Pion capture as a probe of new physics

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Work in progress

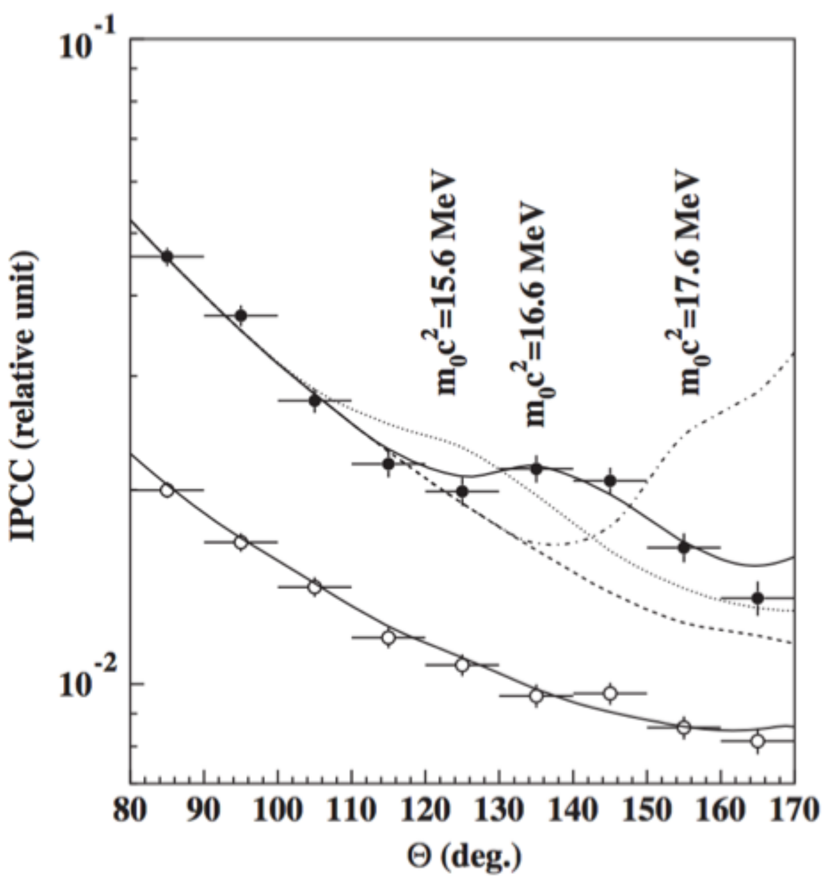
Pheno 2019

May 6, 2019

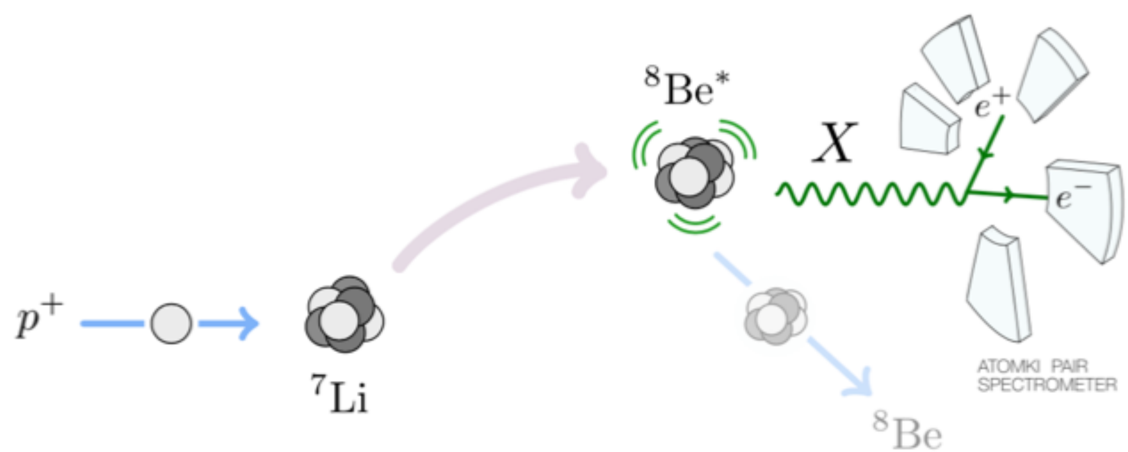
Beryllium anomaly

❖ The 17 MeV Beryllium anomaly ($6.8\ \sigma$): a resonance was observed at around 17 MeV in $^{8}\mathrm{Be}^{*} \to {}^{8}\mathrm{Be}\, e^{+}e^{-}$

[Krasznahorkay et al, 2016, Atomki collaboration]



$$^{8}\mathrm{Be}^{*} \to {}^{8}\mathrm{Be} + X,\ X \to e^{+}e^{-}$$



[Feng et al, 2016]

Beryllium anomaly

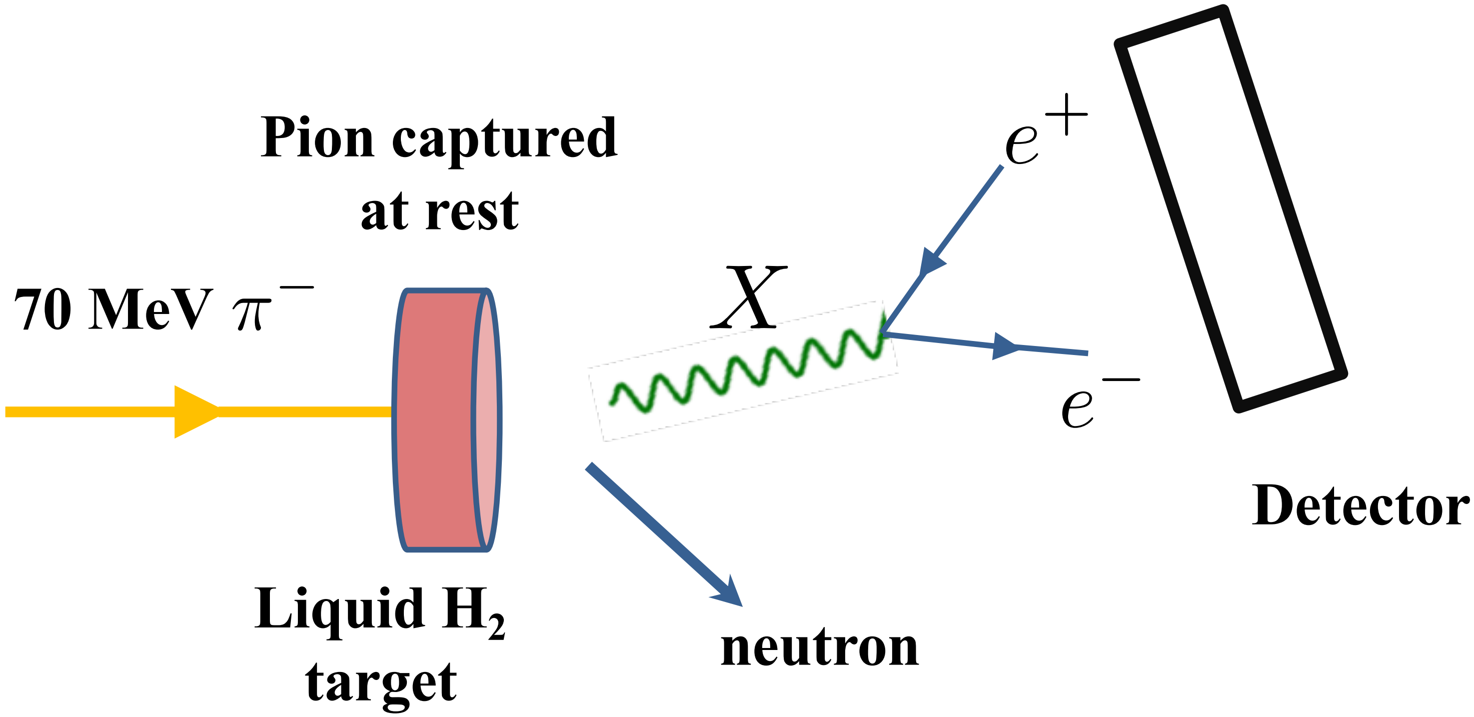
- Possible new physics explanations:
  - scalar: forbid by parity conservation
  - Axion-like particle: the relevant parameter space is ruled out.
  - Vector:
    - Dark photon: ruled out by NA-48.
    - Protophobic vector [Feng et al, 2016]
  - Axial vector: need to consider nuclear matrix element [Kozaczuk et al, 2017]
- Statistical fluctuation due to nuclear physics uncertainties?

Pion capture

- One of the simplest nucleon-involved processes that can be used to search for light weakly coupled states
- No complications from nuclear matrix elements such as those that appear in the Atomki experiment

Pion capture

$$p + \pi^- \rightarrow n + e^+ + e^-$$



- Potential candidate sites: TRIUMF or PSI (Paul Scherrer Institute)

Low energy effective Lagrangian

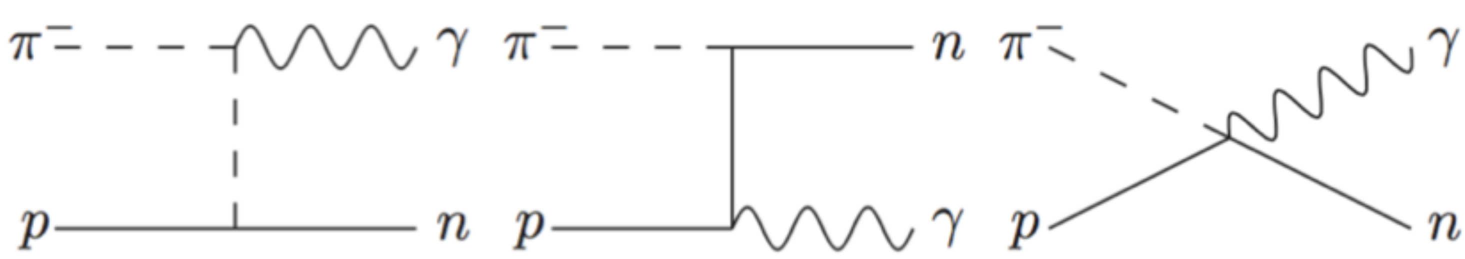
$$
\begin{aligned}
\mathcal{L} \supset & \left|(i\partial_\mu - eA_\mu)\,\pi^-\right|^2 - m_\pi^2 \pi^+\pi^- \\
& + \bar{p}\,(i\not{\partial} + e\not{A} - m_N)\,p + \bar{n}\,(i\not{\partial} - m_N)\,n \\
& - \frac{g_A}{\sqrt{2}F_\pi}\bar{n}\gamma^\mu\gamma^5 p\,(\partial_\mu + ieA_\mu)\,\pi^-
\end{aligned}
$$

$g_A = 1.275$ is the nucleon axial vector coupling
$F_\pi = 92$ MeV is the pion decay constant

- Pion capture rate:

$$
\frac{d\,(\sigma v)_{\pi^- p \to e^+ e^- n}}{(\sigma v)_{\pi^- p \to \gamma n}} = \frac{2\alpha}{3\pi}\frac{dm_{ee}}{m_{ee}} \times f\left(\frac{m_{ee}}{m_N}, \frac{m_\pi}{m_N}\right)
$$

v is the final state velocity



Protophobic vector

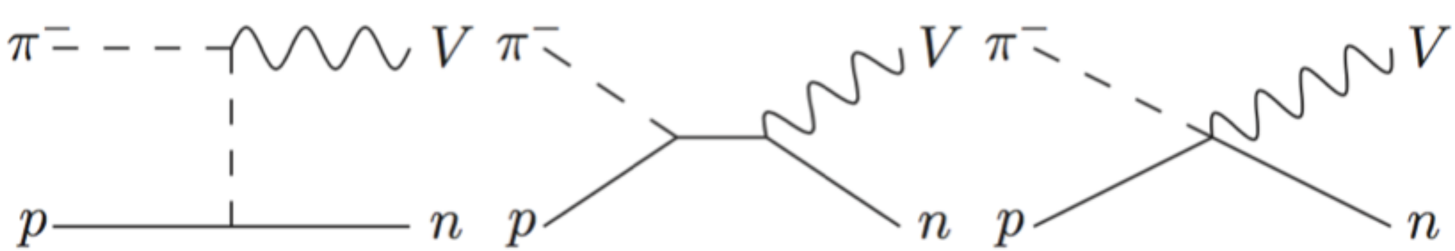
- [8]Be anomaly can be explained if $Q_d = -2Q_u$, [Feng et al, 2016]

$$Q_n = \epsilon$$
$$Q_{\pi^-} = \epsilon$$
$$Q_p = 0$$

$$\begin{aligned}\mathcal{L} \supset & \left|(i\partial_\mu + \epsilon e V_\mu)\,\pi^-\right|^2 - m_\pi^2 \pi^+\pi^- \\ & + \bar{p}\,(i\not{\partial} - m_N)\,p + \bar{n}\,(i\not{\partial} + \epsilon e \not{V} - m_N)\,n \\ & - \frac{g_A}{\sqrt{2}F_\pi}\bar{n}\gamma^\mu\gamma^5 p\,(\partial_\mu - i\epsilon e V_\mu)\,\pi^-\end{aligned}$$

- Relative pion capture rate:

$$\frac{(\sigma v)_{\pi^- p \to V n}}{(\sigma v)_{\pi^- p \to \gamma n}} = \frac{\epsilon^2}{(1 + m_\pi/m_N)^2}\, g\left(\frac{m_V}{m_N}, \frac{m_\pi}{m_N}\right)$$



Results

- 10^{10} pion captures
- ~ 1 day of running
- Require:

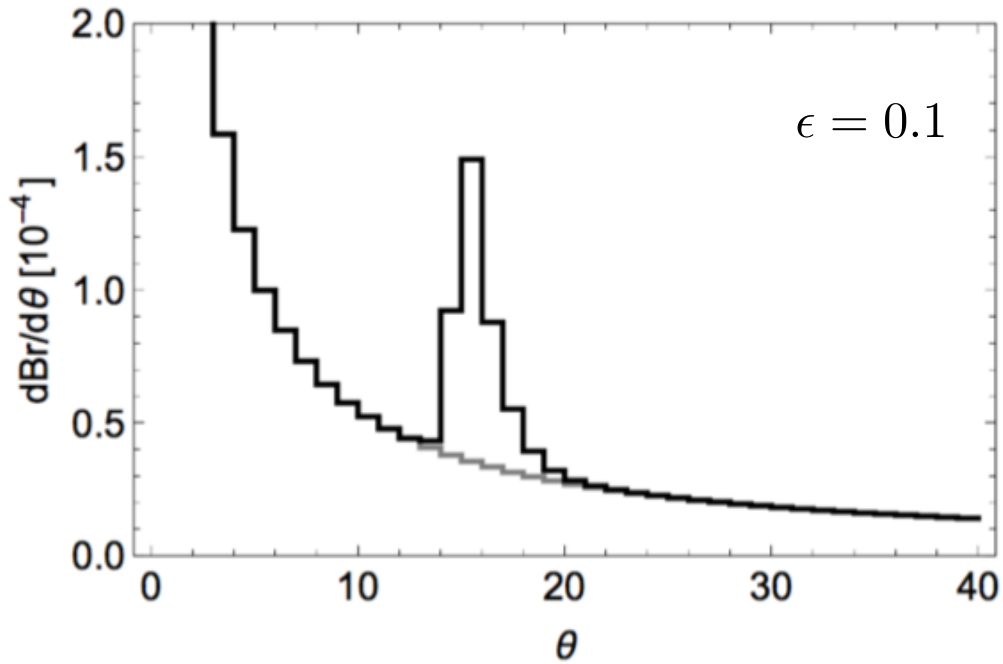
$$-0.5 \leq \frac{E_+ - E_-}{E_+ + E_-} \leq 0.5$$

since signal events have a more symmetric distribution

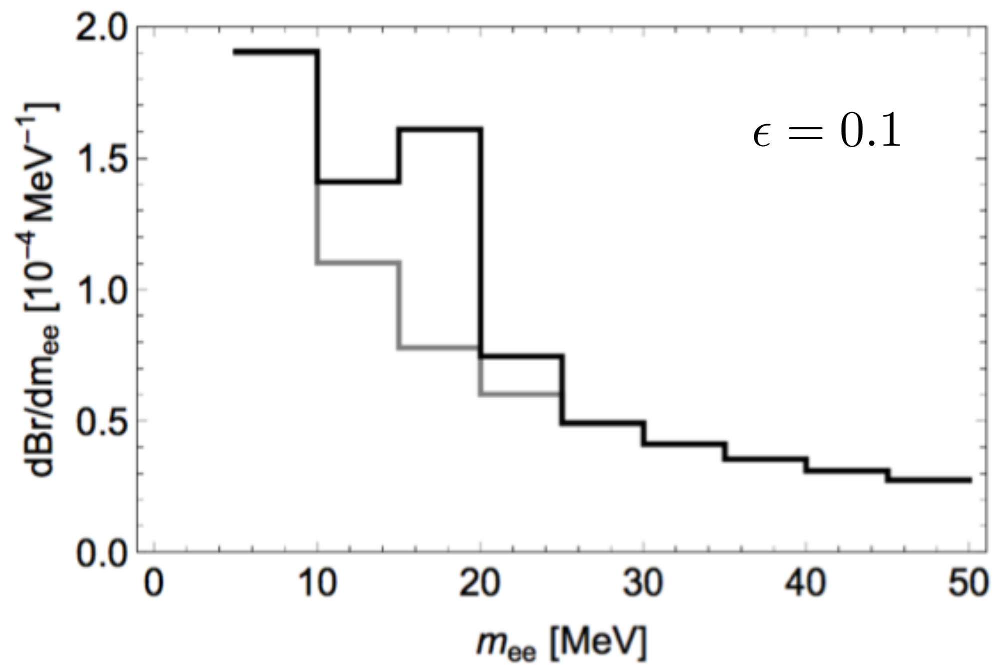
- use $m_V = 17\ \mathrm{MeV}$ for the signal events
- Energy resolution: 30 %
- Angular resolution: 1°

distributions

- Opening angle distribution of e^+e^- pair: promising

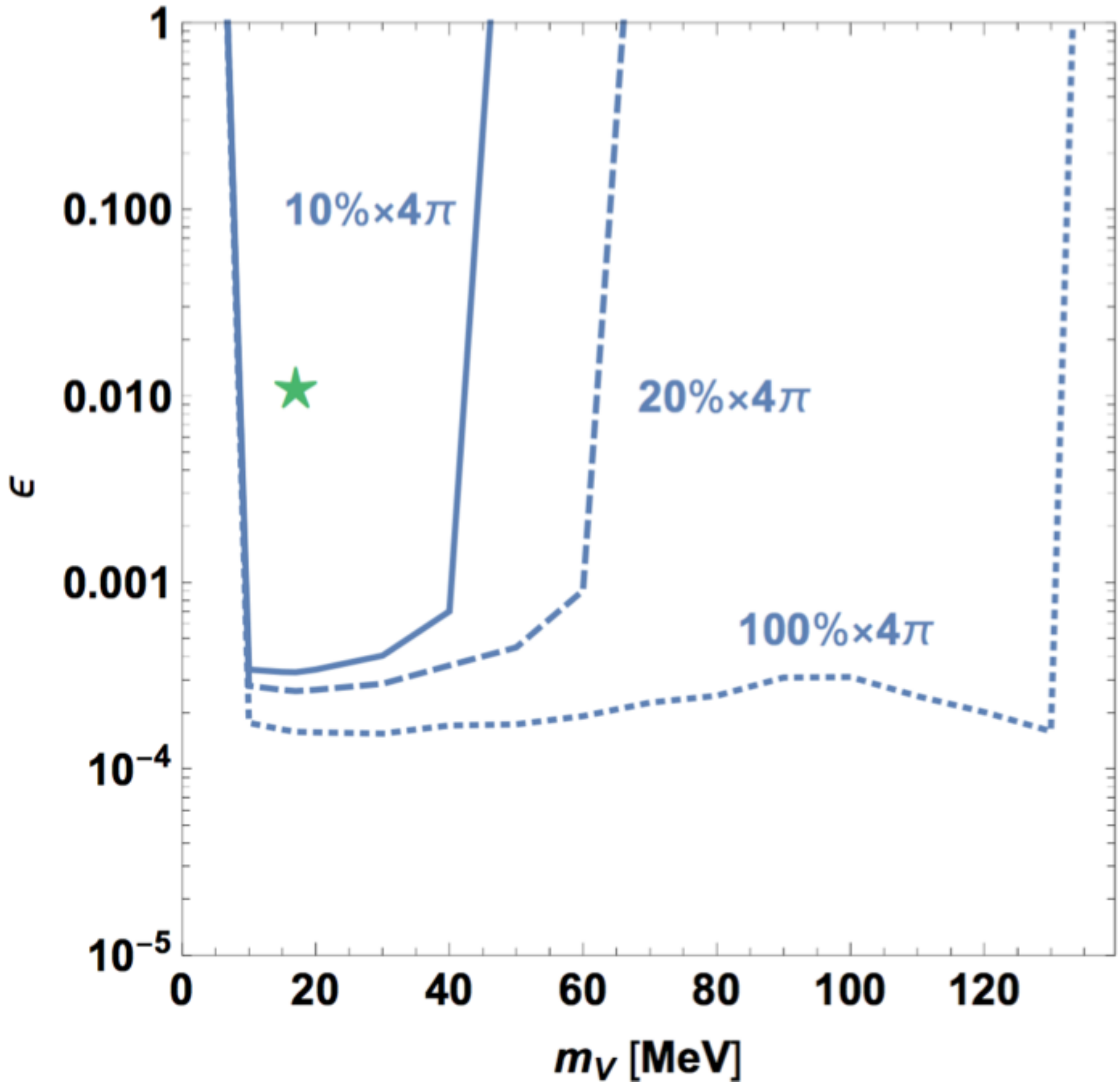


- Invariant mass of e^+e^- pair: challenging



Reach

- Green star: parameter point that can explain ^{8}Be anomaly



Conclusion and outlook

- Pion capture on protons can be use to search for light degrees of freedom coupled to quarks and decaying electromagnetically

- With a powerful source of sub-100 MeV pion, one can probe the dark vector boson parameter space down to epsilon ~ 10^{-3} in the mass range of a few MeV to m_π

- Protophobic dark vector hypothesis can be decisively tested in our proposal without involving any possible nuclear physics complications

- However, powerful sources of pion beam (sub-100 MeV momentum) only exist in a few labs around the world, one can consider other also simple hadronic reactions, such as
$$\mathrm{D}+p \to {}^3\mathrm{He}+\gamma(X)$$

BACKUP SLIDES

- Relative pion capture rates:

$$\frac{d\,(\sigma v)_{\pi^- p \to e^+ e^- n}}{(\sigma v)_{\pi^- p \to \gamma n}} = \frac{2\alpha}{3\pi}\frac{dm_{ee}}{m_{ee}} \times f\left(\frac{m_{ee}}{m_N}, \frac{m_\pi}{m_N}\right)$$

- For dark photon

$$f(x,y) = \sqrt{1-\frac{x^2}{y^2}}\frac{\left(1-z^2\right)^{3/2}}{\left(1-xz\right)^2\left(1-xz/y^2\right)^2} \times \left\{1-\frac{z^2}{2y^2}\left[7-4y^2-\frac{x^2}{y^2}\left(2-2y-4y^2+x^2\right)\right]\right\}$$

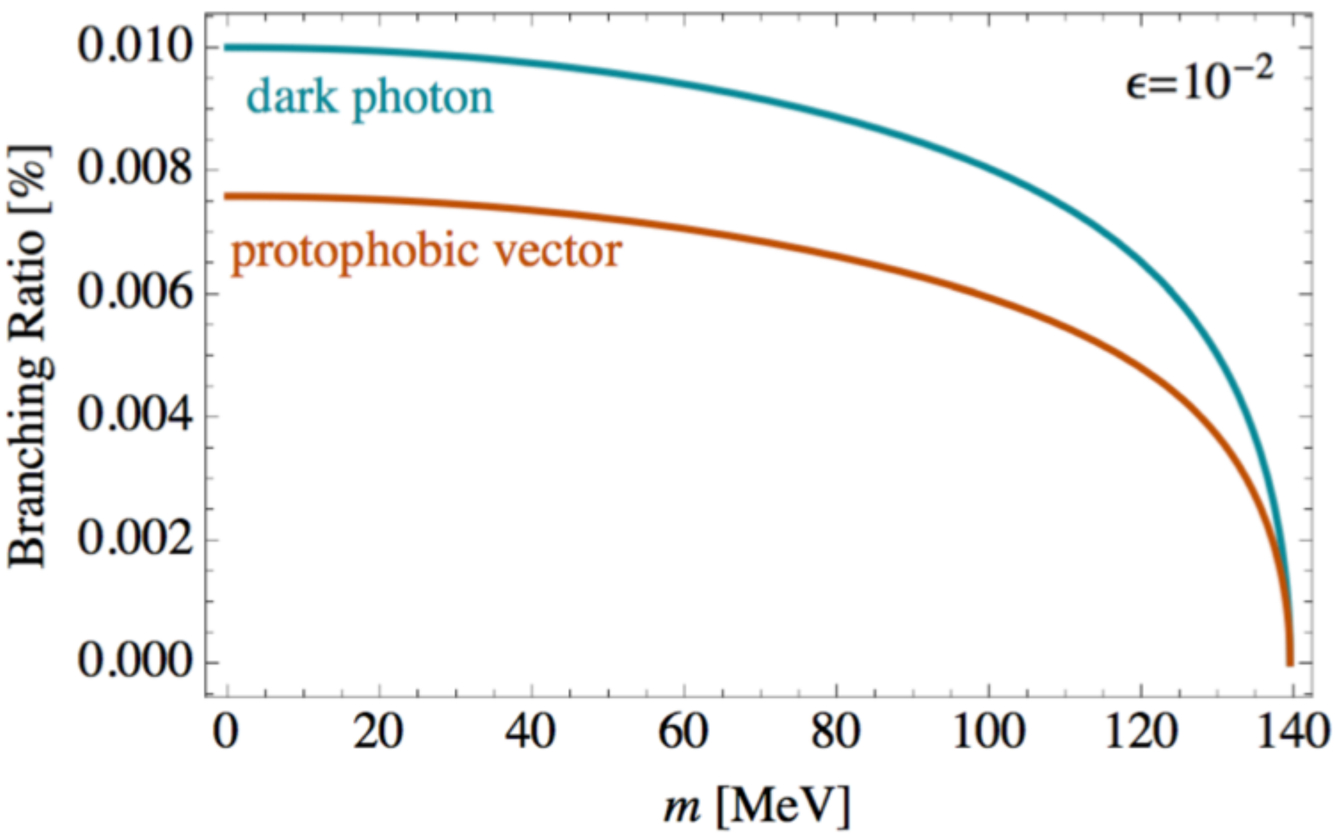
$$\frac{(\sigma v)_{\pi^- p \to A' n}}{(\sigma v)_{\pi^- p \to \gamma n}} = \epsilon^2 f\left(\frac{m_{A'}}{m_N}, \frac{m_\pi}{m_N}\right)$$

- For protophobic vector:

$$\frac{(\sigma v)_{\pi^- p \to V n}}{(\sigma v)_{\pi^- p \to \gamma n}} = \frac{\epsilon^2}{\left(1+m_\pi/m_N\right)^2}\, g\left(\frac{m_V}{m_N}, \frac{m_\pi}{m_N}\right)$$

$$g(x,y) = \sqrt{1-\frac{x^2}{y^2}}\left[1-\left(\frac{x}{2+y}\right)^2\right]^{3/2} \times \left\{1+\frac{1}{2}\left[\frac{xy\,(1+y)}{(2+y)\,y^2-x^2}\right]^2\right\}$$

Branching fraction



NA48/2 Collaboration, 2015