Neutrino and Muon Physics at Forward Detectors at (HL-)LHC

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Physics Potential of Future Colliders

TRIUMF

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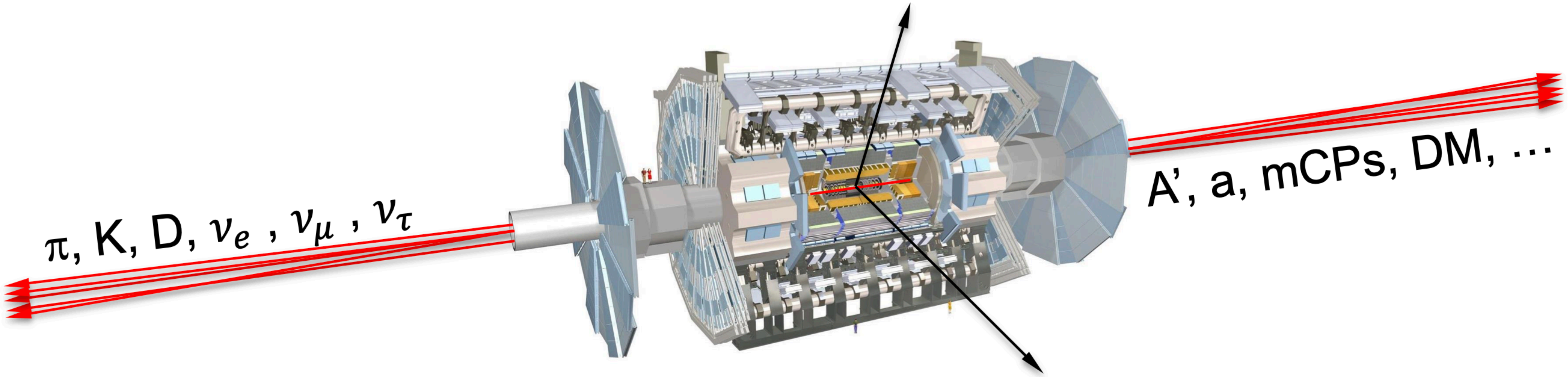
Forward Region at the LHC

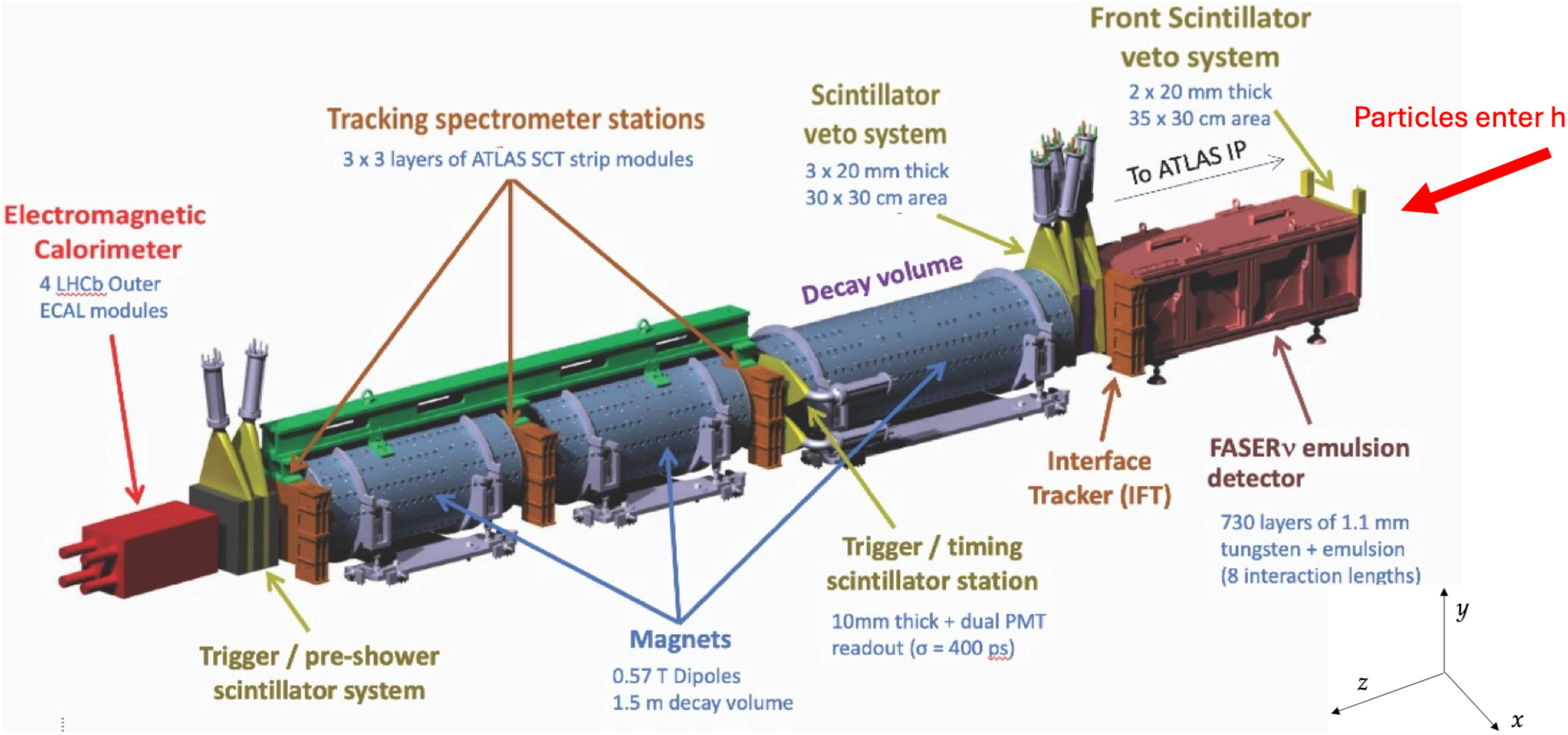


- pp collisions at the LHC produce an intense flux of particles in the forward direction
- These particles are light and weakly coupling:
  - SM (ν, μ, …) and BSM (ALPs, dark photon, DM, …)
- Conventional transverse detectors will miss these particles

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

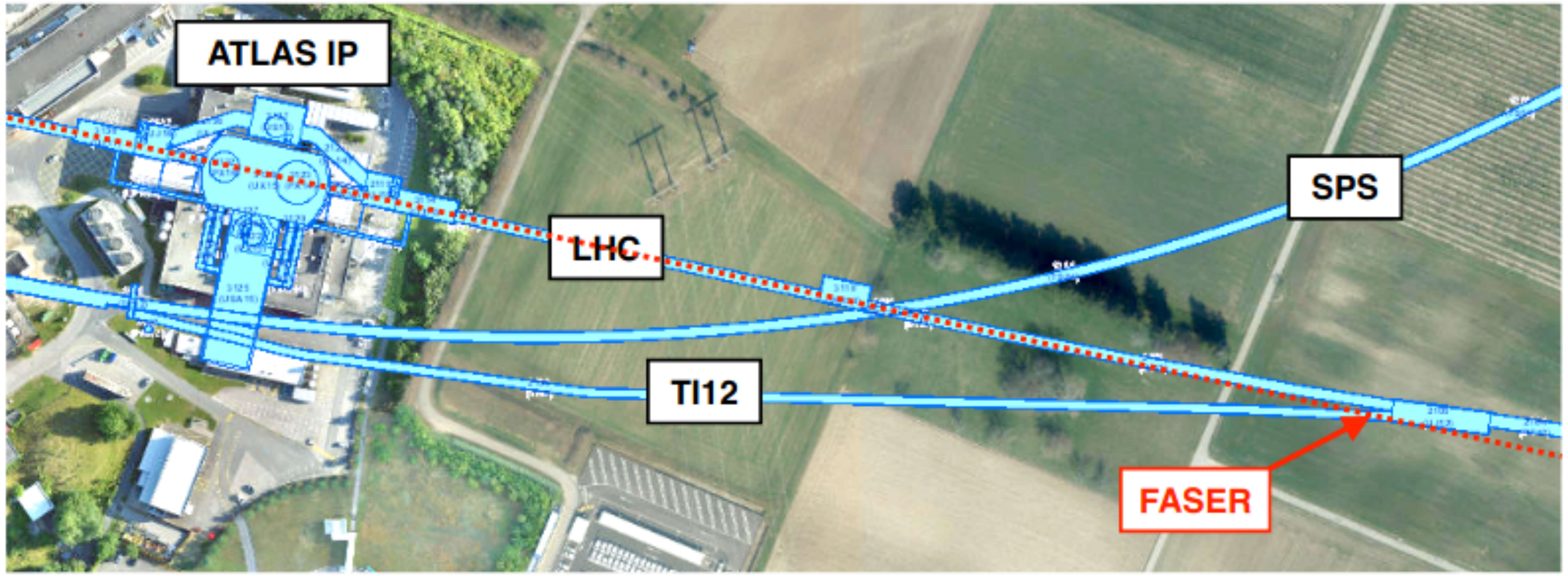
ForwArd Search ExpeRiment(ν) - FASER(ν)

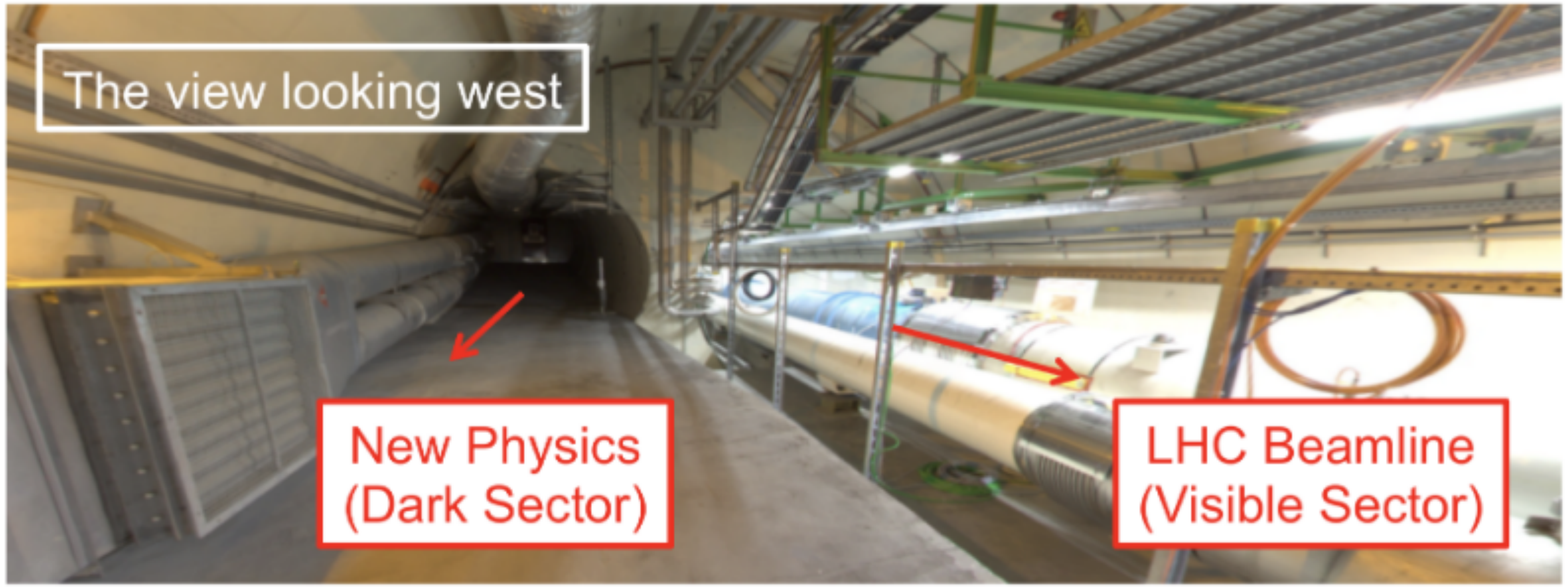
- **FASER: 25cm x 25cm x 1.5m decay volume**
  - **1708.09389 (first paper), 1811.10243 (LOI), 1812.09139**
- **FASERν: 25cm x 25cm x 1m tungsten emulsion detector**
  - **1908.02310, 2001.03073**
- $\eta \gtrsim 8.5$ **coverage.**

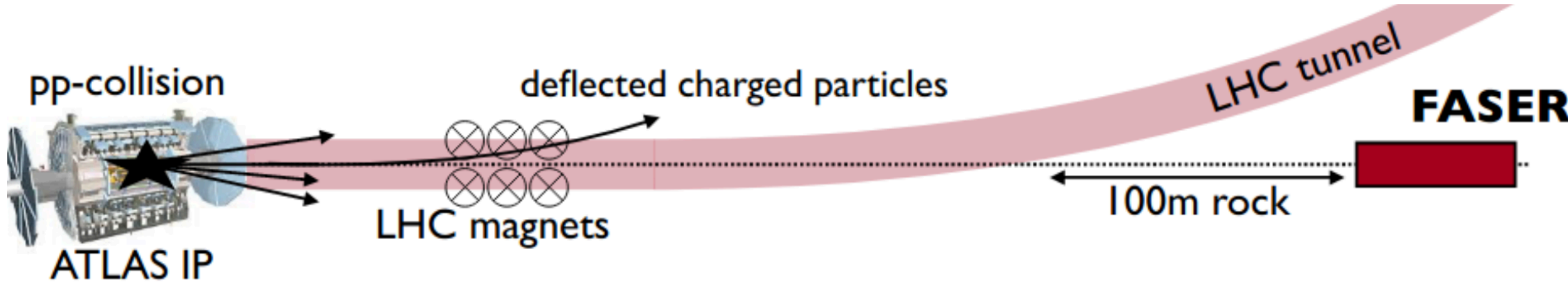


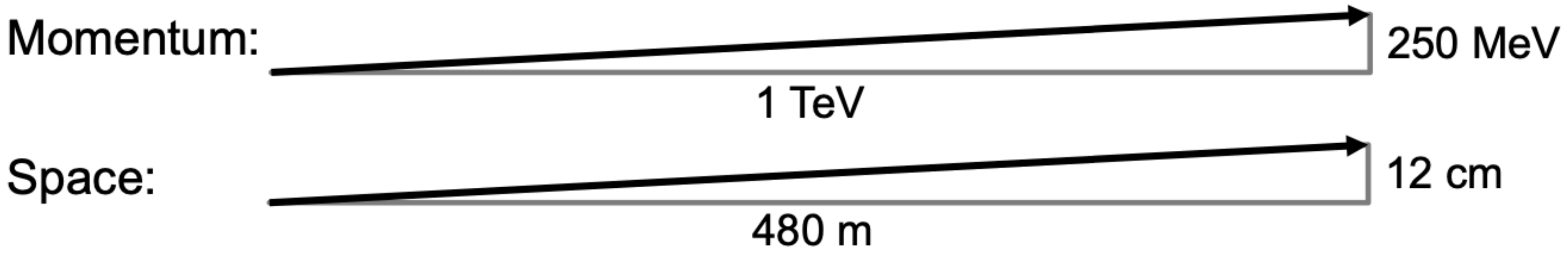
Particles enter here!

Location for forward detectors at LHC









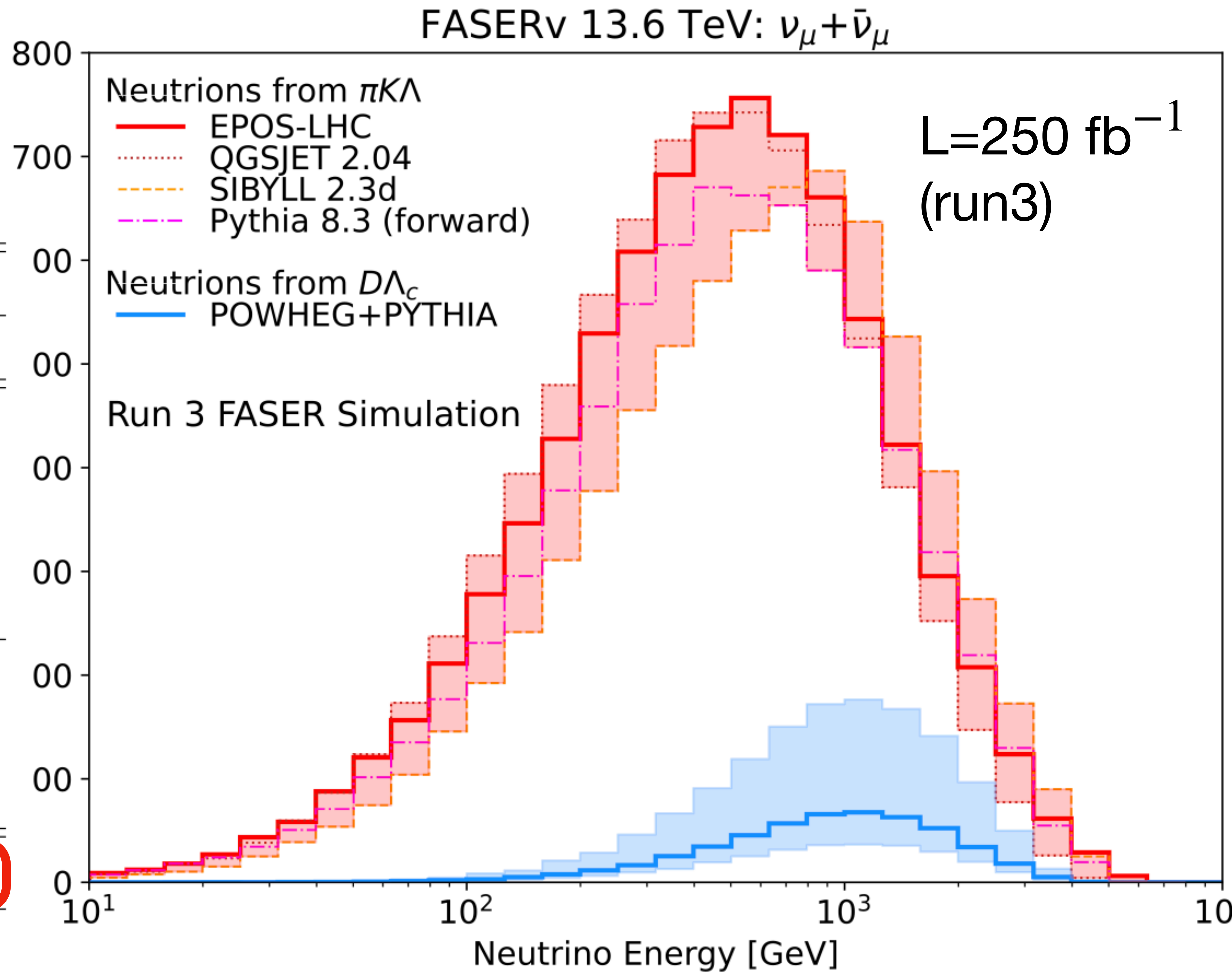
Neutrino Flux at FASER

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

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

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

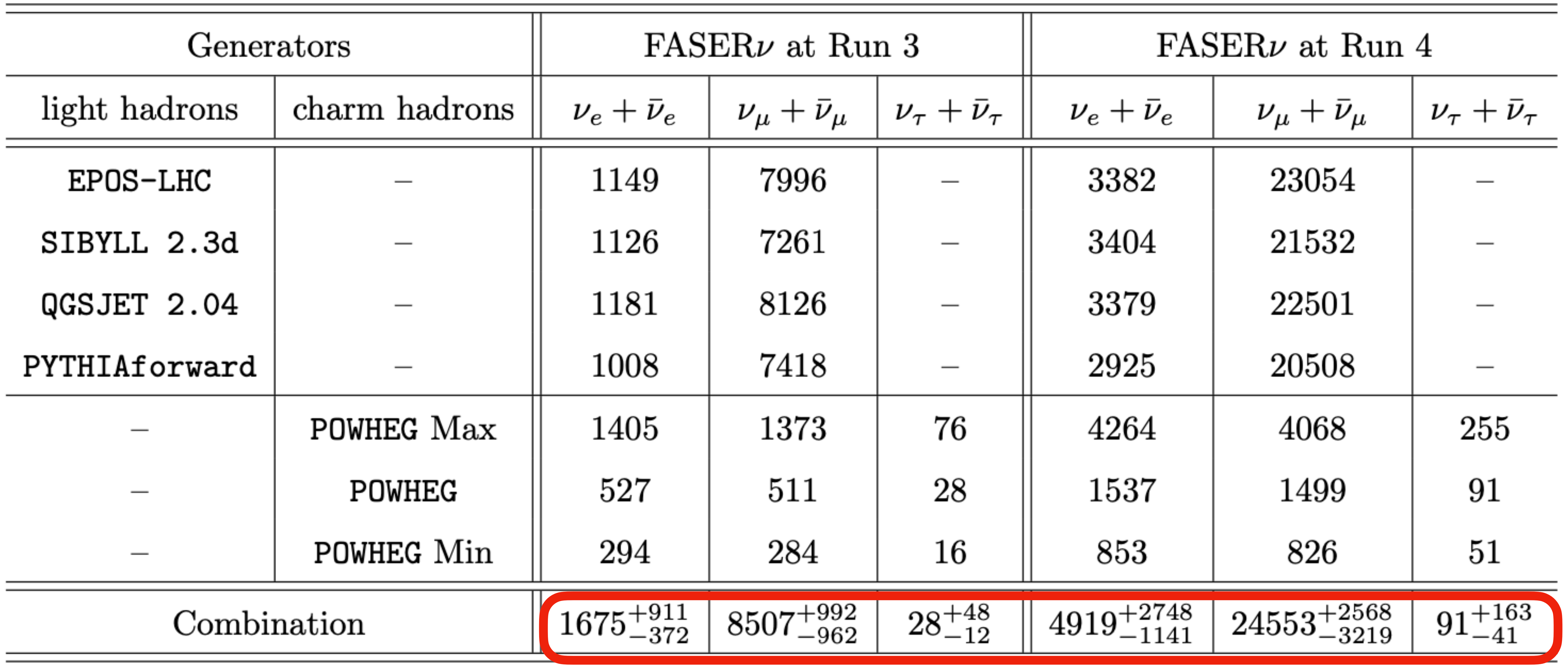


Neutrino Rate Predictions for FASER;
2402.13318

Neutrino Flux at FASER

$$\nu_e\text{: } K \longrightarrow \pi e \nu_e \text{ , } D \longrightarrow K e \nu_e$$

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



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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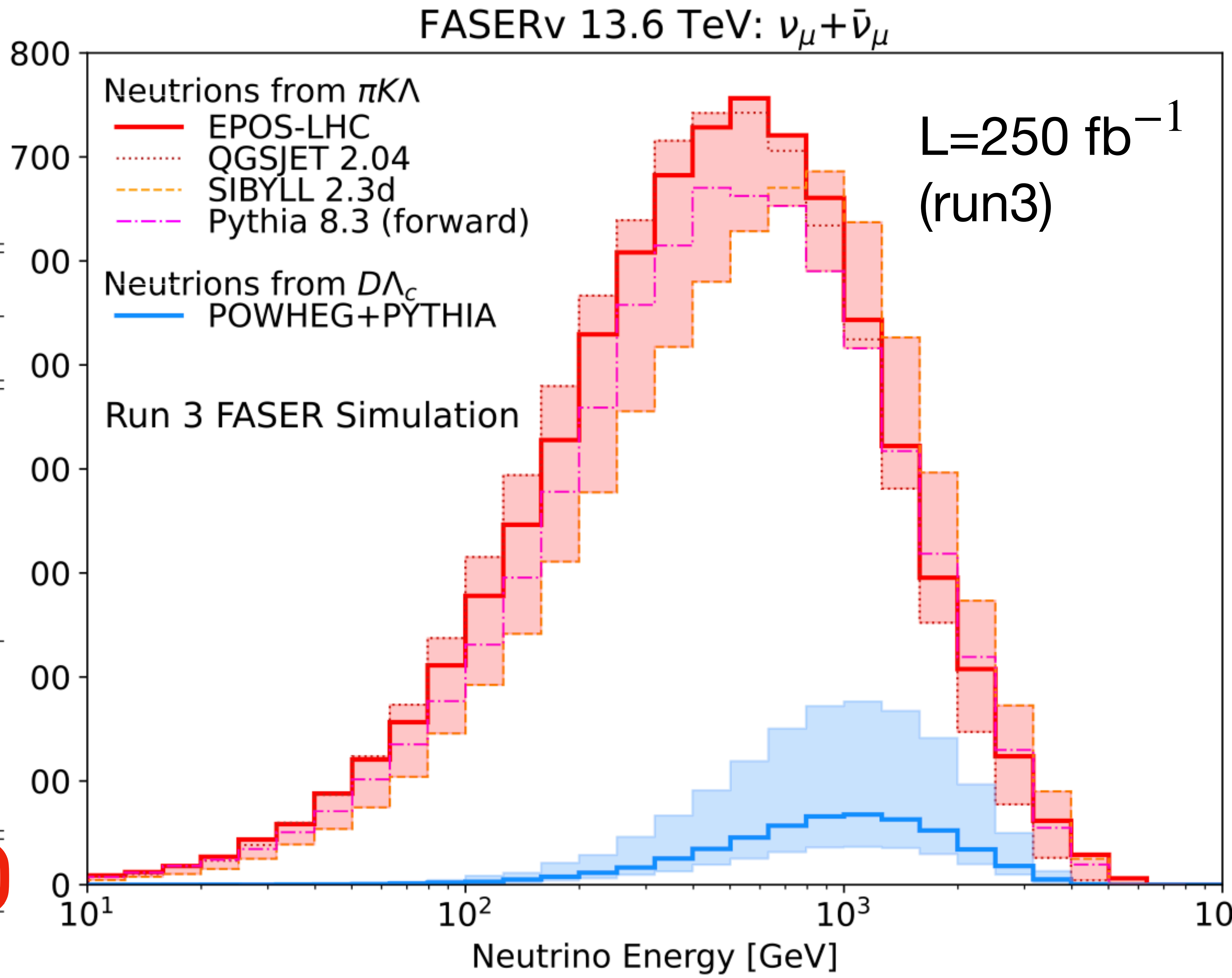
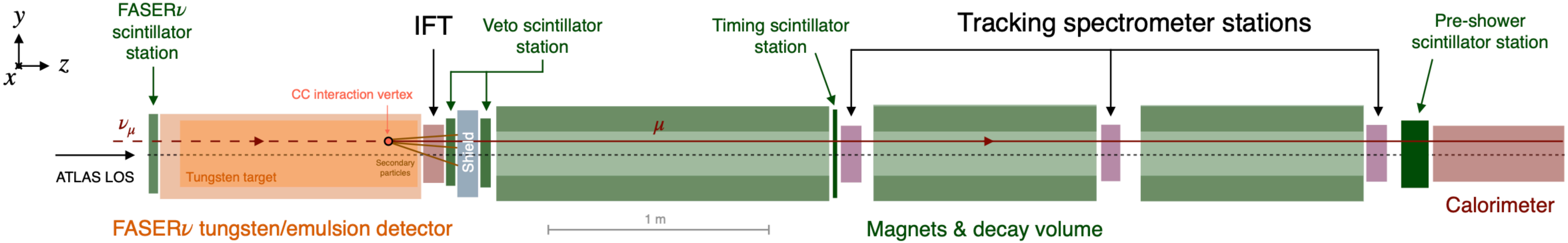


Already many new exciting results!!!

Neutrino Rate Predictions for FASER,
2402.13318

First Observation of Collider Neutrinos

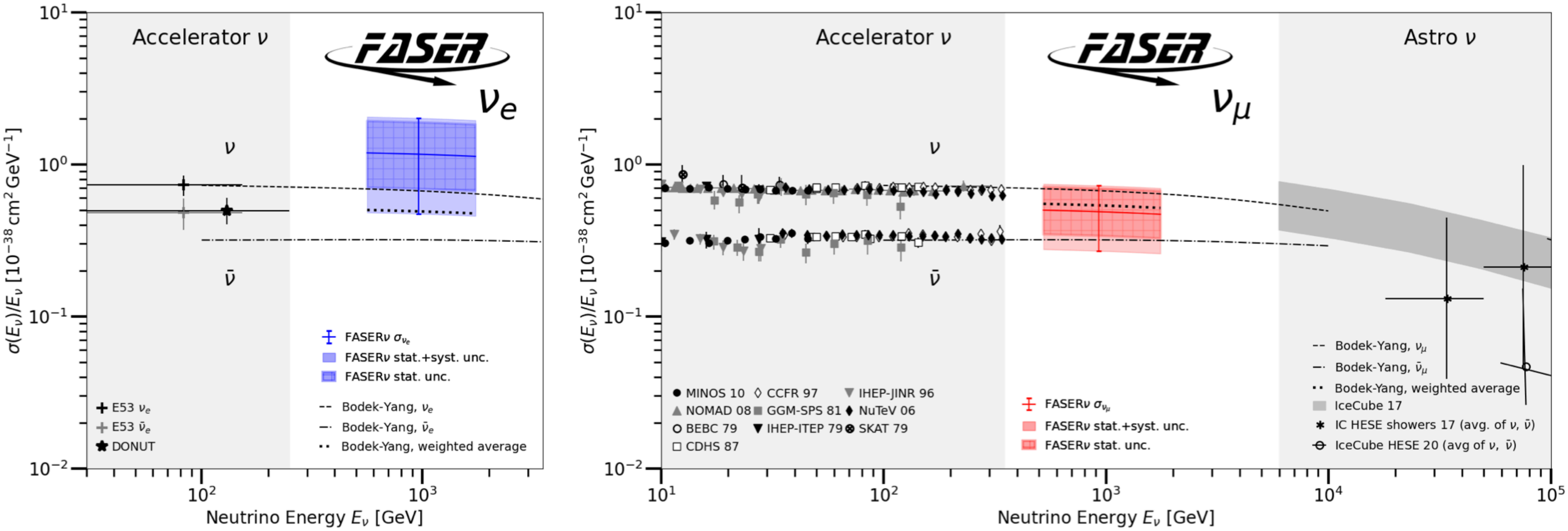


At FASER

~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

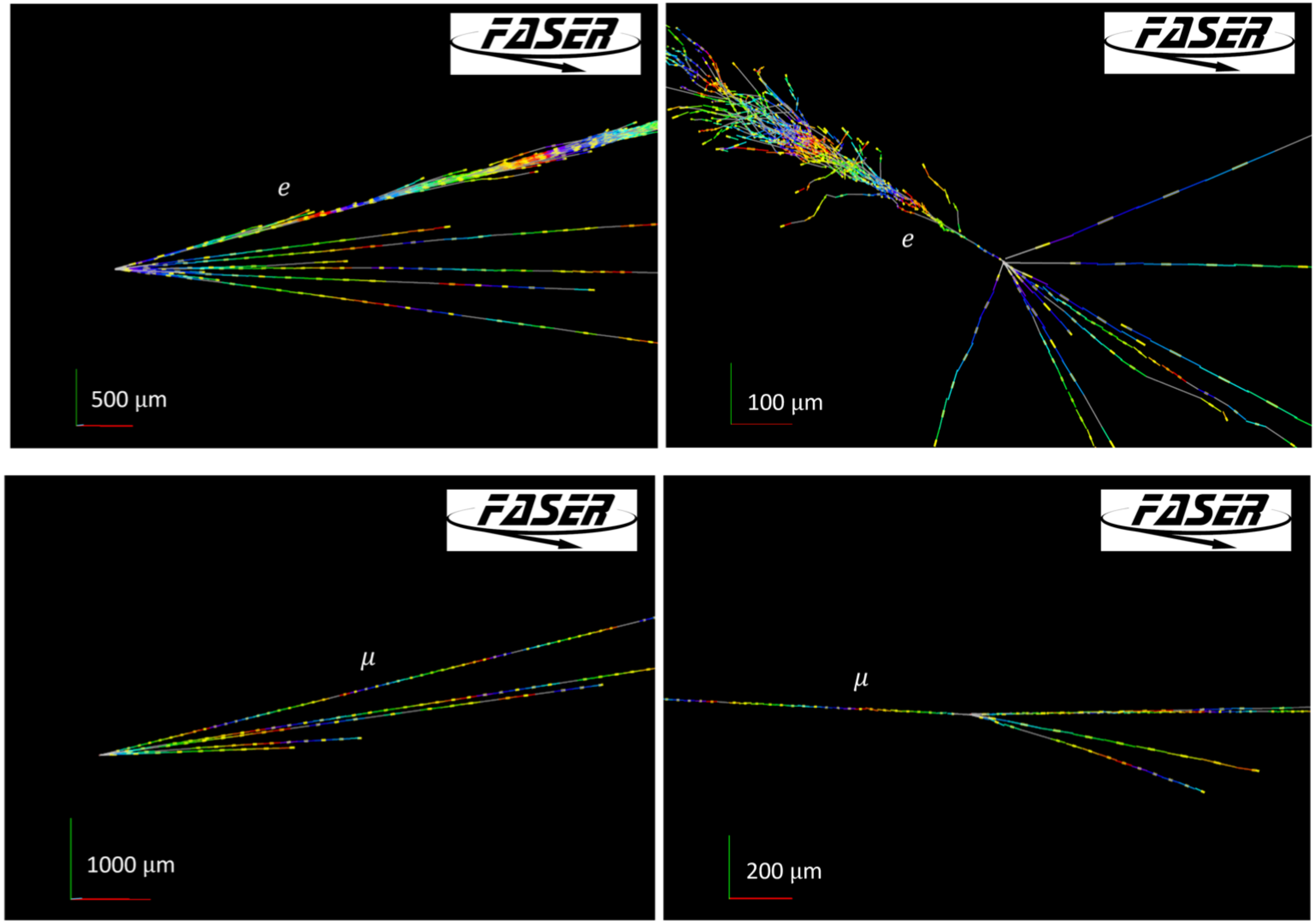
First Neutrino Cross-Section Measurements at LHC



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

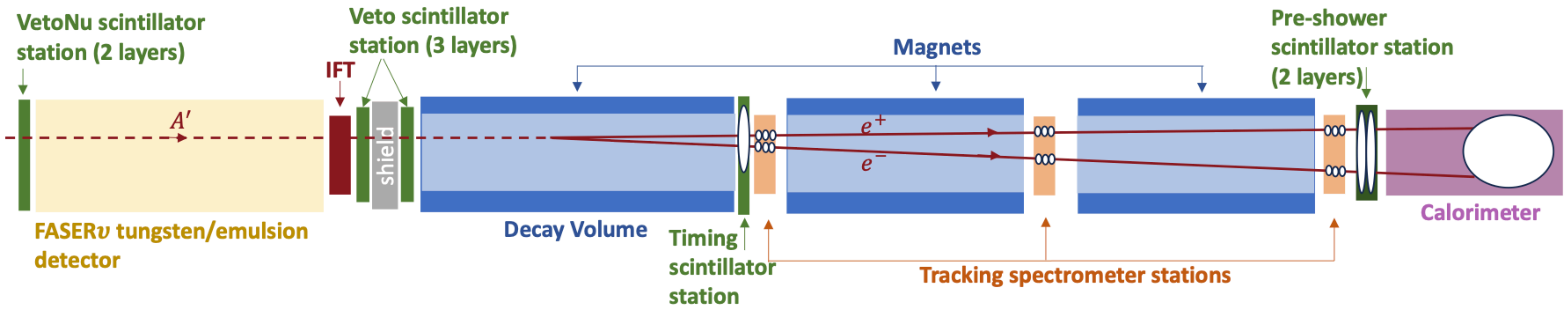
First Measurement of the ν_e and ν_μ Interaction Cross Sections at the LHC with FASER's Emulsion Detector; 2403.12520

ν_e and ν_μ events at FASERν

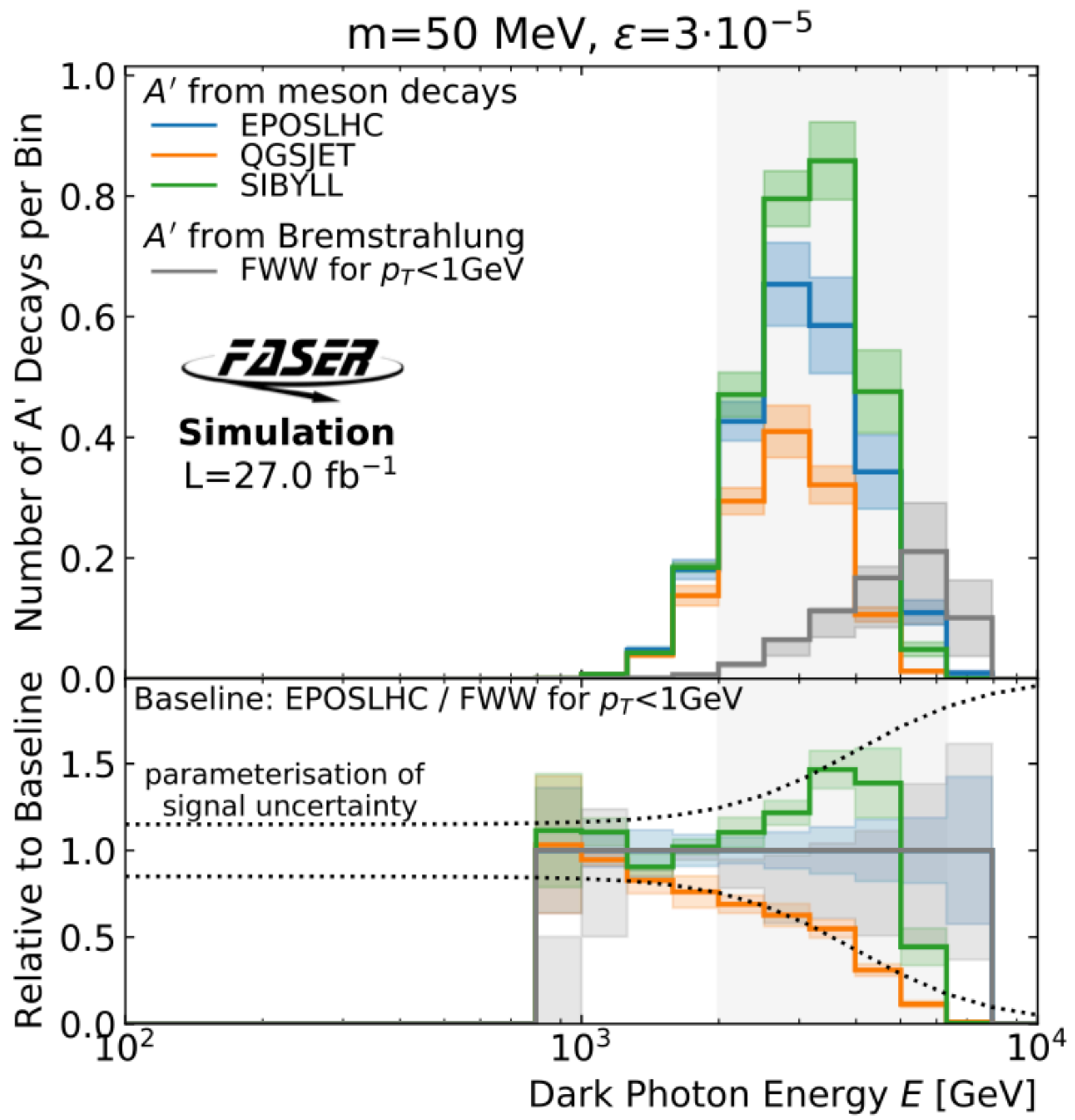


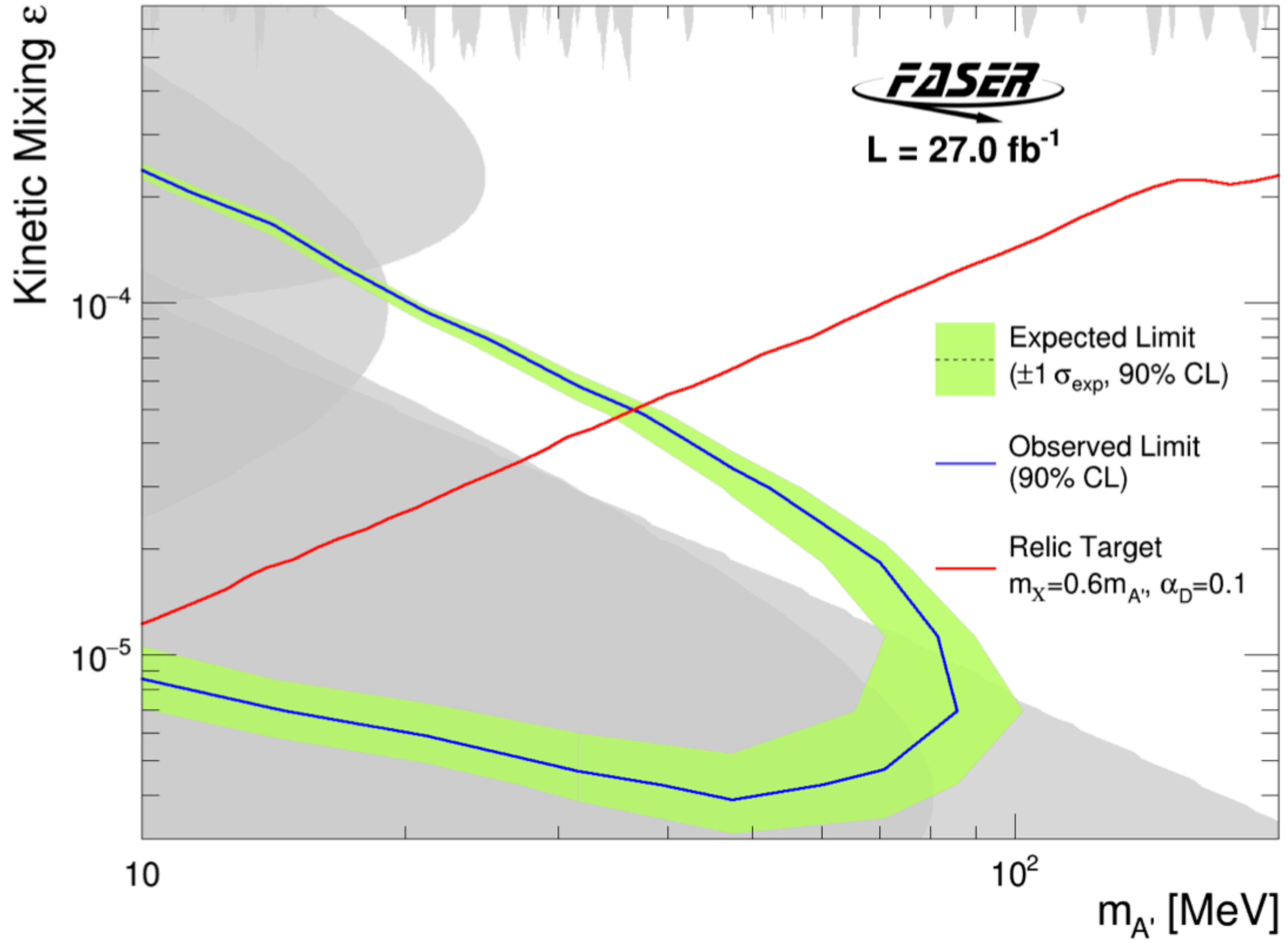
First Measurement of the ν_e and ν_μ Interaction Cross Sections at the LHC with FASER's Emulsion Detector; 2403.12520

Dark Photon Searches at FASER



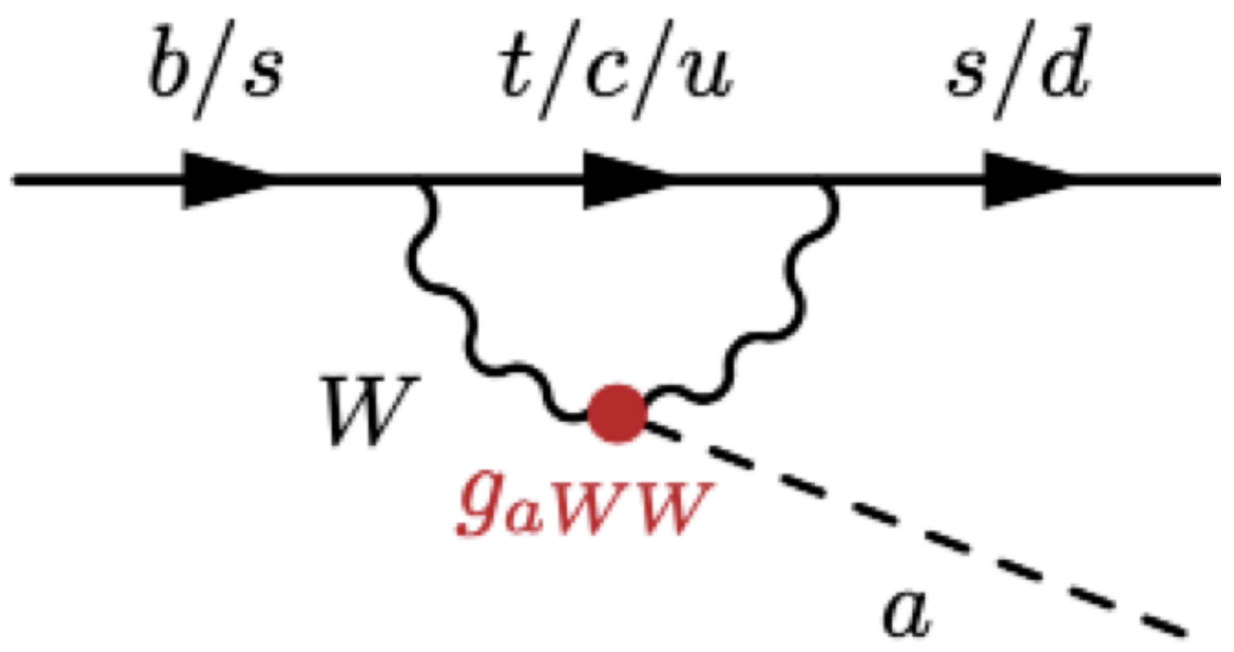
Search for Dark Photons with the FASER detector at the LHC; 2308.05587

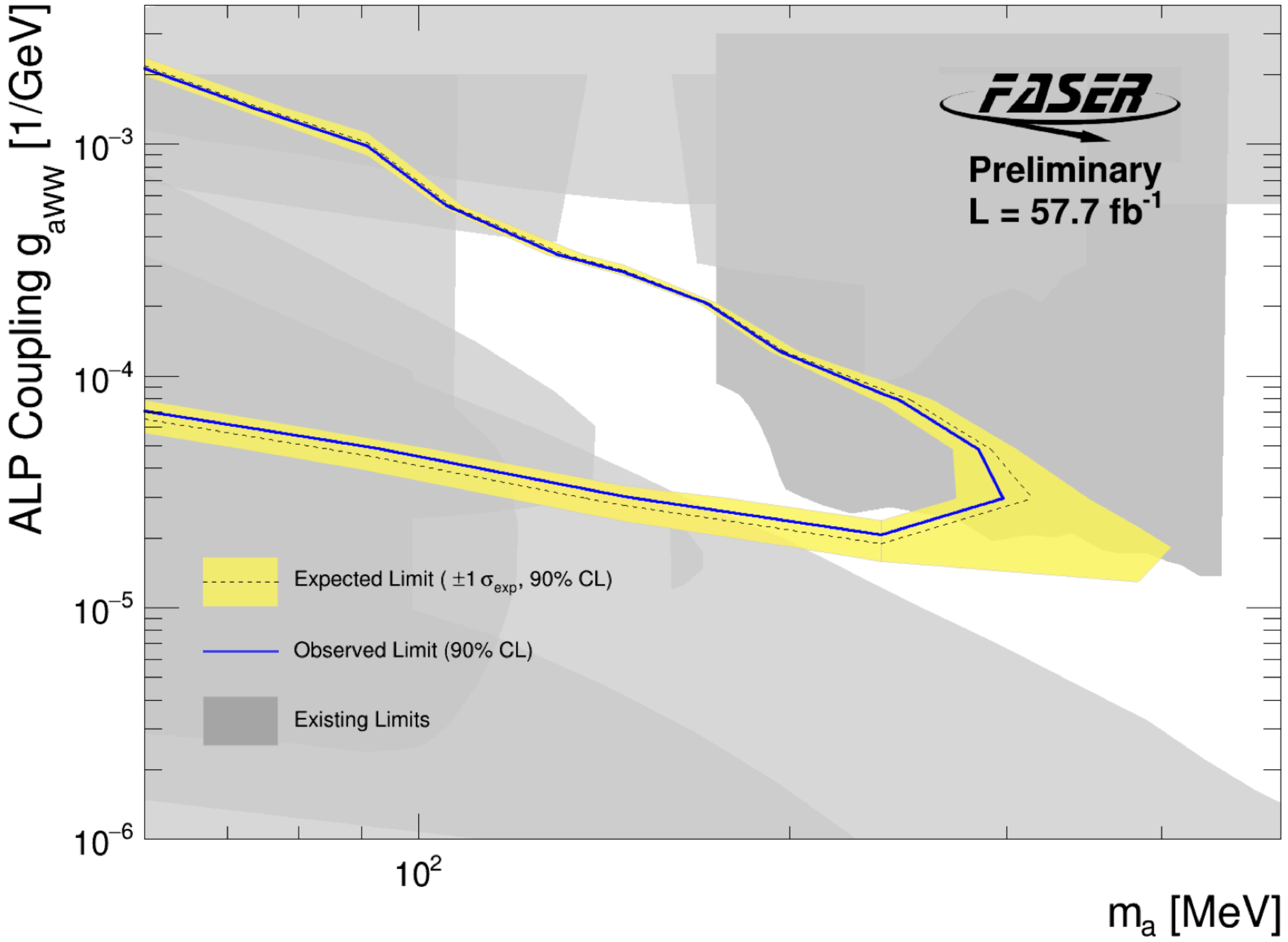




ALP Searches at FASER

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





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

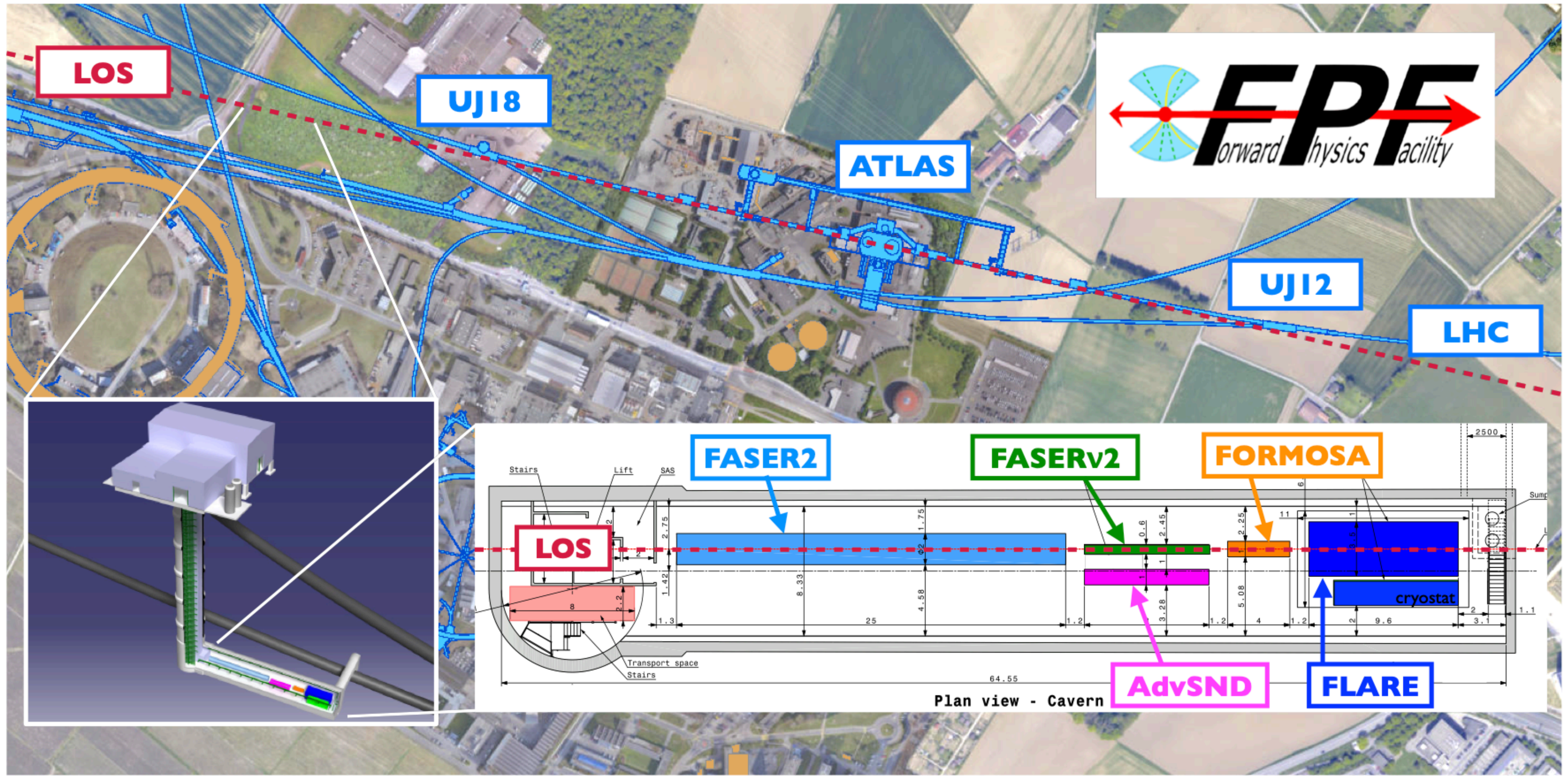


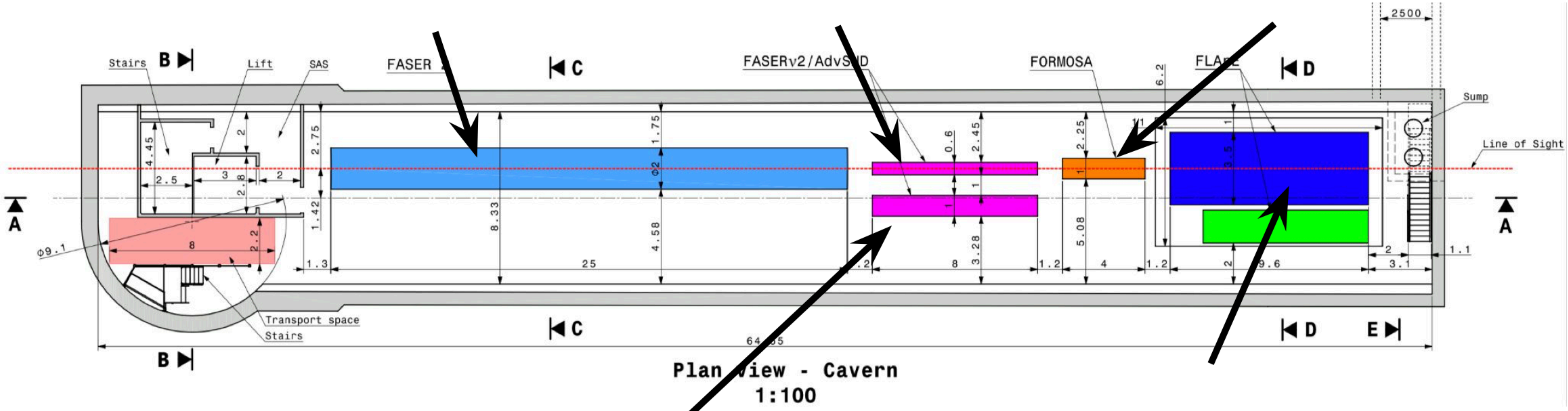
Figure 1: The preferred location for the Forward Physics Facility, a proposed new cavern for the High-Luminosity era. The FPF will be 65 m-long and 8.5 m-wide and will house a diverse set of experiments to explore the many physics opportunities in the far-forward region.

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

FASERν2
emulsion-based
neutrino detector

FORMOSA
plastic scintillator array
for BSM searches

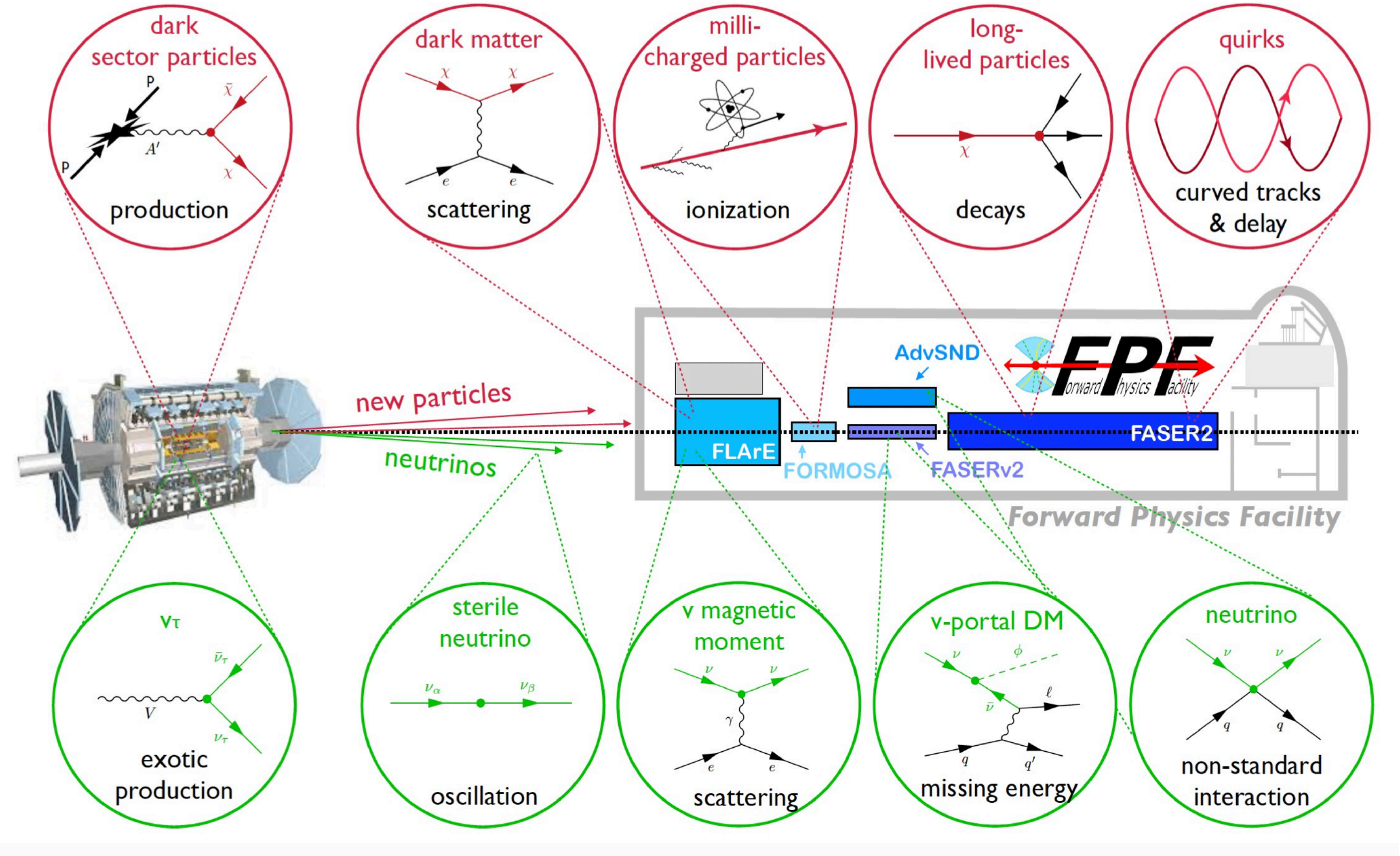
AdvSND
electronic
neutrino detector

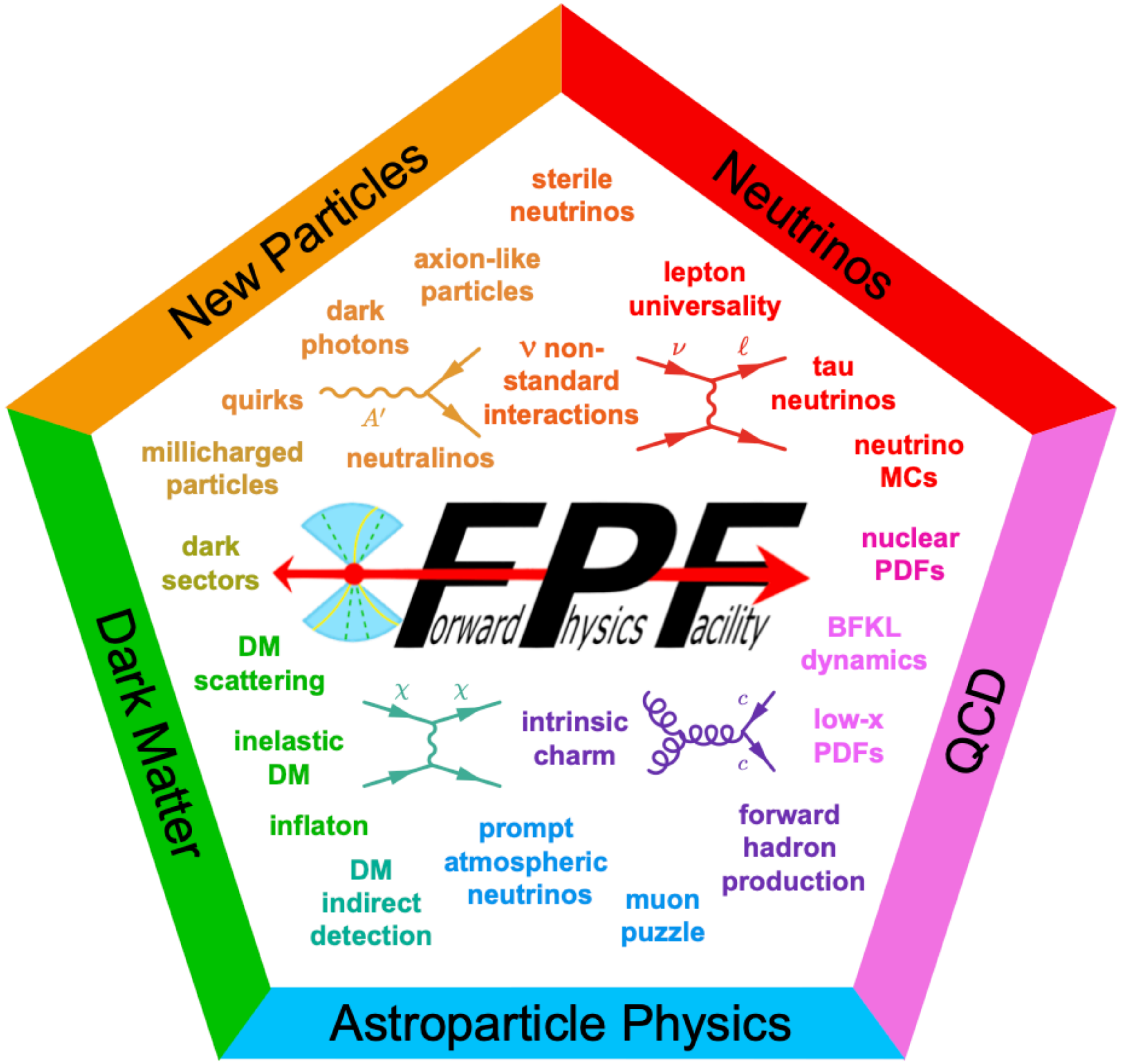
FLArE
LAr based
neutrino detector

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 Work in the Forward Direction

- Neutrino Physics
- Muon Physics

All these neutrinos deserve some BSM 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**
  - $\Lambda^{\mu}_{fi}(q) = \gamma^{\mu}\left(Q_{fi} - \frac{q^2}{6}\langle r^2 \rangle_{fi}\right) - i\sigma^{\mu\nu} q_{\nu} \mu_{fi}$

Carlo Giunti, Alexander Studenikin; 1403.6344

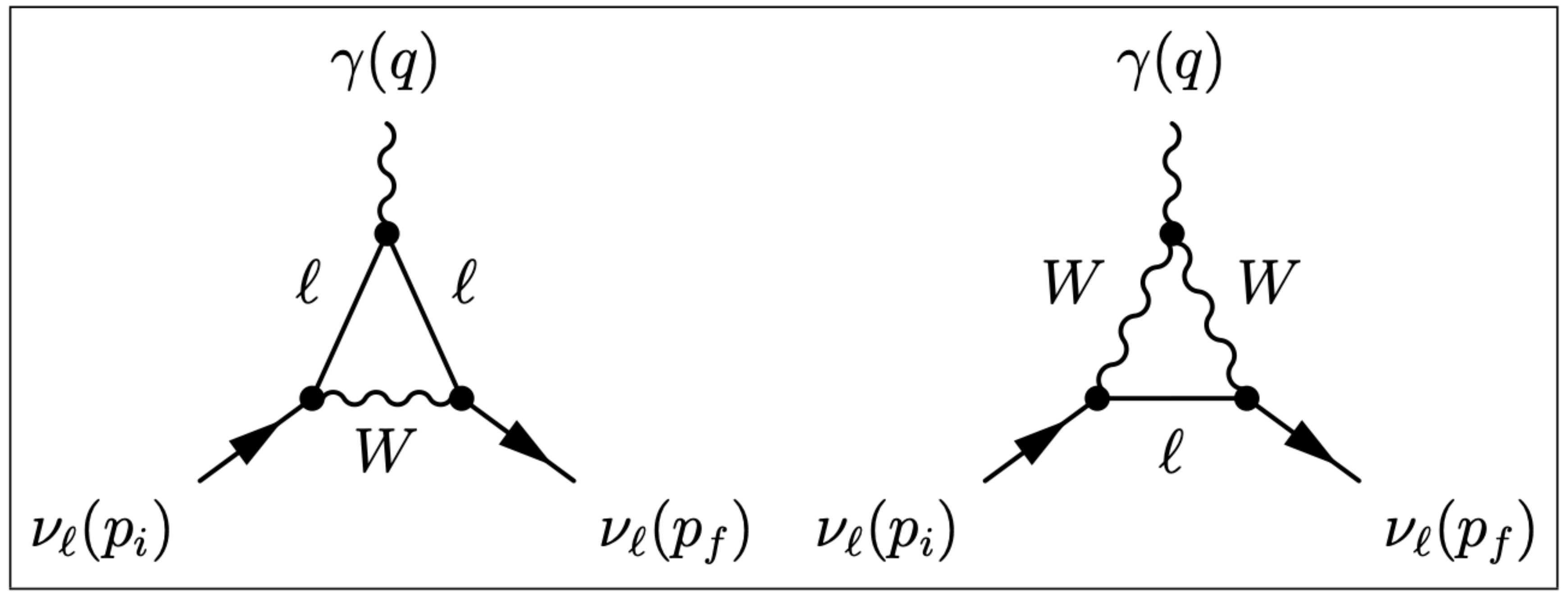
Neutrino Magnetic Moment (NMM)

Neutrino millicharge (NMM)

Neutrino Charge Radius (NCR)

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.
- NCR is generated at loop level within the SM, $\left\langle r^2_{\nu_\ell}\right\rangle_{\text{SM}} = \frac{G_f}{4\sqrt{2}\pi^2}\left[3 - 2\log\frac{m_\ell^2}{m_W^2}\right]$.

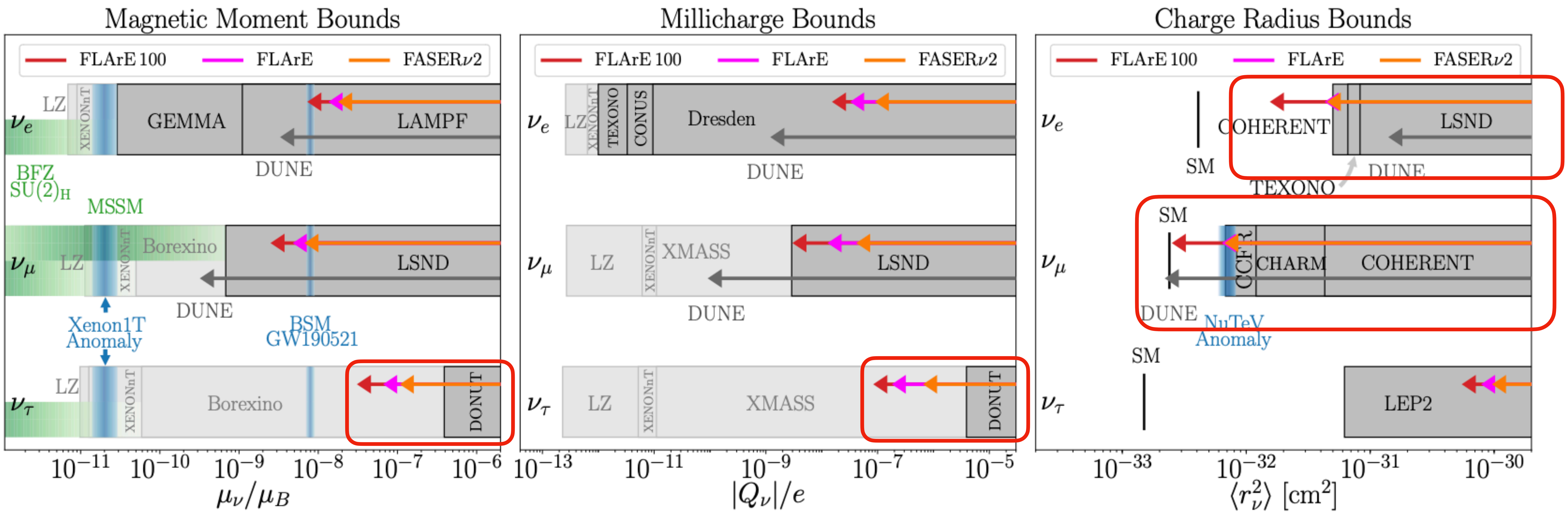


$$\left\langle r^2_{\nu_e}\right\rangle_{\text{SM}} = 4.1\times10^{-33}cm^2$$

$$\left\langle r^2_{\nu_\mu}\right\rangle_{\text{SM}} = 2.4\times10^{-33}cm^2$$

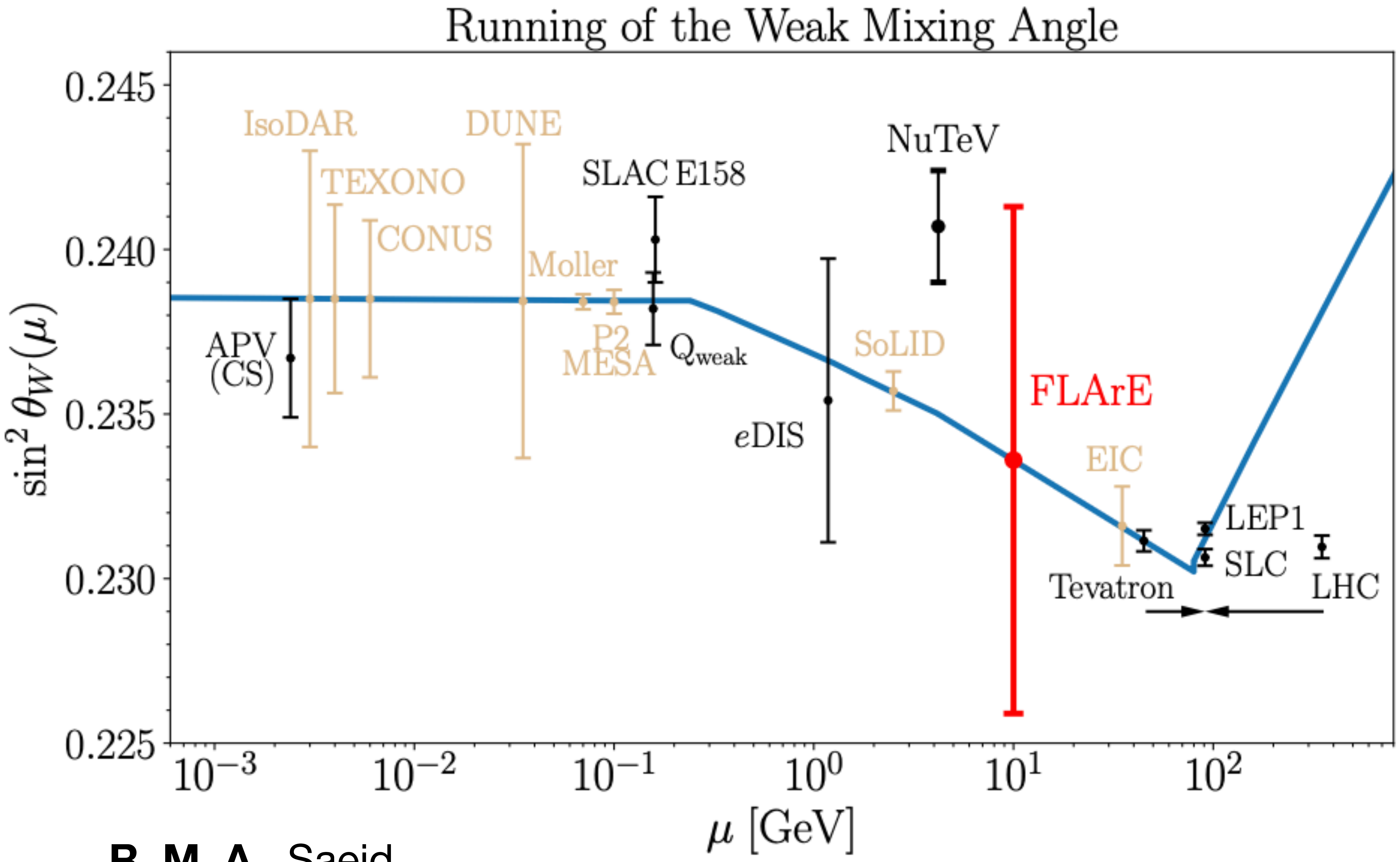
$$\left\langle r^2_{\nu_\tau}\right\rangle_{\text{SM}} = 1.5\times10^{-33}cm^2$$

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.

Muons at Forward Detectors

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

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

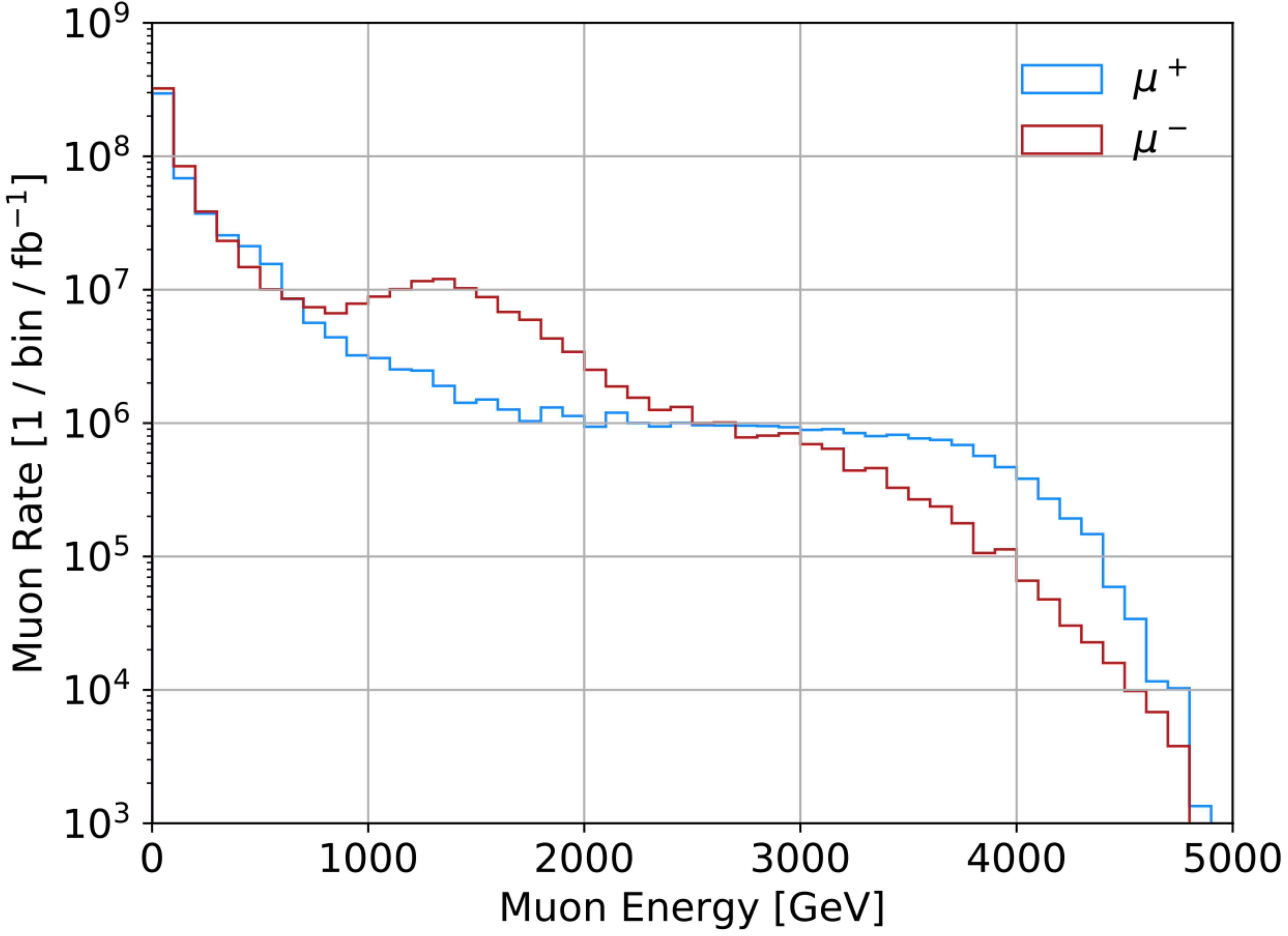
ν_τ: $D_s \longrightarrow \tau \nu_\tau$

But what about all these muons?

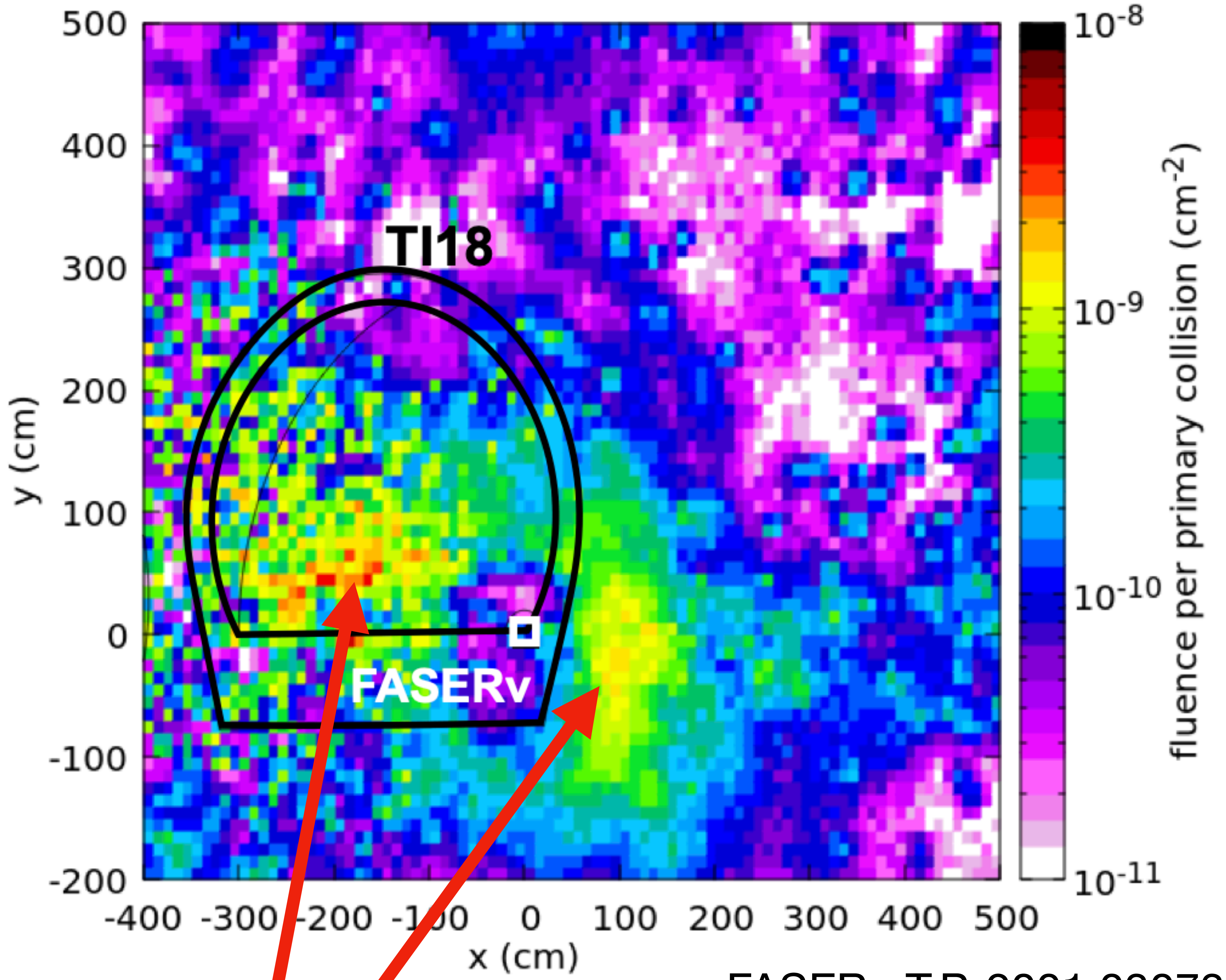
Are they just backgrounds or can we do some physics with them?

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



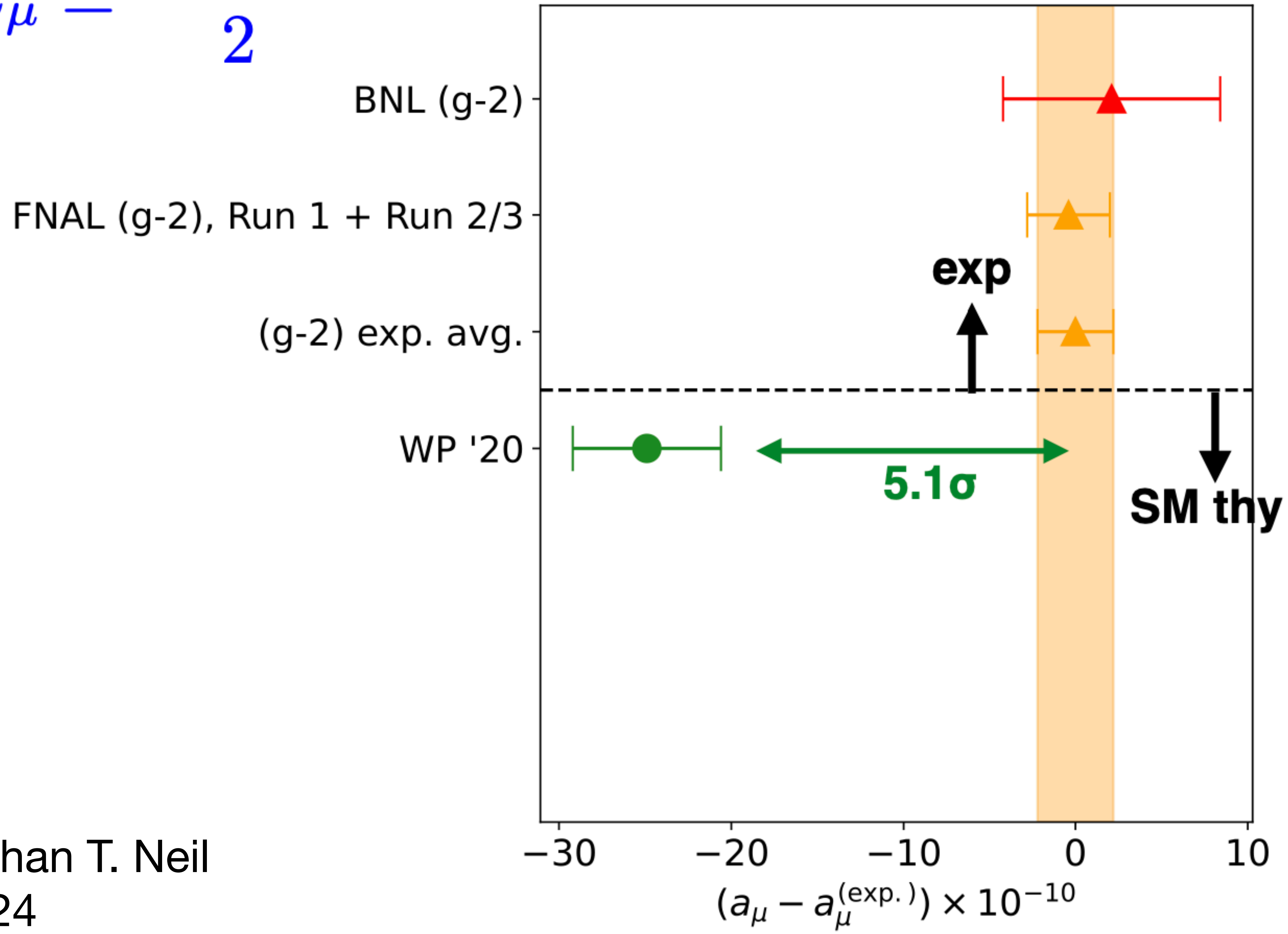
FASERν T.P, 2001.03073

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**

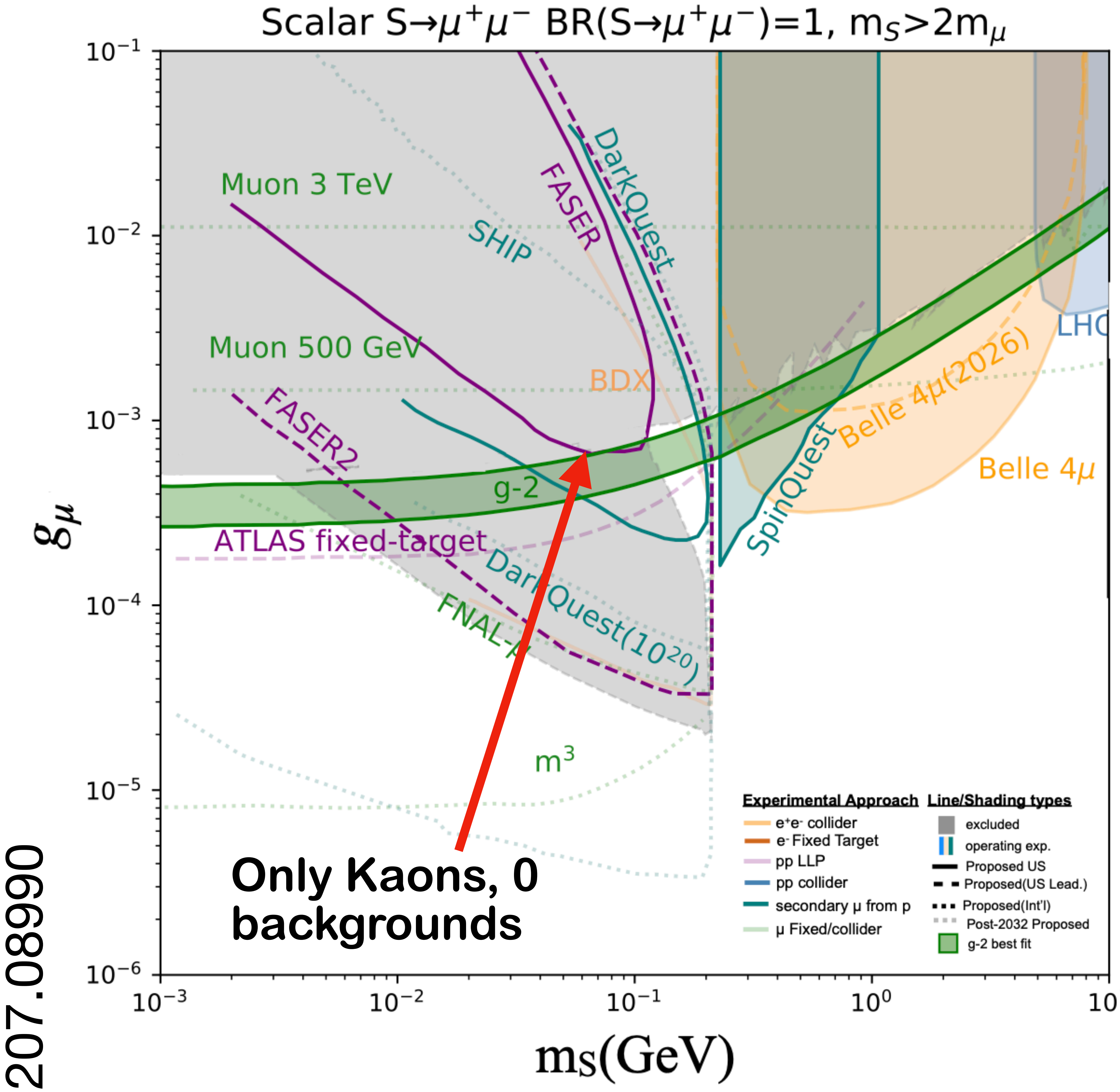
$$\Delta a_\mu = \frac{g_\mu^2}{8\pi^2}\int_0^1 \mathrm{d}z \frac{(1-z)^2(1+z)}{(1-z)^2 + z(m_S/m_\mu)^2}$$

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

Rodolfo Capdevilla, David Curtin, Yonatan Kahn, Gordan Krnjaic; 2112.08377

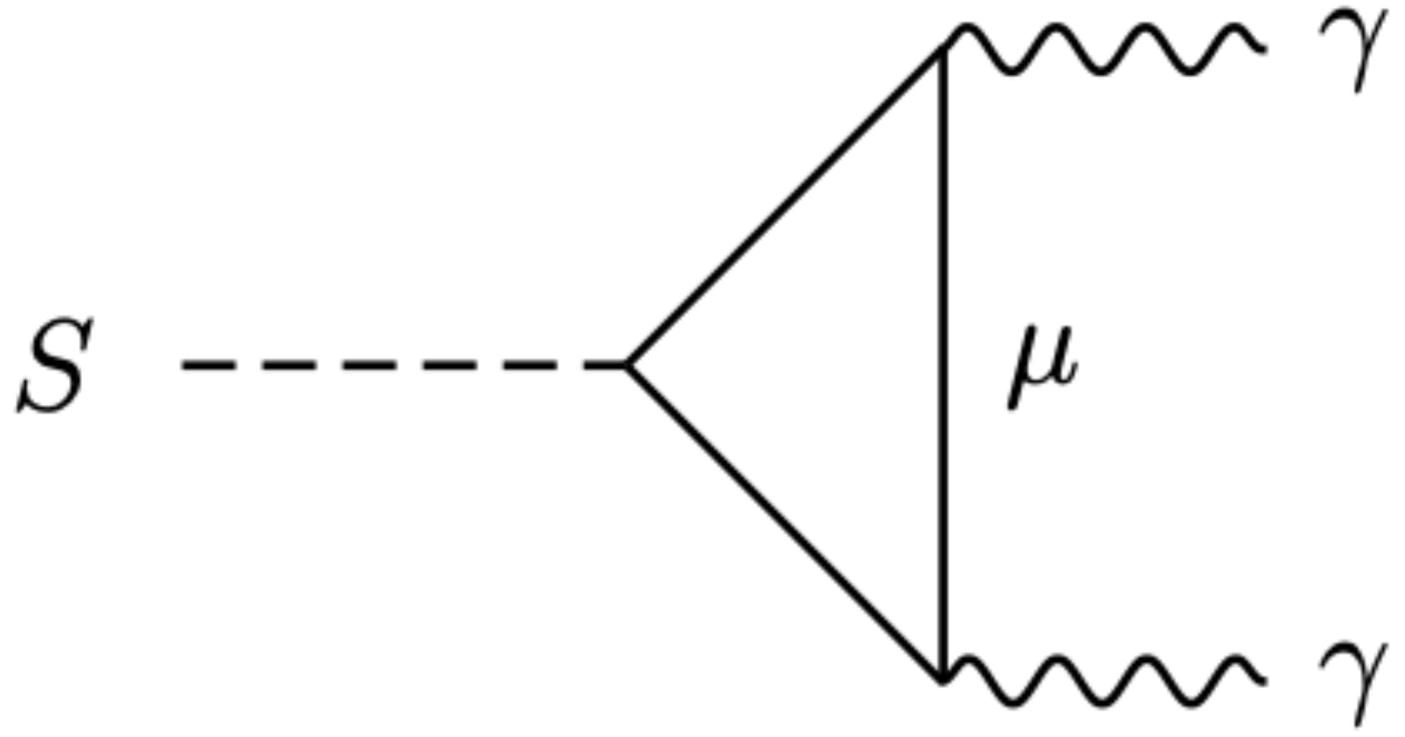
Simple model with a muonphilic scalar (Cont.)

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



Only Kaons, 0 backgrounds

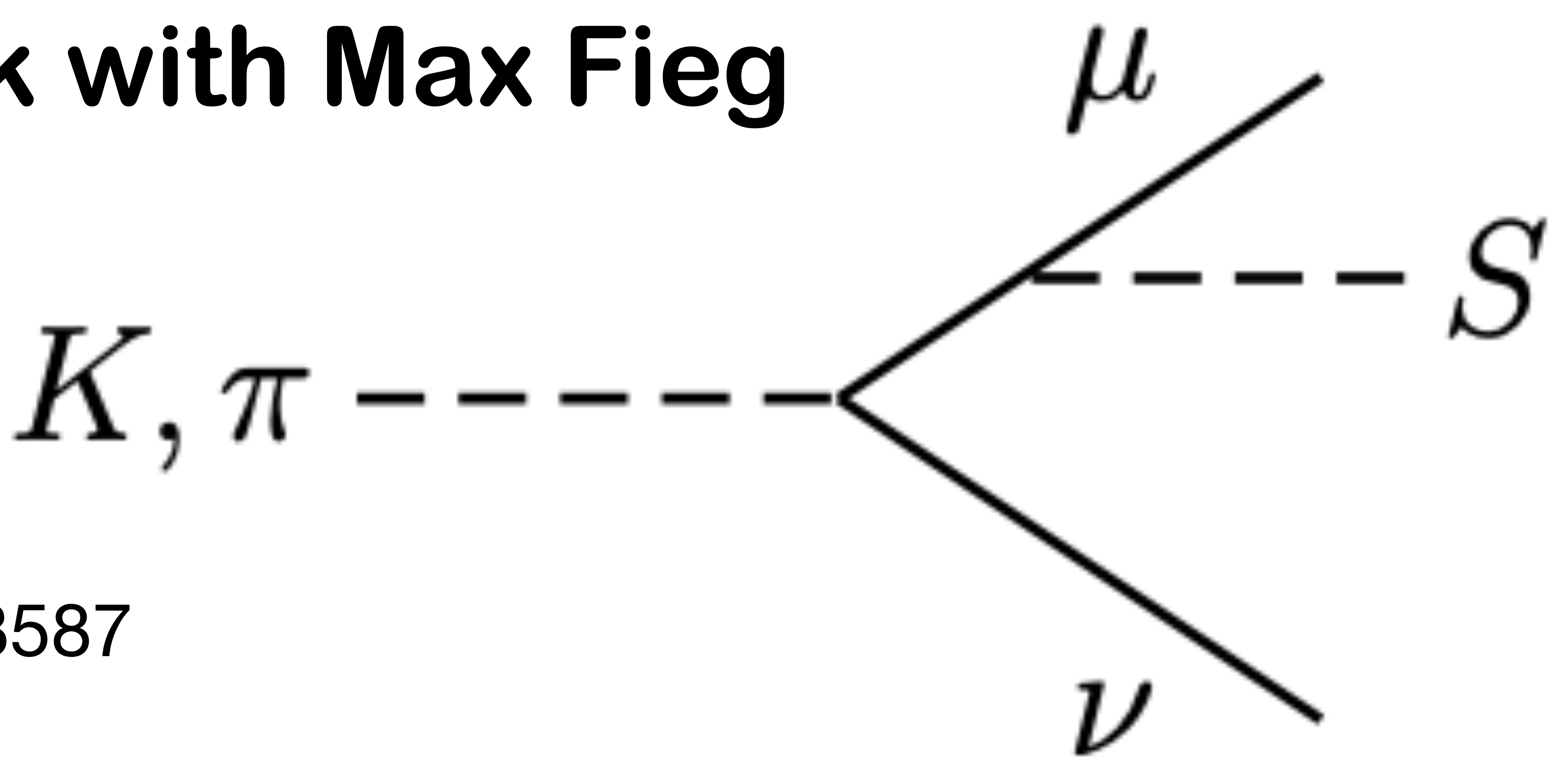
- **Current constraints miss a small region near $m_S \gtrsim 2 * m_\mu$.**
- **For $m_S \lesssim 2 * m_\mu$, S decays to 2 photons.**



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

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

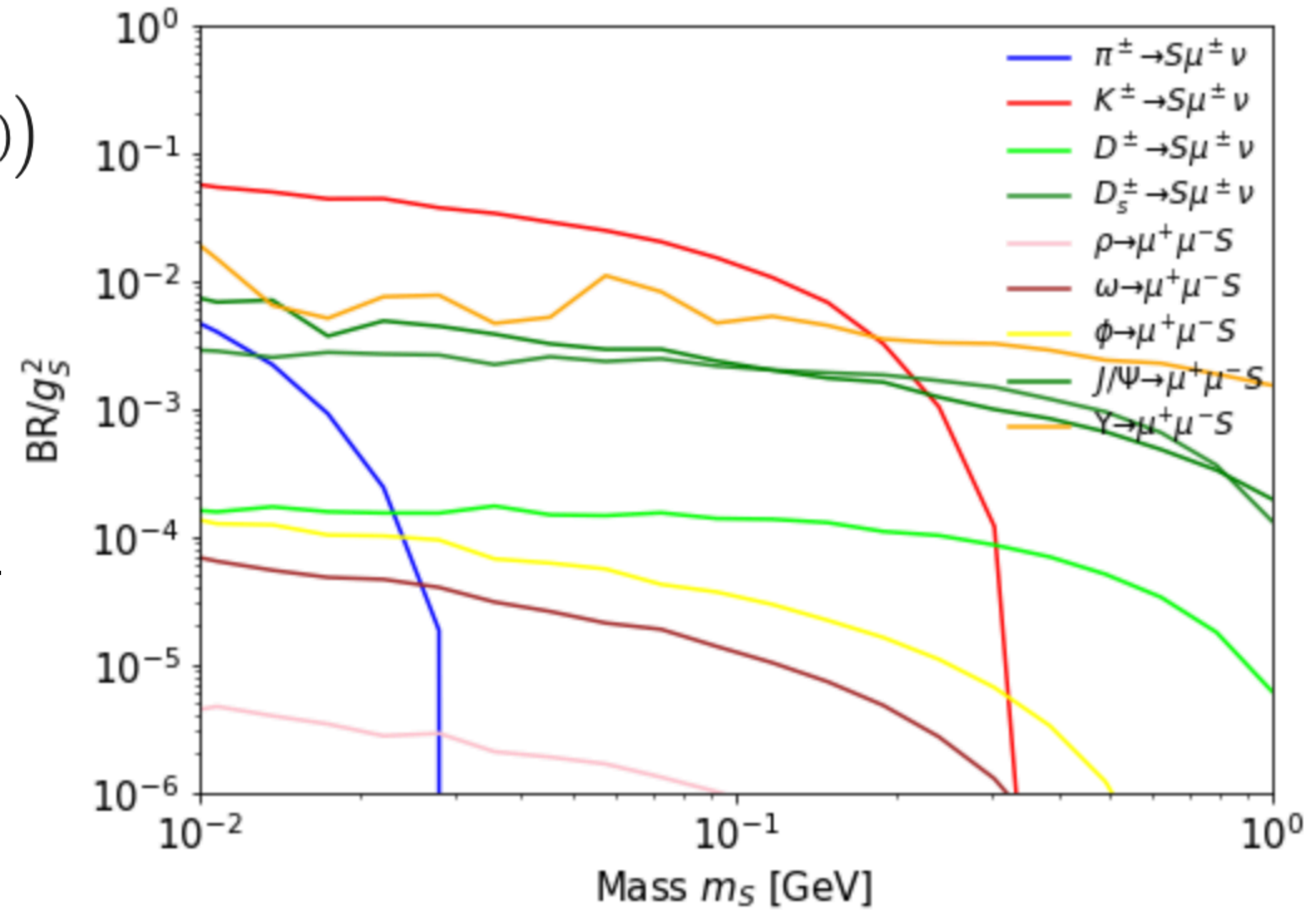
- **Vector decays via γ**

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**

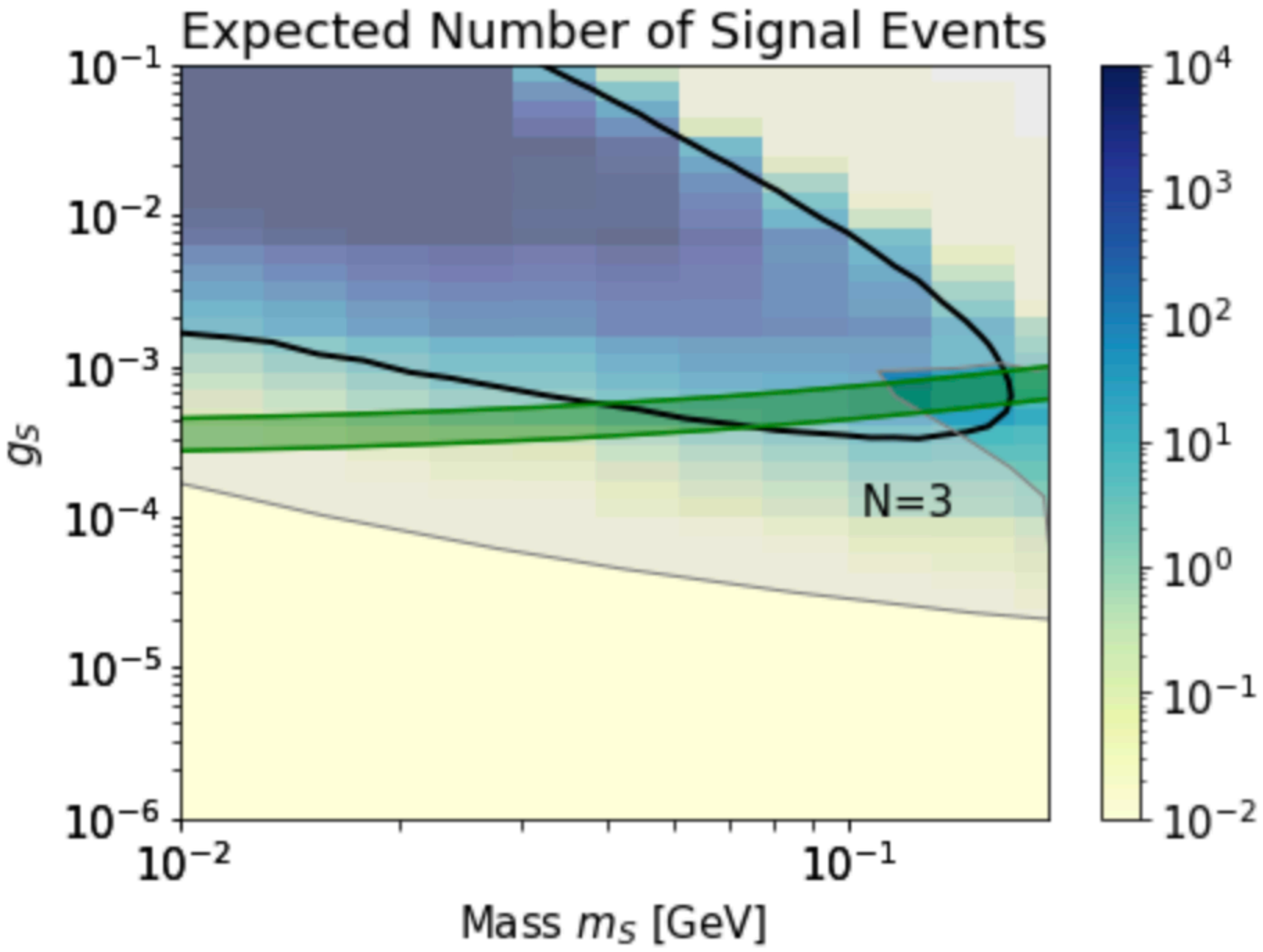


Implemented via FORESEE
Felix Kling, Sebastian Trojanowski,
2105.07077

Production from 3 body decays near ATLAS IP

Significant event rates expected at FASER during Run 3.

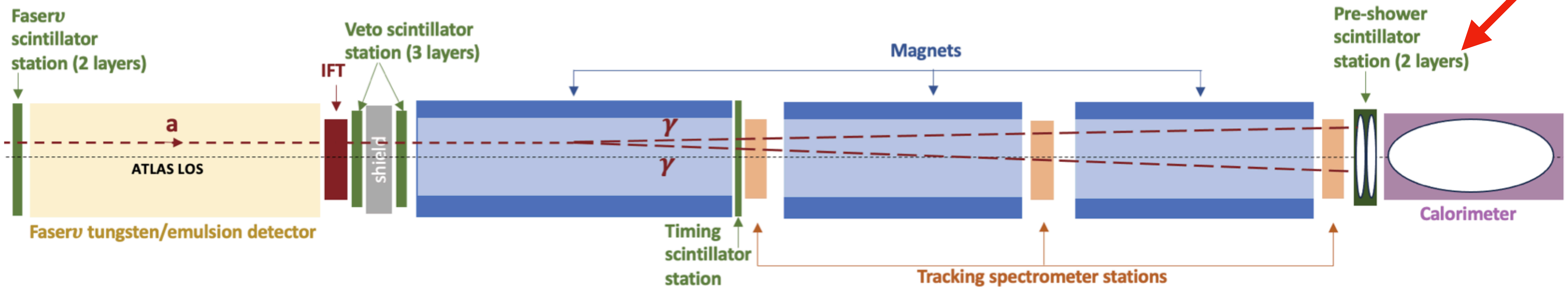
But what about backgrounds?



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

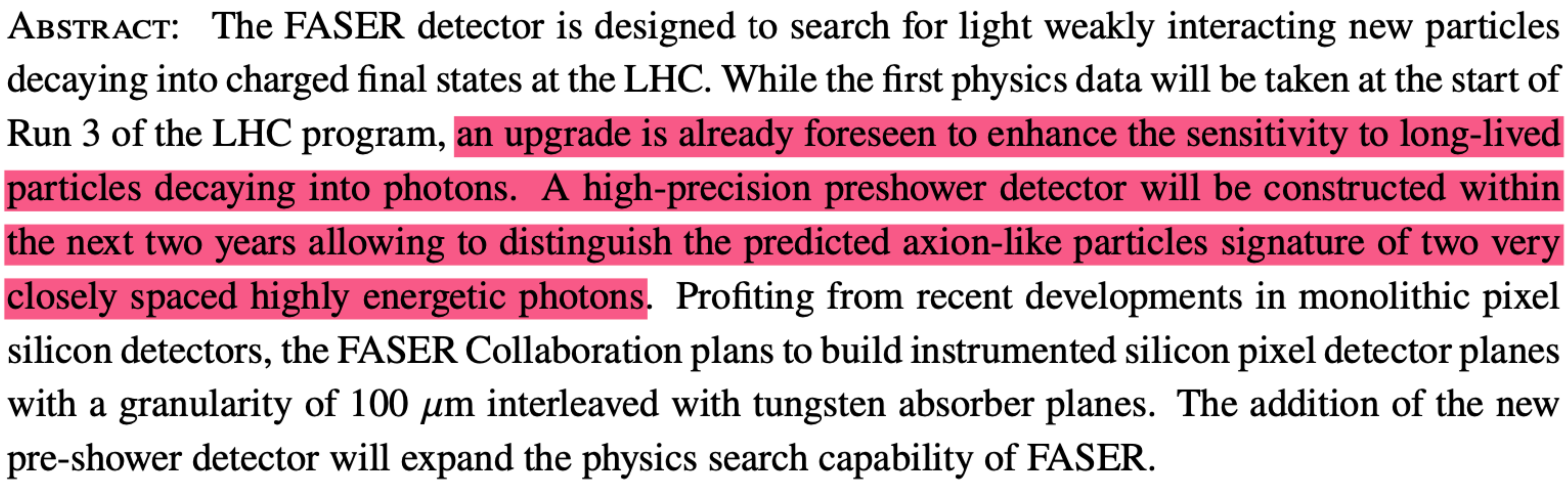


- $E_{calo} > 1.5$ TeV reduces the neutrino backgrounds to ~ 0.42/50 fb^{-1}.
  - Its a non-negligible background as we go to higher luminosities.

High Precision Preshower

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

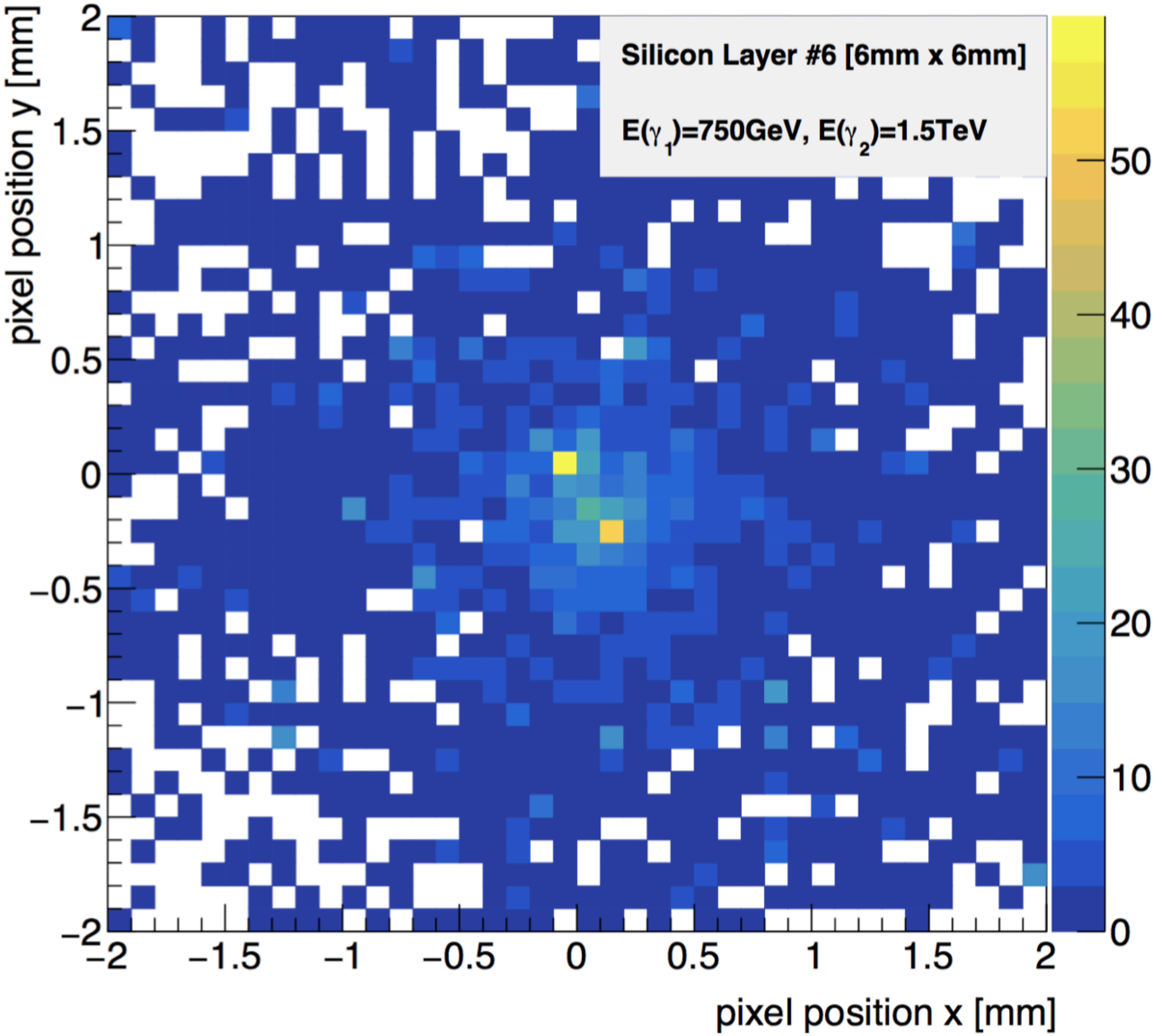
Preshower TP



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.

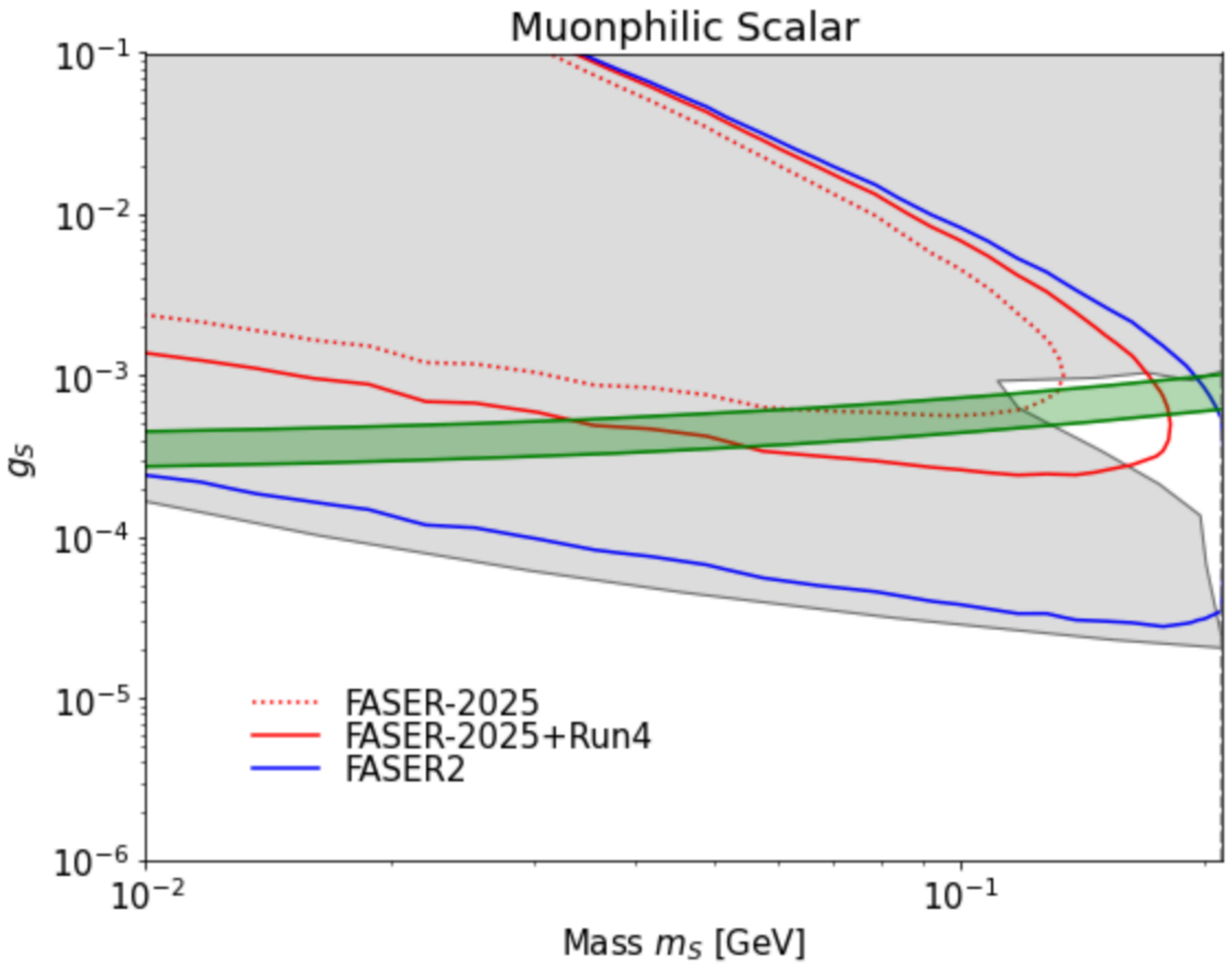
High Precision Preshower

Preshower TP



3 body decays - 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 begin probe the unconstrained (g-2) band below $2 * m_\mu$.



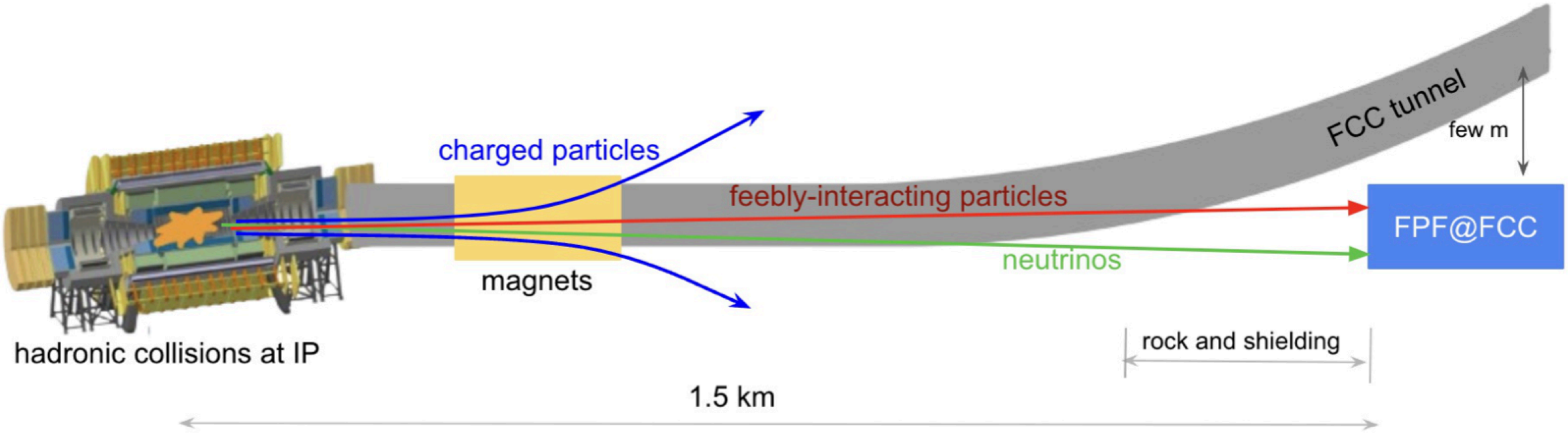
Looking to the Future: FPF@FCC

- LHC: $\sqrt{s} = 13$ TeV, $\mathscr{L} =$ 300 fb^{-1}
- HL-LHC: $\sqrt{s} = 14$ TeV, $\mathscr{L} =$ 3 ab^{-1}
- FCC-hh: $\sqrt{s} = 100$ TeV, $\mathscr{L} =$ 30 ab^{-1}

- FASER, FASERν, SND@LHC
- FPF
- FPF@FCC ?

Forward detectors have proven to be a very cost effective way to expand collider physics scope.

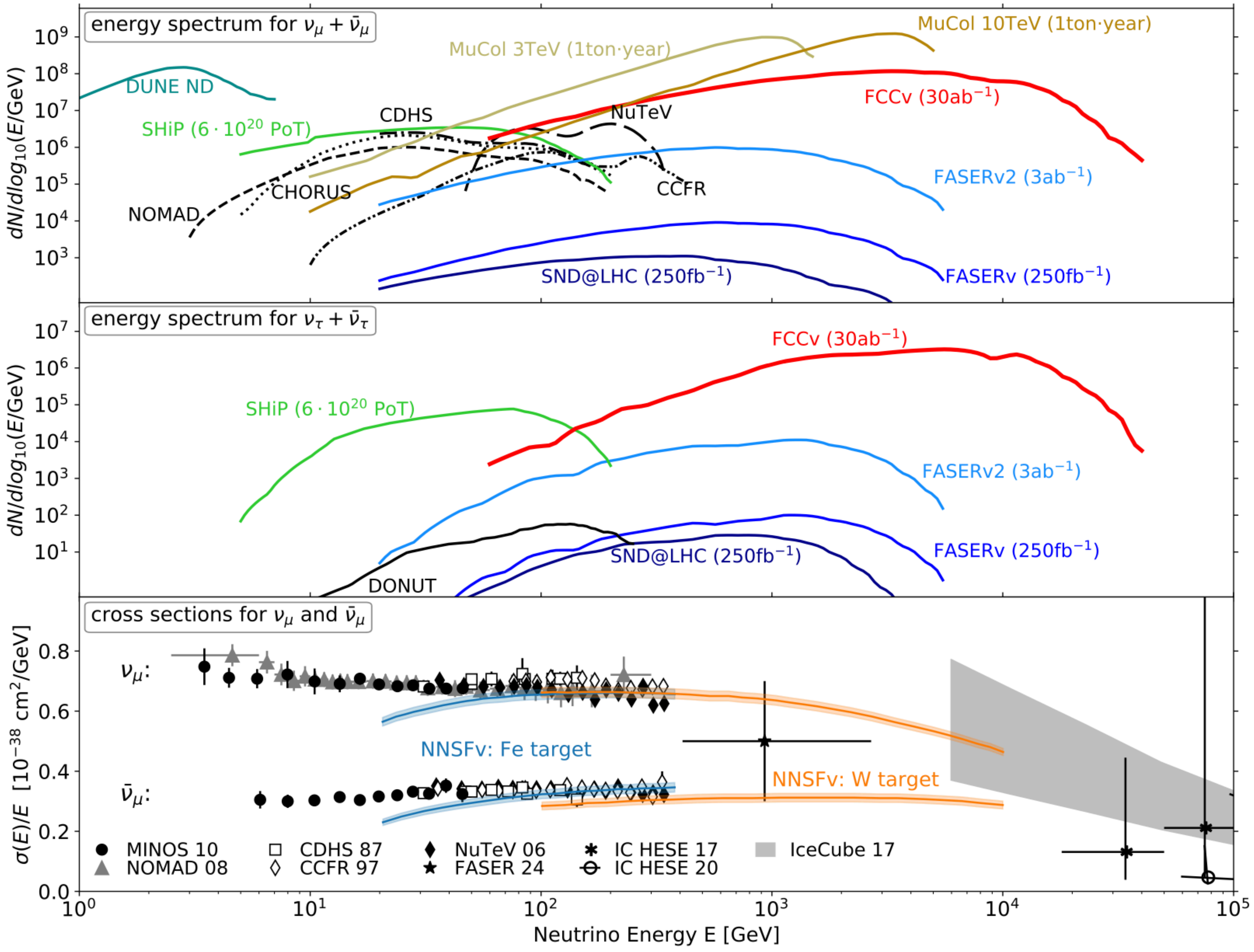
Looking to the Future: FPF@FCC



FCC is decades in the future, but we should already start phenomenological studies for it.

R.M.A, Jyotismita Adhikary, Jonathan L. Feng, Max Fieg, Felix Kling, Jinmian Li, Junle Pei, Tanjona R. Rabemananjara, Juan Rojo, Sebastian Trojanowski; 2409.02163

Looking to the Future: FPF@FCC



- Enormous flux of neutrinos upto 40TeV.
- Comfortably bridges the gap between low energy neutrino experiments and IceCube Neutrinos.
- Significant number of neutrinos produced from p-Pb, Pb-Pb collisions can be detected.

Looking to the Future: FPF@FCC

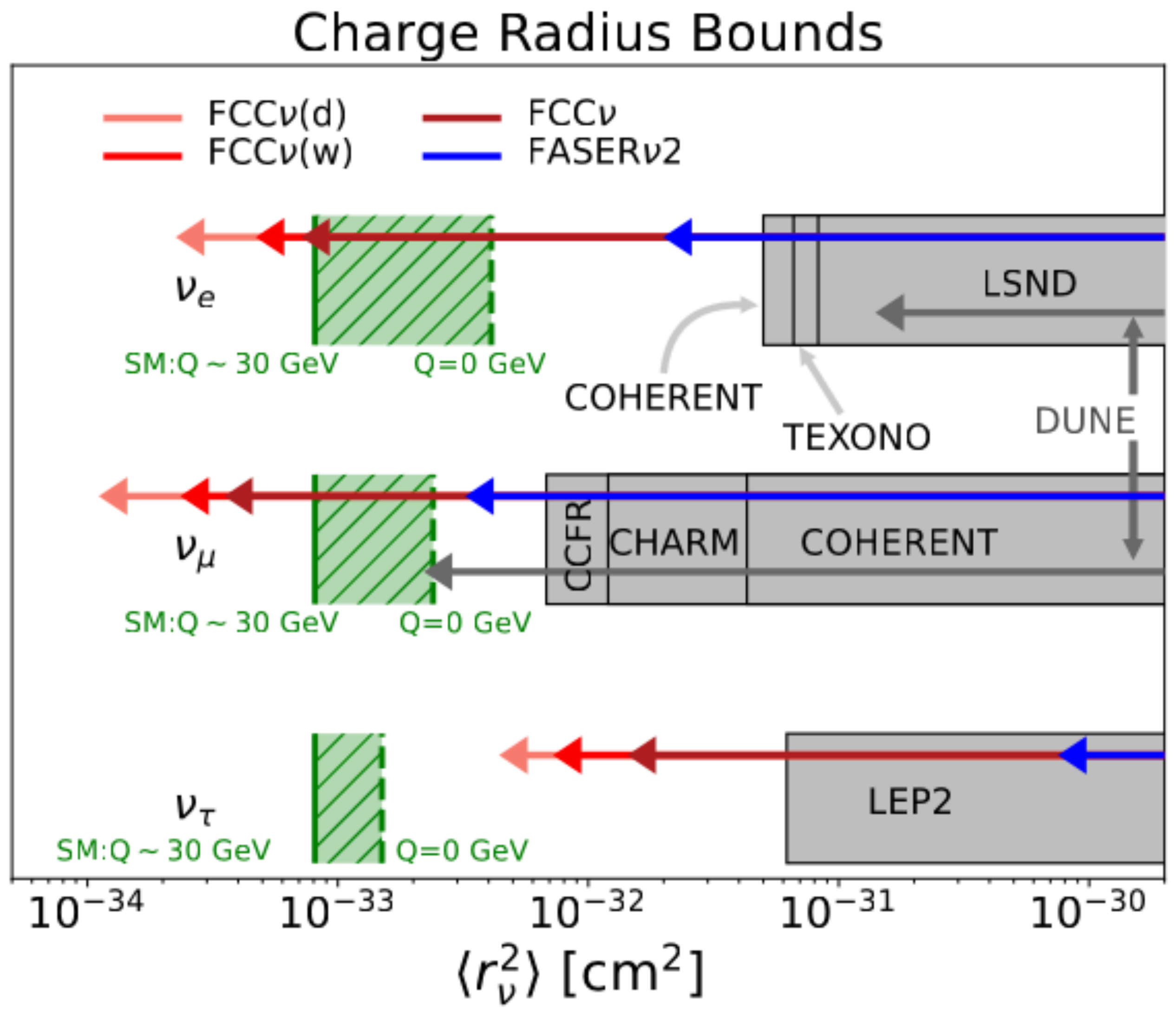
Detector	Geometry	Rapidity	$\mathcal{L}_{\rm pp}$	$\sqrt{s}$	Acceptance
FASERν	25 cm × 30 cm × 103 cm	$\eta_\nu \geq 8.5$	250 fb^{-1}	13.6 TeV	$E_\ell, E_h \gtrsim 100$ GeV, $\theta_\ell \lesssim 0.025$
FASERν2	40 cm × 40 cm × 6.6 m	$\eta_\nu \geq 8.4$	3 ab^{-1}	14 TeV	$E_\ell, E_h \gtrsim 100$ GeV, $\theta_\ell \lesssim 0.05$
FCCν	40 cm × 40 cm × 6.6 m	$\eta_\nu \geq 9.2$	30 ab^{-1}	100 TeV	$E_\ell, E_h \gtrsim 100$ GeV, $\theta_\ell \lesssim 0.05$
FCCν(d)	40 cm × 40 cm × 66 m	$\eta_\nu \geq 9.2$	30 ab^{-1}	100 TeV	$E_\ell, E_h \gtrsim 100$ GeV, $\theta_\ell \lesssim 0.05$
FCCν(w)	1.25 m × 1.25 m × 6.6 m	$\eta_\nu \geq 8.1$	30 ab^{-1}	100 TeV	$E_\ell, E_h \gtrsim 100$ GeV, $\theta_\ell \lesssim 0.05$

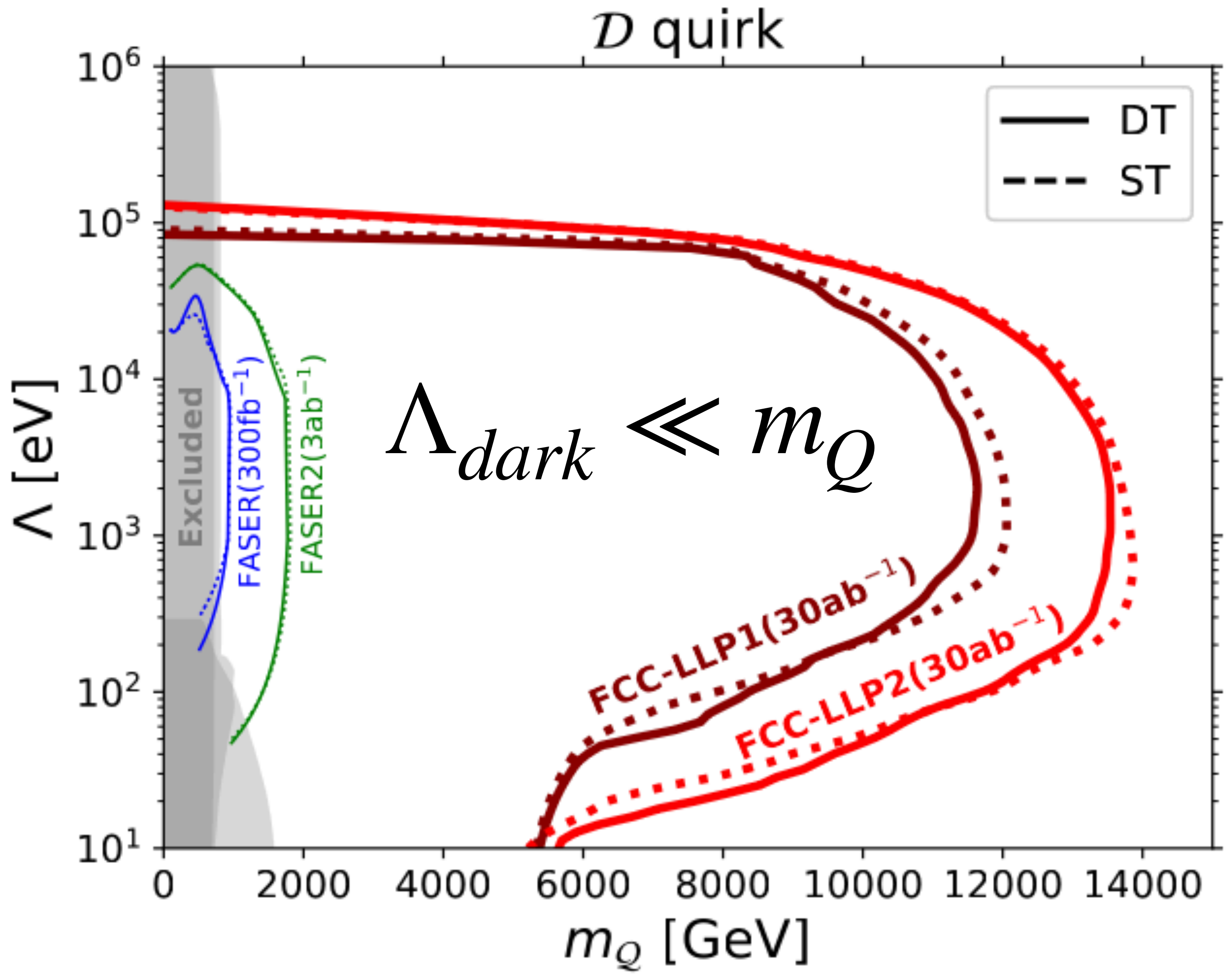
Detector	$N_{\nu_e} + N_{\bar\nu_e}$	$N_{\nu_\mu} + N_{\bar\nu_\mu}$	$N_{\nu_\tau} + N_{\bar\nu_\tau}$
FASERν	2.1k	11k	36
FASERν2	220k	1.1M	4.3k
FCCν	62M	130M	3.2M
FCCν(d)	620M	1.3B	32M
FCCν(w)	170M	370M	11M

- **Similar detector design as proposed for FPF will see tens of millions of neutrinos.**
- **More ambitious detector designs also considered.**

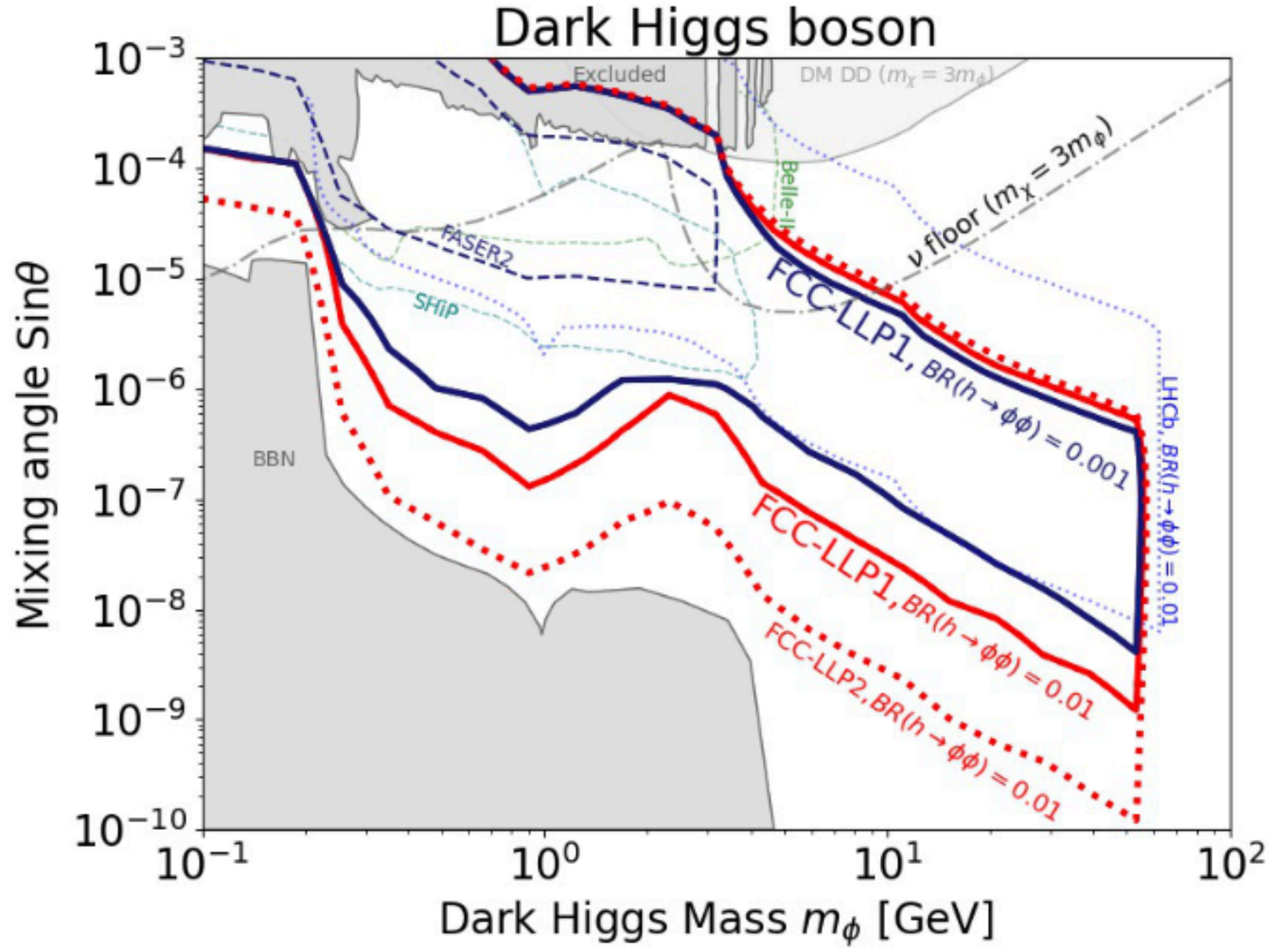
Looking to the Future: FPF@FCC

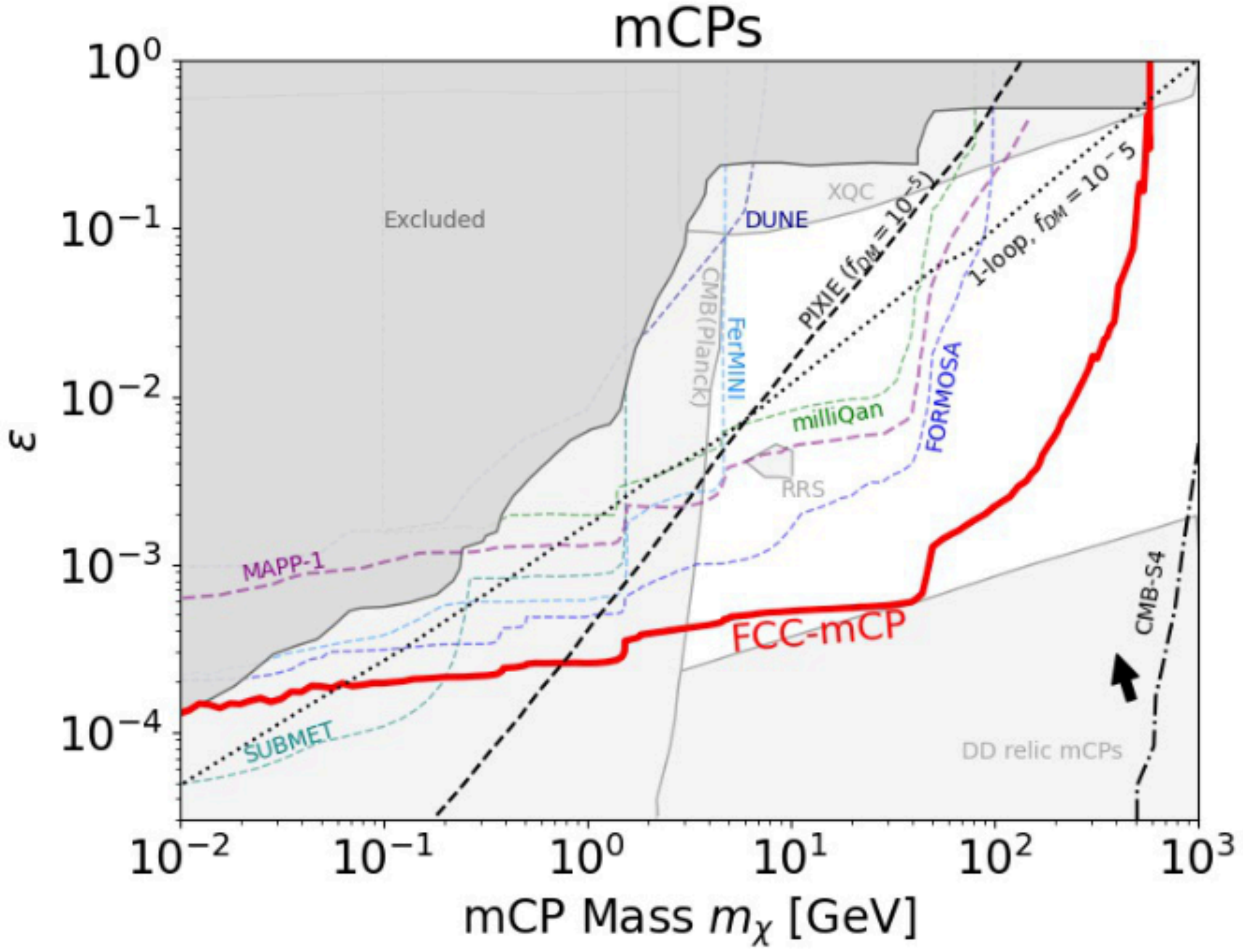
BSM physics





$$\mathcal{L} = -m_\phi^2 \phi^2 - \sin\theta \frac{m_f}{v} \phi \bar{f} f - \lambda v h \phi\phi$$

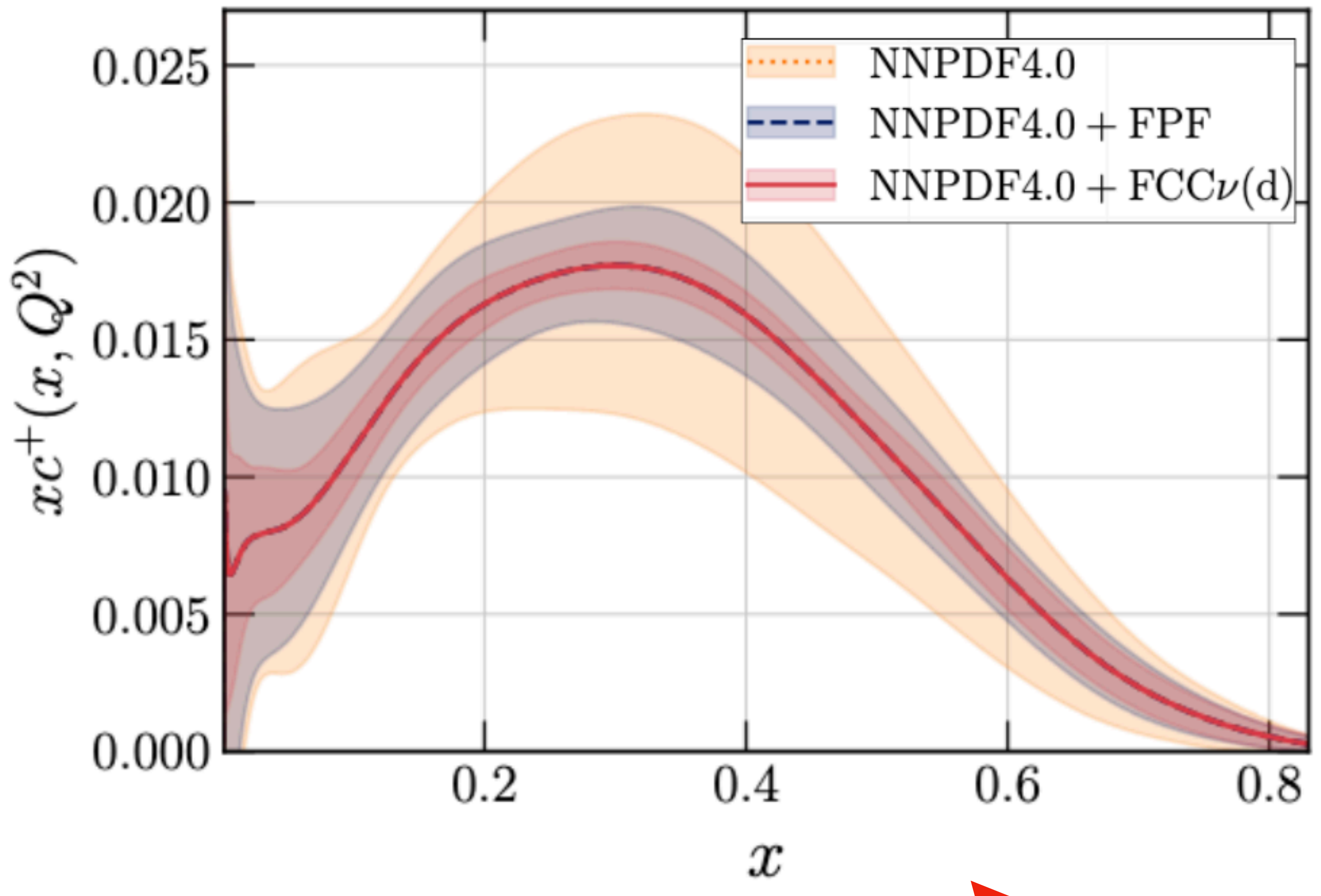


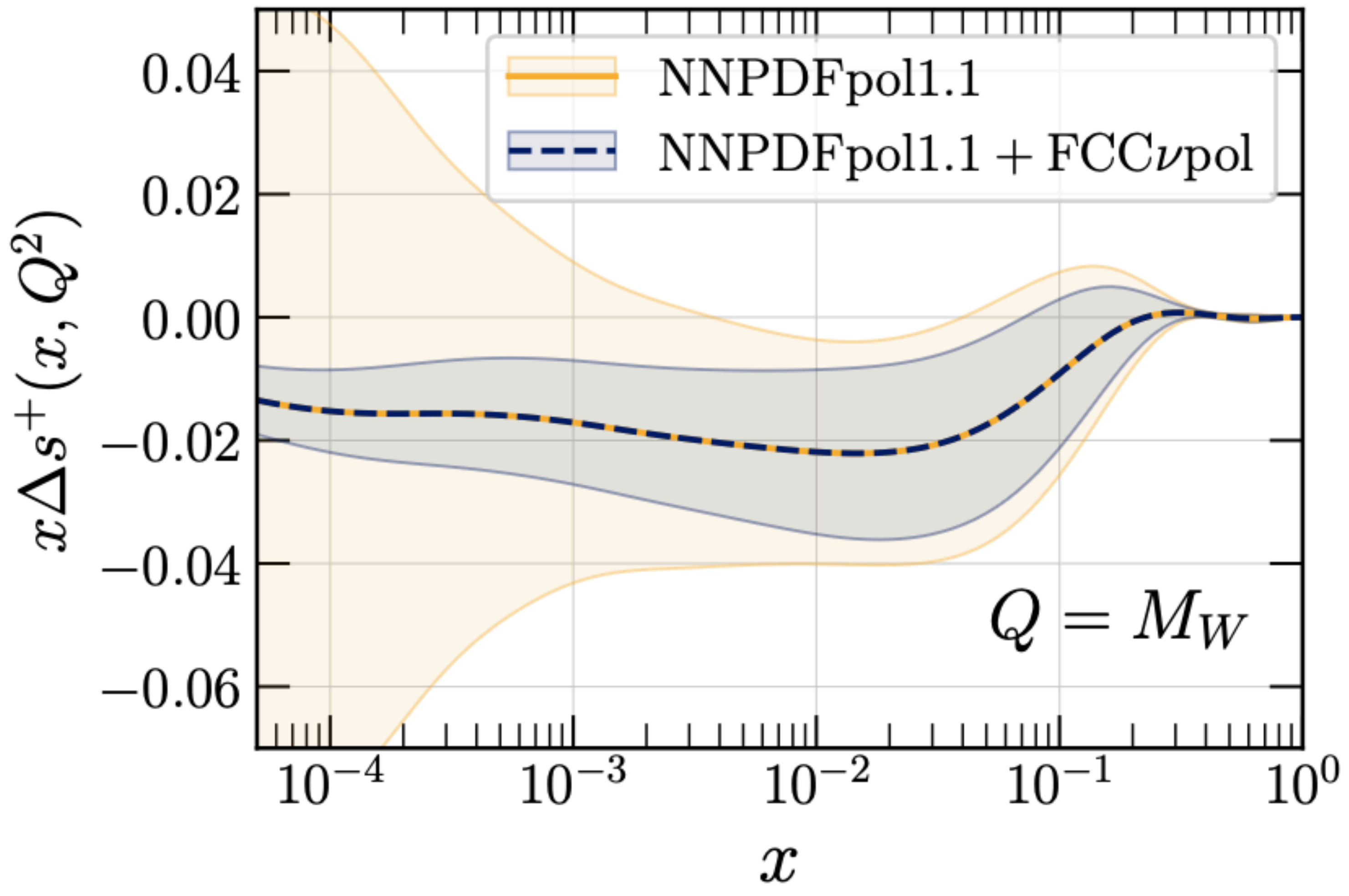


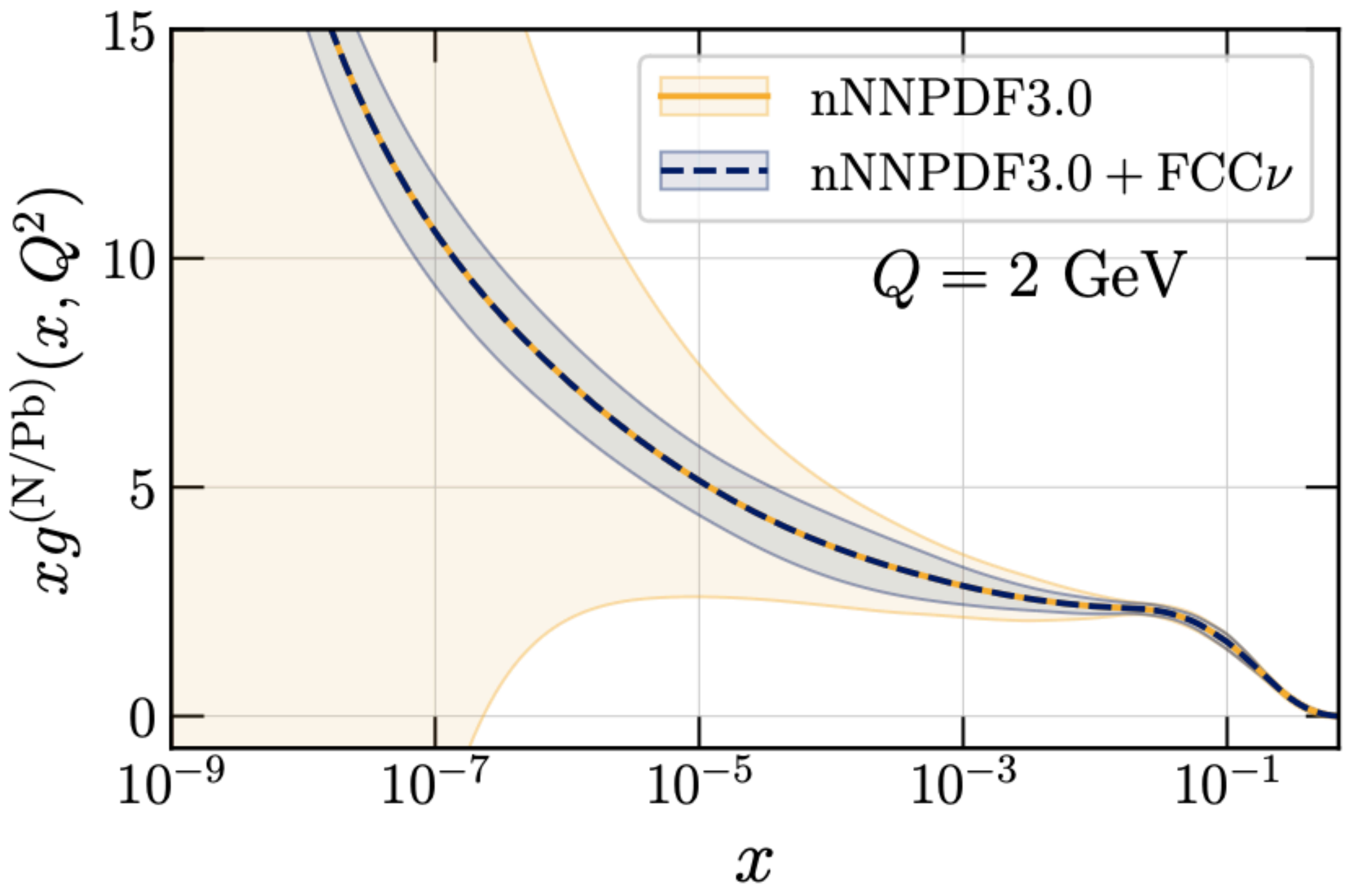
- **Measure the ν charge radius down SM prediction, sensitive to BSM contributions.**
- **Sensitive to LLPs from Higgs decays with masses as large as 62 GeV, and $\theta \sim 10^{-8}$.**
- **Quirks masses upto 14 TeV.**
- **mCPs with masses upto a few 100s of GeV, and $q \sim 10^{-3}e$.**

Looking to the Future: FPF@FCC

QCD physics





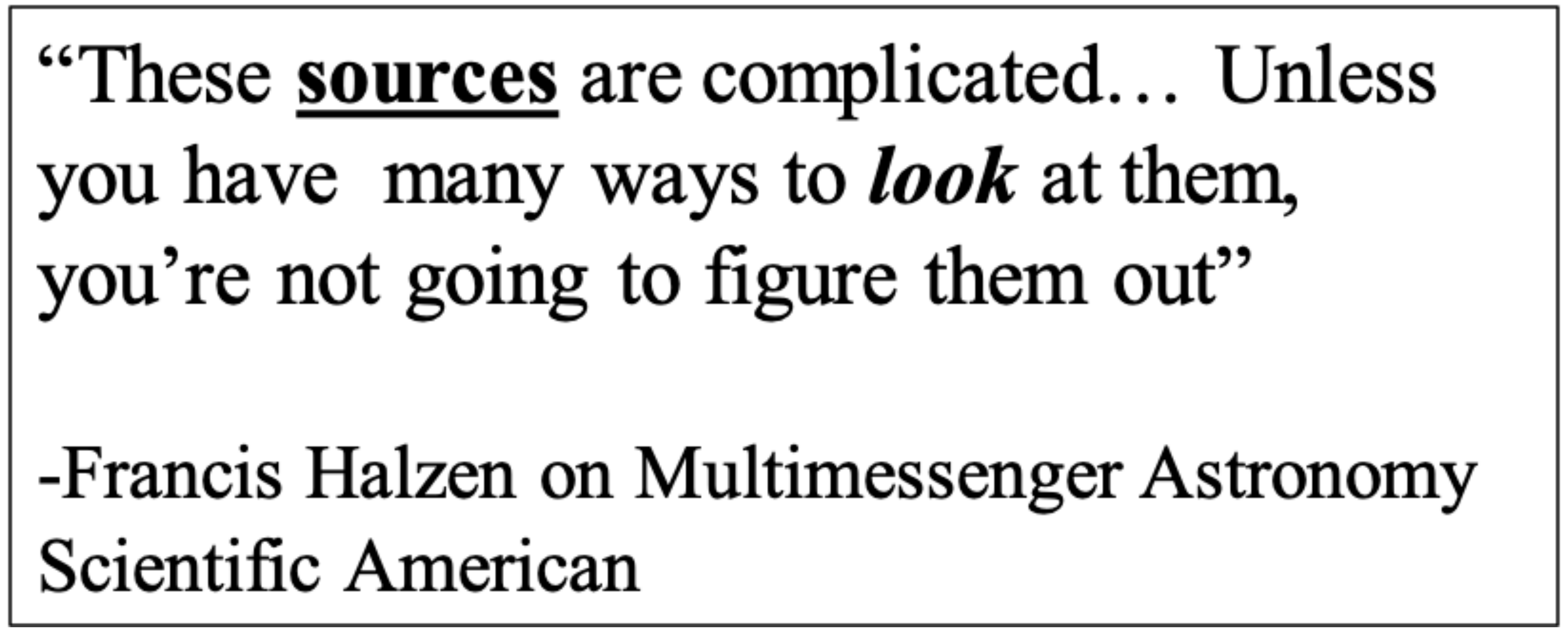


Constraints on unpolarized, polarized and nuclear PDFs.

R.M.A, Jyotismita Adhikary, Jonathan L. Feng, Max Fieg, Felix Kling, Jinmian Li, Junle Pei, Tanjona R. Rabemananjara, Juan Rojo, Sebastian Trojanowski; 2409.02163

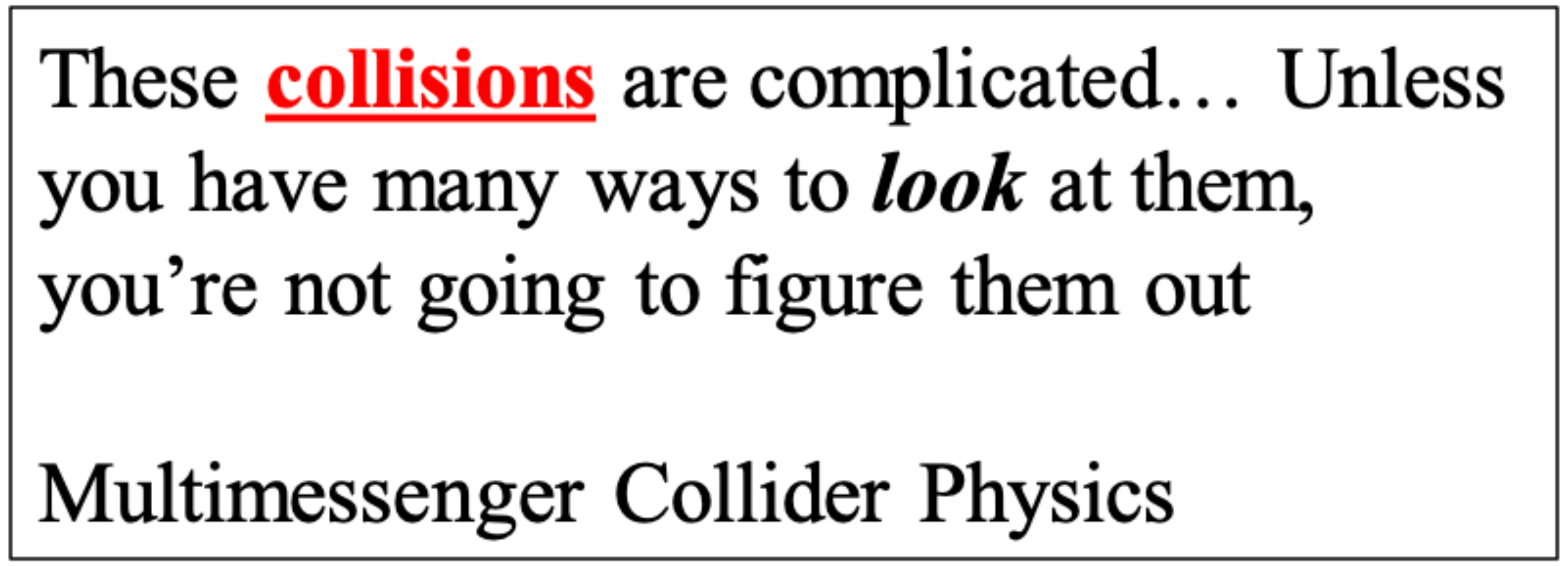
Summary

- There is a lot of physics to be studied in the forward region at LHC, HL-LHC, FCC.
  - 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

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

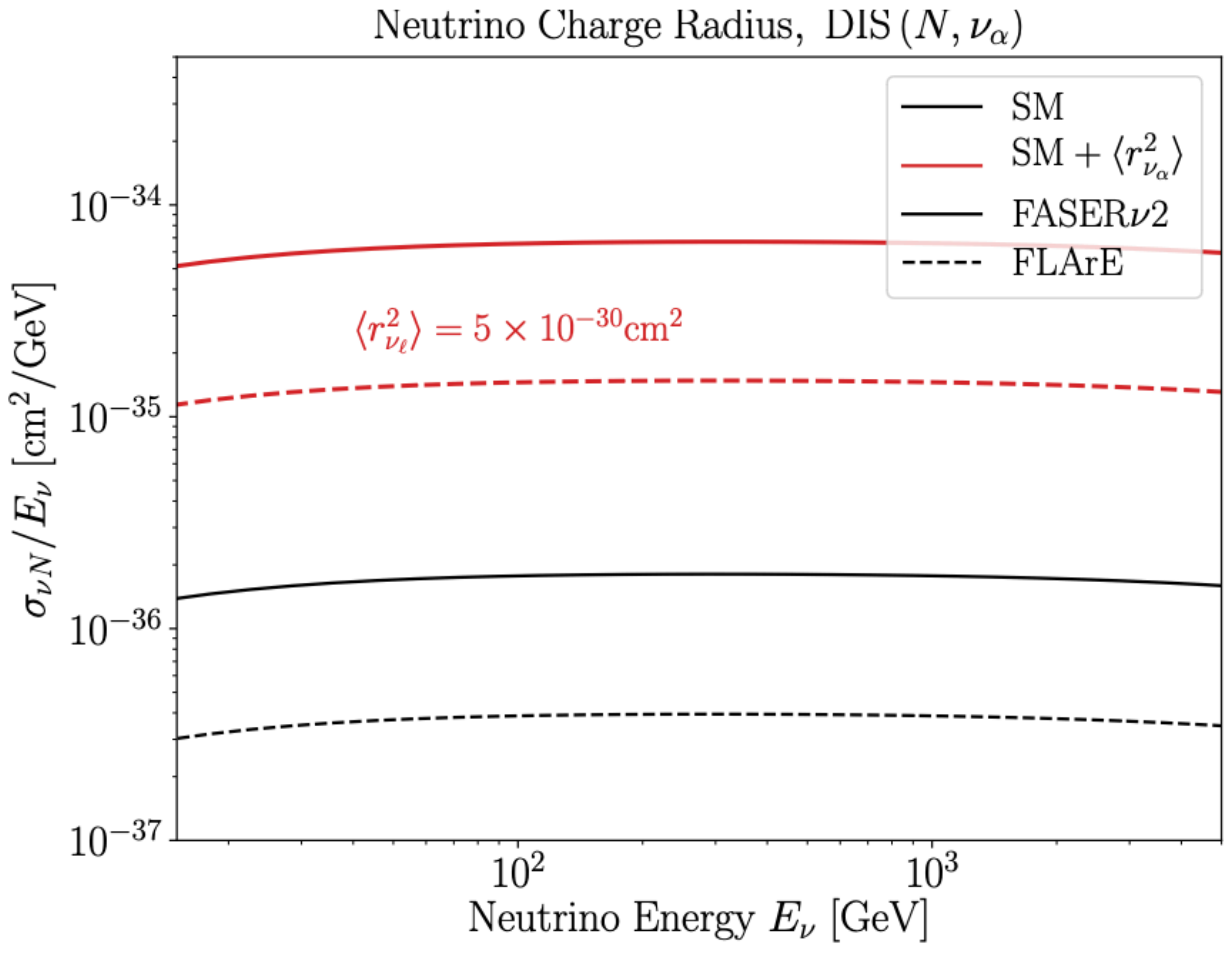
Neutrino Charge Radius:

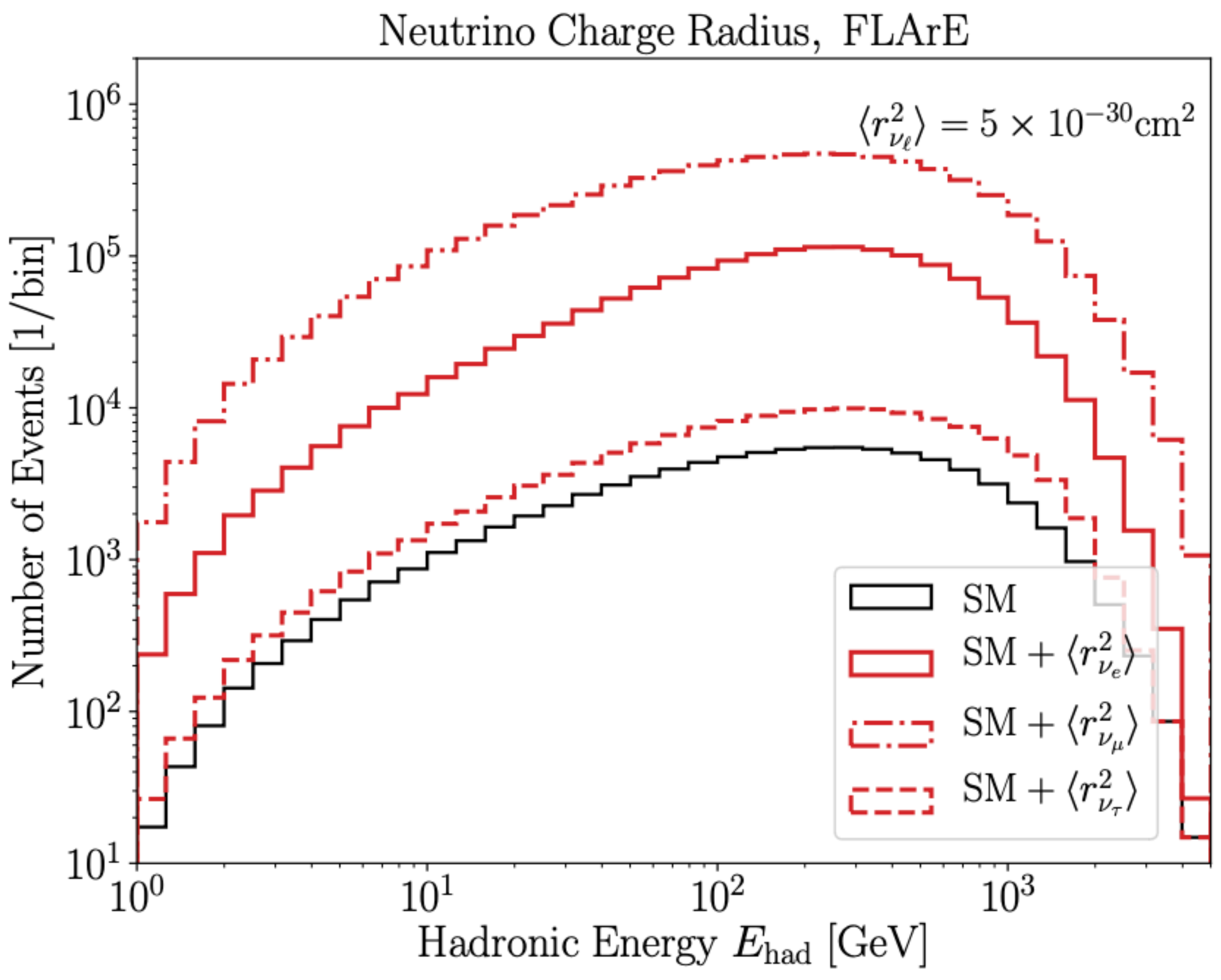
- **Vector coupling in the NC DIS is modified as,**
  - $g_V^q \rightarrow g_V^q - \frac{2}{3} Q_q m_W^2 \langle r_{\nu_\ell}^2 \rangle \sin^2 \theta_w$

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



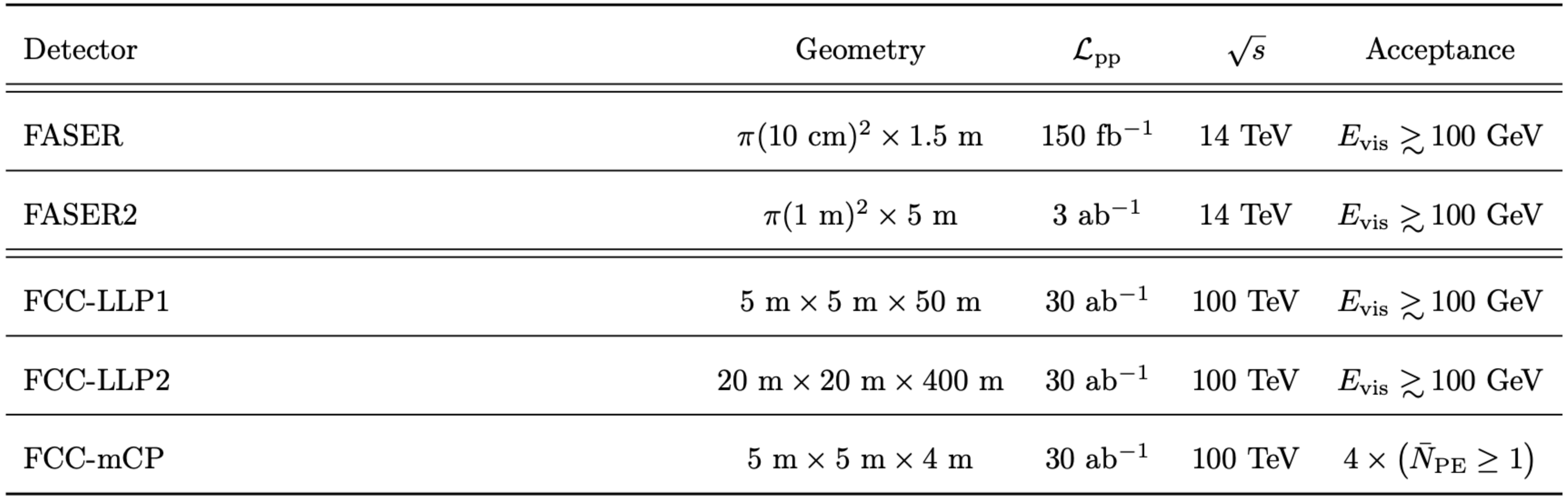


Weak Mixing Angle at FPF

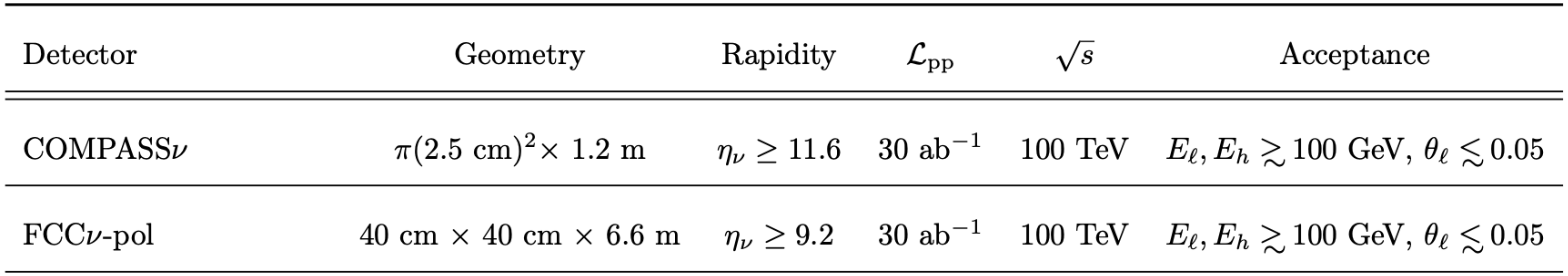
- **If the SM value shifts,** $\sin^2\theta_W \to \sin^2\theta_W + \Delta\sin^2\theta_W$ **then** $g_V^q \to g_V^q - 2Q_q\Delta\sin^2\theta_W$.
- **Modifies NC DIS similarly to NCR.**
- **One can recast NCR results to measure to the** $\sin^2\theta_W$ **at the FPF.**
- **Could be interesting if the NuTeV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

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

LLP and Polarized detectors at FPF@FCC



Detector	Geometry	$\mathcal{L}_{\mathrm{pp}}$	$\sqrt{s}$	Acceptance
FASER	$\pi(10\ \mathrm{cm})^2 \times 1.5\ \mathrm{m}$	$150\ \mathrm{fb}^{-1}$	14 TeV	$E_{\mathrm{vis}} \gtrsim 100$ GeV
FASER2	$\pi(1\ \mathrm{m})^2 \times 5\ \mathrm{m}$	$3\ \mathrm{ab}^{-1}$	14 TeV	$E_{\mathrm{vis}} \gtrsim 100$ GeV
FCC-LLP1	$5\ \mathrm{m} \times 5\ \mathrm{m} \times 50\ \mathrm{m}$	$30\ \mathrm{ab}^{-1}$	100 TeV	$E_{\mathrm{vis}} \gtrsim 100$ GeV
FCC-LLP2	$20\ \mathrm{m} \times 20\ \mathrm{m} \times 400\ \mathrm{m}$	$30\ \mathrm{ab}^{-1}$	100 TeV	$E_{\mathrm{vis}} \gtrsim 100$ GeV
FCC-mCP	$5\ \mathrm{m} \times 5\ \mathrm{m} \times 4\ \mathrm{m}$	$30\ \mathrm{ab}^{-1}$	100 TeV	$4 \times (\bar{N}_{\mathrm{PE}} \geq 1)$



Detector	Geometry	Rapidity	$\mathcal{L}_{\mathrm{pp}}$	$\sqrt{s}$	Acceptance
COMPASSν	$\pi(2.5\ \mathrm{cm})^2 \times 1.2\ \mathrm{m}$	$\eta_\nu \geq 11.6$	$30\ \mathrm{ab}^{-1}$	100 TeV	$E_\ell, E_h \gtrsim 100$ GeV, $\theta_\ell \lesssim 0.05$
FCCν-pol	$40\ \mathrm{cm} \times 40\ \mathrm{cm} \times 6.6\ \mathrm{m}$	$\eta_\nu \geq 9.2$	$30\ \mathrm{ab}^{-1}$	100 TeV	$E_\ell, E_h \gtrsim 100$ GeV, $\theta_\ell \lesssim 0.05$

^{6}LiD target similar to COMPASS detector