Millicharged particles from proton bremsstrahlung in the atmosphere

Rundong Fang
Nanjing University
In collaboration with Zuowei Liu, Mingxuan Du, arXiv:2211.abcde

The 2022 Shanghai Particle Physics and Cosmology Symposium: Neutrino and Dark Matter Physics (SPCS 2022)
2022.11.18

Content

- Motivation
- Production channels
- Earth attenuation and signals
- Constraints from SuperK
- Conclusion

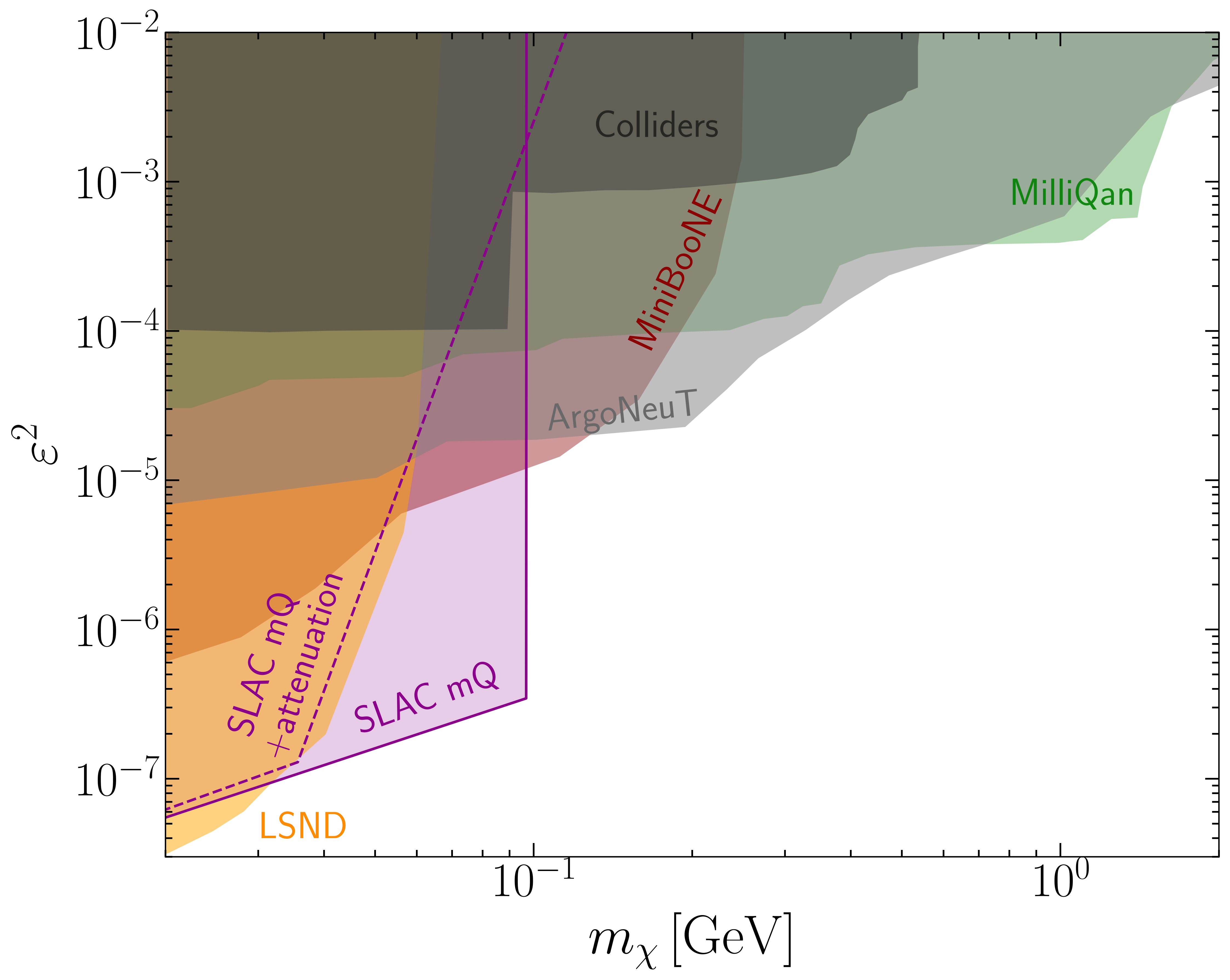
Motivation

- Millicharged particles (MCPs) are well-motivated beyond the Standard Model particles with small electric charge:

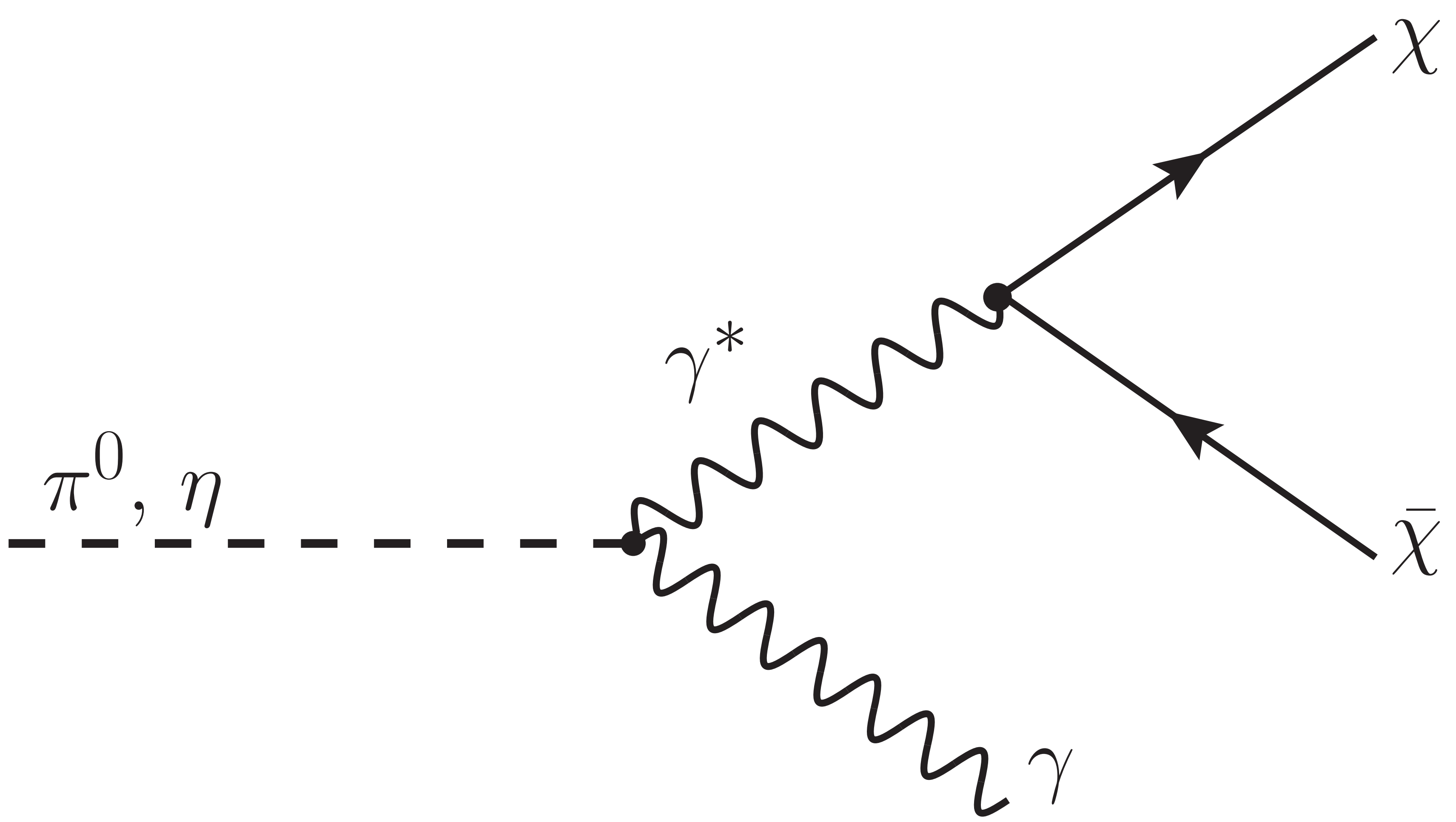
$$\mathscr{L}_{\text{int}} = \varepsilon e A_\mu \bar{\chi}\gamma^\mu \chi$$

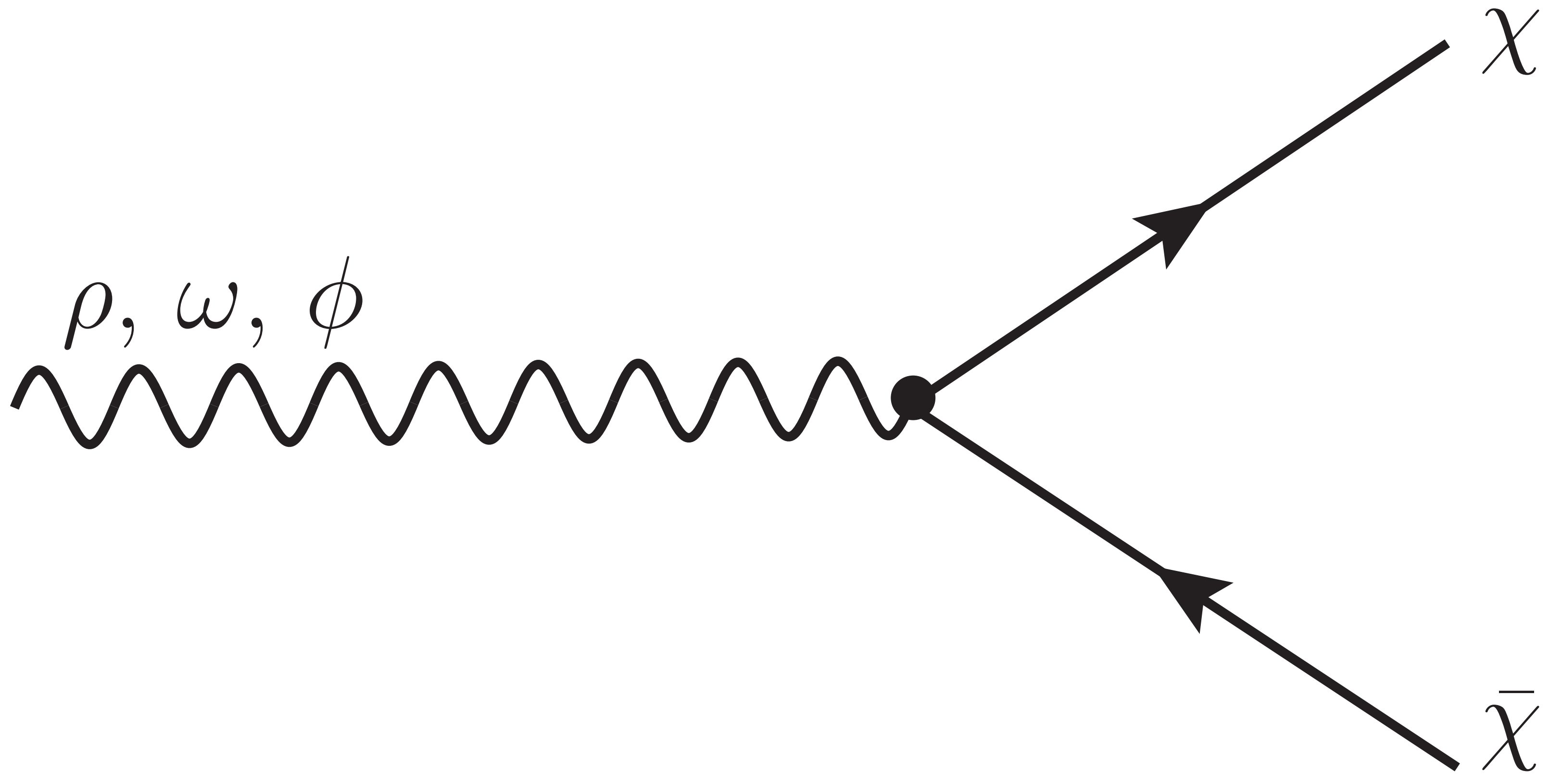
- The collision between cosmic ray protons and the atmosphere can copiously produce MCPs.

- MCPs produced in atmosphere can be detected by underground detectors.



Meson Decay





- In previous studies, the MCPs are produced via meson decay.

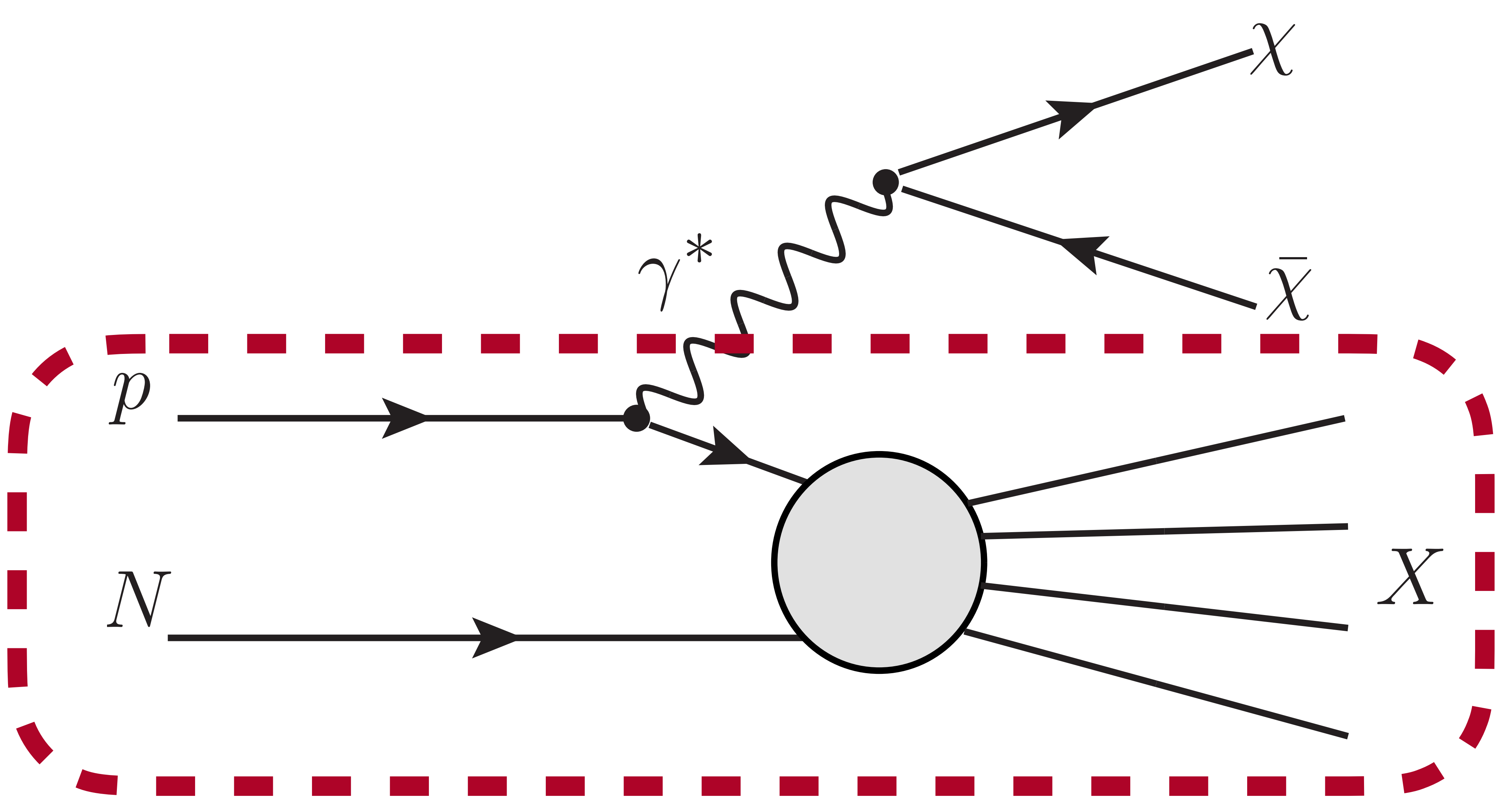
  Plestid et al., 2022.11732

  Kachelriess et al., 2104.06811

  Arguelles et al., 2104.13924

- MCPs can be produced via the Dalitz decay of pseudo-scaler mesons and two body decay of vector mesons.

Proton Bremsstrahlung



We include a new process, proton bremsstrahlung, in the MCP production.

Factorization:

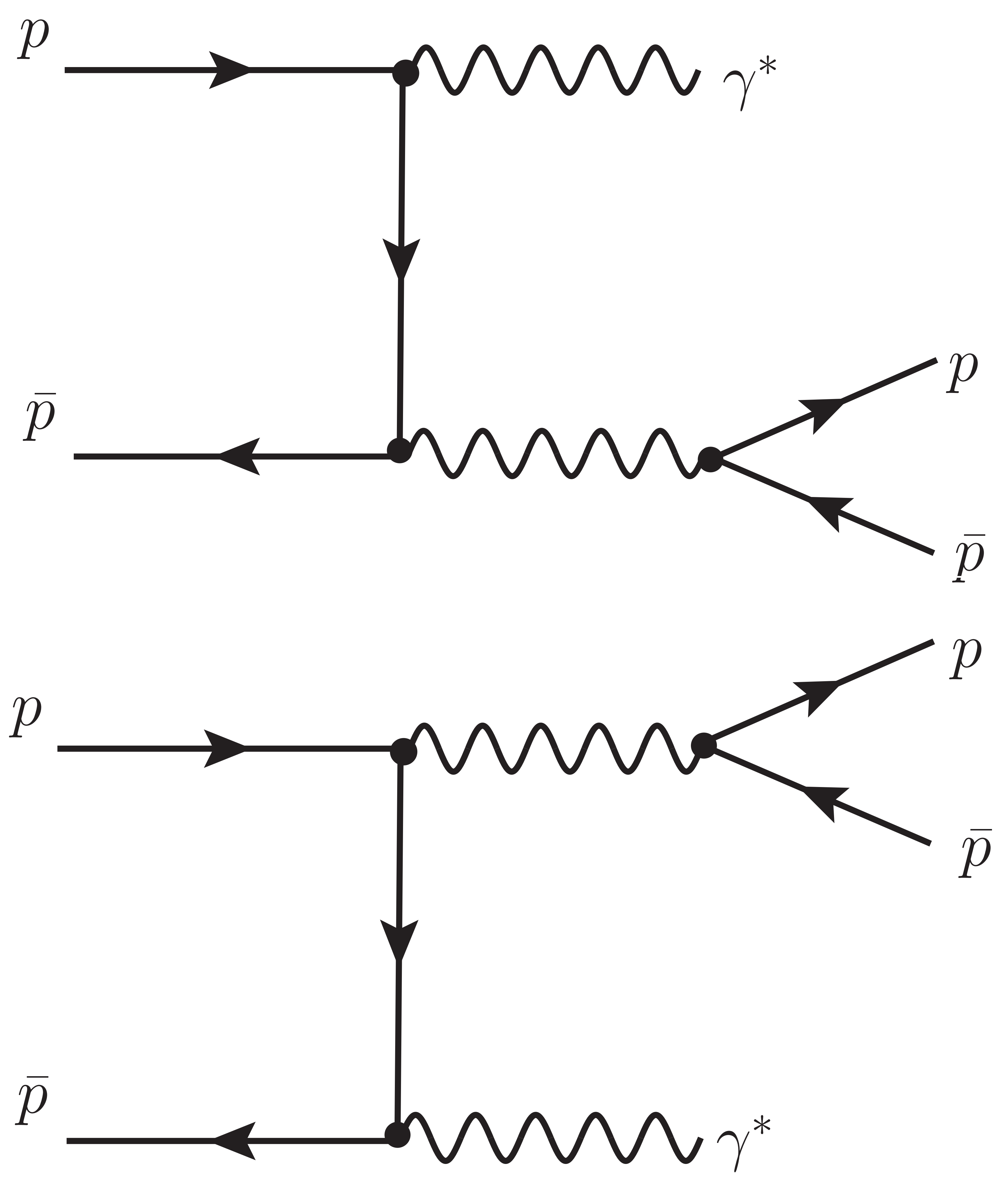
$$d\sigma_{pN\to\gamma^* X}(s) = d\mathscr{P}_{p\to\gamma^* p} \times \sigma_{pN\to X}(s')$$

The $d\mathscr{P}_{p\to\gamma^* p}$ is the splitting kernel.

The splitting kernel is usually given by the FWW approximation when all of the particles are highly relativistic.

Blumlein et al., 1311.3870

Splitting Kernel

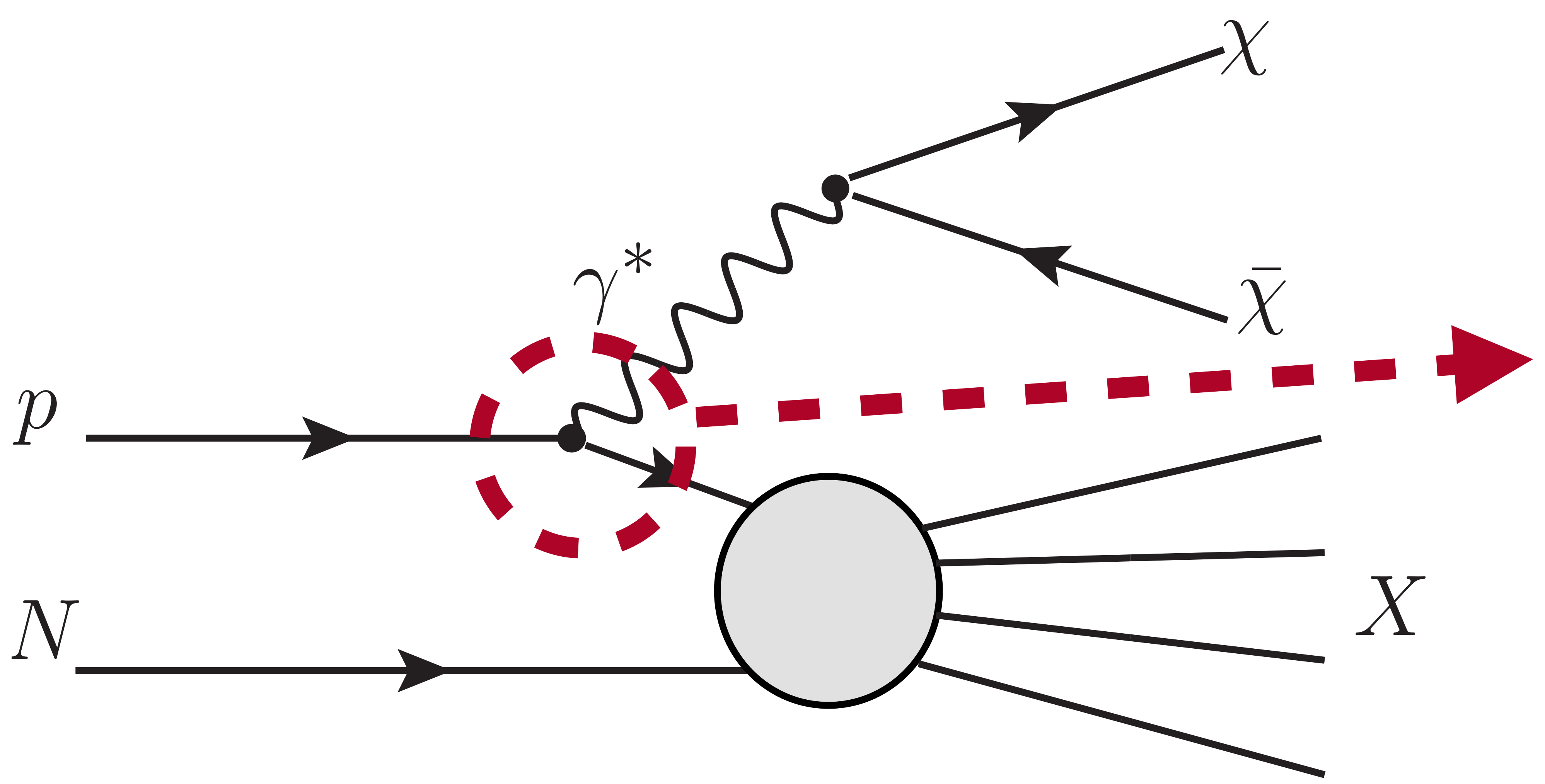


$$\frac{d\Phi_p}{dE_p d\Omega}(h_{\text{max}}) = \frac{0.74 \times 1.8 \times 10^4}{\text{m}^2\ \text{s}\ \text{sr GeV}} \left(\frac{E_p}{\text{GeV}}\right)^{-2.7}$$

The low energy protons are important

$$d\mathscr{P}_{p\to p\gamma^*} = \frac{d\sigma_{p\bar{p}\to\gamma^* p\bar{p}}(s)}{\sigma_{p\bar{p}\to p\bar{p}}(s')}$$

Form Factor



The radiation process is enhanced by the time-like form factor of proton.

$$F_1(q^2) = \sum_{V=\rho\,\rho'\,\rho''\,\omega\,\omega'\,\omega''} \frac{f_V m_V^2}{m_V^2 - q^2 - i m_V \Gamma_V},$$

Faessler et al., 0910.5589

$$m_\rho \approx m_\omega \approx 0.77 \text{ GeV}$$

Cascade Equation

M. Thunman et al., hep-ph/9505417

- The MCP flux at the surface of Earth:

$$\frac{d\Phi_\chi^s}{dE_\chi^s} = \int\int dh dE_p \frac{d\Phi_p}{dE_p}(h) n_T(h) \sigma_{pT}(E_p) \sum_i \frac{dN_\chi^i}{dE_\chi}$$

- The proton flux at a given height:

$$\frac{d}{dh}\left(\frac{d\Phi_p}{dE_p}(h)\right) = \sigma_{pT}(E_p) n_T(h) \frac{d\Phi_p}{dE_p}(h)$$

Earth Attenuation

Gaisser et al., Cosmic Rays and Particle Physics

- MCPs lose energy when travel through Earth:

$$-\frac{dE}{dX} \approx \varepsilon^2(a + bE)$$

- MCP flux after earth attenuation

$$\frac{d^2\Phi_\chi^D(X)}{dE_\chi d\Omega} = e^{\varepsilon^2 bX} \frac{d^2\Phi_\chi^s}{dE_\chi^s d\Omega^s}$$

$$E_\chi^s = (E_\chi + a/b)\ \exp\left(\varepsilon^2 bX\right) - a/b$$

Signal

- The signals of MCP come from the elastic scattering with electron in the detector.

$$\frac{d\sigma}{dE_r} = \varepsilon^2\alpha^2\pi\frac{m_e\left(E_r^2 + 2E_\chi^2\right) - E_r\left(m_e\left(2E_\chi + m_e\right) + m_\chi^2\right)}{E_r^2 m_e^2\left(E_\chi^2 - m_\chi^2\right)}$$

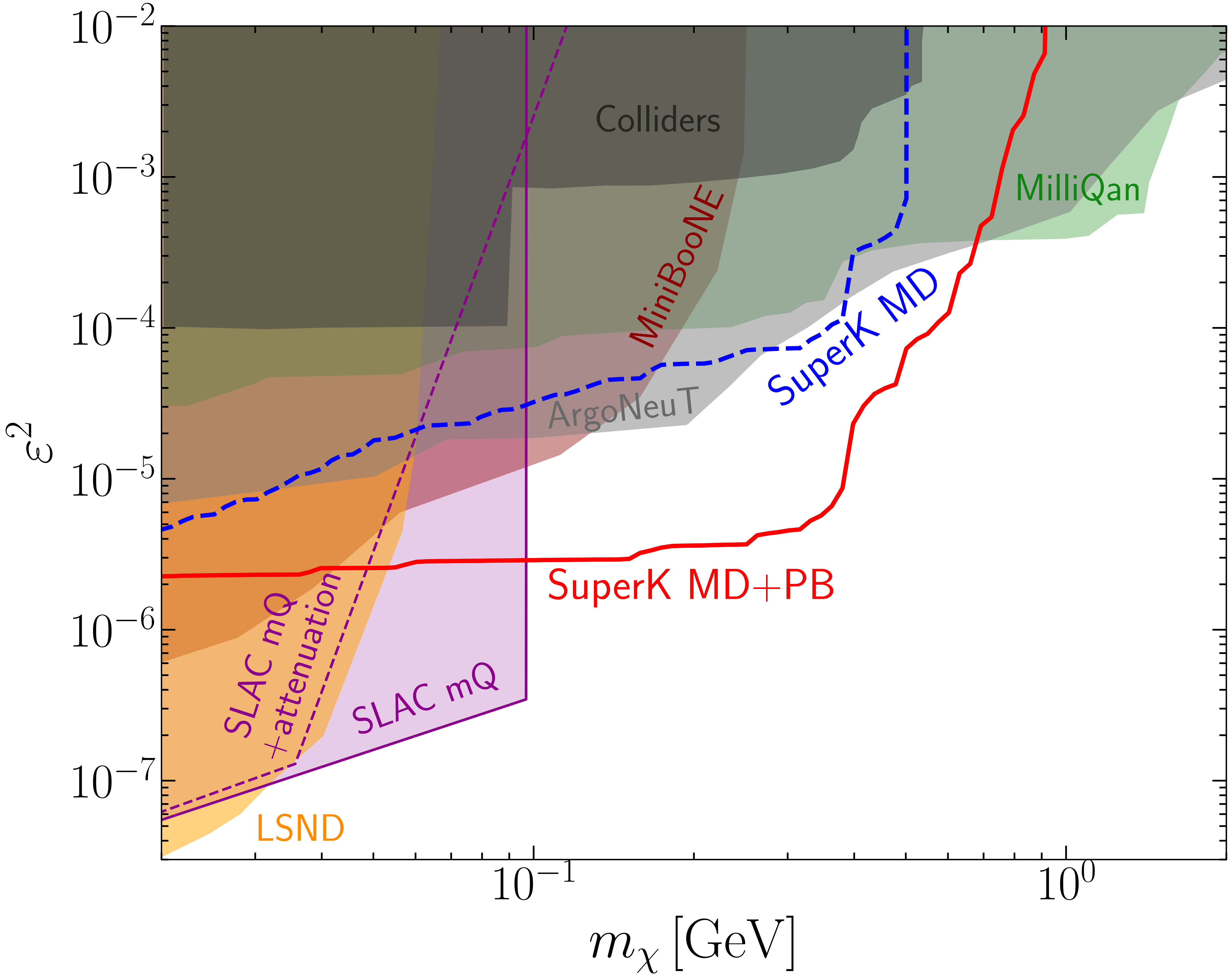
- signals per bin:

$$S_i = 2\pi n_e \mathscr{E}\int dE_r f\left(E_r\right)\int dE_\chi \int d\cos\theta \frac{d^2\Phi_\chi^D}{dE_\chi d\cos\theta}\frac{d\sigma}{dE_r}$$

- We use data and signal efficiency form SuperK phase I to phase III to set the constraint to MCPs.

Arguelles et al., 2104.13924

SuperK constraints



Blue: meson decay
Red: meson decay plus proton bremsstrahlung

Conclusion

- The MCPs can be copiously produced in the collision between cosmic ray protons and the atmosphere.
- We include a new production channel, proton bremsstrahlung, of MCPs which is enhanced by the resonance of the time-like form factor of proton in sub-GeV region.
- After including the PB process, the SuperK constraint for MCPs become much stronger than the meson decay processes.
- These enhancement will also appear in other pN collision experiments.

Thank you !

Detail Calculation of the Splitting Kernel

- The splitting kernel is calculated using the initial state radiation process $p\bar{p} \to p\bar{p}\gamma^*$, and in CM frame:

$$\frac{d^2\mathscr{P}_{p\to\gamma^* p}}{dE^0_{\gamma^*} d\cos\theta^0_{p,\gamma^*}} = \frac{1}{512\pi^4 E^0_p E^0_{\bar{p}} \left| v^0_p - v^0_{\bar{p}} \right|} \frac{\left| F_p(m^2_{\chi\bar{\chi}}) \right|^2}{\sigma^s_{2\to 2}(s'_1)} \int dE^0_{p'} \int d\phi^0_{p',\gamma^*} \left| \mathscr{M}^s_{2\to 3} \right|^2$$

- Then we boost the splitting kernel back to the lab frame to calculate differential cross section:

$$\frac{d\sigma_{\text{PB}}}{dE_{\gamma^*}} = \int dE^0_{\gamma^*} d\cos\theta^0_{p,\gamma^*} \frac{d^2\mathscr{P}_{p\to\gamma^* p}}{dE^0_{\gamma^*} d\cos\theta^0_{p,\gamma^*}} \sigma_{p,\text{air}}(s'_2)\delta(E'_{\gamma^*} - E_{\gamma^*})$$

Proton Bremsstrahlung

$$d\sigma(P_1 + P_2 \to \gamma^* X \to \chi\bar{\chi}X) = d\sigma\left(P_1 + P_2 \to \gamma^* X\right) \times \frac{Q_\chi^2}{12\pi^2}\frac{dk_{\gamma^*}^2}{k_{\gamma^*}^2}\sqrt{1 - \frac{4m_\chi^2}{k_{\gamma^*}^2}}\left(1 + \frac{2m_\chi^2}{k_{\gamma^*}^2}\right).$$

S. N. Gninenko, et al. 1810.06856