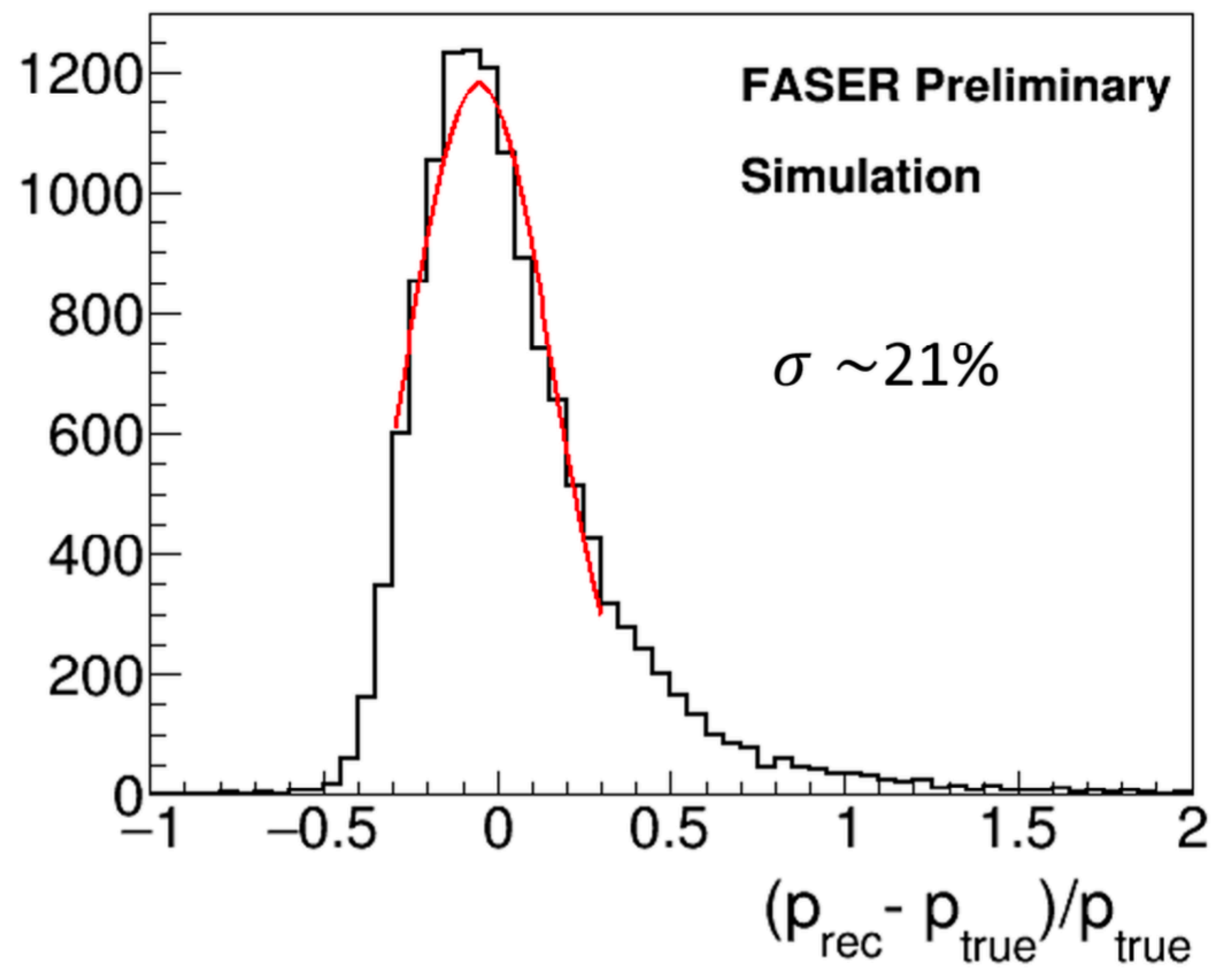

$\delta pos < 100\ \mu m$
$\delta\theta < 10$ mrad
$dmin < 50\ \mu m$




25% for EM energies at 200 GeV. Between 25-40% for higher energies



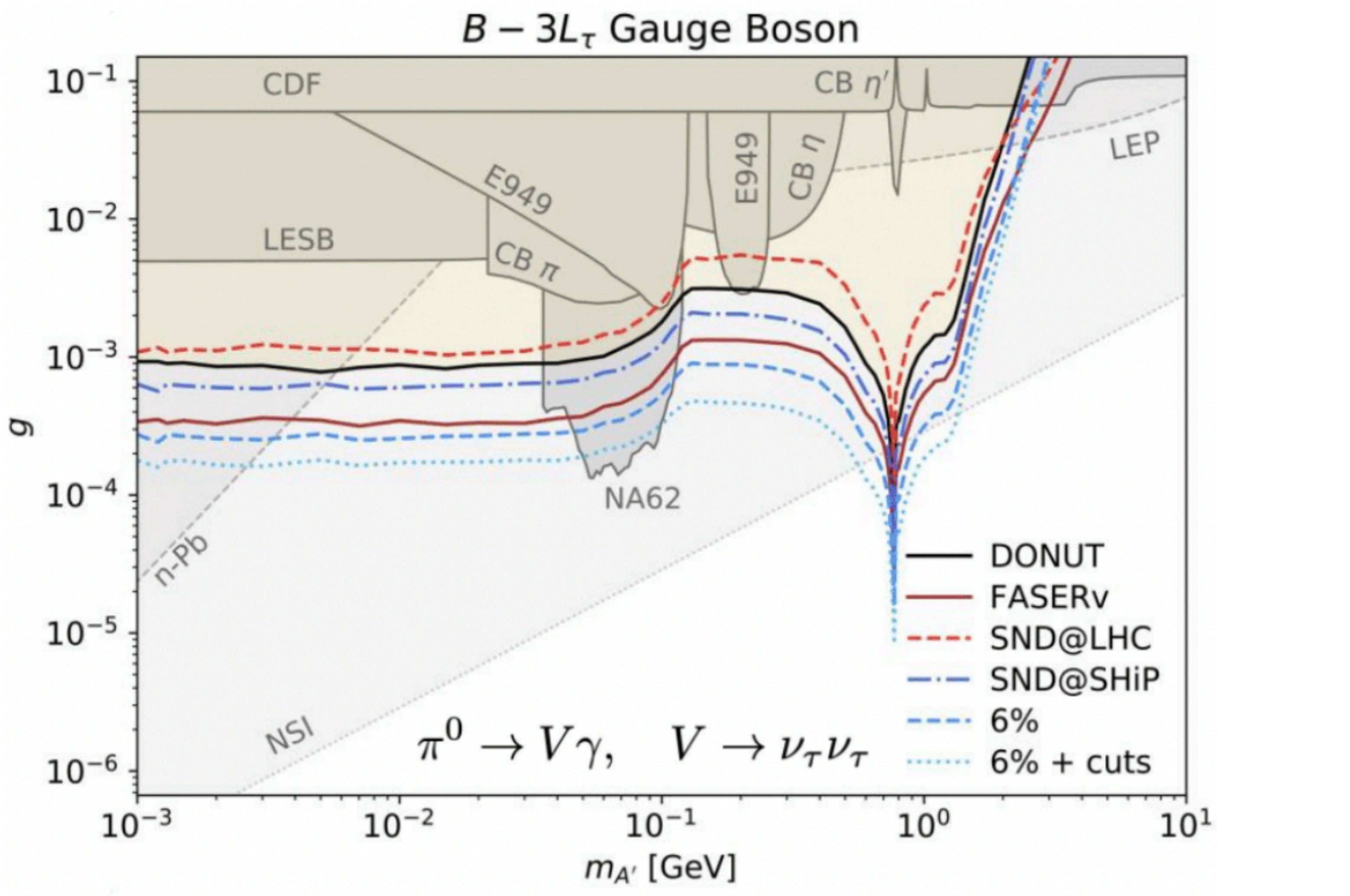
# Emulsion analysis | HTS

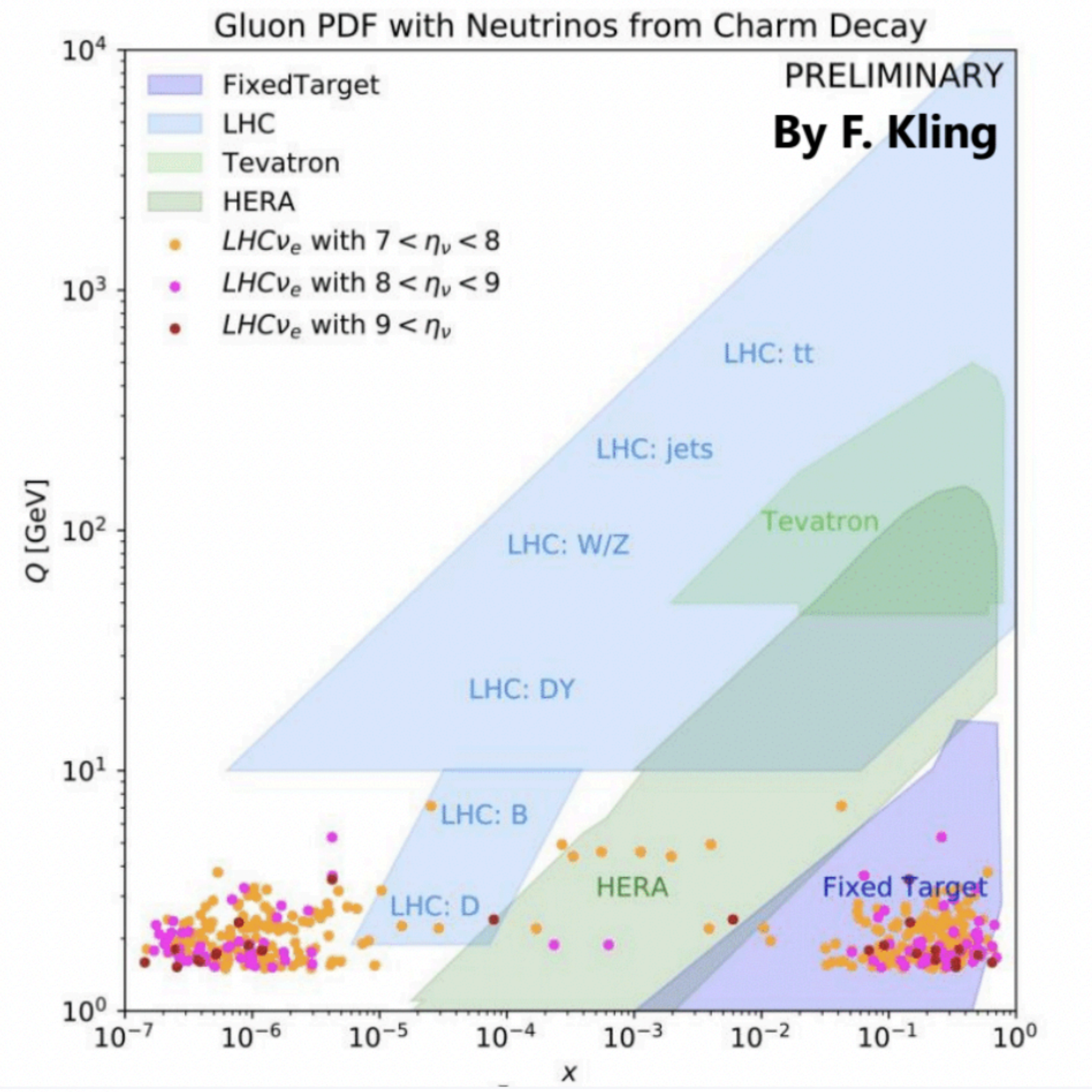
- HTS: https://arxiv.org/abs/1704.06814
- The track reconstruction algorithm is based on that of the NA65/DsTau experiment and is described in http://arxiv.org/abs/1906.03487 .

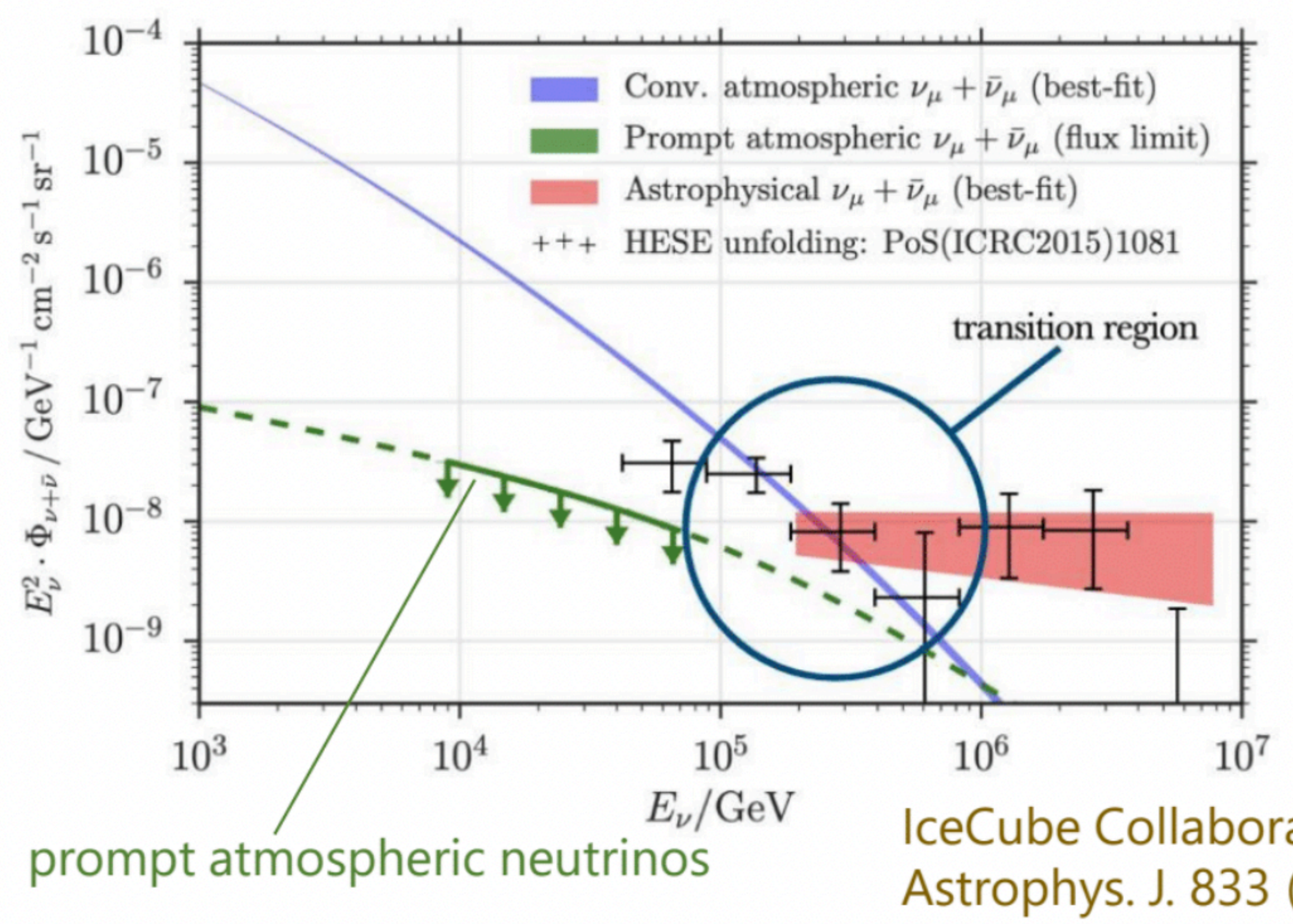
- Vertex: Convergence of >4 tracks, >3 tracks with $\tan(\theta)<0.1$
- Charged vertex: Looser track selection, tracks within 10 films before vertex, with 3 track hits, d0<=5<-μm, min. distance to 3 vertex tracks of <=3μm.

# FASERν | Rich neutrino physics program

- BSM physics
  - New light weakly coupled gauge boson (→$\nu_\tau$) could enhance $\nu_\tau$ flux.
  - Sterile neutrinos with mass ~40 eV can cause oscillations at FASER
- QCD
  - FASER's neutrino flux measurements will provide novel complimentary constraints that can be used to validate/improve MC generator very forward particle production.
  - Neutrinos from charm decay could allow to test transition to small-x factorisation, constrain low-x gluon PDF and probe intrinsic charm
- Cosmic rays and neutrinos
  - IceCube needs measurements of high energy and large rapidity charm for precise measurements of cosmic neutrino flux.
  - Direct measurement of prompt neutrino production at FASER would provide important data for current & future neutrino telescopes



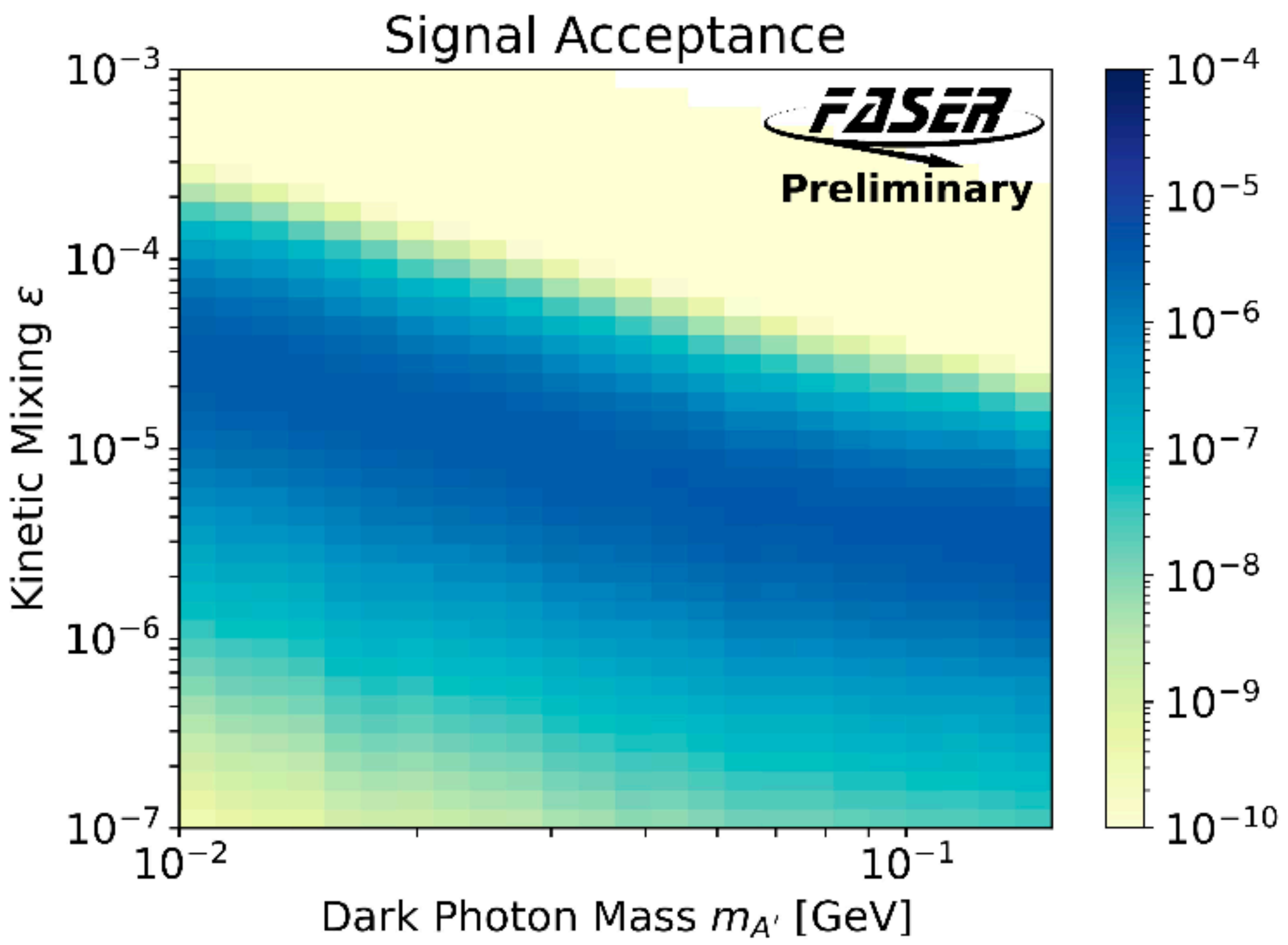



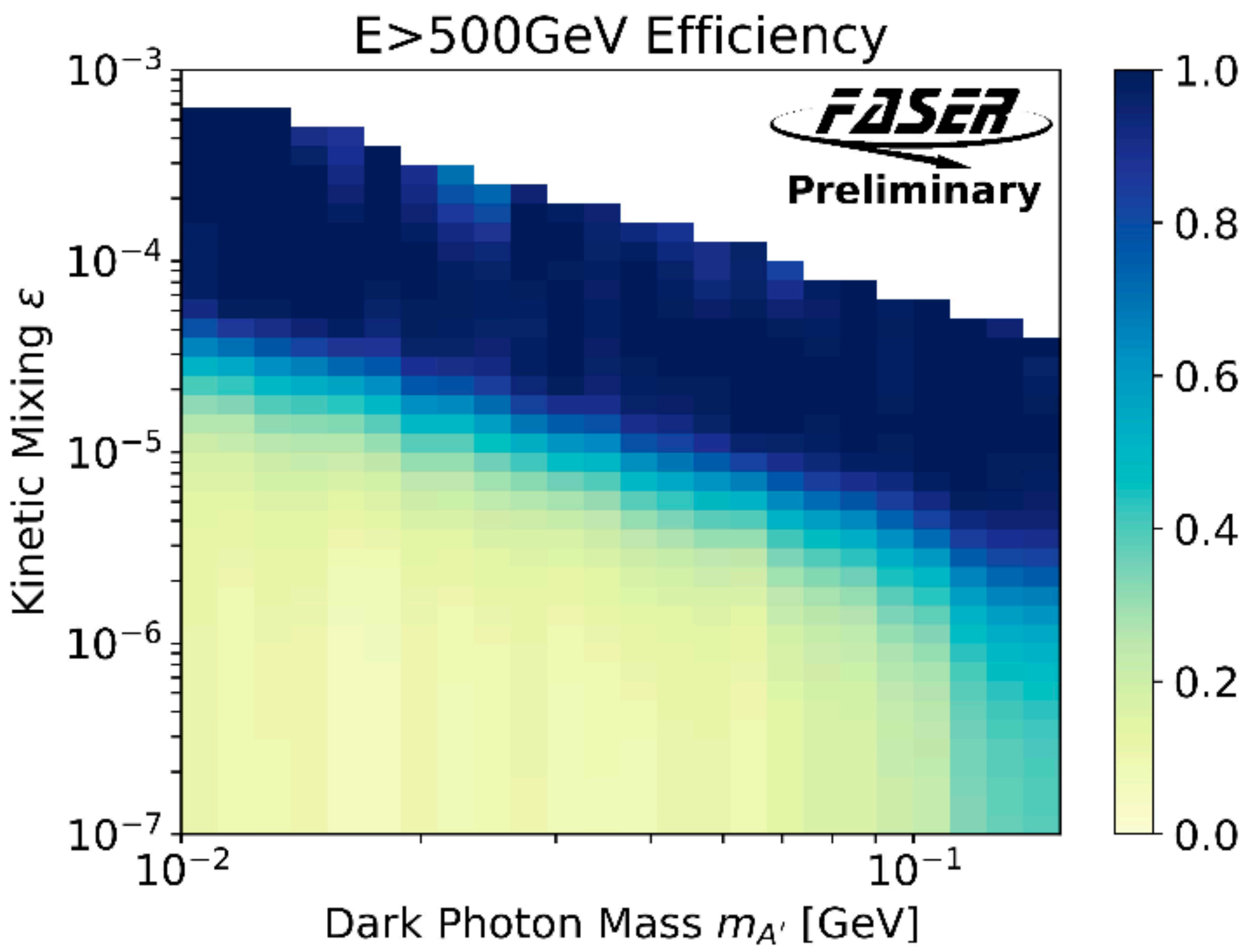




IceCube Collaboration, Astrophys. J. 833 (2016)

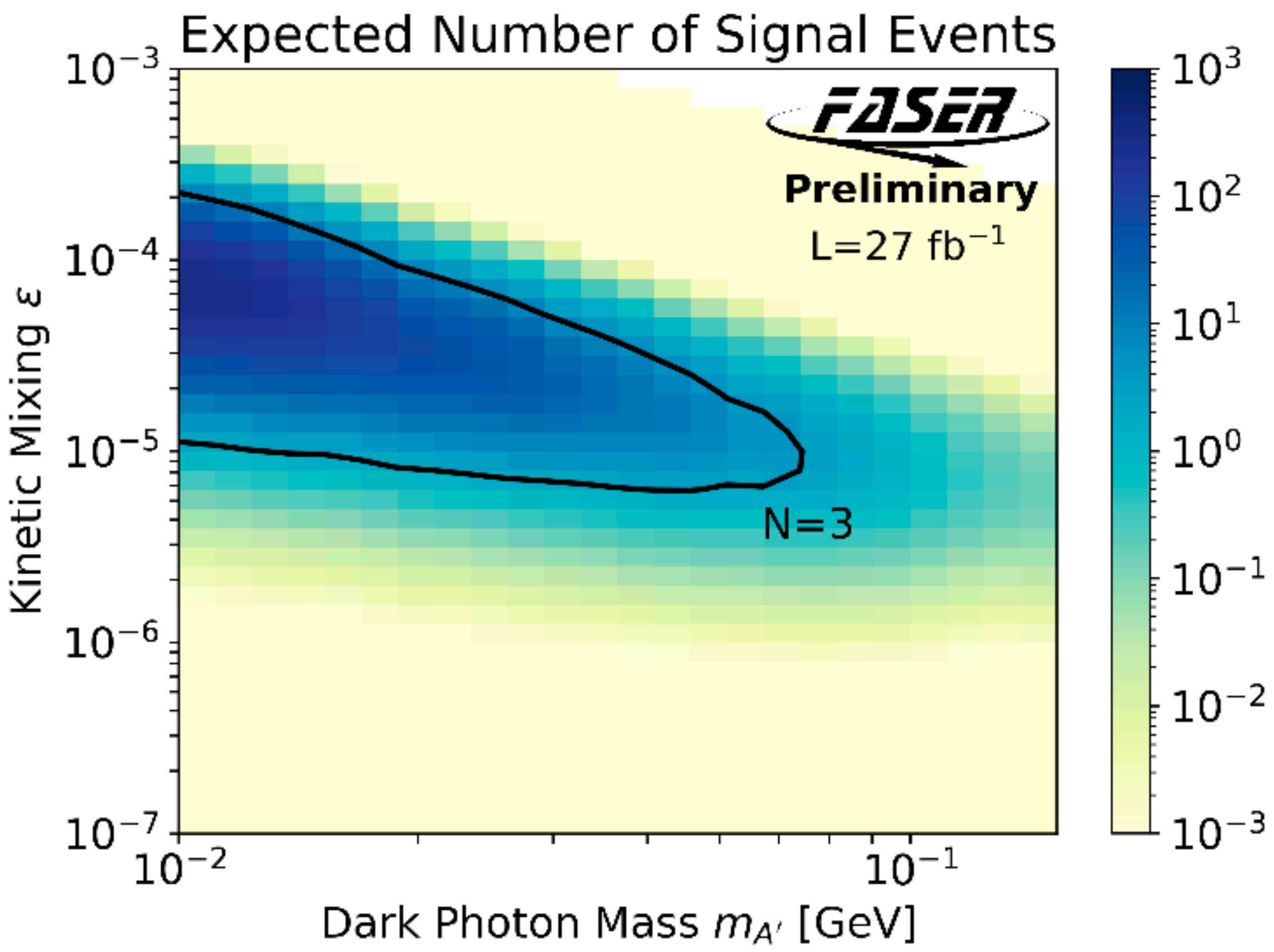
# Dark Photon | Signal

- Acceptance $10^{-6}$
- Decay volume $10^{-8}$ solid angle
- P(decay in FASER) = $10^{-3}$



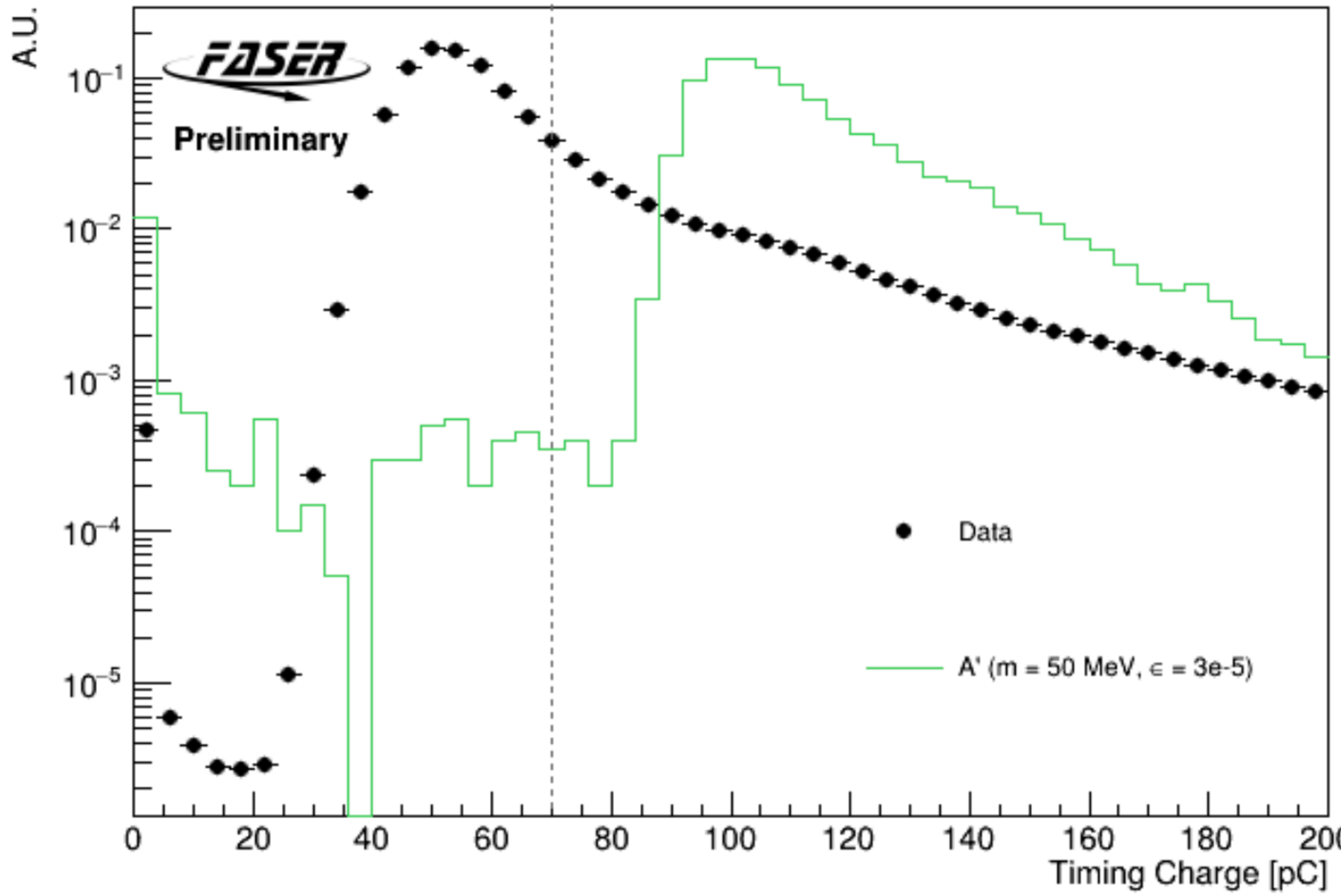

$$L = c\beta\tau\gamma \approx (80\ \mathrm{m}) \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{\mathrm{TeV}}\right] \left[\frac{100\ \mathrm{MeV}}{m_{A'}}\right]^2$$



# Dark Photon | Selection

| Description | Value |
|---|---|
| Pre-selecton | |
| Time consistent with a colliding bunch identifier<br>Timing scintillator trigger | |
| Scintillator | |
| Timing station:<br>Top or Bottom Scintillator charge<br>OR Top and Bottom charge | <br>$> 70$ pC<br>$> 30$ pC |
| Each Preshower scintillator charge<br>Each Veto scintillator charge | >2.5 pC<br><40 pC |
| Tracking | |
| Exactly 2 Good Tracks<br>Momentum<br>$\chi^2$/NDF<br>Number of tracker layers on track<br>Number of tracker hits on track | <br>$> 20$ GeV<br>$< 25$<br>>= 7<br>>= 12 |
| Fiducial selection | |
| Track extrapolated to all scintillators<br>and tracking stations | <br>$< 95$mm |
| Calorimeter | |
| Calorimeter energy (sum of four channels) | $> 500$ GeV |

TABLE I. Summary of selection requirements.




| Selection Criteria | Efficiency |
|---|---|
| Good collision event | 99.7% |
| No Veto Signal | 98.4% |
| Timing/Preshower Signal | 97.3% |
| $\geq 1$ good track | 89.2% |
| $= 2$ good tracks | 44.5% * |
| Track radius $< 95$ mm | 42.3% * |
| Calo energy $> 500$ GeV | 41.6% * |

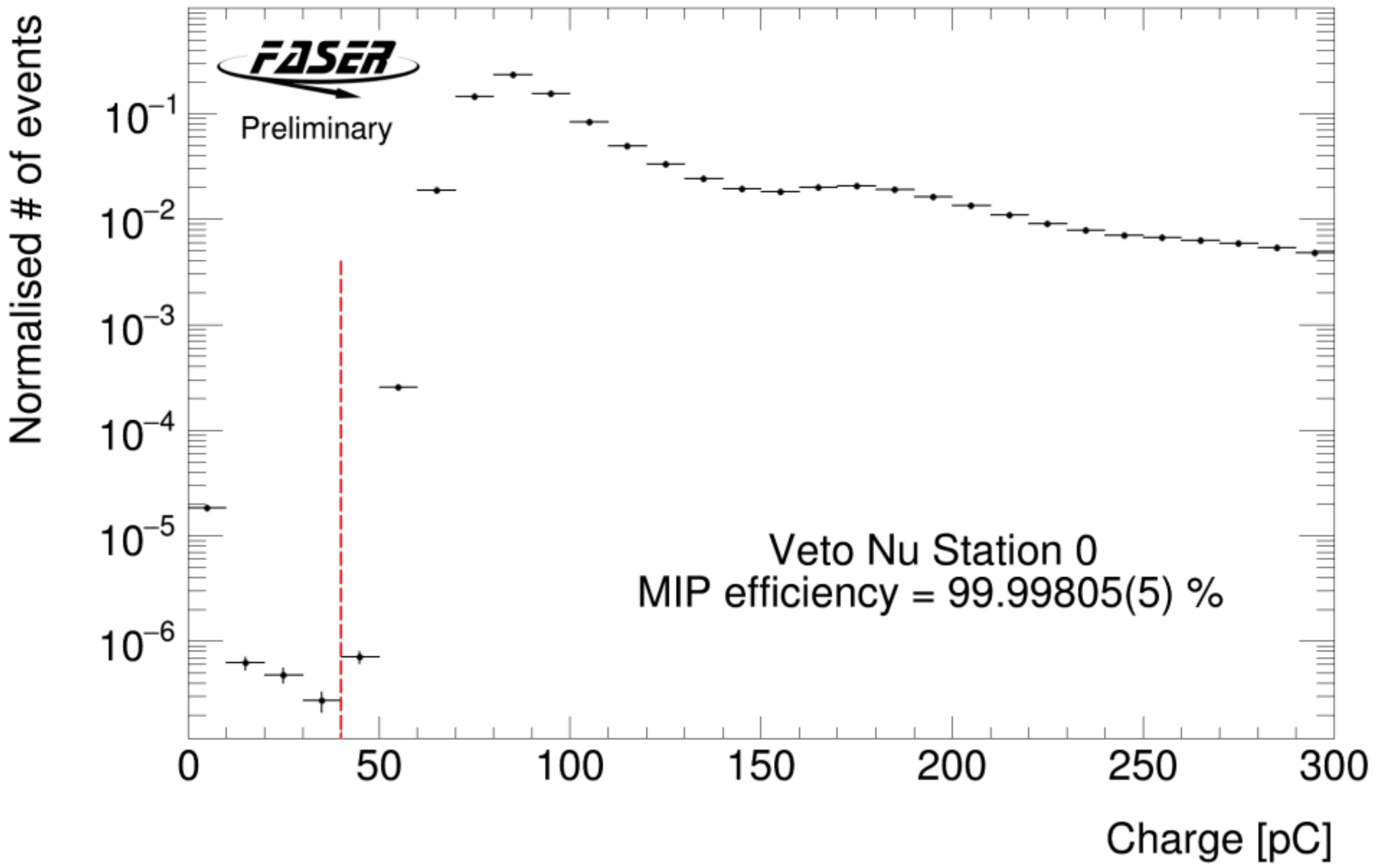
$\epsilon = 3 \times 10^{-5}$ $m_{A'} = 25.1$ MeV

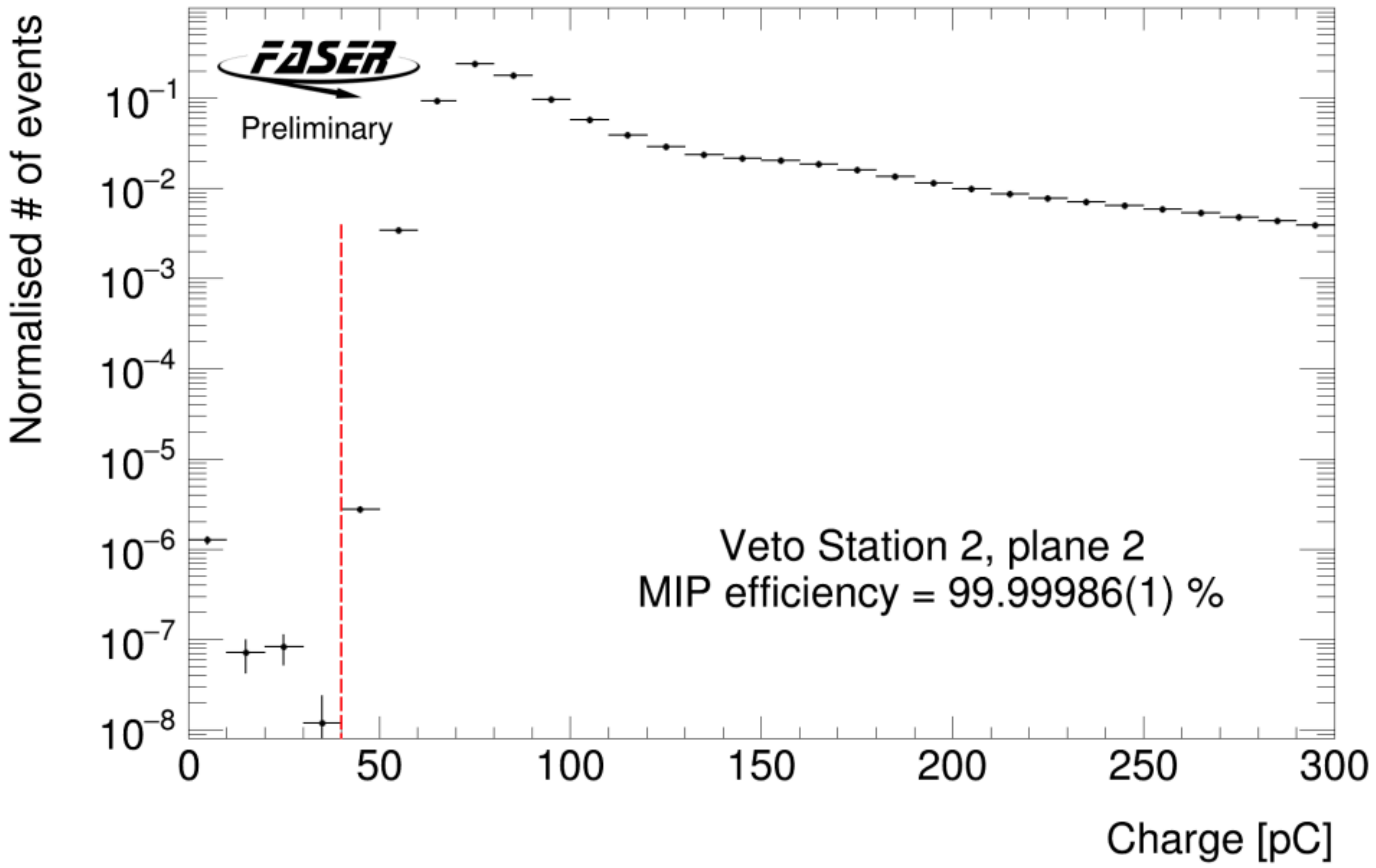
# Dark Photon | ABCD method

| Selection | Nevents E<100 GeV | Nevents E>500 GeV |
|---|---|---|
| 3 tracks (VetoNu signal) | 544.7 | 11.0 |
| 2 tracks (No VetoNu signal) | 1 | Predicted: 0.02 |

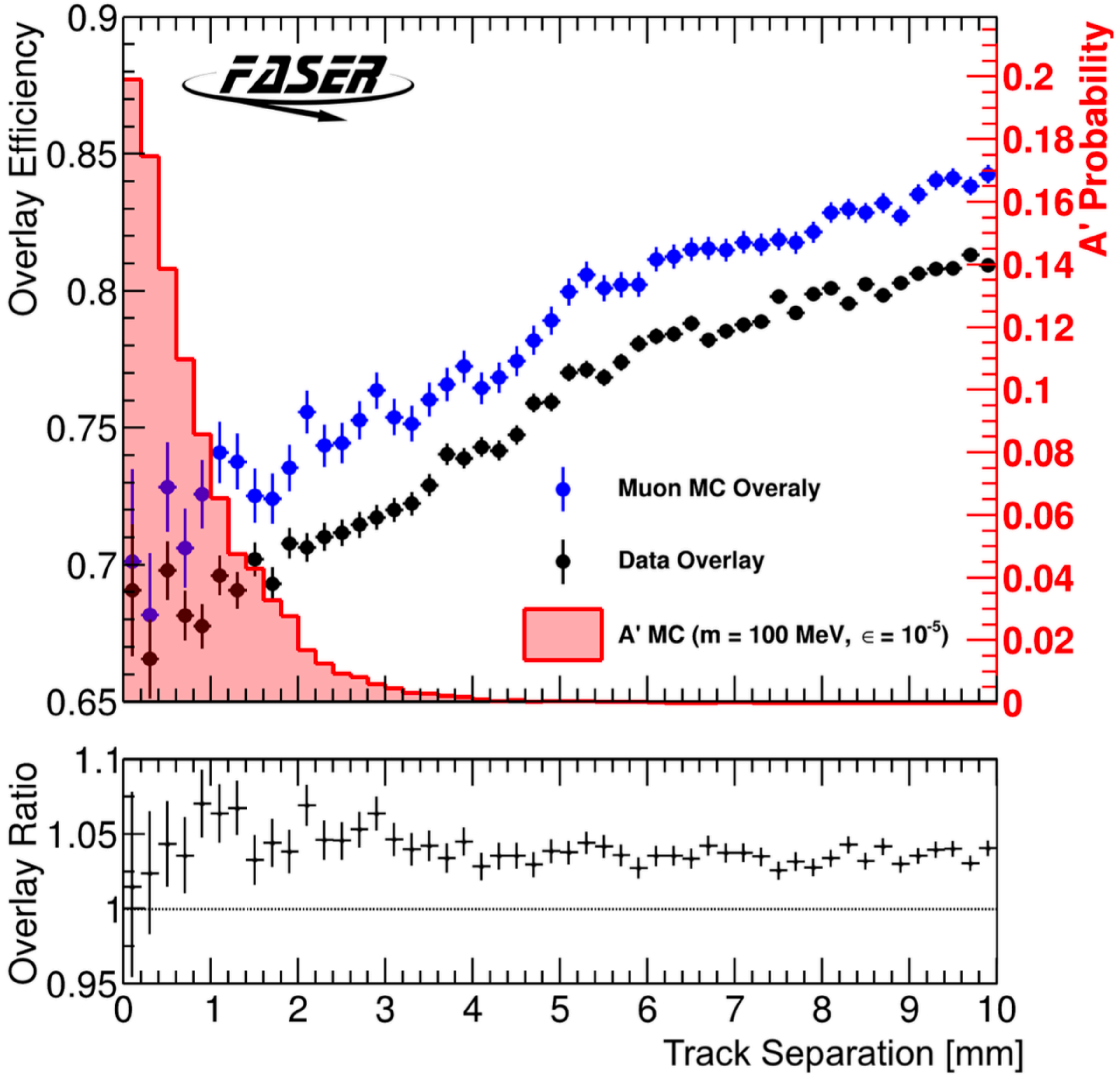
# Dark Photon | Scintillator efficiencies

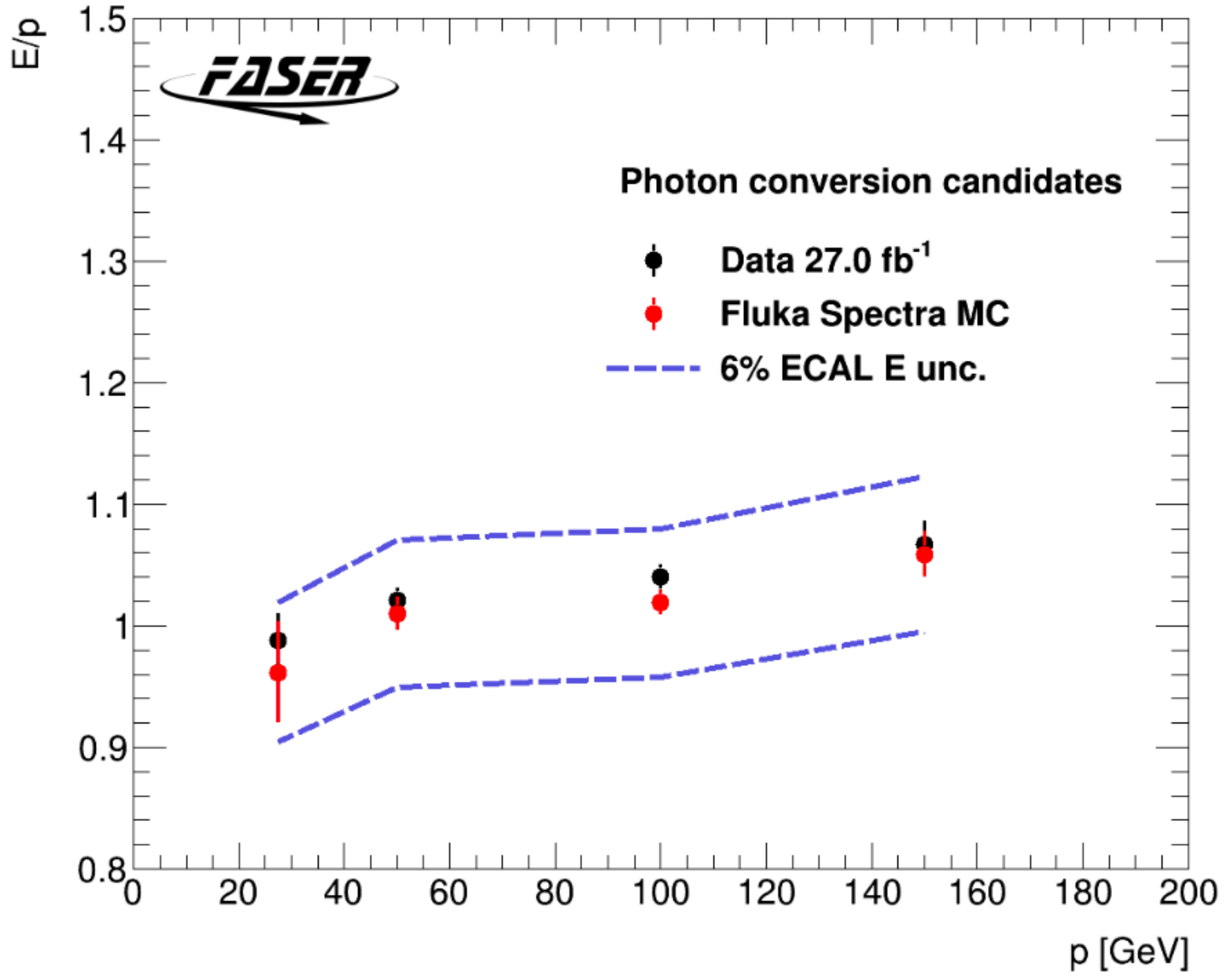
| Scintillator | Efficiency |
|---|---|
| NuVeto-0 | 0.9999805(5) |
| NuVet0-1 | 0.9999810(5) |
| Veto-0 | 0.9999985(1) |
| Veto-1 | 0.9999984(1) |
| Veto-2 | 0.9999986(1) |



# Dark Photon | Performance

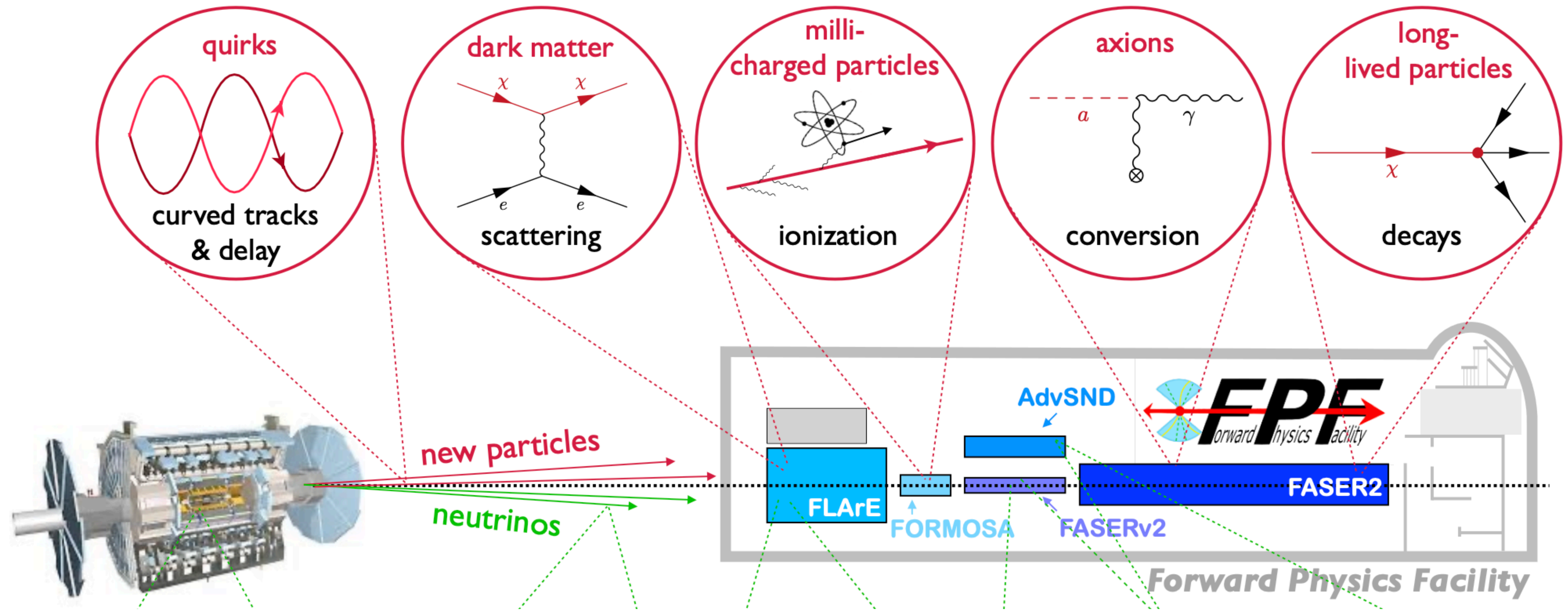


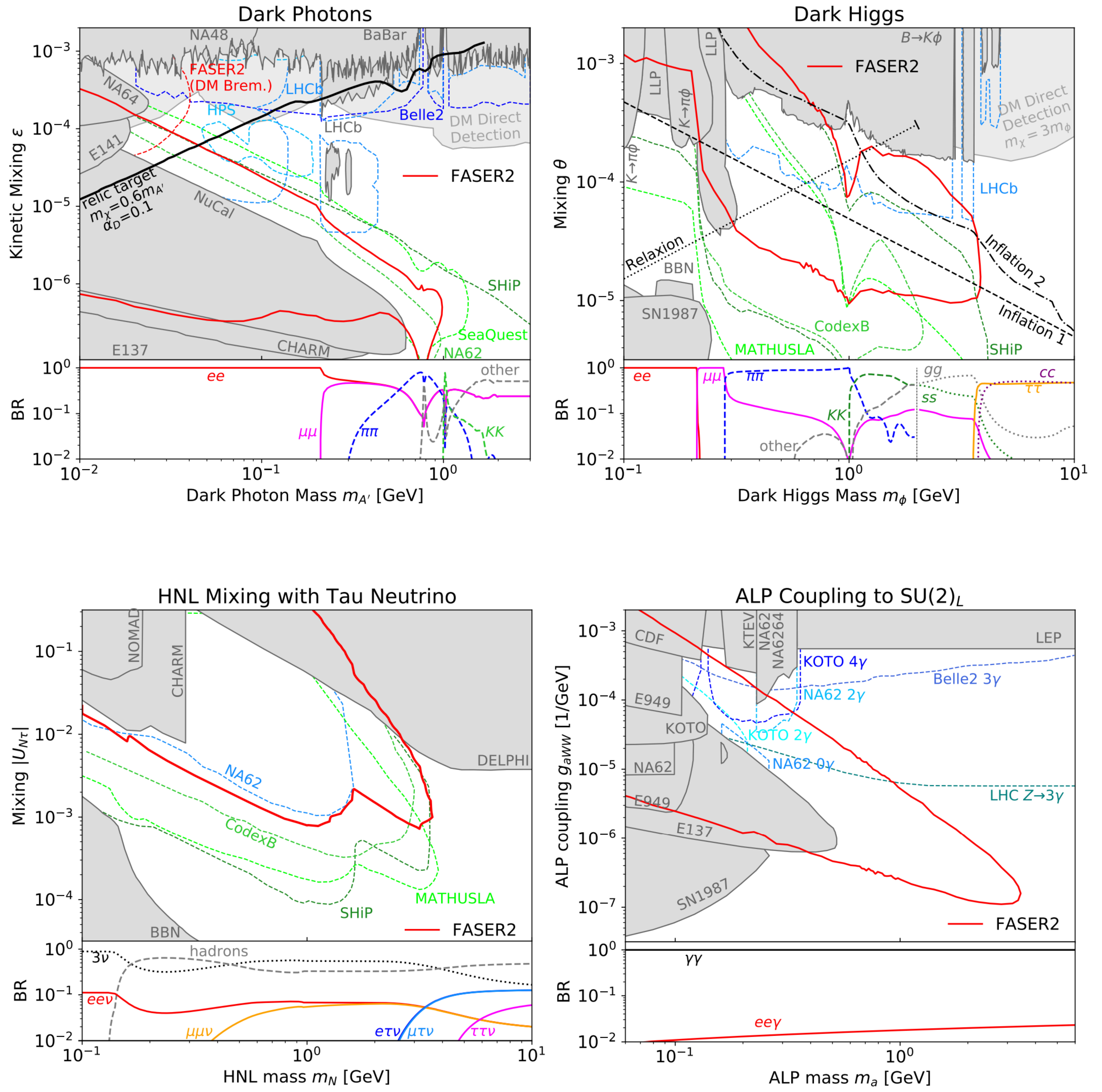




| Source | Value | Effect on signal yield |
|---|---|---|
| Signal Generator | $\frac{0.15+(E_{A'}/4\text{TeV})^3}{1+(E_{A'}/4\text{TeV})^3}$ | 15-65% (15-45%) |
| Luminosity | 2.2% | 2.2% |
| MC Statistics | $\sqrt{\sum W^2}$ | 1-3% (1-2%) |
| Track Momentum Scale | 5% | $< 0.5\%$ |
| Track Momentum Resolution | 5% | $< 0.5\%$ |
| Single Track Efficiency | 3% | 3% |
| Two-track Efficiency | 7% | 7% |
| Calo E scale | 6% | 0-8% ($< 1\%$) |

# Forward Physics Facility | BSM

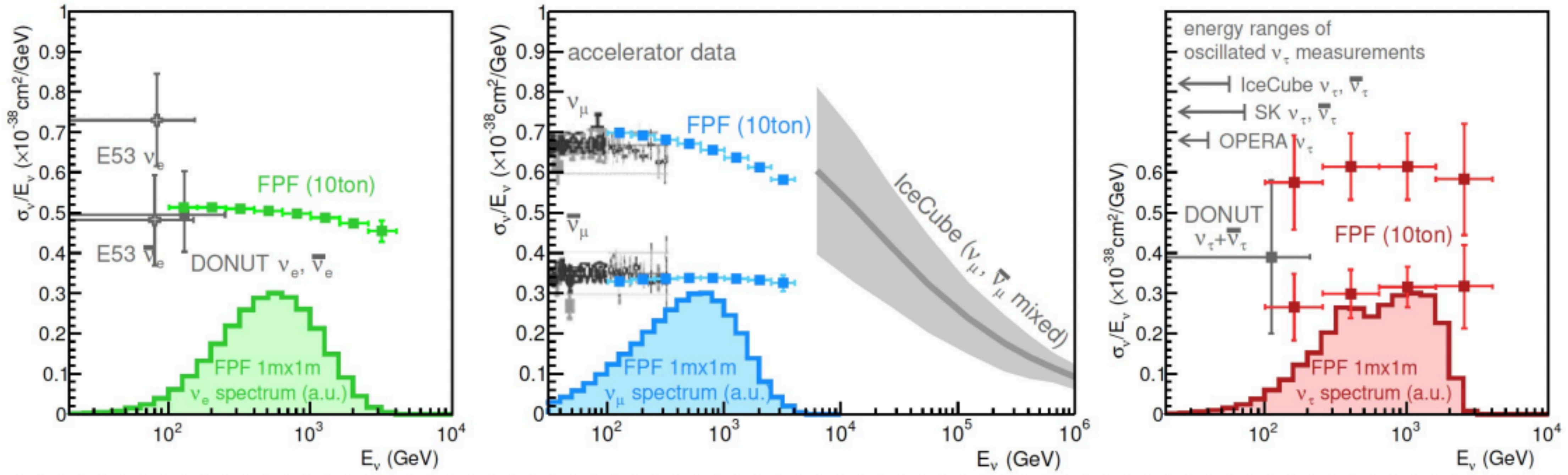
- FPF Papers:
  - FPF “Short” Paper: Phys. Rept. 968, 1 (2022)
  - FPF White Paper: J. Phys. G (2022)

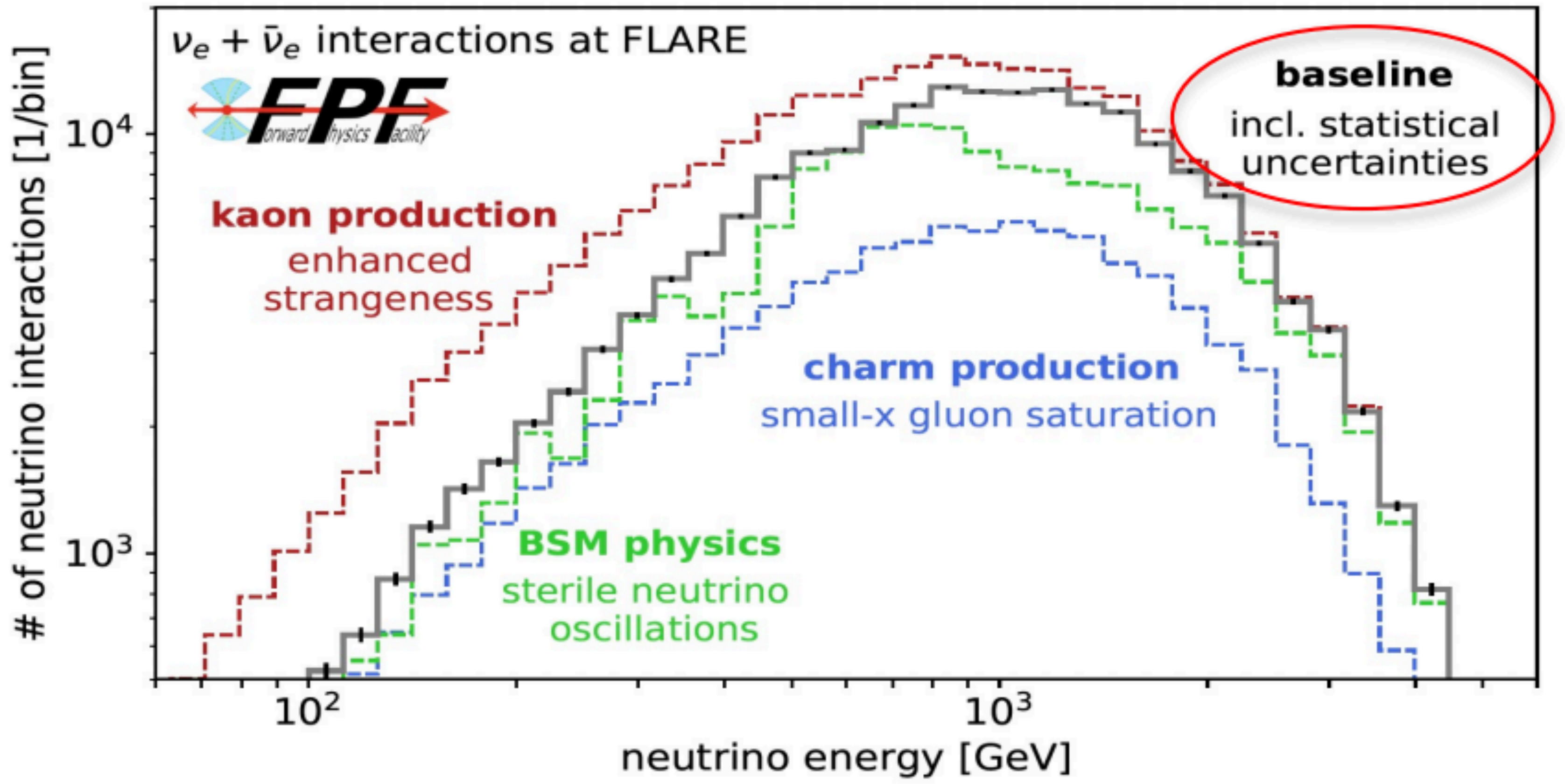


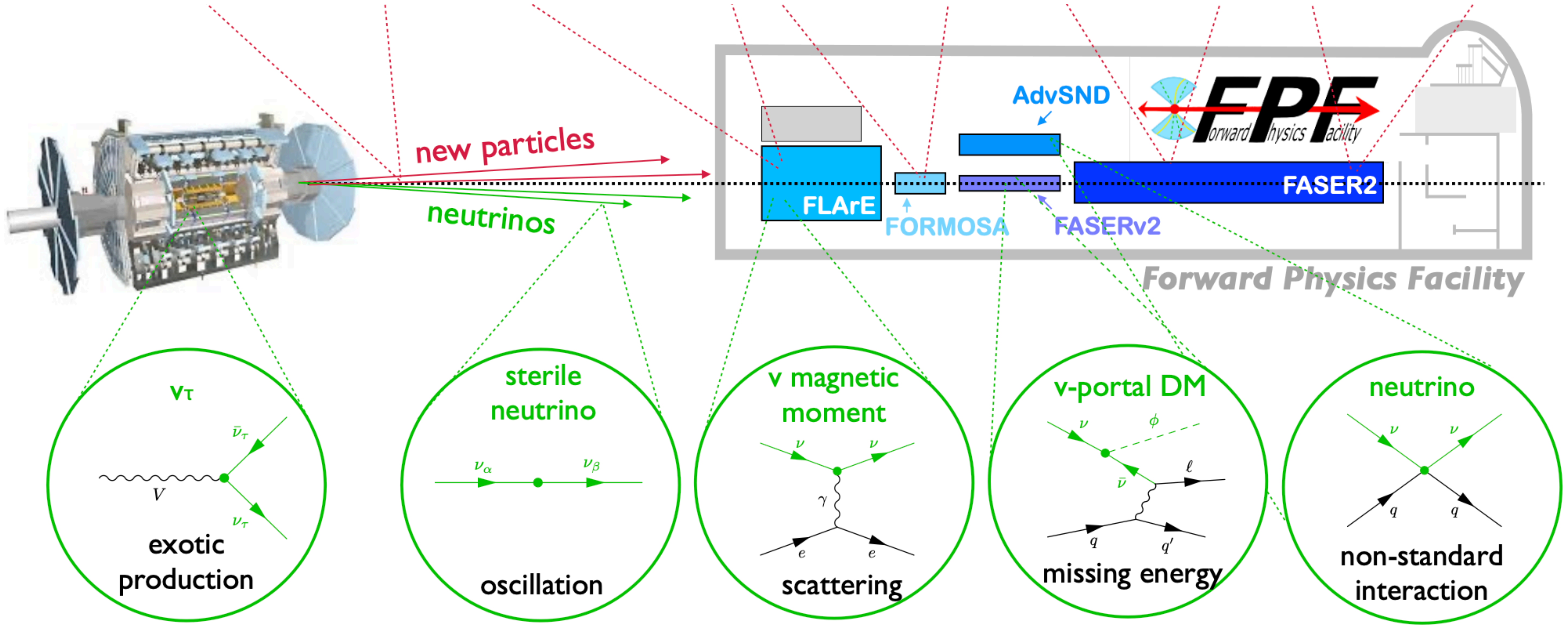



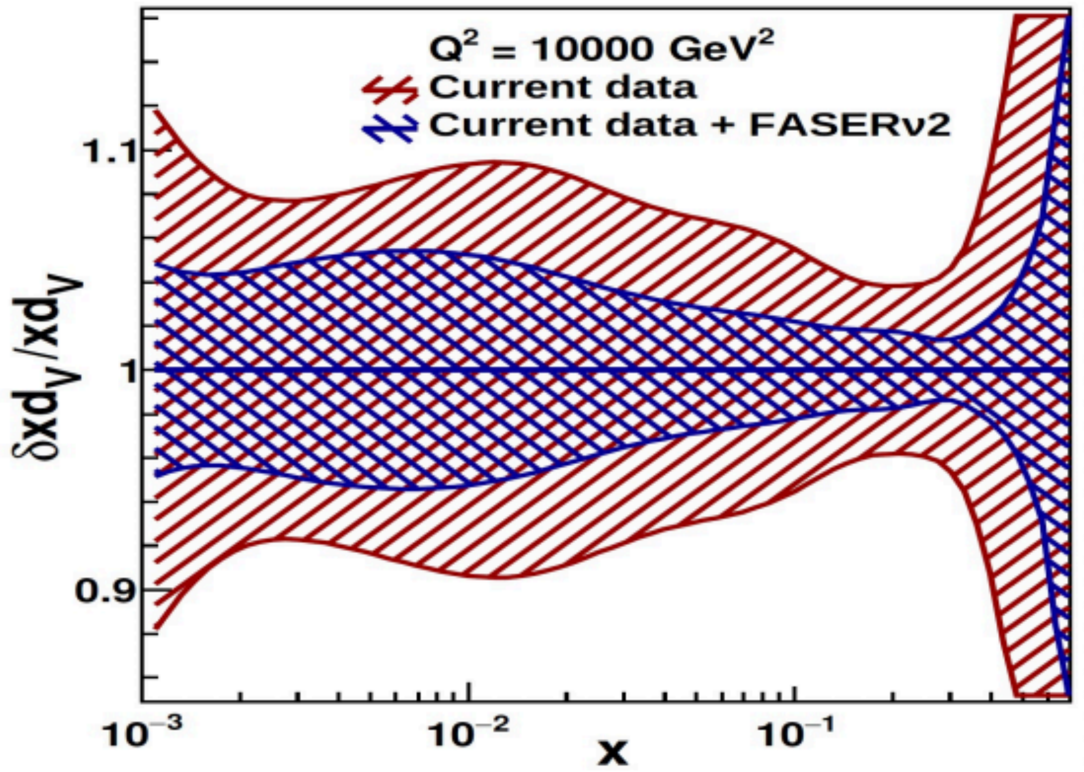
# Forward Physics Facility | Neutrinos

- FPF Papers:
  - FPF “Short” Paper: Phys. Rept. 968, 1 (2022)
  - FPF White Paper: J. Phys. G (2022)



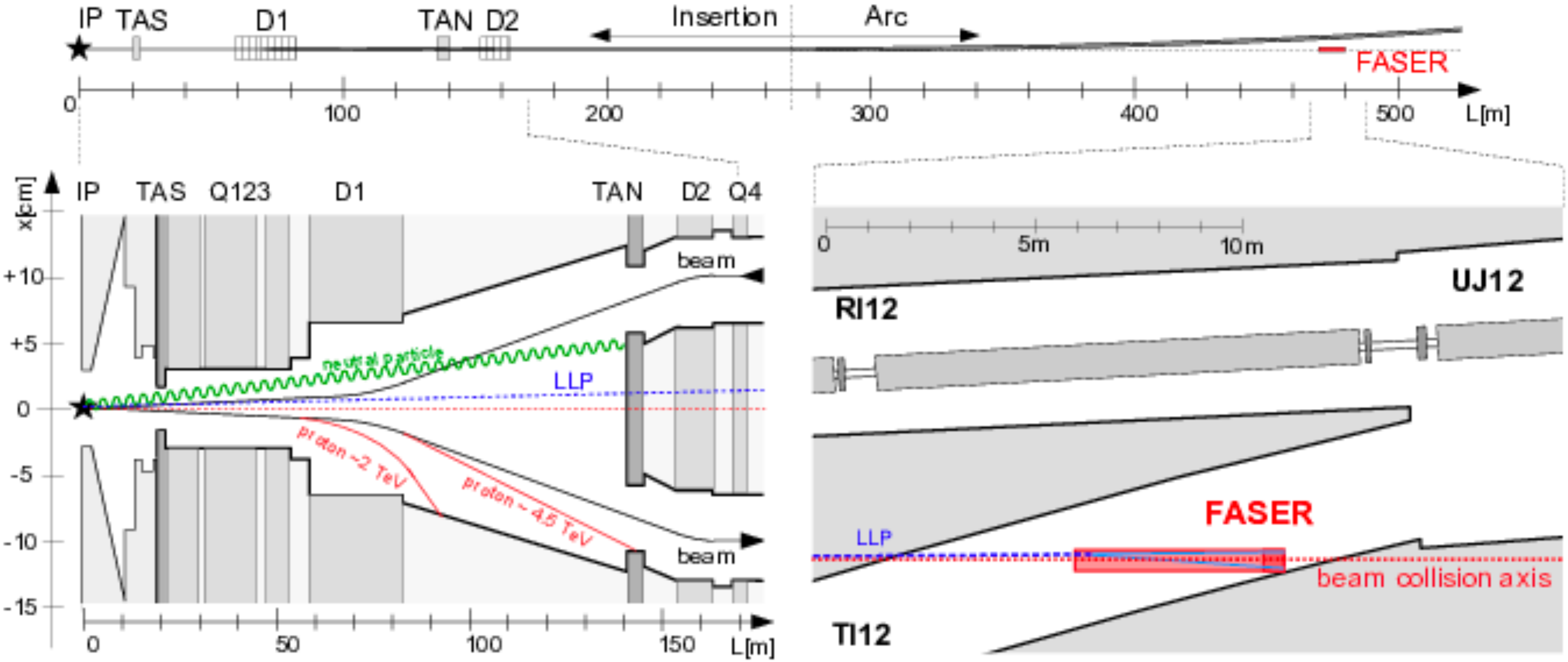




FPF WGs, PDF4LHC21, stat uncertainty only

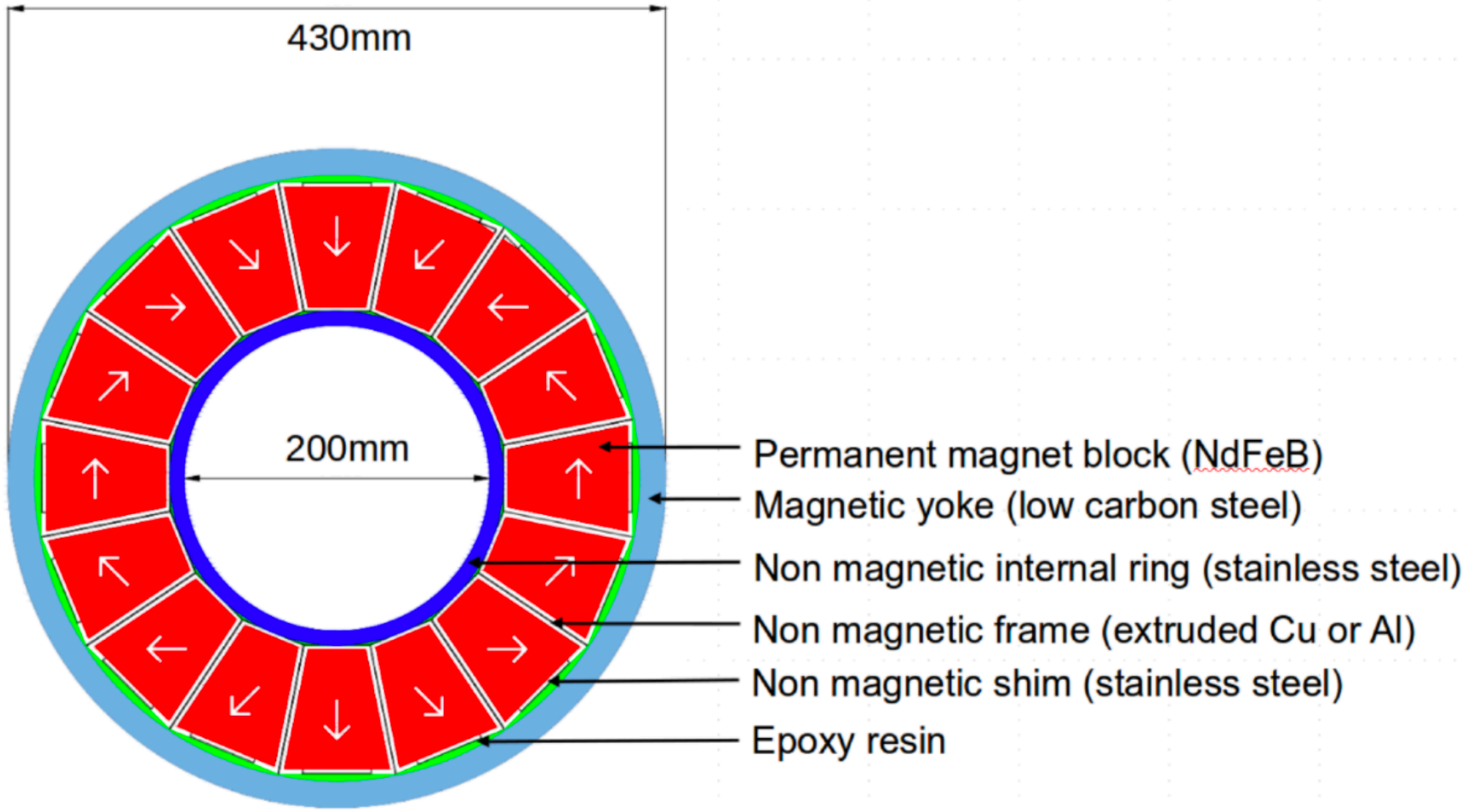
# FASER Location

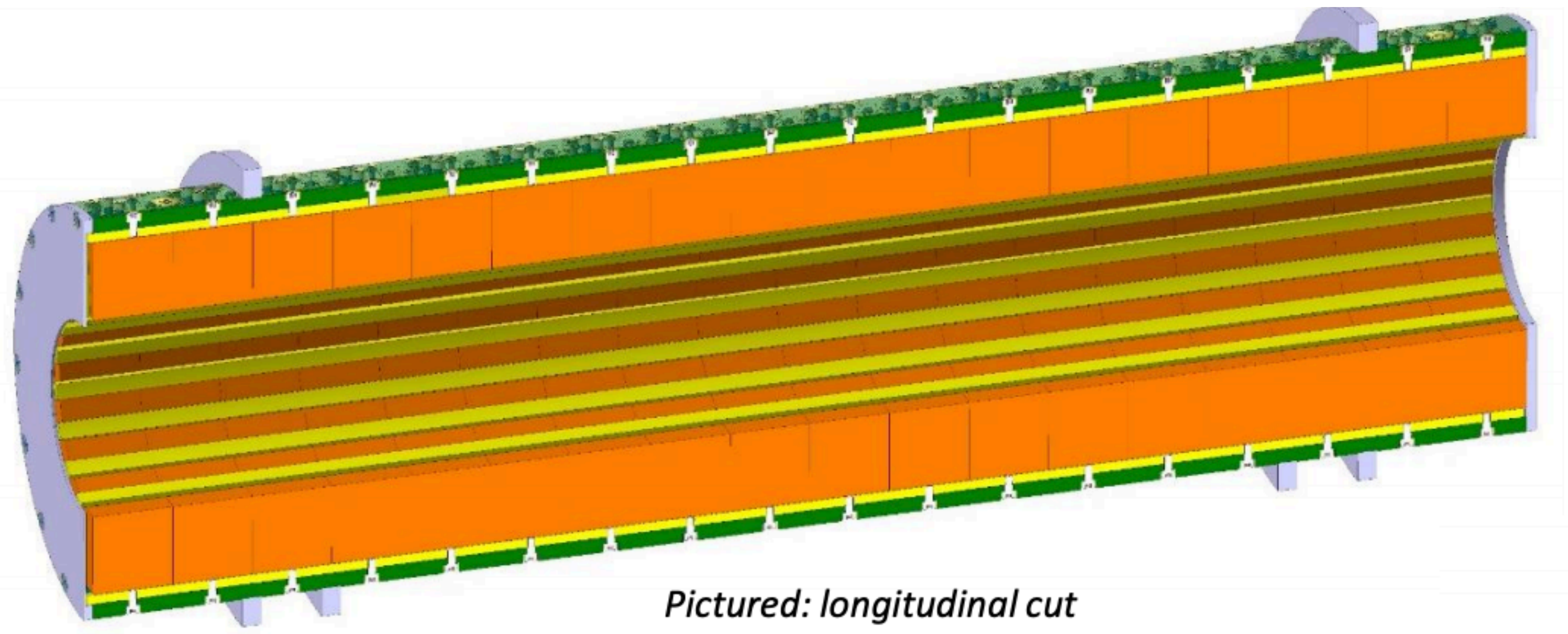
- A closer look at the LHC infrastructure on the line-of-sight:



# Magnets | Overview

- The FASER magnets are 0.55T permanent dipole magnets based on the Halbach array design
  - Thin enough to allow the LOS to pass through the magnet centre with minimum digging to the floor in TI12
  - Minimize needed services (power, cooling etc..)
- Designed and constructed by magnet group at CERN

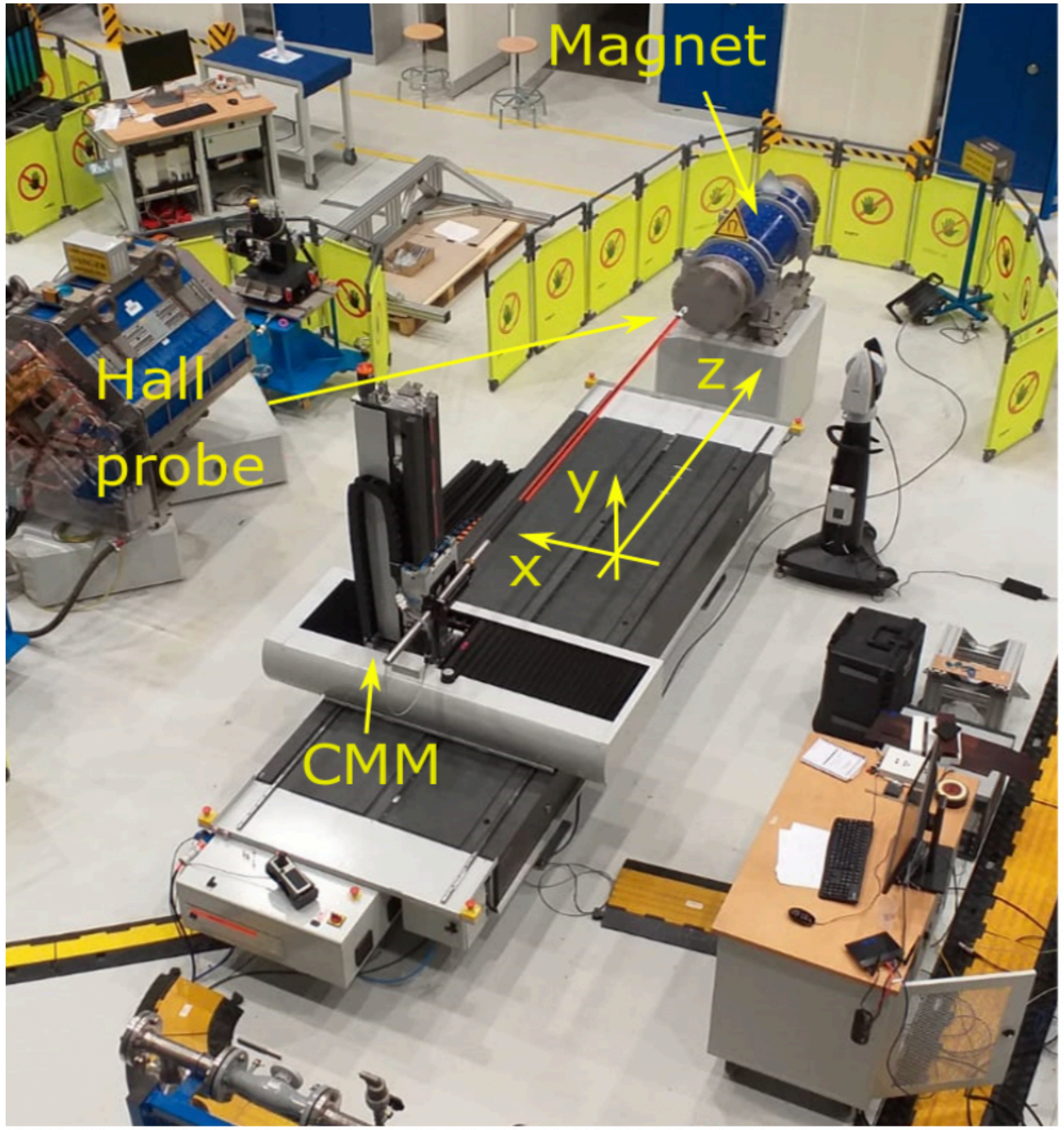


*Pictured: longitudinal cut*

# Magnets | Construction and testing

- Assembly at CERN of all 3 magnets completed, and all magnets measured at CERN
- Measured field quality well within specifications.

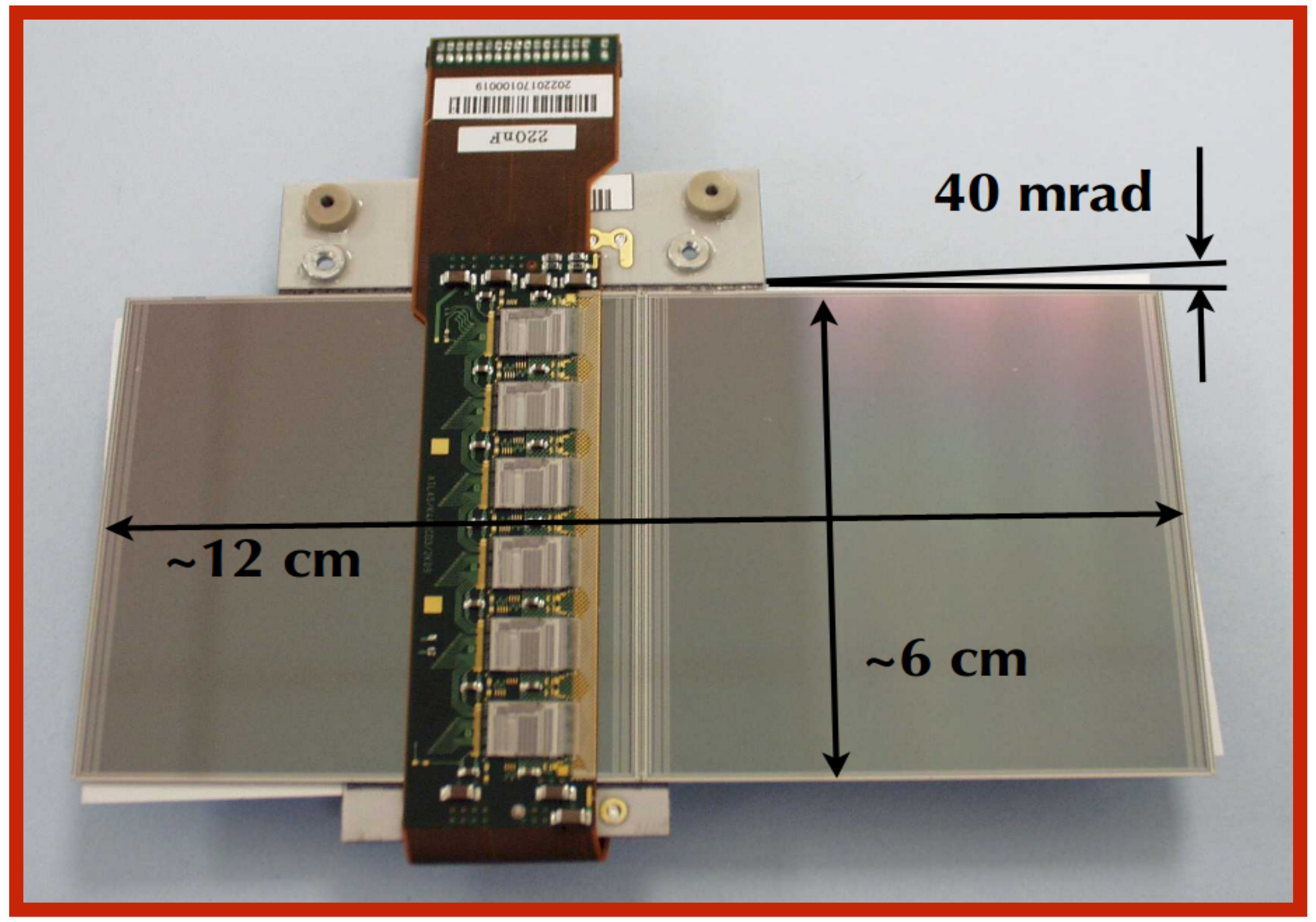


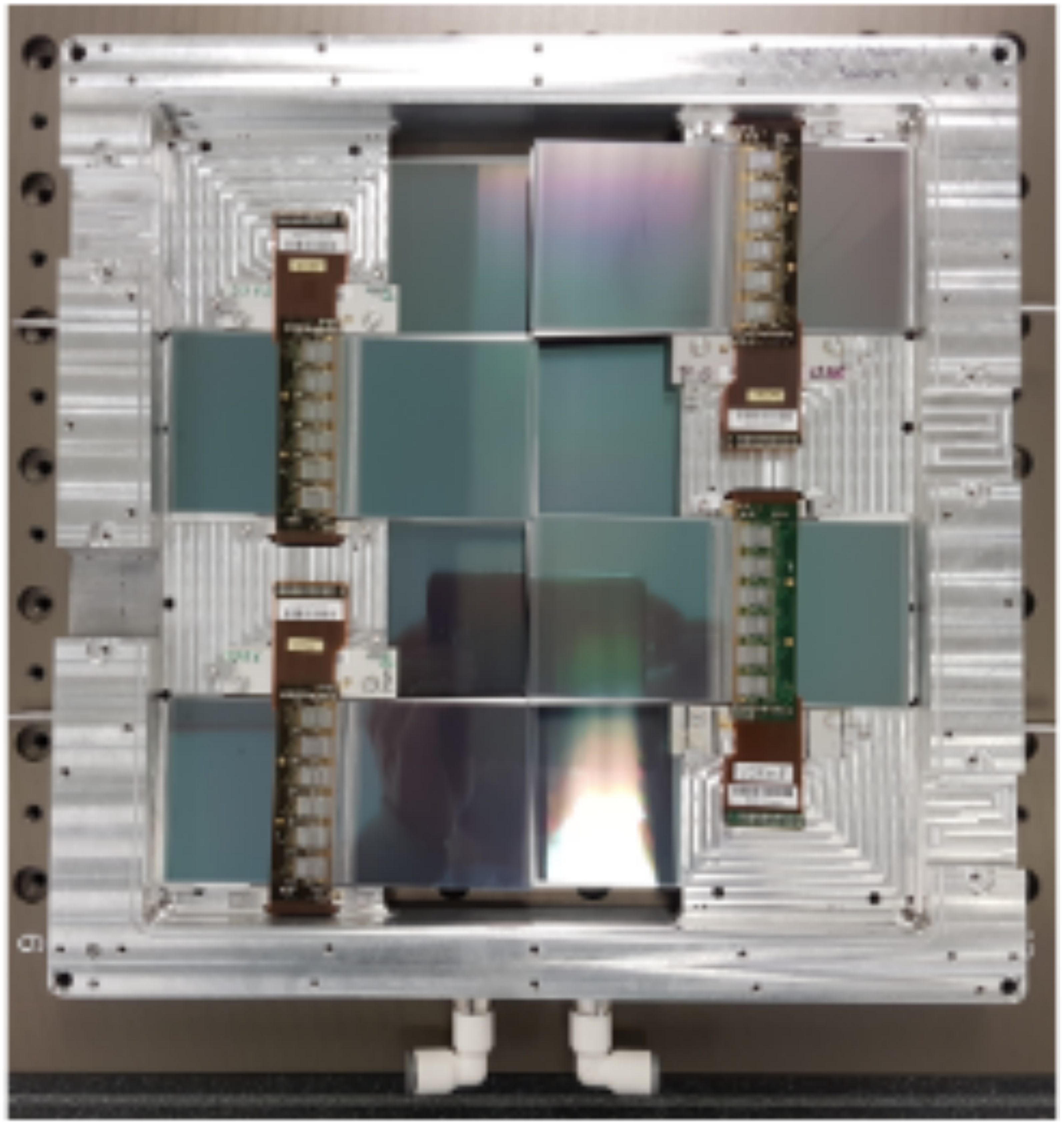

# Magnets | Installation

- Assembly at CERN of all 3 magnets completed, and all magnets measured at CERN
- Measured field quality well within specifications.
- All magnets now installed underground!

# Tracker | Modules

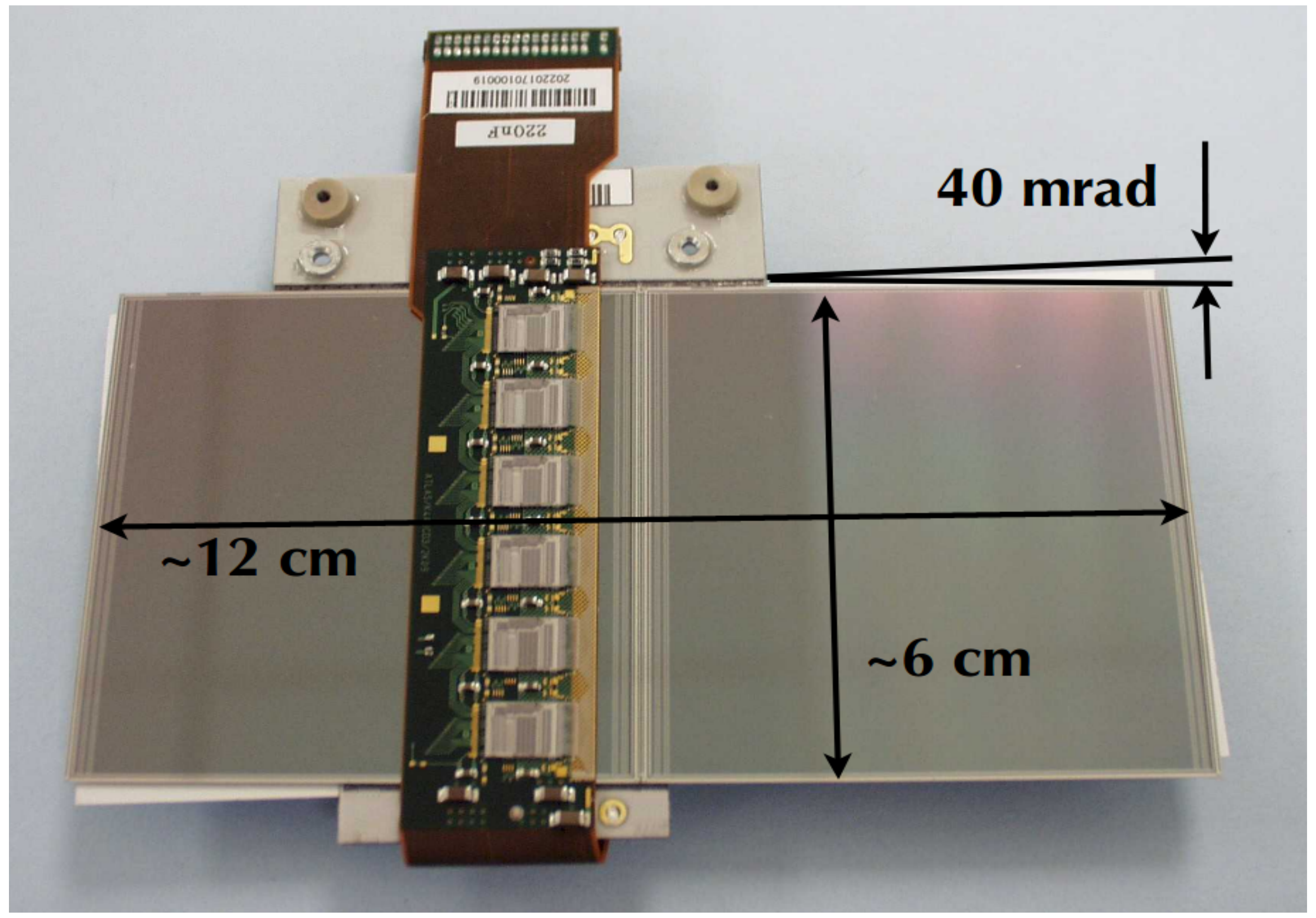
- Spare ATLAS SCT modules are used
  - 80μm strip pitch, 40mrad stereo angle (17μm / 580μm resolution)
    - precision measurement in bending (vertical) plane
  - Many thanks to the ATLAS SCT collaboration!

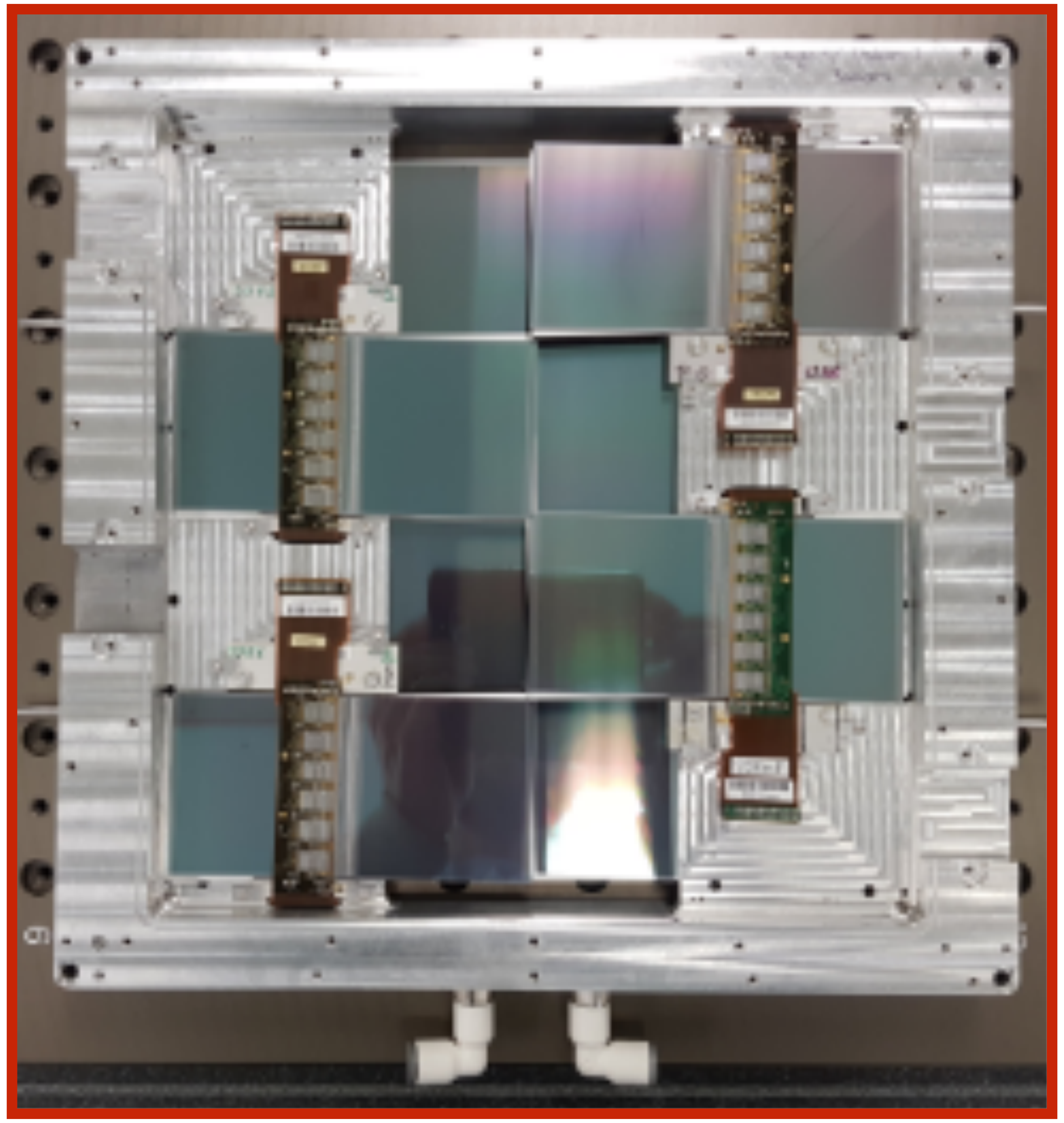


# Tracker | Layers

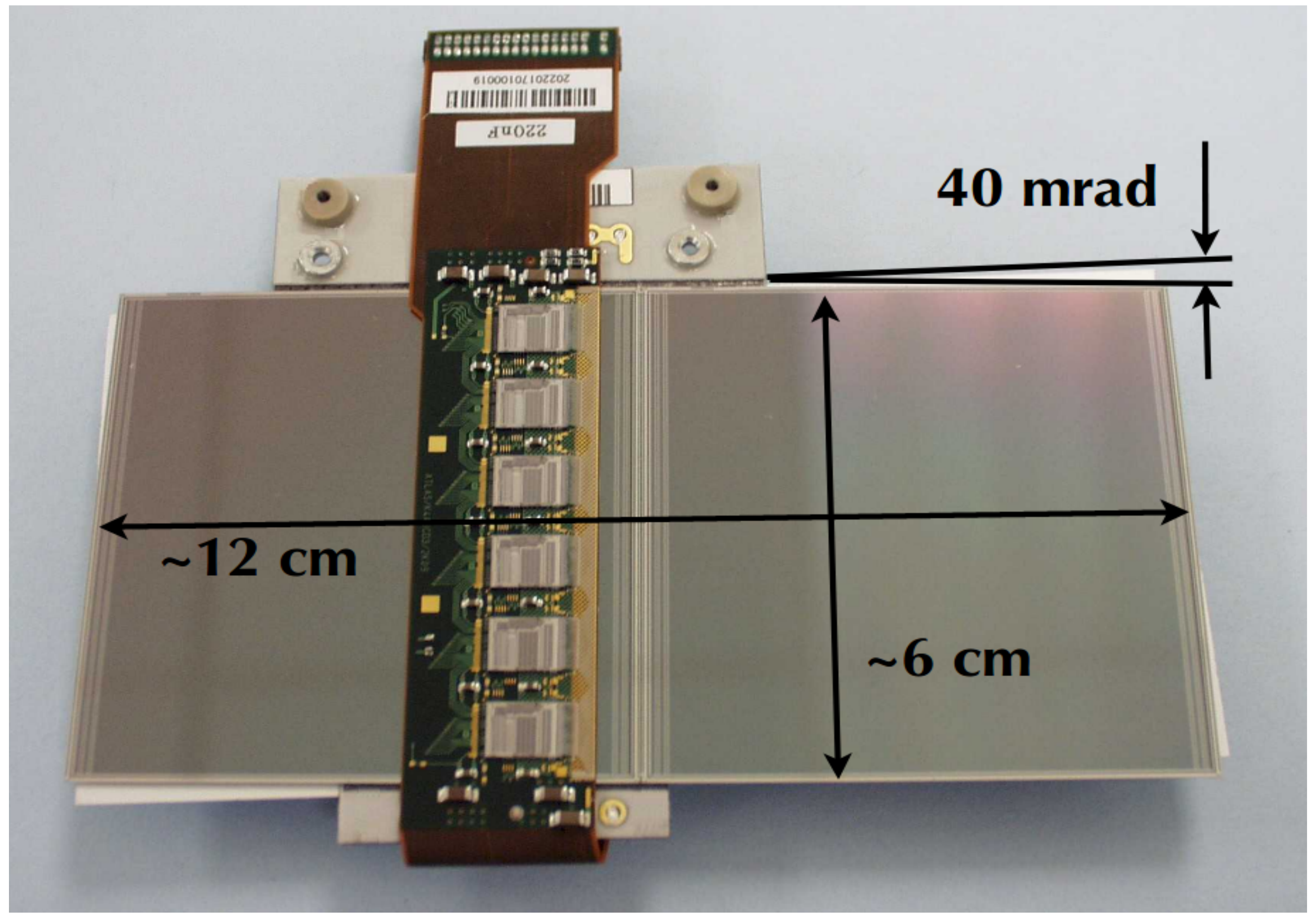
- 8 SCT modules give a 24cm x 24cm tracking layer
- 9 layers (3/station, 3 stations) → 72 SCT modules needed for the full tracker

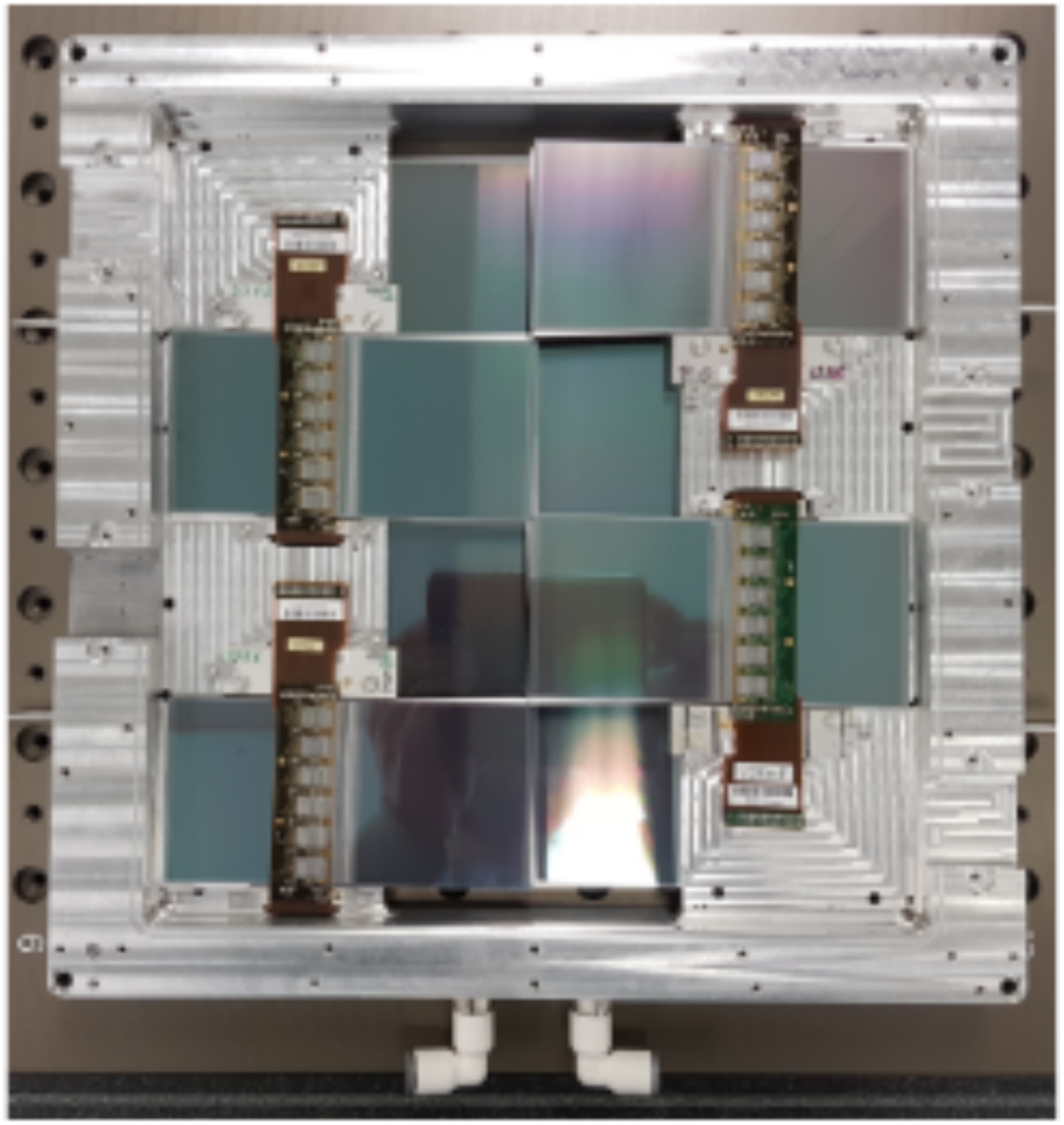


# Tracker | Stations

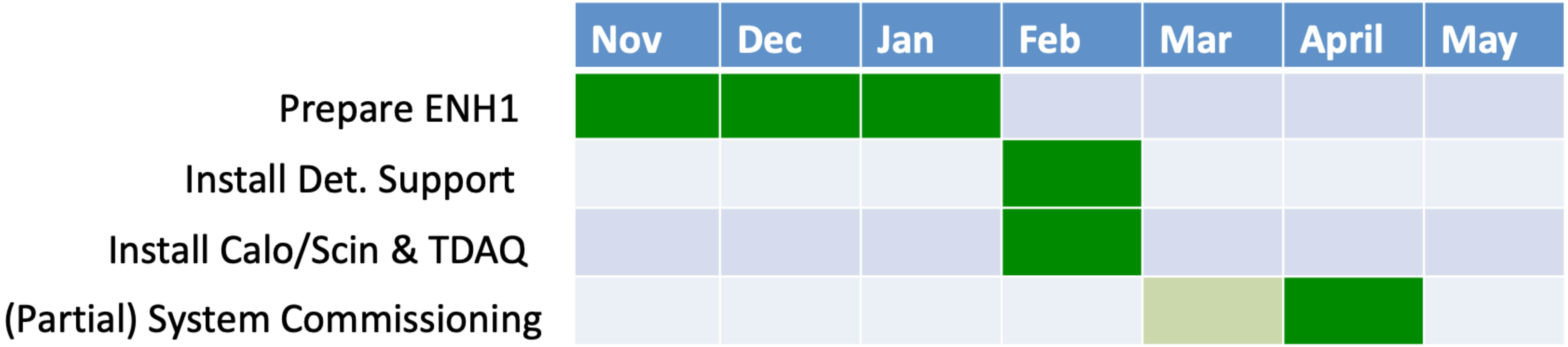
- Low radiation levels in TI12 allows silicon to be operated at room temp.
  - But the detector needs to be cooled to remove heat from the on-detector ASICs
- Tracker readout using FPGA based board from University of Geneva (already used in Baby MIND neutrino experiment)



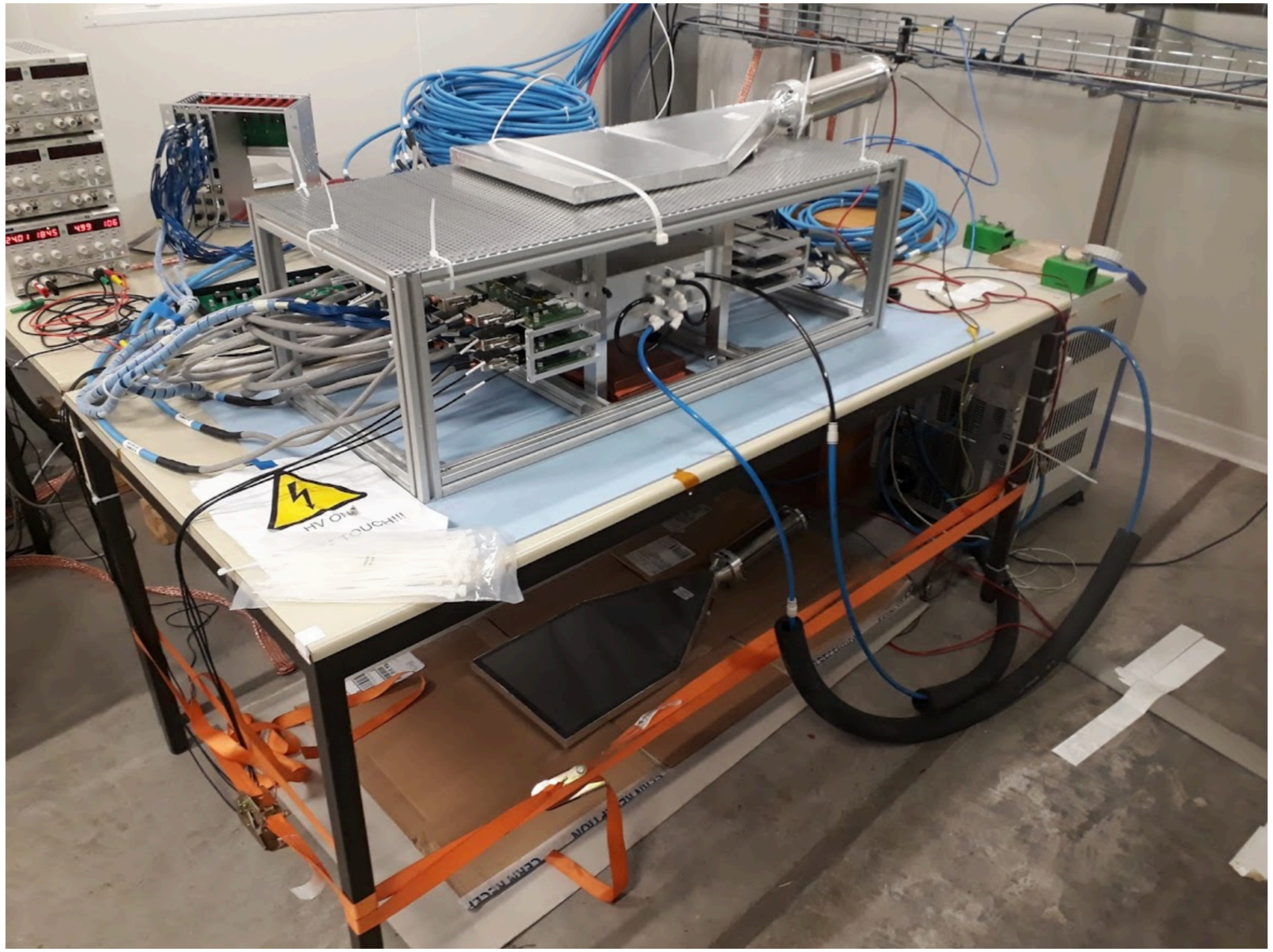
# Overground testing

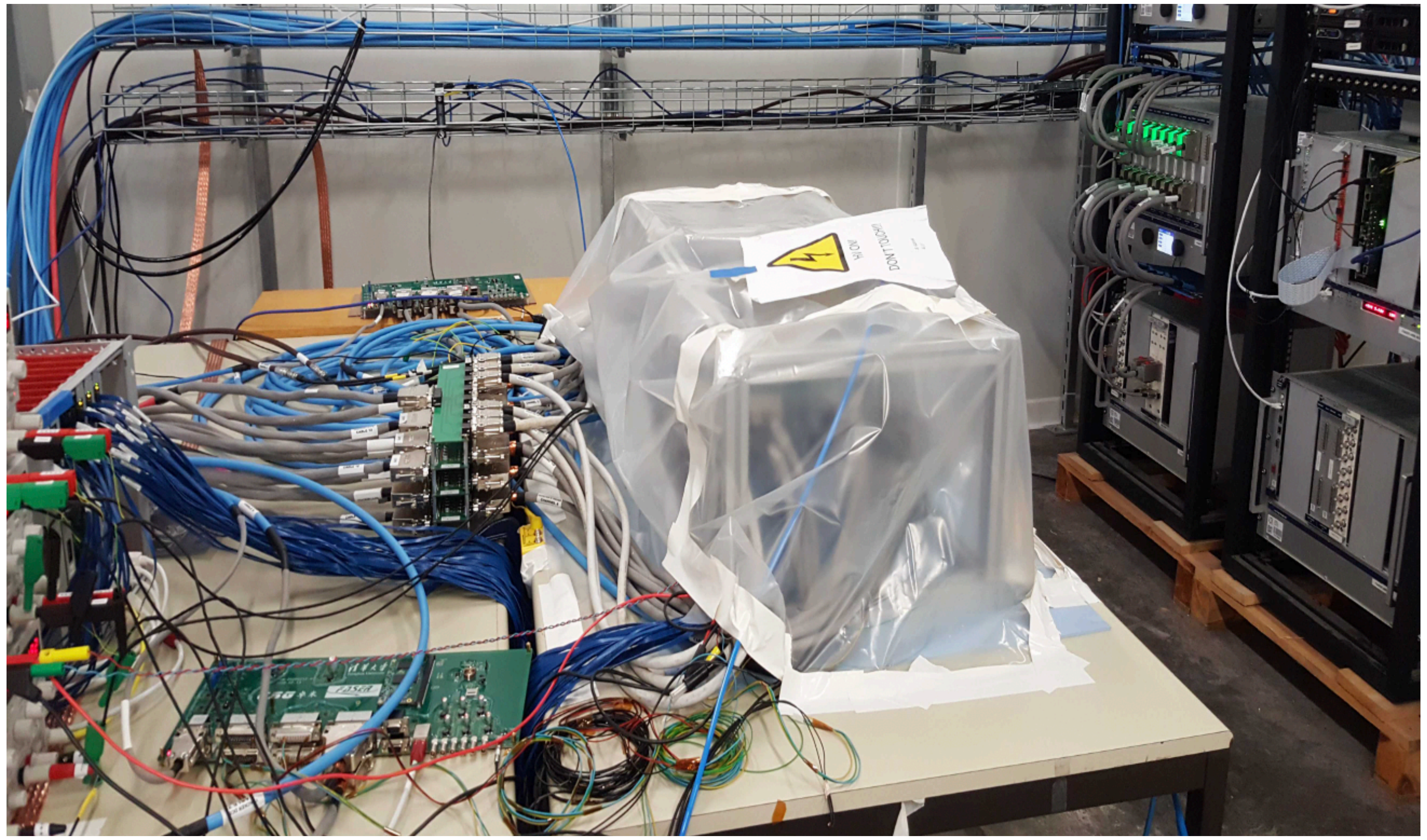
- Have space at CERN Prevessin site (same building as Neutrino Platform)
- Used for dry run above ground
  - Assembly took place in Feb-April 2020
    - Test mechanical assembly
  - Commissioning from March 2020
    - Detector installation
    - Alignment procedures
    - Cabling
    - Cooling
    - TDAQ
    - Cosmics runs



# Overground testing | Tracker

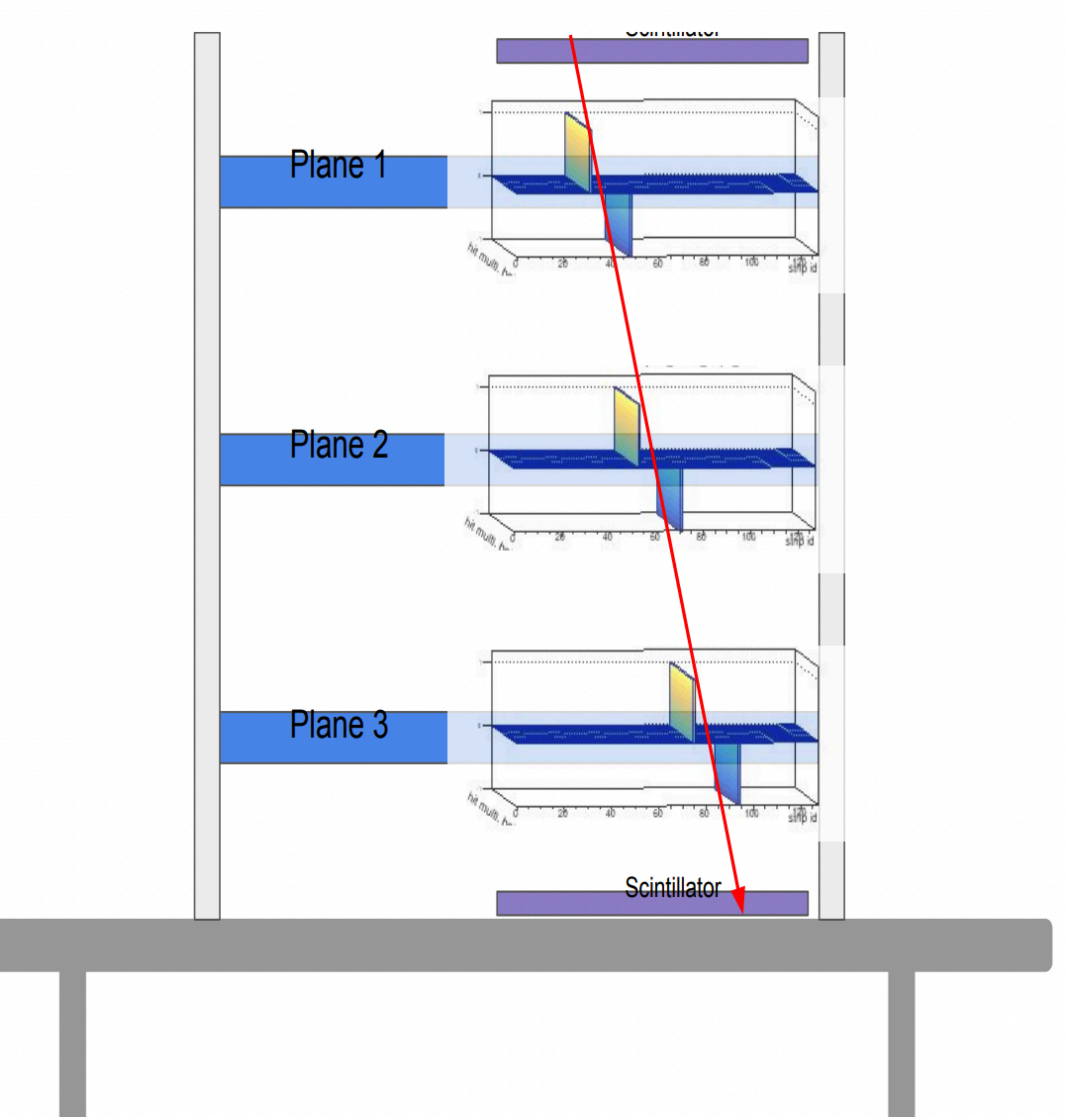
- Cosmic data taking with station on its side, and a scintillator on top/btm.
- Use full FASER TDAQ system to take data.
  - Operational experience
  - Tracker efficiency, resolution and alignment studies
  - Offline s/w debugging

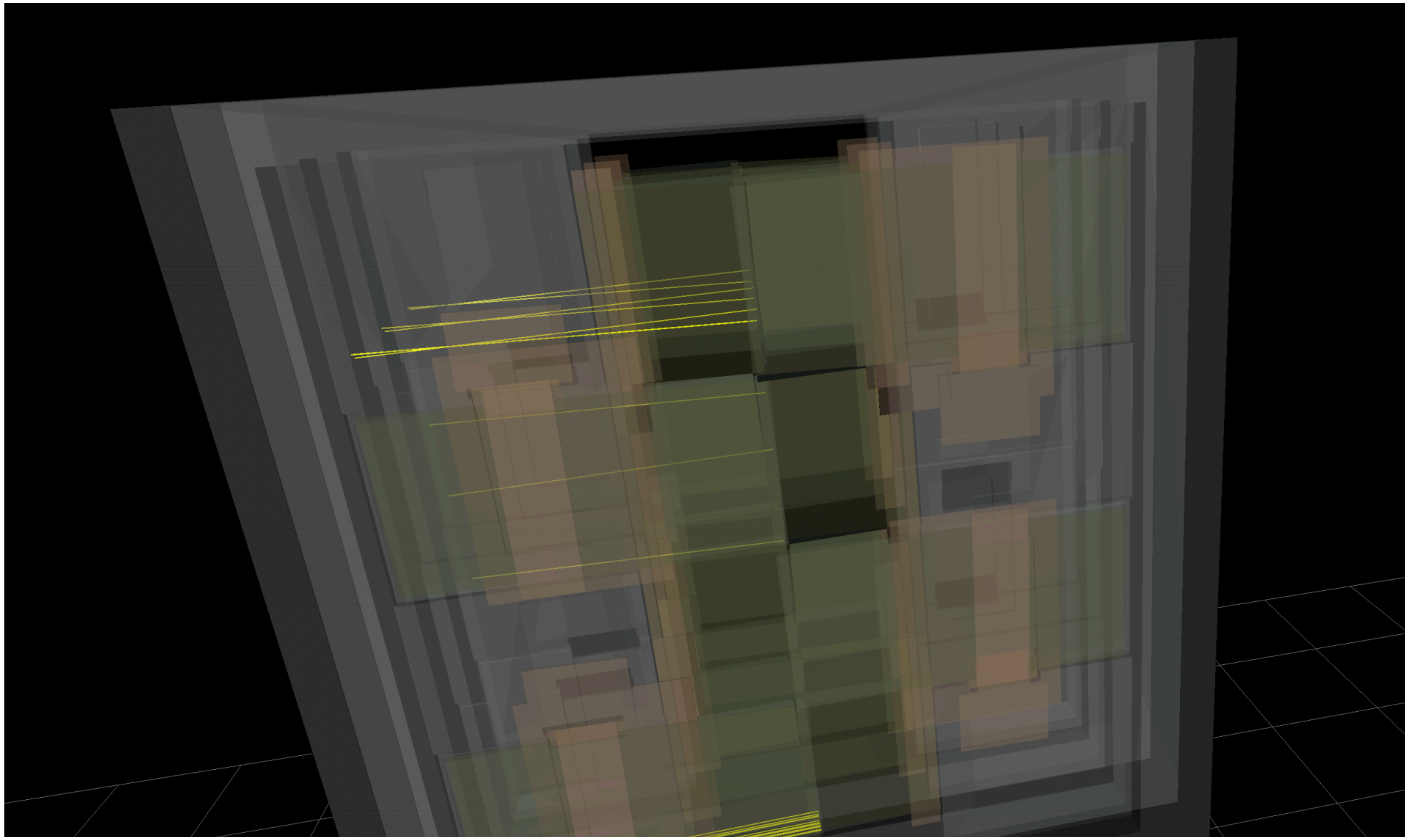




# Overground testing | Tracker

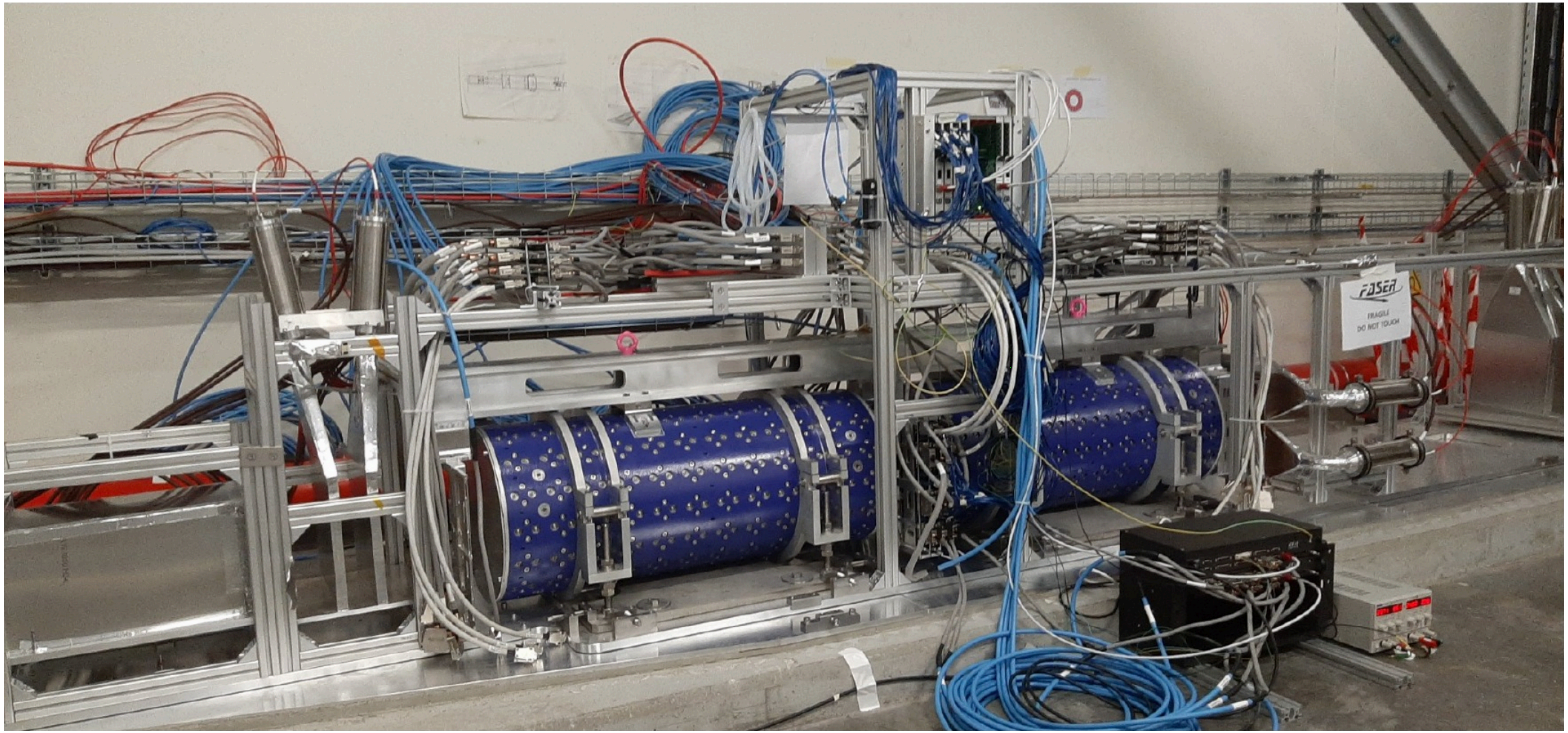
- Straight track candidate along with event display:



# Commissioning | Overground

- Also have partial detector combined run
  - All scintillators and calorimeters with one tracker station

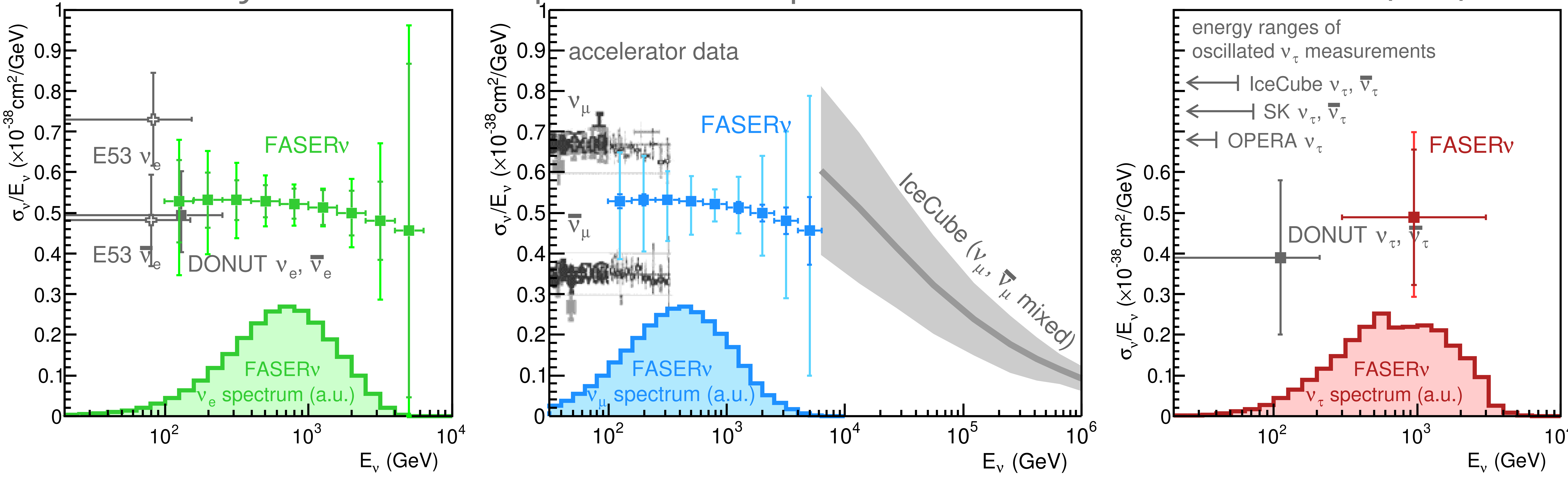


# Commissioning | Overground

- Also have partial detector combined run
  - All scintillators and calorimeters with one tracker station
- In just one week before disassembly started:
  - Common clock provided by Technion clock card (40.08 MHz)
  - Triggering on cosmic showers/random triggers
  - Reading out full detector
  - Tracker readout-timed in with respect to trigger signals
  - Ran with FASER DAQ system, run control GUI and monitoring
  - Data recorded to local disk and copied to EOS

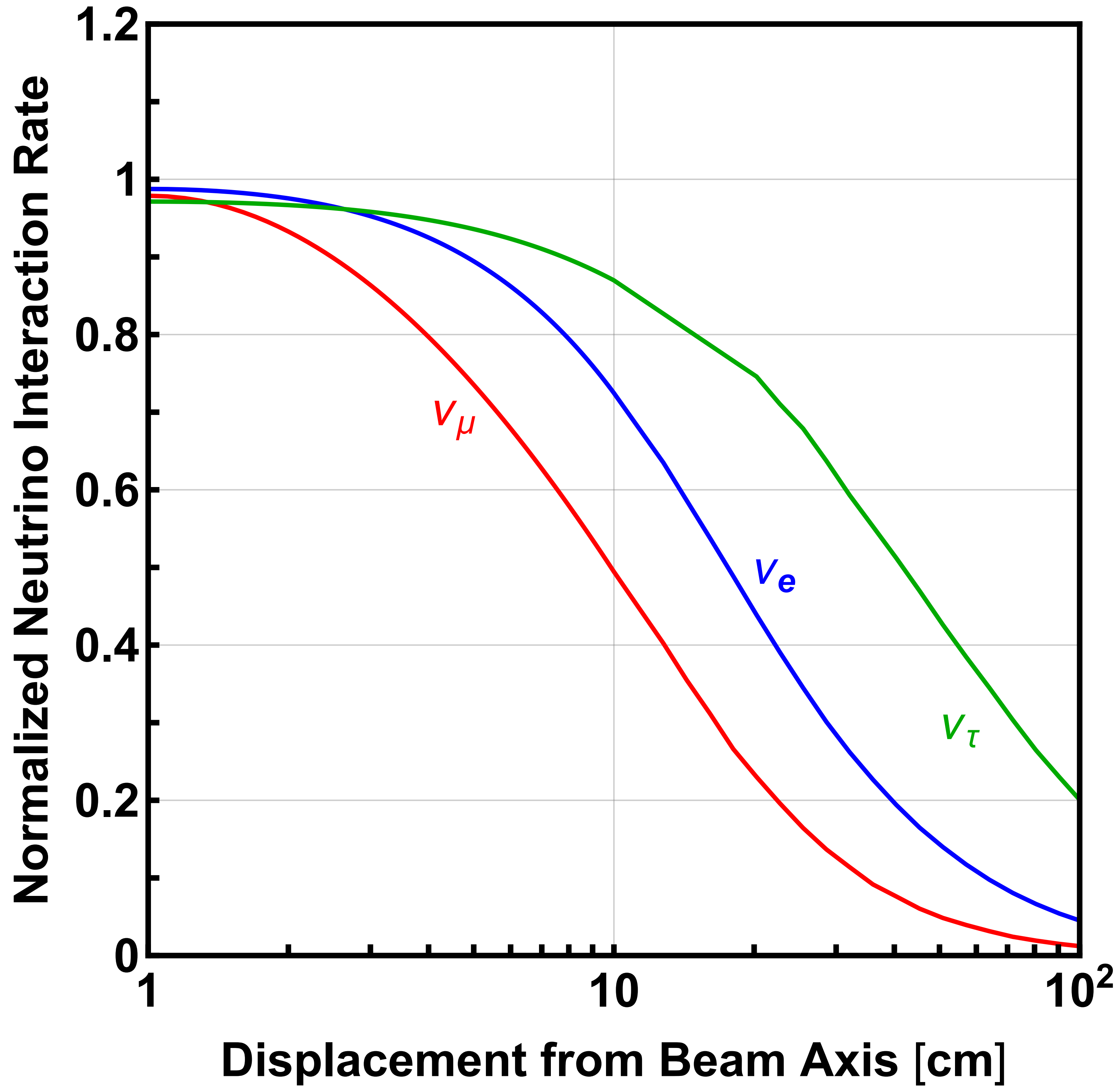
# FASERν | Physics case

- The energy spectrum expected at FASERν is rather complementary to existing neutrino experiments
- Expected cross section sensitivity significantly extends current measurements during Run 3 (150 fb$^{-1}$):
  - Uncertainty from neutrino production important. $E_\nu$ reco resolution ~30% (sim).



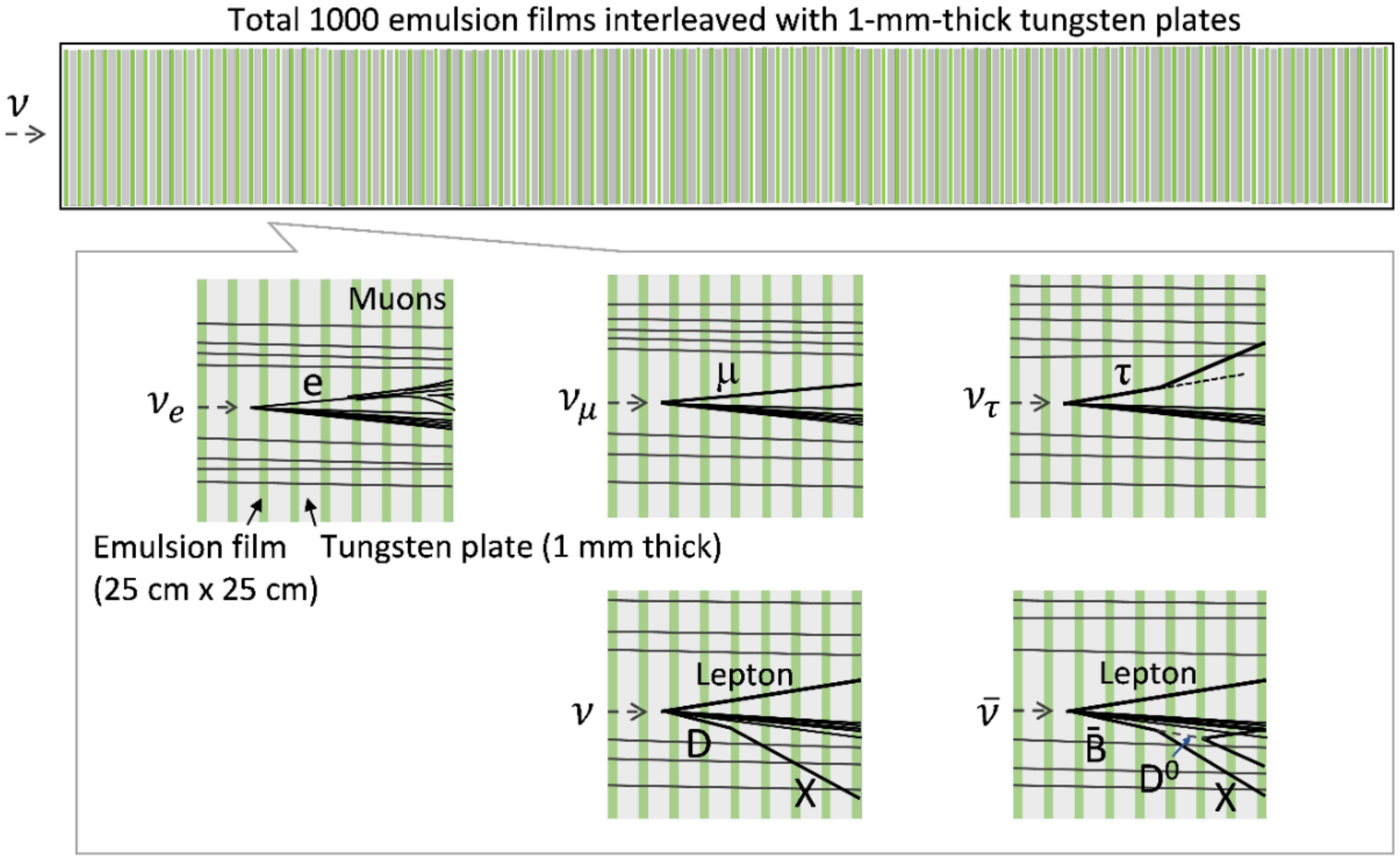
# FASERν | Physics case

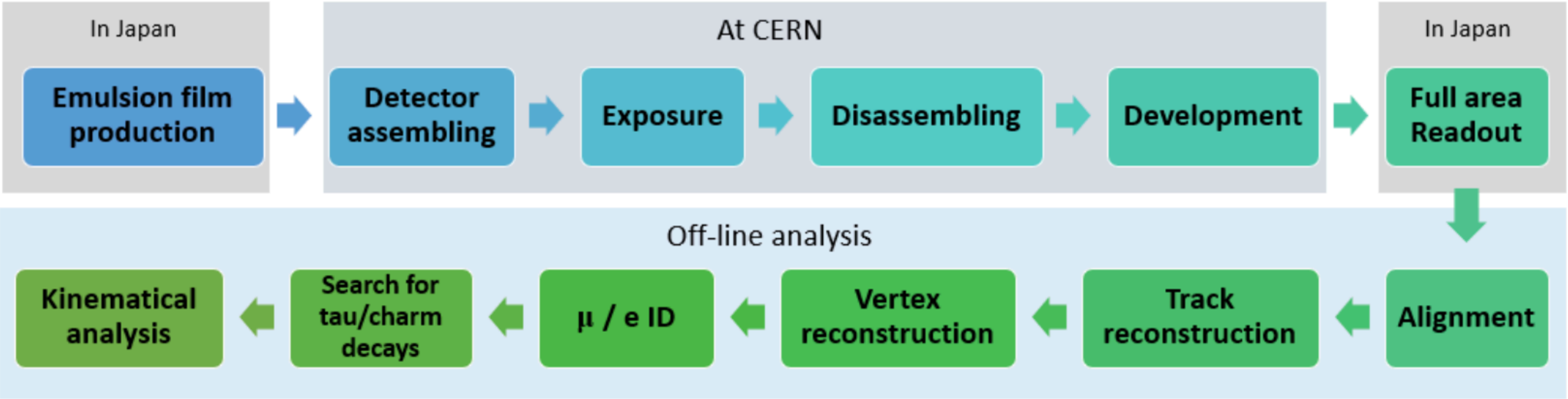
- The energy spectrum expected at FASERν is rather complementary to existing neutrino experiments
- Expected cross section sensitivity significantly extends current measurements during Run 3 (150 $fb^{-1}$)
- Being located on line-of-sight FASERν is able to observe a maximum rate of all neutrino flavours:



# FASERν | Detector design

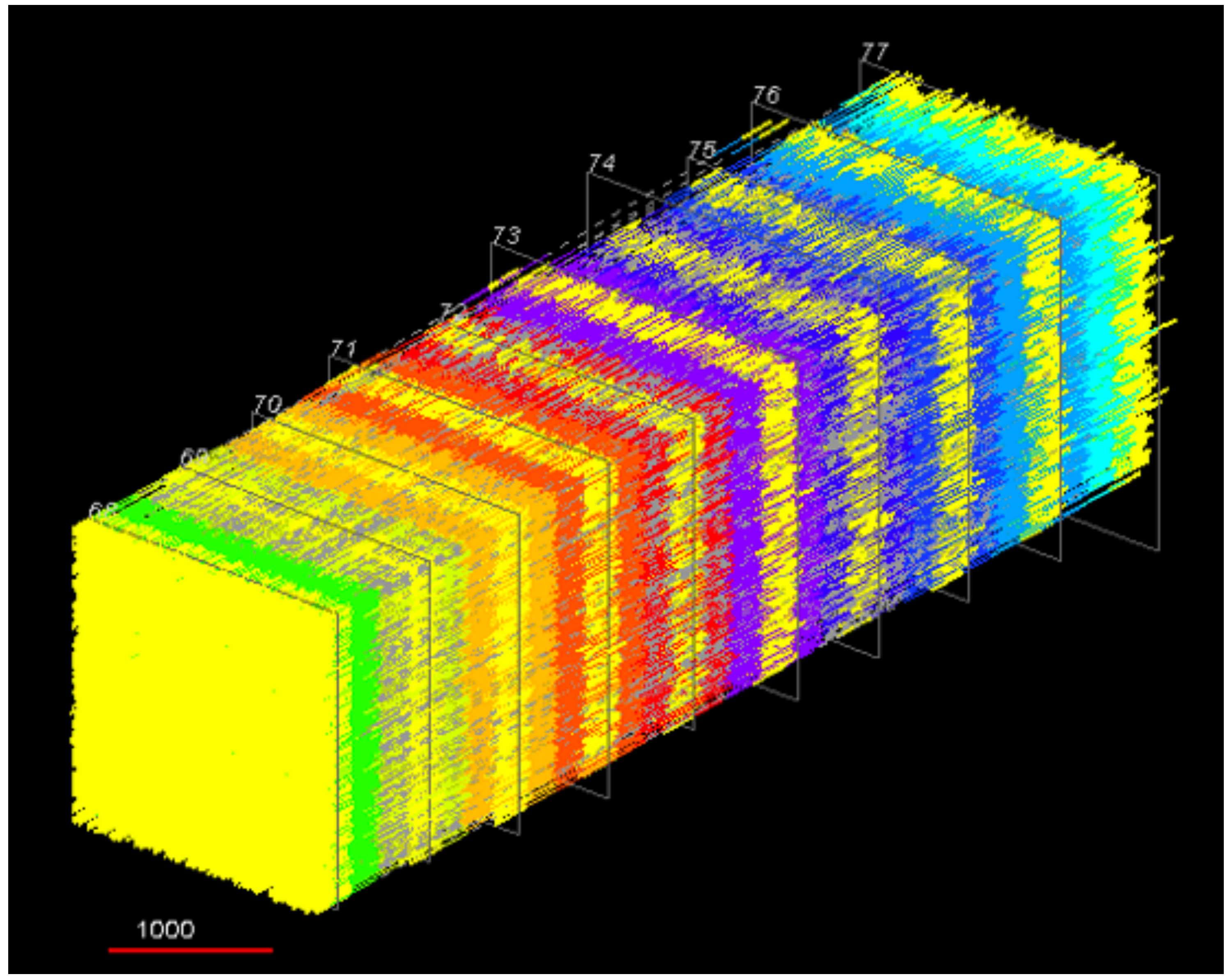
- Emulsion detector with tungsten target
  - 1000 1mm thick tungsten plates interleaved with emulsion film
    - Well understood neutrino detector technology
  - Replace every 20-50 $fb^{-1}$ to maintain track density low
- Challenges:
  - Logistics to transport and replace the 1-ton-scale detector every technical stop (3 times/year)
    - Benefit from transport infrastructure installed in UJ12 and TI12 to install FASER detector
  - Procedure well developed for production and offline analysis:

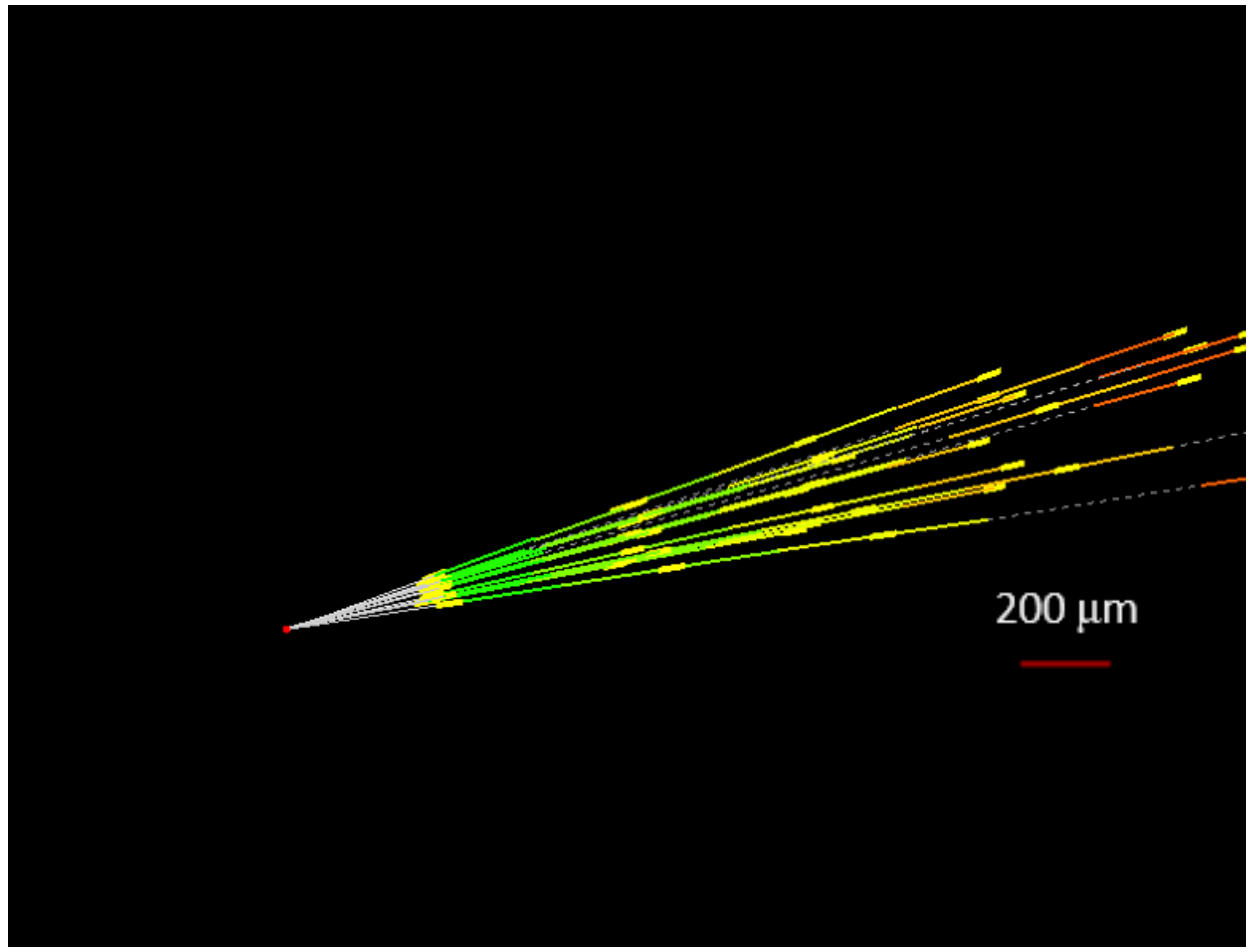


# FASERν | Pilot neutrino detector

- A 30 kg detector was installed in TI18 in 2018
- 12.5 $fb^{-1}$ of data was collected
  - ~30 neutrino interactions in the detector expected to have occurred
- Emulsion data developed, reconstructed and analysis ongoing
- Extremely valuable for validating the FASERnu, optimizing the detector & reconstruction
  - Several neutral vertices identified, likely to be neutrino interactions, could also be neutral hadrons

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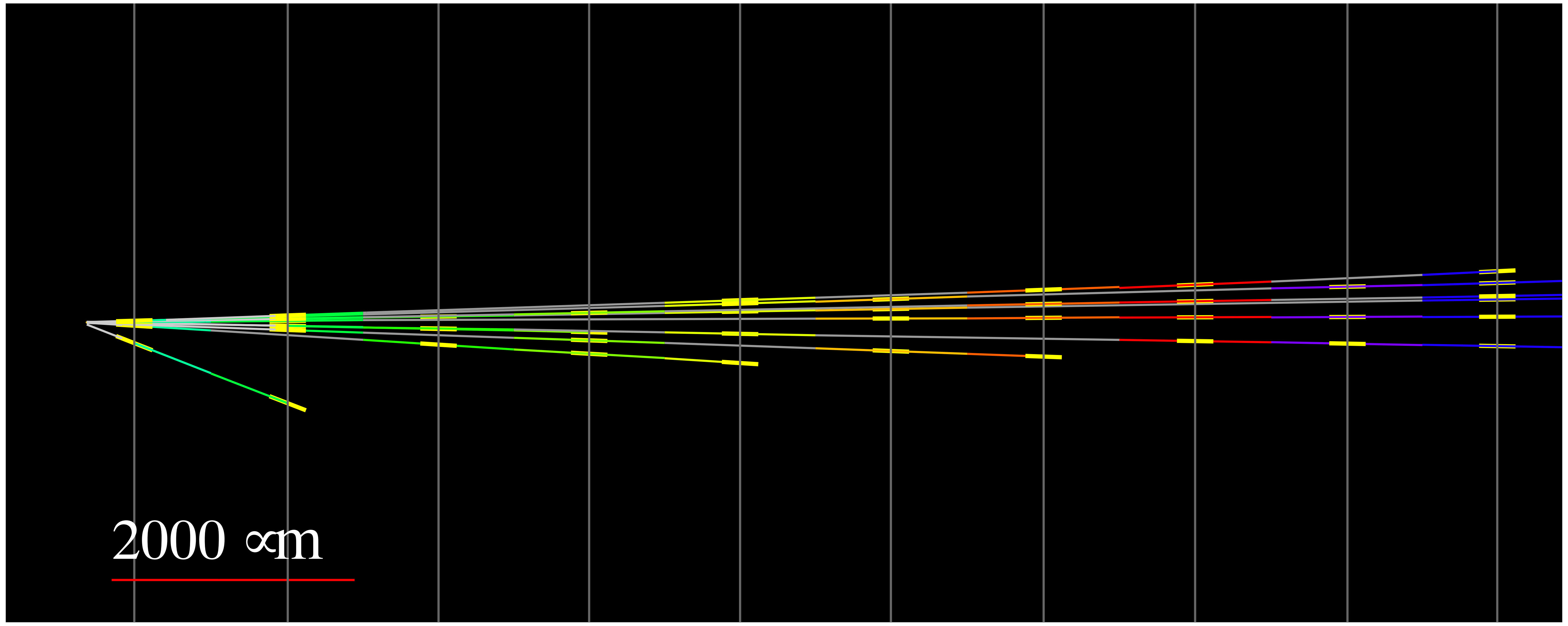


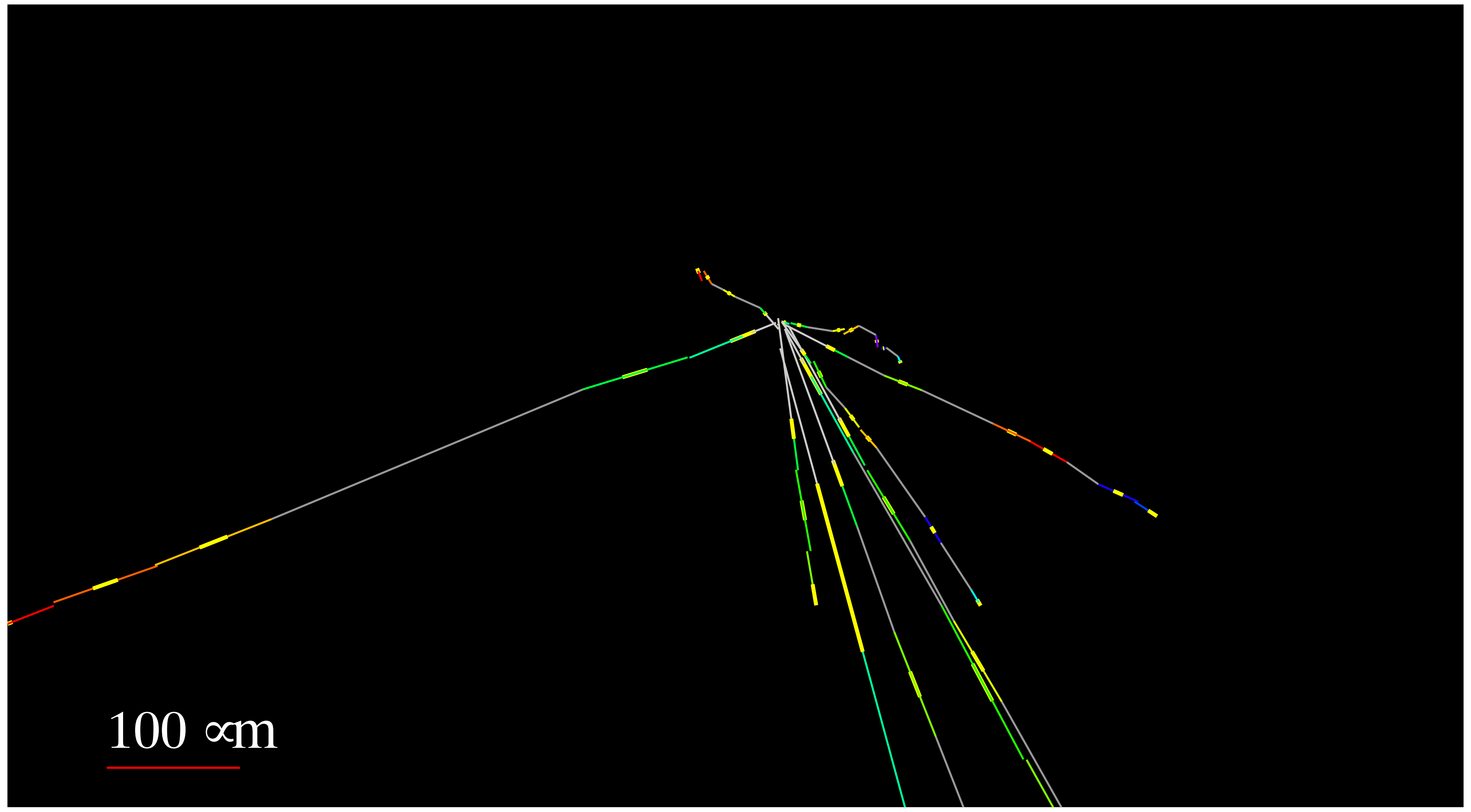

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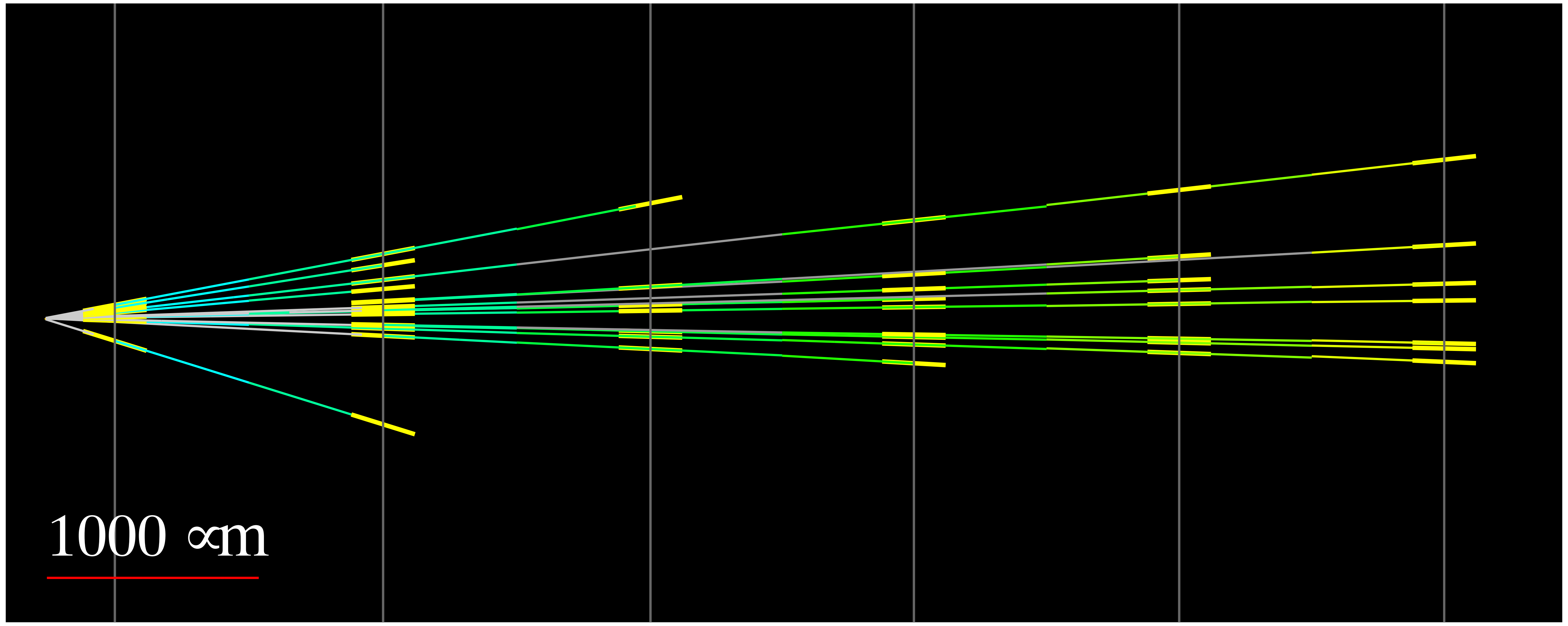
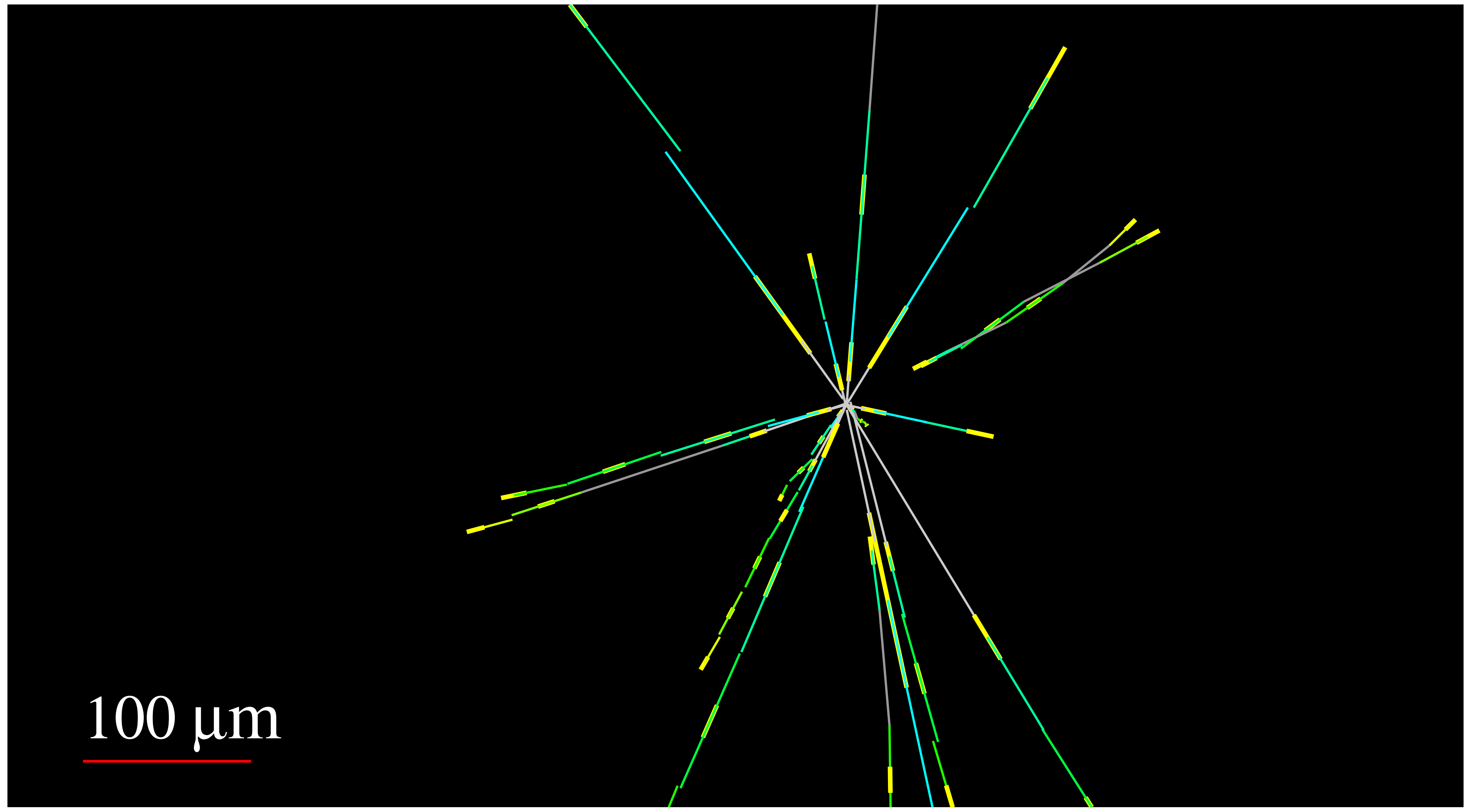
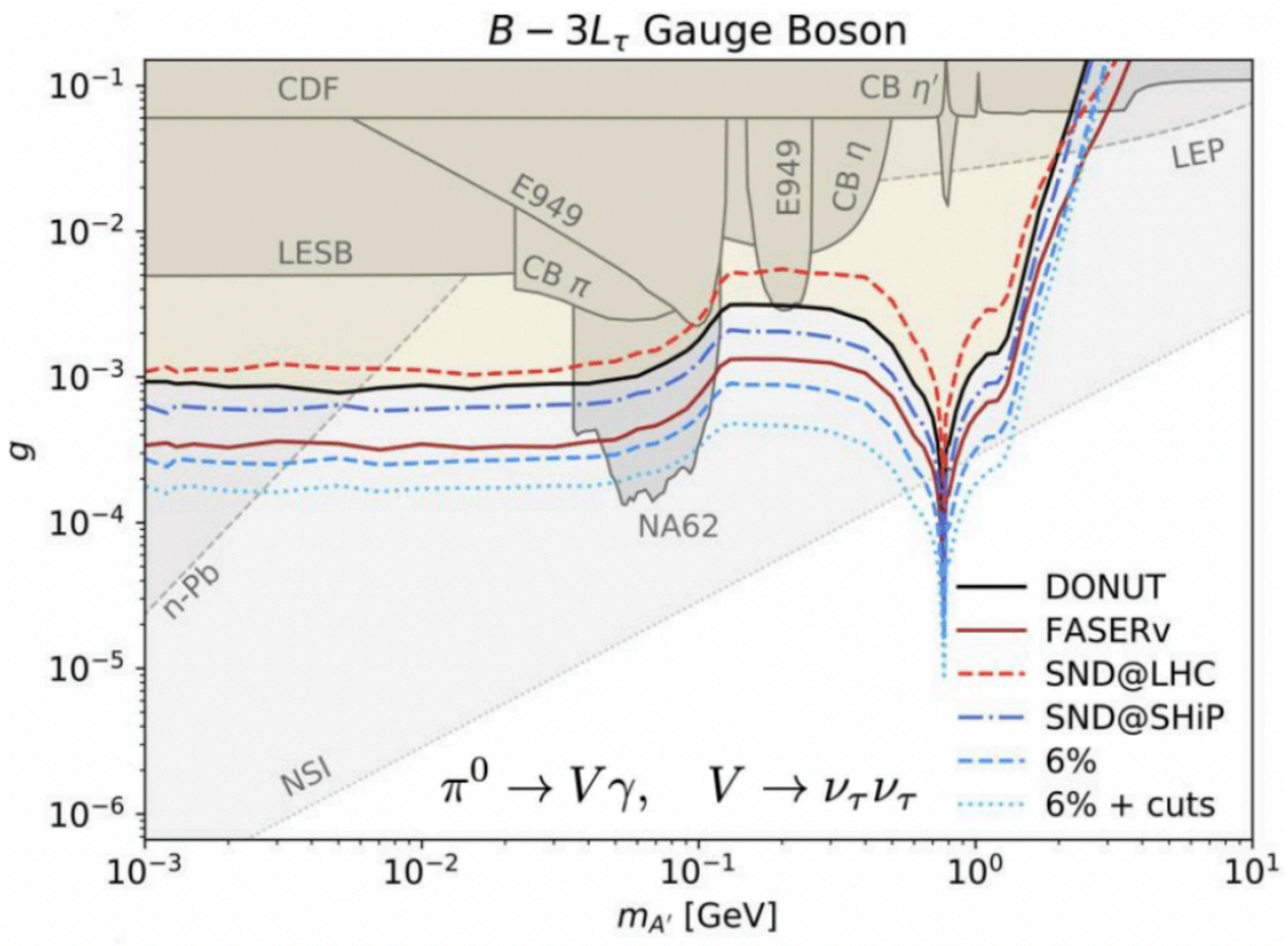
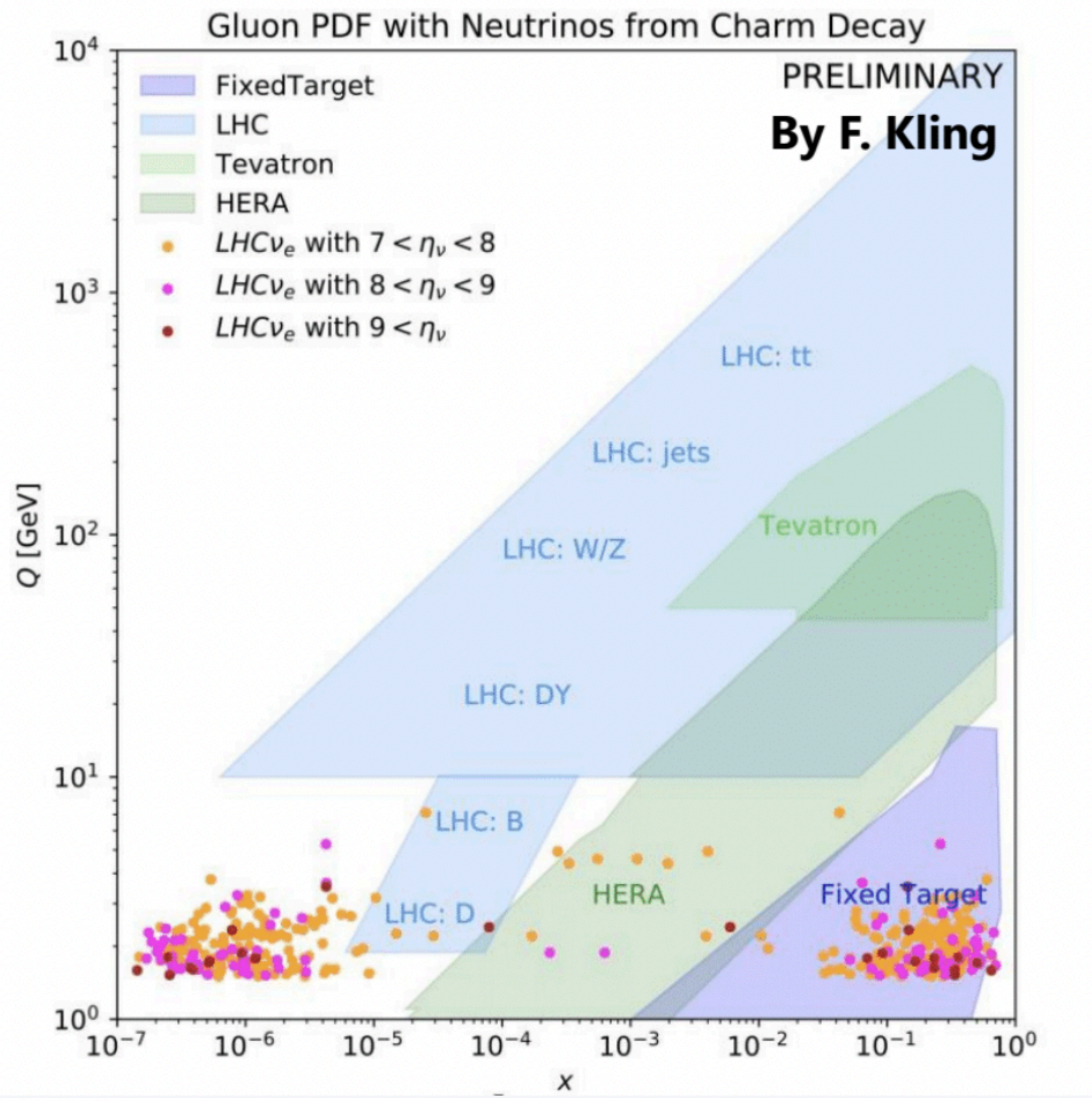


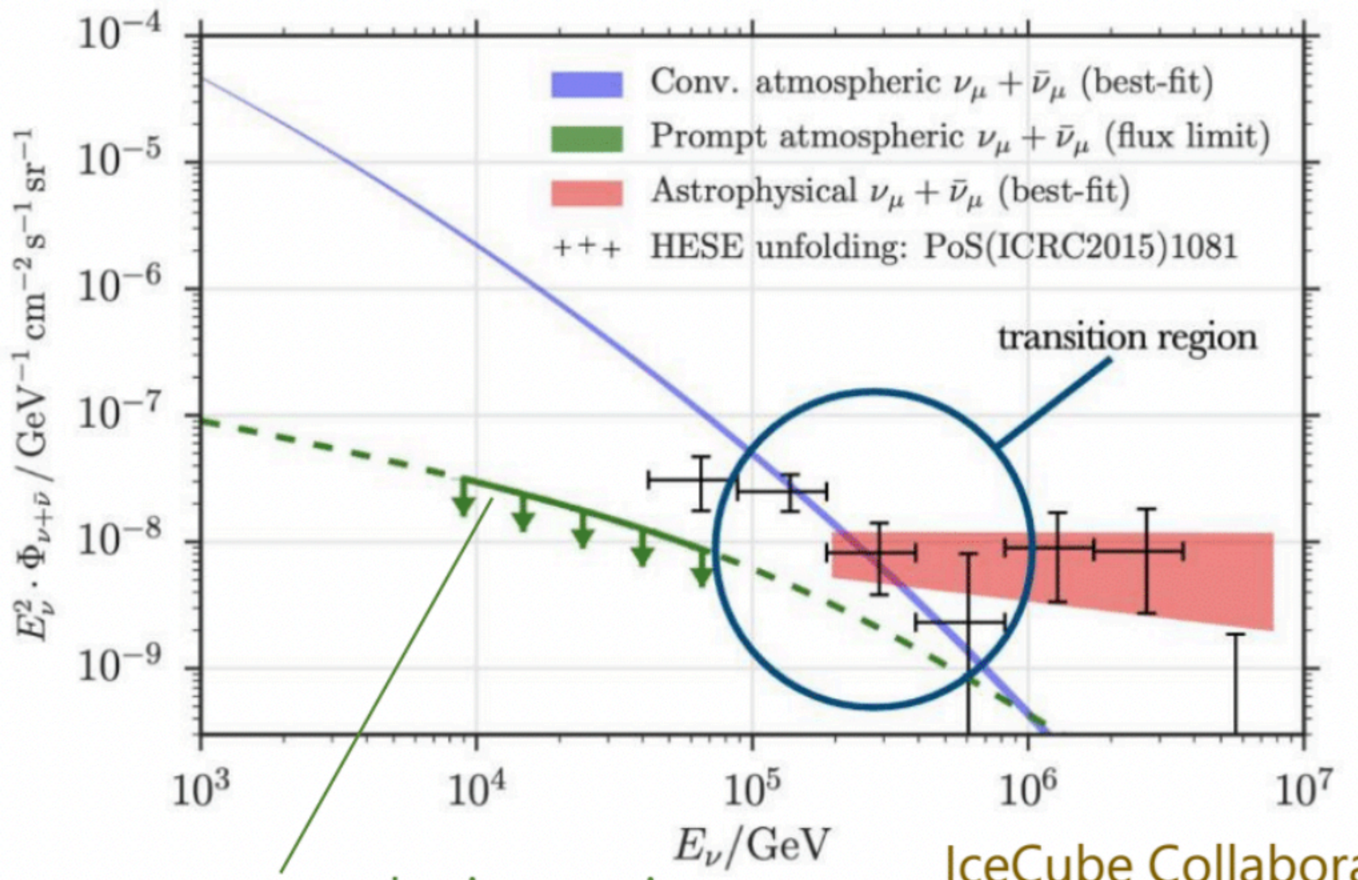



# FASERν | Rich neutrino physics program

- BSM physics
  - New light weakly coupled gauge boson (→$\nu_\tau$) could enhance $\nu_\tau$ flux.
  - Sterile neutrinos with mass ~40 eV can cause oscillations at FASER
- QCD
  - FASER's neutrino flux measurements will provide novel complimentary constraints that can be used to validate/improve MC generator very forward particle production.
  - Neutrinos from charm decay could allow to test transition to small-x factorisation, constrain low-x gluon PDF and probe intrinsic charm
- Cosmic rays and neutrinos
  - IceCube needs measurements of high energy and large rapidity charm for precise measurements of cosmic neutrino flux.
  - Direct measurement of prompt neutrino production at FASER would provide important data for current & future neutrino telescopes




prompt atmospheric neutrinos

IceCube Collaboration, Astrophys. J. 833 (2016)

# FORESEE

- Projections created with the FORSEE tool:
  - Phys. Rev. D 104, 035012
  - https://github.com/KlingFelix/FORESEE

arXiv.org > hep-ph > arXiv:2105.07077

Search...

Help | Adv

High Energy Physics – Phenomenology

*[Submitted on 14 May 2021]*

**FORESEE: FORward Experiment SEnsitivity Estimator for the LHC and future hadron colliders**

Felix Kling, Sebastian Trojanowski

We introduce a numerical package FORward Experiment SEnsitivity Estimator, or FORESEE, that can be used to simulate the expected sensitivity reach of experiments placed in the far-forward direction from the proton-proton interaction point. The simulations can be performed for 14 TeV collision energy characteristic for the LHC, as well as for larger energies: 27 and 100 TeV. In the package, a comprehensive list of validated forward spectra of various SM species is also provided. The capabilities of FORESEE are illustrated for the popular dark photon and dark Higgs boson models, as well as for the search for light up-philic scalars. For the dark photon portal, we also comment on the complementarity between such searches and dark matter direct detection bounds. Additionally, for the first time, we discuss the prospects for the LLP searches in the proposed future hadron colliders: High-Energy LHC (HE-LHC), Super proton-proton Collider (SppC), and Future Circular Collider (FCC-hh).

Comments: 11 pages, 3 figures, FORESEE code available at this https URL
Subjects: **High Energy Physics – Phenomenology (hep-ph)**
Cite as: arXiv:2105.07077 **[hep-ph]**
(or arXiv:2105.07077v1 **[hep-ph]** for this version)

README.md

## FORESEE: FORward Experiment SEnsitivity Estimator

**By Felix Kling and Sebastian Trojanowski**

arXiv 2105.07077

### Introduction

We present the numerical package **FOR**ward Experiment **SE**nsitivity Estimator, or **FORESEE**, that can be used to simulate the expected sensitivity reach of experiments placed in the far-forward direction from the proton-proton interaction point. We also provide a comprehensive list of validated forward spectra of various SM species.

### Paper

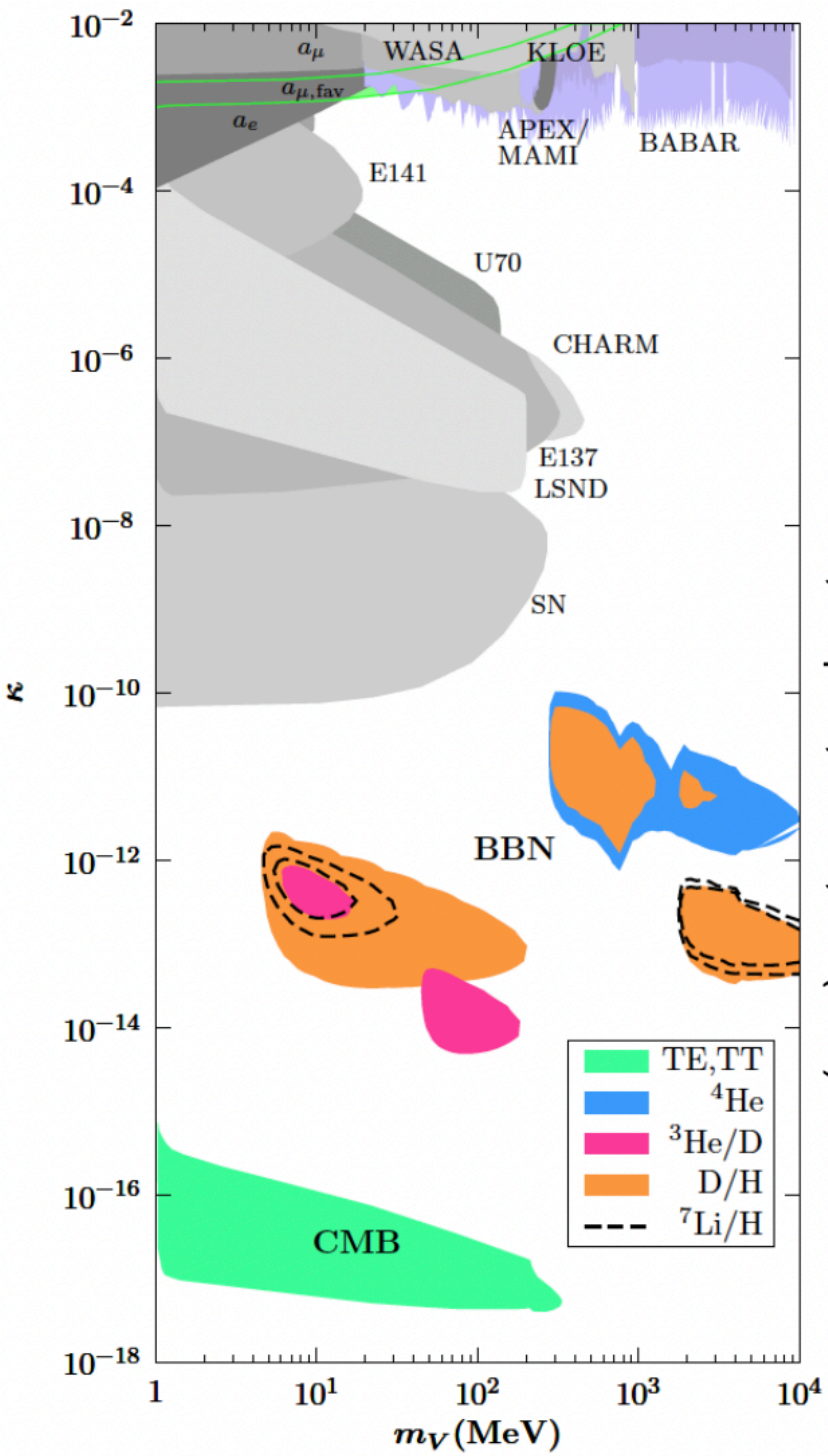
Our main publication FORESEE: FORward Experiment SEnsitivity Estimator for the LHC and future hadron colliders provides an overview over this package. We recommend reading it first before jumping into the code.

### Tutorials

In the main folder in this repository, we provide tutorials for different LLP models: the dark photon, the dark Higgs, the ALP with W couplings and the up-philic scalar.

# Physics Motivation | Dark photons

- Dark photons are particularly interesting for FASER as we have fast sensitivity to new regions of phase space
- There is a vast and largely unexplored parameter space
  - "Bump hunts" exclude larger ε
  - Mostly fixed target experiments exclude the gray region
  - Astrophysics (supernova, BBN, CMB) exclude at very low ε
- Overall, light, weakly-interacting particles are much less constrained than ~TeV, strongly-interacting particles.
- Dark Sector models don't give us too much guidance on expected mass or coupling strengths.
- Some other intriguing observations…

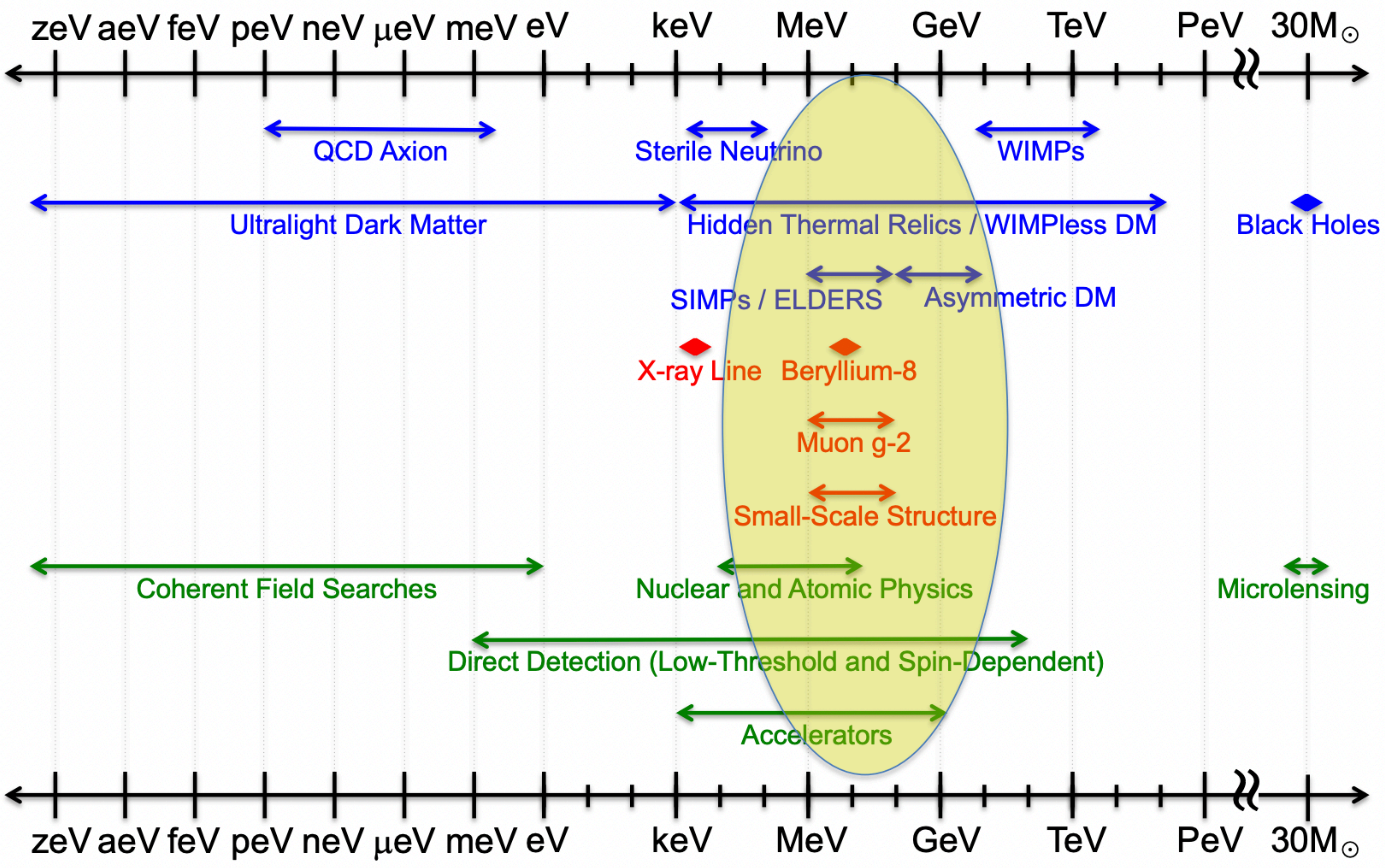



Fradette, Pospelov, Pradler, Ritz (2014)

# Physics Motivation | Intrigue...

- Focusing on the mass scale
  - Dark Sector Candidates
  - Anomalies
  - Search Techniques

- We see some interesting things in the ~MeV range



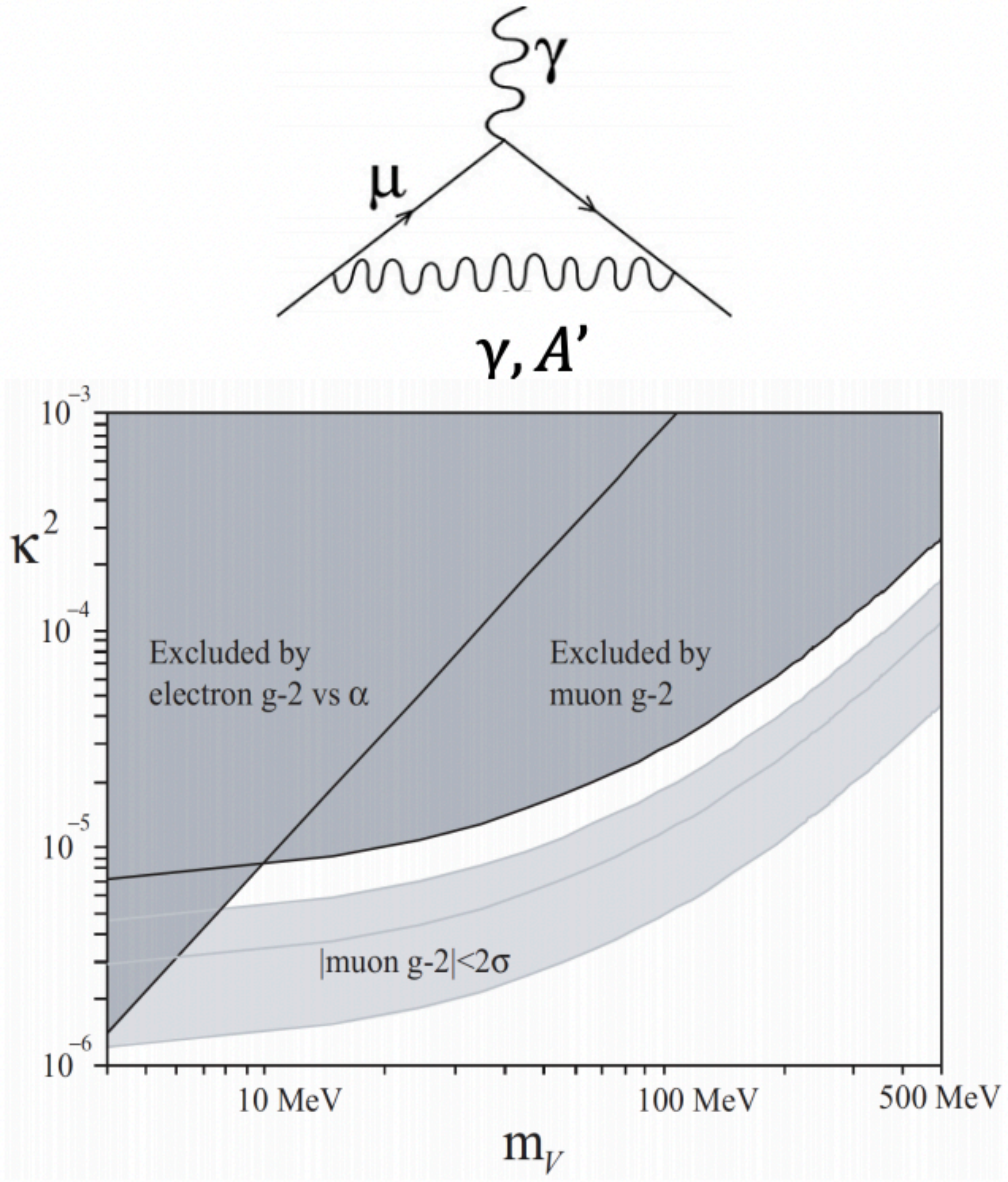
Cosmic Visions Report (2017)

# Physics Motivation | g-2

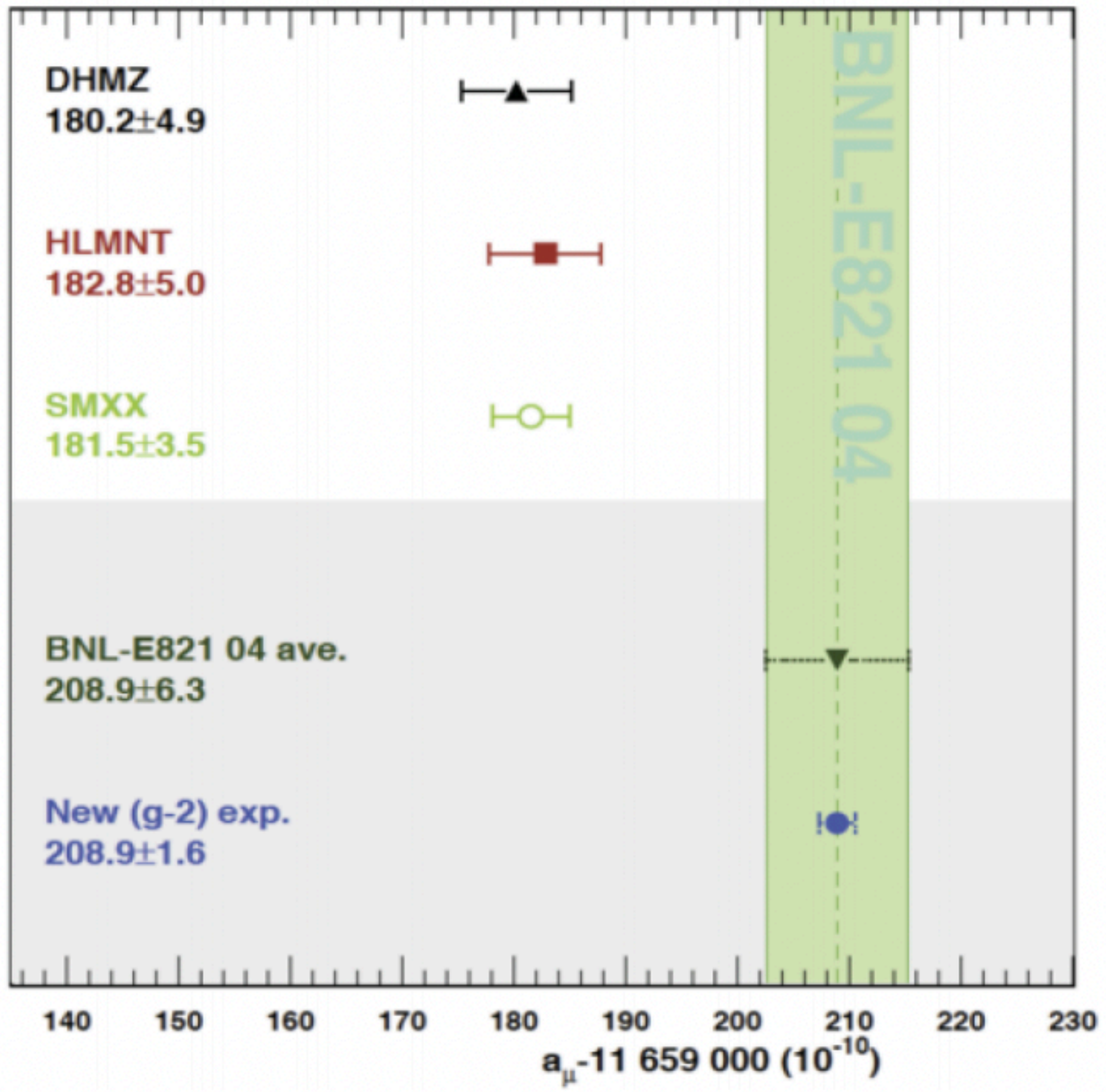
- The 3.7σ discrepancy between the SM and experiment can be resolved by **MeV-GeV particles with $\varepsilon \sim 10^{-3}$**.

- The dark photon is no longer a viable solution

- But other particles with similar masses and couplings are.



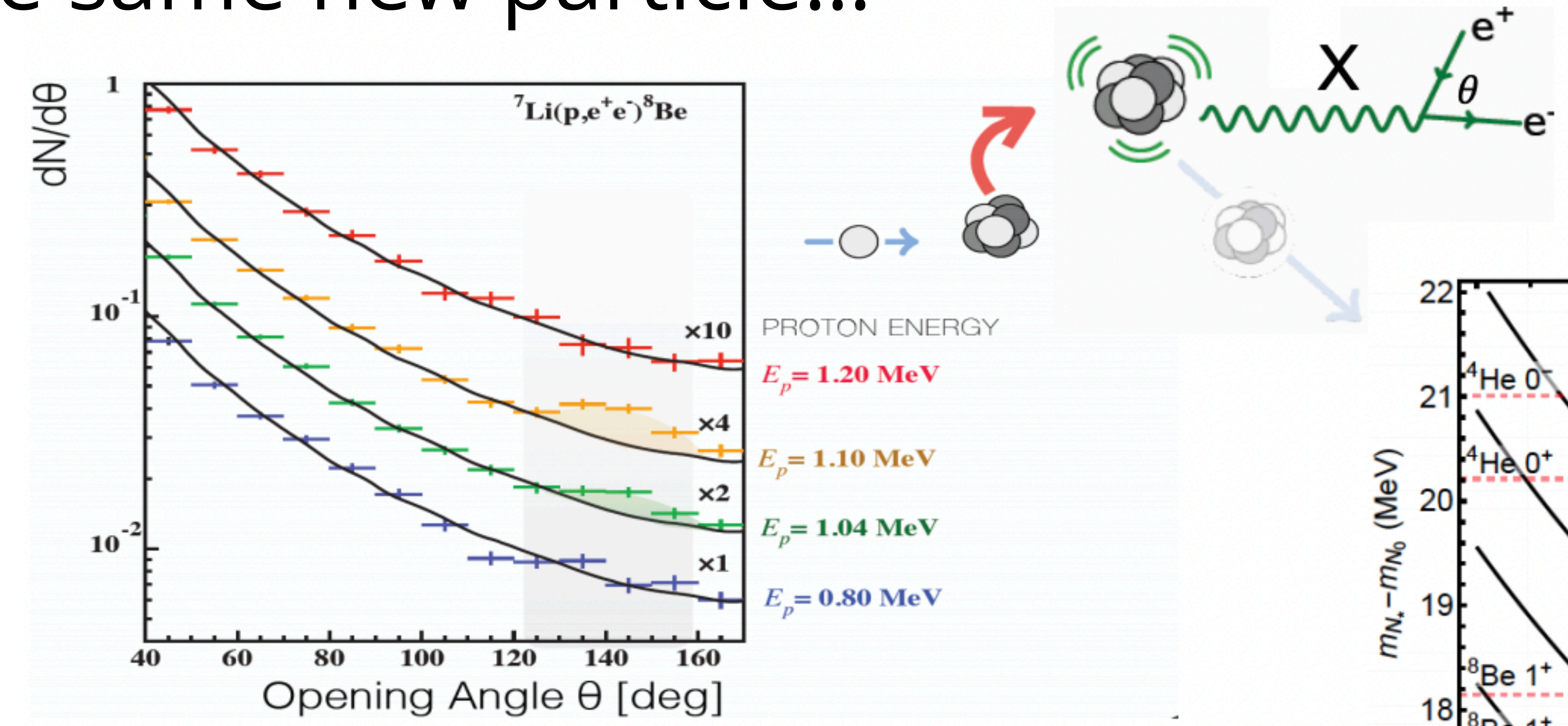

Boehm, Fayet (2003)

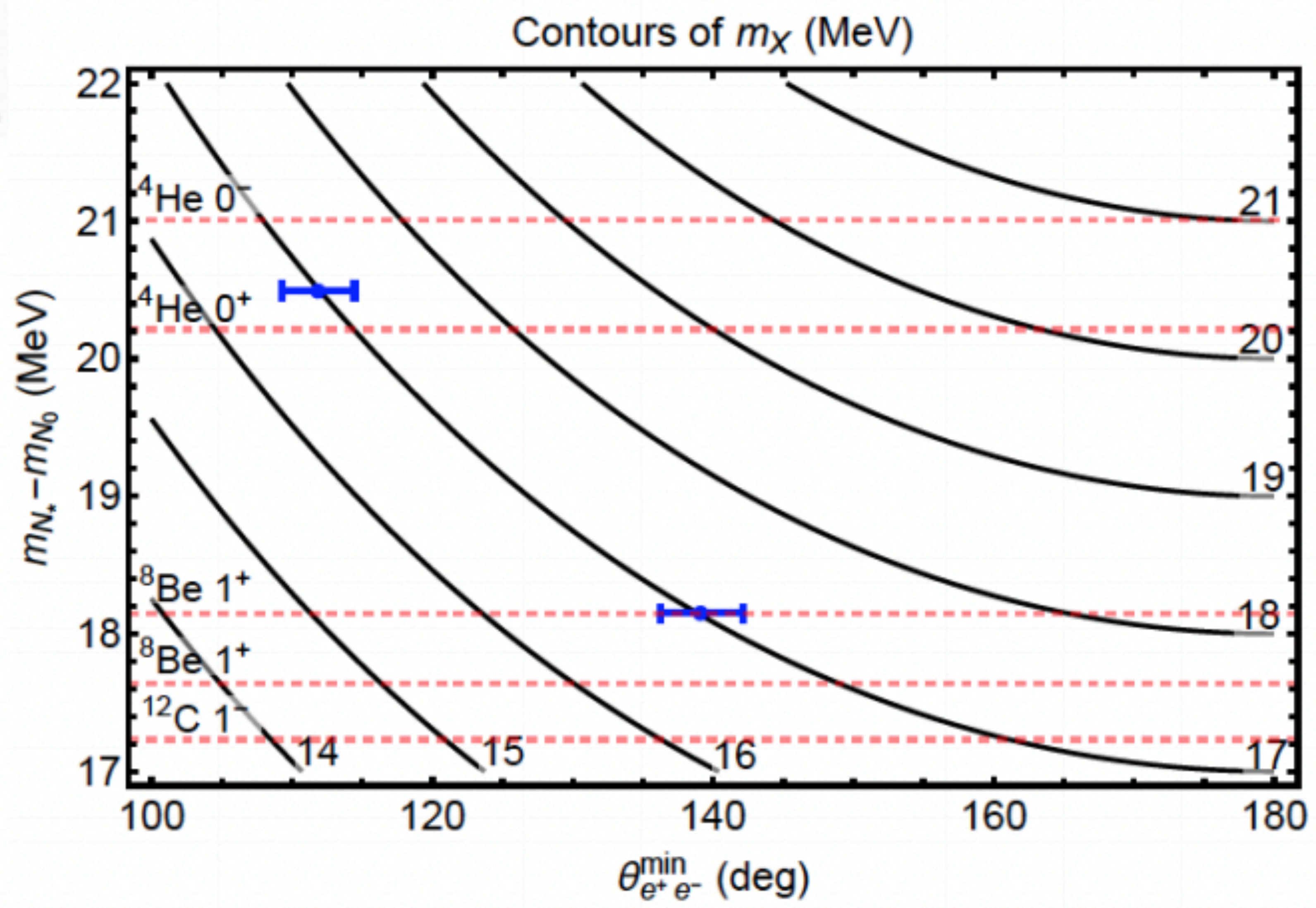



Hagiwara et al. (2017); Aoyama et al. (2020)

# Physics Motivation | He/Be nuclei

- 2016: A 7σ anomaly in the decays of excited $^{8}$Be nuclei can be explained by a **new particle with mass 17 MeV and couplings ~ $10^{-3}$ to $10^{-4}$**.
- 2019: A new 7σ anomaly in the decays of excited $^{4}$He nuclei can be explained by the same new particle…



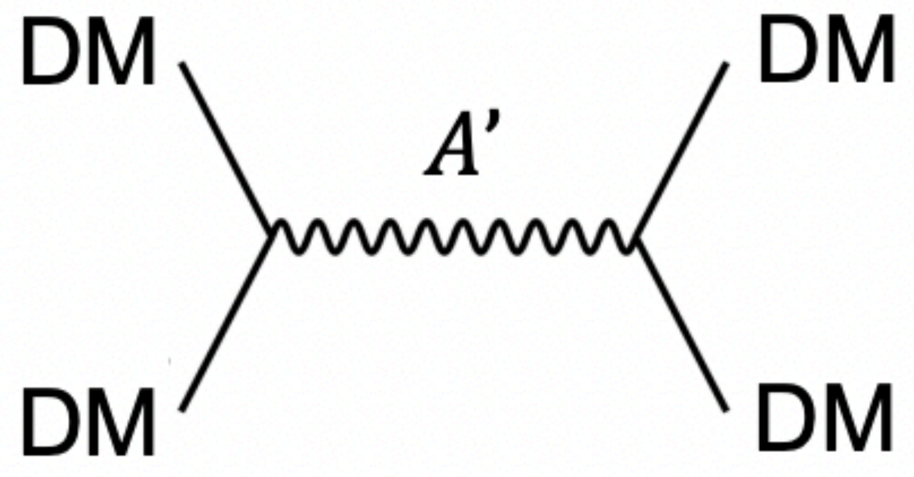

Krasznahorkay et al. (2015, 2019)
Feng, Fornal, Galon, Gardner, Smolinsky, Tanedo, Tait (2016)
Feng, Tait, Verhaaren (2020); Batell, Feng, Verhaaren (in progress)
See also Zhang, Miller (2020)

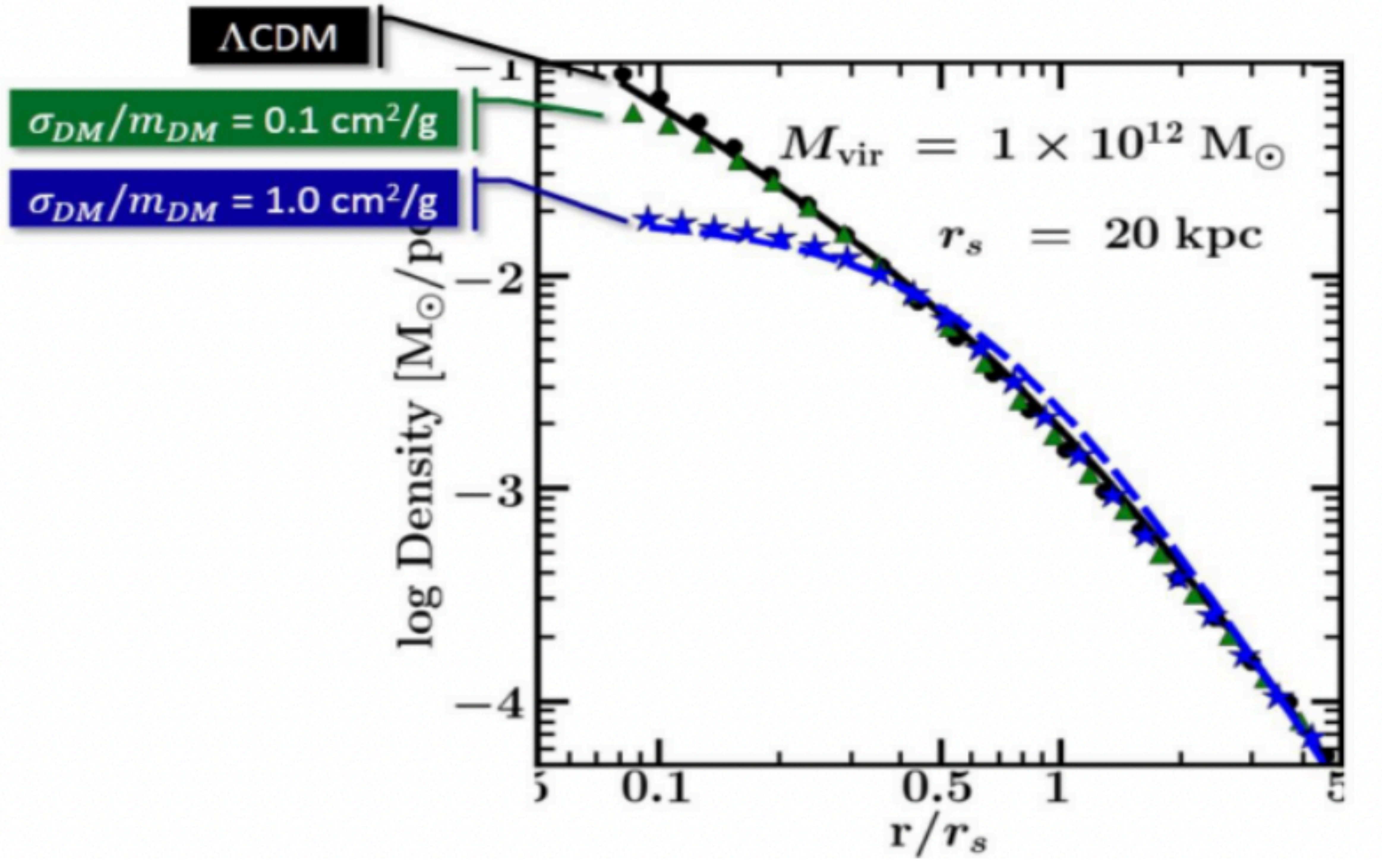
# **Physics Motivation** | Self-interacting DM

- There are indications from small-scale structure that dark matter may be strongly self-interacting.
  - For example, there appear to be halo profiles that are not as cuspy (high central density) as predicted by standard cold dark matter.

- This can be explained by a characteristic **dark sector mass scale of ~ 10-100 MeV**.

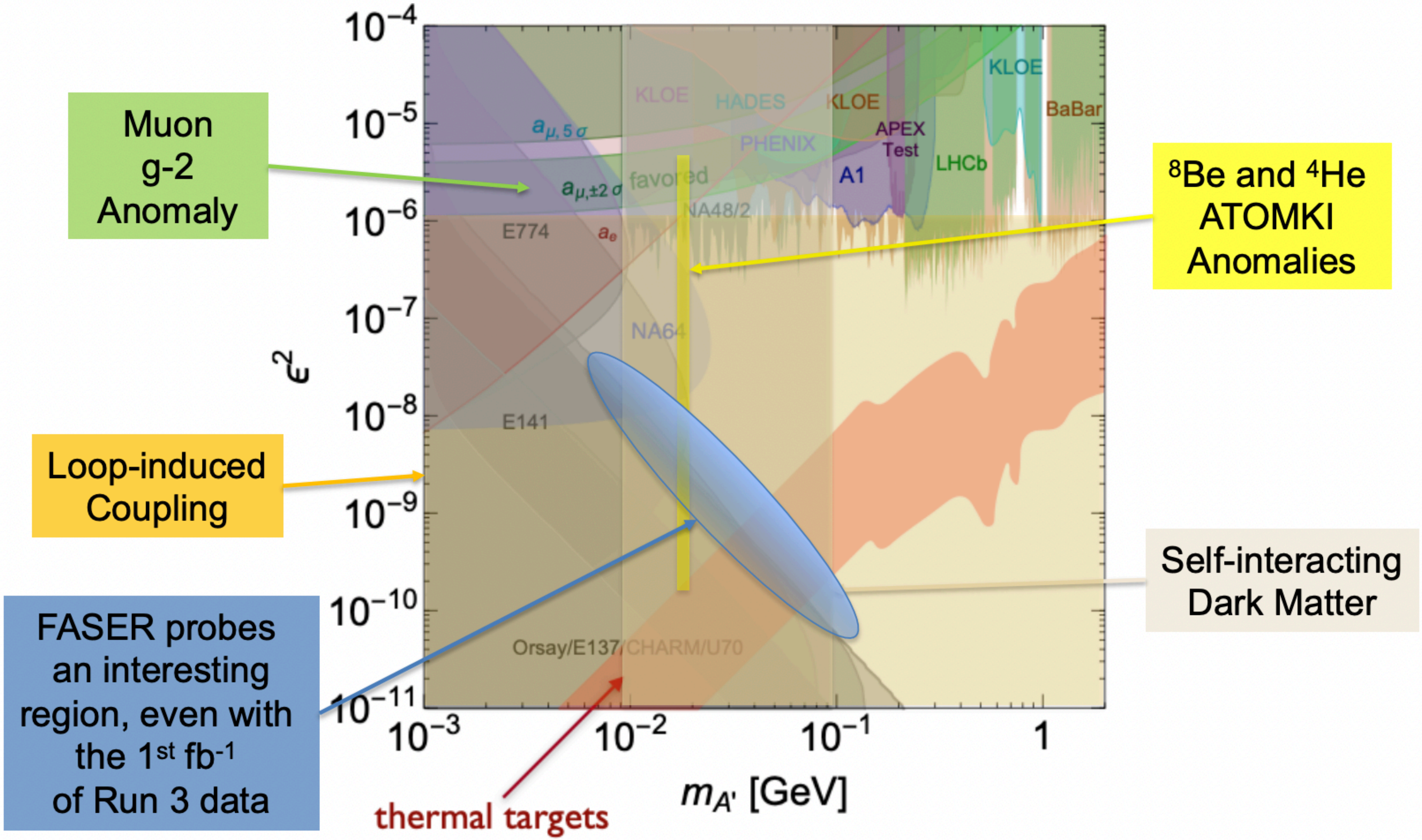
$$\frac{\sigma}{m} \sim \frac{\text{cm}^2}{\text{g}} \sim \frac{\text{barn}}{\text{GeV}} \sim (100\ \text{MeV})^{-3}$$



# Physics Motivation | Dark photon plane

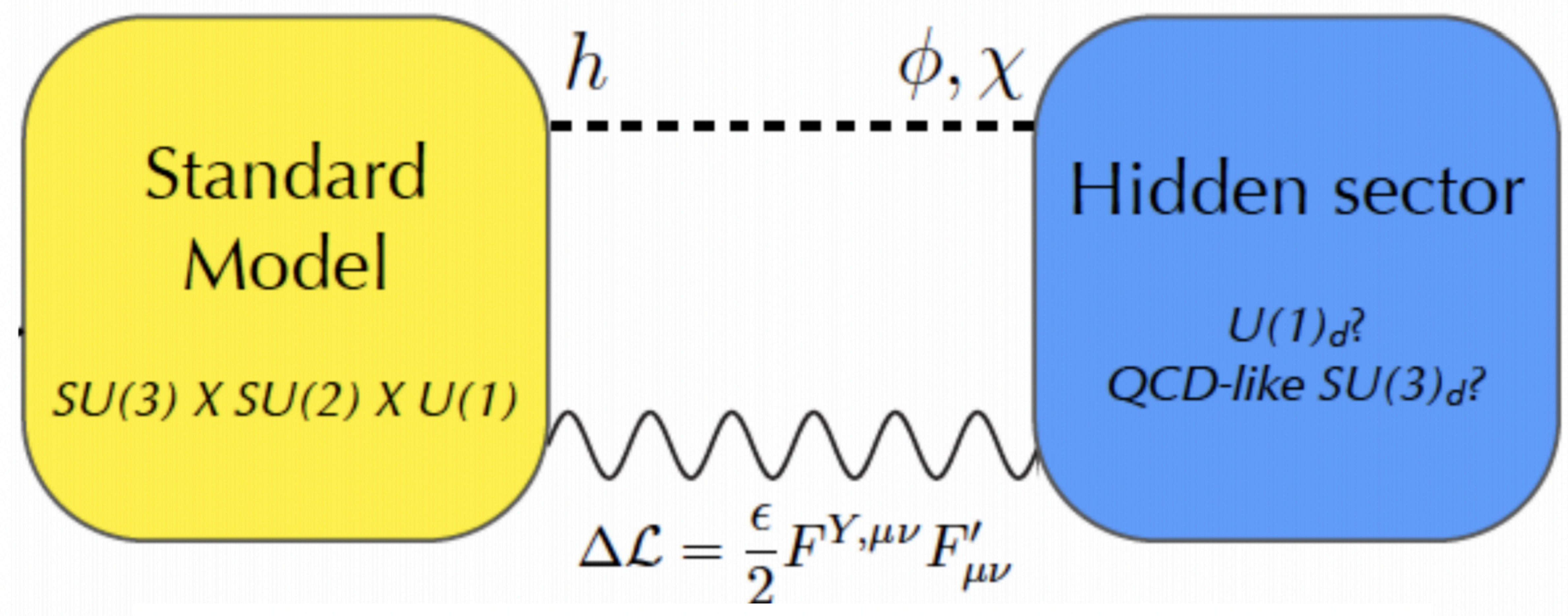
- FASER is probing a very interesting region of phase space
- New sensitivity in this region will come even with only a small fraction of Run 3 data.




Tim Nelson, Snowmass RP6 (2020)

# Physics | Dark portal

- Hidden sector physics:
  - New mediating particles, couplings to SM via mixing with SM "portal" operator
  - Related to nature of DM (mediator or candidate), baryogenesis, neutrino oscillations…
  - Can possibly resolve low-energy experiment anomalies (muon g-2, proton size, Be8)
- Typically long-lived particles (LLPs) that travel macroscopic distances before decaying to SM particles

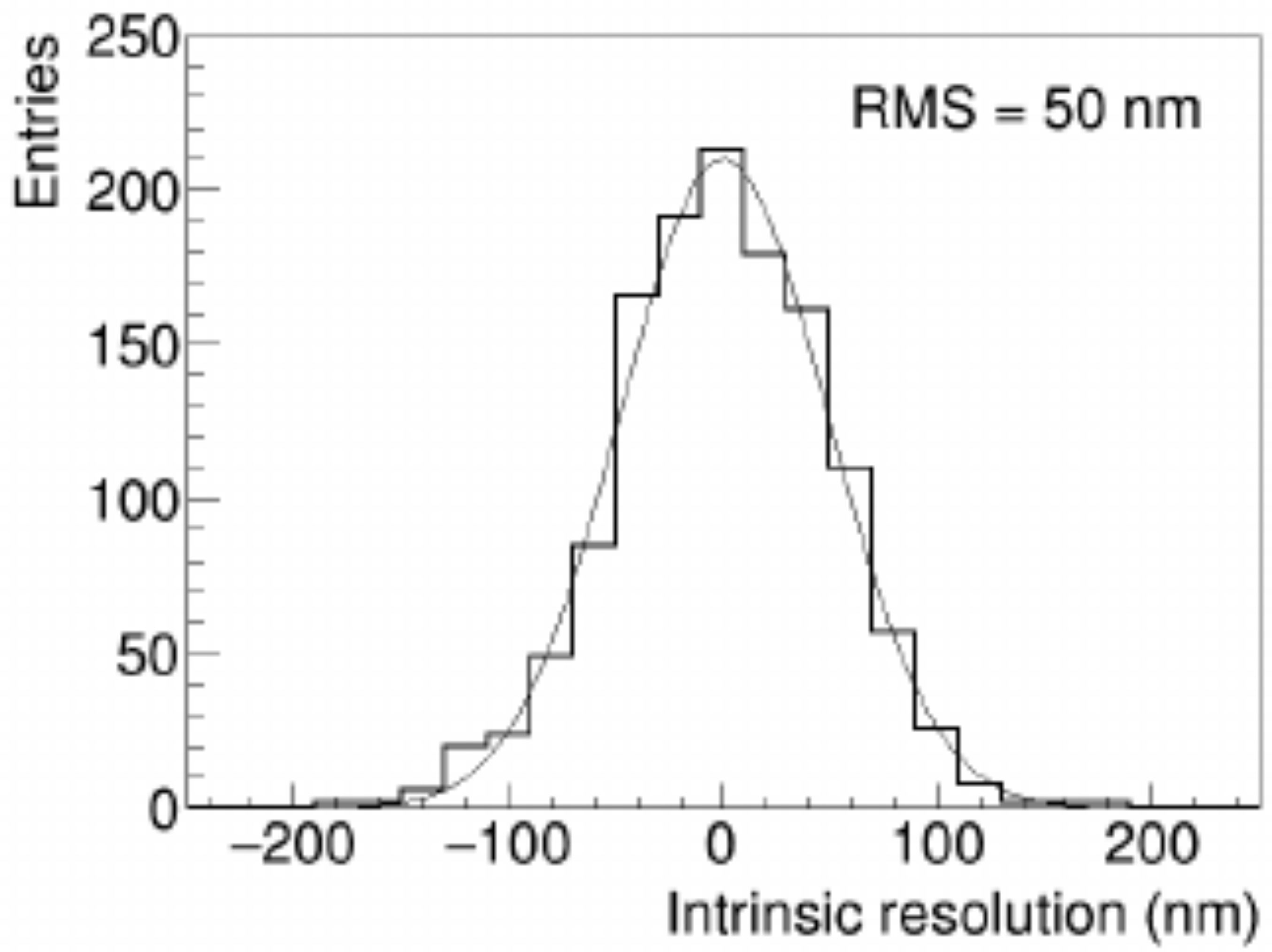


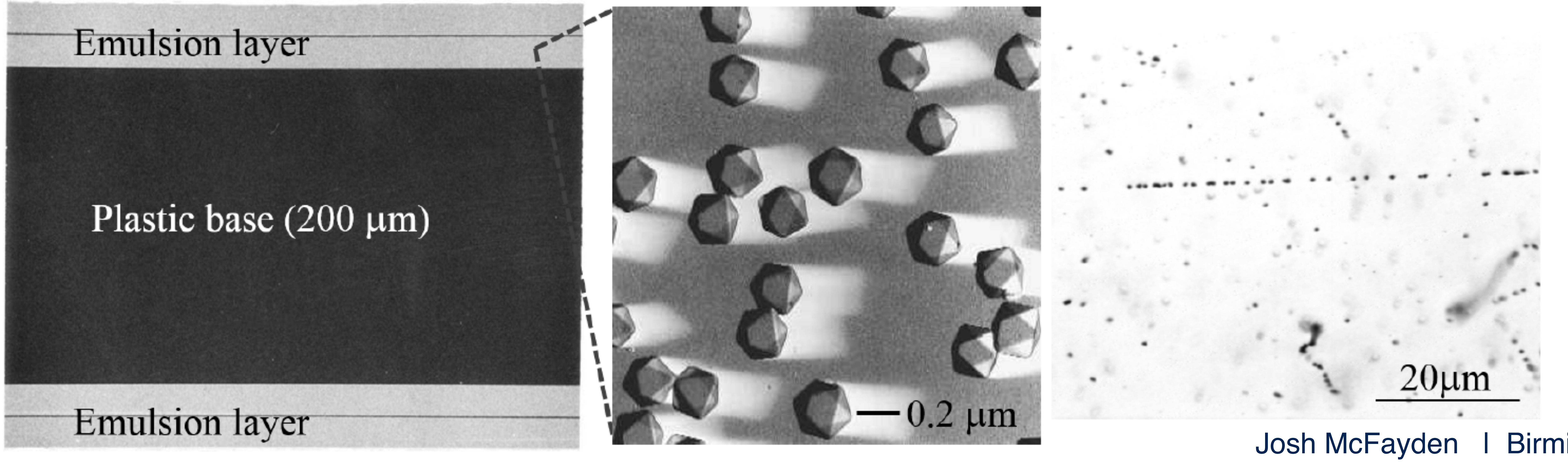

$$\mathcal{L}_{\text{portal}} = \sum O_{\text{SM}} \times O_{\text{DS}}$$

| Portal | Coupling |
|---|---|
| Dark Photon, $A_\mu$ | $-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$ |
| Dark Higgs, $S$ | $(\mu S + \lambda S^2) H^\dagger H$ |
| Axion, $a$ | $\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$ |
| Sterile Neutrino, $N$ | $y_N L H N$ |

# FASERν | Emulsion detection

- Emulsion film made up of ~80μm emulsion layer on either side of 200μm plastic
- Emulsion gel active unit silver bromide crystals (dia. 200nm)
- Charged particle ionization recorded and can be amplified and fixed by chemical development of film
- Track position resolution ~50nm, and angular resolution ~0.35mrad
  - But no time resolution!



# FASERν | Neutrino flux estimates

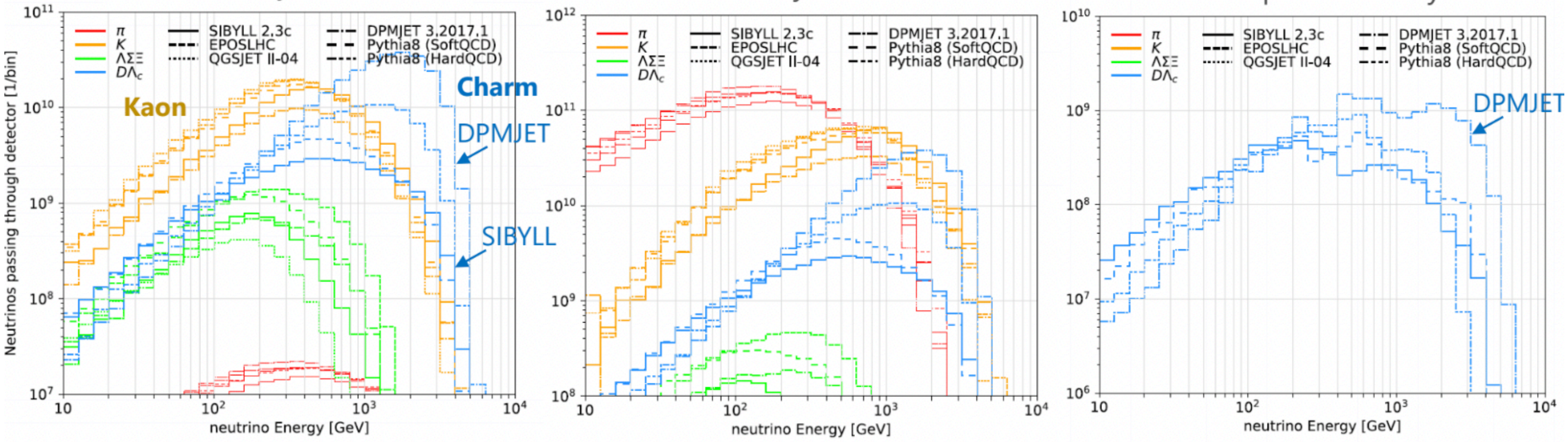
- Checking three simulations.
  - FLUKA (by F. Cerruti's group)
  - BDSIM (by H. Lefebvre, L. Nevay)
  - RIVET-module (by F. Kling)

- **Differences between generators** have been checked with the same propagation model (RIVET-module)

$\nu_e$ mainly from kaon and charm decays

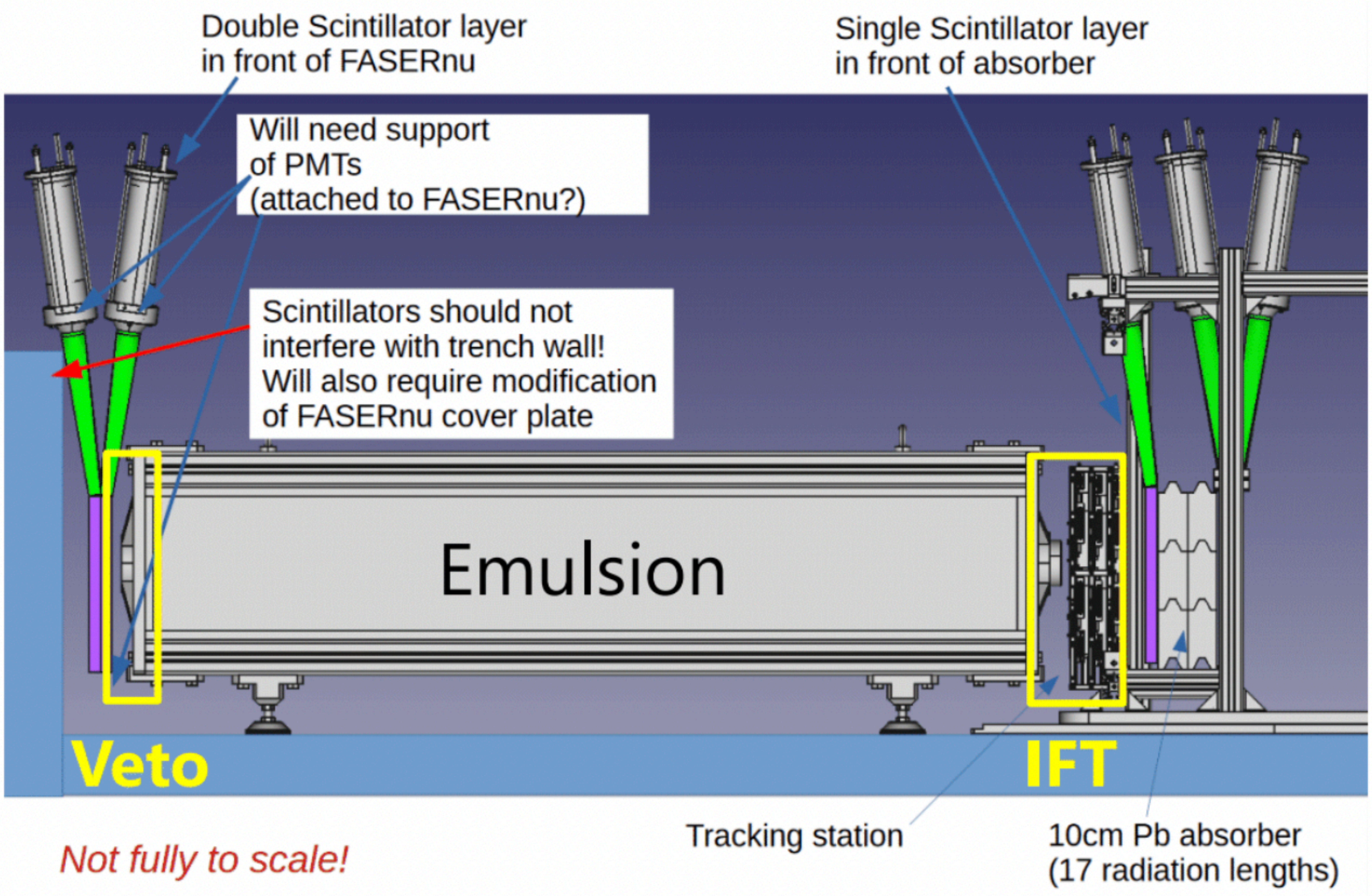
$\nu_\mu$ mainly from pion and kaon decays

$\nu_\tau$ mainly from $D_s$ and subsequent $\tau$ decays



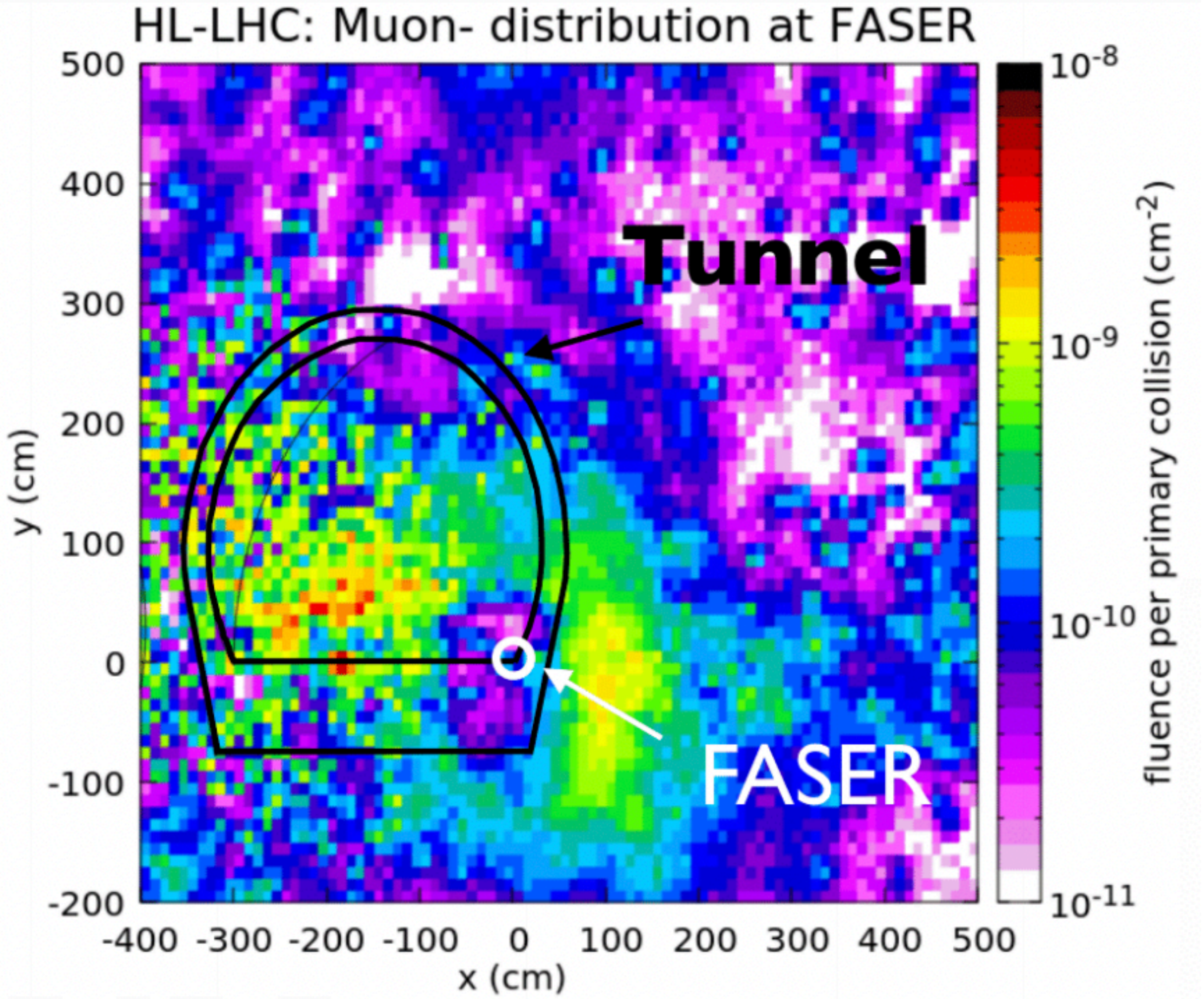
# FASERν | Interface to FASER

- To connect muon tracks from νμ interactions for charge identification etc.
  - Interface tracker (IFT) with 3 layers of silicon strip detector. A copy of FASER tracker station.
  - Veto station consists of 2 scintillator layers with 2 cm thickness. >99.99% veto efficiency for a charged particle coming from upstream of FASER
  - Construction of the IFT will start in January 2021. Installation at FASER site is planned in fall 2021

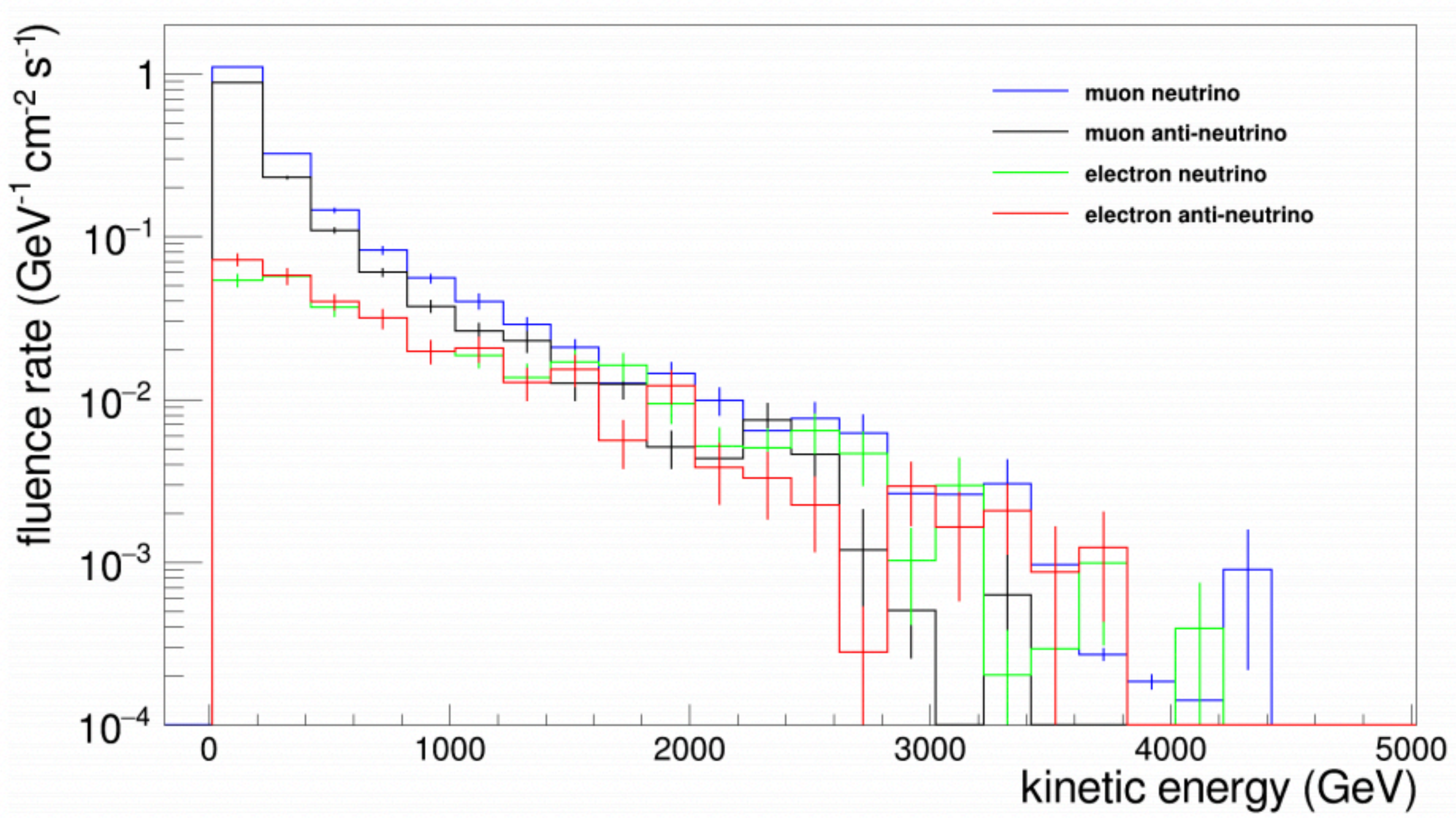


# Conditions | Beam backgrounds

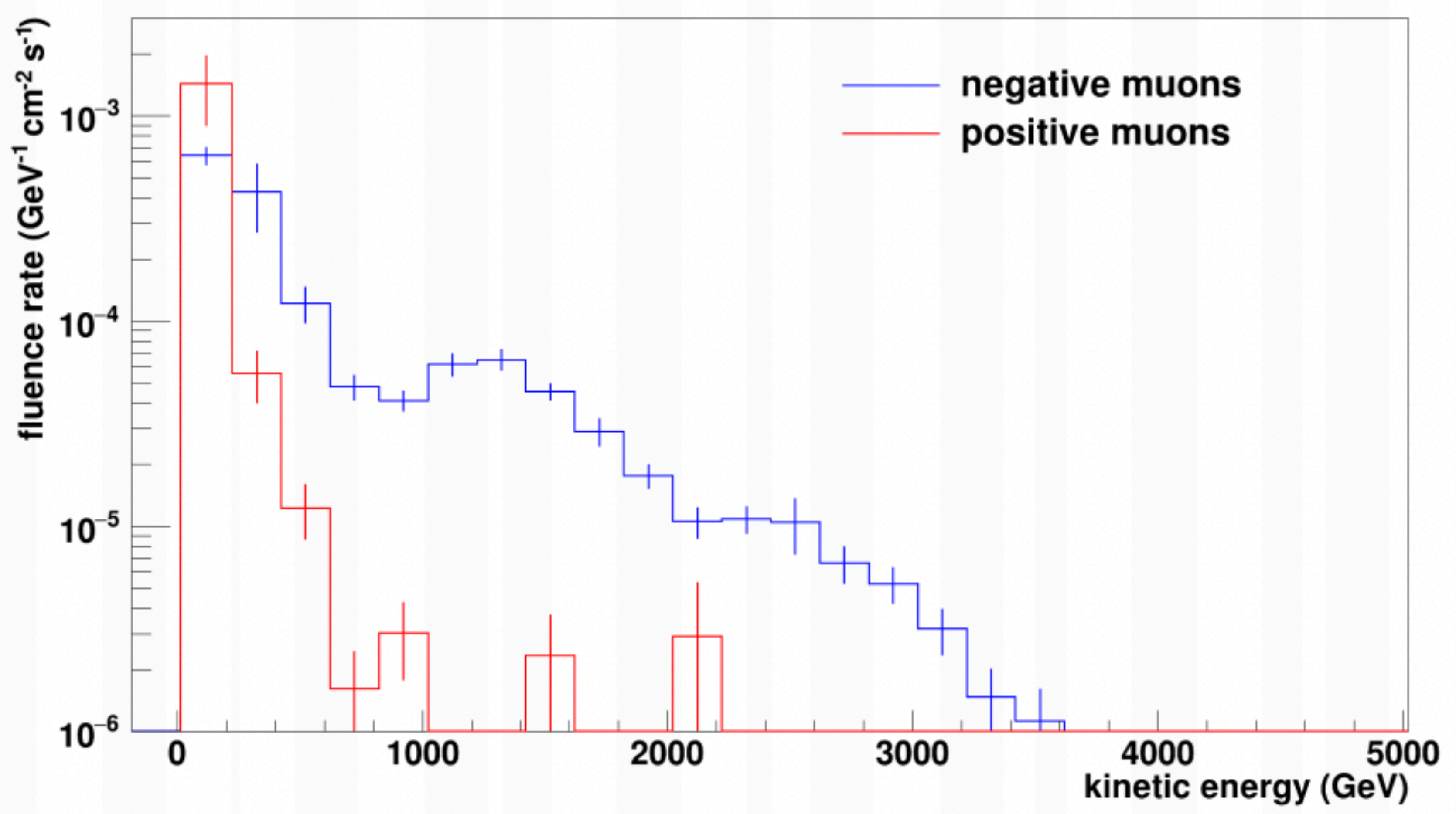
- FLUKA simulations and *in situ* measurements used to assess expected backgrounds.
  - IP1 collisions (shielded by 100m rock)
  - Off-orbit protons hitting beam pipe aperture near TI12 } *Minor*
  - Beam-gas interactions
- Low particle flux along beam axis due to LHC optics.




Fluence rate spectra at FASER (above 10 GeV) for the LHC




Fluence rate (GeV$^{-1}$ cm$^{-2}$ s$^{-1}$) for muons: 10 GeV threshold



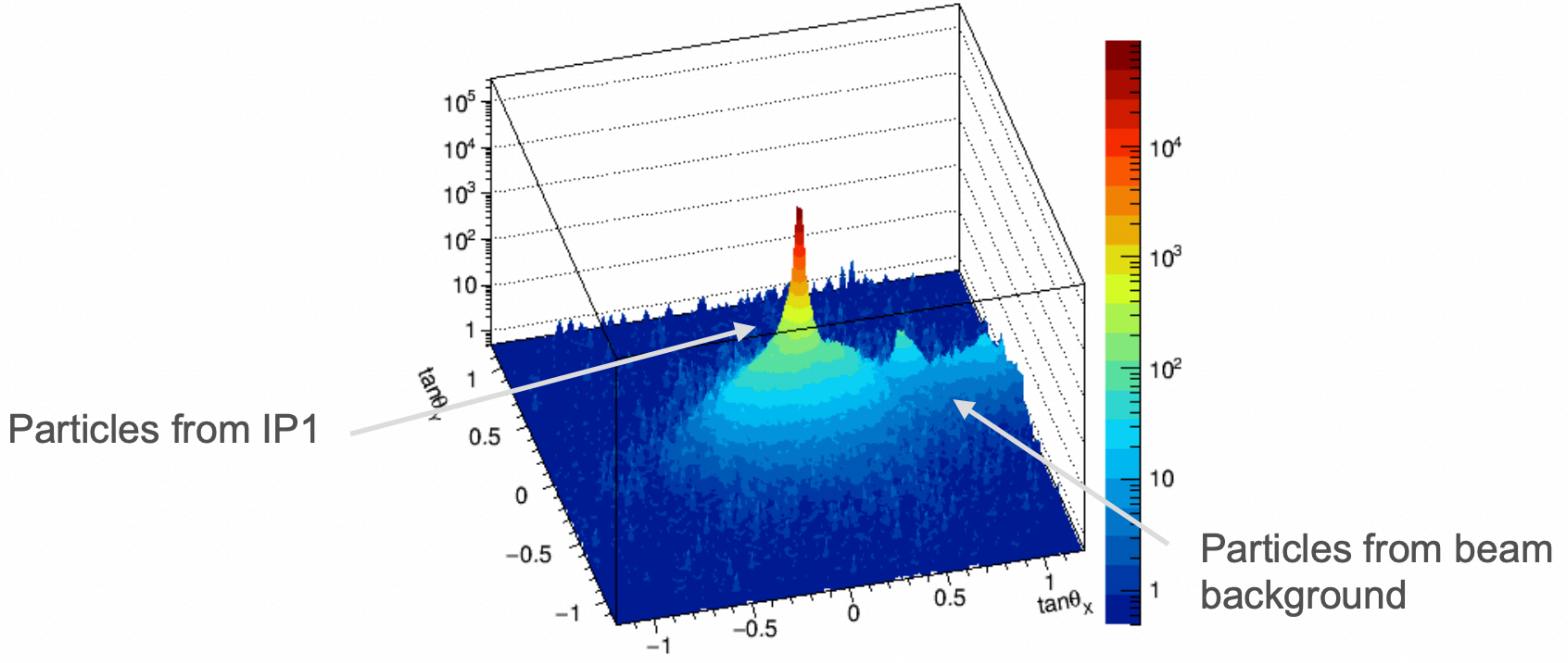

Muon charge asymmetry due to LHC magnets

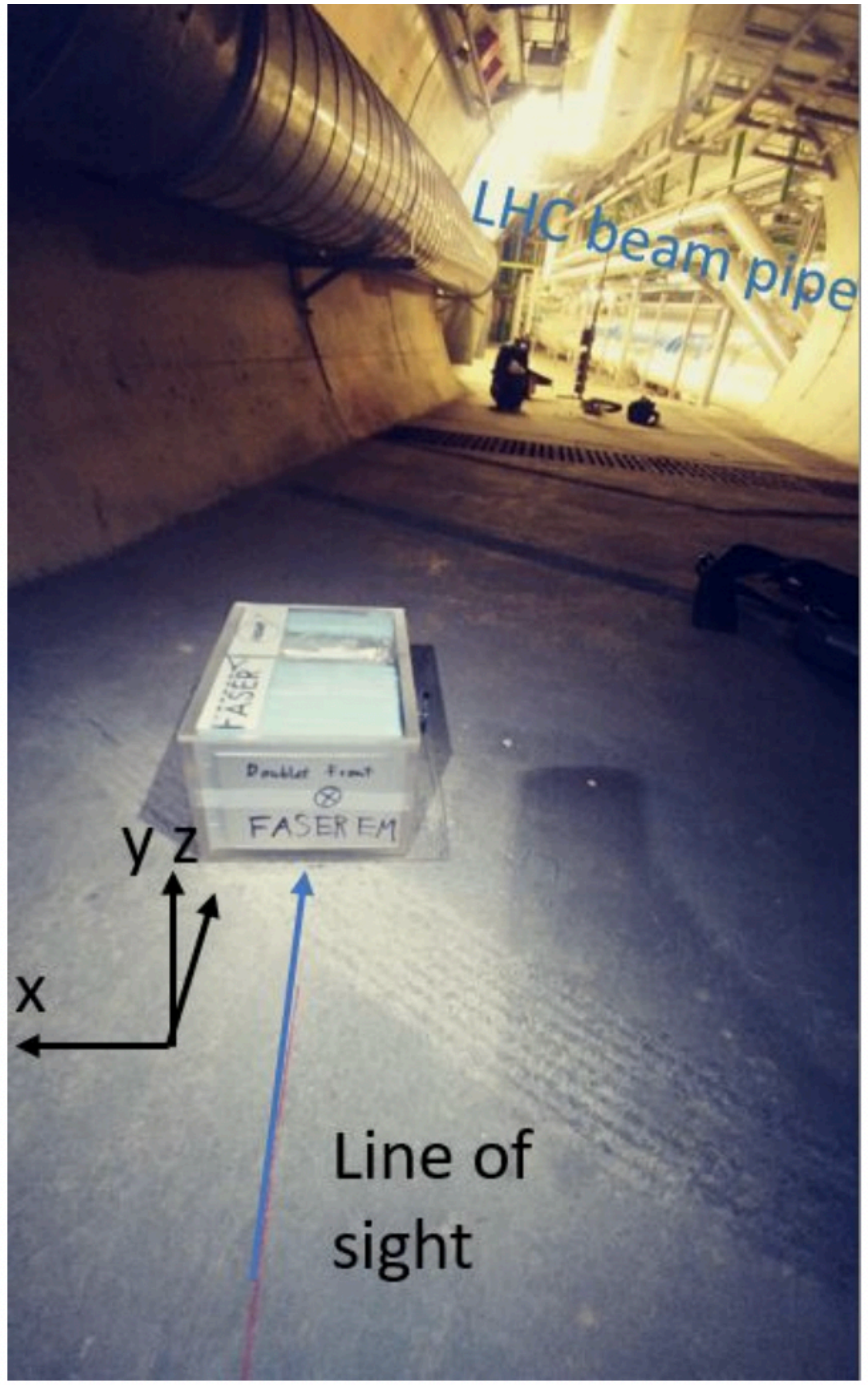
| Muons (@L=2x10$^{-34}$ cm$^{-2}$ s$^{-1}$) | |
|---|---|
| Energy threshold [GeV] | Charged Particle Flux [cm$^{-2}$ s$^{-1}$] |
| 10 | 0.40 |
| 100 | 0.20 |
| 1000 | 0.06 |

# Conditions | Beam backgrounds

- *In situ* measurements using emulsion detectors and TimePix BLM in TI12 in 2018 confirm expected particle flux, and correlation with IP1 luminosity.

Angular distribution of particles in emulsion detector



# Conditions | Beam backgrounds

The FLUKA simulation tracks particle production, deflection, and energy loss with a detailed model of the geometry of the LHC tunnels, including the LHC material map and magnetic field layout. The simulation includes three potential sources of background at the FASER location:

- Particles produced in the *pp* collisions at the IP or by particles produced at the IP that interact further downstream, e.g., in the TAN neutral particle absorber.
- Particles from showers initiated by off-momentum (and therefore off-orbit) protons hitting the beam pipe in the dispersion suppressor region close to FASER.
- Particles produced in beam-gas interactions by the beam passing FASER in the ATLAS direction (for which there is no rock shielding).

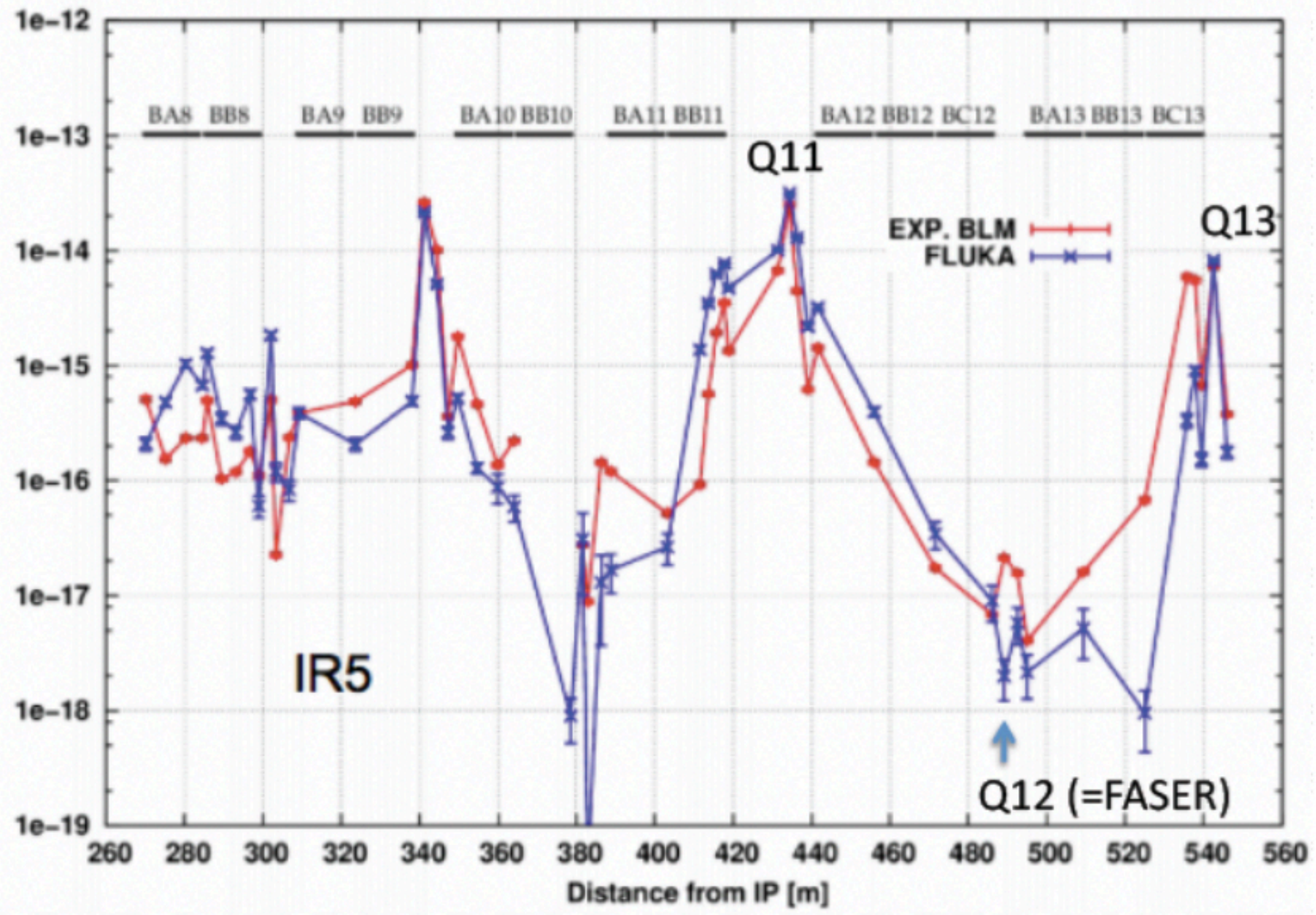
Always co-linear with accompanying muons

- $10^5 \rightarrow 10$ with veto

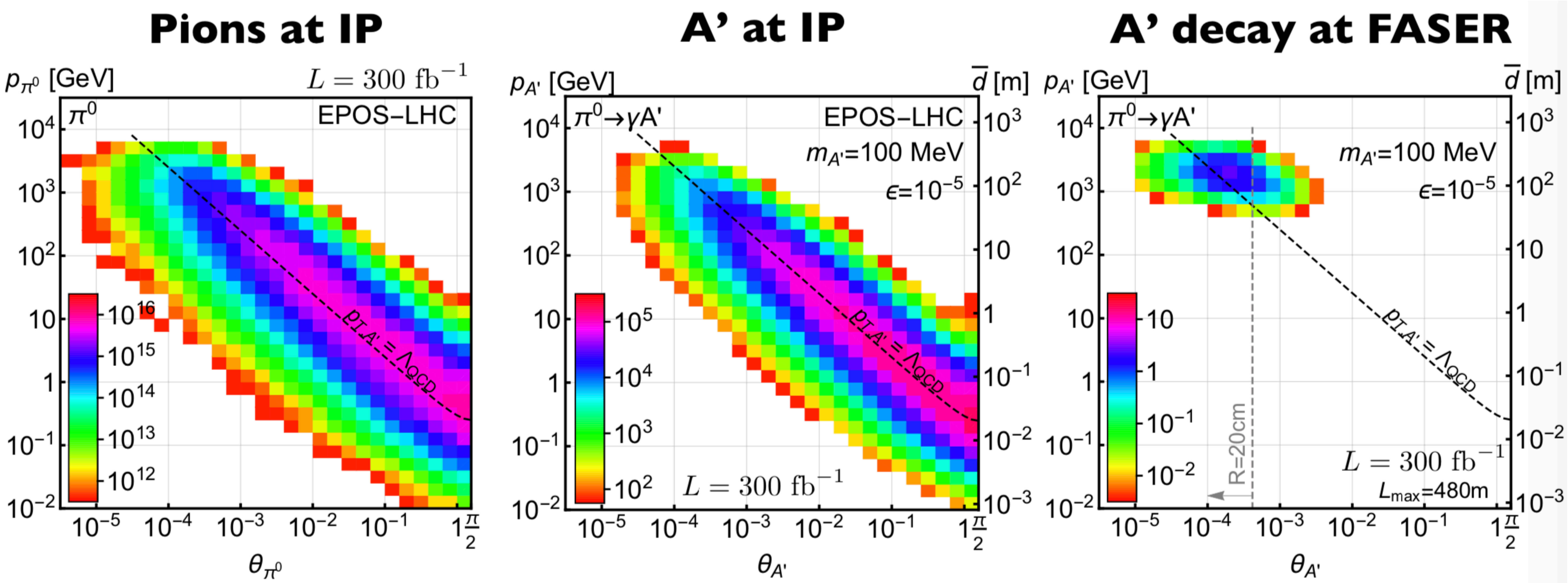
Minor

# **Conditions** | Radiation levels

- Radiation level predicted to be very low in TI12 due to dispersion function of LHC at TI12.
- Measurements using BatMon radiation monitor in 2018 confirm FLUKA expectations:
  - less than $5 \times 10^{-3}$ Gy/year
  - less than $5 \times 10^{7}$ 1 MeV neutron equivalent fluence/year
- **FASER detector does not need radiation hard electronics**




# Overview | Dark photons



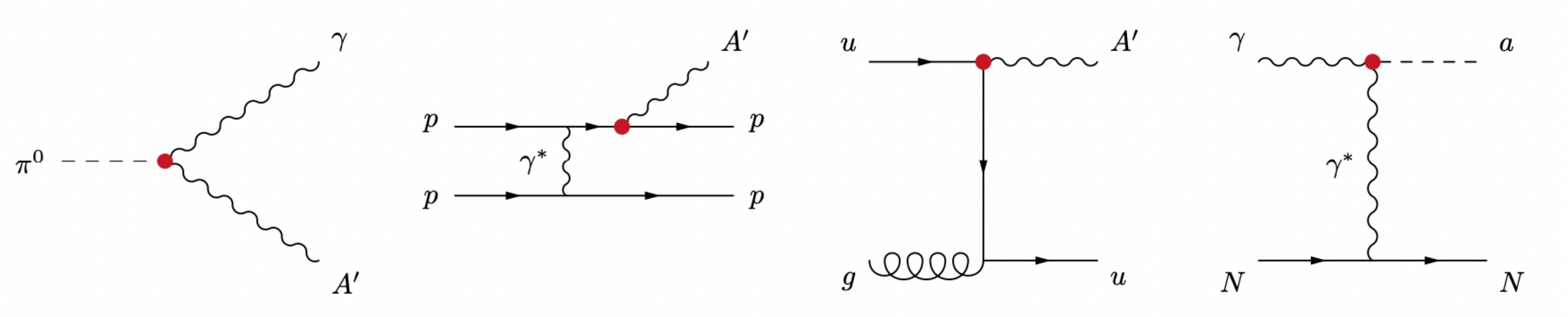

- dedicated hadronic interaction models, grounded on LHC data
- production peaks at pT~ $\Lambda_{QCD}$
- enormous event rates N ~ $10^{15}$ per bin

- production peaks at pT~ $\Lambda_{QCD}$
- rates highly suppressed by $\varepsilon^2$ ~ $10^{-10}$
- still rates N~$10^5$ per bin: LHC could be dark a photon factory

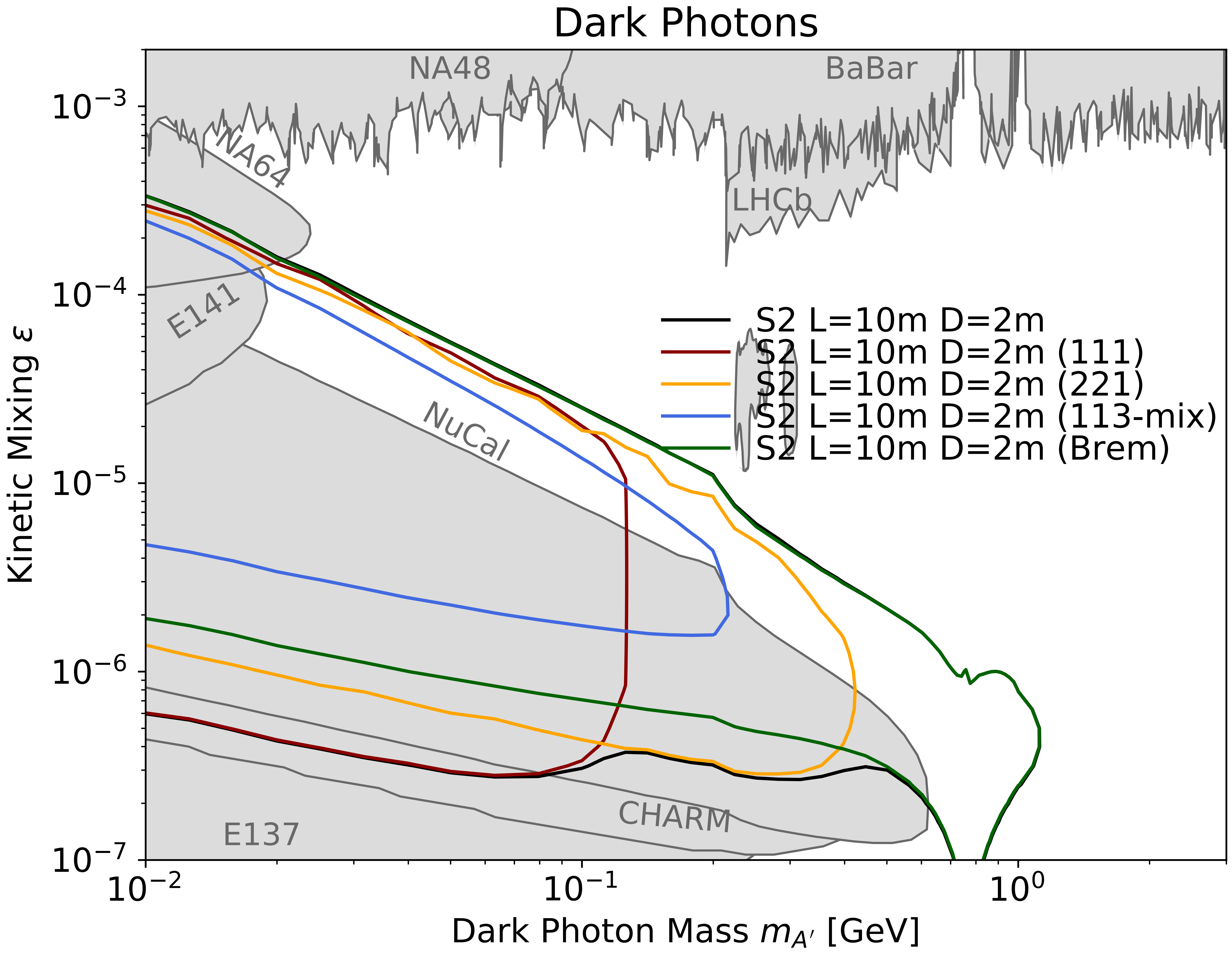
- only highly boosted ~TeV A' arrive at FASER
- rates suppressed by decay requirements
- still rates N~100 signal events within 20cm of beam collision axis

19

# **Overview** | LLP production modes

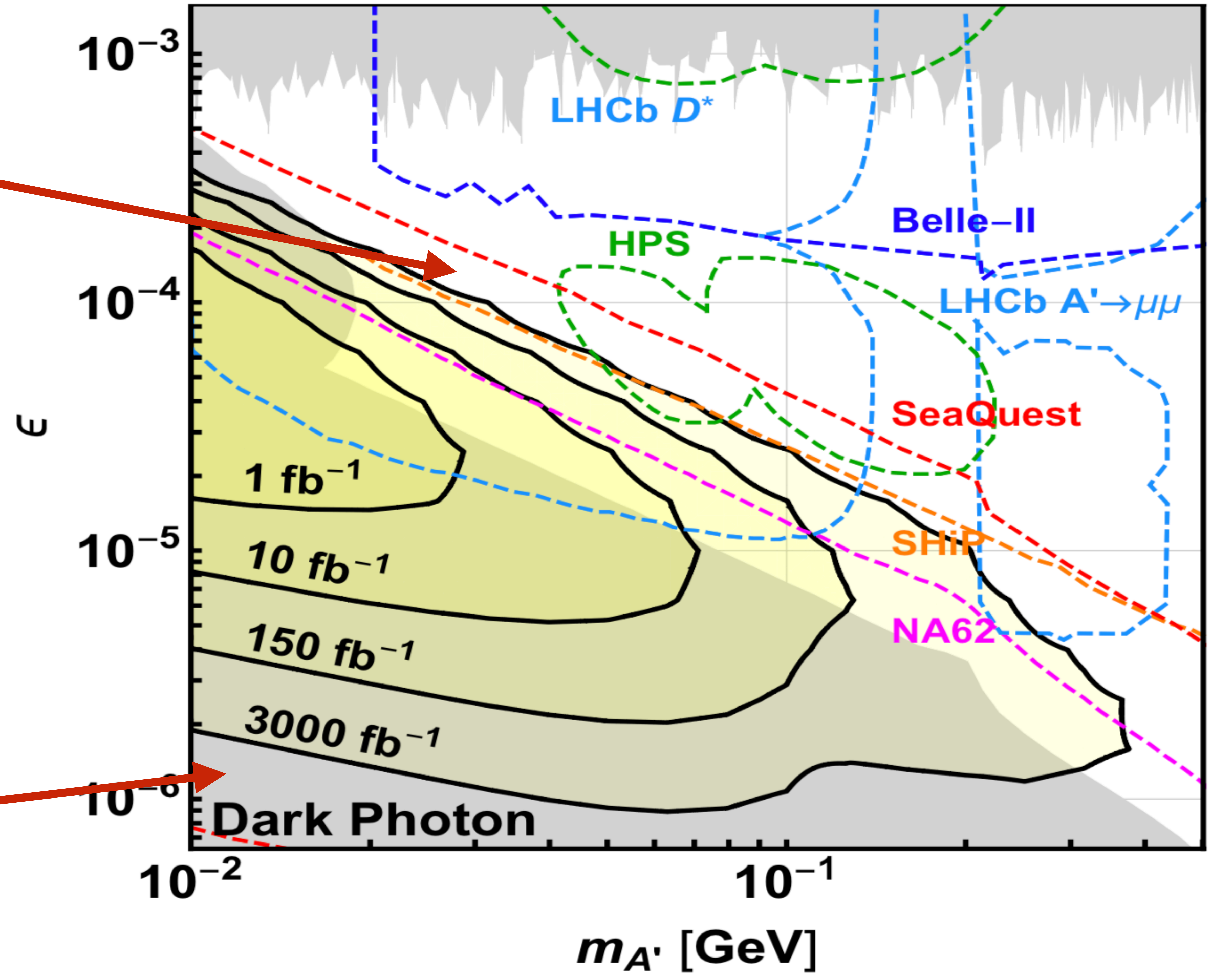


# Overview | Dark photon reach



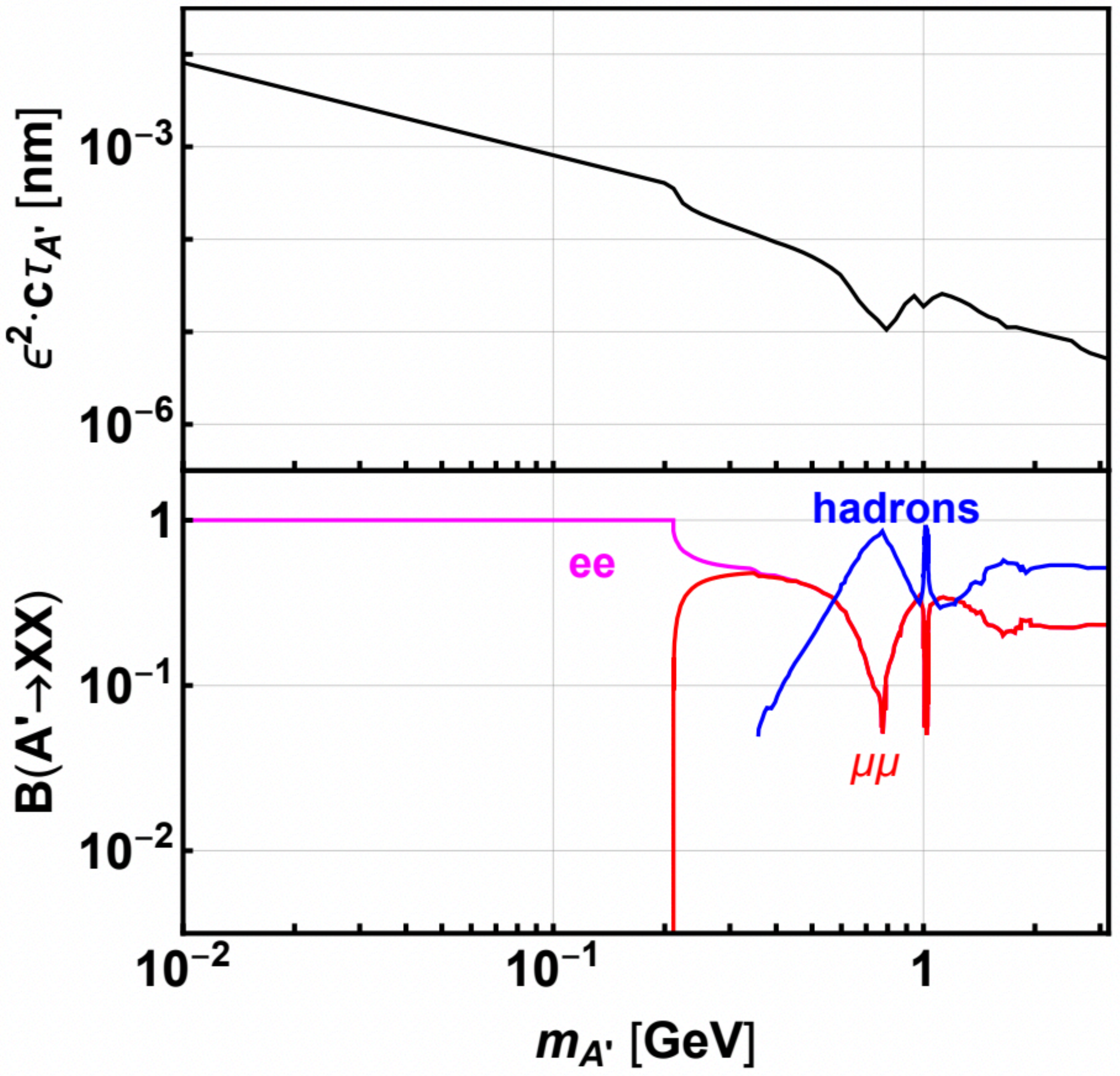
# **Overview** | Dark photon reach

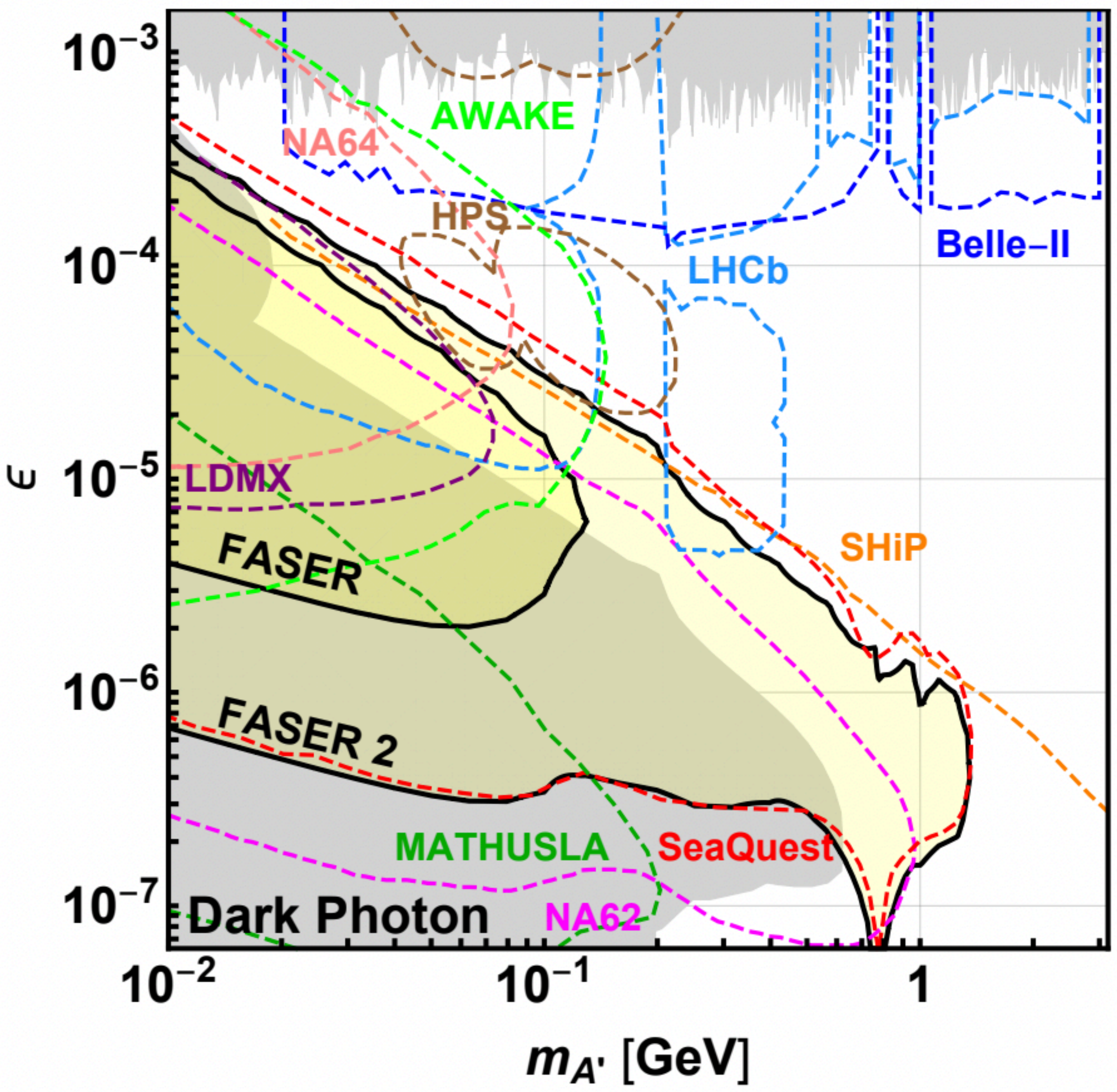
For lower lifetime the number of signal events becomes exponentially suppressed once the A' decay length drops below the distance to the detector



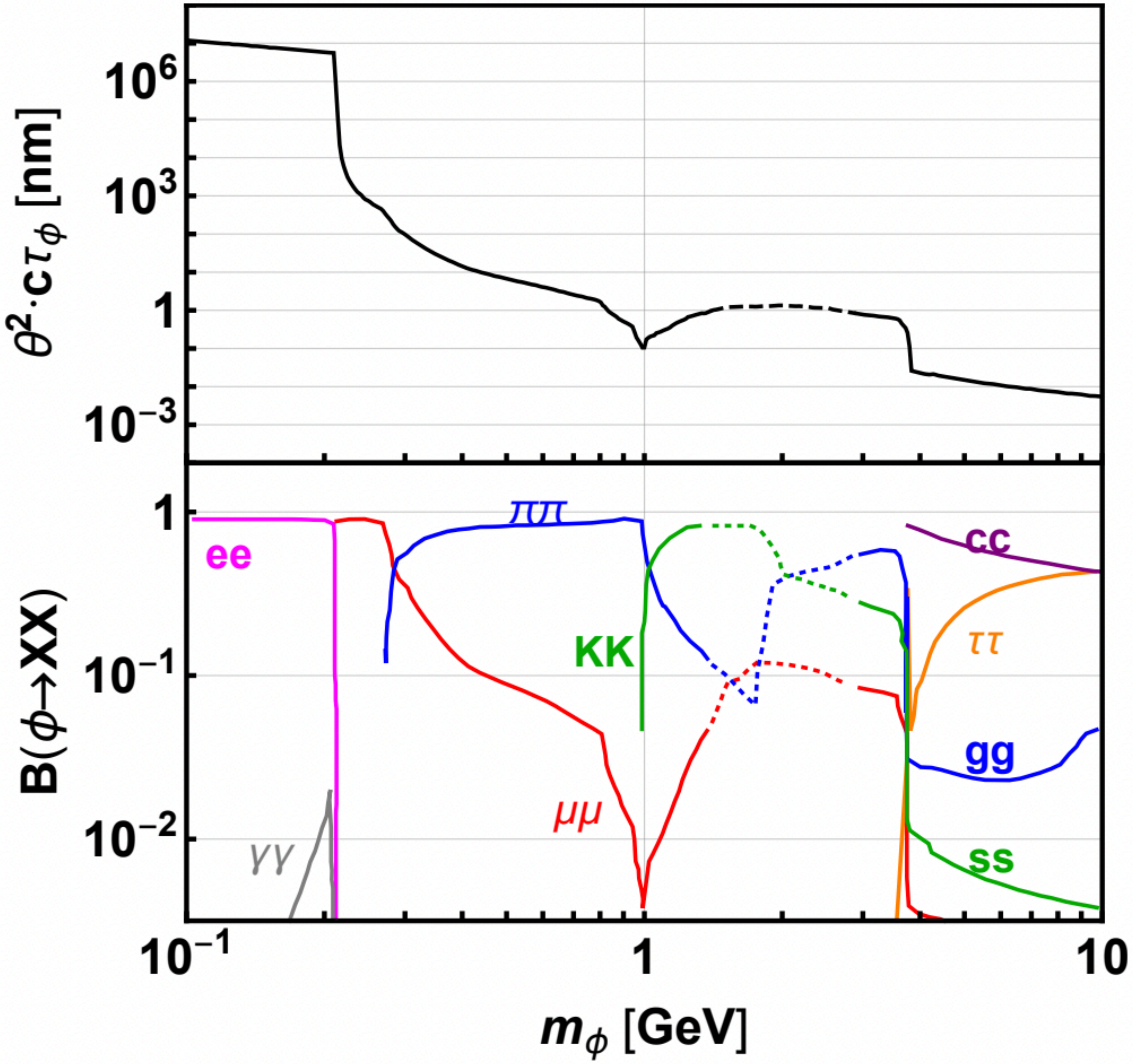

Combining dependence in both production rate and decay width, total number of signal events in the detector scales as $\varepsilon^4$

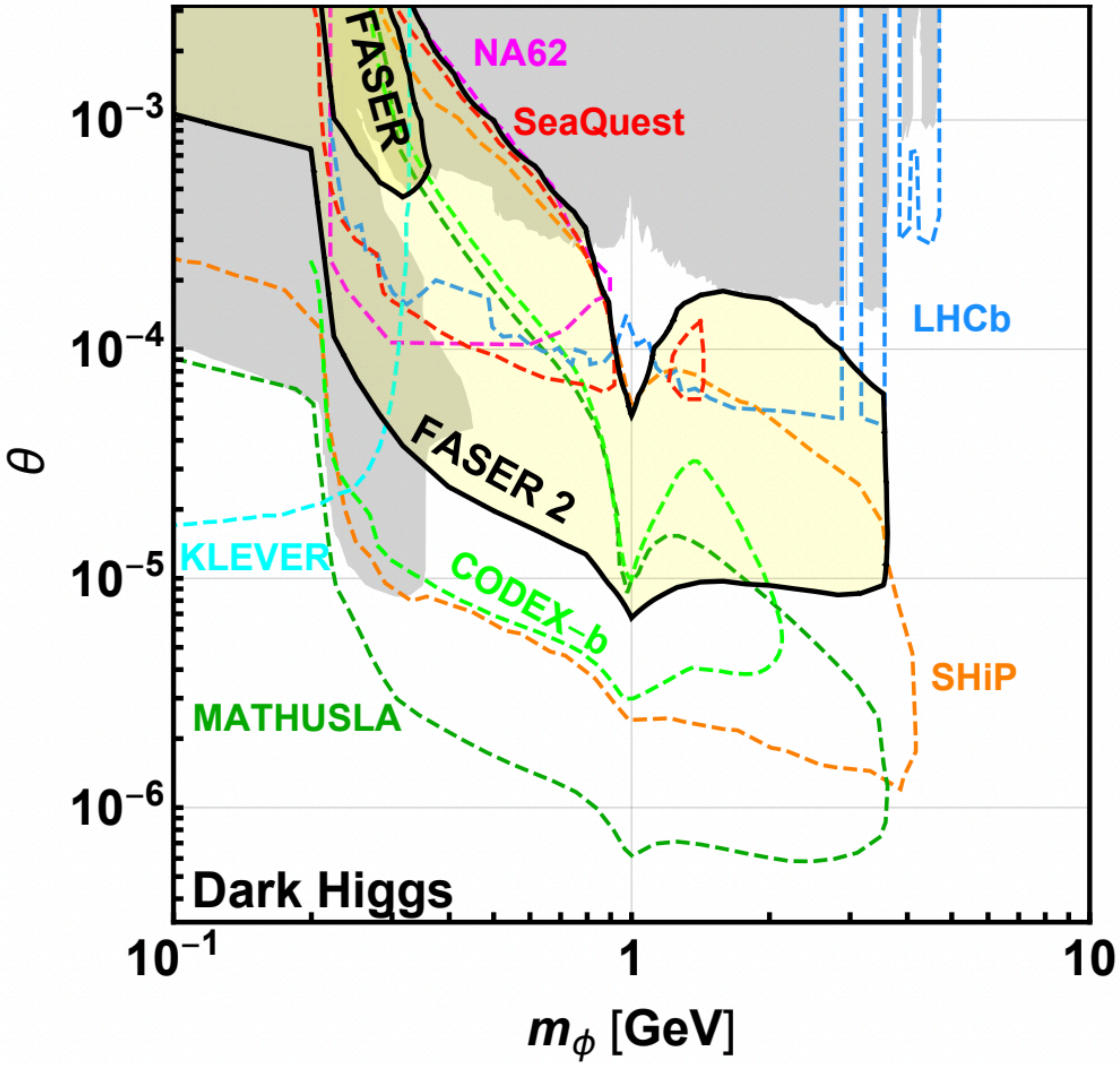
# Target scenarios | Dark Photon



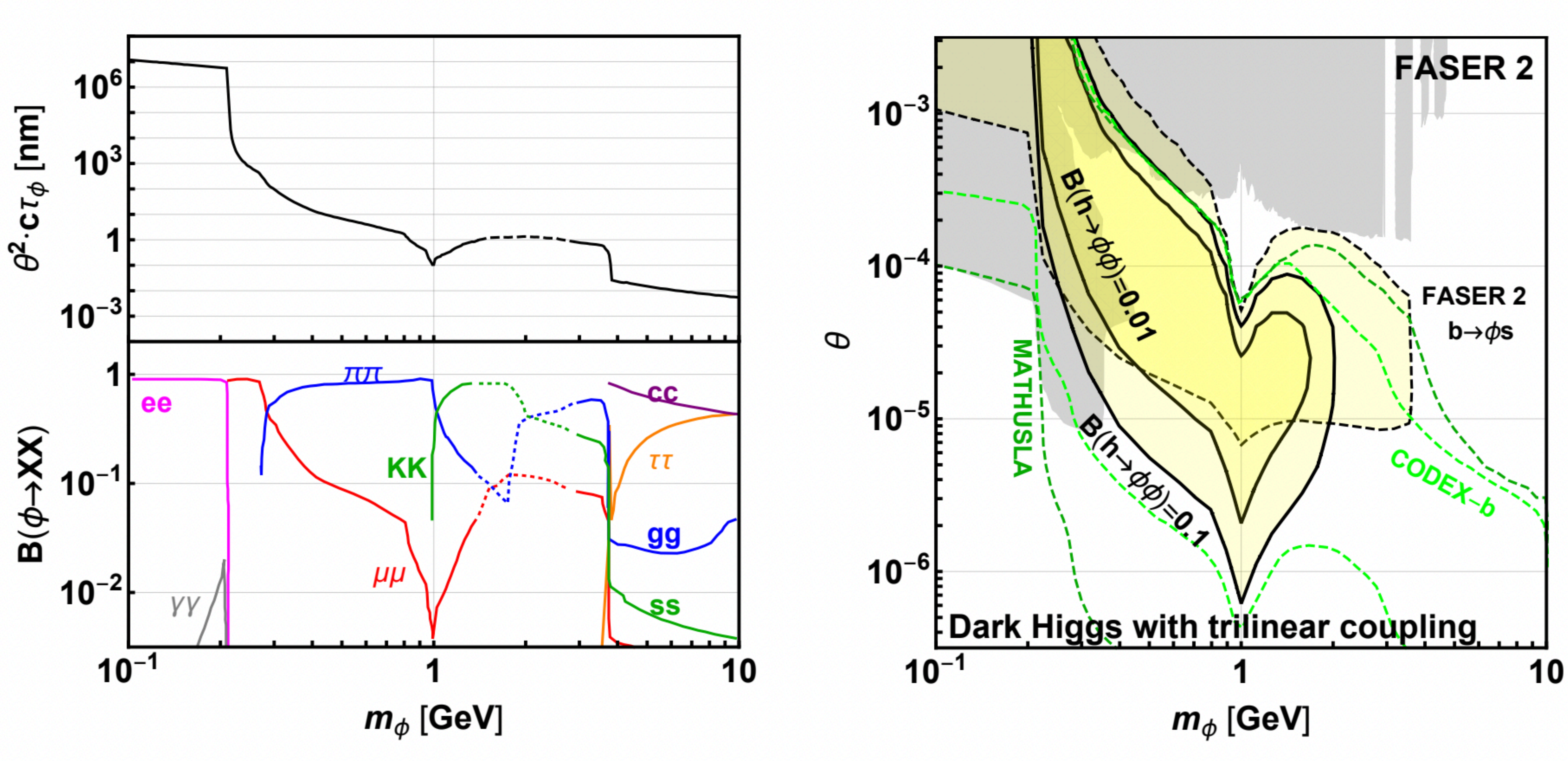



# Target scenarios | Dark Higgs

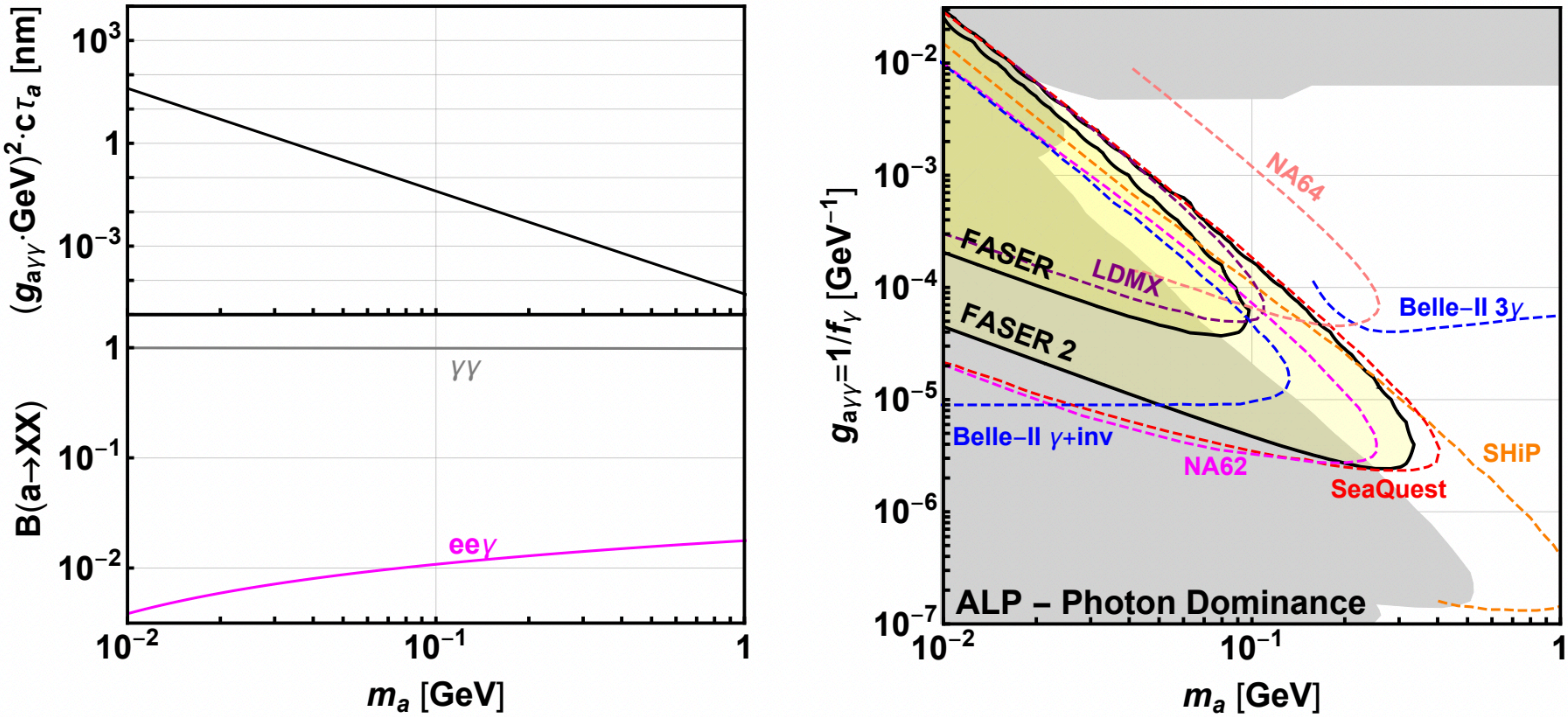


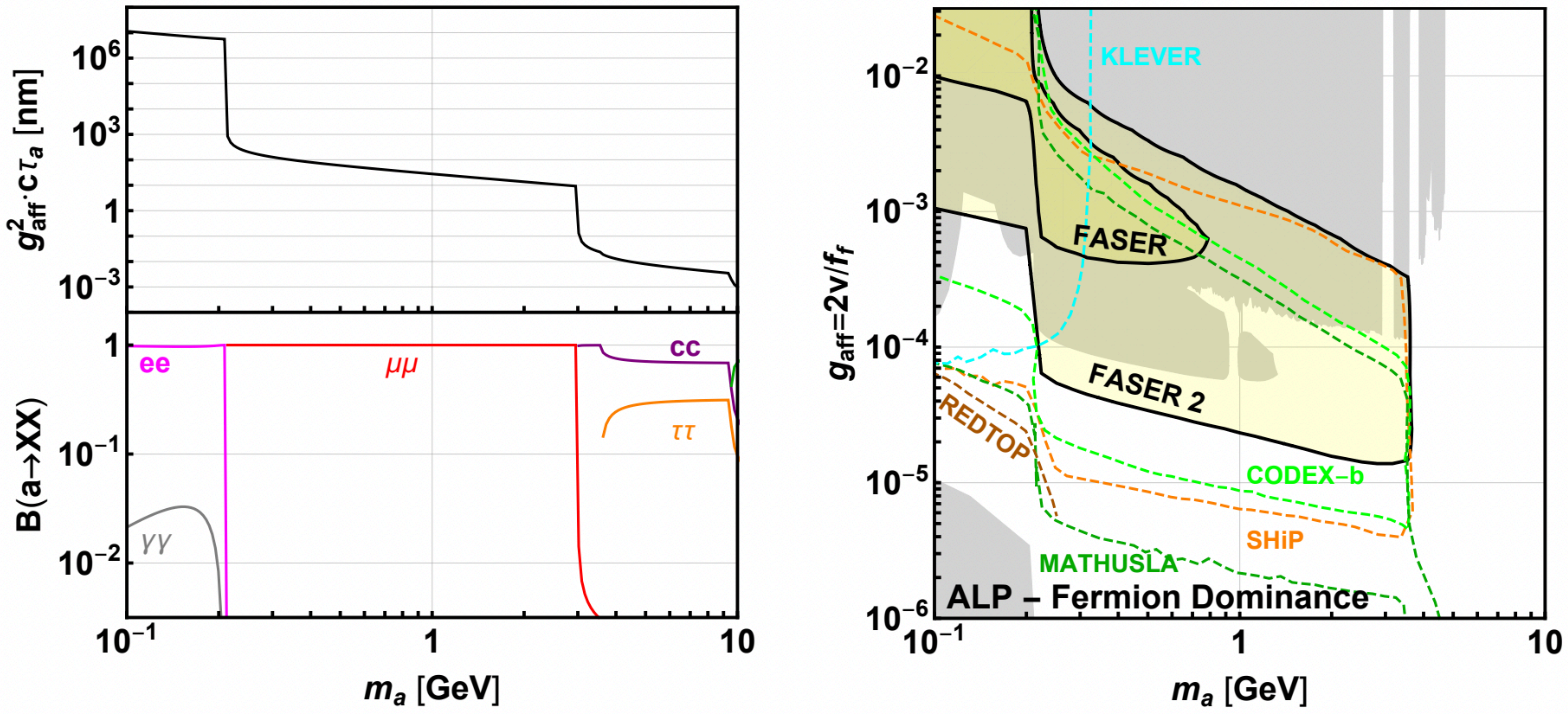
# Target scenarios | Dark Higgs



# Target scenarios | ALP

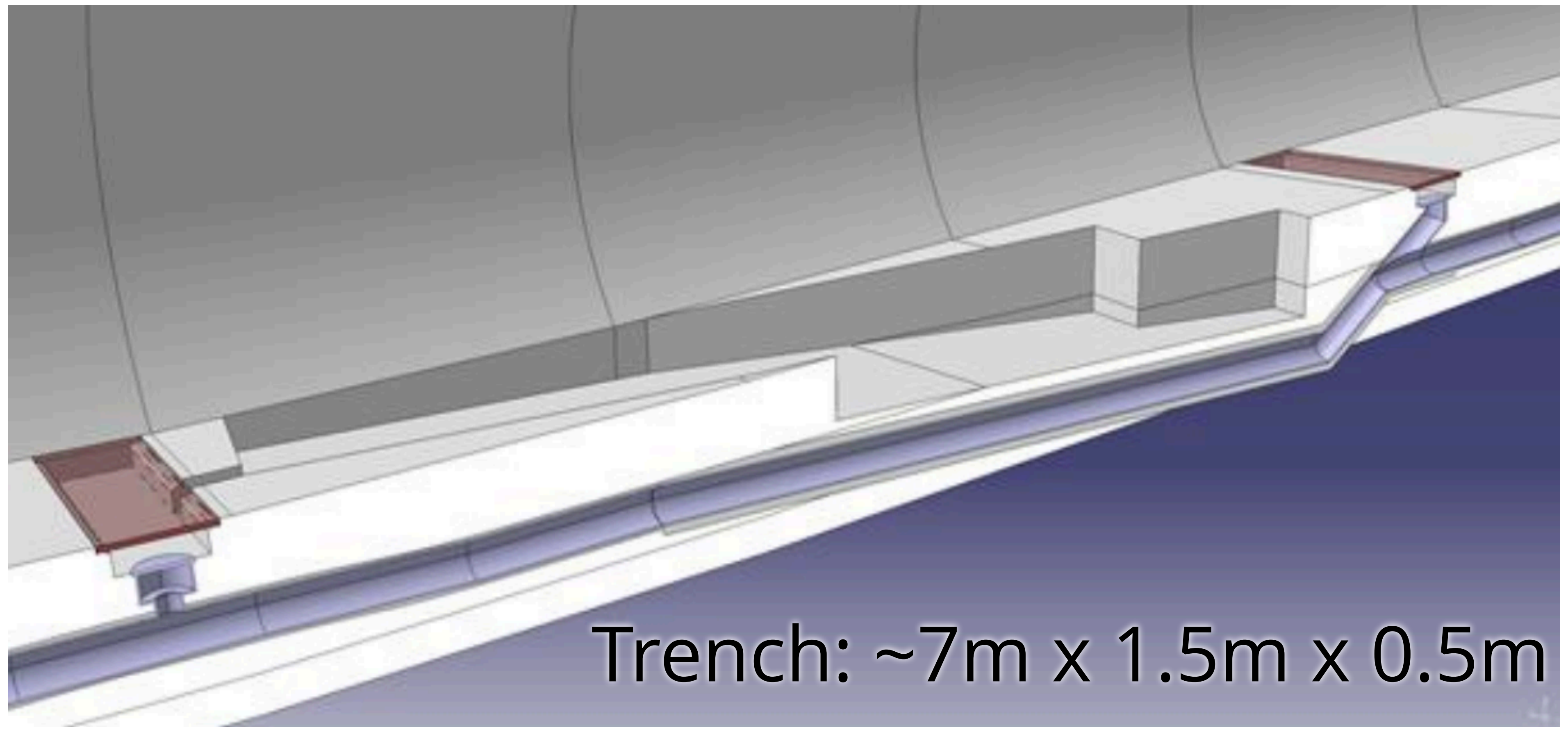


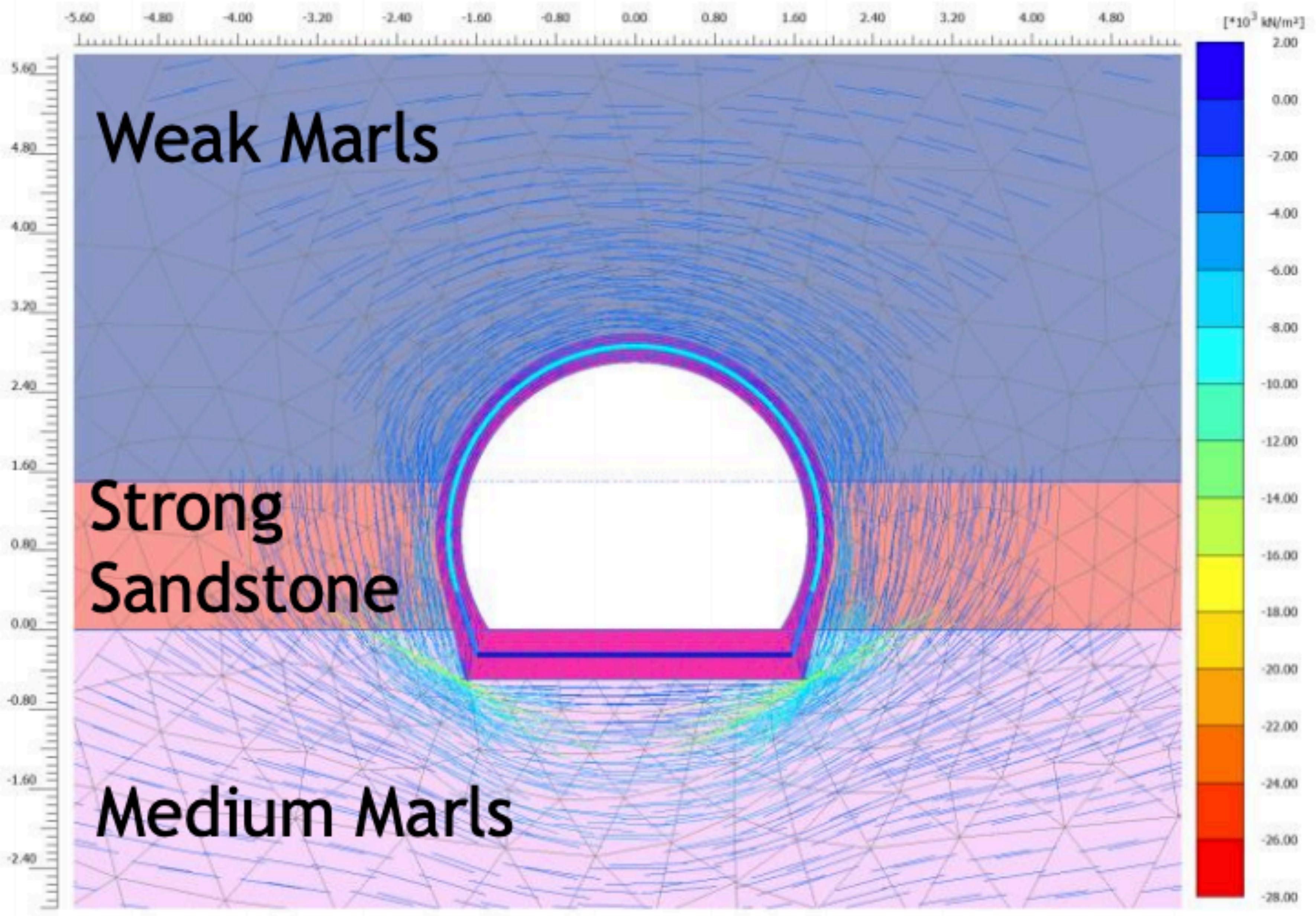
# Target scenarios | ALP



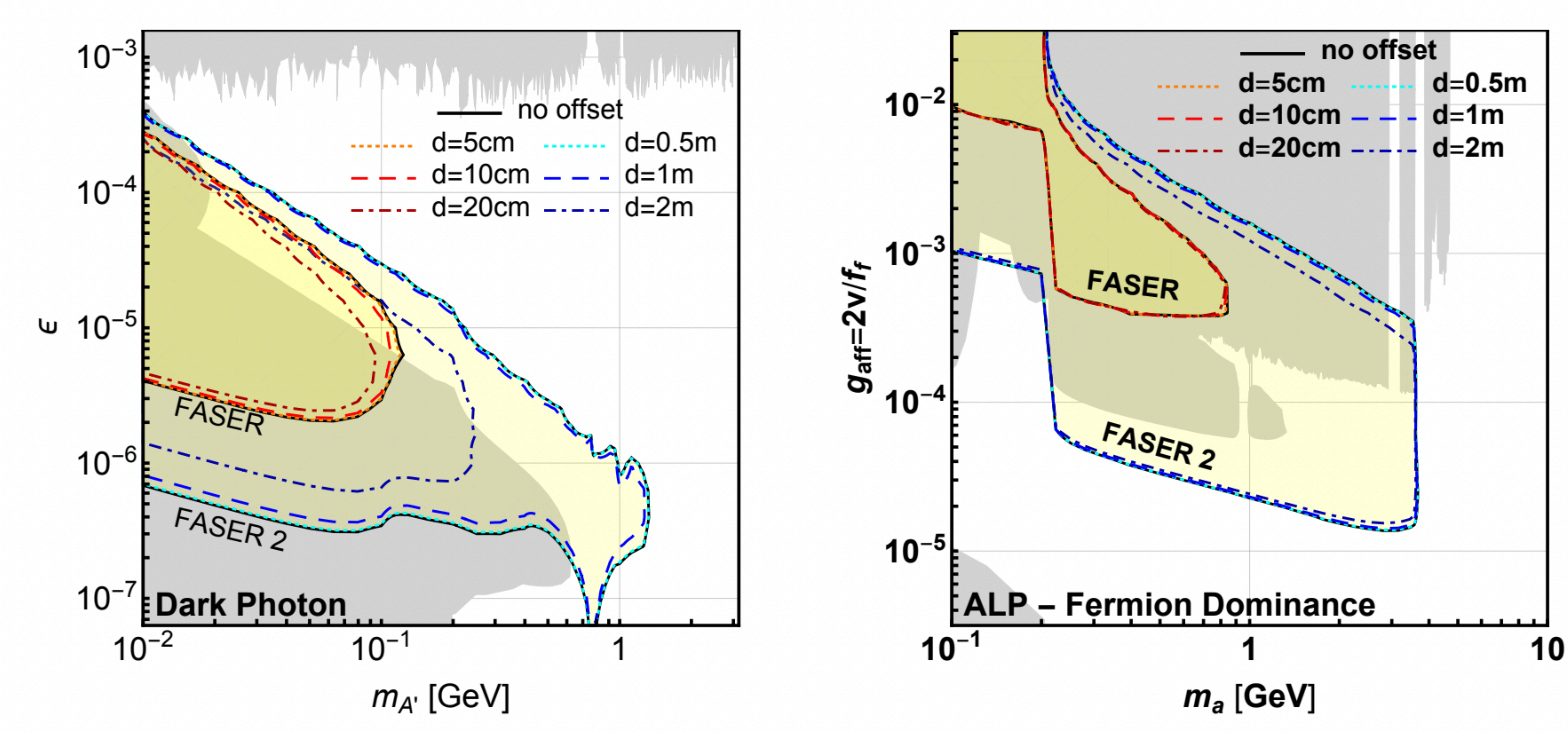
# Civil Engineering in TI12

- Trench
  - To be aligned with the line-of-sight (LOS) in the vertical direction a shallow (<50cm deep) trench was needed in TI12
  - Drain shallower than shown on historical drawings
    - Provided opportunity to increase trench depth - parallel to LOS
  - Plan area increased to allow more space for FASERν
- Trench strengthening
  - Improved rock characteristics enabled removal of steel frame
  - Less complex site works and better ground conditions enabled increased depth



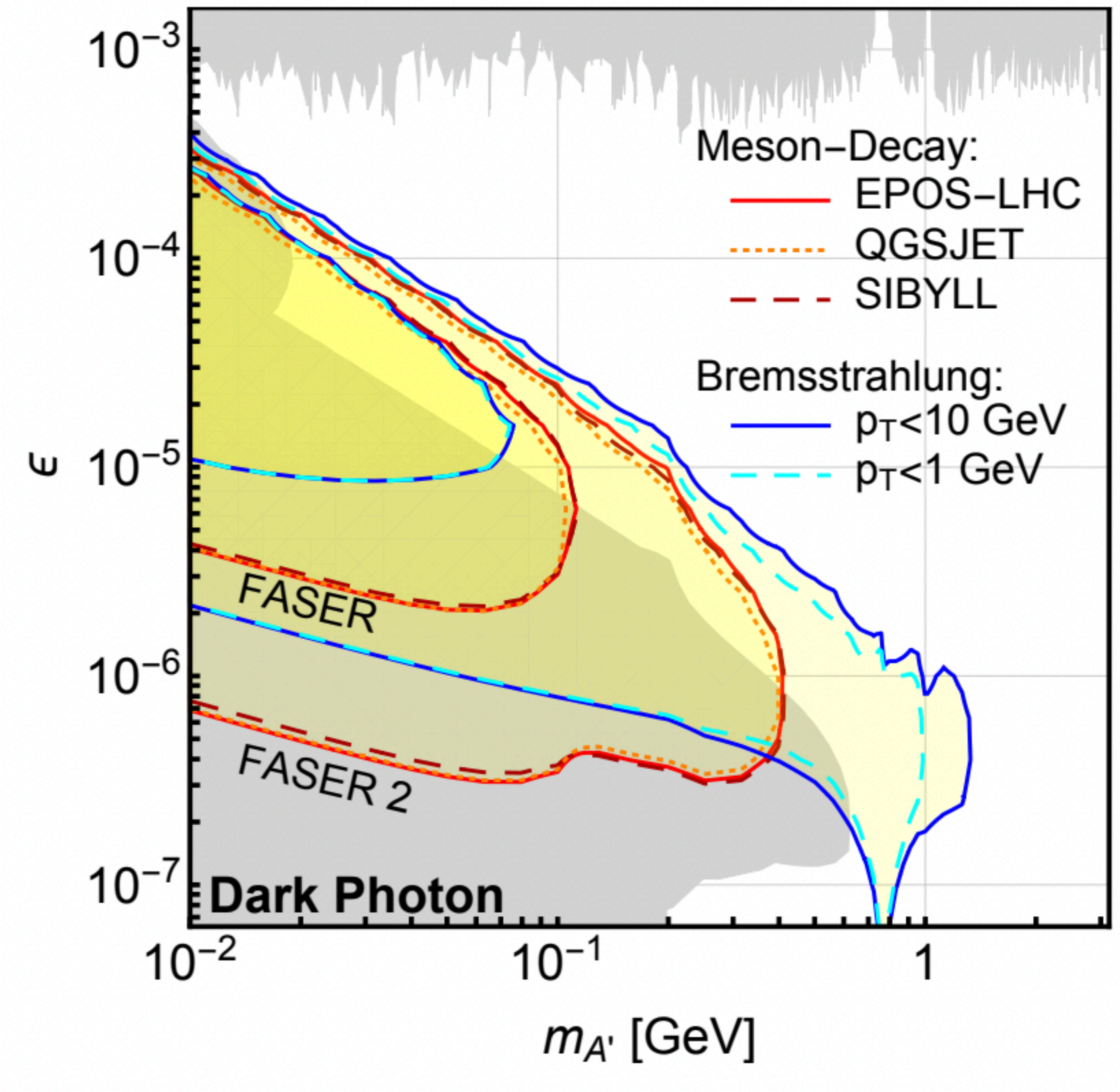



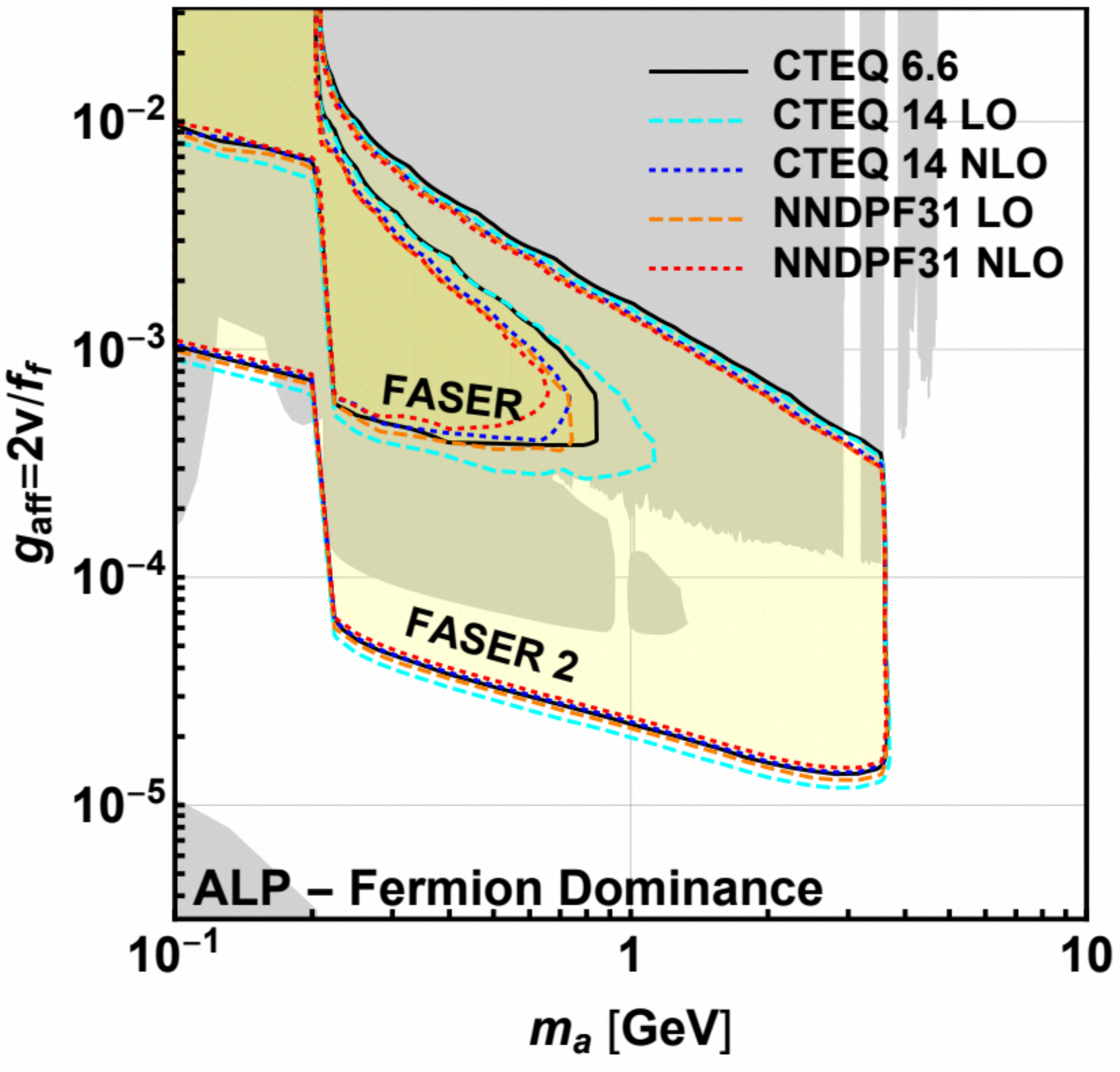
# Beam offset



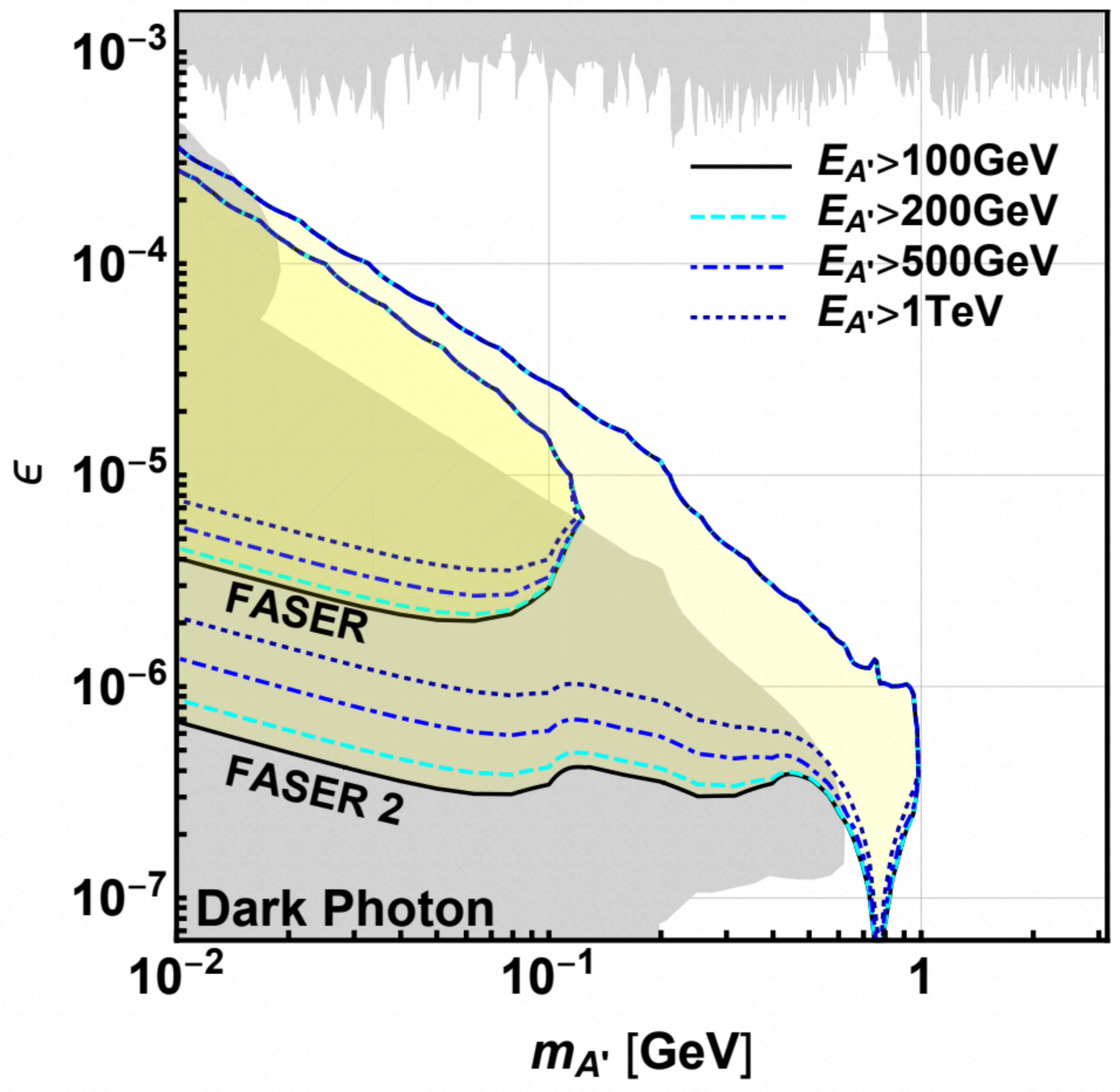
no offset
d=5cm
d=10cm
d=20cm
d=0.5m
d=1m
d=2m
FASER
FASER 2
Dark Photon
$\epsilon$
$m_{A'}$ [GeV]
no offset
d=5cm
d=10cm
d=20cm
d=0.5m
d=1m
d=2m
FASER
FASER 2
ALP – Fermion Dominance
$g_{aff}=2v/f_f$
$m_a$ [GeV]

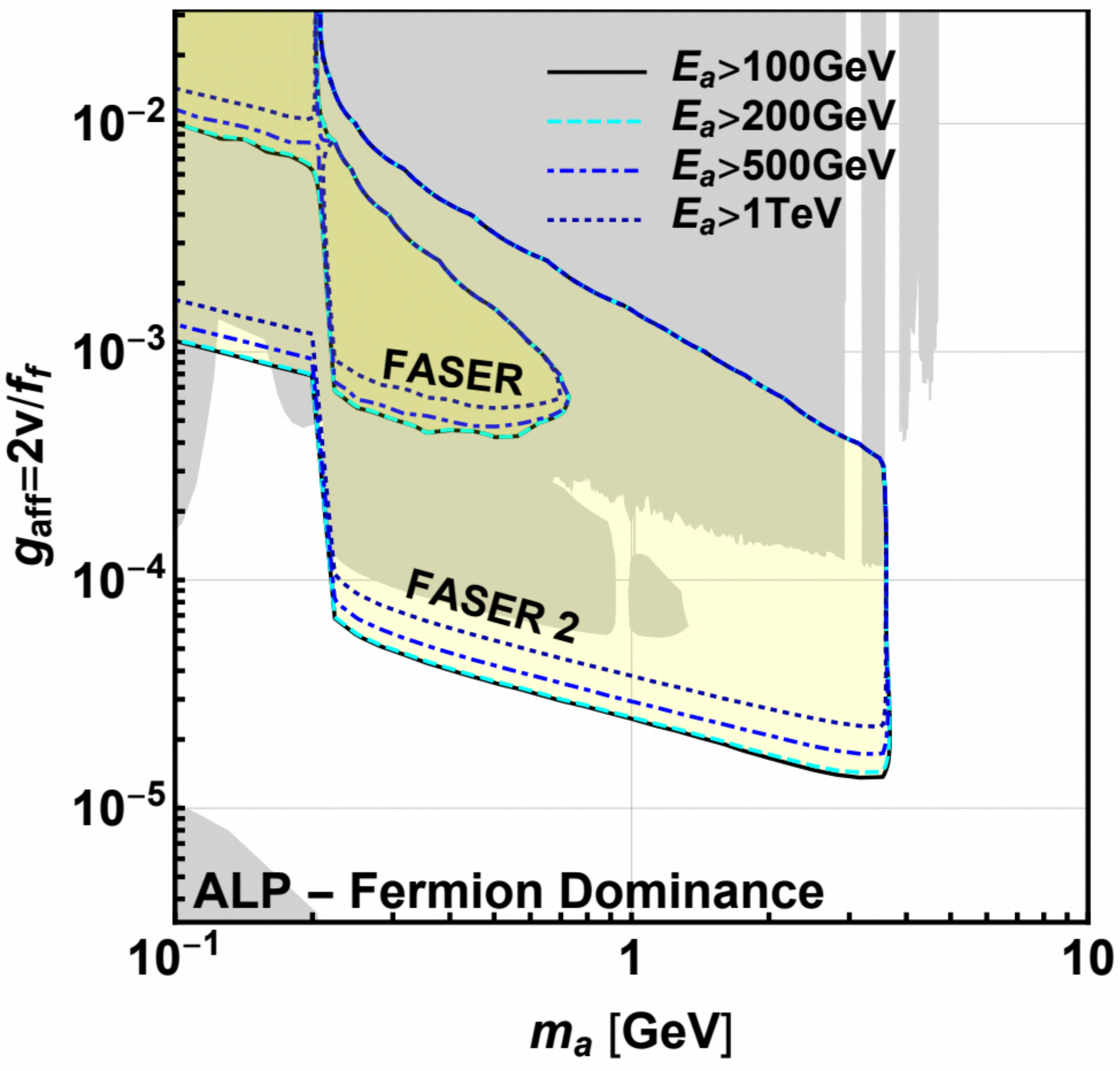
# Modelling uncertainties



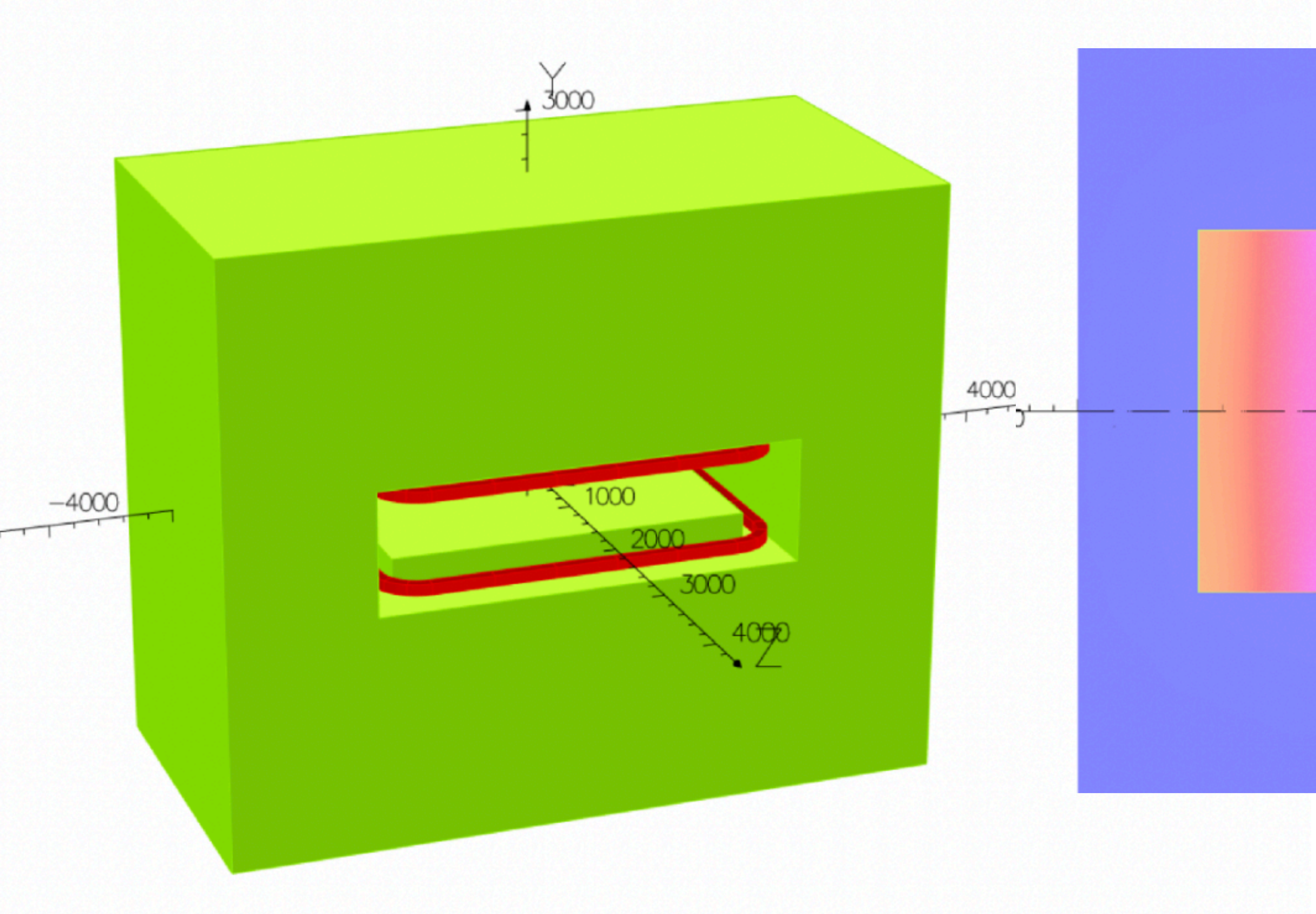



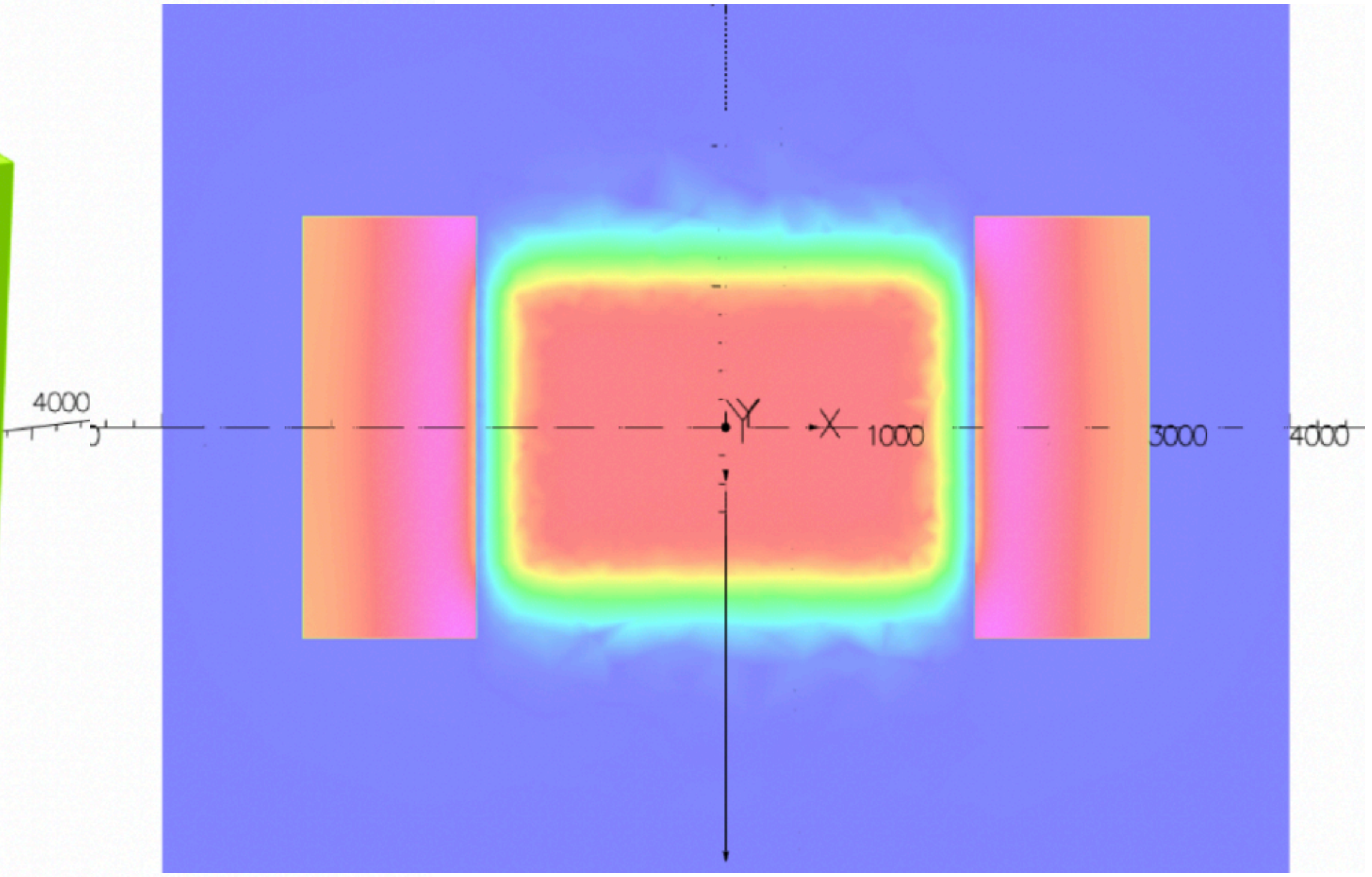
# Energy threshold

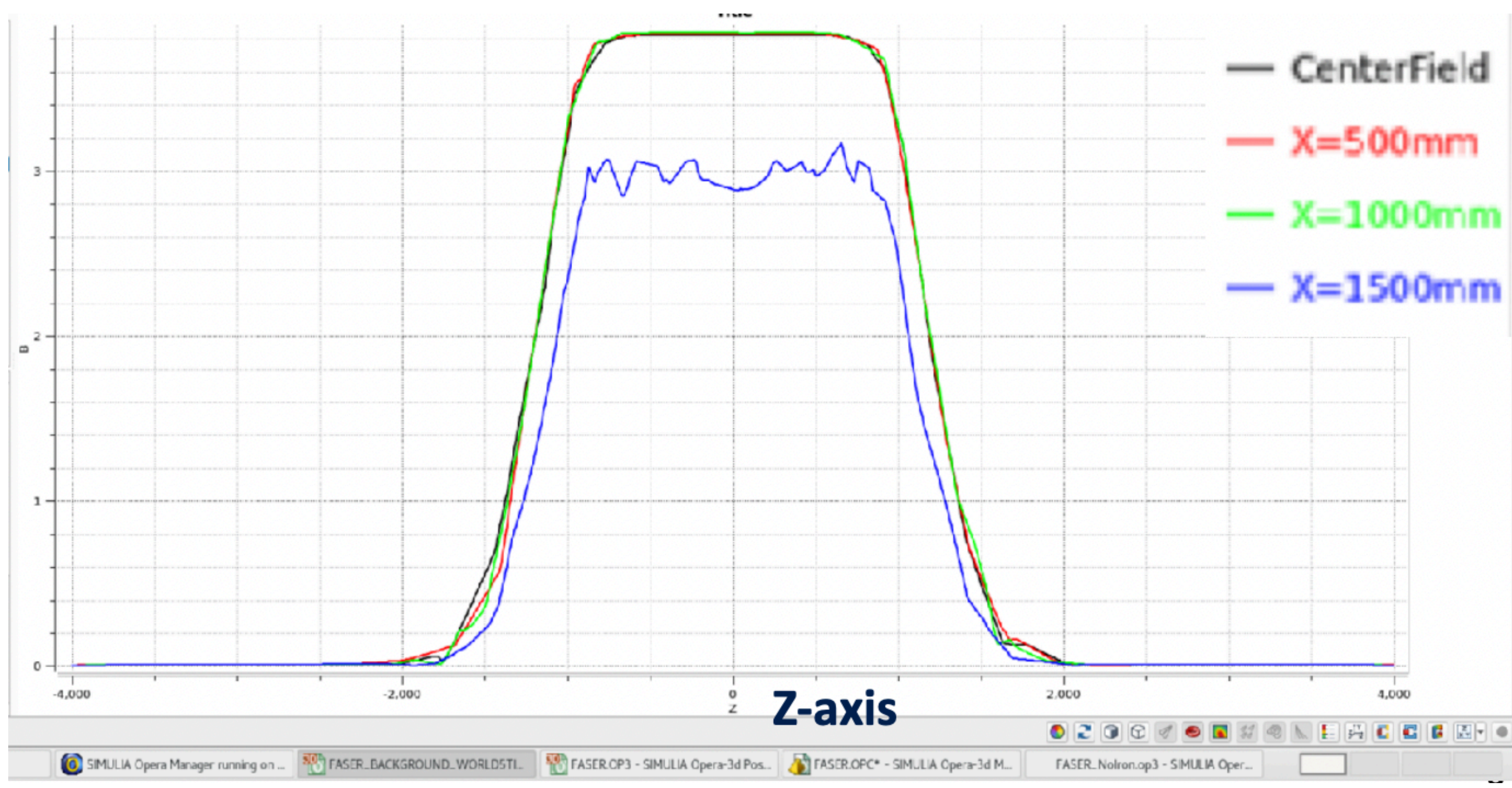


- Rectangular magnet 3 x 0.5 x 2m
- 2 T bending in horizontal direction



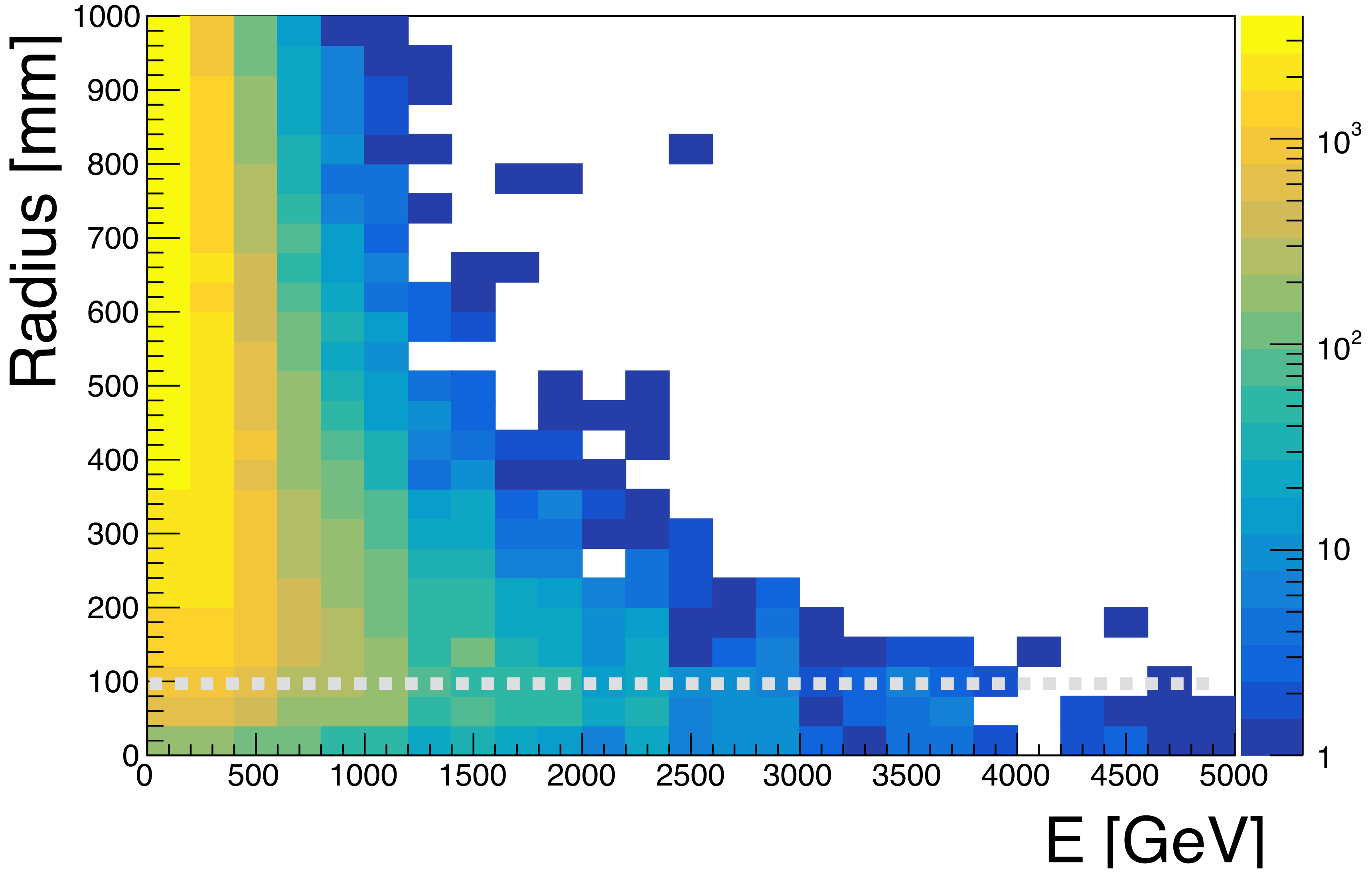



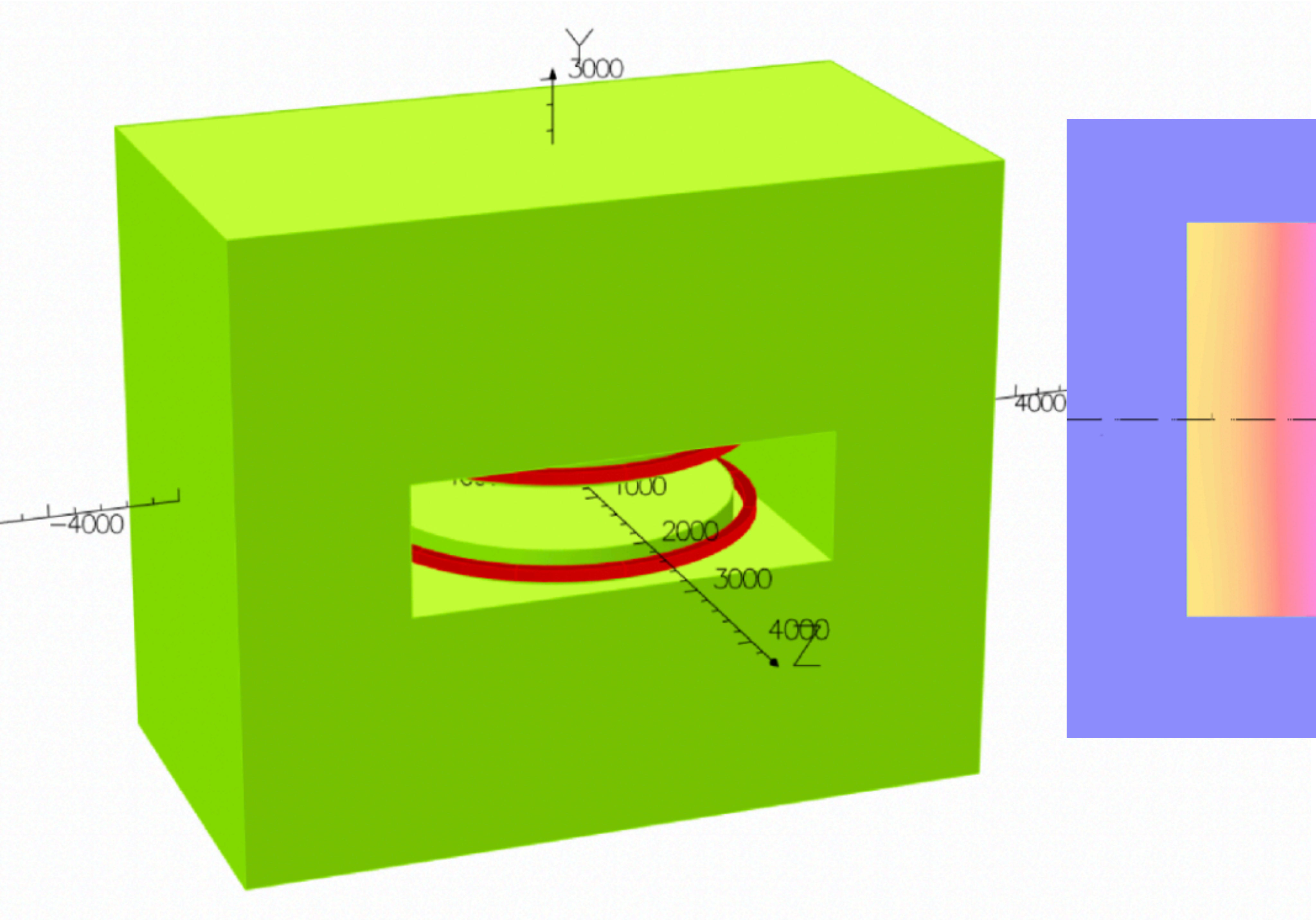



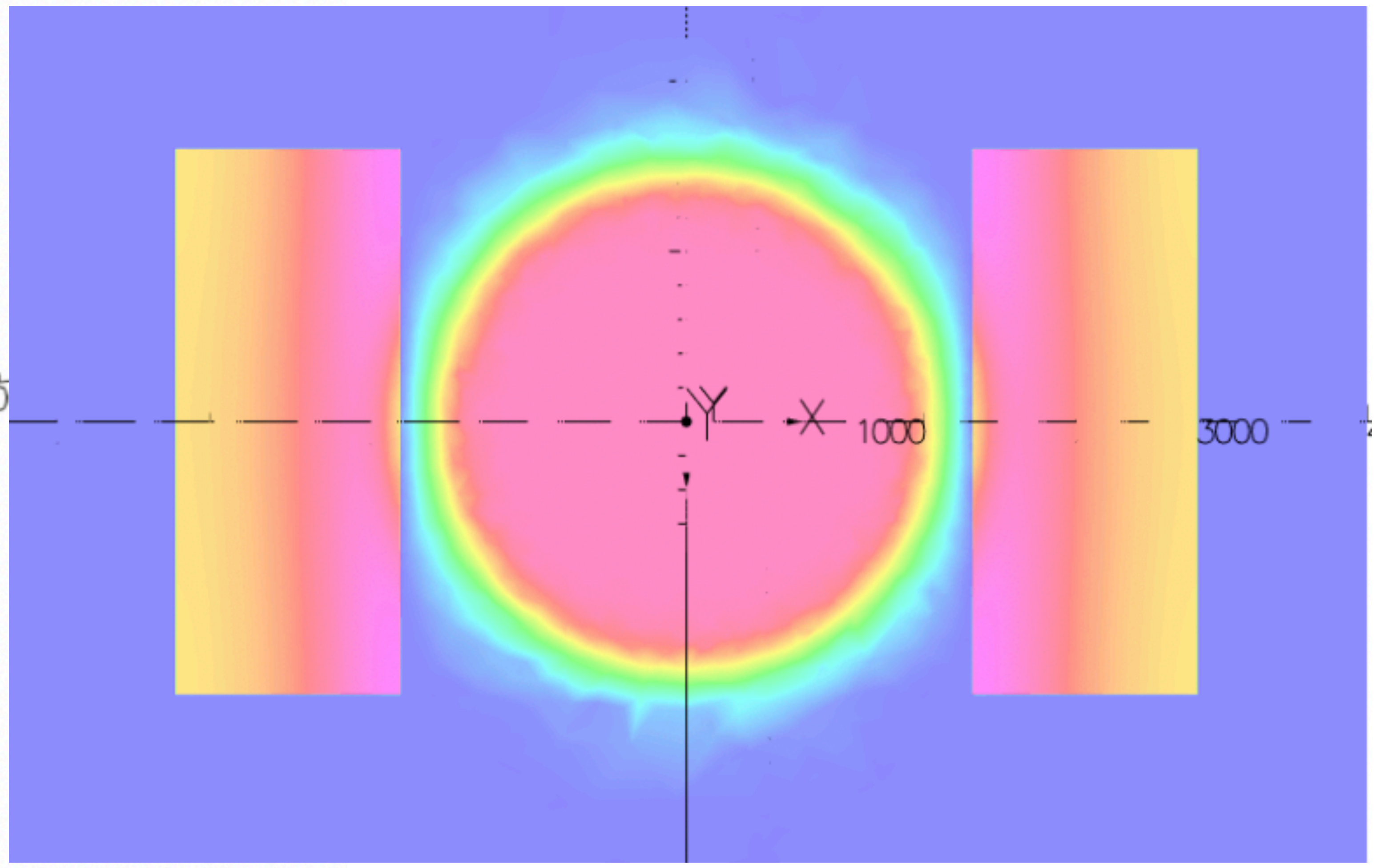

Hide Otono

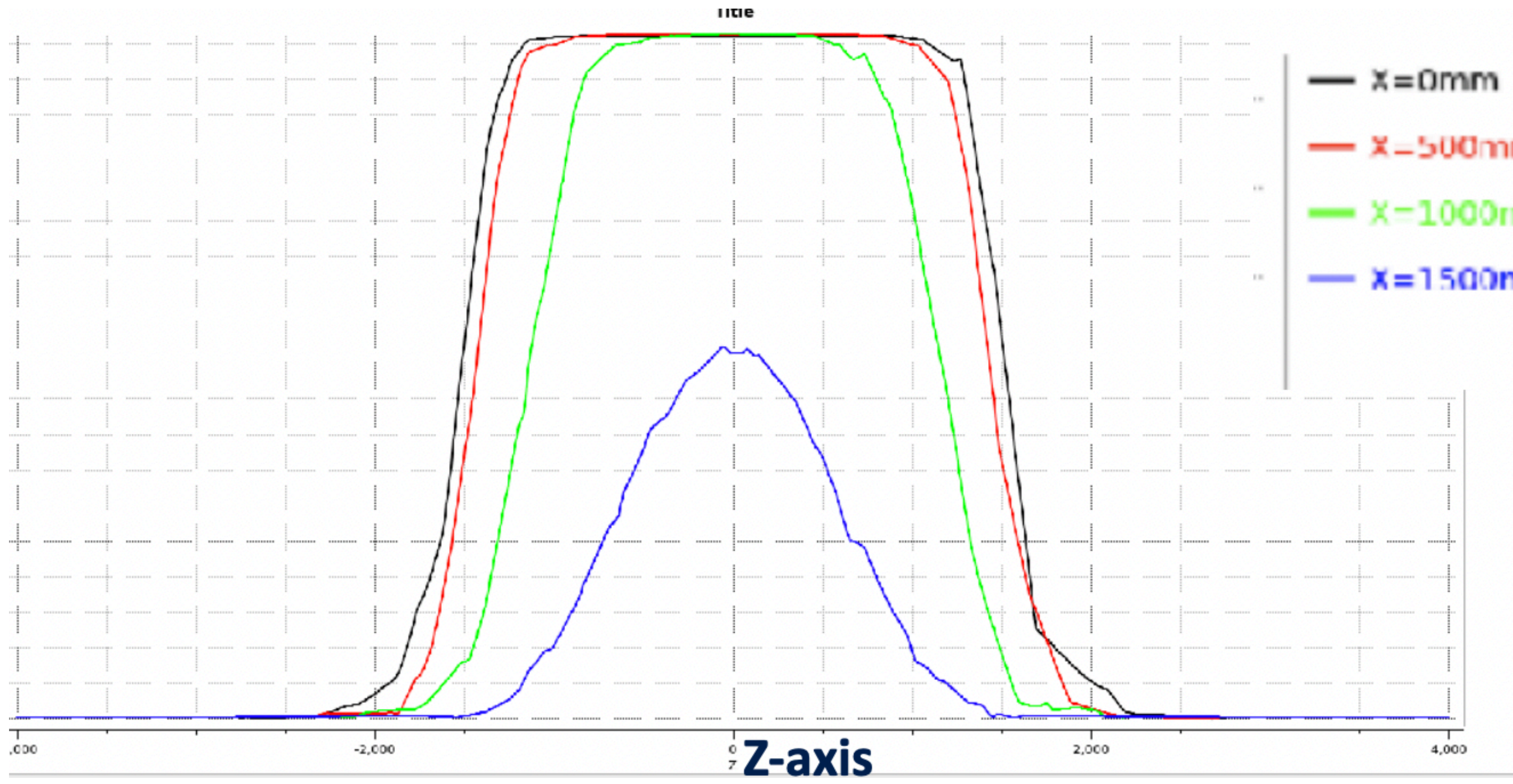
# FASER2 | Magnet

- Circular magnet 1m radius, 0.5m high
  - More bending power in centre - highest energy
  - Less stored energy
- 2 T bending in horizontal direction





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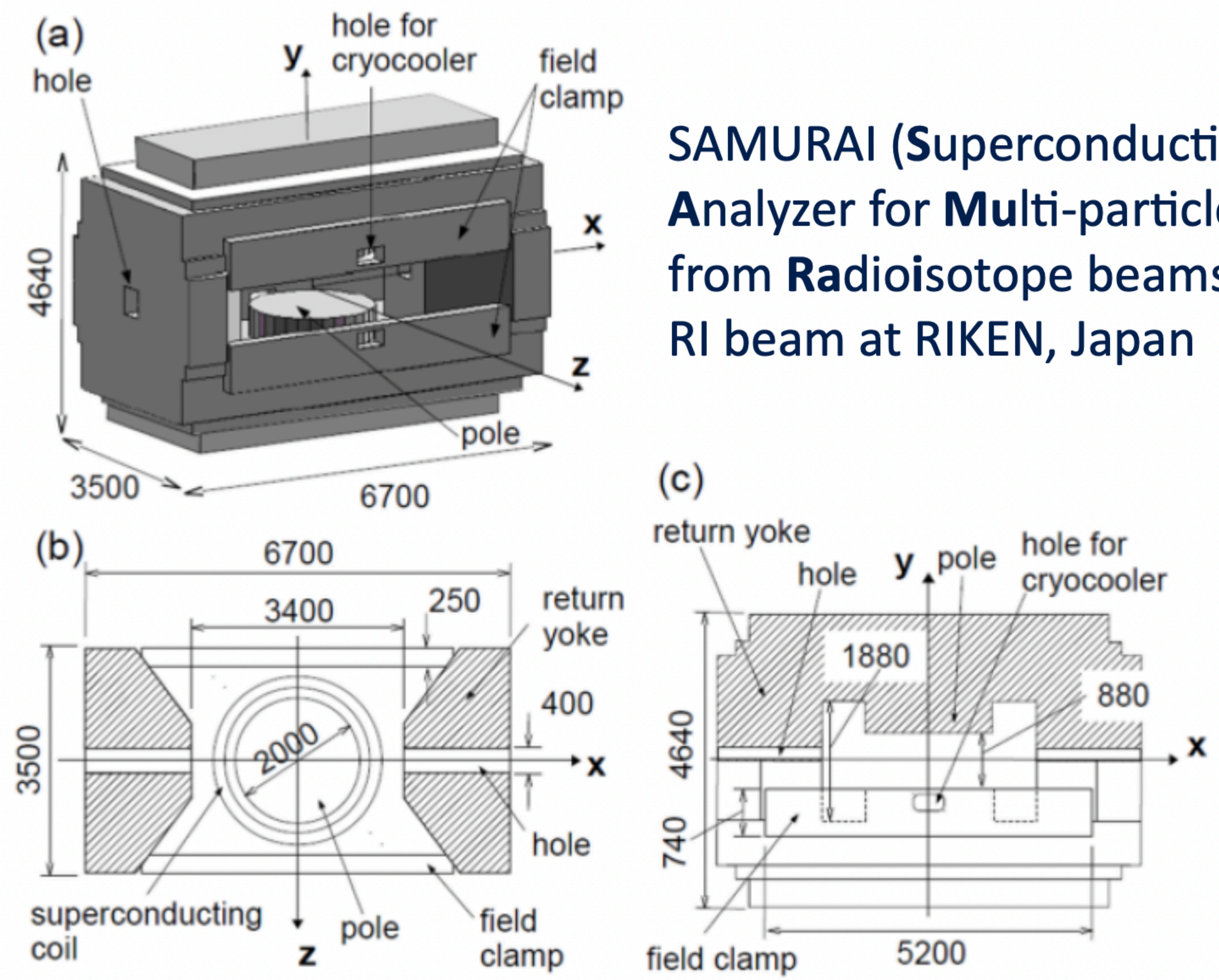
# Cost estimation from TOSHIBA

**Roughly 10 MCHF**
based on their experience on SAMURAI

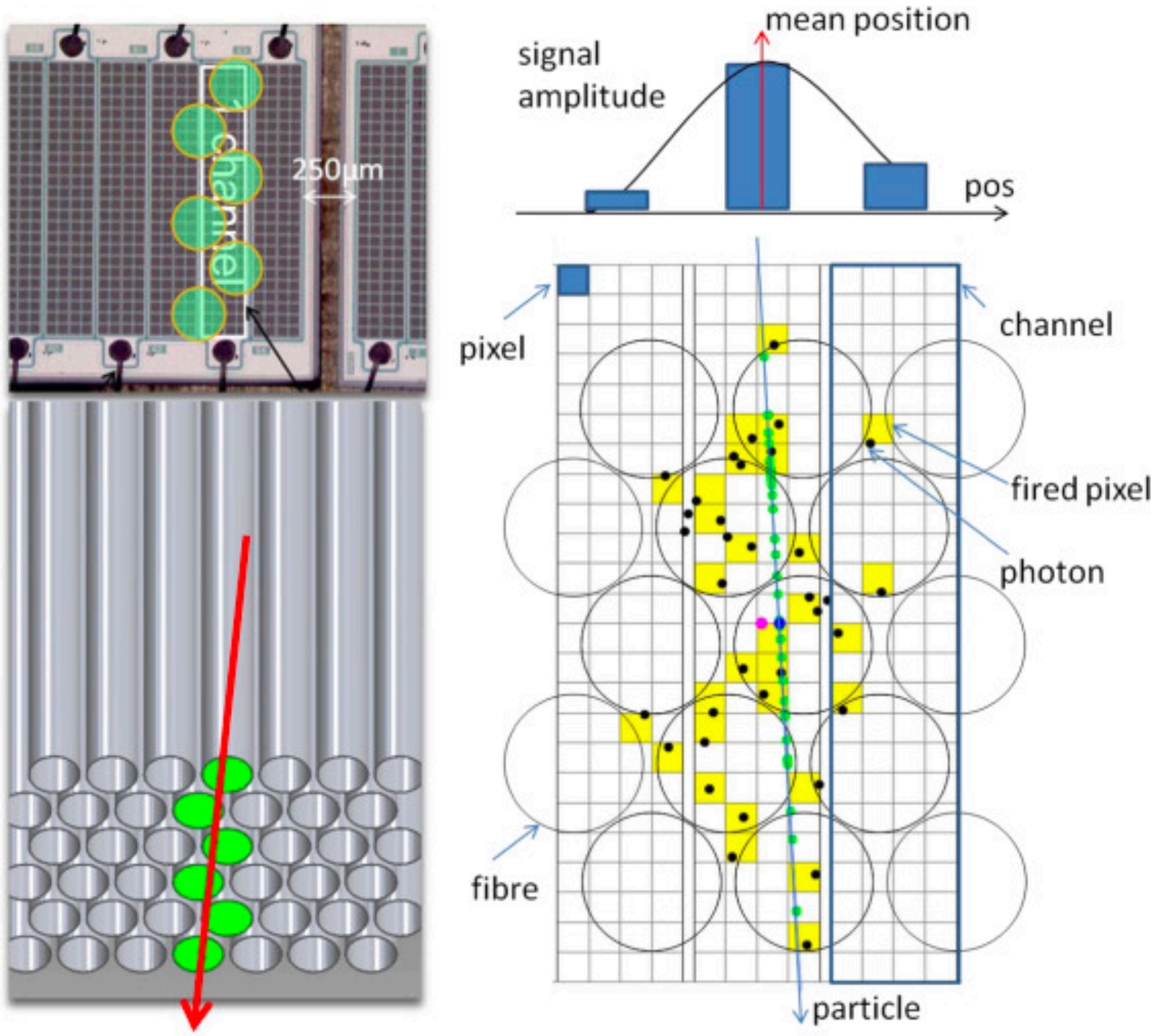
| Item | Unit | Value | Remarks |
|---|---|---|---|
| Magnet | | Dipole magnet | |
| Magnetic field | T | 2 | |
| Magnetic path length | T・m | 4.7 | Rough estimation from SAMURAI |
| Stored energy | MJ | 15 | |
| Magnetic pole gap distance | mm | 880 | same as SAMURAI |
| Magnetic pole radius | mm | 2000 | circular poles |
| Coil | | Solenoid | |
| Total weight | ton | 400 | |



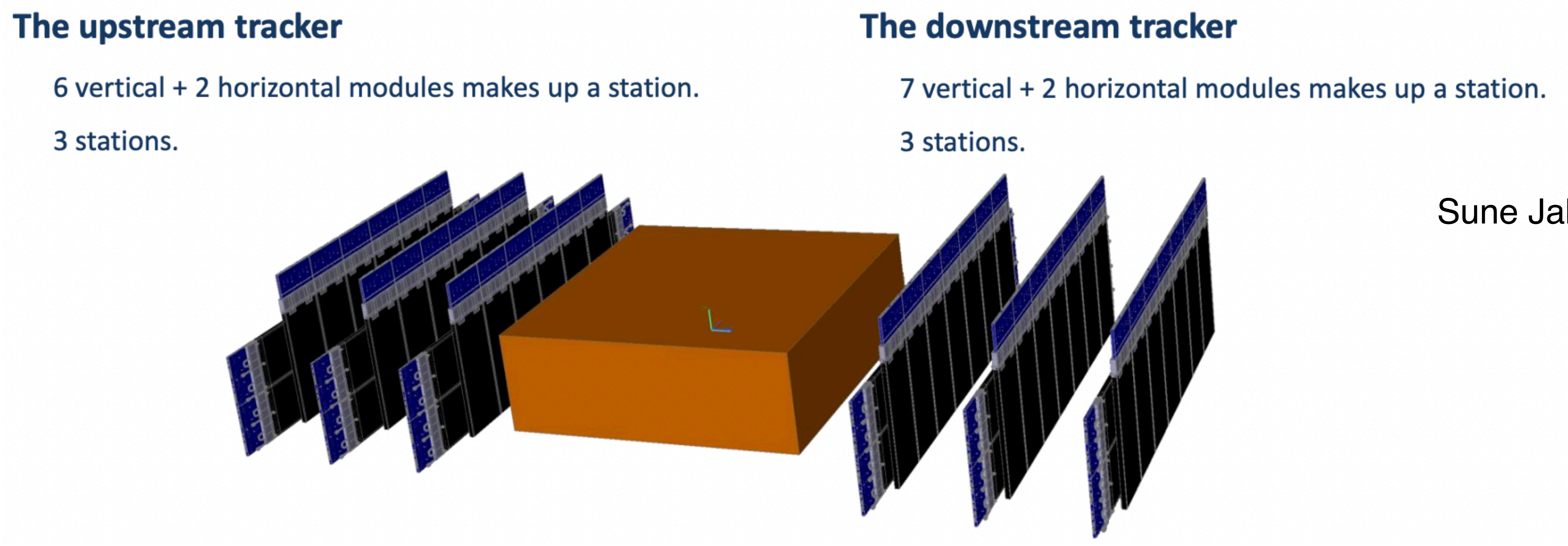

SAMURAI (**S**uperconducting **A**nalyzer for **Mu**lti-particles from **Ra**dio**i**sotope beams) RI beam at RIKEN, Japan

# FASER2 | Tracker design and costing

- Based on SciFi detector installed in LHCb in LS2.
  - SiPM+scintillating fibre design
  - Fibres 250um diamater => 80um resolution.
- Each module consists of a mat of 4 fibres, with >99% efficiency.
- Costing done by scaling LHCb detector to the FASER2 design, and includes readout.
- Cost could be reduced by re-using tooling from LHCb if relevant institutes were involved.



# FASER2 | SciFi Tracker

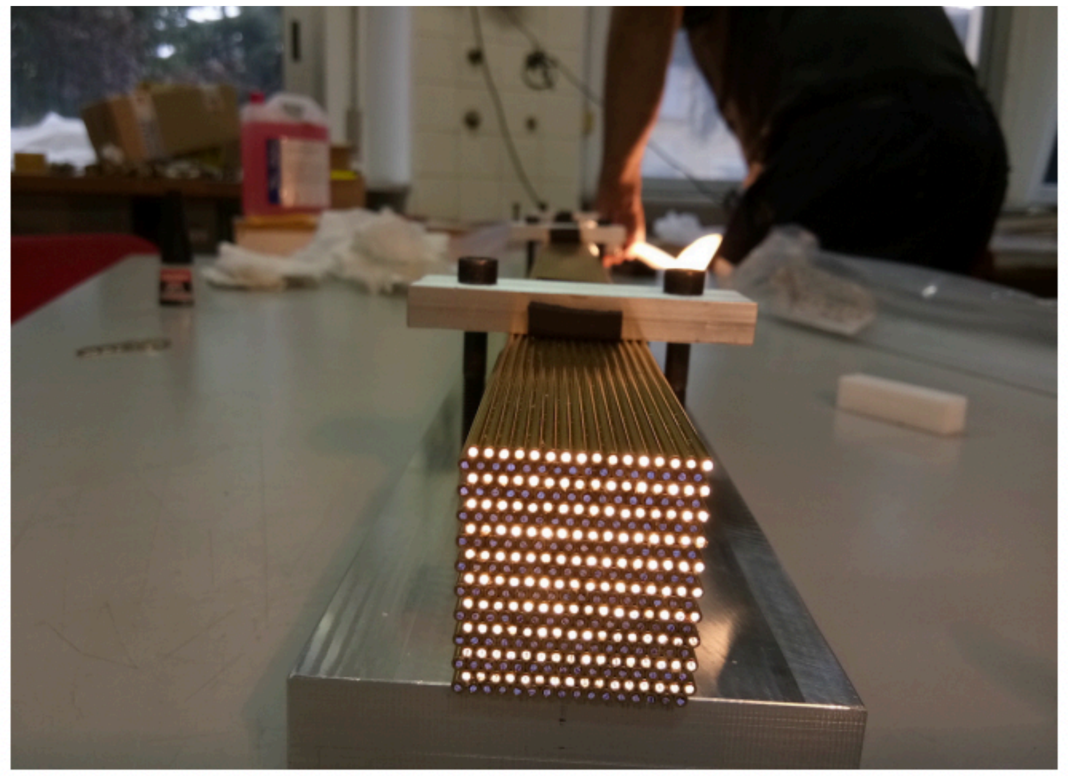


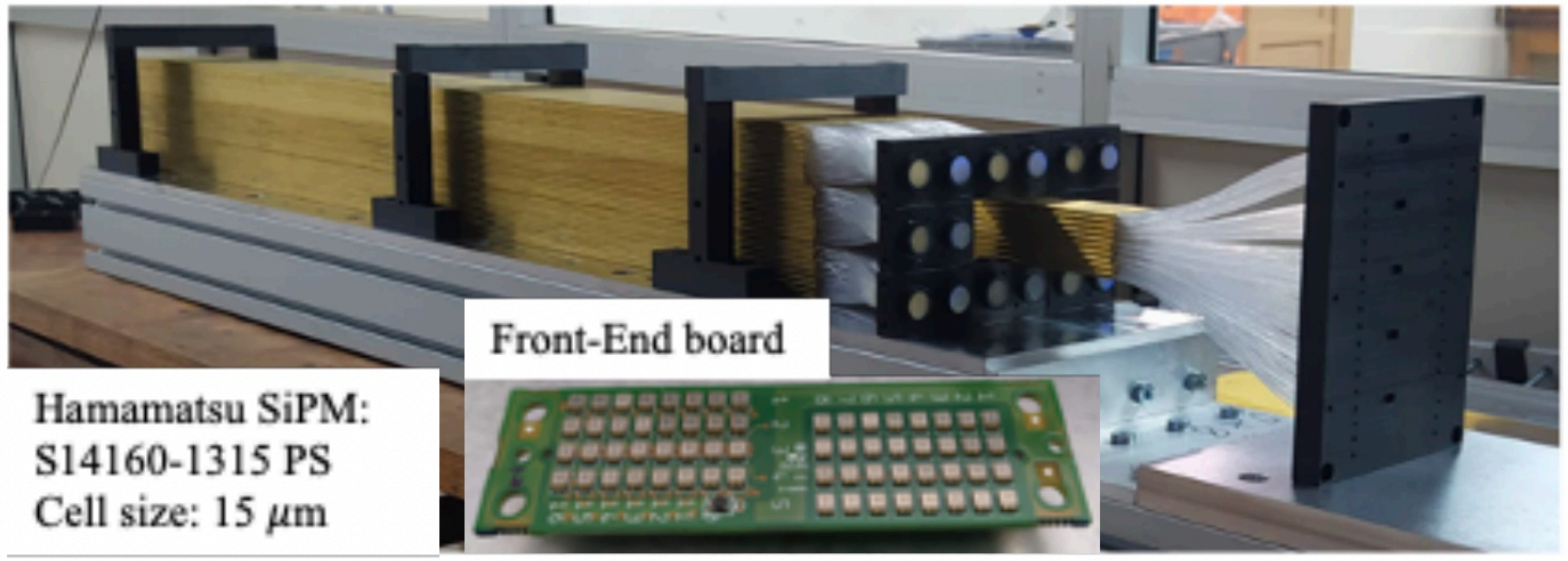

Sune Jakobsen

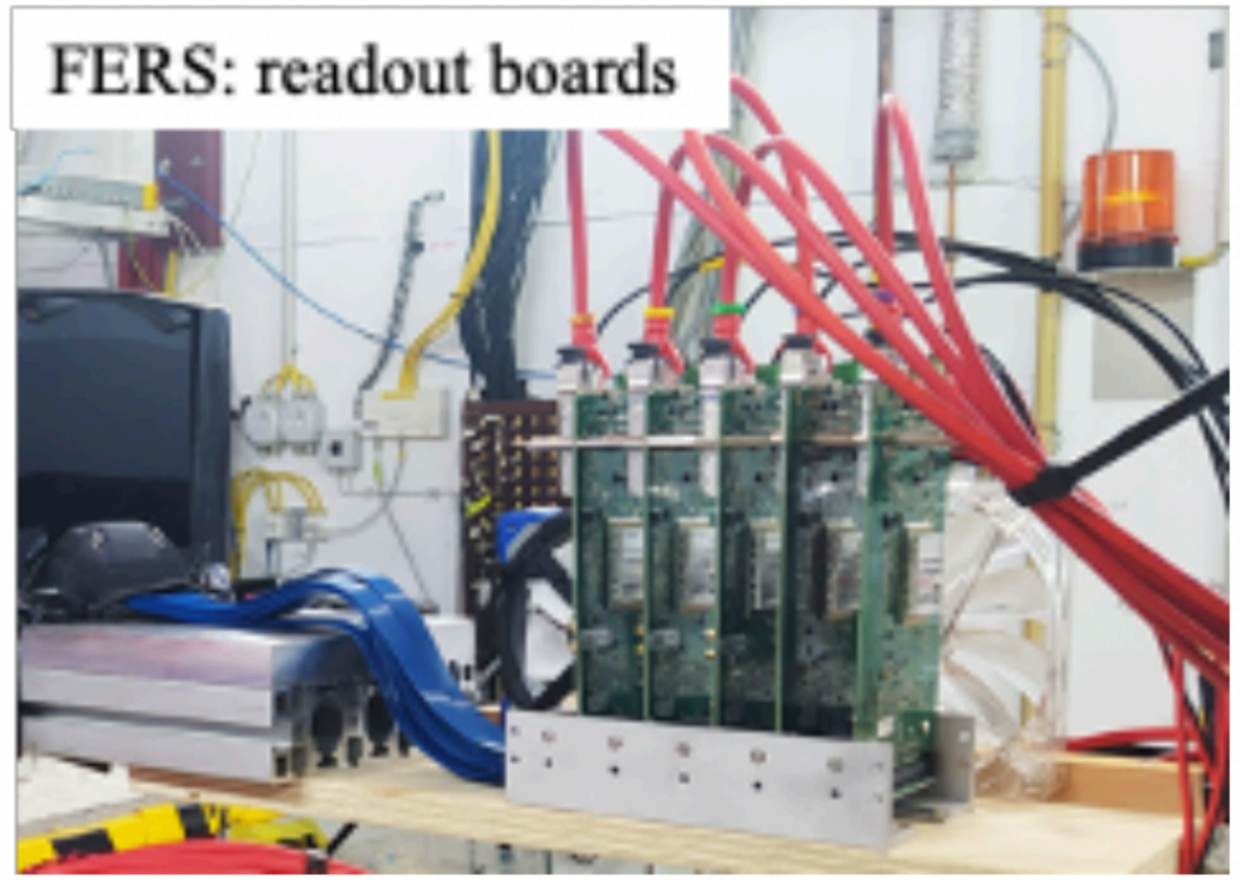
- The stations should be relatively rotated e.g. 1 degree to maximize performance for multi tracks etc.
- Cost: ~3.8M CHF

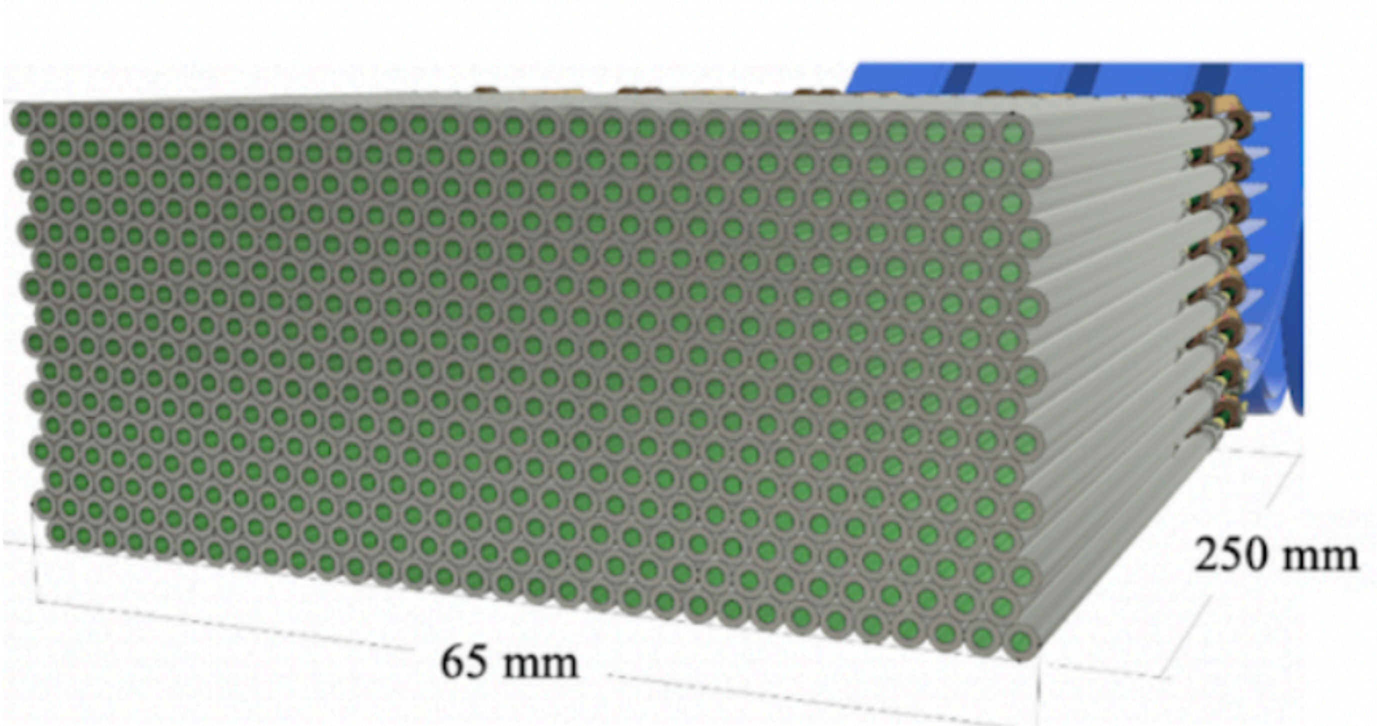
# FASER2 | Dual-readout calorimeter

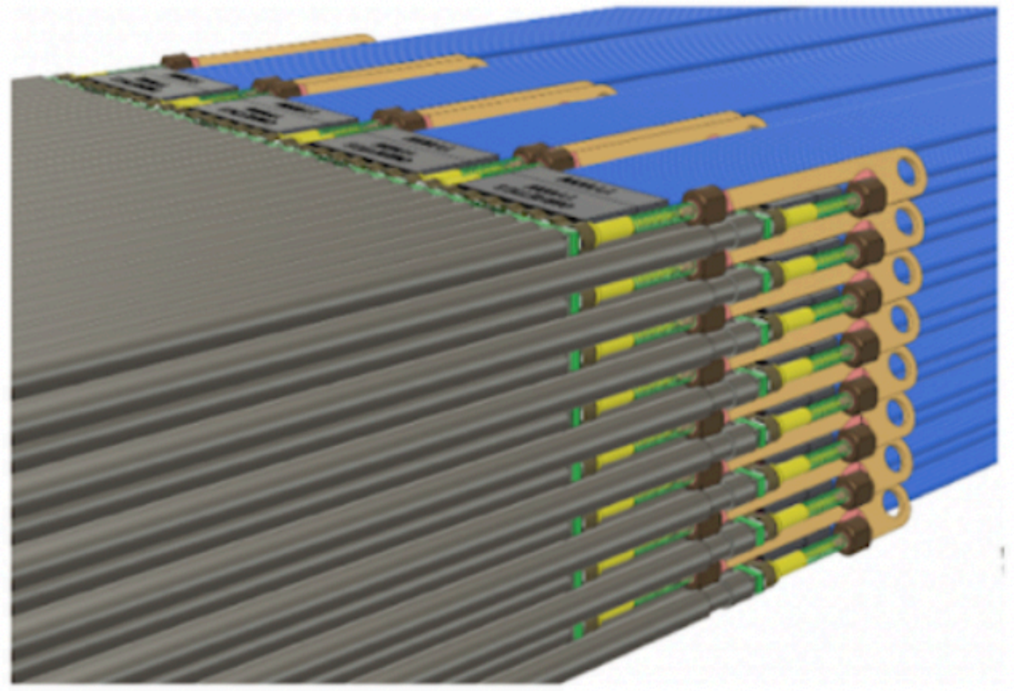
- Existing dual-readout prototypes for Higgs factory detectors
  - EM prototype exists, construction of hadronic-size prototype ongoing
    - Costing based on HiDRa “hadronic size” prototype - INFN
      - 65x65x250 cm (presentation)
      - Aiming for 2023 construction and test beam





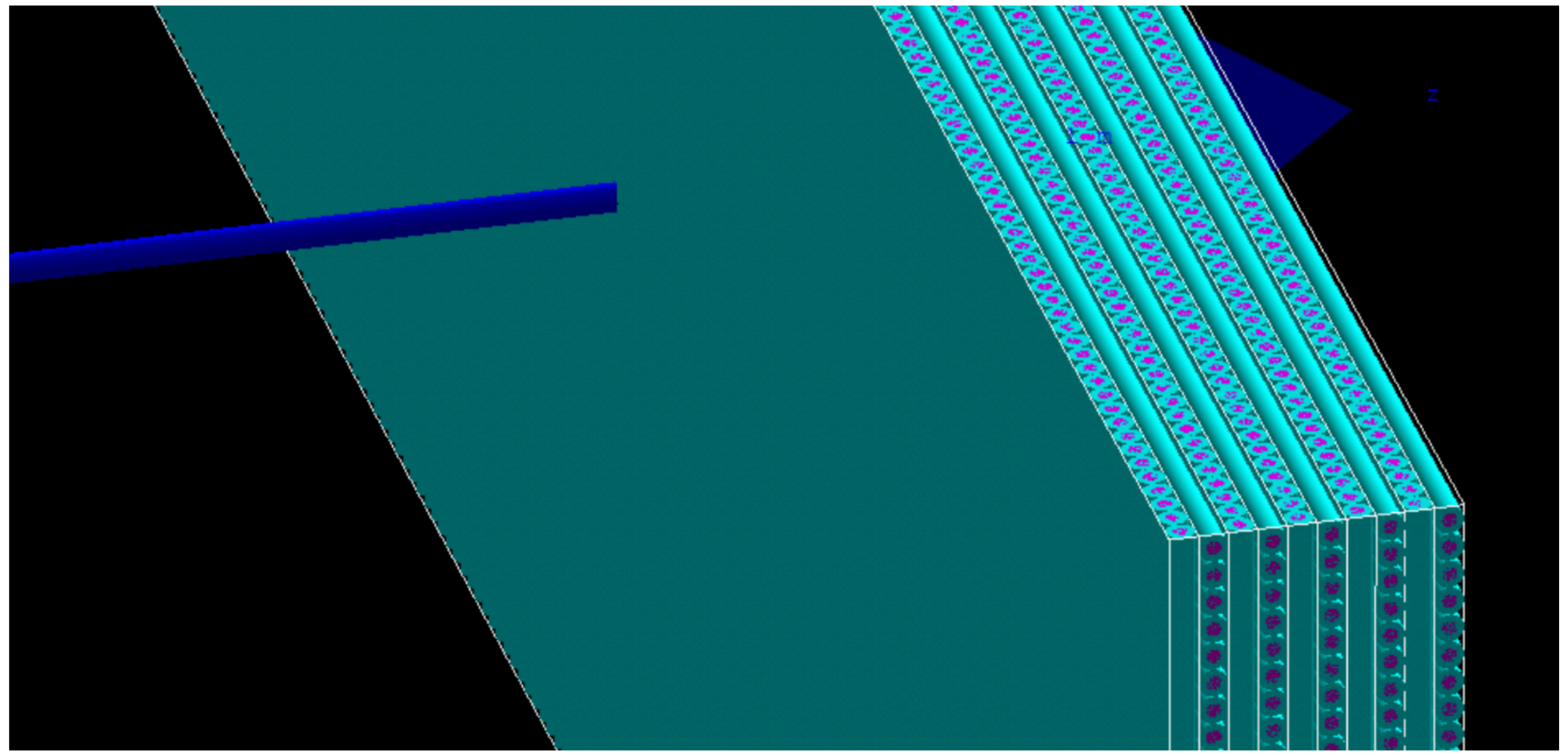



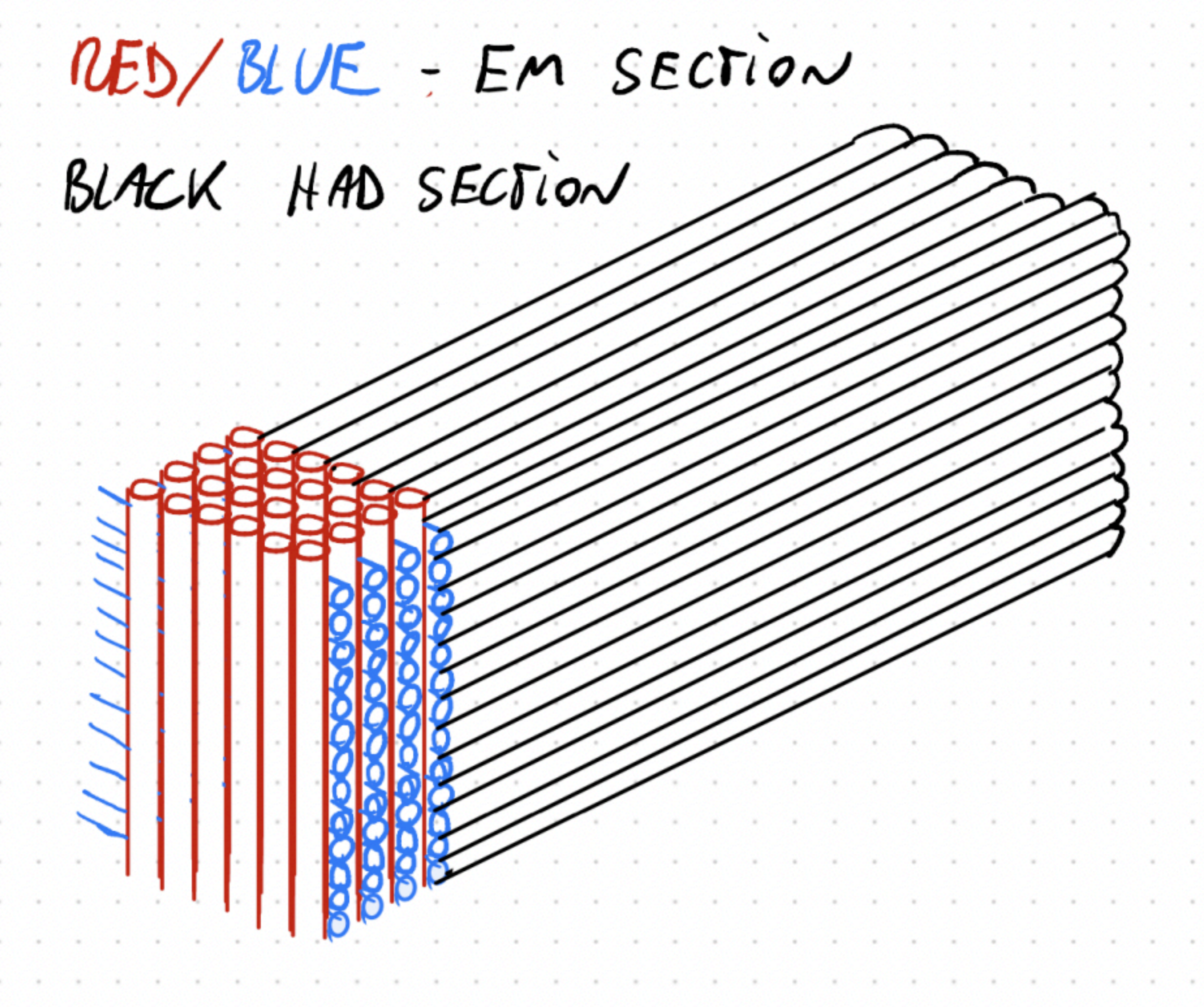
Iacopo Vivarelli

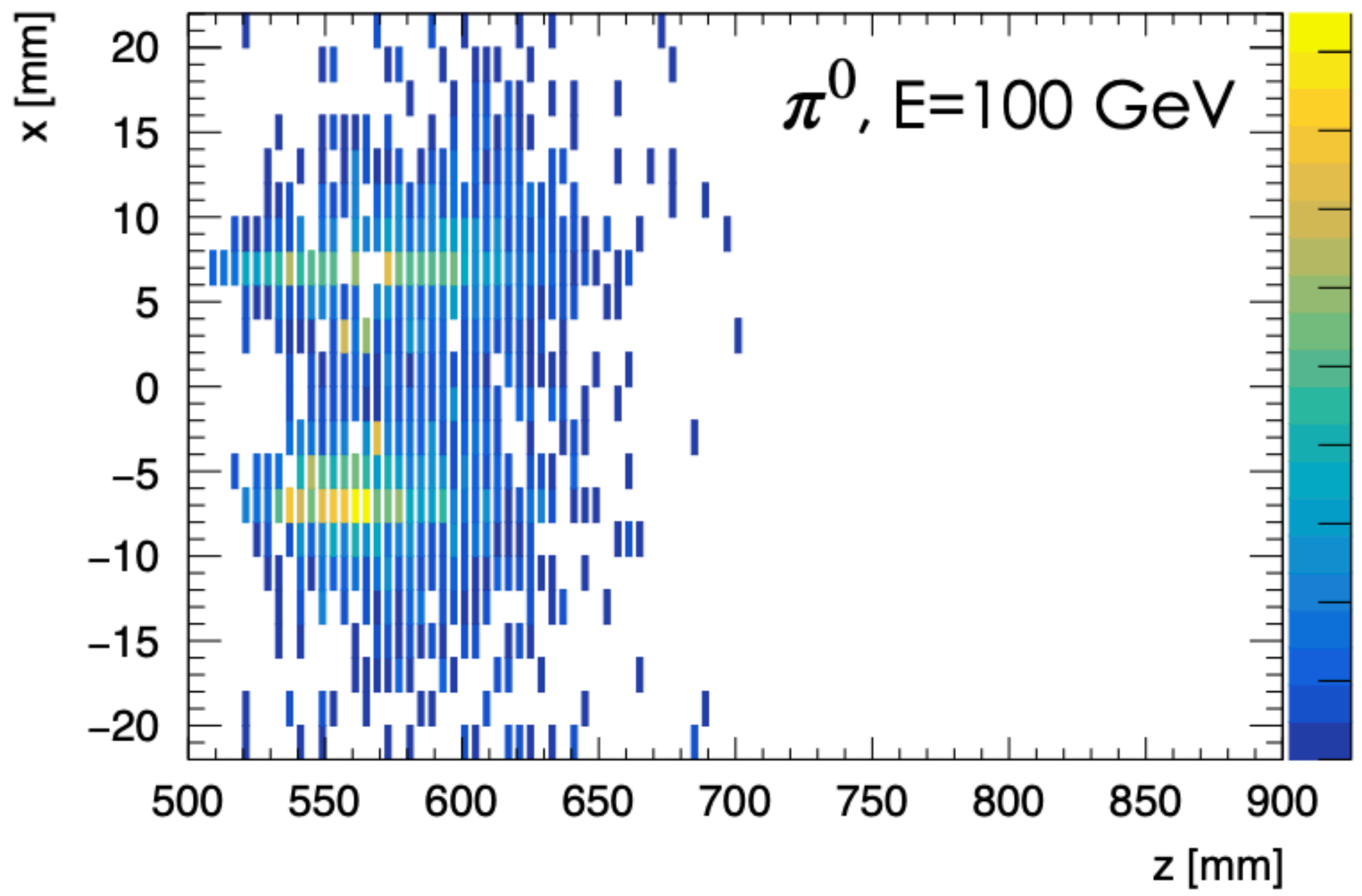
# FASER2 | Calorimeter design

- Fully segmented design
  - Perpendicular crossing of EM layers
  - Don't need dual readout - no Cherenkov fibres



- Costing Option
  3-5M Euros
  - Depending on readout
    and granularity



# FASER2 | Calorimeter design

- Possibility to reuse old LHCb Preshower and Scintillating Pad Detector for FASER2 Calo
  - Active part is made up of scintillator pads with wavelength shifter embedded.
  - Pad size depends on the location and are 12 cm x 12 cm, 6 cm x 6 cm and 4 cm x 4 cm.
  - Pads are supported on "super modules" with an active area of about 1 m x 5.8 m