Neutrino and Muon Physics at Forward Detectors at LHC

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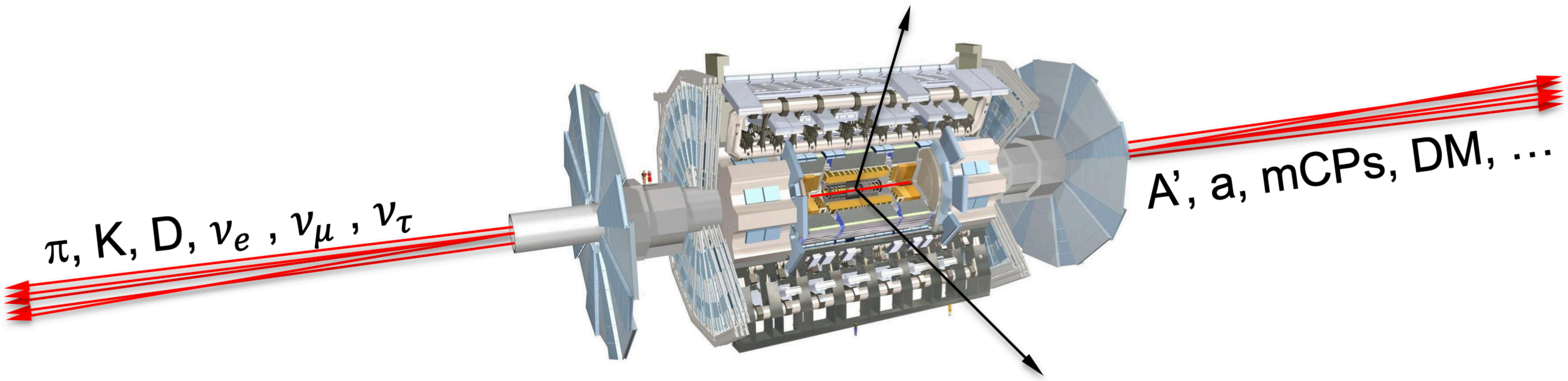
Forward Region at the LHC

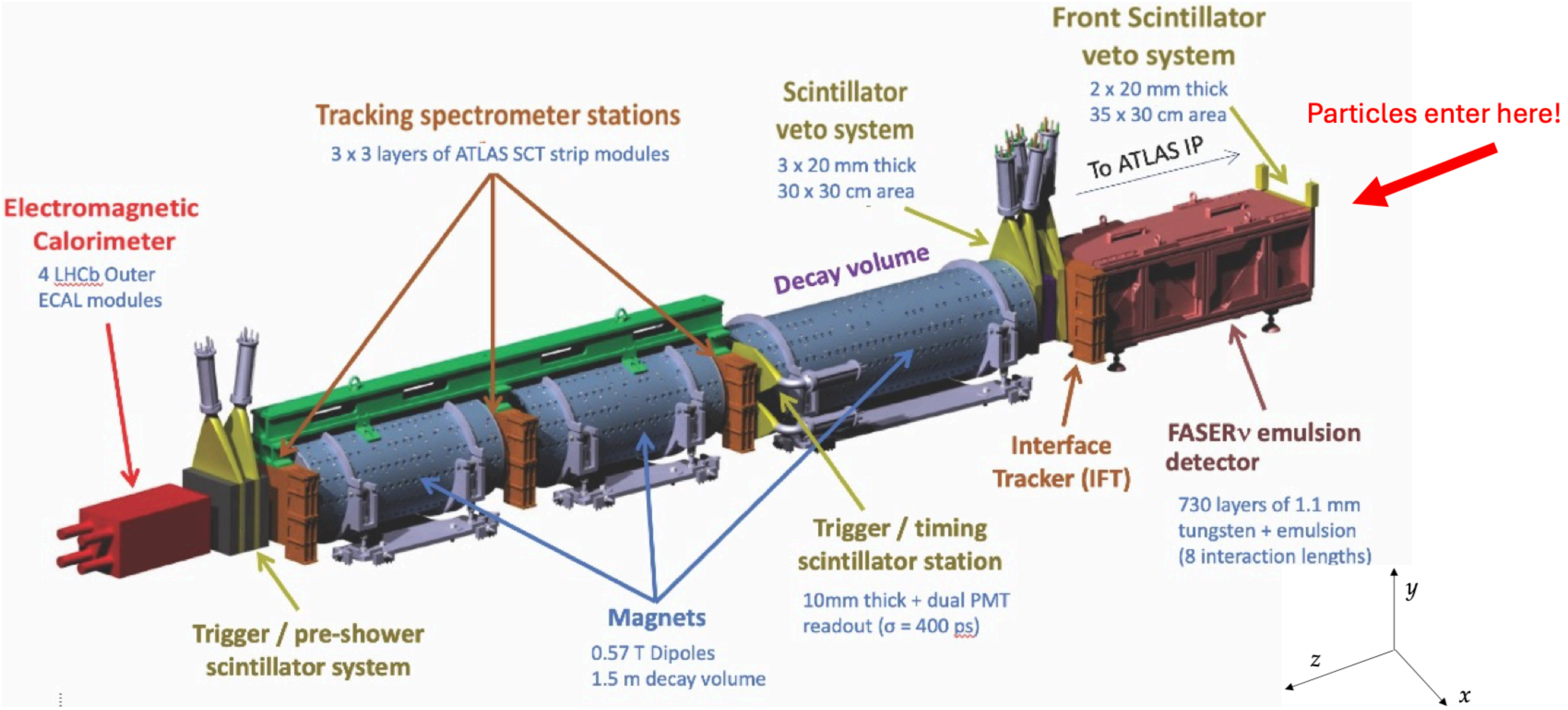


- pp collisions at the LHC produce an intense flux of particles in the forward direction
- These particles are light and weakly coupling:
  - SM (ν, μ, …) and BSM (ALPs, dark photon, DM, …)
- Conventional transverse detectors will miss these particles

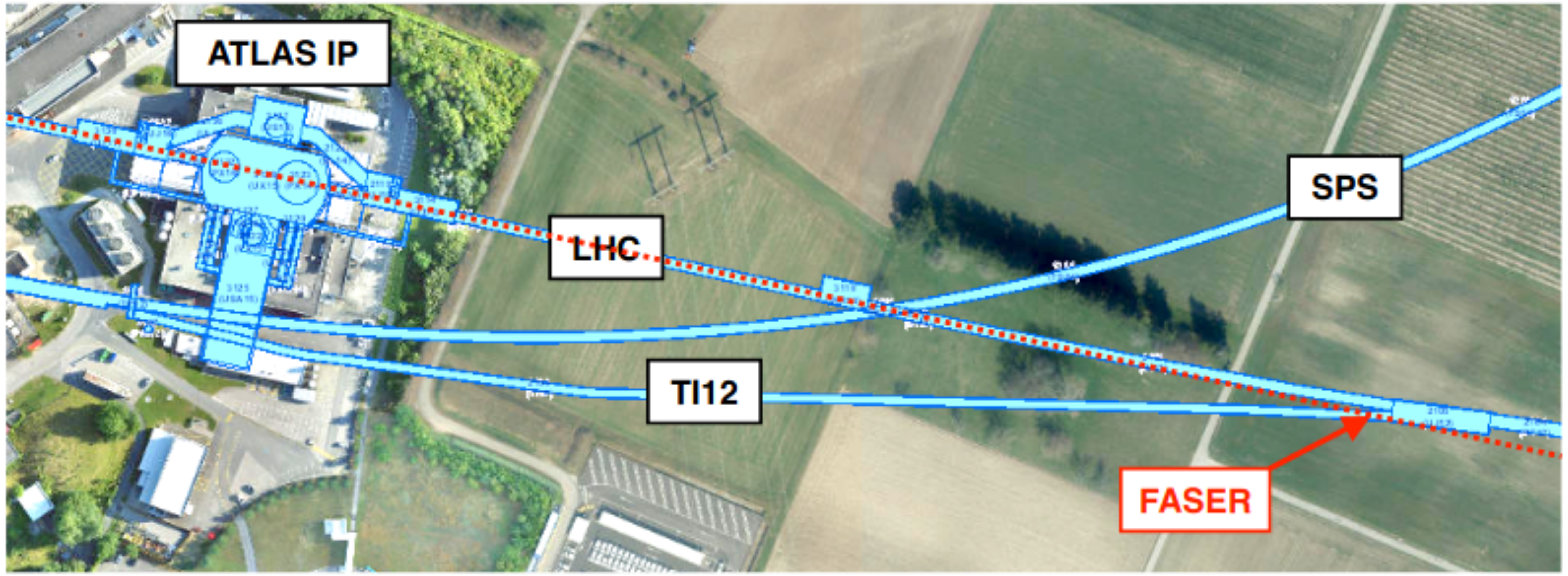
Jonathan L. Feng, Iftah Galon, Felix Kling, Sebastian Trojanowski;1708.09389

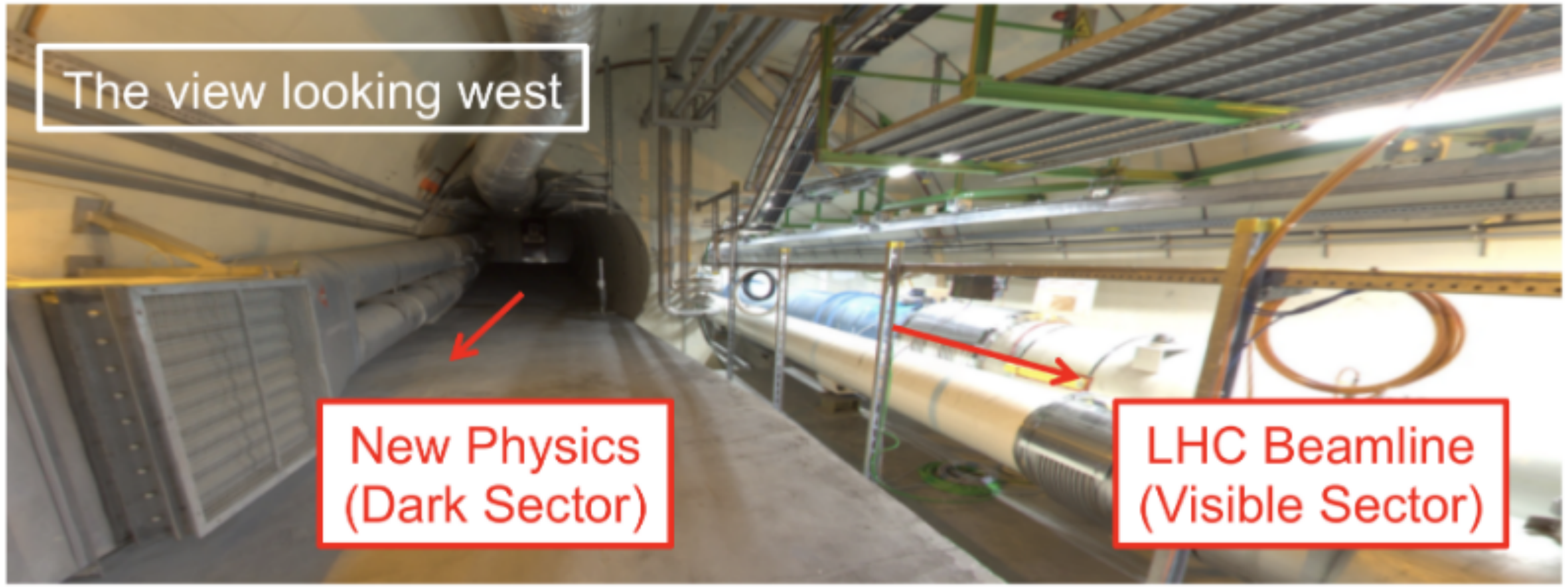
ForwArd Search ExpeRiment(ν) - FASER(ν)

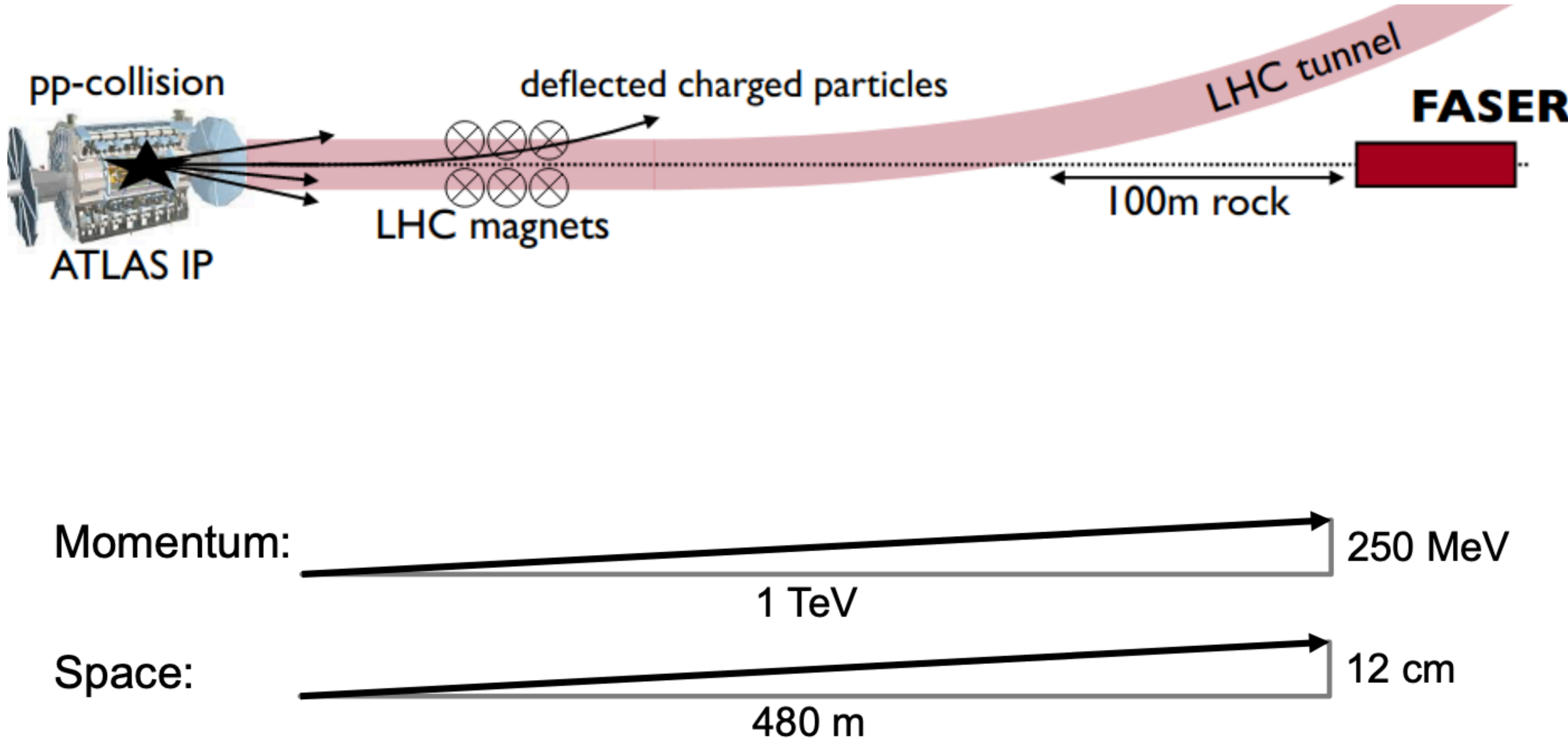
- **FASER: 25cm x 25cm x 1.5m decay volume**
  - **1708.09389 (first paper), 1811.10243 (LOI), 1812.09139**
- **FASERν: 25cm x 25cm x 1m tungsten emulsion detector**
  - **1908.02310, 2001.03073**
- $\eta \gtrsim 8.5$ **coverage.**



Location for forward detectors at LHC







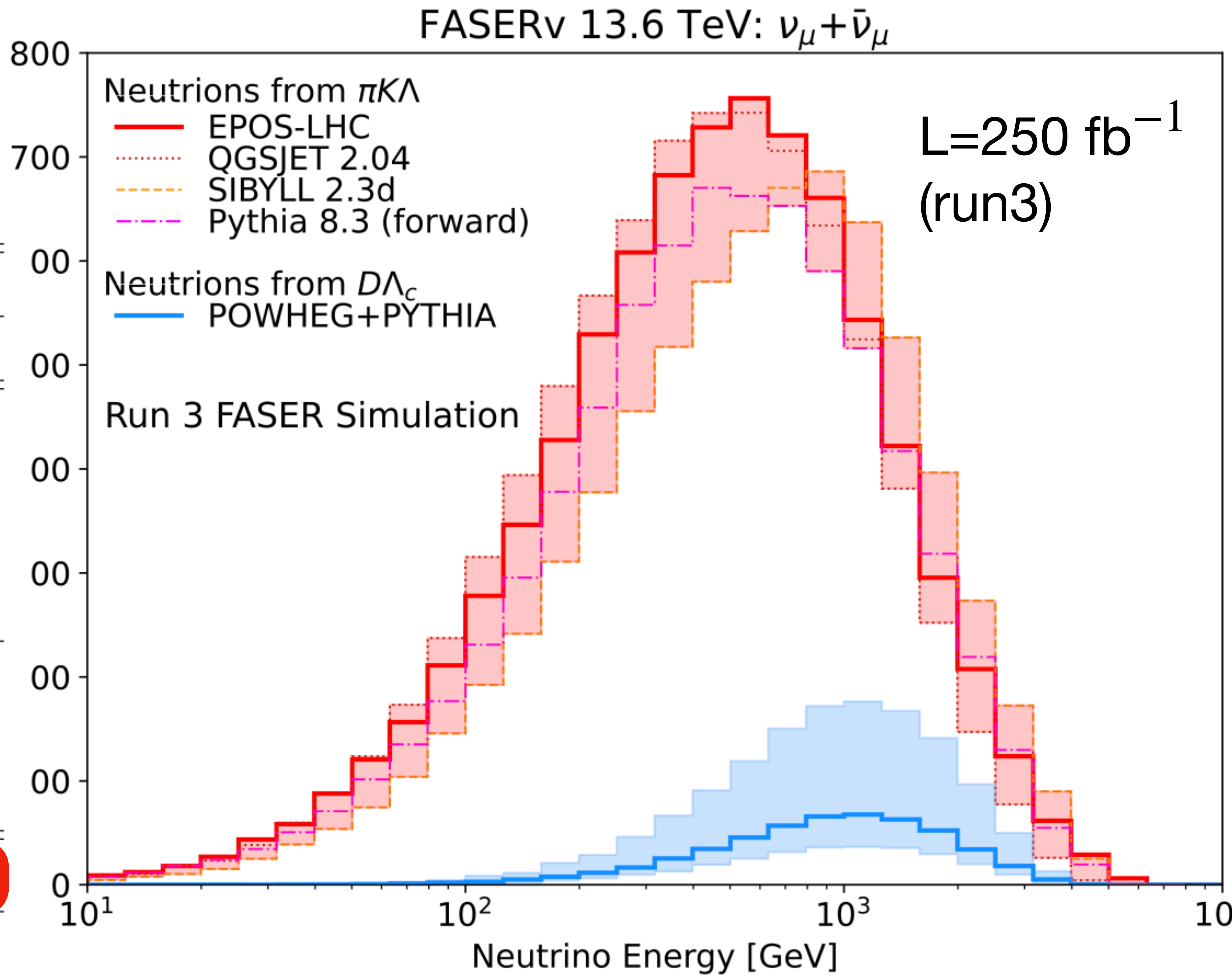
Neutrino Flux at FASER

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



L=250 fb^{-1}
(run3)

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	$\nu_e+\bar\nu_e$	$\nu_\mu+\bar\nu_\mu$	$\nu_\tau+\bar\nu_\tau$	$\nu_e+\bar\nu_e$	$\nu_\mu+\bar\nu_\mu$	$\nu_\tau+\bar\nu_\tau$
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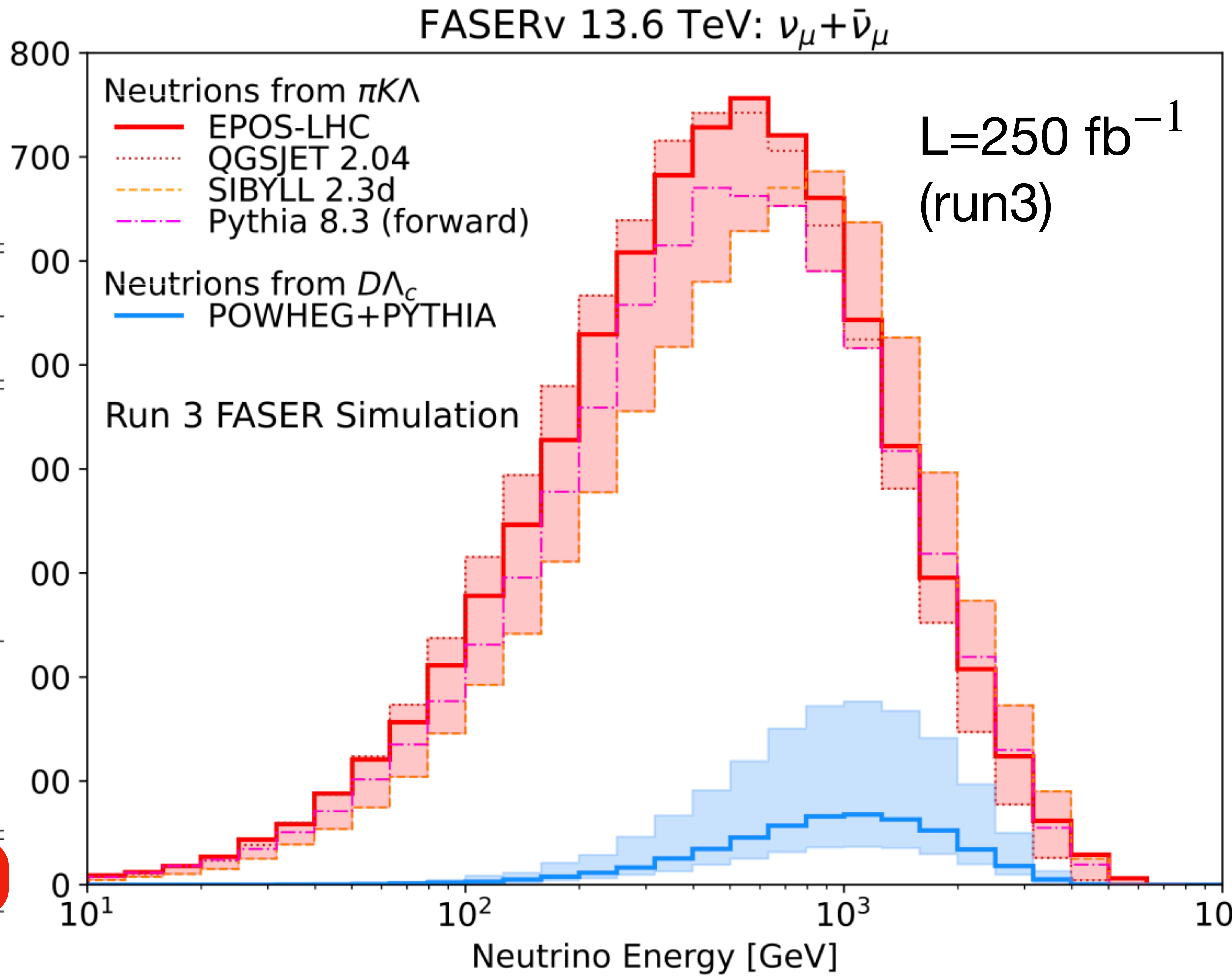
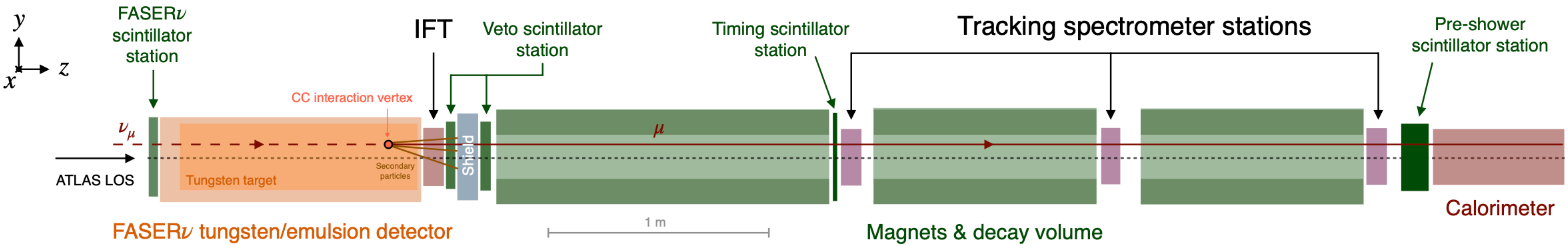


Already many new exciting results!!!

Neutrino Rate Predictions for FASER, 2402.13318

First Observation of Collider Neutrinos

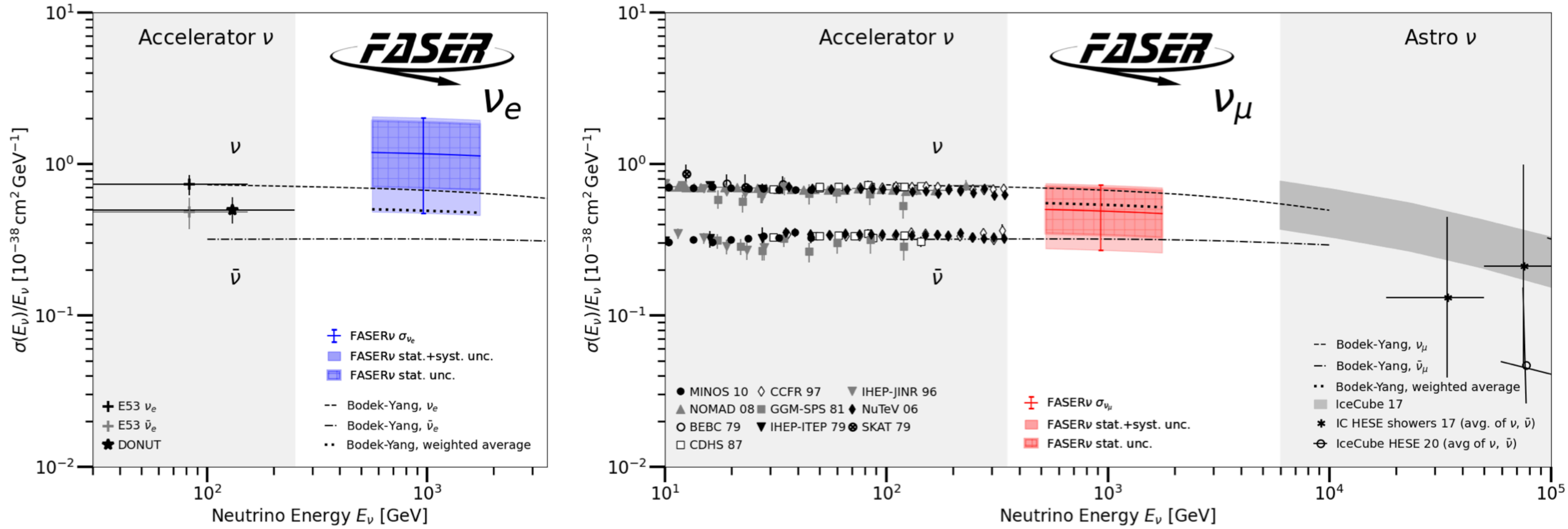


At FASER

~150 ν_μ CC events with 35.4 fb^{-1} of data.

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

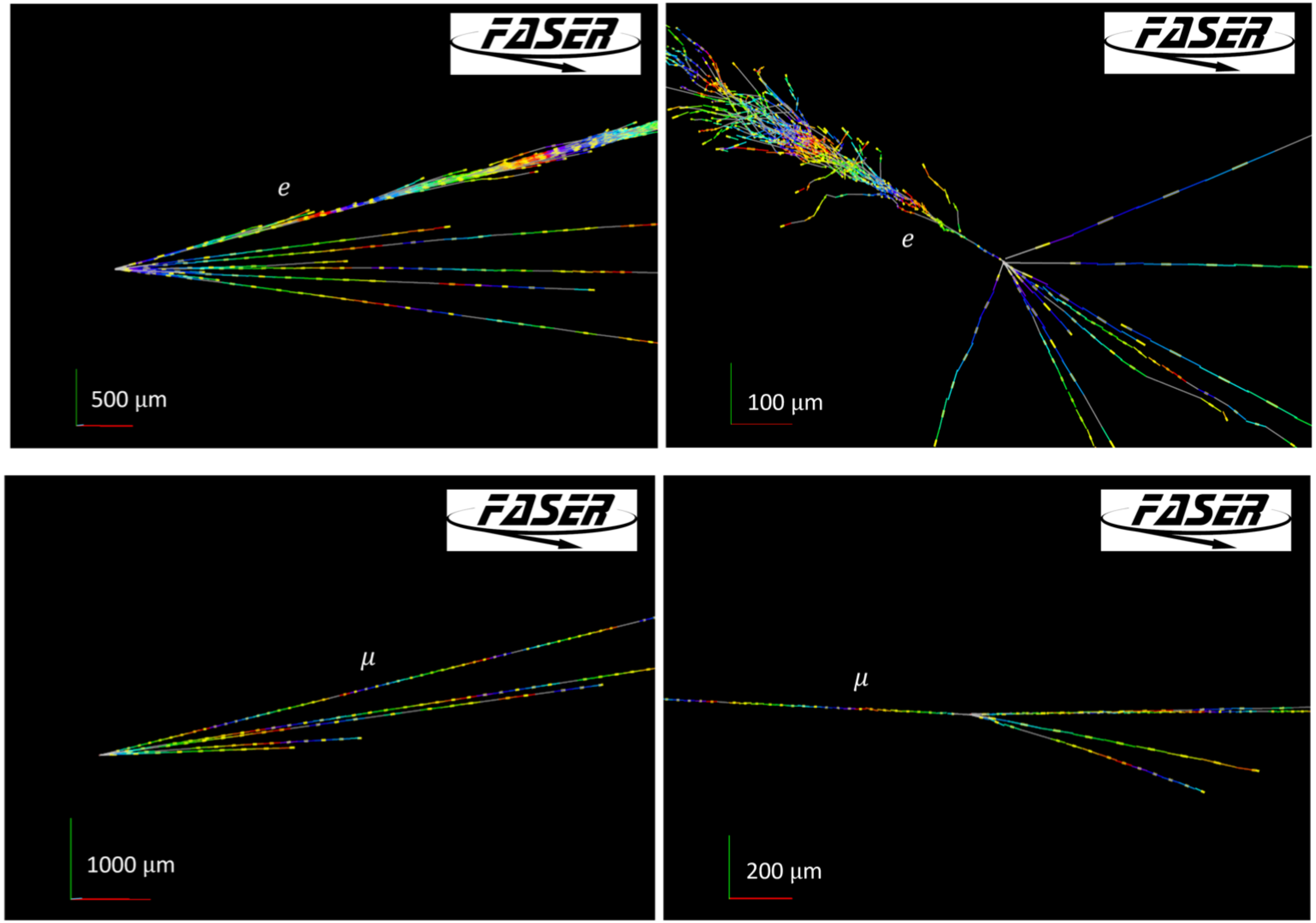
First Neutrino Cross-Section Measurements at LHC



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

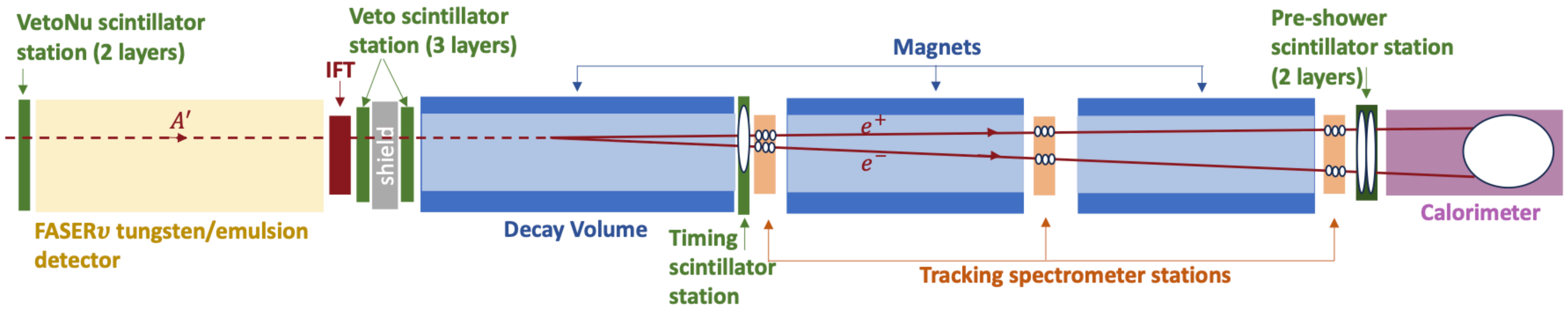
First Measurement of the ν_e and ν_μ Interaction Cross Sections at the LHC with FASER's Emulsion Detector; 2403.12520

ν_e and ν_μ events at FASERν

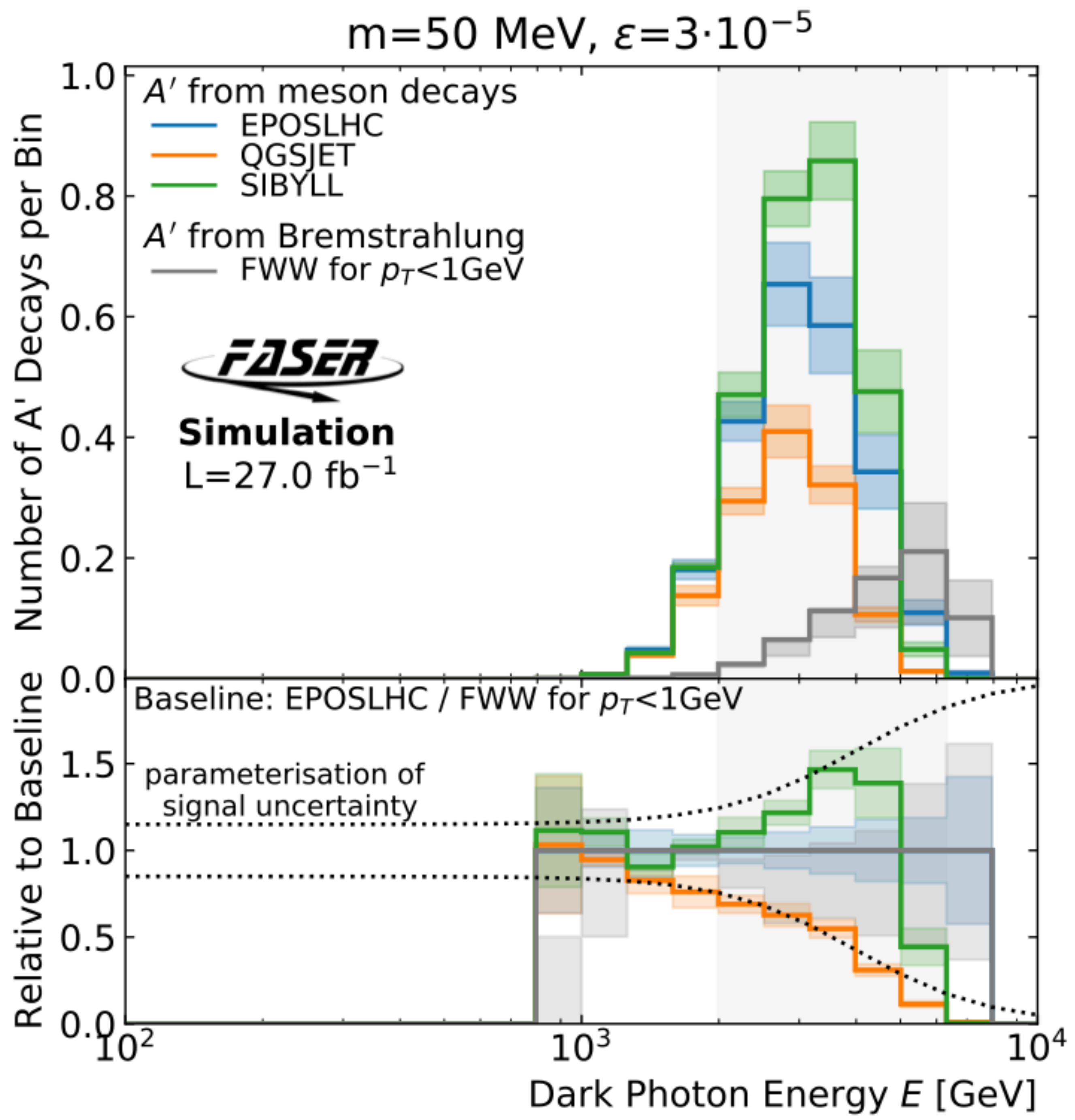


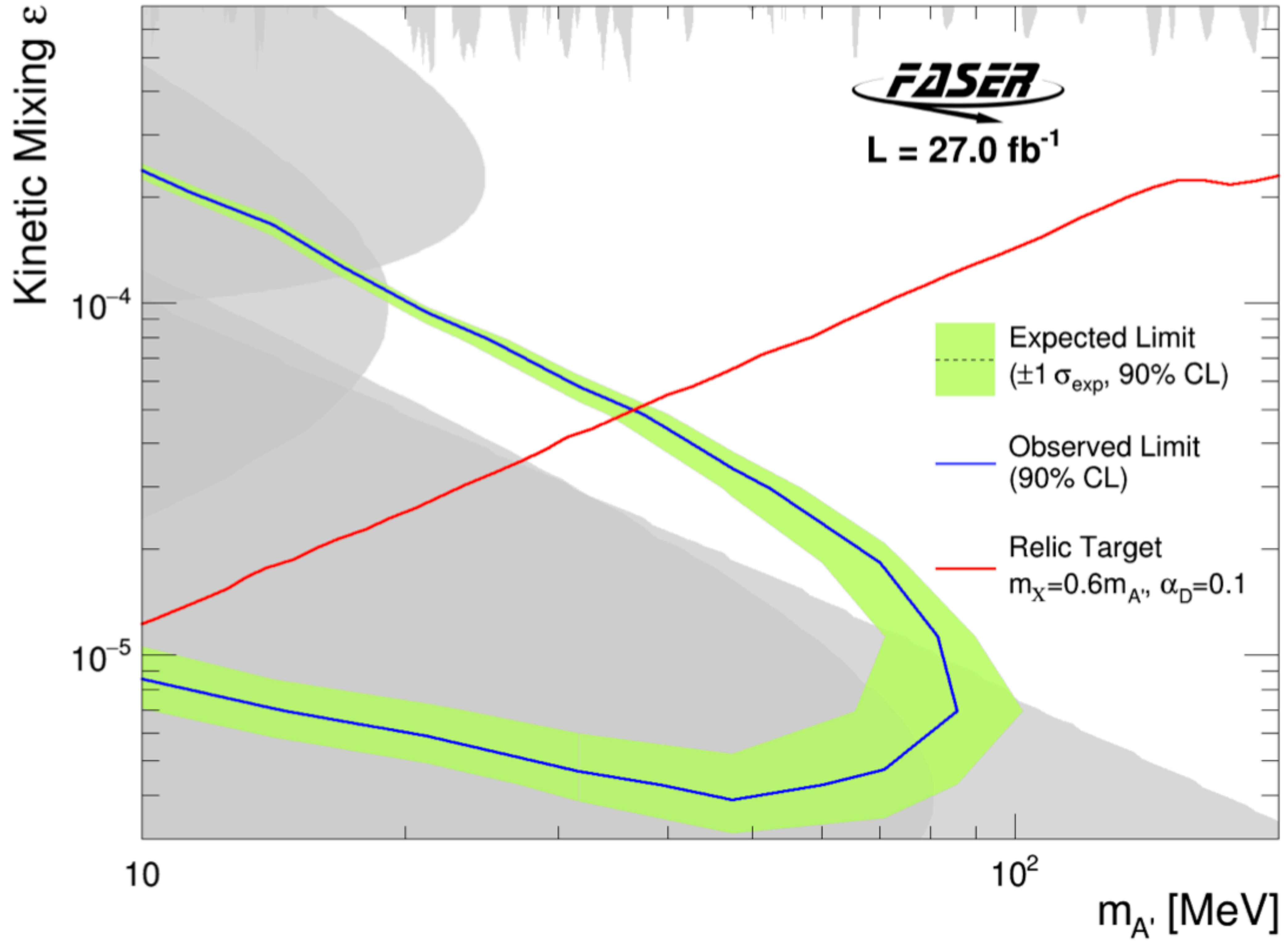
First Measurement of the ν_e and ν_μ Interaction Cross Sections at the LHC with FASER's Emulsion Detector; 2403.12520

Dark Photon Searches at FASER



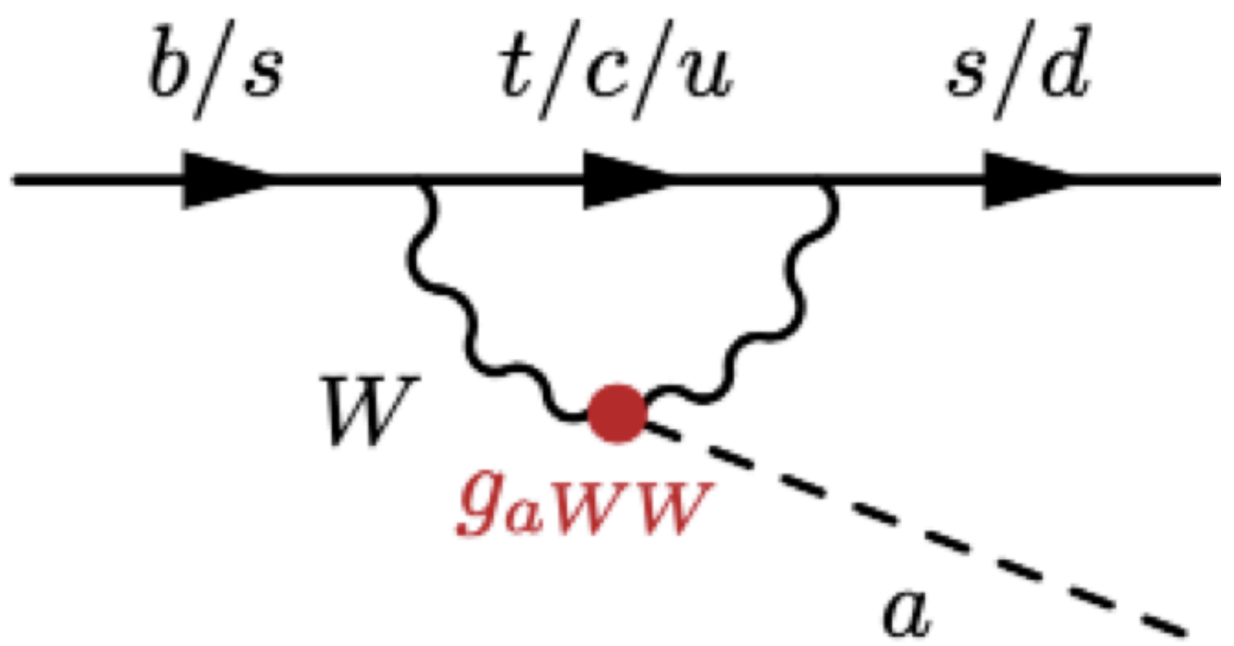
Search for Dark Photons with the FASER detector at the LHC; 2308.05587

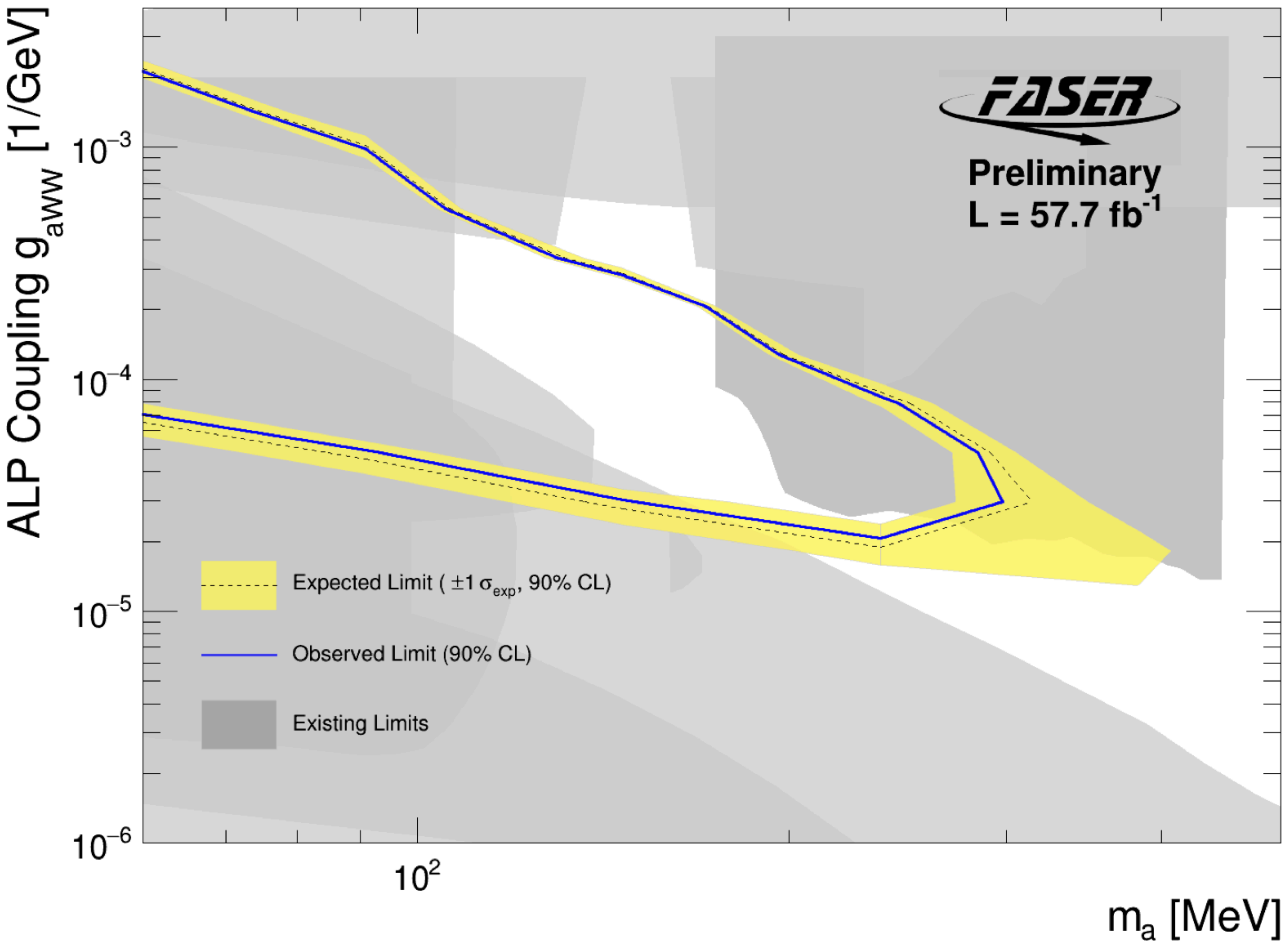




ALP Searches at FASER

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





Search for Axion-Like Particles in Photonic Final States with the FASER Detector at the LHC; Conf note

Proposed Expansion for HL-LHC: Forward Physics Facility

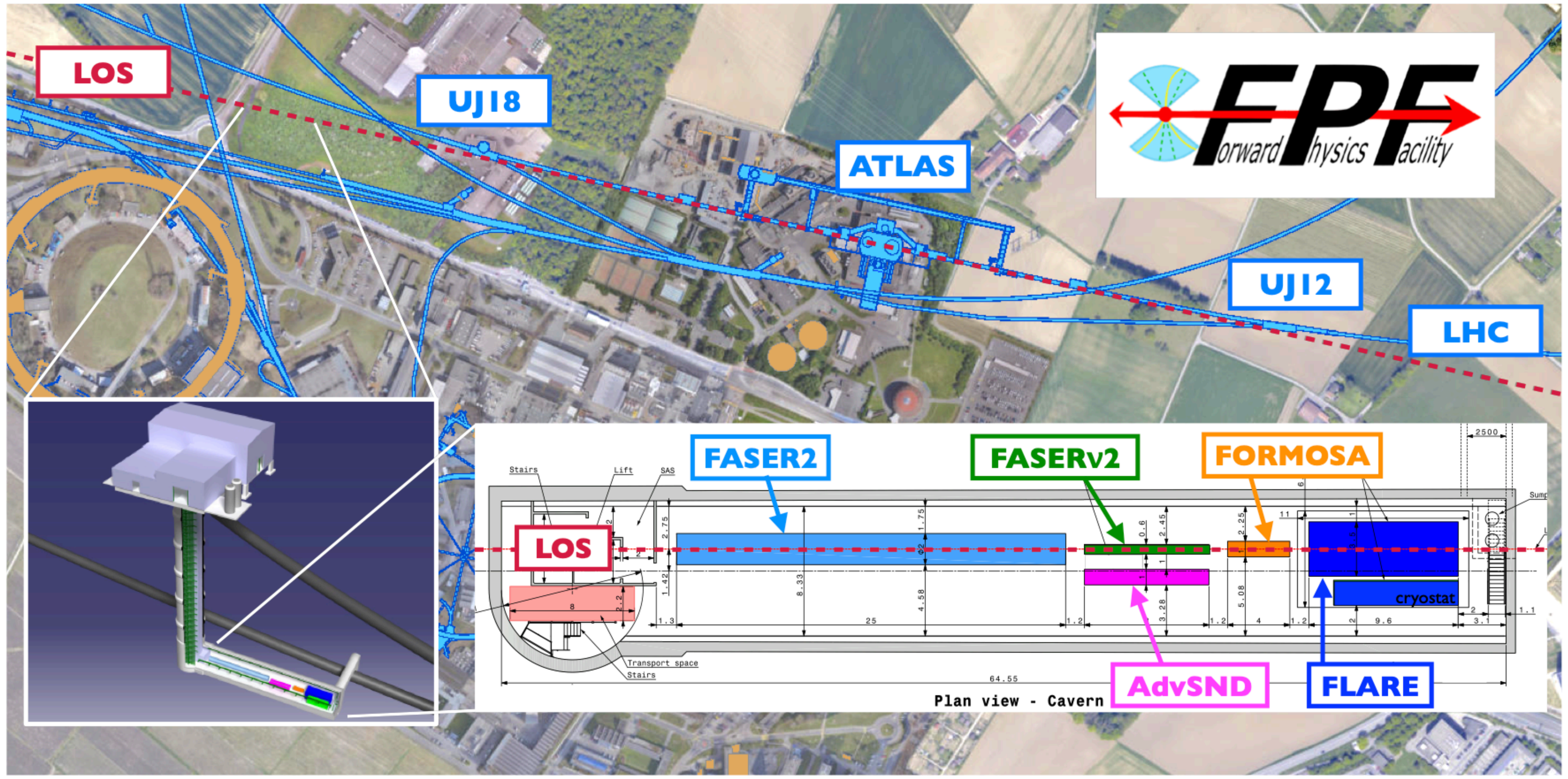


Figure 1: The preferred location for the Forward Physics Facility, a proposed new cavern for the High-Luminosity era. The FPF will be 65 m-long and 8.5 m-wide and will house a diverse set of experiments to explore the many physics opportunities in the far-forward region.

FPF is proposed to house 5 detectors in the forward direction to study SM and BSM physics.

The Forward Physics Facility: Sites, Experiments, and Physics Potential; 2109.10905

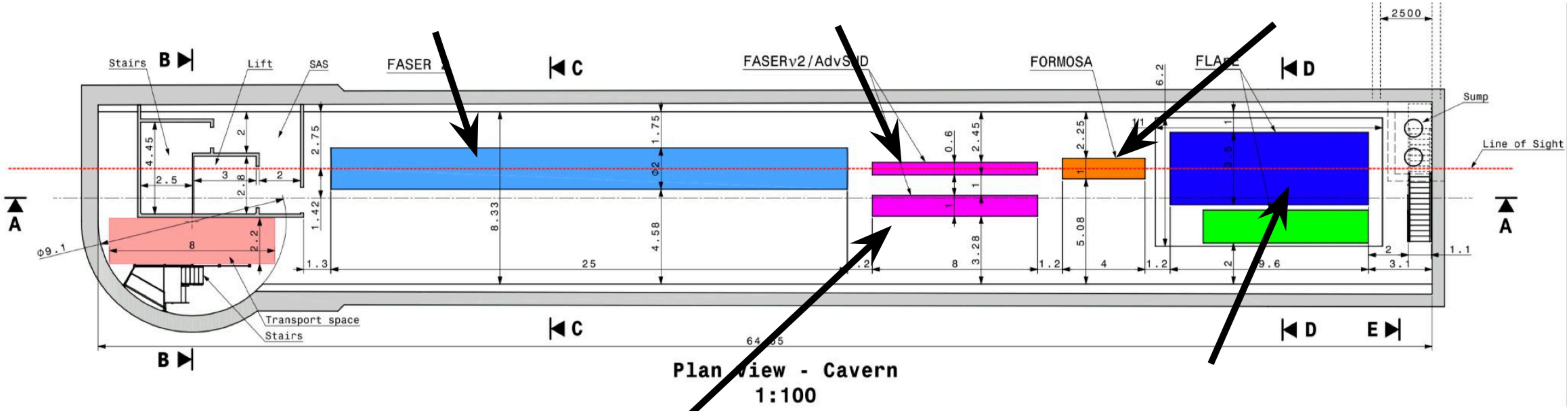
The Forward Physics Facility at the High-Luminosity LHC; 2203.05090

Forward Physics Facility

FASER2
magnetized spectrometer
for BSM searches

FASERv2
emulsion-based
neutrino detector

FORMOSA
plastic scintillator array
for BSM searches

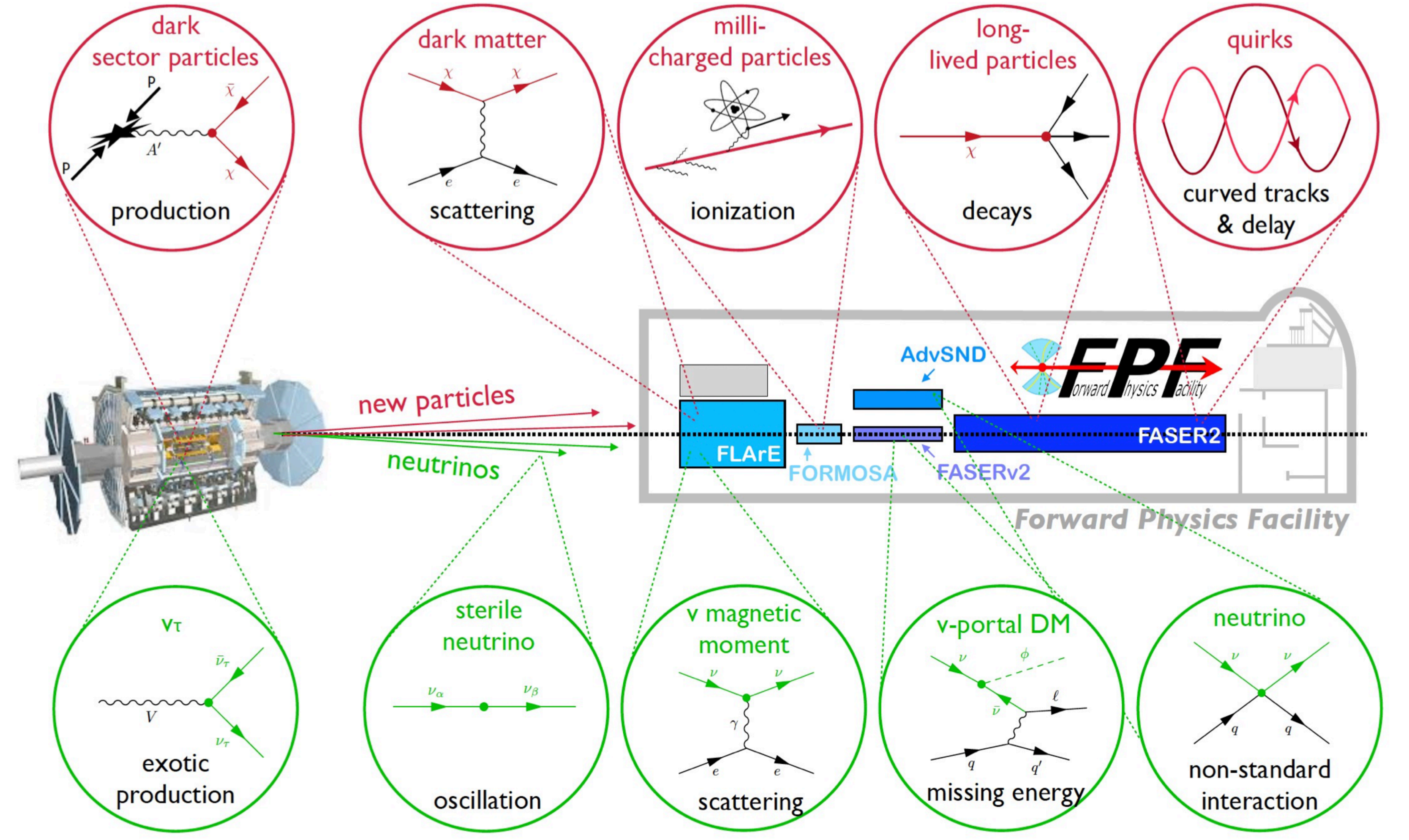


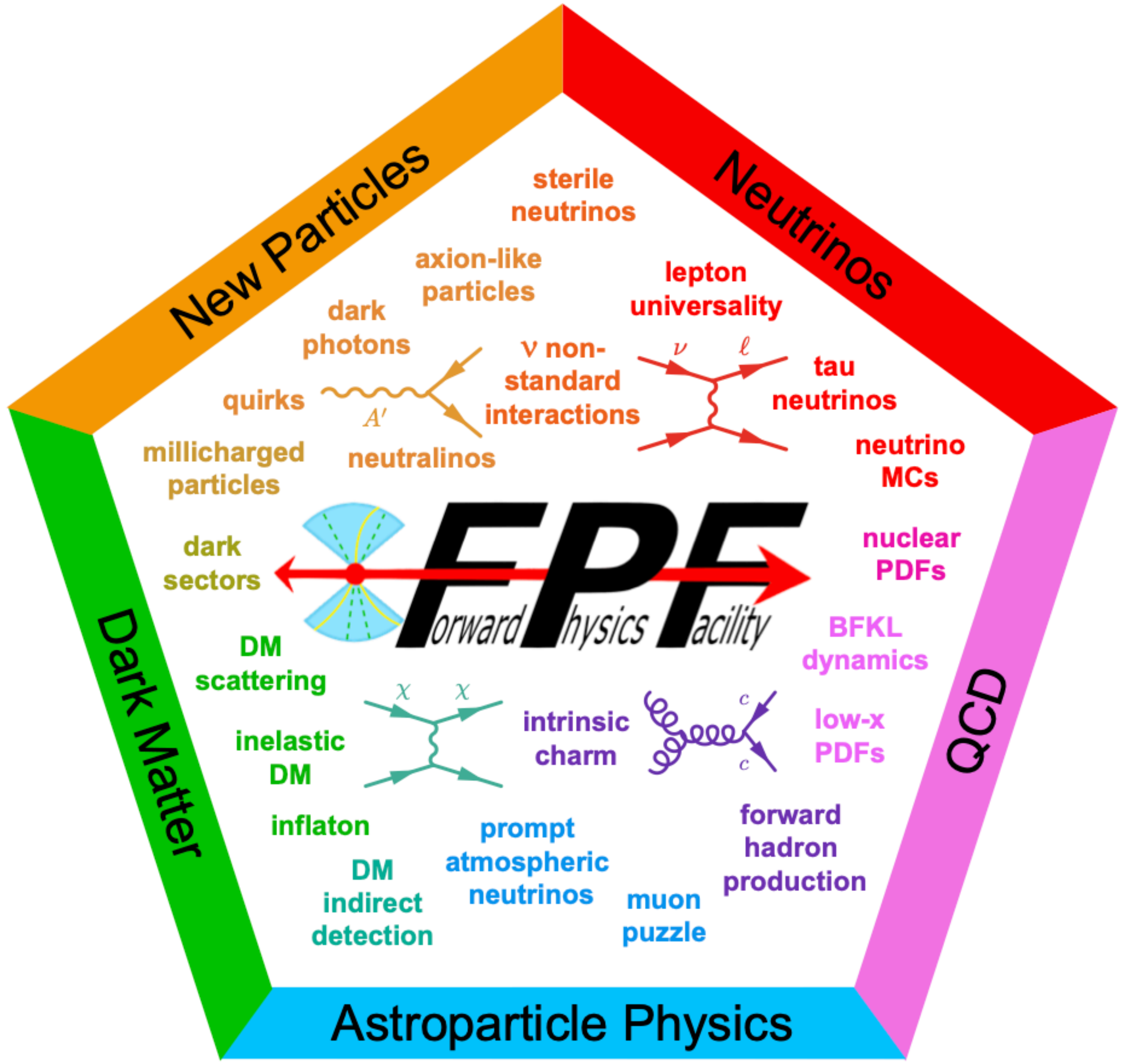
AdvSND
electronic
neutrino detector

FLArE
LAr based
neutrino detector

The Forward Physics Facility: Sites, Experiments, and Physics Potential; 2109.10905
The Forward Physics Facility at the High-Luminosity LHC; 2203.05090

Many Physics opportunities at FPF





Some Theoretical Work in the Forward Direction

- Neutrino Physics
- Muon Physics

All these neutrinos deserve some theoretical attention too!!!

And also the muons, they are not just backgrounds!!!

Neutrino Electromagnetic (EM) Properties

- νs have zero electric charge and no tree-level EM interactions.
- They can arise at loop level or via BSM effects.
- $\nu_f(p_f) j^{\mu}_{\nu,\mathrm{EM}} \nu_i(p_i) = \overline{u}_f(p_f) \Lambda^{\mu}_{fi}(q) u_i(p_i)$
- In the ultra-relativistic limit, where at low-q^2, it reduces to
  - $\Lambda^{\mu}_{fi}(q) = \gamma^{\mu}(Q_{fi} - \frac{q^2}{6} \langle r^2 \rangle_{fi}) - i\sigma^{\mu\nu} q_{\nu} \mu_{fi}$

Carlo Giunti, Alexander Studenikin; 1403.6344

Neutrino Magnetic Moment (NMM)

Neutrino millicharge (NMM)

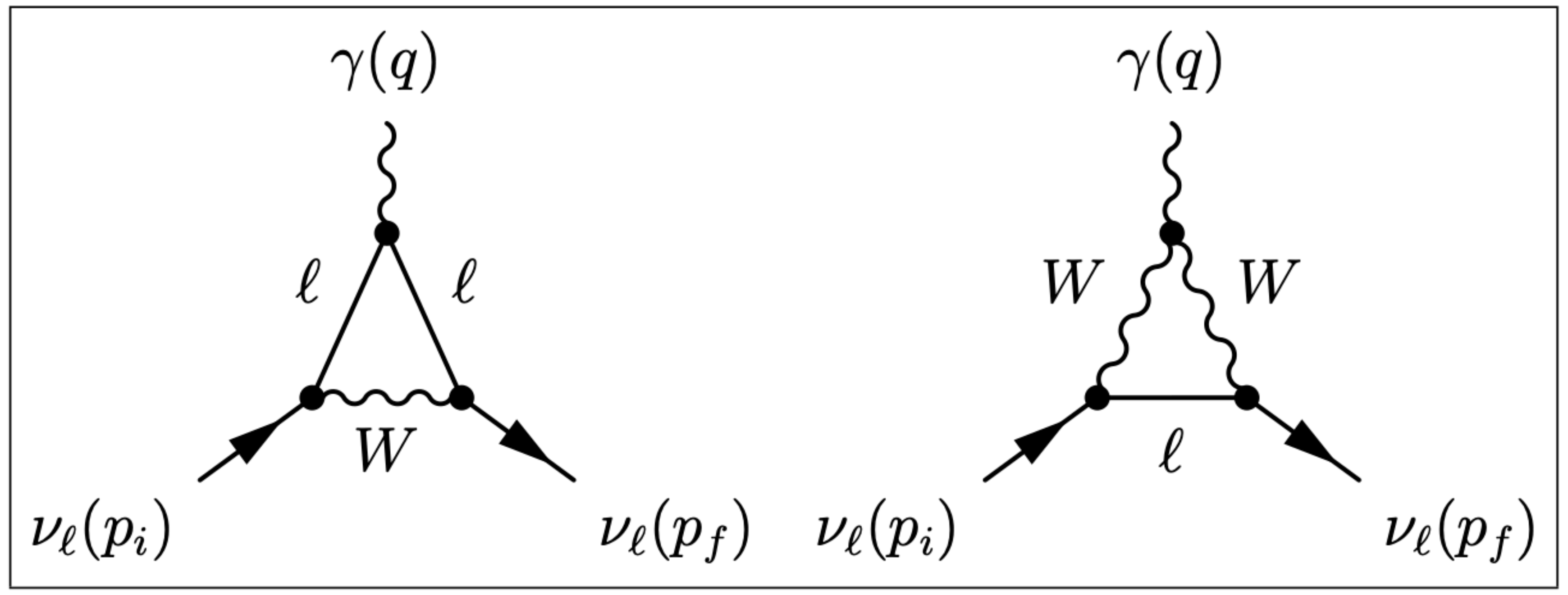
Neutrino Charge Radius (NCR)

SM Value Neutrino CR

- **NCR is generated at loop level within the SM,**

$$\left\langle r^2_{\nu_\ell} \right\rangle_{\rm SM} = \frac{G_f}{4\sqrt{2}\pi^2}\left[3 - 2\log\frac{m^2_\ell}{m^2_W}\right].$$

-



$$\left\langle r^2_{\nu_e} \right\rangle_{\rm SM} = 4.1 \times 10^{-33} cm^2$$

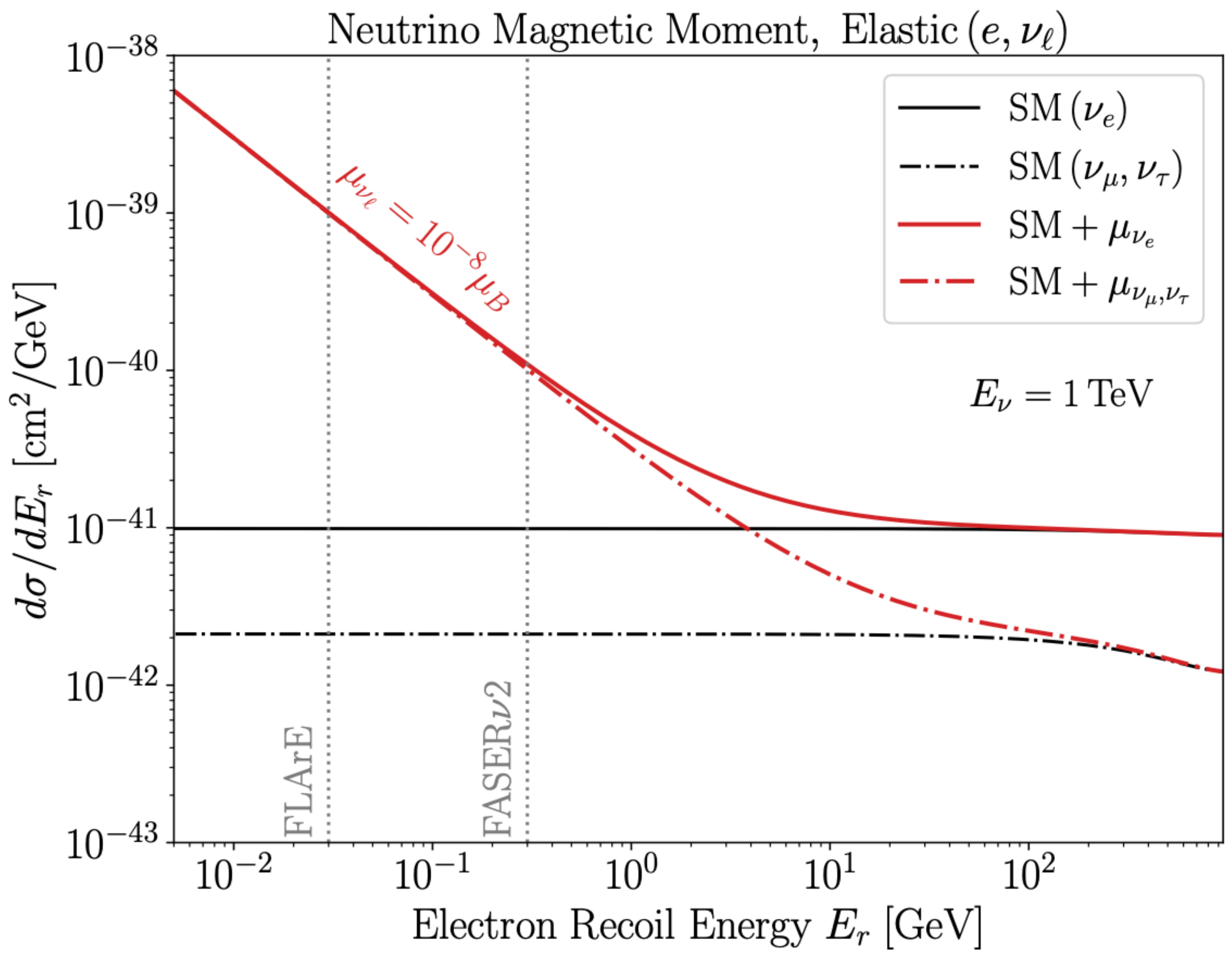
$$\left\langle r^2_{\nu_\mu} \right\rangle_{\rm SM} = 2.4 \times 10^{-33} cm^2$$

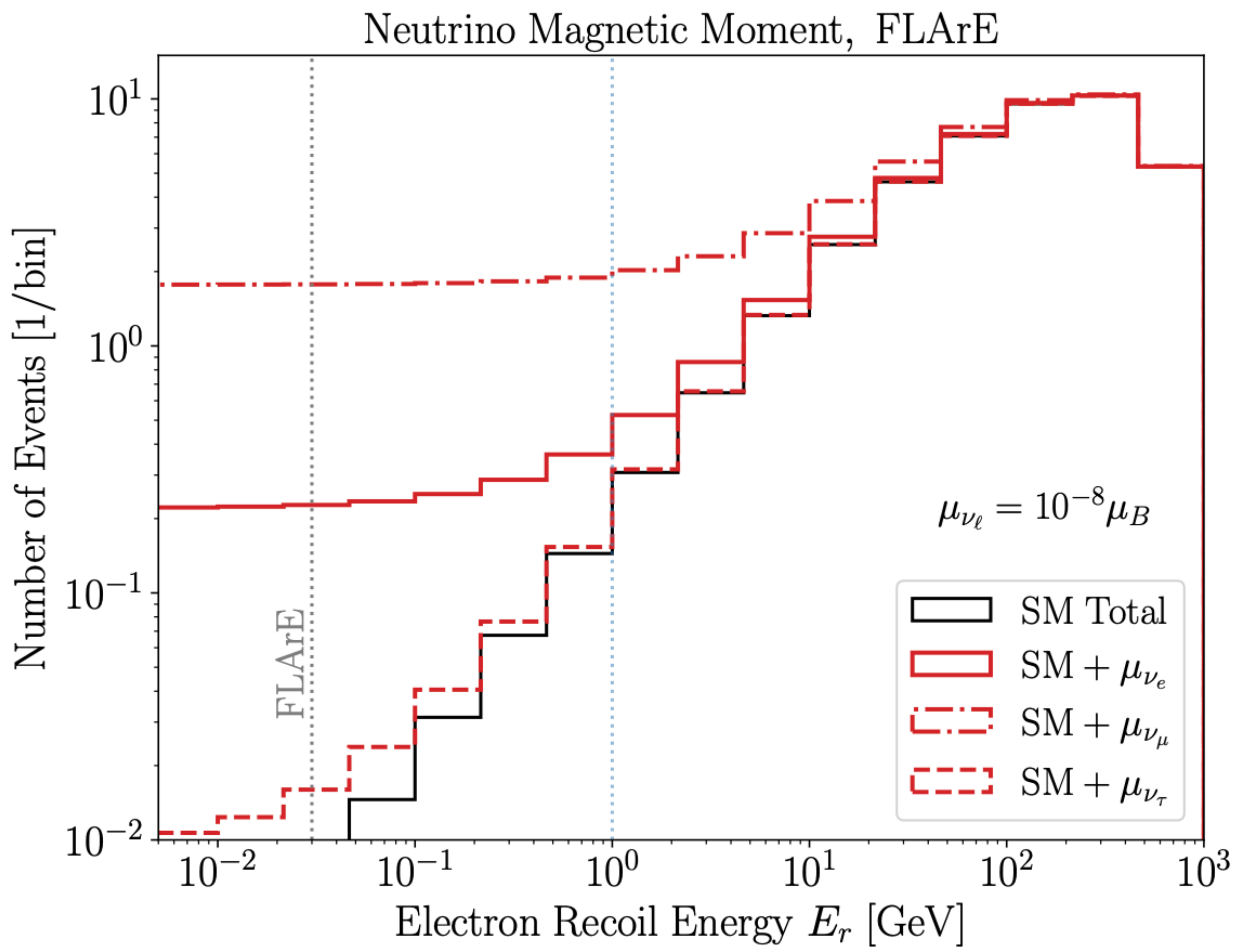
$$\left\langle r^2_{\nu_\tau} \right\rangle_{\rm SM} = 1.5 \times 10^{-33} cm^2$$

Modified Rates at FPF: $\nu - e$ elastic scattering

Neutrino Magnetic Moment:

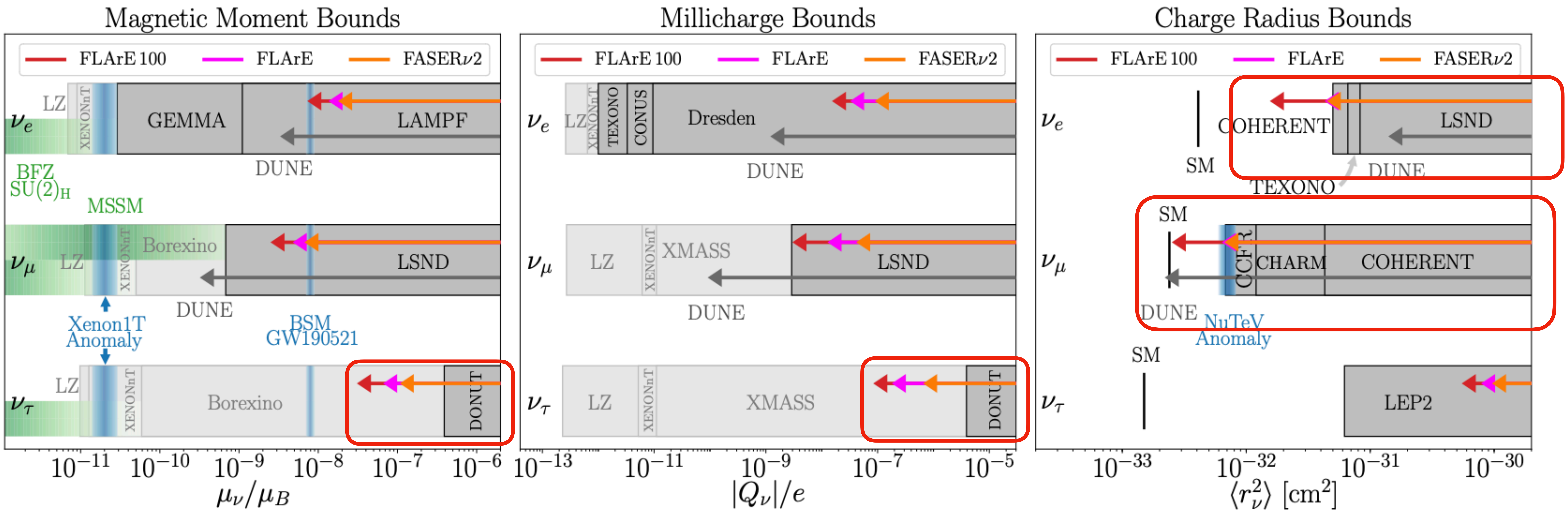
- $\mathscr{L} \supset \mu_\nu(\bar{\nu}\sigma_{\alpha\beta}\nu)F^{\alpha\beta}$, **Chirality flipping like a mass term.**
- $\left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\text{NMM}} \sim \frac{1}{E_r}$ **; excess events at low electron recoil energies**





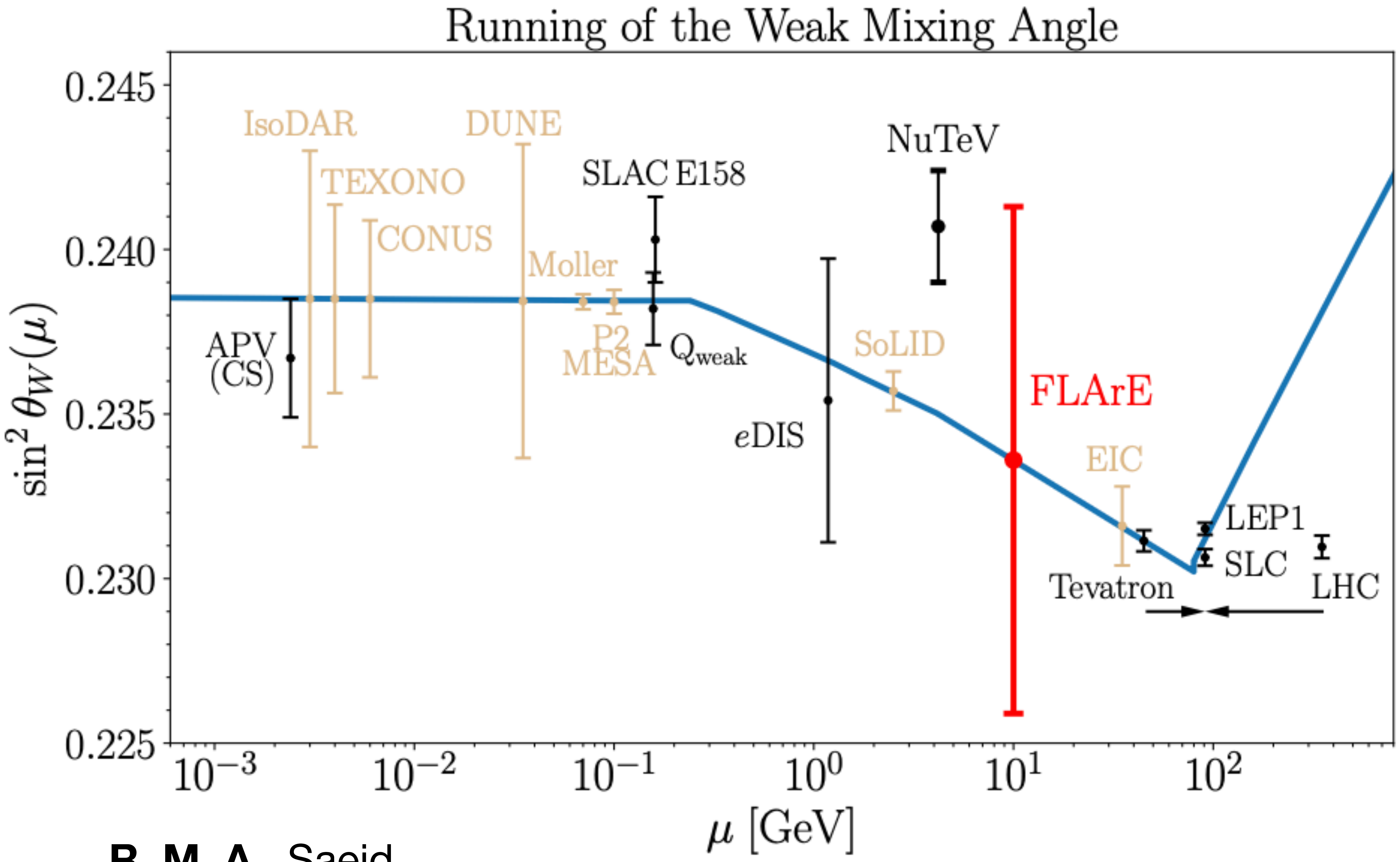
R. M. A., Saeid Foroughi-Abari, Felix Kling, Yu-Dai Tsai; 2301.10254

Results



R. M. A., Saeid Foroughi-Abari, Felix Kling, Yu-Dai Tsai; 2301.10254

Weak Mixing Angle at FPF



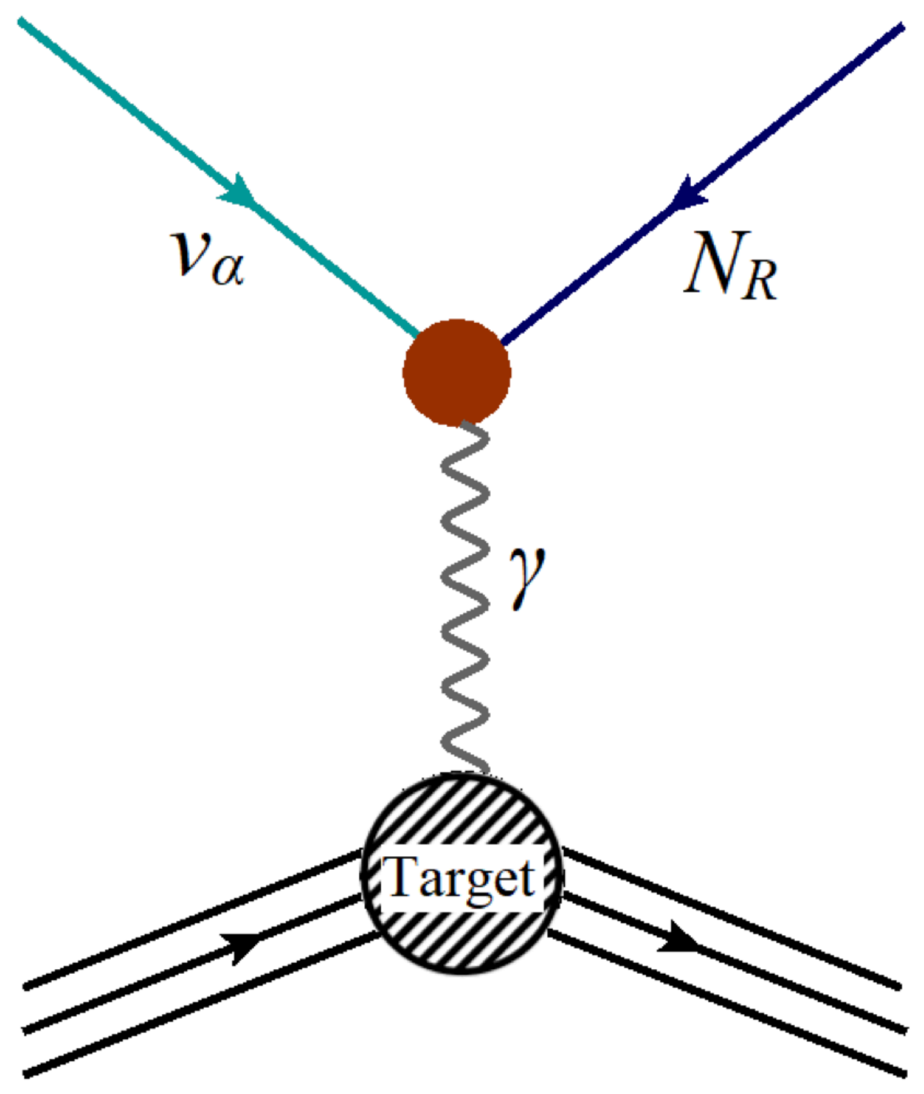
R. M. A., Saeid Foroughi-Abari, Felix Kling, Yu-Dai Tsai; 2301.10254

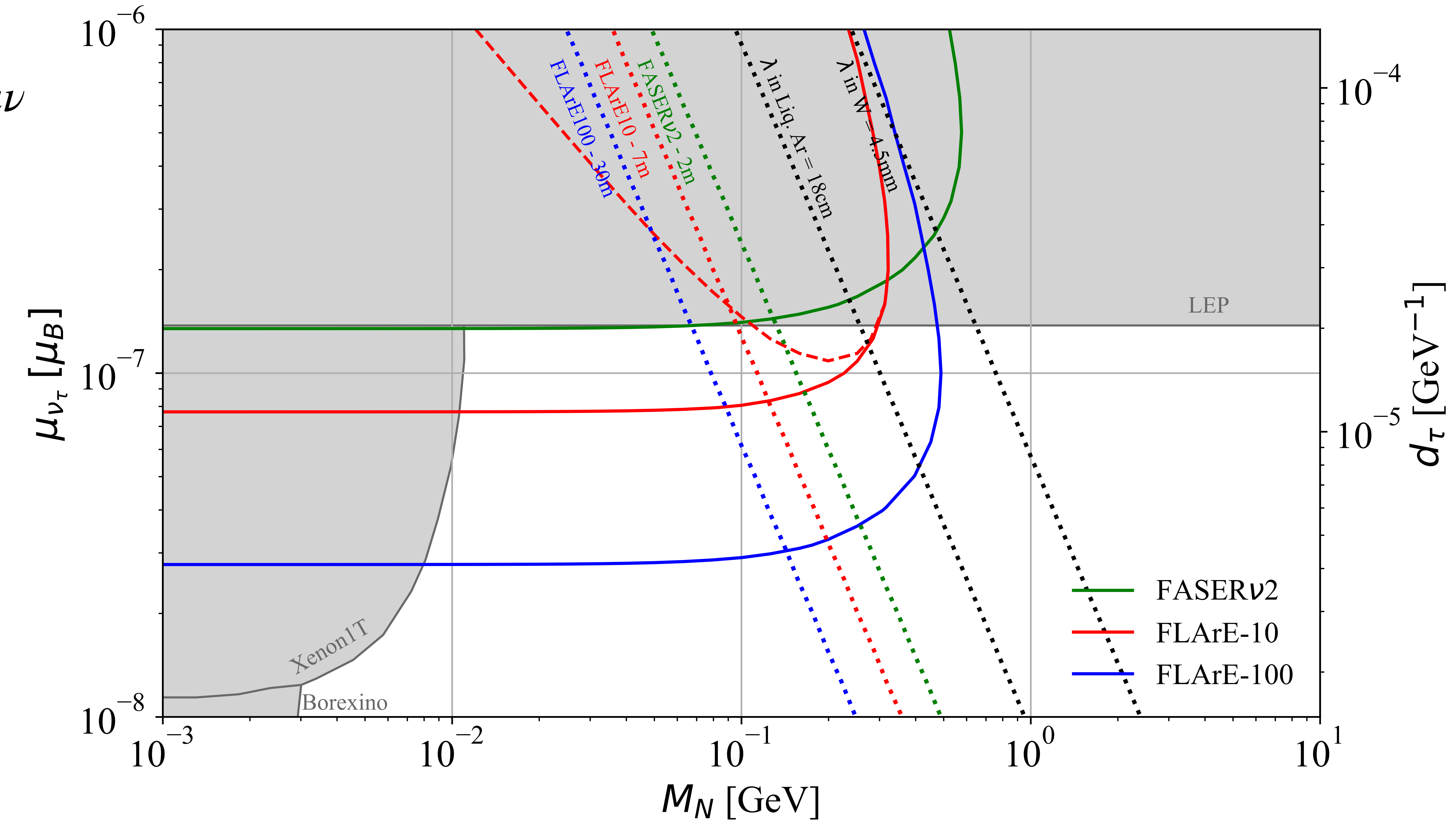
- **If the SM value shifts, $\sin^2\theta_W \to \sin^2\theta_W + \Delta\sin^2\theta_W$ then $g_V^q \to g_V^q - 2Q_q\Delta\sin^2\theta_W$.**
- **Modifies NC DIS similarly to NCR.**

$\sin^2\theta_W$ **can be measured to 3% precision at FLArE10.**

Neutrino Up-scattering via the Dipole Portal

$$\mathscr{L}_{dipole} \supset \frac{1}{2}\mu_\nu^\alpha \bar{\nu}_L^\alpha \sigma^{\mu\nu} N_R F_{\mu\nu}$$





Ahmed Ismail, Sudip Jana, **R. M. A.;** 2109.05032

Muons at Forward Detectors

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

$$\nu_\mu: \; \pi^\pm \longrightarrow \boxed{\mu} \nu_\mu \;, \; K^\pm \longrightarrow \boxed{\mu} \nu_\mu$$

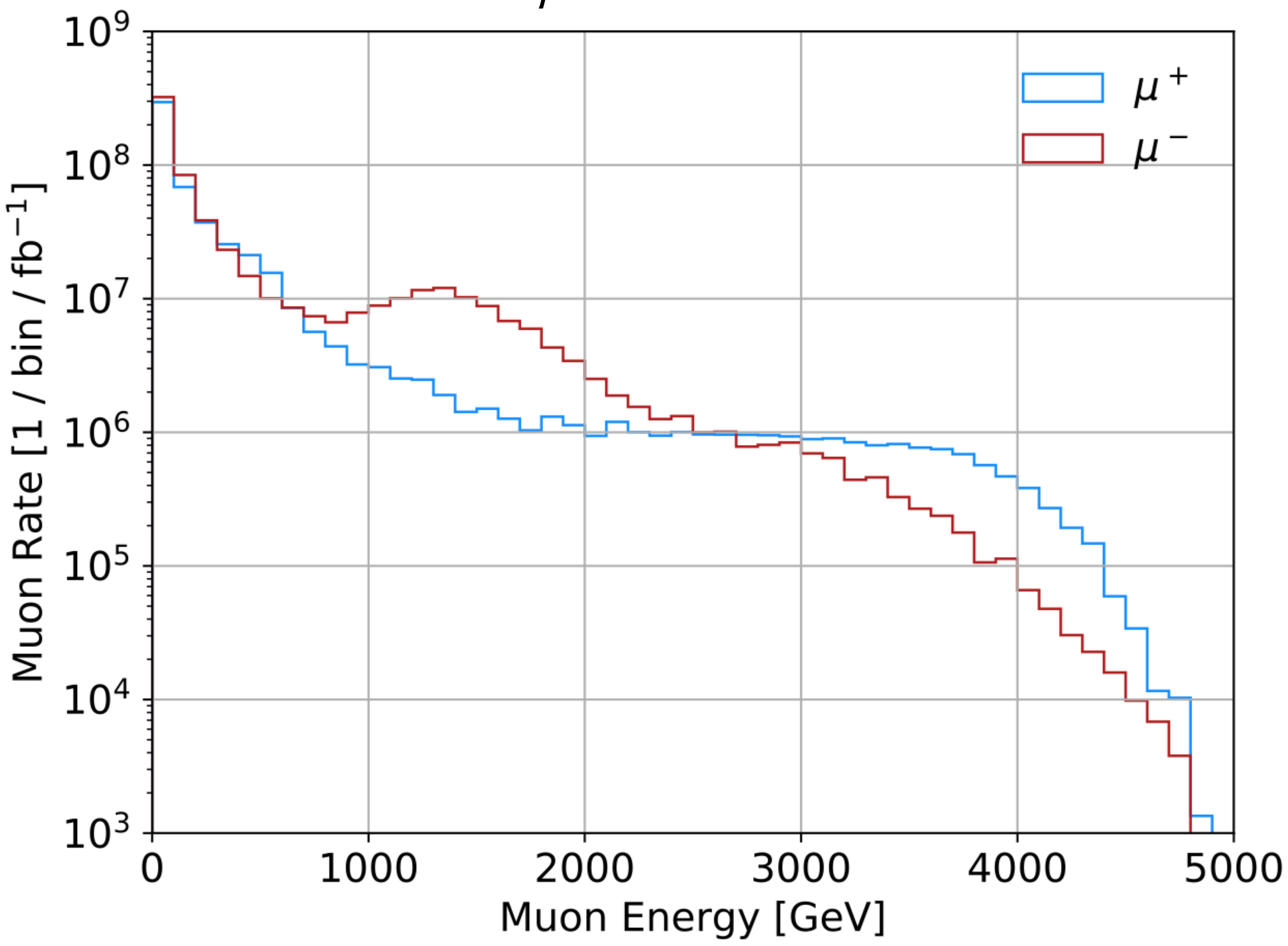
$$\nu_\tau: \; D_s \longrightarrow \tau \nu_\tau$$

But what about all these muons?

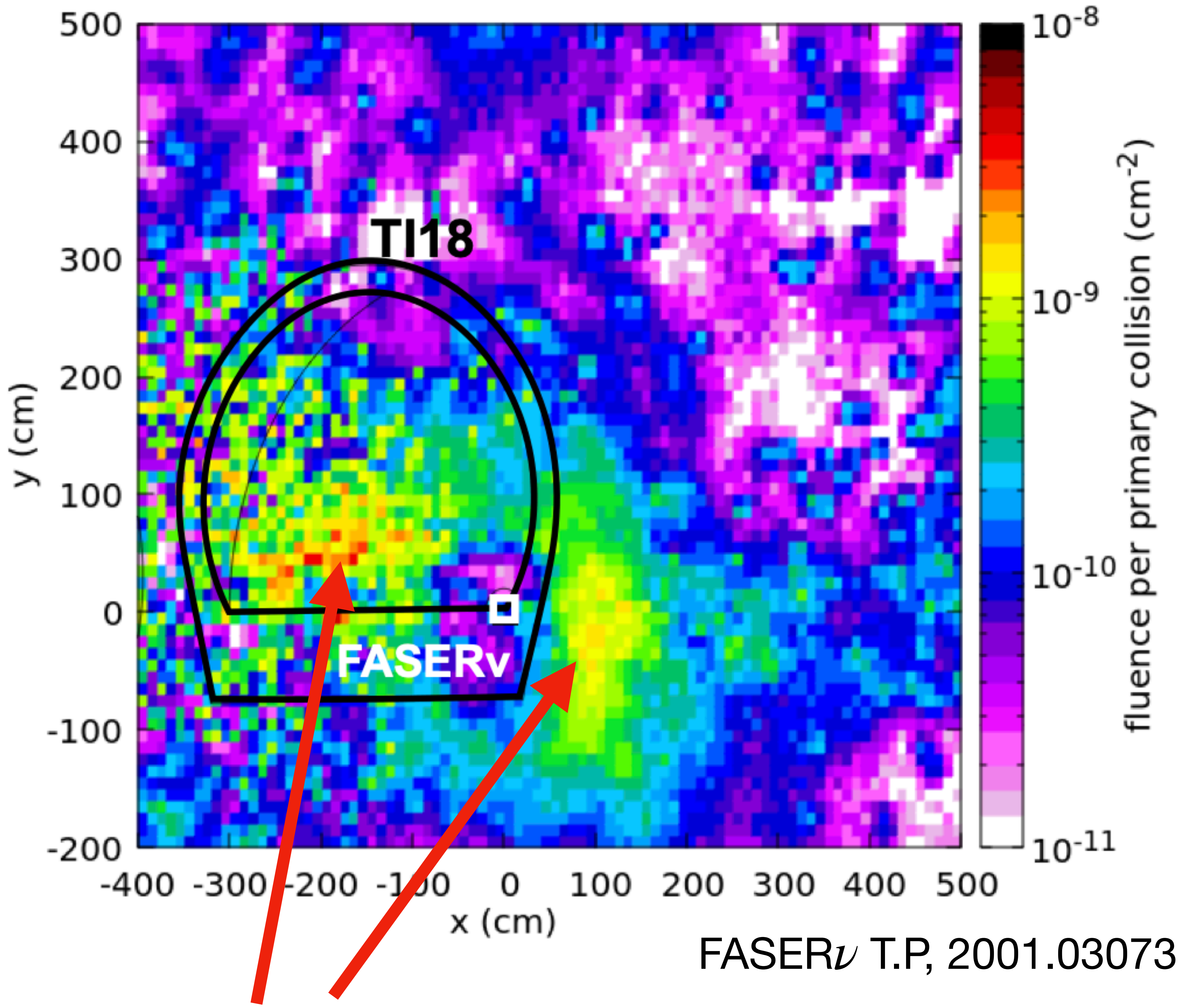
Are they just backgrounds or can we do some physics with them?

One Scientist's Background is Another's Signal

$N_\mu \sim 2 * 10^9$, **through FASER during Run3!!!**



First neutrino interaction candidates at the LHC; 2105.06197



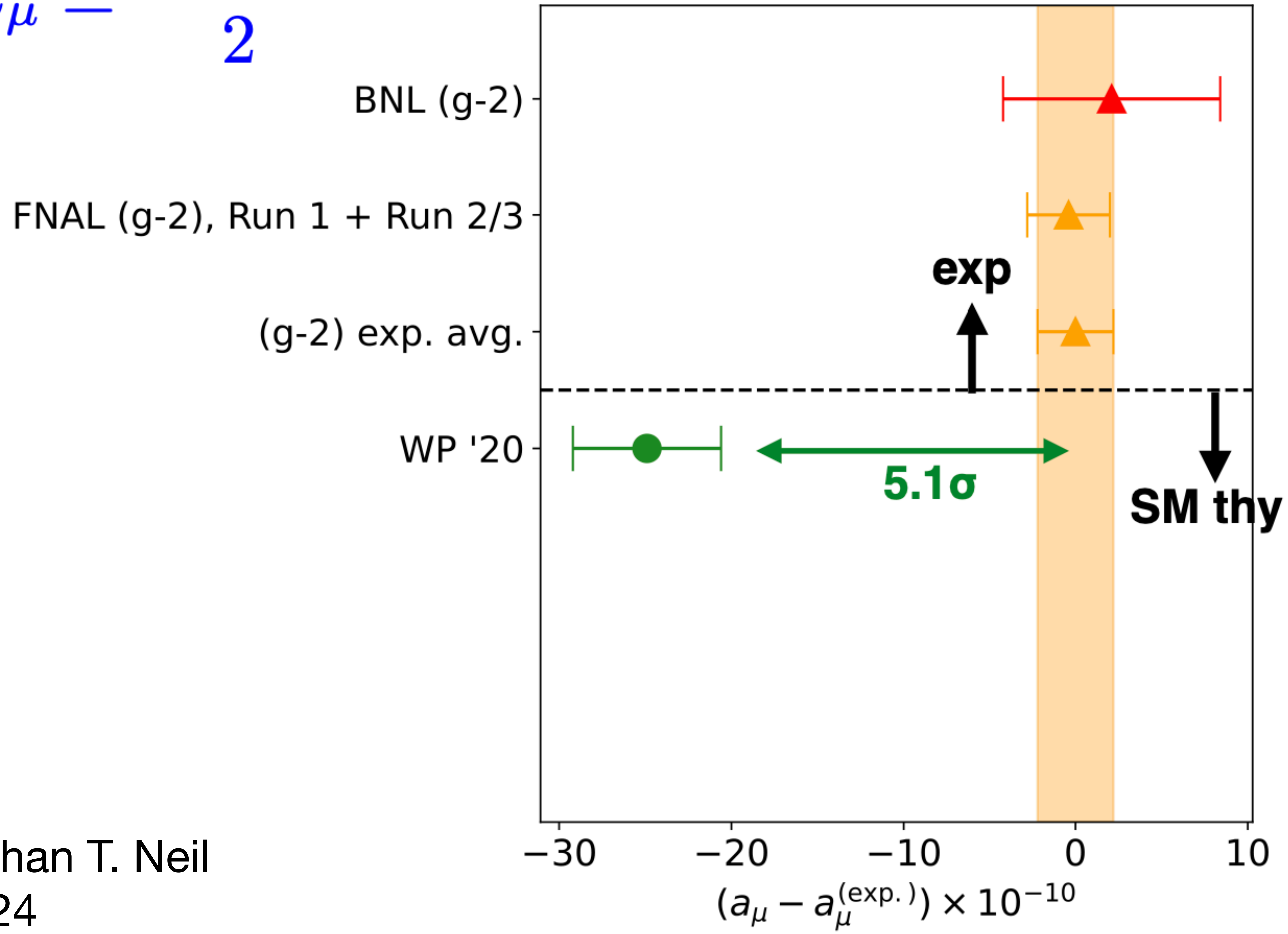
FASERν T.P, 2001.03073

FASER intentionally avoids the maximum flux of muons

Muon (g-2) puzzle

$$a_\mu \equiv \frac{g_\mu - 2}{2}$$

(Latest experiment: FNAL Muon (g-2) Collaboration, PRL **131**, 161802 (2023); arXiv:2308.06230)
(WP '20: T. Aoyama et al (Muon (g-2) Theory Initiative), arXiv:2006.04822)



- Latest FNAL (g-2) results in ~5σ tension with "SM theory" prediction from Theory Initiative whitepaper!

Slide from Ethan T. Neil
DPF-Pheno 24

Simple model with a muonphilic scalar

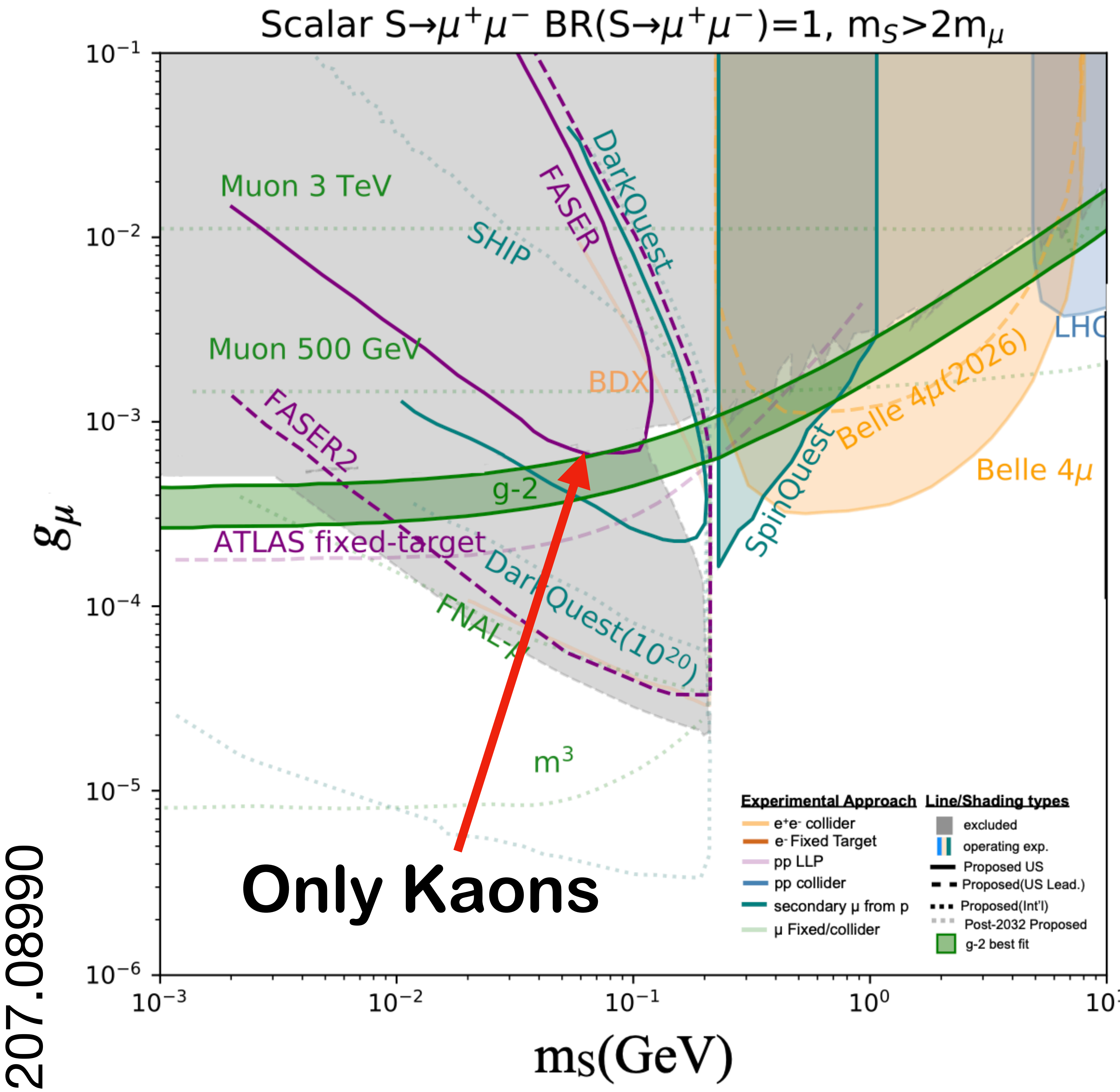
- **A SM singlet scalar, S, that couples only to the muons.**
- $\mathscr{L} \supset \frac{1}{2}\left(\partial_\nu S\right)^2 - \frac{1}{2} m_S^2 S^2 - g_S S \bar{\mu}\mu$
- **Contribution to $\Delta a_\mu = \left(g-2\right)_\mu / 2$ is given by**

$$\Delta a_\mu = \frac{g_\mu^2}{8\pi^2} \int_0^1 \mathrm{d}z \frac{(1-z)^2(1+z)}{(1-z)^2 + z(m_S/m_\mu)^2}$$

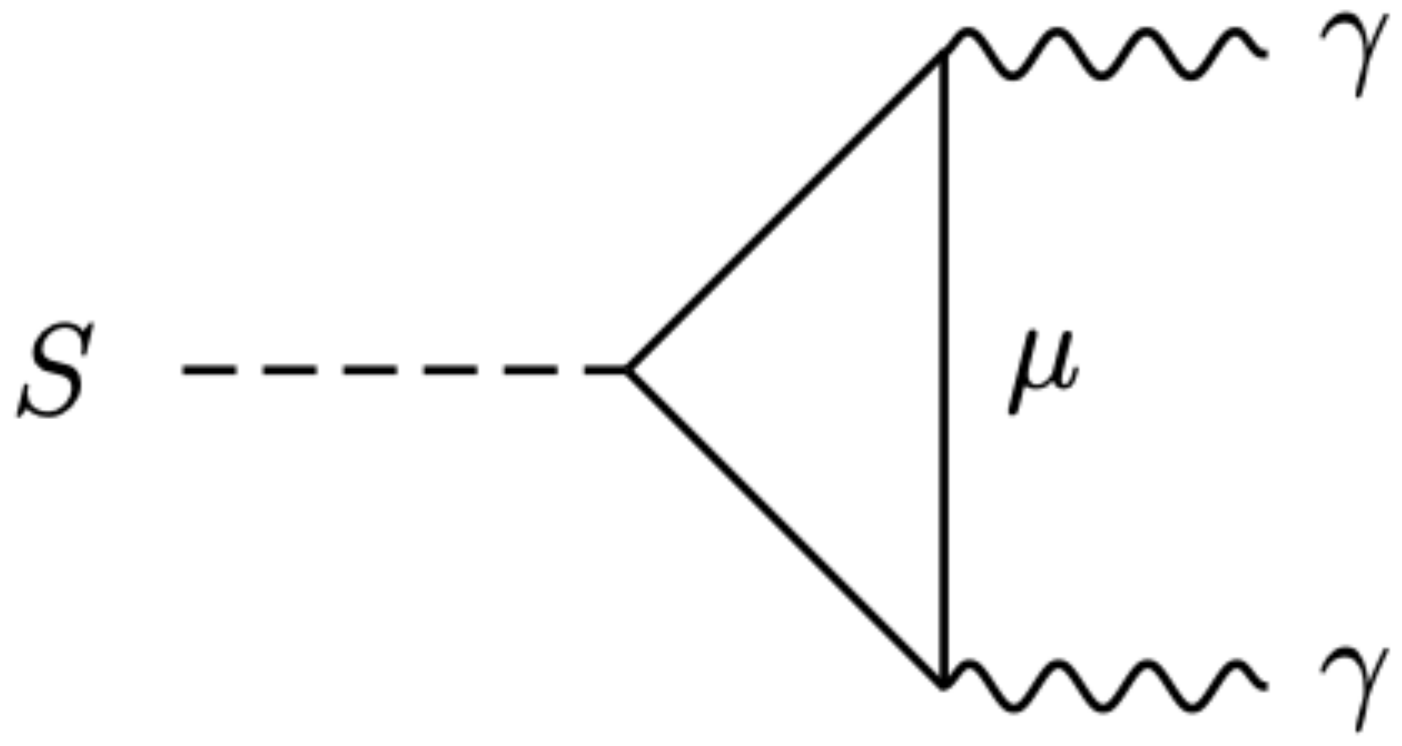
Chien-Yi Chen, Maxim Pospelov, Yi-Ming Zhong; 1701.07437

Simple model with a muonphilic scalar (Cont.)

Snowmass White Paper: New flavors and rich structures in dark sectors
Philip Harris, Philip Schuster, Jure Zupan;
2207.08990



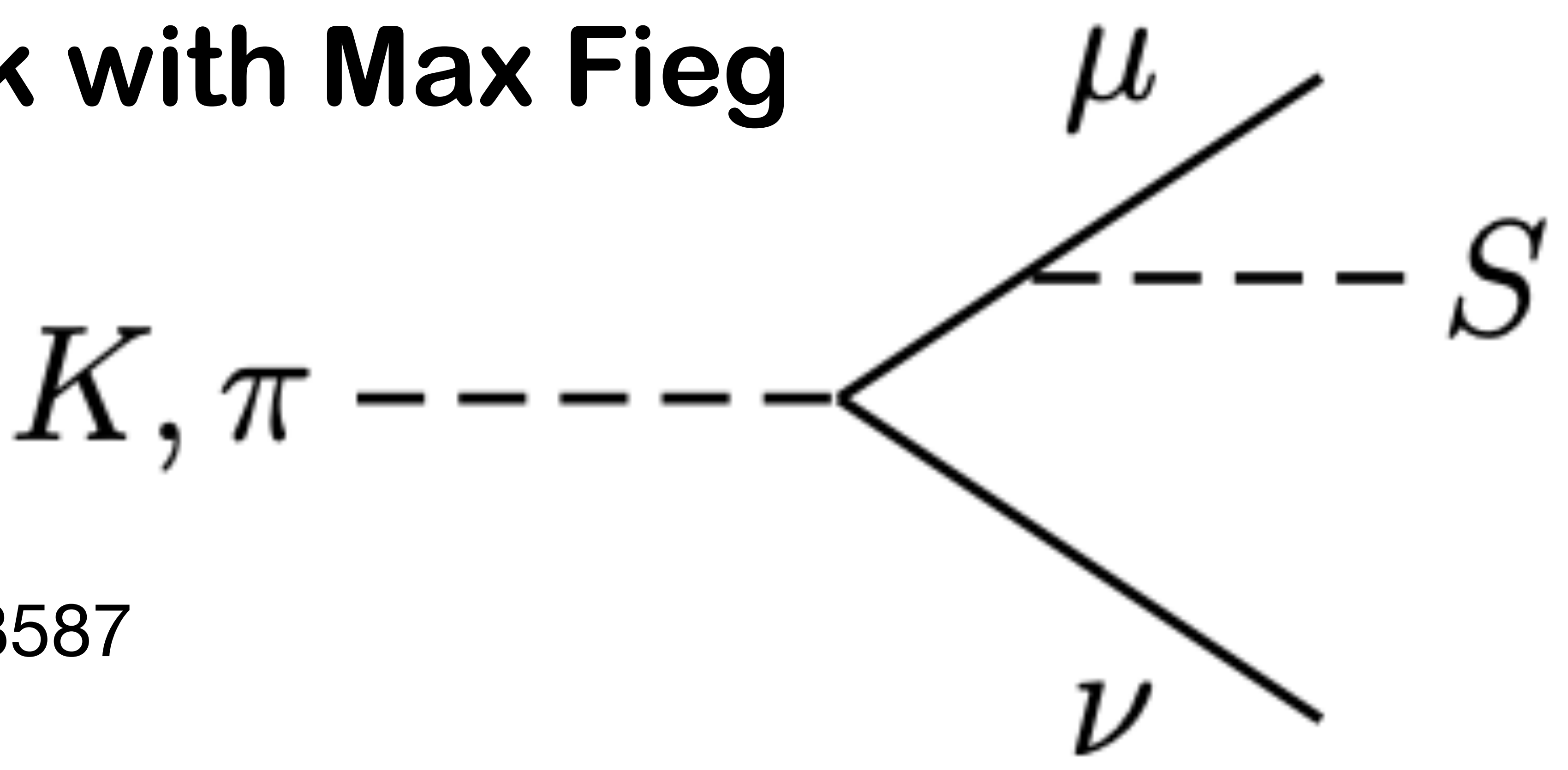
- **Current constraints miss a small region near $m_S \lesssim 2 * m_\mu$.**
- **For $m_S \lesssim 2 * m_\mu$, S decays to 2 photons.**



See also,
Brian Batell, Ayres Freitas, Ahmed Ismail, David McKeen;
1712.10022

Production from 3 body decays near ATLAS IP

Work with Max Fieg



- **Scalar decays via W** Carl E. Carlson, Benjamin C. Rislow; 1206.3587

$$\frac{d\mathrm{BR}(K\to\mu\nu S)}{dE_S dQ^2} = \frac{m_K y^2 \times \mathrm{BR}(K\to\mu\nu)}{8\pi^2 m_\mu^2 (m_K^2 - m_\mu^2)^2 (Q^2 - m_\mu^2)^2} \times \left((m_K^2 - 2m_K E_S + Q^2) Q^2 (Q^2 - m_\mu^2) - (Q^4 - m_\mu^2 m_K^2)(Q^2 + m_\mu^2 - m_S^2) + 2m_\mu^2 Q^2 (m_K^2 - Q^2) \right)$$

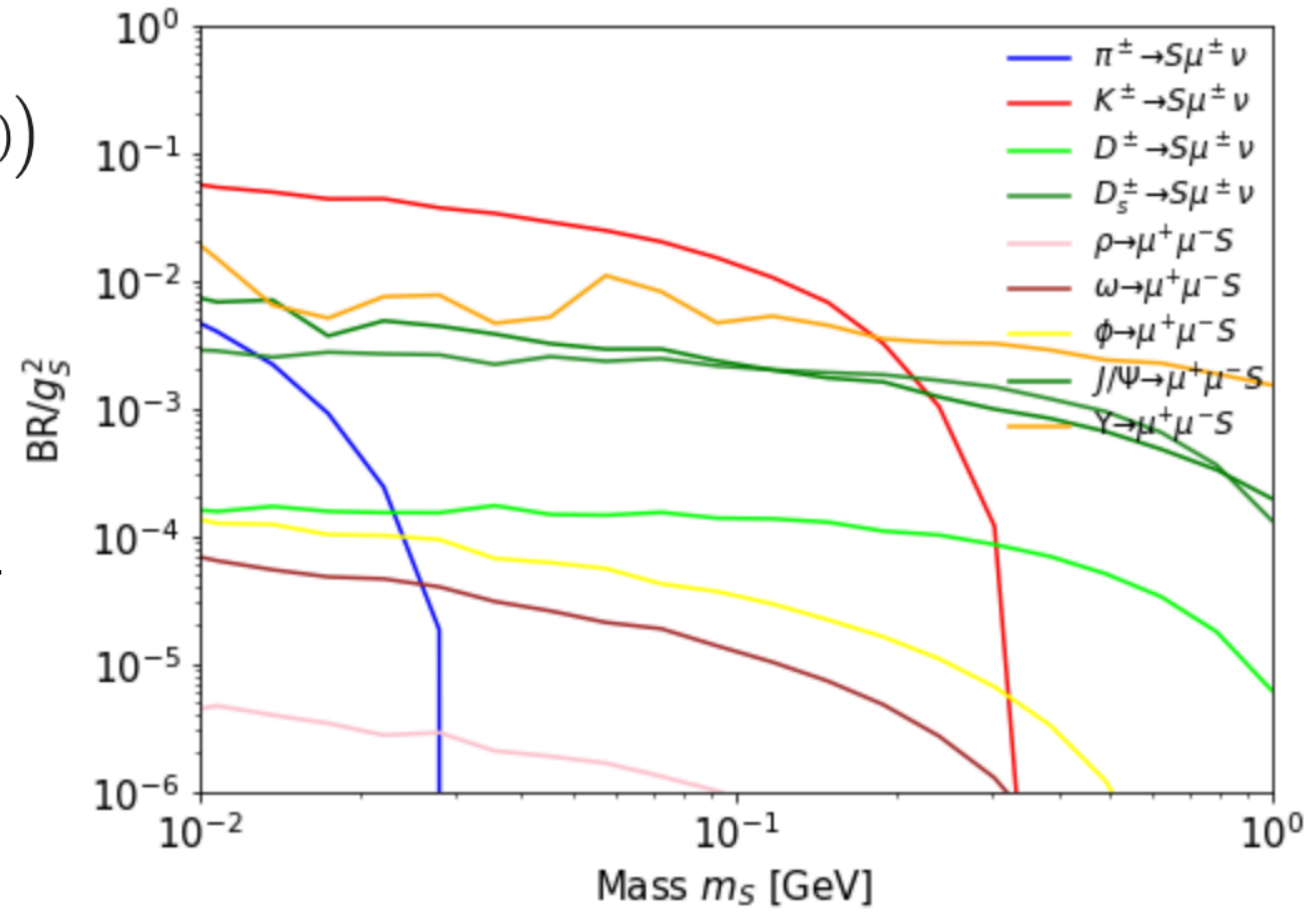
- **Vector decays via γ**

Manimala Mitra, Dibyakrupa Sahoo; 2103.08284

$$\frac{\mathrm{d}^2\Gamma_{s^\pm}}{\mathrm{d}t\ \mathrm{d}u} \equiv \frac{\mathrm{d}^2\Gamma\left(J/\psi \to \mu^-\mu^+ X_{s^\pm}\right)}{\mathrm{d}t\ \mathrm{d}u} = \frac{\alpha^2\, g_{s\pm}^2\, f_J^2}{27\,\pi\, m_J^5\, Y} \left|A_{s^\pm}\right|^2$$

$$Y = \left(t - m_\mu^2\right)^2 \left(u - m_\mu^2\right)^2$$

Decay constant **Squared amplitude**

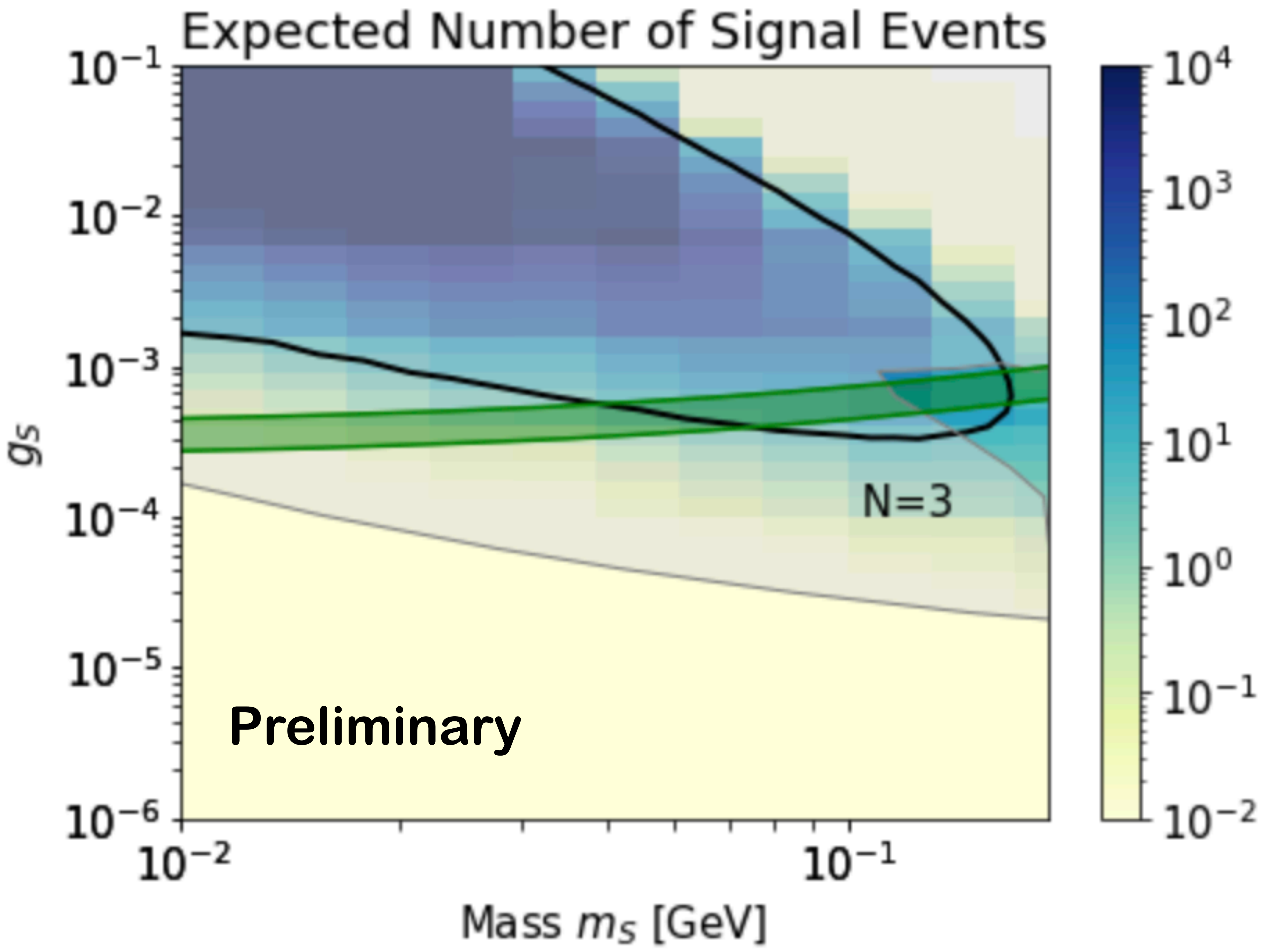


Implemented via FORESEE
Felix Kling, Sebastian Trojanowski, 2105.07077

Production from 3 body decays near ATLAS IP

Significant event rates expected at FASER during Run 3.

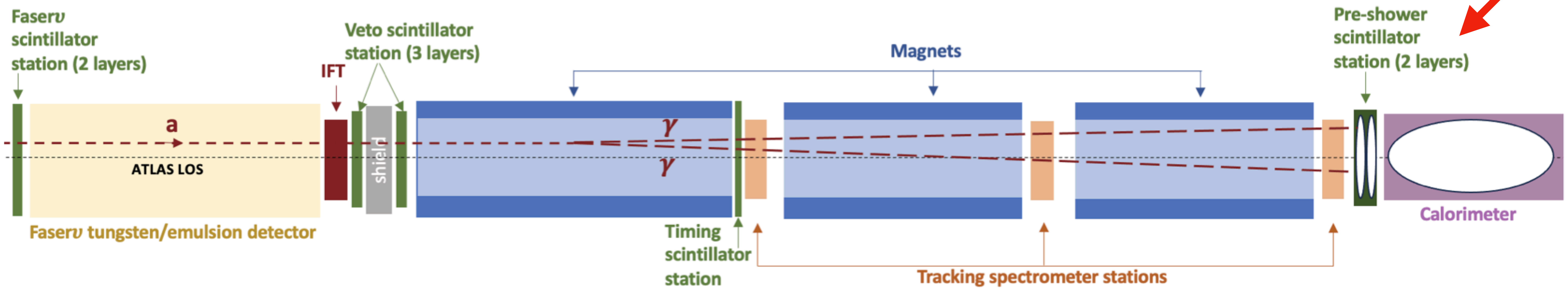
But what about backgrounds?



3 body decays (cont.)

- The signal we expect is "no activity" with some energy deposition in the calorimeter.
- Very similar to FASER's ALPs analysis. (Conf note)
  - The dominant background there is from neutrino interactions.

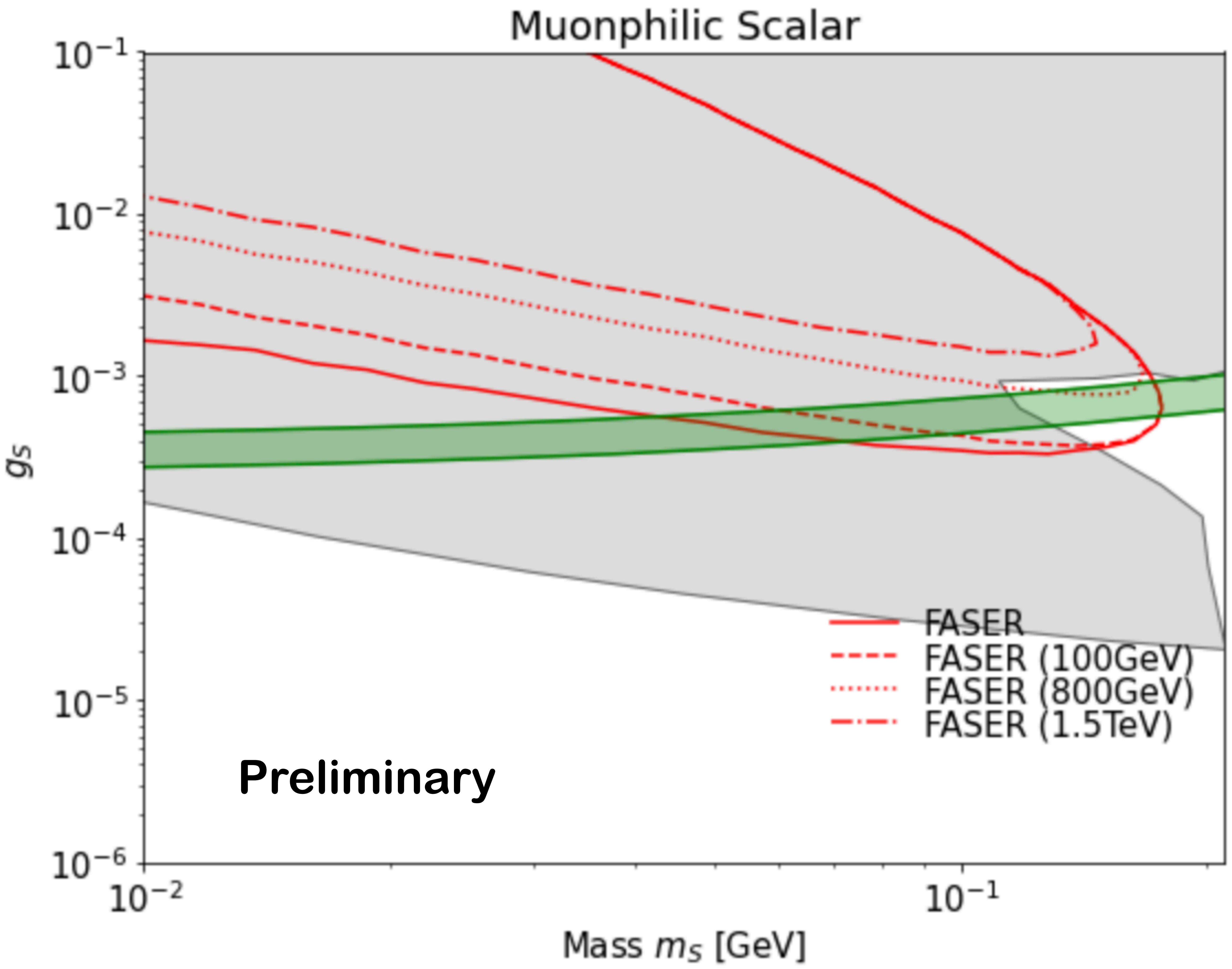
ALP search at FASER



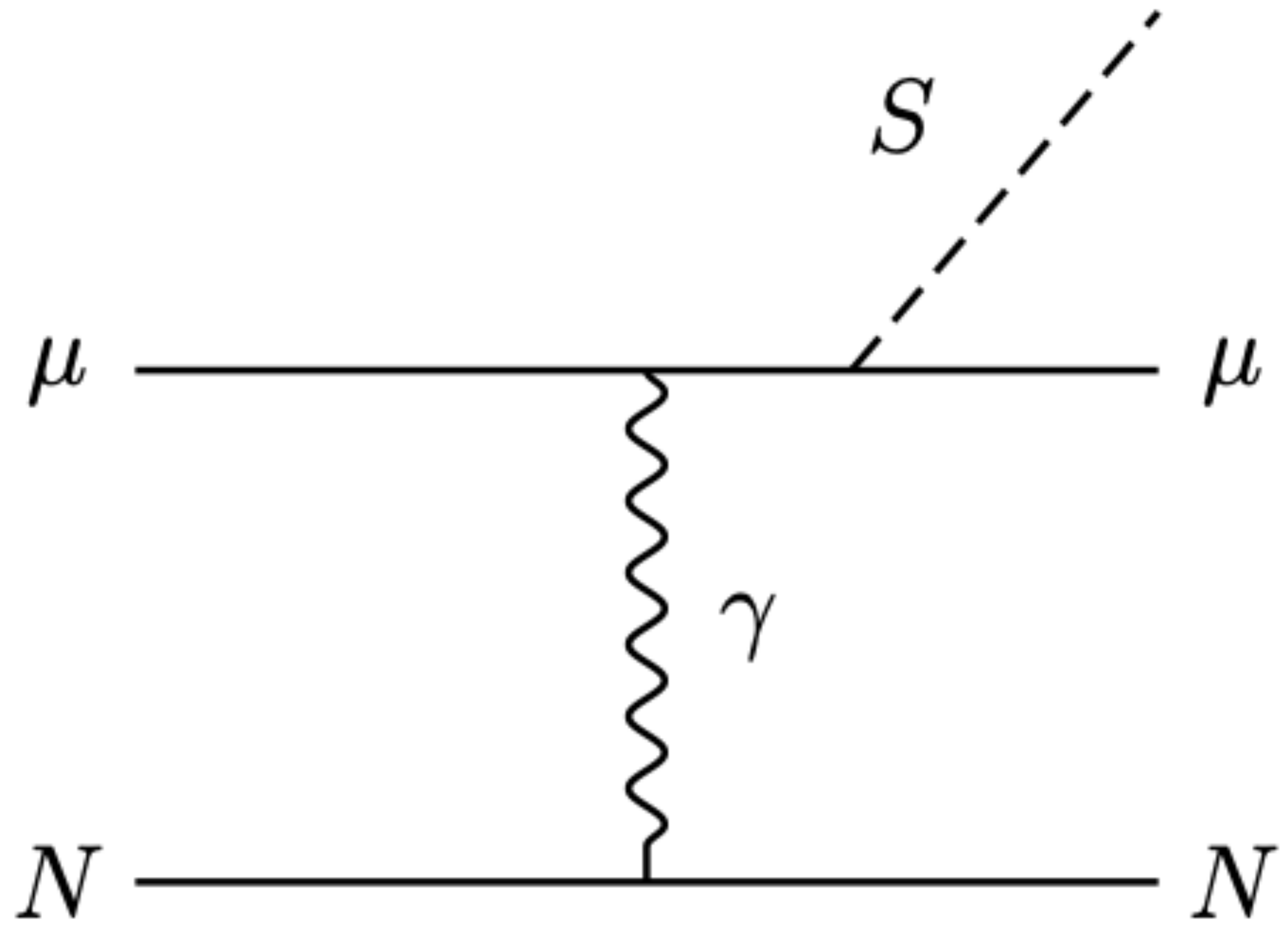
- $E_{calo} > 1.5$ TeV reduces the neutrino backgrounds to ~ 0.42/50 fb^{-1}.

3 body decays (cont.)

Applying the same energy cut, we do not probe the (g-2) band at FASER.



Production from Bremsstrahlung in FASERν

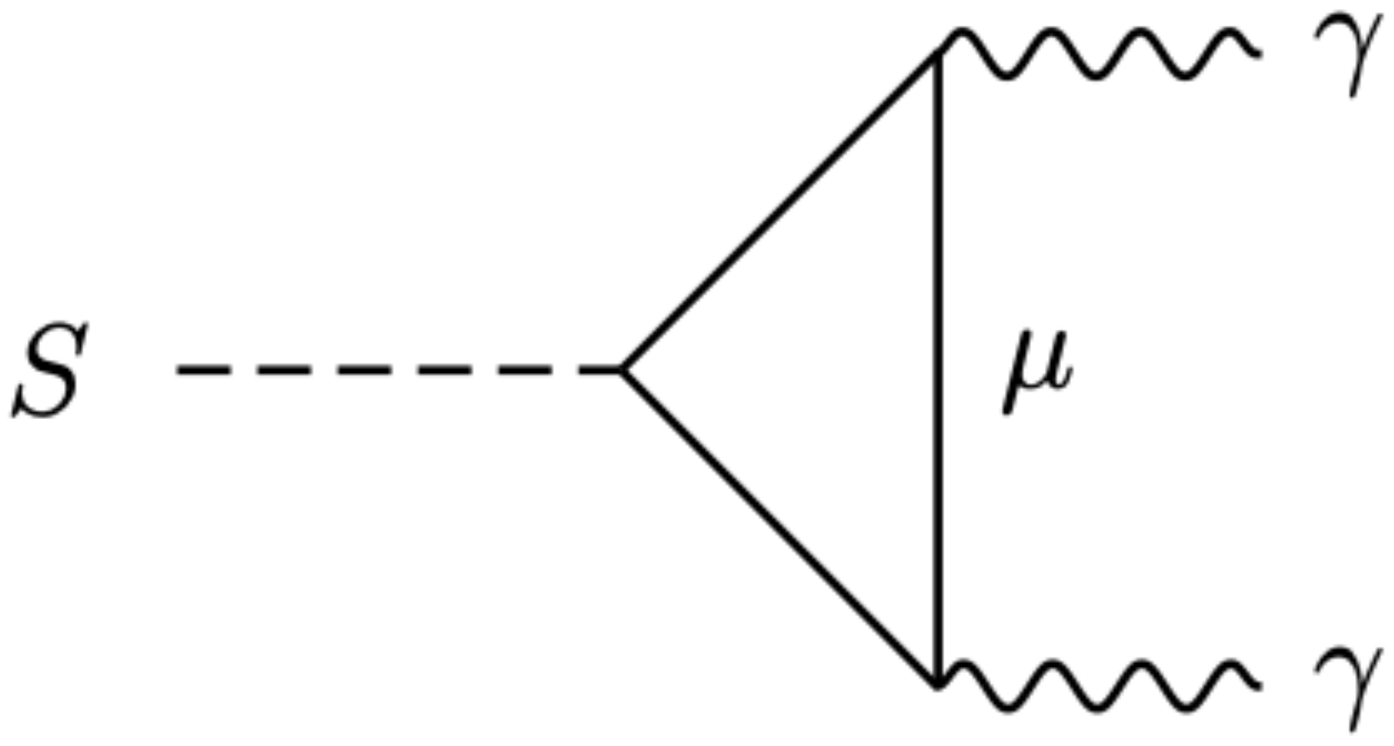


- **Incoming muon bremss off S within the *FASERν* detector*.**
- **If $m_S < 2 * m_\mu$, S can decay to 2 photons.**
- **Decay length is given by**

$$L_S = 20\ m \times \left(\frac{E_s}{3\ GeV}\right) \times \left(\frac{5 \times 10^{-4}}{g_S}\right)^2 \times \left(\frac{100\ MeV}{m_S}\right)^4$$

Signal mainly from low energy S

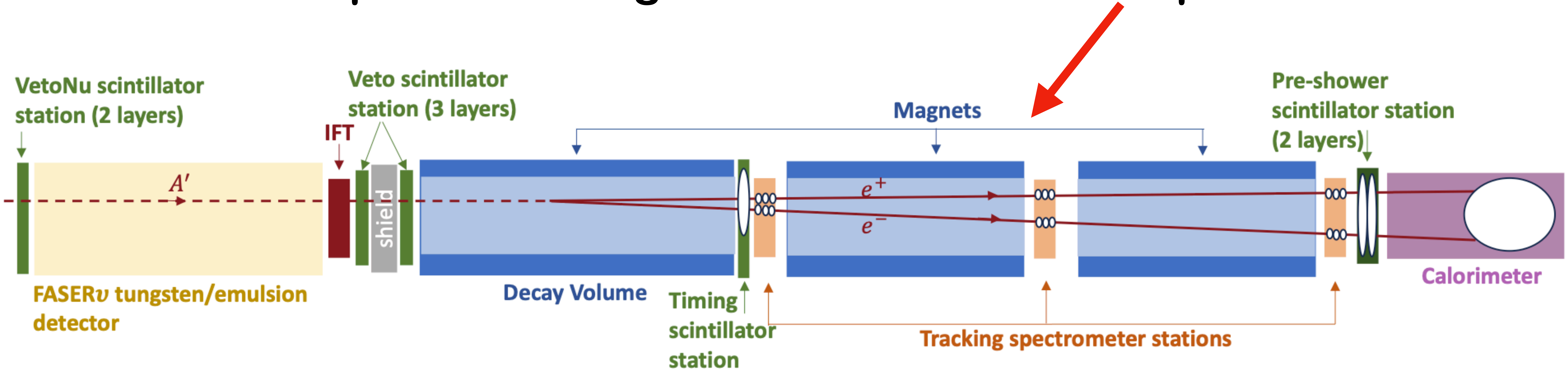
Chien-Yi Chen, Maxi Pospelov, Yi-Ming Zhong; 1701.07437



* S can also be produced from muons in the rock. Work in progress.

Bremsstrahlung (cont.)

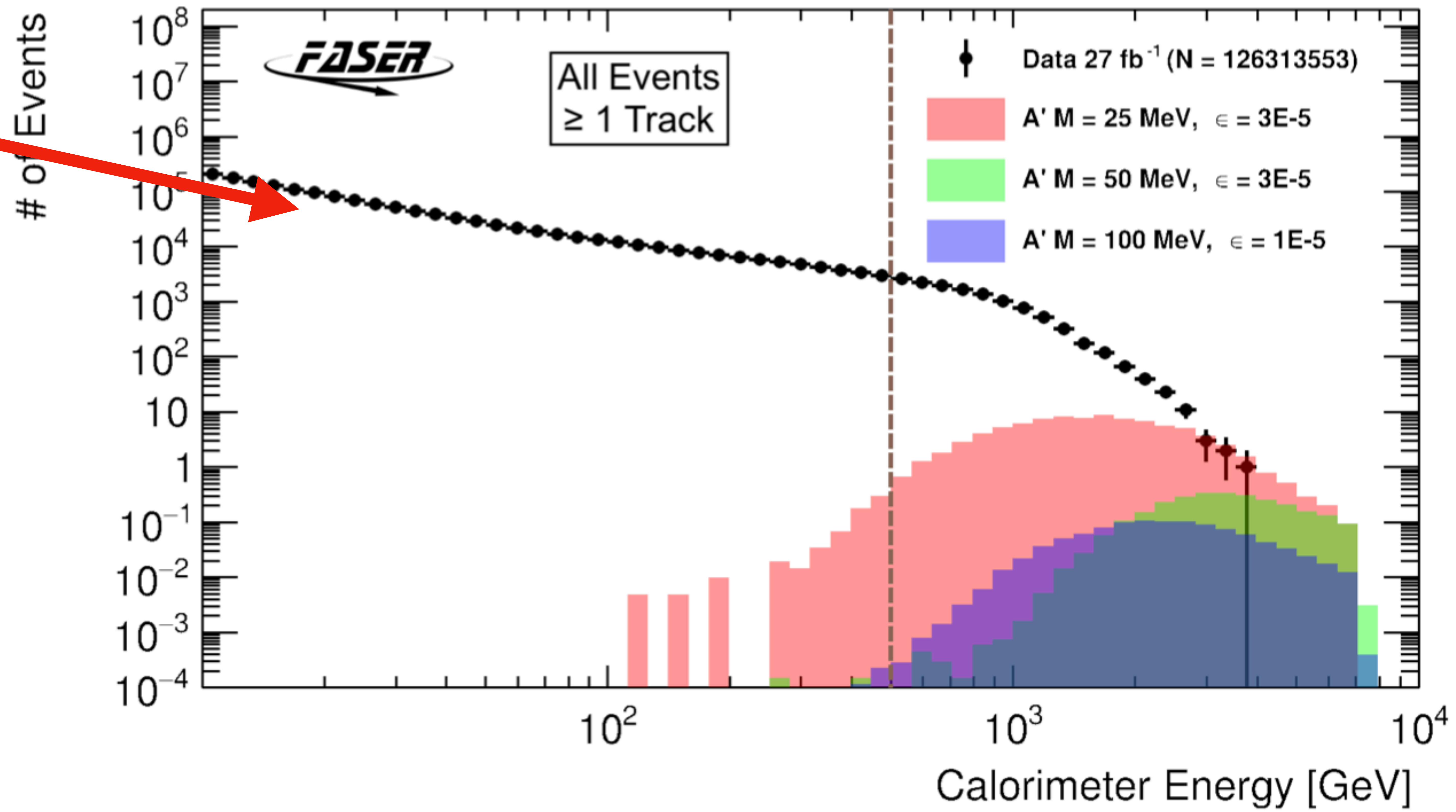
- The signal we expect is 1 muon track with some energy deposition in the calorimeter.
- But this was an important background to FASER's dark photon search.



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

Bremsstrahlung (cont.)

There is an overwhelming number of background events that can mimic our signal.

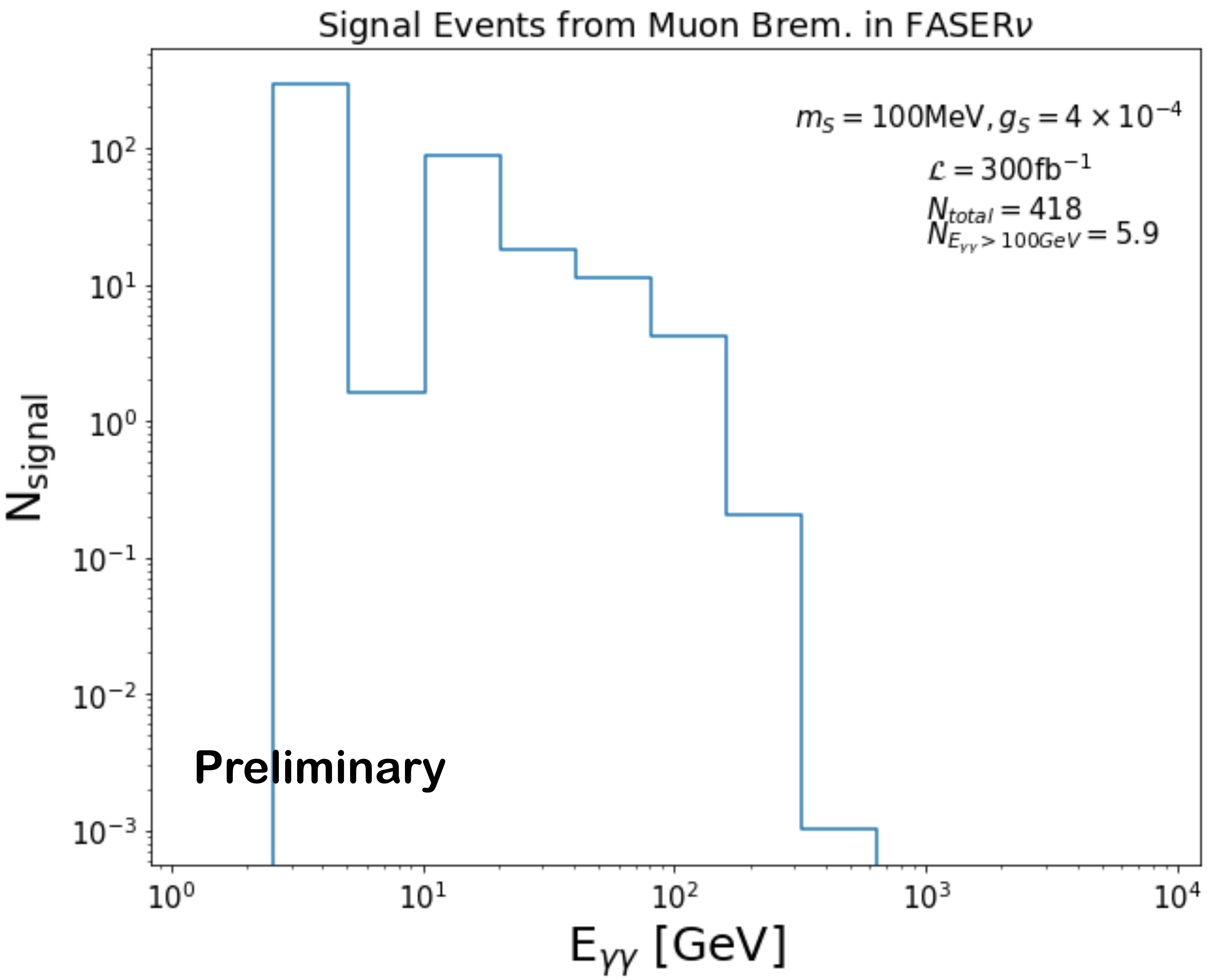


Can we use the fact that low energy S from soft muons dominate our signal reach?

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

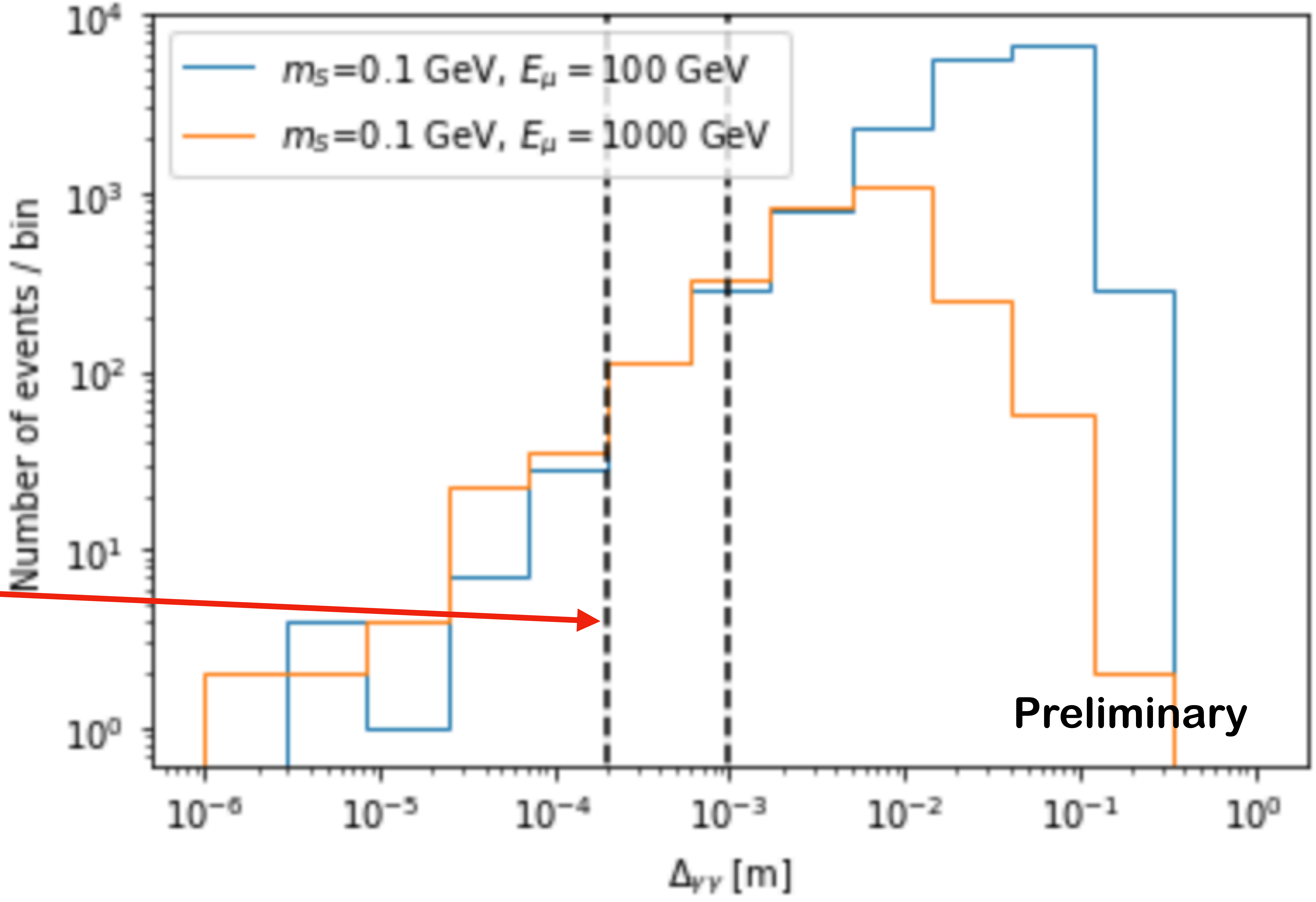
Di-photon Energy Spectrum

- **Most of the signal events have low $E_{\gamma\gamma}$.**
- **This is due to the short decay length requirement.**



Di-photon Seperation Spectrum

- Low energy S tend to decay into 2 photons with greater separation.
- $\Delta_{\gamma\gamma} \sim \frac{m_S}{E_S} * \Delta_z$
- Can we see such small spatial separation between 2 photons?



High Precision Preshower

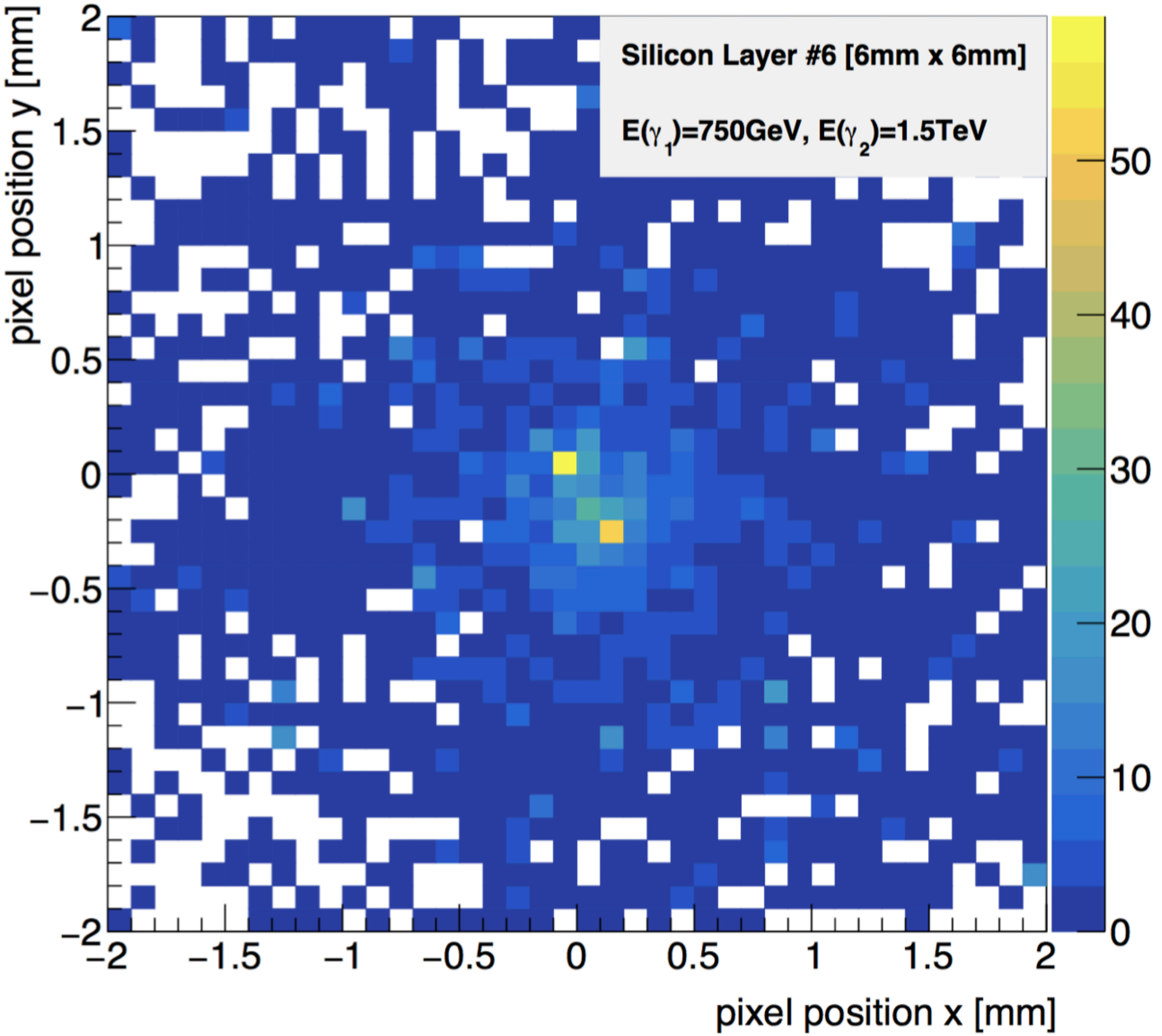
- **The FASER collaboration is working on a High Precision Preshower.**

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.

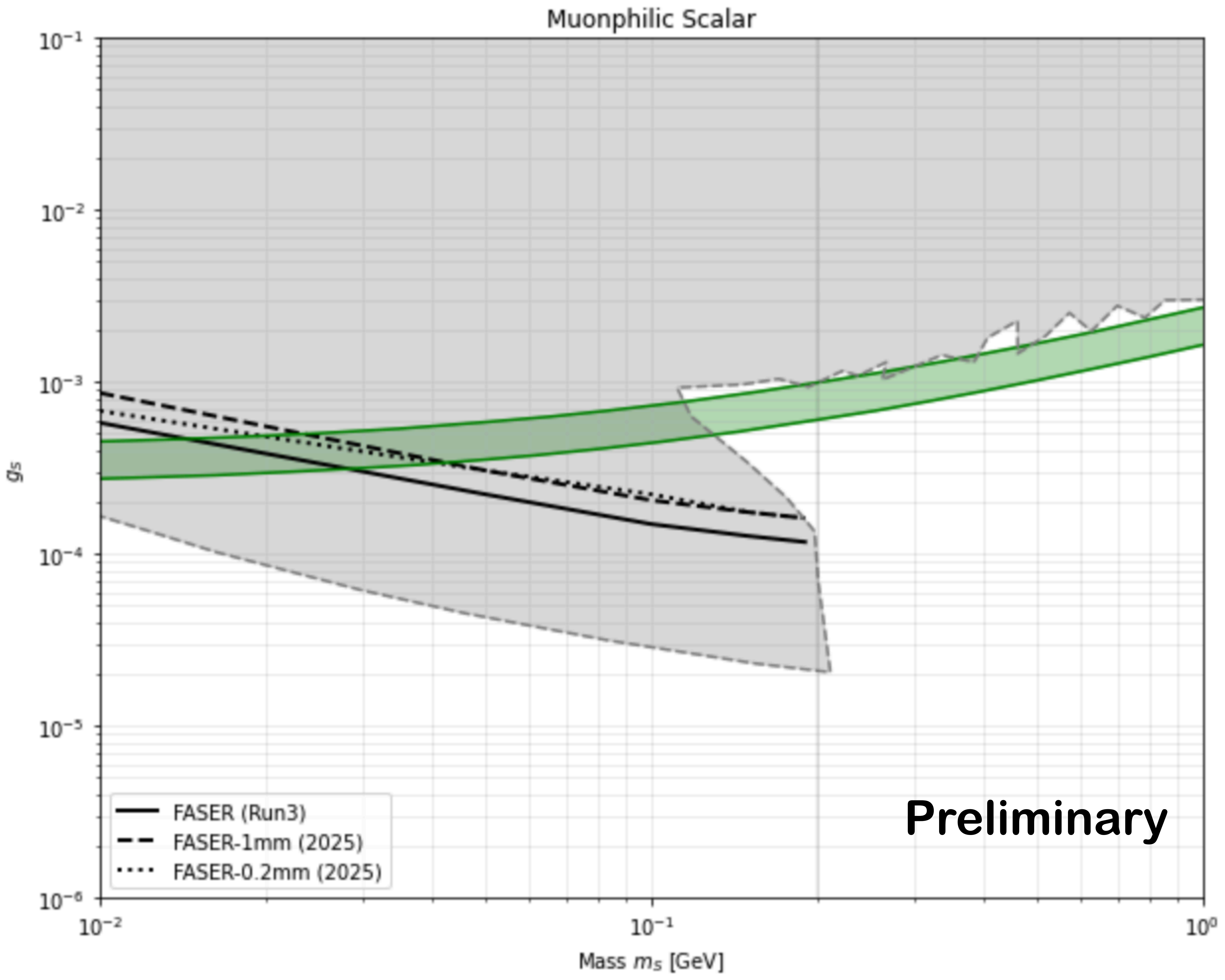
High Precision Preshower

Preshower TP



Bremsstrahlung With High Precision Preshower

- Requiring $\Delta_{\gamma\gamma} > 0.2$ mm suppresses most of the backgrounds.
- In 2025, FASER expects ~ 90 fb^{-1} with preshower. Run 4 proposal for FASER
- This is a reduction in luminosity (300 fb^{-1} -> 90 fb^{-1}).
- But even with only 2025 data, FASER can probe the unconstrained (g-2) band below $2 * m_{\mu}$!!!!



Summary

- There is a lot of physics to be studied in the forward region at LHC.
    - Neutrinos, Muons, QCD, PDFs, DM, ALPs,.....
- It is the era of Multimessenger Collider Physics.

"These **sources** are complicated… Unless you have many ways to ***look*** at them, you're not going to figure them out"

-Francis Halzen on Multimessenger Astronomy
Scientific American

These **collisions** are complicated… Unless you have many ways to ***look*** at them, you're not going to figure them out

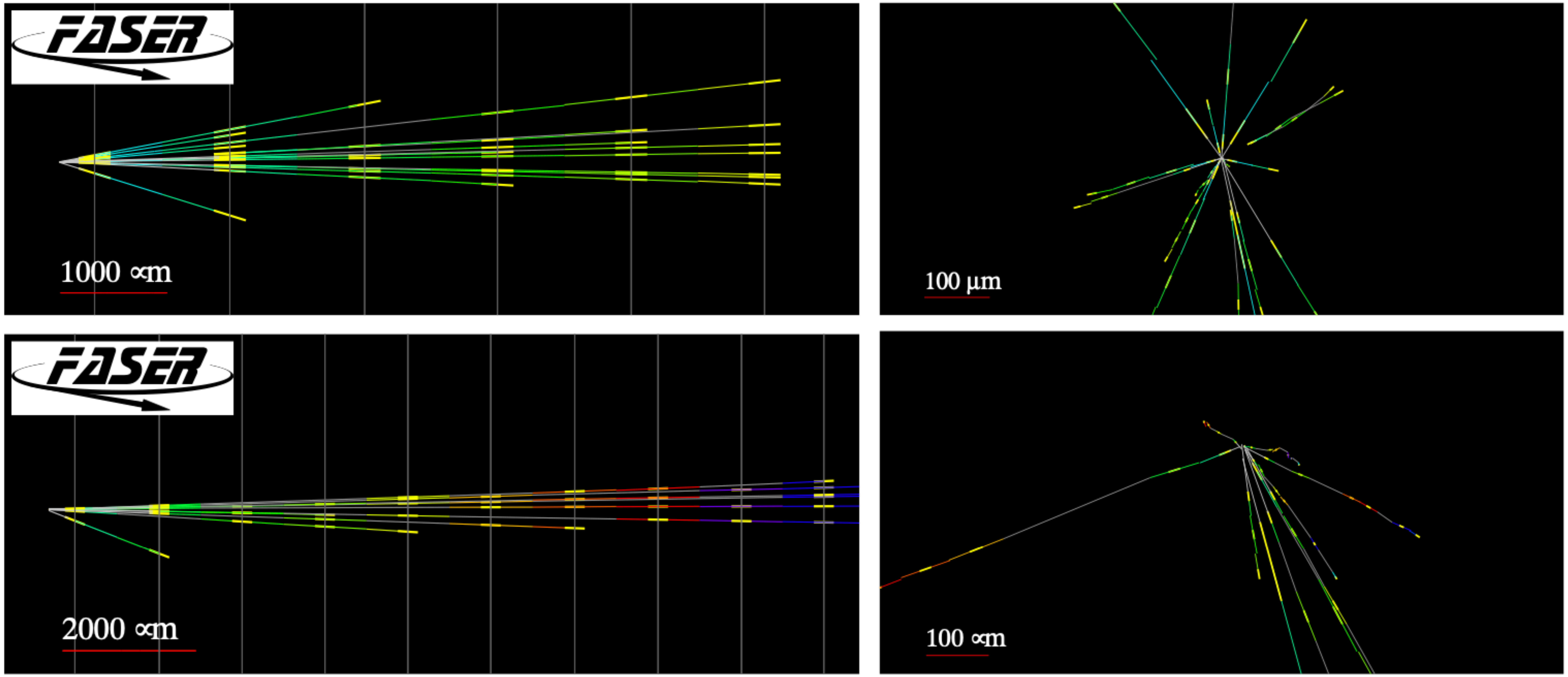
Multimessenger Collider Physics

Borrowed from Max Fieg

Thank You

Back Up Slides

First Neutrino Interaction Candidates



At FASERν

Using a pilot detector in 2018 with 12.2 fb^{-1} of data.

First neutrino interaction candidates at the LHC; 2105.06197

Backup slides - Detectors at FPF

- FASERν2 : 0.5 m x 0.5 m x 2 m tungsten detector with a mass of 10 tonnes, and $E_{threshold}$ = 300MeV.
- FLArE : Liquid argon detector with $E_{threshold}$ = 30MeV and dimensions
  - 1 m x 1 m x 7 m with a mass of 10 tonnes
  - 1.6 m x 1.6 m x 30 m with a mass of 100 tonnes (for illustration)

Neutrino Electromagnetic (EM) Properties

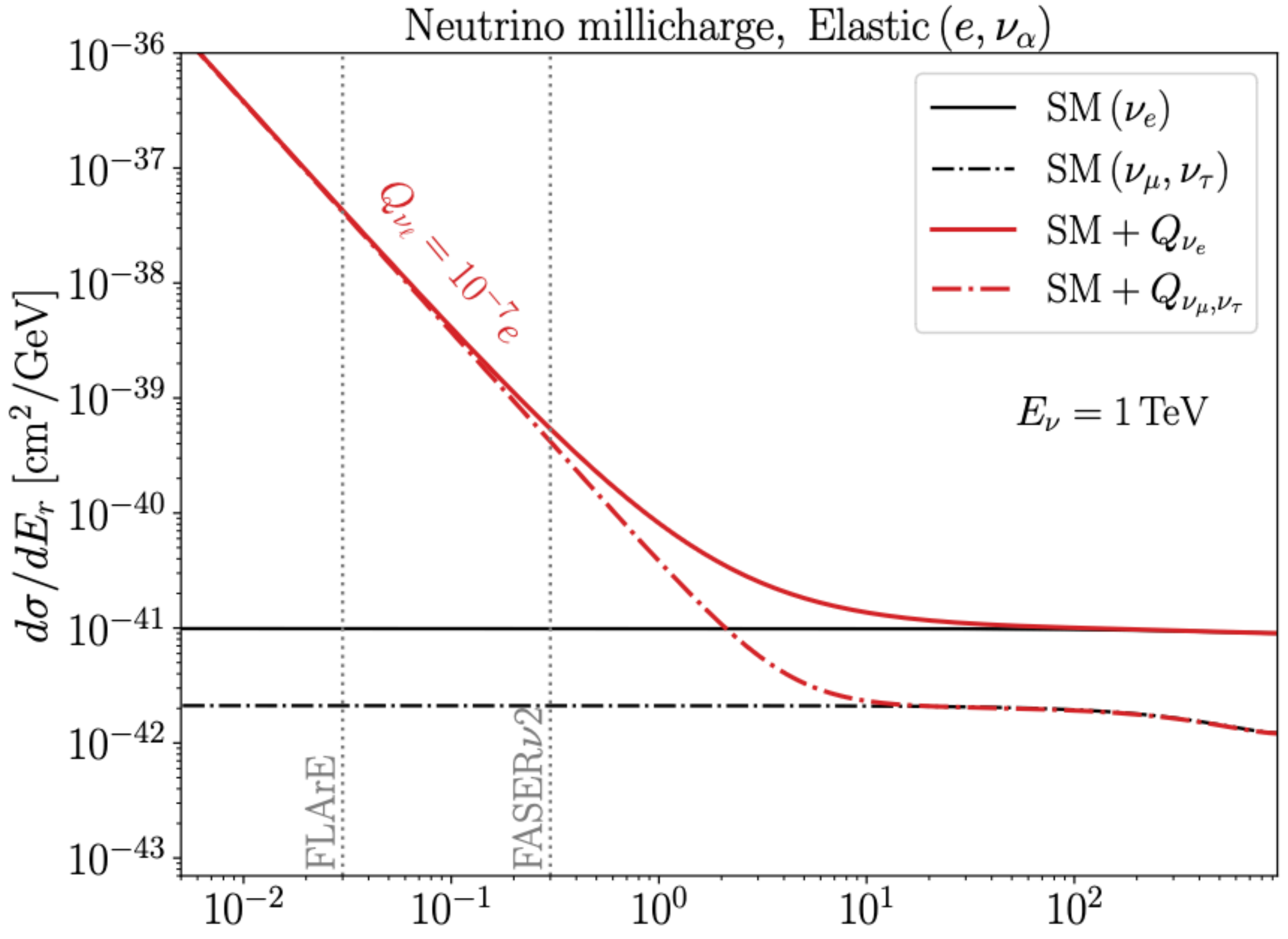
- Non-zero neutrino masses implies non-zero neutrino magnetic moment, $\mu_\nu^D \sim 10^{-19}\left(\frac{m_\nu}{1\text{ev}}\right)\mu_B$, and $\mu_\nu^M \sim 10^{-23}\mu_B$.
- Measuring NMM this can shed light on the nature of neutrinos; Dirac – diagonal and transition, Majorana - transition NMM.
- Neutrino EM properties have been used to explain some experimental anomalies.
- Experiments are very close to the SM value of neutrino charge radius.

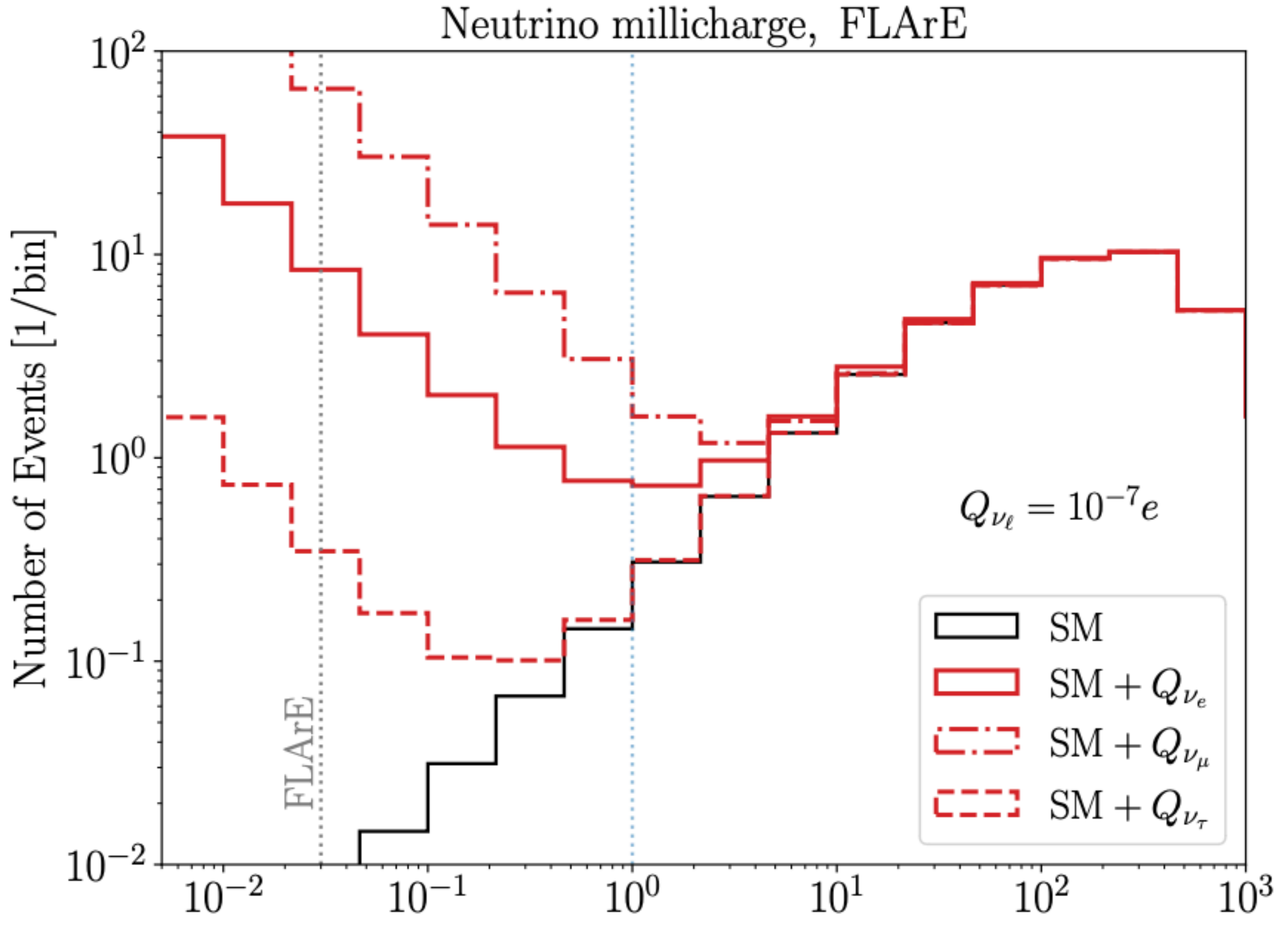
Modified Rates at FPF: $\nu - e$ elastic scattering

Neutrino Millicharge:

- $\mathscr{L} \supset Q_\nu(\bar{\nu}\gamma_\mu\nu)A^\mu$ **, Adds coherently with SM amplitude**
- **Due to the interference term, we are sensitive to the sign of neutrino millicharge.**

R. M. A., Saeid Foroughi-Abari, Felix Kling, Yu-Dai Tsai; 2301.10254





Modified Rates at FPF: $\nu-$nuclear scattering

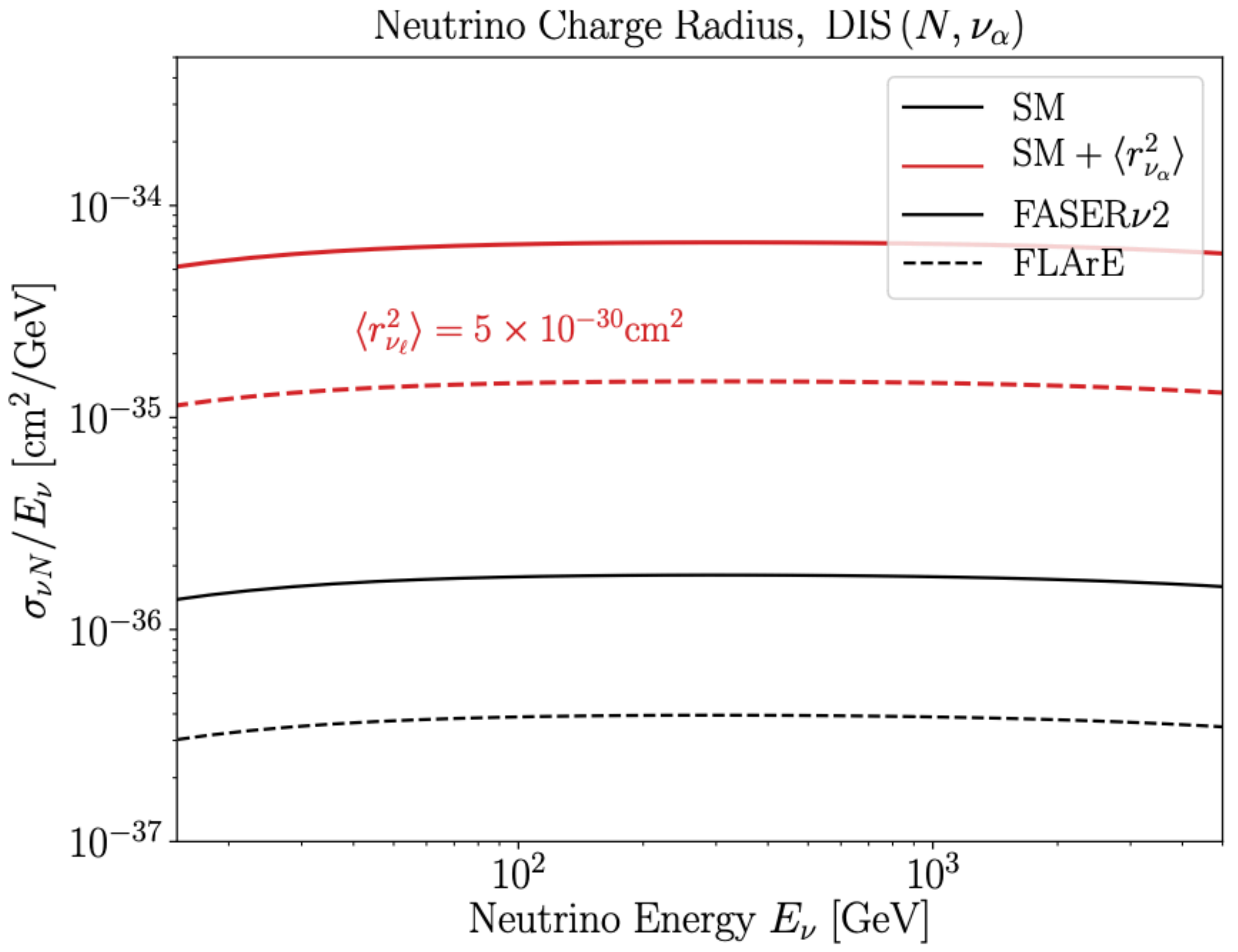
Neutrino Charge Radius:

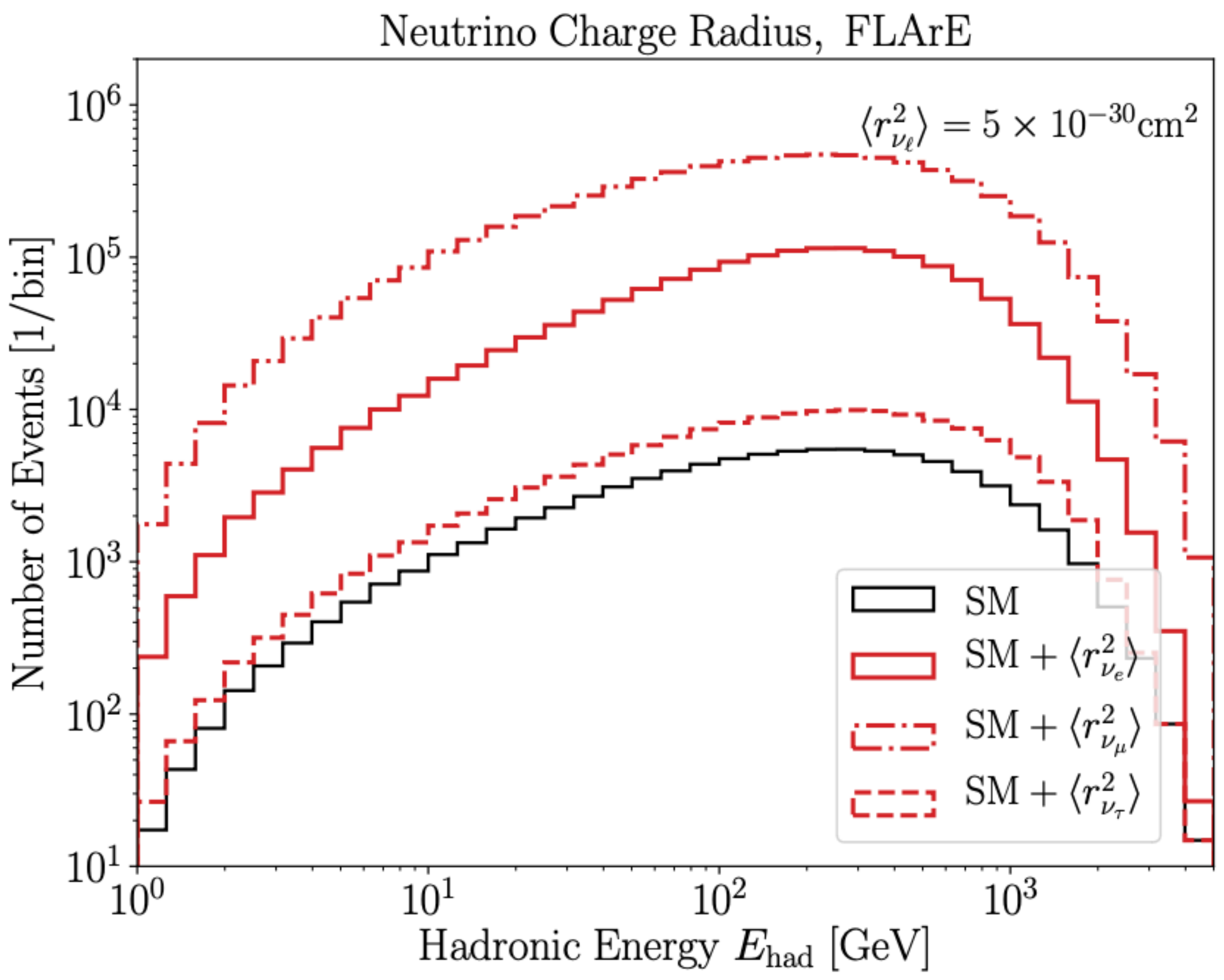
- **Vector coupling in the NC DIS is modified as,**
  - $g_V^q \to g_V^q - \frac{2}{3} Q_q m_W^2 \langle r_{\nu_\ell}^2 \rangle \sin^2 \theta_w$

Vogel and Engel, 89

- **We use a heavier target (nuclear scattering) for higher signal event rates.**

R. M. A., Saeid Foroughi-Abari, Felix Kling, Yu-Dai Tsai; 2301.10254

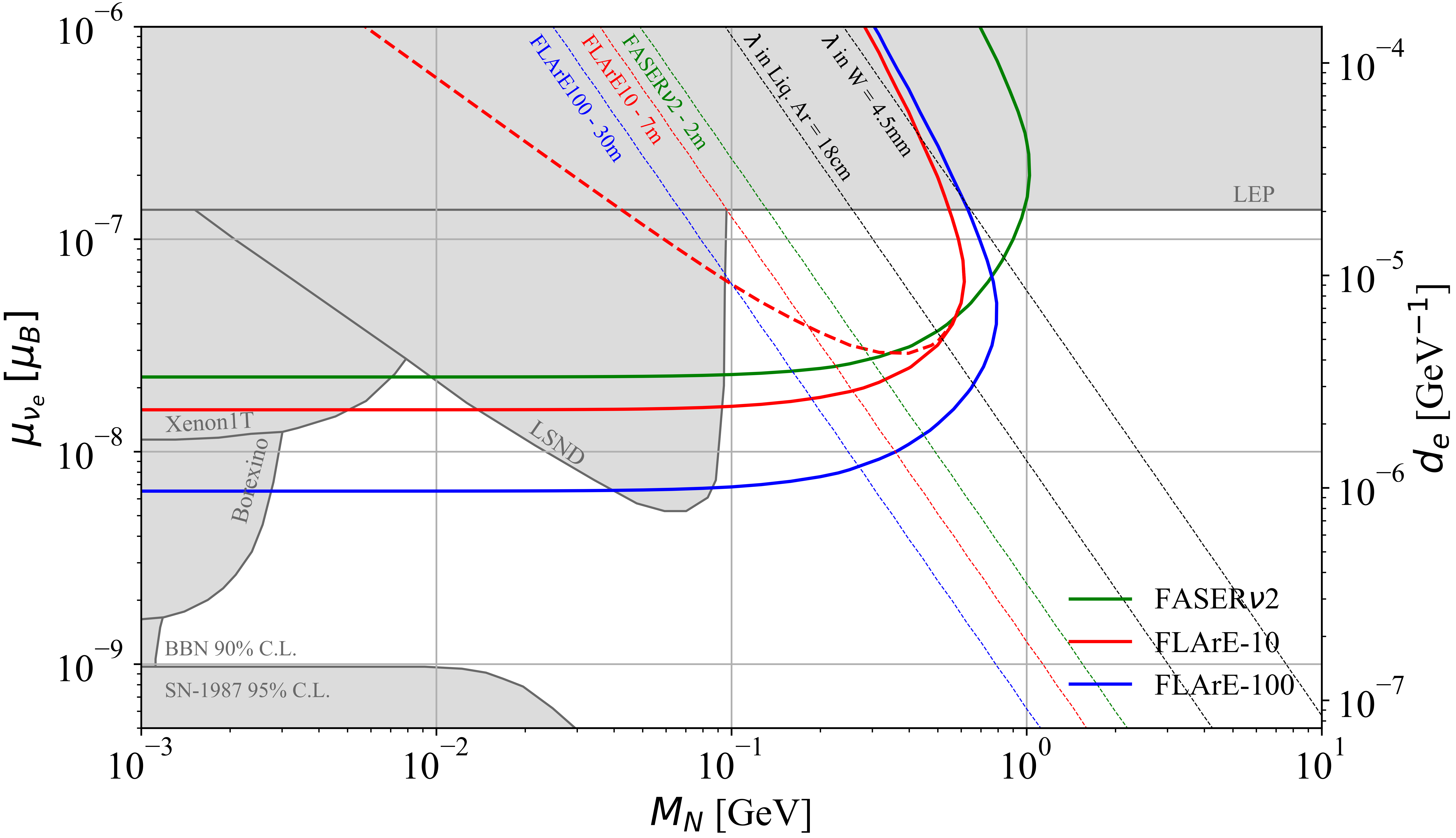




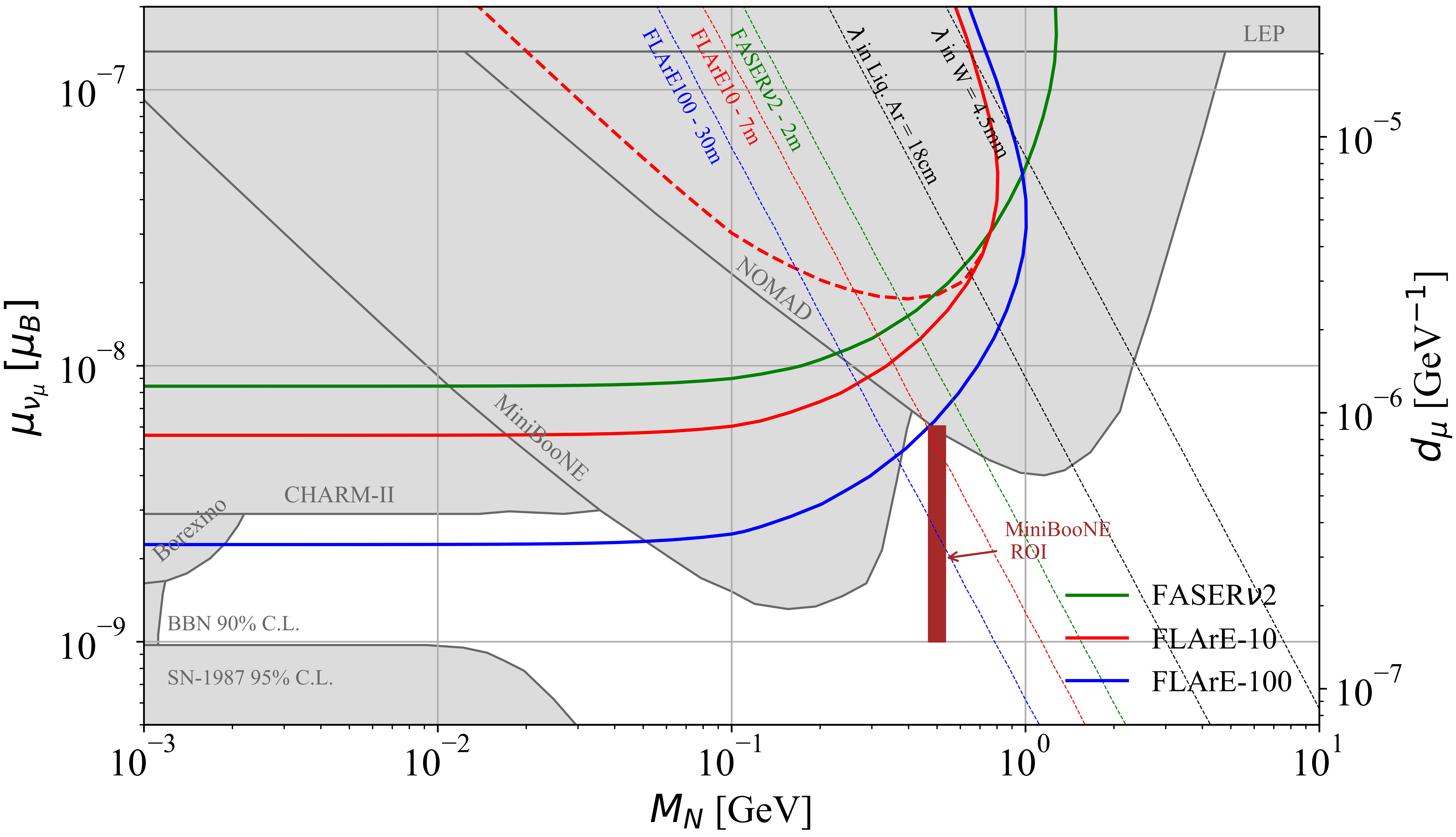
Active to Sterile Neutrino Transition Magnetic Moment

- The decay length of N_R in the lab frame is given by $l_{decay} = \frac{16\pi}{\mu_\nu^2 M_N^4}\sqrt{E_N^2 - M_N^2}$, where E_N = energy of outgoing N_R
- N_R can decay i) outside the detector, ii) within the detector with displaced vertex decays (double bang), and iii) promptly ($l_{decay} < l_{radiation}$).
- We look for signals i) and ii).

Backup slides - μ_{ν_e}



Backup slides - μ_{ν_μ}



Weak Mixing Angle at FPF

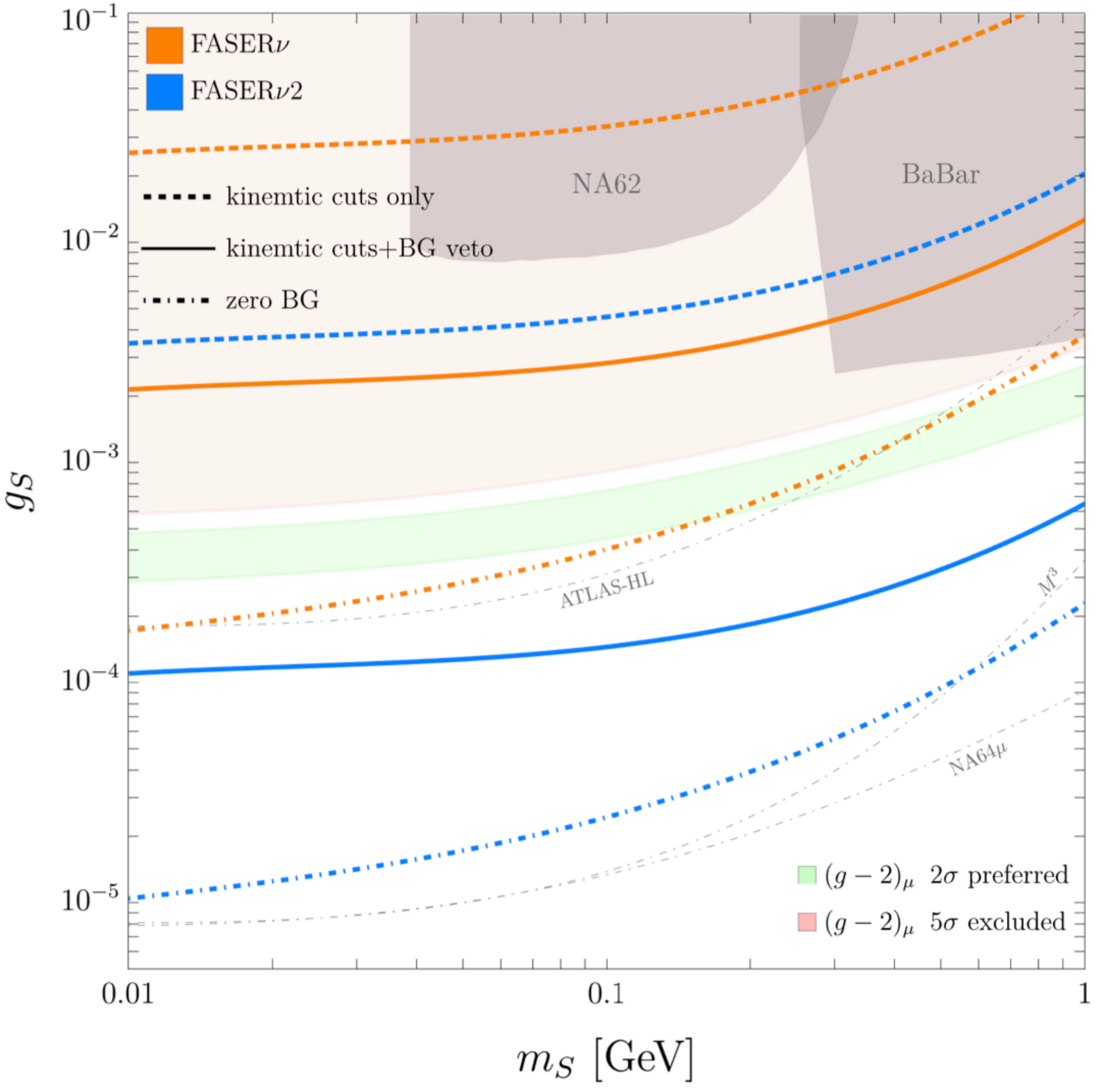
- **If the SM value shifts, $\sin^2\theta_W \to \sin^2\theta_W + \Delta\sin^2\theta_W$ then $g_V^q \to g_V^q - 2Q_q\Delta\sin^2\theta_W$.**
- **Modifies NC DIS similarly to NCR.**
- **One can recast NCR results to measure to the $\sin^2\theta_W$ at the FPF.**
- **Could be interesting if the NuTeV measurement is actually anomalous. Their measured value is 3σ above SM value.**

hep-ex/0110059
https://pdg.lbl.gov/2022/reviews/rpp2022-rev-standard-model.pdf

Using *FASERν* emulsion detector

Backgrounds:

$$N + \mu \to \begin{cases} N + \mu + e^- + e^+ & \text{(Pair production)} \\ N^+ + \mu + e^- & \text{(Ionization)} \\ N + \mu + \gamma & \text{(Bremsstrahlung)} \\ N^* + \mu + \ldots & \text{(Nuclear)} \end{cases}$$



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