Beyond the SM

at Forward Physics Facilities

IAS Program on High Energy Physics, February 2023

Kingman Cheung

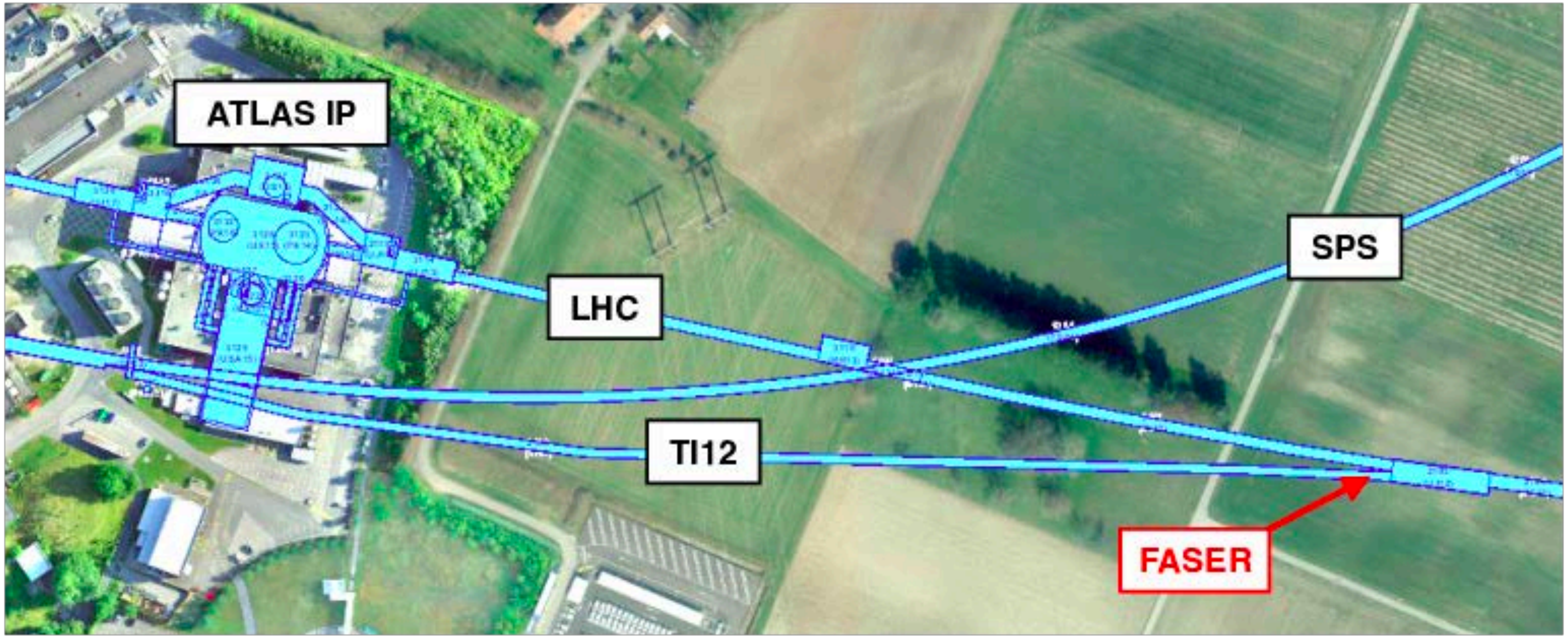
Motivation

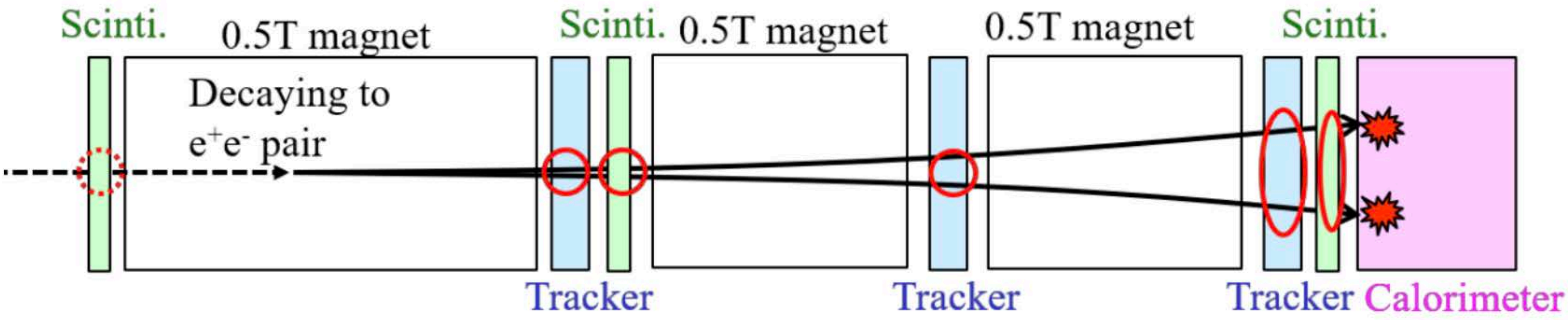
“High energy collisions at the High-Luminosity Large Hadron Collider (LHC) produce a large number of particles along the beam collision axis, outside of the acceptance of existing LHC experiments.”

Outlines

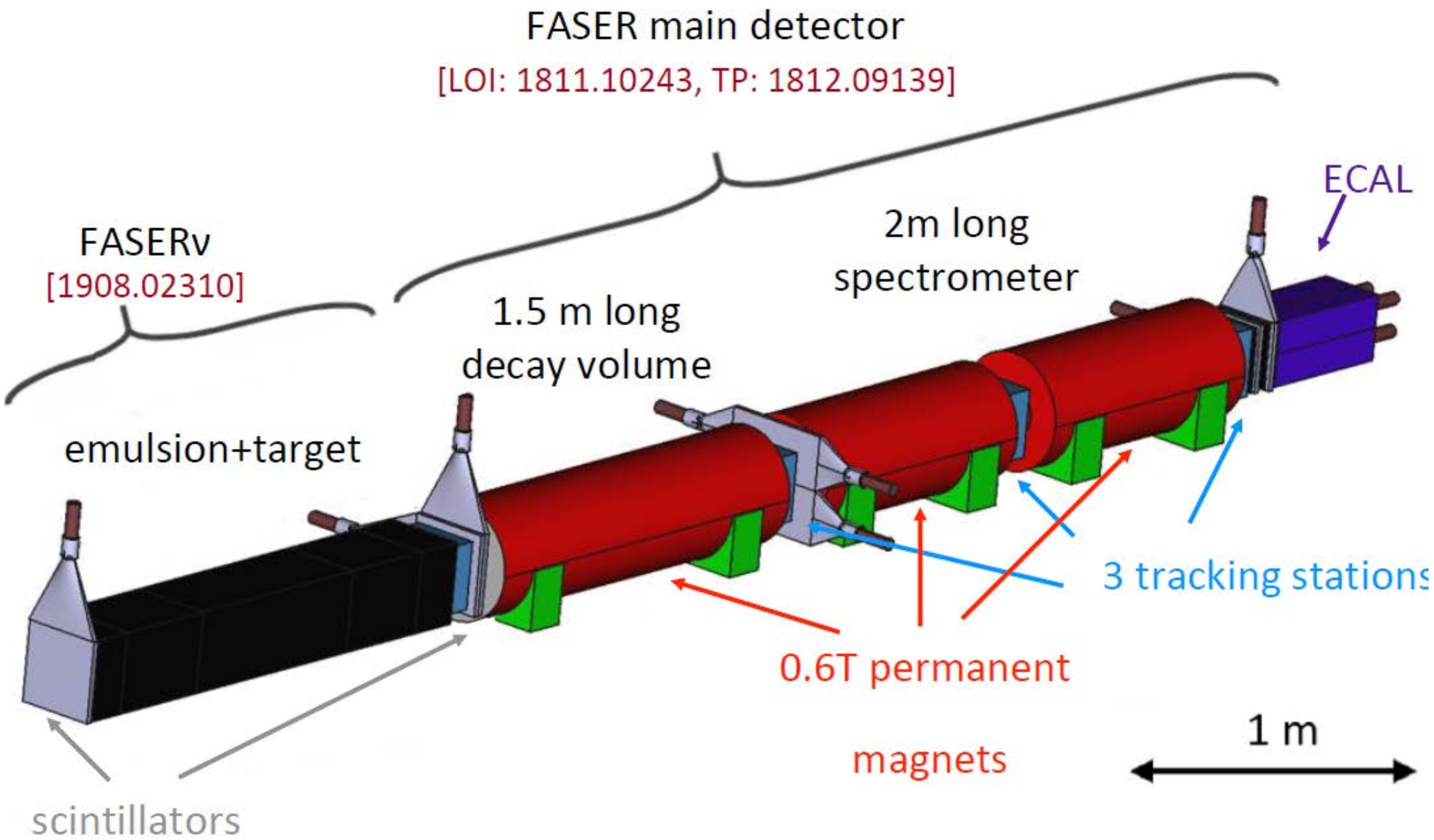
1. Idea of the FASER, FASERν, and Forward Physics Facility (FPF)
2. Beyond the standard model searches at FPF
3. Z′ and NSI
4. Heavy neutrino
5. Dark Photon
6. Leptoquarks

FASER will be located in the unused LHC service tunnel TI12, which is 480m downstream of the proton-proton interaction point (IP) used by the ATLAS experiment. The fluxes of most high-energy standard model background particles at this position are suppressed to negligible levels, with the only exceptions being the most penetrating known particles, namely muons and neutrinos. The FASER detector will be sensitive to new particles that decay in a cylindrical volume with radius R=10 cm and length L=1.5 m.





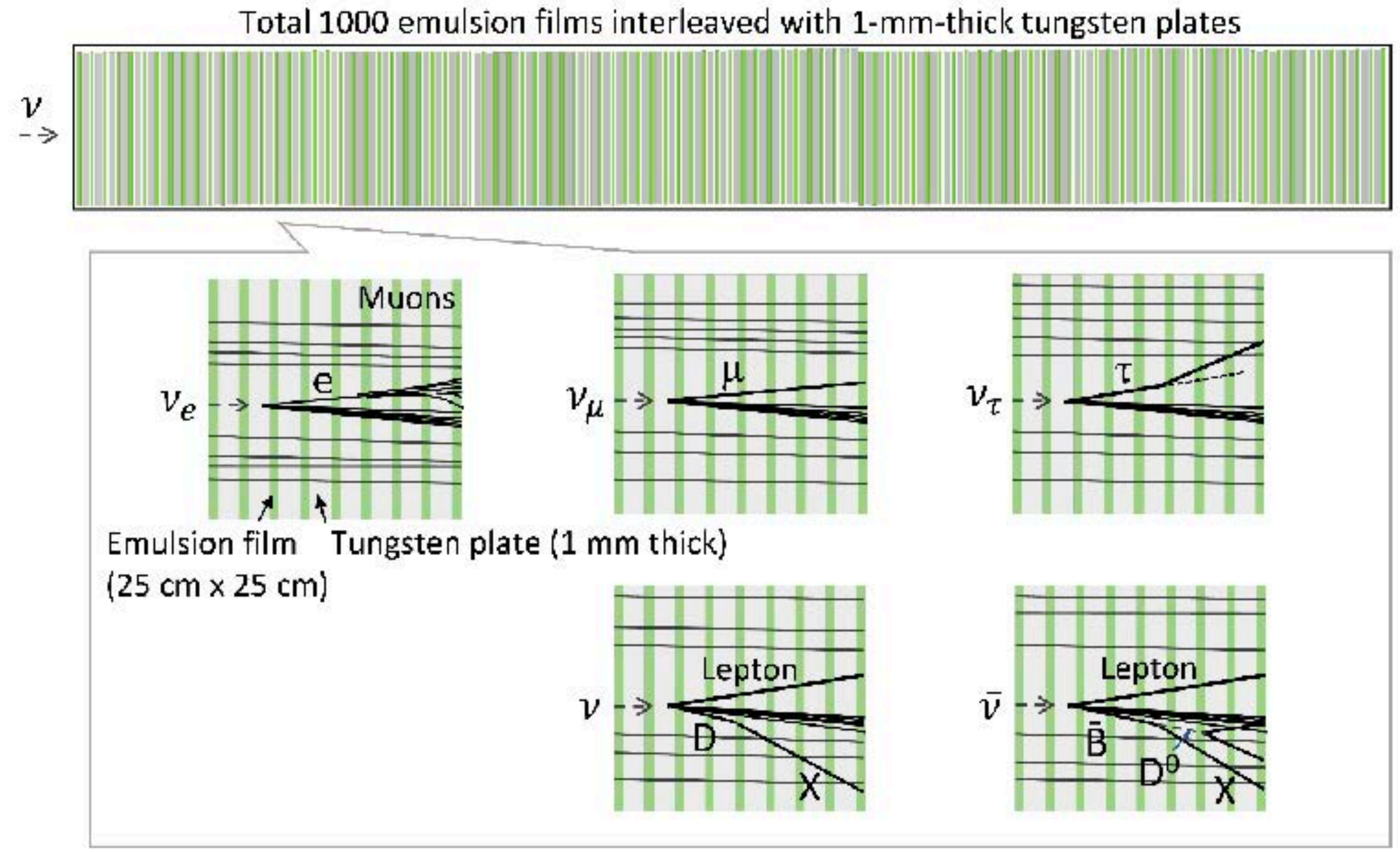
Scinti.
0.5T magnet
Decaying to
e+e- pair
Scinti.
0.5T magnet
0.5T magnet
Scinti.
Tracker
Tracker
Tracker
Calorimeter



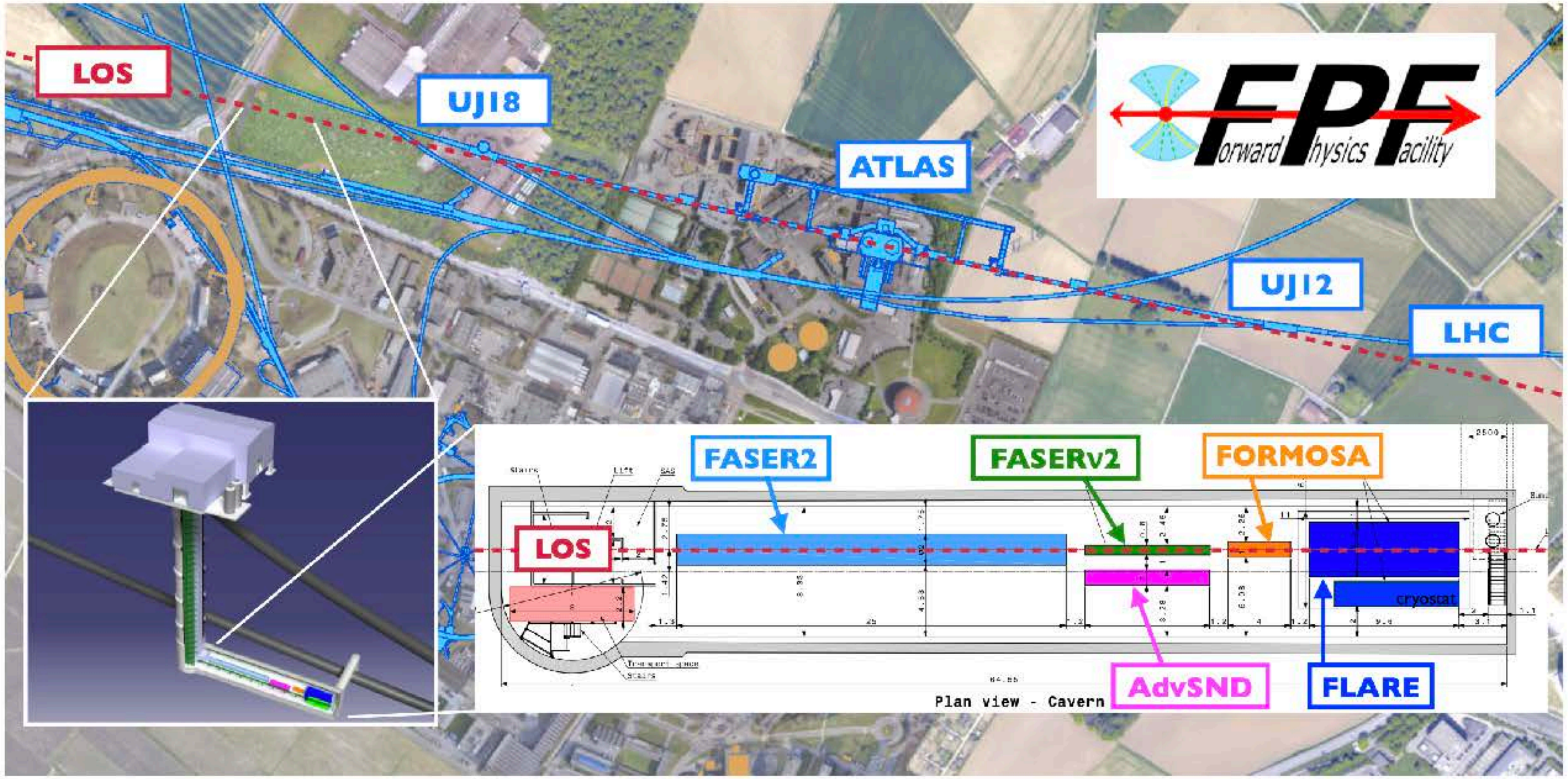
FASER main detector
[LOI: 1811.10243, TP: 1812.09139]
FASERν
[1908.02310]
1.5 m long
decay volume
2m long
spectrometer
ECAL
emulsion+target
3 tracking stations
0.6T permanent
magnets
1 m
scintillators

Cont'd

Muons are identified by their track length in the detector. Since the detector has a total nuclear interaction length of 10.1λ_{int}, all the hadrons from the neutrino interactions will interact, except for hadrons created in the far downstream part of the detector.



Forward Physics Facility (FPF)



Source: arXiv:2109.10905, 2203.

Forward Physics Facility, a proposed new cavern for the High-Luminosity era.
The FPF will be 65 m-long and 8.5 m-wide

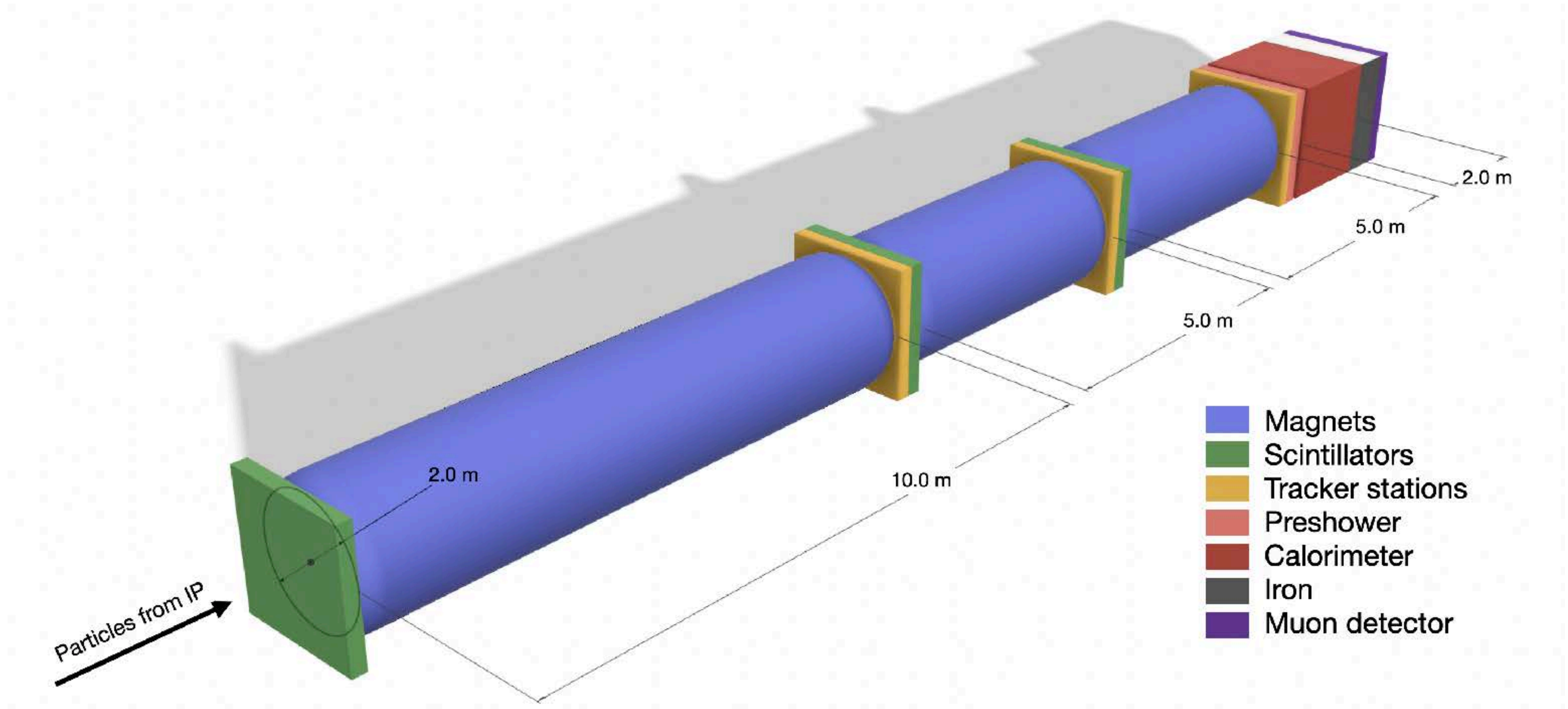
FASER2: a magnetic spectrometer and tracker, will search for light and weakly-interacting states, including long-lived particles, new force carriers, axion-like particles, light neutralinos, and dark sector particles.

FASERν2: Upgraded version of FASERν

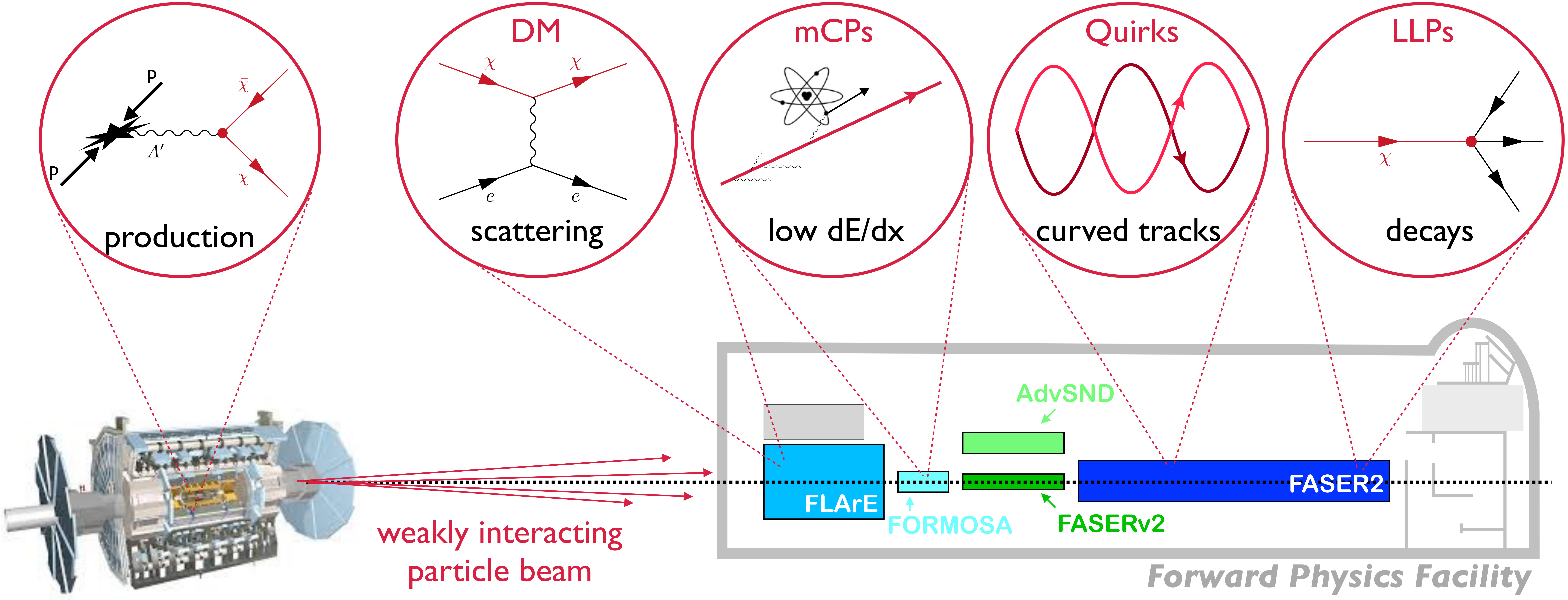
AdvSND: Upgraded version of SND@LHC

FORMOSA: a detector composed of scintillating bars, will provide world-leading sensitivity to millicharged particles and other very weakly-interacting particles across a large range of masses.

FLARE: a proposed 10-tonne-scale noble liquid detector, will detect neutrinos and also search for light dark matter.



Schematic diagram of the proposed FASER2 detector. The design shown has a cylindrical decay volume with 2 m diameter and 10 m length. The total length is approximately 22 m, Schematic illustration of the most important signatures in the FPF searches for BSM physics.



Scattering of DM in the neutrino detectors FLArE, FASERν2 and AdvSND@LHC detectors; ii) non-standard energy deposition of mCPs characterized in the FORMOSA and FLArE detectors; iii) and helical tracks in quirk models at FASER2; and iv) decays of long-lived particles to be studied in FASER2.

BSM Search at FASERν

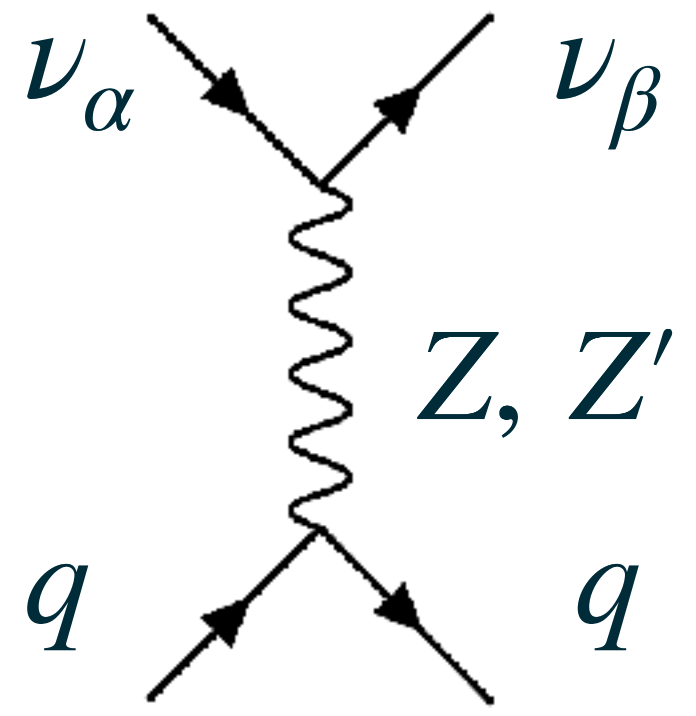
Non-standard neutrino and Z′ interactions at the FASERν and the LHC

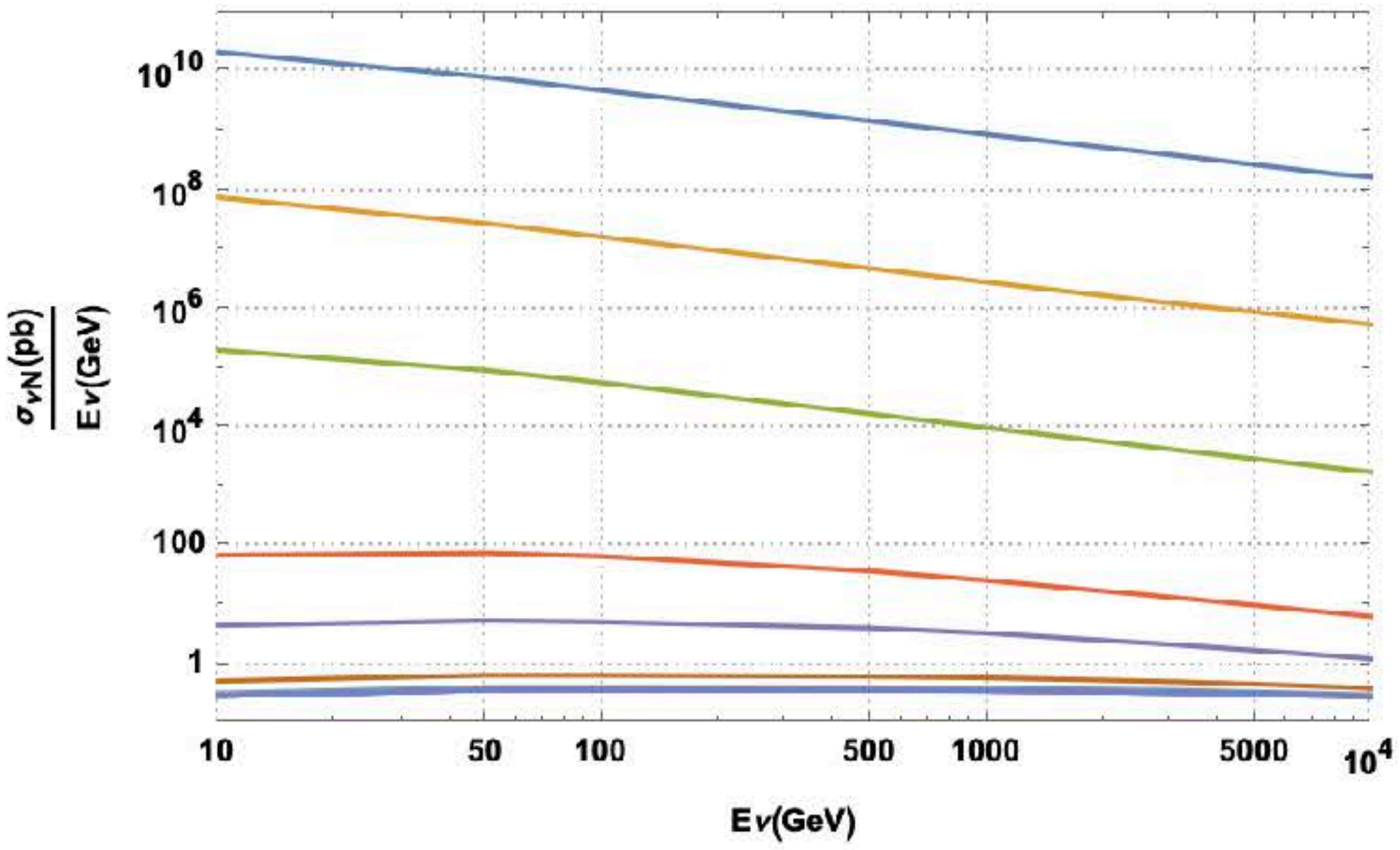
K. Cheung, C. J. Ouseph and T. Wang, JHEP12(2021), 209 doi:10.1007JHEP12(2021)209[arXiv:2111.08375 [hep-ph]]

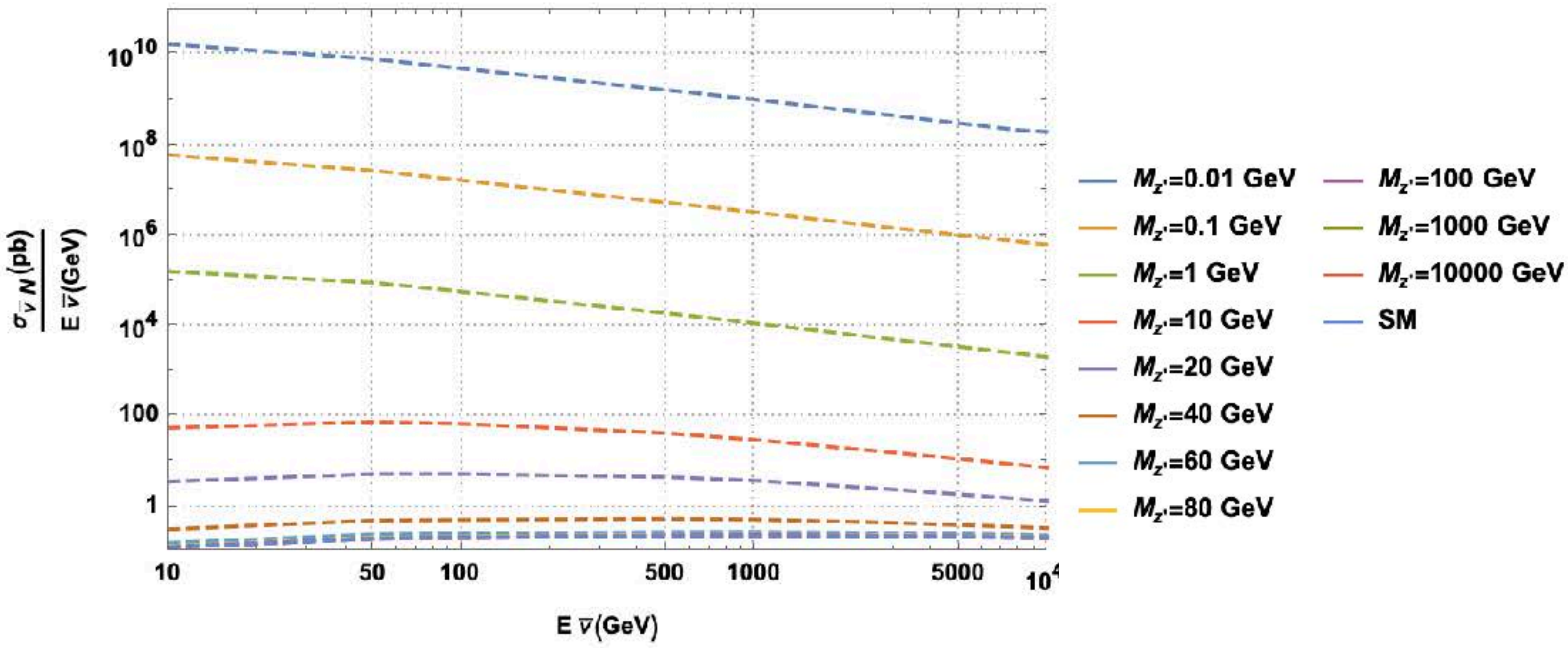
Non-standard neutrino Interactions @ FASERν

$$\mathscr{L}_{NC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \epsilon^{f,P}_{\alpha\beta} \left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right) \left(\bar{f}\gamma_\mu P f\right)$$

$$\mathscr{L}_{Z'} = -\left(g_\nu \bar{l}_\alpha \gamma^\mu P_L l_\alpha + g_q \bar{q}\gamma^\mu q\right) Z'_\mu$$







K. Cheung, C. J. Ouseph and T. Wang, JHEP12(2021)

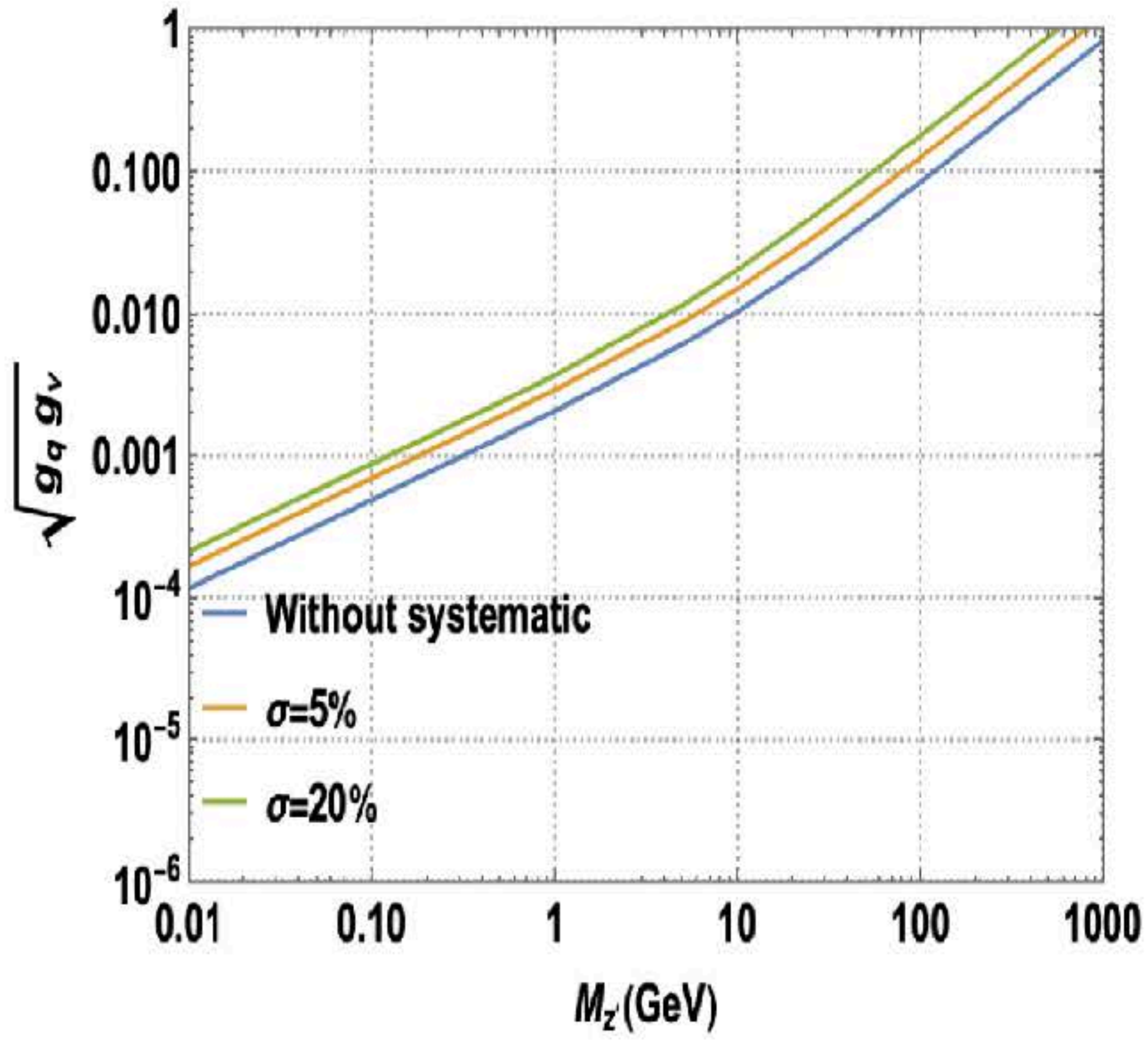
Cont'd

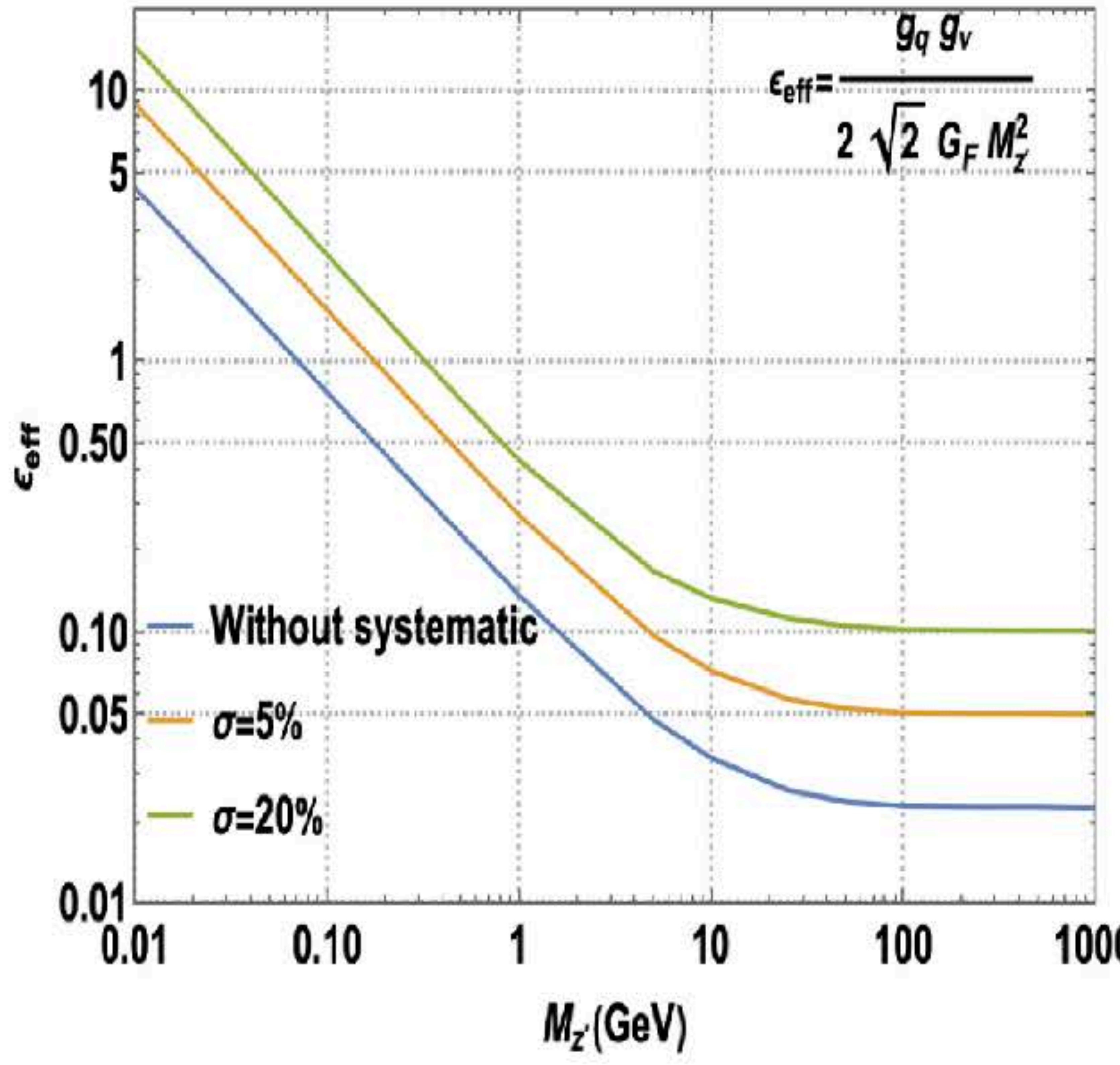
$$\chi^2(g_q g_\nu, \alpha) = \min_\alpha \left[\frac{(N_{BSM}^{\nu_e} - (1+\alpha)N_{SM}^{\nu_e})^2}{N_{BSM}^{\nu_e}} + \frac{(N_{BSM}^{\nu_\mu} - (1+\alpha)N_{SM}^{\nu_\mu})^2}{N_{BSM}^{\nu_\mu}} + \frac{(N_{BSM}^{\nu_\tau} - (1+\alpha)N_{SM}^{\nu_\tau})^2}{N_{BSM}^{\nu_\tau}} + \left(\frac{\alpha}{\sigma_{norm}}\right)^2 \right]$$

The sensitivity of FASERν detectors to Z'

$$N_{BSM} = N_{Z'} + N_{int} + N_{SM}$$

α is the nuisance parameters, σ_{norm} is the systematic uncertainties from the flux and detector



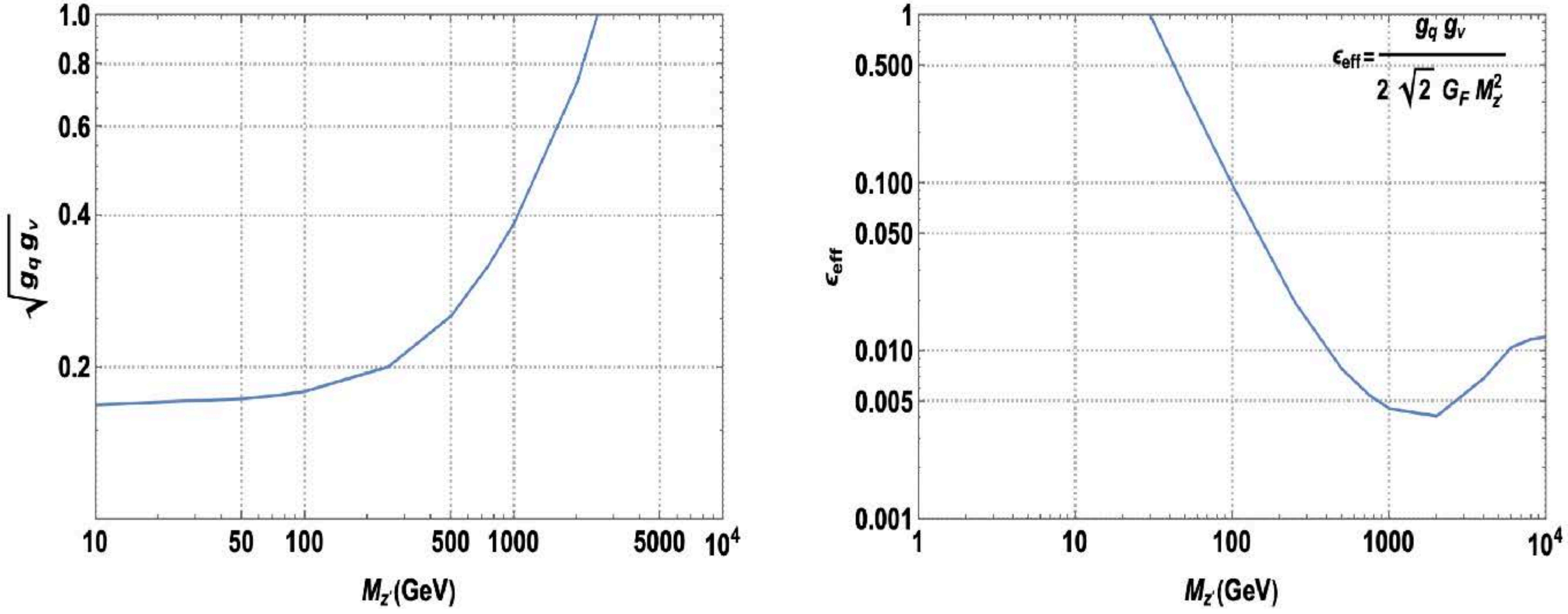


K. Cheung, C. J. Ouseph and T. Wang, JHEP12(2021)

Effects of Z′ on the monojet production @ LHC

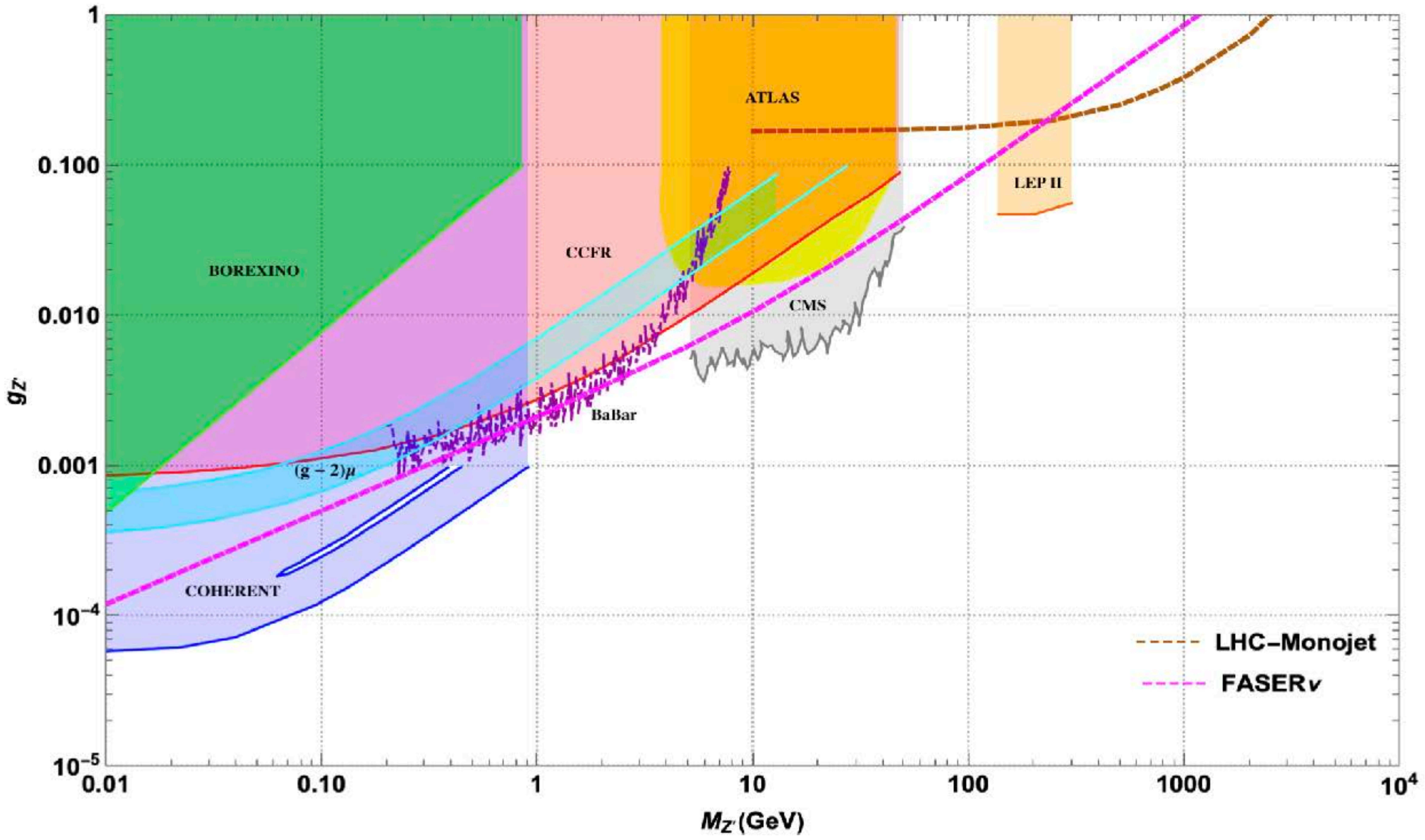
$$pp \to Z' + j \to \nu\nu + j$$

We follow closely the experimental cuts outlined in the ATLAS paper in order to directly use their upper limits on the monojet production cross sections. ATLAS paper results was based on the monojet search at 13 TeV with an integrated luminosity of 139 fb−1 [*Phys. Rev. D* 103 (2021) 112006 [arXiv:2102.10874]]



K. Cheung, C. J. Ouseph and T. Wang, JHEP12(2021)

Complementarity of FASERν with LHC Monojet Results



K. Cheung, C. J. Ouseph and T. Wang, JHEP12(2021)

Sensitivities on dark photon from the Forward Physics Experiments

K Cheung, C.J. Ouseph Journal of High Energy Physics 2022 (10), 1-21

Dark Photon Models

The allowed interactions of the dark photon with the SM particles depend on the theoretical framework. There are two main approaches to the way to couple the dark photon sector with the SM.

Dark photon mix with the photon through a kinetic mixing

$$L \supset \frac{1}{2}\epsilon F_{\mu\nu}F''^{\mu\nu}$$

$\mathrm{U(1)}$ **gauging like** $\mathrm{U(1)_{B-L}}$

$$\mathscr{L}_{B-L} \supset g_{B-L}\left[-\bar{l}\gamma^{\mu}A'_{\mu}l - \bar{\nu}_{\alpha}\gamma^{\mu}A'_{\mu}\nu_{\alpha} + \frac{1}{3}\bar{q}\gamma^{\mu}A'_{\mu}q\right]$$

Cont'd

Dark photon mix with the photon through a kinetic mixing

$$L \supset \frac{1}{2}\epsilon F_{\mu\nu}F''^{\mu\nu}$$

Induce Coupling with charged fermions only

$\mathrm{U(1)}$ **gauging like** $\mathrm{U(1)_{B-L}}$

$$\mathscr{L}_{B-L} \supset g_{B-L}\left[-\bar{l}\gamma^{\mu}A'_{\mu}l - \bar{\nu}_{\alpha}\gamma^{\mu}A'_{\mu}\nu_{\alpha} + \frac{1}{3}\bar{q}\gamma^{\mu}A'_{\mu}q\right]$$

B-L gauging induced coupling with Neutrinos

The $\mathrm{U(1)_{B-L}}$ Model

$$\mathcal{L}_{B-L} \supset g_{B-L}\left[-\bar{l}\gamma^{\mu}A'_{\mu}l - \bar{\nu}_{\alpha}\gamma^{\mu}A'_{\mu}\nu_{\alpha} + \frac{1}{3}\bar{q}\gamma^{\mu}A'_{\mu}q\right]$$

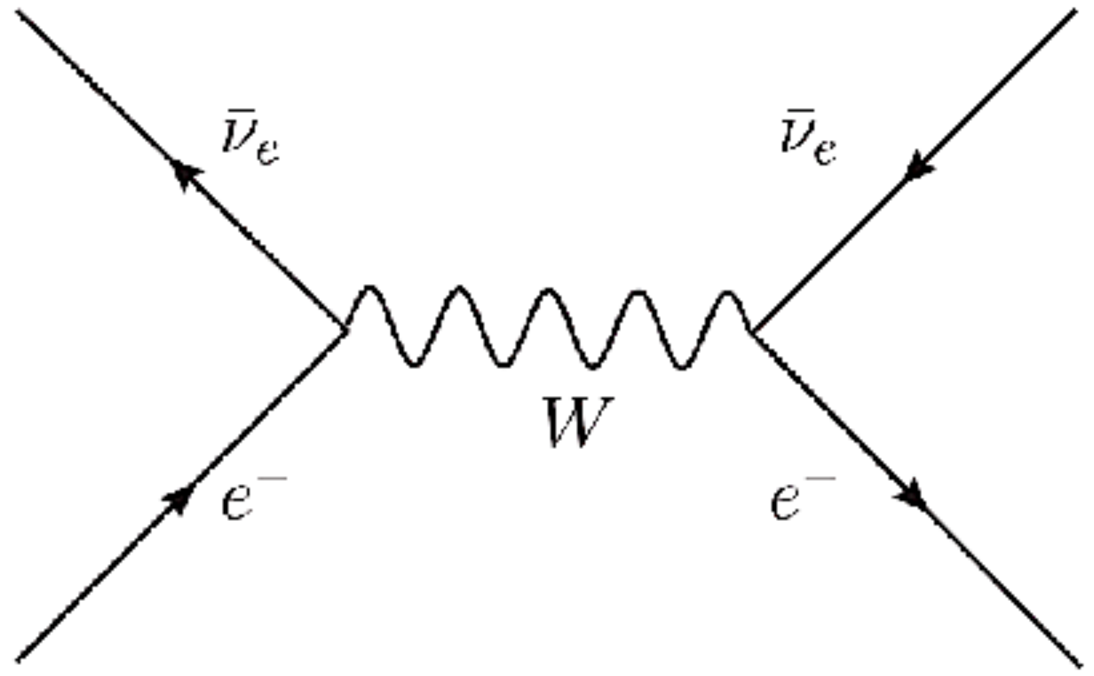
$$\mathcal{L} = -\frac{1}{4}B'^{2}_{\mu\nu} - \frac{1}{4}F''^{2}_{\mu\nu} + \frac{1}{2}\epsilon B'_{\mu\nu}F''^{\mu\nu} + \frac{1}{2}M^2_{A'}A''^{2}_{\mu} - g_Y\frac{Y}{2}B'_{\mu}\bar{f}\gamma^{\mu}f$$

$$B'_{\mu} \simeq B_{\mu} + \epsilon A'_{\mu} \qquad A''_{\mu} \simeq A'_{\mu}$$

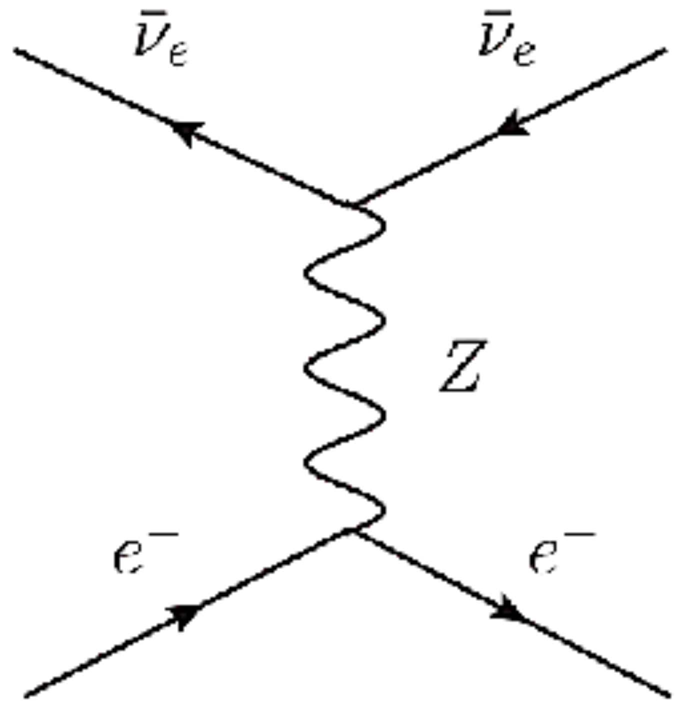
$$\mathcal{L} = -\frac{1}{4}B^{2}_{\mu\nu} - \frac{1}{4}F'^{2}_{\mu\nu} + \frac{1}{2}M^2_{A'}A'^{2}_{\mu} - g_Y\frac{Y}{2}(B_{\mu} + \epsilon A'_{\mu})\bar{f}\gamma^{\mu}f$$

Neutrino Electron Scattering

Neutrino interactions are purely leptonic processes with robust SM predictions. Hence, searching physics beyond the SM in neutrino-electron scattering turns out to be a good alternative to collider searches.



(a)

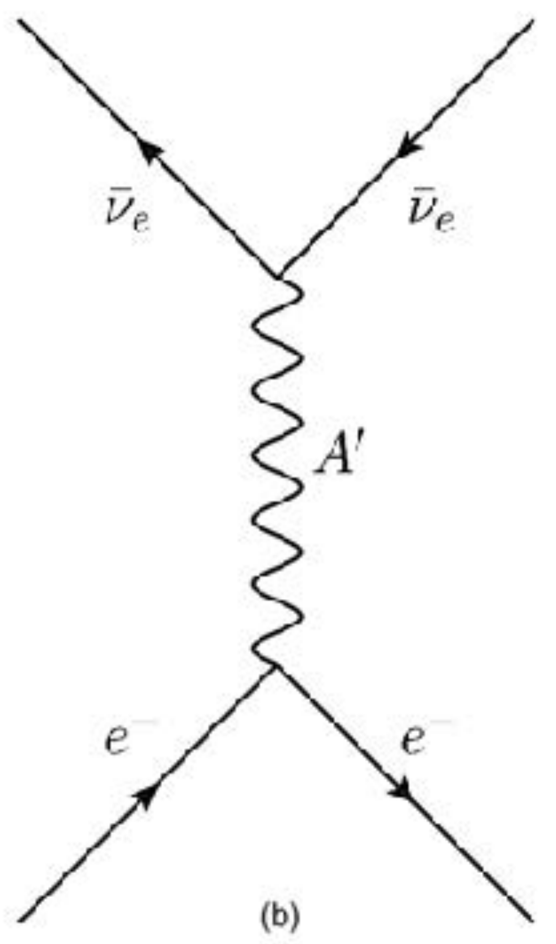


$$\left[\frac{d\sigma}{dT}(\nu e^- \to \nu e^-)\right]_{SM} = \frac{2G_F^2 m_e}{\pi E_\nu^2}\left(a^2 E_\nu^2 + b^2(E_\nu - T)^2 - ab m_e T\right)$$

Process	a	b
$\nu_e e^- \to \nu_e e^-$	$\sin^2\theta_W + \frac{1}{2}$	$\sin^2\theta_W$
$\bar{\nu}_e e^- \to \bar{\nu}_e e^-$	$\sin^2\theta_W$	$\sin^2\theta_W + \frac{1}{2}$
$\nu_\alpha e^- \to \nu_\alpha e^-$	$\sin^2\theta_W - \frac{1}{2}$	$\sin^2\theta_W$
$\bar{\nu}_\alpha e^- \to \bar{\nu}_\alpha e^-$	$\sin^2\theta_W$	$\sin^2\theta_W - \frac{1}{2}$

Cont'd

Contributions of the new light vector boson to the neutrino-electron scattering processes.



$$\left[\frac{d\sigma}{dT}(\nu e^- \to \nu e^-)\right]_{DP} = \frac{g_{B-L}^4 m_e}{4\pi E_\nu^2 (M_{A'}^2 + 2m_e T)^2}(2E_\nu^2 + T^2 - 2TE_\nu - m_e T)$$

$$\frac{d\sigma_{\rm INT}(\nu_e e^-)}{dT} = \frac{g_{B-L}^2 G_F m_e}{2\sqrt{2}\pi E_\nu^2 (M_{A'}^2 + 2m_e T)}(2E_\nu^2 - m_e T + \beta)$$

$$\frac{d\sigma_{\rm INT}(\bar{\nu}_e e^-)}{dT} = \frac{g_{B-L}^2 G_F m_e}{2\sqrt{2}\pi E_\nu^2 (M_{A'}^2 + 2m_e T)}(2E_\nu^2 + 2T^2 - T(4E_\nu + m_e) + \beta)$$

$$\frac{d\sigma_{\rm INT}(\nu_\alpha e^-)}{dT} = \frac{g_{B-L}^2 G_F m_e}{2\sqrt{2}\pi E_\nu^2 (M_{A'}^2 + 2m_e T)}(-2E_\nu^2 + m_e T + \beta)$$

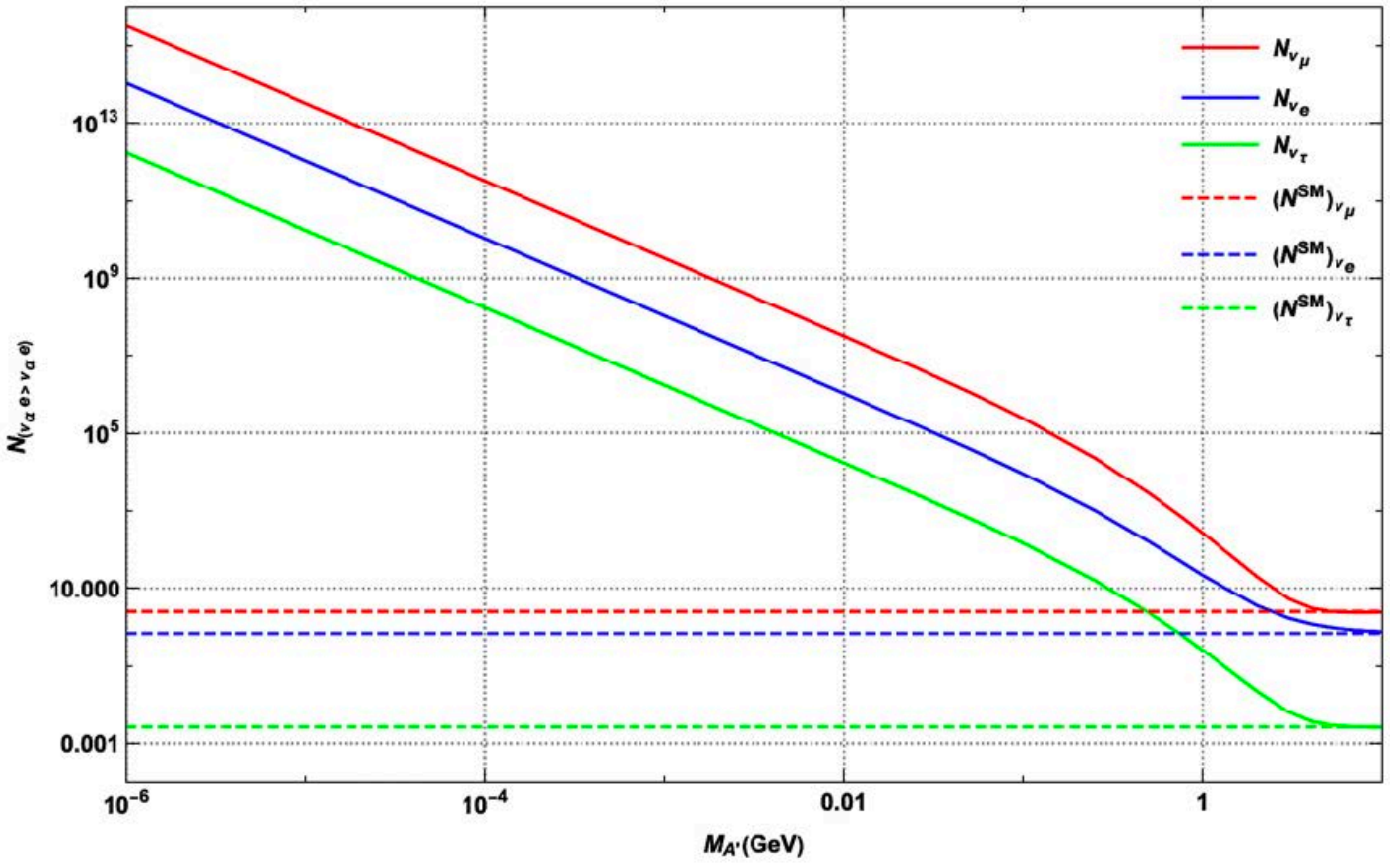
$$\frac{d\sigma_{\rm INT}(\bar{\nu}_\alpha e^-)}{dT} = \frac{g_{B-L}^2 G_F m_e}{2\sqrt{2}\pi E_\nu^2 (M_{A'}^2 + 2m_e T)}(-2E_\nu^2 - 2T^2 - T(4E_\nu + m_e) + \beta)$$

$$\beta = \sin^2\theta_w (8E_\nu^2 - 8E_\nu T - 4m_e T + 4T^2)$$

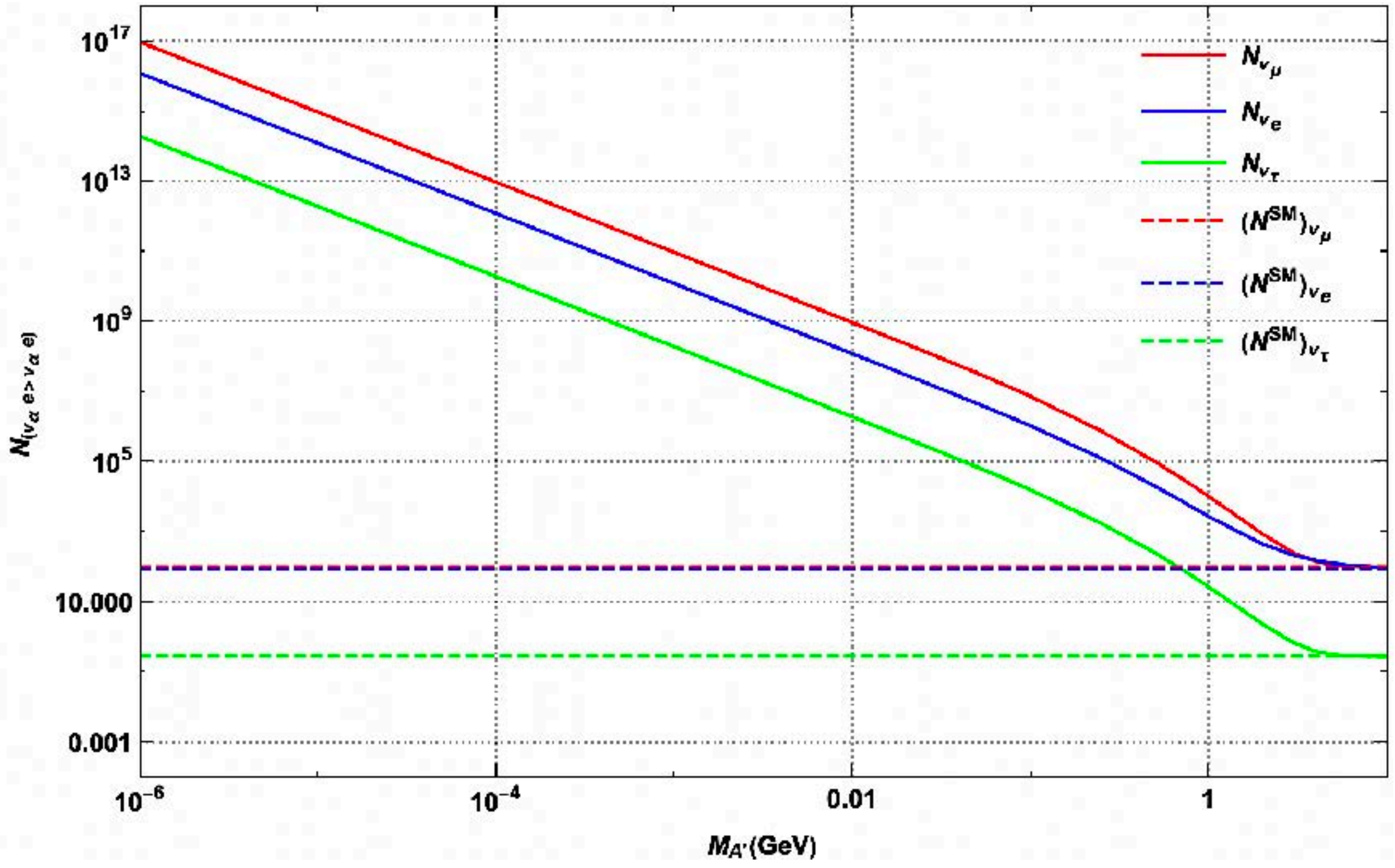
Event Rate

$$\nu_\alpha e \xrightarrow{A'} \nu_\alpha e$$

FASERν



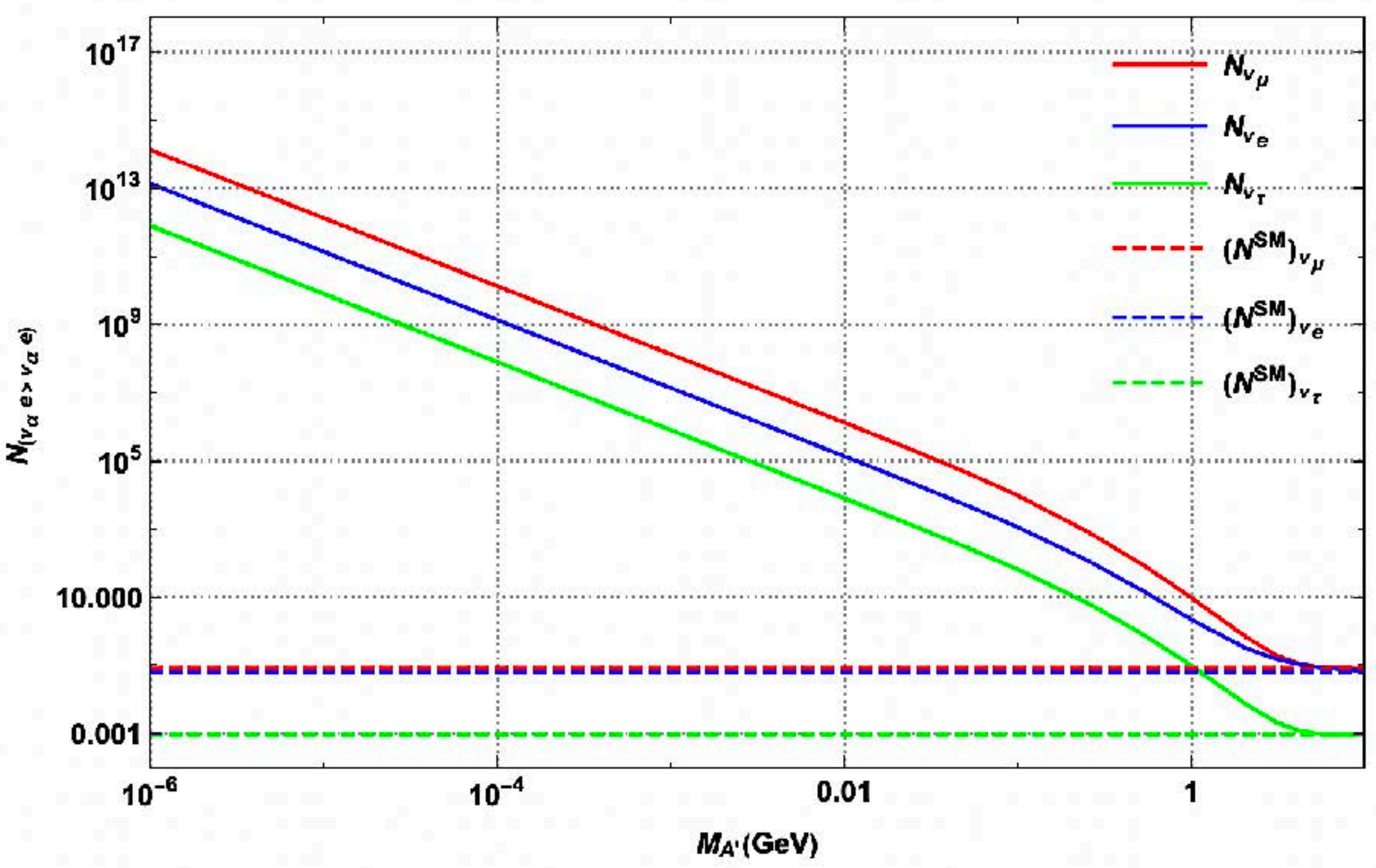
FASER$\nu 2$



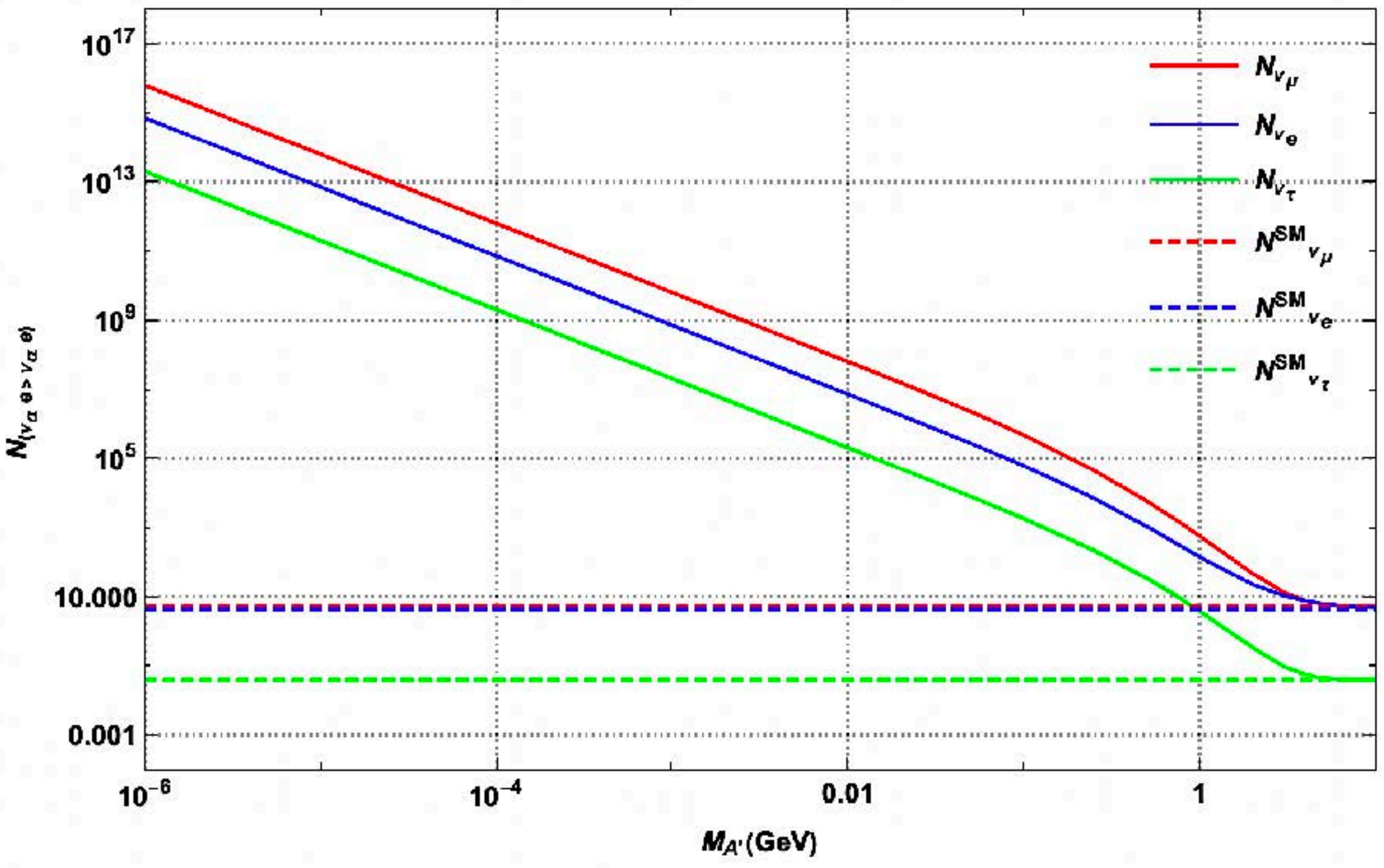
Cont'd

$$\nu_\alpha e \xrightarrow{A'} \nu_\alpha e$$

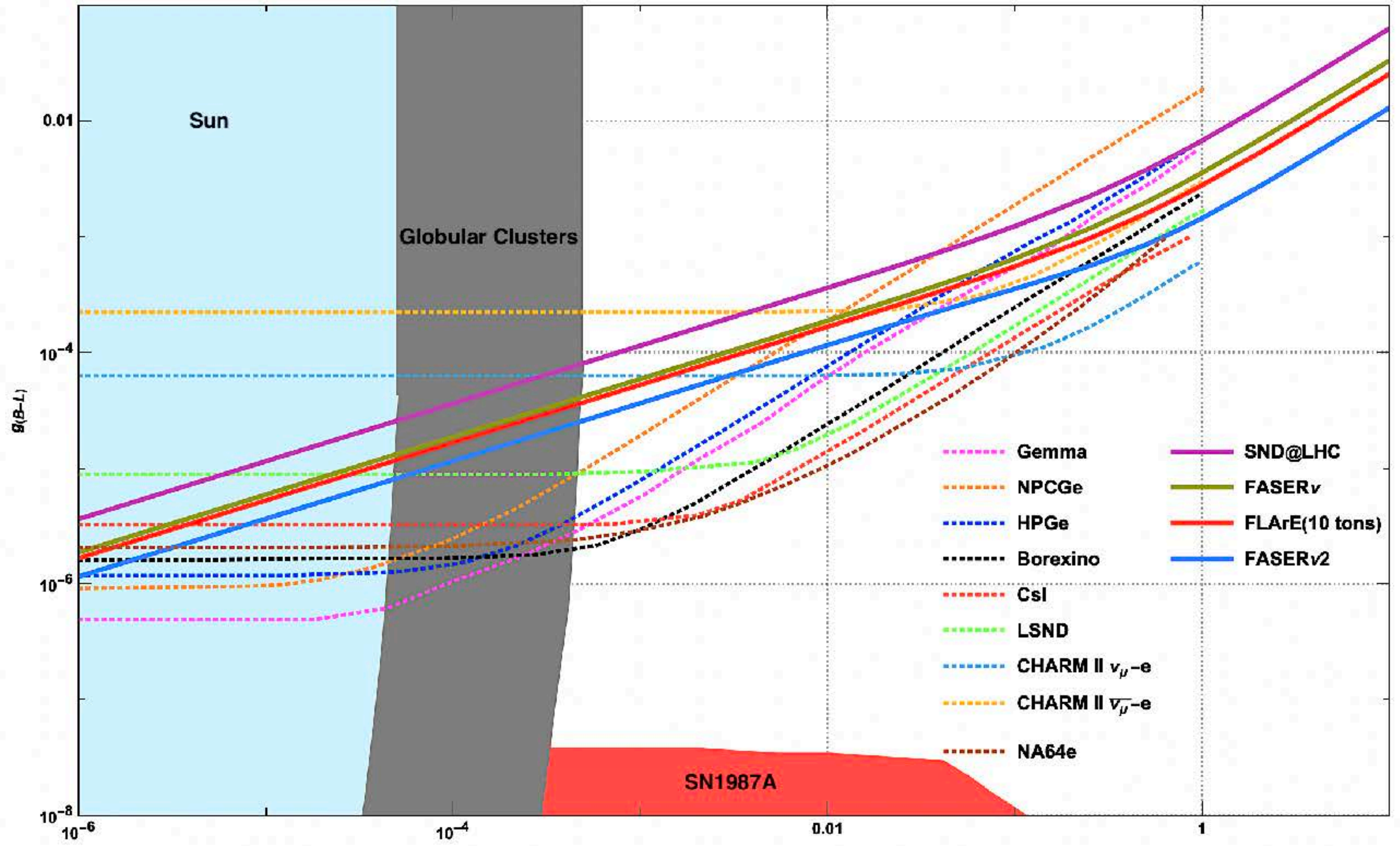
SND@LHC



FLArE(10 tons)



The sensitivity of FPF detectors to DarkPhoton



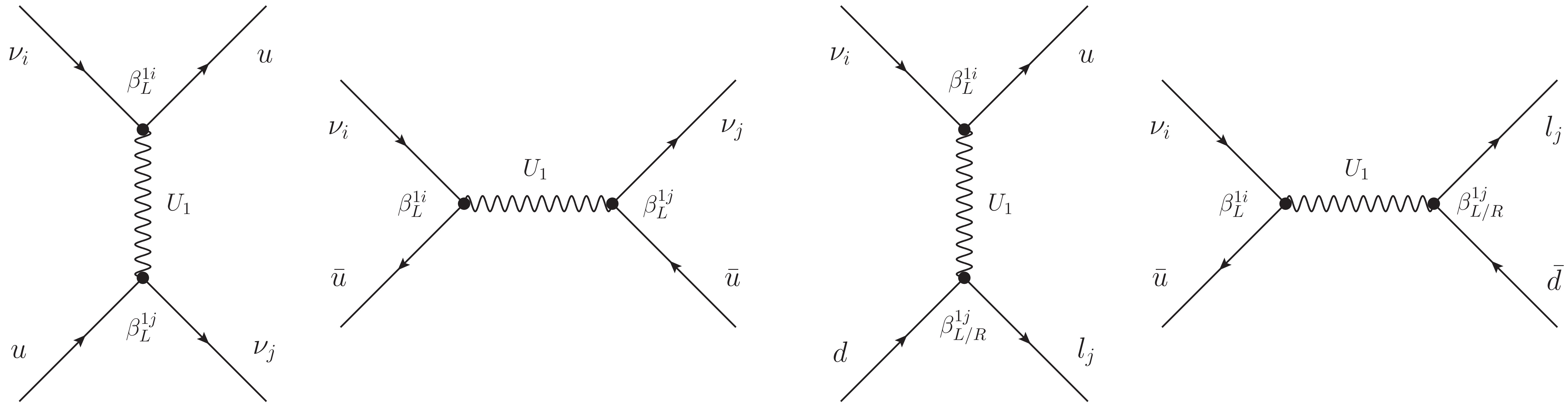
Lepto Quark Search at the Forward Physics Facility(FPF)

Kingman Cheung, C.J. Ouseph , Thong T.Q. Nguyen [In prepration]

The Vector Leptoquark Model

The Iso-singlet vector Leptoquark $\mathrm{U(1)}$, with quantum number (3, 1, 2/3)

$$\mathcal{L}_{U_1} = \frac{g_U}{\sqrt{2}}[U_1^{\mu}\,(\beta_L^{ij}\bar{q}_L^i\gamma_\mu l_L^j + \beta_R^{ij}\bar{d}_R^i\gamma_\mu l_R^j) + \text{h.c.}],$$

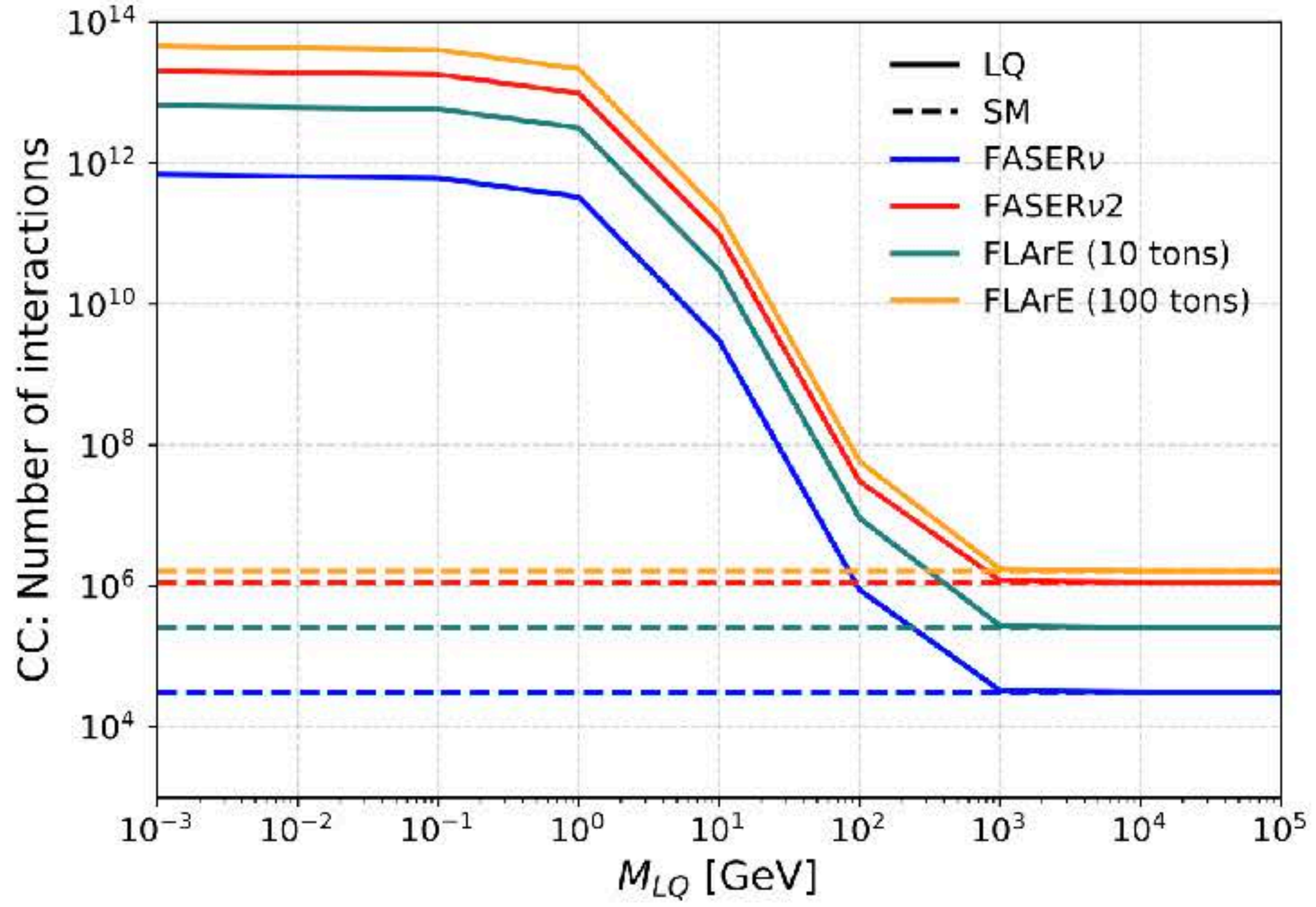


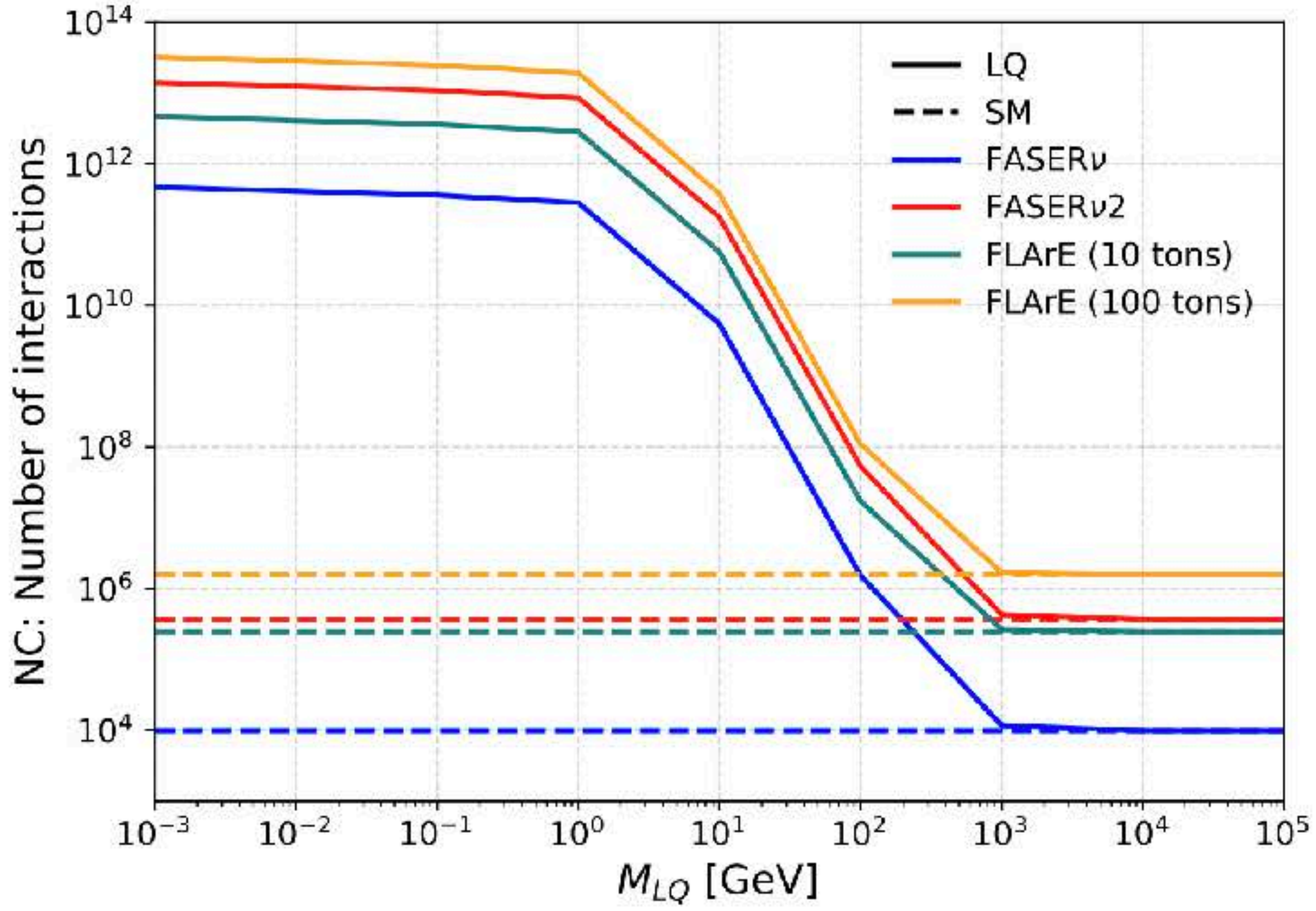
(a) Neutral Current (b) Charged Current

Leptoquark Production at the FPF

The expected number of Neutrino events at FASERν, FASERν2, FLArE(10 tons), and FLArE(100 tons) Neutrino Detectors.

LQ can Enhance both the CC and NC event rates



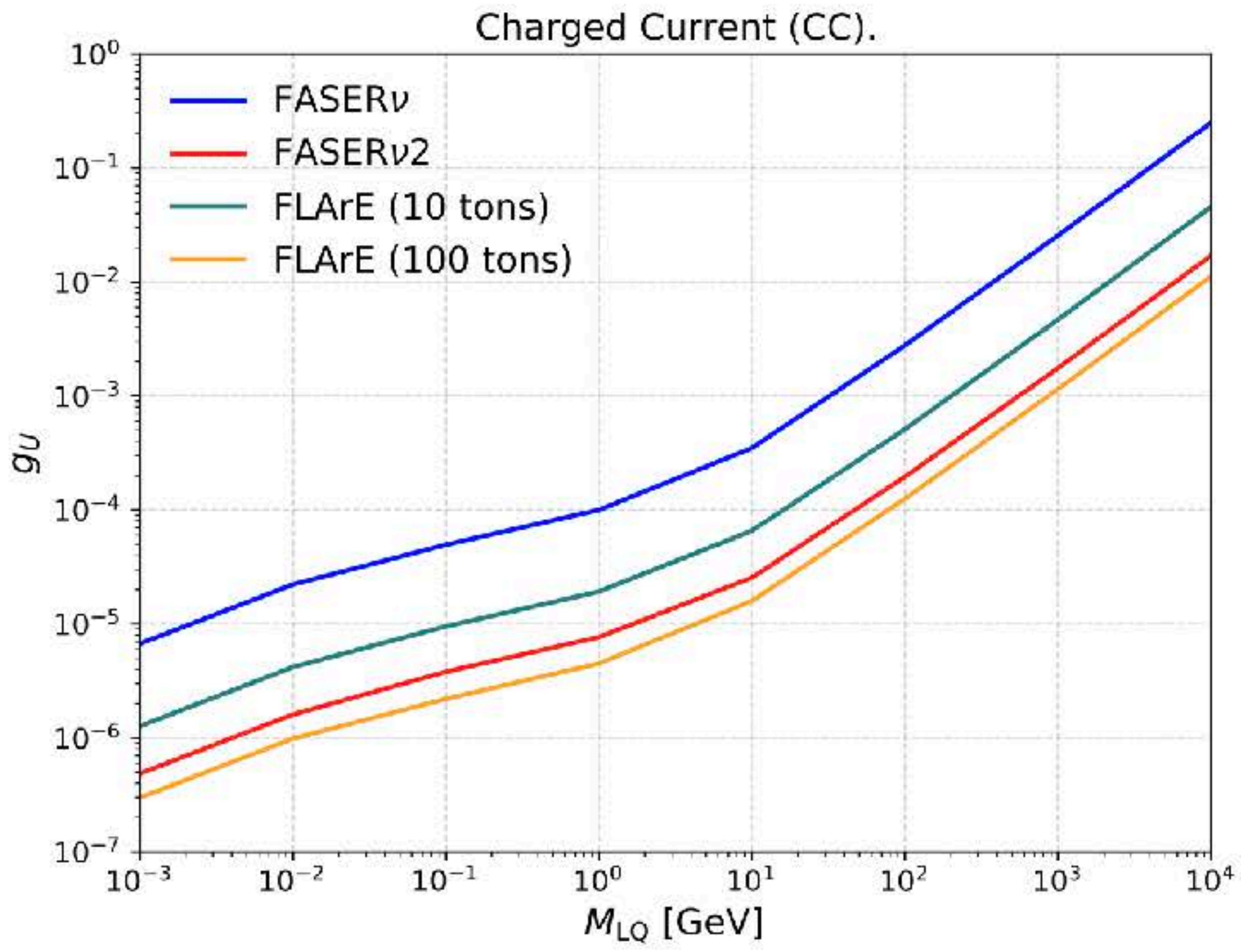


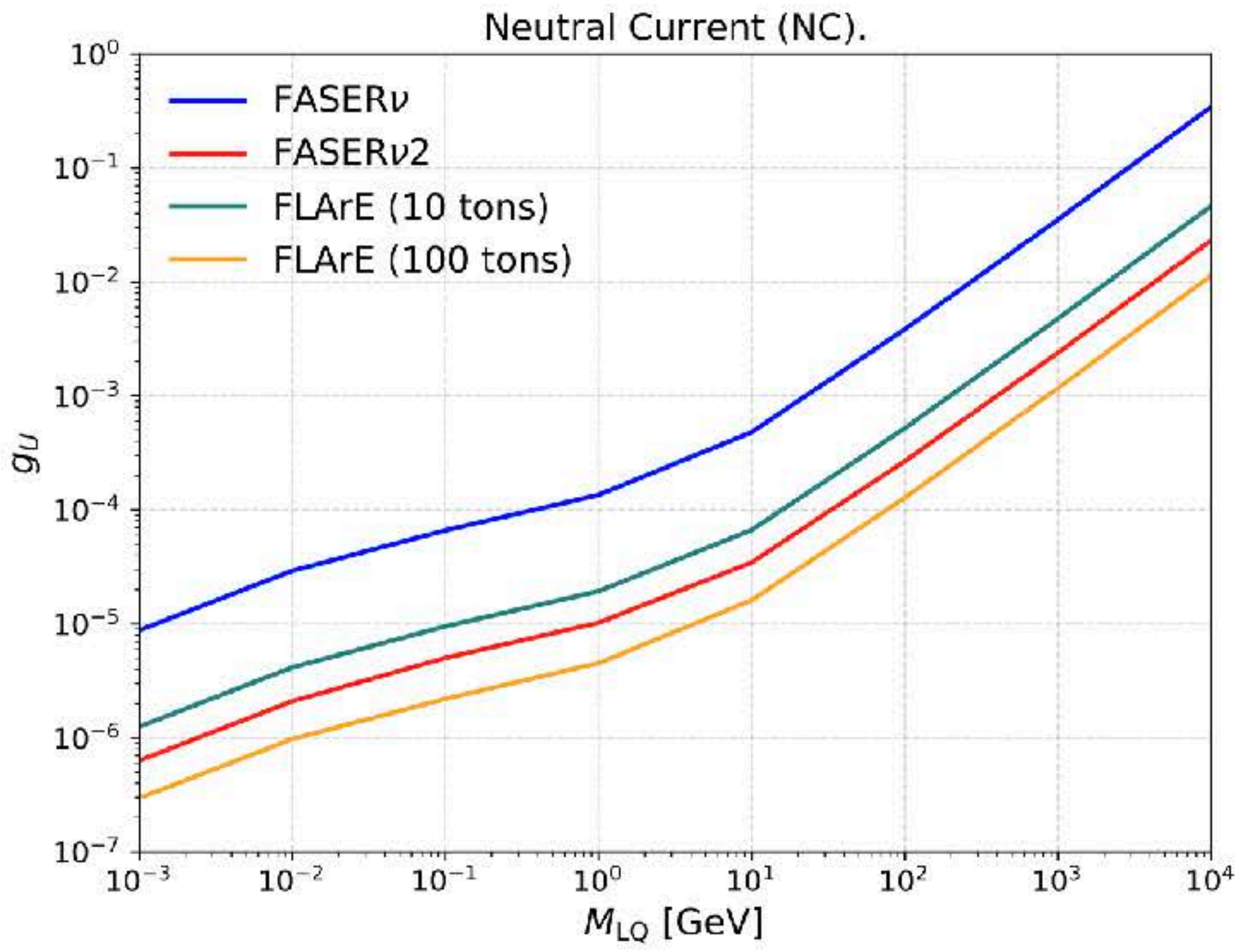
The sensitivity of FPF detectors to the vector LQ

$$L \subset \frac{g_U}{\sqrt{2}}[U_1^\mu(\beta_L^{ij}\bar{q}_L^i\gamma_\mu l_L^j + \beta^{ij}\bar{d}_R^i\gamma_\mu l_R^j) + \mathrm{h.c.}]$$

$$\nu_\alpha N \rightarrow l_\beta N'$$

$$\nu_\alpha N \rightarrow \nu_\beta N'$$



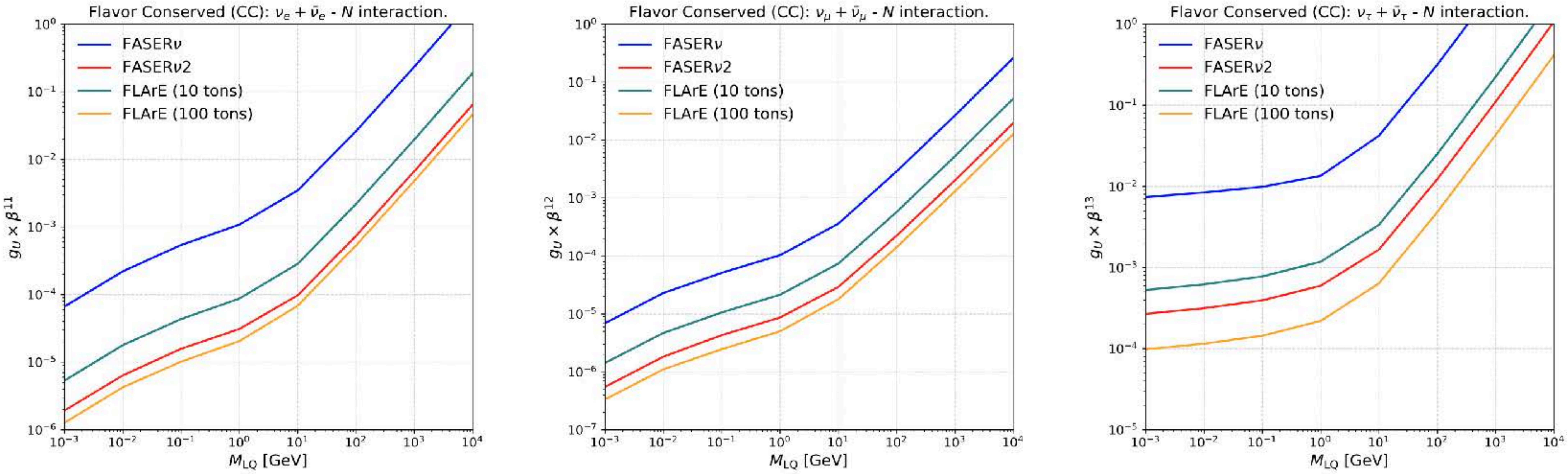


Included both Flavor conserving and Changing vertex

Sensitivity reach on the coupling to each Neutrino Flavor

$$L \subset \frac{g_U}{\sqrt{2}}[U_1^{\mu}(\beta_L^{ij}\bar{q}_L^i\gamma_\mu l_L^j + \beta^{ij}\bar{d}_R^i\gamma_\mu l_R^j) + \mathrm{h.c.}]$$

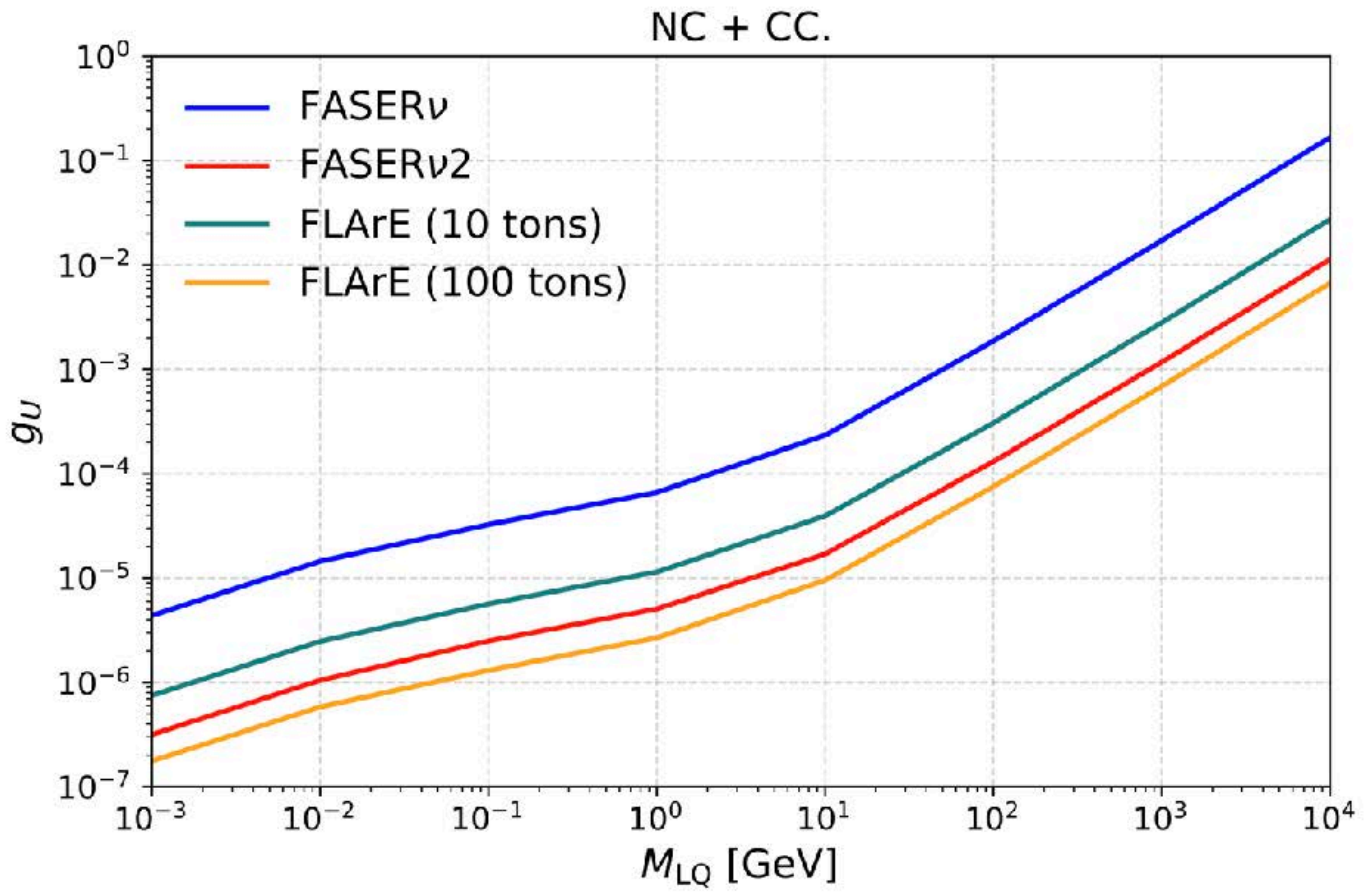
$$\nu_\alpha N \quad \rightarrow \quad l_\alpha N'$$



The sensitivity curves for overall coupling

$$L \subset \frac{g_U}{\sqrt{2}}[U_1^\mu(\beta_L^{ij}\bar{q}_L^i\gamma_\mu l_L^j + \beta^{ij}\bar{d}_R^i\gamma_\mu l_R^j) + \mathrm{h.c.}]$$

We compute the number of events for both CC and NC in the SM w/o the leptoquark. The sensitivity curves for overall coupling are improved

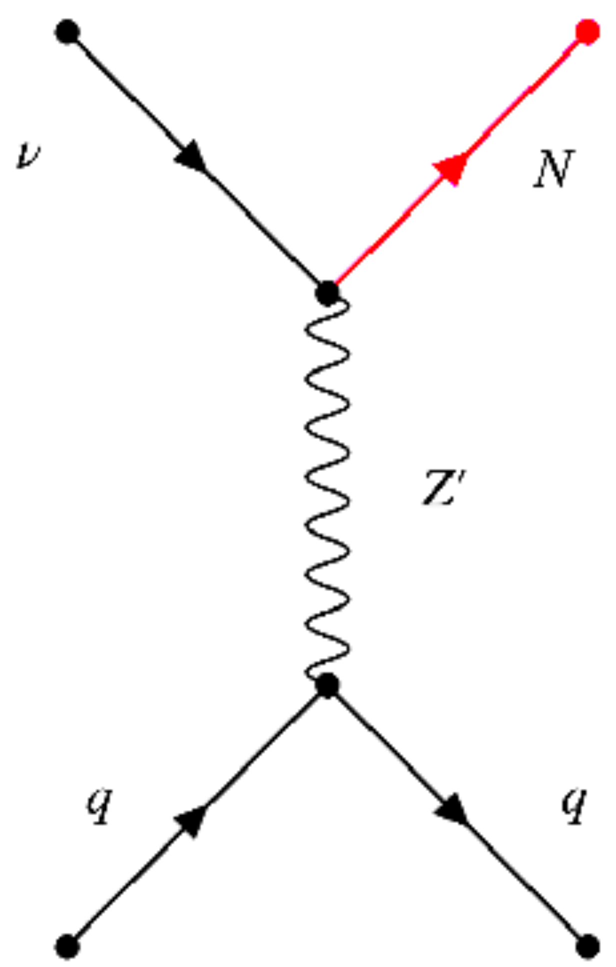


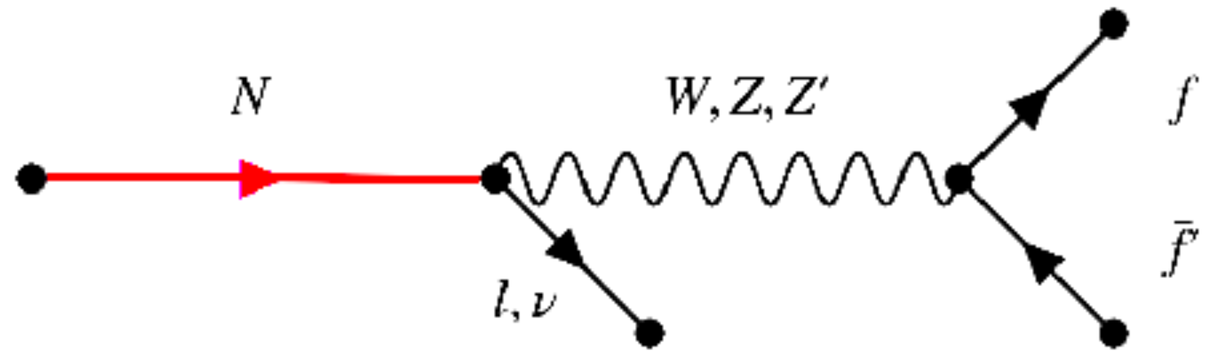
Constraining the Active-to-Heavy-Neutrino Z′ transitional magnetic dipole moment at FASERν

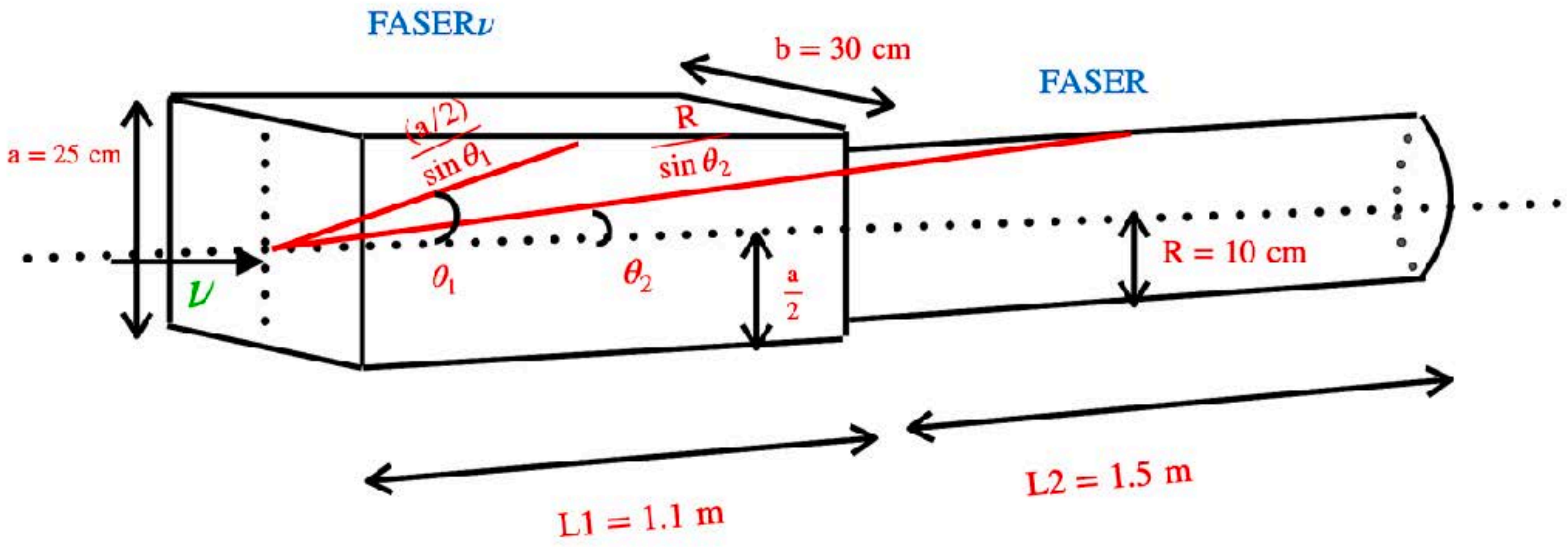
arXiv:2205.11077 (K. Cheung, C. J. Ouseph)

Active-to-Heavy Neutrino Z′ Transitional Magnetic Moment Interactions

$$\mathscr{L}_{\text{eff}} = \sum_{\alpha=e,\mu,\tau}\left[\omega_{\nu_\alpha}\overline{N}\sigma^{\mu\nu}\nu_\alpha Z'_{\mu\nu} - \frac{g}{\sqrt{2}}V_{\alpha N}\overline{N}\gamma^\mu P_L l_\alpha W^+_\mu - \frac{g}{c_W}V_{\alpha N}\overline{N}\gamma^\mu P_L \nu_\alpha Z_\mu + \text{H.c.}\right] - \sum_{q,\nu,l}\left[g_q\bar{q}\gamma^\mu q + g_\nu\bar{\nu}\gamma^\mu P_L\nu + g_l\bar{l}\gamma^\mu l\right]Z'_\mu$$







arXiv:2205.11077

Recasting transtional Magnetic moment μ_{ν_α} to transtional Magnetic type moment ω_{ν_α}

The bound of μ_{ν_α} comes from NOMAD and LEP, $\mu_{\nu_e}, \mu_{\nu_\tau} \leq 1.5 \times 10^{-7} \mu_B$**,** $\mu_{\nu_\mu} \leq 5 \times 10^{-9} - 1.4 \times 10^{-7} \mu_B$**, for** $\mathrm{M_N} = 1 - 10\ \mathrm{GeV}$, **where** μ_B **is theBohr magneton.**

$$\omega_{\nu_\alpha} \simeq \frac{(1\,\mathrm{GeV})^2 + M_{Z'}^2}{(1\,\mathrm{GeV})^2} \times \mu_{\nu_\alpha}$$

$$\omega_{\nu_\alpha} \overline{N} \sigma^{\mu\nu} \nu Z'_{\mu\nu} \longrightarrow \mu_{\nu_\alpha} \overline{N} \sigma^{\mu\nu} \nu F_{\mu\nu}$$

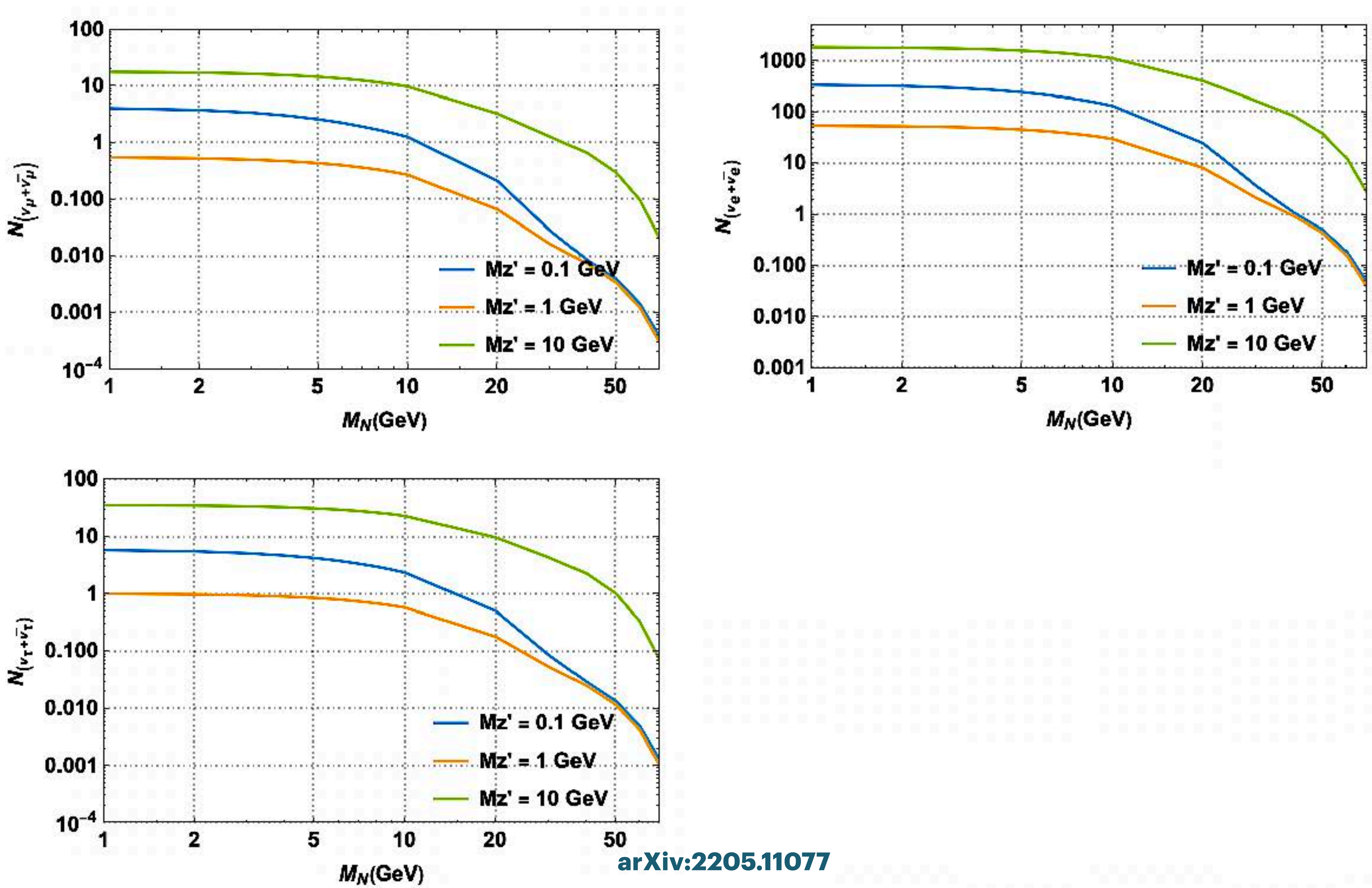
we assume the square of momentum transfer in the photon propagator is about (1GeV)^2.

$M_{Z'}$(GeV)	ω_{ν_μ}	ω_{ν_e}	ω_{ν_τ}
0.1	$4.10 \times 10^{-9} \mu_B$	$1.39 \times 10^{-7} \mu_B$	$1.39 \times 10^{-7} \mu_B$
1	$8.12 \times 10^{-9} \mu_B$	$2.76 \times 10^{-7} \mu_B$	$2.76 \times 10^{-7} \mu_B$
10	$4.10 \times 10^{-7} \mu_B$	$1.39 \times 10^{-5} \mu_B$	$1.39 \times 10^{-5} \mu_B$

arXiv:2205.11077

Heavy Neutrino events at FASERν

$$\nu_\alpha A \to N A'$$

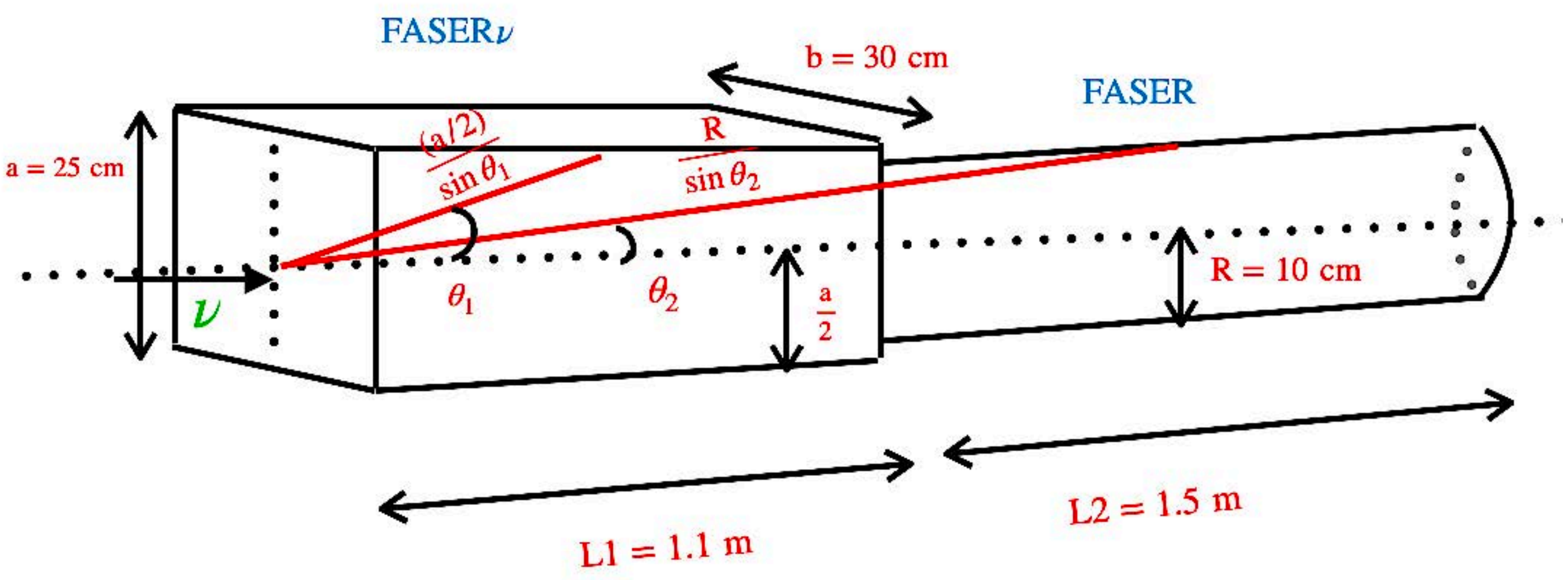


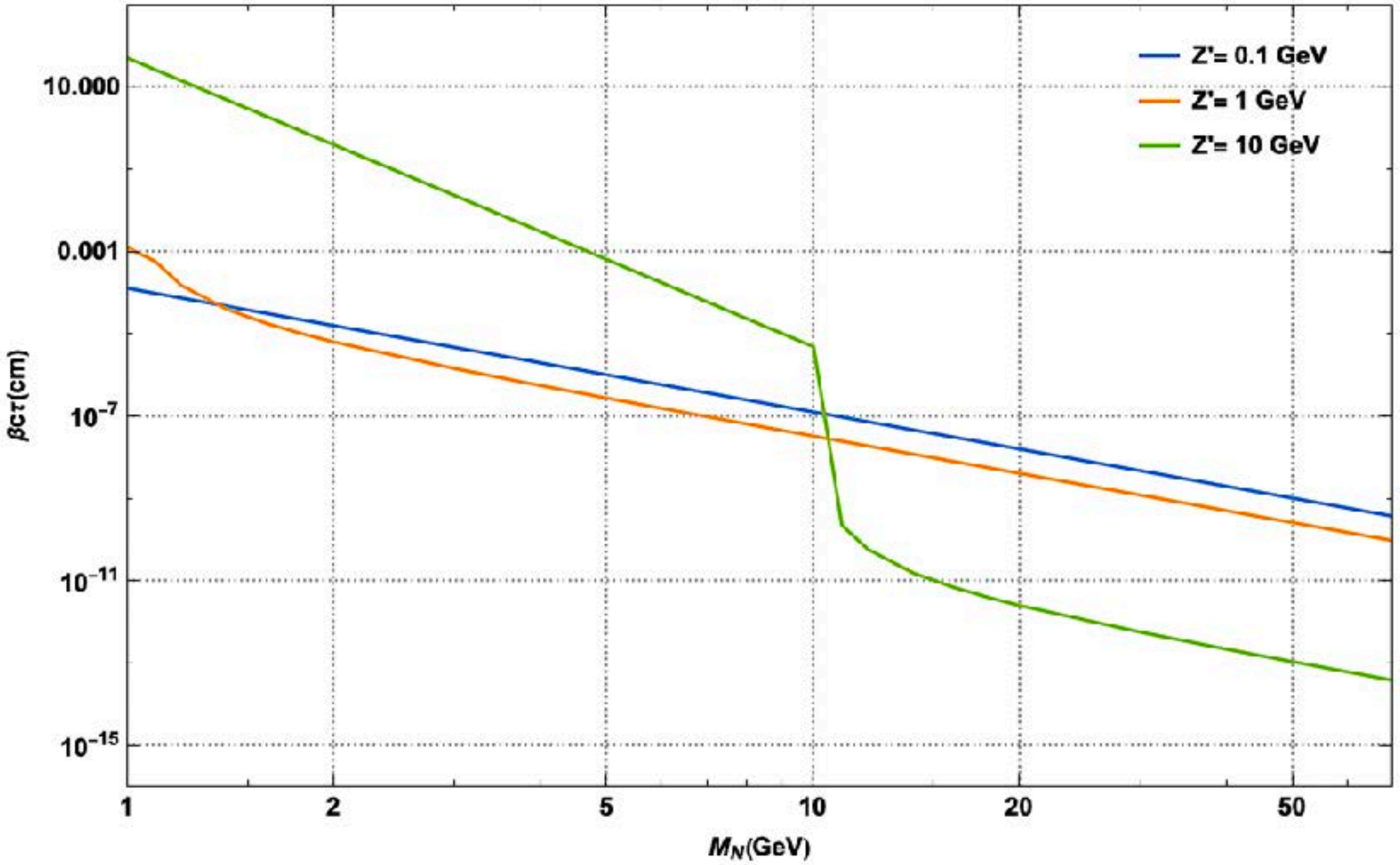
arXiv:2205.11077

FASERν Sensitivity towards Transition Magnetic Moment Type Interactions

$$N_\alpha^{\rm detc} = N_\alpha^{\rm Prod}(\nu_\alpha A \rightarrow NA') \times \mathscr{P}_{detc} \times {\rm BR}(N \rightarrow \nu_\alpha\ l+\ \ l-)$$

$$\mathscr{P}_{\rm detc} = 1 - \exp(\frac{-d}{\beta c \tau}) \quad d = L1 + L2$$

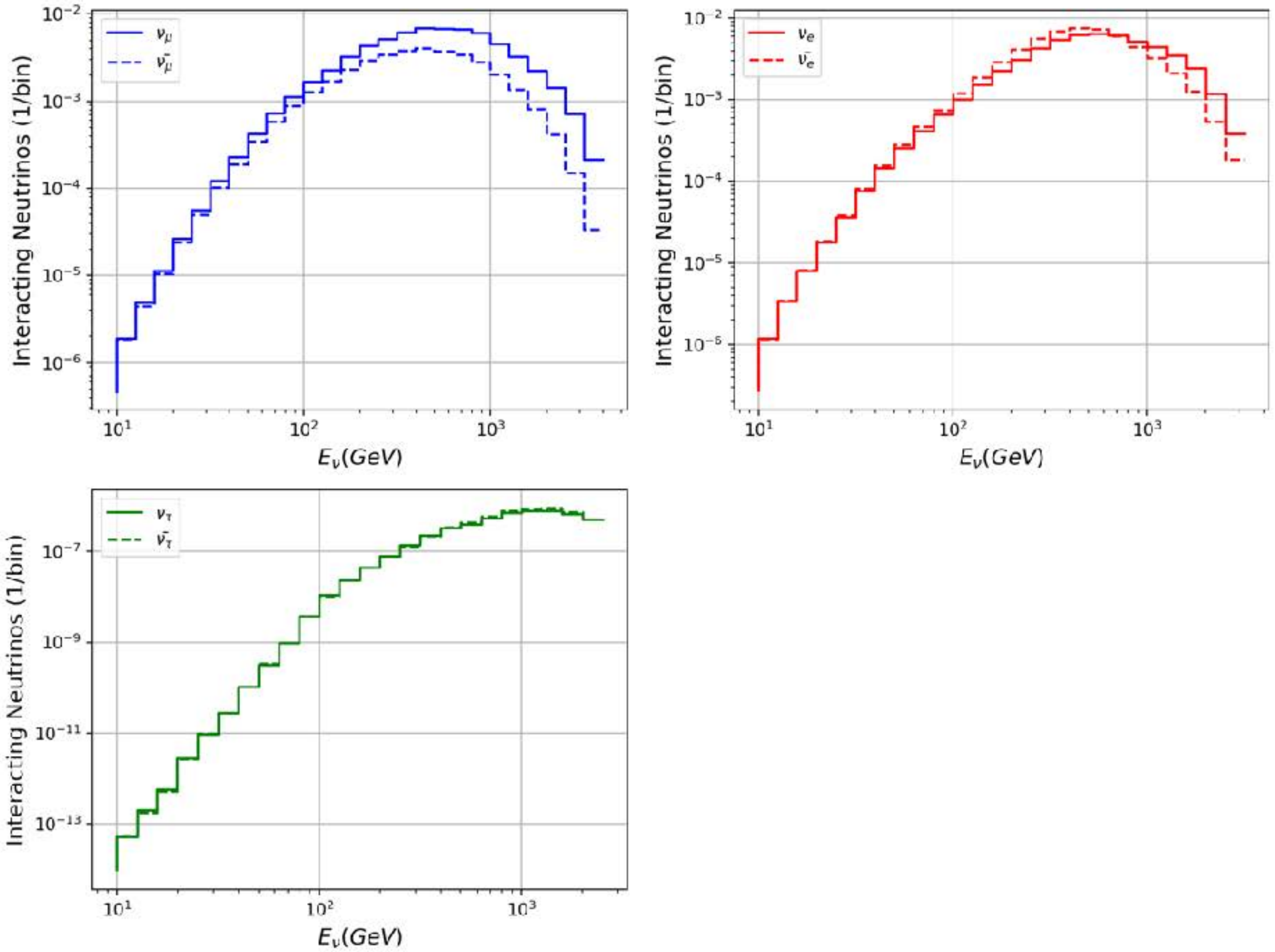




arXiv:2205.11077

Background Study

Background for the decay of N into a pair of charged leptons. Such a final state in the SM can be produced by the process $\nu q \to \nu \mu^+ \mu^- q$, which is similar to the trident production in literature



It is essentially background free. Besides this trident background, there are also other reducible background

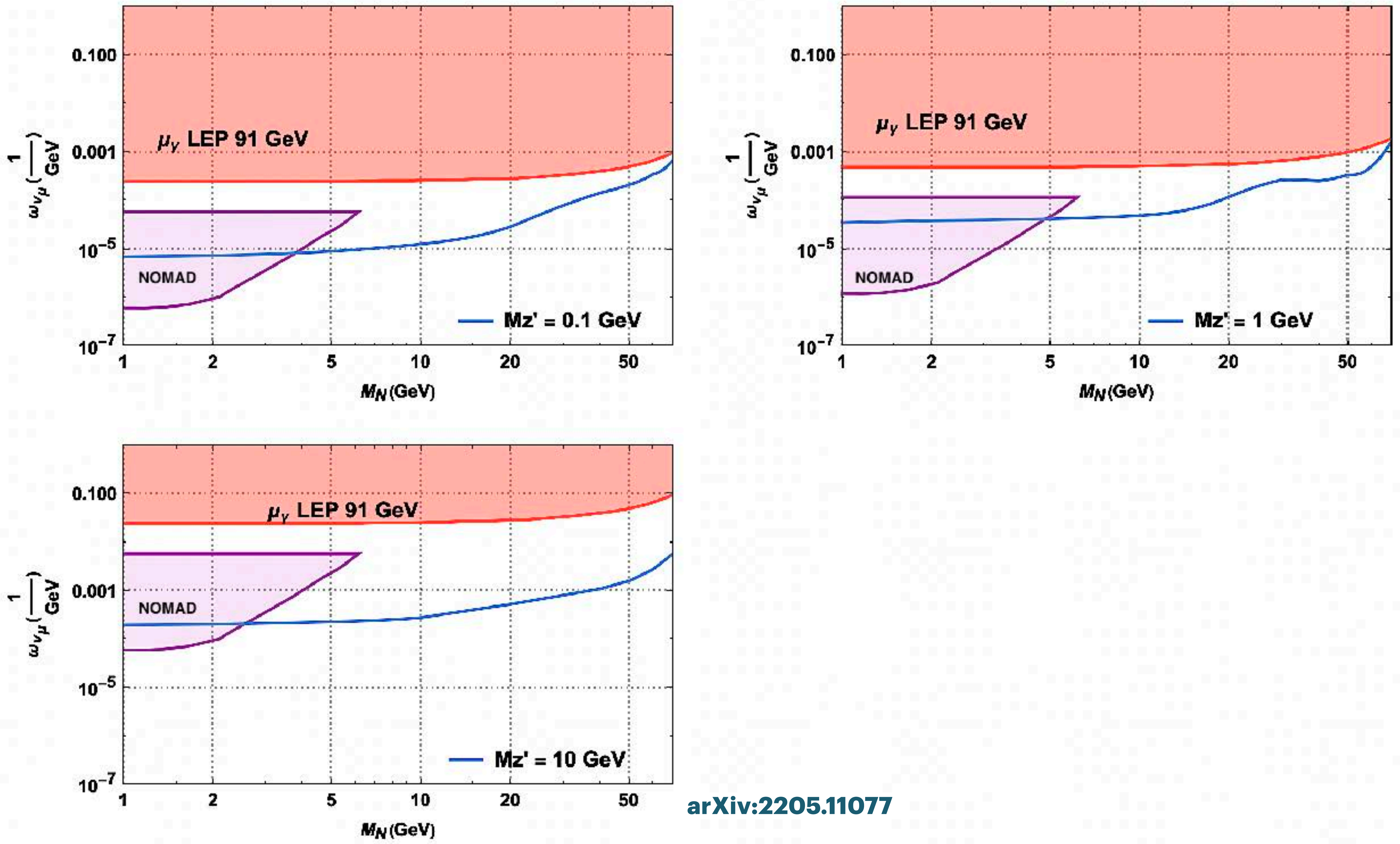
1) **Charged Leptone from ATLAS IP or From Hadron**
2) **Single lepton Production**

$\nu e^- \to \nu e^-$

$\nu N \to l N'$

Bench Mark Model 1

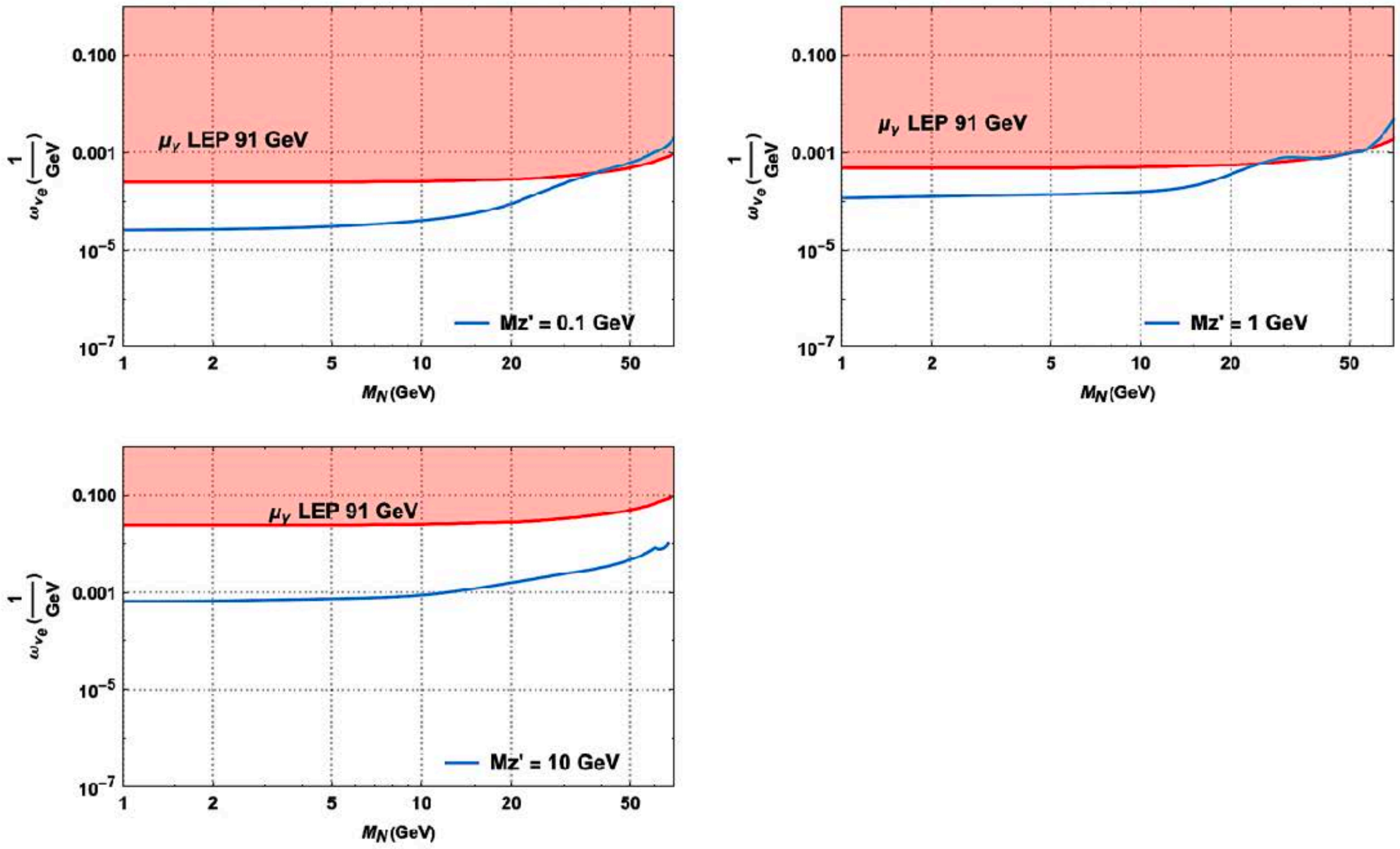
Heavy Neutrino Only coupled to L_μ Doublet



arXiv:2205.11077

Bench Mark Model 2

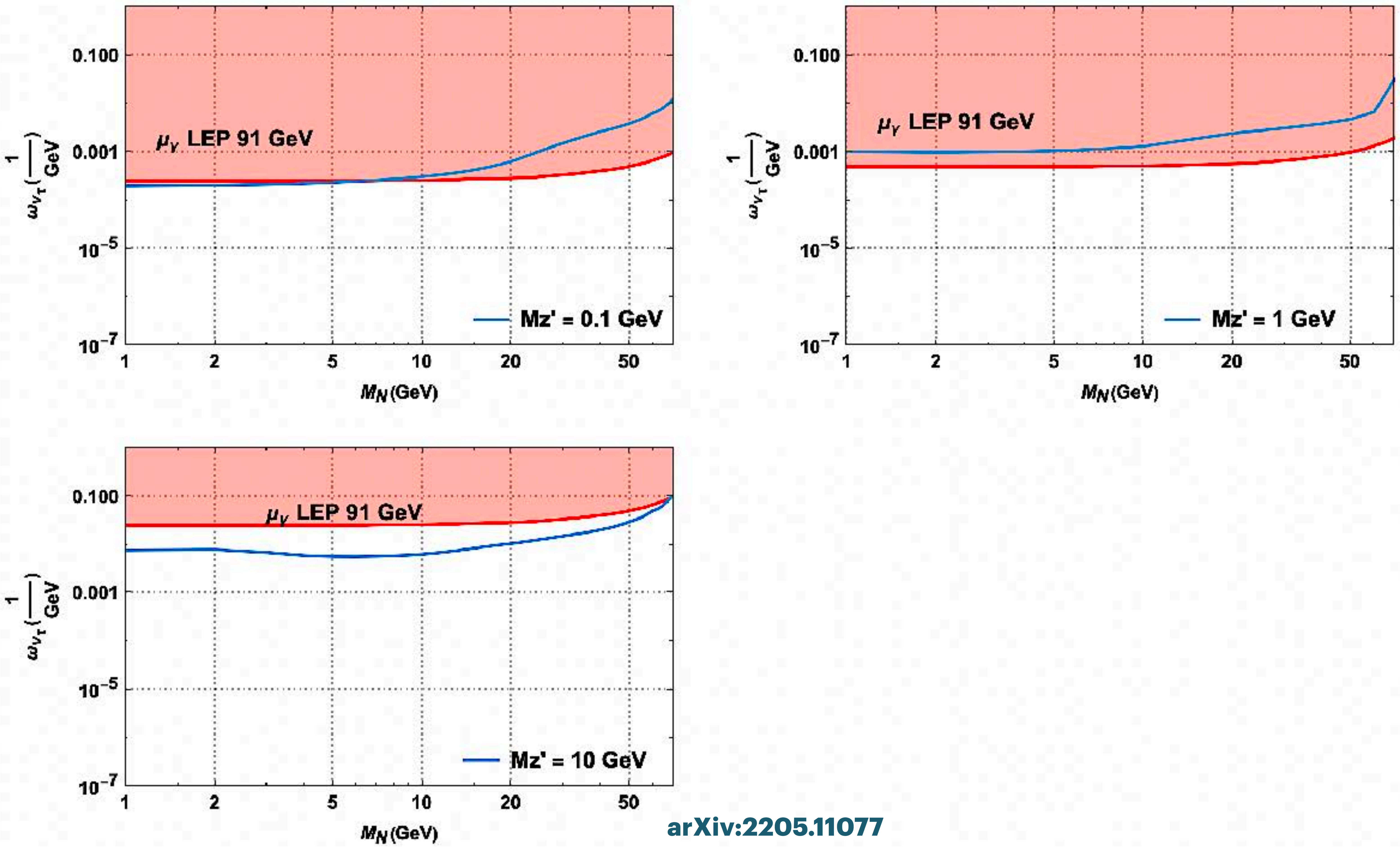
Heavy Neutrino Only coupled to L_e Doublet



arXiv:2205.11077

Bench Mark Model 3

Heavy Neutrino Only coupled to L_τ Doublet



arXiv:2205.11077

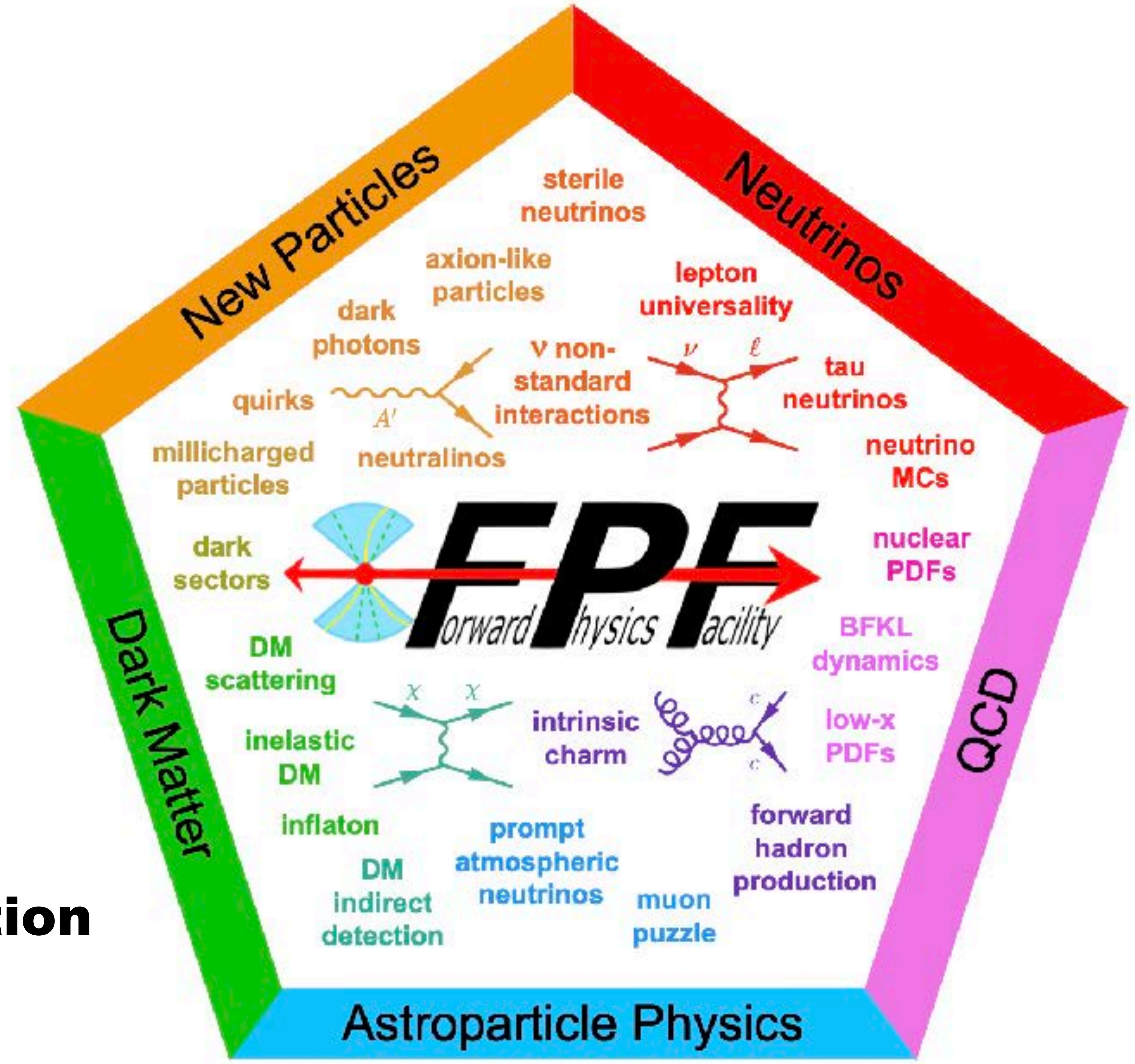
Summary

We Explore the discovery potential of FASERν for the new physics Interactions

Physics abounds in the forward region of the LHC. Many detectors have been proposed in the forward region, such as FASER2, FASERv2, AdVSND@LHC, FLArE(10 tons, 100 tons), and FORMOSA. Our goal is to study different NP interactions using these proposed detectors.

FASERν and SND@LHC just started to take data in LHC's forward direction

The FPF is proposed to continue this program during the HL LHC era



Source: arXiv:2109.10905v1