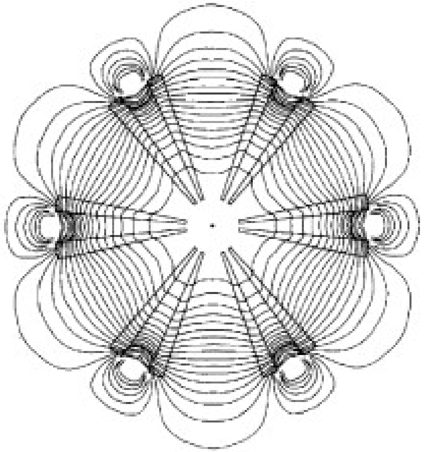
The MiniBooNE Anomaly and Dark Sectors



Adrian Thompson
Texas A&M University

PITT-PACC Workshop: ν Tools for BSM at Neutrino Beam Facilities
December 15, 2022

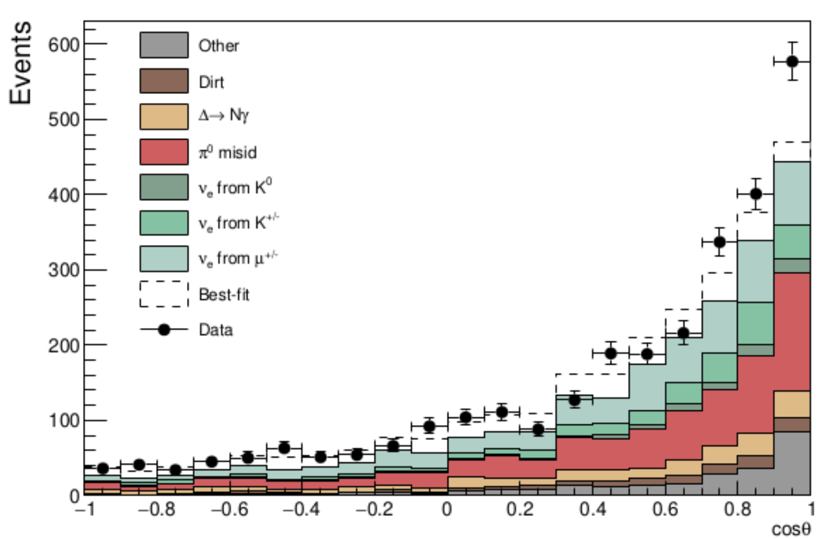
The MiniBooNE Anomaly

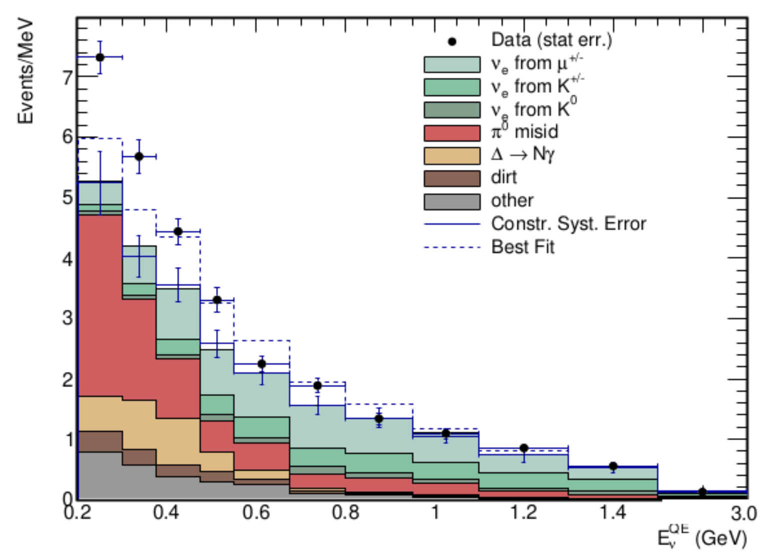
- MiniBooNE, 2021 [2006.16883]
- MiniBooNE, 2019 [1807.06137]
- MiniBooNE, 2018 [1805.12028]

Two main features of the excess:

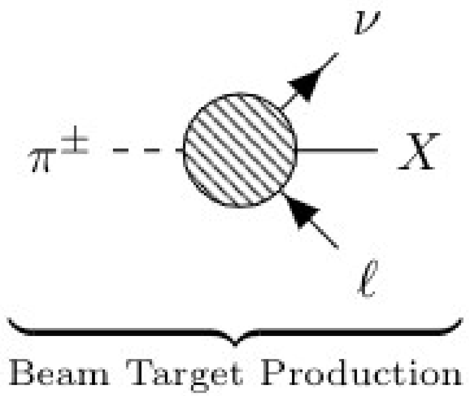
1. Excess in the target-mode runs, no observed excess in the dump-mode run
2. Excess shows distinct angular and energy spectra

		Excess	POT	Charged Mesons Focused?
Target Mode	*Neutrino Mode*	560.6±119.6	1.875E+21	π^+, K^+
	Anti-neutrino Mode	77.4±28.5	1.127E+21	π^-, K^-
Dump Mode		None	1.86E+20	Isotropic





How can we explain this anomaly with a dark sector?



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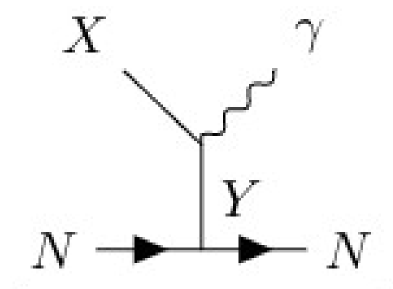
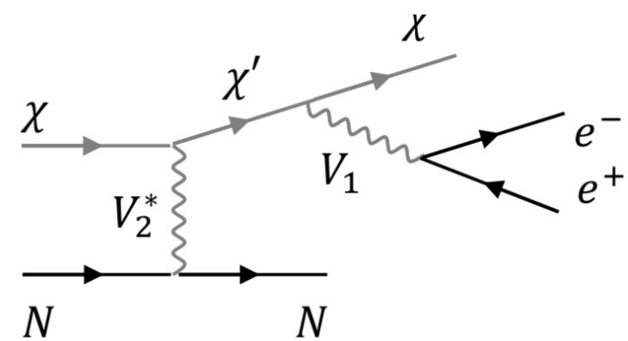
(1): Dark boson photoconversion



(2): $X \to \chi\chi$ into DM upscattering



Examples:

$$\mathcal{L}_S \supset g_\mu \phi \bar{\mu}\mu + g_n Z'_\alpha \bar{u}\gamma^\alpha u + \frac{\lambda}{4}\phi F'_{\mu\nu}F^{\mu\nu} + \text{h.c.},$$

$$\mathcal{L}_P \supset i g_\mu a \bar{\mu}\gamma^5 \mu + g_n Z'_\alpha \bar{u}\gamma^\alpha u + \frac{\lambda}{4} a F'_{\mu\nu}\tilde{F}^{\mu\nu} + \text{h.c.}$$

$$\mathcal{L}_V \supset e(\epsilon_1 V_{1,\mu} + \epsilon_2 V_{2,\mu})J^\mu_{\text{EM}} + (g_1 V_{1,\mu} + g_2 V_{2,\mu})J^\mu_D + (g'_1 V_{1,\mu} + g'_2 V_{2,\mu})J'^\mu_D$$

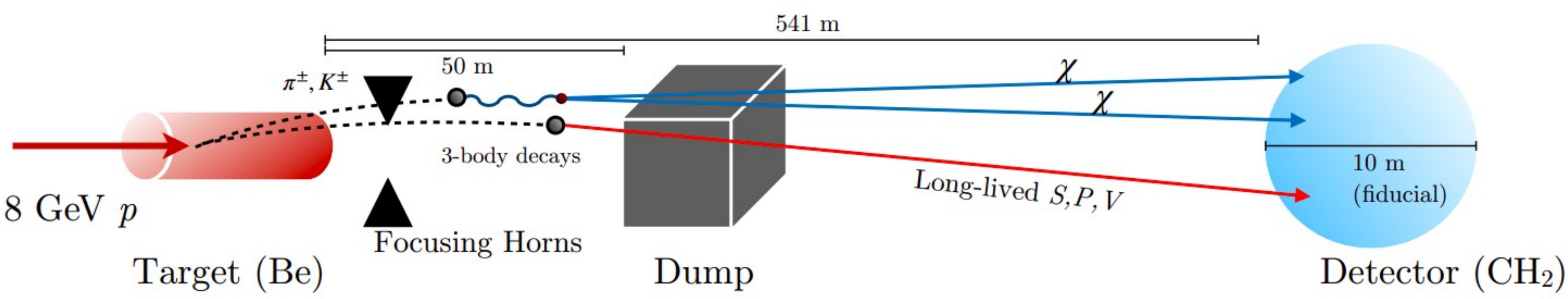
Correlates dark boson flux to target-mode excess

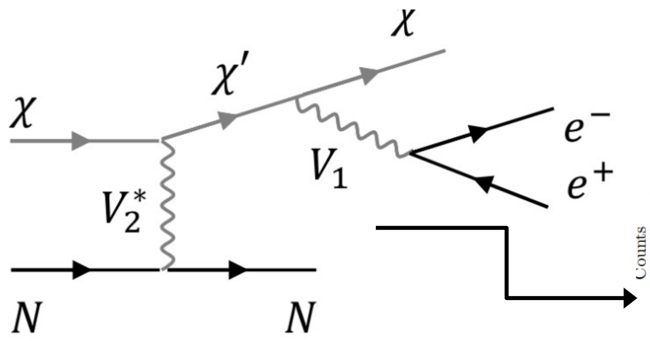
Massive particle in *t*-channel accounts for observed off-forward cosine distribution

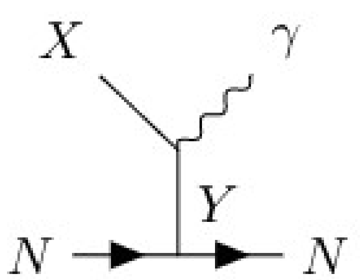
We explored these scenarios here: arXiv:110.11944

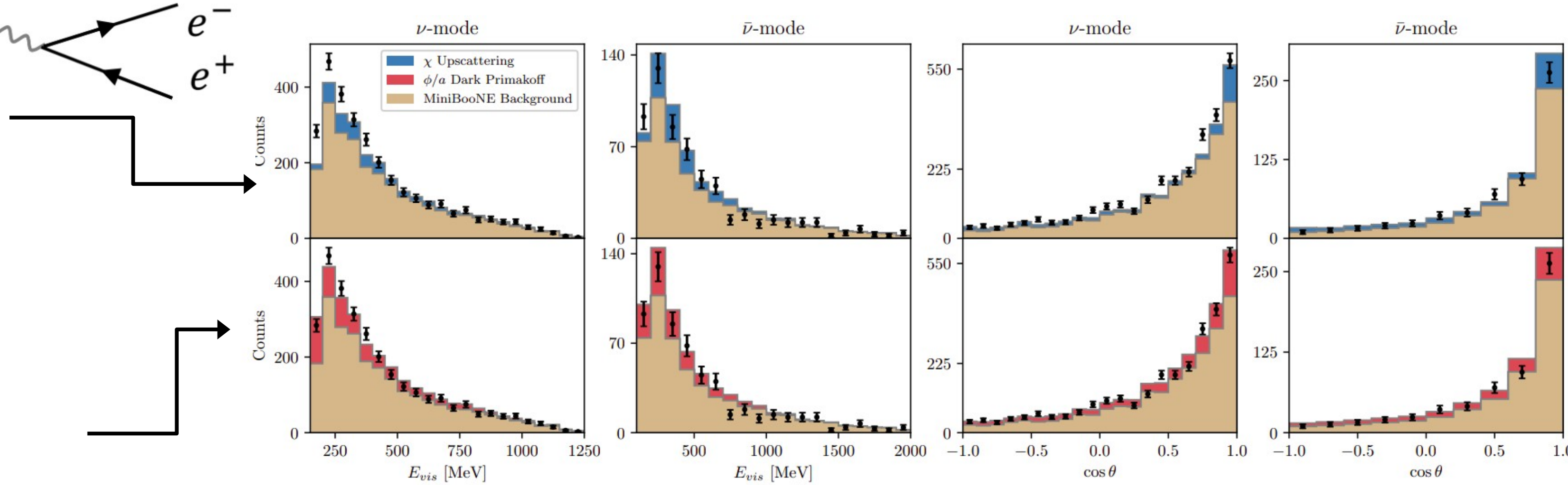
***Phys.Rev.Lett.* 129 (2022) 11, 111803**
Dutta, Kim, Thornton, Thompson, Van de Water

Accomodating the MiniBooNE Observation







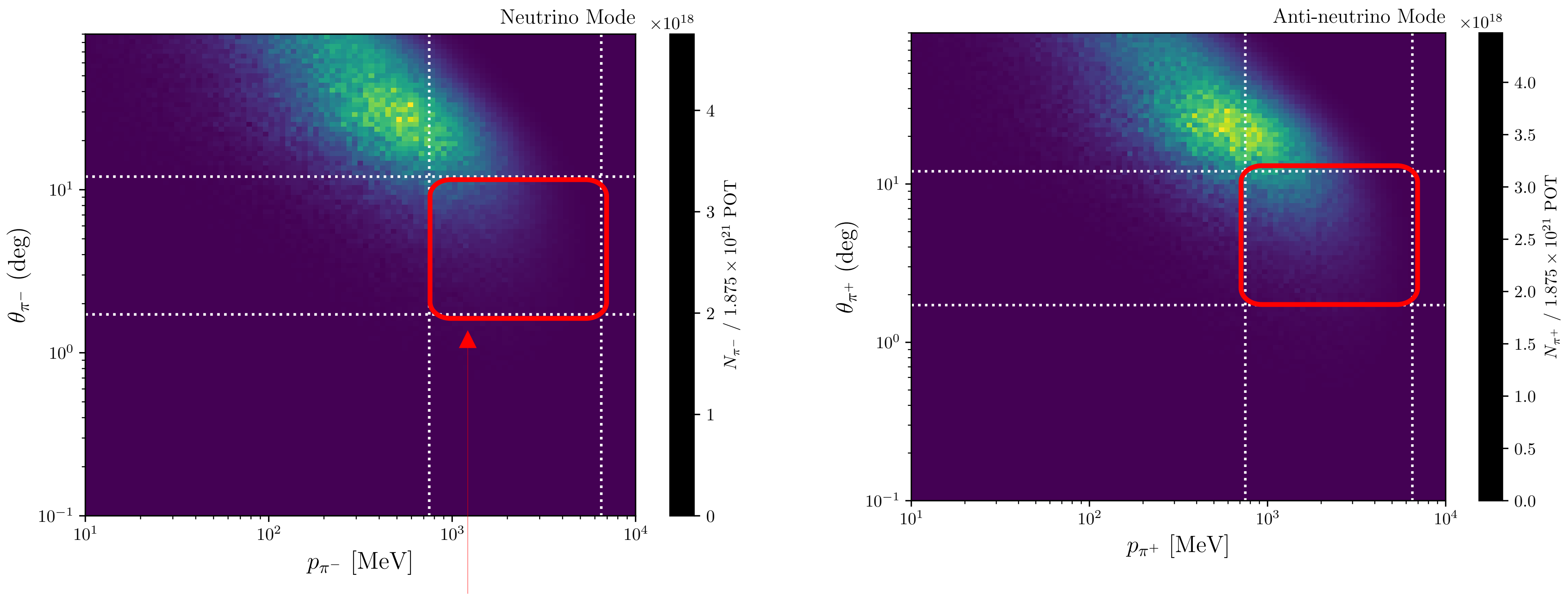


MiniBooNE: Charged Meson Fluxes

- Ordinarily, we would simulate the Be target meson flux with GEANT4
- However, simulation of the focusing horns is not easy!
- Therefore, one can take a parameterized approach: ***PhysRevD* 79.072002**

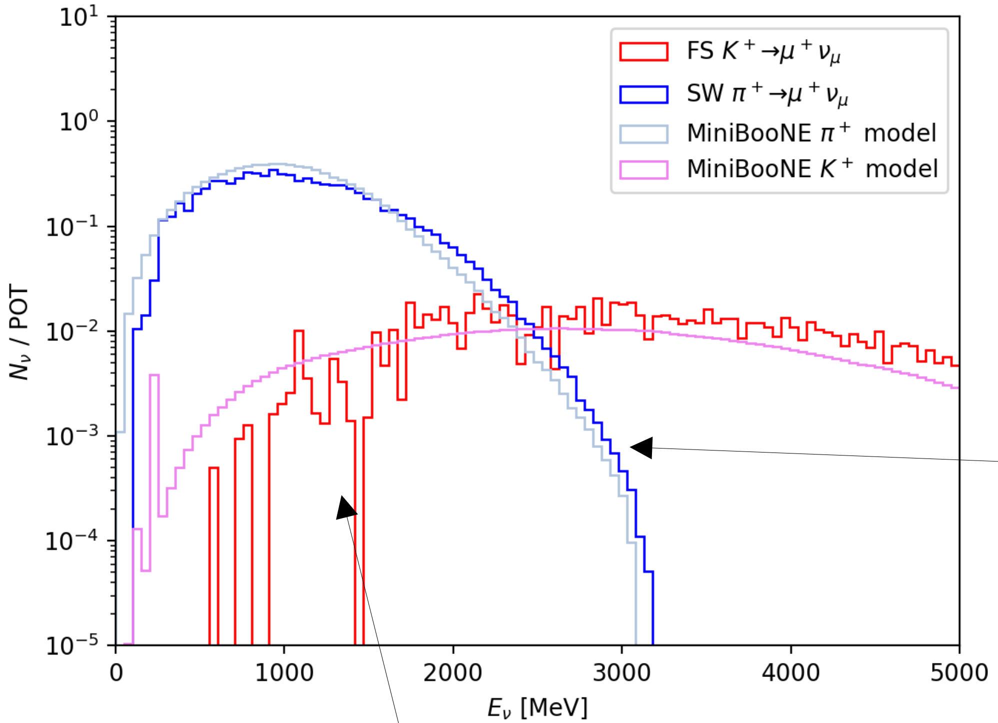
See also: 0609129

Sanford-Wang Parameterization: $$\frac{\partial^2\sigma(p+\mathrm{Be}\to\pi^\pm+X)}{\partial p\partial\Omega}=c_1p^{c_2}\left(1-\frac{p}{p_B-c_9}\right)\exp\left(-c_3\frac{p^{c_4}}{p_B^{c_5}}-c_6\theta(p-c_7p_B(\cos\theta)^{c_8}\right)$$



Apply cuts to the angle and momentum as a heuristic for the horn effect

Validation of the parameterized approach: Check against the MiniBooNE-reported neutrino fluxes



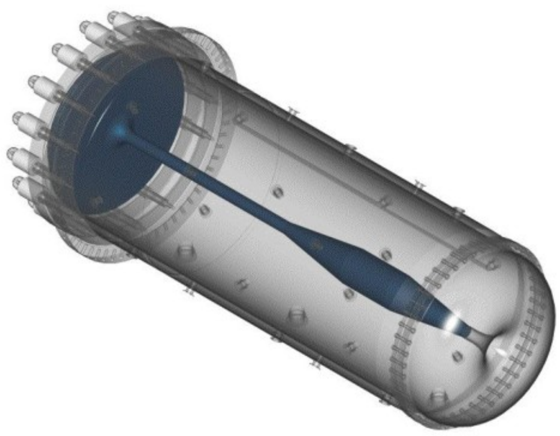
- Monte carlo the π^+, π^- fluxes with SW parameterization
- Apply a simple 2-body decay of the $\pi \to \nu\mu$ along its flight path
- Propagate neutrinos to the MiniBooNE detector and check their energy spectra against the fluxes reported by the literature

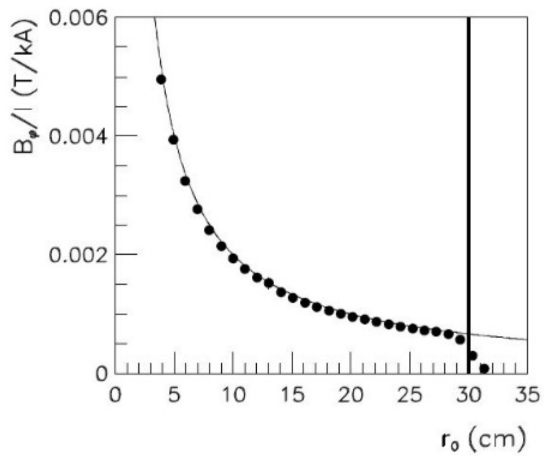
Gives $o(1)$ agreement to SW

(but requires some tweaking of the cut window)

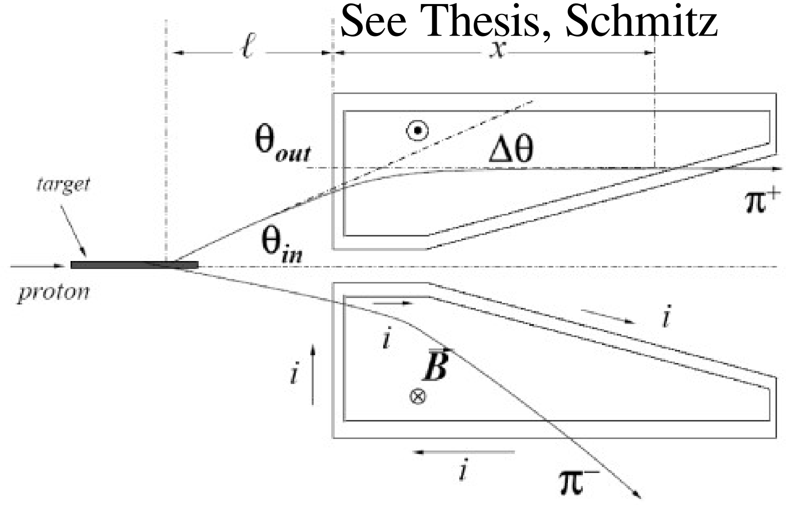
Kaon fluxes (using Feynman-scaling parameterization) agree less-so (KDAR not incorporated)

Next Option: Roll up our sleeves





See Thesis, Schmitz

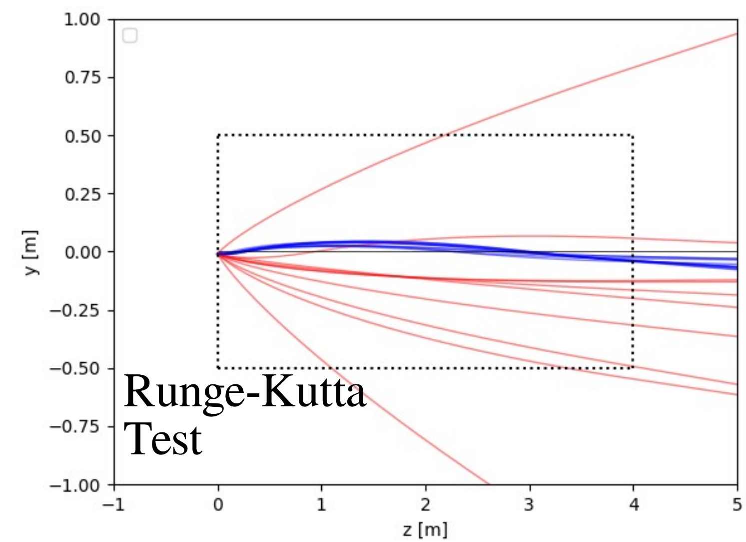


1. Simulate Charged pion fluxes with GEANT4 (without horn system)

2. Transport the charged pions through the horn system by solving

$$\frac{dp^\alpha}{d\tau} = qF^{\alpha\beta}u_\beta.$$

3. MC 3-body decay the pions to generate dark sector fluxes



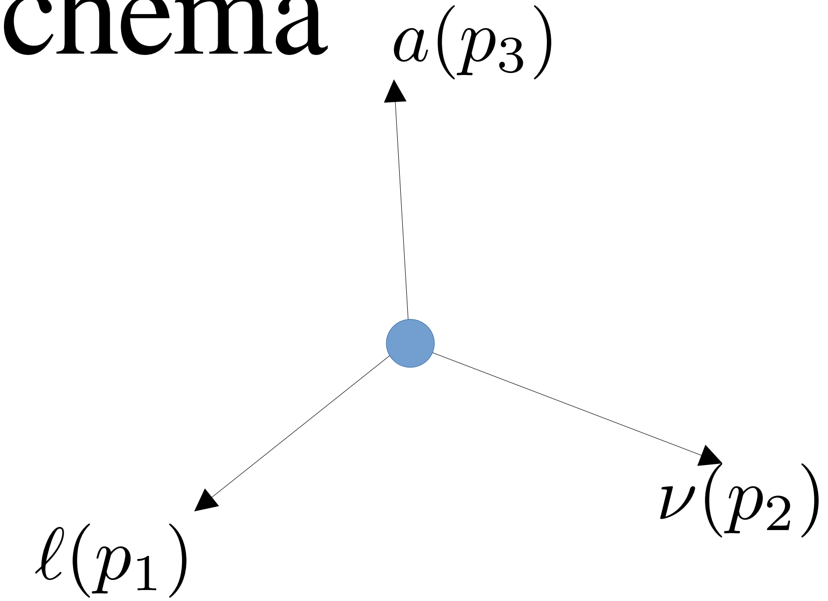
Note: Event Generator Schema

See Byckling, Kajantie: *Particle Kinematics*

Dalitz Variables for 3-body Final State:

$$m_{12}^2 = (p_1 + p_2)^2 = (P - p_3)^2 = M^2 - 2ME_a + m_a^2$$
$$m_{23}^2 = (p_2 + p_3)^2 = (P - p_1)^2 = M^2 - 2ME_\ell + m_\ell^2$$
$$m_{13}^2 = (p_1 + p_3)^2 = (P - p_2)^2 = M^2 - 2ME_\nu$$
$$m_{13}^2 = M^2 + m_\ell^2 + m_a^2 - m_{12}^2 - m_{23}^2.$$

$$\frac{d\Gamma}{dE_a} = \int_{(m_{23}^2)_{min}}^{(m_{23}^2)_{max}} \frac{1}{(2\pi)^3 16 M^2} \langle |M|^2 \rangle \, dm_{23}^2.$$



1. Draw angles on a 2-sphere in the rest frame of the parent meson:

$$u \sim U(0,1), \theta \sim \arccos(1 - 2u)$$

$$\phi \sim U(0, 2\pi)$$

2. Integrate over Dalitz variable m_{23}^2 For a given ALP energy.

3. Boost to the laboratory frame.

4. Weights given by $\frac{1}{\Gamma}\frac{d\Gamma}{dE_a^*}$ x Jacobian

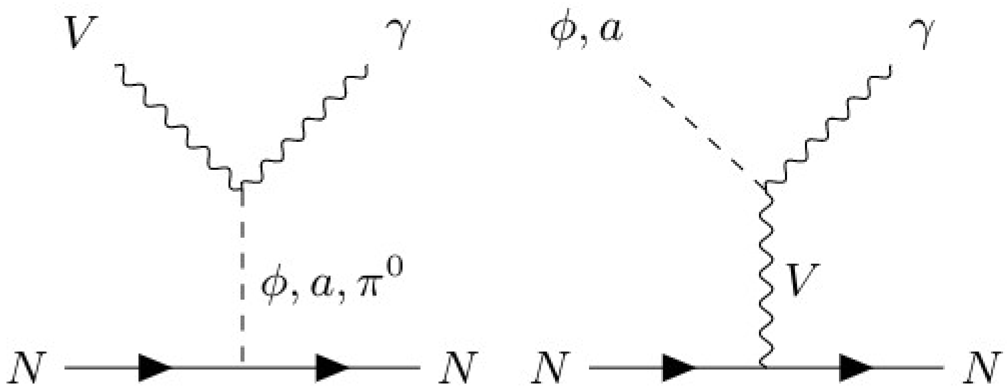
$$(m_{23}^2)_{min}^{max} = (E_2^* + E_3^*)^2 - \left(E_2^* \mp \sqrt{{E_3^*}^2 - m_a^2}\right)$$

$$E_2^* = \frac{m_{12}^2 - m_\ell^2}{2m_{12}}$$
$$E_3^* = \frac{M^2 - m_{12}^2 - m_a^2}{2m_{12}}$$

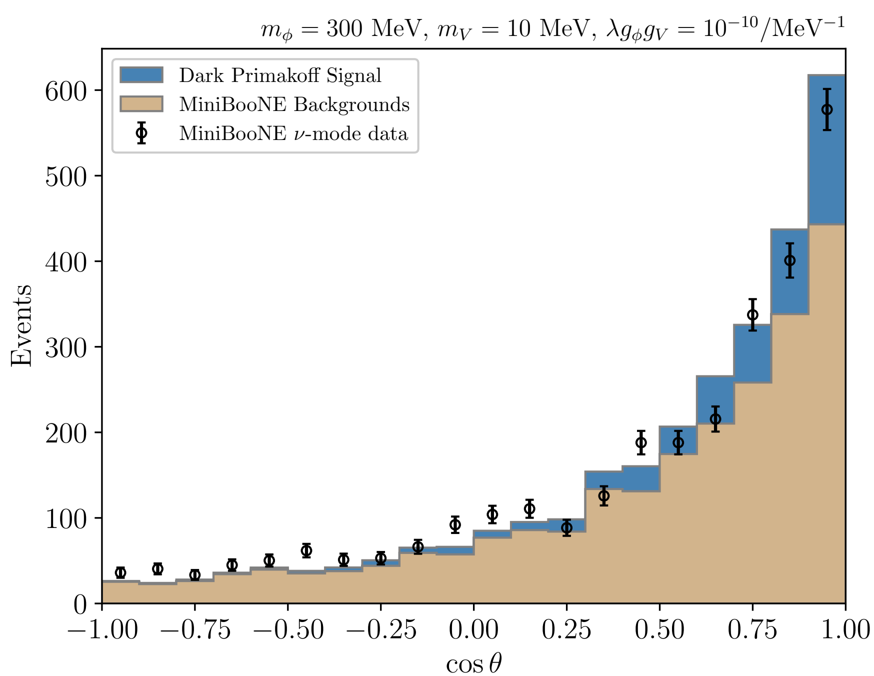
$$m_a < E_a < \frac{M^2 + m_a^2 - m_\ell^2}{2M}.$$

Code available:
https://github.com/athompson-tamu/alplib

Detection Channel: Primakoff-like Photoconversion



$\phi \overline{N} \mathbf{Y}^s_n N$ $\quad i a \overline{N} \gamma^5 \mathbf{Y}^p_n N$ $\quad V_\mu \overline{N} \gamma^\mu \mathbf{Y}^p_n N$



(scalar-vector) (pseudoscalar-vector)

$$\frac{\lambda}{4}\phi F_{\mu\nu} H^{\mu\nu} \qquad \frac{\lambda}{4} a F_{\mu\nu} \tilde{H}^{\mu\nu}$$

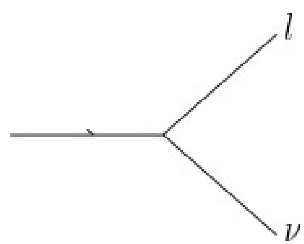
$$H^{\mu\nu} = \partial^\mu V^\nu - \partial^\nu V^\mu$$

- Dimension-5 coupling
- May come from, e.g. extra $U(1)_{T3R}$
- The mediator mass in the *t*-channel gives us a dial to control the momentum transfer, and therefore the "off-forward-ness" of the cosine spectrum at MiniBooNE
- γ and electrons both show up as similar cherenkov rings

Radiative Meson Decays: Standard Model

Gauge invariance: $\partial_\mu \pi^+ \to \partial_\mu \pi^+ - ieA_\mu \pi^+$

$\mathcal{M} \supset$



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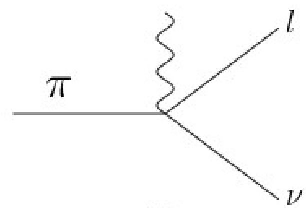
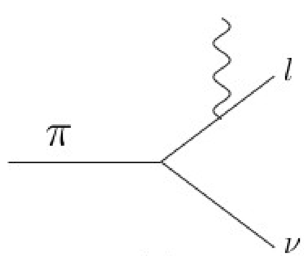


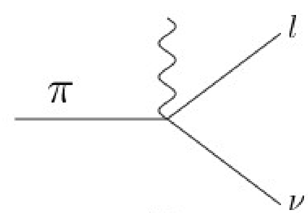
(c)

$$\mathcal{L} \supset i\frac{G_F}{2}(\partial_\mu \pi^+)\bar{\ell}\gamma^\mu(1-\gamma^5)\nu$$



(a)

$$= -\Big($$

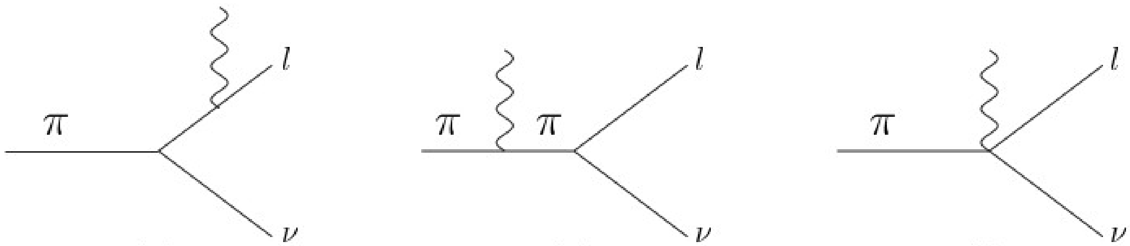


(c)

$$\Big)$$

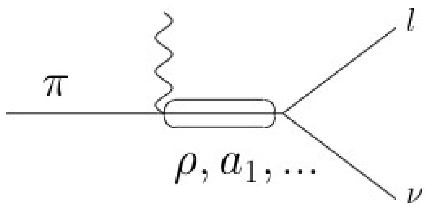
In the “chiral” $m_l \to 0$ limit, recovering the helicity suppression

Radiative Meson Decays: General Structure for a Massive Vector



(a) (b) (c)

$$\mathcal{M} = i\frac{G_F}{\sqrt{2}}\varepsilon^{\mu}\left[\bar{u}_{\ell}\gamma^{\rho}(1-\gamma^5)v_{\nu}\right]T_{\mu\rho}$$



(d)

<u>Covariant decomposition:</u>

$$T_{\mu\rho} = i\int d^4x e^{ikx}\,\langle 0|T[j^V_{\mu}(x)j^+_{\rho}(0)]|\pi^+(p)\rangle$$

$$T_{\mu\rho} = \tilde{a}_0 g_{\mu\rho} + \tilde{b}_0 L_{\mu}k_{\rho} + \tilde{b}_1 L_{\rho}k_{\mu} + \tilde{b}_2 L_{\mu}L_{\rho} + \tilde{b}_3 k_{\mu}k_{\rho} + \epsilon_{\rho\mu\lambda\sigma}L^{\lambda}k^{\sigma}F_V$$

- L is total lepton momentum
- k is the massive vector momentum

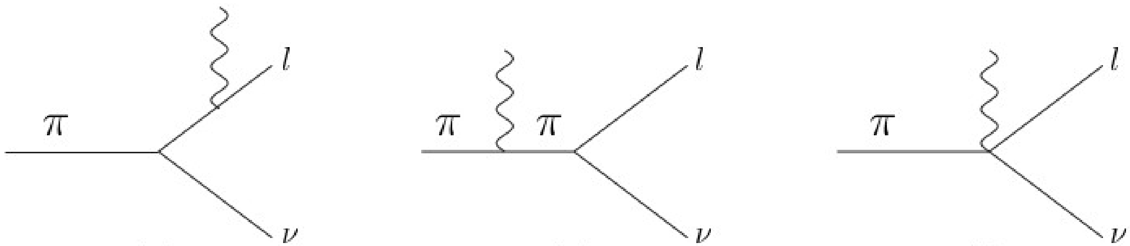
(a)Leptonic terms: lepton couplings

(b)"Internal Brem": quark couplings

(c)Contact terms: gauge invariance

(d)Structure dependent terms: vector meson interactions

Radiative Meson Decays:
General Structure for a Massive Vector



(a) (b) (c)

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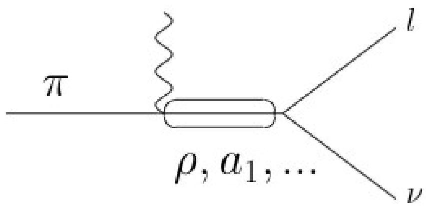

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$$T_{\mu\rho} = i\int d^4x e^{ikx}\,\langle 0|T[j^V_\mu(x)j^+_\rho(0)]|\pi^+(p)\rangle$$

$$T_{\mu\rho} = \tilde{a}_0 g_{\mu\rho} + \tilde{b}_0 L_\mu k_\rho + \tilde{b}_1 L_\rho k_\mu + \tilde{b}_2 L_\mu L_\rho + \tilde{b}_3 k_\mu k_\rho + \epsilon_{\rho\mu\lambda\sigma}L^\lambda k^\sigma F_V$$

- L is total lepton momentum
- k is the massive vector momentum

- For massless photons, the Ward identity applies:
- For massive vectors, it doesn't need to except in gauge invariant cases (e.g. Stückelberg fields) – to be conservative, we admit it:

$$k^\mu T_{\mu\rho} = ip_\rho f_\pi = i(L+k)_\rho f_\pi.$$

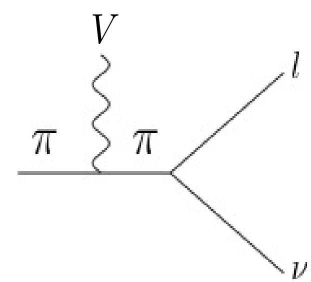
(Ward Identity)

$$\tilde{a}_0 + \tilde{b}_0(L\cdot k) + \tilde{b}_3 m_V^2 = if_\pi$$
$$\tilde{b}_1 m_V^2 + \tilde{b}_2(L\cdot k) = if_\pi$$

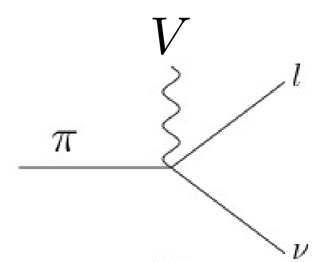
$$\tilde{a}_0 + \tilde{b}_0(L\cdot k) + \tilde{b}_3 m_V^2 = i f_\pi$$
$$\tilde{b}_1 m_V^2 + \tilde{b}_2(L\cdot k) = i f_\pi$$

$$T_{\mu\rho} = \tilde{a}_0 g_{\mu\rho} + \tilde{b}_0 L_\mu k_\rho + \tilde{b}_1 L_\rho k_\mu + \tilde{b}_2 L_\mu L_\rho + \tilde{b}_3 k_\mu k_\rho + \epsilon_{\rho\mu\lambda\sigma} L^\lambda k^\sigma F_V$$

$\tilde{b}_2 = 2\tilde{b}_1$ → Recover IB2 Term



$\tilde{a}_0 = i f_\pi, \tilde{b}_i = 0$ → Traditional contact term



(c)

Dark Sector Chiral Perturbation Theory: What is the larger picture?

$$\mathcal{L} \supset \sum_q g_q V_\mu \bar{q}\gamma^\mu q$$

$$\mathcal{L}_{hp}^{\chi PT} \supset \frac{f_\pi^2}{4}\mathrm{Tr}\left[(\partial_\mu \mathbf{U} - iV_\mu\{\mathbf{g}_X, \mathbf{U}\})(\partial^\mu \mathbf{U} + iV^\mu\{\mathbf{g}_X, \mathbf{U}\})\right] \quad (2)$$

where the octet of meson states are contained in the Goldstone field Φ in the 3-flavor quark basis,

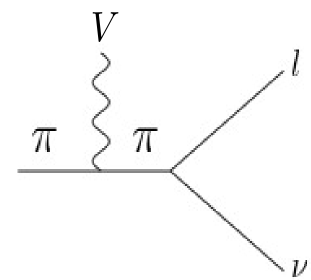
$$\mathbf{U} = e^{i\sqrt{2}\Phi/f_\pi}, \ \ \Phi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & K^0 \\ K^- & \overline{K}^0 & -\frac{2\eta_8}{\sqrt{6}} \end{pmatrix}. \quad (3)$$

Further, for simplicity we select only up- and down-type quark couplings in the coupling matrix $\mathbf{g}_X$;

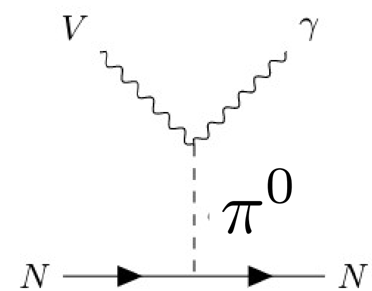
$$\mathbf{g}_X \equiv \begin{pmatrix} g_u & 0 & 0 \\ 0 & g_d & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad (4)$$

Quark couplings →
We generically expect couplings to both neutral and charged mesons!

$$\mathcal{L}_{hp}^{\chi PT} \supset i(g_u - g_d)V_\mu \pi^+(\partial^\mu \pi^-)$$

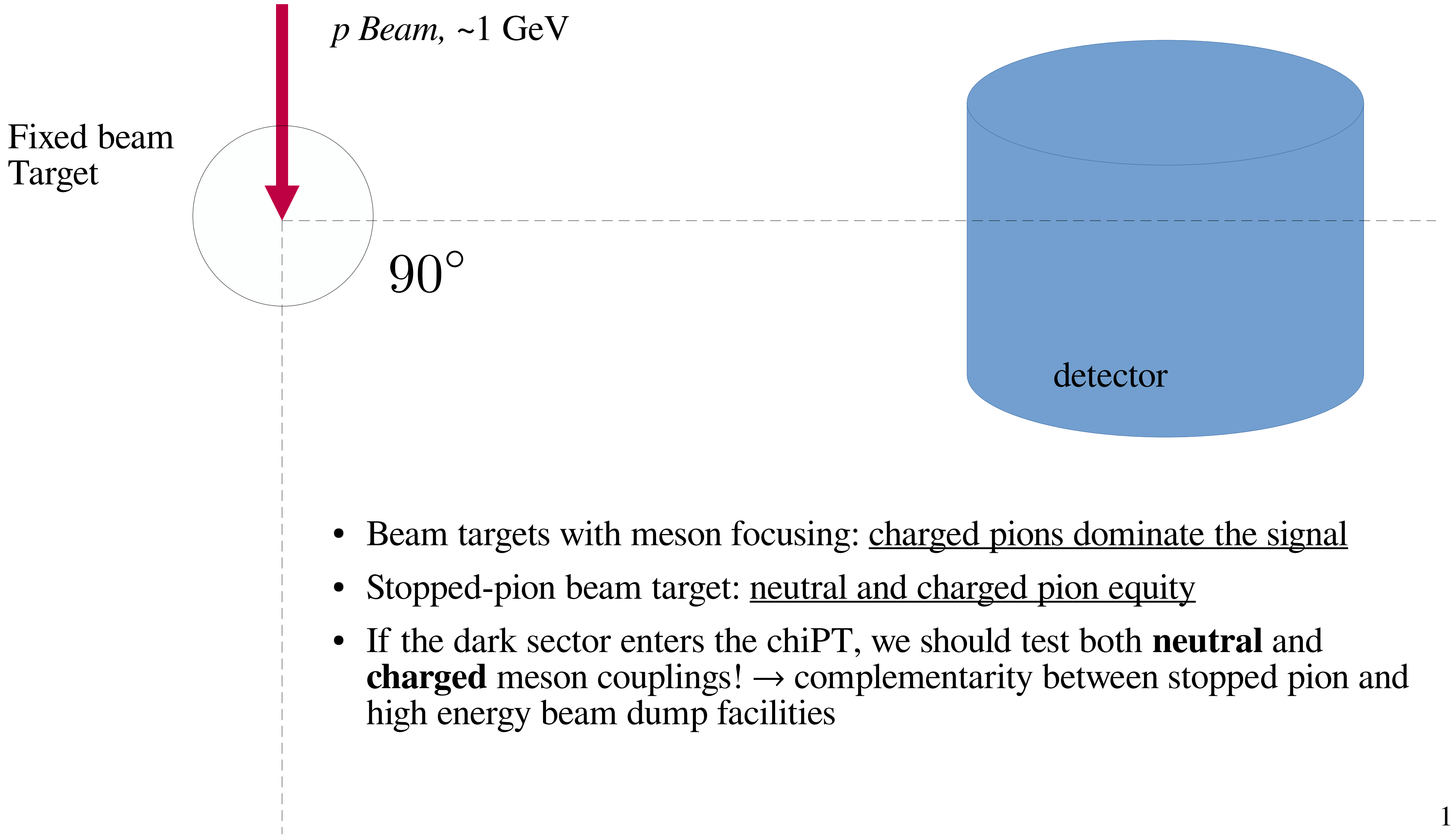


$$\mathcal{L}_{hp}^{\chi PT} \supset (2g_u + g_d)\frac{e}{16\pi f_\pi}\pi^0 F_{\mu\nu}\tilde{H}^{\mu\nu}$$



$g_{\pi NN} = 13$

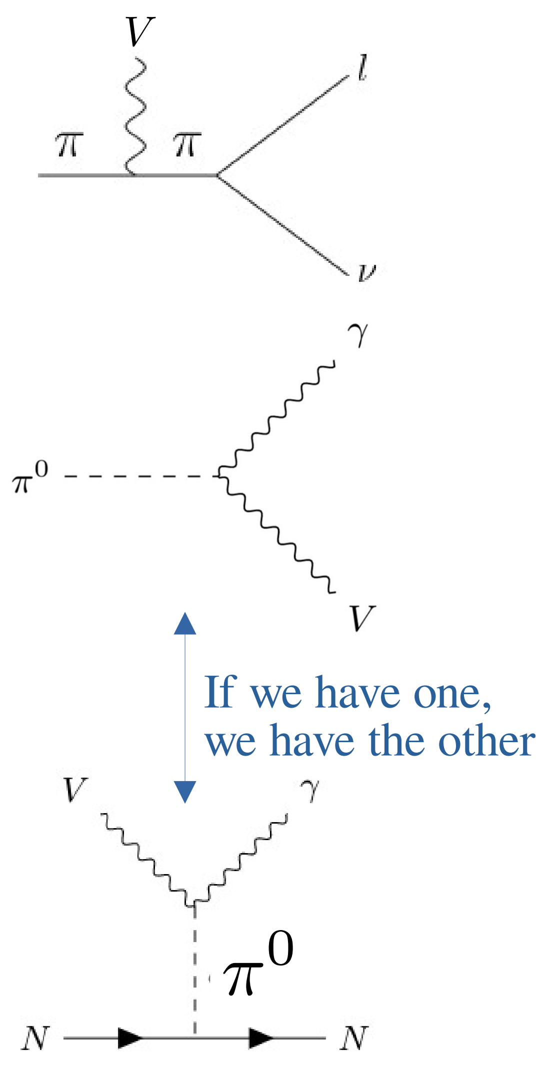
Probing the Meson-portal Dark Sector at Stopped-Pion Facilities

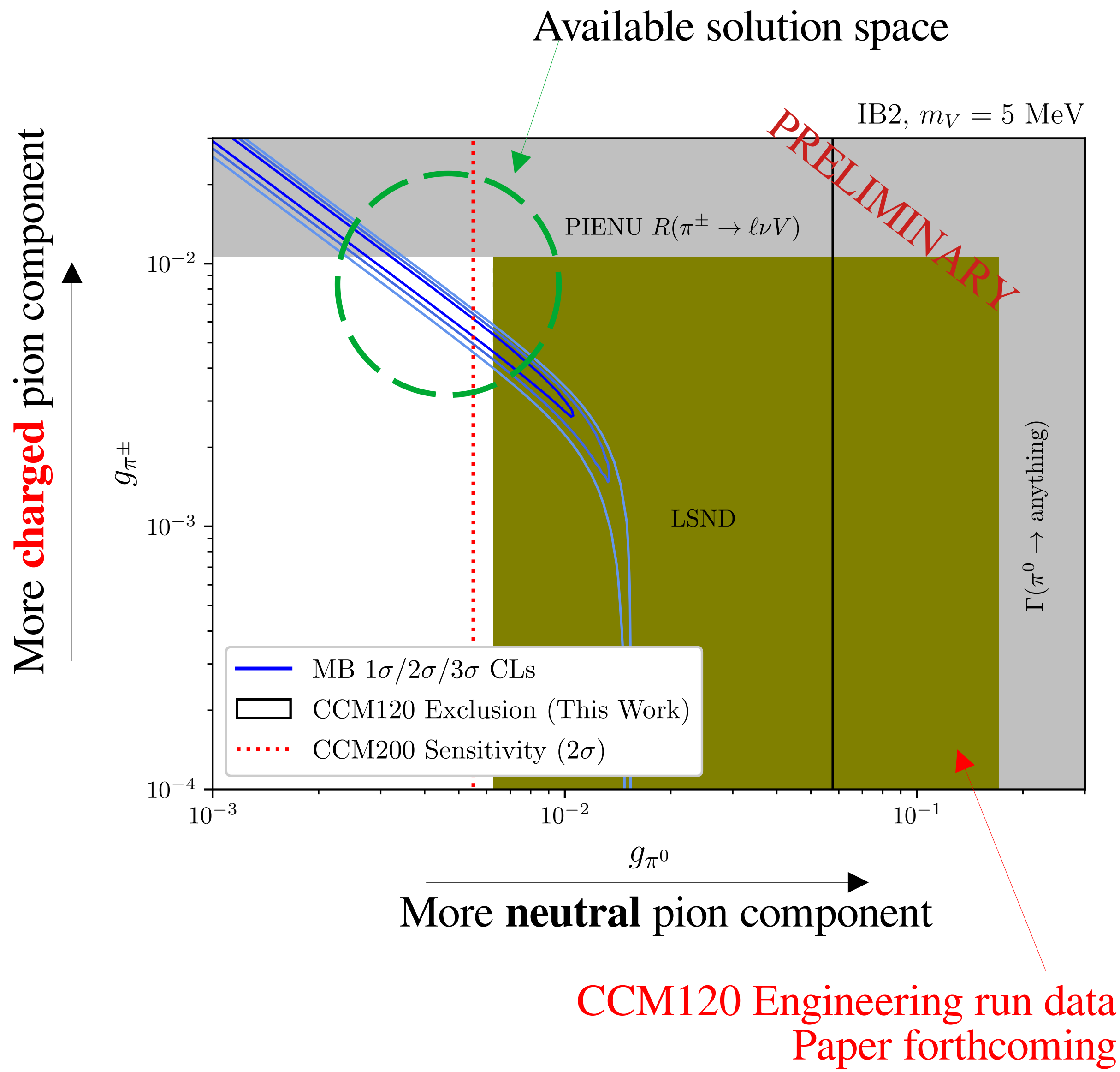


- Beam targets with meson focusing: charged pions dominate the signal
- Stopped-pion beam target: neutral and charged pion equity
- If the dark sector enters the chiPT, we should test both **neutral** and **charged** meson couplings! → complementarity between stopped pion and high energy beam dump facilities

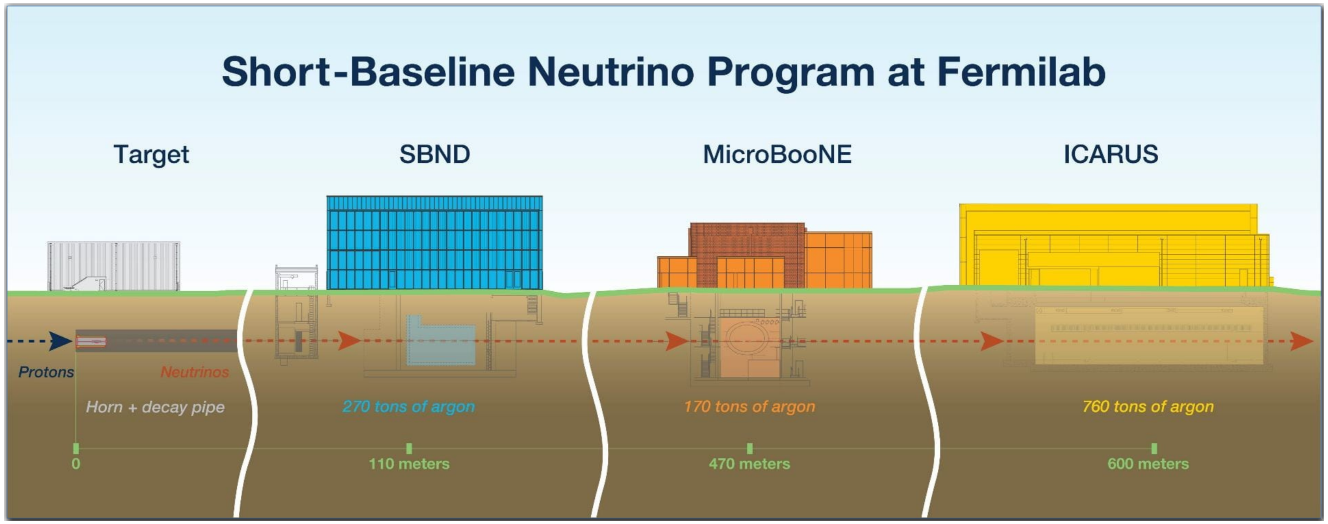
Testing this explanation at CCM (Coherent CAPTAIN-Mills)

- 800 MeV *p* beam on W target at Lujan (LANL)
- 10t LAr liquid scintillator
- ~20m baseline





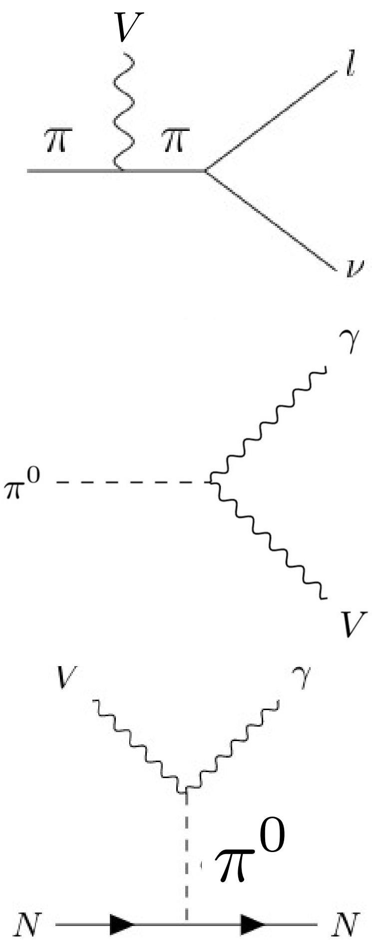
SBND

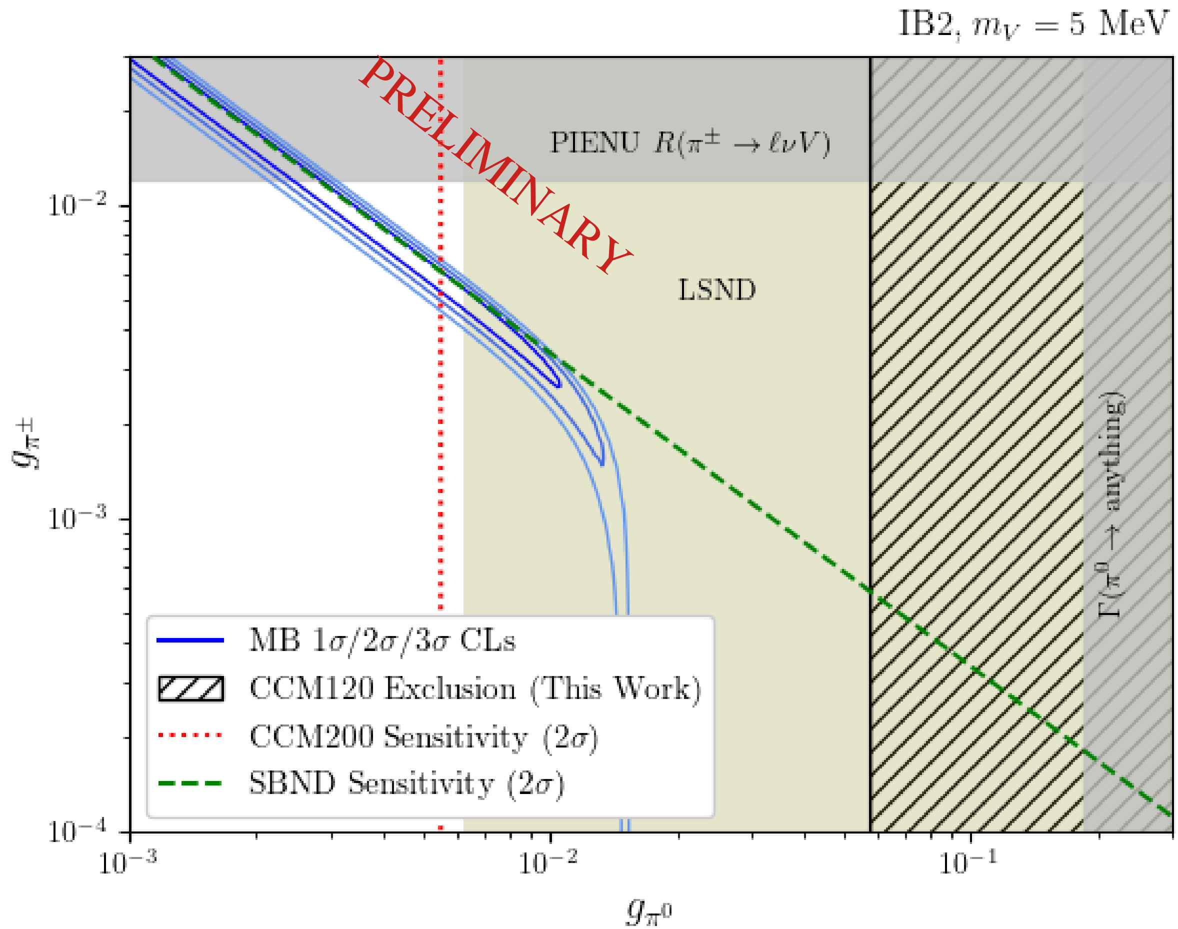


- Expected 6.6E+20 POT from BNB target mode
- 110 m baseline
- 112t fiducial mass LAr TPC; γ, e^- final states can be distinguished
- Short baseline, large active mass $\rightarrow$ great potential to check the MiniBooNE anomaly and charged meson-based explanations

SBND

- Probing the single-mediator scenario: SBND as a complimentary check to stopped-pion facilities
- The charged pion and neutral pion contributions to the excess can both be constrained
- Ability to distinguish between different BSM final states in TPC





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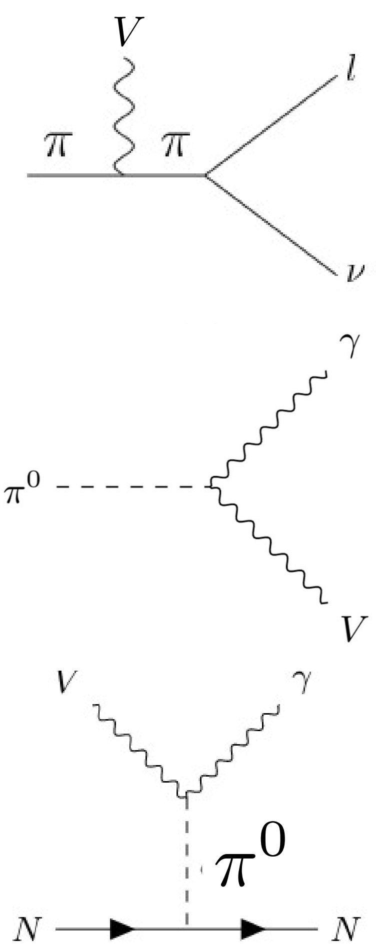
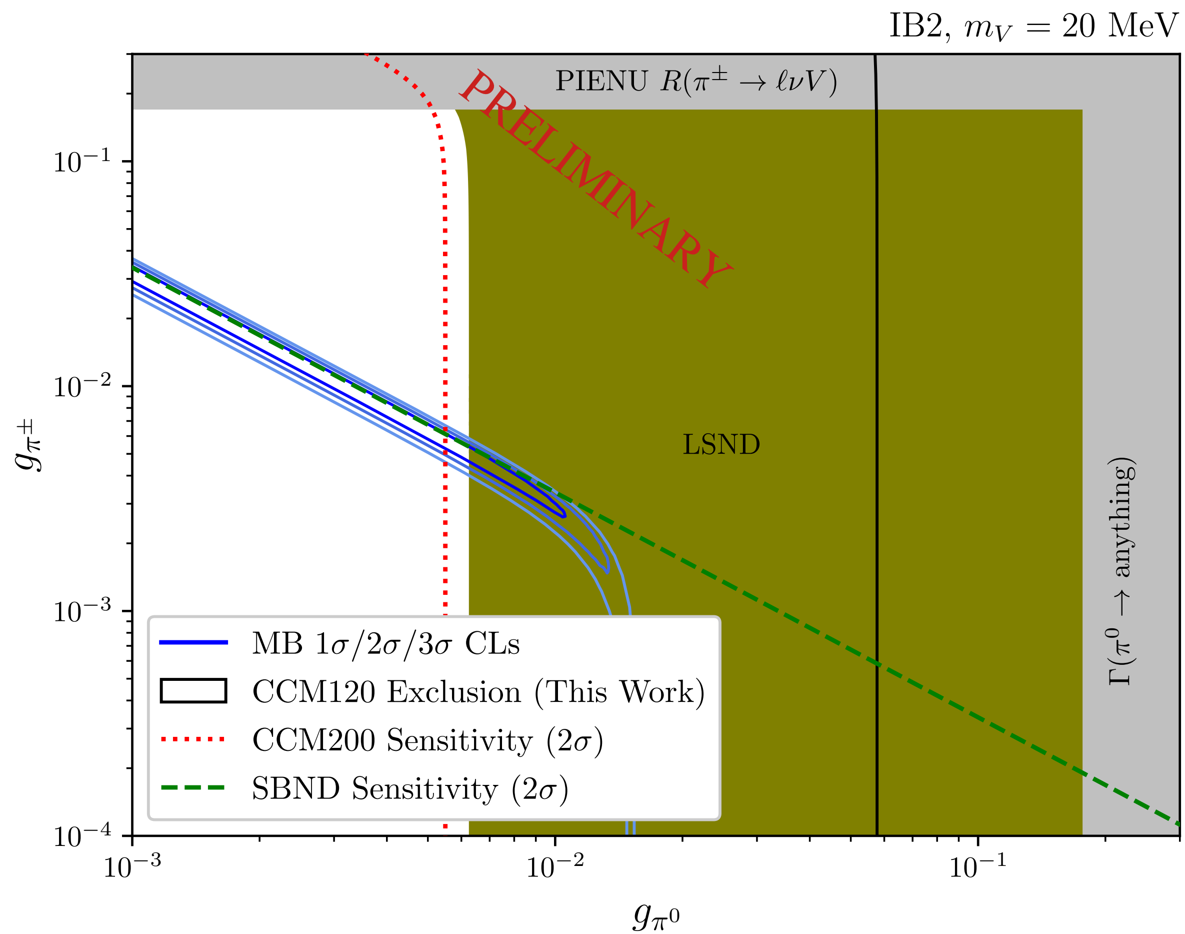




Outlook

- Significant hints that if the MB anomaly is explained by BSM, it should be correlated to the charged mesons
- DM production in 3-body decays are also interesting in their own right, studied now in a flurry of new works
- If there is a meson portal to dark sector states, we could anticipate quark couplings $\rightarrow$ leads to chiPT picture, neutral + charged meson pheno
- This opens the door to look for these production modes at neutrino facilities! CCM, BNB, NuMI...
- More work to be done: modeling of the focusing horns, mapping out the chiPT picture, GEANT4 flux validation…

Acknowledgements

Close Collaborators:

Bhaskar Dutta (Advisor)

Doojin Kim

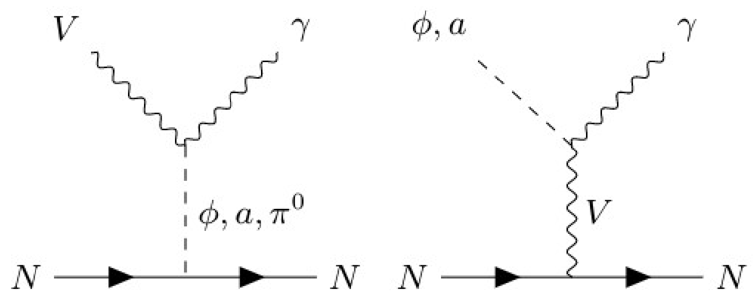
Richard Van de Water

Edward Dunton

Wei-Chih Huang

Backup deck

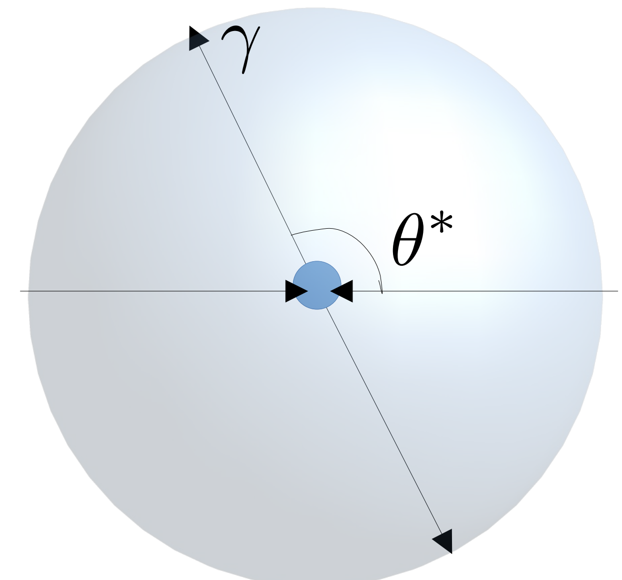
Note: 2-to-2 scattering Monte Carlo



Theorist Input, FeynCalc etc.

$$\frac{d\sigma}{dt} = \frac{1}{16\pi(s-(m_1+m_2)^2)(s-(m_1-m_2)^2)}\langle|\mathcal{M}(s,t)|^2\rangle$$

$$\frac{d\sigma}{d(\cos\theta^*)} = 2p_1^*p_3^*\frac{d\sigma}{dt}$$

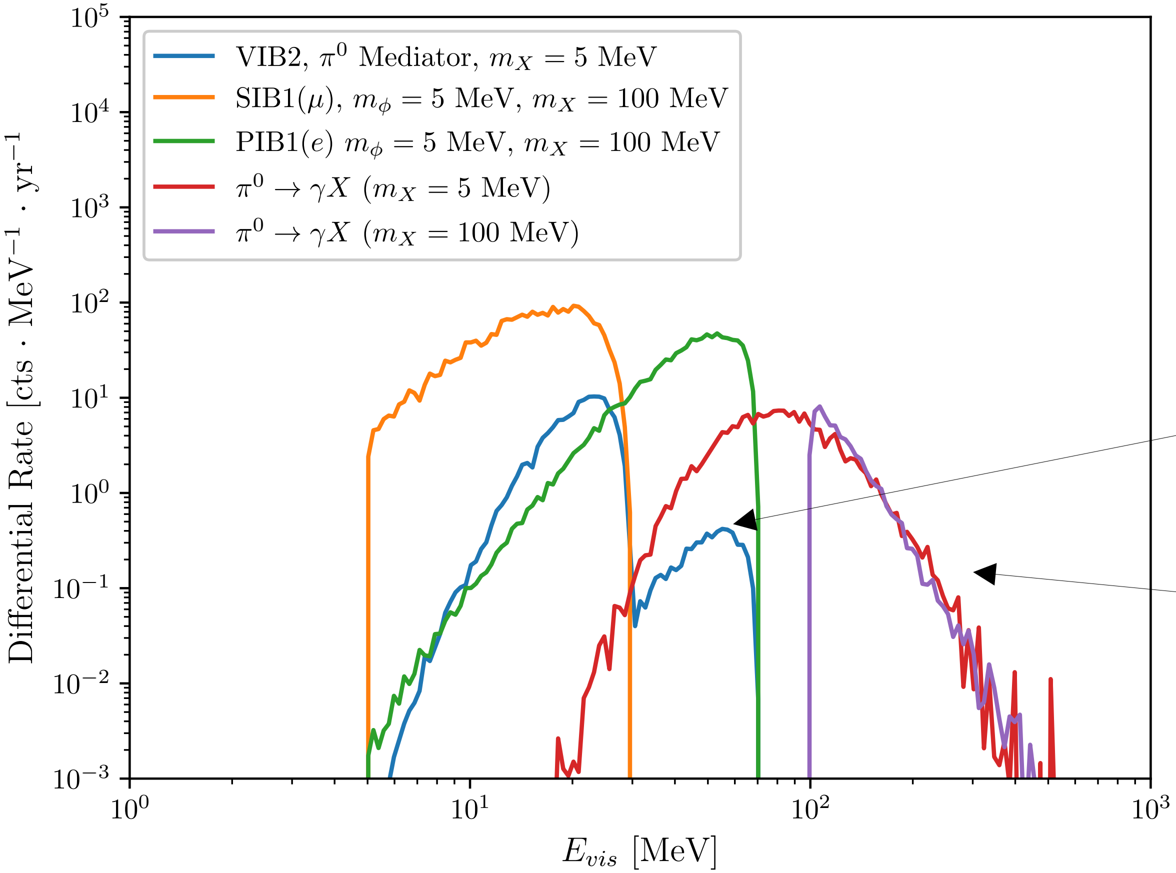


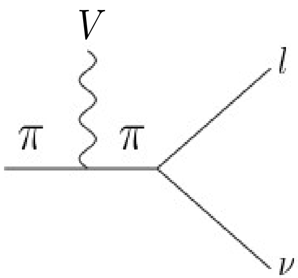
1. Draw uniform angles on the 2-sphere for outgoing momenta in CM frame
2. Boost momenta to lab frame
3. MC weights are $d\sigma_i = \frac{d\sigma}{d(\cos\theta^*)}_i d(\cos\theta^*) \sim \frac{2}{N}\frac{d\sigma(\theta_i)}{d(\cos\theta^*)}$ for N samples. $d\sigma_i$ is frame invariant in the limit of large N.

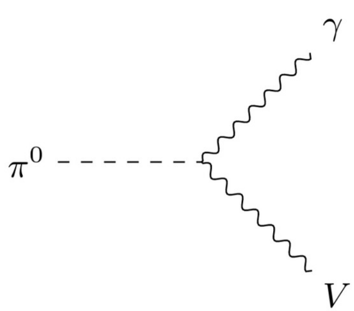
Testing this explanation at CCM (Coherent CAPTAIN-Mills)

- 800 MeV p beam on W target at Lujan (LANL)
- 10t LAr liquid scintillator
- ~20m baseline

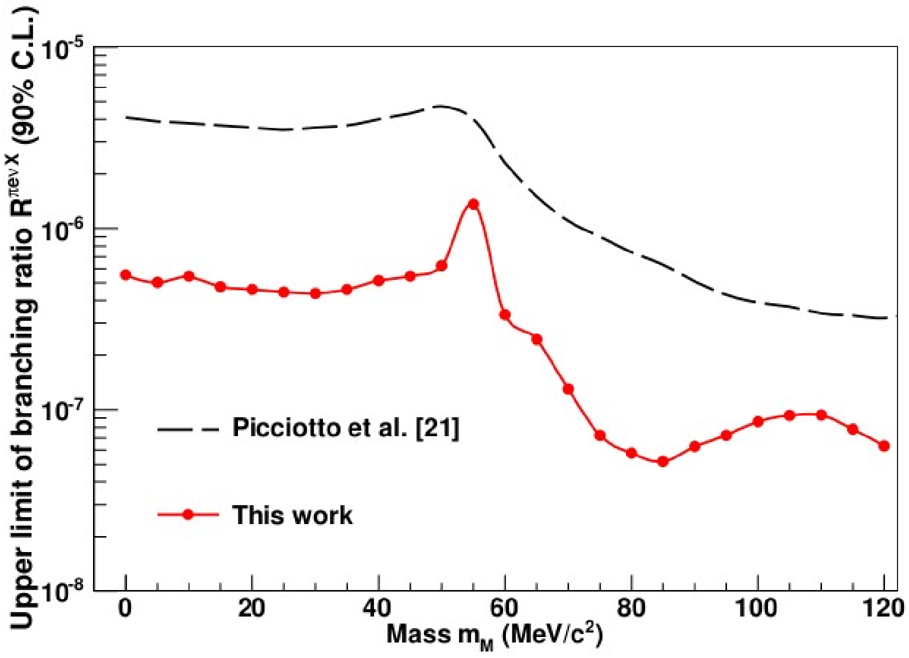
- We get both charged and neutral pi-DAR components
- Decay models (IB1, IB2, IB3, etc.) give control over the spectra
- Neutral pions provide a higher energy component

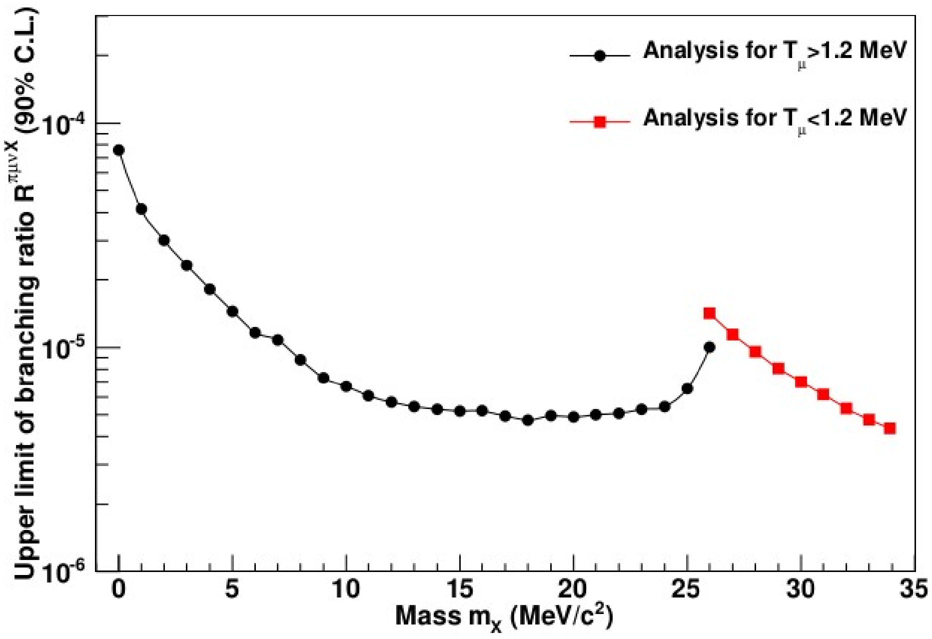






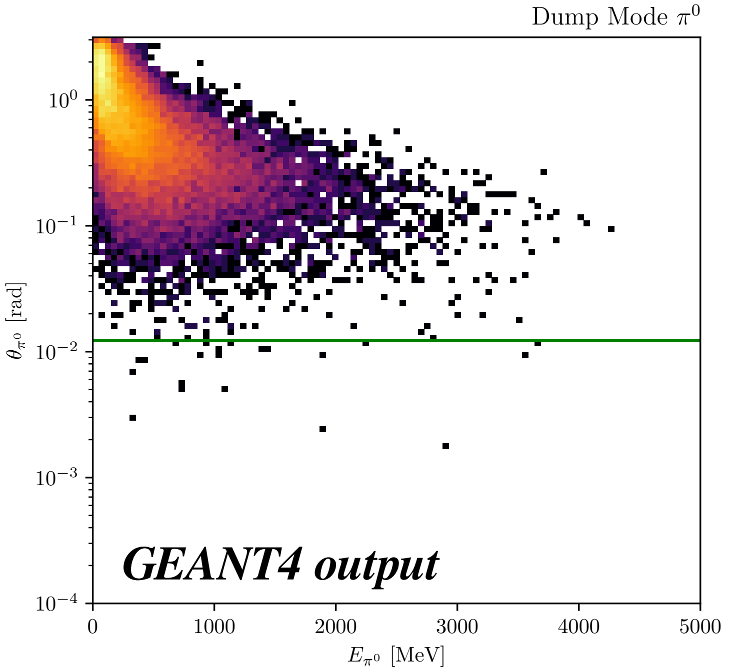
PIENU Constraints on rare pion decays

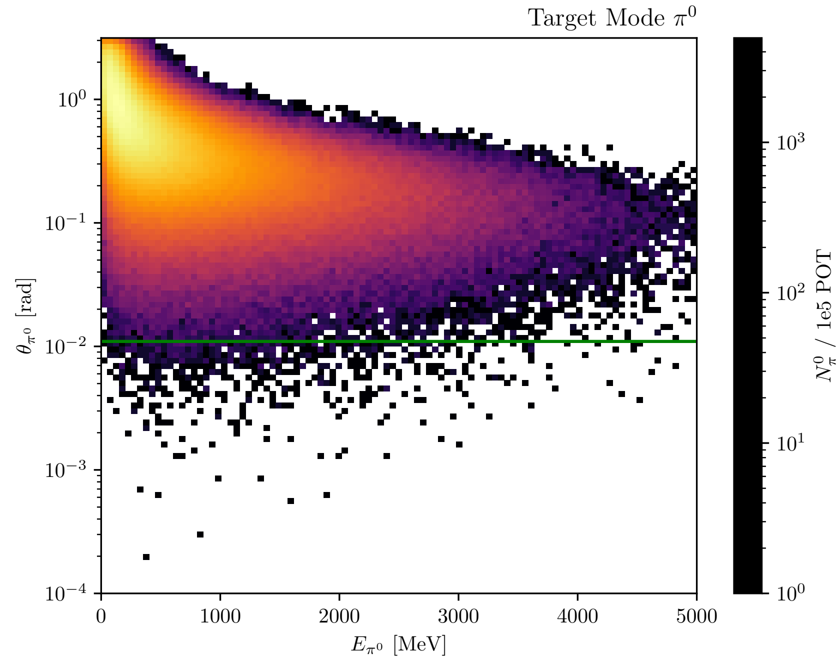




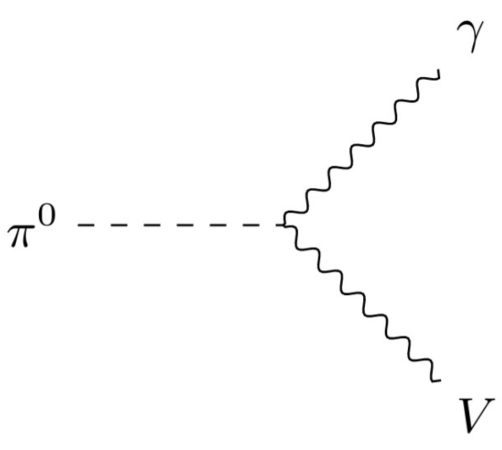
2102.07381, PIENU Collaboration

MiniBooNE: Neutral Meson Fluxes

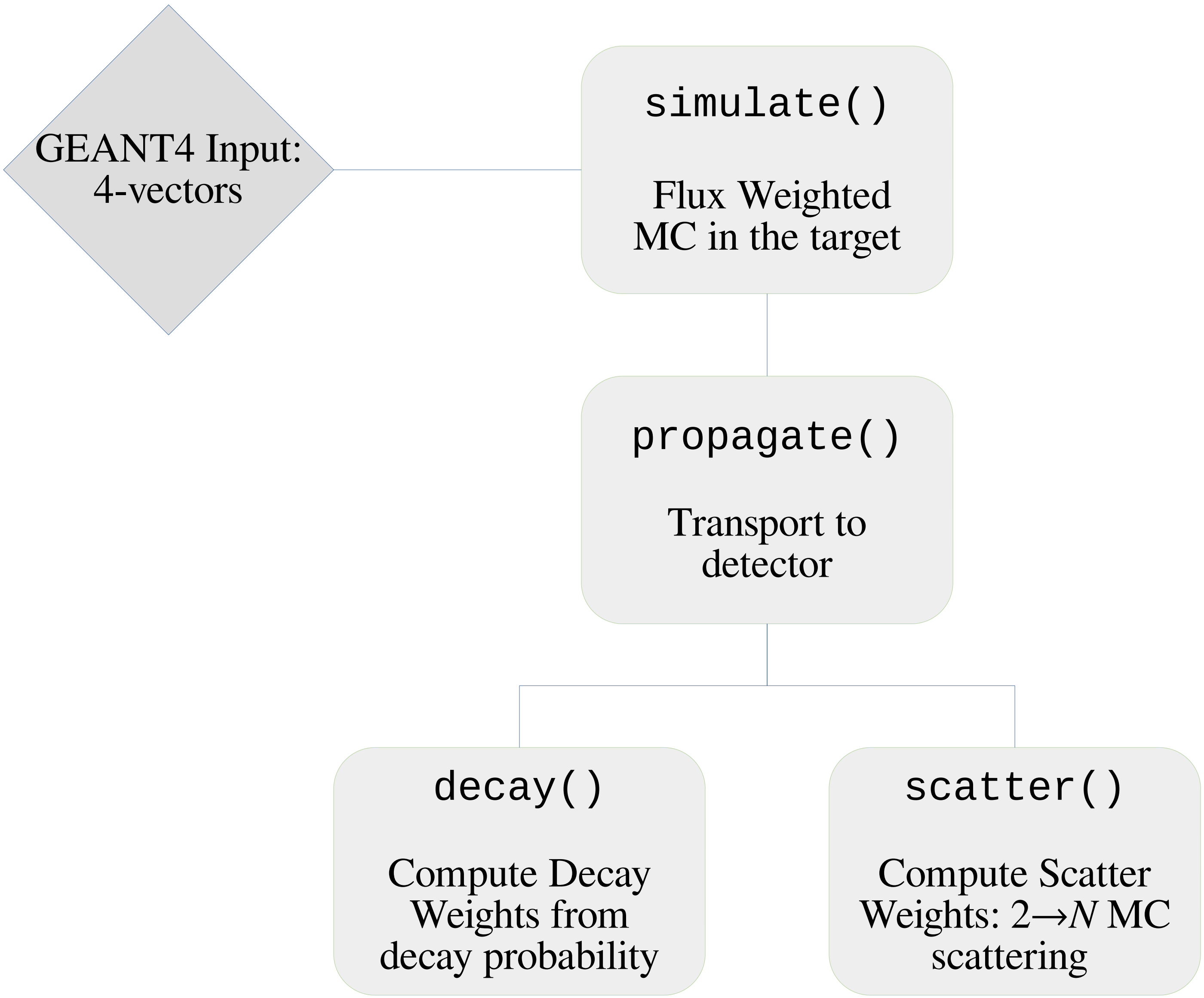


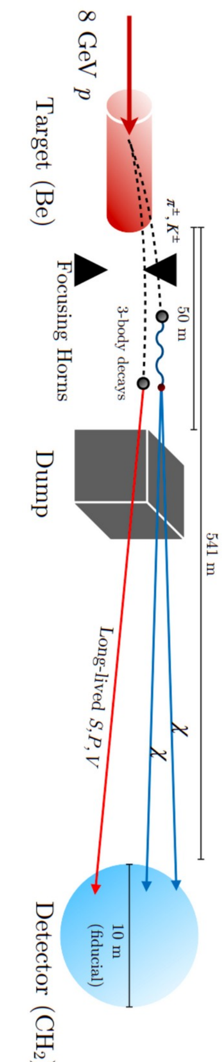


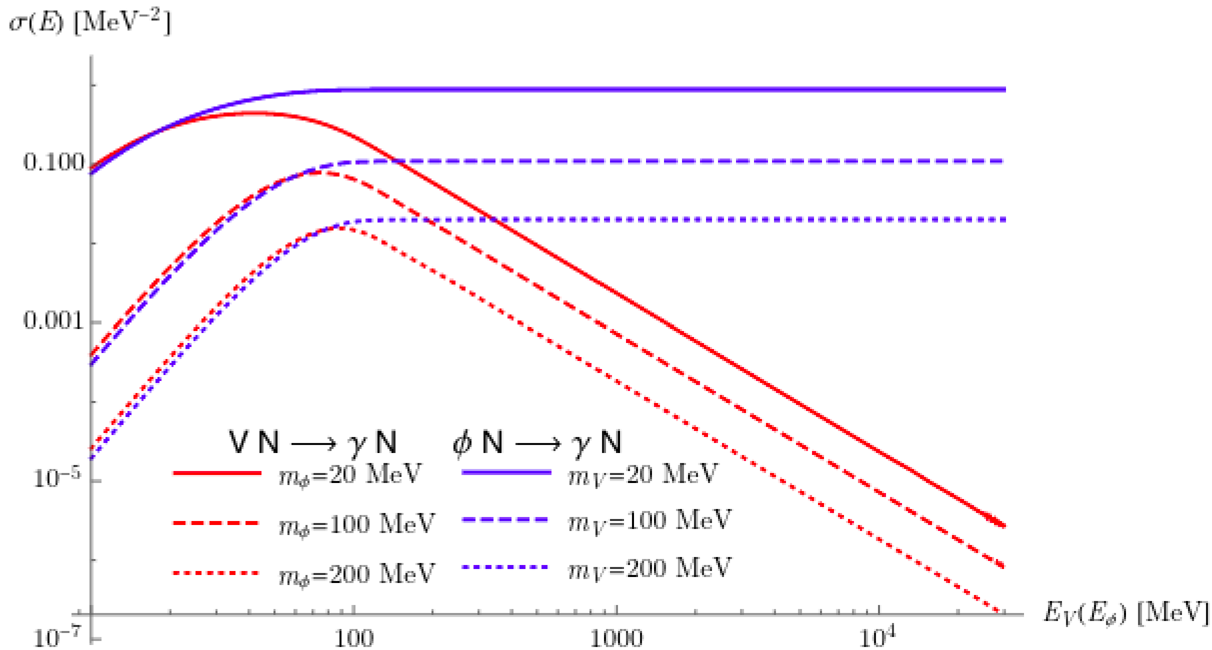
See Wooyoung's talk for more!



ALPlib: Simulation Pipeline







$\sigma(E)$ [MeV^{-2}]
0.100
0.001
10^{-5}
10^{-7}
100
1000
10^4
$E_V(E_\phi)$ [MeV]
V N ⟶ γ N
ϕ N ⟶ γ N
m_ϕ=20 MeV
m_ϕ=100 MeV
m_ϕ=200 MeV
m_V=20 MeV
m_V=100 MeV
m_V=200 MeV