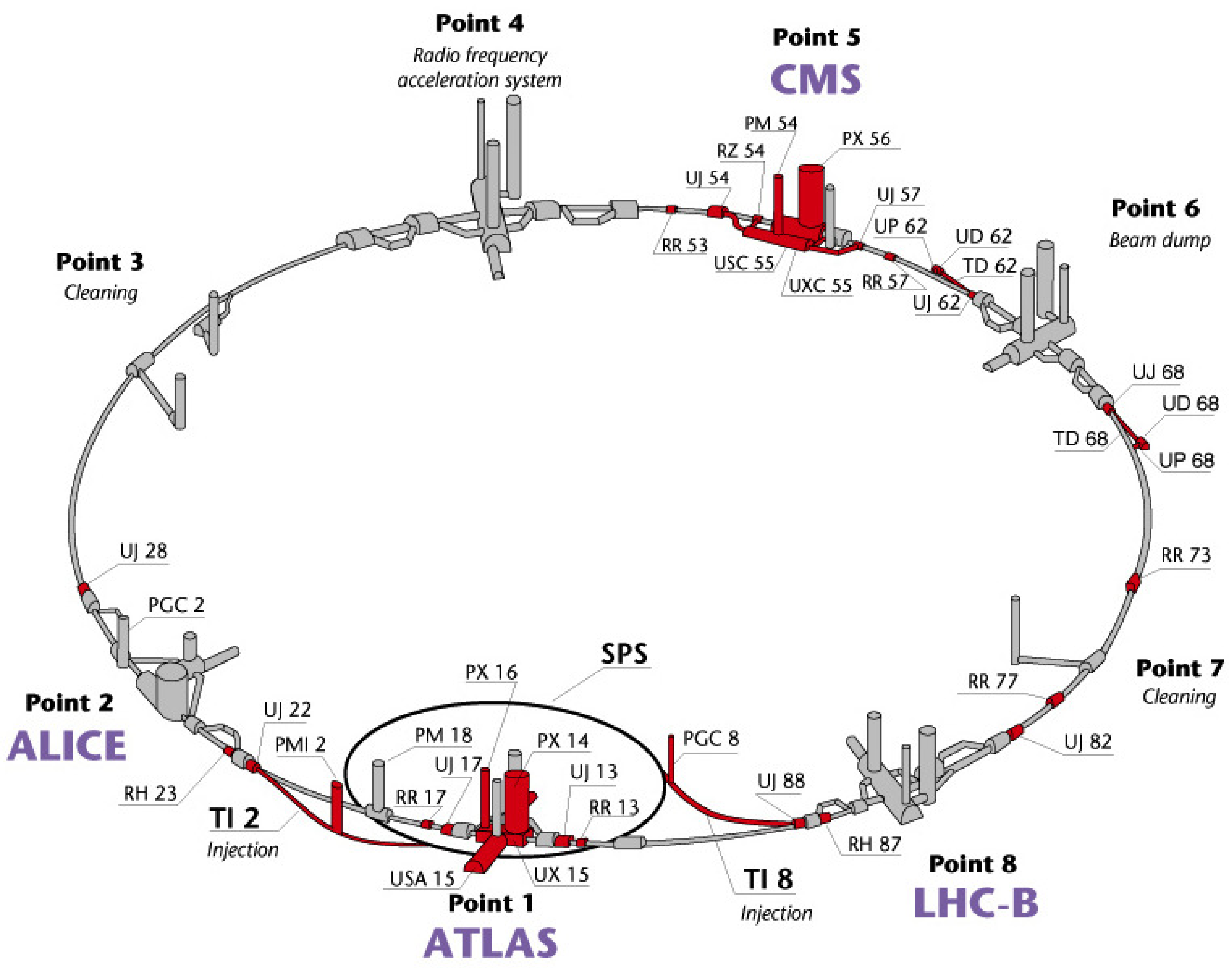
Search for BSM physics at the forward experiments of the LHC

Yu Seon Jeong (Chung-Ang University)

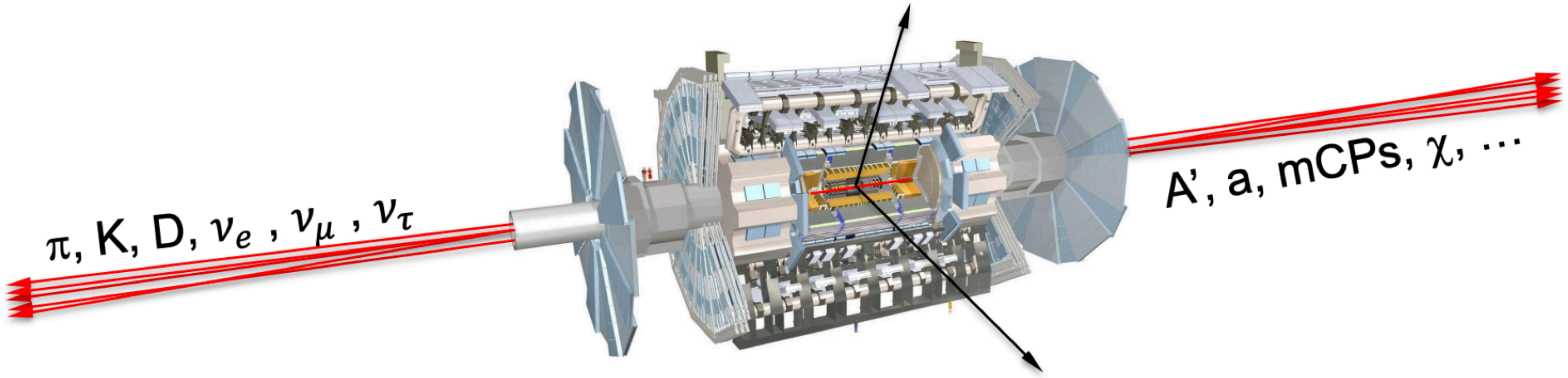
NPN 2024, IBS @ Daejeon
June 3-5, 2024

Motivation of forward experiments

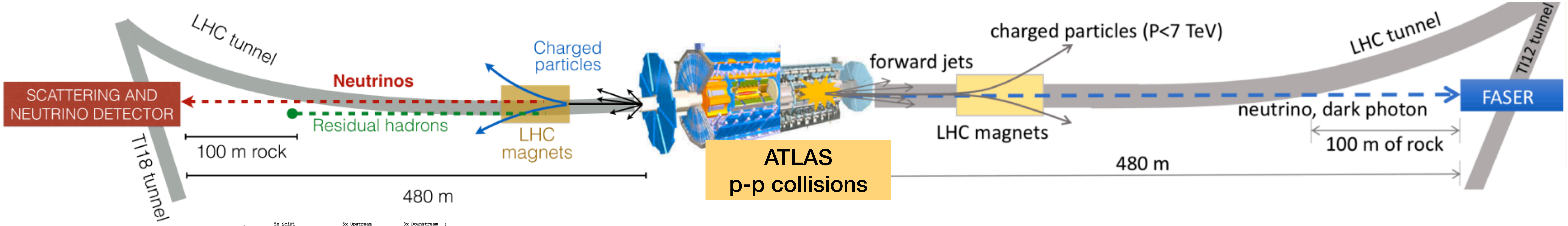


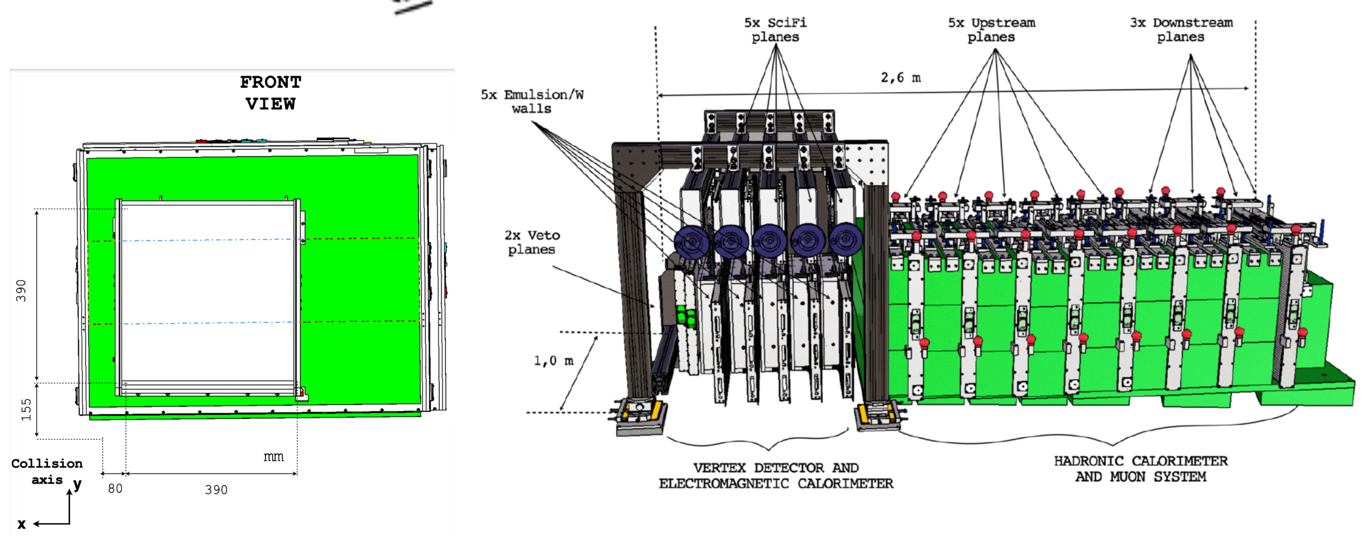
- The major experiments of the LHC have explored the central regions focusing on heavy particles produced with high p_T .
- Most light and weakly interacting particles are emitted into the very forward direction along the beam line.
- Evidence for TeV-scale new physics hasn't been discovered.
- It is worth exploring different kinematic regions.

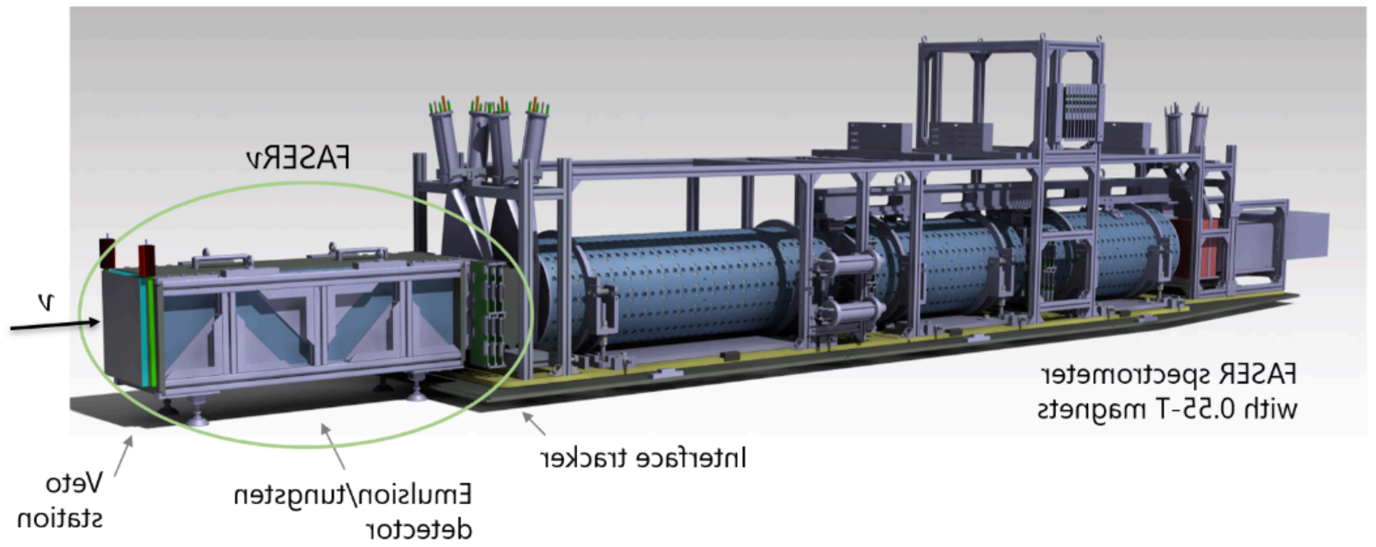
- Earlier discussions about forward neutrinos: deRujula & Ruckl (1984), Winter (1990)



Forward experiments during the Run 3 (2022–2025)





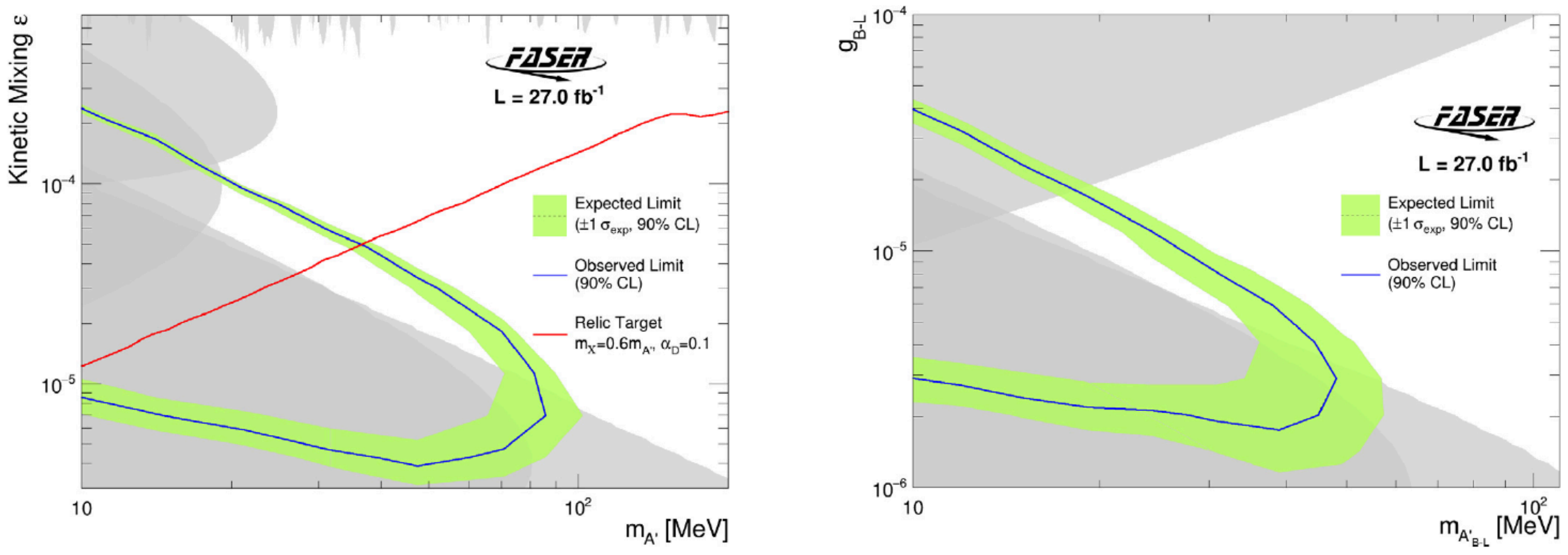


	SND@LHC	FASERν
Rapidity	$7.2 < \eta < 8.4$ (off-axis)	$\eta \gtrsim 8.5$ (on-axis)
Target material	Tungsten (w/ emulsion film)	Tungsten (w/ emulsion film)
Target mass	830 kg	1.1 tons
Surface	39 x 39 cm^2	25 x 30 cm^2 (1.1 m long)

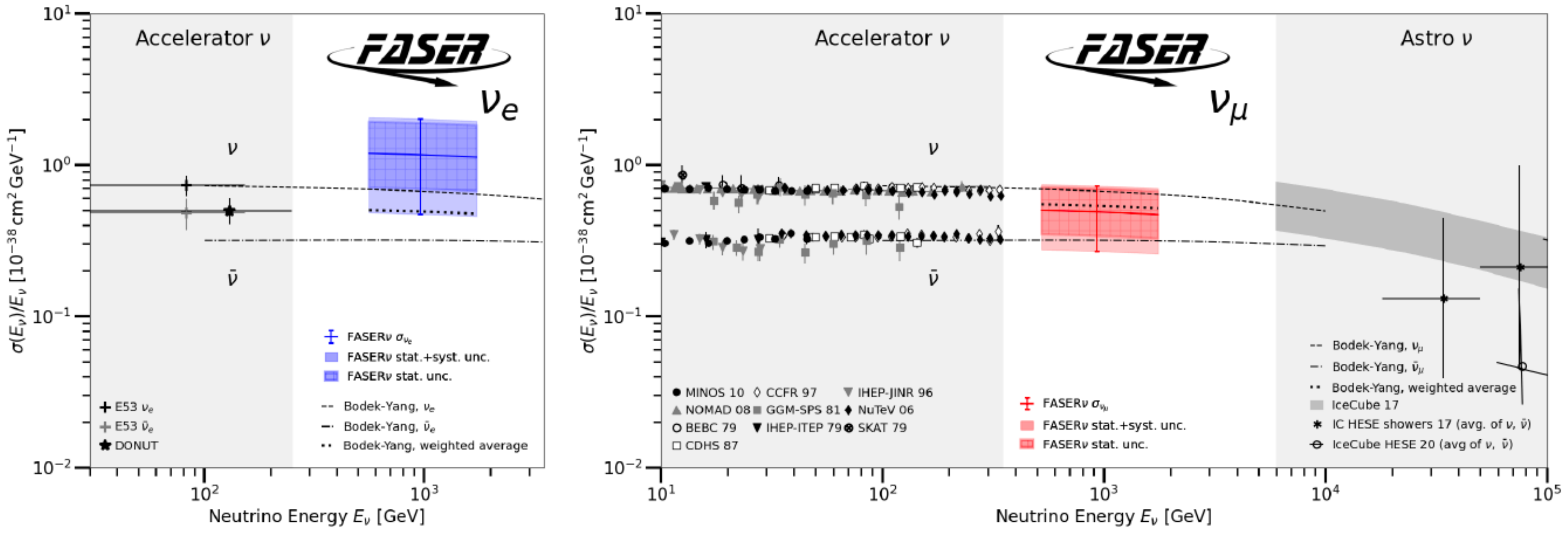
First results from the Run-3 experiments

- First Observation of Collider Neutrinos
  - PRL 131, 031801 (2023.14185; FASER) - 153^{+12}_{-13} muon neutrinos
  - PRL 131, 031802 (2305.09383, SND@LHC) - 8 muon neutrinos

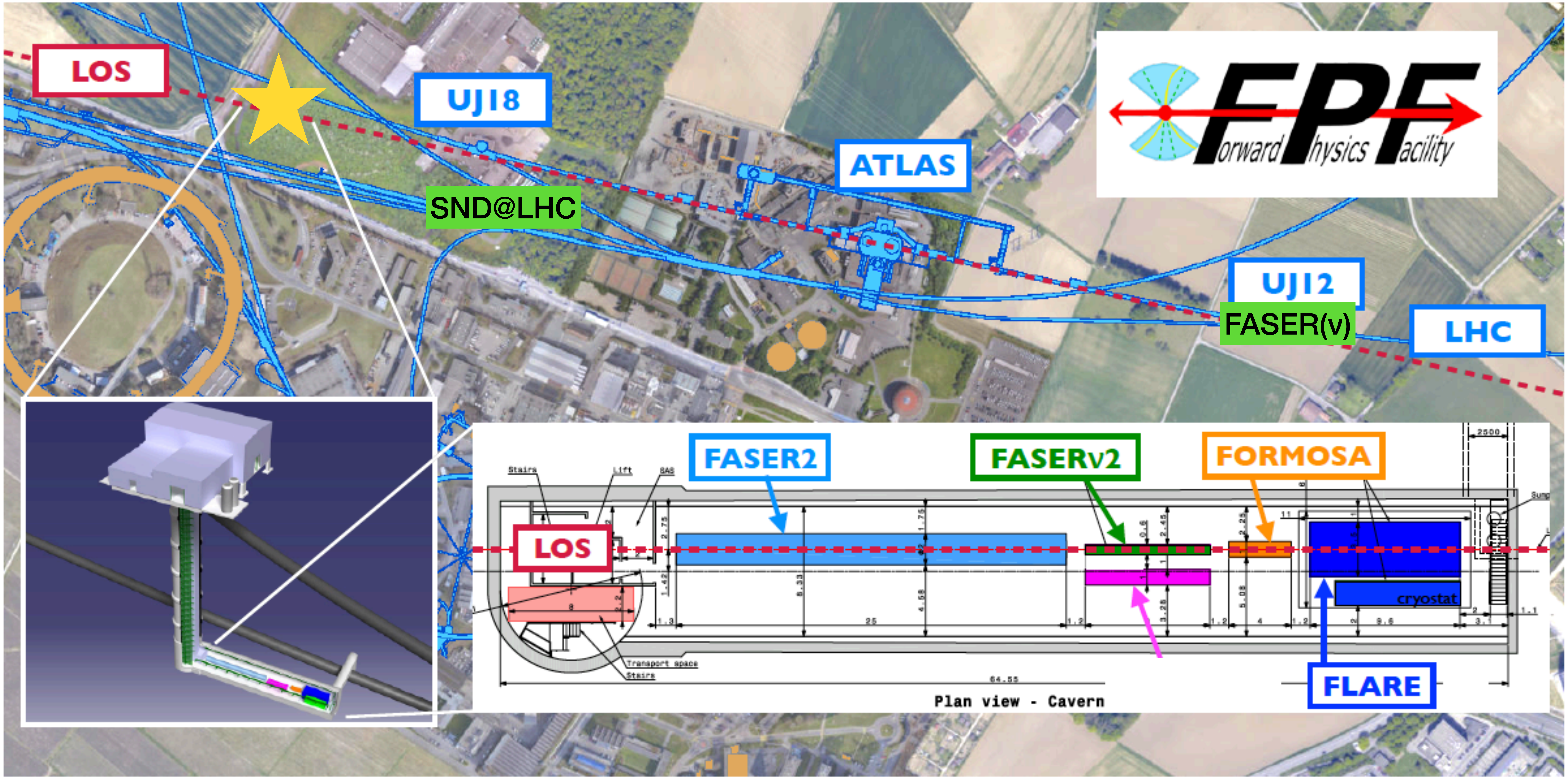
- Search for dark photon and $U(1)_{B-L}$ at FASER
  - PLB 848, 138378 (2308.05587, FASER)



- First measurement of the neutrino interaction cross section (2403.12520, FASER)

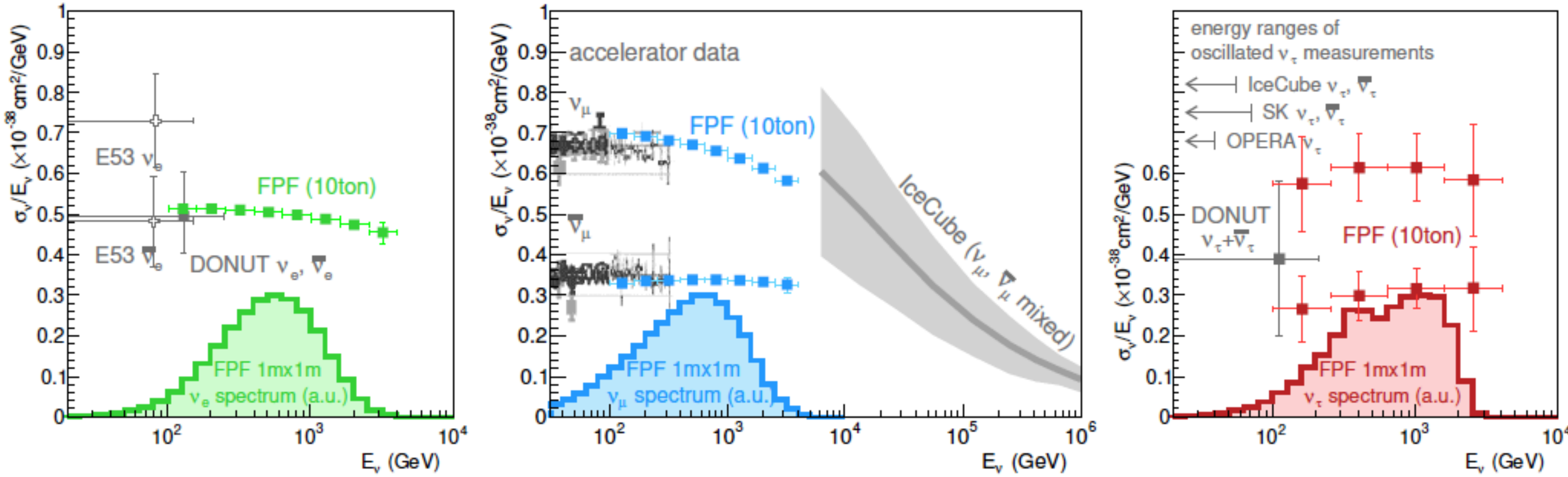


Forward Physics Facility (FPF) during HL-LHC



J. Feng et. al., *J.Phys.G* 50 (2023) 3, 030501

Neutrinos at the FPF



The forward experiments can investigate neutrino interactions with high statistics at a new energy region.

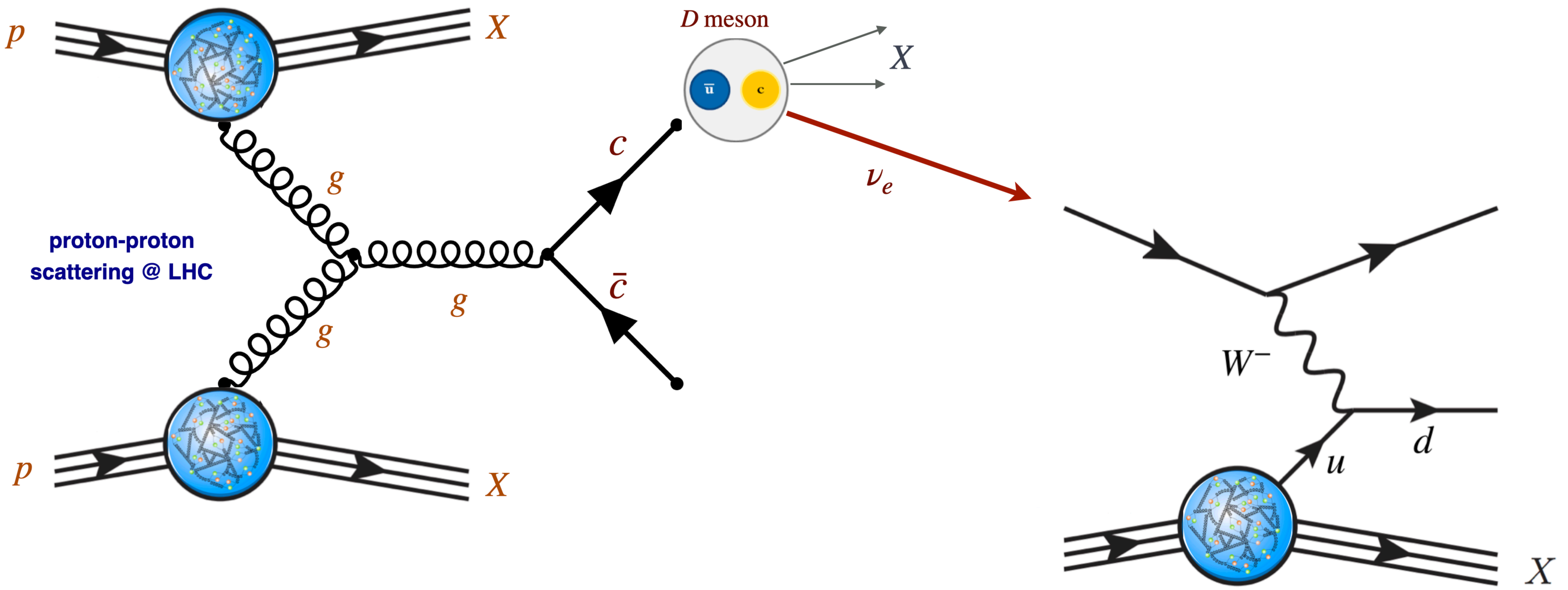
Detector				Number of CC Interactions		
Name	Mass	Coverage	Luminosity	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
FASERν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}	901 / 3.4k	4.7k / 7.1k	15 / 97
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}	137 / 395	790 / 1.0k	7.6 / 18.6
FASERν2	20 tons	$\eta \gtrsim 8.5$	3 ab^{-1}	178k / 668k	943k / 1.4M	2.3k / 20k
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}	36k / 113k	203k / 268k	1.5k / 4k

conventional + prompt

$\ast\ \mathscr{L} = 150\ \text{fb}^{-1} \rightarrow 290\ \text{fb}^{-1}$, the event numbers will be increased accordingly.

J. Feng et. al.,
J.Phys.G 50 (2023) 3, 030501

SM physics potential: probe for QCD

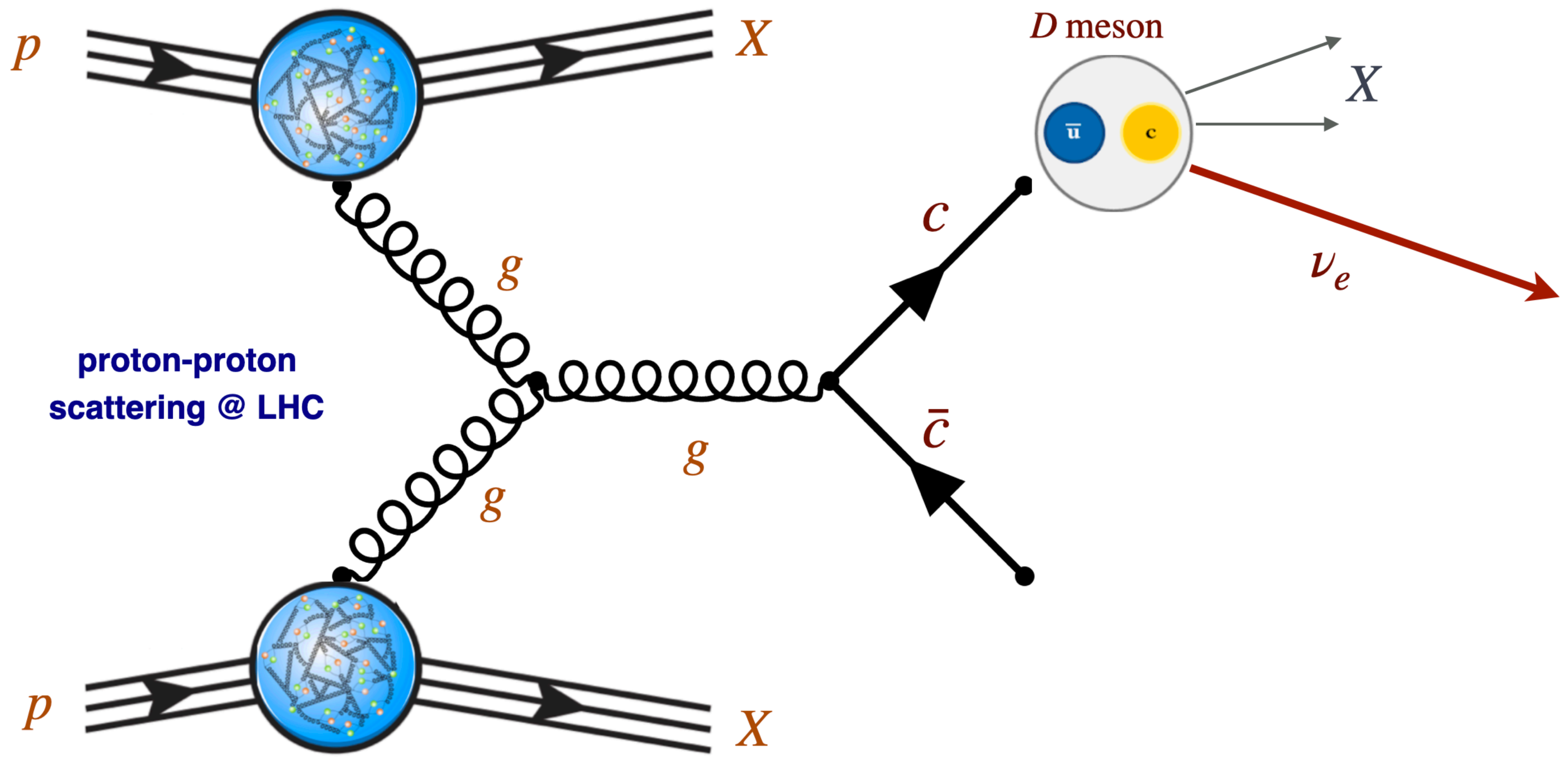


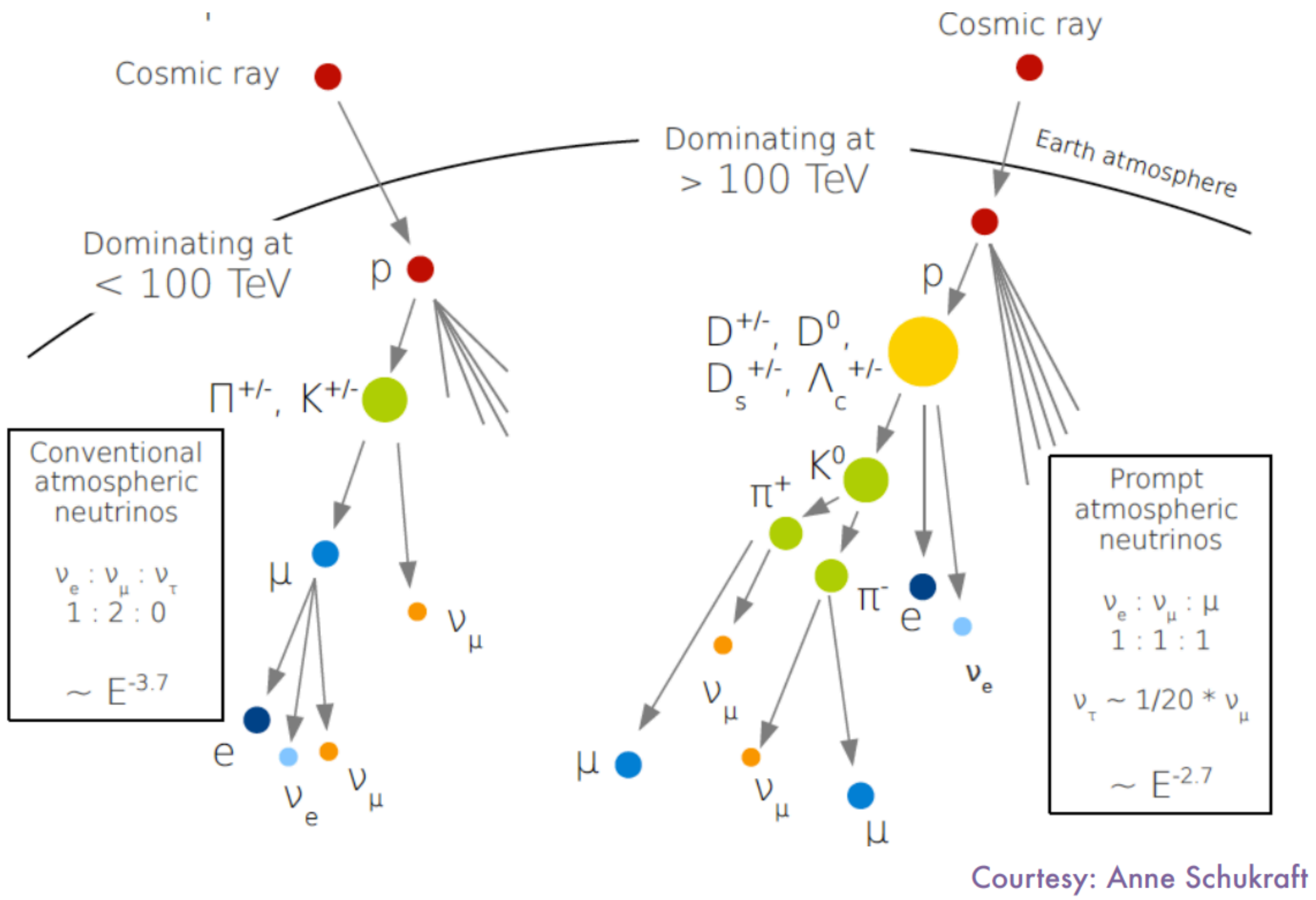
- Forward hadron production
- Small-x physics
  (e.g. constraints on proton PDFs)

- Neutrino structure functions
- Constraints on nucleon/nuclear PDFs

Figures from Juan Rojo's slide (FPF meetings)

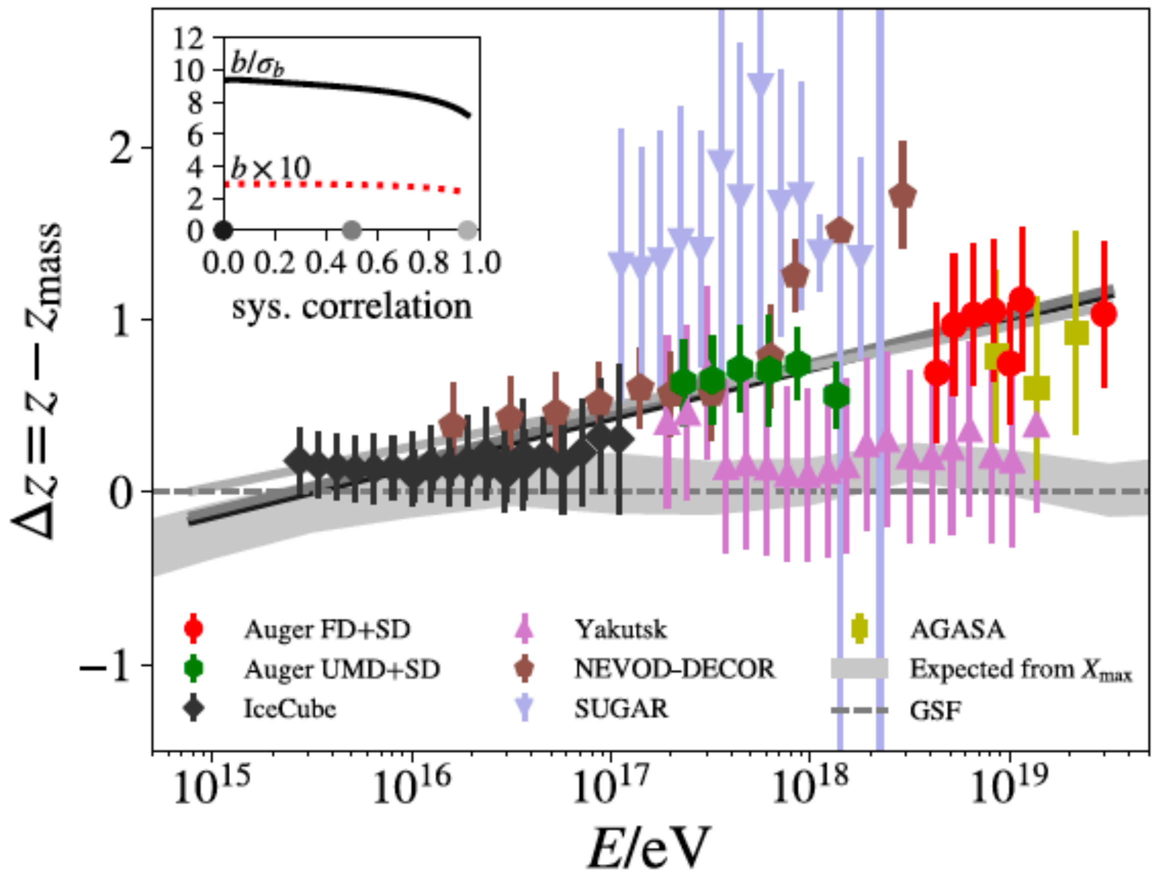
Implication for astroparticle physics



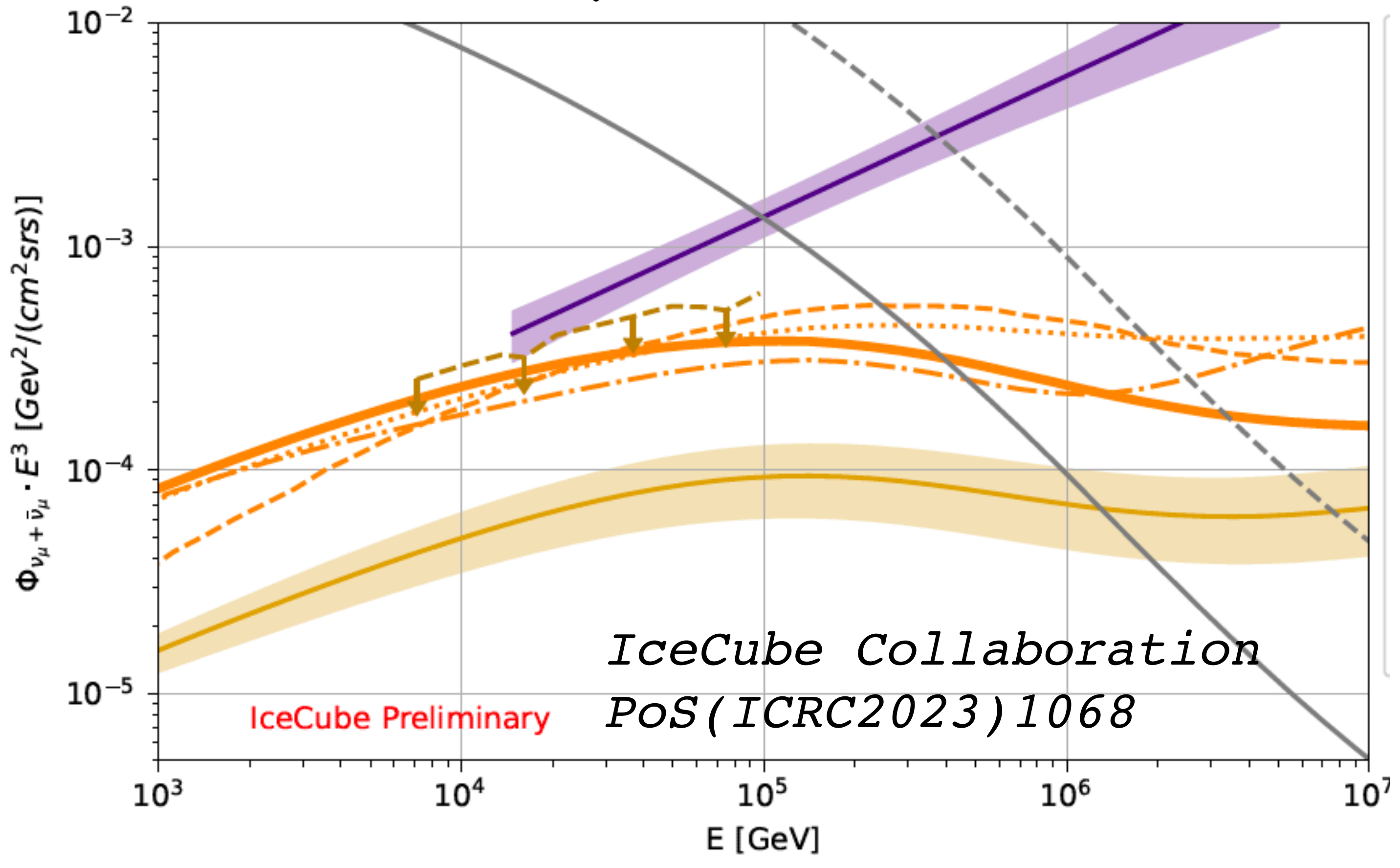


* $\sqrt{s}$ = 14 TeV corresponds to $E_p \simeq 100$ PeV.

Muon puzzle

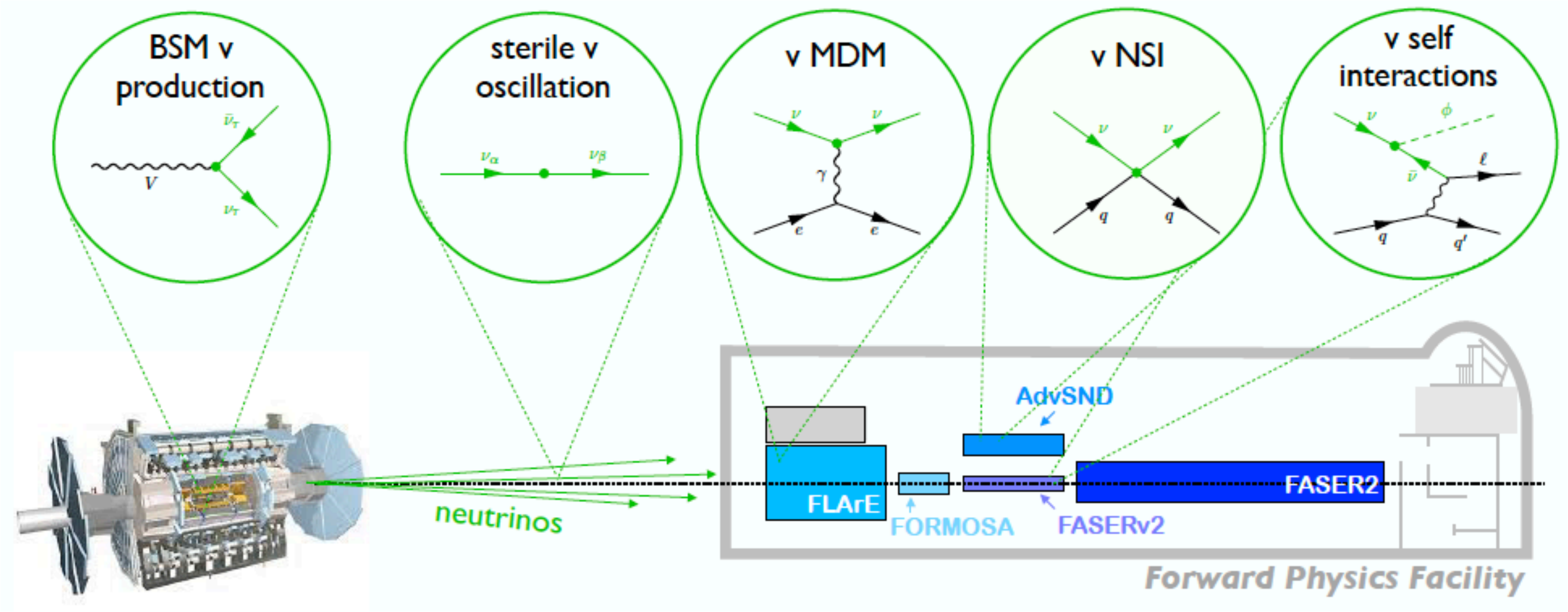


Atmospheric neutrinos



Figures from Juan Rojo's slide (FPF meetings)
+ FPF white paper, *J.Phys.G* 50 (2023) 3, 030501

Neutrino BSM physics at the LHC



- For more informations and physics potentials:
  - Phys. Rept. 968, 1 (2022), arXiv: 2109.10905.
  - J. Phys. G 50 (2023), arXiv: 2203.05090.
  - + 7 FPF Meetings

J. Feng et. al.,
J.Phys.G 50 (2023) 3, 030501

Neutrino BSM (1): oscillation with sterile neutrinos

- With the baseline of 500-600m and the neutrino energy range of 0.1 - O(1) TeV, the forward experiments will not be sensitive to oscillations between active neutrinos in the standard model.

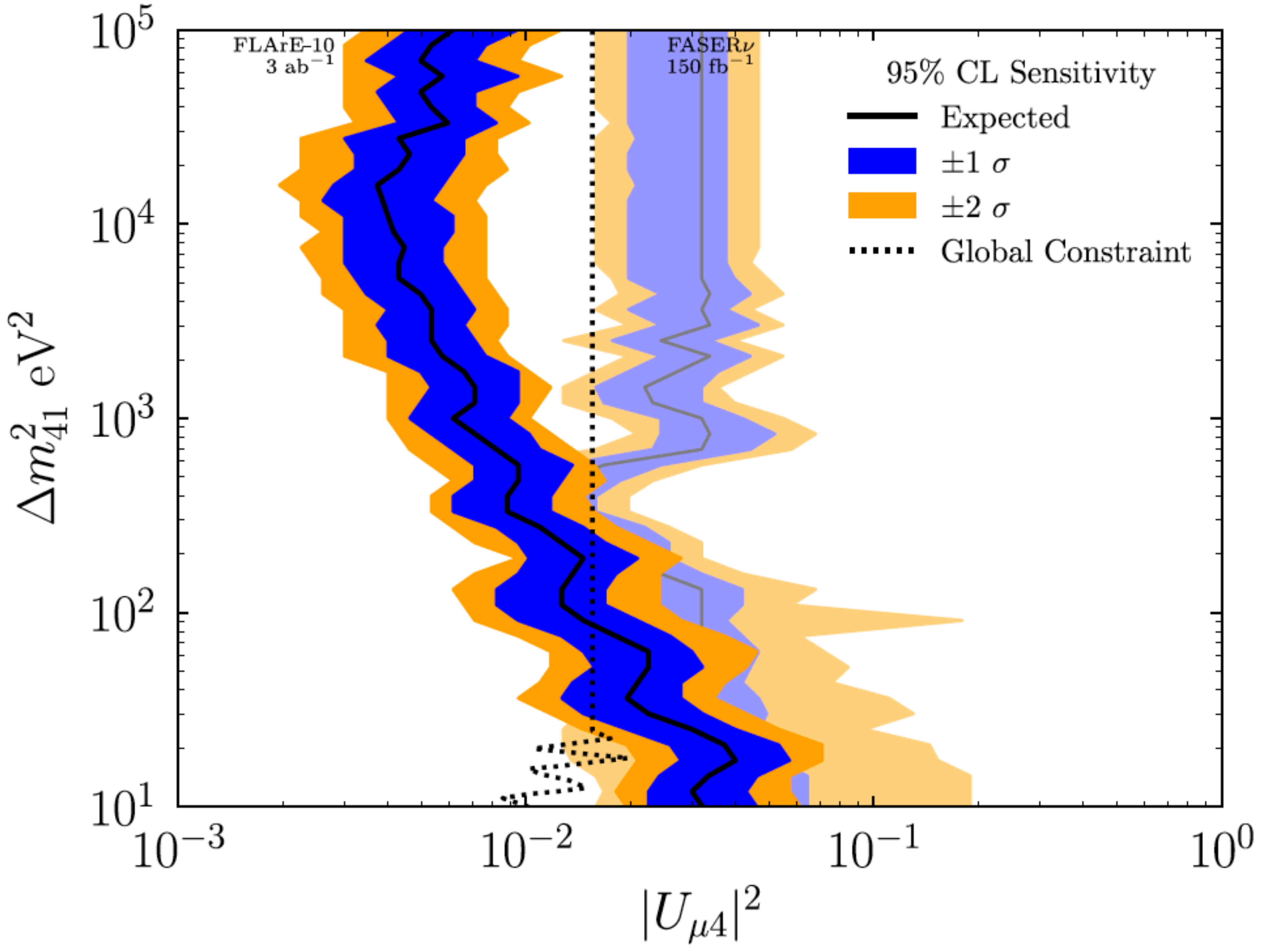
- Distortion in the event spectrum can be interpreted as oscillations between active neutrinos and sterile neutrinos.

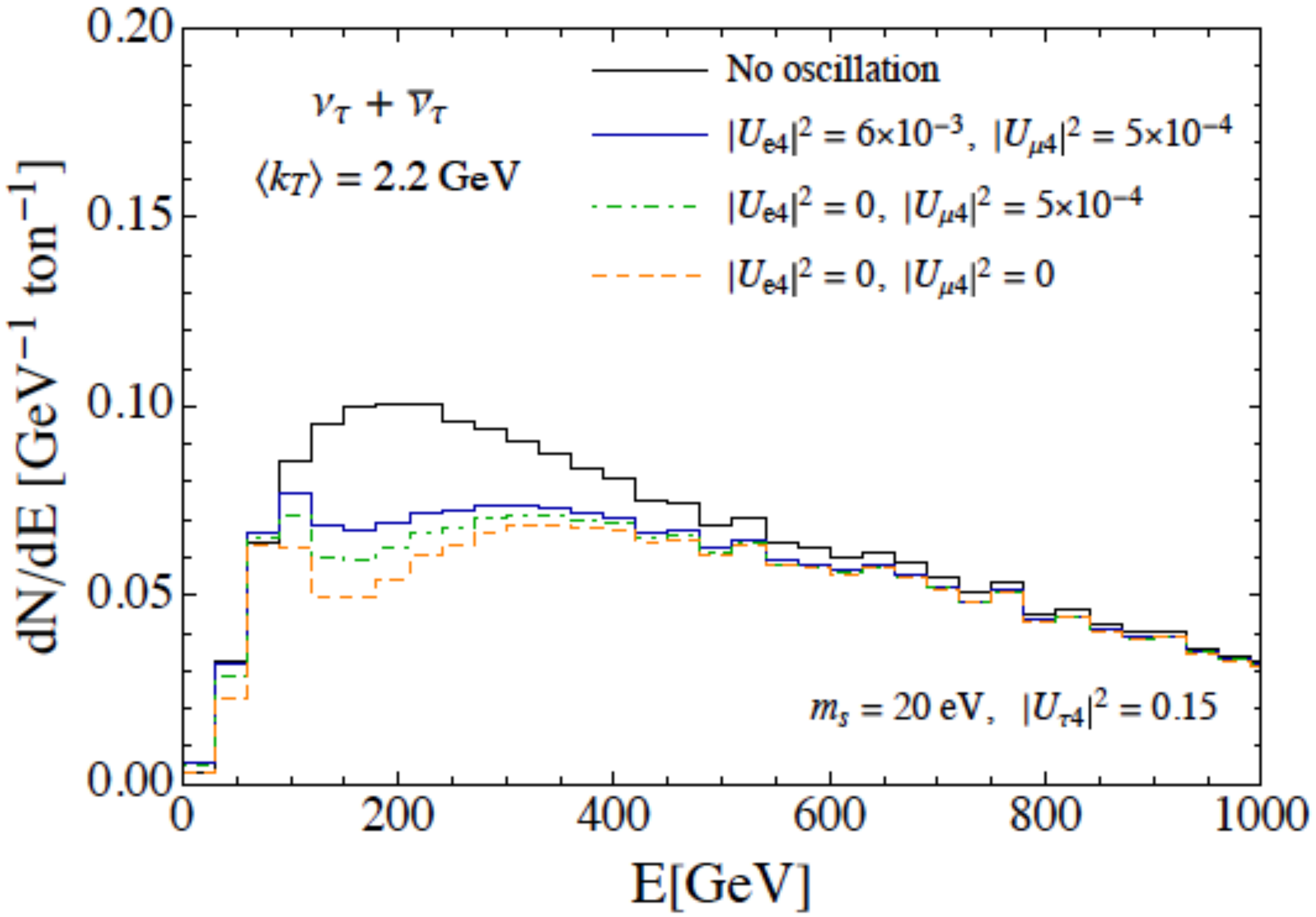
- Forward experiments at the LHC can probe the sterile neutrinos with $m_s \sim \mathcal{O}(10)\,\mathrm{eV}$.
  - Oscillation probability in the 3+1 scenario:

$$P(\nu_\alpha \to \nu_\beta) \simeq \delta_{\alpha\beta} - 4(\delta_{\alpha\beta} - |U_{\beta n_\nu}|^2)|U_{\alpha n_\nu}|^2 \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

  - Condition for significant signal: $\frac{\Delta m^2 L}{4E} \sim \frac{\pi}{2} \quad \to \quad \Delta m^2_{41} \sim 1000\ \mathrm{eV}^2$

Neutrino BSM (1): oscillation with sterile neutrinos





Expected sensitivity from the ν_μ disappearance channel for FASERν (Run-3) and FLArE-10 (HL-LHC).

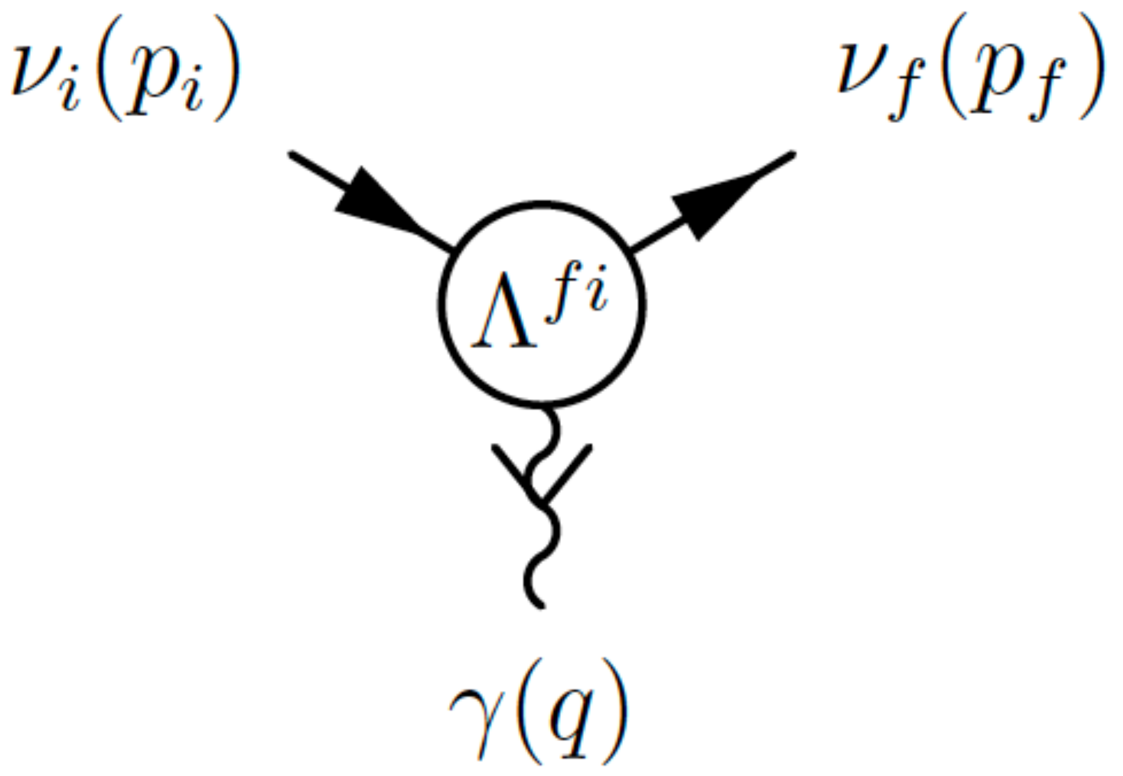
$\Delta m^2 = 400\,\mathrm{eV}^2$ ($m_4 = 20$ eV),
$|U_{e4}|^2 = 6 \cdot 10^{-3}$, $|U_{\mu4}|^2 = 5 \cdot 10^{-4}$, $|U_{\tau4}|^2 = 0.15$

J. Feng et. al.,
J.Phys.G 50 (2023) 3, 030501

W. Bai, M. Diwan, M. V. Garzelli, YSJ, M. H. Reno,
JHEP 06 (2020) 032

Neutrino BSM (2): neutrino magnetic moment

- Neutrino EM properties can arise at the loop level or via the BSM physics.



$$\langle \nu_f(p_f) | j^{\mu}_{\nu,\mathrm{EM}} | \nu_i(p_i) \rangle = \overline{u}_f(p_f) \Lambda^{\mu}_{fi}(q) u_i(p_i)$$

$$\Lambda^{fi}_{\mu}(q) = \left(\gamma_\mu - q_\mu \not{q}/q^2\right) \left[\mathbb{f}^{fi}_{Q}(q^2) + \mathbb{f}^{fi}_{A}(q^2) q^2 \gamma_5\right] - i\sigma_{\mu\nu} q^\nu \left[\mathbb{f}^{fi}_{M}(q^2) + i\mathbb{f}^{fi}_{E}(q^2)\gamma_5\right]$$

$$\rightarrow \gamma^\mu \left(Q_{fi} - \frac{q^2}{6} \left\langle r^2 \right\rangle_{fi}\right) - i\sigma^{\mu\nu} q_\nu \mu_{fi}$$

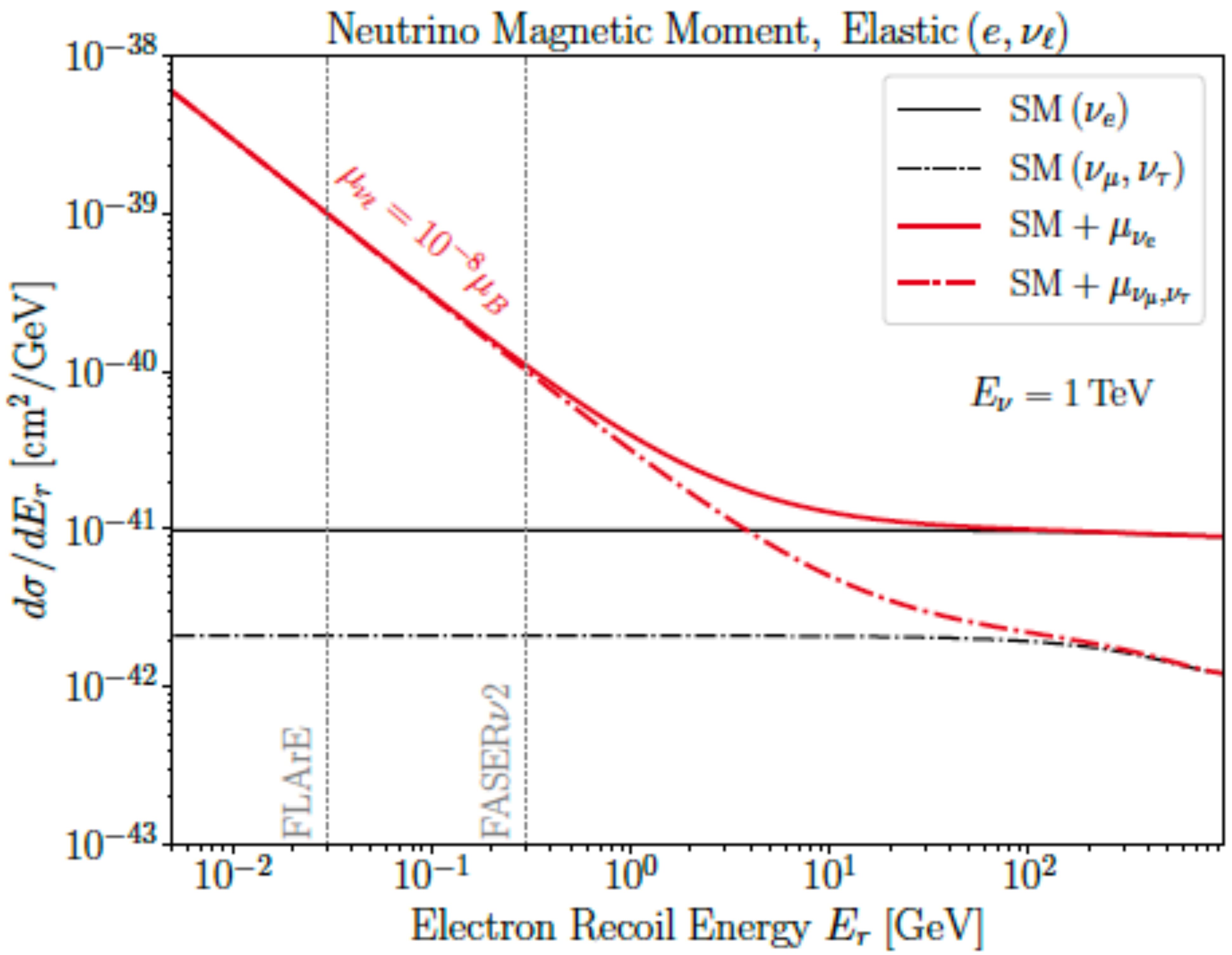
2301.10254)

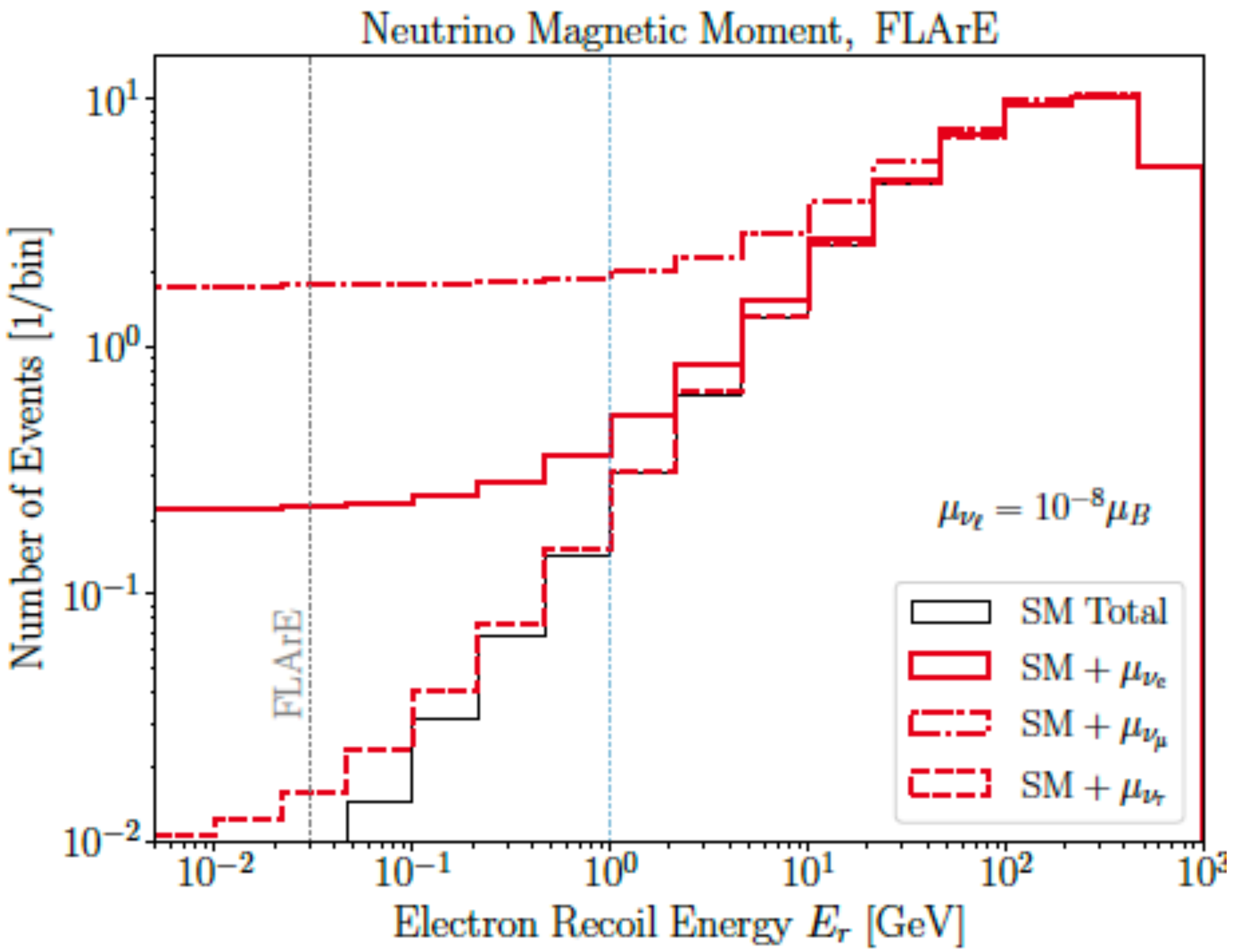
μ_{fi} : Neutrino magnetic moment

Neutrino BSM (2): neutrino magnetic moment

- Non-zero neutrino mass implies the existence of neutrino magnetic moment (NMM).
  - $$\mu_\nu \approx \frac{3eG_F}{8\sqrt{2}\pi^2} m_\nu \approx 3 \cdot 10^{-19} \mu_B \left(\frac{m_\nu}{1\ \text{eV}}\right)$$
- Additional BSM contribution can increase the value of NMM.
- Measurement of neutrino magnetic moment (μ_{fi}) can be used to distinguish neutrino nature, Dirac vs. Majorana.
  - Dirac neutrinos can have diagonal ($i = f$) and transition ($i \neq f$) magnetic moments.
  - Majorna neutrinos have only transition magnetic moment.

Neutrino BSM (2): neutrino magnetic moment

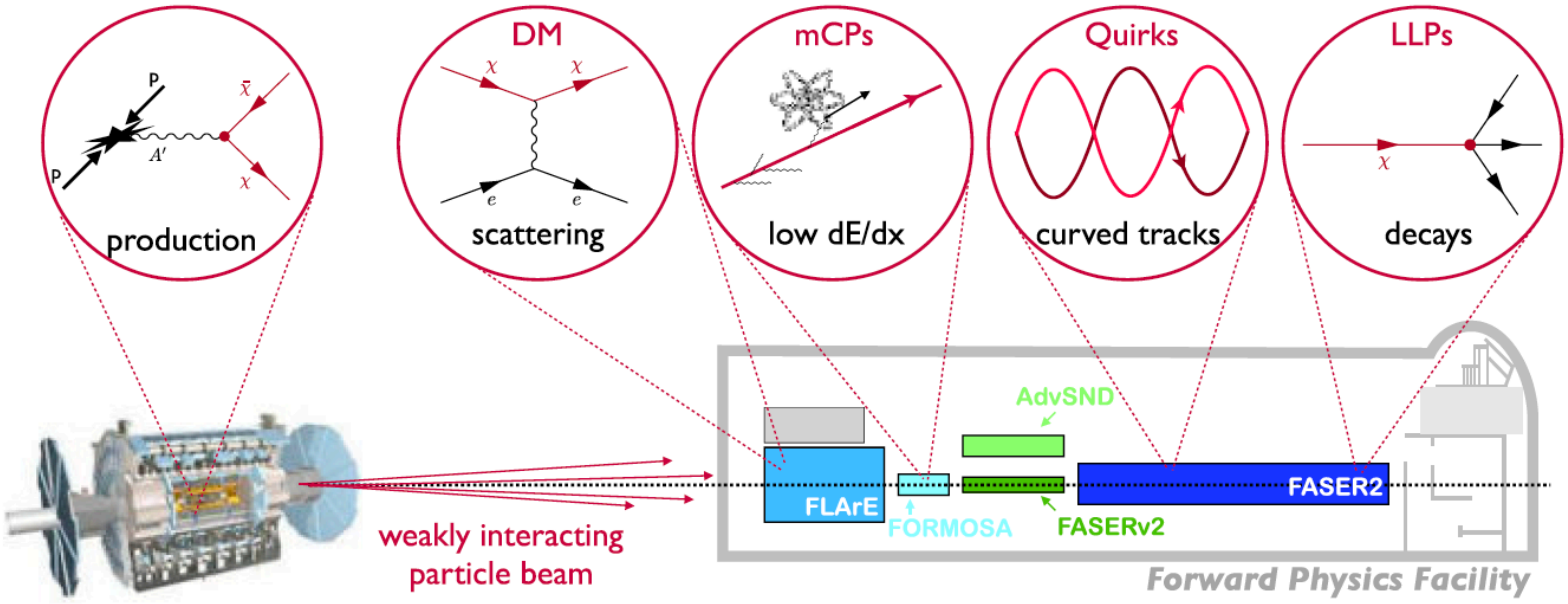




$$\left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\rm NMM} = \left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\rm SM} + \frac{\pi^2}{m_e^2}\left(\frac{1}{E_r} - \frac{1}{E_\nu}\right)\left(\frac{\mu_{\nu_\ell}}{\mu_{\rm B}}\right)^2$$

R. M. Abraham, S. Foroughi-Abari, F. Kling, and Yu-Dai Tsai (arXiv:2301.10254)

BSM physics at the LHC



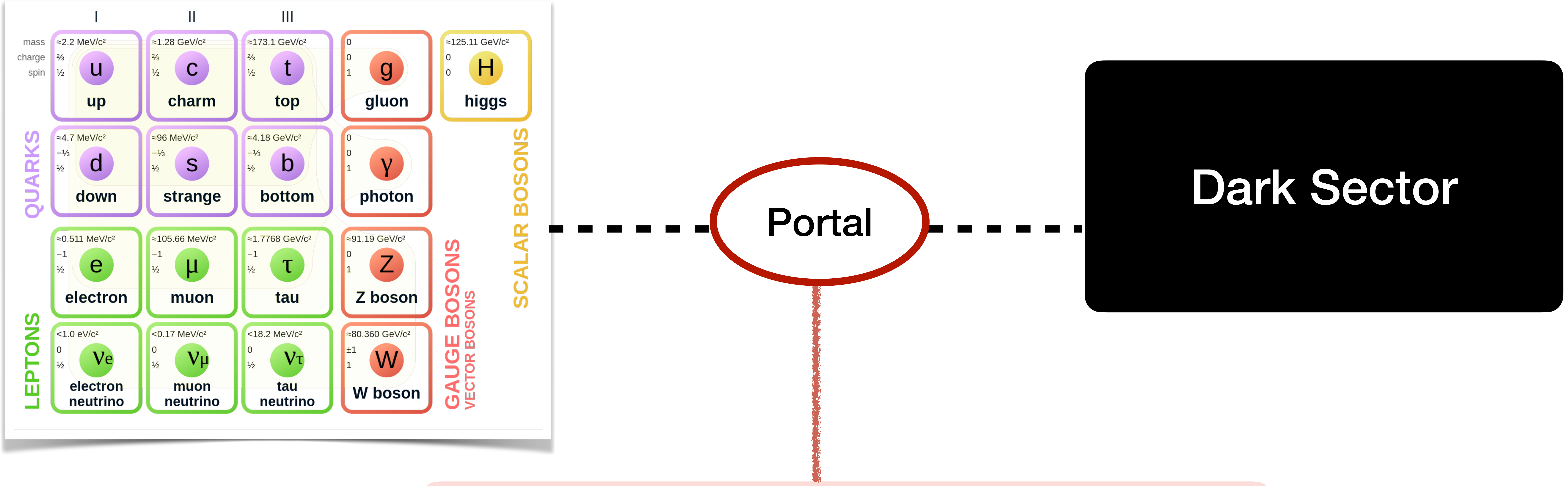
- For more informations and physics potentials:
  - Phys. Rept. 968, 1 (2022), arXiv: 2109.10905.
  - J. Phys. G 50 (2023), arXiv: 2203.05090.
  - + 7 FPF Meetings

J. Feng et. al.,
J.Phys.G 50 (2023) 3, 030501

BSM (1): Long-Lived Particles (LLP)

- Search for light long-lived particle (LLP) is the main program of the FASER experiment.
  - dark photon, dark Higgs, sterile neutrinos and axion.

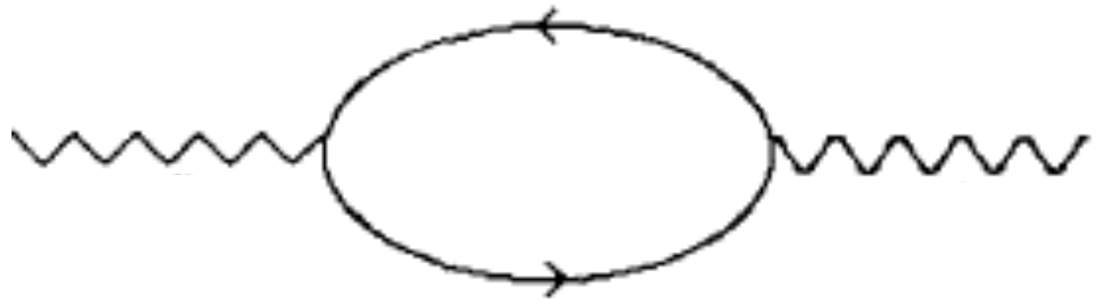
- Common motivation of LLPs can be a portal to mediate SM and dark sector



$\epsilon F^{\mu\nu} F'_{\mu\nu} \quad \kappa\phi^2 |H|^2 \quad yLHN \quad gaF^{\mu\nu}\tilde{F}_{\mu\nu}$

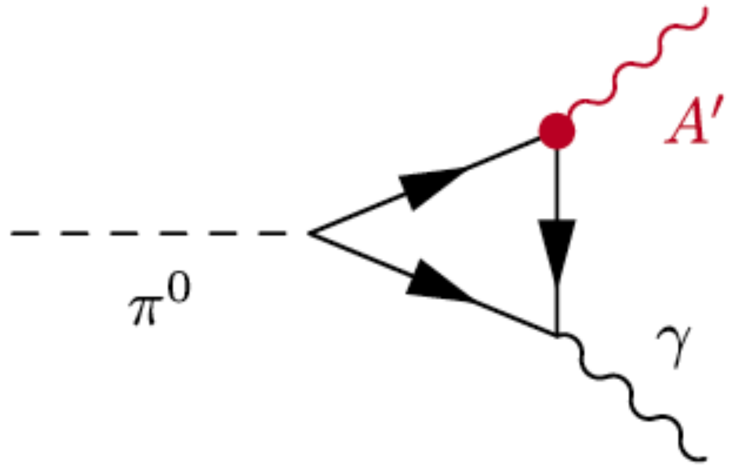
Dark Photon

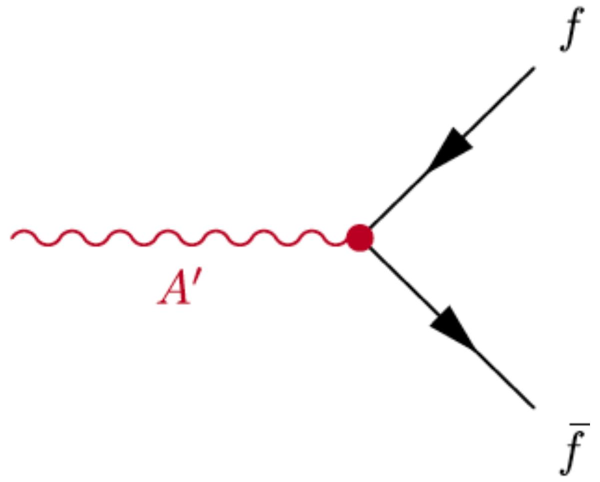
- The dark photon is an additional U(1) gauge boson, and couples to the SM photon by a kinetic mixing.



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

- Dominant production at the LHC can be through meson decays and detection signature is pair of charged particles.





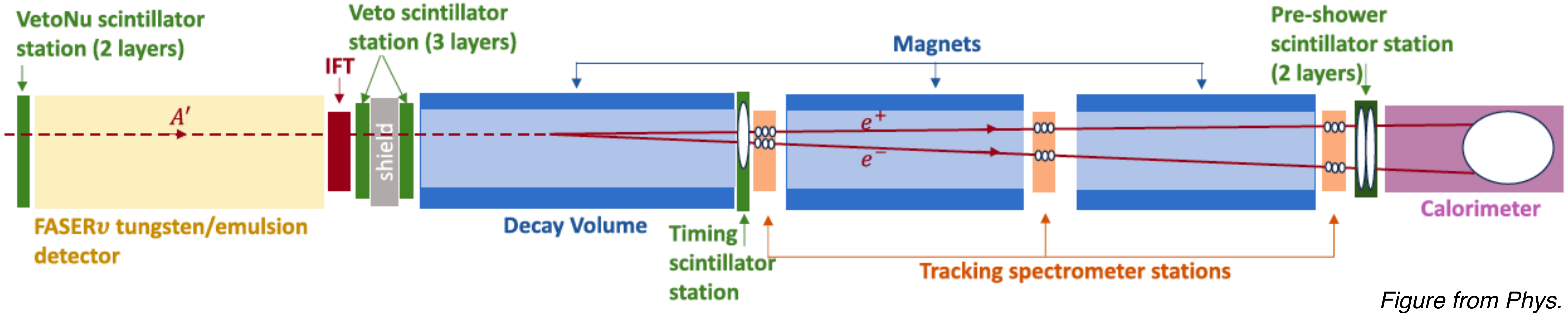
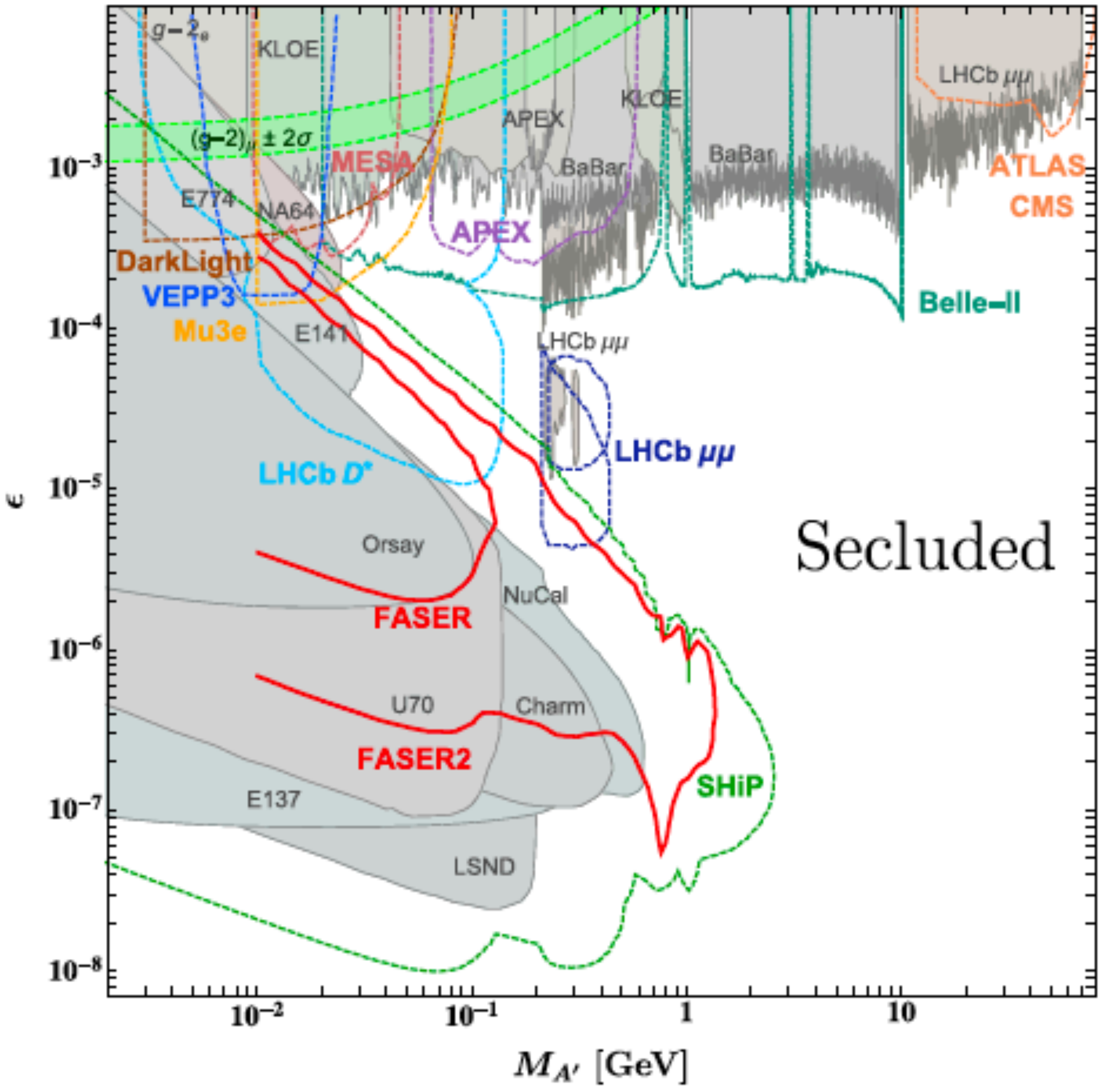


Figure from Phys. Lett. B 848 (2024) 138378 (FASER collaboration)

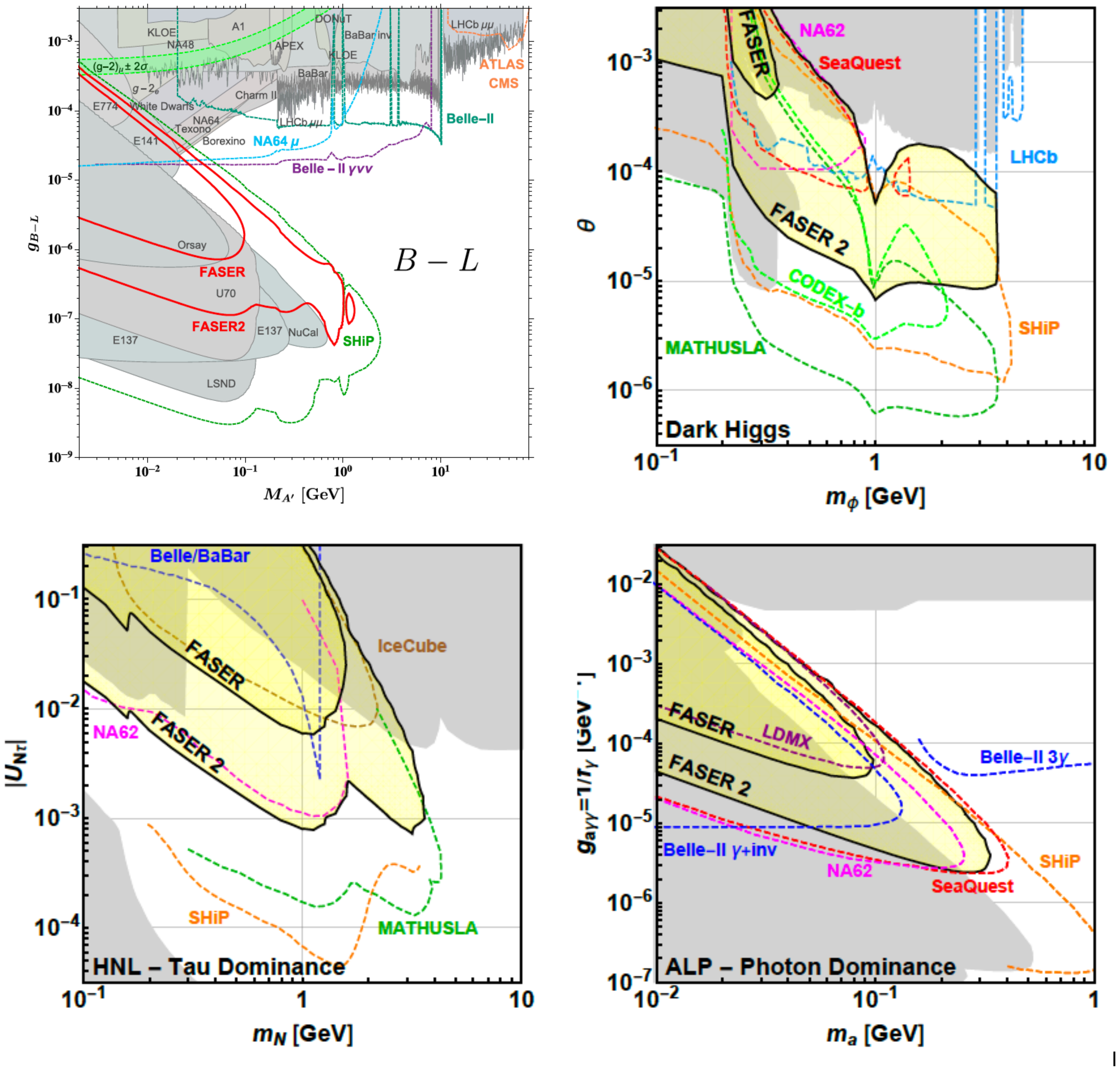
Sensitivity to dark photon search



J. Feng et. al., *J.Phys.G* 50 (2023) 3, 030501

- Benchmark parameters for detectors:
  - FASER: L=1.5m, R=10cm, Luminosity: 150fb^{-1}
  - FASER2: L=5m, R=1m, Luminosity: 3ab^{-1}
- FASER2 significantly improves sensitivity.
- FASER/FASER2 can probe a new region of the parameter space.

Sensitivity to other LLP models



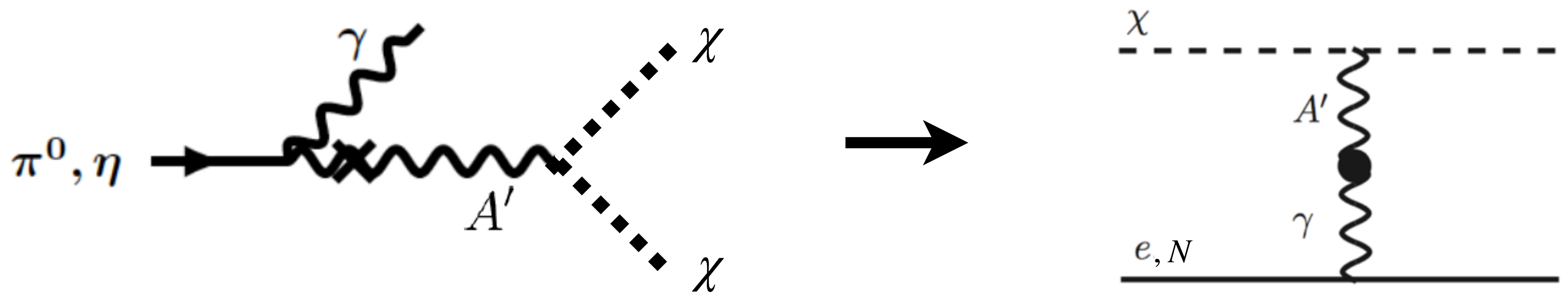
- Benchmark parameters for detectors:
  - FASER: L=1.5m, R=10cm, Luminosity: 150fb^{-1}
  - FASER2: L=5m, R=1m, Luminosity: 3ab^{-1}
- FASER2 significantly improves sensitivity.
- FASER/FASER2 can probe a new region of the parameter space in most cases.

J. Feng et. al., J.Phys.G 50 (2023) 3, 030501
FASER collaboration, arXiv: 1901.04468

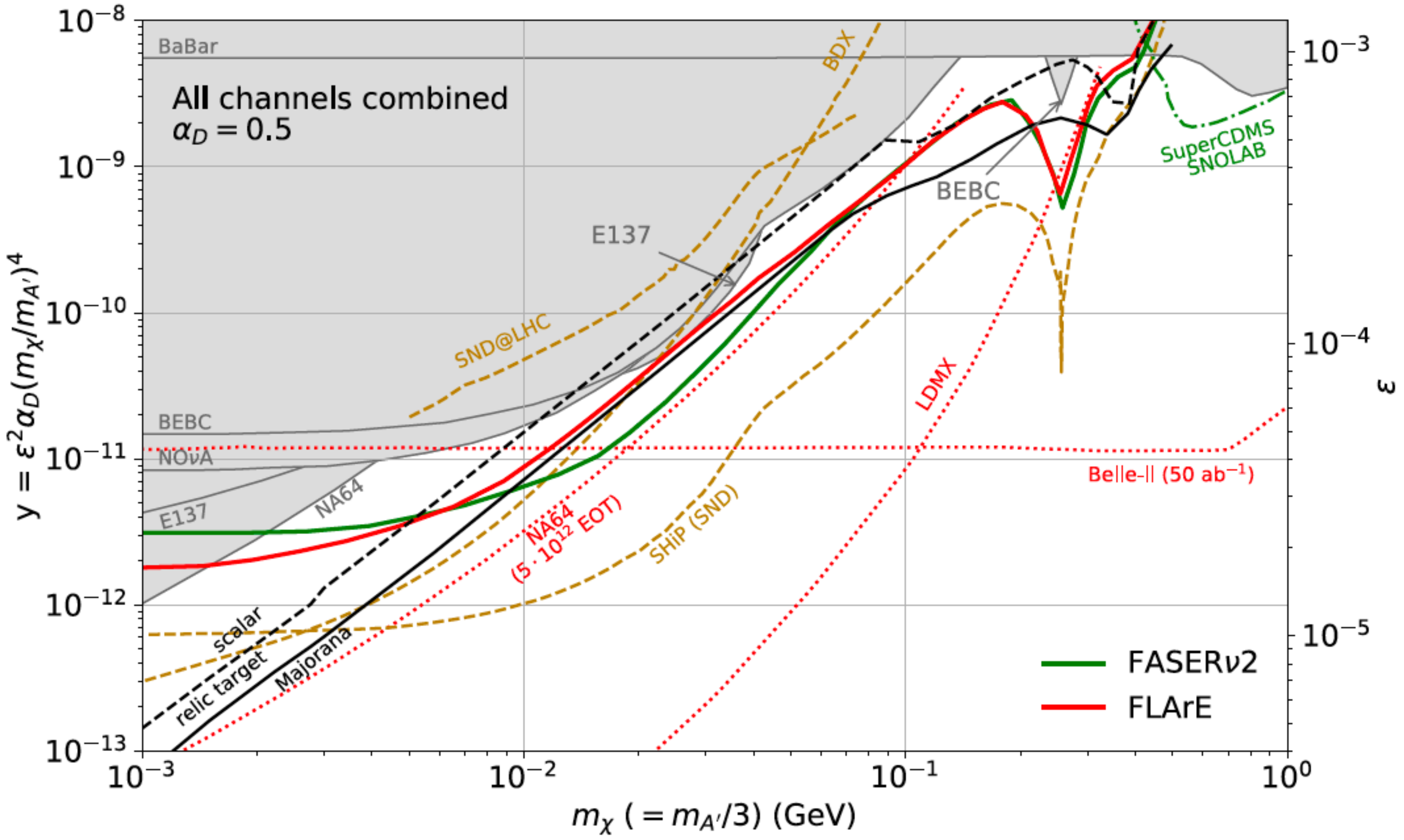
BSM (2): Light dark matter (LDM)

- In case that dark matter is light ($m_{DM} < m_{A'}/2$), the dark photon can decay to dark matters.

- LDM can be directly detected at neutrino detectors through electron or nuclear scattering.



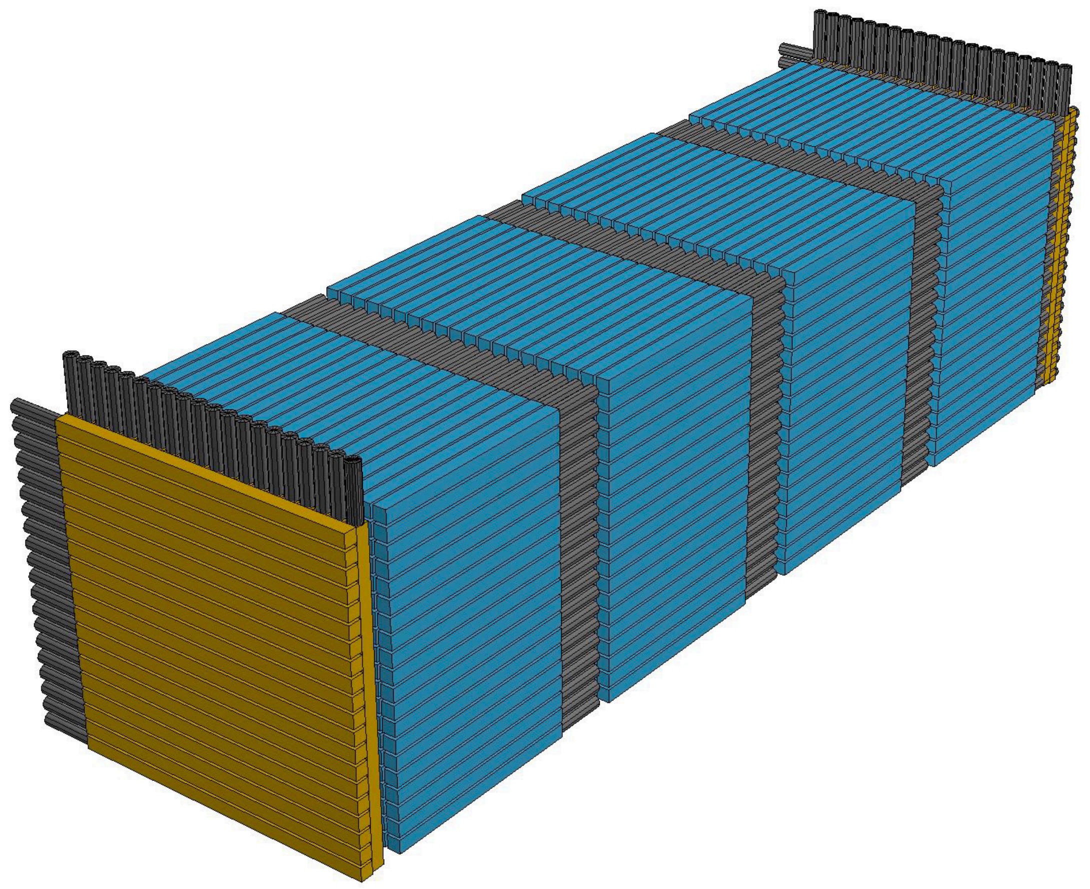
- The neutrino experiments at the FPF can probe the cosmologically favored parameter space.

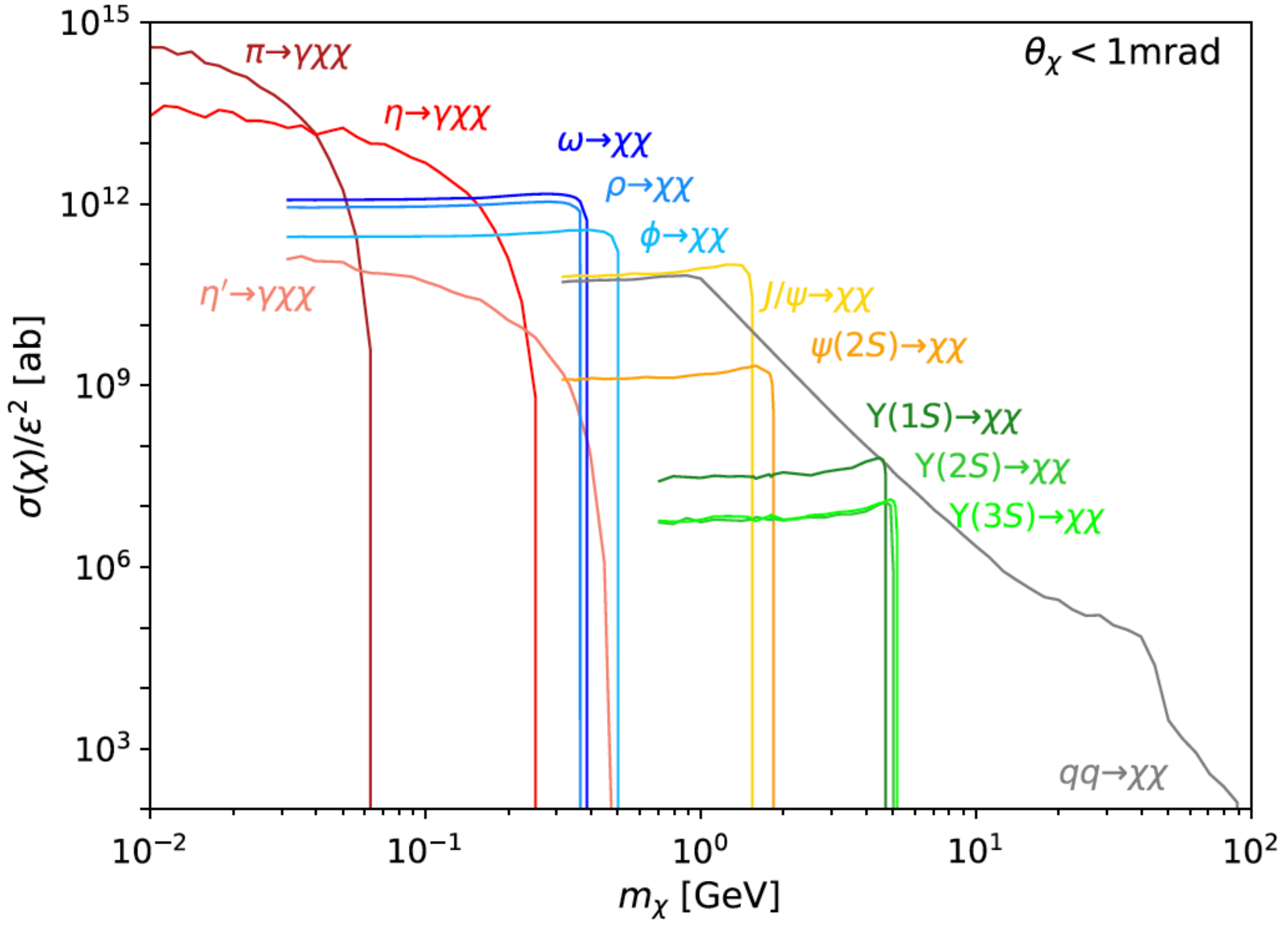


Batell, Feng, Ismail, Kling, Abraham, Trojanowski
Phys. Rev. D 104, 035036 (2021)

BSM (3): millicharged particle (mCP)

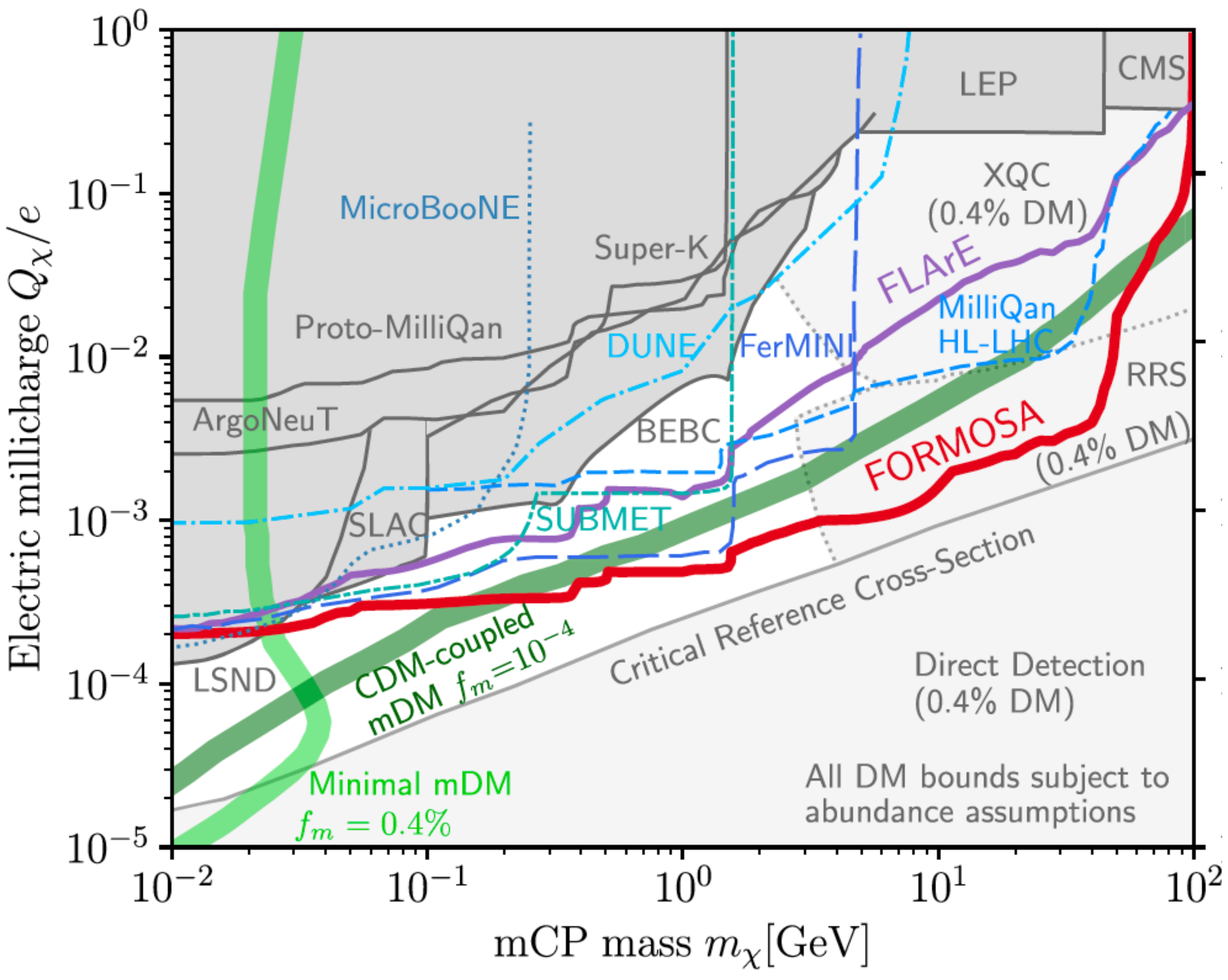
- FORMOSA (FORward MicrOcharge SeArch): to search for millicharged particles (mCPs).
- The mCP is a new dark fermion with $Q = \epsilon e$ $(\epsilon < 1)$.
- At the LHC, mCPs can be produced from secondary meson decays or directly from Drell-Yann process.
- Detector is array of scintillator bars with PMT, which will track energy deposition dE/dx.





Foroughi-Abari, Kling, Tsai
PHYSICAL REVIEW D 104, 035014 (2021)

Sensitivity to mCP



- The FORMOSA can probe the charge ratio as low as $\sim 10^{-4}$.
- It will provide the best limit for the mass range of $100\,\mathrm{MeV} < m_\chi < 100\,\mathrm{GeV}$.
- FLArE can also search for mCP with scattering signal, similar to LDM search.

J. Feng et. al., J.Phys.G 50 (2023) 3, 030501
Foroughi-Abari, Kling, Tsai, Phys. Rev. D 104, 035014 (2021)
Kling, Kuo, Trojanowski, Tsai, Nucl.Phys.B 987 (2023) 116103

Summary

- In the forward regions of the LHC, there are rich physics potentials. The forward experiments offer abundant opportunities to explore such physics in both SM and BSM.

- The forward experiments will significantly advance our knowledge of weakly interacting particles.
  - Open a new window for neutrino studies, and enhance research on related QCD and astroparticle physics.
  - Extensively expand BSM physics program of the LHC with improved sensitivity.

Thank you for your attention