中微子散射及其新物理

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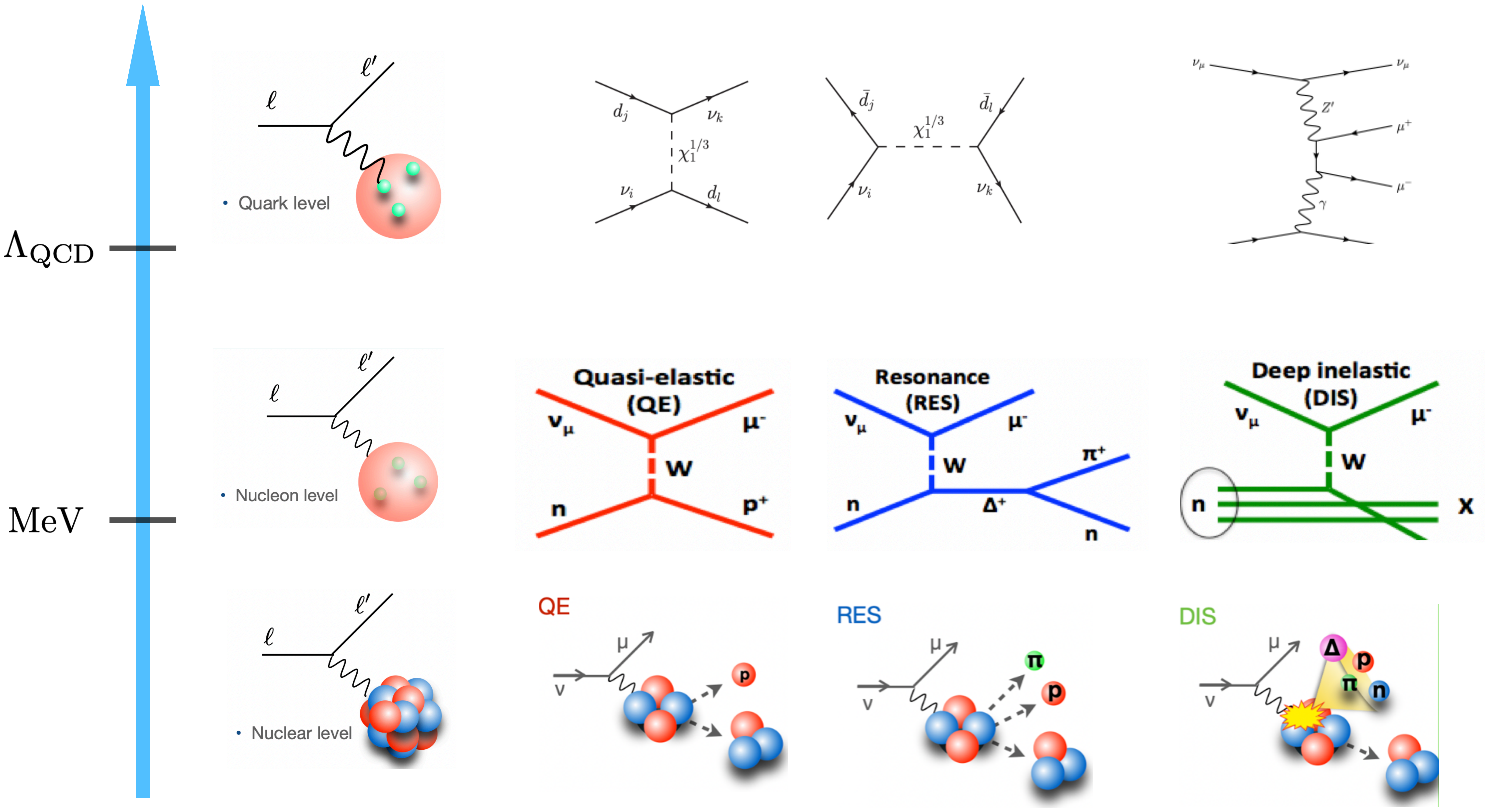
Outline

- Overview of New Physics in Neutrino Scattering
- Search for New Physics at Neutrino Experiment
- Search for New Physics at NA64μ

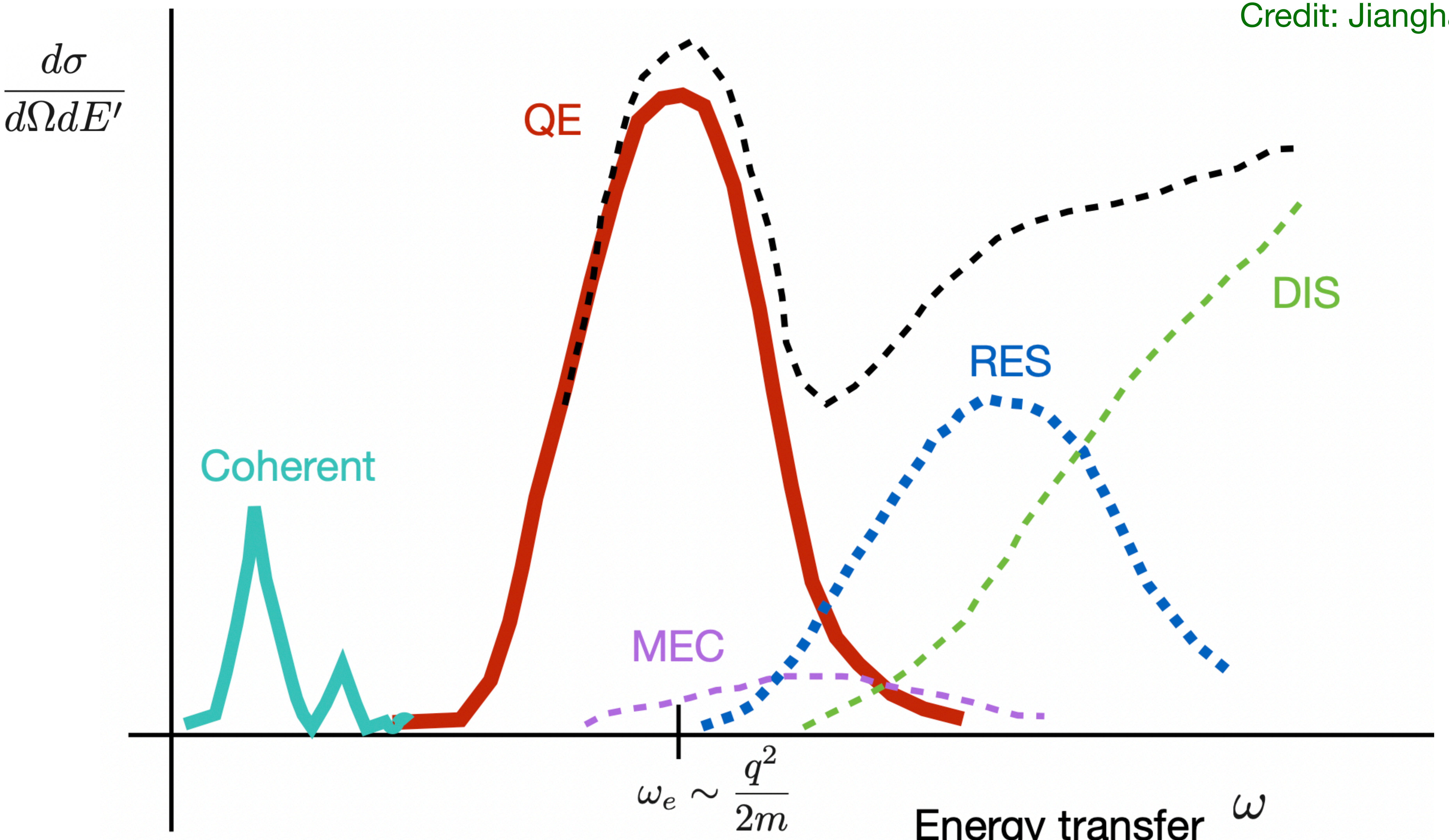
Neutrino Scattering: Charged Current and Neutral Current

Credit: Jianghao Yu et al

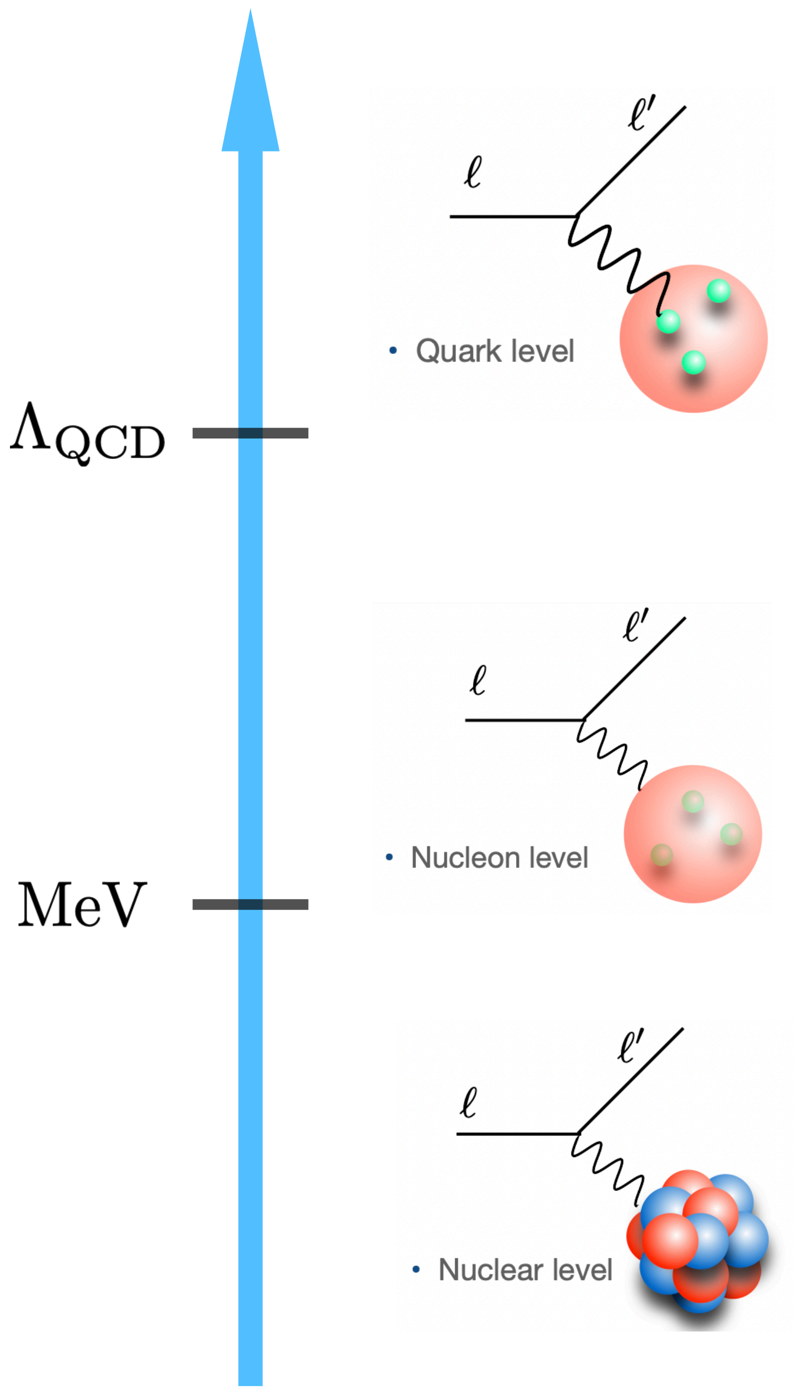


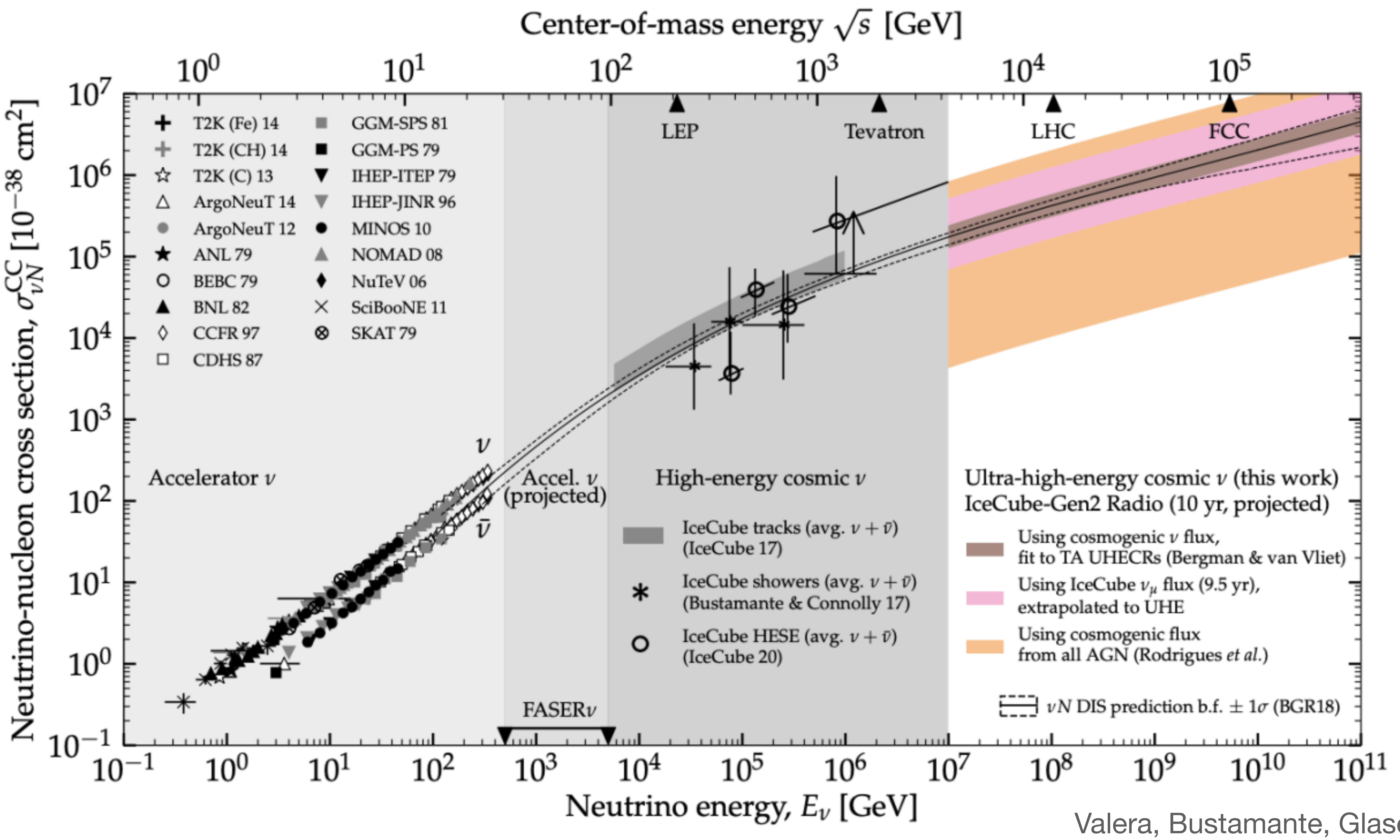
Neutrino Scattering: Charged Current and Neutral Current

Credit: Jianghao Yu et al

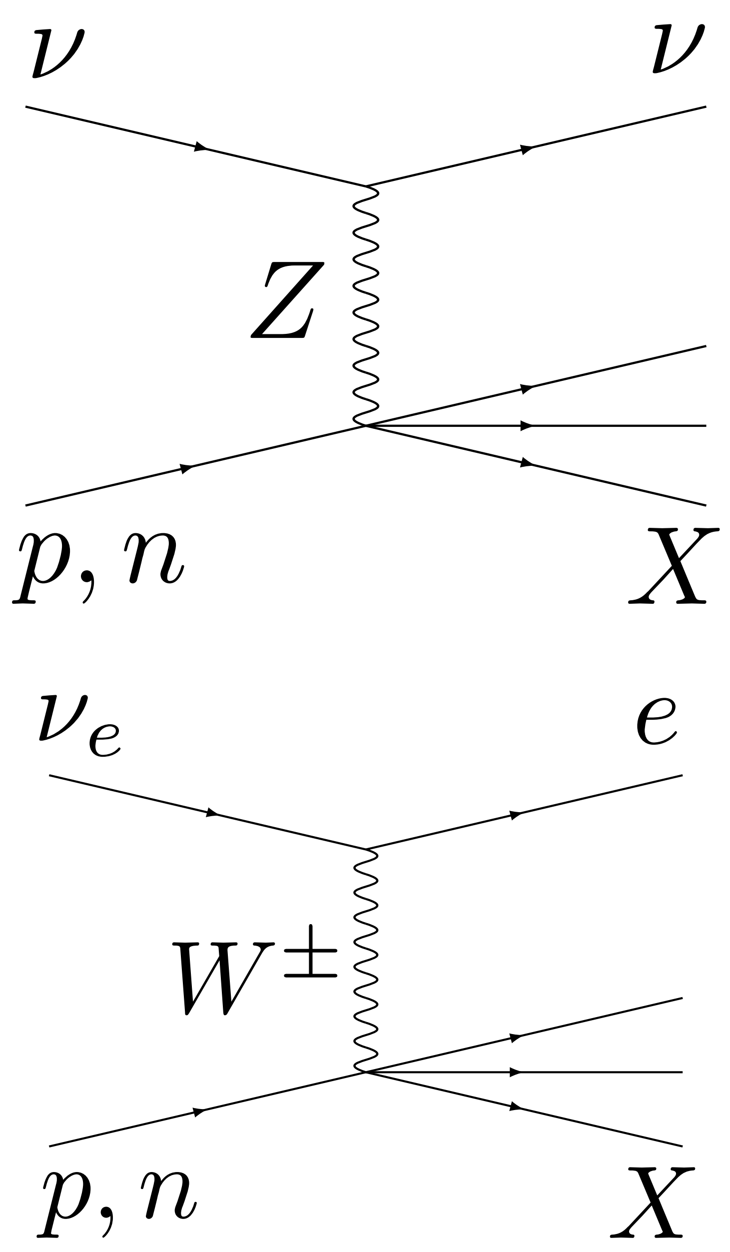


Neutrino Scattering: Charged Current and Neutral Current





Valera, Bustamante, Glaser, JHEP/2204.04237



$$\frac{d^2\sigma(\nu(\bar{\nu})N)}{dx dQ^2} = \frac{G_F^2 M_W^4}{4\pi\left(Q^2 + M_W^2\right)^2 x}\sigma_r(\nu(\bar{\nu})N)$$

Non-standard Interactions and Neutrino Oscillation

Forward elastic scattering in the limit of zero momentum transfer

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon_{\alpha\beta}^{f,P} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)\,,$$

U(1) realization

$$\mathcal{L}_{Z'}^{\rm matter} = -g'\big(a_u\,\bar{u}\gamma^\alpha u + a_d\,\bar{d}\gamma^\alpha d + a_e\,\bar{e}\gamma^\alpha e + b_e\,\bar{\nu}_e\gamma^\alpha P_L\nu_e + b_\mu\,\bar{\nu}_\mu\gamma^\alpha P_L\nu_\mu + b_\tau\,\bar{\nu}_\tau\gamma^\alpha P_L\nu_\tau\big) Z'_\alpha$$

Model	a_u	a_d	a_e	b_e	b_μ	b_τ
$B - 3L_e$	$\frac{1}{3}$	$\frac{1}{3}$	-3	-3	0	0
$B - 3L_\mu$	$\frac{1}{3}$	$\frac{1}{3}$	0	0	-3	0
$B - 3L_\tau$	$\frac{1}{3}$	$\frac{1}{3}$	0	0	0	-3
$B - \frac{3}{2}(L_\mu + L_\tau)$	$\frac{1}{3}$	$\frac{1}{3}$	0	0	$-\frac{3}{2}$	$-\frac{3}{2}$
$L_e - L_\mu$	0	0	1	1	-1	0
$L_e - L_\tau$	0	0	1	1	0	-1
$L_e - \frac{1}{2}(L_\mu + L_\tau)$	0	0	1	1	$-\frac{1}{2}$	$-\frac{1}{2}$
$B_y + L_\mu + L_\tau$ Ref. [22]	$\frac{1}{3}$	$\frac{1}{3}$	0	0	1	1
$L_e + 2L_\mu + 2L_\tau$	0	0	1	1	2	2

$$H_{\rm mat} = \sqrt{2}G_F N_e(\vec{x}) \begin{pmatrix} 1+\mathcal{E}_{ee}(\vec{x}) & 0 & 0 \\ 0 & \mathcal{E}_{\mu\mu}(\vec{x}) & 0 \\ 0 & 0 & \mathcal{E}_{\tau\tau}(\vec{x}) \end{pmatrix}$$

Matter effect: change the neutrino flavour at detection

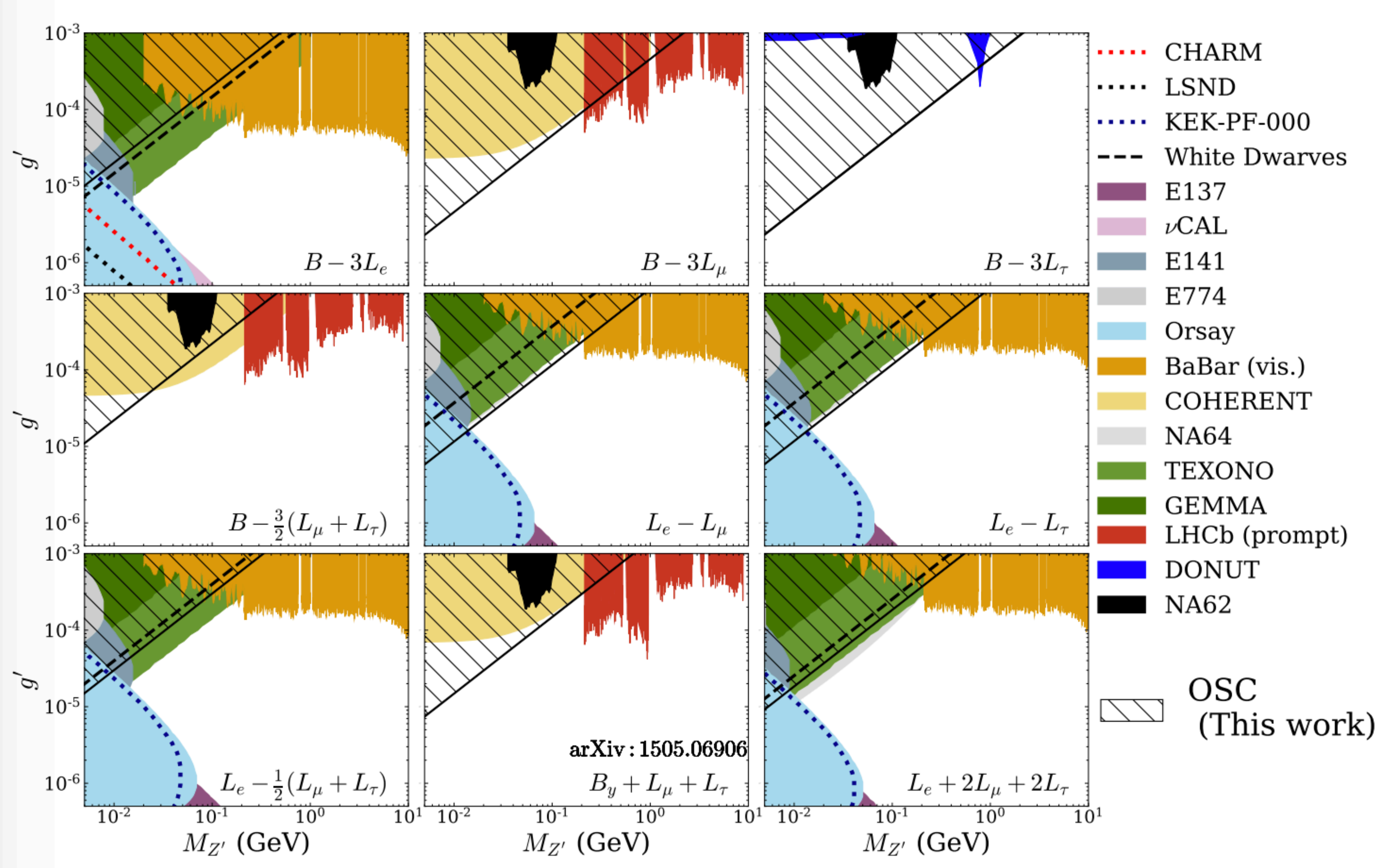
Coloma, Gonalez-Garcia, Maltoni, JHEP/2009.14220

Non-standard Interactions and Neutrino Oscillation

Coloma, Gonalez-Garcia, Maltoni, JHEP/2009.14220

U(1) realization

$$\mathcal{L}_{Z'}^{\text{matter}} = -g'\big(a_u\,\bar{u}\gamma^\alpha u + a_d\,\bar{d}\gamma^\alpha d + a_e\,\bar{e}\gamma^\alpha e + b_e\,\bar{\nu}_e\gamma^\alpha P_L\nu_e + b_\mu\,\bar{\nu}_\mu\gamma^\alpha P_L\nu_\mu + b_\tau\,\bar{\nu}_\tau\gamma^\alpha P_L\nu_\tau\big)Z'_\alpha$$

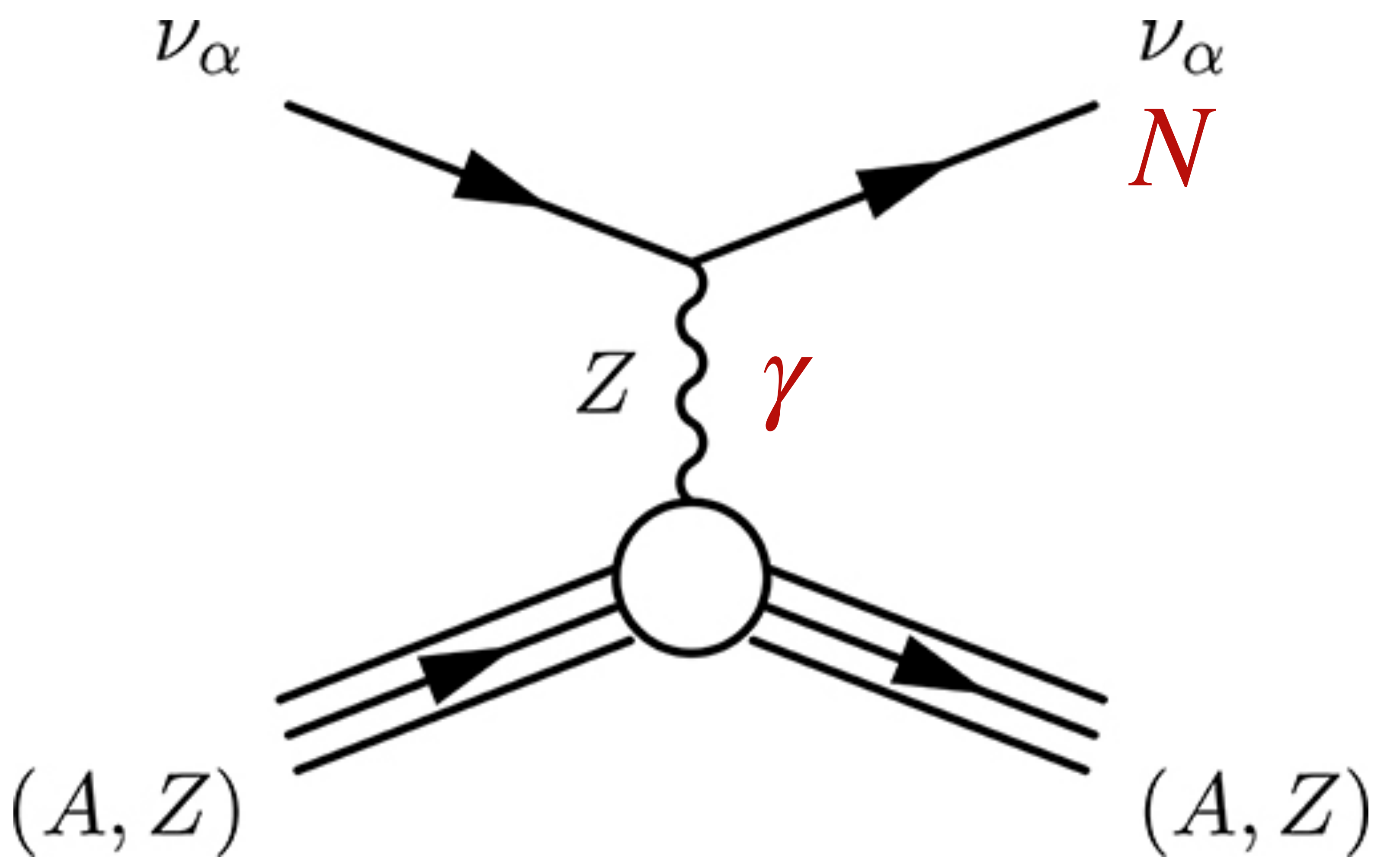


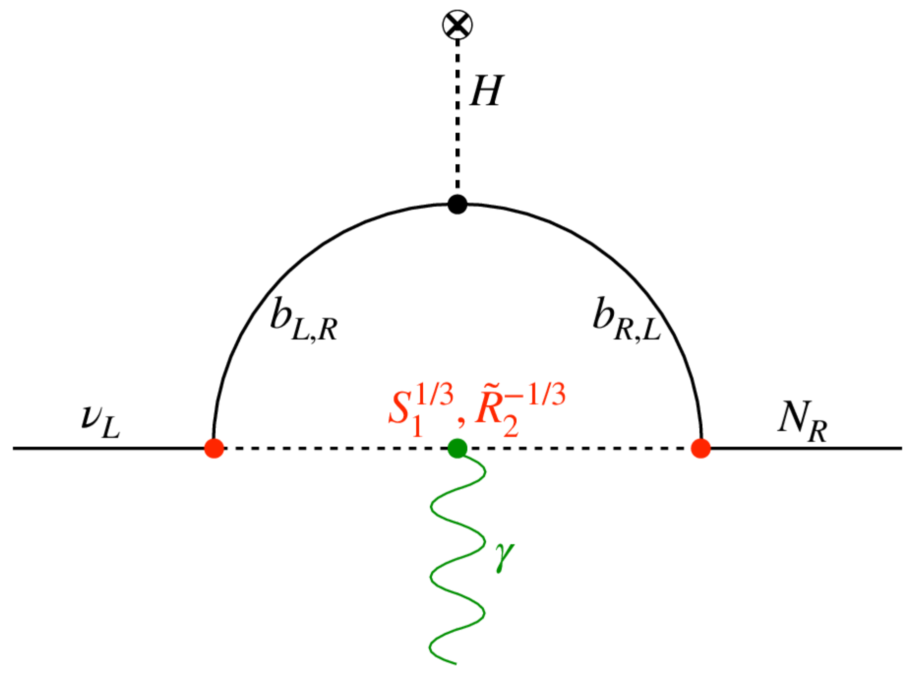
Coherent Scattering and Neutrino Magnetic Moment

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}E_r}\right)_{\mathrm{SM}} = \frac{G_F^2 M}{\pi}(\mathcal{Q}_V)^2\left[1-\frac{E_r}{E_\nu}-\frac{ME_r}{2E_\nu^2}\right],$$

$$\mathcal{L}_\mu = \frac{\mu_\nu^\alpha}{2}\, F_{\mu\nu}\,\bar{\nu}_L^\alpha\sigma^{\mu\nu} N_R + \mathrm{h.c.}$$

$$\frac{d\sigma_\mu(\nu_L X_Z^A \to N_R X_Z^A)}{dE_r} = \alpha\mu_\nu^2 Z^2 F_1^2(E_r)\left[\frac{1}{E_r}-\frac{1}{E_\nu}+M_N^2\frac{E_r-2E_\nu-m_X}{4E_\nu^2 E_r m_X}+M_N^4\frac{E_r-m_X}{8E_\nu^2E_r^2m_X^2}\right]$$
$$+\,\alpha\mu_\nu^2\mu_X^2F_2^2(E_r)\left[\frac{2m_X}{E_\nu^2}\Big((2E_\nu-E_r)^2-2E_rm_X\Big)+M_N^2\frac{E_r-4E_\nu}{E_\nu^2}+M_N^4\frac{1}{E_\nu^2E_r}\right]$$

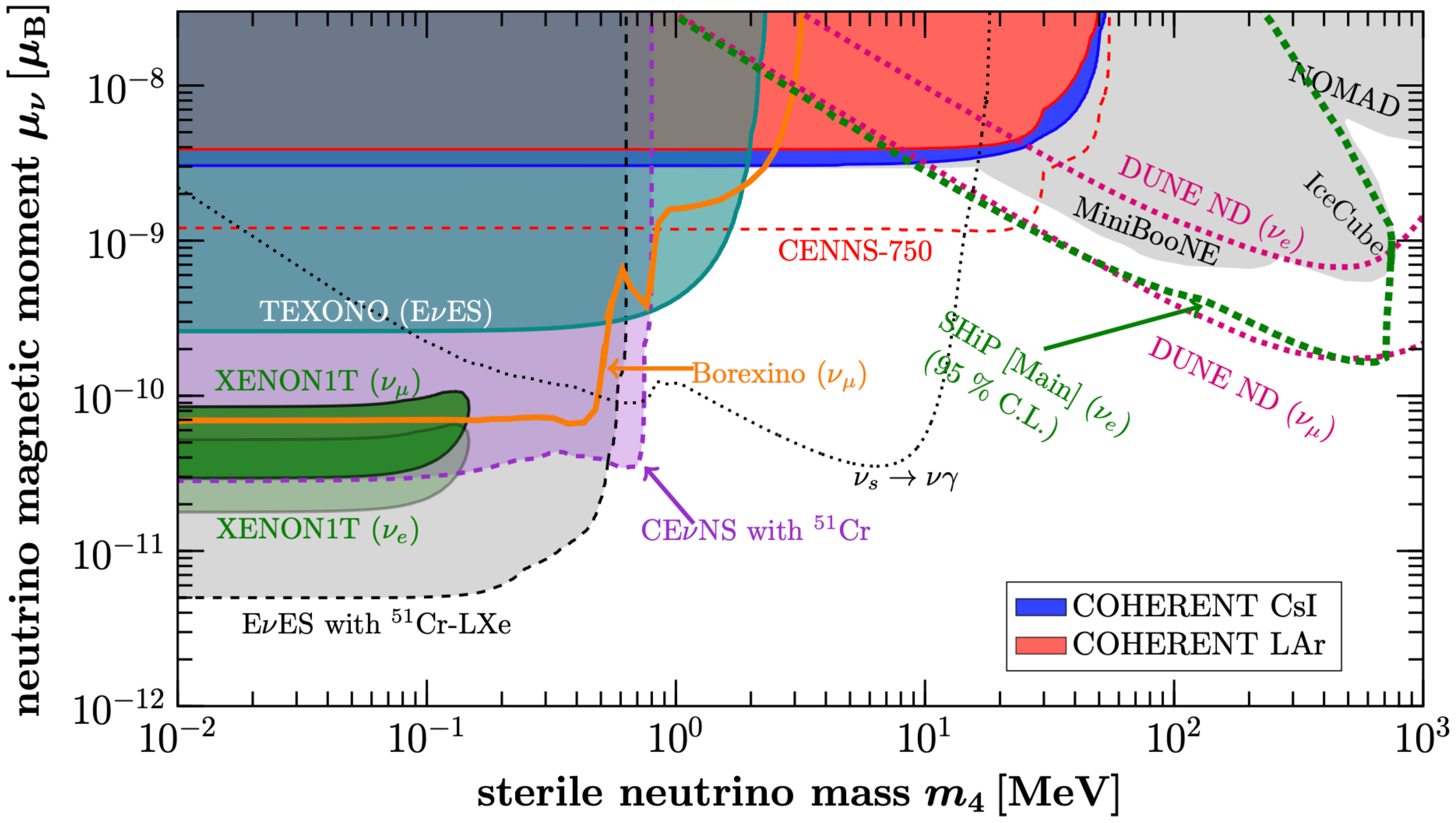




realization $\mathcal{L}_{S_1} \supset y_1\, \overline{b_R^c} N_R\, S_1 + y_2\, \overline{Q_L^3} L_L^{i\,c}\, S_1^\dagger + \mathrm{h.c.}$

Brdar et al, JCAP/2007.15563

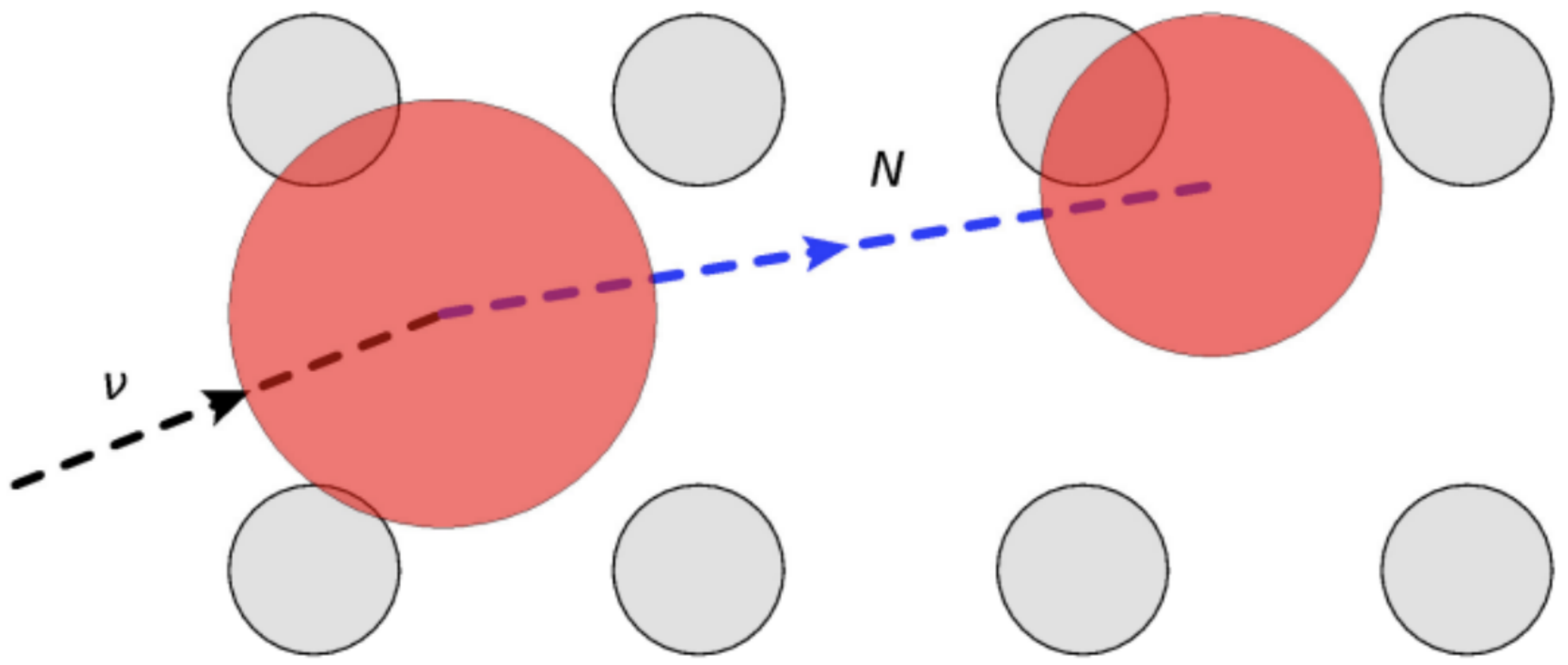
Coherent Scattering and Neutrino Magnetic Moment



Miranda et al, JHEP/2109.09545

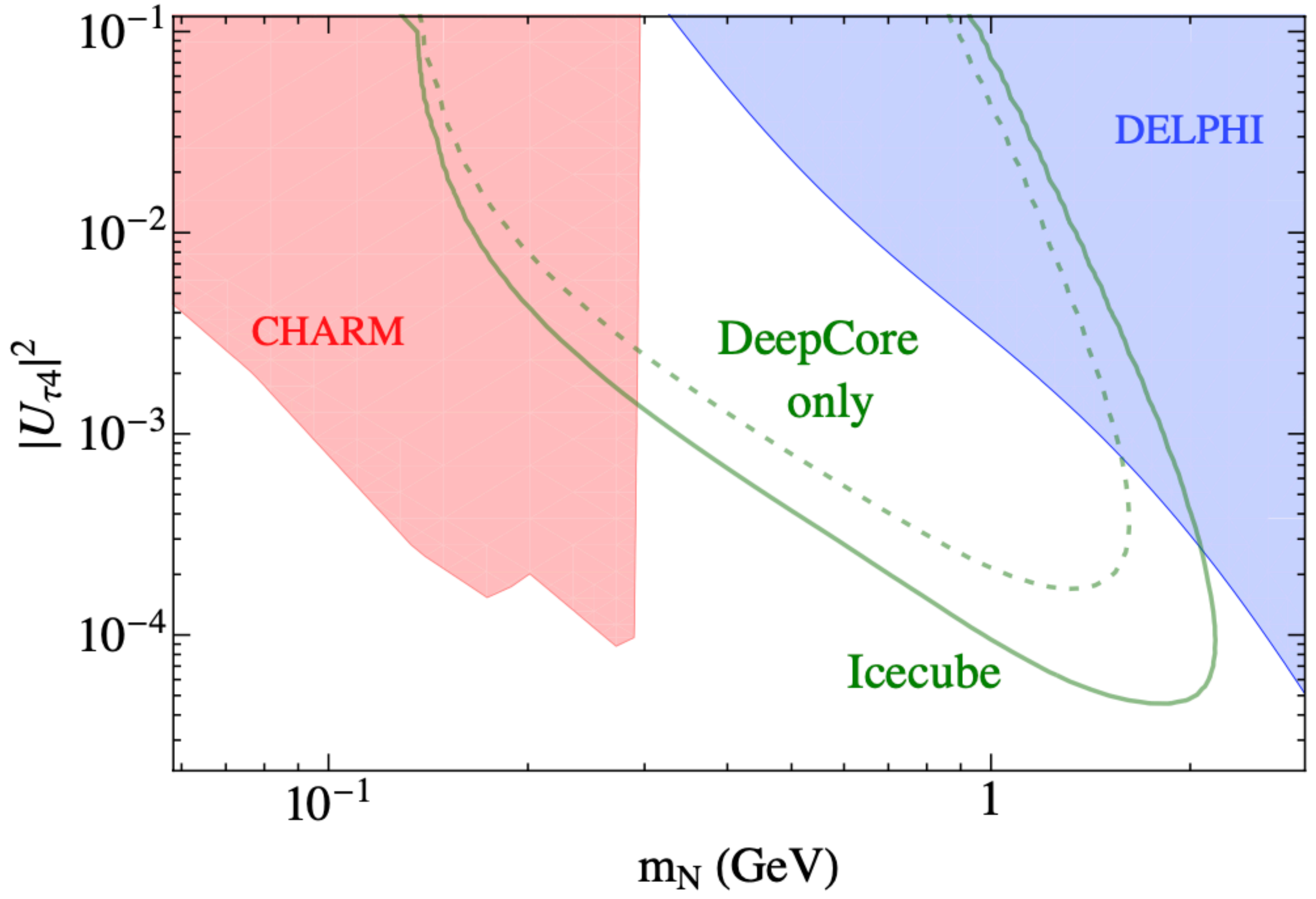
Double Cascade and New Physics

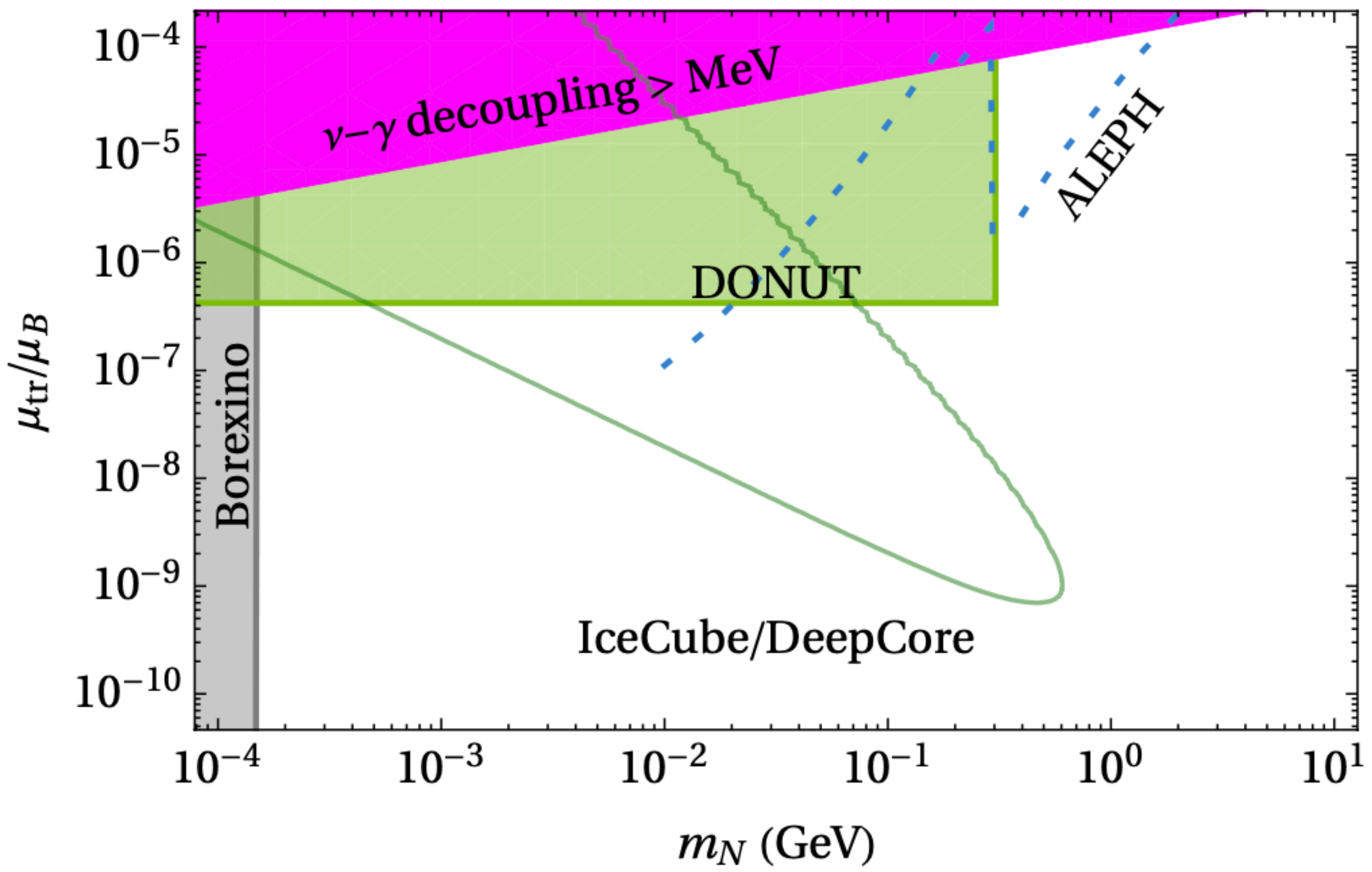
$$\nu_{\alpha L} = \sum_{i=1}^{3} U_{\alpha i}\nu_{iL} + U_{\alpha 4} N^c_{4R}$$



The mixing portal

The dipole portal

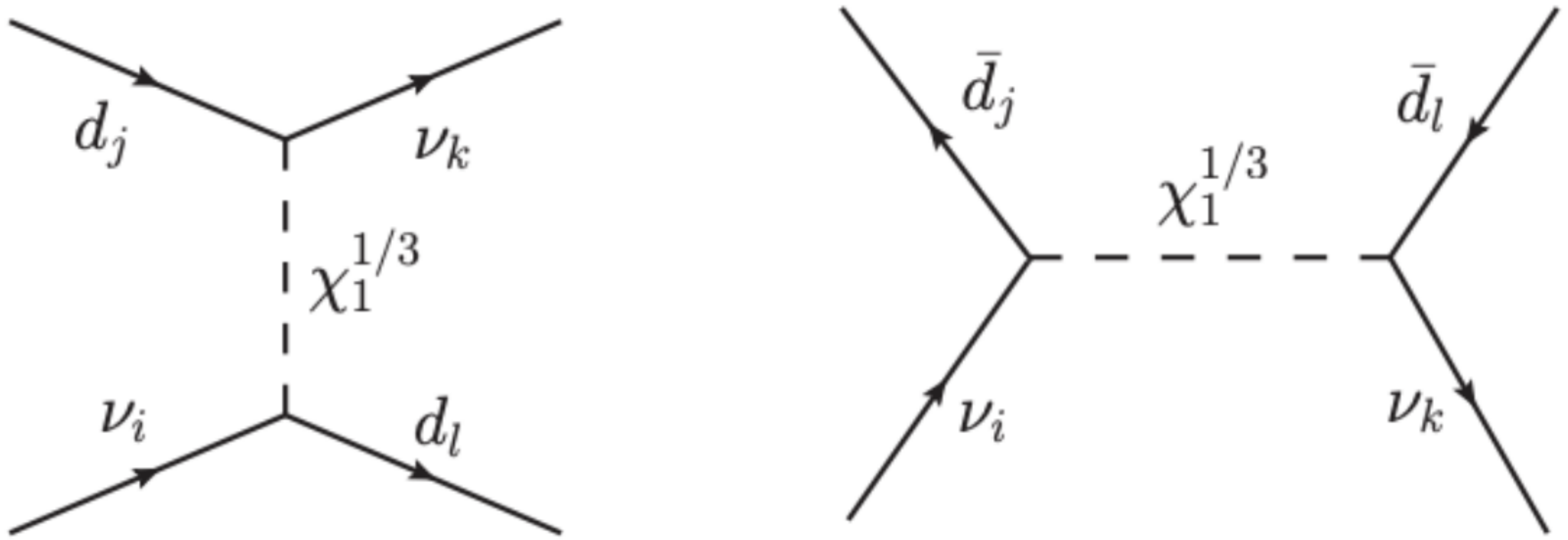


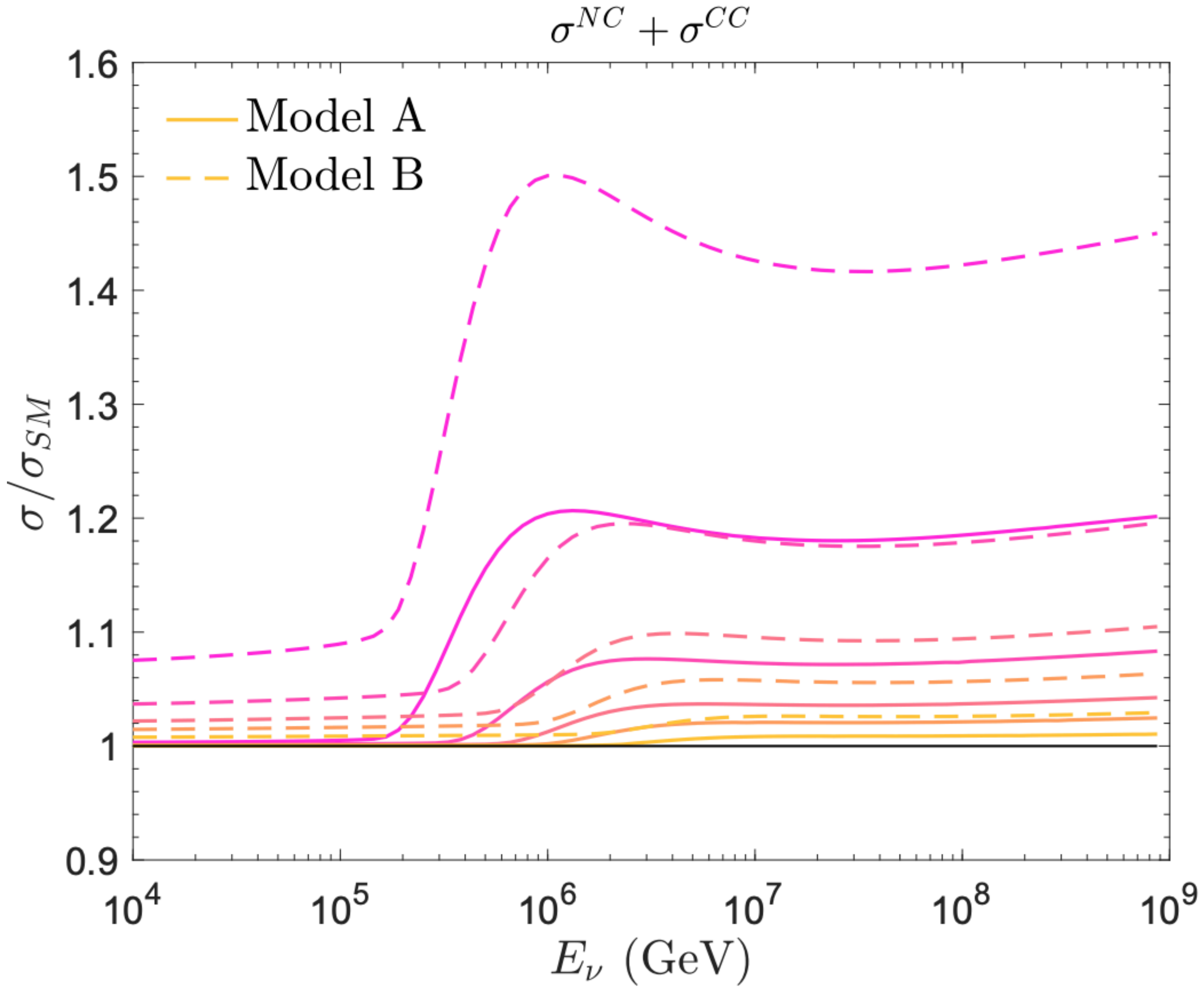


Coloma et al, PRL/1707.08573

Leptoquark

$$\mathcal{L}_\chi = -x_{ij}\bar{d}^i P_L l^j \chi_1^{2/3} + x_{ij}\bar{d}^i P_L \nu^j \chi_1^{-1/3} + \text{ h.c.}$$

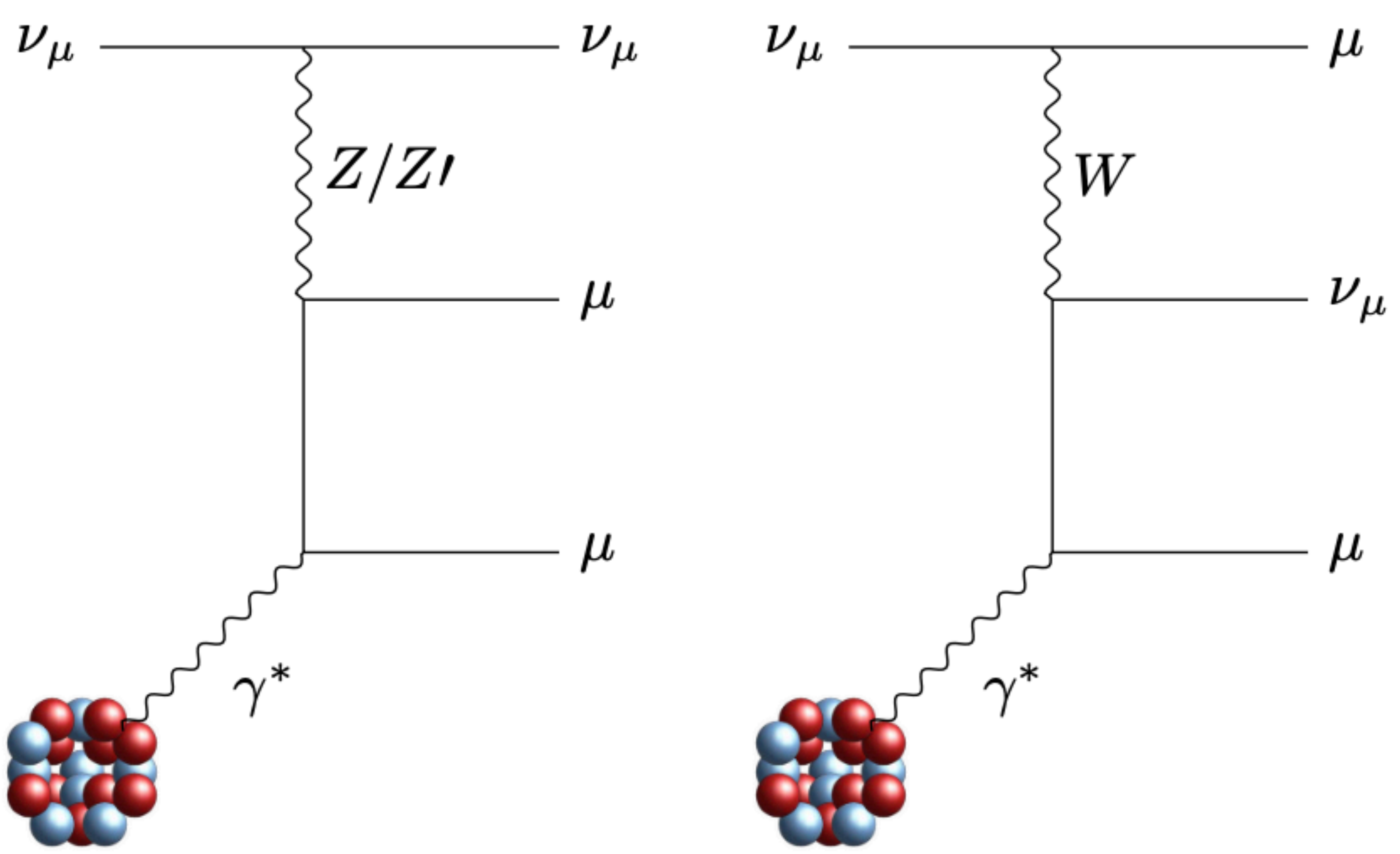


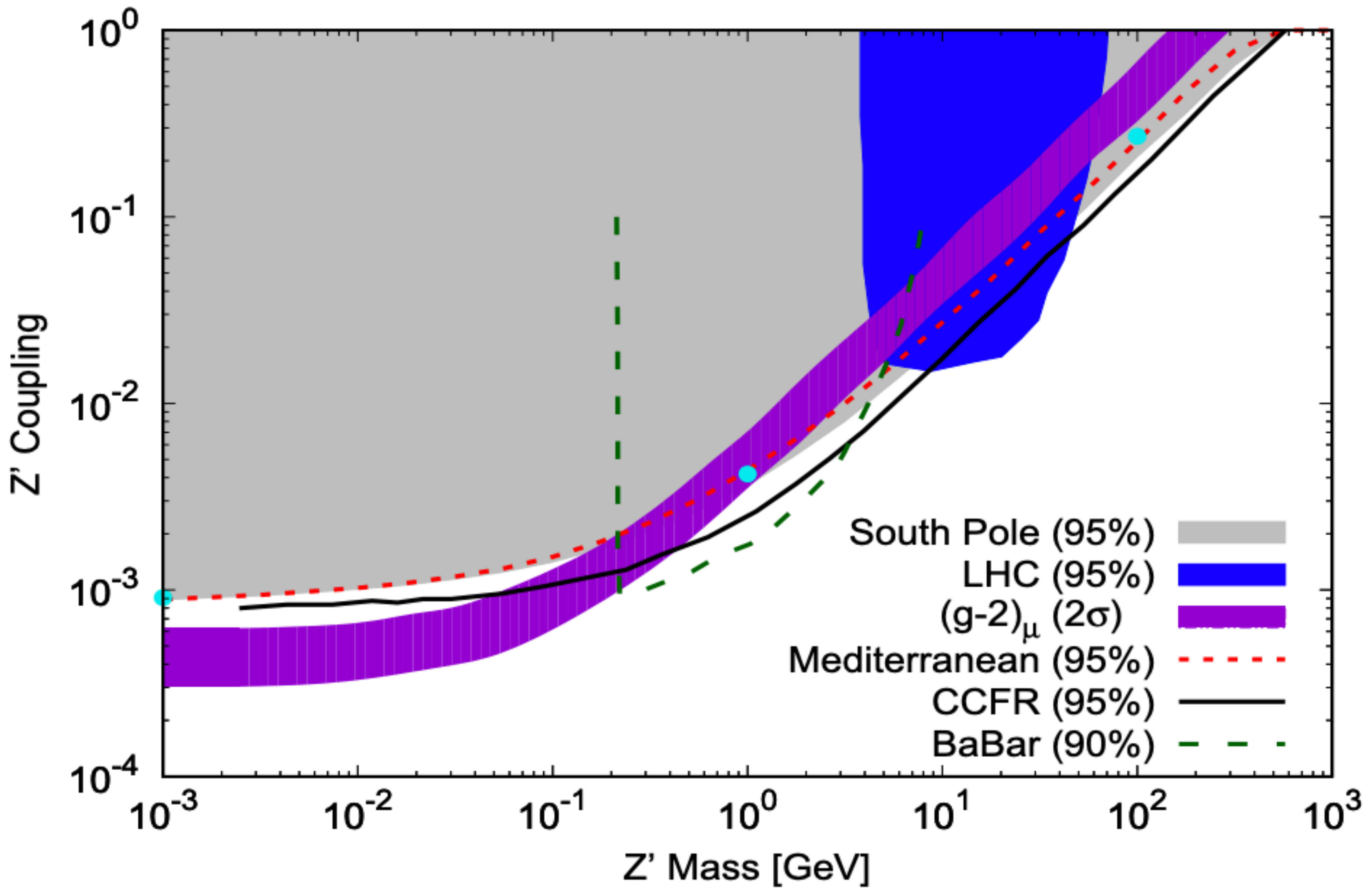


Enhanced cross section due to s-channel resonance in neutrino-quark scattering

Dey et al, PRD/1709.02009

Trident Interaction and New Physics





Double lepton production leads to unique signal in the detector

Altmannshofer et al, PRL/1406.2332

Ge et al, PLB/1702.02617

Zhou, Beacom, PRD/1910.08090

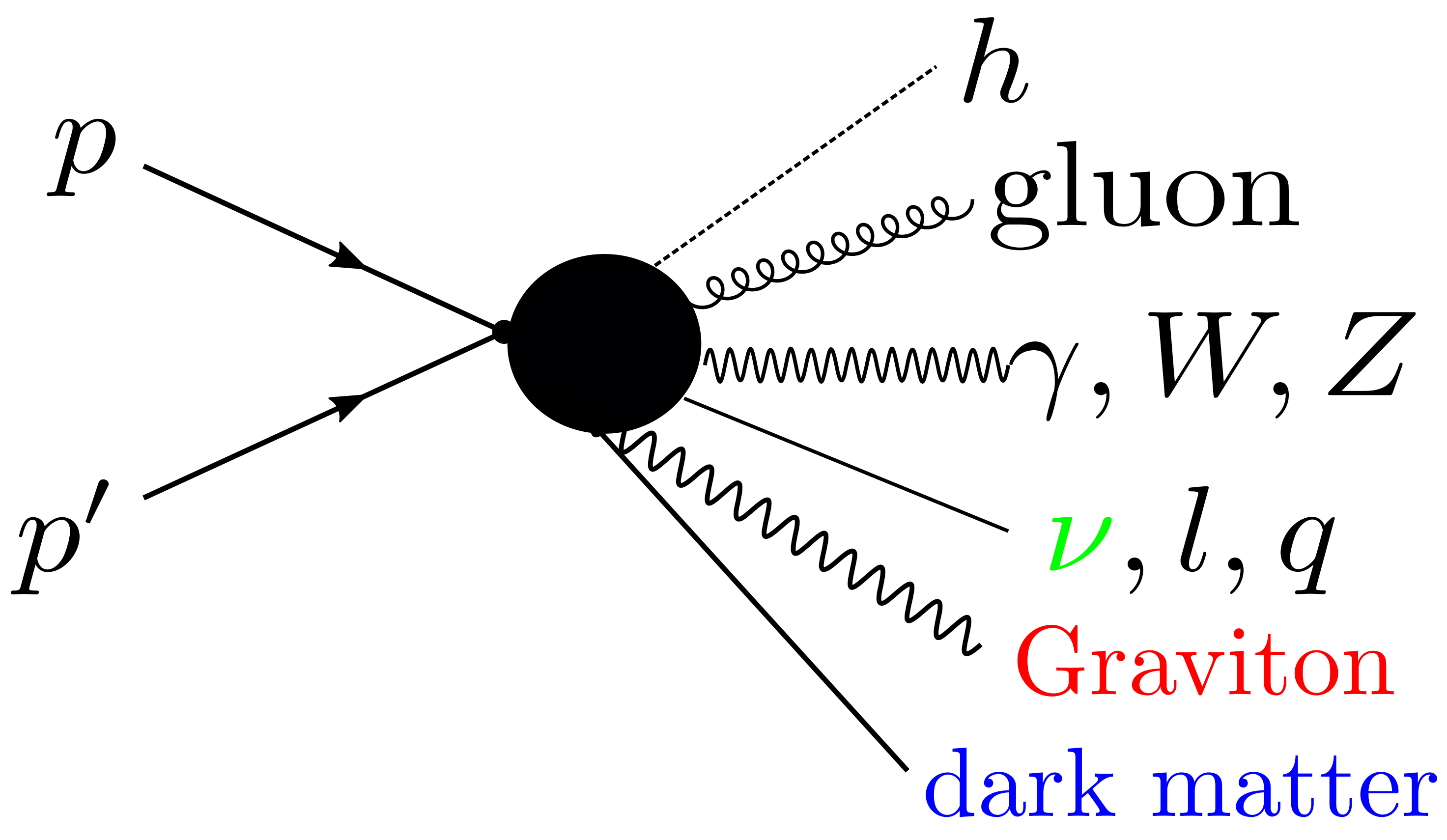
Zhou, Beacom, PRD/1910.10720

Altmannshofer et al, 2406.16803

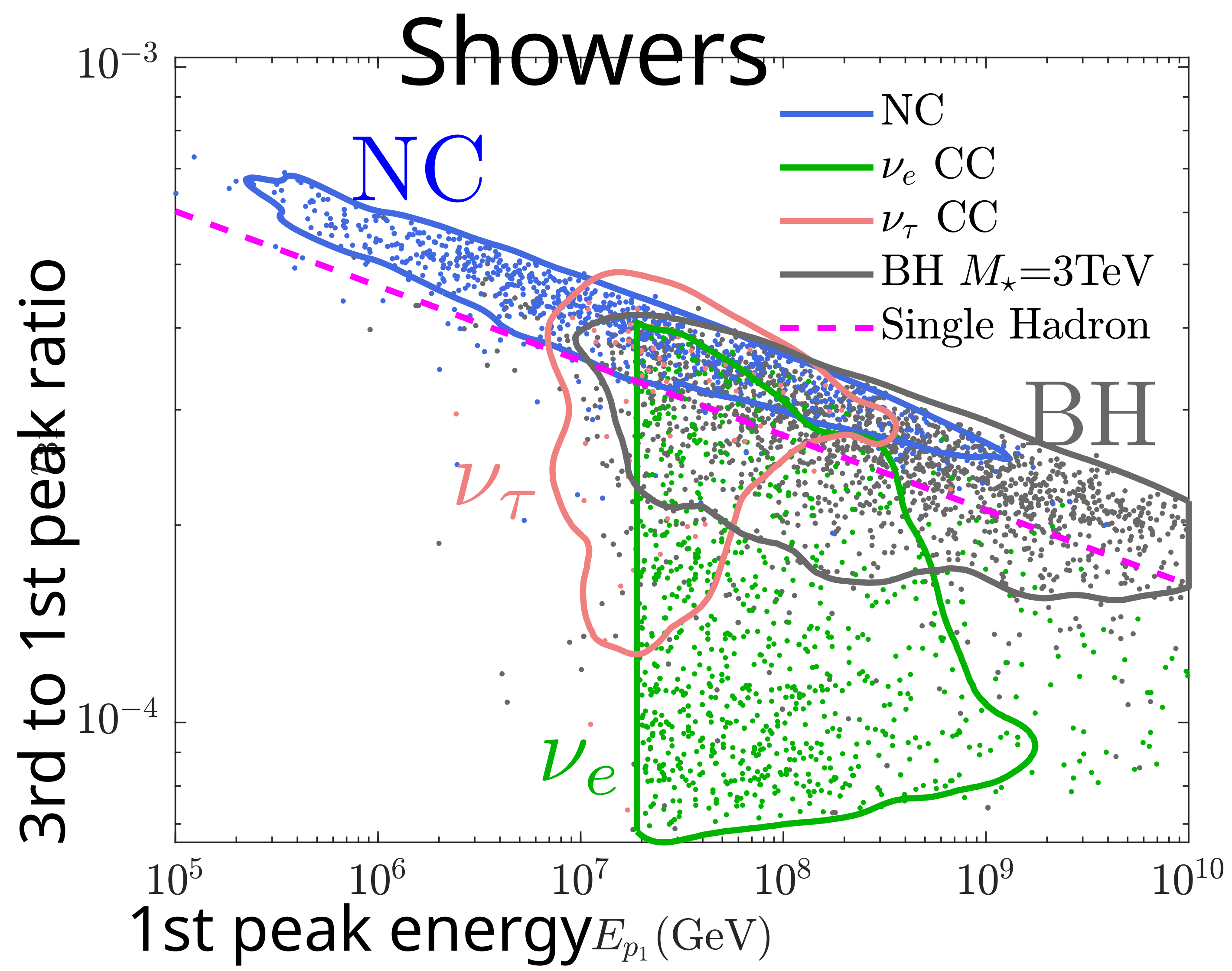
Bigaran et al, 2406.20067

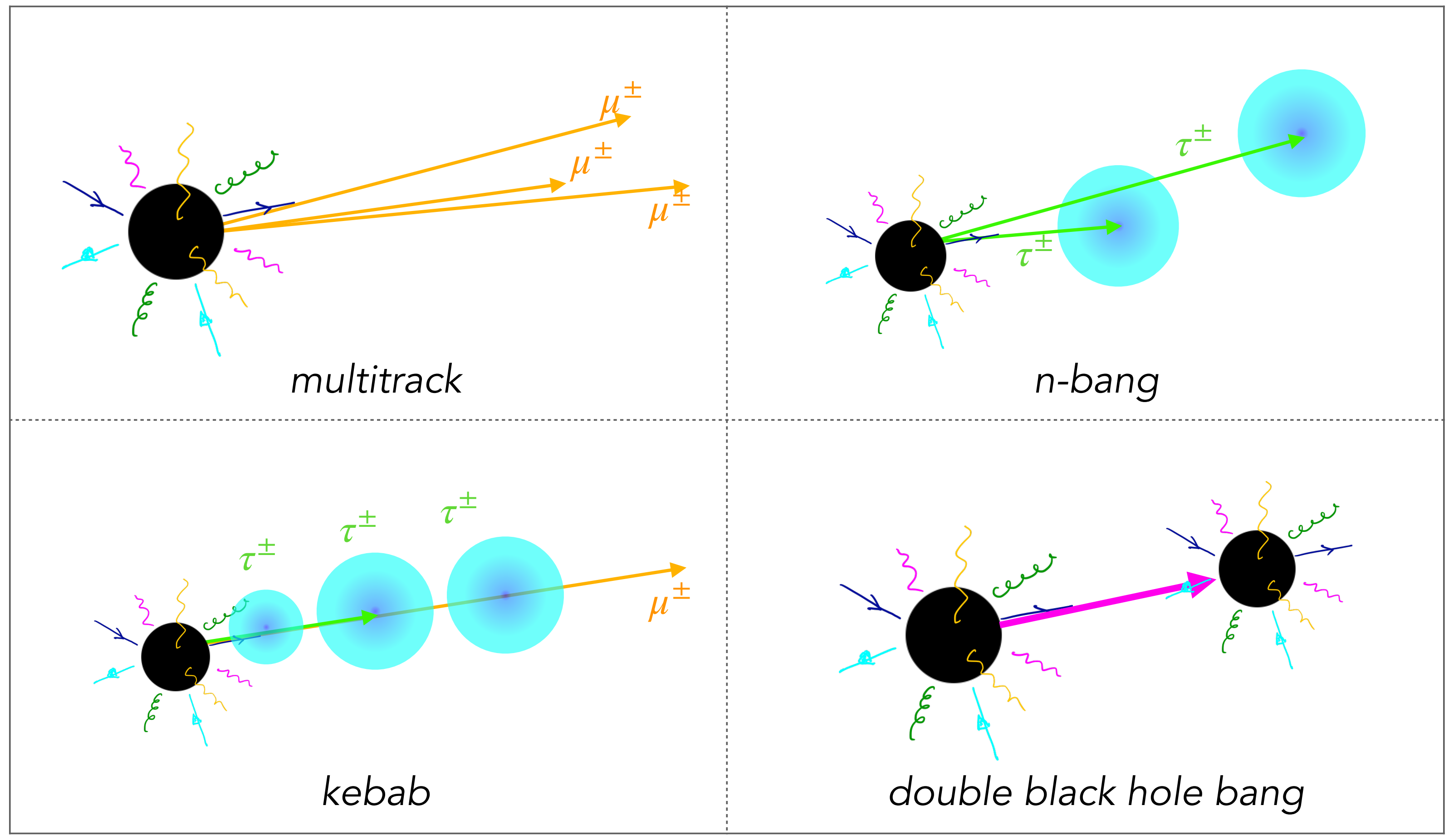
Quantum Gravity

Arkani-Hamed, Dimopoulos, Dvali, PRD 1998



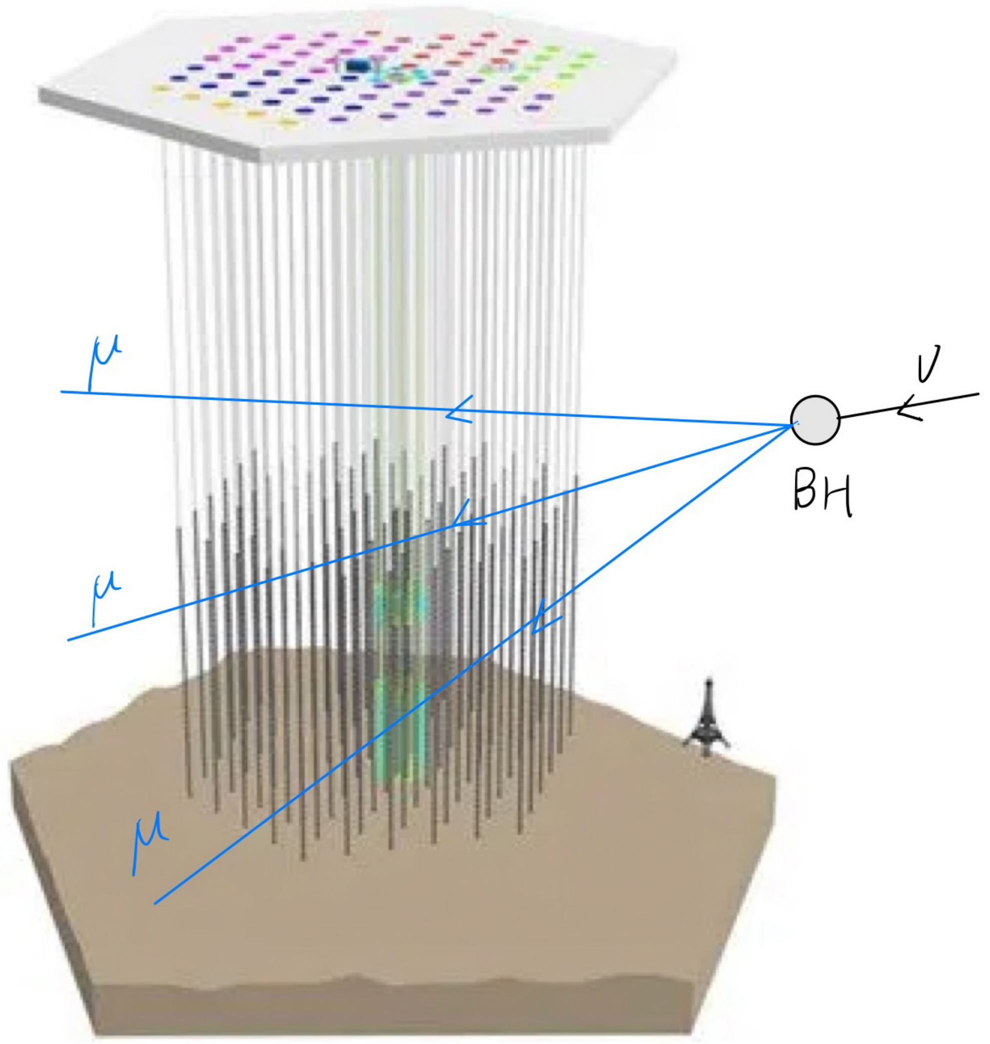
BlackMax+Pythia+Fluka simulations

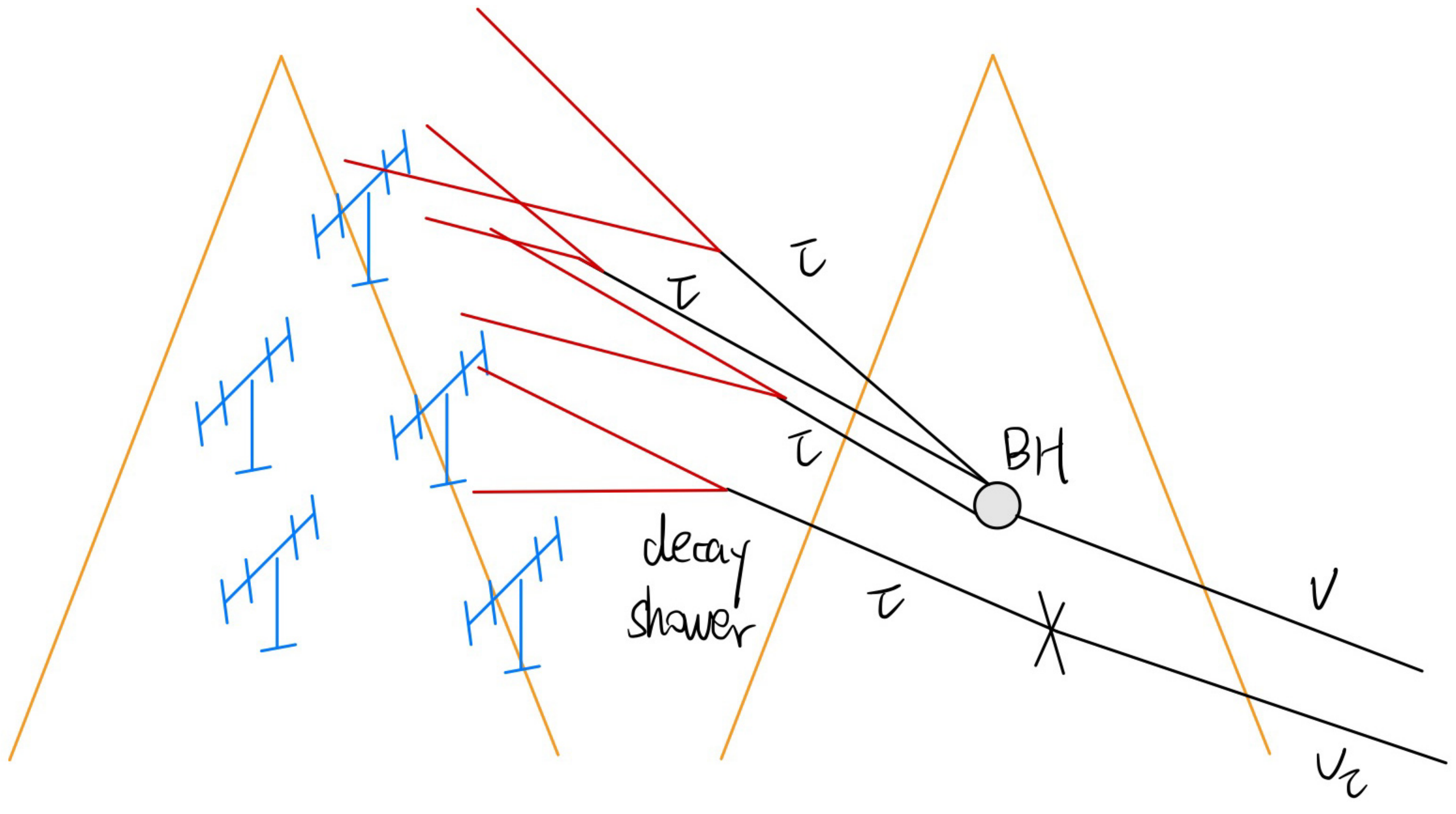




NS, Vincent, PRL/1907.08628

Mack, **NS**, Vincent, JHEP/1912.06656





IceCube: Coincident through-going muons

GRAND: Coincident N-bang radio signals

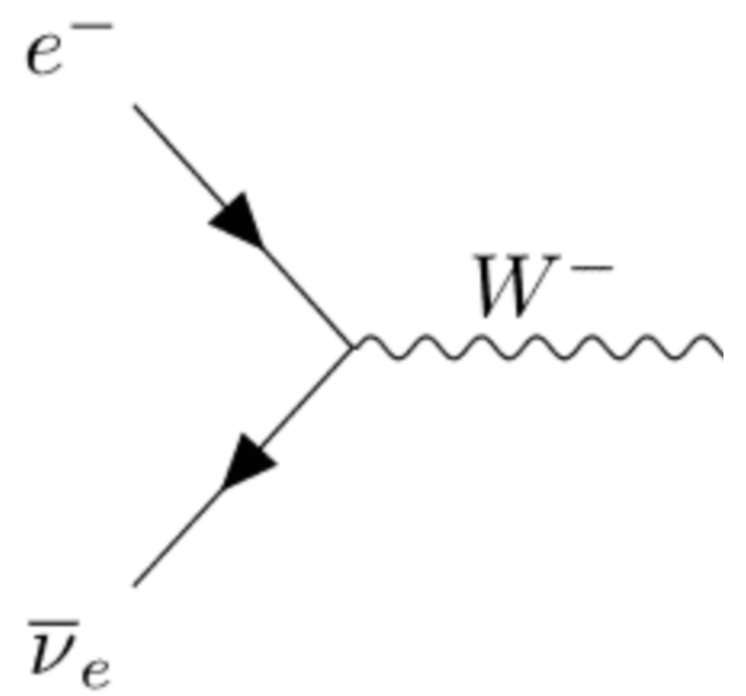
Search for New Physics at Neutrino Experiment

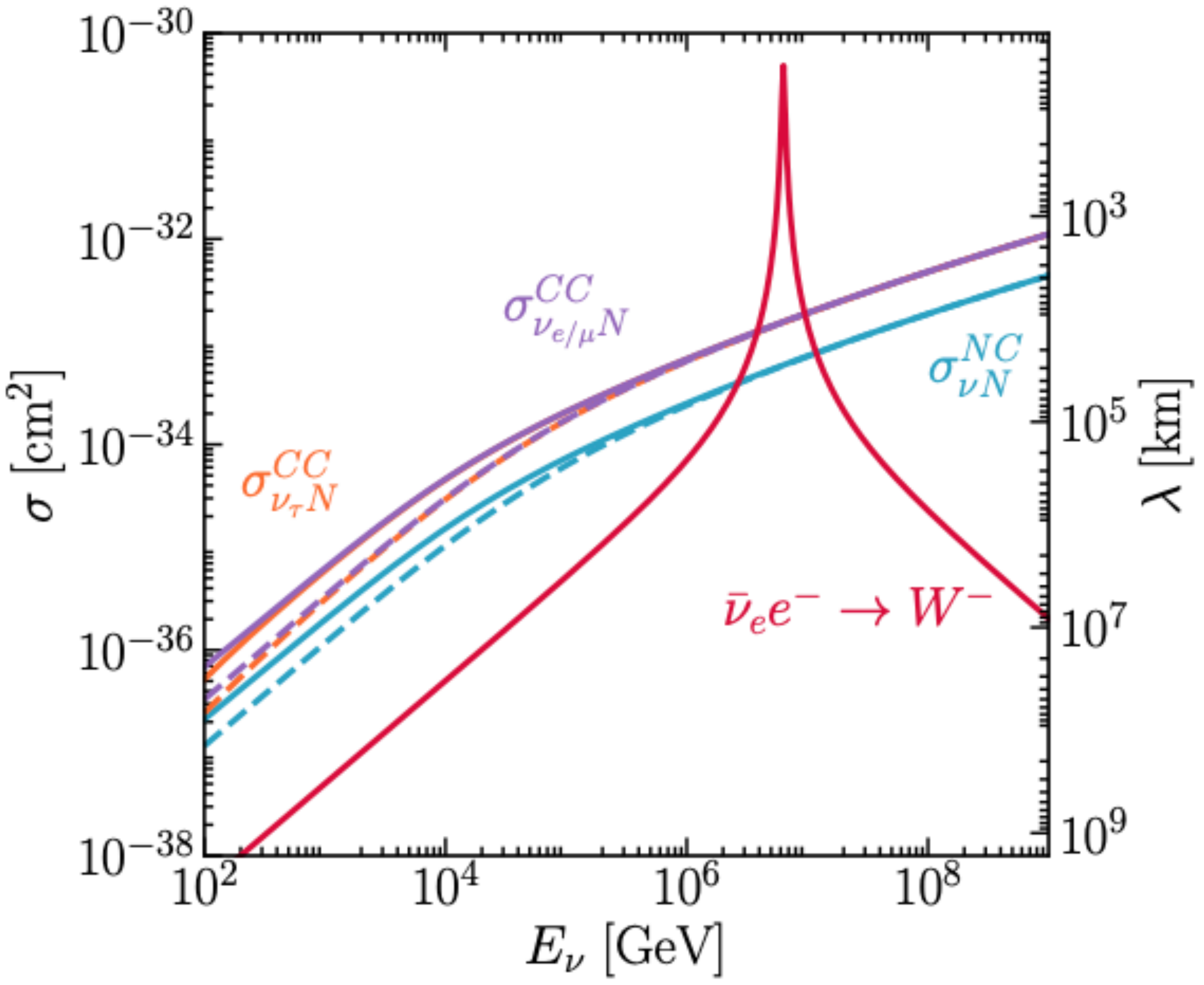
Glashow Resonance (GR)

Huang, Liu , 1912.02976

When the centre of mass energy is close to W boson mass, $\bar{\nu}_e$-electron interaction is enhanced by the resonant production of W

$$\sigma_{\overline{\nu}_e e}(s) = 24\pi\,\Gamma_W^2\,\mathrm{Br}(W^- \to \overline{\nu}_e + e^-) \times \frac{s/M_W^2}{(s - M_W^2)^2 + (M_W\Gamma_W)^2}\,,$$



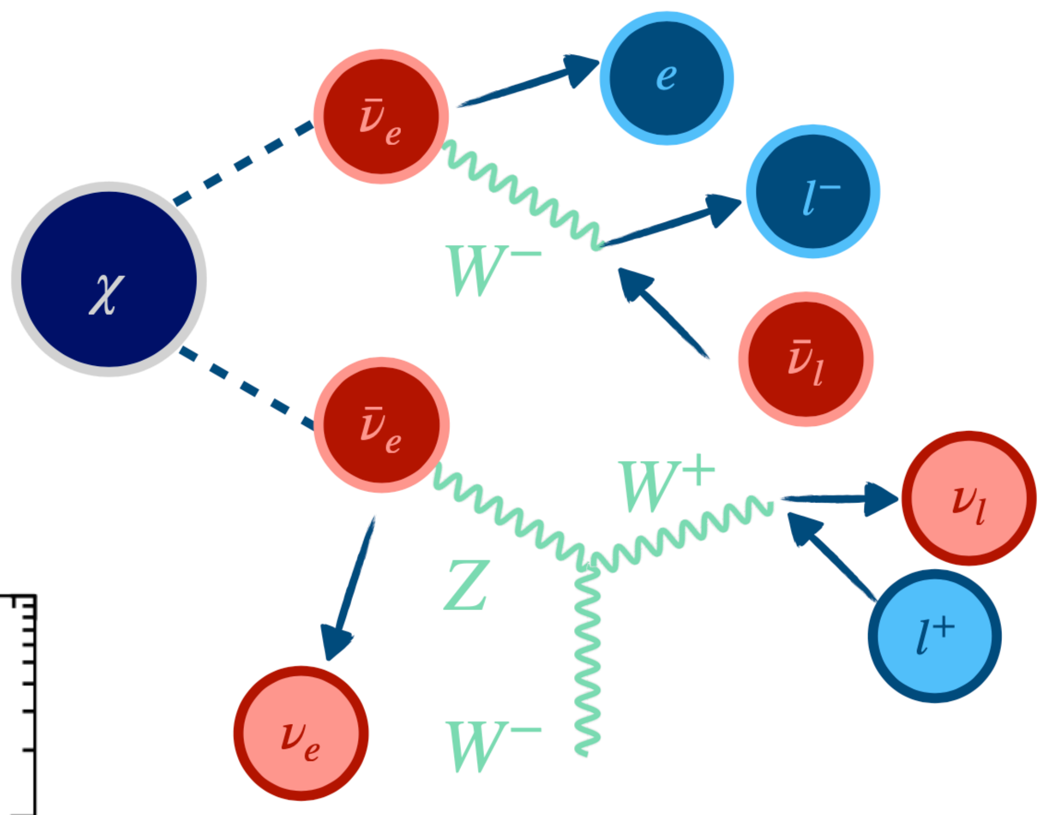


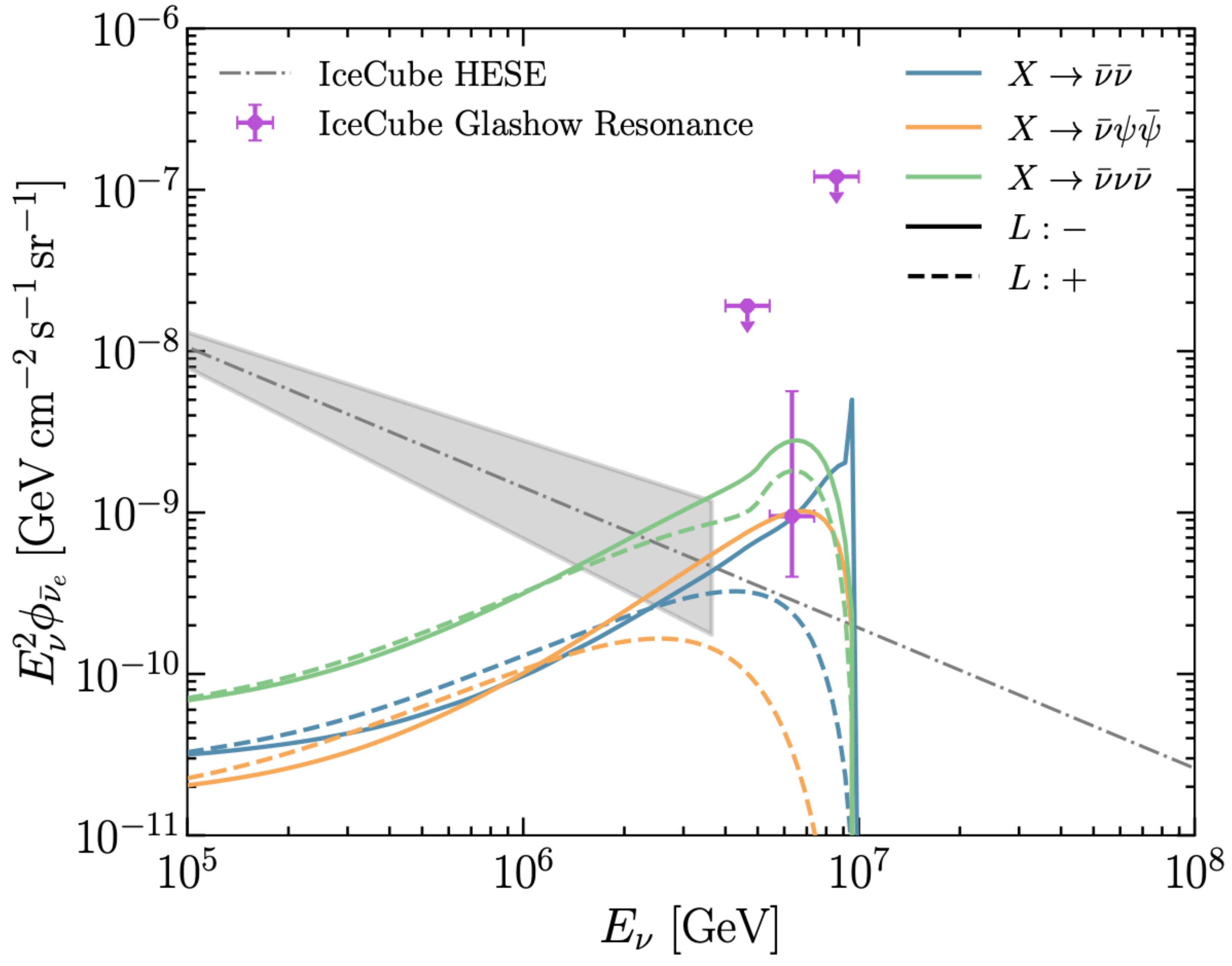
Asymmetric Dark Matter Decay

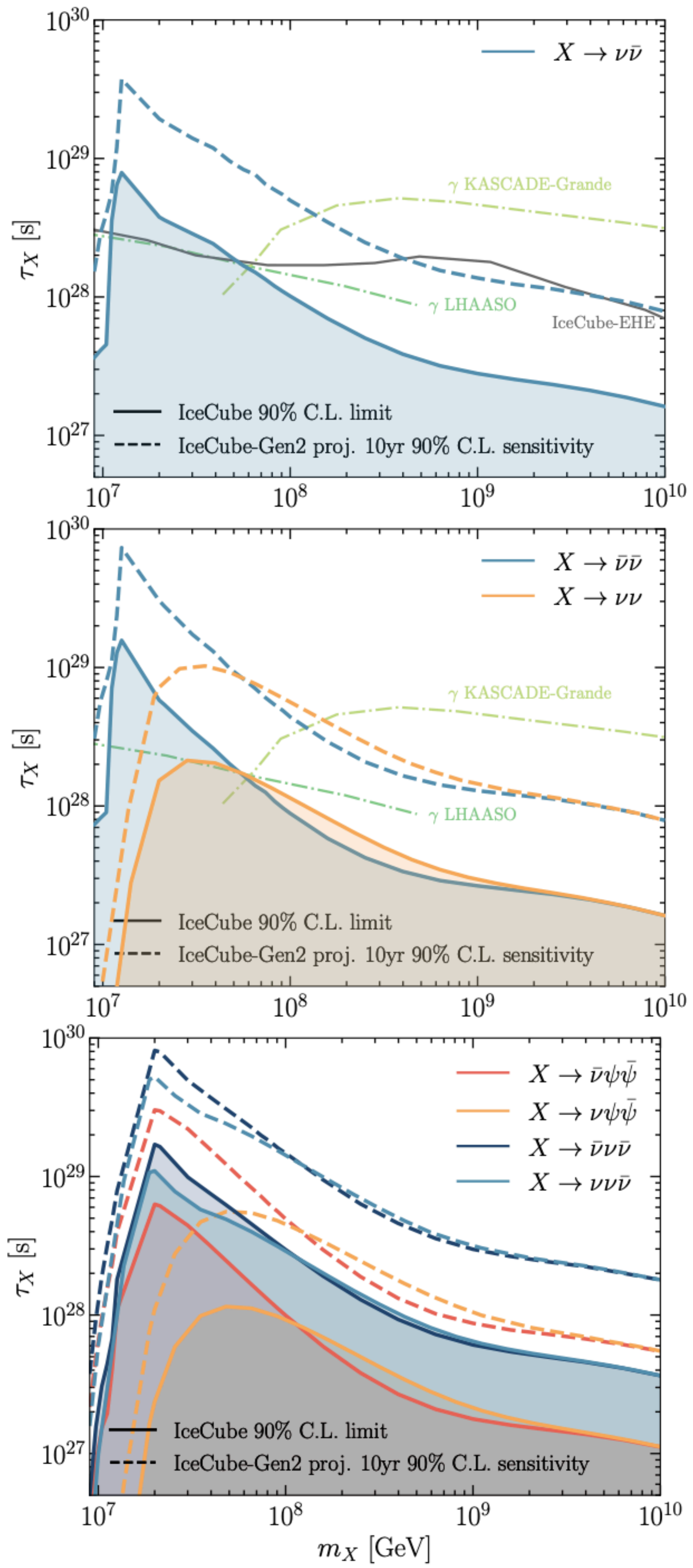
$$\mathcal{O}_{X\to\nu} = \frac{1}{\Lambda^2}X\psi L\Phi\,, \quad \frac{1}{\Lambda^2}X(L\Phi)^2\,, \quad \frac{1}{\Lambda^{3n-1}}\bar{X}l\psi^n$$

$$X \to \bar{\nu}, \;\; X \to \bar{\nu}\bar{\nu}, \;\; X \to \nu\bar{\nu}\bar{\nu}$$

Credit: Qinrui Liu







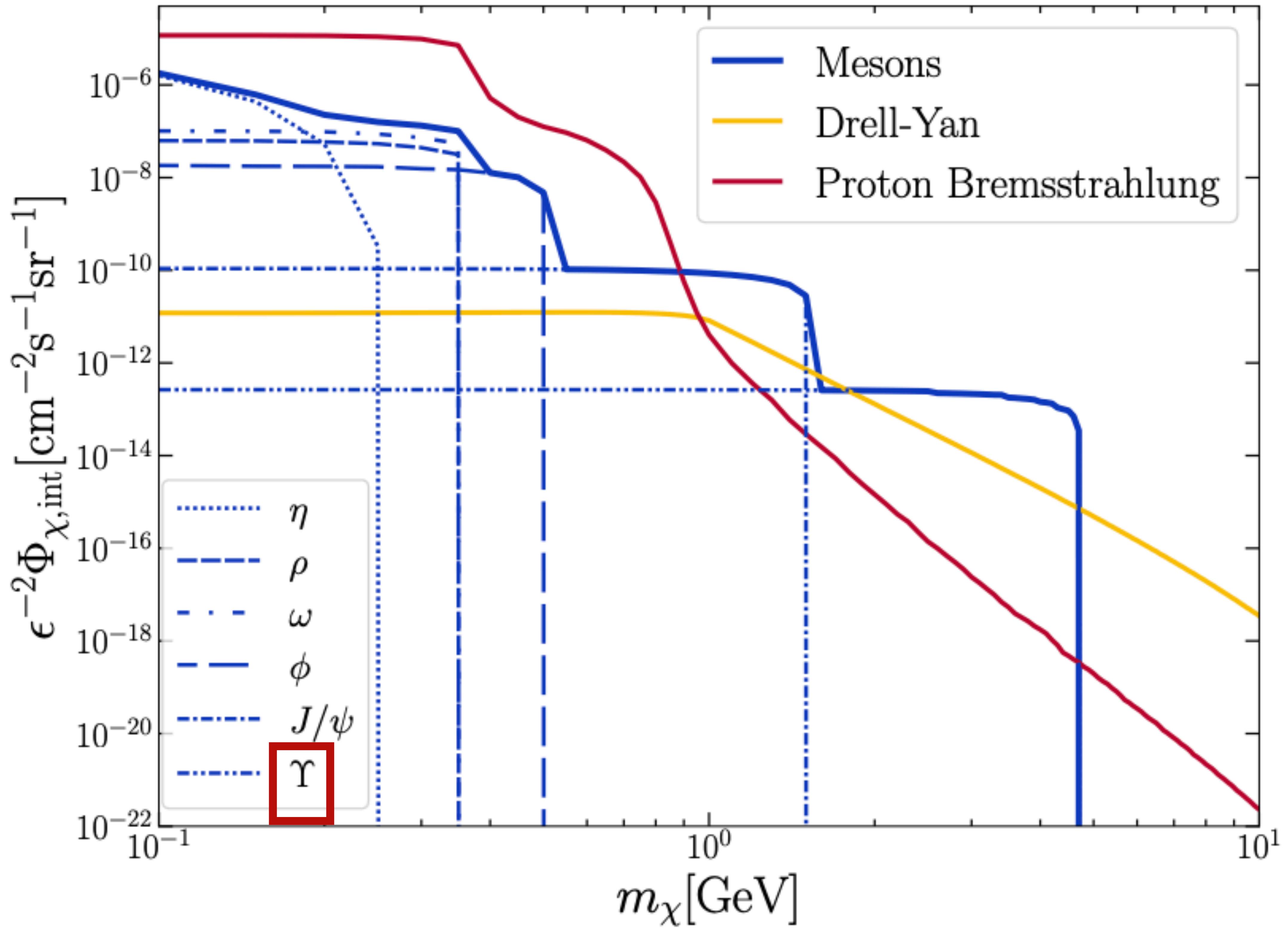
Liu, **NS**, Vincent, arXiv: 2406.14602

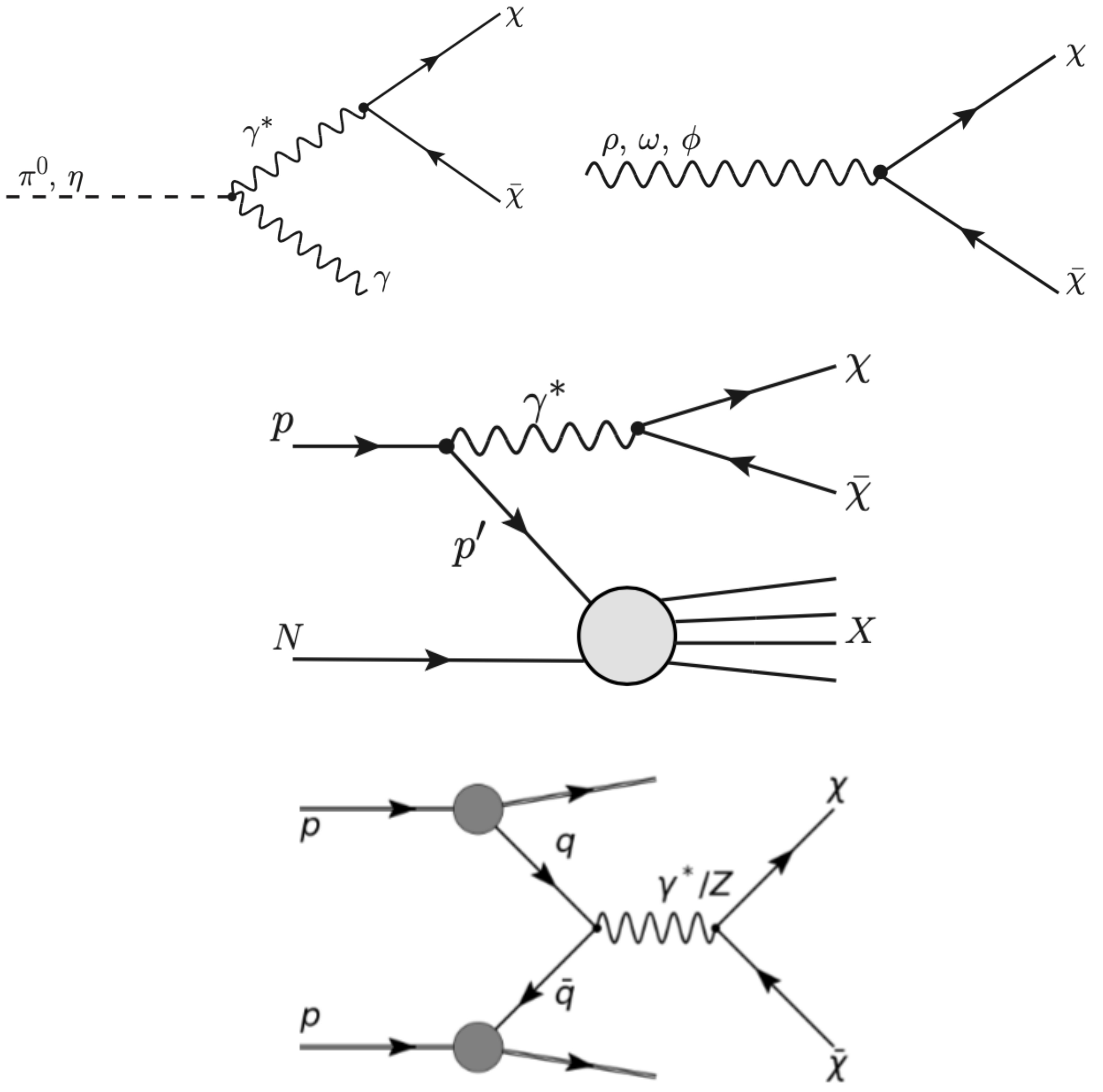
Atmospheric Millicharge Particles

$$\mathcal{L}_0 = -\frac{1}{4}F_{a\mu\nu}F_a^{\mu\nu} - \frac{1}{4}F_{b\mu\nu}F_b^{\mu\nu} - \frac{\varepsilon}{2}F_{a\mu\nu}F_b^{\mu\nu}$$

$$\mathcal{L} = e\,J_\mu A_b^\mu + e' J'_\mu A_a^\mu$$

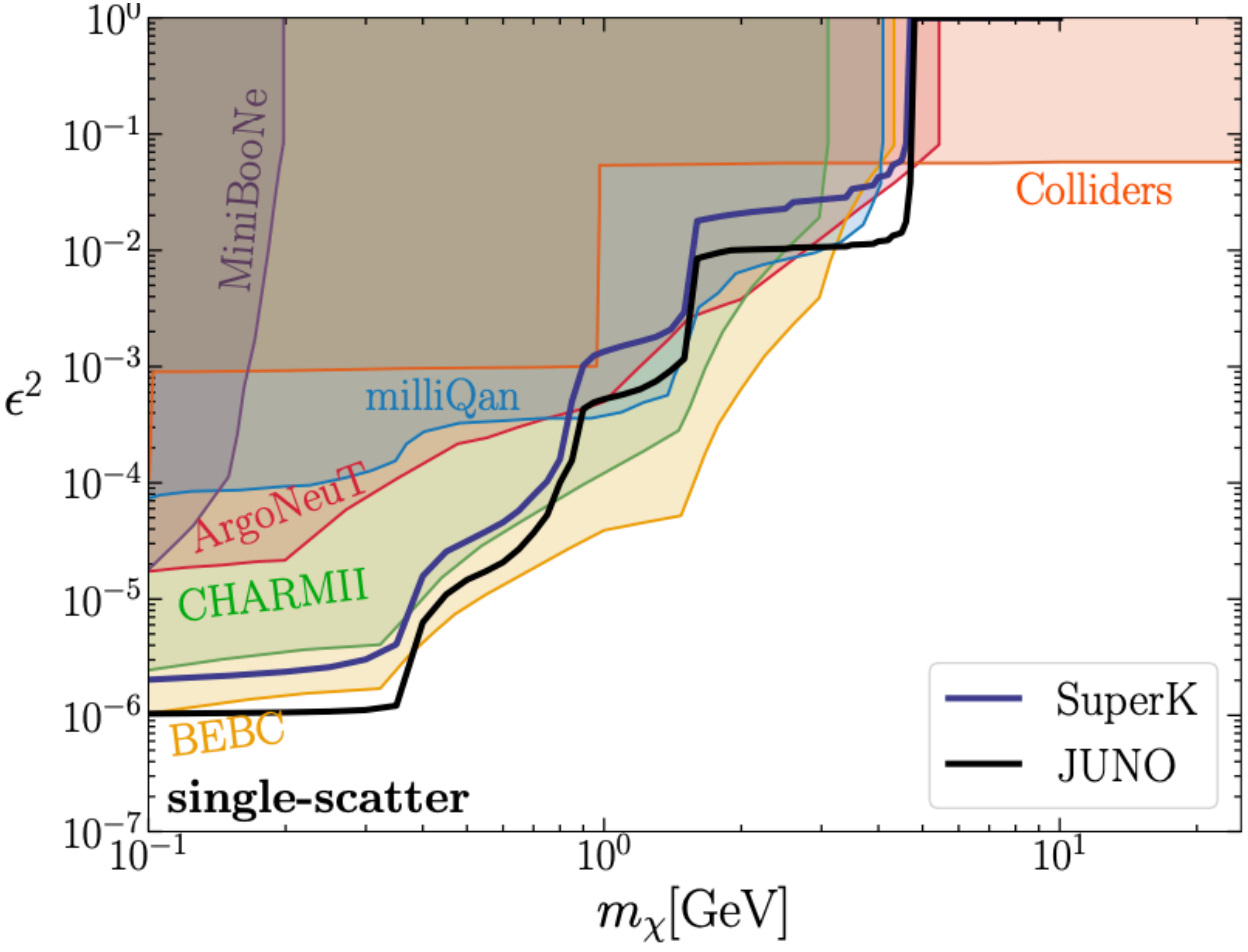
Meson decay+Proton Bremsstrahlung+Drell-Yan





Wu, Hardy, **NS**, arXiv: 2406.01668

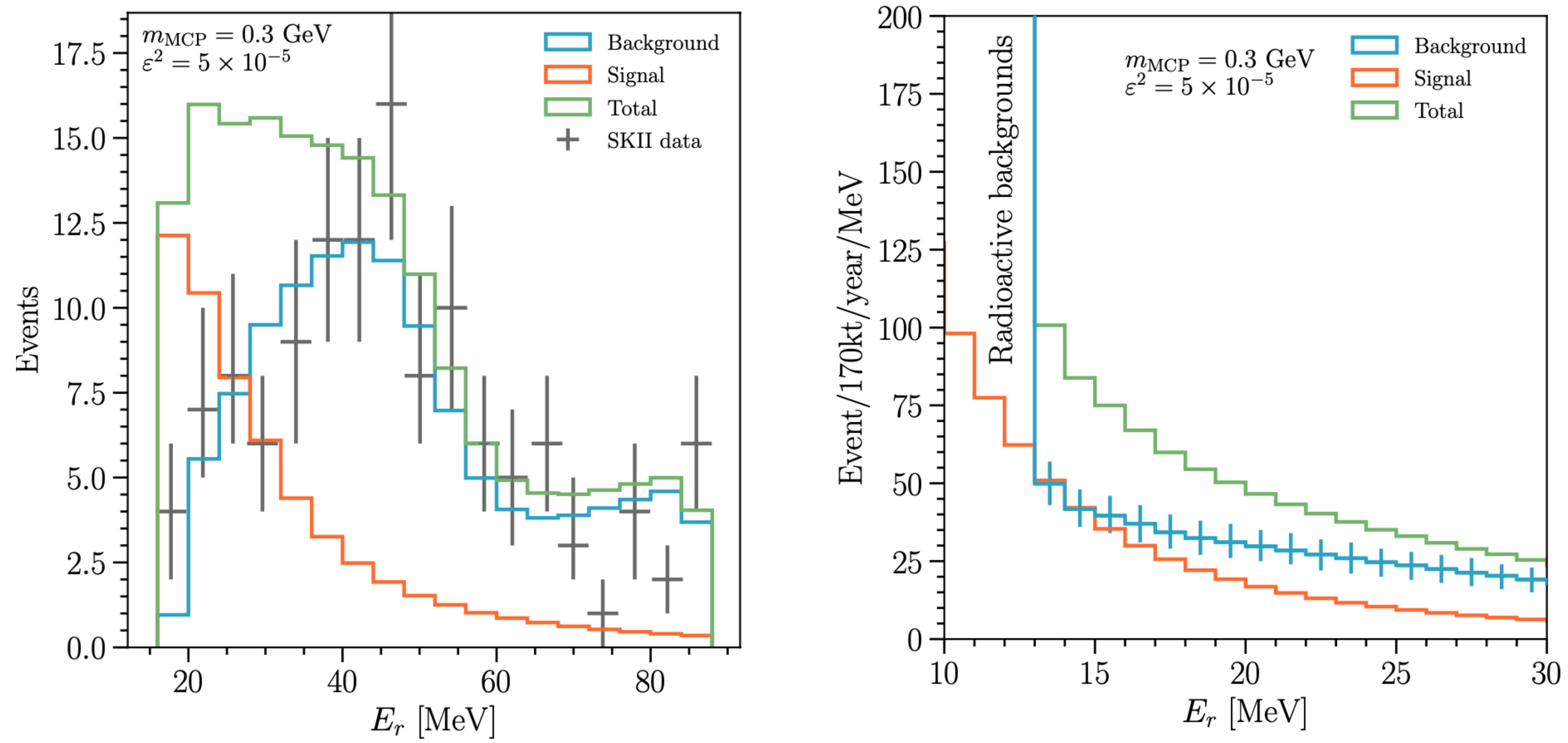
Single Scatter Constraint



$$\frac{d\sigma_{\chi e}}{dE_r} = \pi\epsilon^2\alpha^2 \frac{(E_r^2 + 2E_\chi^2)m_e - ((2E_\chi + m_e)m_e + m_\chi^2)\, E}{E_r^2 m_e^2\,(E_\chi^2 - m_\chi^2)}$$

$$d\sigma_{\chi e}/dE_r \propto 1/E_r^2$$

$$\sigma_{\chi e} \simeq \frac{\pi\alpha_{EM}\epsilon^2}{m_e T_{\min}} = 2.6\times 10^{-25}\epsilon^2\ \mathrm{cm}^2 \frac{\mathrm{MeV}}{T_{\min}}$$

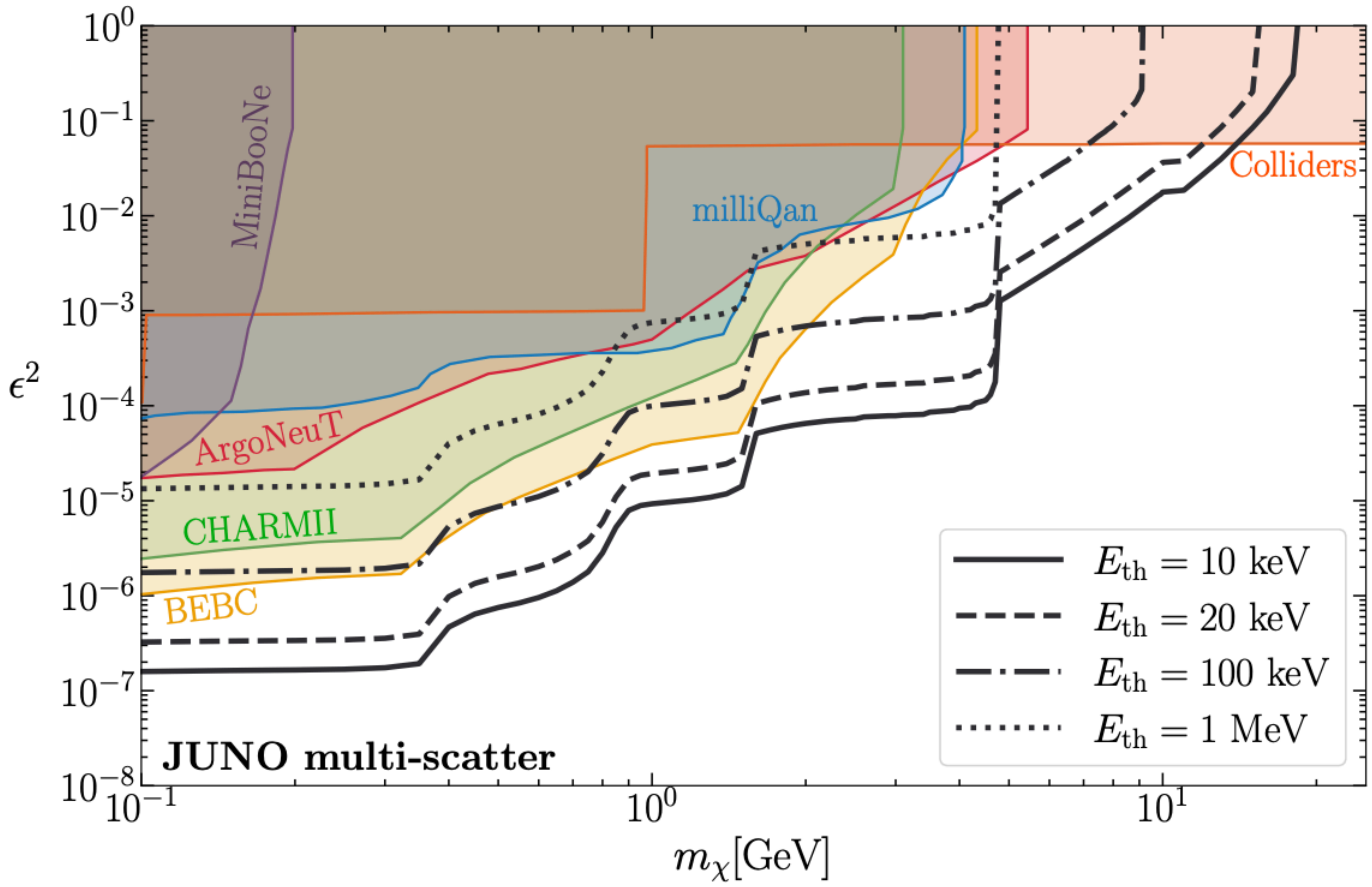


Assuming JUNO 10 MeV threshold+170 kton·yr exposure

Wu, Hardy, **NS**, arXiv: 2406.01668

Arguelles et al JHEP/2104.13924

Multiple Scatter Constraint

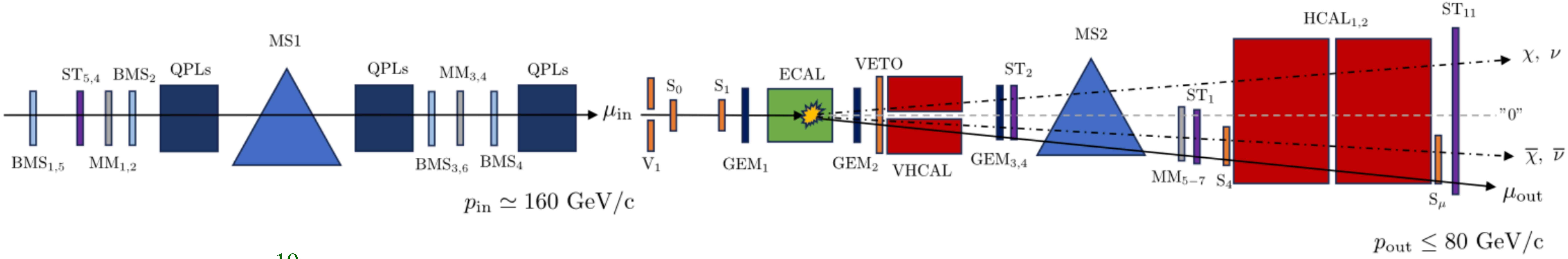


Assuming JUNO 170 kton·yr exposure

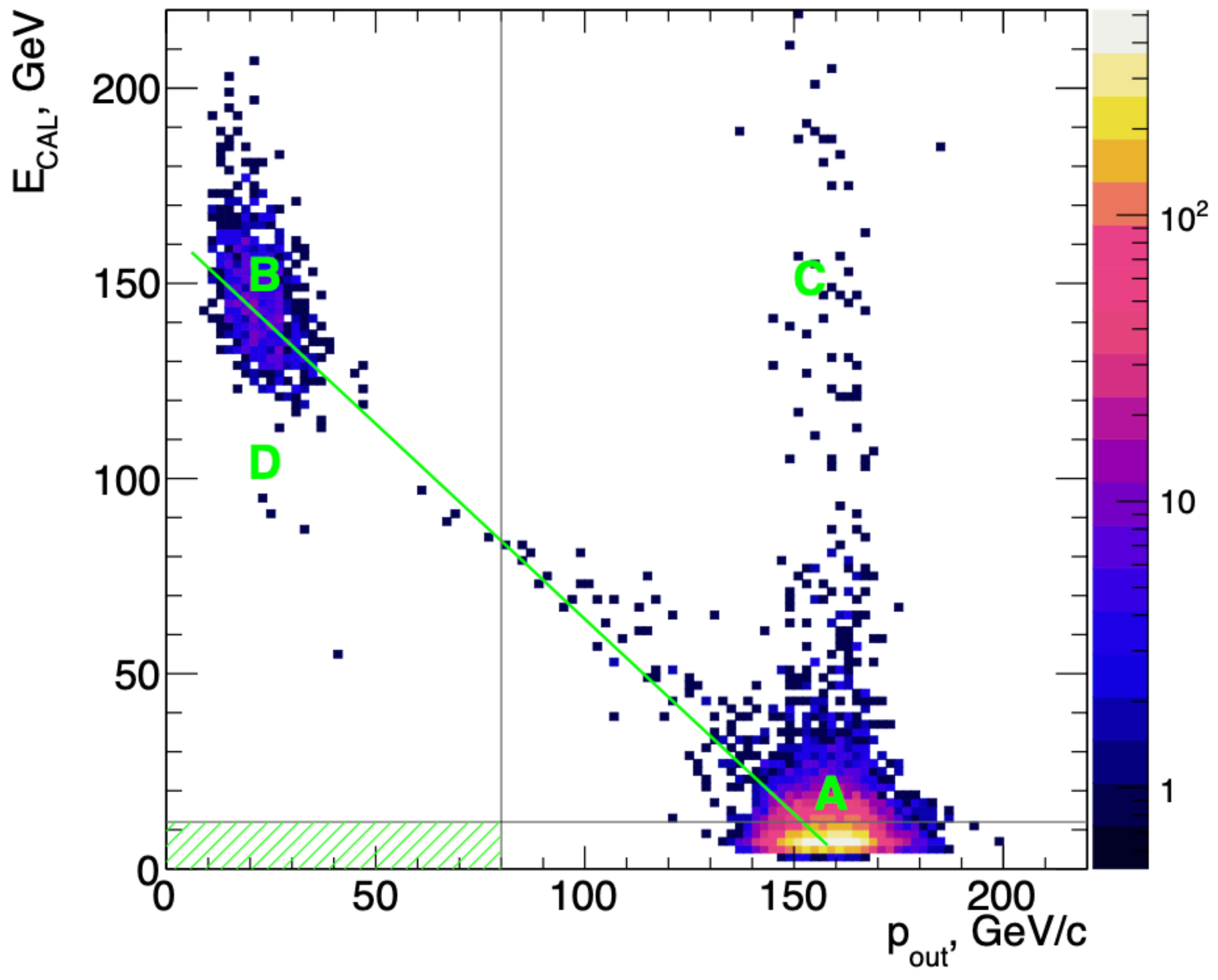
Wu, Hardy, **NS**, arXiv: 2406.01668

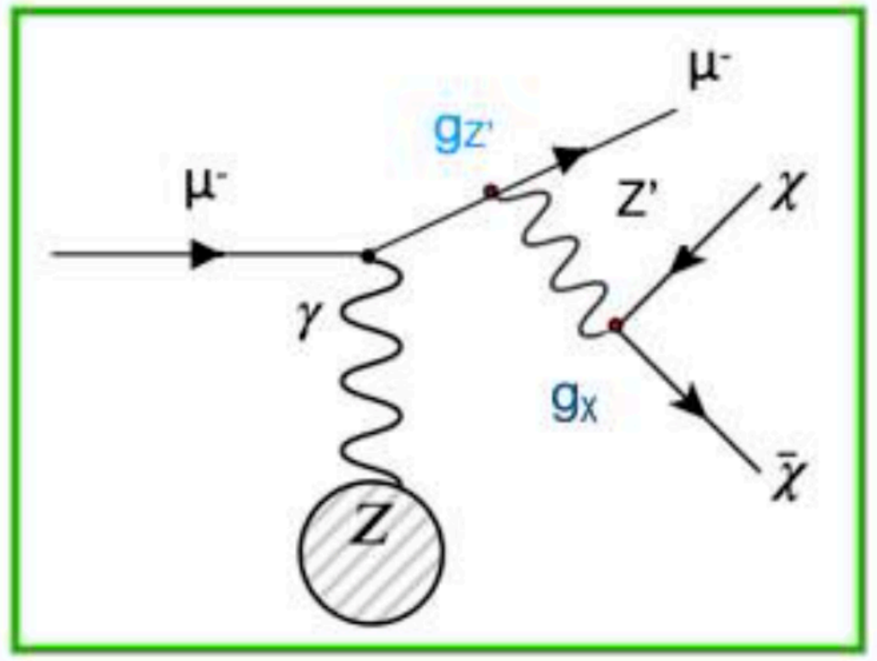
Search for New Physics at NA64

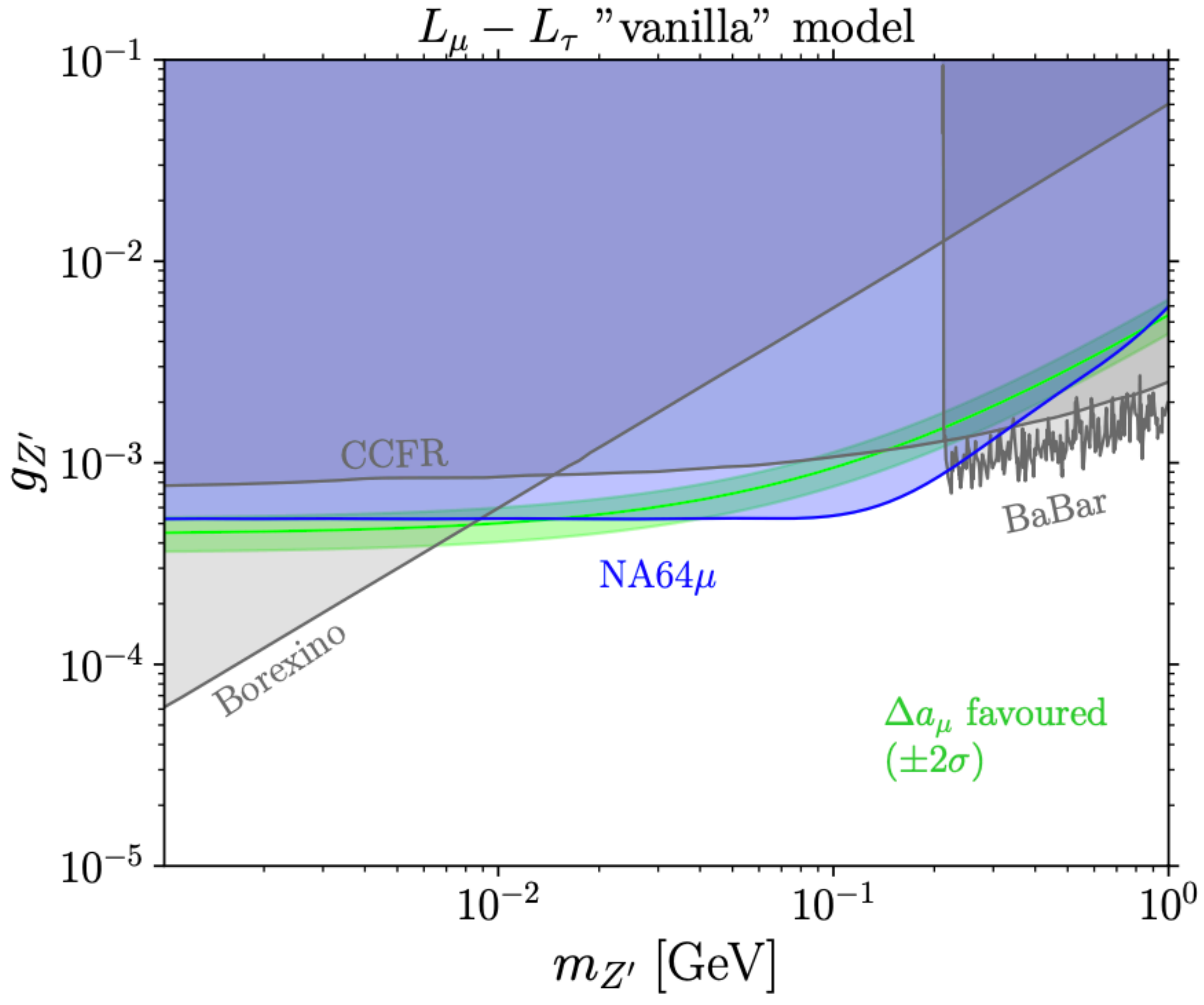
NA64μ



1.98×10^{10} muon on target

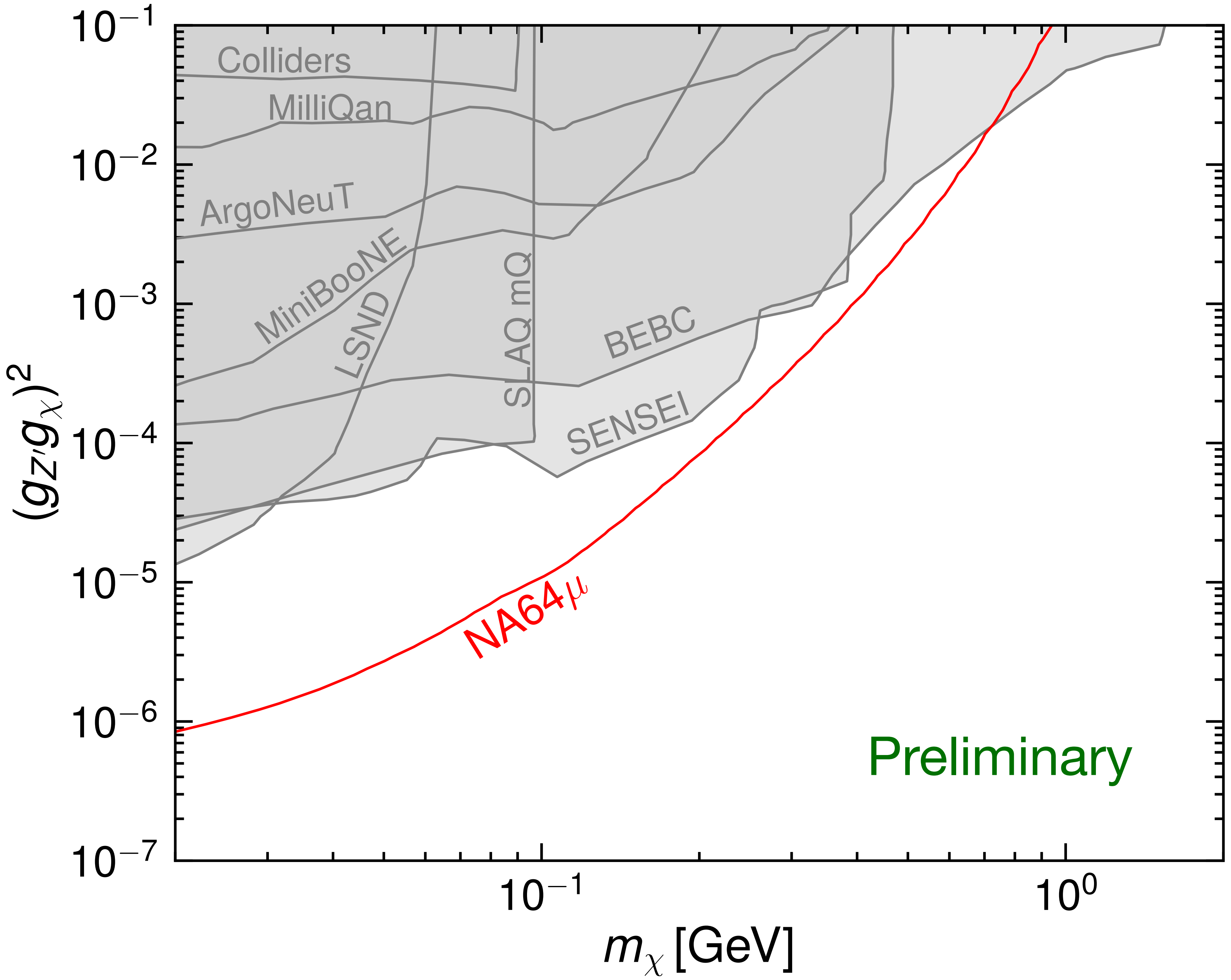


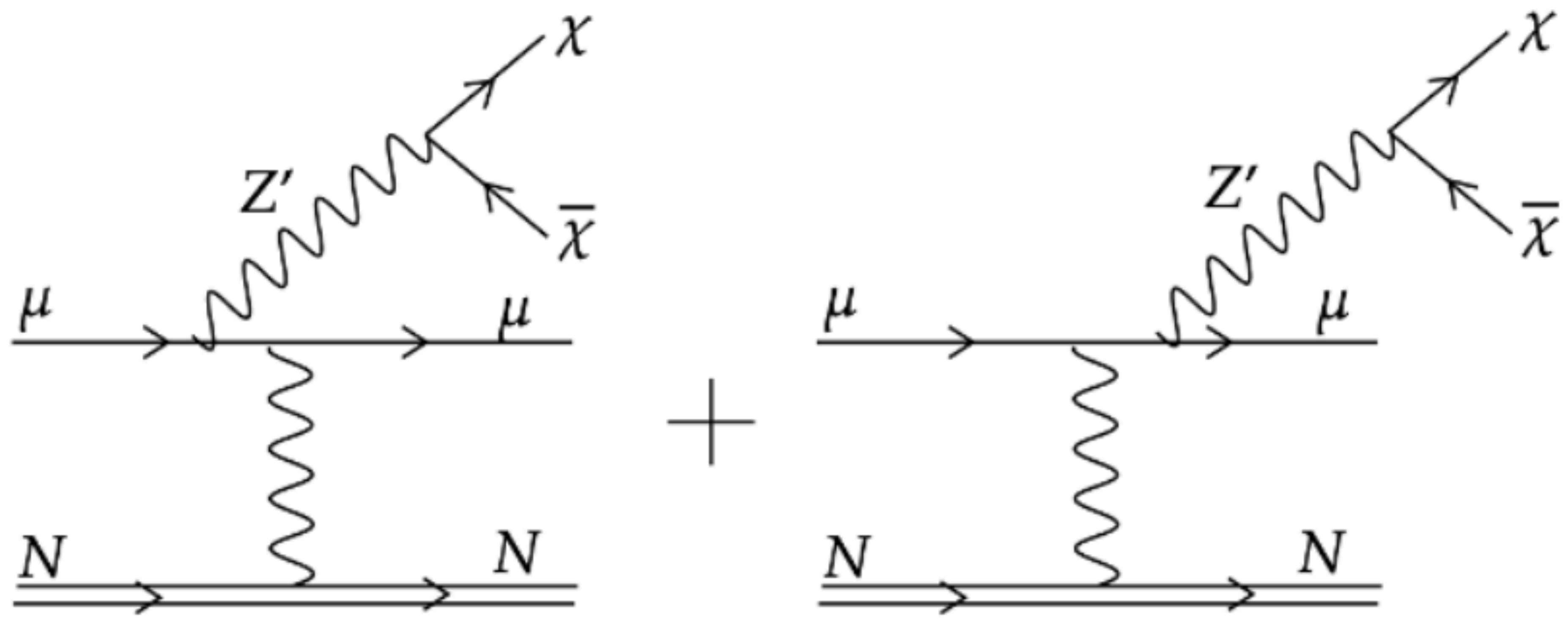


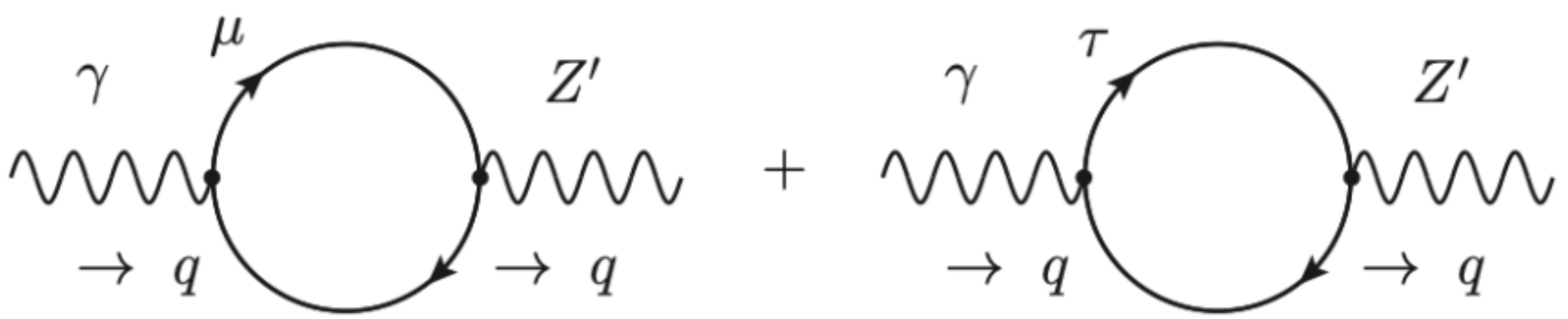


Muophilic Millicharge @NA64μ

$$L \supset -\frac{1}{4}Z'_{\alpha\beta}Z'^{\alpha\beta} + g_{Z'}(\bar{\mu}\gamma_\alpha\mu + \bar{\nu}_{\mu L}\gamma_\alpha\nu_{\mu L} - \bar{\tau}\gamma_\alpha\tau - \bar{\nu}_{\tau L}\gamma_\alpha\nu_{\tau L})Z'^{\alpha} + \bar{\chi}(i\partial\!\!\!/ + g_\chi Z\!\!\!/' - m_\chi)\chi$$



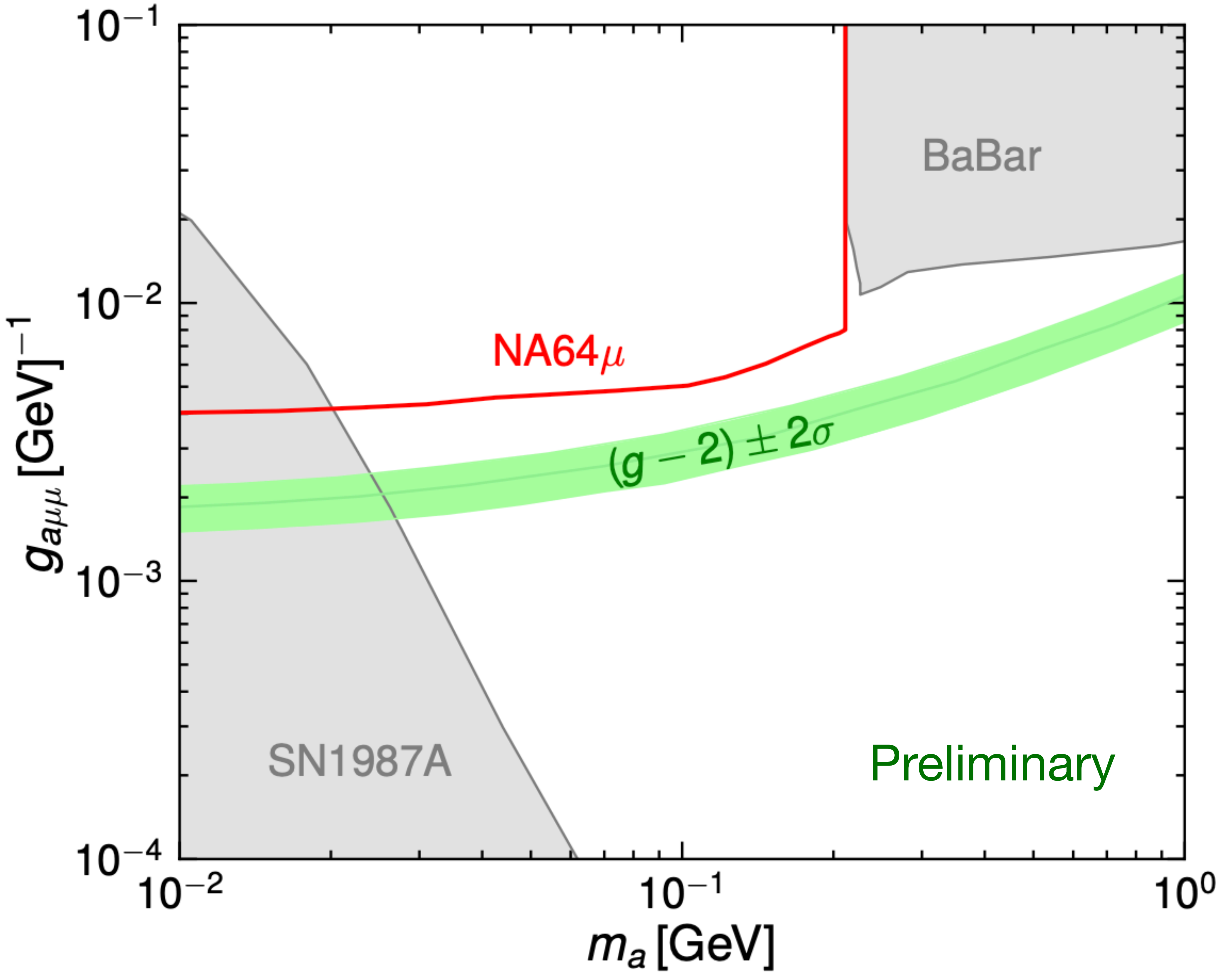


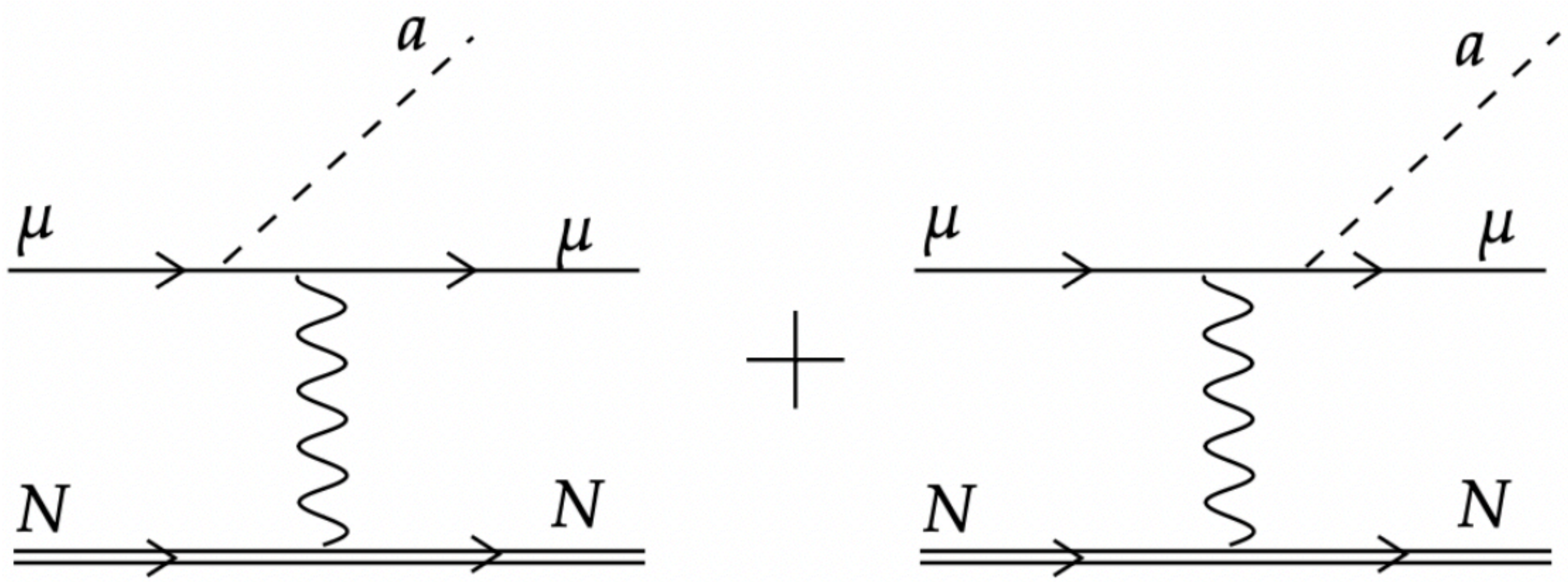


$$\epsilon_{\text{eff}} = \frac{g_{Z'}g_\chi}{2\pi^2}\int_0^1 dx(1-x)\ln\frac{m_\tau^2 - x(1-x)q^2}{m_\mu^2 - x(1-x)q^2}.$$

Axion-Muon Interaction @NA64μ

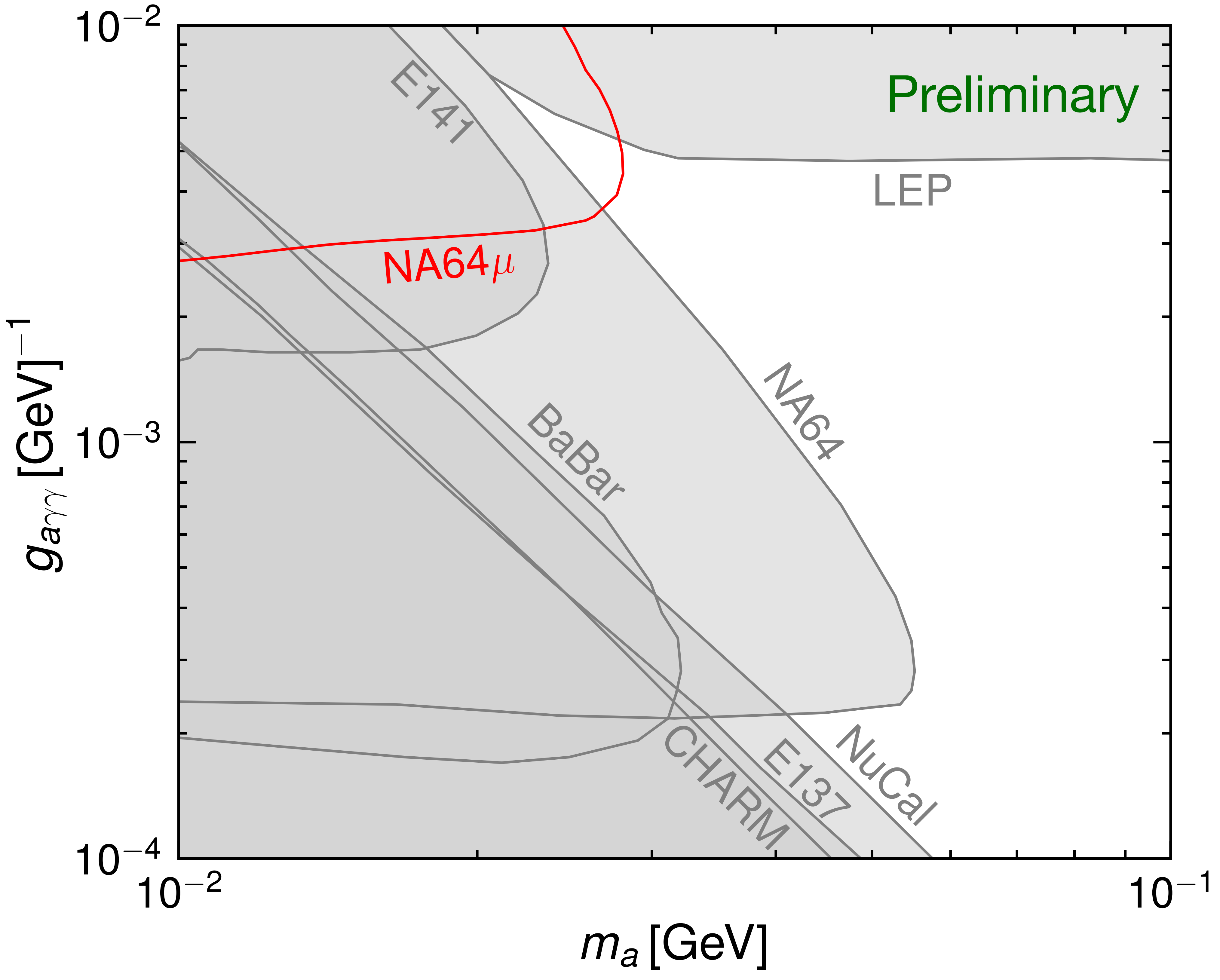
$$\mathcal{L}_{\mathrm{ALP}} \supset \frac{1}{2}(\partial_\sigma a)^2 - \frac{1}{2}m_a^2 a^2 + g_{a\mu\mu}(\partial_\sigma a)\bar{\mu}\gamma^\sigma\gamma_5\mu$$



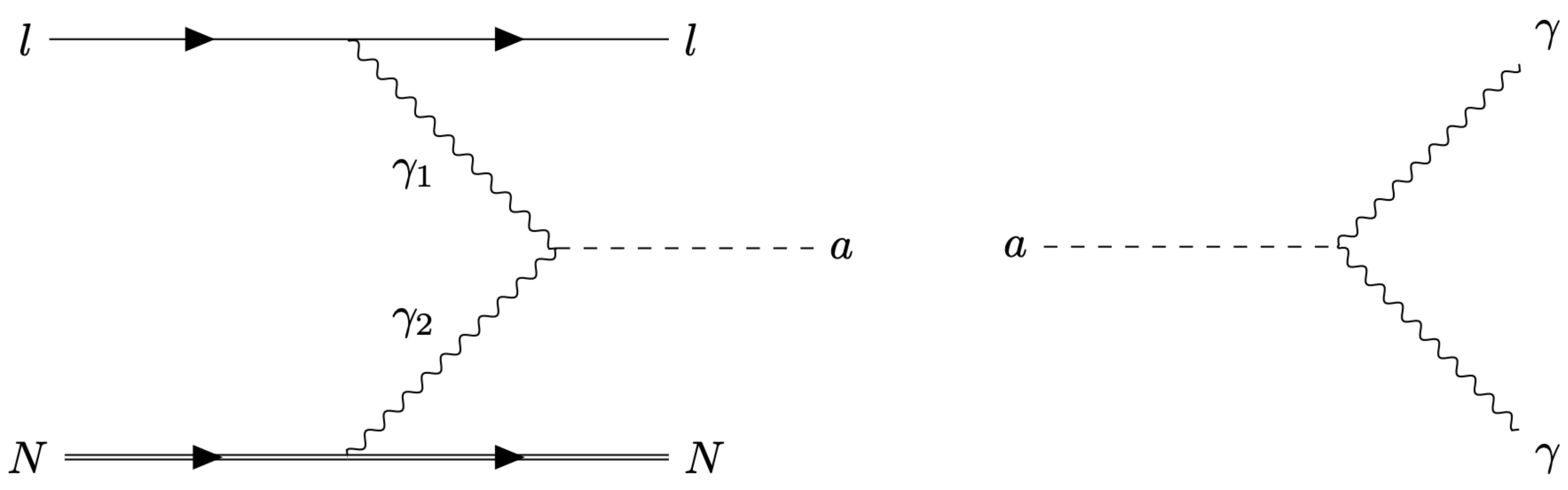


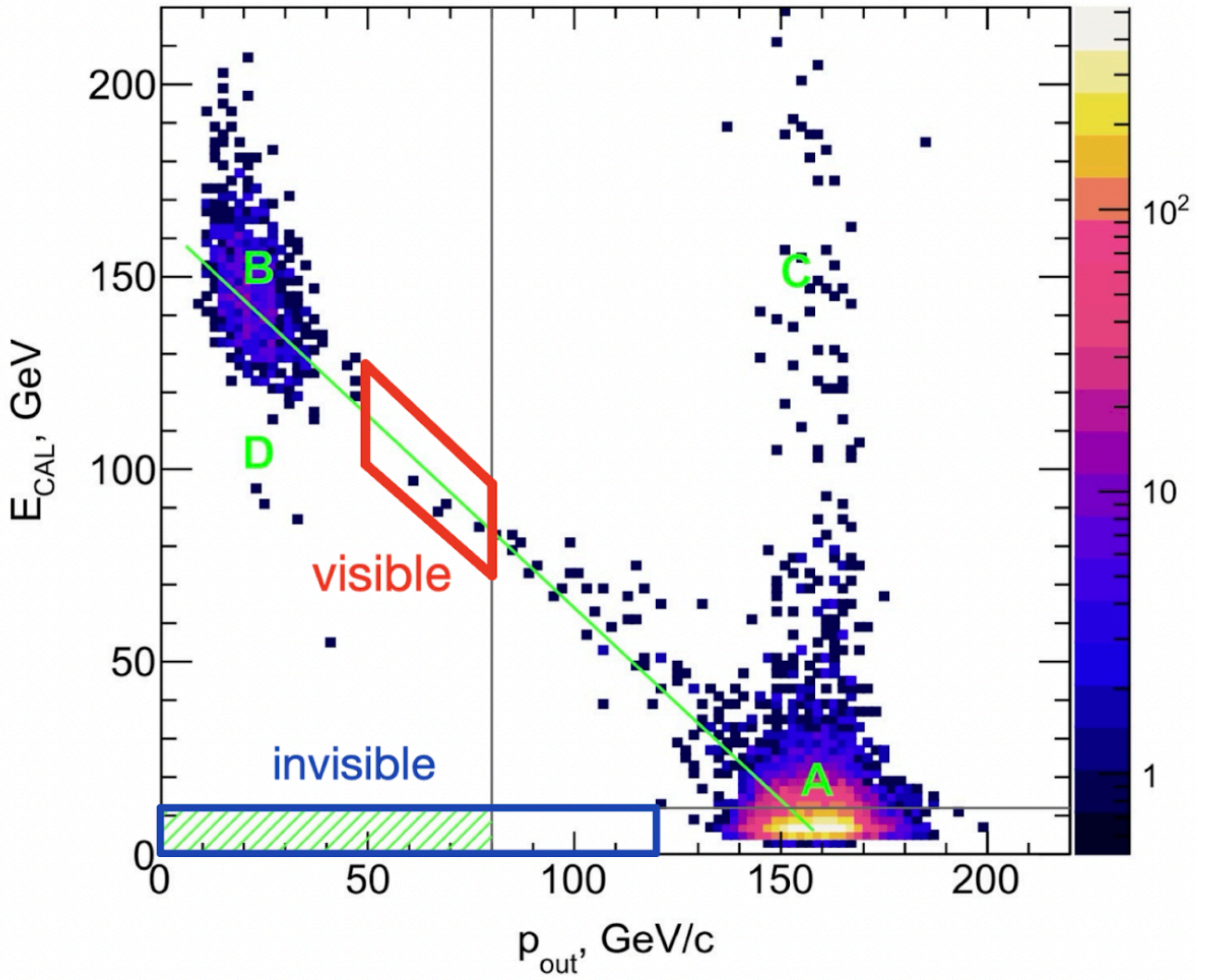
Axion-Photon Interaction @NA64μ

$$\mathcal{L}_{\text{ALP}} \supset \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$



visible+invisible





Summary

- ❖ Overview of New Physics in Neutrino Scattering
- ❖ Search for New Physics at Neutrino Experiment
- ❖ Search for New Physics at NA64μ

Thanks

Back up

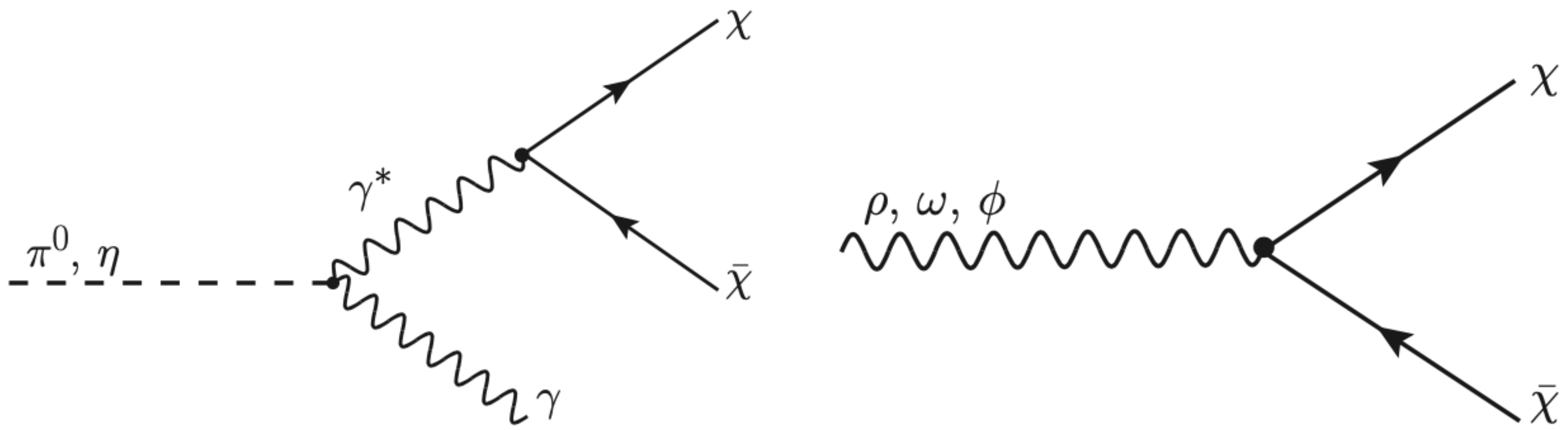
Millicharge Particles from Light Meson Decay

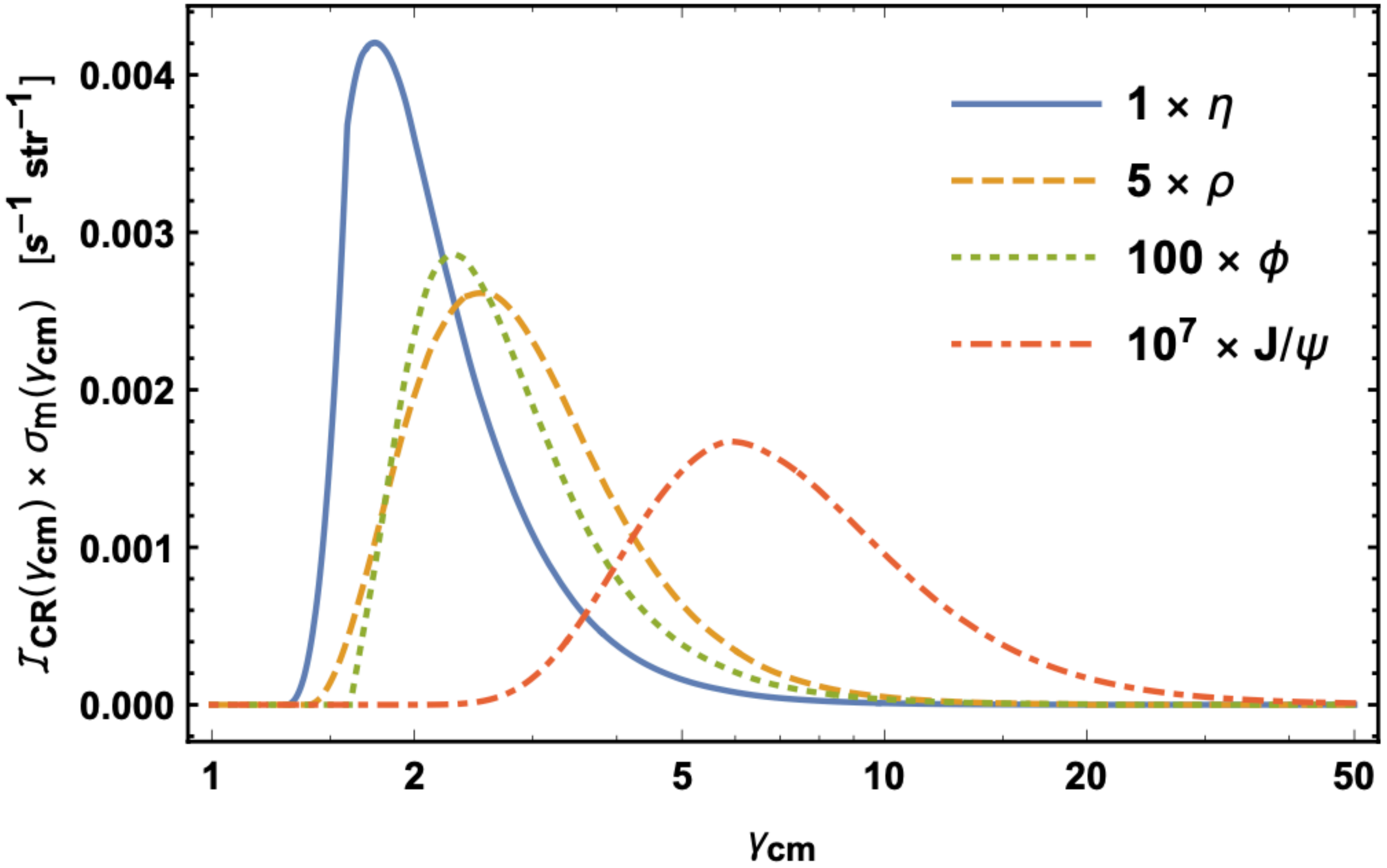
$$\Phi_{\mathfrak{m}}(\gamma_{\mathfrak{m}}) = \Omega_{\text{eff}} \int \mathcal{I}_{\text{CR}}(\gamma_{\text{cm}}) \frac{\sigma_{\mathfrak{m}}(\gamma_{\text{cm}})}{\sigma_{\text{in}}(\gamma_{\text{cm}})} P(\gamma_{\mathfrak{m}}|\gamma_{\text{cm}})\, \mathrm{d}\gamma_{\text{cm}}$$

$$\gamma_{\text{cm}} = \frac{1}{2}\sqrt{s}/m_p$$

$$P(\gamma_{\mathfrak{m}}|\gamma_{\text{cm}}) \approx \sum_{\alpha} \frac{1}{\sigma_{\mathfrak{m}}} \times \frac{\mathrm{d}\sigma_{\mathfrak{m}}}{\mathrm{d}x_F} \times \frac{\mathrm{d}x_F^{(\alpha)}}{\mathrm{d}\gamma_{\mathfrak{m}}}$$

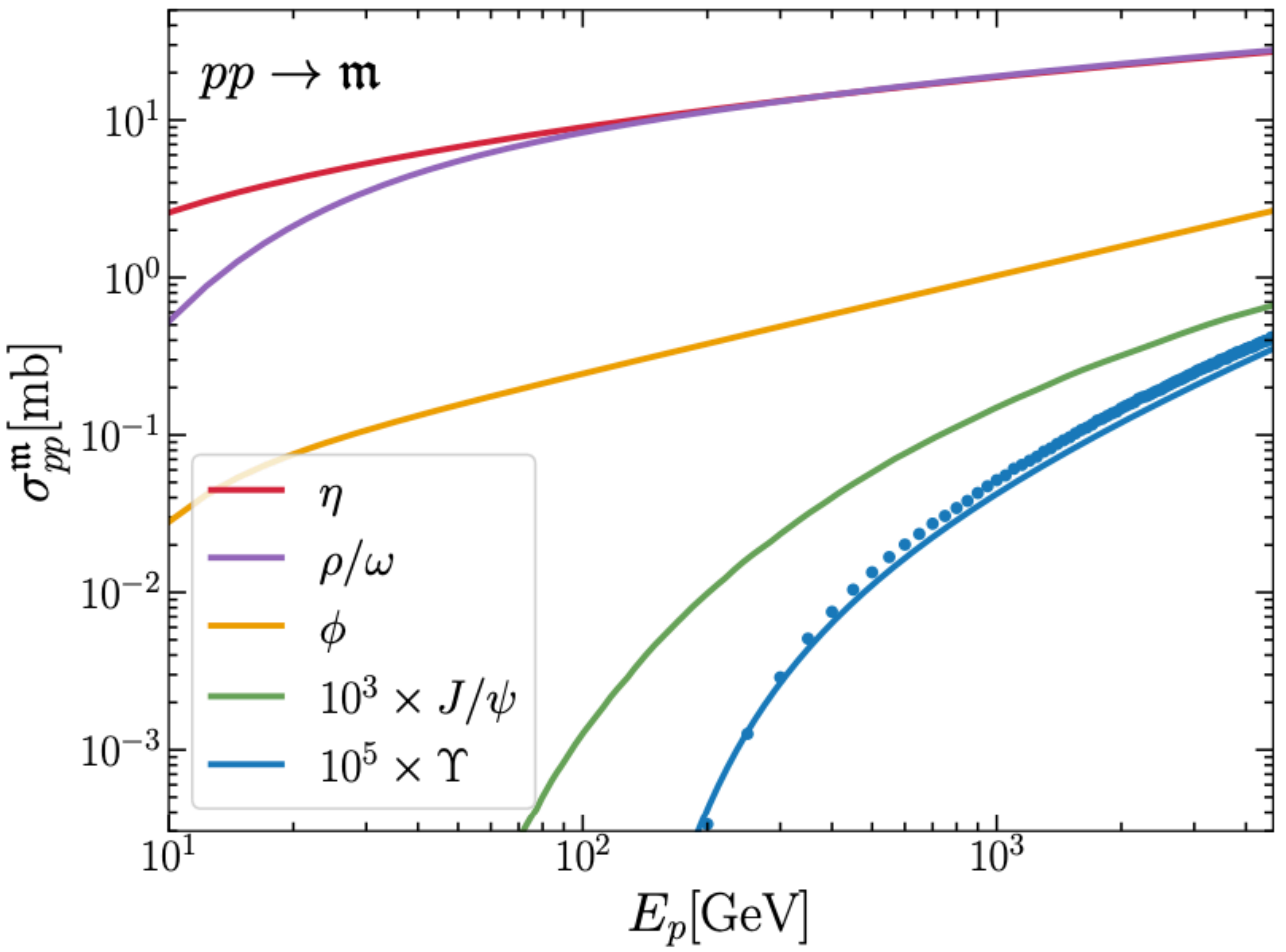
Plestid et al PRD/2002.11732

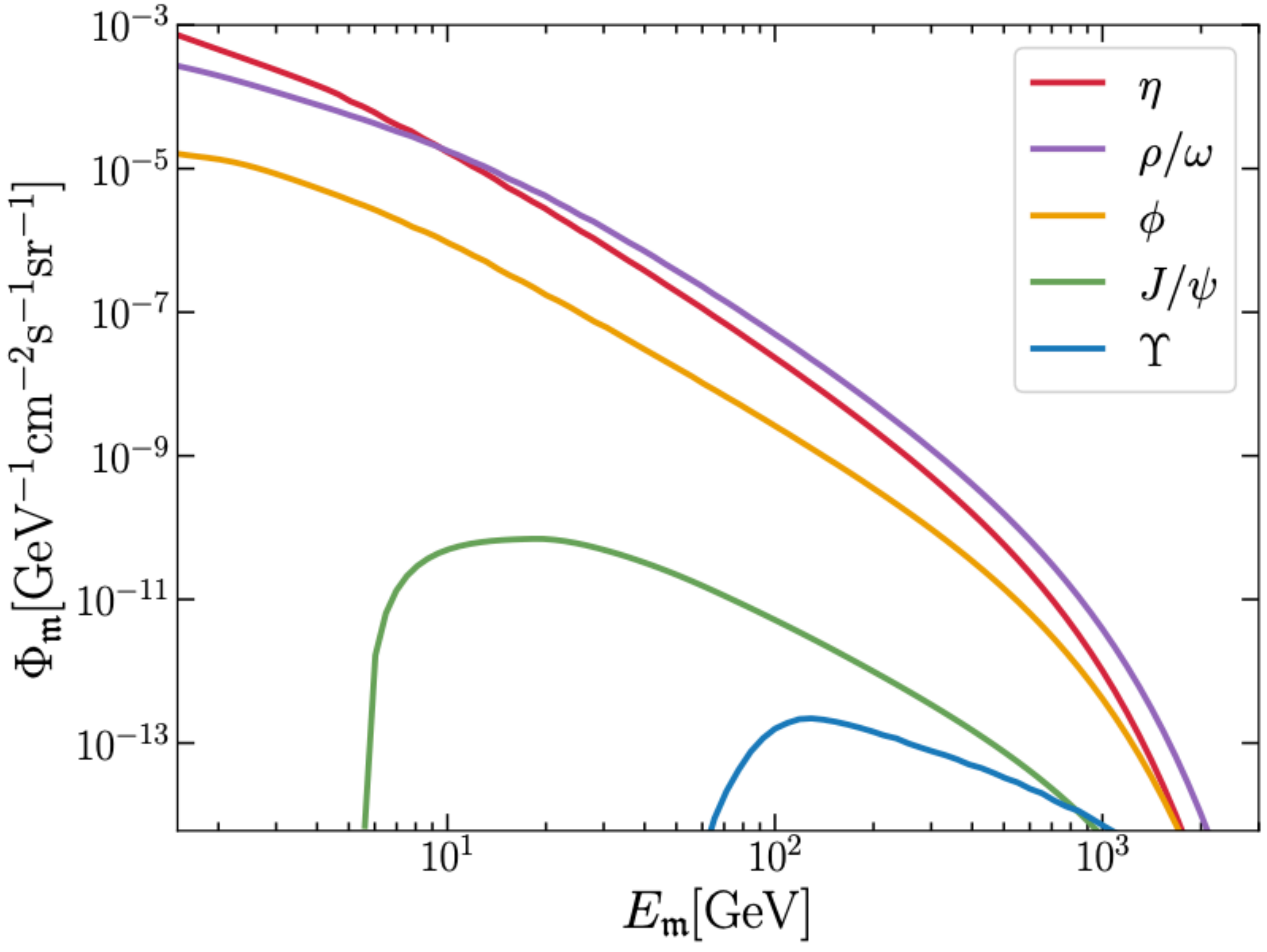




Millicharge Particles from Upsilon Meson Decay

Pythia8 simulations





Wu, Hardy, **NS**, arXiv: 2406.01668

Millicharge Particles from Proton Bremsstrahlung

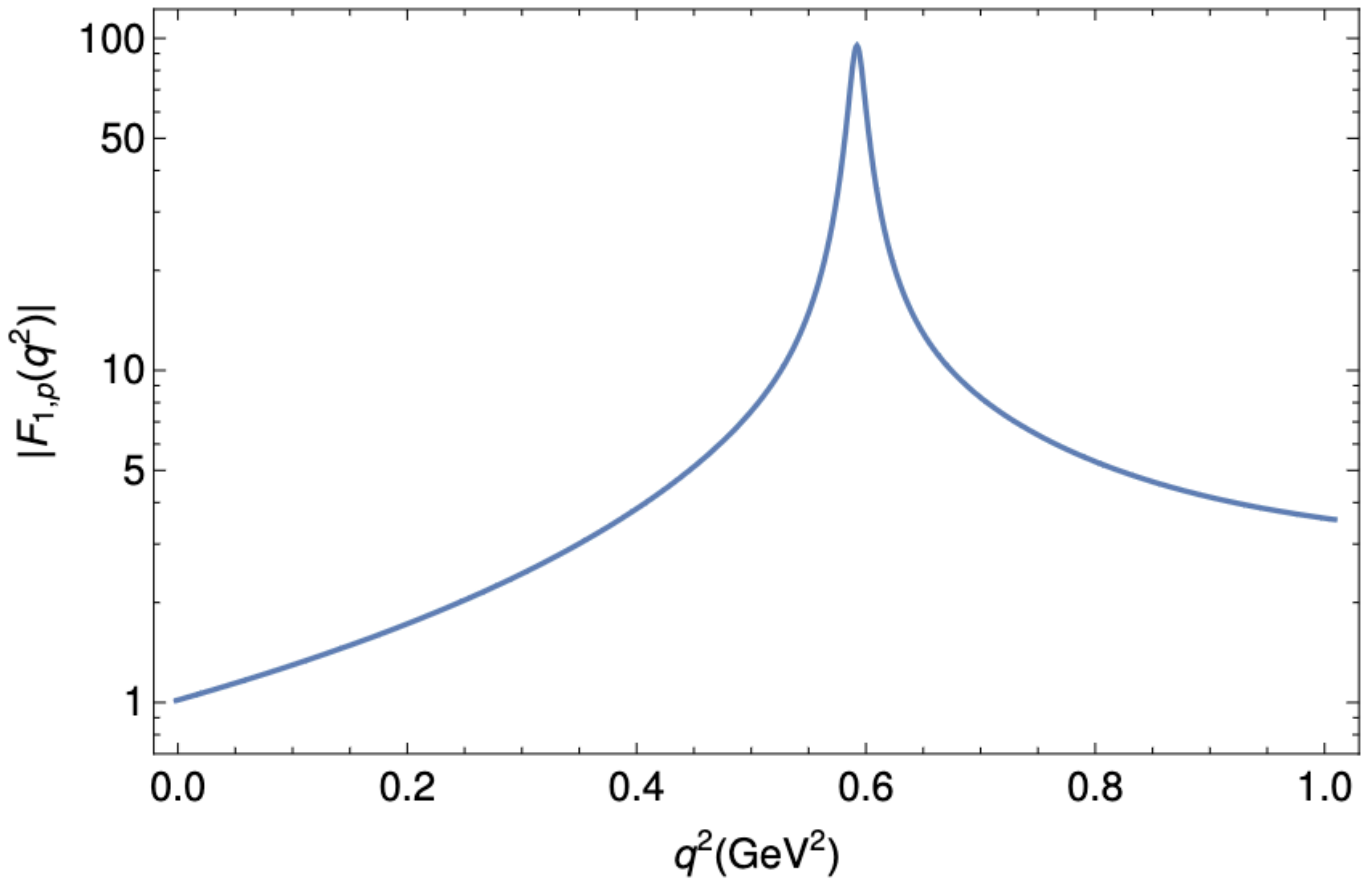
Fermi-Weizsacker-Williams (FWW) approximation with the splitting-kernel approach

$$d\sigma^{\rm PB}(s) \simeq d\mathscr{P}_{p\to\gamma^* p'} \times \sigma_{pN}(s')$$

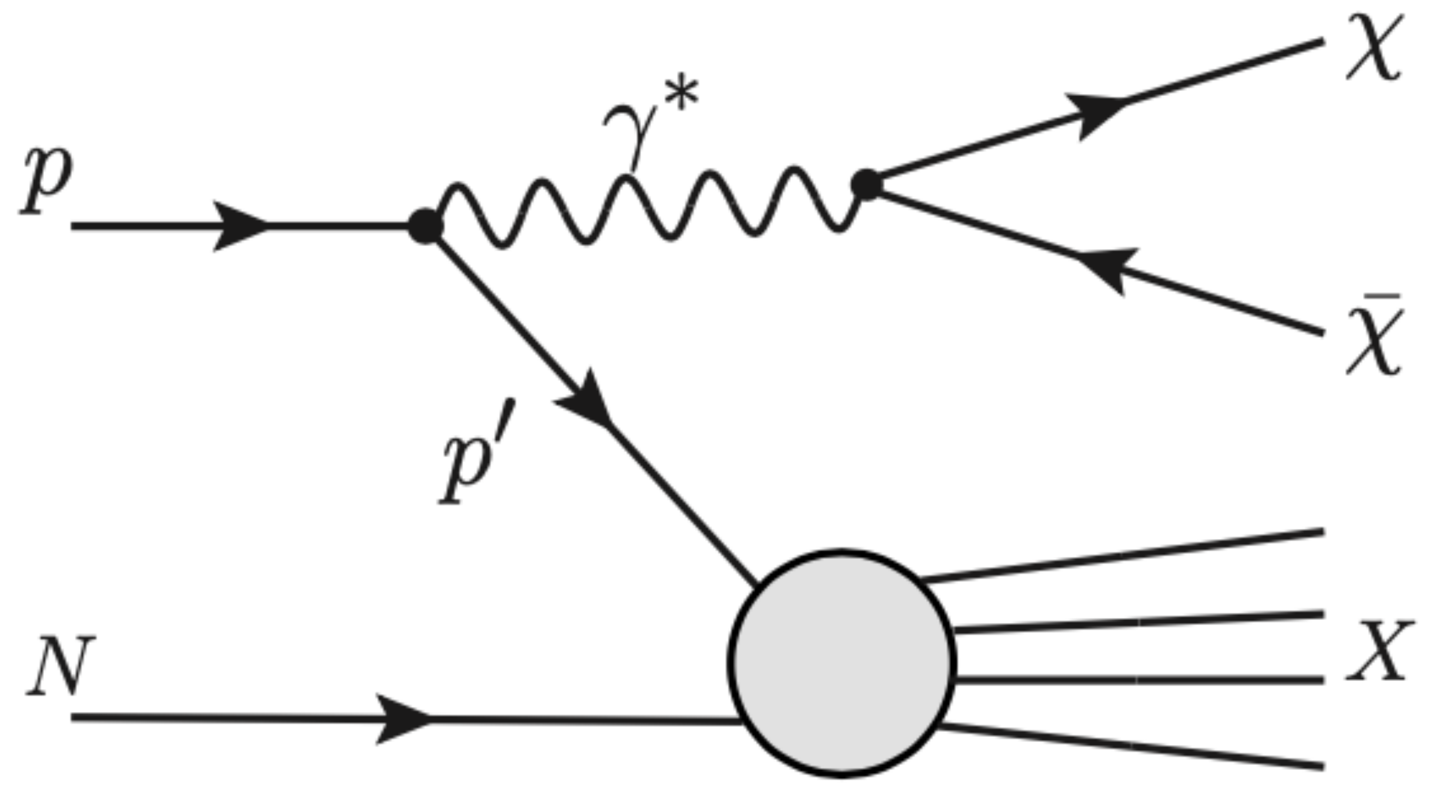
Kernel

$$\frac{d^2\mathcal{P}^{\rm FWW}_{p\to\gamma^* p}}{dE_k\, d\cos\theta_k} = \left|\mathbf{J}(z,p_T^2)\right| \frac{d^2\mathcal{P}^{\rm FWW}_{p\to\gamma^* p}}{dz\, dp_T^2} = \left|\mathbf{J}(z,p_T^2)\right| \left|F_V(k)\right|^2 \omega(z,p_T^2)$$

EM form factor



deNiverville et al PRD/1609.01770



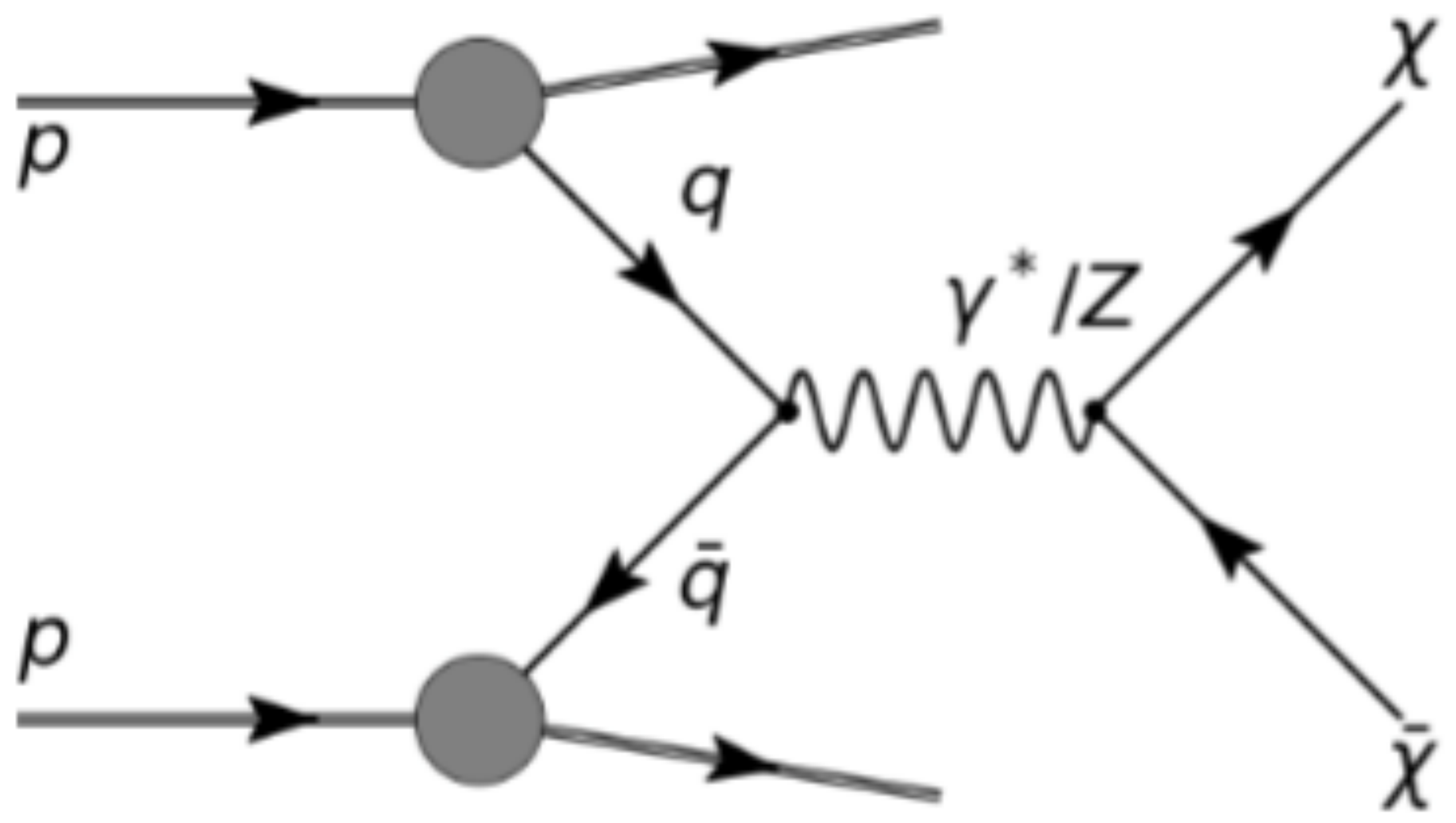
$$\Phi^{\rm PB}_\chi = \int dE_p \Phi_p \frac{\epsilon^2 e^2}{6\pi^2} \int \frac{dk^2}{k^2} \sqrt{1-\frac{4m_\chi^2}{k^2}} \left(1+\frac{2m_\chi^2}{k^2}\right)$$
$$\times \int dE_k \frac{1}{\sigma_{pN}} \frac{d\sigma^{\rm PB}}{dE_k} \frac{\Theta(E_\chi - E_{\rm min})\Theta(E_{\rm max}-E_\chi)}{E_{\rm max}-E_{\rm min}}$$

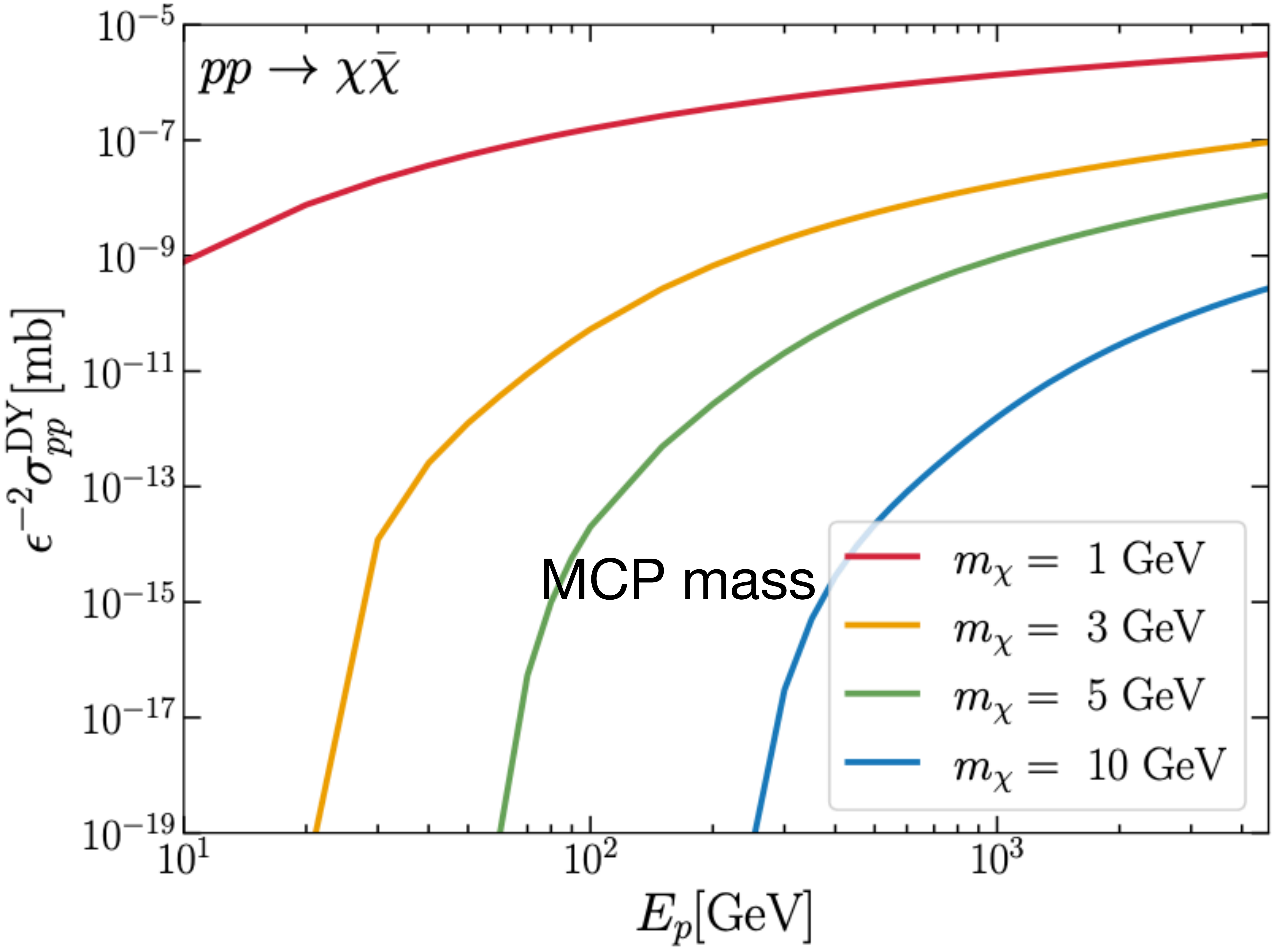
Du et al arXiv: 2211.11469

Du et al arXiv: 2308.05607

Millicharge Particles from Drell-Yan Process

Madgraph simulations



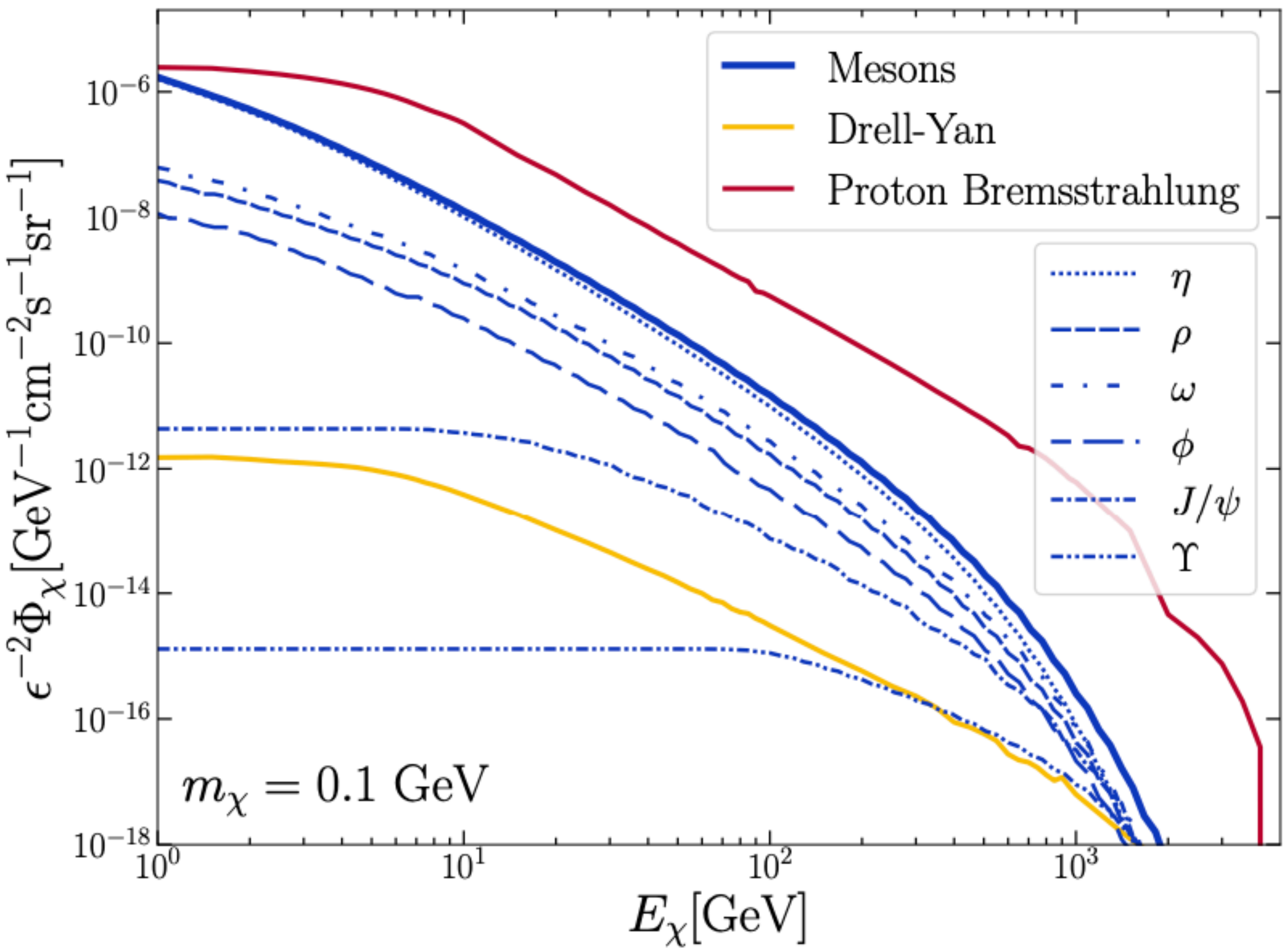


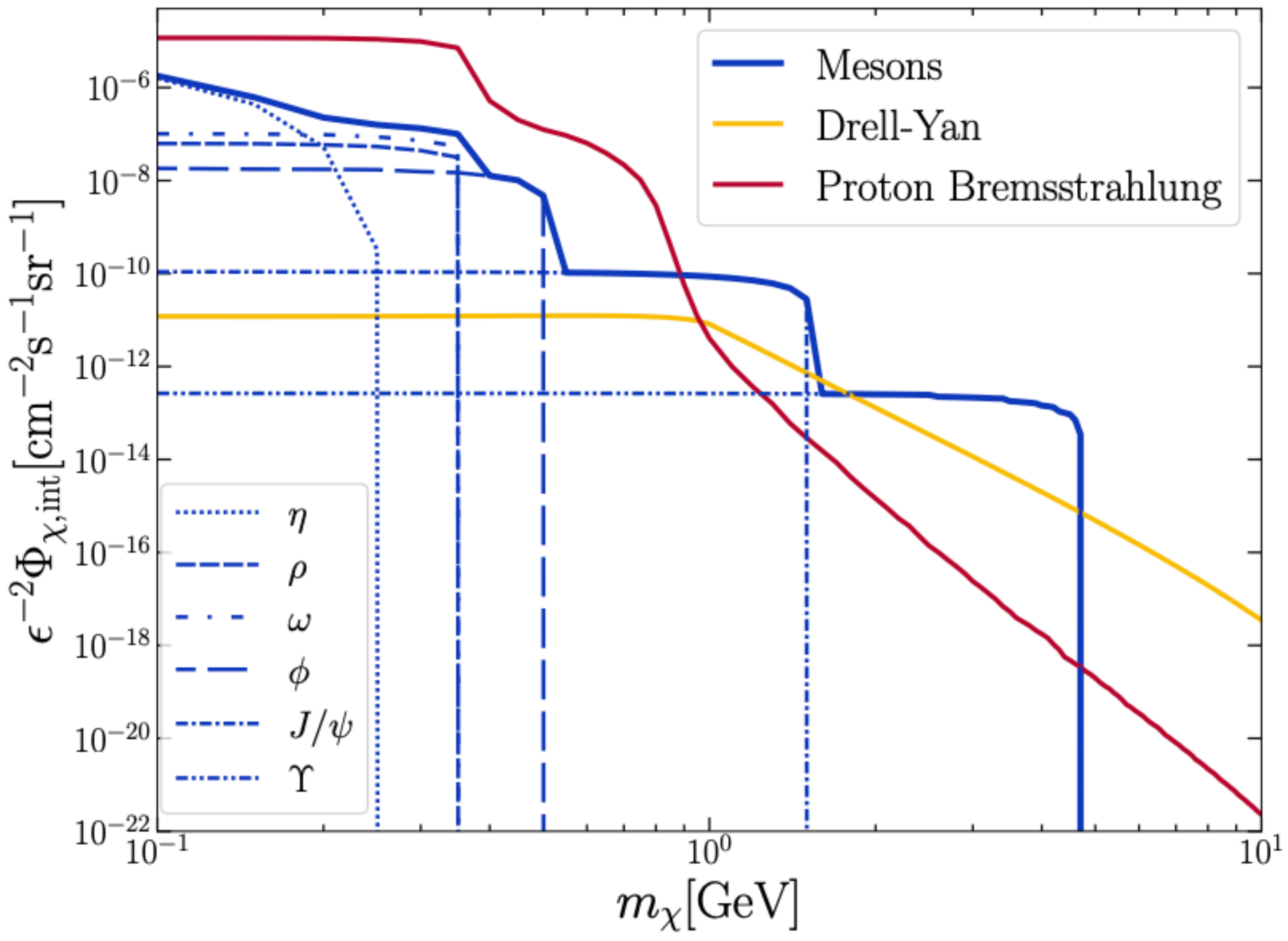
$$\hat{\sigma}\left(q(p_1)\,\bar{q}(p_2) \to l^+l^-\right) = \frac{4\pi\alpha^2}{3\hat{s}}\,\frac{1}{N_c}\,Q_q^2$$

Wu, Hardy, **NS**, arXiv: 2406.01668

Millicharge Particles Flux

Meson decay+Proton Bremsstrahlung+Drell-Yan

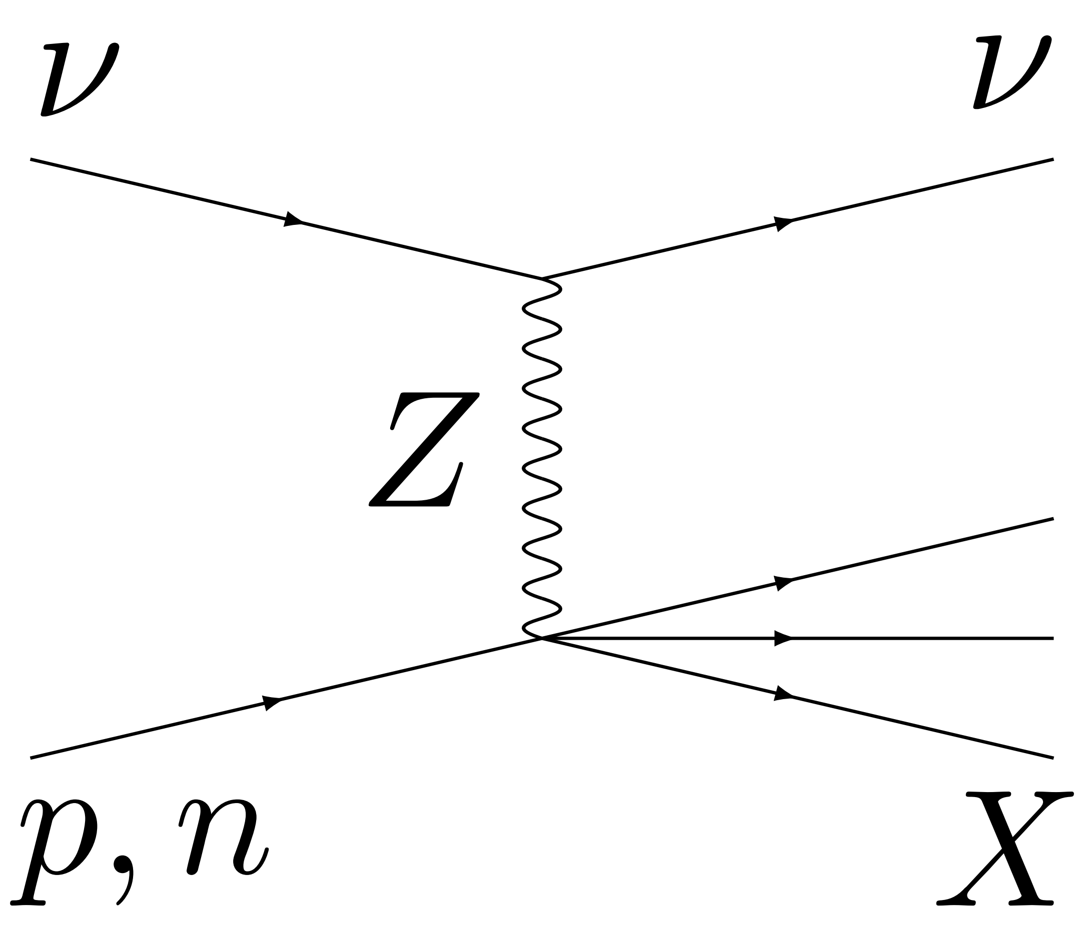


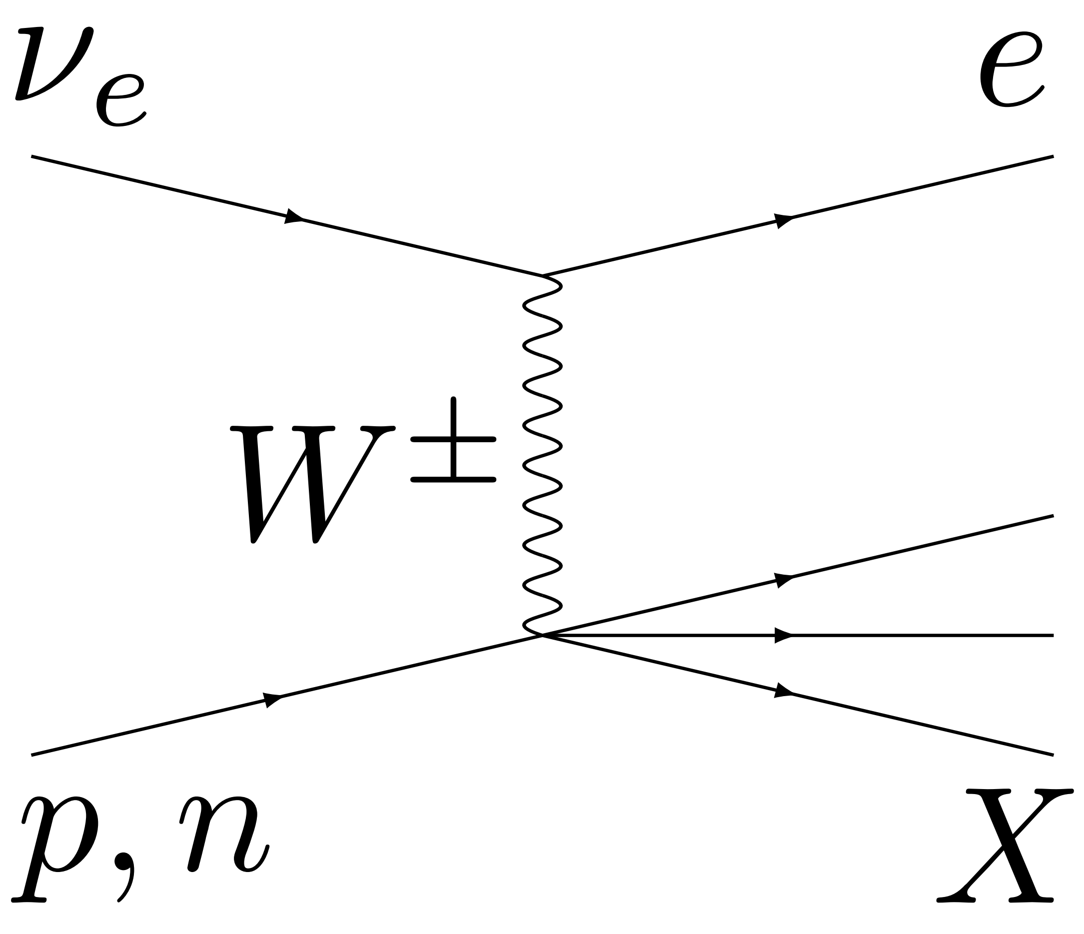


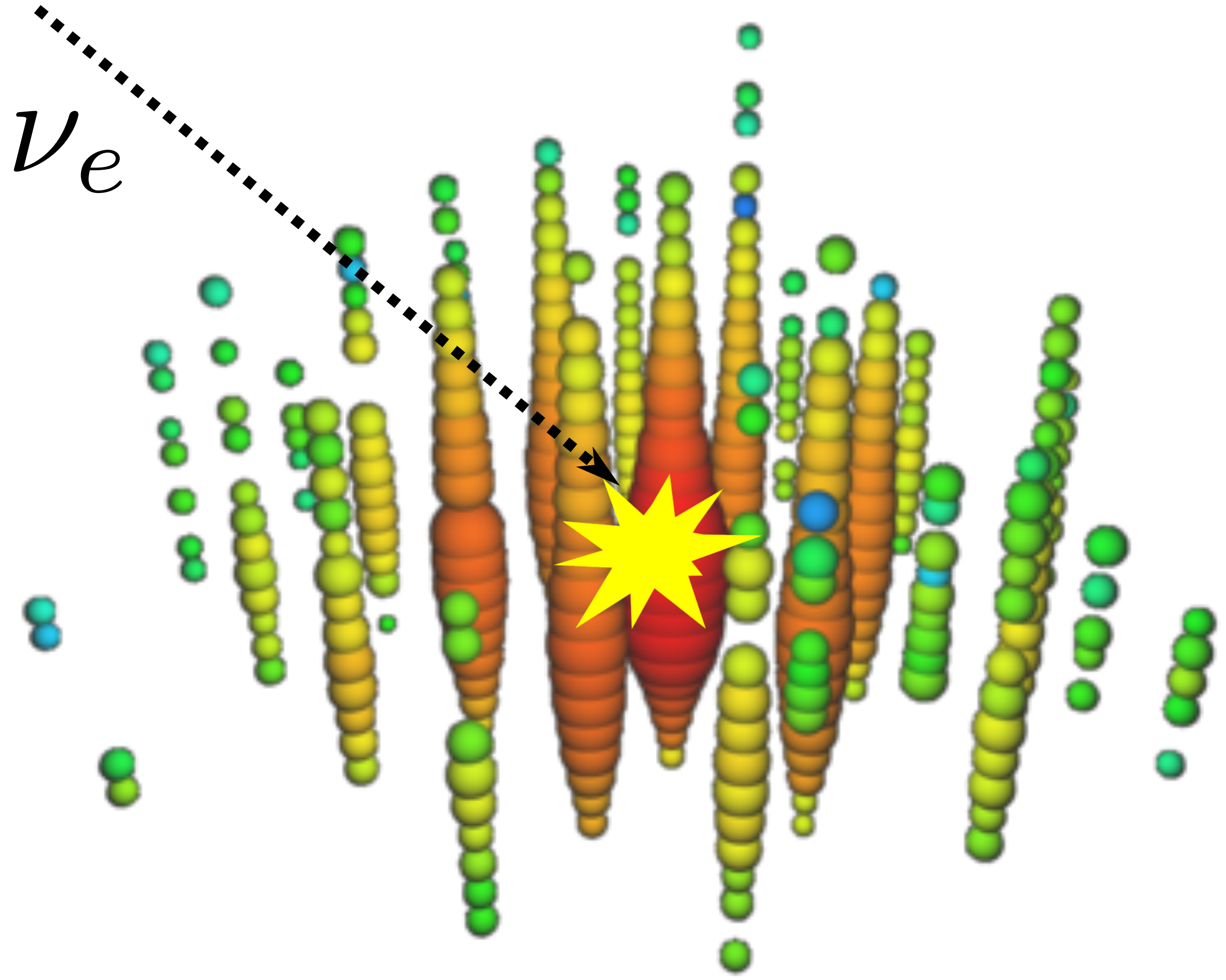
Wu, Hardy, **NS**, arXiv: 2406.01668

Shower

Neutral current (NC) & ν_e charged current (CC) (low energy ν_τ CC)





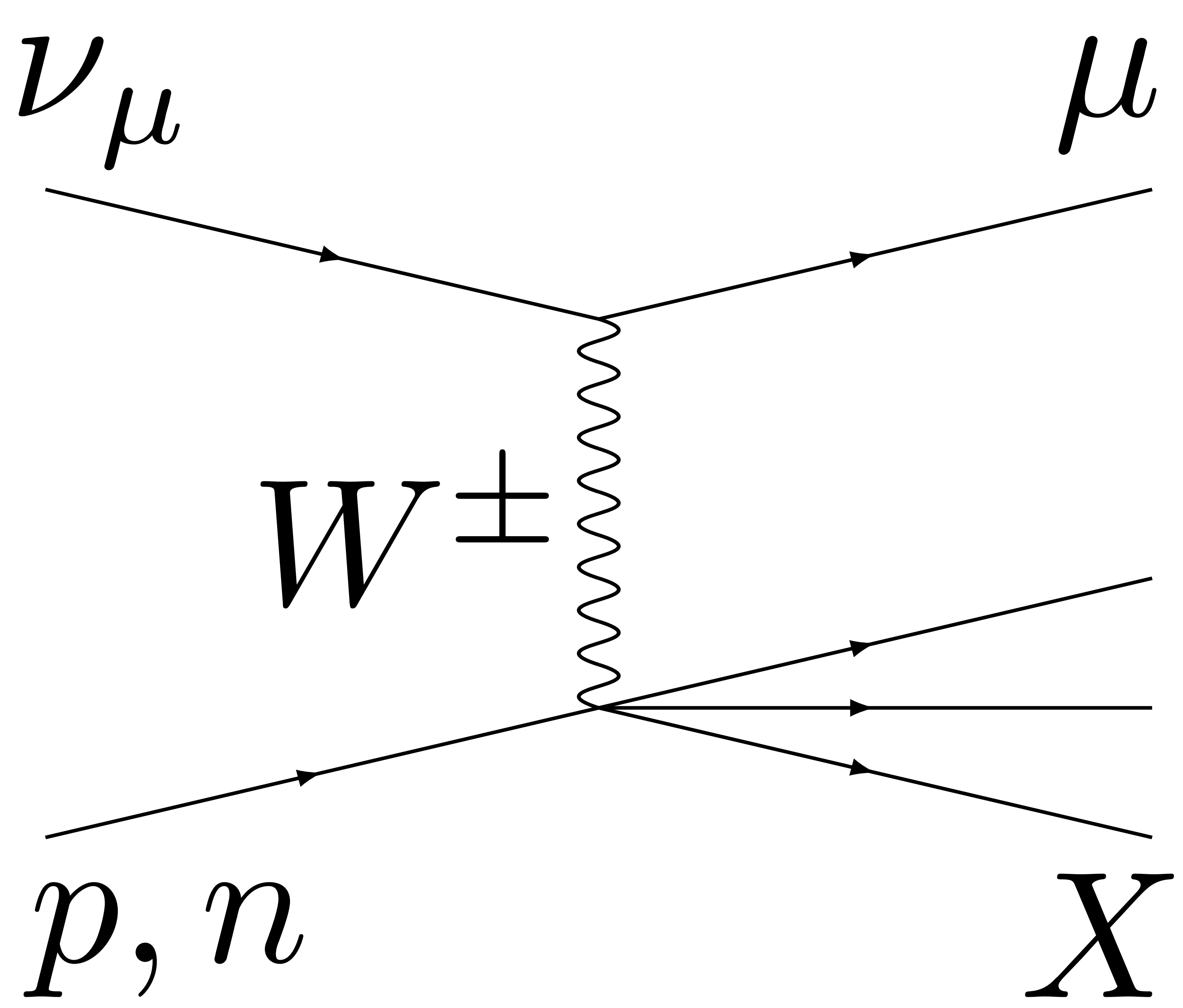


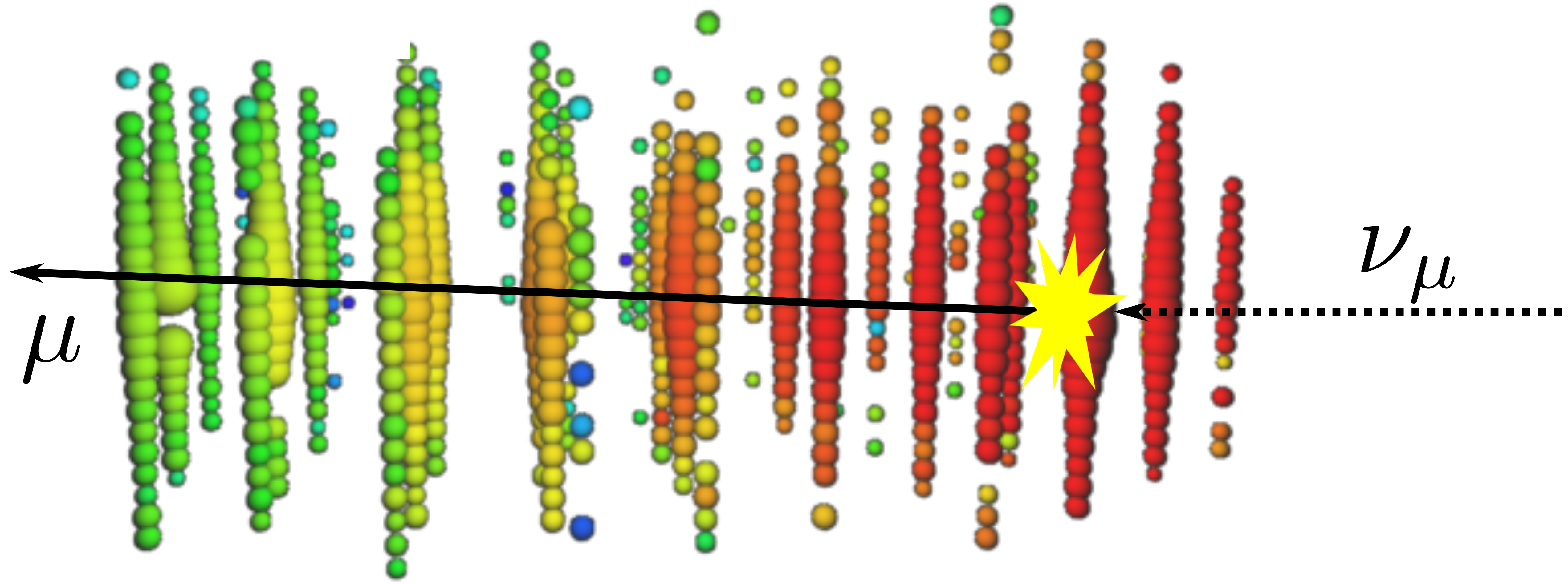
icecube.wisc.edu

Angular resolution ~ 8°, energy resolution ~ 15%

Track

Charged current (CC) (ν_μ CC)





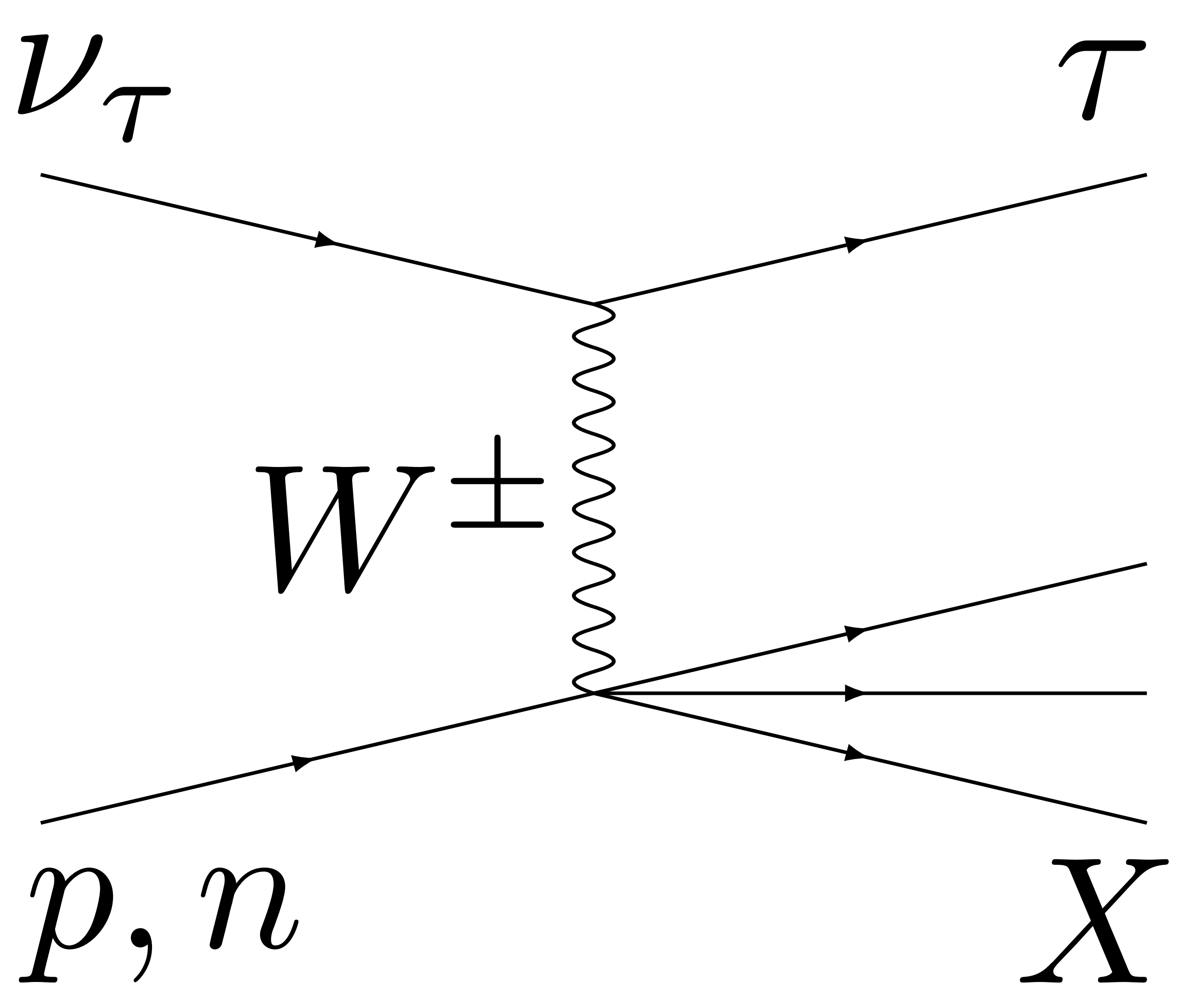
icecube.wisc.edu

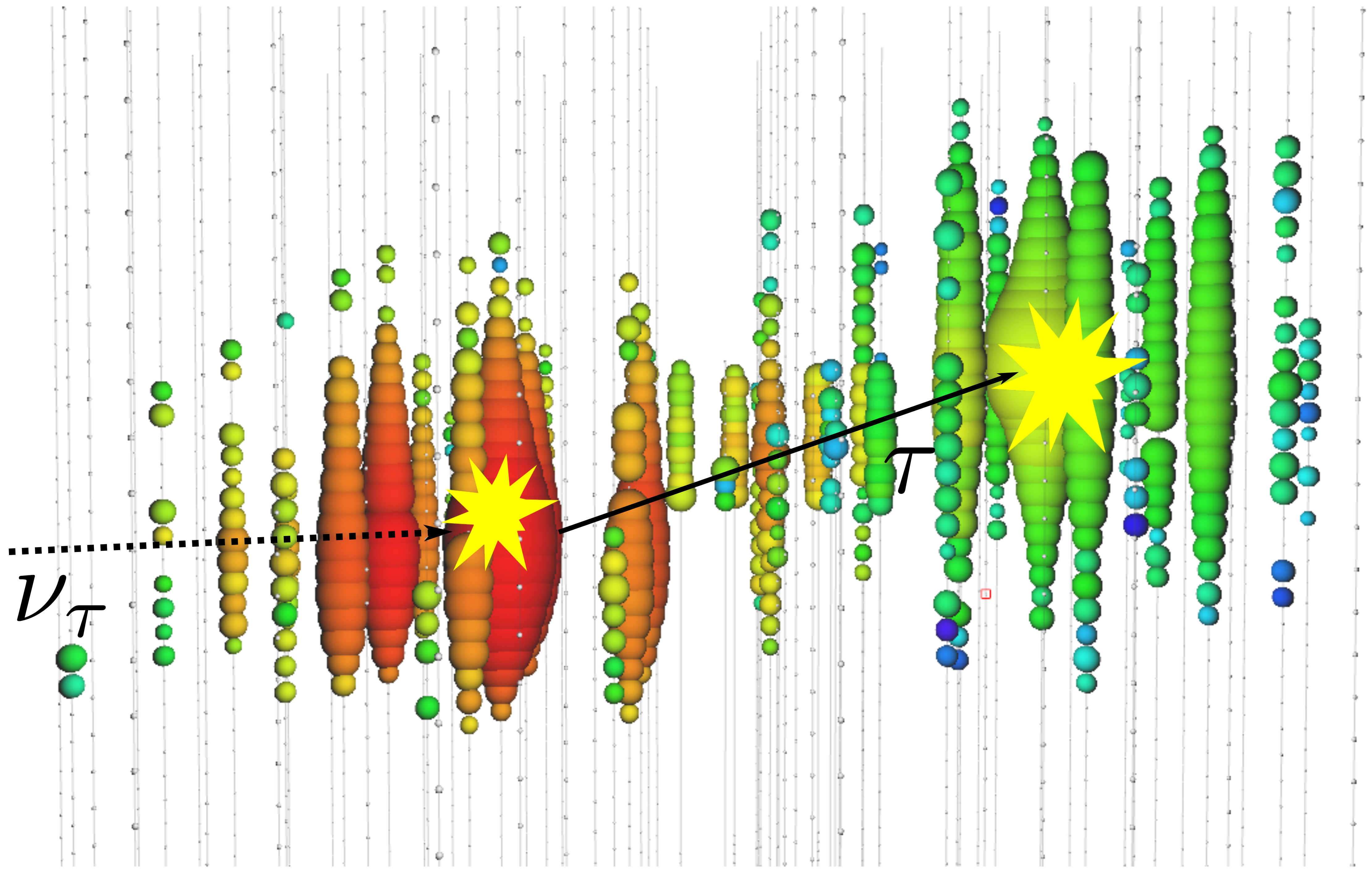
Angular resolution $\leq 1°$, energy resolution ~ 29%

Aswathi Balagopal V., TeVPa 2023

Double bang

Charged current (CC) (high energy ν_τ CC)





icecube.wisc.edu

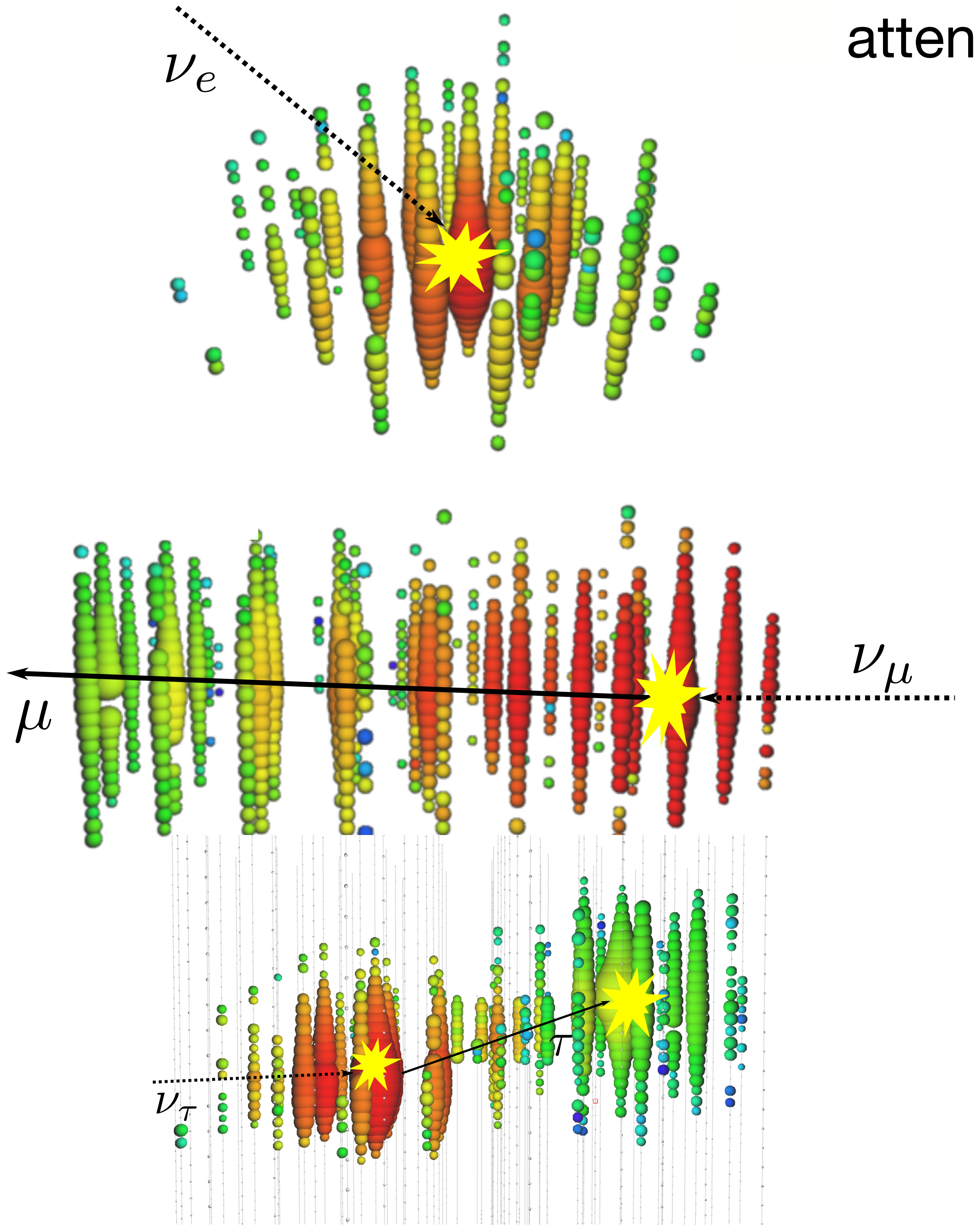
Decay length ~$50\ \mathrm{m}\,\mathrm{E}_\tau/\mathrm{PeV}$, length resolution ~ 2 m

Aswathi Balagopal V., TeVPa 2023

高能中微子探测

$$\frac{dN^{\mathrm{sh,NC},f}_{\nu_\ell}}{dE_{\mathrm{dep}}} = T\,N_A \int_0^\infty dE_\nu\, Att^f_{\nu_\ell}(E_\nu)\, \frac{d\phi^f_{\nu_\ell}(E_\nu)}{dE_\nu} \int_0^1 dy\, M_{\mathrm{eff}}(E^{\mathrm{NC}})\, R(E^{\mathrm{NC}}, E_{\mathrm{dep}}, \sigma(E^{\mathrm{NC}}))\, \frac{d\sigma^{\mathrm{NC}}_{\nu_\ell}(E_\nu, y)}{dy}$$

attenuation ↗ · ν flux ↗ · detector effective mass ↗ · energy resolution ↗ · differential cross section ↗



$$\frac{dN^{\mathrm{sh},f}_{e}}{dE_{\mathrm{dep}}} = \frac{dN^{\mathrm{sh,NC},f}_{\nu_e}}{dE_{\mathrm{dep}}} + \frac{dN^{\mathrm{sh,NC},f}_{\bar\nu_e}}{dE_{\mathrm{dep}}} + \frac{dN^{\mathrm{sh,CC},f}_{\nu_e}}{dE_{\mathrm{dep}}} + \frac{dN^{\mathrm{sh,CC},f}_{\bar\nu_e}}{dE_{\mathrm{dep}}} + \frac{dN^{\mathrm{sh},e,f}_{\nu_e}}{dE_{\mathrm{dep}}} + \frac{dN^{\mathrm{sh},e,f}_{\bar\nu_e}}{dE_{\mathrm{dep}}} + \frac{dN^{\mathrm{sh},e,f}_{\bar\nu_e,\tau}}{dE_{\mathrm{dep}}} + \frac{dN^{\mathrm{sh},e,f}_{\bar\nu_e,h}}{dE_{\mathrm{dep}}}$$

$$\frac{dN^{\mathrm{sh},f}_{\mu}}{dE_{\mathrm{dep}}} = \frac{dN^{\mathrm{sh,NC},f}_{\nu_\mu}}{dE_{\mathrm{dep}}} + \frac{dN^{\mathrm{sh,NC},f}_{\bar\nu_\mu}}{dE_{\mathrm{dep}}} + \frac{dN^{\mathrm{sh},e,f}_{\nu_\mu}}{dE_{\mathrm{dep}}} + \frac{dN^{\mathrm{sh},e,f}_{\bar\nu_\mu}}{dE_{\mathrm{dep}}}\,,$$

$$\frac{dN^{\mathrm{sh},f}_{\tau}}{dE_{\mathrm{dep}}} = \frac{dN^{\mathrm{sh,NC},f}_{\nu_\tau}}{dE_{\mathrm{dep}}} + \frac{dN^{\mathrm{sh,NC},f}_{\bar\nu_\tau}}{dE_{\mathrm{dep}}} + \frac{dN^{\mathrm{sh,CC},f}_{\nu_\tau}}{dE_{\mathrm{dep}}} + \frac{dN^{\mathrm{sh,CC},f}_{\bar\nu_\tau}}{dE_{\mathrm{dep}}} + \frac{dN^{\mathrm{sh},e,f}_{\nu_\tau}}{dE_{\mathrm{dep}}} + \frac{dN^{\mathrm{sh},e,f}_{\bar\nu_\tau}}{dE_{\mathrm{dep}}} + \frac{dN^{\mathrm{sh},e,f}_{\bar\nu_\tau,\tau}}{dE_{\mathrm{dep}}}\,,$$

$$\frac{dN^{\mathrm{tr},f}_{e}}{dE_{\mathrm{dep}}} = \frac{dN^{\mathrm{tr},e,f}_{\bar\nu_e,\mu}}{dE_{\mathrm{dep}}} + \frac{dN^{\mathrm{tr},e,f}_{\bar\nu_e,\tau}}{dE_{\mathrm{dep}}}\,,$$

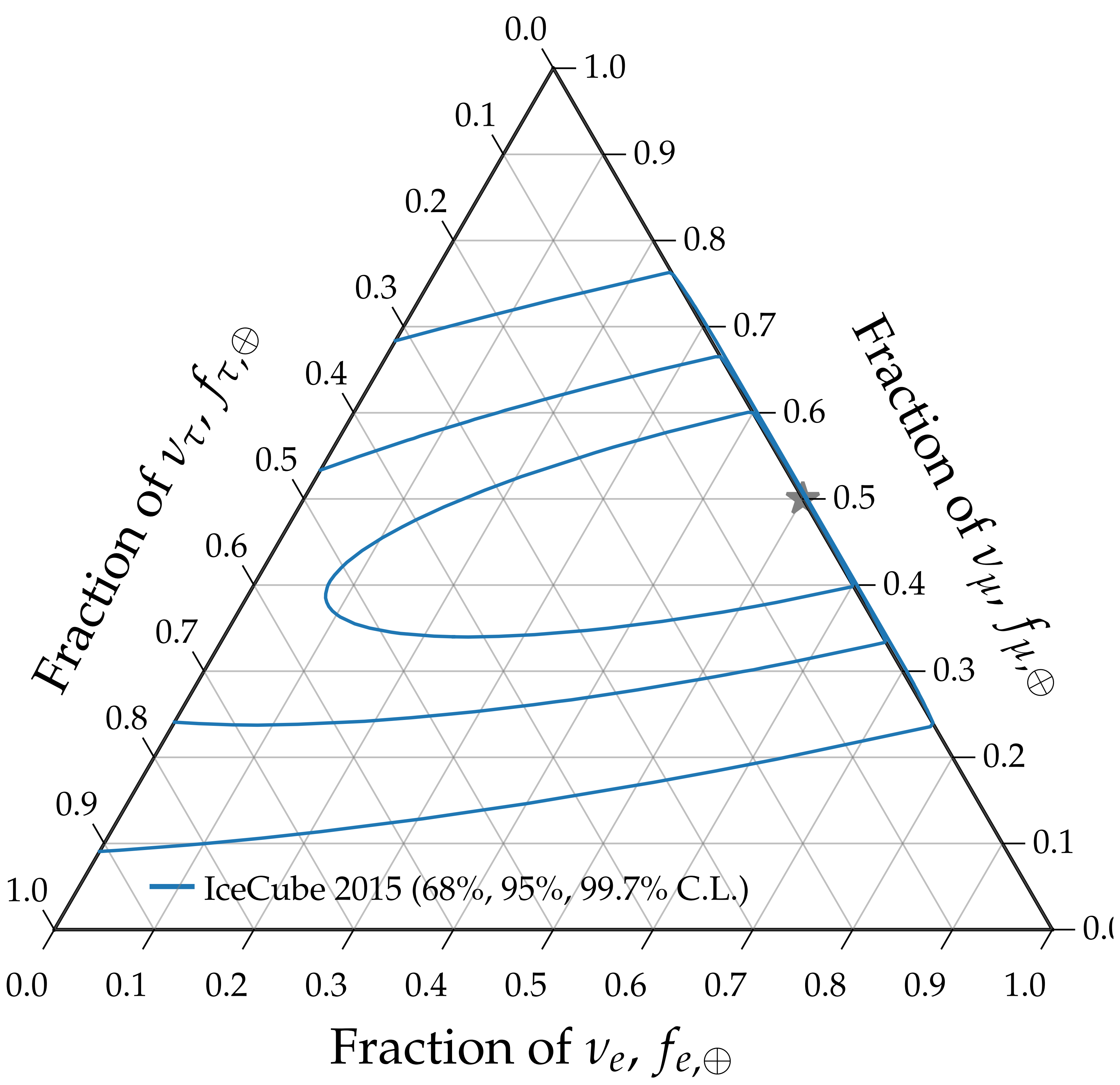
$$\frac{dN^{\mathrm{tr},f}_{\mu}}{dE_{\mathrm{dep}}} = \frac{dN^{\mathrm{tr,CC},f}_{\nu_\mu}}{dE_{\mathrm{dep}}} + \frac{dN^{\mathrm{tr,CC},f}_{\bar\nu_\mu}}{dE_{\mathrm{dep}}} + \frac{dN^{\mathrm{tr},e,f}_{\nu_\mu,\mu}}{dE_{\mathrm{dep}}}\,,$$

$$\frac{dN^{\mathrm{tr},f}_{\tau}}{dE_{\mathrm{dep}}} = \frac{dN^{\mathrm{tr,CC},f}_{\nu_\tau}}{dE_{\mathrm{dep}}} + \frac{dN^{\mathrm{tr,CC},f}_{\bar\nu_\tau}}{dE_{\mathrm{dep}}} + \frac{dN^{\mathrm{tr},e,f}_{\nu_\tau,\tau}}{dE_{\mathrm{dep}}}\,,$$

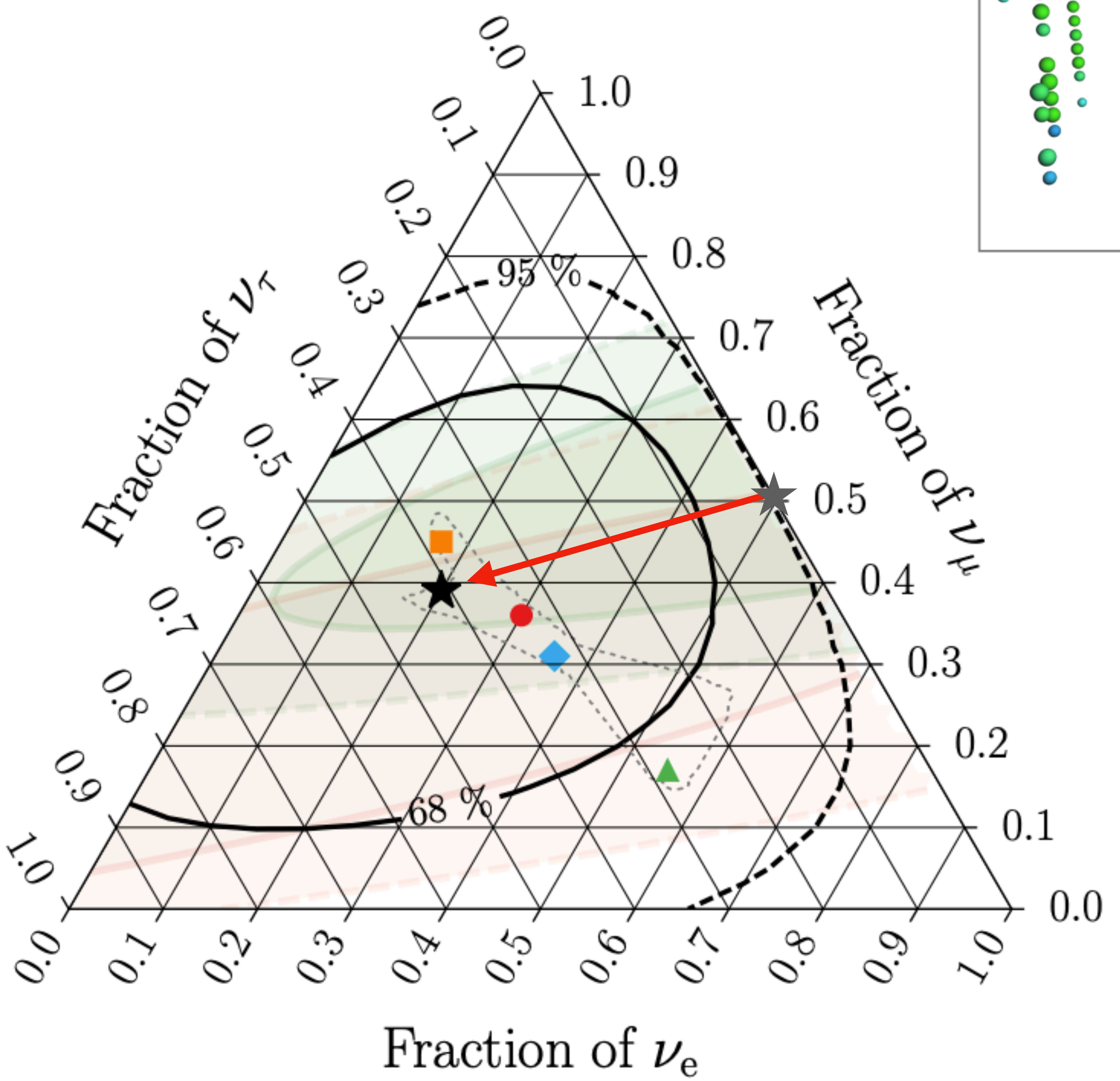
Palomares-Ruiz, Vincent, Mena, PRD/1502.02649

高能天体物理学中微子测量结果

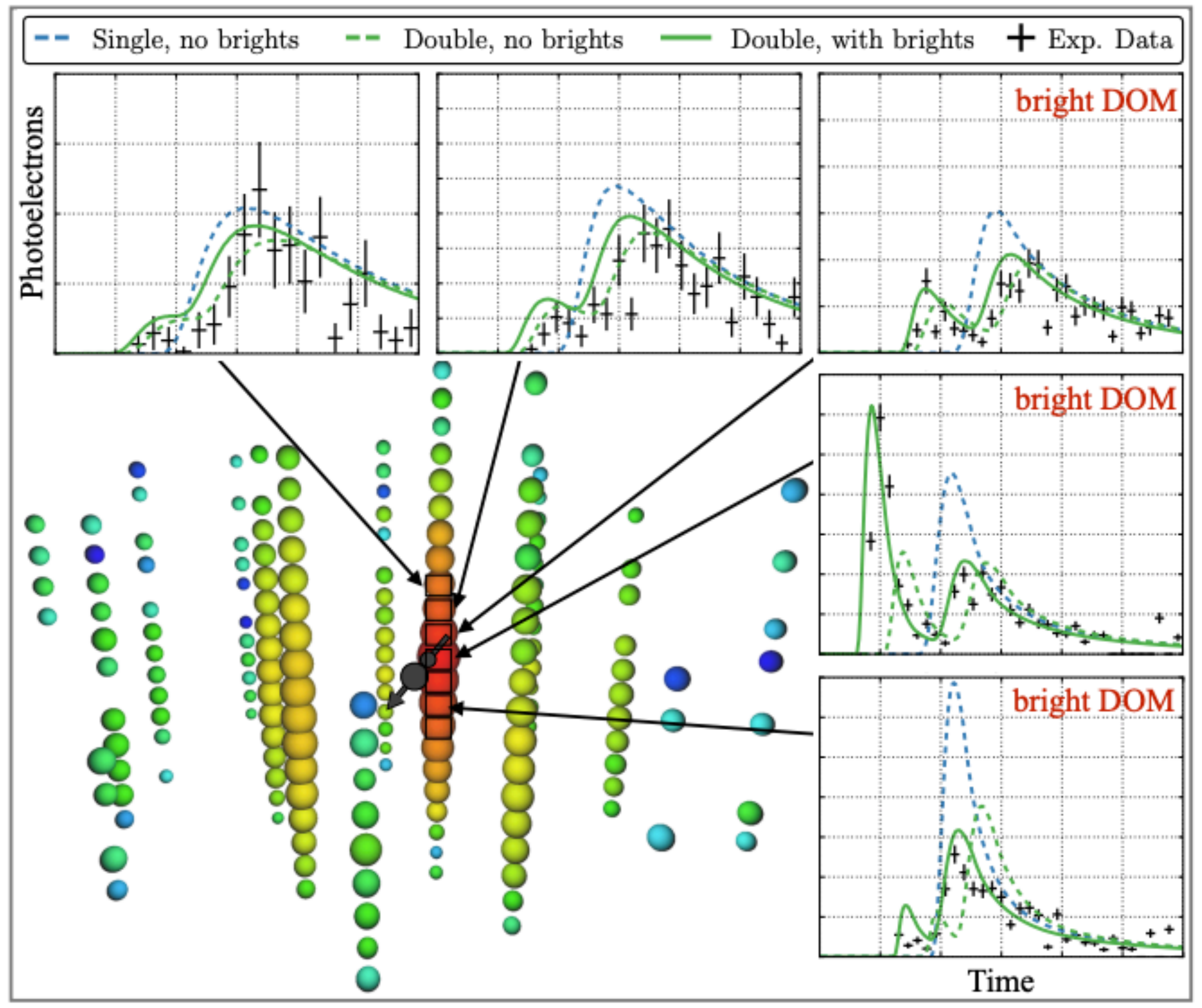
- HESE data + through-going muons



IceCube Collaboration, 1507.03991



IceCube Collaboration, 2011.03561



First detection of tau neutrino double bangs

$$\Phi \propto E^{-\gamma}$$

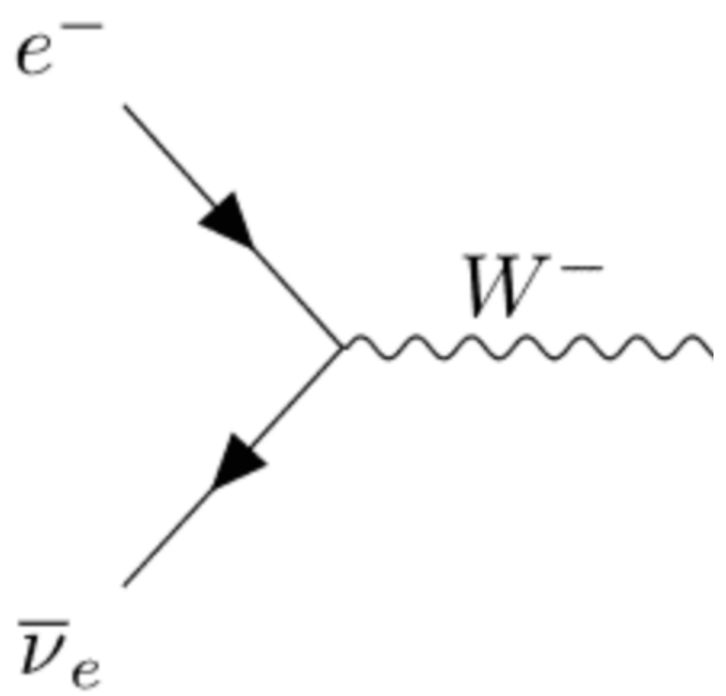
$$\gamma_{\text{astro}} = 2.87^{+0.20}_{-0.19}$$

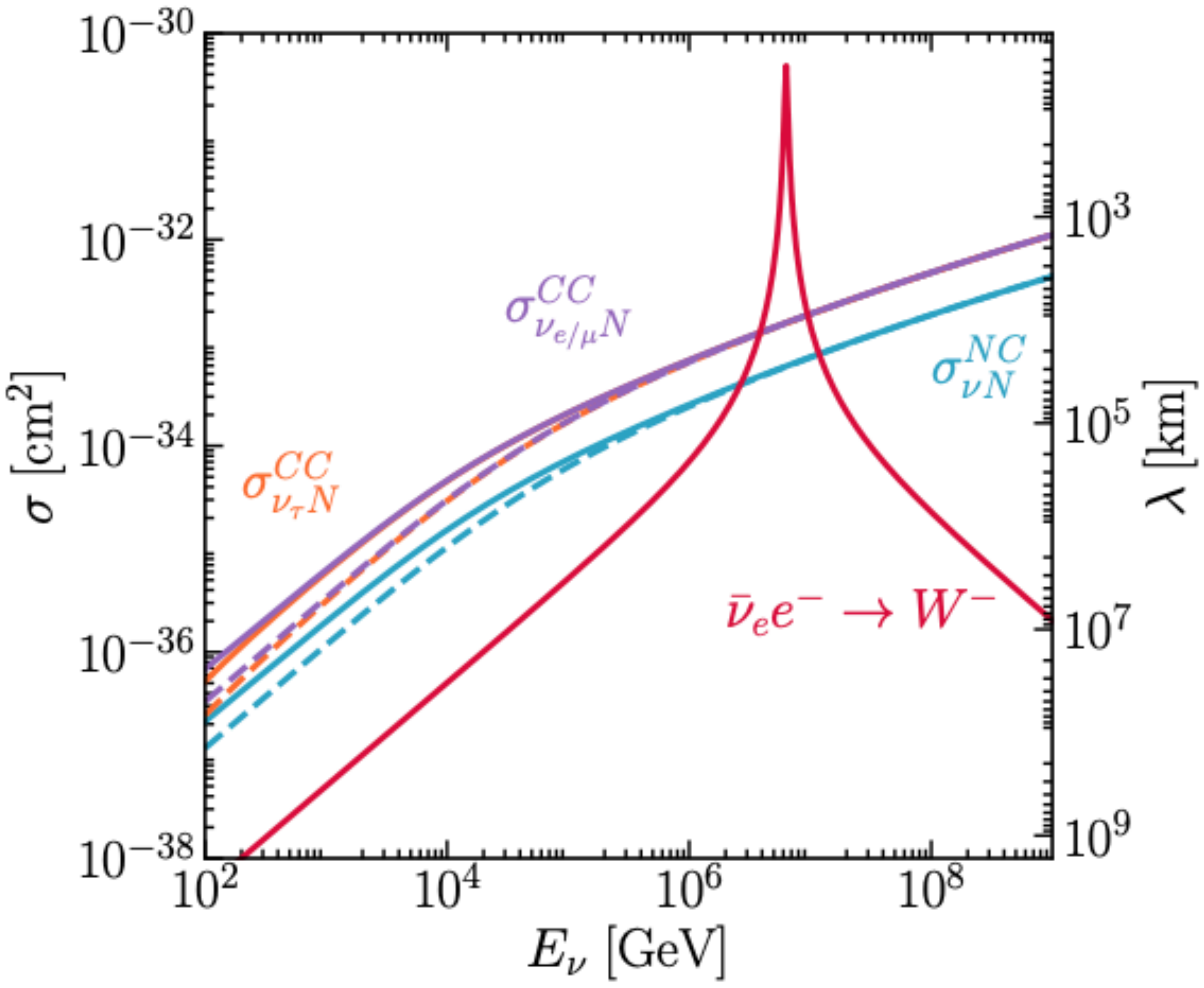
高能中微子-电子相互作用：Glashow共振

Huang, Liu , 1912.02976

When the centre of mass energy is close to W boson mass, $\bar{\nu}_e$-electron interaction is enhanced by the resonant production of W

$$\sigma_{\overline{\nu}_e e}(s) = 24\pi\,\Gamma_W^2\,\mathrm{Br}(W^- \to \overline{\nu}_e + e^-) \times \frac{s/M_W^2}{(s-M_W^2)^2 + (M_W\Gamma_W)^2}\,,$$





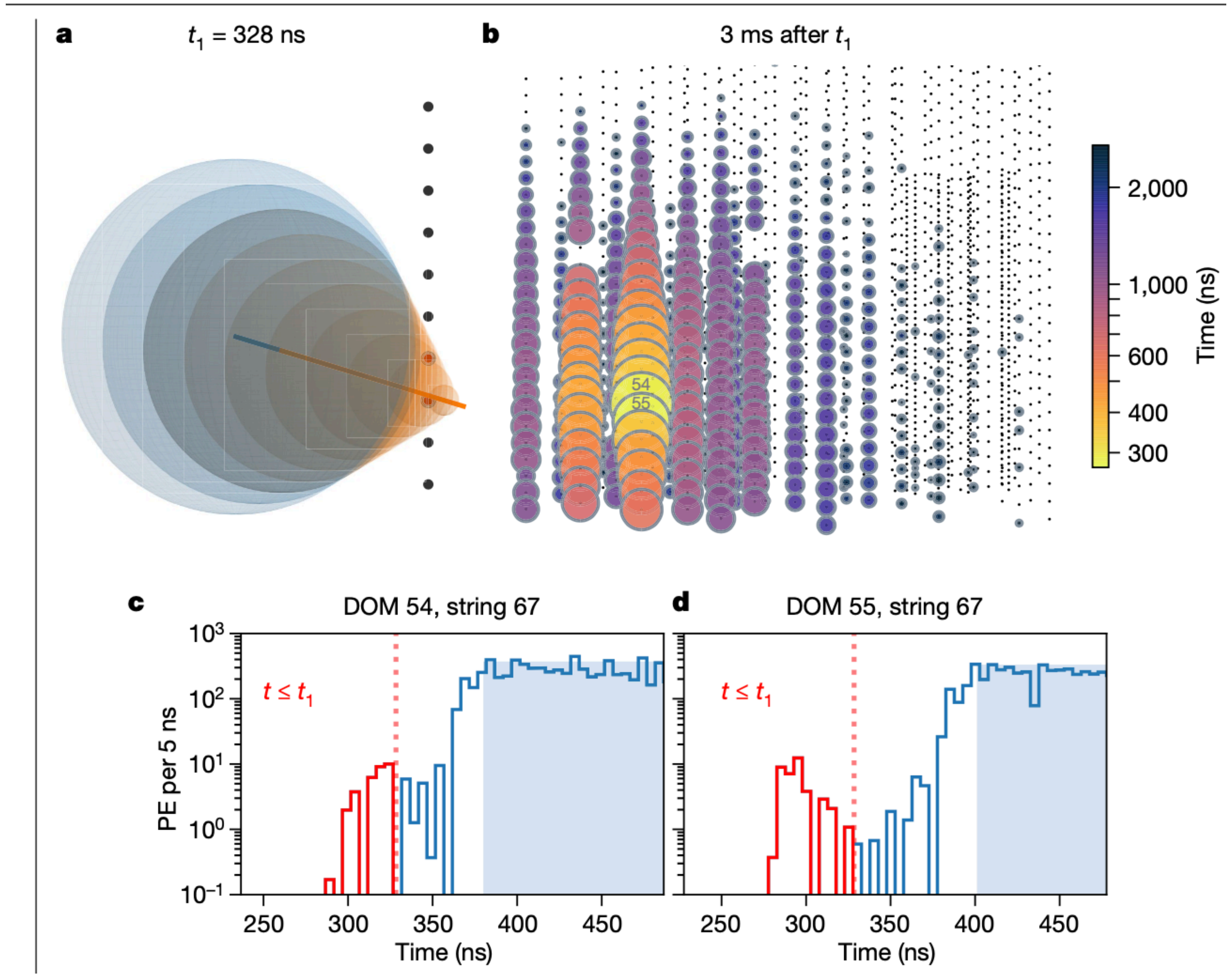
IceCube探测到Glashow共振

Article | Published: 10 March 2021

Detection of a particle shower at the Glashow resonance with IceCube

The IceCube Collaboration

Nature **591**, 220–224 (2021) | Cite this article



- Glashow resonance candidate was identified with 2.3 σ significance assuming $E^{-2.5}$ spectrum
- The cascade is partially contained (PEPE), with muon early pulses consistent with W decay

高能中微子源的简并性

Production	Source flavor ratio	Earth flavor ratio $\nu + \bar{\nu}$	Earth flavor ratio	$f_{\bar{\nu}_e}$
pp	$\{1,1\}:\{2,2\}:\{0,0\}$	$0.33:0.34:0.33$	$\{0.17,0.17\}:\{0.17,0.17\}:\{0.16,0.16\}$	0.17
$pp\,\mu$ damped	$\{0,0\}:\{1,1\}:\{0,0\}$	$0.23:0.39:0.38$	$\{0.11,0.11\}:\{0.20,0.20\}:\{0.19,0.19\}$	0.11
$p\gamma$	$\{1,0\}:\{1,1\}:\{0,0\}$	$0.33:0.34:0.33$	$\{0.26,0.08\}:\{0.21,0.13\}:\{0.20,0.13\}$	0.08
$p\gamma\,\mu$ damped	$\{0,0\}:\{1,0\}:\{0,0\}$	$0.23:0.39:0.38$	$\{0.23,0.00\}:\{0.39,0.00\}:\{0.38,0.00\}$	0

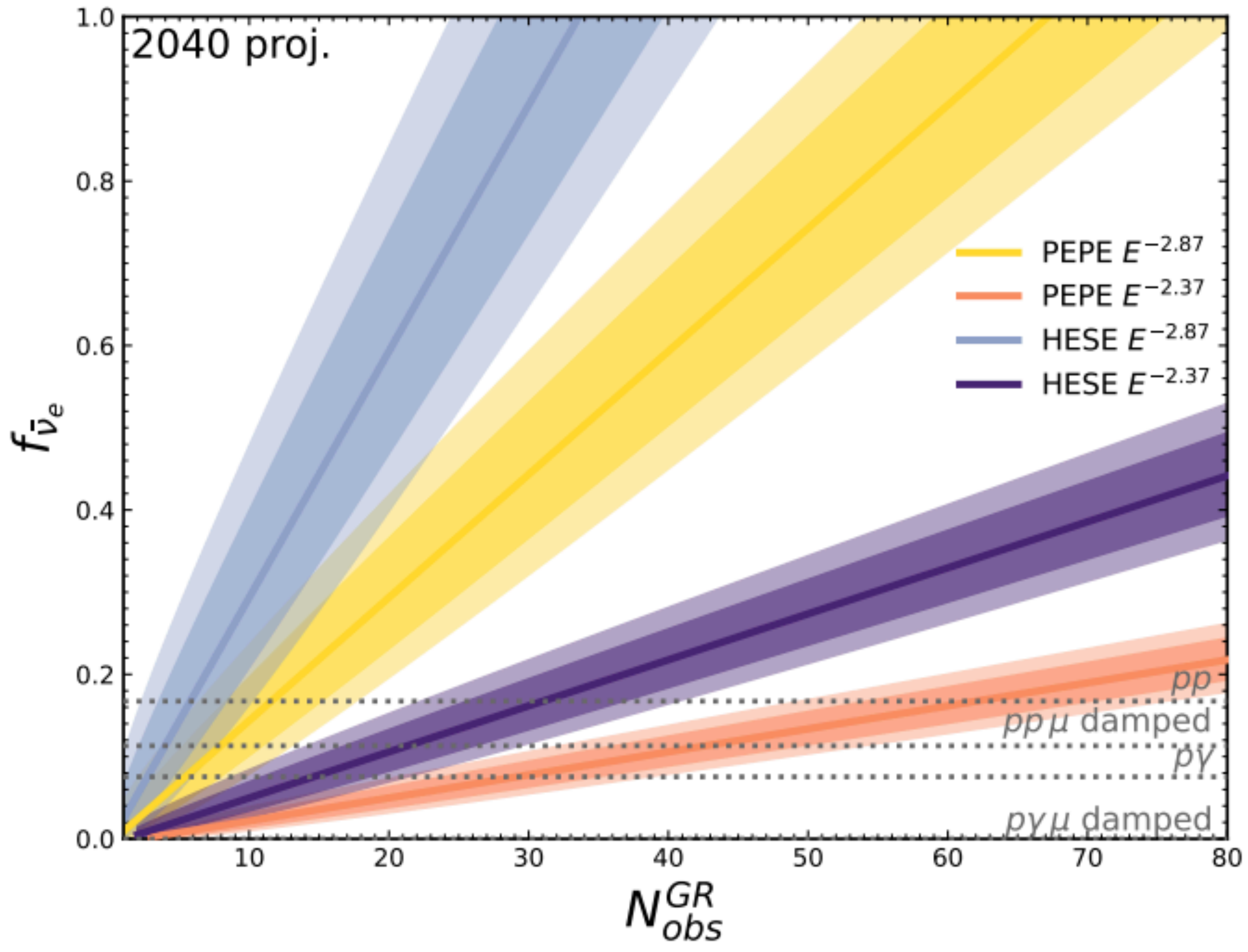
- $p\gamma$ produces more neutrinos than antineutrinos $p + \gamma \to \Delta^+ \to \pi^+ + n$, if μ damped, no antineutrinos are produced
- pp produces equal amount of neutrinos and antineutrinos $p + p \to n_\pi\,[\pi^0 + \pi^+ + \pi^-]$, which holds even if μ damped
- pp is indistinguishable from $p\gamma$ if only $\nu + \bar{\nu}$ is analyzed

Glashow共振打破高能中微子源的简并性

- GR cascade (W hadronic decay, e, τ leptonic decay) indistinguishable from NC DIS. However, NC cascades are less energetic
- GR track without cascade at interaction vertex distinguishable from ν_μ CC
- $2\,\% \leq f_{\bar{\nu}_e} \leq 72\,\%$ with 4.6 years of PEPE, $f_{\bar{\nu}_e} \leq 51\,\%$ with 7.5 years of HESE, assuming hard spectrum
- pp separated from $p\gamma$ at more than 2 σ significance regardless of flux assumption

See also 2303.13706

All future ν telescopes



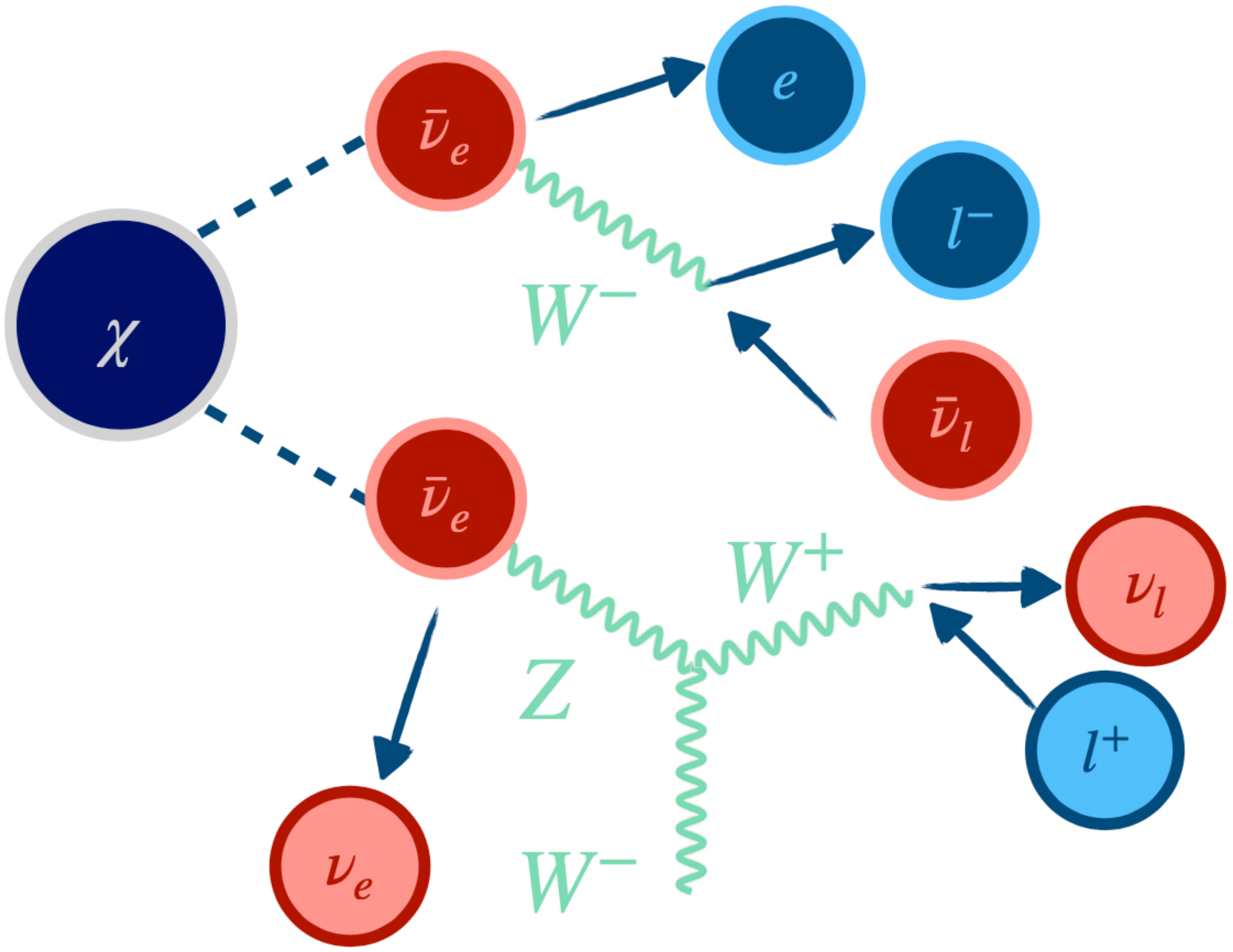
Liu, **NS**, Vincent, PRD/2304.06068

Asymmetric Dark Matter Decay

Credit: Qinrui Liu

$$\mathcal{O}_{X\to\nu} = \frac{1}{\Lambda^2} X\psi L\Phi\,, \quad \frac{1}{\Lambda^2} X(L\Phi)^2\,, \quad \frac{1}{\Lambda^{3n-1}} \bar{X} l \psi^n$$

$$X \to \bar{\nu},\ \ X \to \bar{\nu}\bar{\nu},\ \ X \to \nu\bar{\nu}\bar{\nu}$$



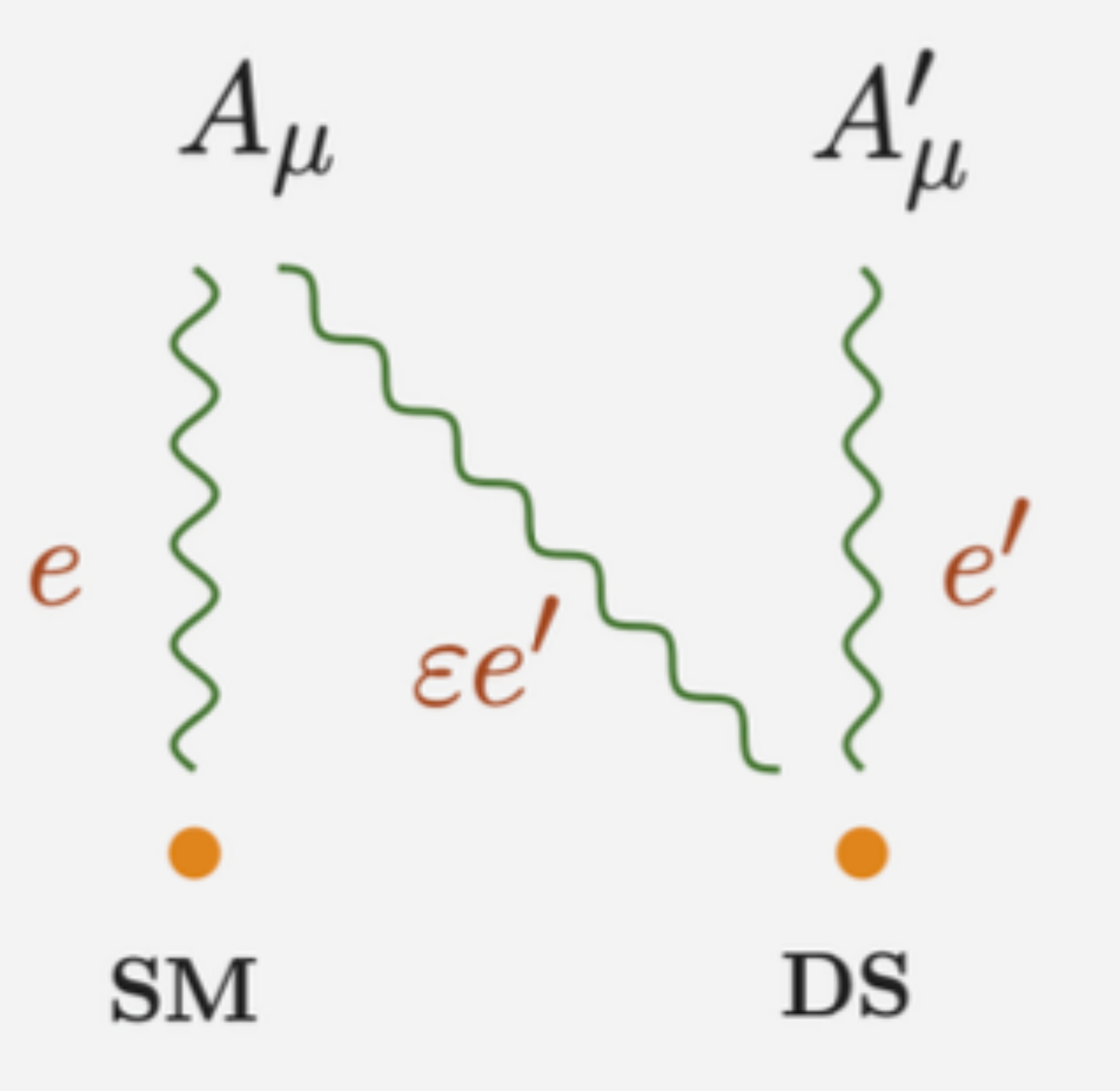
Millicharge Particles

Massless dark photon $\mathcal{L}_0 = -\frac{1}{4}F_{a\mu\nu}F_a^{\mu\nu} - \frac{1}{4}F_{b\mu\nu}F_b^{\mu\nu} - \frac{\varepsilon}{2}F_{a\mu\nu}F_b^{\mu\nu}$ $\mathcal{L} = e\,J_\mu A_b^\mu + e' J'_\mu A_a^\mu$

$$\begin{pmatrix} A_a^\mu \\ A_b^\mu \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{1-\varepsilon^2}} & 0 \\ -\frac{\varepsilon}{\sqrt{1-\varepsilon^2}} & 1 \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A'^\mu \\ A^\mu \end{pmatrix}$$

$$\begin{aligned} \mathcal{L}' \;&=\; \left[\frac{e'\cos\theta}{\sqrt{1-\varepsilon^2}}J'_\mu + e\left(\sin\theta - \frac{\varepsilon\cos\theta}{\sqrt{1-\varepsilon^2}}\right)J_\mu\right]A'^\mu \\ &+\; \left[-\frac{e'\sin\theta}{\sqrt{1-\varepsilon^2}}J'_\mu + e\left(\cos\theta + \frac{\varepsilon\sin\theta}{\sqrt{1-\varepsilon^2}}\right)J_\mu\right]A^\mu \end{aligned}$$

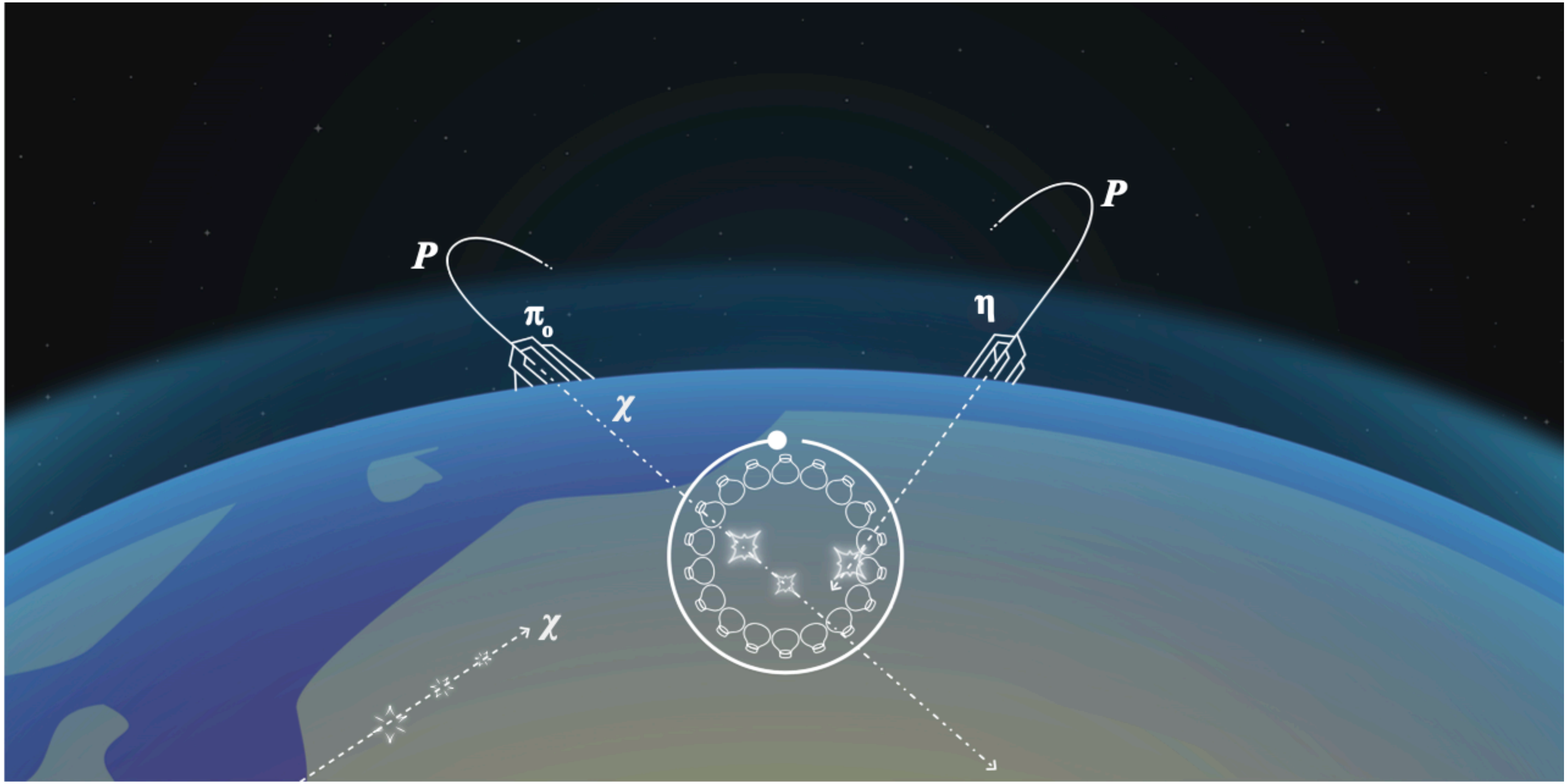
$$\boxed{\mathcal{L}' = e'J'_\mu A'^\mu + \left[-\frac{e'\varepsilon}{\sqrt{1-\varepsilon^2}}J'_\mu + \frac{e}{\sqrt{1-\varepsilon^2}}J_\mu\right]A^\mu}$$



$\sin\theta = \varepsilon\,,\ \cos\theta = \sqrt{1-\varepsilon^2}$

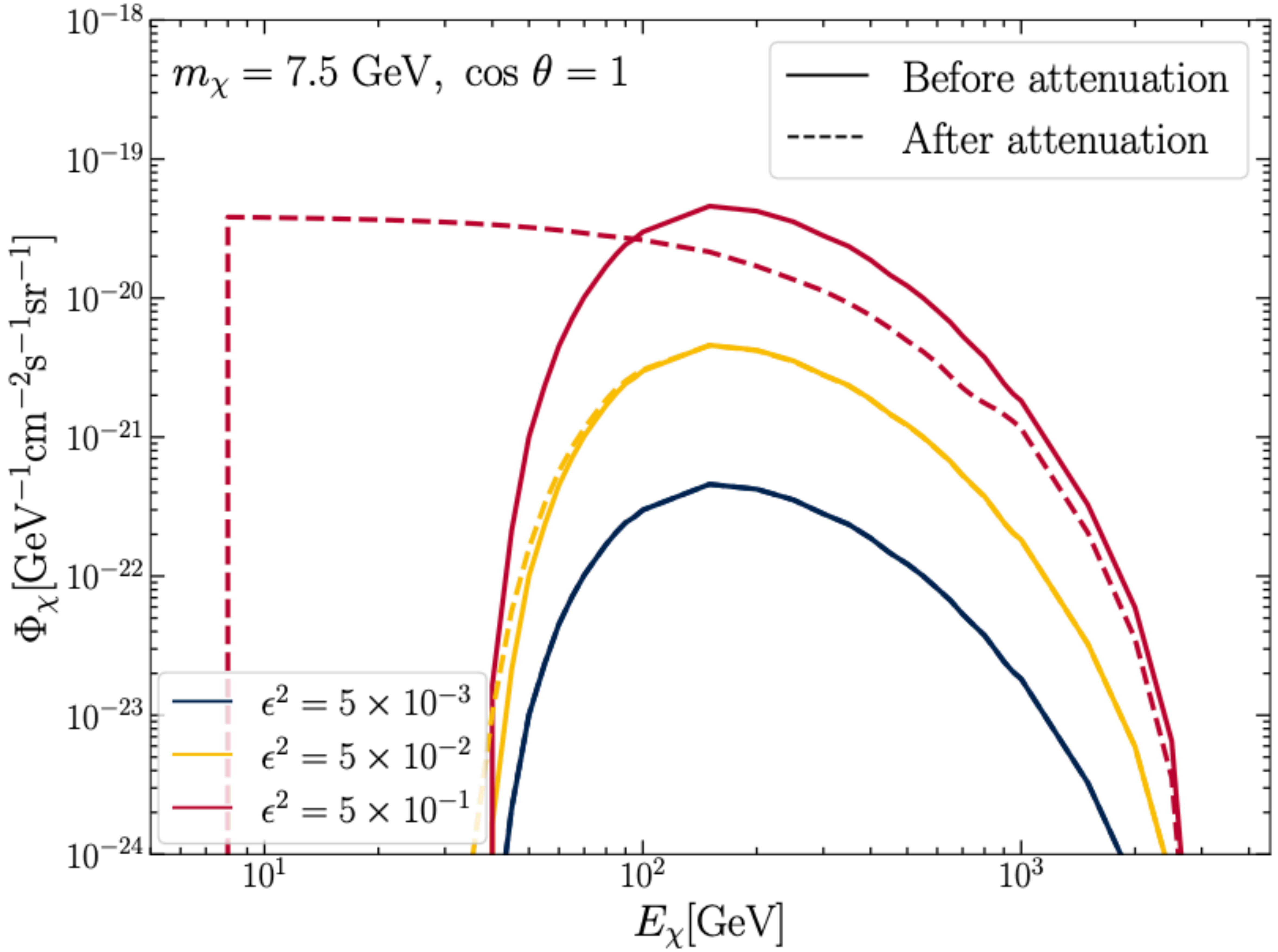
Fabbrichesi et al arXiv: 2005.01515

Atmospheric Beam Dump



Earth Attenuation

$$-\frac{dE}{dX} = \varepsilon^2 \left(a_{\text{ion.}} + b_{\text{el.-brem.}} \varepsilon^2 E + b_{\text{inel.-brem.}} E + b_{\text{pair}} E + b_{\text{photo-had.}} E \right) \approx \varepsilon^2 (a + bE)$$



Wu, Hardy, **NS**, arXiv: 2406.01668

For $\epsilon^2 \gtrsim 10^{-2}$, the down-going flux becomes significantly attenuated

Multiple Scatter Constraint

Single scatter probability $$P_1 = 1 - \exp\left(-\frac{L_D}{\lambda(T_{\min})}\right)$$

Multiple scatter probability $$P_{n\geq 2}(T_{\min}) = 1 - \exp\left(-\frac{L_D}{\lambda}\right)\left(1 + \frac{L_D}{\lambda}\right)$$

Number of observed events $$N_{\text{multi}} = N_{\text{single}} P_{n\geq 2}(T_{\min,\text{multi}}) / P_1(T_{\min,\text{single}})$$

$$N_{\text{single}}\left(m_\chi, \epsilon\right) = N_e T \int_{E_{i,\min}}^{E_{i,\max}} dE_r \epsilon_D(E_r) \times \int dE_\chi d\Omega \Phi_\chi^D\left(E_\chi, \Omega\right) \frac{d\sigma_{\chi e}}{dE_r}$$