Search for millicharged particles from the atmosphere and beam dumps

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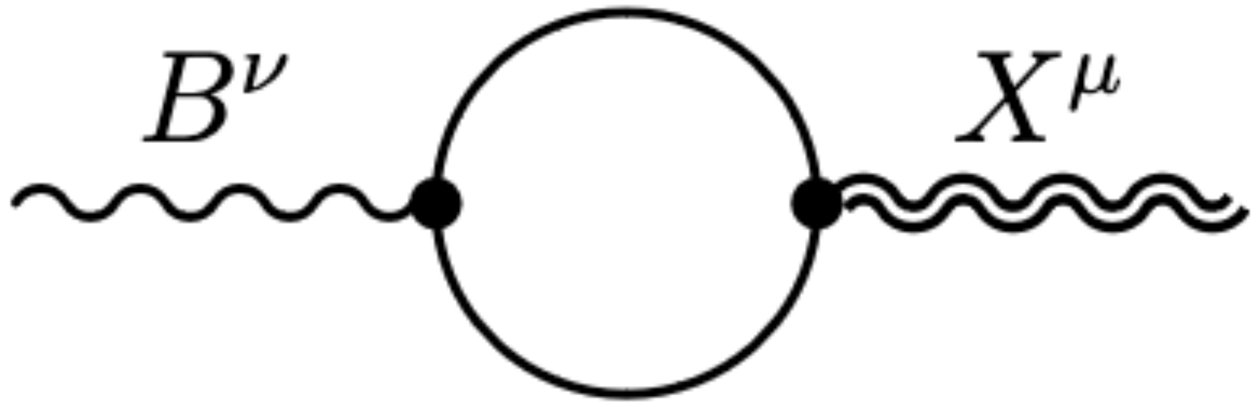
Dark Photon Kinetic Mixing

Extra $U(1)$? $\quad SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)'$

Pospelov' 2008
Ackerman, Buckley, Carrol, Kamionkowsk' 2008
Arkani-Hame, Finkbeine, Slatyer, Weiner' 2008

$$\mathscr{L} = -\frac{1}{4}(F_{\mu\nu}F^{\mu\nu} - 2\epsilon F_{\mu\nu}F'^{\mu\nu} + F'_{\mu\nu}F'^{\mu\nu}) - J^\mu A_\mu$$



$$\epsilon = -\frac{g' g_X}{16\pi^2}\sum_i Y_i q_i \ln\frac{M_i^2}{\mu^2} \sim 10^{-1} - 10^{-3}$$

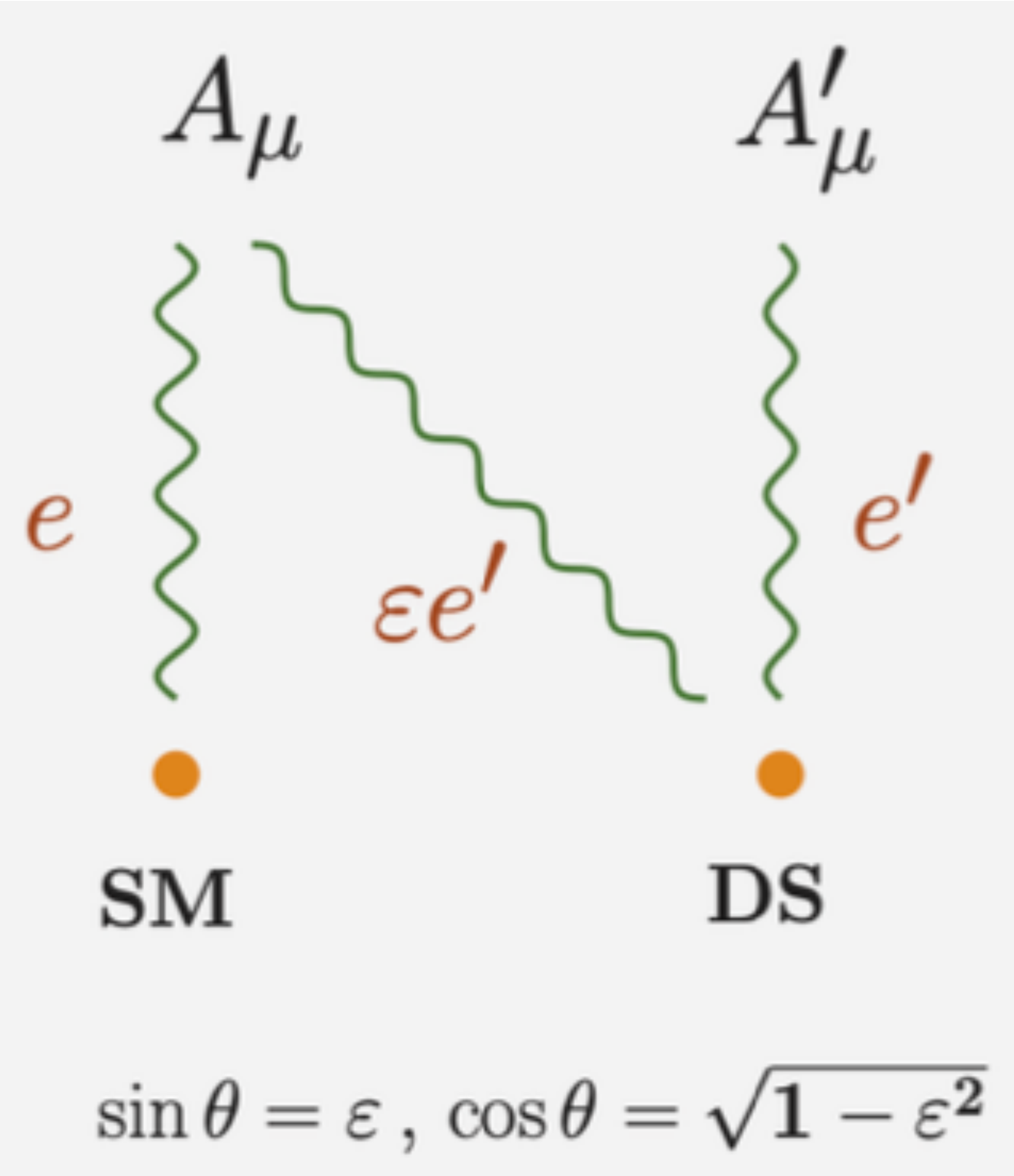
Millicharge Particles

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

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

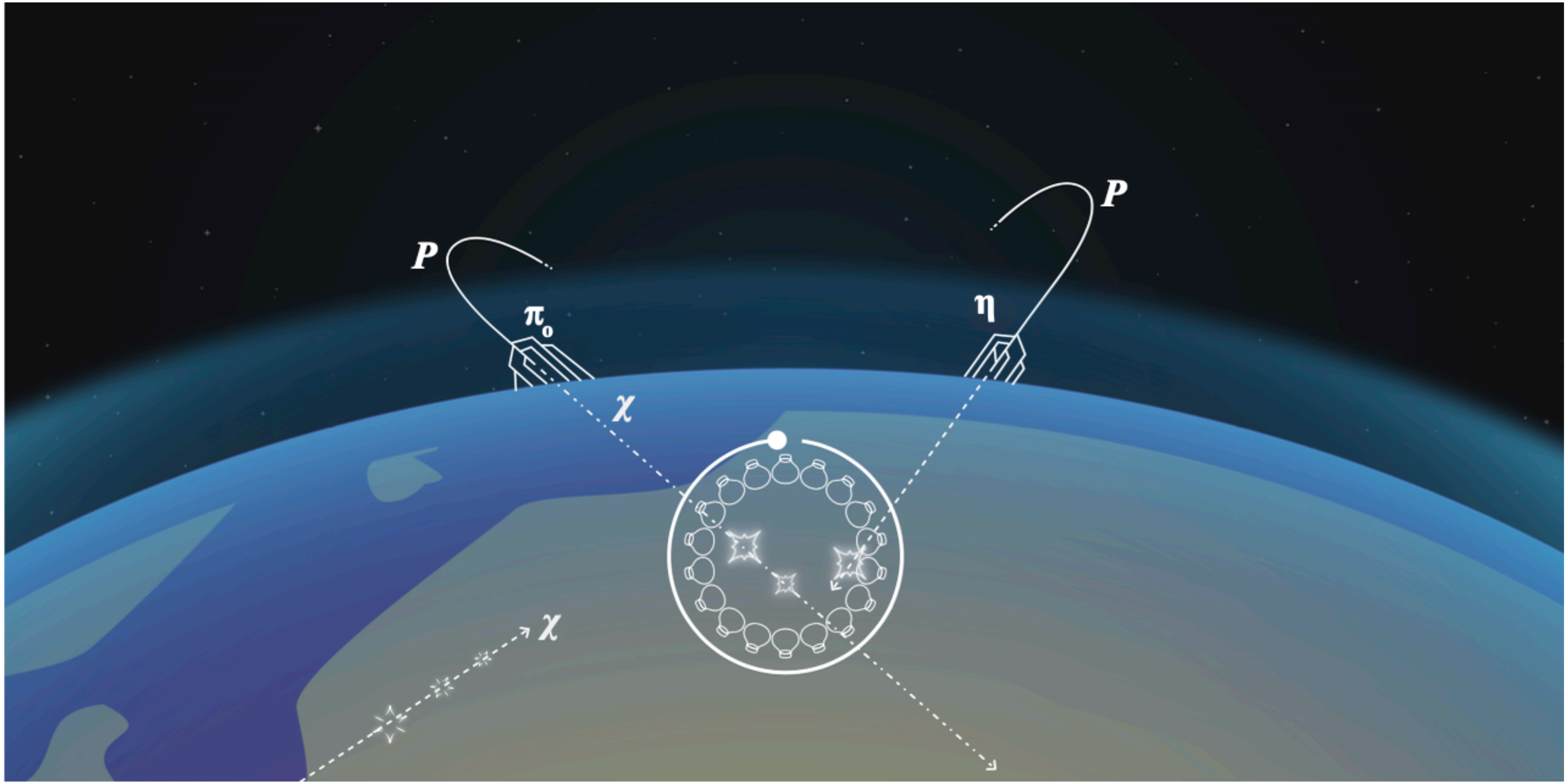
$$\begin{aligned} \mathcal{L}' \;=\; & \left[\frac{e'\cos\theta}{\sqrt{1-\varepsilon^2}} J'_\mu + e\left(\sin\theta - \frac{\varepsilon\cos\theta}{\sqrt{1-\varepsilon^2}}\right) J_\mu\right] A'^\mu \\ + & \left[-\frac{e'\sin\theta}{\sqrt{1-\varepsilon^2}} J'_\mu + e\left(\cos\theta + \frac{\varepsilon\sin\theta}{\sqrt{1-\varepsilon^2}}\right)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

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



Fabbrichesi et al arXiv: 2005.01515

Atmospheric Beam Dump



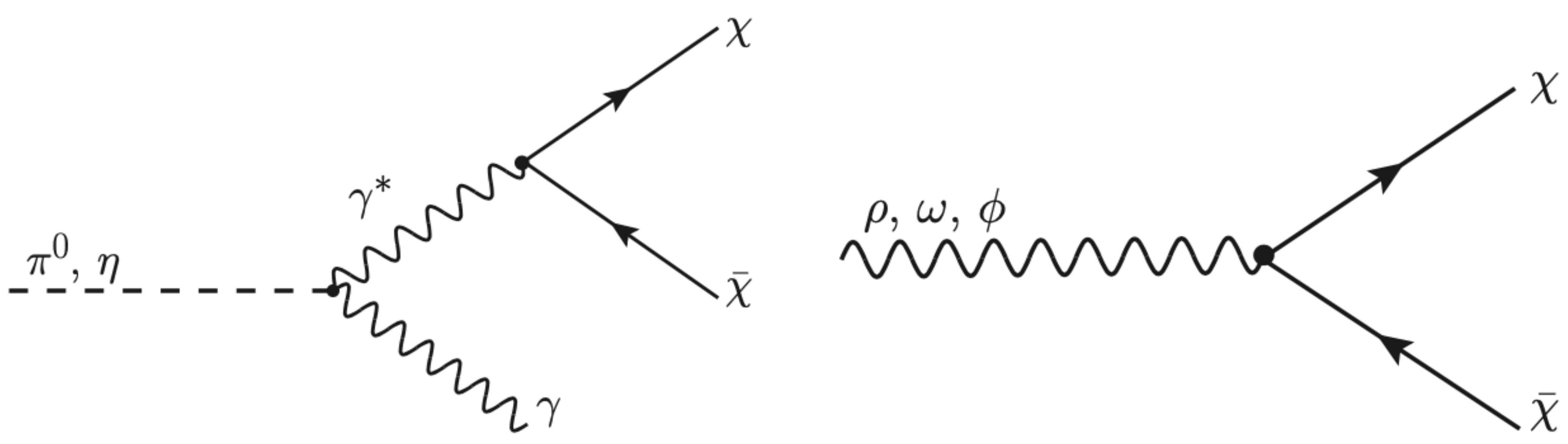
Millicharge Particles from Meson Decay

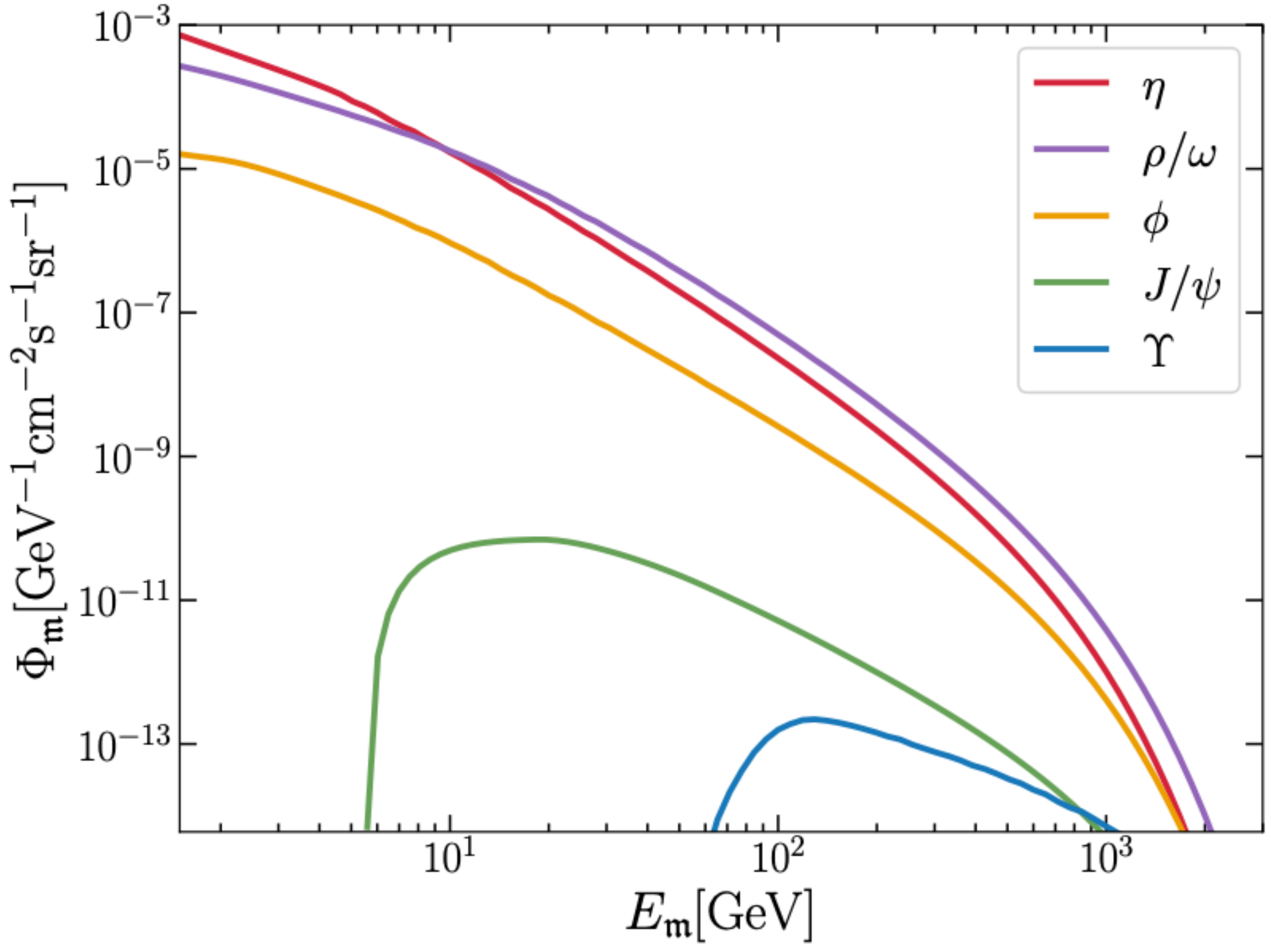
$$\Phi_{\mathfrak{m}}(\gamma_{\mathfrak{m}}) = \Omega_{\text{eff}} \int \mathcal{I}_{\text{CR}}(\gamma_{\text{cm}}) \frac{\sigma_{\mathfrak{m}}(\gamma_{\text{cm}})}{\sigma_{\text{in}}(\gamma_{\text{cm}})} P(\gamma_{\mathfrak{m}}|\gamma_{\text{cm}})\, \mathrm{d}\gamma_{\text{cm}}$$

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

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

Plestid et al PRD/2002.11732





Millicharge Particles from Proton Bremsstrahlung

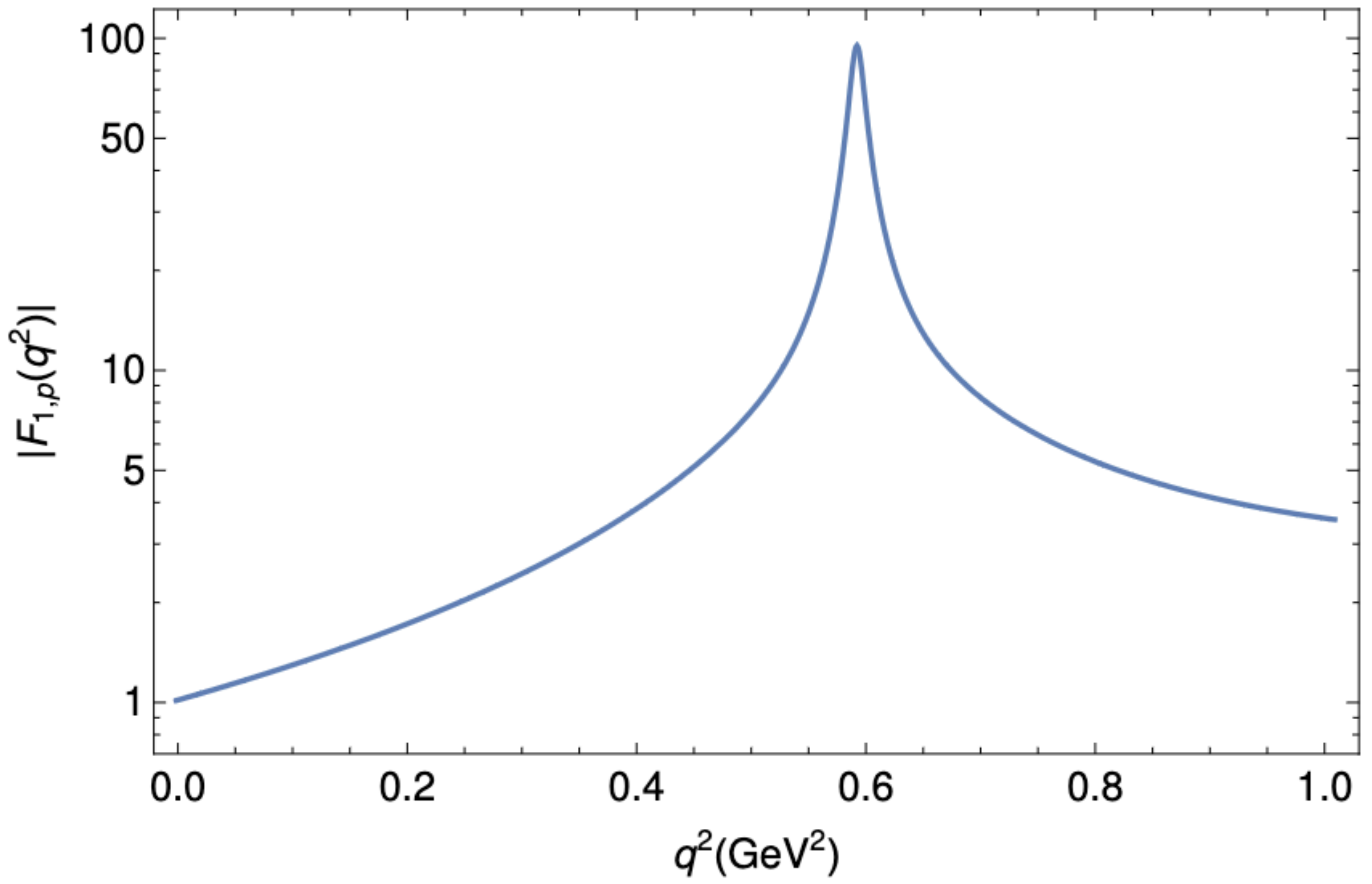
Fermi-Weizsacker-Williams (FWW) approximation with the splitting-kernel approach

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

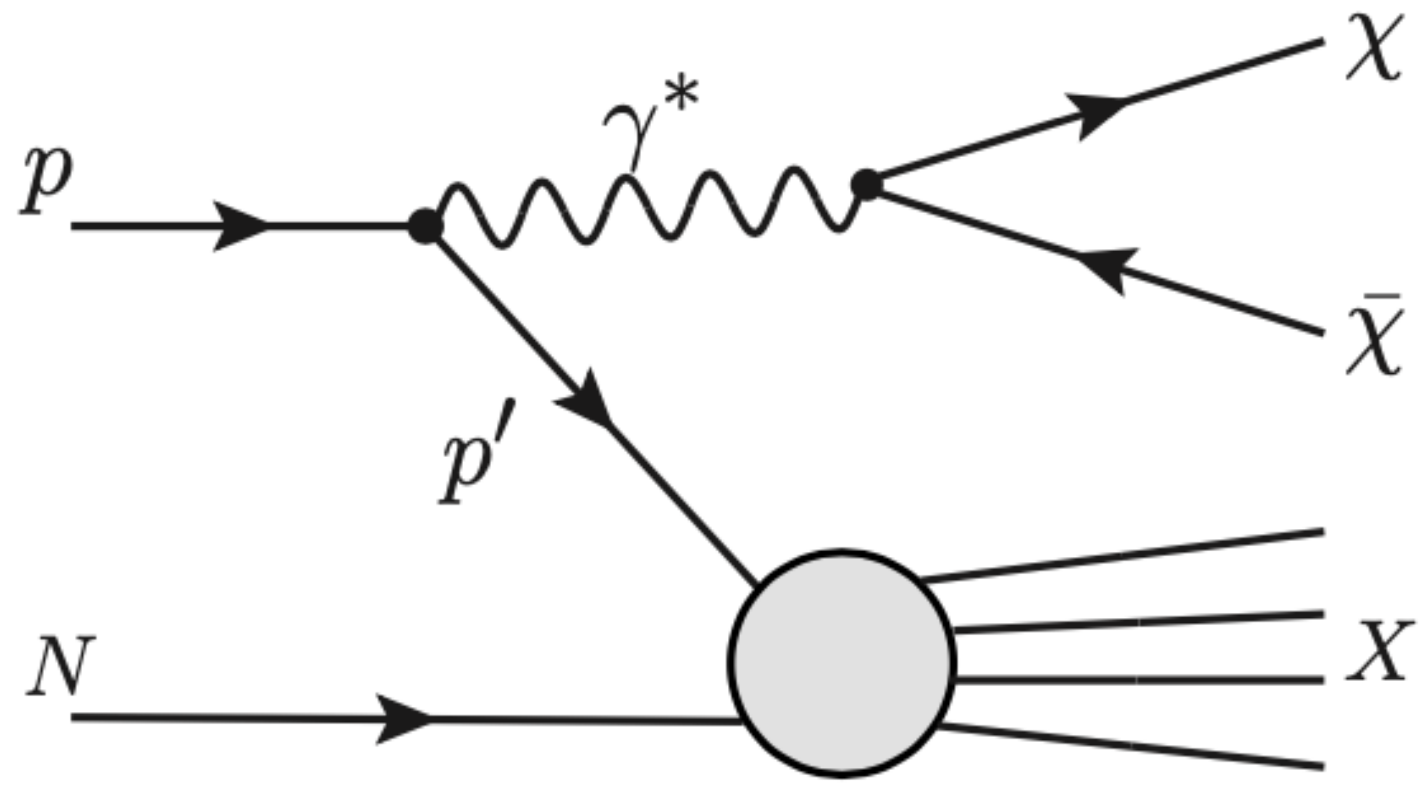
Kernel

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

EM form factor



deNiverville et al PRD/1609.01770



$$\Phi_\chi^{\mathrm{PB}} = \int dE_p \Phi_p \frac{\epsilon^2 e^2}{6\pi^2} \int \frac{dk^2}{k^2} \sqrt{1 - \frac{4m_\chi^2}{k^2}} \left(1 + \frac{2m_\chi^2}{k^2}\right)$$

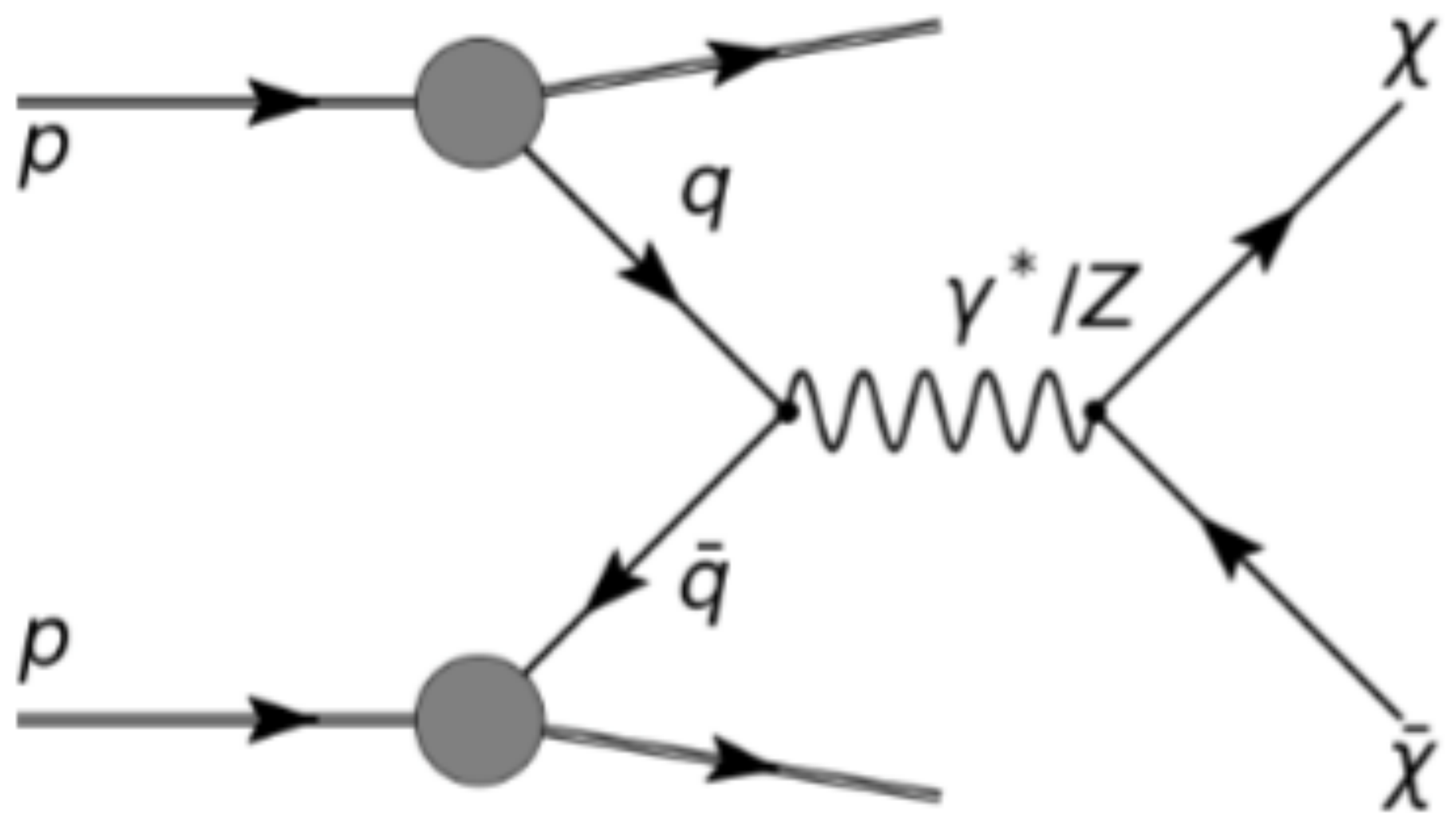
$$\times \int dE_k \frac{1}{\sigma_{pN}} \frac{d\sigma^{\mathrm{PB}}}{dE_k} \frac{\Theta(E_\chi - E_{\mathrm{min}})\Theta(E_{\mathrm{max}} - E_\chi)}{E_{\mathrm{max}} - E_{\mathrm{min}}}$$

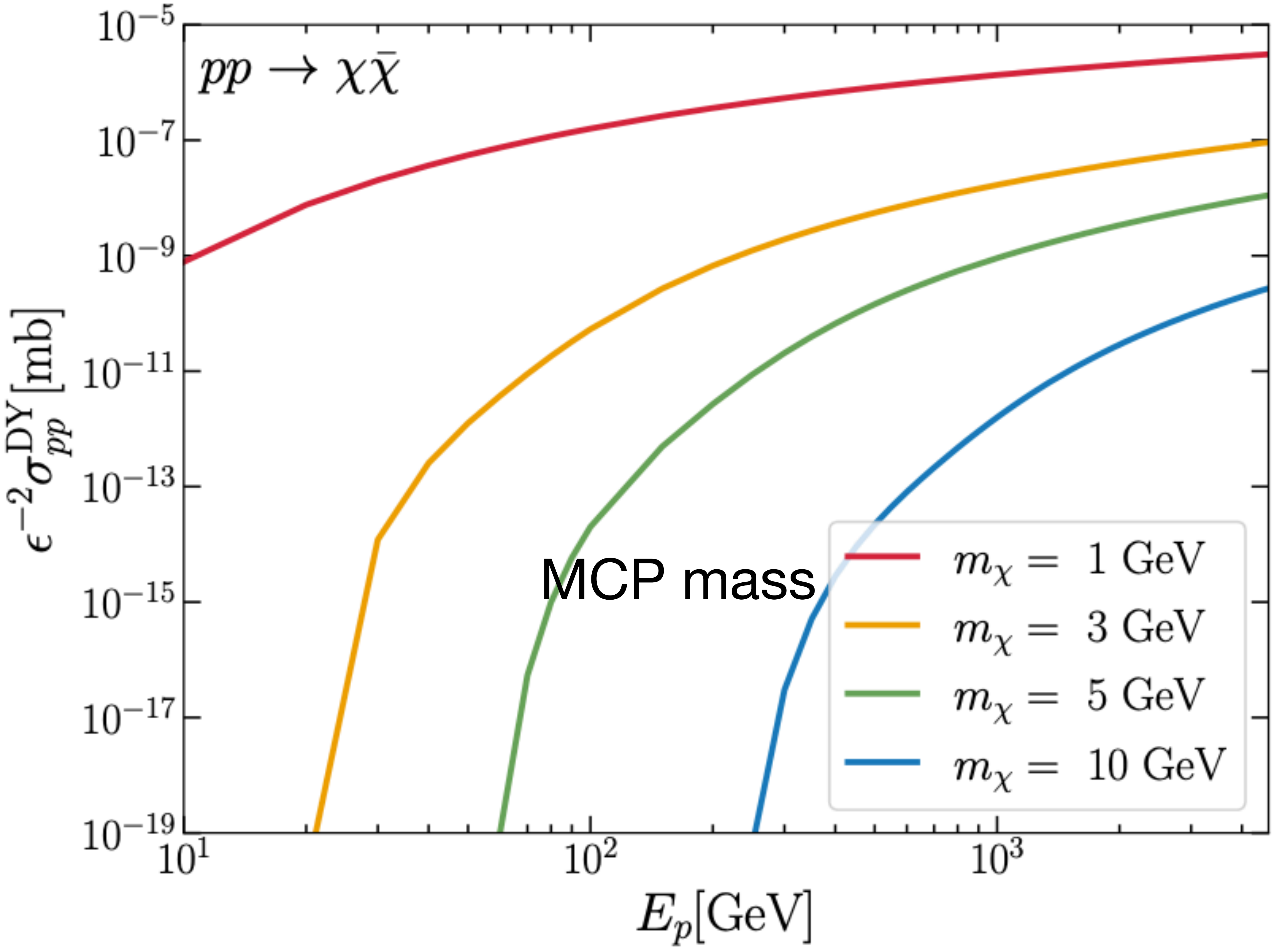
Du et al arXiv: 2211.11469

Du et al arXiv: 2308.05607

Millicharge Particles from Drell-Yan Process

Madgraph simulations



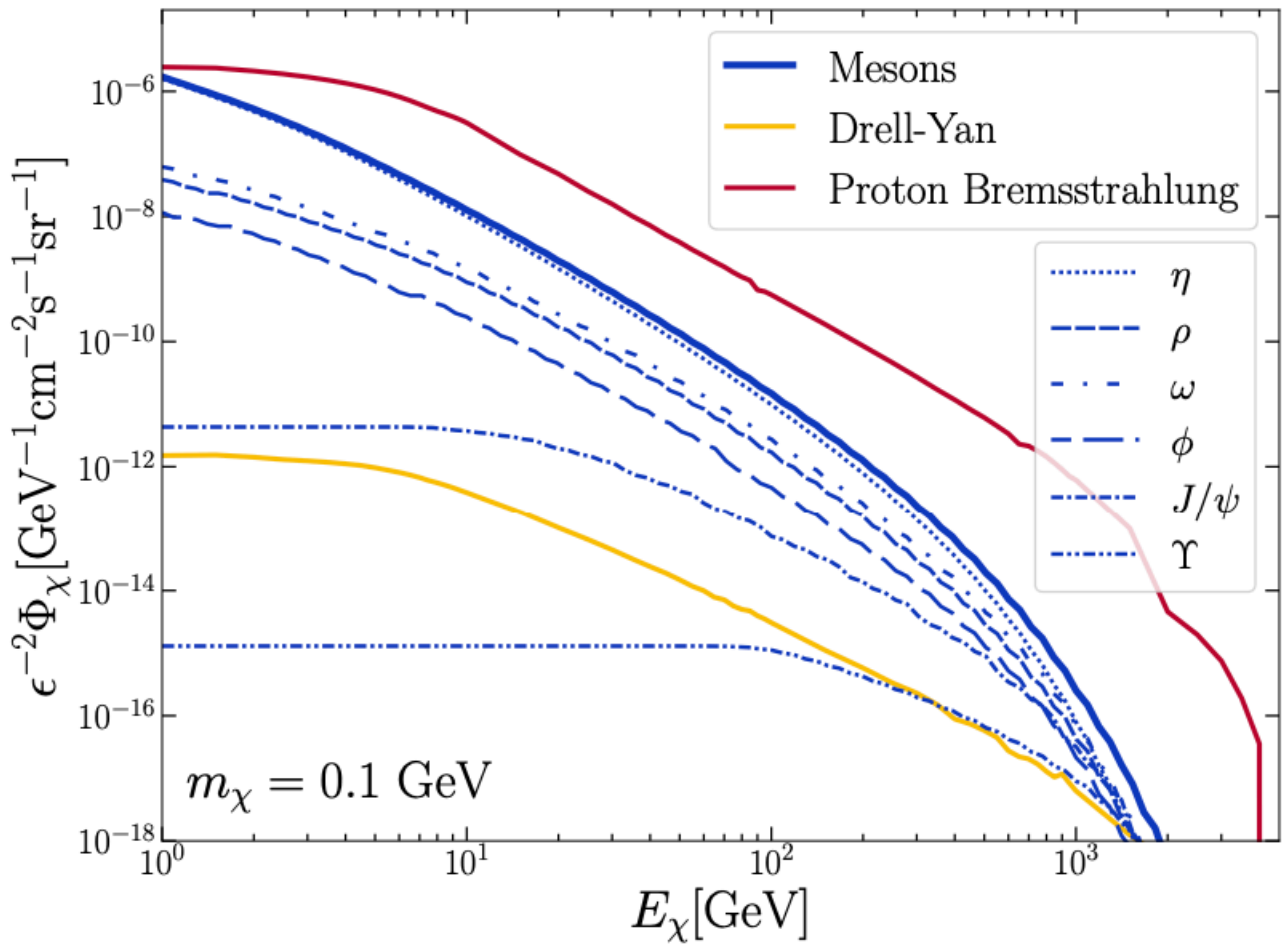


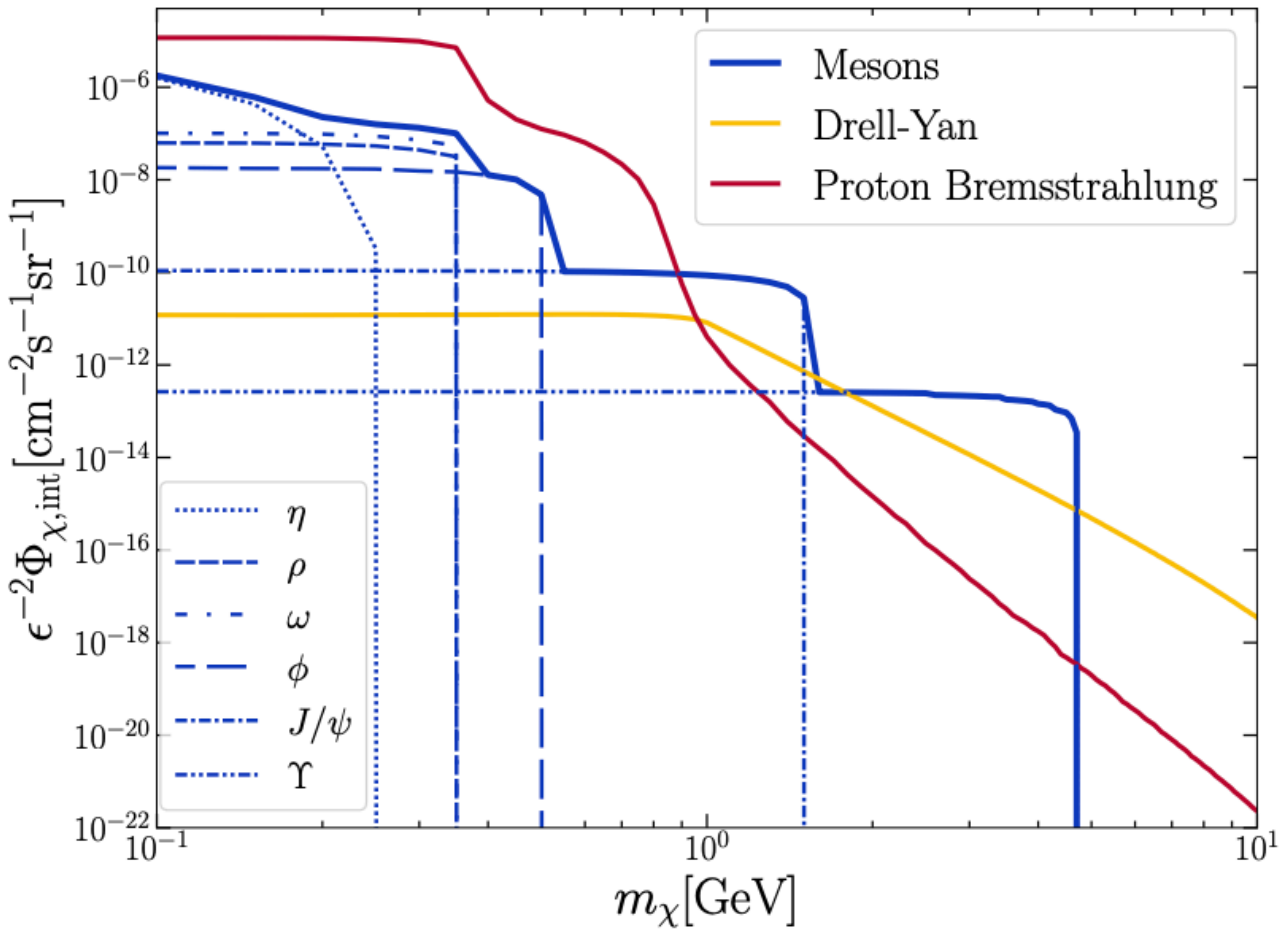
$$\hat{\sigma}\left(q(p_1)\,\bar{q}(p_2) \to l^+ l^-\right) = \frac{4\pi\alpha^2}{3\hat{s}}\frac{1}{N_c}Q_q^2$$

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

Millicharge Particle Flux

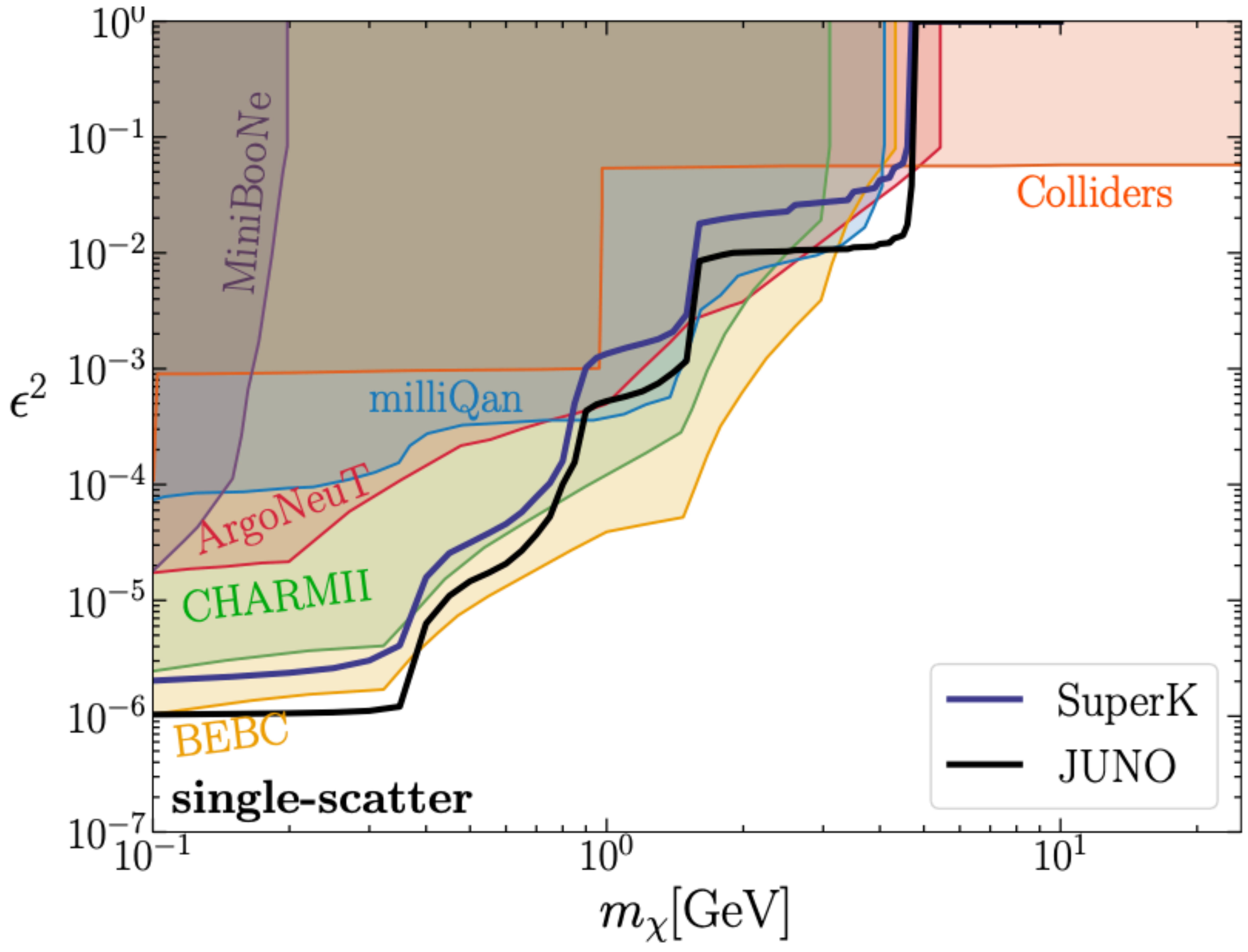
Meson decay+Proton Bremsstrahlung+Drell-Yan





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

Single Scatter Constraint



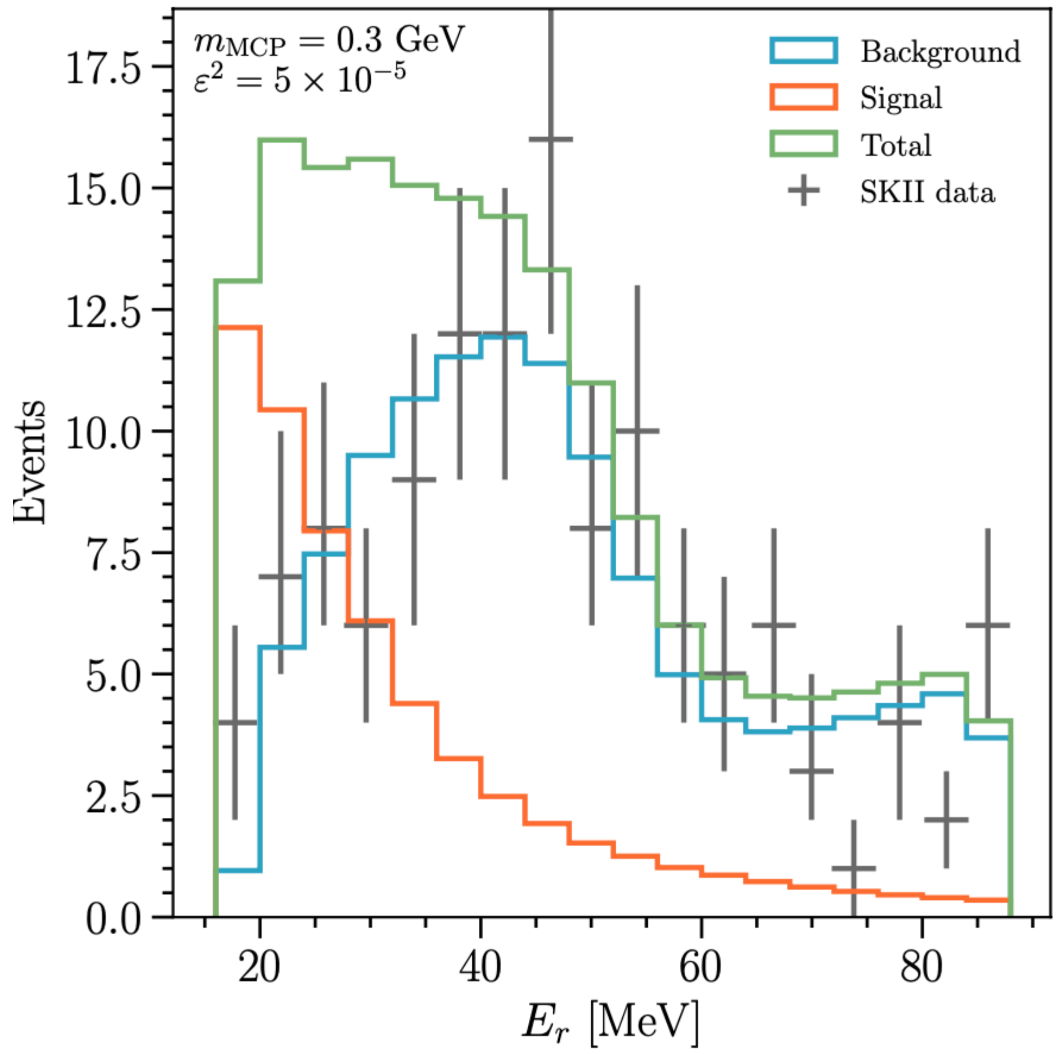
Assuming JUNO 10 MeV threshold+170 kton·yr exposure

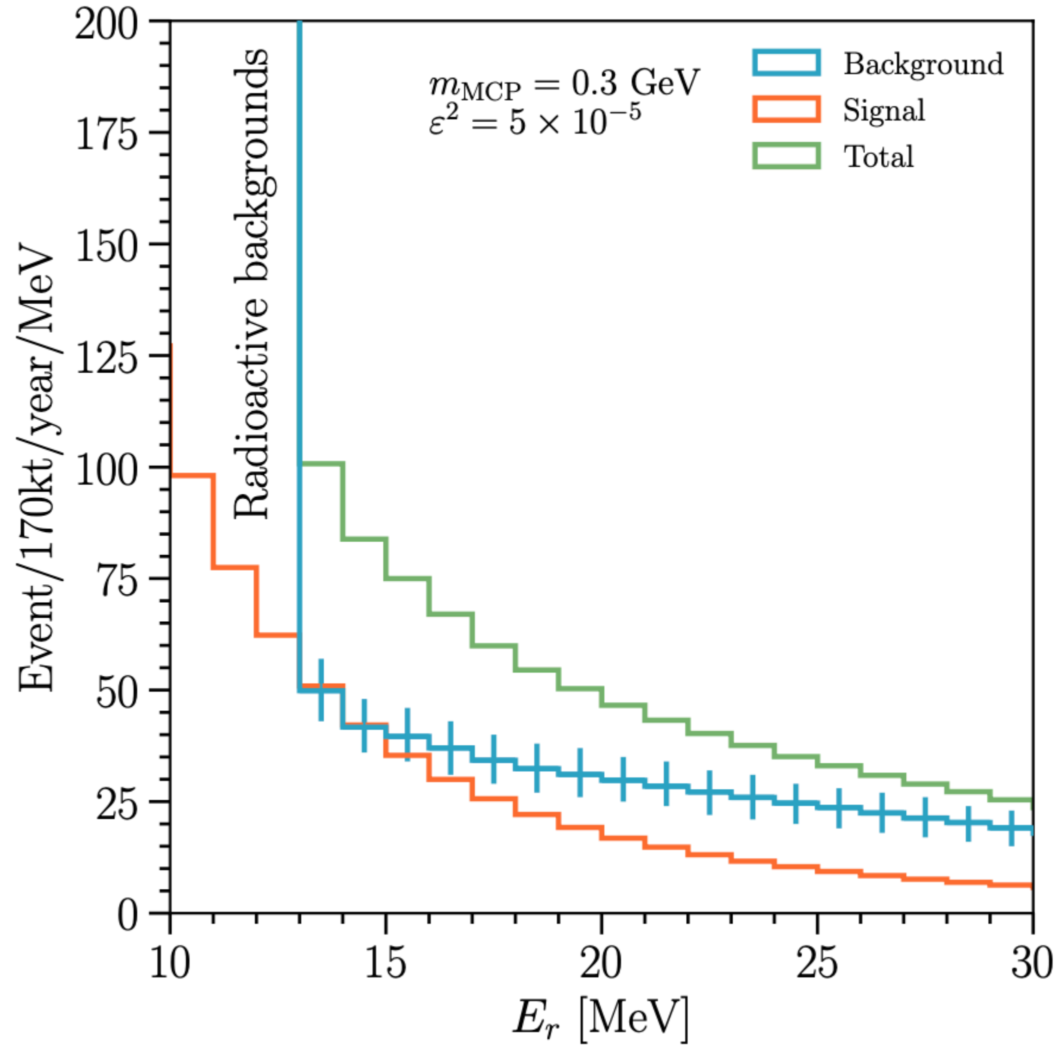
Wu, Hardy, **NS**, PRD/arXiv: 2406.01668

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

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

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





Arguelles et al JHEP/2104.13924

Multiple Scatter Constraint

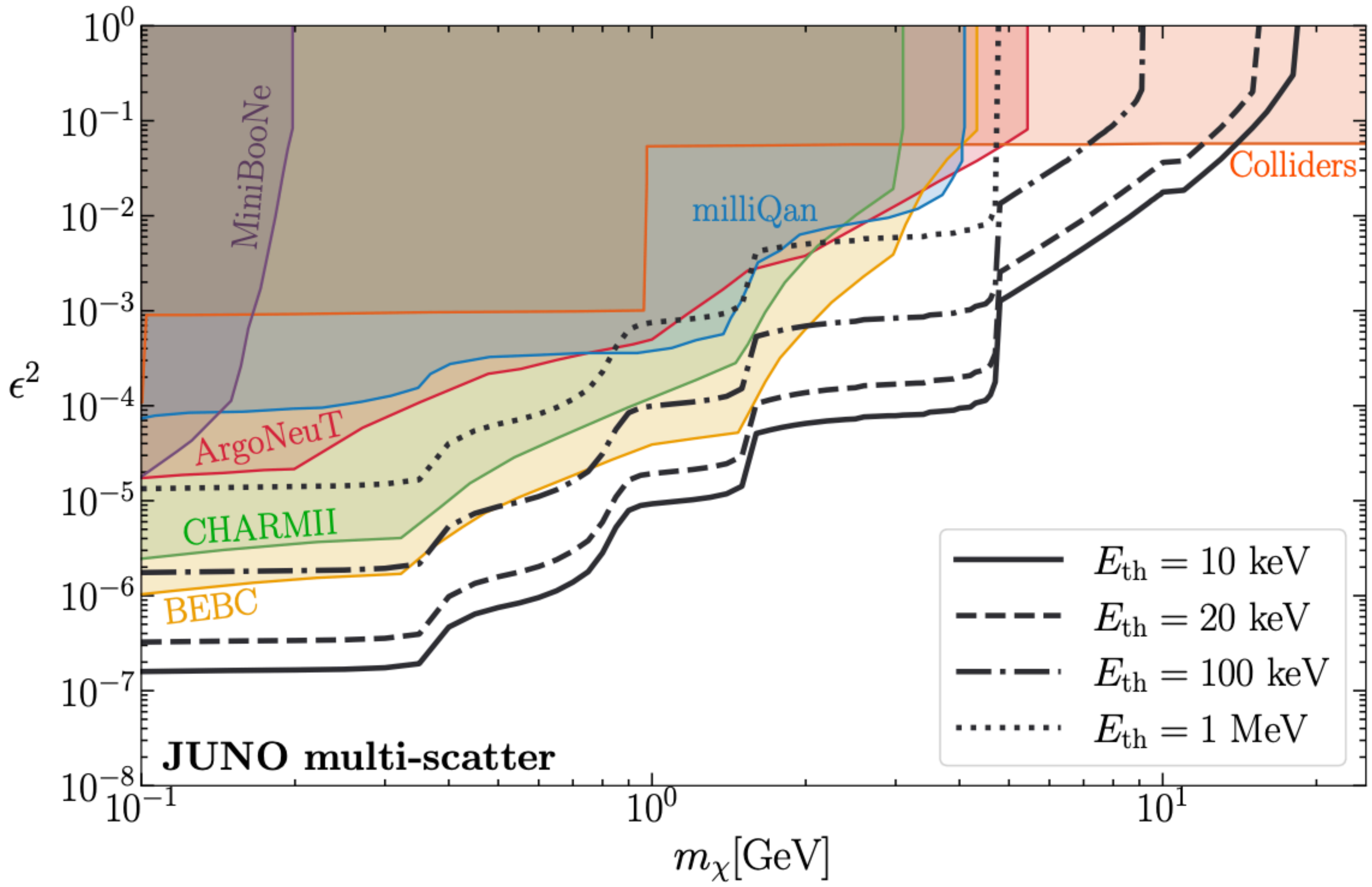
Single scatter probability $$P_1 = 1 - \exp\left(-\frac{L_D}{\lambda(T_{\min})}\right)$$

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

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

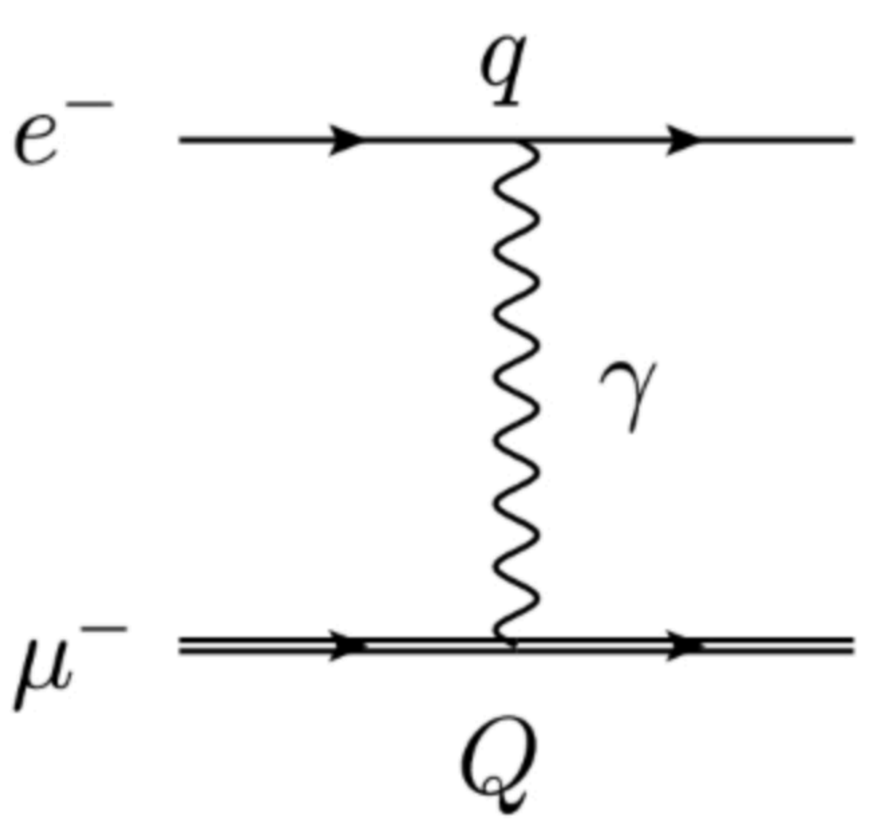
Multiple Scatter Constraint



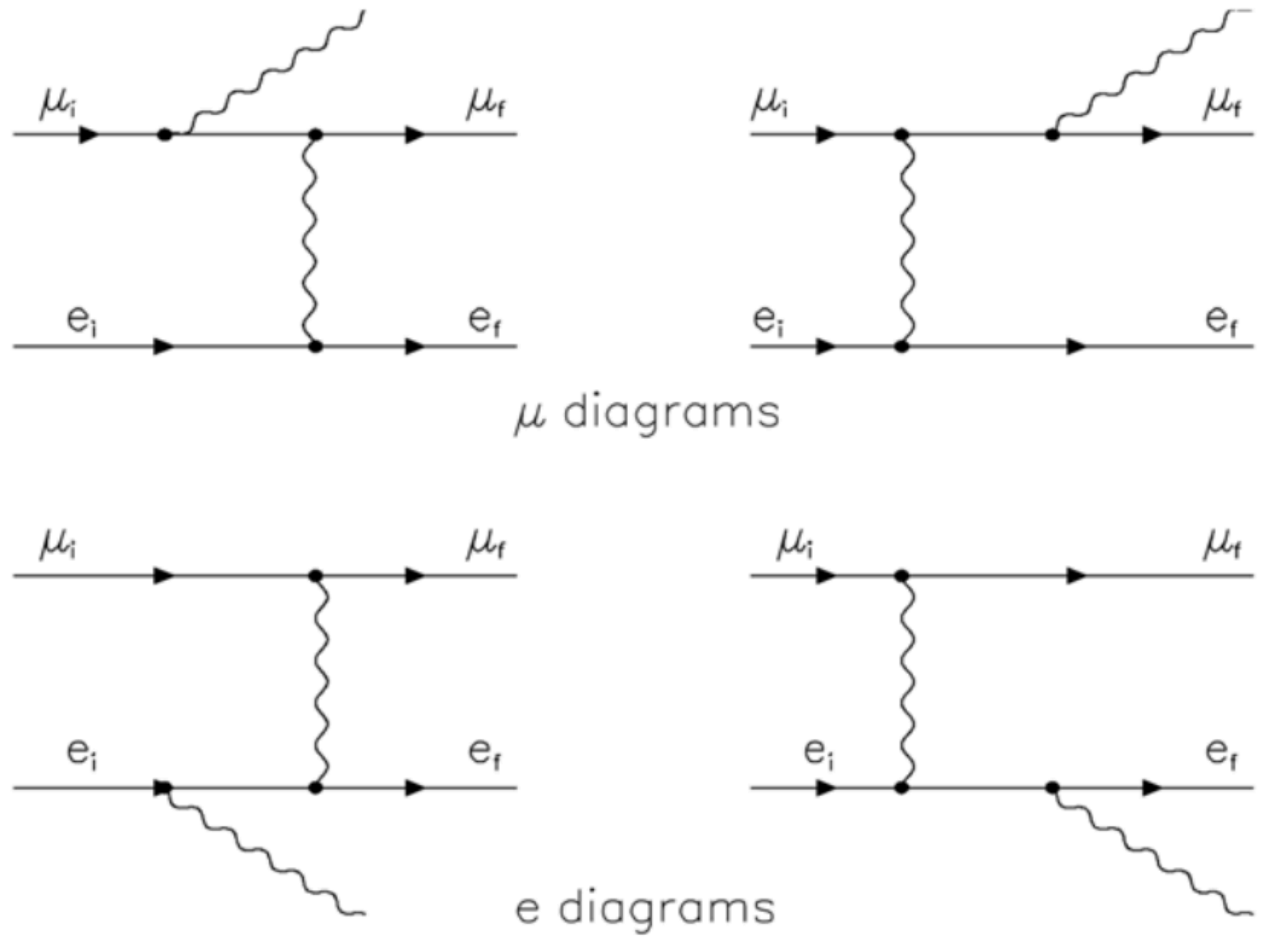
Assuming JUNO 170 kton·yr exposure

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

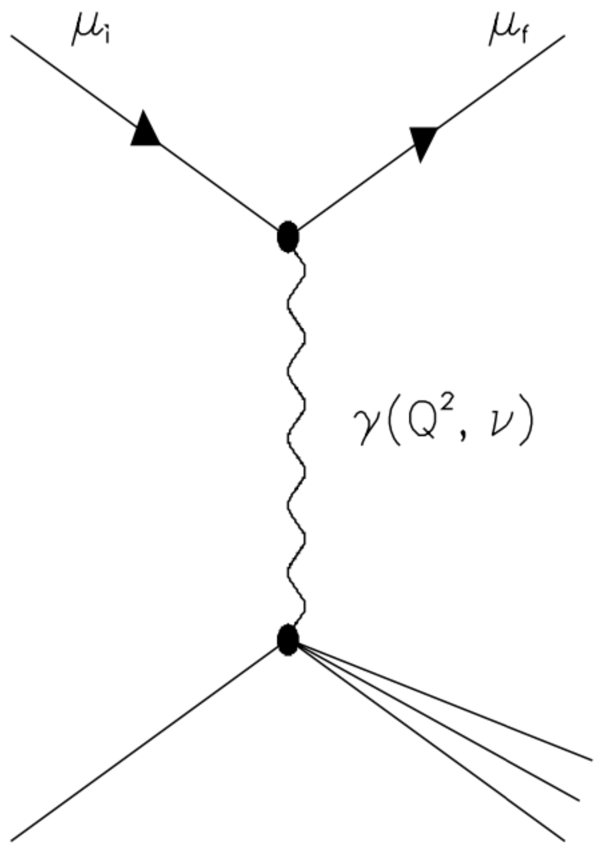
Muon Energy Loss



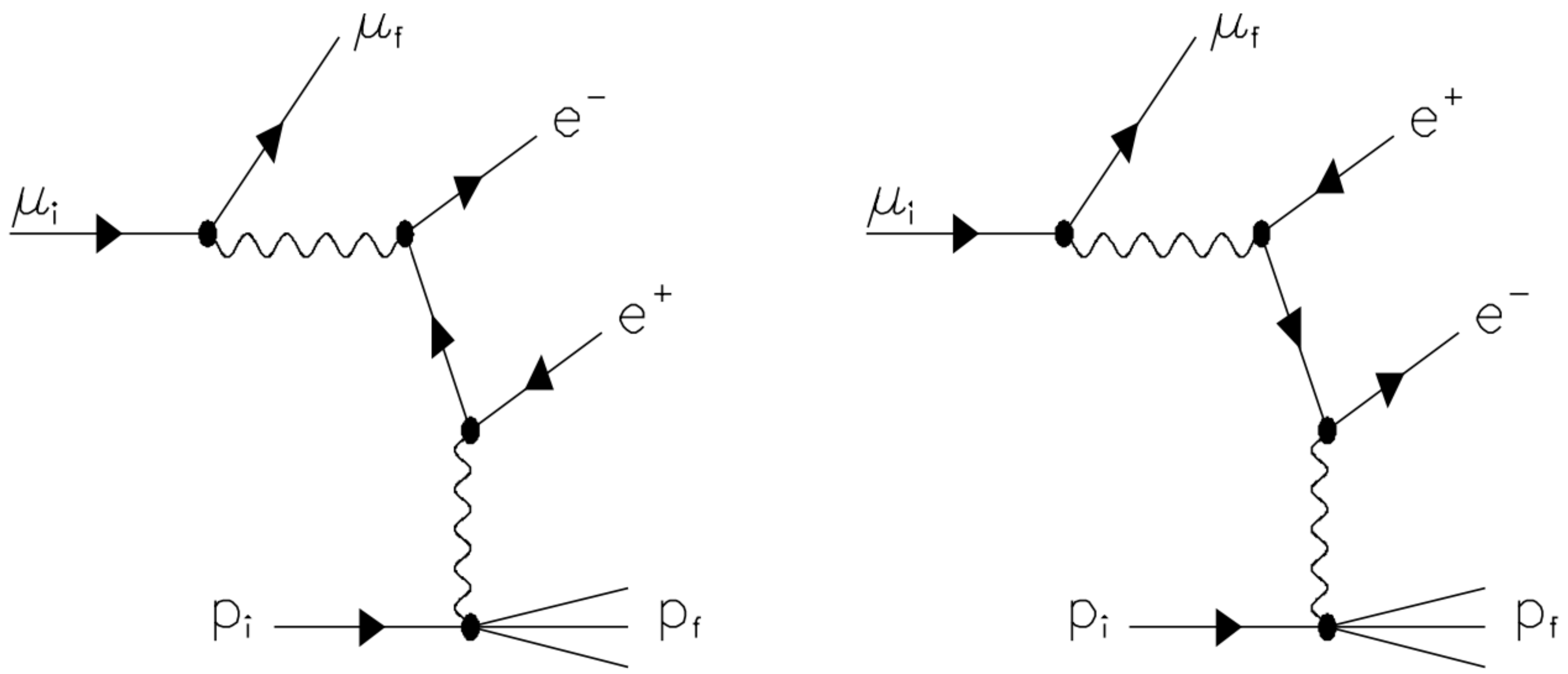
ionization



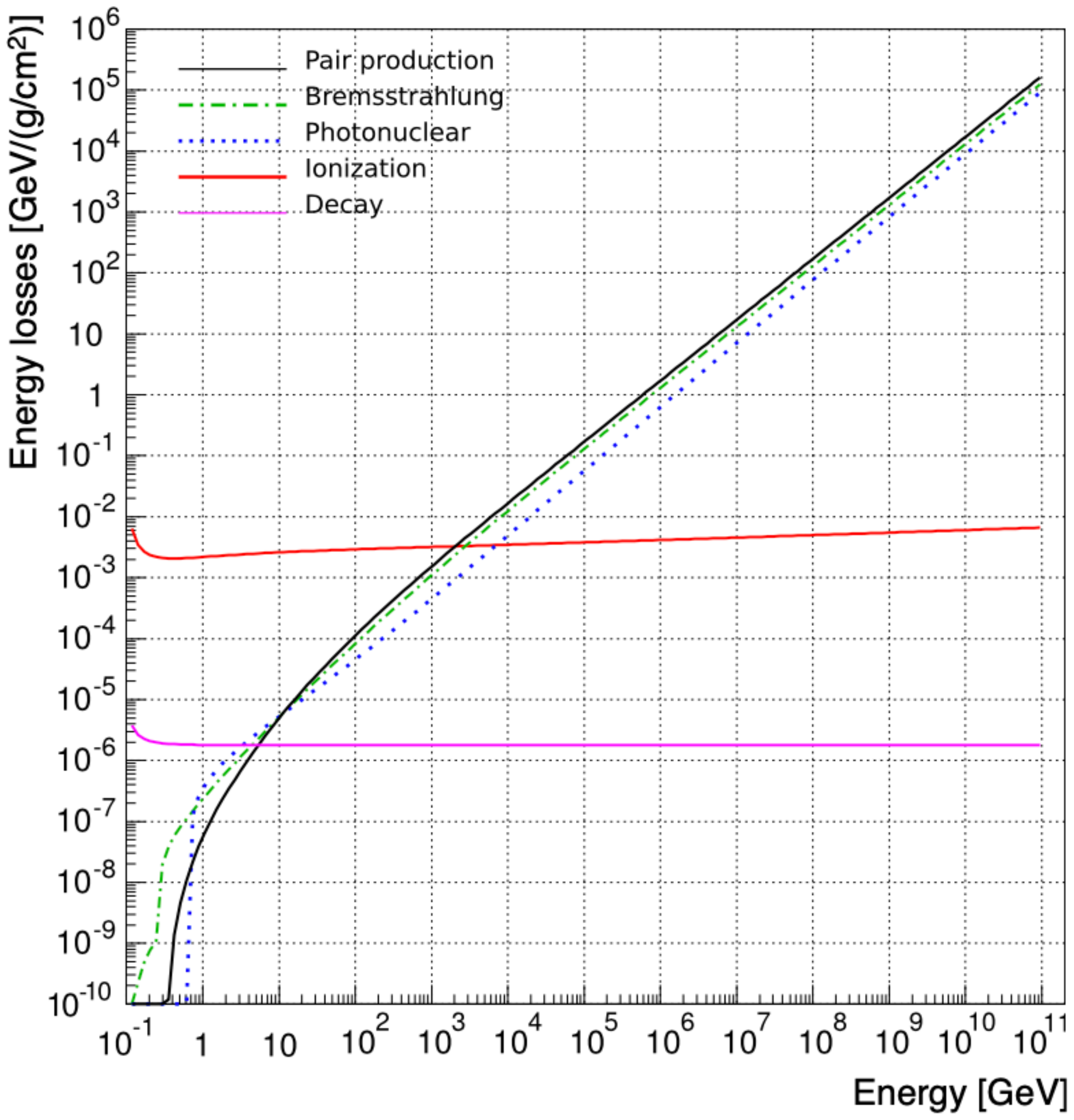
bremsstrahlung



photonuclear



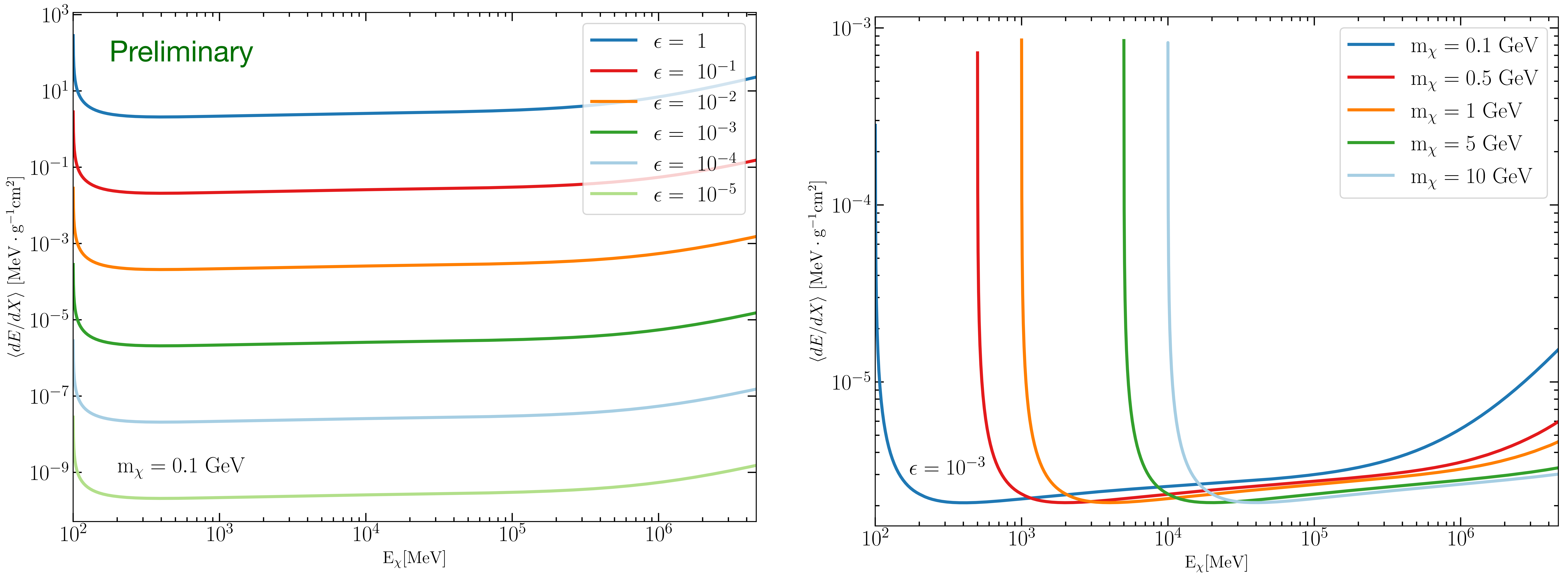
pair production



Koehne et al PROPOSAL

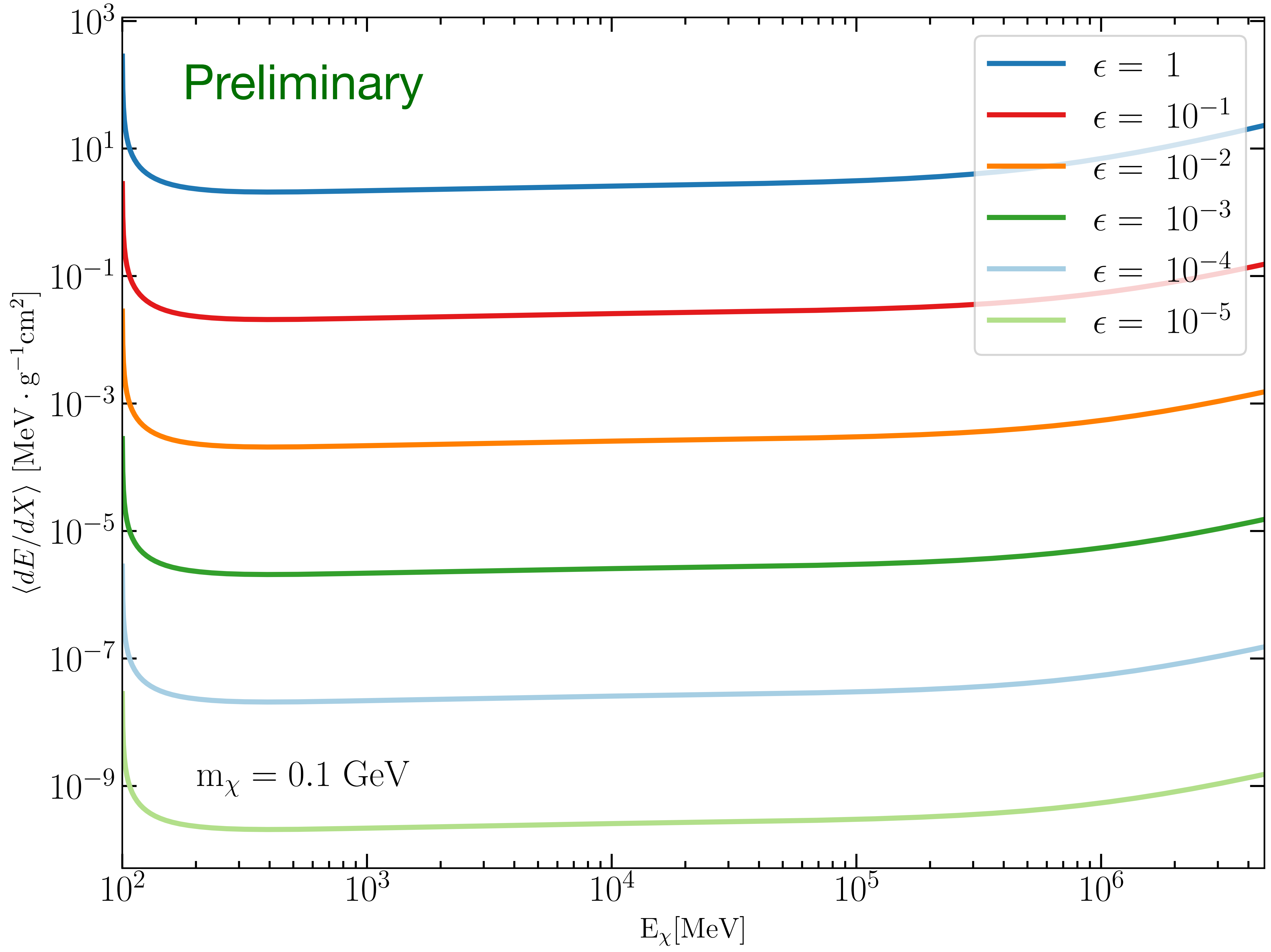
MCP Energy Loss

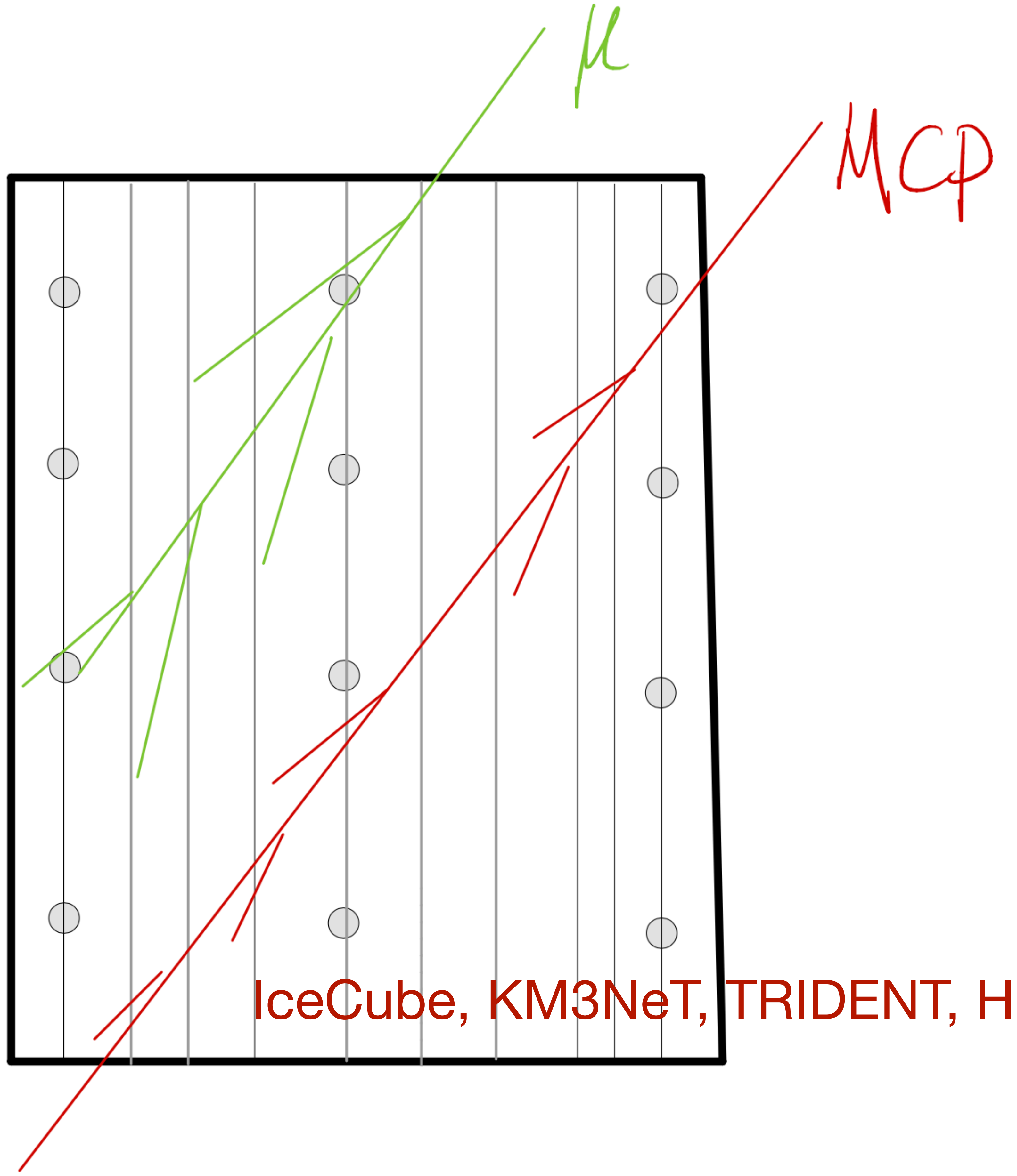
$$-\frac{dE}{dX} = \varepsilon^2 \left(a_{\text{ion.}} + b_{\text{el.-brem.}}\varepsilon^2 E + b_{\text{inel.-brem.}} E + b_{\text{pair}} E + b_{\text{photo-had.}} E\right) \approx \varepsilon^2 (a + bE)$$



MCP at Neutrino Telescopes

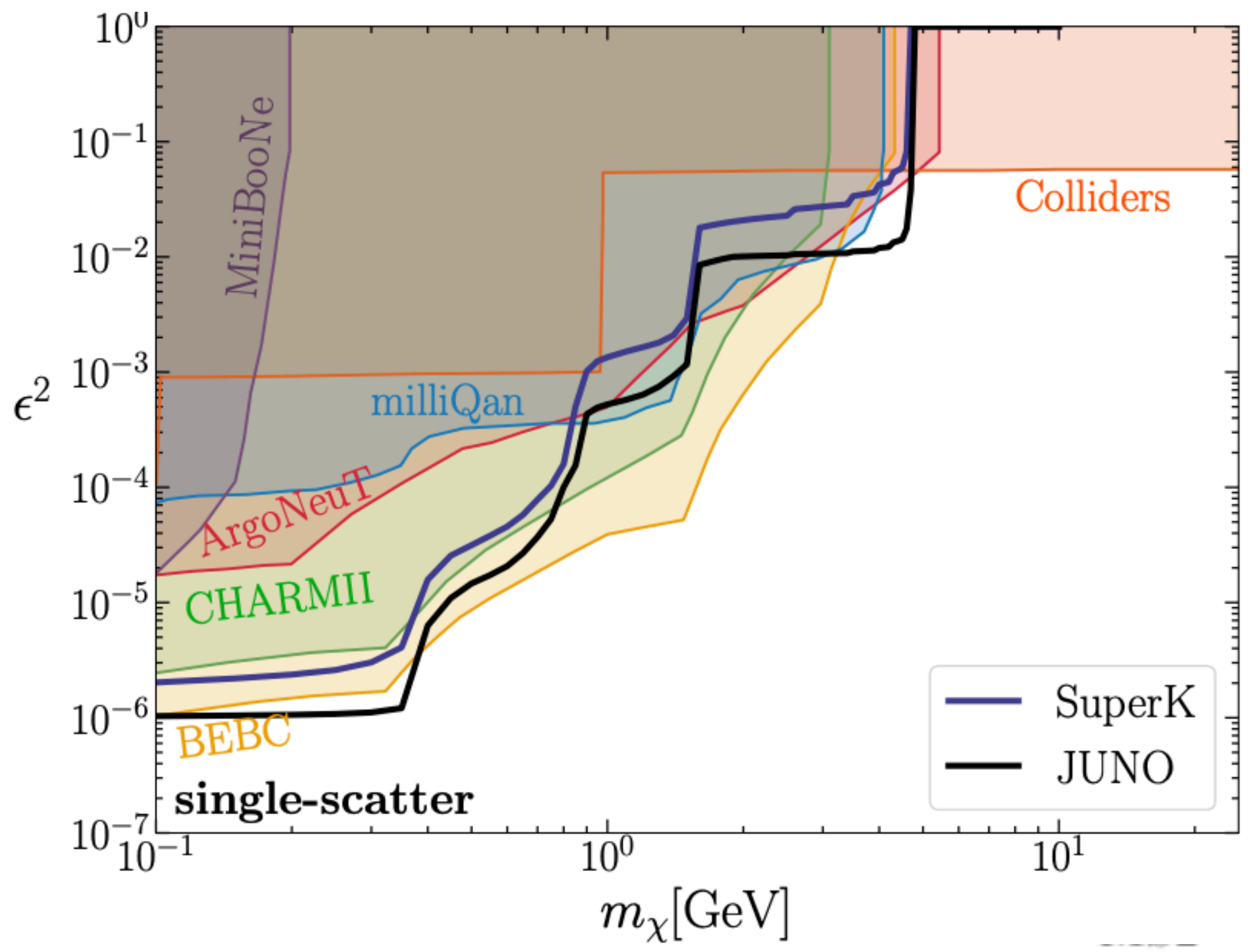
$$-\frac{dE}{dX} = \varepsilon^2 \left(a_{\rm ion.} + b_{\rm el.-brem.}\varepsilon^2 E + b_{\rm inel.-brem.}E + b_{\rm pair}E + b_{\rm photo-had.}E\right) \approx \varepsilon^2 \left(a + bE\right)$$



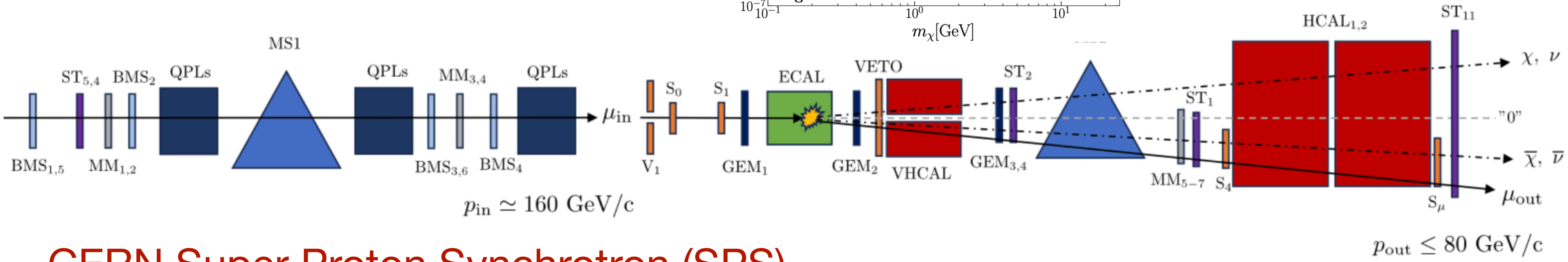


IceCube, KM3NeT, TRIDENT, HUNT…

The NA64μ Experiment



2022 pilot run



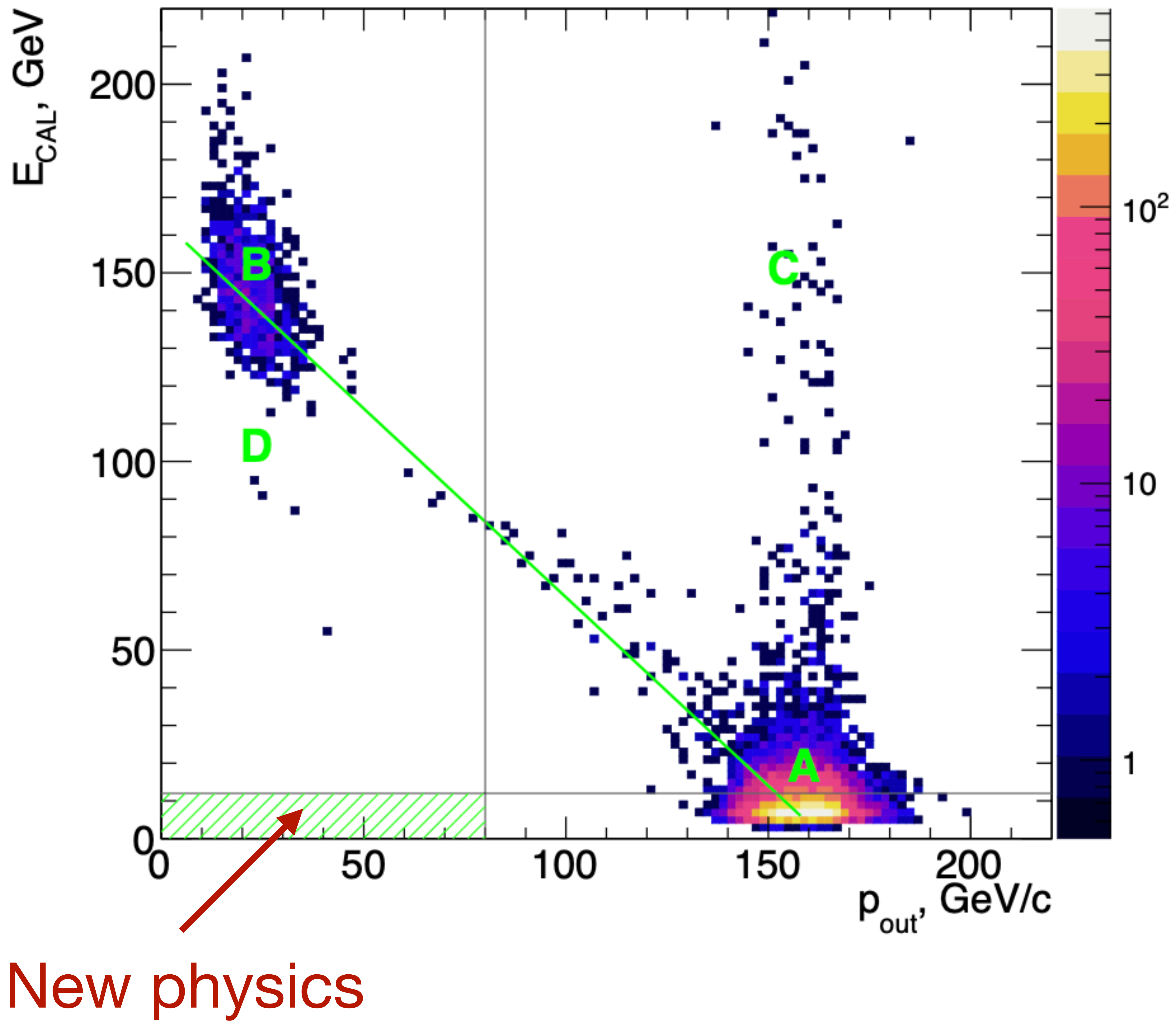
CERN Super Proton Synchrotron (SPS)

160 GeV muon beam

1.98×10^{10} muon on target

NA64 collaboration, PRL/2401.01708

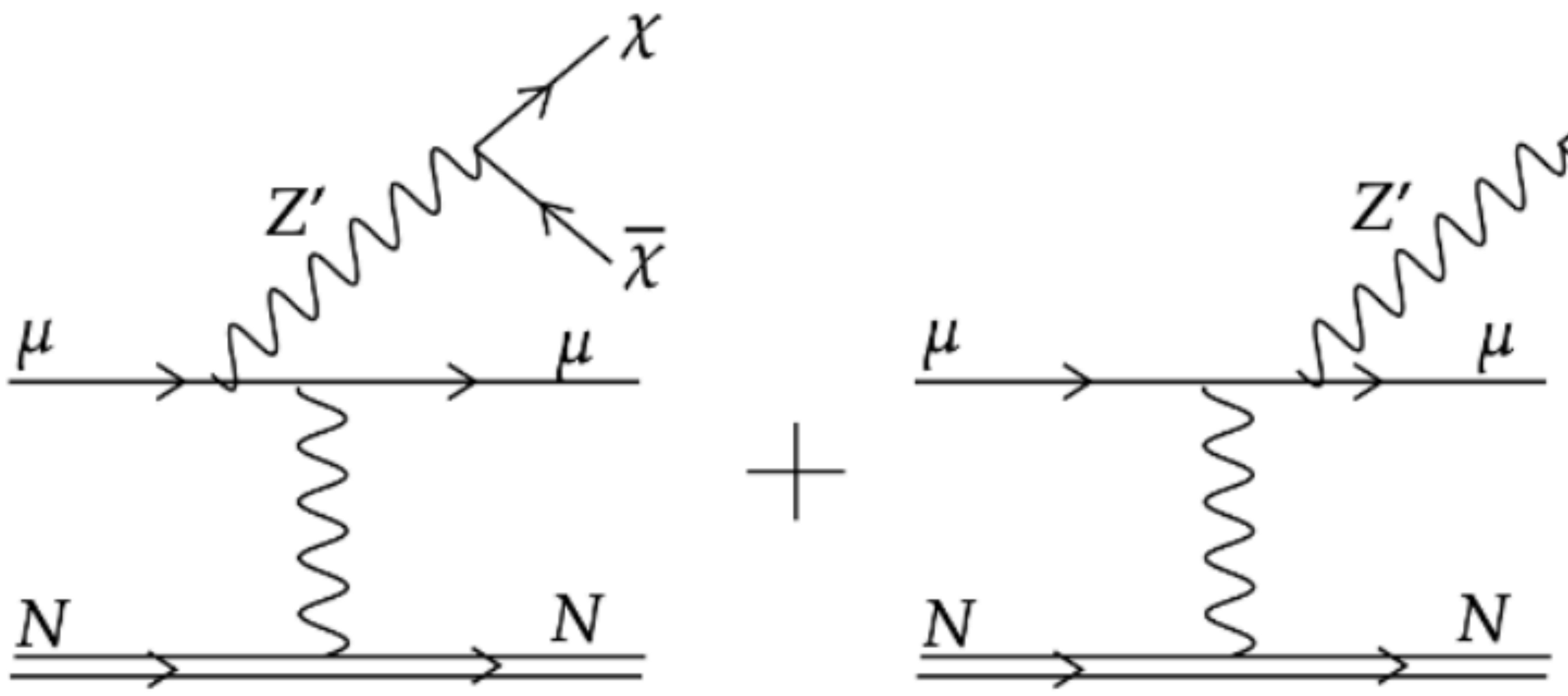
Events at NA64μ



- Region A: soft muon scattering with small energy deposition
- Region B: hard scattering and large energy deposition in the target
- Region C: soft scattering and large energy deposition in the last calorimeter
- Region D: Hard scattering in the target with hadrons left out

Muonphilic Dark Sector

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



Massless $L_\mu - L_\tau$ mediator with a dark sector

Production Rate

Target length

Decay probability

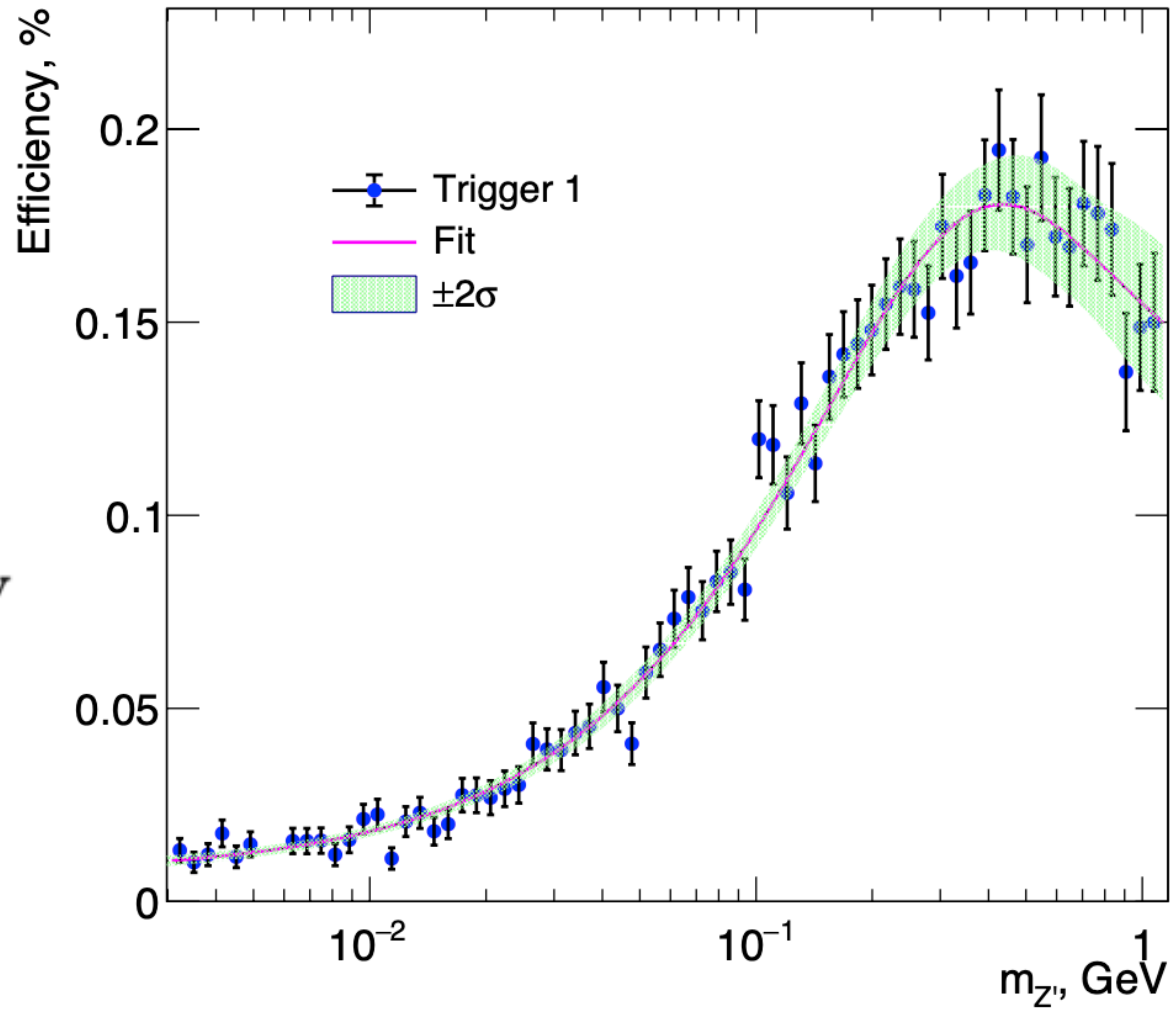
$$N_{\rm signal} = N_{\rm MOT} n_{\rm Pb} L_{\rm tar} \int d\sigma(\mu N \to \mu N X) \epsilon P_{\rm inv}$$

Muon on target
1.98×10^{10}

Pb target density

Scattering cross section

Efficiency



NA64 collaboration, 2409.10128

Cross Section

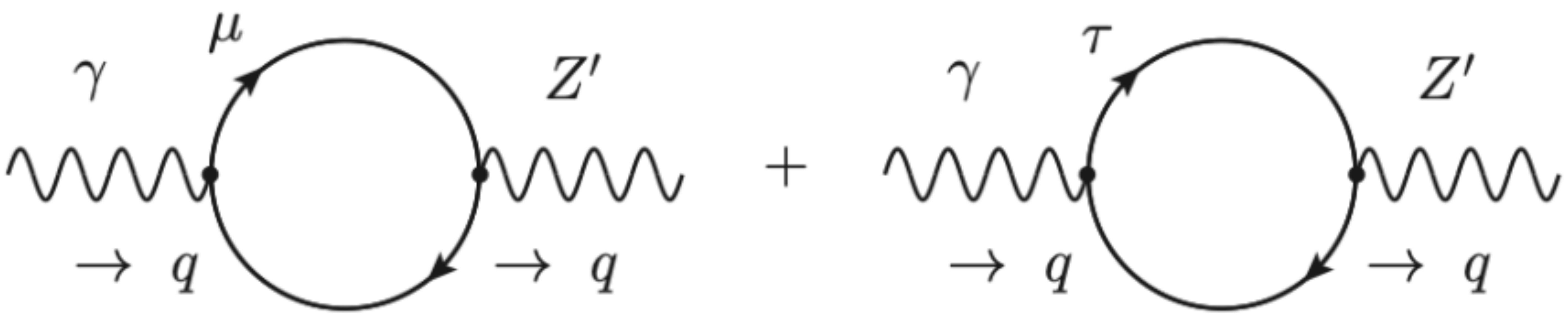
$$N_{\text{signal}} = N_{\text{MOT}} n_{\text{Pb}} L_{\text{tar}} \int d\sigma(\mu N \to \mu N X) \epsilon P_{\text{inv}}$$

$$\begin{aligned} \mathrm{d}\sigma(\mu N \to \mu N \chi\bar{\chi}) =& \mathrm{d}\sigma(\mu N \to \mu N Z') \\ & \times \frac{g_\chi^2}{12\pi^2} \frac{\mathrm{d}Q^2}{Q^2} \sqrt{1 - \frac{4m_\chi^2}{Q^2}} (1 + \frac{2m_\chi^2}{Q^2}) \end{aligned}$$

$$\begin{aligned} \mathcal{A}_{Z'-\chi} =& e^2 g_{Z'}^2 \Big[2\frac{x^2 - 2x + 2}{1 - x} + 4\frac{Q^2 + 2m_\mu^2}{\tilde{u}} \\ & + 4\frac{2m_\mu^4 x^2 + Q^4(1 - x) + m_\mu^2 Q^2 (x^2 - 2x + 2)}{\tilde{u}^2} \Big] \end{aligned}$$

Muophilic Millicharge?

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

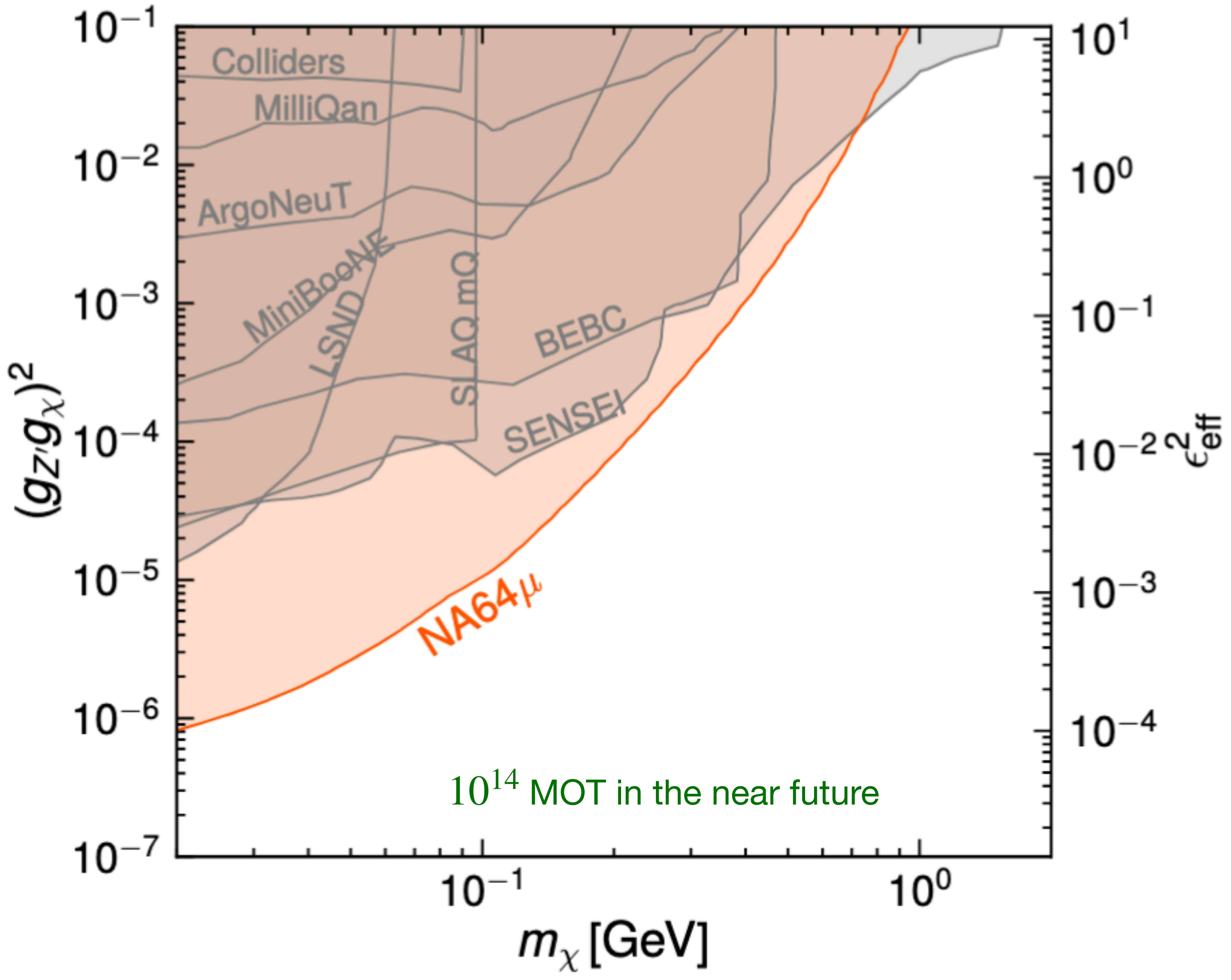


$$\mathcal{L}_{\mathrm{kin}} \supset \frac{\Pi(q^2)}{2} Z'_{\mu\nu}F^{\mu\nu}$$

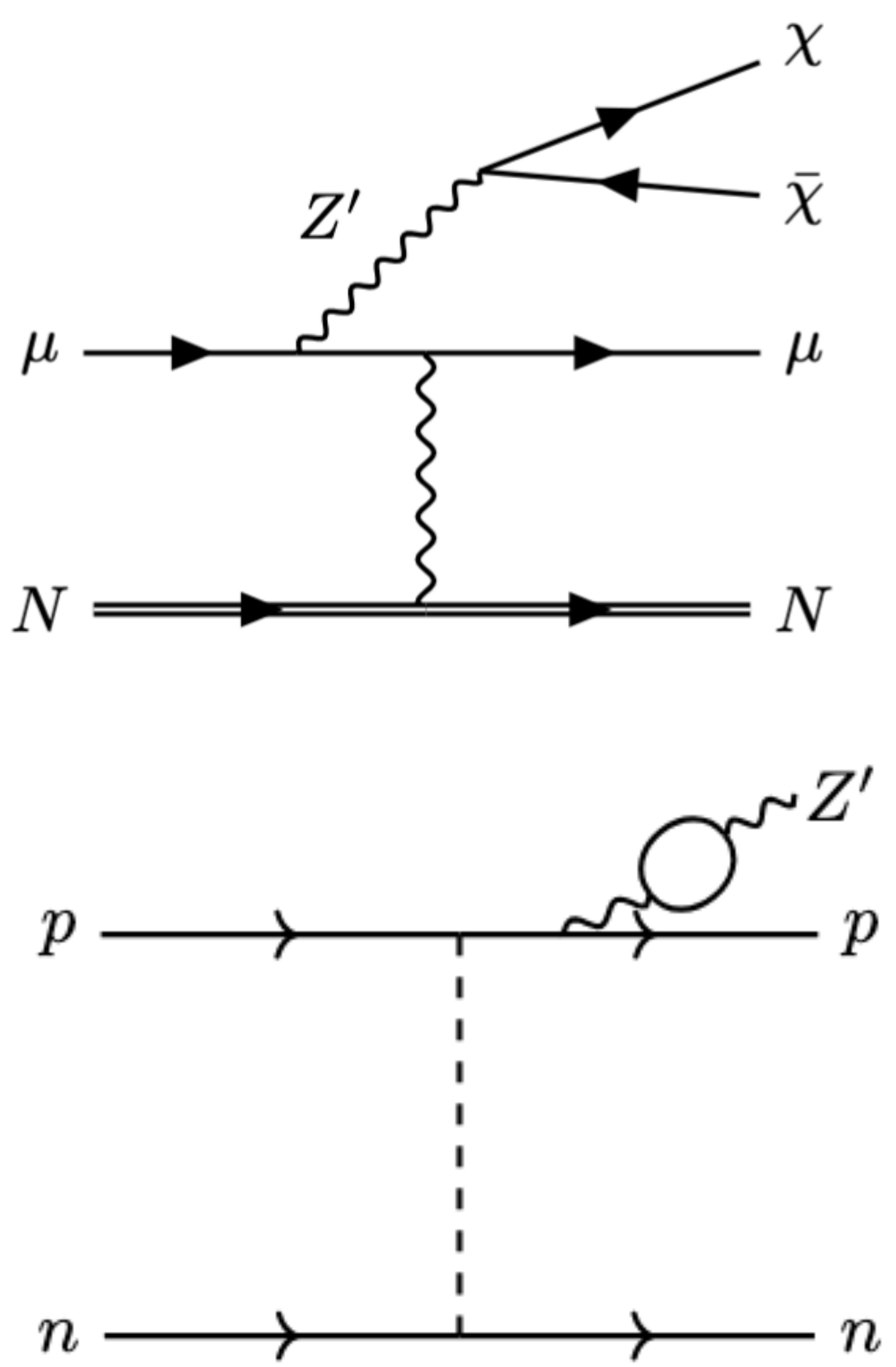
$$\Pi(q^2) = \frac{e g_{Z'}}{2\pi^2}\int_0^1 \mathrm{d}x(1-x)\ln\frac{m_\tau^2 - x(1-x)q^2}{m_\mu^2 - x(1-x)q^2}$$

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

Constraints on Muonphilic Dark Sector



Croon et al, JHEP/2006.13942



Li, Liu, **NS**, arXiv: 2501.06294

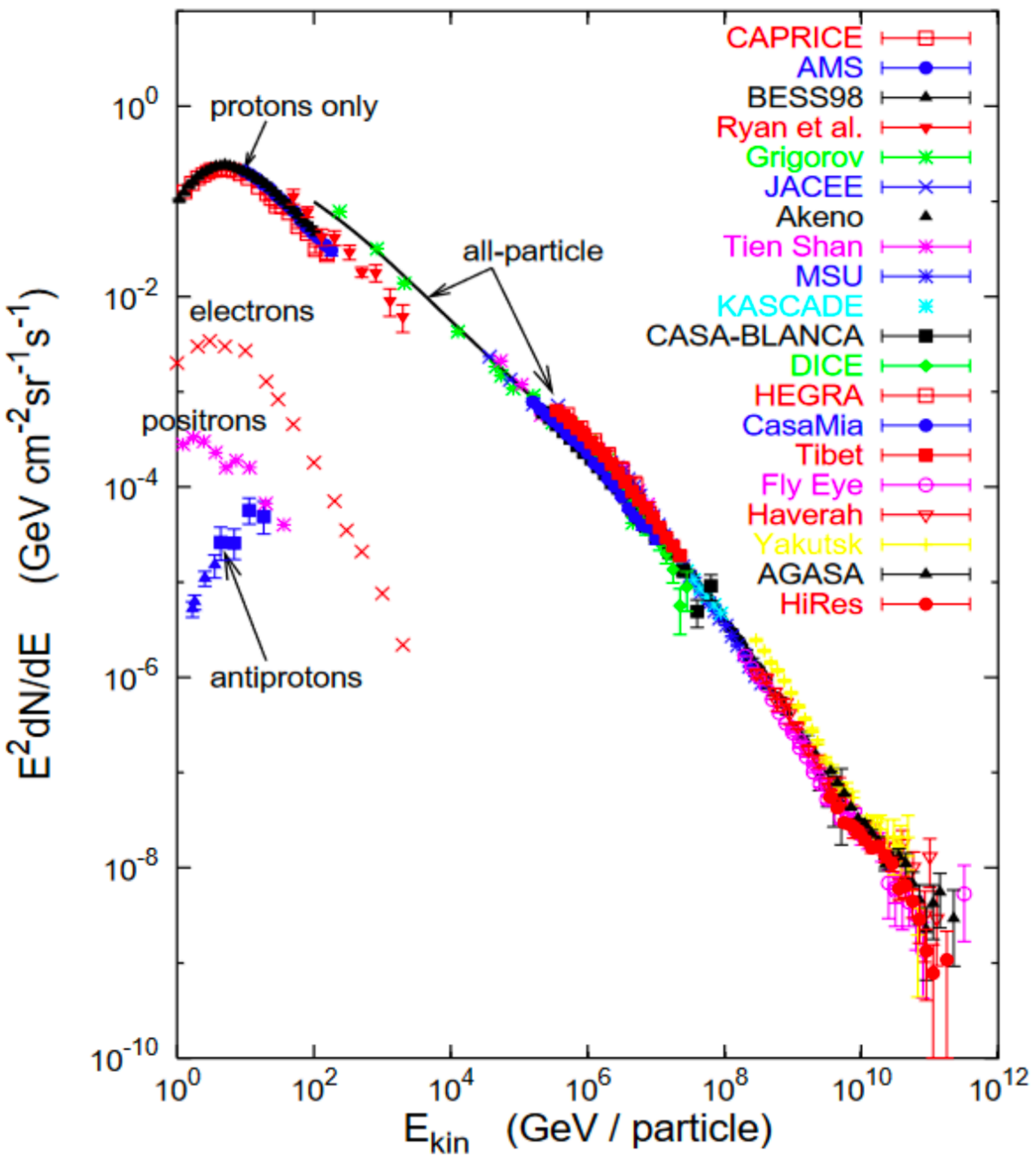
Summary

- Search for millicharged particles from atmospheric beam dump at JUNO and SuperK
- Multiple scattering could be more sensitive than single scattering
- New signature of MCP at neutrino telescopes
- Flavor-specific dark sector could be searched with muon beam dump

谢谢

Atmospheric beam dump and new physics

- Heavy neutral leptons
- Hadrophilic dark matter
- Axion-like particles
- Long-lived neutralinos
- Monopoles
- Dark photon
- Millicharged particles
- …



Millicharge particles from light meson decay

$$\Phi_\chi(\gamma_\chi) = 2\sum_{\mathfrak{m}} \mathrm{BR}(\mathfrak{m}\to\chi\bar{\chi}) \int \mathrm{d}\gamma_{\mathfrak{m}} \Phi_{\mathfrak{m}}(\gamma_{\mathfrak{m}}) P(\gamma_\chi|\gamma_{\mathfrak{m}})$$

Vector mesons $\rho, \omega, \phi, J/\psi$ decay to MCP pairs

$$\frac{\mathrm{BR}\left(\mathfrak{m}\to\chi\bar{\chi}\right)}{\mathrm{BR}\left(\mathfrak{m}\to\mu^+\mu^-\right)} = \epsilon^2\sqrt{\frac{m_{\mathfrak{m}}^2-4m_\chi^2}{m_{\mathfrak{m}}^2-4m_\mu^2}}$$

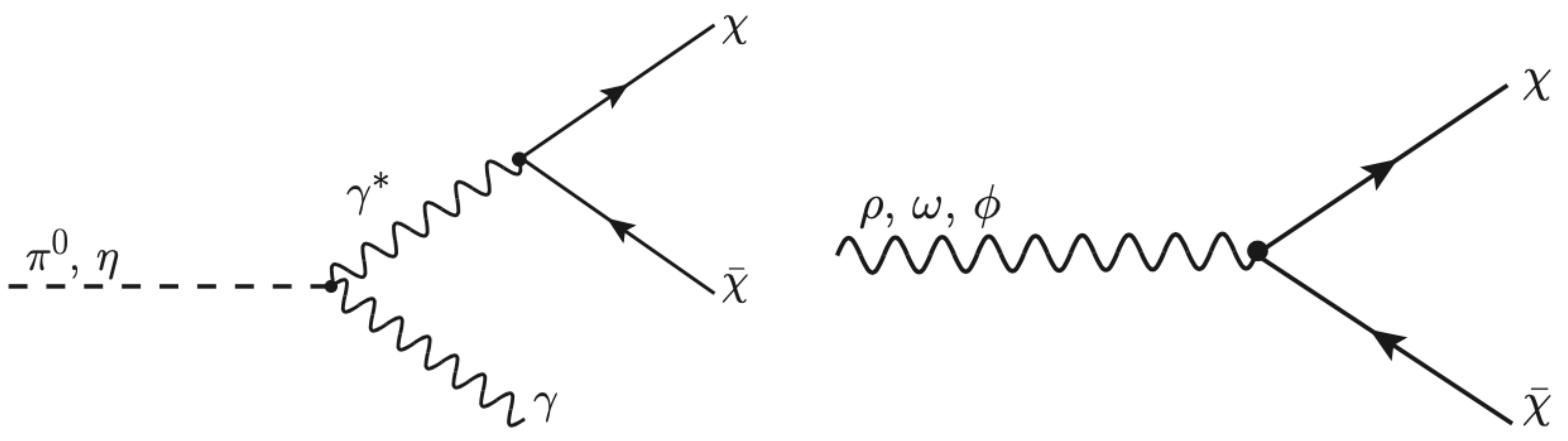
$$P\left(E_\chi|E_{\mathfrak{m}}\right) = \frac{1}{\Gamma_{\mathfrak{m}}}\frac{d\Gamma_{\mathfrak{m}}}{dE_\chi} = \frac{1}{E_\chi^+ - E_\chi^-}$$

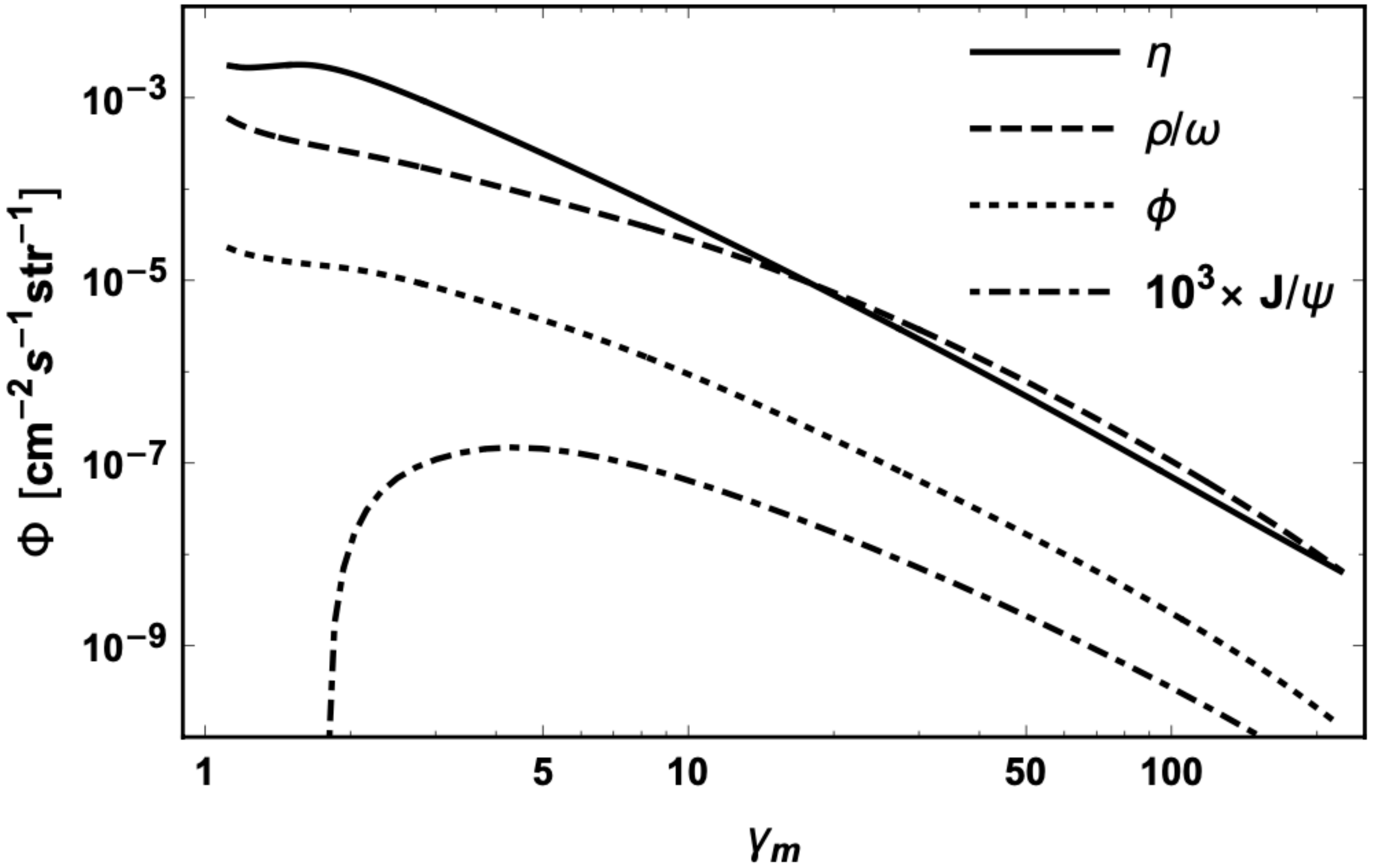
η decay to MCP pairs+photon

$$\mathrm{BR}\left(\eta\to\gamma\chi\chi\right) = 2\epsilon^2\alpha\mathrm{BR}(\eta\to\gamma\gamma)I^{(3)}\left(\frac{m_\chi^2}{m_\eta^2}\right)$$

$$\frac{1}{\Gamma_\eta}\frac{d\Gamma_\eta}{dz} = \frac{m_\eta - z}{72z^3F_1(m_\chi)}F_2\left(z, m_\chi\right)$$

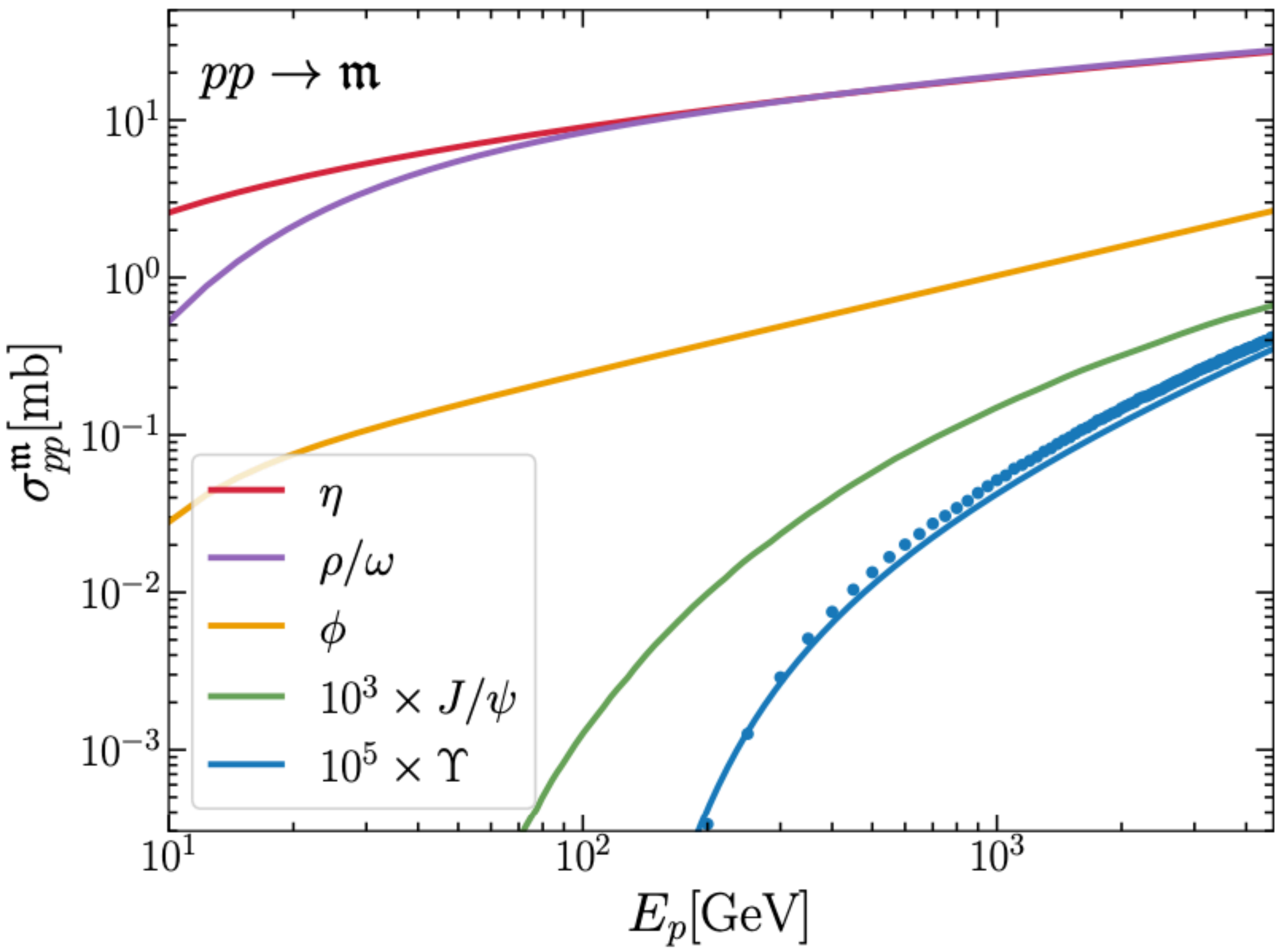
Plestid et al PRD/2002.11732

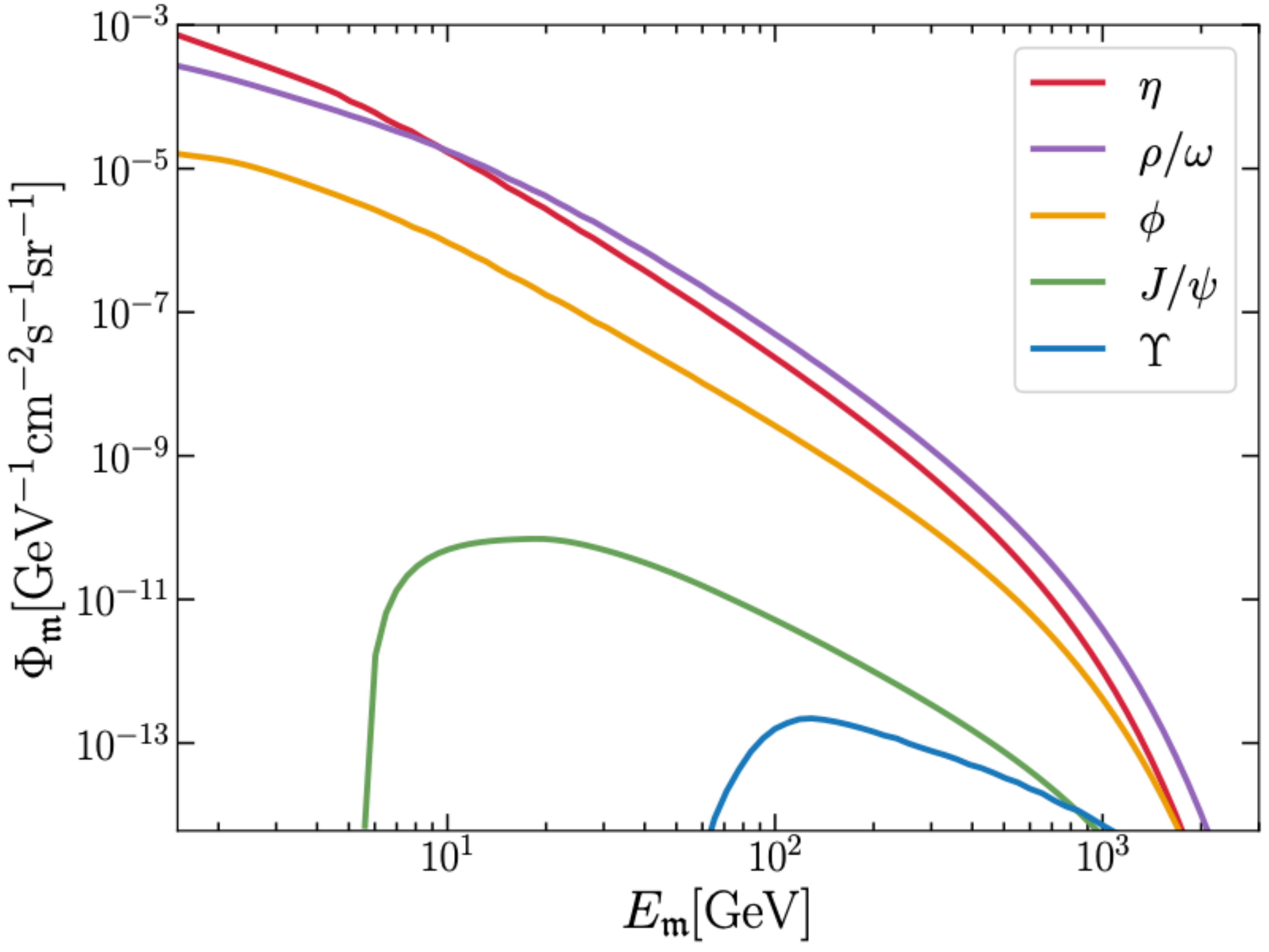




Millicharge Particles from Upsilon Meson Decay

Pythia8 simulations





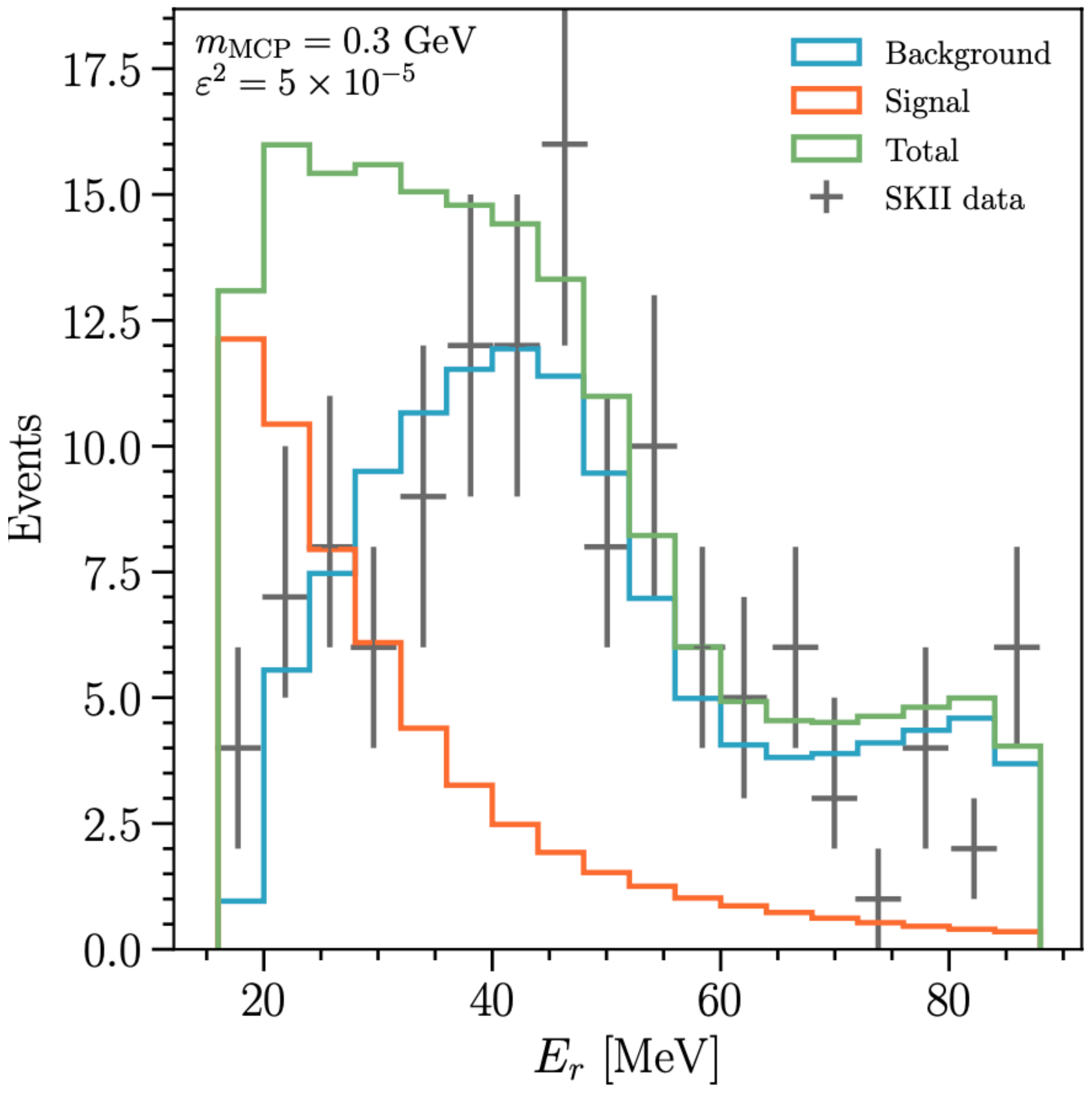
Wu, Hardy, **NS**, PRD/arXiv: 2406.01668

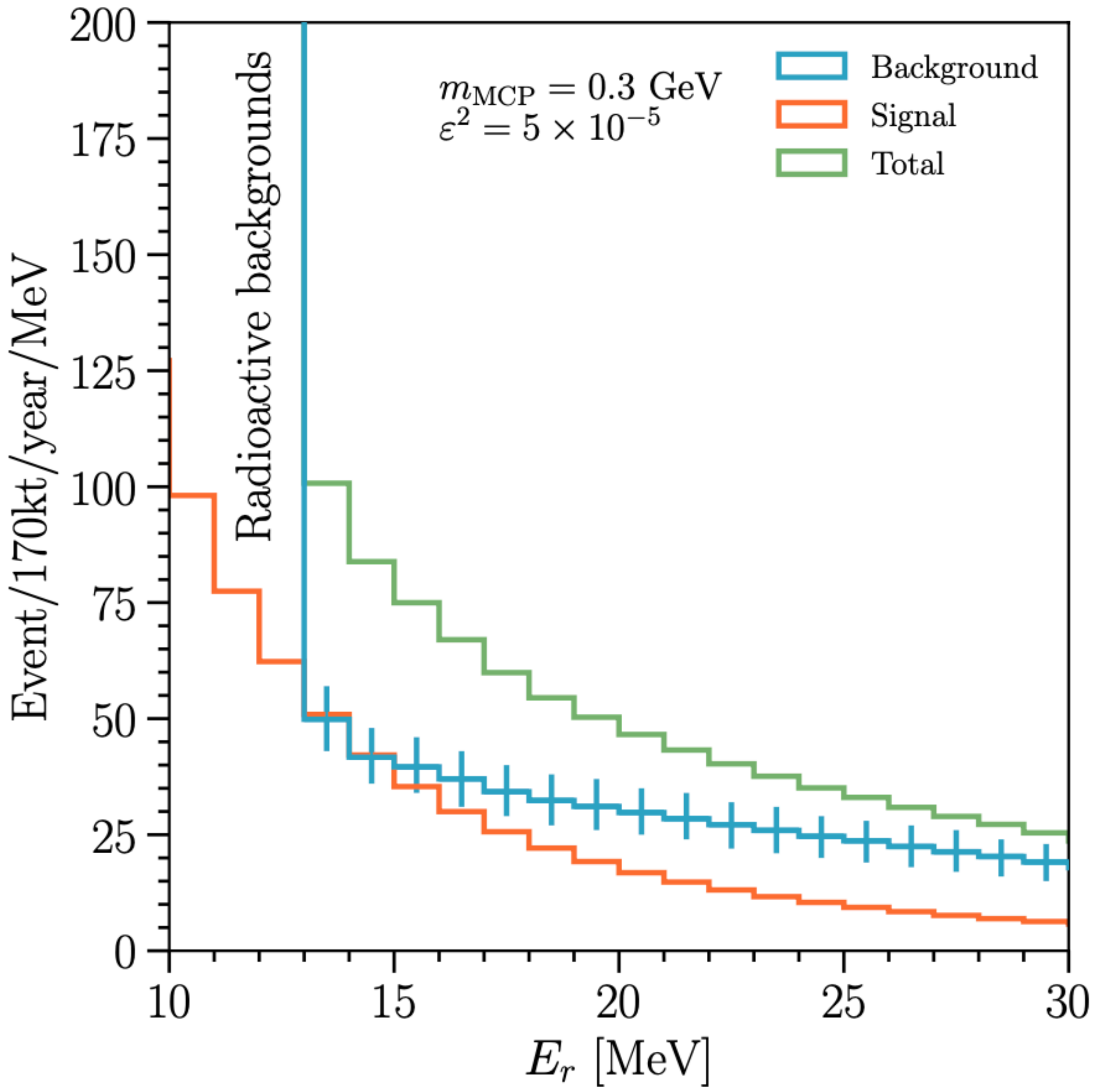
Single scatter

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

$$d\sigma_{\chi e}/dE_r \propto 1/E_r^2 \qquad \sigma_{\chi e} \simeq \frac{\pi\alpha_{EM}\epsilon^2}{m_e T_{\min}} = 2.6\times10^{-25}\epsilon^2\ \mathrm{cm}^2\frac{\mathrm{MeV}}{T_{\min}}$$

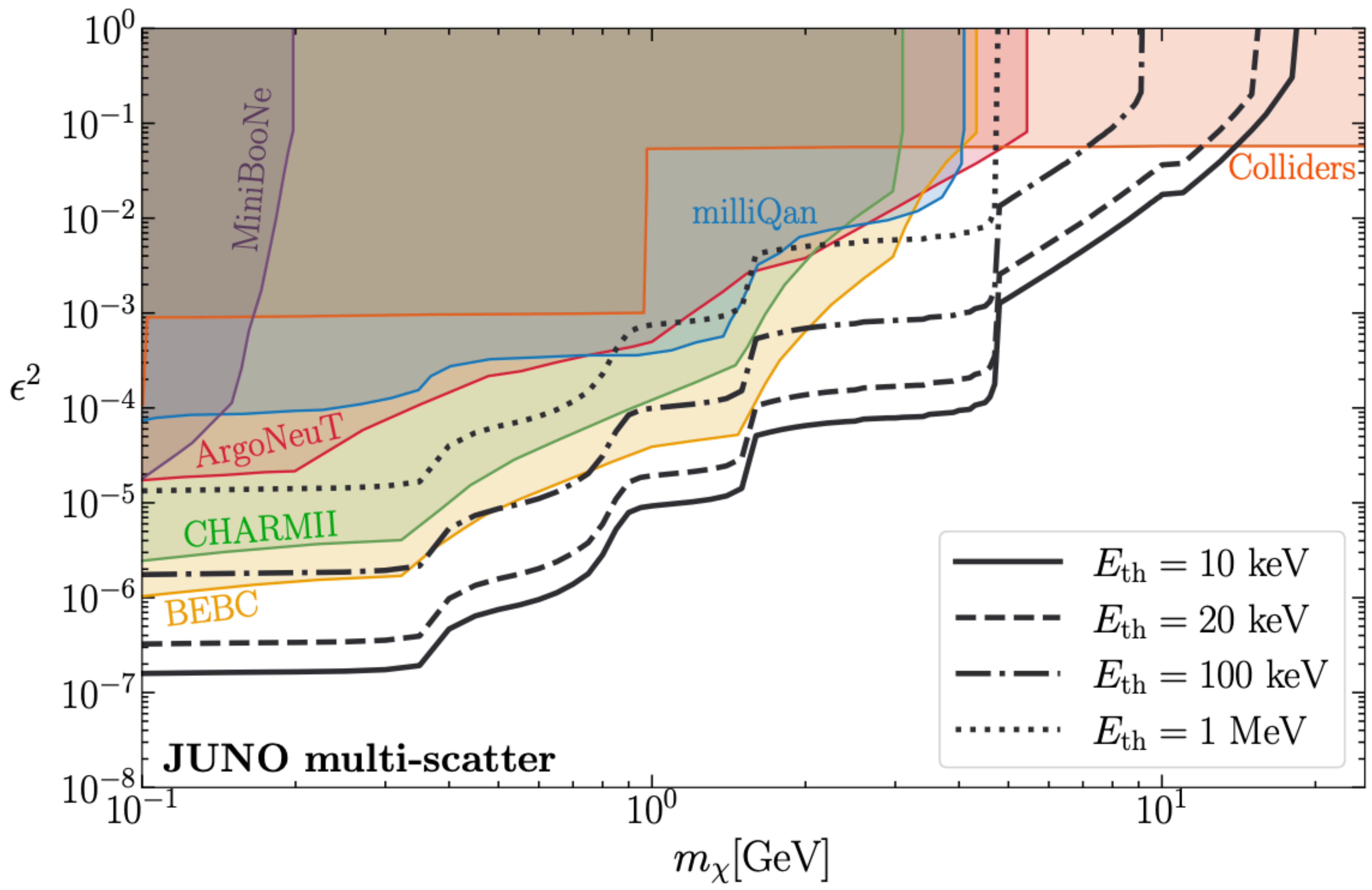
$$N_i(m_\chi,\epsilon) = N_e T\int_{E_{i,\min}}^{E_{i,\max}} dE_r \epsilon_D(E_r) \times \int dE_\chi d\Omega \Phi_\chi^D(E_\chi,\Omega)\frac{d\sigma_{\chi e}}{dE_r}$$

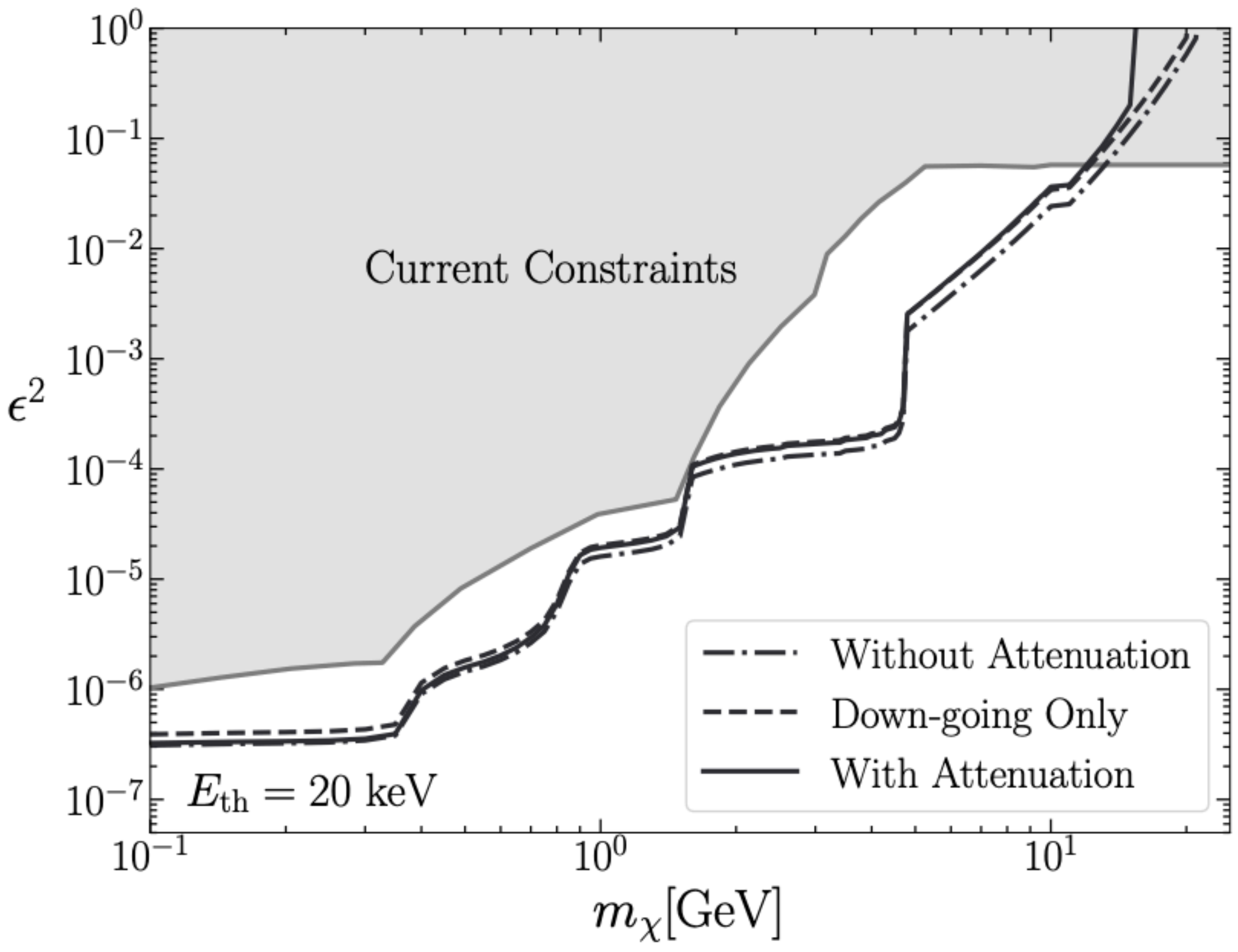




Arguelles et al JHEP/2104.13924

Multiple scatter constraint



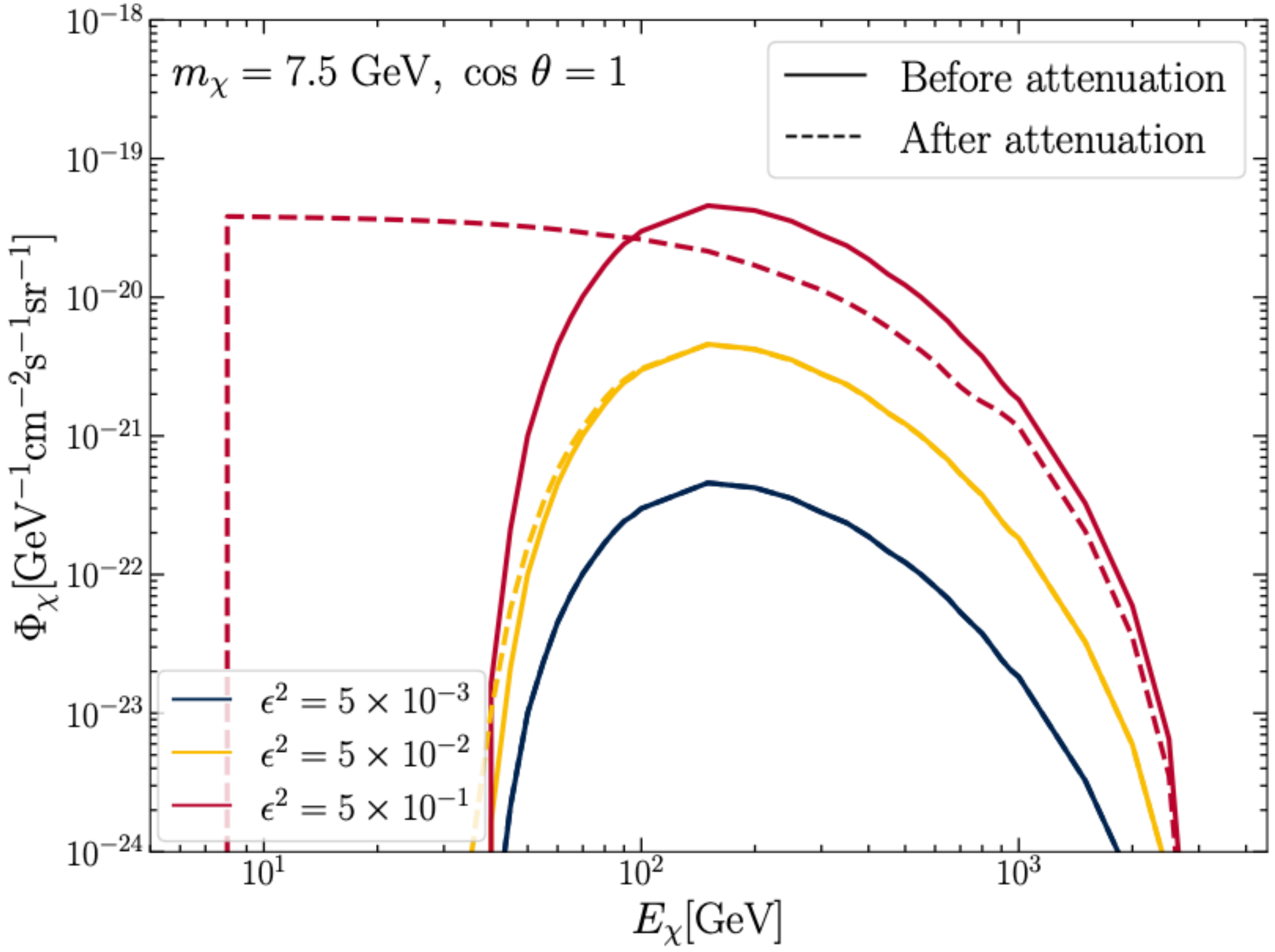


Assuming JUNO 170 kton·yr exposure

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

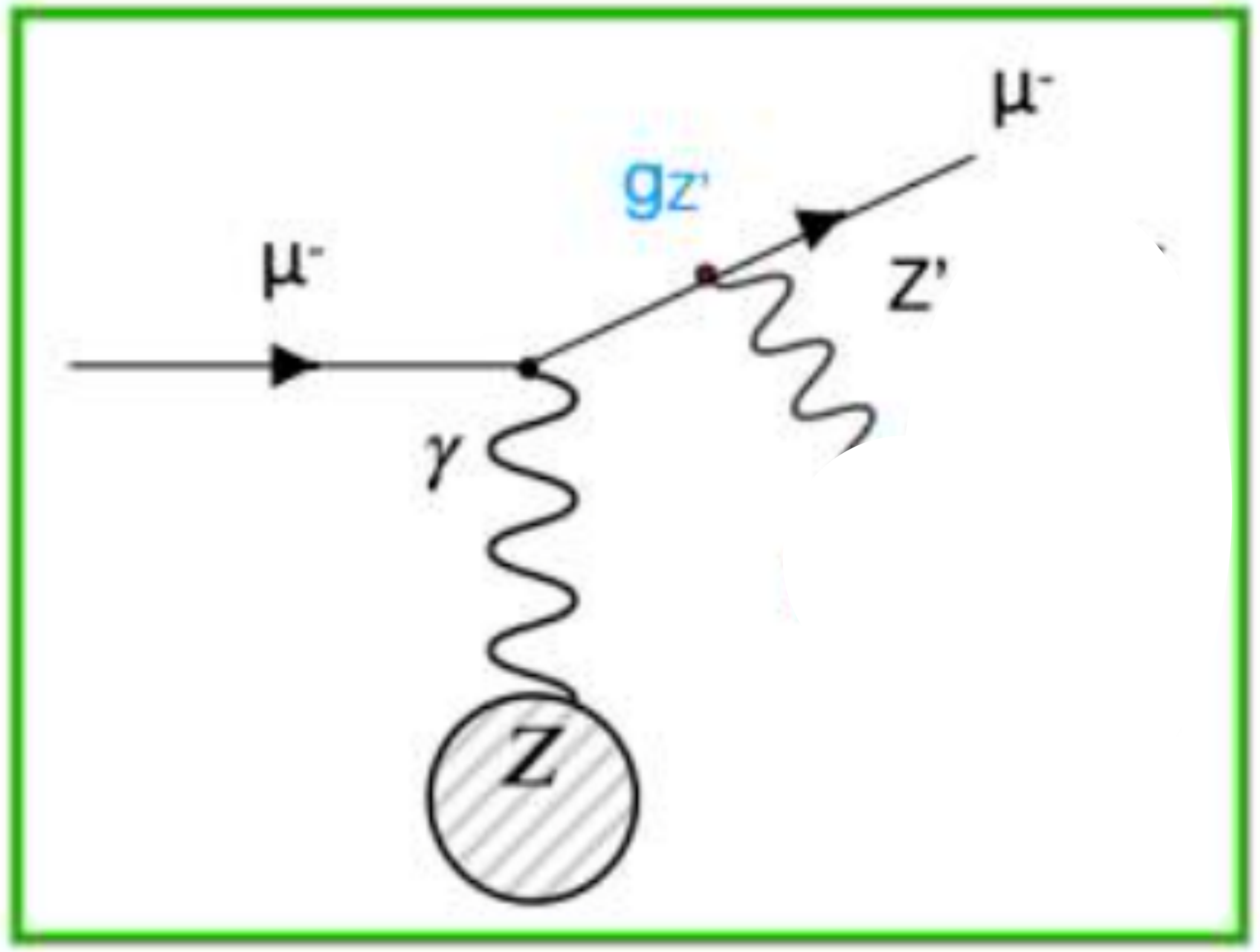
Earth Attenuation

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



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

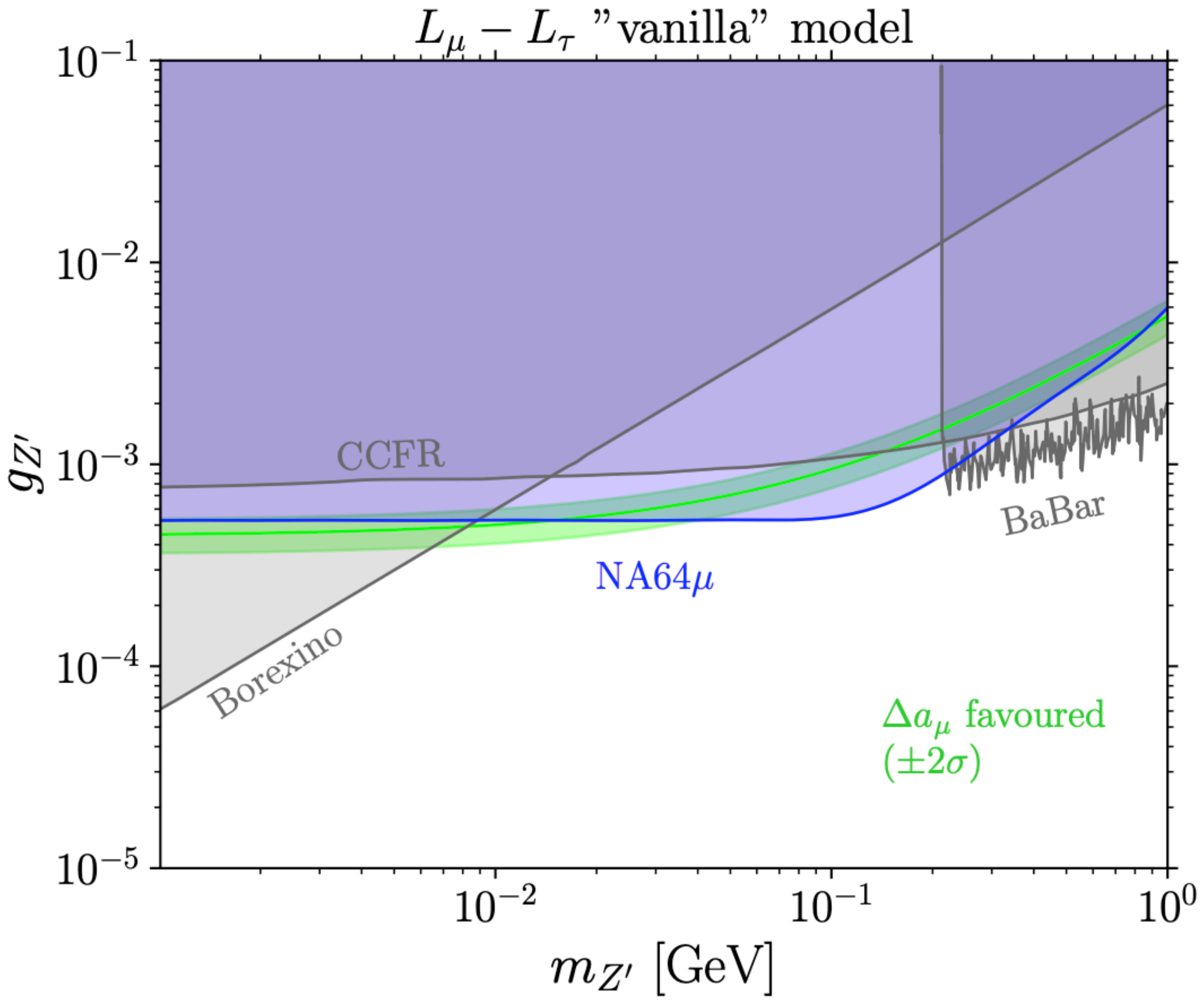
New Physics Search at NA64μ



$Z' \to \nu\bar{\nu}$

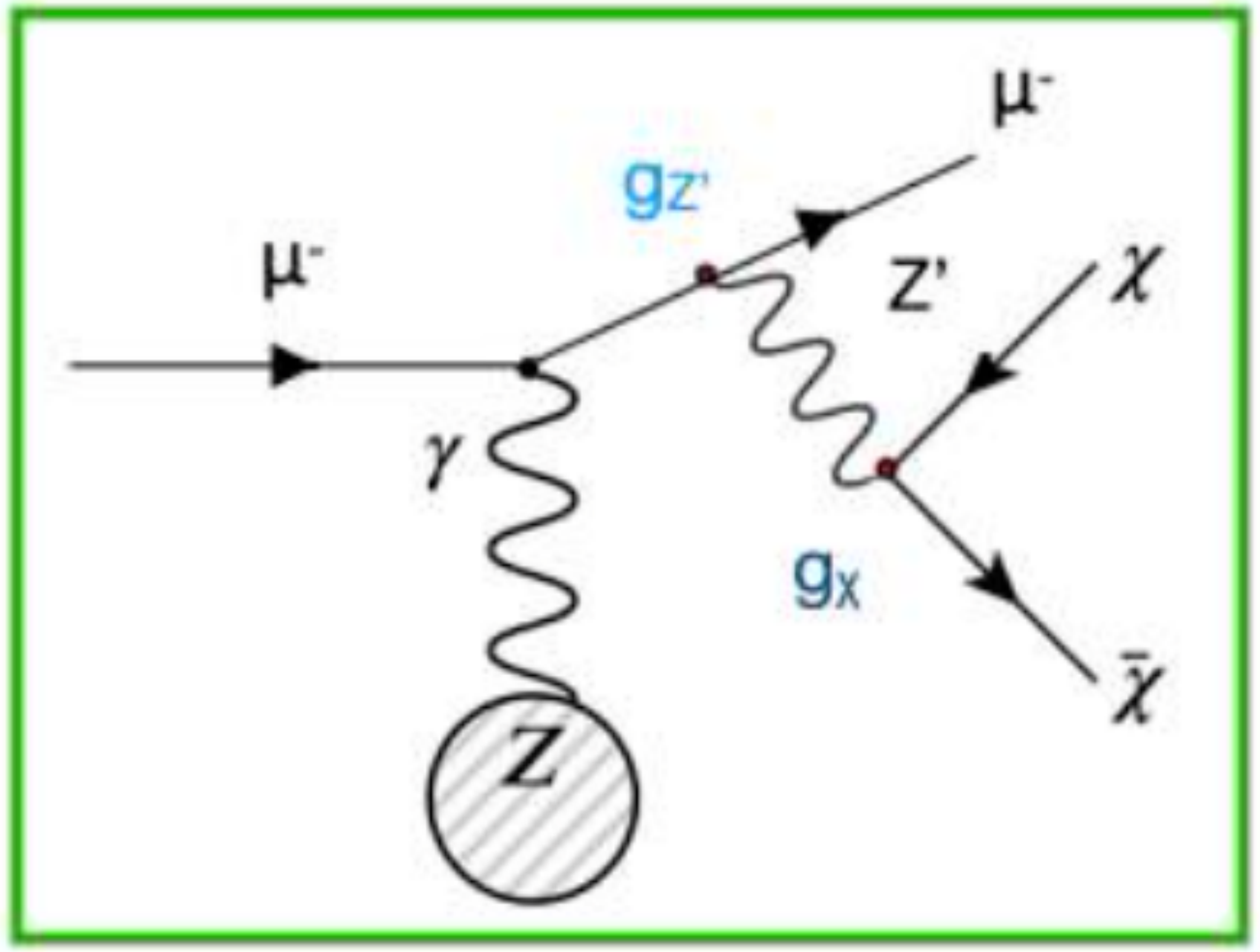
$Z' \to \mu\bar{\mu}$

Search for missing energy



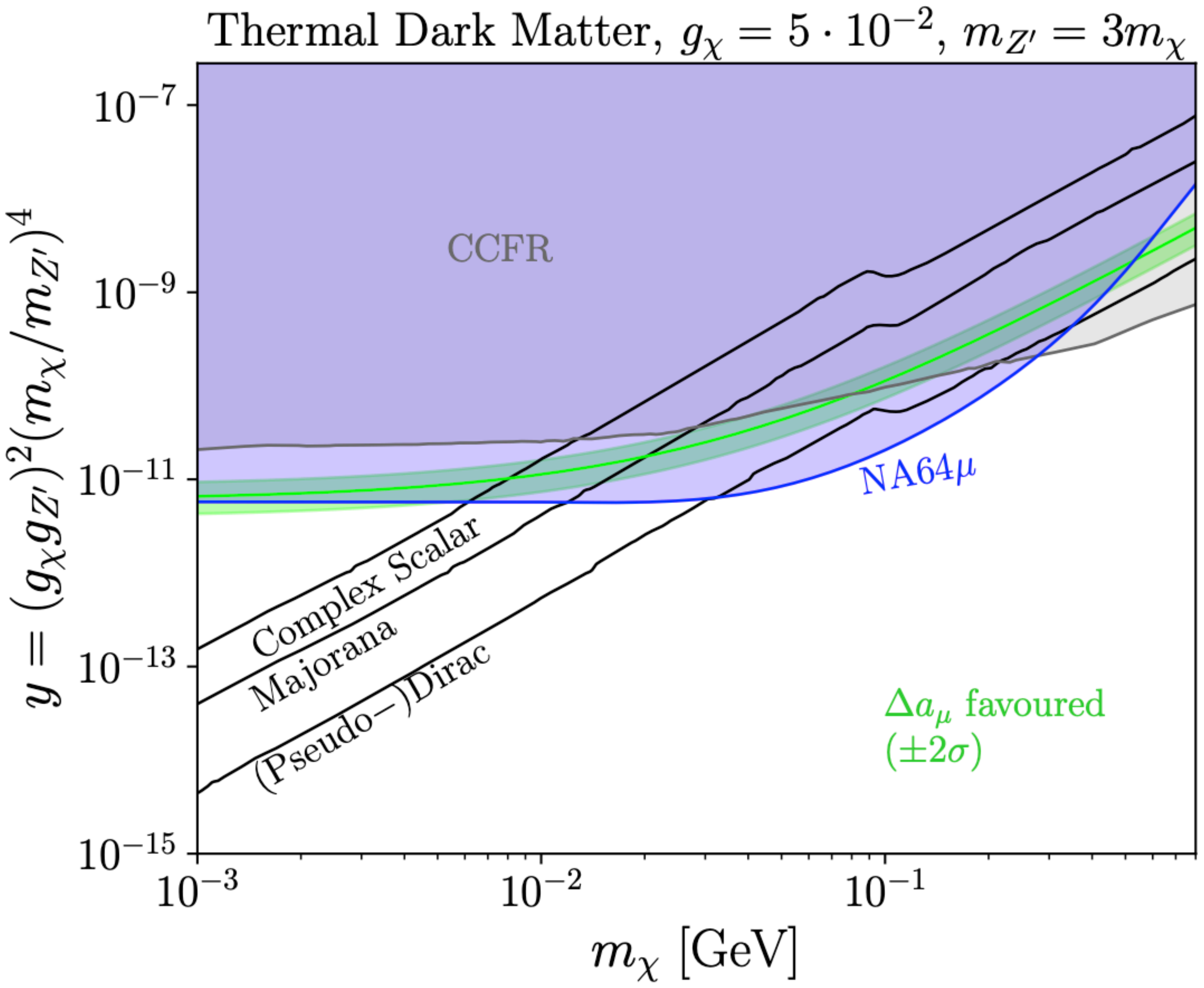
NA64 collaboration, PRL/2401.01708

New Physics Search at NA64μ



$Z' \to \chi\bar{\chi}$

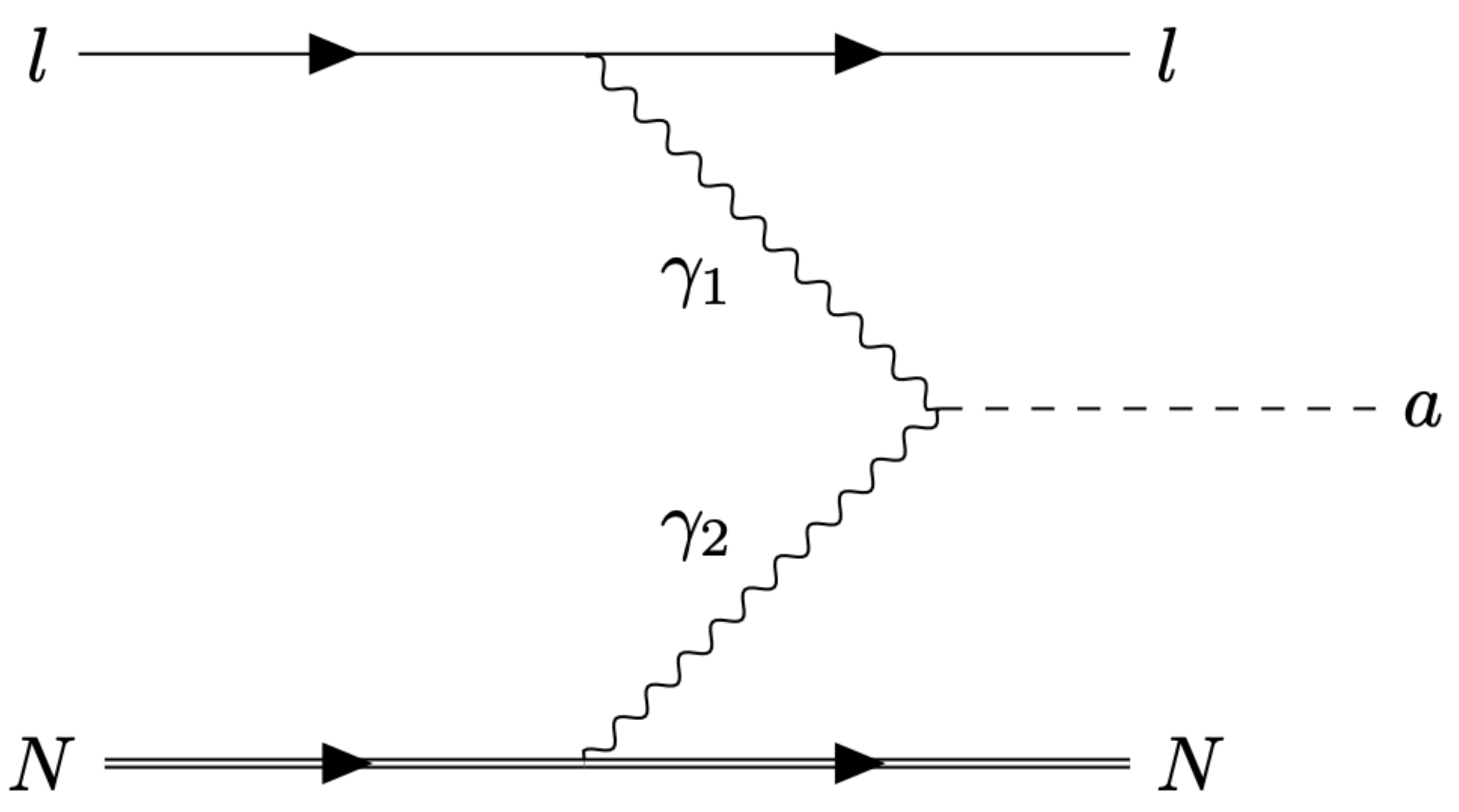
Search for missing energy

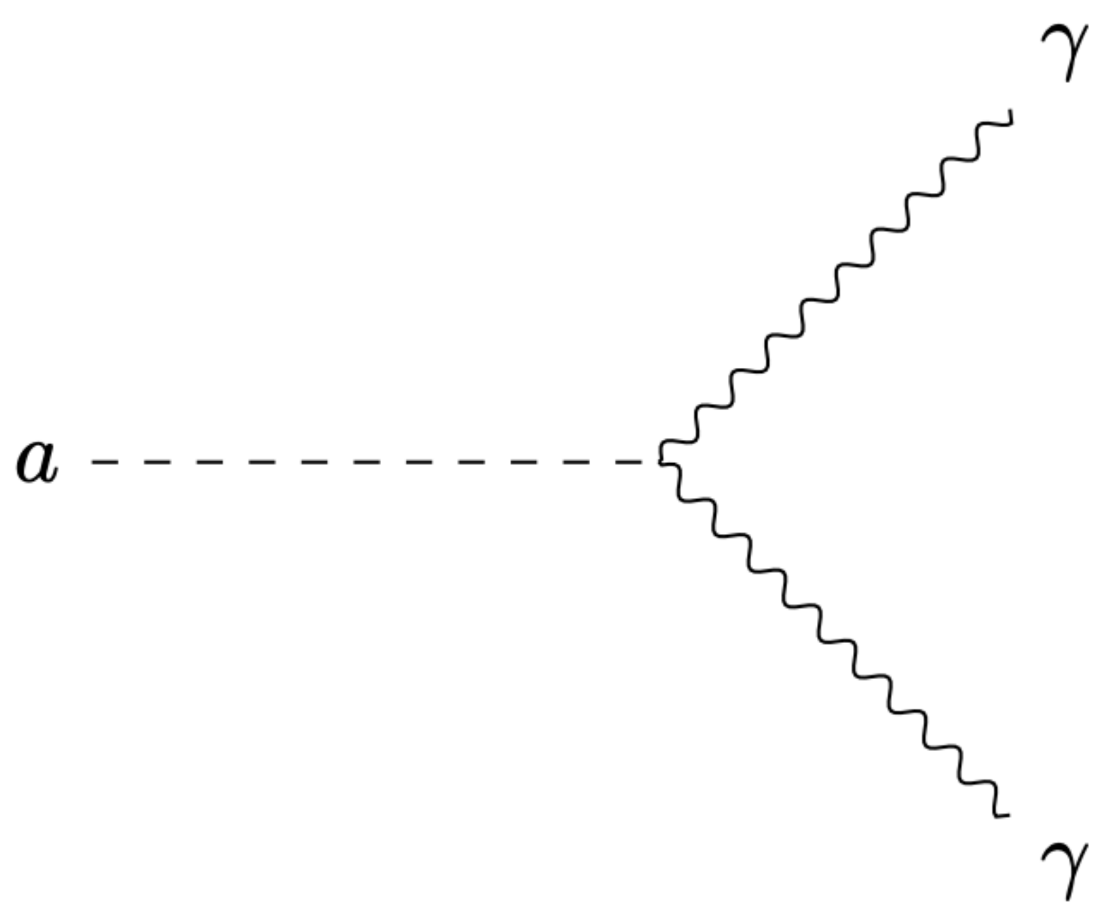


NA64 collaboration, PRL/2401.01708

Axion-Photon Interaction

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





Axion production through photon-photon fusion

Cross Section

$$N_{\text{signal}} = N_{\text{MOT}} n_{\text{Pb}} L_{\text{tar}} \int d\sigma(\mu N \to \mu N X) \epsilon P_{\text{inv}}$$

Weizsacker-William approxmation

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = \frac{\alpha}{8\pi^2}\sqrt{E_a^2 - m_a^2} E_\mu (1-x) \int \mathrm{d}\cos\theta \frac{\chi}{\tilde{u}^2} \mathcal{A}$$

effective photon flux

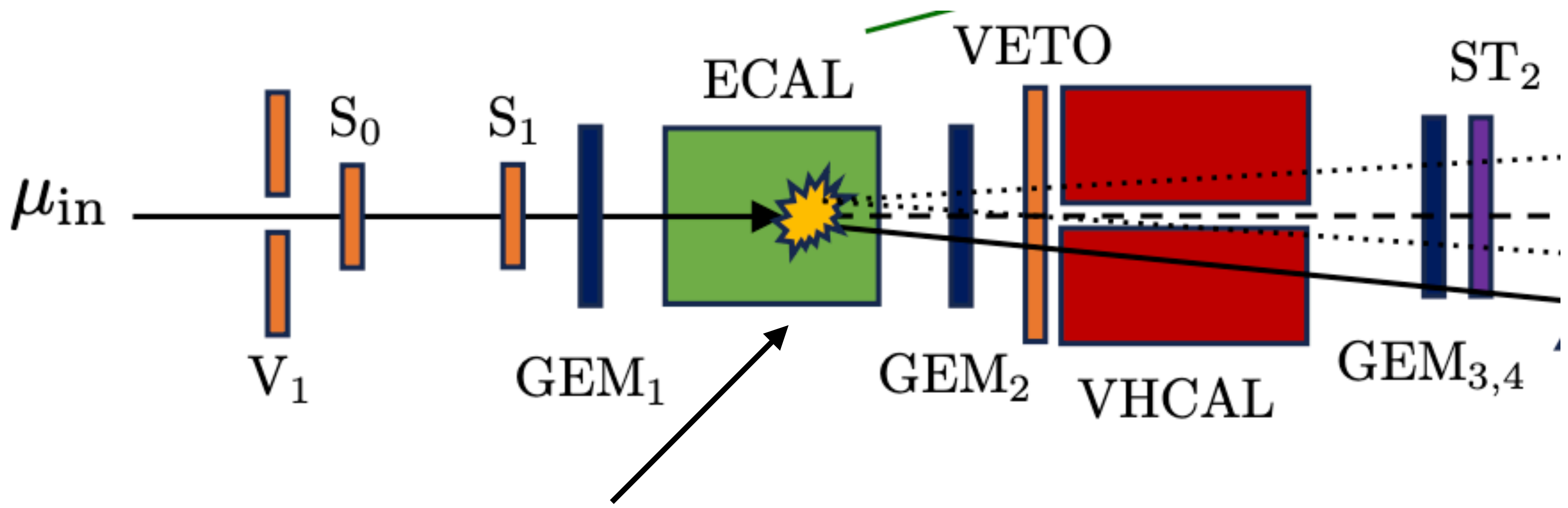
$$\chi = \int_{t_{\text{min}}}^{t_{\text{max}}} \mathrm{d}t \frac{t - t_{\text{min}}}{t^2} F^2(t)$$

Nucleus elastic form factor

$$F(t) \simeq Z(\frac{b^2 t}{1 + b^2 t})(\frac{1}{1 + t/d})$$

$$\mathcal{A}_{a-\gamma} = -e^2 g_{a\gamma\gamma}^2 \tilde{u}^2 \frac{\tilde{u}x(2-x) + 2m_\mu^2 x^2 + m_a^2(1-x)(2-x)}{(m_a^2(1-x) + x\tilde{u})^2}$$

Decay Probability



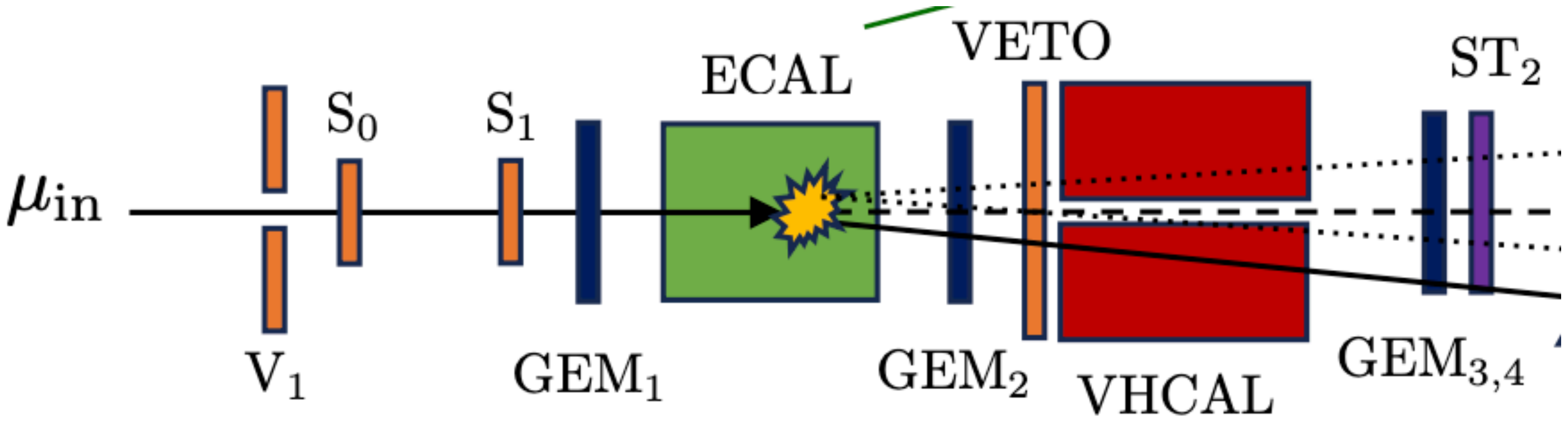
The target ECAL consists of 150 layers of Pb

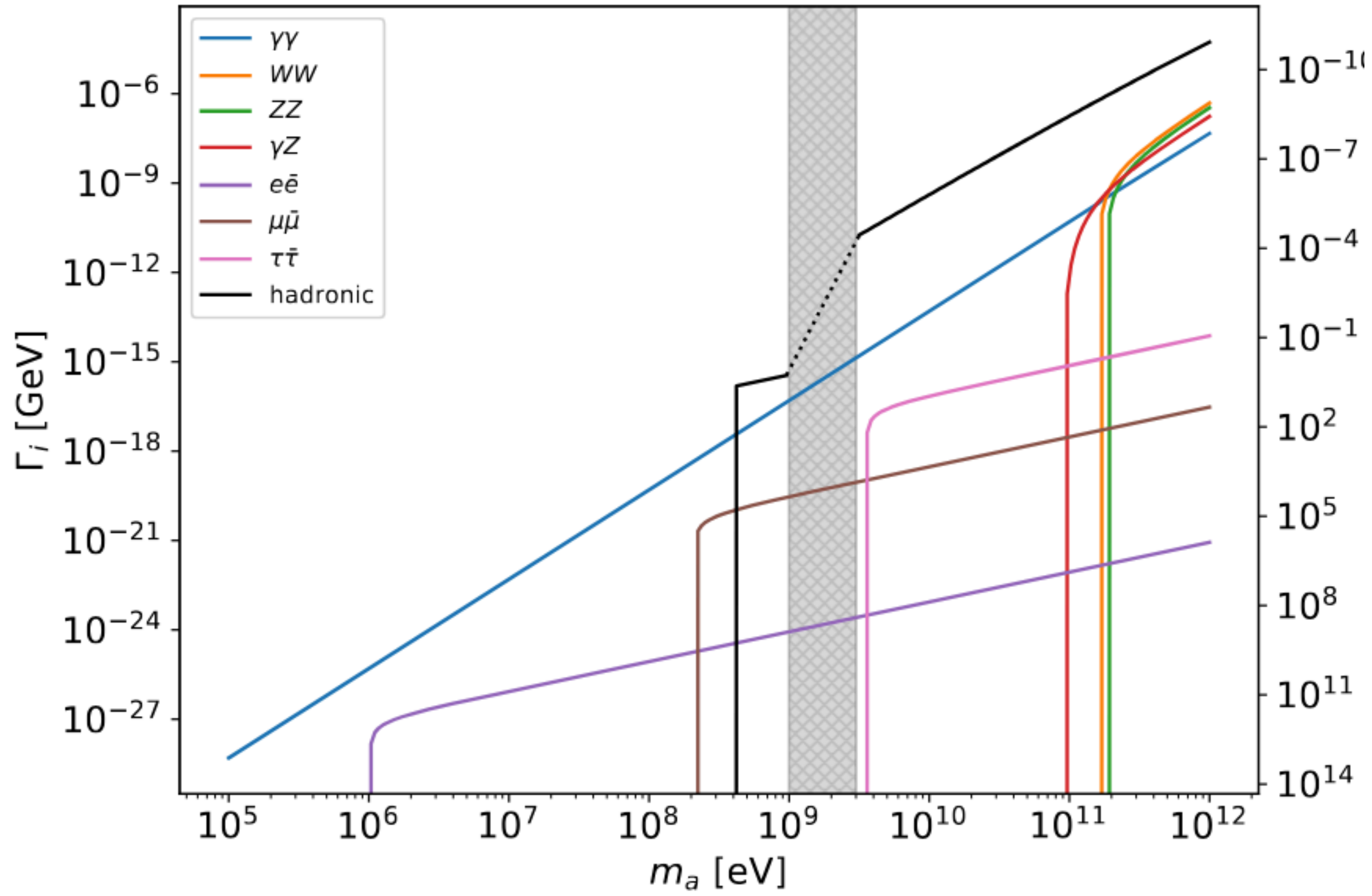
$$P_{\rm invisible} = (e^{-L_{\rm ECAL}/l_a} - e^{-L_V/l_a}) + (e^{-(L_V + L_{\rm VHCAL})/l_a} - e^{-L_H/l_a}) + e^{-(L_H + 2L_{\rm HCAL})/l_a}$$

$$\bar{P}_{\rm inv} = \frac{1}{N}\sum_{i=0}^{N} P_i$$

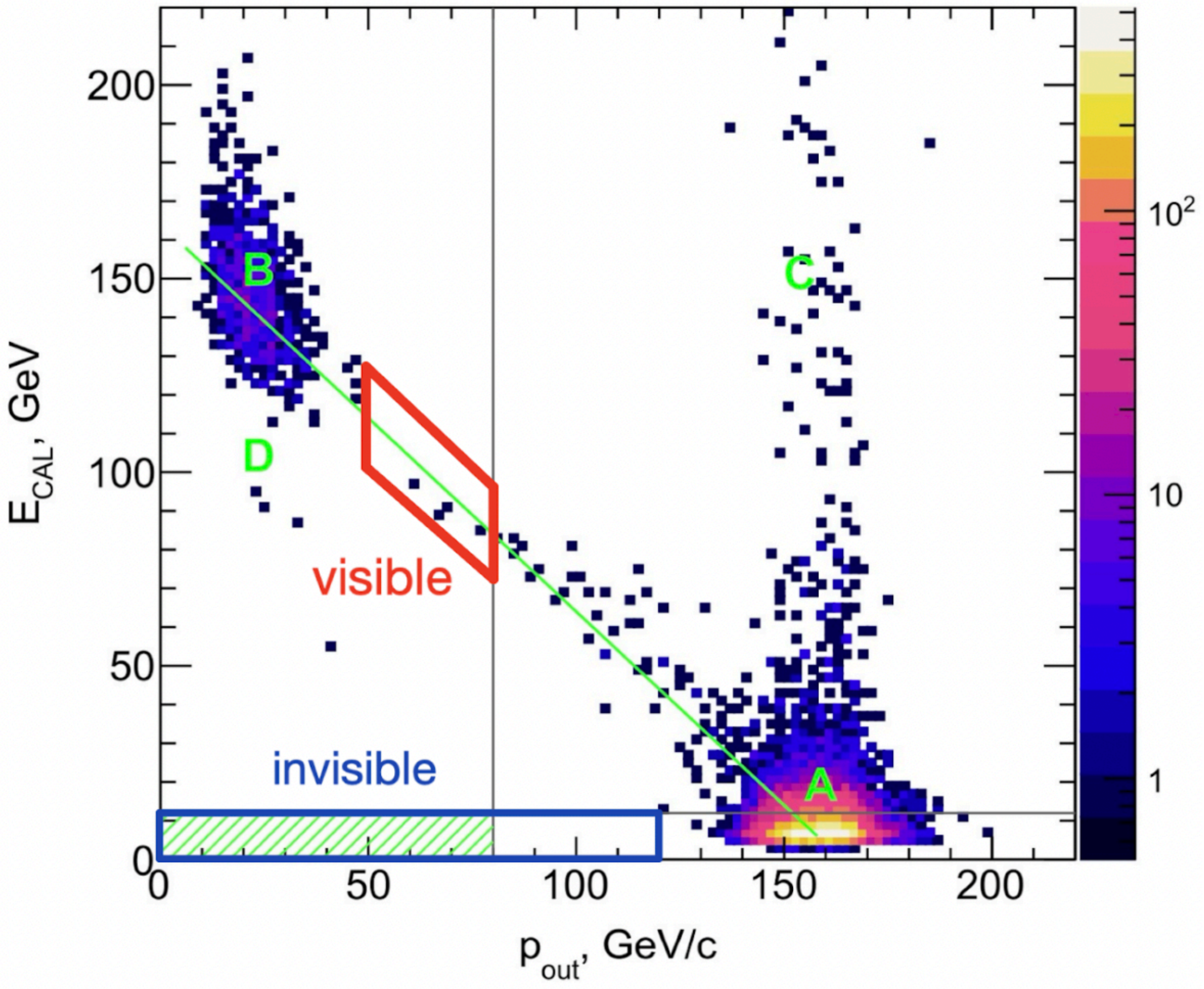
Average over the decay probability from axion production in each ECAL layer

Visible vs Invisible

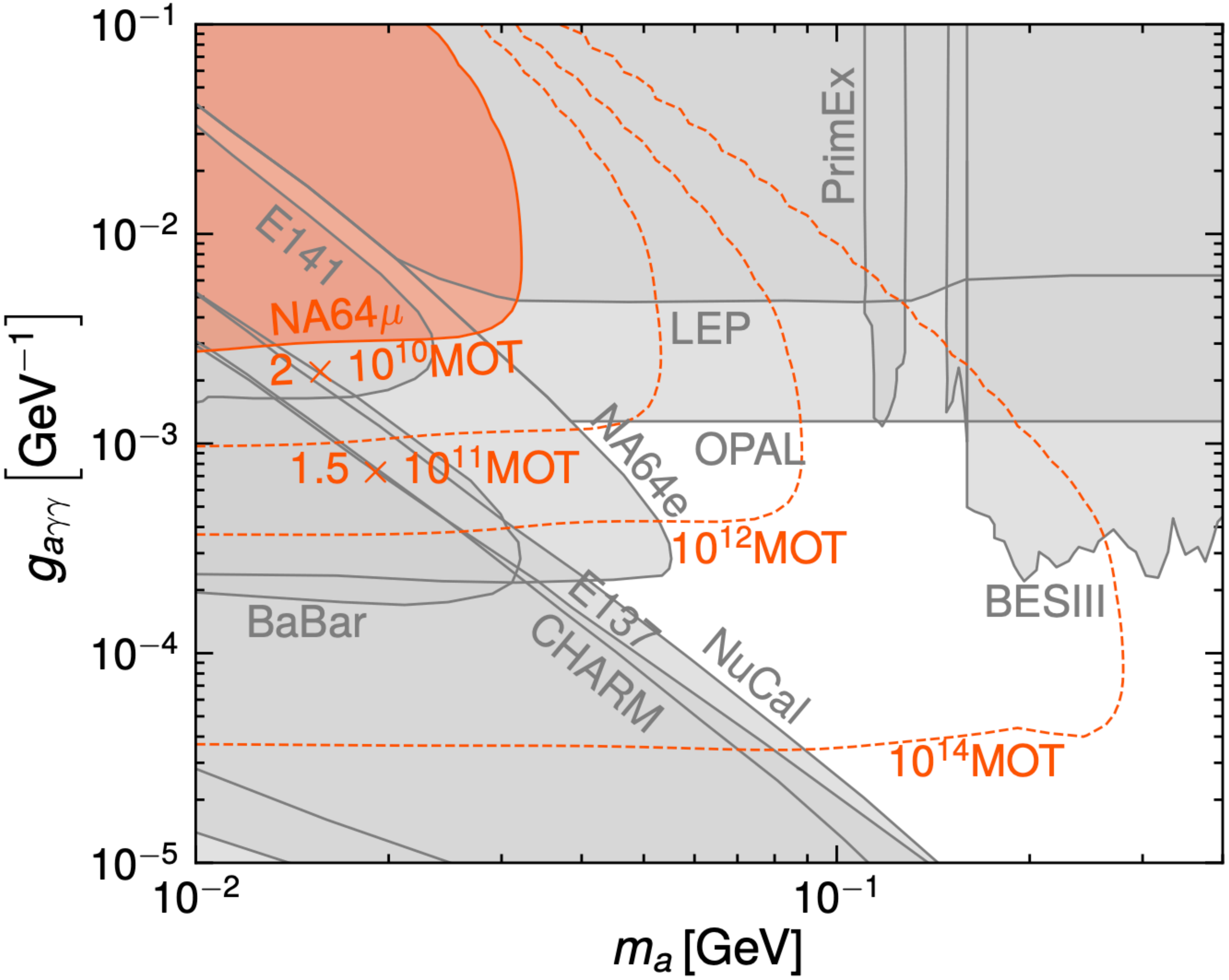




Alonso-Álvarez et al, EPJC/1811.05466

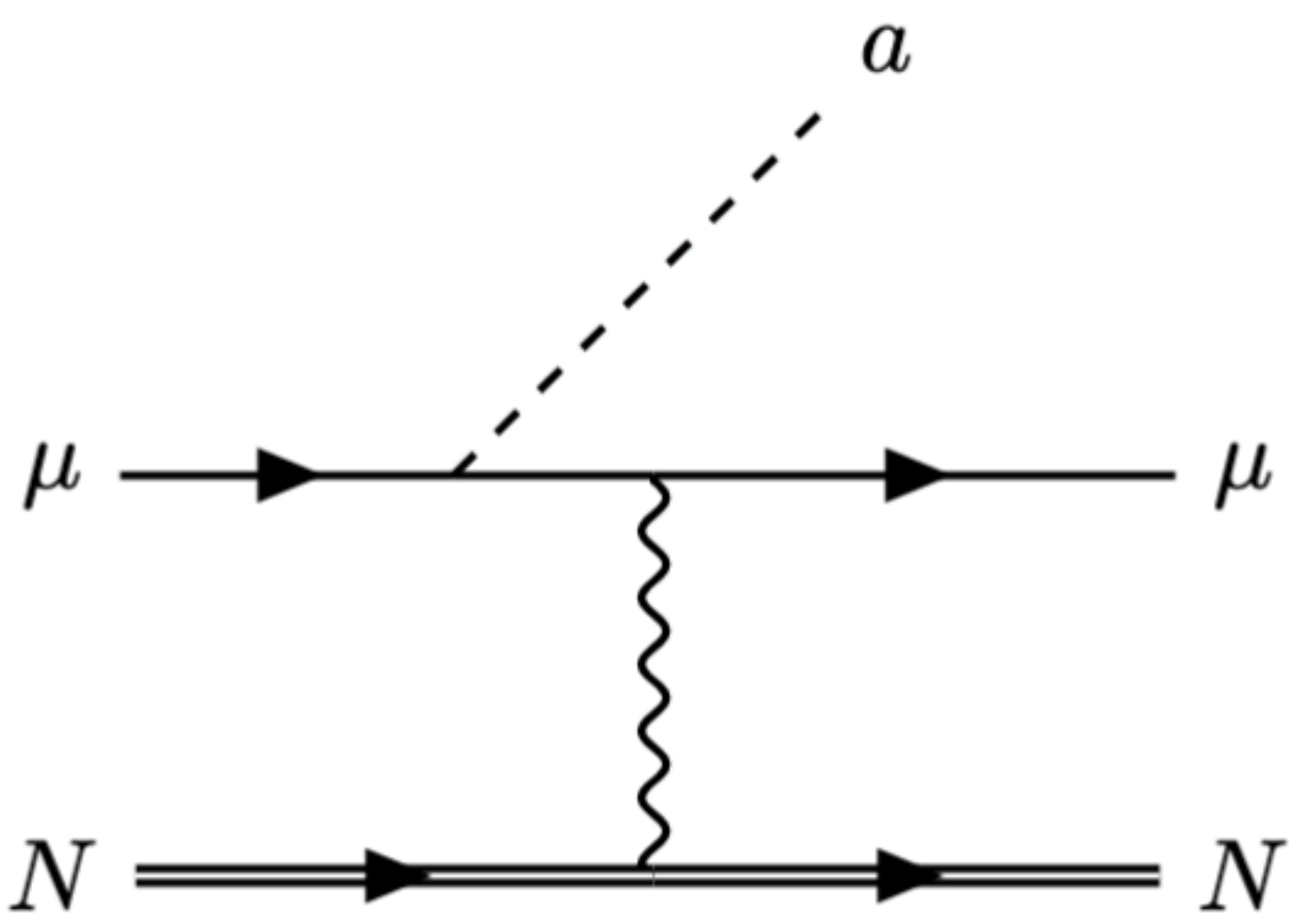


Constraints on Axion-Photon Interaction



Axion-Muon Interaction

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



Axion production through muon bremsstrahlung

Cross Section

$$N_{\mathrm{signal}} = N_{\mathrm{MOT}} n_{\mathrm{Pb}} L_{\mathrm{tar}} \int d\sigma(\mu N \to \mu N X) \epsilon P_{\mathrm{inv}}$$

Weizsacker-William approxmation

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x} = \frac{\alpha}{8\pi^2}\sqrt{E_a^2 - m_a^2}E_\mu(1-x)\int \mathrm{d}\cos\theta \frac{\chi}{\tilde{u}^2}\mathcal{A}$$

effective photon flux

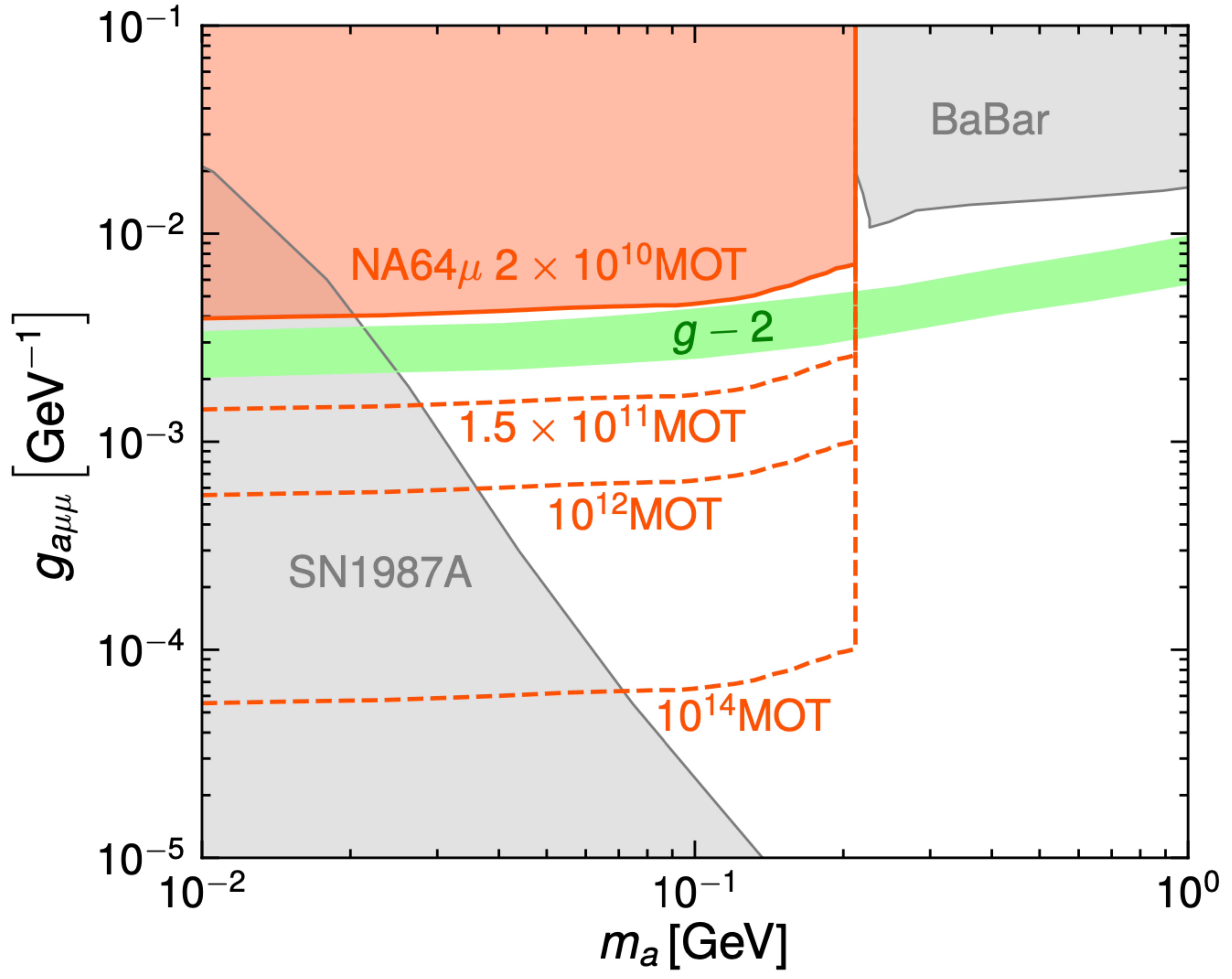
$$\chi = \int_{t_{\mathrm{min}}}^{t_{\mathrm{max}}} \mathrm{d}t \frac{t - t_{\mathrm{min}}}{t^2} F^2(t)$$

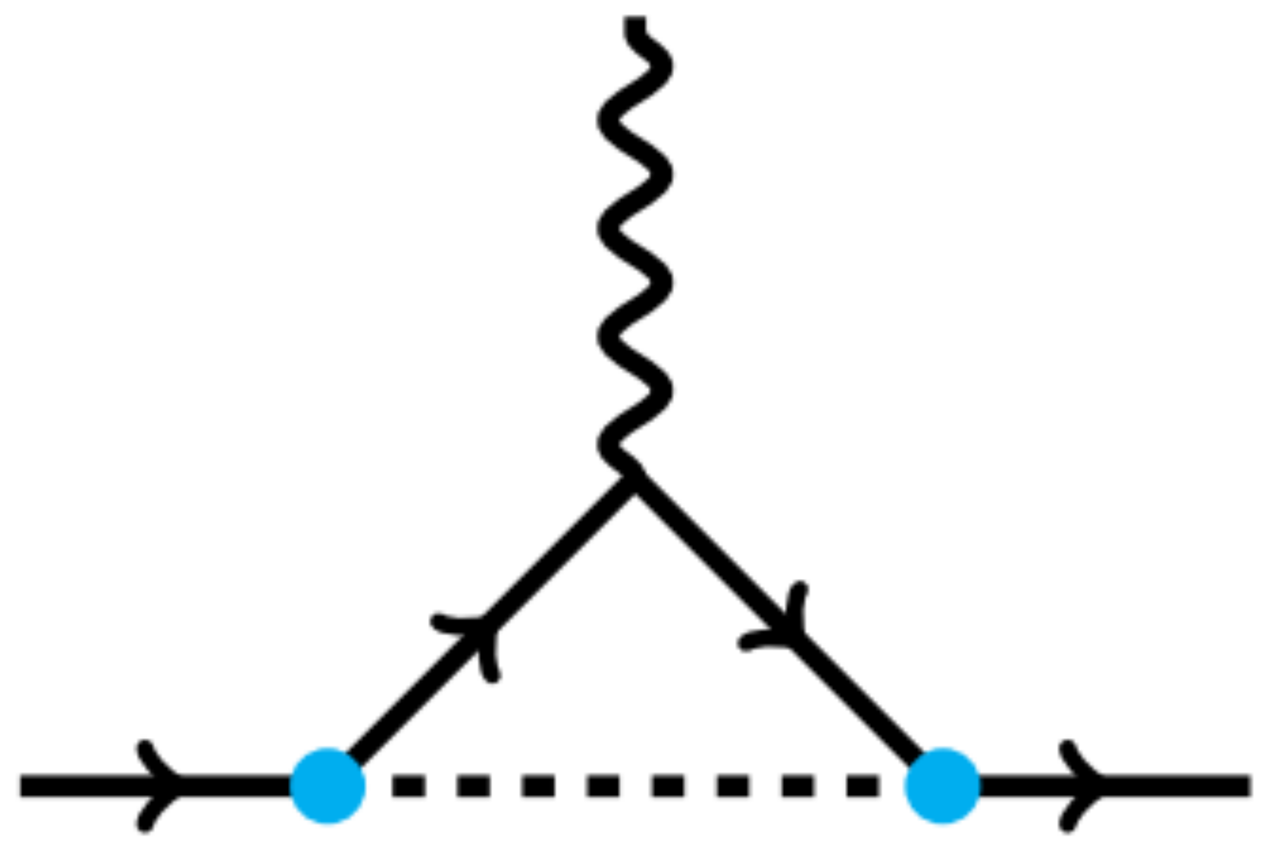
Nucleus elastic form factor

$$F(t) \simeq Z\left(\frac{b^2 t}{1 + b^2 t}\right)\left(\frac{1}{1 + t/d}\right)$$

$$\mathcal{A}_{a-\mu} = e^2 g_{a\mu\mu}^2 4m_\mu^2 \left[\frac{x^2}{1-x} + 2m_a^2 \frac{\tilde{u}x + m_a^2(1-x) + m_\mu^2 x^2}{\tilde{u}^2}\right]$$

Constraints on Axion-Muon Interaction





Buen-Abad et al, JHEP/2104.03267