

THE
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US
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OF SUSSEX

FASER

FASER: First Results

Warwick Seminar

19/10/2023

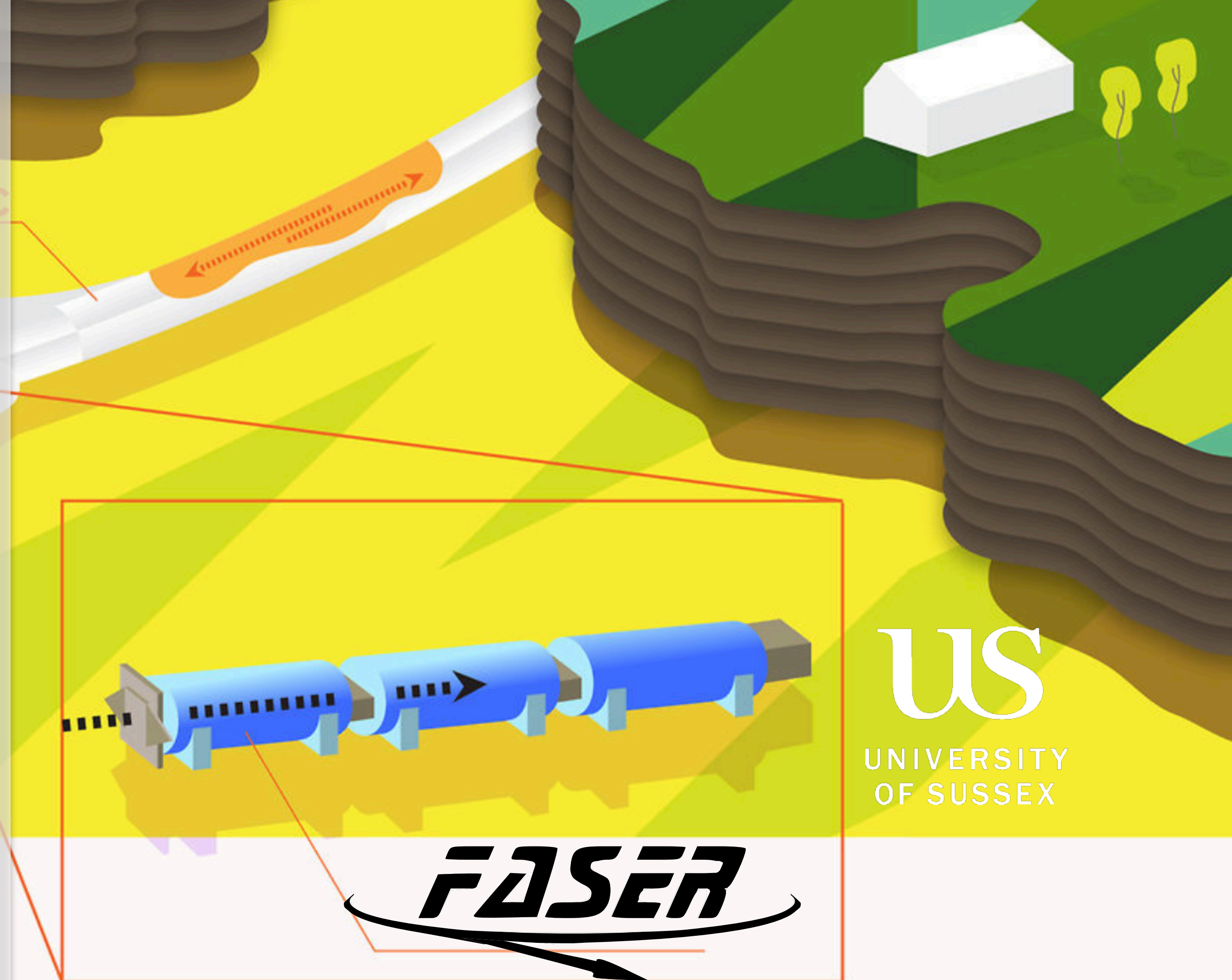
Josh McFayden (University of Sussex)

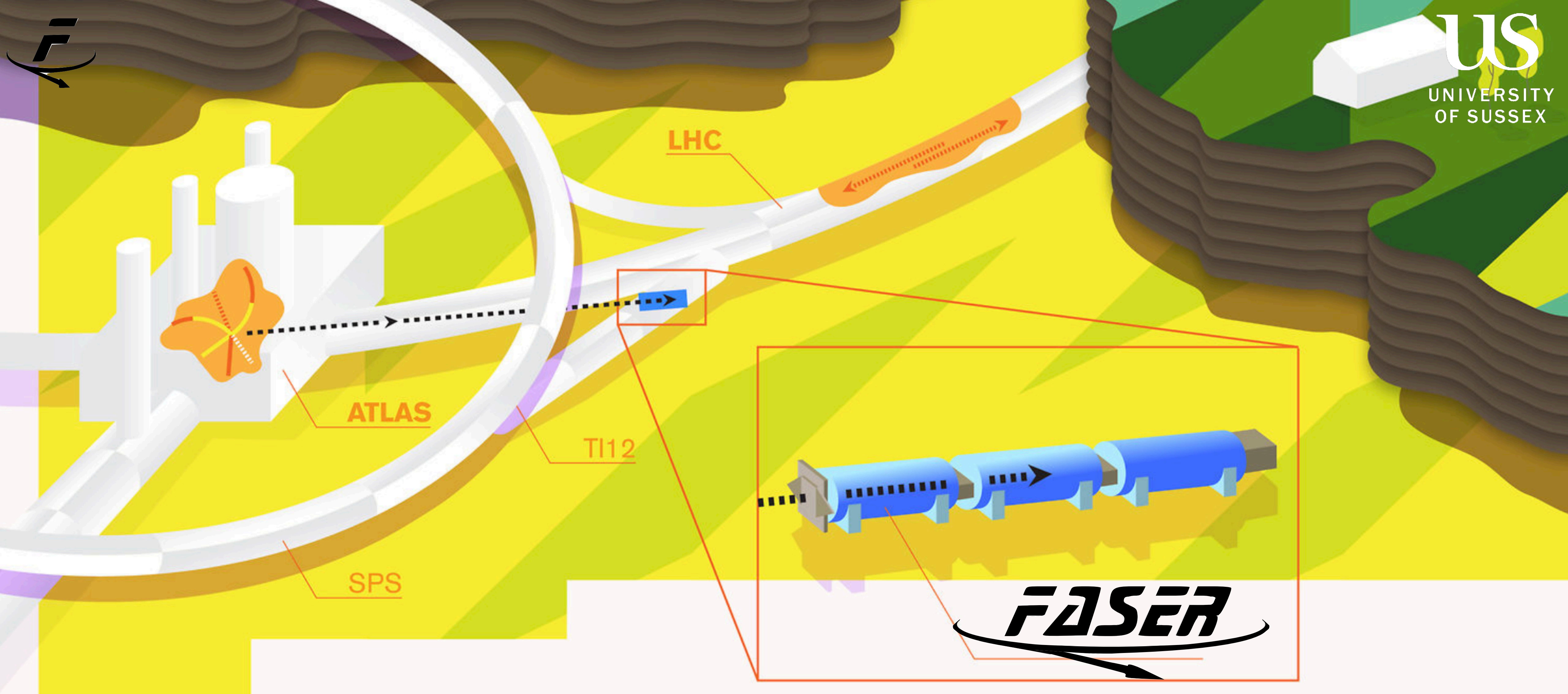
 @JoshMcFayden

 faser.web.cern.ch

Outline

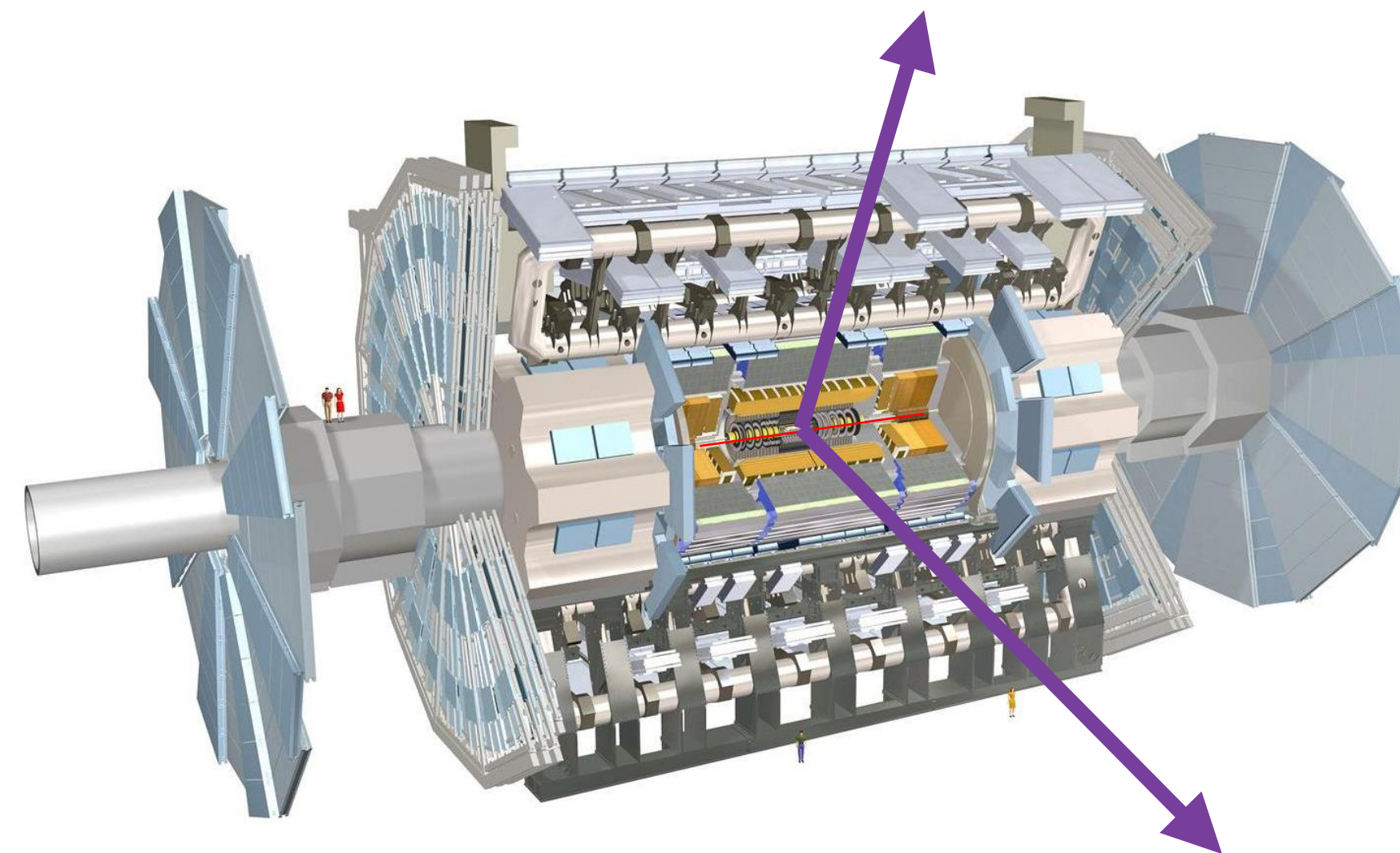
- ▶ Background & Motivation
- ▶ FASER construction & operation
- ▶ First direct observation of collider neutrinos
- ▶ First observation of ν_e at collider
- ▶ First FASER Dark Photon search
- ▶ Looking ahead to HL-LHC



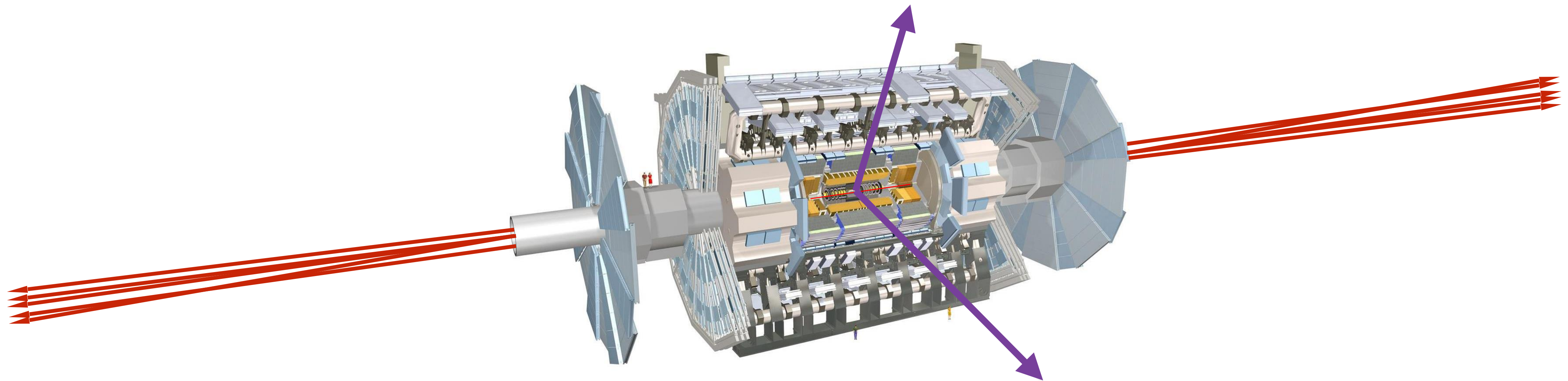


Background and Motivation

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



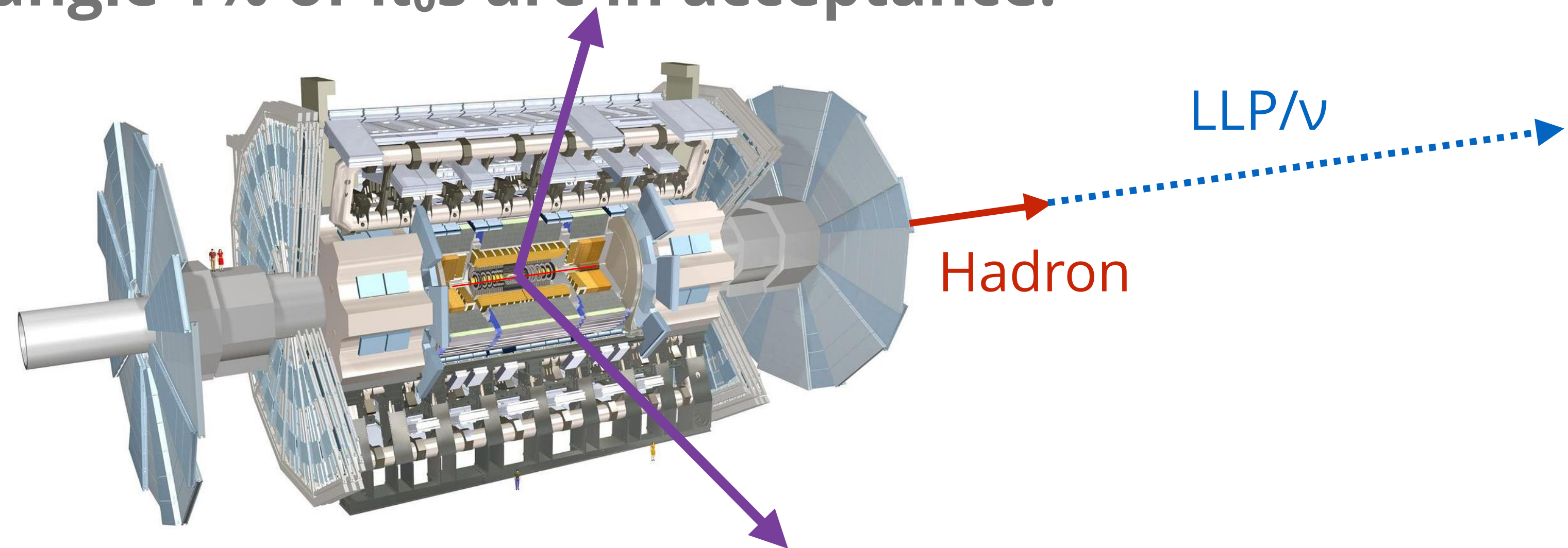
- ▶ Could be misguided - Need to target light and weakly interacting particles
 - ▶ Lack of new physics in “traditional” searches.
 - ▶ Scenarios that e.g. satisfy Dark Matter relic density.
 - ▶ Exploit huge inelastic pp cross section $\rightarrow 10^{16}$ collisions in Run 3 $\rightarrow 10^{17} \pi,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



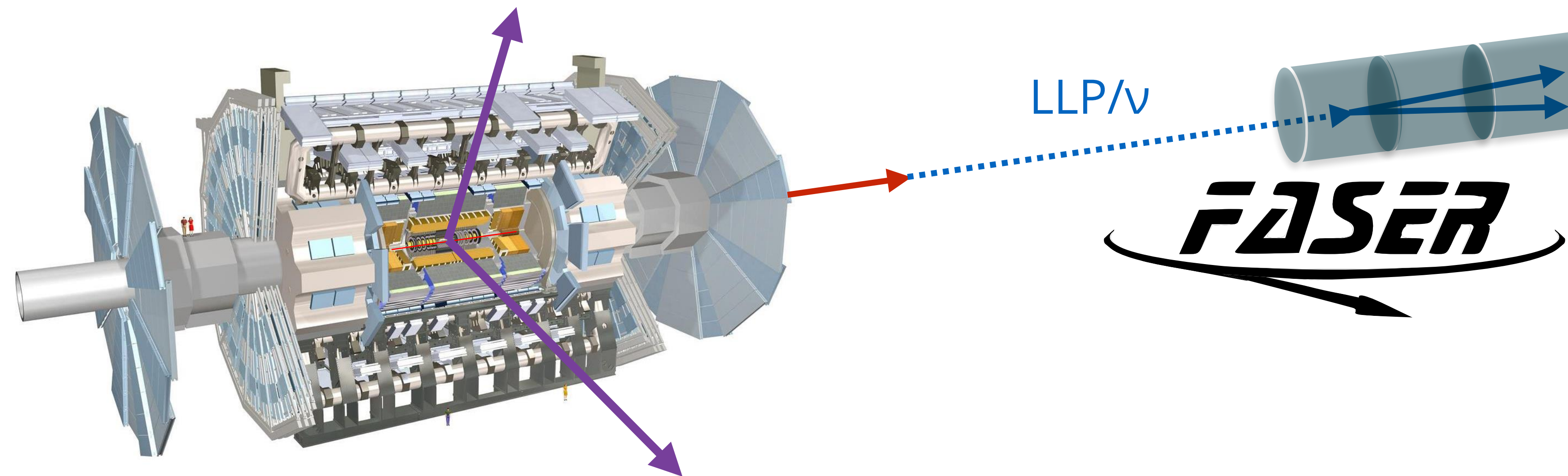


FASER Philosophy

- ▶ 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 $\rightarrow 10^{16}$ collisions in Run 3 $\rightarrow 10^{17} \pi, 10^{13} B$
 - ▶ **Light meson**: low $p_T \sim \Lambda_{QCD} \rightarrow$ particles are collimated:
 - ▶ $\theta \sim \Lambda_{QCD}/E \sim \text{mrad}$
 - ▶ From only 10^{-8} of solid angle 1% of π_0 s are in acceptance.
- ▶ Gain sensitivity to **long-lived particles with very weak couplings and neutrinos**

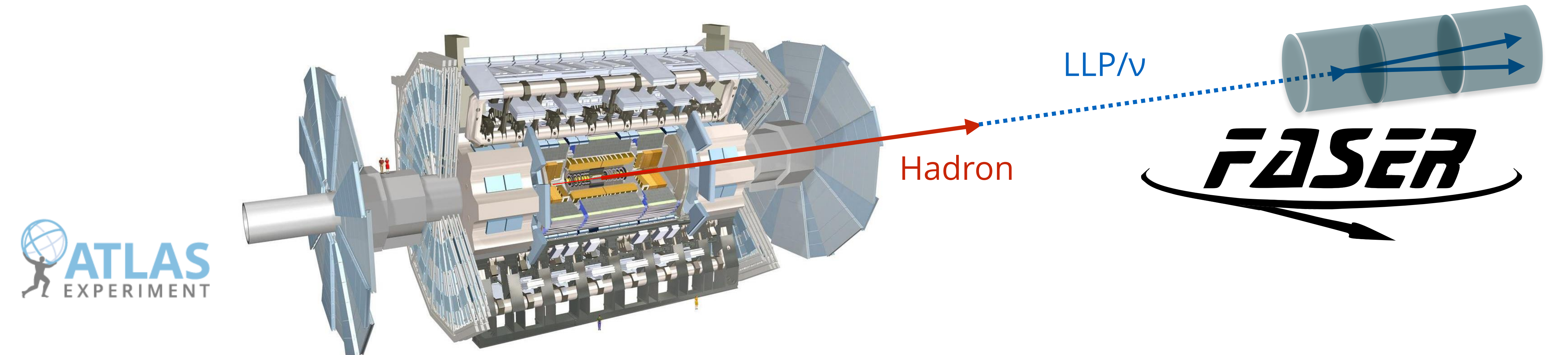


- **FASER** is a new experiment designed to cover this scenario at the LHC.





FASER Overview

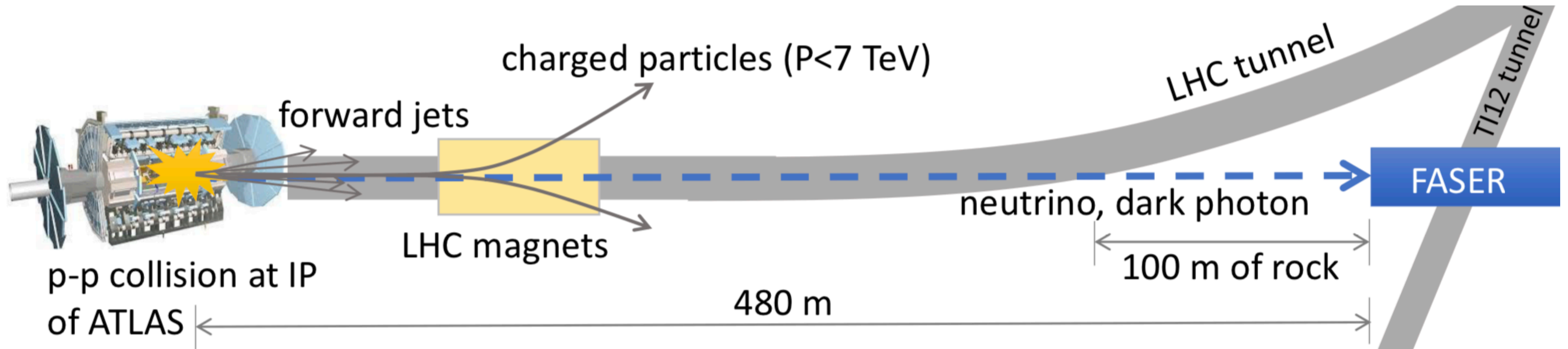


- ▶ Detector is 480m from ATLAS IP1
 - ▶ In line with beam collision axis. Transverse size of 10cm → mrad regime ($\eta > 9.1$)
- ▶ **Neutrinos produced copiously in decays of forward hadrons**
- ▶ **Very weakly interacting LLPs could be produced in significant numbers**



Concept and Location

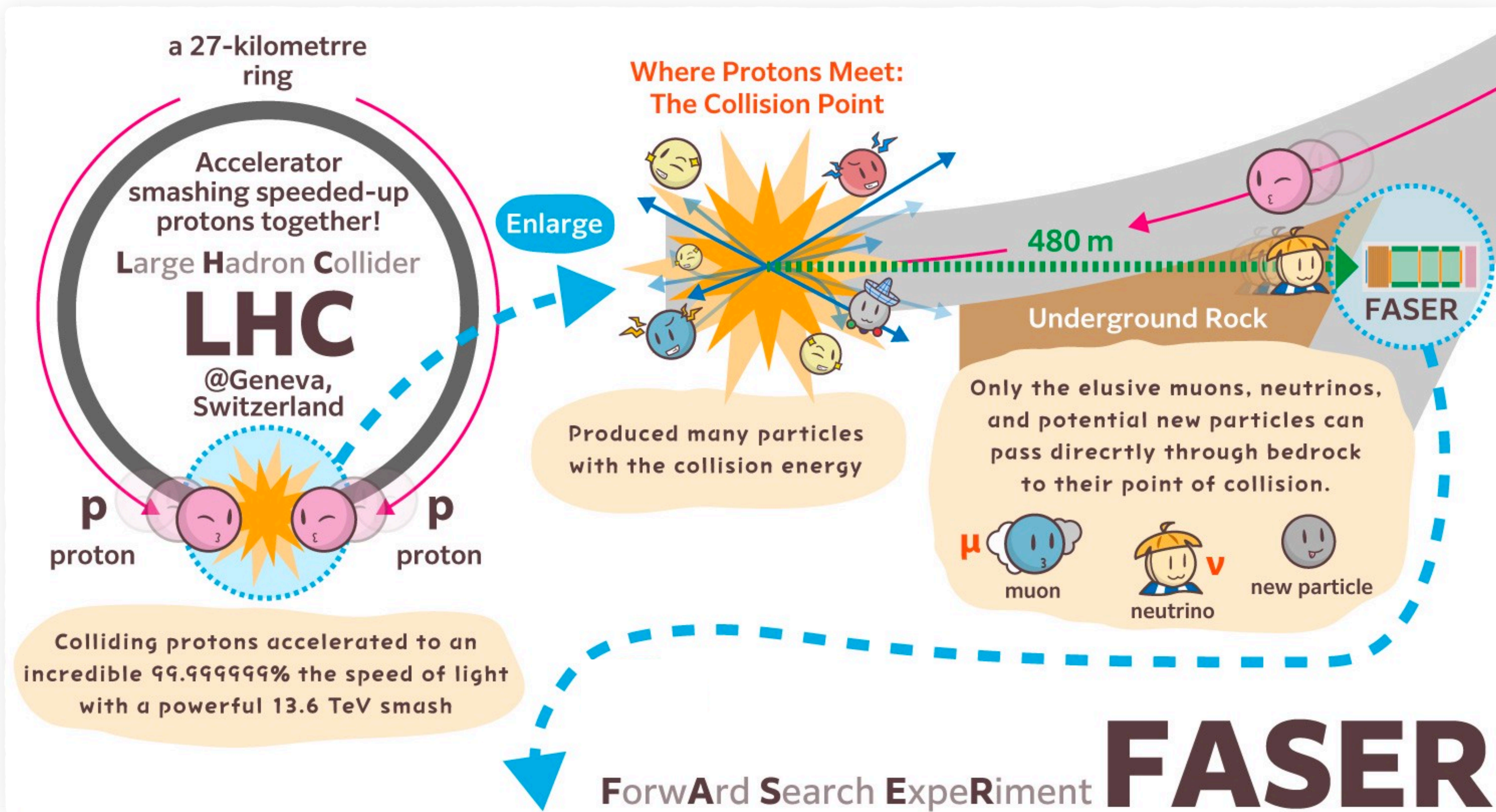
- ▶ First concept in 2017 (Feng, Galon, Kling, Trojanowski)
- ▶ Approved by CERN in March 2019 (limited budget ~ \$2M)
- ▶ The TI12 service tunnel happens to be in just the right place for FASER:



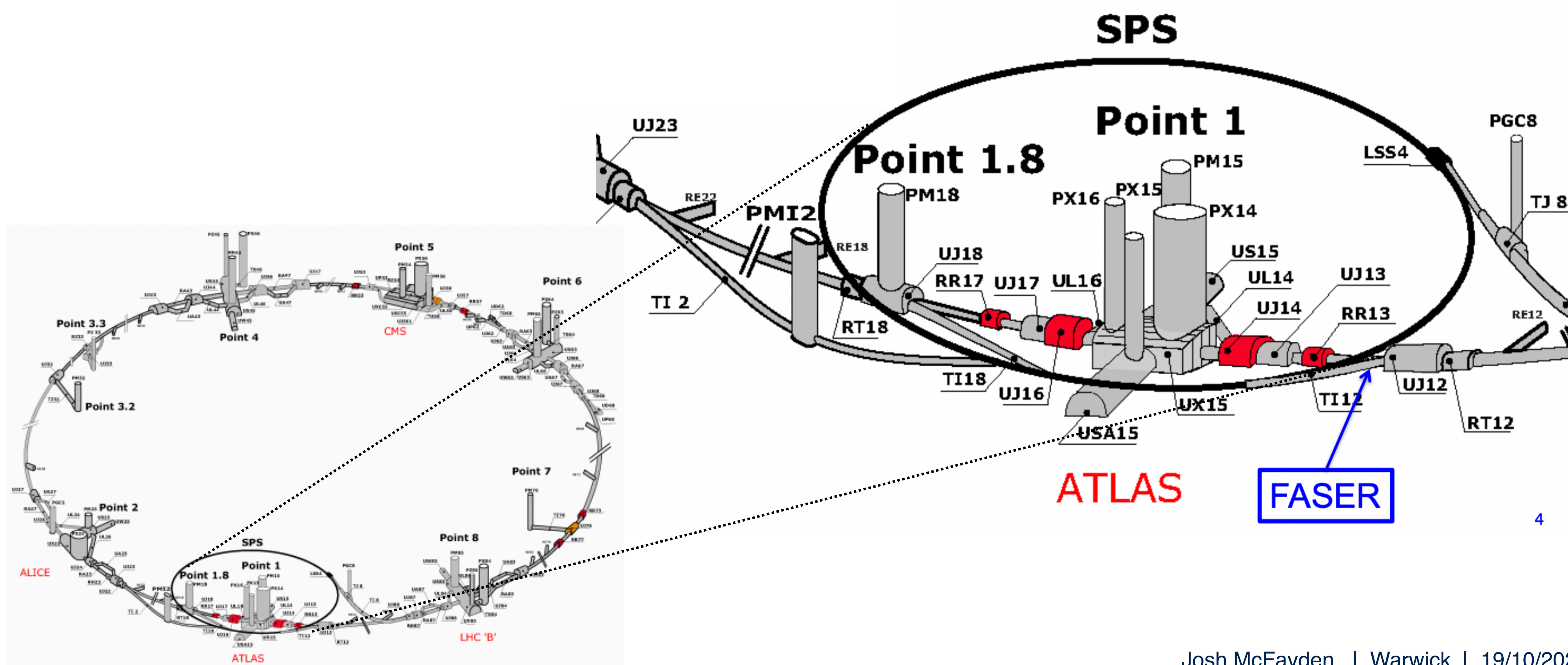
- ▶ Old SPS → LEP tunnel
- ▶ On line-of-sight (with some digging)
- ▶ Shielded by ~100m rock/concrete
- ▶ Low beam backgrounds - Charged particles bent by LHC magnets



Concept and Location

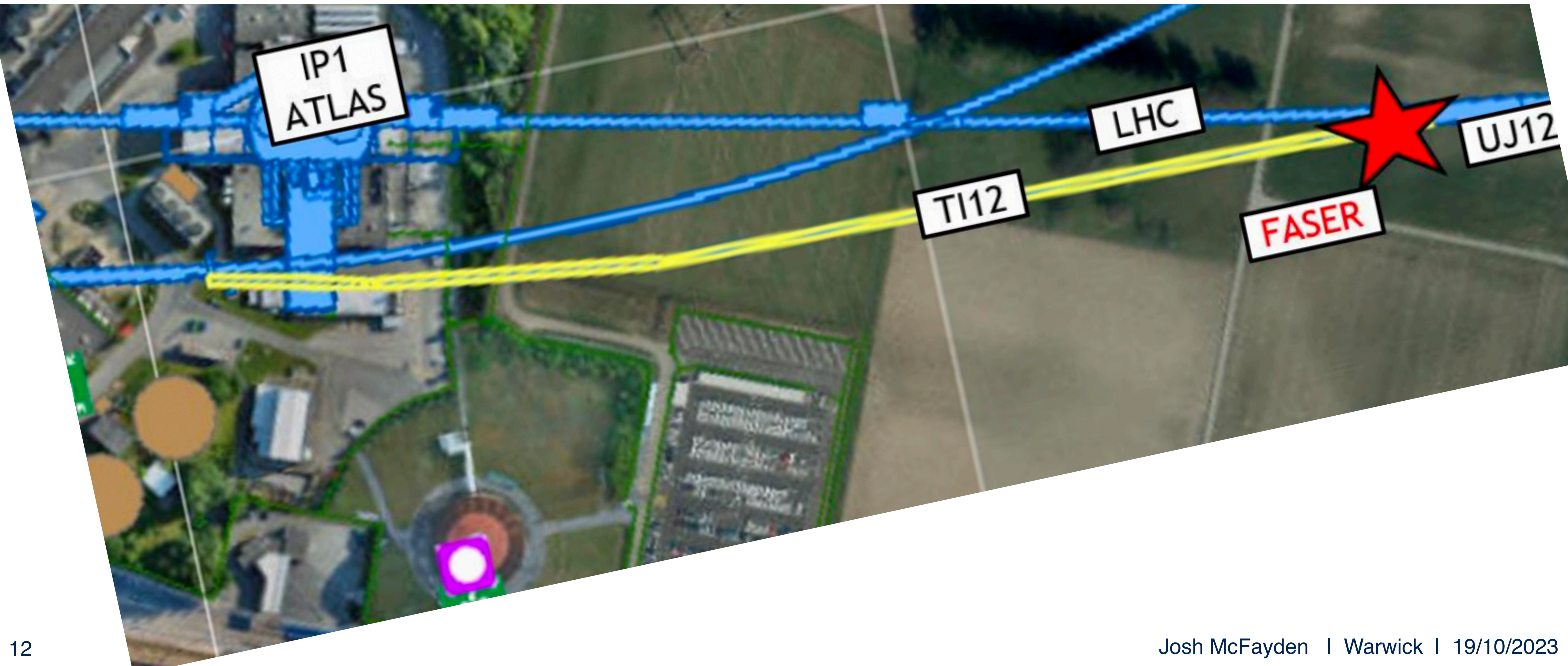


- Wider setting at the LHC



FASER Location

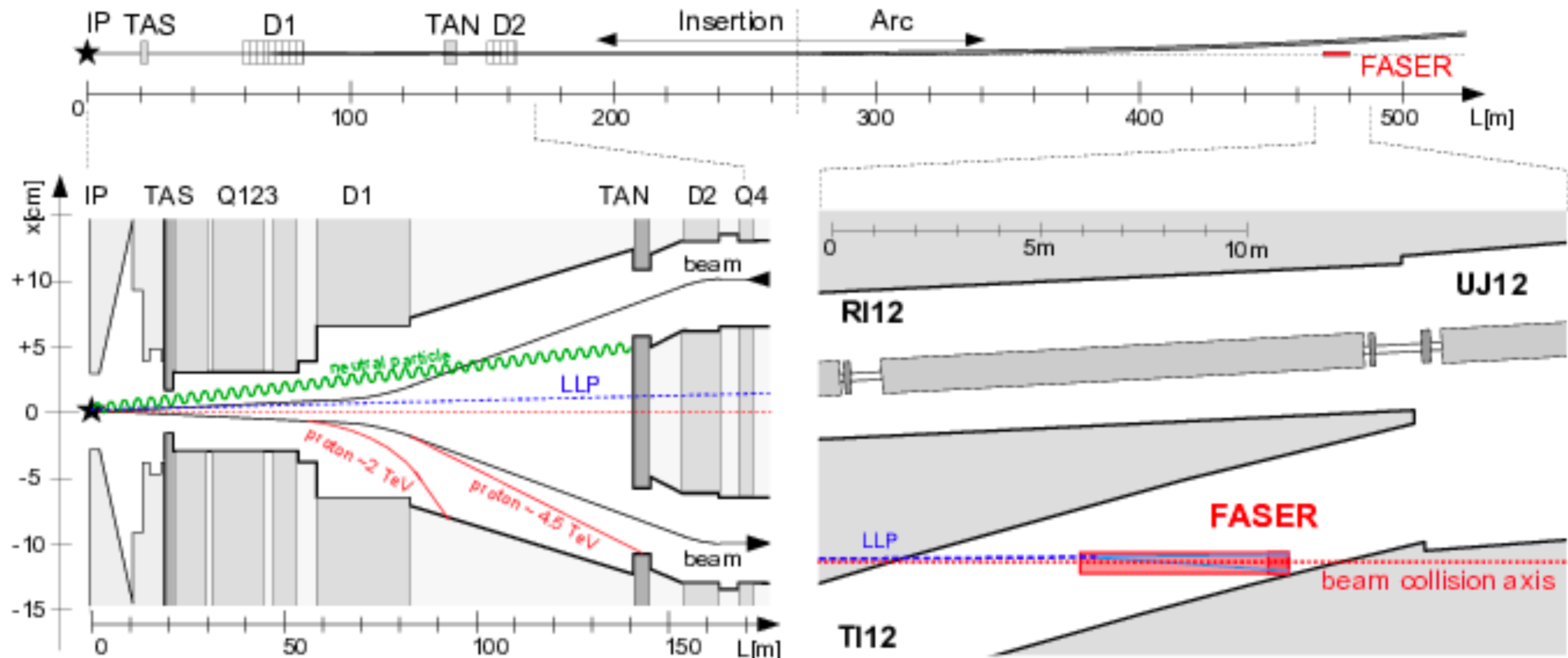
- ▶ In relation to ATLAS at Point 1





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,§}

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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, **ForwArd Search ExpeRiment**, 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



Making the case

FASER: ForwArd Search ExpeRiment at the LHC

14th June 2017

18th July 2018

Jonathan L. Feng,^{1,*} Iftah Galon,^{1,†} Felix Kling

Submitted to the LHCC, 18 July 2018

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

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Abstract

New physics has traditionally been expected in the LHC experiments. If new particles are light and weakly-coupled, the search is misguided: light particles are typically highly concentrated in the very forward region and operated concurrently the are studied: a far location, 400 m from the IP and just 150 m from the IP and right behind the TAN neutrino detector. We examine leading neutrino- and beam-induced backgrounds.

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 Trojanowski⁸

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CERN-LHCC-2018-036, LHCC-P-013
UCI-TR-2018-22, KYUSHU-RCAPP-2018-07

7th Nov 2018

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New physics has traditionally been expected in the LHC experiments. If new particles are light and weakly-coupled, they are misguided: light particles are typically highly concentrated in the very forward region and operated concurrently the LHC are studied: a far location, 400 m from the IP and just behind the TAN neutrino detector, just 150 m from the IP and right behind the TAN neutrino detector. We propose a new experiment or FASER, which would be placed downstream of the LHC, we examine leading neutrino- and beam-induced backgrounds.

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TECHNICAL PROPOSAL

FASER

FORWARD SEARCH EXPERIMENT AT THE LHC

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Francesco Cerutti,³ Salvatore Danzeca,³ Liam Dougherty,³ Yannick Favre,⁴
Jonathan L. Feng,^{5,†} Didier Ferrere,⁴ Jonathan Gall,³ Iftah Galon,⁶ Sergio
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Kling,⁵ Susanne Kuehn,³ Mike Lamont,³ Lorne Levinson,⁹ Hidetoshi Otono,² John
Osborne,³ Brian Petersen,³ Osamu Sato,¹⁰ Marta Sabaté-Gilarte,^{3,11} Matthias
Schott,¹² Anna Sfyrla,⁴ Jordan Smolinsky,⁵ Aaron M. Soffa,⁵ Yosuke Takubo,¹³
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[arXiv:1708.09389]

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[arXiv:1811.10243]

TECHNICAL DESIGN REPORT

FASER

FORWARD SEARCH EXPERIMENT

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[arXiv:1812.09139]

29th Nov 2018



FASER's Physics Reach for Long-Lived Particles

FASER Collaboration

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Yannick Favre,⁴ Jonathan L. Feng,⁵ Didier Ferrere,⁴ Iftah Galon,⁶ Sergio Gonzalez-Sevilla,⁴
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[arXiv:1811.12522] Josh McFayden | Warwick | 19/10/2023



Making the case

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



FASER's Physics Reach for Long-Lived Particles

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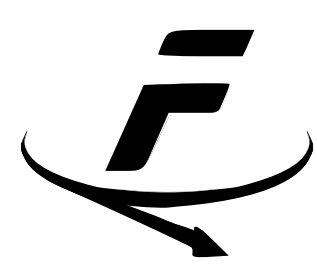
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29th Nov 2018

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

Approved by CERN in March 2019

~18 months from theory paper to
start of construction!

PREPARED FOR SUBMISSION TO JINST

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The FASER Detector

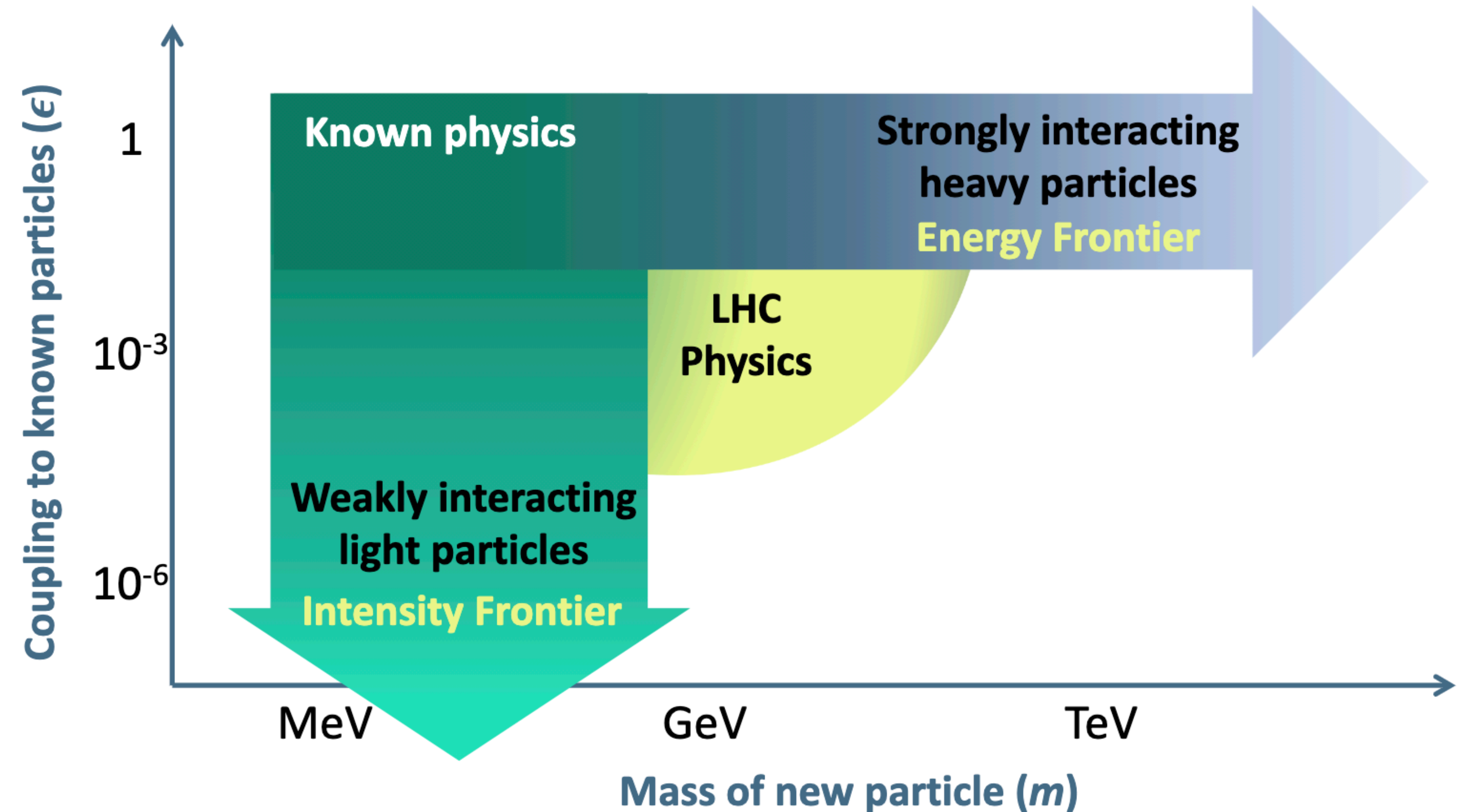
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Henso Abreu¹, Elham Amin Mansour², Claire Antel², Akitaka Ariga^{3,4}, Tomoko Ariga⁵, Florian Bernlochner⁶, Tobias Boeckh⁶, Jamie Boyd⁷, Lydia Brenner⁸, Franck Cadoux², David W. Casper⁹, Charlotte Cavanagh¹⁰, Xin Chen¹¹, Andrea Coccaro¹², Olivier Crespo-Lopez⁷, Stéphane Débieux², Monica D'Onofrio¹⁰, Liam Dougherty⁷, Candan Dozen¹³, Abdallah Ezzat¹⁴, Yannick Favre², Deion Fellers¹⁵, Jonathan L. Feng⁹, Didier Ferrere², Edward Karl Galantay², Jonathan Gall¹⁶, Enrico Gamberini⁷, Stephen Gibson¹⁷, Sergio Gonzalez-Sevilla², Carl Gwilliam¹⁰, Daiki Hayakawa⁴, Shih-Chieh Hsu¹⁸, Zhen Hu¹¹, Giuseppe Iacobucci², Tomohiro Inada¹¹, Sune Jakobsen⁷, Elliott Johnson², Enrique Kajomovitz¹, Hiroaki Kawahara⁵, Felix Kling¹⁹, Umut Kose⁷, Rafaella Kotitsa⁷, Jesse Krusse^{20,21}, Susanne Kuehn⁷, Helena Lefebvre¹⁷, Lorne Levinson²², Ke Li¹⁸, Jinfeng Liu¹¹, Chiara Magliocca², Fulvio Martinelli², Josh McFayden²³, Sam Meehan^{7,24}, Matteo Milanese², Manato Miura⁴, Dimitar Mladenov⁷, Théo Moretti², Magdalena Munker²,

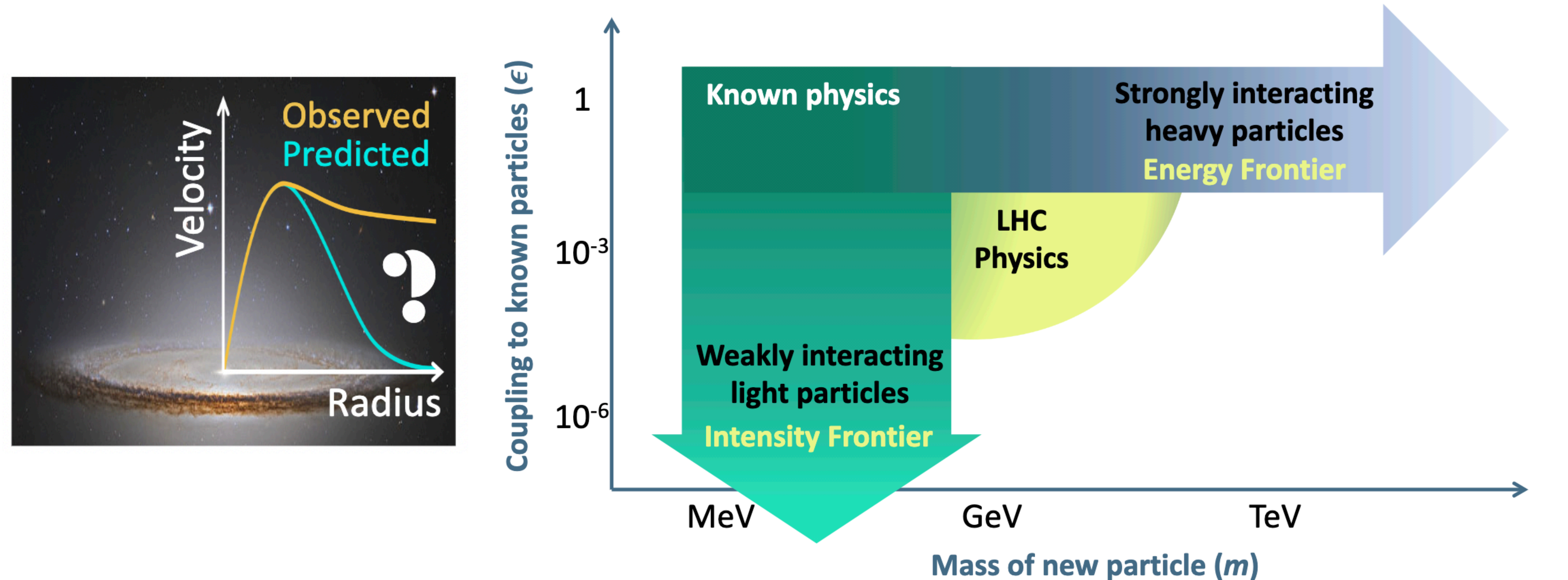
- ▶ **FASER: ForwArd Search ExpeRiment**
- ▶ “The acronym recalls another marvelous instrument that harnessed highly collimated particles and was used to explore strange new worlds.”



- ▶ 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 (yet!) motivates **looking elsewhere** too.

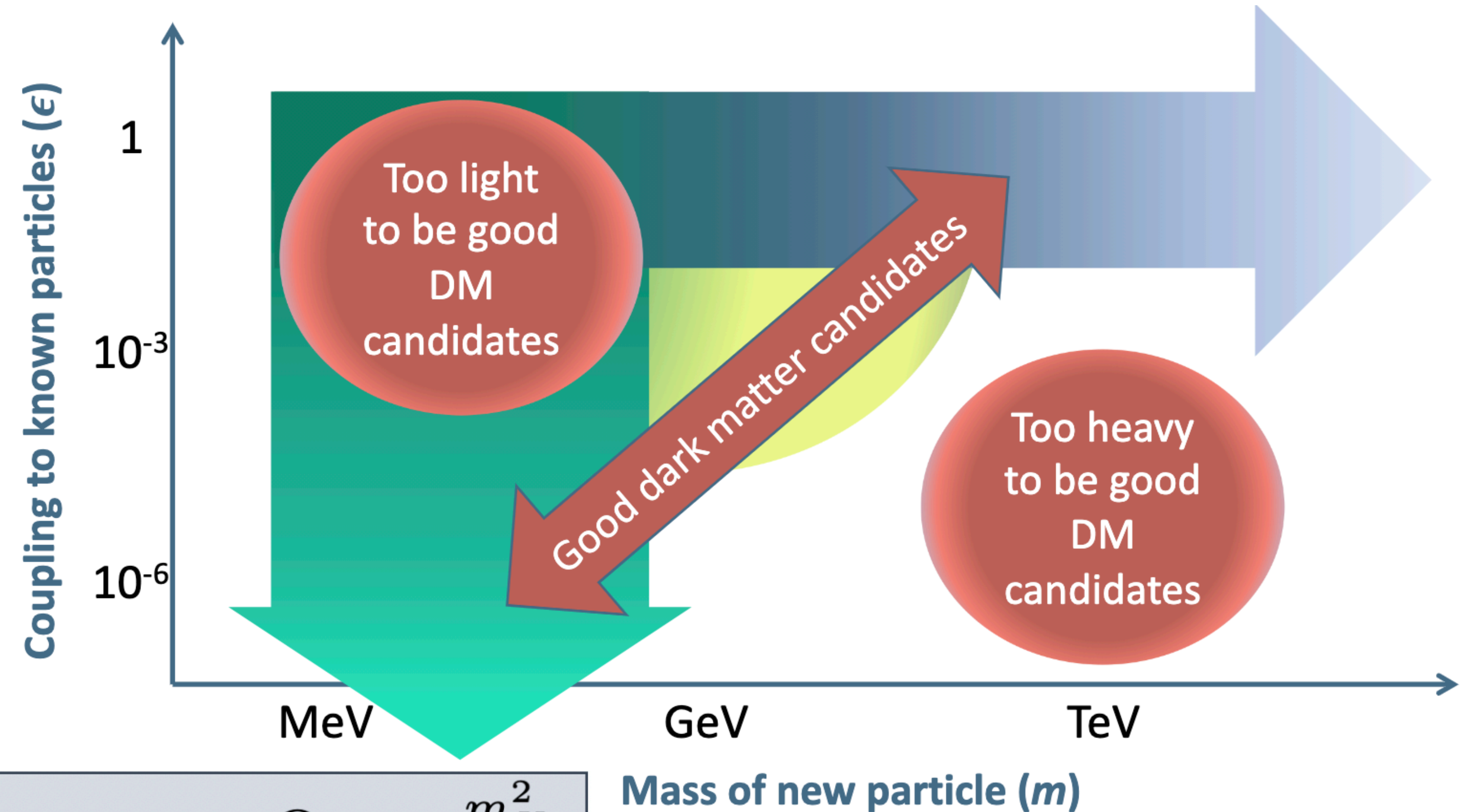


- The indirect observations of **dark matter** offers one of the most tangible indications of BSM physics and strongly motivates closer attention.

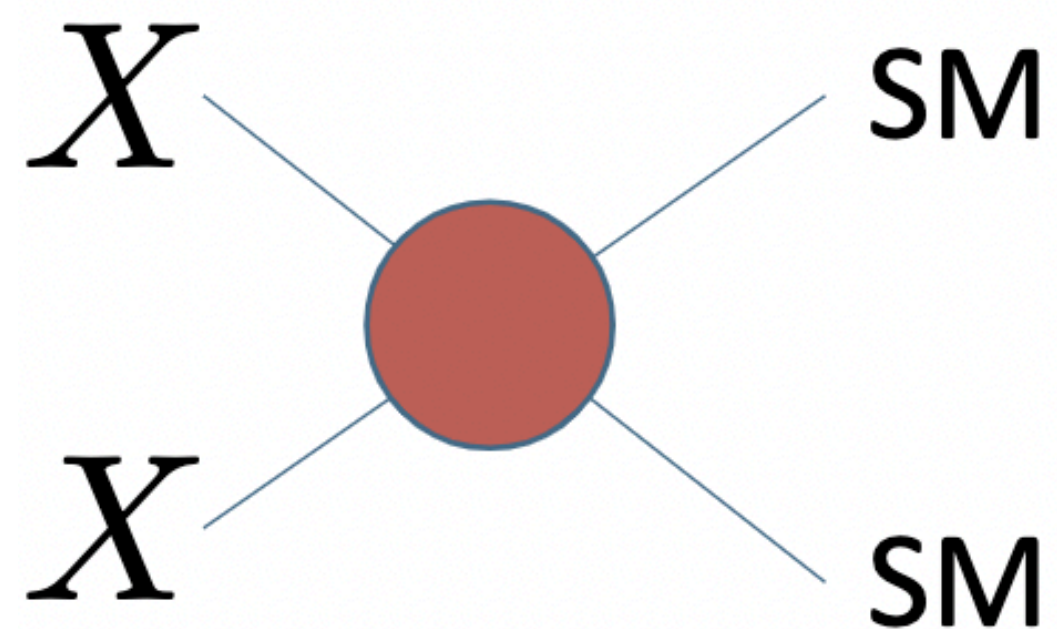


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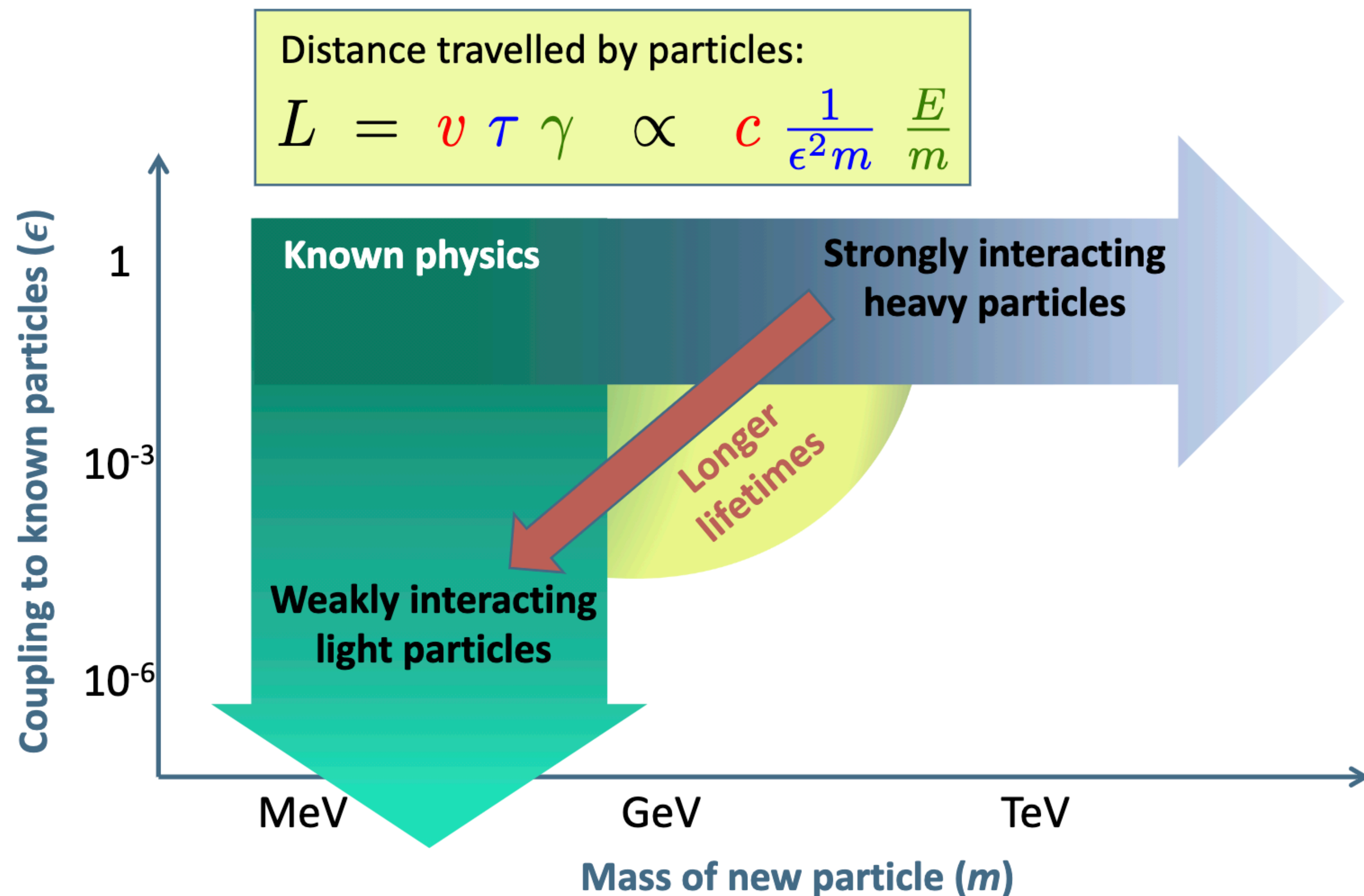
► Main region of interest is for new particles that satisfy DM relic density requirements.



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

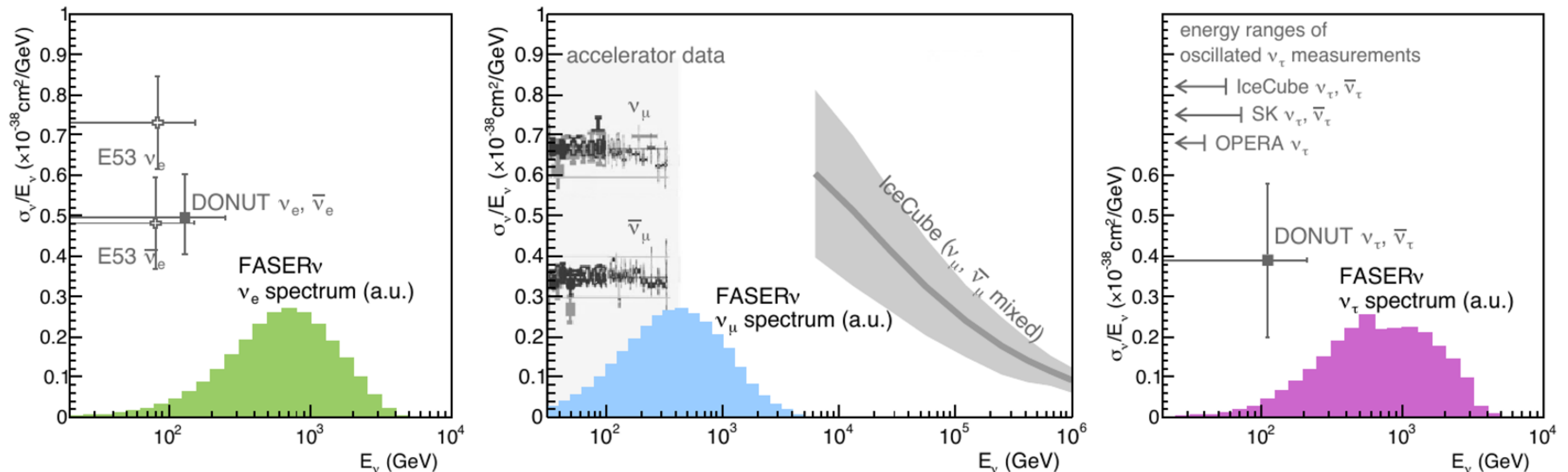


- ▶ One of the defining characteristics of weakly interacting light particles is their **long lifetime**.
- ▶ Distinct signatures
- ▶ Opportunity for exploration!



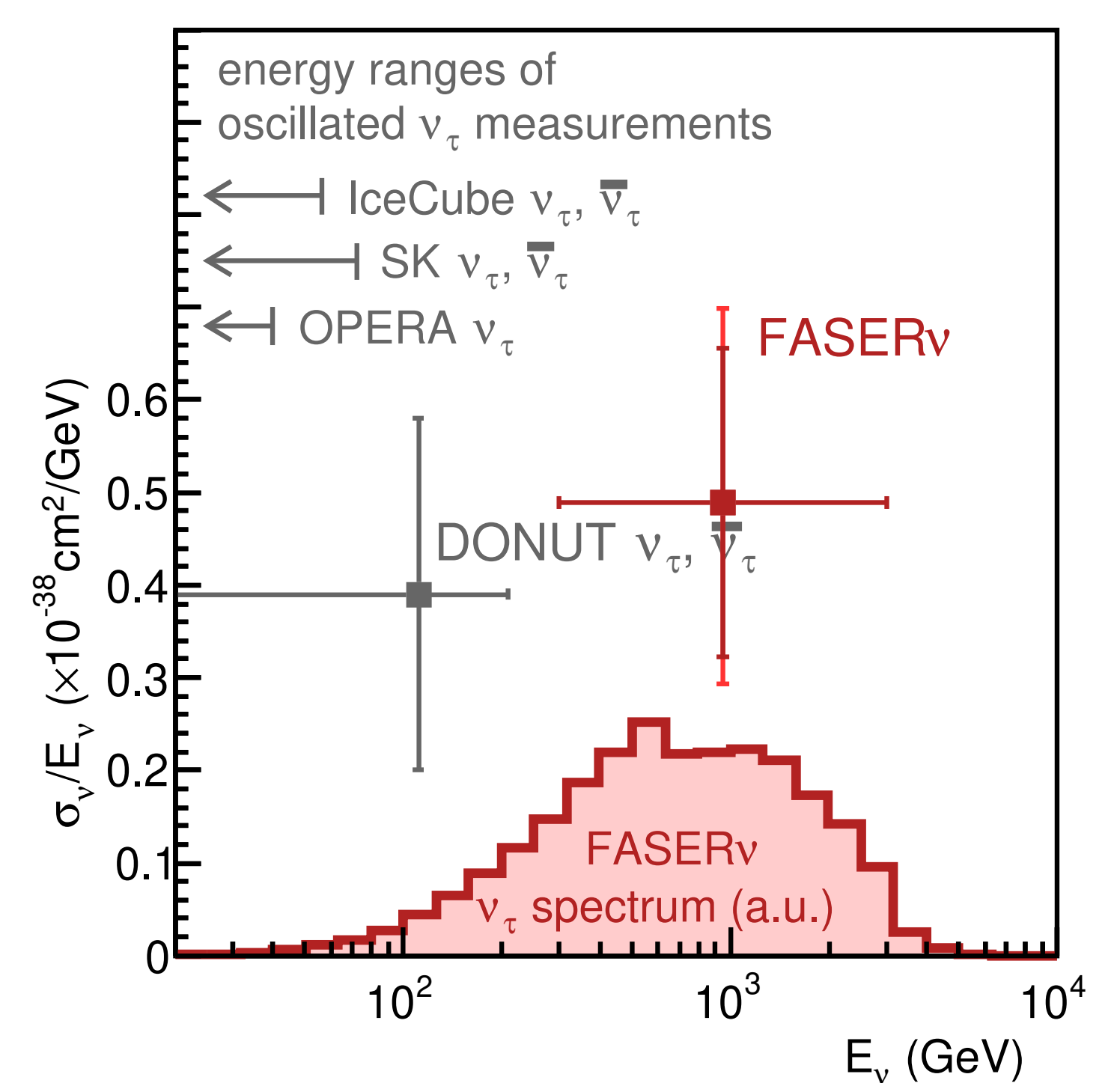
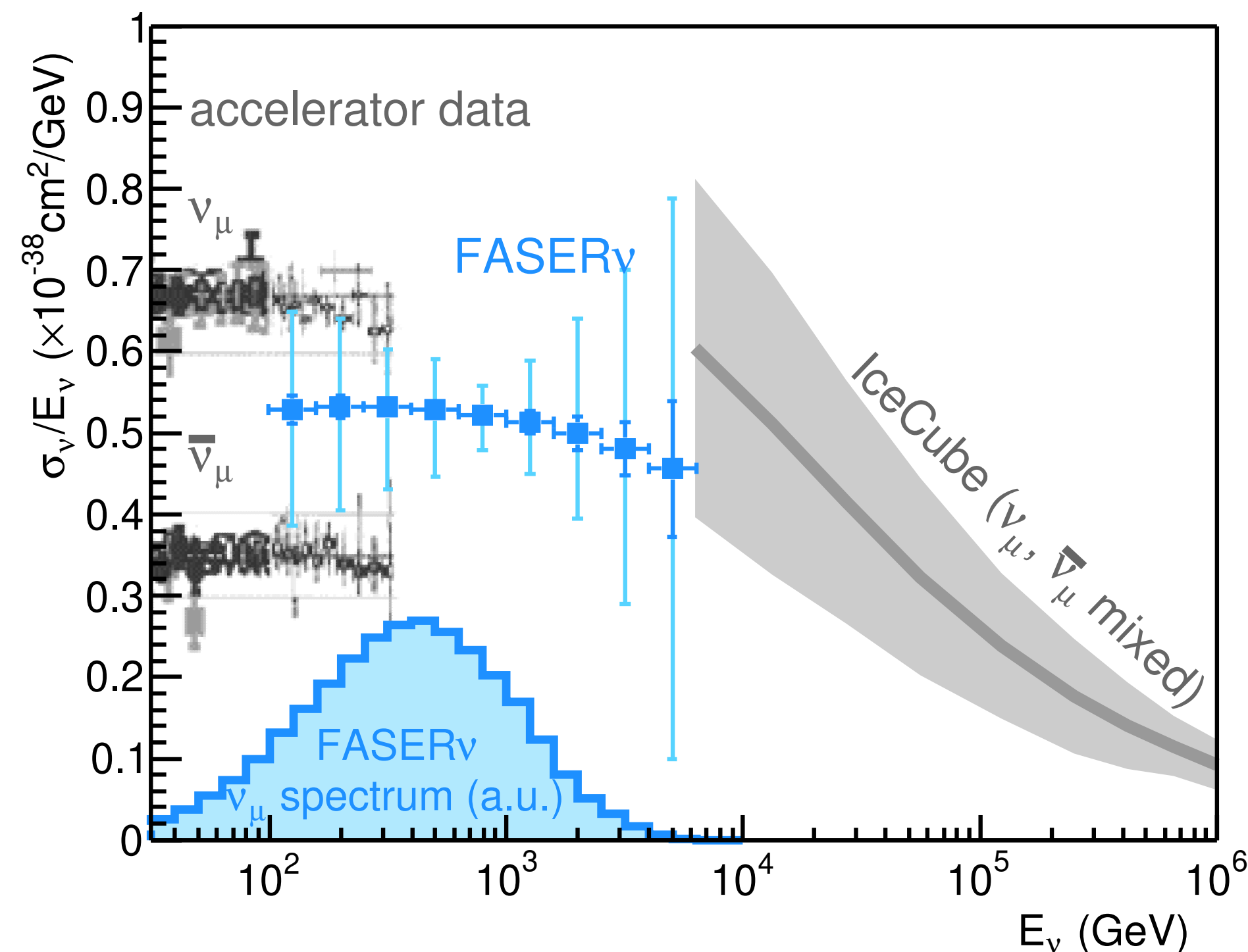
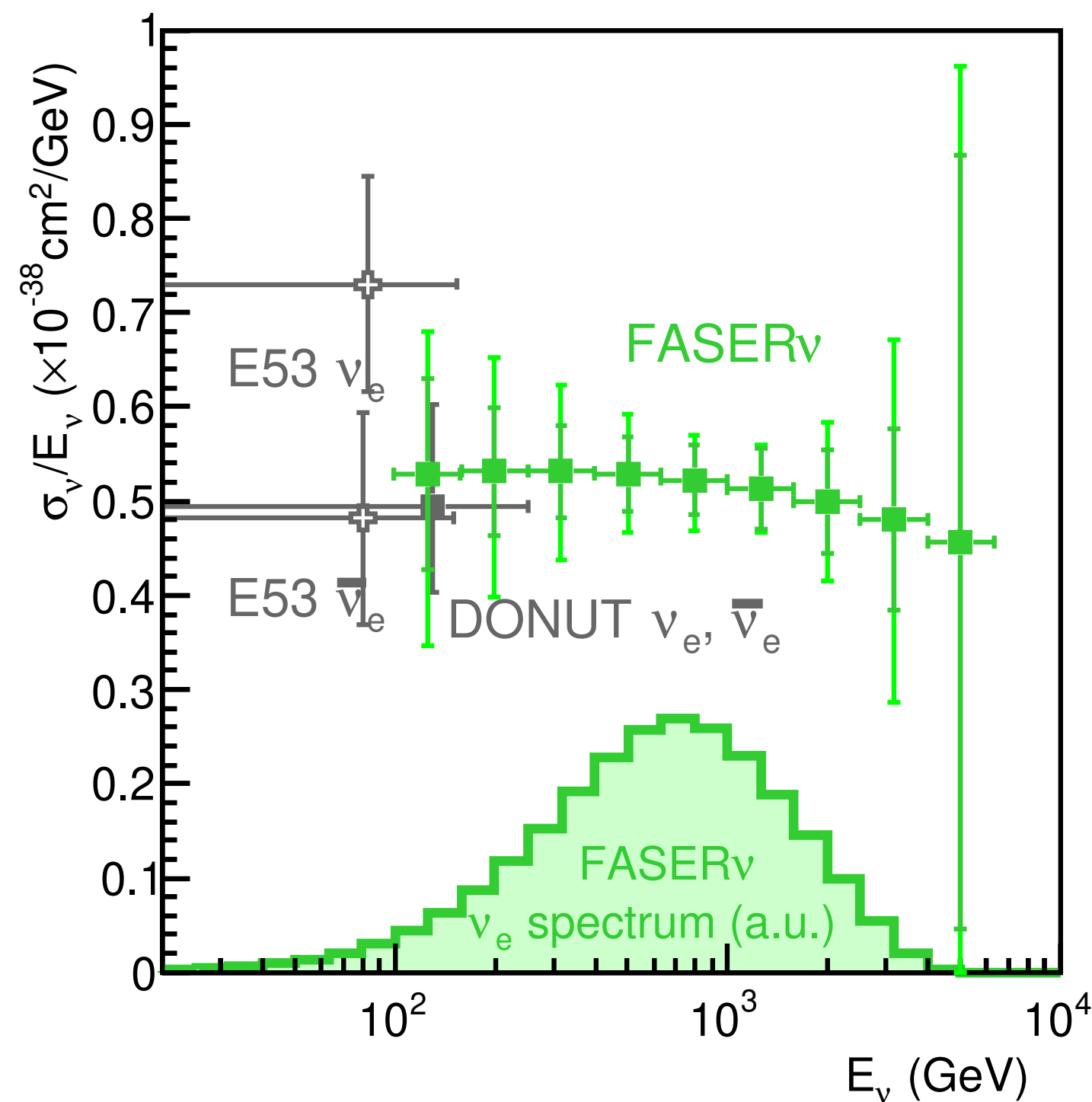
Physics Motivation | Neutrinos

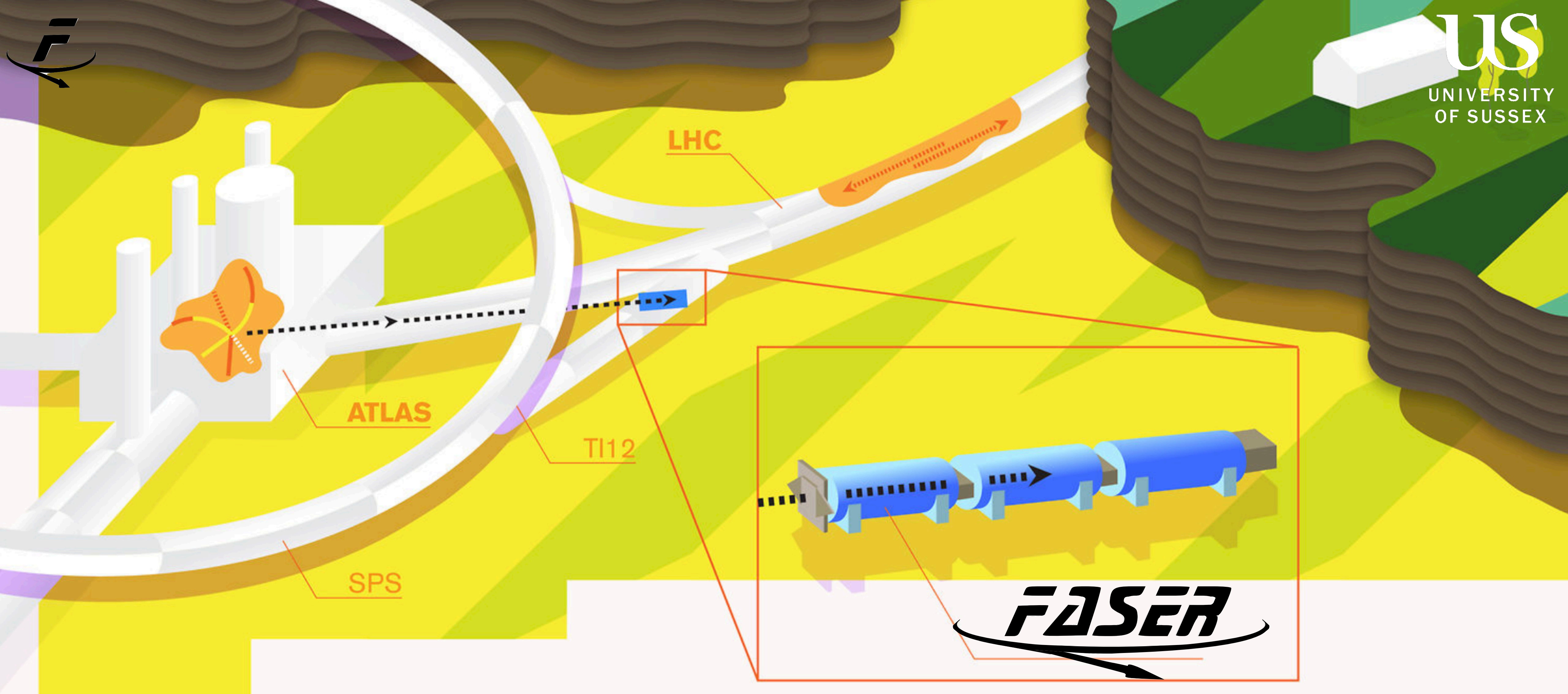
- ▶ Neutrinos produced copiously in decays of forward hadrons
 - ▶ Highly energetic (TeV scale) → high interaction cross section
- ▶ Extends FASER physics program into SM measurements
 - ▶ Targets measurement of highest energy human-made neutrinos
 - ▶ Energy range complementary to existing neutrino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



Physics Motivation | Neutrinos

- ▶ 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





Detector Construction and Operation

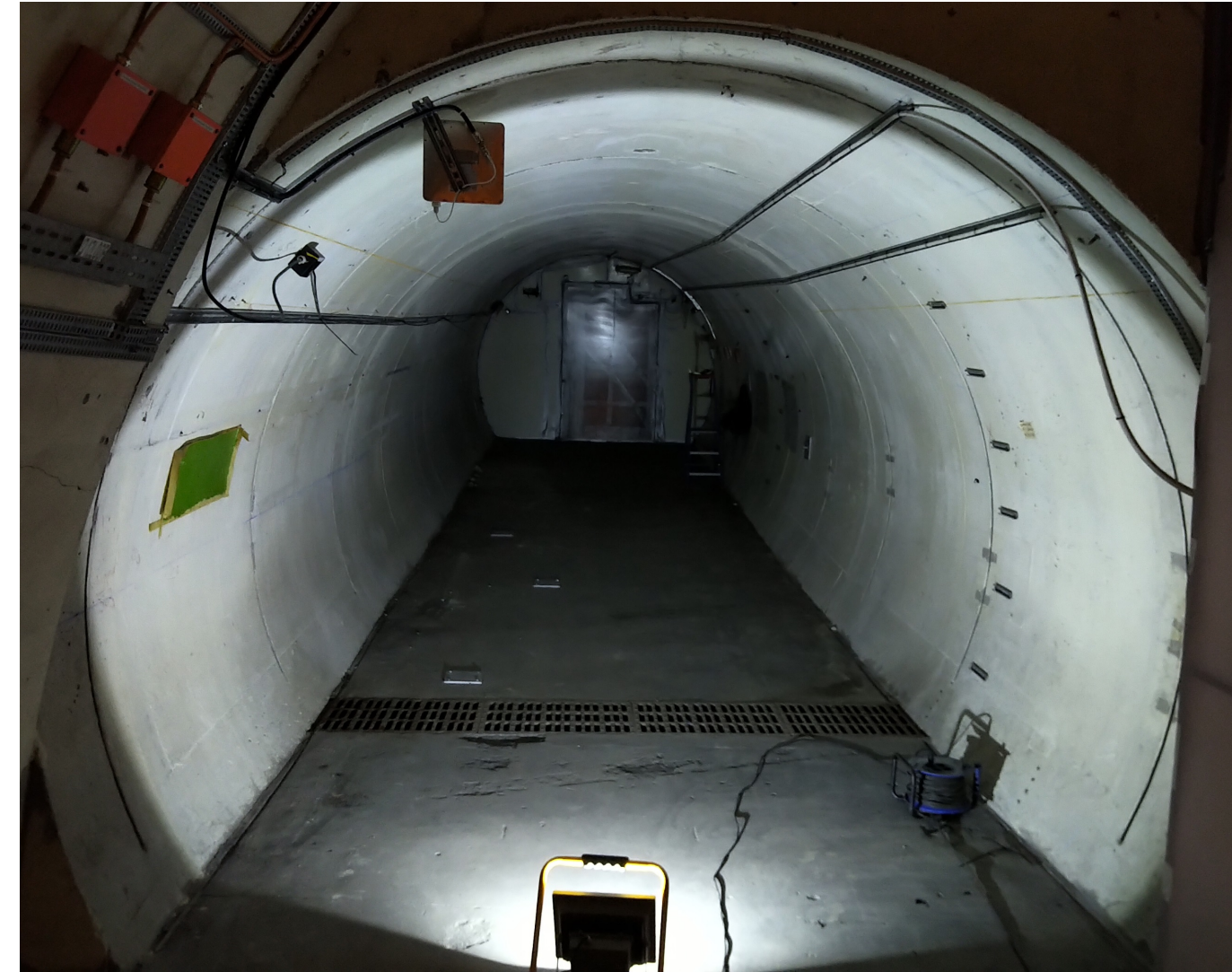
- ▶ Given the very tight timeline between experiment approval and installation & the limited budget we have focused on:
 - ▶ Detector that can be constructed and installed **quickly & cheaply**
 - ▶ Have tried to **re-use existing detector components** where possible
 - ▶ Aimed for a **simple, robust 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



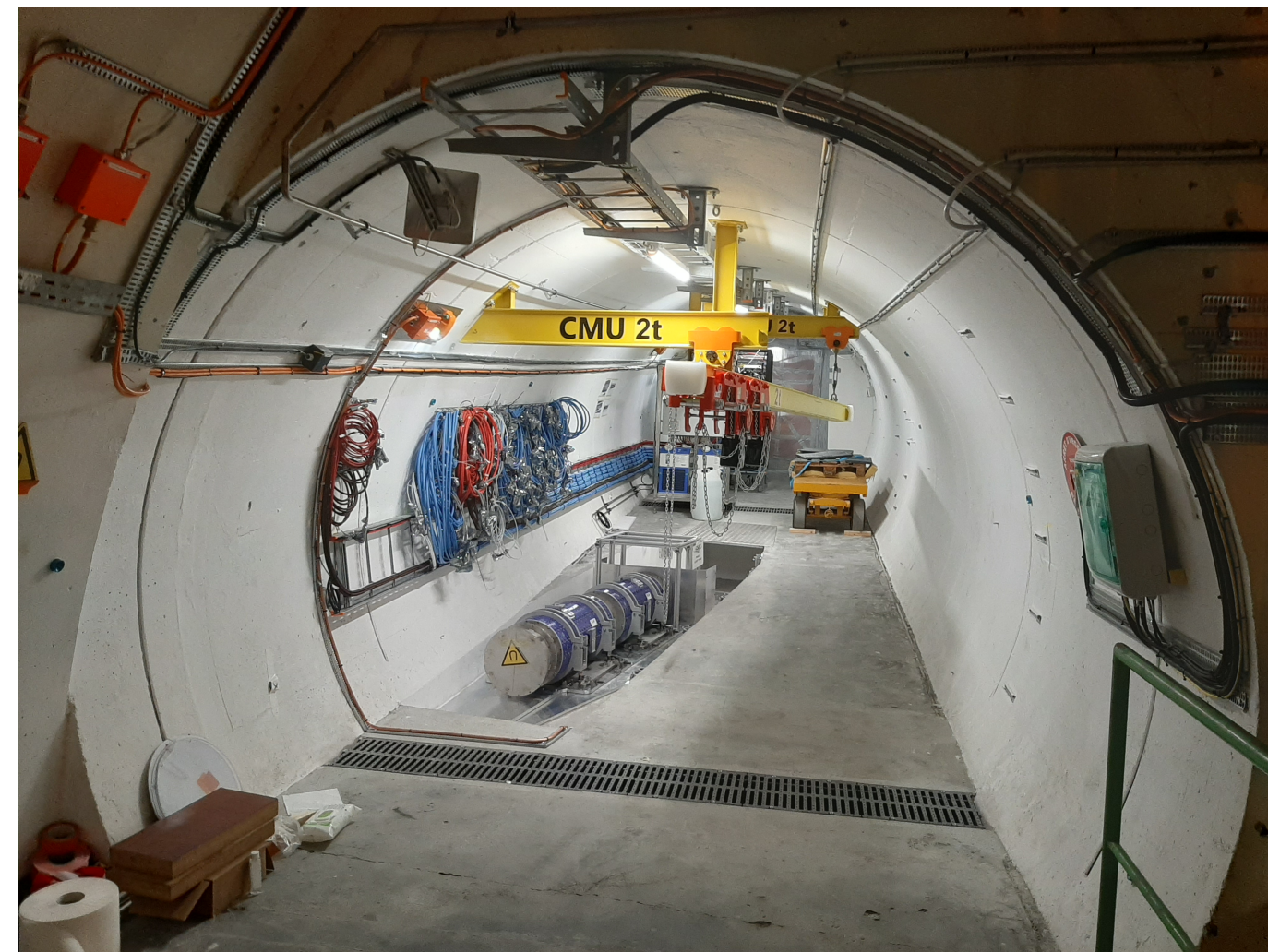
8/2018



8/2019



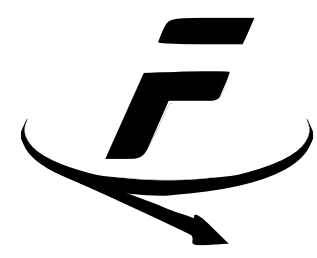
4/2020



11/2020



3/2021



Installation



8/201

11/2020

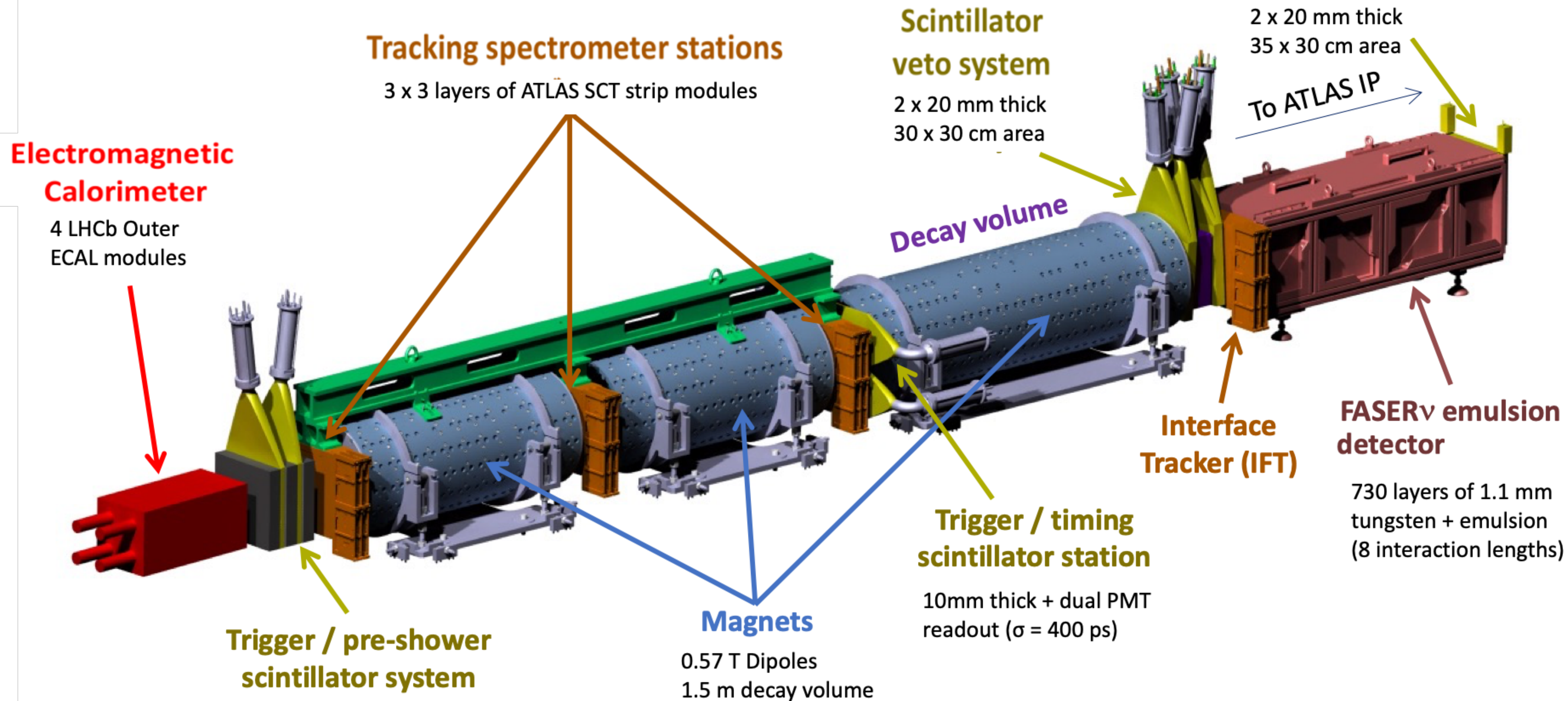
3/2021

Josh McFayden | Warwick | 19/10/2023



Detector design

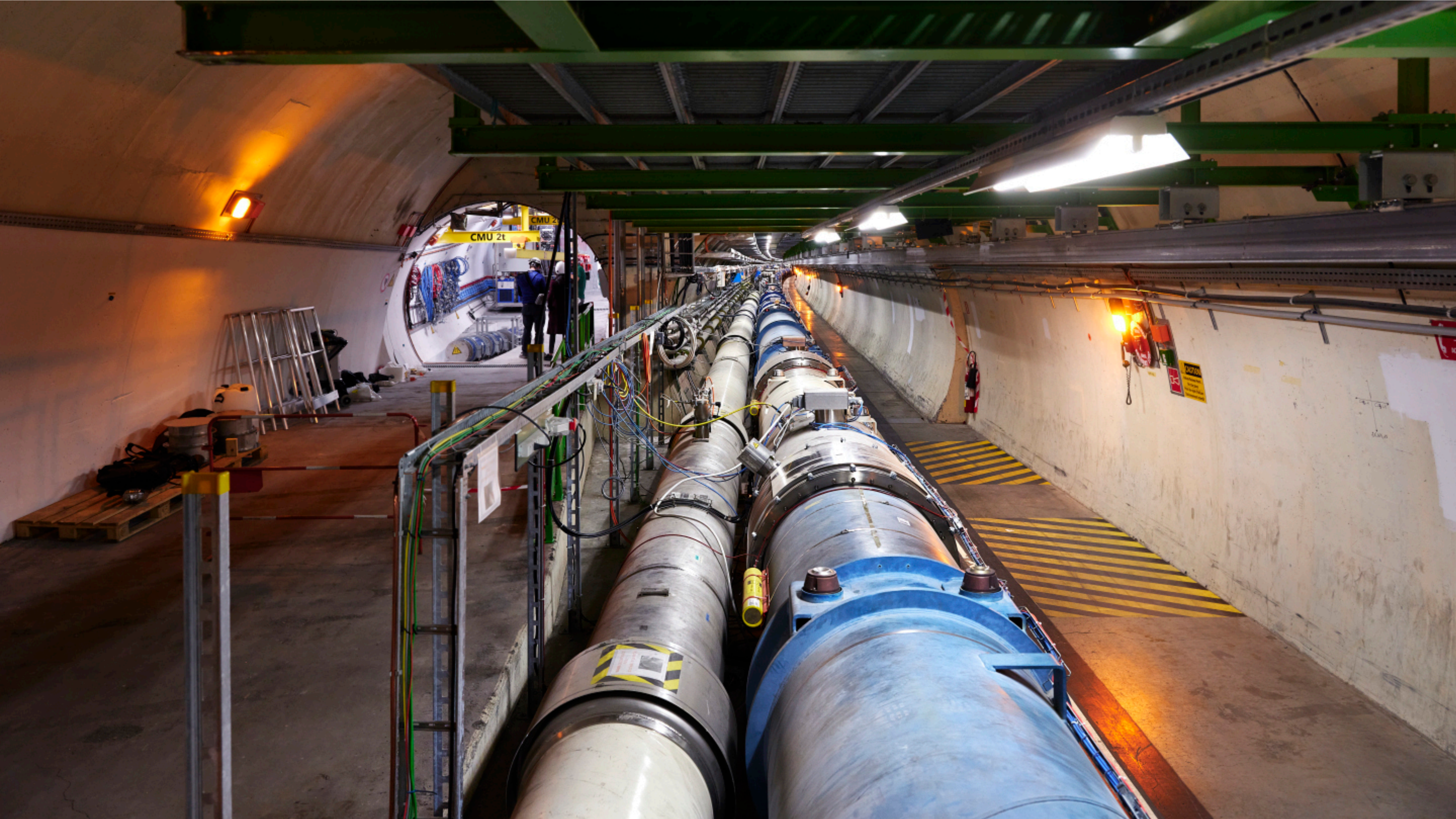
- Small inexpensive design [2207.11427]

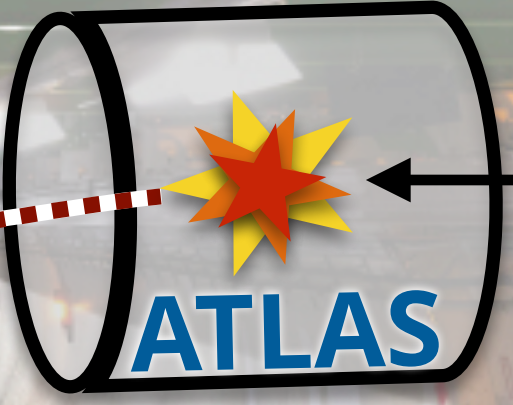




Installation







LHC collision

Long-lived particle

Decay

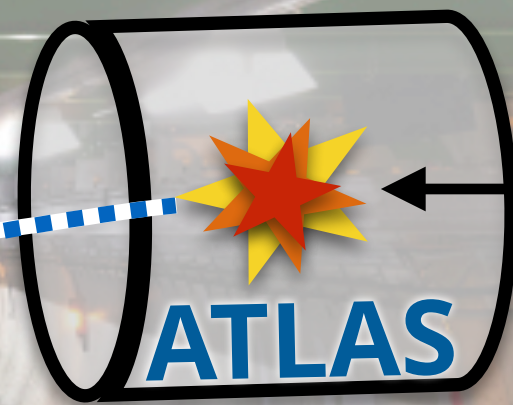
FASER



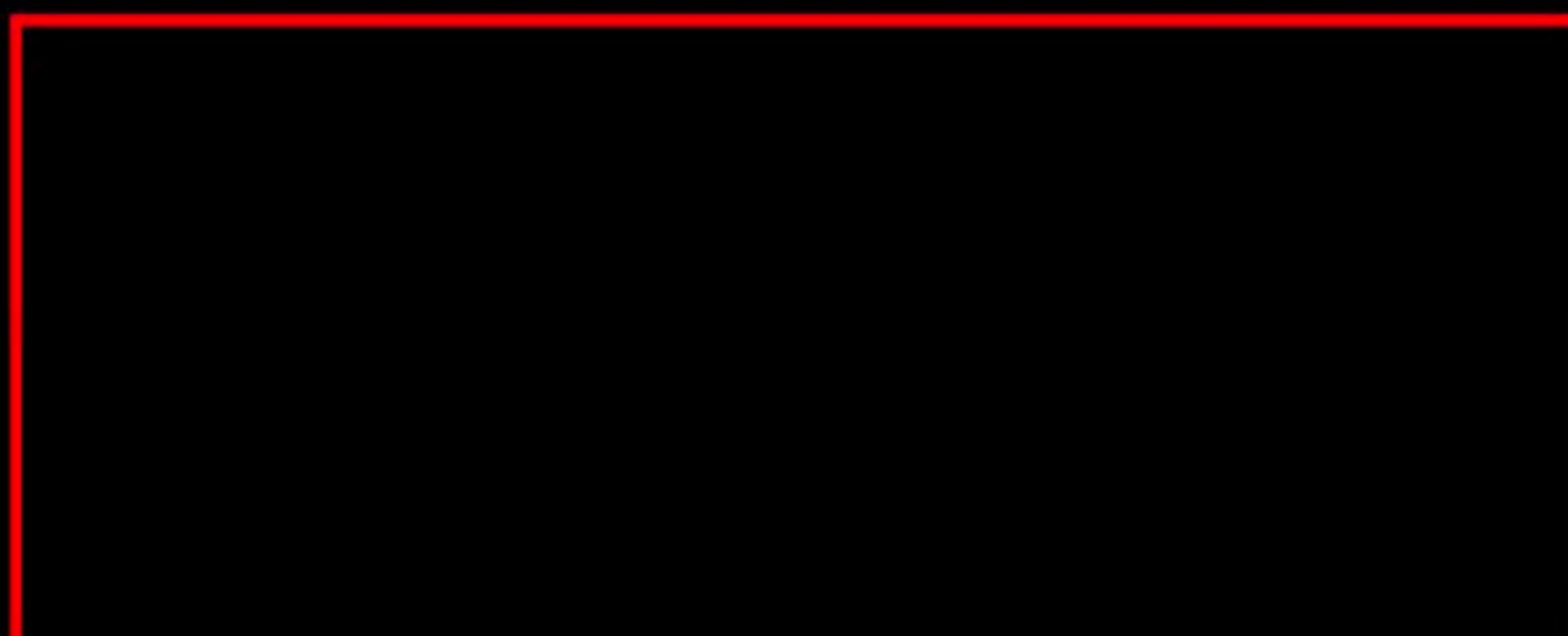
FASER

Interaction

Neutrino



LHC collision

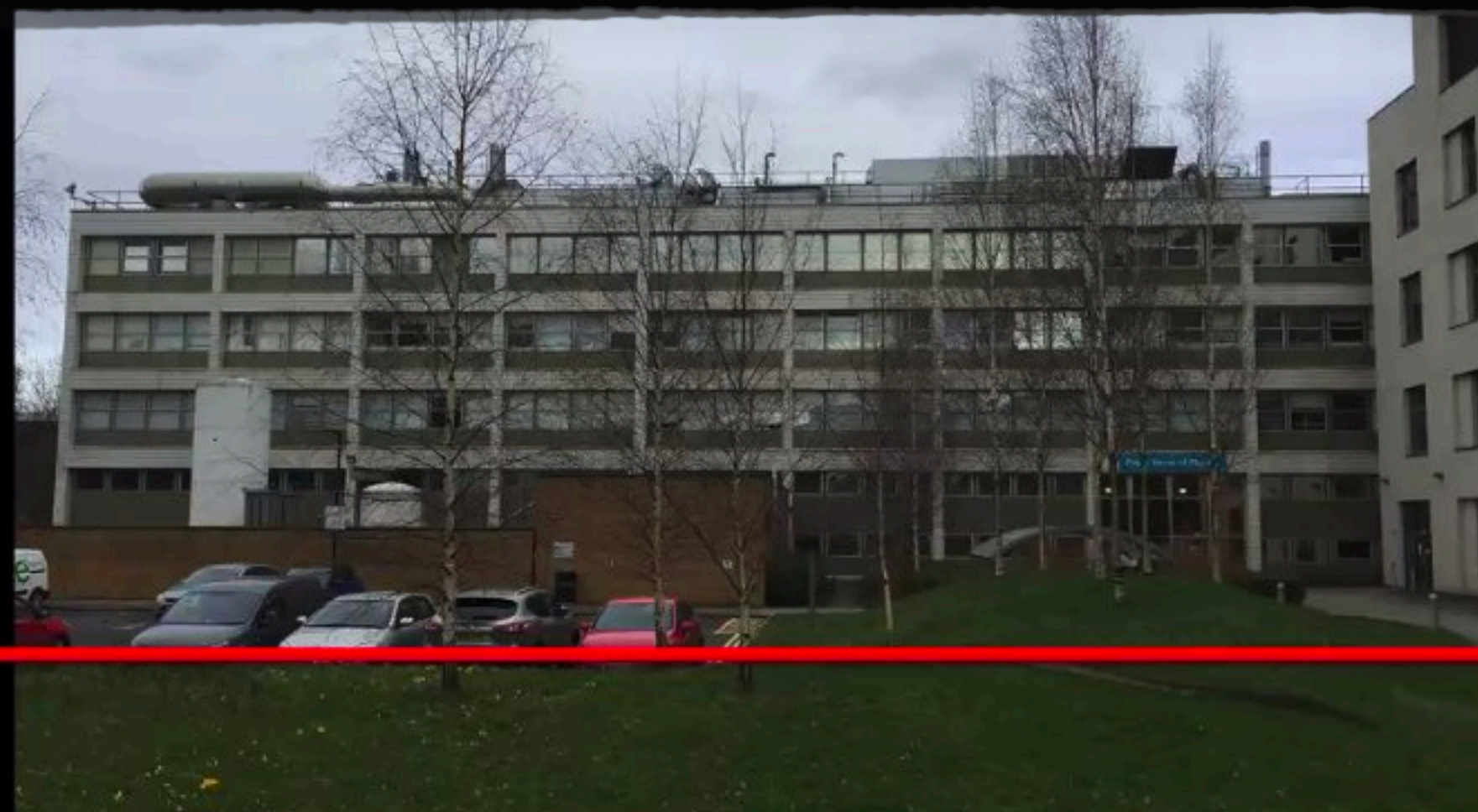


Hyper-K

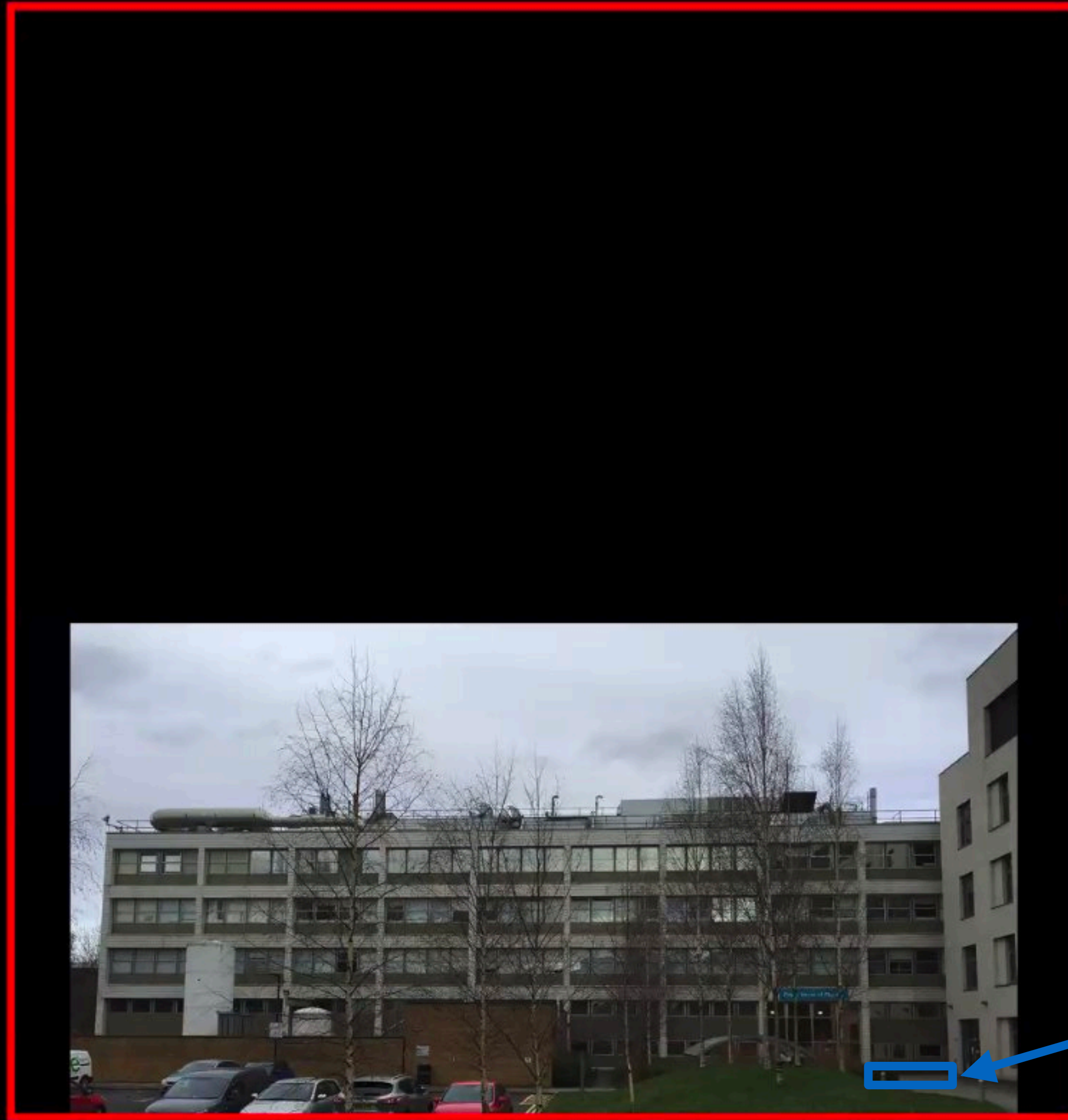


Mika Vesterinen @MikaVesteri · Feb 25

I could never quite grasp the scale of @HyperKamiokande . I just needed to see it next to the @warwickuni physics building 😊



University of Warwick Physics building
(Photo by Ares Osborn)



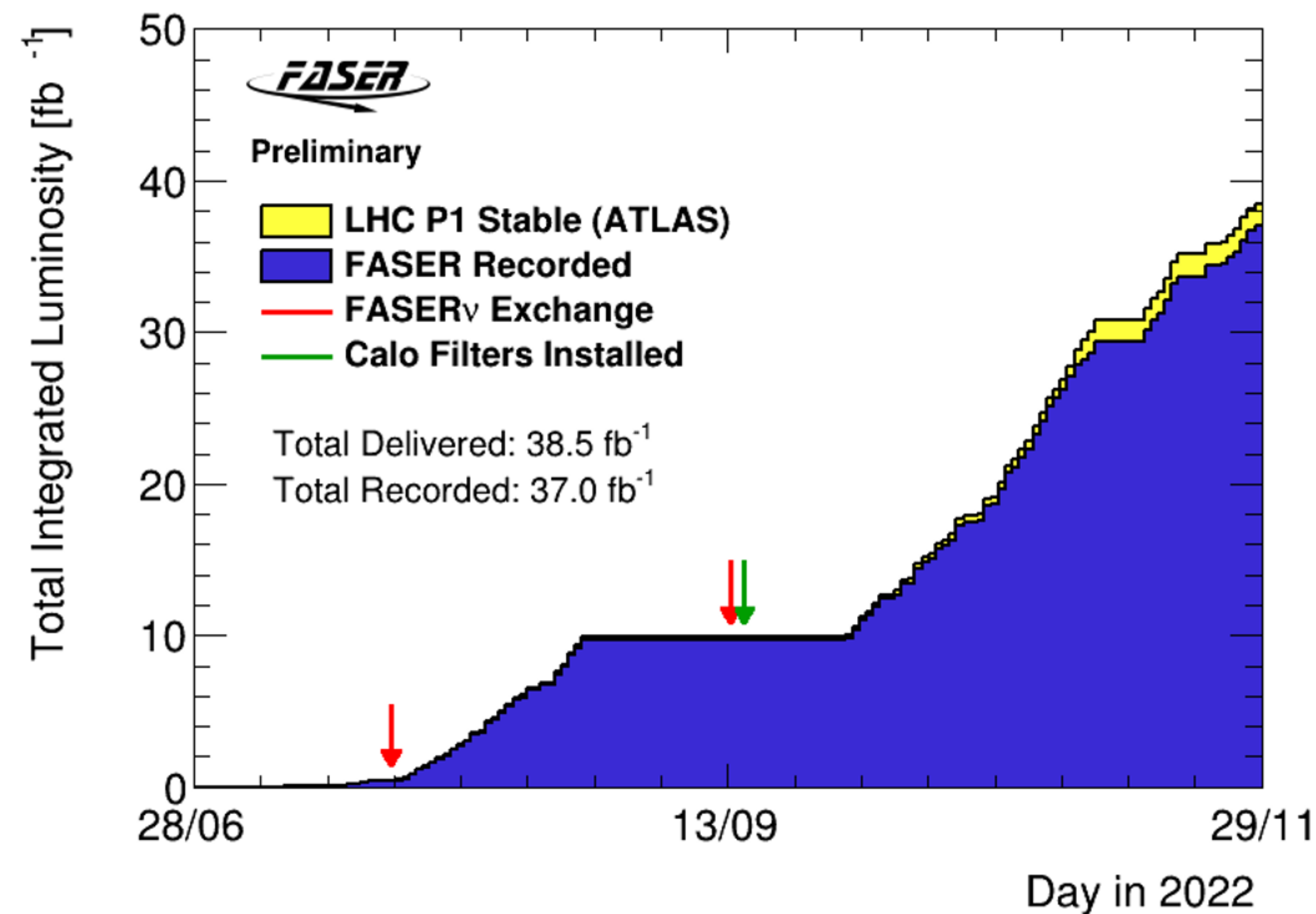
Hyper-K

FASER

University of Warwick Physics building
(Photo by Ares Osborn)

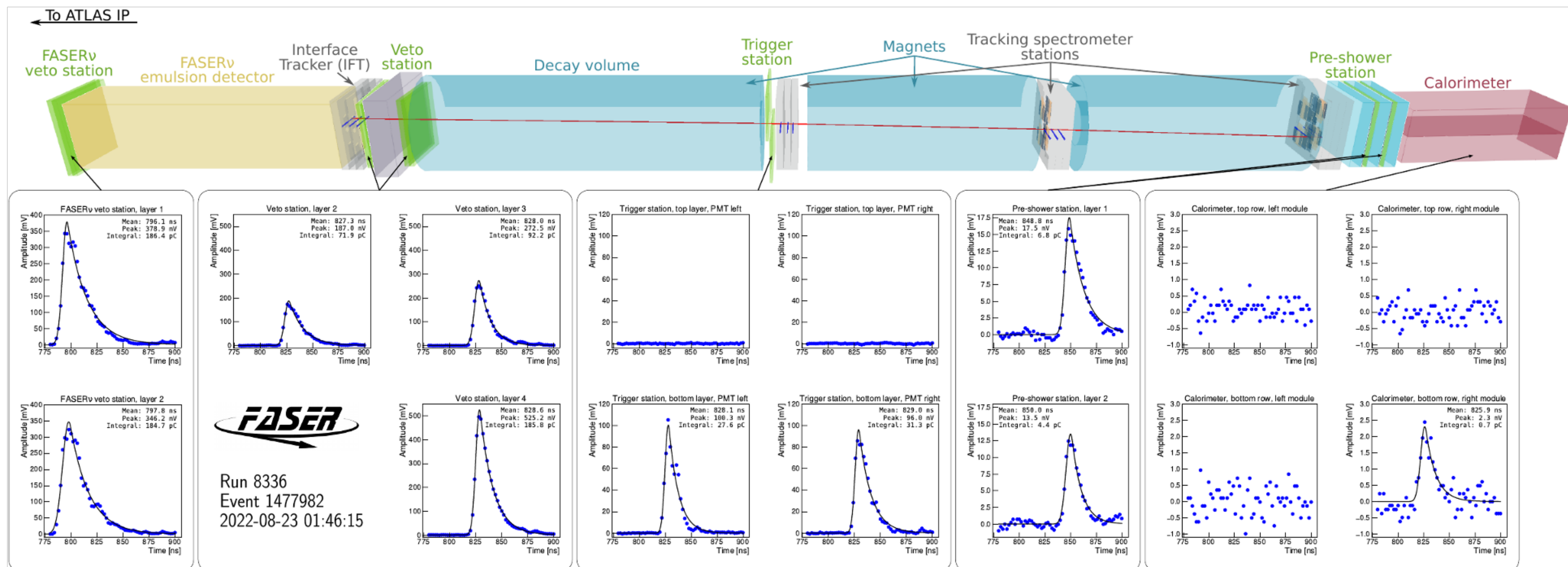
Operations

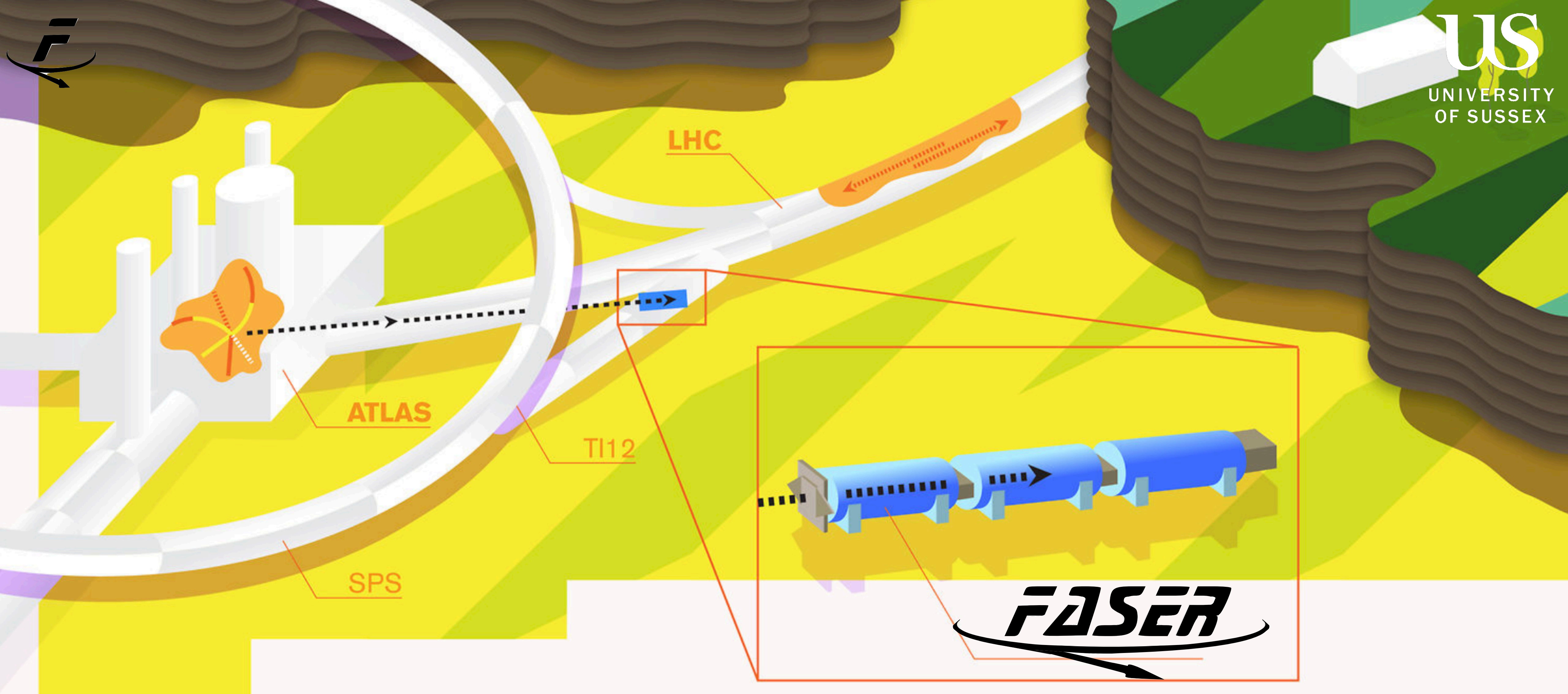
- ▶ Successfully operated throughout 2022
 - ▶ Continuous data taking
 - ▶ Largely automated
 - ▶ Up to 1.3 kHz
- ▶ Recorded 96.1% of delivered lumi.
 - ▶ DAQ dead-time of 1.3%
 - ▶ couple of DAQ crashes
- ▶ Emulsion detector exchanged twice
 - ▶ Needed to manage occupancy
 - ▶ First box only partially 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

- ▶ 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 man-made neutrinos
 - ▶ Energy range complementary to existing neutrino experiments

For 35 fb ⁻¹	ν_e	ν_μ	ν_τ
Main source	Kaons	Pions	Charm
# traversing FASERv	$\sim 10^{10}$	$\sim 10^{11}$	$\sim 10^8$
# interacting in FASERv	≈ 200	≈ 1200	≈ 4

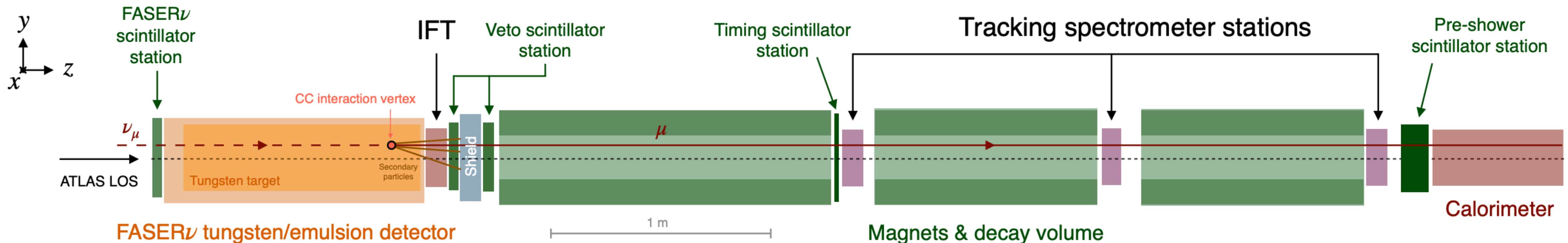
[[PRD 104, 113008](#)]

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

Neutrino analysis | Selection

[2303.14185]

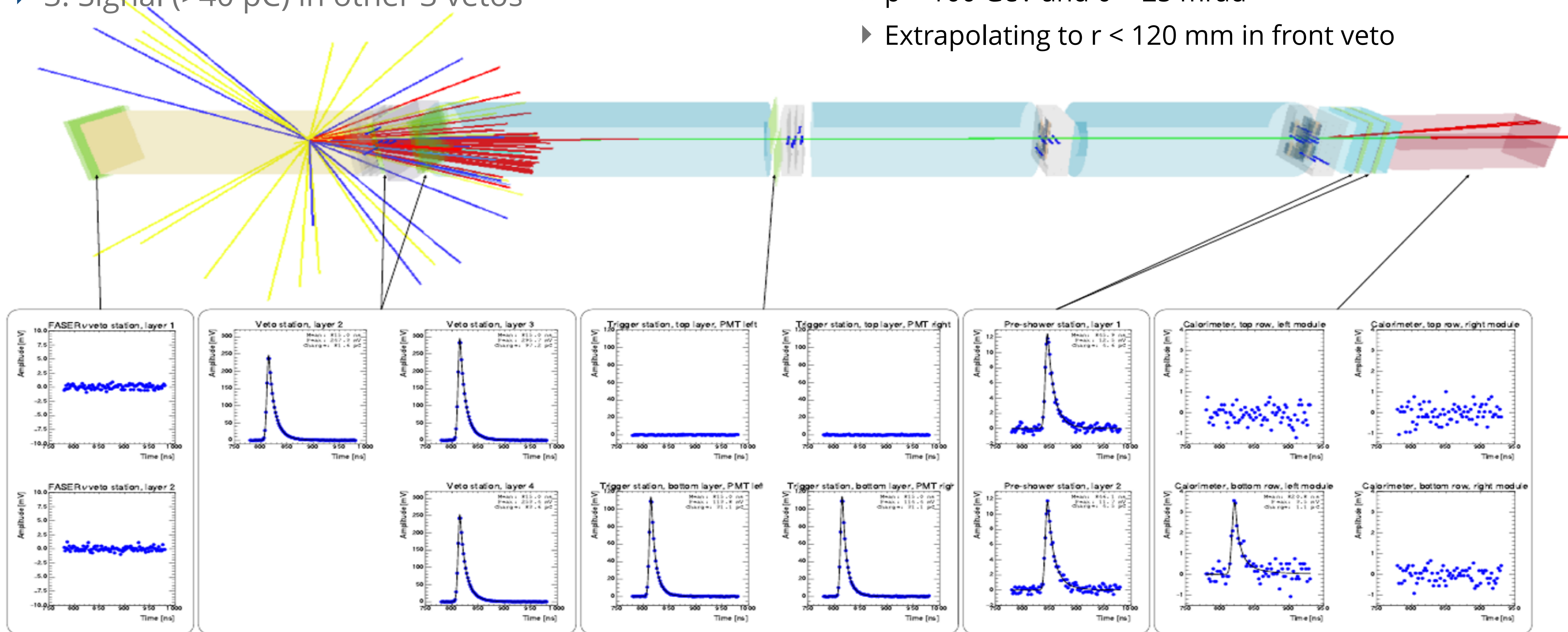
- ▶ 1. Collision event with good data quality
- ▶ 2. No signal (<40 pc) in 2 front vetos
- ▶ 3. Signal (>40 pC) in other 3 vetos
- ▶ 4. Timing and preshower consistent with ≥ 1 MIP
- ▶ 5. Exactly 1 good fiducial ($r < 95$ mm) track
 - ▶ $p > 100$ GeV and $\theta < 25$ mrad
 - ▶ Extrapolating to $r <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



Neutrino analysis | Selection

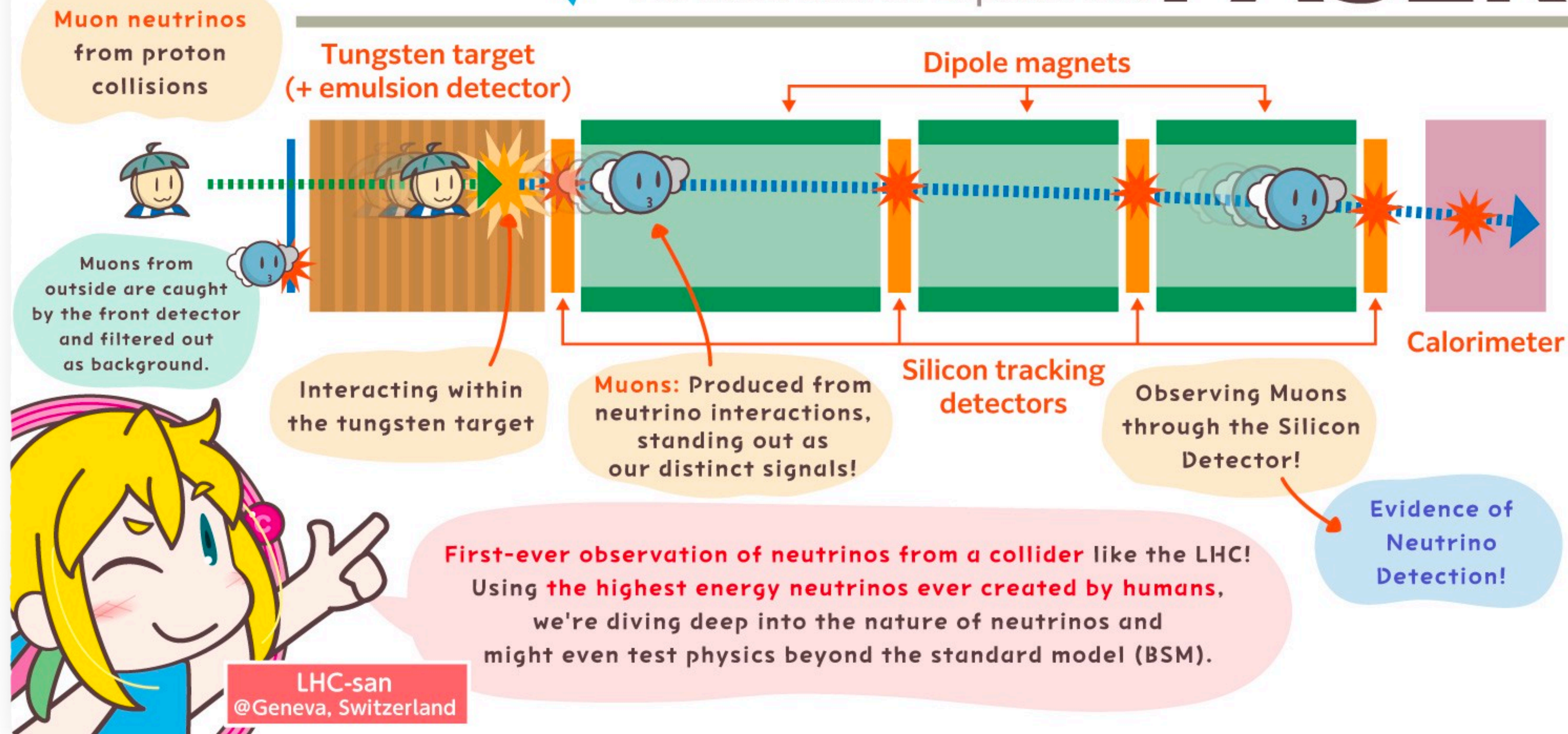
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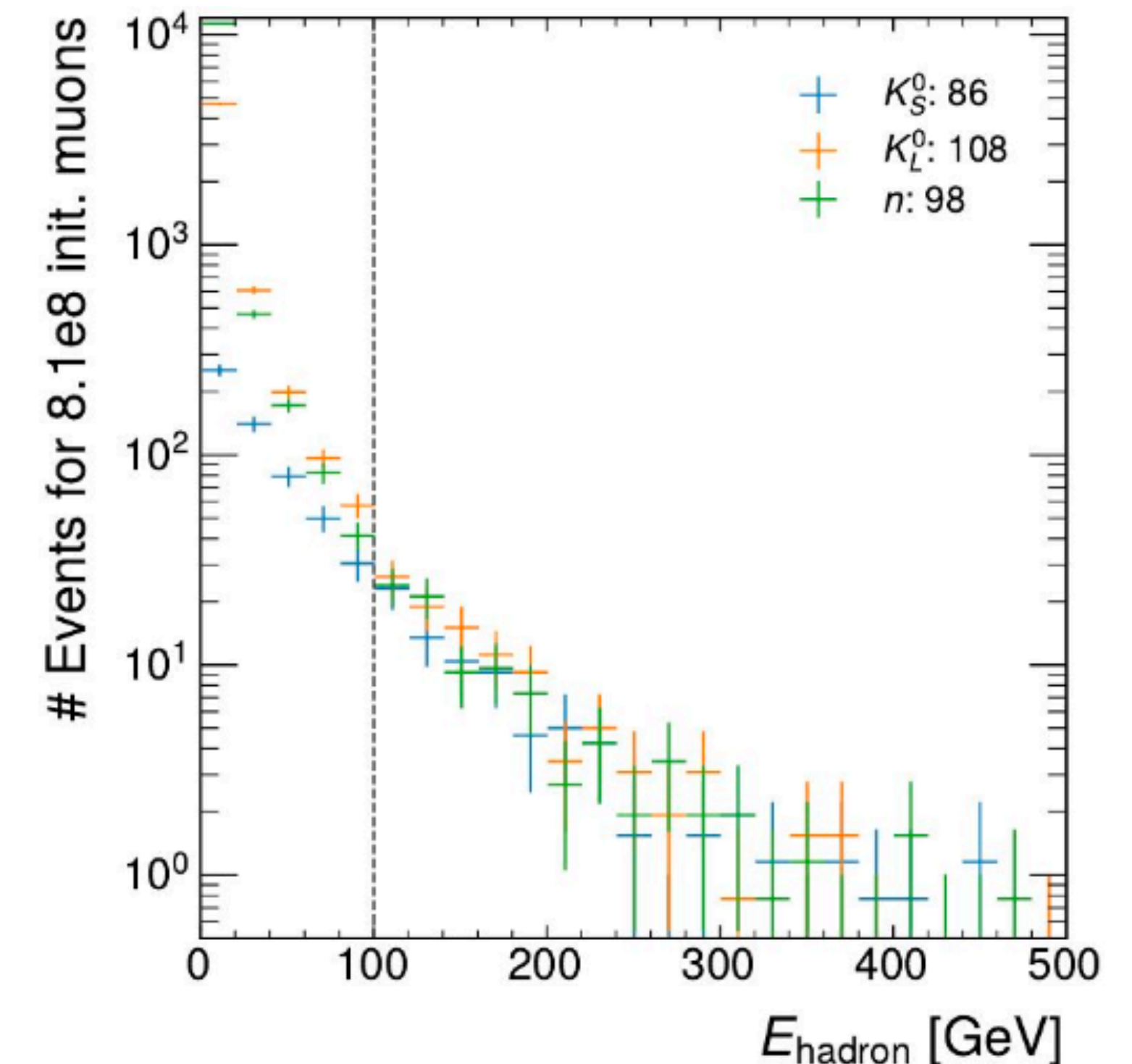
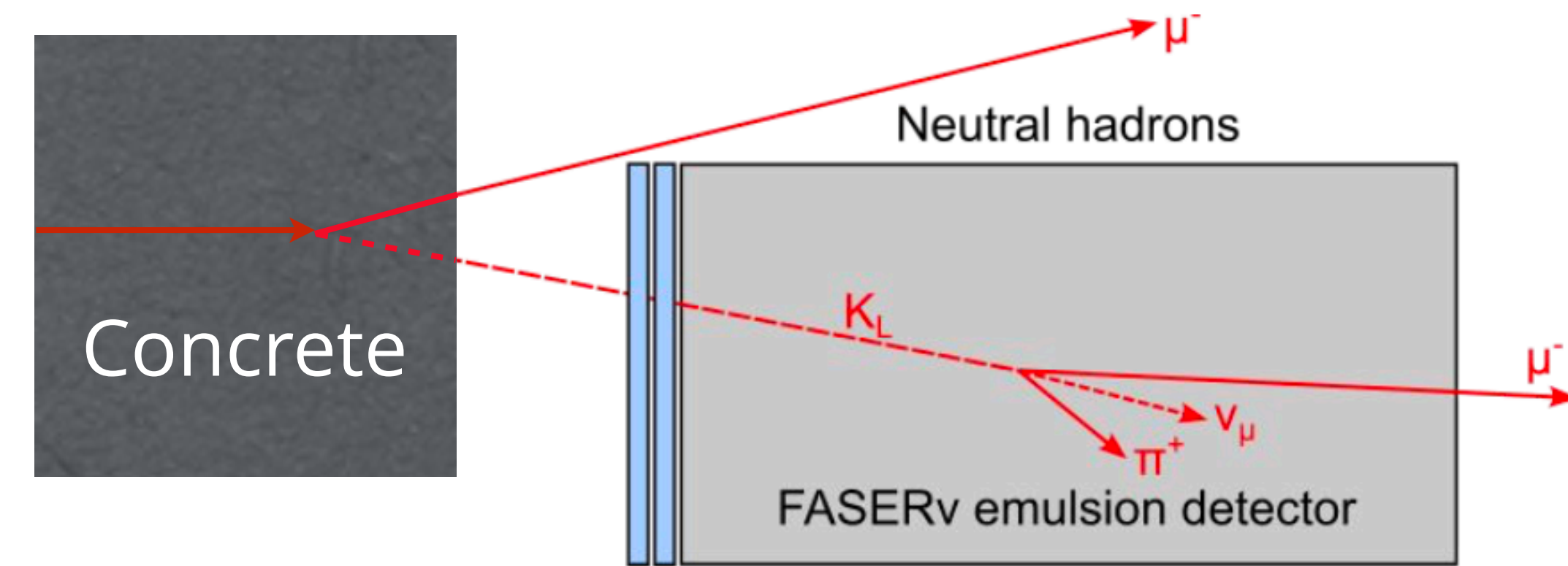
FASER

ForwArd Search ExpeRiment

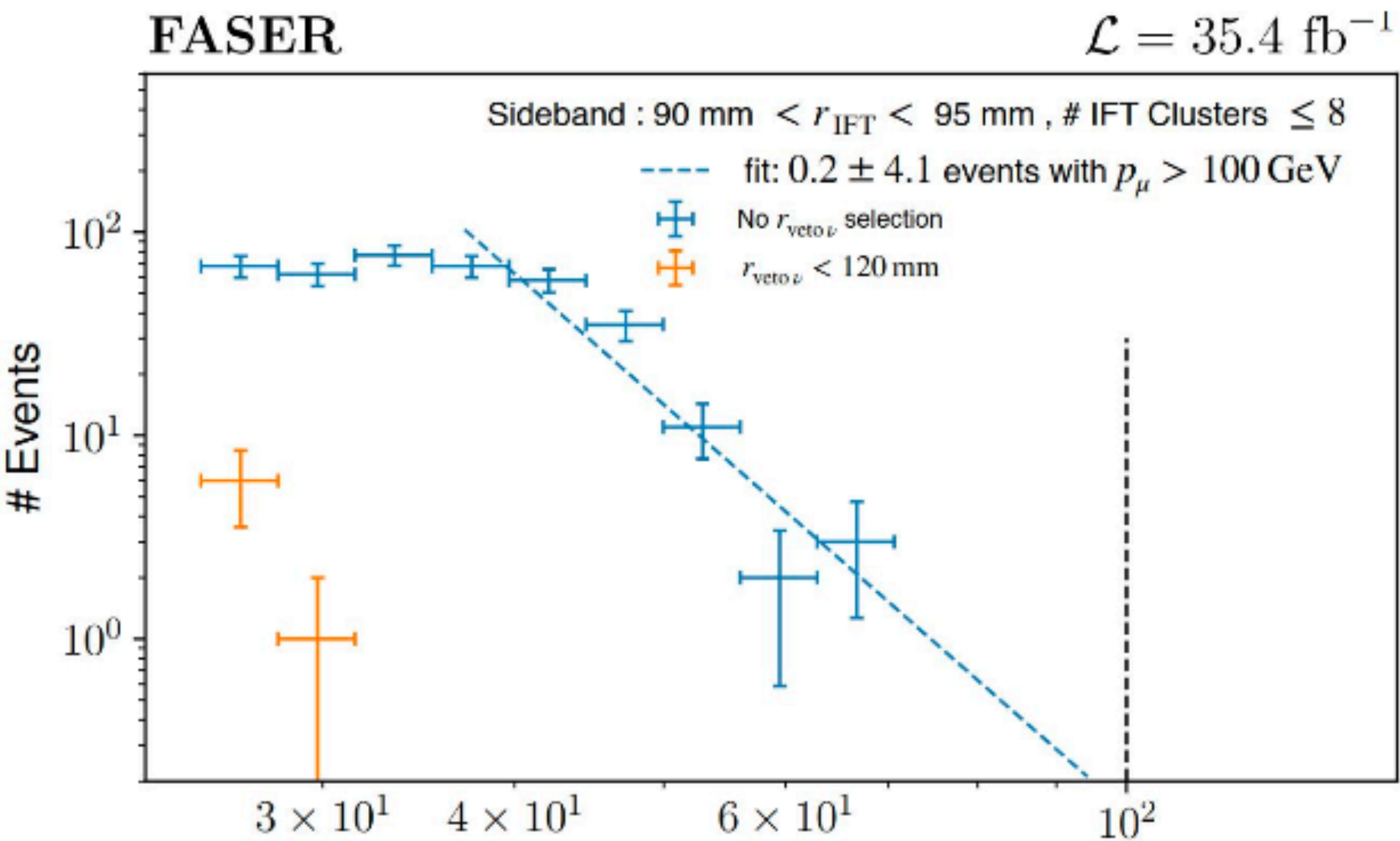
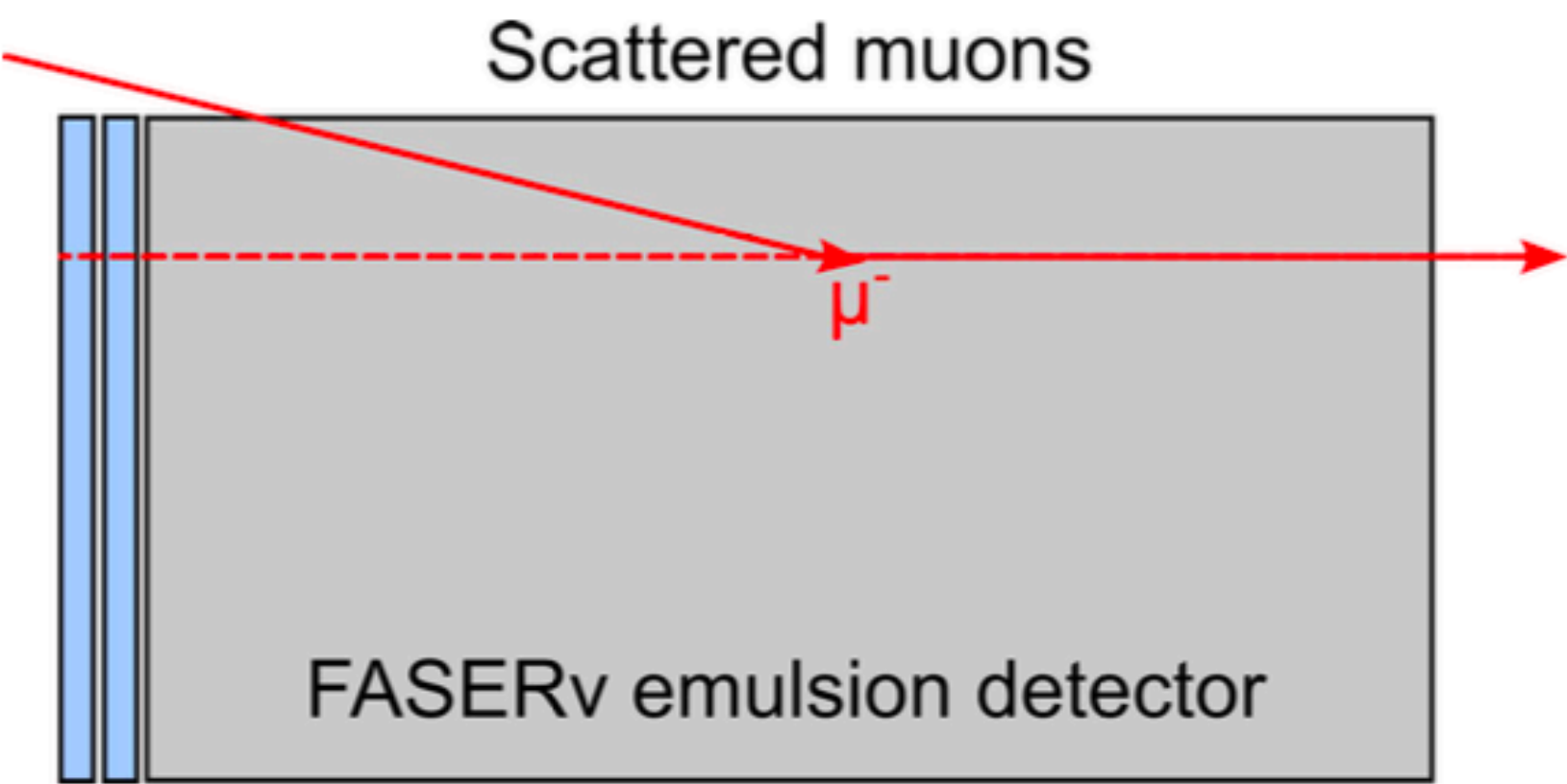


► Neutral hadrons

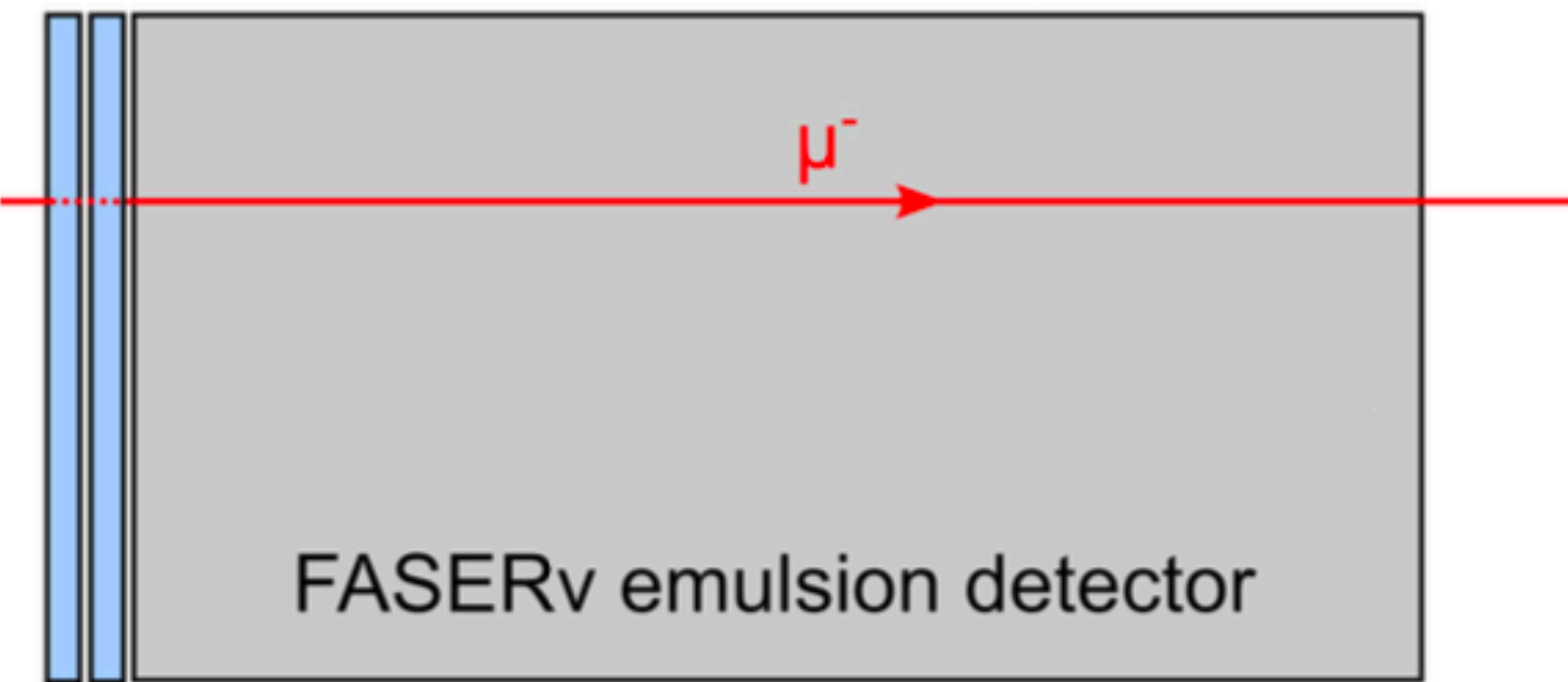
- Estimated from 2-step simulation
- Expect ~300 neutral hadrons with $E > 100$ GeV reaching FASERv
- Most accompanied by μ but conservatively assume missed
- Estimate fraction of these passing event selection
- Most are absorbed in tungsten with no high-momentum track
- Predict $N = 0.11 \pm 0.06$ events



- ▶ 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 $N = 0.08 \pm 1.83$ events
 - ▶ Uncertainty from varying selection



- ▶ 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



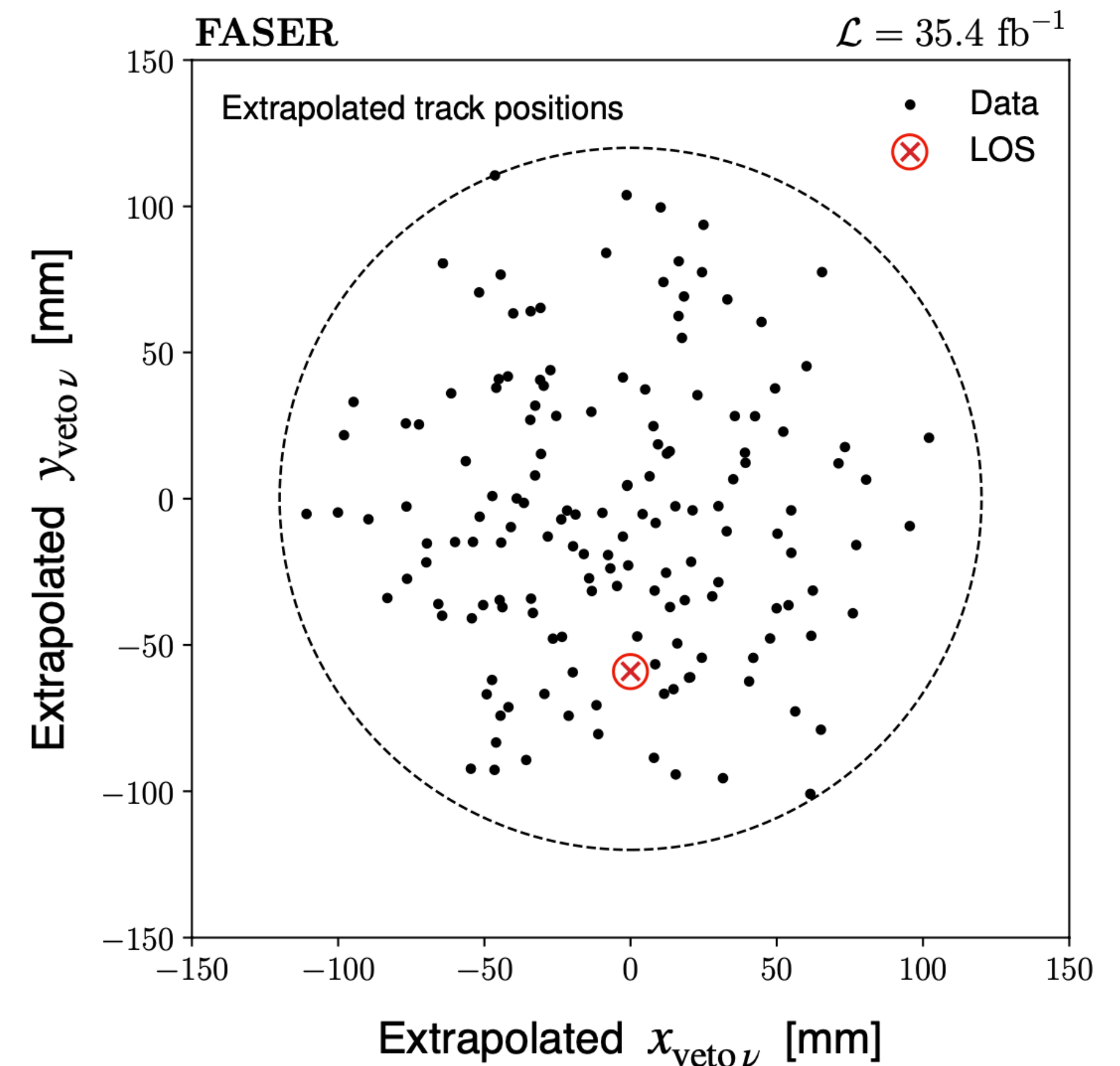
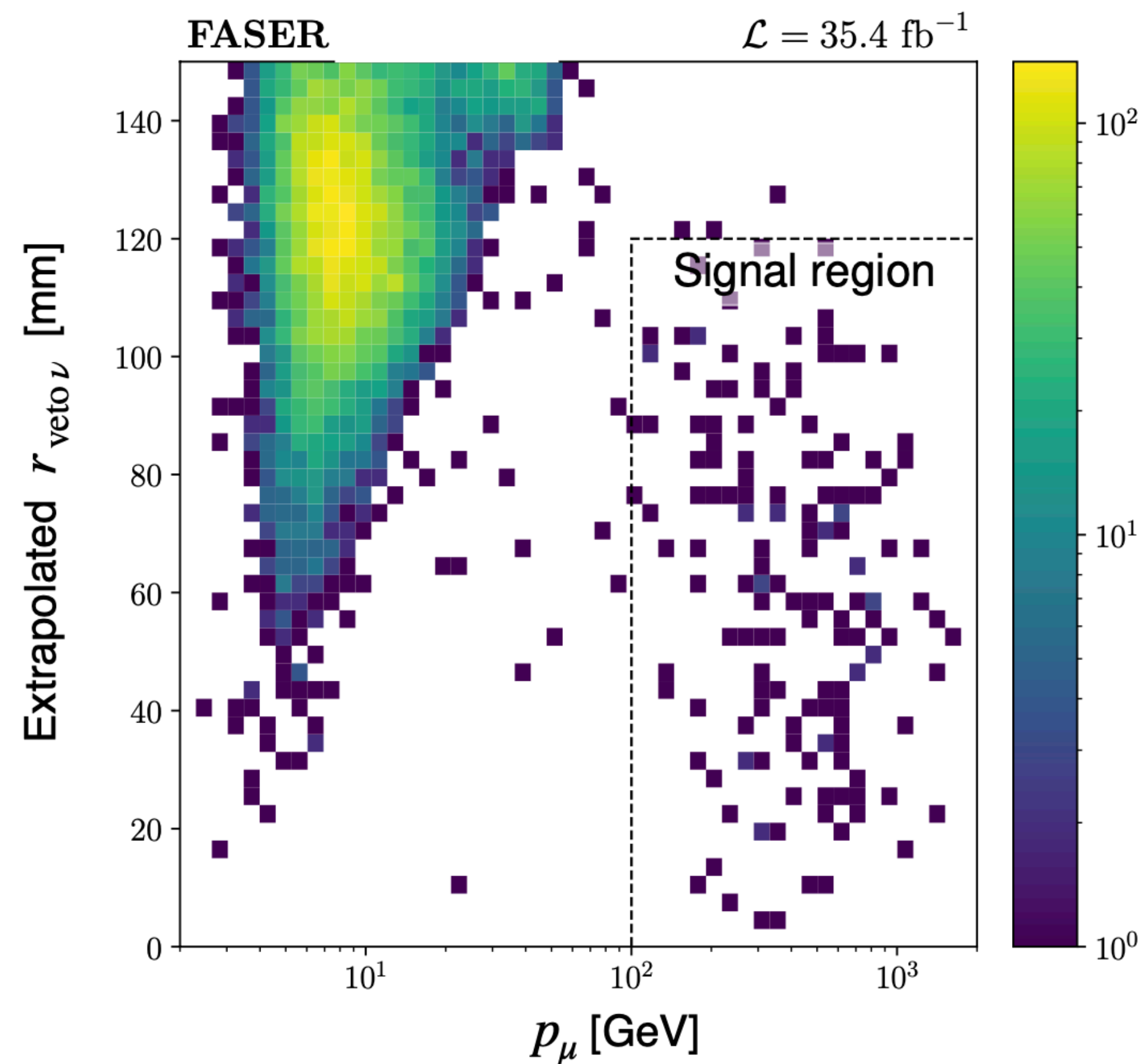
Category	Events	Expectation
Signal		$n_\nu + n_b \cdot p_1 \cdot p_2 + n_{\text{had}} + n_{\text{geo}} \cdot f_{\text{geo}}$
n_{10}	4	$n_b \cdot (1 - p_1) \cdot p_2$
n_{01}	6	$n_b \cdot p_1 \cdot (1 - p_2)$
n_2	64014695	$n_b \cdot (1 - p_1) \cdot (1 - p_2)$

Neutrino analysis | Results

[2303.14185]

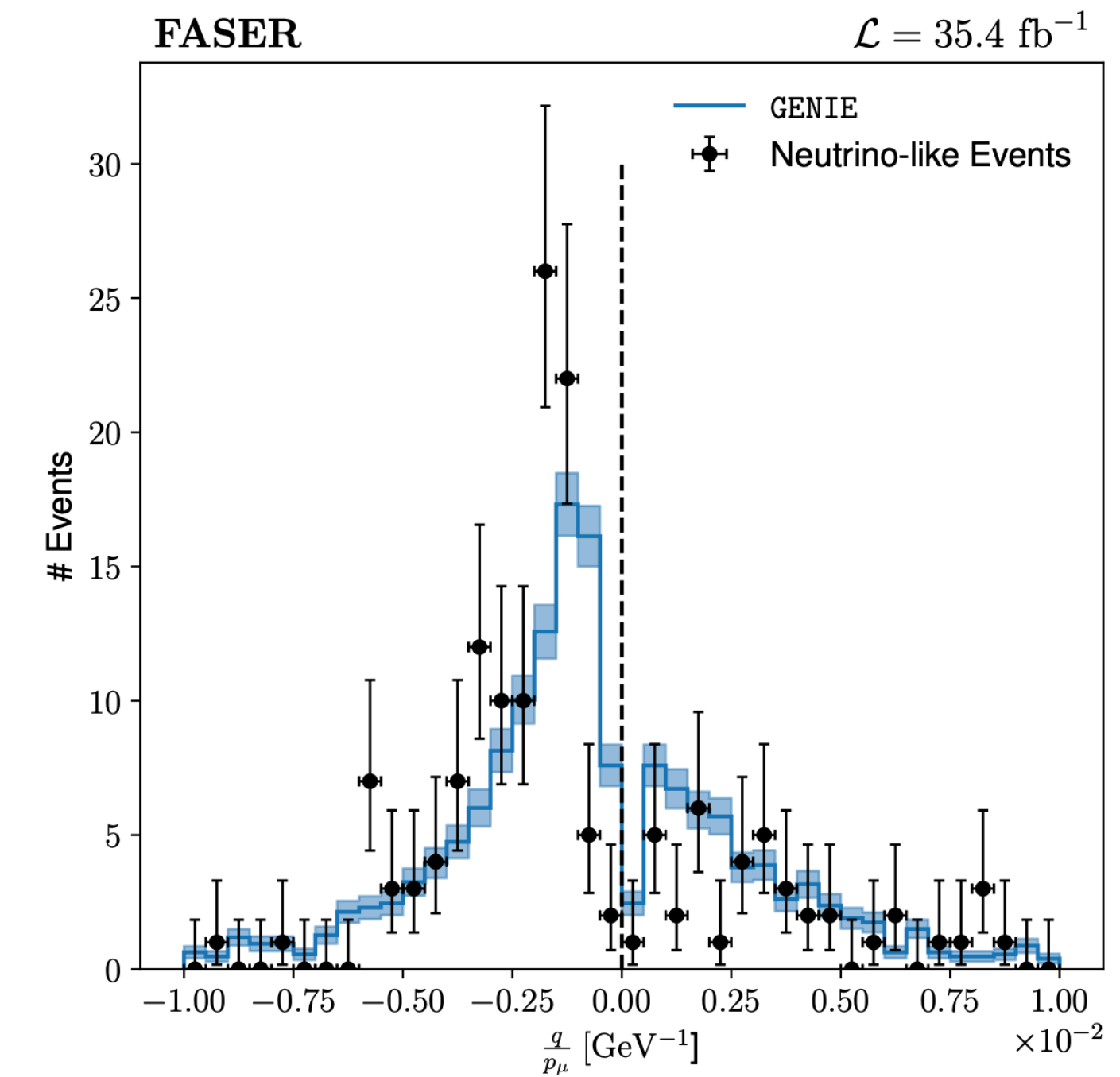
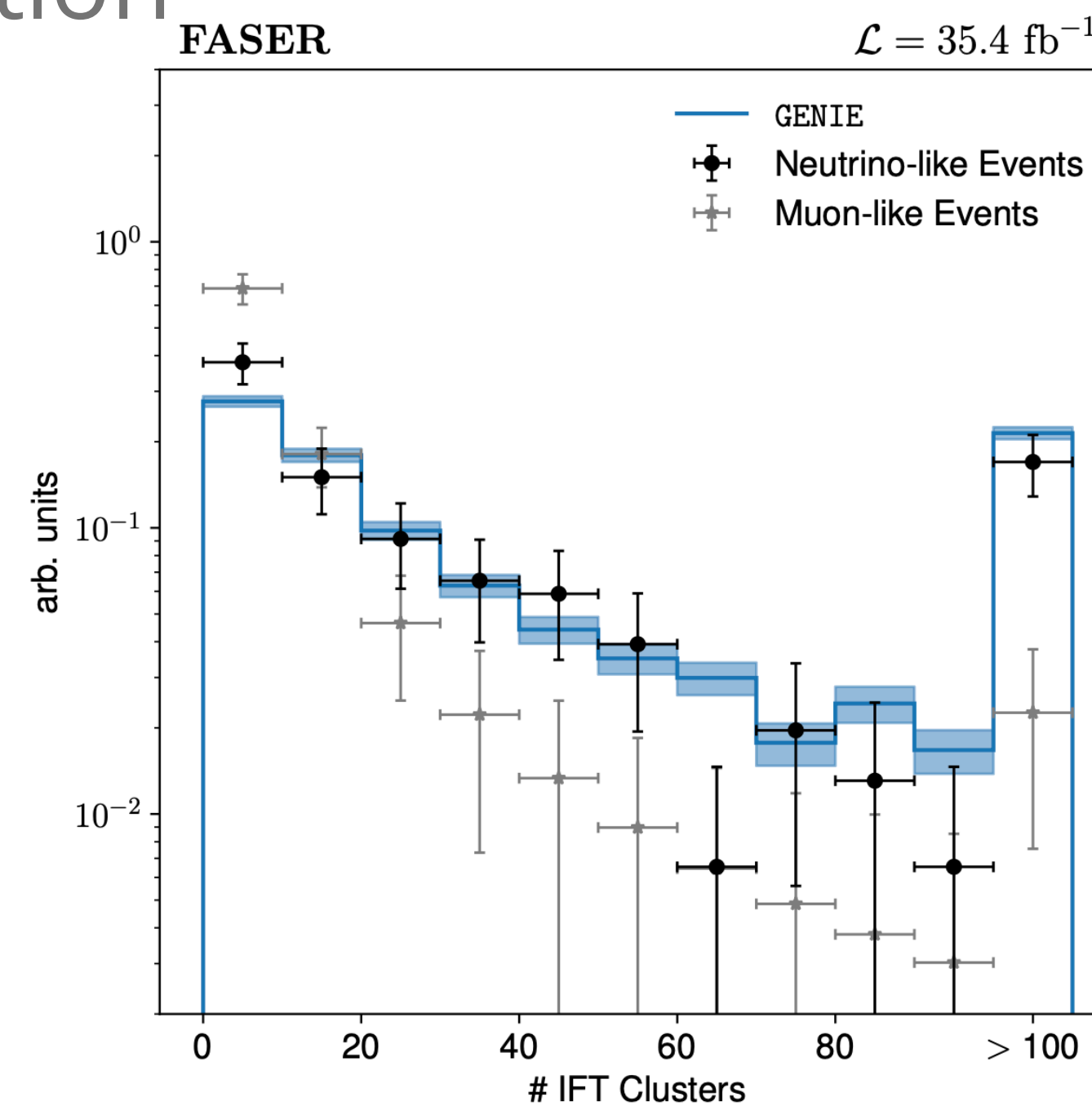
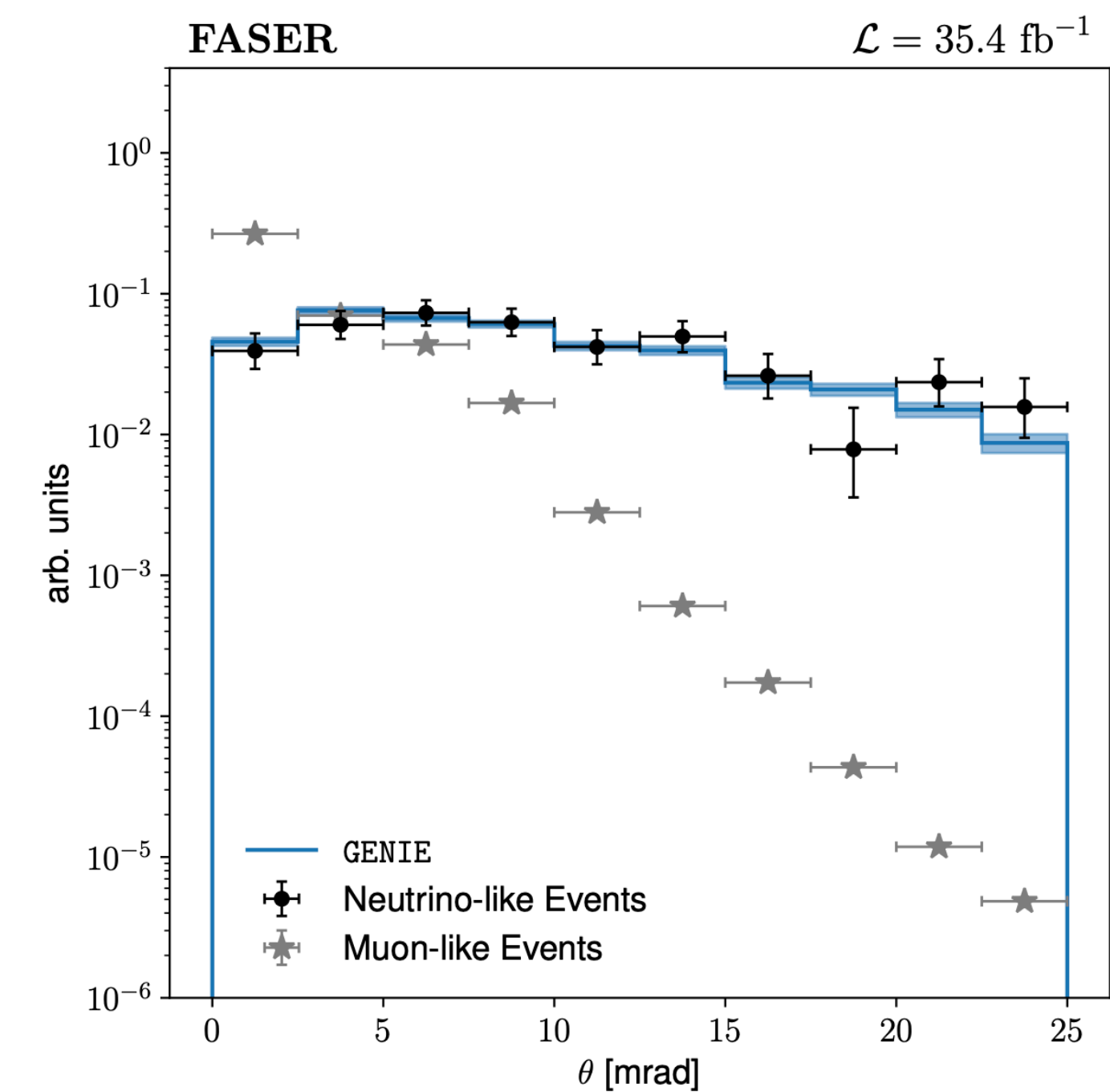
- ▶ Unblinded to find 153 events with no veto signal
 - ▶ Just 10 events with one veto signal
- ▶ **First direct detection of collider neutrinos!**

- ▶ With signal significance of 16σ
- ▶ Expected 151 ± 41 events from GENIE simulation



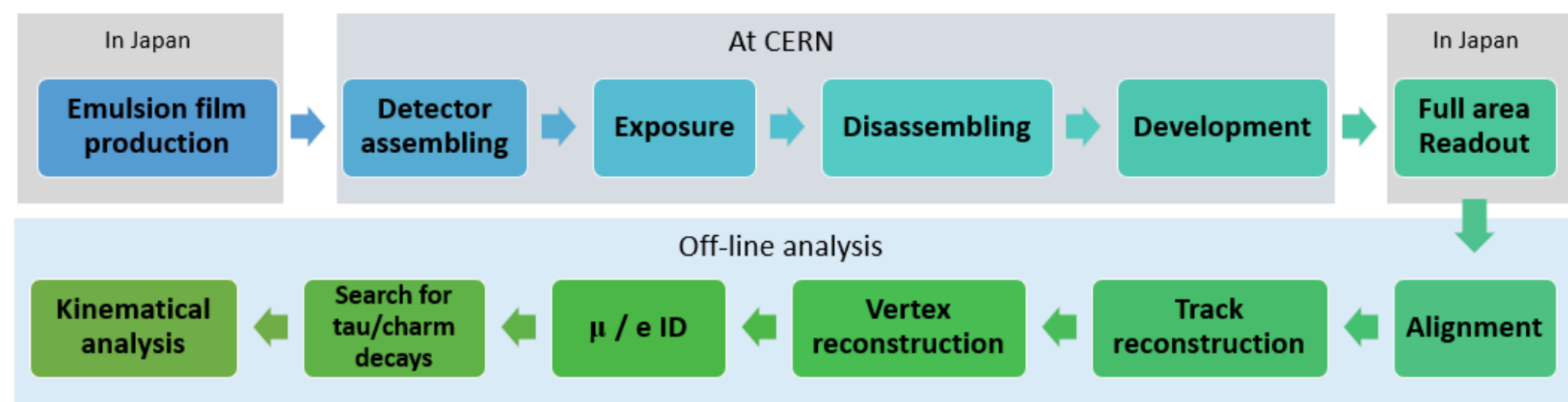
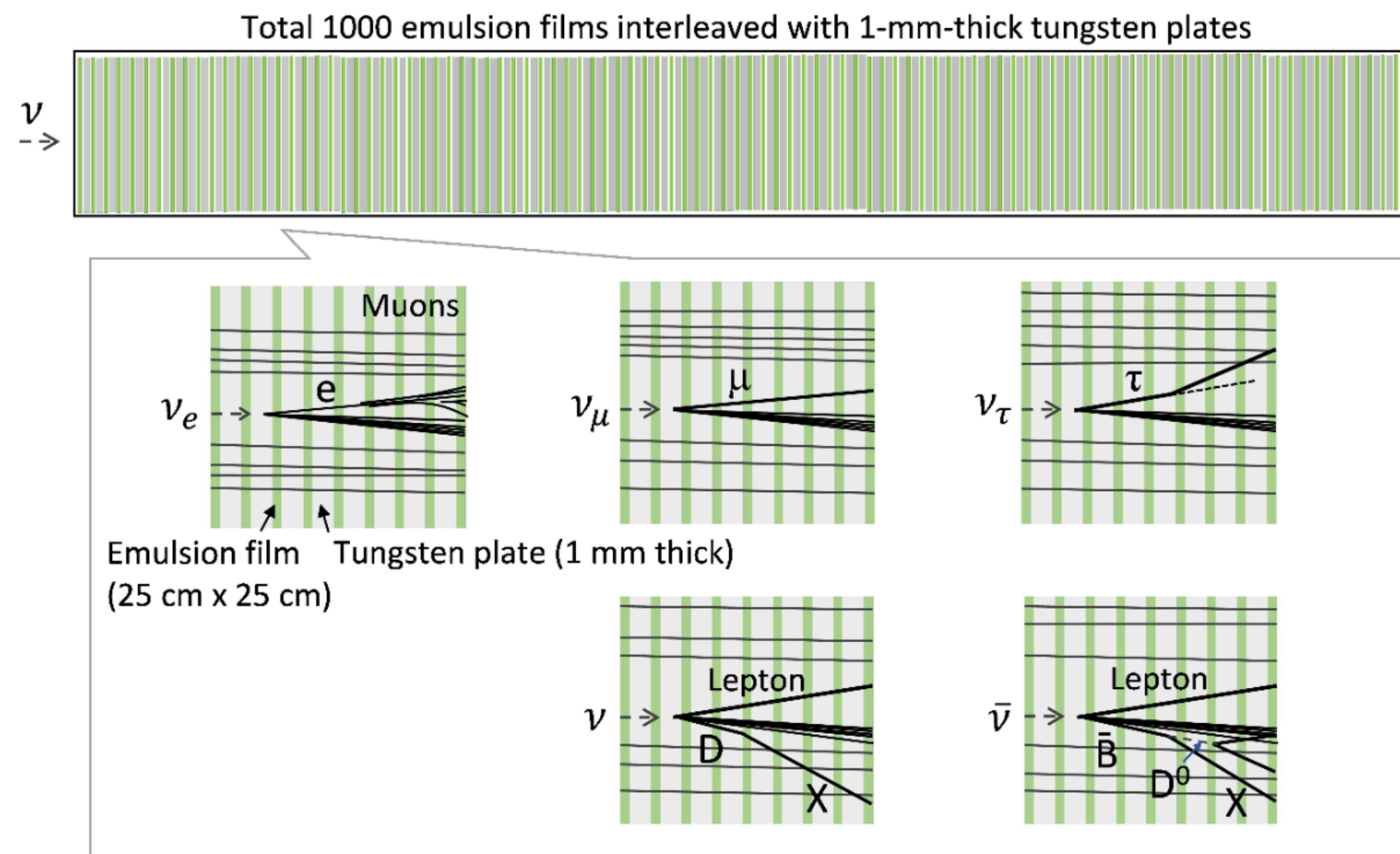
Neutrino analysis | Results

- ▶ Candidate neutrino events match expectation from signal
- ▶ High occupancy in front tracker station
- ▶ Most events have high μ momentum
- ▶ More ν_μ than anti- ν_μ
- ▶ High occupancy in front tracker station
- ▶ Large angle θ with respect to LOS
- ▶ NB: no acceptance corrections nor any systematic uncertainties in these plots



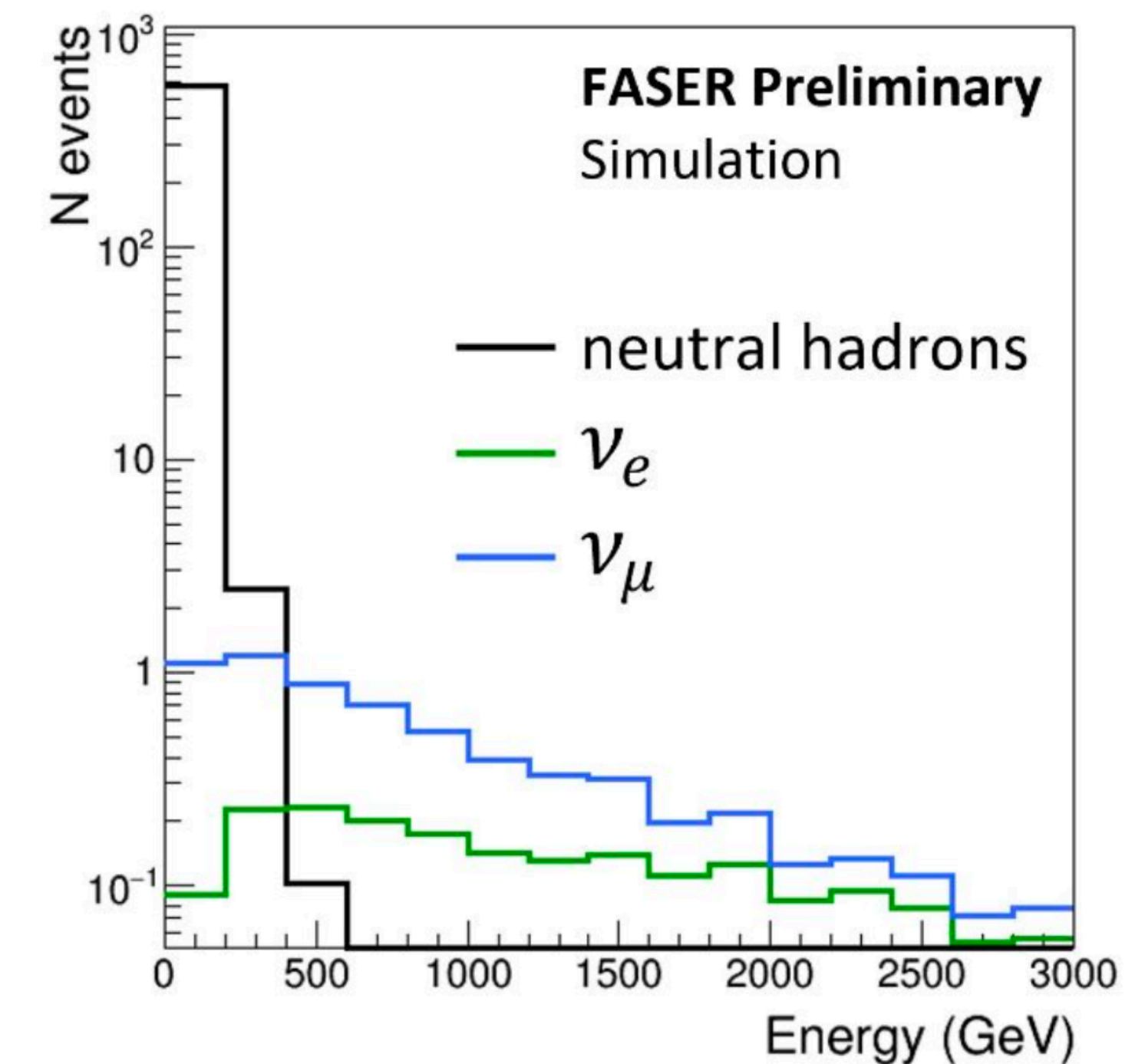
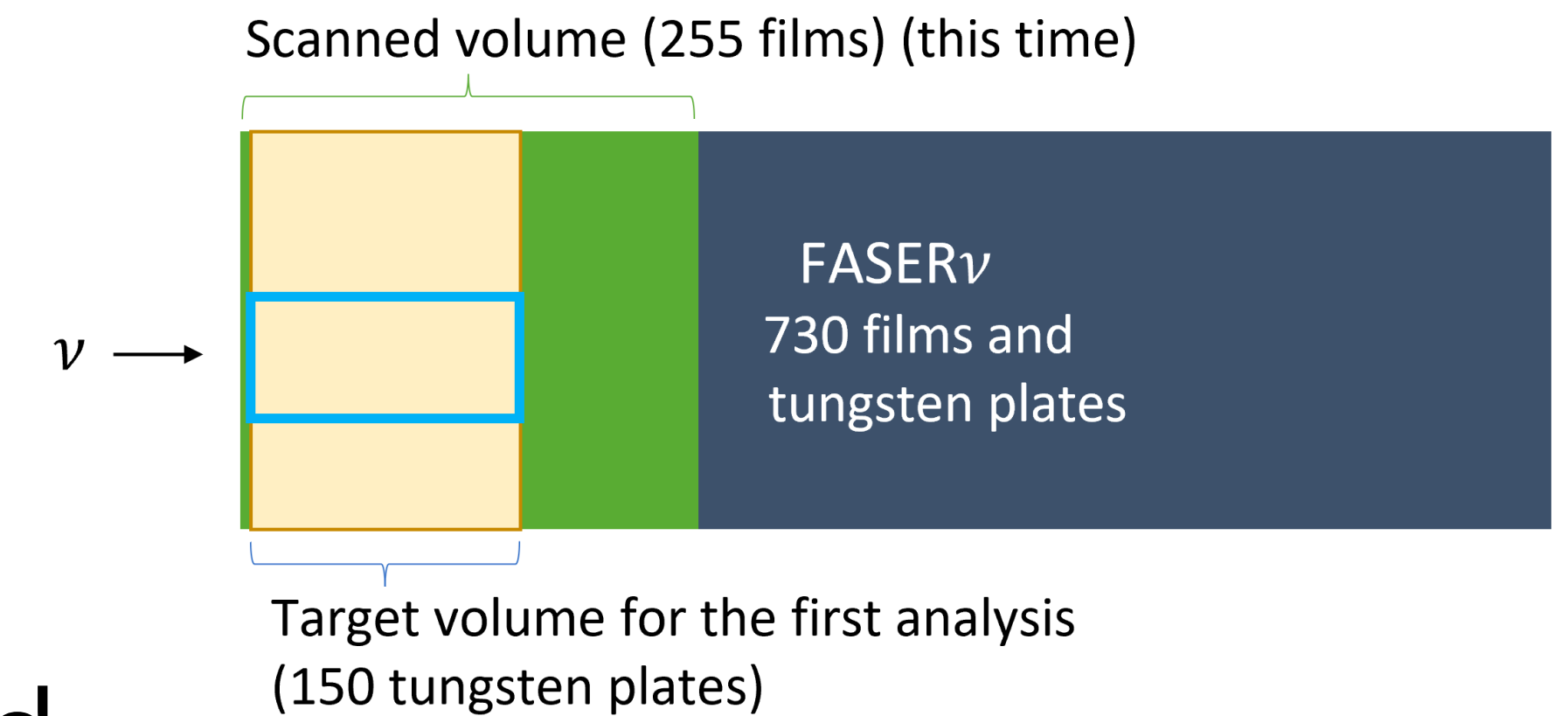
Emulsion analysis | Detector

- ▶ 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!



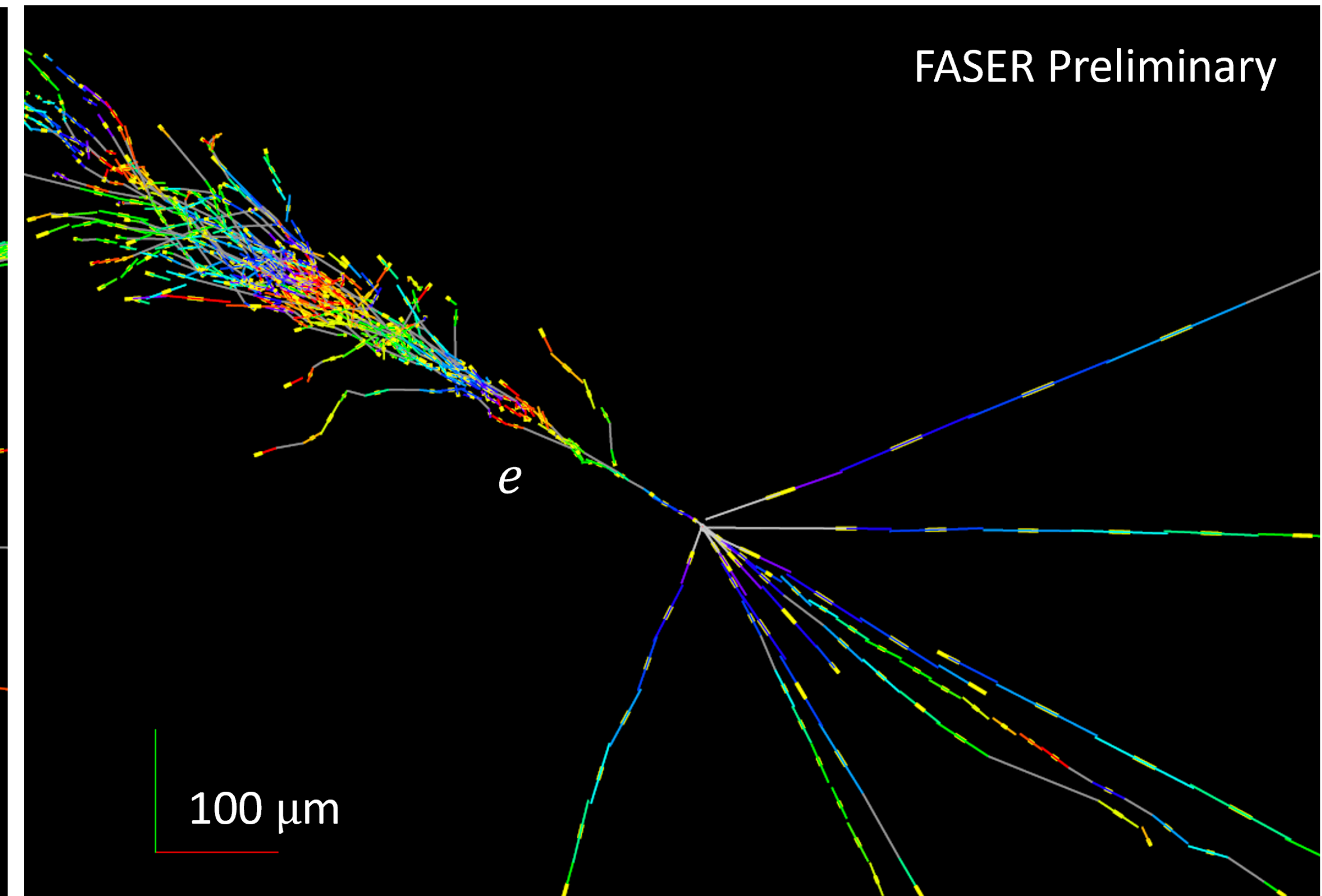
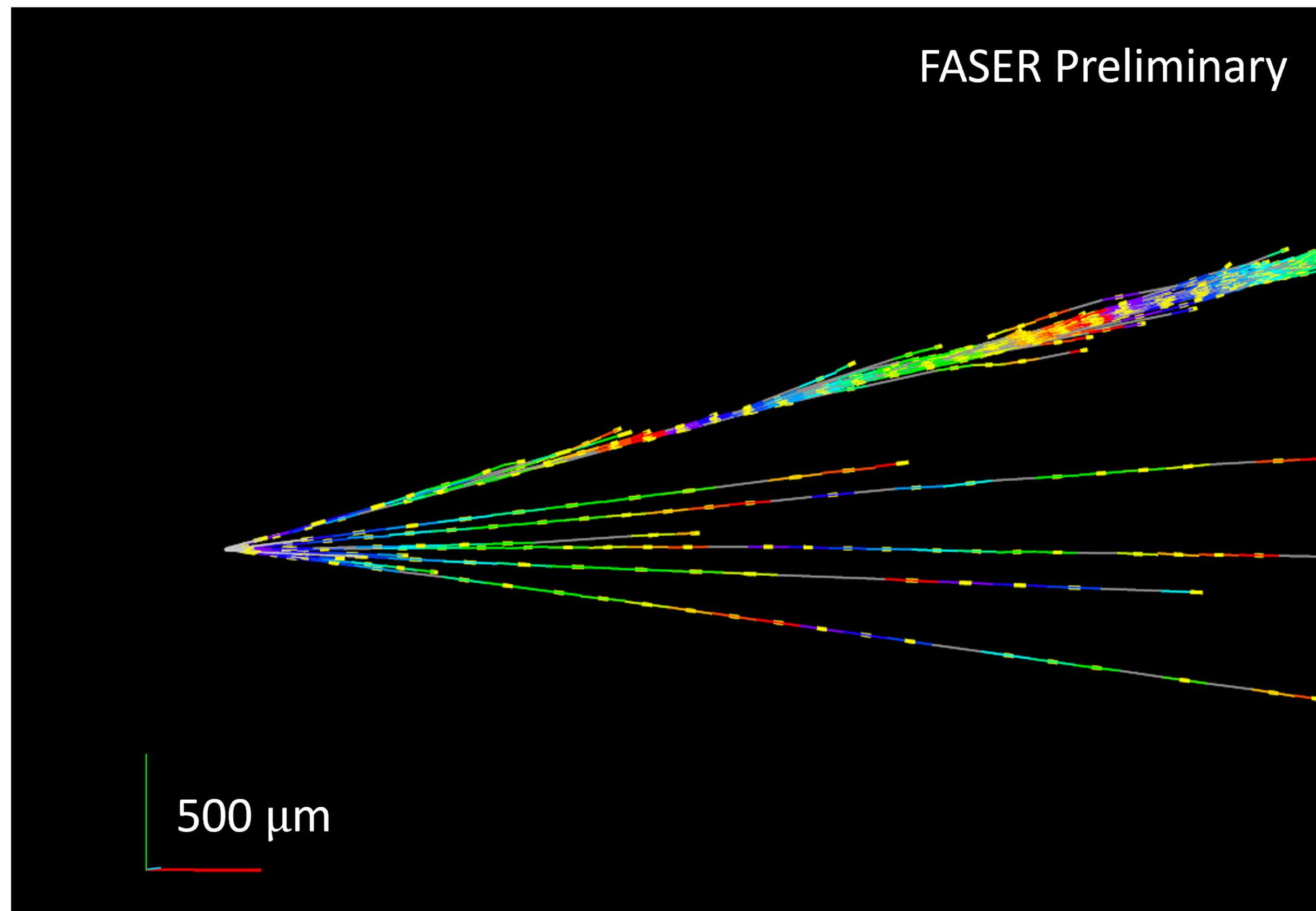
Emulsion analysis | Dataset & Bkgds

- ▶ 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 (ν_μ) and 11.8 ± 7.5 (ν_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



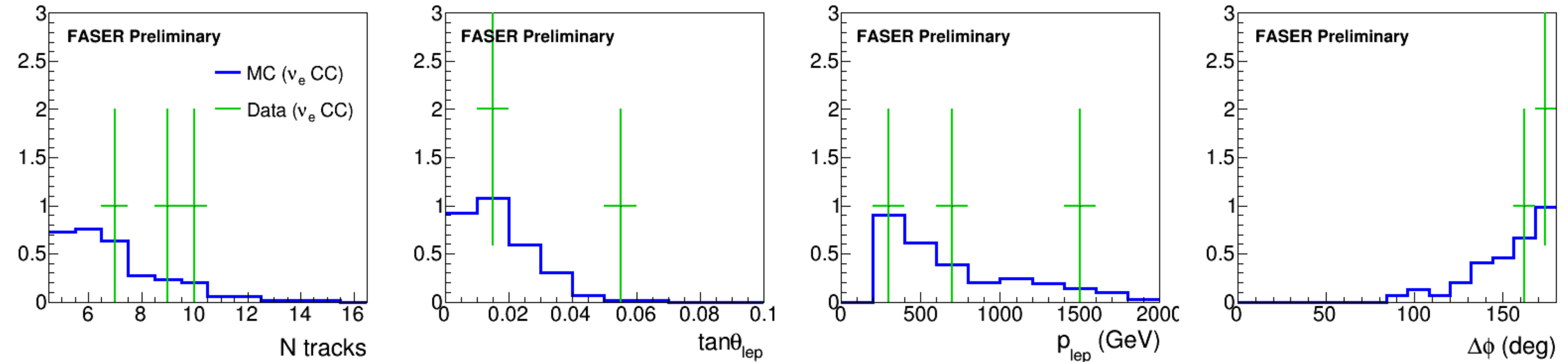
Emulsion analysis | Results

- ▶ Preliminary results: CERN-FASER-CONF-2023-002
- ▶ Expected 0.6–5.2 (ν_e CC) and 3.0–8.6 (ν_μ CC) passing selection
- ▶ Observed 3 ν_e vertices (5σ), and 4 ν_μ vertices (2.5σ) - **Candidates with $E \sim 1\text{TeV}$!**



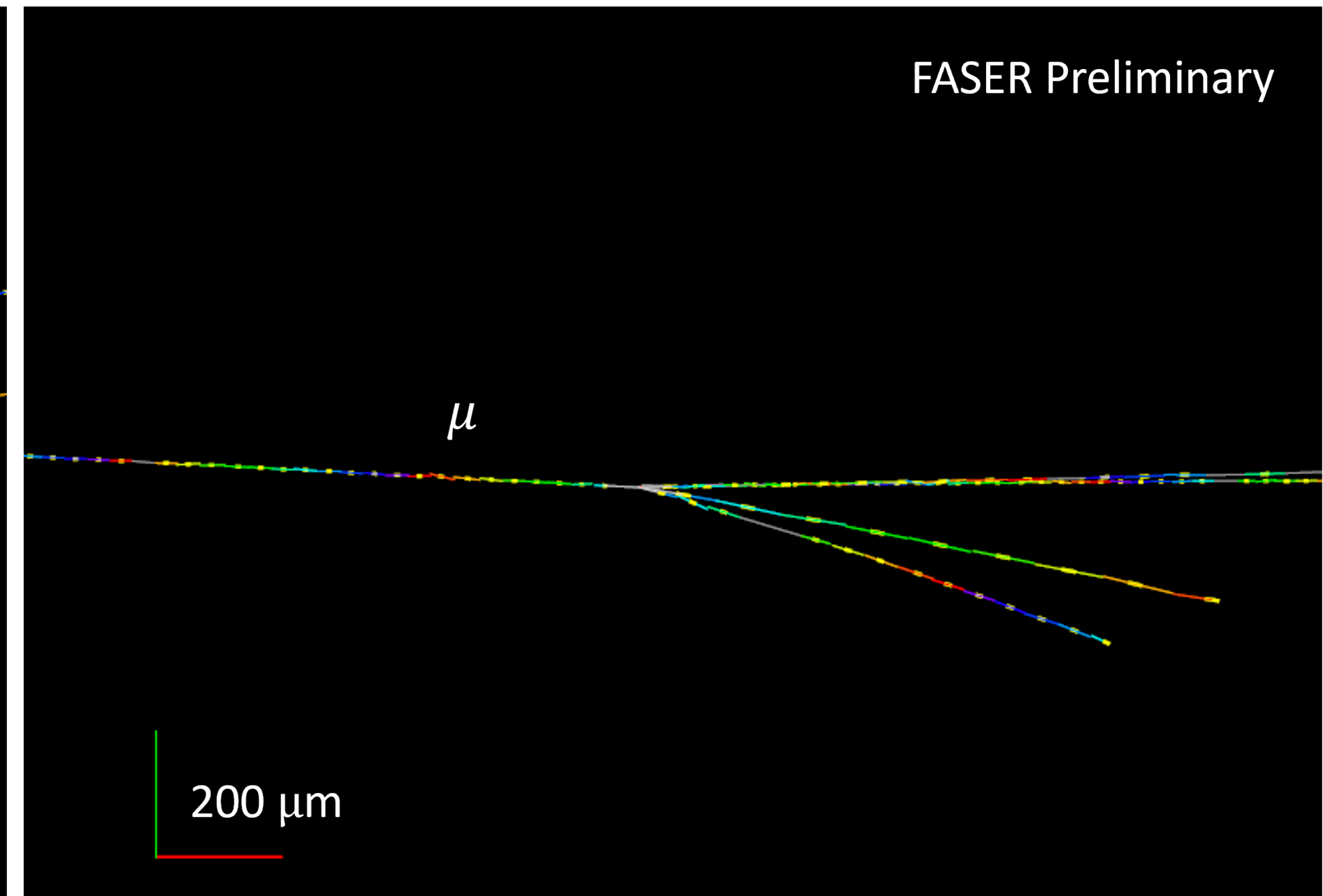
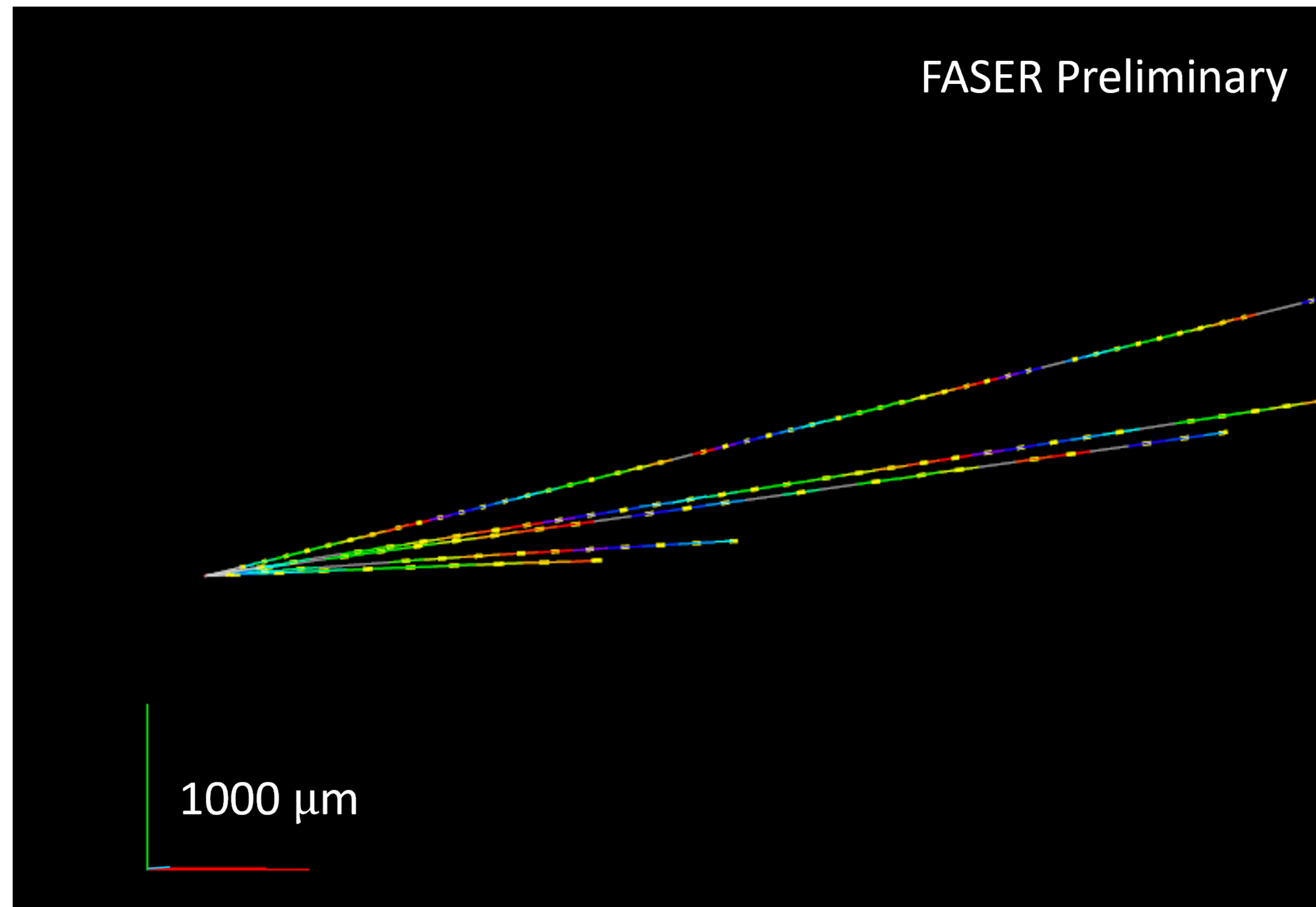
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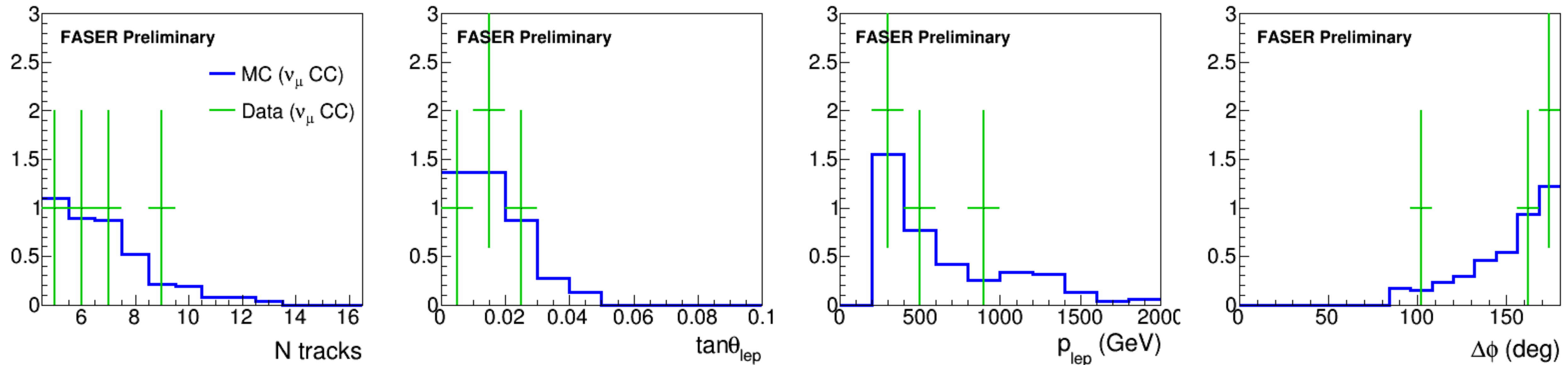
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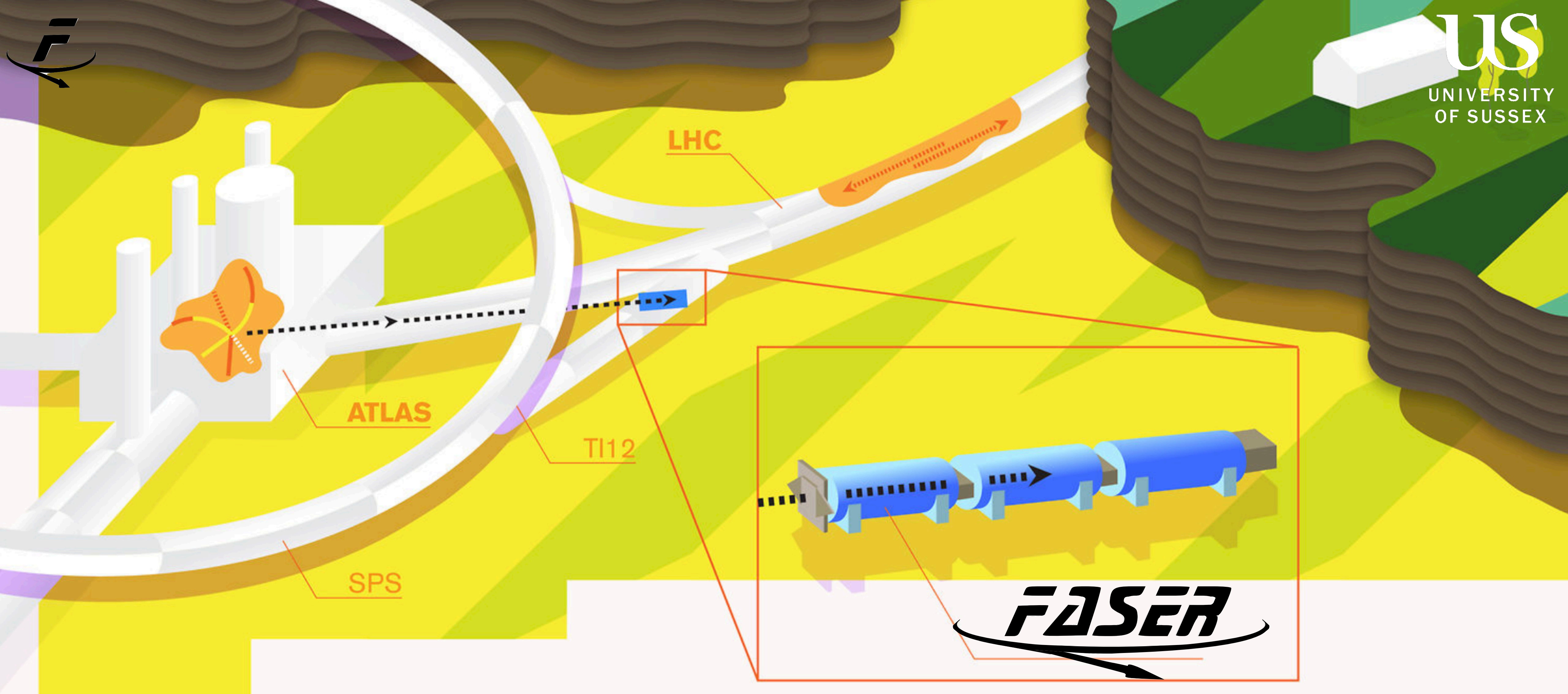


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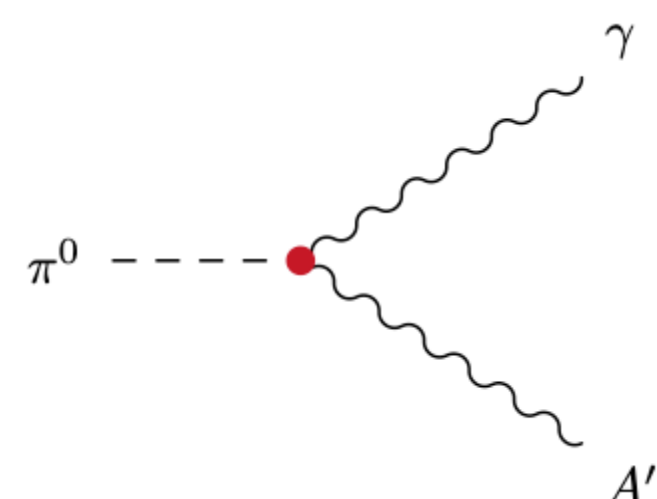
Dark Photon Search

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



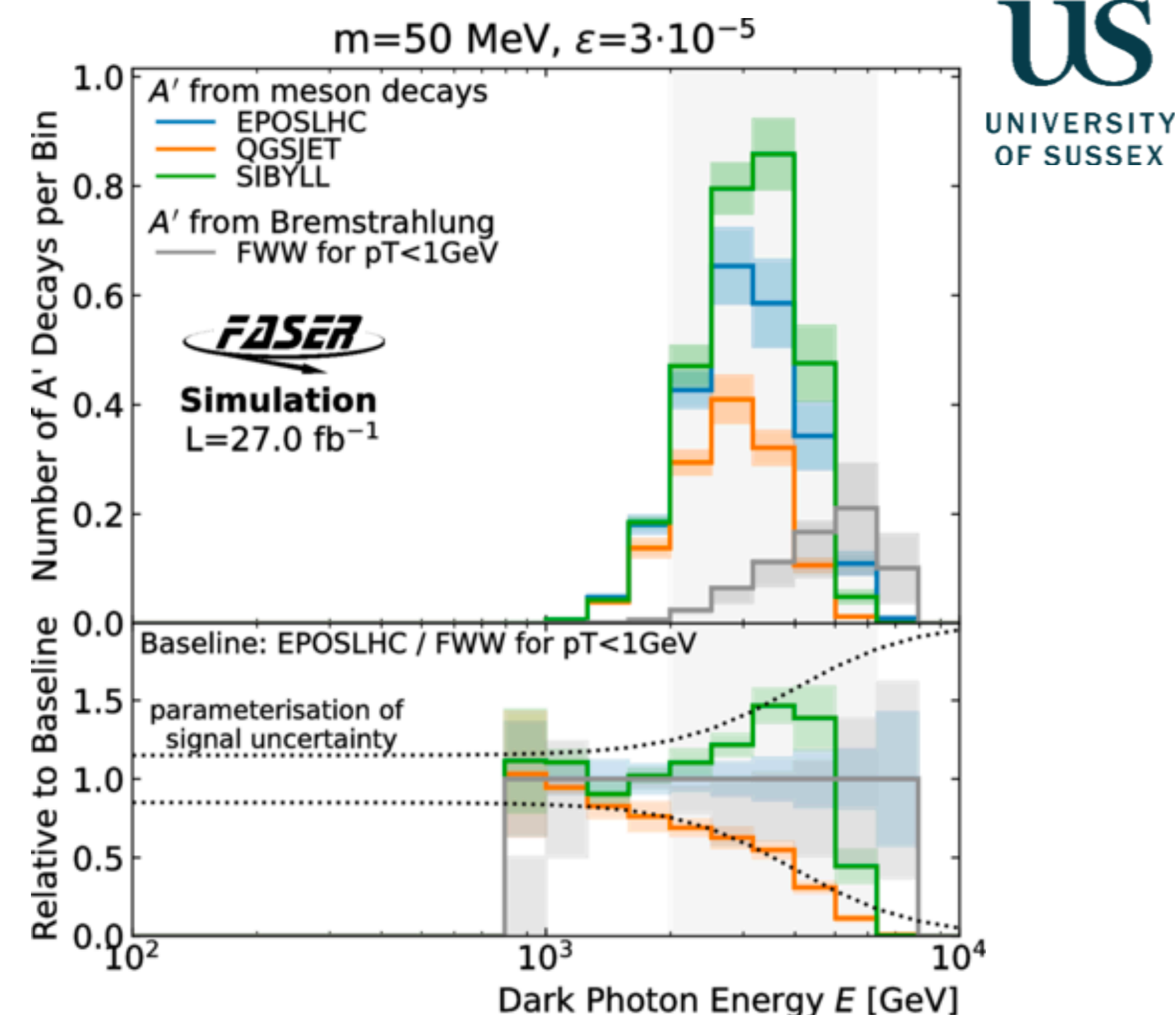
$$B(\pi^0 \rightarrow A' \gamma) = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 B(\pi^0 \rightarrow \gamma \gamma)$$

- ▶ 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

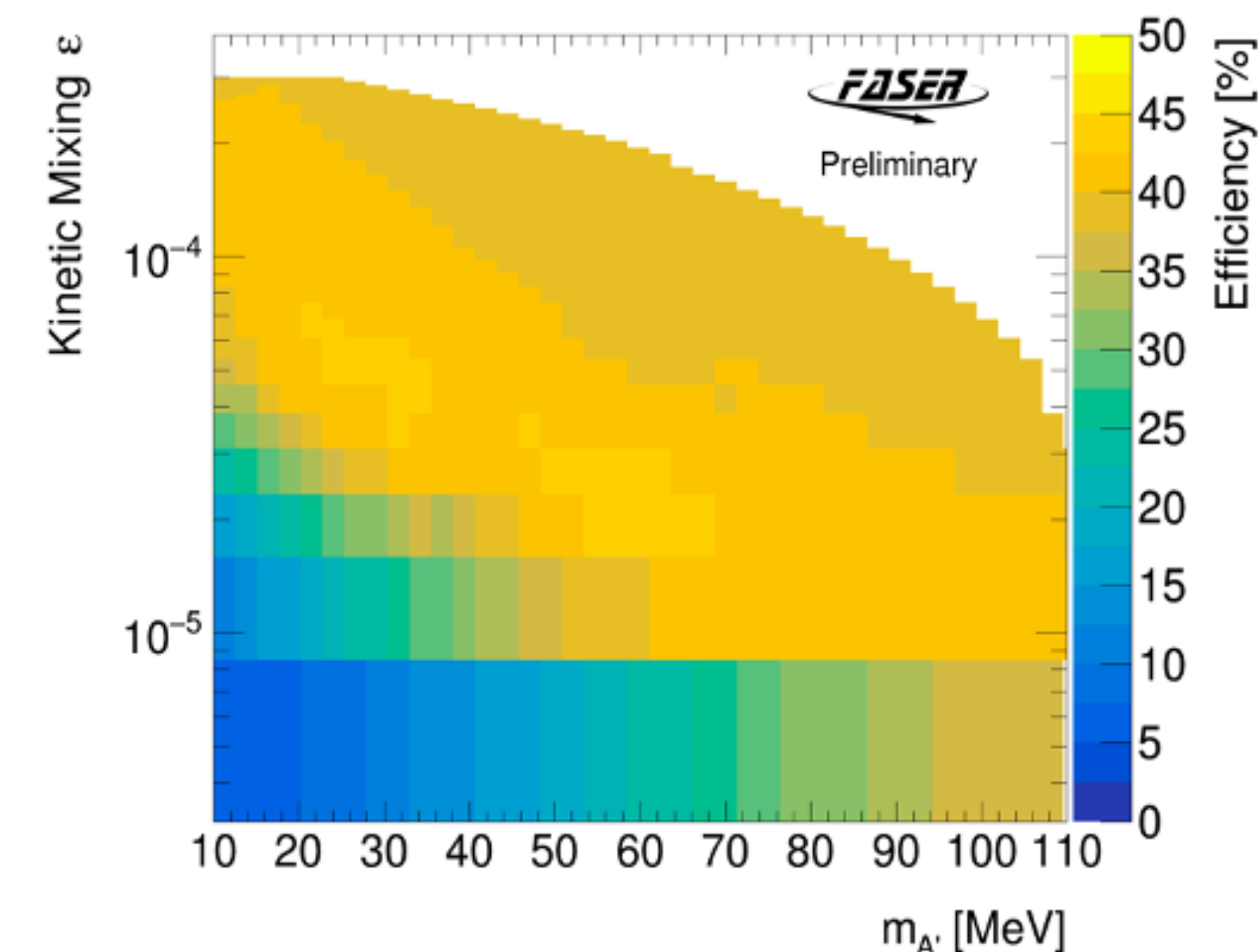
* arXiv:2105.07077



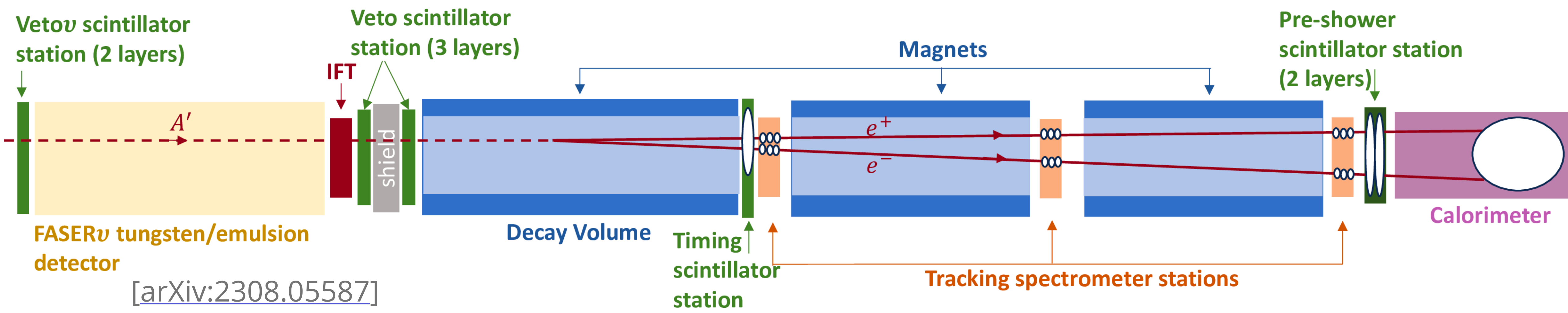
- ▶ $A' \rightarrow e^+e^-$ simulated with FORESEE*
 - ▶ π_0 and η via EPOS-LHC generator
 - ▶ Subdominant dark brem. via FWW
- ▶ Generator uncertainty dominates
 - ▶ Difference to QGSJET/SIBYLL
 - ▶ Parameterised based on A' energy

Dark Photon Search | Selection

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

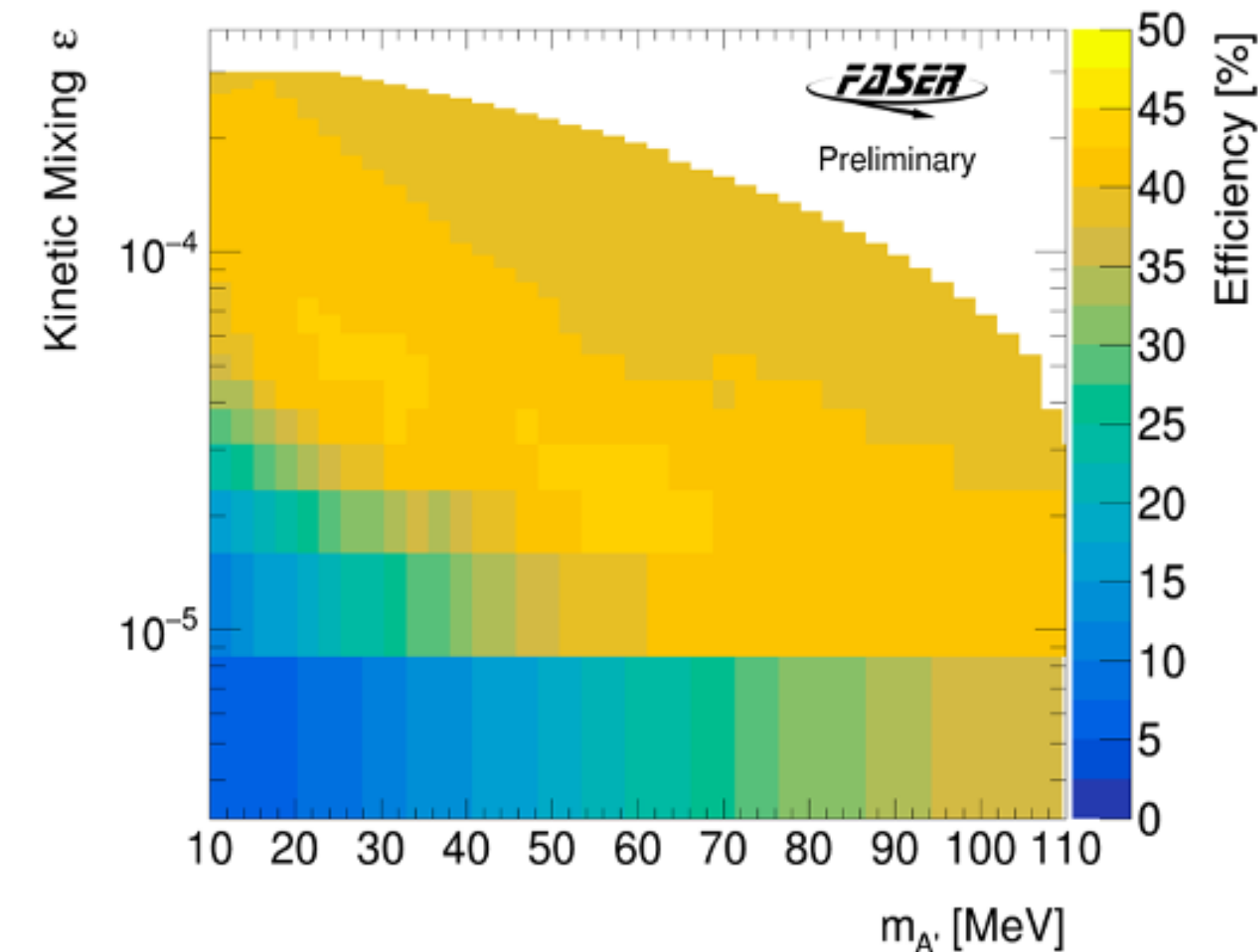


- ▶ Efficiency of $\sim 40\%$ across sensitive region

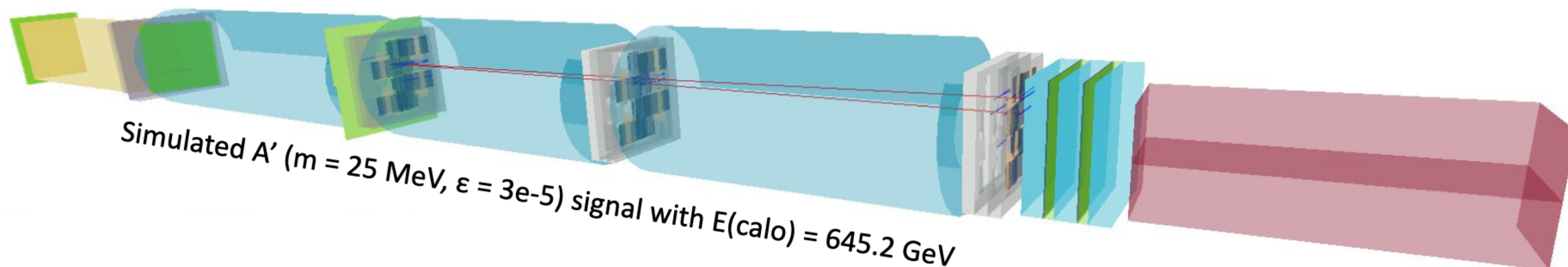


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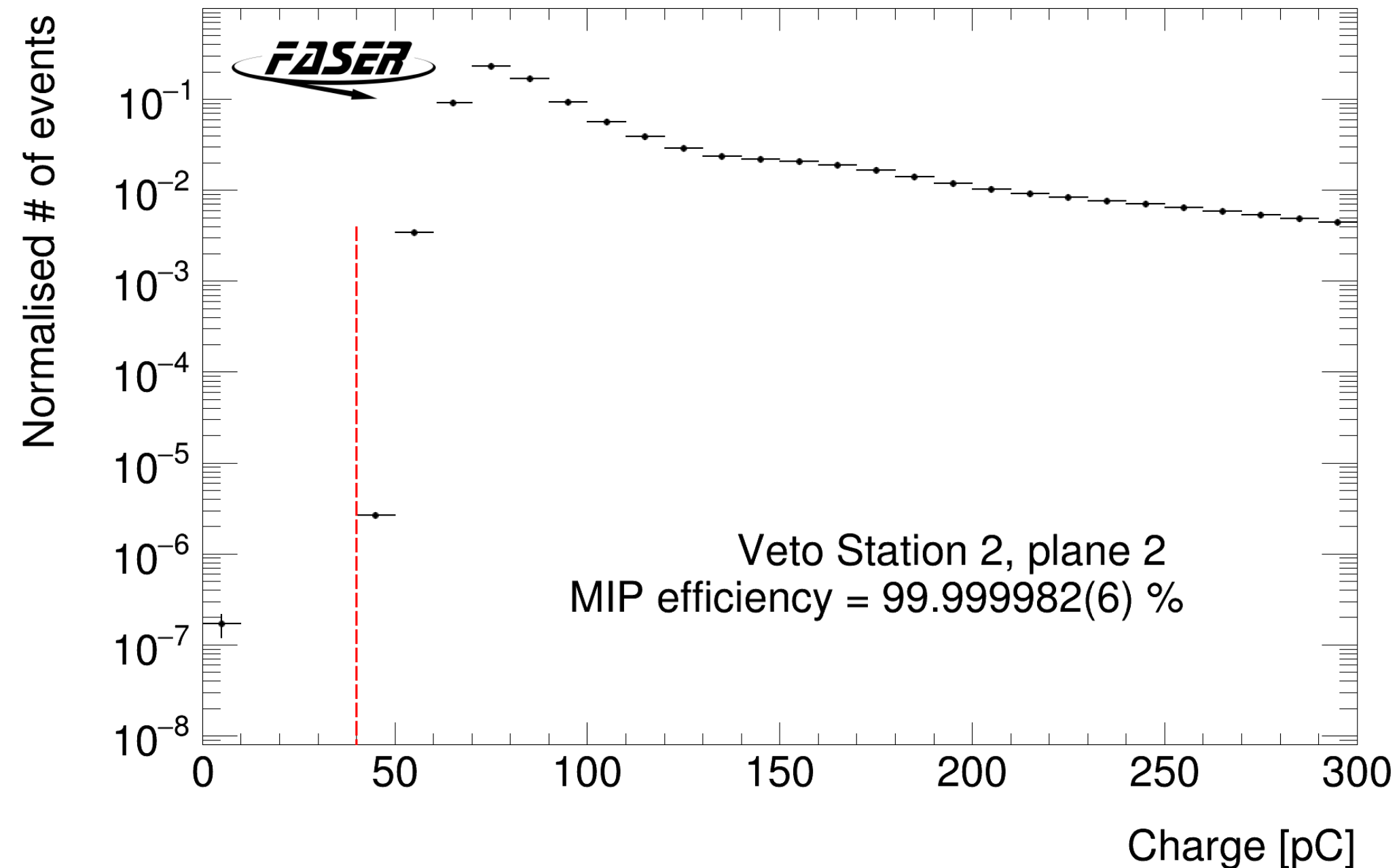


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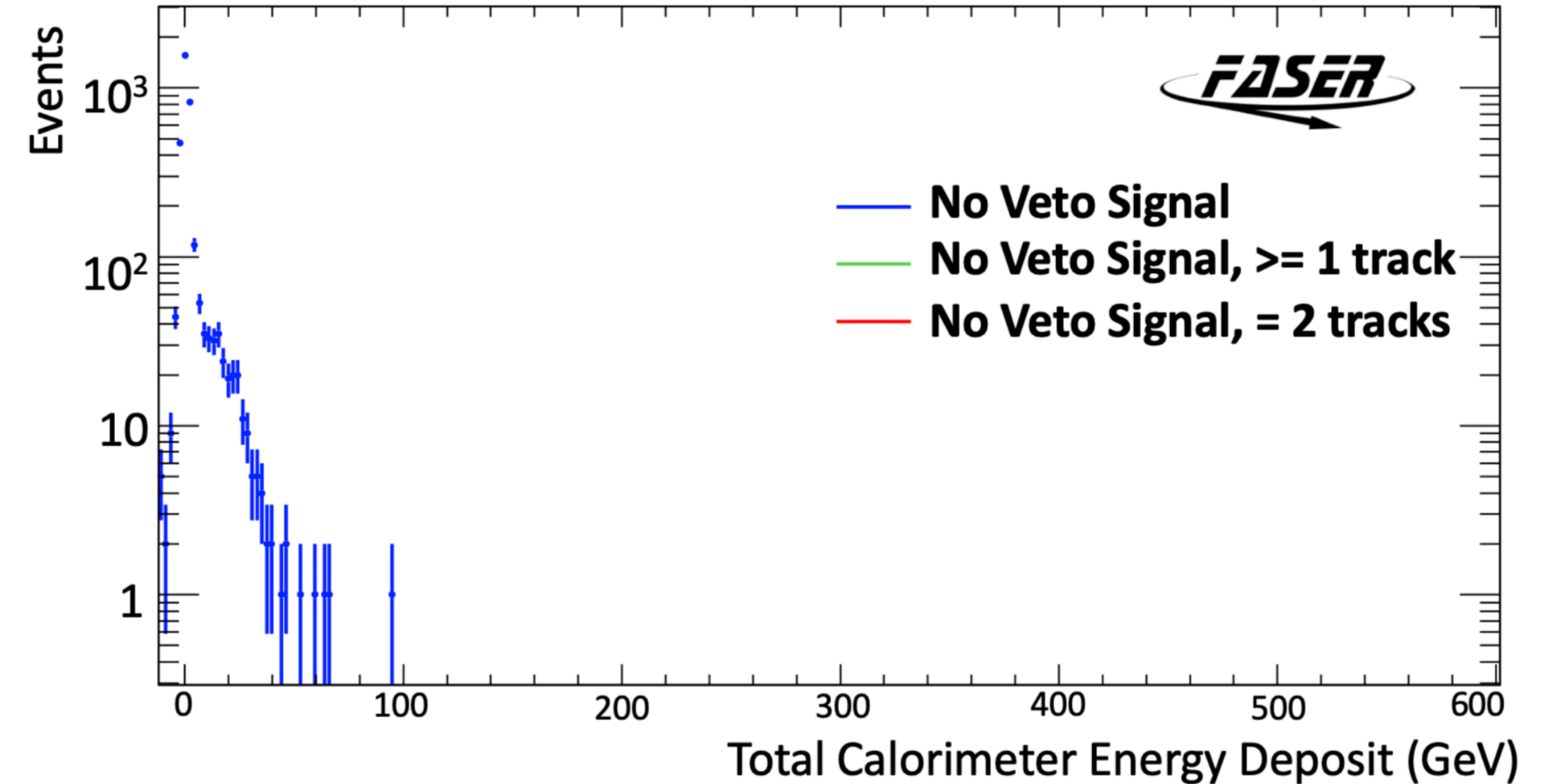
► Veto inefficiency

- Measured layer-by-layer via muons with tracks pointing back to vetos
- Layer efficiency $> 99.9998\%$
- 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 $E(\text{calo}) > 500$ GeV individually

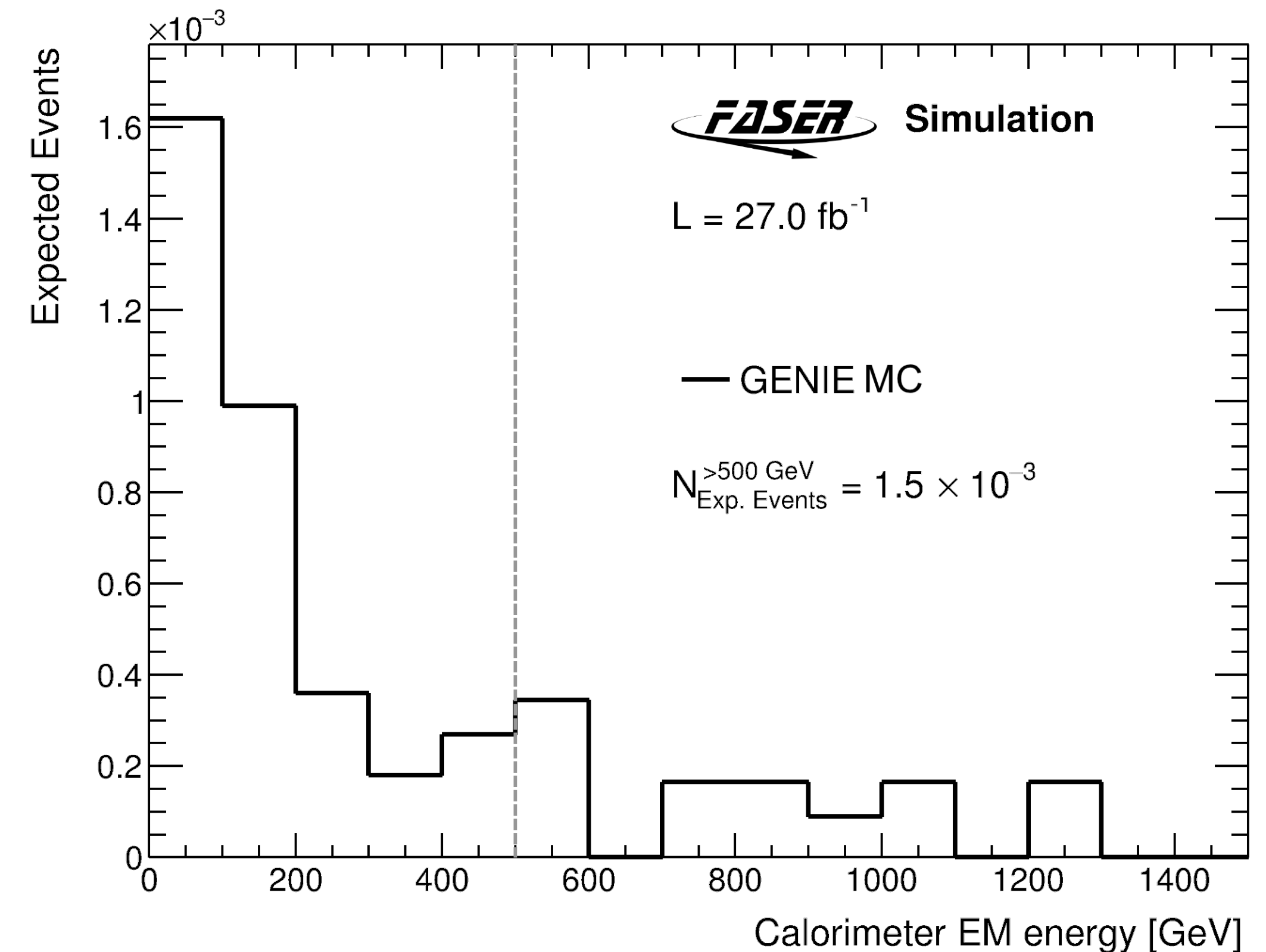


- ▶ Main background is from Neutrino interactions
 - ▶ Primarily coming from vicinity of timing detector
 - ▶ Estimated from GENIE simulation (300 ab⁻¹)
 - ▶ Uncertainties from neutrino flux & mismodelling
 - ▶ Predicted events with E(calor) > 500 GeV

$$N = (1.5 \pm 2.0) \times 10^{-3}$$

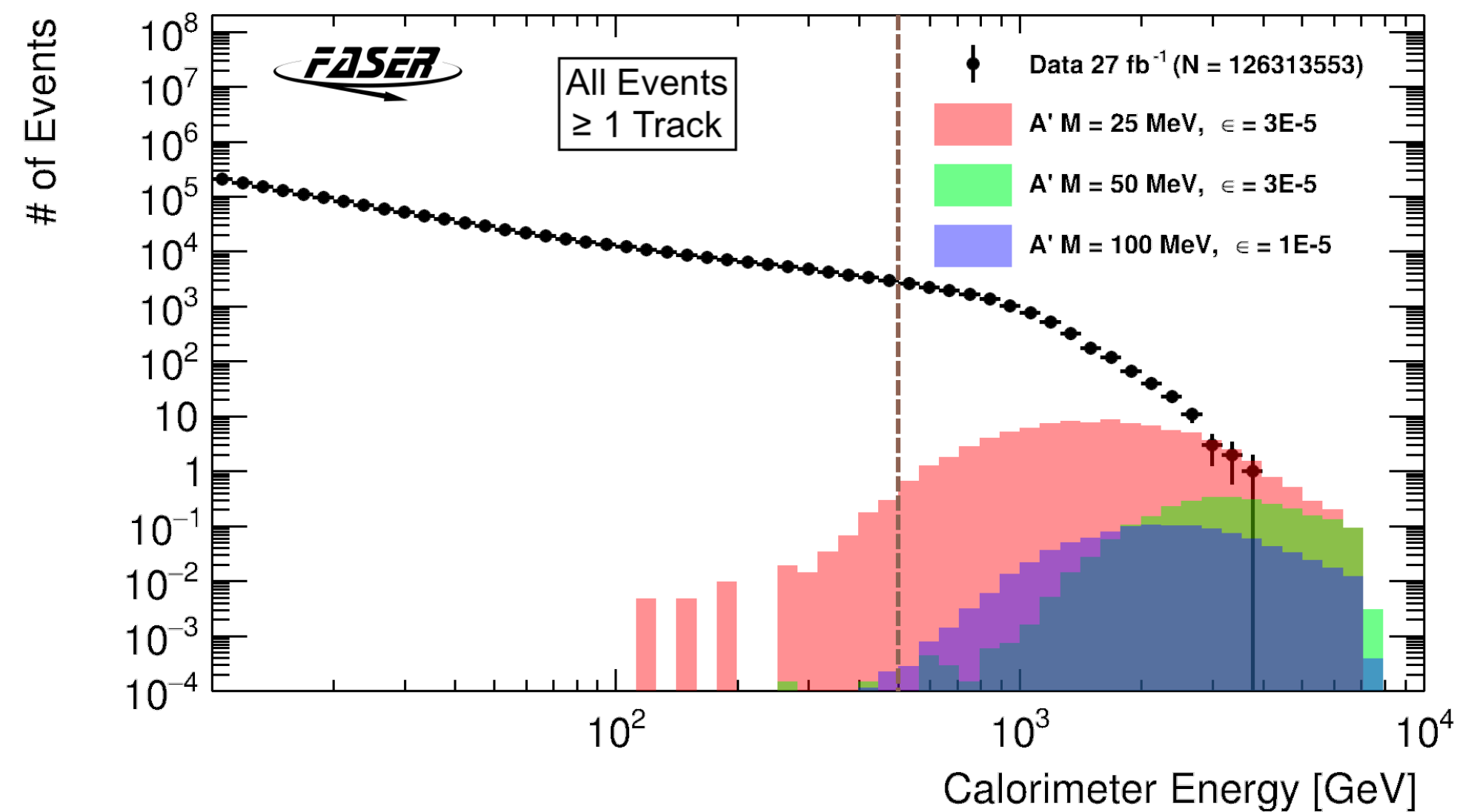
- ▶ Neutral hadrons (e.g. Ks) from upstream muons interacting in rock in front of FASER
 - ▶ Heavily suppressed since:
 - ▶ muon nearly always continues after interaction
 - ▶ has to pass through 8 interaction lengths (FASERv)
 - ▶ decay products have to leave E(calor) > 500 GeV
 - ▶ Estimated from lower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

$$N = (0.8 \pm 1.2) \times 10^{-3}$$

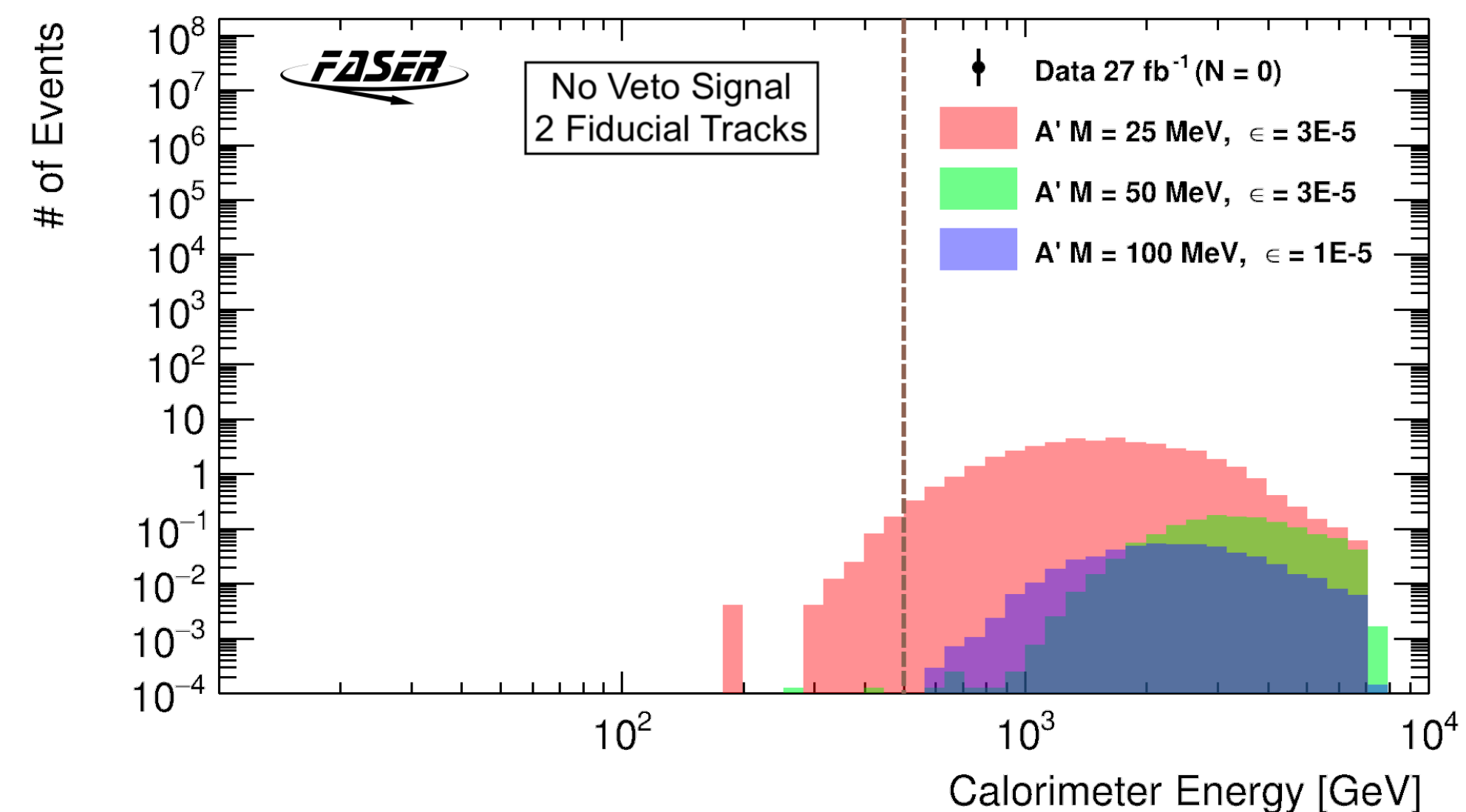
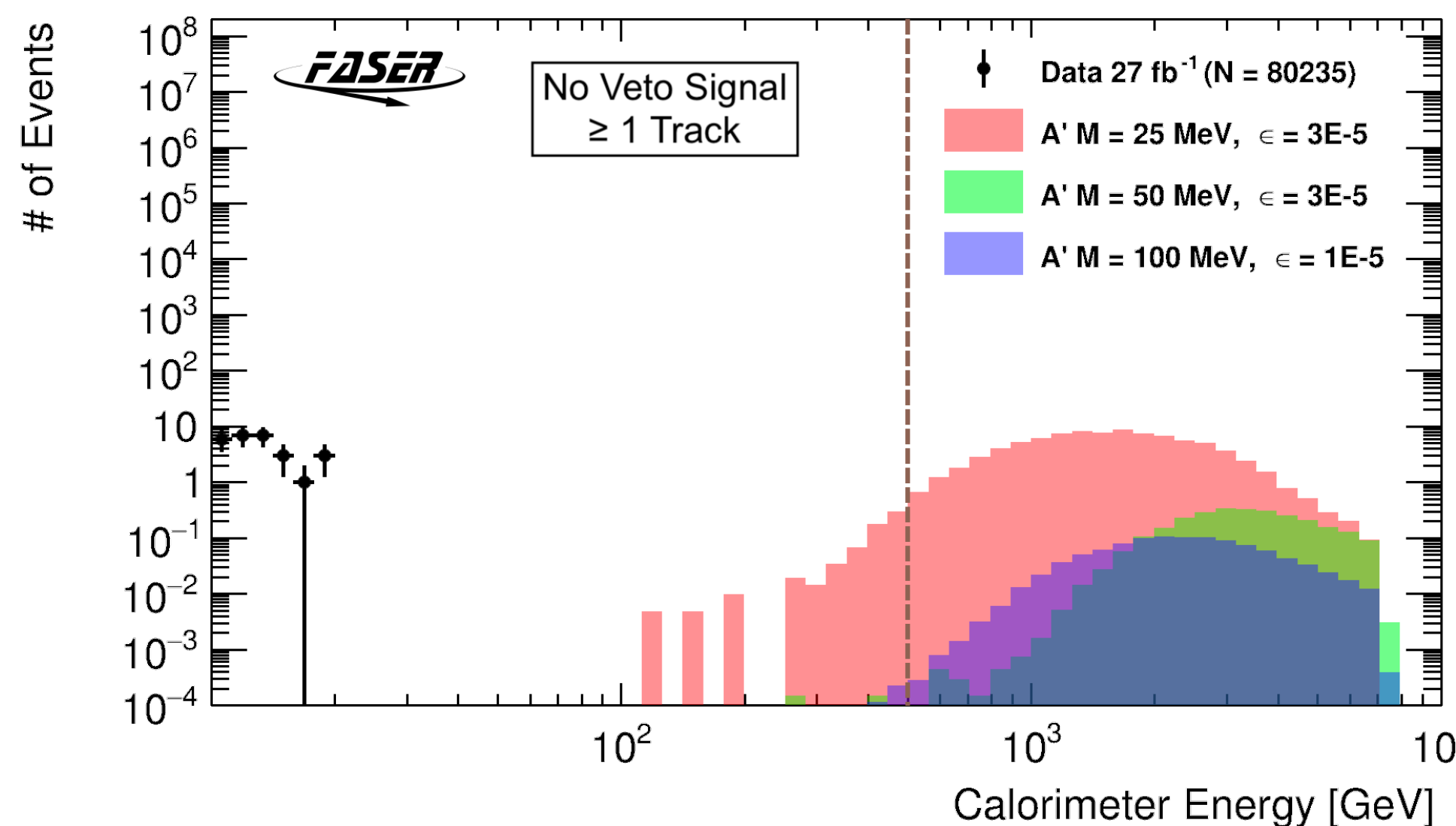


Dark Photon Search | Results

- ▶ No events in unblinded signal region
- ▶ Not even any with ≥ 1 fiducial track

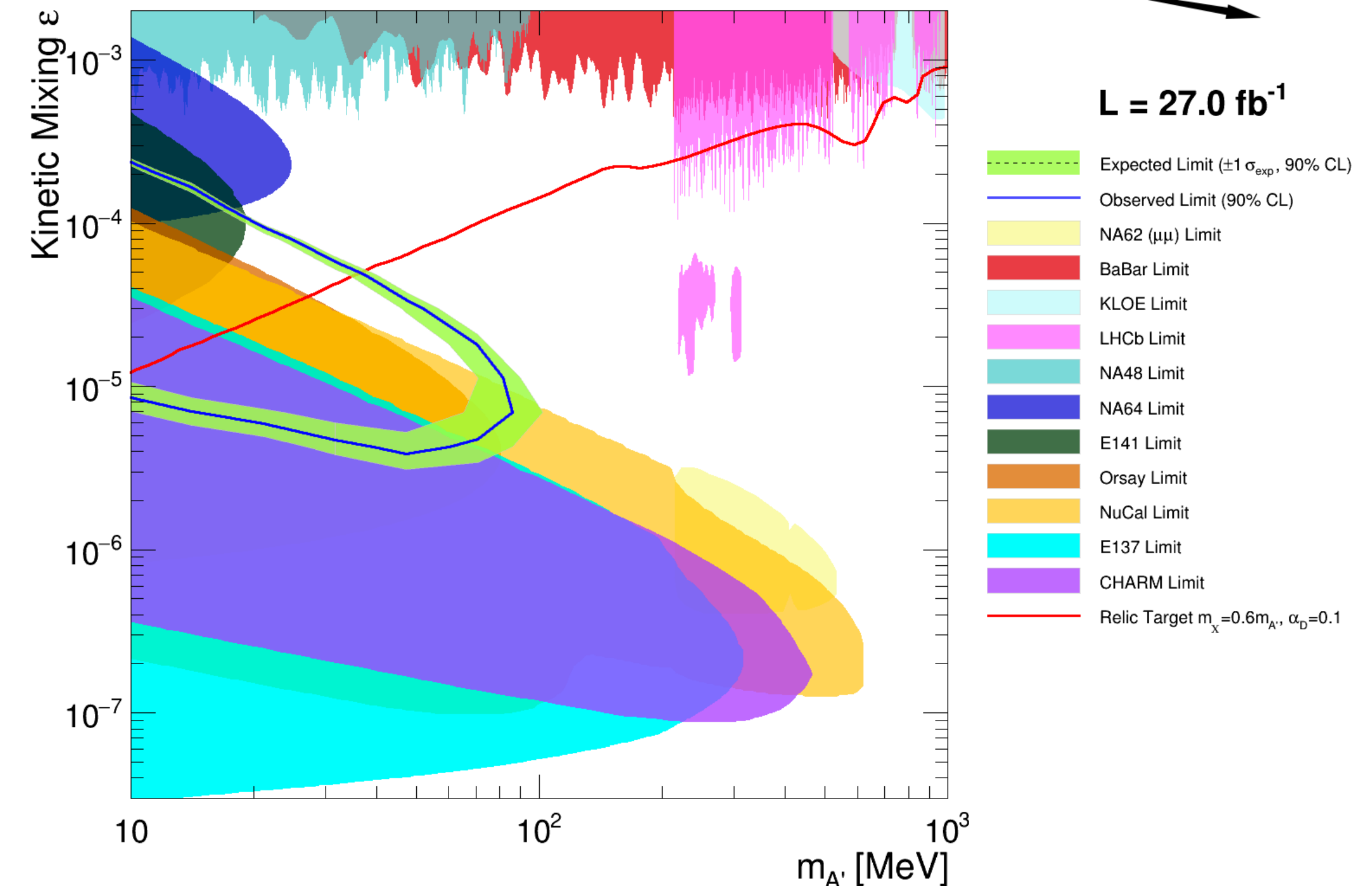
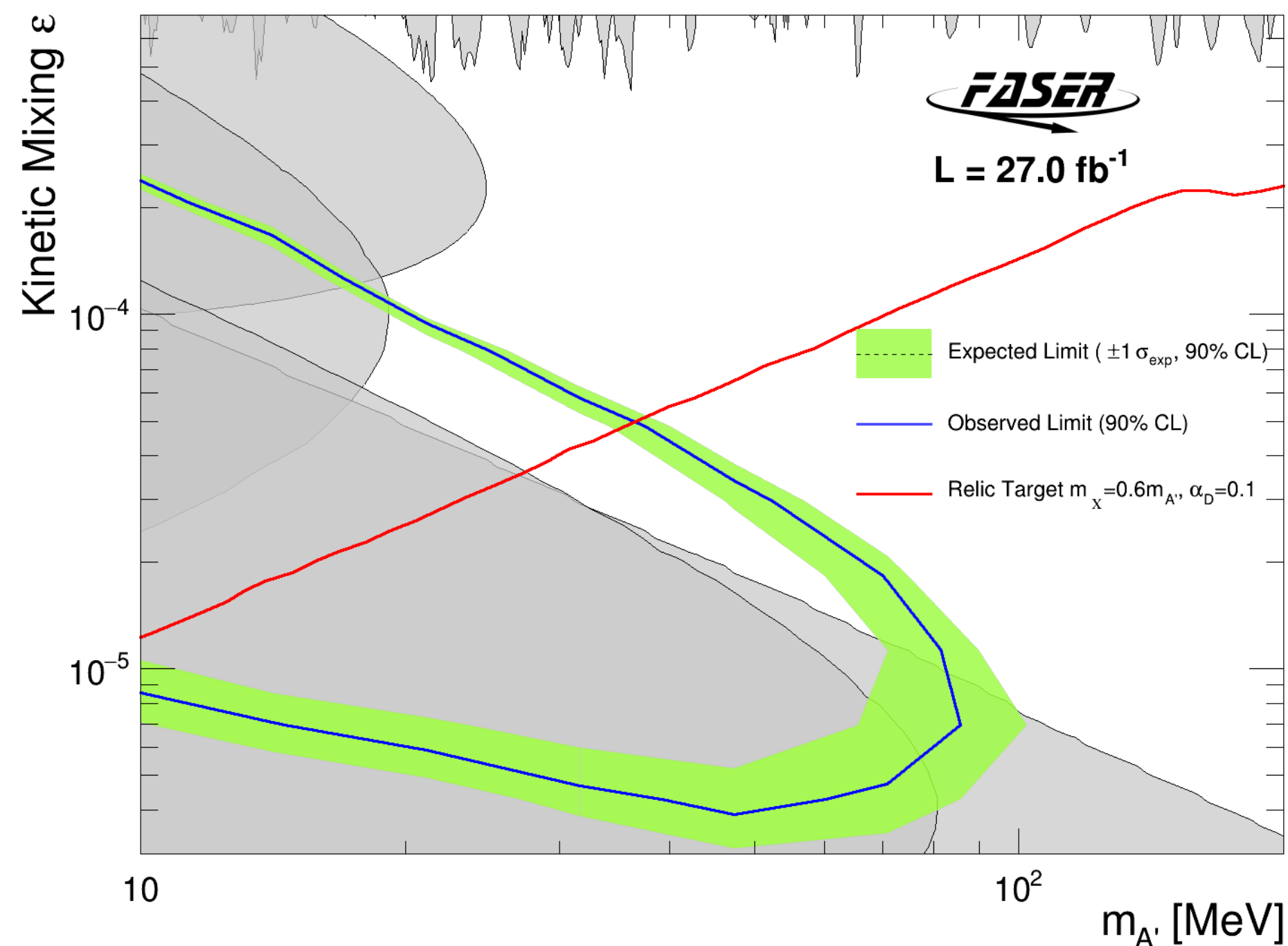


- ▶ Expected background
- ▶ 0.0023 ± 0.0023



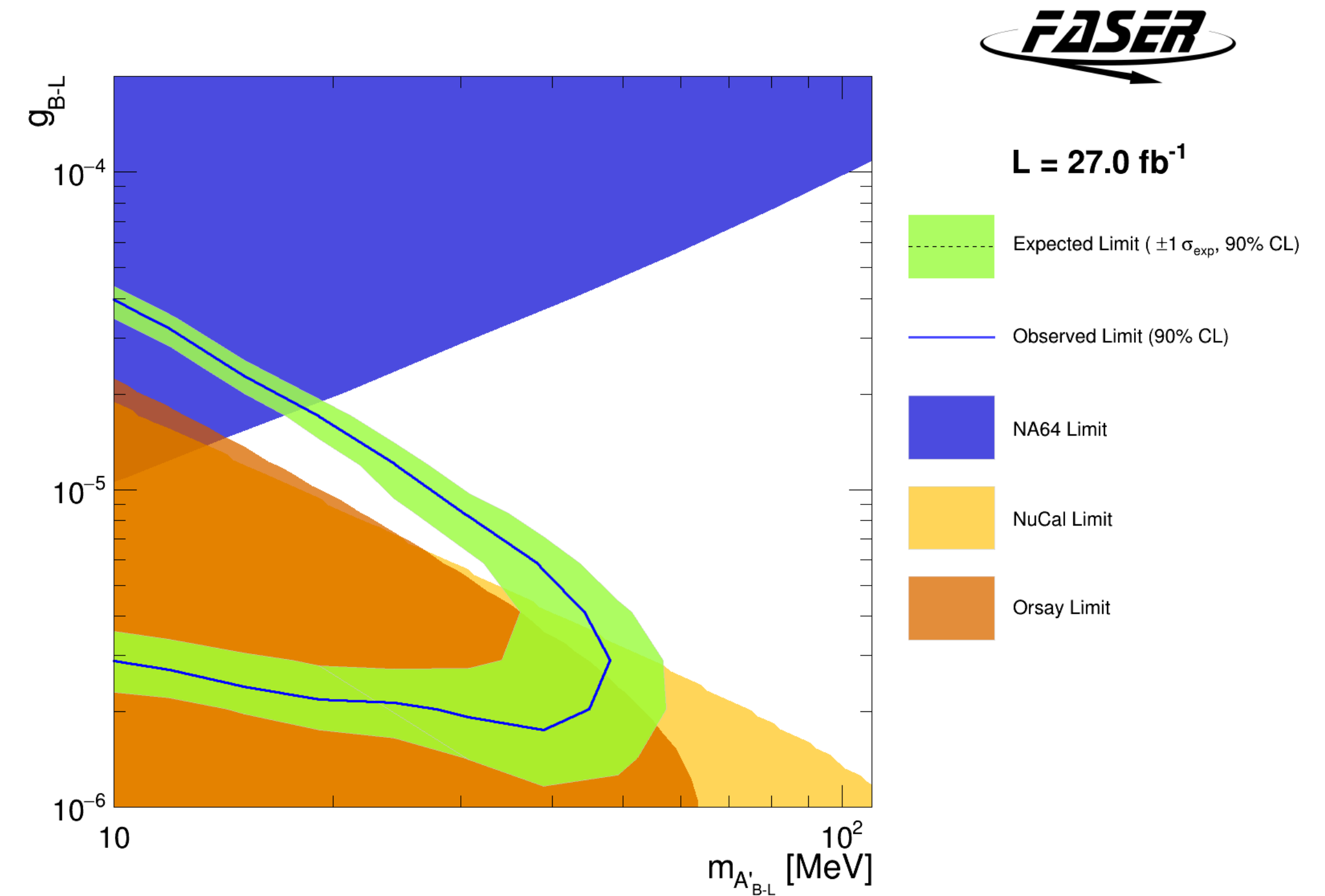
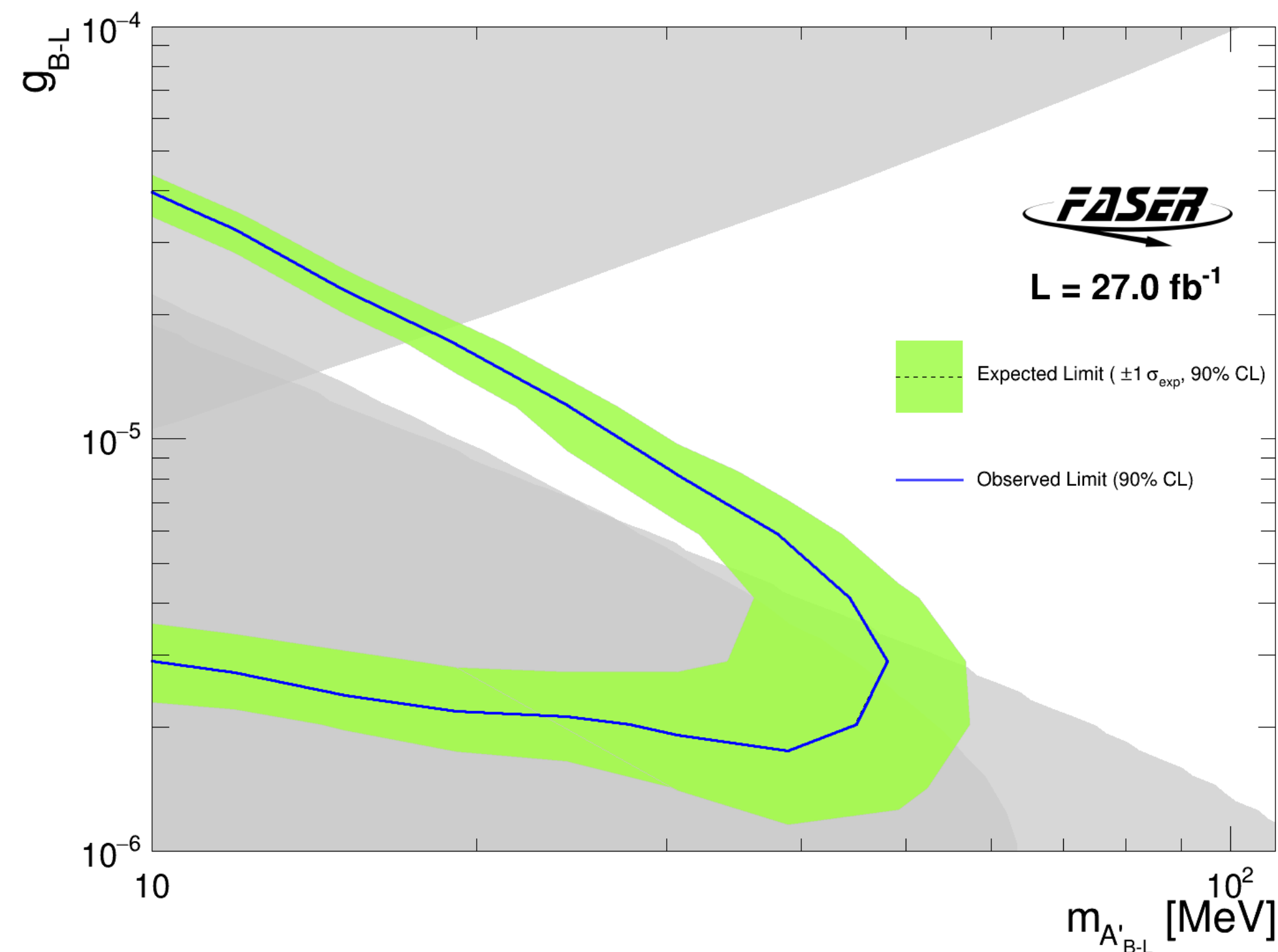
Dark Photon Search | Limits

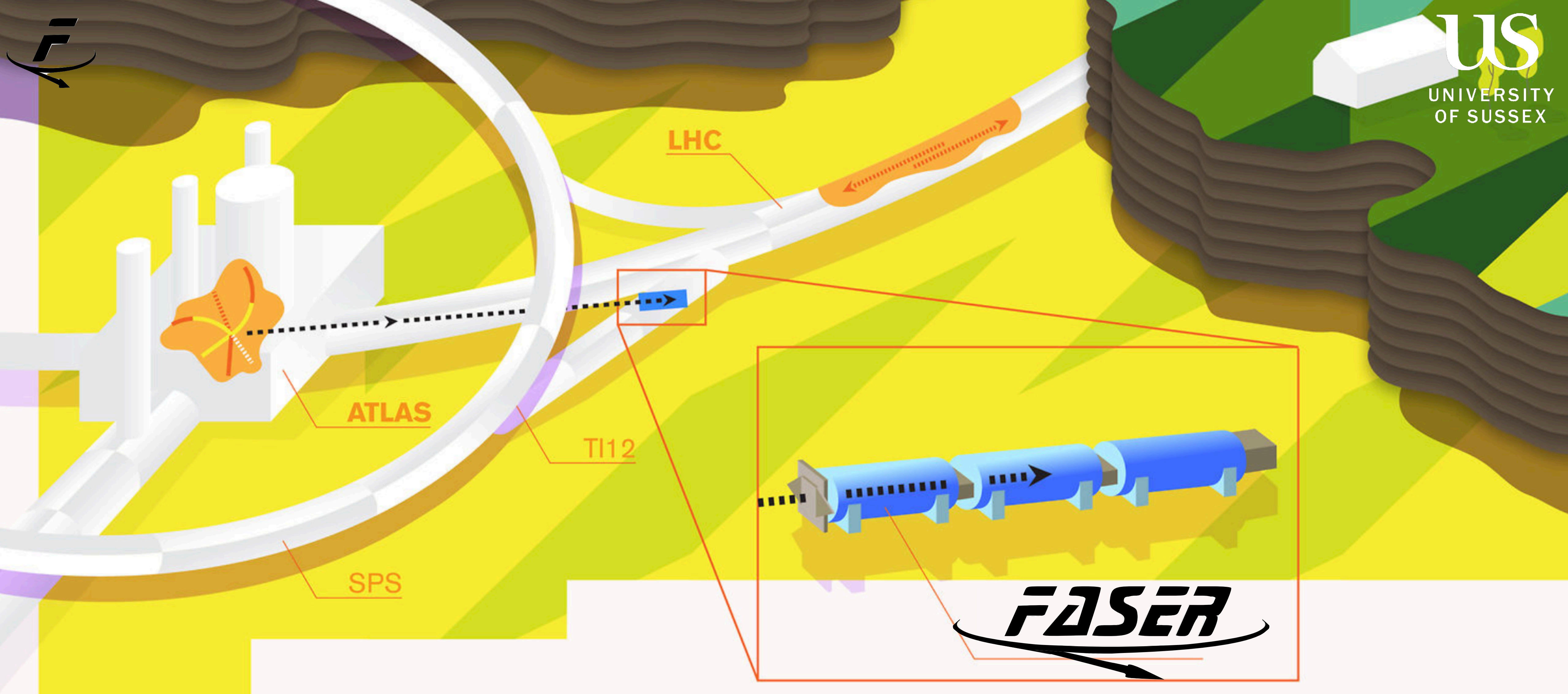
- ▶ After unblinding, no events seen in signal region, FASER sets limits on previously unexplored parameter space.
- ▶ First incursion (with NA62) into thermal relic region from low ε since 1990's.
- ▶ Background-free analysis bodes well for future sensitivity.
- ▶ Expect $\sim 10\text{fb}^{-1}$ luminosity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



B-L Gauge Boson Search | Limits

- ▶ The region probed is cosmologically relevant
 - ▶ Assuming a dark matter particle with mass $\frac{1}{2}m(A'_{B-L}) - m(A'_{B-L})$ & 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.

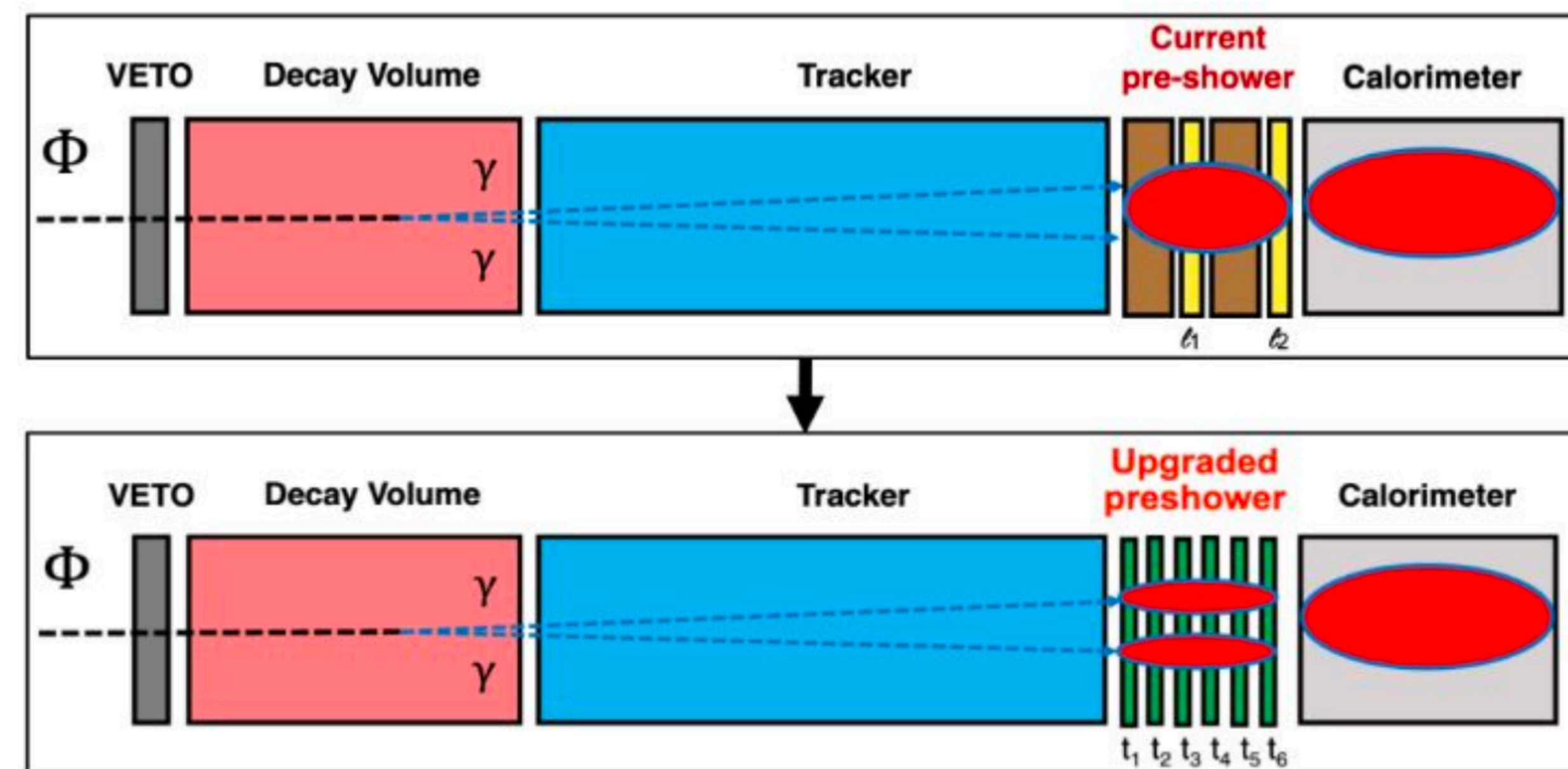




Next for FASER

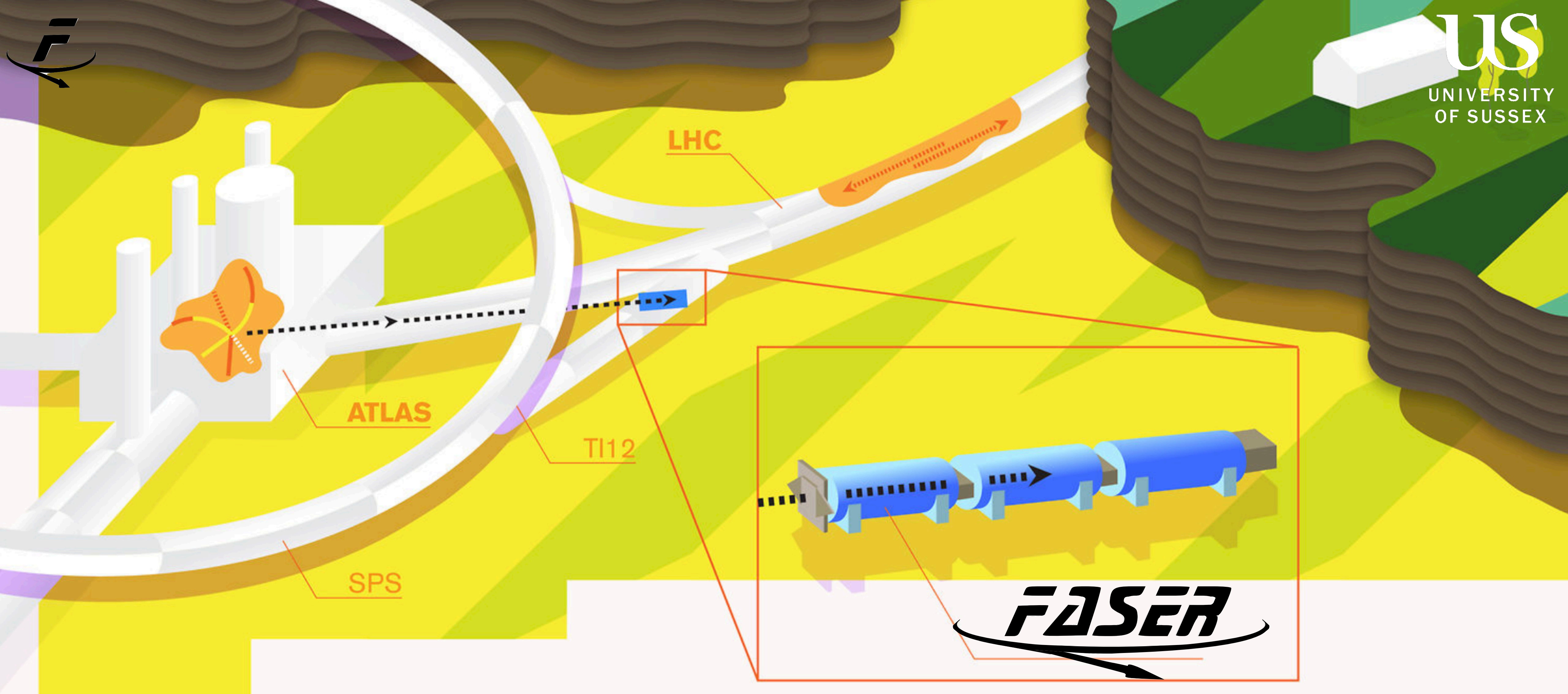
► Preshower Upgrade

- 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/FASERv2 in the planned Forward Physics Facility (FPF) during the HL-LHC era



Forward Physics Facility

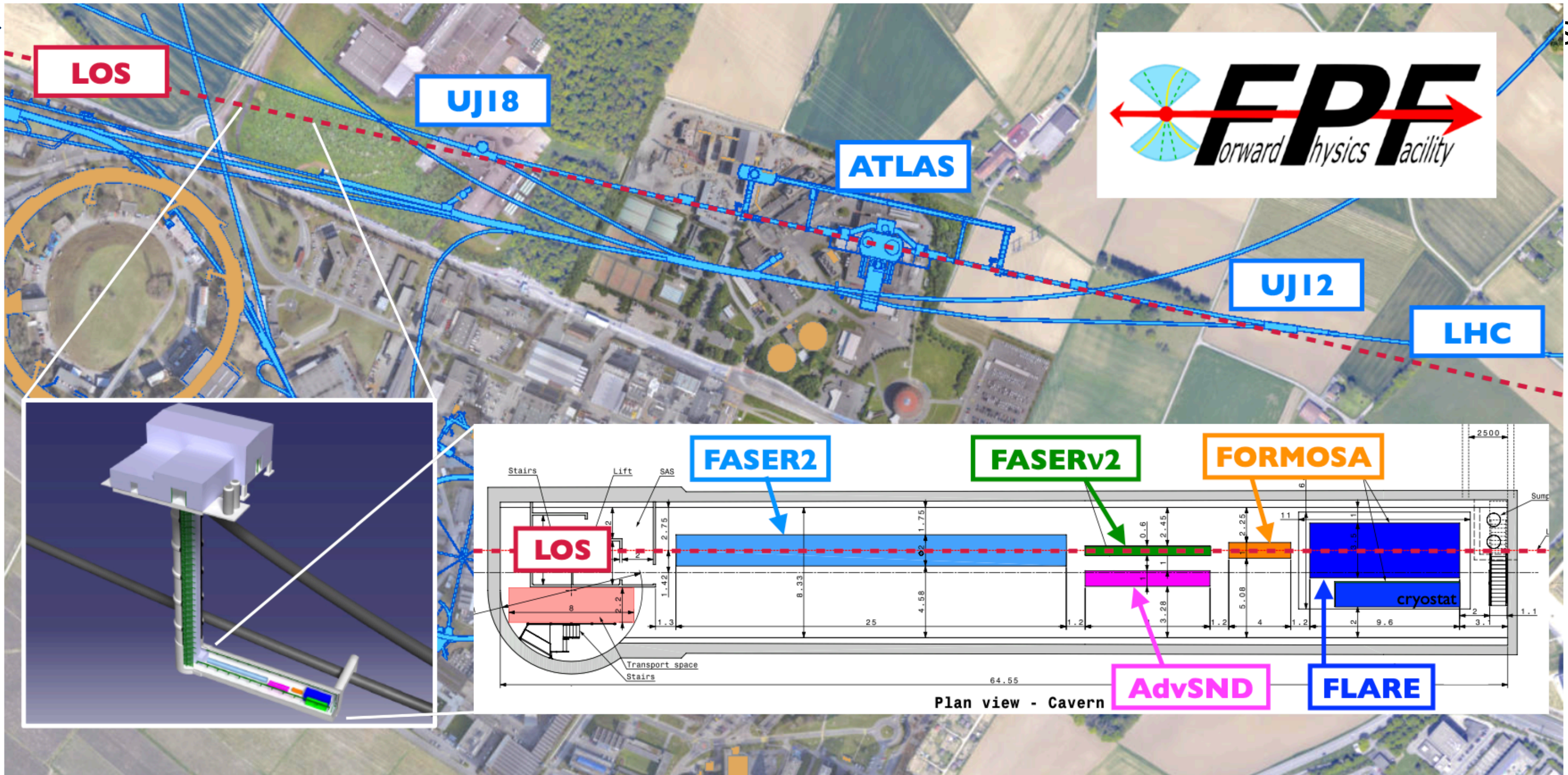
- ▶ FASER, FASER ν , and other proposed detectors are currently highly **constrained by tunnels and infrastructure** that was never designed to support experiments.
- ▶ At the same time, it is becoming clear that there is a **rich physics program in the far-forward region**, spanning long-lived particle 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



- ▶ 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 construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades”*



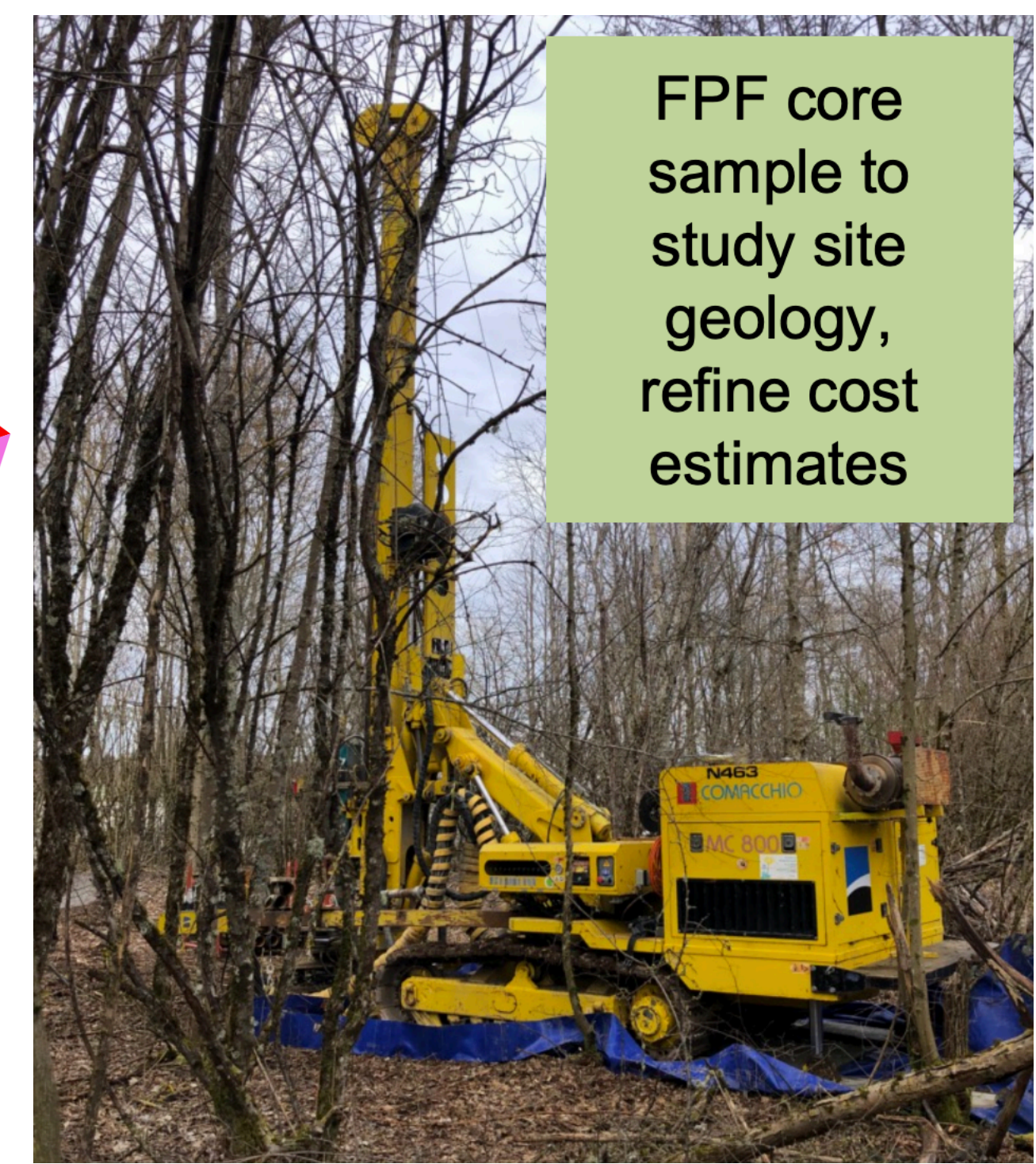
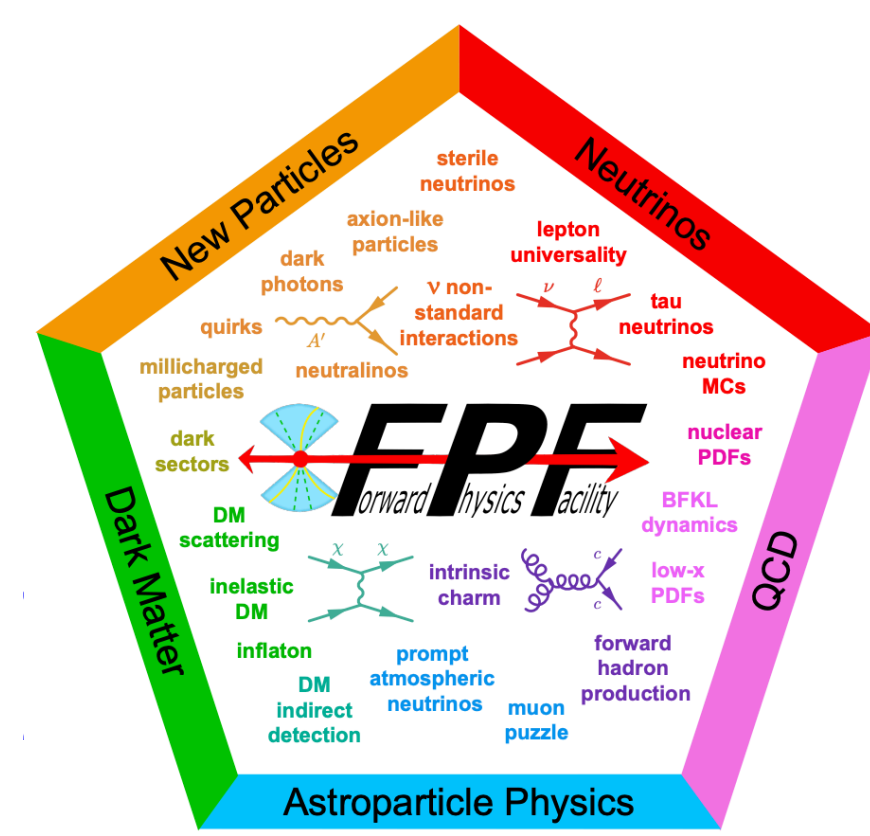
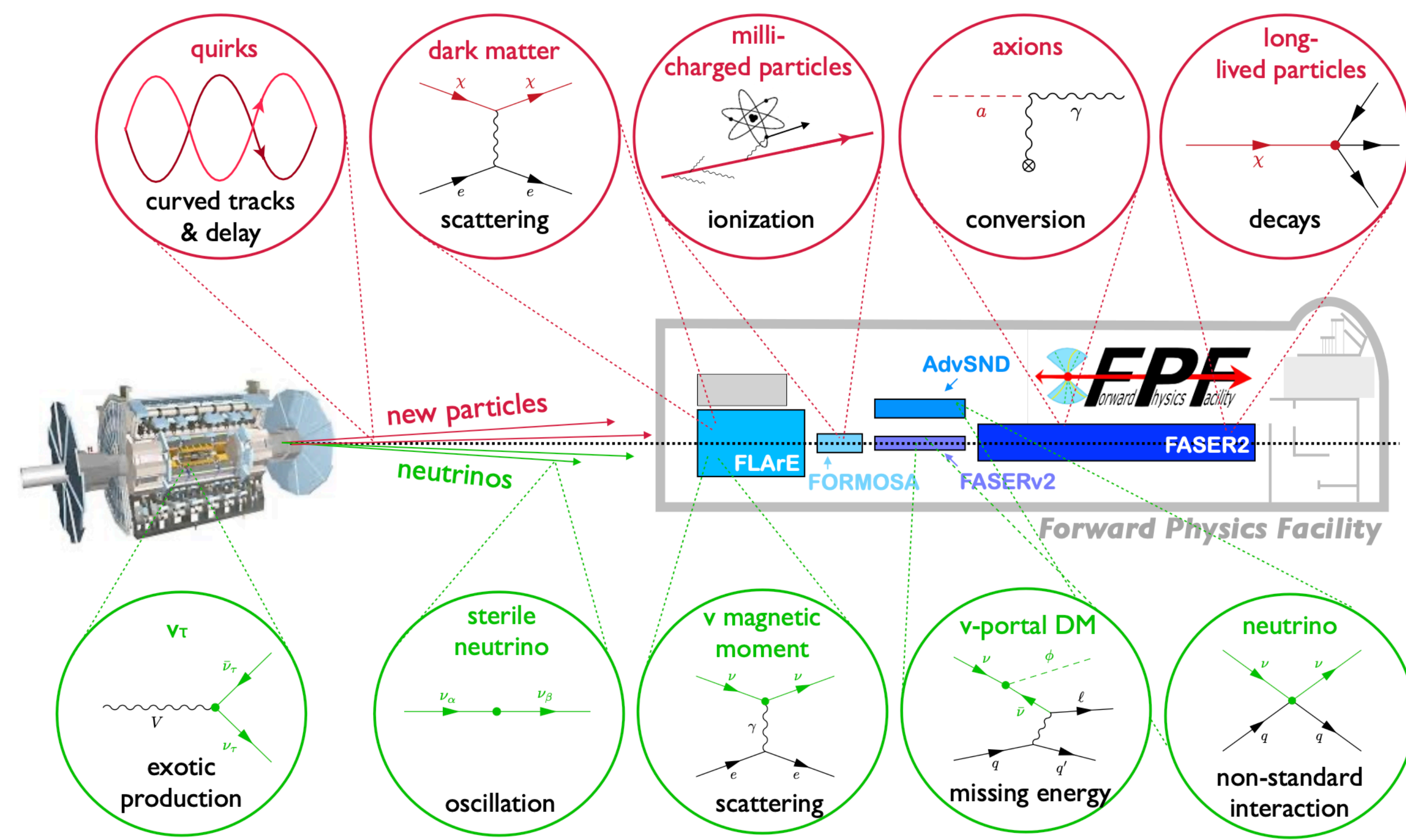
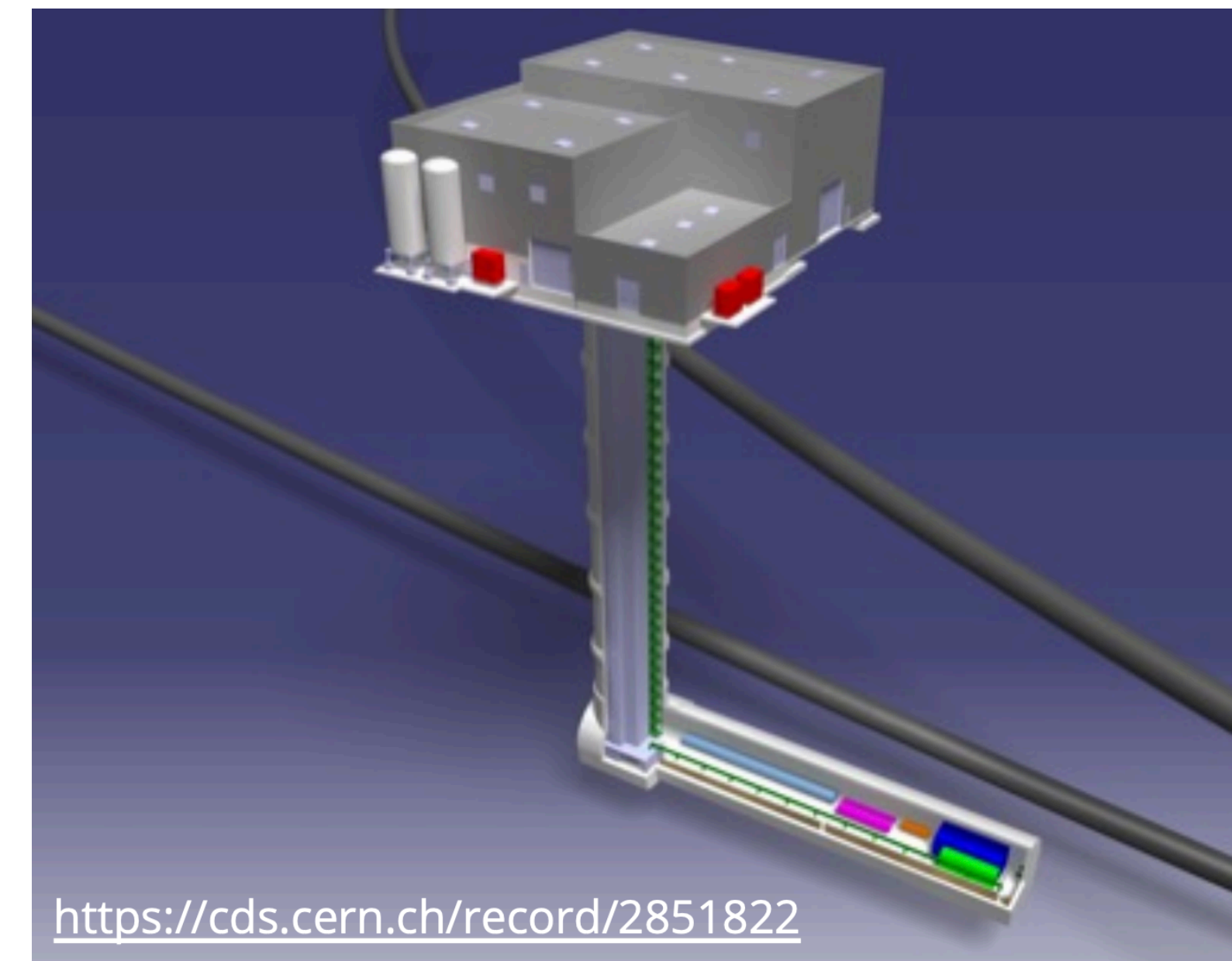
Forward Physics Facility



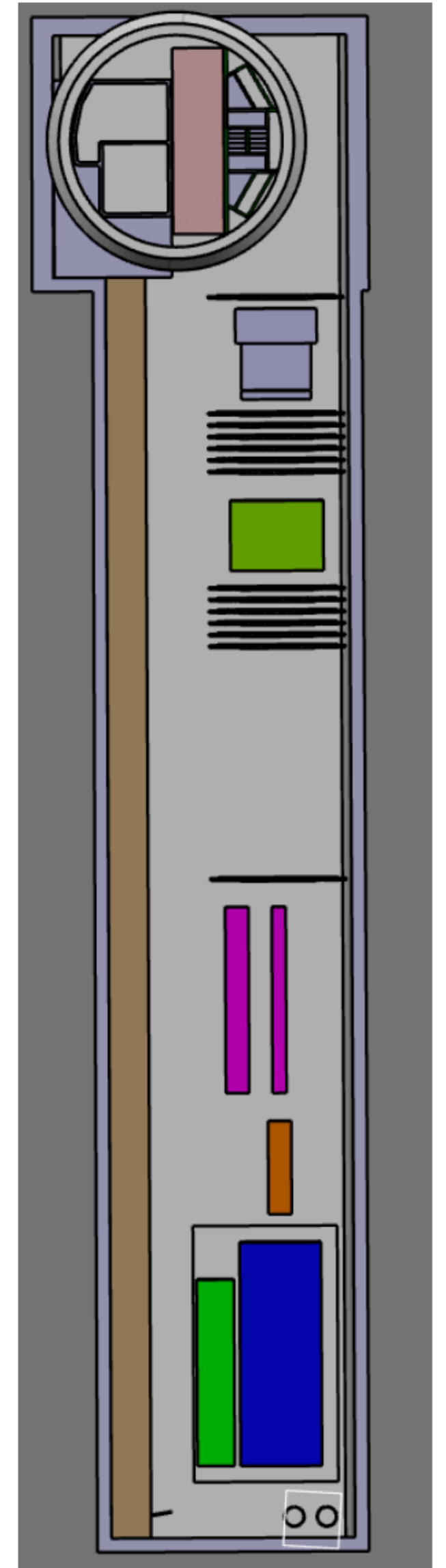
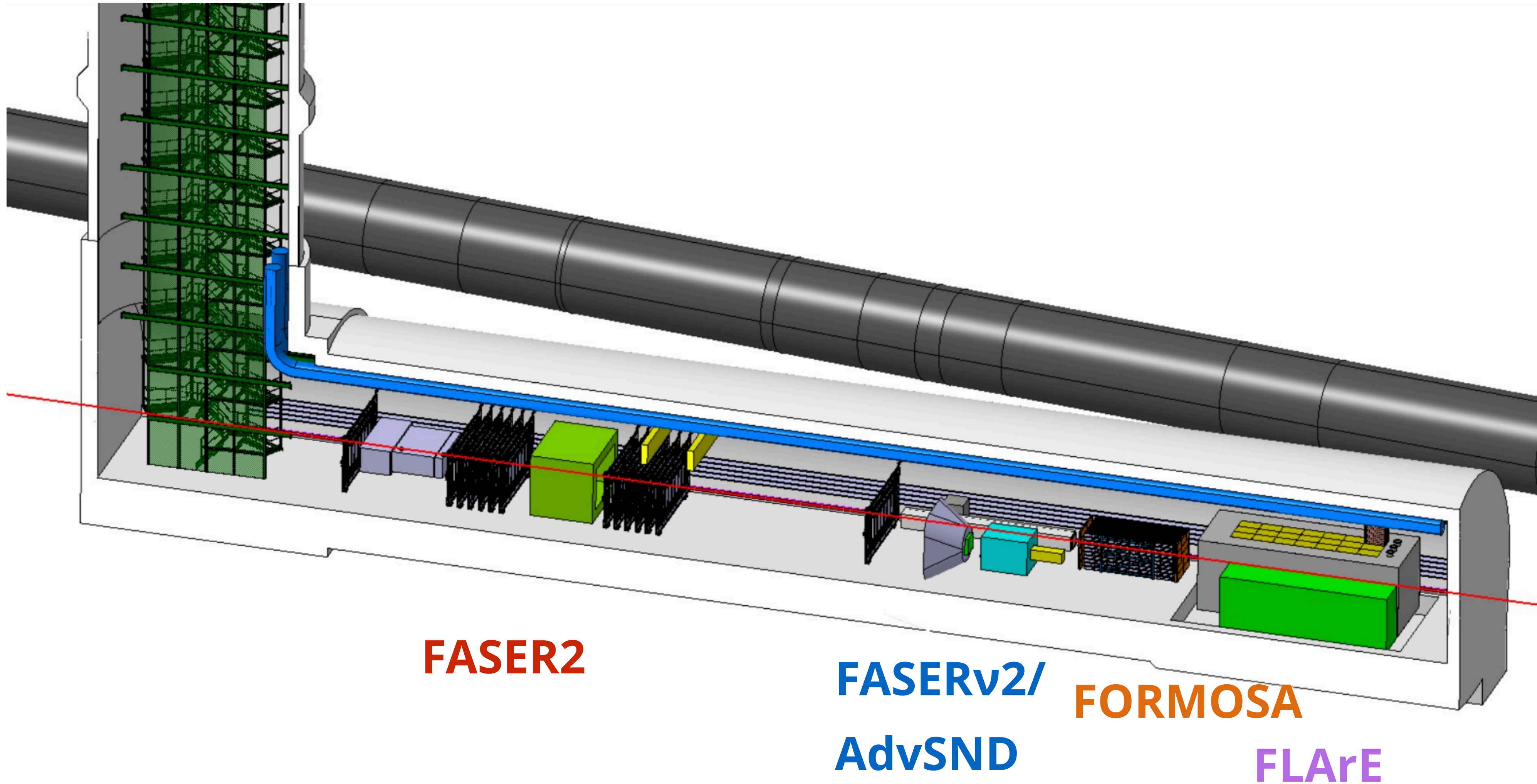
Forward Physics Facility

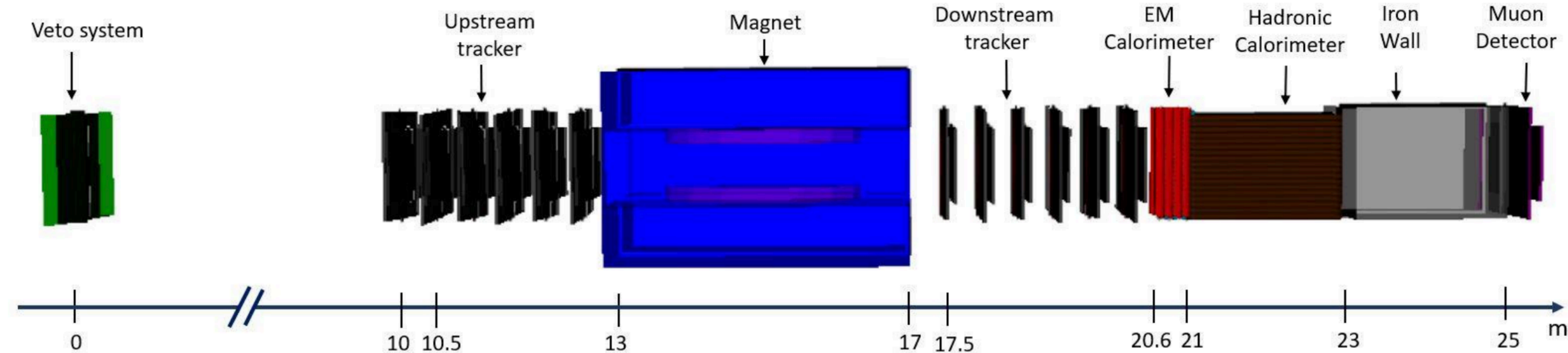
► FPF Papers:

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

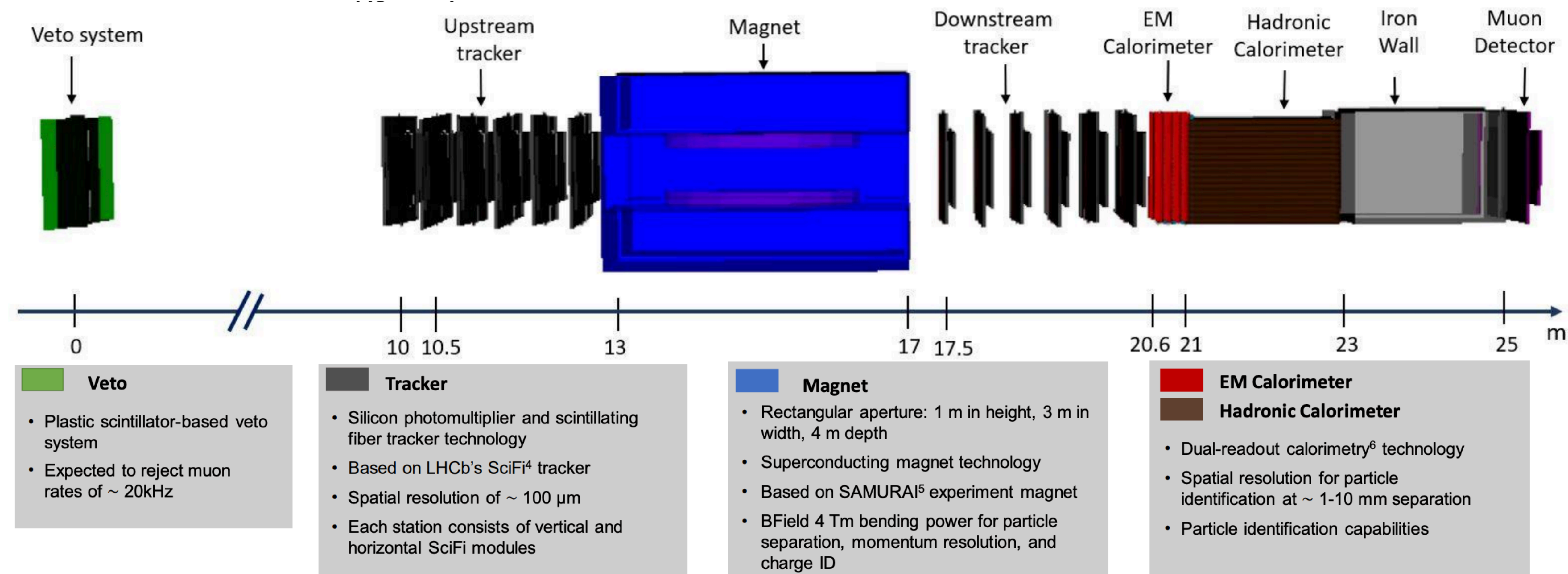


► Hot off the press!

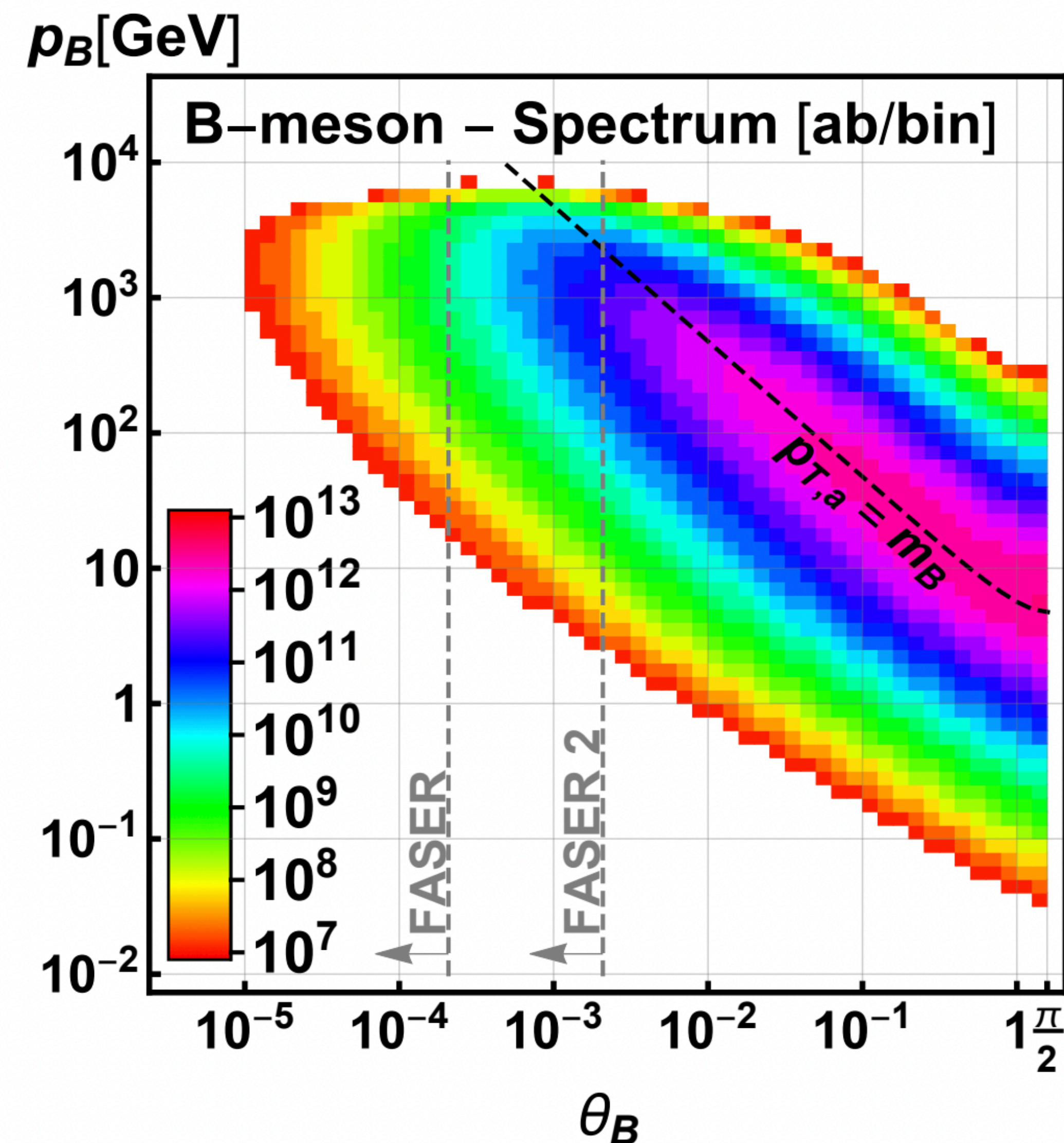




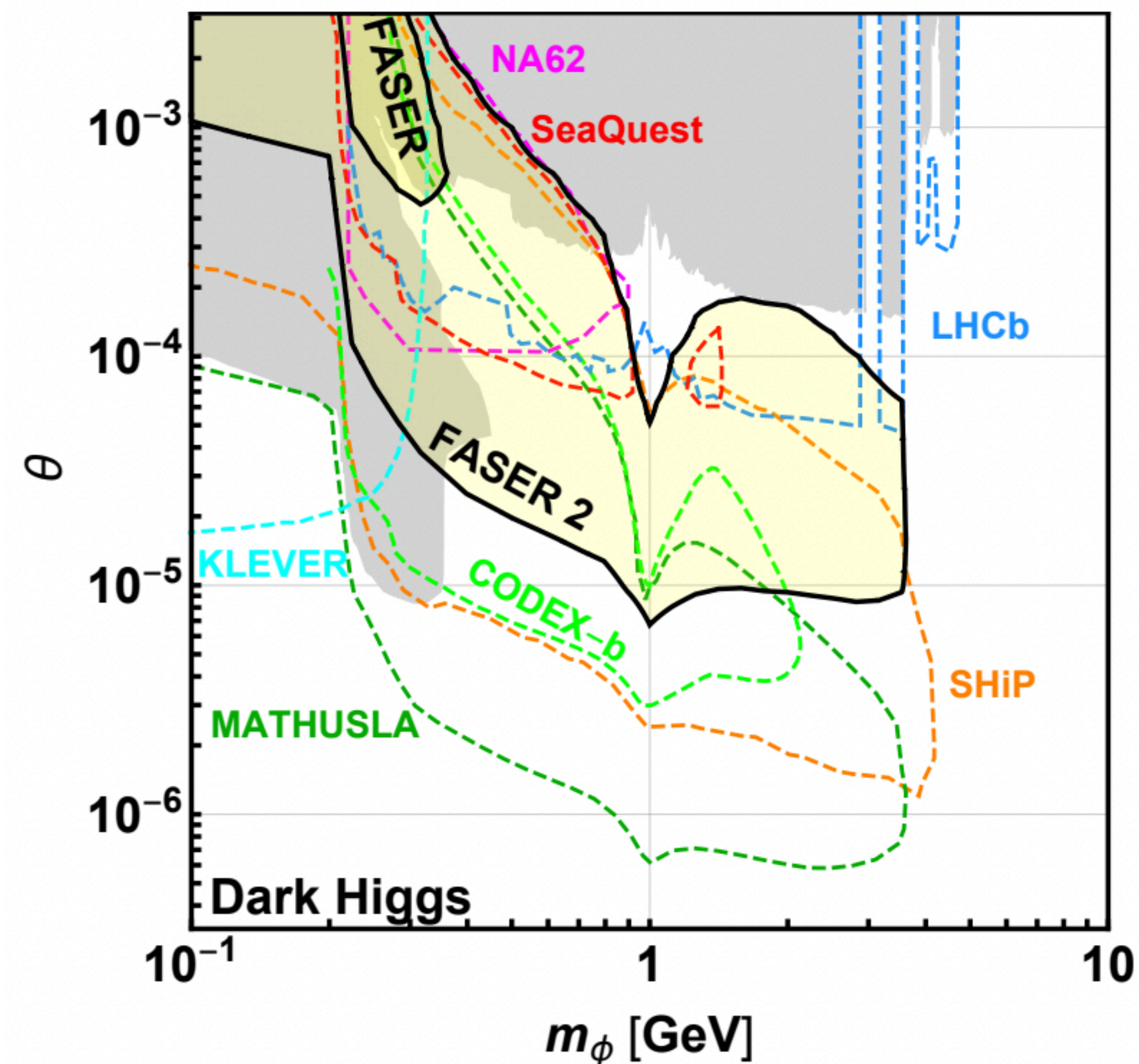
- ▶ Proof of principle now exists from FASER
- ▶ Slightly different design philosophy limited by large aperture magnet technologies
- ▶ Program for BSM and SM physics (main spectrometer to neutrino exps.)
- ▶ Currently considering, SciFi tracker and dual-readout calorimetry.



- 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.



- ▶ 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)



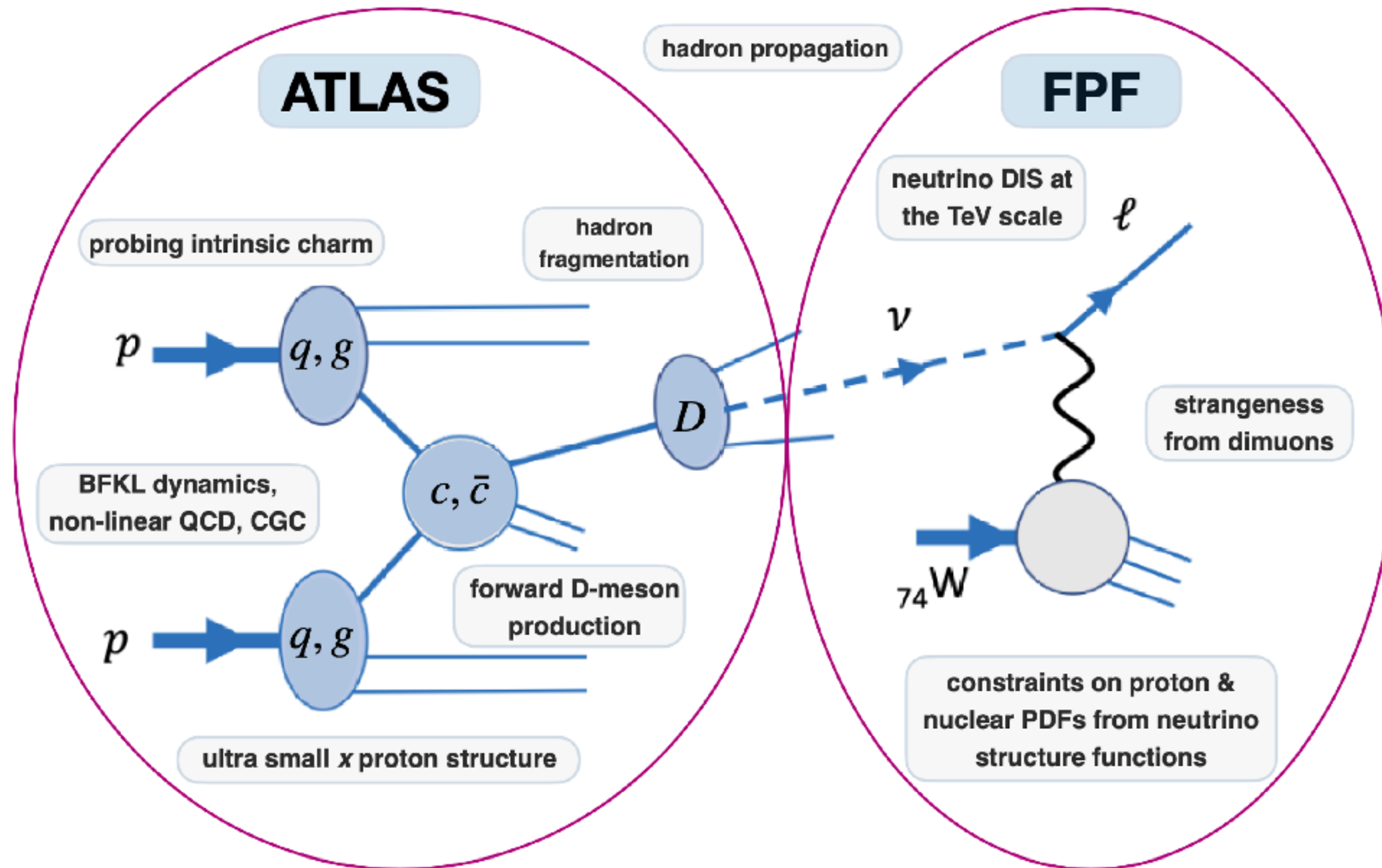
- ▶ FASER2 ($R = 1$ m, $L = 5$ -20 m) can discover
 - ▶ All candidates with renormalizable couplings (dark photon, dark Higgs, HNL)
 - ▶ ALPs with all types of couplings (γ , f , g)
 - ▶ and many other particles.
- ▶ Among the PBC benchmark scenarios, FASER2's discovery potential extends to all benchmark 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 μ	–	✓
BC8: HNL with τ	✓	✓
BC9: ALP with photon	✓	✓
BC10: ALP with fermion	✓	✓
BC11: ALP with gluon	✓	✓



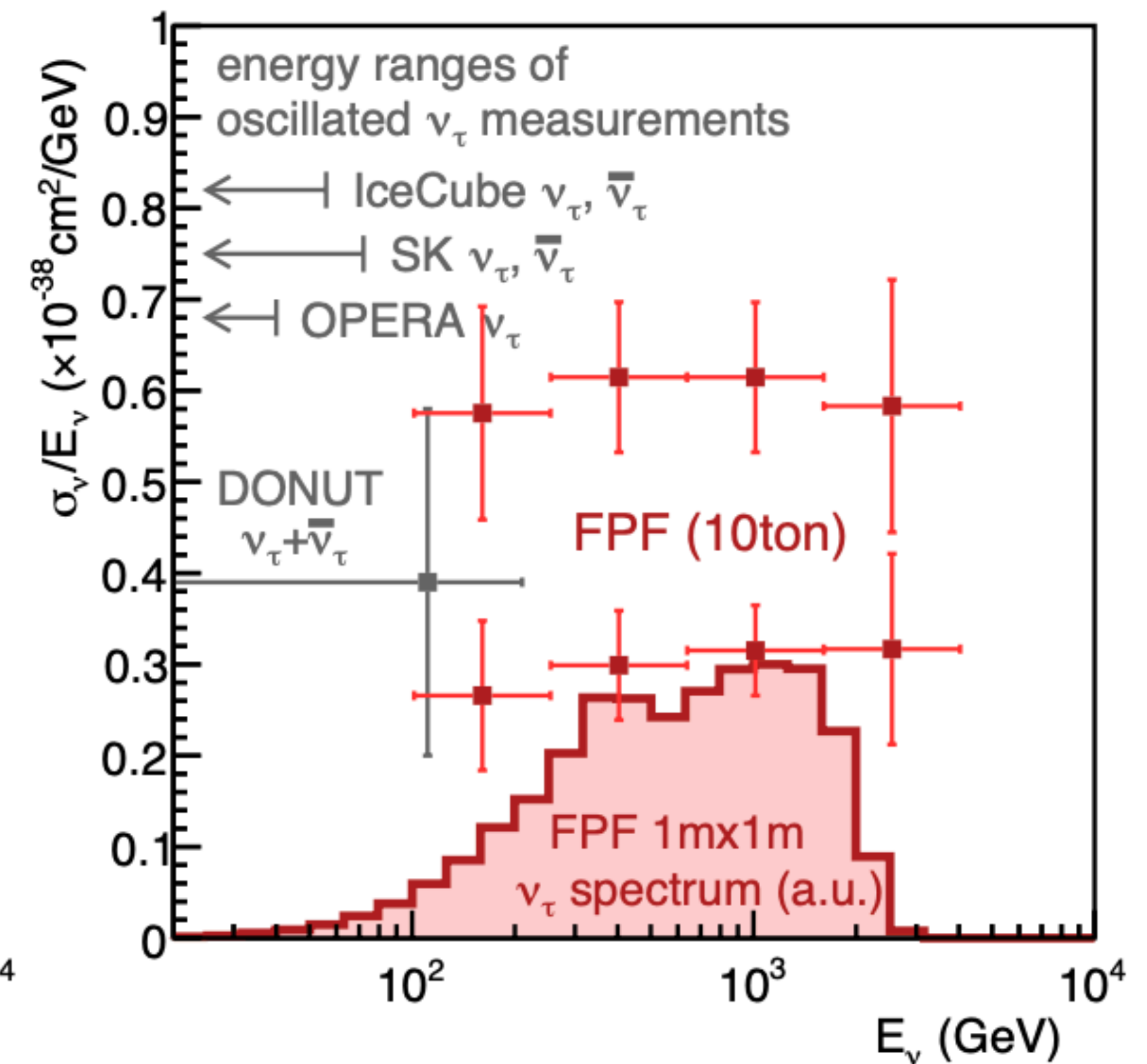
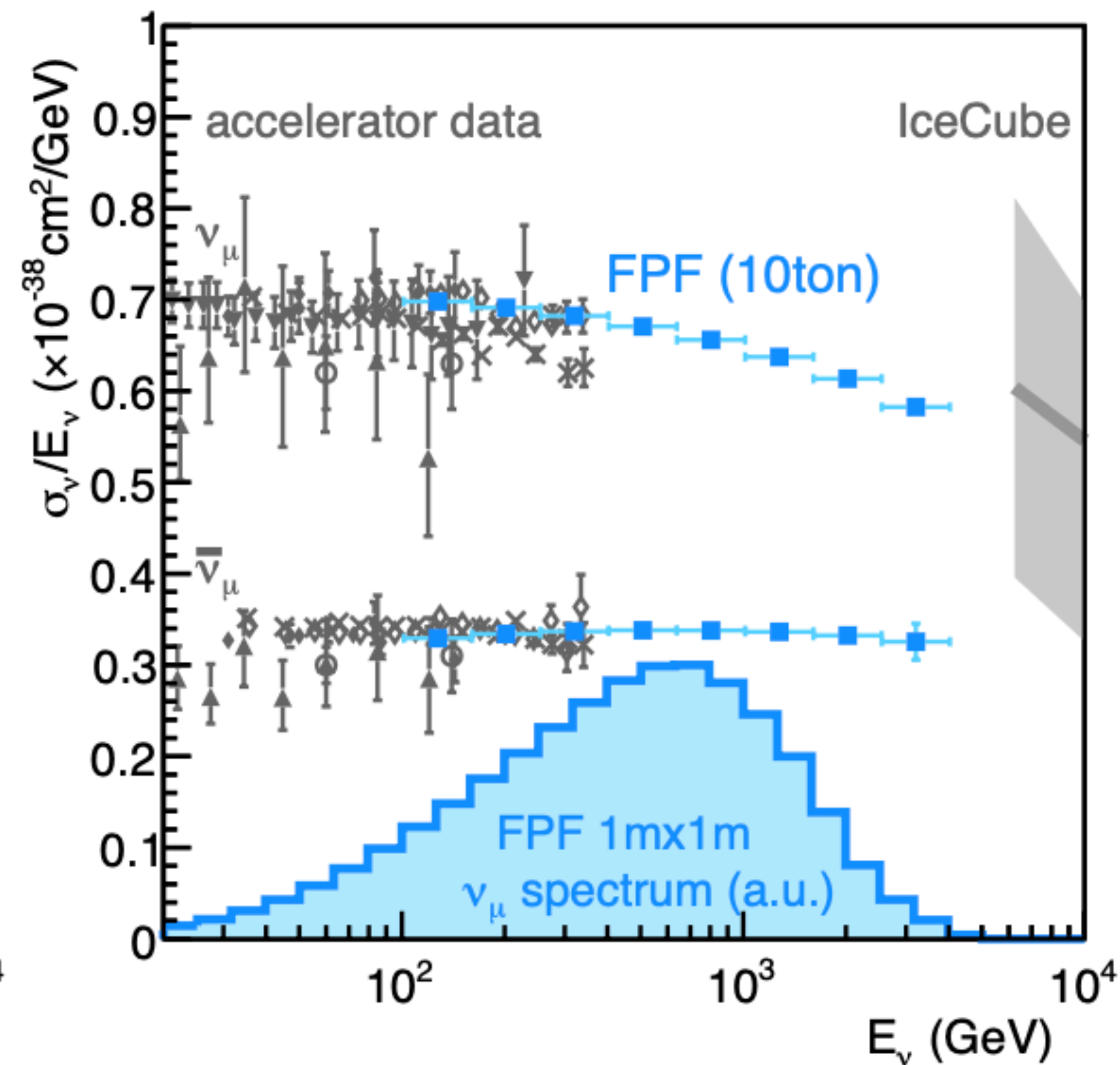
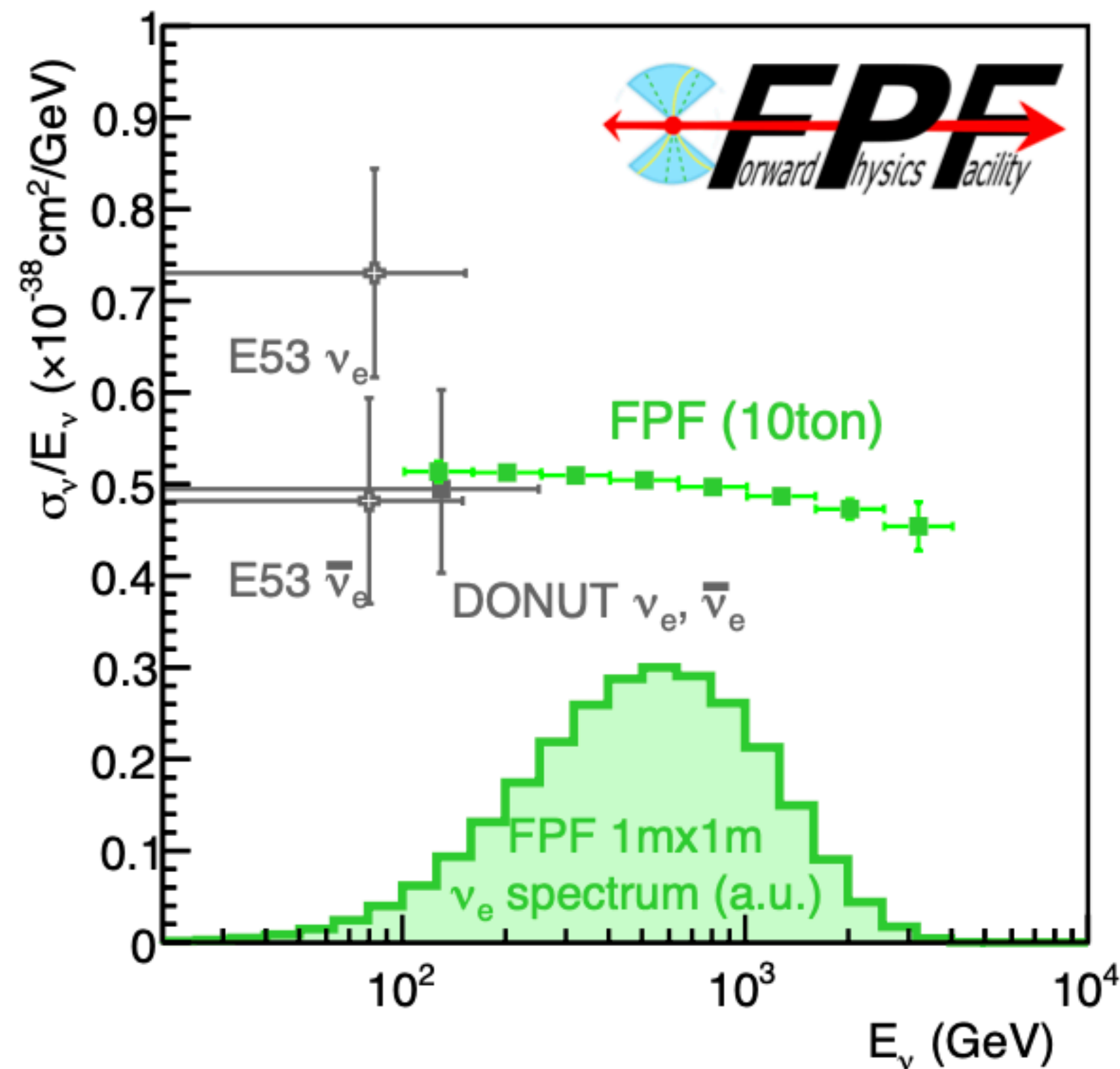
Neutrino physics

- ▶ 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

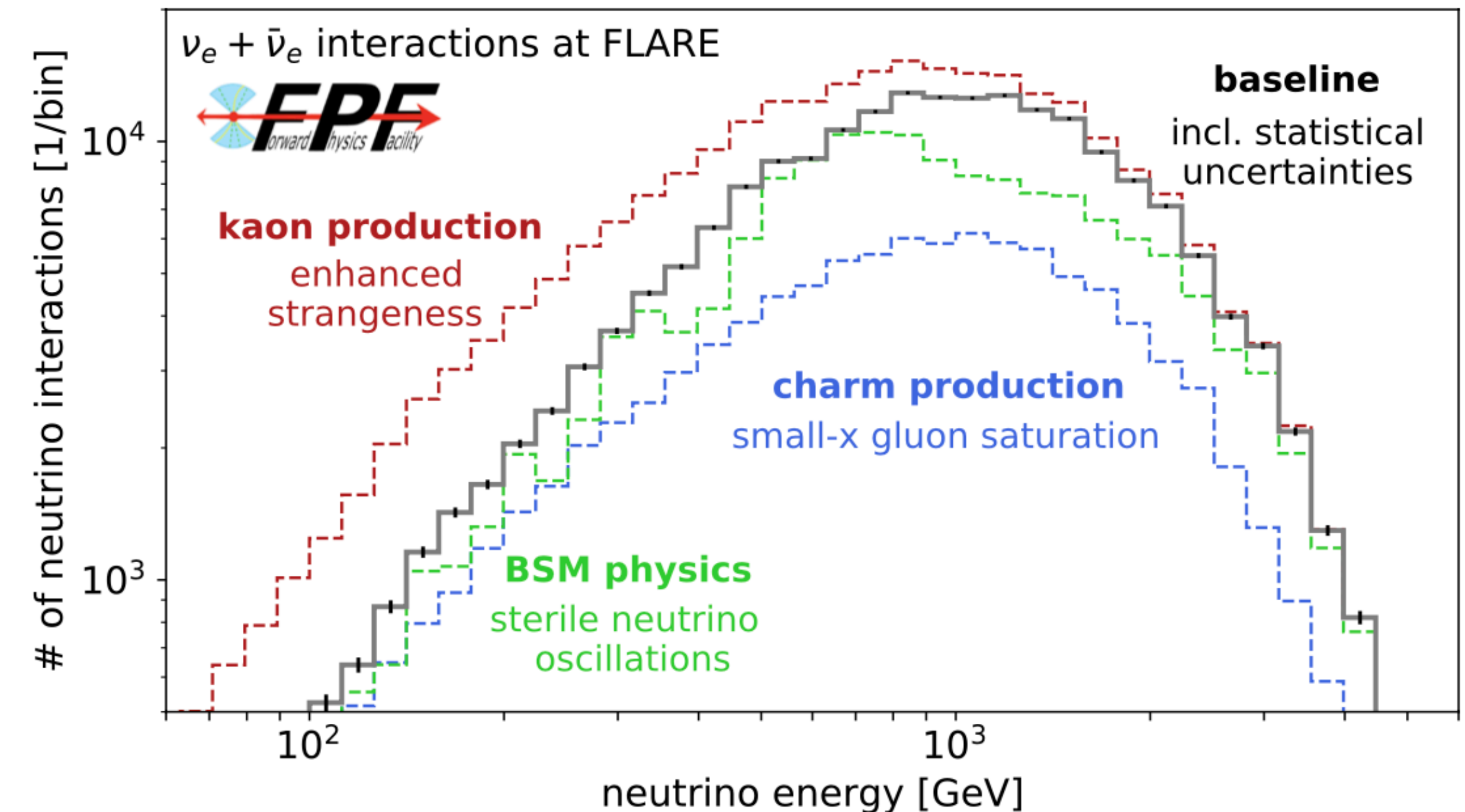


Forward Physics Facility | Neutrinos

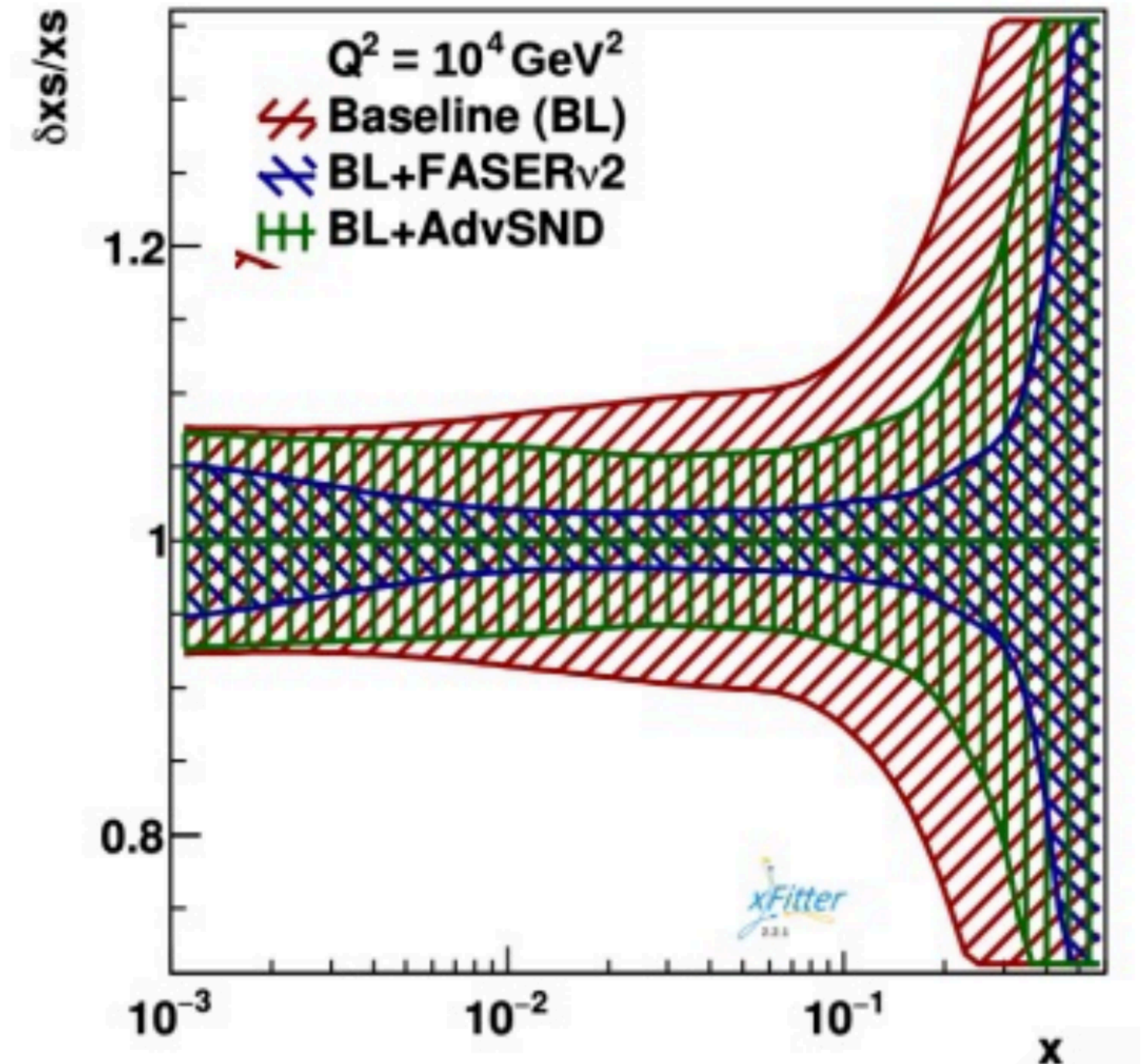
- ▶ The FPF experiments will see $10^5 \nu_e$, $10^6 \nu_\mu$ and $10^4 \nu_\tau$ interactions at $E \sim \text{TeV}$ where there is currently no data



- ▶ 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, ...
- ▶ Neutrino properties: short-baseline neutrino experiment. Sensitive to sterile neutrinos



- ▶ Neutrinos are produced by forward hadron production: π , K, D...
- ▶ A neutrino-ion collider!
- ▶ 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, ...
 - ▶ Neutrino properties [\[arXiv:2309.09581\]](#) or baseline neutrino experiment. Sensitive to sterile neutrinos
- ▶ Fully differential neutrino DIS scattering XS will improve constraints on pdfs



[\[arXiv:2309.09581\]](#)

Forward Physics Facility | UK

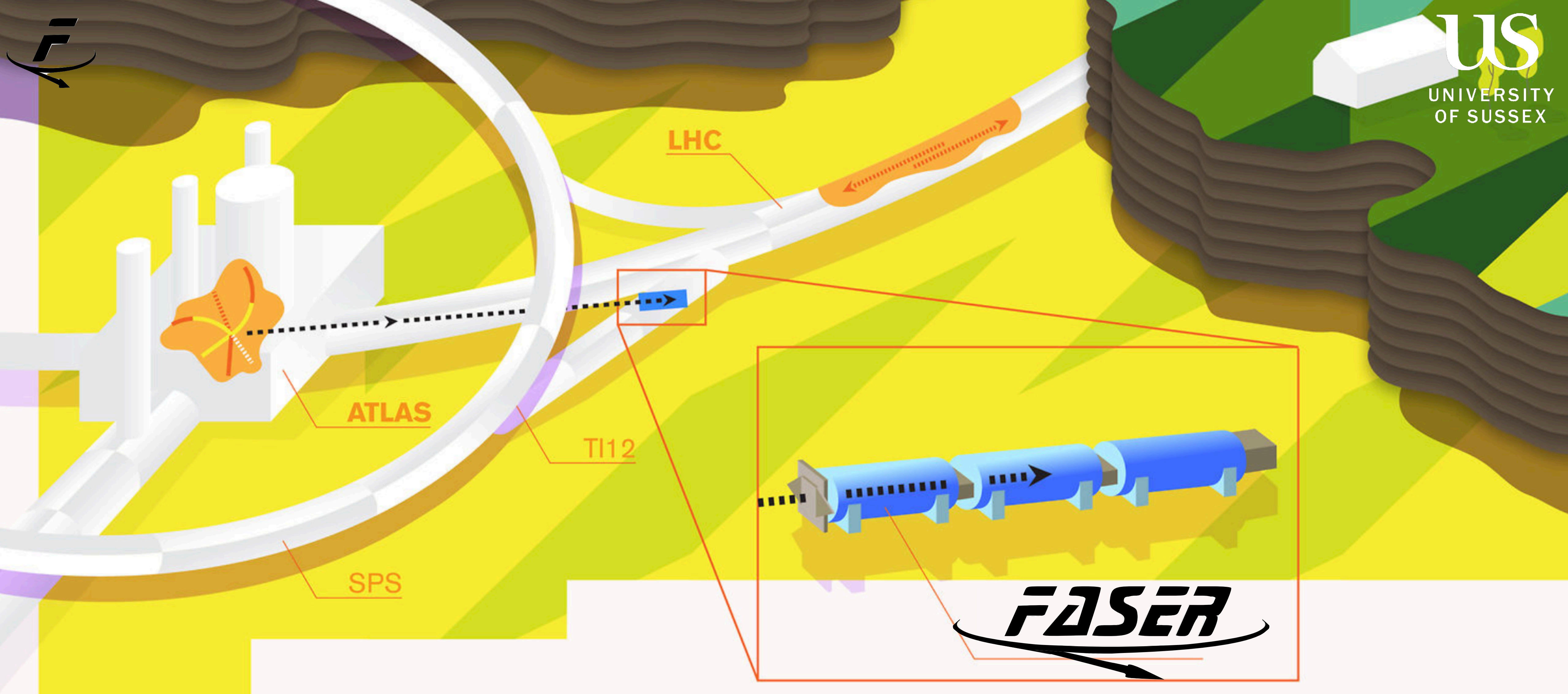


- ▶ Significant input from UK institutes in FPF R&D
 - ▶ Emphasis on FASER2, beam sim. and theory so far.
- ▶ Existing experiments, providing proof-of-principle for FPF, running successfully with UK involvement and leadership.
- ▶ Timescale for FPF Lol to CERN in early 2025 is not too far away
 - ▶ Next step is to formalise, and ideally increase, UK participation.
 - ▶ Involving Visions and then Sol submissions to STFC.

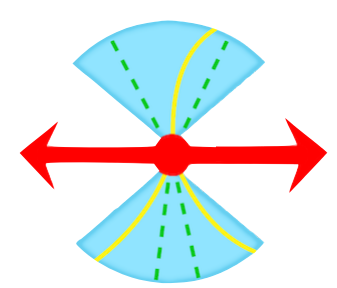


Science & Technology Facilities Council
Rutherford Appleton Laboratory



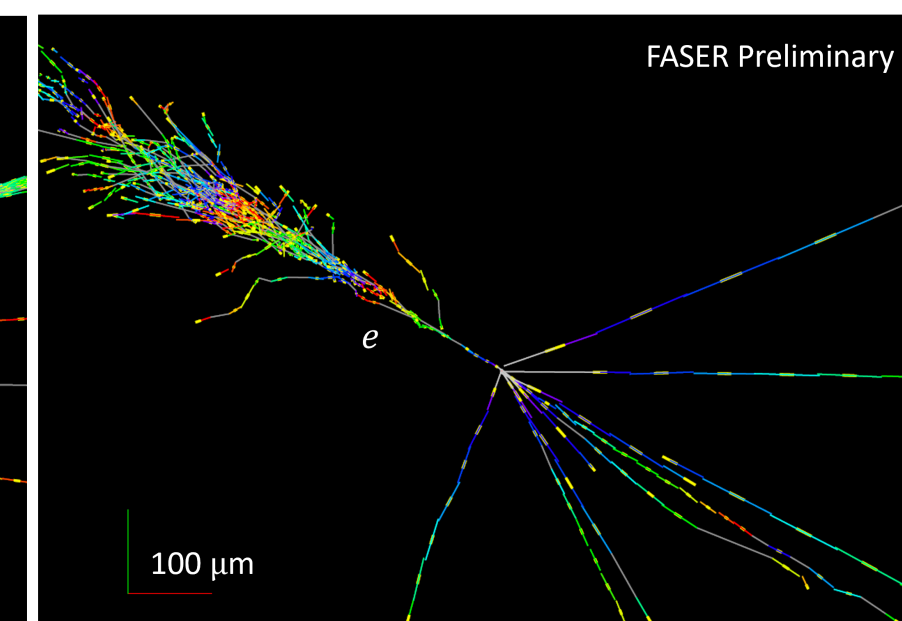
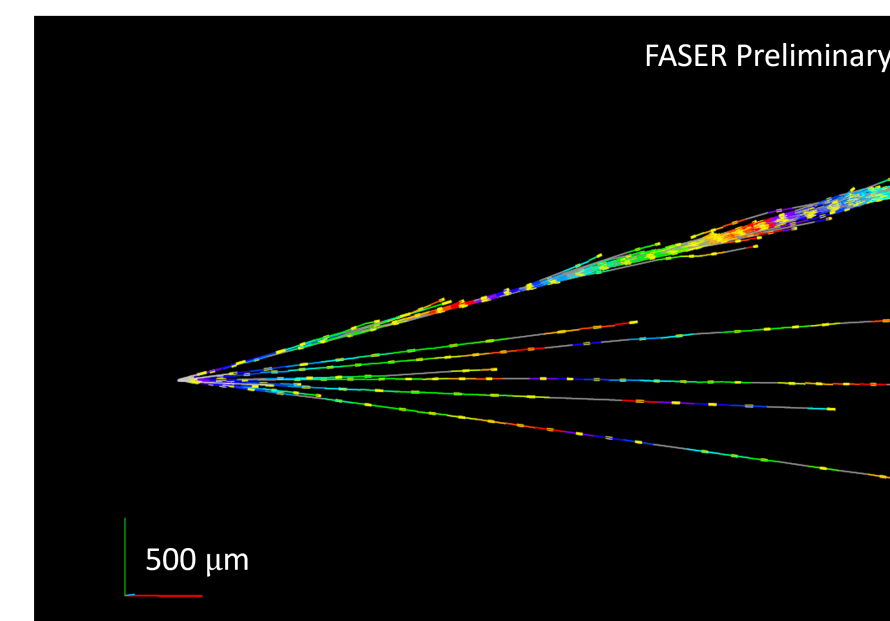
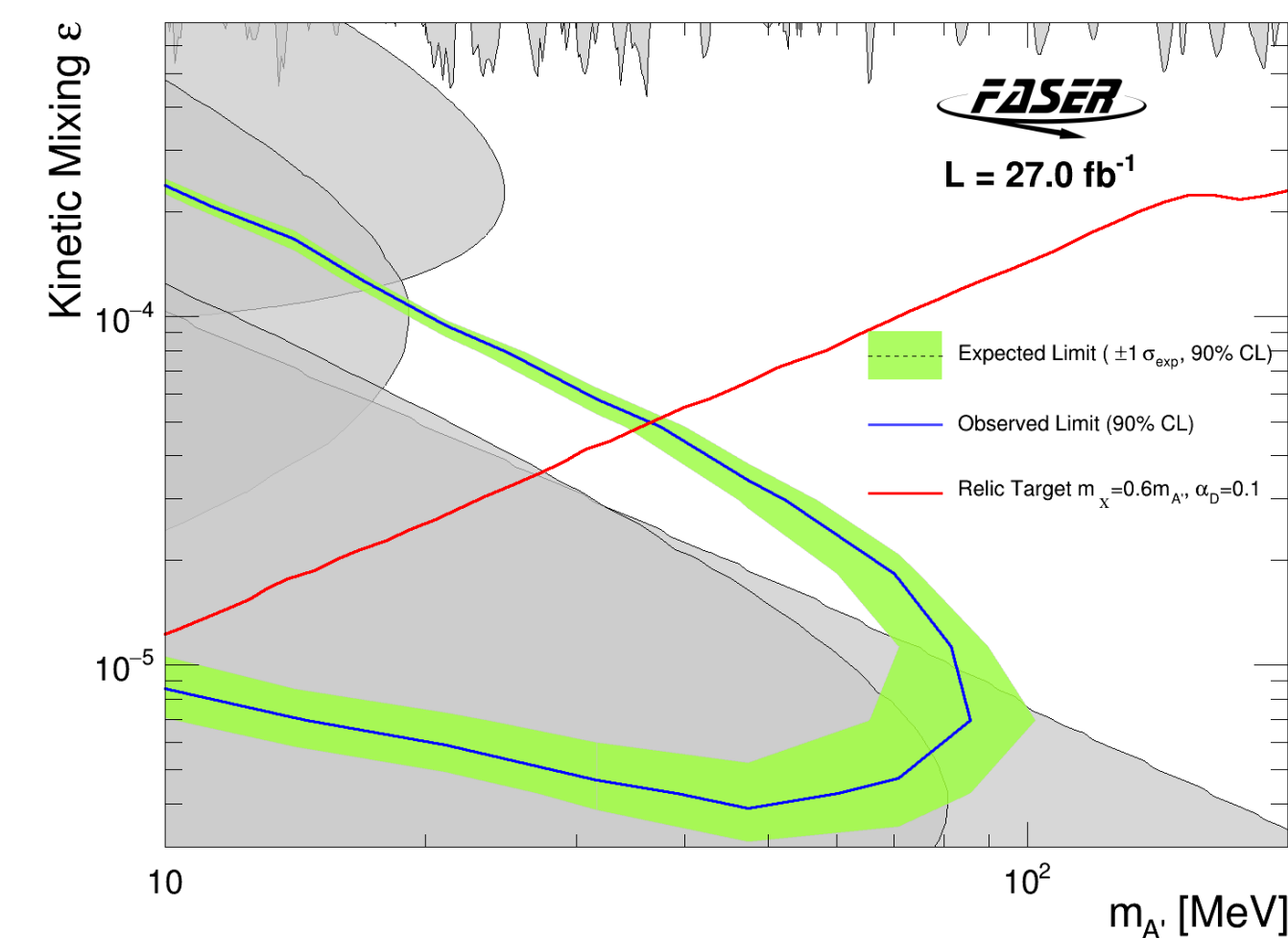
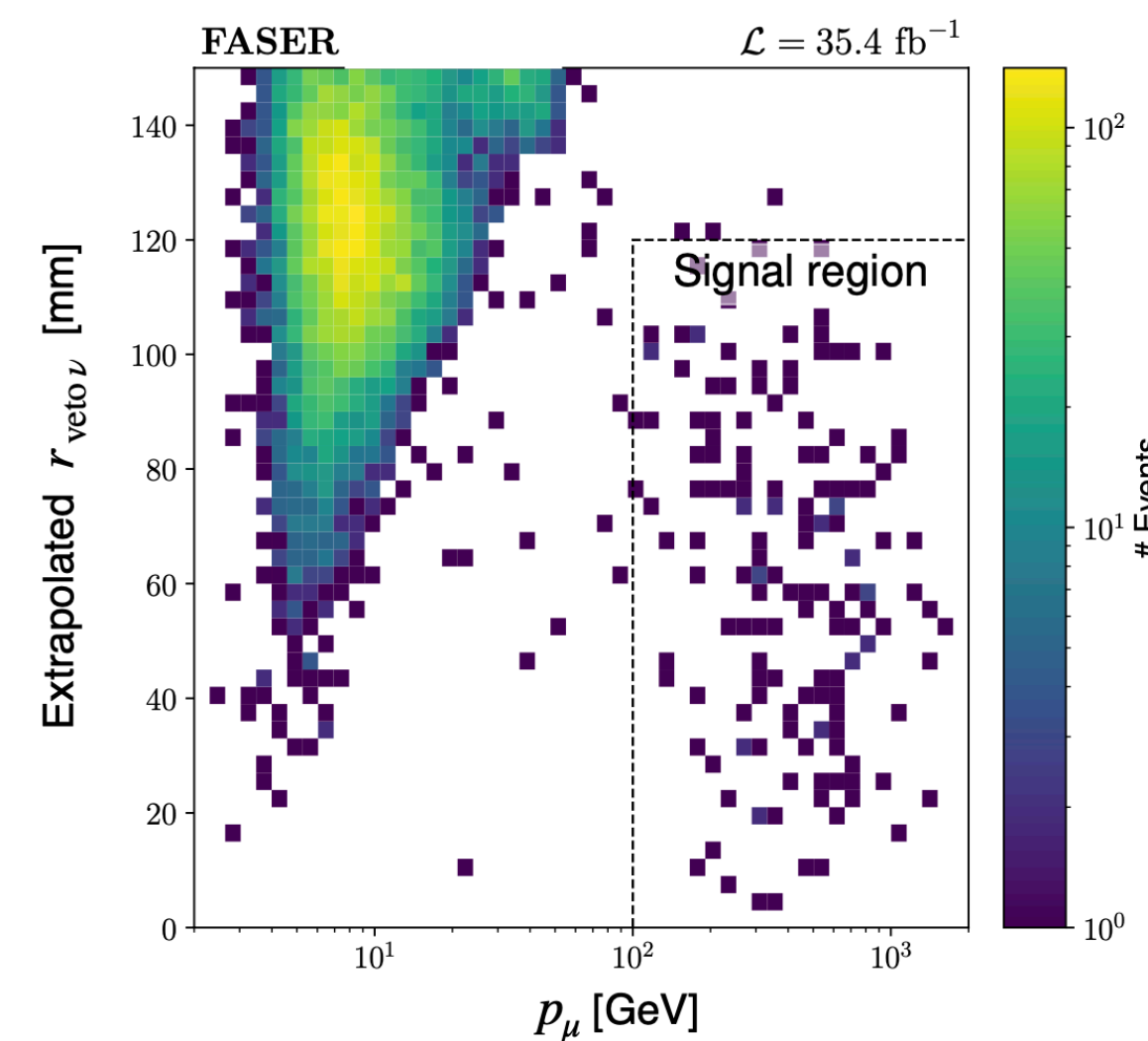


Summary



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 ν_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

- ▶ First direct observation of collider neutrinos
- ▶ Opens a new field of study and offers ways to test the limits of the standard model
- ▶ Published in *Physics Review Letters*
- ▶ First Dark Matter relic target
- ▶ First limits on the relic target
- ▶ Submitted to *Physics Review Letters*
- ▶ High-energy neutrino physics
- ▶ [CERN-FASER]
- ▶ More neutrino physics
- ▶ Including
- ▶ Strongly motivates FPF & FASER2 for HL-LHC era



Journals ▾ Physics Magazine APS News

ABOUT BROWSE PRESS COLLECTIONS

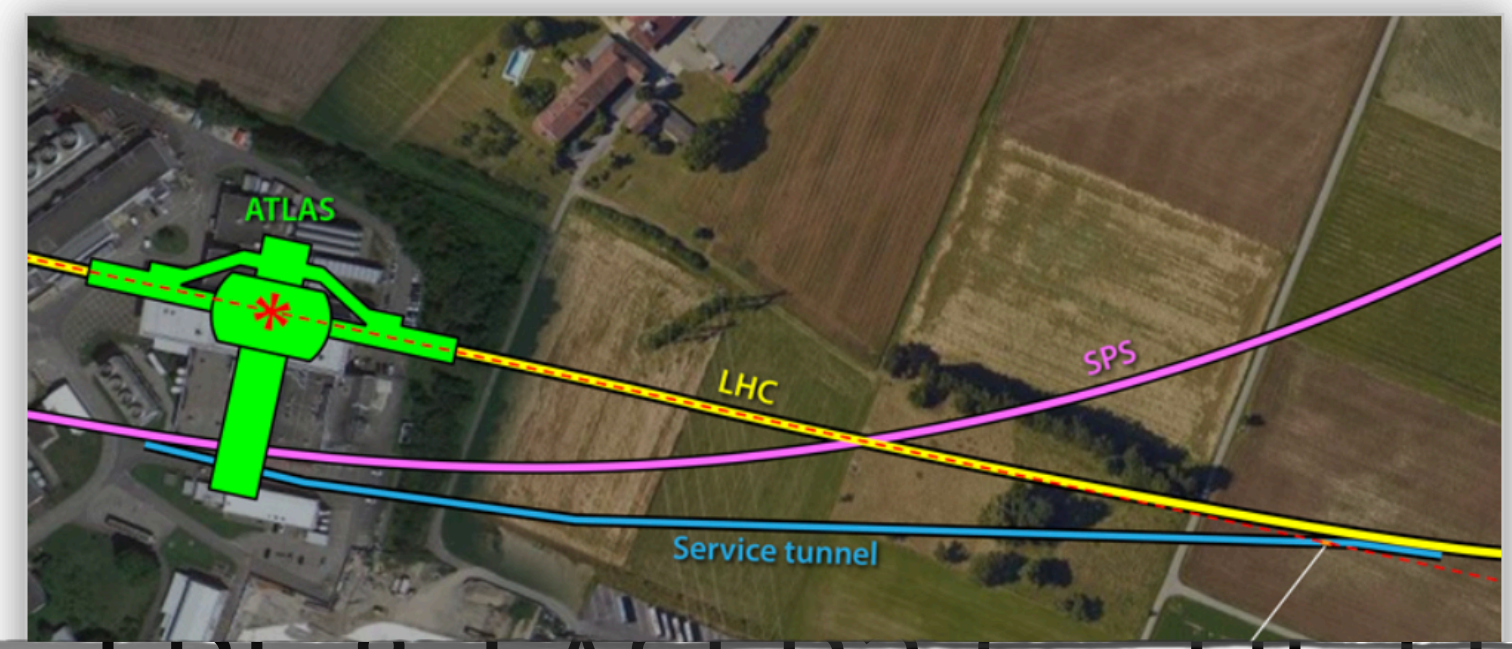
VIEWPOINT

PDF Version   

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

Read PDF

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

85

Josh McFayden | Warwick | 19/10/2023

Acknowledgements

► FASER is supported by:



- 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



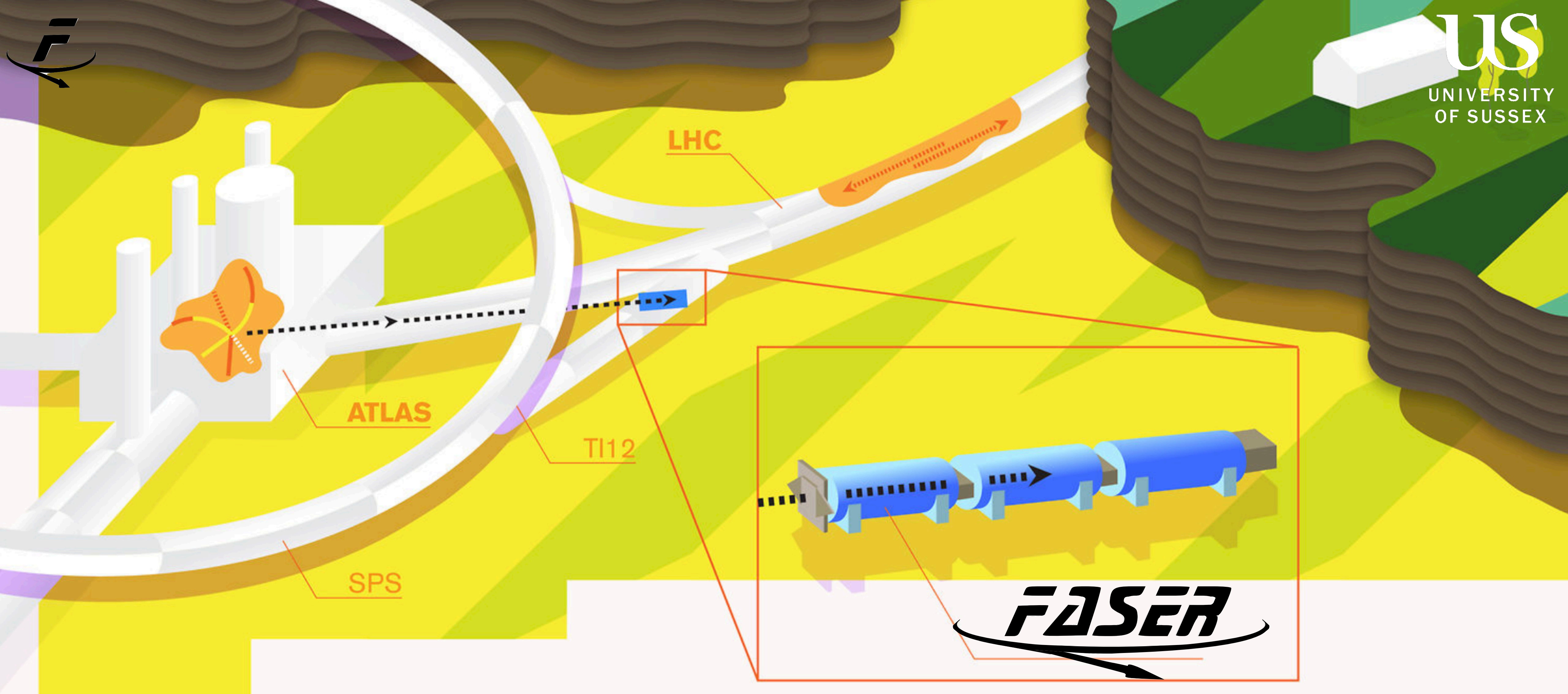
Collaboration

- ▶ 87 members
- ▶ 24 institutions
- ▶ 10 countries



International laboratory
covered by a cooperation
agreement with CERN

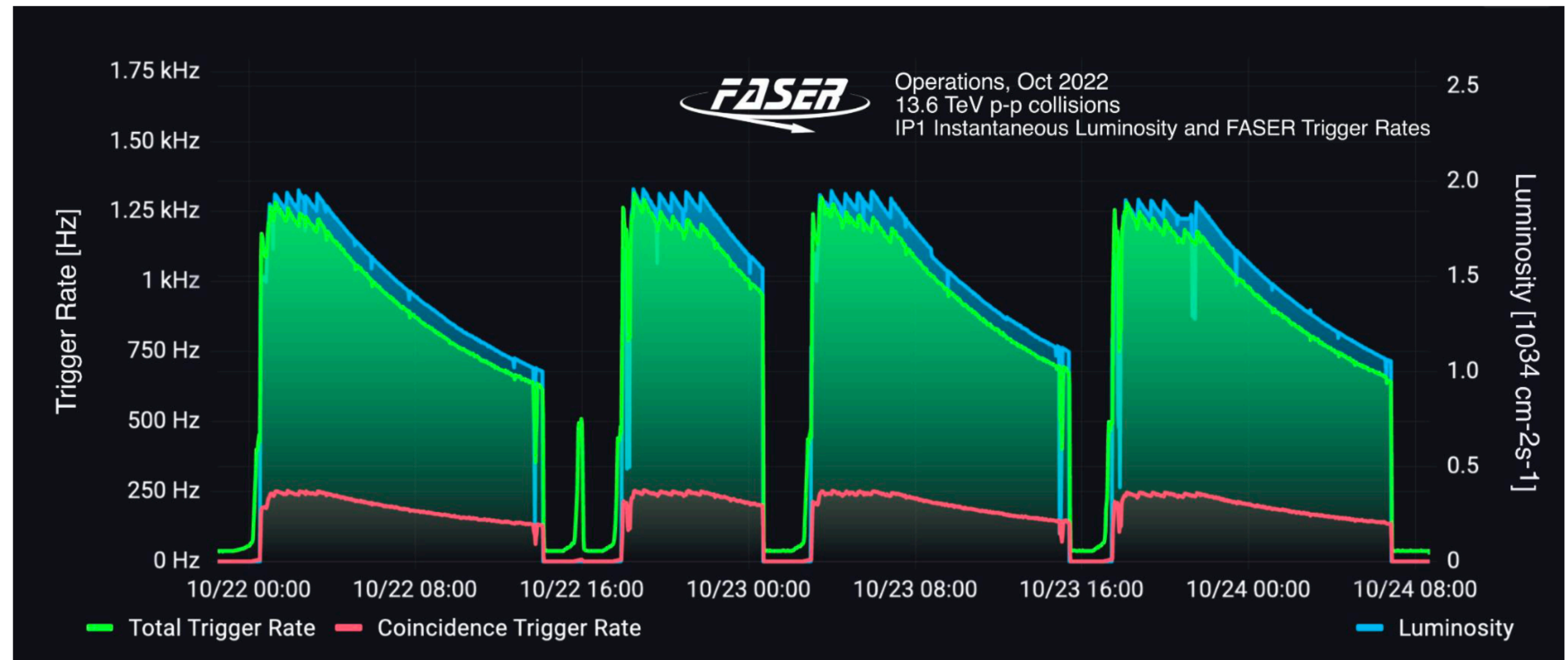




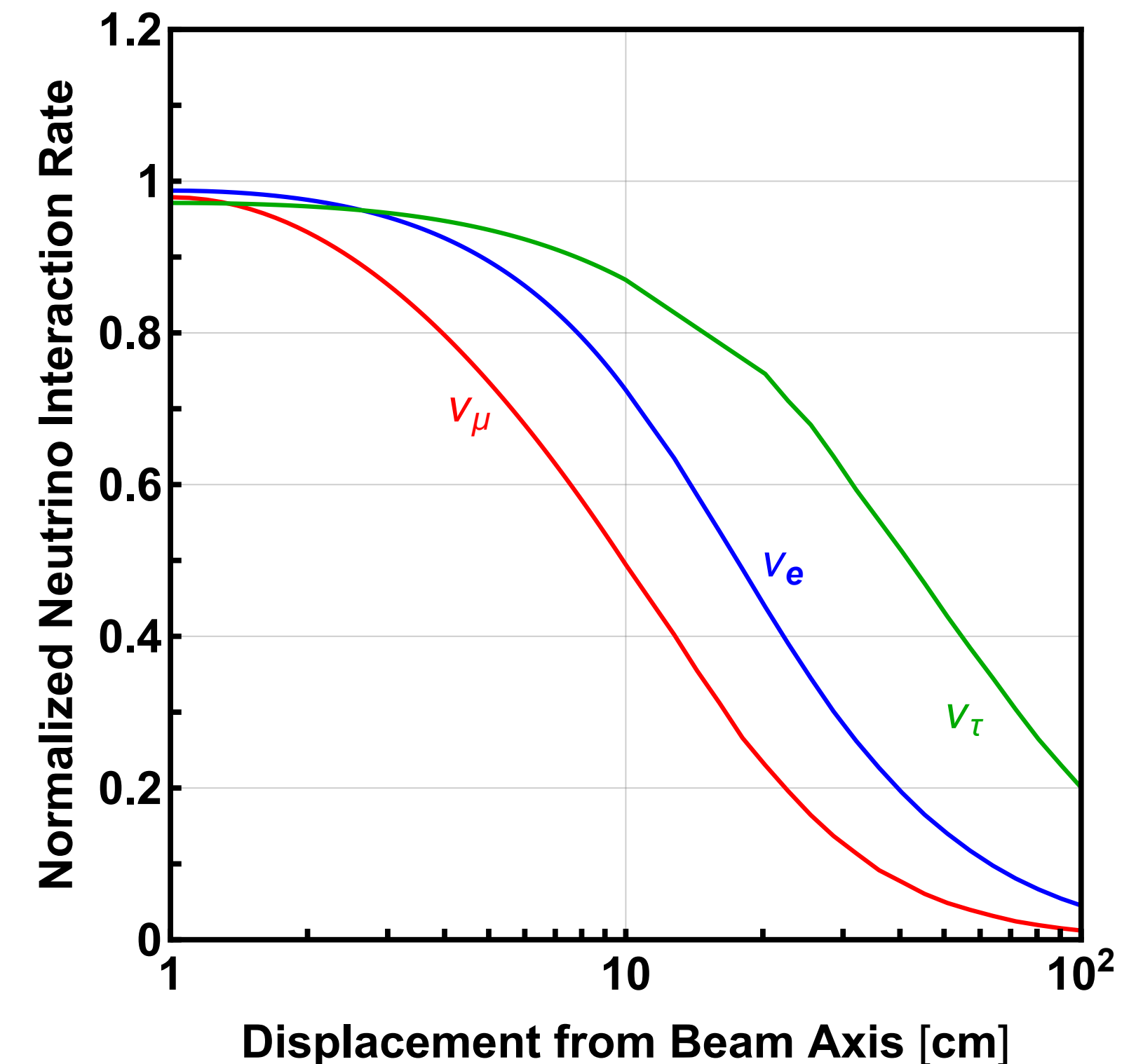
Back-ups

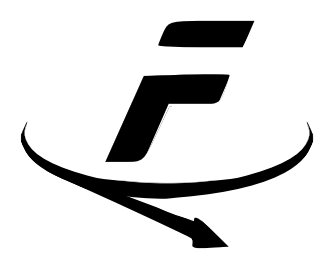
Detector Performance: Trigger + DAQ

- ▶ 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



- ▶ 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:

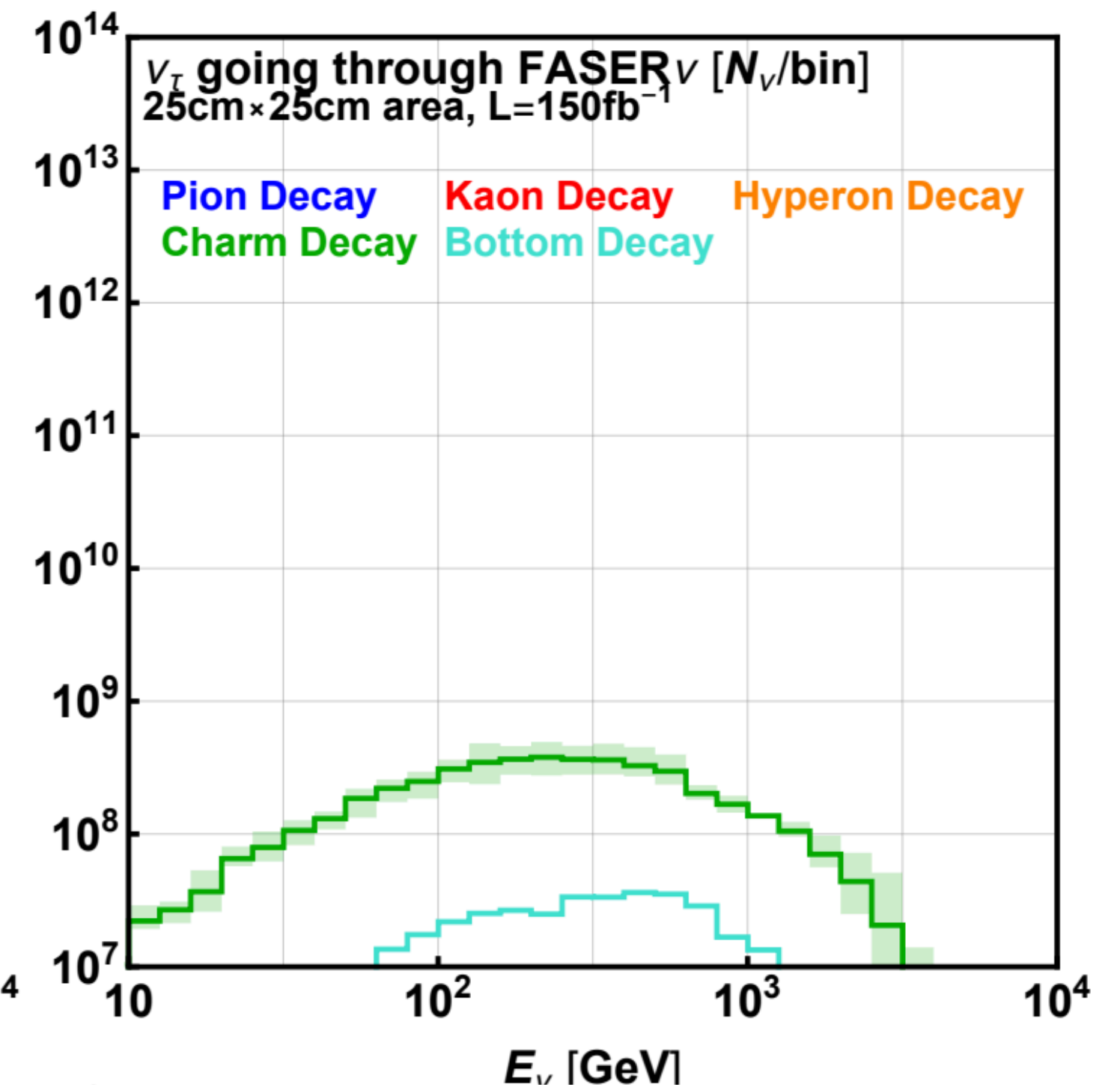
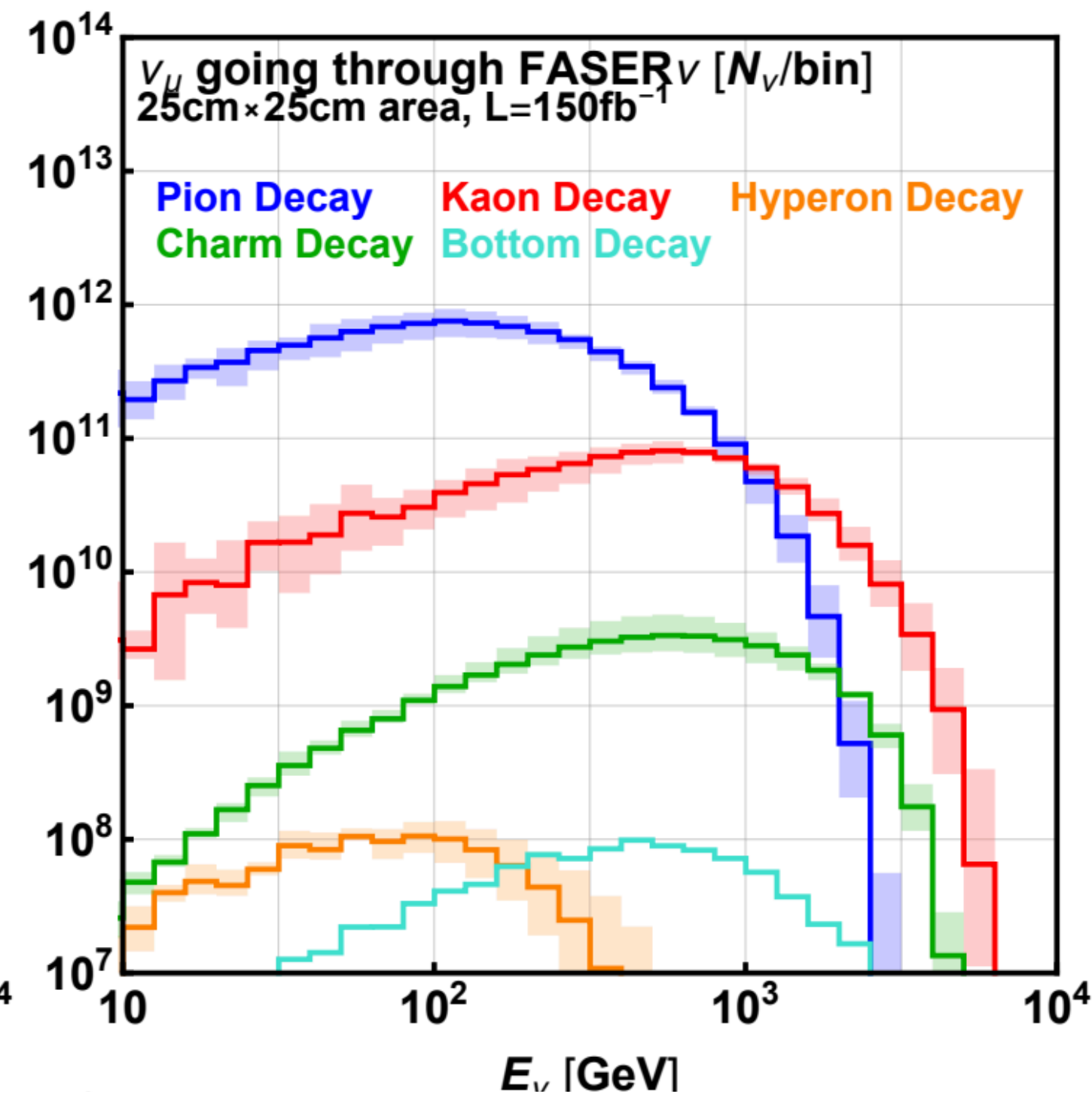
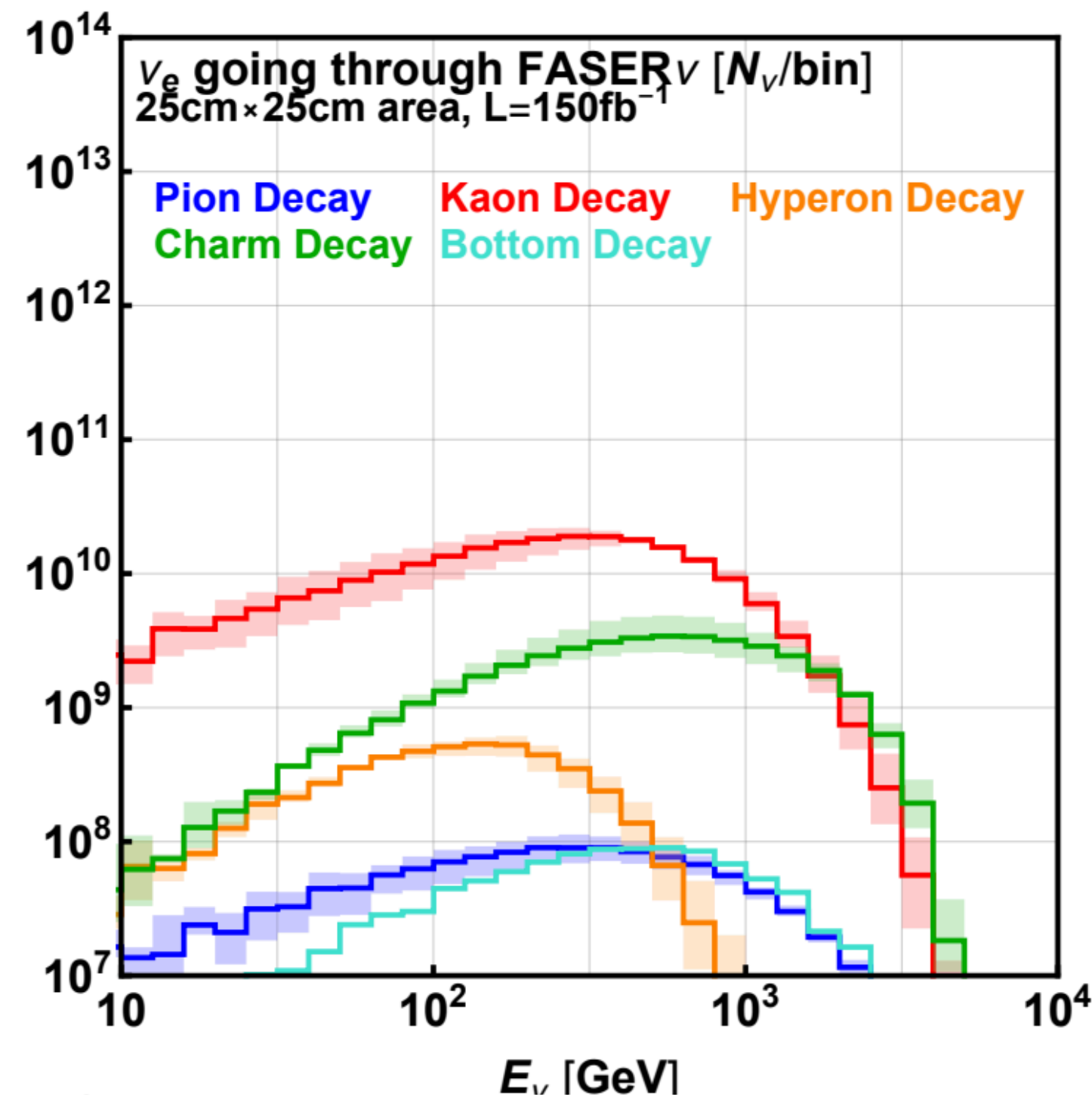


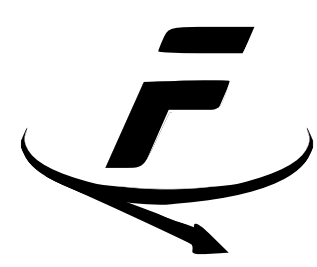


Neutrino analysis

[arXiv:1908.02310]

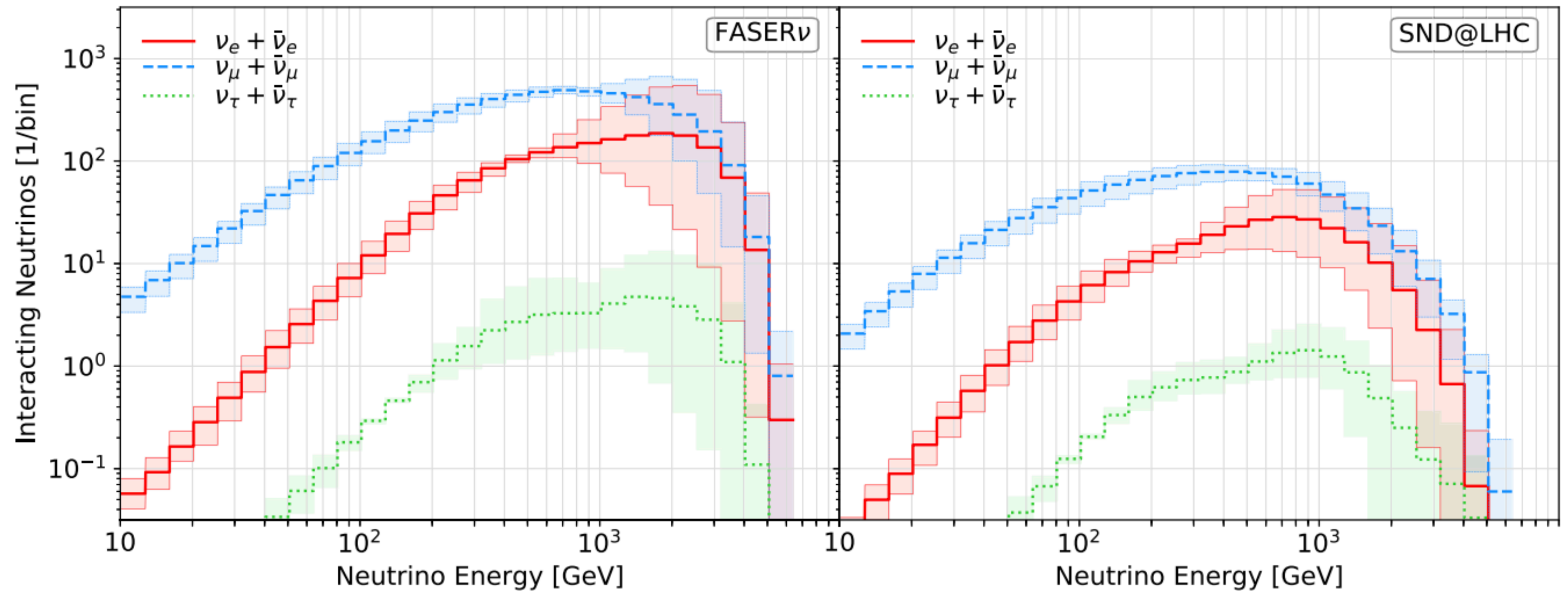
Type	Particles	Main Decays	E	Q	S	P
Pions	π^+	$\pi^+ \rightarrow \mu\nu$	✓	✓	✓	—
Kaons	K^+, K_S, K_L	$K^+ \rightarrow \mu\nu, K \rightarrow \pi\ell\nu$	✓	✓	✓	—
Hyperons	$\Lambda, \Sigma^+, \Sigma^-, \Xi^0, \Xi^-, \Omega^-$	$\Lambda \rightarrow p\ell\nu$	✓	✓	✓	—
Charm	$D^+, D^0, D_s, \Lambda_c, \Xi_c^0,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

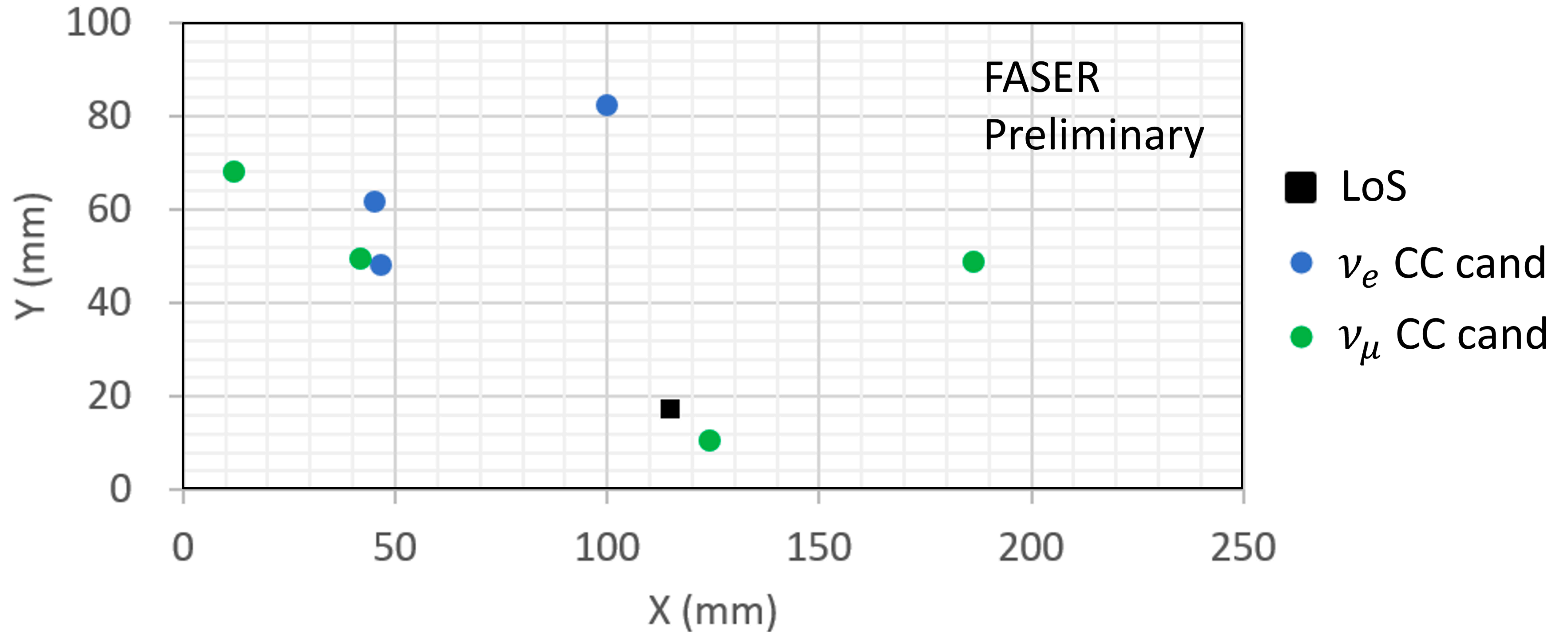




Neutrino analysis

[[PRD 104, 113008](#)]



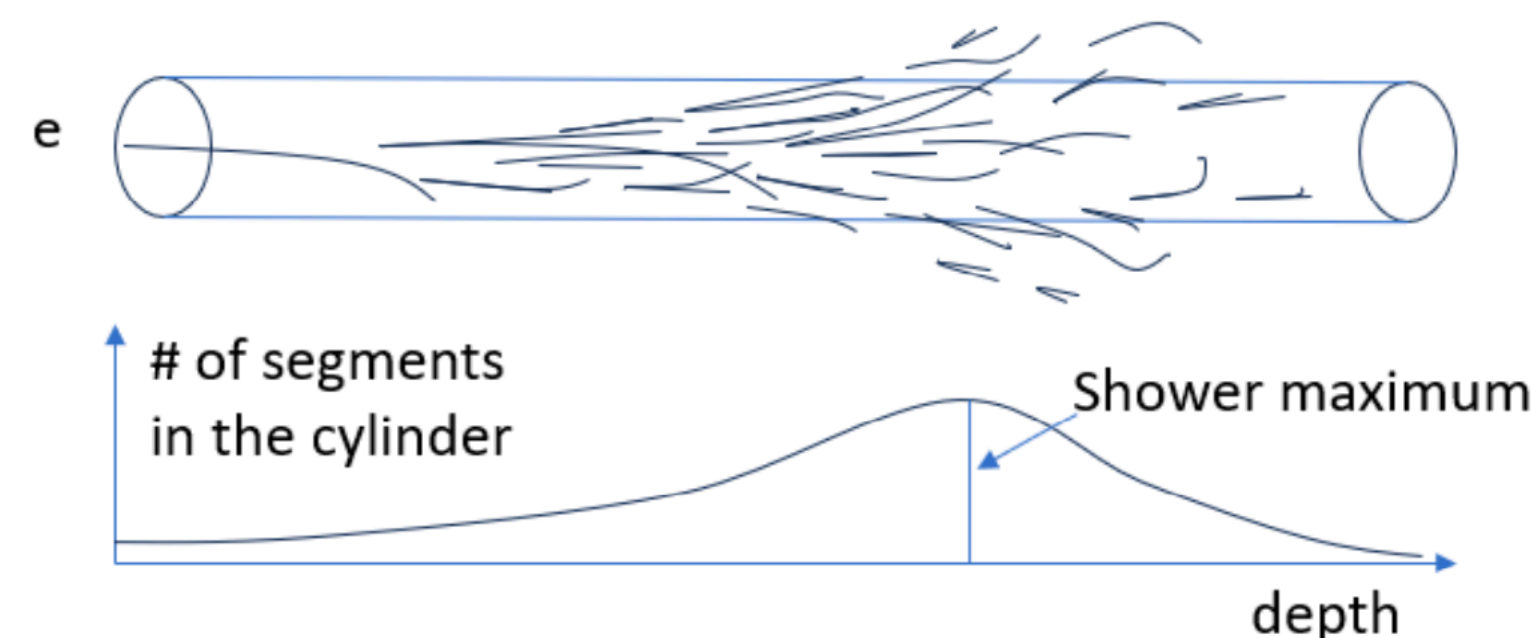
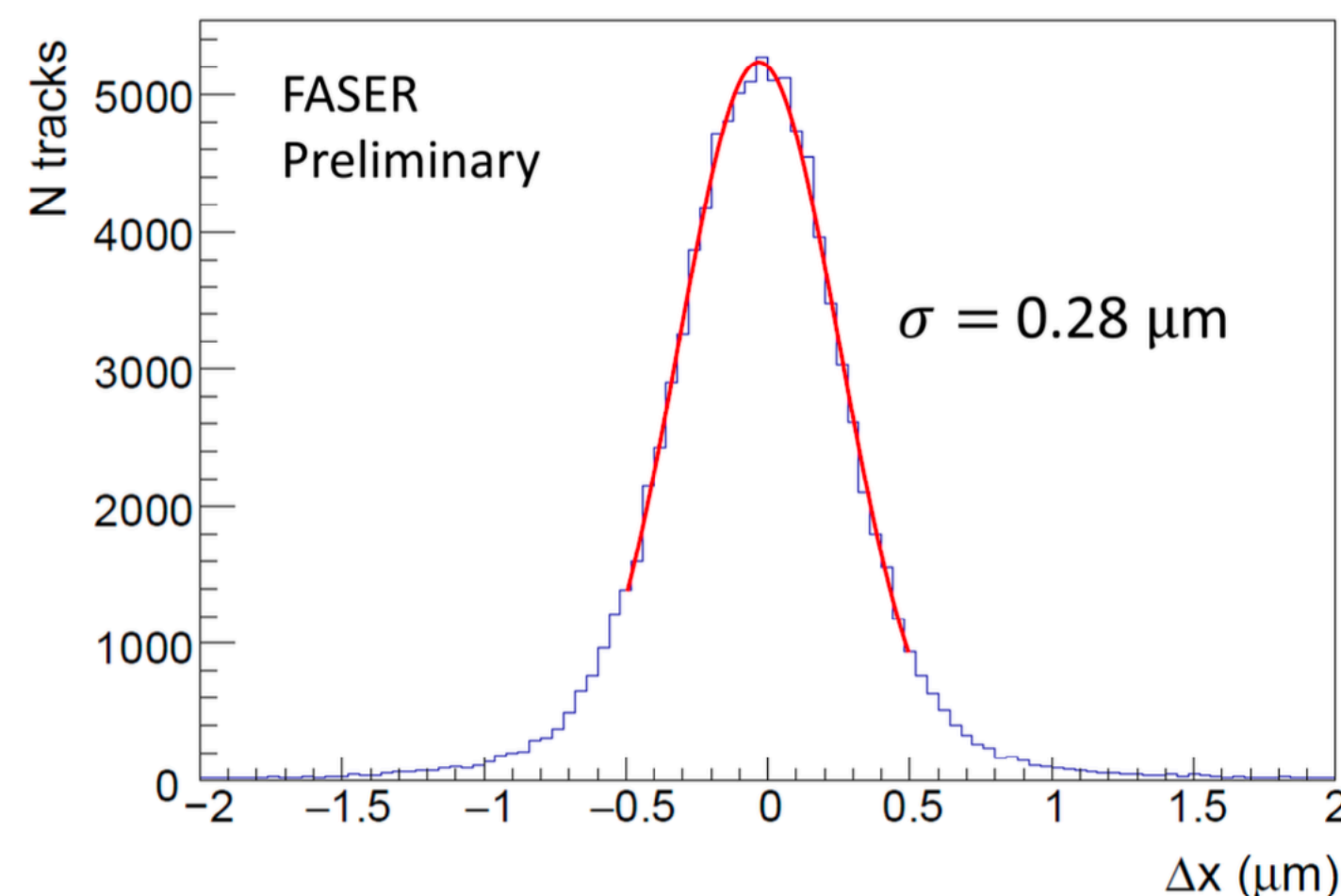


Selection	Quantity	K_L	n	Λ	Total
ν_μ selection $E > 50$ GeV	Raw MC events	77	71	70	-
ν_μ selection $E > 200$ GeV	Raw MC events	1	3	2	-
	Scaled to analysis dataset	0.07	0.16	0.10	0.32
ν_e selection $E > 50$ GeV	Raw MC events	0	1	0	-
ν_e selection $E > 200$ GeV	Raw MC events	0	0	0	-
	Scaled to analysis dataset	0	0	0	0

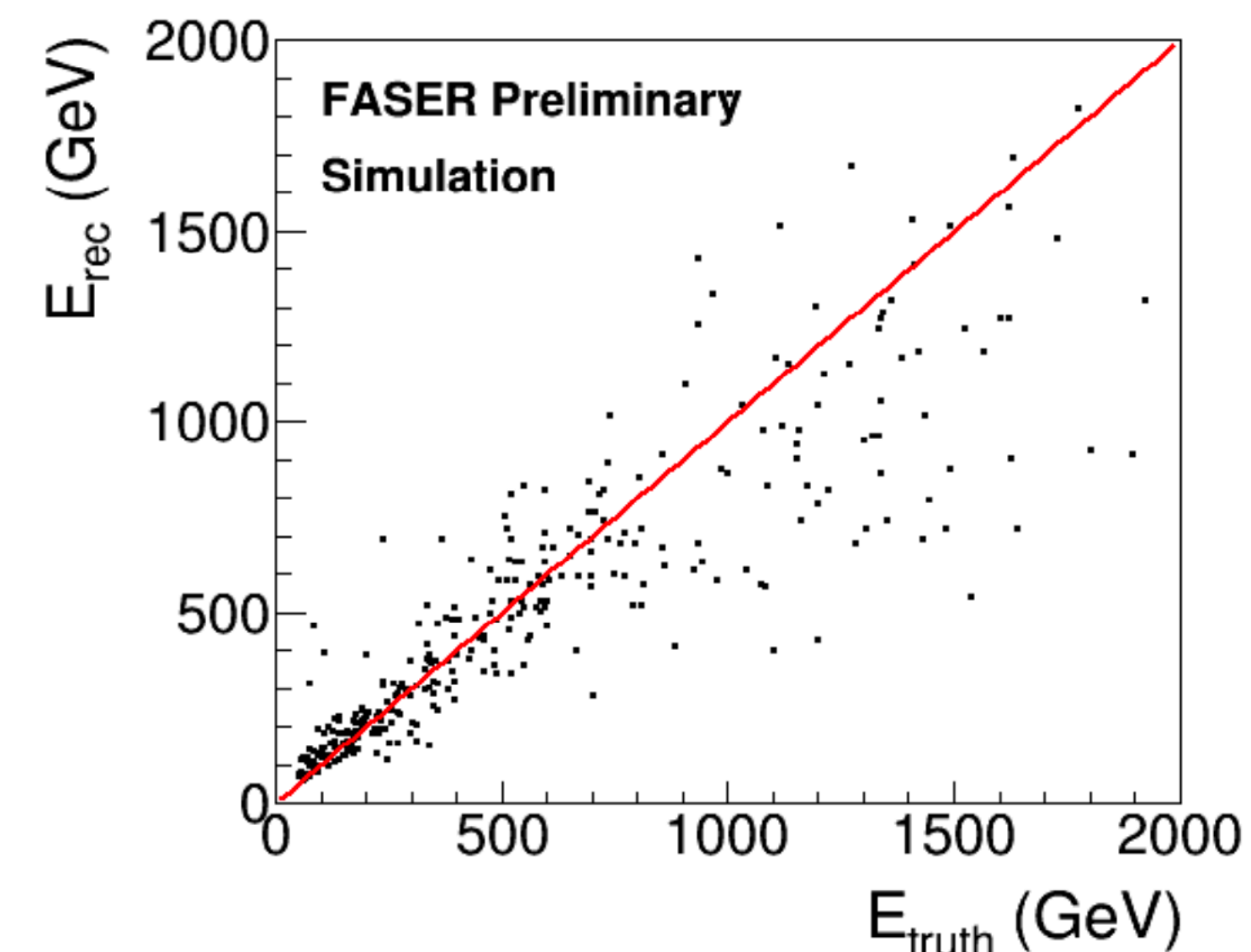
Background	ν_μ CC	ν_e CC
Neutral-hadron interactions	0.32 ± 0.15 (stat.) ± 0.16 (syst.)	0.002 ± 0.002 (stat.) ± 0.002 (syst.)
NC neutrino interactions	0.19 ± 0.15	-
Total	0.51 ± 0.27	0.002 ± 0.003



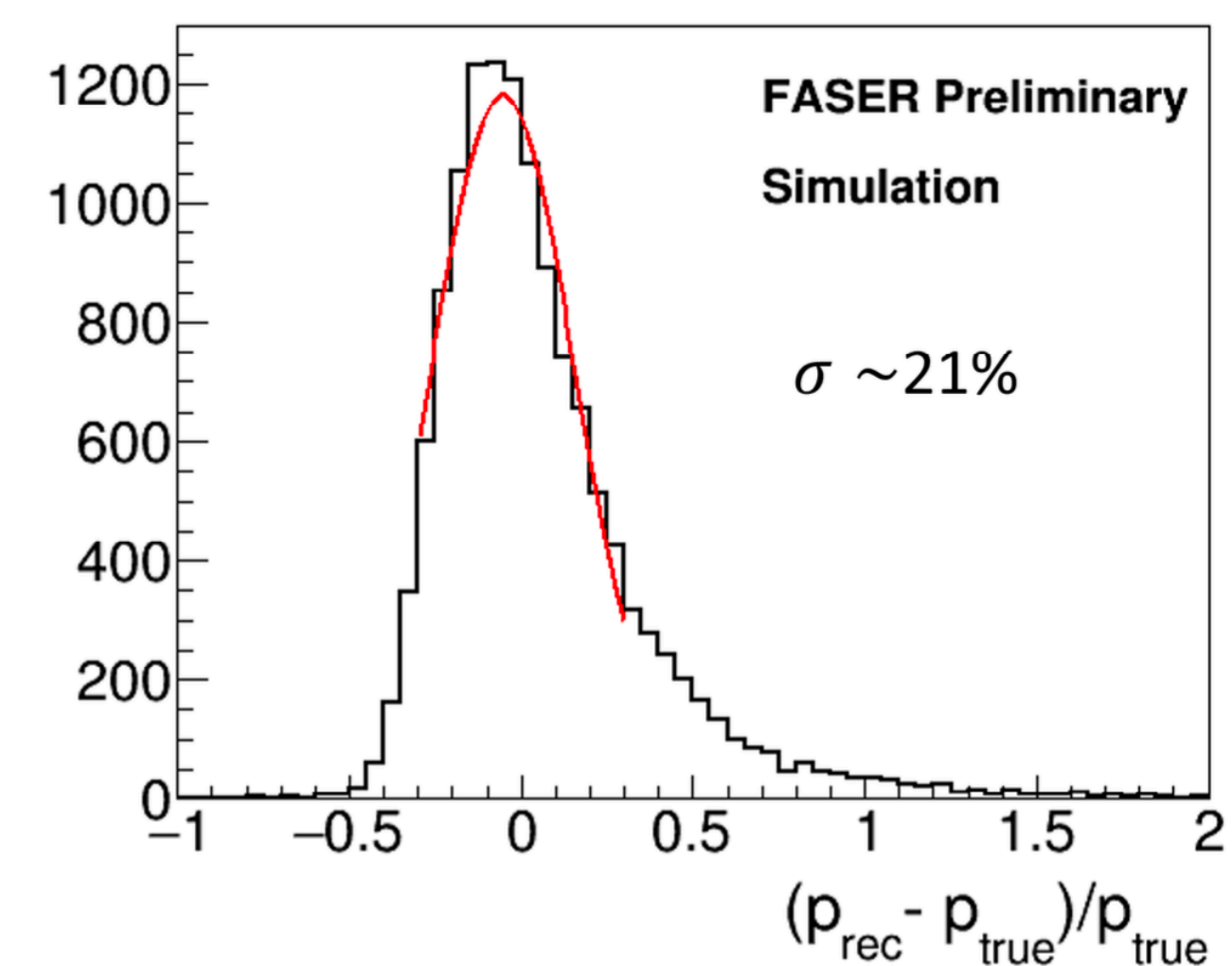
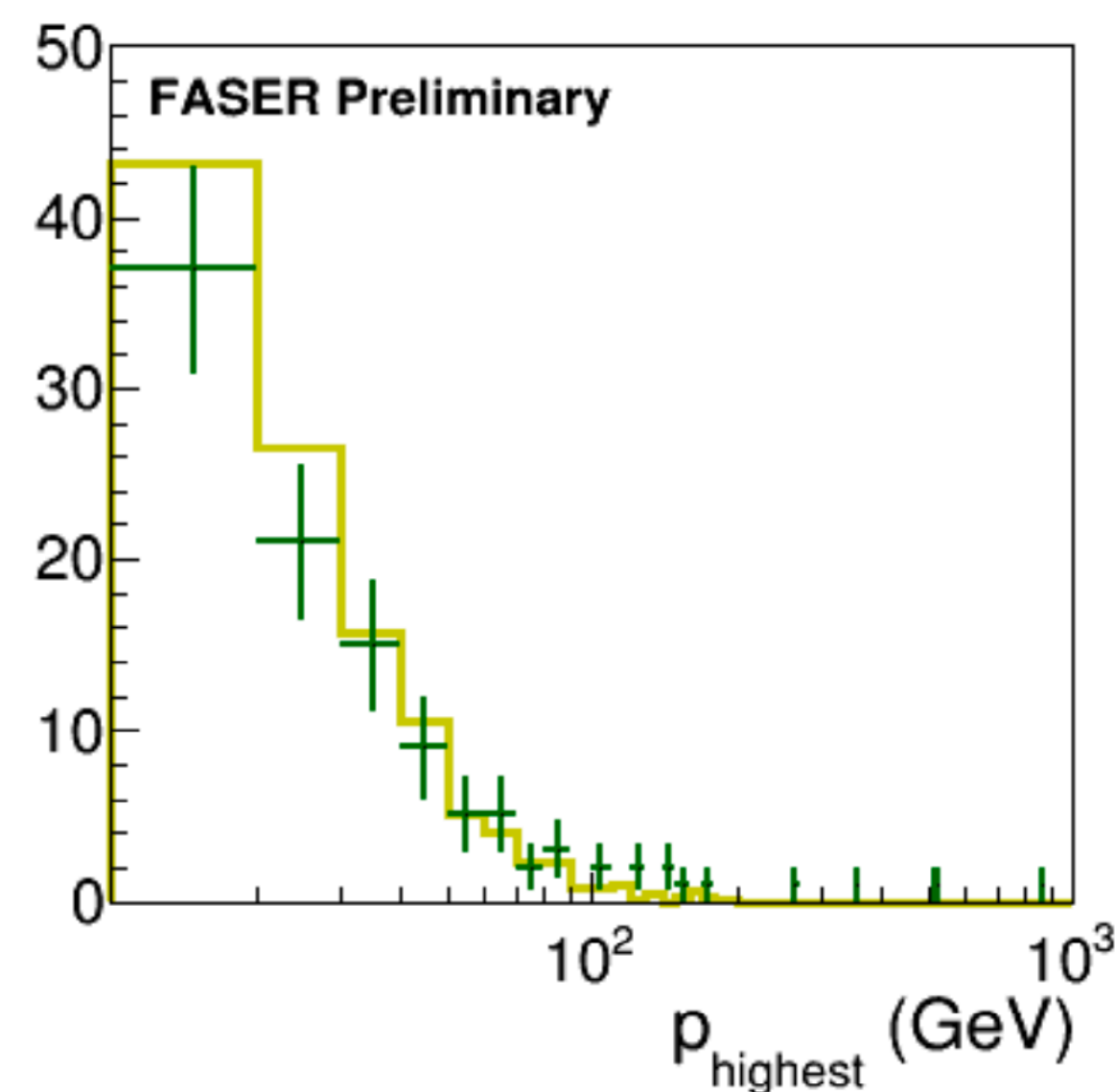
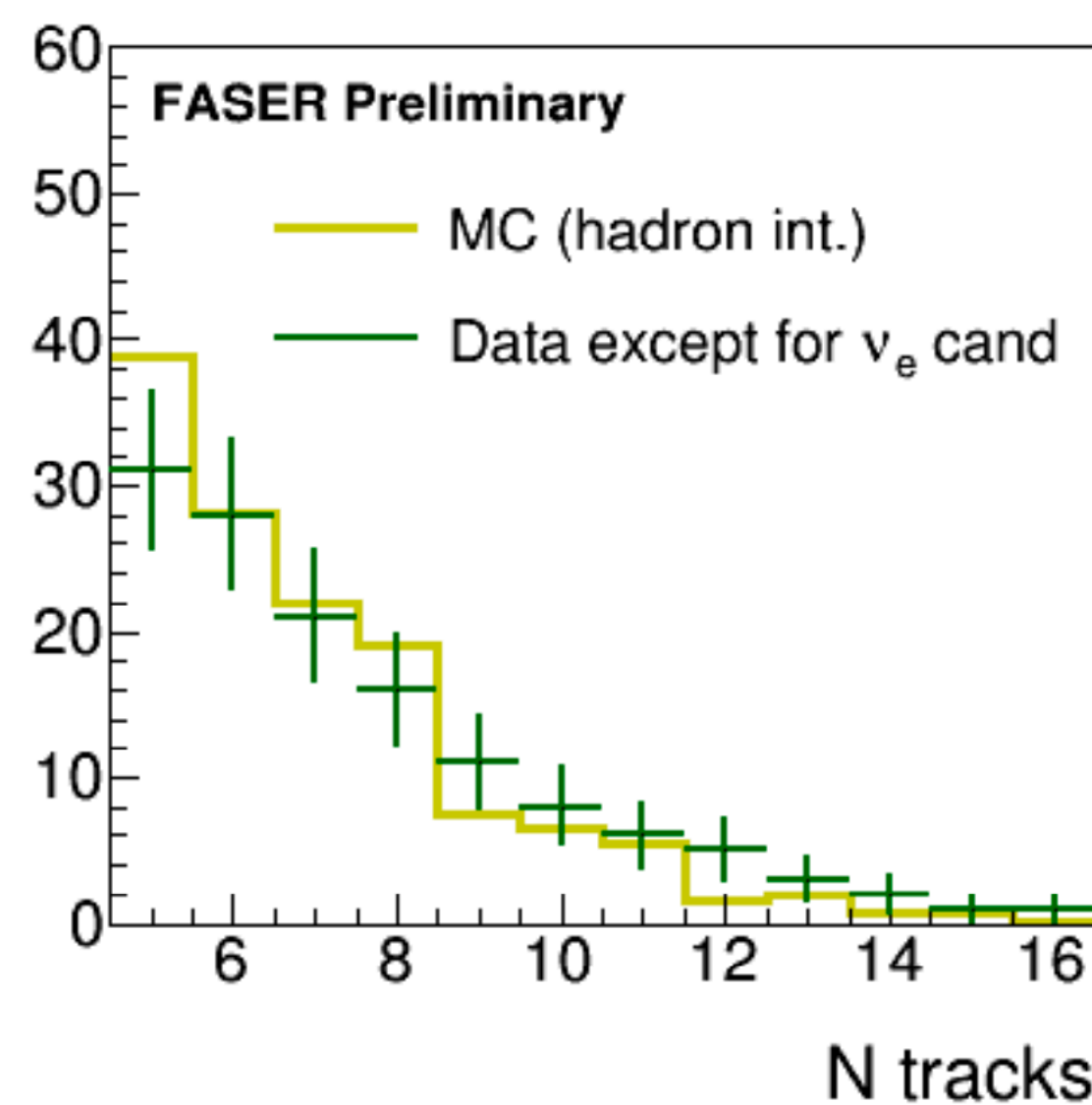
Emulsion analysis | Performance



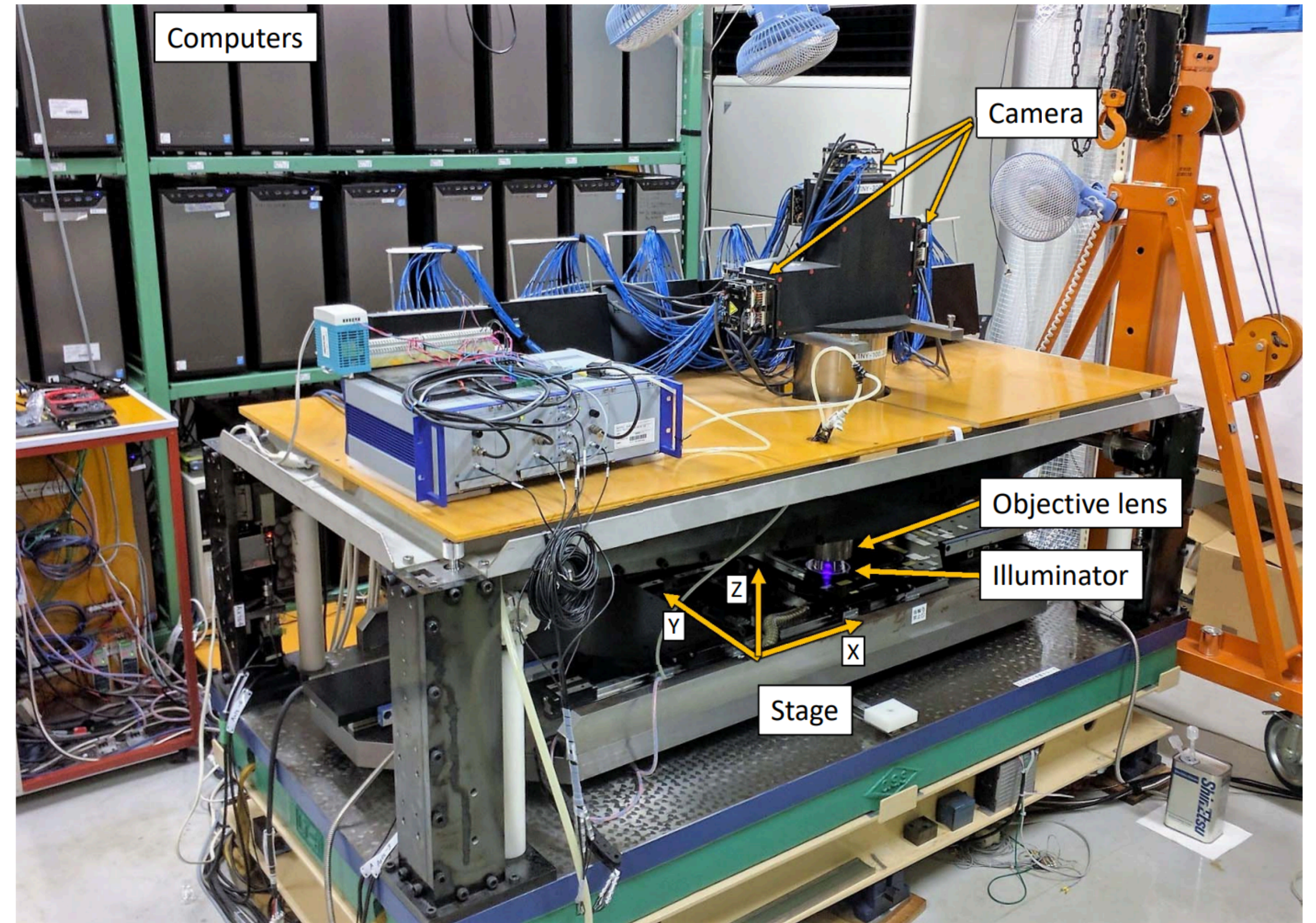
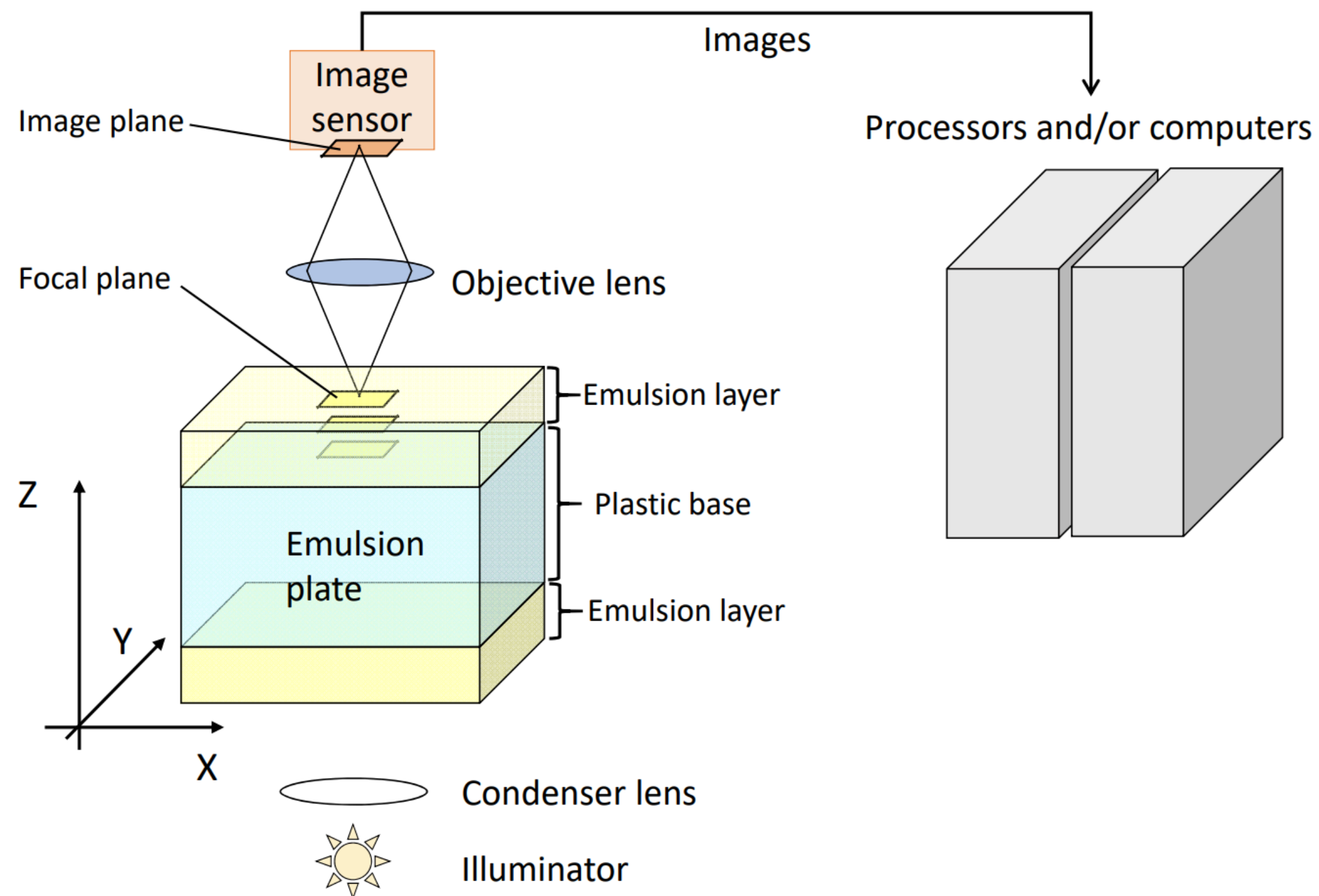
$$\begin{aligned}\delta\text{pos} &< 100 \mu\text{m} \\ \delta\theta &< 10 \text{ mrad} \\ d_{\text{min}} &< 50 \mu\text{m}\end{aligned}$$



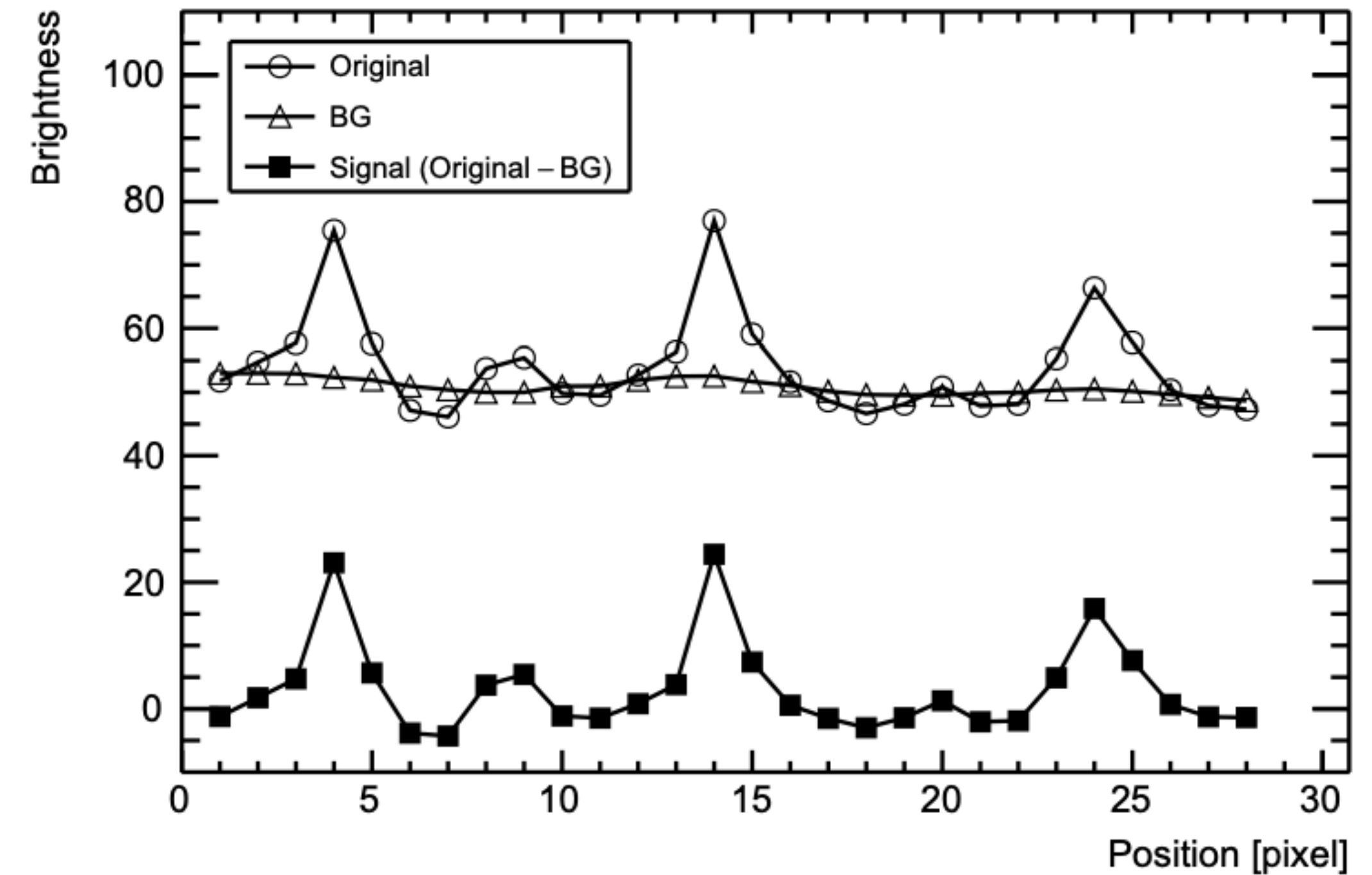
25% for EM energies at 200 GeV. Between 25-40% for higher energies



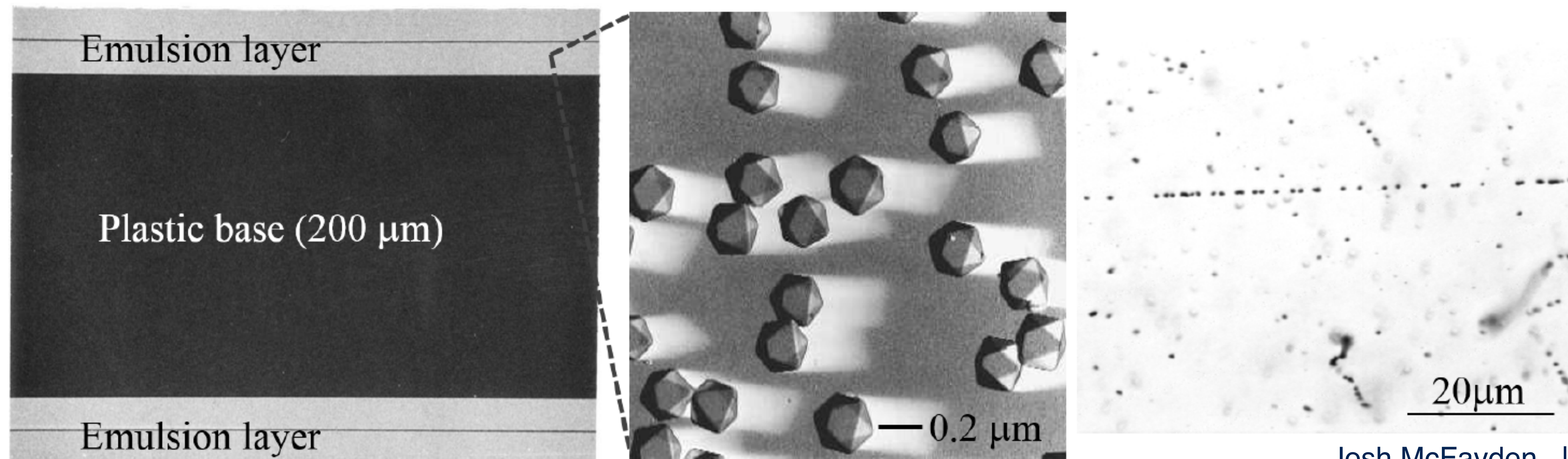
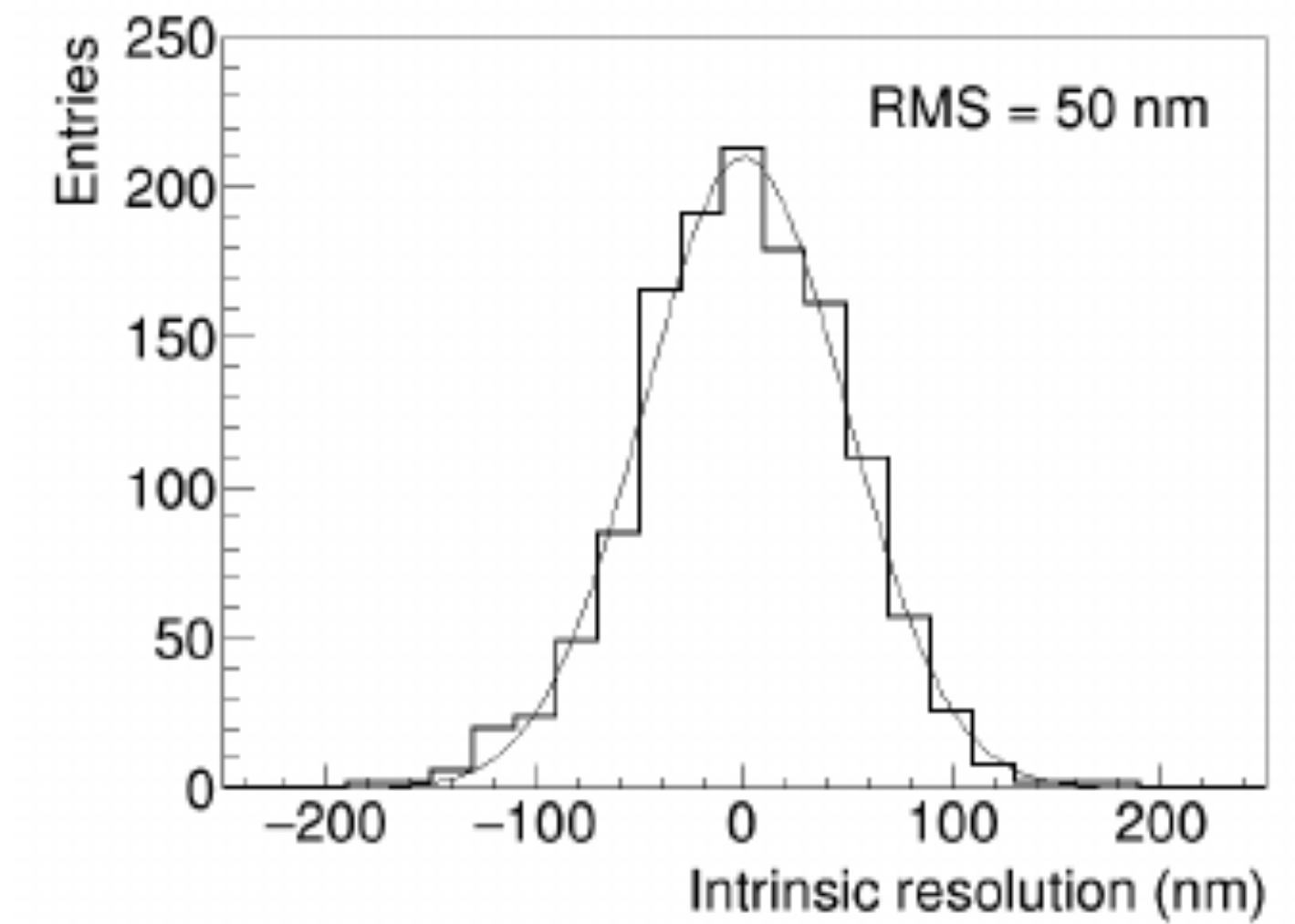
► Hyper Track Selector: [arXiv:1704.06814]



- ▶ 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, $d_0 \leq 5 \mu\text{m}$, min. distance to 3 vertex tracks of $\leq 3 \mu\text{m}$.



- ▶ Emulsion film made up of $\sim 80\mu\text{m}$ emulsion layer on either side of $200\mu\text{m}$ 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 $\sim 50\text{nm}$, and angular resolution $\sim 0.35\text{mrad}$
- ▶ But no time resolution!

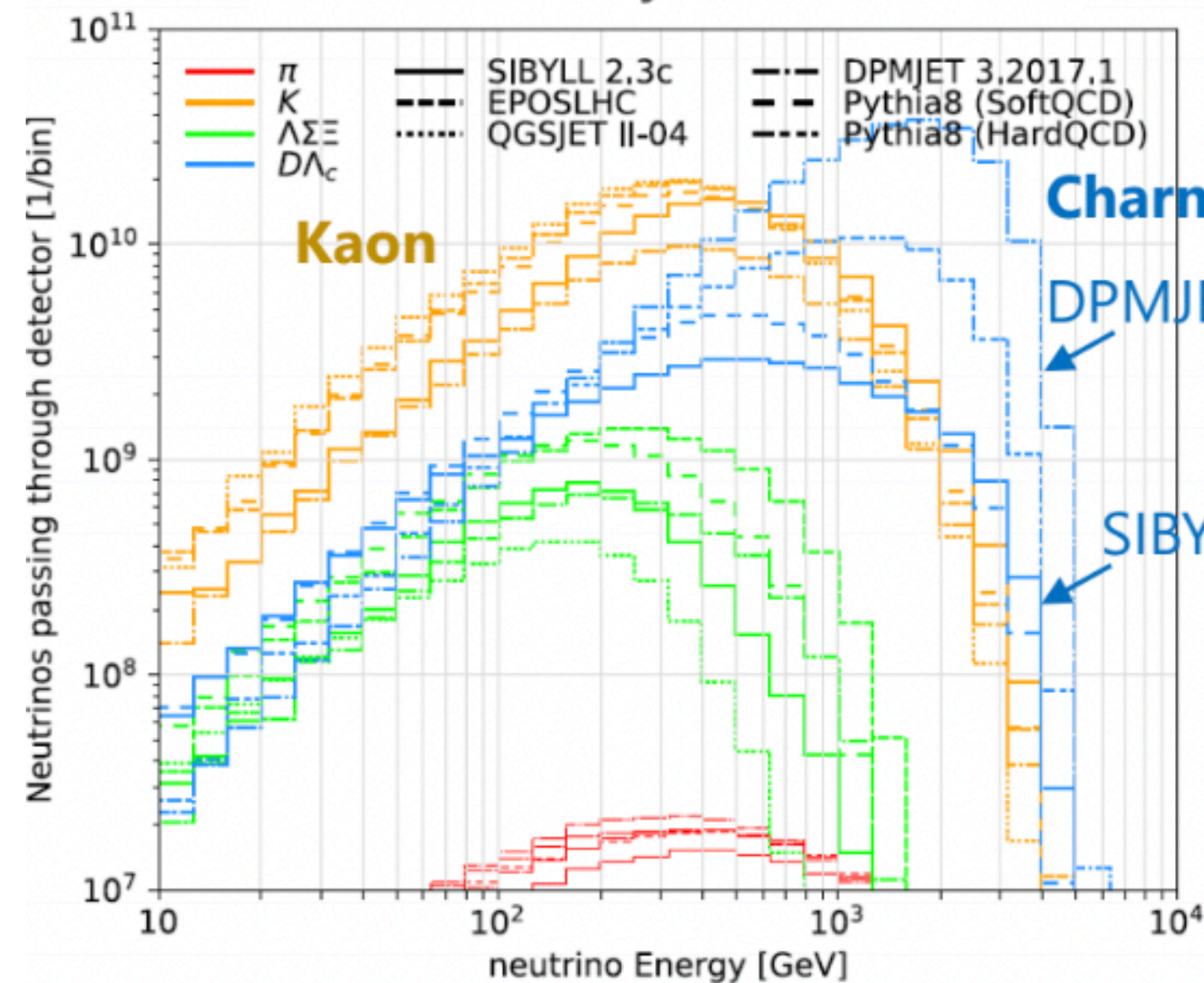




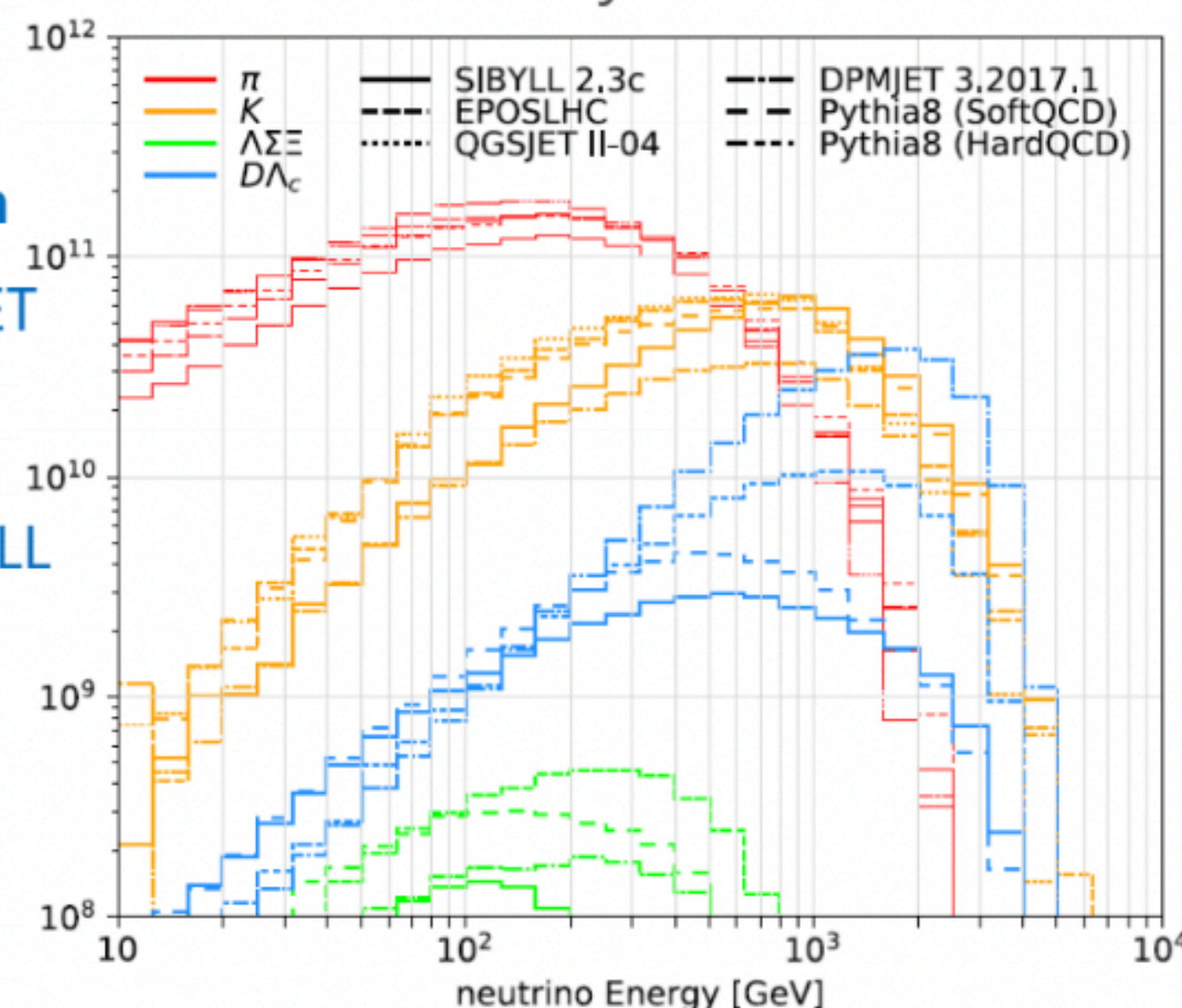
FASERν | Neutrino flux estimates

- 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)

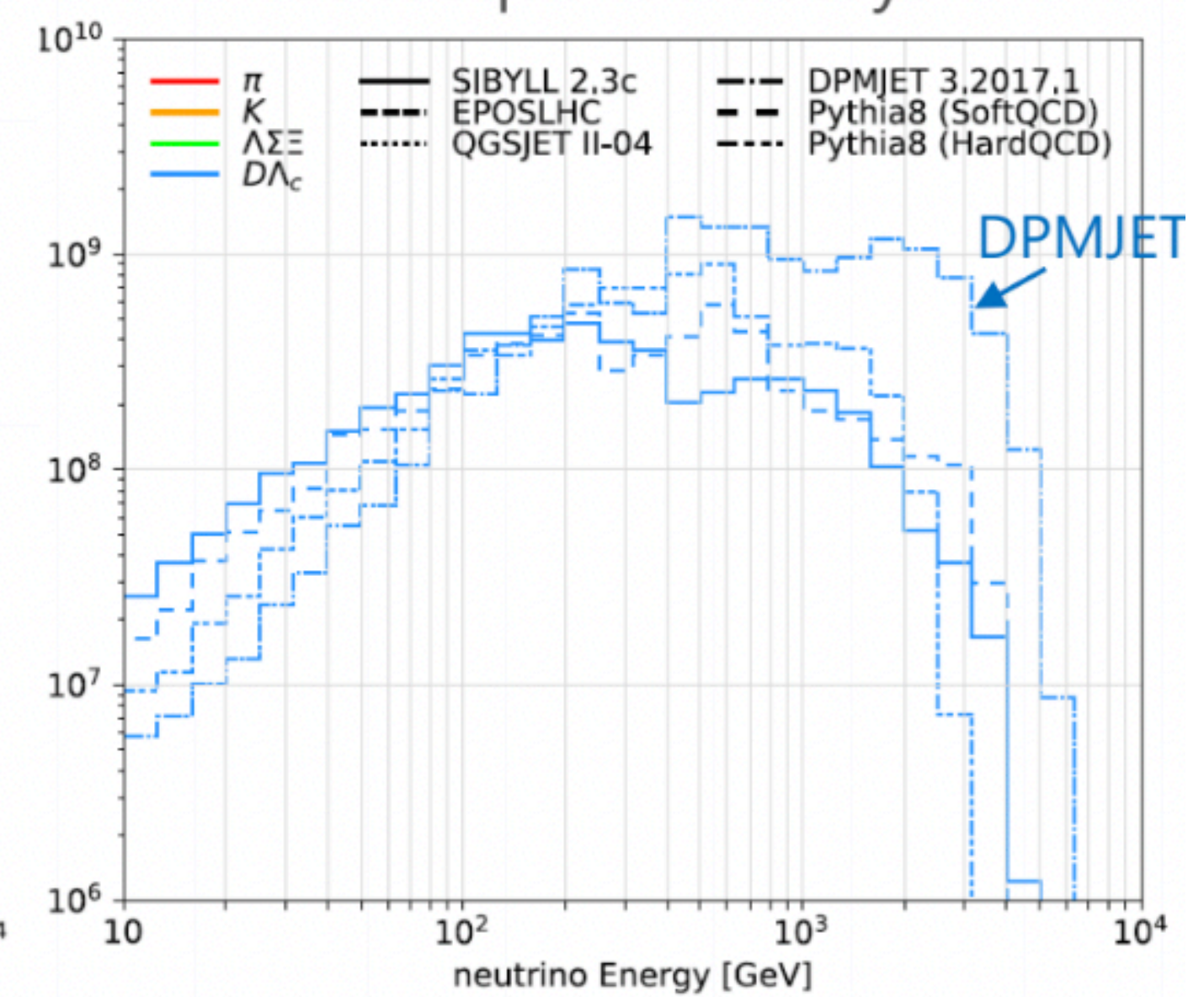
ν_e mainly from kaon and charm decays



ν_μ mainly from pion and kaon decays

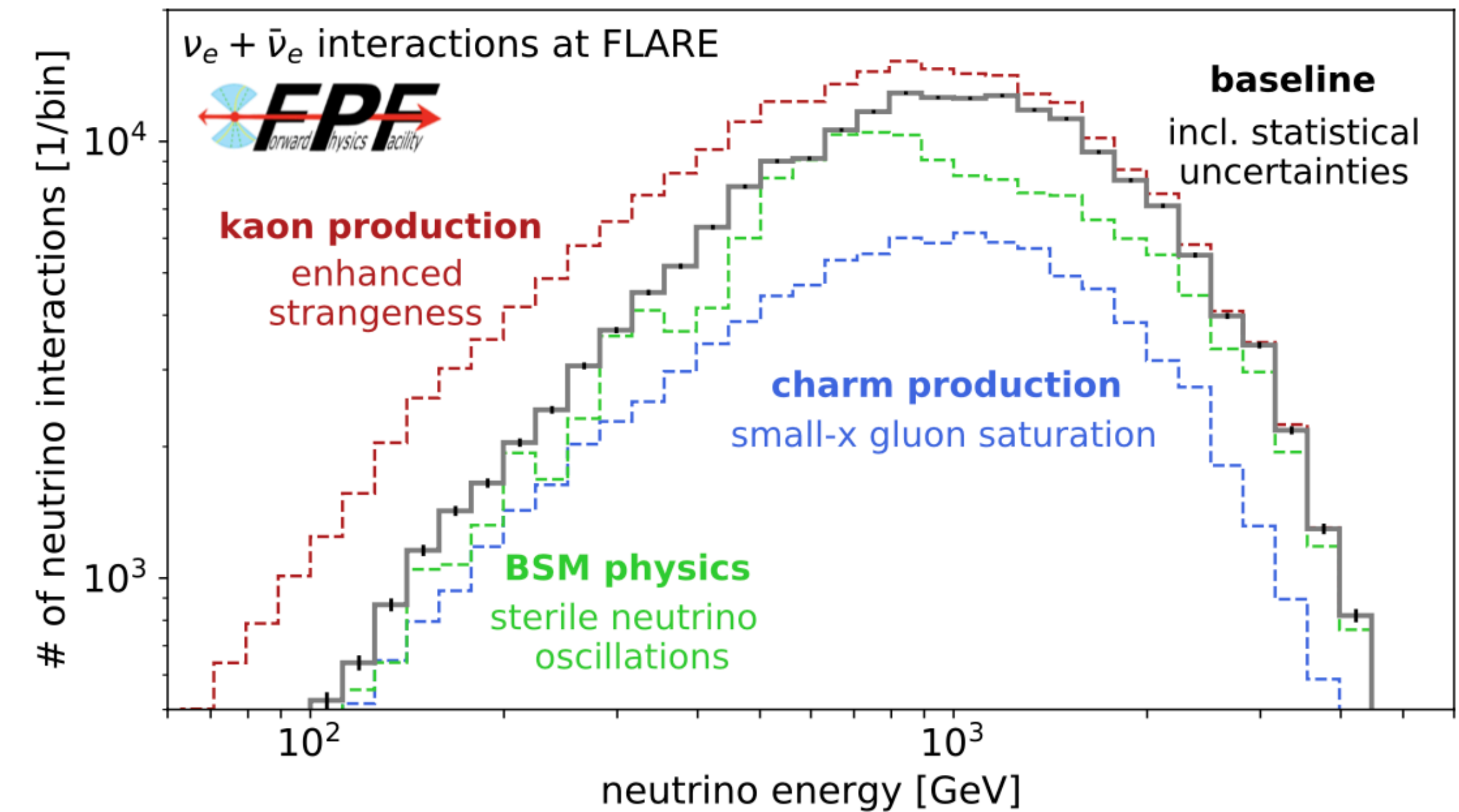
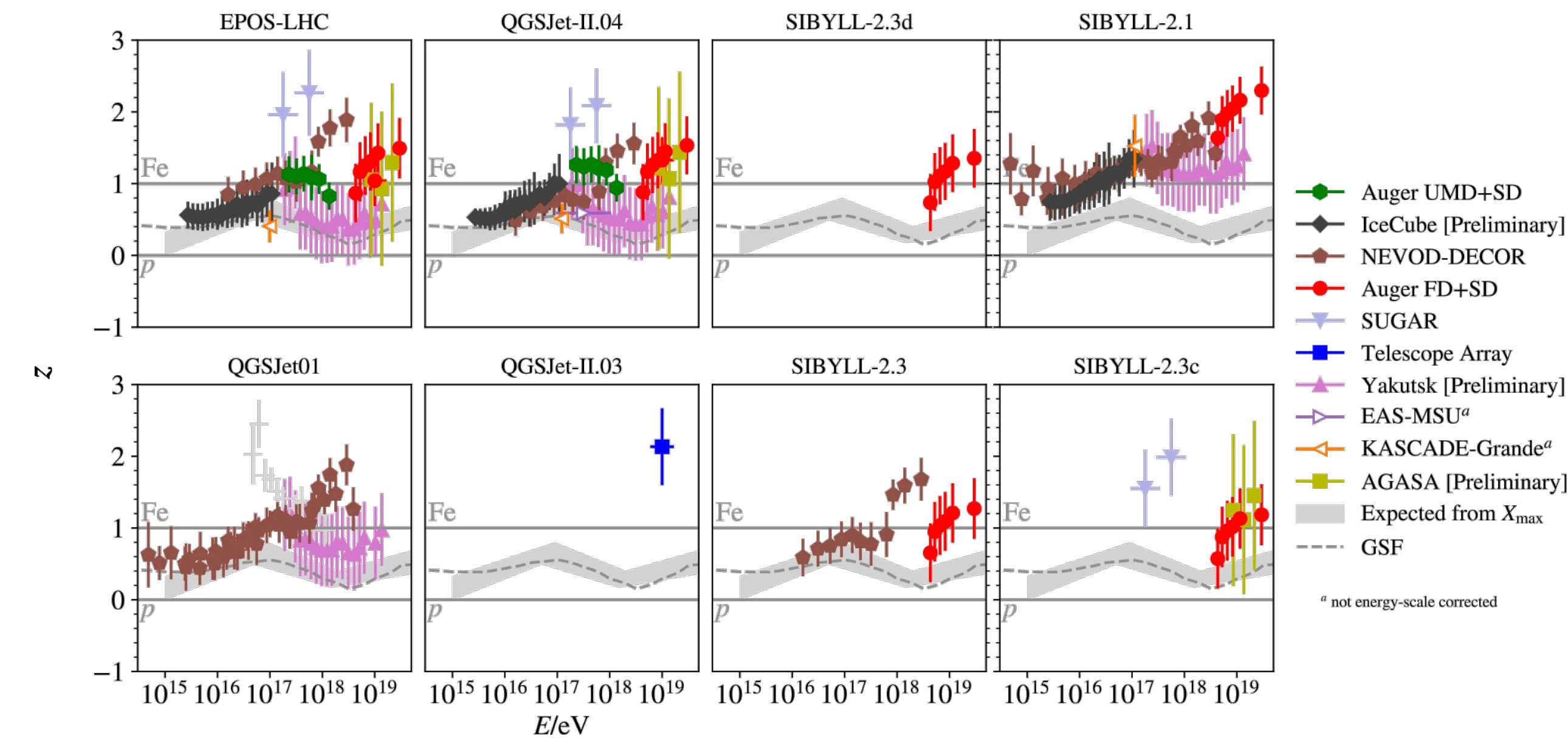
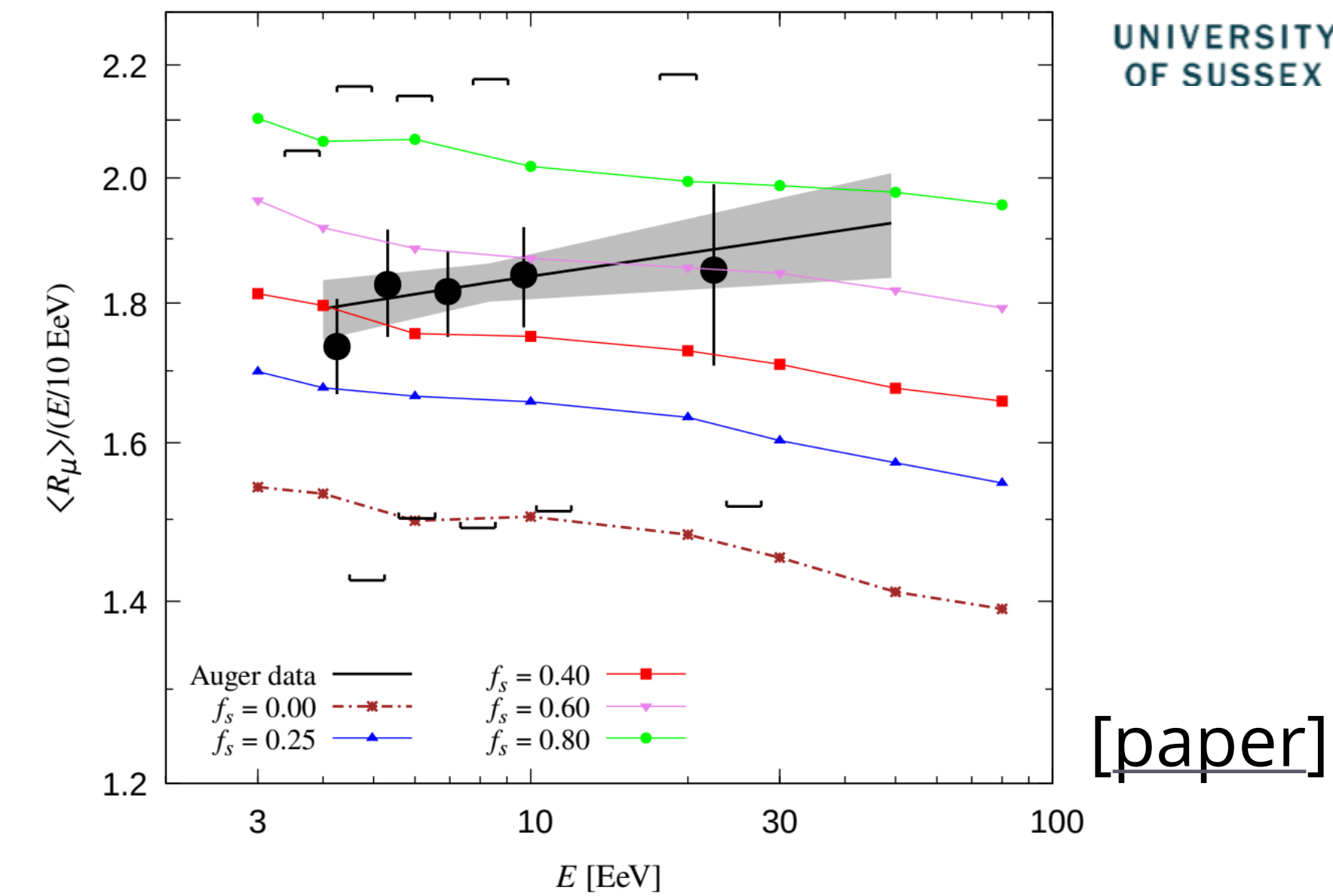


ν_τ mainly from D_s and subsequent τ decays



Atmospheric muon puzzle

- Predictions show significant deficit compared to data in high energy muon rates from cosmic rays
- Cannot be tuned away with current MCs
- Strangeness enhancement could solve the issue
- Testable at FPF



► BSM physics

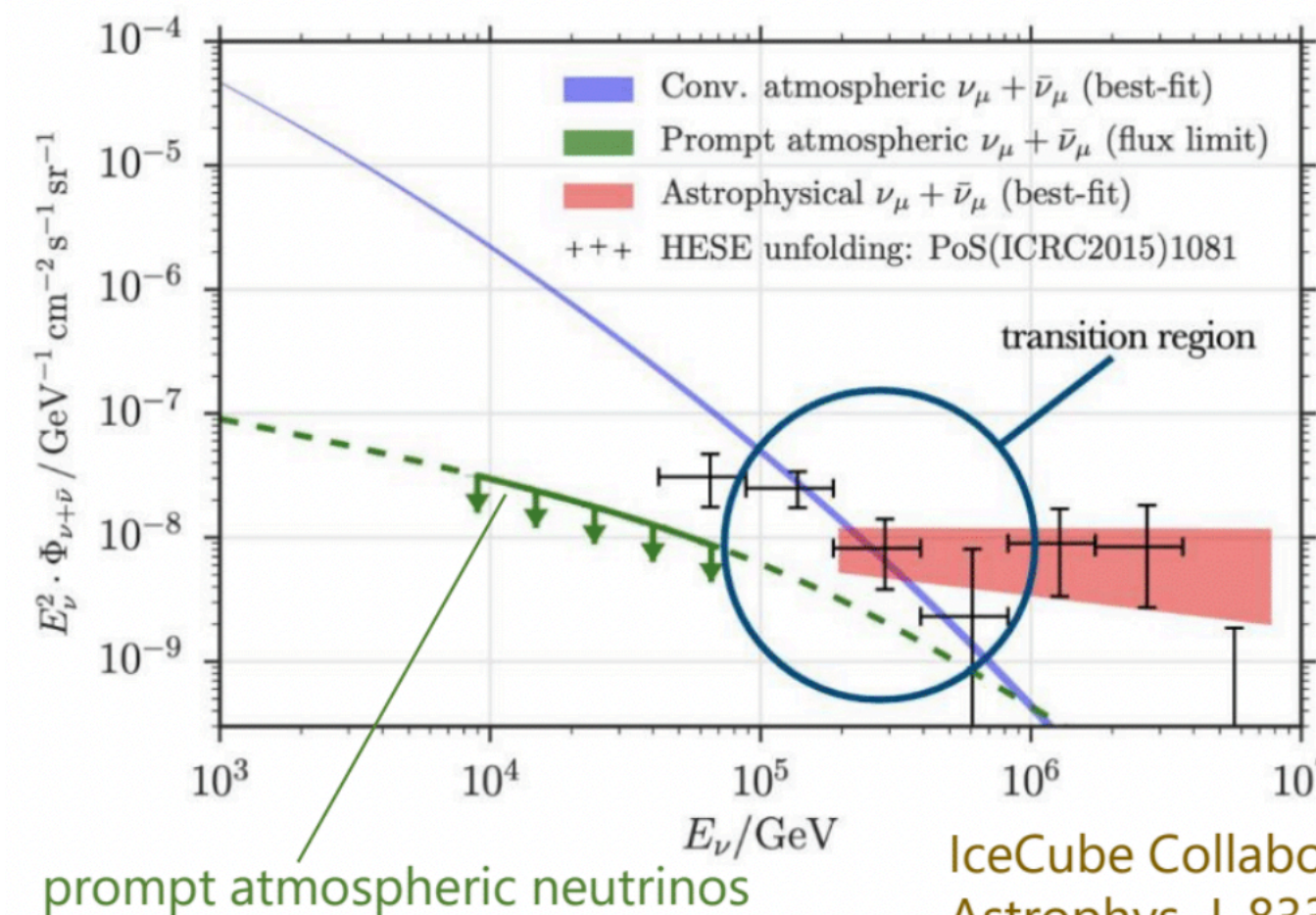
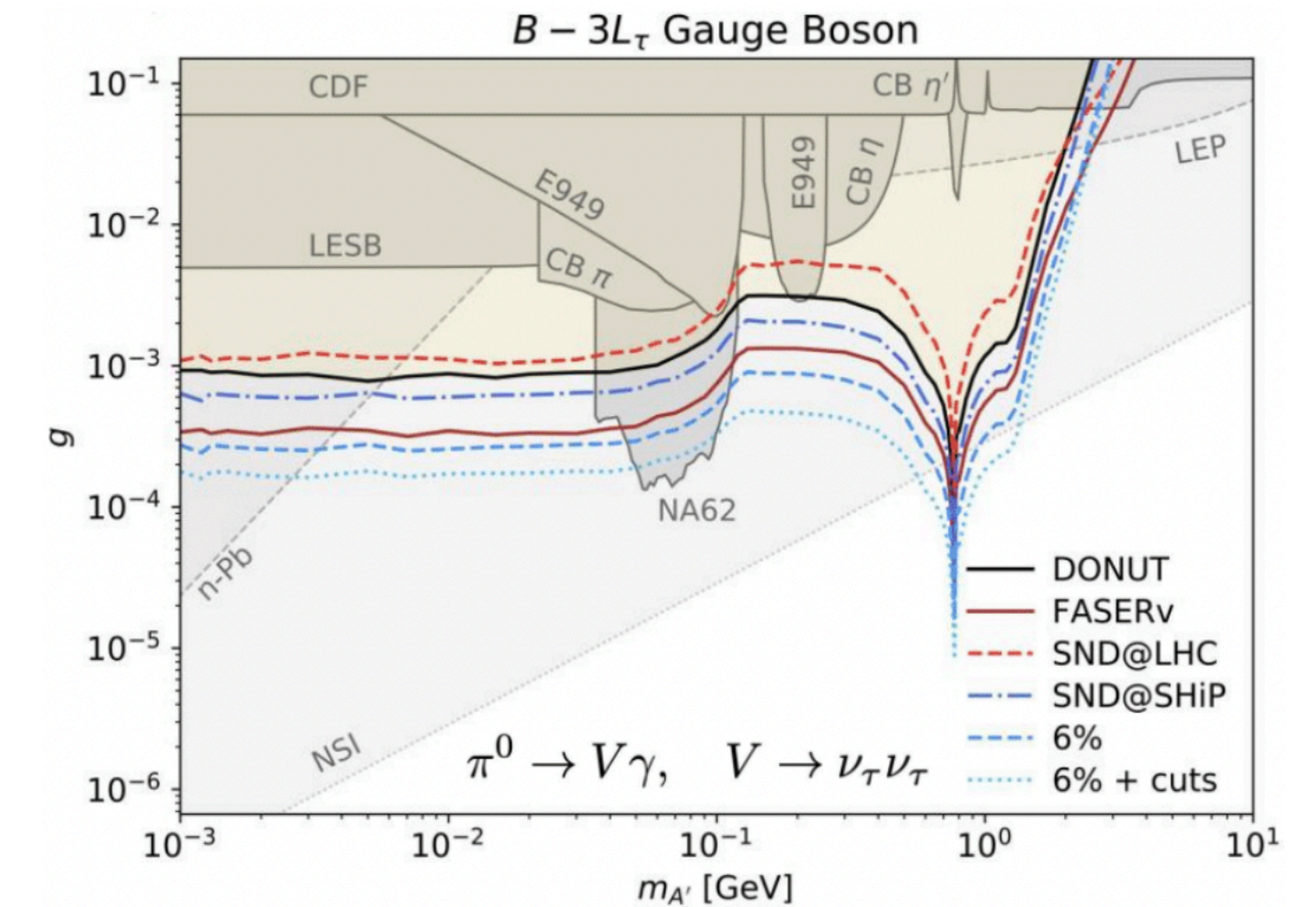
- New light weakly coupled gauge boson ($\rightarrow \nu_\tau$) could enhance ν_τ flux.
- Sterile neutrinos with mass ~ 40 eV can cause oscillations at FASER

► QCD

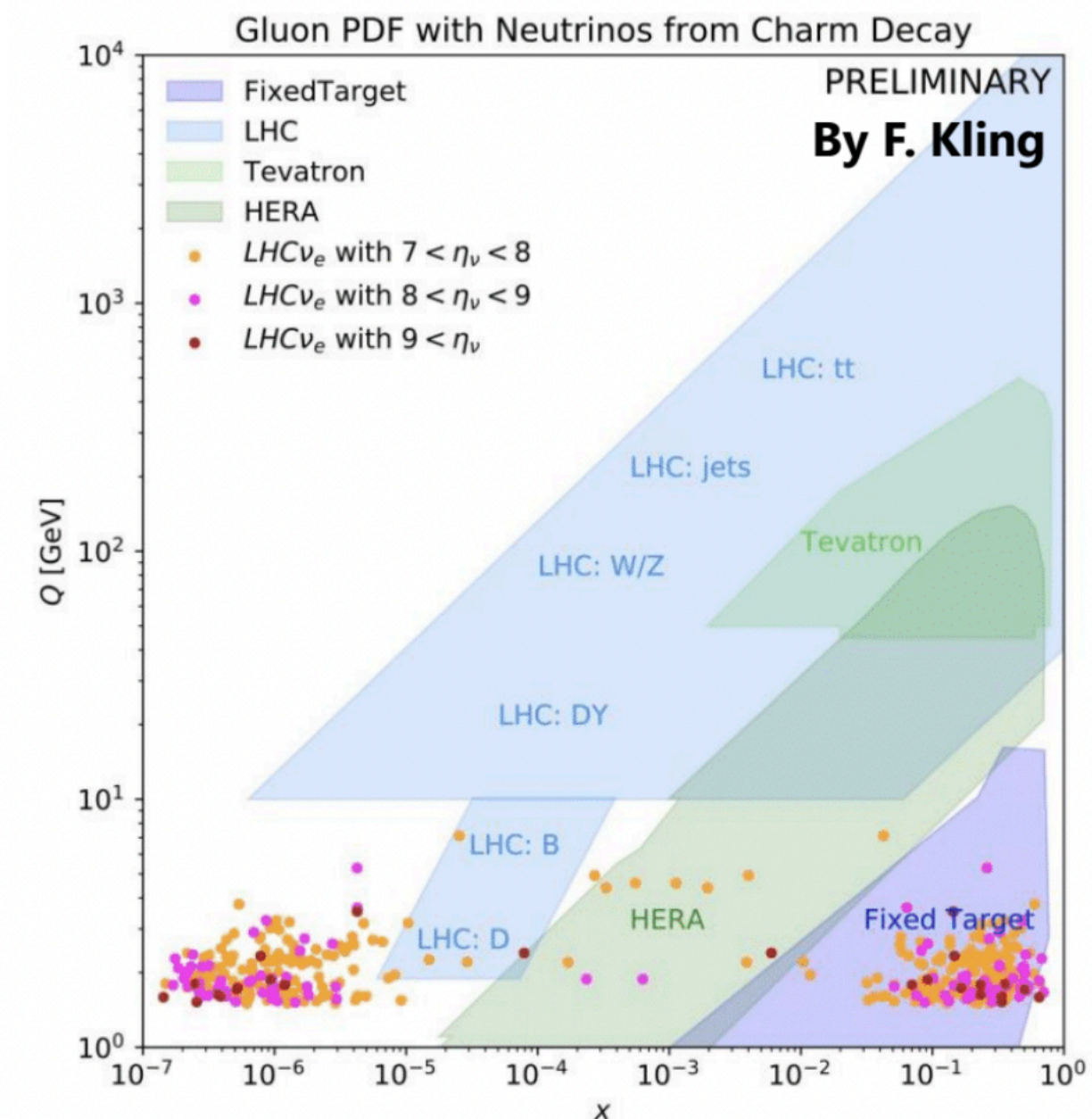
- FASER's neutrino flux measurements will provide novel complimentary constraints that can be used to validate/improve MC generator very forward particle production.
- Neutrinos from charm decay could allow to test transition to small-x factorisation, constrain low-x gluon PDF and probe intrinsic charm

► 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

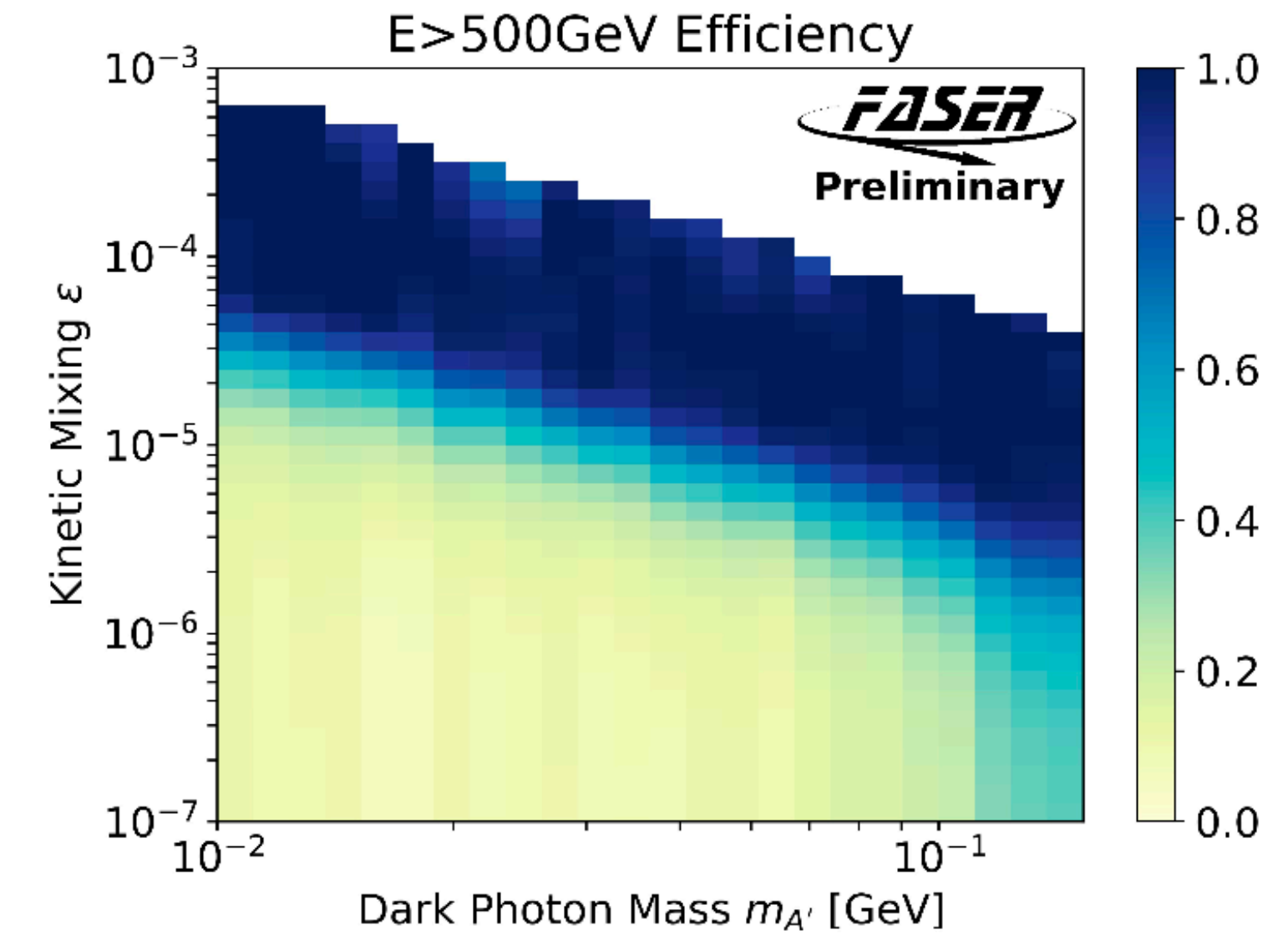
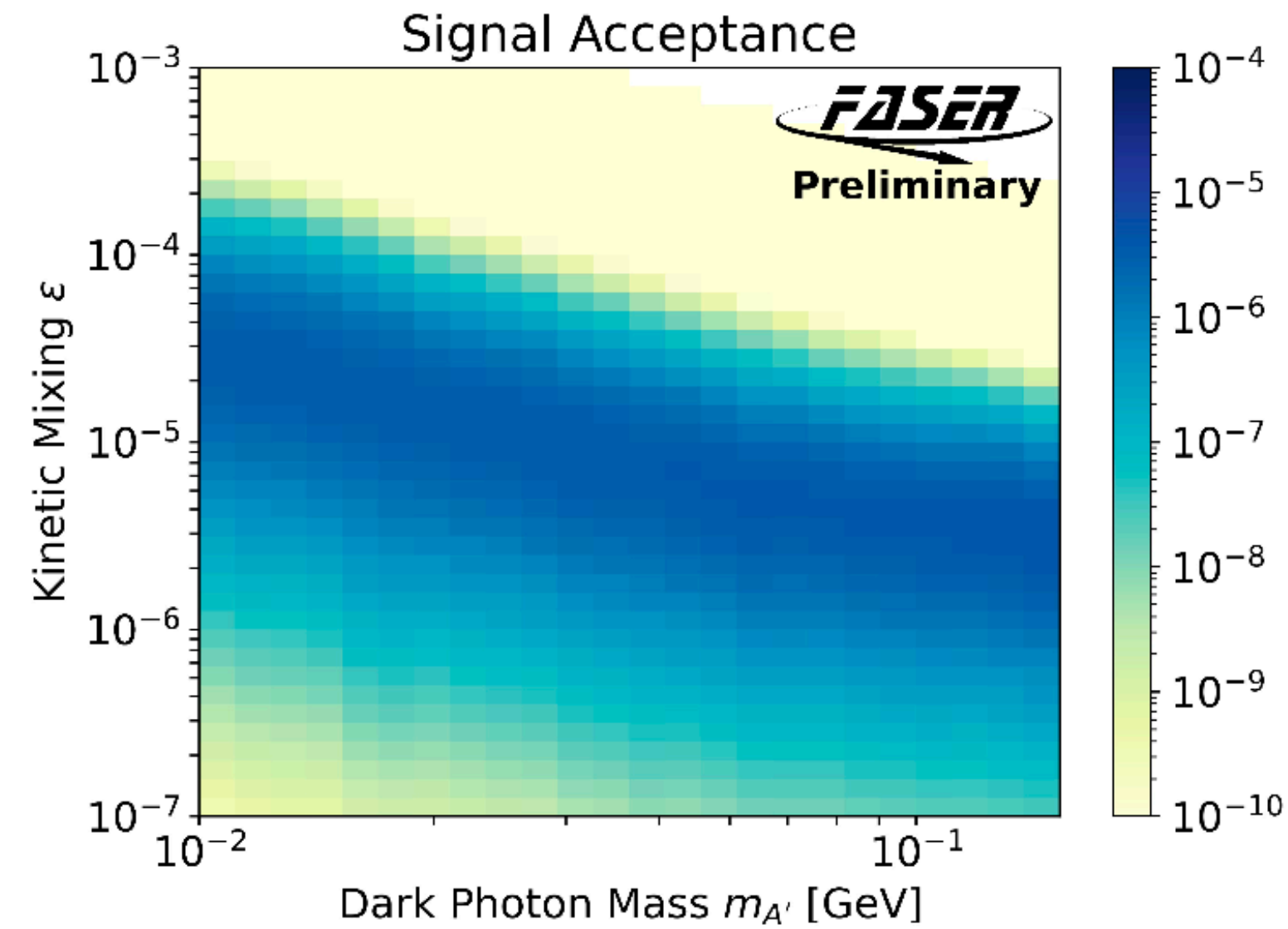


IceCube Collaboration,
Astrophys. J. 833 (2016)

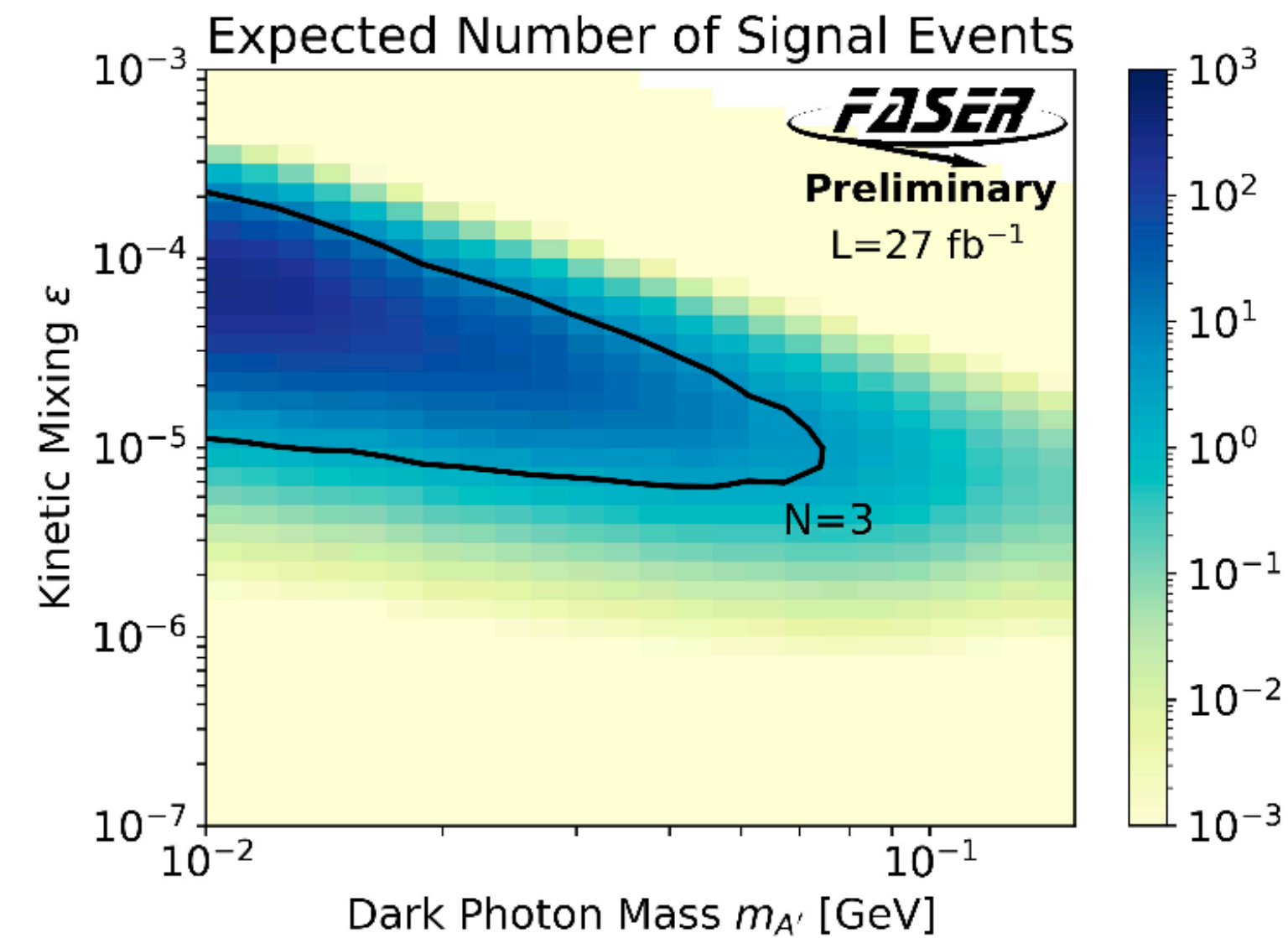


Dark Photon | Signal

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



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

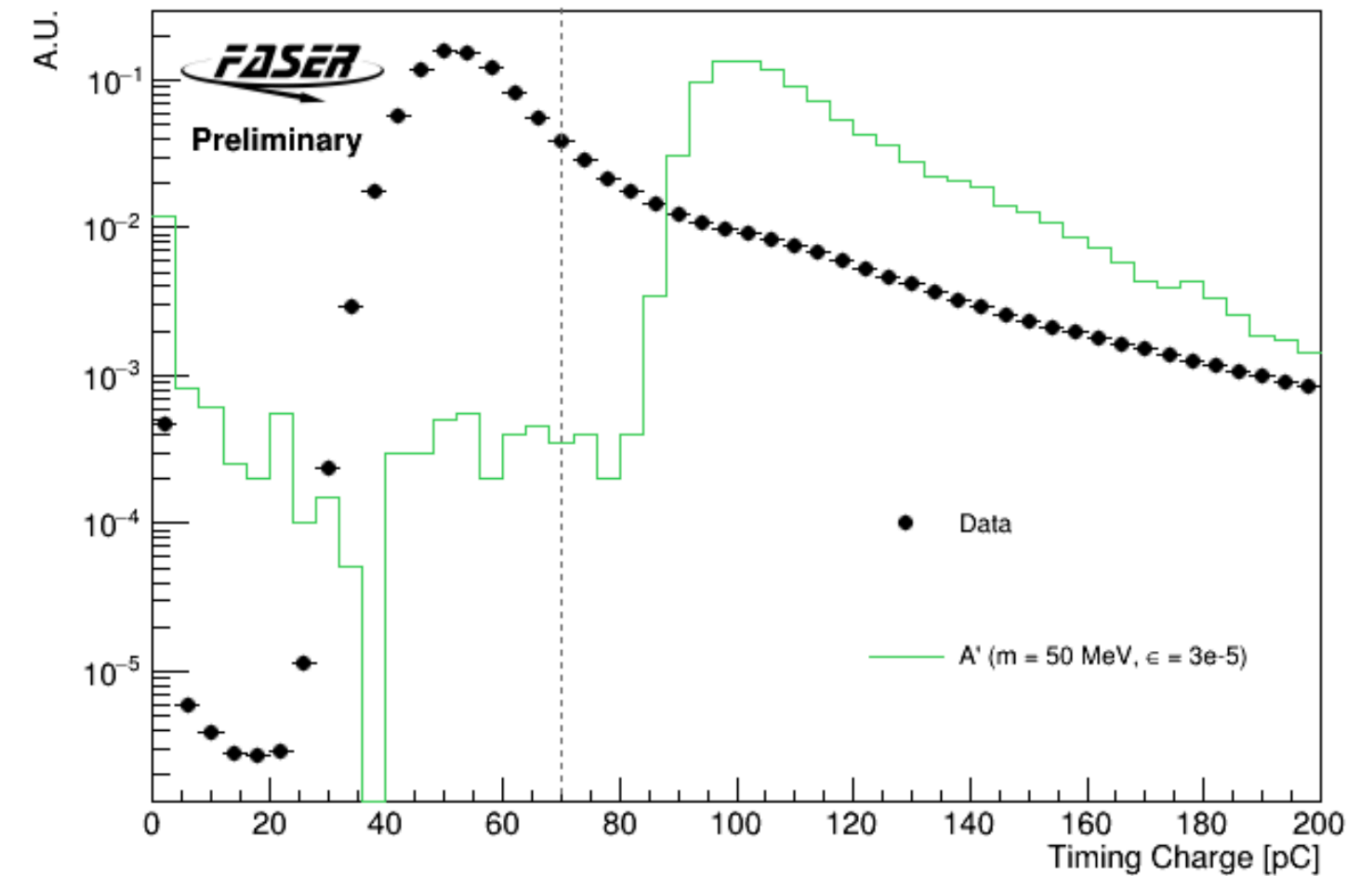




Dark Photon | Selection

Description	Value
Pre-selecton	
Time consistent with a colliding bunch identifier Timing scintillator trigger	
Scintillator	
Timing station: Top or Bottom Scintillator charge OR Top and Bottom charge	> 70 pC > 30 pC
Each Preshower scintillator charge Each Veto scintillator charge	> 2.5 pC < 40 pC
Tracking	
Exactly 2 Good Tracks Momentum χ^2/NDF	> 20 GeV < 25
Number of tracker layers on track Number of tracker hits on track	≥ 7 ≥ 12
Fiducial selection	
Track extrapolated to all scintillators and tracking stations	$< 95\text{mm}$
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%
≥ 1 good track	89.2%
$= 2$ good tracks	44.5% *
Track radius < 95 mm	42.3% *
Calo energy > 500 GeV	41.6% *

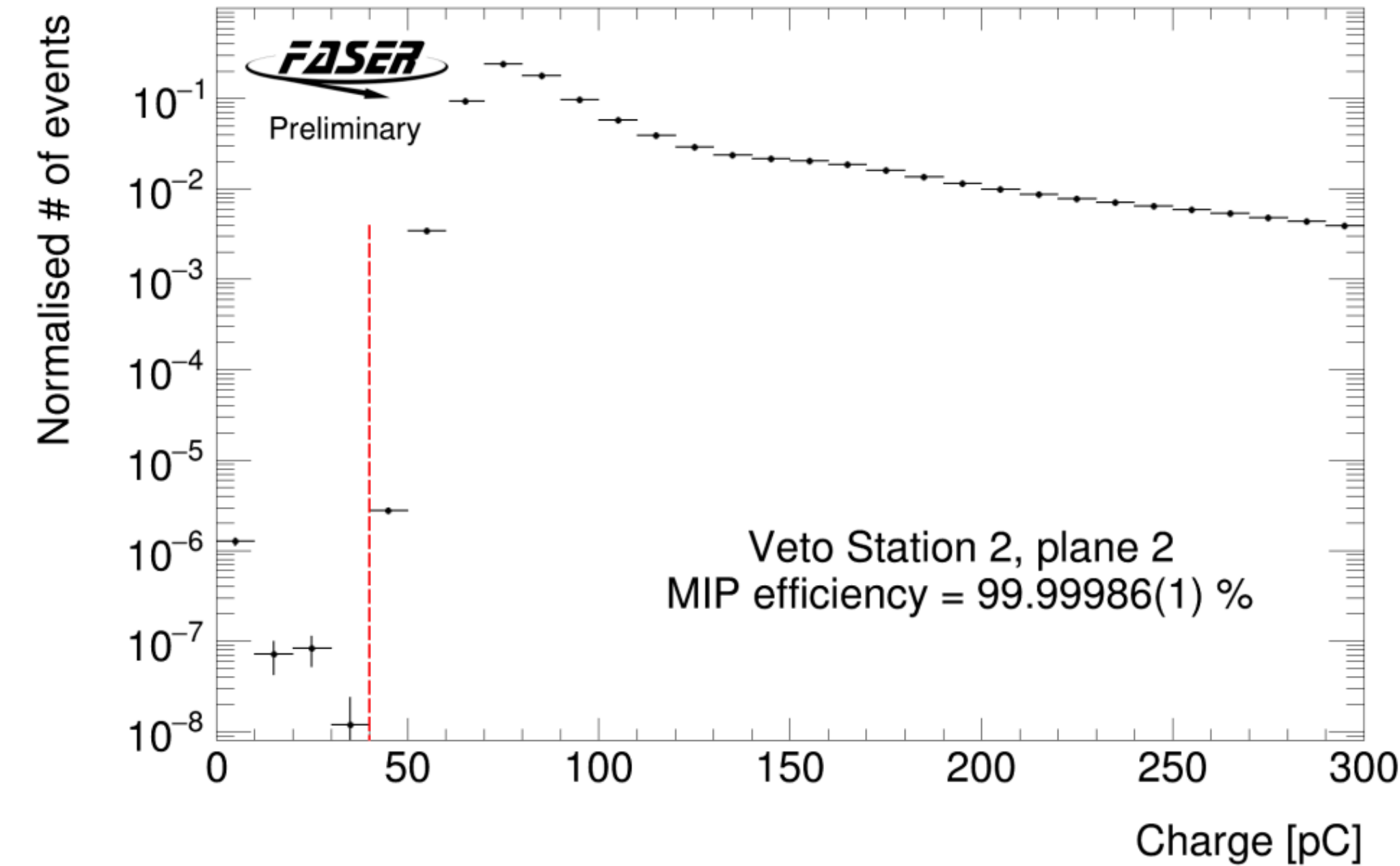
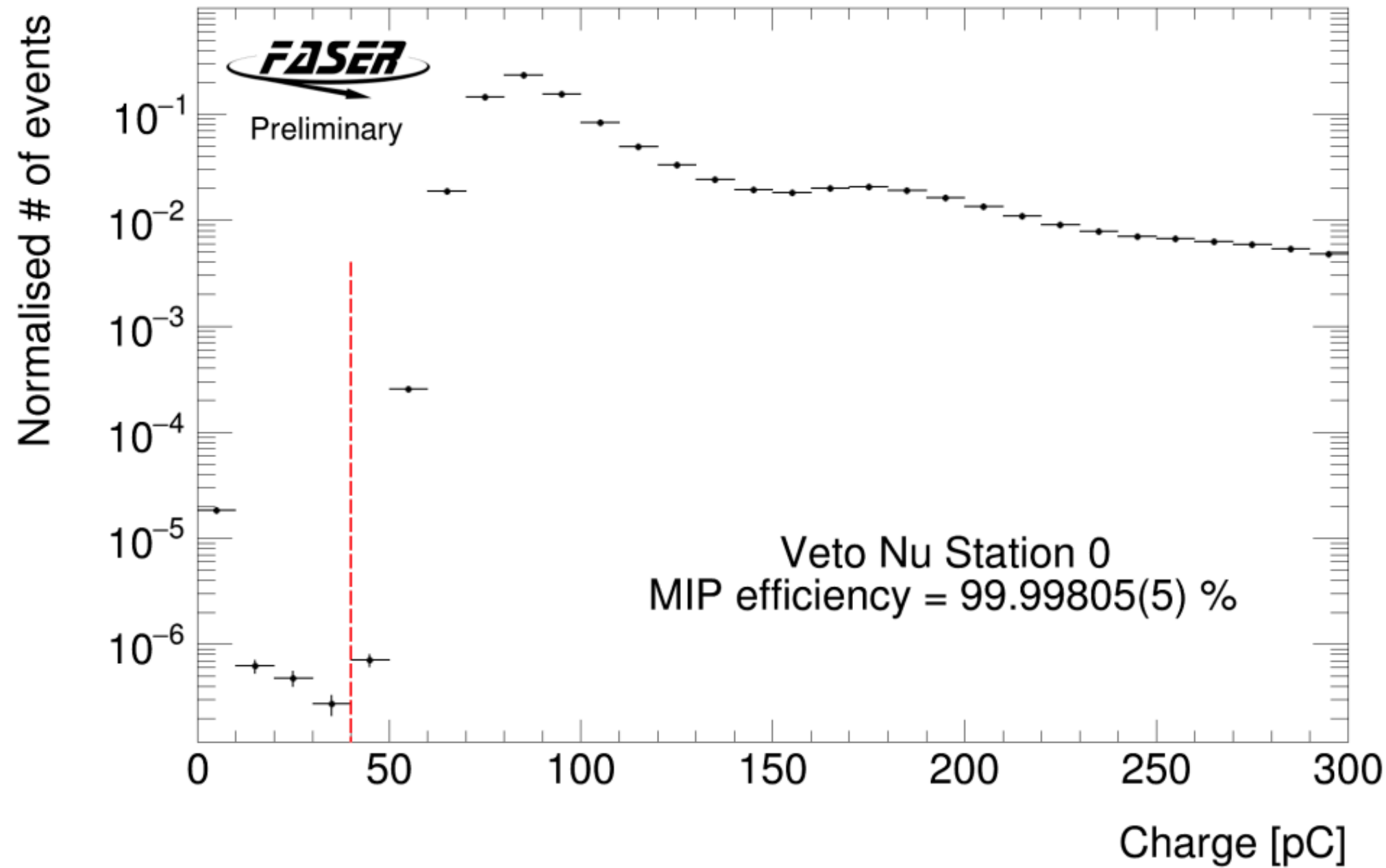
$$\epsilon = 3 \times 10^{-5} \quad m_{A'} = 25.1 \text{ MeV}$$

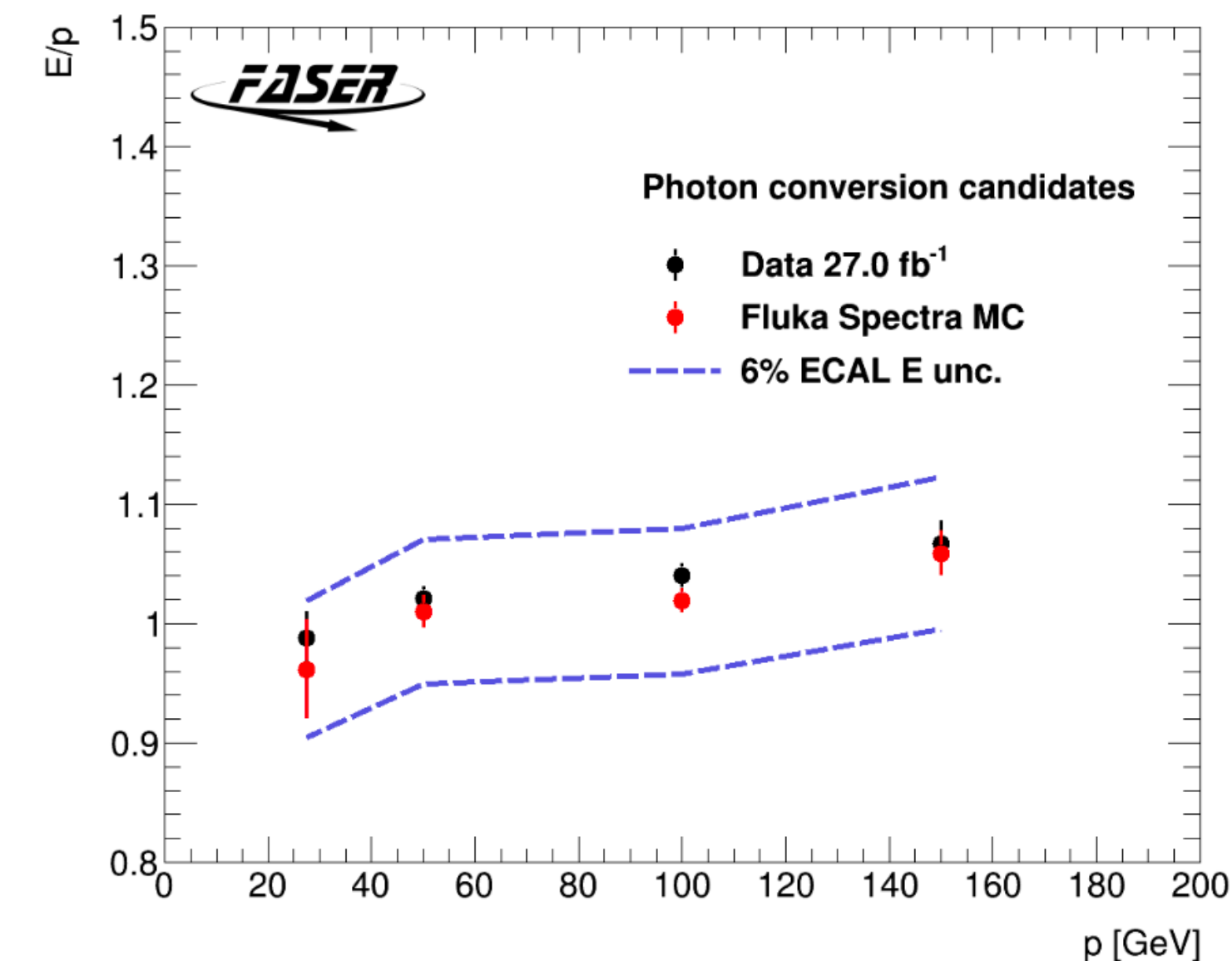
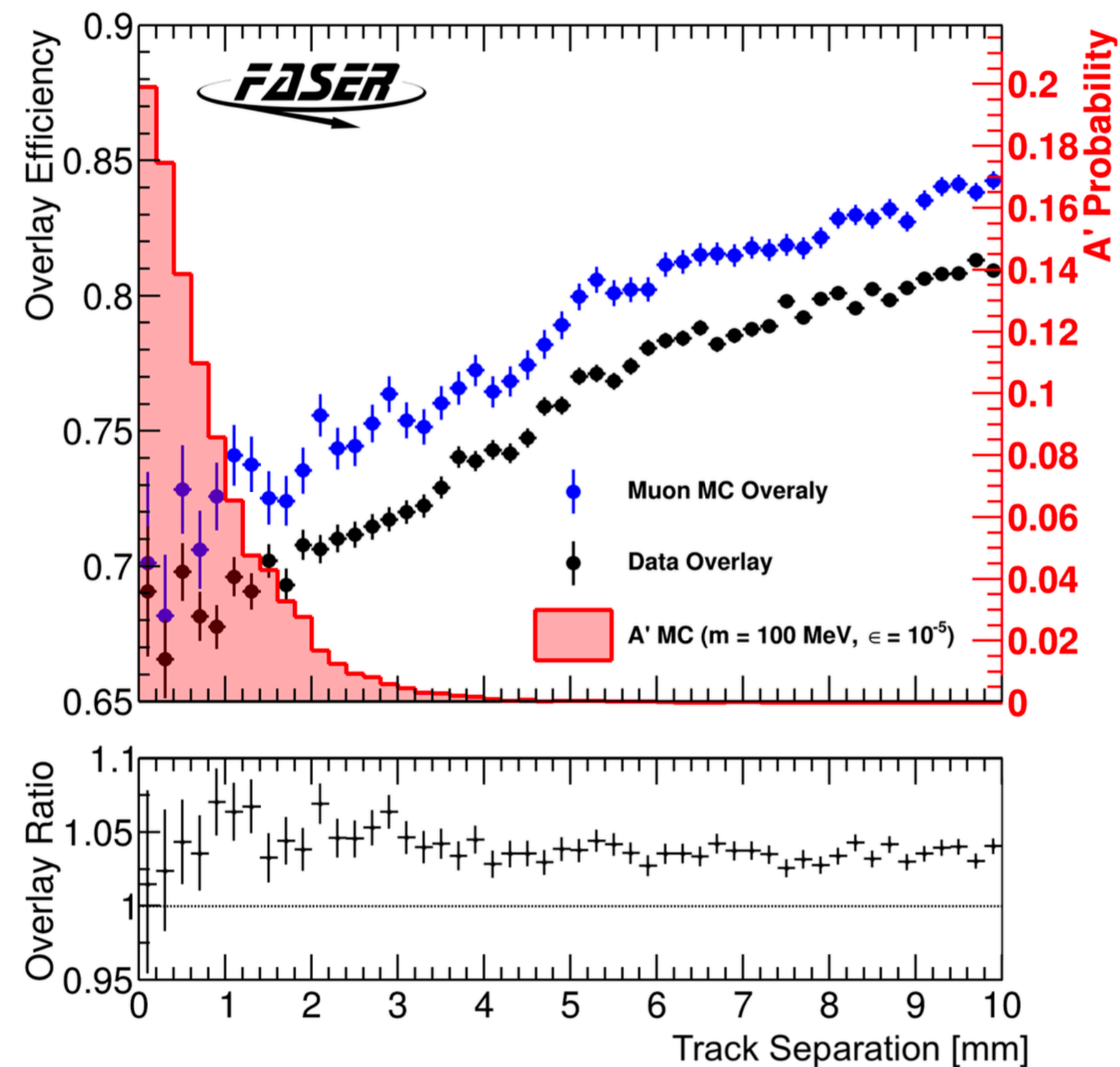
Selection	Nevents $E < 100$ GeV	Nevents $E > 500$ GeV
3 tracks (VetoNu signal)	544.7	11.0
2 tracks (No VetoNu signal)	1	Predicted: 0.02



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)



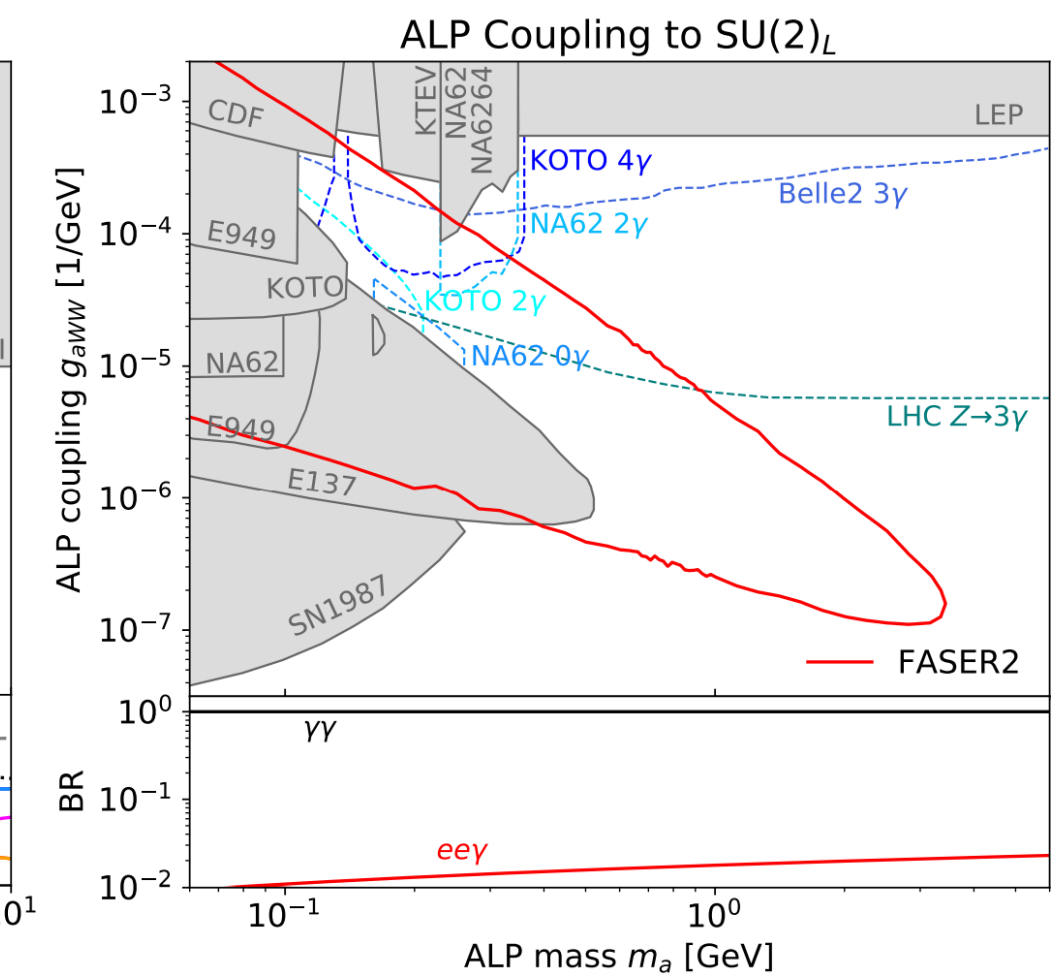
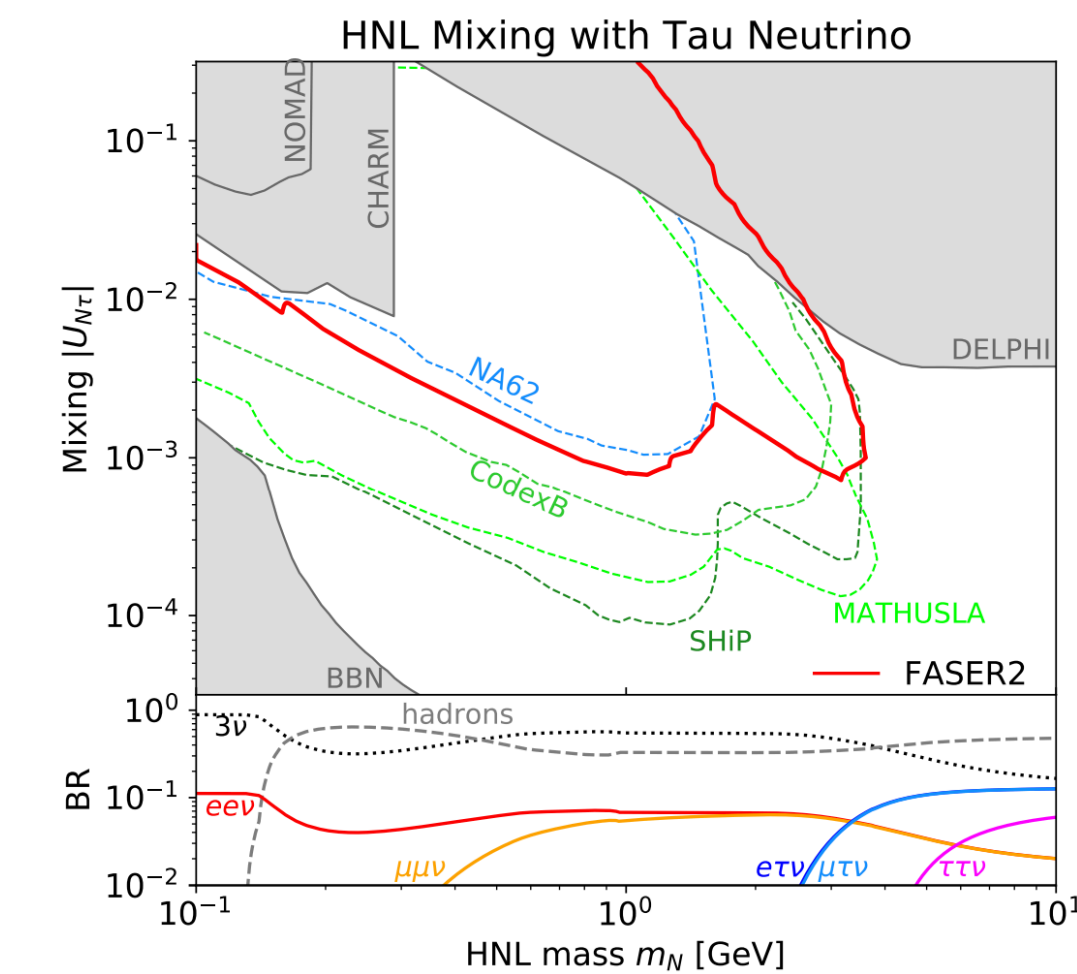
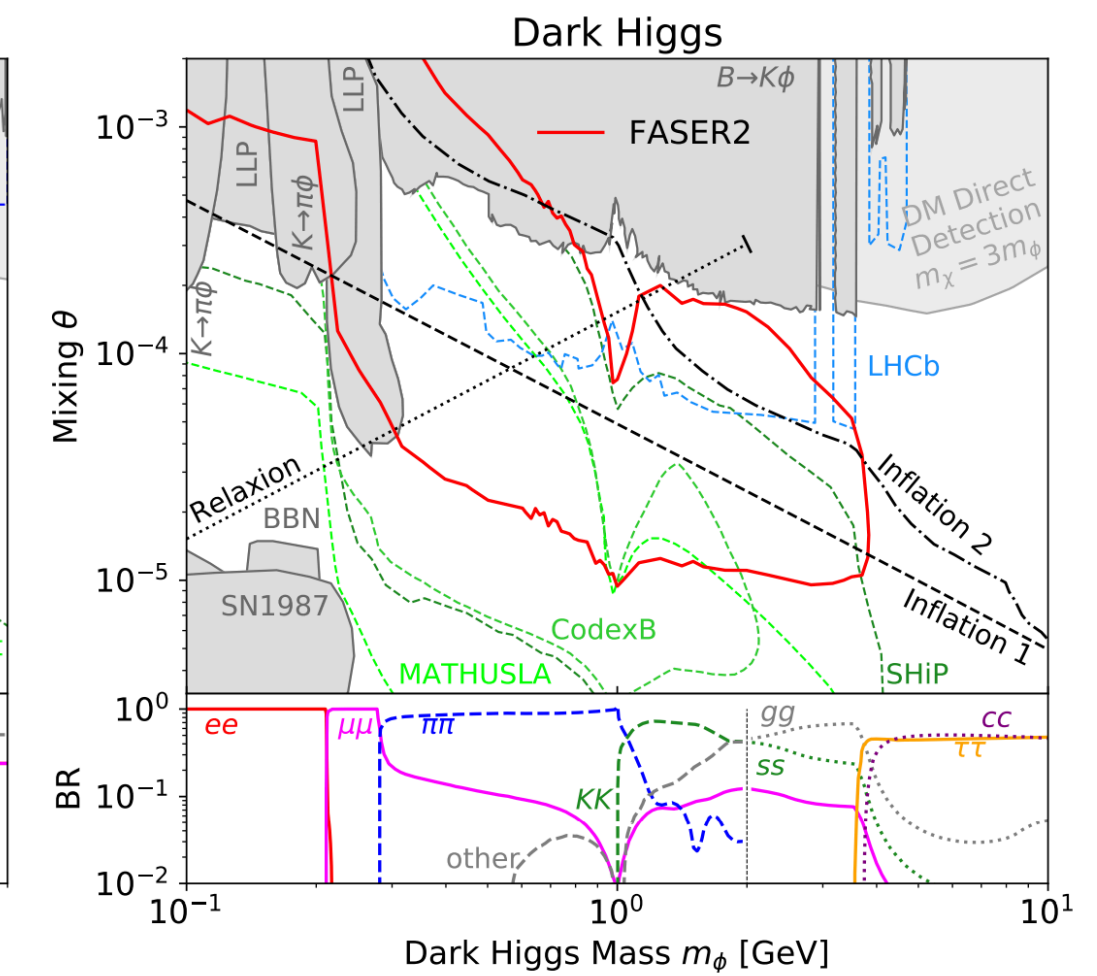
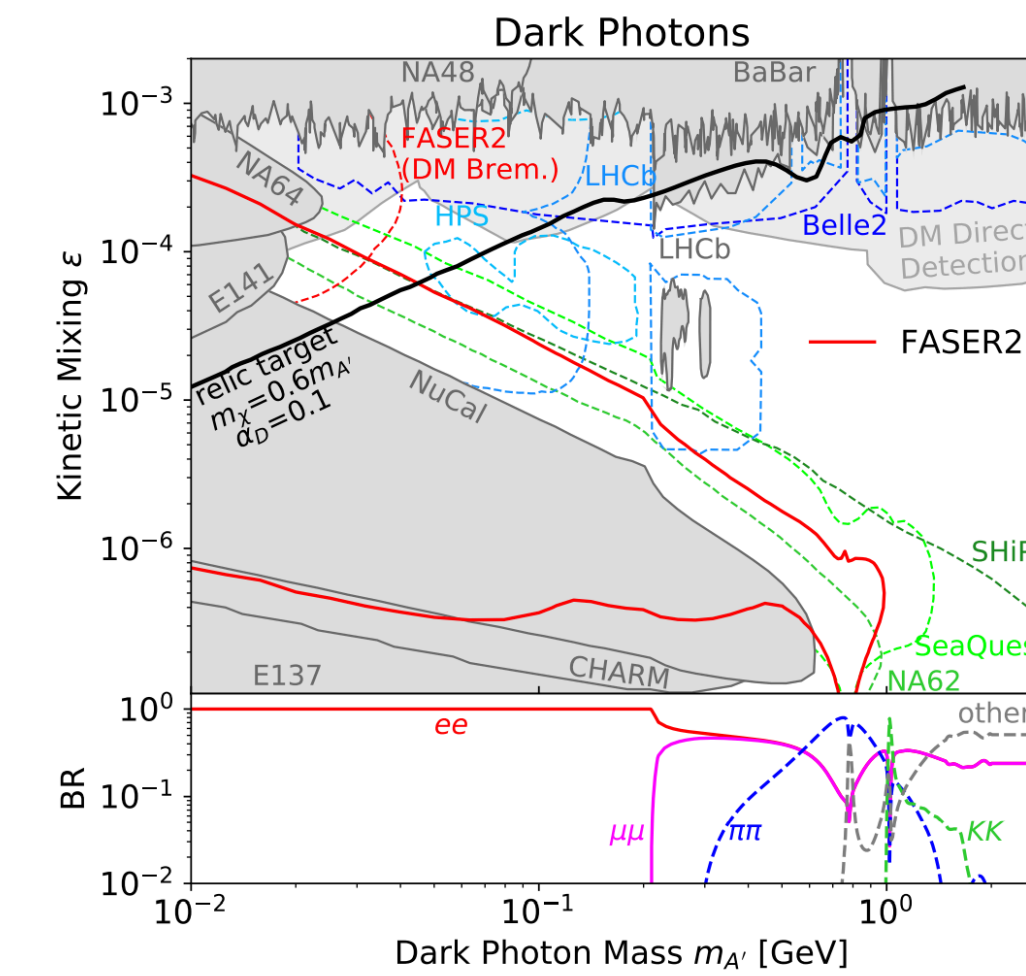
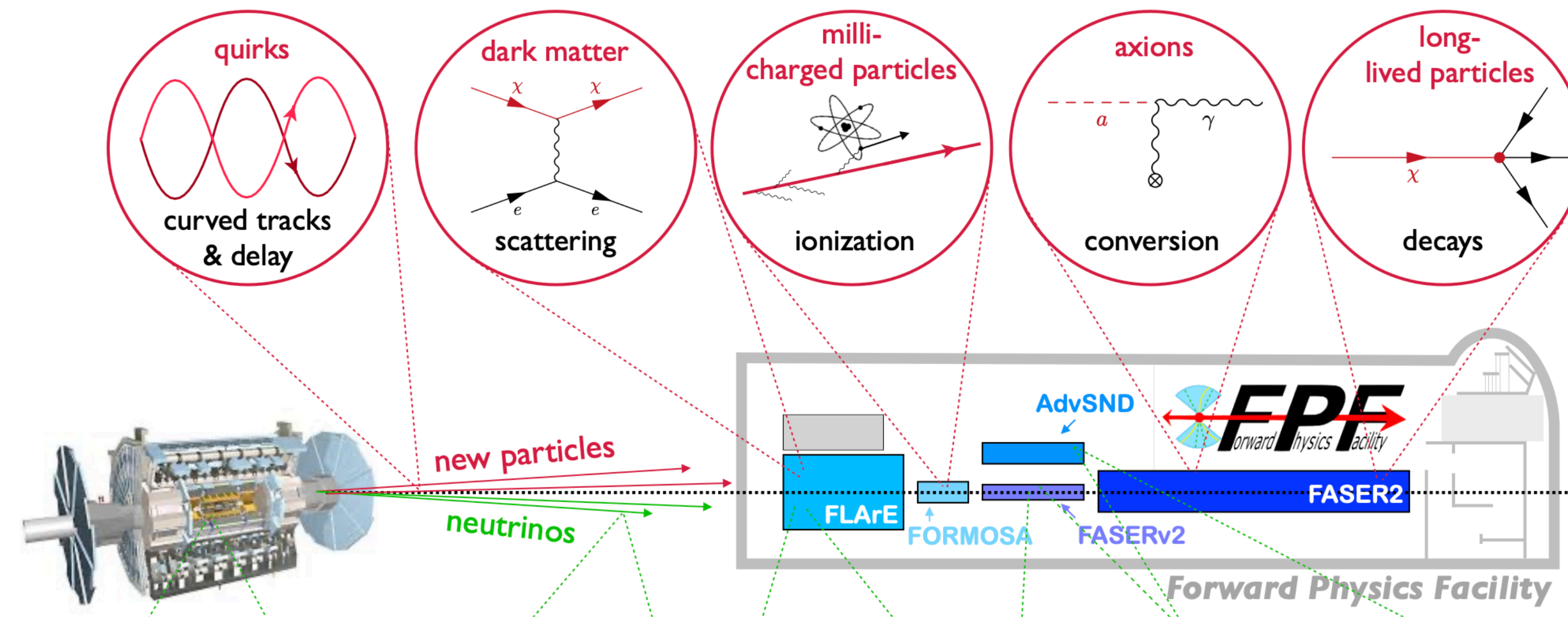


Source	Value	Effect on signal yield
Signal Generator	$\frac{0.15+(E_{A'}/4\text{TeV})^3}{1+(E_{A'}/4\text{TeV})^3}$	15-65% (15-45%)
Luminosity	2.2%	2.2%
MC Statistics	$\sqrt{\sum W^2}$	1-3% (1-2%)
Track Momentum Scale	5%	< 0.5%
Track Momentum Resolution	5%	< 0.5%
Single Track Efficiency	3%	3%
Two-track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

Forward Physics Facility | BSM

► FPF Papers:

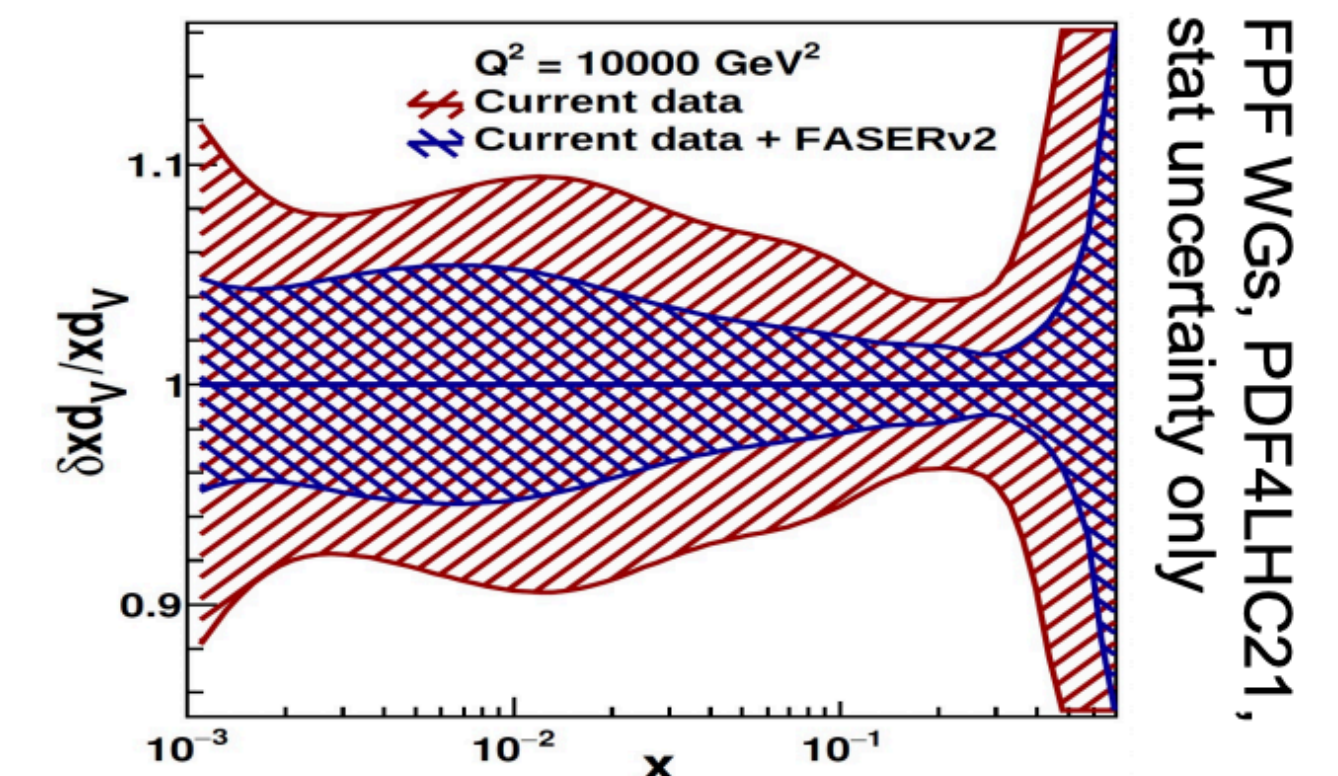
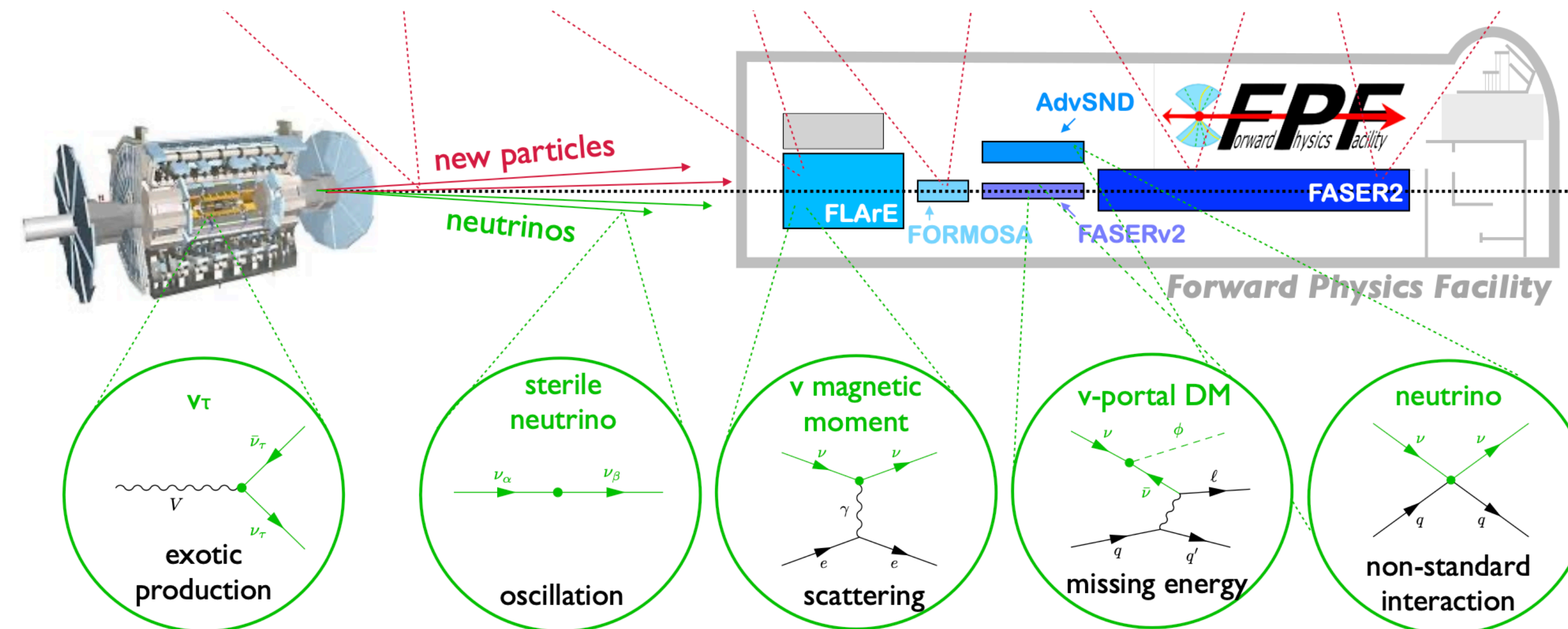
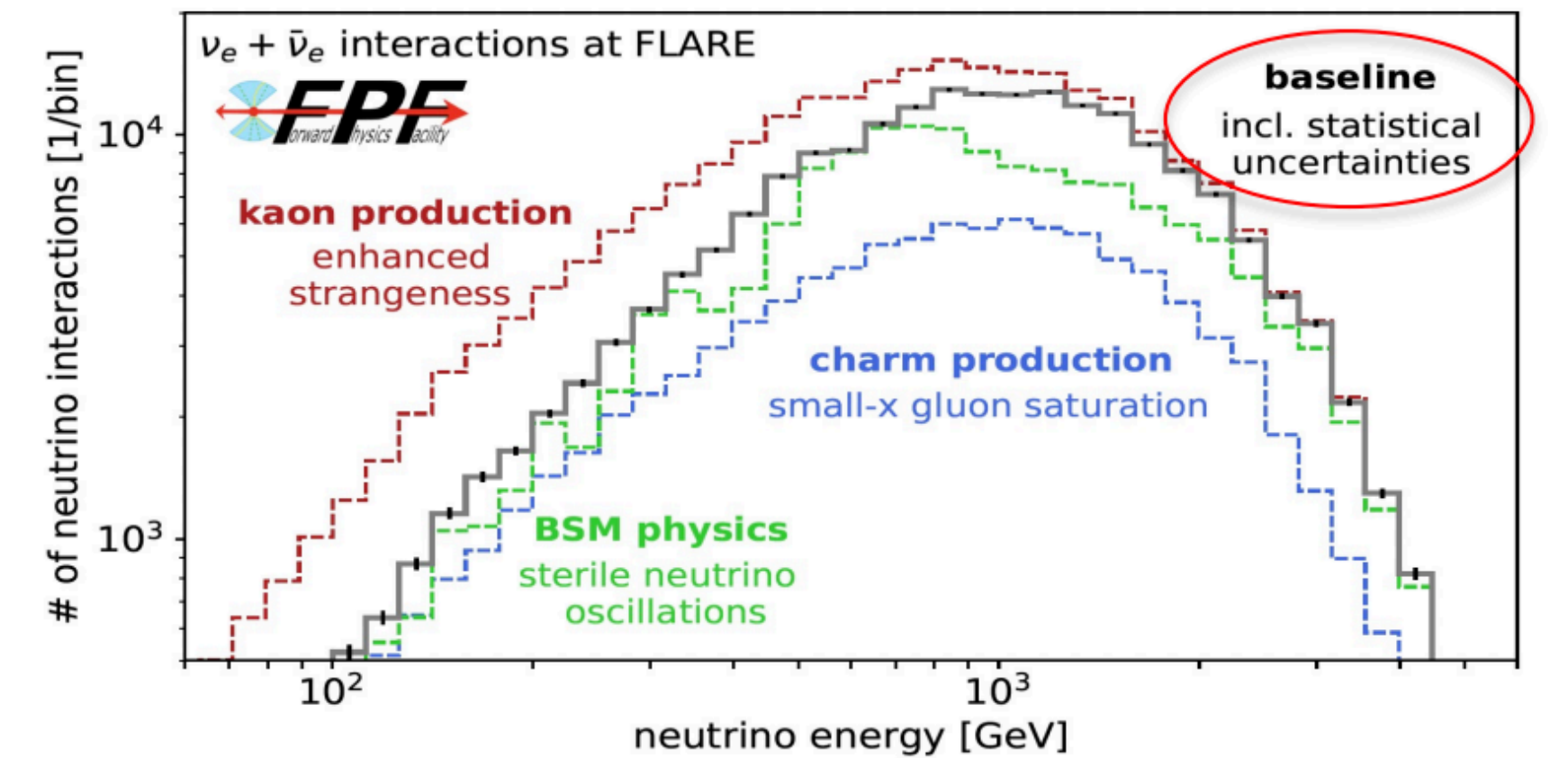
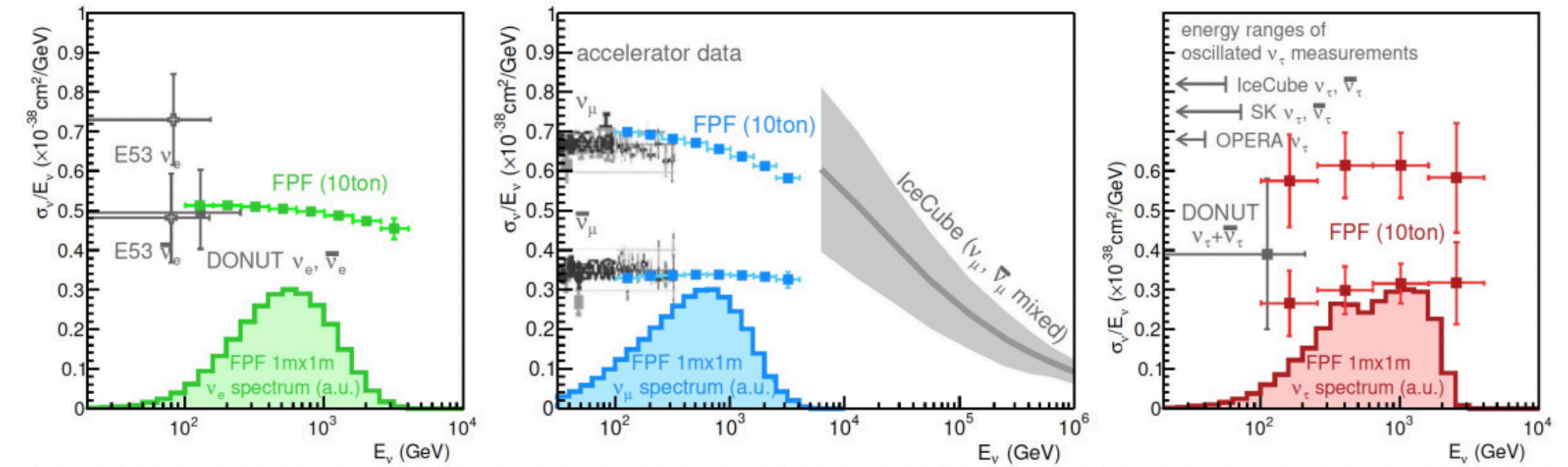
- FPF “Short” Paper: Phys. Rept. 968, 1 (2022)
- FPF White Paper: J. Phys. G (2022)



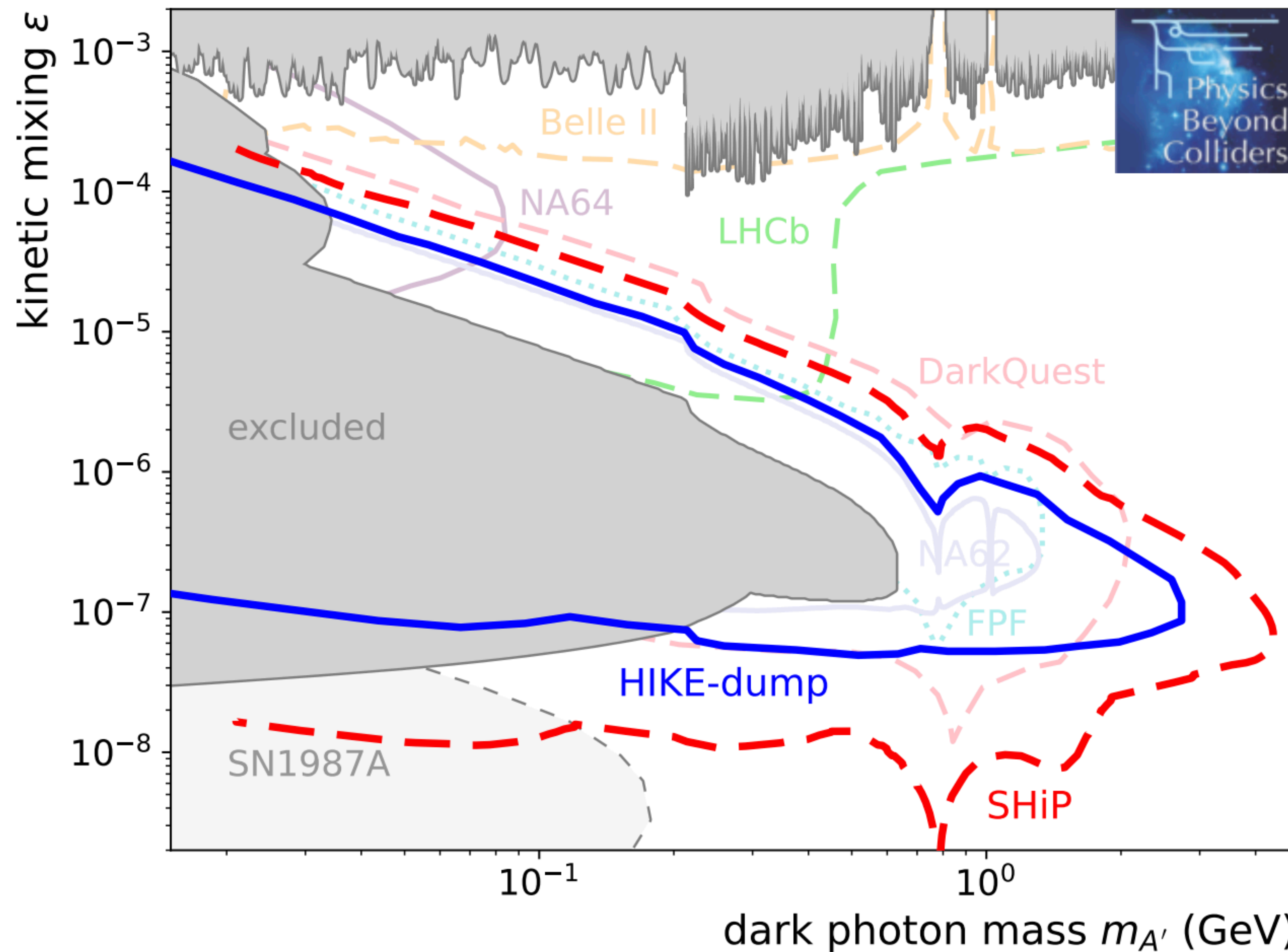
Forward Physics Facility | Neutrinos

► FPF Papers:

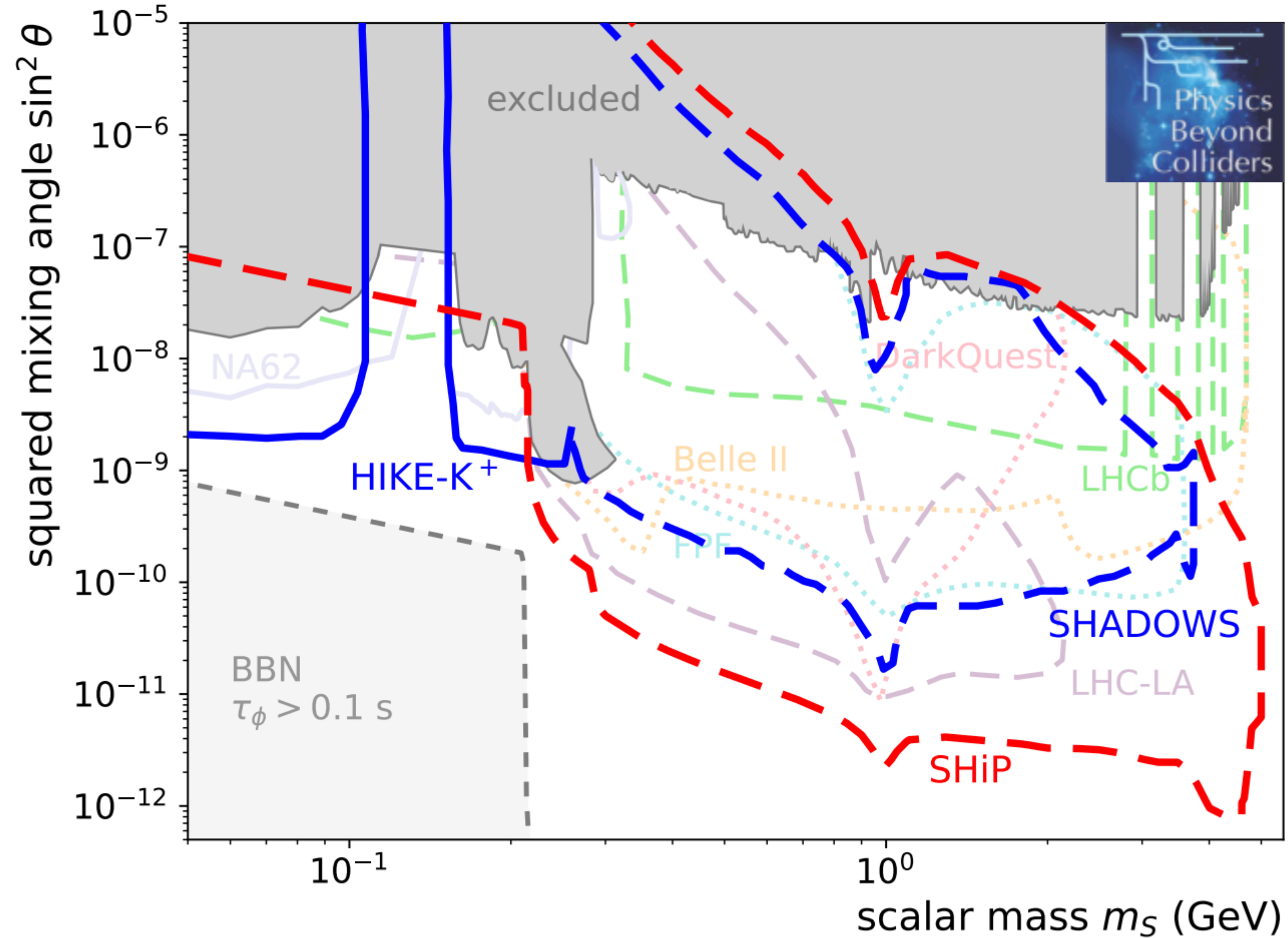
- FPF "Short" Paper: Phys. Rept. 968, 1 (2022)
- FPF White Paper: J. Phys. G (2022)



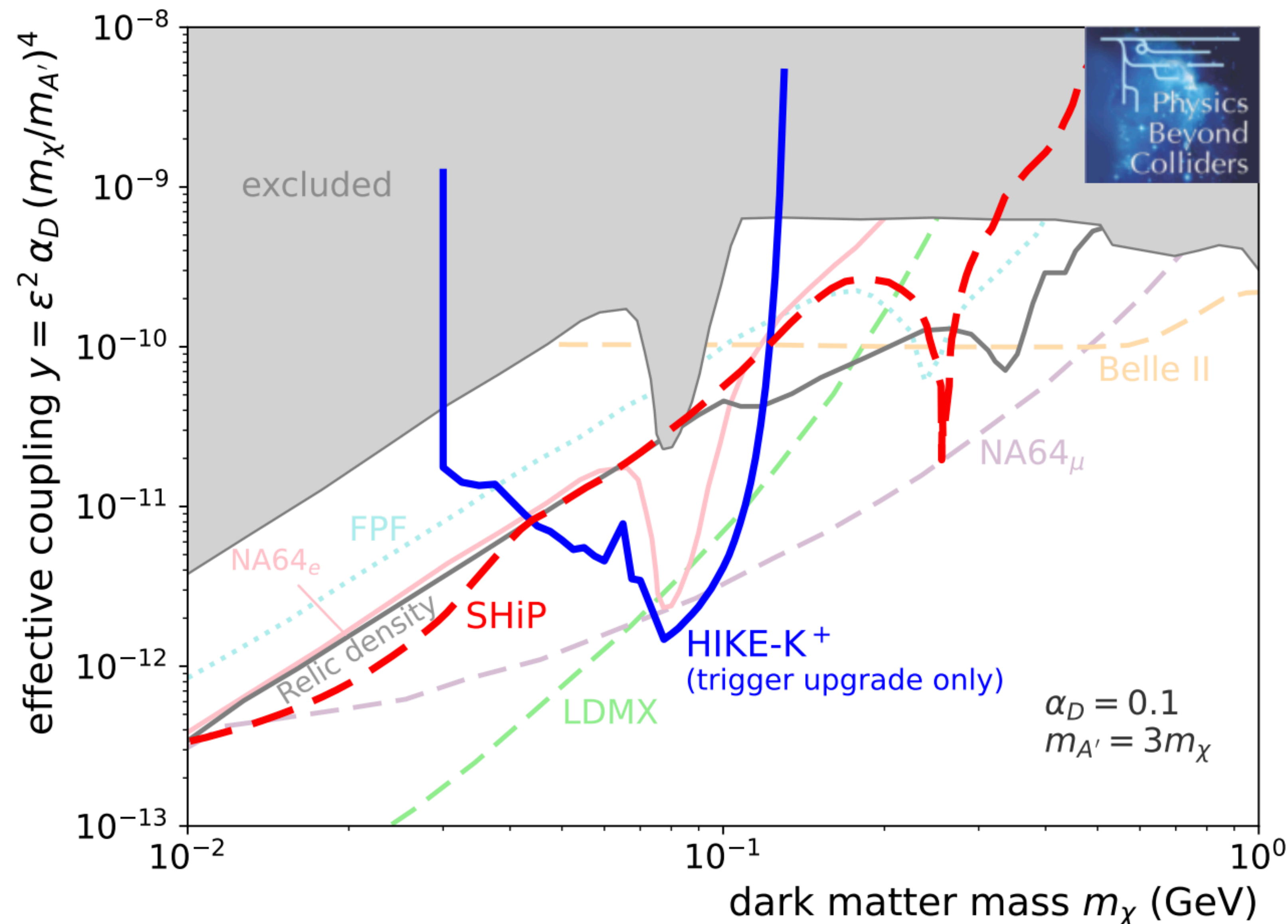
- **FPF**
- **HIKE+SHADOWS**
- **SHiP**
- CDS record

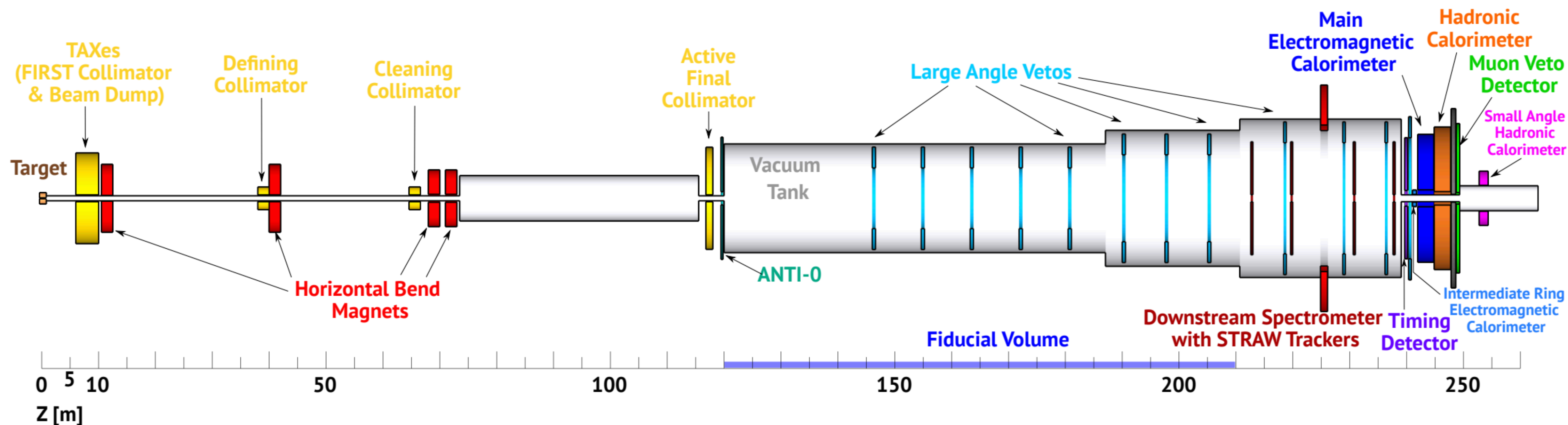
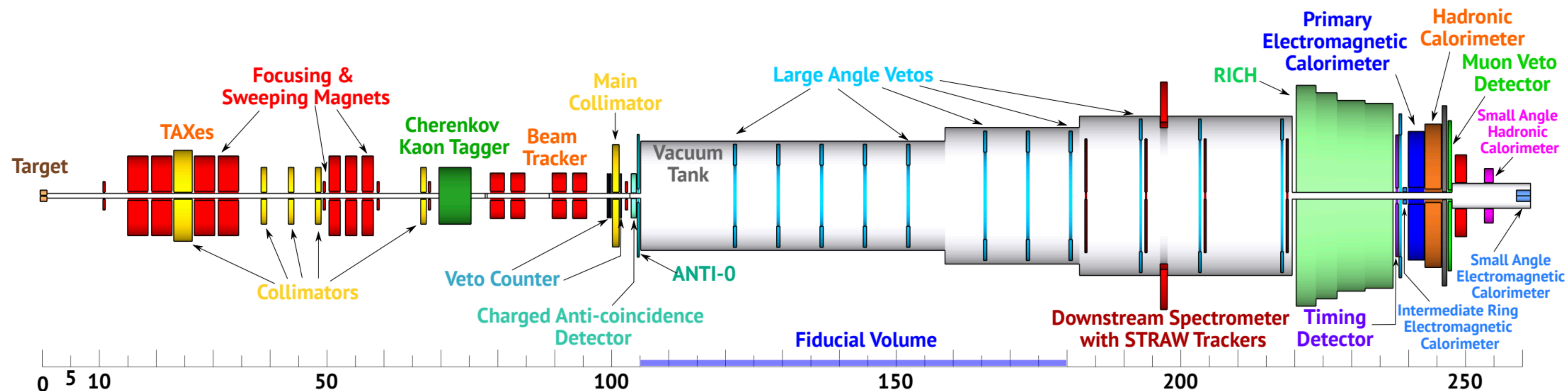


- ▶ **FPF**
- ▶ **HIKE+SHADOWS**
- ▶ **SHiP**
- ▶ CDS record



- **FPF**
- **HIKE+SHADOWS**
- **SHiP**
- CDS record





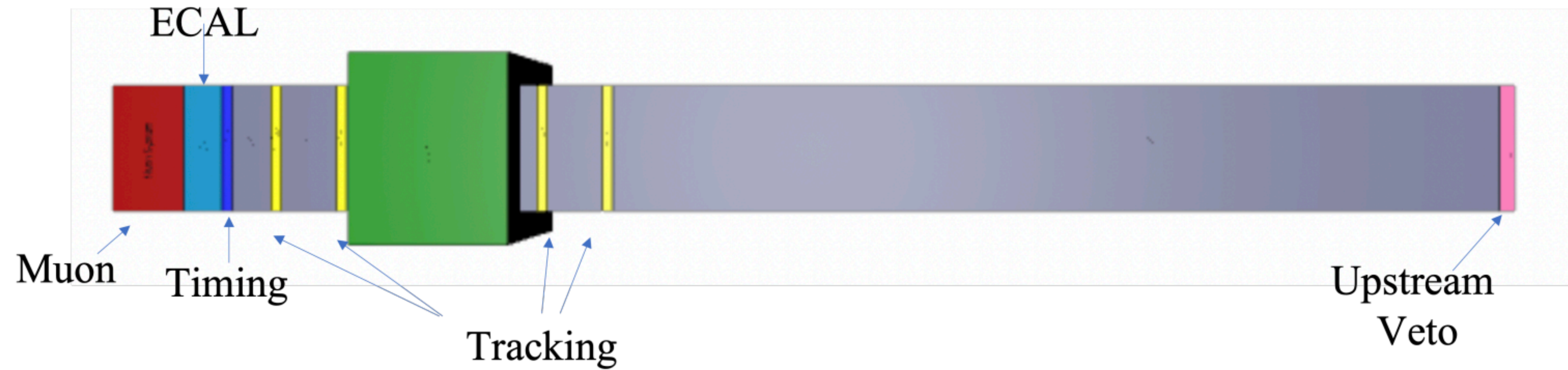
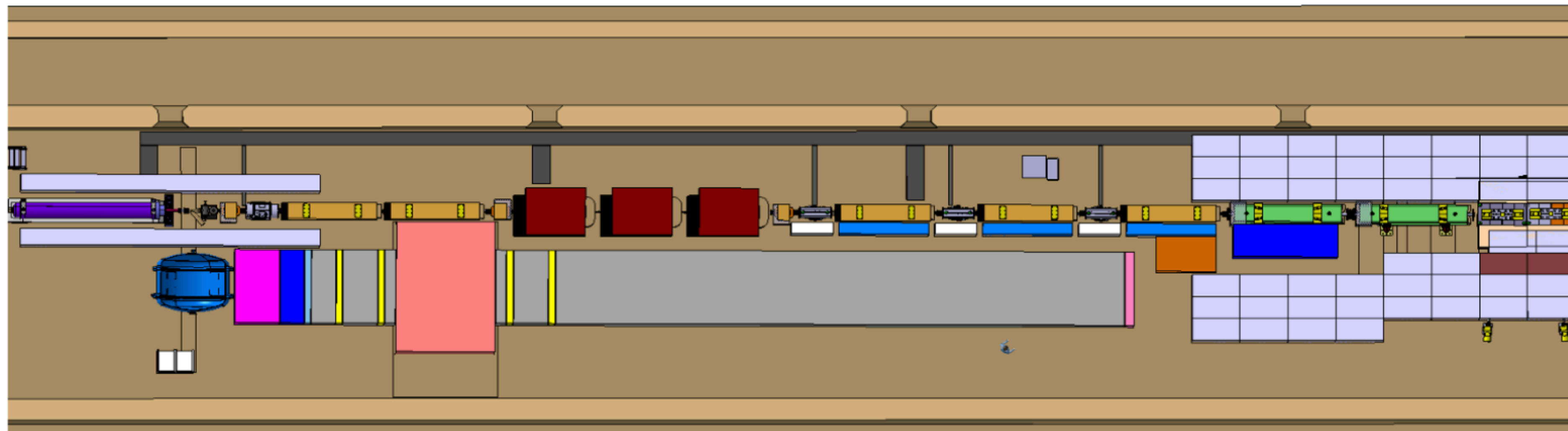
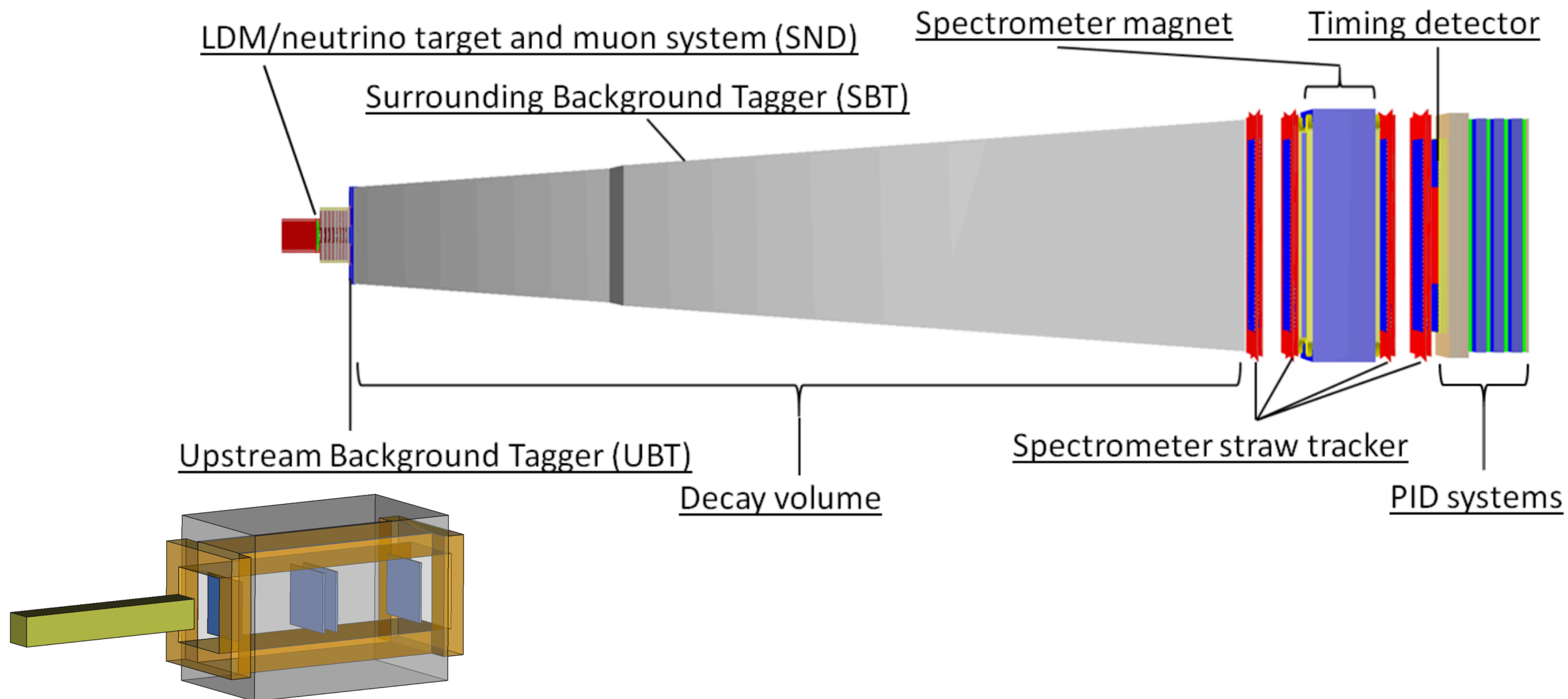


Figure 6: Schematic layout of the SHADOWS spectrometer.

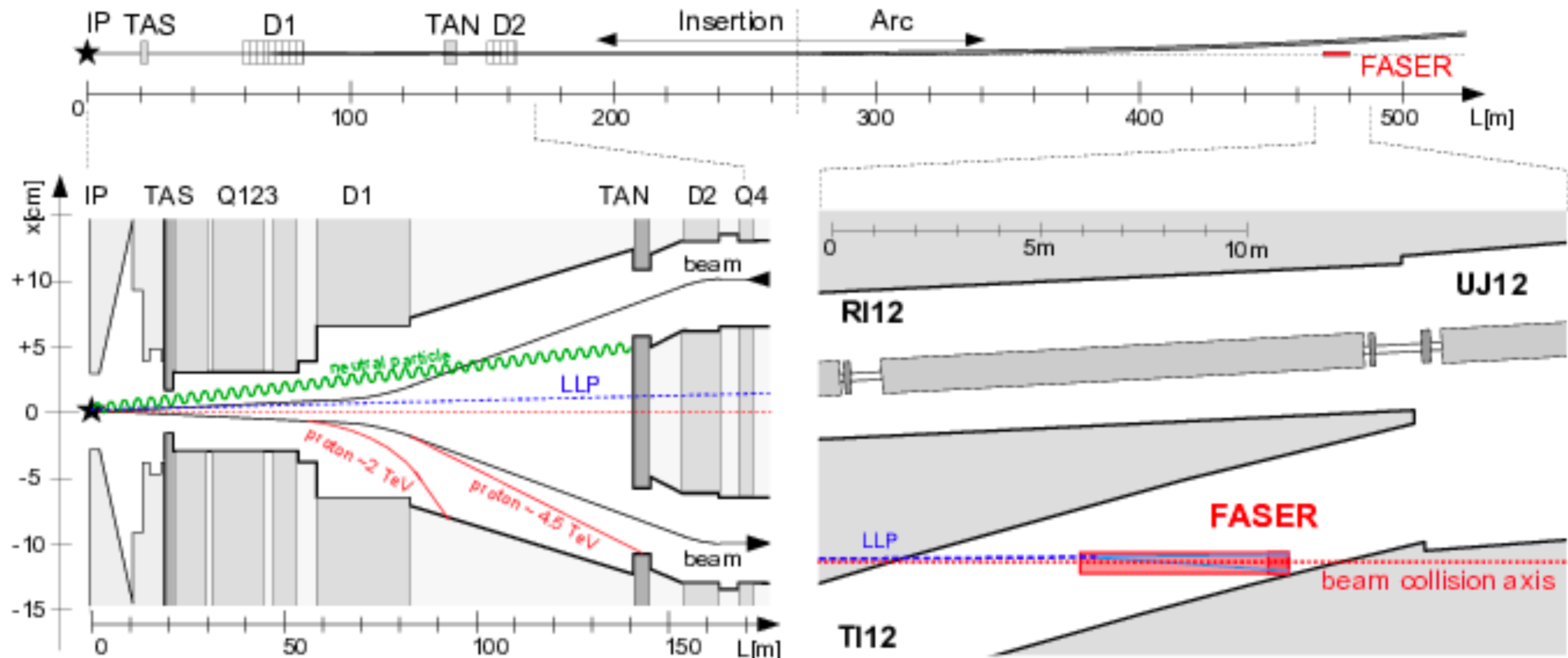






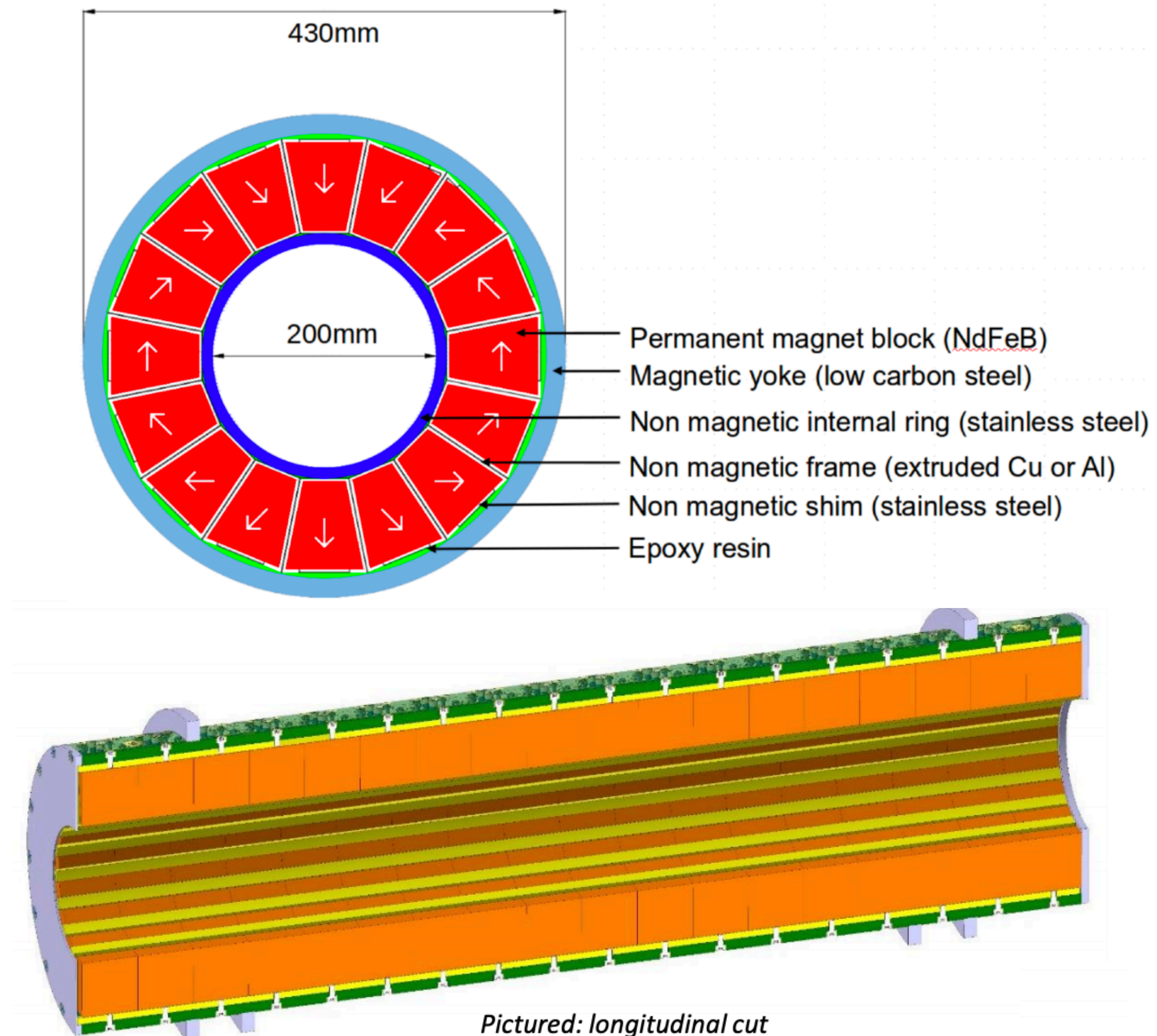
FASER Location

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



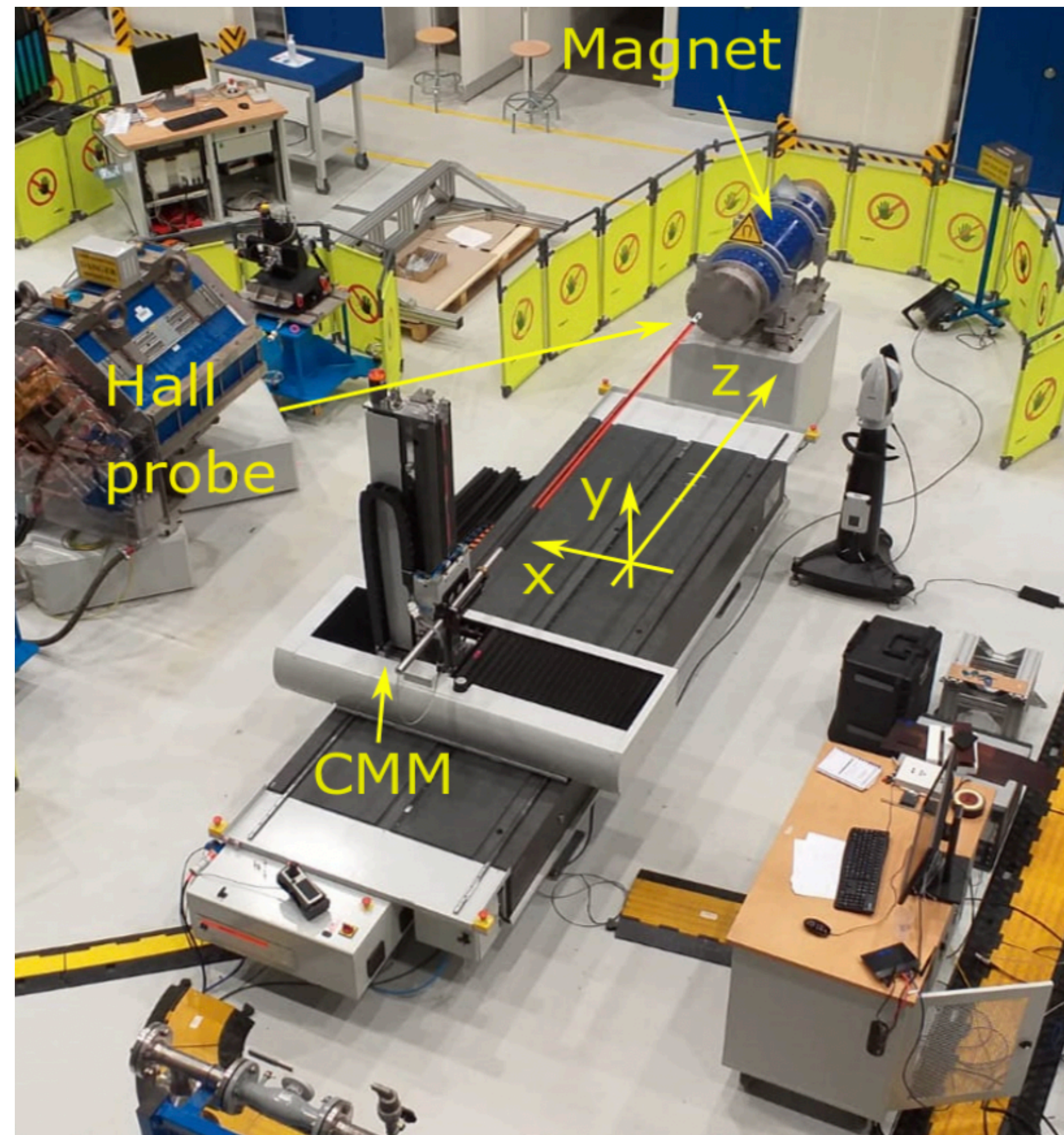
Magnets | Overview

- ▶ 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 T112
- ▶ Minimize needed services (power, cooling etc..)
- ▶ Designed and constructed by magnet group at CERN



Magnets | Construction and testing

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



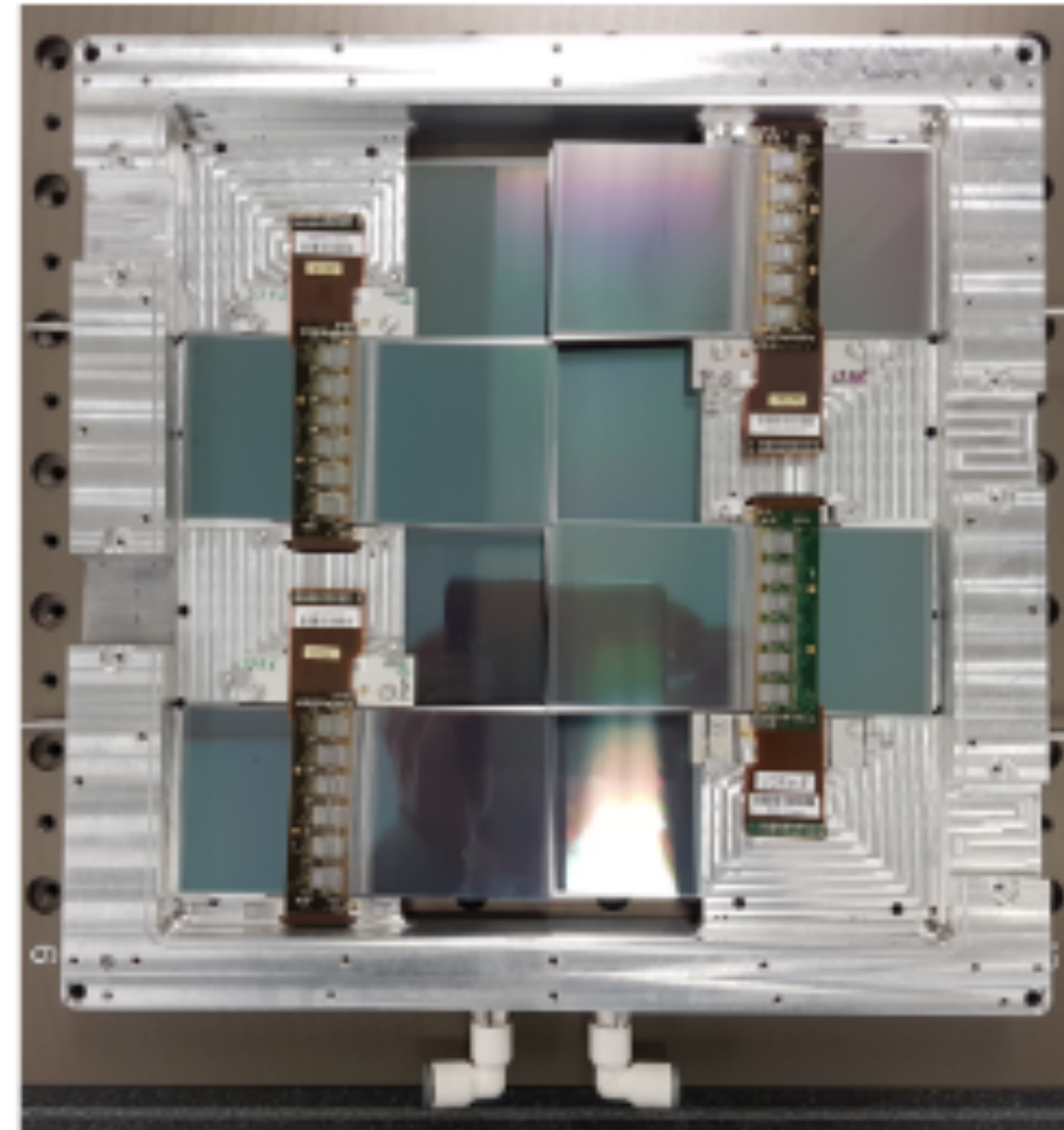
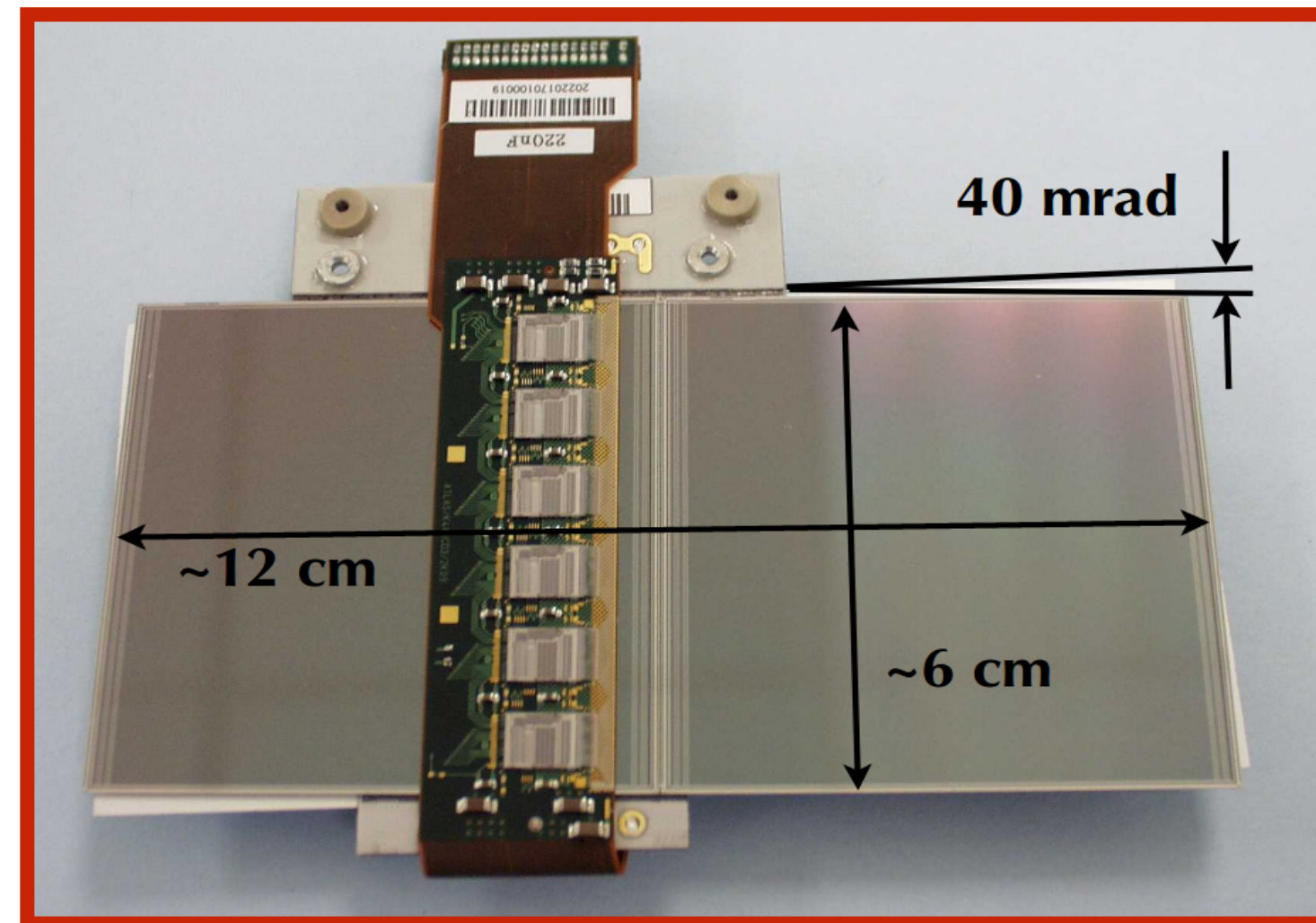
Magnets | Installation

- ▶ 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!



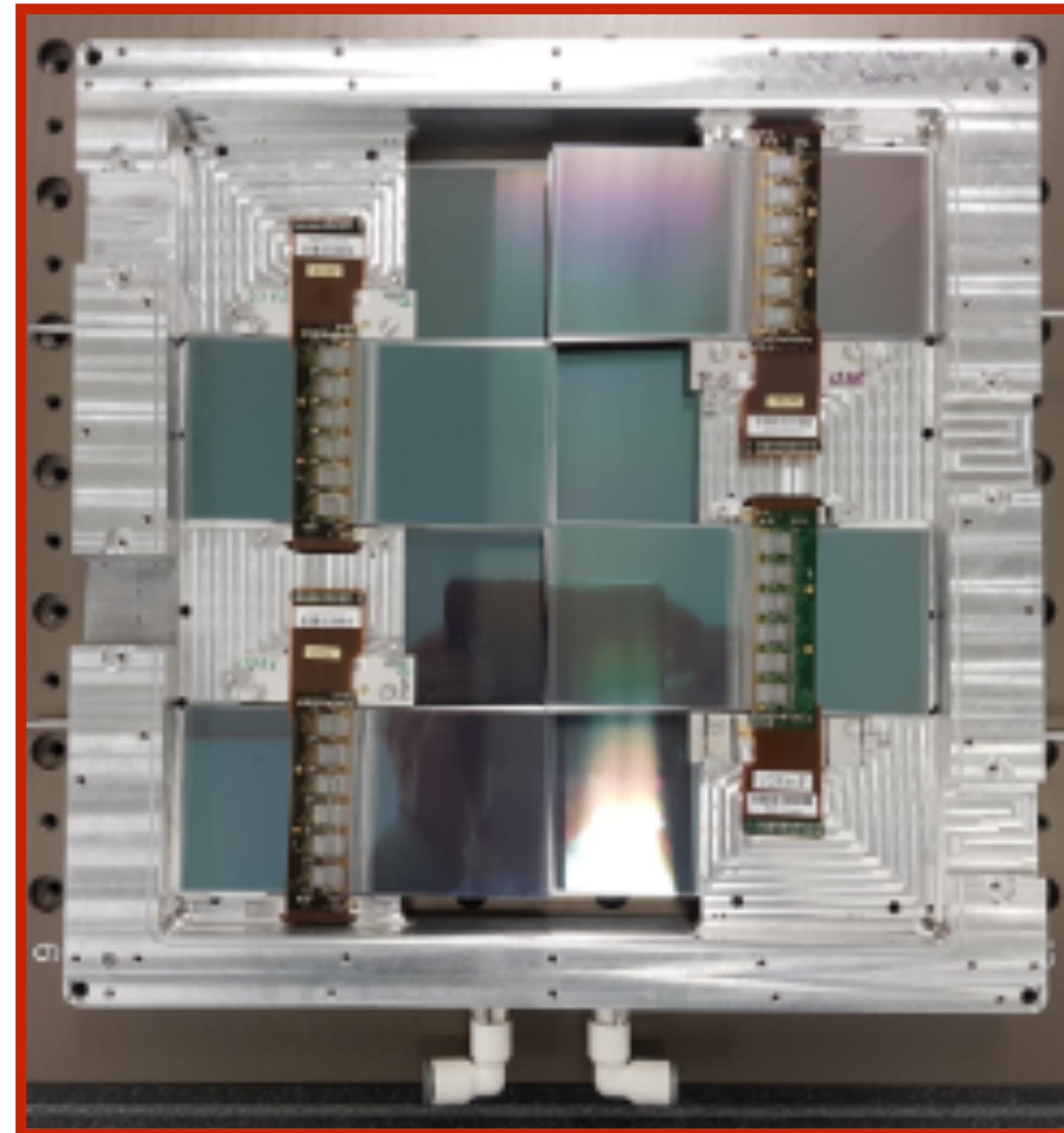
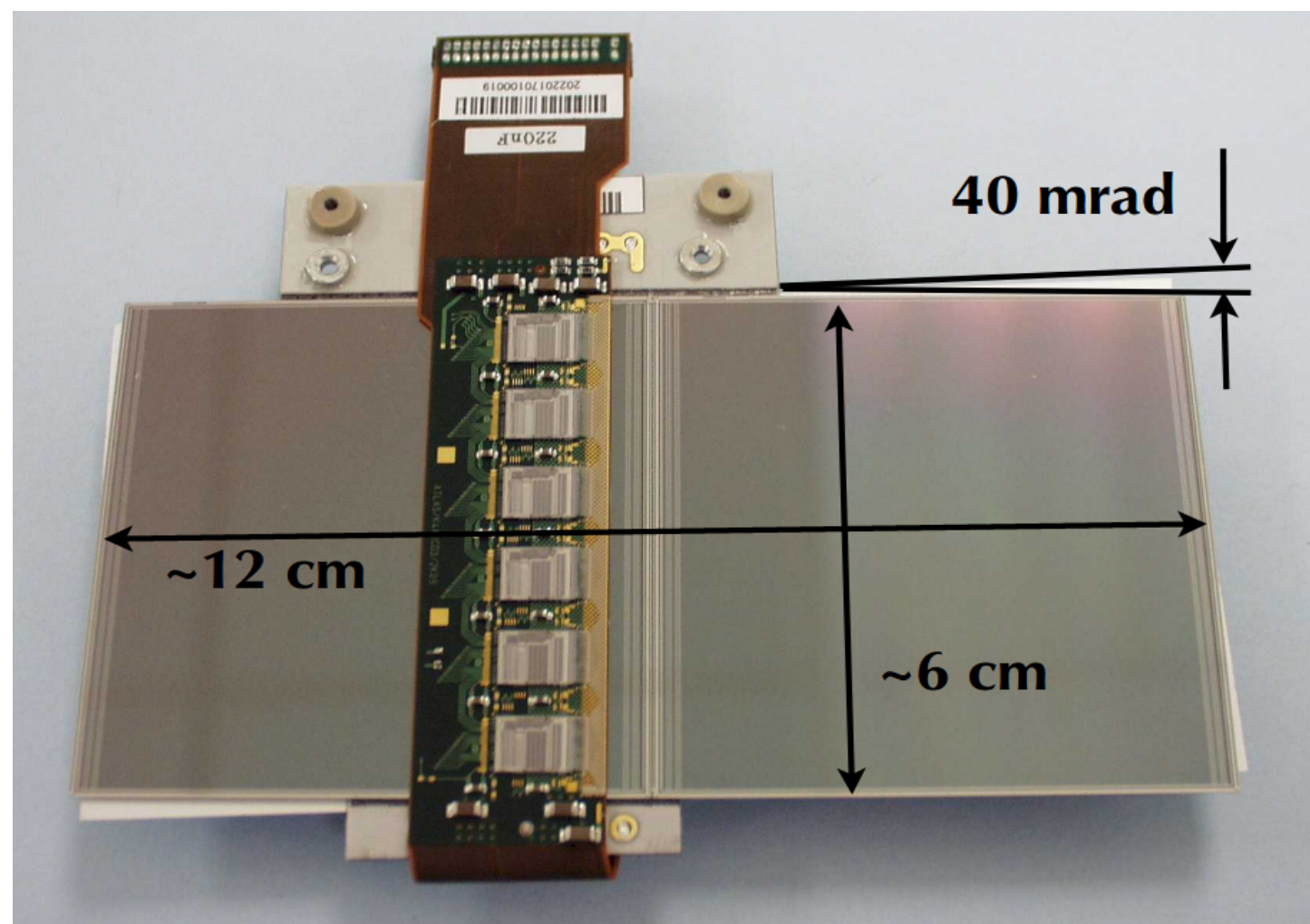
Tracker | Modules

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

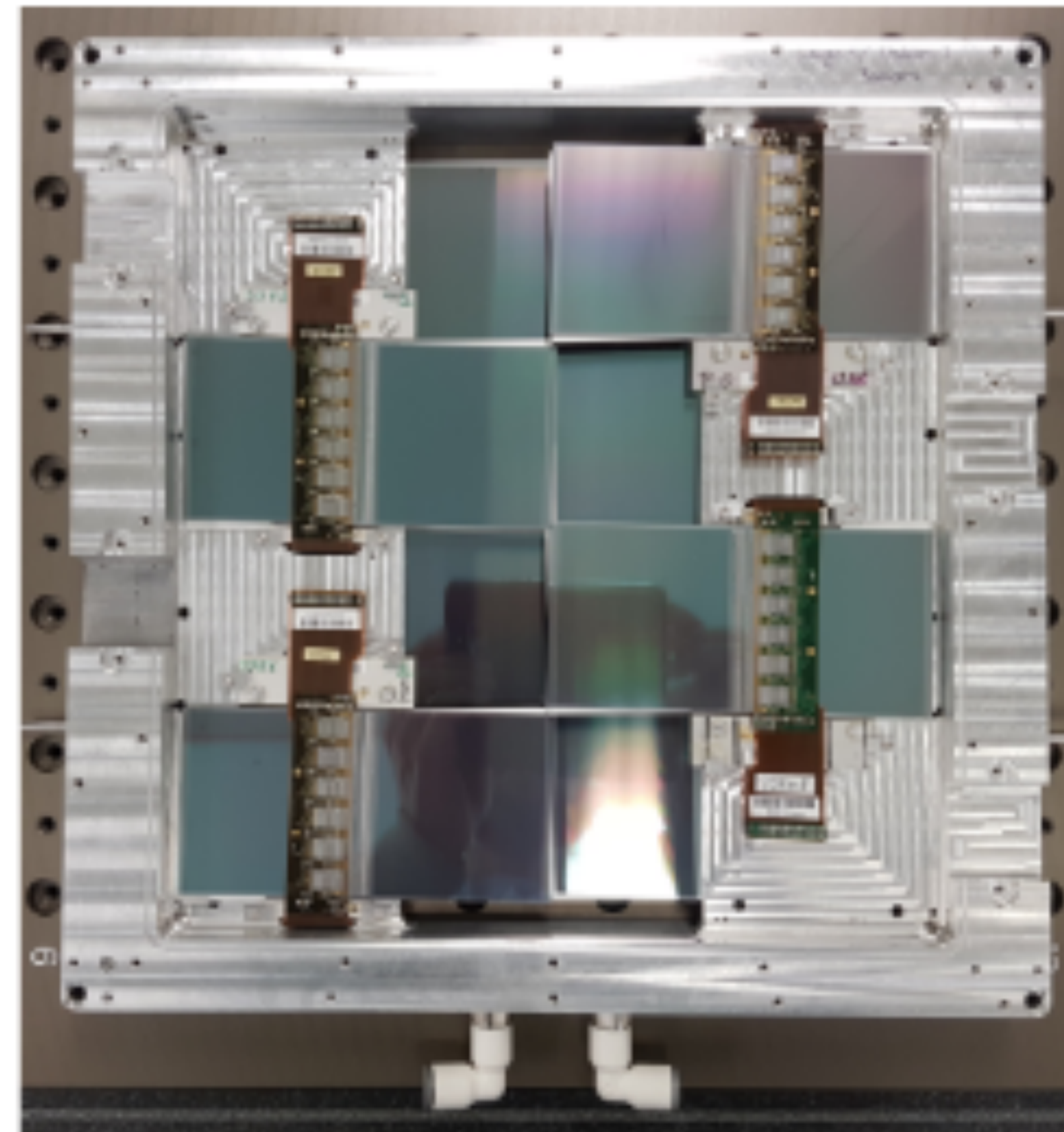
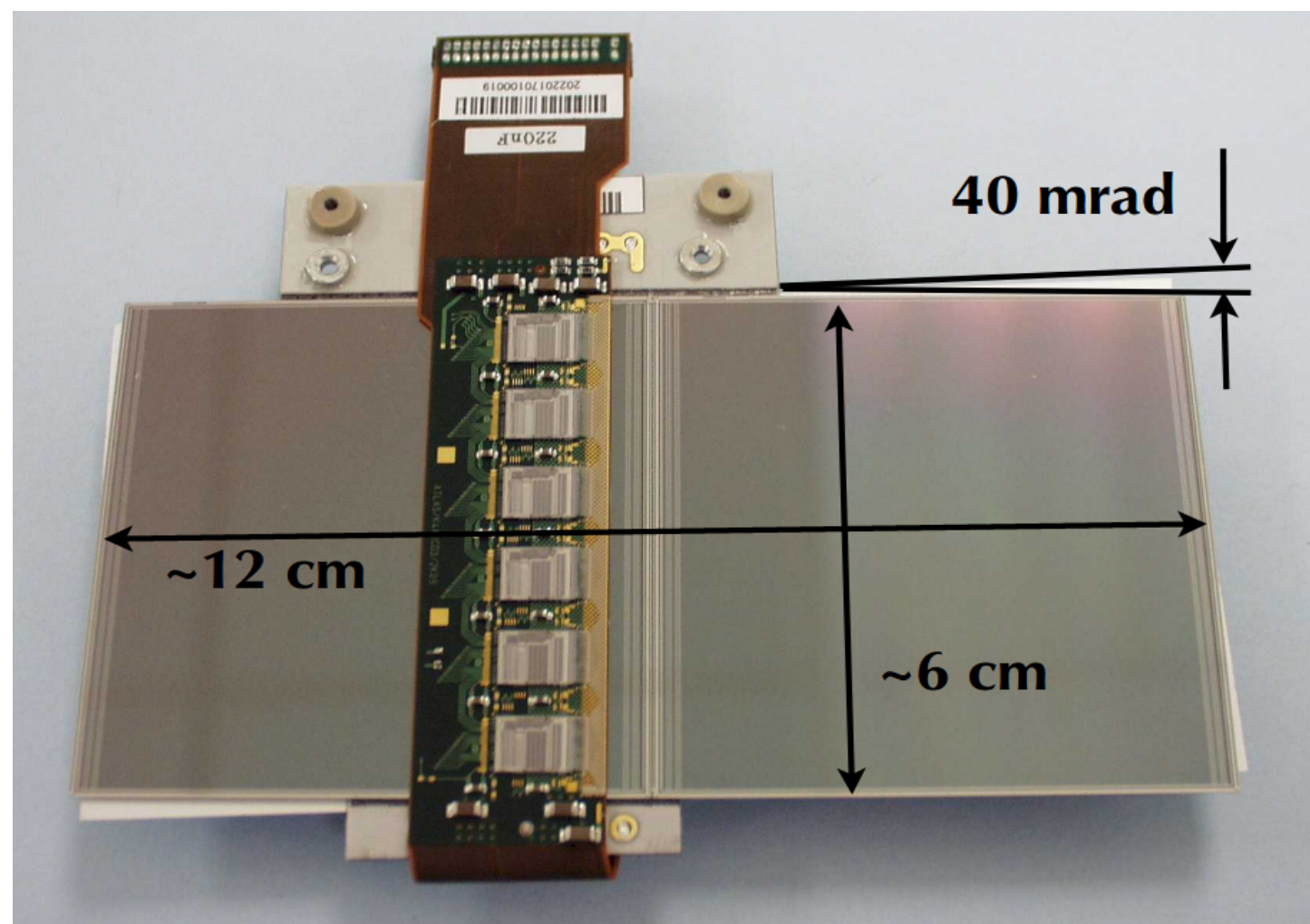


Tracker | Layers

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



- ▶ Low radiation levels in T112 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 Preveessin 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
- Prepare EM
- Install Det. Supp



Prepare ENH1

Install Det. Support

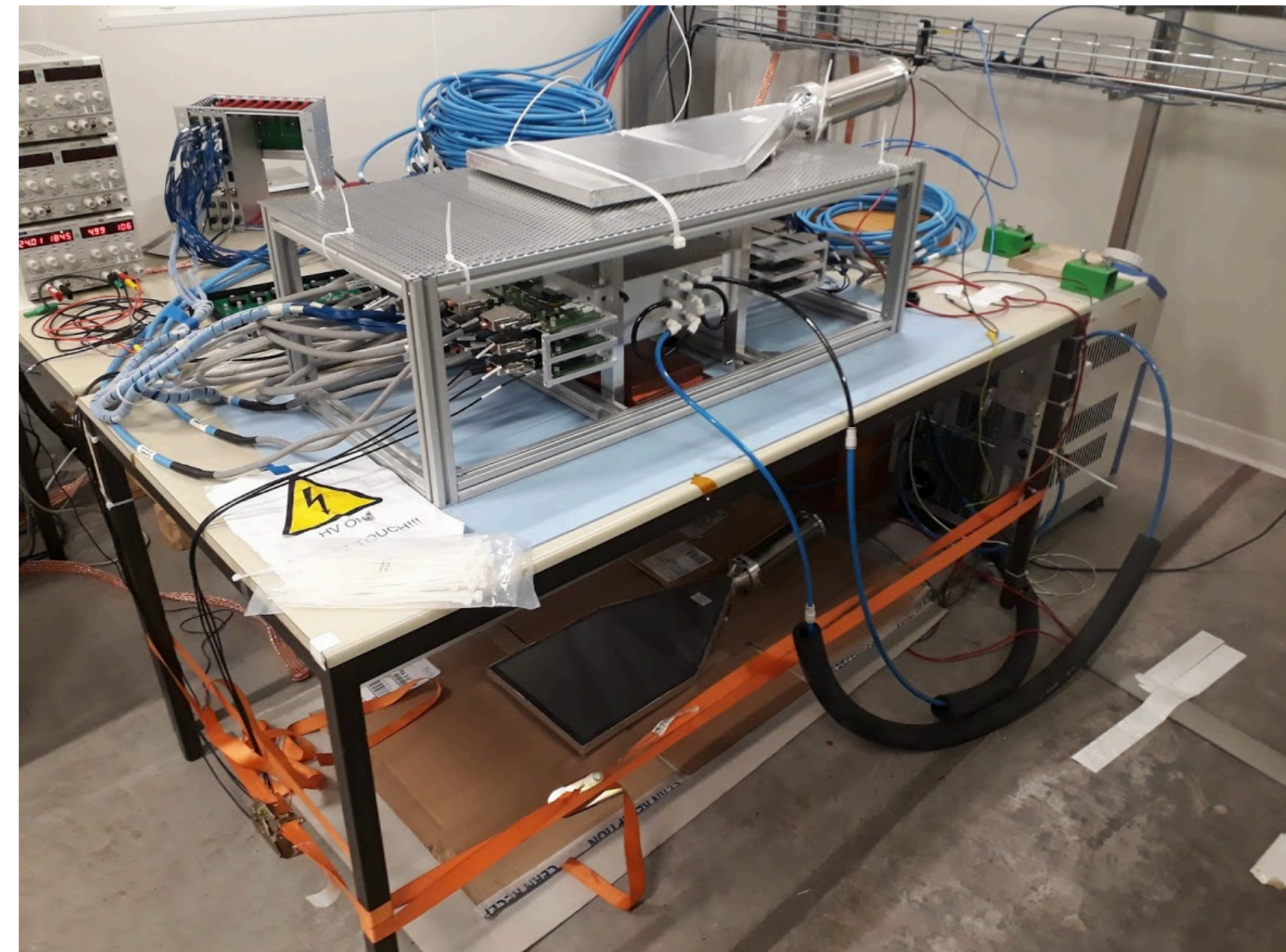
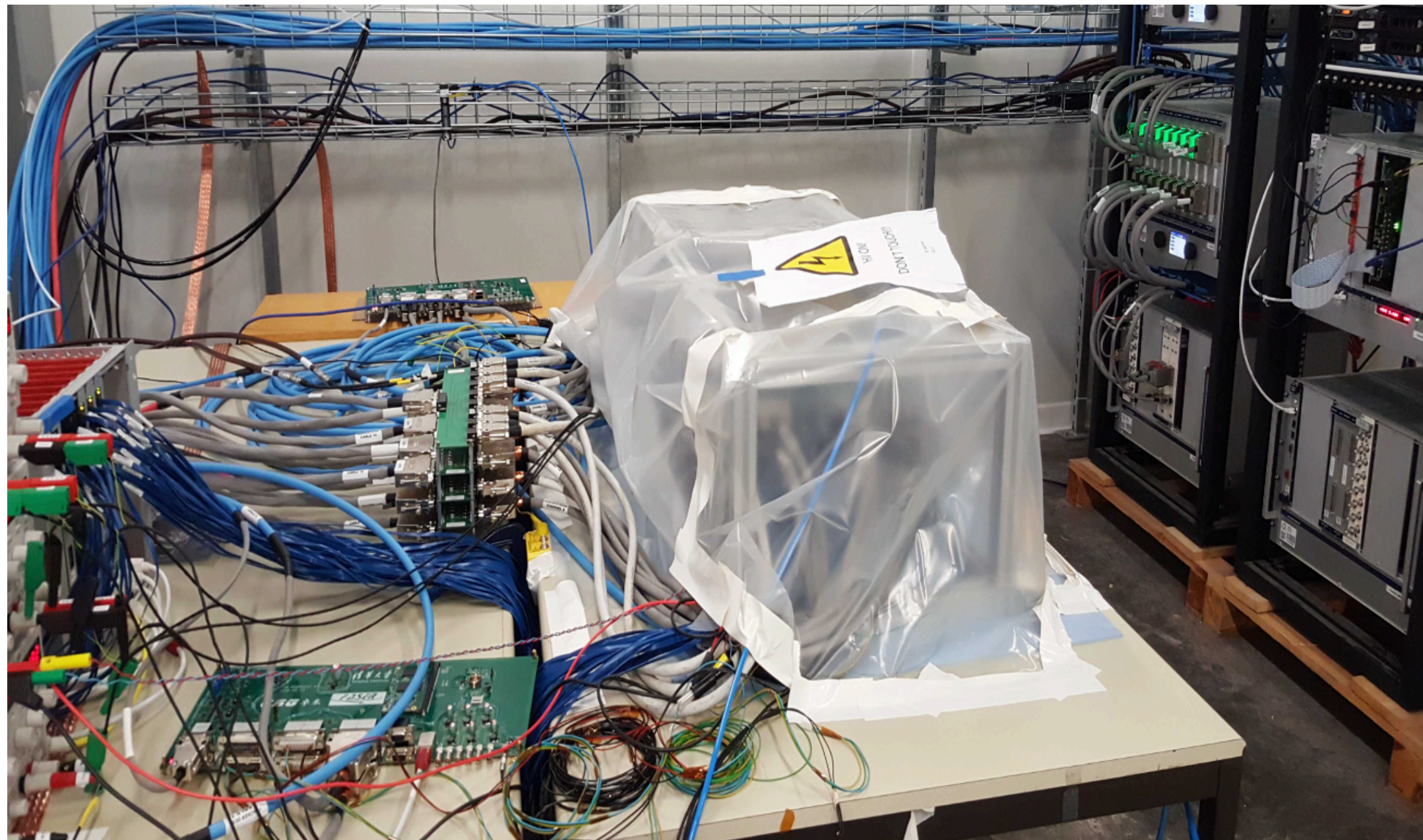
Install Calo/Scin & TDAQ

(Partial) System Commissioning

Nov	Dec	Jan	Feb	Mar	April	May

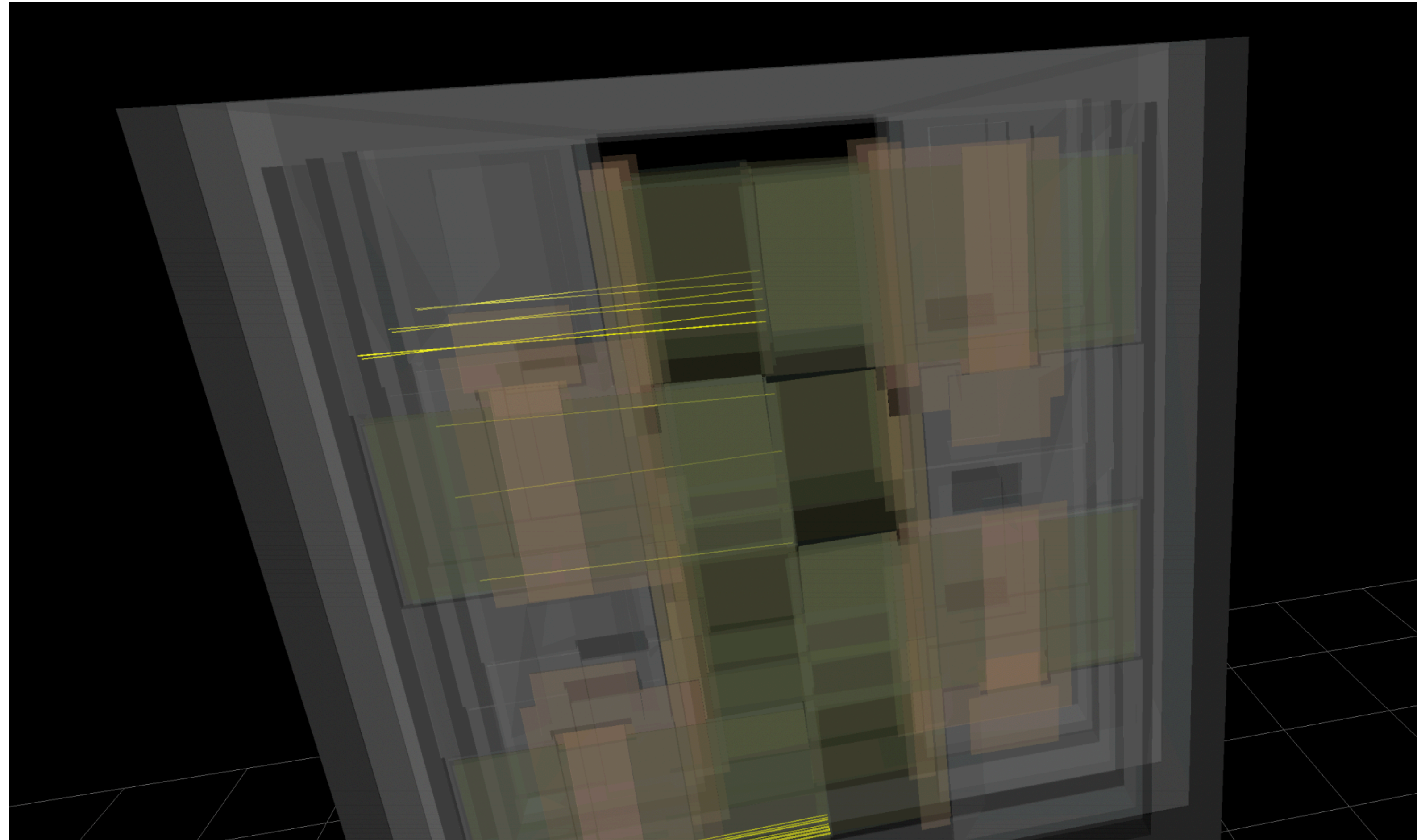
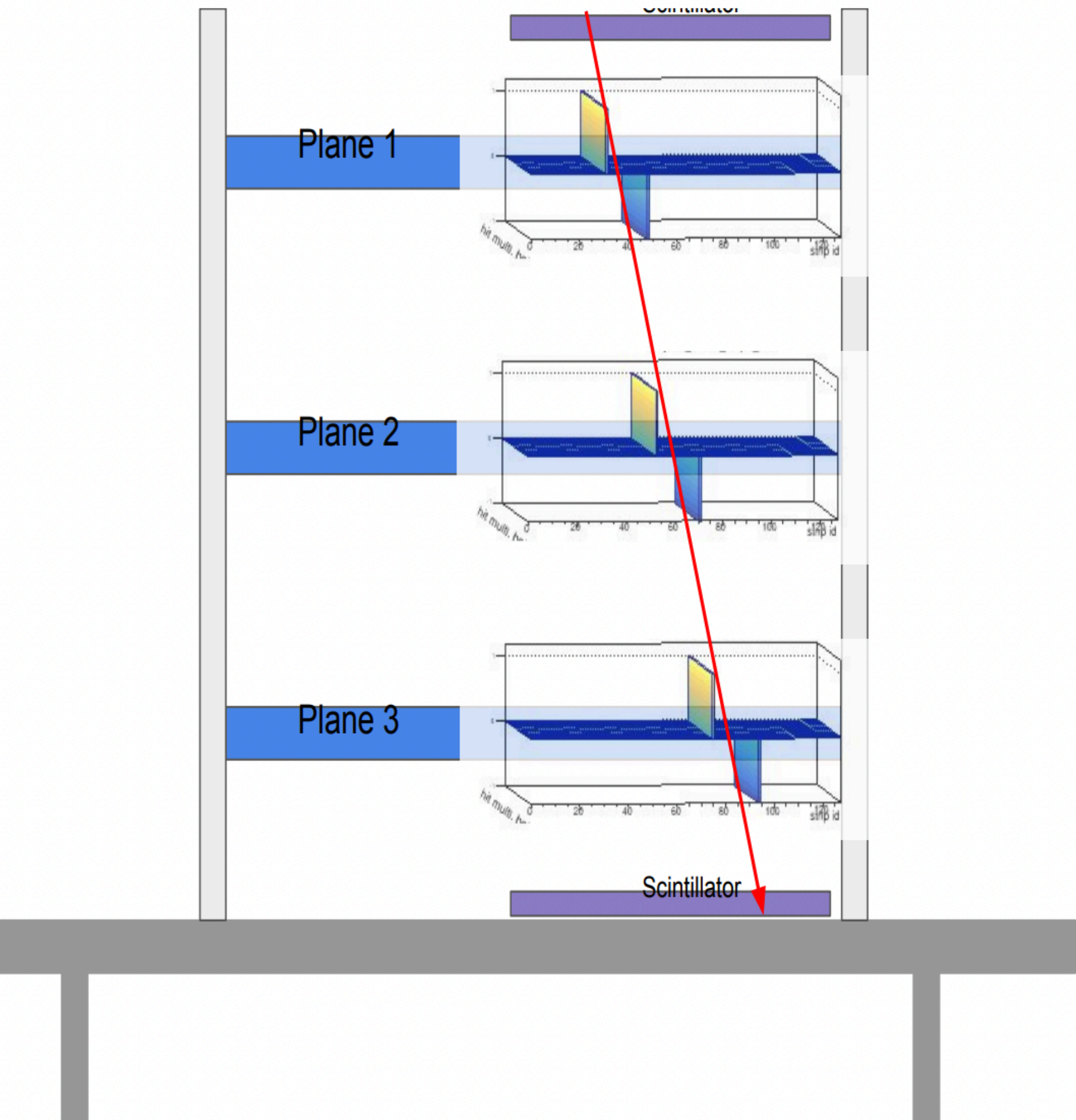
Overground testing | Tracker

- ▶ 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



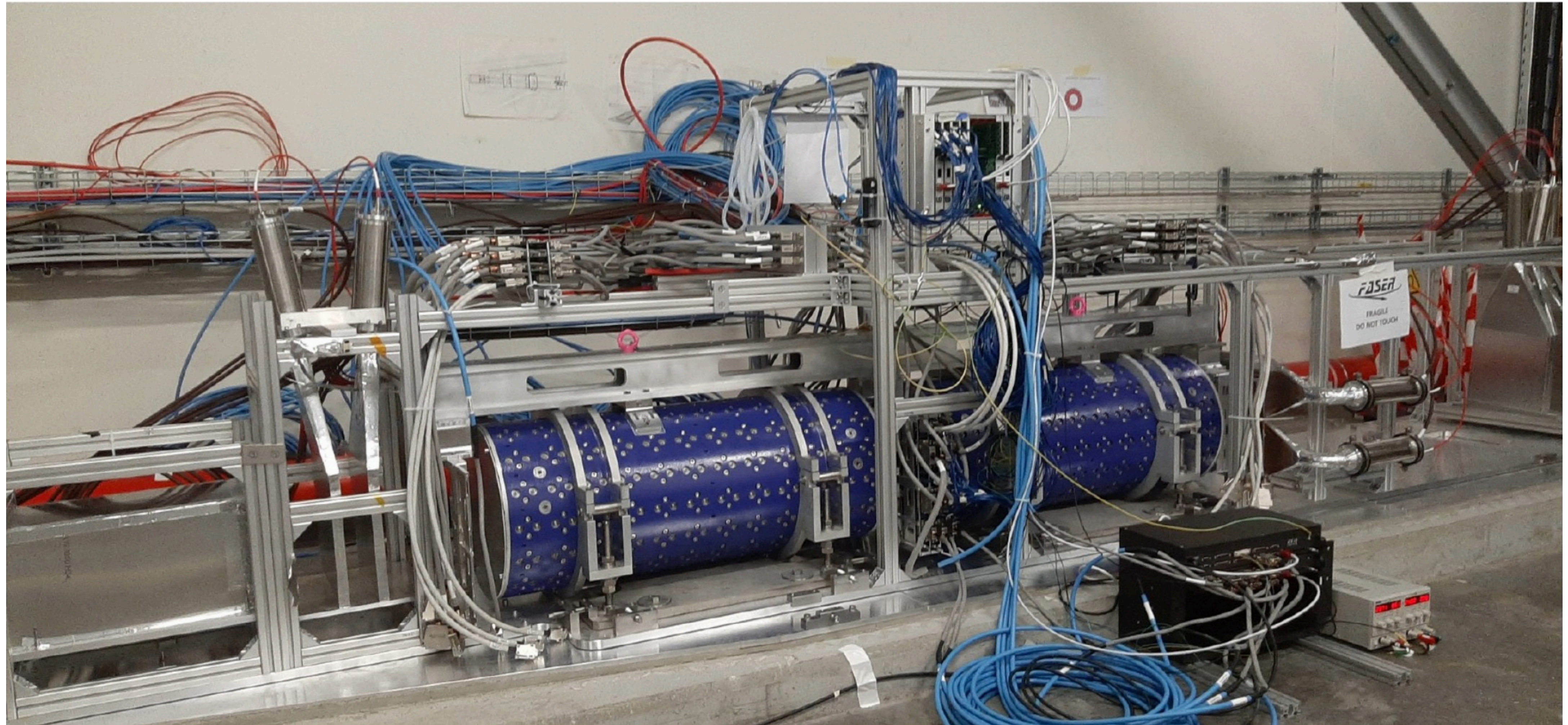
Overground testing | Tracker

- ▶ 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

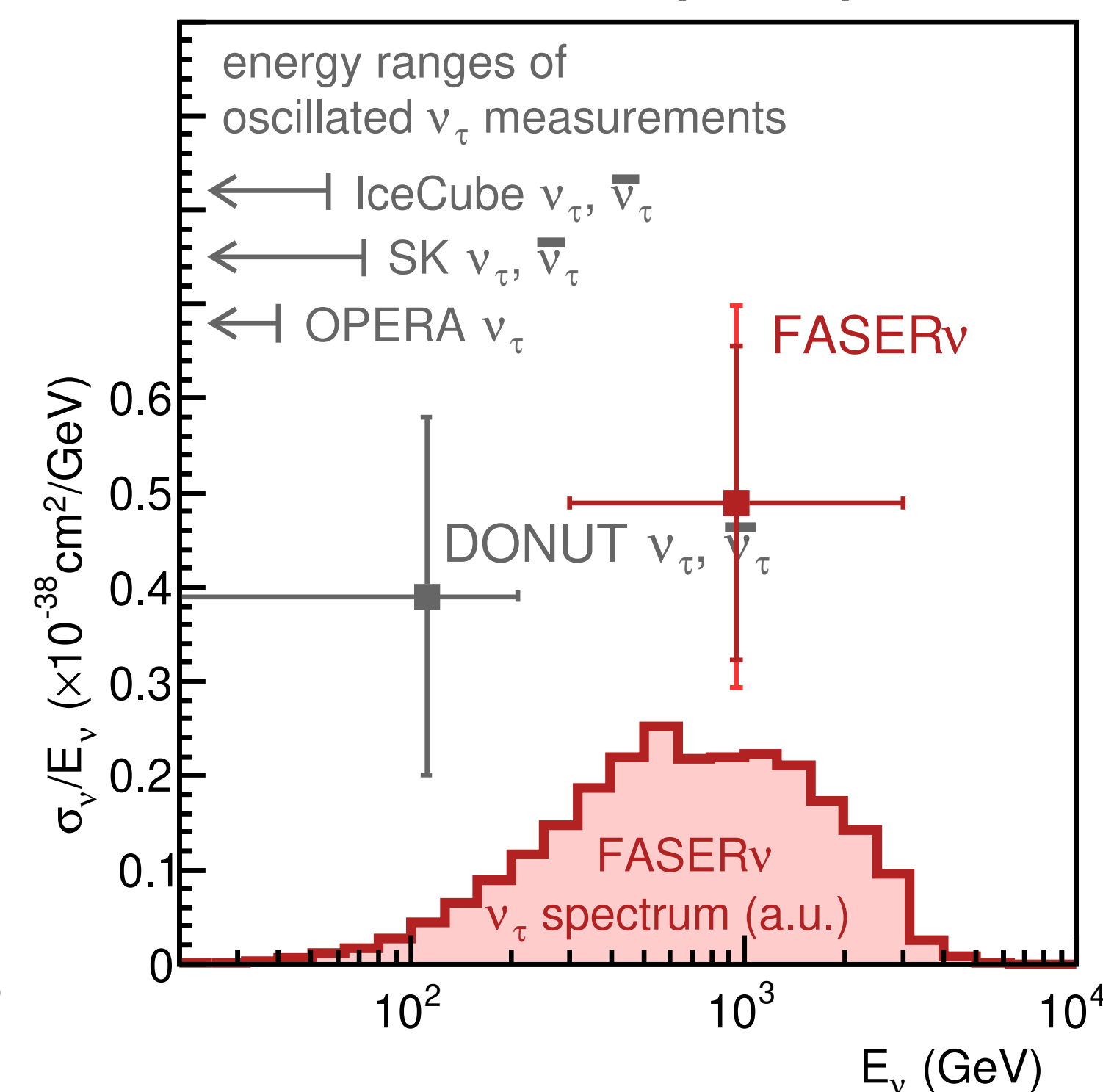
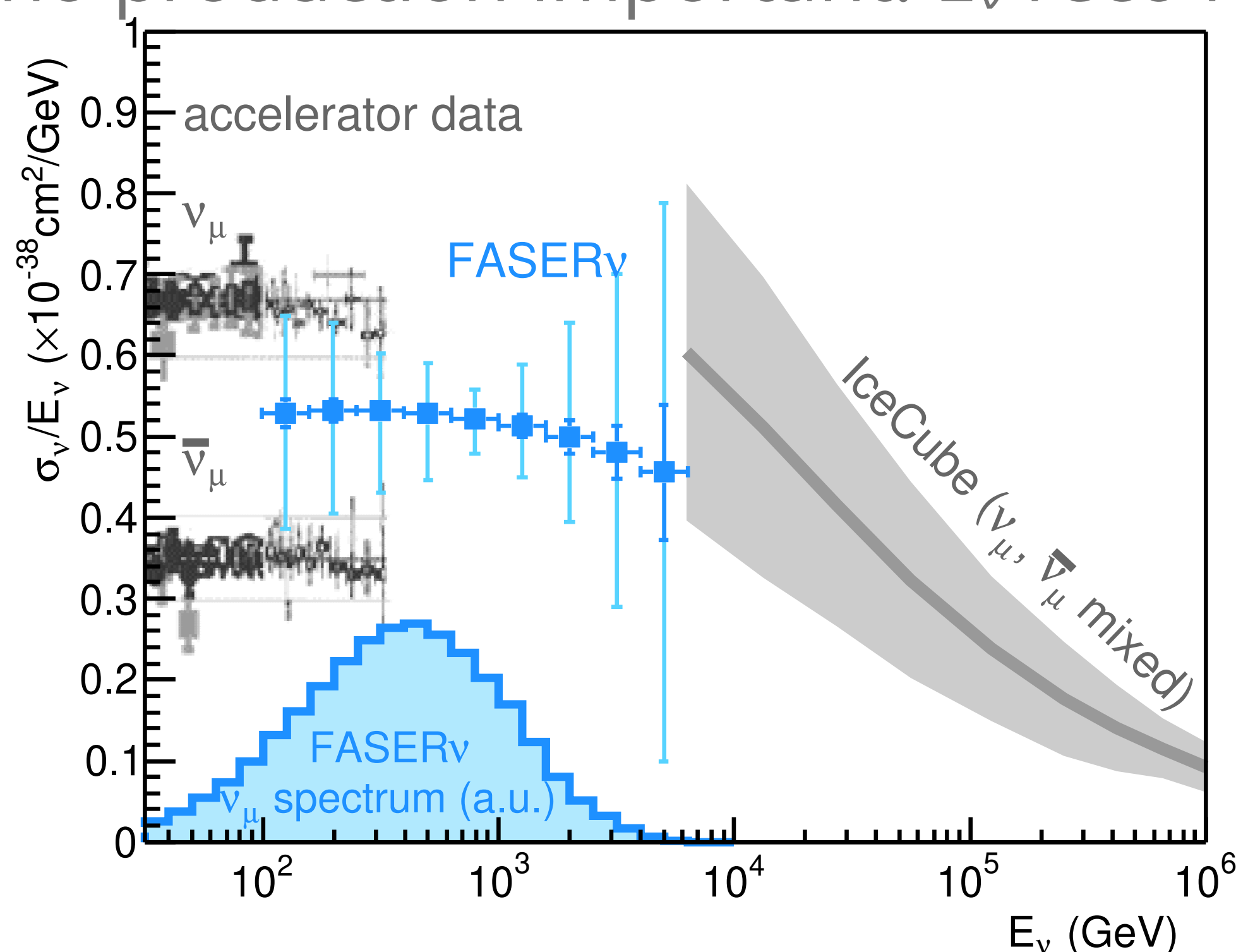
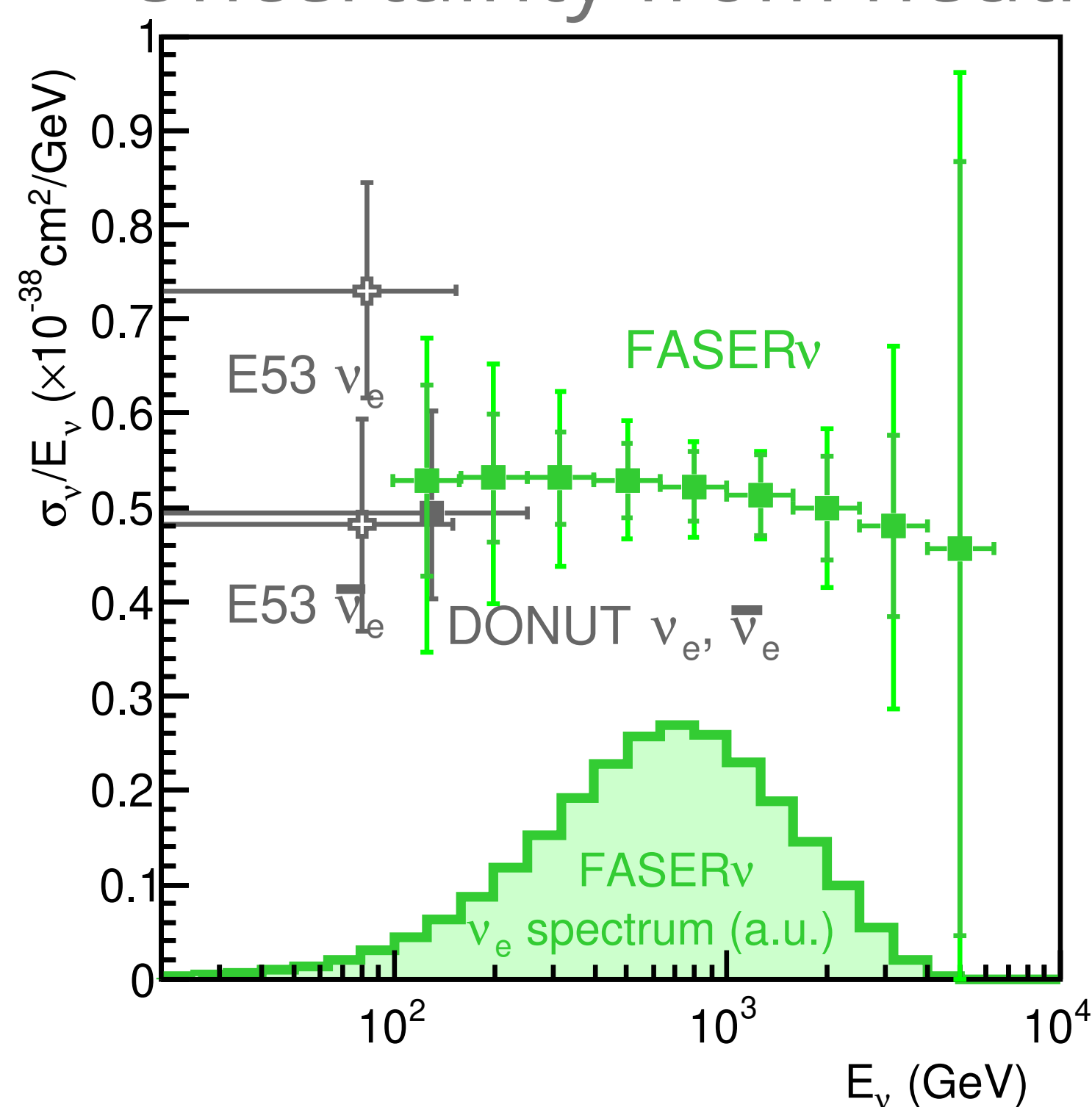
- ▶ Also have partial detector combined run
 - ▶ All scintillators and calorimeters with one tracker station
- ▶ In just one week before disassembly started:
 - ▶ Common clock provided by Technion clock card (40.08 MHz)
 - ▶ Triggering on cosmic showers/random triggers
 - ▶ Reading out full detector
 - ▶ 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



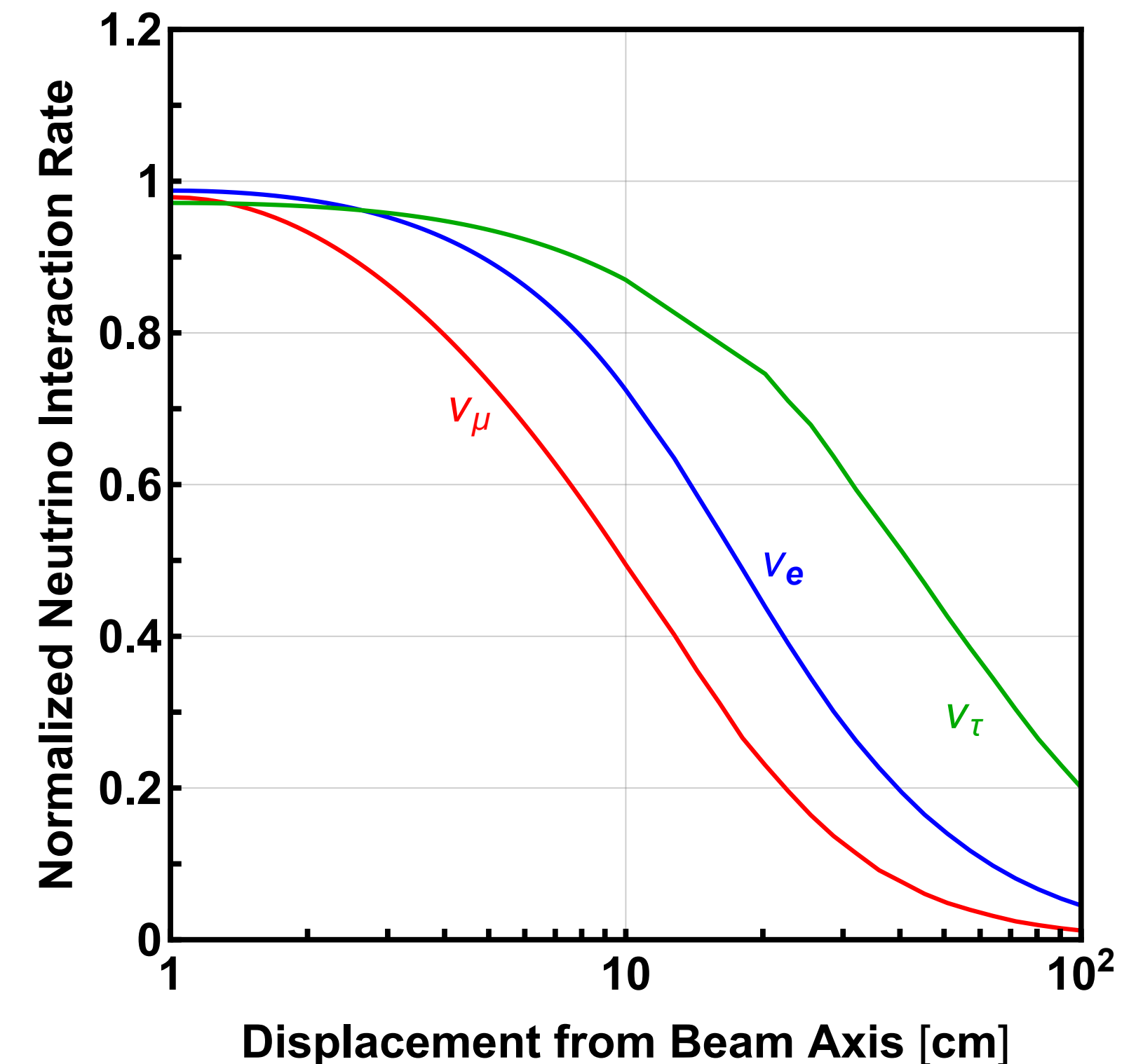


FASERν | Physics case

- ▶ 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_ν reco resolution ~30% (sim).



- ▶ 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:





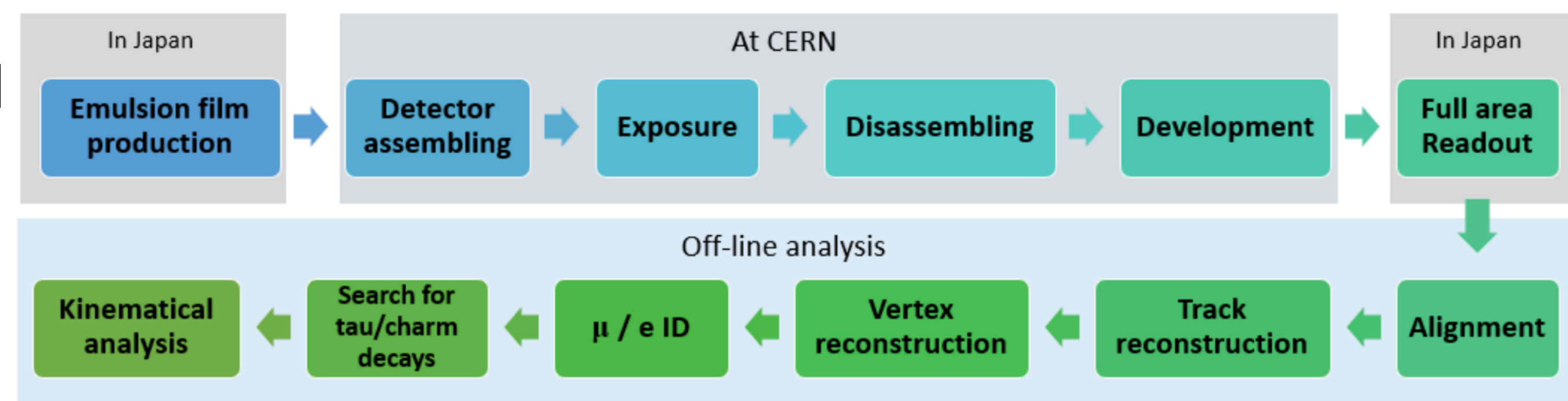
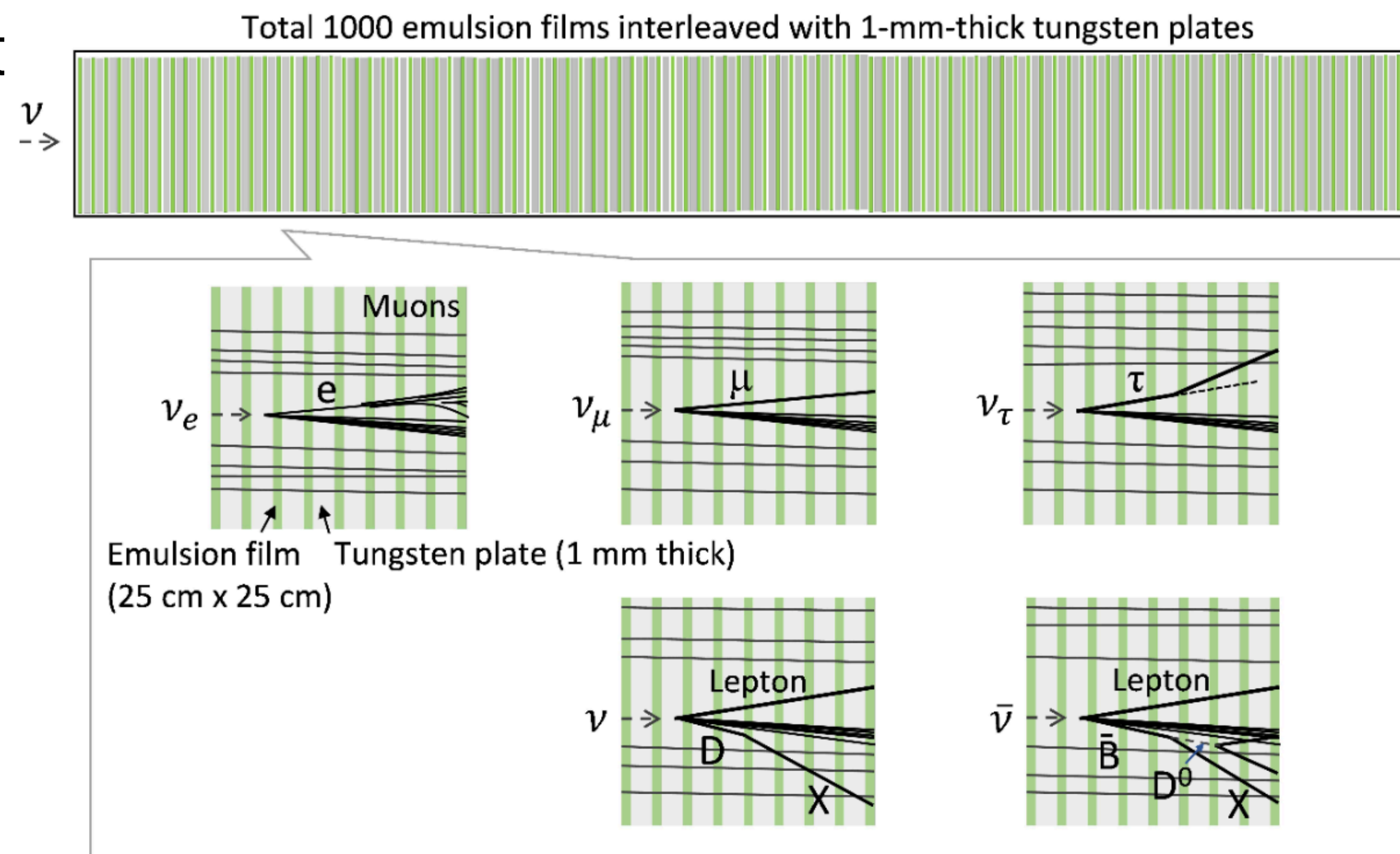
FASER ν | Detector design

► Emulsion detector with tungsten target

- 1000 1 mm thick tungsten plates interleaved with emulsion film
- Well understood neutrino detector technology
- Replace every 20-50 fb⁻¹ to maintain track density low

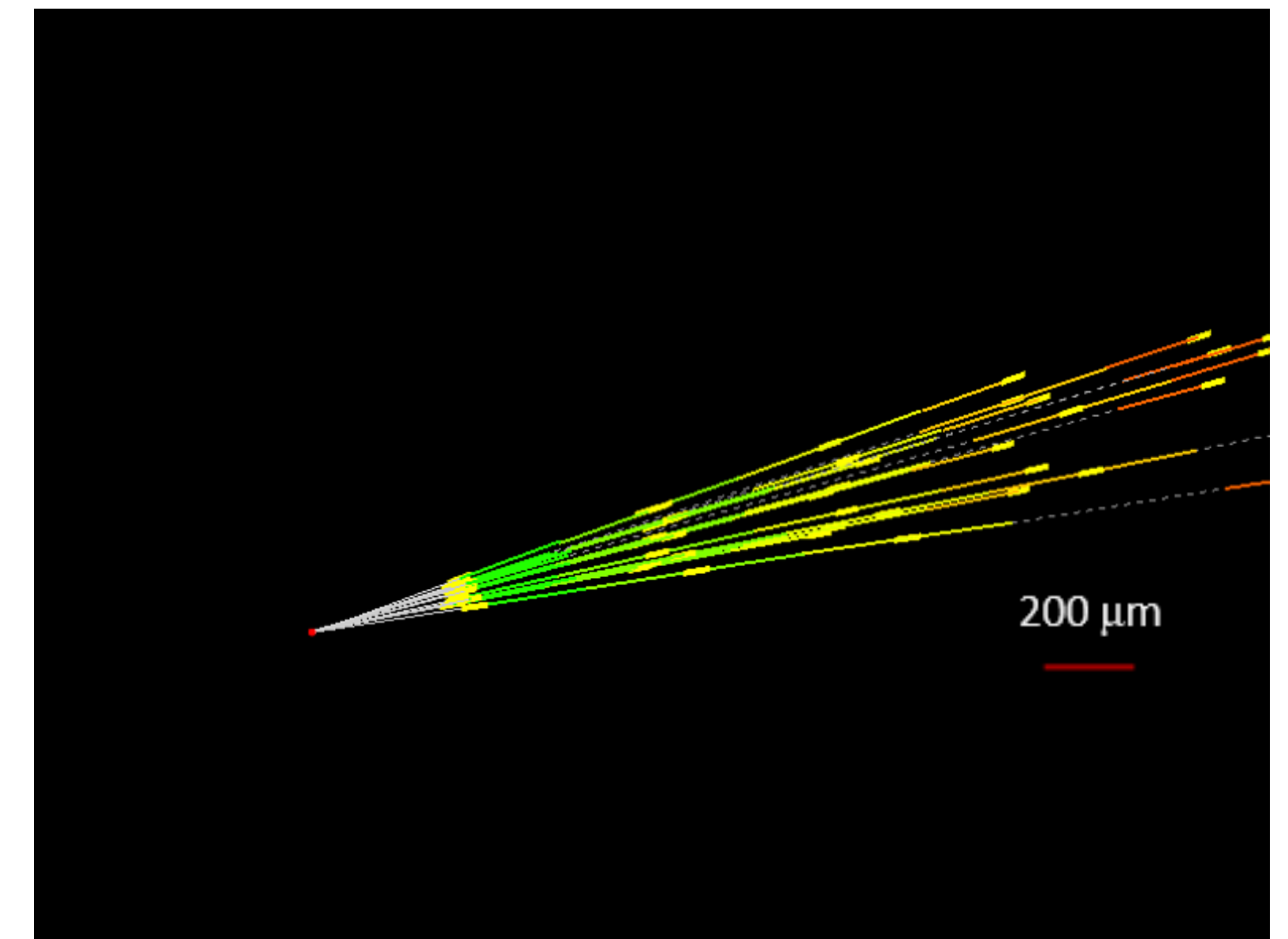
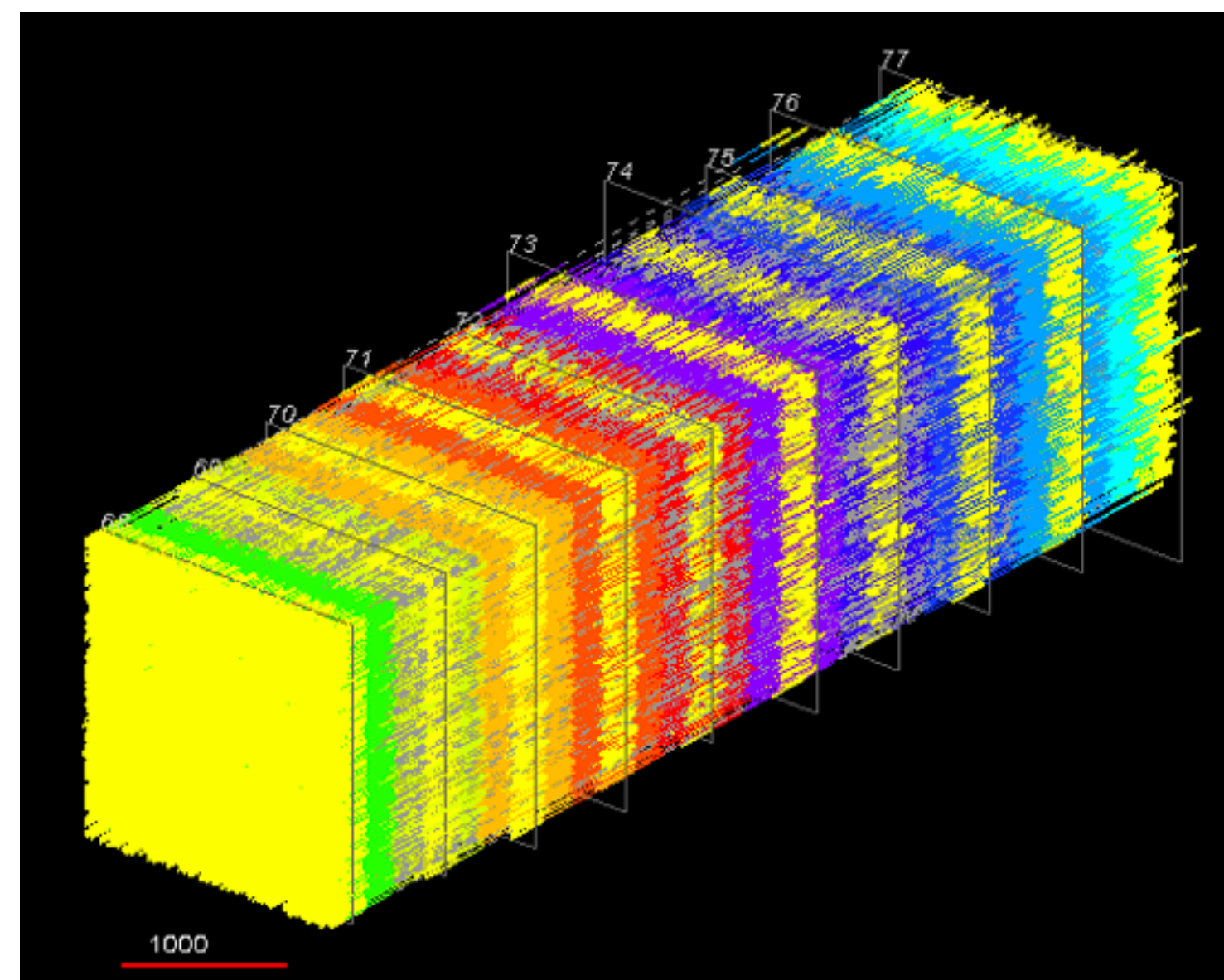
► Challenges:

- Logistics to transport and replace the 1-ton-scale detector every technical stop (3 times/year)
- Benefit from transport infrastructure installed in UJ12 and T112 to install FASER detector
- Procedure well developed for production and offline analysis:

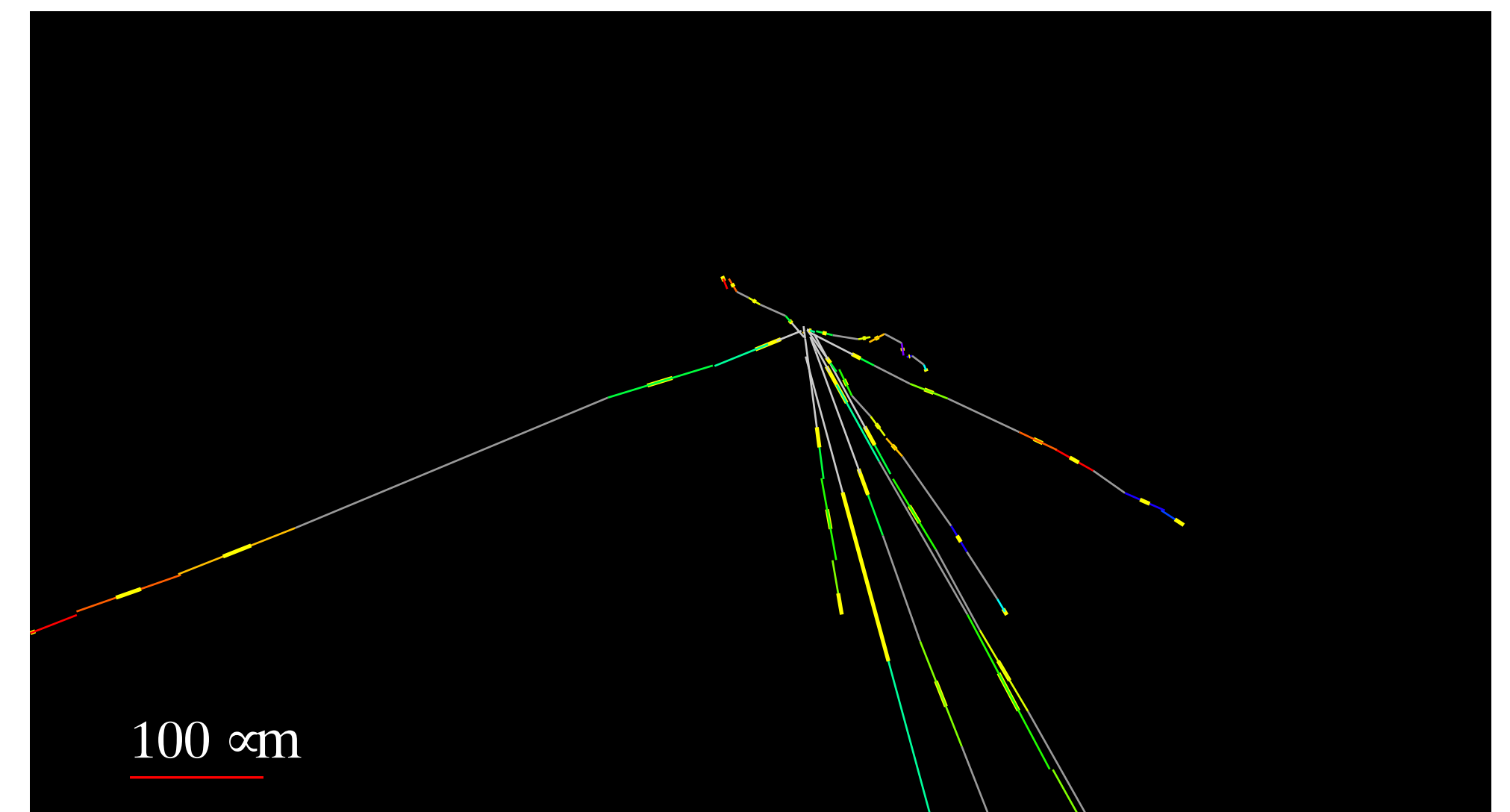
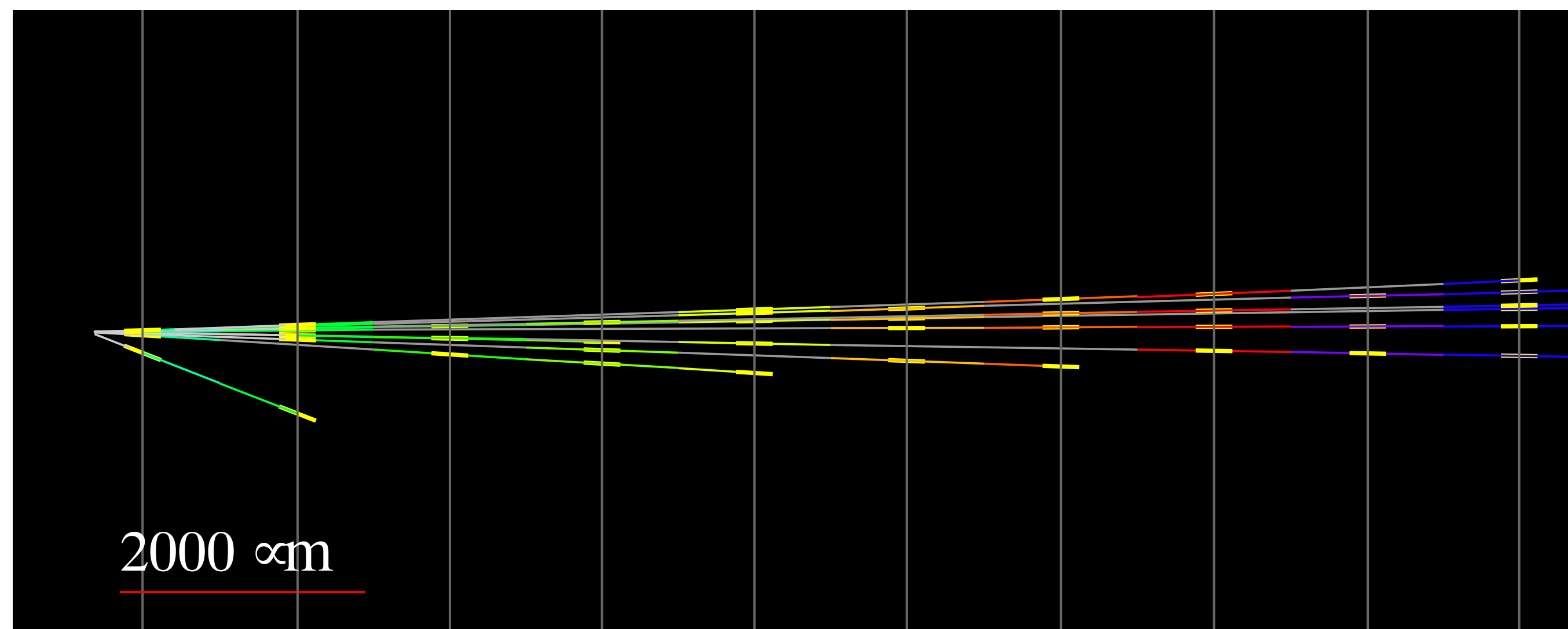


FASER ν | Pilot neutrino detector

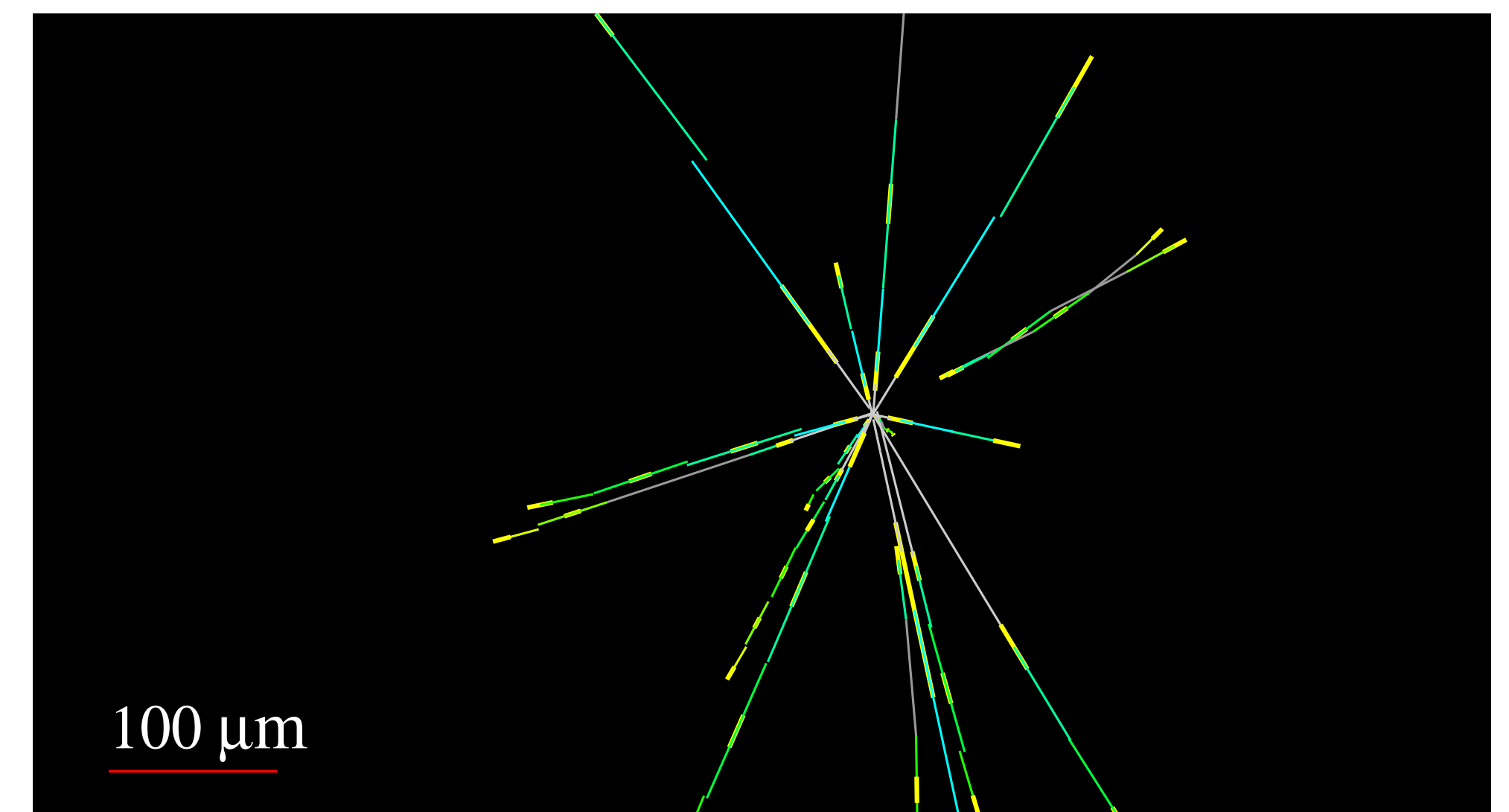
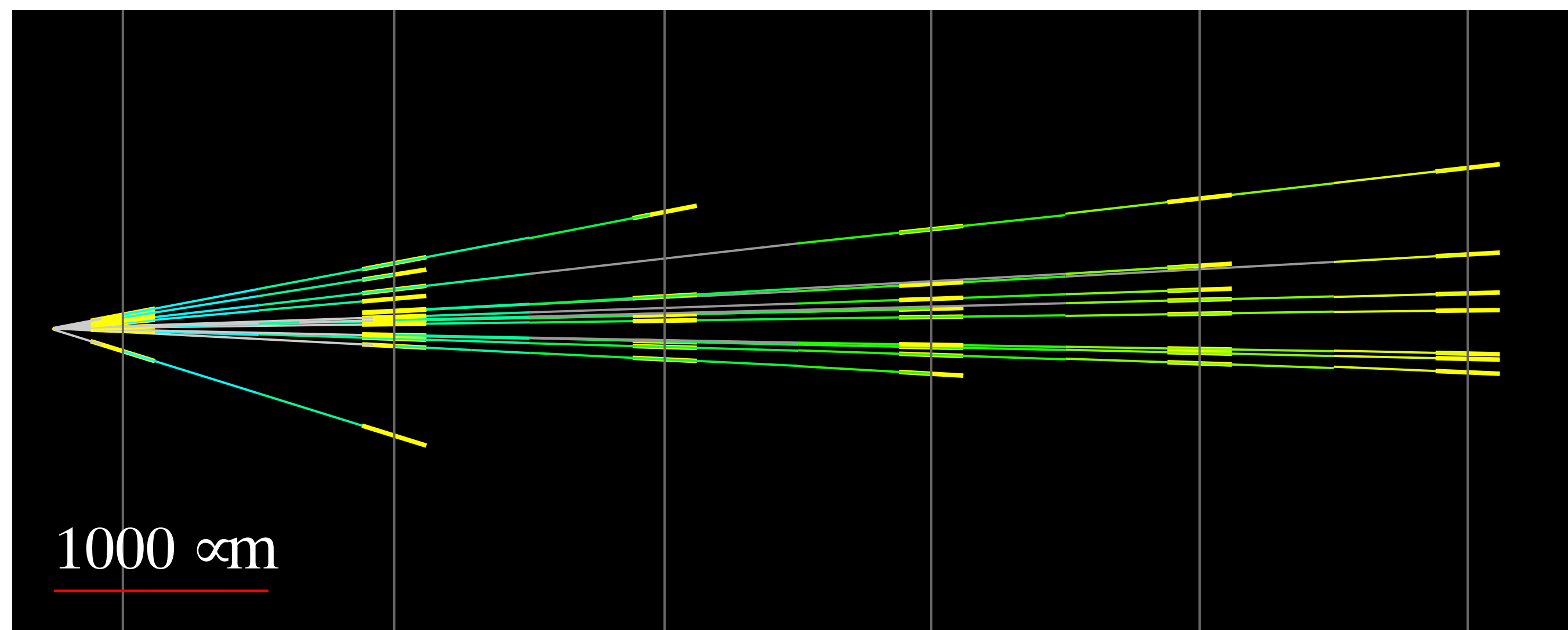
- ▶ A 30 kg detector was installed in T118 in 2018
- ▶ 12.5 fb⁻¹ of data was collected
 - ▶ ~30 neutrino interactions in the detector expected to have occurred
- ▶ Emulsion data developed, reconstructed and analysis ongoing
- ▶ Extremely valuable for validating the FASERnu, optimizing the detector & reconstruction
 - ▶ Several neutral vertices identified, likely to be neutrino interactions, could also be neutral hadrons



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► BSM physics

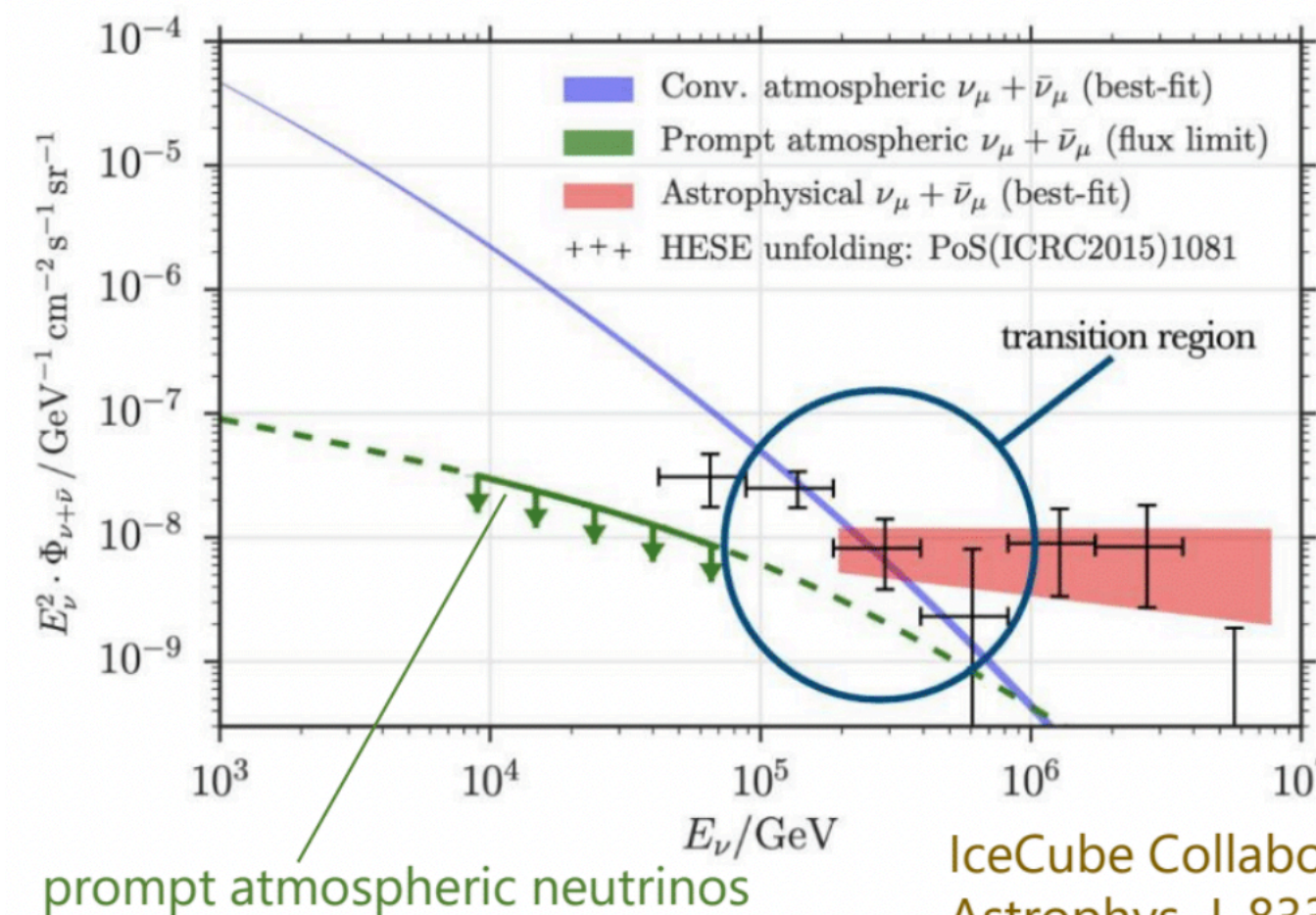
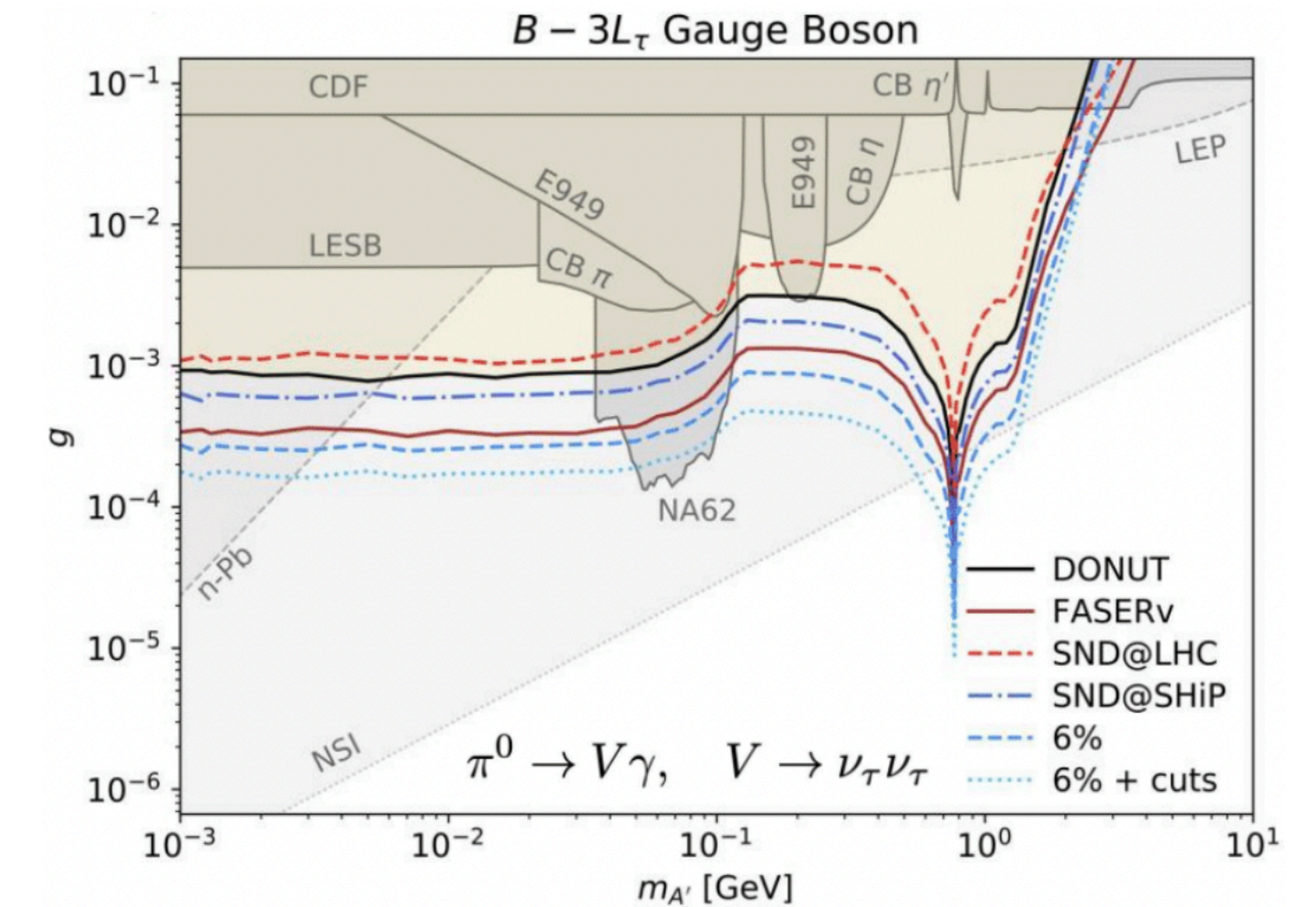
- New light weakly coupled gauge boson ($\rightarrow \nu_\tau$) could enhance ν_τ flux.
- Sterile neutrinos with mass ~ 40 eV can cause oscillations at FASER

► QCD

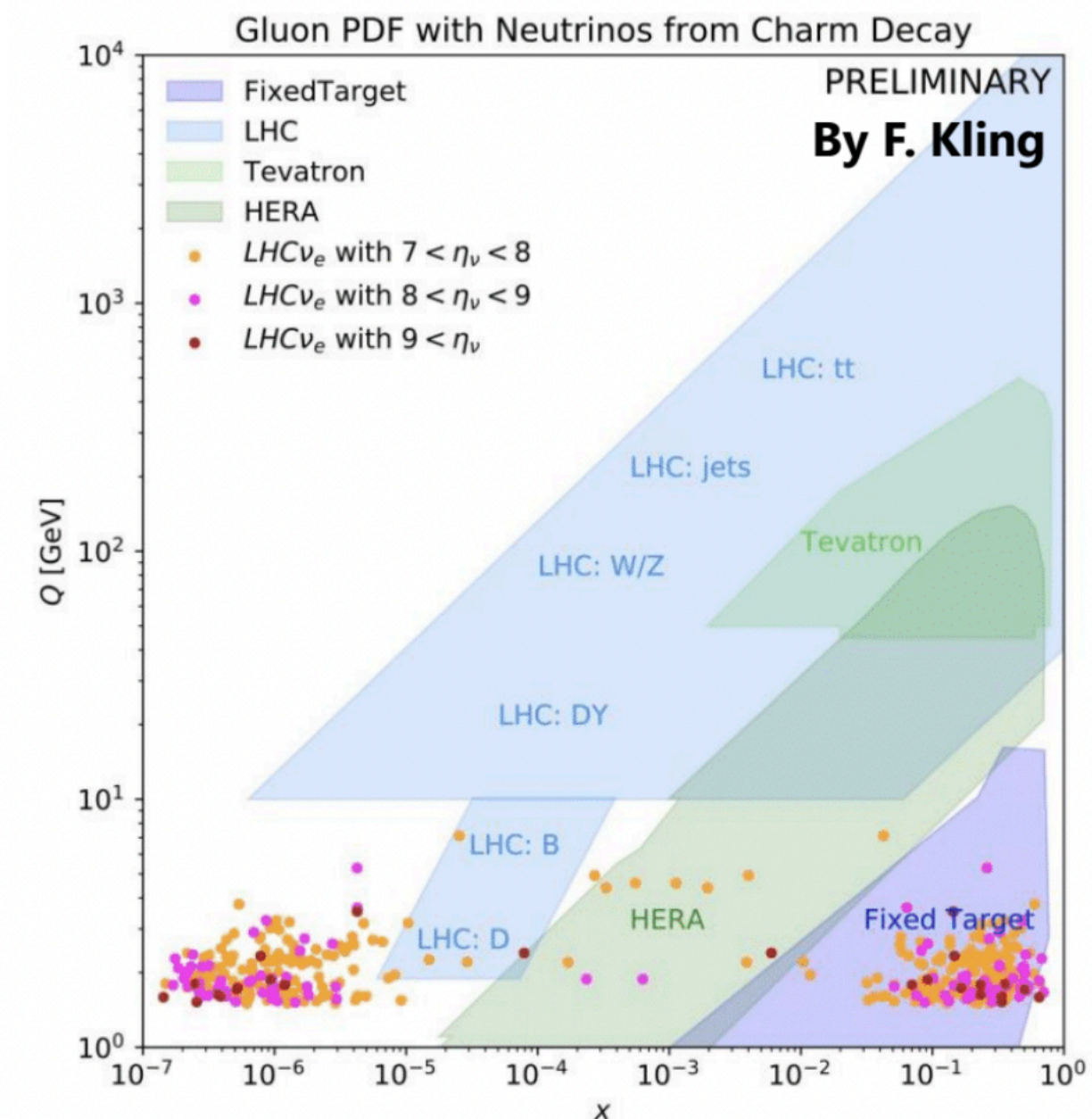
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- Neutrinos from charm decay could allow to test transition to small-x factorisation, constrain low-x gluon PDF and probe intrinsic charm

► 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)



► Projections created with the FORESEE tool:

- [Phys. Rev. D 104, 035012](#)
- <https://github.com/KlingFelix/FORESEE>

arXiv.org > hep-ph > arXiv:2105.07077

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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 **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. We also provide a comprehensive list of validated forward spectra of various SM species.

Paper

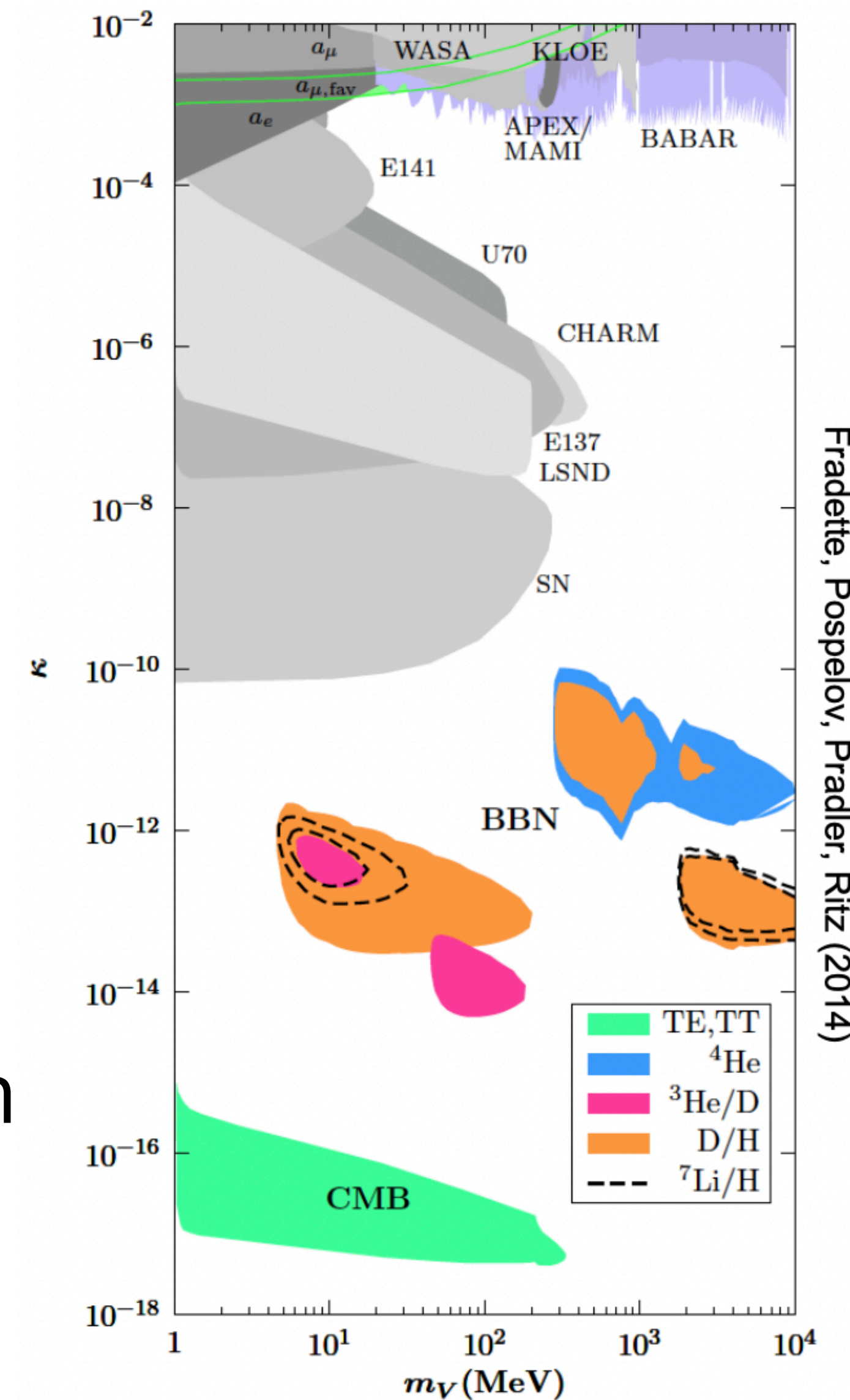
Our main publication [FORESEE: FORward Experiment SEnsitivity Estimator for the LHC and future hadron colliders](#) provides an overview over this package. We recommend reading it first before jumping into the code.

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.

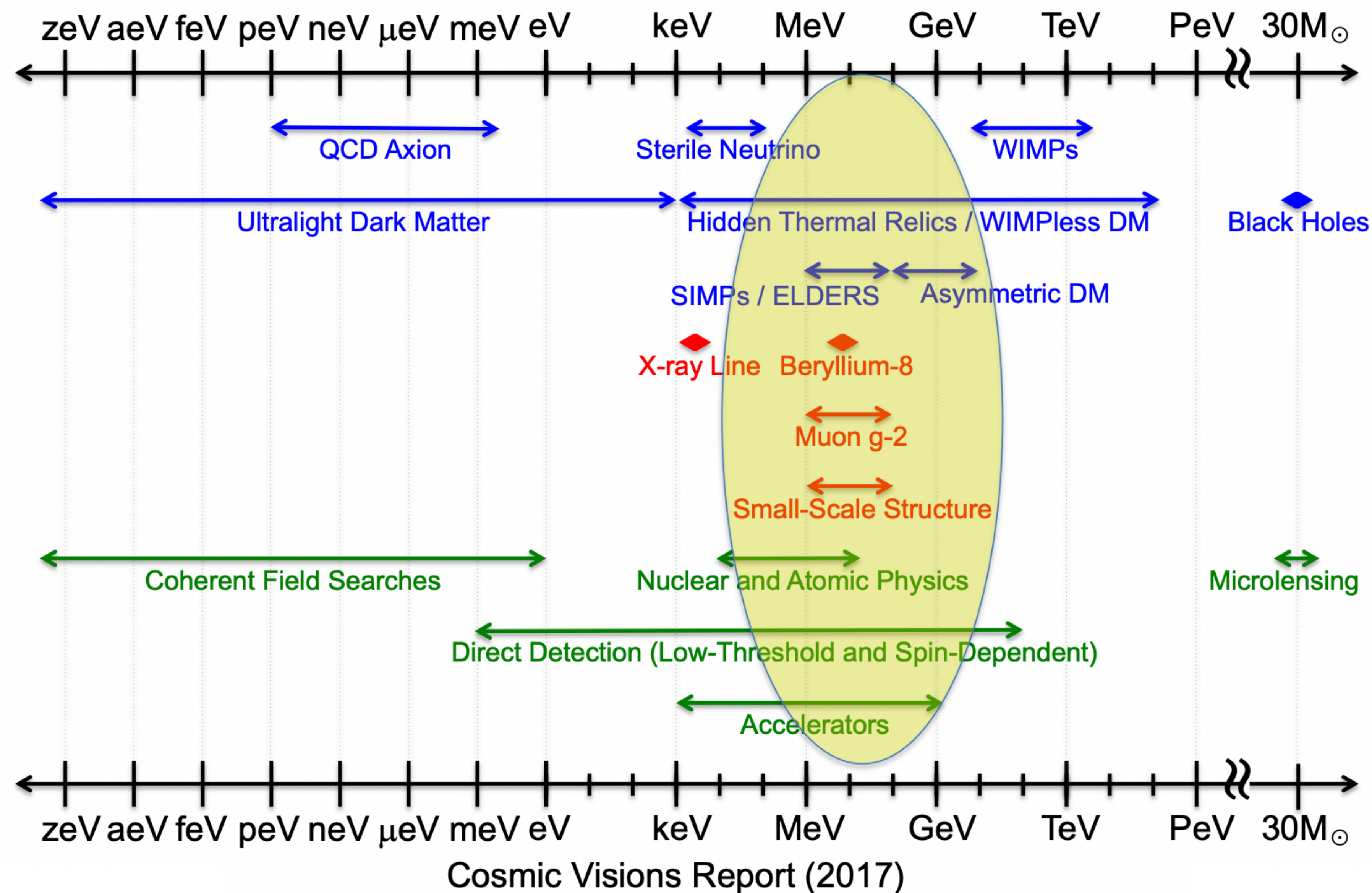
Physics Motivation | Dark photons

- ▶ 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 $\sim$ TeV, strongly-interacting particles.
- ▶ Dark Sector models don't give us too much guidance on expected mass or coupling strengths.
- ▶ Some other intriguing observations...



Physics Motivation | Intrigue...

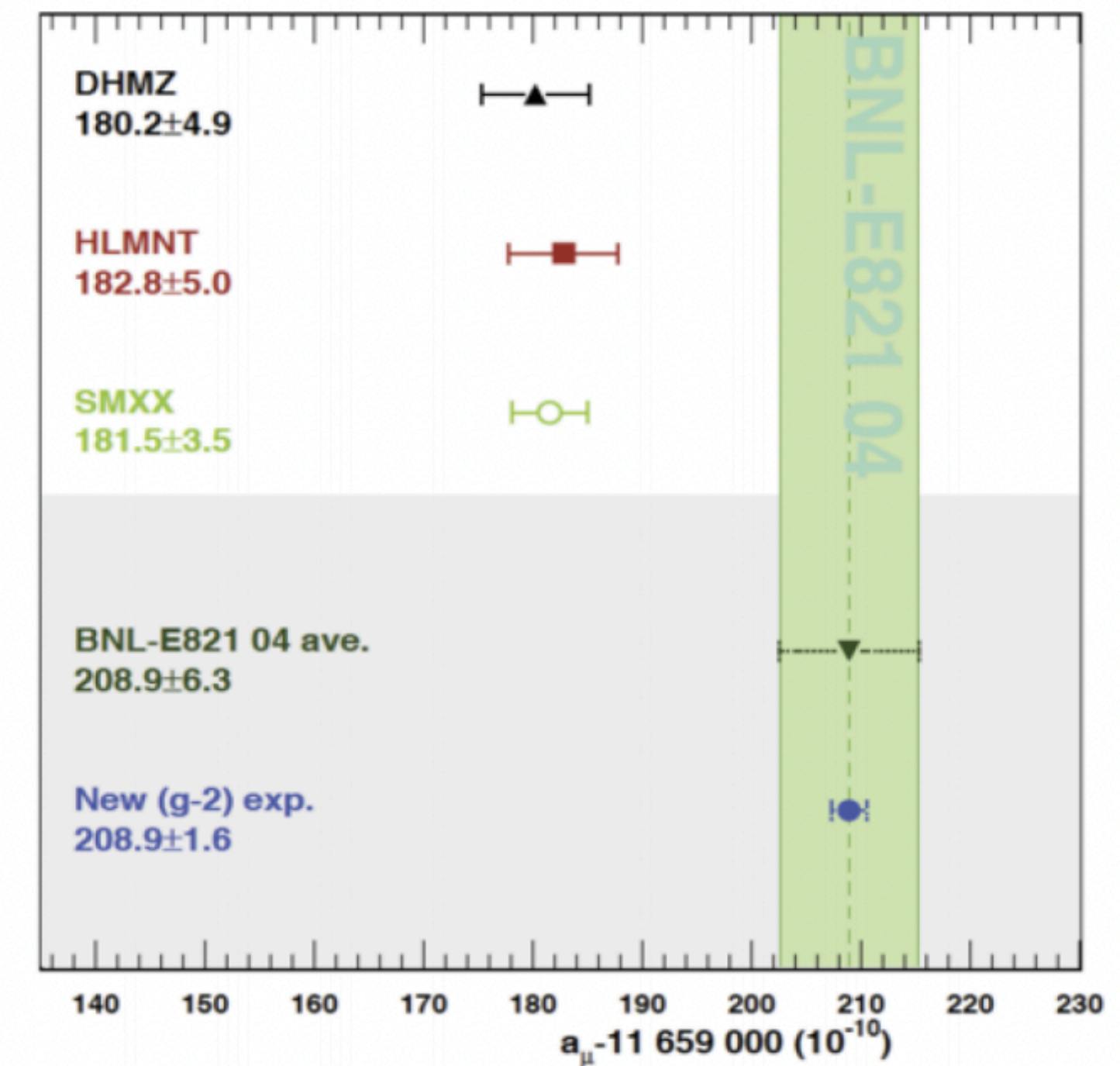
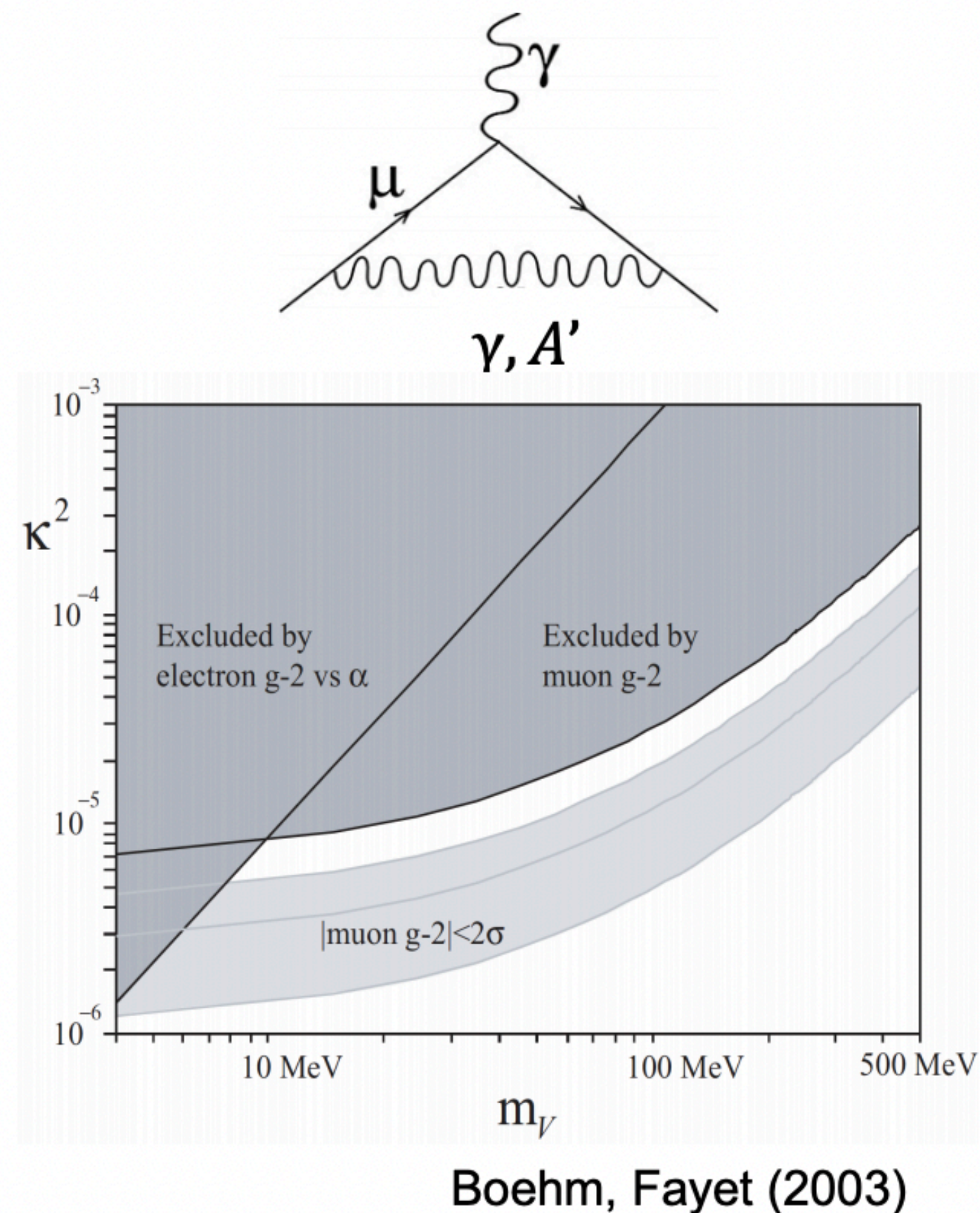
- Focusing on the mass scale
 - Dark Sector Candidates
 - Anomalies
 - Search Techniques
-
- We see some interesting things in the $\sim$ MeV range





Physics Motivation | g-2

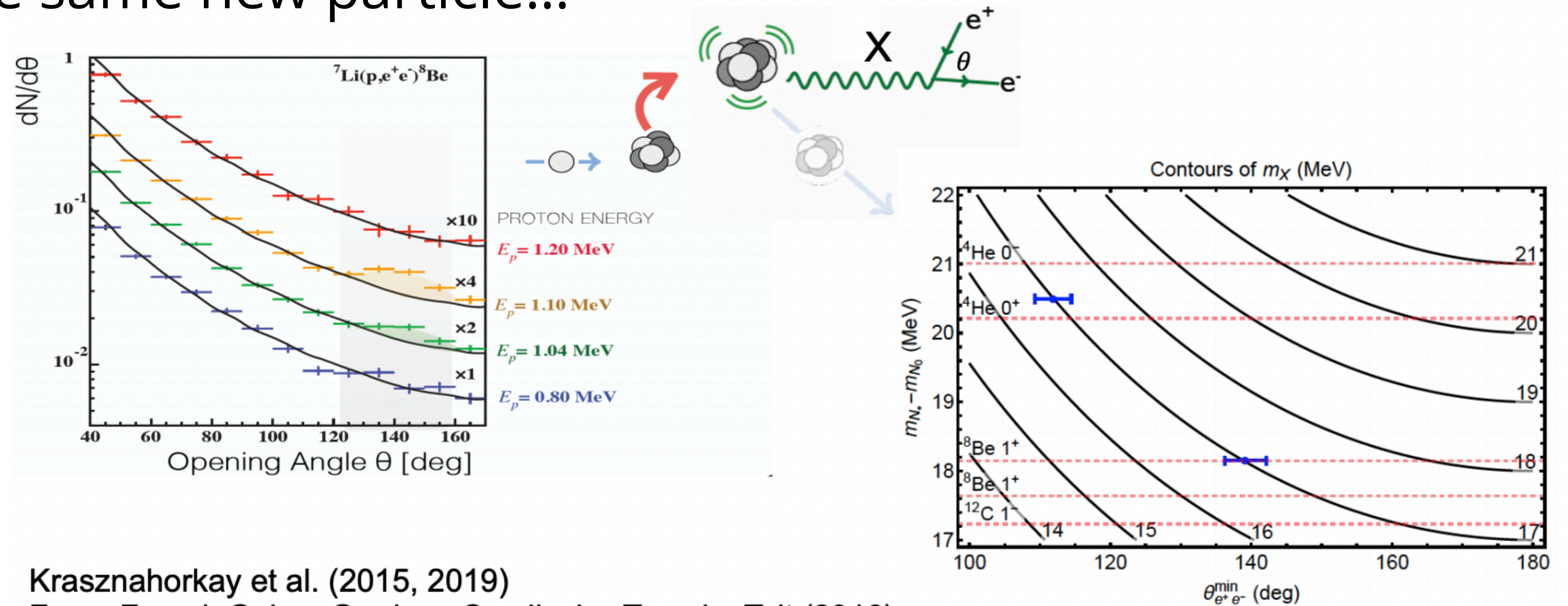
- ▶ The 3.7σ discrepancy between the SM and experiment can be resolved by **MeV-GeV particles with $\epsilon \sim 10^{-3}$** .
- ▶ The dark photon is no longer a viable solution
- ▶ But other particles with similar masses and couplings are.



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

Physics Motivation | He/Be nuclei

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



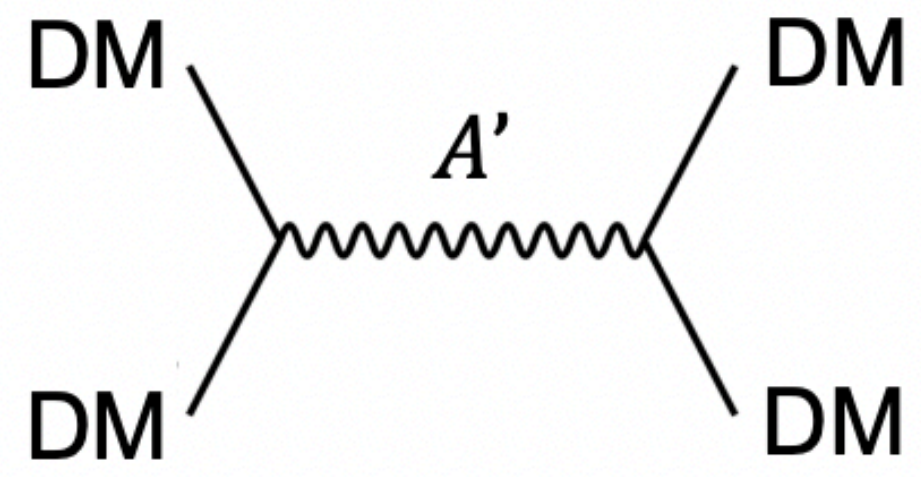
Krasznahorkay et al. (2015, 2019)

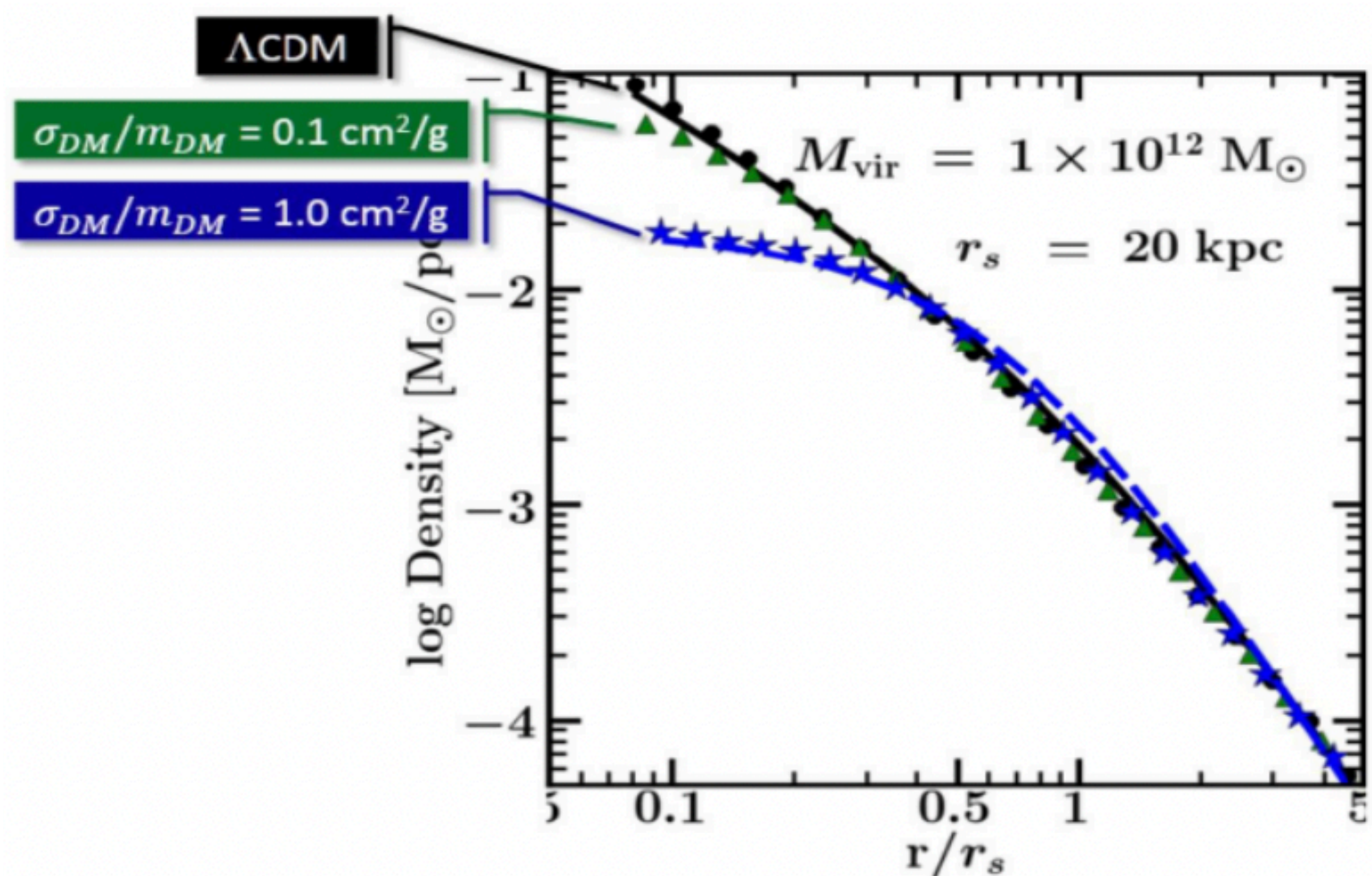
Feng, Fornal, Galon, Gardner, Smolinsky, Tanedo, Tait (2016)

Feng, Tait, Verhaaren (2020); Batell, Feng, Verhaaren (in progress)

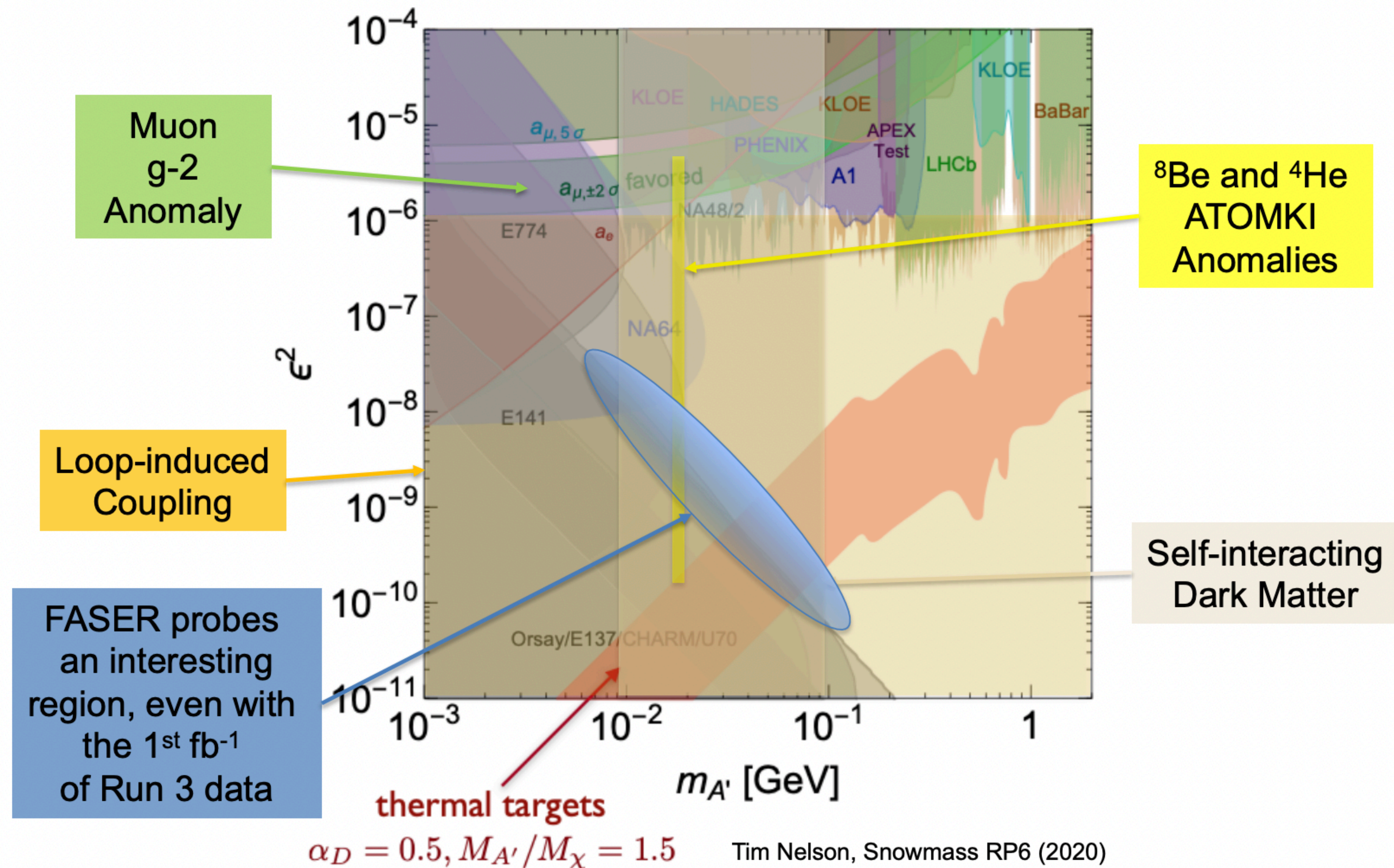
See also Zhang, Miller (2020)

- ▶ 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 $\sim 10\text{-}100\text{ MeV}$** .

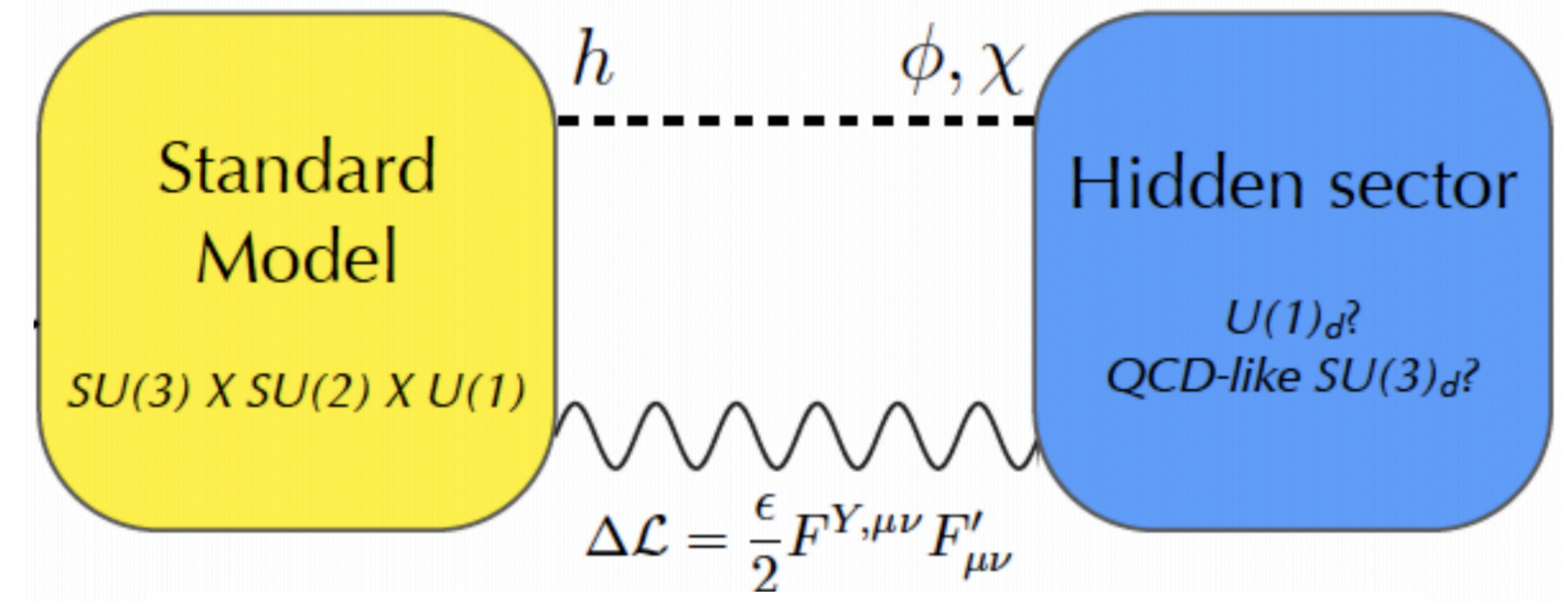
$$\frac{\sigma}{m} \sim \frac{\text{cm}^2}{\text{g}} \sim \frac{\text{barn}}{\text{GeV}} \sim (100\text{ MeV})^{-3}$$




- ▶ 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.



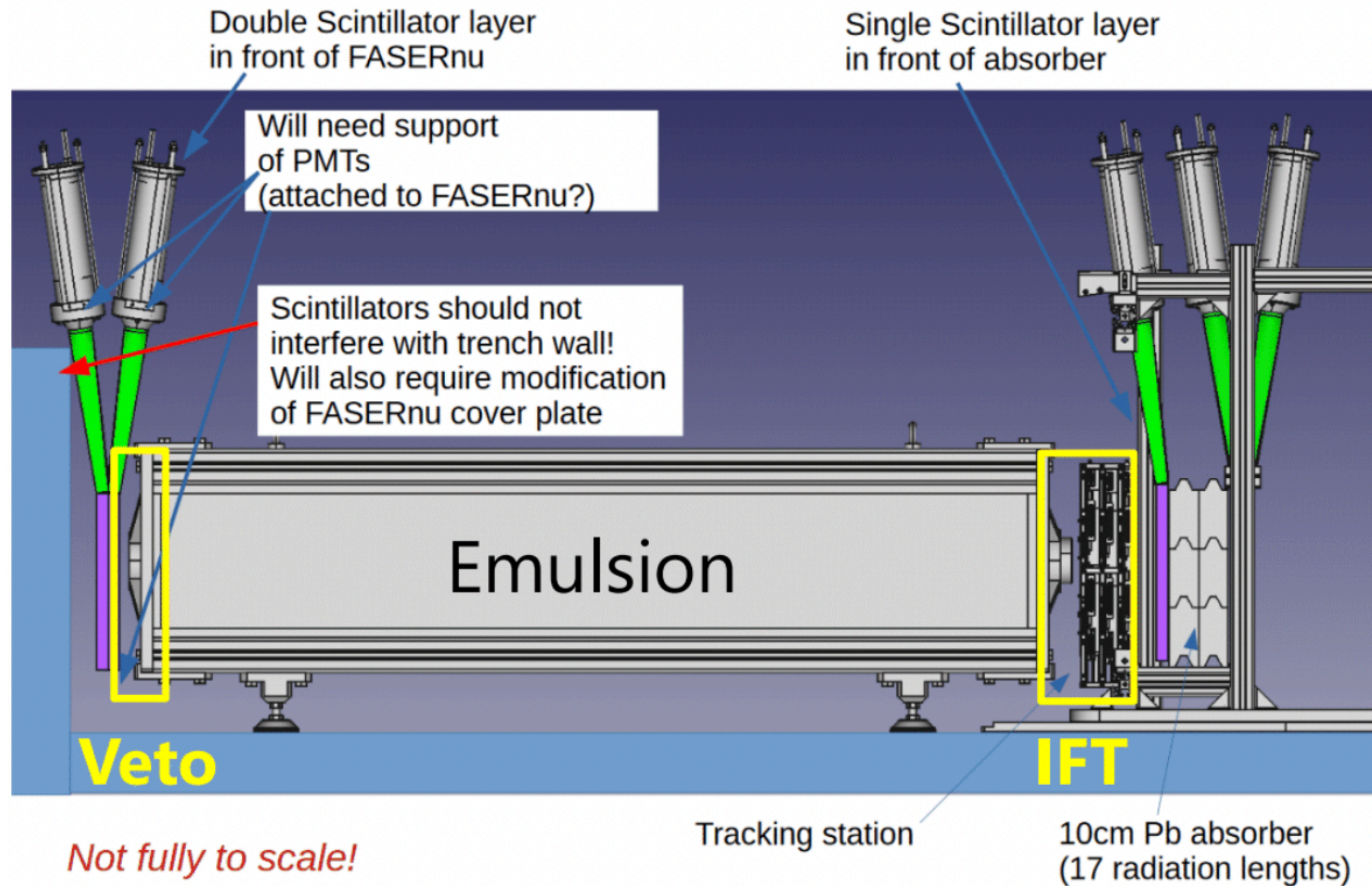
- ▶ Hidden sector physics:
 - ▶ New mediating particles, couplings to SM via mixing with SM “portal” operator
 - ▶ Related to nature of DM (mediator or candidate), baryogenesis, neutrino oscillations...
 - ▶ Can possibly resolve low-energy experiment anomalies (muon g-2, proton size, Be8)
- ▶ Typically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



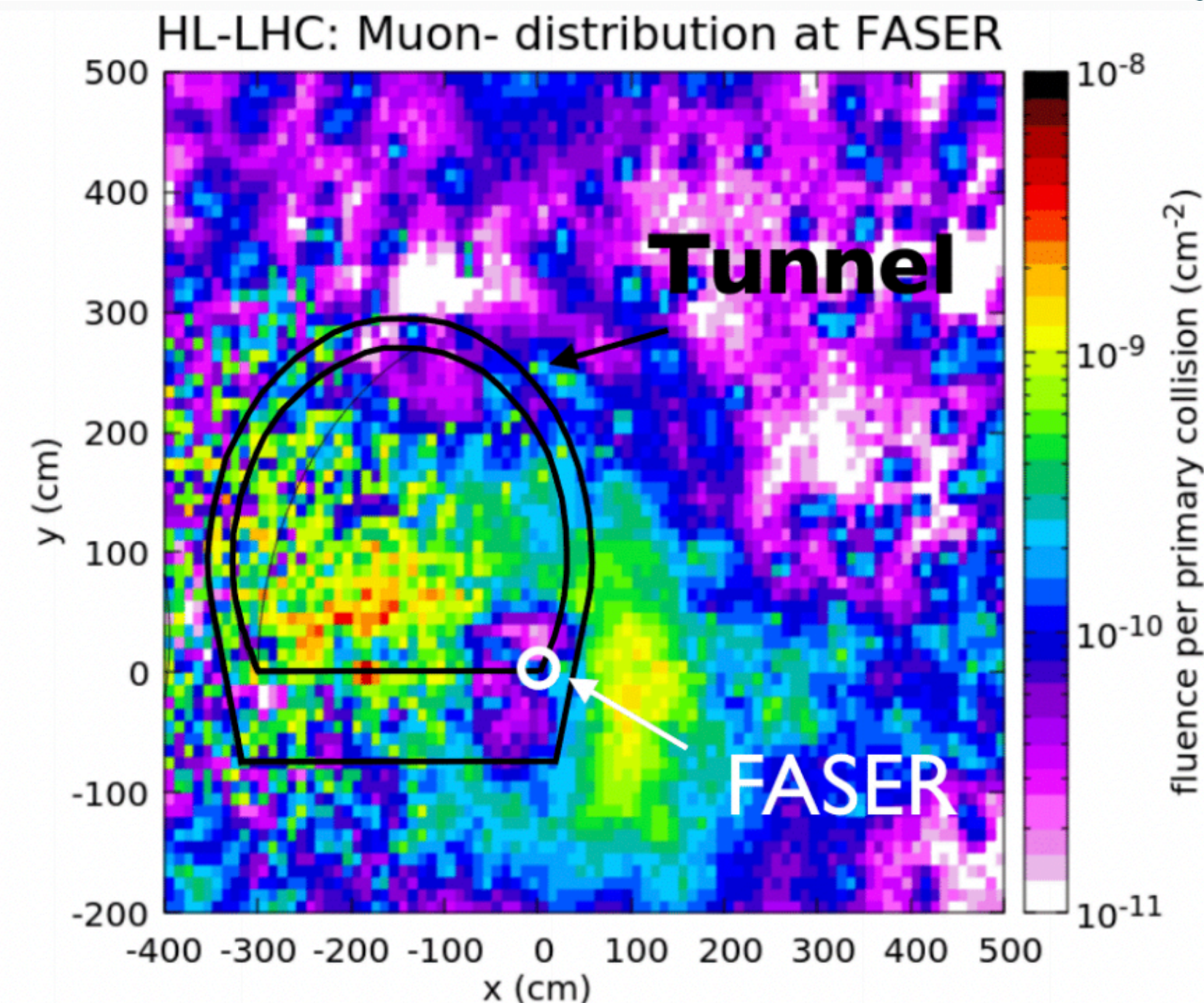
$$\mathcal{L}_{\text{portal}} = \sum O_{\text{SM}} \times O_{\text{DS}}$$

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

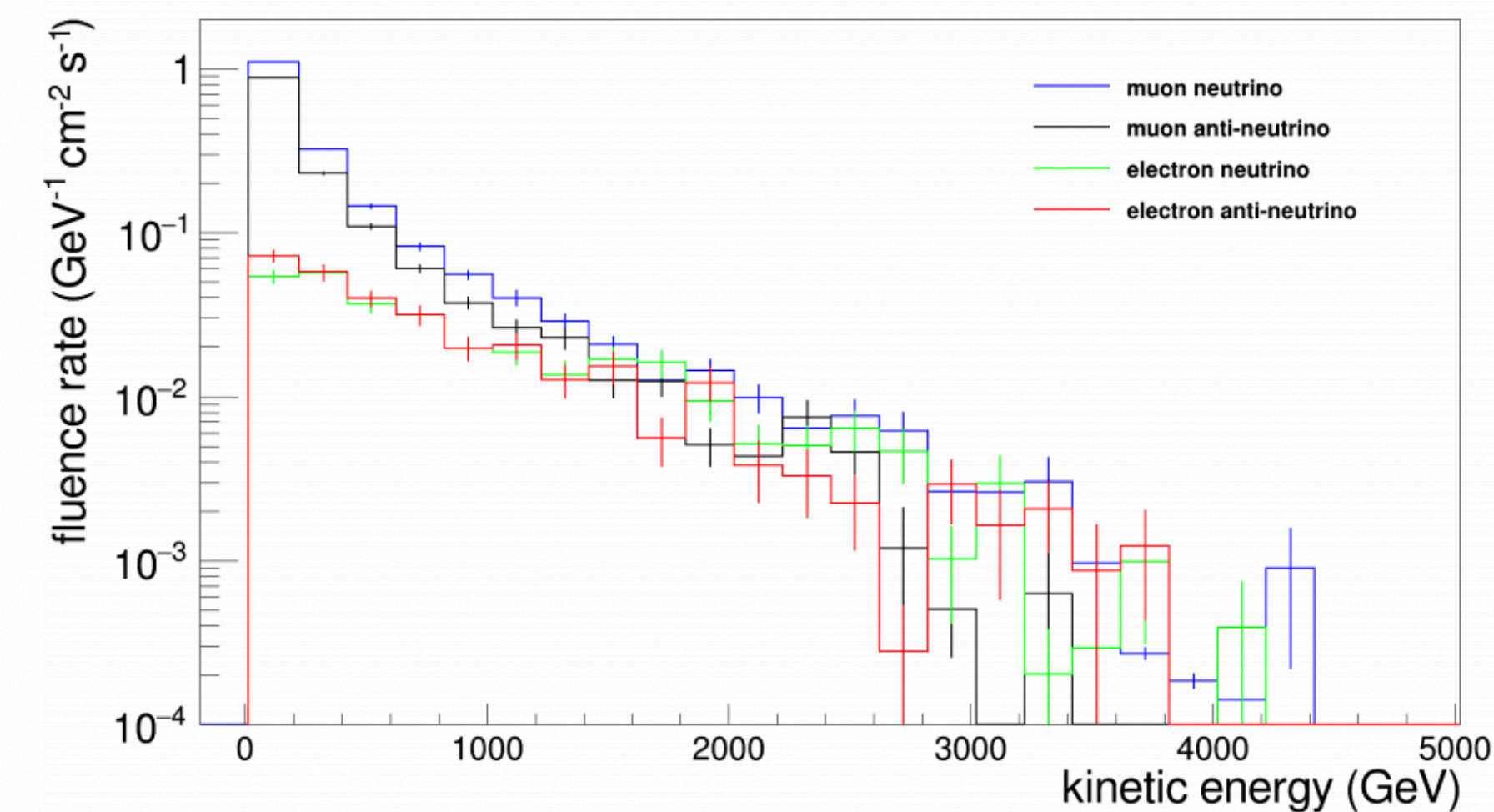
- ▶ To connect muon tracks from $\nu\mu$ interactions for charge identification etc.
- ▶ Interface tracker (IFT) with 3 layers of silicon strip detector. A copy of FASER tracker station.
- ▶ Veto station consists of 2 scintillator layers with 2 cm thickness. >99.99% veto efficiency for a charged particle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



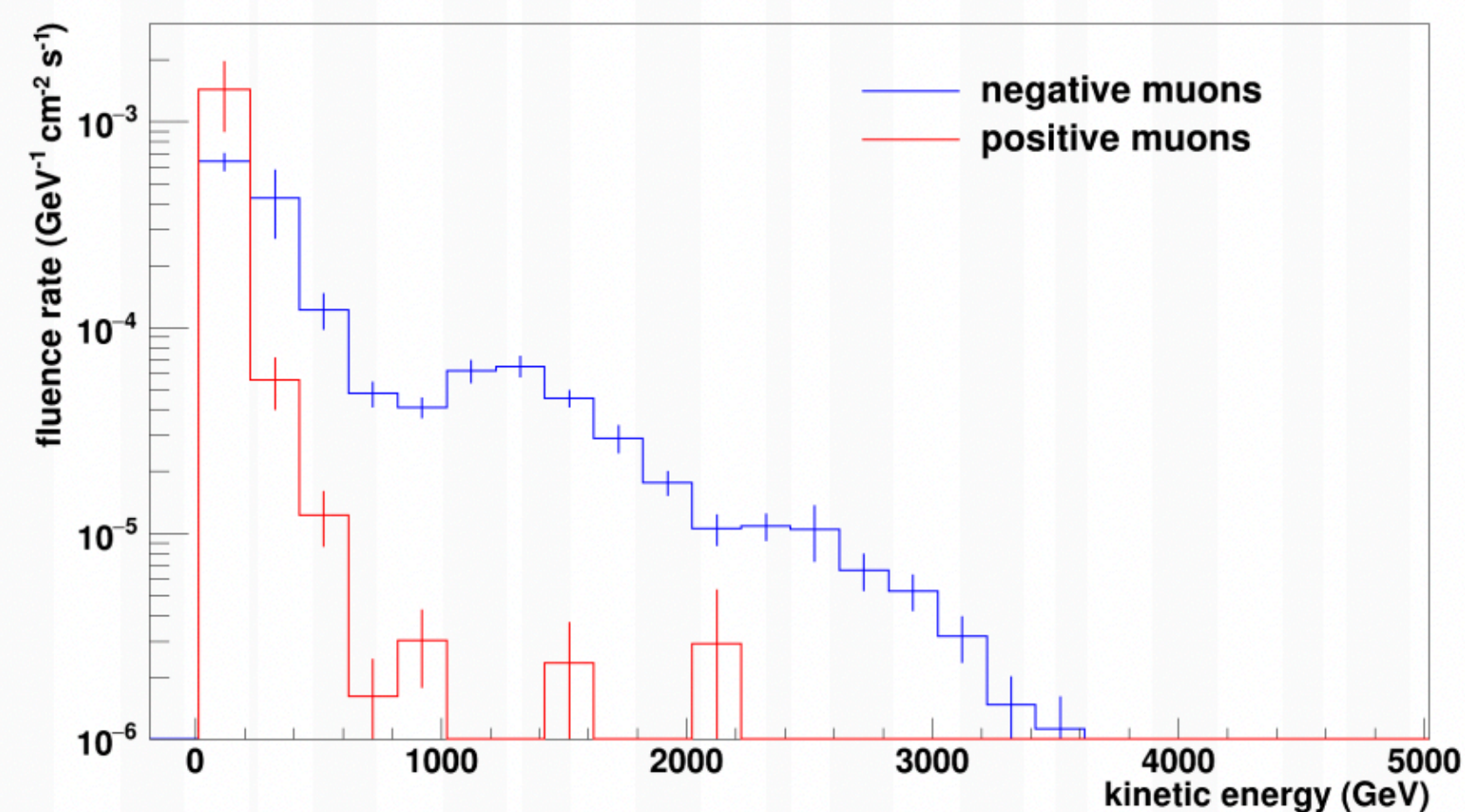
- FLUKA simulations and *in situ* measurements used to assess expected backgrounds.
 - IP1 collisions (shielded by 100m rock)
 - Off-orbit protons hitting beam pipe aperture near TI12
 - Beam-gas interactions
 - Low particle flux along beam axis due to LHC optics.
- } Minor



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



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

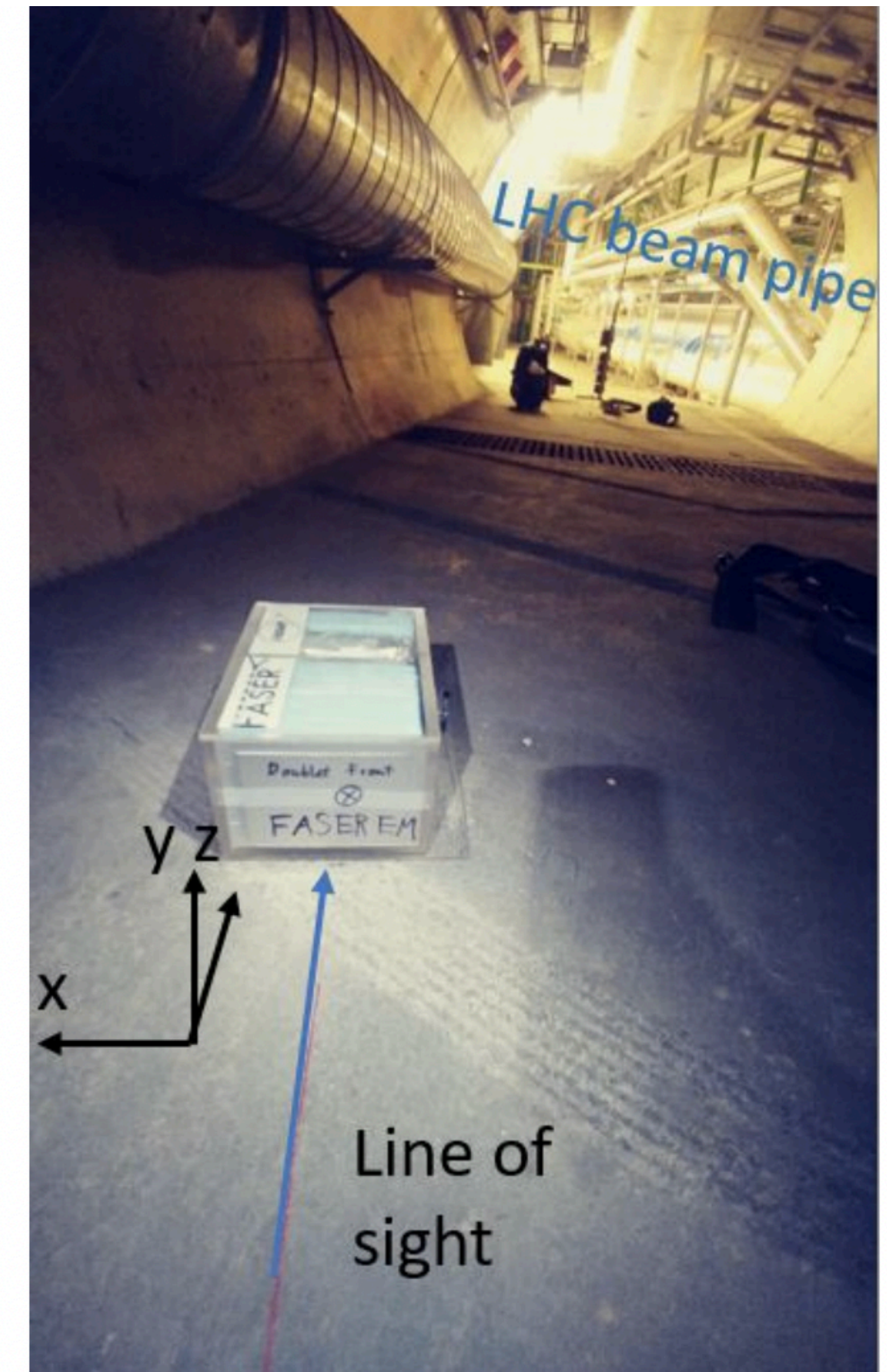
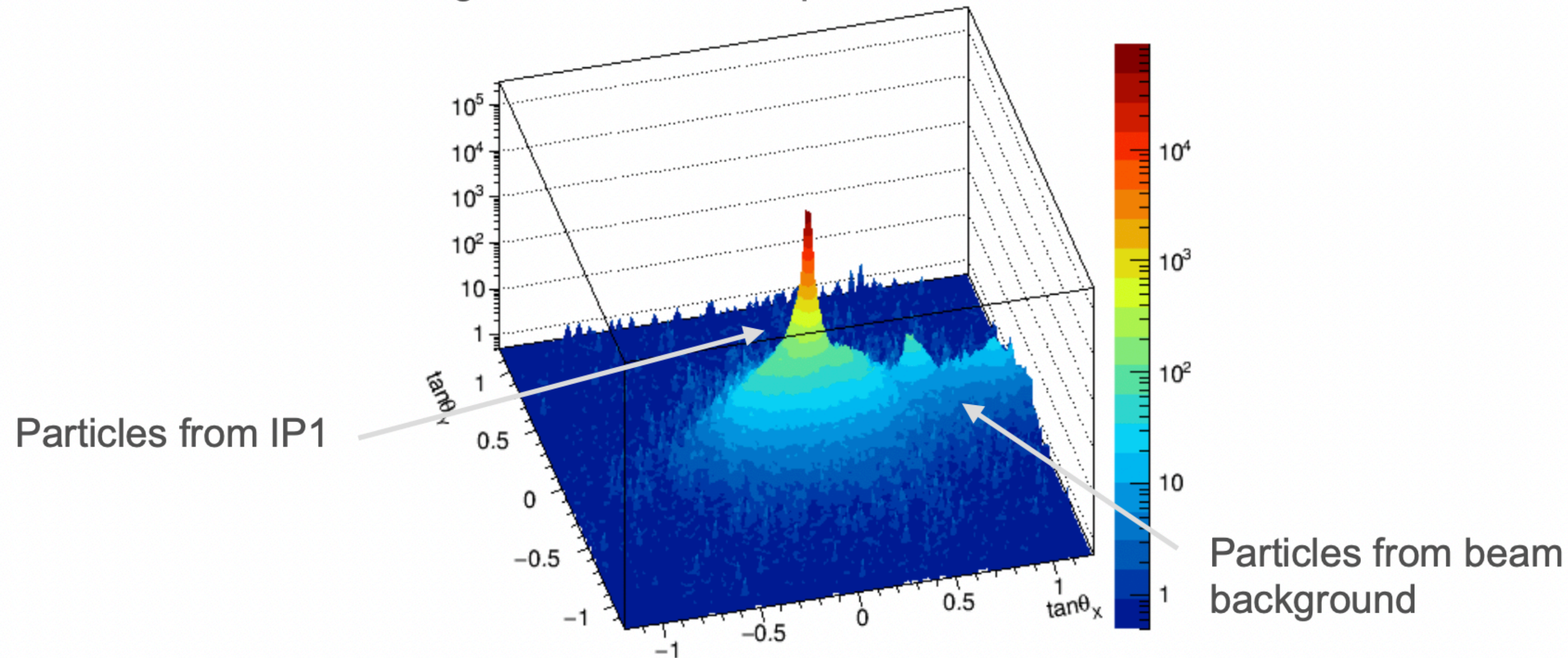


Muon charge asymmetry due to LHC magnets

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

- *In situ* measurements using emulsion detectors and TimePix BLM in T112 in 2018 confirm expected particle flux, and correlation with IP1 luminosity.

Angular distribution of particles in emulsion detector



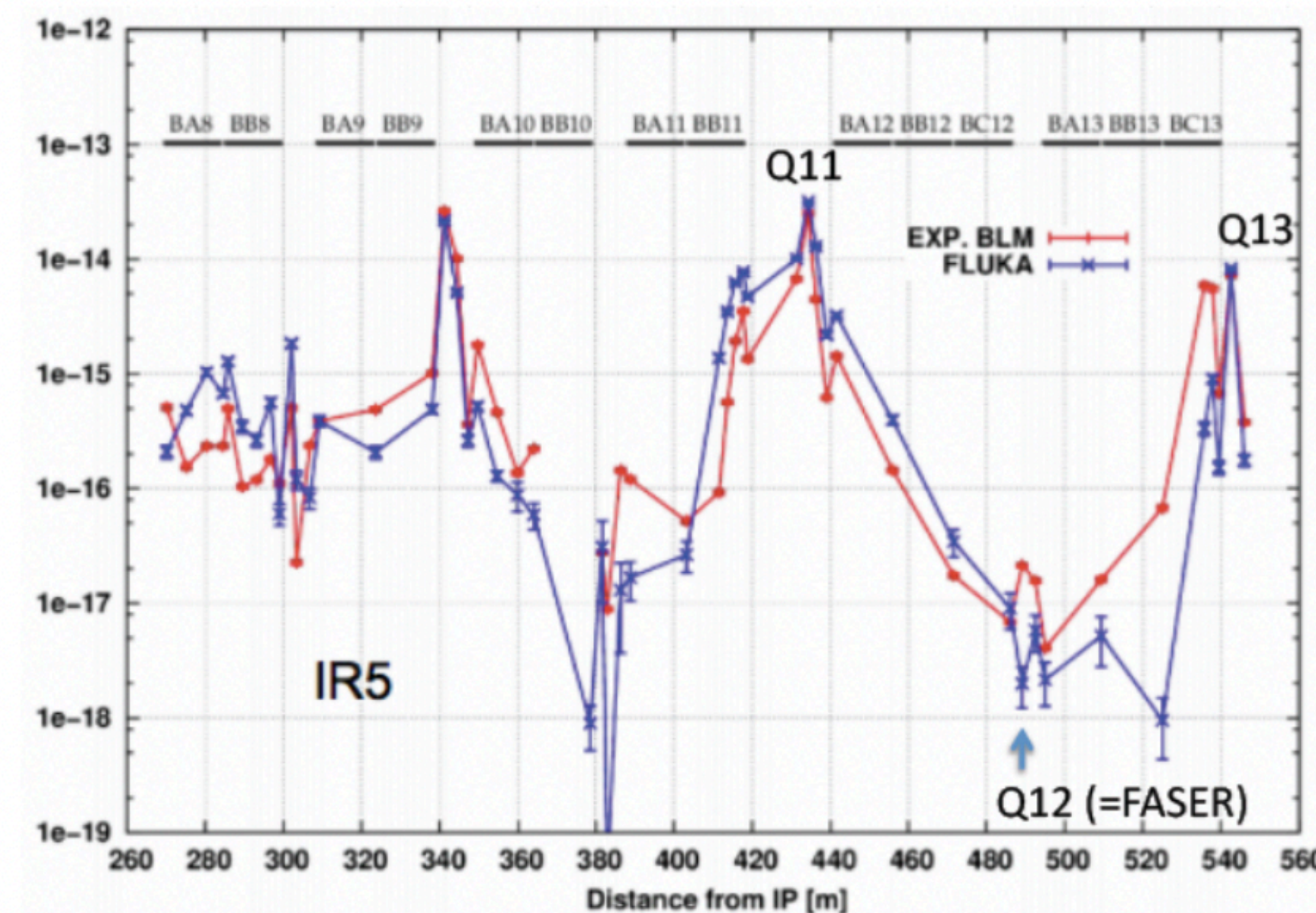
The FLUKA simulation tracks particle production, deflection, and energy loss with a detailed model of the geometry of the LHC tunnels, including the LHC material map and magnetic field layout. The simulation includes three potential sources of background at the FASER location:

- 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).

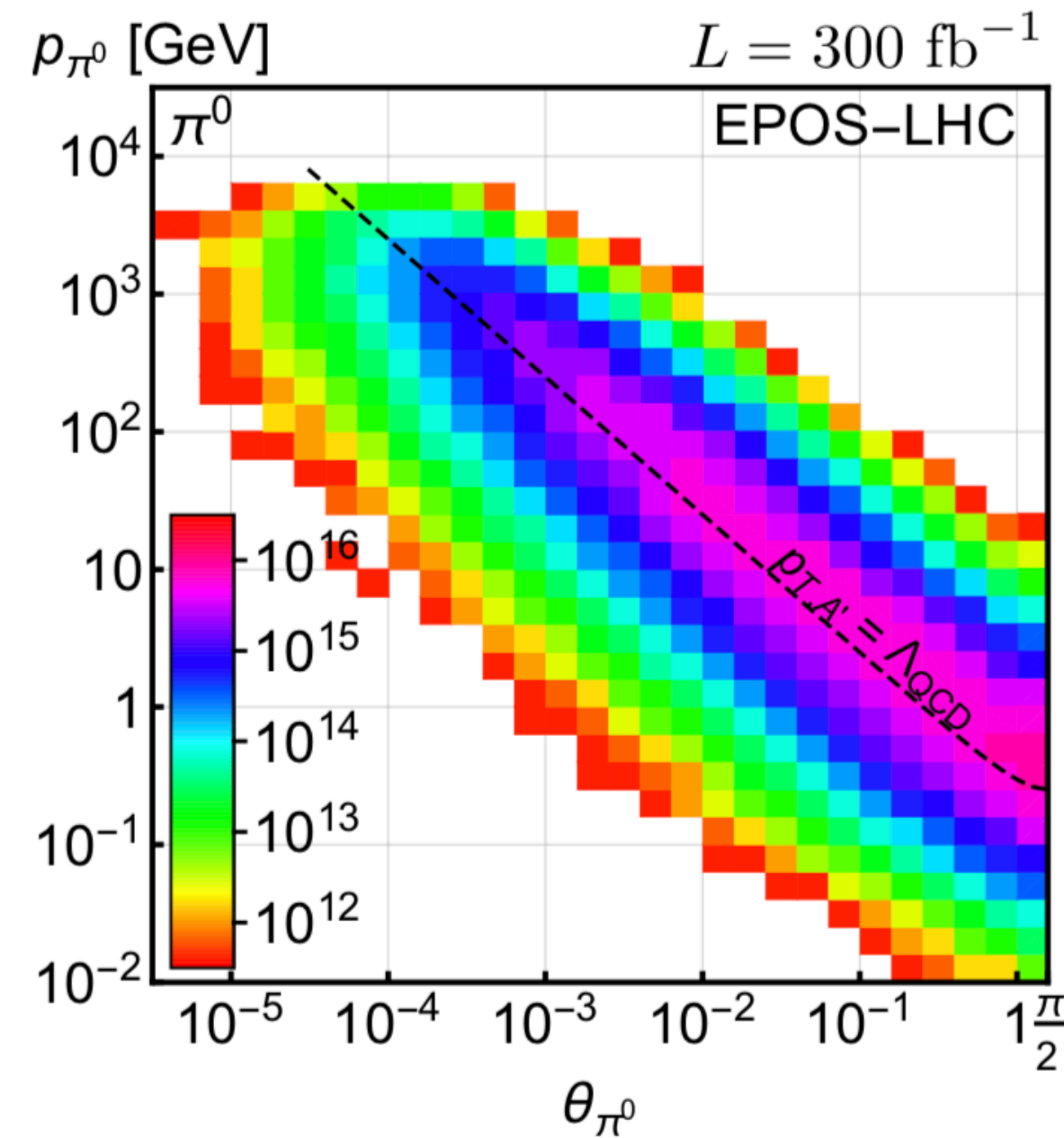
Always co-linear with
accompanying muons
- $10^5 \rightarrow 10$ with veto

Minor

- 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 5×10^{-3} Gy/year
 - less than 5×10^7 1 MeV neutron equivalent fluence/year
- **FASER detector does not need radiation hard electronics**

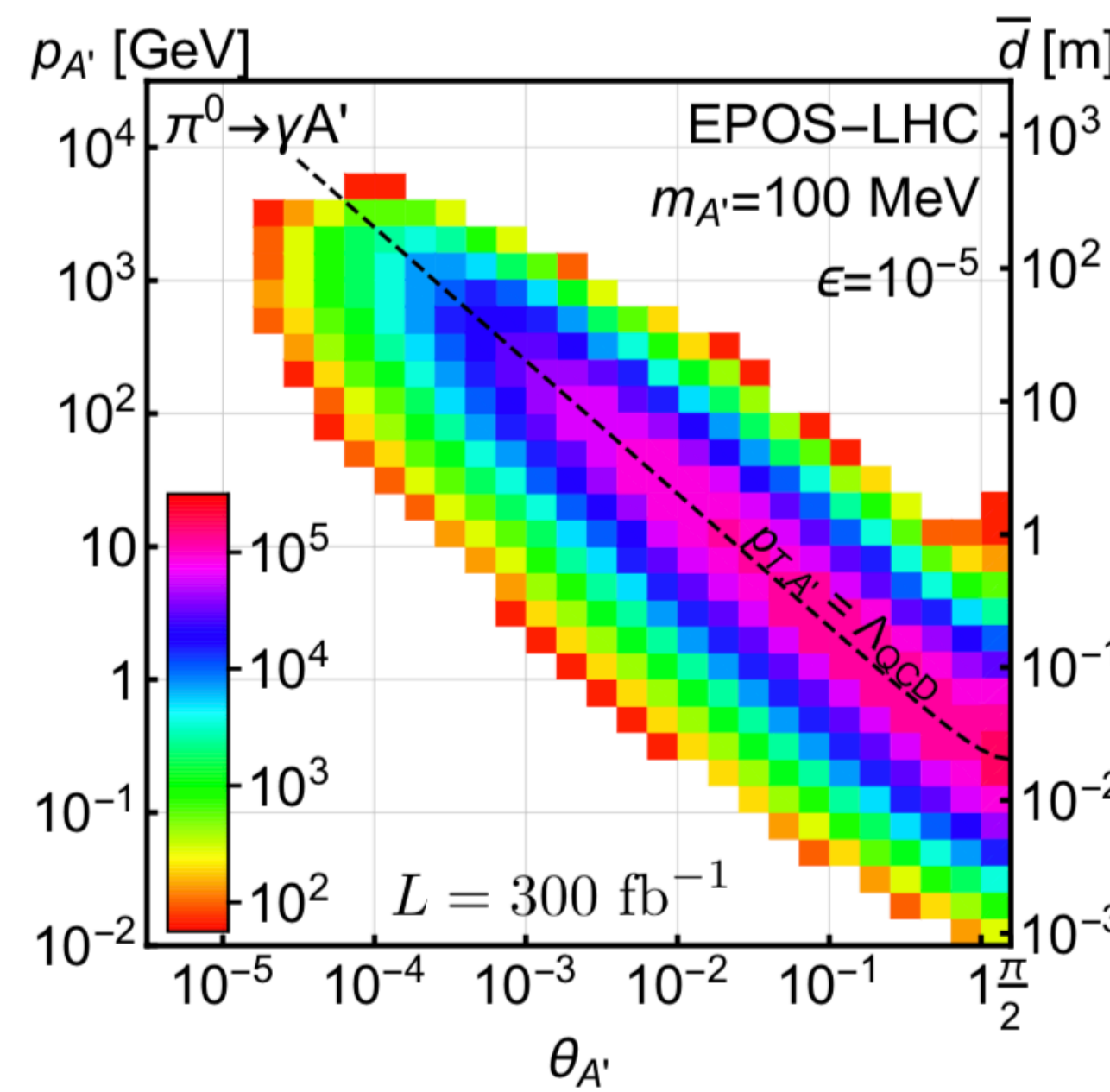


Pions at IP



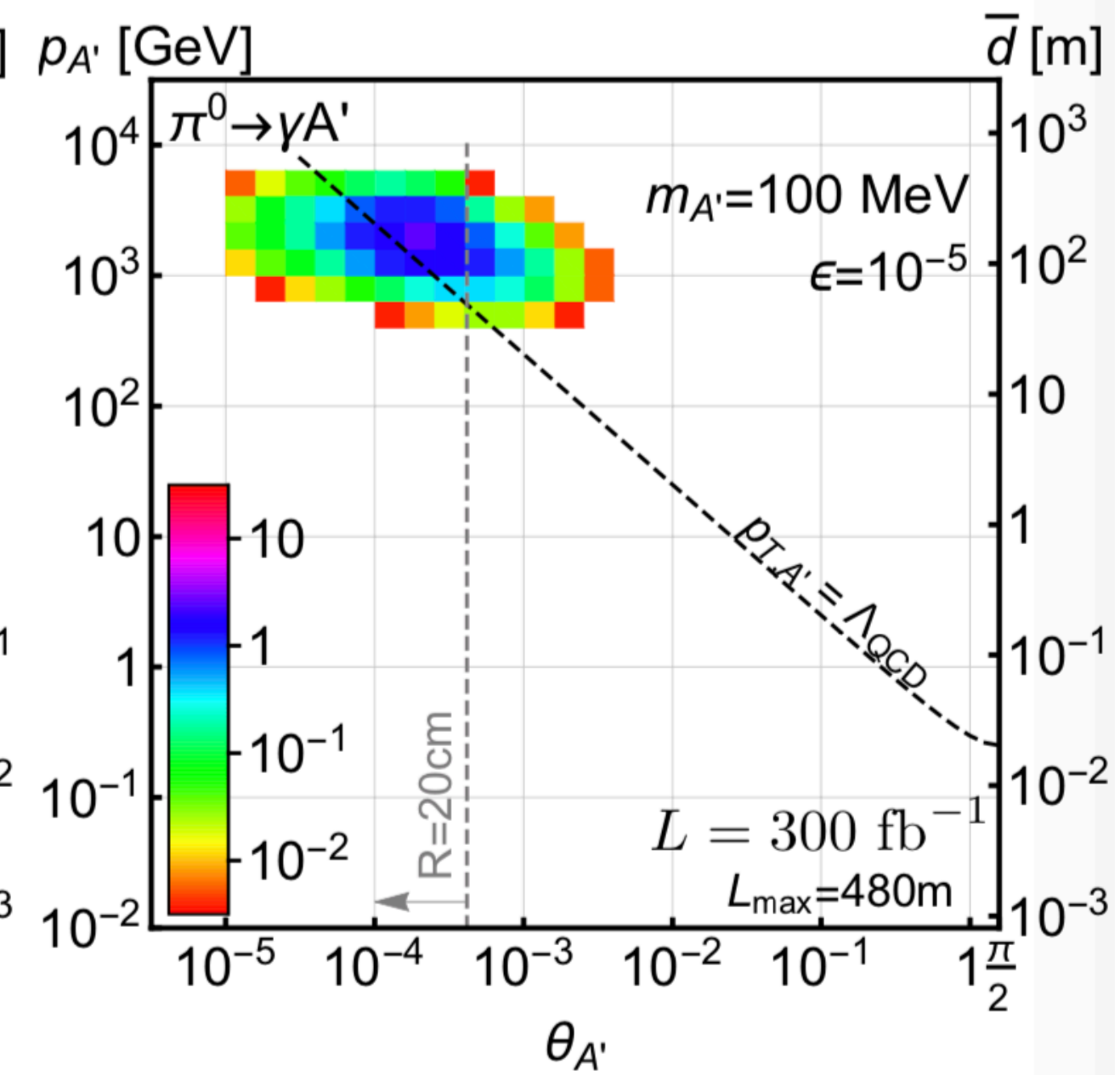
- dedicated hadronic interaction models, grounded on LHC data
- production peaks at $p_T \sim \Lambda_{\text{QCD}}$
- enormous event rates $N \sim 10^{15}$ per bin

A' at IP

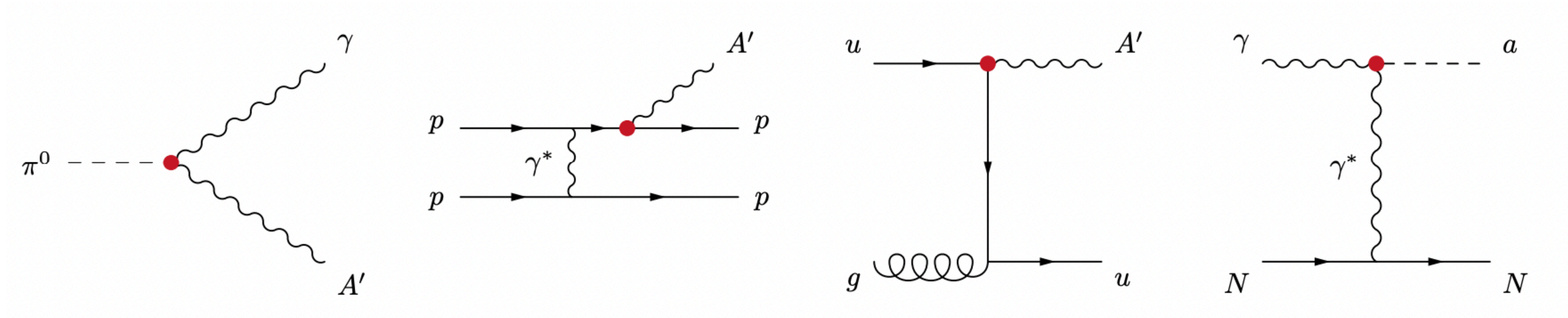


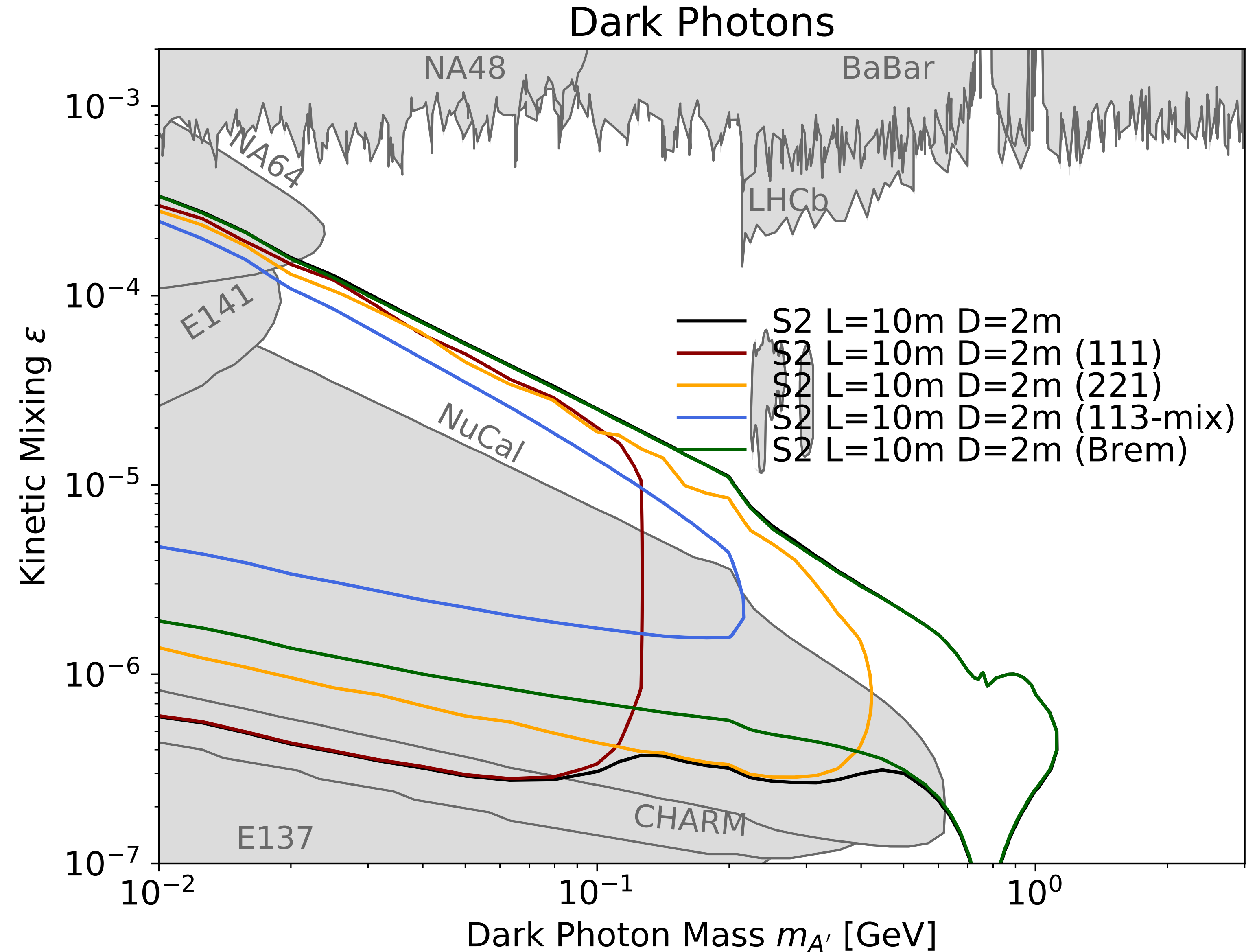
- production peaks at $p_T \sim \Lambda_{\text{QCD}}$
- rates highly suppressed by $\epsilon^2 \sim 10^{-10}$
- still rates $N \sim 10^5$ per bin: LHC could be dark a photon factory

A' decay at FASER



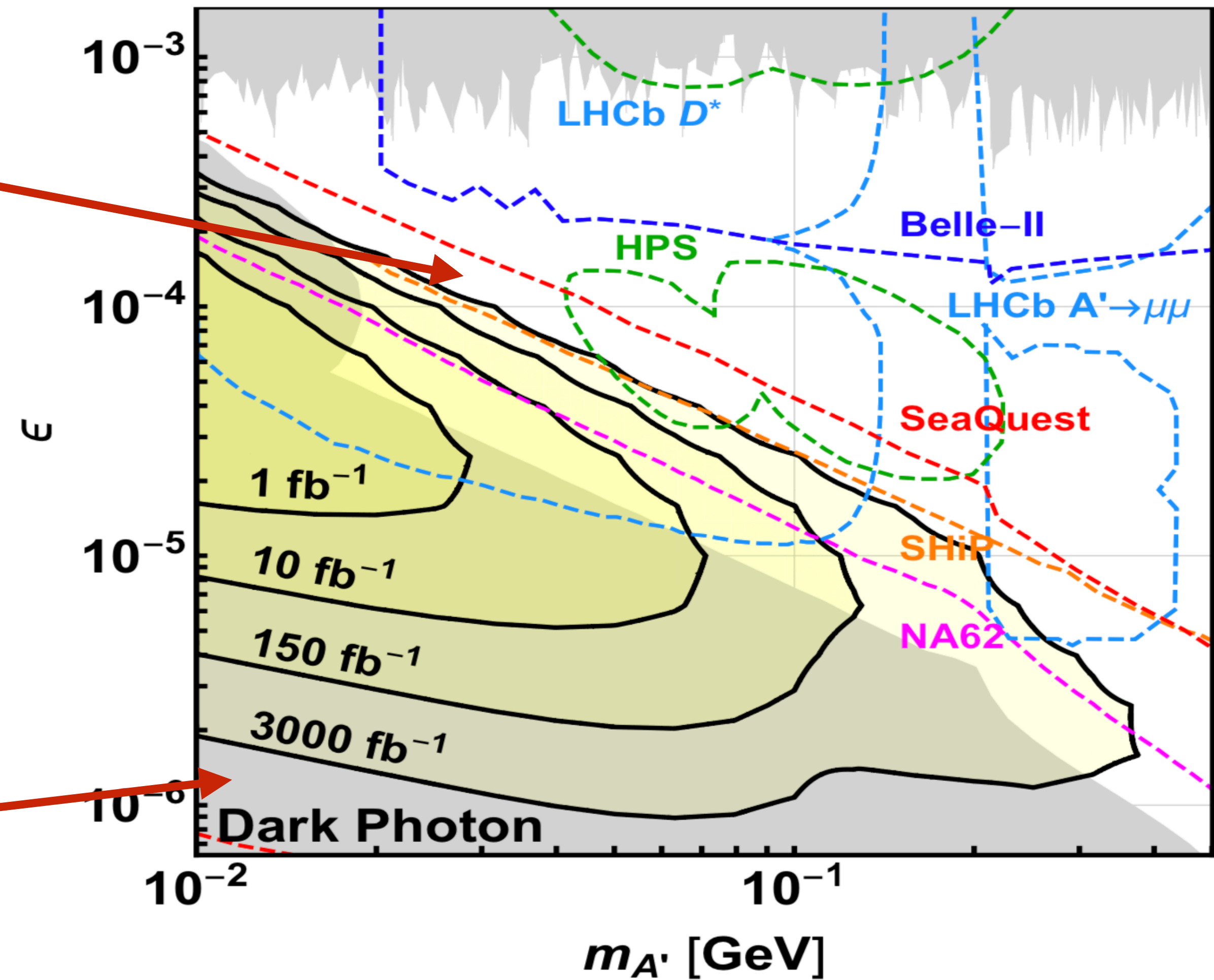
- only highly boosted $\sim \text{TeV } A'$ arrive at FASER
- rates suppressed by decay requirements
- still rates $N \sim 100$ signal events within 20cm of beam collision axis



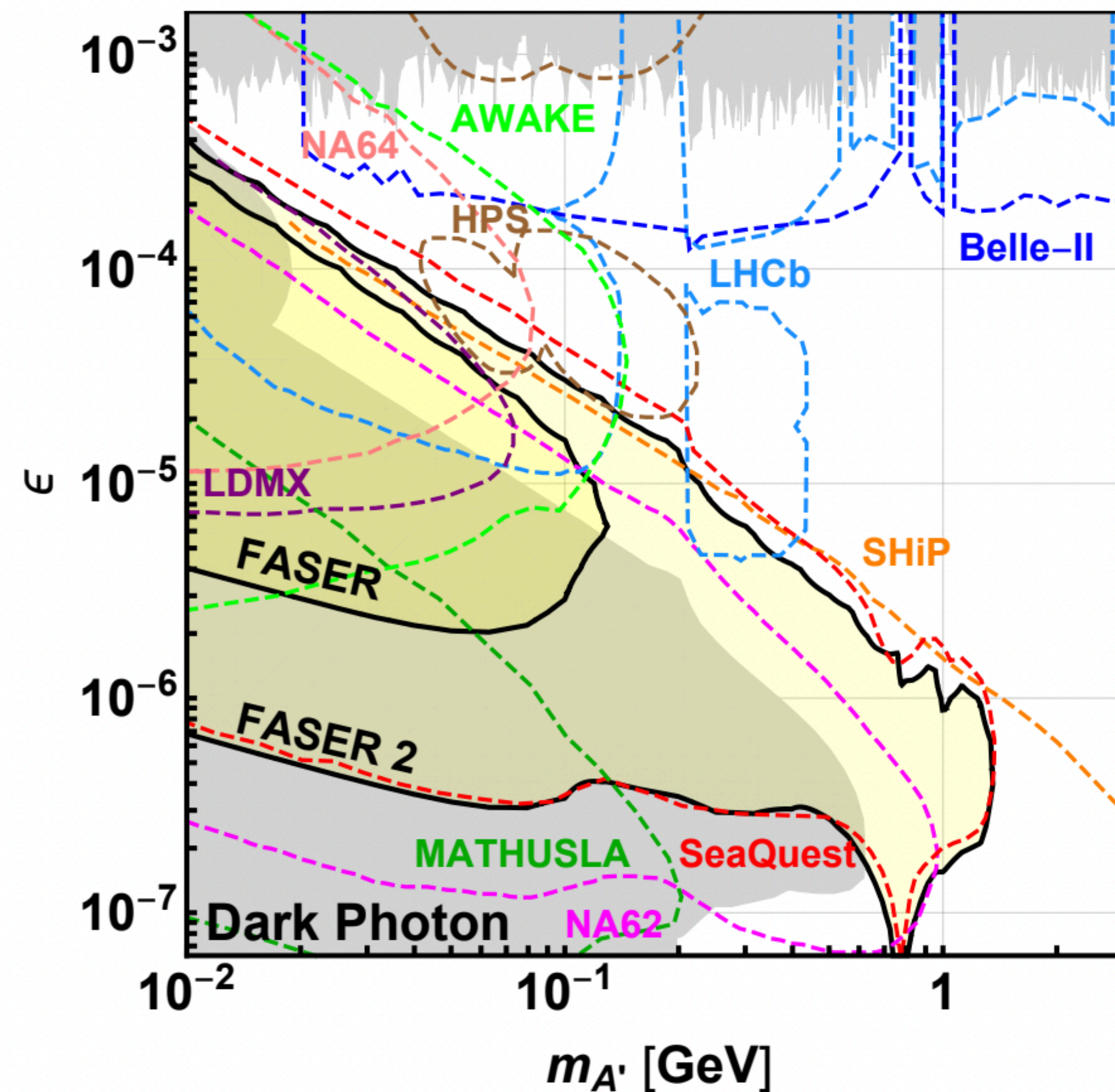
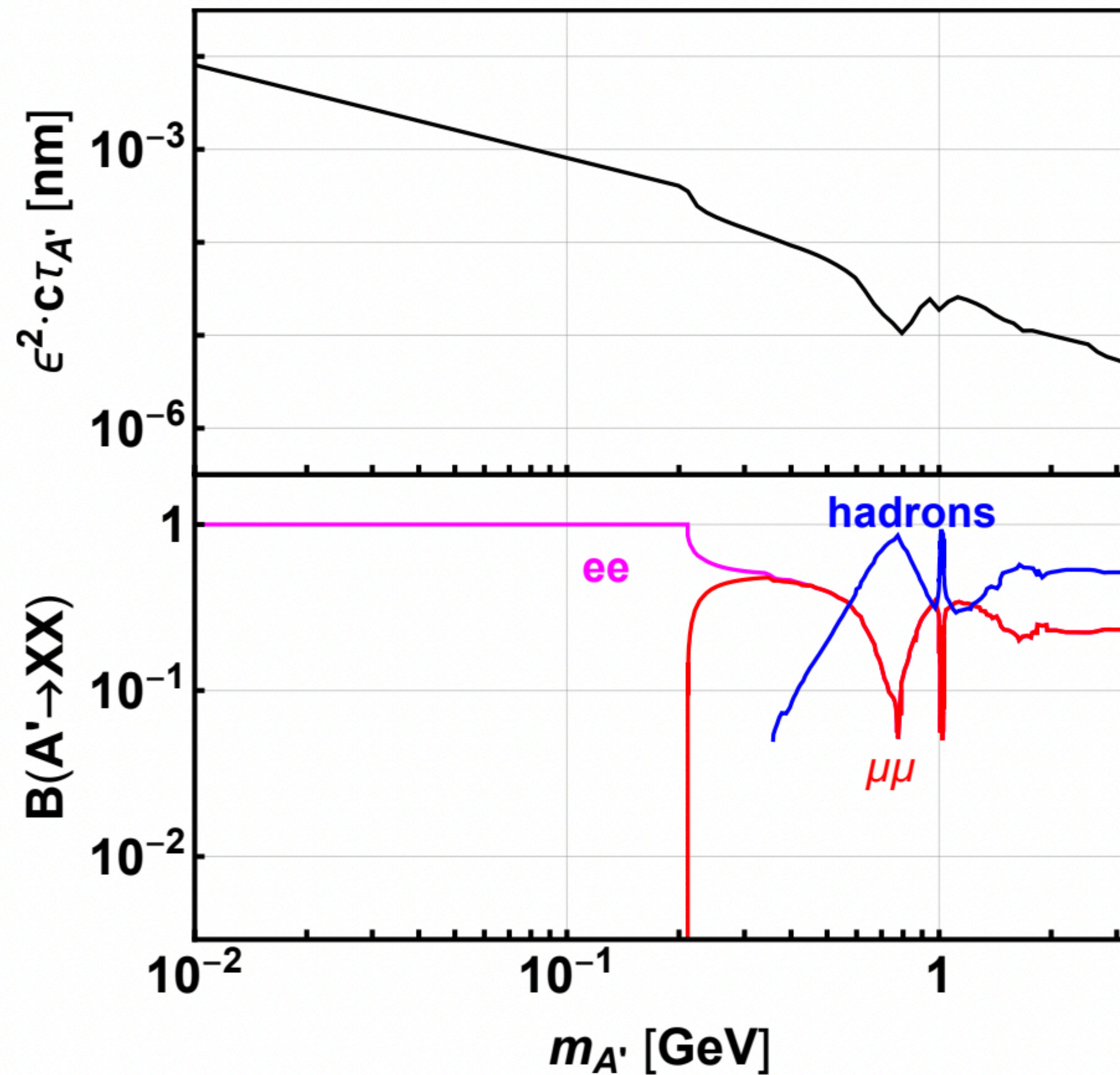


For lower lifetime the number of signal events becomes exponentially suppressed once the A' decay length drops below the distance to the detector

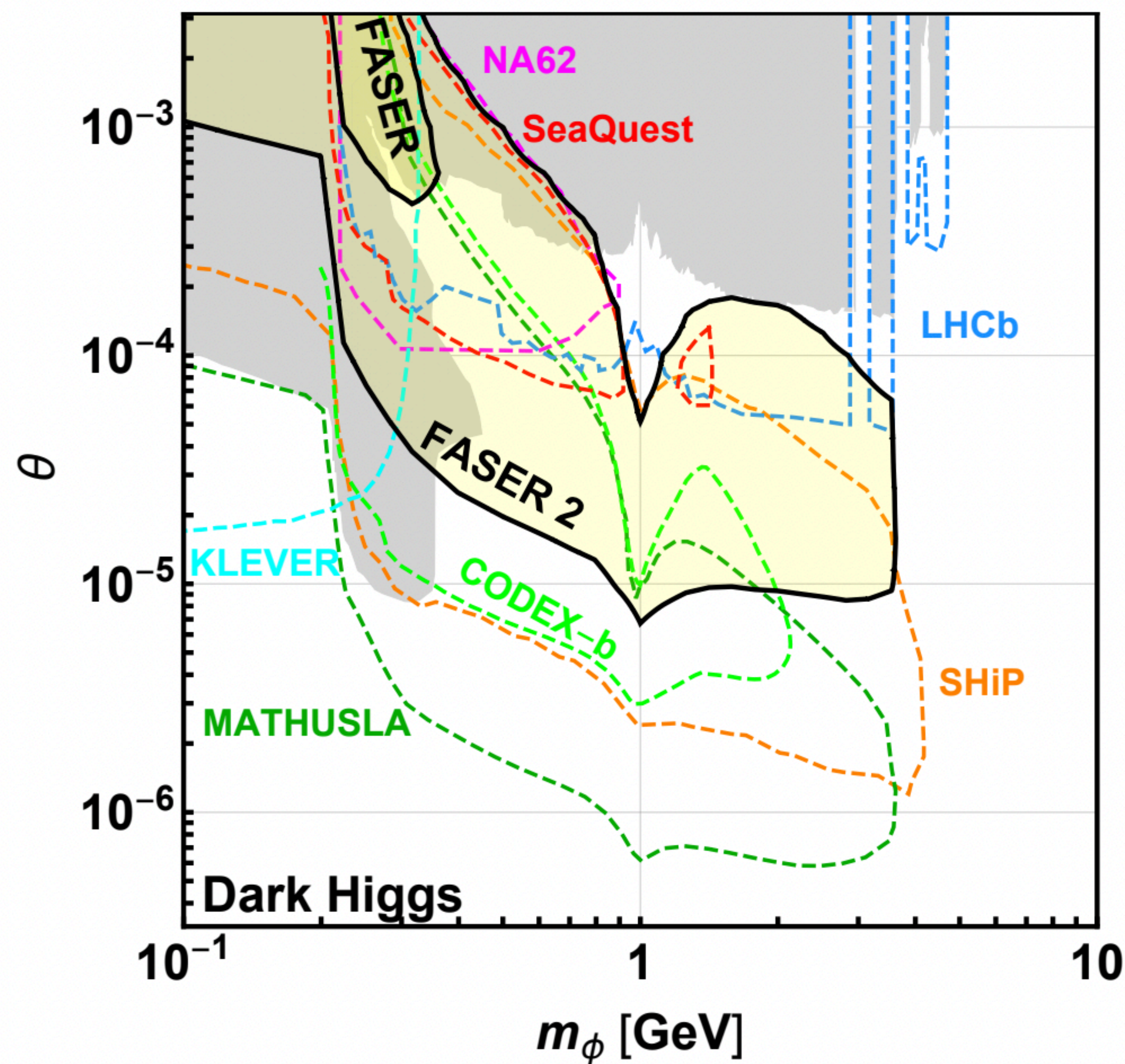
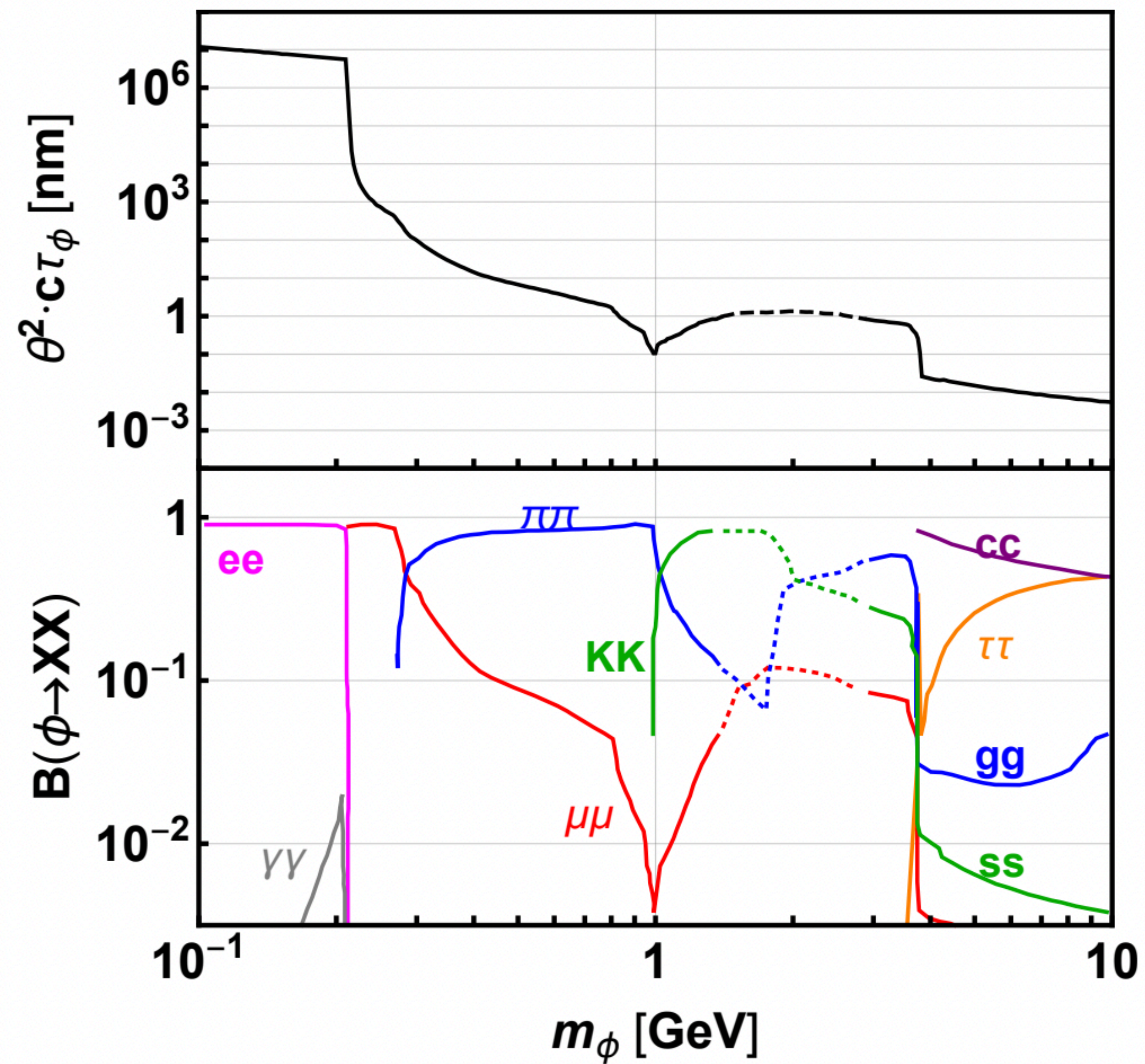
Combining dependence in both production rate and decay width, total number of signal events in the detector scales as ϵ^4



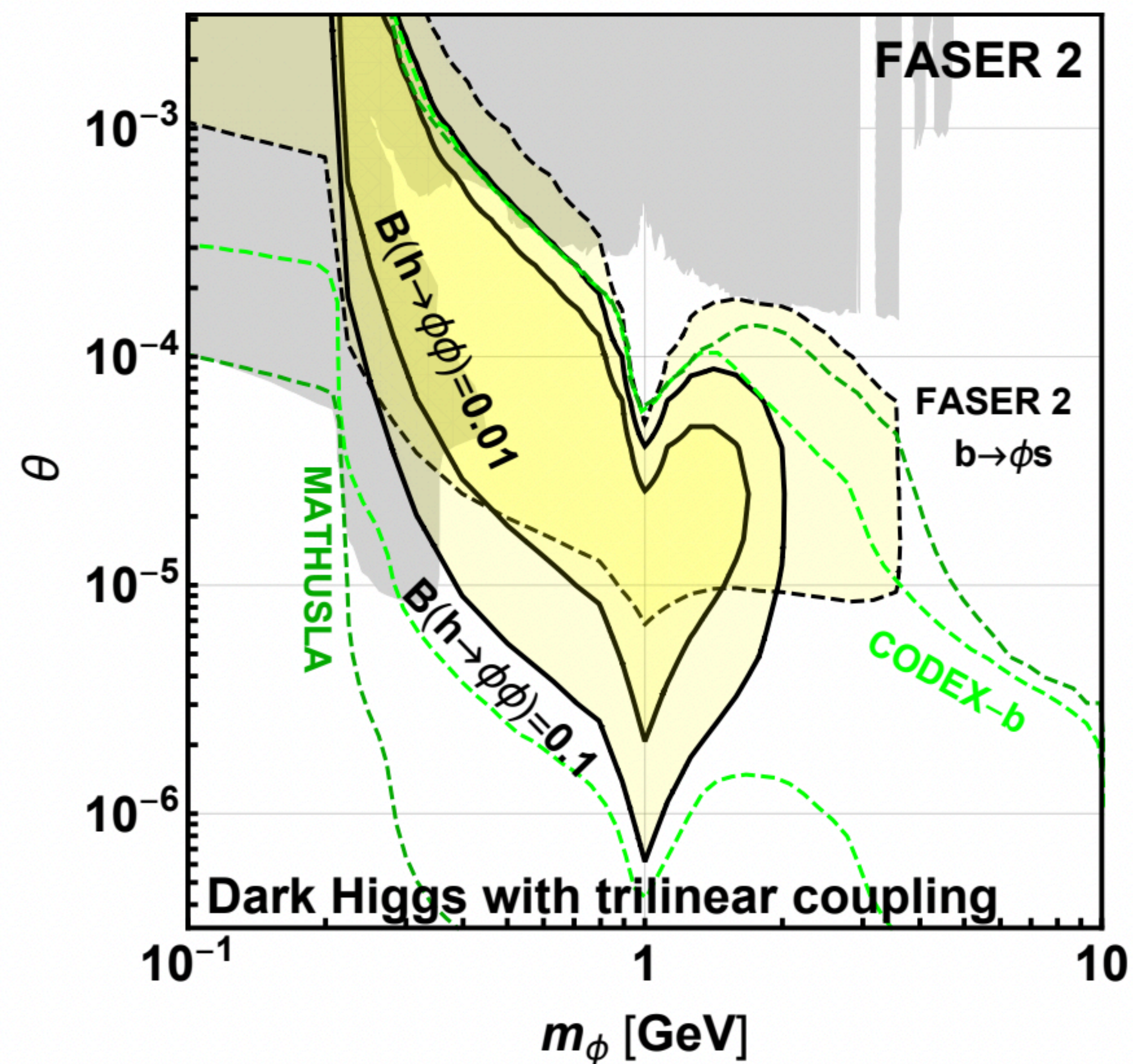
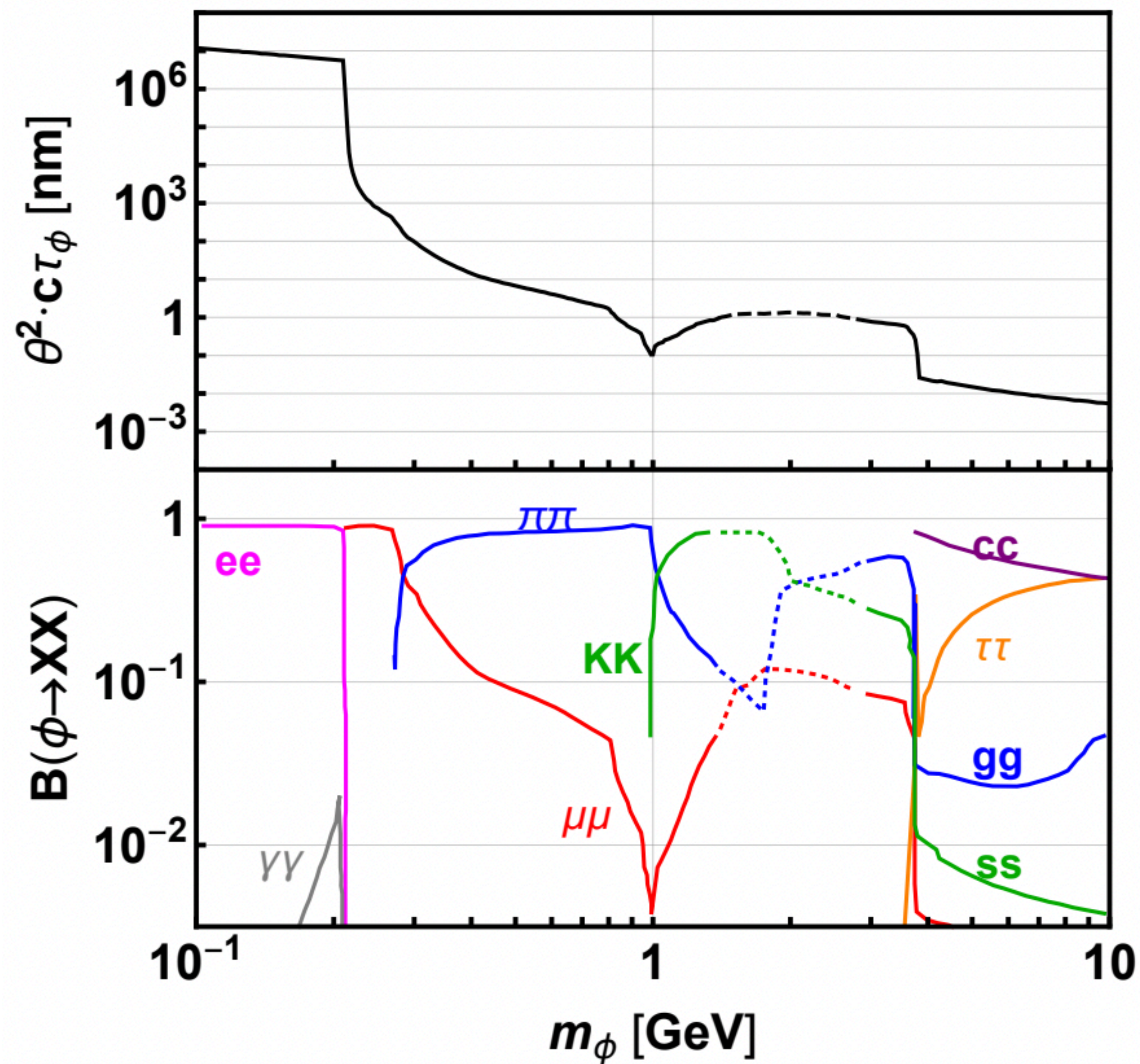
Target scenarios | Dark Photon

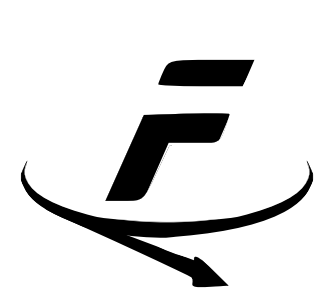


Target scenarios | Dark Higgs

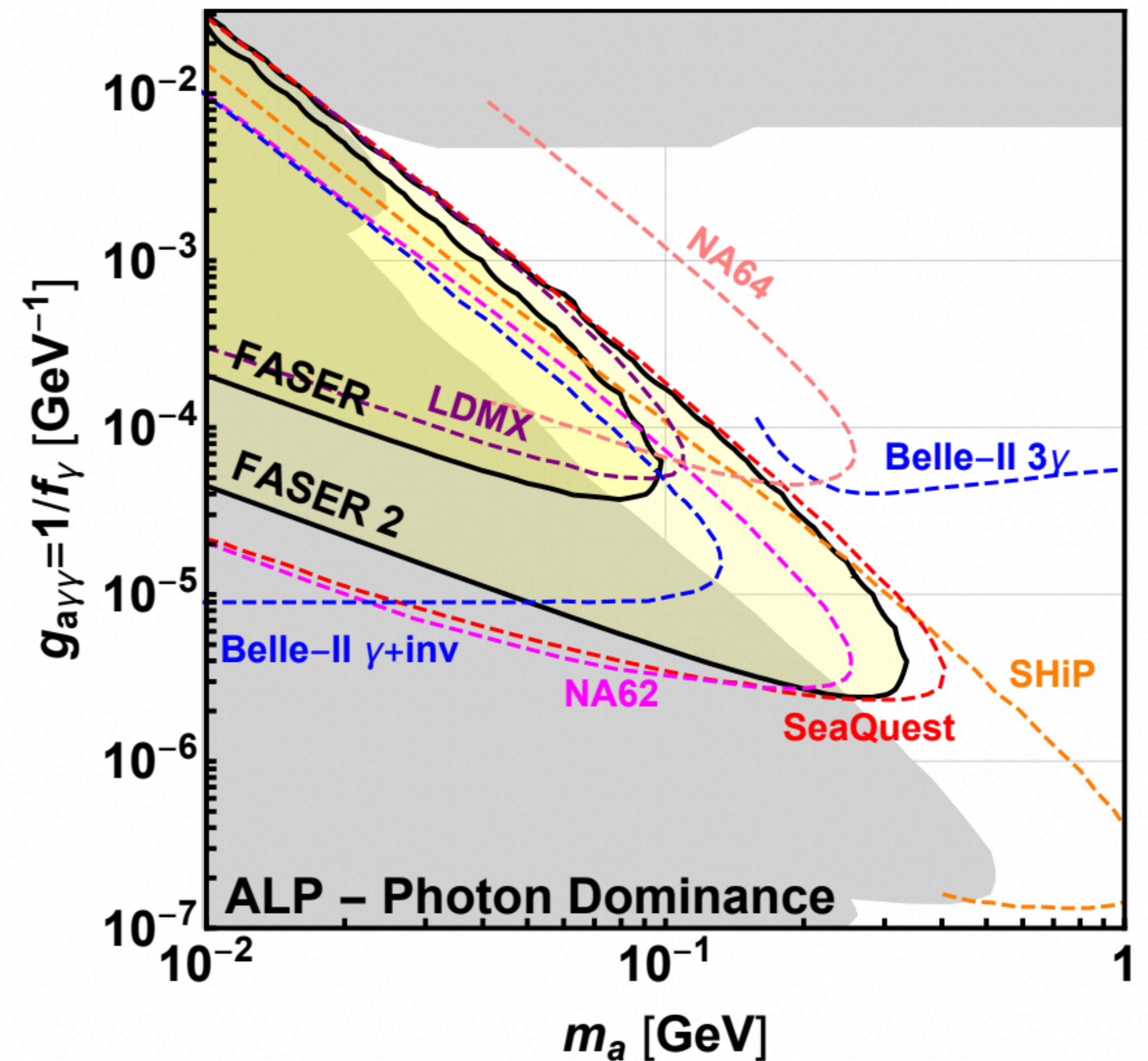
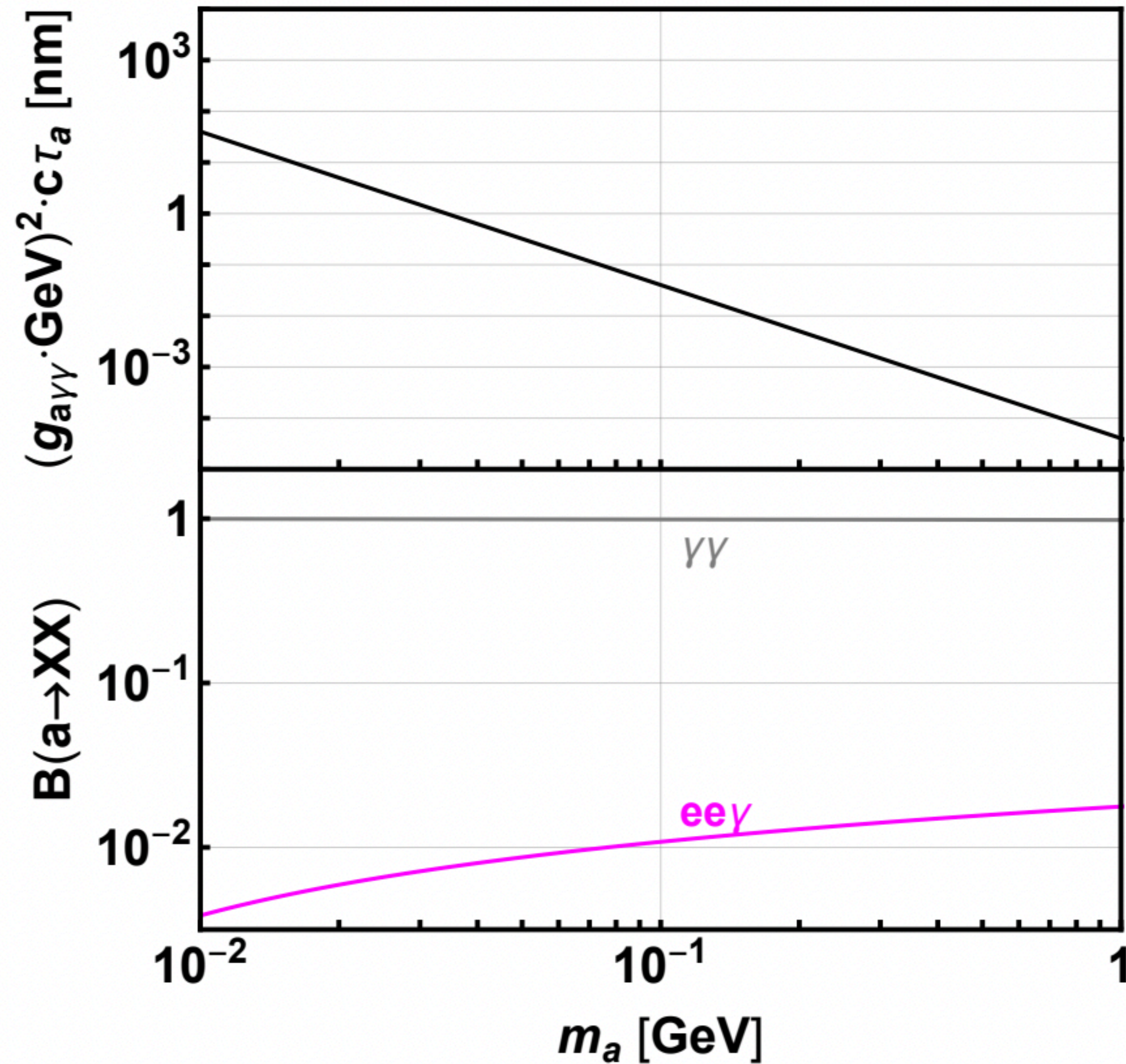


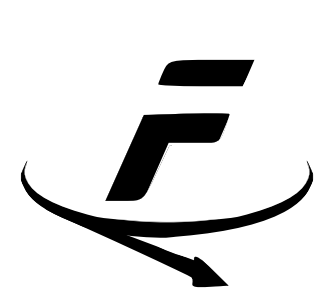
Target scenarios | Dark Higgs



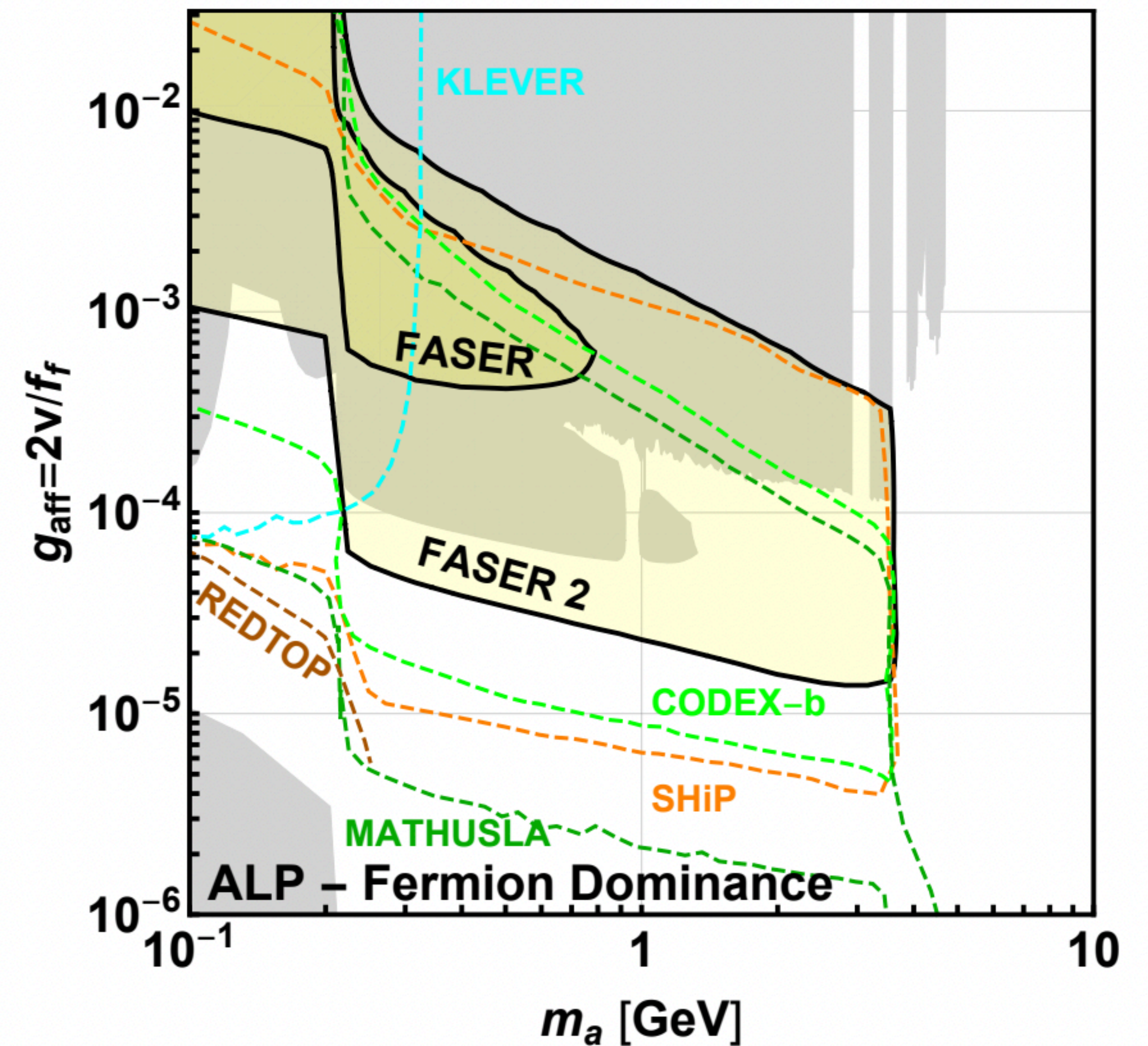
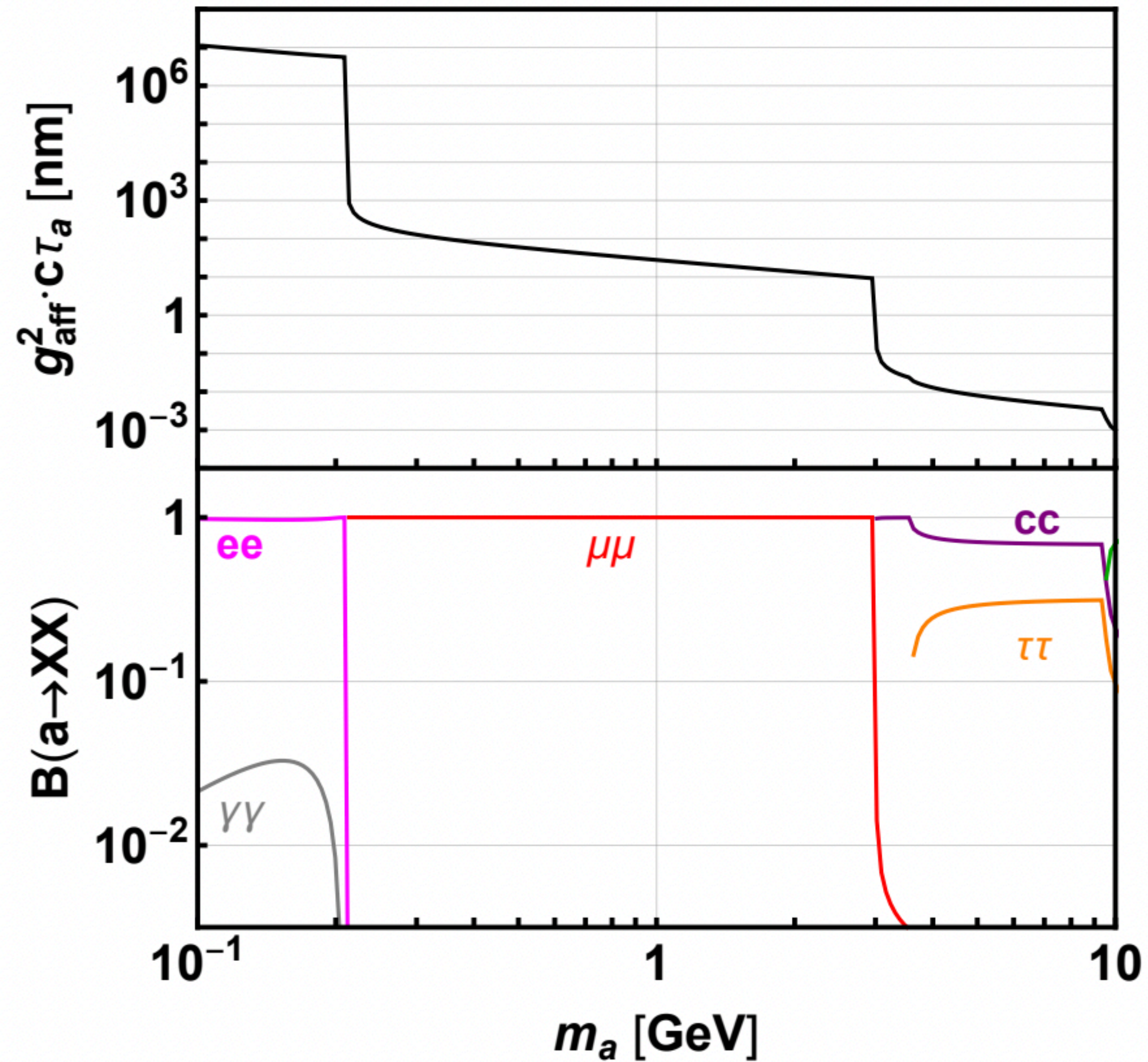


Target scenarios | ALP





Target scenarios | ALP



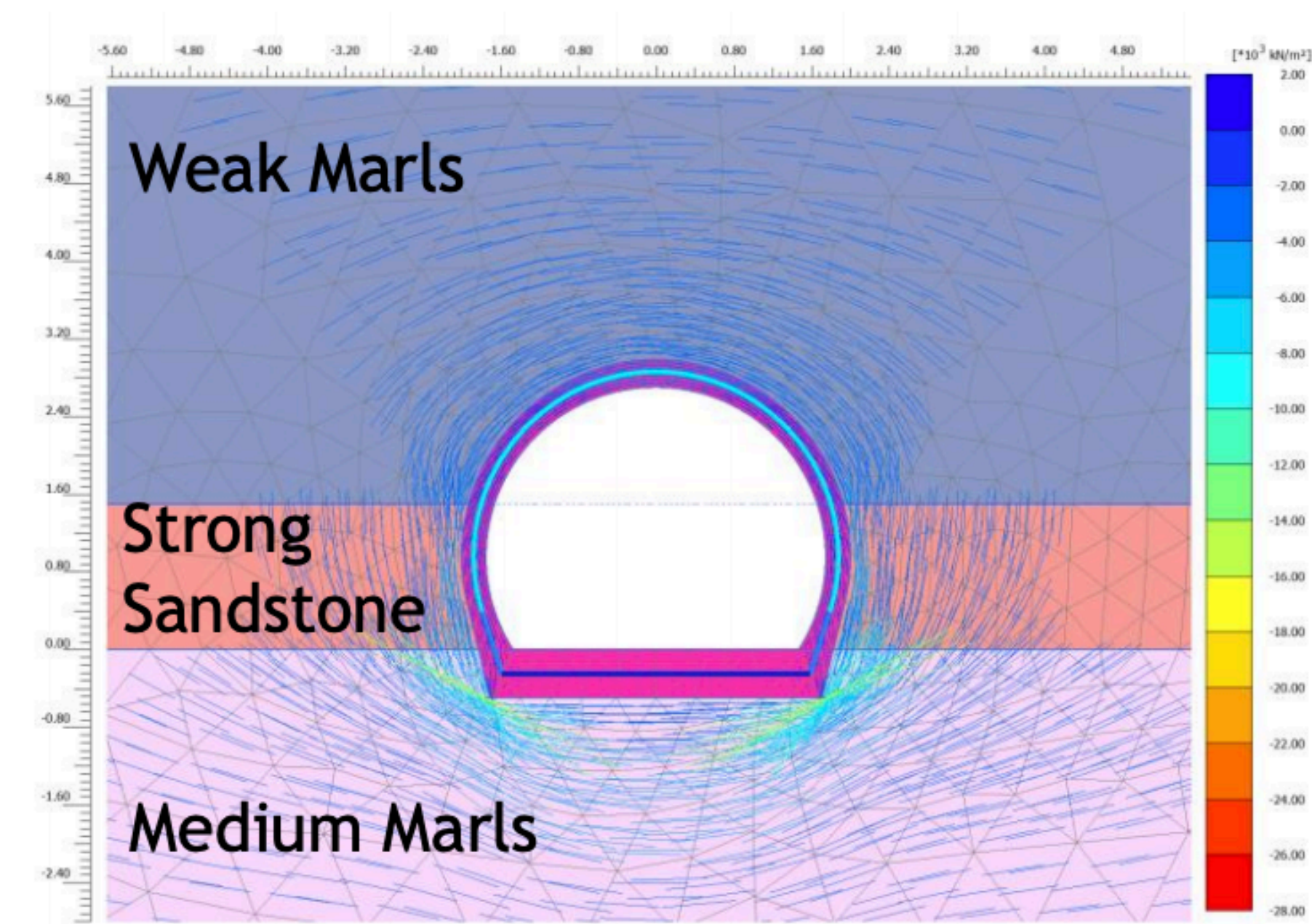
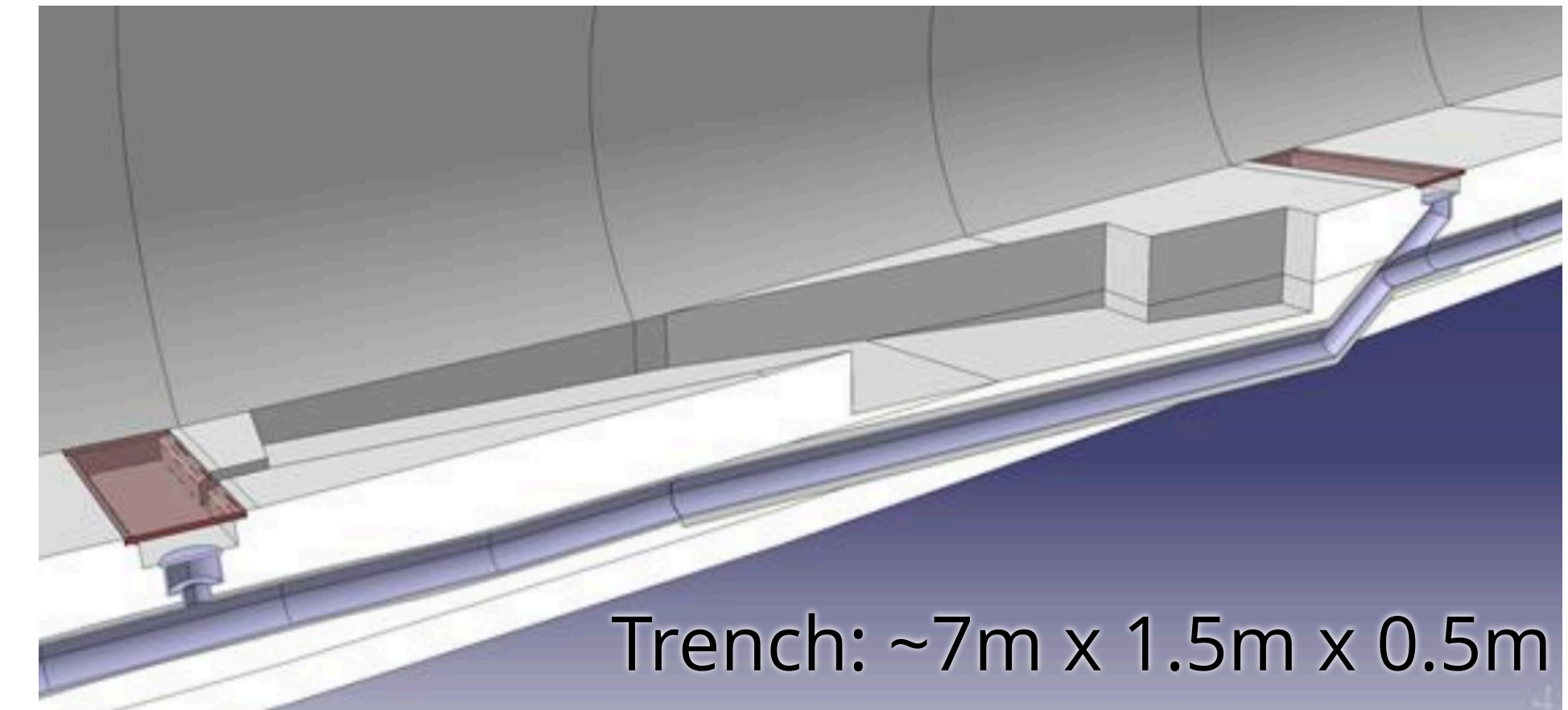
► Trench

- To be aligned with the line-of-sight (LOS) in the vertical direction a shallow (<50cm deep) trench was needed in T112
- Drain shallower than shown on historical drawings
 - Provided opportunity to increase trench depth - parallel to LOS

- Plan area increased to allow more space for FASERv

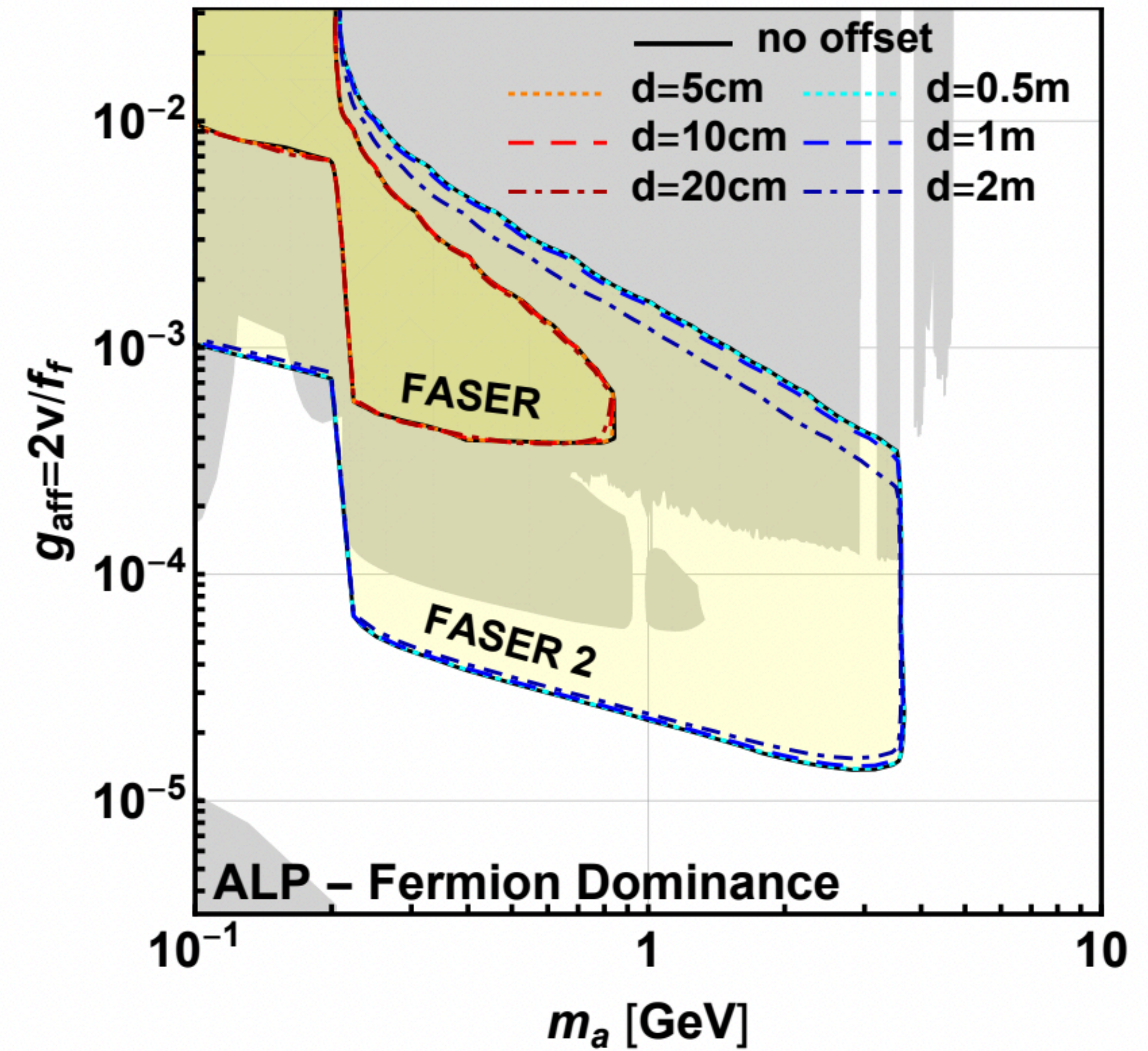
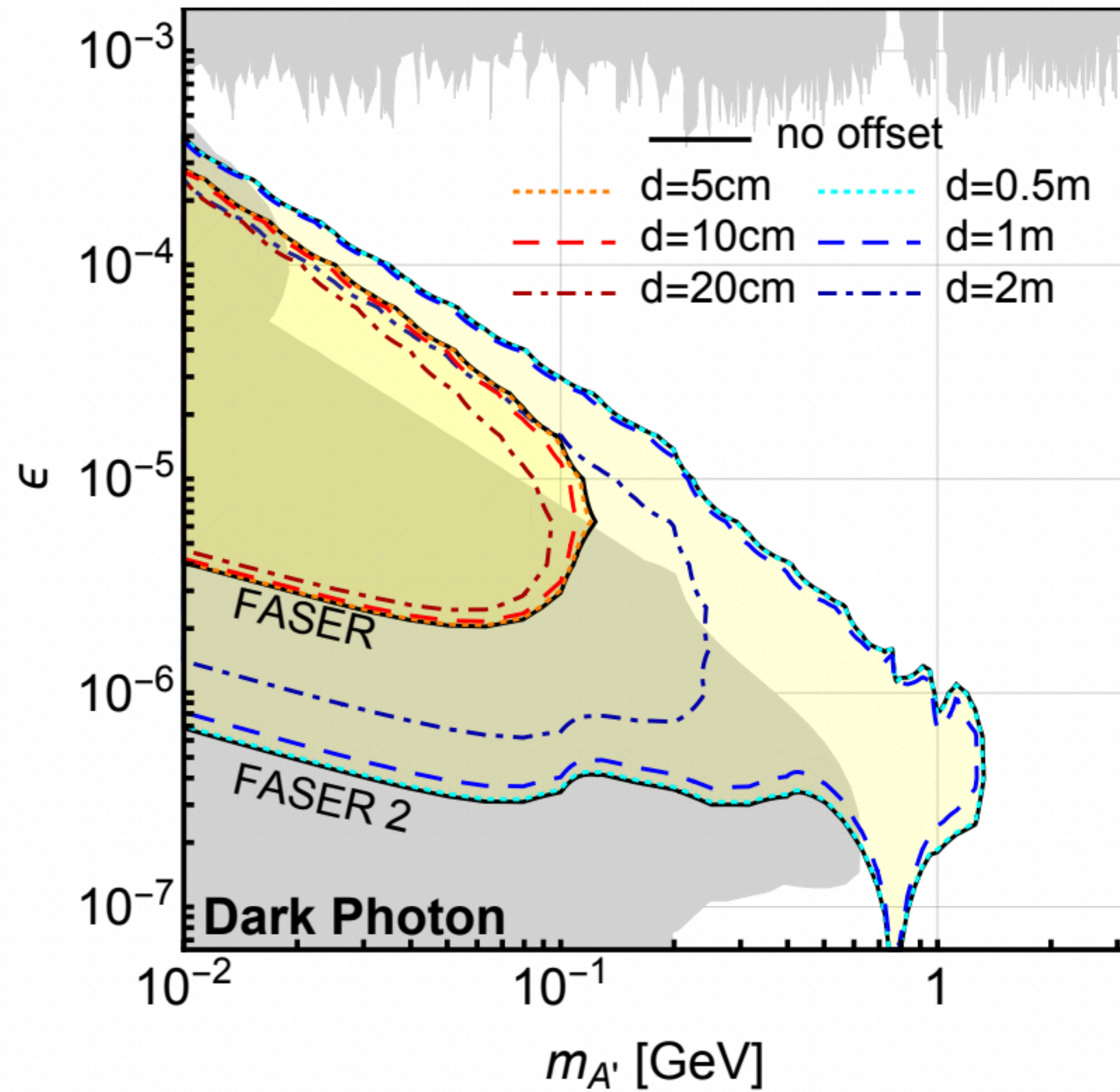
► Trench strengthening

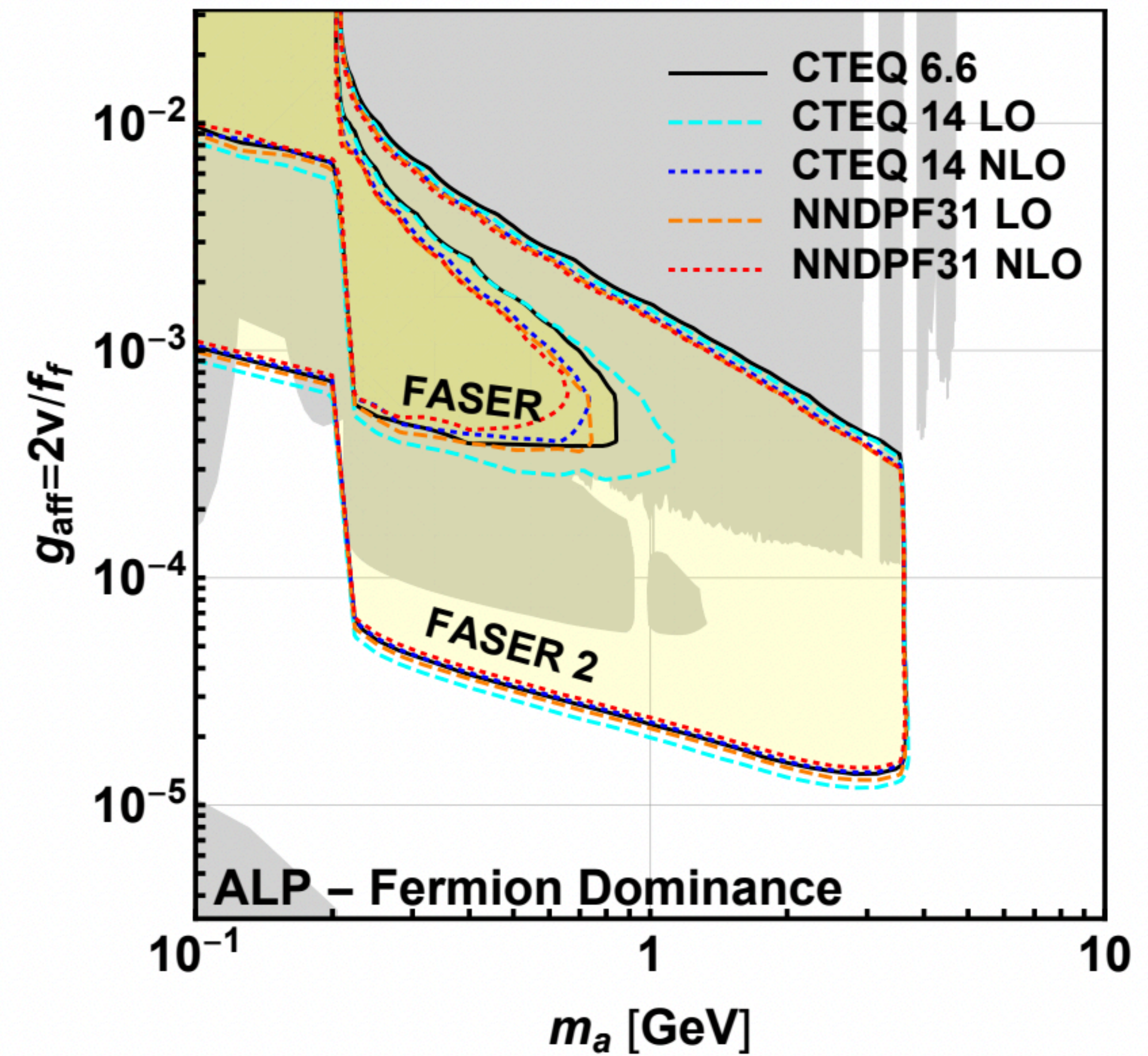
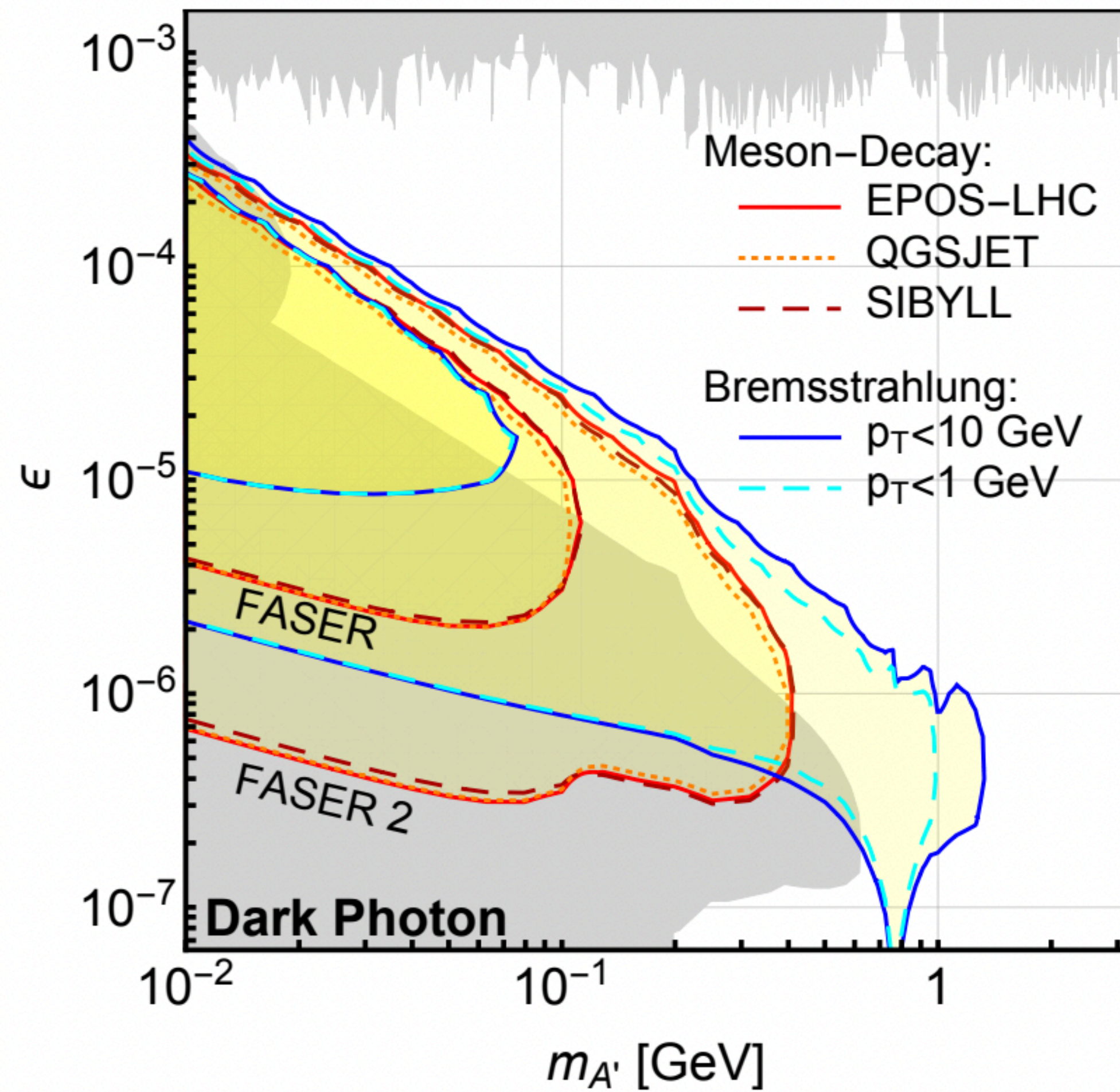
- Improved rock characteristics enabled removal of steel frame
- Less complex site works and better ground conditions enabled increased depth





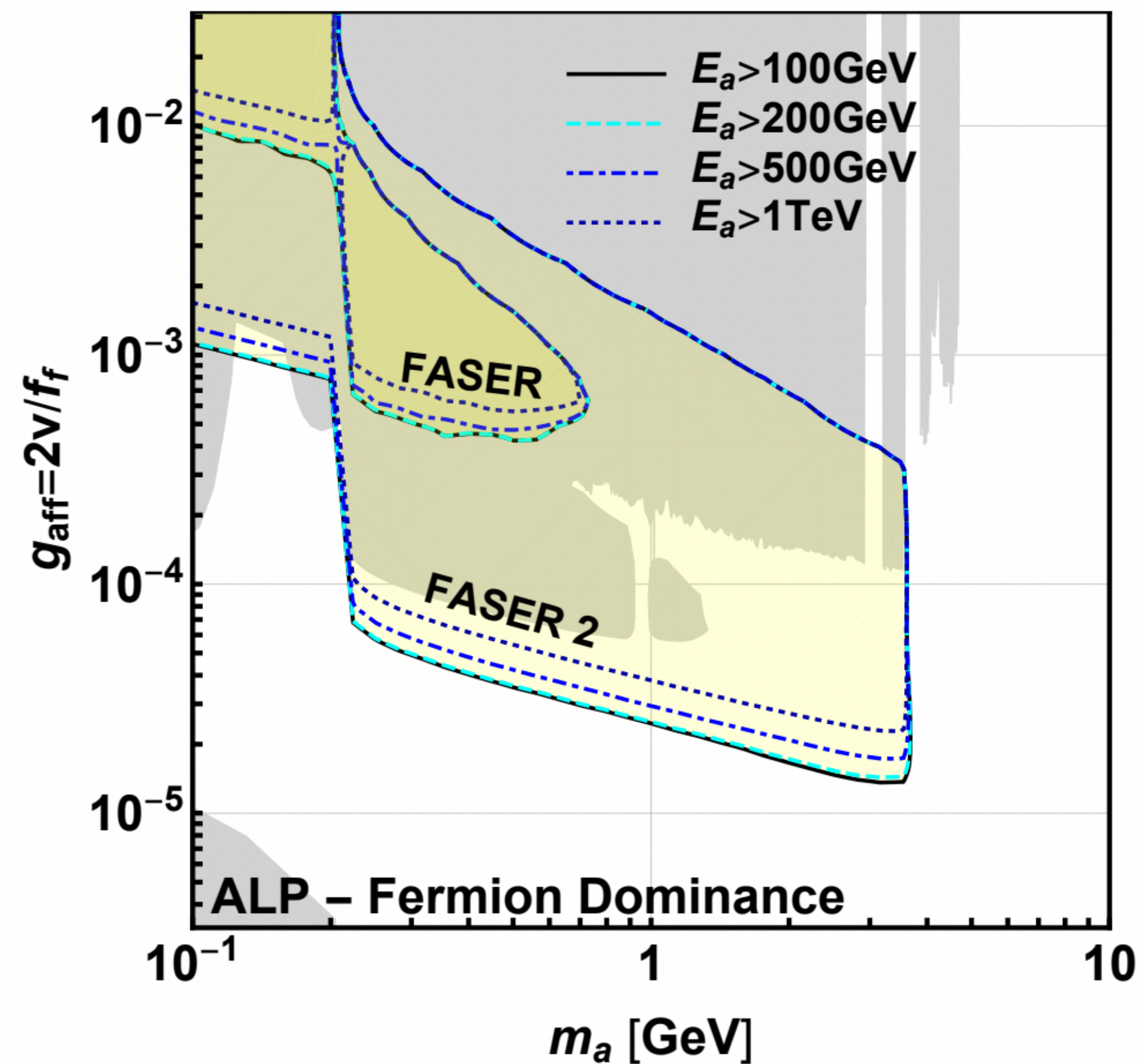
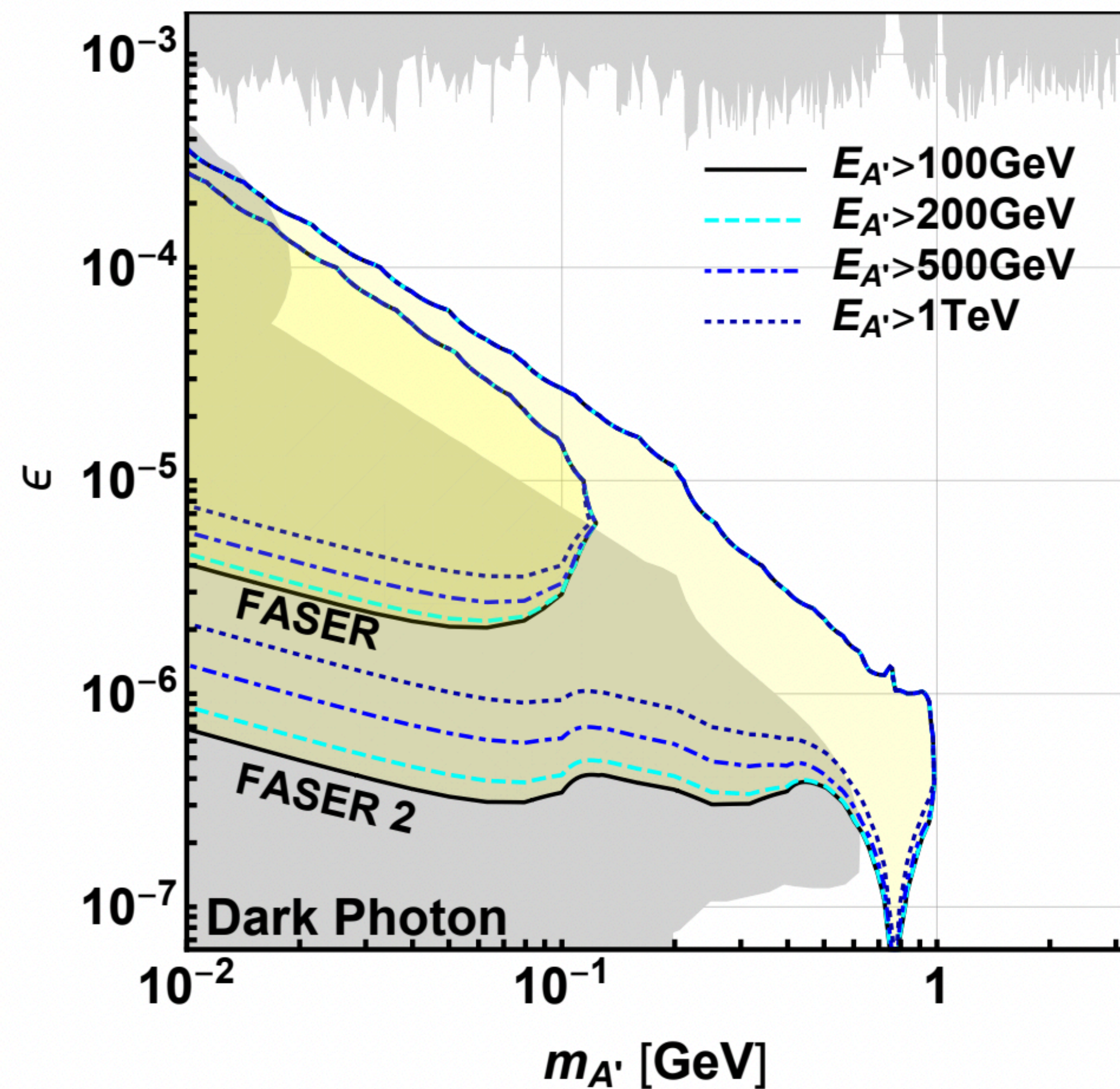
Beam offset



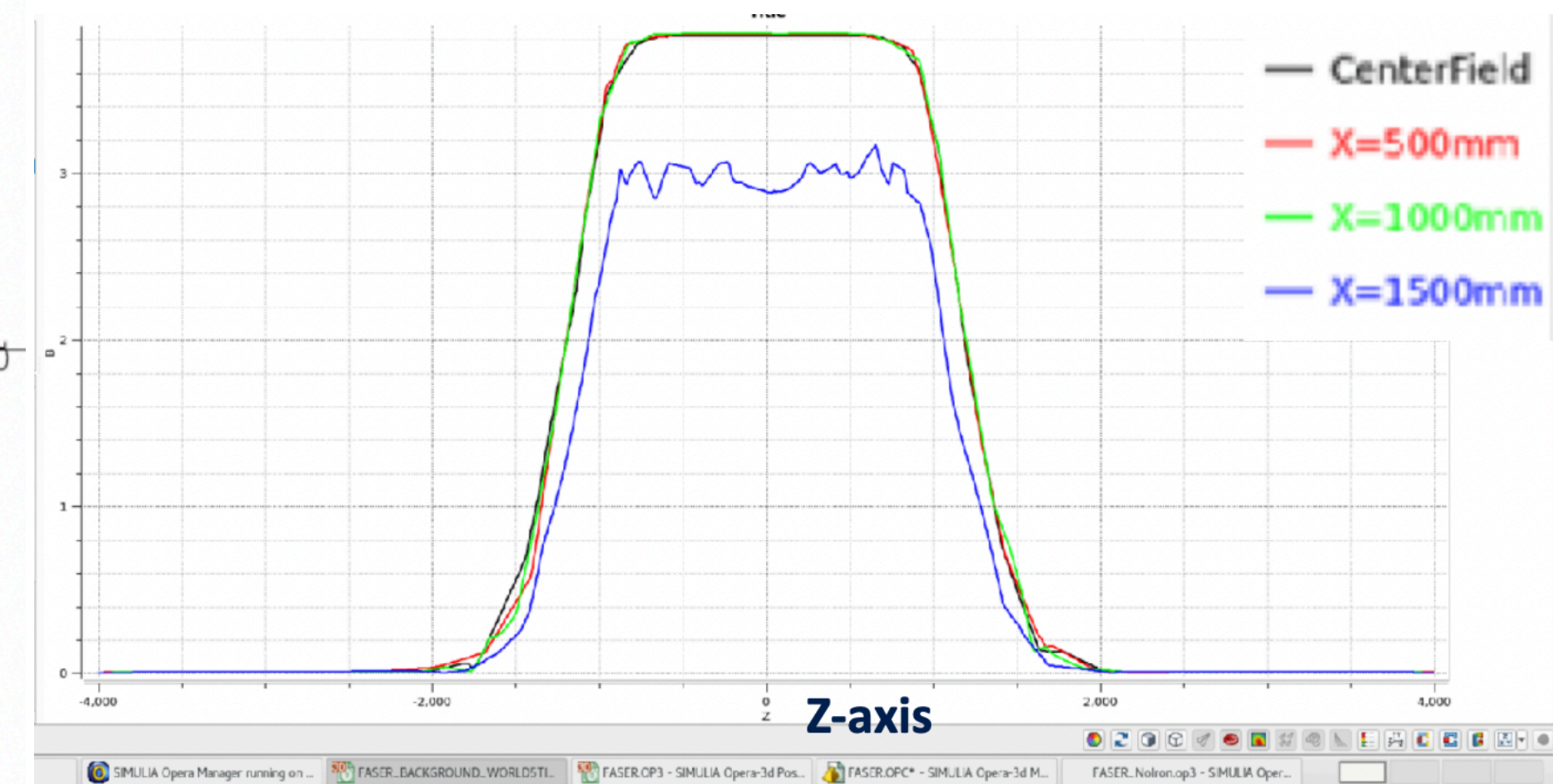
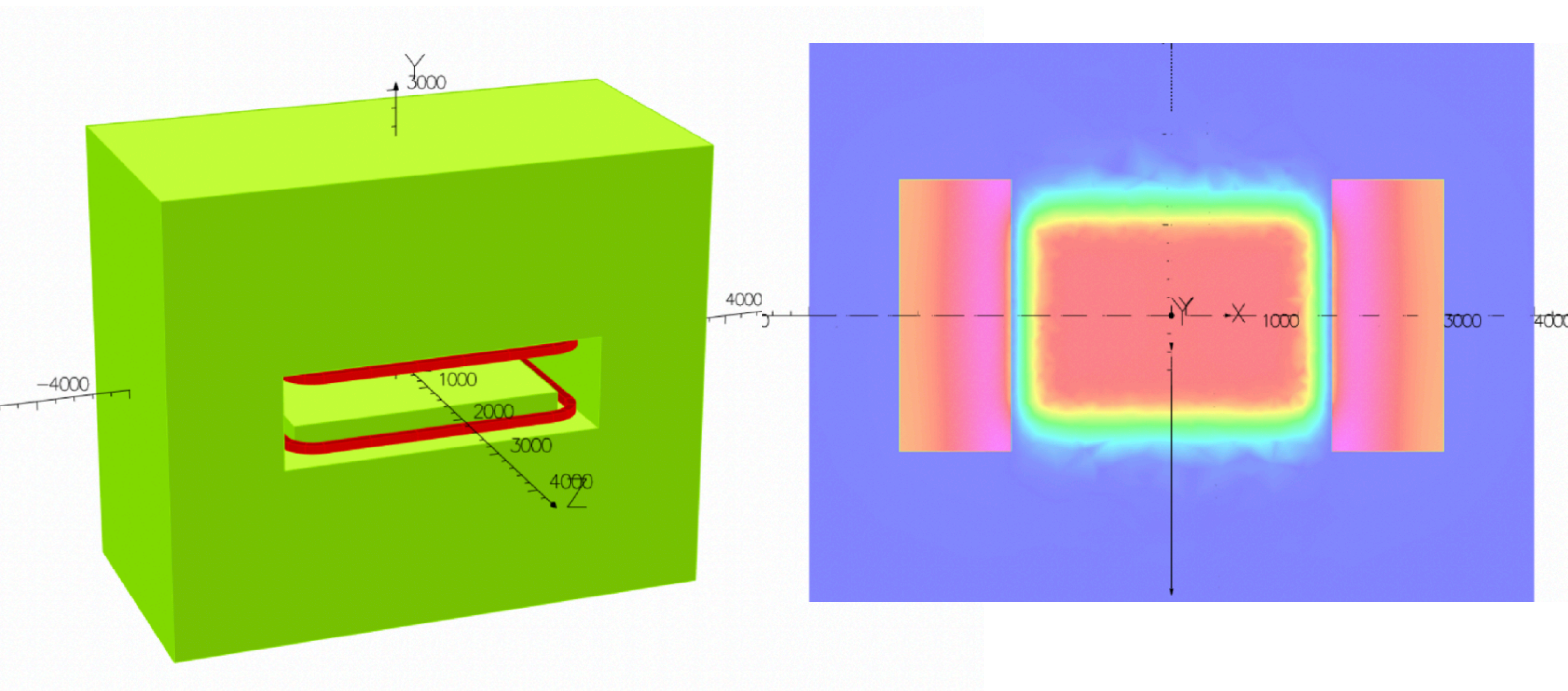




Energy threshold



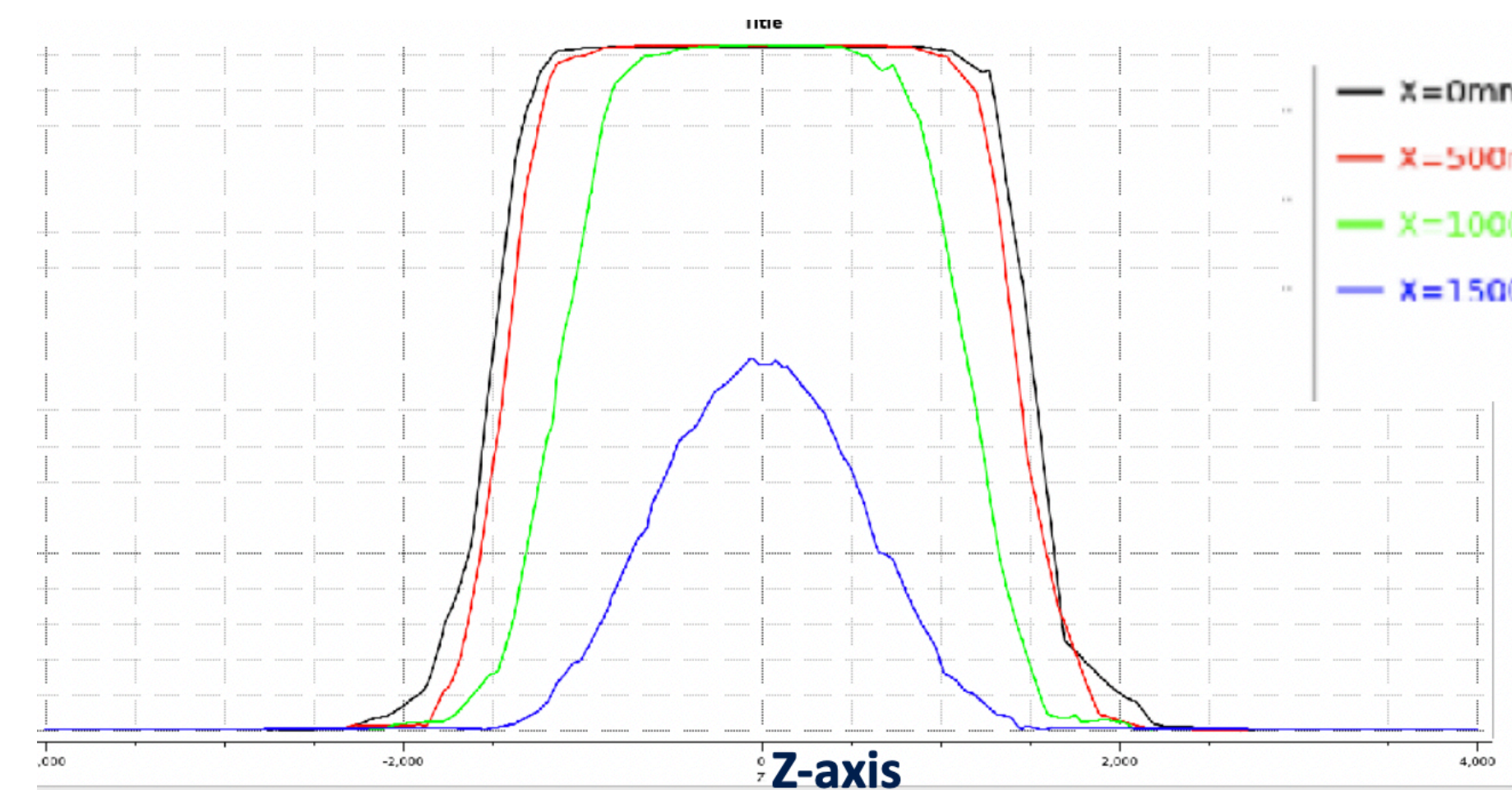
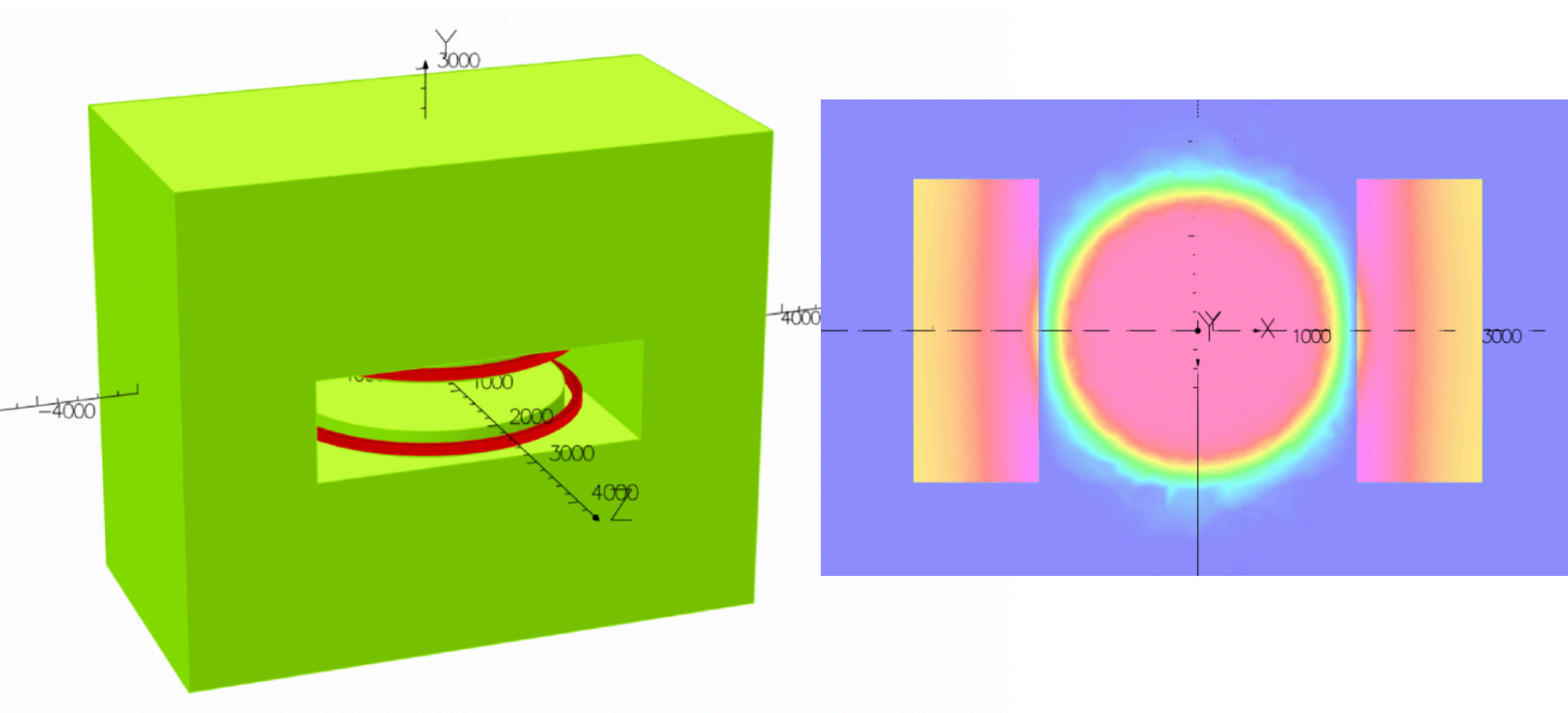
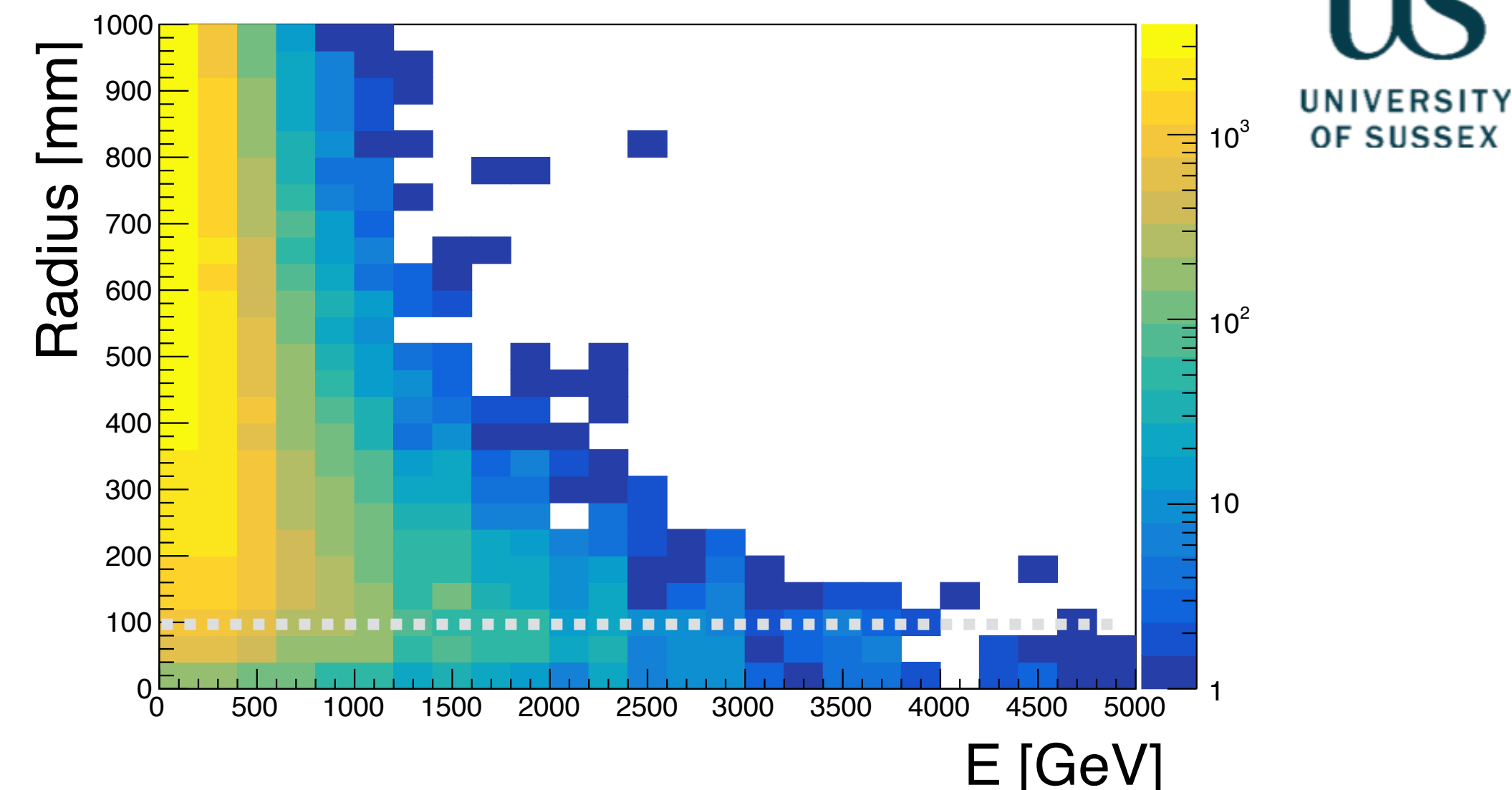
- ▶ Rectangular magnet 3 x 0.5 x 2m
- ▶ 2 T bending in horizontal direction



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



Hide Otono



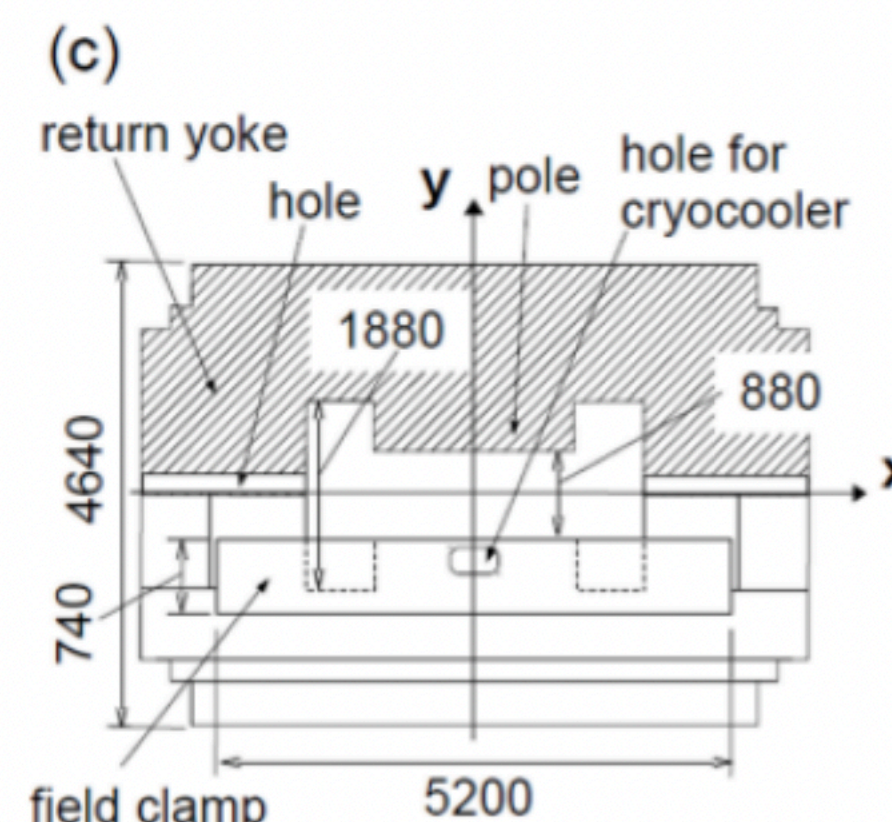
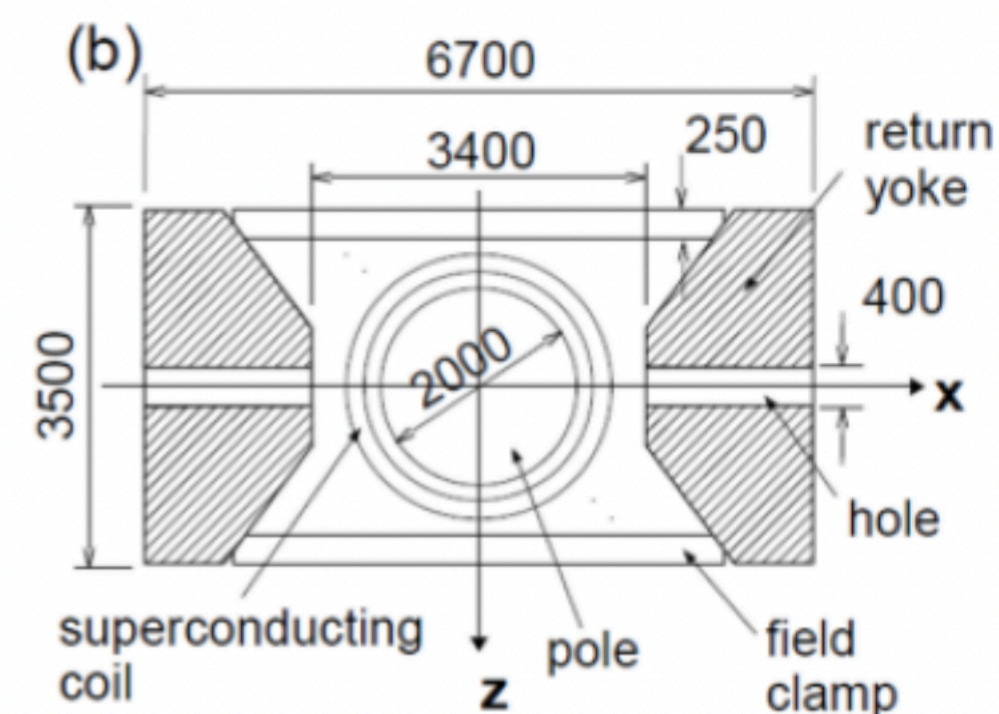
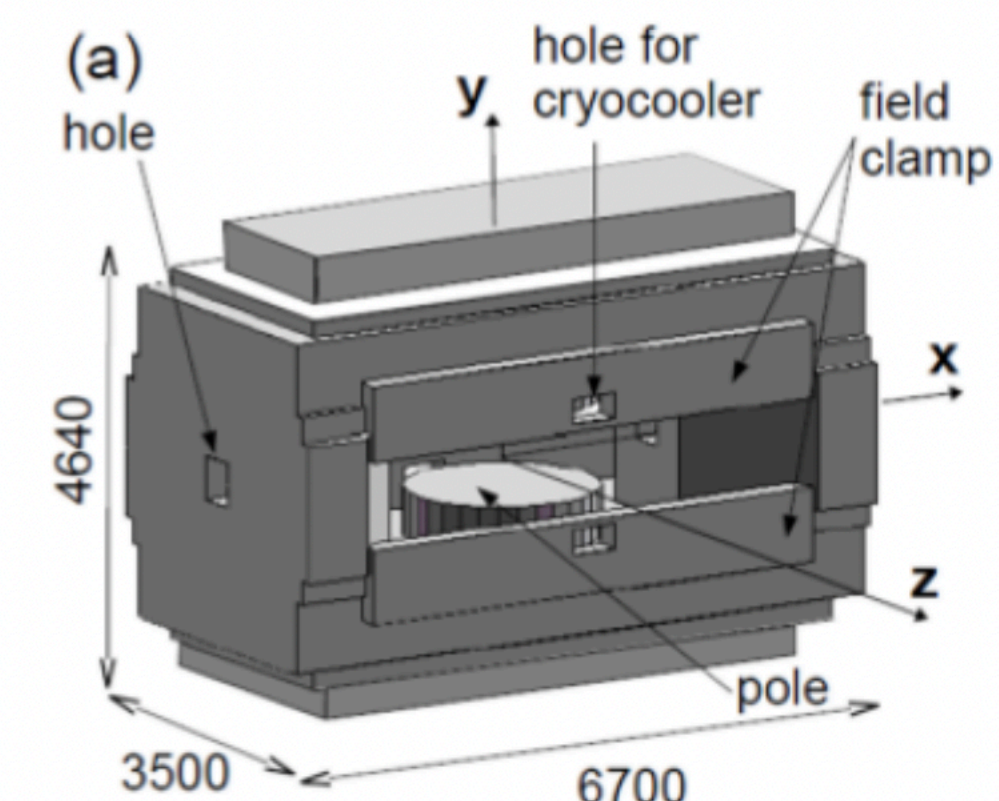
FASER2 | Magnet

Cost estimation from TOSHIBA

Roughly 10 MCHF

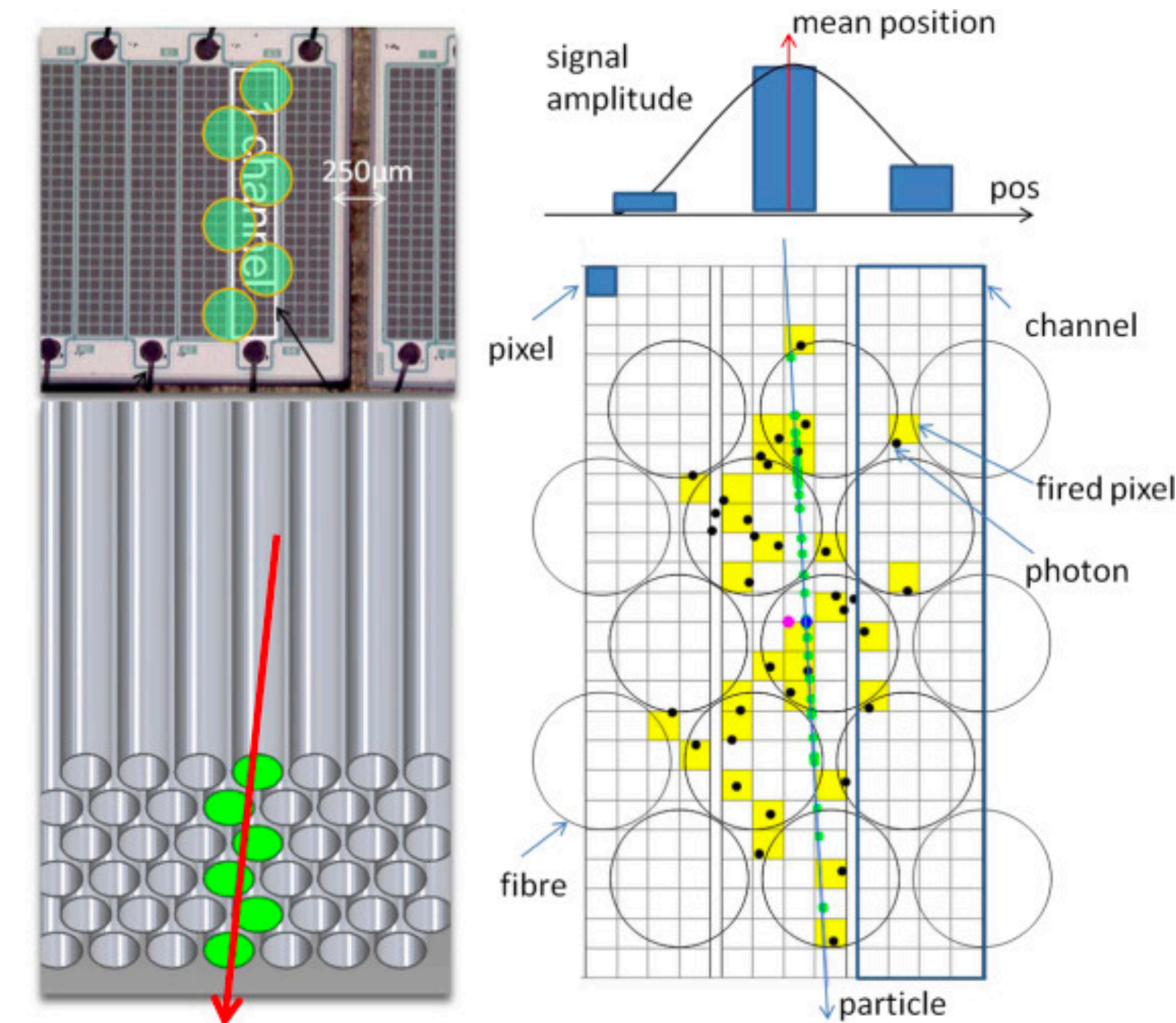
based on their experience on SAMURAI

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 (Superconducting Analyzer for Multi-particles from Radioisotope beams)
RI beam at RIKEN, Japan

- ▶ Based on SciFi detector installed in LHCb in LS2.
 - ▶ SiPM+scintillating fibre design
 - ▶ Fibres 250um diameter => 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.

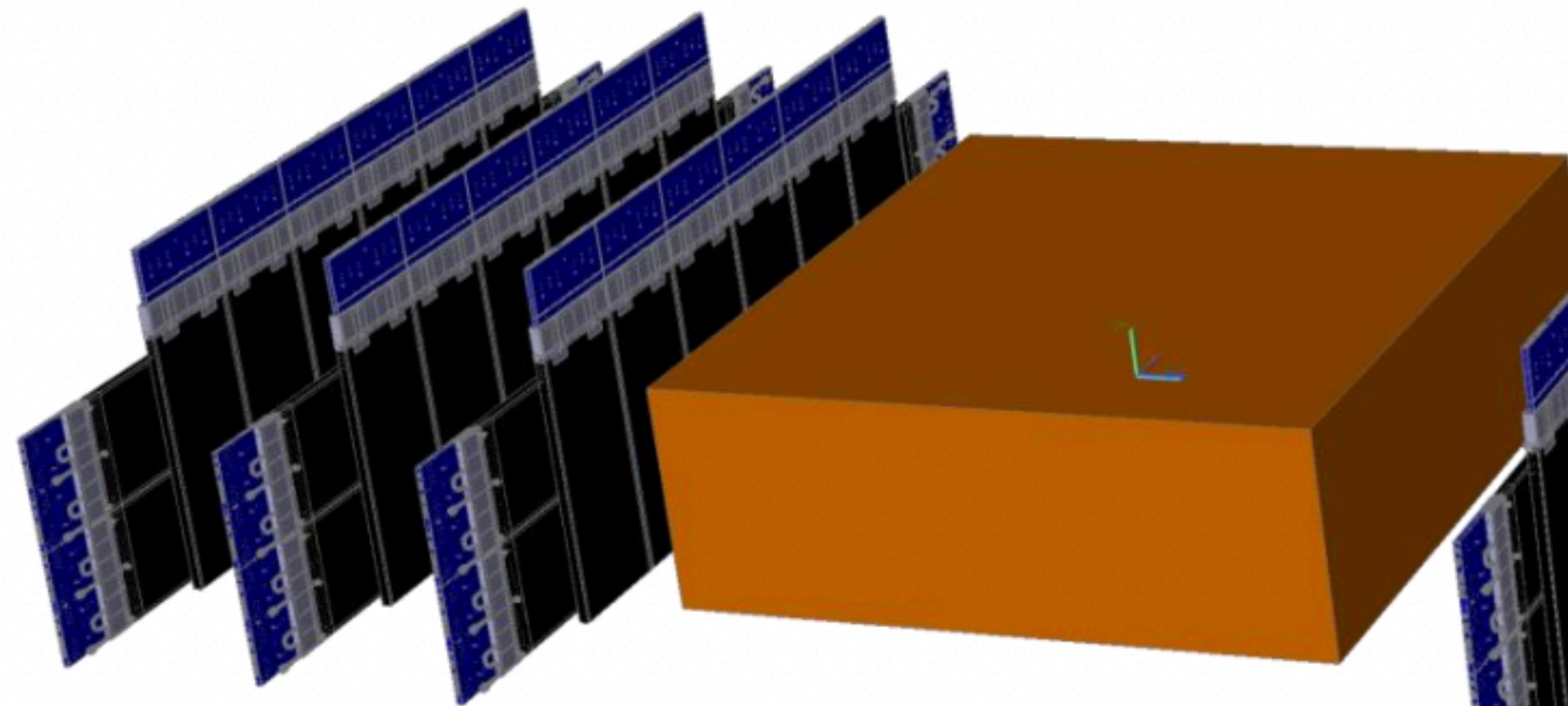




The upstream tracker

6 vertical + 2 horizontal modules makes up a station.

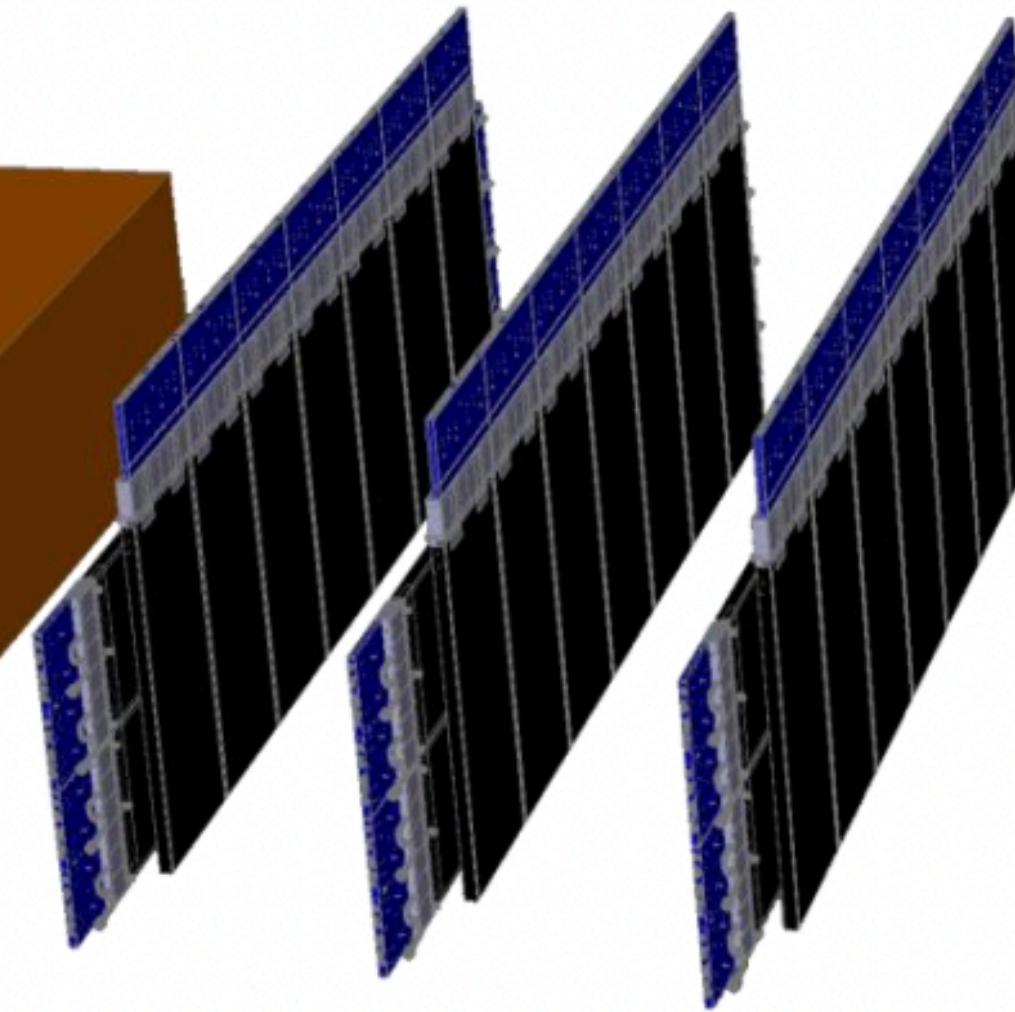
3 stations.



The downstream tracker

7 vertical + 2 horizontal modules makes up a station.

3 stations.

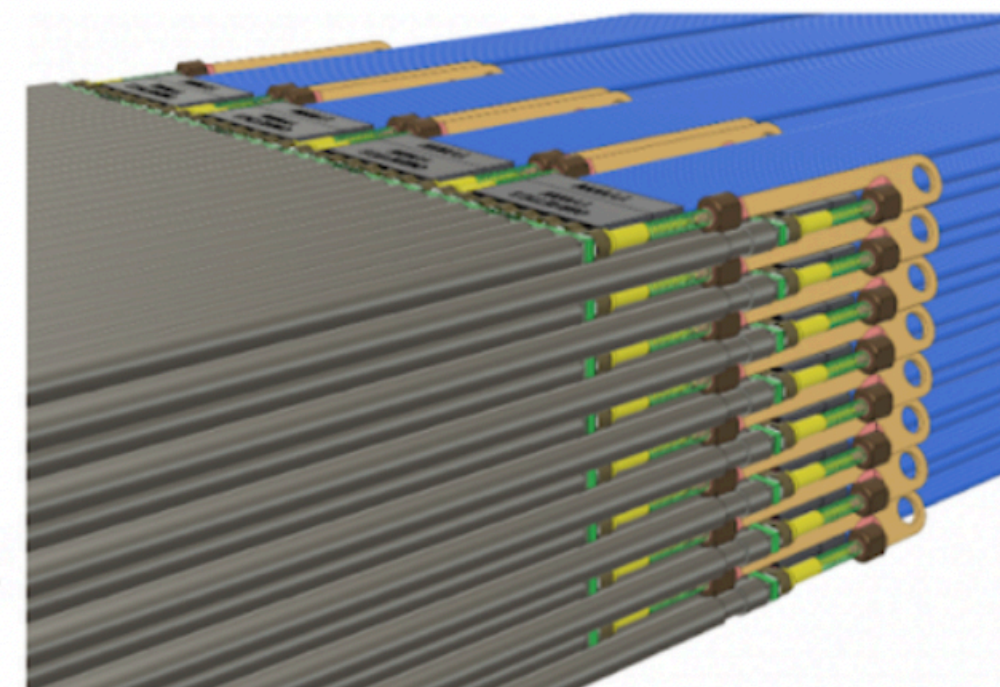
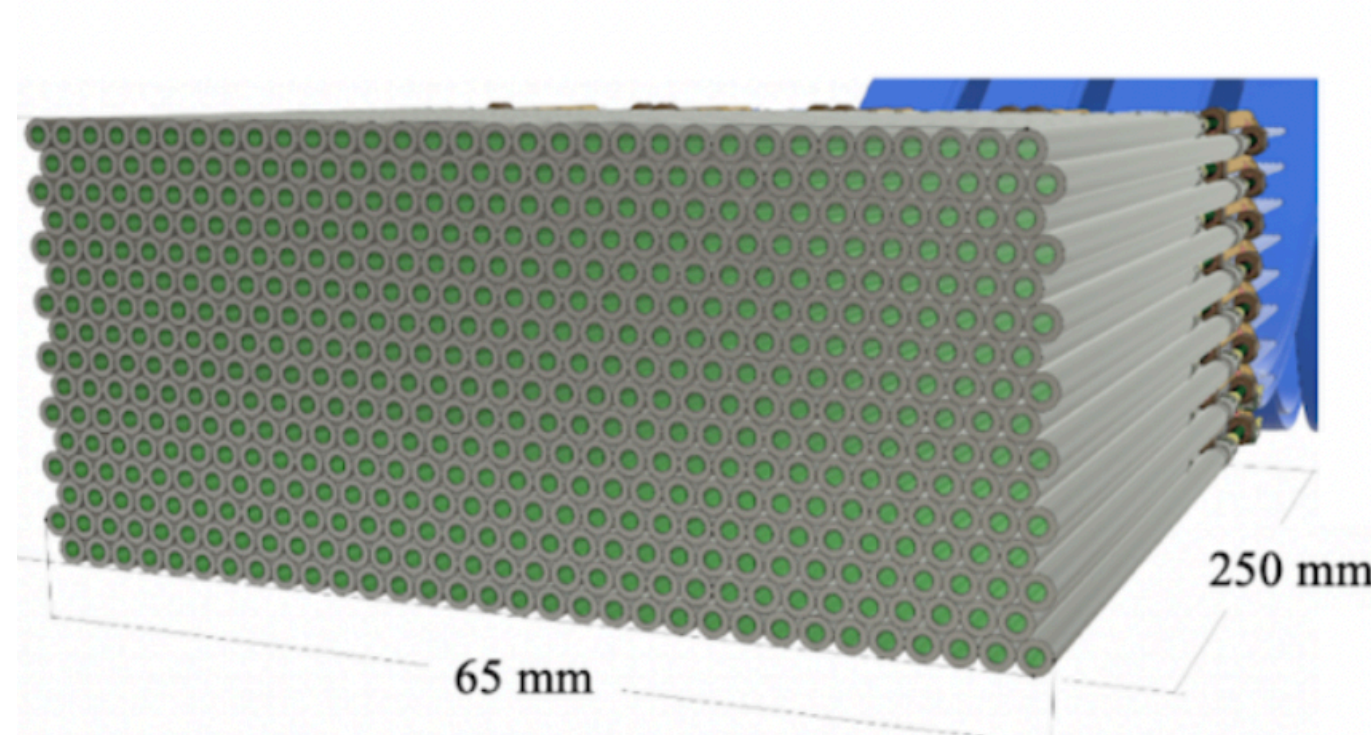
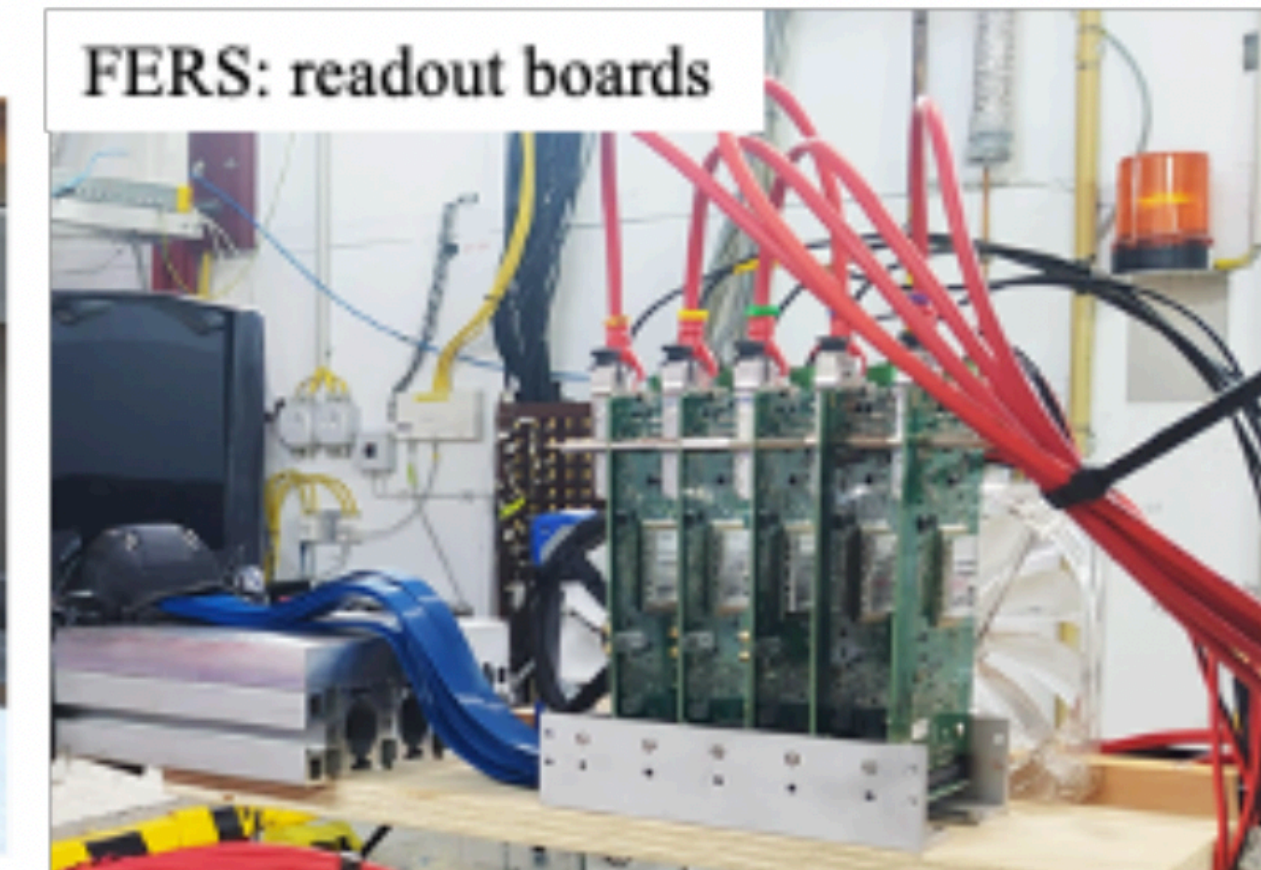
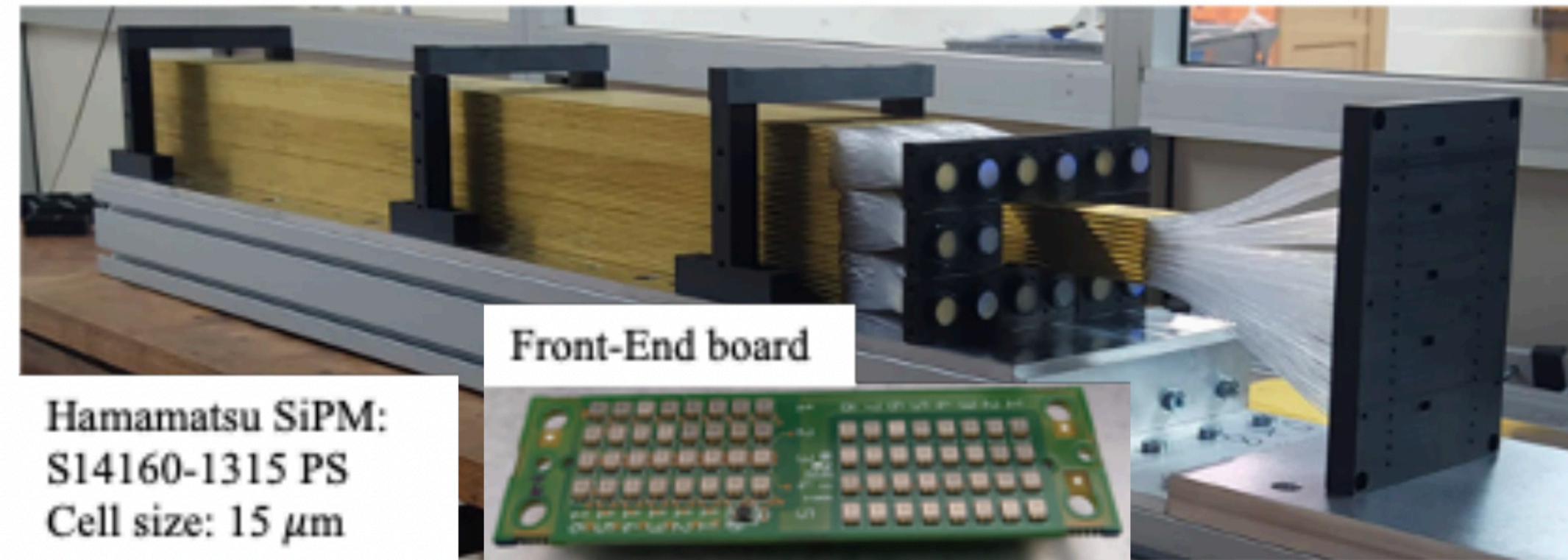
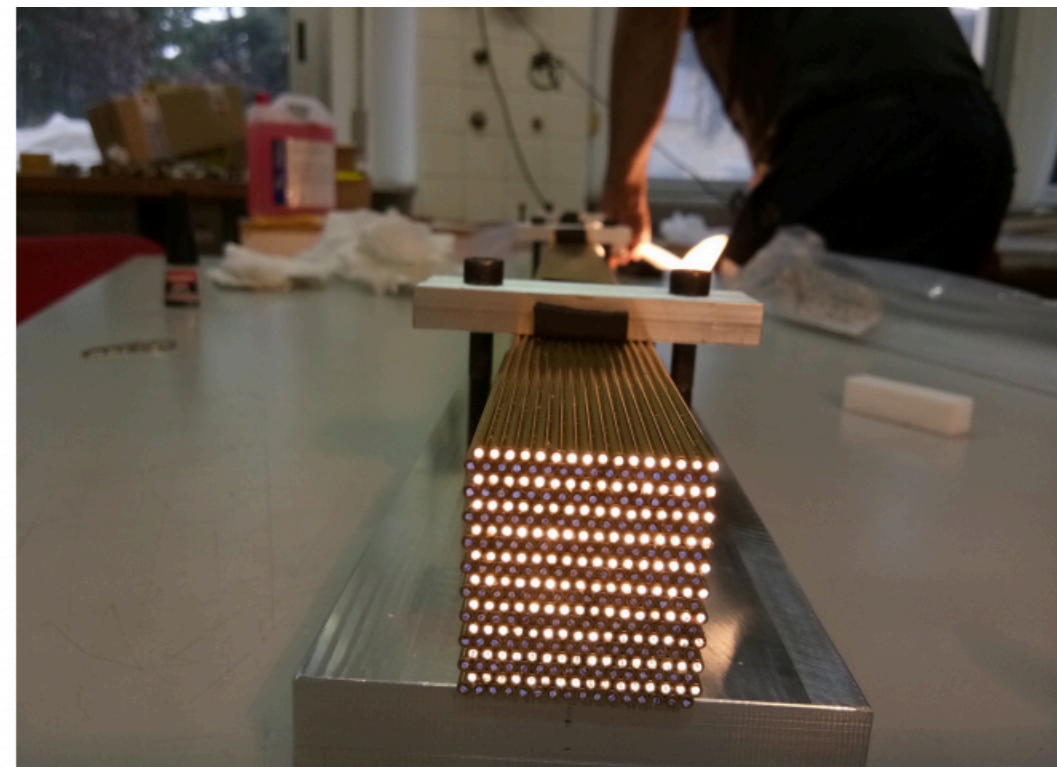


Sune Jakobsen

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

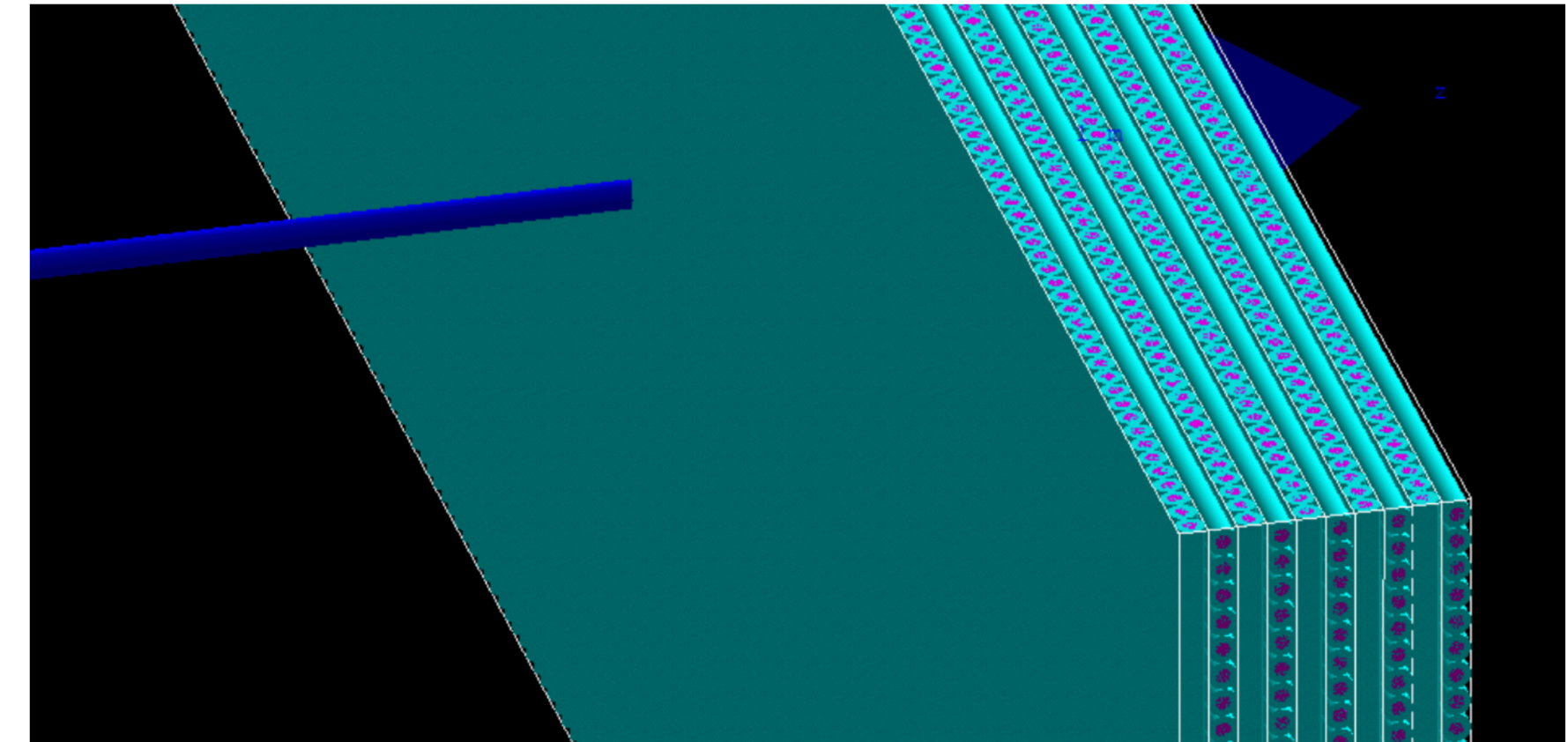
FASER2 | Dual-readout calorimeter

- ▶ 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

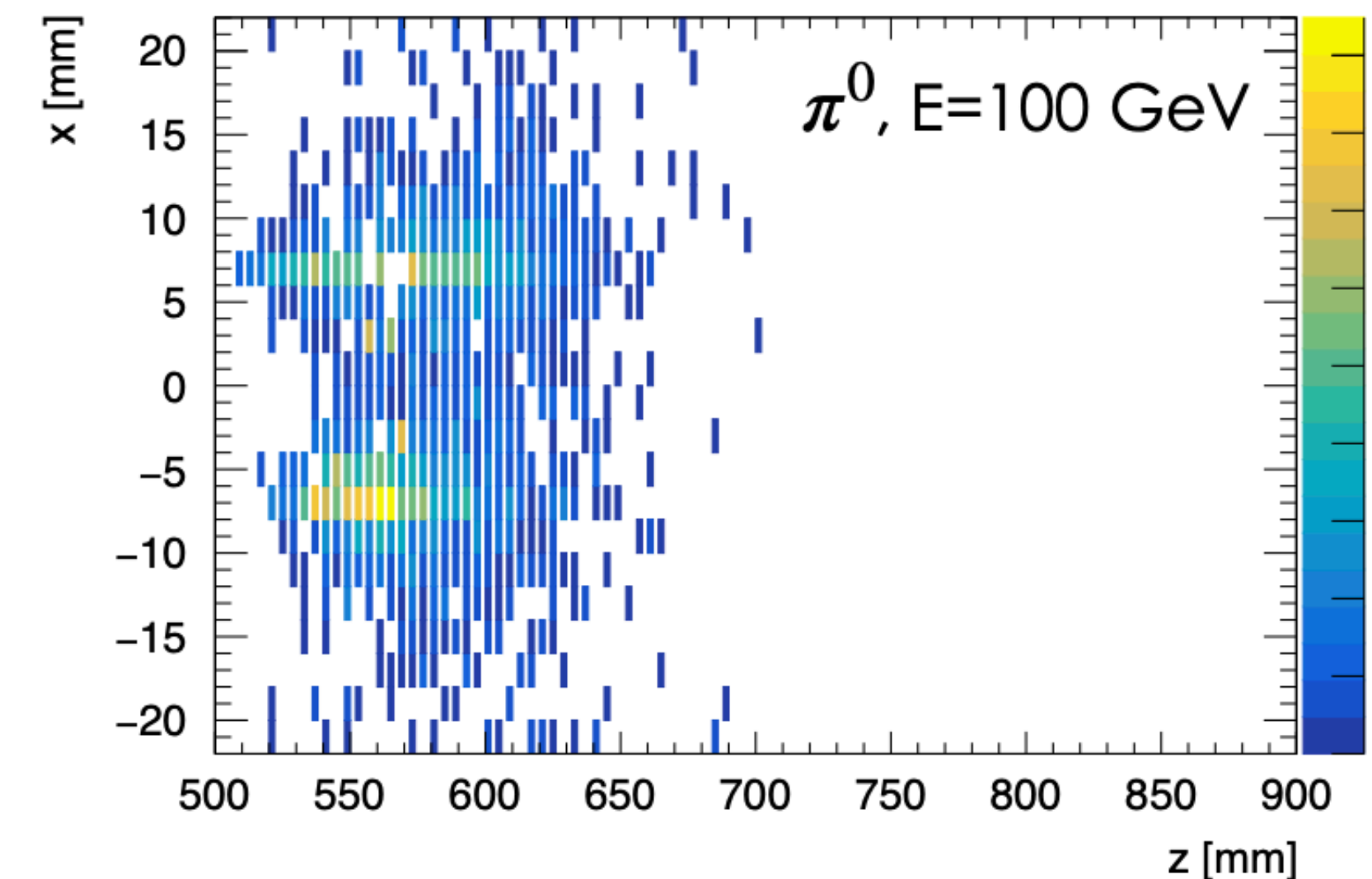
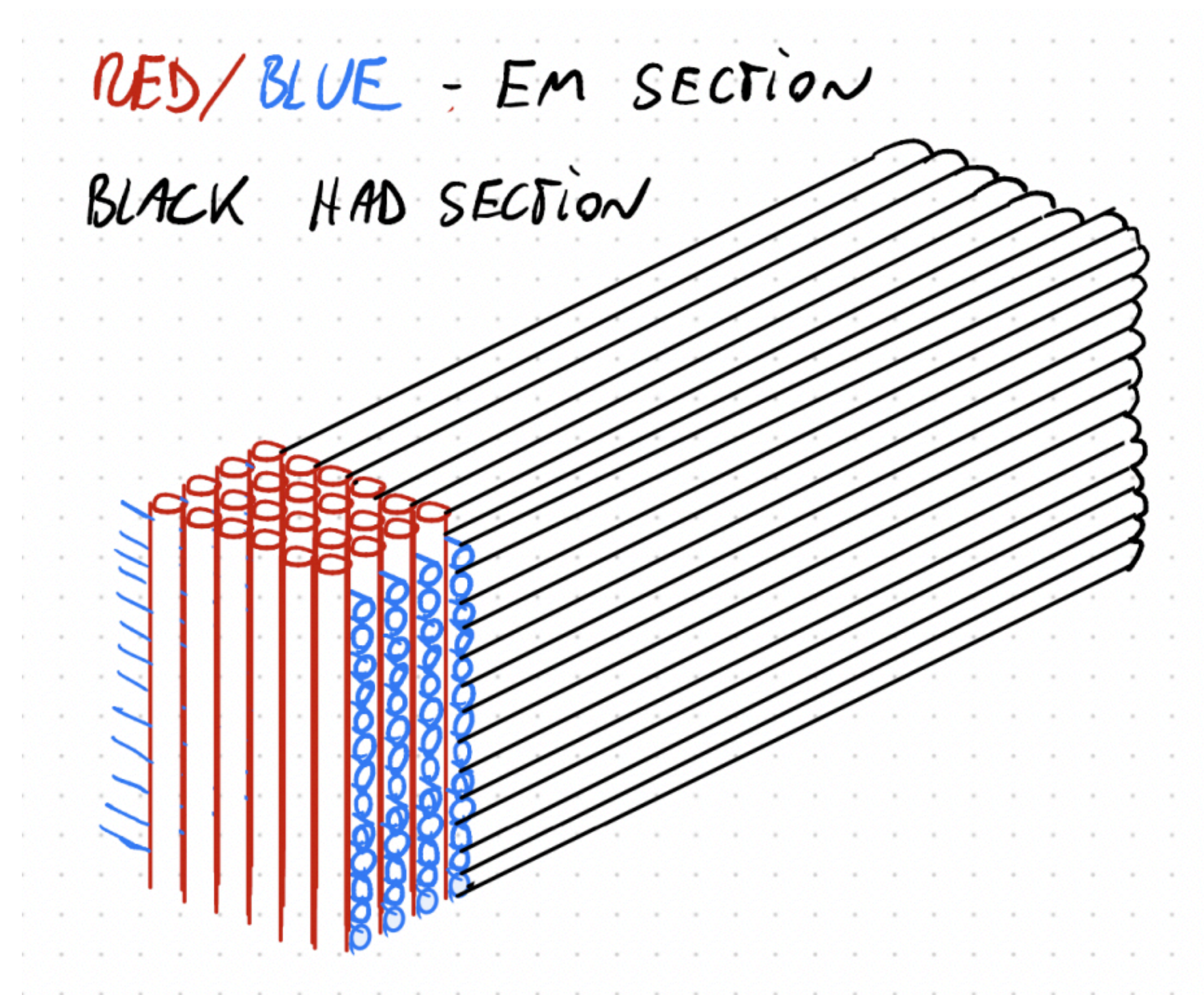


Iacopo Vivarelli

- ▶ 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

