Searches For Exotic Particles

NuFact 2022: The 23rd International Workshop on Neutrinos from Accelerators

August 4, 2022

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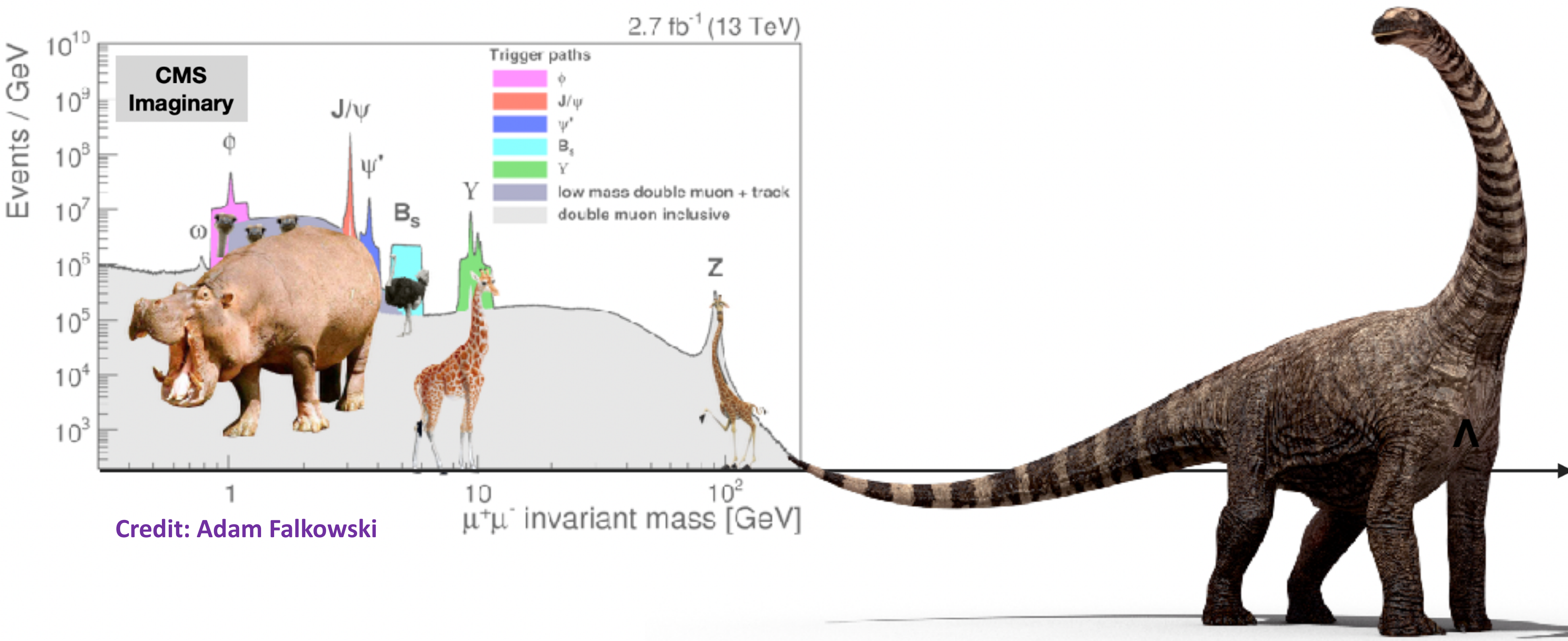
Northwestern University

Fantastic Beasts and Where To Find Them

NuFact 2022: The 23rd International Workshop on Neutrinos from Accelerators



Credit: Adam Falkowski

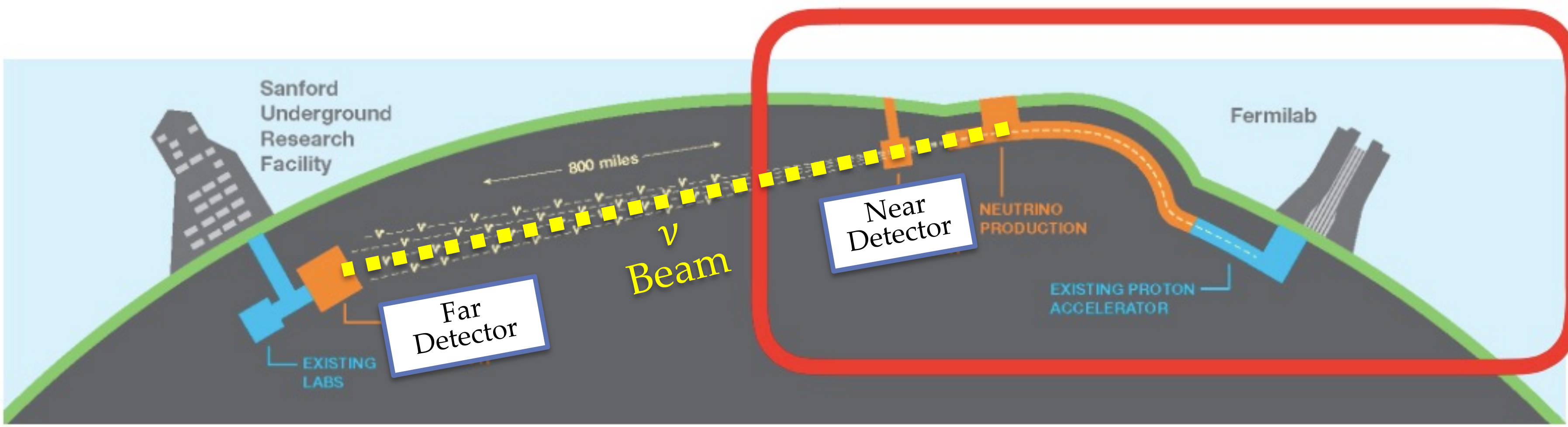
Physics goals of near detectors:

Primary role: Understanding Systematic Uncertainties

High beam luminosity + Large fiducial mass → Ideal to investigate **rare/new** neutrino interactions

$\sigma < 10^{-44}$ cm^2

- Test SM predictions
- Search for BSM physics



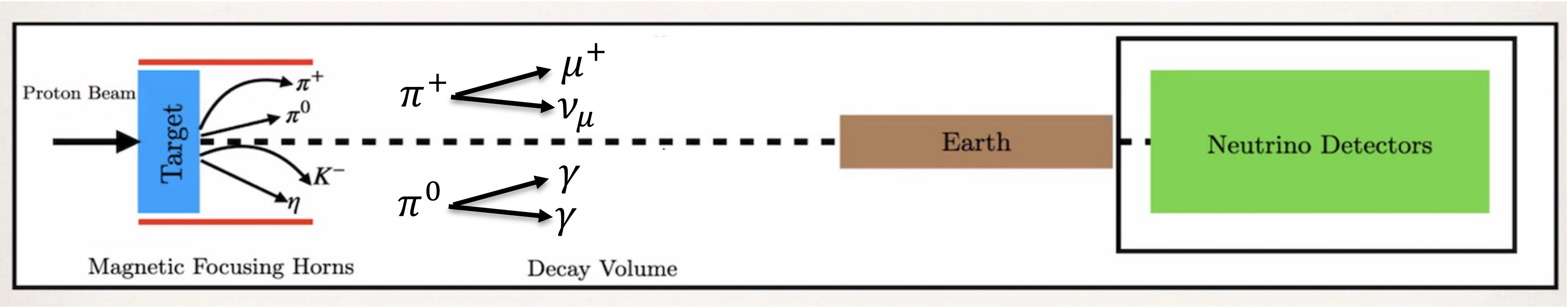
Question:

- **How can we fully leverage neutrino experiments to search for New Particles?**

- **Can neutrino experiments probe compelling new physics beyond the reach of high energy colliders?**

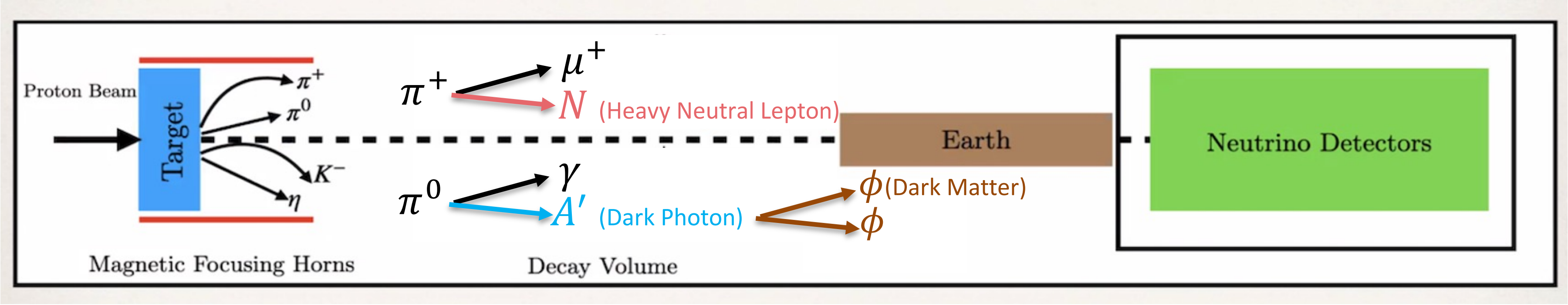
- I am biased;
- Taking DUNE as an example for most cases, while the overall search strategies are applicable to other similar experiments, e.g. Hyper-K, JUNO, etc.;
- See the talks by Georgia Karagiorgi, Supraja Balasubramanian and Joshua Berger for BSM searches at SBN detectors;

Neutrino Experiments as Dark Sector factories!



Credit: Kevin Kelly

The huge fluxes of neutrinos and photons can be used for BSM searches



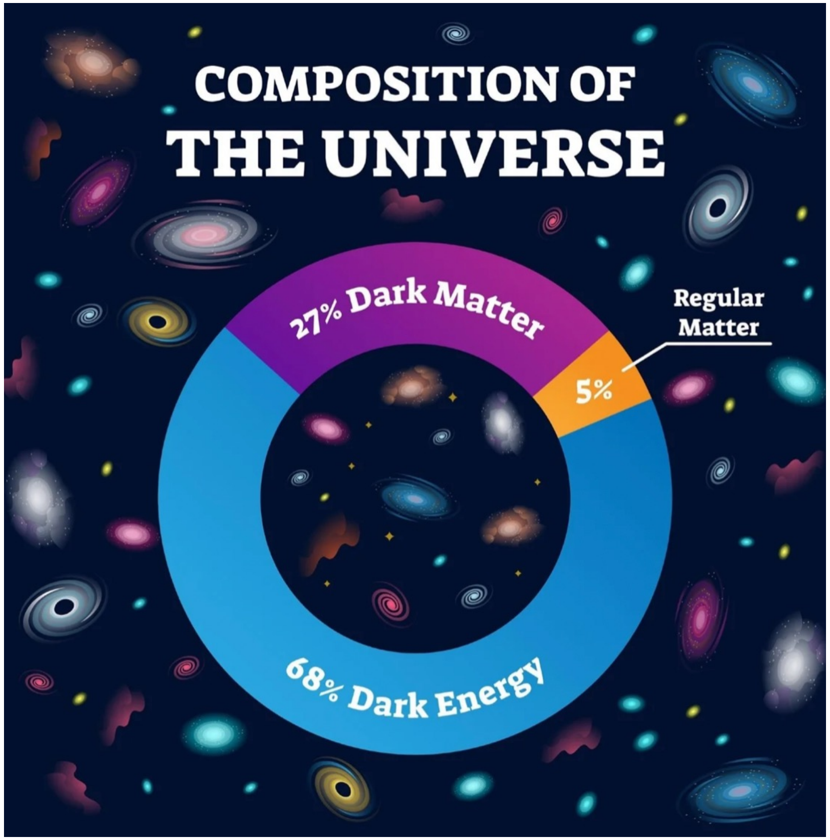
- **Heavy Neutral Leptons, Dark Photon, light DM, etc**

Berryman et al, PRD (2018)
Breitbach et al, JHEP (2022)
De Romeri et al, PRD (2019)
Magill et al, PRL (2019)

➢ See Patrick Green's talk for HNL

Exotic Particles at Neutrino Experiments:

- Light Dark Matter
- Axion-Like articles
- Light Z’



➢ See also Doojin Kim’s talk

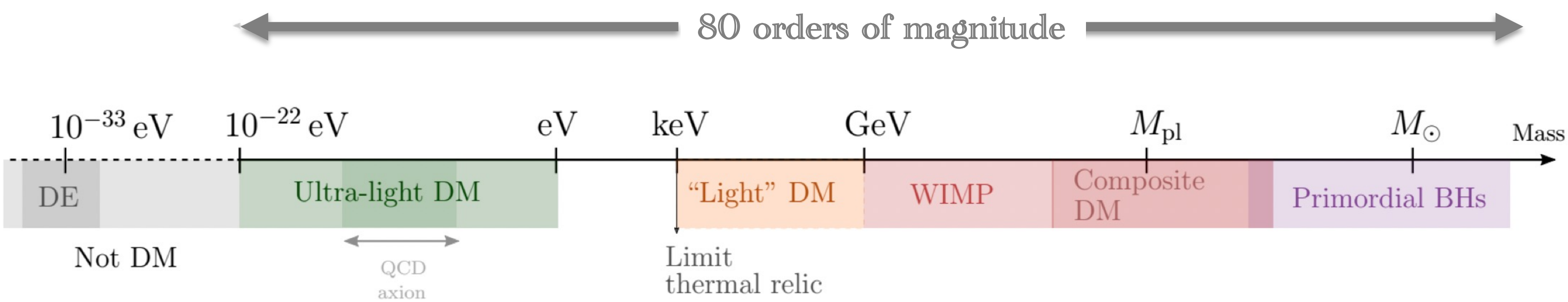
"What is Dark Matter?"

We don't know!

There could be several kinds, making up a whole "dark sector"

“Where is Dark Matter?”

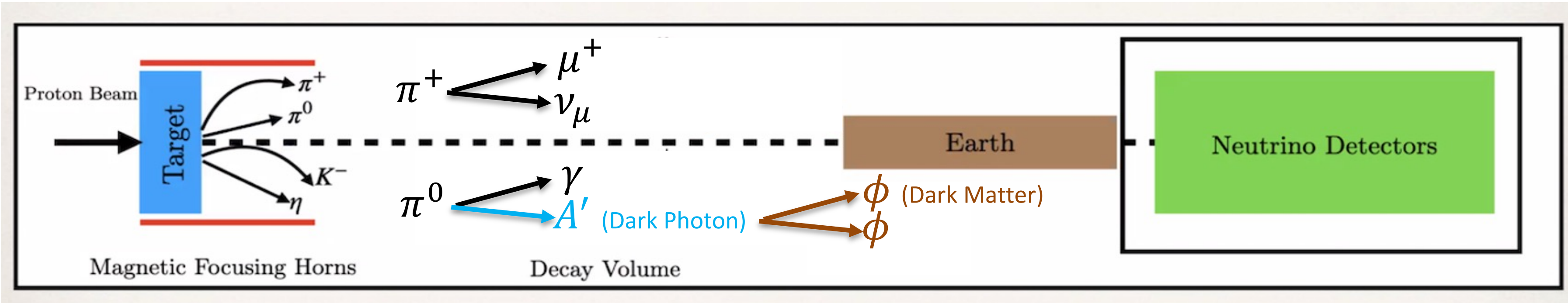
We don’t know!



Elisa G. M. Ferreira, arXiv:2005.03254

“How is Dark Matter?”

Light Dark Matter (LDM)

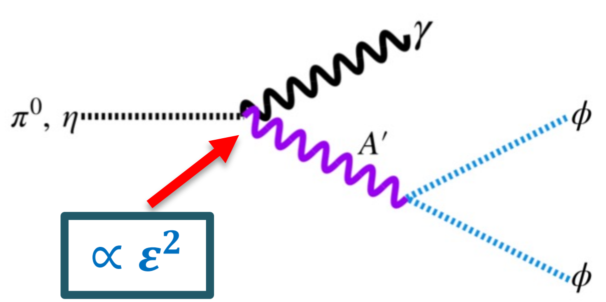


Photons at the target kinetically produce Dark Photons, which decay into dark matter:

$$\mathcal{L} \supset -\frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \frac{M^2_{A'}}{2} A'_\mu A'^\mu + |D_\mu \phi|^2 - M^2_\phi \, |\phi|^2$$

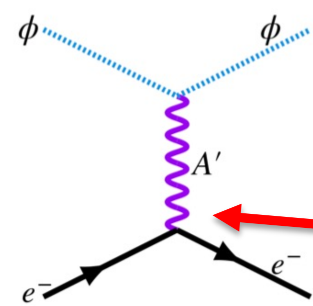
$$\boxed{D_\mu = \partial_\mu - i g_D A'_\mu, \;\; g_D = \sqrt{4\pi\alpha_D}}$$

DM production



$\boxed{\propto \varepsilon^2}$

DM detection



$\boxed{\propto \varepsilon^2}$

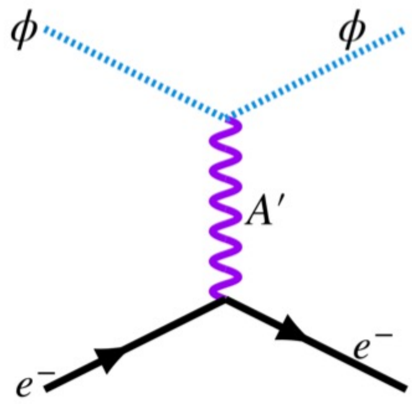
De Romeri, Kelly, Machado, PRD (2019)

(also Beam bremsstrahlung and Resonance production)

$\boxed{\text{DM event rate} \sim \varepsilon^4 \alpha_D}$

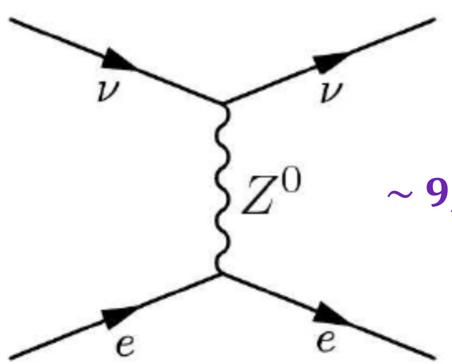
Light Dark Matter

DM signal: elastic scattering on electrons



How can we get rid of neutrinos in a neutrino detector?

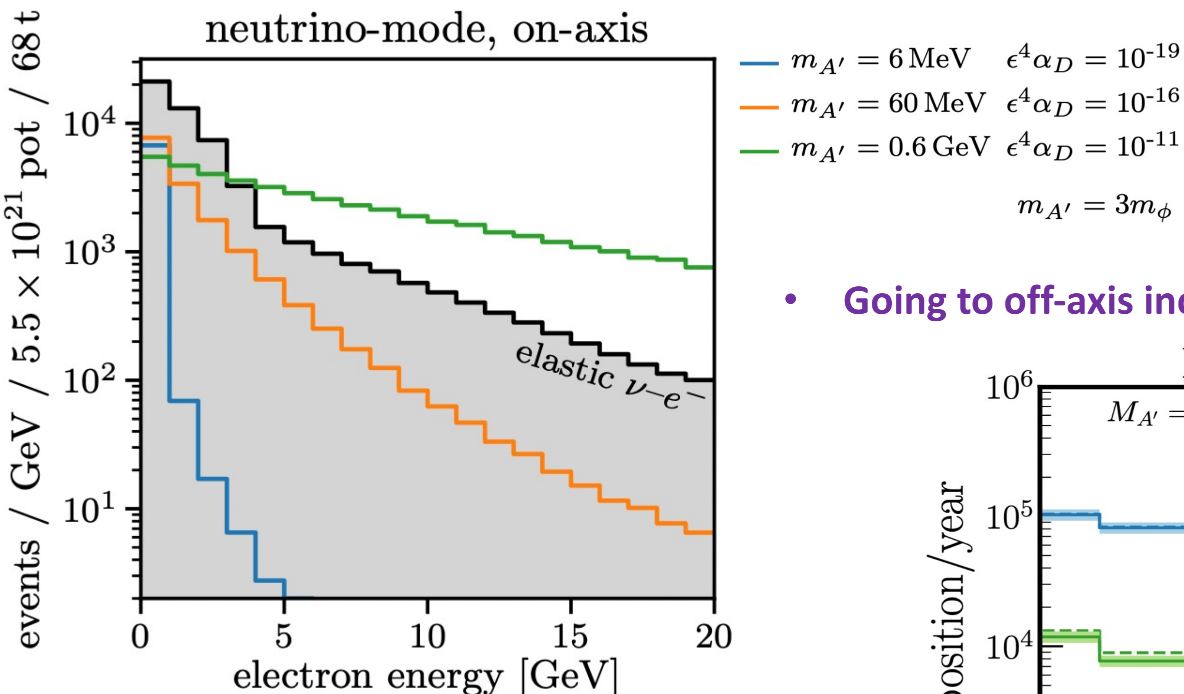
But so do neutrinos!



$\sim \mathbf{9,400}\ \boldsymbol{\nu - e}$ events / year!

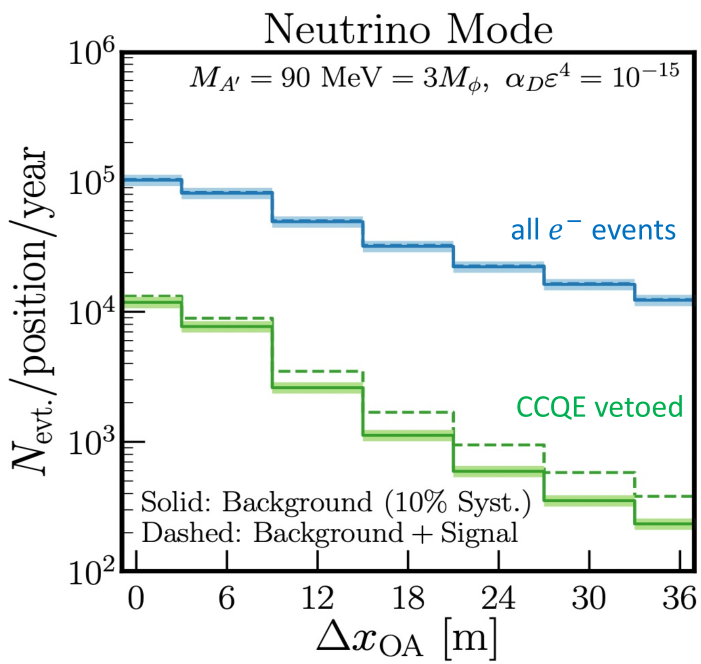
Light Dark Matter

- **Challenge: elastic neutrino-electron scattering is a huge background!**



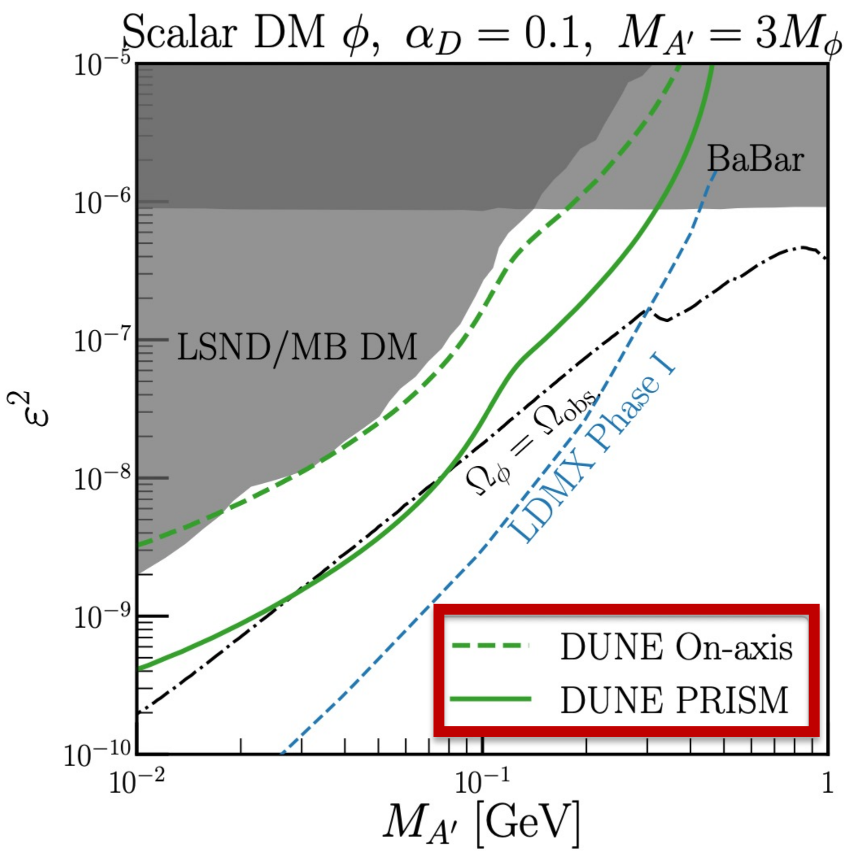
Breitbach, Buonocore, Frugiuele, Kopp, Mittnacht, JHEP (2022)

- **Going to off-axis increases DM signal/background**

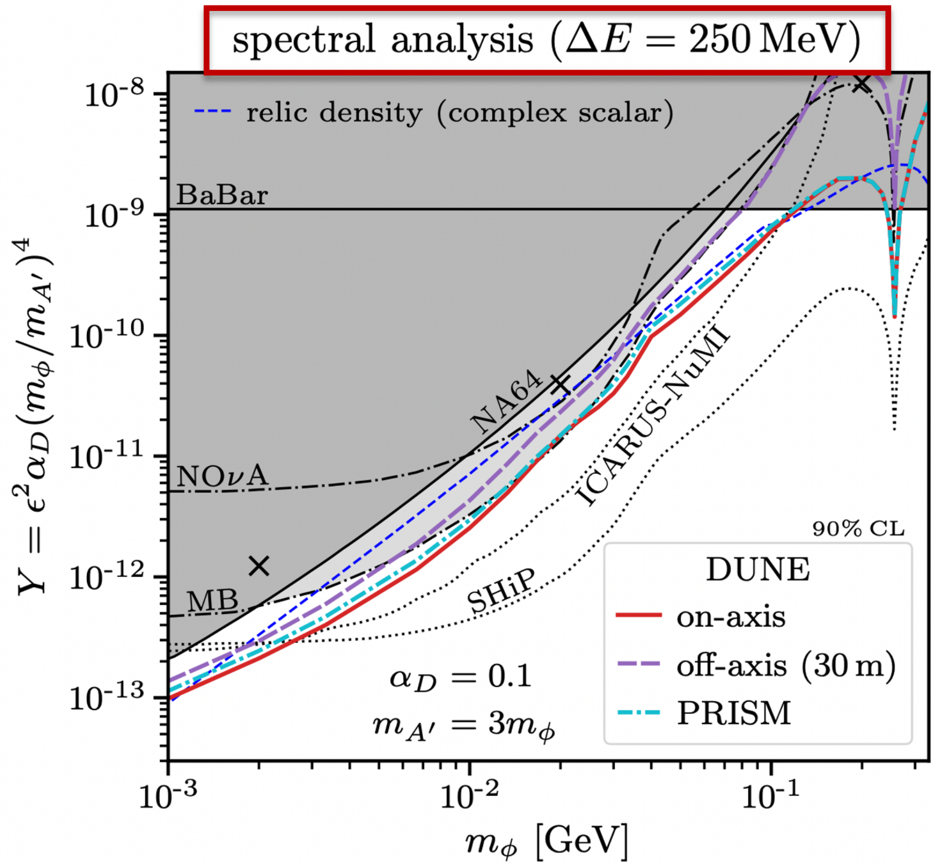


De Romeri, Kelly, Machado, PRD (2019)

Light Dark Matter



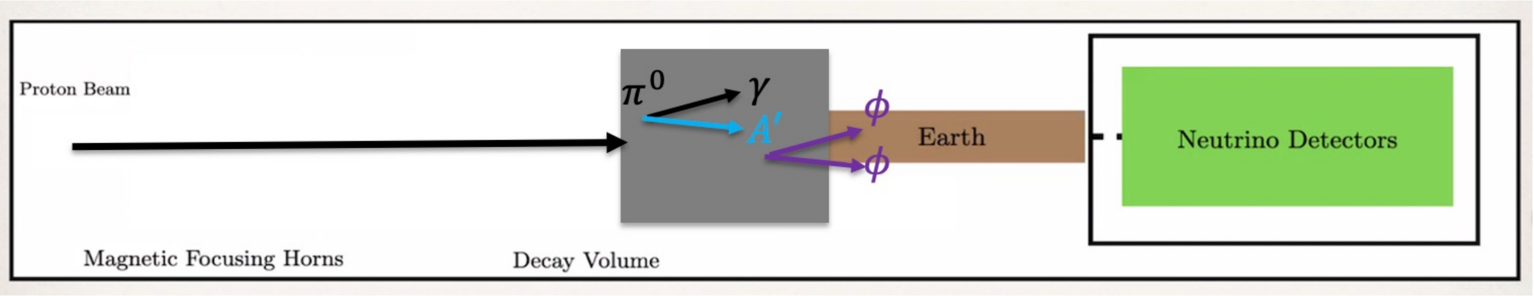
De Romeri, Kelly, Machado, PRD (2019)



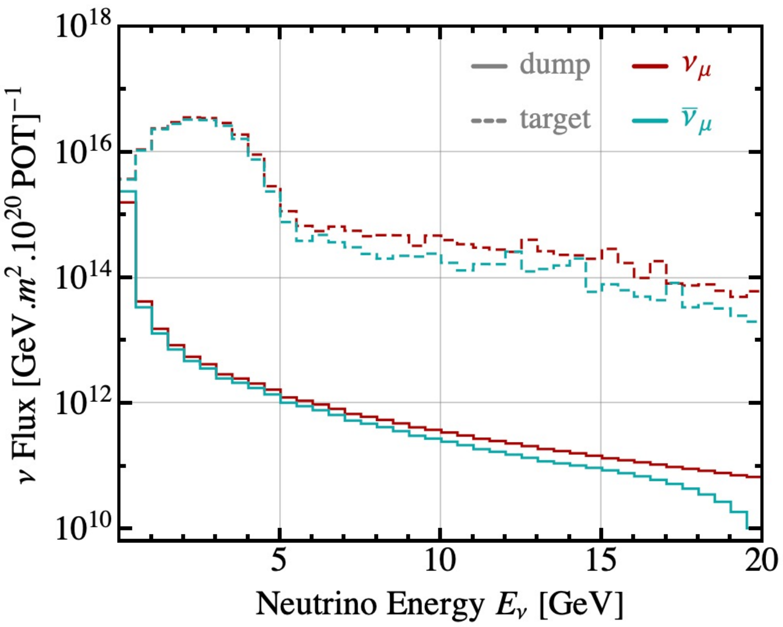
Breitbach, Buonocore, Frugiuele, Kopp, Mittnacht, JHEP (2022)

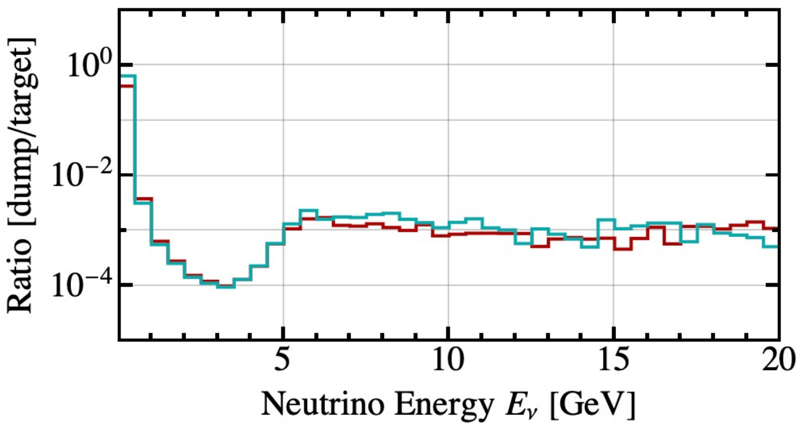
- See Wes Ketchum talk on LDMX

LDM at a Target-less DUNE



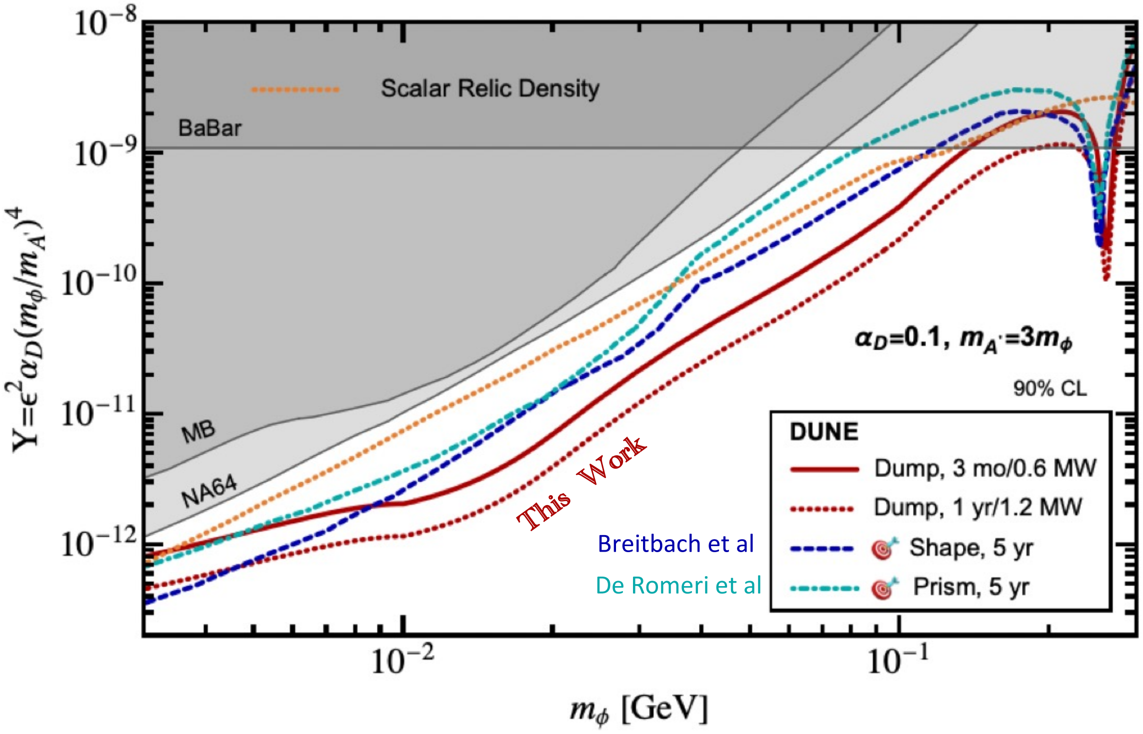
- Impinging protons directly to the dump area;
- Shorter distance between the source point and the detector → more DM signal;
- Charged mesons absorbed in the Al beam dump before decay;
- **The ν flux decreases by 3 orders of magnitude → Only 0.5 ν-e background in 3 mo-0.6 MW!**





Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu
arXiv: 2206.06380

LDM at a Target-less DUNE



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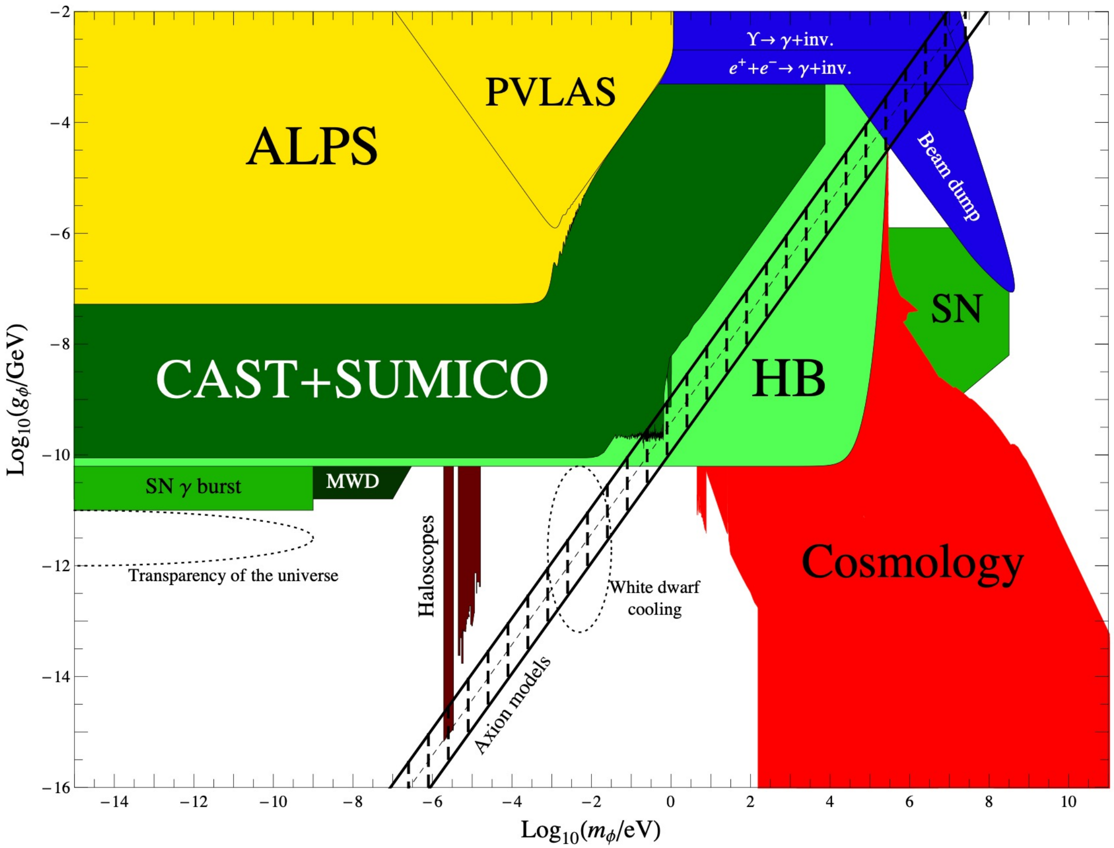
Target-less DUNE can probe the parameter space for thermal relic DM in only 3 months!

Exotic Particles at Neutrino Experiments:

- Light Dark Matter ✓
- Axion-Like articles
- Light Z’

Axion-Like Particles (ALPs)

- (pseudo)scalars, strongly motivated by theory and cosmology;
- Why is CP conserved in QCD? Solution to the strong CP problem (QCD axion);
- DM candidates;



D. Cadamuro, 1210.3196 [hep-ph]

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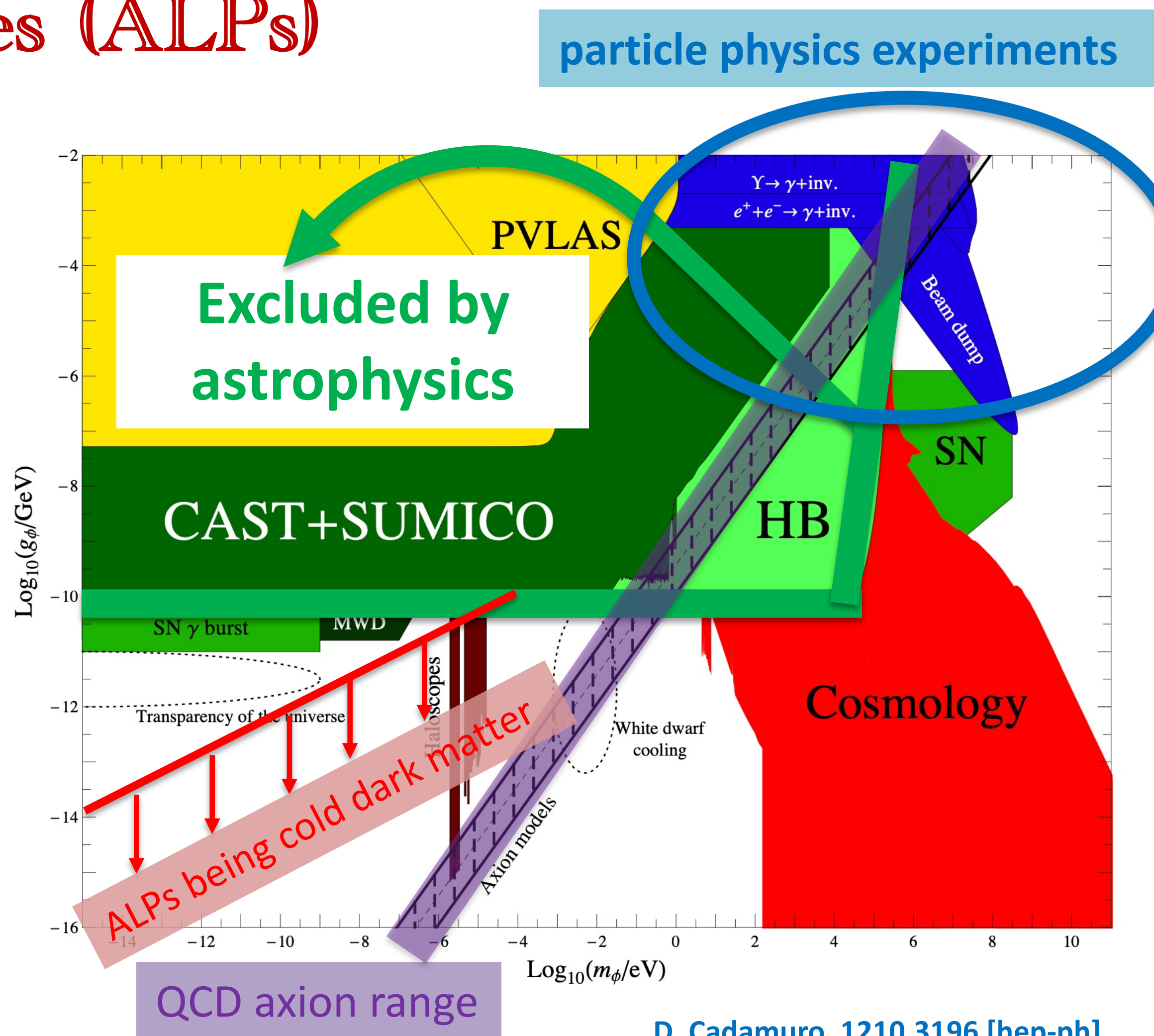

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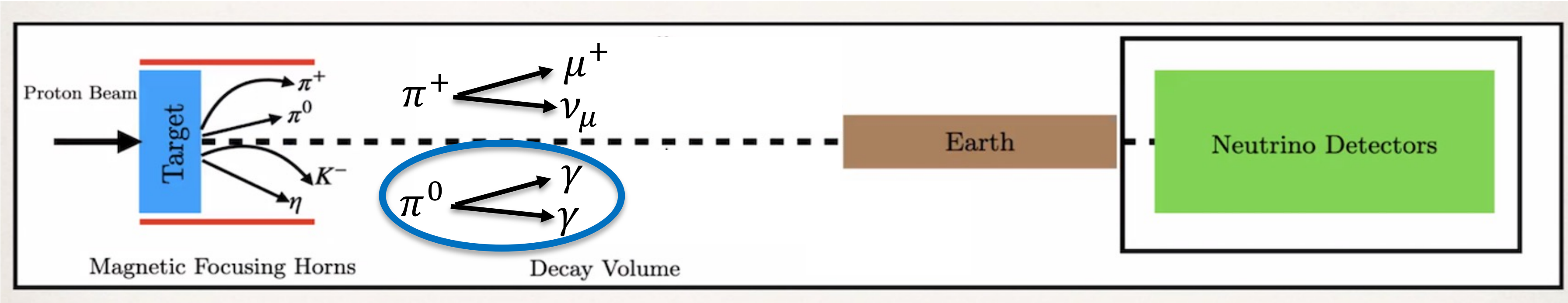
ALPs at Neutrino Experiments

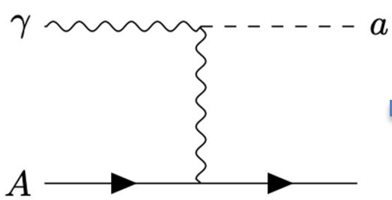


Credit: Kevin Kelly

Using photons to produce ALPs:

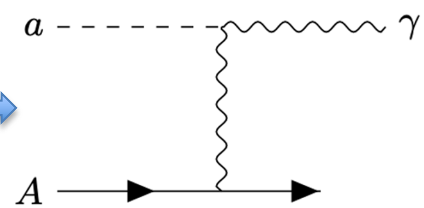
$$\mathcal{L}_{a\gamma\gamma} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

ALP production

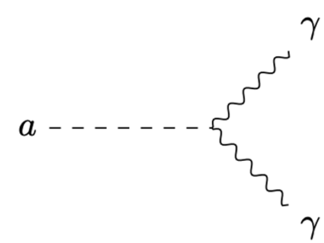


Primakoff scattering

ALP detection

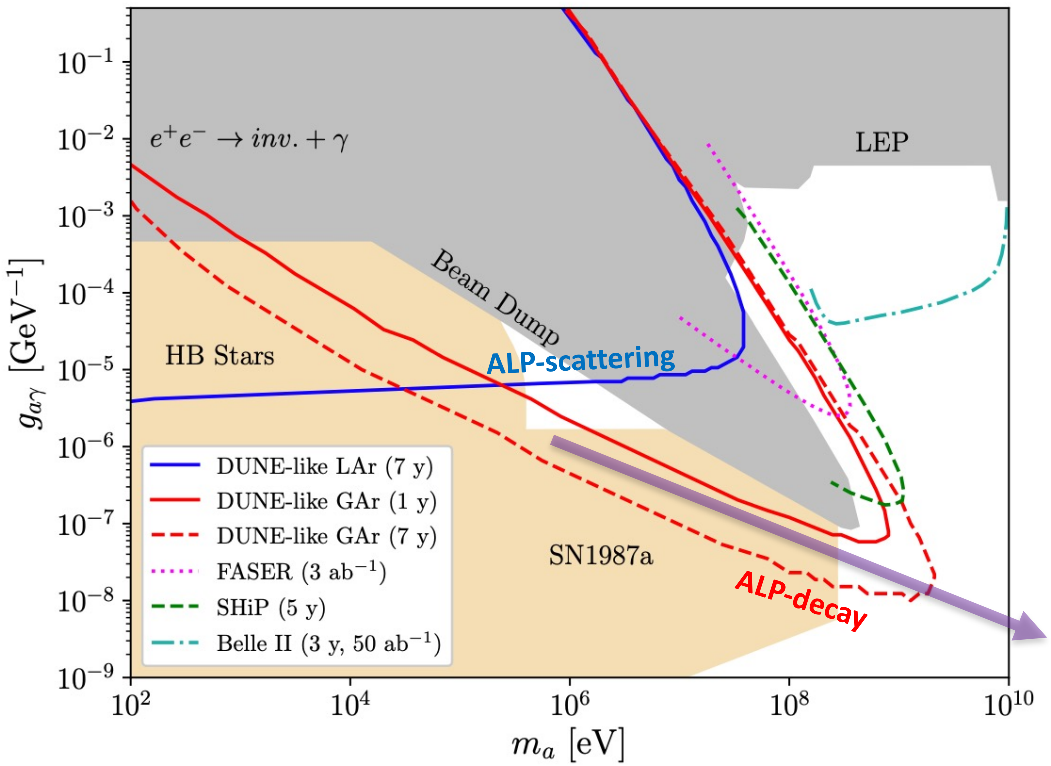


Inverse Primakoff scattering



ALP decay

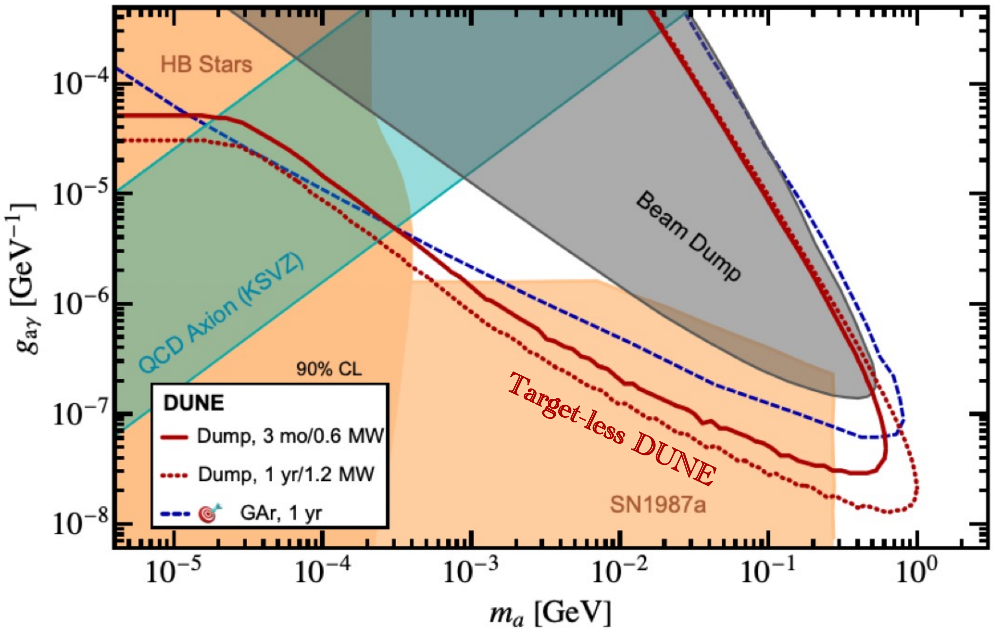
ALPs at GAr-DUNE



Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu
PRL (2021)

- The only lab-based constraints!
- Gas-detector is the key, due to significantly low background!

ALPs at Target-less DUNE



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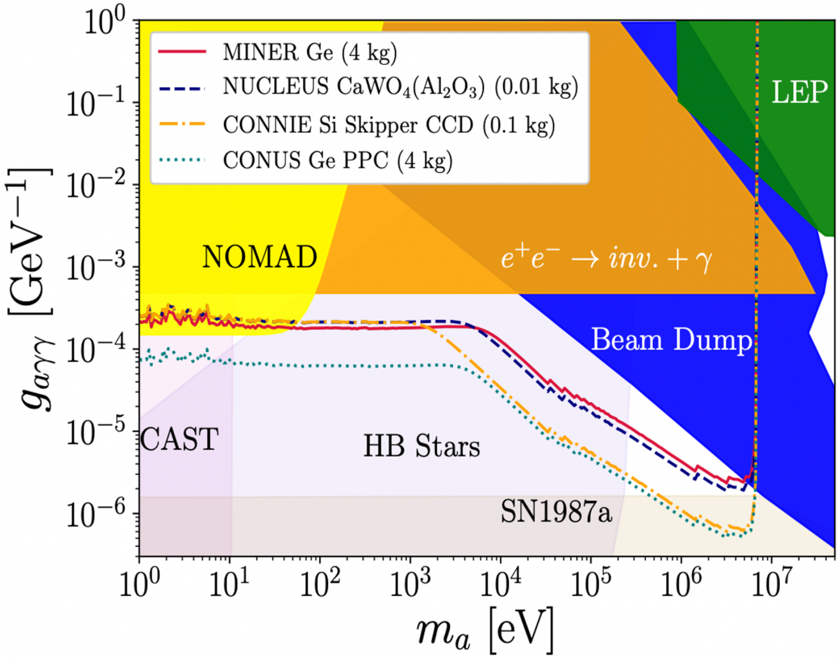
- Can probe QCD-axion
- 3 months target-less DUNE can do better than 1 yr Gar

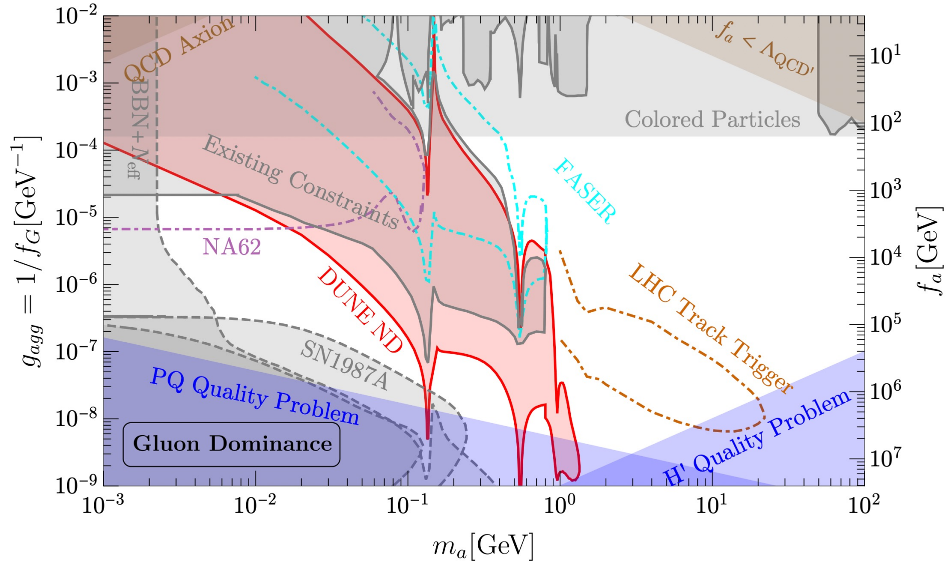
ALPs at Neutrino Experiments

Reactors



Dent, Dutta, Kim, Liao, Mahapatra, Sinha, Thompson,
Phys.Rev.Lett. 124 (2020) 21, 211804

Heavy ALPs at DUNE

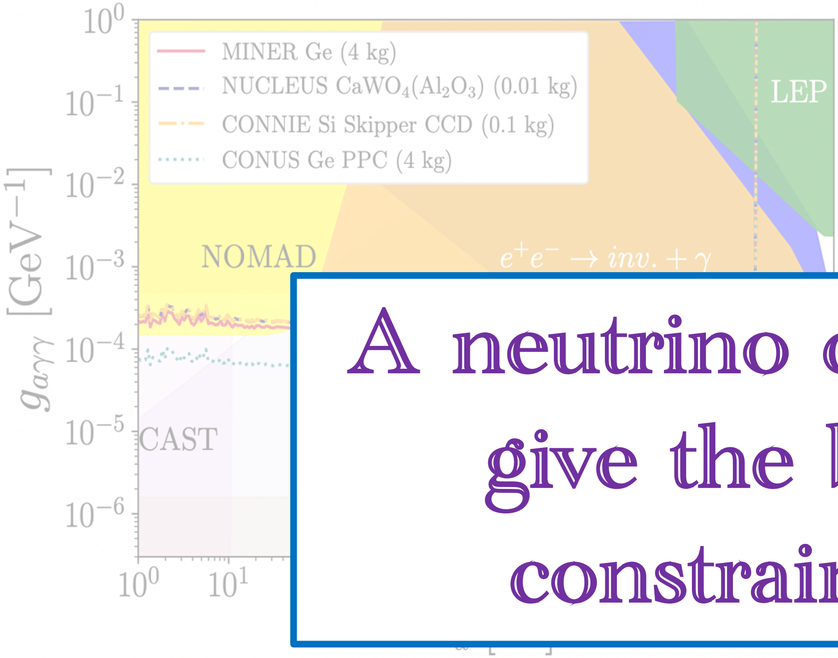


Kelly, Kumar, Liu,
Phys.Rev.D 103 (2021) 9, 095002

Production via mixing with SM mesons or gluon/gluon fusion

ALPs at Neutrino Experiments

Reactors

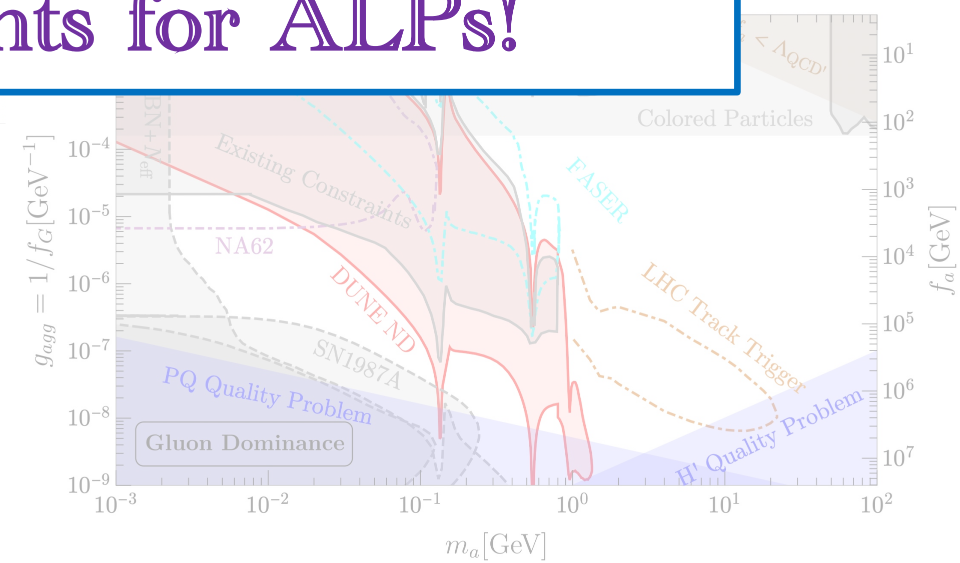


Dent, Dutta, Kim, Liao, Mahapatra, Sinha, Thompson, Phys.Rev.Lett. 124 (2020) 21, 211804

A neutrino detector can even give the best lab-based constraints for ALPs!

Kelly, Kumar, Liu, Phys.Rev.D 103 (2021) 9, 095002

Production via mixing with SM mesons or gluon/gluon fusion



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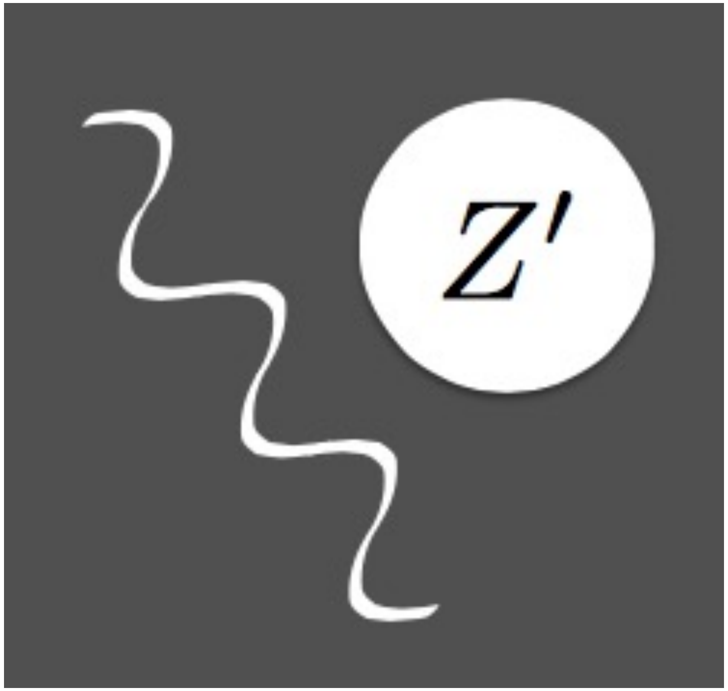
- Light Dark Matter ✓
- Axion-Like articles ✓
- Light Z'



Light Z'

- **Low Energy Experiments**
  - Miranda et al, JHEP (2020)
  - Coloma et al, JHEP (2021)
  - Caddedu et al, JHEP (2021)
- **Fixed Target Experiments**
  - Gninenko, PLB (2012)
  - Tsai et al, PRL (2021)
  - Bauer et al, JHEP (2018)
- **Neutrino Trident Searches**
  - Altmannshofer et al, PRL (2014)
  - Ballet et al, JHEP (2019)
- **Neutrino-Electron Scattering**
  - Harnic et al, JCAP (2012)
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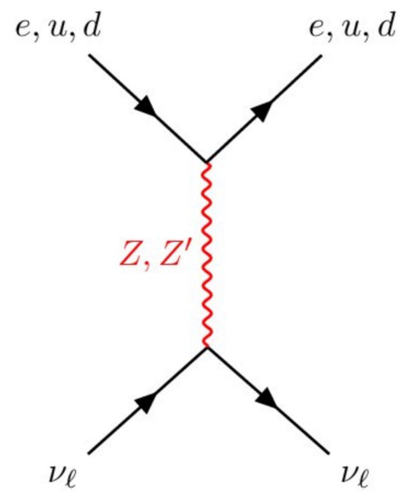
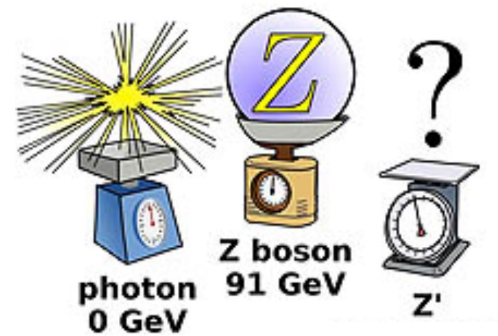
- **Colliders**
  - BaBar Collaboration, PRL (2014)
  - BaBar Collaboration, PRL (2017)
- **Cosmology**
  - Escudero et al, JHEP (2019)

What can we learn from neutrino experiments?

$$\mathcal{L}_{Z'}^{\text{matter}} = -g'\big(a_u\,\bar{u}\gamma^\alpha u + a_d\,\bar{d}\gamma^\alpha d + a_e\,\bar{e}\gamma^\alpha e + b_e\,\bar{\nu}_e\gamma^\alpha P_L\nu_e + b_\mu\,\bar{\nu}_\mu\gamma^\alpha P_L\nu_\mu + b_\tau\,\bar{\nu}_\tau\gamma^\alpha P_L\nu_\tau\big)Z'_\alpha$$





news.fnal.gov

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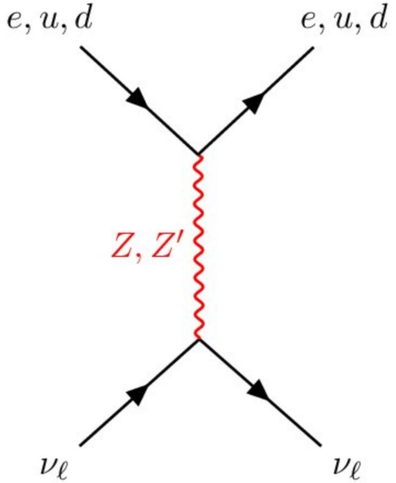
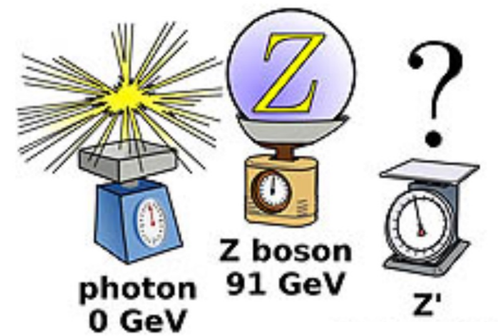
$$+\, b_e\,\bar{\nu}_e\gamma^\alpha P_L\nu_e + b_\mu\,\bar{\nu}_\mu\gamma^\alpha P_L\nu_\mu + b_\tau\,\bar{\nu}_\tau\gamma^\alpha P_L\nu_\tau\big)Z'_\alpha$$





news.fnal.gov

The list is far from being exhaustive!

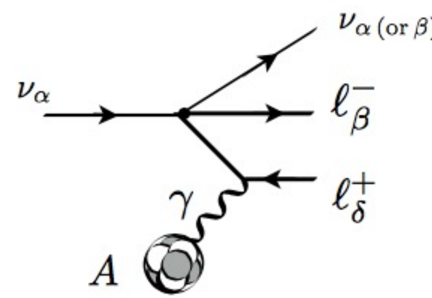
Neutrino Trident Scattering

Production of a **charged lepton pair**

in the scattering of a **neutrino**

in the Coulomb field of a **heavy nucleus/nucleon**

$$\boxed{\nu_\alpha + \mathcal{N} \to \nu_\beta + \ell_\gamma^+ + \ell_\delta^- + \mathcal{N}}$$



CHARM II
PLB (1990)

$$\frac{\sigma_{\text{CHARM II}}}{\sigma_{\text{SM}}} = 1.58 \pm 0.57$$

CCFR
PRL (1991)

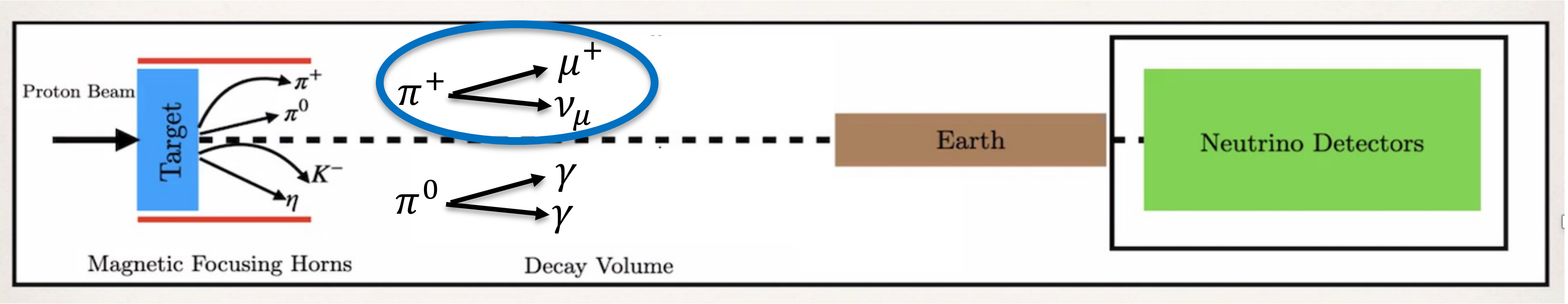
$$\frac{\sigma_{\text{CCFR}}}{\sigma_{\text{SM}}} = 0.82 \pm 0.28$$

NuTeV
Vancouver 1998,
High energy physics, vol 1

$$\frac{\sigma_{\text{NuTeV}}}{\sigma_{\text{SM}}} = 0.67 \pm 0.27$$

- Very large uncertainties
- Very few events observed (~100)

Trident rates at LAr Detectors



Channel	SBND	μBooNE	ICARUS	DUNE ND
Total $e^{\pm}\mu^{\mp}$	10	0.7	1	2993 (2307)
	2	0.1	0.2	692 (530)
Total e^+e^-	6	0.4	0.7	1007 (800)
	0.7	0.0	0.1	143 (111)
Total $\mu^+\mu^-$	0.4	0.0	0.0	286 (210)
	0.4	0.0	0.0	196 (147)

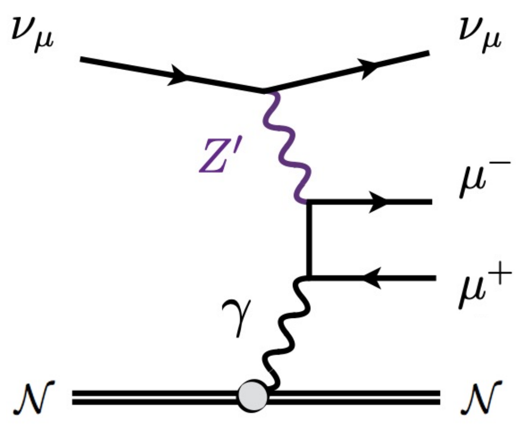
Coherent (upper) and diffractive (lower) trident events for (anti)neutrino mode

More than 9,000 trident events at DUNE!

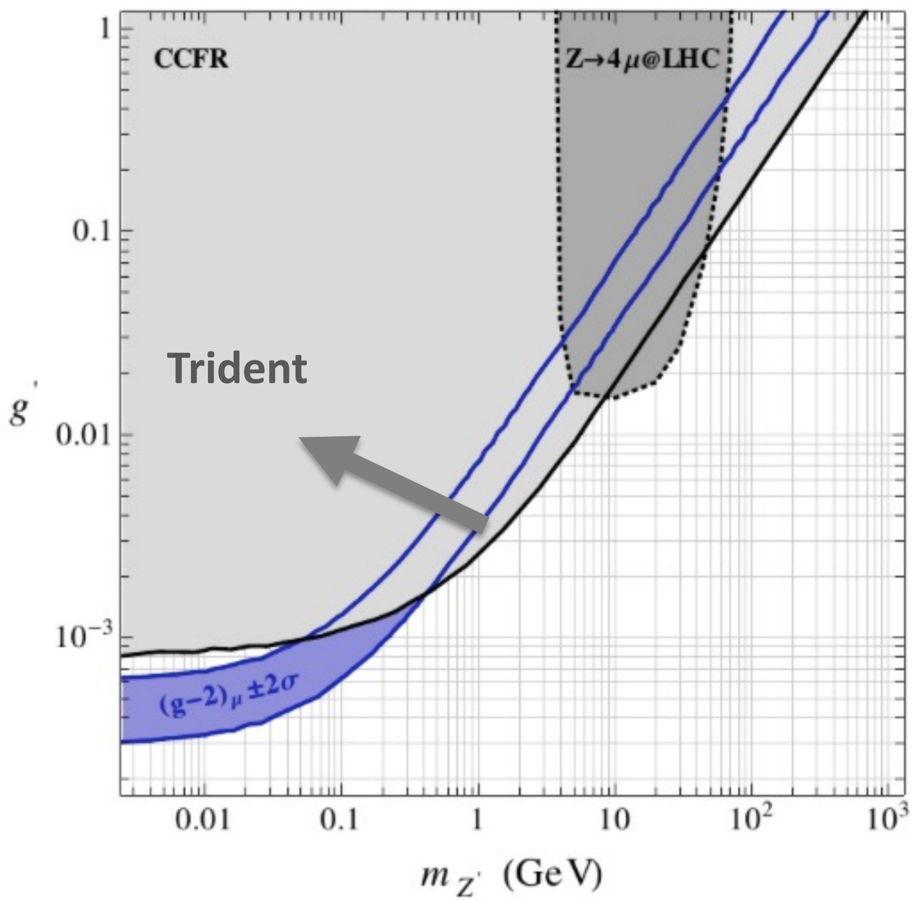
Ballett, Hostert, Pascoli, Perez-Gonzalez, *ZT* and Funchal, PRD (2019)

Light Z': L_μ-L_τ Model

- Z' only couples to muon and tau, but not to electrons;
- It can explain the muon (g-2) anomaly;
- Can be best probed using tridents;



HE colliders only have access to large masses!



Altmannshofer, Gori, Pospelov, Yavin, PRL (2014)

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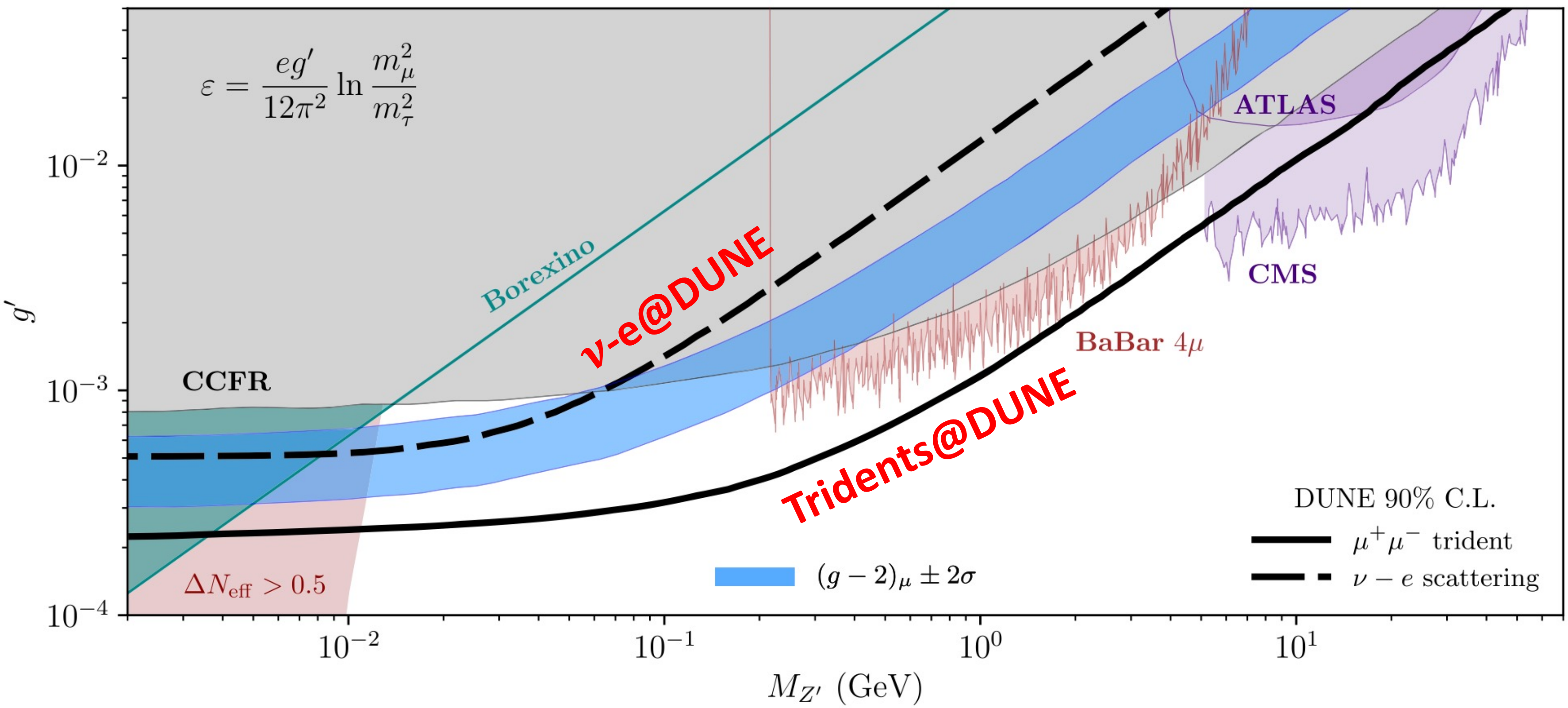
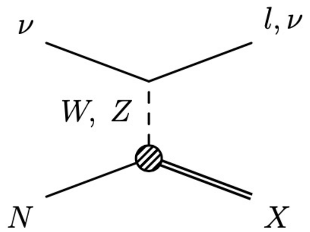


The whole g-2 region can be probed by DUNE data!

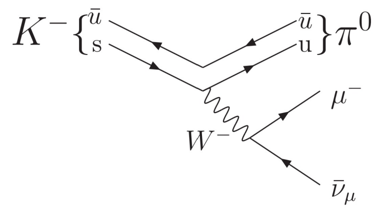
Direct Search of Dark Sectors:

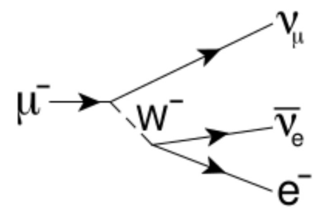
- Light Dark Matter ✓
- Axion-Like articles ✓
- Light Z’ ✓

DIS: FASERν

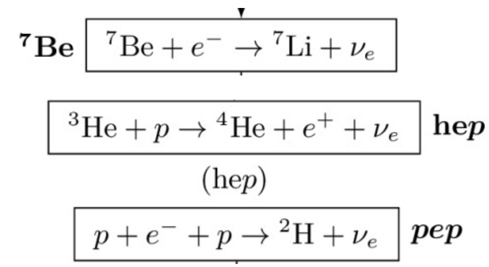


Kaon/Muon decay: ISODAR, KDAR

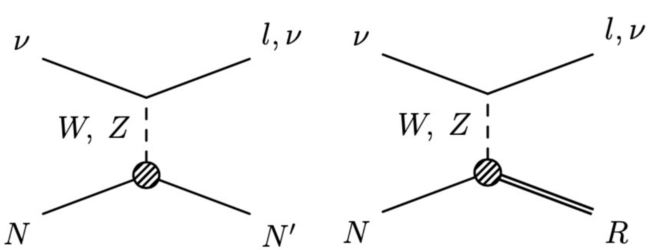




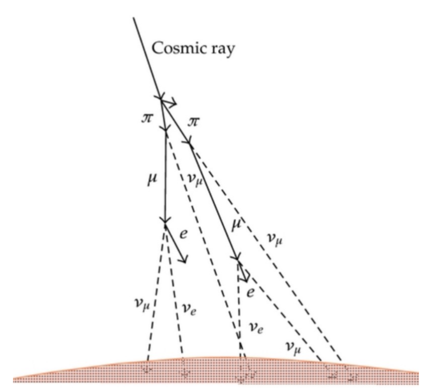
Solar neutrinos: Borexino



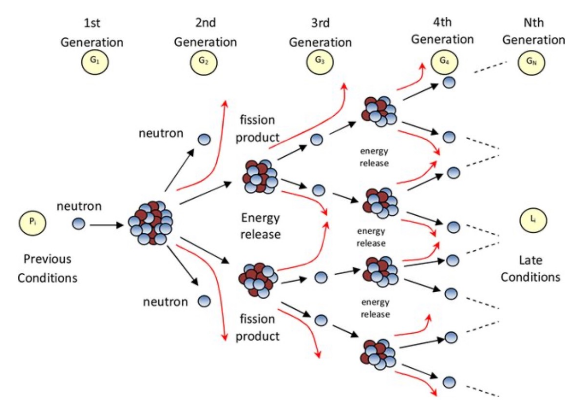
QE, Resonances: MINOS, NOvA, DUNE



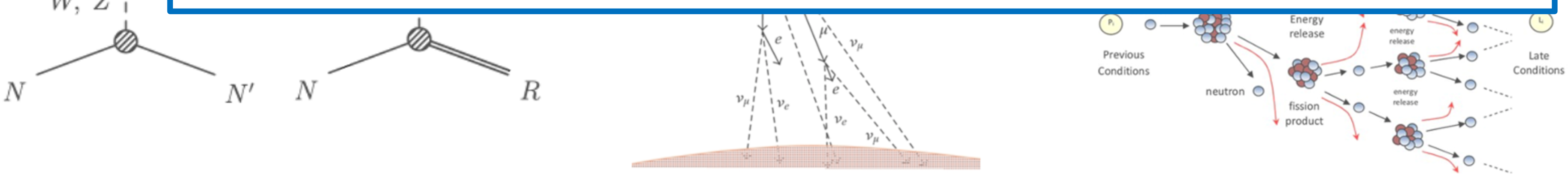
Atmospheric Neutrinos: IceCube



Beta decay and IBD: Reactor Experiments



Neutrino experiments give us a powerful tool to search for new physics, either by direct production or by precision measurements!



Conclusion:

- We can use the near detectors to directly search for dark sector (e.g.: light DM, ALPs, Light Z', etc.);
- For several BSM models, near detectors give the best constraints;
- Target-less DUNE can probe the parameter space for thermal relic DM in only 3 months;
- Both DUNE GAr and Target-less DUNE place best lab-based bounds on ALPs parameter space and can probe the QCD axion region;
- The whole g-2 region explained by L_μ-L_τ Model can be probed by DUNE data.

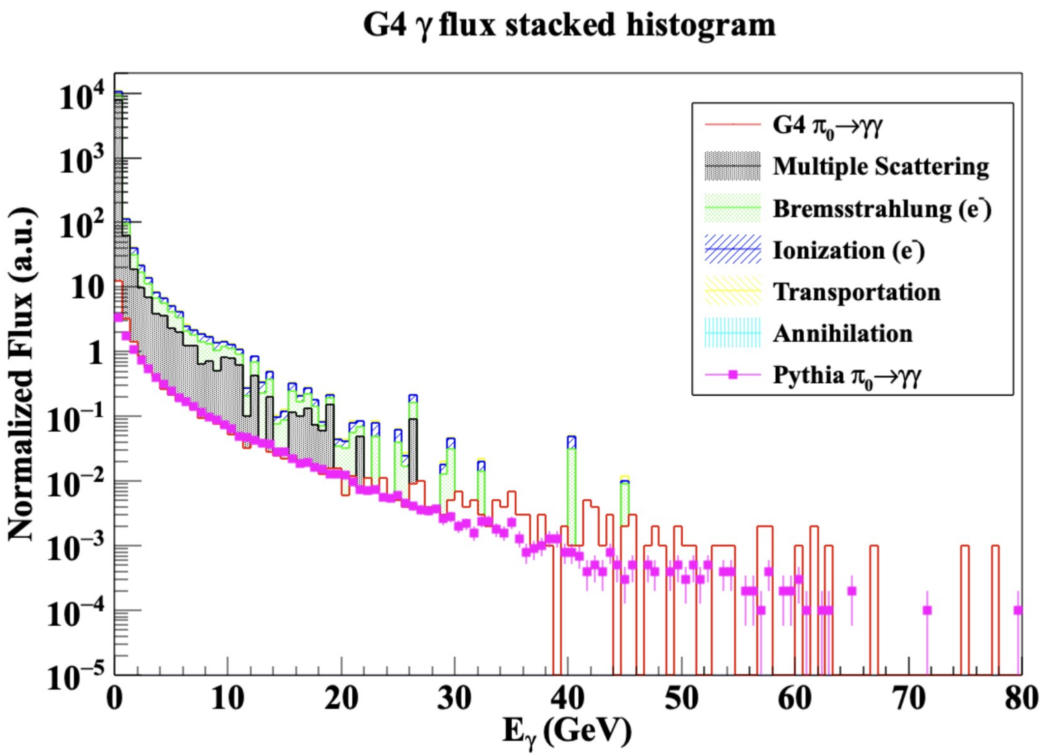
Any Questions?

I'M NOW GOING TO OPEN THE FLOOR TO QUESTIONS.

Back up Slides

Axion Like Particles (ALPs) at DUNE:

Photon Flux from GEANT4 Simulation



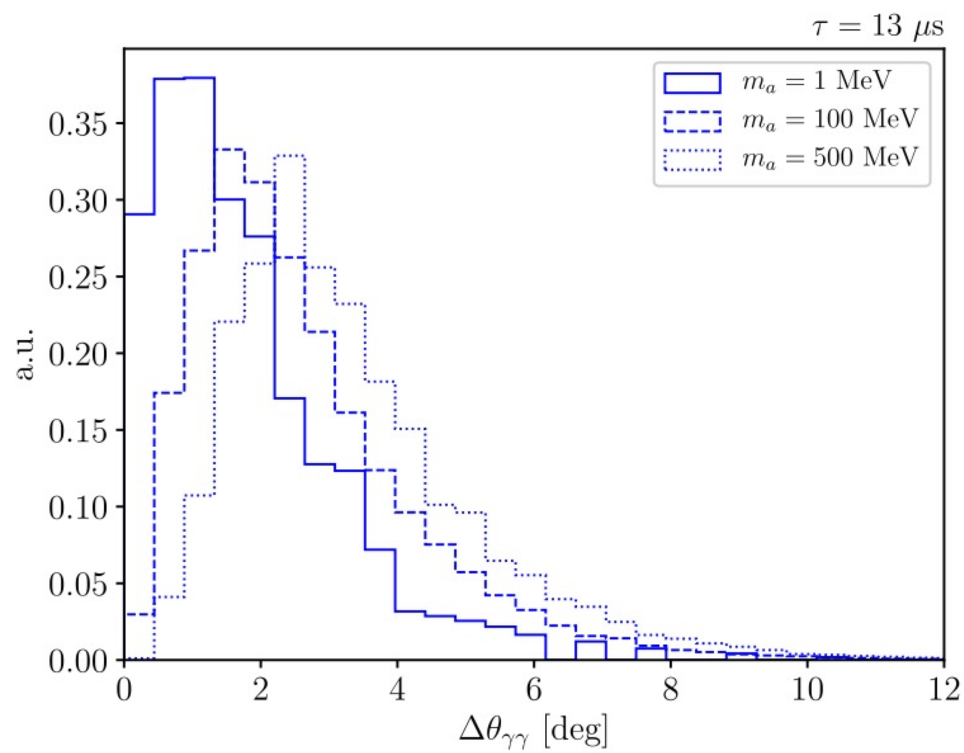
V. Brdar, B. Dutta, W. Jang, D. Kim, I. Shoemaker, **ZT**, A. Thompson, J. Yu
Phys.Rev.Lett. 126 (2021) 20, 201801

Axion Like Particles (ALPs) at DUNE:

- Coherent π^0 production $\nu + A \to \nu + A + \pi^0$

In GAr:

- We expect ~ 10^6 NC events;
- Vetoing events with hadronic activity remove ~ 80%;
- A cut on the opening angle removes the rest;



V. Brdar, B. Dutta, W. Jang, D. Kim, I. Shoemaker, **ZT**, A. Thompson, J. Yu
Phys.Rev.Lett. 126 (2021) 20, 201801

EPA assumptions

1) Neglecting the L contribution ($h^{\mathrm{L}}(q^2,\hat{s})\,\sigma^{\mathrm{L}}_{\nu\gamma}(q^2,\hat{s}) \approx 0$).

2) Taking the T contribution of the cross section to be on-shell ($\sigma^{\mathrm{T}}_{\nu\gamma}(q^2,\hat{s}) \approx \sigma^{\mathrm{T}}_{\nu\gamma}(0,\hat{s})$).

$$\sigma_{\mathrm{t}}(P_i + C_s \to P_f + C_s) \approx \int dP(Q^2,\hat{s})\,\sigma_\gamma(P_i + \gamma \to P_f; \hat{s}, Q^2 = 0)$$

QED

$$\sigma_\gamma^{\mathrm{QED}}(P_i + \gamma \to P_f; \hat{s}, 0) \propto \frac{1}{\hat{s}}$$

Decreases with increasing transferred four-momentum

On-shell >> off-shell

Fermi Limit of the SM

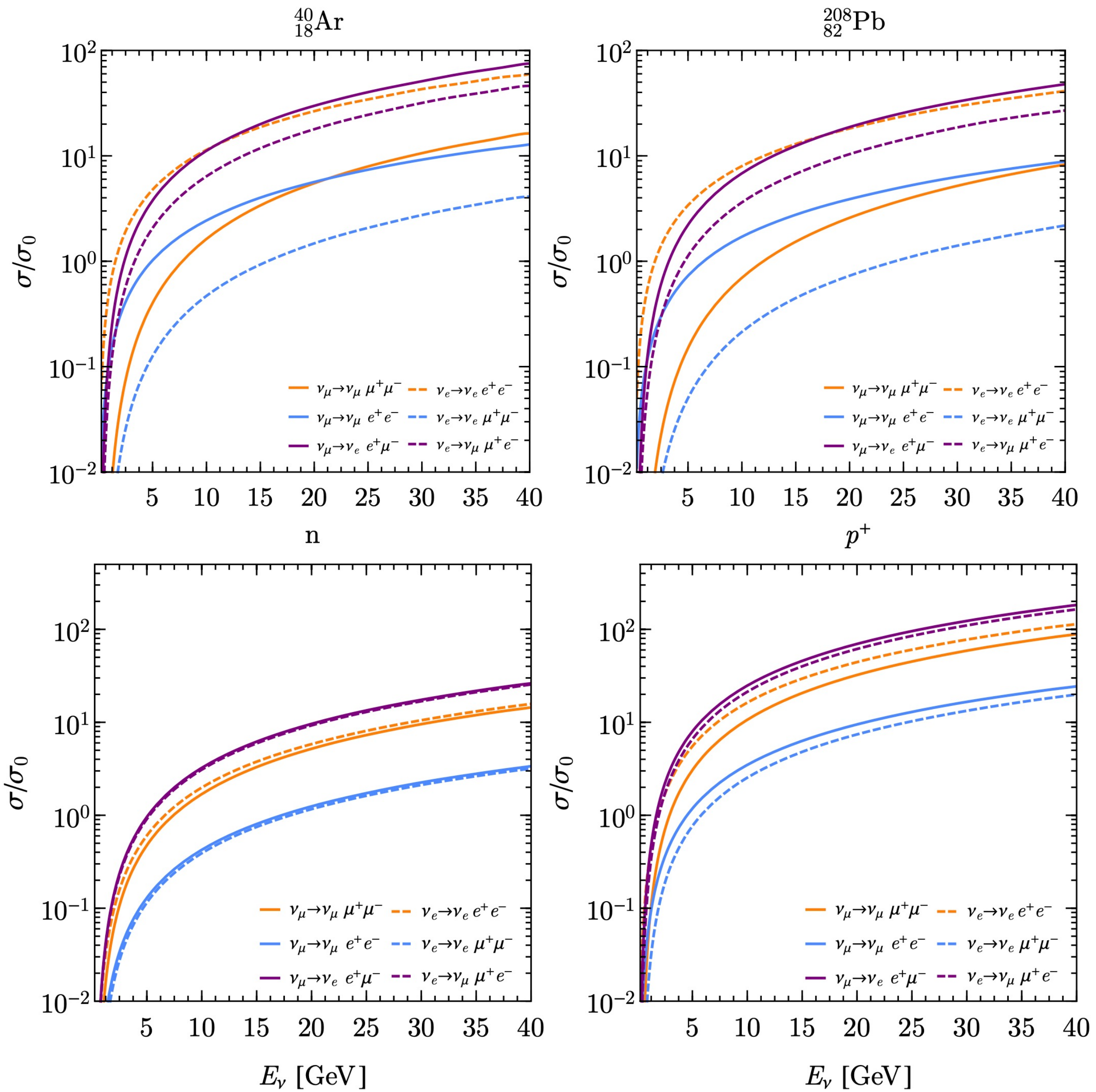
$$\sigma_\gamma^{\mathrm{FL}}(P_i + \gamma \to P_f; \hat{s}, 0) \propto G_{\mathrm{F}}^2\,\hat{s}$$

Increases with increasing transferred four-momentum

On-shell << off-shell

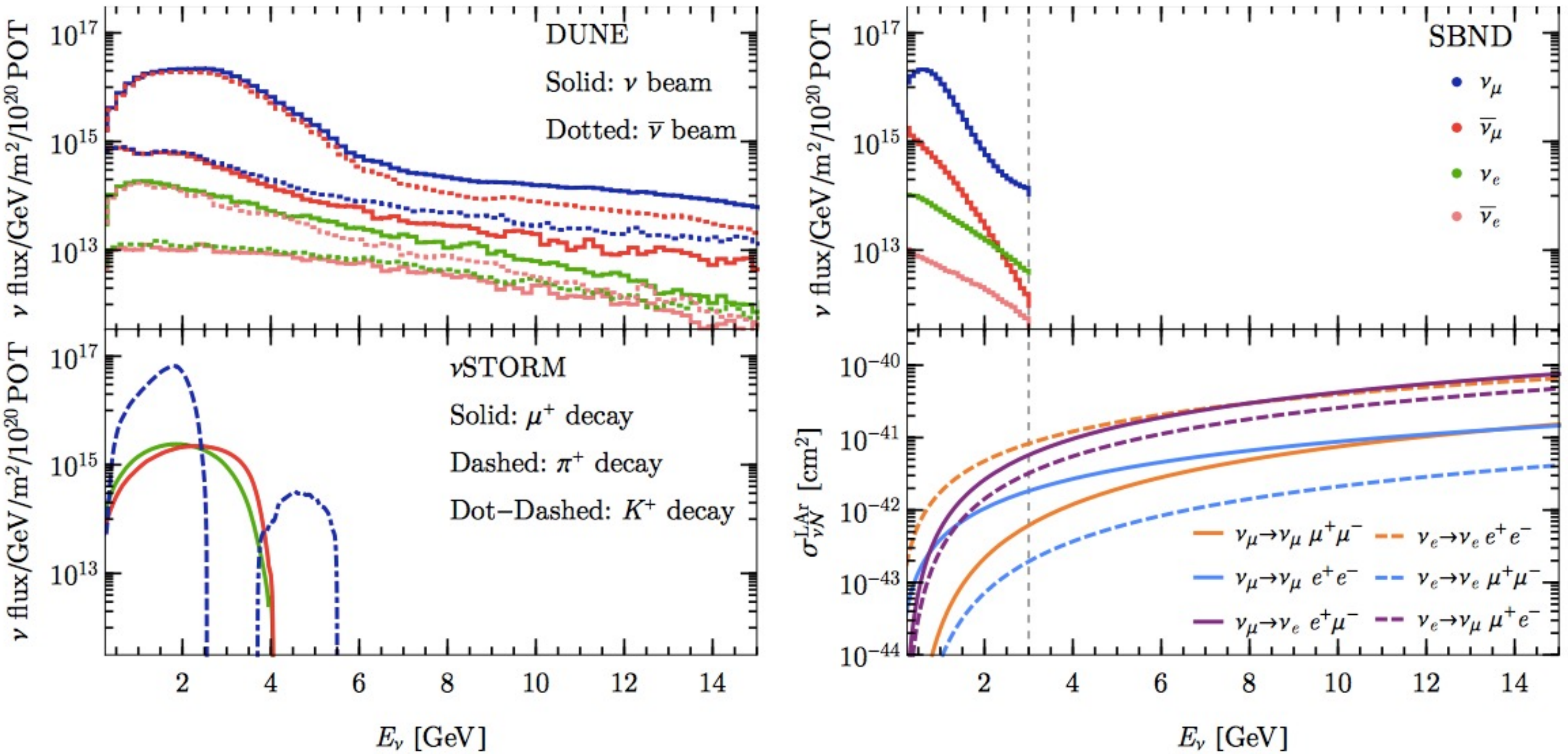
Ballett, Hostert, Pascoli, Perez, **ZT** and Funchal
JHEP **1901**, 119 (2019)

Trident Cross Sections



Trident rates at LAr Detectors

$$N = \text{time} \times \#\text{ of targets} \times \text{efficiency} \times \int_{E_i}^{E_f} dE_\nu \frac{d\phi(E_\nu)}{dE_\nu} \sigma(E_\nu)$$



Ballett, Hostert, Pascoli, Perez, **ZT** and Funchal
JHEP **1901**, 119 (2019)

Trident background analysis

Genuine dilepton production is rare, but misID of particles is the problem.

misID
γ as $e^{\pm}$
γ as e^+e^-
$\pi^{\pm}$ as $\mu^{\pm}$

Channel	$\mathbf{N}_{\mathrm{B}}^{\mathrm{misID}}/\mathbf{N}_{\mathrm{CC}}$	$\mathbf{N}_{\mathrm{B}}^{\mathrm{had}}/\mathbf{N}_{\mathrm{CC}}$	$\mathbf{N}_{\mathrm{B}}^{\mathrm{kin}}/\mathbf{N}_{\mathrm{CC}}$
$e^{\pm}\mu^{\mp}$	$1.67\ (1.62) \times 10^{-4}$	$2.68\ (4.31) \times 10^{-5}$	$4.40\ (3.17) \times 10^{-7}$
e^+e^-	$2.83\ (4.19) \times 10^{-4}$	$1.30\ (2.41) \times 10^{-4}$	$6.54\ (14.1) \times 10^{-6}$
$\mu^+\mu^-$	$2.66\ (2.73) \times 10^{-3}$	$10.4\ (9.75) \times 10^{-4}$	$3.36\ (3.10) \times 10^{-8}$

	N_{tot}^{CC}	$r_{\nu_\mu}^{CC}$	$r_{\overline{\nu}_\mu}^{CC}$	$r_{\nu_e}^{CC}$	$r_{\overline{\nu}_e}^{CC}$
ν-mode	4.25×10^8	0.964	0.028	0.007	0.001
$\overline{\nu}$-mode	1.74×10^8	0.201	0.790	0.004	0.005
	N_{tot}^{NC}	$r_{\nu_\mu}^{NC}$	$r_{\overline{\nu}_\mu}^{NC}$	$r_{\nu_e}^{NC}$	$r_{\overline{\nu}_e}^{NC}$
ν-mode	1.48×10^8	0.956	0.037	0.006	0.001
$\overline{\nu}$-mode	7.58×10^7	0.157	0.835	0.003	0.005

Reaching background rates of $O(10^{-6}$–$10^{-5})$ times the CC rate is necessary to observe trident events at DUNE ND, which is an attainable goal in a LAr detectors.

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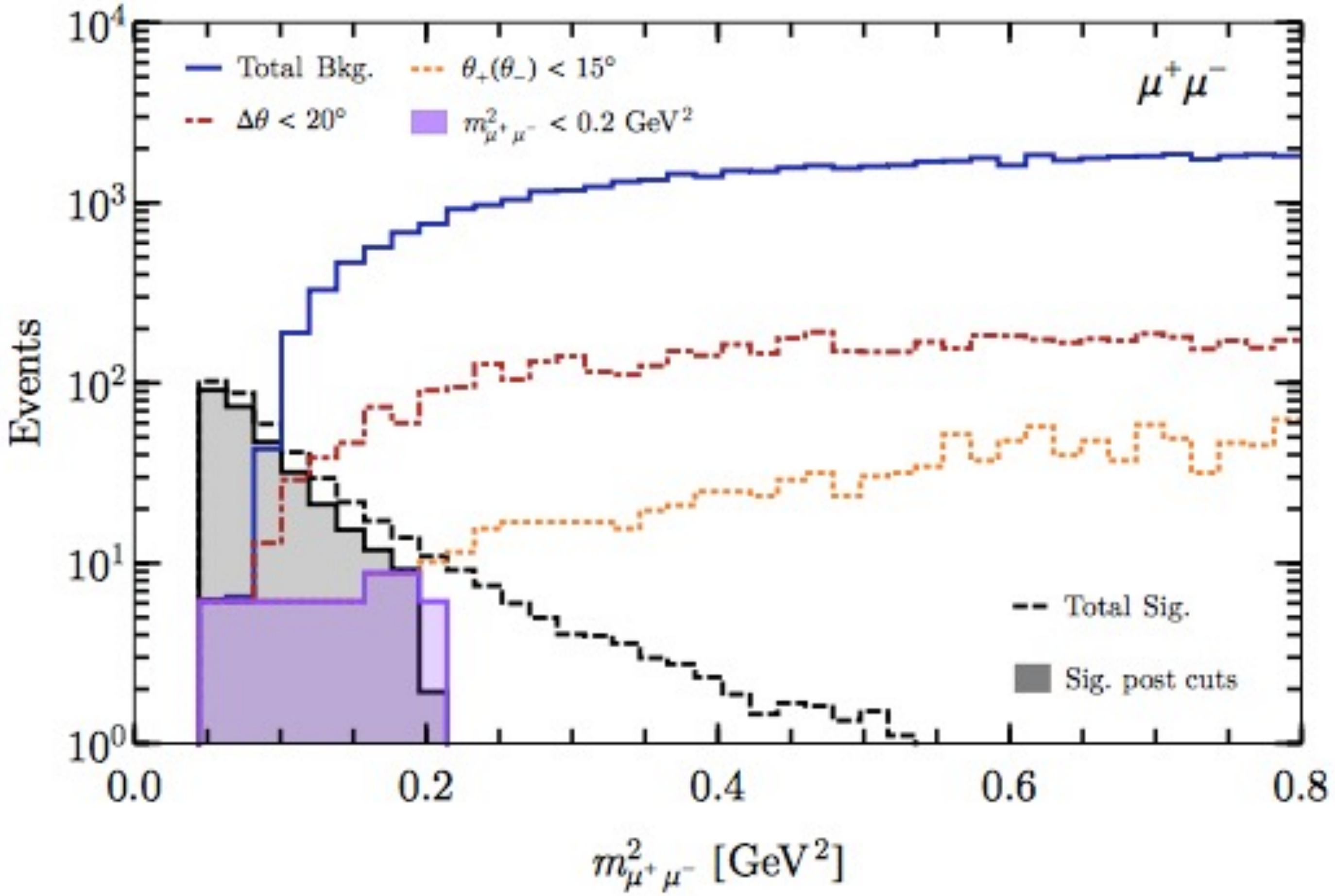
JHEP **1901**, 119 (2019)



We apply consecutive cuts on the background, starting with cuts on the separation angle $\Delta\theta$ (red), both charged lepton angles to the beamline (θ_+ and θ_-) (orange) and the invariant mass.

Ballett, Hostert, Pascoli, Perez, **ZT** and Funchal
JHEP **1901**, 119 (2019)

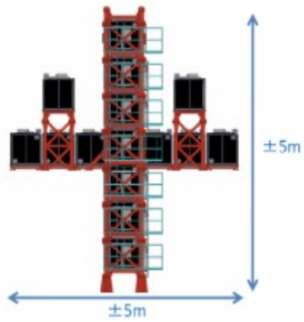
Trident rates at other Near Detectors

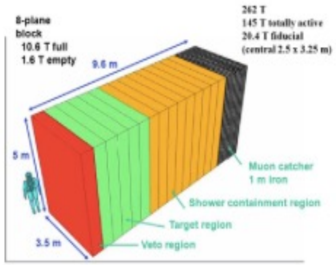
Experiment	Material	Baseline (m)	Exposure (POT)	Fiducial Mass (t)	E_ν (GeV)
INGRID	Fe	280	3.9×10^{21} $[10^{22}]$ T2K-I [T2K-II]	99.4	$0 - 4$
MINOS[+]	Fe and C	1040	$10.56(3.36)[9.69] \times 10^{20}$	28.6	$0 - 20$
NOνA	C_2H_3Cl and CH_2	1000	$8.85(6.9)$ $[36(36)] \times 10^{20}$ [NOνA-II]	231	$0 - 20$
MINERνA	CH, H_2O, Fe, Pb, C	1035	$12(12) \times 10^{20}$	7.98	$0 - 20$

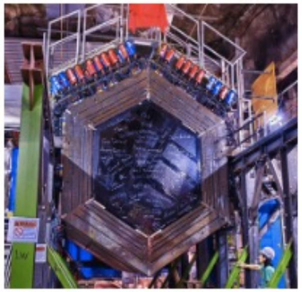
All have finished data taking or are still running

Trident rates at other Near Detectors

INGRID







Channel	T2K-I	T2K-II	MINOS	MINOS+	NOνA-I	NOνA-II	MINERνA
Total $e^{\pm}\mu^{\mp}$	563	1444	222 (56)	730	83 (72)	340 (374)	149 (102)
	96	246	46 (11)	151	25 (22)	102 (114)	56 (39)
Total e^+e^-	277	711	61 (15)	62	29 (22)	119 (114)	39 (27)
	24	62	9 (2)	8	4 (4)	16 (21)	10 (7)
Total $\mu^+\mu^-$	30	76	26 (6)	86	9 (9)	37 (47)	18 (13)
	21	54	15 (3)	49	8 (8)	34 (36)	18 (13)

Coherent (upper) and diffractive (lower) trident events for (anti)neutrino mode.

Ballett, Hostert, Pascoli, Perez, **ZT** and Funchal
JHEP **1901**, 119 (2019)

- We study potential constraints which can be placed on a general set of leptophilic Z′ models in the two most likely channels for BSM scattering at the near detector of DUNE: neutrino-electron scattering and neutrino trident scattering.

$$\mathcal{L} \supset -g' Z'_\mu \left[Q^{\mathrm{L}}_\alpha \, \overline{L^\alpha_L} \gamma^\mu L^\alpha_L + Q^{\mathrm{R}}_\alpha \, \overline{\ell^\alpha_R} \gamma^\mu \ell^\alpha_R + \sum_{\mathrm{N}} Q_{\mathrm{N}} \, \overline{N_R} \gamma^\mu N_R \right]$$

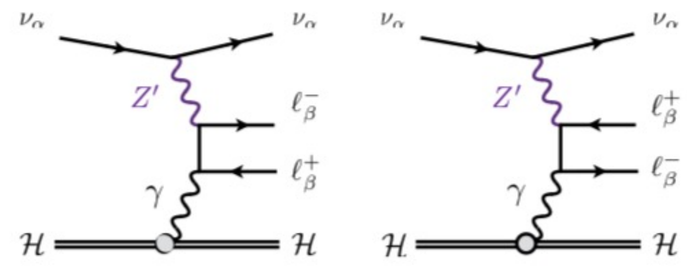
- We focus on the anomaly free leptophilic extensions of the SM:
  $L_\alpha - L_\beta$, $\alpha,\beta = \{e,\mu,\tau\}$, $\alpha \neq \beta$.

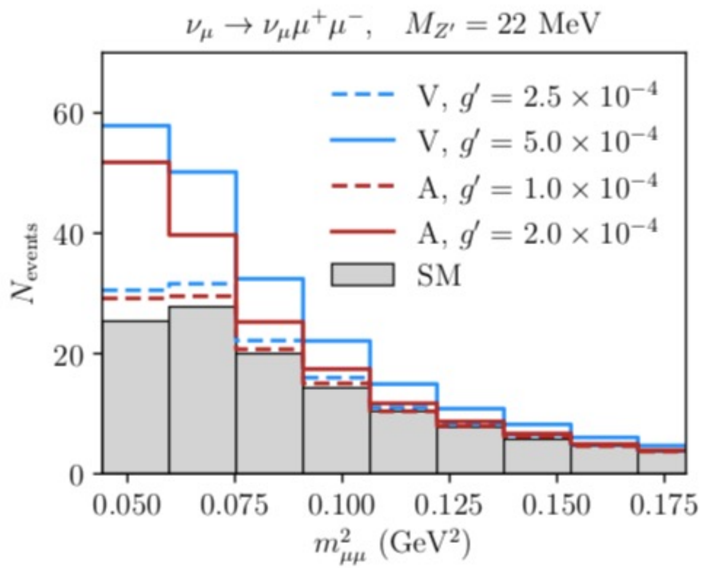
- Anomaly free conditions fix the charges

Ballett, Hostert, Pascoli, Perez-Gonzalez, **ZT** and Funchal
Phys.Rev. **D100** (2019) no.5, 055012

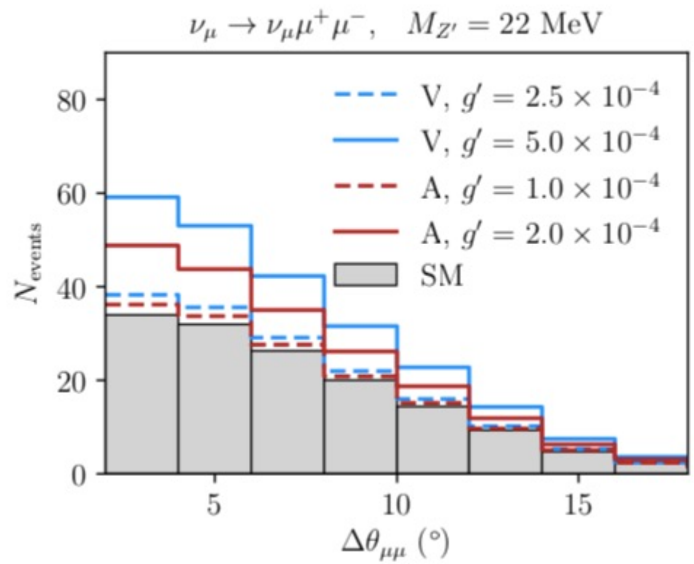
Trident kinematical distributions

$$\hat{V}_{\alpha\beta} = g_V^{\ell_\beta} + \delta_{\alpha\beta} + \frac{Q_\alpha^L Q_\beta^V}{2\sqrt{2}G_F}\frac{(g')^2}{K^2 + M_{Z'}^2}, \quad \hat{A}_{\alpha\beta} = g_A^{\ell_\beta} + \delta_{\alpha\beta} + \frac{Q_\alpha^L Q_\beta^A}{2\sqrt{2}G_F}\frac{(g')^2}{K^2 + M_{Z'}^2}$$





The invariant mass



Charged lepton separation angle

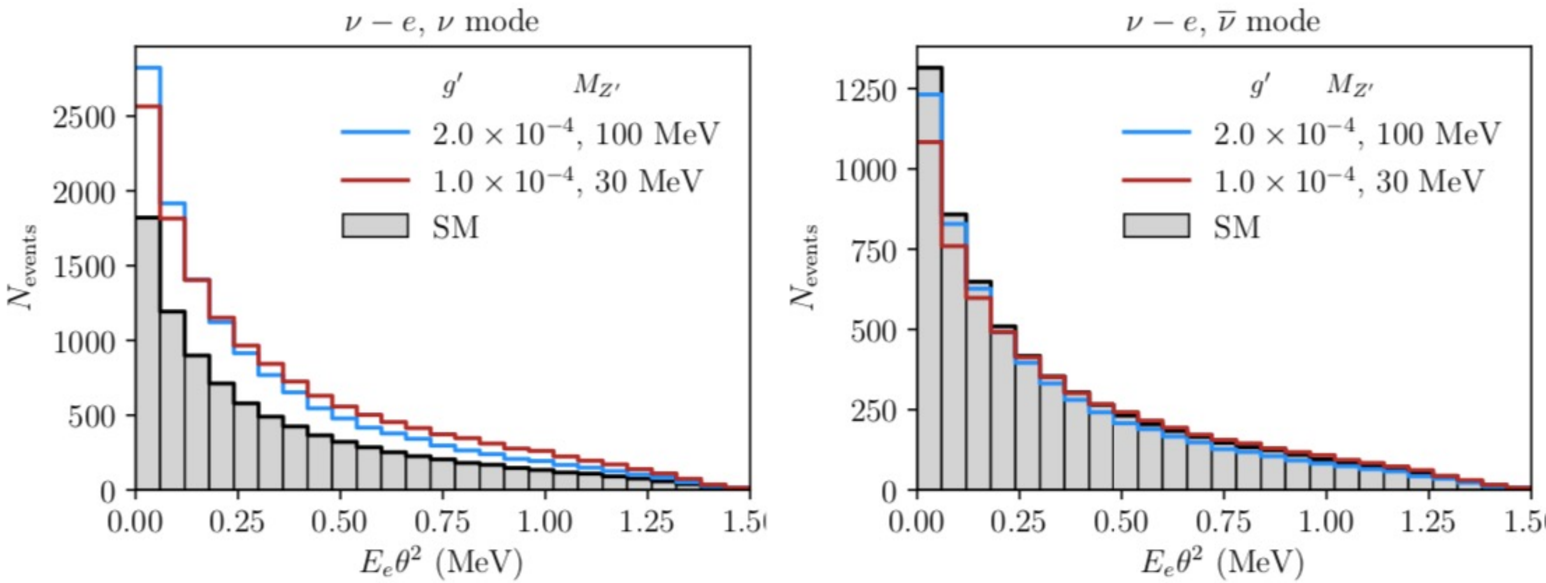
Ballett, Hostert, Pascoli, Perez-Gonzalez, **ZT** and Funchal
Phys.Rev. **D100** (2019) no.5, 055012

Neutrino-Electron scattering

The vector and axial couplings with Z':

$$C_\alpha^{\mathrm{V}} = -\frac{1}{2} + 2s_{\mathrm{W}}^2 + \delta_{\alpha e} + \frac{Q_e^{\mathrm{V}} Q_\alpha^{\mathrm{L}}}{2\sqrt{2}G_F} \frac{(g')^2}{M_{Z'}^2 + 2m_e T_e},$$

$$C_\alpha^{\mathrm{A}} = -\frac{1}{2} + \delta_{\alpha e} + \frac{Q_e^{\mathrm{A}} Q_\alpha^{\mathrm{L}}}{2\sqrt{2}G_F} \frac{(g')^2}{M_{Z'}^2 + 2m_e T_e},$$



Ballett, Hostert, Pascoli, Perez-Gonzalez, **ZT** and Funchal
Phys.Rev. **D100** (2019) no.5, 055012

Neutrino-Electron scattering

The vector and axial couplings with Z':

$$C_\alpha^{\mathrm{V}} = -\frac{1}{2} + 2s_{\mathrm{W}}^2 + \delta_{\alpha e} + \frac{Q_e^{\mathrm{V}} Q_\alpha^{\mathrm{L}}}{2\sqrt{2}G_F} \frac{(g')^2}{M_{Z'}^2 + 2m_e T_e},$$

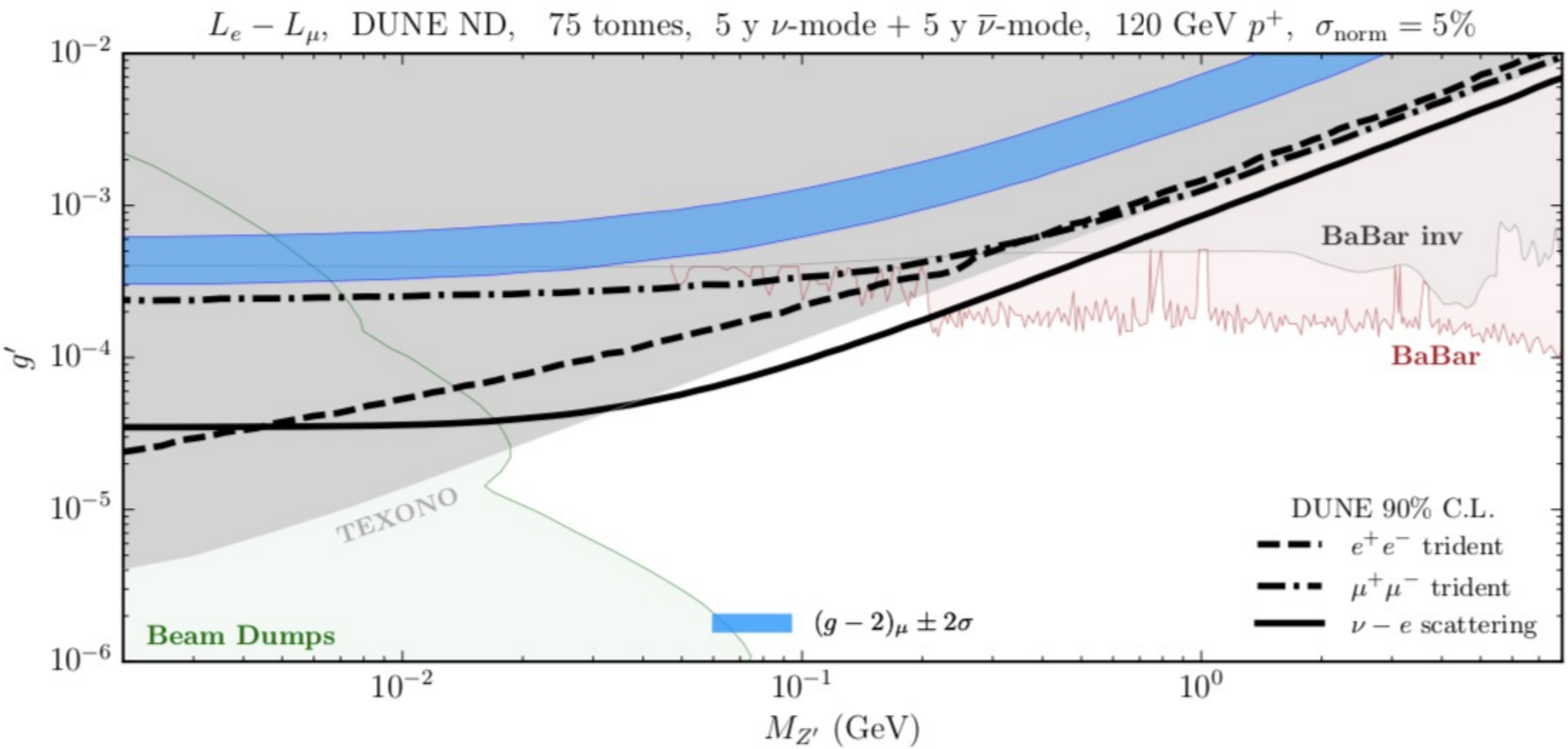
$$C_\alpha^{\mathrm{A}} = -\frac{1}{2} + \delta_{\alpha e} + \frac{Q_e^{\mathrm{A}} Q_\alpha^{\mathrm{L}}}{2\sqrt{2}G_F} \frac{(g')^2}{M_{Z'}^2 + 2m_e T_e},$$

If we allow for kinetic mixing between the Z' and the SM gauge bosons, this kinetic mixing in the $L_\mu - L_\tau$ model also induces a $\nu - e$ coupling:

$$C_\alpha^{\mathrm{V}} = -\frac{1}{2} + 2s_{\mathrm{W}}^2 + \delta_{\alpha e} + \frac{1}{\sqrt{2}G_F} \frac{g'\, e\, \varepsilon(q^2)}{M_{Z'}^2 + 2m_e T_e}$$

L_e-L_μ Model at DUNE:

Ballett, Hostert, Pascoli, Perez-Gonzalez, **ZT** and Funchal
Phys.Rev. **D100** (2019) no.5, 055012



- The main constraint is from neutrino-electron scattering.
- The sensitive trident channels are:

  $\mu^+\mu^-$ and e^+e^-