A Bird's-Eye View of the MiniBooNE Anomaly

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Short Baseline Neutrino Workshop 2024

2nd Short-Baseline Experiment/Theory Workshop
ν
Santa Fe, New Mexico
April 2nd to 5th 2024

Outline

1. Features of the MB Anomaly
2. Models
3. Methodology: Simulating the Focusing Horns
4. Fits and Phase Space
5. The nucleus
6. The SBN program

How sensitive are the short baseline experiments to the MiniBooNE anomaly?

What is the outlook for BSM physics?

CCM Collaboration, [2309.02599], to appear in *PRD*

Dutta, Kim, Thornton, Thompson, Van de Water
PRL 129 (2022) 11, 111803 [2110.11944]

The MiniBooNE Excess

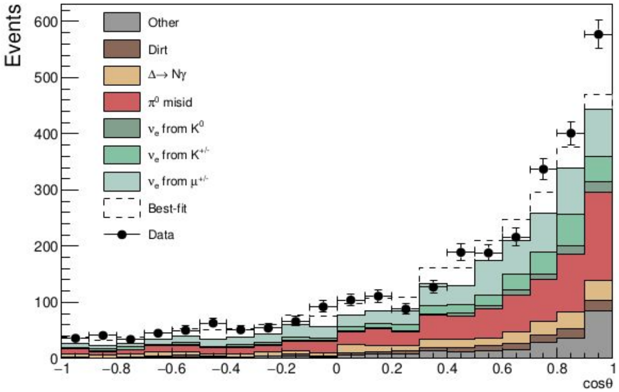
- MiniBooNE, 2021 [2006.16883]
- MiniBooNE, 2019 [1807.06137]
- MiniBooNE, 2018 [1805.12028]

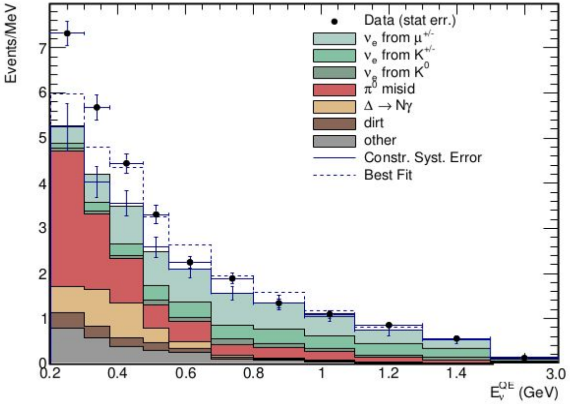
Two main features of the excess:

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



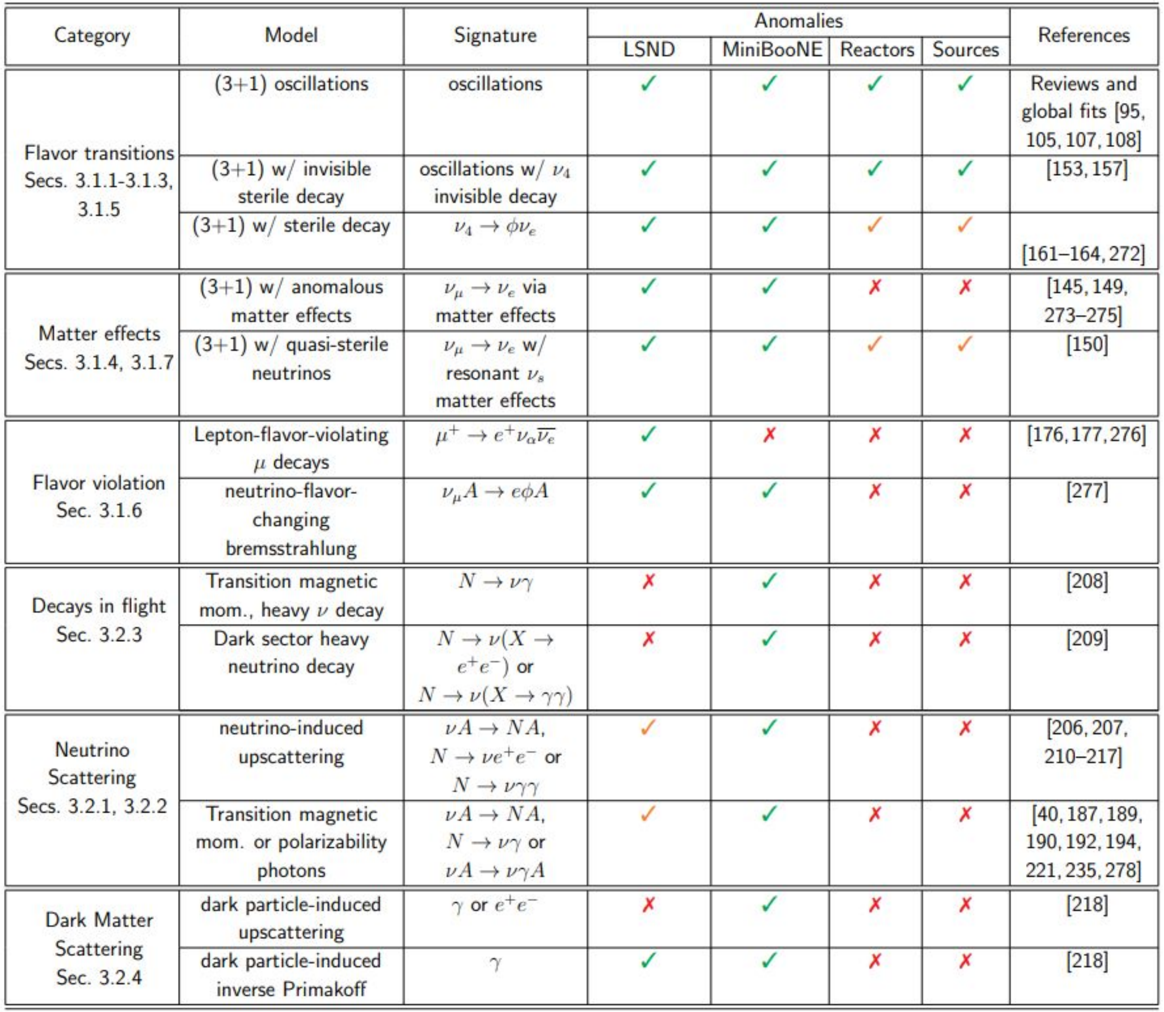


Big Picture: Lots of Models

- Sterile Neutrinos: short baseline oscillations
  - With matter effects
  - With decays
- Flavor violation
- HNLs
  - Decays
  - Upscattering
- Dark sector
  - DM Fermion upscattering
  - LLP Primakoff

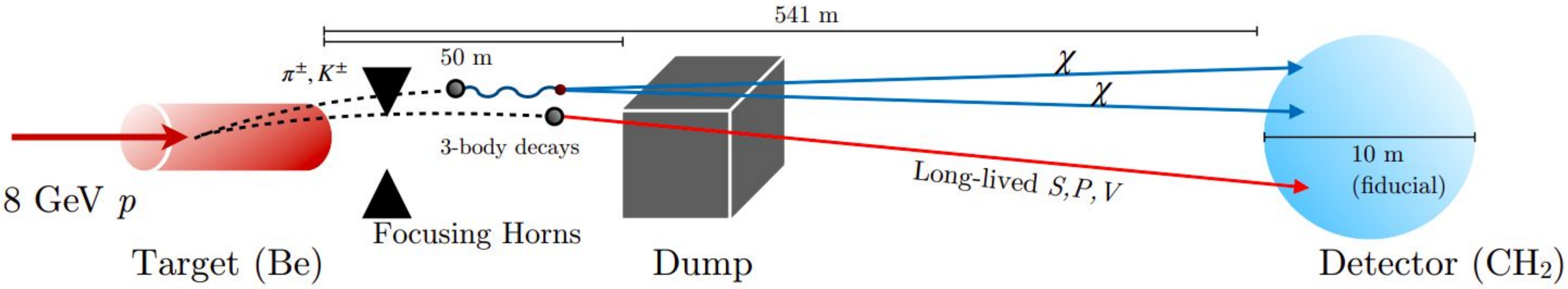
1γ, collinear 2γ, and collinear e^+e^- *final state topologies*

White Paper on Light Sterile Neutrino Searches and Related Phenomenology [2203.07323]

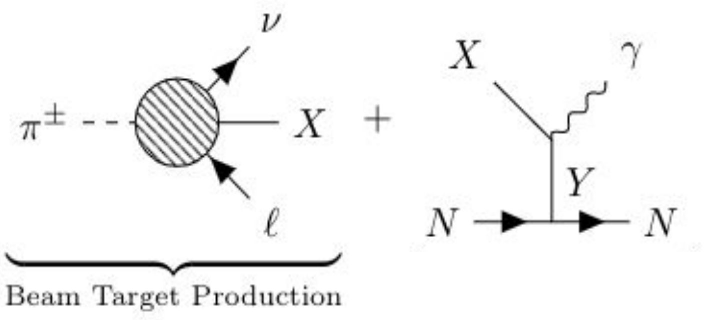


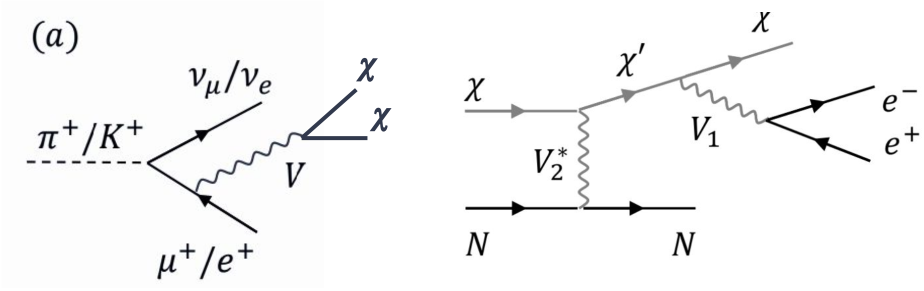
Category	Model	Signature	Anomalies				References
			LSND	MiniBooNE	Reactors	Sources	
Flavor transitions Secs. 3.1.1-3.1.3, 3.1.5	(3+1) oscillations	oscillations	✓	✓	✓	✓	Reviews and global fits [95, 105, 107, 108]
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 invisible decay	✓	✓	✓	✓	[153, 157]
	(3+1) w/ sterile decay	$\nu_4 \to \phi\nu_e$	✓	✓	✓	✓	[161–164, 272]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \to \nu_e$ via matter effects	✓	✓	✗	✗	[145, 149, 273–275]
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \to \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	✓	[150]
Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	$\mu^+ \to e^+\nu_\alpha\overline{\nu_e}$	✓	✗	✗	✗	[176, 177, 276]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \to e\phi A$	✓	✓	✗	✗	[277]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \to \nu\gamma$	✗	✓	✗	✗	[208]
	Dark sector heavy neutrino decay	$N \to \nu(X \to e^+e^-)$ or $N \to \nu(X \to \gamma\gamma)$	✗	✓	✗	✗	[209]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$\nu A \to NA$, $N \to \nu e^+e^-$ or $N \to \nu\gamma\gamma$	✓	✓	✗	✗	[206, 207, 210–217]
	Transition magnetic mom. or polarizability photons	$\nu A \to NA$, $N \to \nu\gamma$ or $\nu A \to \nu\gamma A$	✓	✓	✗	✗	[40, 187, 189, 190, 192, 194, 221, 235, 278]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	γ or e^+e^-	✗	✓	✗	✗	[218]
	dark particle-induced inverse Primakoff	γ	✓	✓	✗	✗	[218]

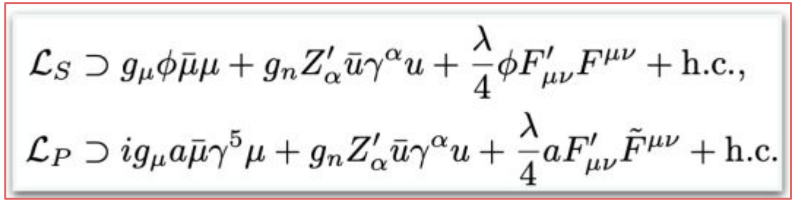
Dark Sector Particles and Long-lived Particles (LLPs) From the three-body decays of the charged pions



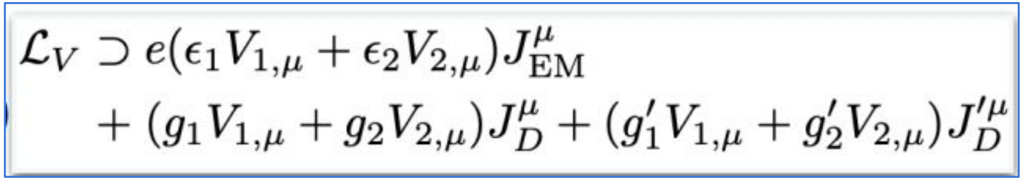
Generic Model Setup: some examples







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



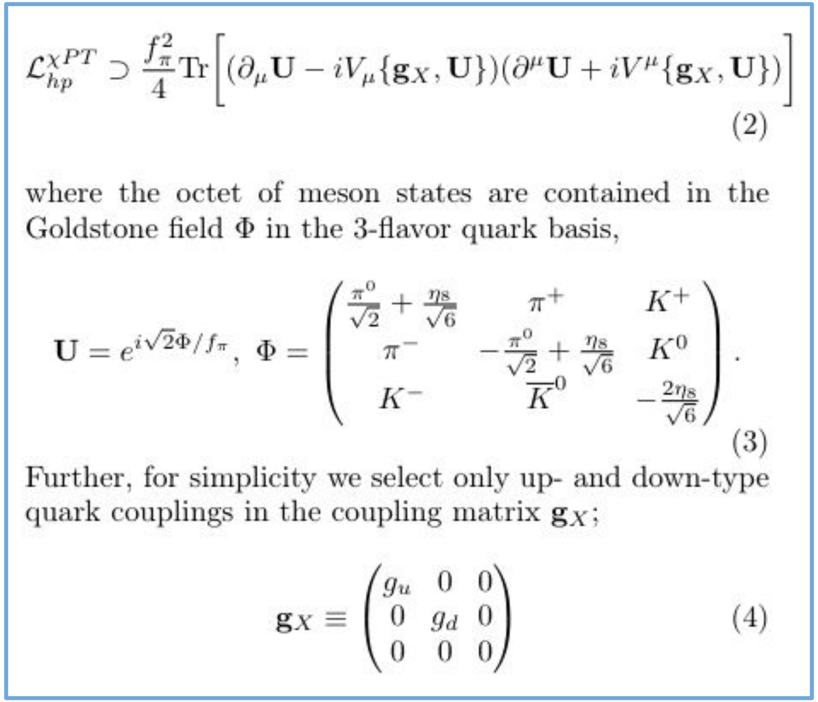
$$\mathcal{L}_V \supset e(\epsilon_1 V_{1,\mu} + \epsilon_2 V_{2,\mu})J^\mu_{\text{EM}} + (g_1 V_{1,\mu} + g_2 V_{2,\mu})J^\mu_D + (g'_1 V_{1,\mu} + g'_2 V_{2,\mu})J'^\mu_D$$

(1) Long-lived particle (LLP) boson *X*, Primakoff scattering in the detector

(2) Promptly decaying boson tto DM pairs, DM scattering in the detector

Specific Example: Single Vector Mediator Coupled to Pions

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



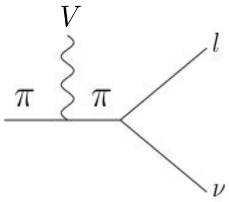
$$\mathcal{L}^{\chi PT}_{hp} \supset \frac{f_\pi^2}{4}\mathrm{Tr}\Big[(\partial_\mu \mathbf{U} - iV_\mu\{\mathbf{g}_X, \mathbf{U}\})(\partial^\mu \mathbf{U} + iV^\mu\{\mathbf{g}_X, \mathbf{U}\})\Big] \tag{2}$$

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

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

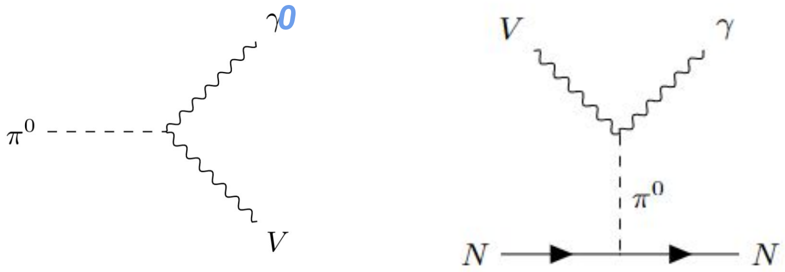
Further, for simplicity we select only up- and down-type quark couplings in the coupling matrix $\mathbf{g}_X$;

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



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

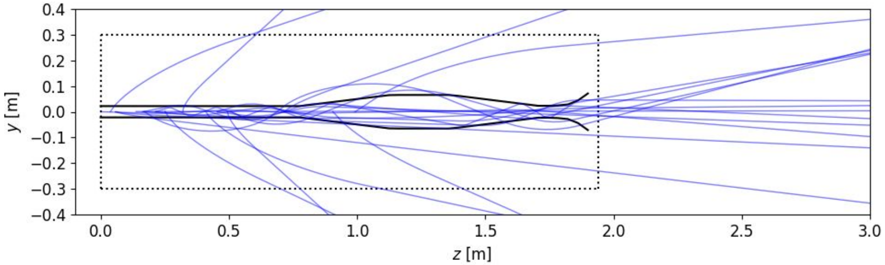
$$\mathcal{L}^{\chi PT}_{hp} \supset (\underset{\underset{g_\pi}{}}{\underset{\downarrow}{2g_u + g_d}})\frac{e}{16\pi f_\pi}\pi^0 F_{\mu\nu}\tilde{H}^{\mu\nu}$$



At the meson level, we get a scattering mediated by the Pi0-N-N interaction for free - this is incoherent but elastic in the low energy limit

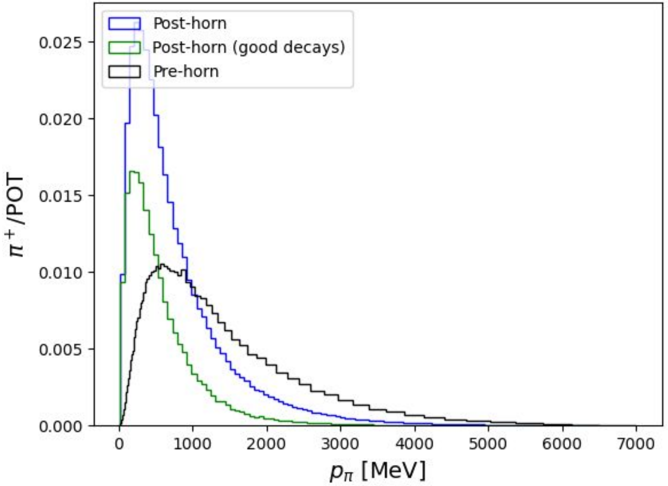
…more discussion on inelasticity later

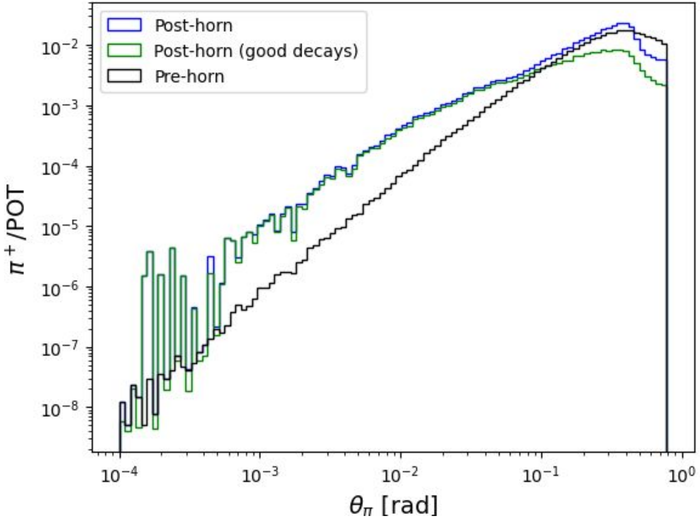
Vignette: RKHorn Simulation



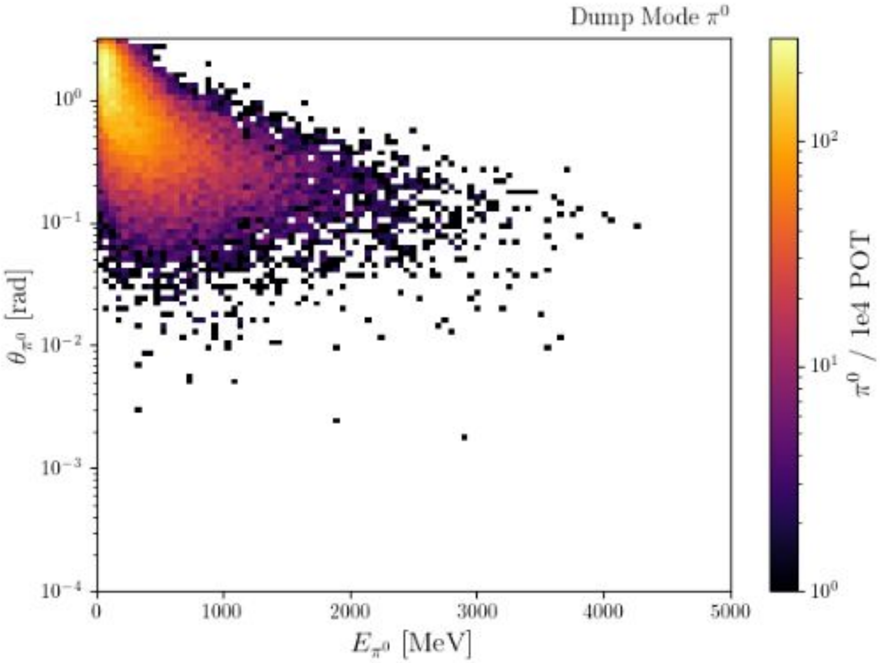
1. Simulate the proton beam spot
2. Simulate pi+/- production in the target
3. Propagate pions out of the target and through the toroidal magnetic field of the horn system via Runge-Kutta

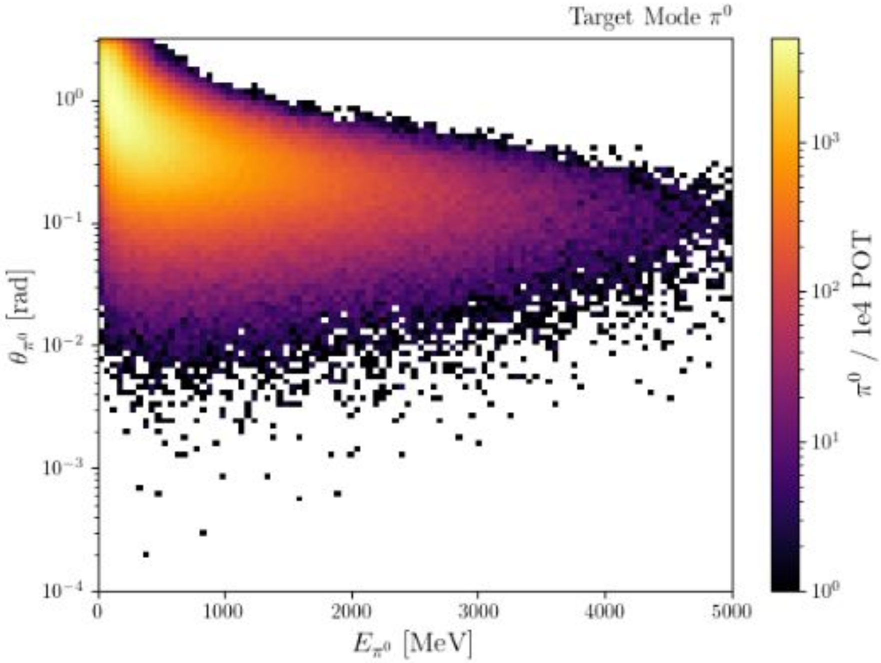
- Based on modelB routine used for MiniBooNE
- Work in progress; more sophistication and improvements planned: github



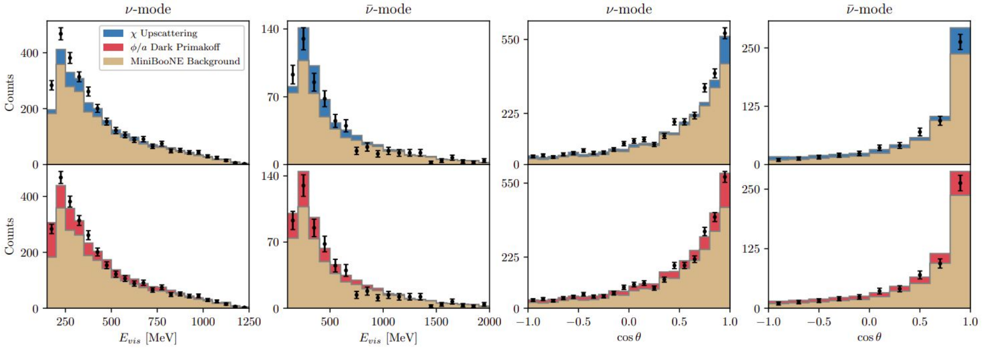


Dump vs. Target Mode Pion Fluxes



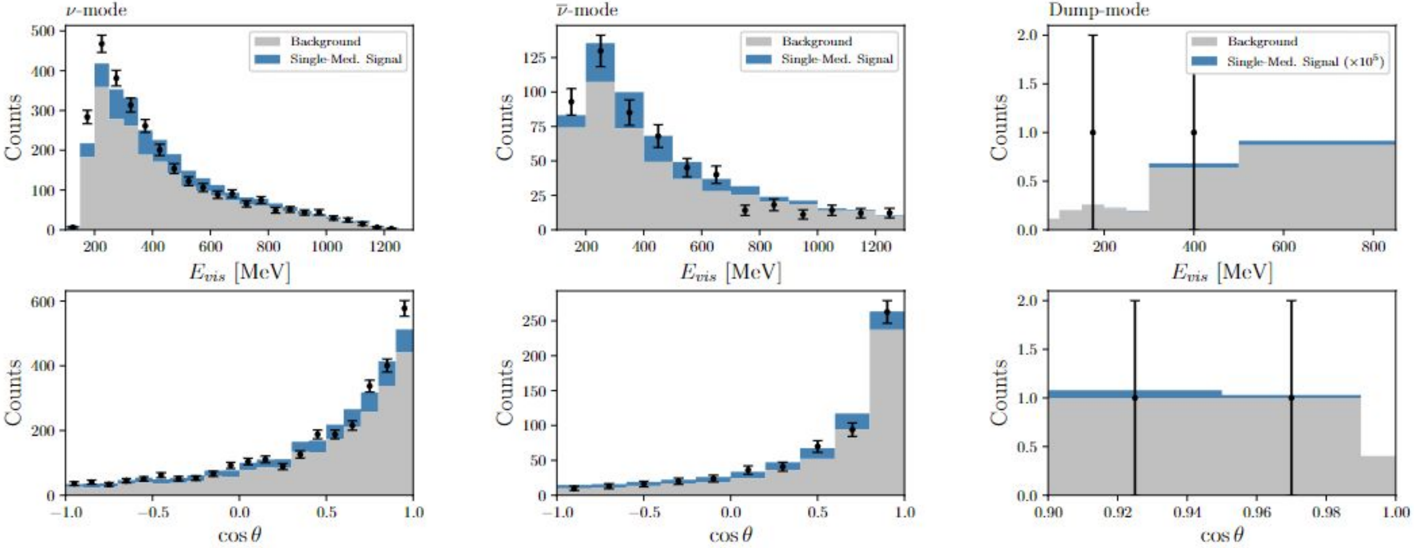


Result: Fits to the target mode distributions at MiniBooNE



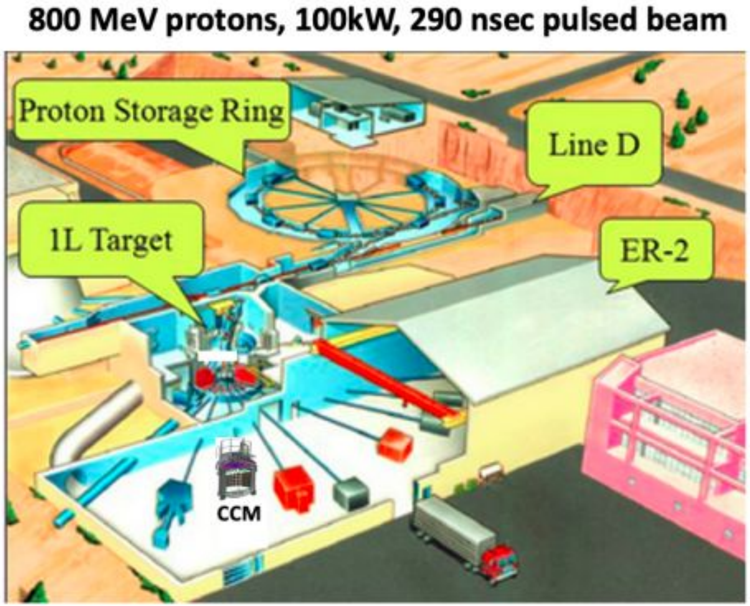
Dutta, Kim, Thornton, Thompson, Van de Water *PRL 129 (2022) 11, 111803* [2110.11944]

We fit the resulting photoconversion rate to the combined Evis and cosine distributions in both target and dump mode with a binned log-likelihood

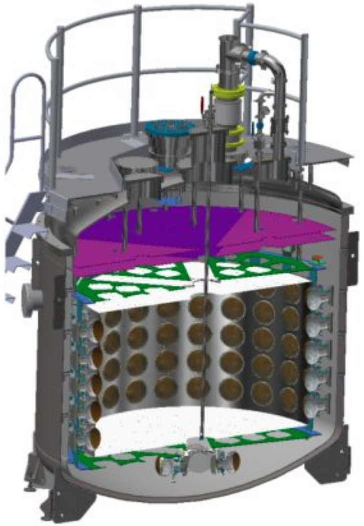


CCM Collaboration, [2309.02599], to appear in *PRD*

Coherent Captain Mills (CCM)



- CCM
- 90 degrees off-axis
- 23m target-to-detector
- 800 MeV *p* beam on W target
- Collected 1.79e21 POT in six week engineering run with the **CCM120** detector (120 PMTs)
- **CCM200** is online and taking data

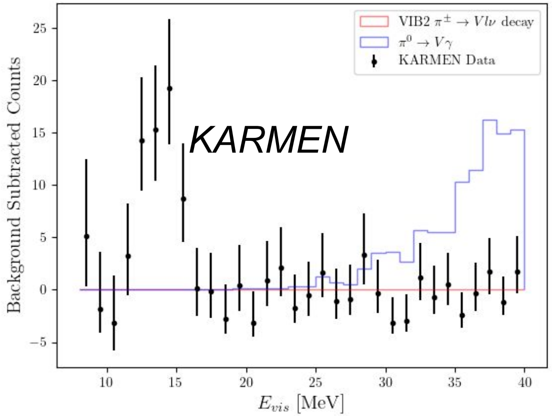


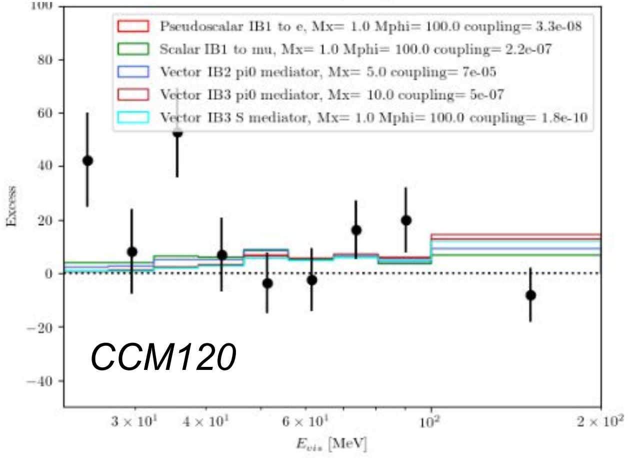
Charged and neutral pions both unfocused and more isotropic at these lower energies → offers a complementarity to the BNB source and an independent test of g_{π^0}

Complementarity at *o*(1 GeV) Proton Targets: CCM, LSND, KARMEN

- KARMEN:
  - 110 degrees off-axis
  - 17.5m target-to-detector
  - 800 MeV *p* beam
  - 4.6e22 POT
- LSND
  - 12 degrees off-axis
  - 30m target-to-detector
  - 800 MeV *p* beam
  - Prompt and delayed searches (null results only)
- CCM
  - 90 degrees off-axis
  - 23m target-to-detector
  - 800 MeV *p* beam
  - Collected 1.79e21 POT in six week engineering run: **CCM120**

Analysis	E_{vis} Range	$\cos\theta$ Range
DAR	$[18, 35]$ MeV	$-1 \leq \cos\theta \leq 1$
DIF	$[60, 200]$ MeV	$\cos\theta < 0.8$

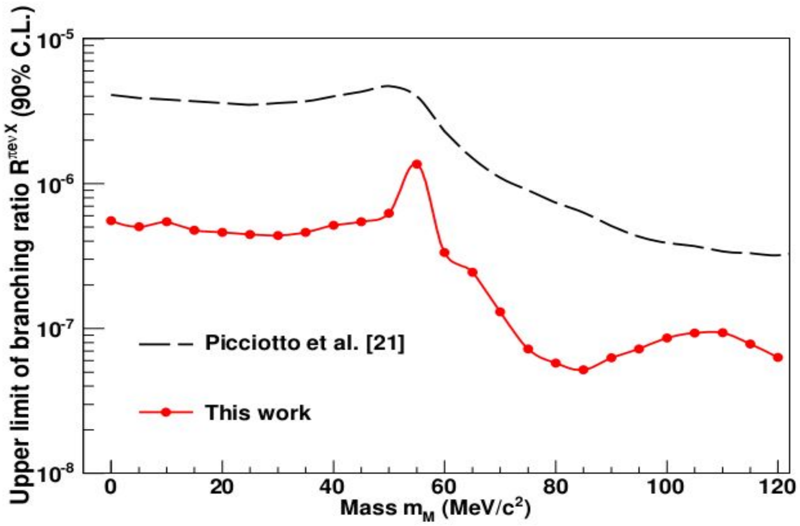


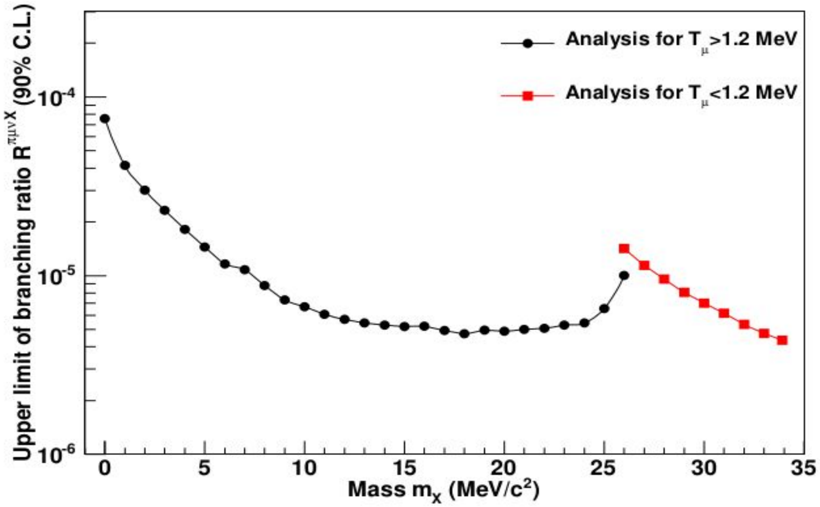


CCM Collaboration, [2309.02599], to appear in *PRD*

Other Constraints: Rare Pion Decays at PIENU

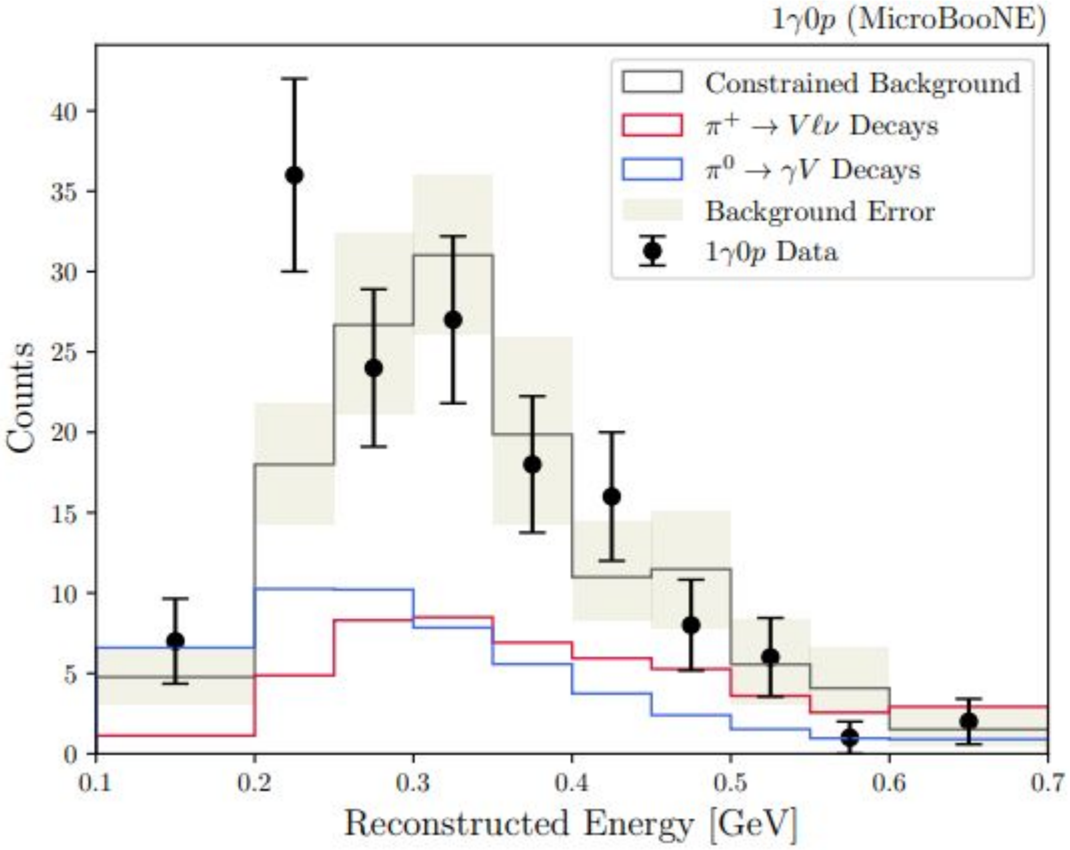
PRD **103**, 052006, [2101.07381] PIENU Collaboration





→ Constrains the total branching fraction for our charged pion decay production mechanism

MicroBooNE: 1g0p analysis from the delta resonance search

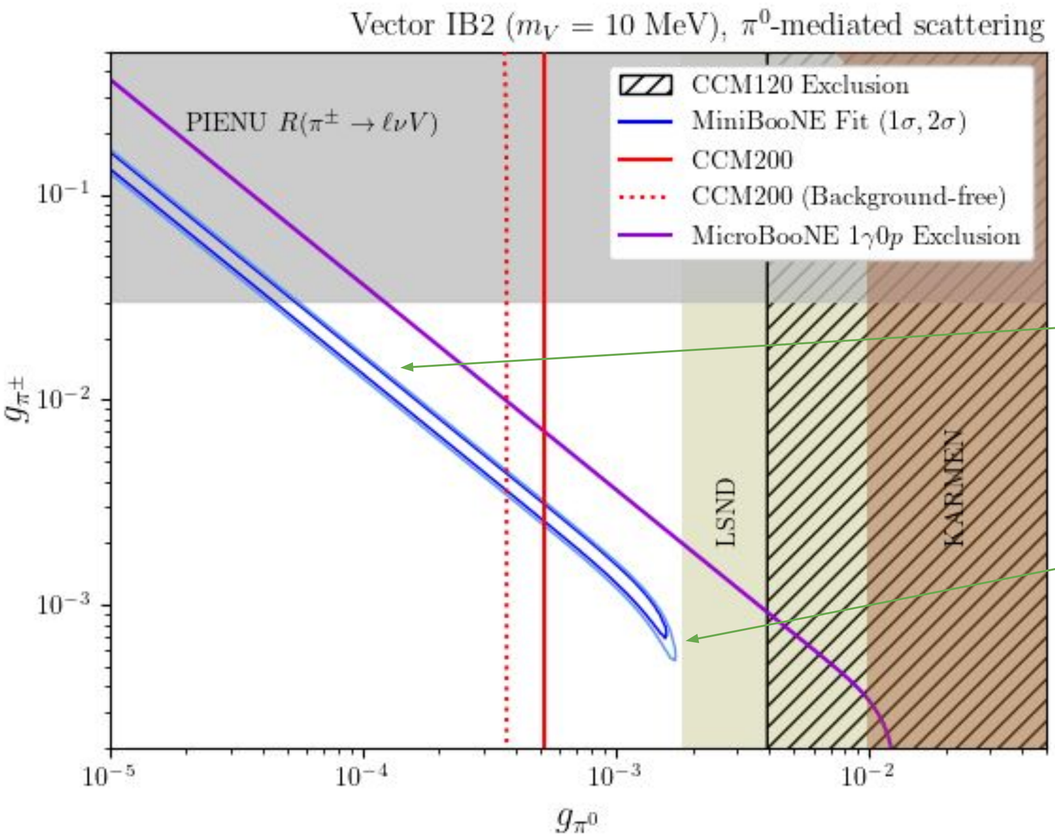


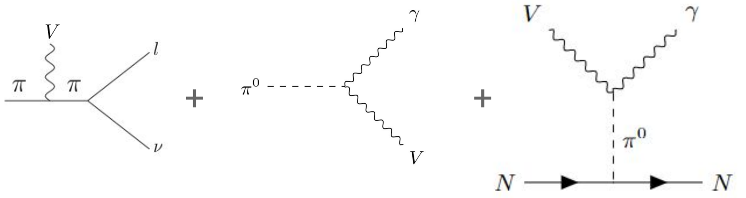
We also take the existing data from the 1γ0p search

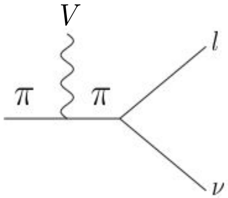
(*MicroBooNE collaboration,* [2110.00409] *PRL* **128**, 111801)

We obtain a conservative limit from a binned log-likelihood on the visible energy data

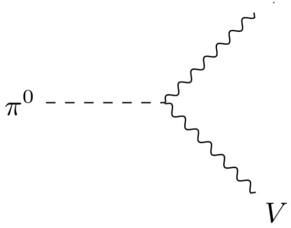
Single Vector LLP Coupling to Pions: m_V=10 MeV Fits and Projections







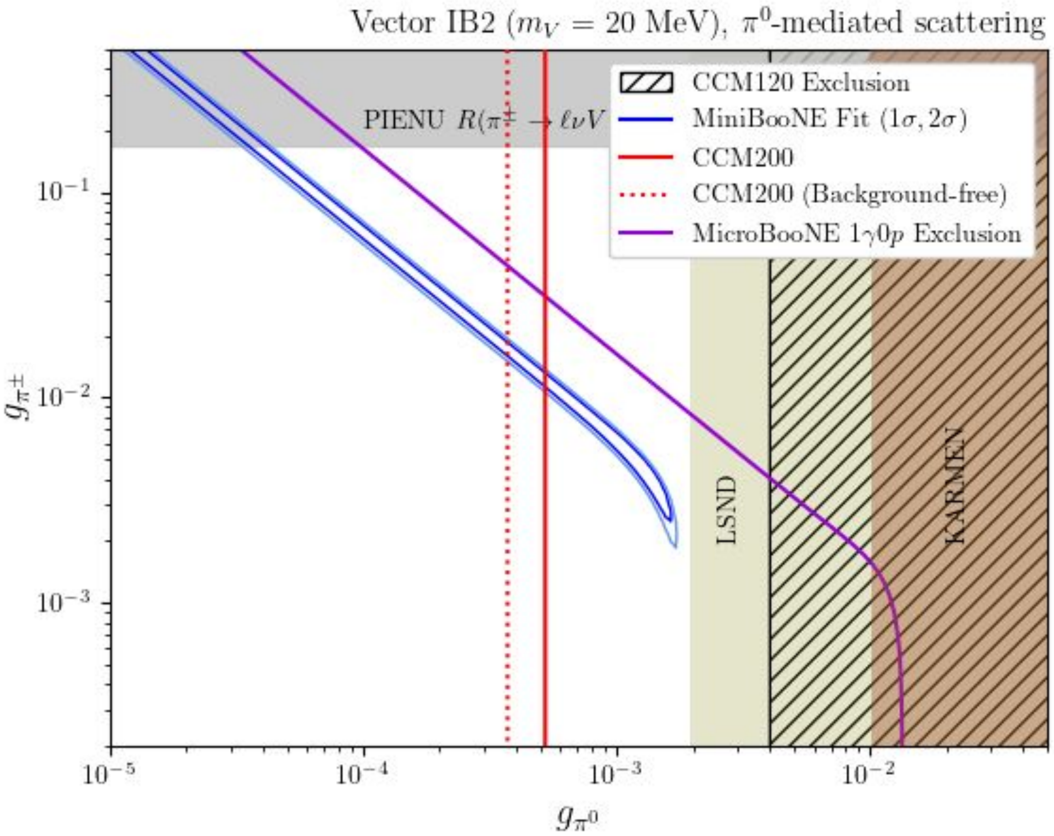
Charged pion production limit

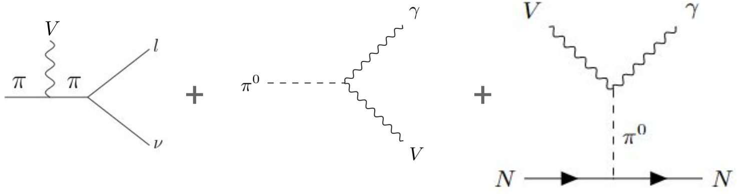


Neutral pion production limit

$$\mathcal{L}_{int} \supset i g_{\pi^\pm} V_\mu \pi^+ (\partial^\mu \pi^-) + g_{\pi^0} \frac{e}{16\pi f_\pi} \pi^0 F_{\mu\nu} \tilde{H}^{\mu\nu} - i g_{\pi N N} \pi^0 \overline{N} \gamma^5 \tau_3 N$$

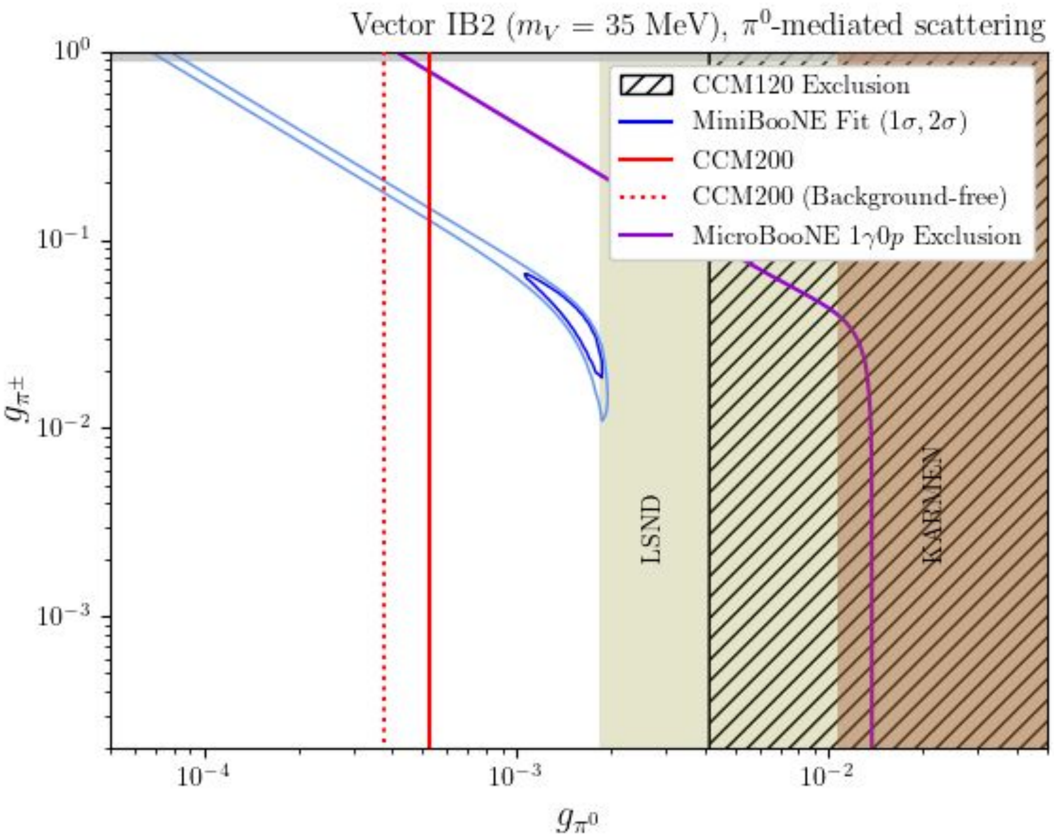
Single Vector LLP Coupling to Pions: m_V=20 MeV Fits and Projections

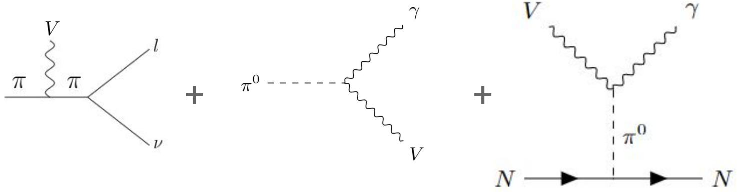




- Moving to higher mass LLP vector bosons, the branching ratio for charged pion production drops
  - PIENU constraint becomes weaker on the coupling

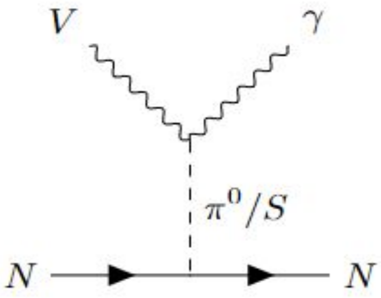
Single Vector LLP Coupling to Pions: m_V=35 MeV Fits and Projections



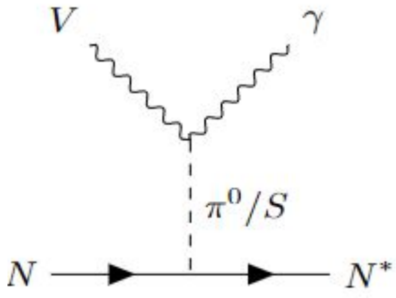


- Moving to higher mass LLP vector bosons, the branching ratio for charged pion production drops
  - PIENU constraint becomes weaker on the coupling
- Moving beyond 35 MeV in the vector mass, we see that the preferred region for MB at 1sigma favours a combination of neutral and charged components
  - The softer spectra from neutral pion decays balances the harder spectra from the 3-body decays at high mass
  - Dump mode also constrains arbitrarily large neutral pion coupling

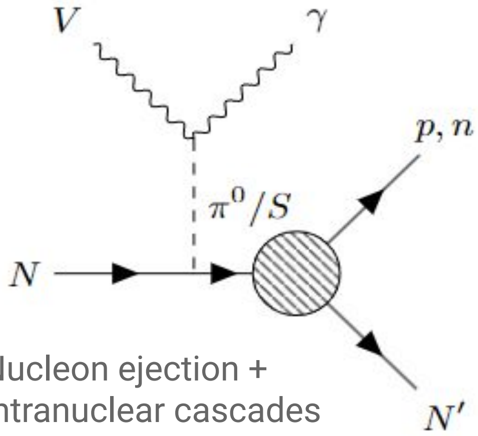
Achilles Integration: Getting the full picture of Coherent + Incoherent Scattering Topologies



Coherent



Nuclear Excitation
→ De-excitation

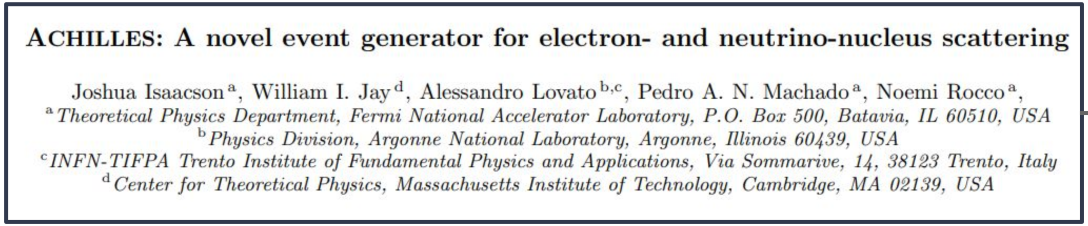


Nucleon ejection +
Intranuclear cascades

Incoherent / Inelastic

$1\gamma0p + 1\gamma1p + 1\gamma1n$

Final state topologies!



ACHILLES: A novel event generator for electron- and neutrino-nucleus scattering

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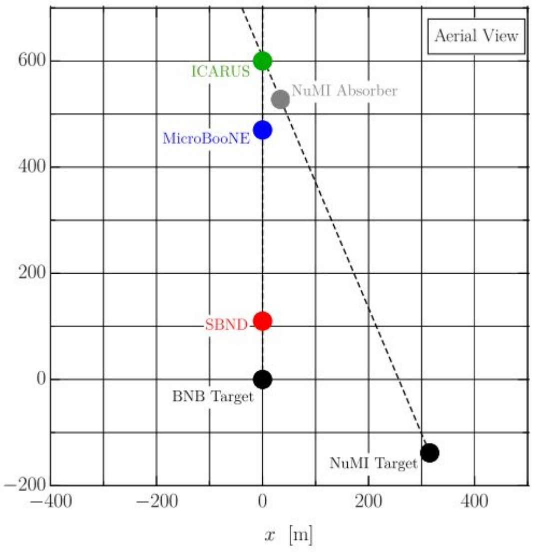
[d] Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

How does this picture look for the SBN program?

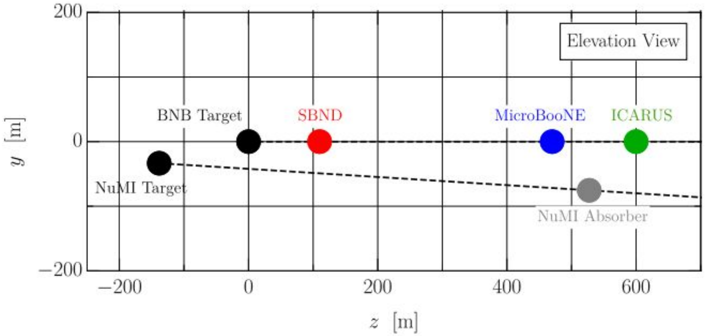
The Short Baseline Program: SBND, MicroBooNE & ICARUS

Forecasts:

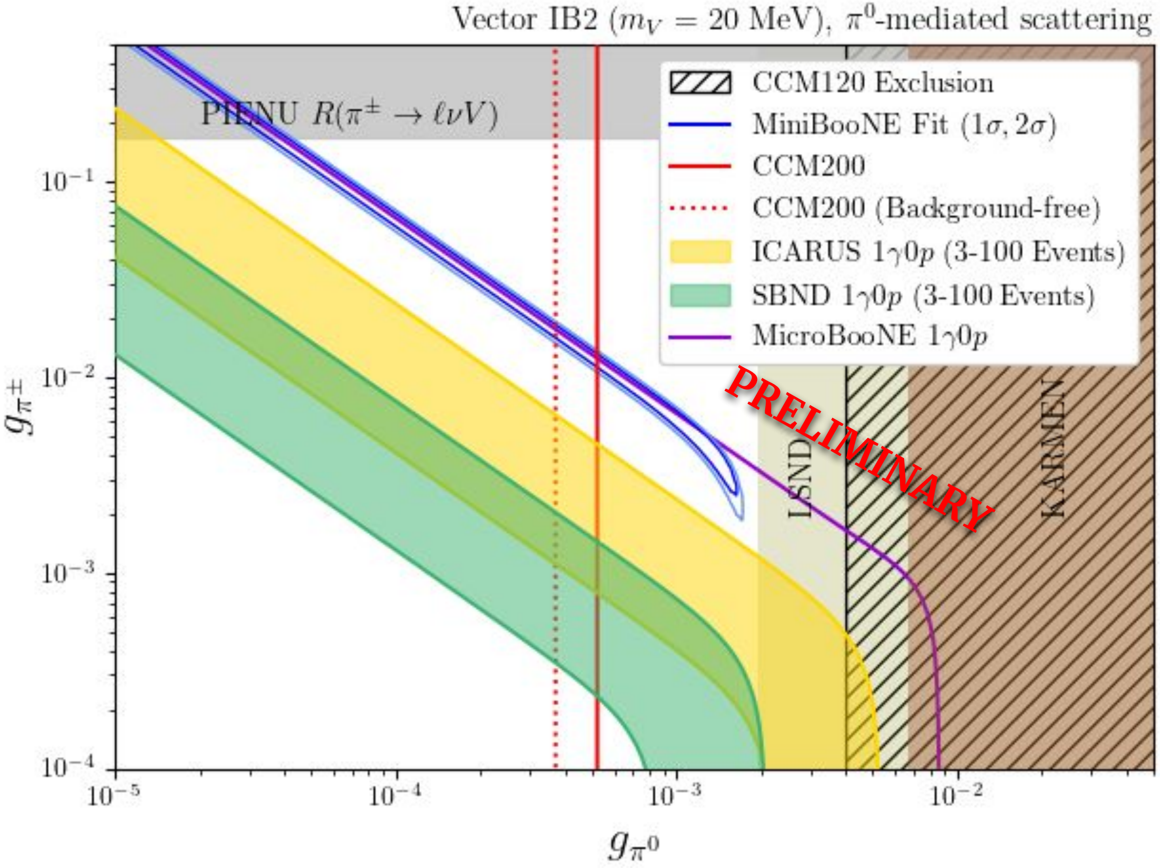
Experiment	Distance (m)	Fiducial Volume (m^3)	Energy Threshold	POT
SBND	110	4m x 4m x 5m long	100 MeV	6.6e20
MicroBooNE	470	2.3m x 2.6m x 10.4 m long	100 MeV	13.2e20
ICARUS	600	2 x (3.0m x 3.16m x 17.95 m long)	100 MeV	6.6e20



Batell, Berger, Ismail [1909.11670]

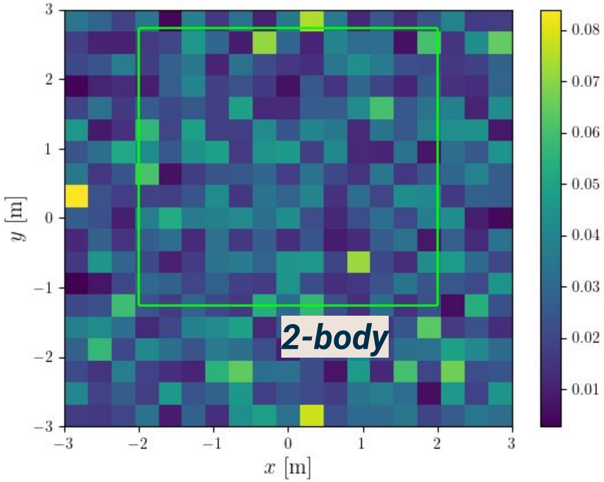


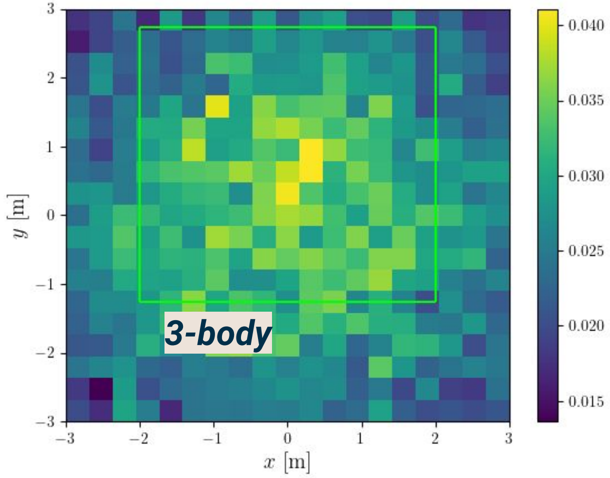
Projections for Sensitivity to the MiniBooNE Excess: SBND, MicroBooNE, ICARUS



- We now forecast future sensitivity reaches for
- MicroBooNE
  - assuming ~2x POT and 3x efficiency w.r.t. the delta resonance search, scaling backgrounds
- SBND and ICARUS for 50% signal efficiency and a range of critical event rates (3-100) which may depend on backgrounds
- In each case, we see that the SBN program is sensitive to MB excess!

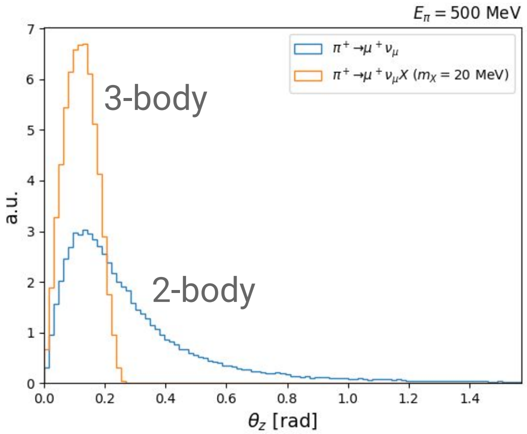
The spatial distribution at the detector face: [X,Y]





- Variations in the angular distribution of the signal flux vs. that of the neutrino signal
- may be visible in the x,y distributions at the detector

PRELIMINARY



The different kinematics of 2-body and 3-body pion decays may be differentiable…

… depending on the mass, decay model

Conclusions

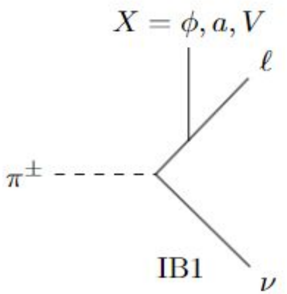
- We explored a **large variety of LLP models** as solutions to the MB excess
- We find a **valuable complementarity between stopped-pion** / 1 GeV-scale proton target experiments **and the higher energy beam dumps** / SBN program
  - BSM signal may be connected to both the neutral and charged pions
- Better modeling of scattering in generic MB-anomaly-solving models (e.g. photoconversion and upscattering) is needed to model the 1γ**N**p or inelastic + intranuclear cascade channels → **`Achilles`**
- Ultimately the SBN program with MicroBooNE, SBND, and ICARUS will be sensitive to the MB anomaly

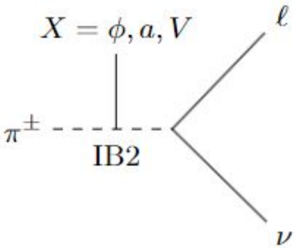
Backup

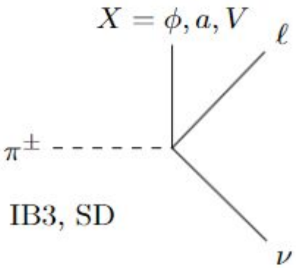
More Models!

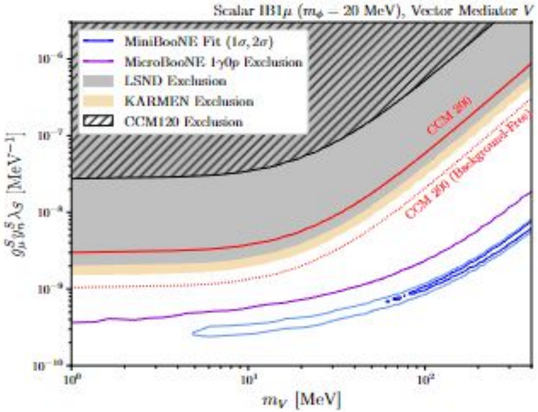
$$\mathcal{L}_{int} \supset g_\mu^S \phi \bar{\mu}\mu + y_n^V V_\mu \bar{N}\gamma^\mu N - \frac{\lambda_S}{4}\phi F_{\mu\nu} H^{\mu\nu} + \text{h.c.}$$

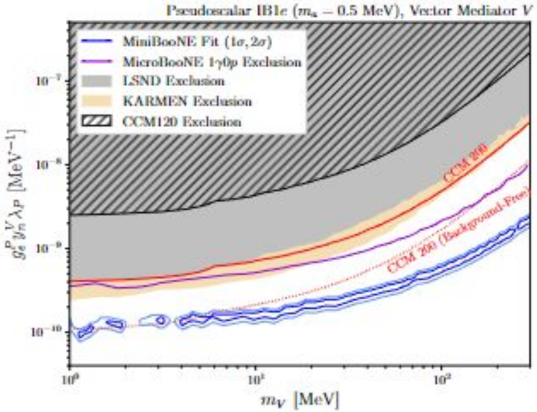
$$\mathcal{L}_{int} \supset -i g_e^P a \bar{\mu}\gamma^5 \mu + y_n^V V_\mu \bar{N}\gamma^\mu N - \frac{\lambda_P}{4} a F_{\mu\nu} \tilde{H}^{\mu\nu}$$

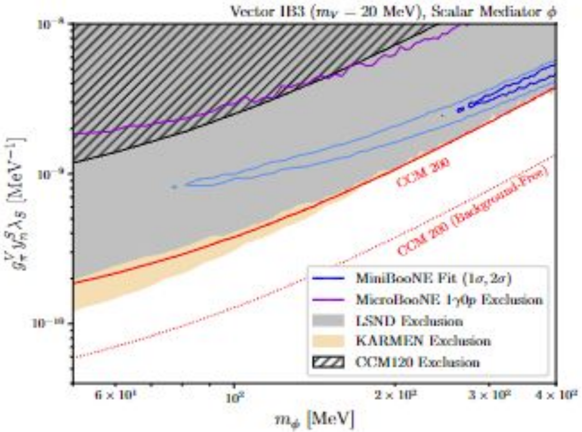







Scalar IB1μ ($m_\phi = 20$ MeV), Vector Mediator V


Pseudoscalar IB1e ($m_a = 0.5$ MeV), Vector Mediator V

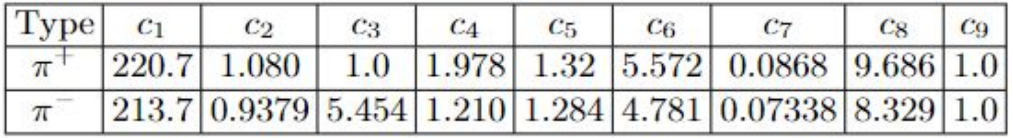

Vector IB3 ($m_V = 20$ MeV), Scalar Mediator ϕ

CCM Collaboration, [2309.02599]

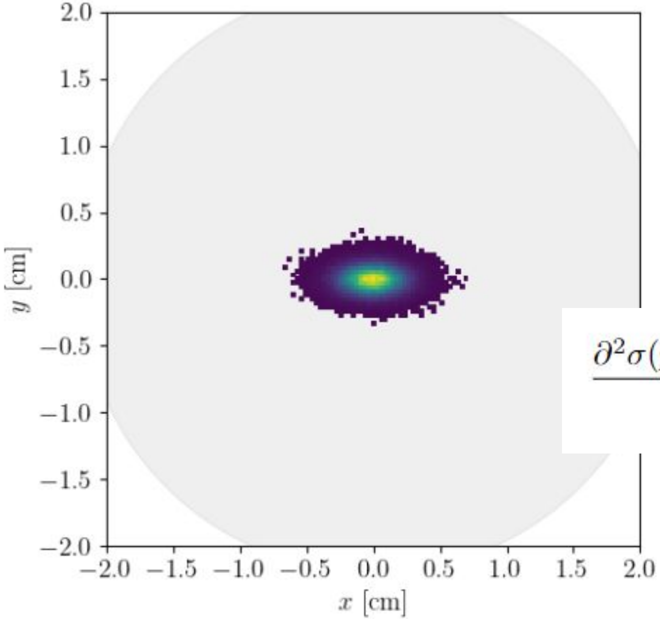
$$\mathcal{L}_{int} \supset y_n^S \phi \overline{N} N - \frac{\lambda_S}{4} a F_{\mu\nu}\tilde{H}^{\mu\nu} - i g_\pi^V \pi^+ \bar{\mu}\gamma^\rho (1-\gamma^5)\nu V_\rho + \text{h.c.}$$

Modeling the BNB Beam spot

Beam spot parameters: see D. W. Schmitz thesis



Type	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9
π^+	220.7	1.080	1.0	1.978	1.32	5.572	0.0868	9.686	1.0
π^-	213.7	0.9379	5.454	1.210	1.284	4.781	0.07338	8.329	1.0

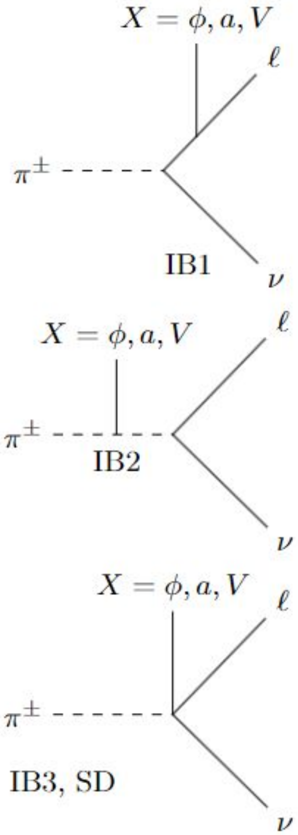


$$\frac{\partial^2\sigma(p+\mathrm{Be}\to\pi^\pm+X)}{\partial p\,\partial\Omega} = c_1 p^{c_2}\left(1-\frac{p}{p_B-c_9}\right)\exp\left(-c_3\frac{p^{c_4}}{p_B^{c_5}} - c_6\theta(p-c_7 p_B(\cos\theta)^{c_8}\right)$$

Sanford-Wang parameterization of the pion production XS: see e.g. *MiniBooNE collaboration* [0806.1449

General Pion Decays

See Khodjamirian, Wyler, 2001



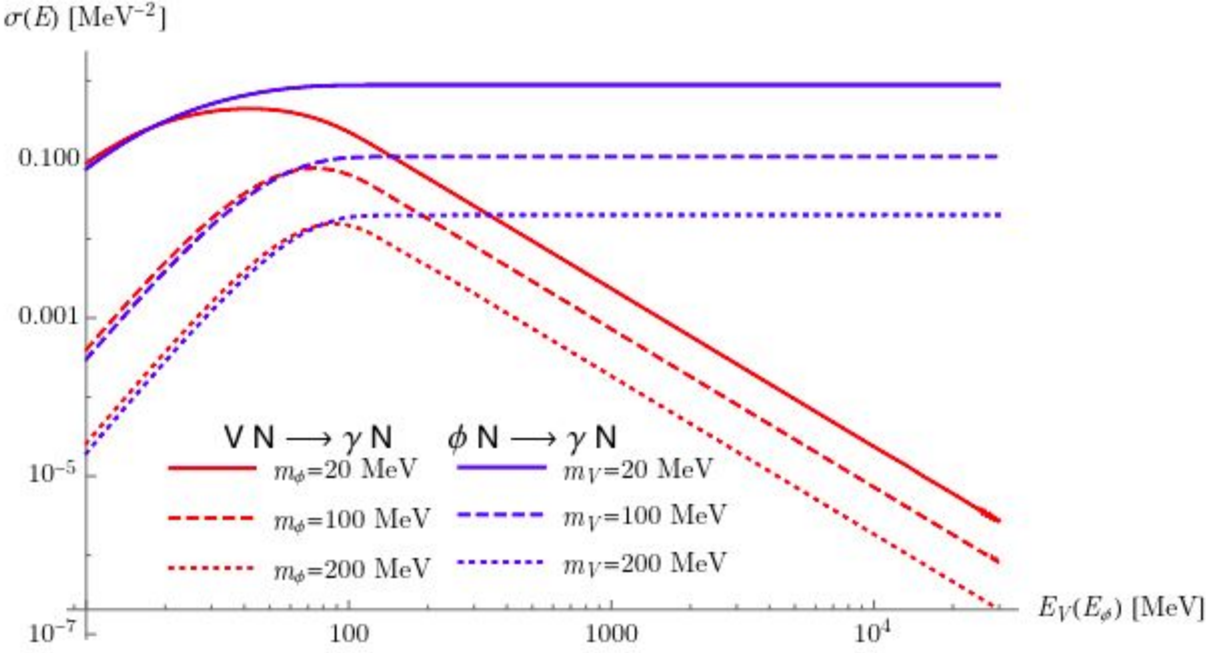
$$\mathcal{M} = i\frac{G_F}{\sqrt{2}}\varepsilon^\mu\left[\bar{u}_\ell\gamma^\rho(1-\gamma^5)v_\nu\right]T_{\mu\rho}$$

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

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

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

Cross Sections: Photoconversion for a variety of Lorentz Represenations



Branching Fractions: Rare 3-body decays