Millicharged particles from proton bremsstrahlung in the atmosphere

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与杜明轩和方润东合作 [2211.11469]

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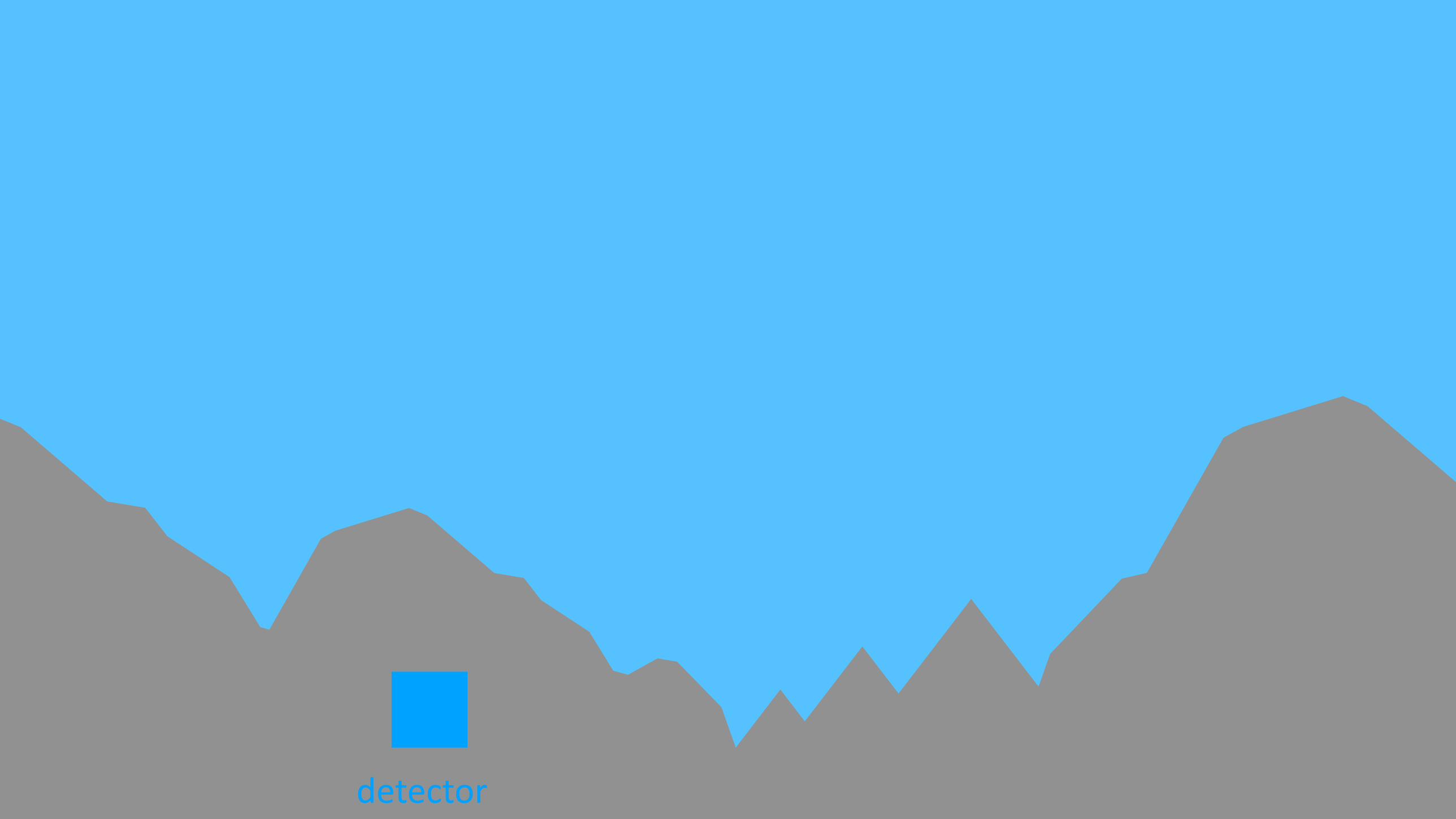
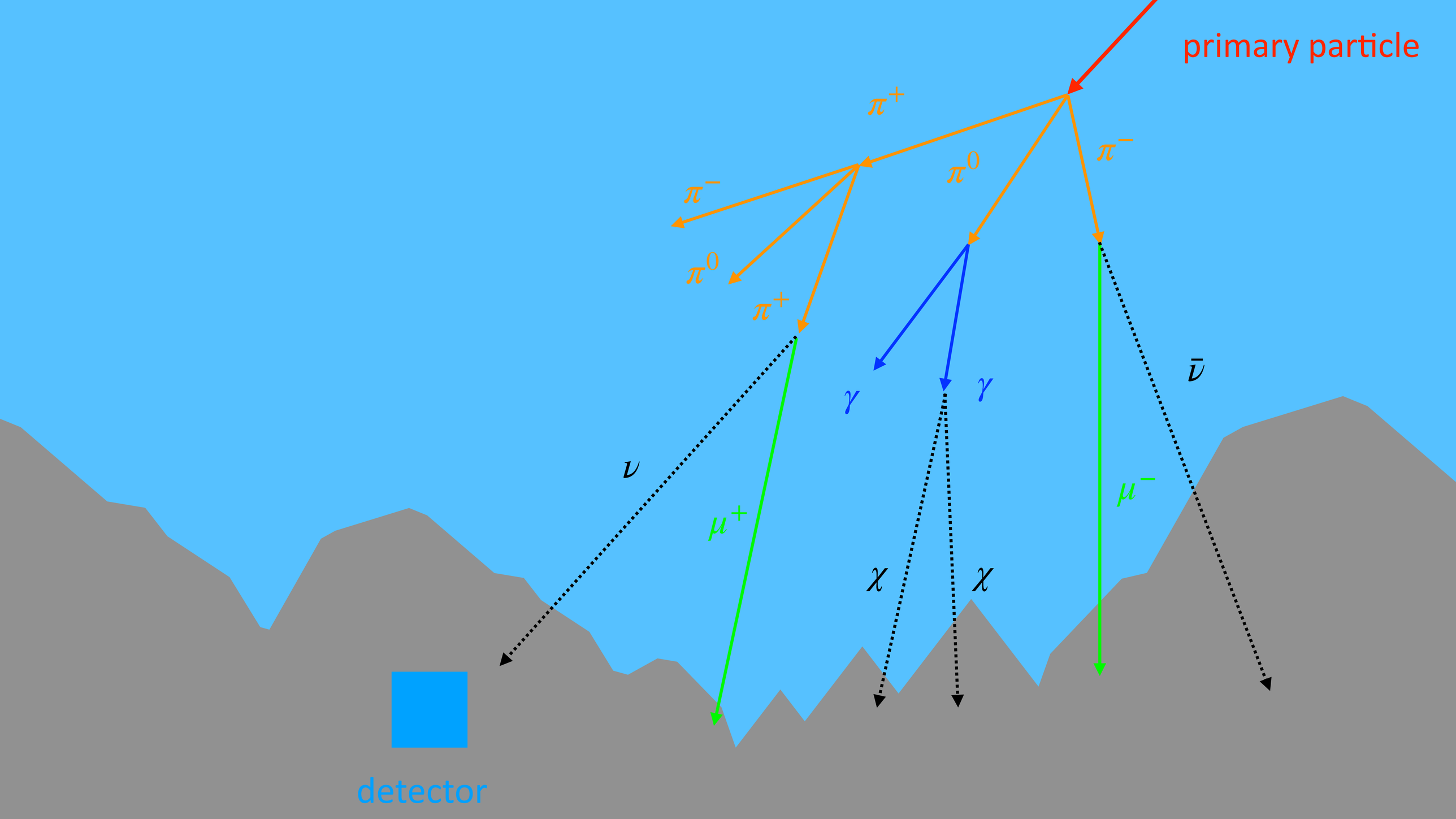
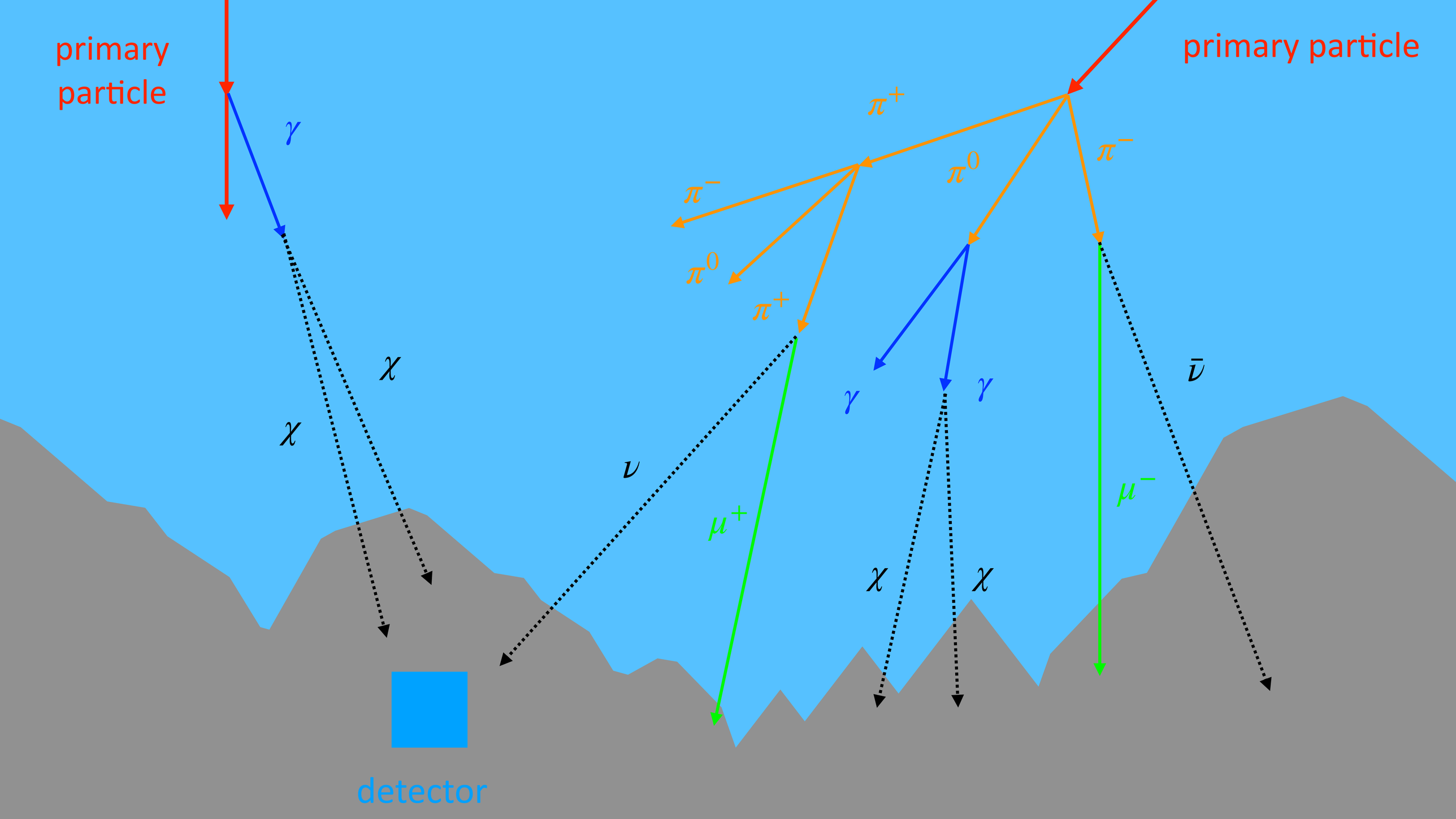
国科大杭高院基地（千岛湖两山高层次人才聚集区）

2023年5月8日


detector


primary particle
π^+
π^-
π^0
π^-
π^0
π^+
γ
γ
$\bar{\nu}$
ν
μ^+
μ^-
χ
χ
detector


primary particle
γ
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μ^+
π^+
π^-
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π^+
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χ
π^0
π^-
μ^-
$\bar{\nu}$
primary particle
detector

Outline

1. Millicharged particles
2. Proton bremsstrahlung
3. Atmospheric flux
4. Earth attenuation
5. SuperK signal & limits

[Mingxuan Du, Rundong Fang, ZL, 2211.11469]

1 Millicharged particles

Millicharged particles

$$\mathscr{L} = e\epsilon A_\mu \bar{\chi}\gamma^\mu \chi + m_\chi \bar{\chi}\chi$$

A_μ : photon

χ : millicharged particles (MCPs)

m_χ : mass

ϵ : millicharge $\ll 1$

Millicharged particles from atmospheric collisions

- millicharged partciles

$$\mathscr{L} = e\epsilon A_\mu \bar{\chi}\gamma^\mu \chi$$

only meson decay (MD)

[R. Plestid et al., arXiv:2002.11732]

[M. Kachelriess et al., arXiv:2104.06811]

[C. A. Arguelles et al., arXiv:2104.13924]

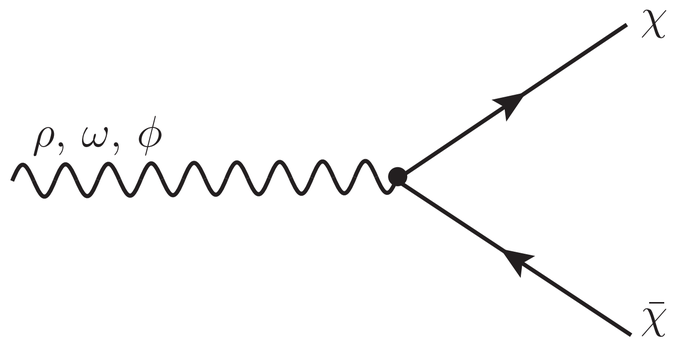
- Other BSM particles

see e.g.,

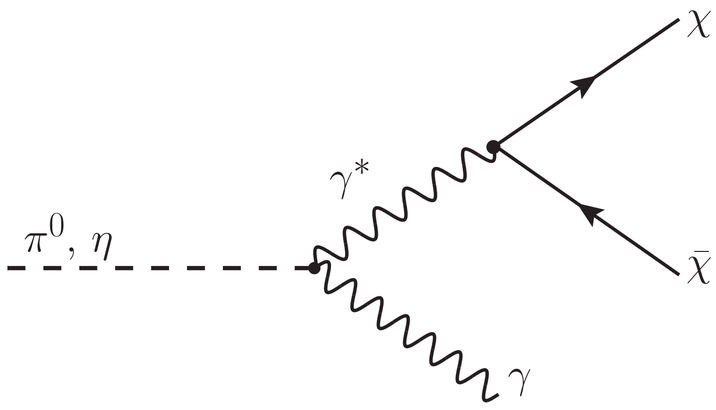
[J. Alvey et al., arXiv:1905.05776]

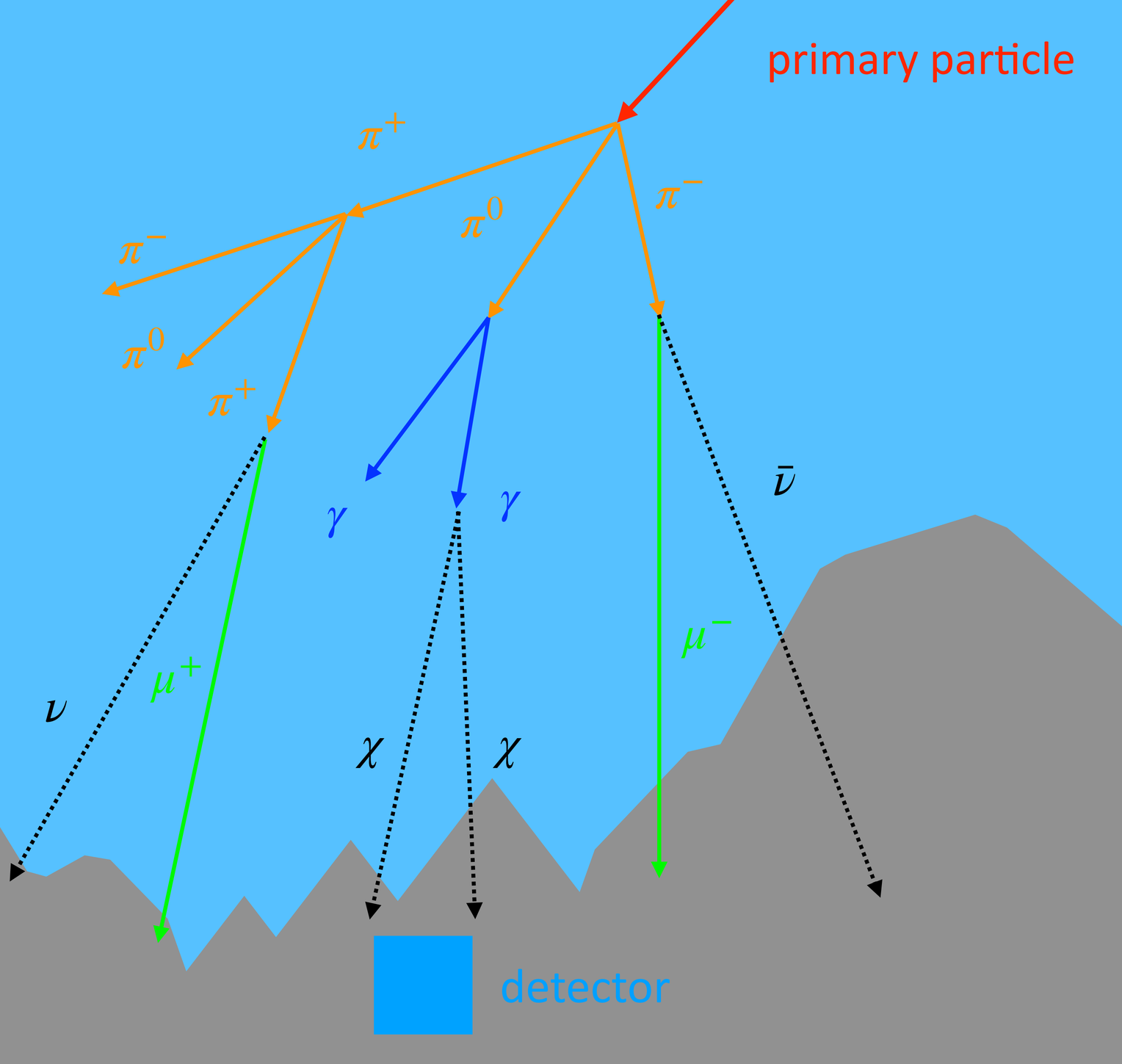
[L. Su et al., arXiv:2006.11837]

2-body meson decay



3-body meson decay





[R. Plestid et al., arXiv:2002.11732]

[M. Kachelriess et al., arXiv:2104.06811]

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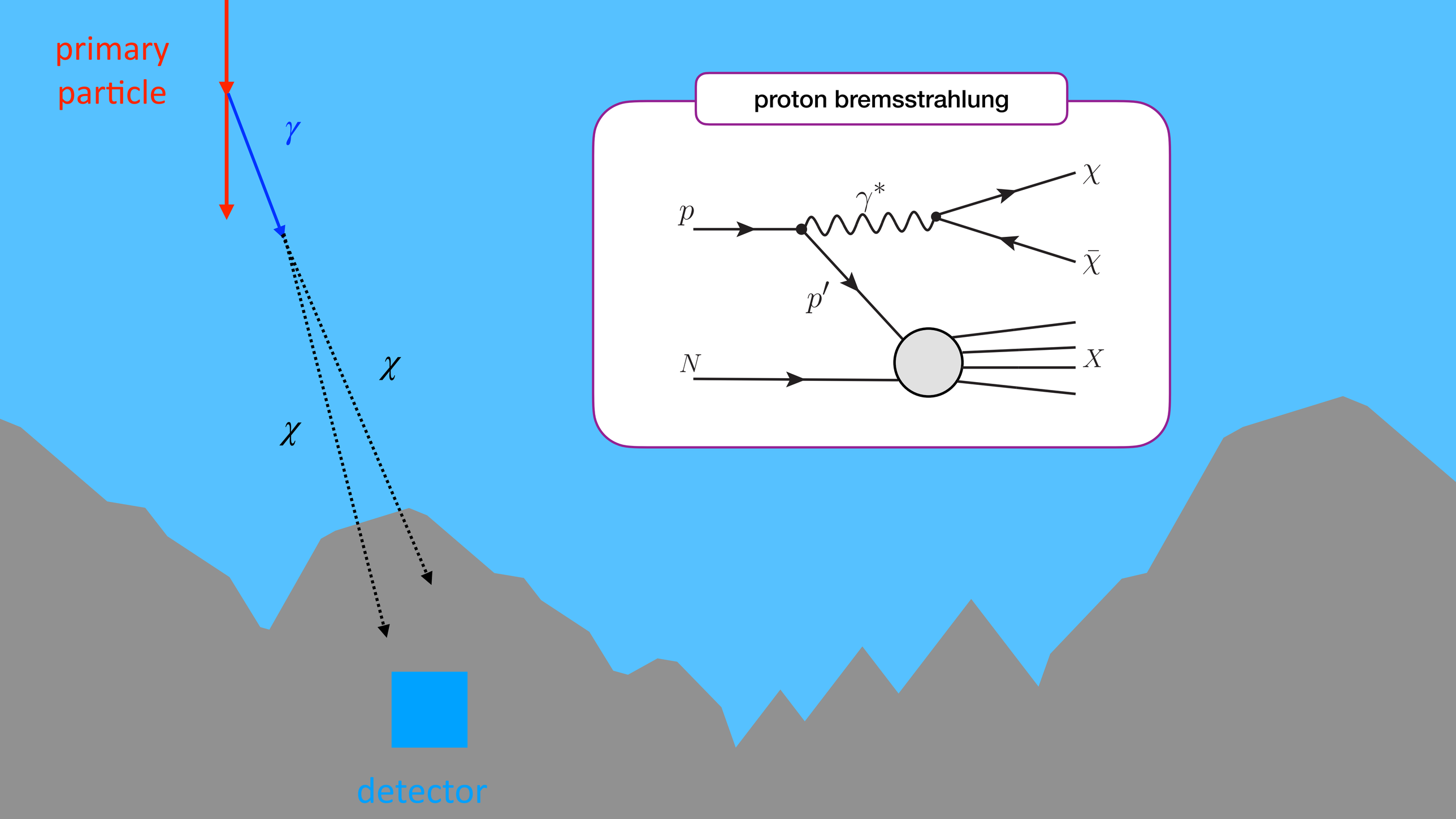
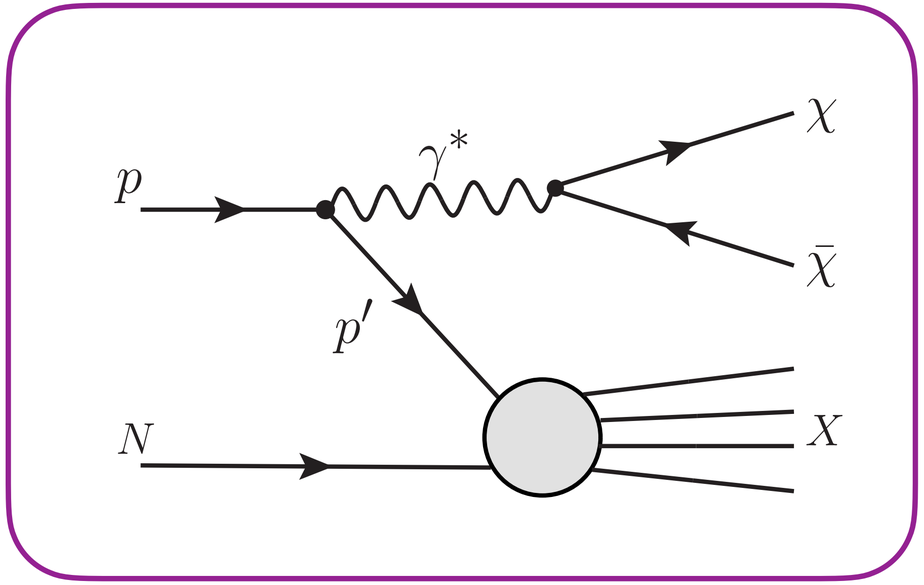
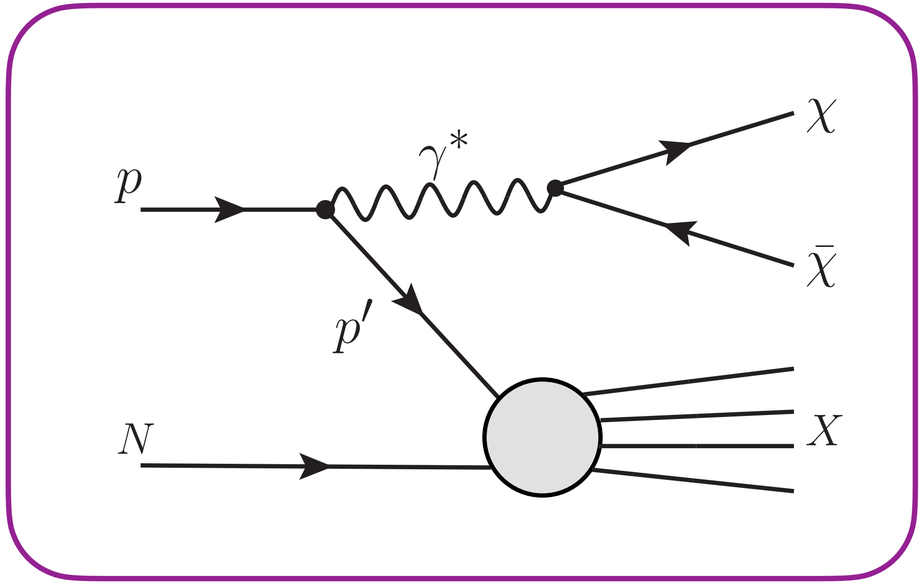
2 Proton bremsstrahlung

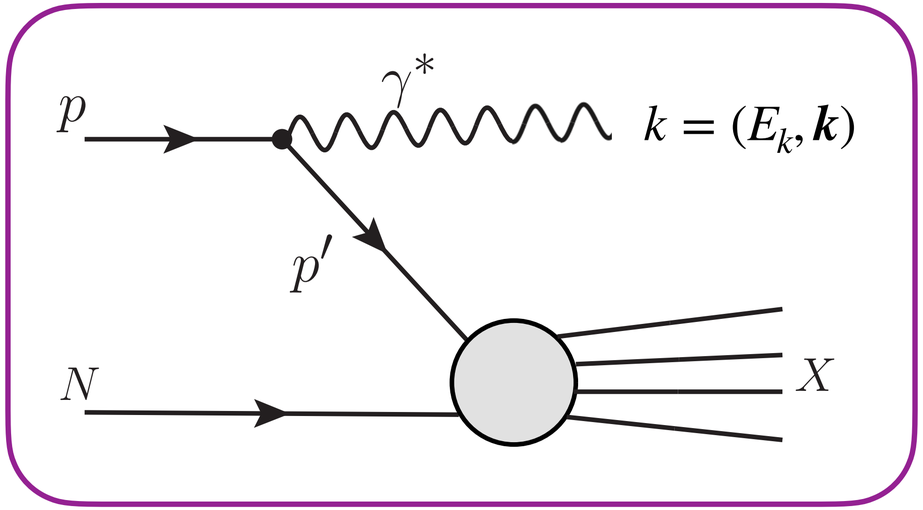

primary particle
γ
χ
χ
detector
proton bremsstrahlung
p
γ^*
χ
$\bar{\chi}$
p'
N
X

Proton bremsstrahlung (PB) in the atmosphere

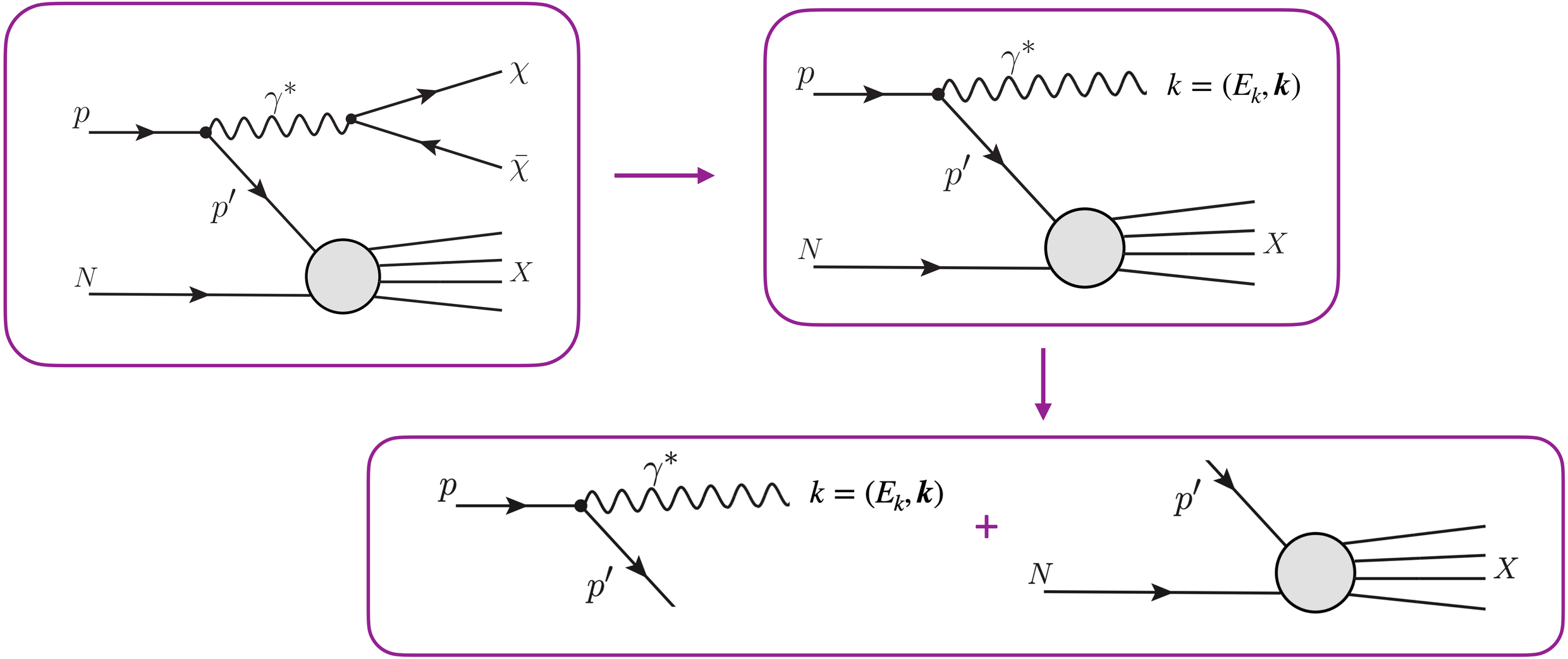


Proton bremsstrahlung (PB) in the atmosphere

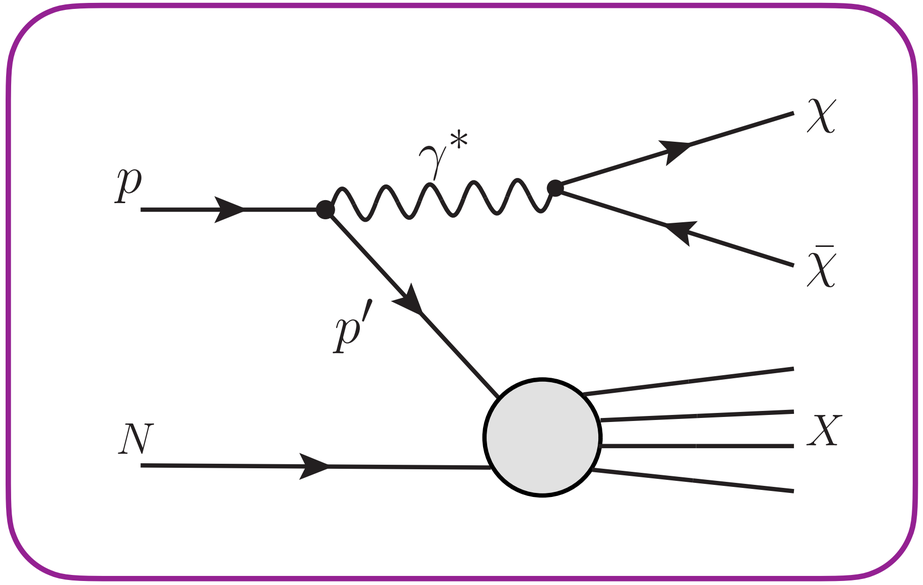


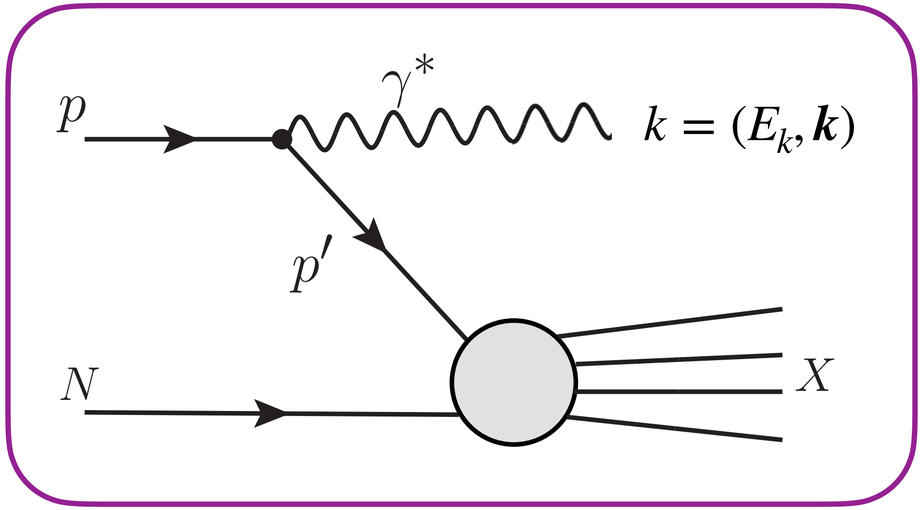


Proton bremsstrahlung (PB) in the atmosphere



Proton bremsstrahlung (PB) in the atmosphere



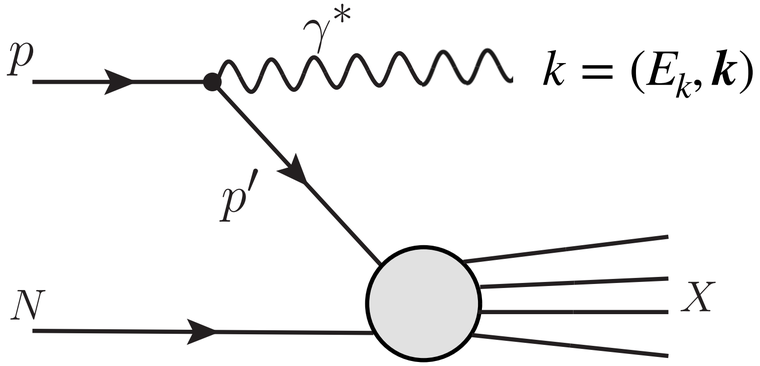


$$\frac{dN_\chi^{\mathrm{PB}}}{dE_\chi}$$

Energy spectrum in the proton bremsstrahlung process

$$\frac{dN_\chi^{\rm PB}}{dE_\chi} = \frac{\varepsilon^2 e^2}{6\pi^2}\int \frac{dk^2}{k^2}\sqrt{1-\frac{4m_\chi^2}{k^2}}\left(1+\frac{2m_\chi^2}{k^2}\right)\int dE_k \frac{1}{\sigma_{pT}}\frac{d\sigma_{\rm PB}}{dE_k}\frac{\Theta\left(E_\chi - E_-\right)\Theta\left(E_+ - E_\chi\right)}{E_+ - E_-}$$

[see e.g. 1810.06856, 2111.15533]



proton-nitrogen xsec $\sigma_{pT} \simeq 253\,\mathrm{mb}$

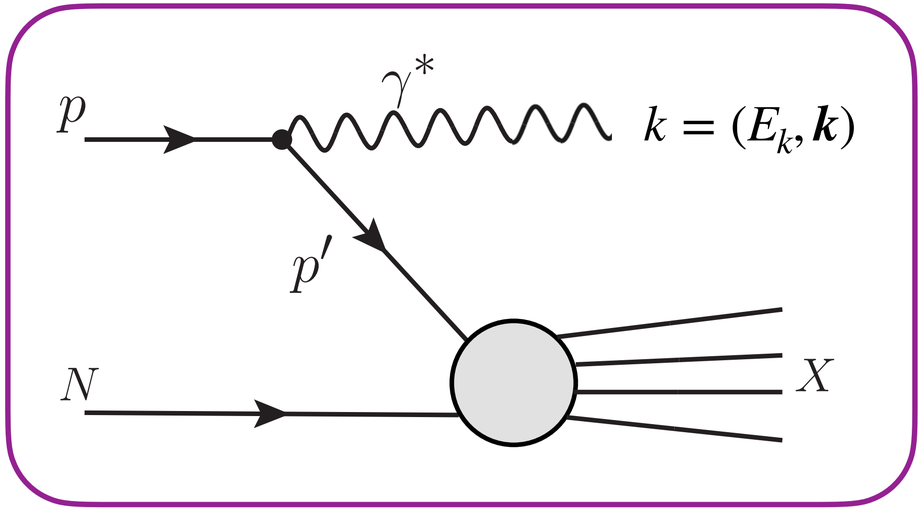
k^2 = off-shell photon mass

ϵ = millicharge

$E_\pm$ = max & min E of MCPs

$$\sum_i \epsilon_\mu^i(k)\epsilon_\nu^{i*}(k) = -g_{\mu\nu} + \frac{k_\mu k_\nu}{k^2},$$

Splitting kernel



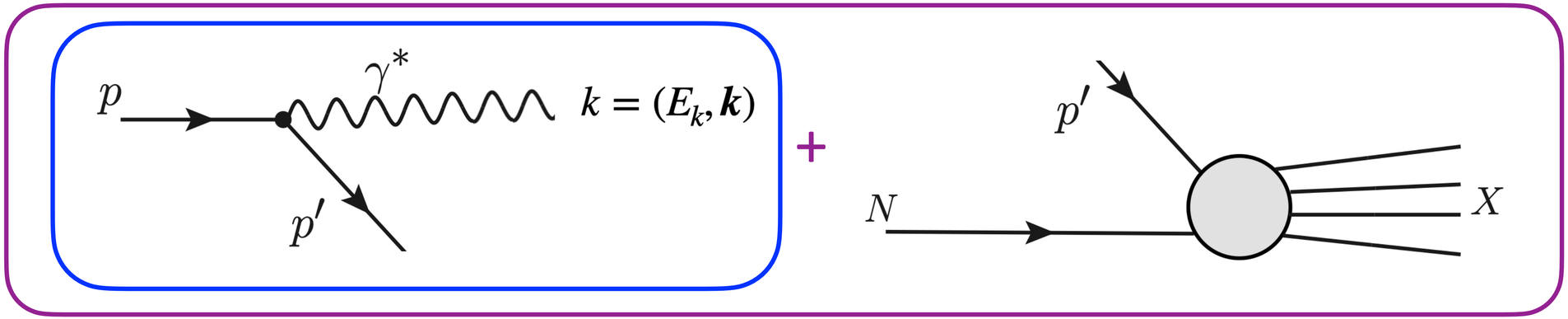
- FWW (Fermi-Williams-Weizsacker)

  Relativistic & collider conditions

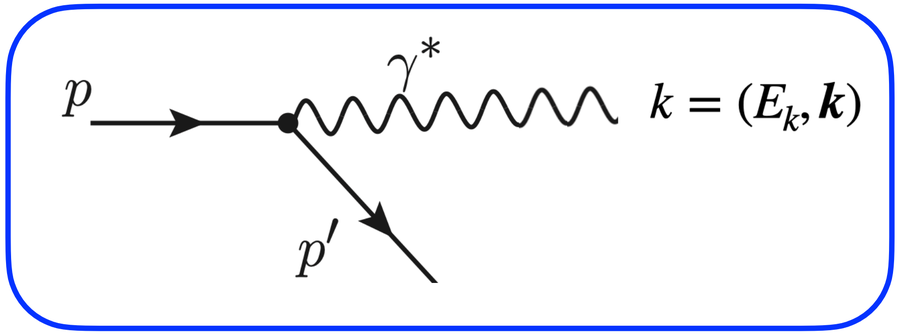
  [see e.g. 1311.3870]

- Our method

  [see also 2108.05900]



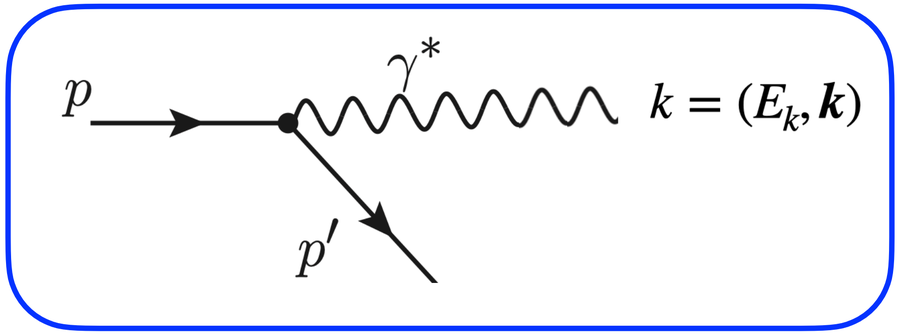
Our method to compute the splitting kernel

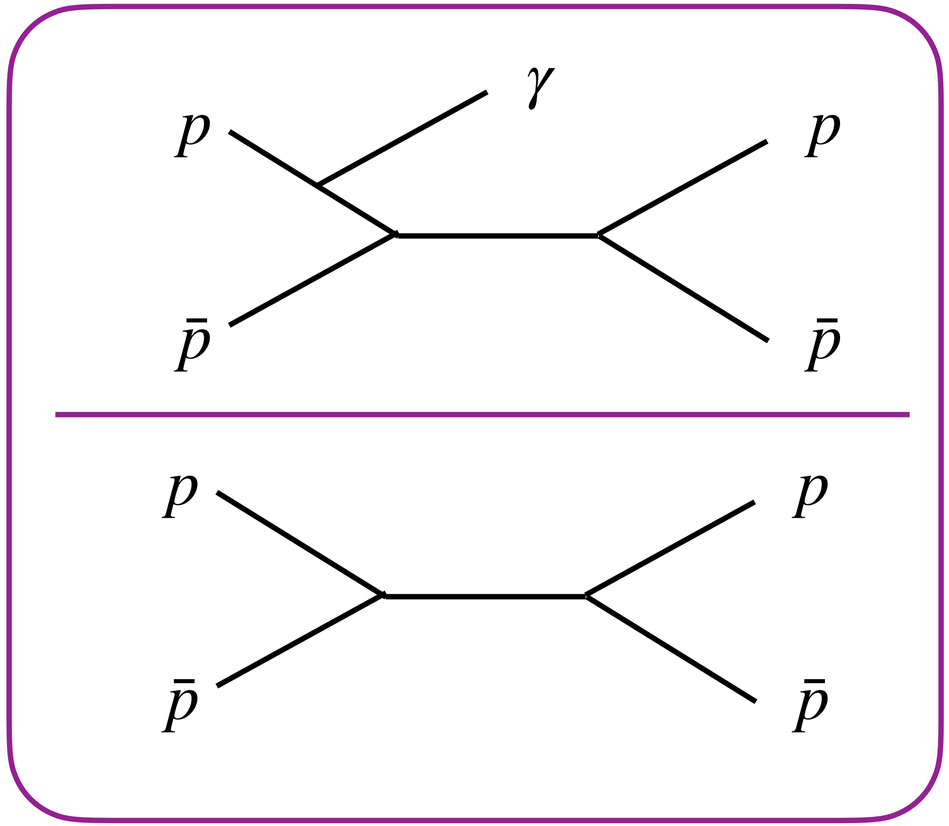


Our method to compute the splitting kernel

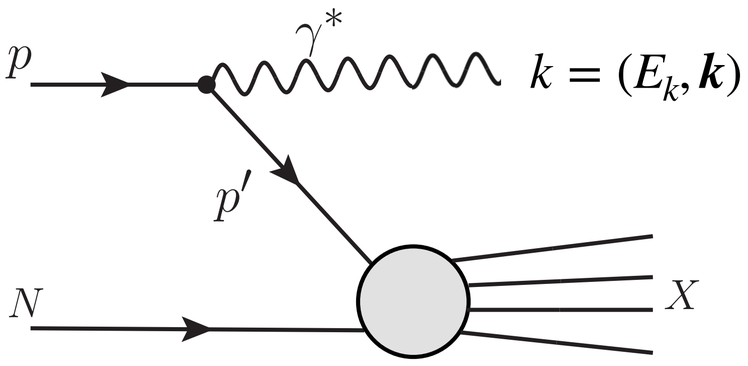
ratio of $d\sigma(p(p_1)\bar{p}(p_2) \to p(p_3)\bar{p}(p_4)\gamma^*(k))$
to $\sigma(p\bar{p} \to p\bar{p})$ at $s_{34} = (p_3 + p_4)^2$

$$\frac{d^2\mathscr{P}_{p\to\gamma^* p}}{dE_k \cos\theta_k} = \frac{1}{\sigma(p\bar{p} \to p\bar{p})(s_{34})} \frac{d^2\sigma(p\bar{p} \to \gamma^* p\bar{p})}{dE_k \cos\theta_k} =$$





xsec of $pN \to \gamma^* X$



splitting in CM

$p'N$ xsec

$$\frac{d\sigma_{\rm PB}}{dE_k} = \int dE_k^0 d\cos\theta_k^0 \, \frac{d^2\mathscr{P}_{p\to\gamma^* p}}{dE_k^0 d\cos\theta_k^0} \, \left|F_V(k)\right|^2 \, \sigma_{pT}(s_2') \, \delta(E_k'(E_k^0, \theta_k^0) - E_k)$$

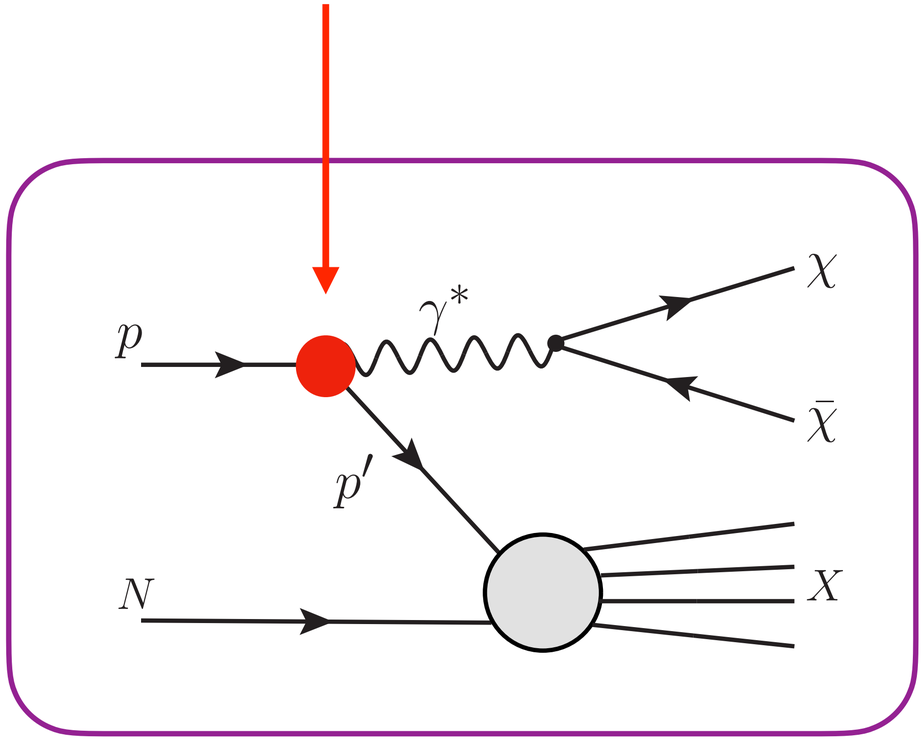
lab frame

form factor

Lorentz transformation

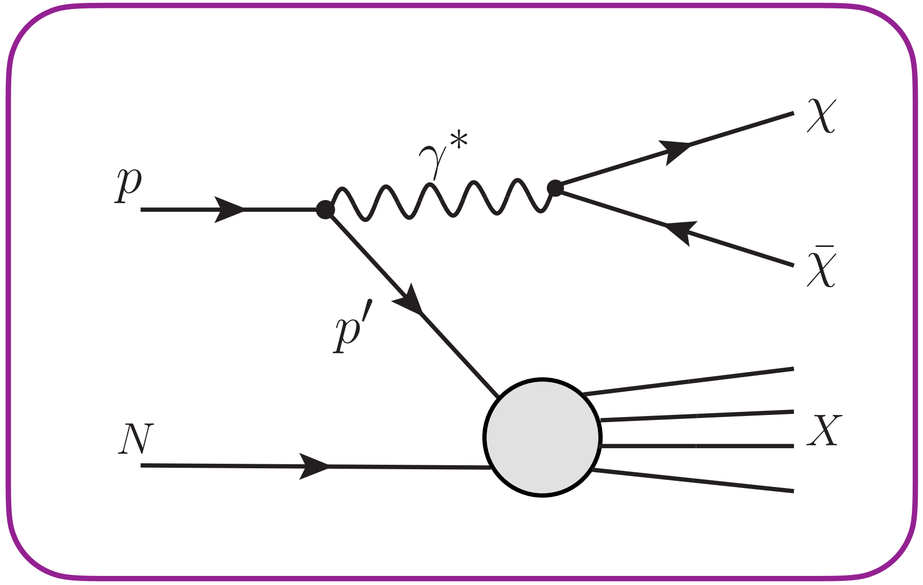
Time-like form factor

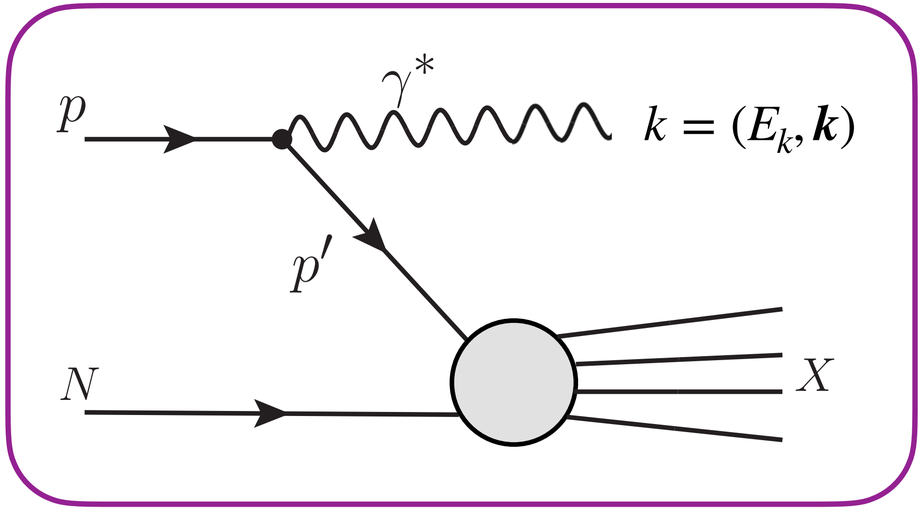
$$F_V(k) = \sum_{V=\rho\,\rho'\,\rho''\,\omega\,\omega'\,\omega''} \frac{f_V m_V^2}{m_V^2 - k^2 - i m_V \Gamma_V},$$



	m_V (GeV)	Γ_V (GeV)	f_V
ρ	0.77	0.159	0.616
ω	0.77	0.0085	1.011
ρ'	1.25	0.3	0.223
ω'	1.25	0.3	-0.881
ρ''	1.45	0.5	-0.339
ω''	1.45	0.5	0.369

Energy spectrum in proton bremsstrahlung (PB)





$$\frac{dN_\chi^{\mathrm{PB}}}{dE_\chi} = \frac{\varepsilon^2 e^2}{6\pi^2} \int \frac{dk^2}{k^2} \sqrt{1 - \frac{4m_\chi^2}{k^2}} \left(1 + \frac{2m_\chi^2}{k^2}\right) \int dE_k \frac{1}{\sigma_{pT}} \frac{d\sigma_{\mathrm{PB}}}{dE_k} \frac{\Theta\left(E_\chi - E_-\right)\Theta\left(E_+ - E_\chi\right)}{E_+ - E_-}$$

3 Atmospheric flux

Proton energy spectrum

Proton energy spectrum at the top of the atmosphere

both power-law (PL) and actual data (PDG)

PL

$$\frac{d^2\Phi_p}{dE_p d\Omega_p}(h_{\max} = 65\,\mathrm{km}) = \frac{0.74 \times 1.8 \times 10^4}{\mathrm{m}^2\ \mathrm{s}\ \mathrm{sr}\ \mathrm{GeV}} \left(\frac{E_p}{\mathrm{GeV}}\right)^{-2.7}$$

Proton energy spectrum at height h via cascade equation

$$\frac{d}{dh}\left[\frac{d^2\Phi_p}{dE_p d\Omega_p}(h)\right] = \sigma_{pT} n_T(h) \frac{d^2\Phi_p}{dE_p d\Omega_p}(h)$$

σ_{pT} = interaction xsec $\simeq$ 253 mb

Atmospheric MCP flux in one-dimension approximation

$$\frac{d^2\Phi_\chi^s}{dE_\chi^s d\Omega_\chi^s} = \iint dh dE_p \frac{d^2\Phi_p(h)}{dE_p d\Omega_p} n_T(h)\sigma_{pT} \sum_i \frac{dN_\chi^i}{dE_\chi^s}$$

MCP flux at Earth surface

$\frac{d^2\Phi_p(h)}{dE_p d\Omega_p}$ = proton flux at height h

$n_T(h)$ = air density at height h (NRLMSISE-00)

σ_{pT} = interaction xsec $\simeq$ 253 mb

$\frac{dN_\chi^i}{dE_\chi^s}$ = MCP energy spectrum in channel i (PB or MD)

- neglect air attenuation for MCP
- isotropic (1D approximation)

4 Earth attenuation

Earth attenuation for MCP

Energy loss in rock $$-\frac{dE}{dX} = \varepsilon^2(a + bE)$$

X = slant depth traversed

adopt paras for muon in standard rock **[Comput. Phys. Commun. 184 (2013) 2070–2090]**

$a = 0.233$ GeV/mwe

$b = 4.64 \times 10^{-4}$ mwe^{-1}

mwe $= 100\ \mathrm{g/cm^2}$

MCP flux underground

Flux @ detector

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

$$X = \rho L = \rho\sqrt{\left(R_e - d\right)^2 + R_e^2 - 2\left(R_e - d\right)R_e\cos\left(\theta - \theta_s\right)}$$

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

[see e.g. Gaisser, Engel, Resconi (2016)]

5 SuperK signal & limits

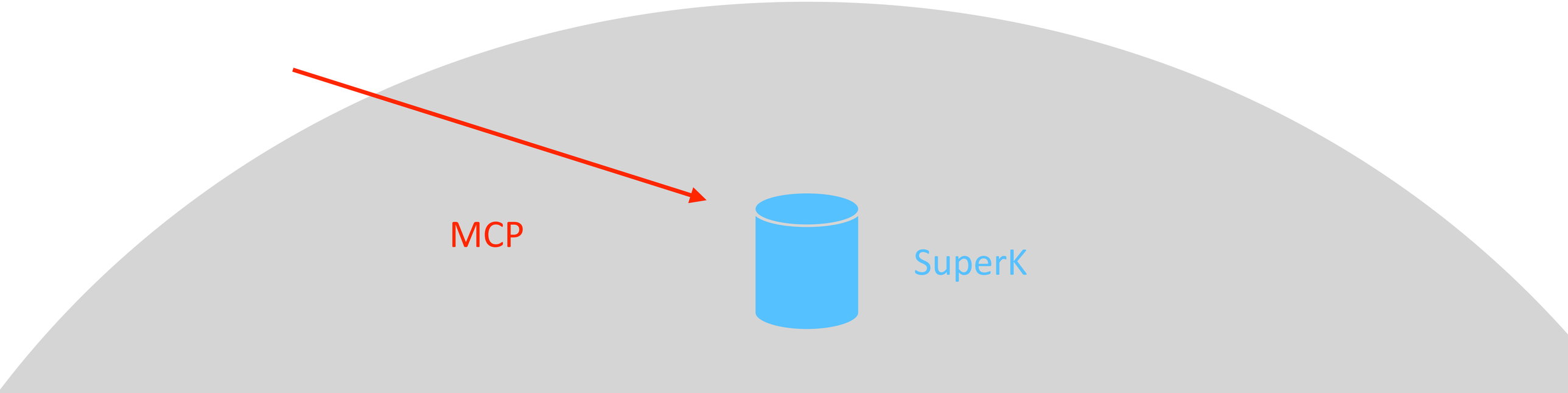
MCP signal events at SuperK

- water-Cherenkov detector
- fiducial volume = 22.5 kton of water
- rock = 1000 m

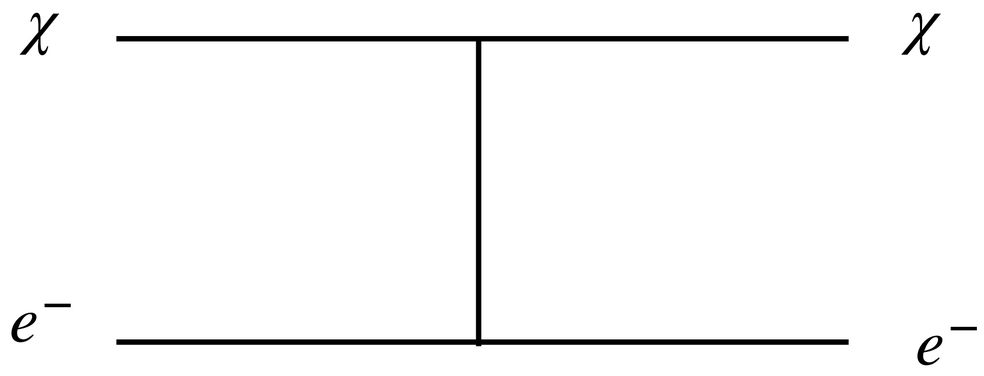
[R. Plestid et al., arXiv:2002.11732]

[M. Kachelriess et al., arXiv:2104.06811]

[C. A. Arguelles et al., arXiv:2104.13924]



Electron recoil in SuperK



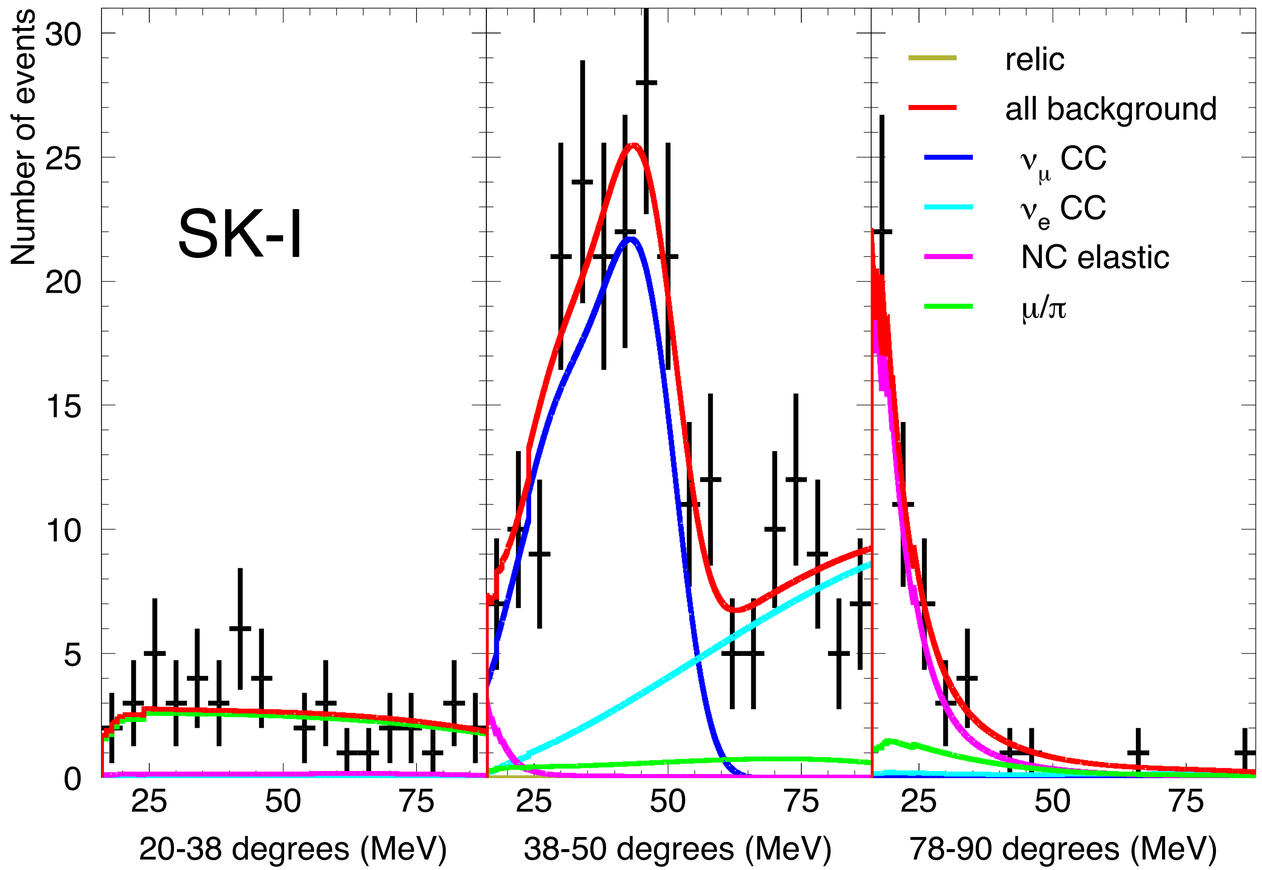
$$\frac{d\sigma}{dE_r} = \varepsilon^2 \alpha^2 \pi \frac{E_r + 2E_\chi^2/E_r - 2E_\chi - m_e - m_\chi^2/m_e}{E_r m_e \left(E_\chi^2 - m_\chi^2\right)}$$

E_χ = MCP energy

E_r = electron recoil energy

SuperK data & statistics

[SK, 1111.5031] 3 runs: 1497, 794, 562 days



18 bins in 16-88 MeV (38-50 deg)

Likelihood (only for $S_i > D_i$)

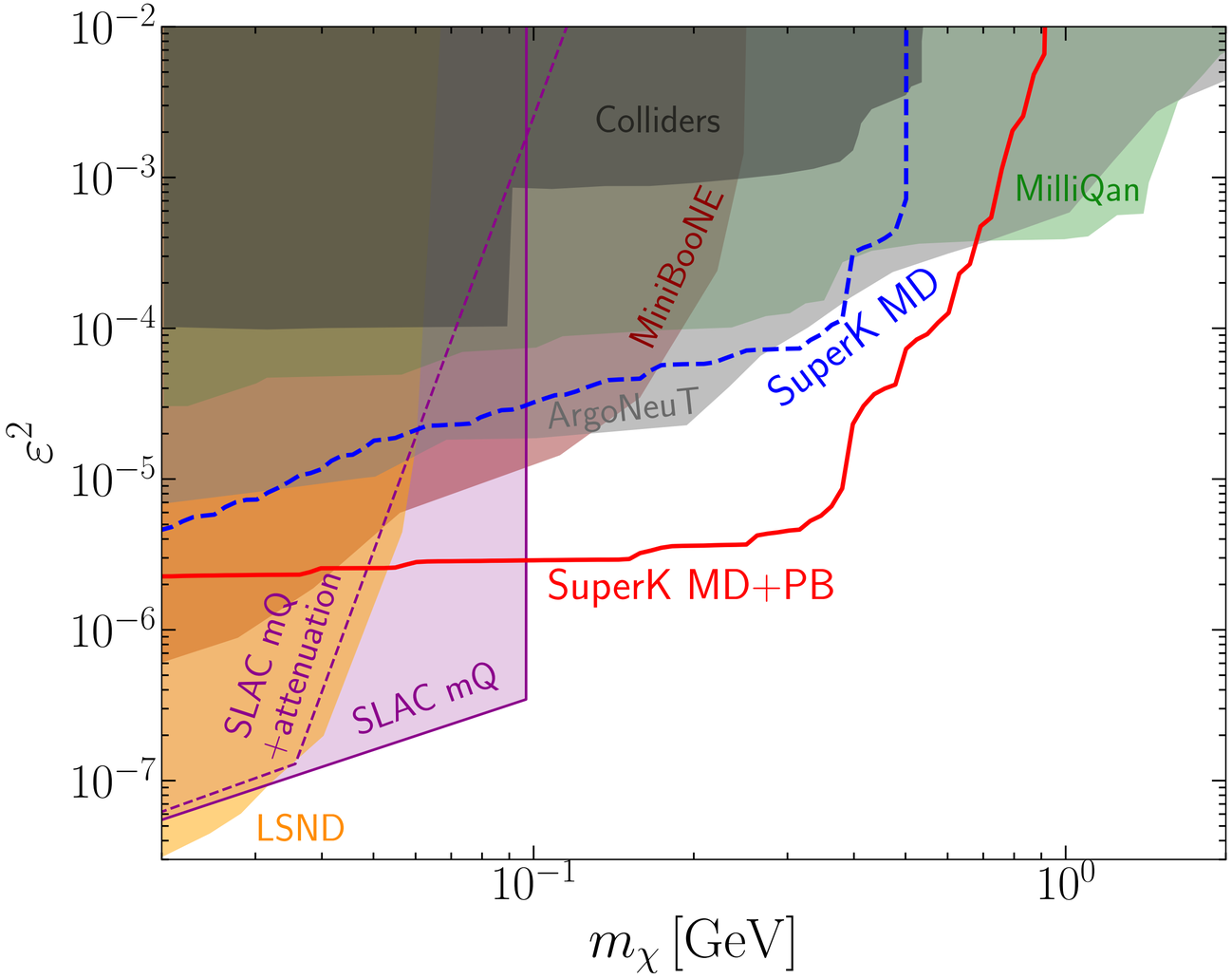
$$\mathscr{L} = \Pi_i \mathscr{L}_i = \Pi_i \frac{S_i^{D_i} \exp(-S_i)}{D_i!}$$

90% CL limit

$$TS = -2 \log \left[\frac{\mathscr{L}(m_\chi, \varepsilon)}{\mathscr{L}(m_\chi, \varepsilon = 0)} \right] < 4.6$$

SuperK limits on millicharged particles

[Mingxuan Du, Rundong Fang, ZL, 2211.11469]



- order-of-magnitude improvement on ϵ^2
- better than ArgoNeuT & MiniBooNE
- start to lose sensitivity above 0.4 GeV
- probe para space below 0.1 GeV

Summary

- We compute millicharged particles from the proton bremsstrahlung process in the atmosphere
- The light millicharged particle flux from the proton bremsstrahlung process is much larger than the previously studied meson decay process
- This leads to an order-of-magnitude improvement in the constraint on ϵ^2 (where ϵ is the millicharge), surpassing the current best experimental limits, such as ArgoNeuT and MiniBooNE, in the mass range of 0.1-0.4 GeV.

[Mingxuan Du, Rundong Fang, ZL, 2211.11469]

additional slides

splitting kernel in the CM frame

$$\frac{d^2\mathscr{P}_{p\to\gamma^* p}}{dE_k^0 d\cos\theta_k^0} = \frac{1}{\sigma_{2\to 2}(s_{34})} \frac{\int dE_3^0 \int d\phi_{3,k}^0 \overline{\left|\mathscr{M}_{2\to 3}\right|}^2}{512\pi^4 E_1^0 E_2^0 \left|\vec{v}_1^{\,0} - \vec{v}_2^{\,0}\right|},$$

- $\mathscr{M}_{2\to 3}$ = the matrix elementof the $p\bar{p} \to \gamma^* p\bar{p}$ process
- $\sigma_{2\to 2}(s_{34})$ = the cross section of the $p\bar{p} \to p\bar{p}$ process
- E_3^0 = the energy of the final state proton
- $\phi_{3,k}^0$ = the azimuth angle of $\vec{p}_3$ in the transverse plane of $\vec{k}$
- θ_k^0 = the angle between γ^* and the initial state proton

Atmospheric MCP flux in the MD process

The calculation for the MD process is the same as the PB process, except the energy spectrum of atmospheric MCPs in Eq. (1). For the MD process, one has

$$\frac{\mathrm{d}N_\chi^{\mathrm{MD}}}{\mathrm{d}E_\chi^s} = 2\sum_m \int_1^\infty \mathrm{d}\gamma_m \frac{dN_m(E_p)}{d\gamma_m} F_m(E_\chi^s, \gamma_m), \tag{A1}$$

where m denotes the parent meson in the decay process, $\gamma_m = E_m/m_m$ is the meson boost factor, $dN_m(E_p)/d\gamma_m$ is the spectra of the averaged multiplicity of mesons, the factor 2 comes from the fact that two MCPs are produced in each meson decay, and $F_m(E_\chi^s, \gamma_m)$ is the MCP energy spectra in the lab frame, which is obtained by boosting the spectra in the rest frame of meson m to the lab frame. We use the EPOS model [78] in the CRMC package [79] to compute $dN_m(E_p)/d\gamma_m$.

FWW

The splitting kernel in the FWW approximation is given by [69, 83, 84]

$$\frac{d^2\mathcal{P}^{\rm FWW}_{p\to\gamma^* p}}{dE_k d\cos\theta_k} = \left|\mathbf{J}(z,p_T^2)\right| \frac{d^2\mathcal{P}^{\rm FWW}_{p\to\gamma^* p}}{dz dp_T^2} = \left|\mathbf{J}(z,p_T^2)\right| \left|F_V(k)\right|^2 \omega(z,p_T^2), \tag{B1}$$

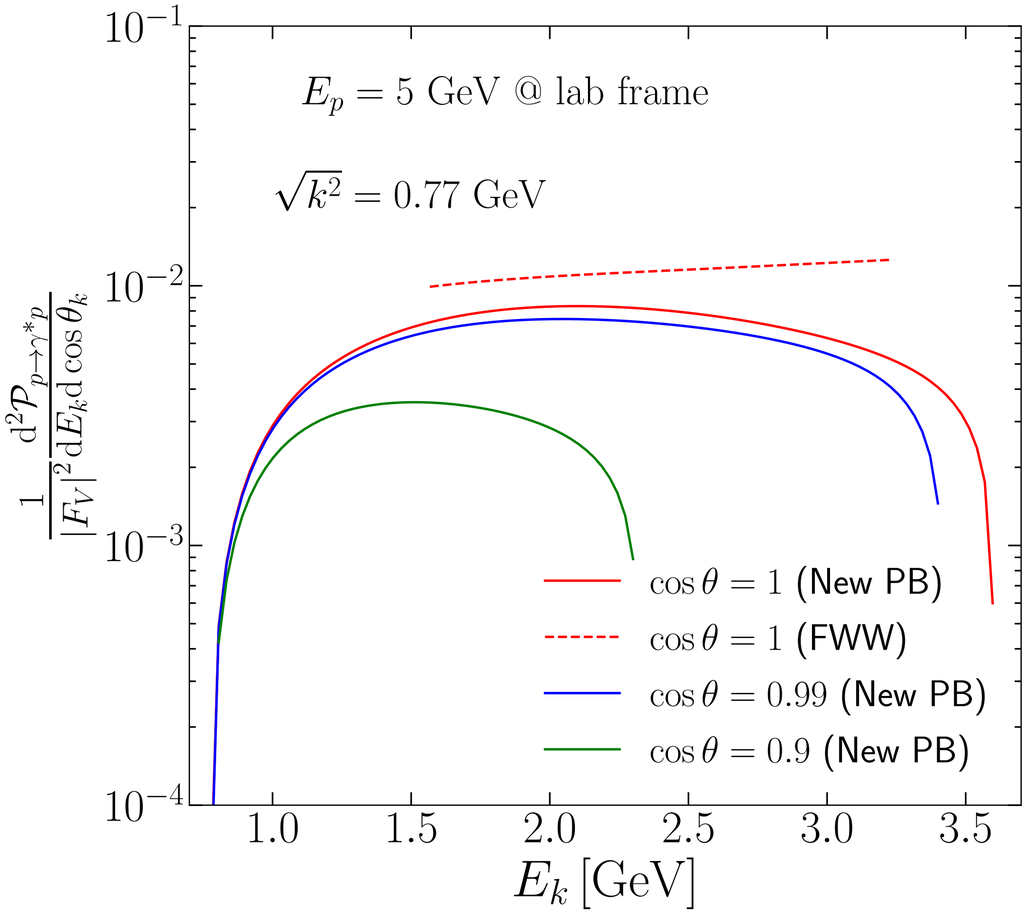
where $k^\mu = (E_k, \vec{k})$ is the 4-momentum of the virtual photon, θ_k is the angle between the virtual photon and the initial proton, $p_T = |\vec{k}|\sin\theta_k$ is the transverse momentum, $z = \cos\theta_k|\vec{k}|/|\vec{p}_p|$ with $\vec{p}_p$ being the momentum of the initial proton, $\left|\mathbf{J}(z,p_T^2)\right|$ is the determinant of the Jacobian matrix between (z,p_T^2) and $(E_k,\cos\theta_k)$, and $\omega(z,p_T^2)$ is given by [69, 83, 84]

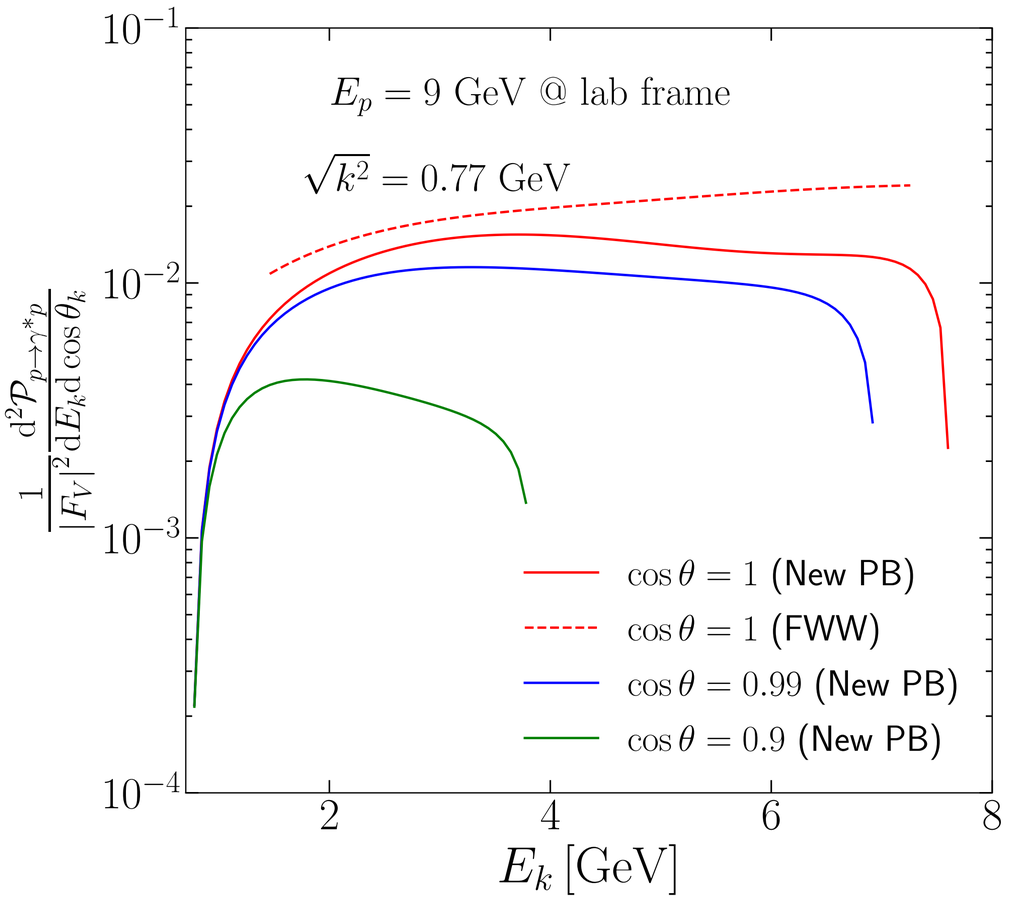
$$\begin{aligned}\omega\left(z,p_T^2\right) \simeq \quad & \frac{\alpha}{2\pi H}\left\{\frac{1+(1-z)^2}{z} - 2z(1-z)\left(\frac{2m_p^2+k^2}{H} - z^2\frac{2m_p^4}{H^2}\right)\right. \\ & \left. + \; 2z(1-z)\left(z+(1-z)^2\right)\frac{m_p^2k^2}{H^2} + 2z(1-z)^2\frac{k^4}{H^2}\right\},\end{aligned} \tag{B2}$$

where $H = p_T^2 + (1-z)k^2 + z^2m_p^2$. We note that the FWW approximation is valid in the relativistic and collinear limit: $E_p, E_k, E_{p'} \gg m_p, \sqrt{k^2}, p_T$ [69–74, 83, 84]. Thus, in our analysis, we impose in the lab frame the following three conditions for the FWW approximation (denoted as the "FWW cuts"):

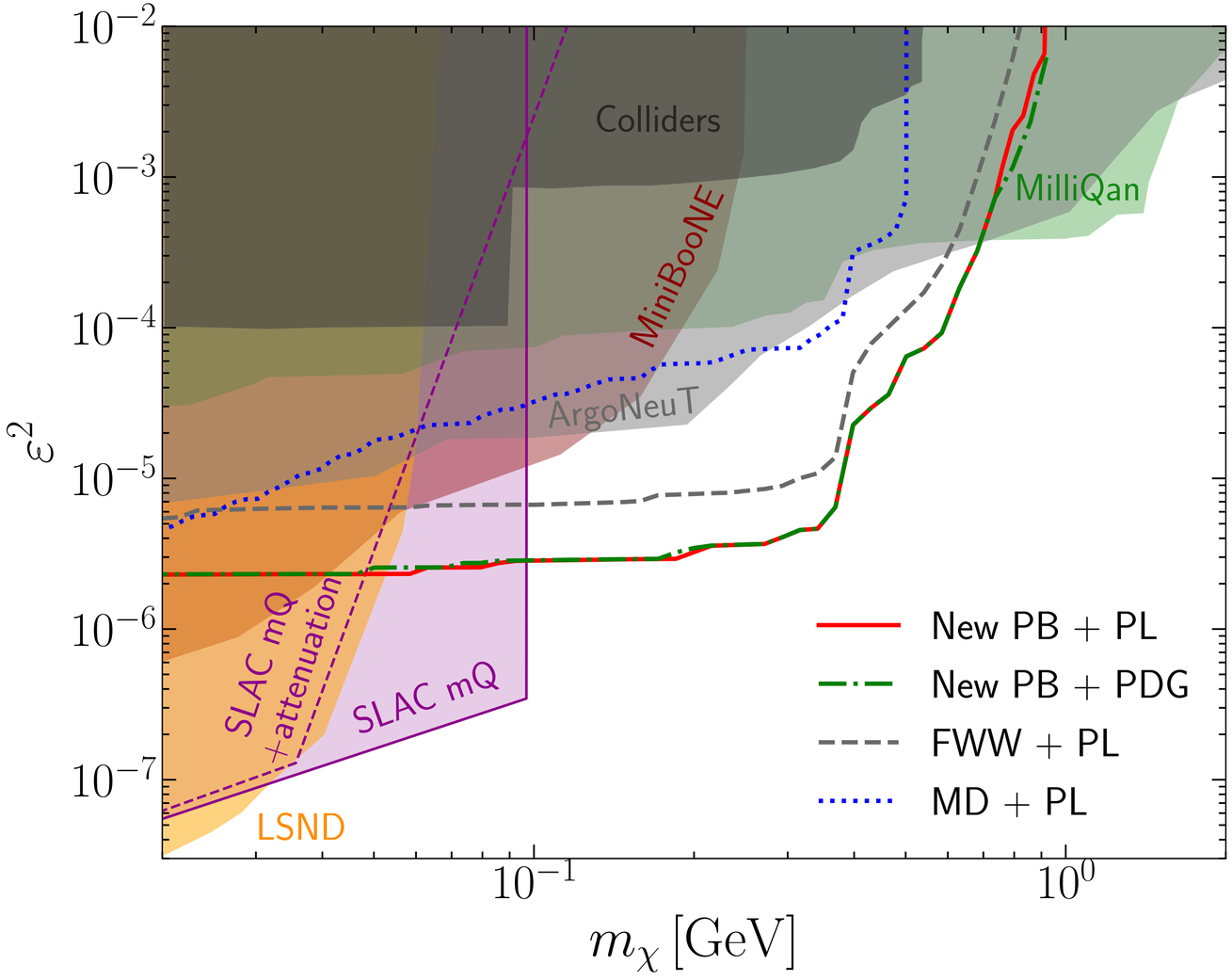
1. $p_T < 0.1\ E_k$ [69, 70],
2. $p_T < 1$ GeV [69, 70],
3. $\left|q^2_{\rm min}\right| < \Lambda^2_{\rm QCD}$ [72], where $\left|q^2_{\rm min}\right| \approx \left[p_T^2 + (1-z)k^2 + z^2m_p^2\right]^2 / \left[4E_p^2z^2(1-z)^2\right]$ [83, 84] and $\Lambda_{\rm QCD} \simeq 0.25$ GeV is the QCD scale.

Diff PB methods

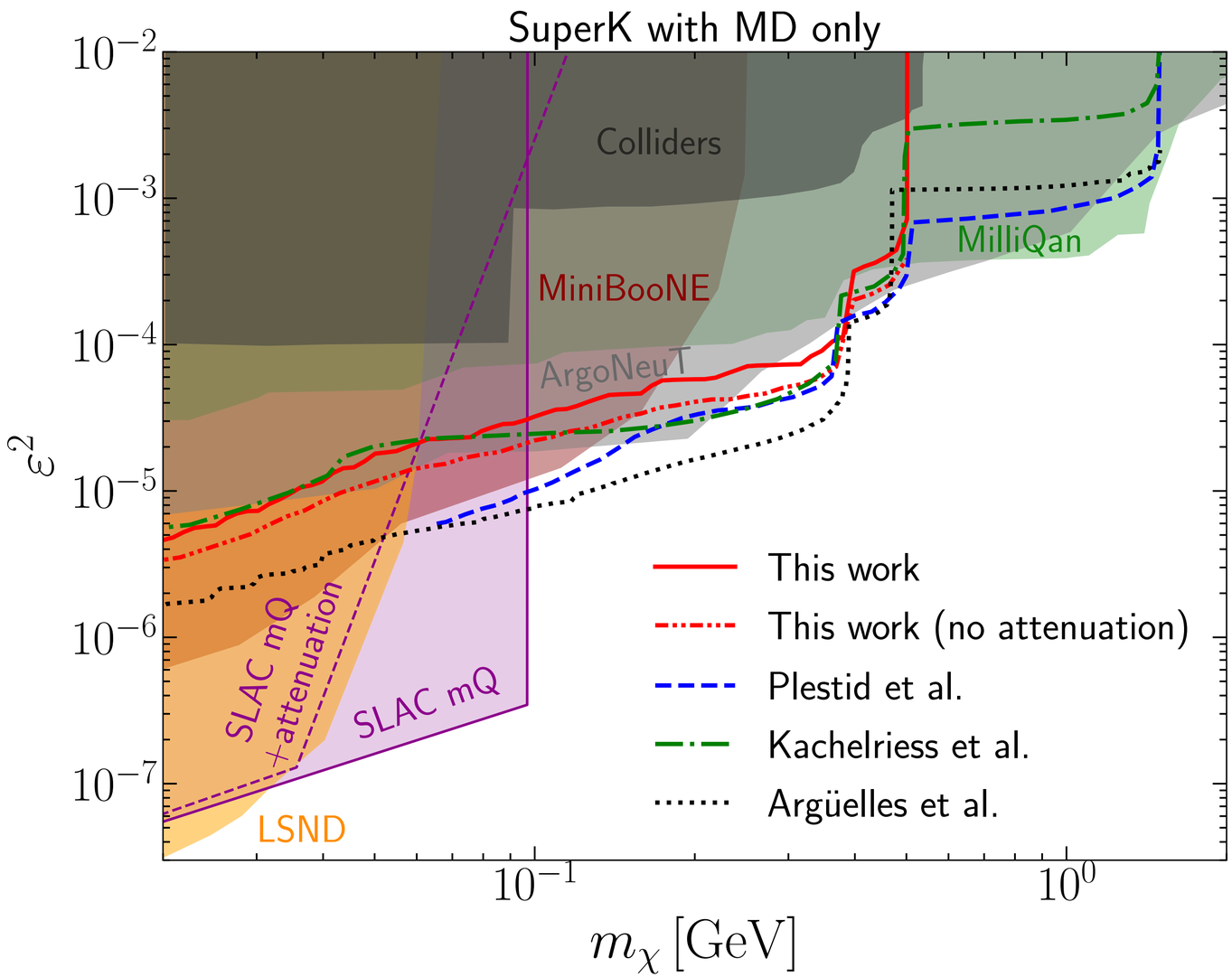




Diff PB methods & diff CR proton spectra



Comparison with other papers in the MD process

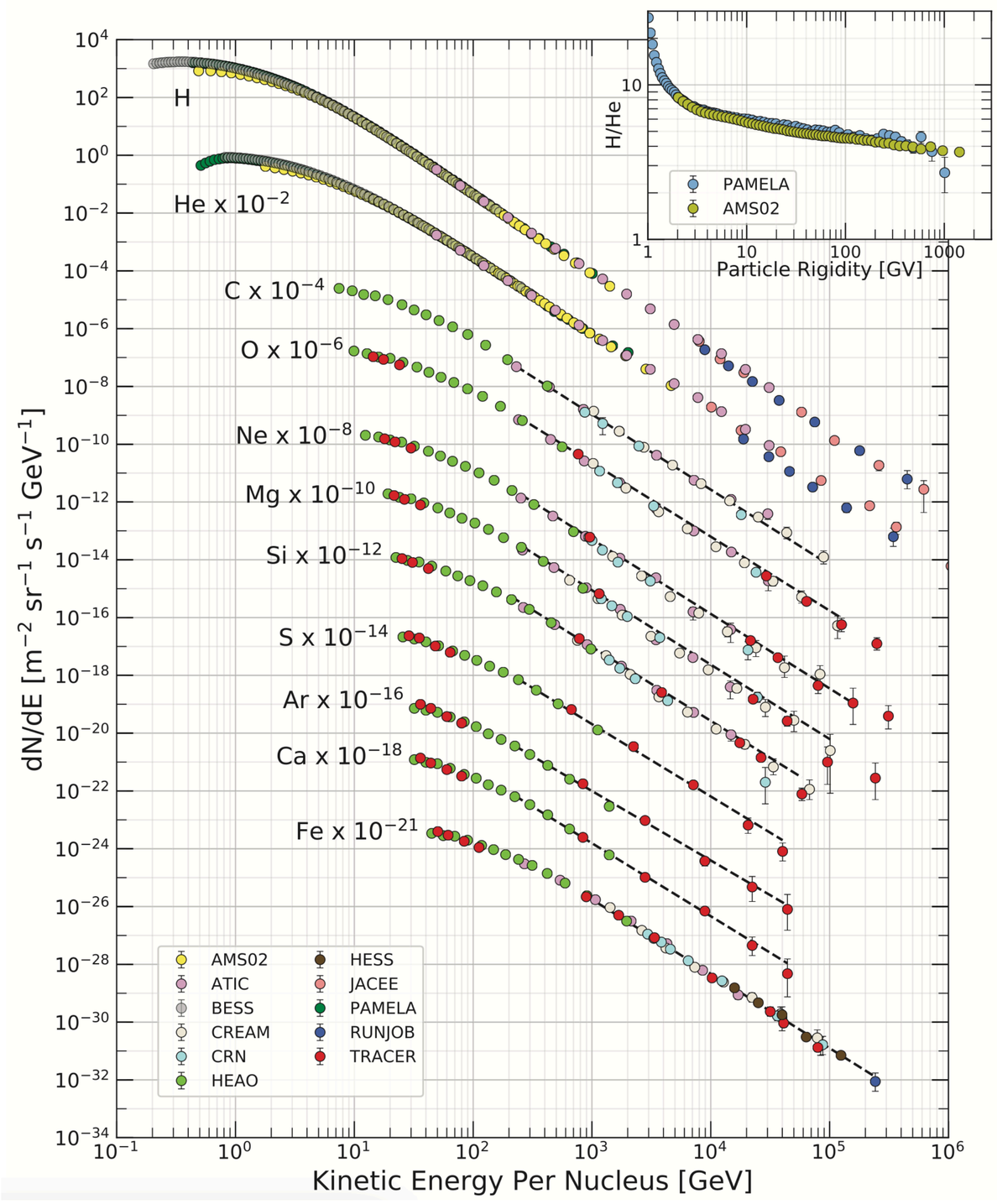


[R. Plestid et al., arXiv:2002.11732]

[M. Kachelriess et al., arXiv:2104.06811]

[C. A. Arguelles et al., arXiv:2104.13924]

CR spectrum



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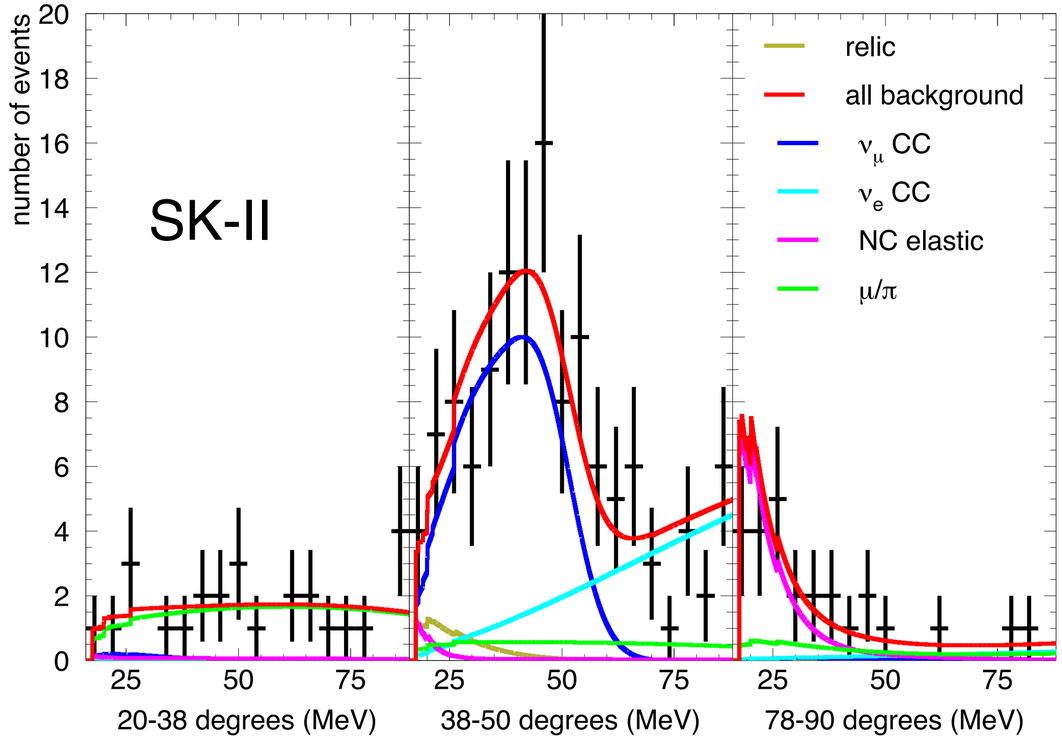
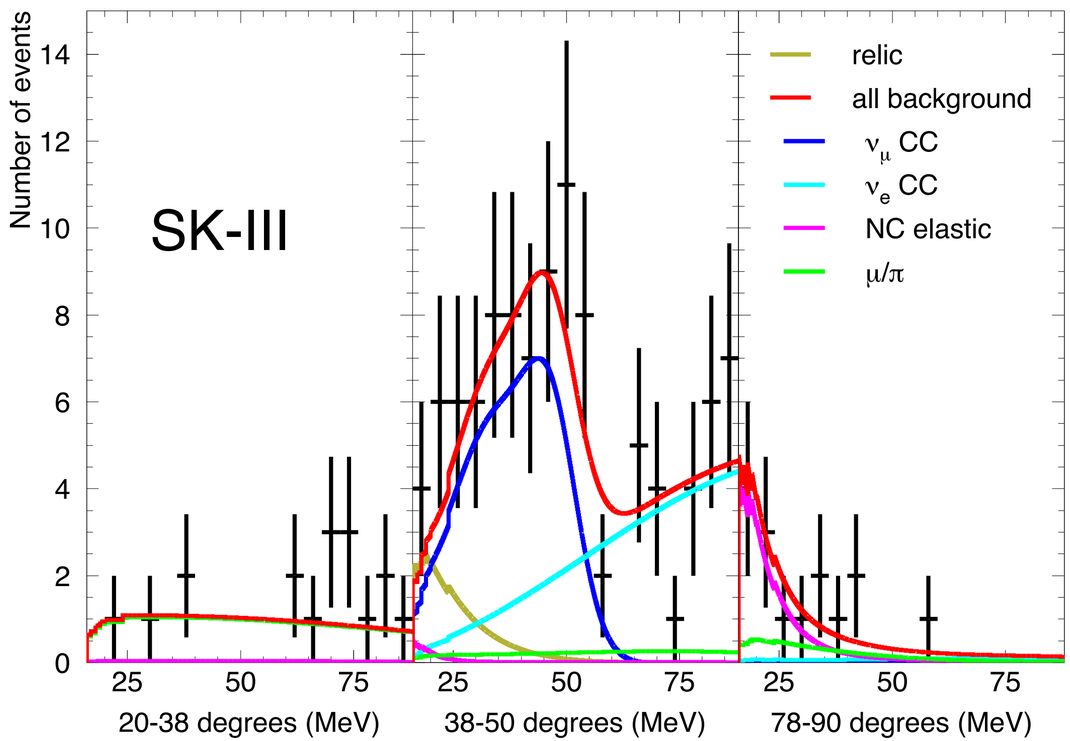
Other SuperK data sets





[SK, 1111.5031]