Dark Sector Physics at Neutrino Experiments

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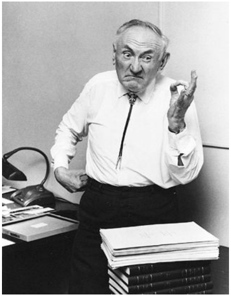
w/ **Bhaskar Dutta** (Texas A&M), **Tao Han** (Pittsburgh), and **Doojin Kim** (Texas A&M),
arXiv:2304.02031 and ongoing.

Particle and Astroparticle Theory Seminar

MPIK, Heidelberg

June 19, 2023

Dark Matter: a 90 years old puzzle



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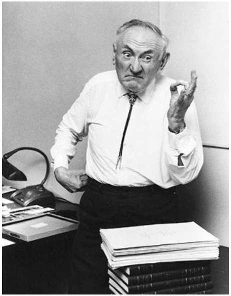

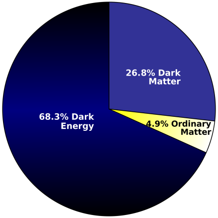

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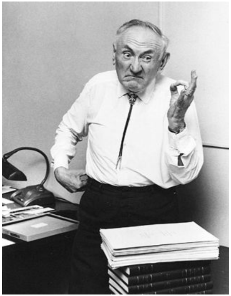

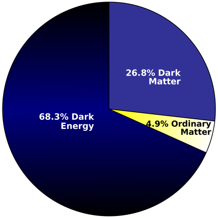

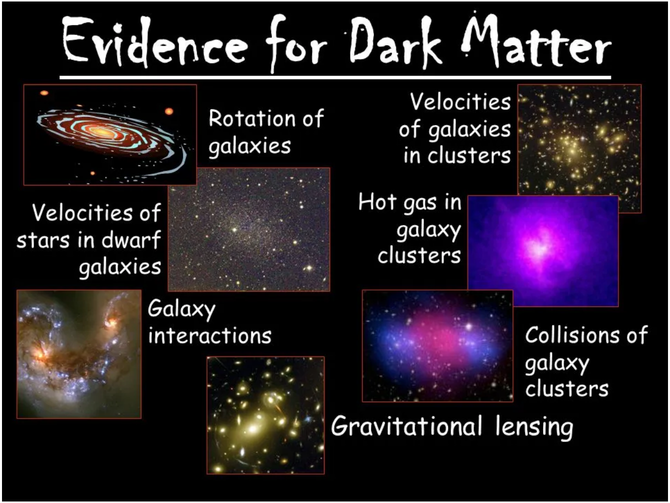

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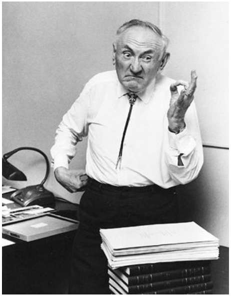
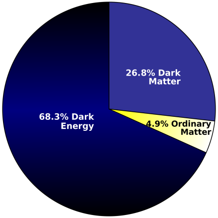
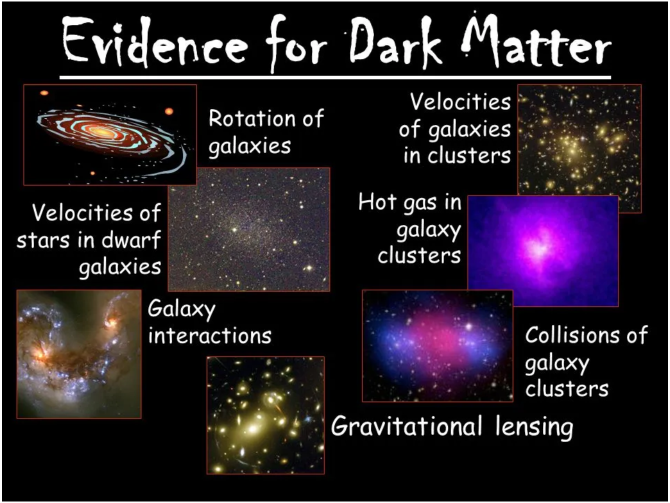




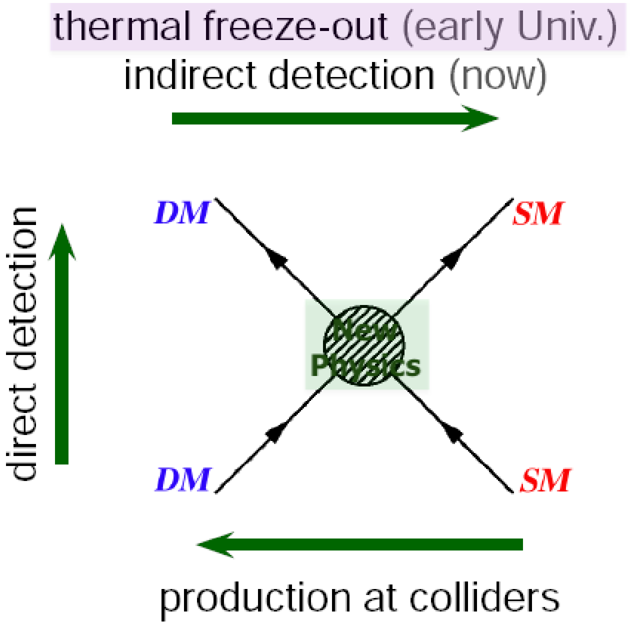


But no evidence of non-gravitational interactions of DM.

Many ideas, but which is the right one?

[G. Bertone and T. Tait, *Nature* **562**, 51 (2018)]

Why expect non-gravitational interactions?

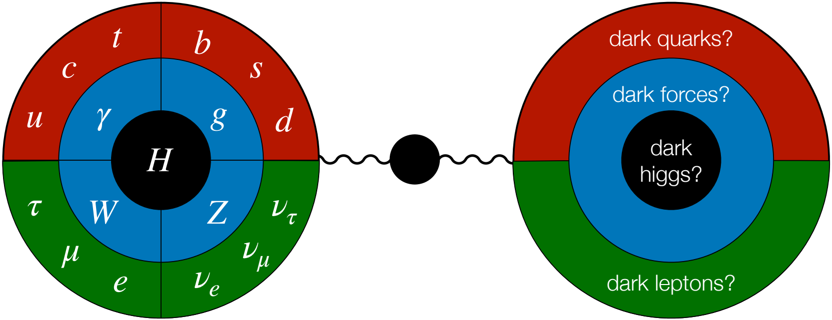


What if the dark matter experiences new ‘dark’ forces?

(*Symmetry* Magazine)

Portals to the Dark Sector

[Snowmass reports: 2207.06898, 2207.06905, 2209.04671]



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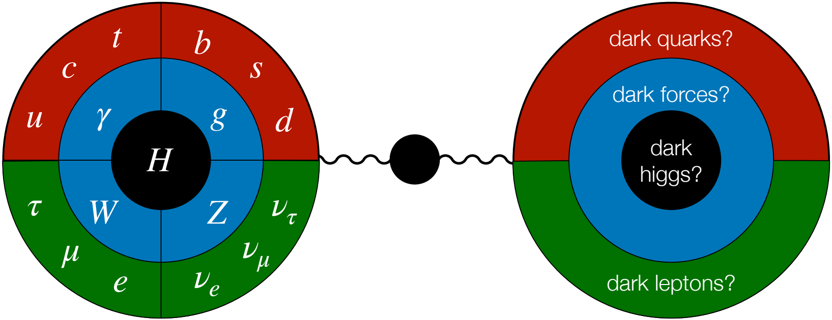
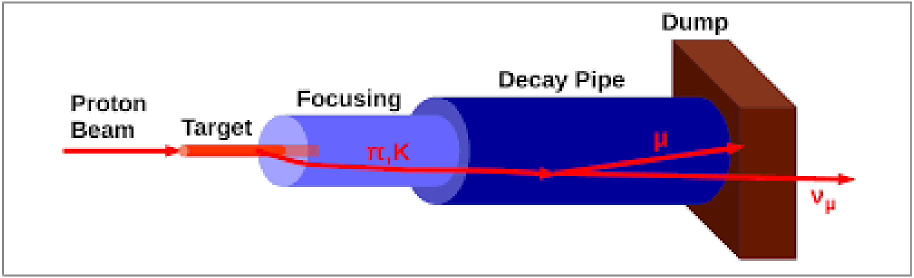


Examples

Vector portal	$\frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu}$	[Dutra, Lindner *et al.* (JCAP '18); Berryman *et al.* (JHEP '20)]
Neutrino portal	$y\bar{L}HN$	[Smirnov '19; Kelly, Machado (PRD '21); MicroBooNE (PRD '22)]
Higgs portal	$(\mu S + \lambda S^2) H^\dagger H$	[Batell, Berger, Ismail (PRD '19); MicroBooNE (PRL '21)]
Axion portal	$\frac{1}{f_a} a F^{\mu\nu} \tilde{F}_{\mu\nu}$	[Kelly, Kumar, Liu (PRD '21); ArgoNeuT (PRL '23)]

Why in accelerator neutrino experiments?

Beam-focused neutrino experiments



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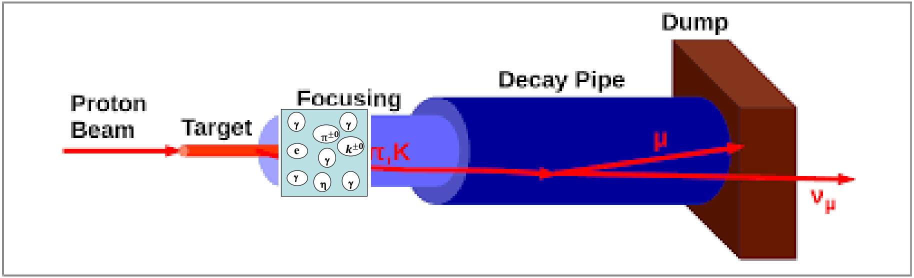

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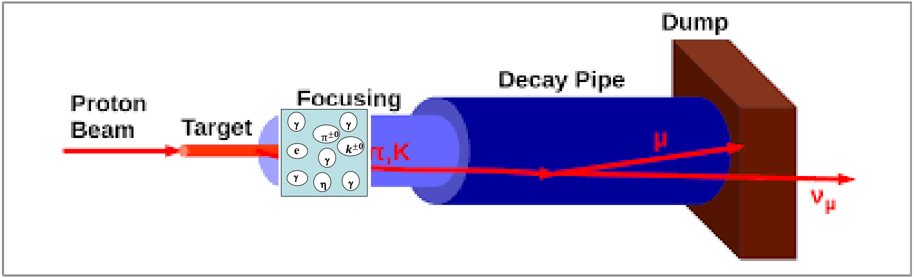
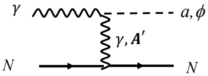


Various DS Production Modes:



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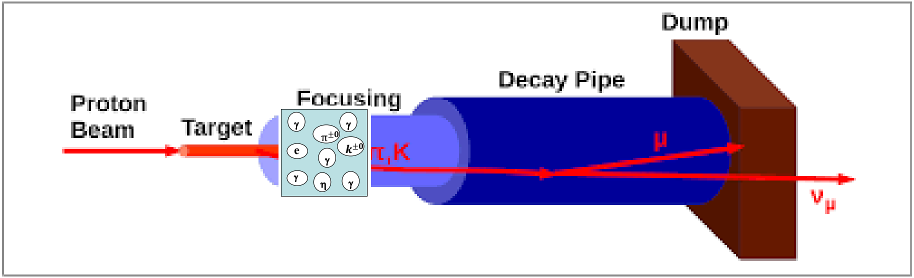

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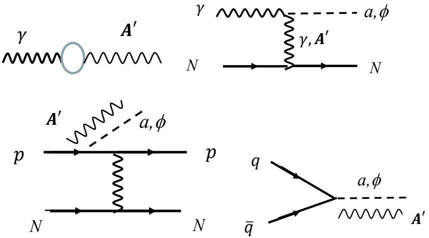

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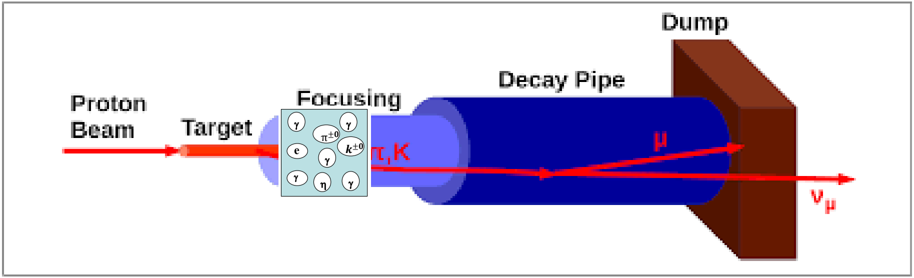

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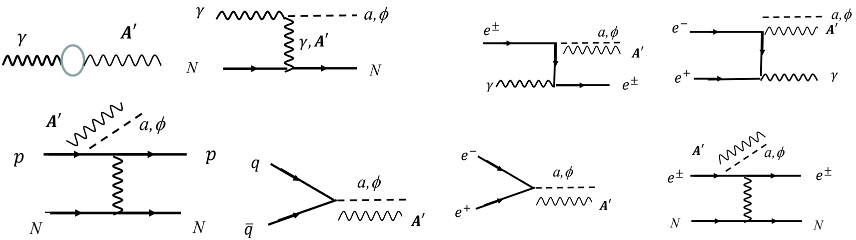
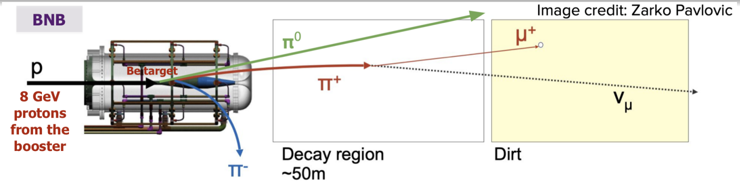


Short-Baseline Neutrino Experimental Setup at Fermilab



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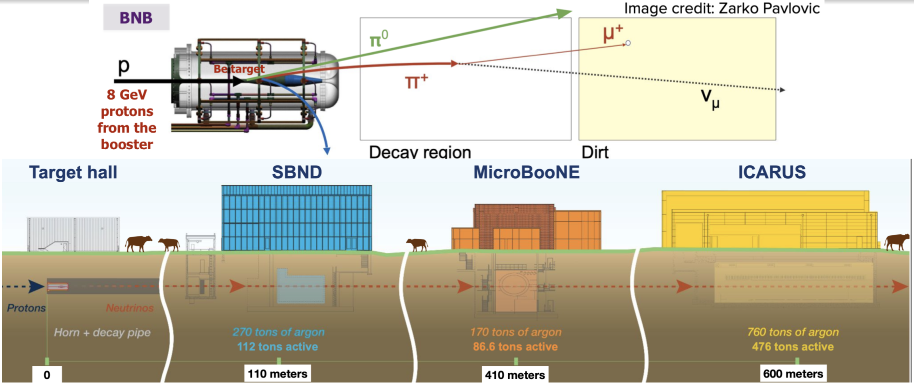

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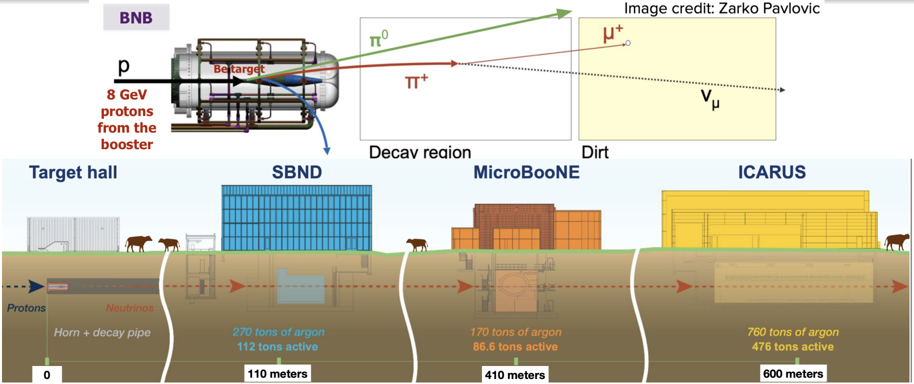
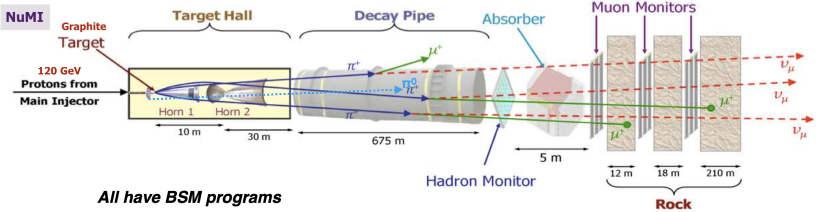
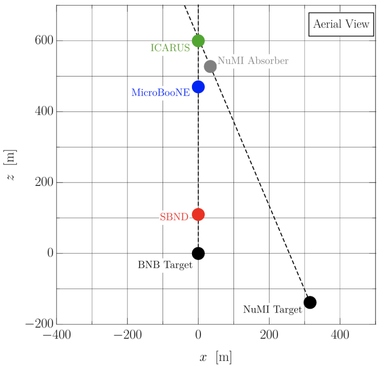


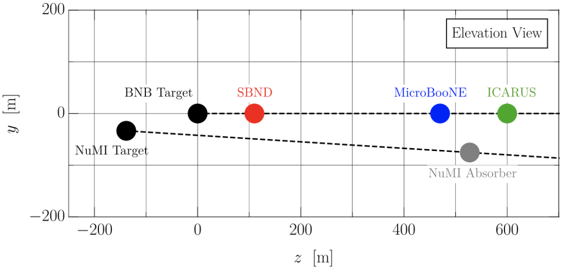


All have BSM programs

~1Km from target: NOvA ND, MINOS ND, MINERvA and ArgoNeuT

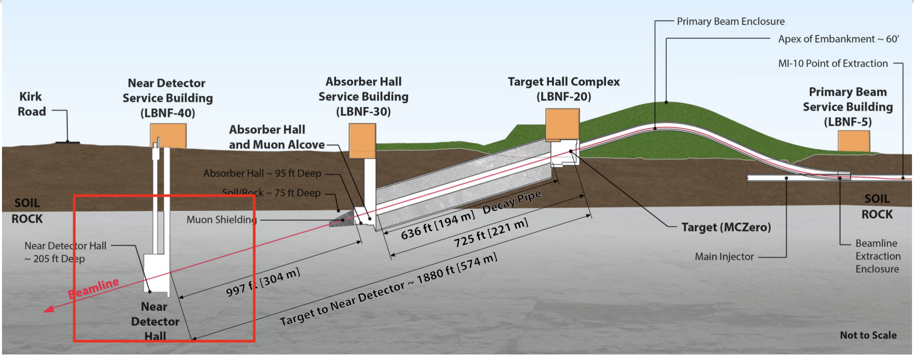
Current SBN Experiments





1909.11670

Future: DUNE Near Detector



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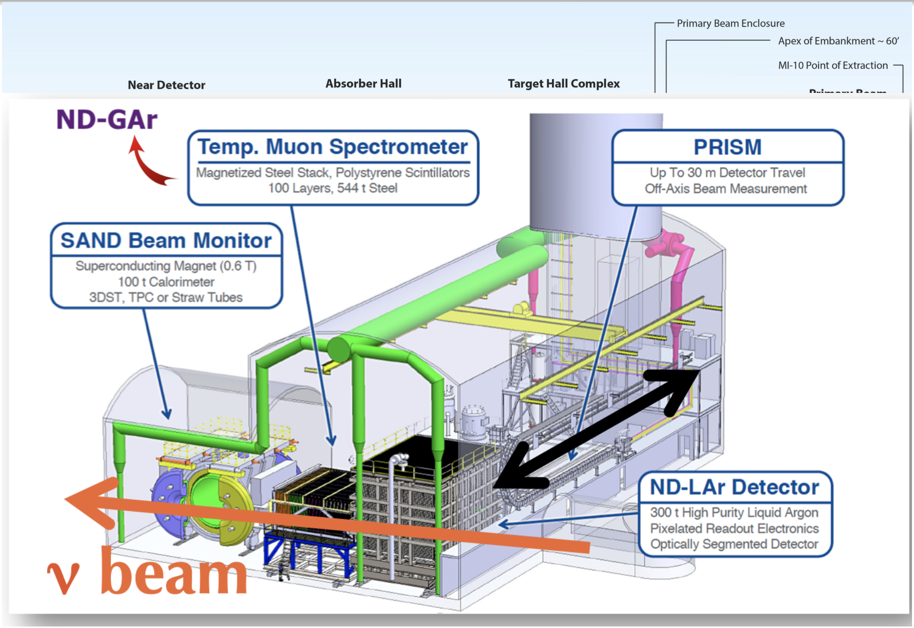
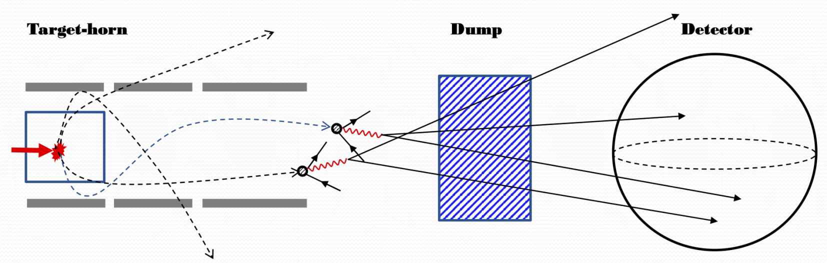
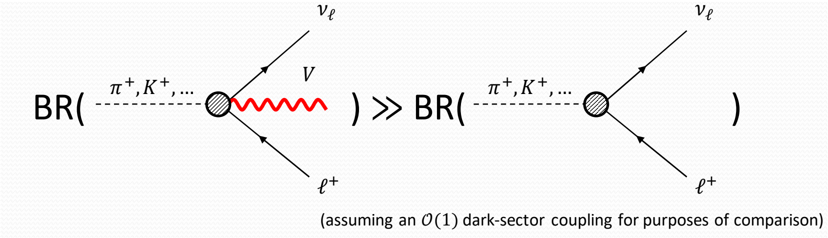


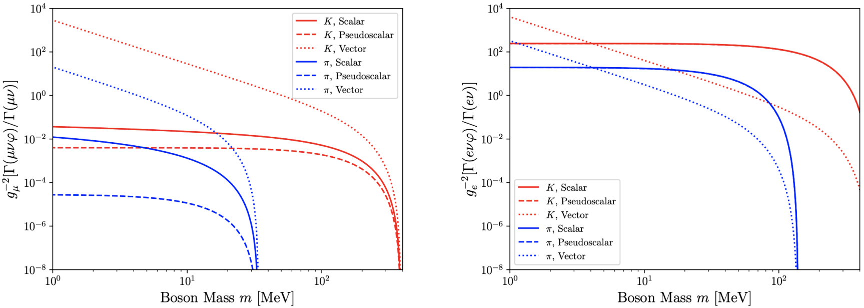
[Image Credit: Georgia Karagiorgi]

Dark Sector Production from Charged Meson Decays



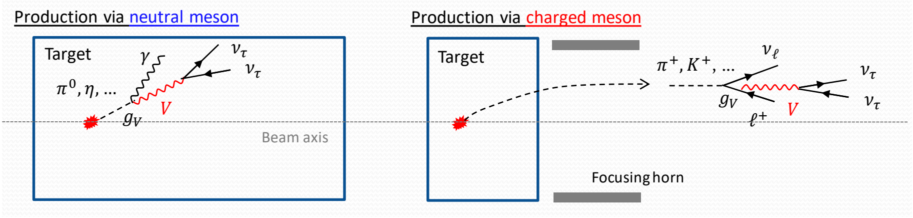
1. Large BR enhancement for 3-body decays.





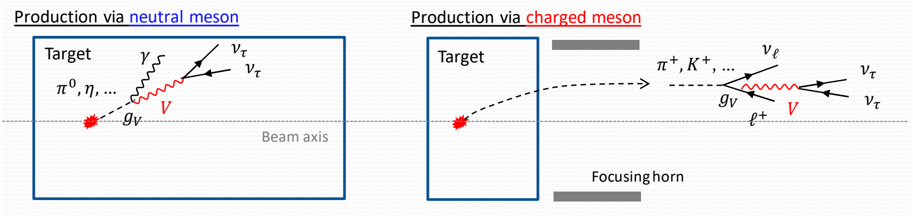
Dutta, Kim, Thompson, Thornton, Van de Water, 2110.11944 (PRL '22)

2. Focusing of charged mesons.

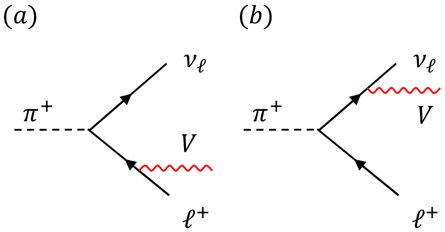


Why this is important?

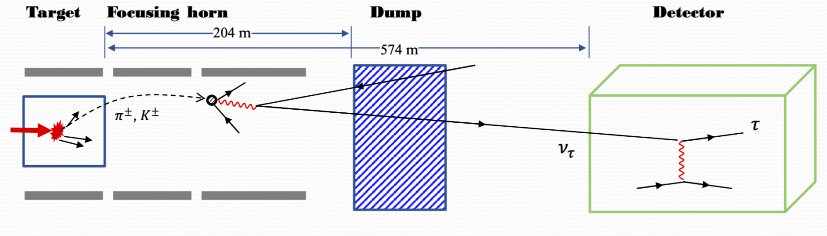
2. Focusing of charged mesons.



3. Dominant production channel for leptophilic dark-sector particles.



Anomalous Tau Neutrino Appearance at Near Detector



Why single out the taus?

$$P_{\mu \to \tau} = \sin^2(2\theta_{23}) \sin^2 \left[1.267 \frac{\left(\frac{\Delta m^2_{23}}{\text{eV}^2}\right) \left(\frac{L}{\text{km}}\right)}{E/\text{GeV}} \right]$$

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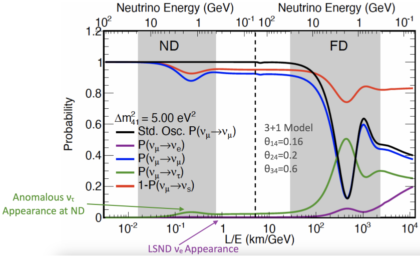
- A popular example: **Sterile neutrinos**.



[Plot credit: Alex Sousa]

- Nice interplay of ND and FD effects.

A new mechanism for anomalous tau production

$$\boxed{\pi^\pm/K^\pm \to \ell^\pm \overset{(-)}{\nu}_\ell\, V \quad \text{with}\ \ V \to \nu_\tau \bar{\nu}_\tau}$$

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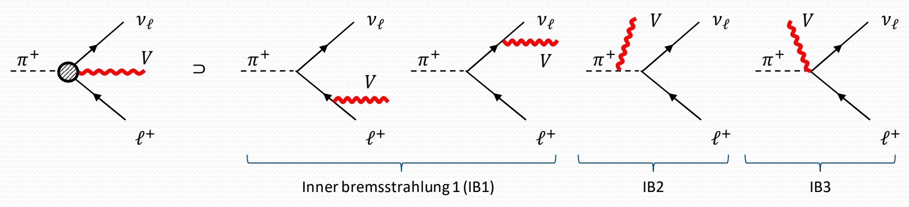

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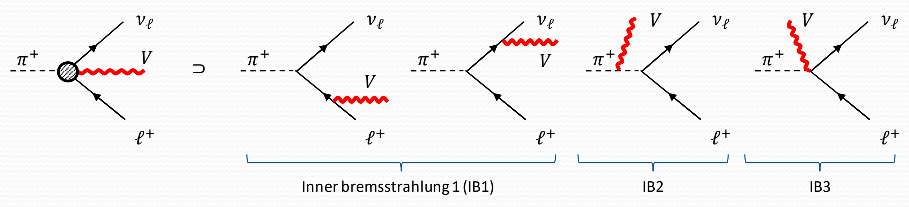
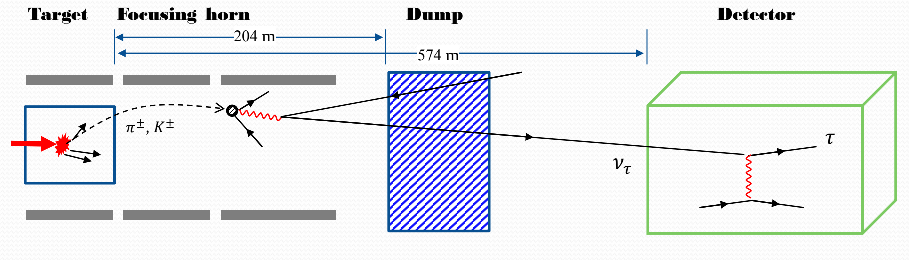
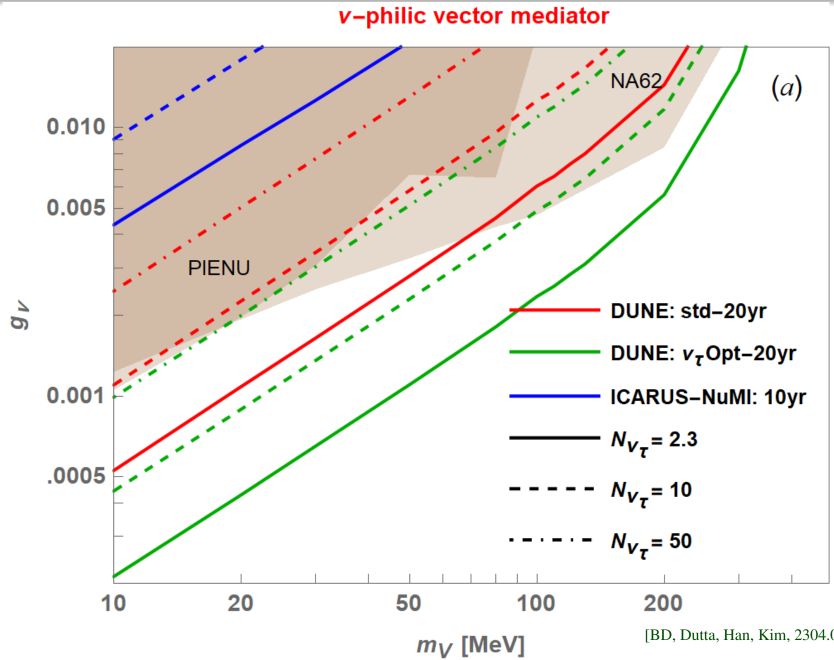


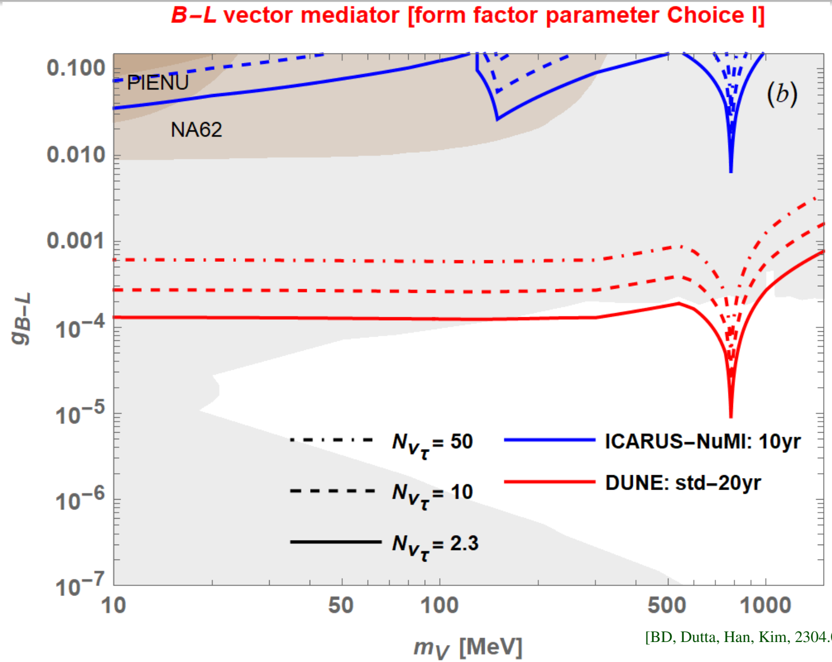


Neutrinophilic Case



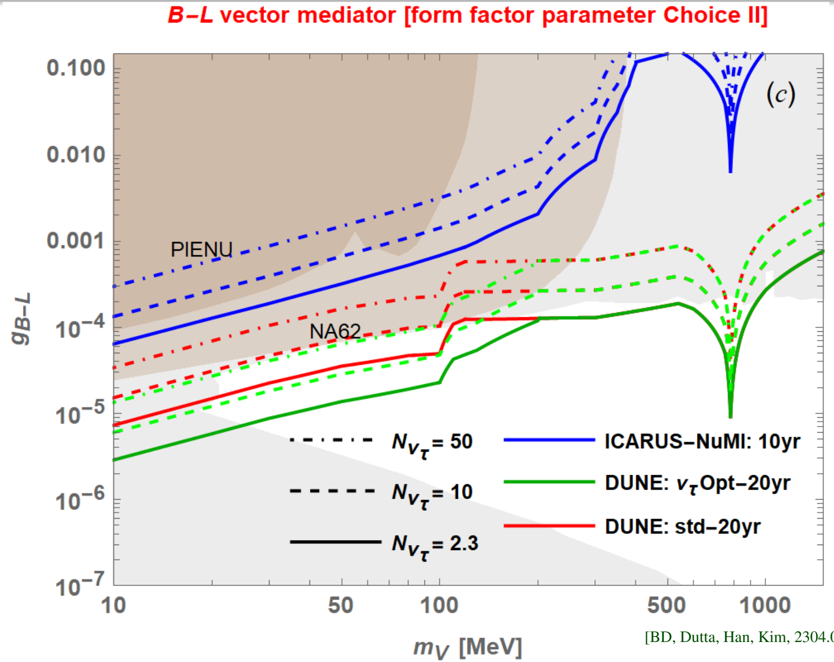
[BD, Dutta, Han, Kim, 2304.02031]

$B - L$ Case I



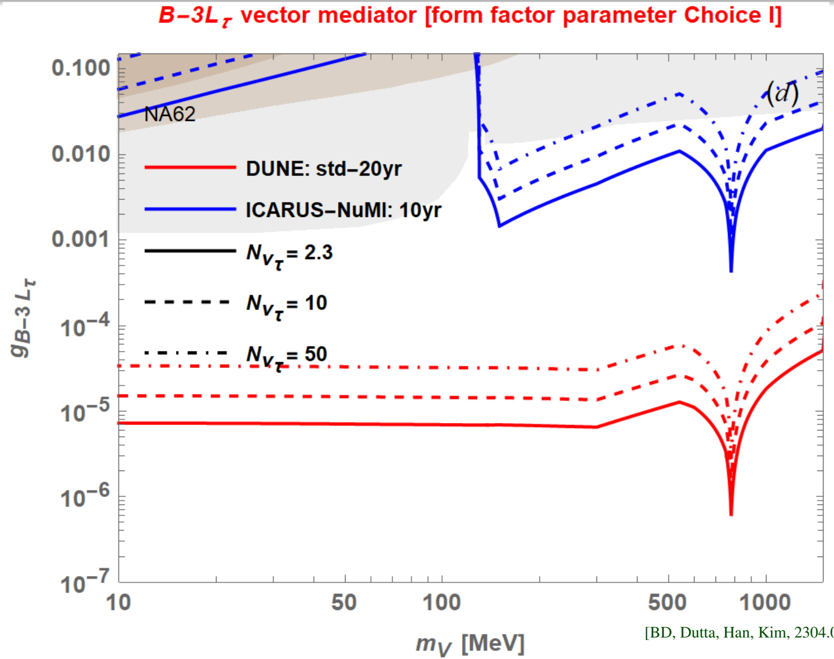
[BD, Dutta, Han, Kim, 2304.02031]

$B - L$ Case II



[BD, Dutta, Han, Kim, 2304.02031]

$B - 3L_\tau$ Case



[BD, Dutta, Han, Kim, 2304.02031]

DUNE vs ICARUS

	DUNE ND-LAr	ICARUS-NuMI
Beam energy	120 GeV	120 GeV
Dist. to dump	204 m	715 m
Dist. to detector	575 m	800 m
Detector angle	On axis	$\sim 5.7^\circ$ off-axis
Active volume $(w \times h \times l)$ [m^3]	$3 \times 4 \times 5$	$2.96 \times 3.2 \times 18$ ($\times$ 2 modules)
POT	2×10^{22}	10^{22}
Run-time	$\sim$ 20 years	$\sim$ 10 years

- Beam-focusing does not benefit ICARUS much.
- Loses the advantage of using charged mesons.
- ICARUS can only benefit from proton-brem-induced (or neutral meson-induced) BSM production.

Unknown form factors

- For a massive V coupling to quarks, unknown form factors in the hadronic current:

$$\begin{aligned} T^{\mu\rho} &= c_1 g^{\mu\rho} + c_2 (p_\ell + p_\nu)^\mu p_V^\rho + c_3 (p_\ell + p_\nu)^\rho p_V^\mu \\ &+ c_4 (p_\ell + p_\nu)^\mu (p_\ell + p_\nu)^\rho + c_5 p_V^\mu p_V^\rho \\ &+ F_V \epsilon^{\mu\rho\lambda\sigma} (p_\ell + p_\nu)_\lambda p_{V,\sigma} \, . \end{aligned}$$

- For a massless case, can use Ward identities to write [Khodjamirian, Wyler, hep-ph/0111249]

$$\begin{aligned} c_1 + c_2 (p_\ell + p_\nu) \cdot p_V &= f_{\mathfrak{m}} \, , \\ c_4 (p_\ell + p_\nu) \cdot p_V &= f_{\mathfrak{m}} \, . \end{aligned}$$

- F_V can be inferred from $\pi^+ \to e^+ \nu_e \gamma$ data [Bryman, Depommier, Leroy (Phy. Rep. '82); Donoghue, Golowich, Holstein (OUP '14)].
- Should not blindly use the photon form factors, as often done in the literature; see e.g. [Chiang, Tseng, 1612.06985 (PLB '17)].

Background is always an issue

- In real life, tau identification efficiency is not 100%.
- Neutrino energy threshold of 3.5 GeV.
- Will be limited by statistics, because event-by-event reconstruction is not possible.
- Any mis-ID would cause backgrounds (especially for hadronic tau decays).
- Can isolate a ν_τ-rich event sample where 30% of hadronically-decaying taus are successfully identified while only 0.5% of NC background contamination. [Conrad, de Gouvea, Shalgar, Spitz (PRD '10); de Gouvea, Kelly, Stenico, Pasquini (PRD '19)]

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	Standard LBNF ν beam	τ optimized beam
$\tau \to$ **e**		
$\nu_\tau(\tau \to e)$	22.4 ± 0.2	151.6 ± 1.2
ν_e osc.	87.0 ± 0.5	143.6 ± 0.5
ν_e beam	63.6 ± 1.5	82.3 ± 2.0
ν_e total	150.6 ± 1.5	225.9 ± 2.1
Significance	1.8 ± 0.0	9.2 ± 0.1
$\tau \to \rho$		
$\nu_\tau(\tau \to \rho)$	18.8 ± 0.2	116.2 ± 0.9
NC($\geq 1\pi^{\pm}1\pi_0$)	40.0 ± 1.2	122.5 ± 3.3
Significance	2.8 ± 0.0	9.3 ± 0.1
$\tau \to 1\pi$ (QEL-like)		
$\nu_\tau(\tau \to 1\pi)$	2.8 ± 0.1	16.4 ± 0.6
NC($\geq 1\pi^{\pm}$)	12.3 ± 0.7	26.9 ± 1.3
Significance	0.8 ± 0.0	2.9 ± 0.1
3 channels combined		
ν_τ	44.0 ± 0.3	284.2 ± 1.6
Backgrounds	202.9 ± 2.1	375.4 ± 4.1
Significance	3.0 ± 0.0	13.2 ± 0.1

[Thomas Kosc, PhD Thesis, 2021 (Lyon)]

- Naively, 200 mistagged tau events at FD, which scales to $\sim 10^6$ at ND.
- However, the leptonic tau decays are less affected by bkg contamination.
- DUNE collaboration is actively working on improving the ν_τ-efficiency, using machine learning.

Conclusion

- Accelerator neutrino experiments can be made versatile.
- Beam-based neutrino experiments are sensitive to a diverse set of dark sector models.
- Can provide competitive/best limits on (or discover) light dark sector physics.
- The future of dark (sector physics) is bright.