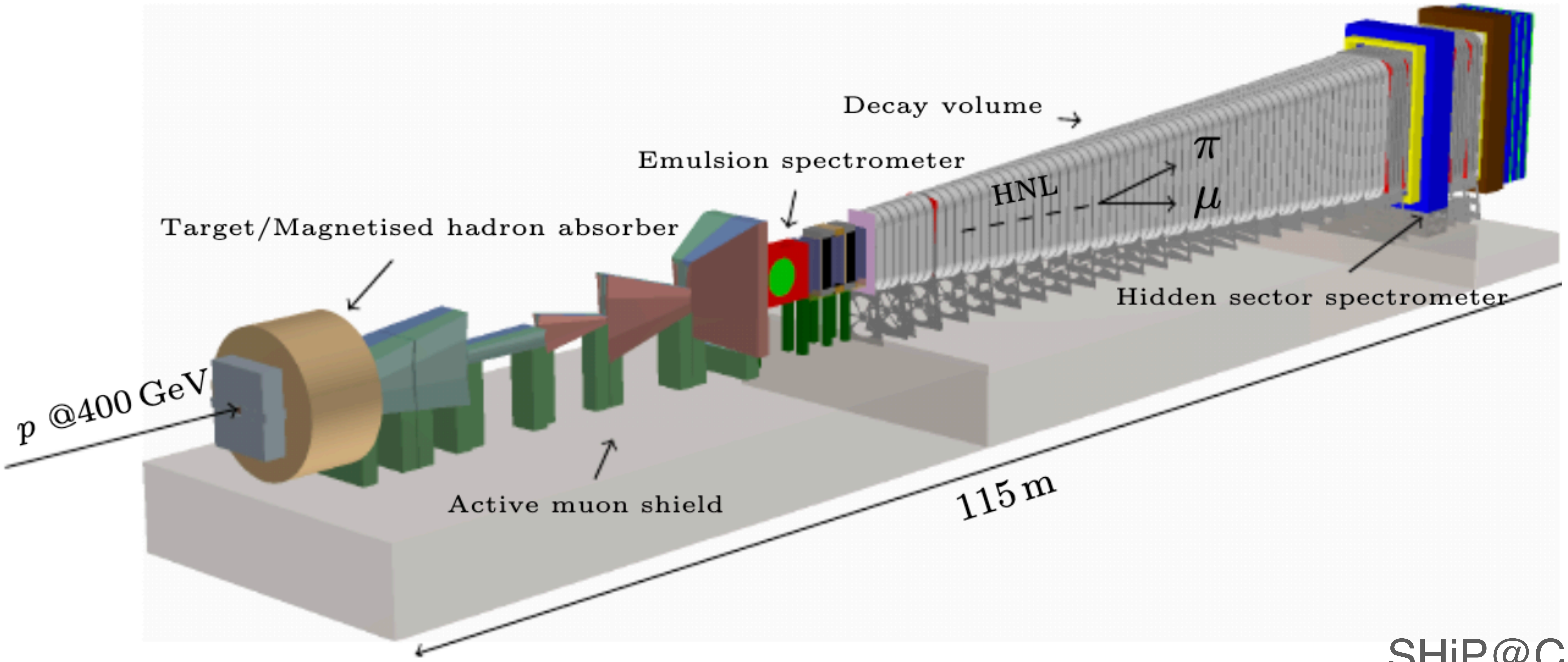
# Searching for heavy millicharged particles from the atmosphere at neutrino detectors

**Ningqiang Song**

**宋宁强**

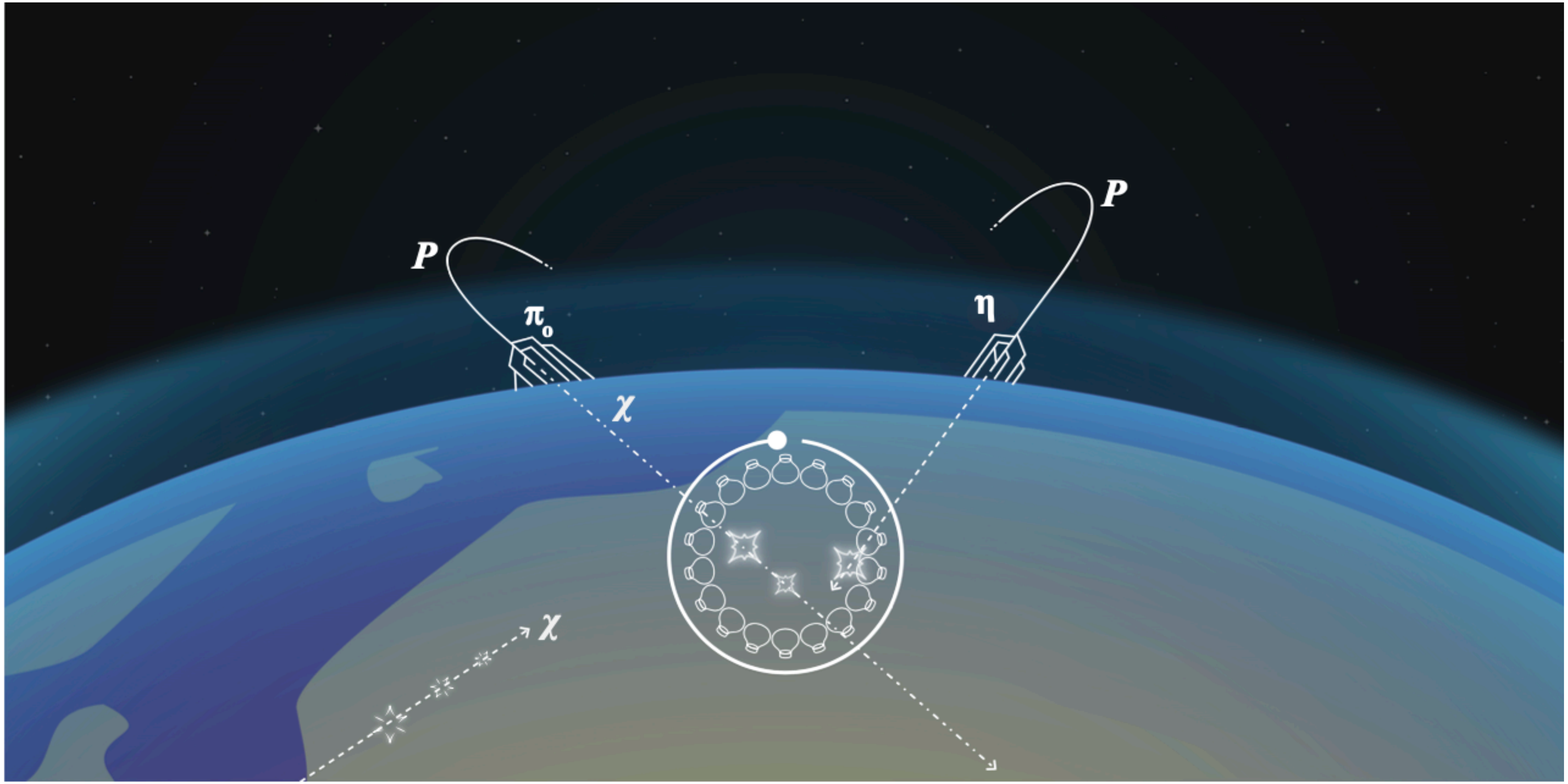
**April 29, 2024**

# Beam dump experiments



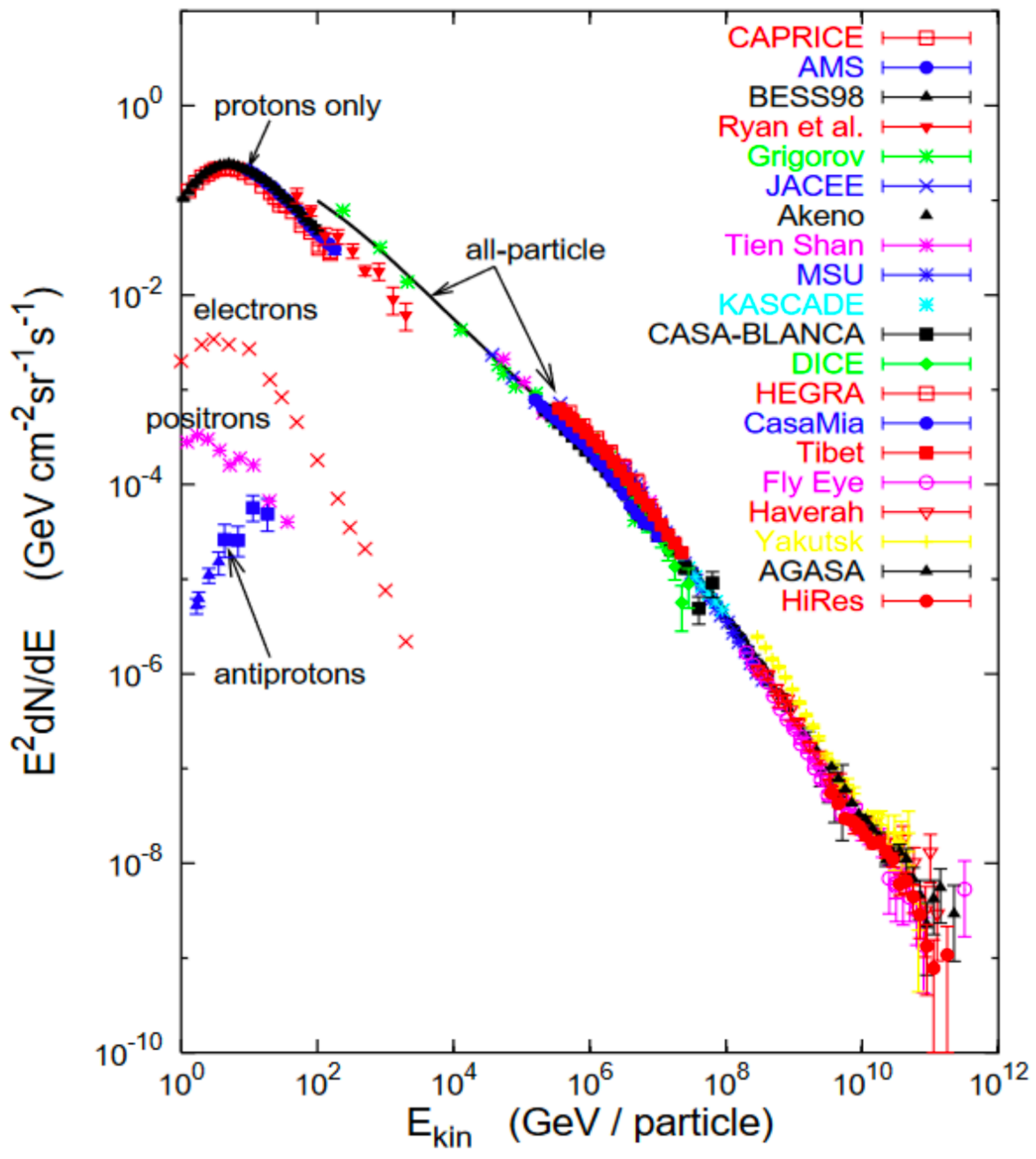

SHiP@CERN

# Atmospheric beam dump



# Atmospheric beam dump and new physics

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



# Heavy neutral leptons

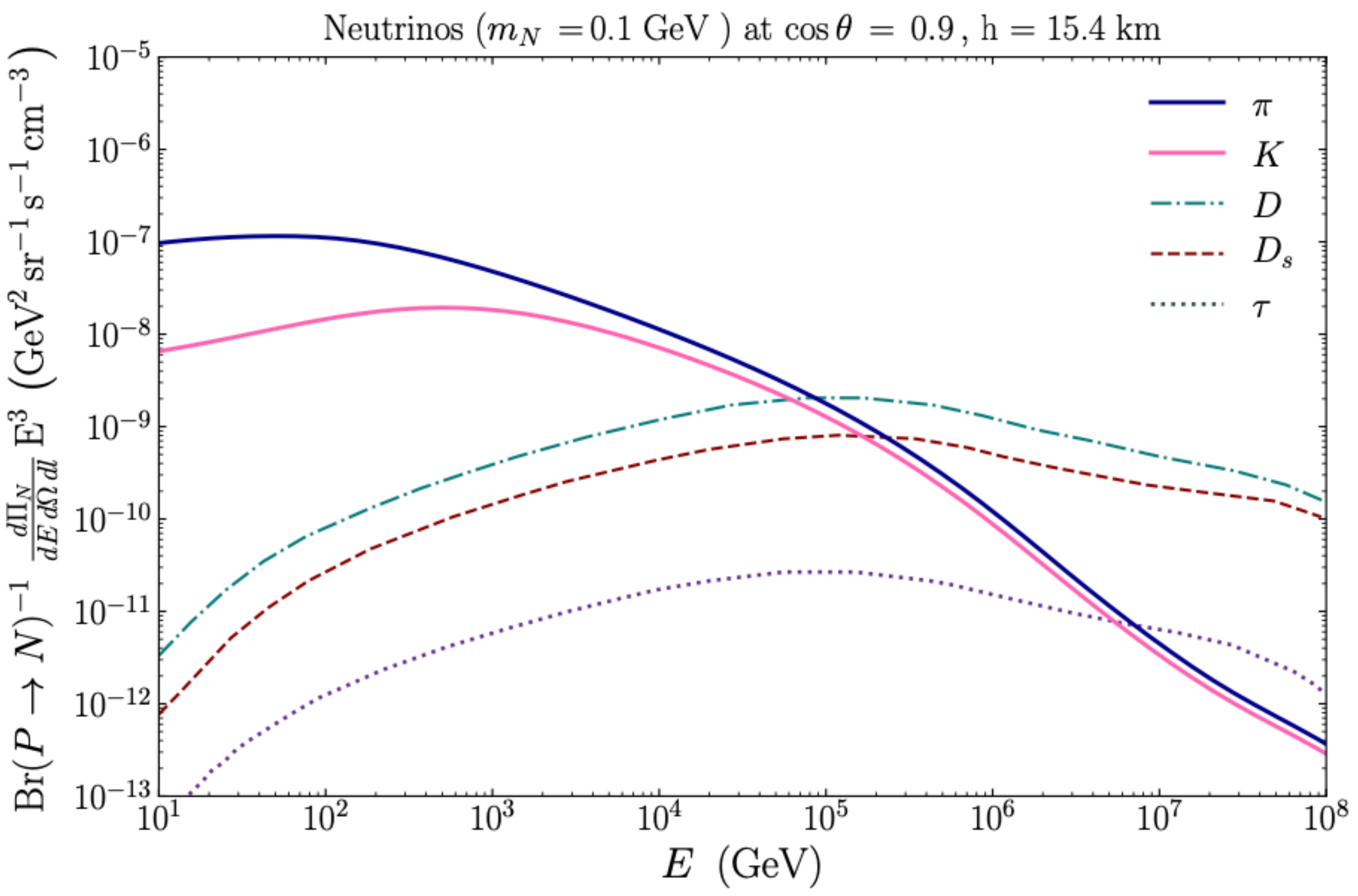
Type-I seesaw $$\mathcal{L}_N = \mathcal{L}_{SM} + \sum_j i\bar{N}_j \gamma^\mu \partial_\mu N_j - \left( Y_{\alpha j} \bar{L}_\alpha \tilde{\Phi} N_j + \frac{m_{N_j}}{2} \bar{N}_j N_j^c \right)$$

Neutrino mass $m_\nu \propto \frac{(Y\nu)^2}{m_N}$ mixing $U_{\alpha j} \propto \frac{Y\nu}{m_N}$

Meson and lepton decay

$$M \to l + N$$

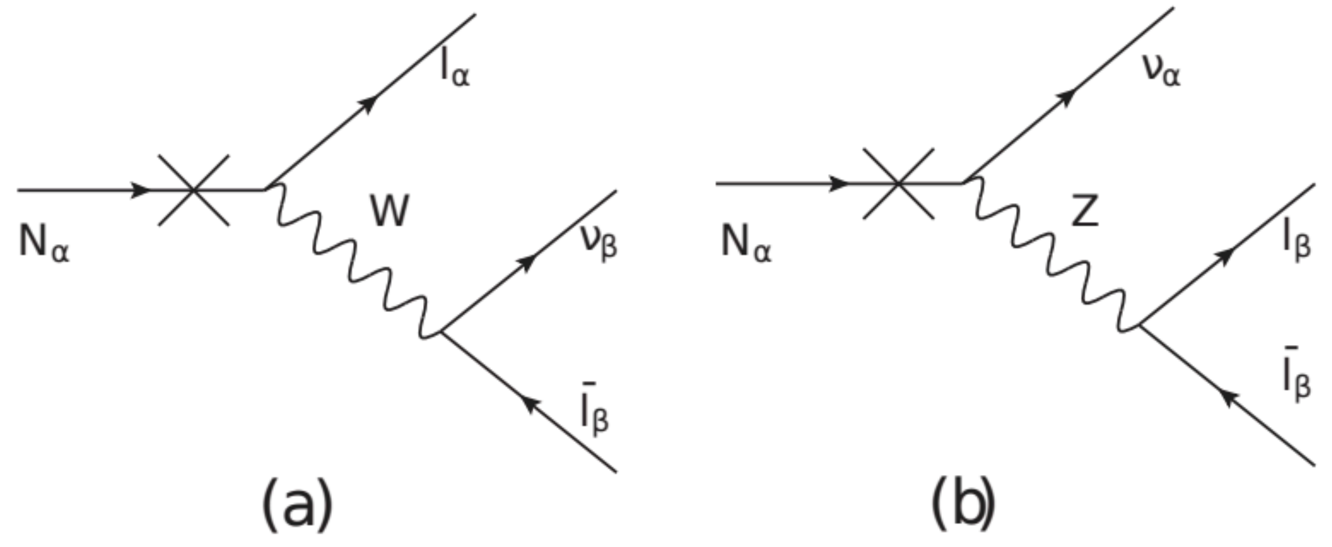
$$\tau \to l + \nu + N$$




Coloma et al EPJC/1911.09129

# Heavy neutral leptons

Heavy neutral lepton decay to electron/muon at neutrino detectors





Coloma et al EPJC/1911.09129

# Hydrophilic dark matter

$$\mathcal{L} \supset i\overline{\chi}(\not{D} - m_\chi)\chi + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_S^2 S^2$$
$$- \left(g_\chi S \overline{\chi}_L \chi_R + g_u S \overline{u}_L u_R + h.c.\right),$$

Meson decay

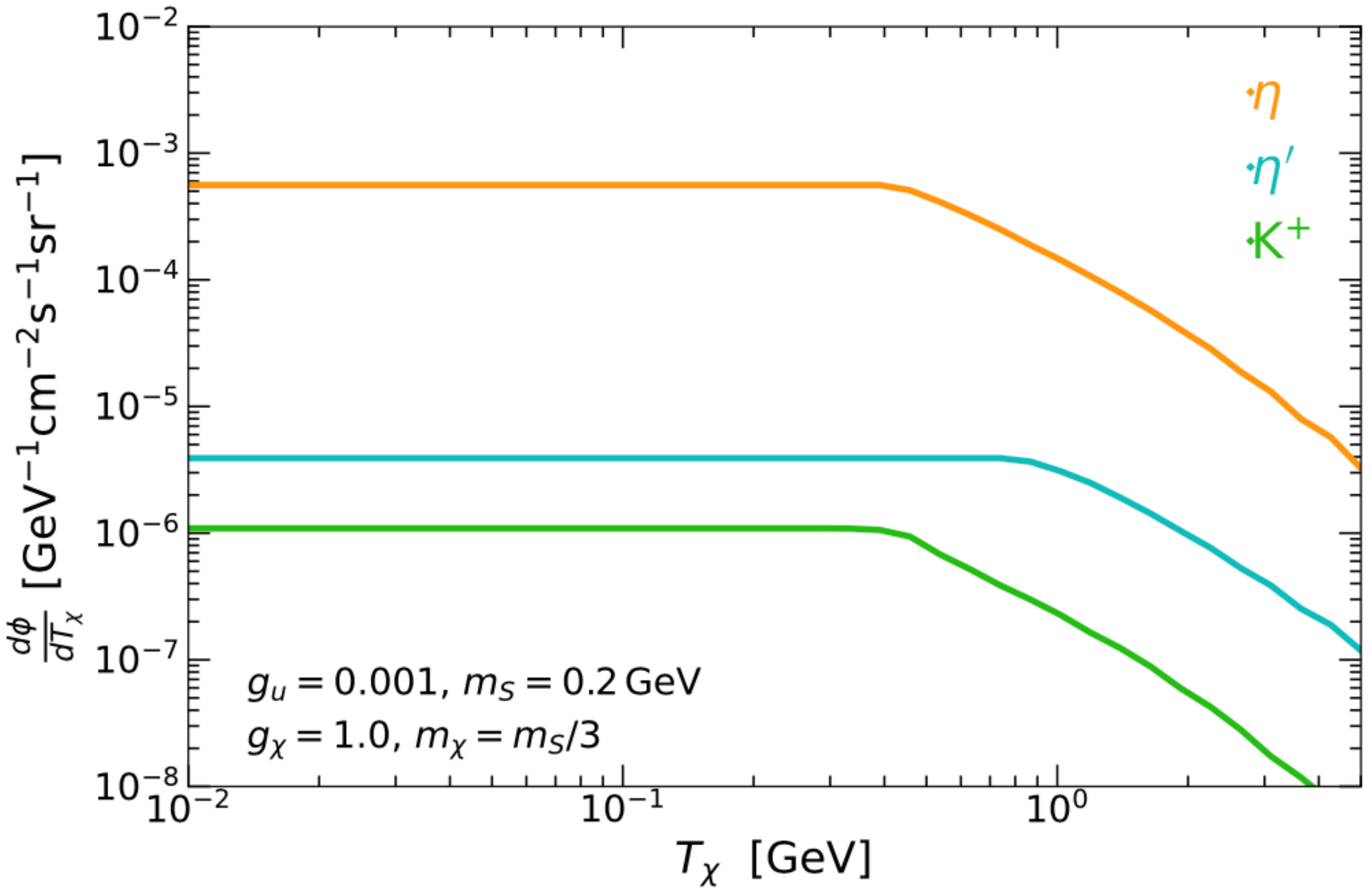
$\eta \to \pi^0 + S$

$\eta' \to \pi^0 + S$

$K^+ \to \pi^+ + S$

$S \to 2\chi$

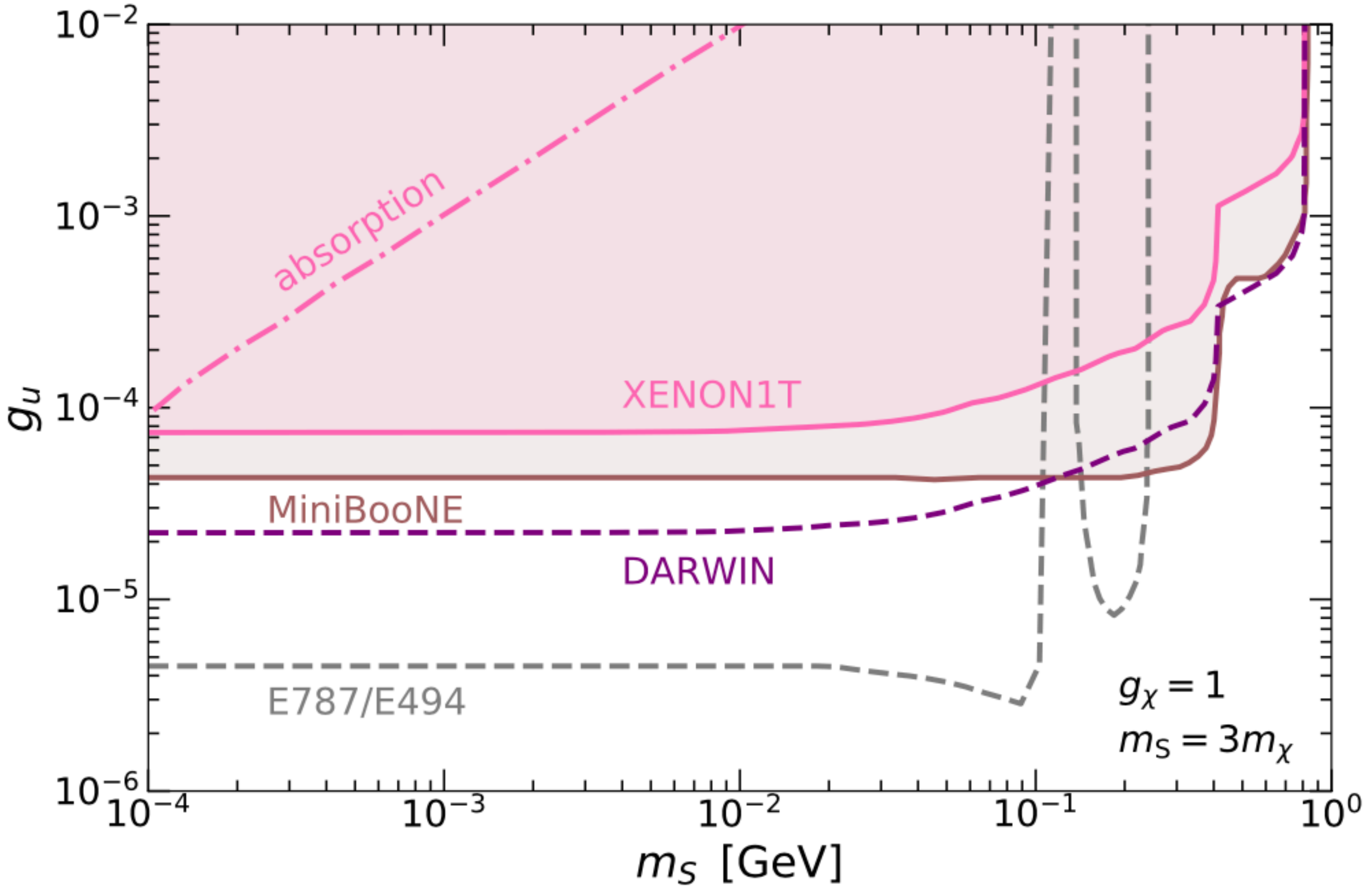
Arguelles et al PLB/2203.12630

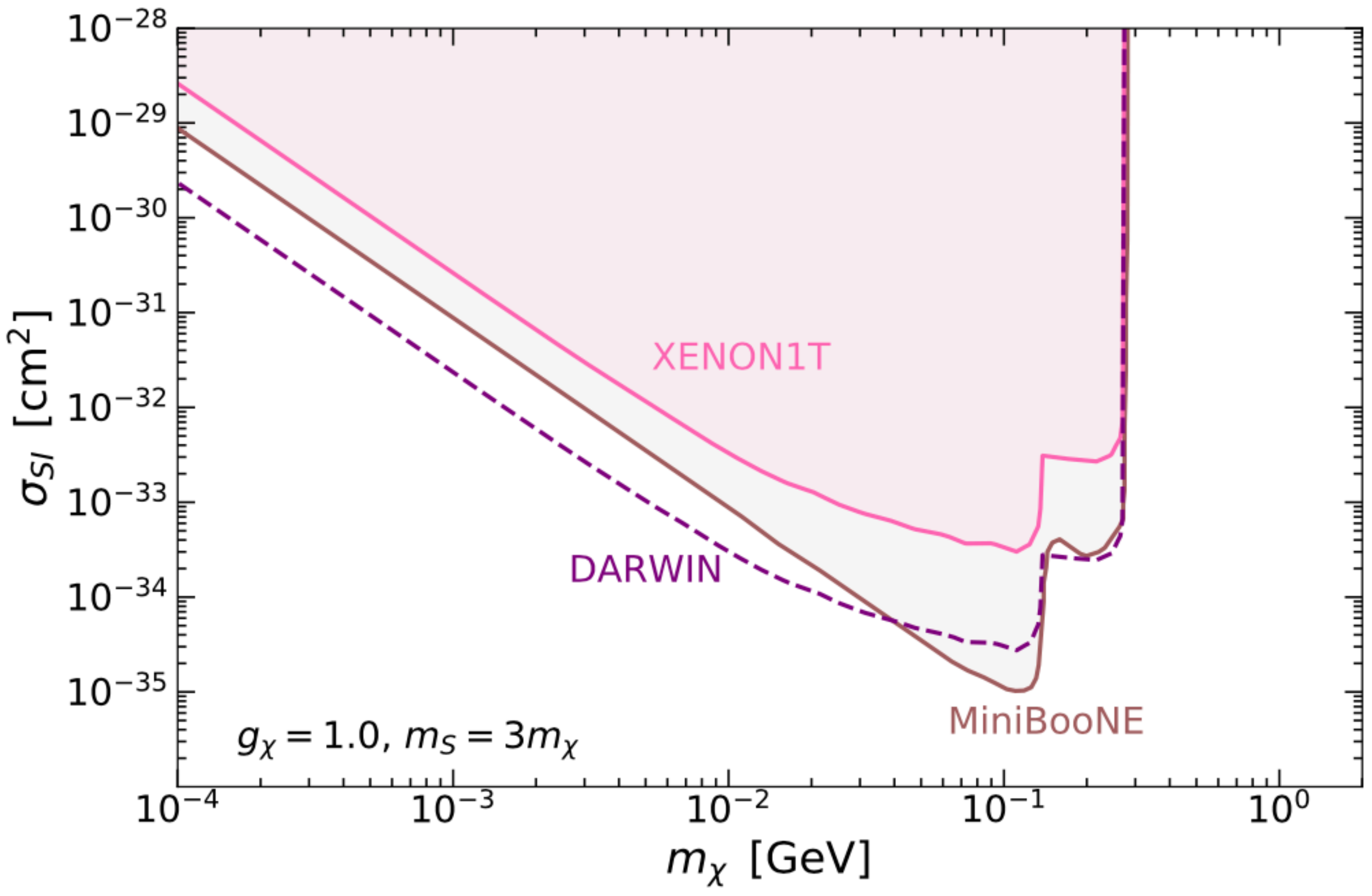


# Hydrophilic dark matter

$S \to 2\chi$

Dark matter scatters at neutrino and dark matter detectors



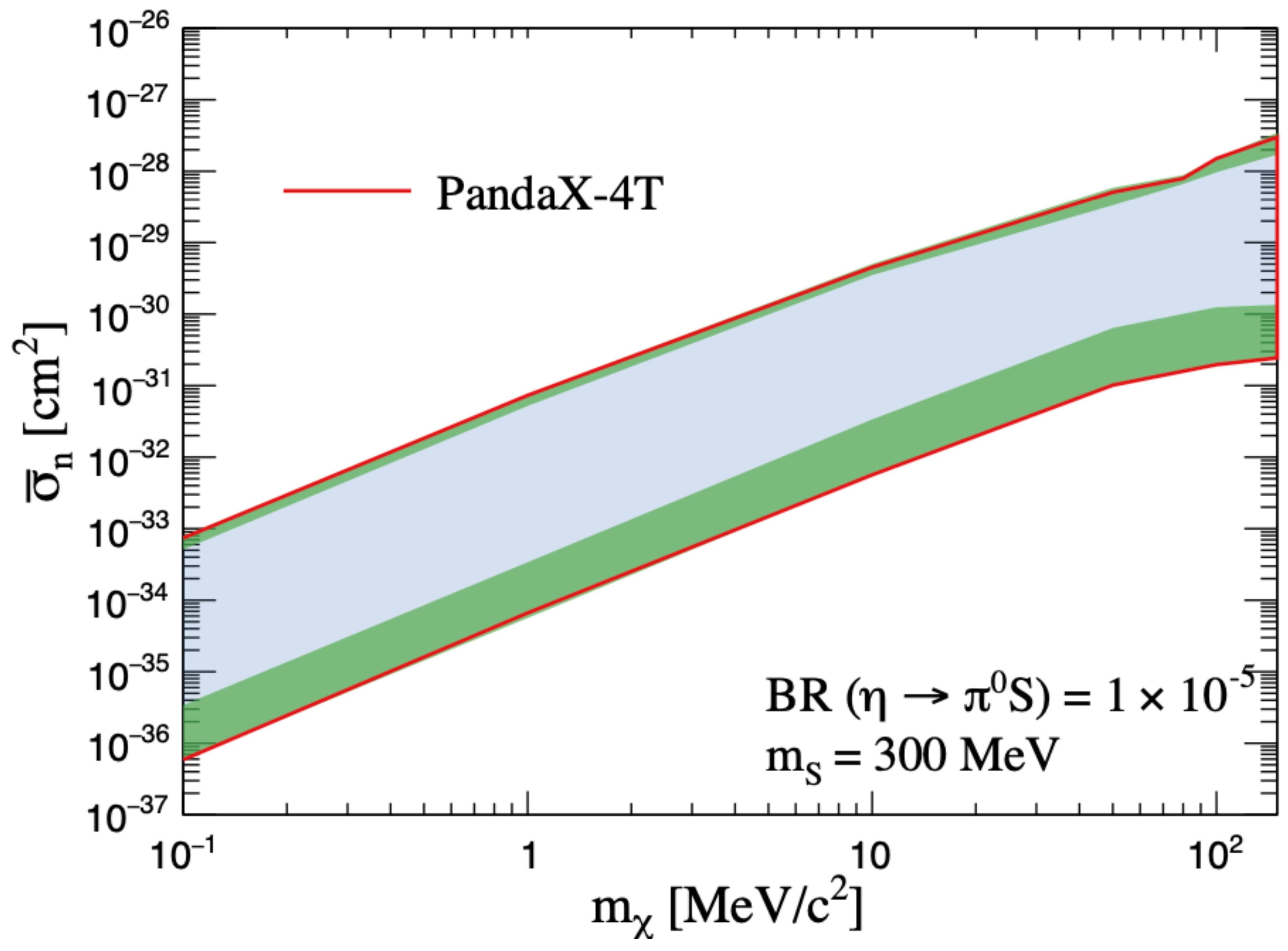



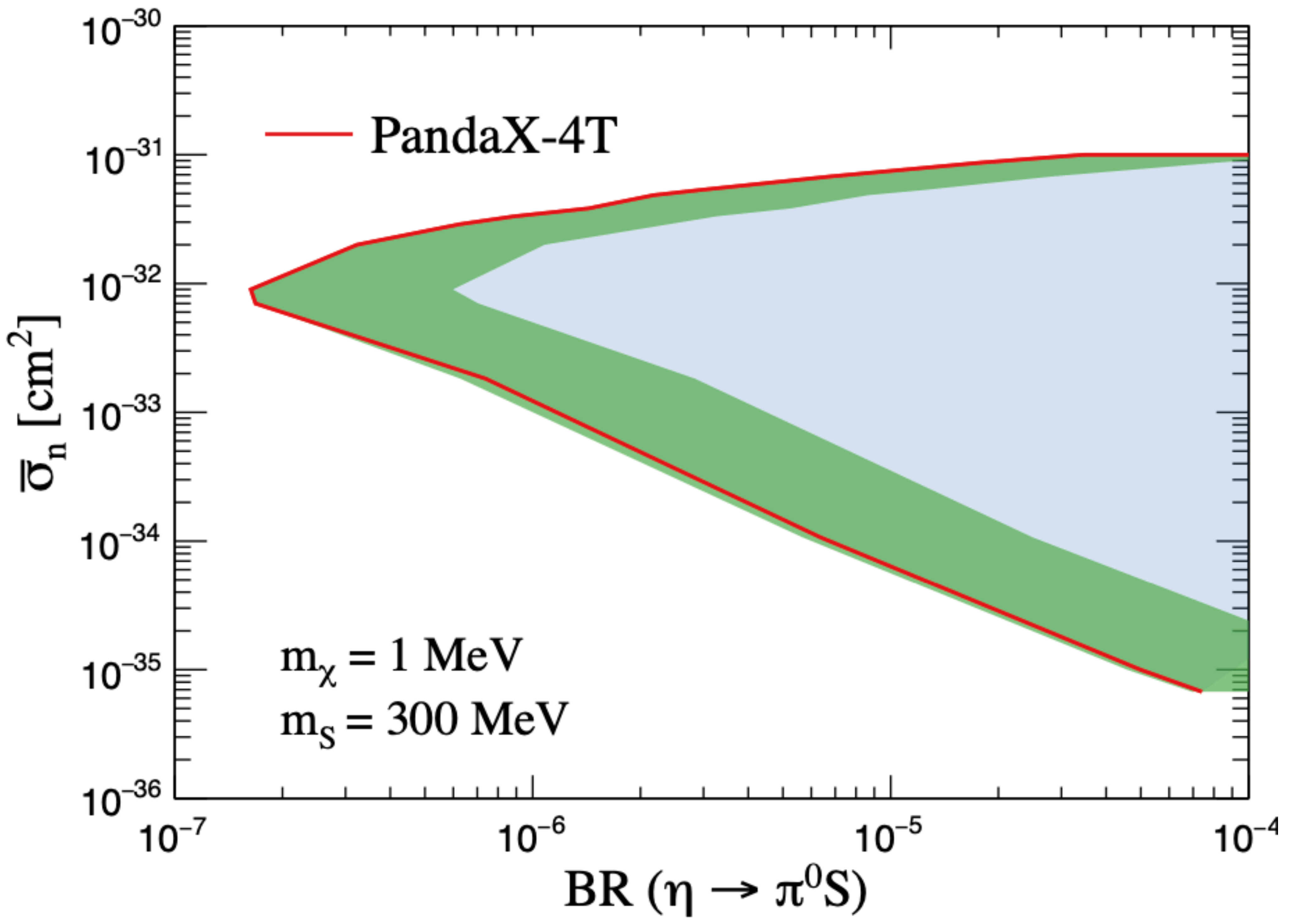

Arguelles et al PLB/2203.12630

# Hydrophilic dark matter

Including both elastic and quasi-elastic scattering in the overburden

$$\chi(k) + A\,(p_A) \rightarrow \chi\,(k') + X(\rightarrow n + Y)$$




PandaX PRL/2301.03010

Su et al PRD/2006.11837

# Axion-like particles

$$\mathcal{L} \supset -i g_{a\mu\mu} a \bar{\mu} \gamma_5 \mu$$

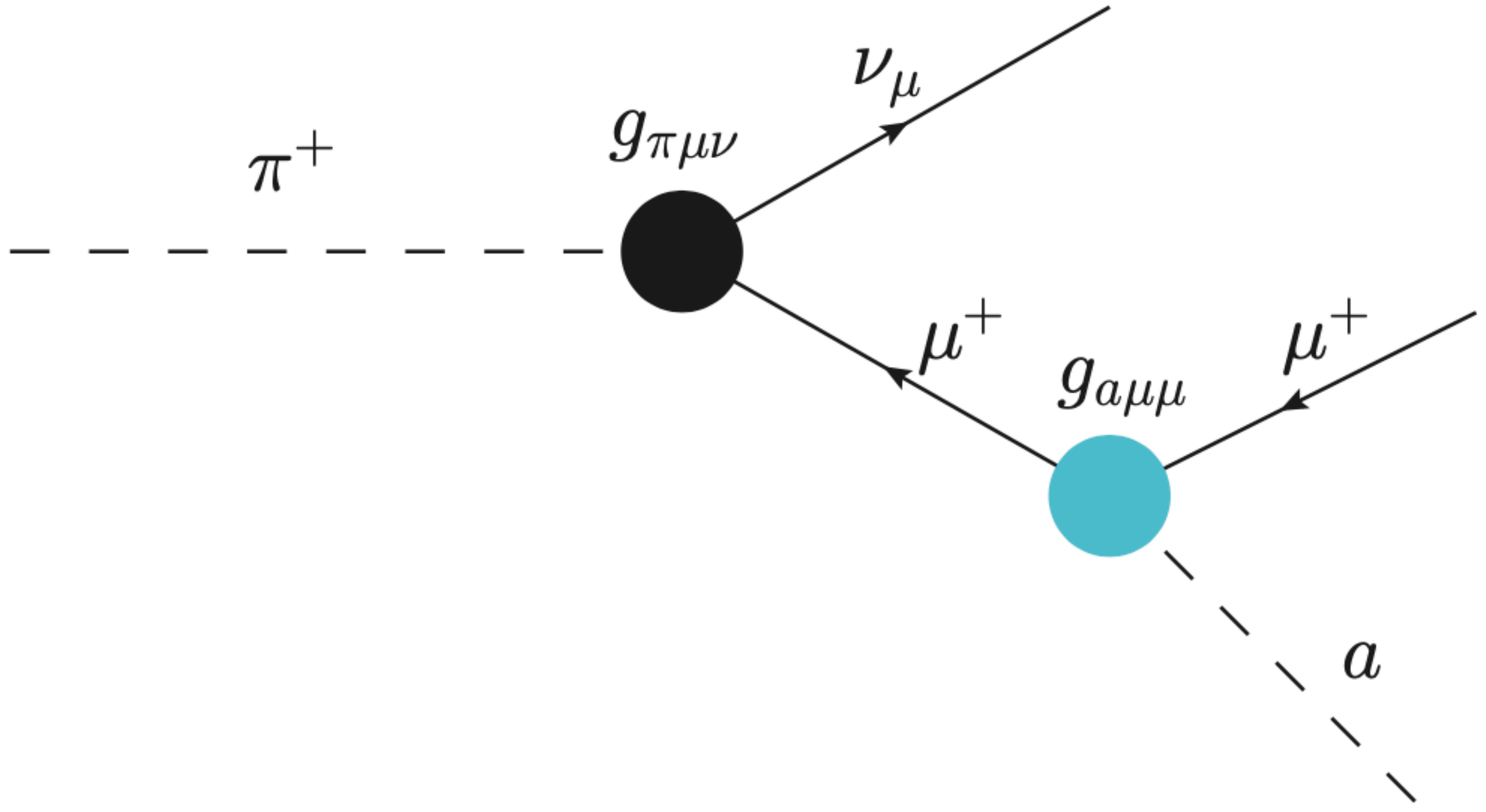
$$\mathcal{L}_{\text{loop}} \supset -\frac{1}{4} g^{\text{eff}}_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

$$g^{\text{eff}}_{a\gamma\gamma} = \frac{g_{a\mu\mu}\alpha}{m_\mu \pi}\left[1 - \frac{4m_\mu^2}{m_a^2}\arcsin^2\left(\frac{m_a}{2m_\mu}\right)\right]$$

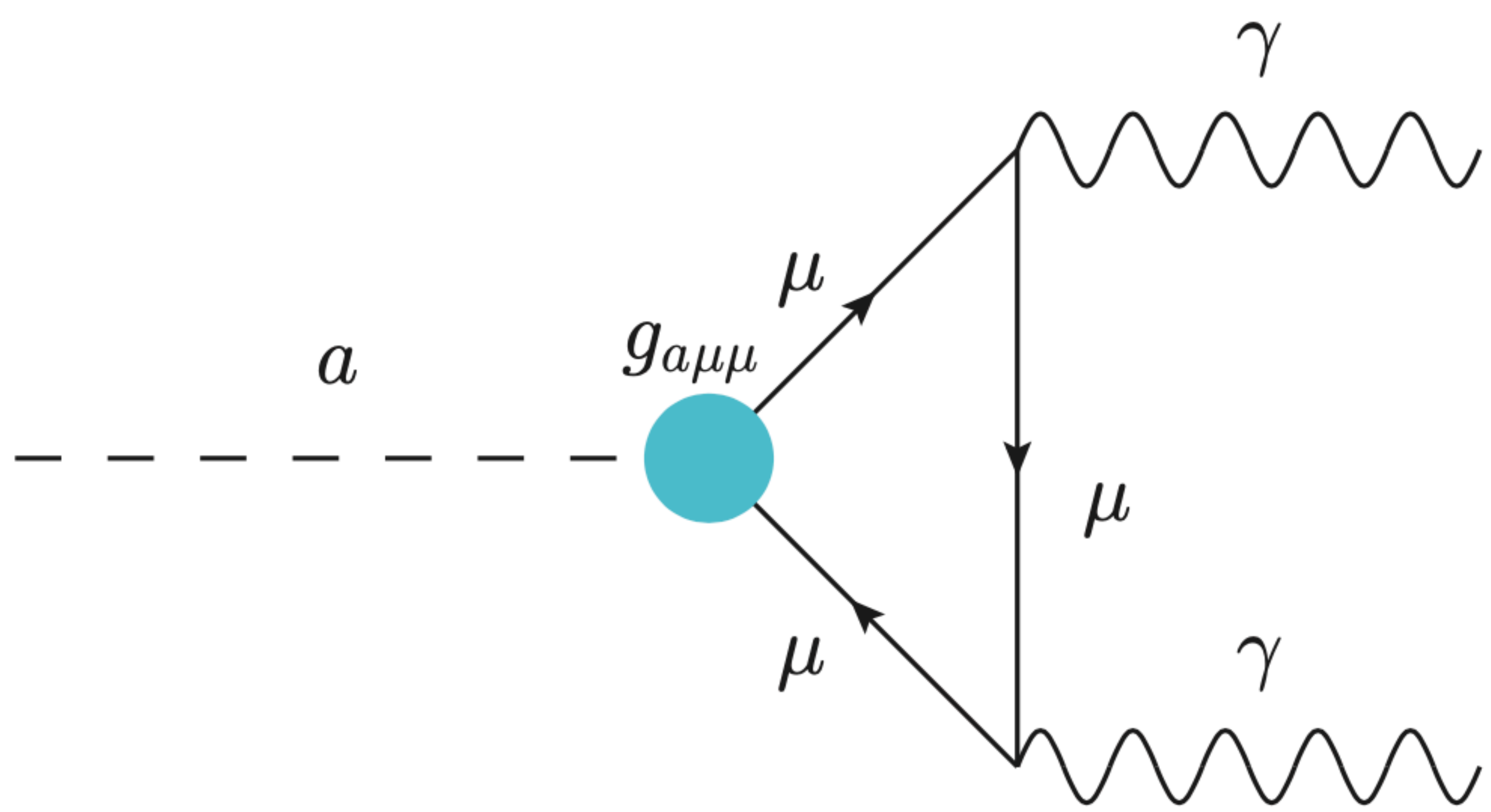
$$\tau_a = \Gamma^{-1}_{a\to\gamma\gamma} = \frac{64\pi}{(g^{\text{eff}}_{a\gamma\gamma})^2 m_a^3}$$

Cheung et al PRD/2208.05111

$$\pi^+ \to \mu^+ + \nu_\mu + a$$



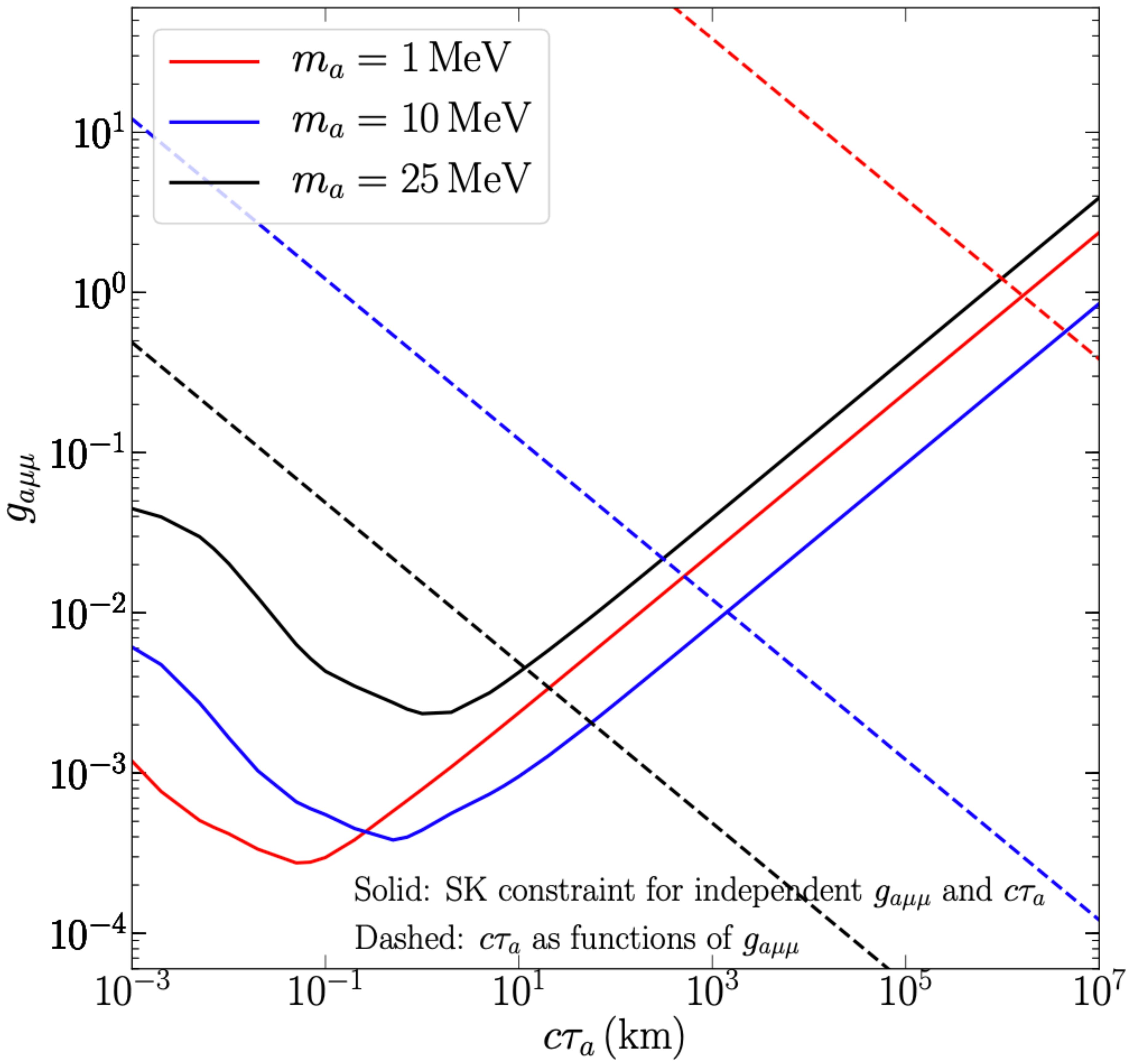

$m_a < 2m_\mu$ $\quad a \to \gamma + \gamma$

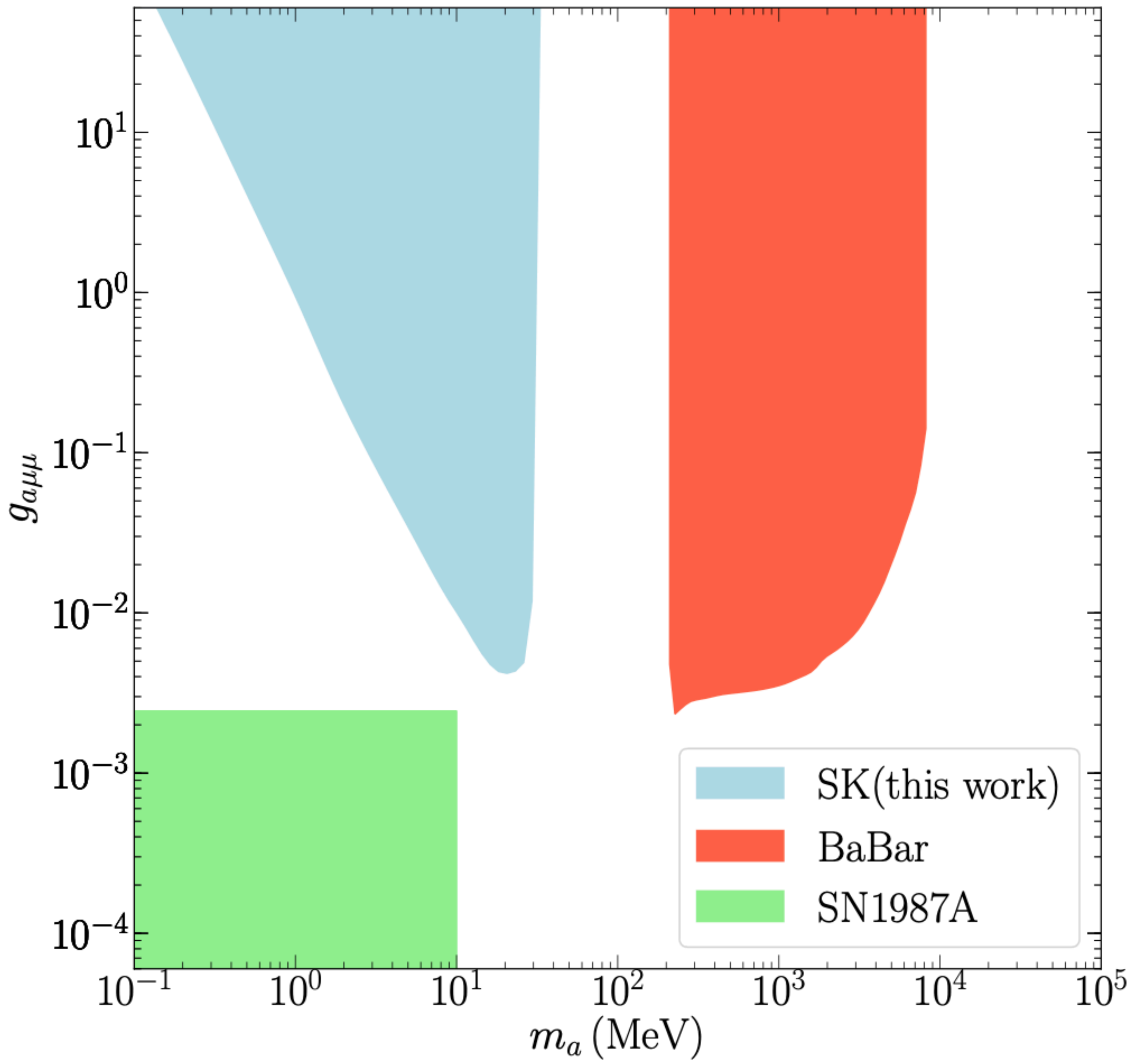


# Axion-like particles

Two electron-like Chenrekov rings at neutrino detectors

$a \to \gamma + \gamma$

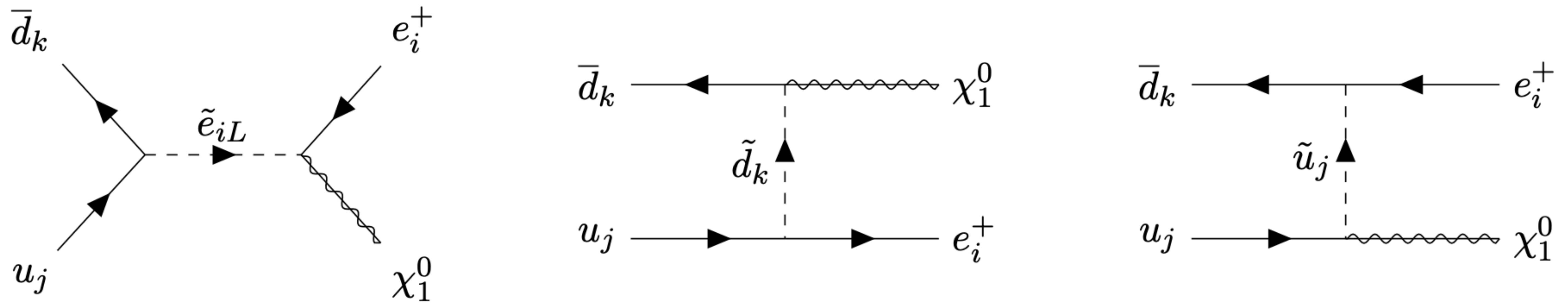


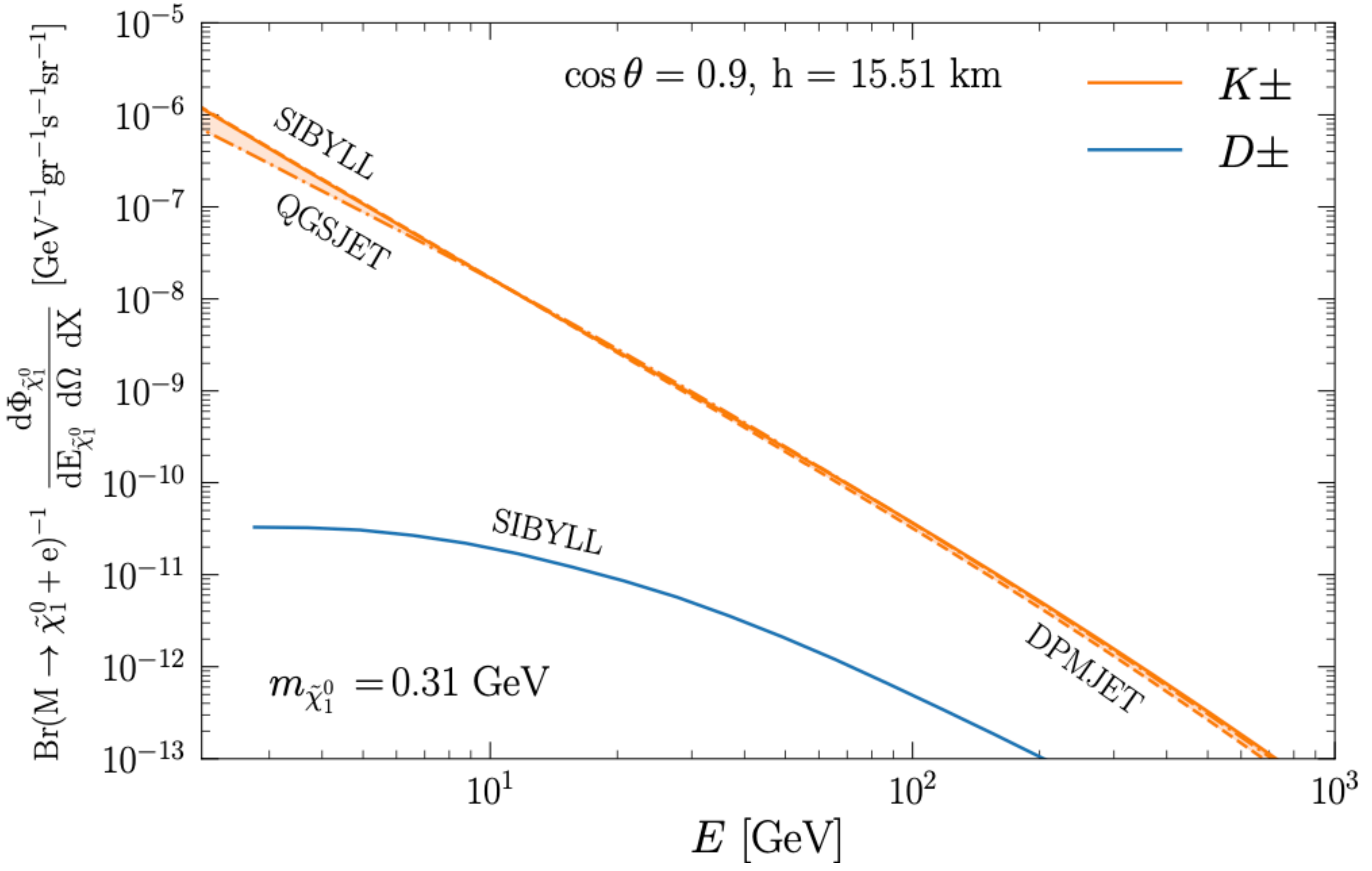

Cheung et al PRD/2208.05111

# Long-lived neutralinos

$$\mathcal{L} \supset \lambda'_{ijk} \widehat{L}_i \widehat{Q}_j \widehat{D}^c_k$$



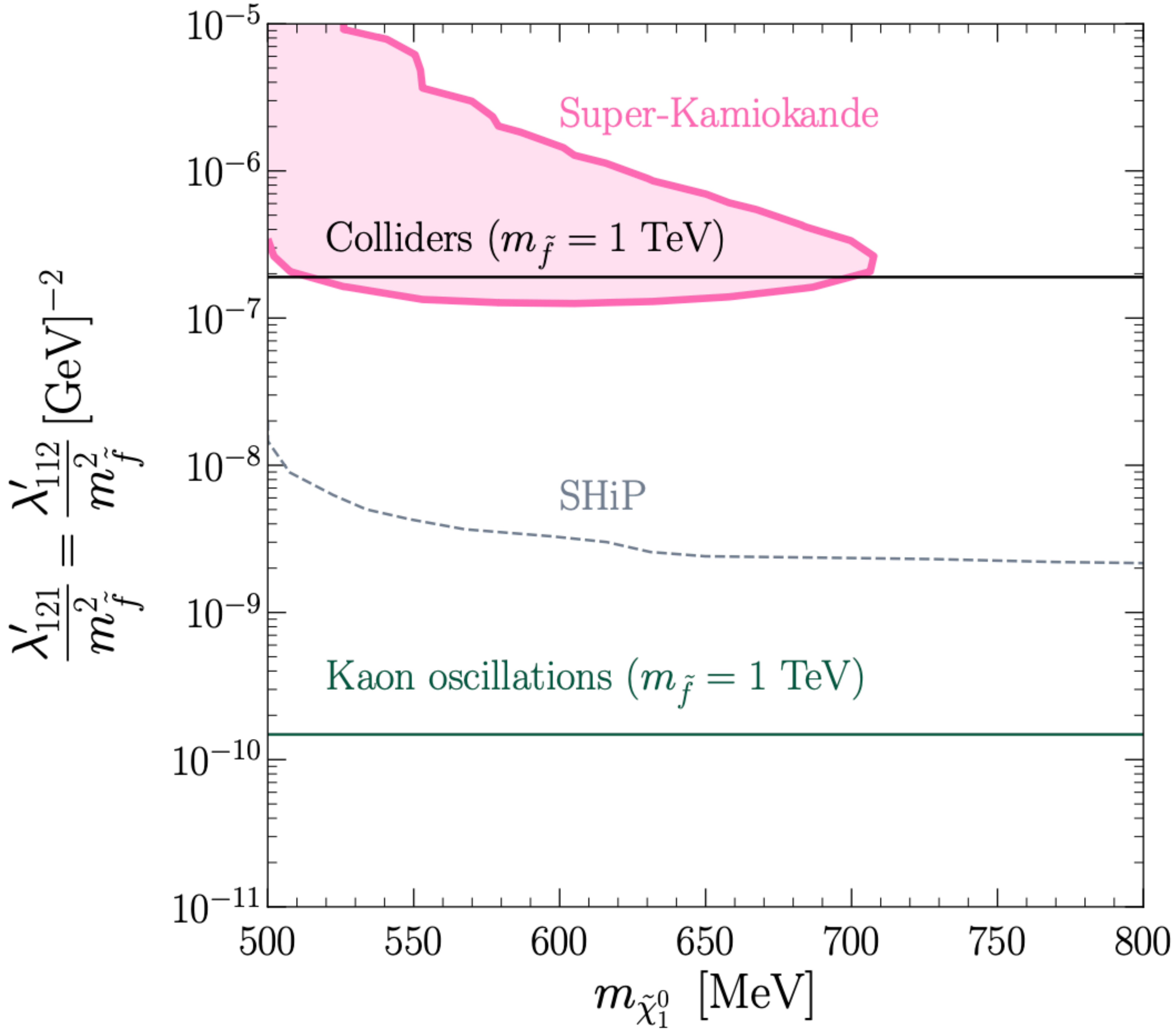

| | RPV coupling | Production | Decay mode |
|---|---|---|---|
| **B1** | $\lambda'_{121}, \lambda'_{112}$ | $D^\pm \xrightarrow{\lambda'_{121}} e^\pm + \tilde{\chi}_1^0$ | $\tilde{\chi}_1^0 \xrightarrow{\lambda'_{121}} K_S^0 + \nu_e$<br>$\tilde{\chi}_1^0 \xrightarrow{\lambda'_{121}} K^{*0} + \nu_e$<br>$\tilde{\chi}_1^0 \xrightarrow{\lambda'_{112}} K^{(*)+} + e^-$<br>$\tilde{\chi}_1^0 \xrightarrow{\lambda'_{112}} K_S^0 + \nu_e$<br>$\tilde{\chi}_1^0 \xrightarrow{\lambda'_{112}} K^{*0} + \nu_e$ |
| **B2** | $\lambda'_{112}, \lambda'_{111}$ | $K^\pm \xrightarrow{\lambda'_{112}} e^\pm + \tilde{\chi}_1^0$ | $\tilde{\chi}_1^0 \xrightarrow{\lambda'_{111}} \pi^+ + e^-$<br>$\tilde{\chi}_1^0 \xrightarrow{\lambda'_{111}} \pi^0 + \nu_e$ |

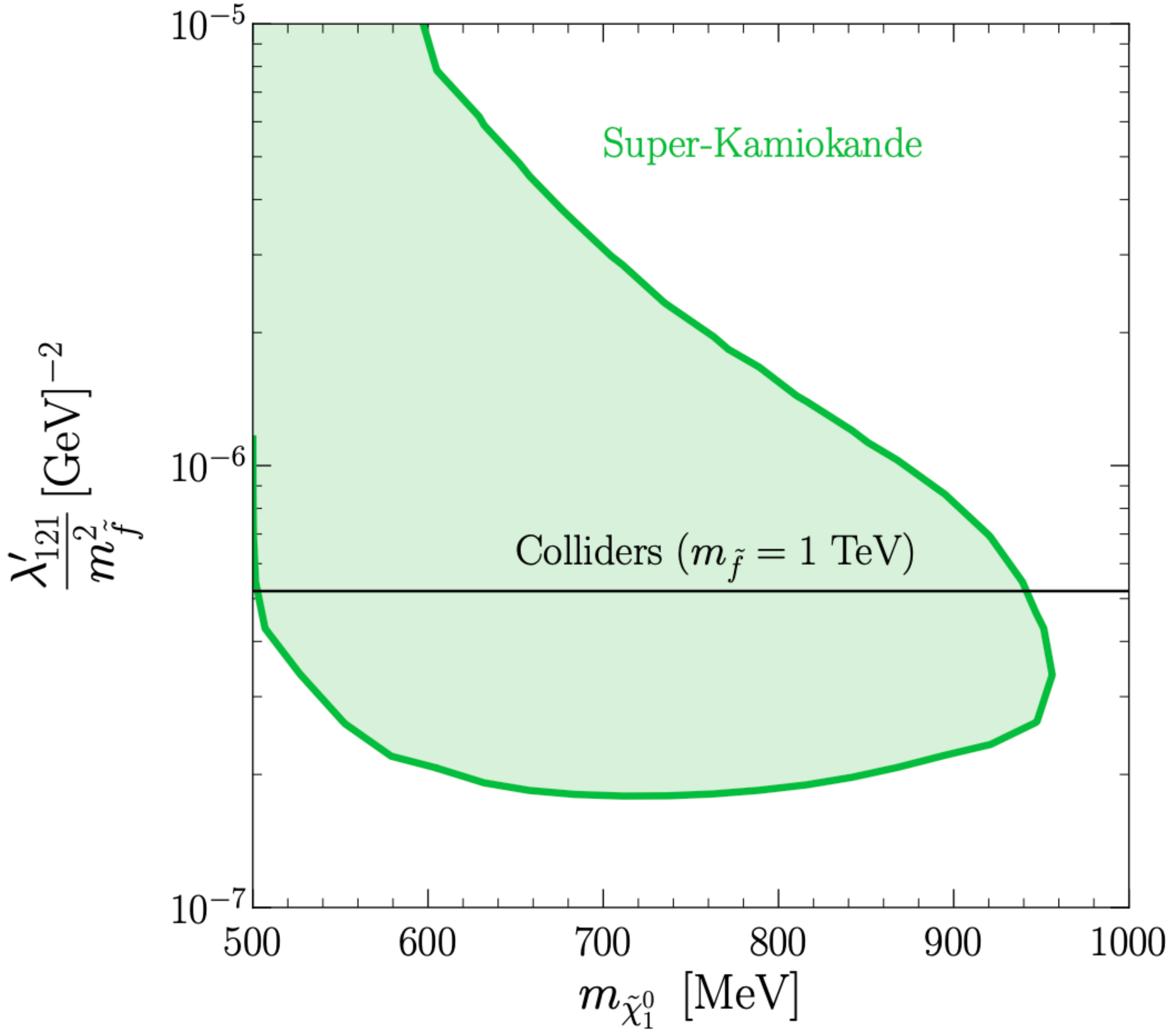



Cheung et al PRD/2208.05111

# Long-lived neutralinos

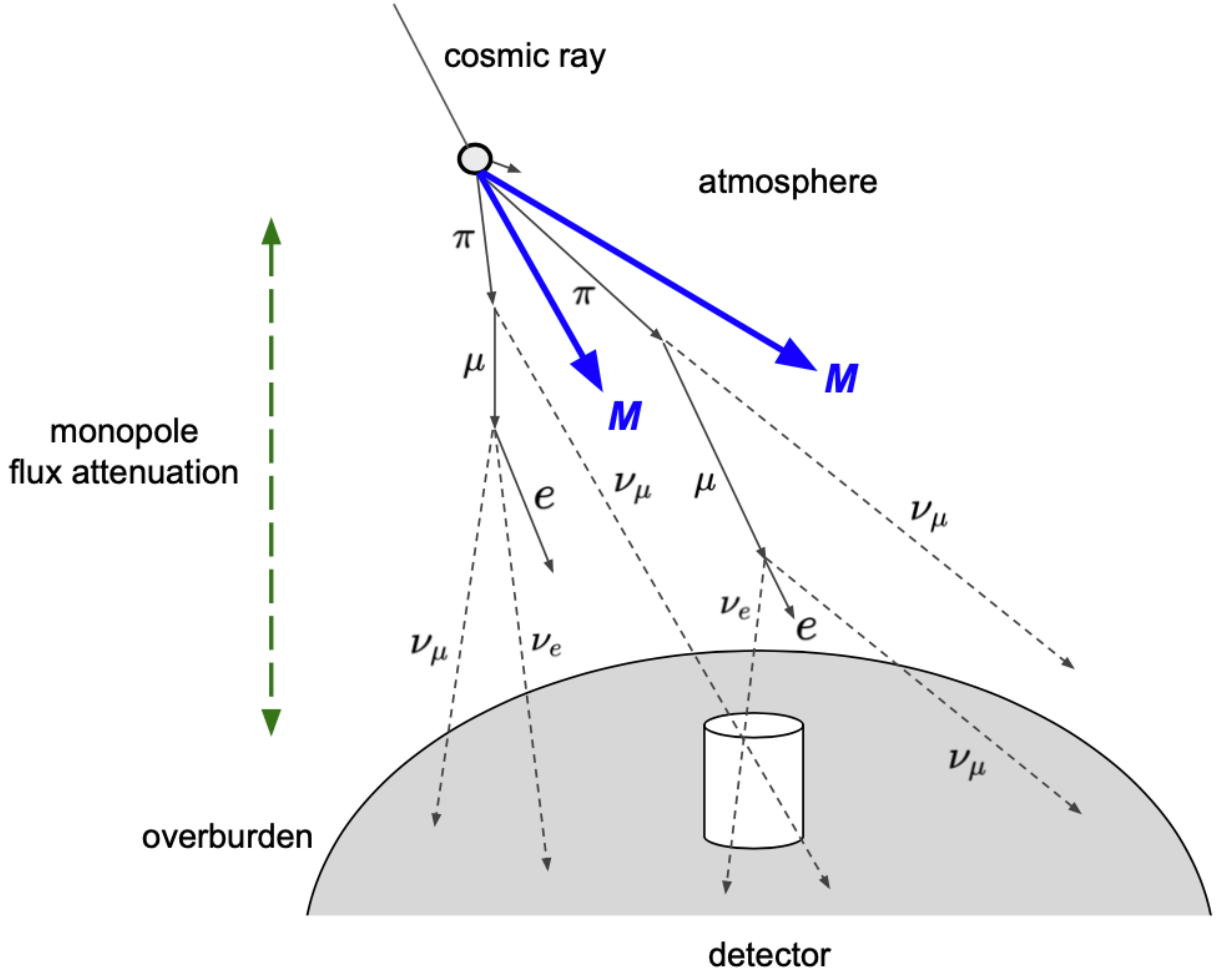
Benchmark 1



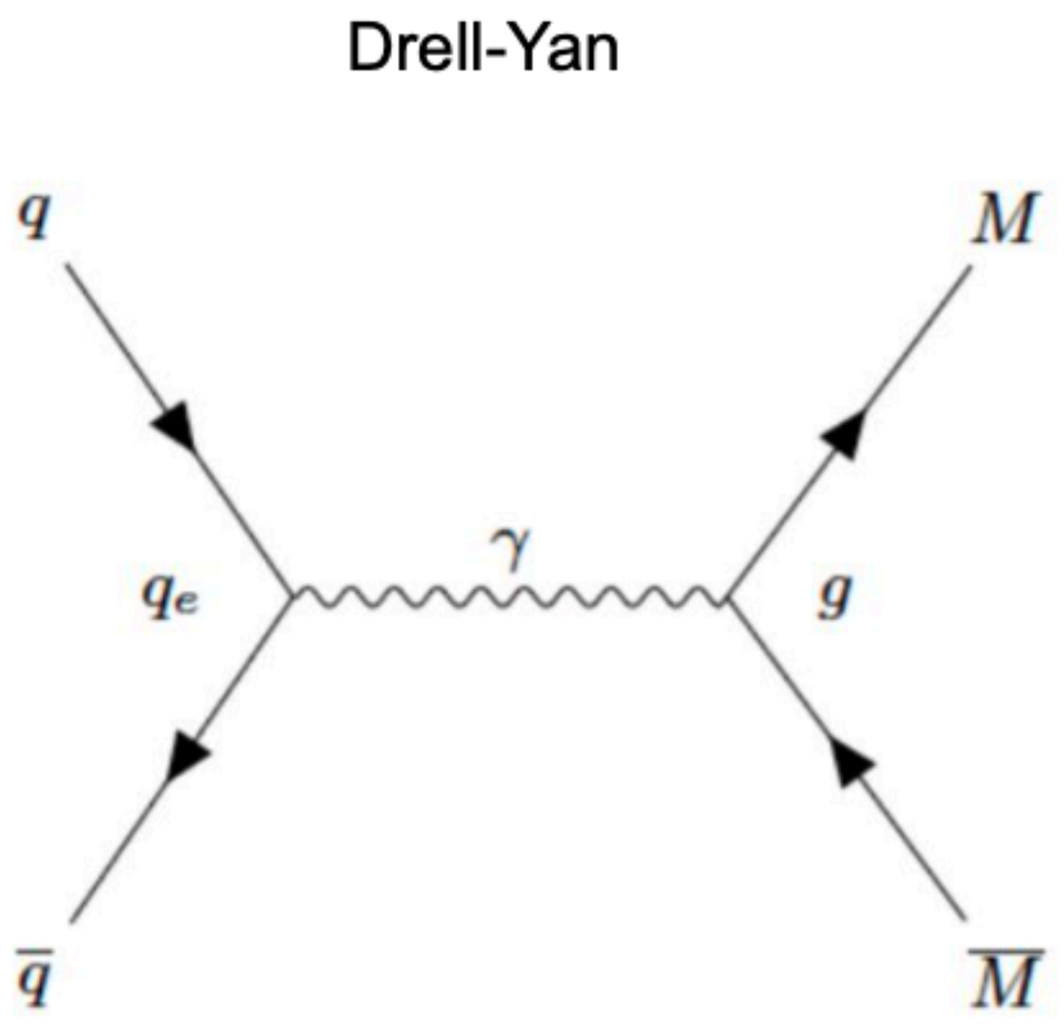

Candia et al PRD/2107.02804

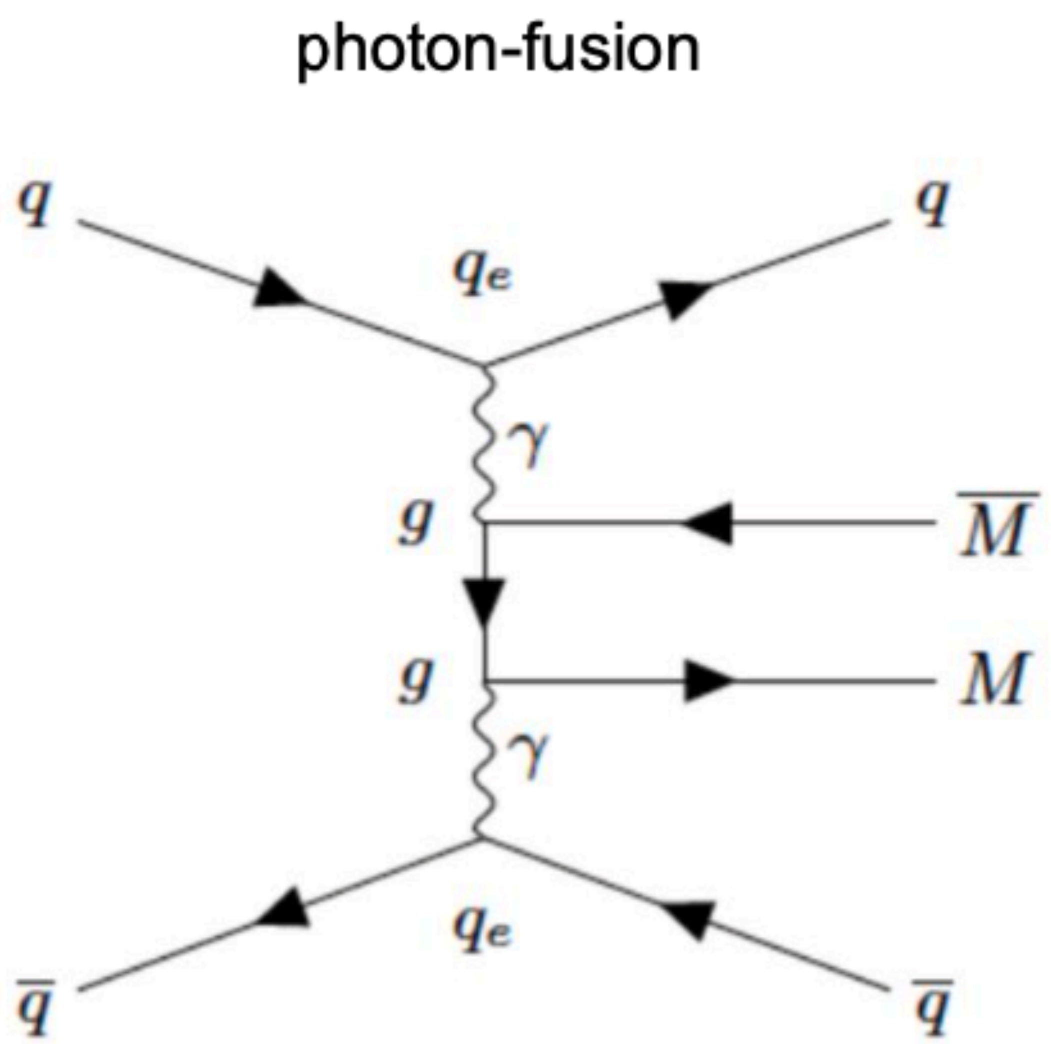
# Magnetic monopoles




Iguro et al PRL/2111.12091

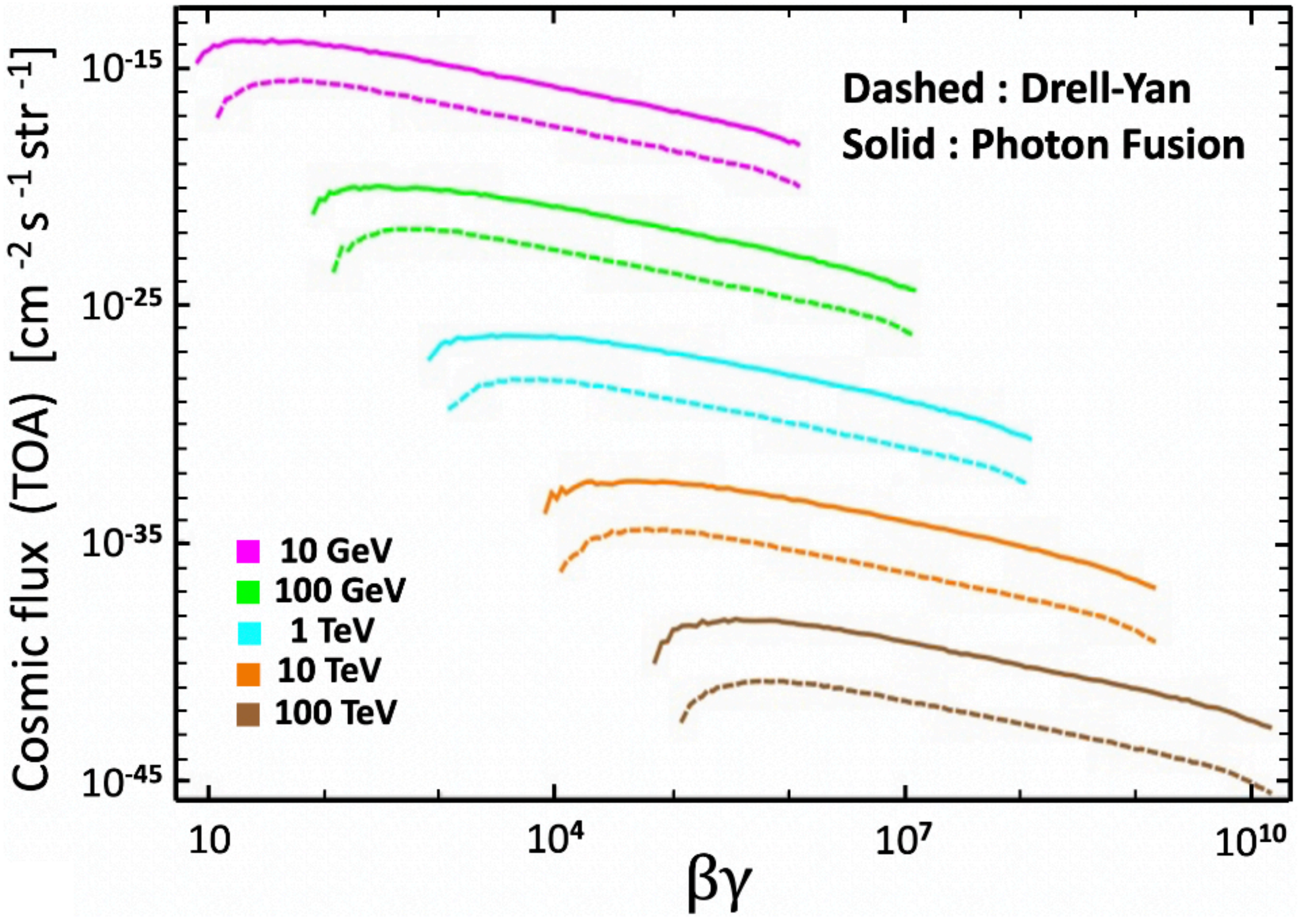
$$\sigma(pp \to M\overline{M}) = \kappa \times \sigma_{\mathrm{sim}}$$

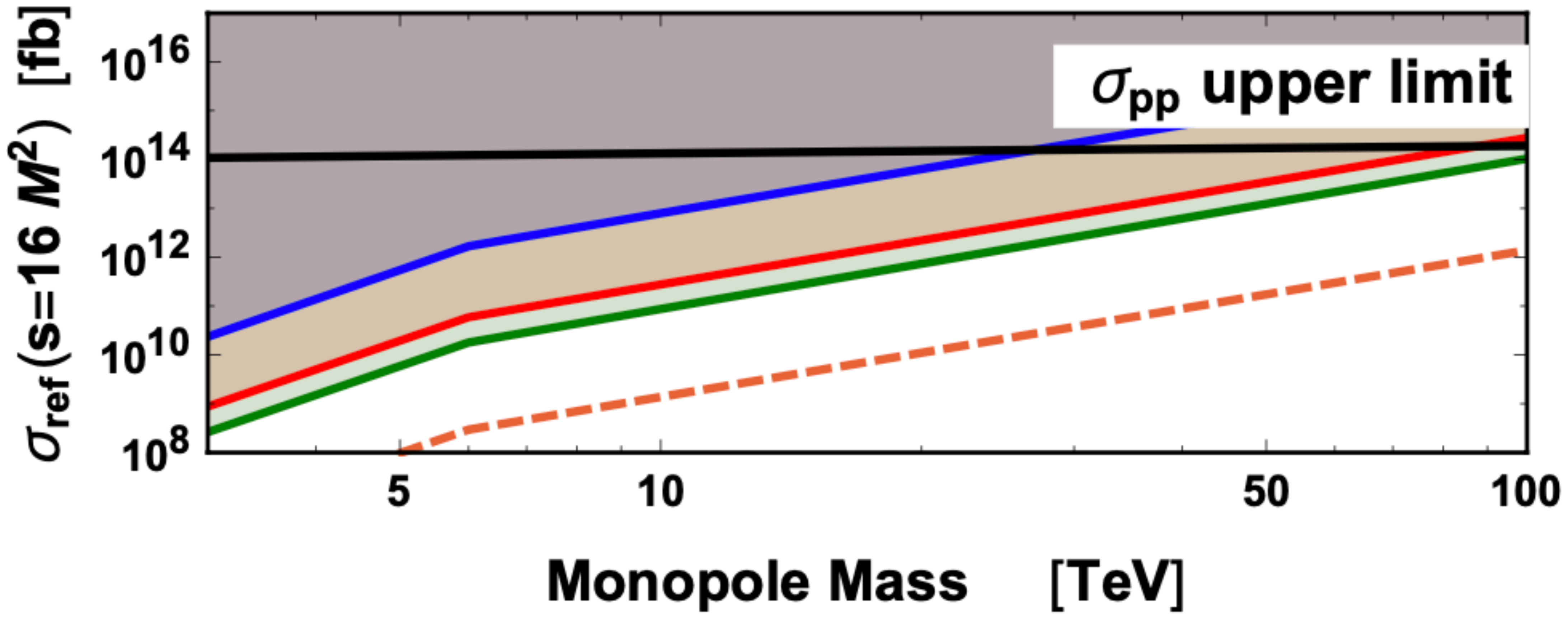


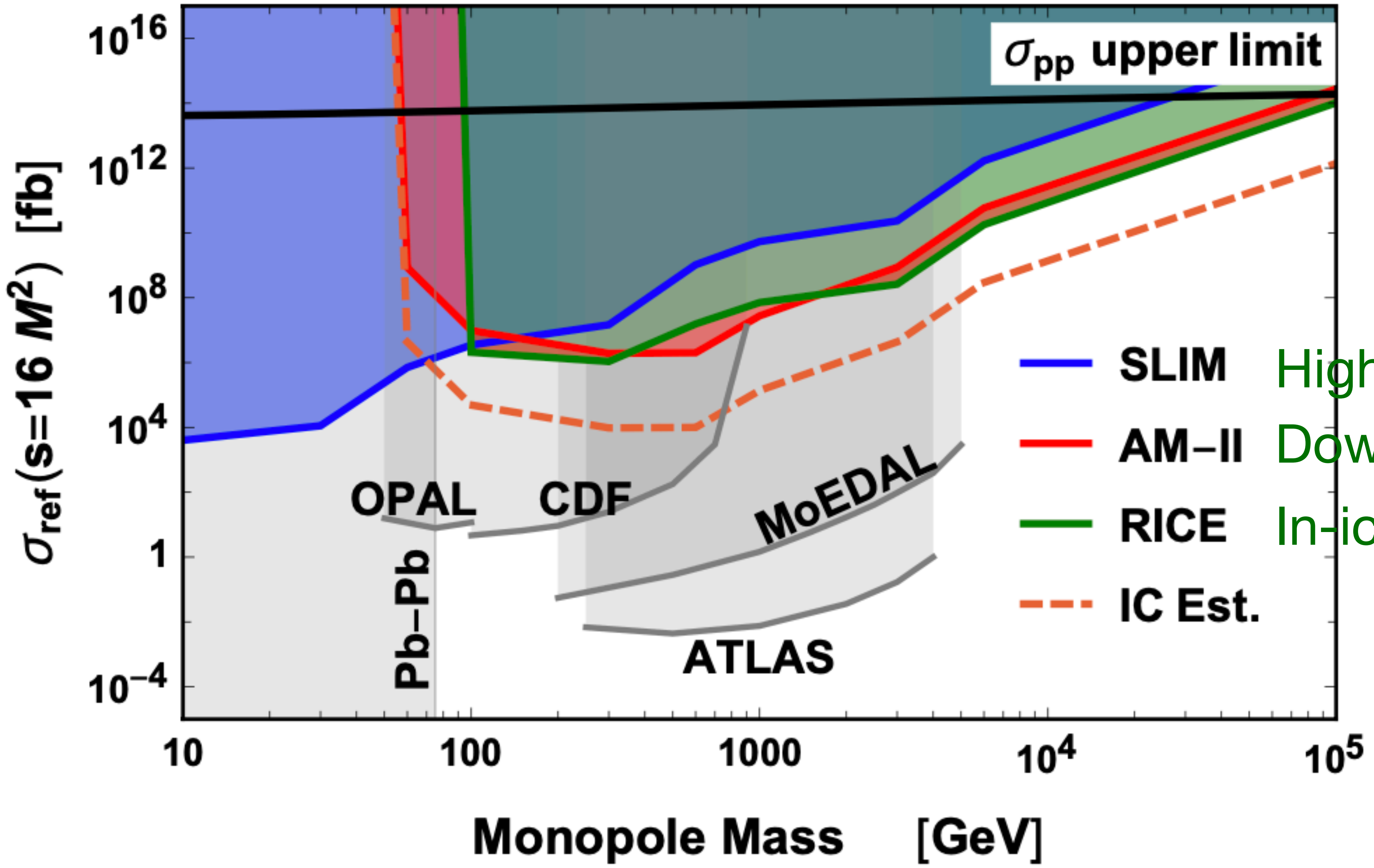



# Magnetic monopoles

$$\sigma(pp \to M\overline{M}) = \kappa \times \sigma_{\rm sim}$$




High elevation NTD
Downgoing tracks
In-ice radio

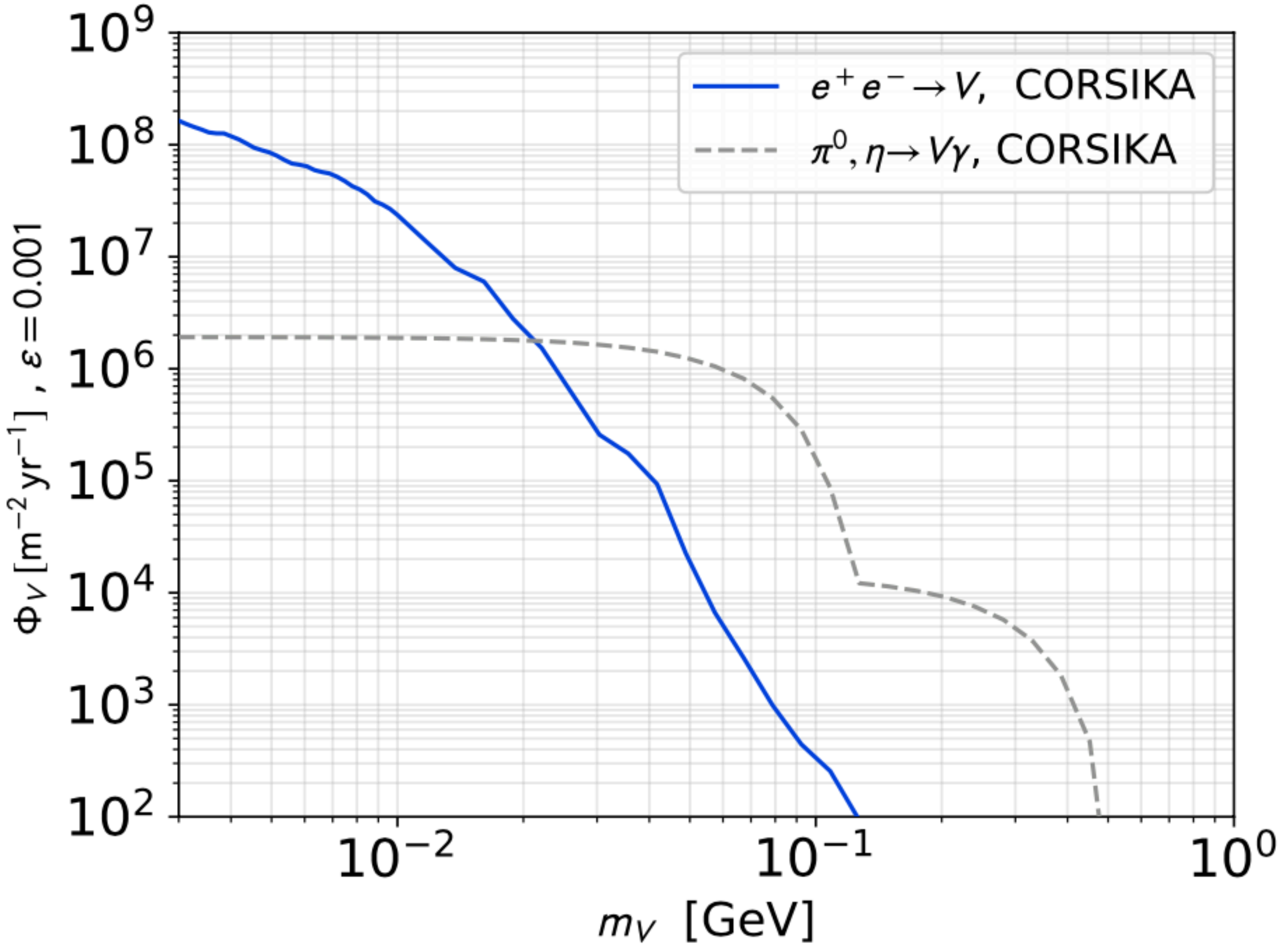
Iguro et al PRL/2111.12091

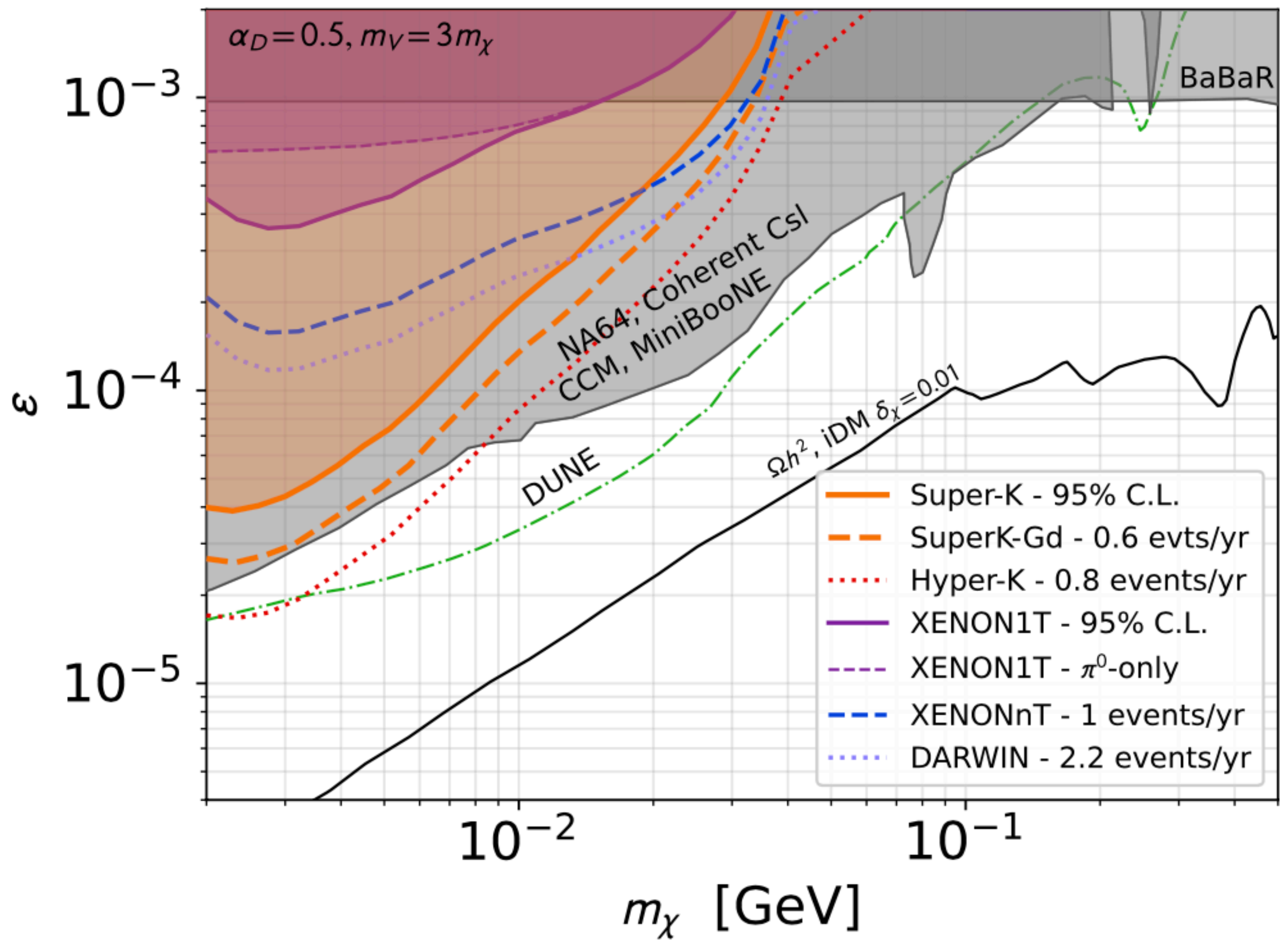
# Dark photon

$$\mathcal{L} \supset -V_\mu \left(e\varepsilon \mathcal{J}^\mu_{\rm em} + g_D \mathcal{J}^\mu_D\right)$$

$$\mathcal{J}^\mu_D = -i\, \overline{\chi}_2 \gamma^\mu \chi_1$$

$$\sigma_{\rm res} = \frac{2\pi^2\varepsilon^2\alpha_{\rm em}}{m_e}\delta(E_+ - \frac{m_V^2}{2m_e}) \equiv \tilde{\sigma}_{\rm res}\,\delta(E_+ - E_{\rm res})$$



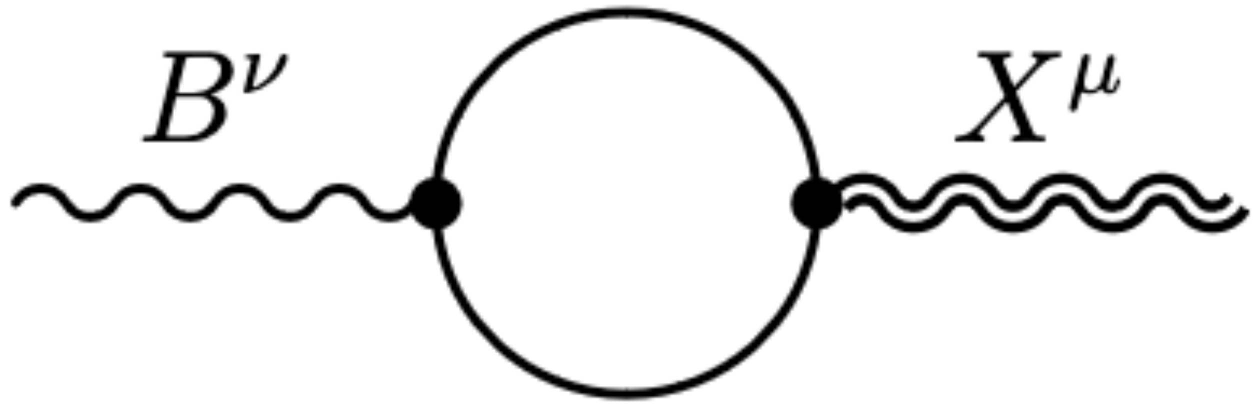

Luc Darmé PRD/2205.09773

# Dark photon kinetic mixing

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

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

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




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

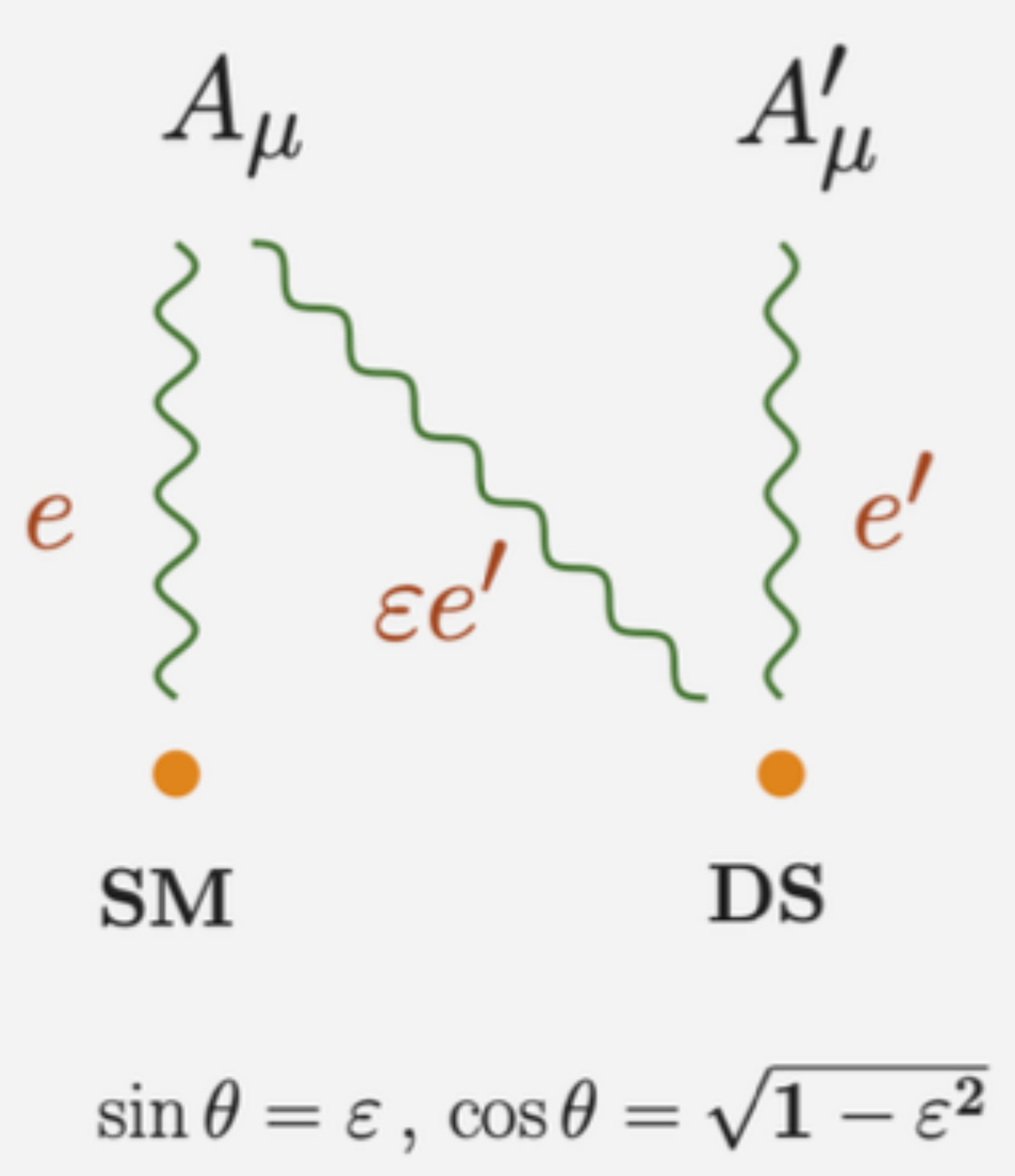
# Millicharge particles

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

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

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

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



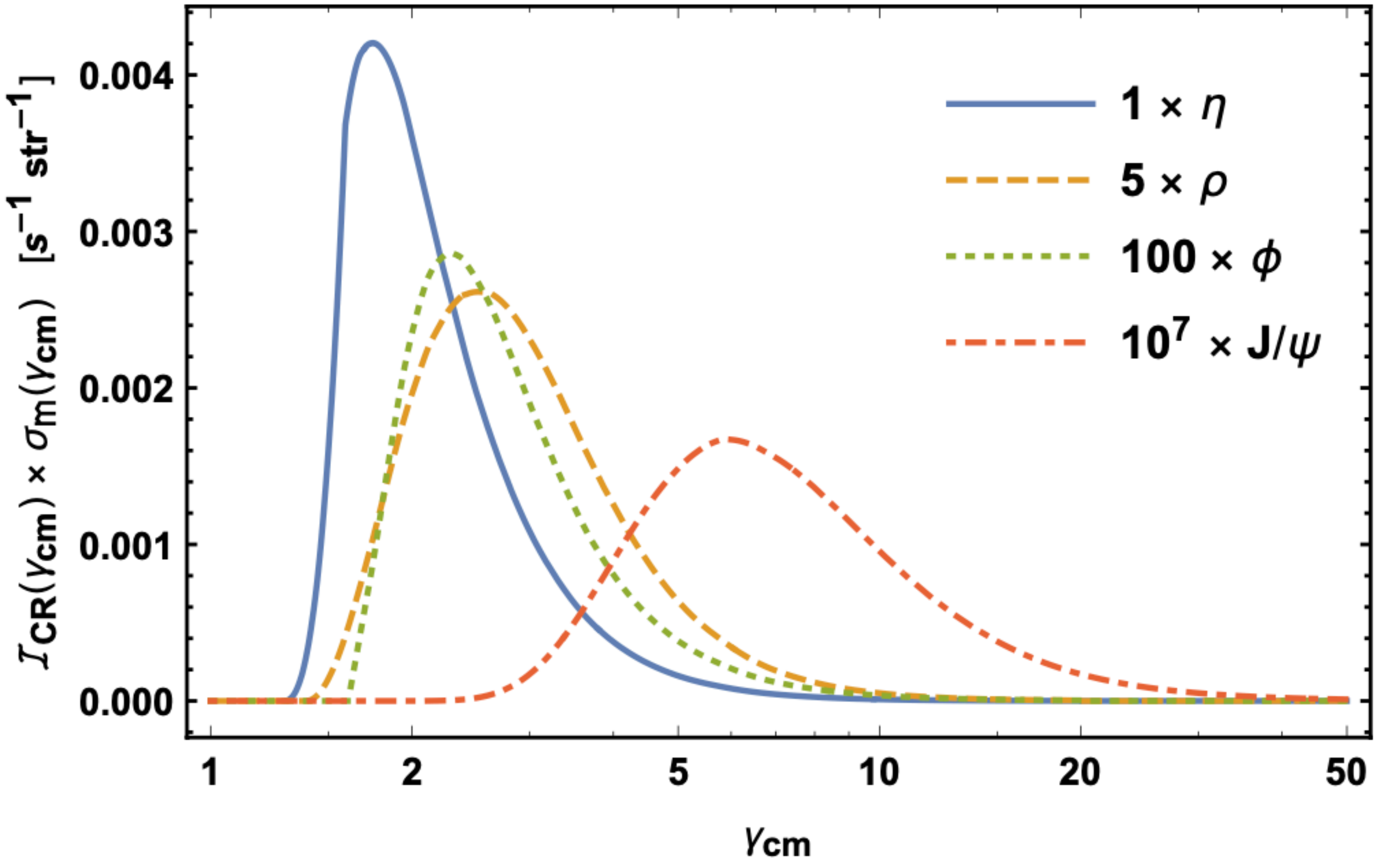

Fabbrichesi et al arXiv: 2005.01515

# Millicharge particles from light meson decay

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

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

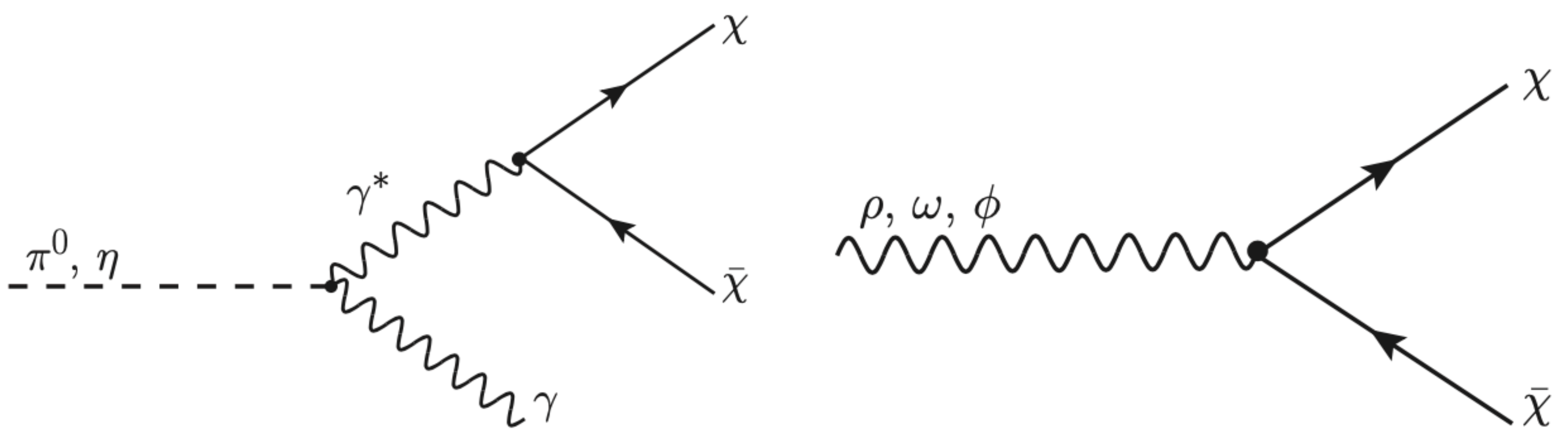
$$P(\gamma_{\mathfrak{m}}|\gamma_{\text{cm}}) \approx \sum_{\alpha} \frac{1}{\sigma_{\mathfrak{m}}} \times \frac{\mathrm{d}\sigma_{\mathfrak{m}}}{\mathrm{d}x_F} \times \frac{\mathrm{d}x_F^{(\alpha)}}{\mathrm{d}\gamma_{\mathfrak{m}}}$$




Plestid et al PRD/2002.11732

# Millicharge particles from 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

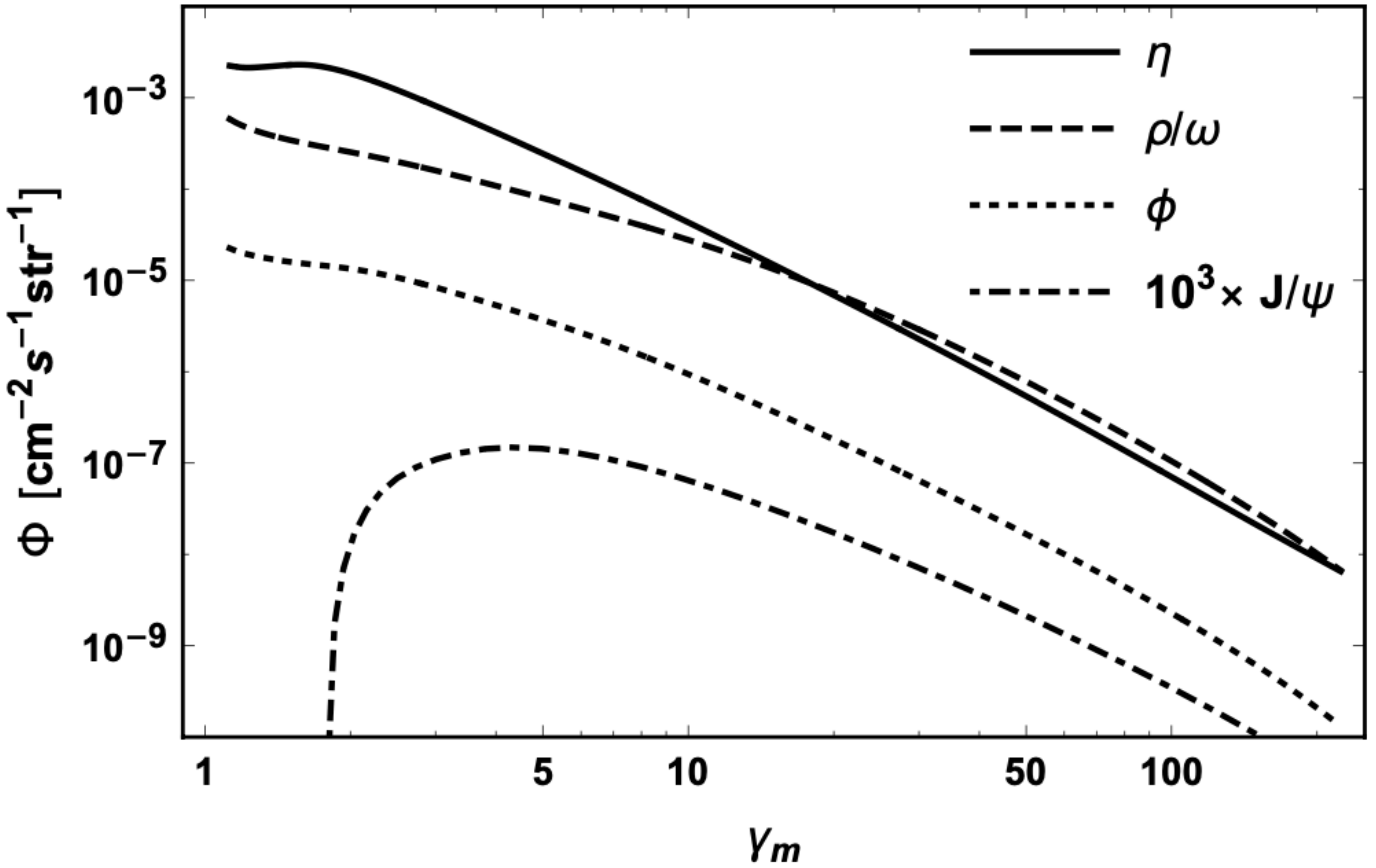
$$\frac{\mathrm{BR}\,(\mathfrak{m}\to\chi\bar{\chi})}{\mathrm{BR}\,(\mathfrak{m}\to\mu^+\mu^-)} = \epsilon^2\sqrt{\frac{m_{\mathfrak{m}}^2 - 4m_\chi^2}{m_{\mathfrak{m}}^2 - 4m_\mu^2}}$$

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

$\eta$ decay to MCP pairs+photon

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

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




Plestid et al PRD/2002.11732

# Millicharge particles from proton bremsstrahlung

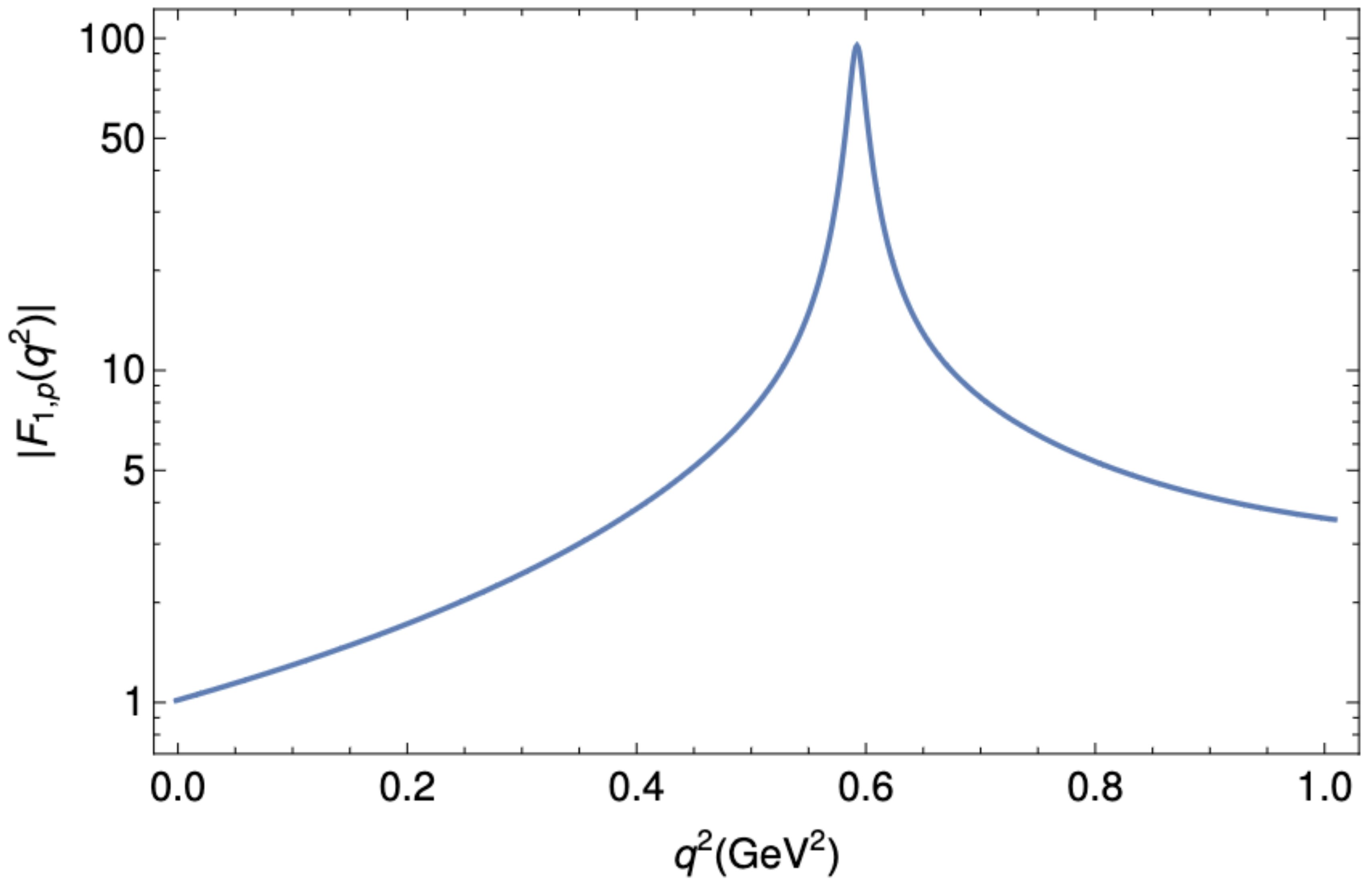
Fermi-Weizsacker-Williams (FWW) approximation with the splitting-kernel approach

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

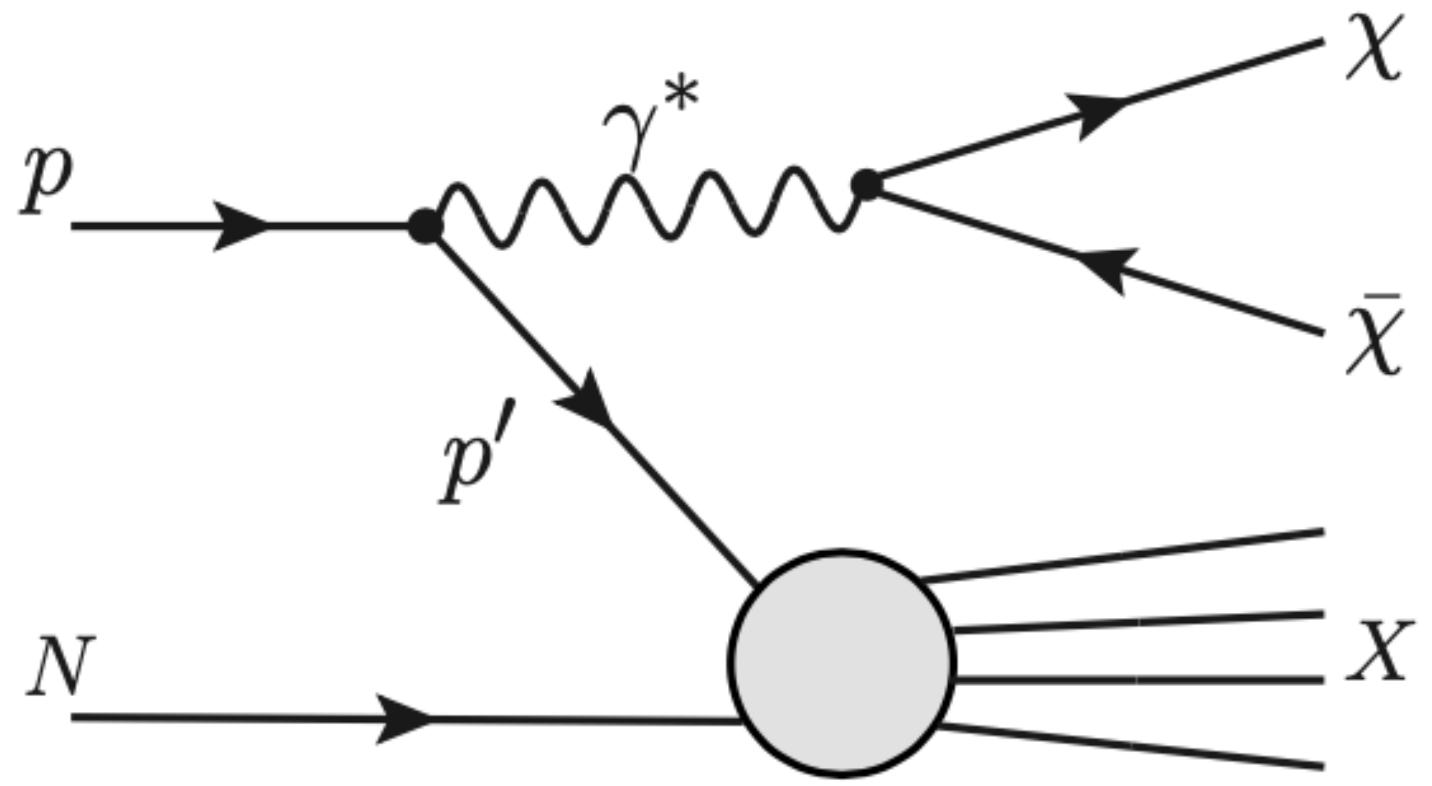
$$\frac{d^2\mathcal{P}^{\rm FWW}_{p\to\gamma^* p}}{dE_k\, d\cos\theta_k} = \left|\mathbf{J}(z,p_T^2)\right| \frac{d^2\mathcal{P}^{\rm FWW}_{p\to\gamma^* p}}{dz\, dp_T^2} = \left|\mathbf{J}(z,p_T^2)\right| \left|F_V(k)\right|^2 \omega(z,p_T^2)$$

Kernel

EM form factor




deNiverville et al PRD/1609.01770



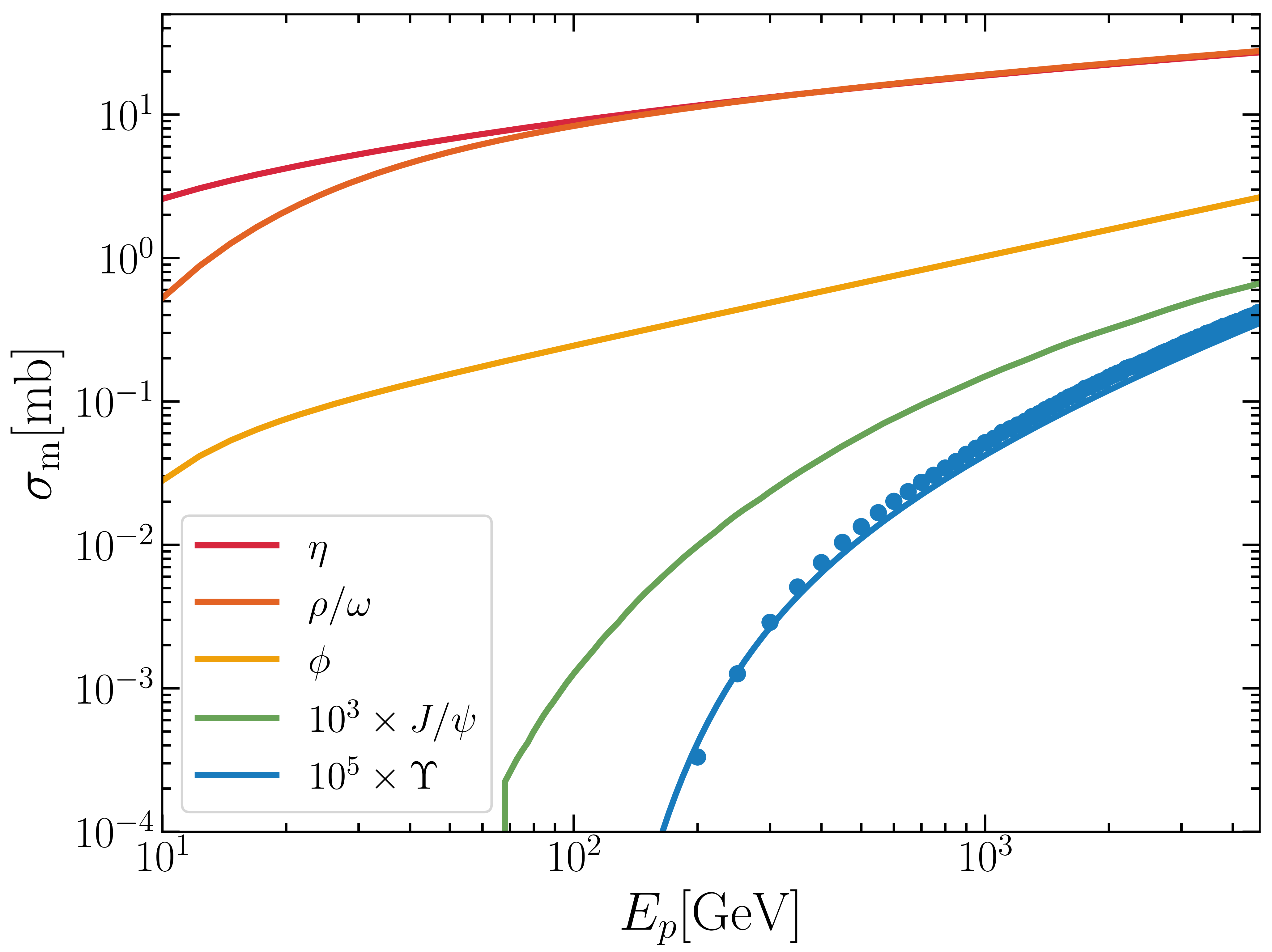

$$\Phi_\chi^{\rm PB} = \int dE_p \Phi_p \frac{\epsilon^2 e^2}{6\pi^2} \int \frac{dk^2}{k^2} \sqrt{1 - \frac{4m_\chi^2}{k^2}} \left(1 + \frac{2m_\chi^2}{k^2}\right)$$
$$\times \int dE_k \frac{1}{\sigma_{pN}} \frac{d\sigma^{\rm PB}}{dE_k} \frac{\Theta(E_\chi - E_{\rm min})\Theta(E_{\rm max} - E_\chi)}{E_{\rm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

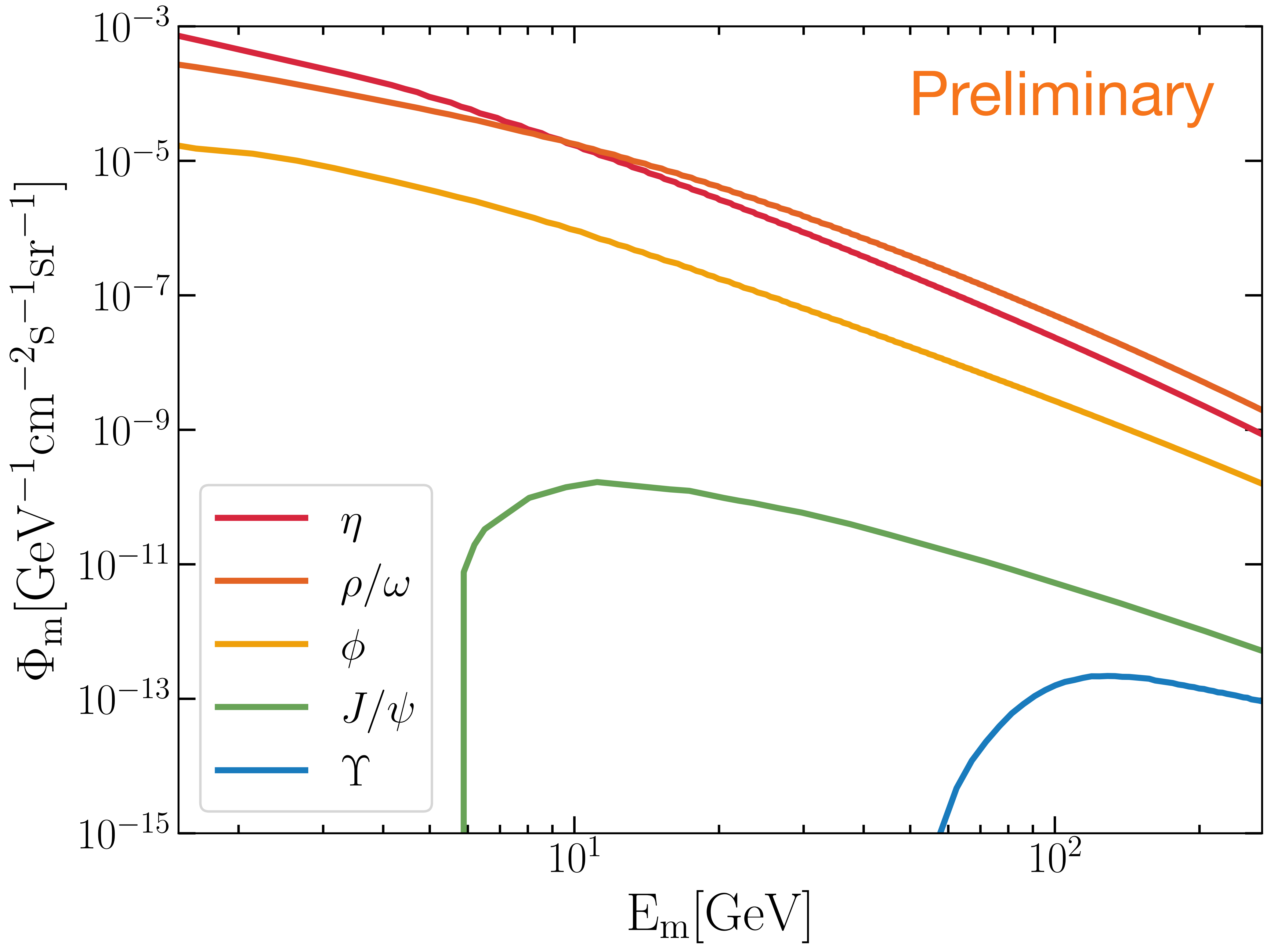
Du et al arXiv: 2211.11469

Du et al arXiv: 2308.05607

# Millicharge particles from Upsilon meson decay

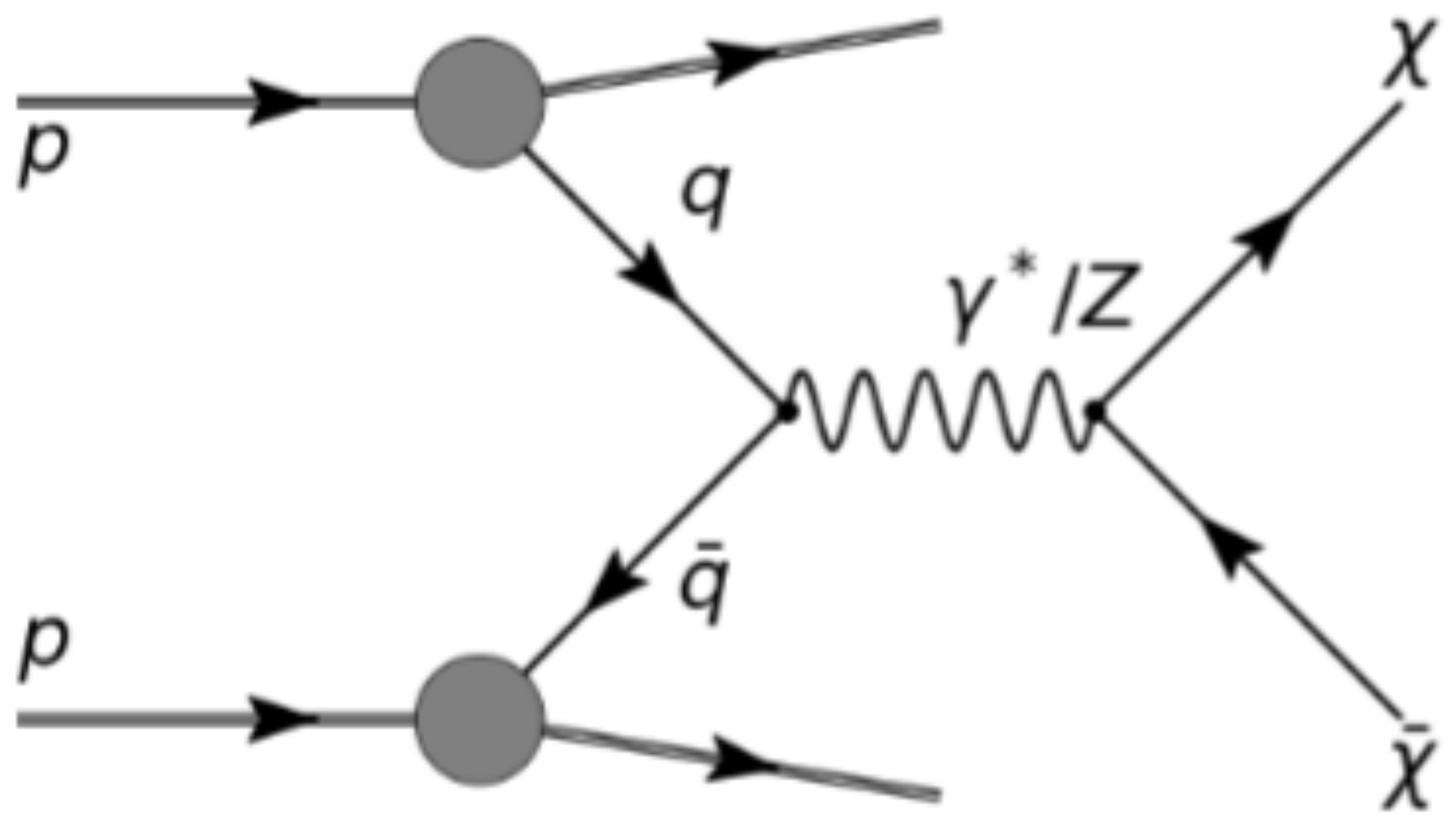
Pythia8 simulations



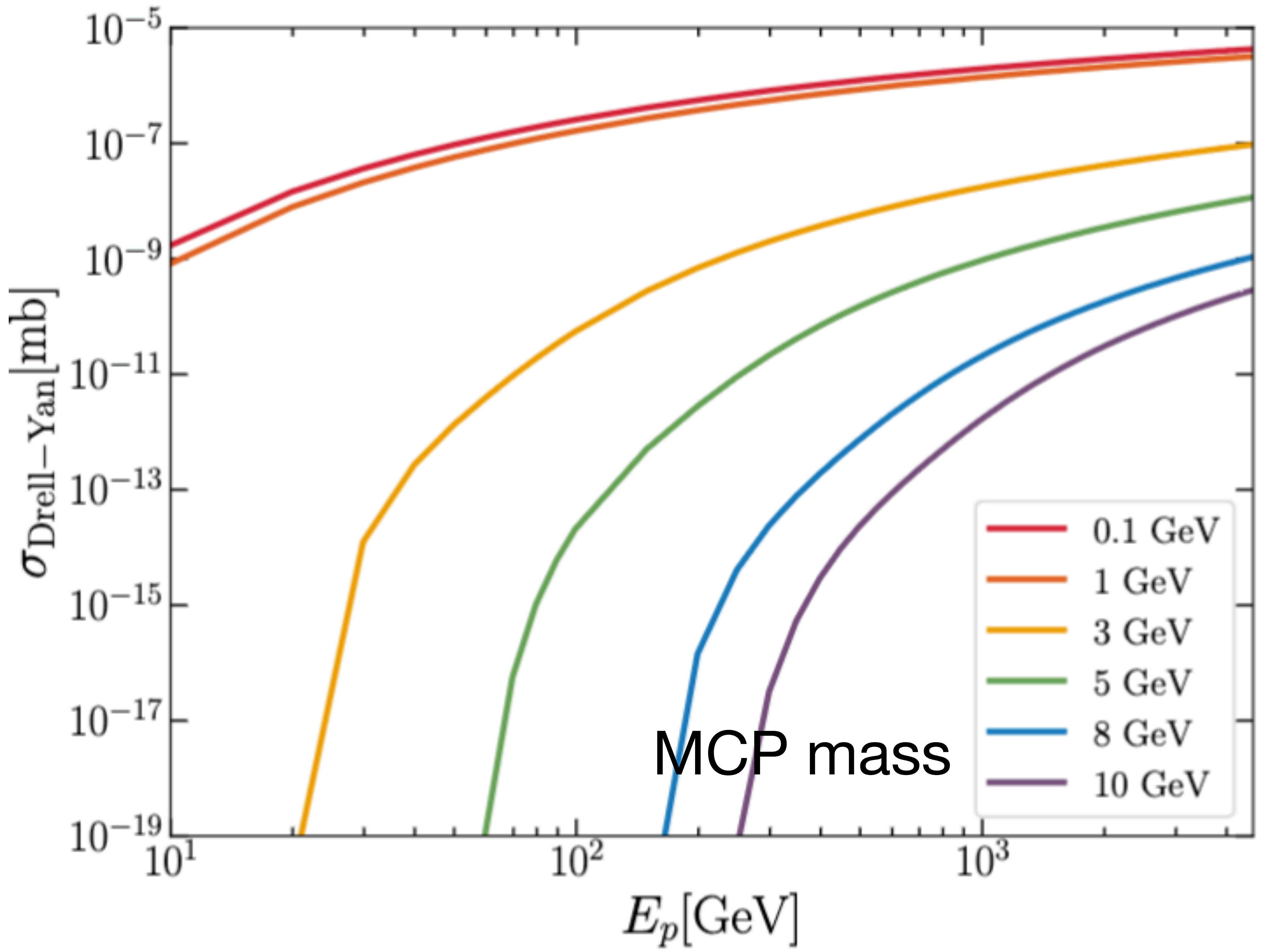



# Millicharge particles from Drell-Yan process

Madgraph simulations



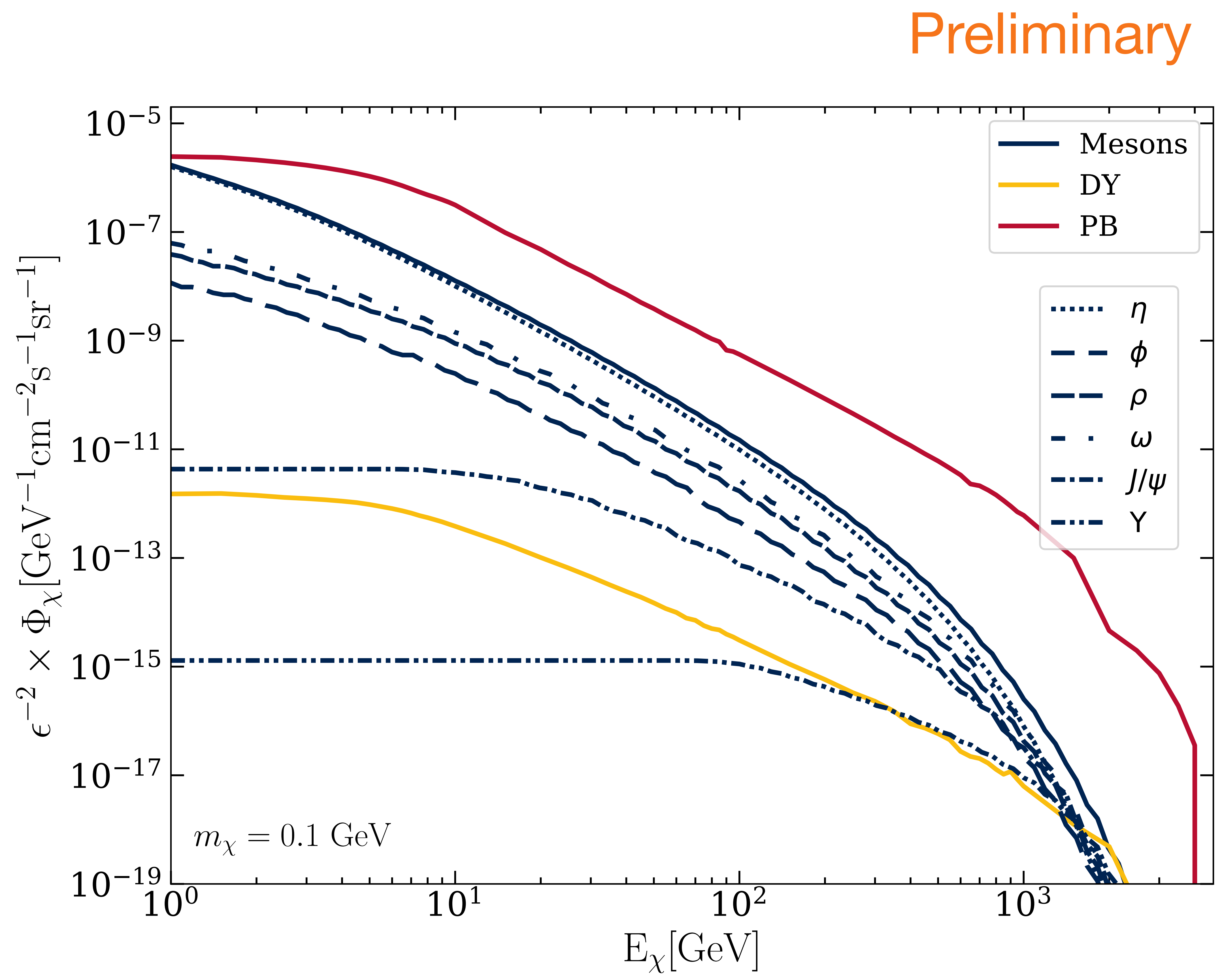

Preliminary

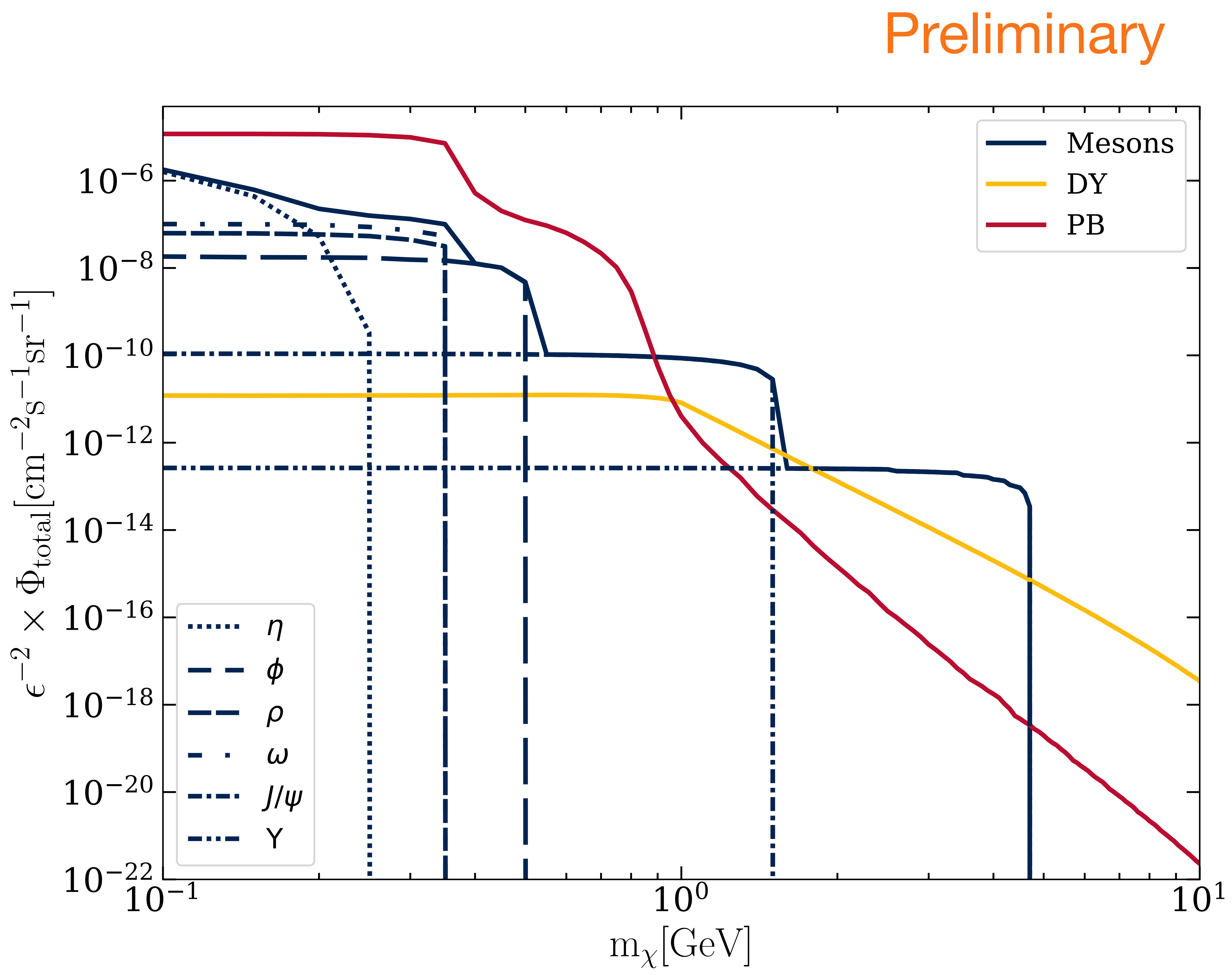



$$\hat{\sigma}\left(q(p_1)\,\bar{q}(p_2) \to l^+ l^-\right) = \frac{4\pi\alpha^2}{3\hat{s}}\,\frac{1}{N_c}\,Q_q^2$$

# Millicharge particles flux

Meson decay+Proton Bremsstrahlung+Drell-Yan

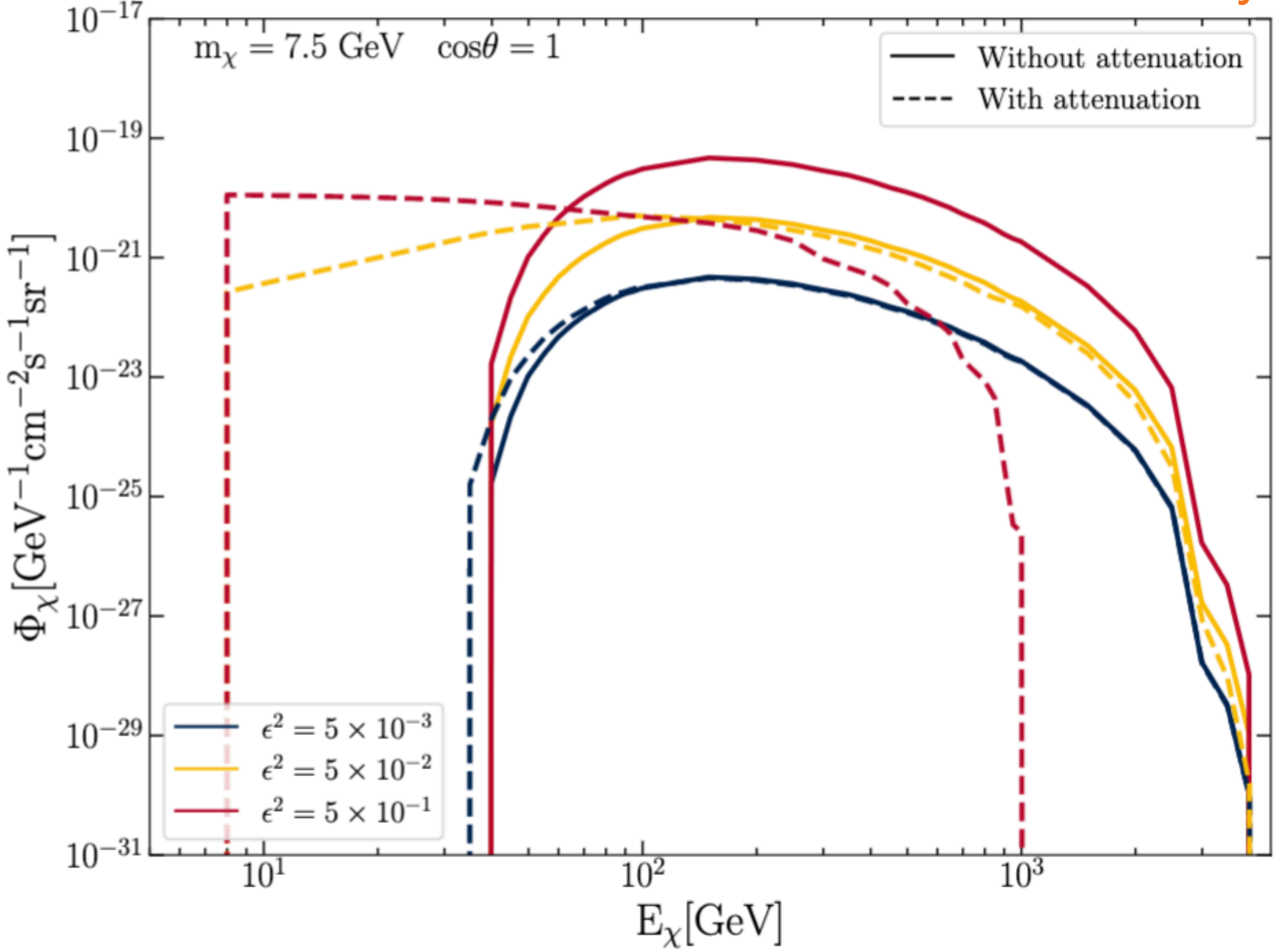


# Earth attenuation

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

Preliminary



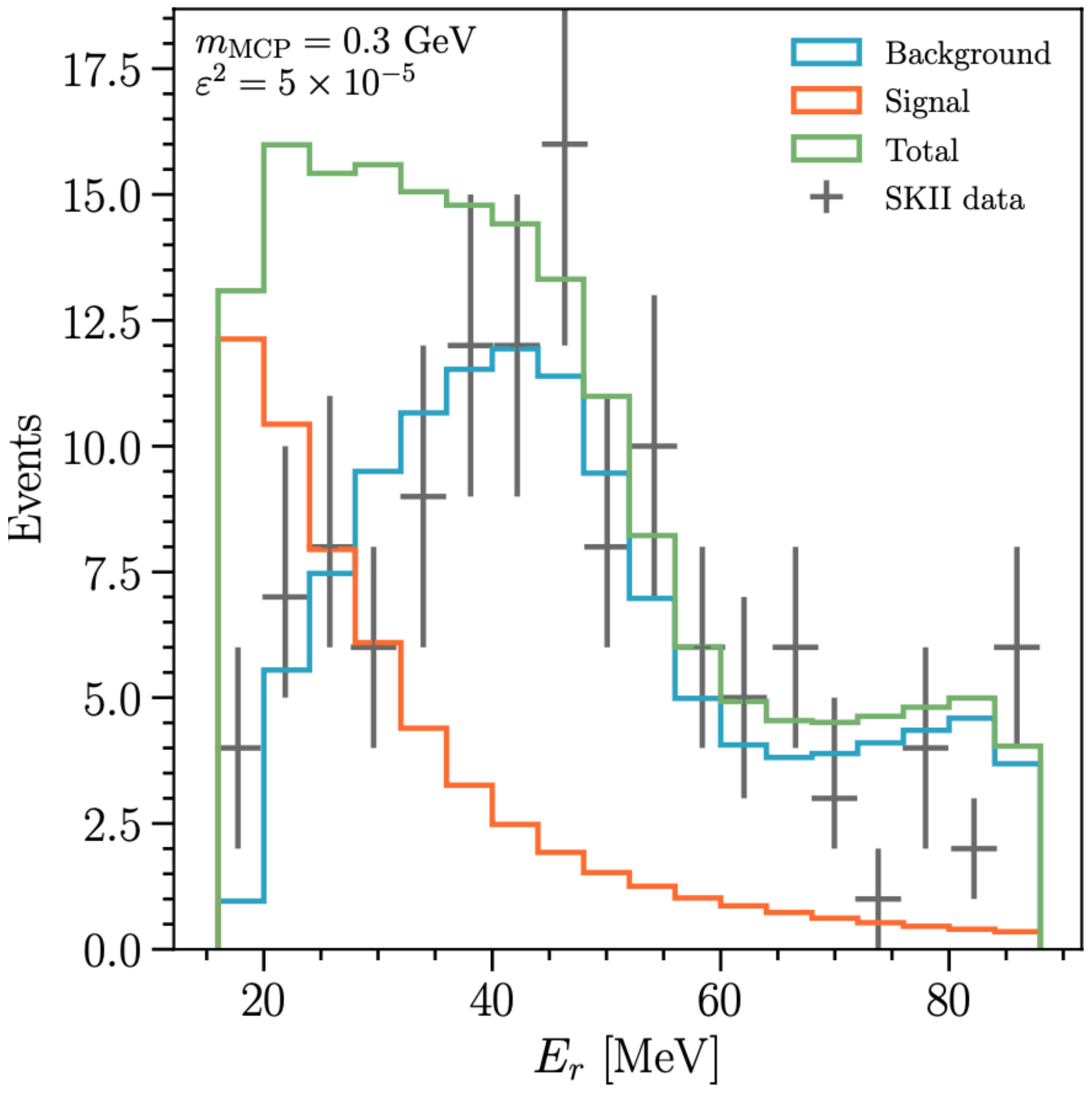

For $\epsilon^2 \gtrsim 10^{-2}$, the down-going flux becomes significantly attenuated

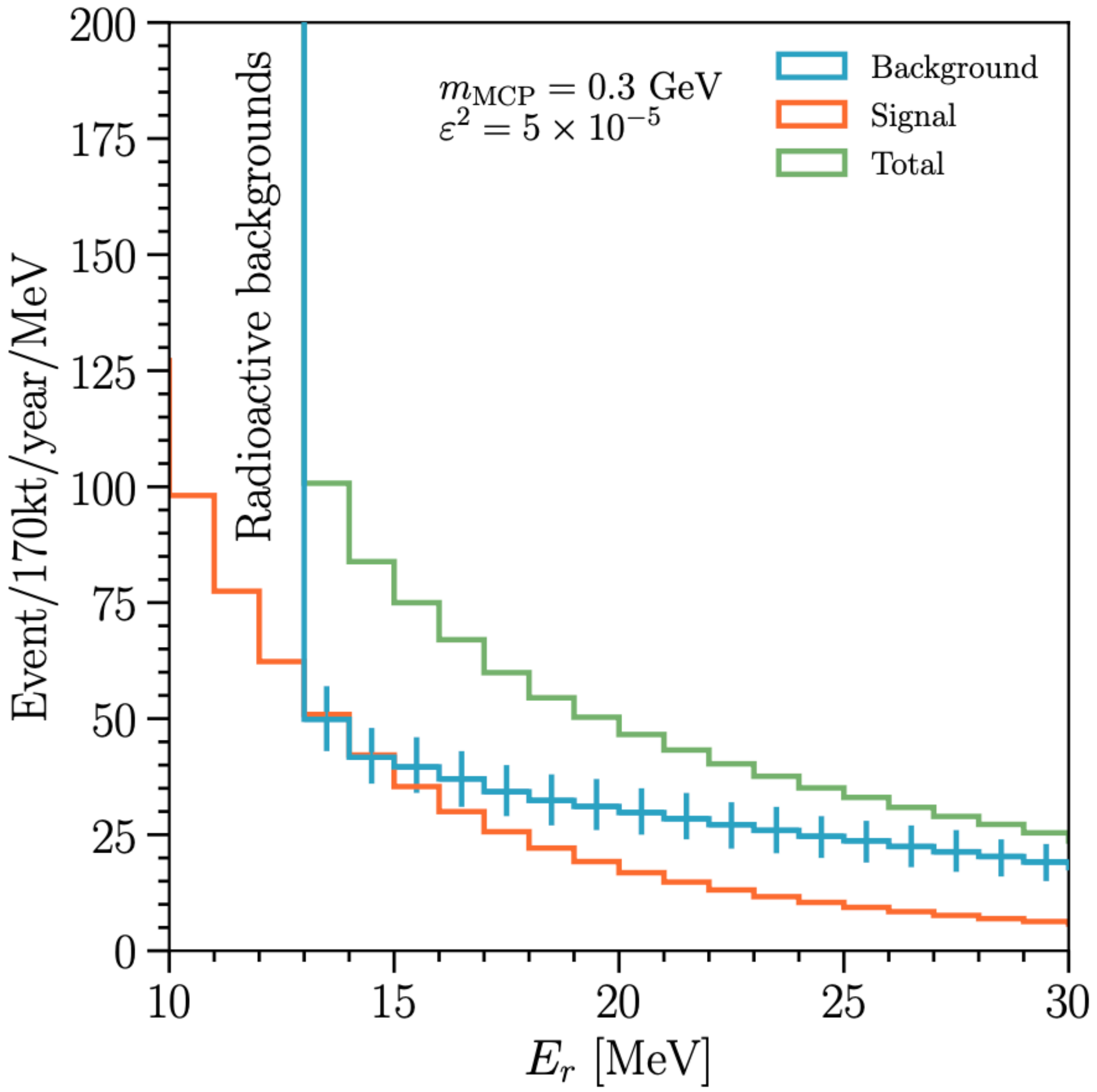
# Single scatter

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

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

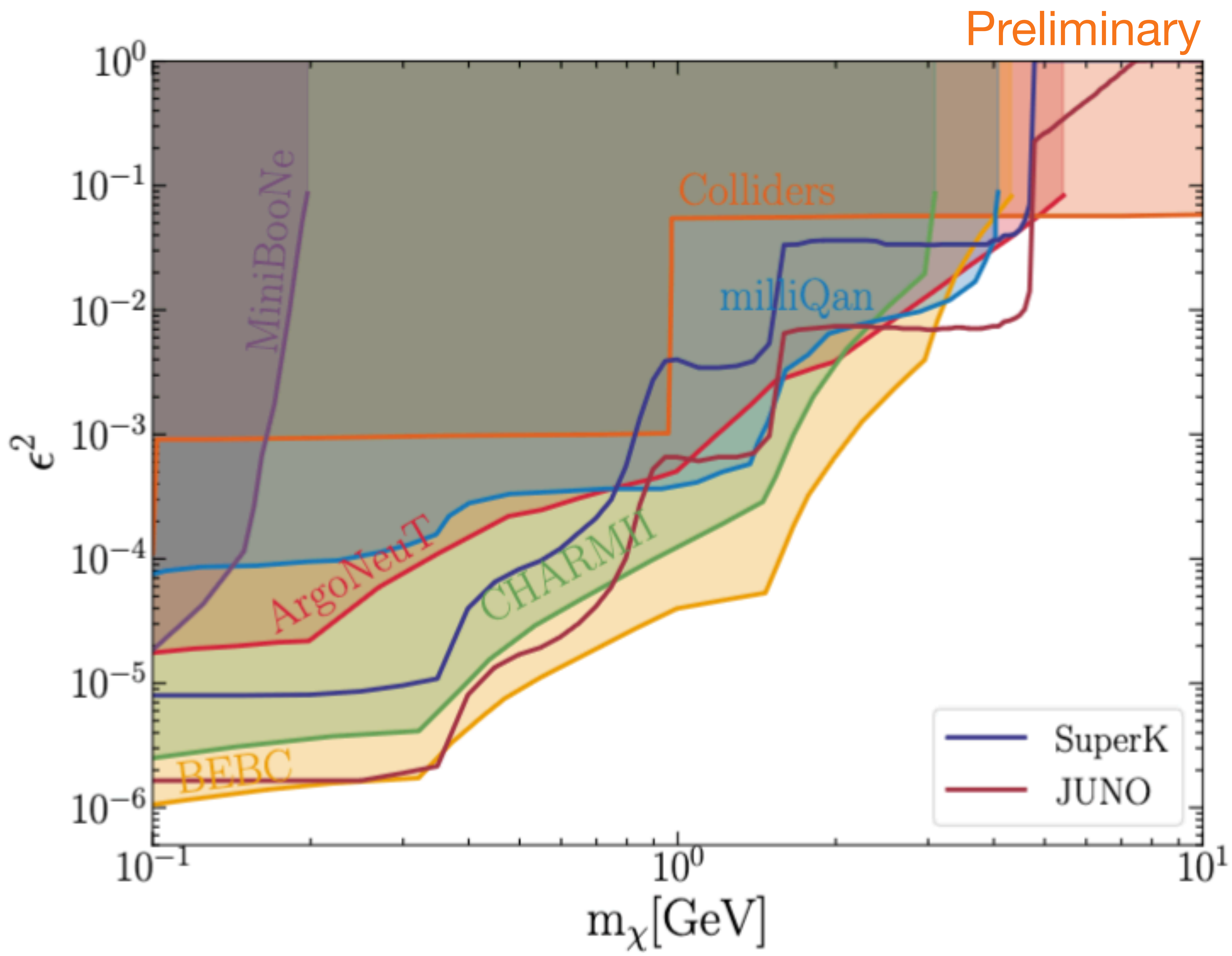
$$N_i\left(m_\chi, \epsilon\right) = N_e T \int_{E_{i,\min}}^{E_{i,\max}} dE_r \epsilon_D(E_r) \times \int dE_\chi d\Omega \Phi_\chi^D\left(E_\chi, \Omega\right) \frac{d\sigma_{\chi e}}{dE_r}$$




Arguelles et al JHEP/2104.13924

# Single scatter constraint




Assuming JUNO 10 MeV threshold+170 kton·yr exposure

# Multiple scatter constraint

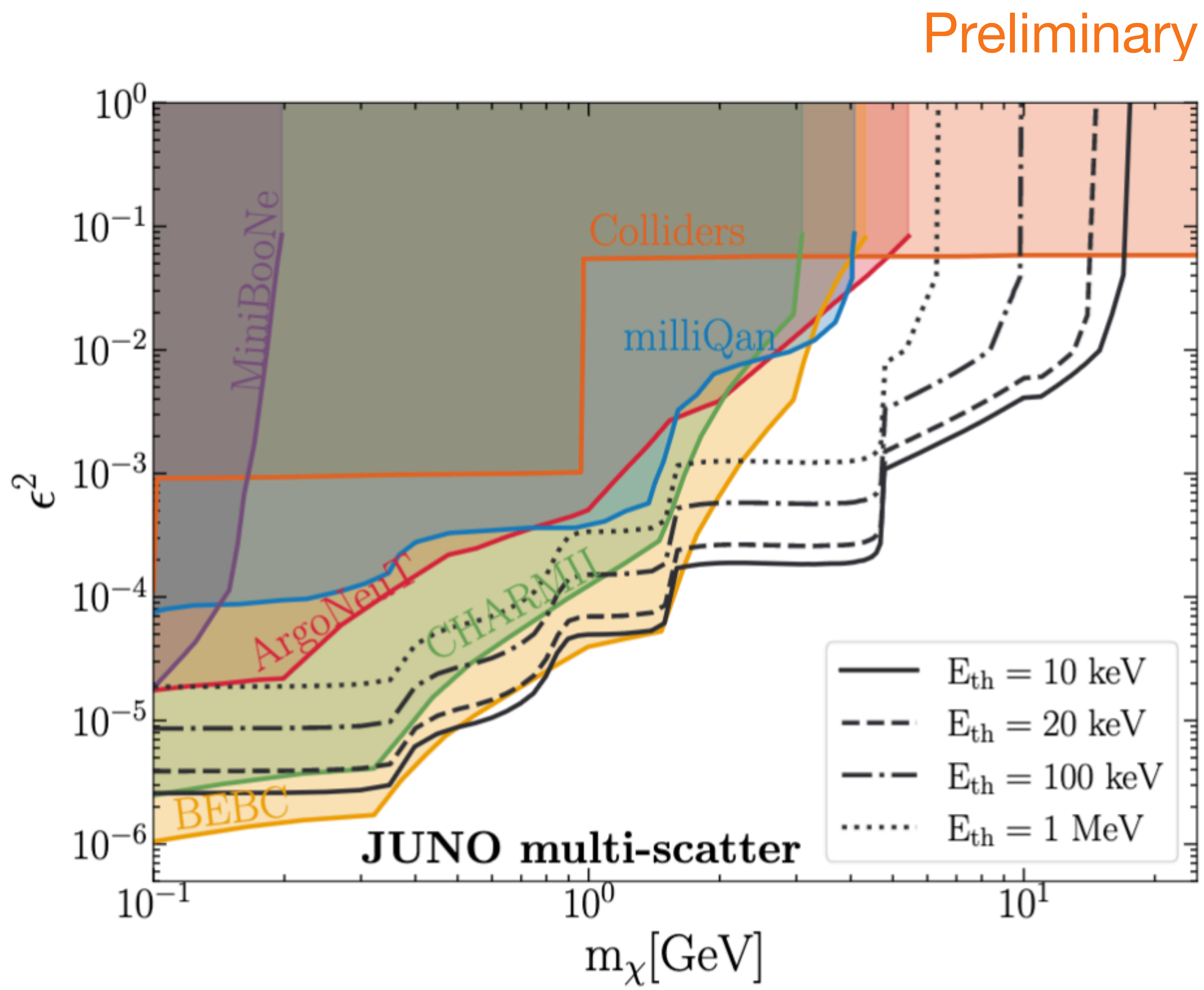
Single scatter probability $$P_1 = 1 - \exp\left(-\frac{L_D}{\lambda(T_{\min})}\right)$$

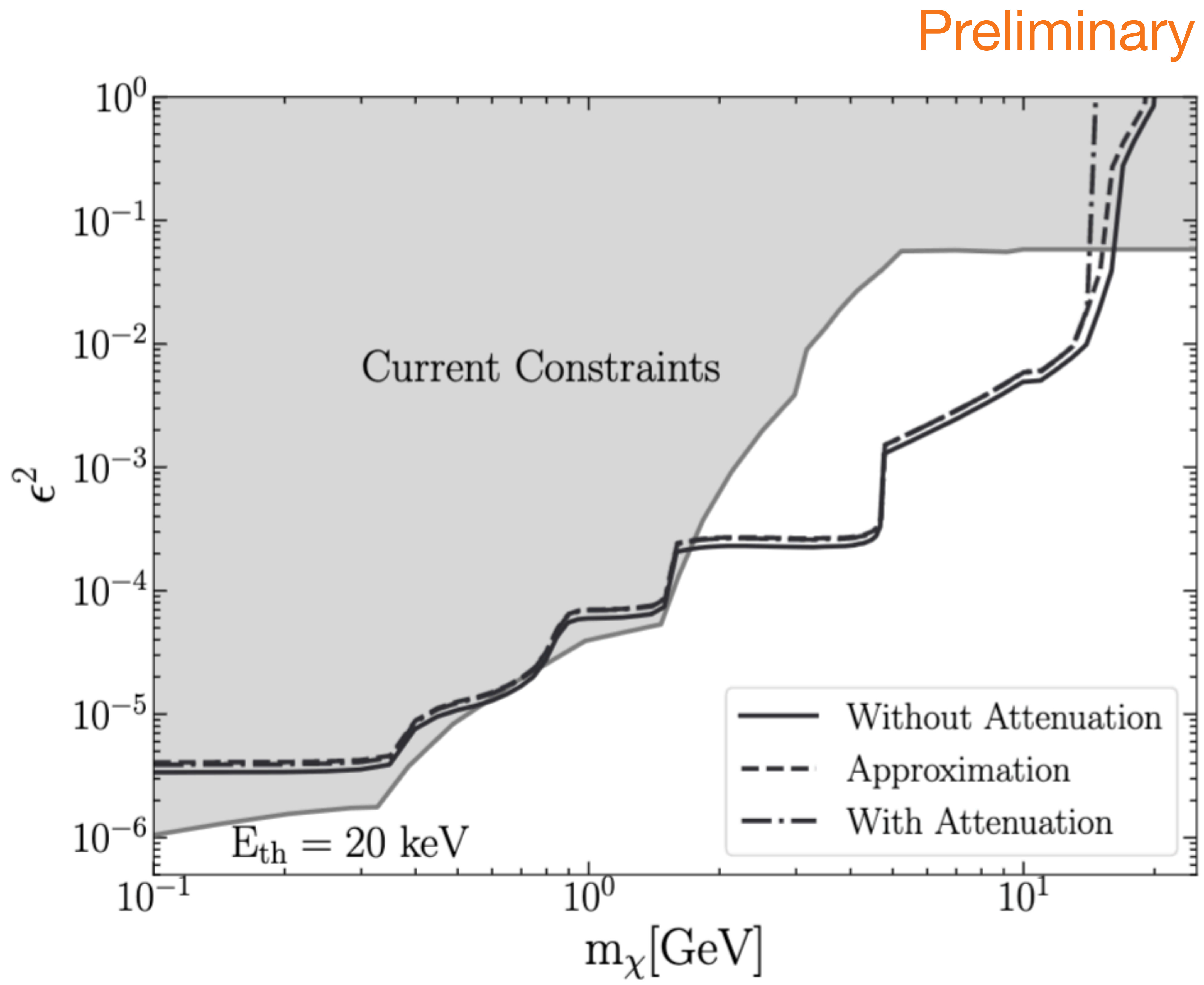
Multiple scatter probability $$P_{n\geq 2}(T_{\min}) = 1 - \exp\left(-\frac{L_D}{\lambda}\right)\left(1 + \frac{L_D}{\lambda}\right)$$

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

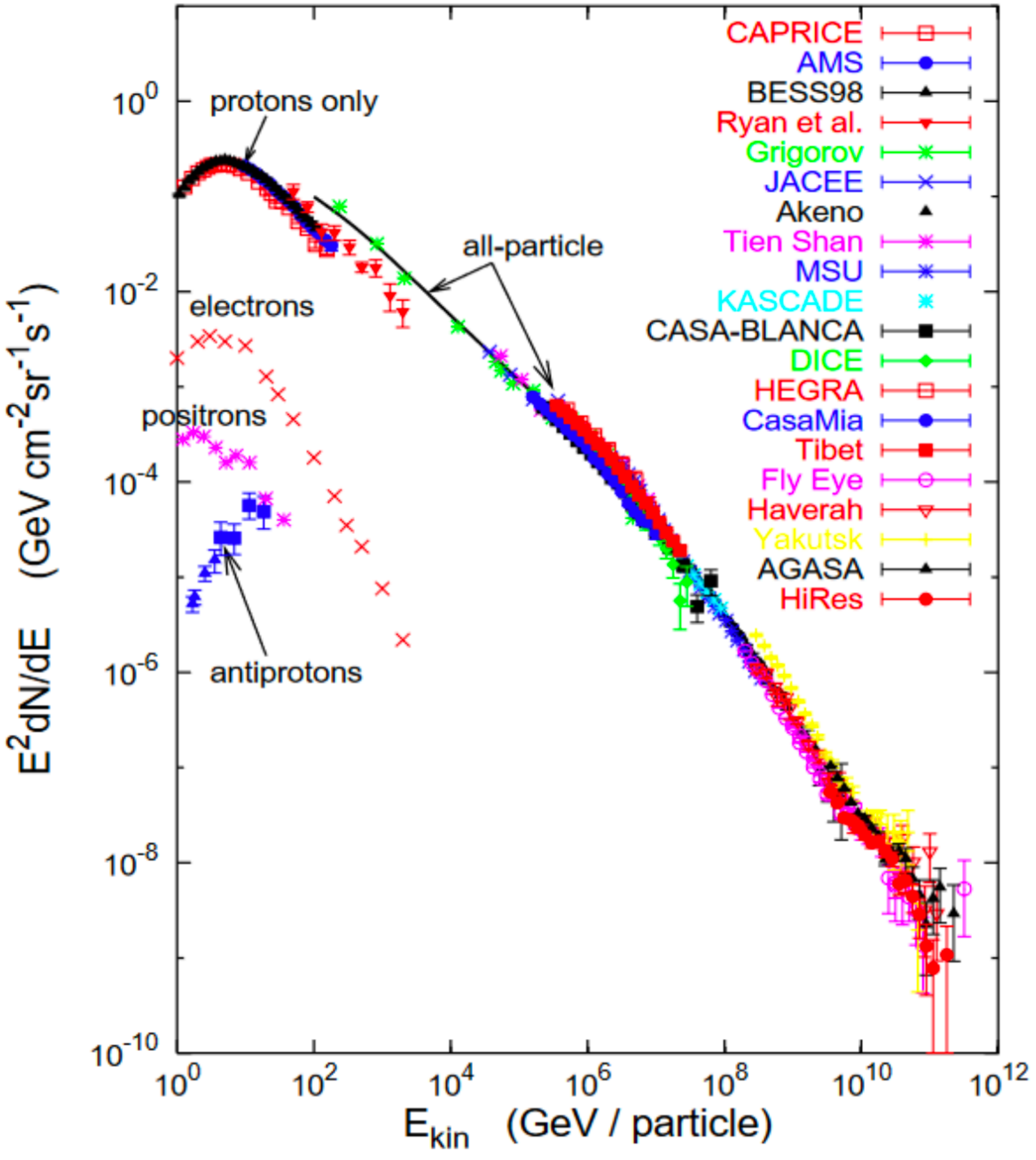



Assuming JUNO 170 kton·yr exposure

# Atmospheric beam dump and new physics

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



# 谢谢