Probing axion and new physics at muon collider

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October 14, 2024

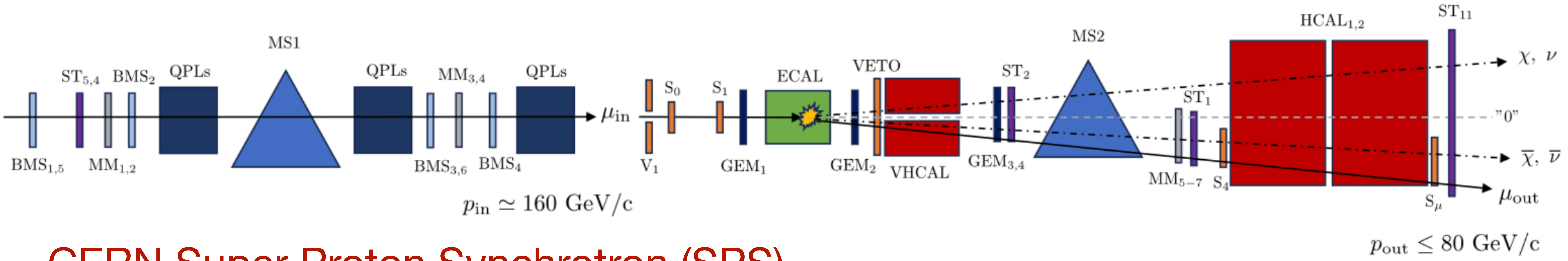
Why Muon Collider?

- Precise measurement ⇒ lepton collider
- Higher energy ⇒ hadron collider
- A balance between the two?

Low background and high energy muon collider

The NA64μ Experiment

2022 pilot run



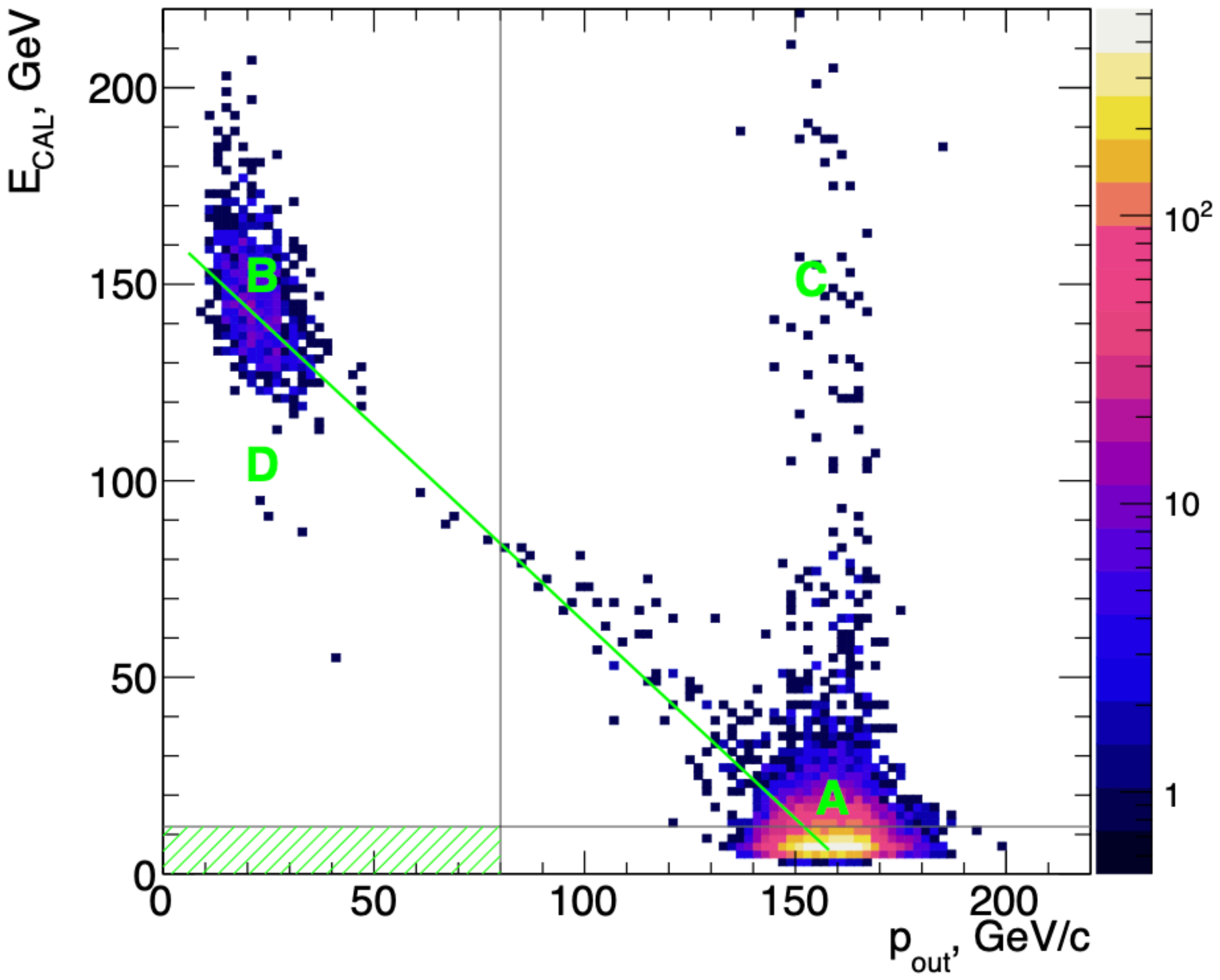
CERN Super Proton Synchrotron (SPS)

160 GeV muon beam

1.98×10^{10} muon on target

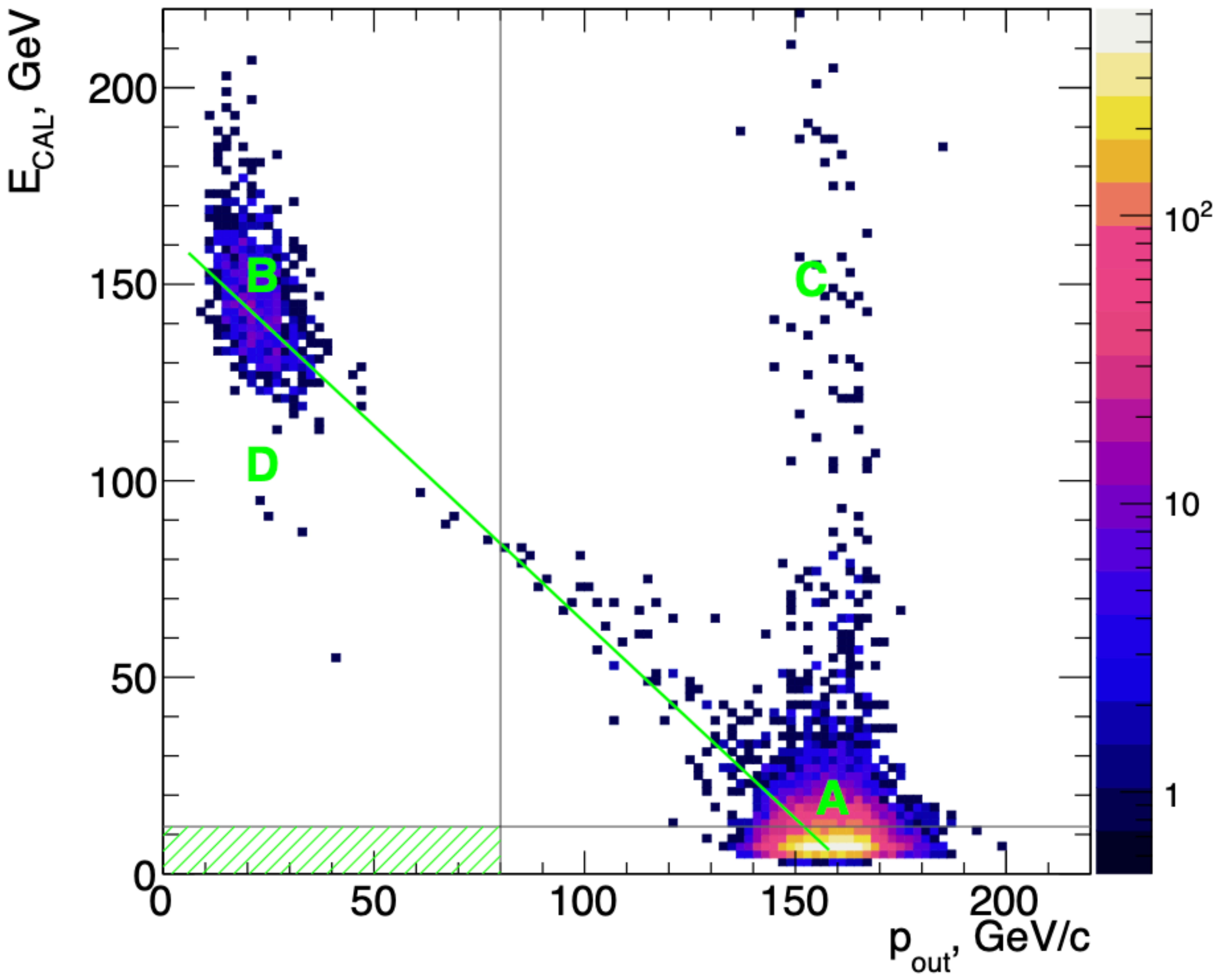
NA64 collaboration, PRL/2401.01708

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

Events at NA64μ



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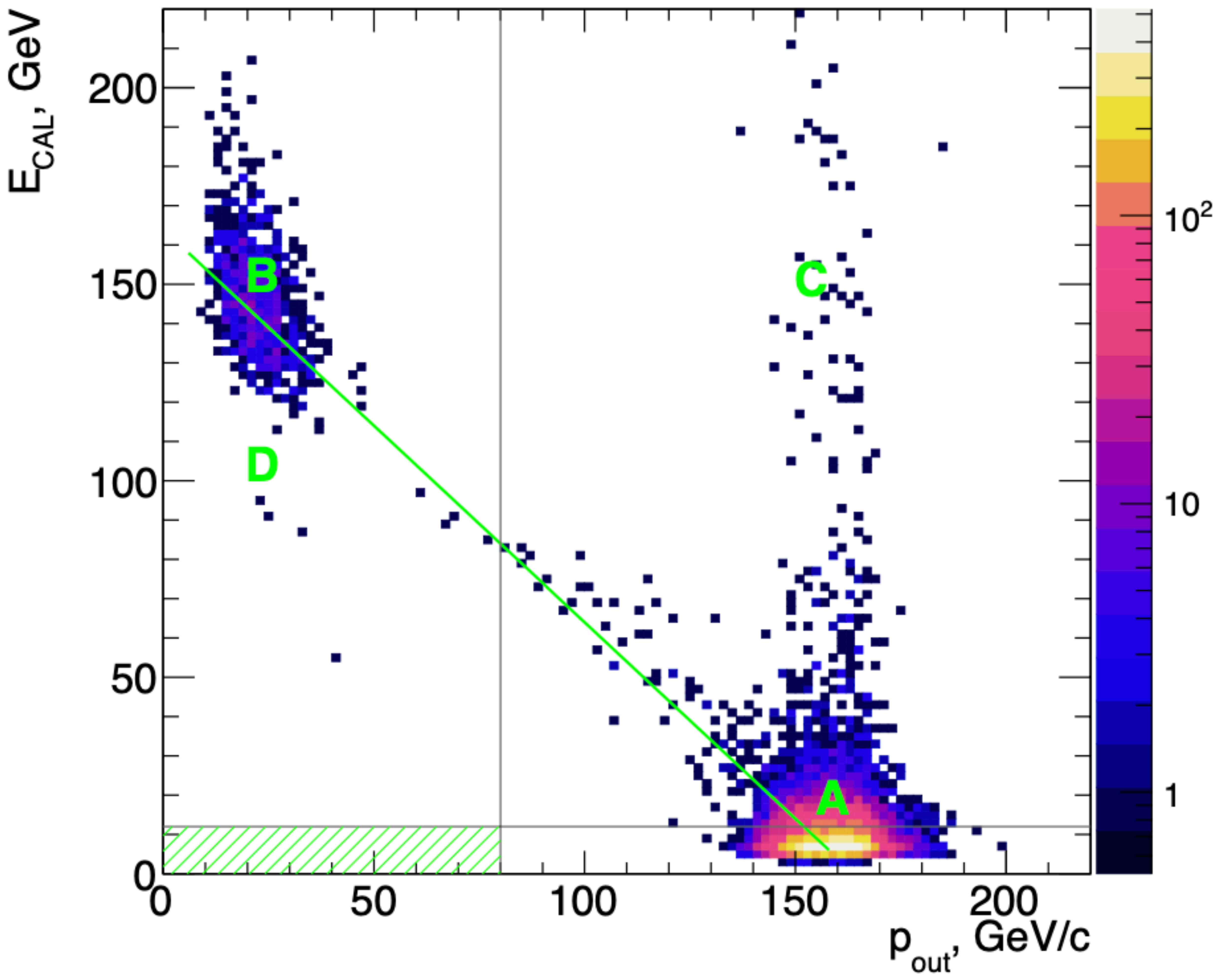

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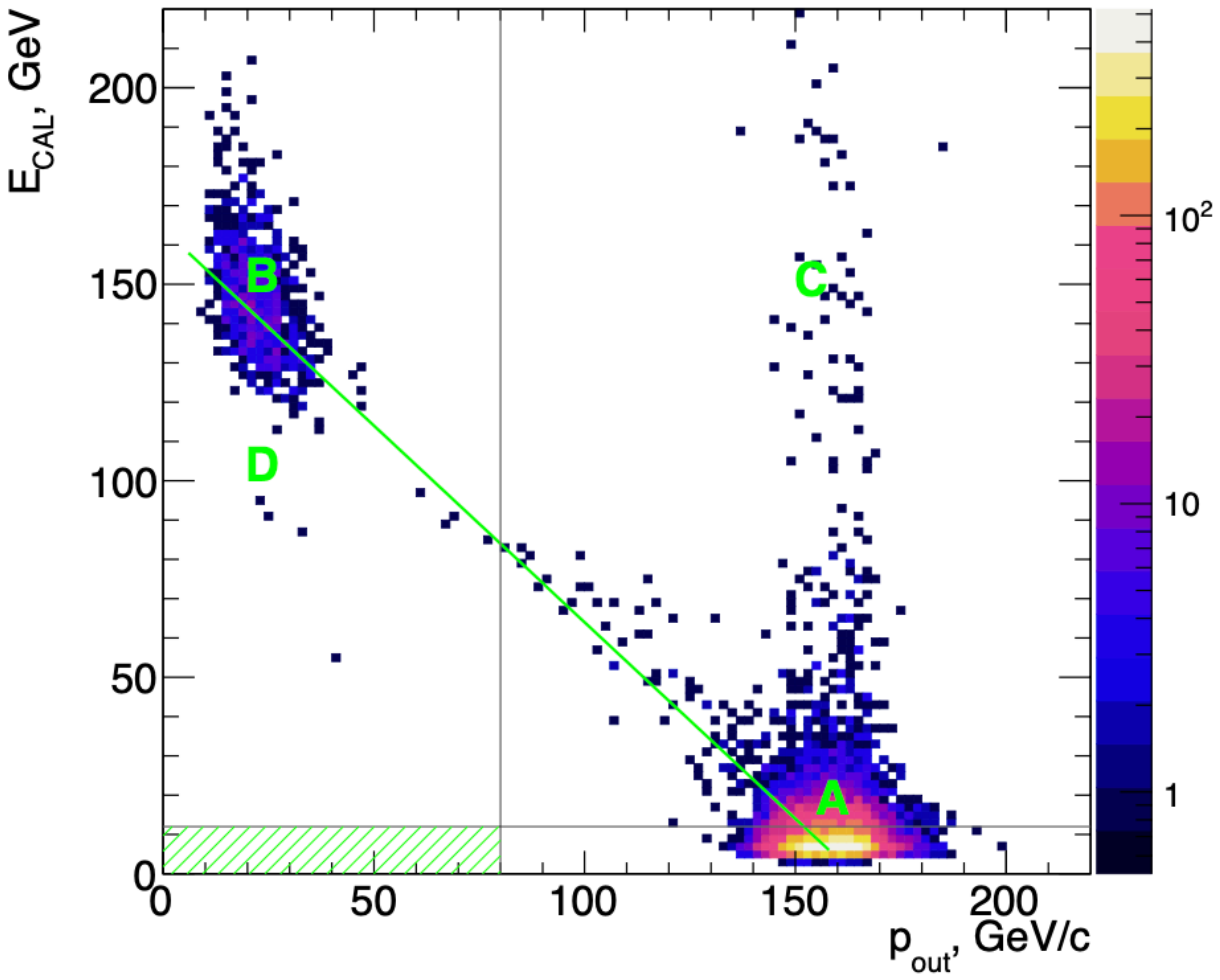

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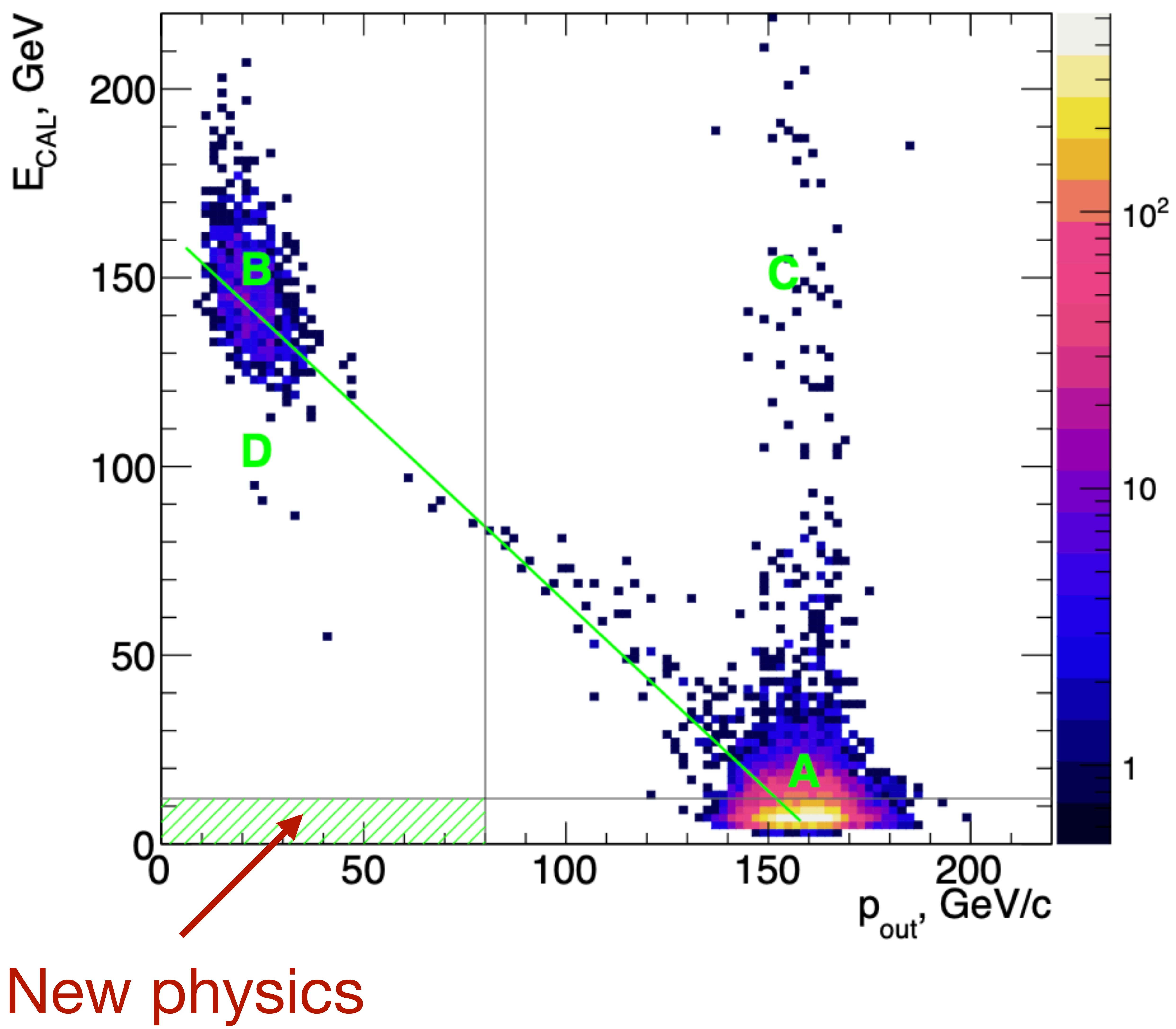

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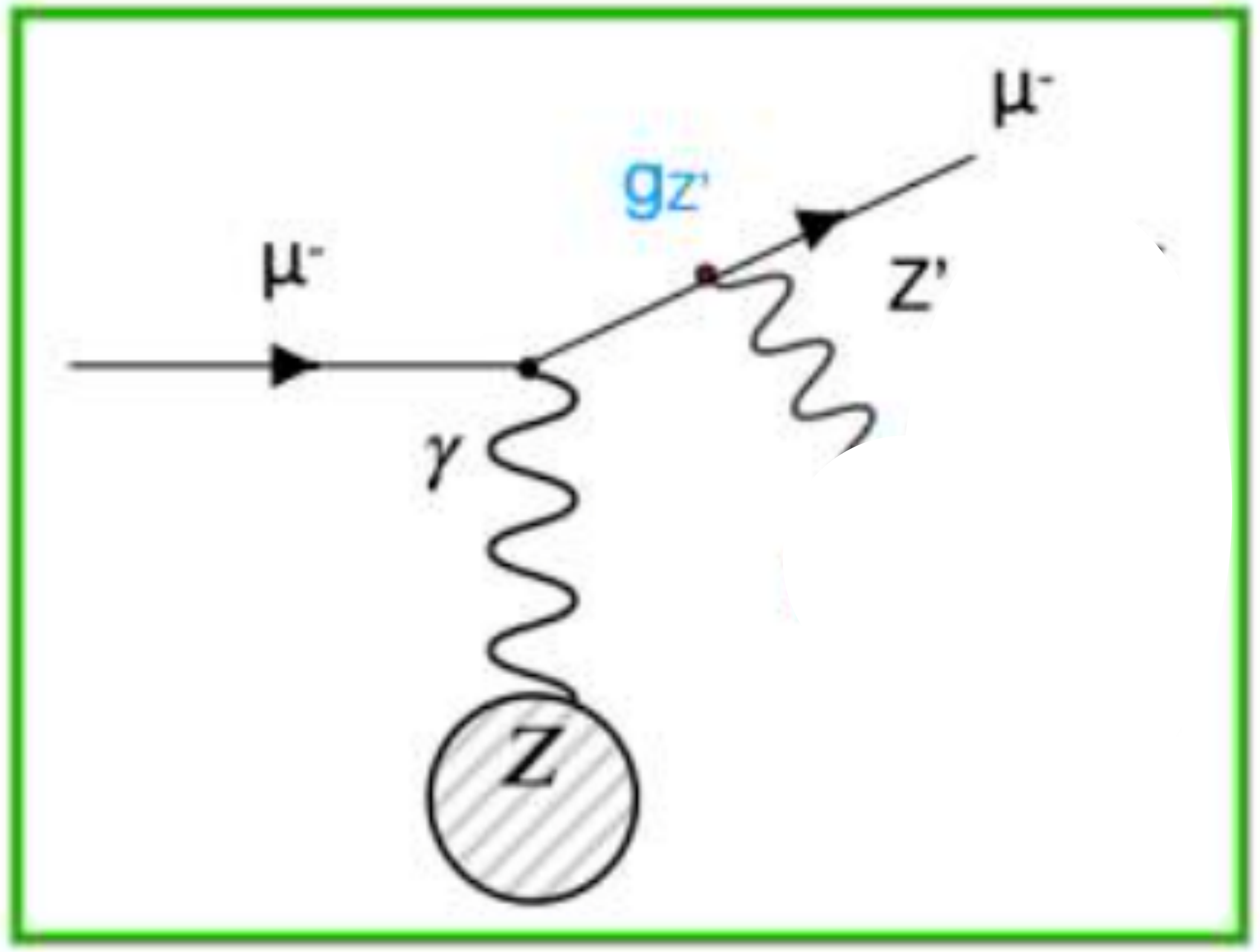
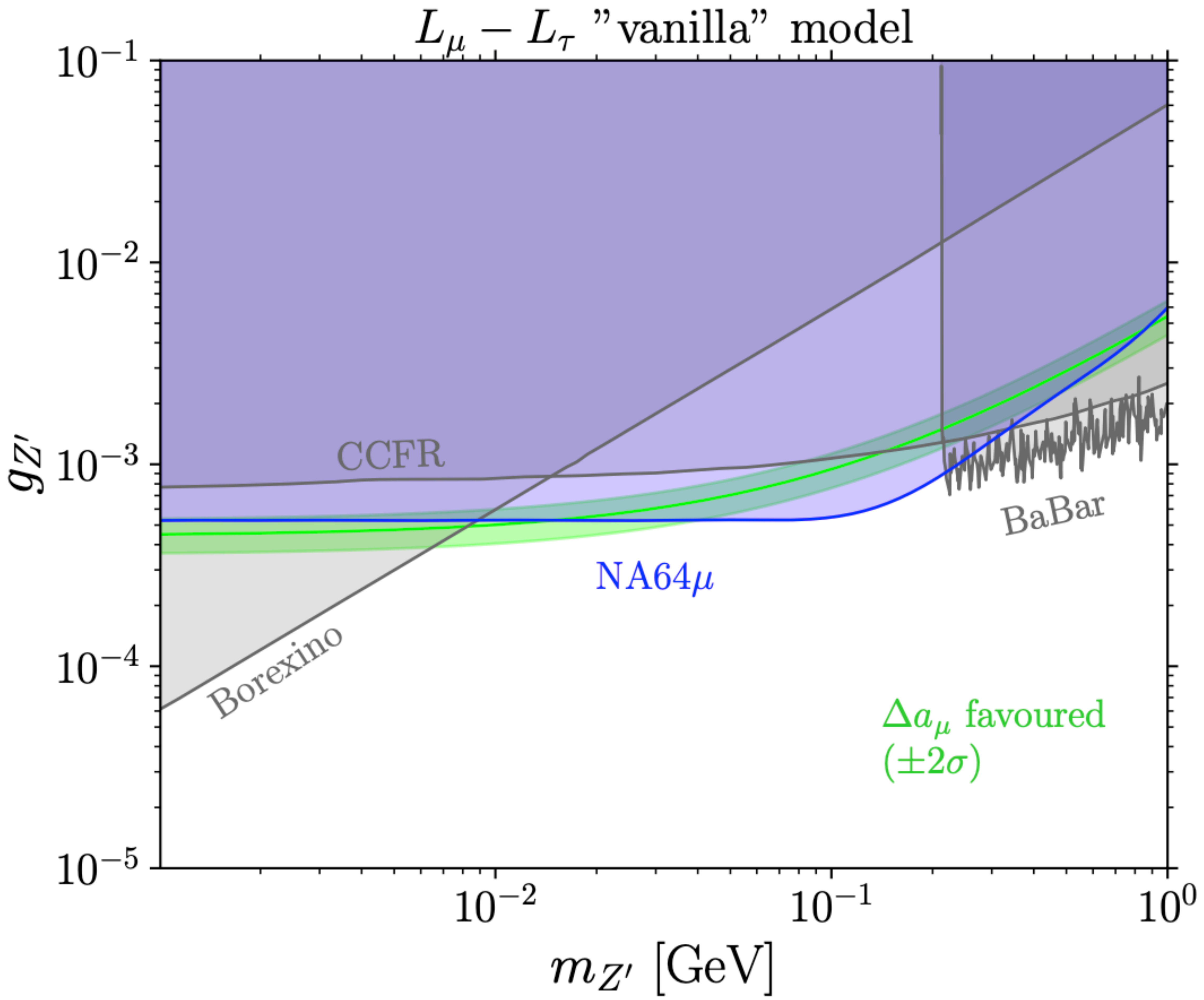
New Physics Search at NA64μ



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

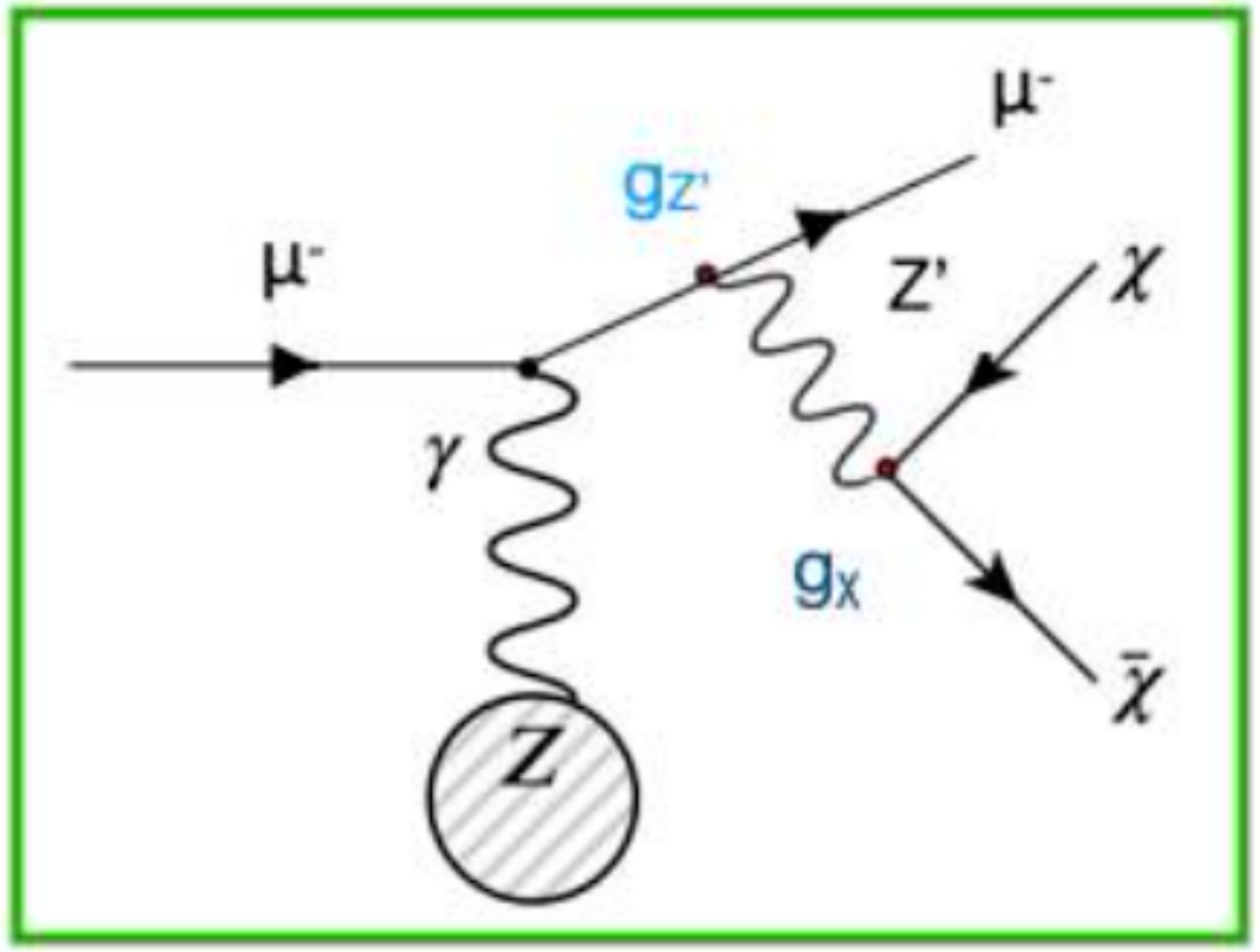
$Z' \to \mu\bar{\mu}$

Search for missing energy



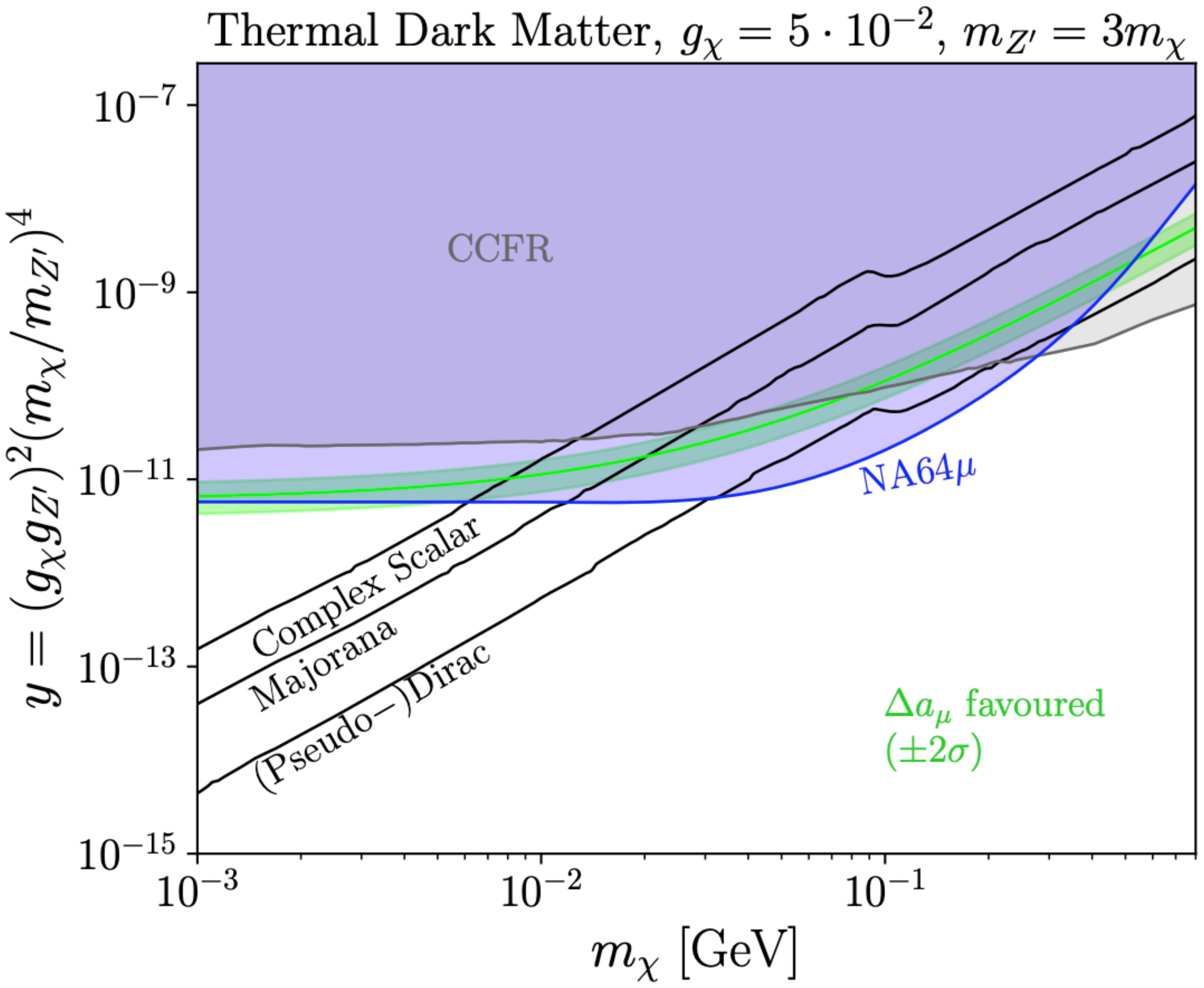
NA64 collaboration, PRL/2401.01708

New Physics Search at NA64μ



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

Search for missing energy

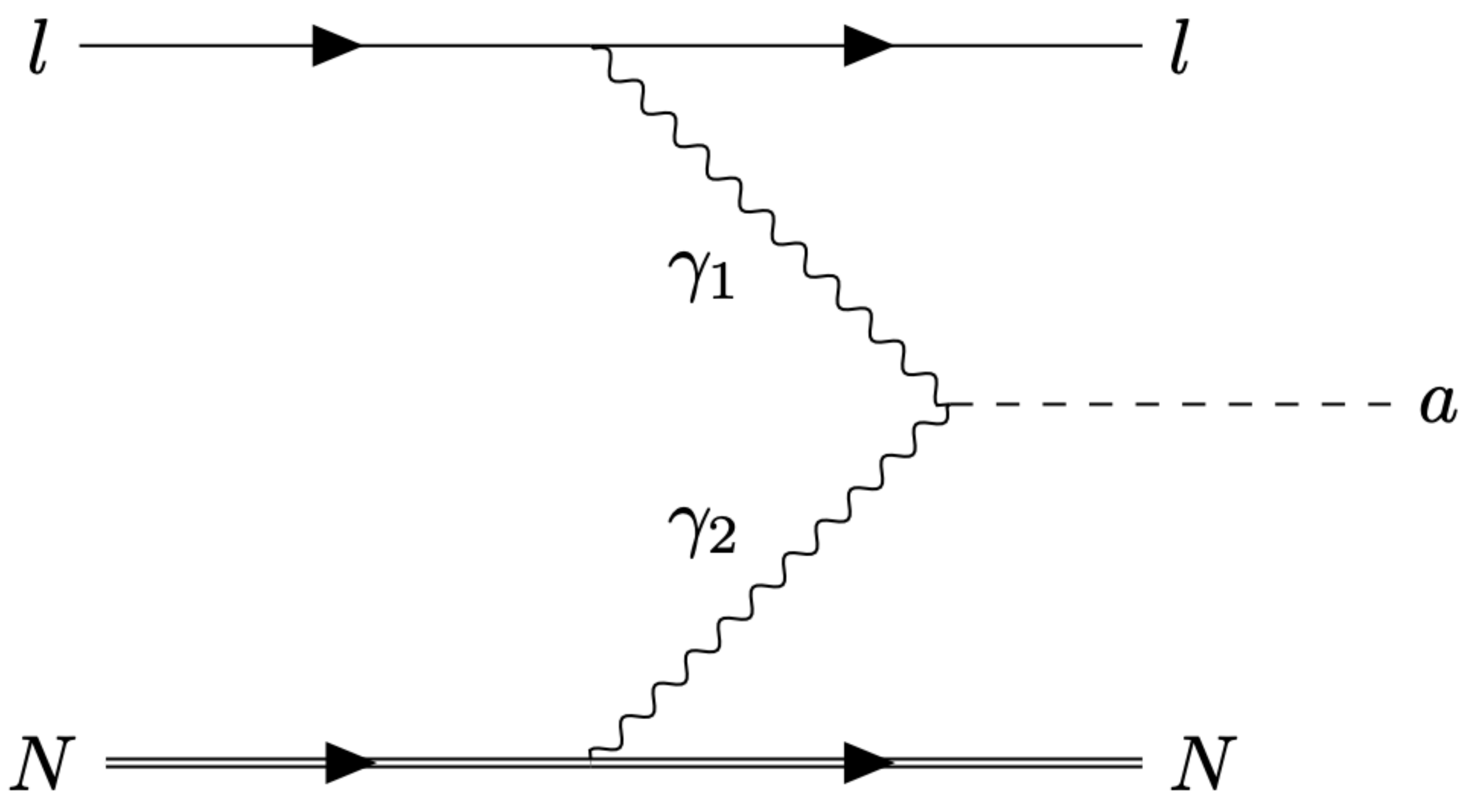


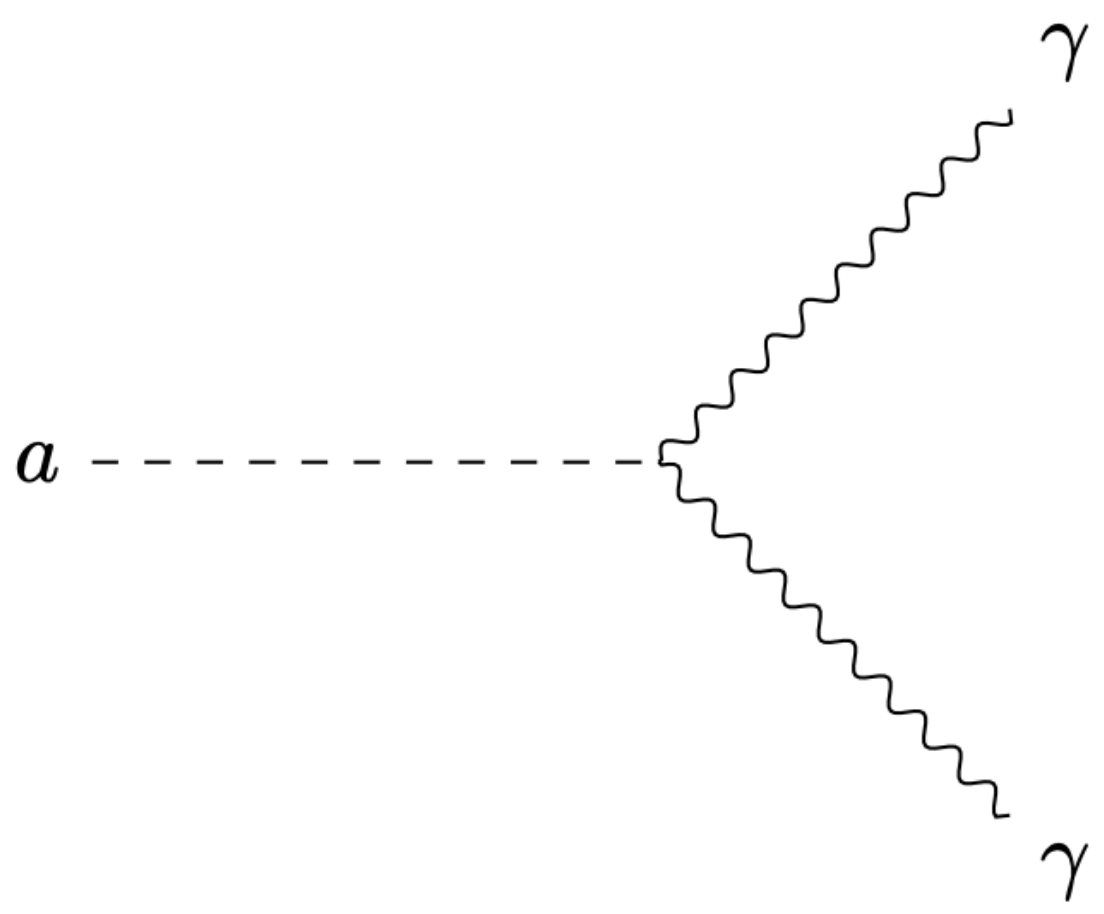
NA64 collaboration, PRL/2401.01708

What else?

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

Production Rate

Target length

Decay probability

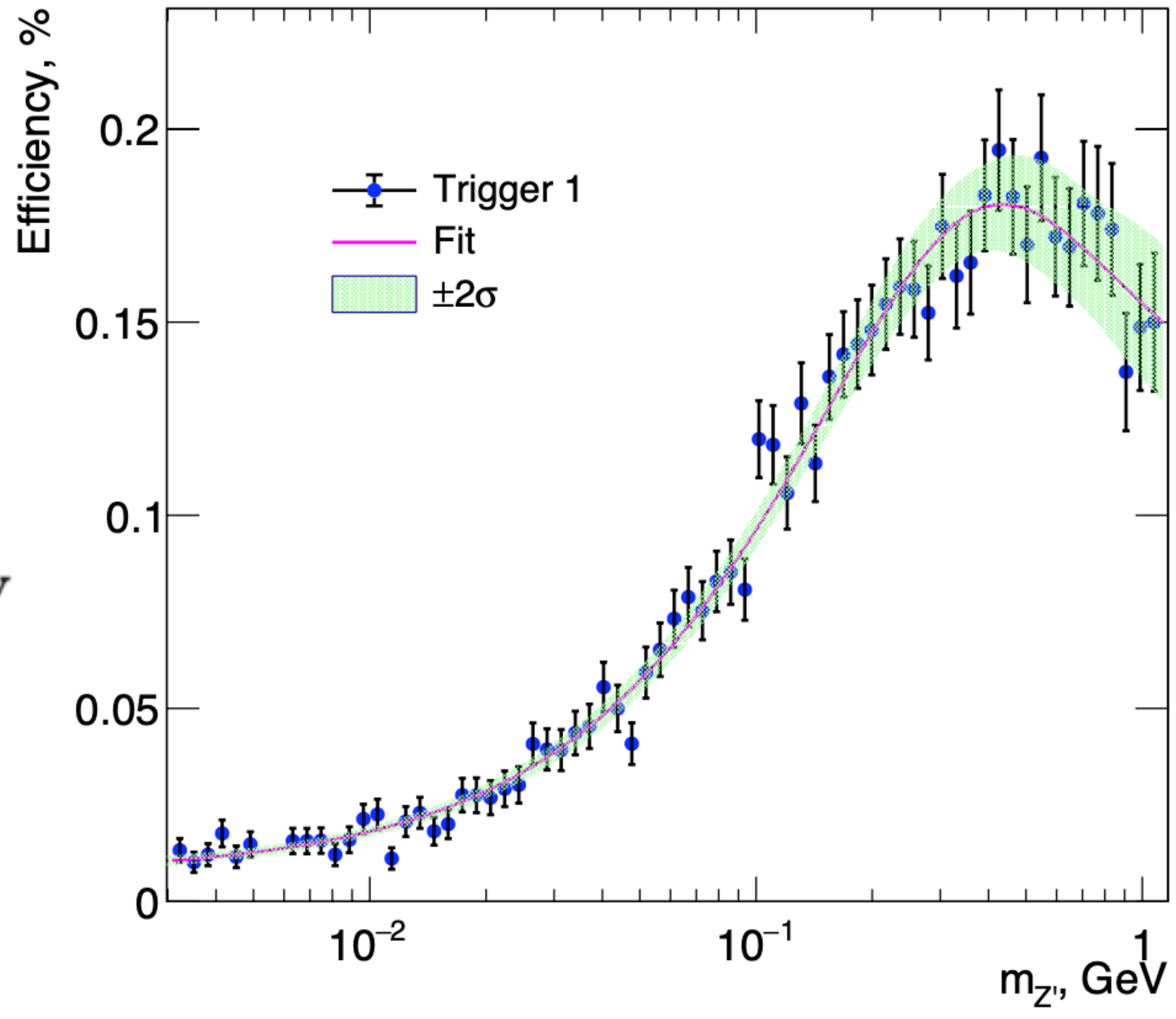
$$N_{\mathrm{signal}} = N_{\mathrm{MOT}} n_{\mathrm{Pb}} L_{\mathrm{tar}} \int d\sigma(\mu N \to \mu N X) \epsilon P_{\mathrm{inv}}$$

Muon on target
1.98×10^{10}

Scattering cross section

Efficiency

Pb target density



NA64 collaboration, 2409.10128

Cross Section

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

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

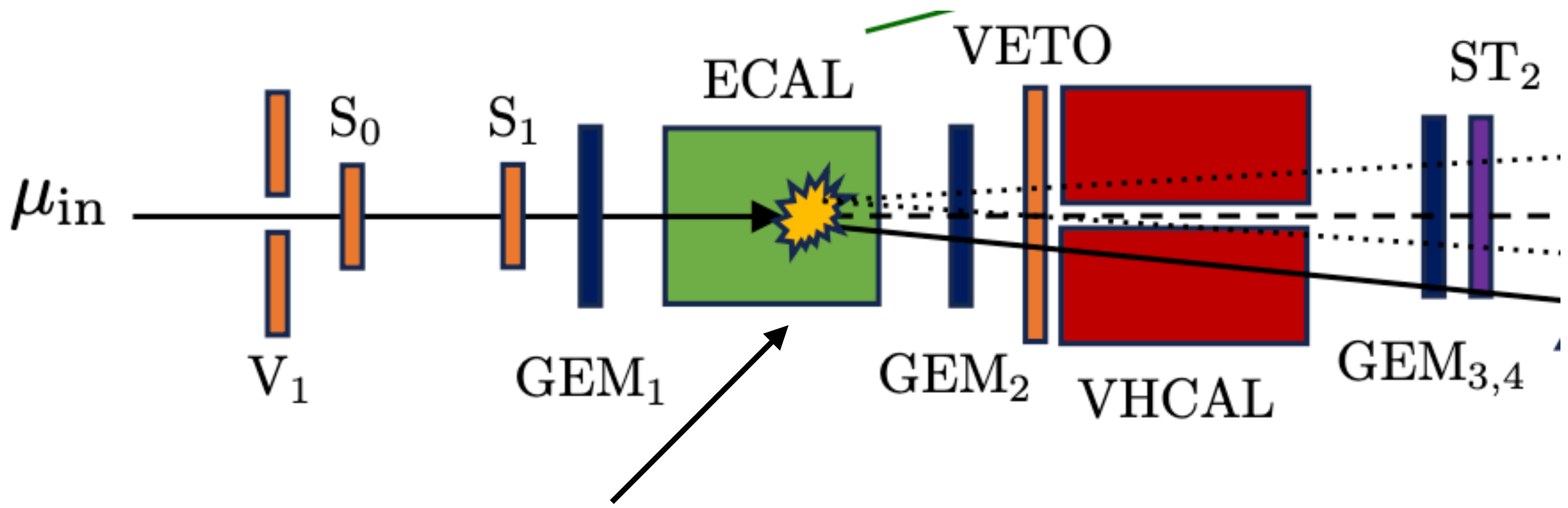
$$\chi = \int_{t_{\text{min}}}^{t_{\text{max}}} \mathrm{d}t \frac{t - t_{\text{min}}}{t^2} F^2(t)$$

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



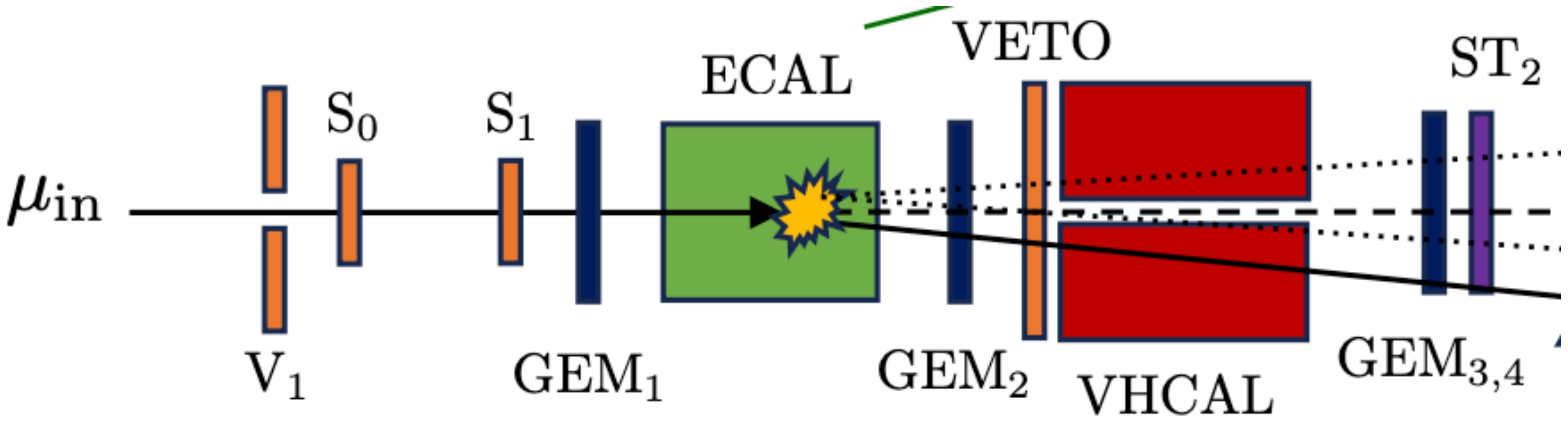
The target ECAL consists of 150 layers of Pb

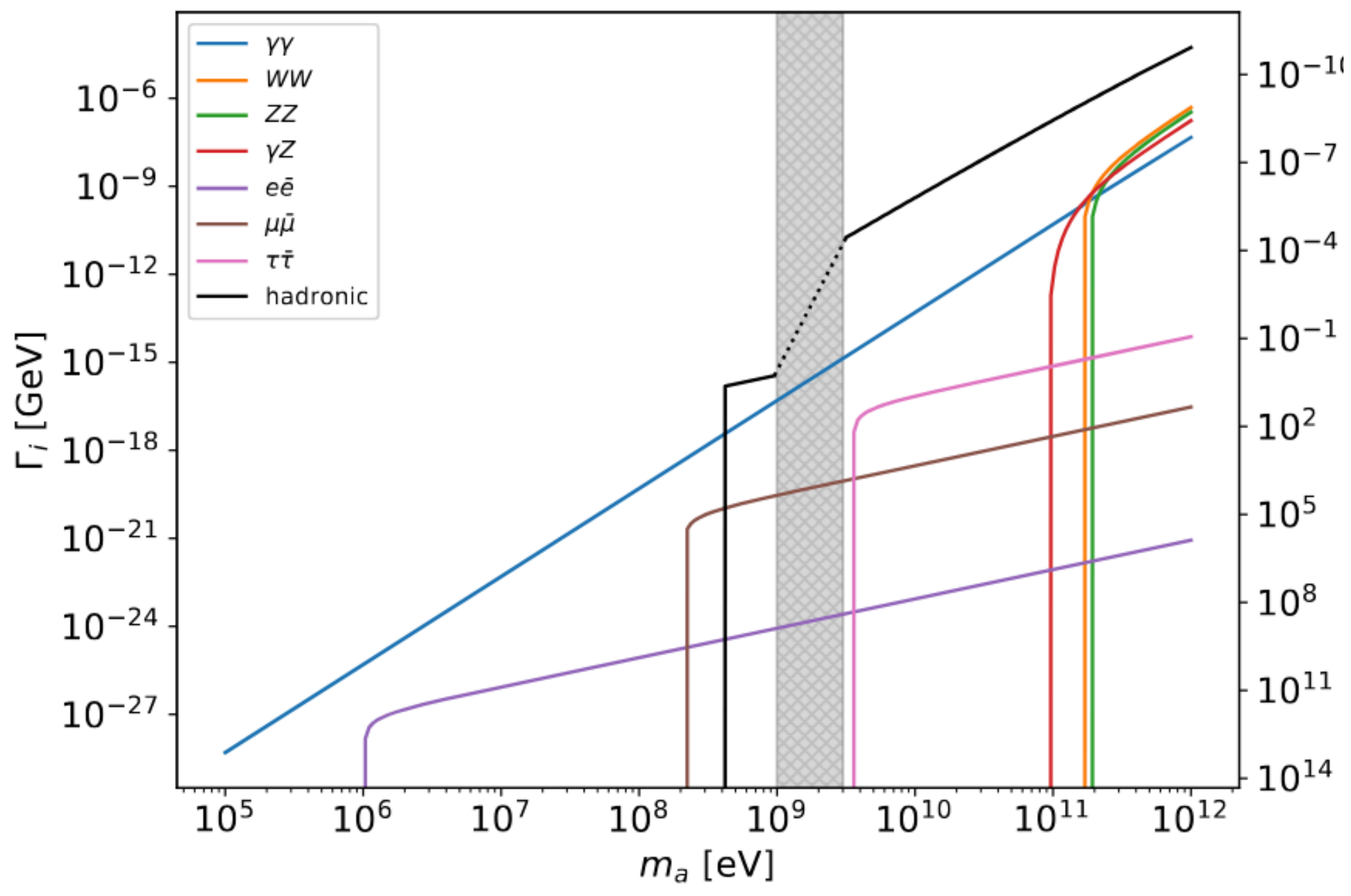
$$P_{\text{invisible}} = (\mathrm{e}^{-L_{\text{ECAL}}/l_a} - \mathrm{e}^{-L_V/l_a}) + (\mathrm{e}^{-(L_V + L_{\text{VHCAL}})/l_a} - \mathrm{e}^{-L_H/l_a}) + \mathrm{e}^{-(L_H + 2L_{\text{HCAL}})/l_a}$$

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

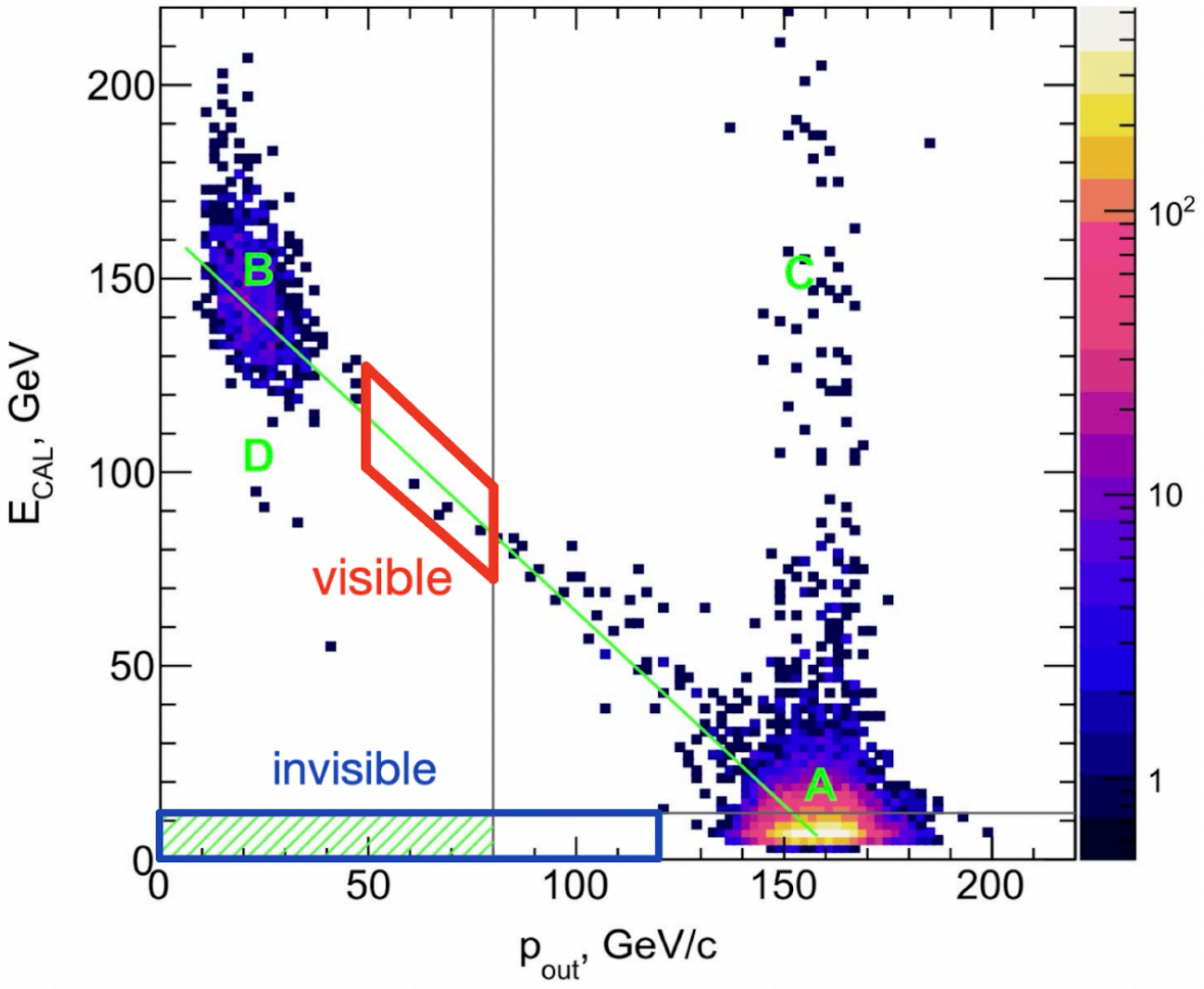
Average over the decay probability from axion production in each ECAL layer

Visible vs Invisible

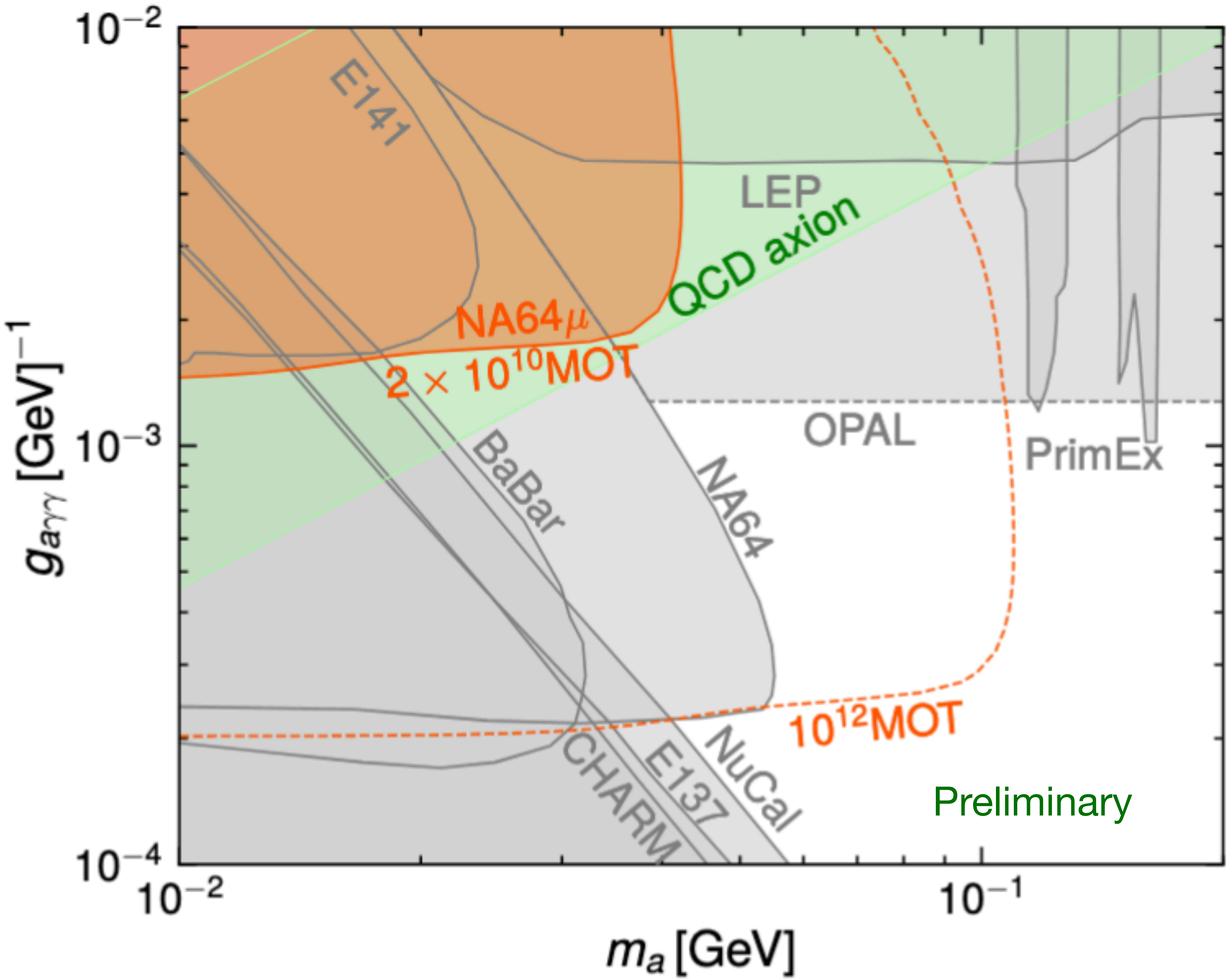




Alonso-Álvarez et al, EPJC/1811.05466

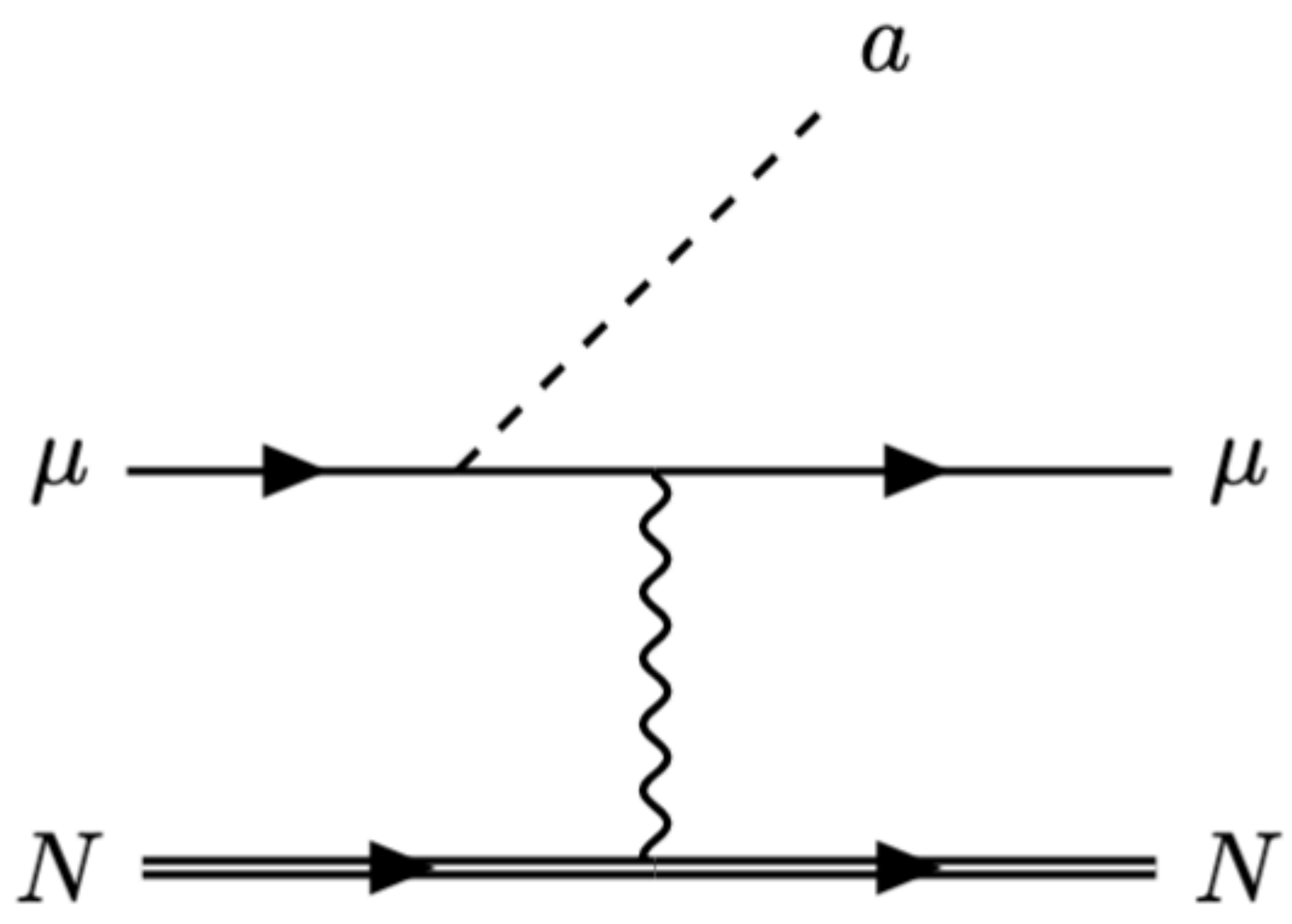


Constraints on Axion-Photon Interaction



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

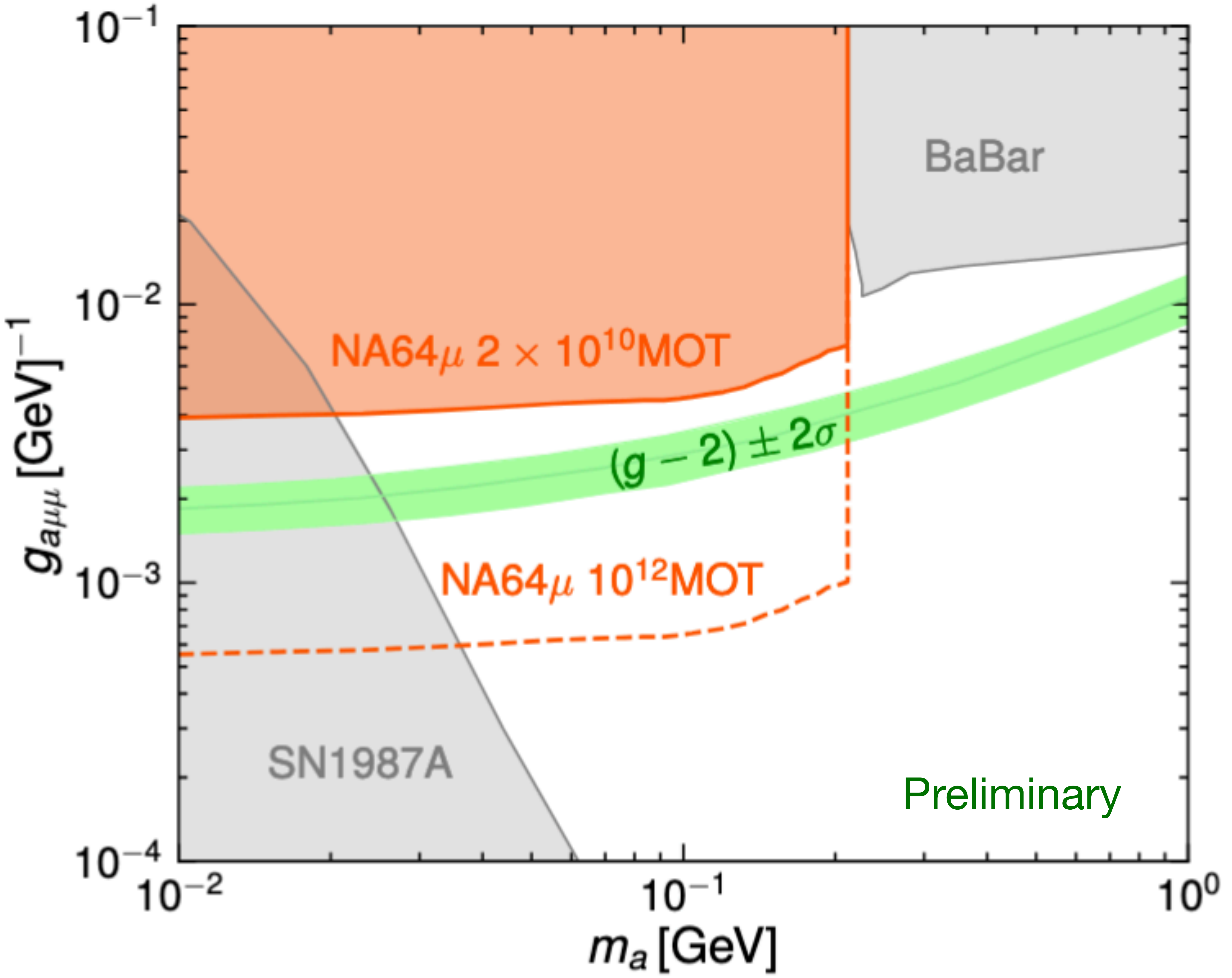
$$\chi = \int_{t_{\mathrm{min}}}^{t_{\mathrm{max}}} \mathrm{d}t \frac{t - t_{\mathrm{min}}}{t^2} F^2(t)$$

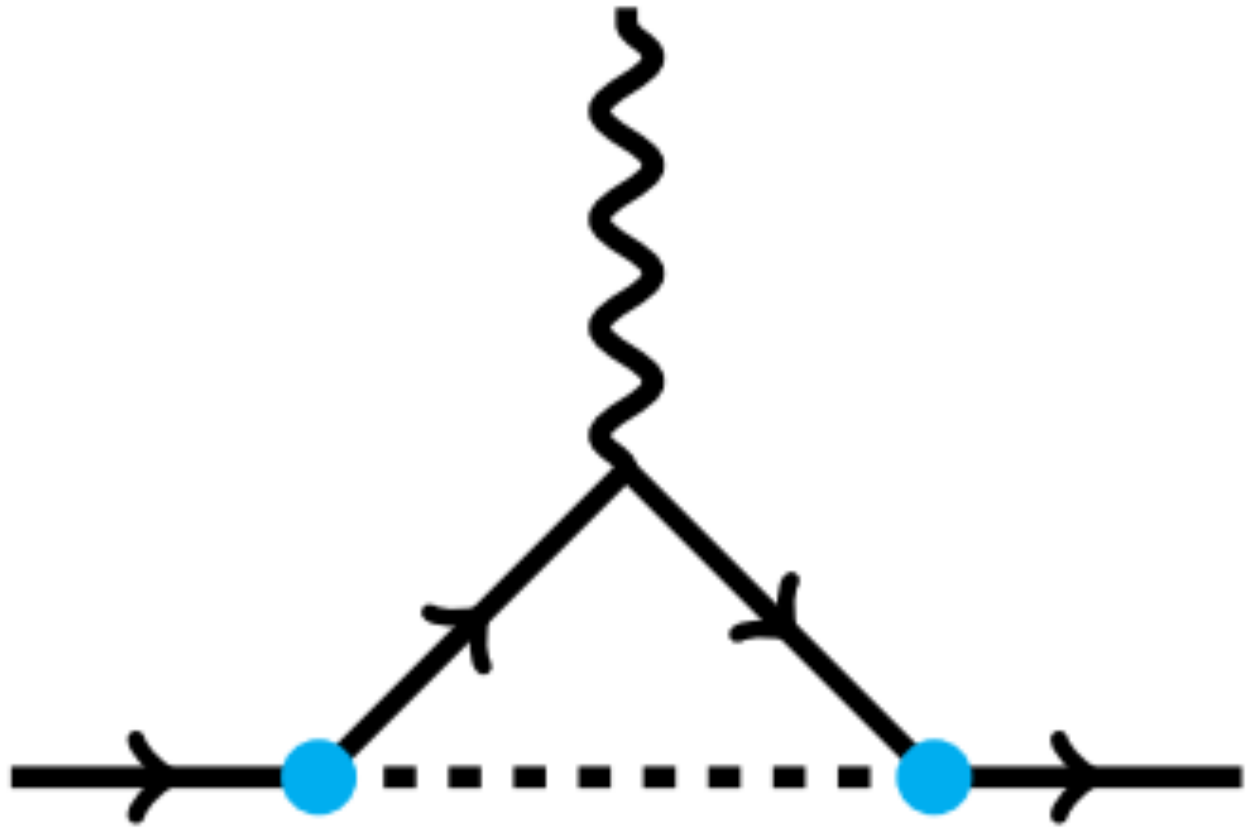
Nucleus elastic form factor

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

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

Constraints on Axion-Muon Interaction

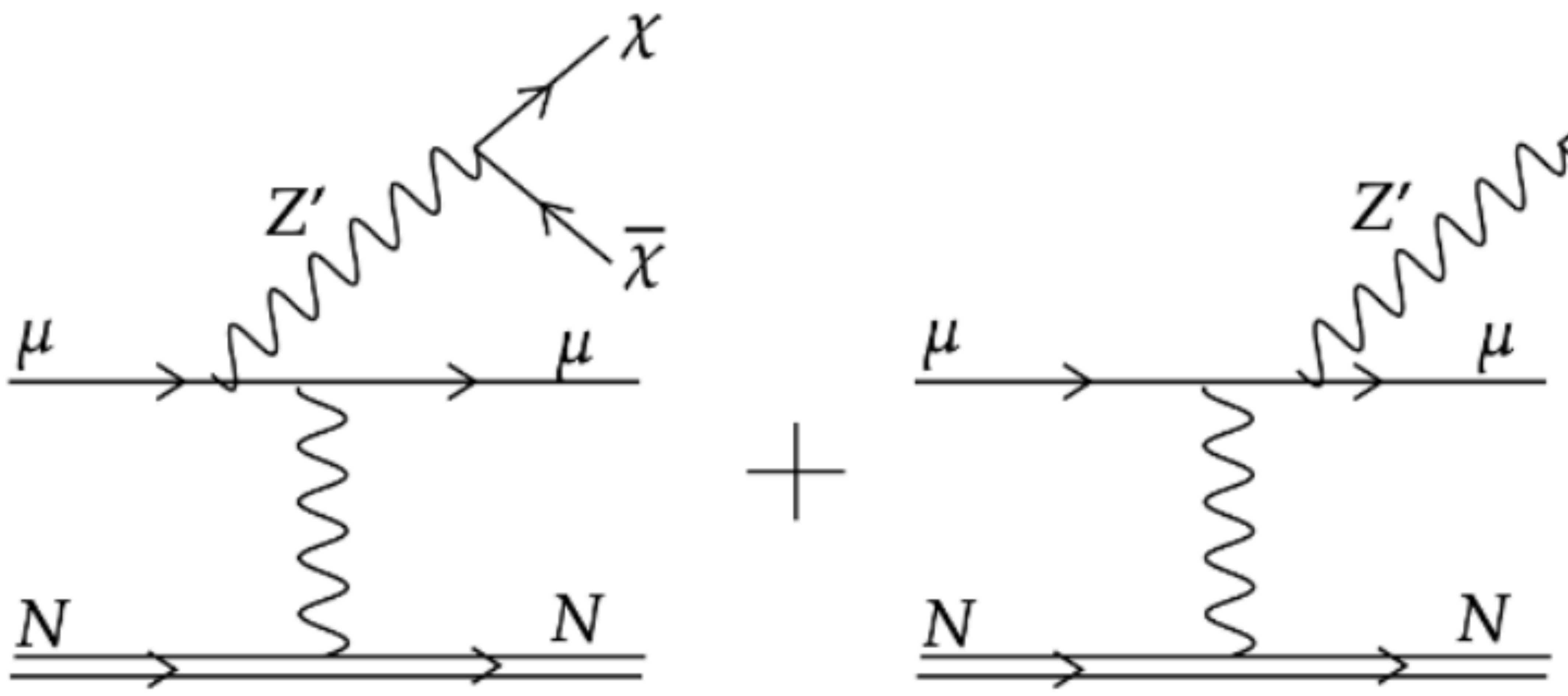




Buen-Abad et al, JHEP/2104.03267

Muonphilic Dark Sector

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



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

Cross Section

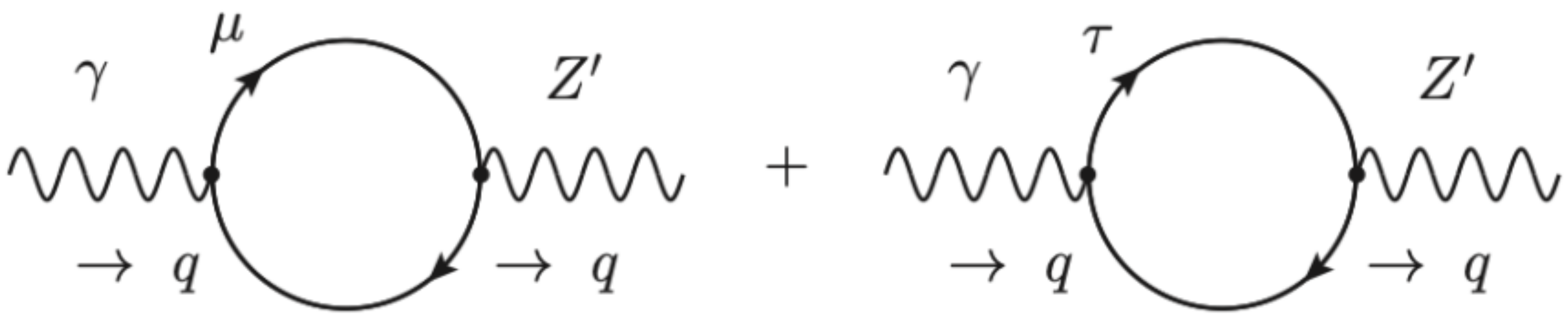
$$N_{\text{signal}} = N_{\text{MOT}} n_{\text{Pb}} L_{\text{tar}} \int d\sigma(\mu N \to \mu N X) \epsilon P_{\text{inv}}$$

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

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

Muophilic Millicharge?

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

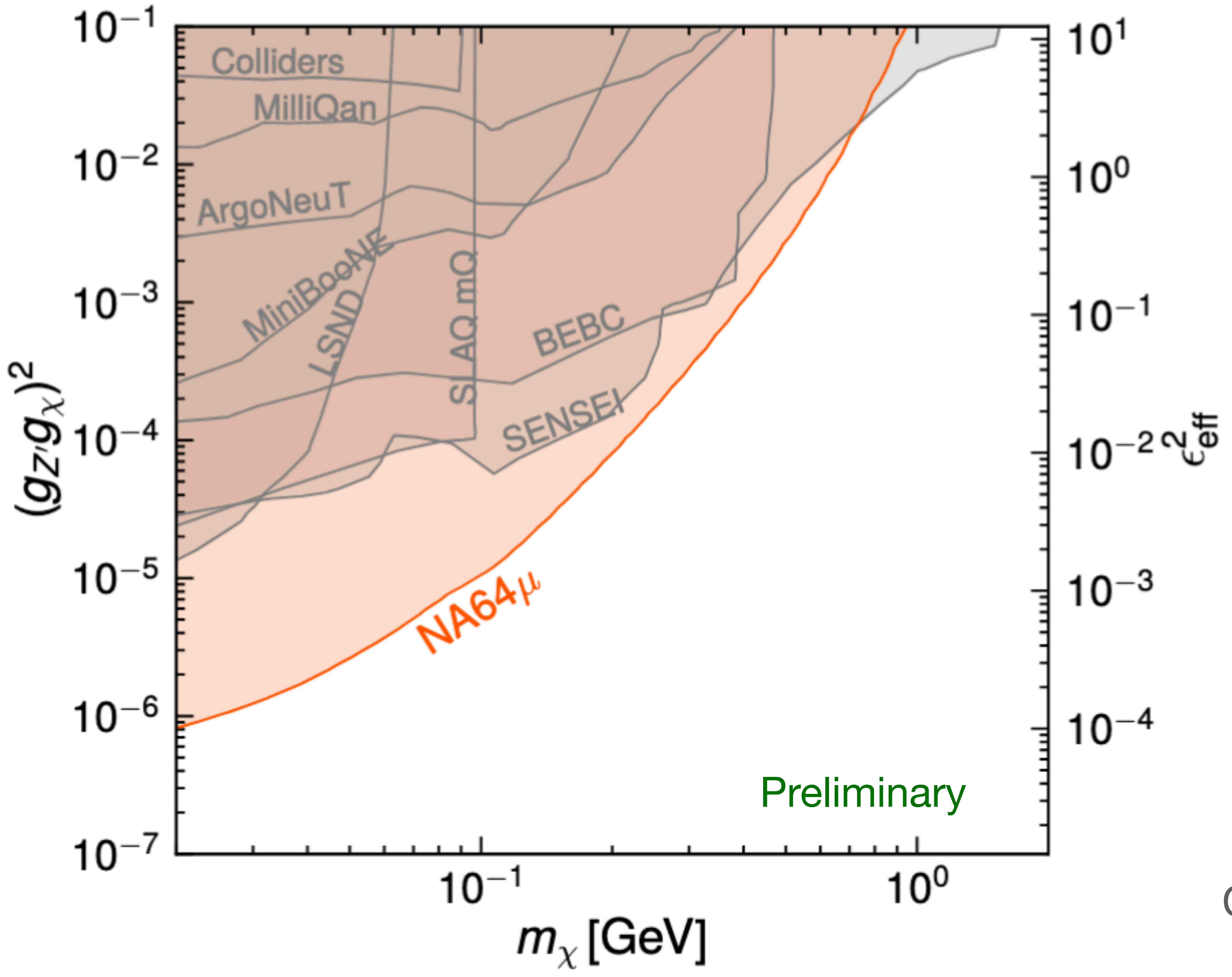


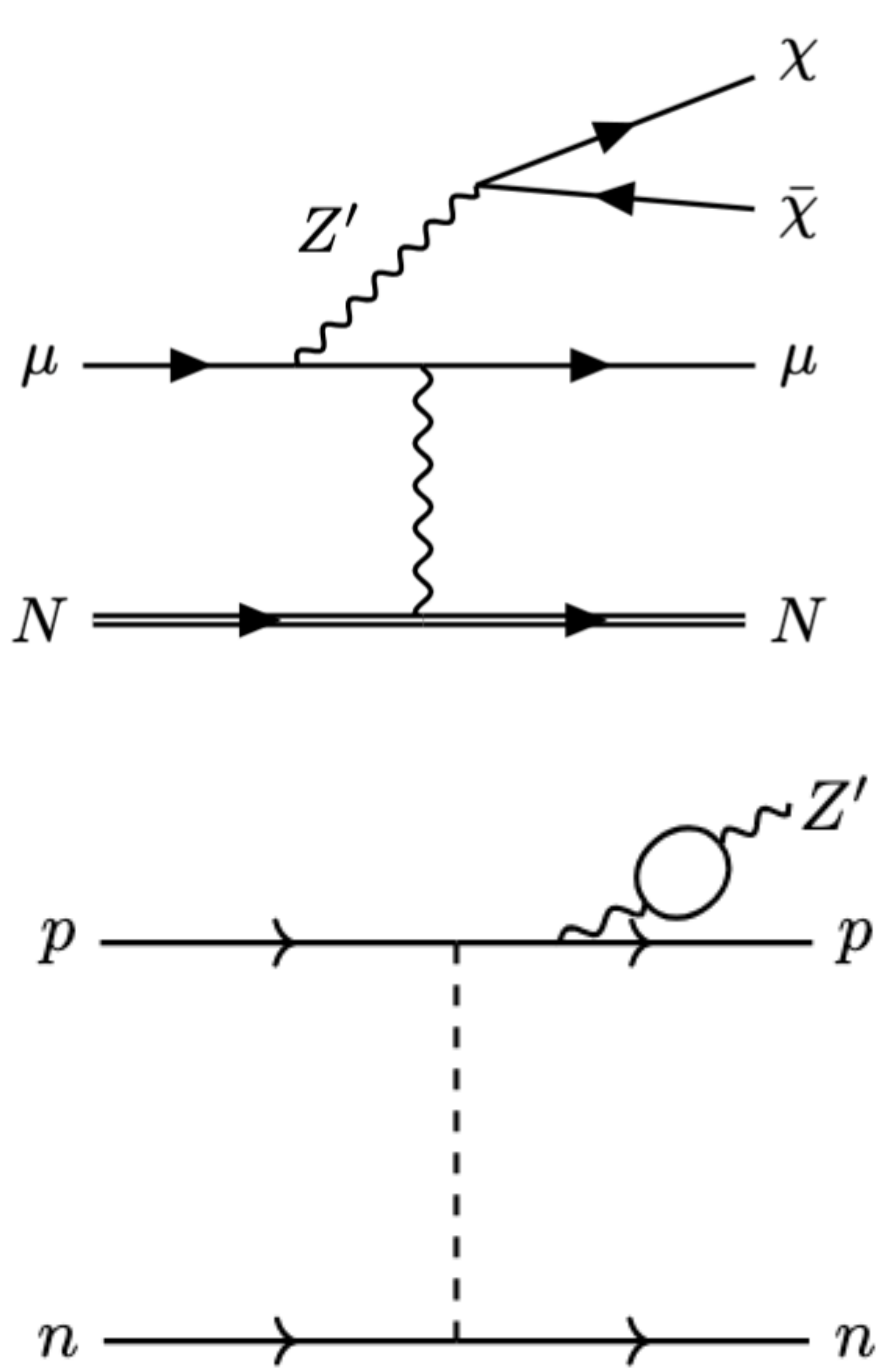
$$\mathcal{L}_{\mathrm{kin}} \supset \frac{\Pi(q^2)}{2} Z'_{\mu\nu}F^{\mu\nu}$$

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

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

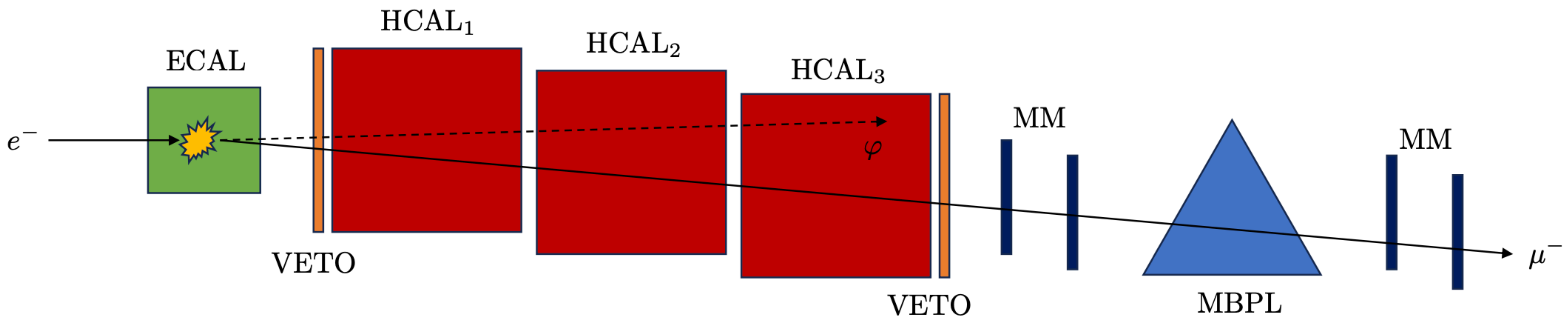
Constraints on Muonphilic Dark Sector





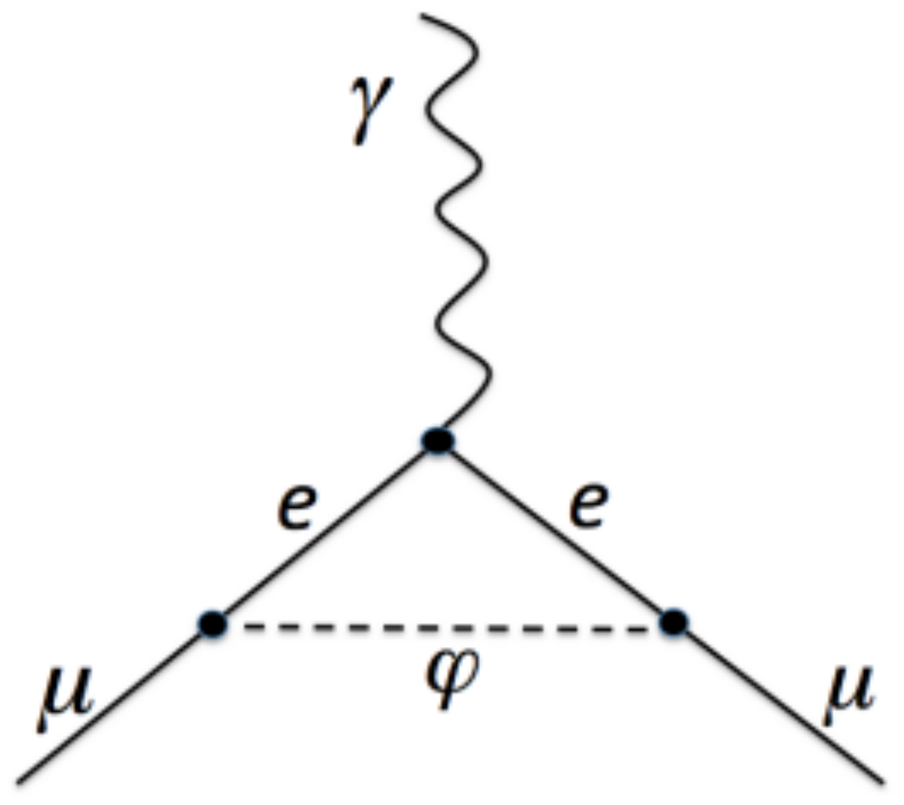
Croon et al, JHEP/2006.13942

Flavor Changing Scalar?



$$L_{\rm int} = -h\bar{e}P_R\mu\varphi + h.c.$$

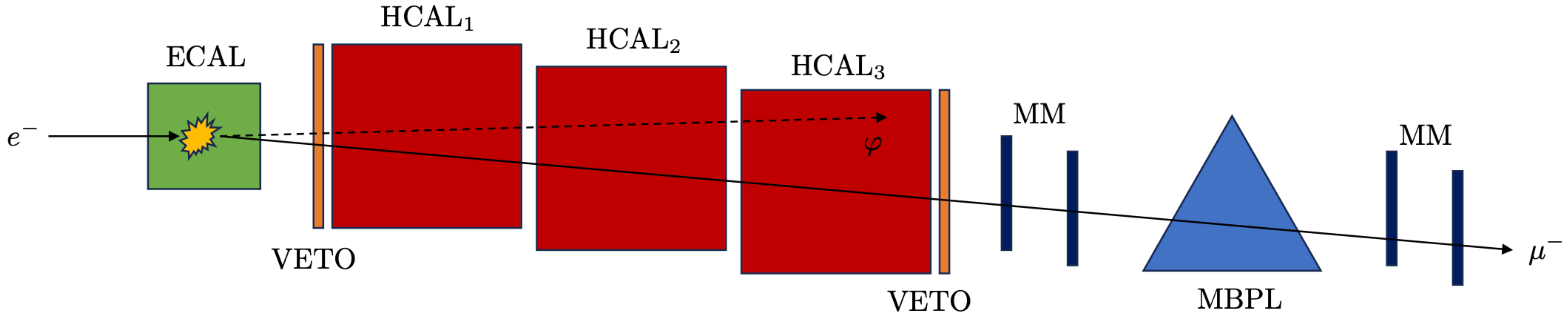
$$\left(\frac{d^2\sigma}{d\cos\psi dy}\right)_{\rm WW} = \frac{\alpha^2 h^2}{2\pi}E_i^2\beta_f\chi^{\rm WW}(1-y)^3 \times\left(\frac{1}{2\tilde{t}^2} - \frac{\Delta m^2}{\tilde{t}^3} + \frac{\Delta m^2[m_f^2 + y(m_i^2 y + \Delta m^2)]}{y\tilde{t}^4}\right)$$



Ponten et al, 2404.15931

Gninenko et al, PRD/2202.04410

Flavor Changing Scalar?



Flavor changing interaction $\mu \to \tau + \varphi$

τ decays to μ promptly in ECAL

Summary

- Muon collider as a good option for precise measurement at high energies
- Search for New Physics at NA64μ
  - New gauge boson
  - Axion-photon interaction
  - Axion-muon interaction
  - Muonphilic dark sector
  - Flavor changing scalar

Thanks

Back up

Millicharge Particles from Proton Bremsstrahlung

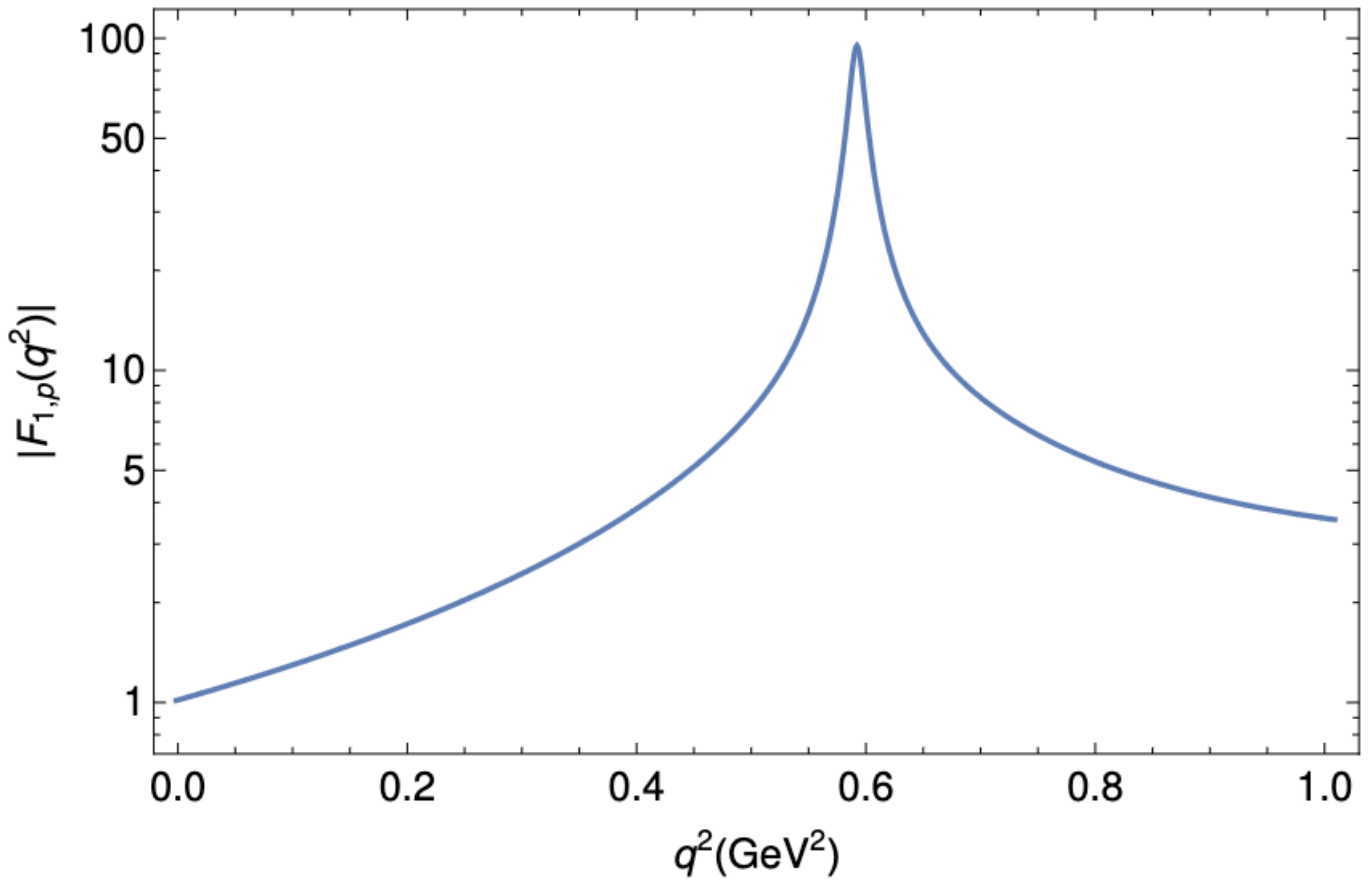
Fermi-Weizsacker-Williams (FWW) approximation with the splitting-kernel approach

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

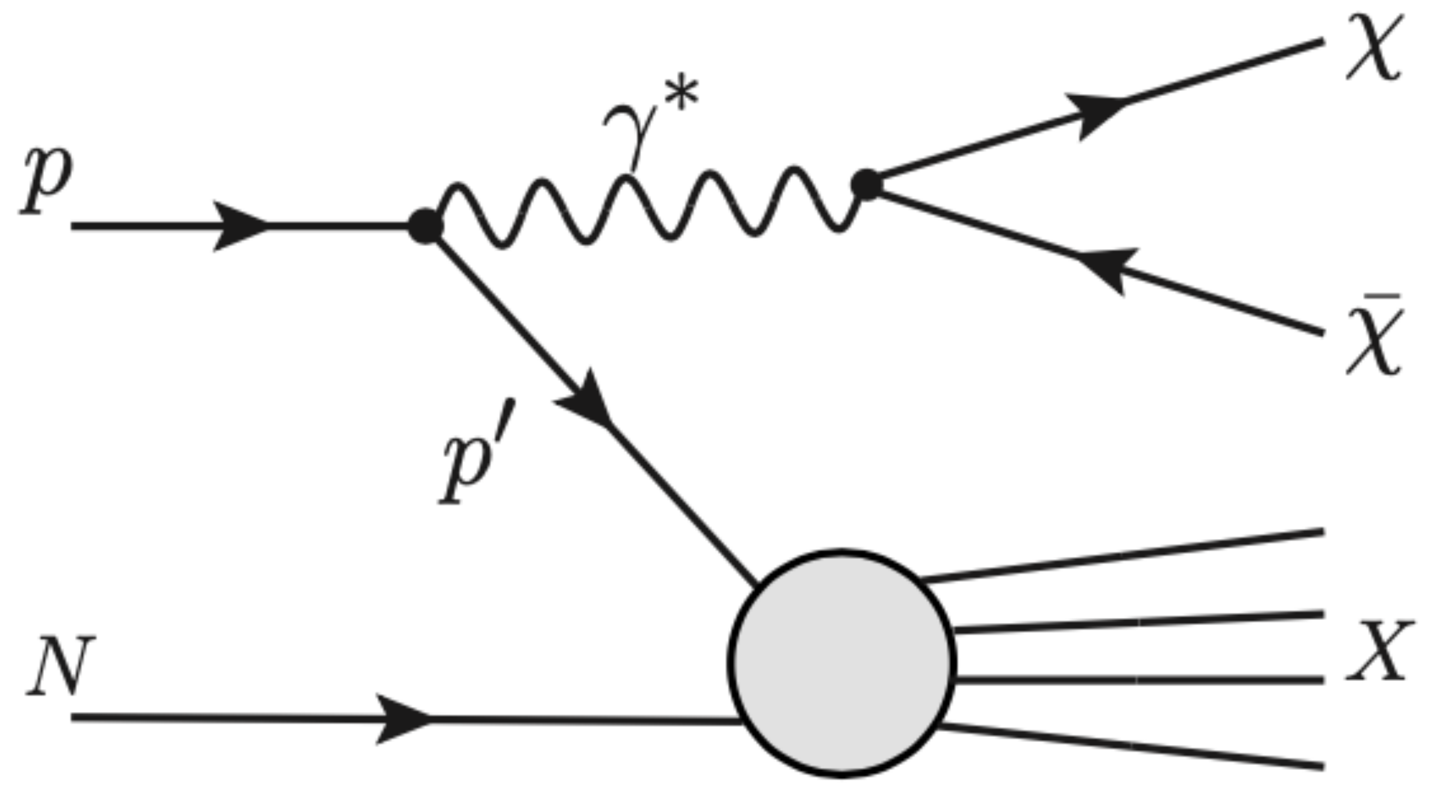
$$\frac{d^2\mathcal{P}^{\mathrm{FWW}}_{p\to\gamma^*p}}{dE_k\, d\cos\theta_k} = \left|\mathbf{J}(z,p_T^2)\right| \frac{d^2\mathcal{P}^{\mathrm{FWW}}_{p\to\gamma^*p}}{dz\, dp_T^2} = \left|\mathbf{J}(z,p_T^2)\right| \left|F_V(k)\right|^2 \omega(z,p_T^2)$$

Kernel

EM form factor



deNiverville et al PRD/1609.01770



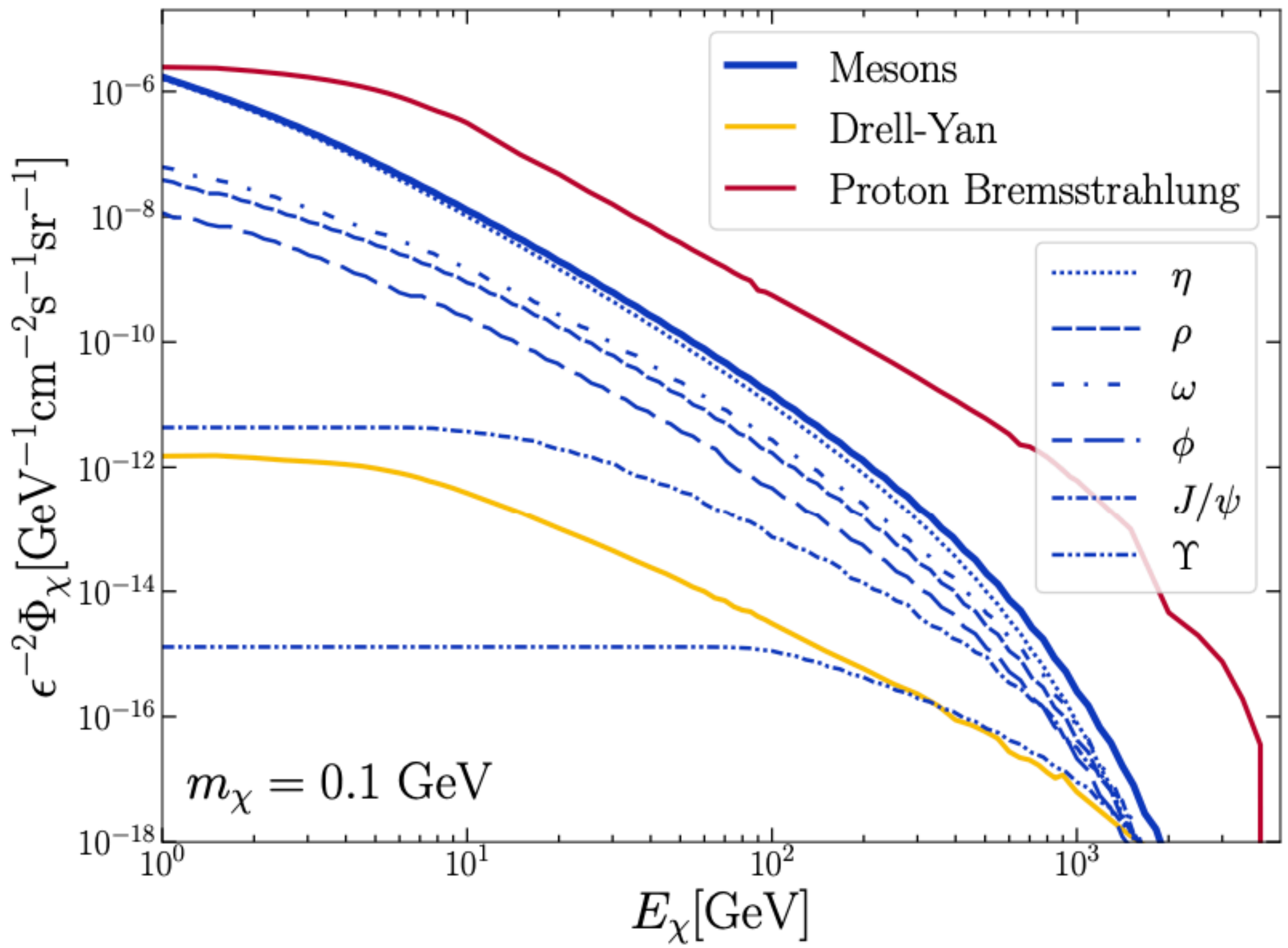
$$\Phi_\chi^{\mathrm{PB}} = \int dE_p \Phi_p \frac{\epsilon^2 e^2}{6\pi^2} \int \frac{dk^2}{k^2} \sqrt{1 - \frac{4m_\chi^2}{k^2}} \left(1 + \frac{2m_\chi^2}{k^2}\right)$$
$$\times \int dE_k \frac{1}{\sigma_{pN}} \frac{d\sigma^{\mathrm{PB}}}{dE_k} \frac{\Theta(E_\chi - E_{\min})\Theta(E_{\max} - E_\chi)}{E_{\max}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

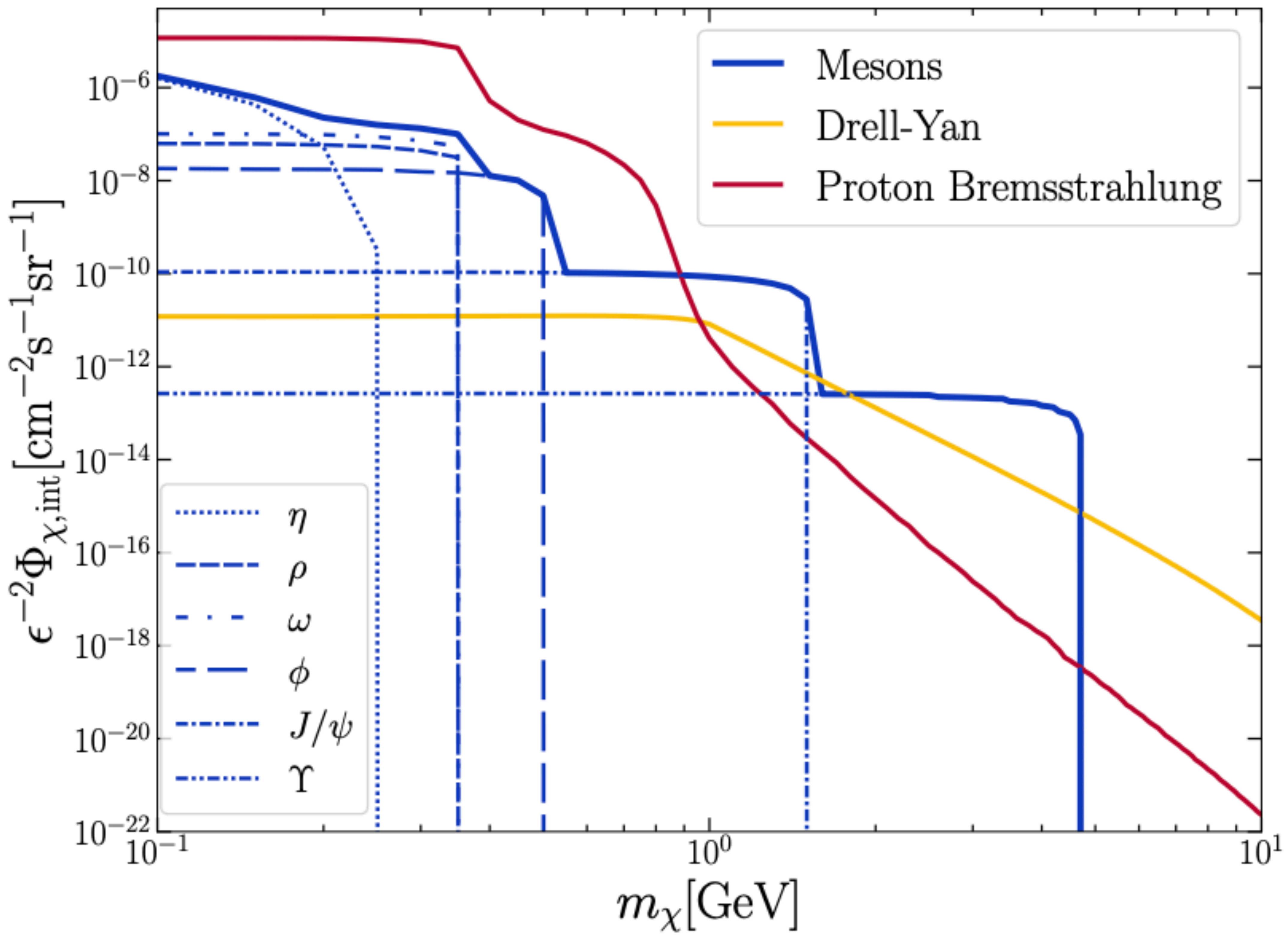
Du et al arXiv: 2211.11469

Du et al arXiv: 2308.05607

Millicharge Particles Flux

Meson decay+Proton Bremsstrahlung+Drell-Yan





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