

Searching for Dark Photons through Charged Pion Bremsstrahlung

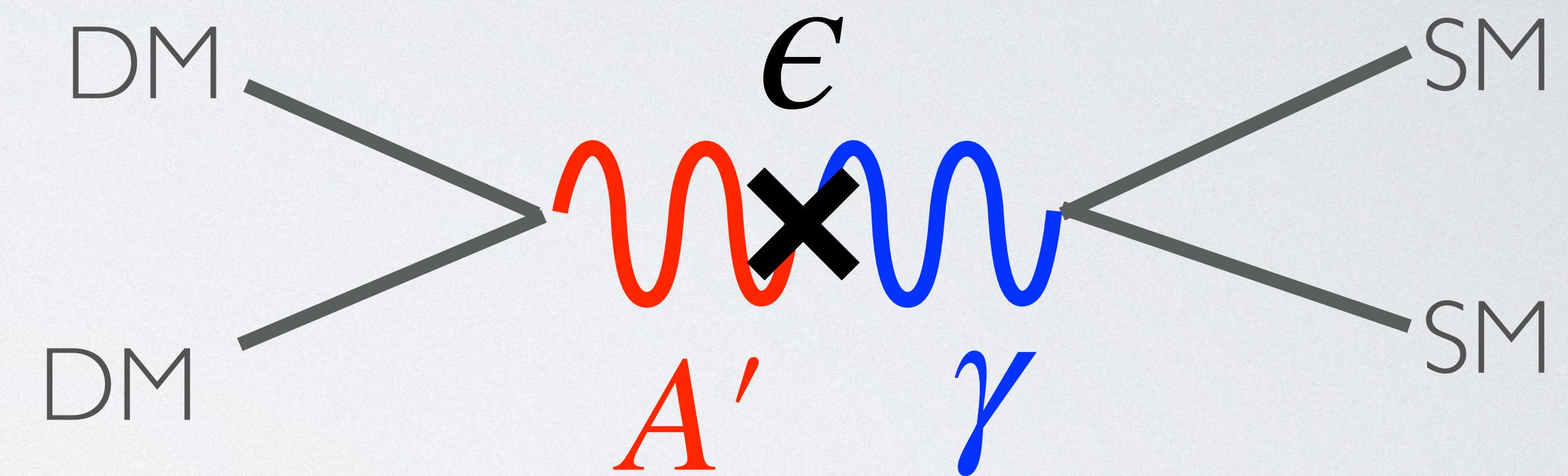
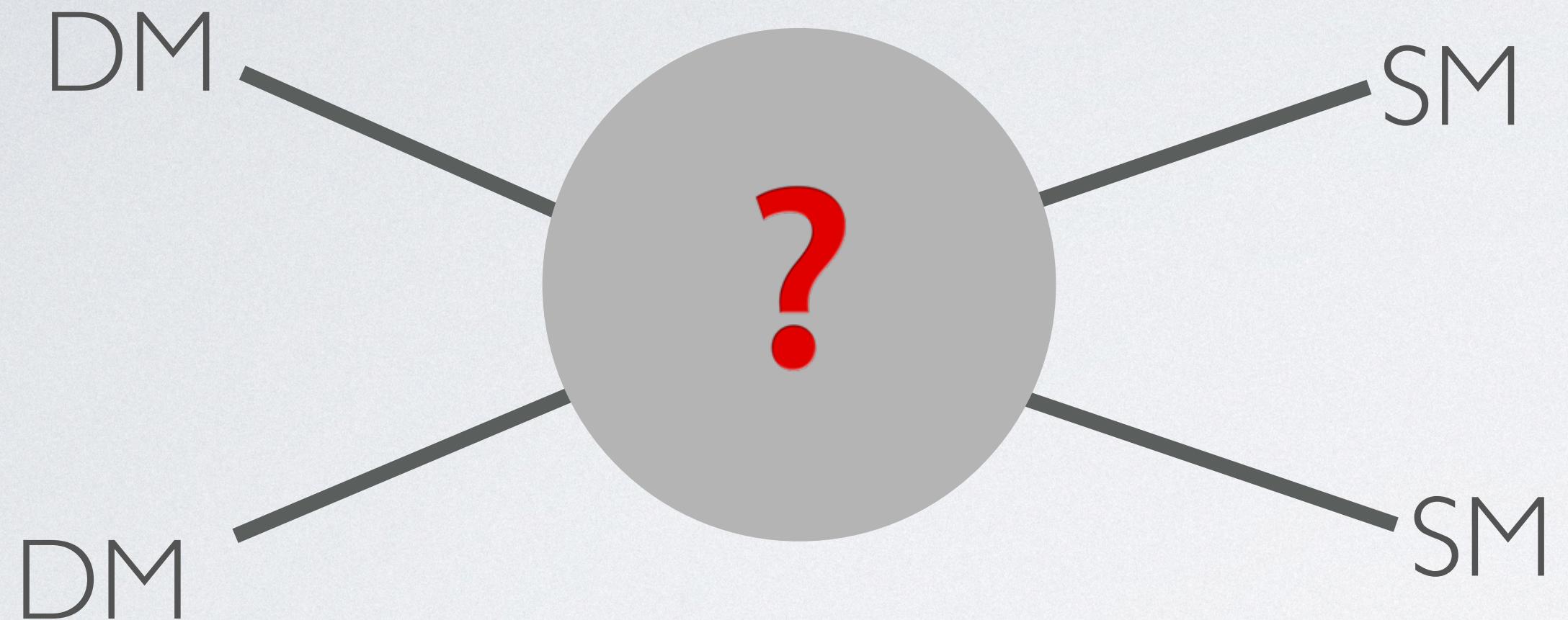
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In collaboration with Yoni Kahn and David Curtin

Phenomenology 2023 Symposium

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Dark photons are a possible portal between the dark sector and Standard Model



Dark photon couples to SM photon through kinetic mixing:

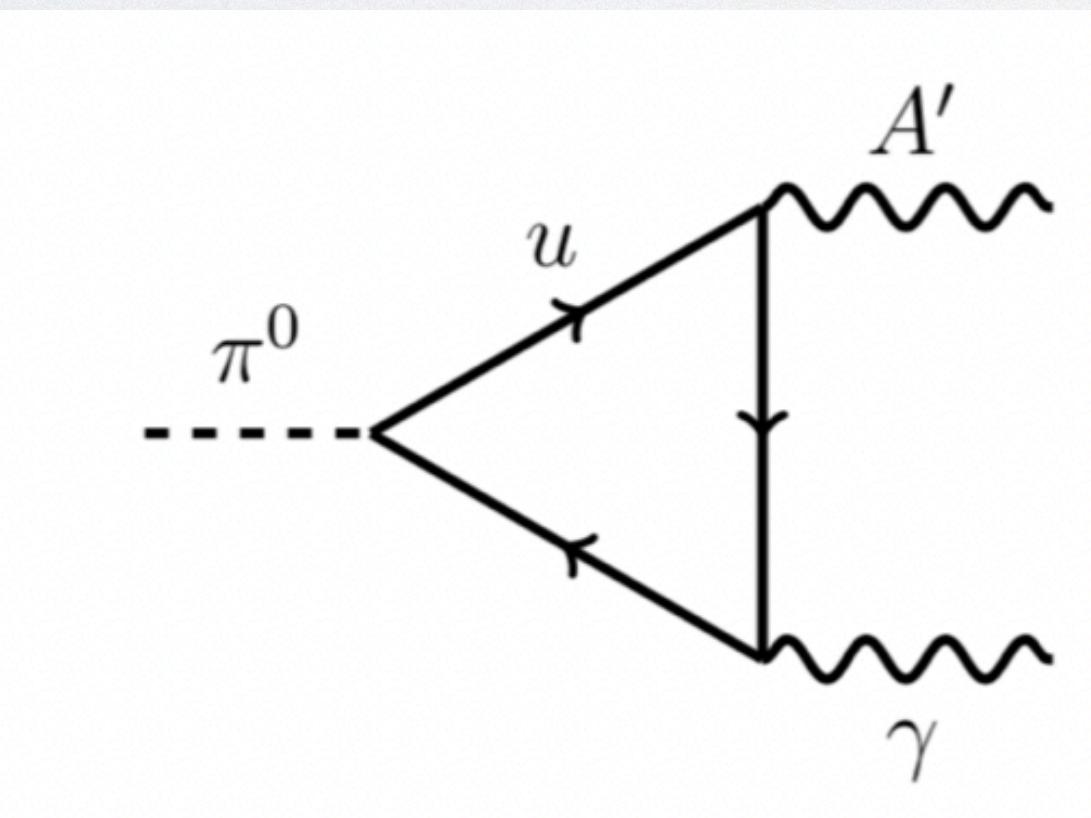
$$\mathcal{L} \supset \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

Dark photons can be produced through a variety of different mechanisms

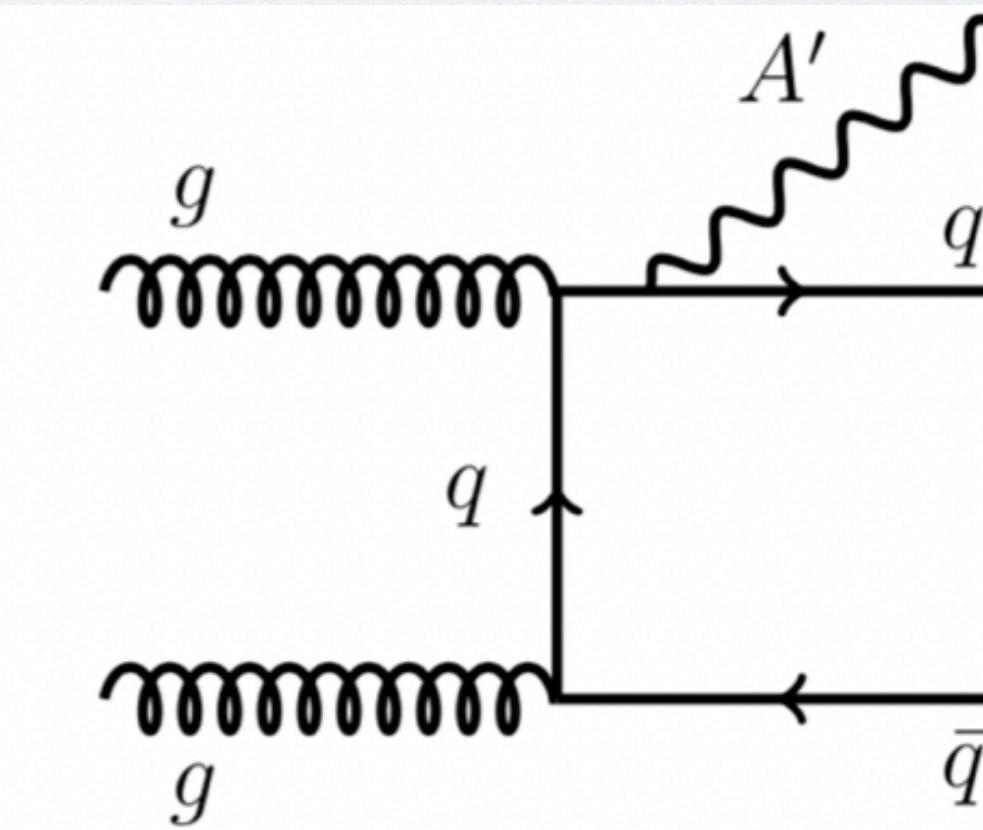
$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m_{A'}A'_{\mu}A'^{\mu} - e\epsilon A'_{\mu}\bar{\psi}\gamma^{\mu}\psi$$

dark photon - fermion coupling

Meson decay:



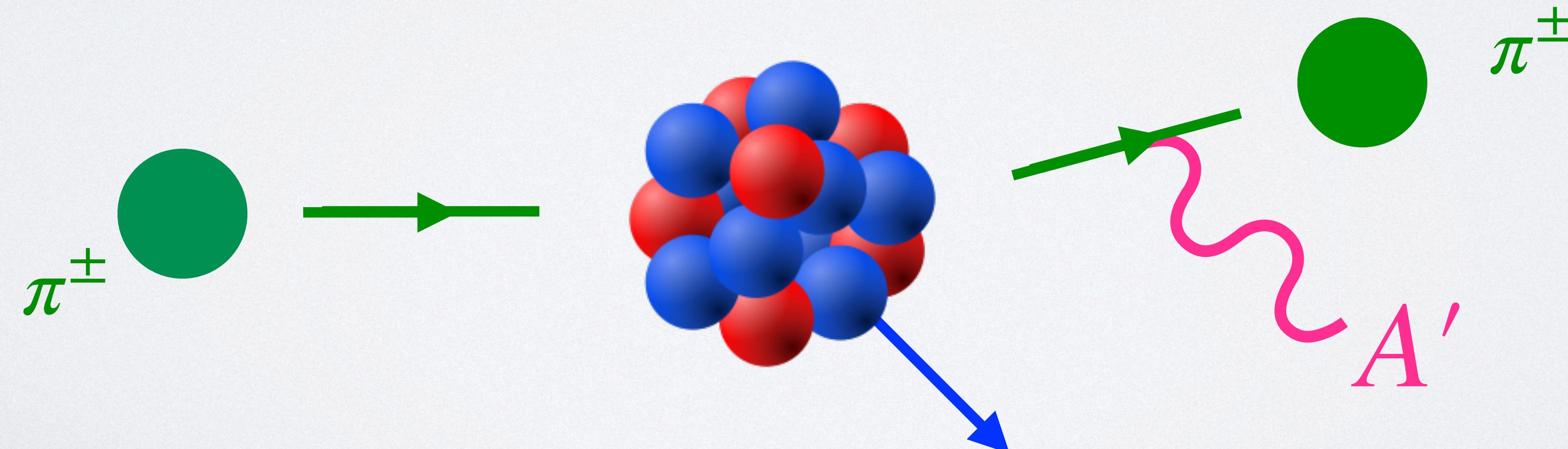
Proton Bremsstrahlung:



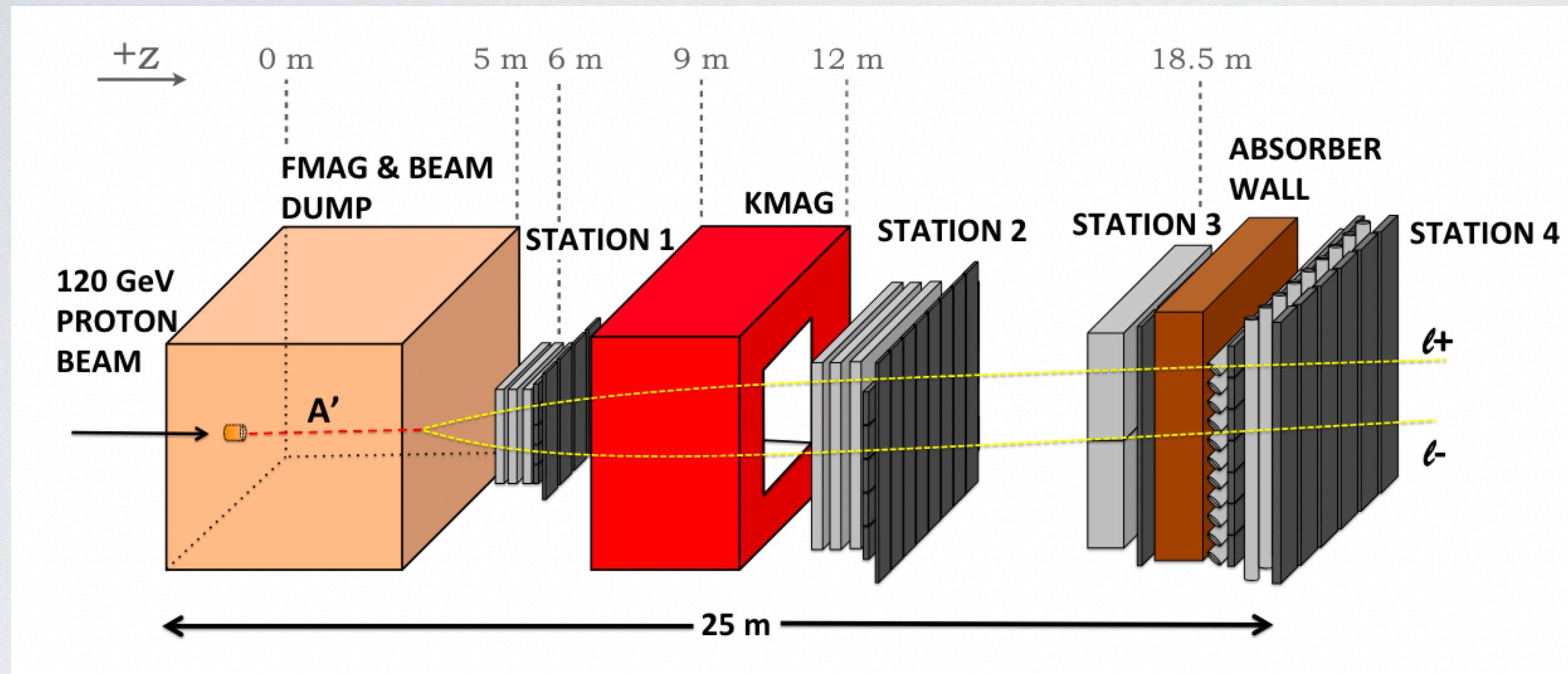
Dark photons can be produced through charged pion Bremsstrahlung

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m_{A'}A'_\mu A'^\mu - \boxed{ie\epsilon A'_\mu(\pi^+ \partial_\mu \pi^- - \pi^- \partial_\mu \pi^+)}$$

dark photon - charged pion coupling



SpinQuest Experiment at FermiLab



[arXiv:1804.00661]

Phase 1: $\sim 10^{18}$ POT
 $N_{\pi^\pm} \sim 6.5$ per proton

Currently taking data!!

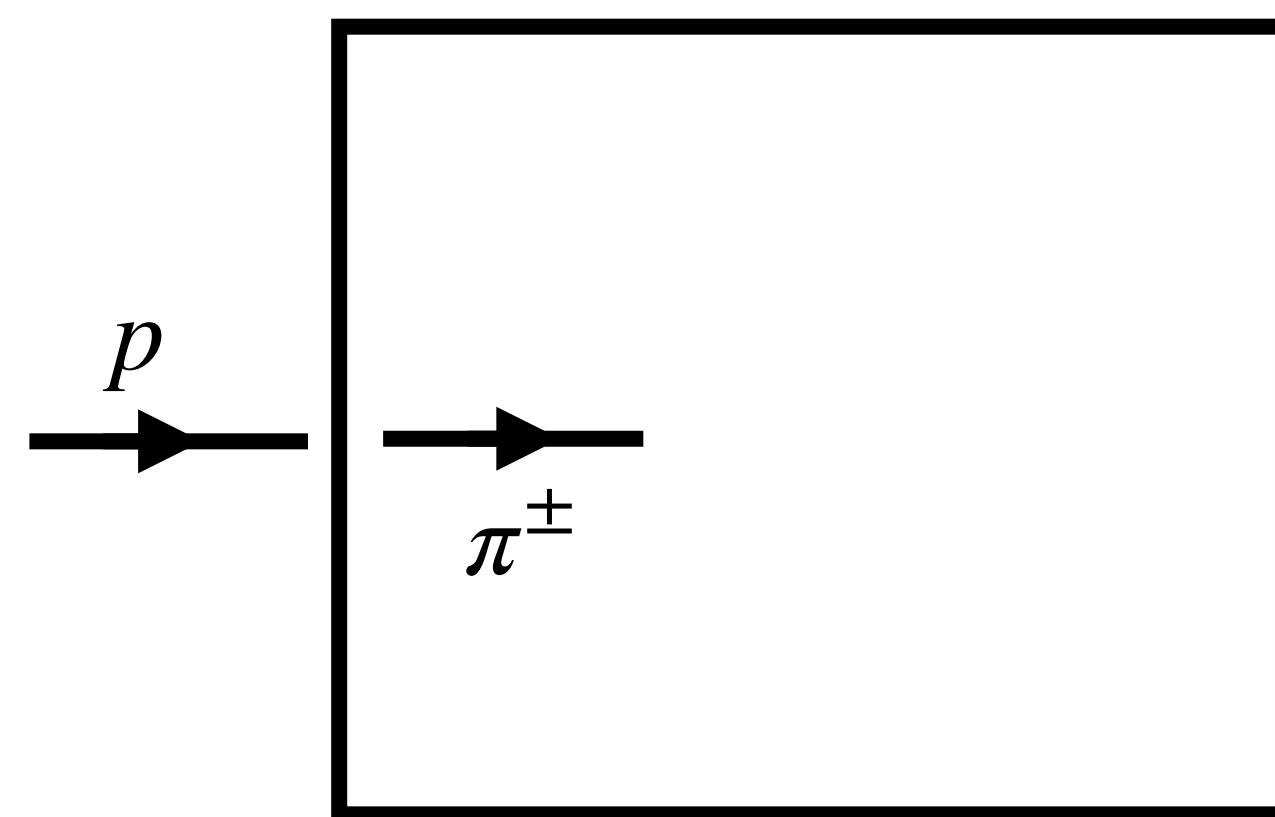
$$L_{A'} \equiv bc\tau_{A'} \approx 10m \left(\frac{E_{A'}}{5 \text{ GeV}} \right) \left(\frac{\text{GeV}}{m_{A'}} \right) \left(\frac{10^{-7}}{\epsilon} \right)^2$$

Monte Carlo method to simulate A' detection

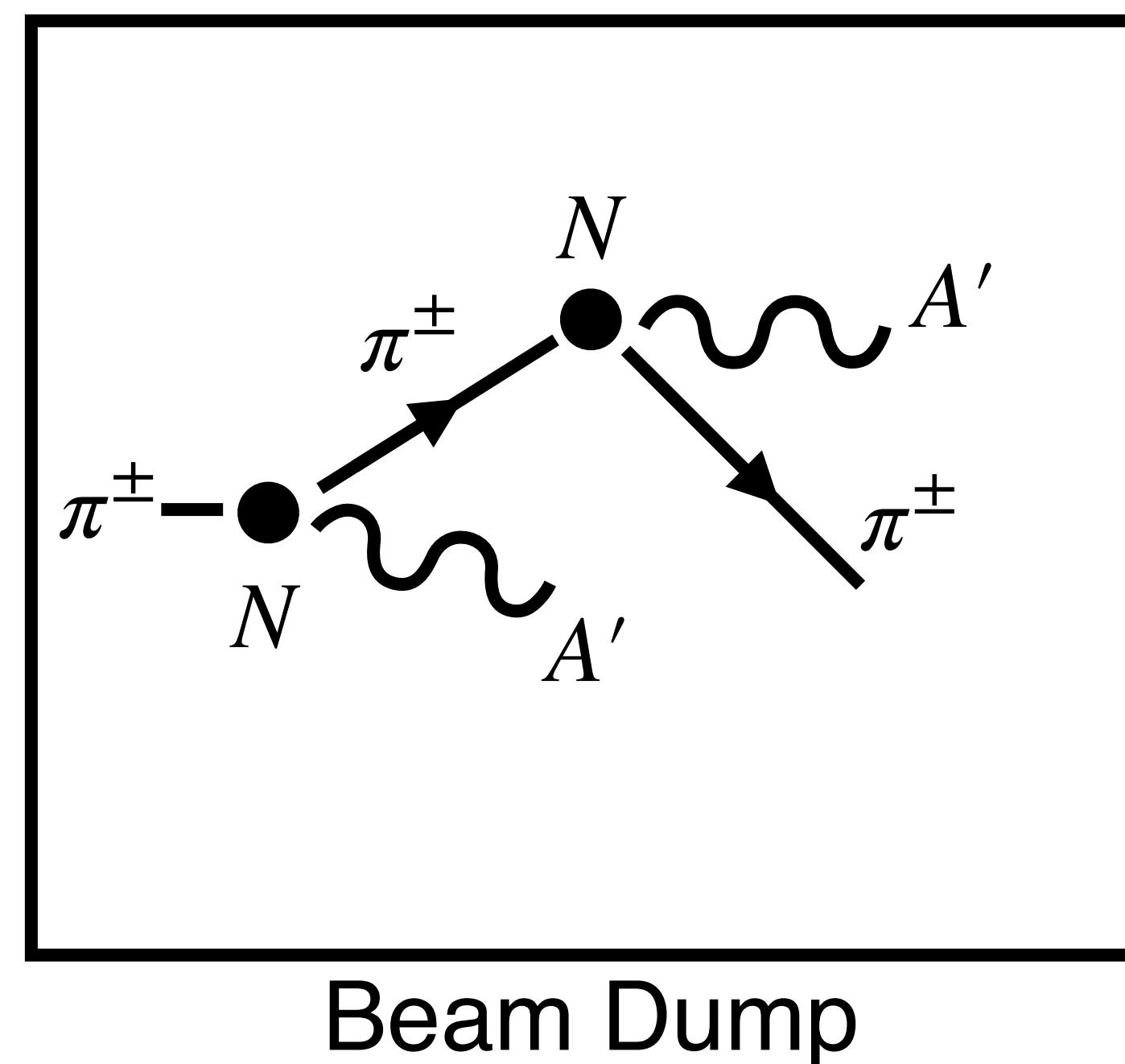
Create distribution of charged pions

Calculate number of dark photons produced from charged pion Bremsstrahlung

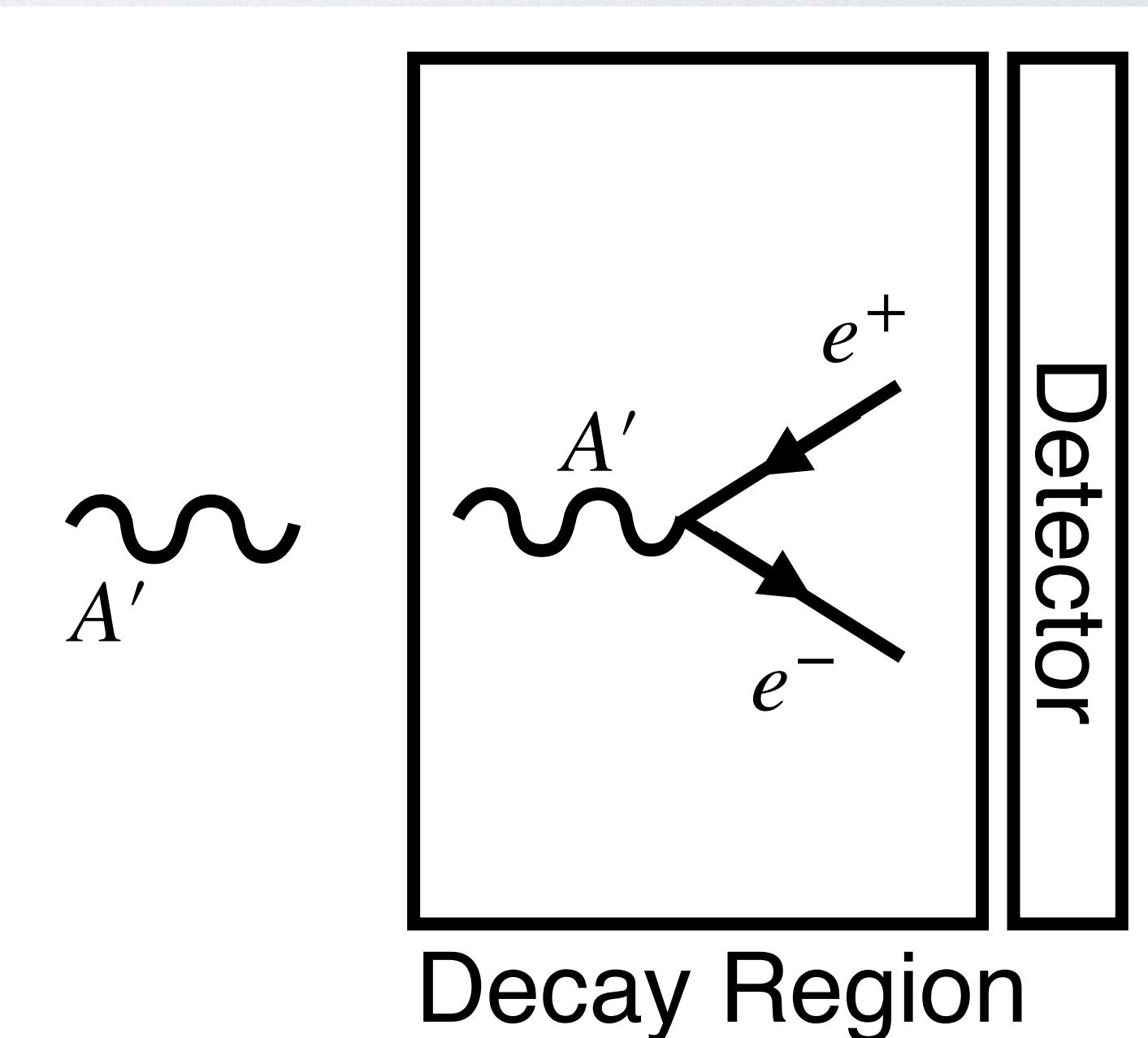
Calculate number of dark photons that decay in a detector



Beam Dump



Beam Dump



Decay Region

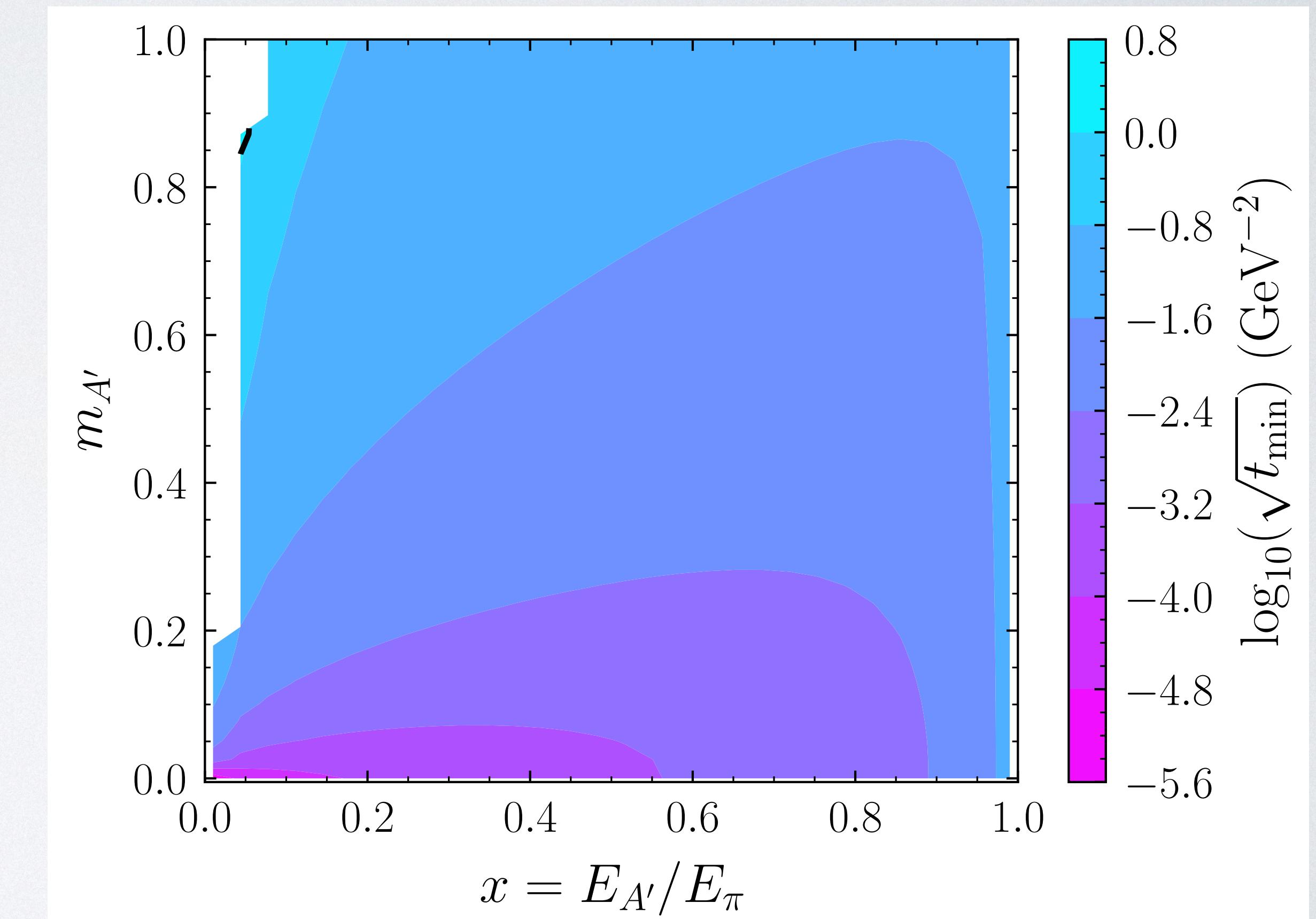
The QED Scattering process is suppressed compared to Chiral Perturbation theory

$$\sigma_{\text{QED}} \sim \frac{\epsilon^2 \alpha^3}{t_{\min}}$$

$$\sigma_{\chi\text{PT}} \sim \frac{\alpha \epsilon^2}{f_\pi^2}$$

For $m_{A'} \sim 1 \text{ GeV}$, $t_{\min} \sim f_\pi^2$:

$$\frac{\sigma_{\text{QED}}}{\sigma_{\chi\text{PT}}} \sim \alpha^2 \approx 5 \times 10^{-5}$$



Use Chiral Perturbation Theory to scatter pions and nucleons

$$\mathcal{L} = \frac{f_\pi^2}{4} \text{Tr}(D_\mu U^\dagger D^\mu U) + \frac{1}{4} m_\pi^2 f_\pi^2 \text{Tr}(U + U^\dagger - 2) + \bar{N} \left(i\gamma^\mu \mathcal{D}_\mu + \frac{g_A}{2} \gamma^\mu \gamma^5 u_\mu - M \right) N$$

Pion Matrix: $U(x) = \exp \left[\frac{i}{f_\pi} \pi^a(x) \sigma^a \right] = \exp \left[\frac{i}{f_\pi} \begin{pmatrix} \pi^0 & \sqrt{2}\pi^- \\ \sqrt{2}\pi^+ & -\pi^0 \end{pmatrix} \right]$

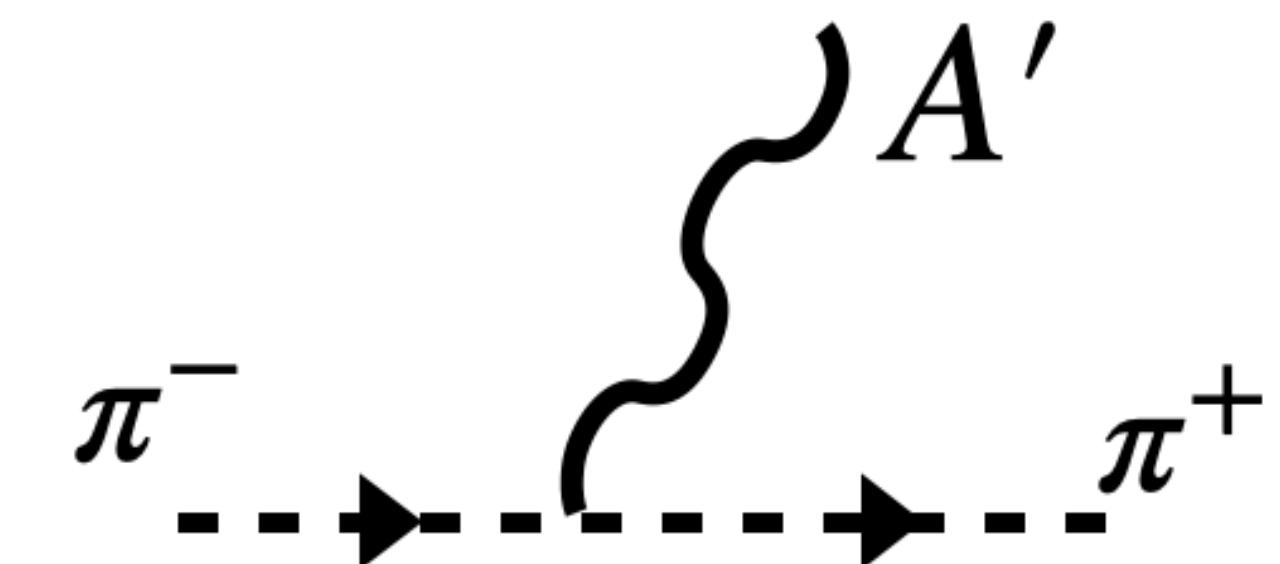
Nucleons: $N = \binom{p}{n}$

Use Chiral Perturbation Theory to construct cross section

$$\mathcal{L} = \boxed{\frac{f_\pi^2}{4} \text{Tr}(D_\mu U^\dagger D^\mu U) + \frac{1}{4} m_\pi^2 f_\pi^2 \text{Tr}(U + U^\dagger - 2)} + \bar{N} \left(i\gamma^\mu \mathcal{D}_\mu + \frac{g_A}{2} \gamma^\mu \gamma^5 u_\mu - M \right) N$$

Kinetic terms + mass terms + $\mathcal{L}_{\pi A'}$

$$\mathcal{L}_{\pi A'} = ie\epsilon A'_\mu \left[\pi^-(\partial_\mu \pi^+) - (\partial_\mu \pi^-)\pi^+ \right]$$



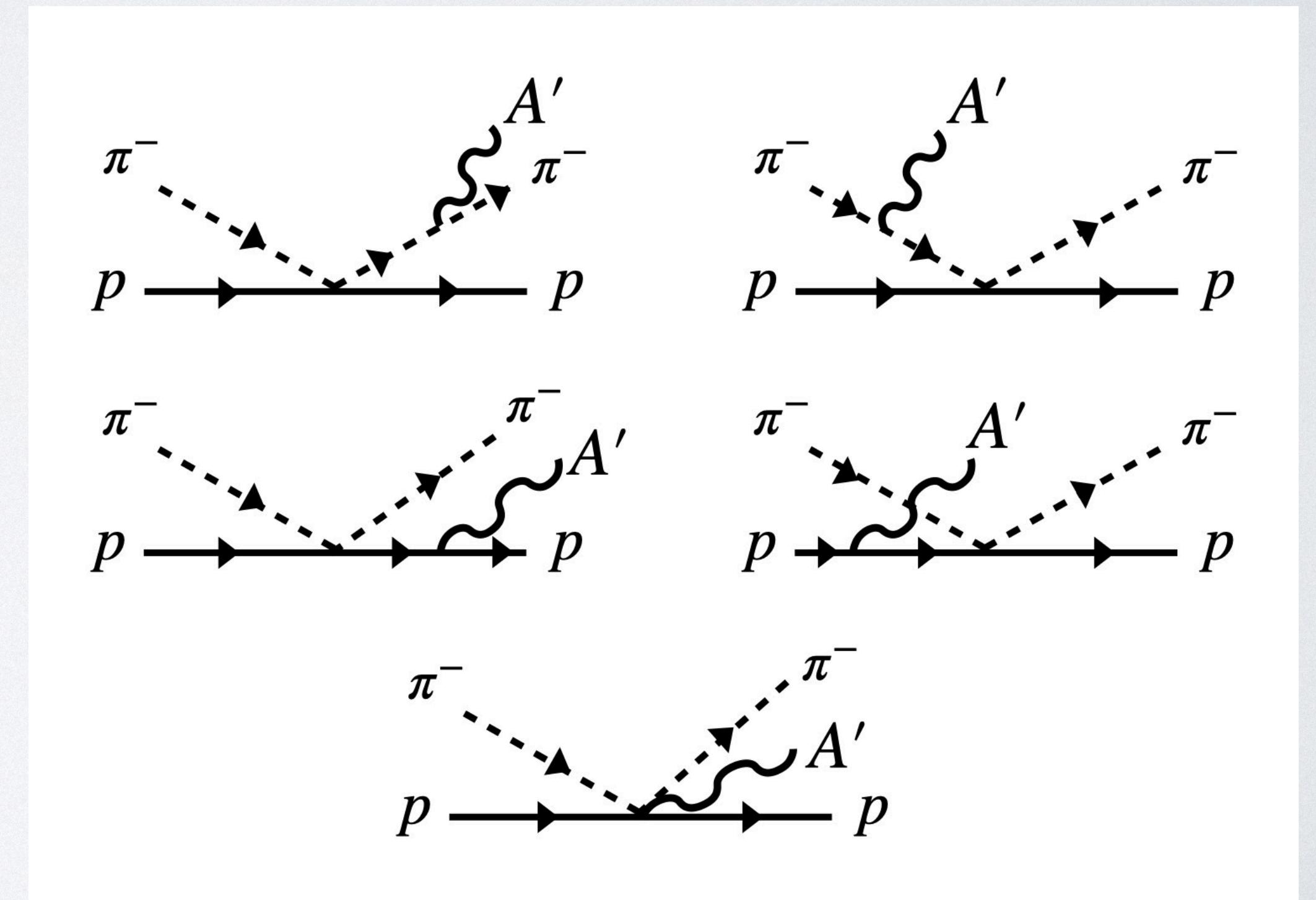
Use Chiral Perturbation Theory to construct cross section

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$$\bar{\mathcal{N}} \gamma^\mu \mathcal{D}_\mu \mathcal{N} = \bar{\mathcal{N}} \gamma^\mu (\partial_\mu + \boxed{\Gamma_\mu} + \boxed{i\nu_\mu^{(s)}}) \mathcal{N}$$

Adds $\pi\pi NN$ and $\pi\pi NNA'$ and ppA' interactions

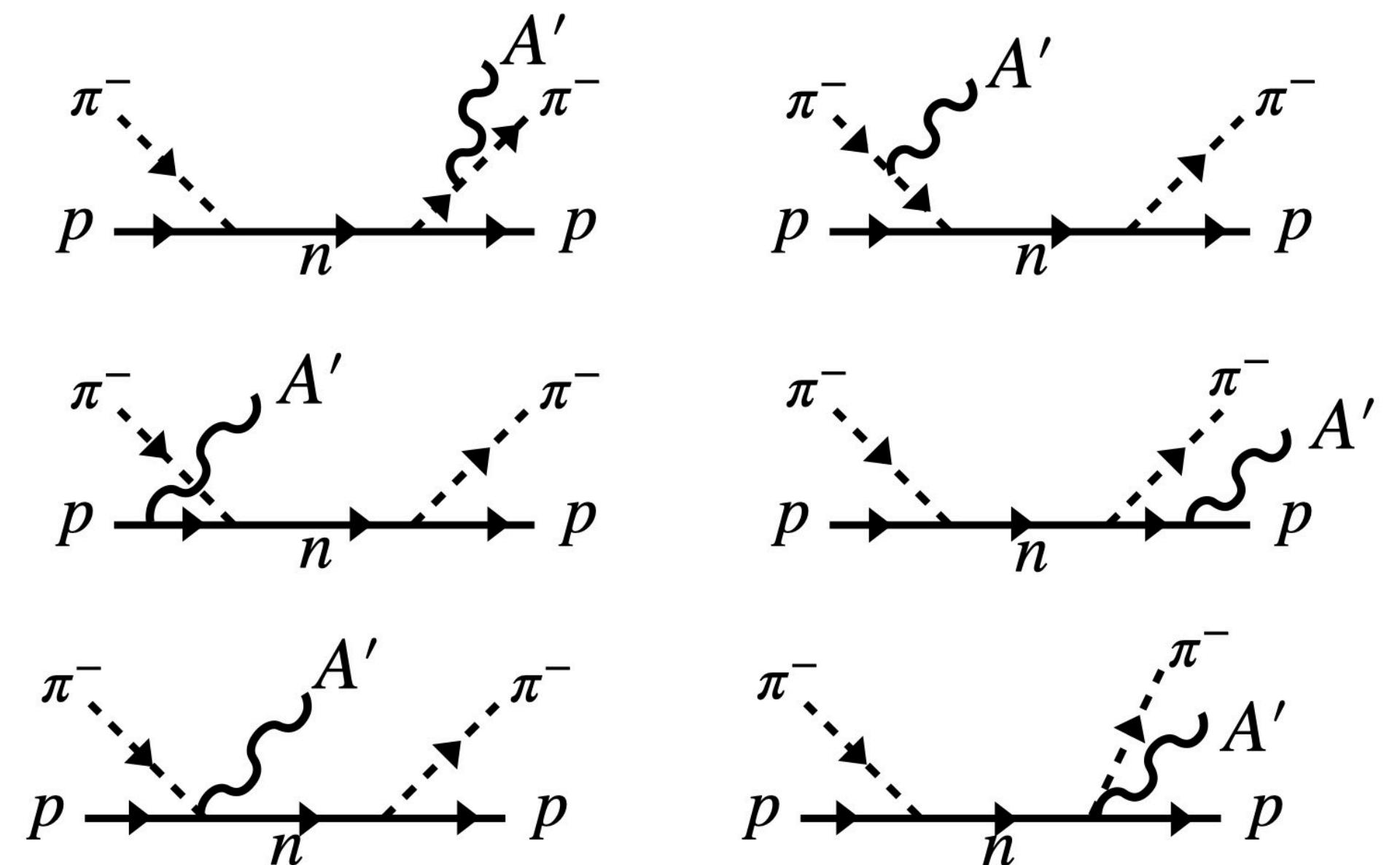
Ensures no nnA' interactions



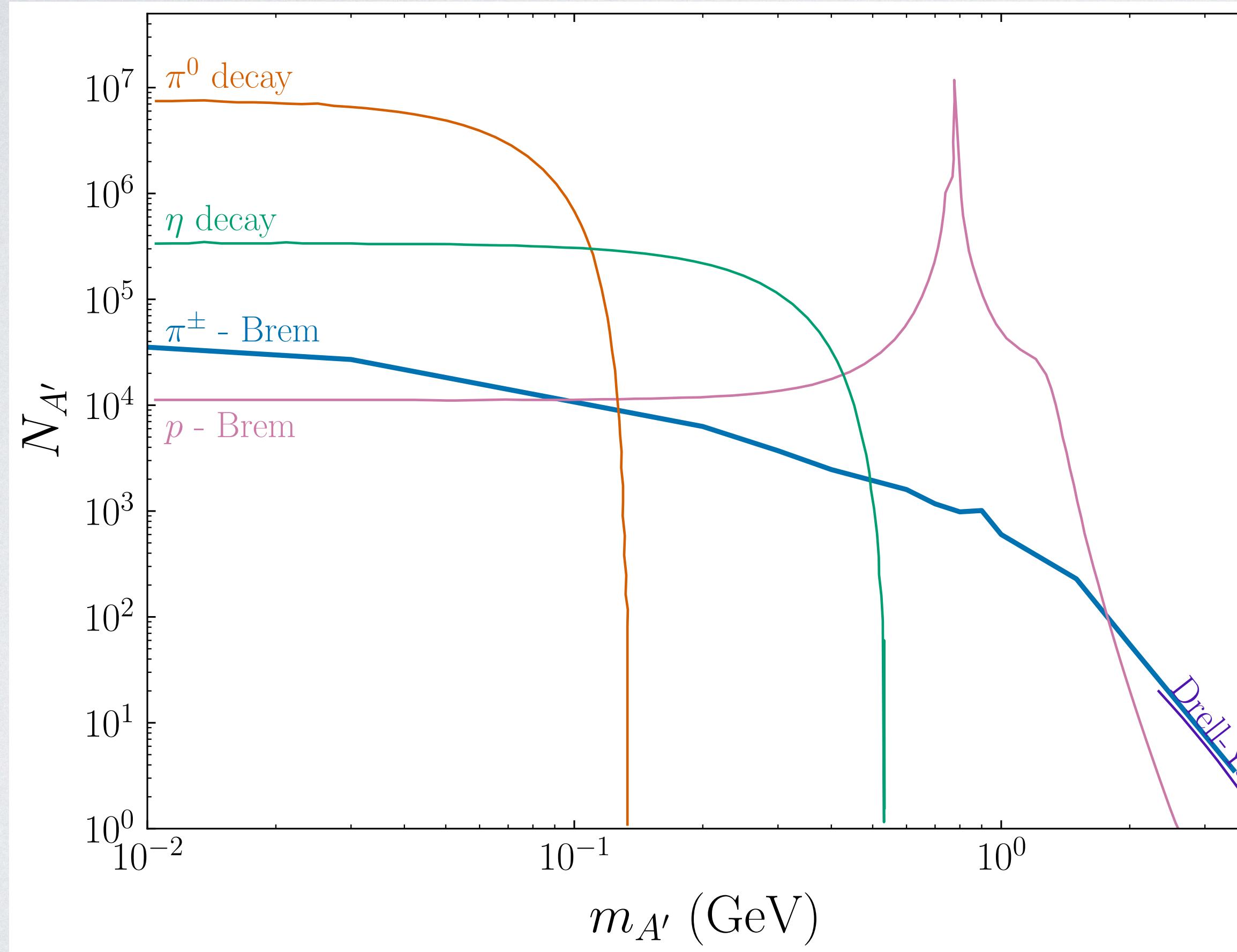
Use Chiral Perturbation Theory to construct cross section

$$\mathcal{L} = \frac{f_\pi^2}{4} \text{Tr}(D_\mu U^\dagger D^\mu U) + \frac{1}{4} m_\pi^2 f_\pi^2 \text{Tr}(U + U^\dagger - 2) + \bar{N} \left(i\gamma^\mu \mathcal{D}_\mu + \boxed{\frac{g_A}{2} \gamma^\mu \gamma^5 u_\mu} - M \right) N$$

Adds πNN and $\pi NNA'$ interactions



Number of A' produced at SeaQuest

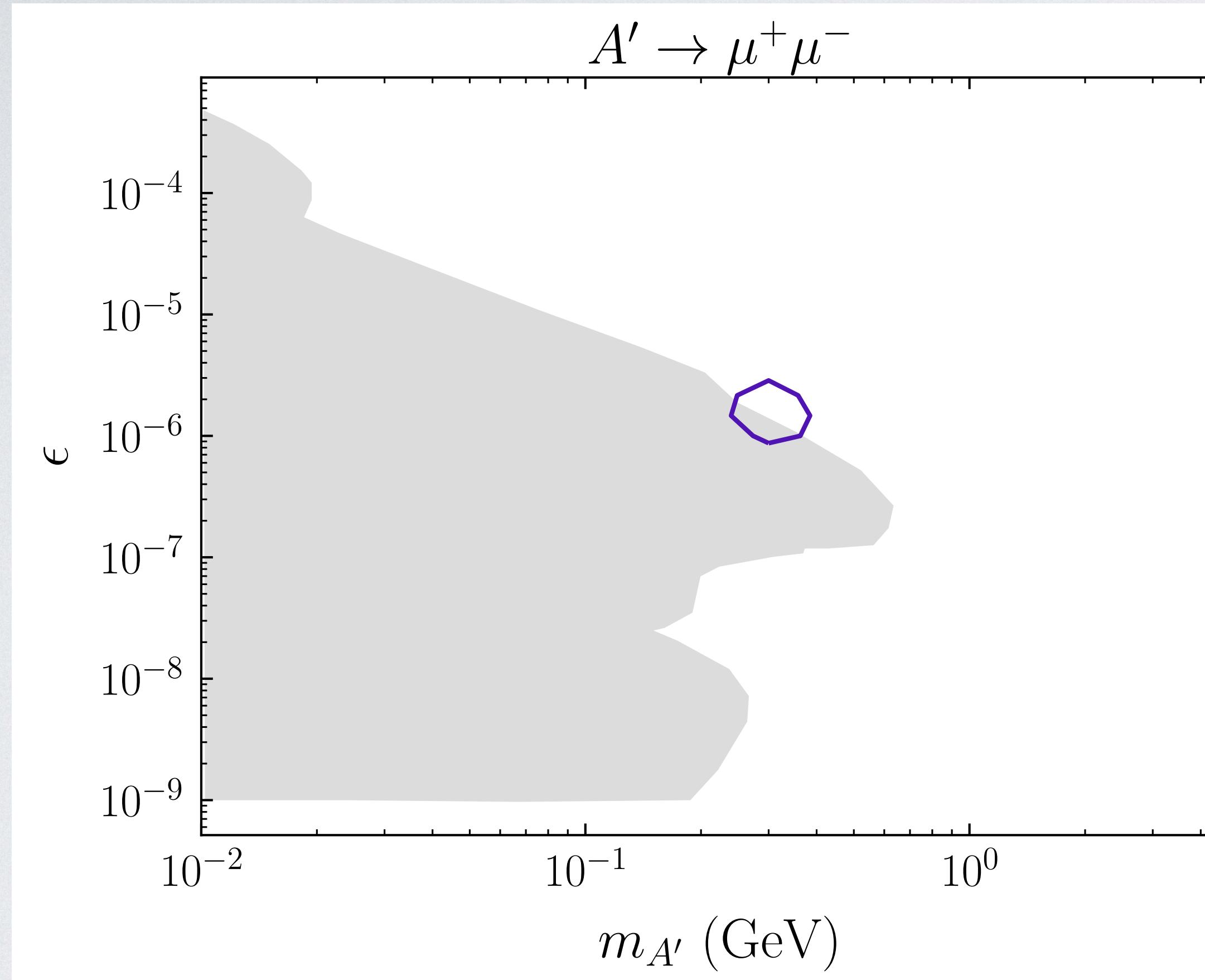


Charged pion bremsstrahlung
resembles Drell-Yan production
at large $m_{A'}$

More A' produced helps us
beat suppression by small ϵ

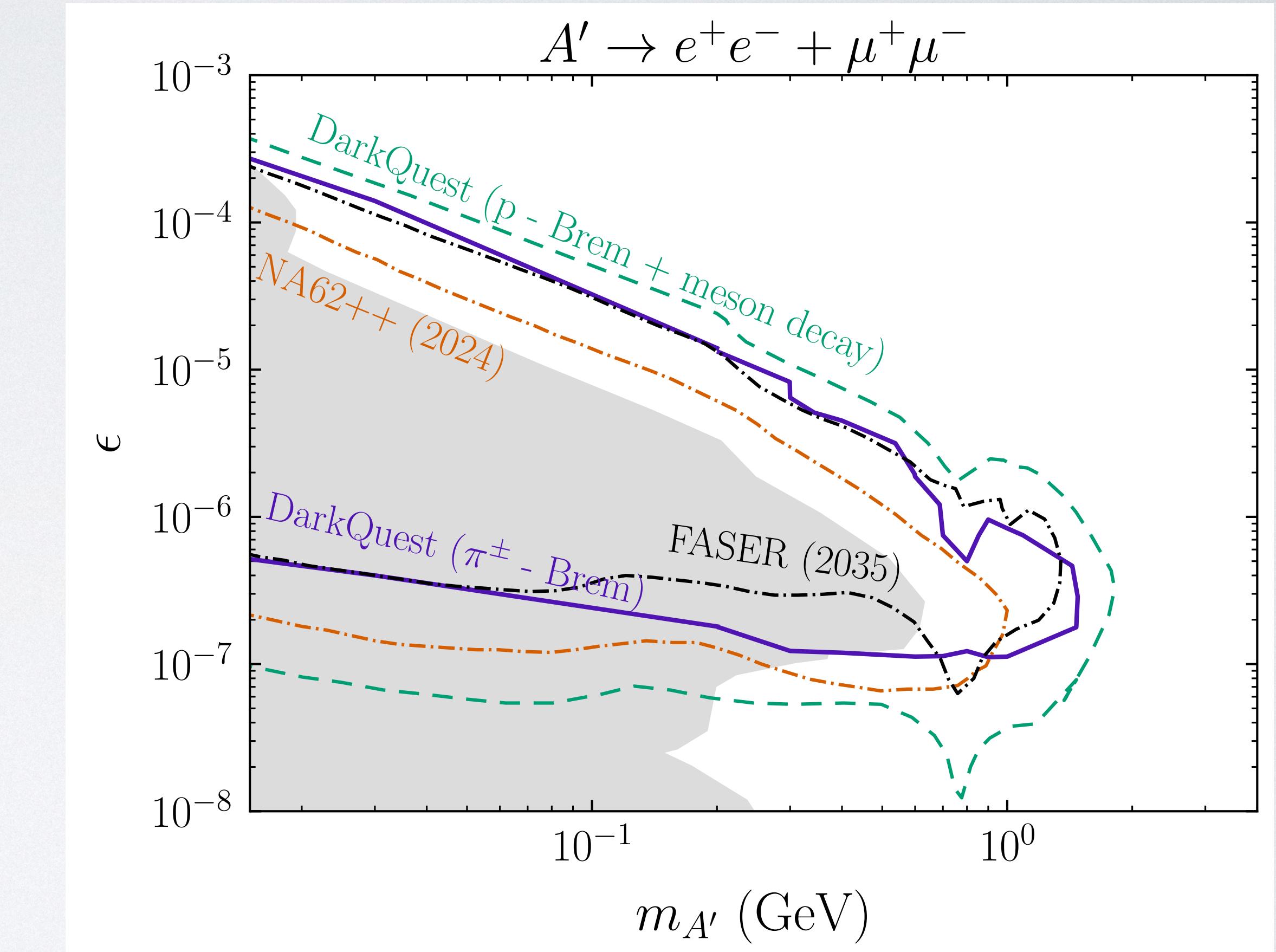
Neutral meson decay and p -Brem curves from [arXiv:1804.00661]

Sensitivity of SpinQuest to A'



10^{18} POT (2024)

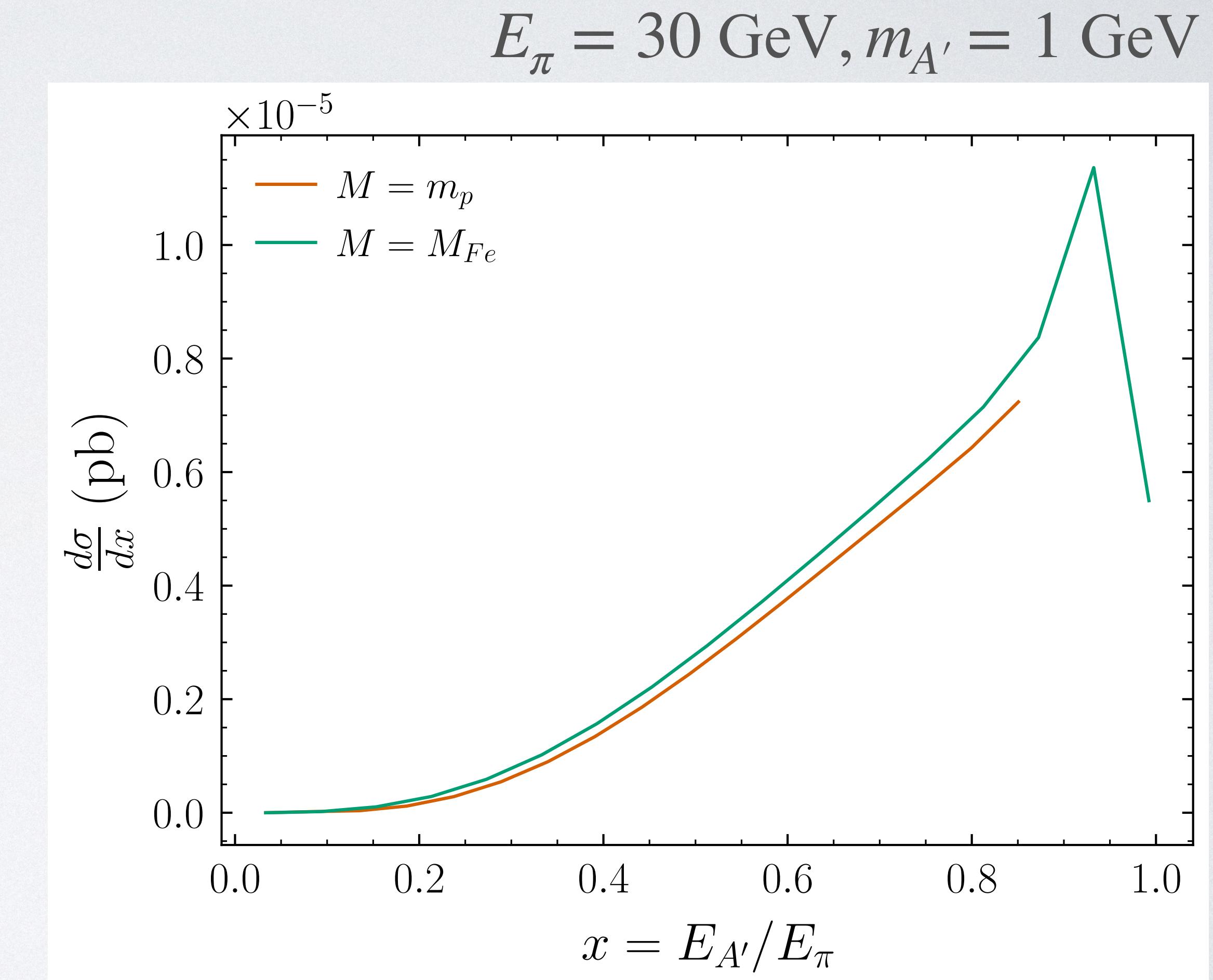
$N_{\text{signal}} = 10$ events



10^{20} POT (2030s)

Chiral Perturbation theory limits access to full phase space

- We cut off our momentum transfer at $t \sim (4\pi f_\pi)^2 \sim 1 \text{ GeV}$
- Without incorporating PDFs of pions and nucleus, we can't access full phase space
- $$x_{\max} = \frac{2E_\pi M - m_{A'}^2 - 2Mm_\pi}{2E_\pi(M + m_\pi)}$$



Conclusions and Future Work

- With just chiral perturbation theory we do not gain any significant sensitivity at large $m_{A'}$
- Next steps: incorporate PDFs of pions and nucleus to gain access to full phase space

