LHC Searches for New Physics with Far Forward Detectors

Roshan Mammen Abraham*
UC Irvine
(On behalf of the FASER collaboration)

Dark Interactions 2024
Simon Fraser University Harbour Center
Oct 17th, 2024

*rmammena@uci.edu

Forward Region at the LHC

- The importance of the forward direction at the LHC was recognized as early as 1984.

NEUTRINO AND MUON PHYSICS IN THE COLLIDER MODE OF FUTURE ACCELERATORS*)

A. De Rújula and R. Rückl

CERN, Geneva, Switzerland

ABSTRACT

Extracted beams and fixed target facilities at future colliders (the SSC and the LHC) may be (respectively) impaired by economic and "ecological" considerations. Neutrino and muon physics in the multi-TeV range would appear not to be an option for these machines. We partially reverse this conclusion by estimating the characteristics of the "prompt" ν_μ, ν_e, ν_τ and μ beams necessarily produced (for free) at the pp or $\bar{p}p$ intersections. The neutrino beams from a high luminosity (pp) collider are not much less intense than the neutrino beam from the collider's dump, but require no muon shielding. The muon beams from the same intersections are intense and energetic enough to study μp and μN interactions with considerable statistics and a Q^2-coverage well beyond the presently available one. The physics program allowed by these lepton beams is a strong advocate of machines with the highest possible luminosity: pp (not $\bar{p}p$) colliders.

Forward Region at the LHC

FASER: ForwArd Search ExpeRiment at the LHC

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

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

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

Abstract

New physics has traditionally been expected in the high-p_T region at high-energy collider experiments. If new particles are light and weakly-coupled, however, this focus may be completely misguided: light particles are typically highly concentrated within a few mrad of the beam line, allowing sensitive searches with small detectors, and even extremely weakly-coupled particles may be produced in large numbers there. We propose a new experiment, **F**orw**A**rd **S**earch **E**xpe**R**iment, or FASER, which would be placed downstream of the ATLAS or CMS interaction point (IP) in the very forward region and operated concurrently there. Two representative on-axis locations are studied: a far location, 400 m from the IP and just off the beam tunnel, and a near location, just 150 m from the IP and right behind the TAN neutral particle absorber. For each location, we examine leading neutrino- and beam-induced backgrounds. As a concrete example of light, weakly-coupled particles, we consider dark photons produced through light meson decay and proton bremsstrahlung. We find that even a relatively small and inexpensive cylindrical detector, with a radius of ~ 10 cm and length of $5-10$ m, depending on the location, can discover dark photons in a large and unprobed region of parameter space with dark photon mass $m_{A'} \sim 10$ MeV $-$ 1 GeV and kinetic mixing parameter $\epsilon \sim 10^{-7} - 10^{-3}$. FASER will clearly also be sensitive to many other forms of new physics. We conclude with a discussion of topics for further study that will be essential for understanding FASER's feasibility, optimizing its design, and realizing its discovery potential.

More than 30 years later this idea was resurrected as FASER, ForwArd Search ExpeRiment at the LHC .

Jonathan L. Feng, Iftah Galon, Felix Kling, Sebastian Trojanowski; 1708.09389

FORWARD SEARCH EXPERIMENT AT THE LHC

- **Idea in 2017, experiment proposed in 2018.**
- **Detector installed in 2021 and taking data during Run3.**
- **FASER is small compact experiment, leveraging LHC infrastructure and producing fantastic physics results quickly.**

Jonathan L. Feng, Iftah Galon, Felix Kling, Sebastian Trojanowski; 1708.09389 → 4 authors, 2 institutes

LOI: 1811.10243 → 14 authors, 8 institutes

Technical Proposal: 1812.09139

FASER COLLABORATION

111 collaborators, 28 institutions, 11 countries

CERN

UNIVERSITÉ DE GENÈVE

KYUSHU UNIVERSITY

UC IRVINE

u^b UNIVERSITÄT BERN

Technion Israel Institute of Technology

NAGOYA UNIVERSITY

UNIVERSITY of WASHINGTON

JOHANNES GUTENBERG UNIVERSITÄT MAINZ JG|U

מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE

CHIBA UNIVERSITY

UNIVERSITY OF OREGON

DESY.

INFN

ISS

International laboratory covered by a cooperation agreement with CERN

清華大学 Tsinghua University

ROYAL HOLLOWAY UNIVERSITY OF LONDON

UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

UNIVERSITY OF LIVERPOOL

ZHENGZHOU UNIVERSITY

NATIONAL INSTITUTE OF TECHNOLOGY (KOSEN), NIIHAMA COLLEGE

US UNIVERSITY OF SUSSEX

Nikhef

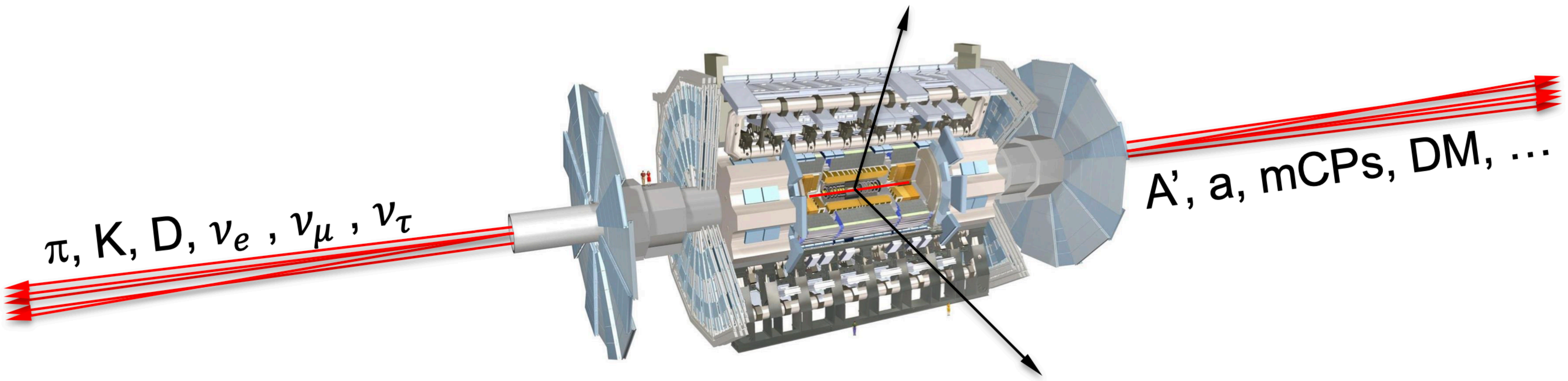
UNIVERSITÄT BONN

ETH zürich

UKRI Science and Technology Facilities Council Rutherford Appleton Laboratory

MANCHESTER 1824 The University of Manchester

Forward Region at the LHC



- pp collisions at the LHC produce an intense flux of particles in the forward direction
- These particles are light and weakly coupling:
  - SM (ν, μ, …) and BSM (ALPs, dark photon, DM, …)
- Conventional transverse detectors will miss these particles

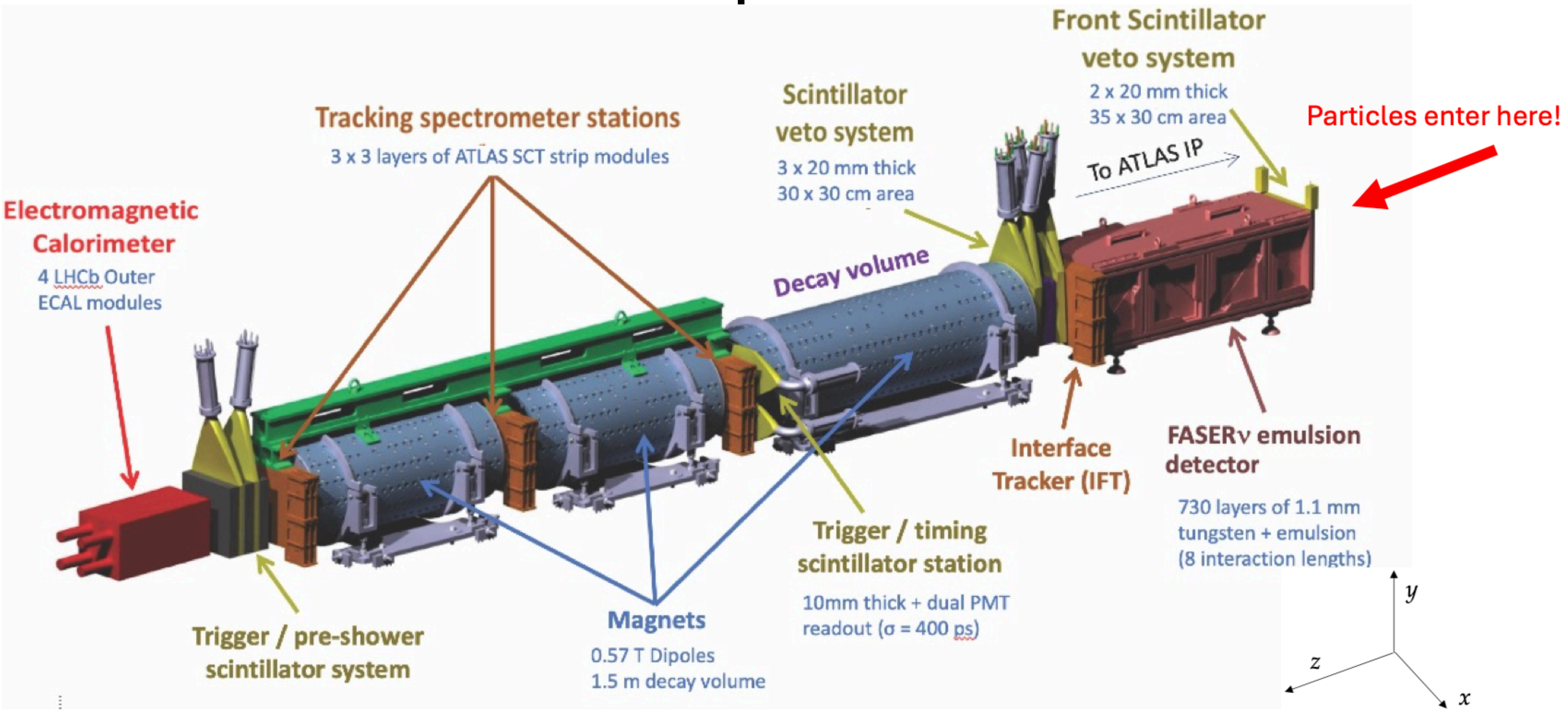
Jonathan L. Feng, Iftah Galon, Felix Kling, Sebastian Trojanowski; 1708.09389

ForwArd Search ExpeRiment(ν) - FASER(ν)

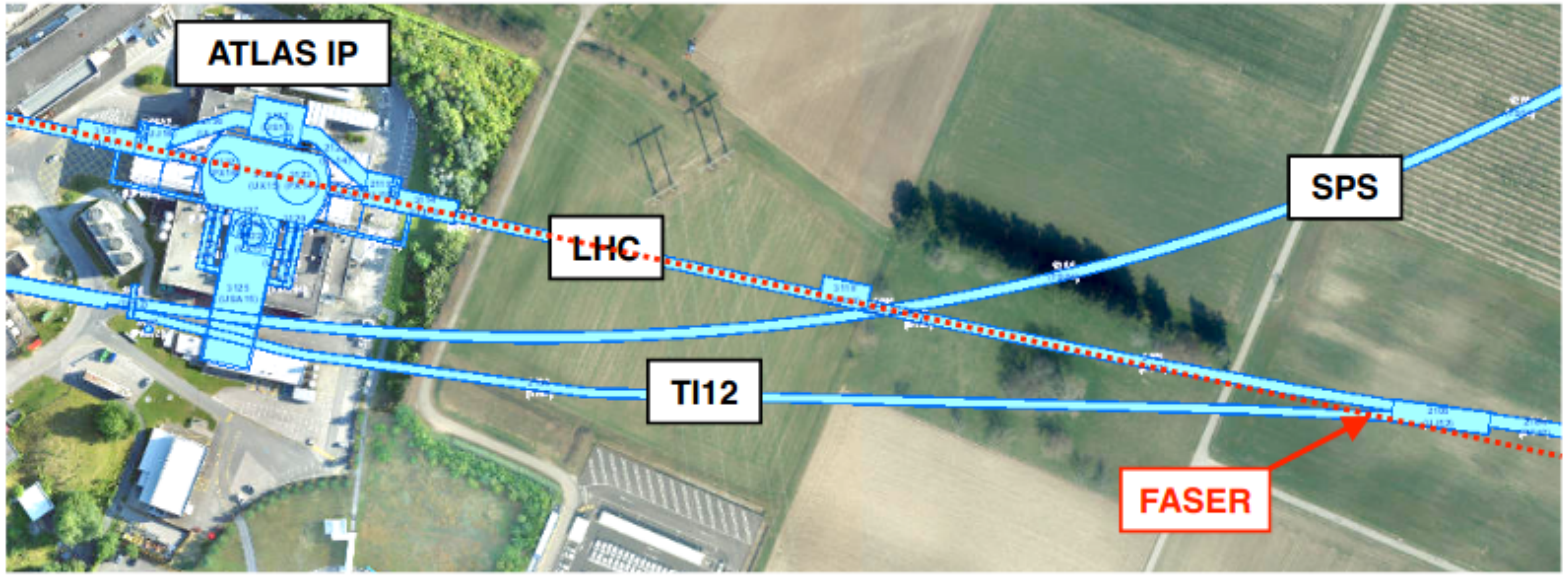
- **FASER: 25cm x 25cm x 1.5m decay volume.**
- **FASERν: 25cm x 30cm x 1m tungsten emulsion detector.**
- **Located 480m downstream of ATLAS interaction point.**

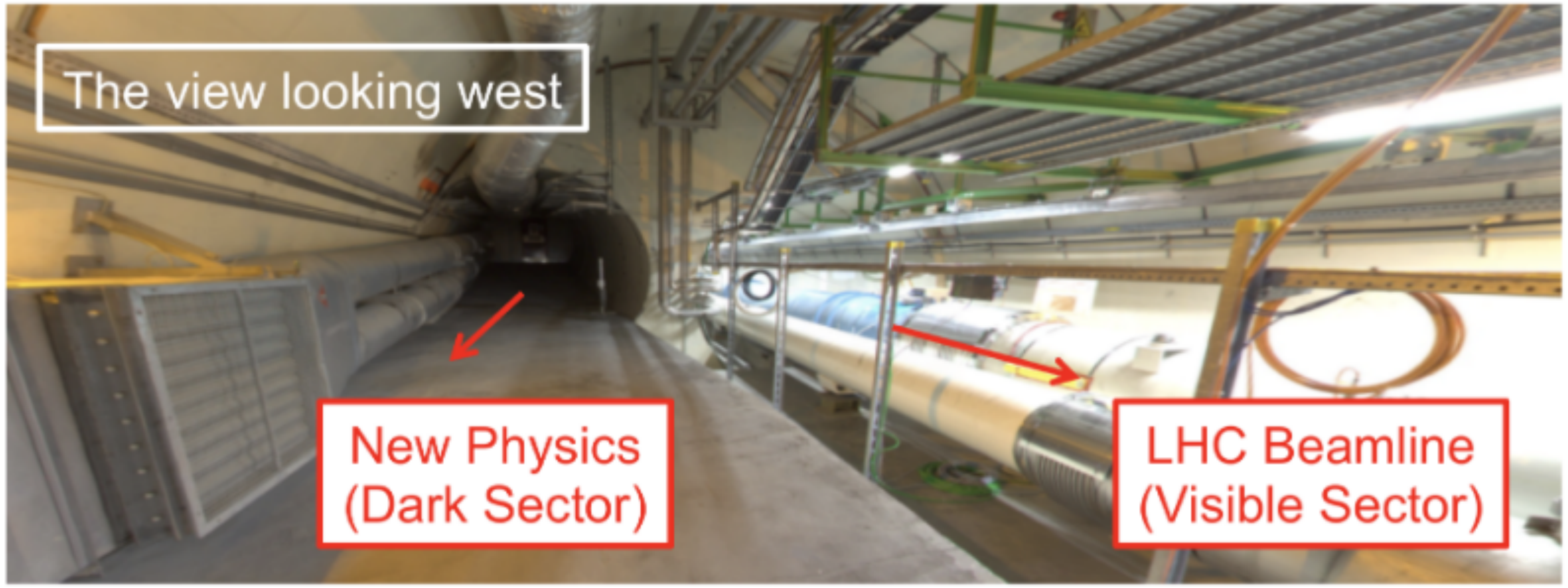
FASERν: 1908.02310, 2001.03073

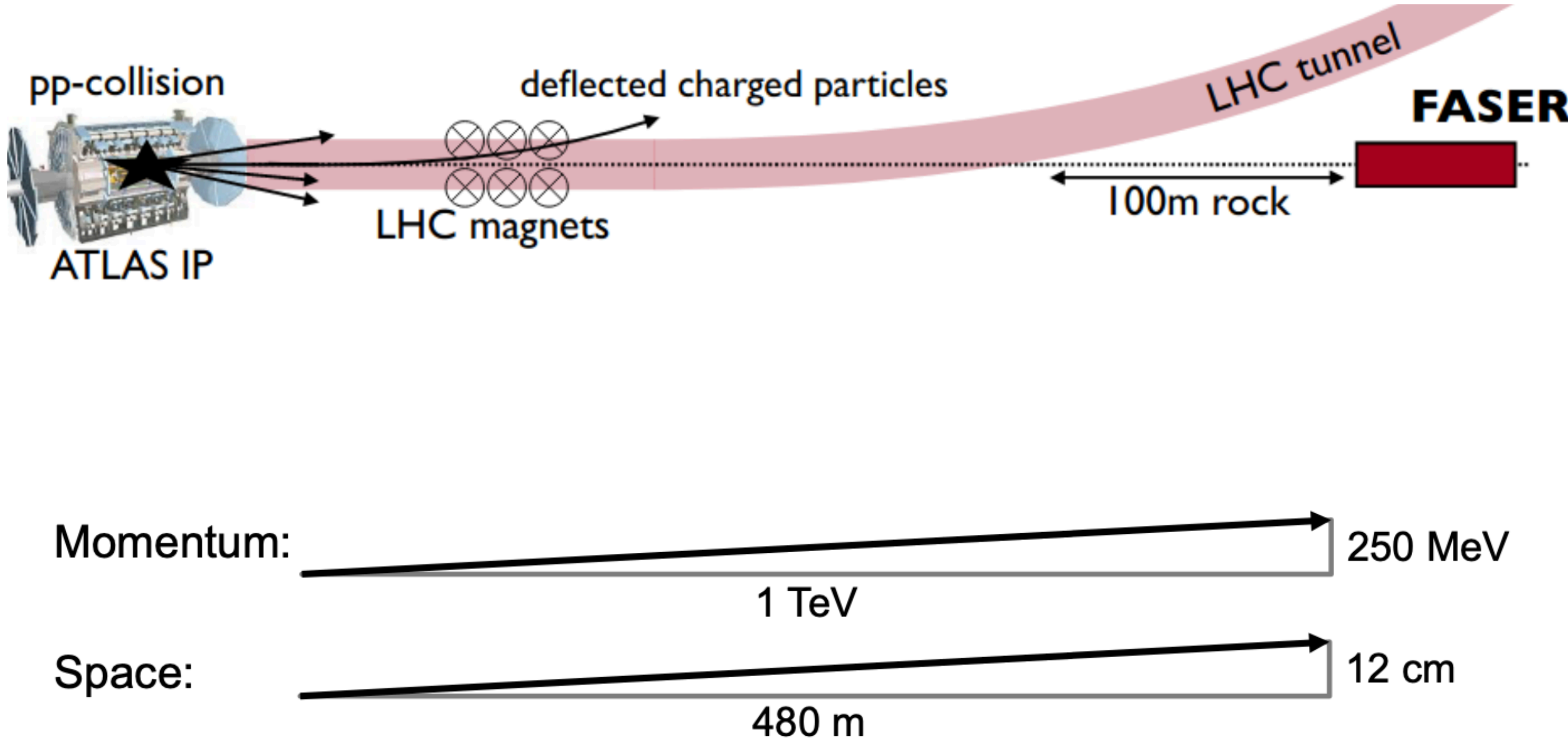
Detector paper: 2207.11427



Location of FASER at LHC







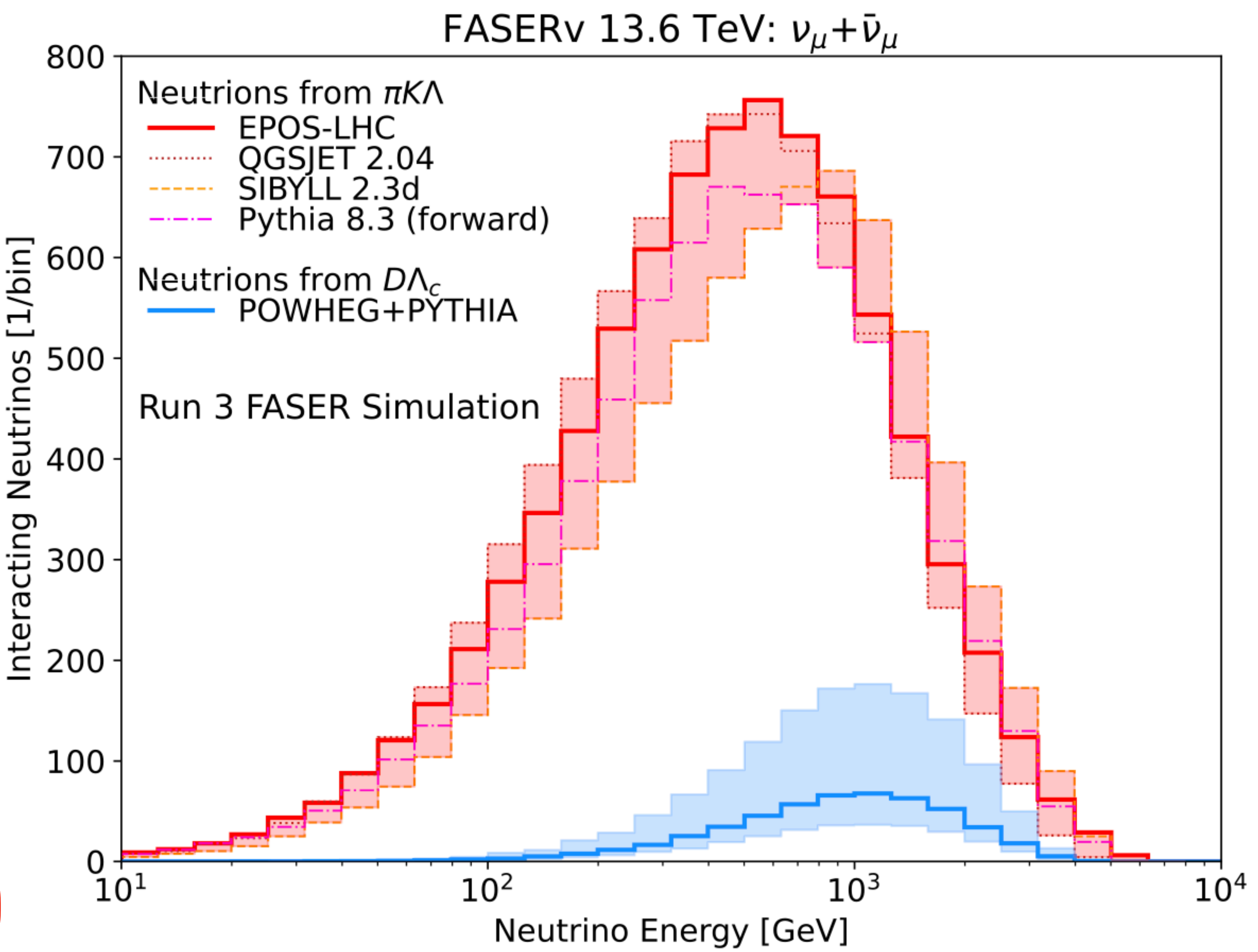
Neutrino Flux at FASER

ν_e: $K \longrightarrow \pi e \nu_e$, $D \longrightarrow K e \nu_e$

ν_μ: $\pi^\pm \longrightarrow \mu\nu_\mu$, $K^\pm \longrightarrow \mu\nu_\mu$

Generators		FASERν at Run 3			FASERν at Run 4		
light hadrons	charm hadrons	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
EPOS-LHC	–	1149	7996	–	3382	23054	–
SIBYLL 2.3d	–	1126	7261	–	3404	21532	–
QGSJET 2.04	–	1181	8126	–	3379	22501	–
PYTHIAforward	–	1008	7418	–	2925	20508	–
–	POWHEG Max	1405	1373	76	4264	4068	255
–	POWHEG	527	511	28	1537	1499	91
–	POWHEG Min	294	284	16	853	826	51
Combination		1675^{+911}_{-372}	8507^{+992}_{-962}	28^{+48}_{-12}	4919^{+2748}_{-1141}	24553^{+2568}_{-3219}	91^{+163}_{-41}

CC events



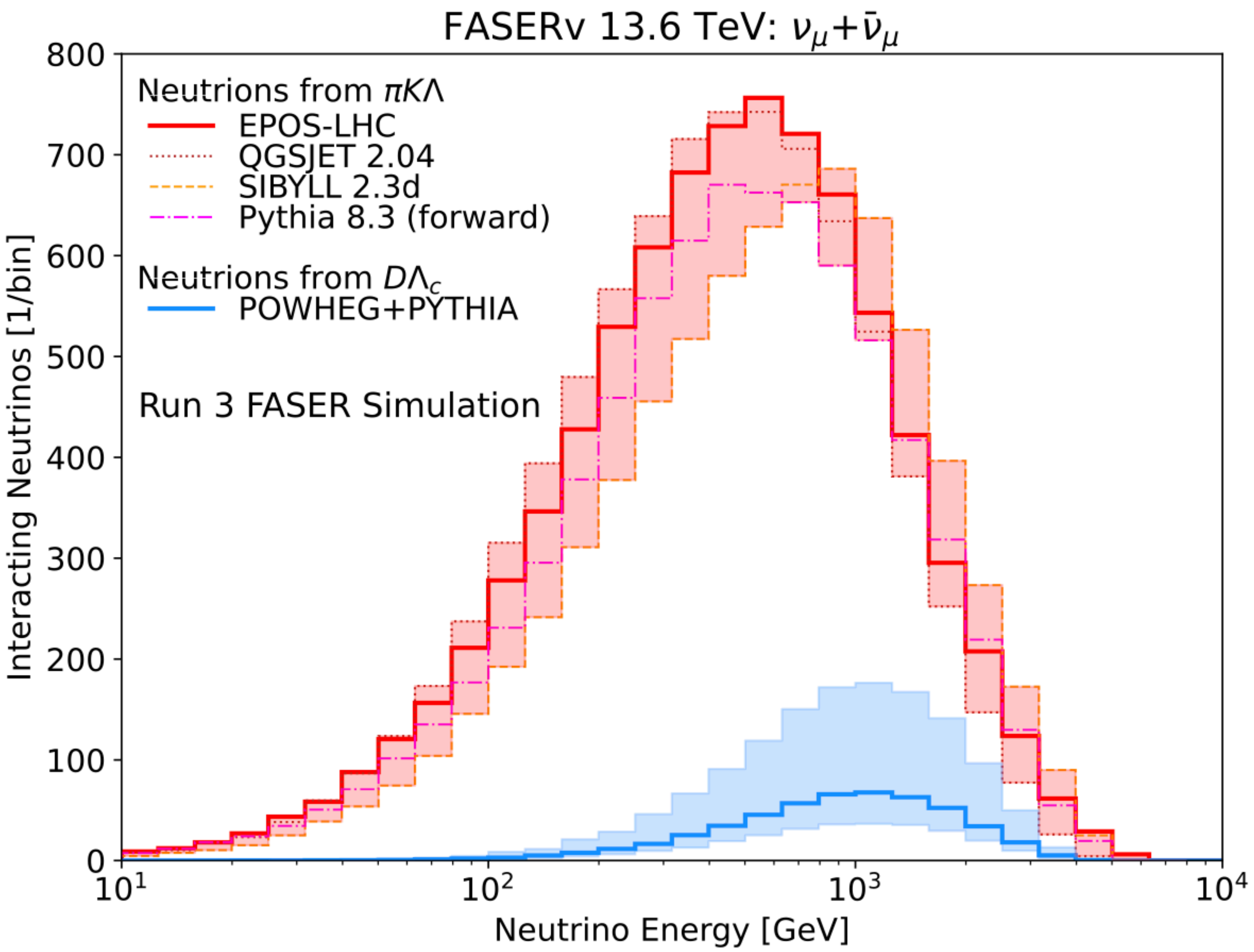
Neutrino Rate Predictions for FASER; 2402.13318

Neutrino Flux at FASER

ν_e: $K \longrightarrow \pi e \nu_e$, $D \longrightarrow K e \nu_e$

ν_μ: $\pi^\pm \longrightarrow \mu \nu_\mu$, $K^\pm \longrightarrow \mu \nu_\mu$

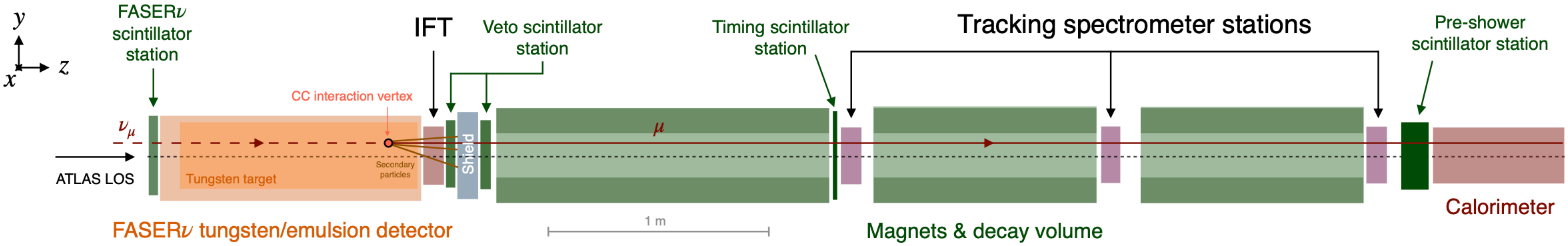
Generators		FASERν at Run 3			FASERν at Run 4		
light hadrons	charm hadrons	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
EPOS-LHC	–	1149	7996	–	3382	23054	–
SIBYLL 2.3d	–	1126	7261	–	3404	21532	–
QGSJET 2.04	–	1181	8126	–	3379	22501	–
PYTHIAforward	–	1008	7418	–	2925	20508	–
–	POWHEG Max	1405	1373	76	4264	4068	255
–	POWHEG	527	511	28	1537	1499	91
–	POWHEG Min	294	284	16	853	826	51
Combination		1675^{+911}_{-372}	8507^{+992}_{-962}	28^{+48}_{-12}	4919^{+2748}_{-1141}	24553^{+2568}_{-3219}	91^{+163}_{-41}

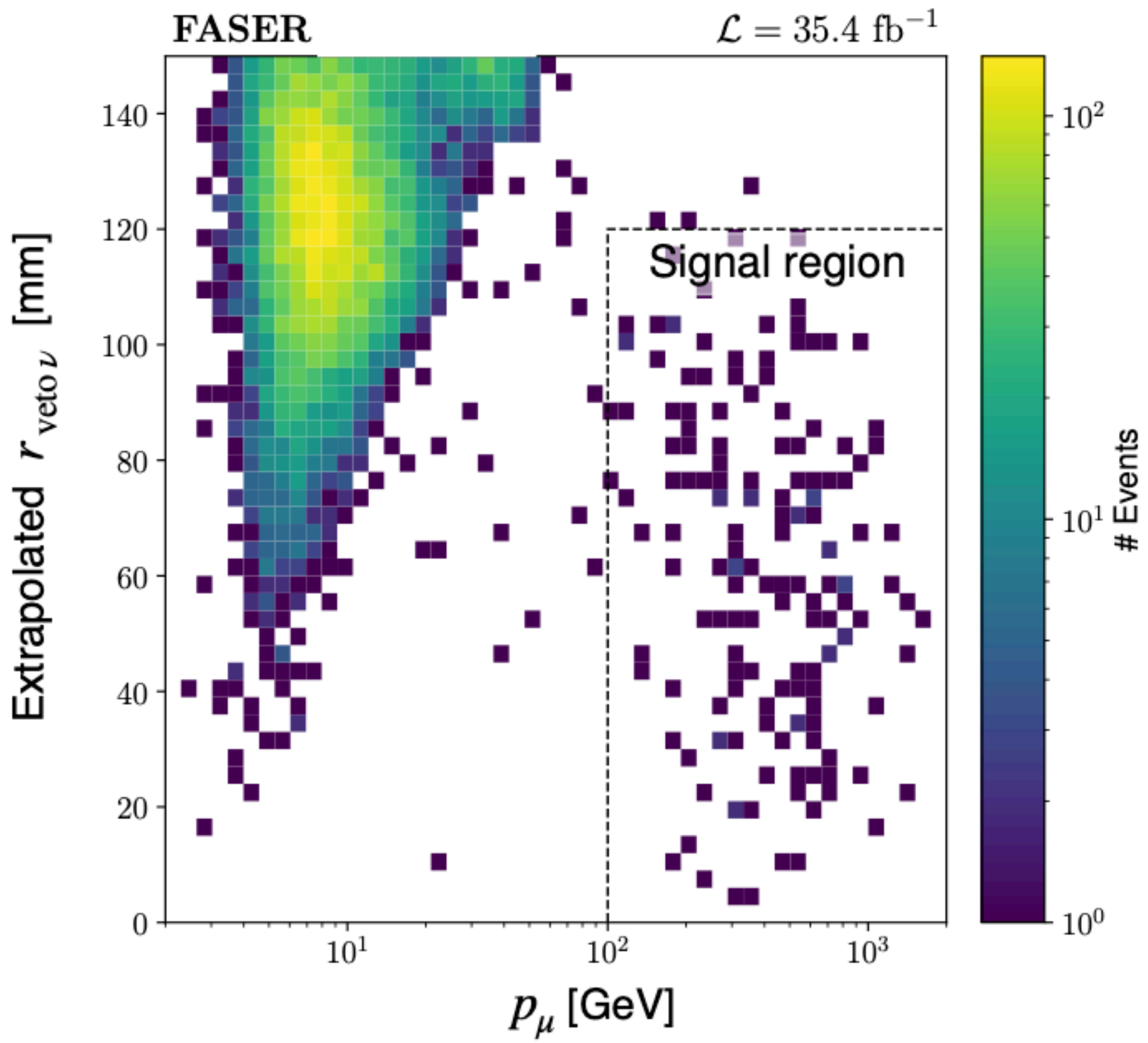


Already many new exciting neutrino results!!!

Neutrino Rate Predictions for FASER; 2402.13318

First Observation of Collider Neutrinos

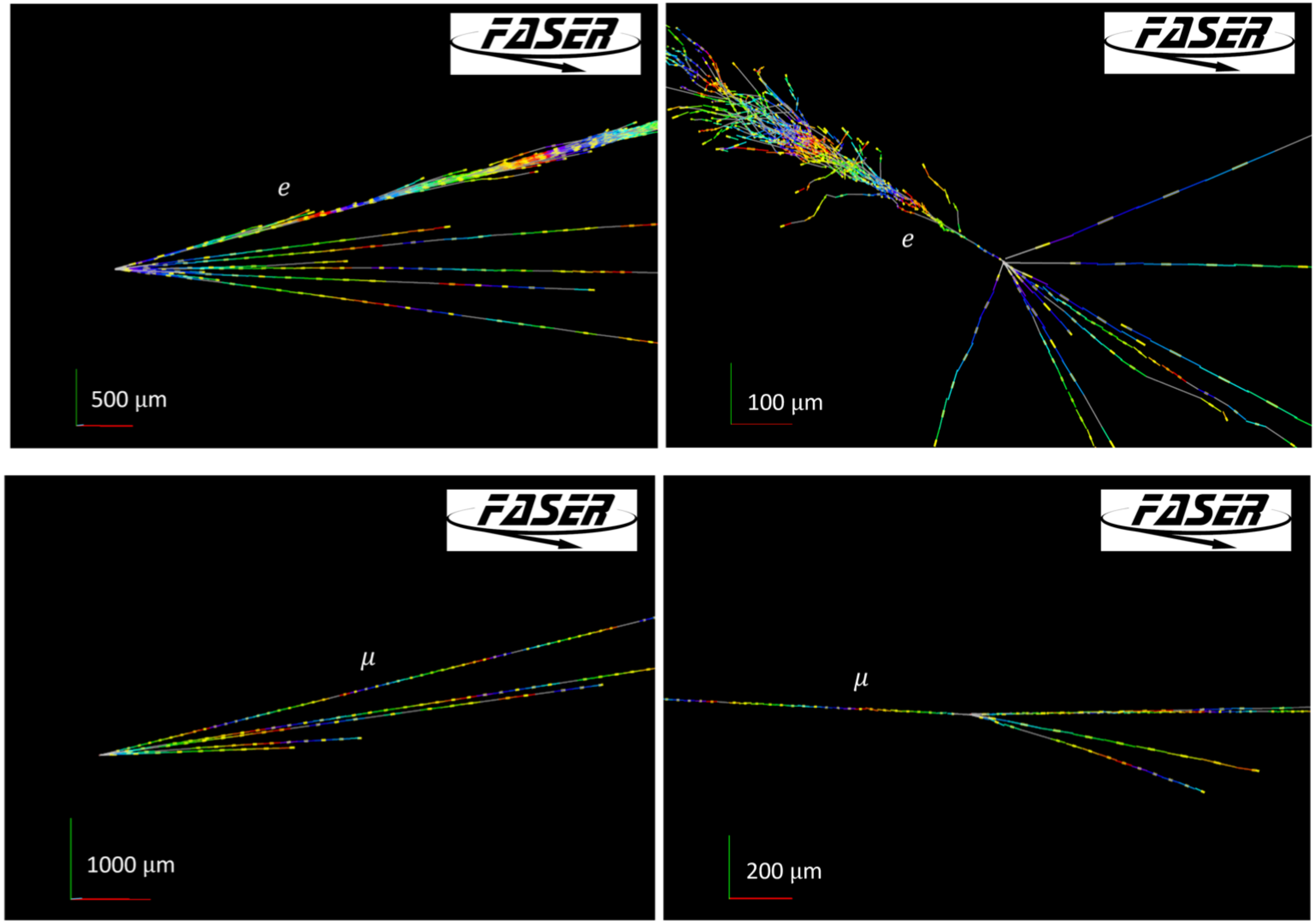




~150 ν_μ CC events with 35.4 fb^{-1} of data using only the electronic components of the detector.

First Direct Observation of Collider Neutrinos with FASER at the LHC; 2303.14185

ν_e and ν_μ events at FASERν



First Measurement of the ν_e and ν_μ Interaction Cross Sections at the LHC with FASER's Emulsion Detector; 2403.12520

ν_e and ν_μ events at FASERν

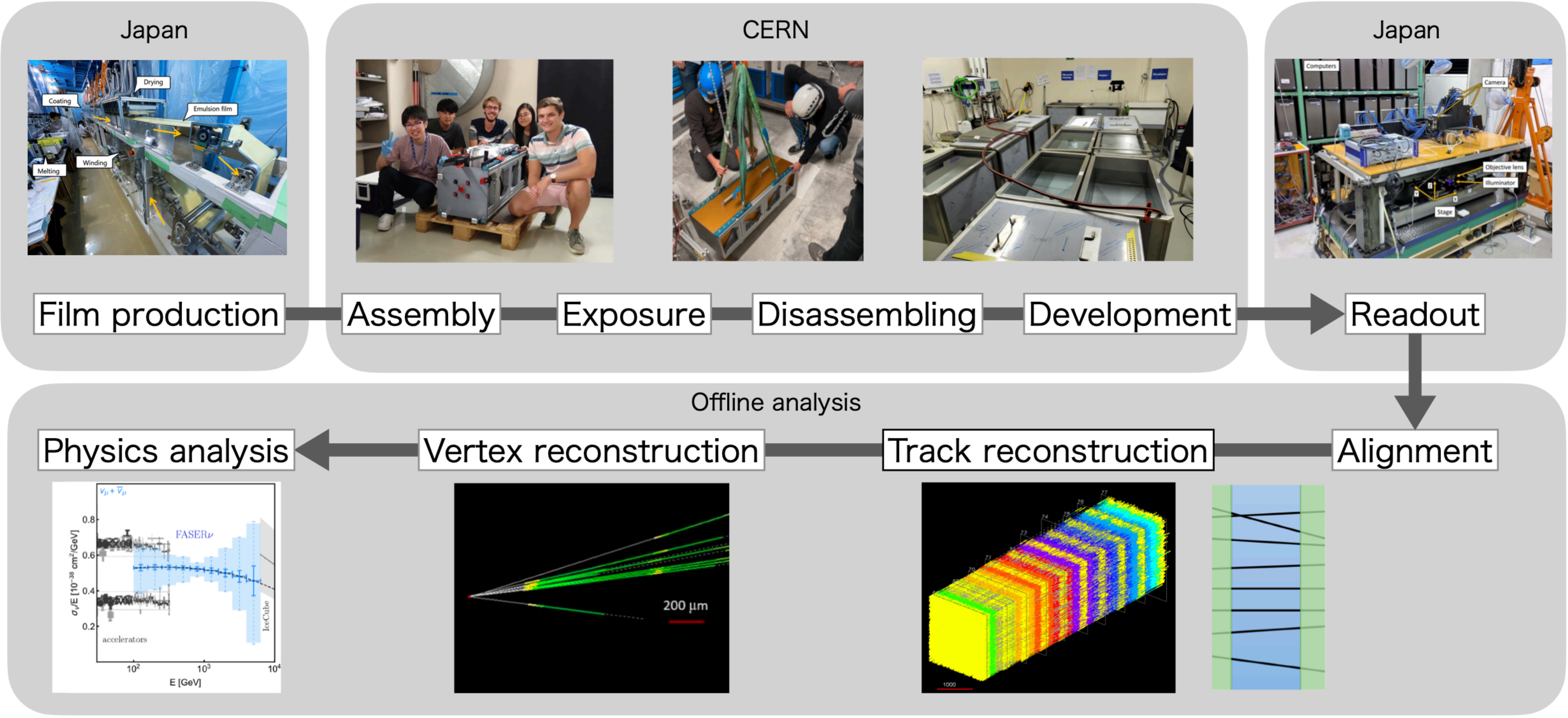


Image courtesy Tomohiro Inada's slides, NOW 2024

First Measurement of the ν_e and ν_μ Interaction Cross Sections at the LHC with FASER's Emulsion Detector; 2403.12520

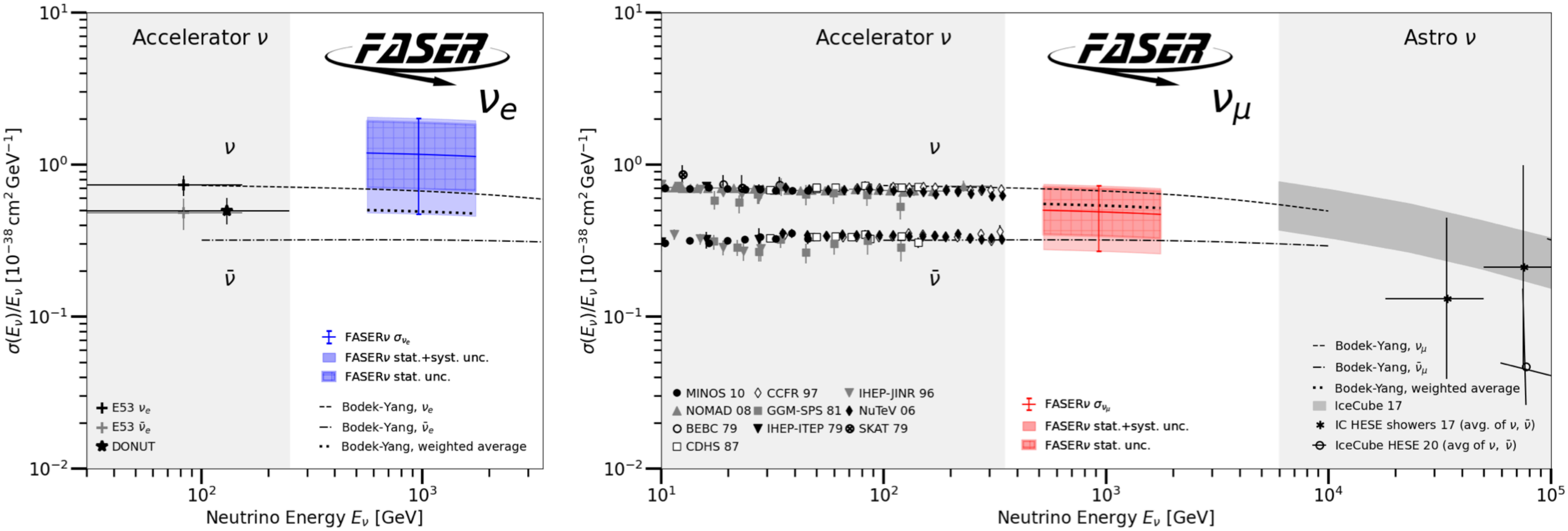
ν_e and ν_μ events at FASERν

- **Vertex selection**
  - **Neutral vertex**
  - **N$_{\text{track}}$**$(\tan(\theta) \leq 0.1) \geq 4$
- **Lepton selection**
  - **E**$_l > 200$ **GeV**
  - $\tan(\theta) > 0.005$
  - $\Delta\phi > \pi/2$

Interaction	Backgrounds (Mainly NHs)	Expected Signal	Observed
ν_e CC	$0.025^{+0.015}_{-0.010}$	1.1-3.3	4
ν_μ CC	$0.22^{+0.09}_{-0.07}$	6.5-12.4	8

First Measurement of the ν_e and ν_μ Interaction Cross Sections at the LHC with FASER's Emulsion Detector; 2403.12520

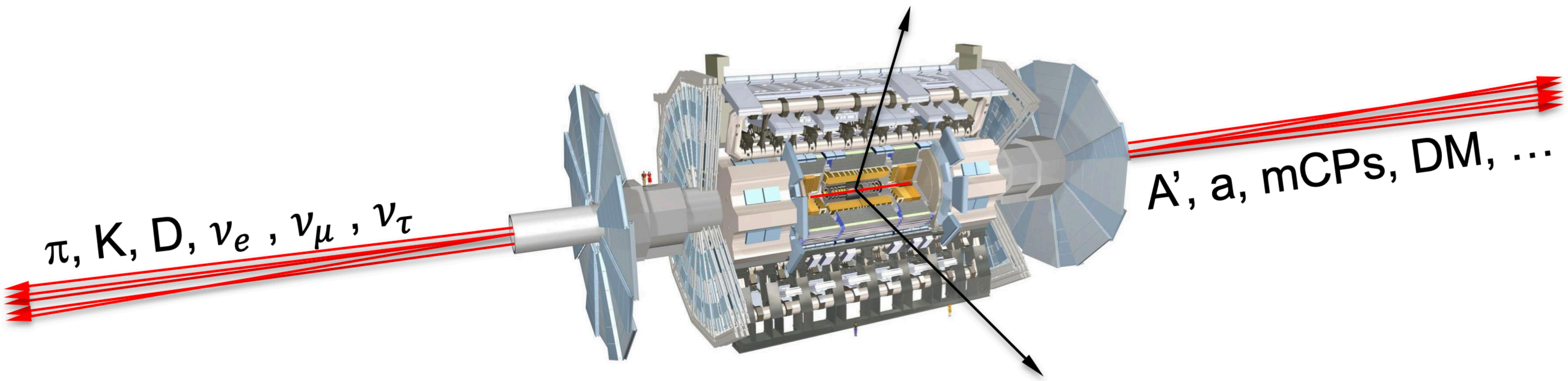
First Neutrino Cross-Section Measurements at LHC



4 ν_e and 8 ν_μ events with 9.5 fb^{-1} of data.

First Measurement of the ν_e and ν_μ Interaction Cross Sections at the LHC with FASER's Emulsion Detector; 2403.12520

BSM Searches: Long Lived Particle searches at FASER



$$pp \rightarrow LLP \xrightarrow{480\text{m}} \gamma\gamma,\ ee,\ \mu\mu\ \cdots$$

Dark Photon Searches at FASER

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

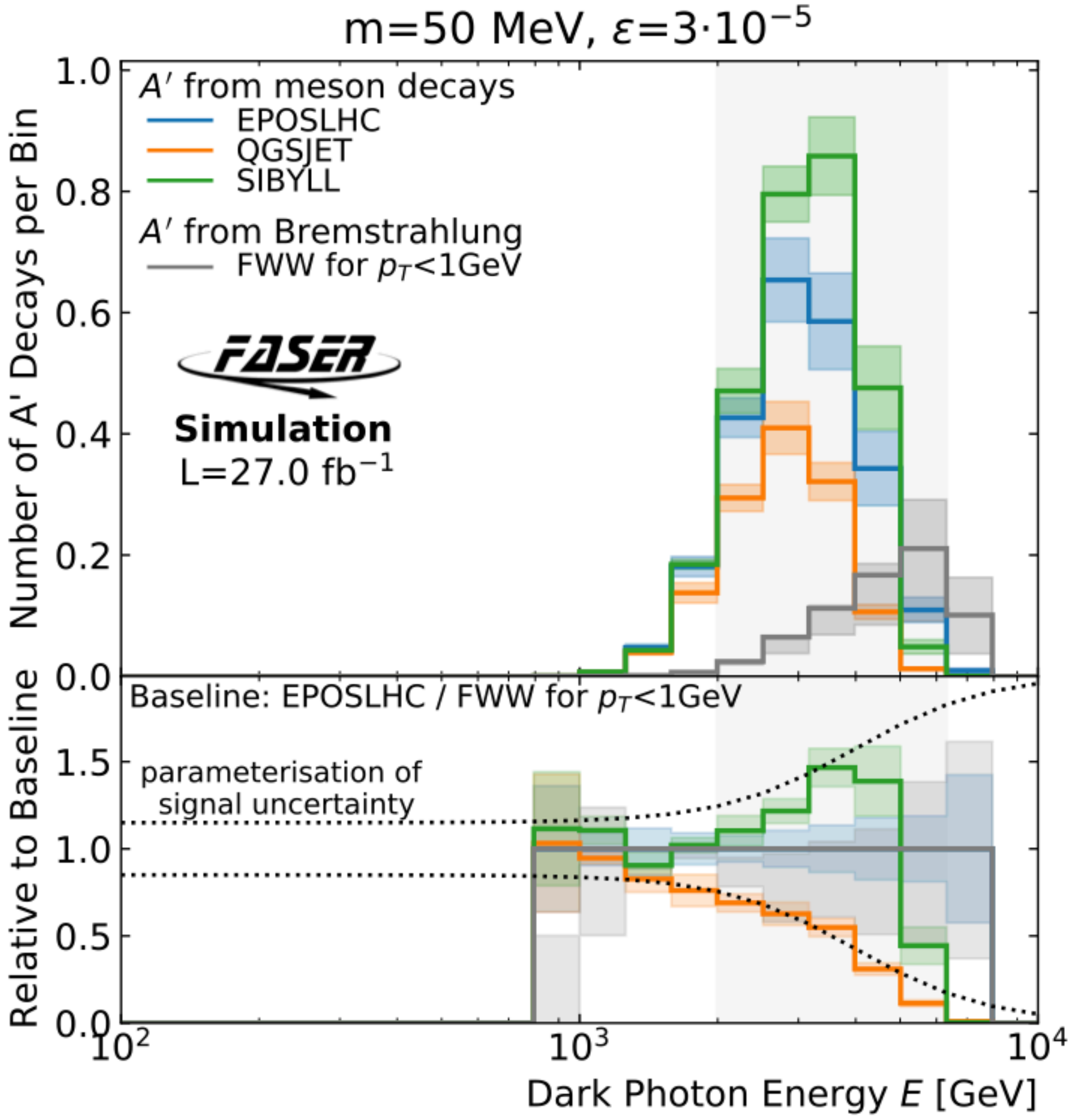
2 parameter model: $m_{A'},\ \epsilon$

Production:

- $\pi^0 \to A'\gamma\,; m_{A'} < m_{\pi^0} \sim 135$ **MeV**
- $\eta \to A'\gamma\ ;\ m_{A'} < m_\eta \sim 548$ **MeV**
- $pp \to ppA'\ ;\ m_{A'} > \mathcal{O}(2$ **GeV**$)$

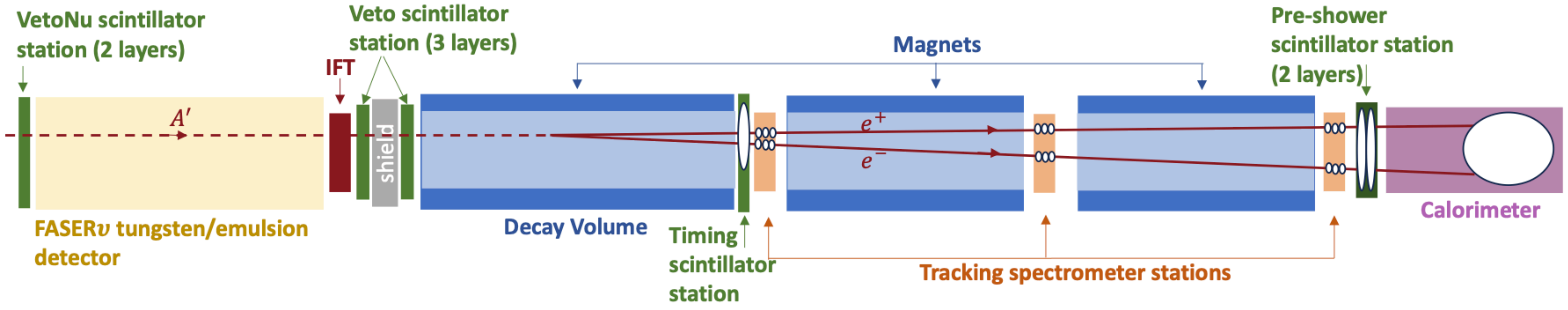
Decay:

- $A' \to ee\ ;\ 2m_e < m_{A'} < 2m_\mu$



Search for Dark Photons with the FASER detector at the LHC; 2308.05587

Dark Photon Searches at FASER



Search for Dark Photons with the FASER detector at the LHC; 2308.05587

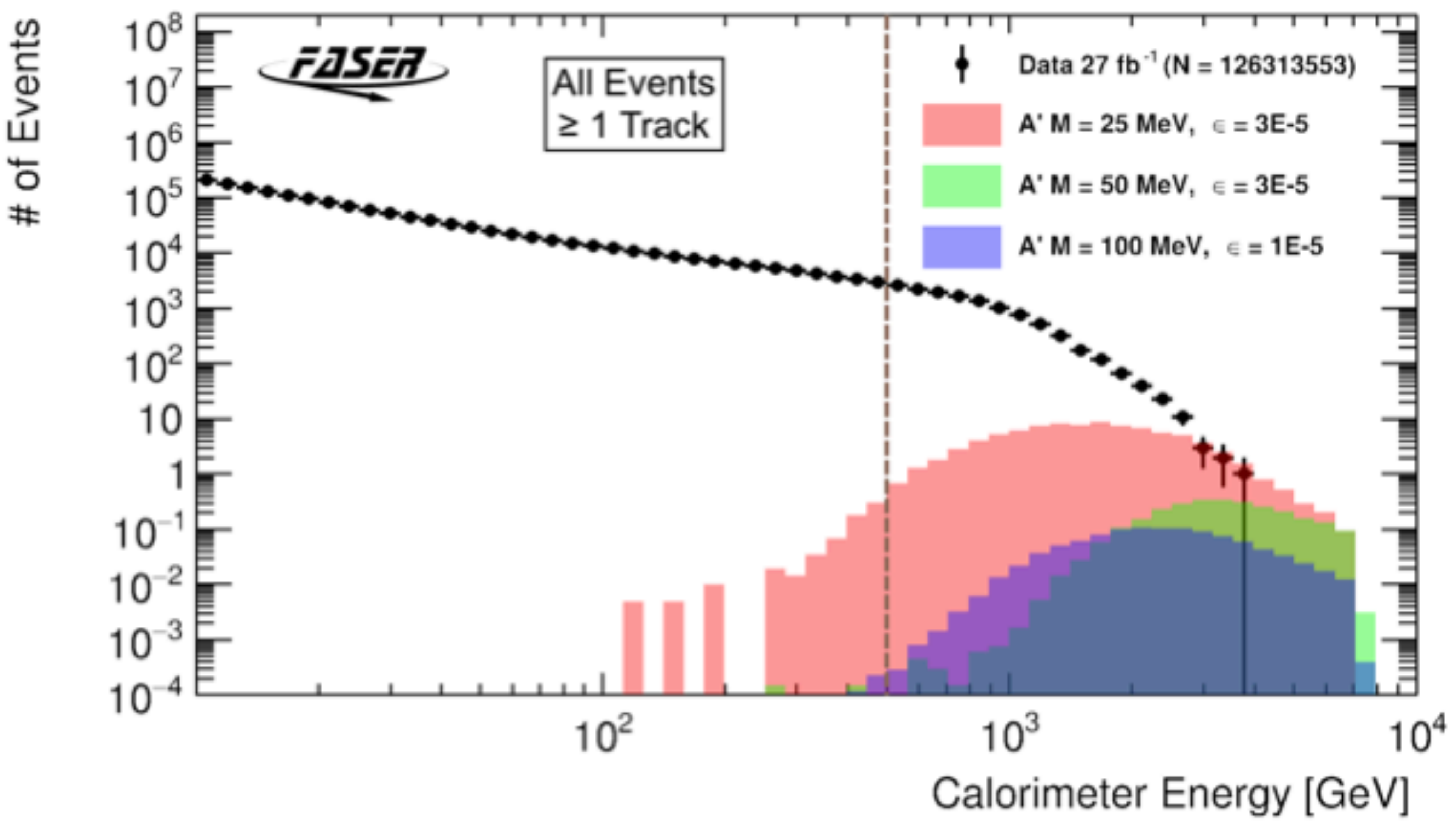
Signal Selection:

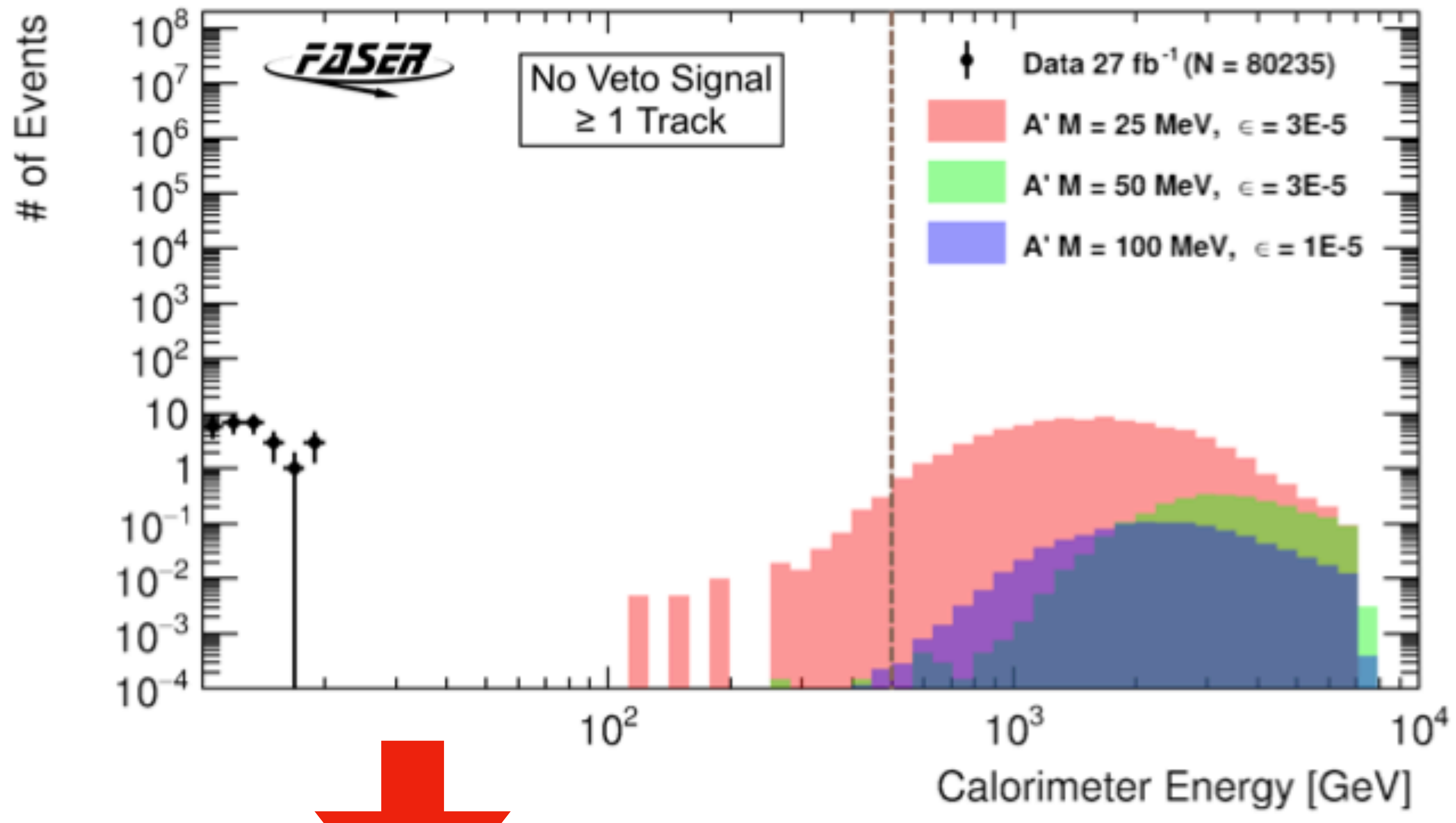
- **Event time consistent with collisions at IP1**
- **No signal in the veto scintillators**
- **2 charged tracks**
  - **p>20 GeV**
  - **Within the fiducial volume (r<9.5cm)**
- **Calorimeter E>500 GeV**

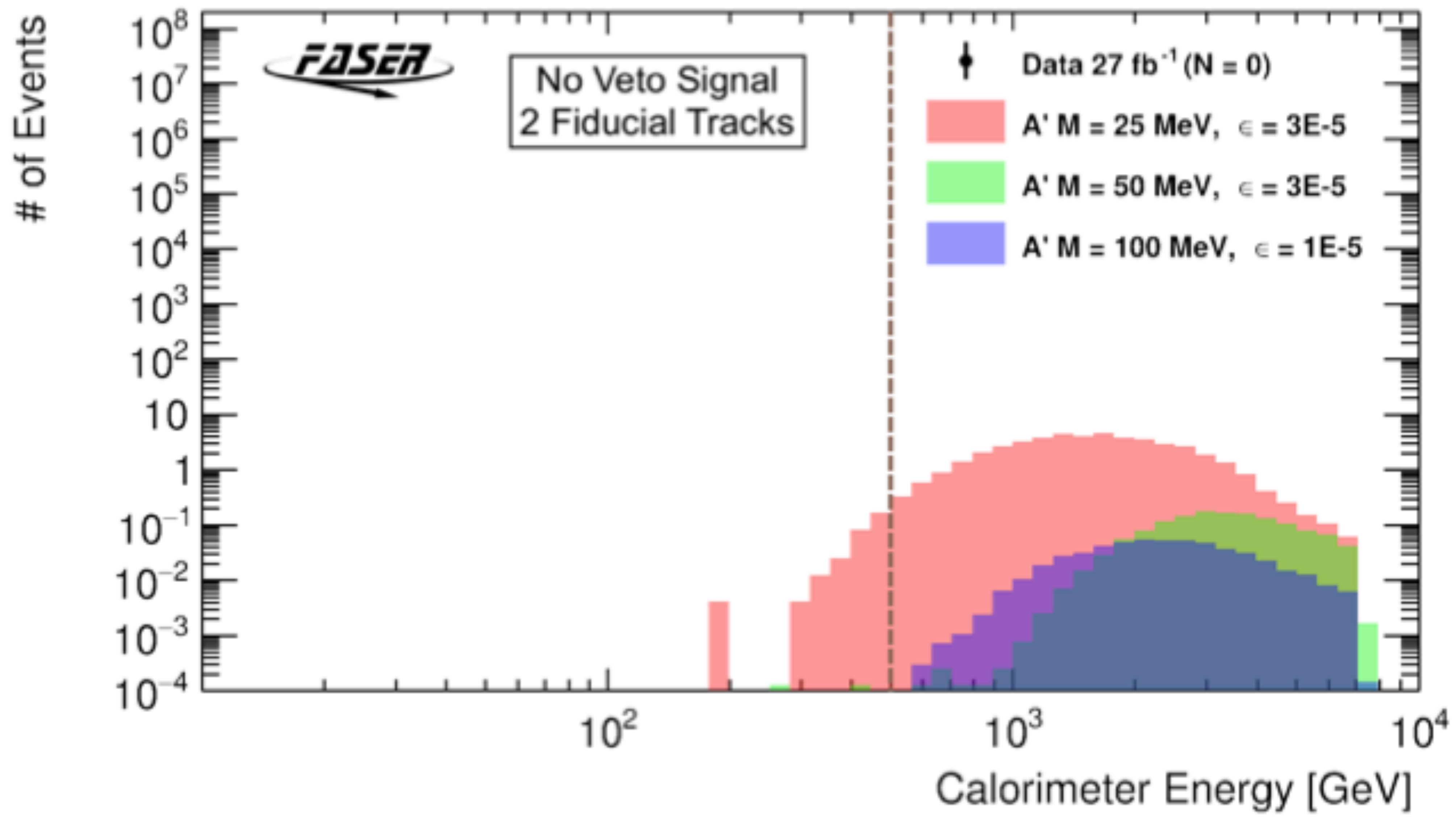
Backgrounds (for 27 fb^{-1}):

- **Neutral Hadrons from muons in rock**
  - $(8.4 \pm 11.9) \cdot 10^{-4}$
- **Neutrinos**
  - $(1.5 \pm 1.9) \cdot 10^{-3}$
- **Total =** $(2.3 \pm 2.3) \cdot 10^{-3}$

Dark Photon Searches at FASER



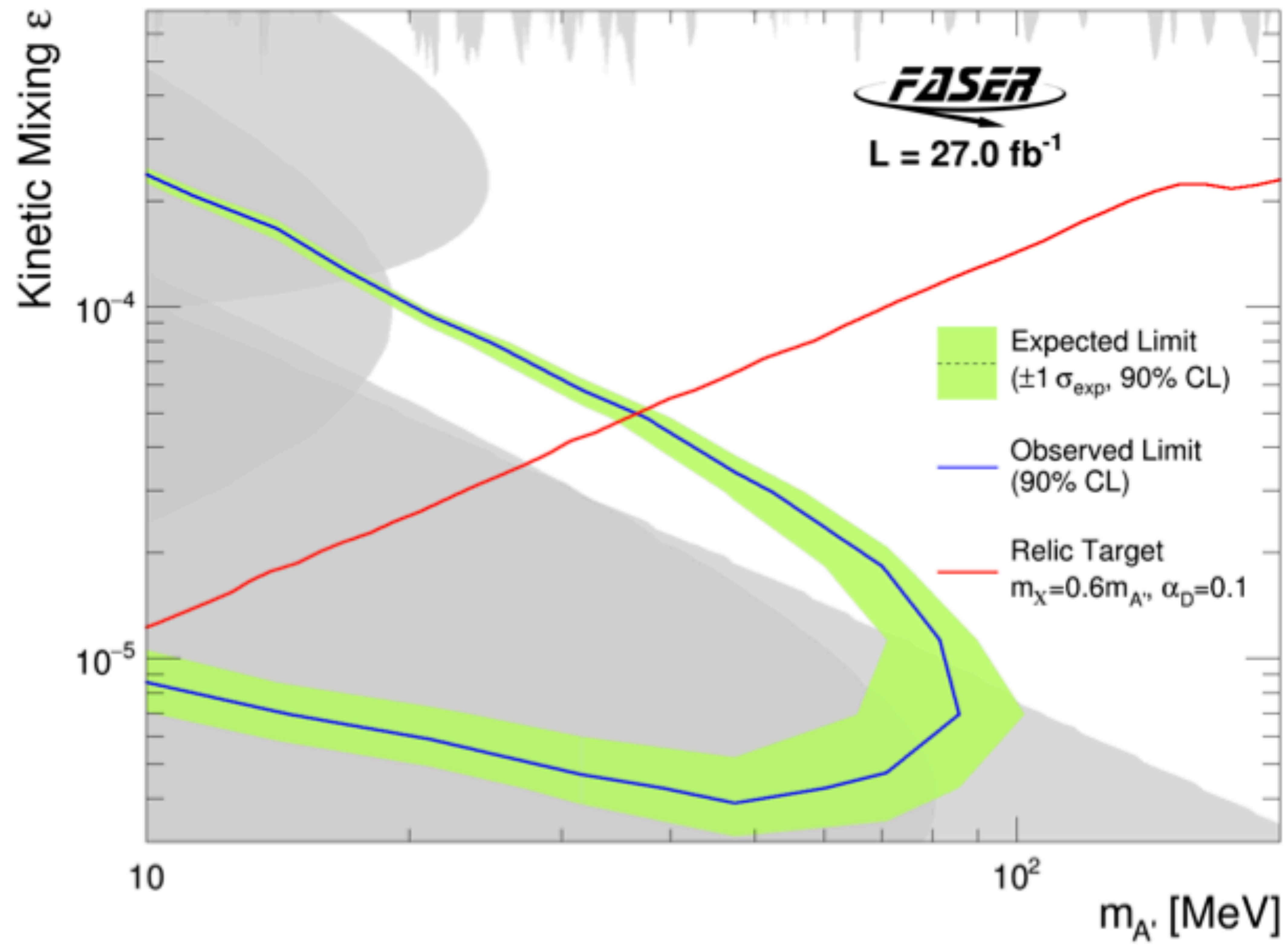


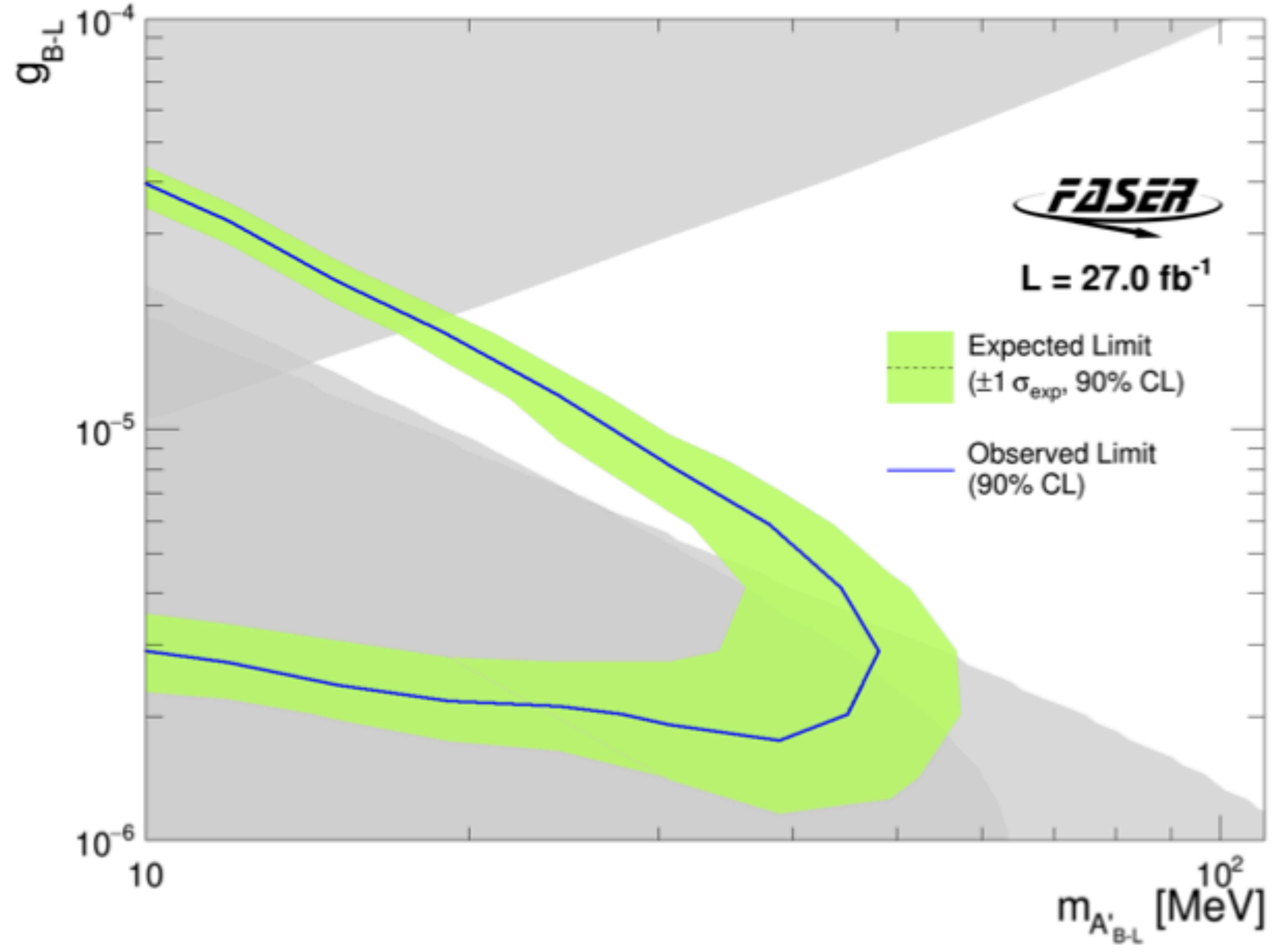


0 events observed with an expected background of $(2.3 \pm 2.3) \cdot 10^{-3}$

Search for Dark Photons with the FASER detector at the LHC; 2308.05587

Dark Photon Searches at FASER





New parameter space is probed by FASER

Can re-interpret the result for $U(1)_{B-L}$ model as well

Search for Dark Photons with the FASER detector at the LHC; 2308.05587

ALP Searches at FASER

ALP coupling to $SU(2)_L$ gauge boson

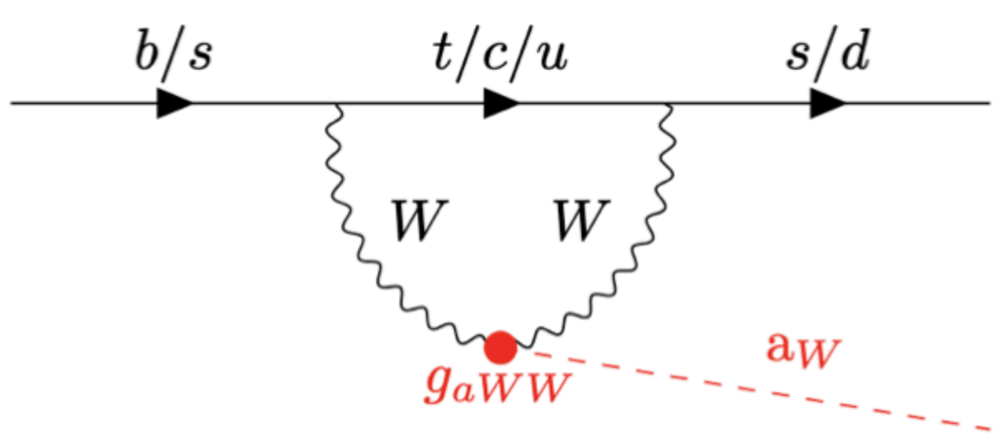
$$\mathcal{L} \supset -\frac{1}{2}m_a^2 a^2 - \frac{1}{4} g_{aWW} a W^{a,\mu\nu} \tilde{W}^a_{\mu\nu}$$

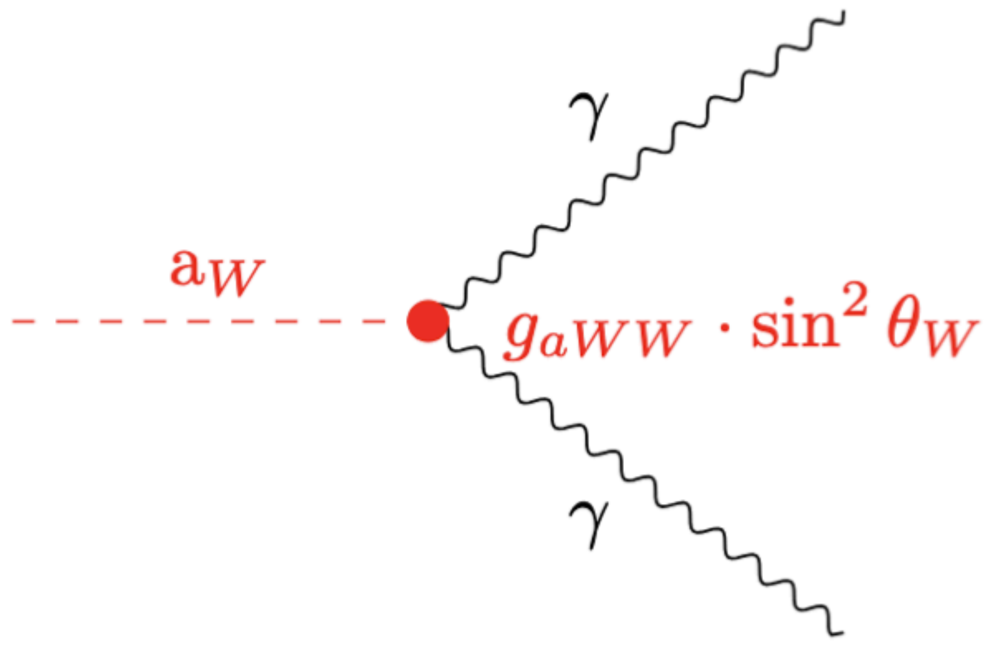
Production:

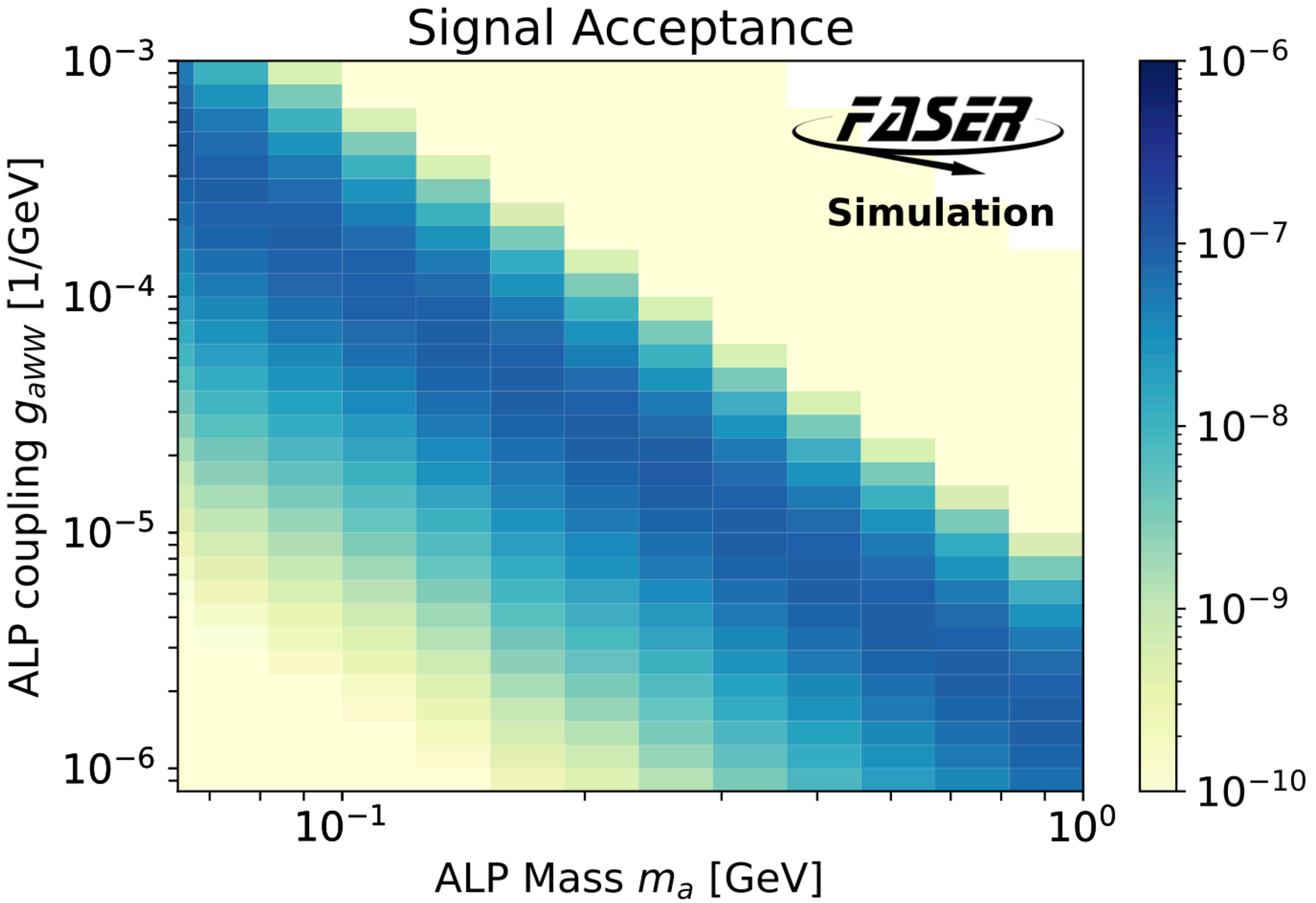
- **FCNC decays of B mesons**

Decay:

- $a \to \gamma\gamma$



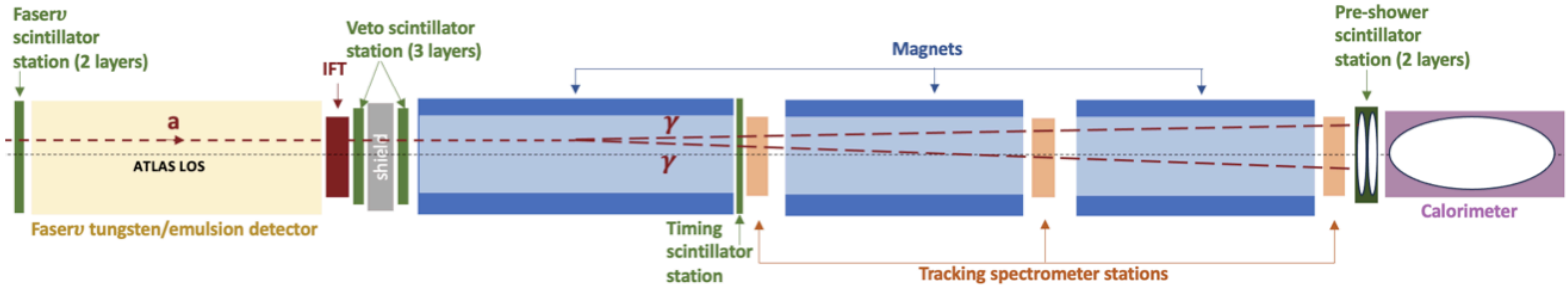




The acceptance for events from the ALP model at truth level to decay inside FASER.

Shining Light on the Dark Sector: Search for Axion-like Particles and Other New Physics in Photonic Final States with FASER; 2410.10363

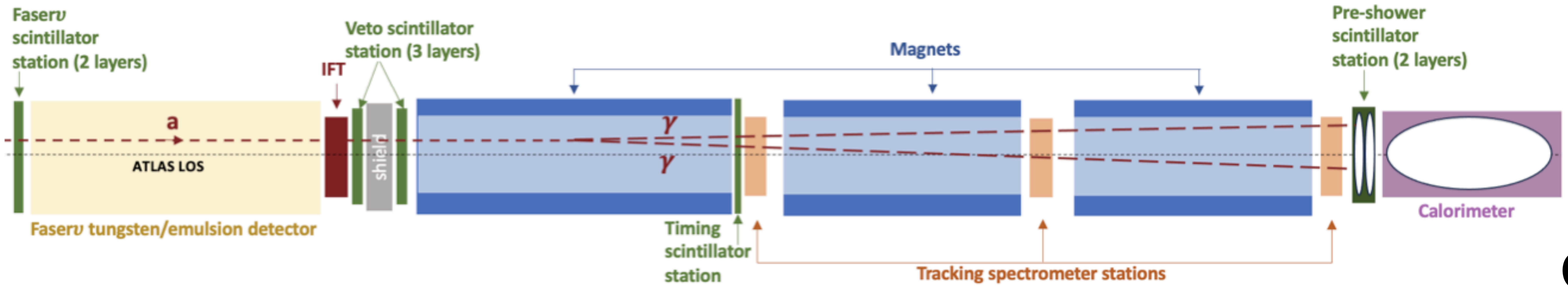
ALP Searches at FASER



- **Unlike the dark photon search, we are now looking for photonic final states.**
- **This changes the backgrounds and signal selection criteria.**

Shining Light on the Dark Sector: Search for Axion-like Particles and Other New Physics in Photonic Final States with FASER; 2410.10363

ALP Searches at FASER



Overall signal selection efficiency of ~ 75%

Signal Selection:

- **No signal in the veto scintillators**
- **No signal in the timing scintillators**
- **Preshower ratio to have EM shower in preshower (> 4.5)**
- **2nd preshower layer to have a signal (>10 MIPs)**
- **Calorimeter E>1.5 TeV**

Selection	Efficiency	Cum. Efficiency
$m_a = 140$ MeV, $g_{aWW} = 2 \times 10^{-4}$ GeV^{-1}		
Veto Signal nMIP < 0.5	99.6%	99.6%
Timing Scintillator Signal nMIP < 0.5	97.8%	97.4%
Preshower Ratio > 4.5	85.7%	83.5%
Second Preshower nMIP > 10	98.6%	82.3%
Calo $E > 1.5$ TeV	91.6%	75.4%

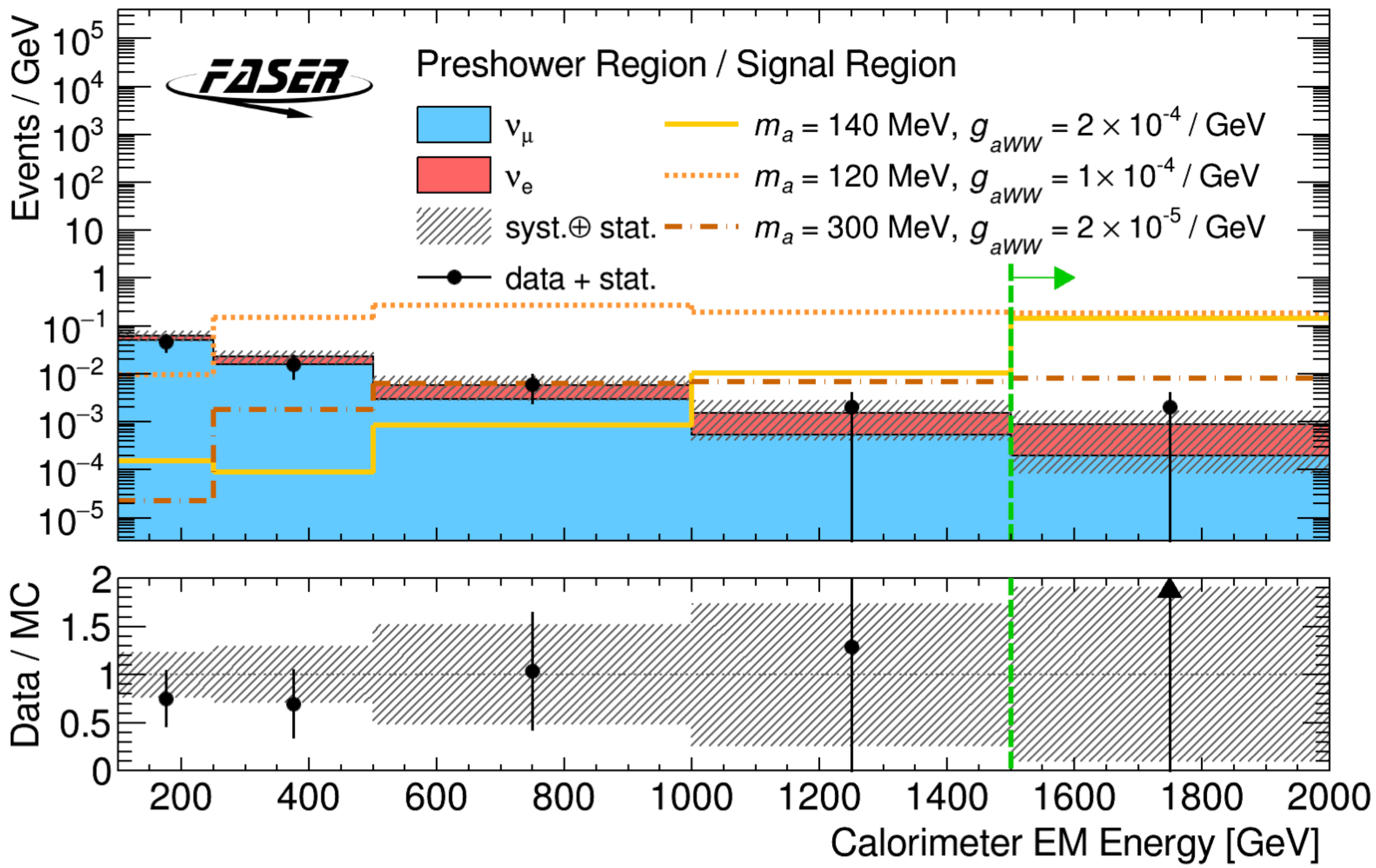
Shining Light on the Dark Sector: Search for Axion-like Particles and Other New Physics in Photonic Final States with FASER; 2410.10363

ALP Searches at FASER

Shining Light on the Dark Sector: Search for Axion-like Particles and Other New Physics in Photonic Final States with FASER; 2410.10363

Backgrounds:

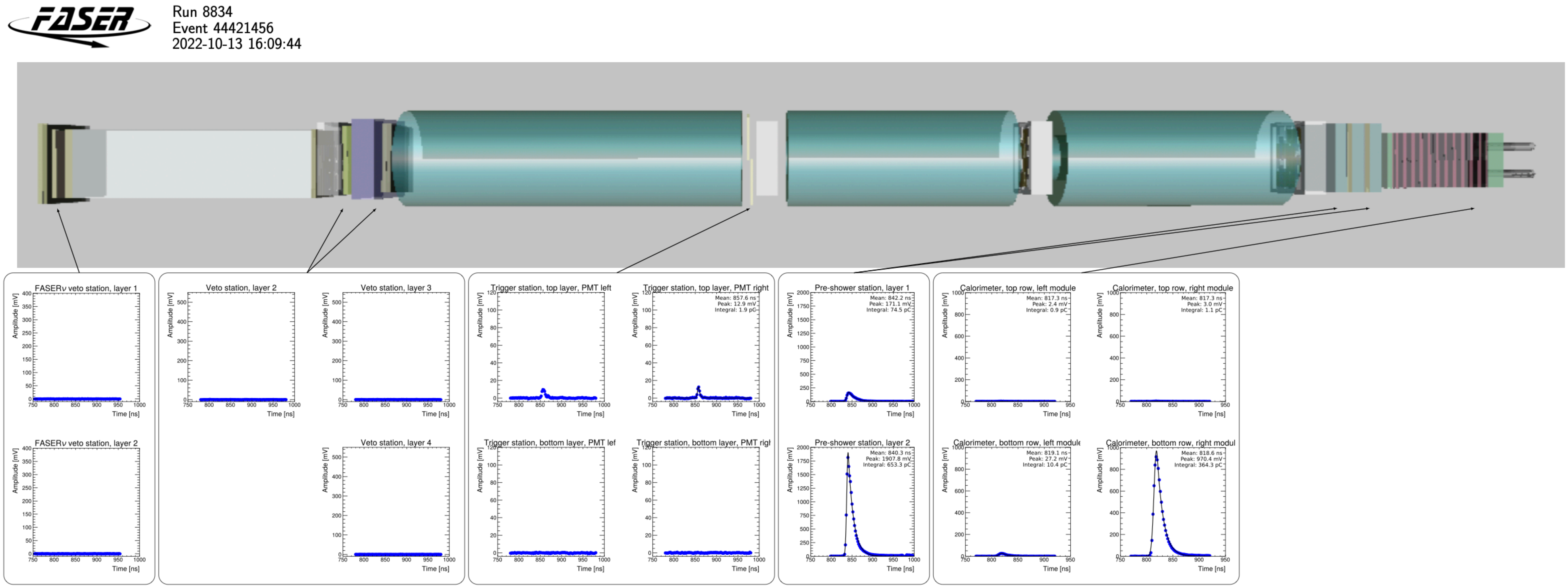
- **Neutral Hadrons from muons in rock**
  - **Negligible with the higher 1.5 TeV cut**
- **Neutrinos**
  - **Neutrino CC and NC interaction with components within FASER**
  - (0.42 ± 0.38) **for 57.7 fb**$^{-1}$



1 event observed, consistent with signal and neutrino background: "ALPtrino".

ALP Searches at FASER

Shining Light on the Dark Sector: Search for Axion-like Particles and Other New Physics in Photonic Final States with FASER; 2410.10363



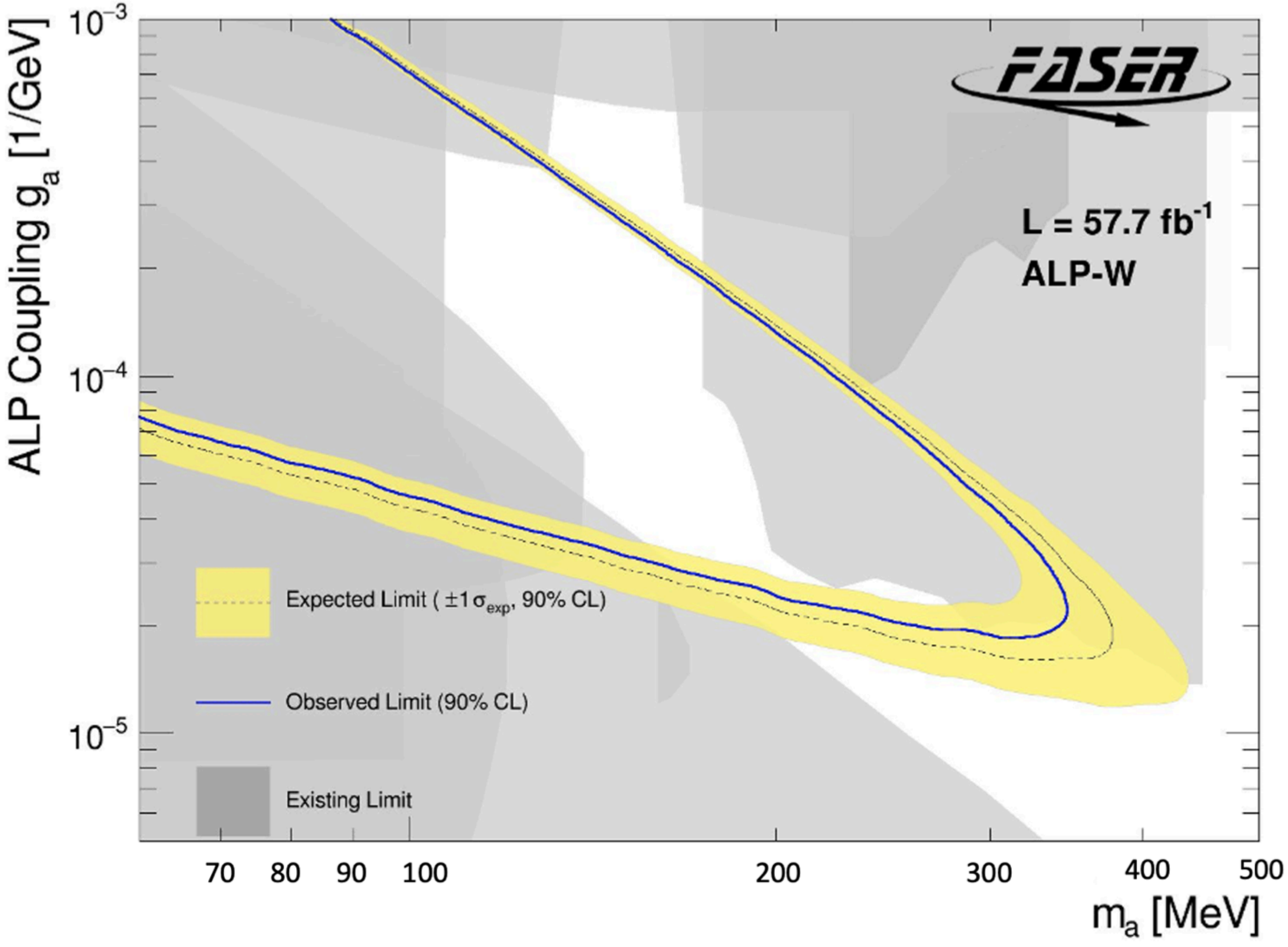
Event display of ALPtrino recorded on 13th October 2022.

ALP Searches at FASER

Shining Light on the Dark Sector: Search for Axion-like Particles and Other New Physics in Photonic Final States with FASER; 2410.10363

ALP coupling to $SU(2)_L$ gauge boson

$$\mathcal{L} = -\frac{1}{2}{m_a}^2 a^2 - \frac{g_a}{4} a W^{a,\mu\nu} \tilde{W}^a_{\mu\nu}$$



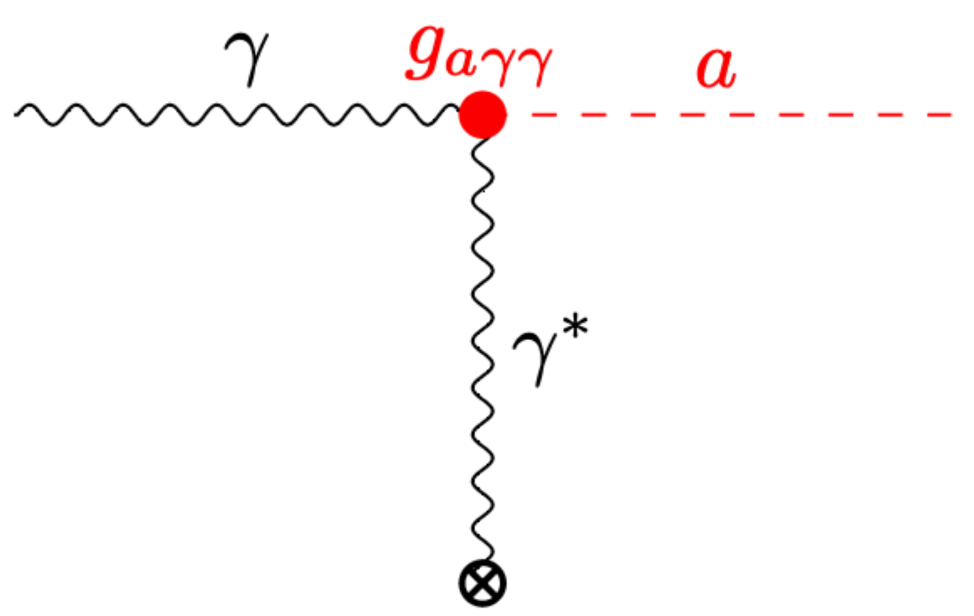
One Analysis To Bound Them All

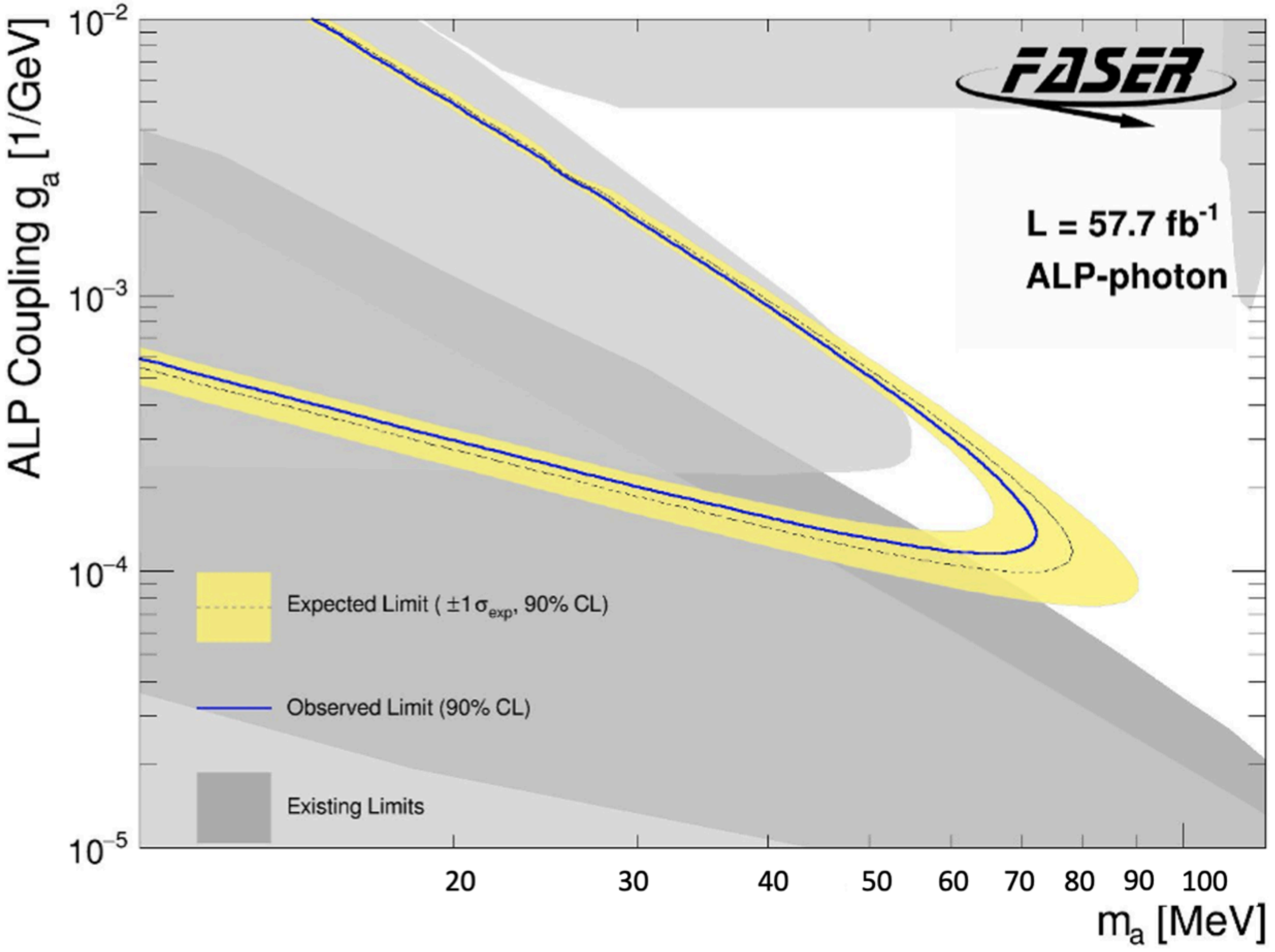
ALP-photon (PBC BC 9)

$$\mathcal{L} = -\frac{1}{2}{m_a}^2 a^2 - \frac{1}{4} g_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

Production:

- **Primakoff process**





Shining Light on the Dark Sector: Search for Axion-like Particles and Other New Physics in Photonic Final States with FASER; 2410.10363

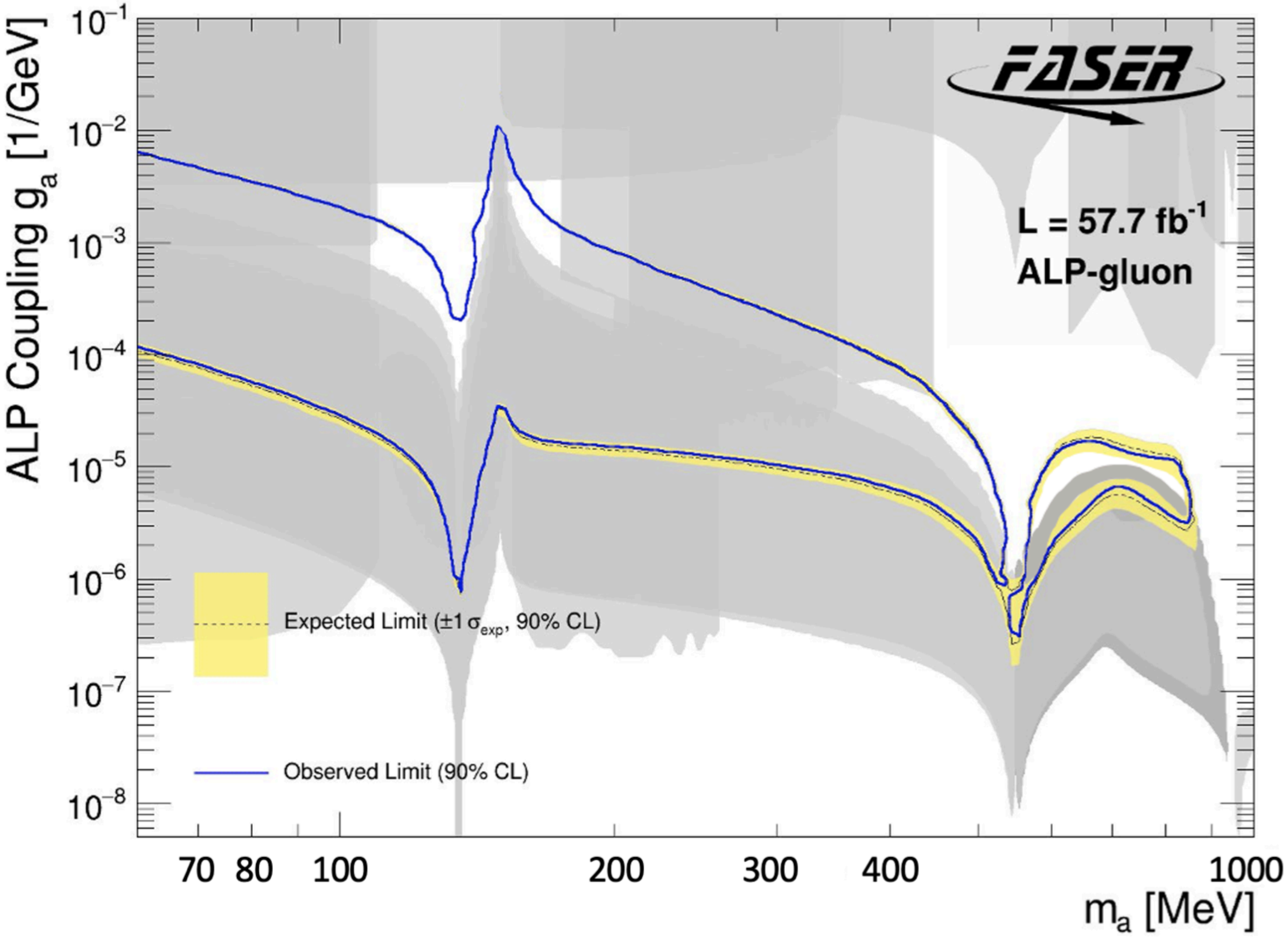
One Analysis To Bound Them All

ALP-gluon (PBC BC 11)

$$\mathcal{L} = -\frac{1}{2}{m_a}^2 a^2 - \frac{g_s^2}{8} g_a G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

Production:

- **Mixing with pseudo-scalars**



Shining Light on the Dark Sector: Search for Axion-like Particles and Other New Physics in Photonic Final States with FASER; 2410.10363

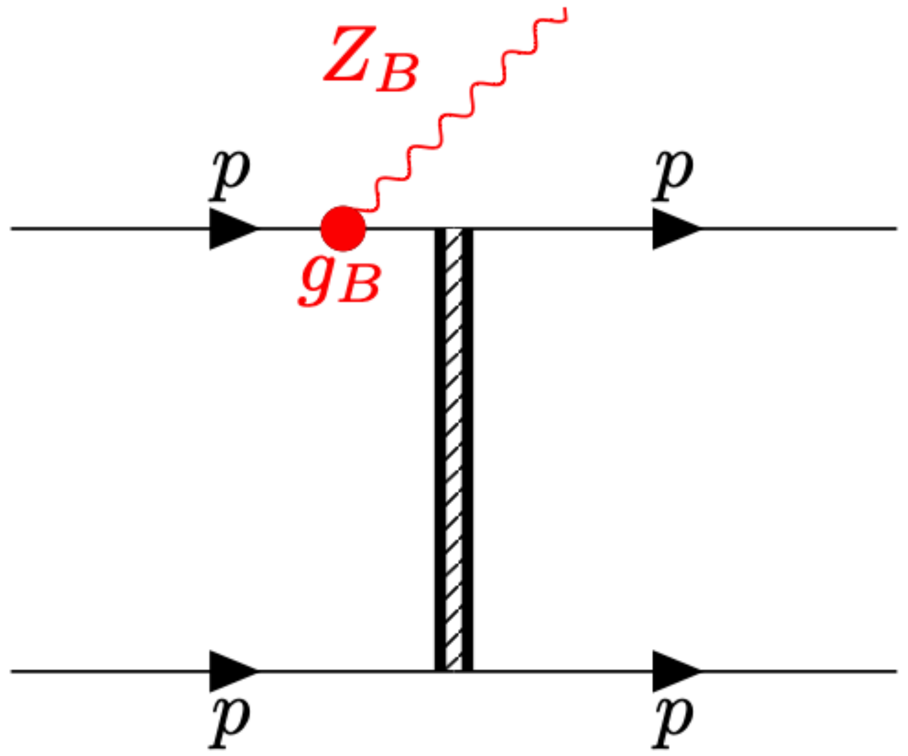
One Analysis To Bound Them All

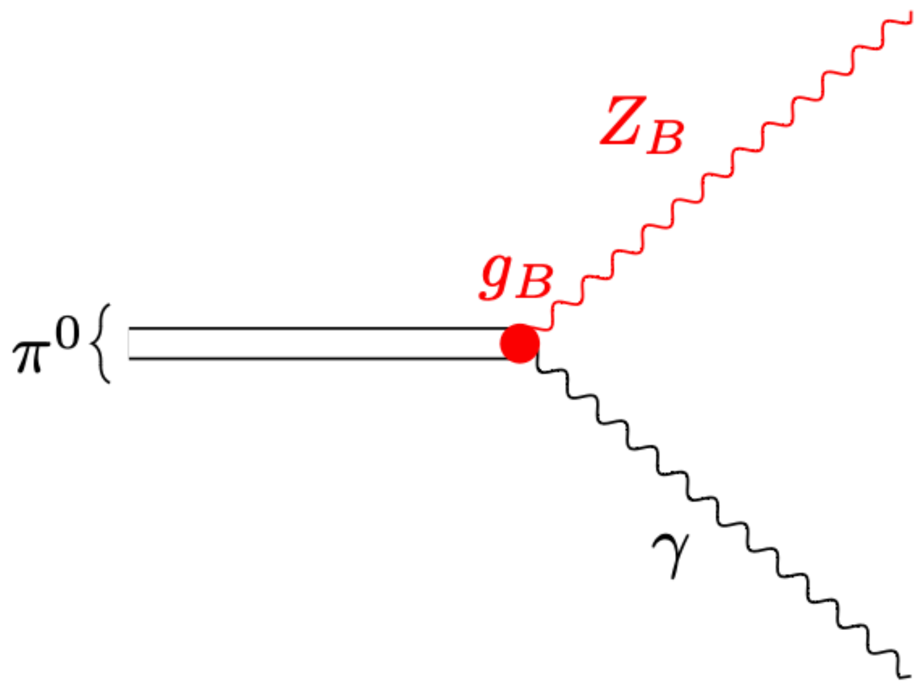
$U(1)_B$

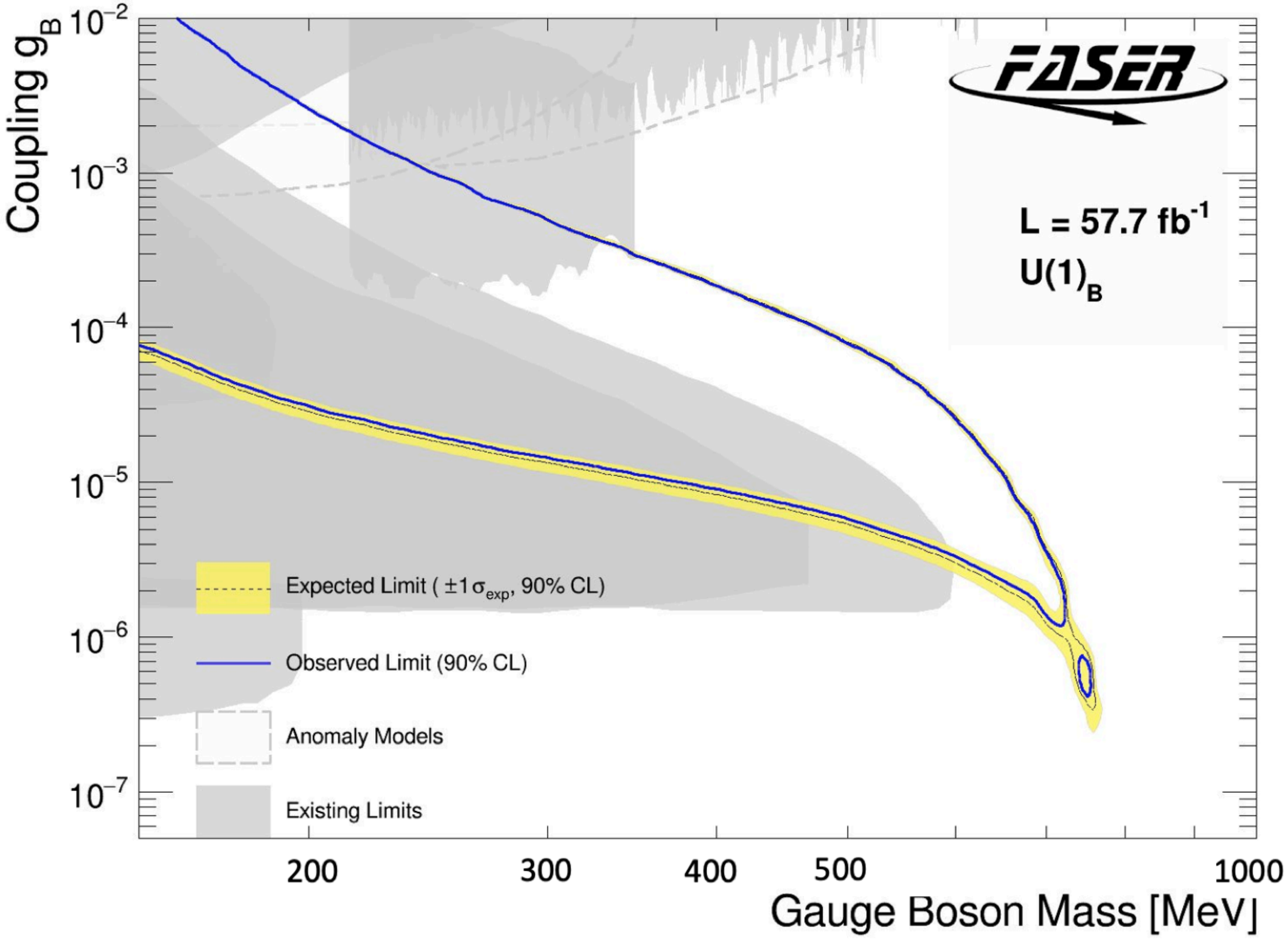
$$\mathcal{L} = \frac{1}{2} {m_{Z_B}}^2 Z_B^2 - g_B \sum x_f \; \bar{f}\gamma^\mu f X_\mu$$

Production:

- **Bremsstrahlung and π^0 decay**







Shining Light on the Dark Sector: Search for Axion-like Particles and Other New Physics in Photonic Final States with FASER; 2410.10363

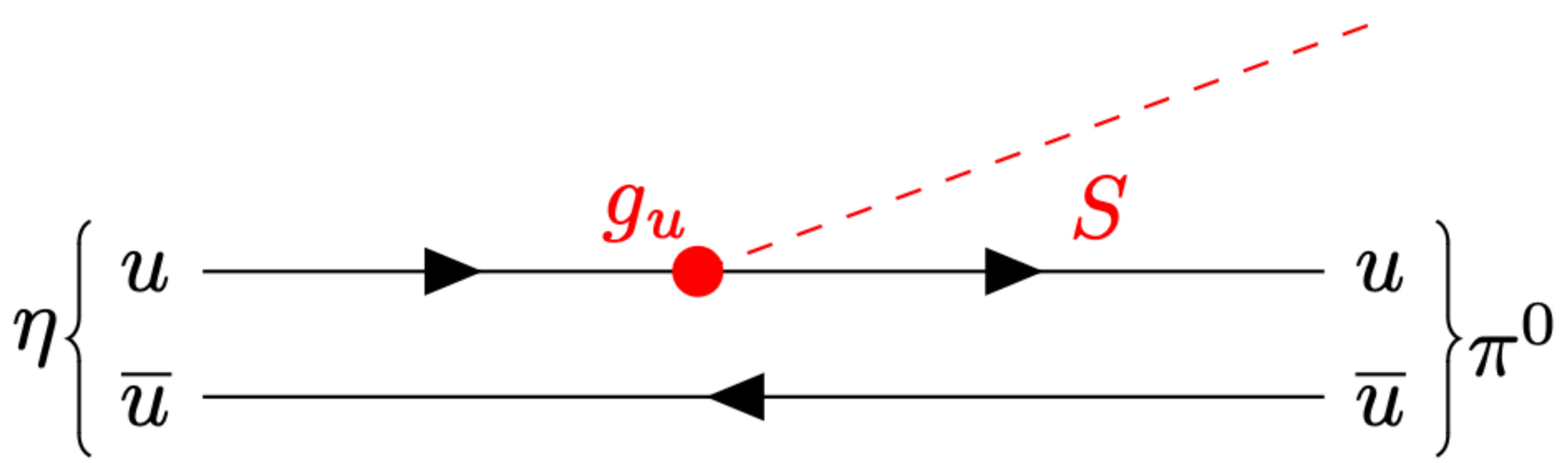
One Analysis To Bound Them All

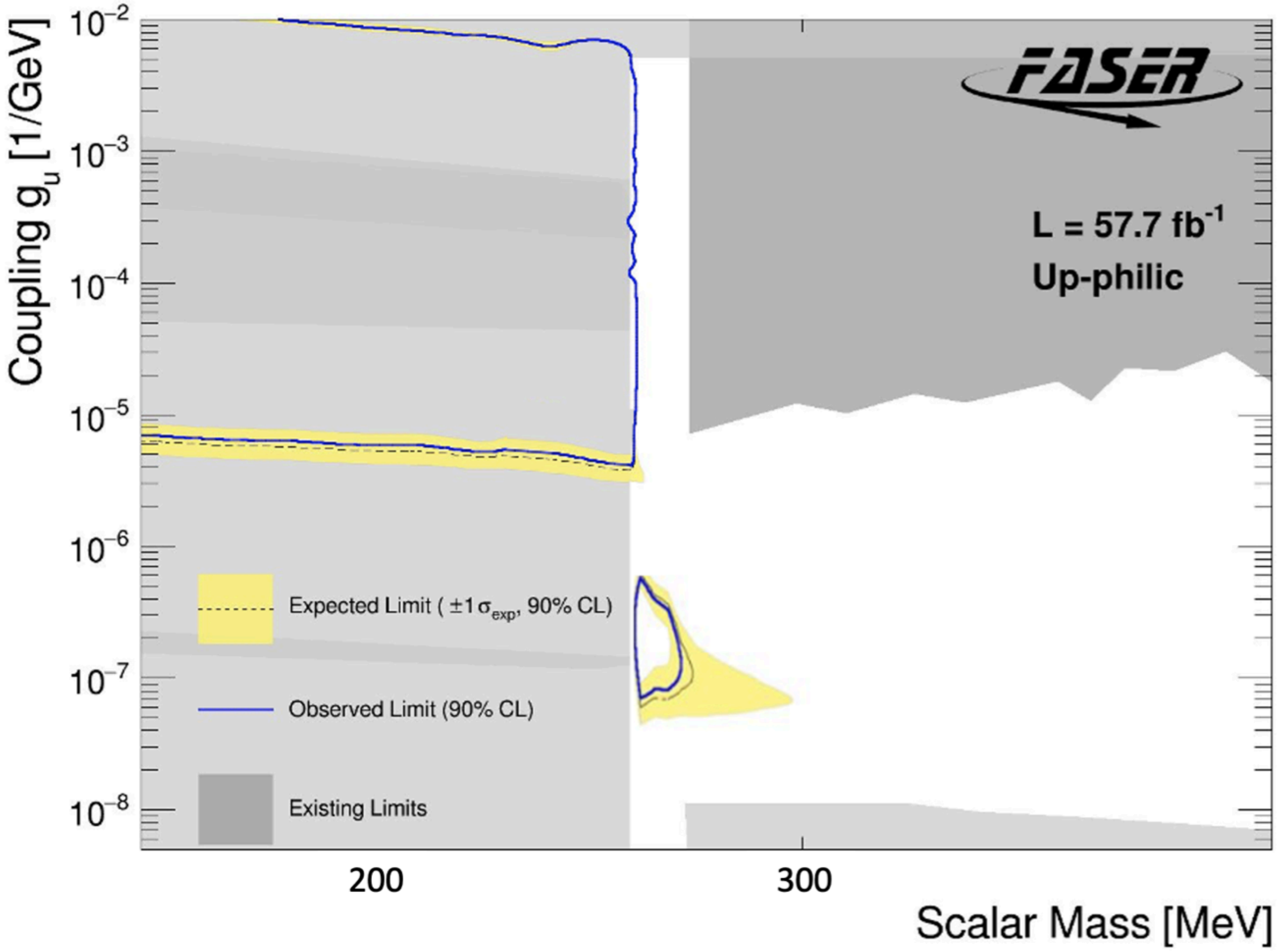
Up-philic

$$\mathcal{L} = -\frac{1}{2}{m_S}^2\ S^2 - g_u \bar{u}\ u\ S.$$

Production:

- **Rare decays of η', η**





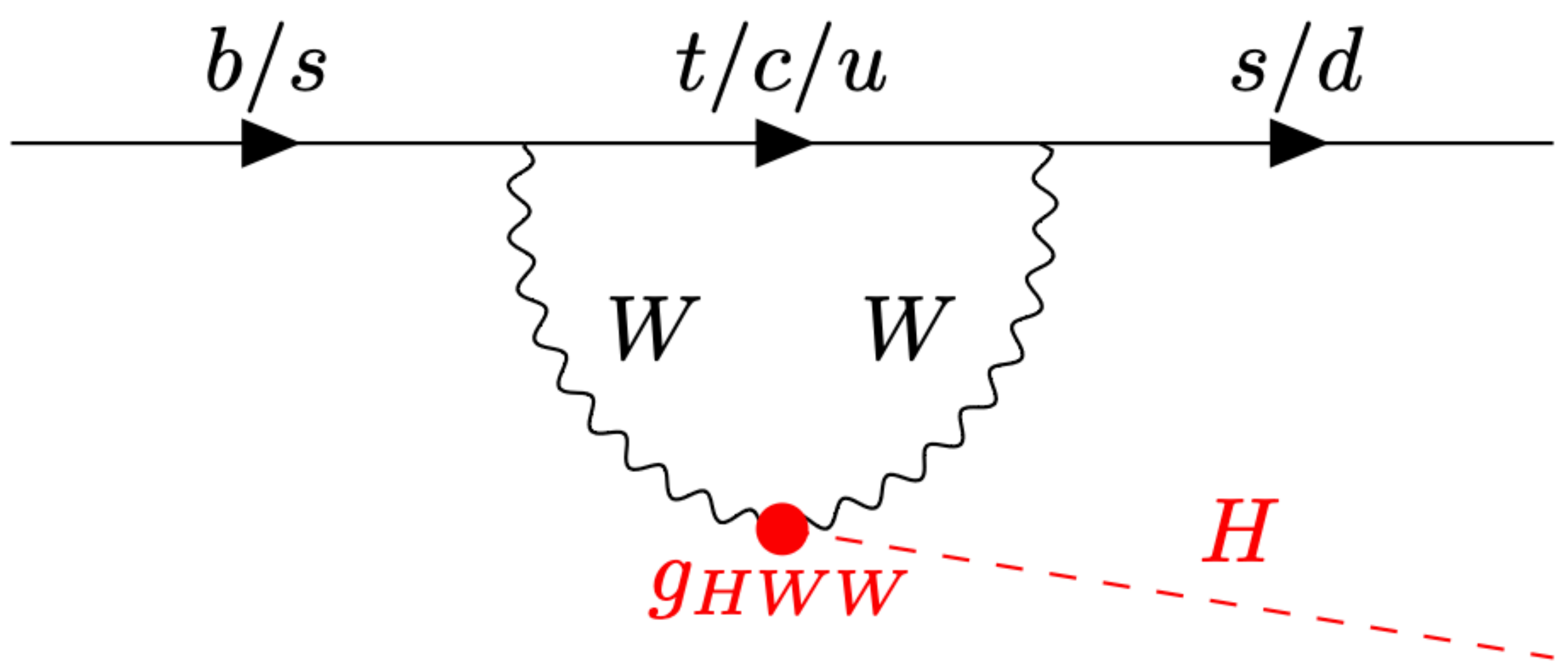
Shining Light on the Dark Sector: Search for Axion-like Particles and Other New Physics in Photonic Final States with FASER; 2410.10363

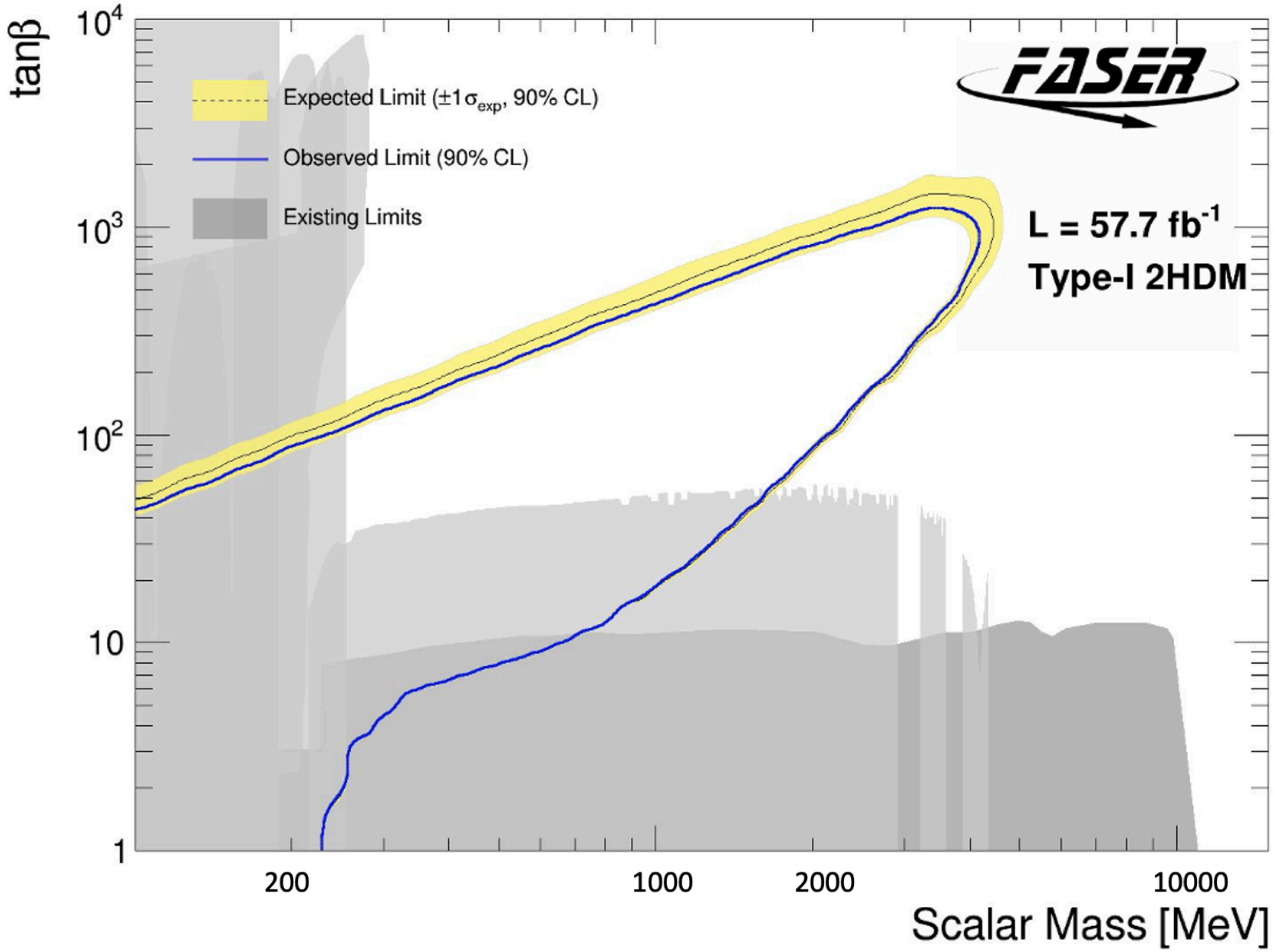
One Analysis To Bound Them All

Type-1 2HDM

Production:

- **FCNC decays of B mesons**





Light Scalars at FASER; 2212.06186

Shining Light on the Dark Sector: Search for Axion-like Particles and Other New Physics in Photonic Final States with FASER; 2410.10363

So what’s next?

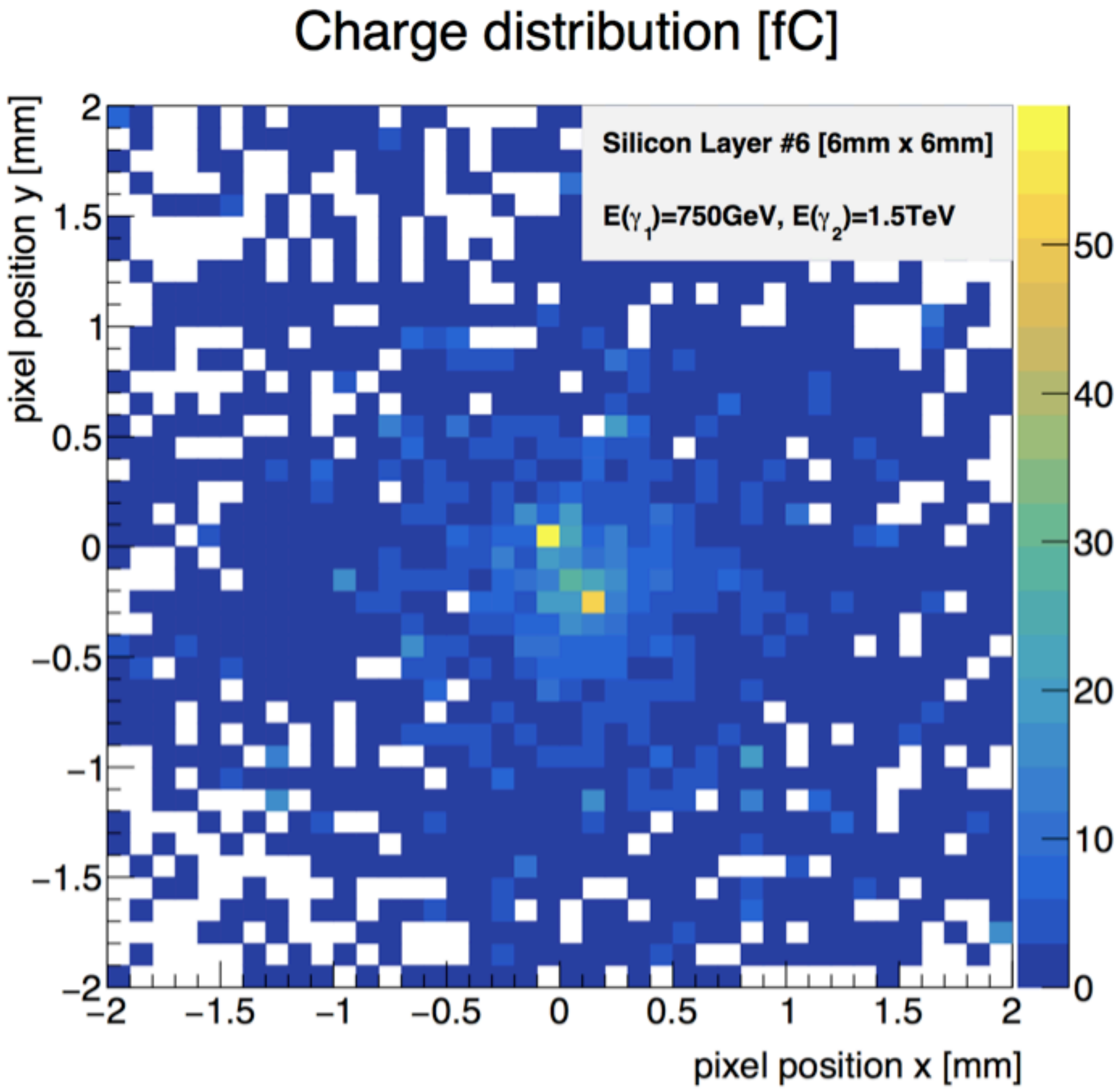
High Precision Preshower

Preshower TP

Abstract: The FASER detector is designed to search for light weakly interacting new particles decaying into charged final states at the LHC. While the first physics data will be taken at the start of Run 3 of the LHC program, an upgrade is already foreseen to enhance the sensitivity to long-lived particles decaying into photons. A high-precision preshower detector will be constructed within the next two years allowing to distinguish the predicted axion-like particles signature of two very closely spaced highly energetic photons. Profiting from recent developments in monolithic pixel silicon detectors, the FASER Collaboration plans to build instrumented silicon pixel detector planes with a granularity of 100 μm interleaved with tungsten absorber planes. The addition of the new pre-shower detector will expand the physics search capability of FASER.

Planned to be installed in time for 2025 data taking.

High Precision Preshower

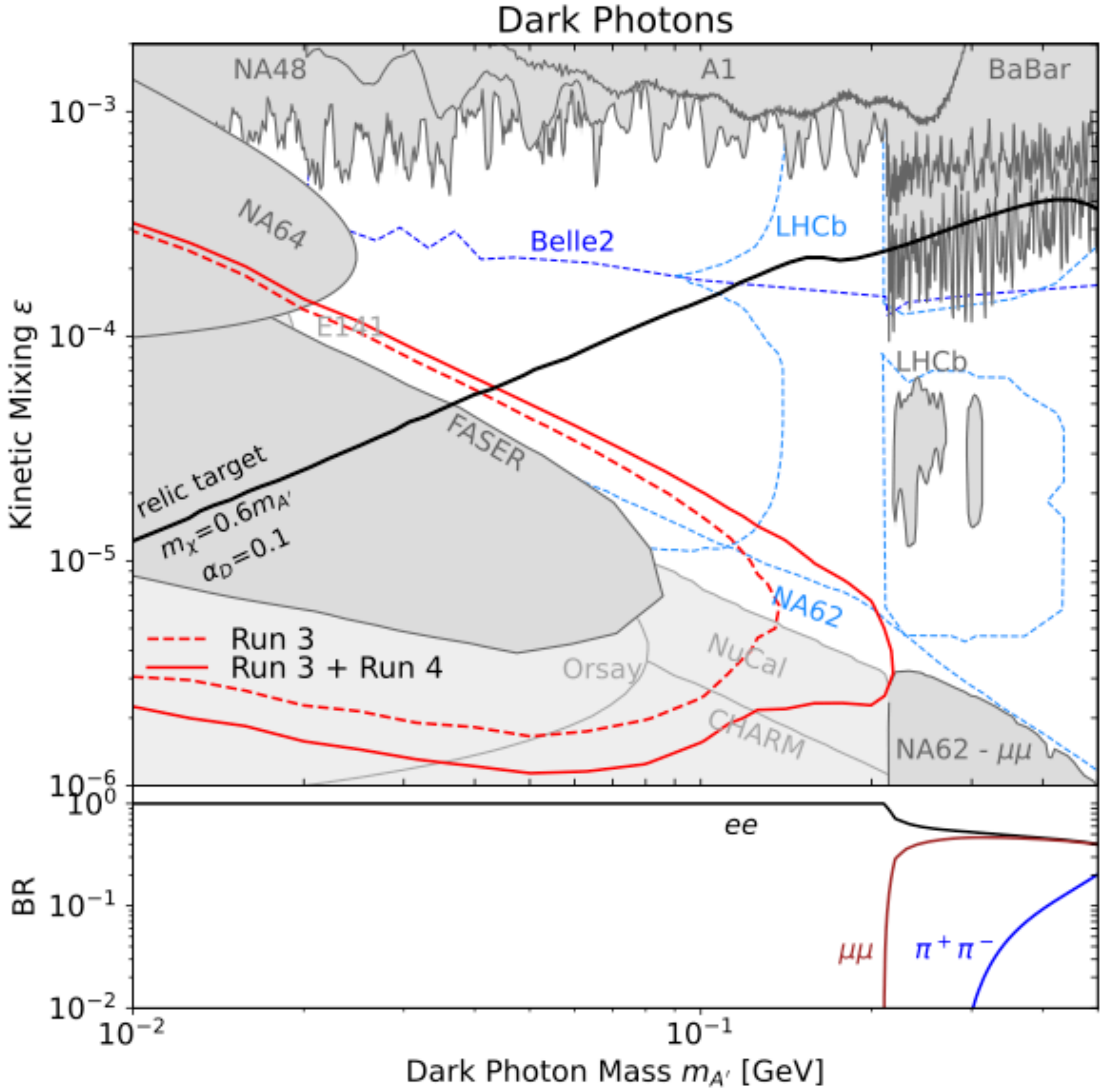


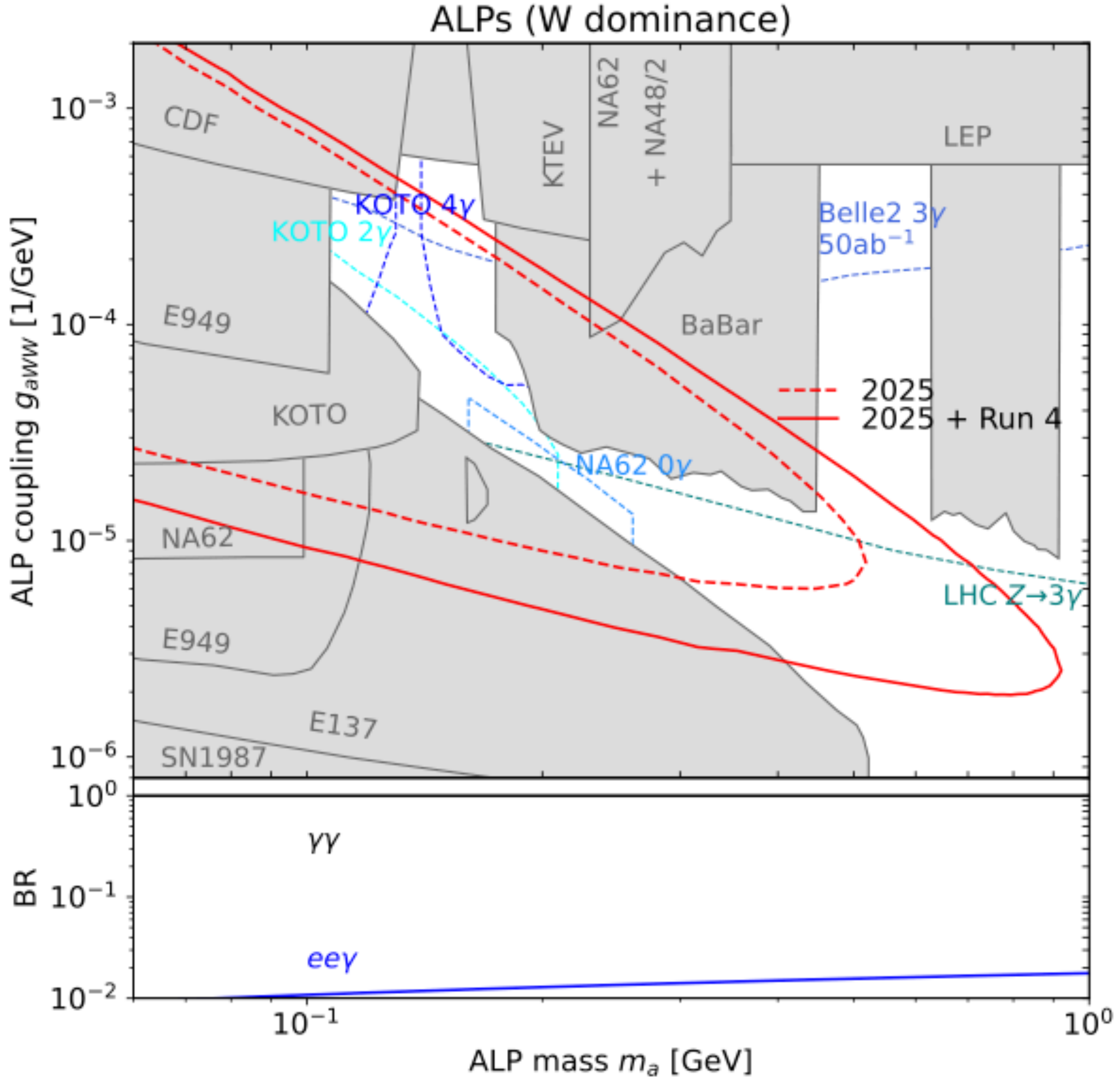
Preshower TP

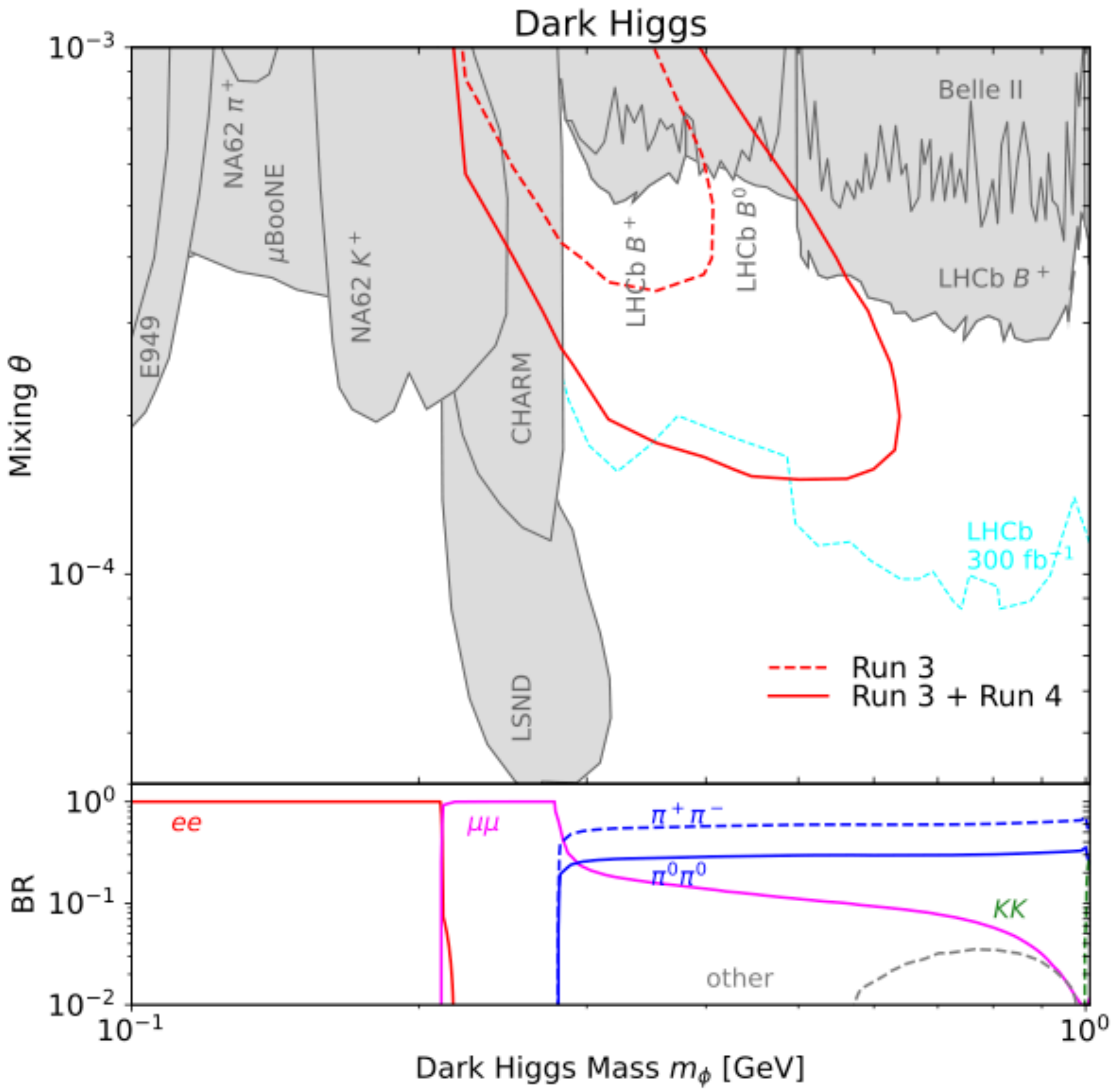
- Can resolve photons as finely separated as 0.2mm.
- This can significantly enhance the physics potential of the FASER detector.

FASER approved for Run 4

Run 4 proposal for FASER



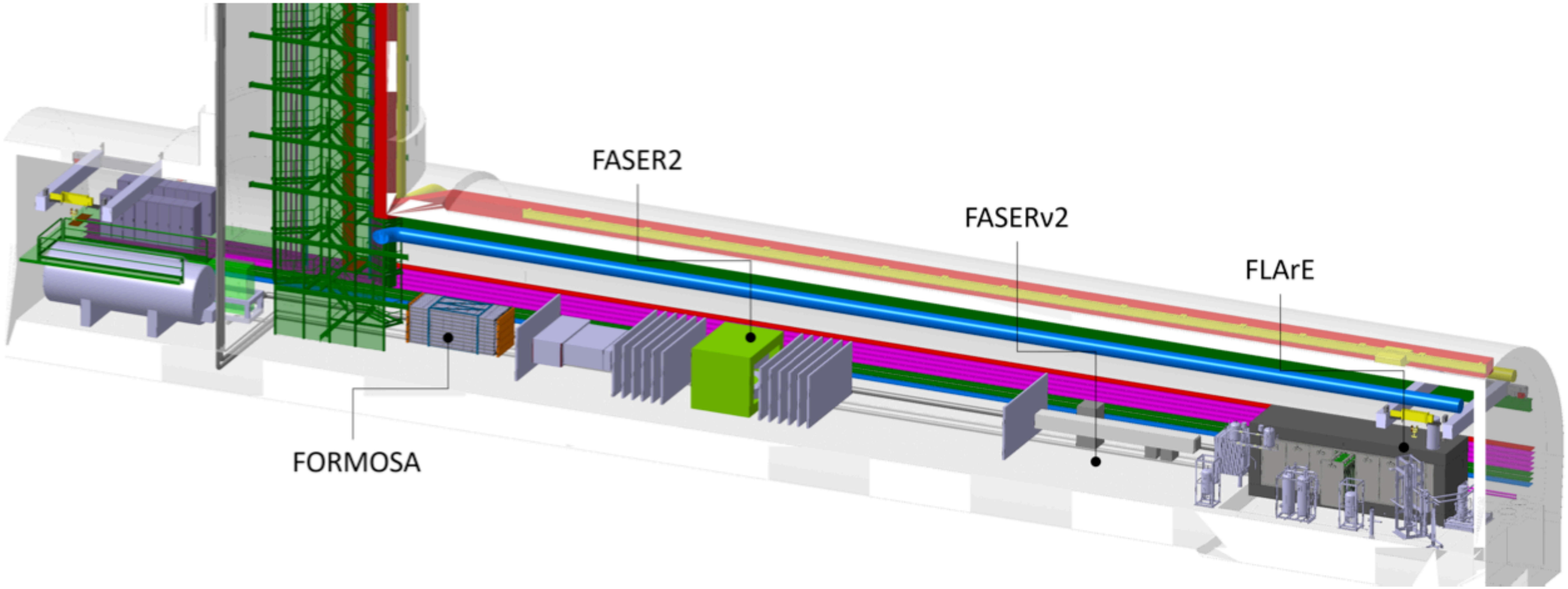


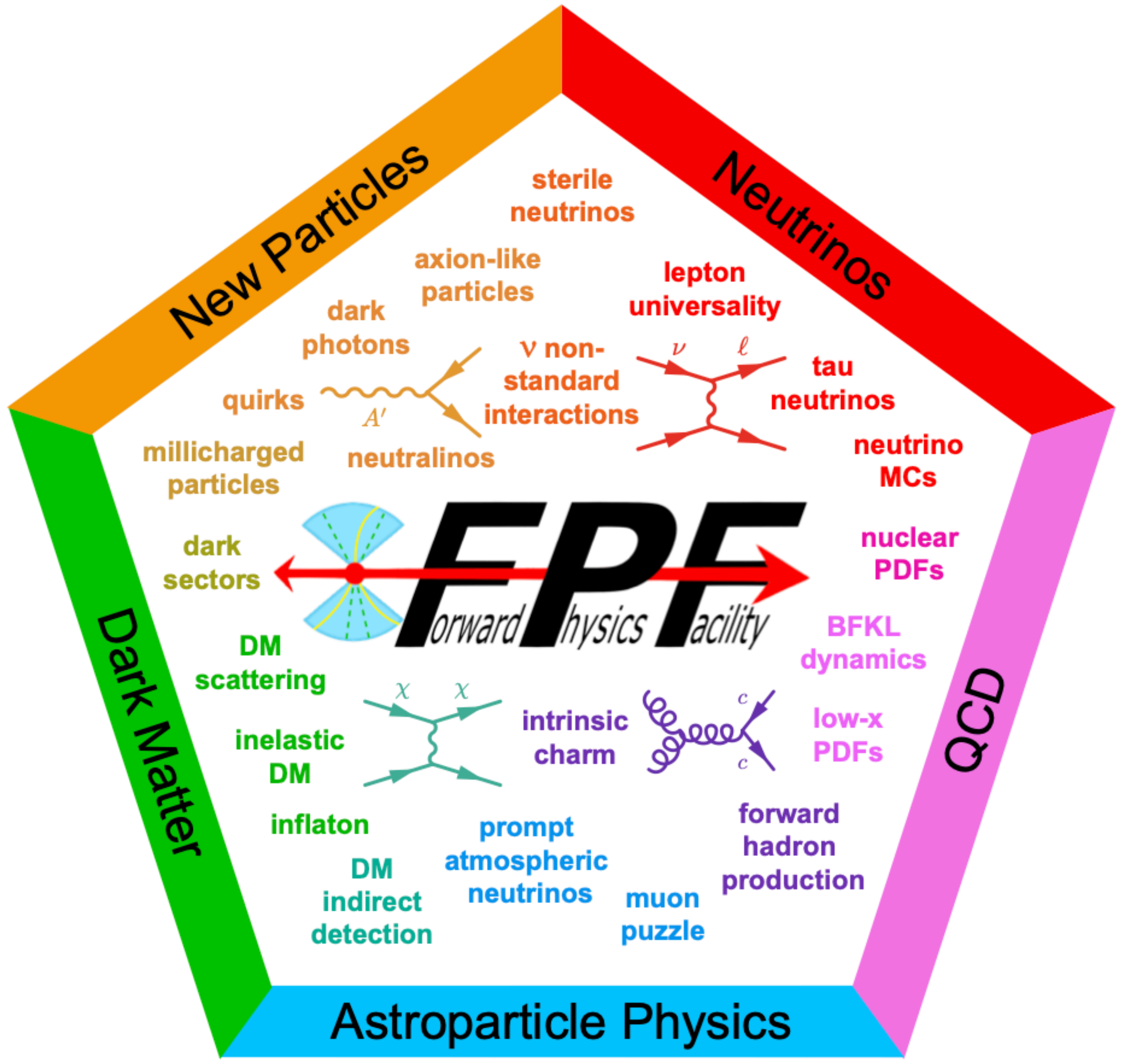


Many more models to be explored …..

And after that?

Proposed Expansion for HL-LHC: Forward Physics Facility



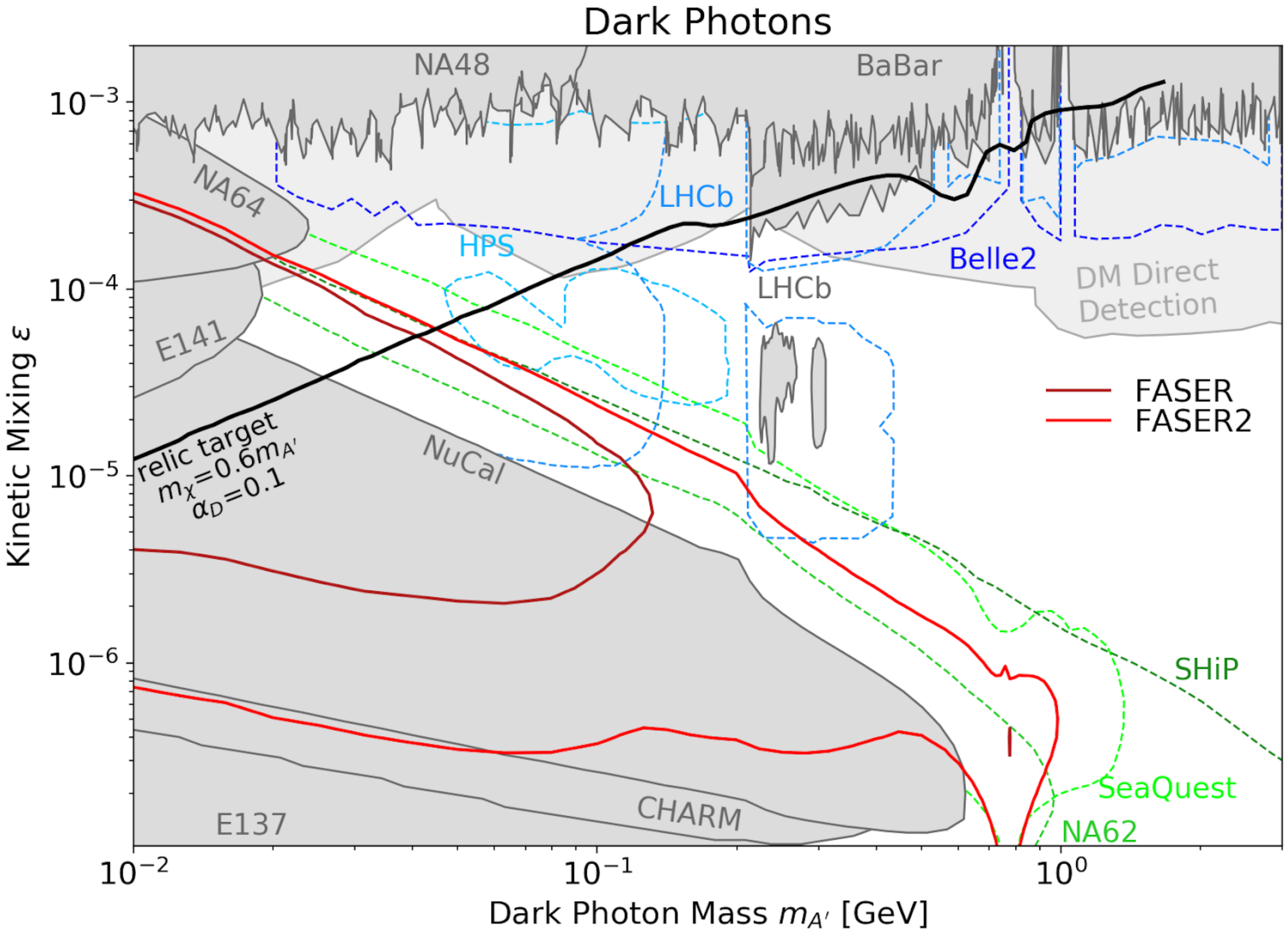


FPF is proposed to house 4 detectors in the forward direction to study SM and BSM physics.

The Forward Physics Facility: Sites, Experiments, and Physics Potential; 2109.10905
The Forward Physics Facility at the High-Luminosity LHC; 2203.05090
Update of Facility Technical Studies for the FPF; CERN-PBC-NOTE 2024-004

Dark Photon Searches at FASER2

$$\mathscr{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon e \bar{f} \gamma_\mu f A'^\mu$$



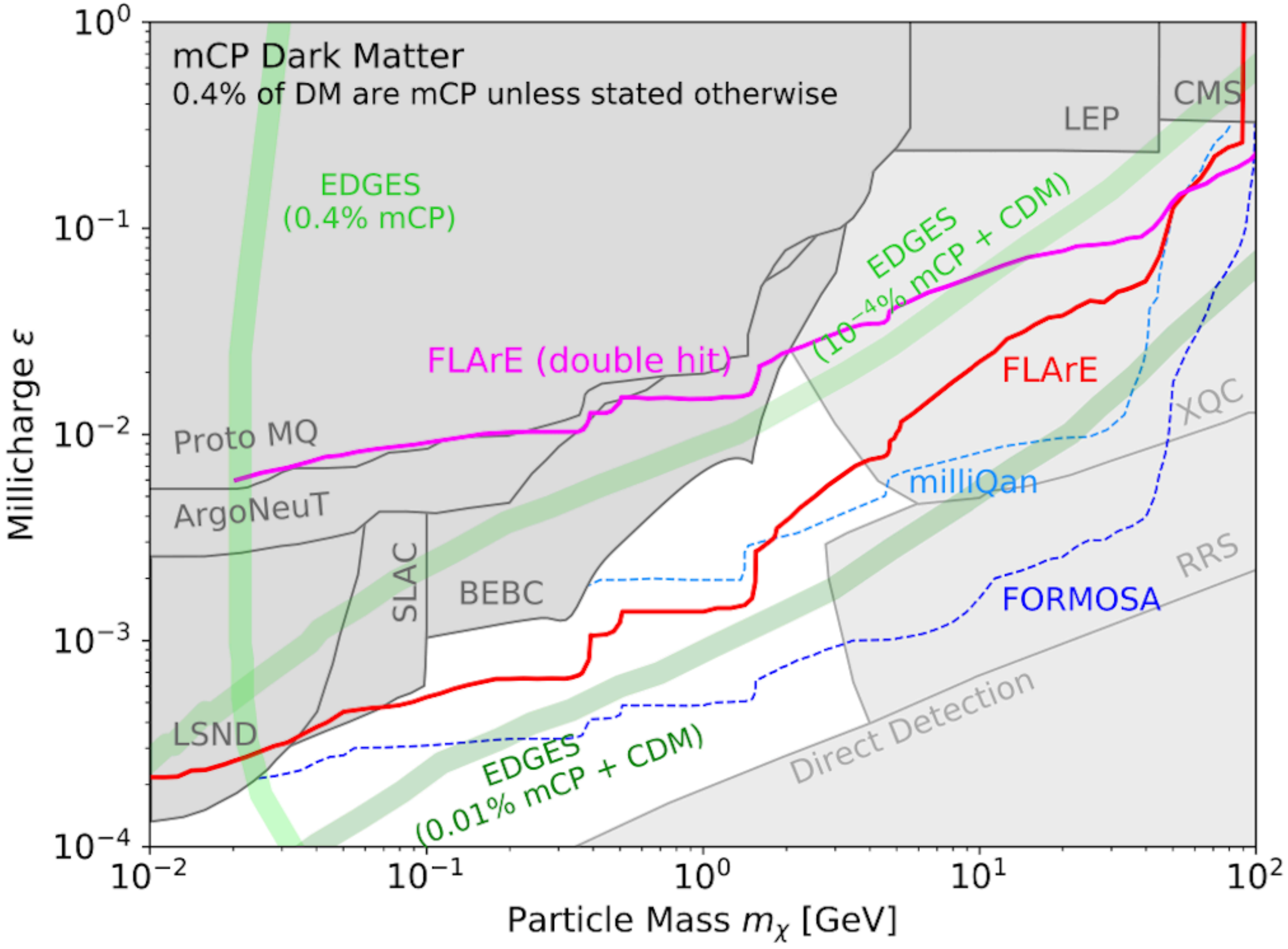
Felix Kling, Sebastian Trojanowski; 2105.07077

mCP Searches at FORMOSA

mCPs passing through the detector can result in scattering, and ionization signatures

Saeid Foroughi-Abari, Felix Kling, Yu-Dai Tsai; 2010.07941

Felix Kling, Jui-Lin Kuo, Sebastian Trojanowski, Yu-Dai Tsai; 2205.09137



FASER collaboration meeting, 2024

The future is FORWARD