Beyond the Standard Model in the Neutrino Sector

Snowmass Neutrino Colloquium

20 April, 2022

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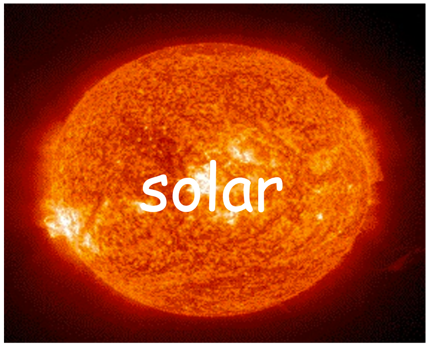
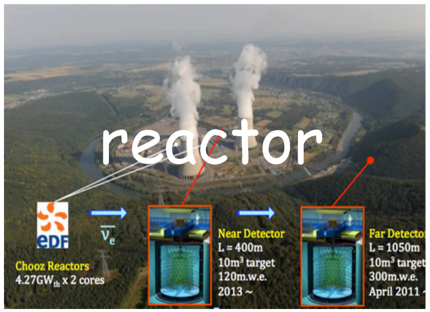
Northwestern University

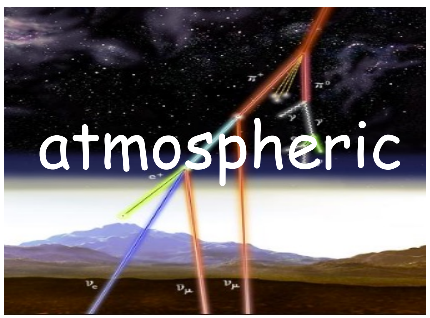
Status of Neutrino Physics in 2022



Super-Kamiokande, Borexino, SNO



MBL: Daya Bay, RENO, Double Chooz
LBL: KamLAND



IceCube, Super-Kamiokande

T2K, MINOS, NOvA

mixing angles:

$sin^2\theta_{12}$ @ 4%

$sin^2\theta_{13}$ @ 3%

$sin^2\theta_{23}$ @ 3%

mass squared differences:

Δm^2_{21} @ 3%

$|\Delta m^2_{31}|$ @ 1%

Future: DUNE, T2HK , JUNO

- Increase the precision
- CP-phase
- Mass hierarchy

Also:
Mass scale? Dirac or Majorana?
Sterile?

Questions:

- **How can we systematically use different neutrino experiments for BSM searches?**

- **How can we connect results to other particle physics experiments?**

- **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 of Joachim Kopp and Georgia Karagiorgi for a more complete picture;

Physics goals of near detectors:

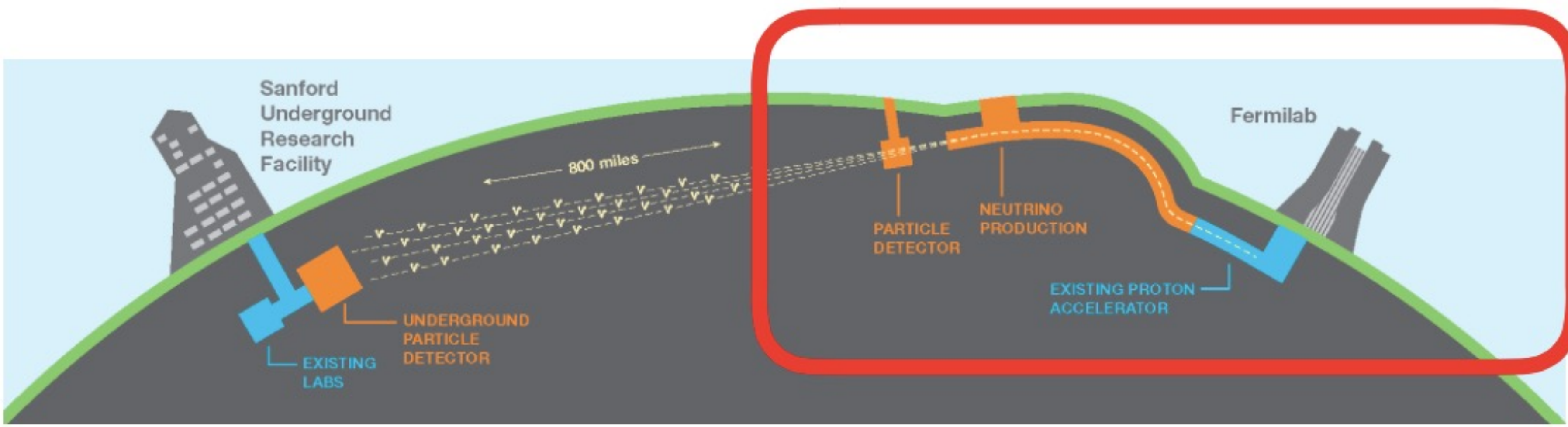
Primary role: Understanding Systematic Uncertainties

High beam luminosity +
Large fiducial mass

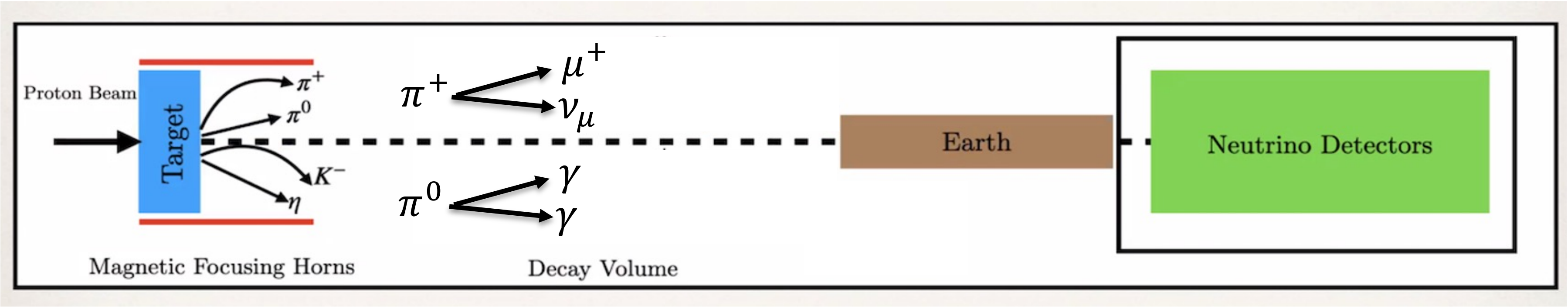
Ideal to investigate
rare/new neutrino
interactions

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

- Test SM predictions
- Search for BSM physics

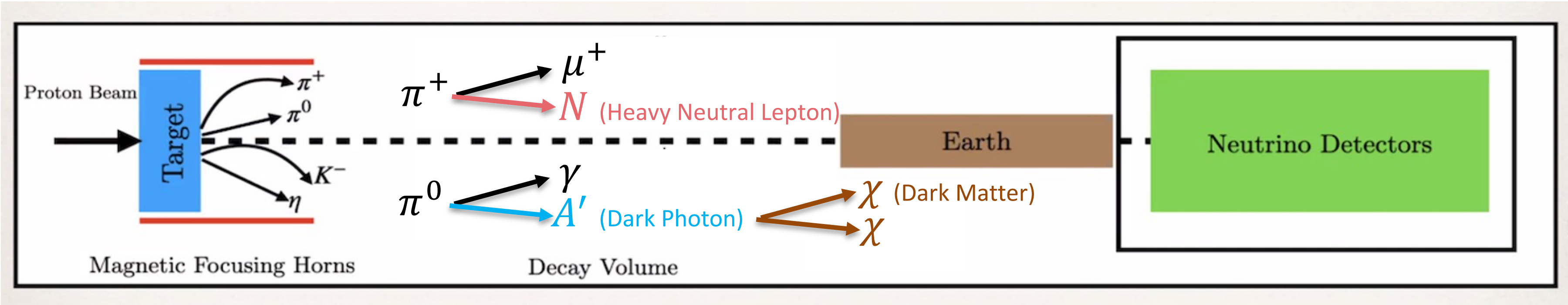


Neutrino Experiments as Dark Sector factories!



Credit: Kevin Kelly

The huge fluxes of neutrinos and photos 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)

Outline

- Dark Sector at the Near Detectors:
  - ALPs
  - Light Dark Matter
  - Light Z'
- Model independent approach:
  - Why EFT?
  - EFT ladder
  - EFT at Neutrino Experiments
- Conclusion

Dear google: not all ALPs are Mountains!

ALPs

All · Maps · Images · News · Videos · More · Tools

About 1,950,000,000 results (0.78 seconds)

https://en.wikipedia.org › wiki › Alps

Alps - Wikipedia

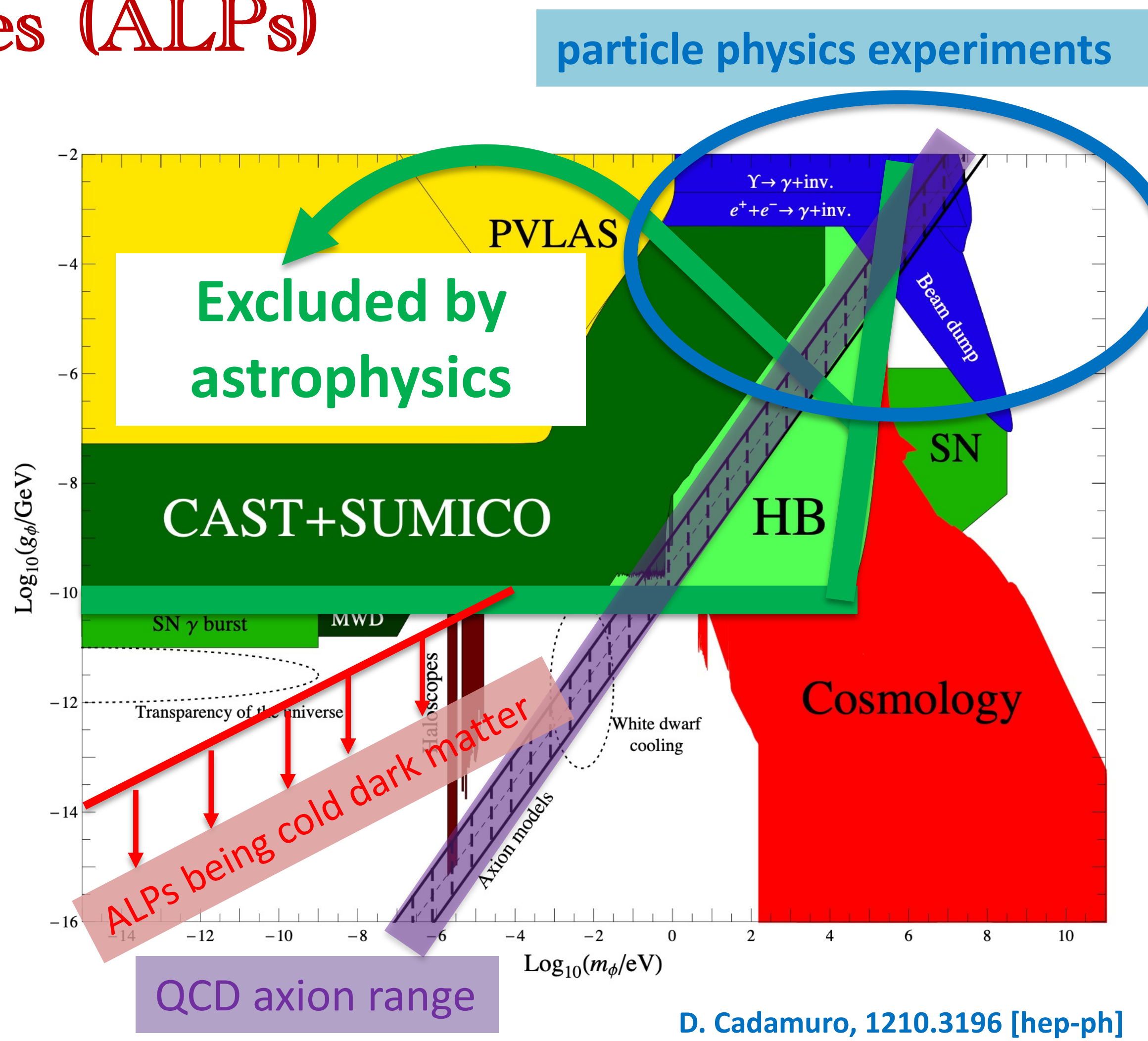
The **Alps** are the highest and most extensive mountain range system that lies entirely in Europe, stretching approximately 750 mi (1,210 km) across eight ...

Age of rock: Tertiary
Peak: Mont Blanc
Width: 250 km (160 mi)
Area: 200,000 km2 (77,000 sq mi)

Geography of the Alps · Alps (disambiguation) · Alpine mountains above 3000 m

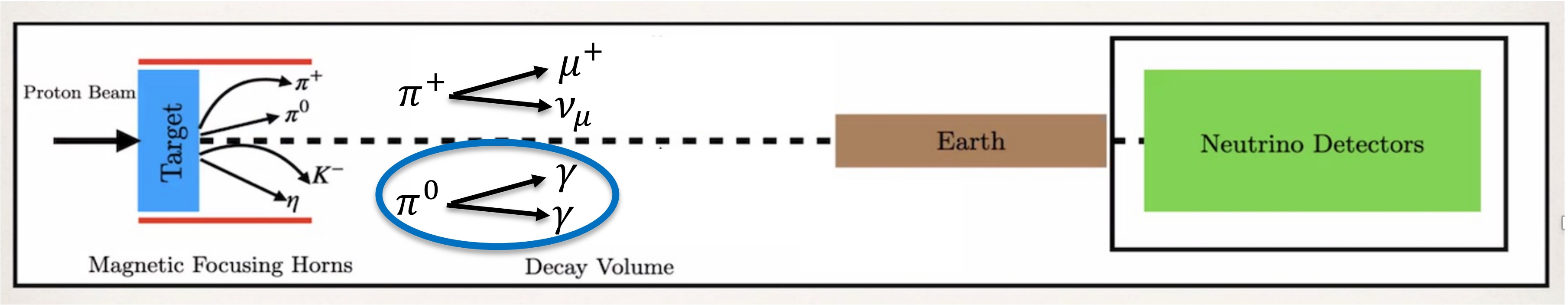
Axion-Like Particles (ALPs)

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



D. Cadamuro, 1210.3196 [hep-ph]

ALPs at Neutrino Experiments



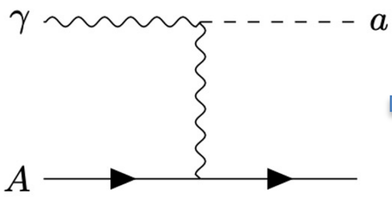
Credit: Kevin Kelly

Using photons to produce ALPs:

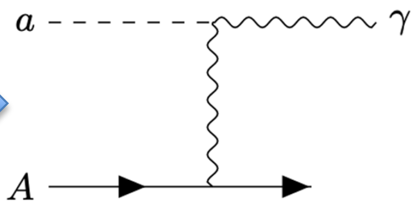
$$\mathcal{L}_{a\gamma\gamma} \supset -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

ALP production

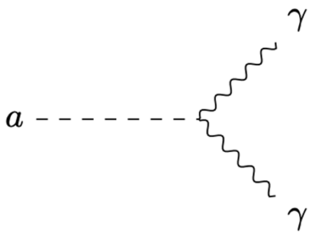
ALP detection



Primakoff scattering

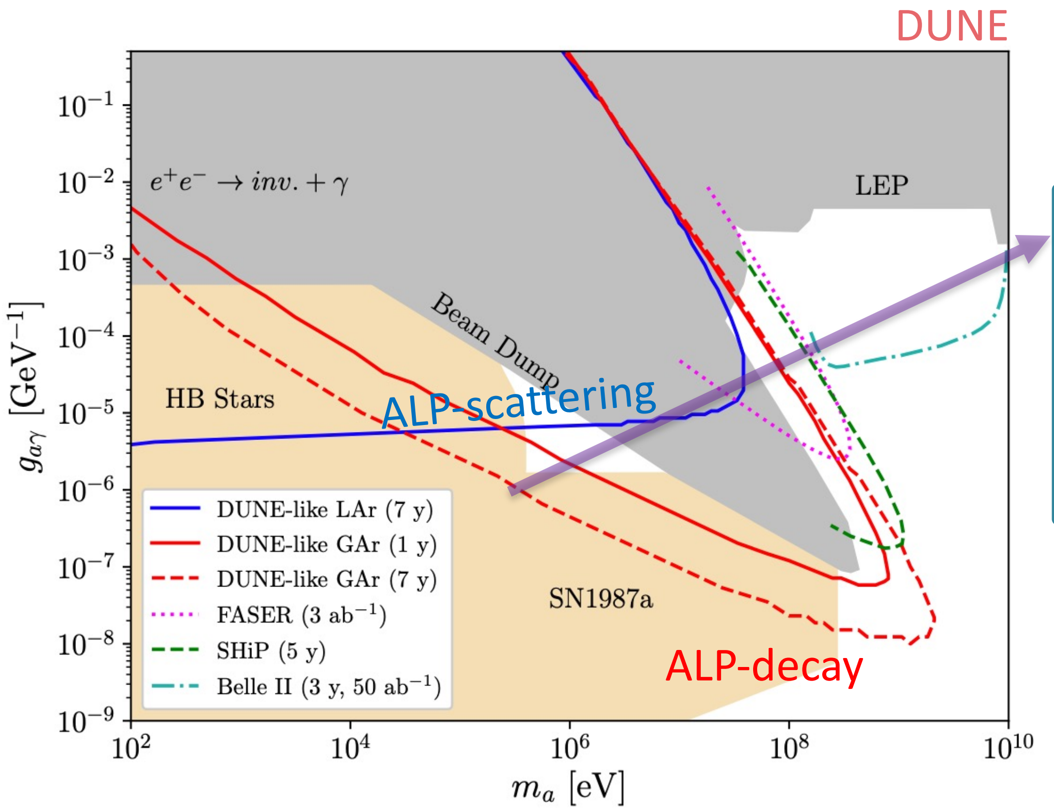


Inverse Primakoff scattering



ALP decay

ALPs at Neutrino Experiments

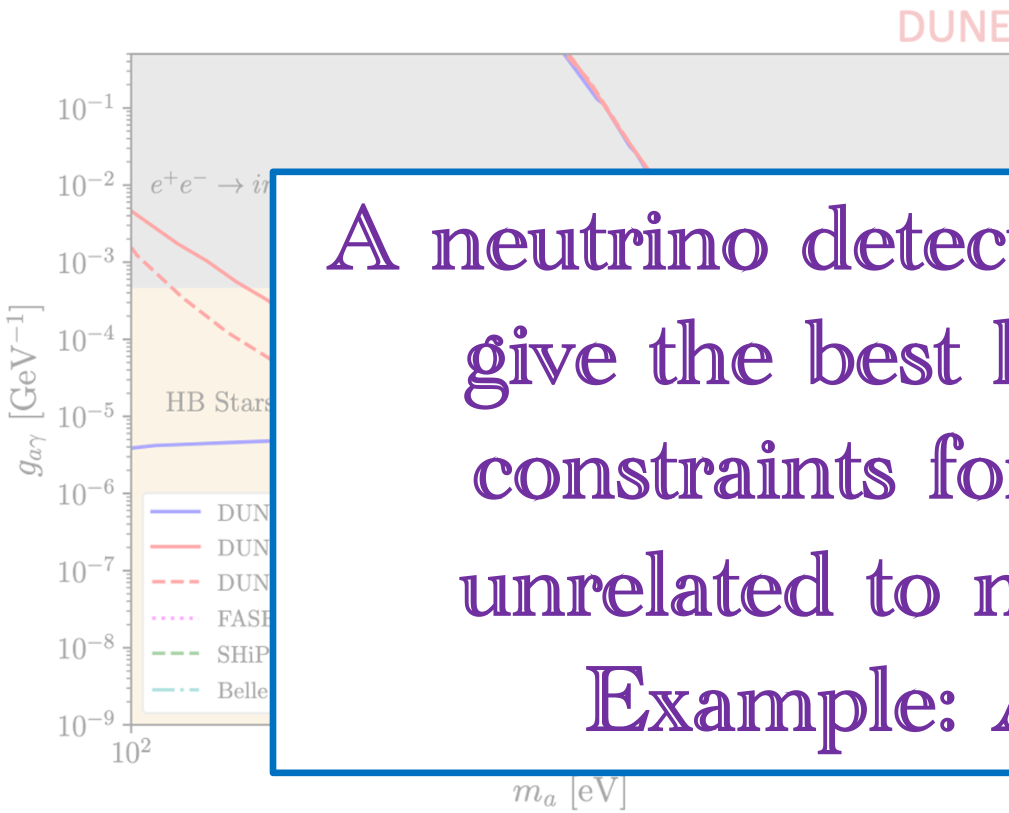


Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu
PRL (2021)

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

See Joachim Kopp's talk about Gas detectors

ALPs at Neutrino Experiments



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

constraints!

key, due to
kground!

Gas detectors

A neutrino detector can even give the best lab-based constraints for models unrelated to neutrinos. Example: ALPs!

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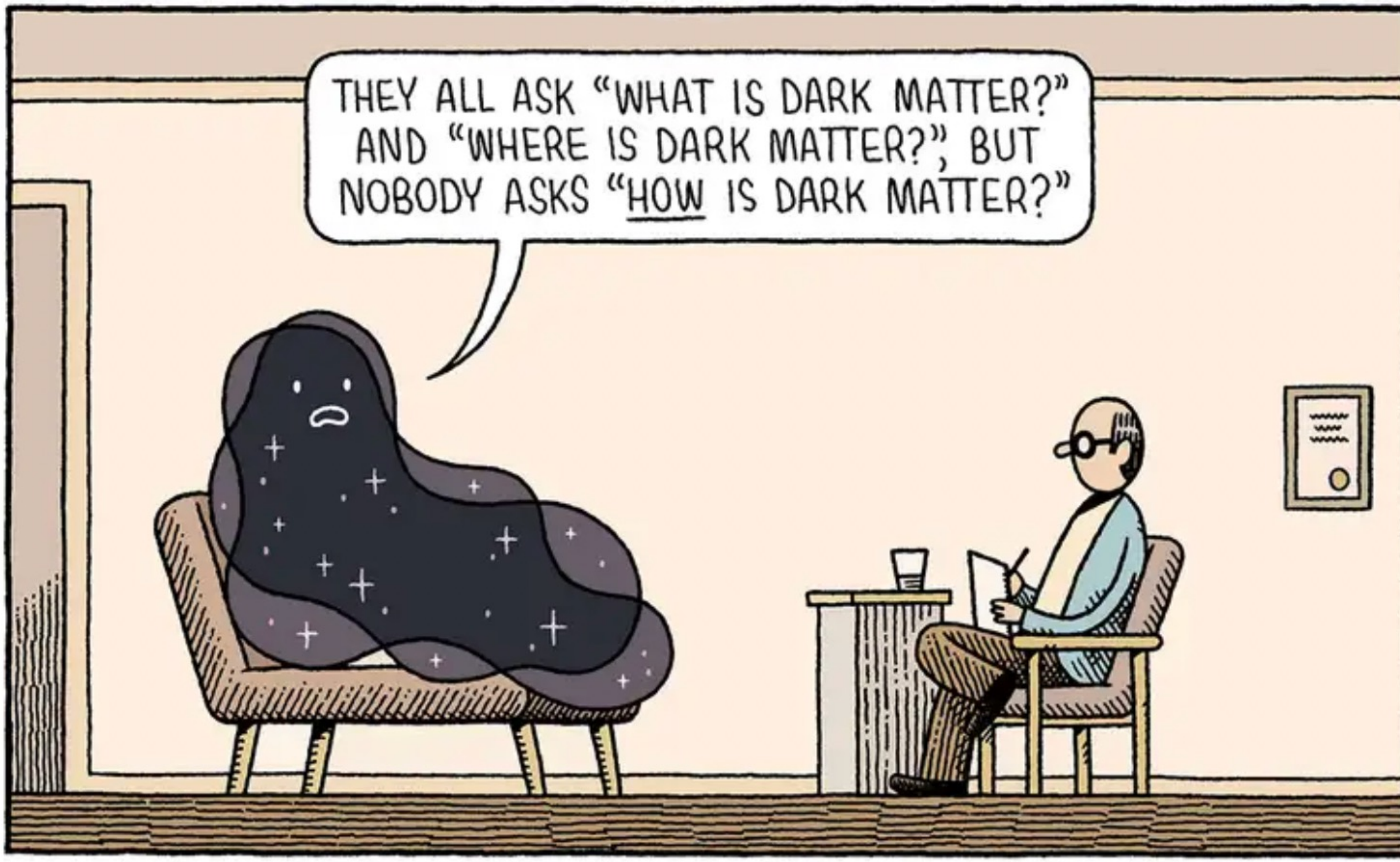
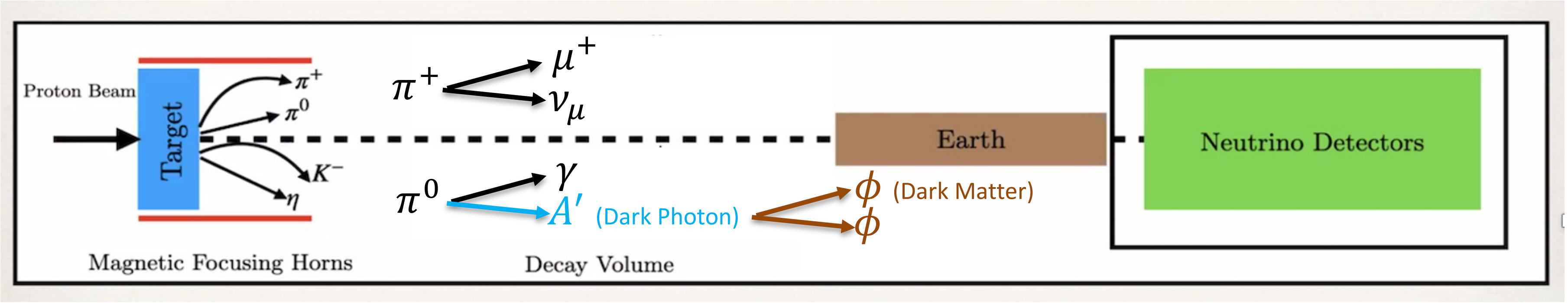
“How is Dark Matter?”



TOM GAULD for NEW SCIENTIST

Light Dark Matter

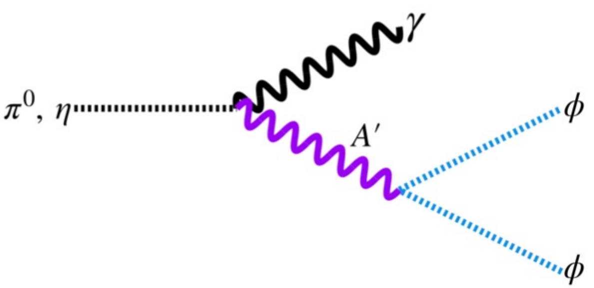


Photons at the target kinetically produce Dark Photons, which decay into dark matter:

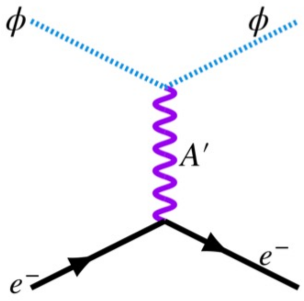
$$\mathcal{L} \supset -\frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \frac{M_{A'}^2}{2} A'_\mu A'^\mu + |D_\mu \phi|^2 - M_\phi^2 |\phi|^2$$

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

DM production



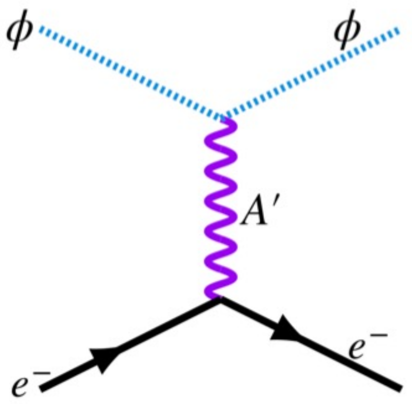
DM detection



De Romeri, Kelly, Machado, PRD (2019)

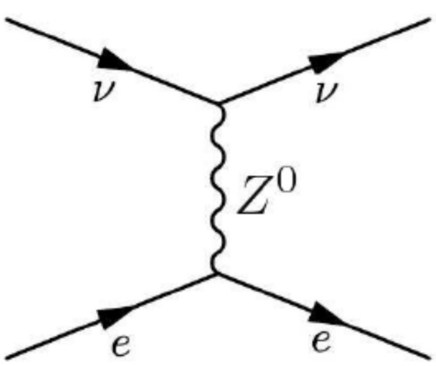
Light Dark Matter

DM signal: elastic scattering on electrons



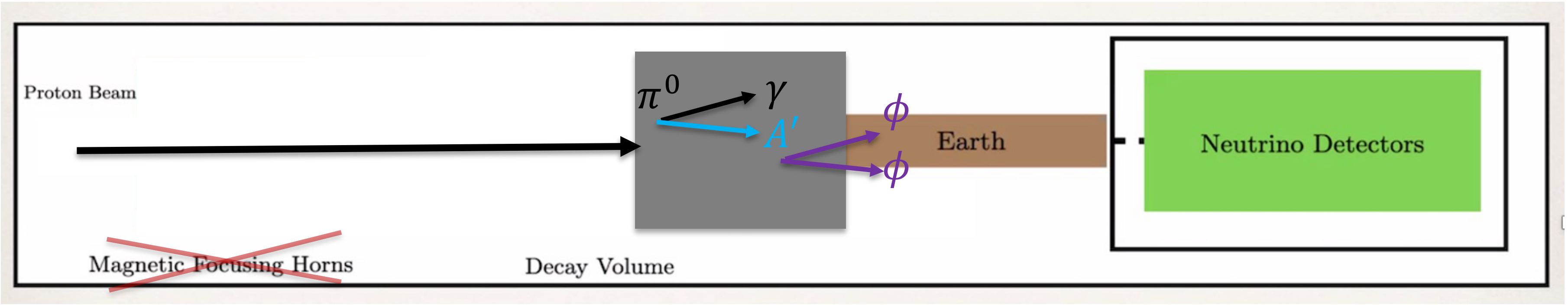
How can we get rid of neutrinos in a neutrino detector?

But so do neutrinos!



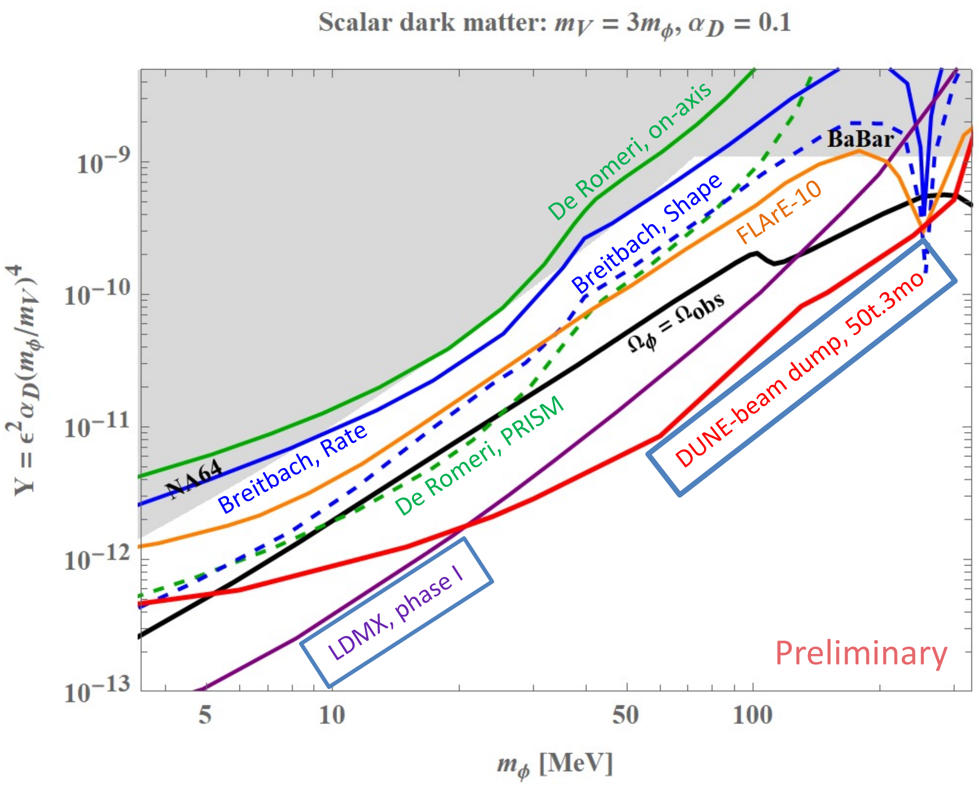
Light Dark Matter---DUNE Beam Dump

- Similar to MiniBooNE beam dump DM search



- Reduce ν production by steering beam to miss the target (horn powered off)
- Charged mesons absorbed in the Al beam dump before decay → reduces the ν flux

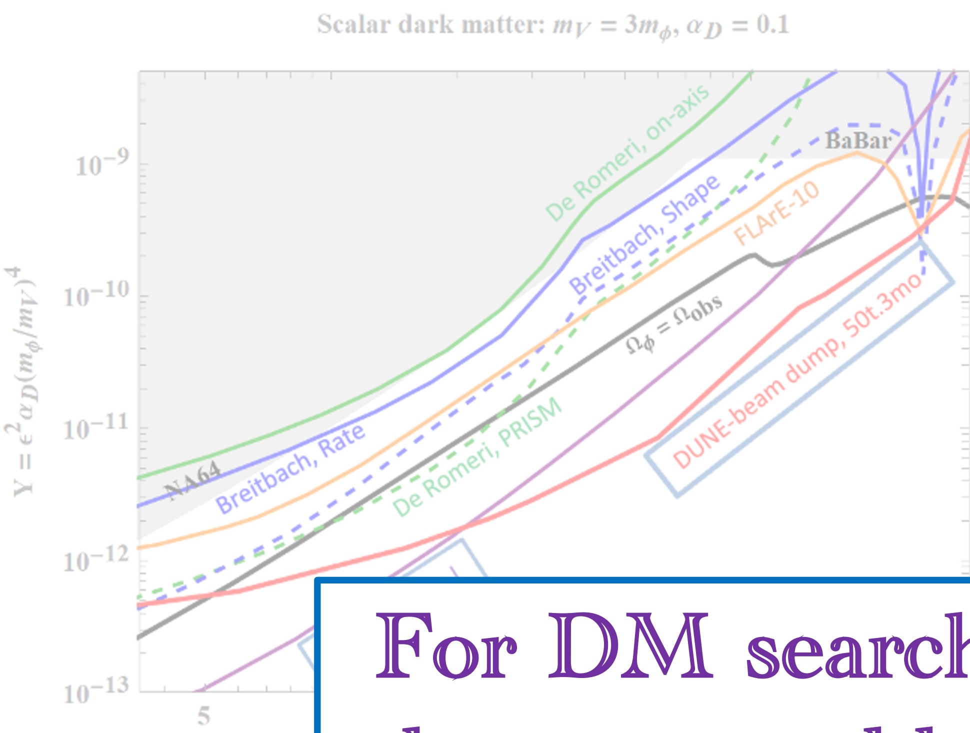
Light Dark Matter---DUNE Beam Dump



DUNE-beam dump can do even better than LDMX in just 3 months!

Bhattarai, Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu (In preparation)

Light Dark Matter---DUNE Beam Dump



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Brdar, Dutta, Ja
(In preparation

For DM searches, a neutrino detector could even do better than a dedicated DM experiment!

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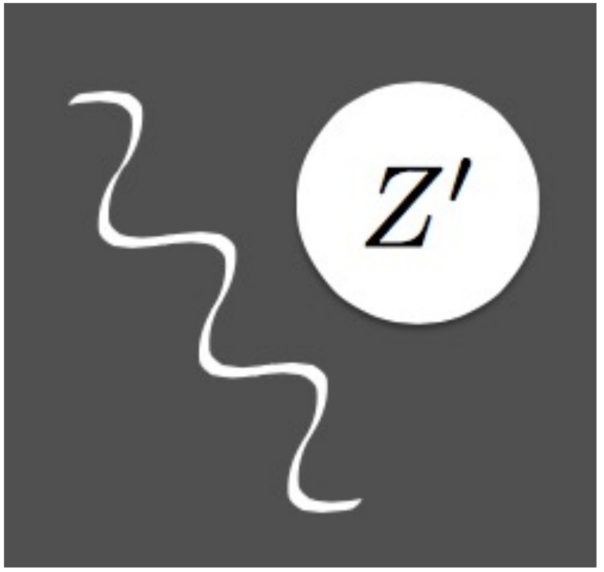

Light Z'

- **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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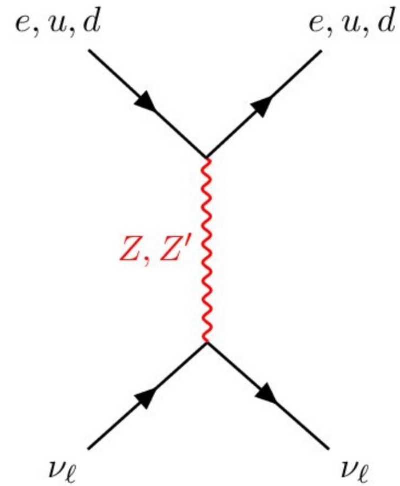
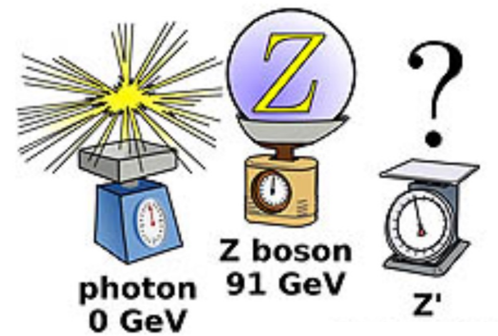
- **Colliders**
  - BaBar Collaboration, PRL (2014)
  - BaBar Collaboration, PRL (2017)
- **Cosmology**
  - Escudero et al, JHEP (2019)

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

The list is far from being exhaustive!

Light Z'

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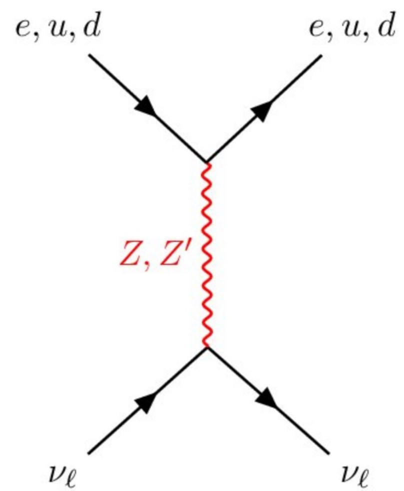

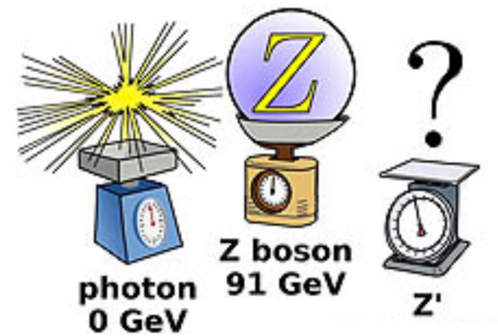

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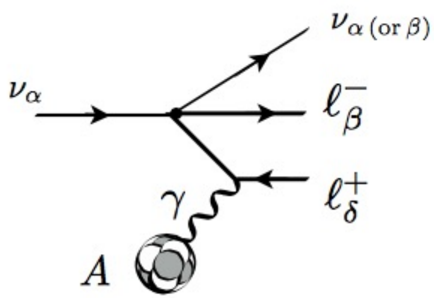
Neutrino Trident Scattering

Production of a **charged lepton pair**
in the scattering of a **neutrino**
in the Coulomb field of a **heavy nucleus/nucleon**

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



CHARM II
PLB (1990)

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

CCFR
PRL (1991)

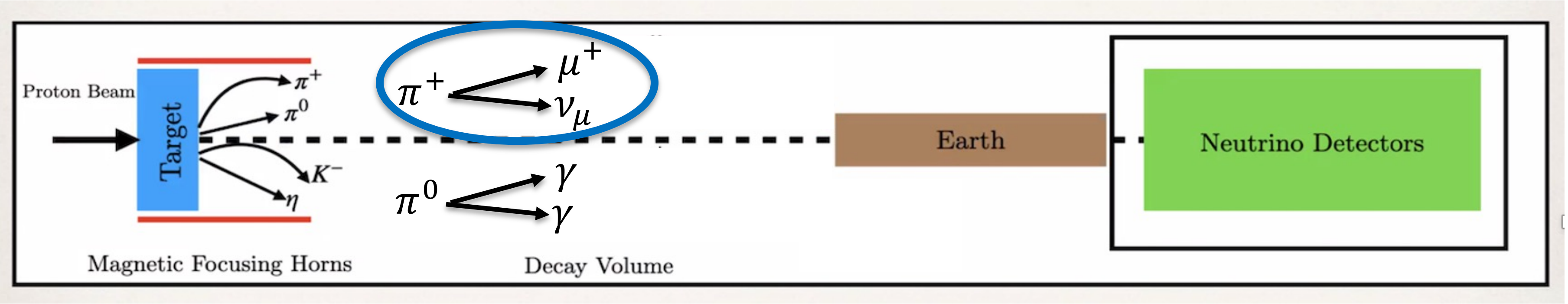
$$\frac{\sigma_{\text{CCFR}}}{\sigma_{\text{SM}}} = 0.82 \pm 0.28$$

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)

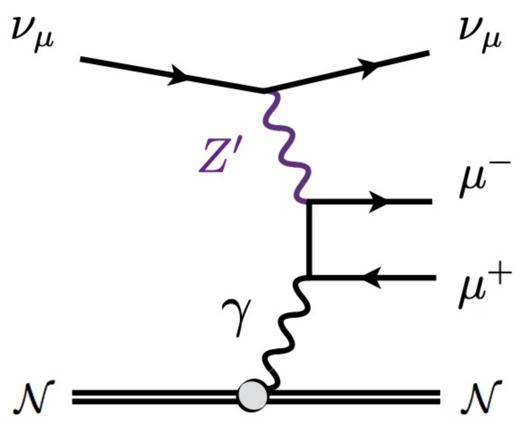
Coherent (upper) and diffractive (lower) trident events for (anti)neutrino mode

More than 9,000 trident events at DUNE!

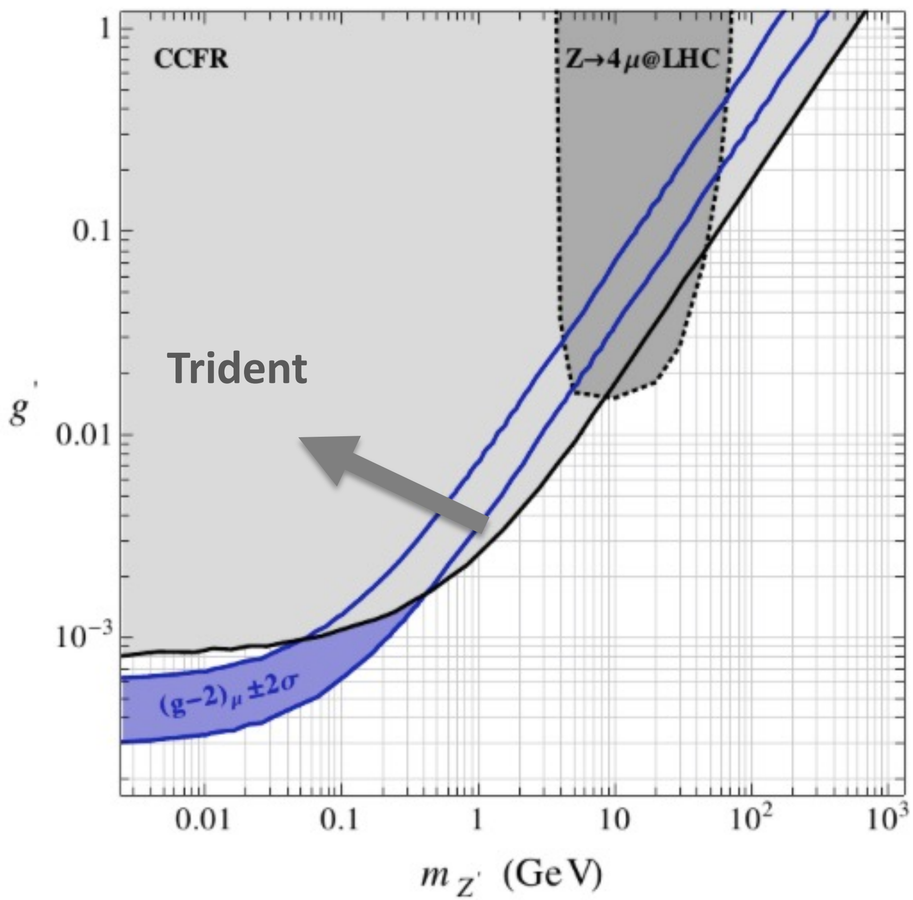
Ballett, Hostert, Pascoli, Perez-Gonzalez, *ZT* and Funchal, PRD (2019)

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!

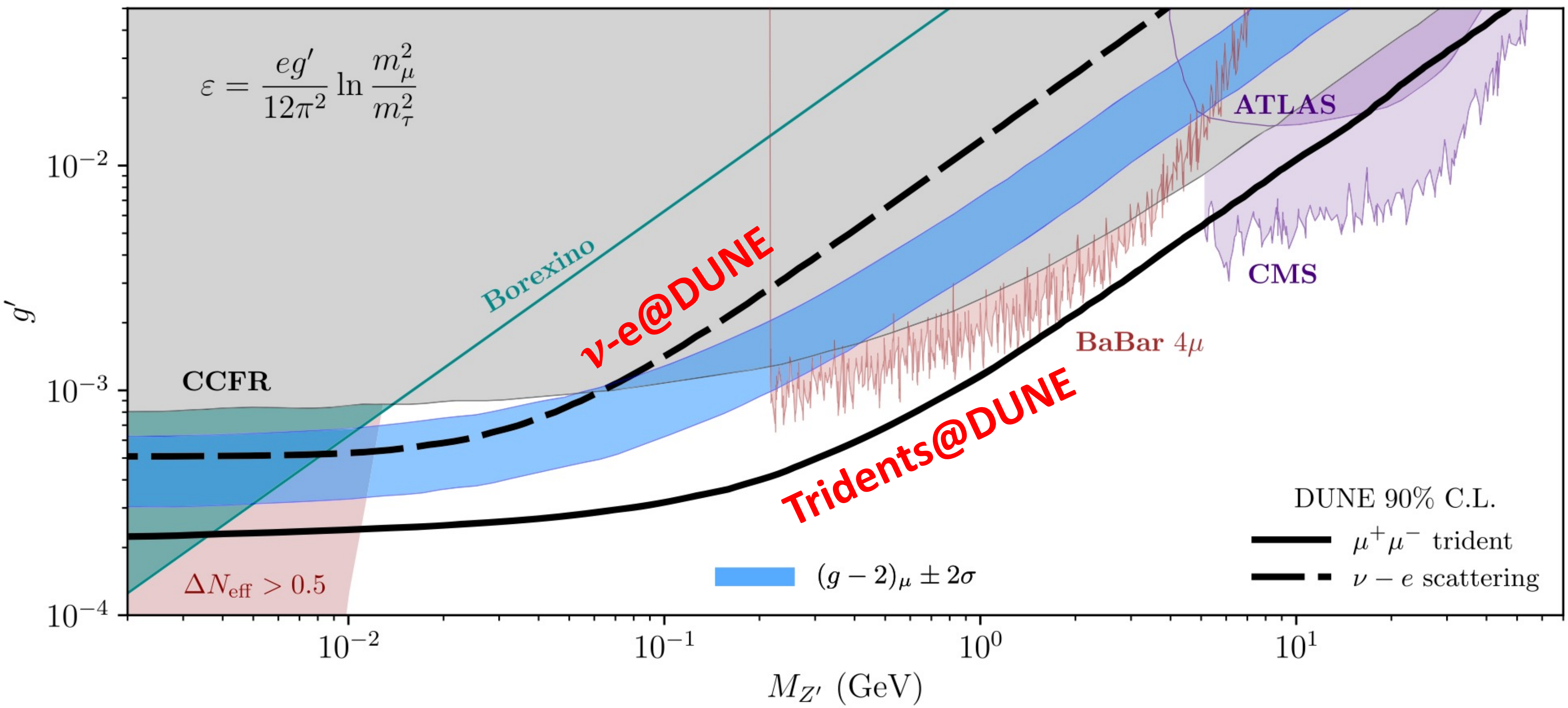


Altmannshofer, Gori, Pospelov, Yavin, PRL (2014)

Light Z': L_μ-L_τ Model

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

DUNE



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

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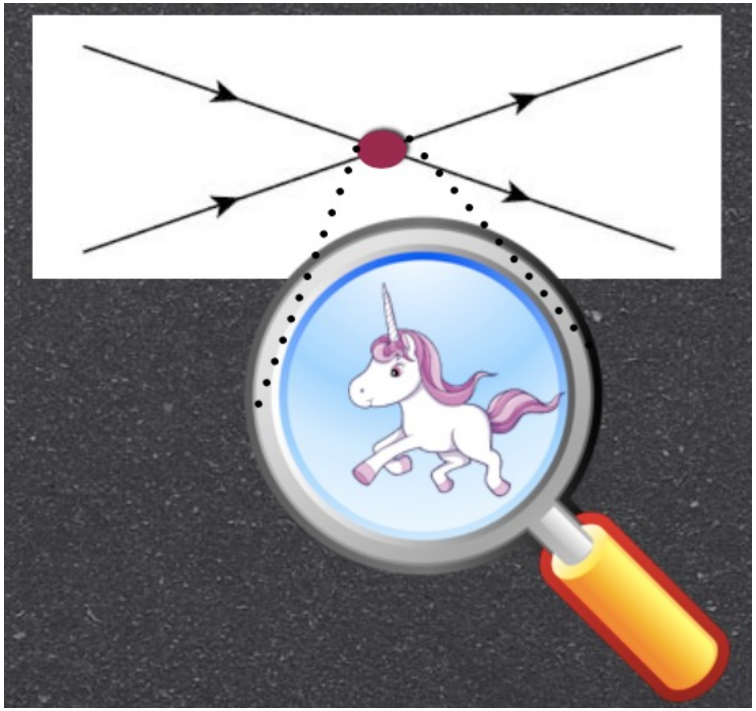
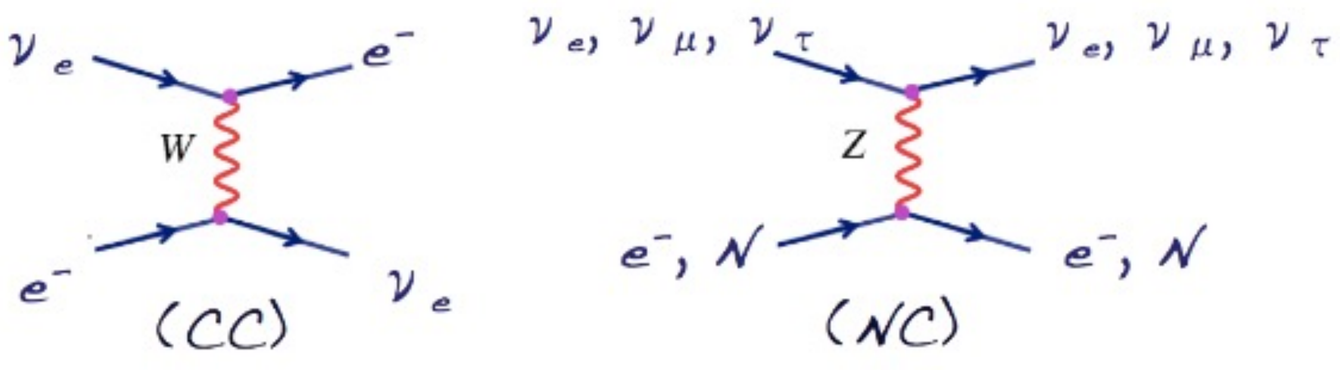
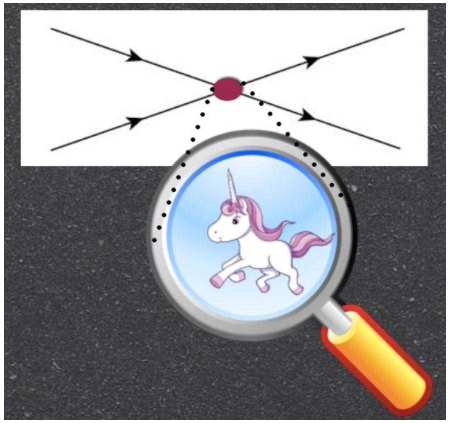


- Coherent CC and NC forward scattering of neutrinos

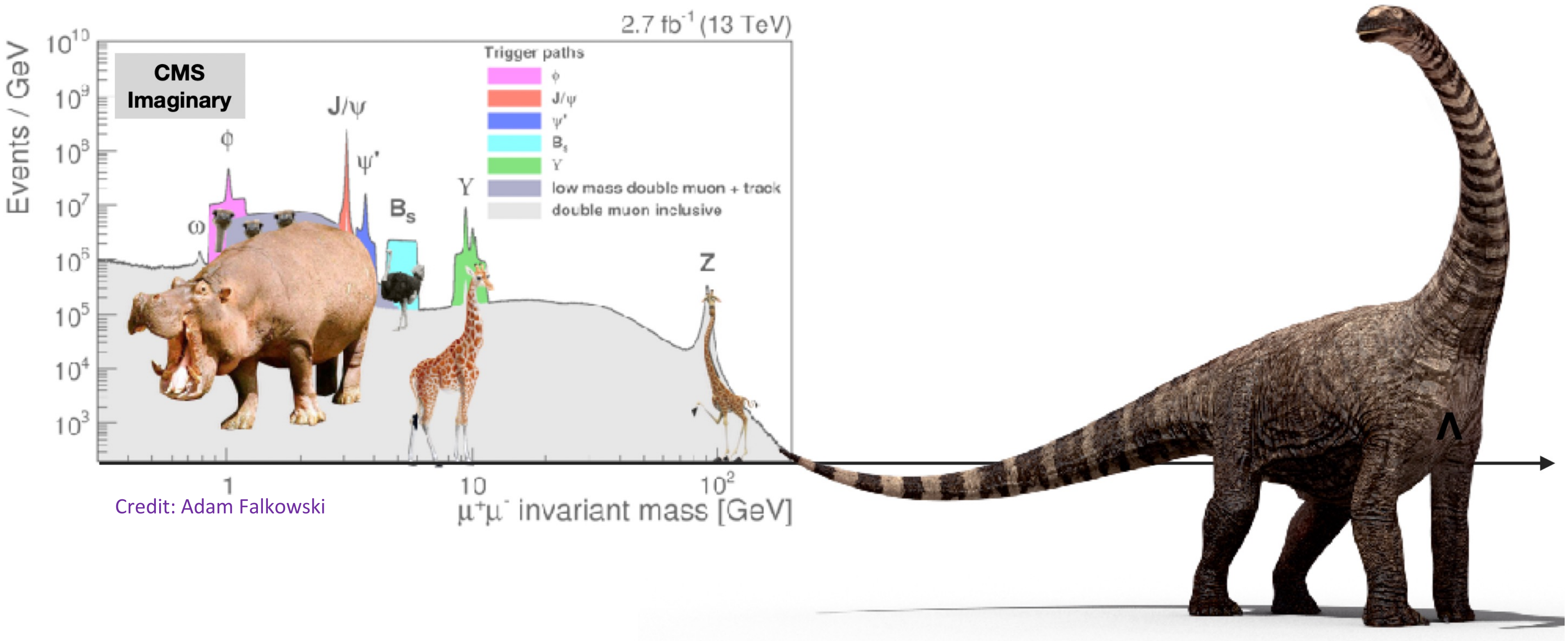


- New 4-fermion interactions



- Observable effects at neutrino production/propagation/detection?
- Using "EFT" formalism to "systematically" explore NP beyond the neutrino masses and mixing

Fantastic Beasts and Where To Find Them

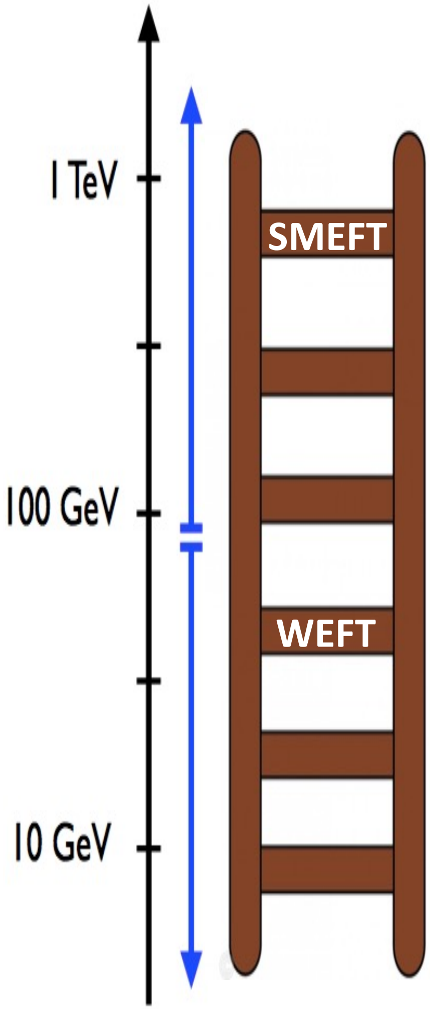


Credit: Adam Falkowski

- **It is likely the new degrees of freedom beyond the SM may not be directly available at LHC or even future colliders.**

- **However, even if it's not possible to see the head, perhaps we can see the tail?**

EFT ladder



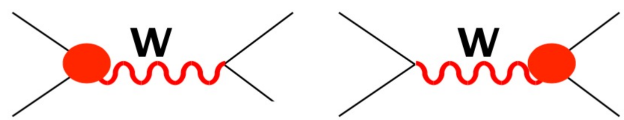
SMEFT: minimal EFT above the weak scale

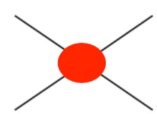
$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \mathscr{L}_{D=5} + \boxed{\mathscr{L}_{D=6}}$$

Known SM Lagrangian → $\mathscr{L}_{\text{SM}}$

Gives neutrino Masses → $\mathscr{L}_{D=5}$

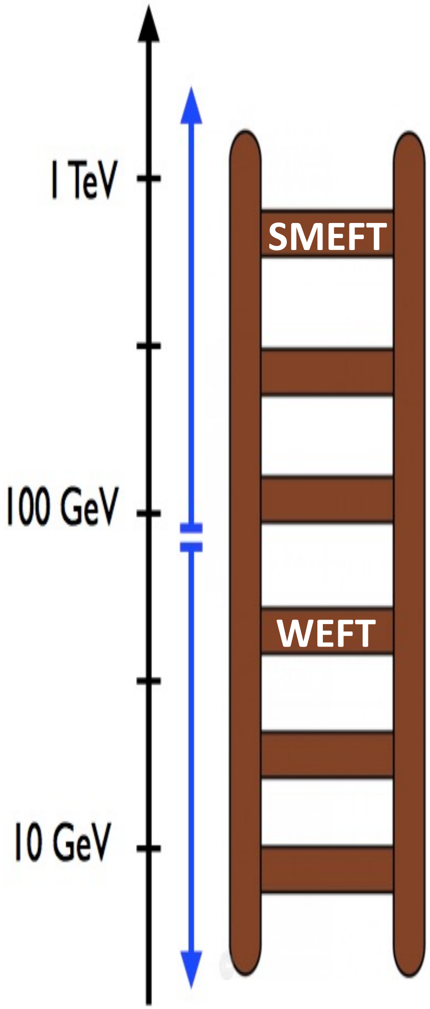
+





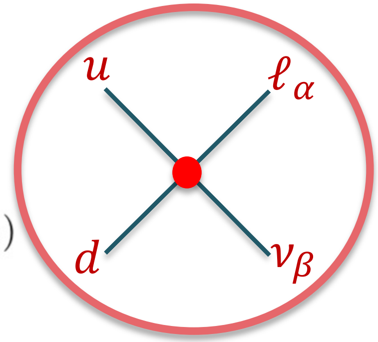
$$O_{lq}^{(3)} = (\bar{l}\gamma^\mu\sigma^a l)(\bar{q}\gamma_\mu\sigma^a q)$$
$$O_{qde} = (\bar{l}e)(\bar{d}q) + \text{h.c.}$$
$$O_{lq} = (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.}$$
$$O_{lq}^{t} = (\bar{l}_a\sigma^{\mu\nu}e)\epsilon^{ab}(\bar{q}_b\sigma_{\mu\nu}u) + \text{h.c.}$$

EFT ladder WEFT: Effective Lagrangian defined at a low scale μ ~ 2 GeV



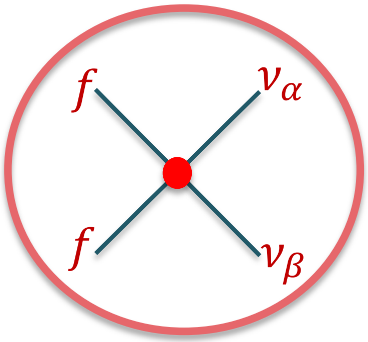
- CC: New left/right handed, (pseudo)scalar and tensor interactions

$$\begin{aligned}\mathcal{L}_{\rm WEFT} \supset & -\frac{2V_{ud}}{v^2}\{[\mathbf{1}+\epsilon_L]_{\alpha\beta}(\bar{u}\gamma^\mu P_L d)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta)\\ & +[\epsilon_R]_{\alpha\beta}(\bar{u}\gamma^\mu P_R d)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta)\\ & +\frac{1}{2}[\epsilon_S]_{\alpha\beta}(\bar{u}d)(\bar{\ell}_\alpha P_L\nu_\beta)-\frac{1}{2}[\epsilon_P]_{\alpha\beta}(\bar{u}\gamma_5 d)(\bar{\ell}_\alpha P_L\nu_\beta)\\ & +\frac{1}{4}[\hat{\epsilon}_T]_{\alpha\beta}(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{\ell}_\alpha\sigma_{\mu\nu}P_L\nu_\beta)+\text{h.c.}\}\end{aligned}$$



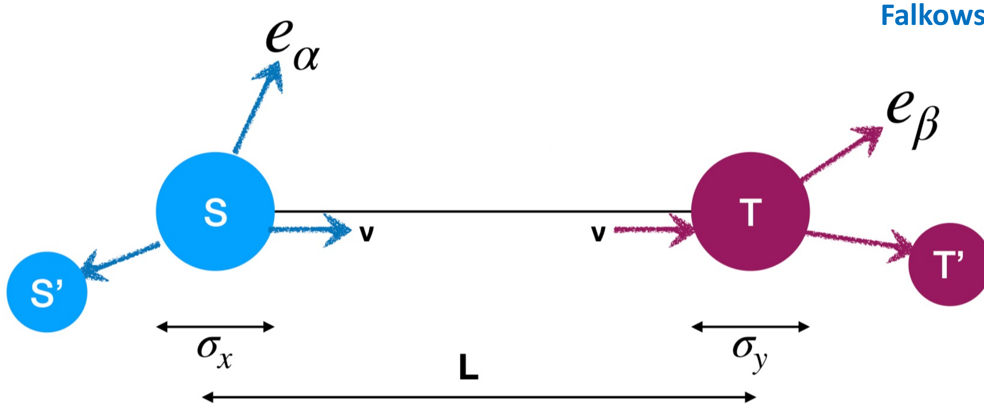
- NC: New left and right handed interactions

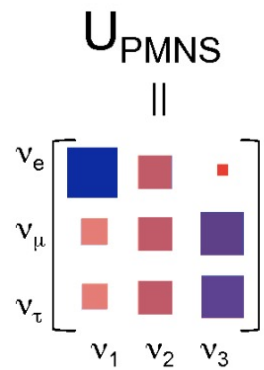
$$\mathcal{L}_{\rm WEFT} \supset -\frac{2}{v^2}\epsilon^{fX}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)\,(\bar{f}\gamma_\mu P_X f)$$



EFT at neutrino experiments

Falkowski, González-Alonso, ZT, JHEP (2020)





Observable: rate of detected events

~(flux)×(det. cross section)×(oscillation)

CC EFT

NC EFT

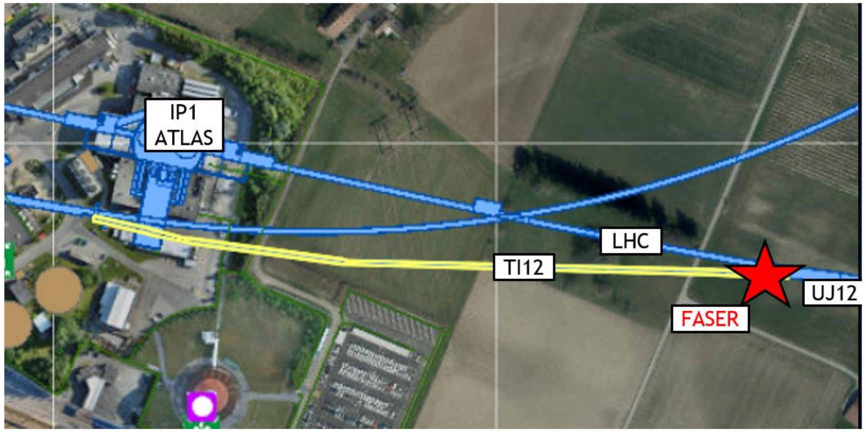
See Joachim Kopp's talk for NC constraints

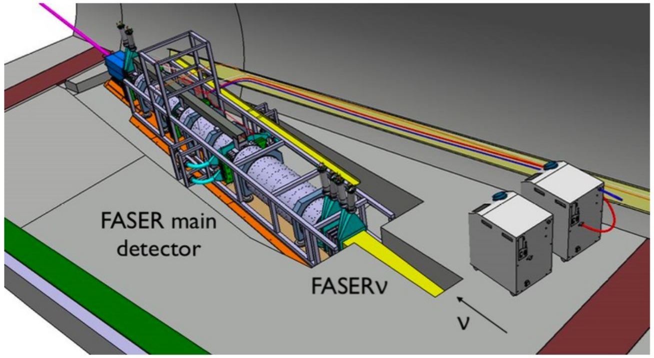
$$-\frac{2V_{ud}}{v^2}\Bigg[\left[1+\epsilon_L\right]_{\alpha\beta}\bar{e}_\alpha\gamma_\mu P_L\nu_\beta\cdot\bar{u}_L\gamma^\mu d_L$$
$$+\left[\epsilon_R\right]_{\alpha\beta}\bar{e}_\alpha\gamma_\mu P_L\nu_\beta\cdot\bar{u}_R\gamma^\mu d_R$$
$$+\frac{1}{2}\bar{e}_\alpha P_L\nu_\beta\cdot\bar{u}\left[\epsilon_S-\epsilon_P\gamma_5\right]_{\alpha\beta}d$$
$$+\frac{1}{4}\left[\epsilon_T\right]_{\alpha\beta}\bar{e}_\alpha\sigma_{\mu\nu}P_L\nu_\beta\cdot\bar{u}_R\sigma^{\mu\nu}d_L\Bigg]+\mathrm{h.c.}$$

Depend on the kinematics and spin variables!

EFT at FASERν

- Downstream of ATLAS at of 480 m;
- Ideal for detecting high-energy neutrinos at LHC;
- 1.1-t of tungsten material;
- Several production modes;
- Pion and Kaon decays are the dominant ones;
- All (anti)neutrino flavors are available;



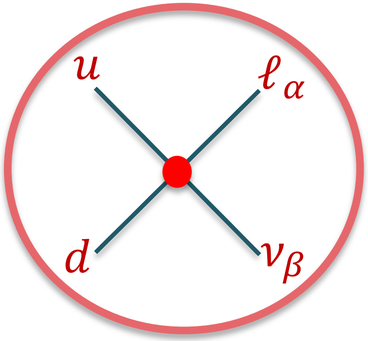


Within the SM:

$\nu_e \sim 1000$, $\nu_\mu \sim 5000$, $\nu_\tau \sim 10$

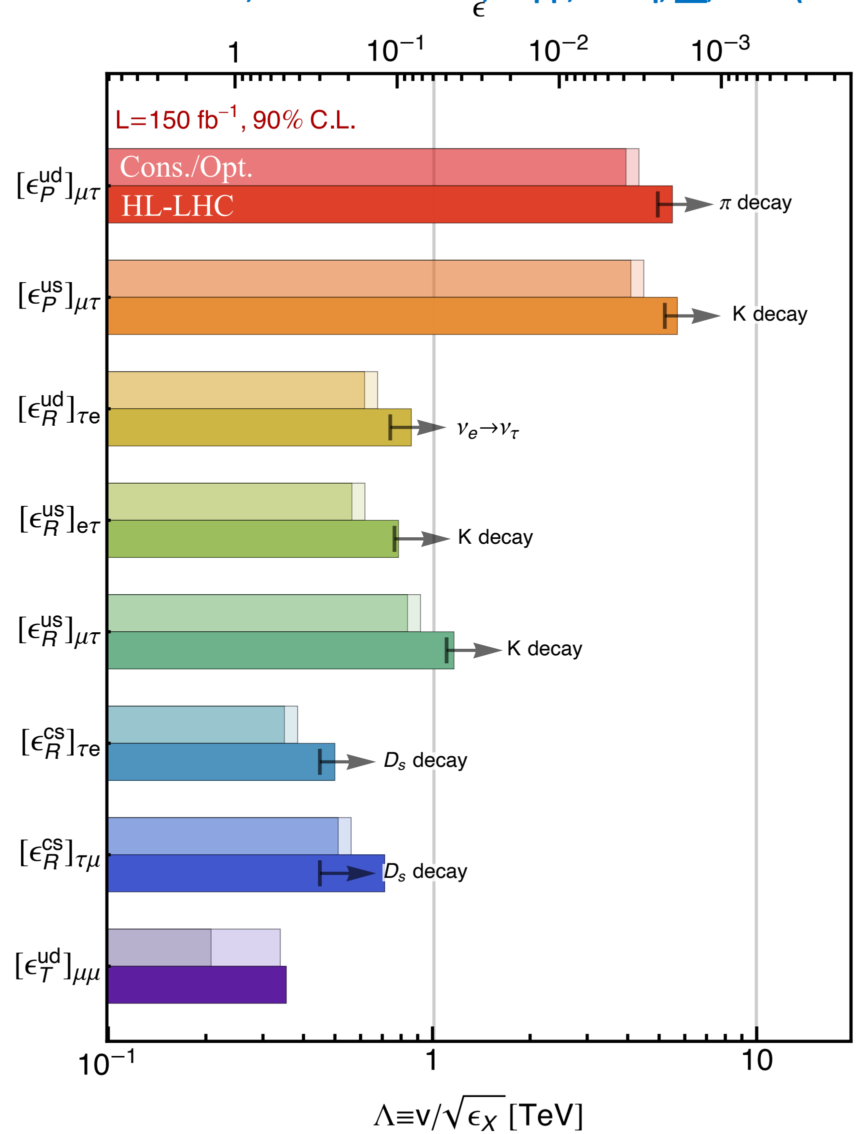
EFT at FASERν

- FASERν: colored bars
- Top: Conservative/Optimistic flux uncertainties
- Bottom: High luminosity LHC



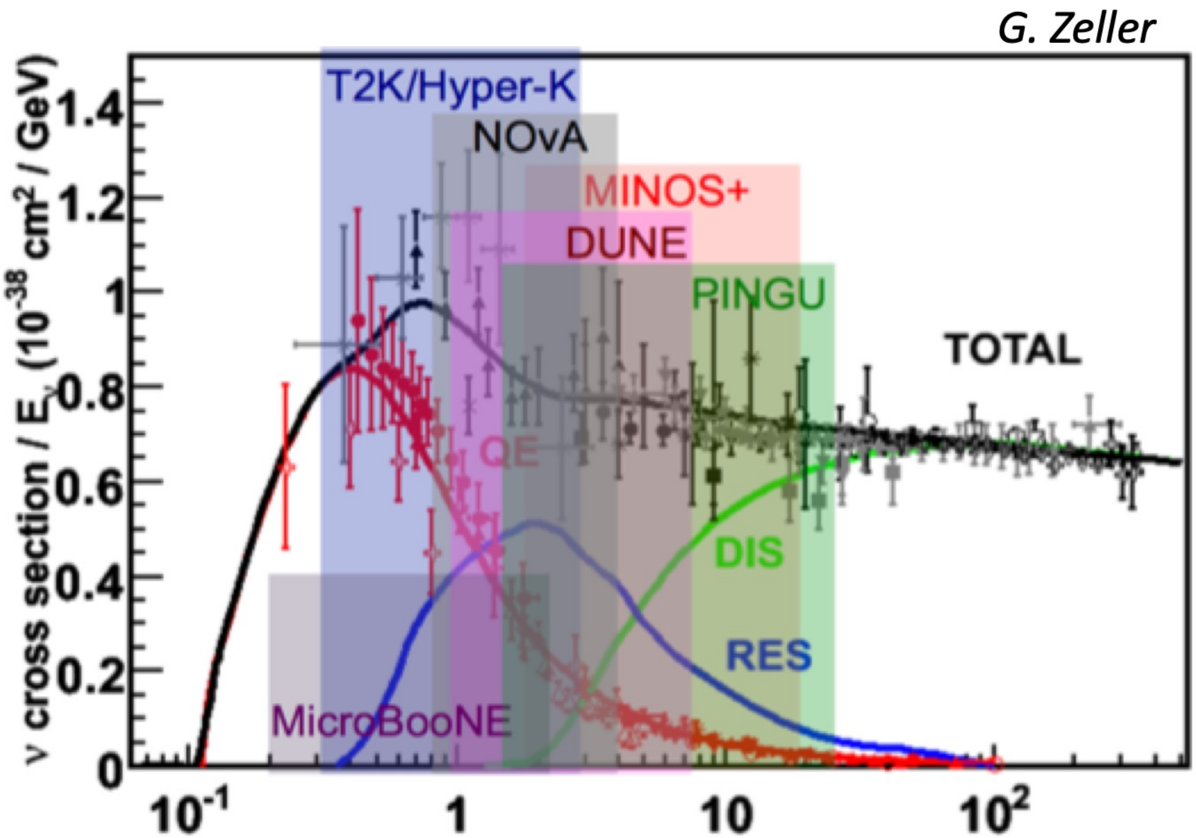
- Neutrino detectors can identify flavor: 81 operators at FASERν
- New physics reach at multi-TeV
- Complementary or dominant constraints

Falkowski, González-Alonso, Kopp, Soreq, ZT, JHEP (2021)



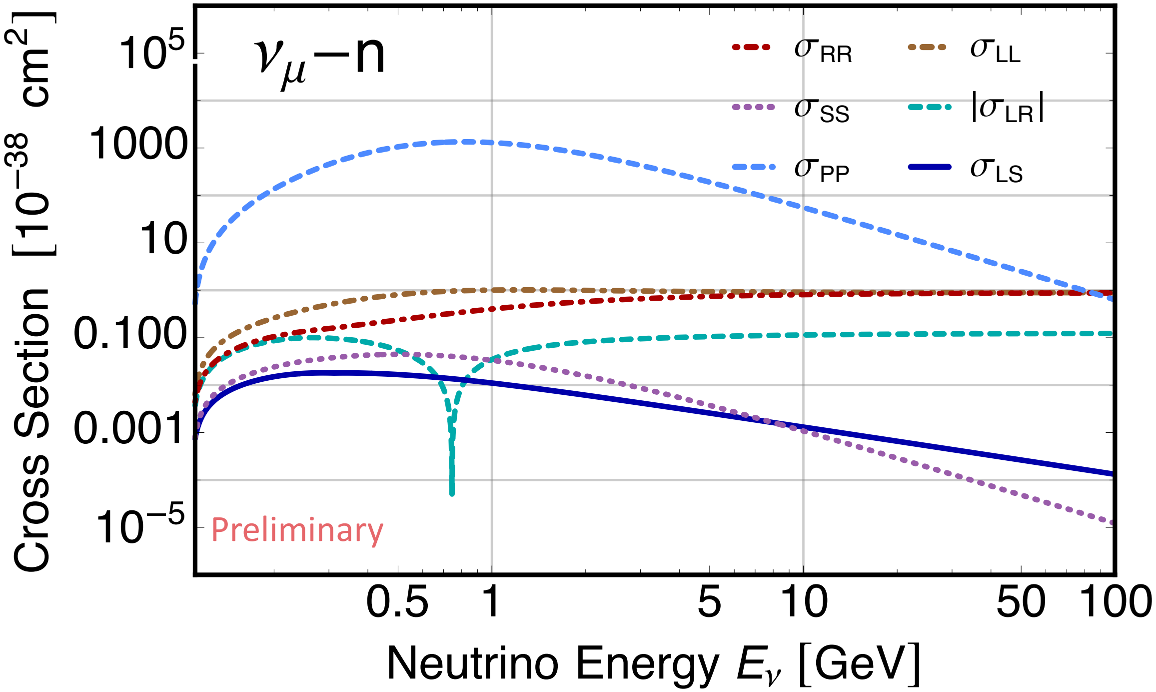
How about DUNE-like experiments?

- 0.1-10 GeV energy range: cross section is much more involved!



J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)

e.g.: Quasi-Elastic scattering at the nucleon level

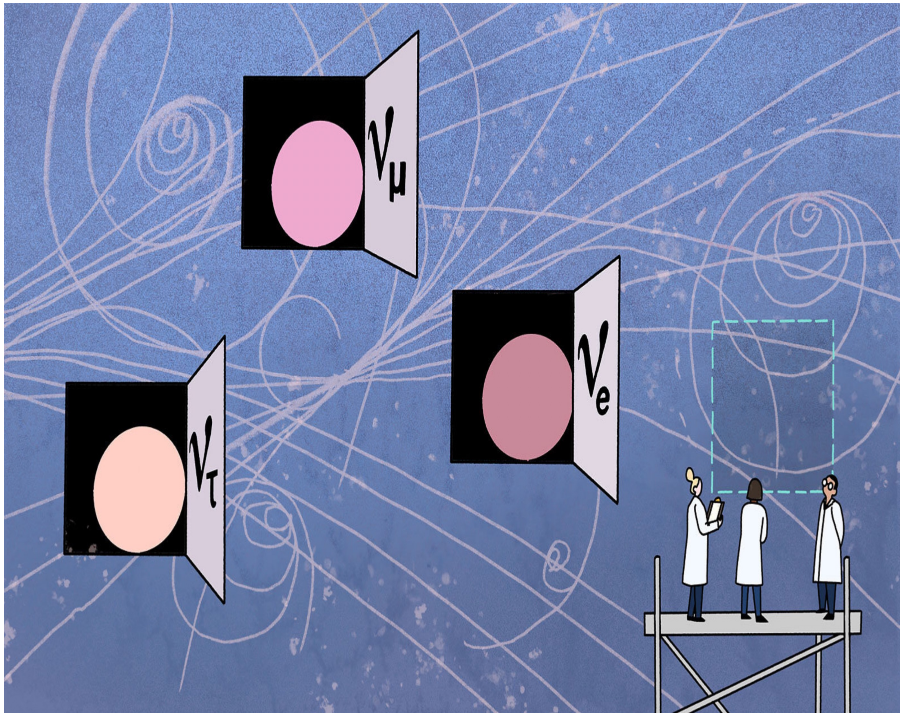


Kopp, Rocco, ZT, in preparation

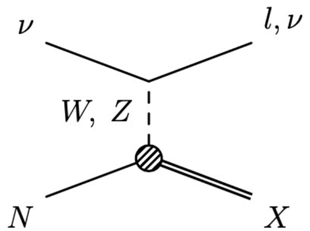
Can these detectors have access to new physics at 100 TeV scale?

Outline

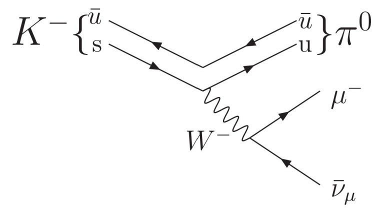
- Dark Sector at the Near Detectors:
  - ALPs ✓
  - Light Dark Matter ✓
  - Light Z' ✓
- Model independent approach:
  - Why EFT? ✓
  - EFT ladder ✓
  - EFT an Neutrino Experiments ✓
- Conclusion

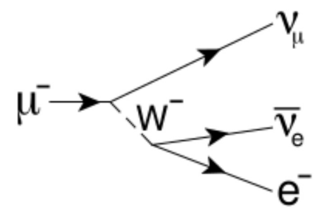


DIS: FASERν



Kaon/Muon decay: ISODAR, KDAR





Solar neutrinos: Borexino

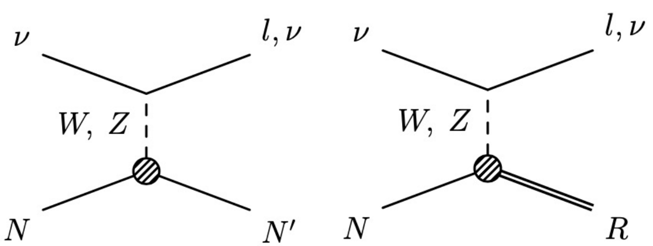
^{7}Be $^7\mathrm{Be} + e^- \to {}^7\mathrm{Li} + \nu_e$

$^3\mathrm{He} + p \to {}^4\mathrm{He} + e^+ + \nu_e$ **hep**

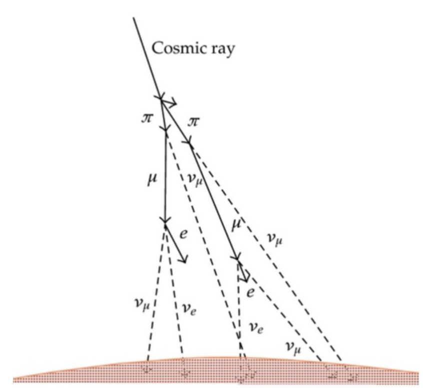
(hep)

$p + e^- + p \to {}^2\mathrm{H} + \nu_e$ ***pep***

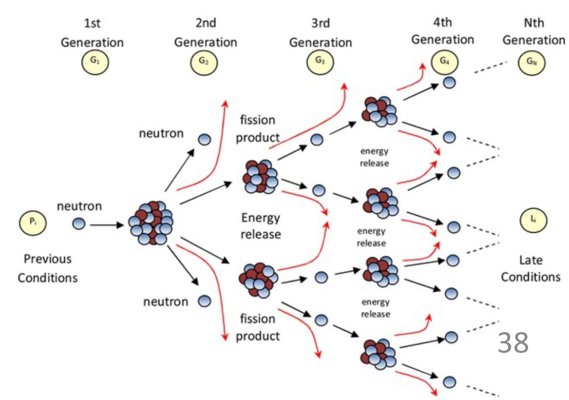
QE, Resonances: MINOS, NOvA, DUNE

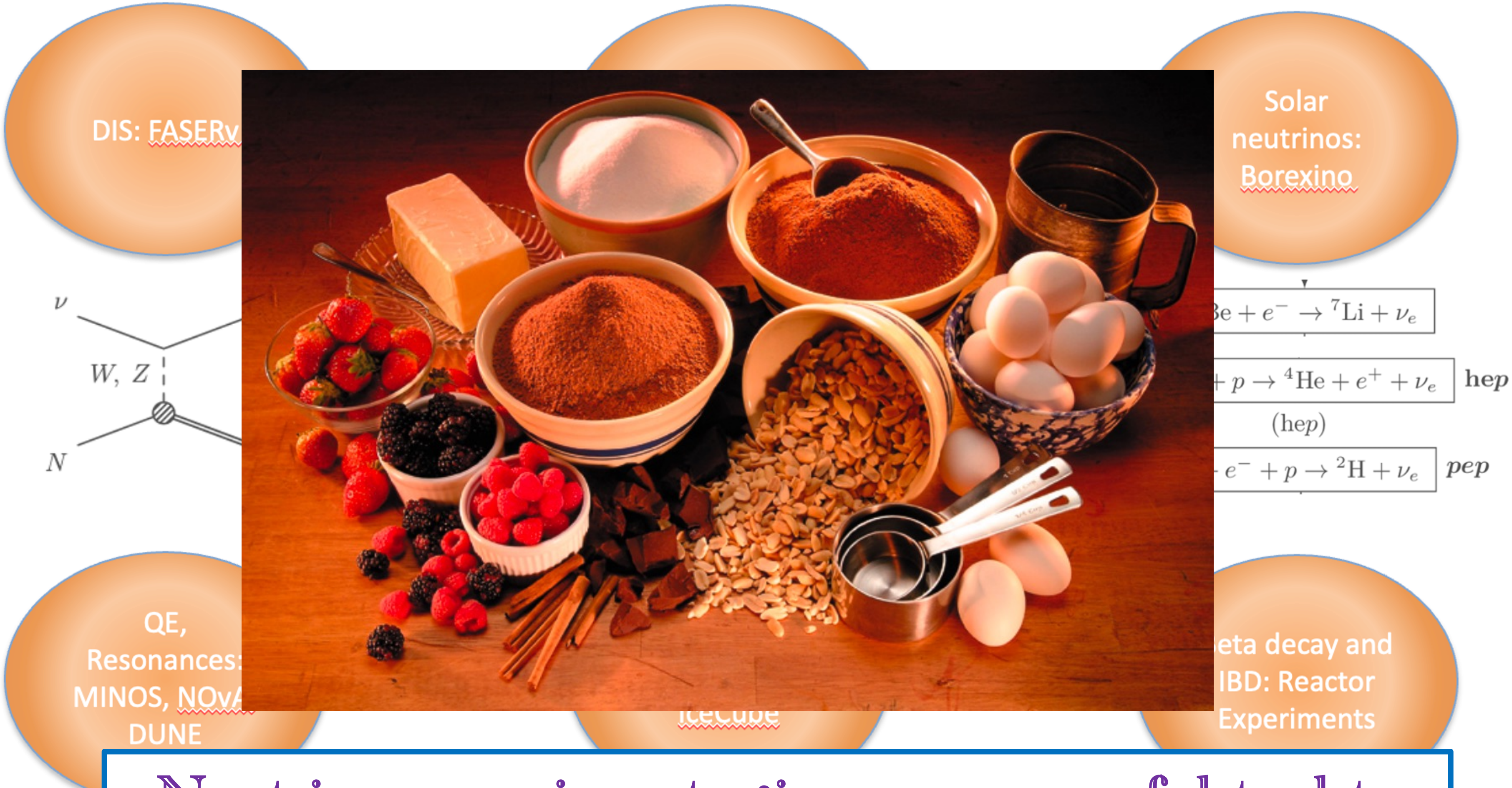


Atmospheric Neutrinos: IceCube

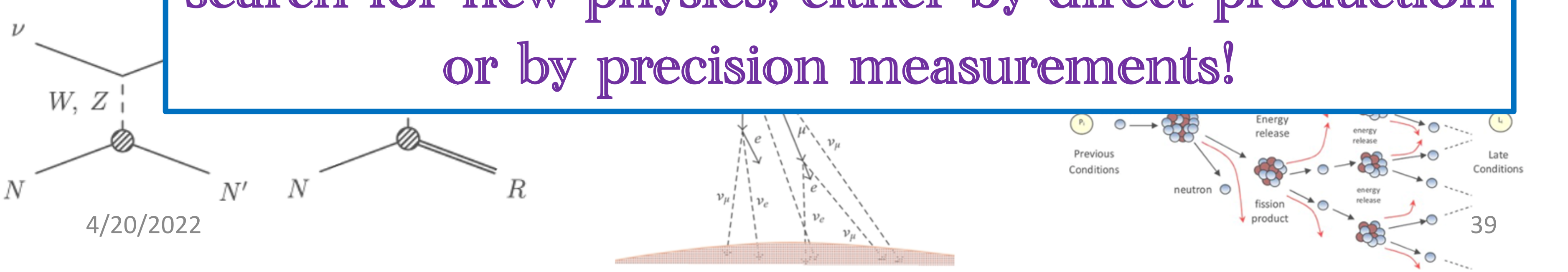


Beta decay and IBD: Reactor Experiments





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



Conclusion:

- New generation of neutrino experiments are being built to answer many unknowns in the neutrino sectors;
- We can use the near detectors to directly search for dark sector (e.g.: ALPs, light DM, Light Z', etc.);
- For several BSM models, near detectors give the best constraints;
- We can probe very heavy particles, often beyond the reach of present colliders, by precisely measuring low-energy observables using the EFT formalism;
- Unlike other probes (meson decays, ATLAS and CMS analyses, etc.) neutrino experiments have the unique capability to identify the neutrino flavor. This is crucial complementary information in case excesses are found elsewhere in the future;
- Future directions: Systematic model-independent global analyses of new physics in neutrino oscillation experiments with:
  - i) Power counting of EFT effects;
  - ii) Extraction of oscillation parameters in presence of general new physics;
  - iii) Comparison between the sensitivity of oscillation and other experiments.

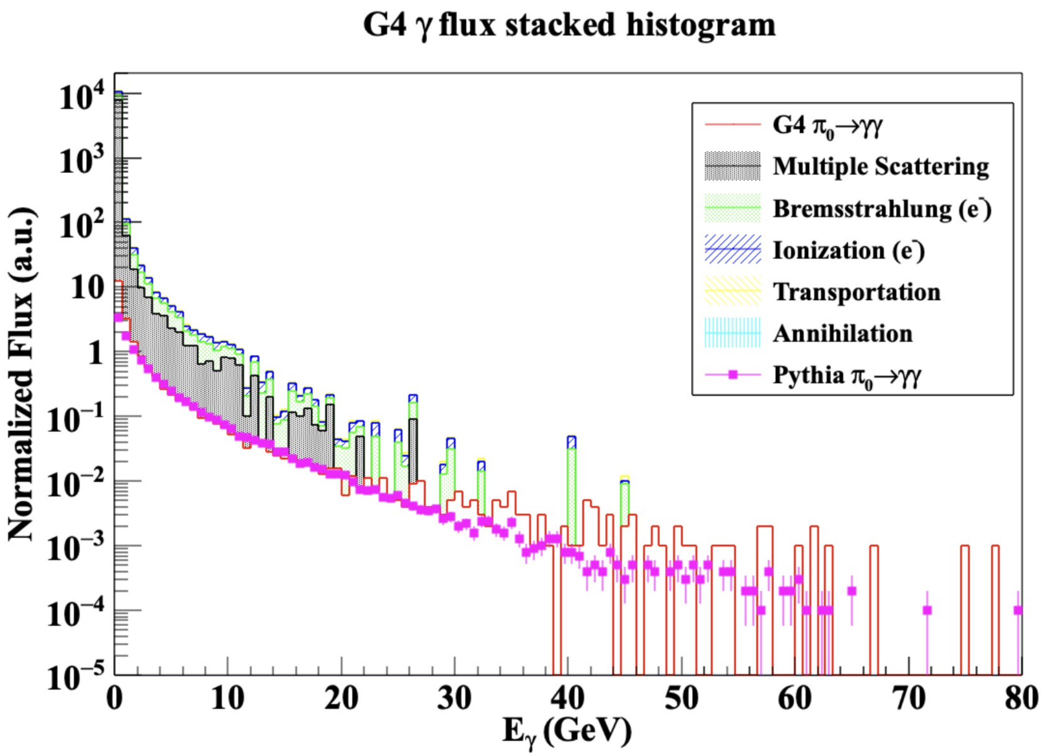
Any Questions?

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

Back up Slides

Axion Like Particles (ALPs) at DUNE:

Photon Flux from GEANT4 Simulation



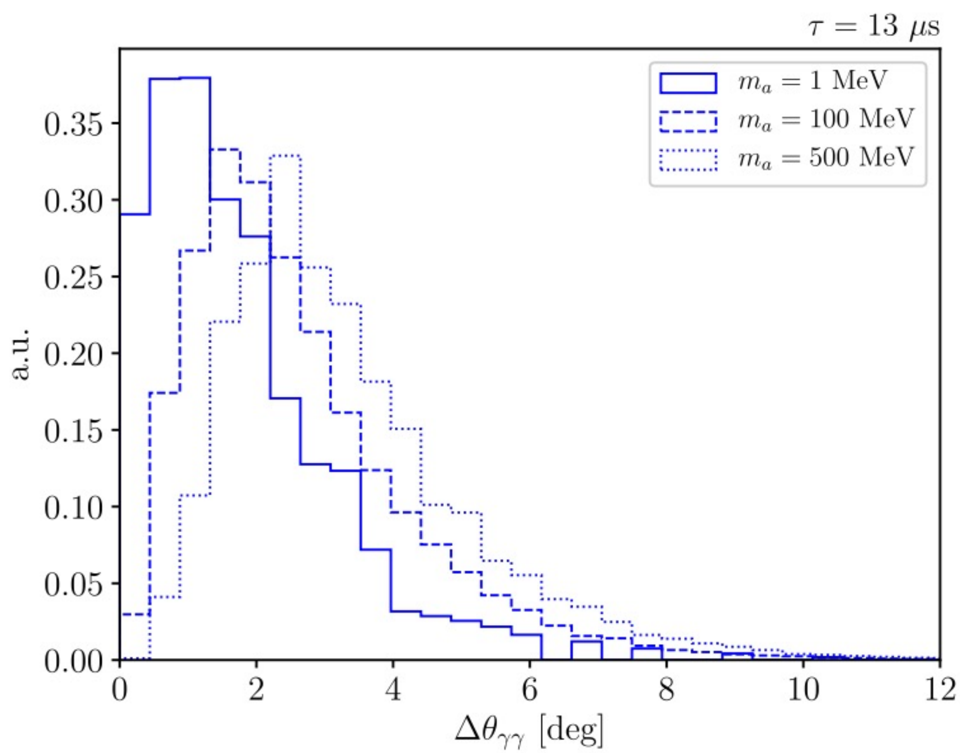
V. Brdar, B. Dutta, W. Jang, D. Kim, I. Shoemaker, **ZT**, A. Thompson, J. Yu
Phys.Rev.Lett. 126 (2021) 20, 201801

Axion Like Particles (ALPs) at DUNE:

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

In GAr:

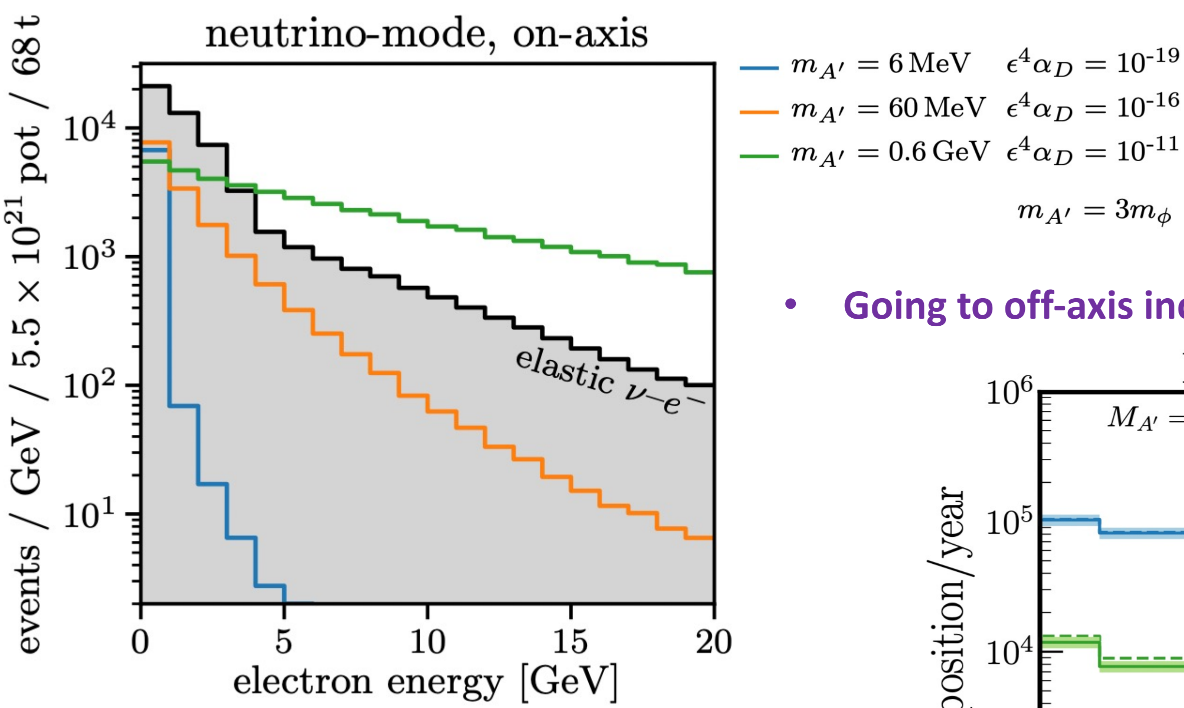
- We expect ~ 10^6 NC events;
- Vetoing events with hadronic activity remove ~ 80%;
- A cut on the opening angle removes the rest;



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

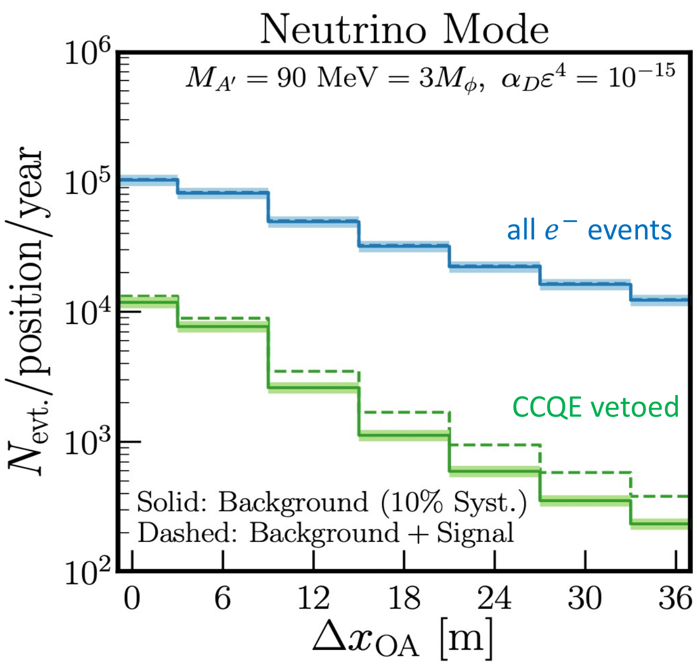
Light Dark Matter

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



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

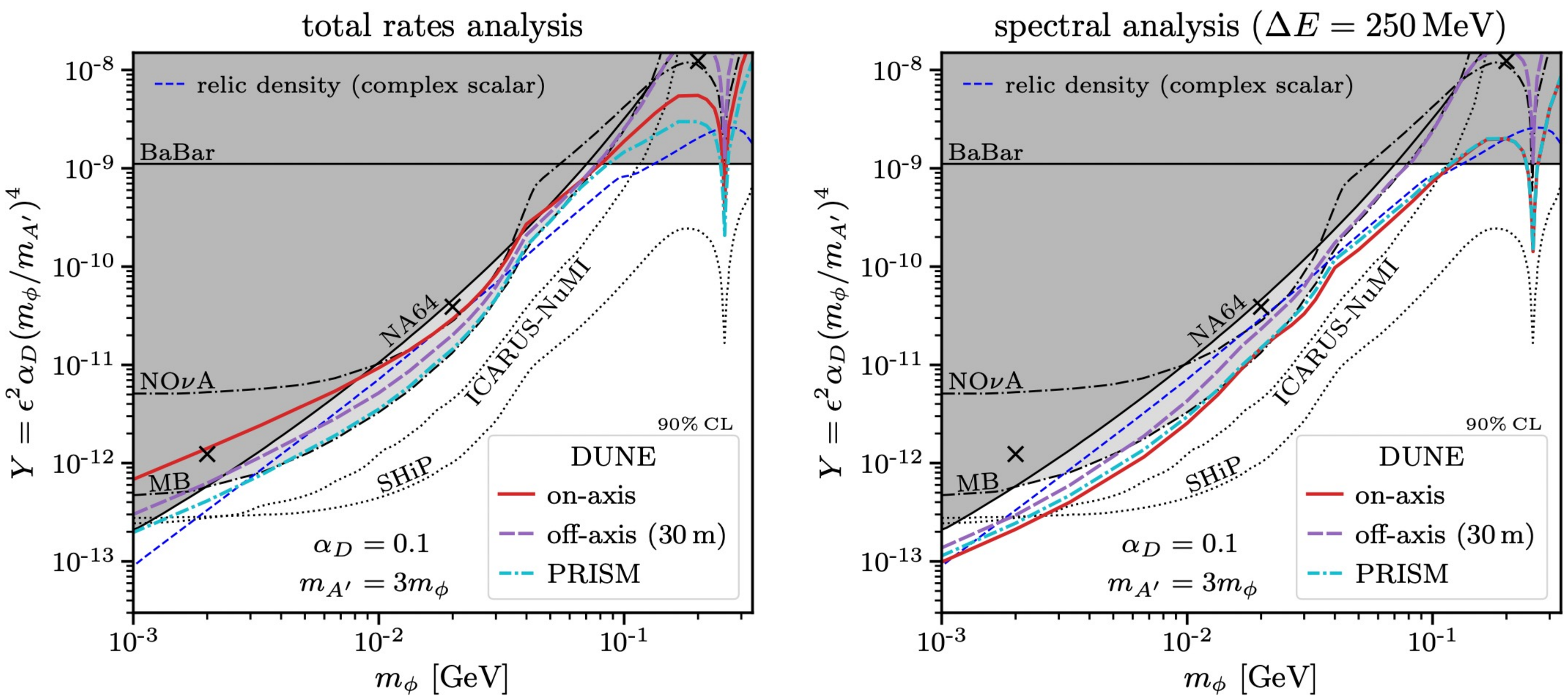
- **Going to off-axis increases DM signal/background**



De Romeri, Kelly, Machado, PRD (2019)

Light Dark Matter

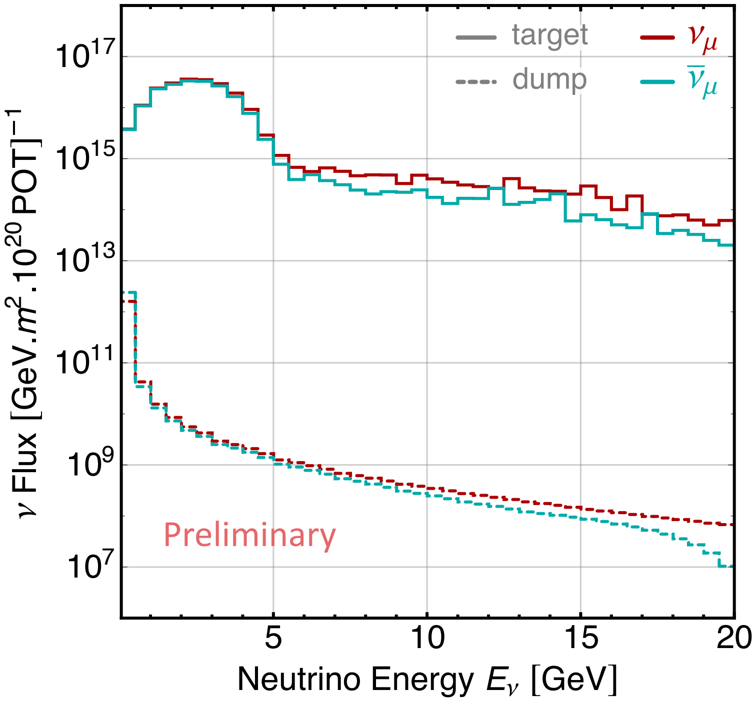
- DUNE can do half an order of magnitude better than existing constraints



Breitbach, Buonocore, Frugiuele, Kopp, Mittnacht, JHEP (2022)
Also: De Romeri, Kelly, Machado, PRD (2019)

Light Dark Matter---DUNE Beam Dump

- The ν flux decreases by 5 orders of magnitude → No ν-e background!



Brdar, Dutta, Jang, Kim, Shoemaker, *ZT*, Thompson, Yu (In preparation)

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

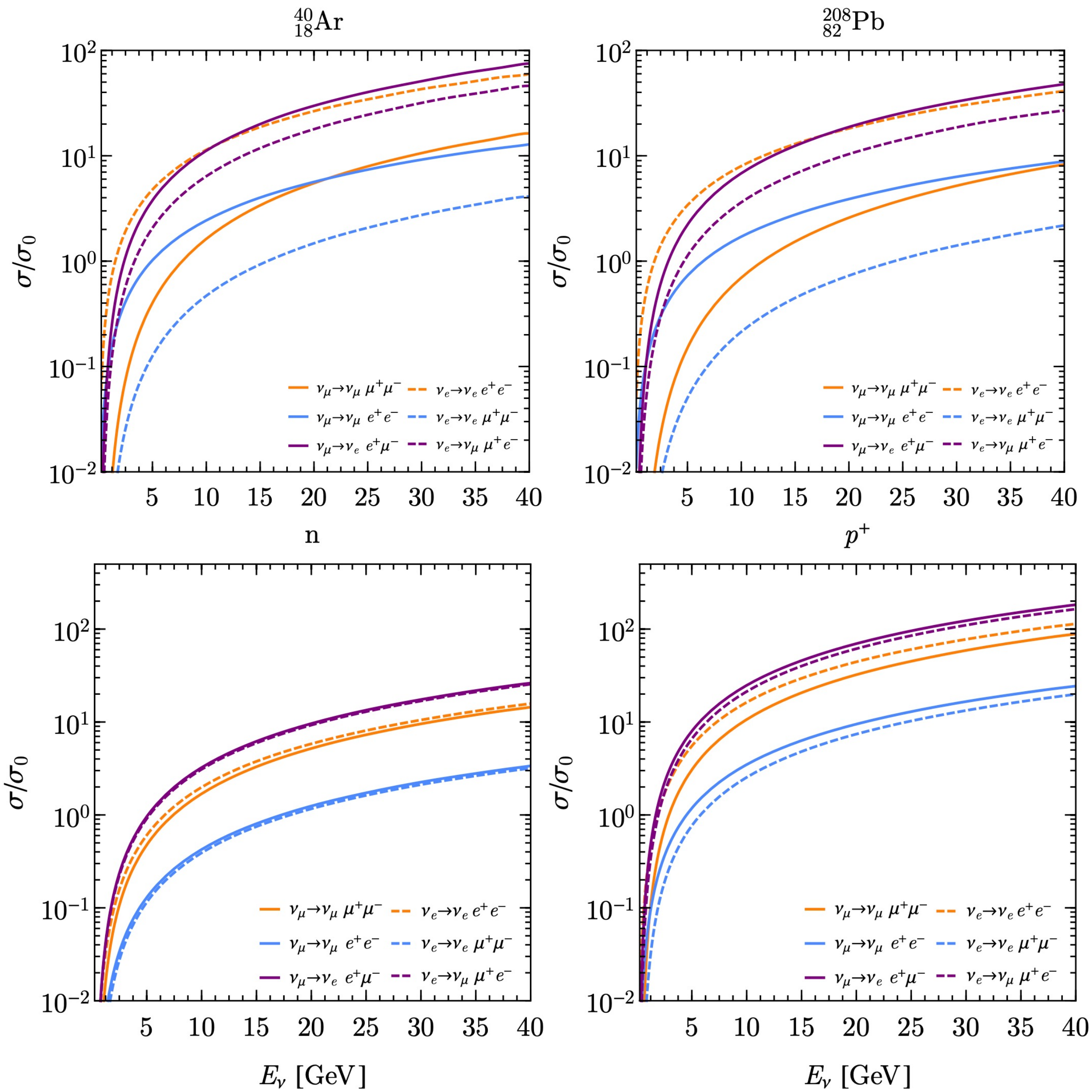
$$\sigma_\gamma^{\mathrm{FL}}(P_i + \gamma \to P_f; \hat{s}, 0) \propto G_{\mathrm{F}}^2\,\hat{s}$$

Increases with increasing transferred four-momentum

On-shell << off-shell

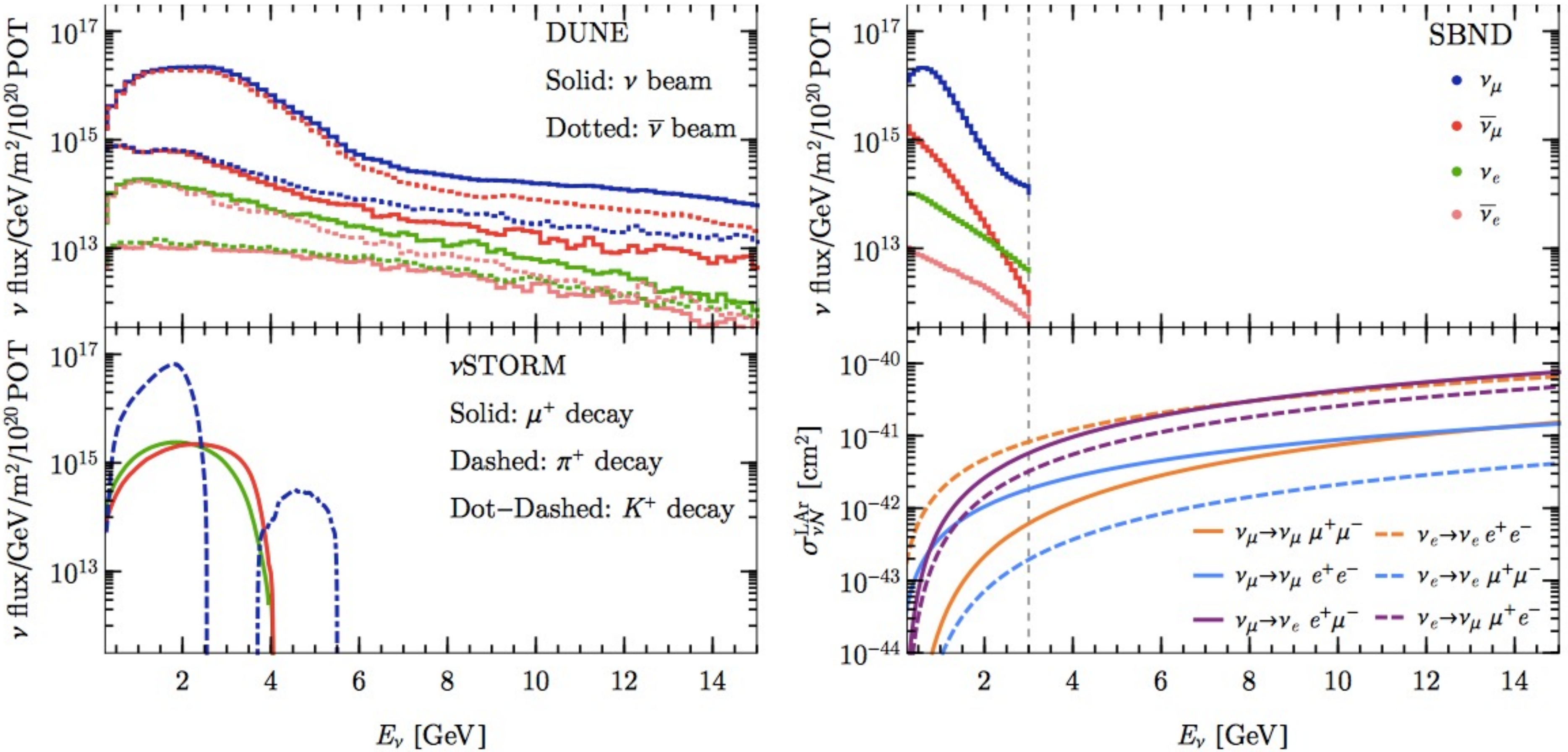
Ballett, Hostert, Pascoli, Perez, **ZT** and Funchal JHEP **1901**, 119 (2019)

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.

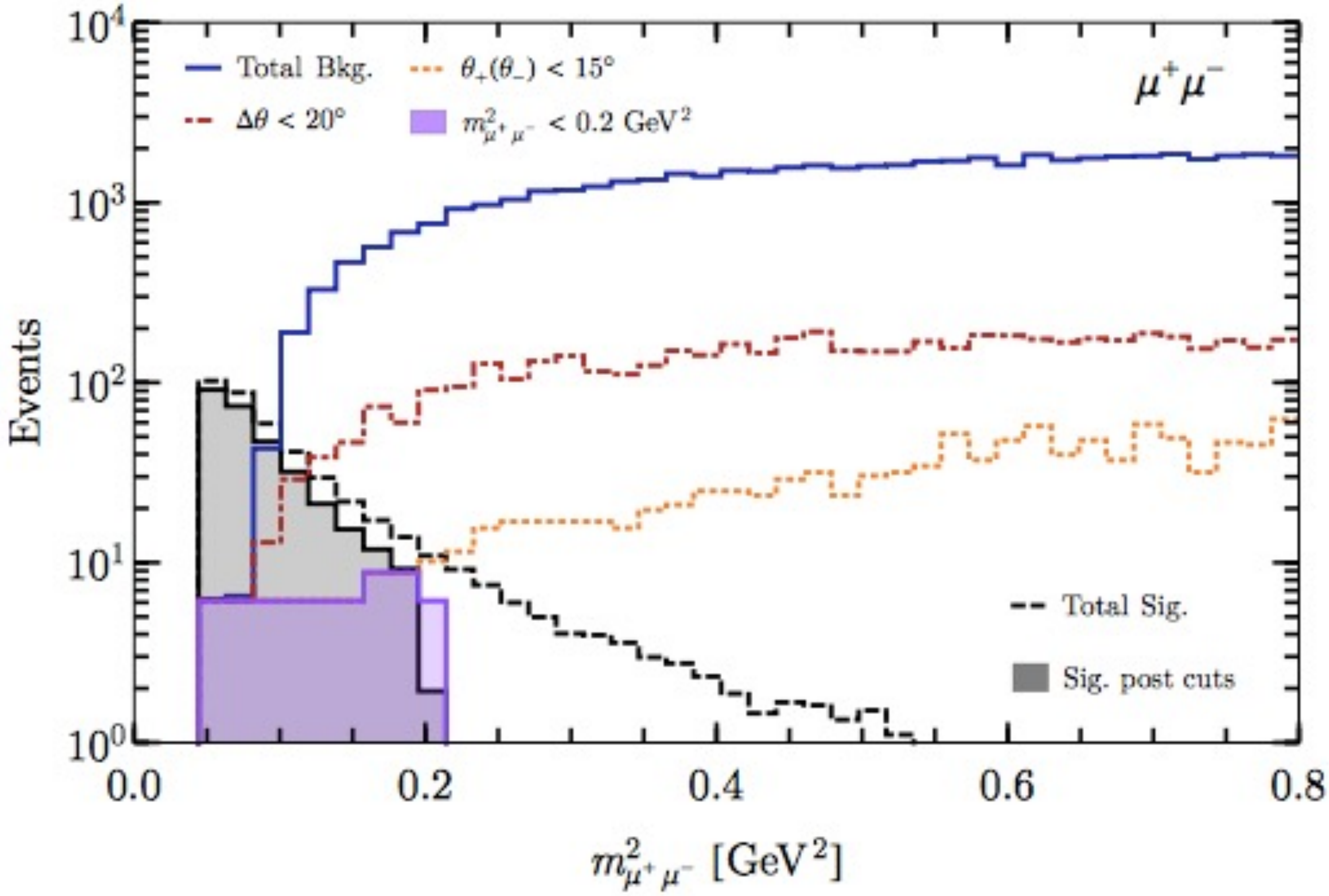
misID
γ as $e^\pm$
γ as e^+e^-
$\pi^\pm$ as $\mu^\pm$

Channel	$N_B^{\text{misID}}/N_{CC}$	N_B^{had}/N_{CC}	N_B^{kin}/N_{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.

Ballett, Hostert, Pascoli, Perez, **ZT** and Funchal
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)

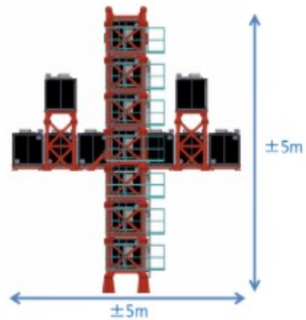
Trident rates at other Near Detectors

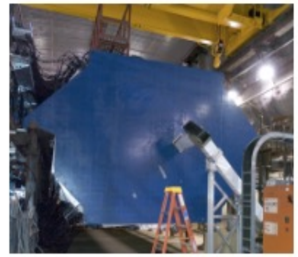
Experiment	Material	Baseline (m)	Exposure (POT)	Fiducial Mass (t)	E_ν (GeV)
INGRID	Fe	280	3.9×10^{21} [10^{22}] T2K-I [T2K-II]	99.4	$0-4$
MINOS[+]	Fe and C	1040	$10.56(3.36)[9.69] \times 10^{20}$	28.6	$0-20$
NOνA	C_2H_3Cl and CH_2	1000	$8.85(6.9)$ $[36(36)] \times 10^{20}$ [NOνA-II]	231	$0-20$
MINERνA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

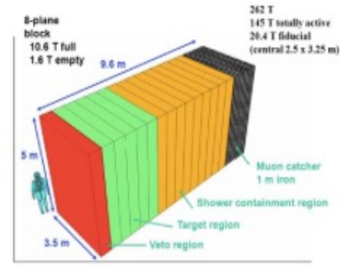
All have finished data taking or are still running

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.

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

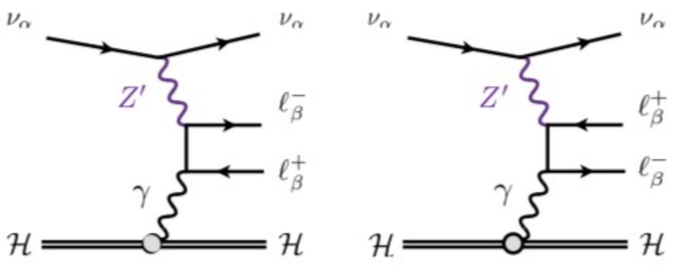
- We focus on the anomaly free leptophilic extensions of the SM:
  $L_\alpha - L_\beta$, $\alpha,\beta = \{e,\mu,\tau\}$, $\alpha \neq \beta$.

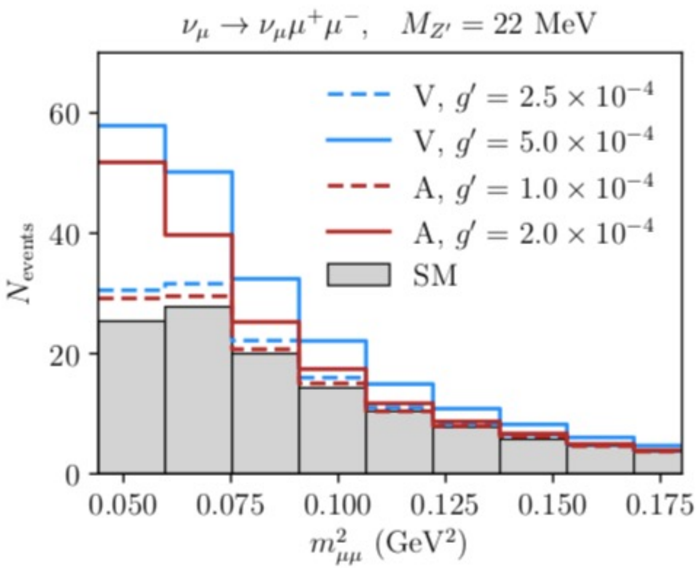
- Anomaly free conditions fix the charges

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

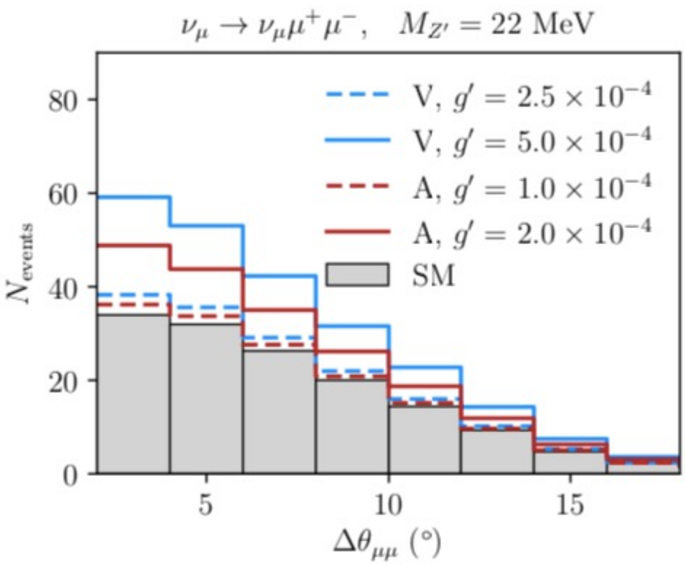
Trident kinematical distributions

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





The invariant mass



Charged lepton separation angle

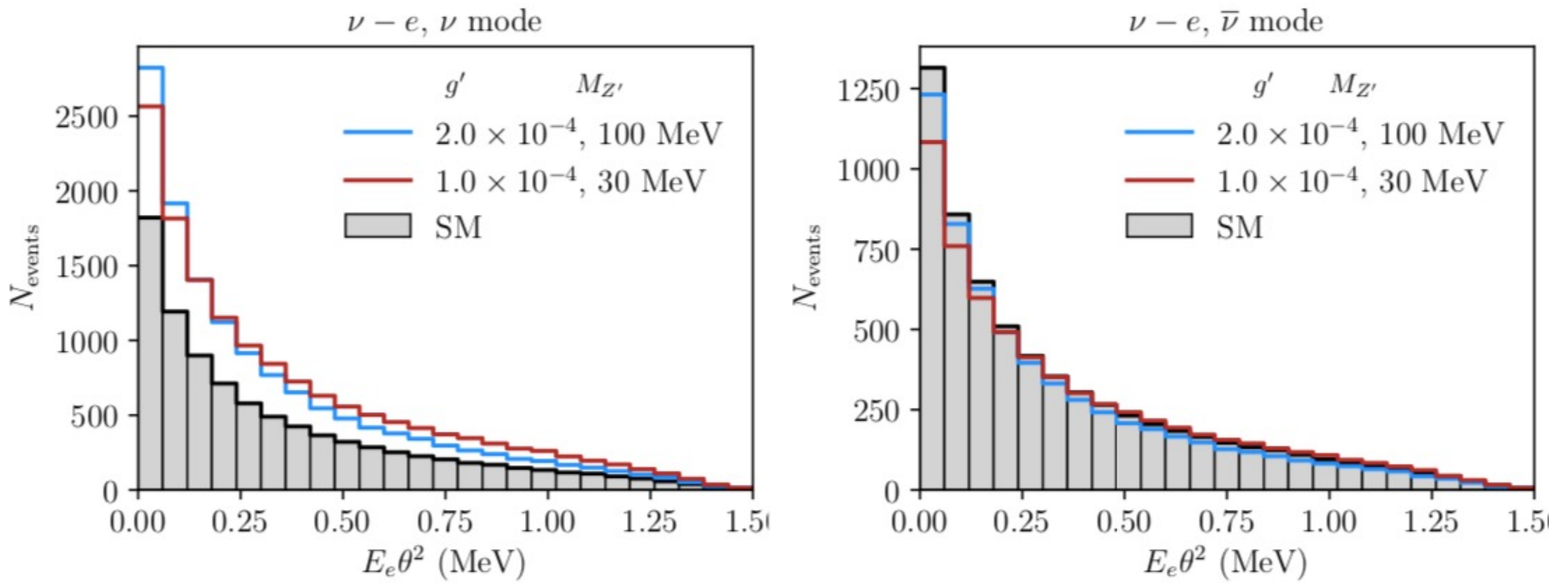
Ballett, Hostert, Pascoli, Perez-Gonzalez, **ZT** and Funchal
Phys.Rev. **D100** (2019) no.5, 055012

Neutrino-Electron scattering

The vector and axial couplings with Z':

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

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



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':

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

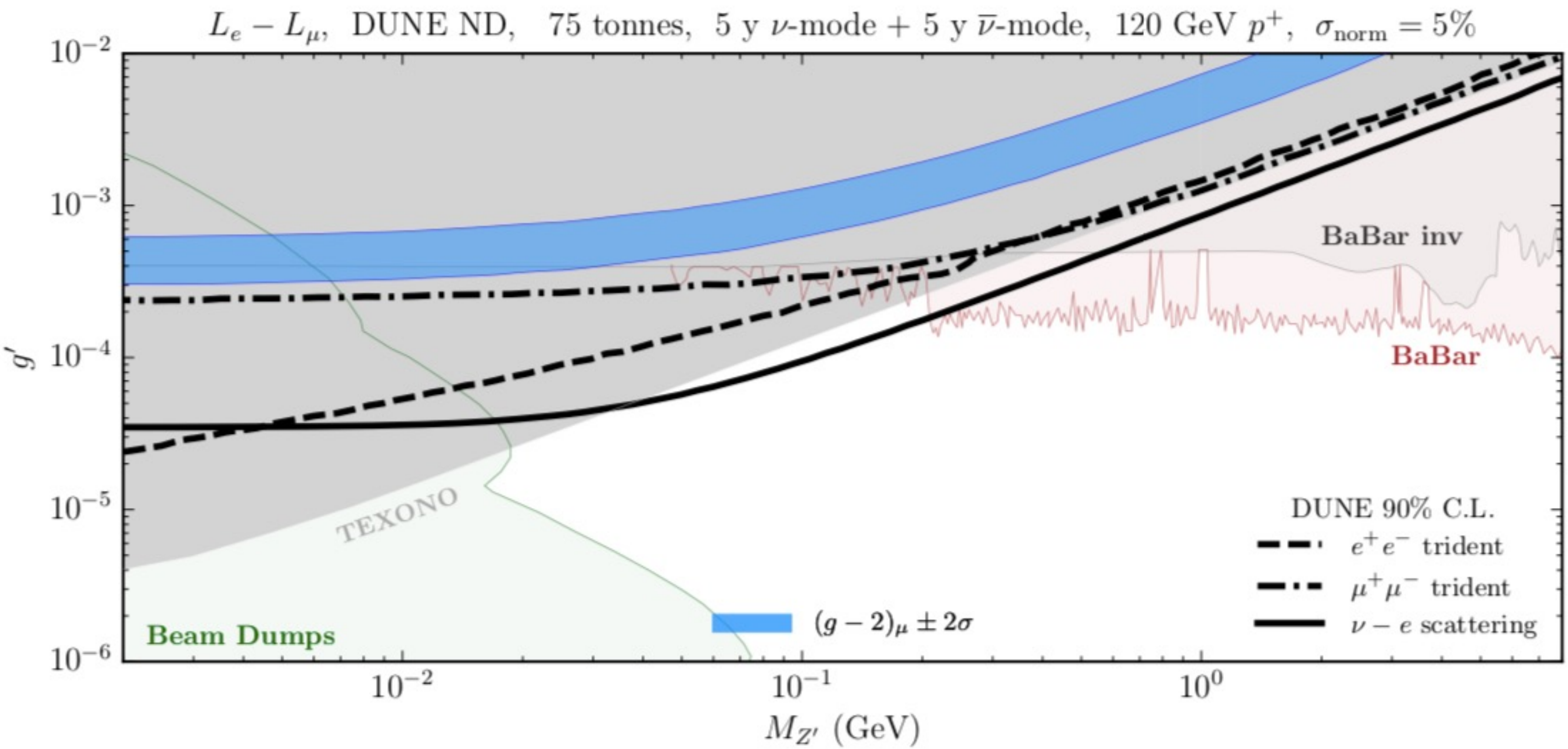
$$C_\alpha^{\mathrm{A}} = -\frac{1}{2} + \delta_{\alpha e} + \frac{Q_e^{\mathrm{A}} Q_\alpha^{\mathrm{L}}}{2\sqrt{2}G_F} \frac{(g')^2}{M_{Z'}^2 + 2m_e T_e},$$

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^-

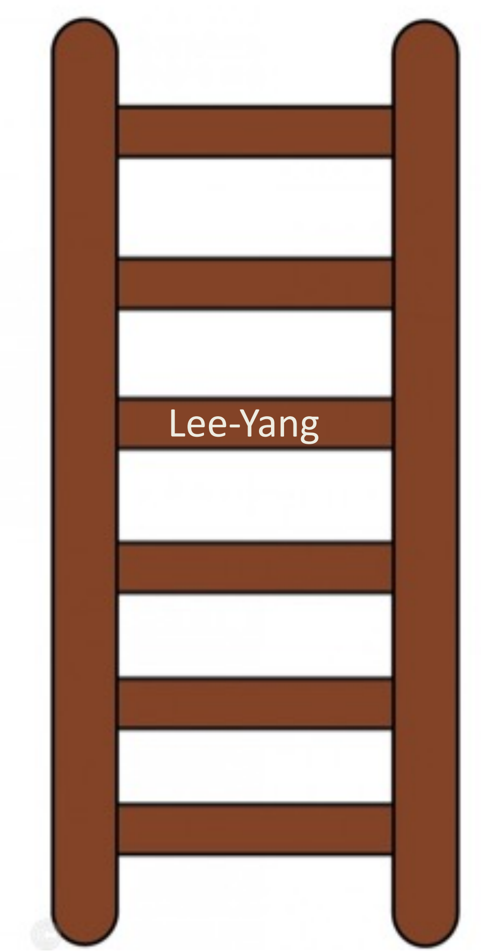
WEFT Power Counting

- Dim-6: $$\frac{\Delta R}{R_{SM}} = c\ \epsilon_X^2$$
- Dim-7: Cannot interfere with the SM amplitudes, suppressed!

Liao et al, *JHEP* 08 (2020) 162

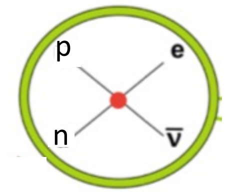
- Dim-8: $$\frac{\Delta R}{R_{SM}} = \sqrt{c}\ \epsilon_8\ E^2/v^2$$

EFT ladder



$E \ll m_Z$

- At the energy scale of reactor neutrino experiments the relevant degrees of freedom are not quarks, but nucleons and nuclei. Matching this EFT to the WEFT Lagrangian we obtain the Lee-Yang Lagrangian:



$$
\begin{aligned}
\mathcal{L}_{\mathrm{LY}} \supset\; & -\frac{V_{ud}}{v^2}\{g_V\,[\mathbf{1}+\epsilon_L+\epsilon_R]_{\alpha\beta}\,(\bar{p}\gamma^\mu n)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta) \\
& -g_A\,[\mathbf{1}+\epsilon_L-\epsilon_R]_{\alpha\beta}\,(\bar{p}\gamma^\mu\gamma_5 n)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta) \\
& +g_S[\epsilon_S]_{\alpha\beta}(\bar{p}n)(\bar{\ell}_\alpha P_L\nu_\beta)-g_P[\epsilon_P]_{\alpha\beta}(\bar{p}\gamma_5 n)(\bar{\ell}_\alpha P_L\nu_\beta) \\
& +\frac{1}{2}g_T[\hat{\epsilon}_T]_{\alpha\beta}(\bar{p}\sigma^{\mu\nu}P_L n)(\bar{\ell}_\alpha\sigma_{\mu\nu}P_L\nu_\beta)+\mathrm{h.c.}\},
\end{aligned}
$$

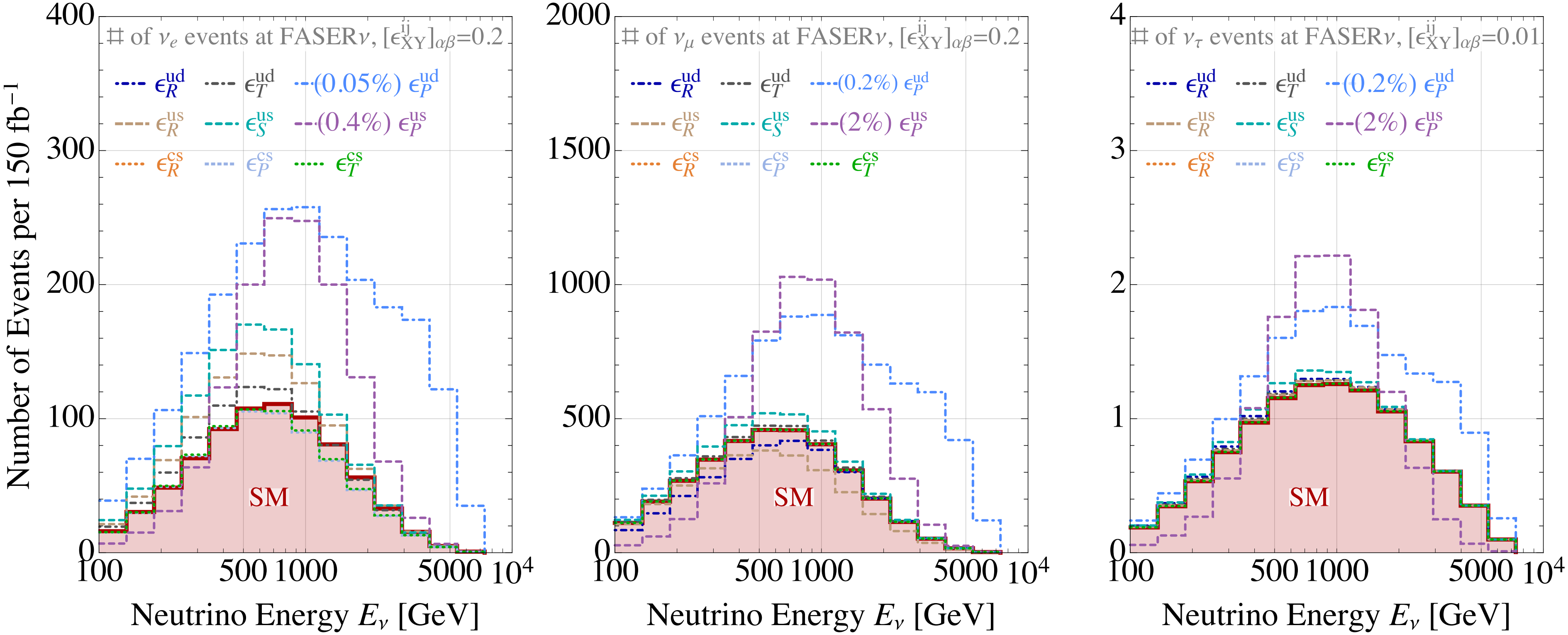
- Lattice+theory fix the non-perturbative parameters with good precision

$$g_A = 1.2728 \pm 0.0017, \quad g_S = 1.02 \pm 0.11, \quad g_P = 349 \pm 9, \quad g_T = 0.987 \pm 0.055.$$

- T. Bhattacharya et al, Phys. Rev. D94 (2016), no. 5 054508
- M. Gonzalez-Alonso and J. Martin Camalich, Phys. Rev. Lett. 112 (2014), no. 4 042501
- M. Gonzalez-Alonso et al, Prog. Part. Nucl. Phys. 104 (2019) 165–223

EFT at FASERν

Falkowski, González-Alonso, Kopp, Soreq, *ZT*, JHEP (2021)



- Analysis is statistics dominated: $\nu_e \sim 1000$, $\nu_\mu \sim 5000$, $\nu_\tau \sim 10$
- Optimistic systematic uncertainties: 5% on ν_e, 10% on ν_μ, 15% on ν_τ
- Pessimistic systematic uncertainties: 30% on ν_e, 40% on ν_μ, 50% on ν_τ

RESULTS

Turning on one interaction at a time: Right handed

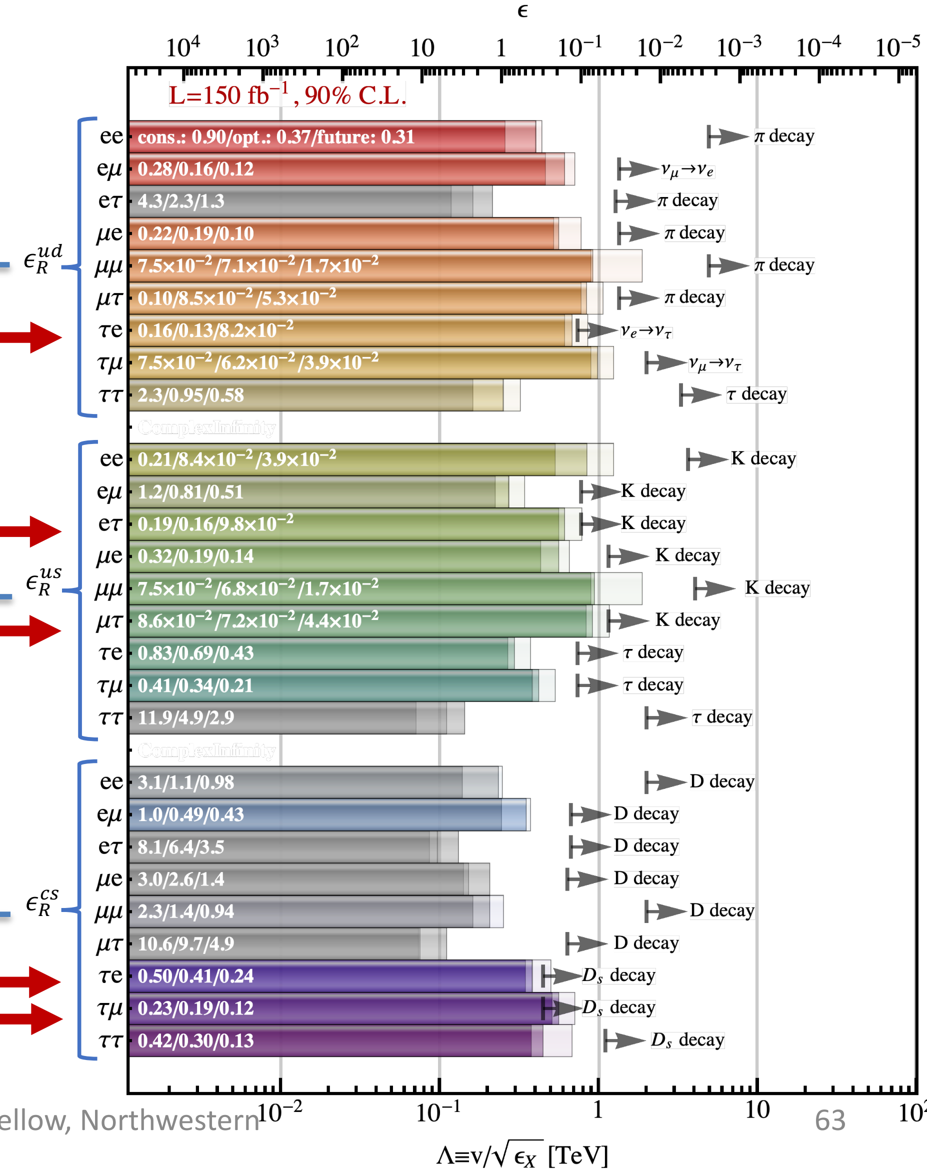
A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, ZT
JHEP 10 (2021) 086

Optimistic (5%, 10%, 15%) and Pessimistic (30%, 40%, 50%), uncertainties on electron muon and tau neutrinos

From pion decay and DIS

From kaon decay and DIS

From charm decay and DIS



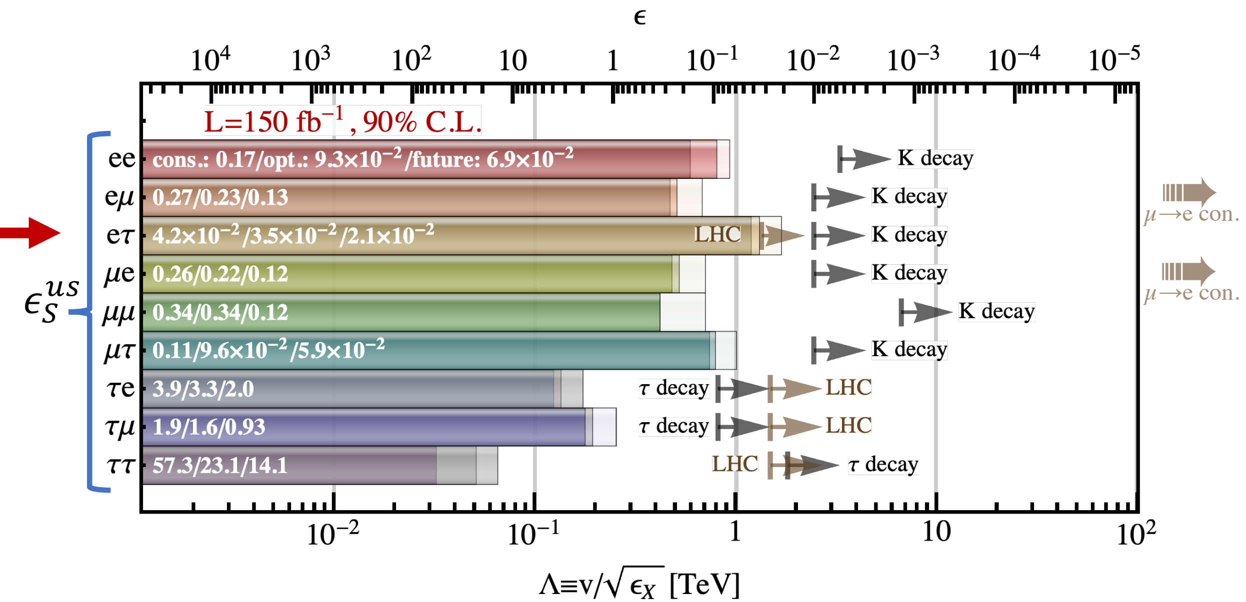
RESULTS

Turning on one interaction at a time: Scalar

A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, **ZT**
JHEP 10 (2021) 086

Optimistic (5%, 10%, 15%) and Pessimistic (30%, 40%, 50%), uncertainties on electron muon and tau neutrinos

From kaon decay



RESULTS

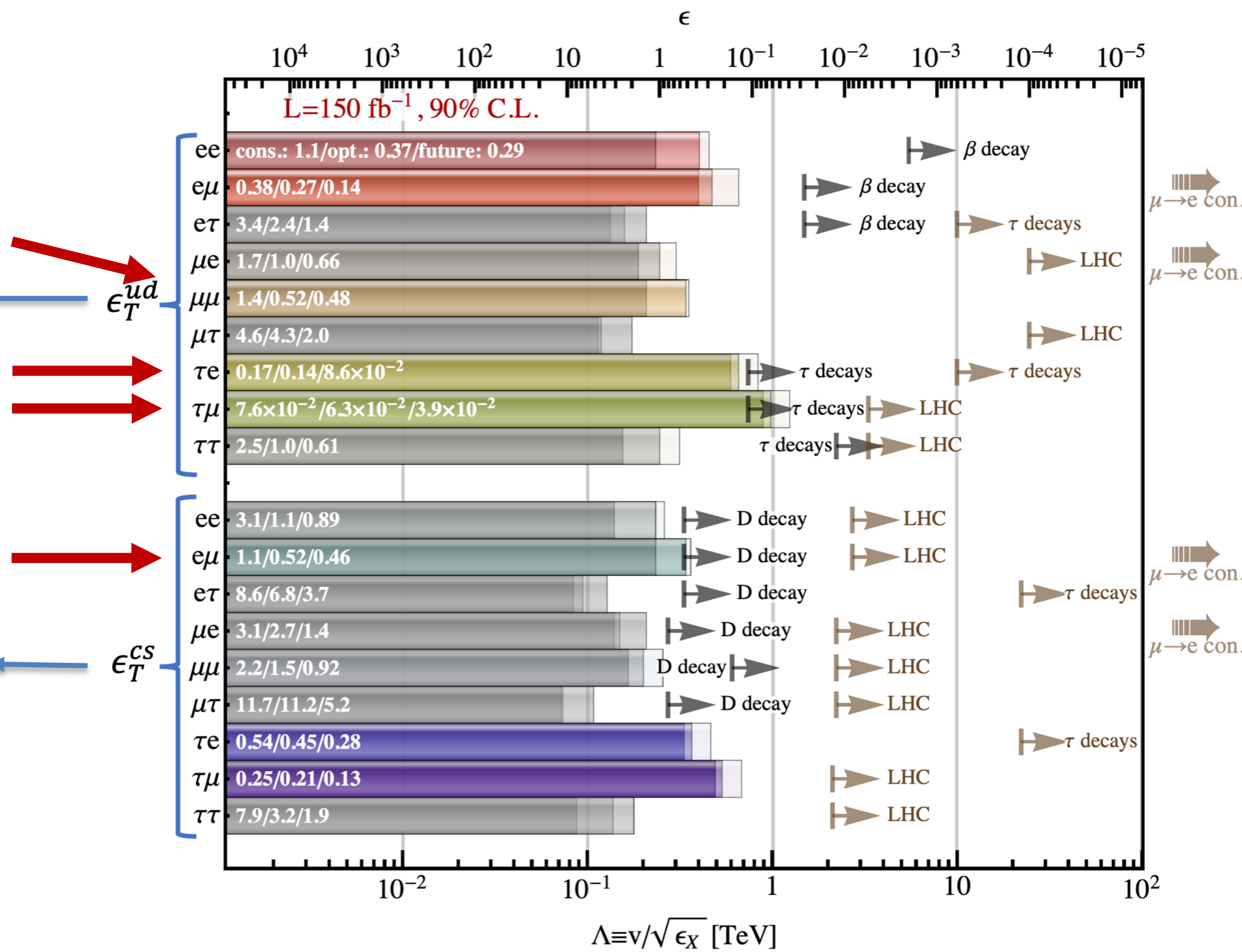
Turning on one interaction at a time: Tensor

A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, ZT
JHEP 10 (2021) 086

Optimistic (5%, 10%, 15%) and Pessimistic (30%, 40%, 50%), uncertainties on electron muon and tau neutrinos

From DIS

From charm decay and DIS



EFT at FASERν

A. Falkowski, M. González-Alonso, J. Kopp, Y. Soreq, **ZT**
JHEP 10 (2021) 086

FASERν Flavor Experiments Colliders

Neutrino experiments:

- Many more operators can be probed (81 at FASERν)

Low energy:

- Independent of the underlying high-energy theory

High-Energy:

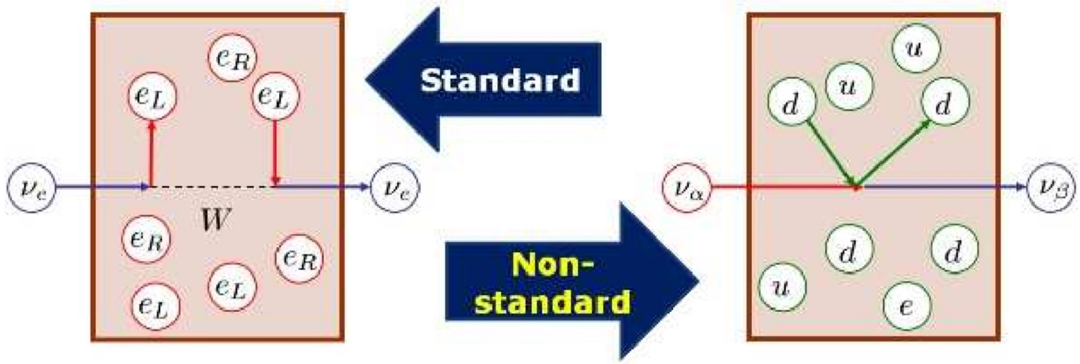
- SMEFT is the underlying theory
- Bounds are less robust

Bounds shown in bold face have been calculated in this work

Coupling	Low energy (WEFT) 90 % CL bound	Low energy (WEFT) process	High energy / CLFV (SMEFT) 90 % CL bound	High energy / CLFV (SMEFT) process
$[\epsilon_P^{ud}]_{ee}$	$\mathbf{4.6 \times 10^{-7}}$	$\mathbf{\Gamma_{\pi\to e\nu}/\Gamma_{\pi\to\mu\nu}}$		
$[\epsilon_P^{ud}]_{e\mu}$	7.3×10^{-6}	$\Gamma_{\pi\to e\nu}/\Gamma_{\pi\to\mu\nu}$ [7]	$\mathbf{2.0 \times 10^{-8}}$	**$\mu \to e$ conversion**
$[\epsilon_P^{ud}]_{e\tau}$	7.3×10^{-6}	$\Gamma_{\pi\to e\nu}/\Gamma_{\pi\to\mu\nu}$ [7]	2.5×10^{-3}	LHC [64]
$[\epsilon_P^{ud}]_{\mu e}$	$\mathbf{2.6 \times 10^{-3}}$	$\mathbf{\Gamma_{\pi\to e\nu}/\Gamma_{\pi\to\mu\nu}}$	$\mathbf{2.0 \times 10^{-8}}$	**$\mu \to e$ conversion**
$[\epsilon_P^{ud}]_{\mu\mu}$	$\mathbf{9.4 \times 10^{-5}}$	$\mathbf{\Gamma_{\pi\to e\nu}/\Gamma_{\pi\to\mu\nu}}$		
$[\epsilon_P^{ud}]_{\mu\tau}$	$\mathbf{2.6 \times 10^{-3}}$	$\mathbf{\Gamma_{\pi\to e\nu}/\Gamma_{\pi\to\mu\nu}}$		
$[\epsilon_P^{ud}]_{\tau e}$	$\mathbf{9.0 \times 10^{-2}}$	$\mathbf{\Gamma_{\tau\to\pi\nu}}$	$5.8 \times 10^{-3(*)}/4.4 \times 10^{-4}$	LHC [65] / τ decay [64]
$[\epsilon_P^{ud}]_{\tau\mu}$	$\mathbf{9.0 \times 10^{-2}}$	$\mathbf{\Gamma_{\tau\to\pi\nu}}$	$5.8 \times 10^{-3(*)}$	LHC [65]
$[\epsilon_P^{ud}]_{\tau\tau}$	8.4×10^{-3}	τ-decay [65]	$5.8 \times 10^{-3(*)}$	LHC [65]
$[\epsilon_P^{us}]_{ee}$	$\mathbf{1.1 \times 10^{-6}}$	$\mathbf{\Gamma_{K\to e\nu}/\Gamma_{K\to\mu\nu}}$		
$[\epsilon_P^{us}]_{e\mu}$	$\mathbf{2.1 \times 10^{-5}}$	$\mathbf{\Gamma_{K\to e\nu}/\Gamma_{K\to\mu\nu}}$	$\mathbf{6.2 \times 10^{-7}}$	**$\mu \to e$ conversion**
$[\epsilon_P^{us}]_{e\tau}$	$\mathbf{2.1 \times 10^{-5}}$	$\mathbf{\Gamma_{K\to e\nu}/\Gamma_{K\to\mu\nu}}$	7.1×10^{-2}	LHC [64]
$[\epsilon_P^{us}]_{\mu e}$	$\mathbf{2.3 \times 10^{-3}}$	$\mathbf{\Gamma_{K\to e\nu}/\Gamma_{K\to\mu\nu}}$	$\mathbf{6.2 \times 10^{-7}}$	**$\mu \to e$ conversion**
$[\epsilon_P^{us}]_{\mu\mu}$	$\mathbf{2.2 \times 10^{-4}}$	$\mathbf{\Gamma_{K\to e\nu}/\Gamma_{K\to\mu\nu}}$		
$[\epsilon_P^{us}]_{\mu\tau}$	$\mathbf{2.3 \times 10^{-3}}$	$\mathbf{\Gamma_{K\to e\nu}/\Gamma_{K\to\mu\nu}}$		
$[\epsilon_P^{us}]_{\tau e}$	$\mathbf{6.4 \times 10^{-2}}$	$\mathbf{\Gamma_{\tau\to K\nu}/\Gamma_{K\to\mu\nu}}$	$\mathbf{3.1 \times 10^{-2(*)}}/8.1 \times 10^{-2}$	**LHC (data [66])**/τ-decay [64]
$[\epsilon_P^{us}]_{\tau\mu}$	$\mathbf{6.4 \times 10^{-2}}$	$\mathbf{\Gamma_{\tau\to K\nu}/\Gamma_{K\to\mu\nu}}$	$\mathbf{3.1 \times 10^{-2(*)}}$	**LHC (data [66])**
$[\epsilon_P^{us}]_{\tau\tau}$	1.3×10^{-2}	τ-decay [67]	$\mathbf{3.1 \times 10^{-2(*)}}$	**LHC (data [66])**
$[\epsilon_P^{cs}]_{ee}$	$\mathbf{4.8 \times 10^{-3}}$	$\mathbf{\Gamma_{D_s\to e\nu}}$	1.3×10^{-2}	LHC [68]
$[\epsilon_P^{cs}]_{e\mu}$	$\mathbf{4.6 \times 10^{-3}}$	$\mathbf{\Gamma_{D_s\to e\nu}}$	1.3×10^{-2} / $\mathbf{2.7 \times 10^{-6}}$	LHC [68] / **$\mu \to e$ conversion**
$[\epsilon_P^{cs}]_{e\tau}$	$\mathbf{4.6 \times 10^{-3}}$	$\mathbf{\Gamma_{D_s\to e\nu}}$	1.3×10^{-2} / 1.9×10^{-2}	LHC / τ-decays [64, 68]
$[\epsilon_P^{cs}]_{\mu e}$	$\mathbf{8.9 \times 10^{-3}}$	$\mathbf{\Gamma_{D_s\to \mu\nu}}$	2.0×10^{-2} / $\mathbf{2.7 \times 10^{-6}}$	LHC [68] / **$\mu \to e$ conversion**
$[\epsilon_P^{cs}]_{\mu\mu}$	$\mathbf{1.0 \times 10^{-3}}$	$\mathbf{\Gamma_{D_s\to \mu\nu}}$	2.0×10^{-2}	LHC [68]
$[\epsilon_P^{cs}]_{\mu\tau}$	$\mathbf{8.9 \times 10^{-3}}$	$\mathbf{\Gamma_{D_s\to \mu\nu}}$	2.0×10^{-2}	LHC [68]
$[\epsilon_P^{cs}]_{\tau e}$	$\mathbf{2.0 \times 10^{-1}}$	$\mathbf{\Gamma_{D_s\to \tau\nu}}$	1.6×10^{-2} / 1.9×10^{-2}	LHC / τ-decays [64]
$[\epsilon_P^{cs}]_{\tau\mu}$	$\mathbf{2.0 \times 10^{-1}}$	$\mathbf{\Gamma_{D_s\to \tau\nu}}$	2.5×10^{-2}	LHC [68]
$[\epsilon_P^{cs}]_{\tau\tau}$	$\mathbf{3.2 \times 10^{-2}}$	$\mathbf{\Gamma_{D_s\to \tau\nu}}$	2.5×10^{-2}	LHC [68]

QM-NSI Description

Neutrinos are not pure flavor states:



Standard NSI approach

NSI parameters

$$|\nu_\alpha^s\rangle = \frac{1}{N_\alpha^s}\left[|\nu_\alpha\rangle + \sum_{\gamma=e,\mu,\tau} \epsilon^s_{\alpha\gamma}|\nu_\gamma\rangle\right]$$

Rotation of flavor states at the source

$$\langle\nu_\beta^d| = \frac{1}{N_\beta^d}\left[\langle\nu_\beta| + \sum_{\gamma=e,\mu,\tau} \langle\nu_\gamma|\epsilon^d_{\gamma\beta}\right]$$

Rotation of flavor states at the detector

Normalization

QM-NSI Description

Neutrinos are not pure flavor states:

$$|\nu_\alpha^s\rangle = \frac{(1+\epsilon^s)_{\alpha\gamma}}{N_\alpha^s}|\nu_\gamma\rangle\ ,\quad \langle\nu_\beta^d| = \langle\nu_\gamma|\frac{(1+\epsilon^d)_{\gamma\beta}}{N_\beta^d}$$

Observable: **rate of detected events**

~(flux)×(det. cross section)×(oscillation)

$$R_{\alpha\beta}^{\rm QM} = \Phi_\alpha^{\rm SM}\sigma_\beta^{\rm SM}\sum_{k,l} e^{-i\frac{L\Delta m_{kl}^2}{2E_\nu}}[x_s]_{\alpha k}[x_s]_{\alpha l}^*[x_d]_{\beta k}[x_d]_{\beta l}^*$$

$$x_s \equiv (1+\epsilon^s)U^*\ \&\ x_d \equiv (1+\epsilon^d)^T U$$

Falkowski, González-Alonso, *ZT*, JHEP (2019)

QM-NSI Description

- Can one “validate” QM-NSI approach from the QFT results?
- If yes, relation between NSI parameters and Lagrangian (EFT) parameters?
- Does the matching hold at all orders in perturbation?

QM-NSI Description

- Can one "validate" QM-NSI approach from the QFT results? Yes…
- If yes, relation between NSI parameters and Lagrangian (EFT) parameters?
- Does the matching hold at all orders in perturbation? No…

Observable is the same, we can match the two

(only at the linear level)

$$\epsilon^s_{\alpha\beta} = \sum_X p_{XL} [\epsilon_X]^*_{\alpha\beta}, \quad \epsilon^d_{\beta\alpha} = \sum_X d_{XL} [\epsilon_X]_{\alpha\beta}$$

Falkowski, González-Alonso, *ZT*, JHEP (2019)

Comparing QM and QFT

Only at the linear order:

Falkowski, González-Alonso, ZT, JHEP (2019)

Neutrino Process	NSI Matching with EFT
ν_e produced in beta decay	$\epsilon^s_{e\beta} = [\epsilon_L]^*_{e\beta} - [\epsilon_R]^*_{e\beta} - \frac{g_T}{g_A}\frac{m_e}{f_T(E_\nu)}[\epsilon_T]^*_{e\beta}$
ν_e detected in inverse beta decay	$\epsilon^d_{\beta e} = [\epsilon_L]_{e\beta} + \frac{1-3g_A^2}{1+3g_A^2}[\epsilon_R]_{e\beta} - \frac{m_e}{E_\nu - \Delta}\left(\frac{g_S}{1+3g_A^2}[\epsilon_S]_{e\beta} - \frac{3g_A g_T}{1+3g_A^2}[\epsilon_T]_{e\beta}\right)$
ν_μ produced in pion decay	$\epsilon^s_{\mu\beta} = [\epsilon_L]^*_{\mu\beta} - [\epsilon_R]^*_{\mu\beta} - \frac{m_\pi^2}{m_\mu(m_u+m_d)}[\epsilon_P]^*_{\mu\beta}$

- Different NP interactions appear at the source or detection simultaneously
- Some of the p_{XL}/d_{XL} coefficients depend on the neutrino energy
- There are chiral enhancements in some cases

These correlations, energy dependence etc. cannot be seen in the traditional QM approach.

Comparing QM and QFT

Beyond the linear order in new physics parameters, the NSI formula matches the (correct) one derived in the EFT only if the consistency condition is satisfied

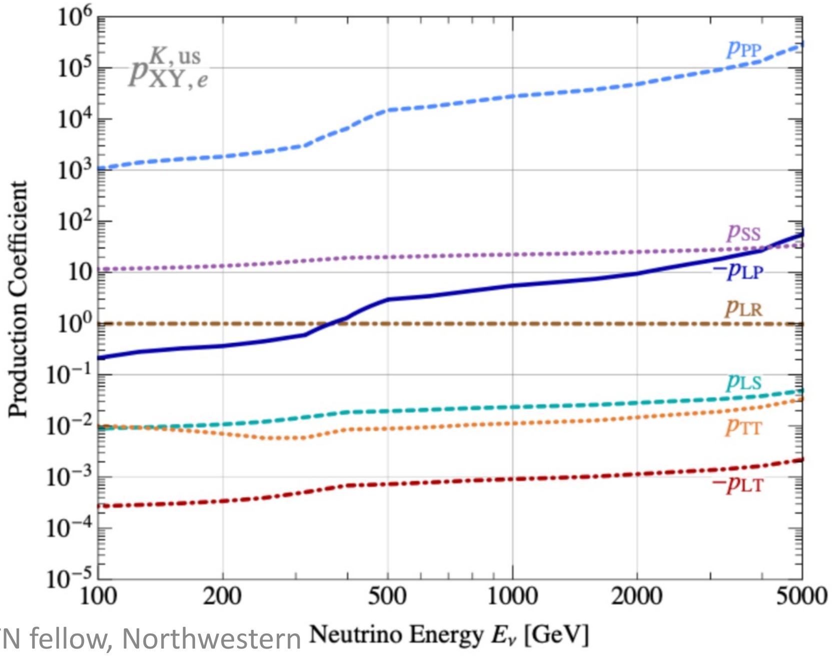
$$p_{XL}p^*_{YL} = p_{XY}, \quad d_{XL}d^*_{YL} = d_{XY}$$

This is always satisfied for new physics correcting V-A interactions only as $p_{LL} = d_{LL} = 1$ by definition

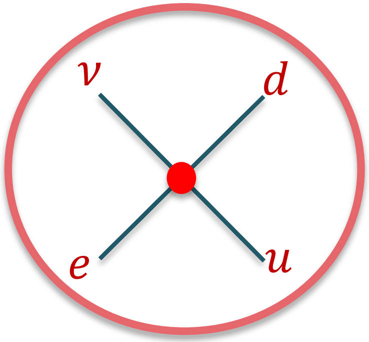
However for non-V-A new physics the consistency condition is not satisfied in general

Falkowski, González-Alonso, *ZT*, JHEP (2019)

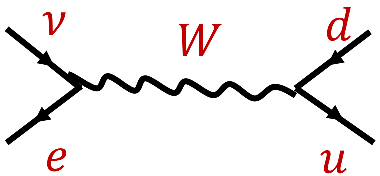
$$p_{XY} \equiv \frac{\int d\Pi_{P'} A^P_X \bar{A}^P_Y}{\int d\Pi_{P'} |A^P_L|^2}, \quad d_{XY} \equiv \frac{\int d\Pi_D A^D_X \bar{A}^D_Y}{\int d\Pi_D |A^D_L|^2}.$$



Specific New Physics Models

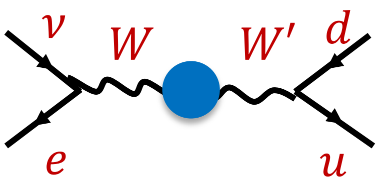


ε_L: measures deviations of the W boson to quarks and leptons, compared to the SM prediction



$$-\frac{g^W_{\nu e} g^W_{ud}}{4m_W^2} V_{ud}\bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d$$

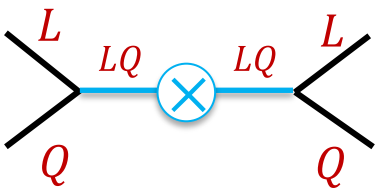
ε_R : left-right symmetric $SU(3)_C xSU(2)_L xSU(2)_R xU(1)_X$ models introduce new charged vector bosons W' coupling to right-handed quarks



$$\bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1+\gamma_5)d$$

$$\epsilon_R \sim \frac{m_W^2}{m_{W'}^2}$$

$\varepsilon_{S,P,T}$: In leptoquark models, new scalar particles couple to both quarks and leptons



$$(LQ)(LQ)$$

$$\epsilon_{S,P,T} \sim \frac{\mathrm{v}^2}{m_{LQ}^2}$$