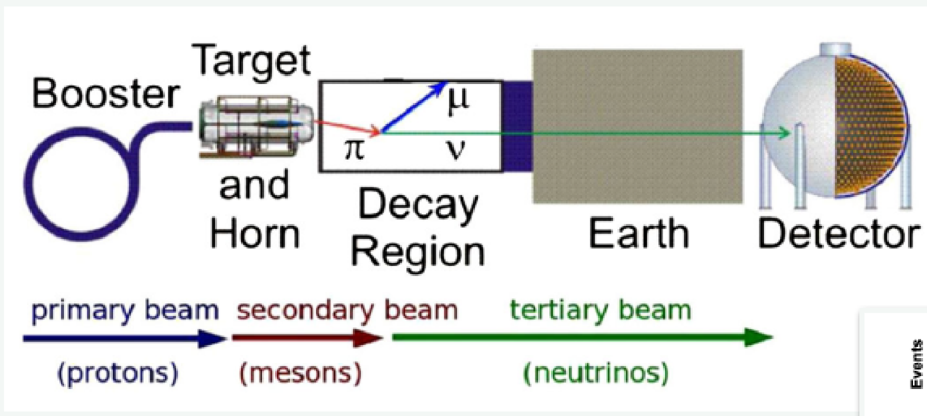
Solutions of MiniBooNE Anomaly using Dark Sector Models

Bhaskar Dutta

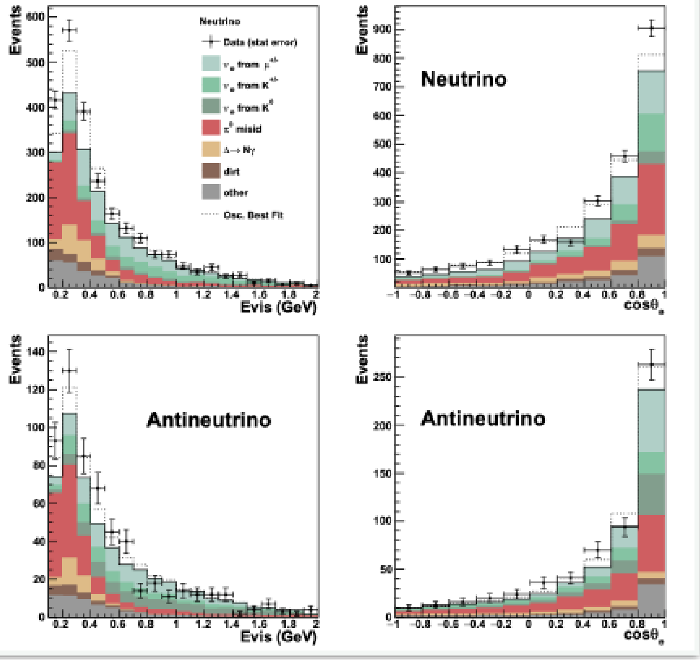
Texas A&M University

Rabi-Fest, University of Maryland, October, 2022

MiniBooNE Anomaly

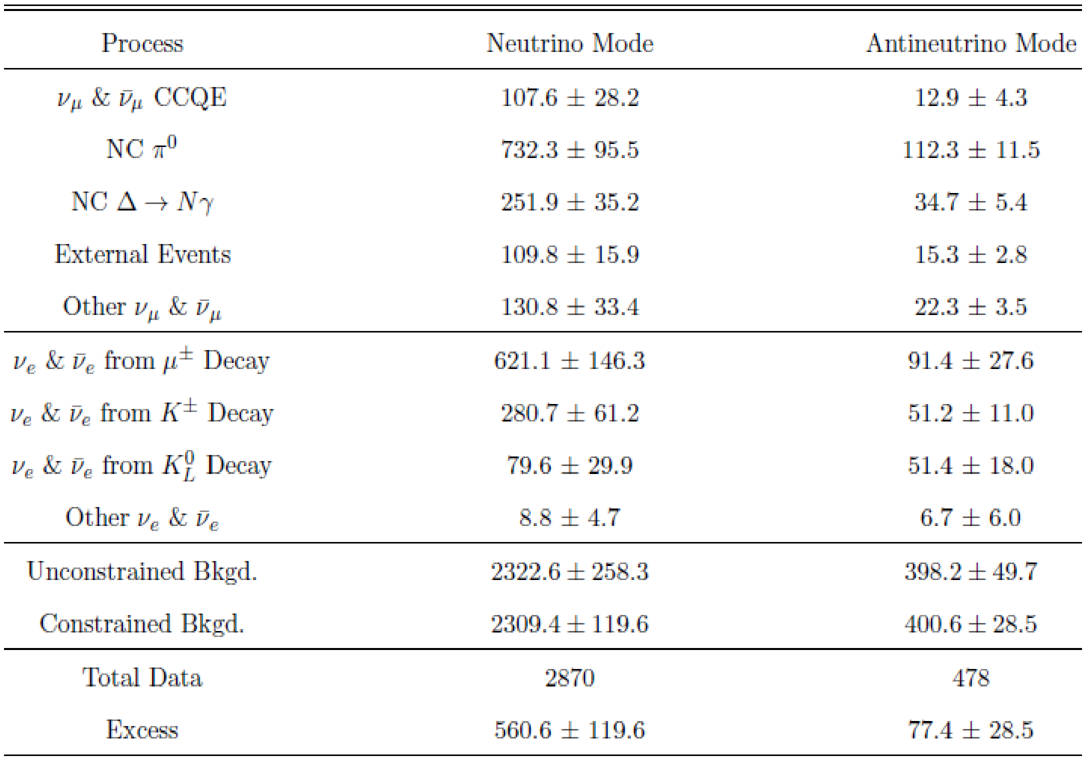


- MiniBooNE, 2021 [2006.16883]
- MiniBooNE, 2019 [1807.06137]
- MiniBooNE, 2018 [1805.12028]

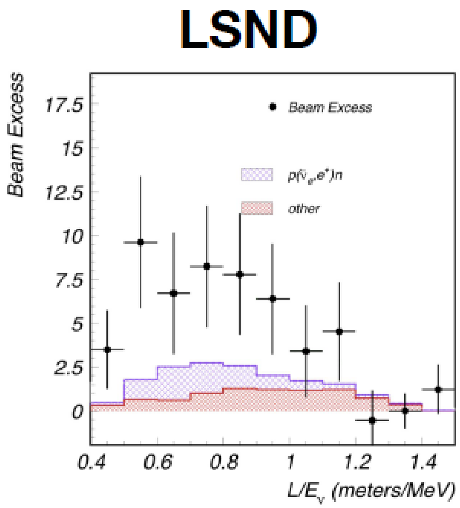


- 8 GeV proton beam on Be target
- Magnetic horns focus charged meson decays for neutrino production
- 12m diameter, 818 tonne mineral oil (CH2) detector
- 489m downstream from dump

MiniBooNE Anomaly



Process	Neutrino Mode	Antineutrino Mode
ν_μ & $\bar{\nu}_\mu$ CCQE	107.6 ± 28.2	12.9 ± 4.3
NC π^0	732.3 ± 95.5	112.3 ± 11.5
NC $\Delta \to N\gamma$	251.9 ± 35.2	34.7 ± 5.4
External Events	109.8 ± 15.9	15.3 ± 2.8
Other ν_μ & $\bar{\nu}_\mu$	130.8 ± 33.4	22.3 ± 3.5
ν_e & $\bar{\nu}_e$ from $\mu^\pm$ Decay	621.1 ± 146.3	91.4 ± 27.6
ν_e & $\bar{\nu}_e$ from $K^\pm$ Decay	280.7 ± 61.2	51.2 ± 11.0
ν_e & $\bar{\nu}_e$ from K^0_L Decay	79.6 ± 29.9	51.4 ± 18.0
Other ν_e & $\bar{\nu}_e$	8.8 ± 4.7	6.7 ± 6.0
Unconstrained Bkgd.	2322.6 ± 258.3	398.2 ± 49.7
Constrained Bkgd.	2309.4 ± 119.6	400.6 ± 28.5
Total Data	2870	478
Excess	560.6 ± 119.6	77.4 ± 28.5



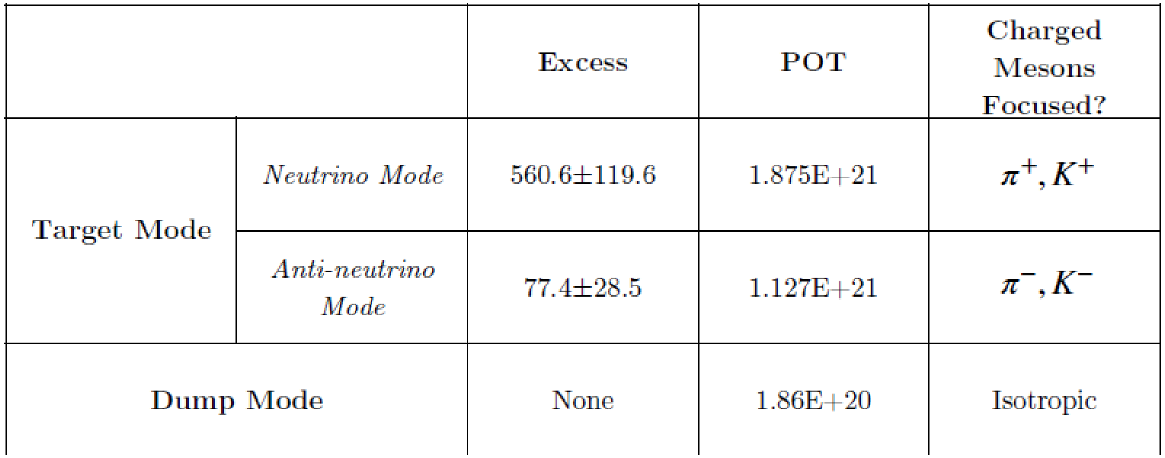
3.8 σ excess

$\bar{\nu}_e$ signal was detected via The reaction $\bar{\nu}_e\, p \to e^+\, n$ with e^+ energy between 36 and 60 MeV, followed by γ from $np \to d\,\gamma$ (2.2MeV)

4.8 σ excess: electron-like event

Nucl-ex/9504002

MiniBooNE Anomaly



		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

- *When a proton beam hits a target, a lot of charged and neutral mesons are Produced about one pion/POT, 0.1 kaon/POT*
- *Almost all the charged pions, and kaons are horn focused on the direction of the detector (the neutral mesons fraction is smaller)*

Solutions:

- *All the solutions which are proposed are neutrino-based new physics*
- *Dark sector attempts to use* π^0 *decay are ruled out by the dump mode data*

$\pi^0 \to X + \gamma$

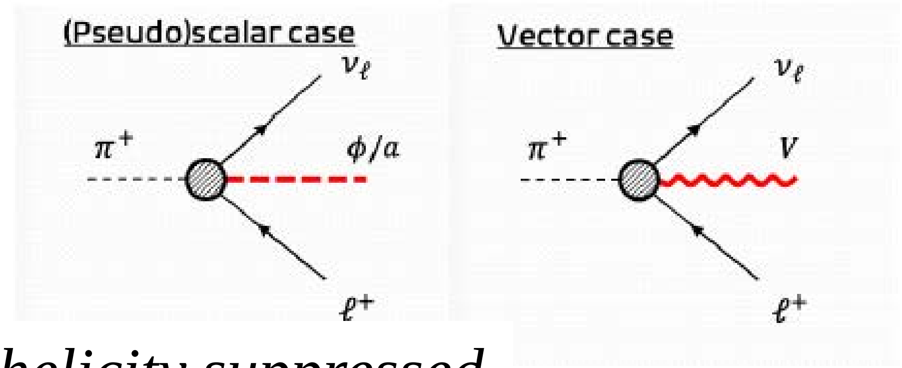
Jordan, Kahn, Moschell, Krnjaic, Spttz, Phys.Rev.Lett. **122 (2019) 8, 081801**

- *Can we use the charged pion decays for the dark sector based solution?*

Neutrino-anti-neutrino mode excess difference can be accommodated

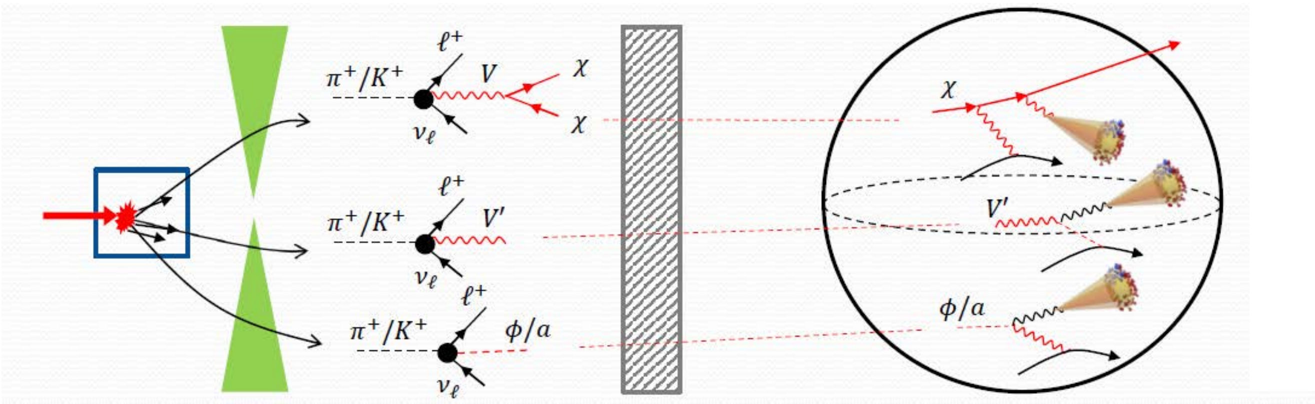
MiniBooNE Anomaly

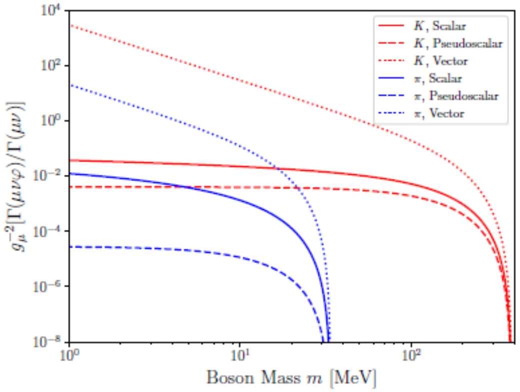
- $\mathscr{L}_S \supset g_f \phi \bar{f} f$
- $\mathscr{L}_P \supset i g_f a \bar{f} \gamma^5 f$
- $\mathscr{L}_V \supset g_f V_\alpha \bar{f} \gamma^\alpha f$



3-body decay is not helicity suppressed

Large flux of new particle flux can be expected: limited by the pion Br to e,μ+ ν+missing ~ 10^{-6}



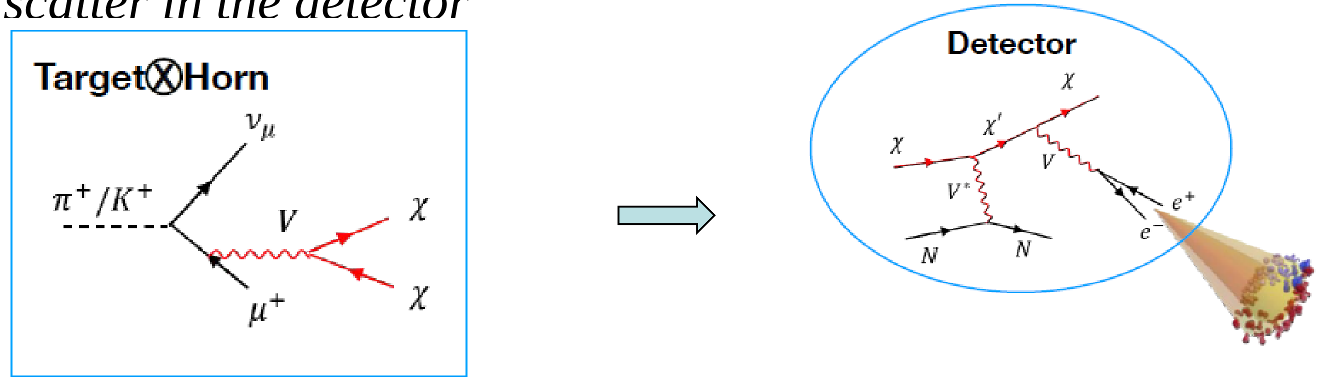


Magnetic focusing horn provides more charged pions compared to neutral pions: beam dump constraint does not apply anymore

MiniBooNE Anomaly

Two dark sector scenarios:

- *Short-lived mediators: Promptly decay to dark matter particles which then up scatter in the detector*

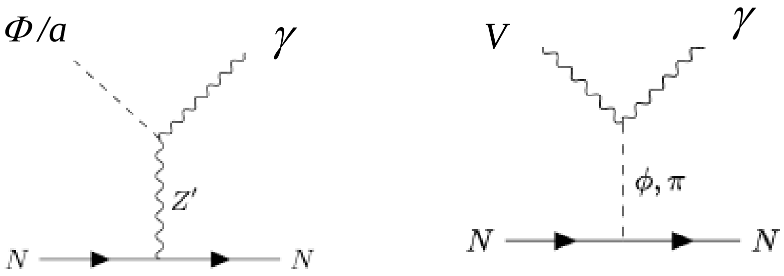


$$\mathcal{L}_V \supset \sum_{i=1,2} \left(e\epsilon_i J^\mu_{\rm EM} + g_i J^\mu_D + g'_i J'^\mu_D\right) V_{i,\mu}$$

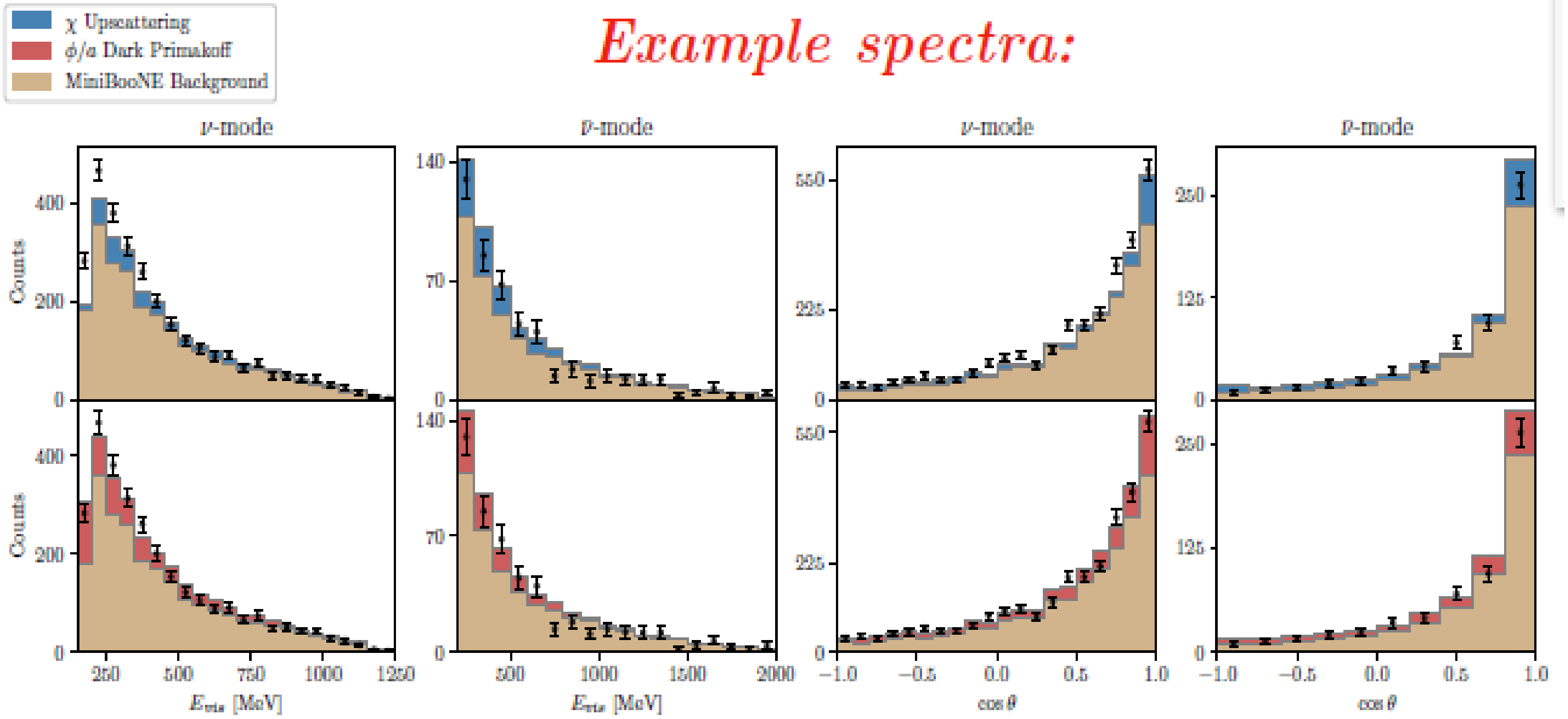
- *Long-lived mediators: get scattered at the detector producing photon via inverse Primakoff like scattering*

$$\mathcal{L}_{S(P)} \supset g_n Z'_\alpha \bar{u}\gamma^\alpha u + \begin{cases} g_\mu \phi\bar{\mu}\mu + \frac{\lambda}{4}\phi F'_{\mu\nu}F^{\mu\nu} \\ i g_\mu a\bar{\mu}\gamma^5\mu + \frac{\lambda}{4} a F'_{\mu\nu}\tilde{F}^{\mu\nu} \end{cases} + \text{h.c.},$$

$$\mathcal{L}_V \supset \sum_{i=1,2} \left(e\epsilon_i J^\mu_{\rm EM} + \xcancel{g_i J^\mu_D + g'_i J'^\mu_D}\right) V_{i,\mu}$$



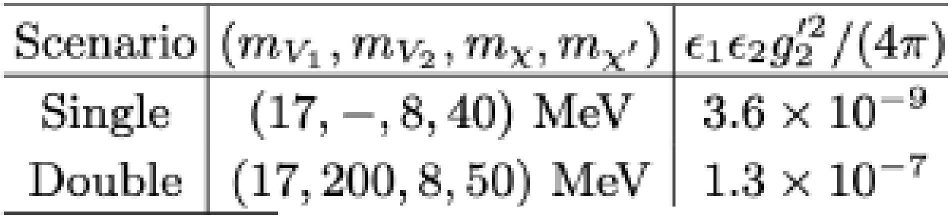
MiniBooNE Anomaly



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

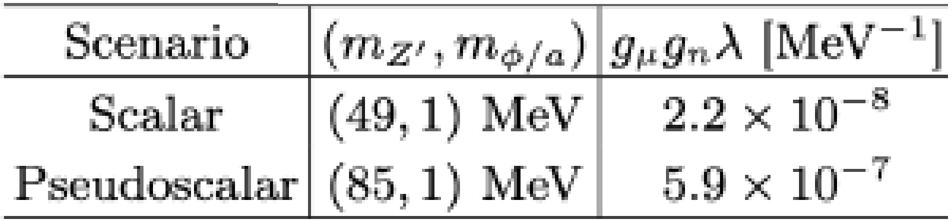
MiniBooNE Anomaly

Vector portal dark matter



Scenario	$(m_{V_1}, m_{V_2}, m_\chi, m_{\chi'})$	$\epsilon_1\epsilon_2 g_2'^2/(4\pi)$
Single	$(17, -, 8, 40)$ MeV	3.6×10^{-9}
Double	$(17, 200, 8, 50)$ MeV	1.3×10^{-7}

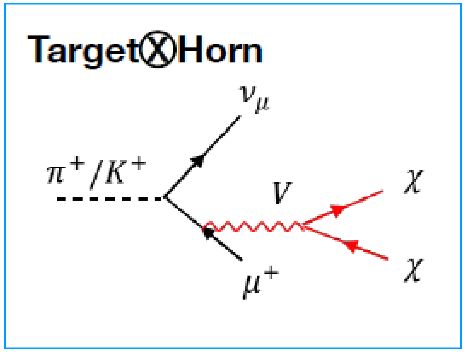
Long lived scalar/ pseudo-scalar

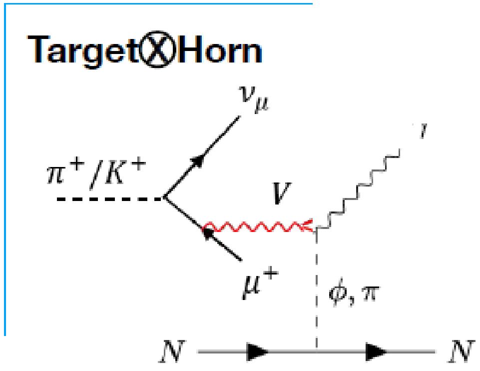


Scenario	$(m_{Z'}, m_{\phi/a})$	$g_\mu g_n \lambda$ [MeV^{-1}]
Scalar	$(49, 1)$ MeV	2.2×10^{-8}
Pseudoscalar	$(85, 1)$ MeV	5.9×10^{-7}

Long-lived Vector couplings leptons-quarks

m_χ [MeV]	m_ϕ [MeV]	$\bar{g}$ [MeV^{-1}]
5	650	$9 \cdot 10^{-8}$
10	550	$1.3 \cdot 10^{-8}$

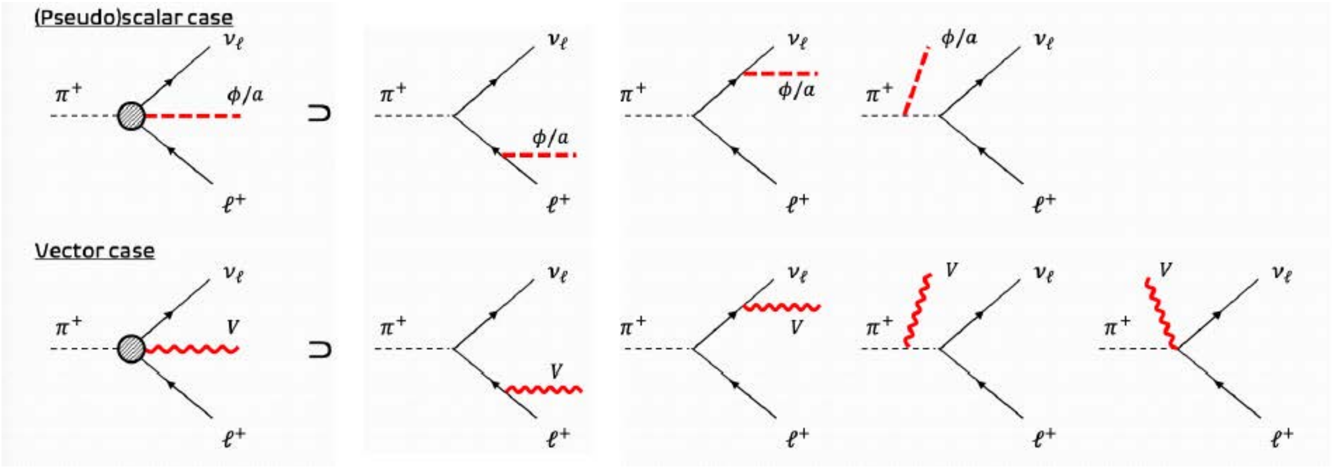




Dutta, Kim,Thompson,Thornton,Van de Water, Phys.Rev.Lett. 129 (2022) 11, 111803

MiniBooNE Anomaly

Many different model scenarios



Brymer, Depommier, Leroy, PHYSICS REPORTS
Physics Letters. No. 3 (1962) 151

Using the charged and neutral mesons, these light mediators can be investigated in other experiments, e.g., CHARM, T2K, MINERvA, CCM, COHERENT, SBND

MiniBooNE Anomaly

- The excess is not constrained by CHARM-II, T2K, MINERvA:
  size of the detector, distance, pion production rate
  The photon, electron-positron production rate remains constant or decreases depending the mediator type as the beam energy increases

- Prediction for MicroBooNE: 20 events (channels: 1 gamma+0 proton, e^+e^-+ 0p)

- LSND: neutron ejection from the inverse Primakoff scattering can occur and 2.2 MeV γ can appear from neutron capture.
  The dark matter scenario does not work since the proton beam energy is 800 MeV

- SBND, ICARUS, DUNE, FASER can investigate these scenarios

Predictions for other ν experiments

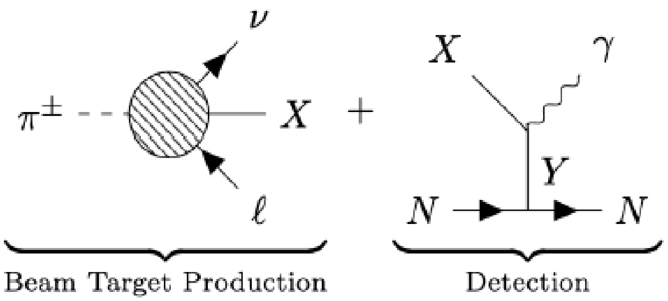
CCM at LANL use 800 MeV proton beam

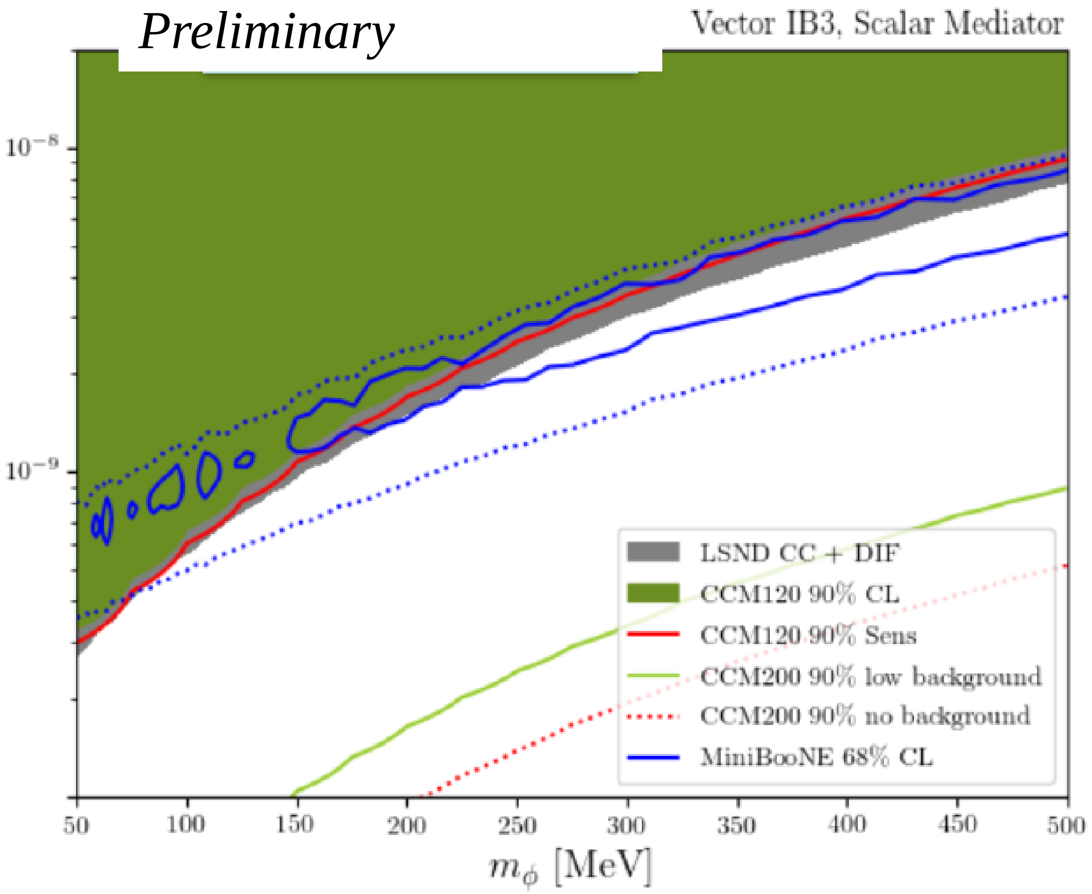
Sensitive to 0.1-100 MeV signal region: e, g

CCM 200 is ongoing

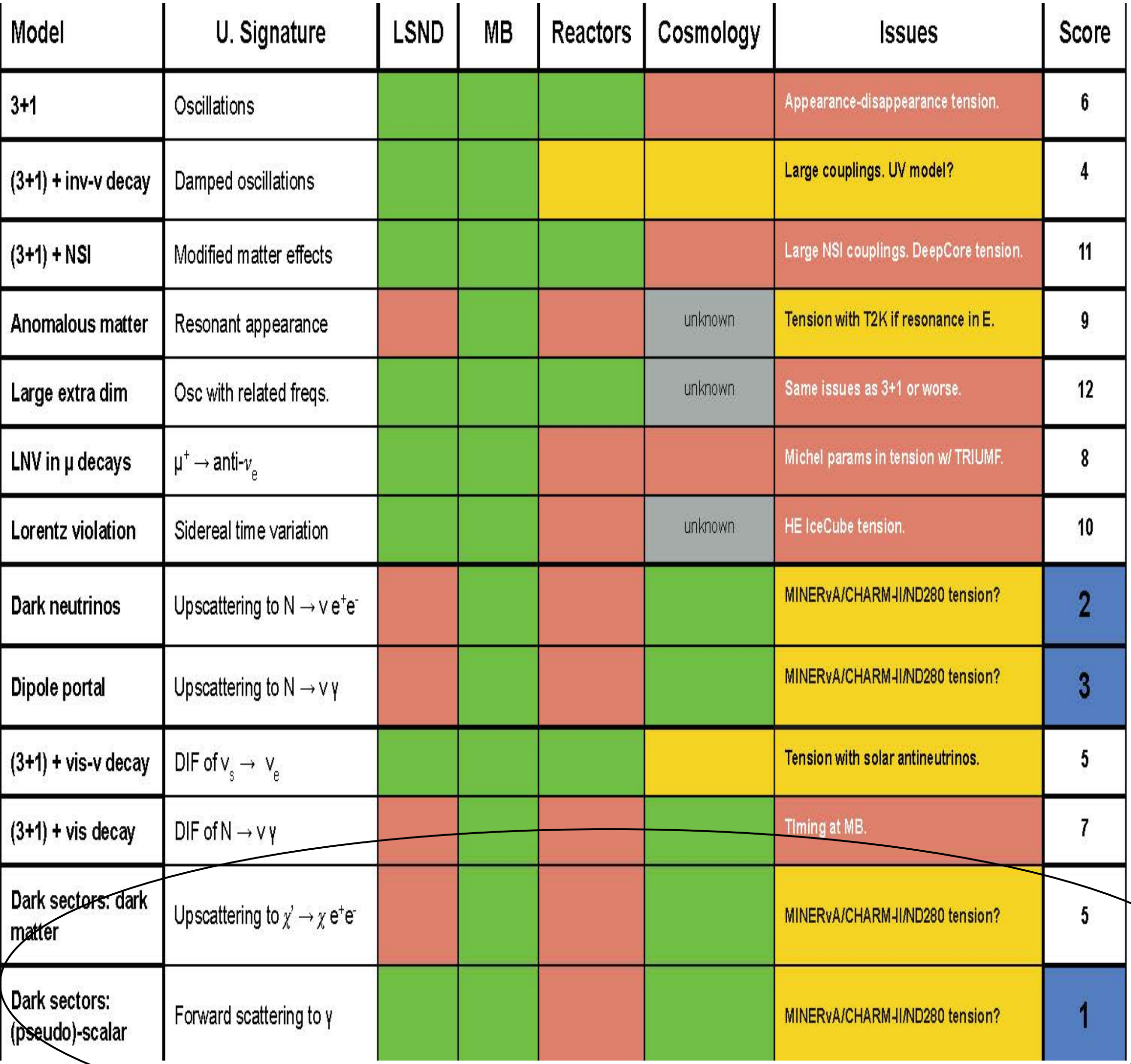
X (if it is a vector) can be produced From both π^0 and $\pi^\pm$

$$\pi^0 \rightarrow X + \gamma$$

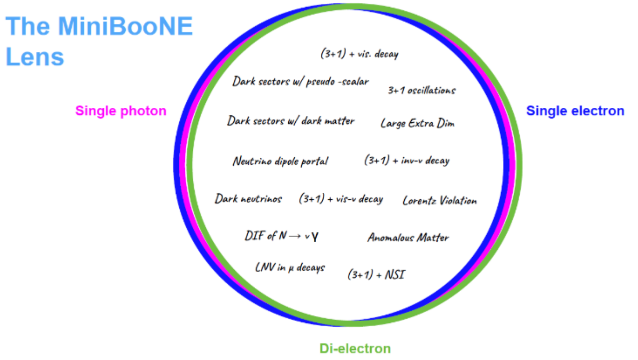




MiniBooNE Anomaly and models



Model	U. Signature	LSND	MB	Reactors	Cosmology	Issues	Score
3+1	Oscillations	🟩	🟩	🟩	🟥	🟥 Appearance-disappearance tension.	6
(3+1) + inv-ν decay	Damped oscillations	🟩	🟩	🟨	🟨	🟨 Large couplings. UV model?	4
(3+1) + NSI	Modified matter effects	🟩	🟩	🟩	🟥	🟥 Large NSI couplings. DeepCore tension.	11
Anomalous matter	Resonant appearance	🟥	🟩	🟥	unknown	🟨 Tension with T2K if resonance in E.	9
Large extra dim	Osc with related freqs.	🟩	🟩	🟩	unknown	🟥 Same issues as 3+1 or worse.	12
LNV in μ decays	$\mu^+ \to$ anti-ν_e	🟩	🟩	🟥	🟥	🟥 Michel params in tension w/ TRIUMF.	8
Lorentz violation	Sidereal time variation	🟩	🟩	🟥	unknown	🟥 HE IceCube tension.	10
Dark neutrinos	Upscattering to $N \to \nu e^+e^-$	🟥	🟩	🟥	🟩	🟨 MINERvA/CHARM-II/ND280 tension?	2
Dipole portal	Upscattering to $N \to \nu \gamma$	🟥	🟩	🟥	🟩	🟨 MINERvA/CHARM-II/ND280 tension?	3
(3+1) + vis-ν decay	DIF of $\nu_s \to \nu_e$	🟩	🟩	🟩	🟨	🟨 Tension with solar antineutrinos.	5
(3+1) + vis decay	DIF of $N \to \nu \gamma$	🟥	🟩	🟥	🟩	🟥 Timing at MB.	7
Dark sectors: dark matter	Upscattering to $\chi' \to \chi e^+e^-$	🟥	🟩	🟥	🟩	🟨 MINERvA/CHARM-II/ND280 tension?	5
Dark sectors: (pseudo)-scalar	Forward scattering to γ	🟩	🟩	🟥	🟩	🟨 MINERvA/CHARM-II/ND280 tension?	1



SBN Workshop, 2021

MiniBooNE Anomaly and models

- New Physics: Dark matter, neutrino masses and mixing, g-2 of muon, LHCb, MiniBooNE etc.

  Are they all correlated? Is there a model?

- The explanations for g-2 of the muon, LHCb, MiniBooNE can be done using a model, for example, with quark and muon couplings

- The model will involve light mediators

- Requirements: light vector mediator, scalar/pseudo-scalar mediator, inelastic DM

↘

Required

$SU(2)_L \times U(1)_Y \times U(1)_{T3R}$

Model with a sub GeV DM and Light mediators

E.g., there may be a new symmetry breaking scale around GeV
➔2nd and 1st generation fermion masses (~MeV to few GeV)

Anomaly free

field	q_{T3R}
q_R^u	-2
q_R^d	2
ℓ_R	2
ν_R	-2
η_L	1
η_R	-1
ϕ	-2

Dutta, Ghosh, Kumar,
Phys.Rev.D 100 (2019) 075028

$SU(2)_L \times U(1)_Y \times U(1)_{T3R}$

$U(1)_{T3R}$ is broken at 1-10 GeV down to Z_2

➔Low mass dark matter, gauge and scalar mediators

Predictions are testable at various low energy experiments

Dark matter is made out of η_1, η_2:

$$\eta_1 = -\frac{i}{\sqrt{2}} \begin{pmatrix} \eta_L - \eta_R^c \\ -\eta_L^c + \eta_R \end{pmatrix} \qquad \eta_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \eta_L + \eta_R^c \\ \eta_L^c + \eta_R \end{pmatrix}$$

Dark Matter (parity odd): $\eta_{1,2}$ and can be inelastic with small mass gap among η_1, η_2

$U(1)_{T3R}$

In SM, the Yukawa couplings are hierarchical:

$\lambda_t^{(SM)} \sim 1$, $\lambda_c^{(SM)} \sim 10^{-2}$, $\lambda_{s,\mu}^{(SM)} \sim 10^{-3}$, $\lambda_{u,d}^{(SM)} \sim 10^{-5}$, $\lambda_e^{(SM)} \sim 10^{-6}$

$$\begin{aligned}\mathcal{L}_{Yuk} = &\boxed{-\frac{\lambda_u}{\Lambda}\tilde{H}\phi^*}\bar{Q}_L q_R^u - \frac{\lambda_d}{\Lambda}H\phi\bar{Q}_L q_R^d - \frac{\lambda_\nu}{\Lambda}\tilde{H}\phi^*\bar{L}_L\nu_R - \frac{\lambda_l}{\Lambda}H\phi\bar{L}_L\ell_R \\ &- \lambda\phi\bar{\eta}_R\eta_L - \frac{1}{2}\lambda_L\phi\bar{\eta}_L^c\eta_L - \frac{1}{2}\lambda_R\phi^*\bar{\eta}_R^c\eta_R - \mu_\phi^2\phi^*\phi - \lambda_\phi(\phi^*\phi)^2 + H.c.,\end{aligned}$$

- **Scalar ϕ vev** $V = (-\mu_\phi^2/2\lambda_\phi)^{1/2}$ **breaks $U(1)_{T3R}$ to Z_2 ,**
- **vev is around 1-10 GeV**

➔ We can have $\lambda_x \sim 0.1 - 1$ since (<H> < ϕ >) /Λ helps to fit the fermion masses

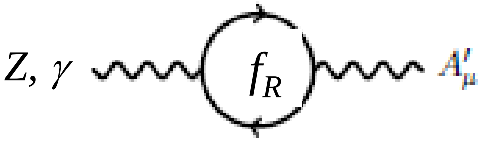
U(1)$_{T3R}$

- **New scalar and gauge boson: ϕ’ , A’ are light in this model**

- **The couplings of ϕ’ , A’ with quarks and leptons are fixed once we choose the vev of <ϕ> and the A’ mass**

$$\mathcal{L}_{Yuk} = -m_u \bar{q}^u_L q^u_R - m_d \bar{q}^d_L q^d_R - m_\nu \bar{\nu}_L \nu_R - m_\ell \bar{\ell}_L \ell_R - \frac{1}{2} m_1 \bar{\eta}_1 \eta_1 - \frac{1}{2} m_2 \bar{\eta}_2 \eta_2$$
$$-\boxed{\frac{m_u}{V}} \bar{q}^u_L q^u_R \phi' - \frac{m_d}{V} \bar{q}^d_L q^d_R \phi' - \frac{m_{\nu D}}{V} \bar{\nu}_L \nu_R \phi' - \boxed{\frac{m_\ell}{V}} \bar{\ell}_L \ell_R \phi' - \frac{1}{2} \frac{m_1}{V} \bar{\eta}_1 \eta_1 \phi' - \frac{1}{2} \frac{m_2}{V} \bar{\eta}_2 \eta_2 \phi' + ...$$

A’ also mixes with photon and Z



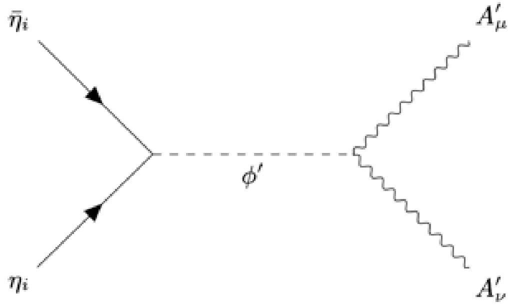
DM Abundance in U(1)T3R

Thermal relic is easier to satisfy due to the existence of two mediators

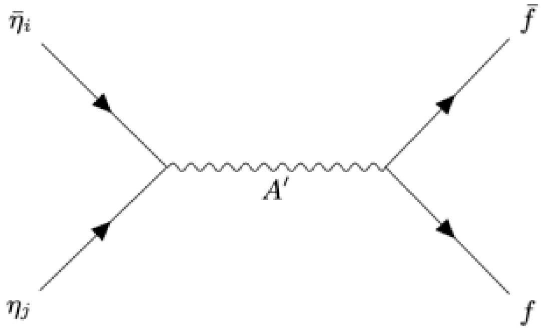
Dominant two body final states: $\bar{\ell}\ell,\ \bar{\nu}\nu,\ \pi\pi,\ \pi^0(\phi',A',\gamma)$

$+$

$A'A',\ \phi'\phi'$ and $\phi'A'$



P-wave



S-wave

+ …

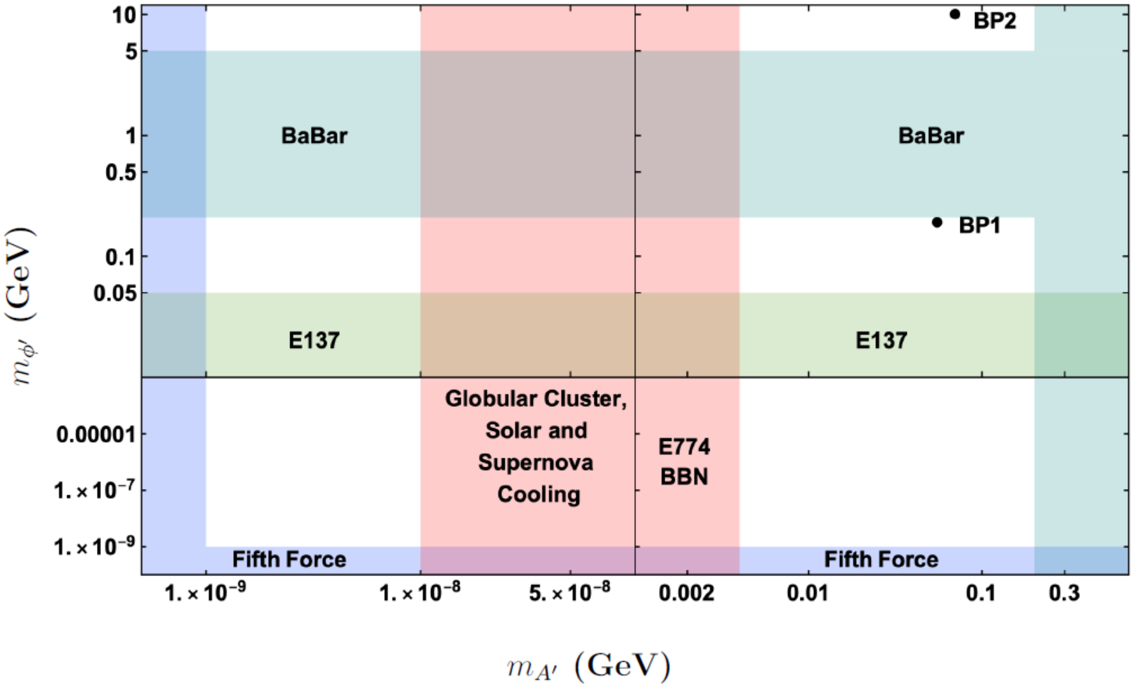
Resonance/non-resonance:

$m_{A'}$ (MeV)	$m_{\phi'}$ (MeV)	m_η (MeV)	m_{ν_s}(MeV)	$m_{\nu D}$(MeV)	$\langle\sigma v\rangle$ (cm^3/sec)	$\sigma_{\rm SI}^{scalar}$(pb)	$\sigma_{\rm SI}^{vector}$(pb)
150	80	40	10	10^{-3}	3×10^{-26}	0.58	1.17
180	76	38	10	10^{-3}	3×10^{-26}	0.58	1.06

Parameter Space

Various scenarios: Gauge boson (A')-scalar (ϕ') mediators parameter space

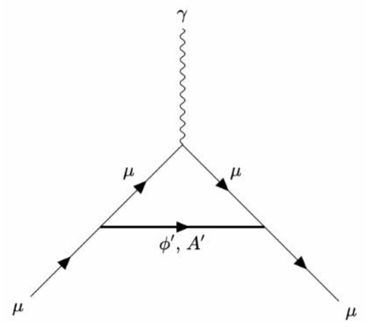
- ***E.g., Muon model: u_R, d_R, ν_R, μ_R***

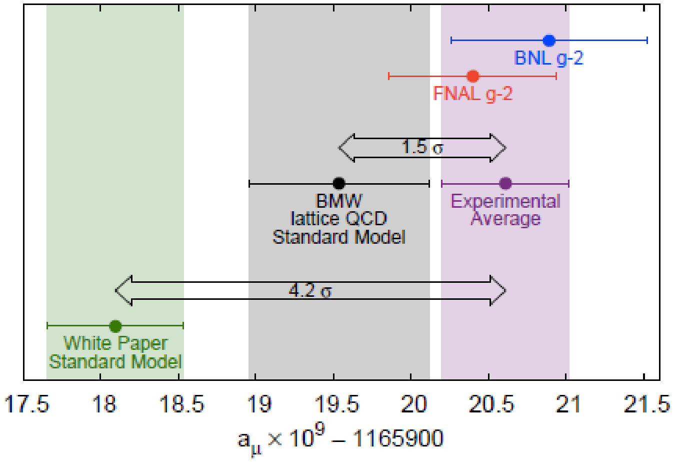


- ***Electron model: u_R, d_R, ν_R, e_R***

- ***Similarly, models with second generation quarks***

g-2 of muon, $R_{k(*)}$ anomaly

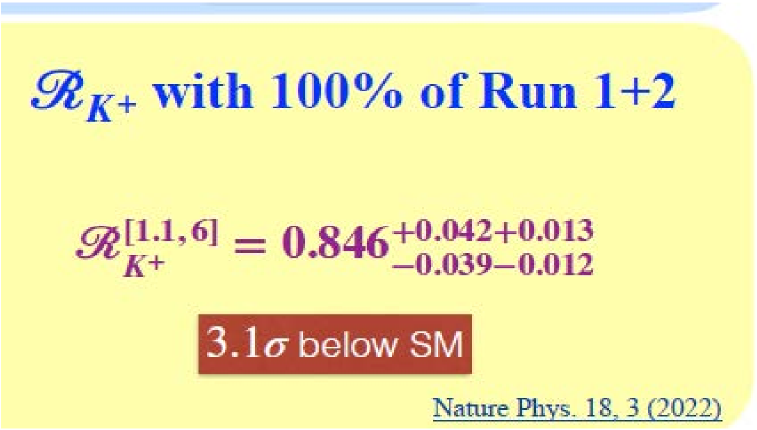




$$\Delta a_\mu = (6.98 \times 10^{-7})\left(\frac{V}{10\ GeV}\right)^{-2}(C_{\phi'} - C_{A'})$$

- ***Fixes $M_{\phi'}$=70-100 MeV for $M_{A'}$~5-200MeV***

$$R_K = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)}, \quad R_{K^*} = \frac{\mathcal{B}(B \to K^*\mu^+\mu^-)}{\mathcal{B}(B \to K^*e^+e^-)}.$$

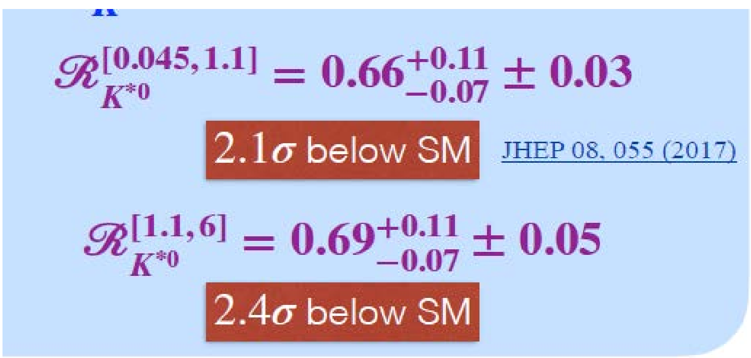


$\mathcal{R}_{K^+}$ with 100% of Run 1+2

$$\mathcal{R}_{K^+}^{[1.1,6]} = 0.846^{+0.042+0.013}_{-0.039-0.012}$$

3.1σ below SM

Nature Phys. 18, 3 (2022)



$$\mathcal{R}_{K^{*0}}^{[0.045,1.1]} = 0.66^{+0.11}_{-0.07} \pm 0.03$$

2.1σ below SM

JHEP 08, 055 (2017)

$$\mathcal{R}_{K^{*0}}^{[1.1,6]} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

2.4σ below SM

UV completion and R_k anomaly

Origin of $\boxed{\frac{\lambda_d}{\Lambda}} H\phi\bar{Q}_L q_R^d = \frac{m_f}{\sqrt{2}V}\bar{f}f\phi$ ***V: vev of ϕ***

Z. Berezhiani, PLB 129, 99 (1983); D. Chang and R. N. Mohapatra, PRL. 58, 1600 (1987). A. Davidson and K. C. Wali, PRL 59, 393(1987) , A. De Pace, H. Muther, and A. Faessler, PLB 188, 307 (1987); S. Rajpoot, MPLA 2, 307 (1987), K. S. Babu and R. N. Mohapatra, PRL 62, 1079 (1989; PRD 41,1286 (1990).

$$-\mathcal{L}_Y \supset \lambda_{Ld}\bar{q}'_L X'_{dR} H + \lambda_{Rd}\bar{X}'_{dL} d'_R \phi + m_{X_d}\bar{X}'_{dL} X'_{dR}$$

$m_{\chi'_f}$ is heavy ➔ $m_f = \frac{\lambda_{Lf}\lambda_{Rf} v V}{\sqrt{2} m_{\chi'_f}}$

$$M_f = \begin{pmatrix} 0 & \frac{\lambda_{Lf} v}{\sqrt{2}} \\ \lambda_{Rf} V & m_{\chi'_f} \end{pmatrix} \cdot \boxed{\begin{pmatrix} f_{L,R} \\ \chi_{f_{L,R}} \end{pmatrix} = \begin{pmatrix} \cos\theta_{f_{L,R}} & \sin\theta_{f_{L,R}} \\ -\sin\theta_{f_{L,R}} & \cos\theta_{f_{L,R}} \end{pmatrix} \begin{pmatrix} f'_{L,R} \\ \chi_{f'_{L,R}} \end{pmatrix}}$$

Now we use these new fields to calculate b—> s l^+l^- :

- Lepton non-universality is obtained from the A’ and ϕ couplings
- Quark flavor violation is obtained from the UV completion: $\bar{b}\,\gamma^\mu P_{L,R} s(Z^\mu, A'^\mu)$,

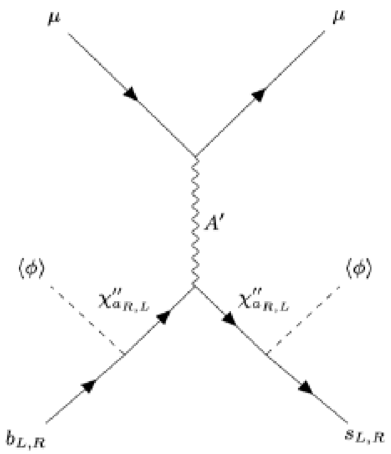
UV completion and R_k anomaly

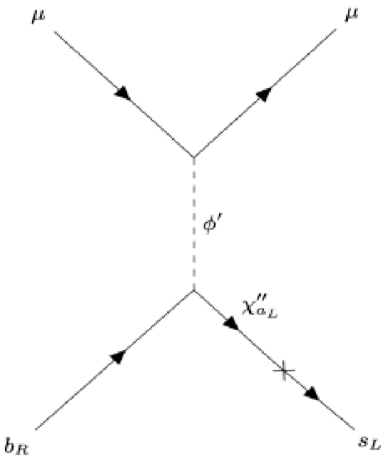
We can have:

Universal term

$\mathcal{L} \supset \lambda'_{b,s} H \bar{Q}_L^{b,s} P_R \chi'_a + m'_{b,s} \bar{\chi}'_a P_R q_R^{b,s}$ +h.c. ➔ $\bar{b}\gamma^{\mu} P_L s Z^{\mu}$, $\bar{b}\gamma^{\mu} P_L\, s A'^{\mu}$

$\mathcal{L} \supset \lambda''_{b,s} \phi \chi''_a P_R q_{b,s}$ +h.c. ➔ $\bar{b}\gamma^{\mu} P_{L,R} s A'^{\mu}$, $\phi \bar{q}_{L(b,s)} q_{R(b,s)} sin\theta'_{(s,b)L}$





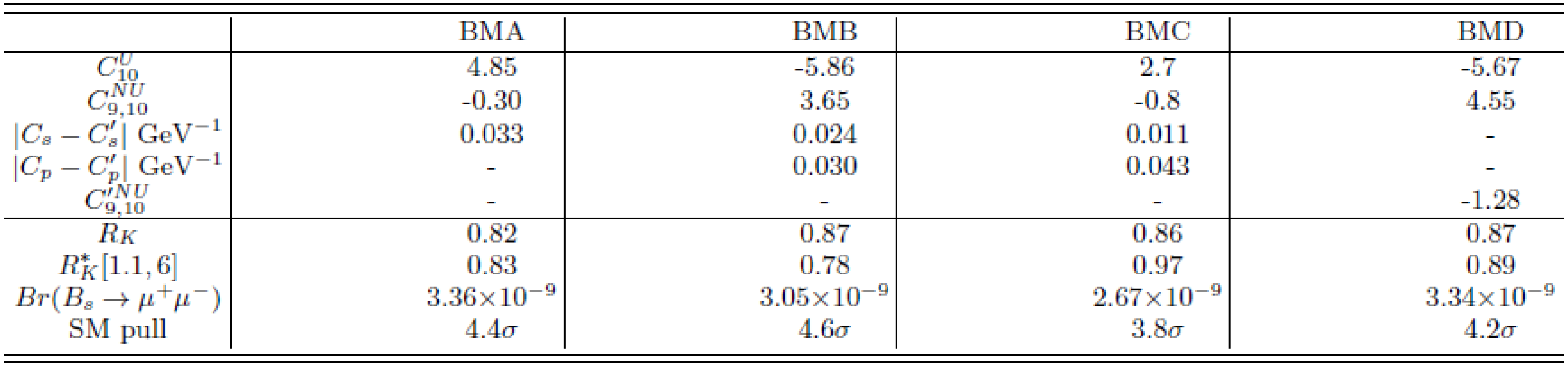
$$O_9^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10}^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,$$

$$\mathcal{O}_9^{\prime bs\ell\ell} = (\bar{s}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu \ell),$$
$$\mathcal{O}_{10}^{\prime bs\ell\ell} = (\bar{s}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu \gamma^5 \ell).$$

$$\mathcal{O}_S^{bs\ell\ell} = m_b(\bar{s}P_R b)(\bar{\ell}\ell),$$
$$\mathcal{O}_S^{\prime bs\ell\ell} = m_b(\bar{s}P_L b)(\bar{\ell}\ell),$$
$$\mathcal{O}_P^{bs\ell\ell} = m_b(\bar{s}P_R b)(\bar{\ell}\gamma^5 \ell).$$
$$\mathcal{O}_P^{\prime bs\ell\ell} = m_b(\bar{s}P_L b)(\bar{\ell}\gamma^5 \ell).$$

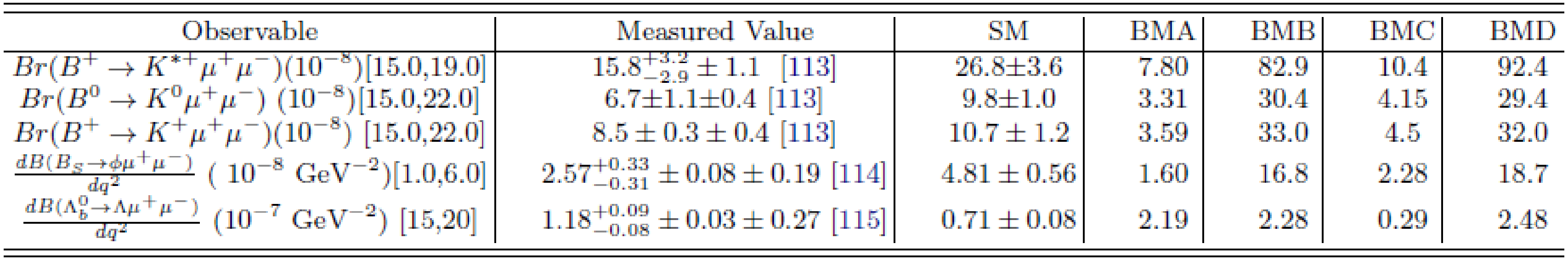
Fit to R_k anomaly and predictions

Fits:



	BMA	BMB	BMC	BMD
C_{10}^{U}	4.85	-5.86	2.7	-5.67
$C_{9,10}^{NU}$	-0.30	3.65	-0.8	4.55
$\lvert C_s - C_s' \rvert$ GeV^{-1}	0.033	0.024	0.011	-
$\lvert C_p - C_p' \rvert$ GeV^{-1}	-	0.030	0.043	-
$C_{9,10}^{\prime NU}$	-	-	-	-1.28
R_K	0.82	0.87	0.86	0.87
$R_K^*[1.1,6]$	0.83	0.78	0.97	0.89
$Br(B_s \to \mu^+\mu^-)$	3.36×10^{-9}	3.05×10^{-9}	2.67×10^{-9}	3.34×10^{-9}
SM pull	4.4σ	4.6σ	3.8σ	4.2σ

Predictions:



Observable	Measured Value	SM	BMA	BMB	BMC	BMD
$Br(B^+ \to K^{*+}\mu^+\mu^-)(10^{-8})[15.0,19.0]$	$15.8^{+3.2}_{-2.9} \pm 1.1$ [113]	26.8±3.6	7.80	82.9	10.4	92.4
$Br(B^0 \to K^0\mu^+\mu^-)$ $(10^{-8})[15.0,22.0]$	6.7±1.1±0.4 [113]	9.8±1.0	3.31	30.4	4.15	29.4
$Br(B^+ \to K^+\mu^+\mu^-)(10^{-8})$ [15.0,22.0]	$8.5 \pm 0.3 \pm 0.4$ [113]	10.7 ± 1.2	3.59	33.0	4.5	32.0
$\frac{dB(B_S \to \phi\mu^+\mu^-)}{dq^2}$ (10^{-8} GeV^{-2})[1.0,6.0]	$2.57^{+0.33}_{-0.31} \pm 0.08 \pm 0.19$ [114]	4.81 ± 0.56	1.60	16.8	2.28	18.7
$\frac{dB(\Lambda_b^0 \to \Lambda\mu^+\mu^-)}{dq^2}$ (10^{-7} GeV^{-2}) [15,20]	$1.18^{+0.09}_{-0.08} \pm 0.03 \pm 0.27$ [115]	0.71 ± 0.08	2.19	2.28	0.29	2.48

UV completion and R_k anomaly

- *The model fits R_K and R_{K^*} and $B_s \longrightarrow \mu^+\mu^-$*

For $M_{\phi'}$=70-100 MeV for $M_{A'}$~5-200MeV

Dutta, Ghosh, Huang, Kumar, Phys.Rev.D 105 (2022) 1, 015011

- The light scalar and vector of this model can be explored at the neutrino experiments and can explain the MB anomaly using DM, light mediators

Explanation of the anoamly

For $M_{\phi'}$ ***=70-100 MeV for*** $M_{A'}$ ***~5-200MeV***

- ***Fits*** R_K ***and*** R_{K^*} ***and*** $B_s \longrightarrow \mu^+\mu^-$
- ***Fits MiniBooNE anomaly***
- ***Couplings (e.g., V*** $\overline{q}q$***) : ~*** 10^{-4}***: Fixed by the masses and the vev in this model***
- ***Many other models can also fit, e.g., B-xL type***

(For vector particles: quark coupling dominates)

Outlook

- MiniBooNE anomaly can be explained using dark sector models using light mediators: utilize charge meson decays and horn focusing

- The solution can be obtained by short and long lived-mediators:
  Short-lived mediators: Inelastic dark matter
  Long-lived mediator: Inverse Primakoff

- Many model possibilities

- Light mediator models can explain various anomalies and puzzles

- SBND, ICARUS, DUNE, FASER, CCM, COHERENT, JSNS2 can check this scenario

Thank You Rabi for your Mentorship and Collaboration