BSM Physics

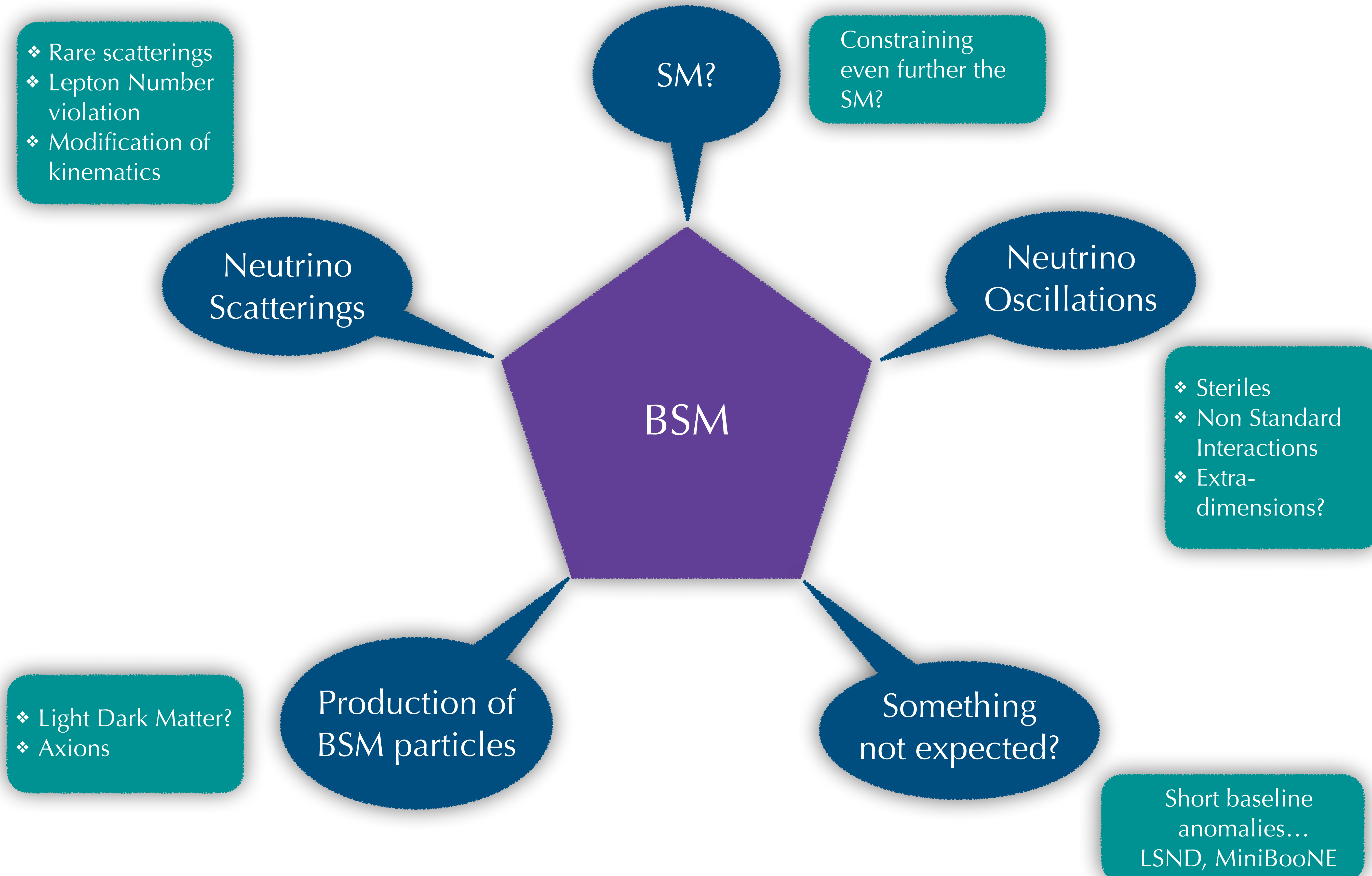
Yuber F. Perez-Gonzalez

Autumn Meeting — Neutrinos from STORed Muons (nuSTORM)

November 23rd, 2023

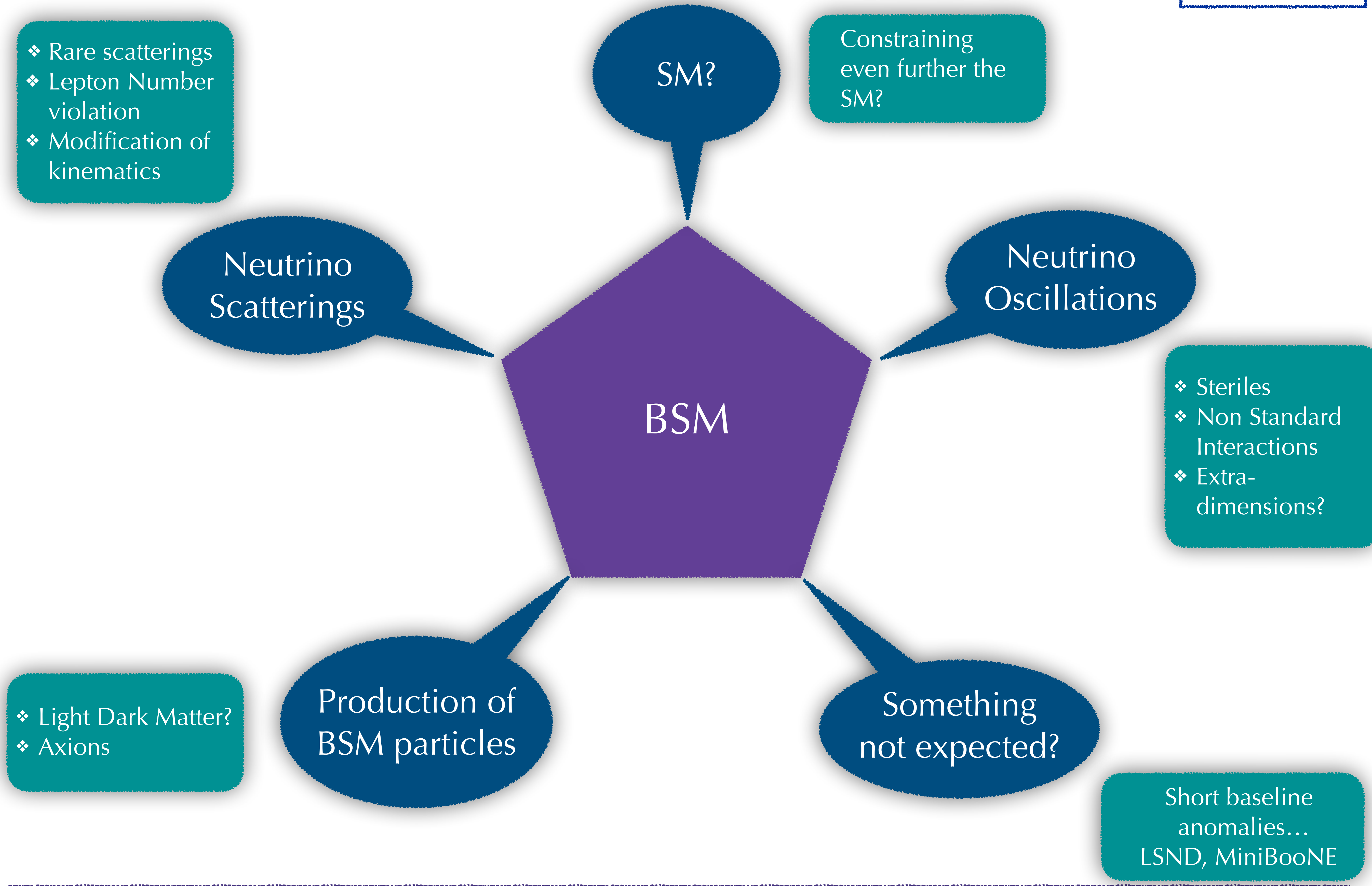
Durham University

IP3


BSM
SM?
Constraining even further the SM?
Neutrino Scatterings
❖ Rare scatterings
❖ Lepton Number violation
❖ Modification of kinematics
Neutrino Oscillations
❖ Steriles
❖ Non Standard Interactions
❖ Extra-dimensions?
Production of BSM particles
❖ Light Dark Matter?
❖ Axions
Something not expected?
Short baseline anomalies… LSND, MiniBooNE

What nuSTORM could do?

More questions than answers



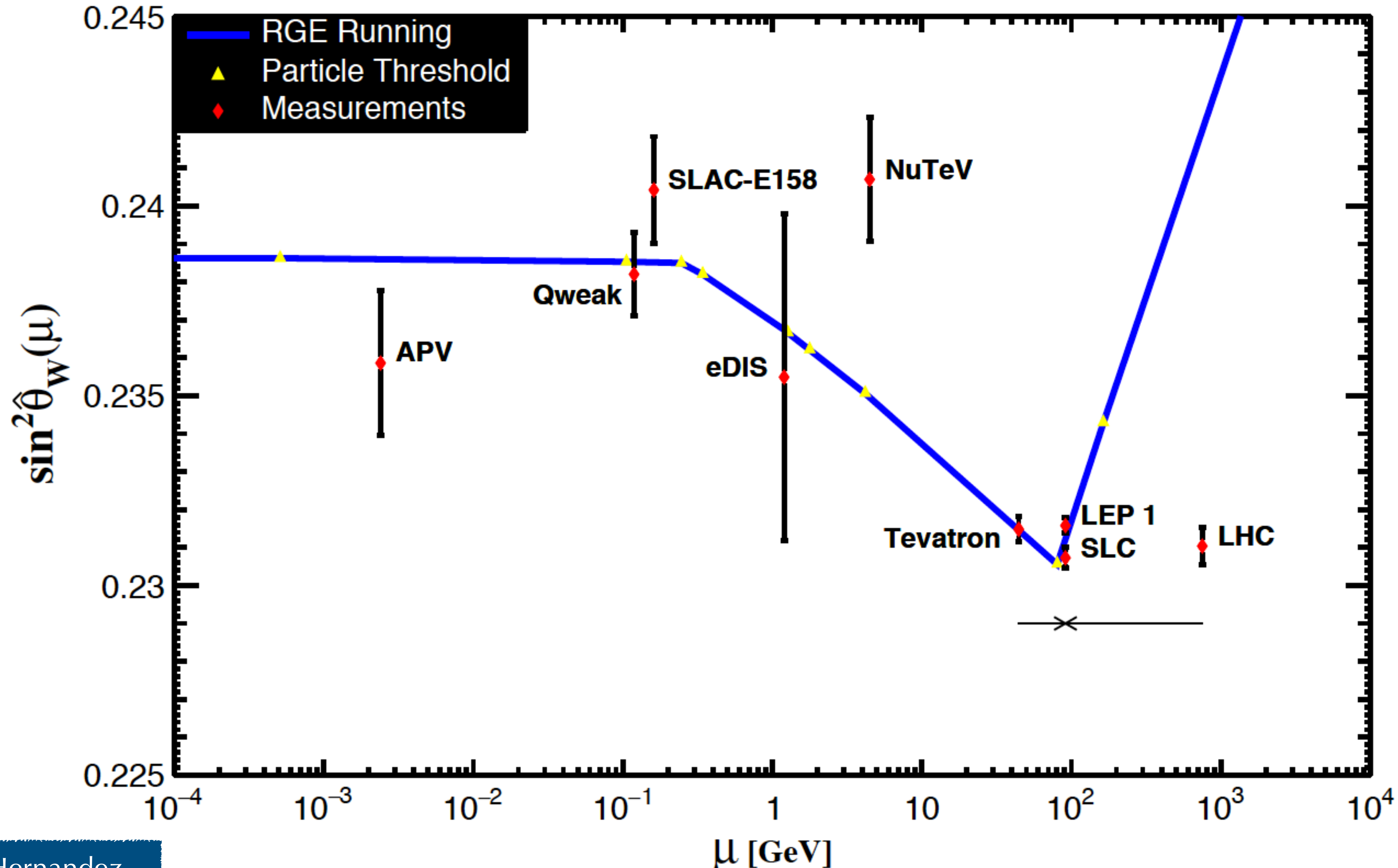
Let’s start with some SM…

Weak mixing angle

Fermion Couplings

$$g_V^f = t_3^f - 2q_f \sin^2\theta_W$$
$$g_A^f = t_3^f$$

$\overline{\text{MS}}$: $$\sin^2\theta_W(\mu) \equiv \frac{g'(\mu)^2}{g(\mu)^2 + g'(\mu)^2}$$



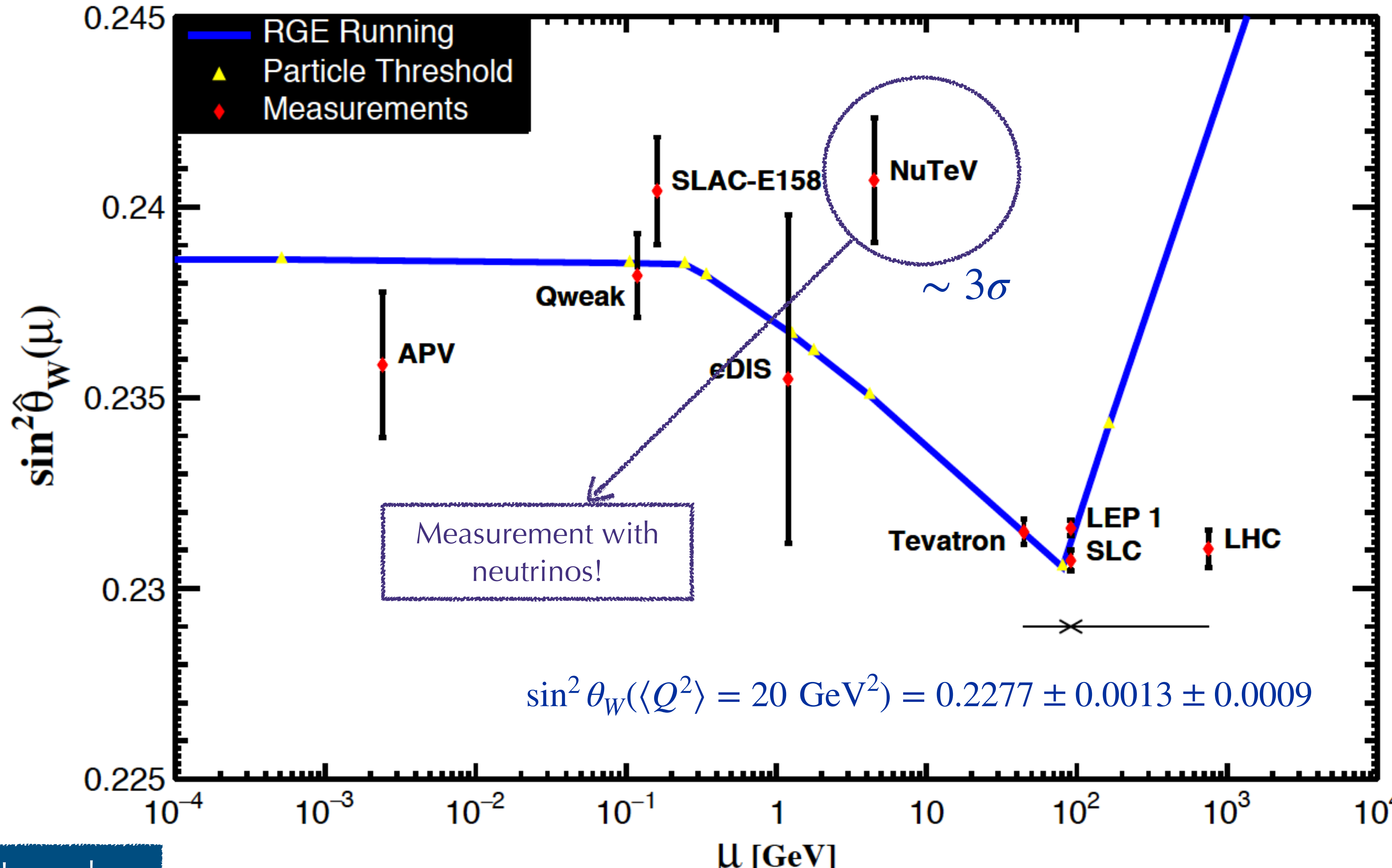
Erler, Ferro-Hernandez, JHEP 1803, 196

Weak mixing angle

Fermion Couplings

$$g_V^f = t_3^f - 2q_f \sin^2\theta_W$$
$$g_A^f = t_3^f$$

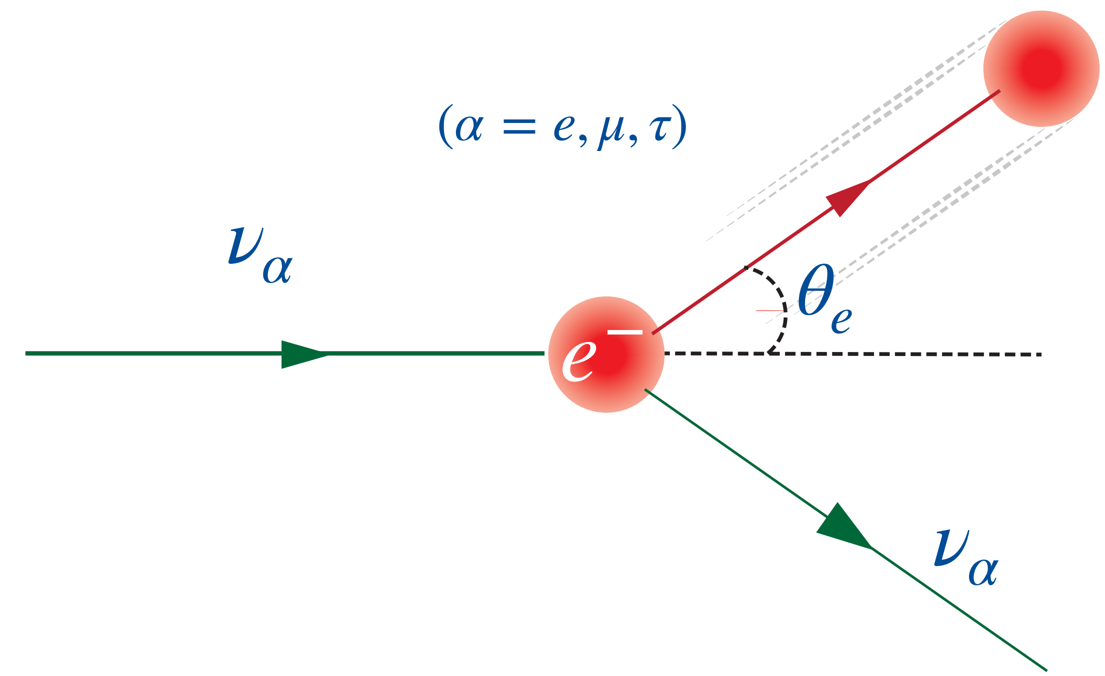
$\overline{\text{MS}}$: $\sin^2\theta_W(\mu) \equiv \dfrac{g'(\mu)^2}{g(\mu)^2 + g'(\mu)^2}$



Erler, Ferro-Hernandez, JHEP 1803, 196

Neutrino-electron scattering

$$\frac{d\sigma}{dE_R} \propto g_1^2 + g_2^2 \left(1 - \frac{E_R}{E_\nu}\right)^2$$



For $\nu_\alpha e^- \to \nu_\alpha e^-$:

$g_1 = g_V + g_A + 2\delta_{\alpha e}$

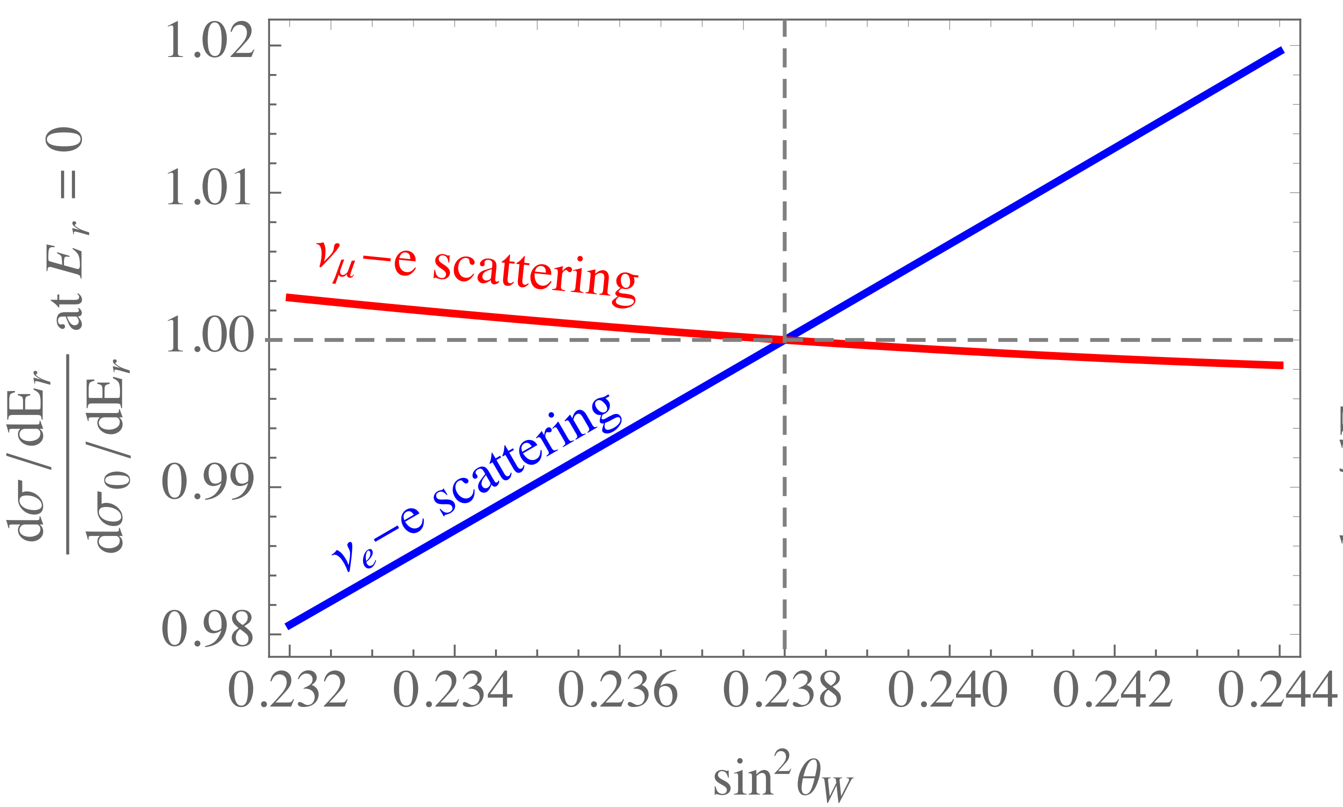
$g_2 = g_V - g_A$

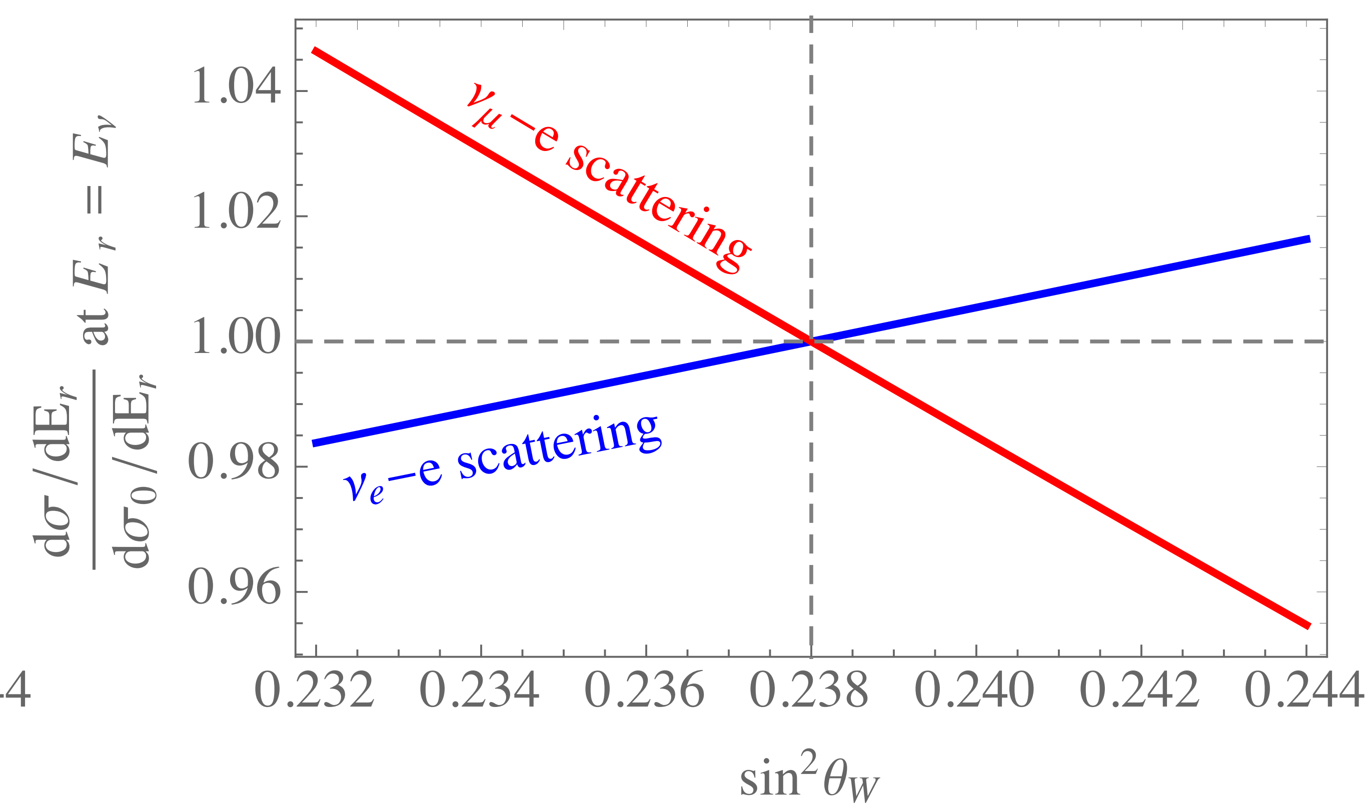
CC contribution

For $\overline{\nu_\alpha} e^- \to \overline{\nu_\alpha} e^-$:

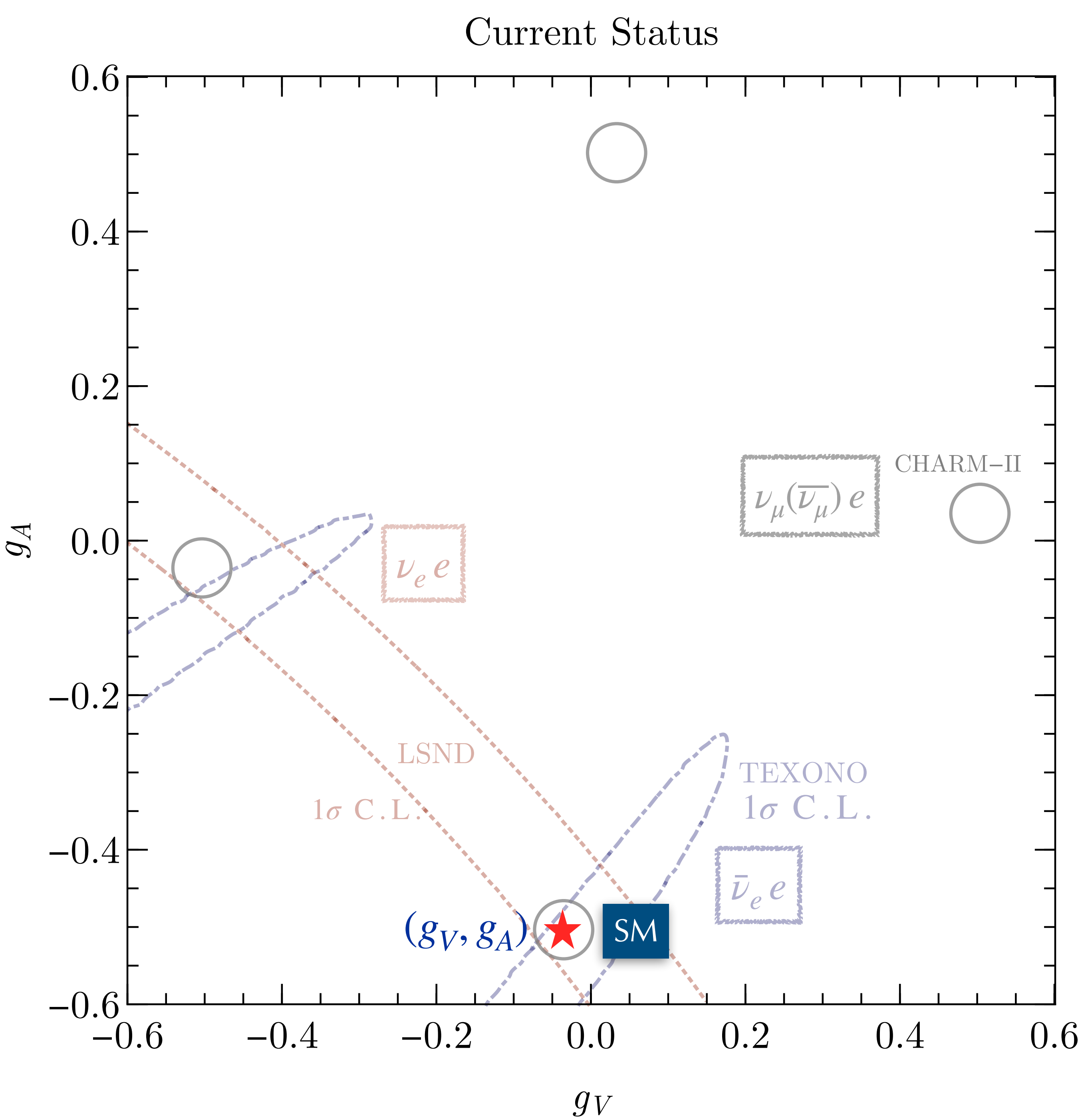
$g_2 \leftrightarrow g_1$

In the SM: $g_A = -\frac{1}{2}, \quad g_V = -\frac{1}{2} + 2\sin^2\theta_W$



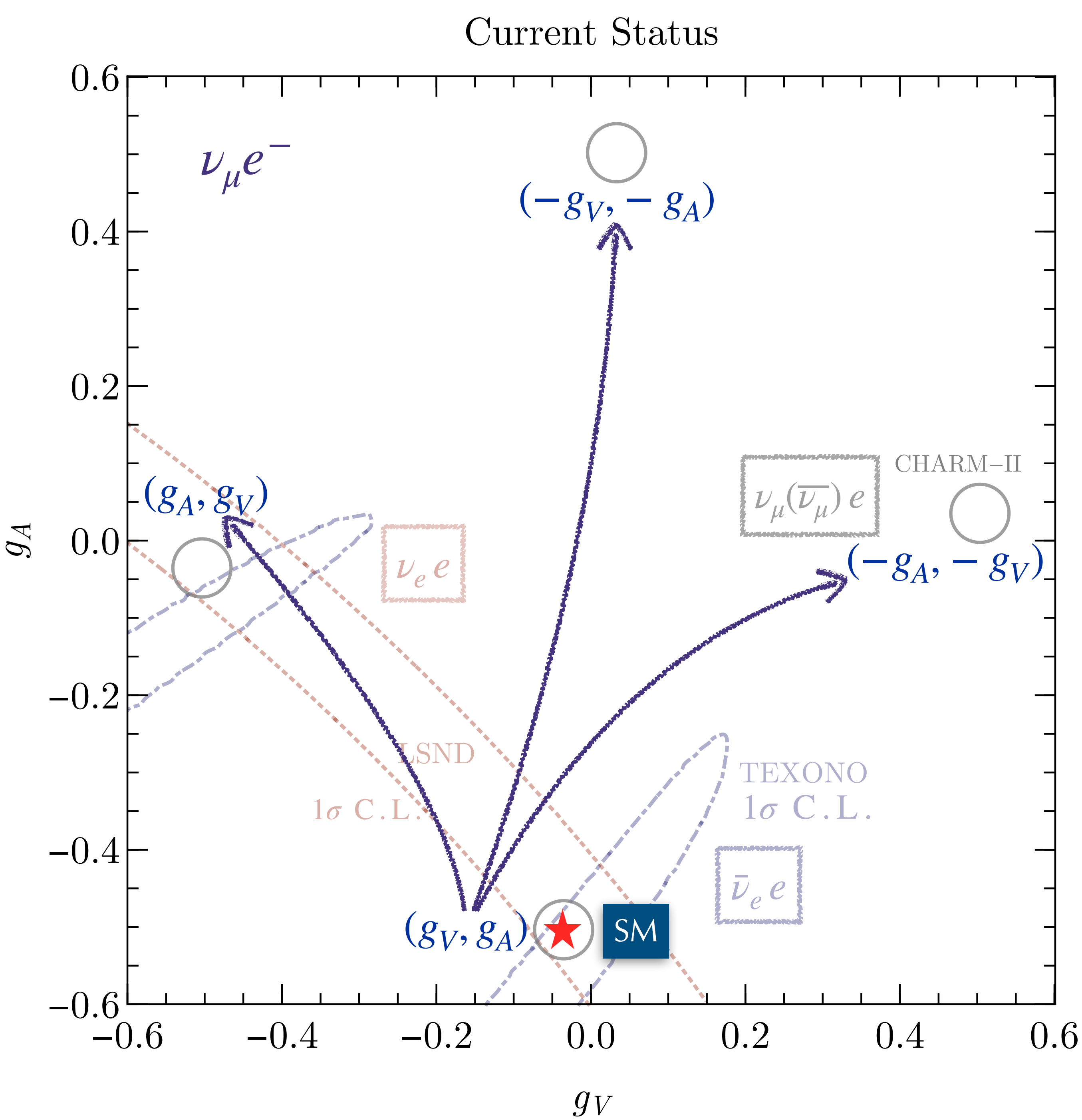


Neutrino-electron scattering



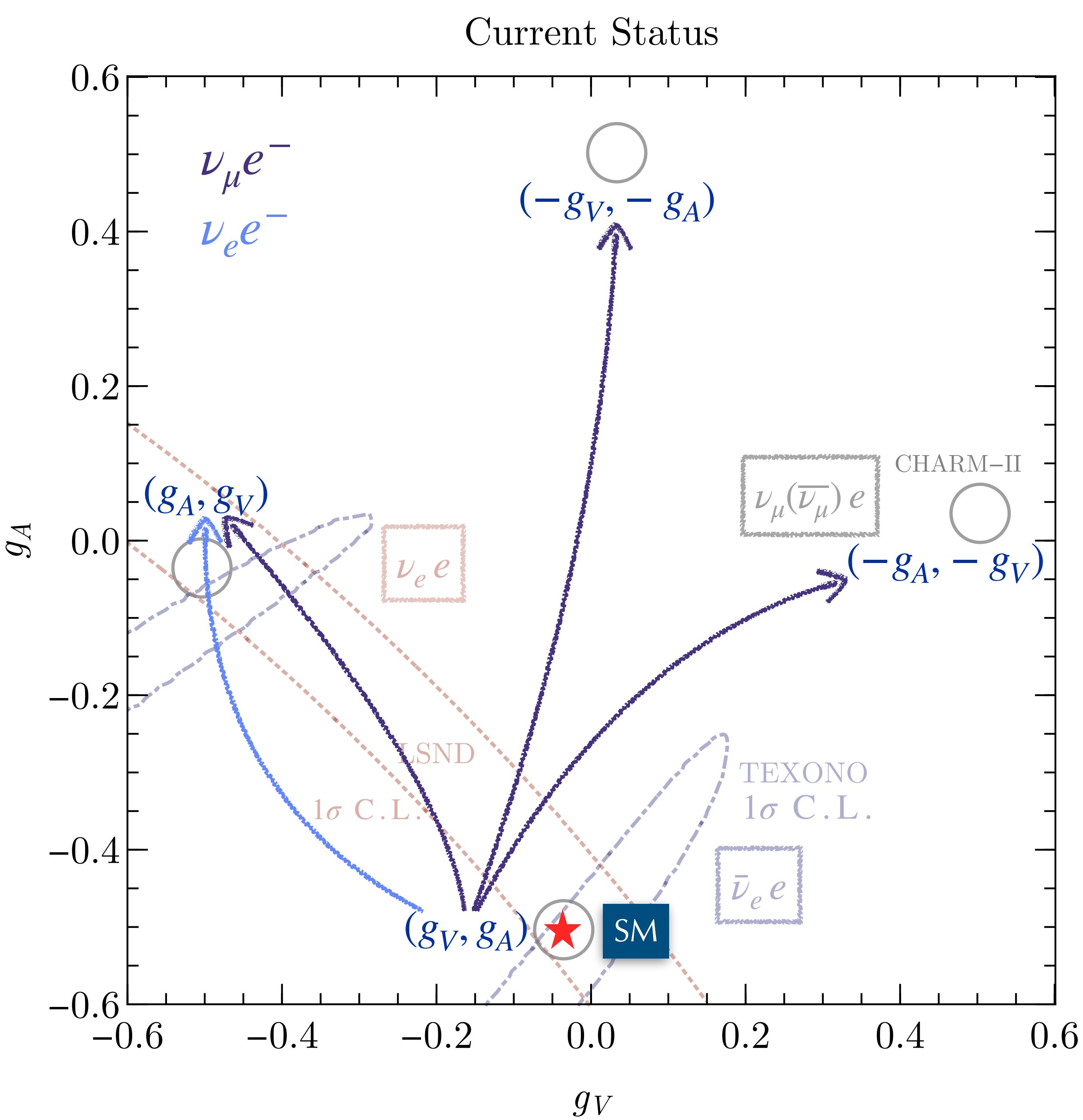
Model independent

Neutrino-electron scattering



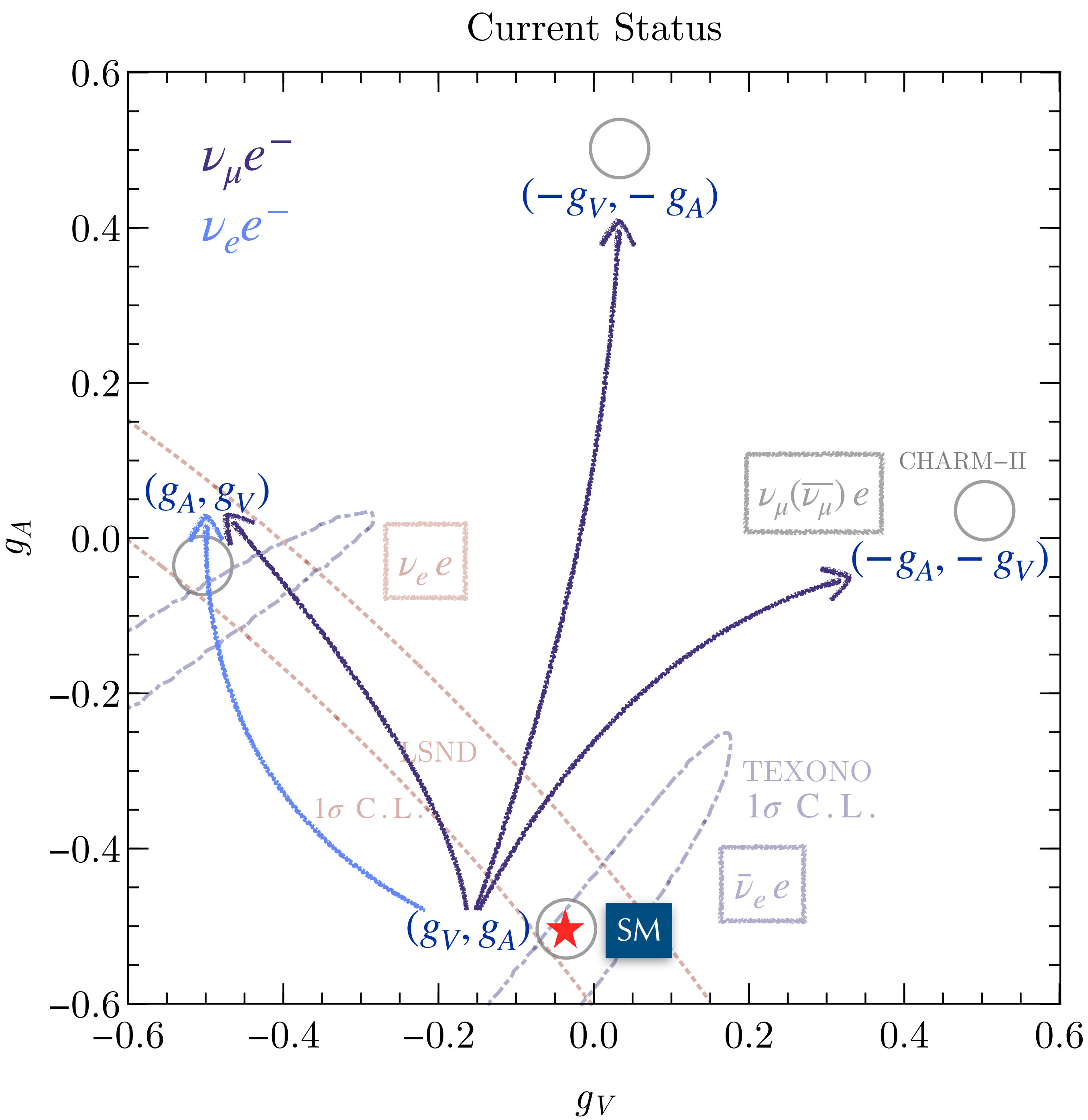
Model independent

Neutrino-electron scattering

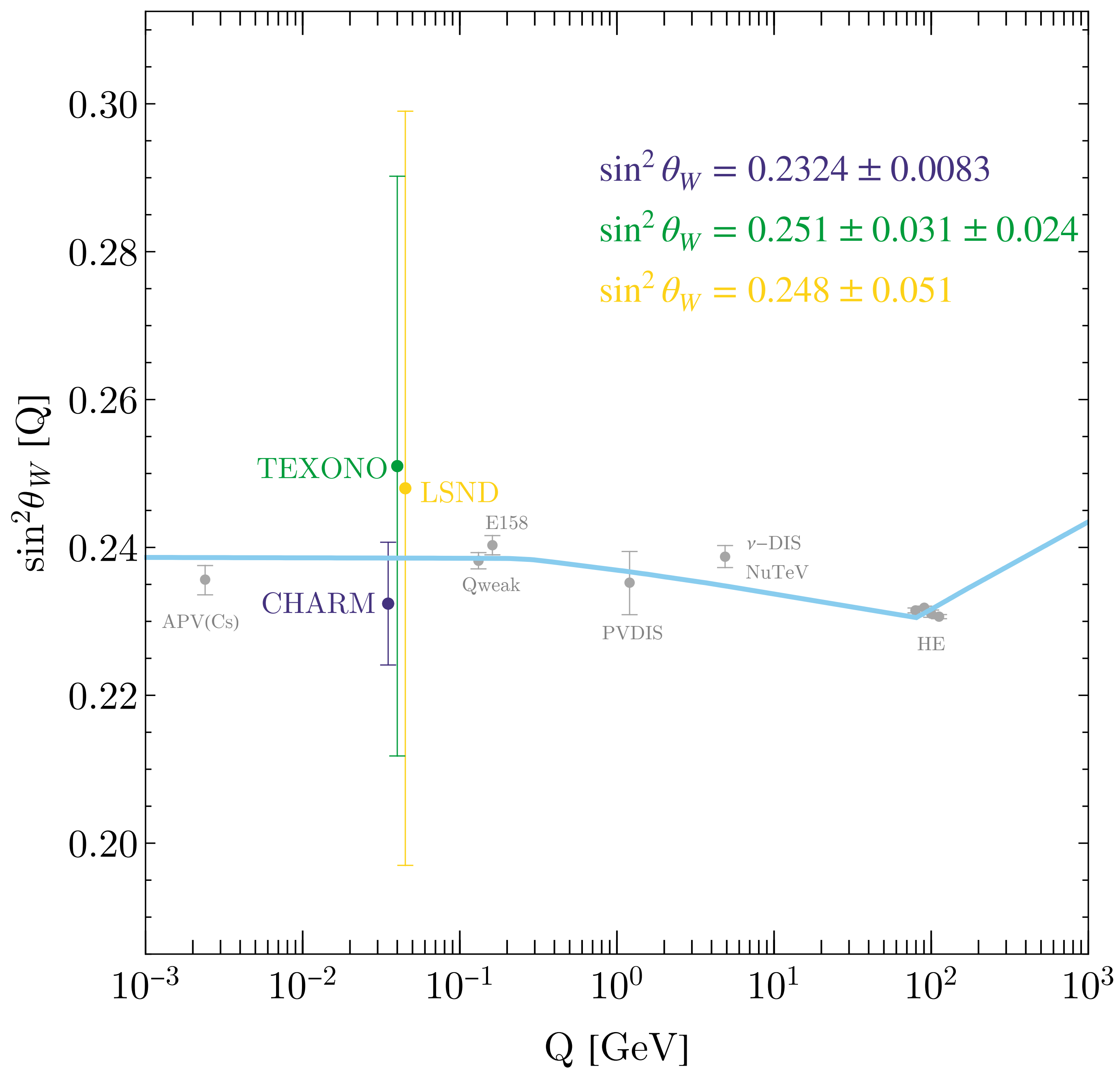


Model independent

Neutrino-electron scattering



Model independent



Assuming the SM

Backgrounds

NuWro

- ν_e CCQE, $\nu_e A \to e^- A'$, without visible hadronic activity.

Cut events with at least one proton with $K_p > 50$ MeV

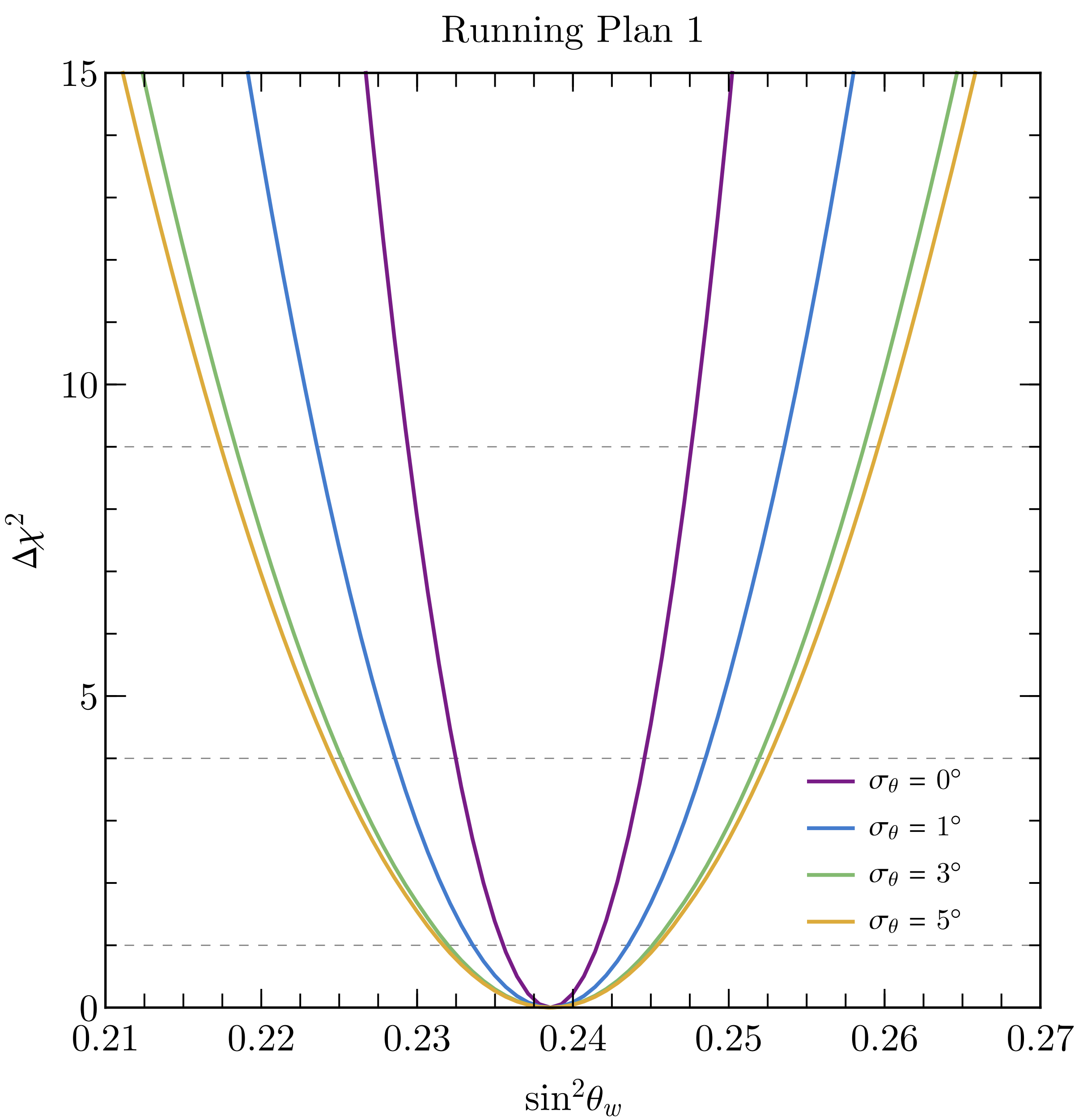
- Misidentified $\nu A \to \nu \pi^0 A'$ events with no or invisible hadronic activity.

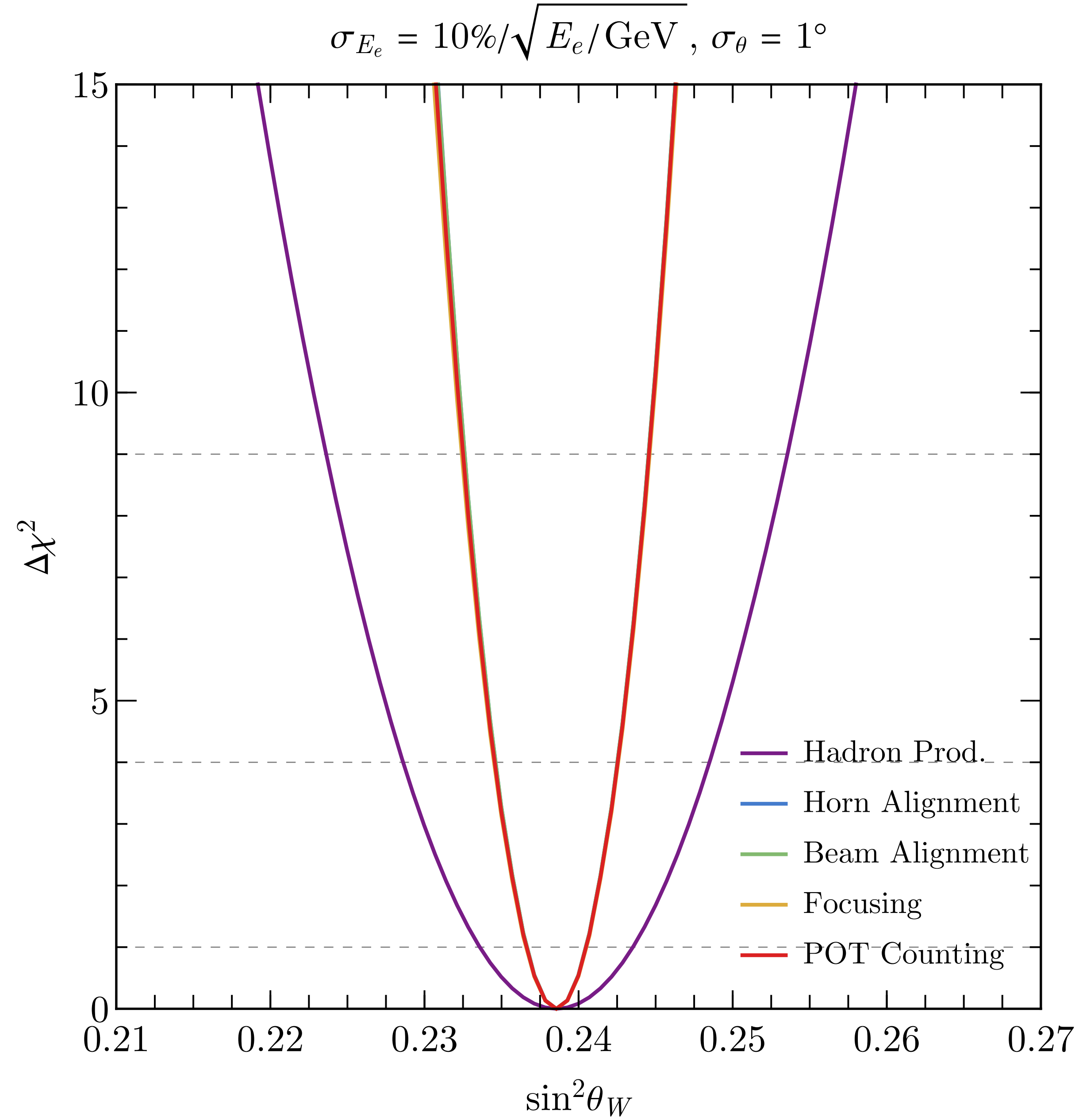
One soft photon: $K_\gamma < 30$ MeV

We do not include information from dE/dx

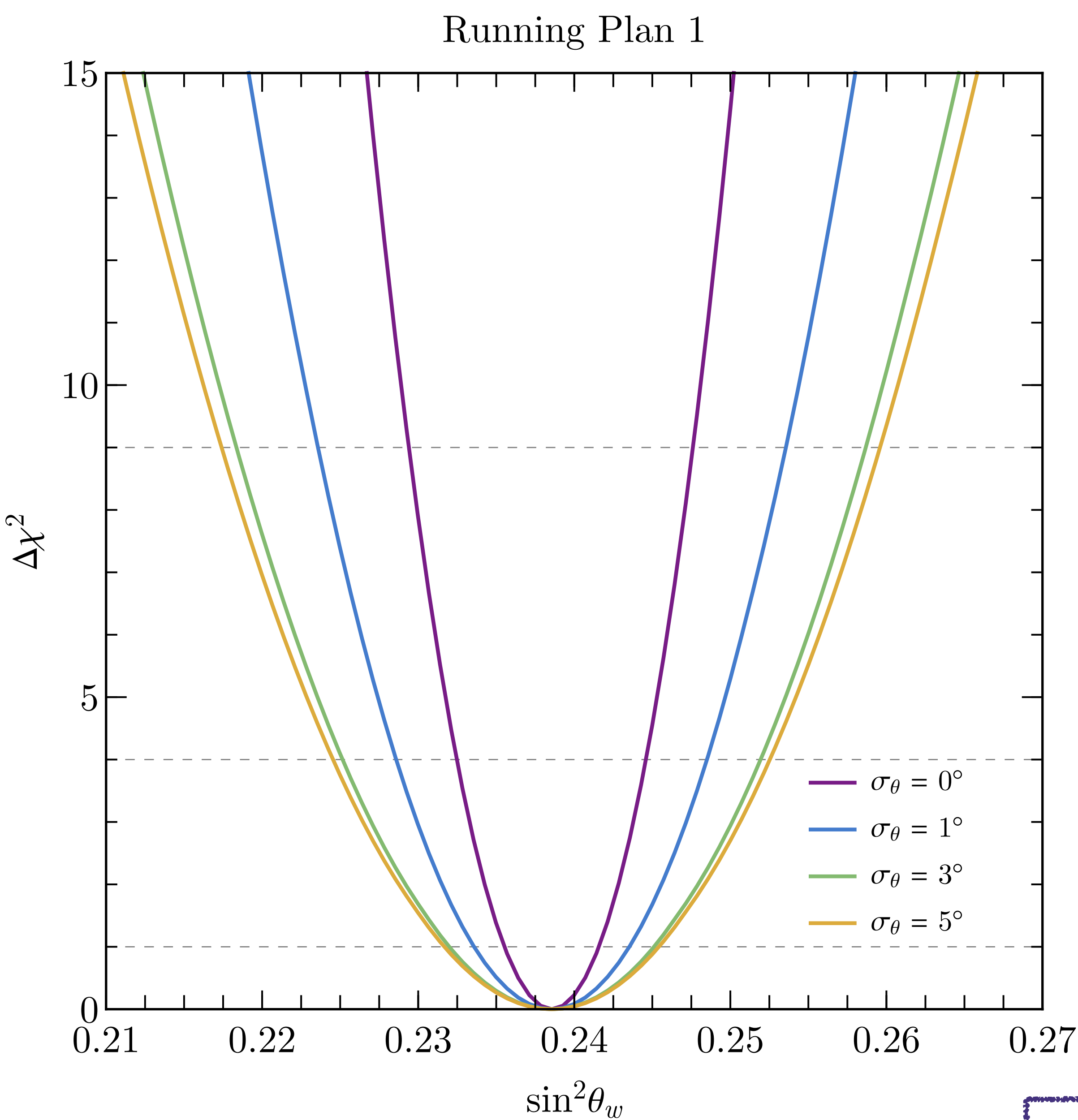
We used $E_e \theta_e^2$ kinetic variable to improve background rejection

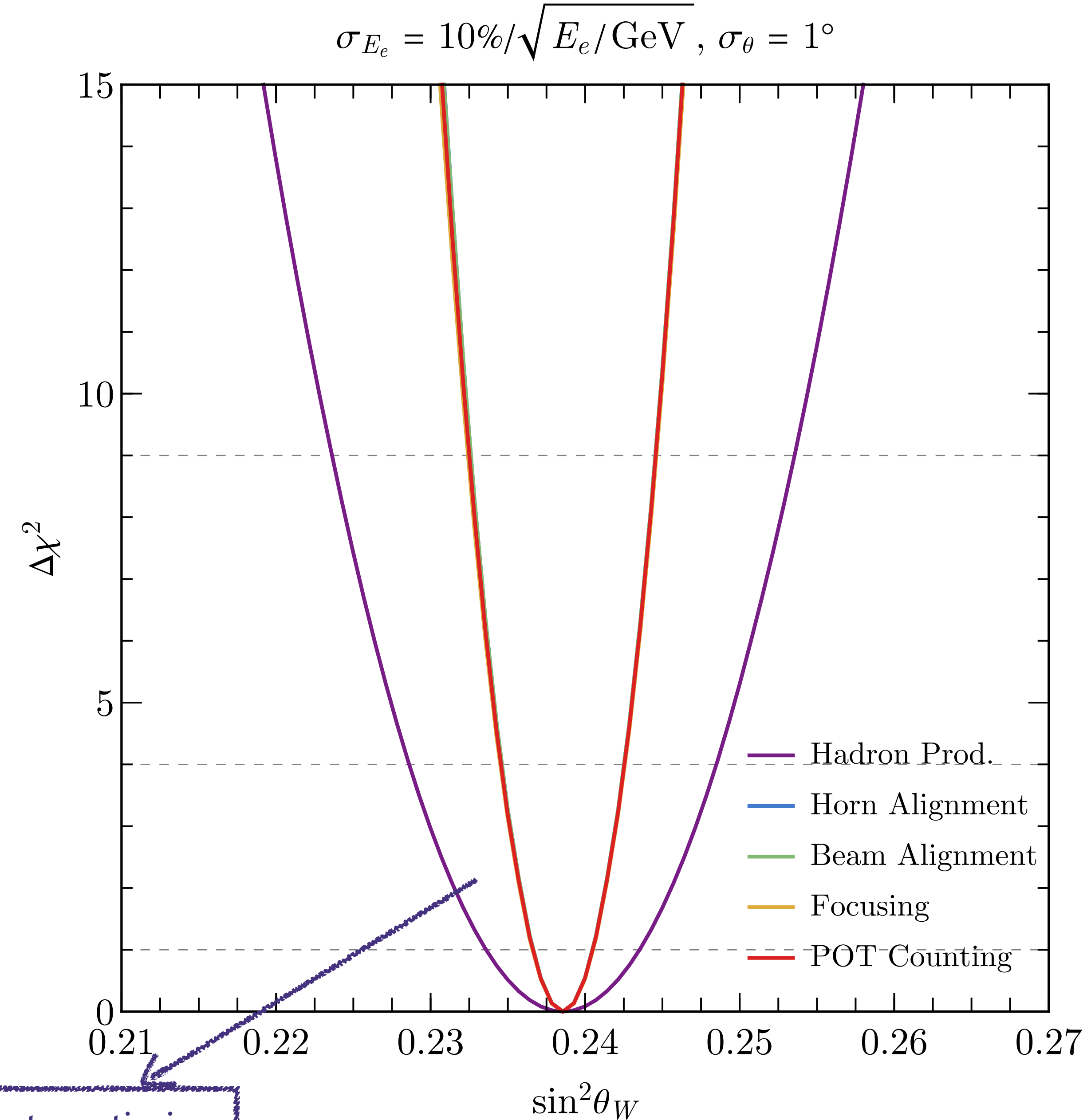
Systematics — DUNE





Systematics — DUNE

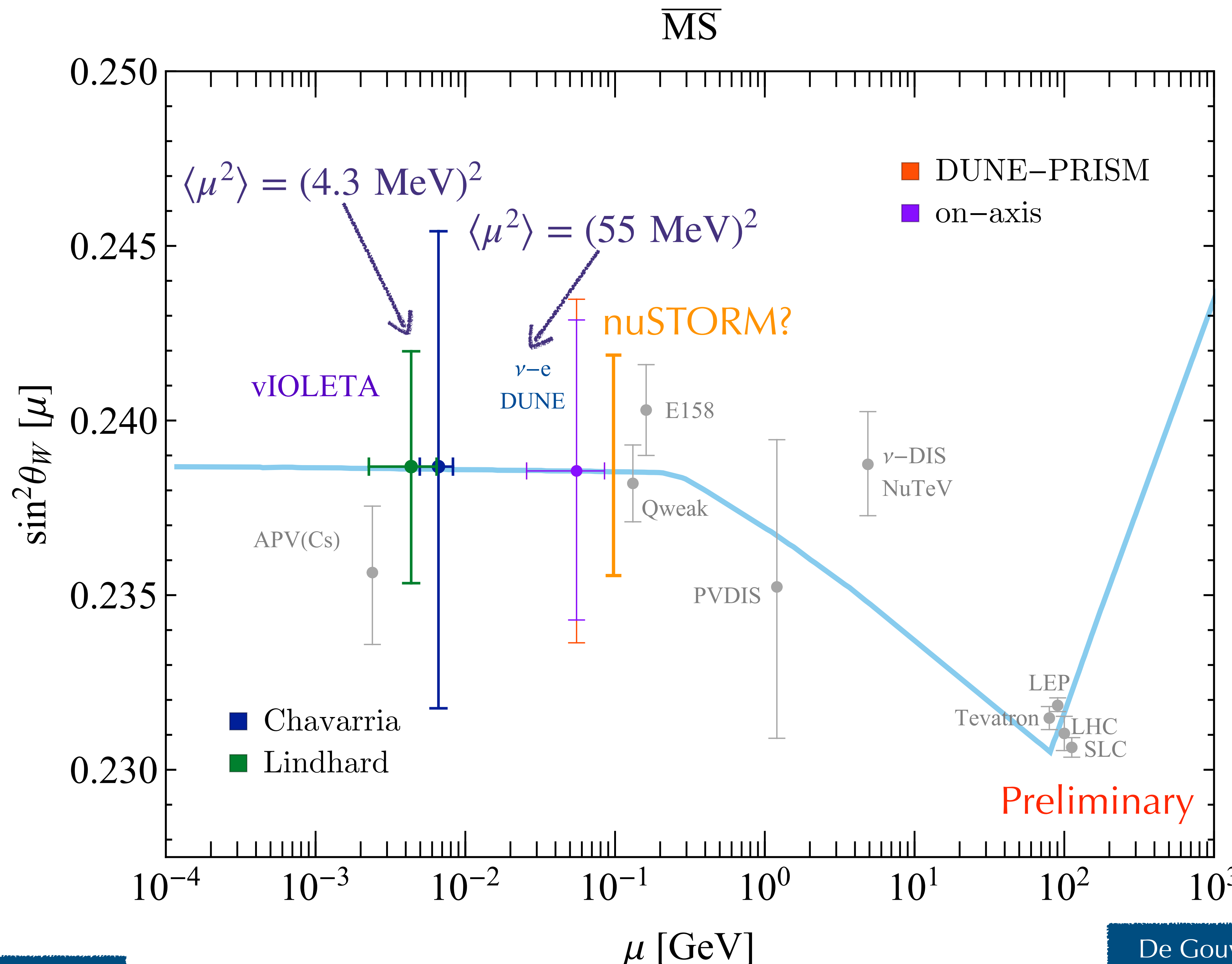




Main systematic is hadron production

Otherwise the measurement would be statistics limited

Measuring $\sin^2\theta_W$ with neutrino scatterings



Fernandez-Morini et al
2009.10741

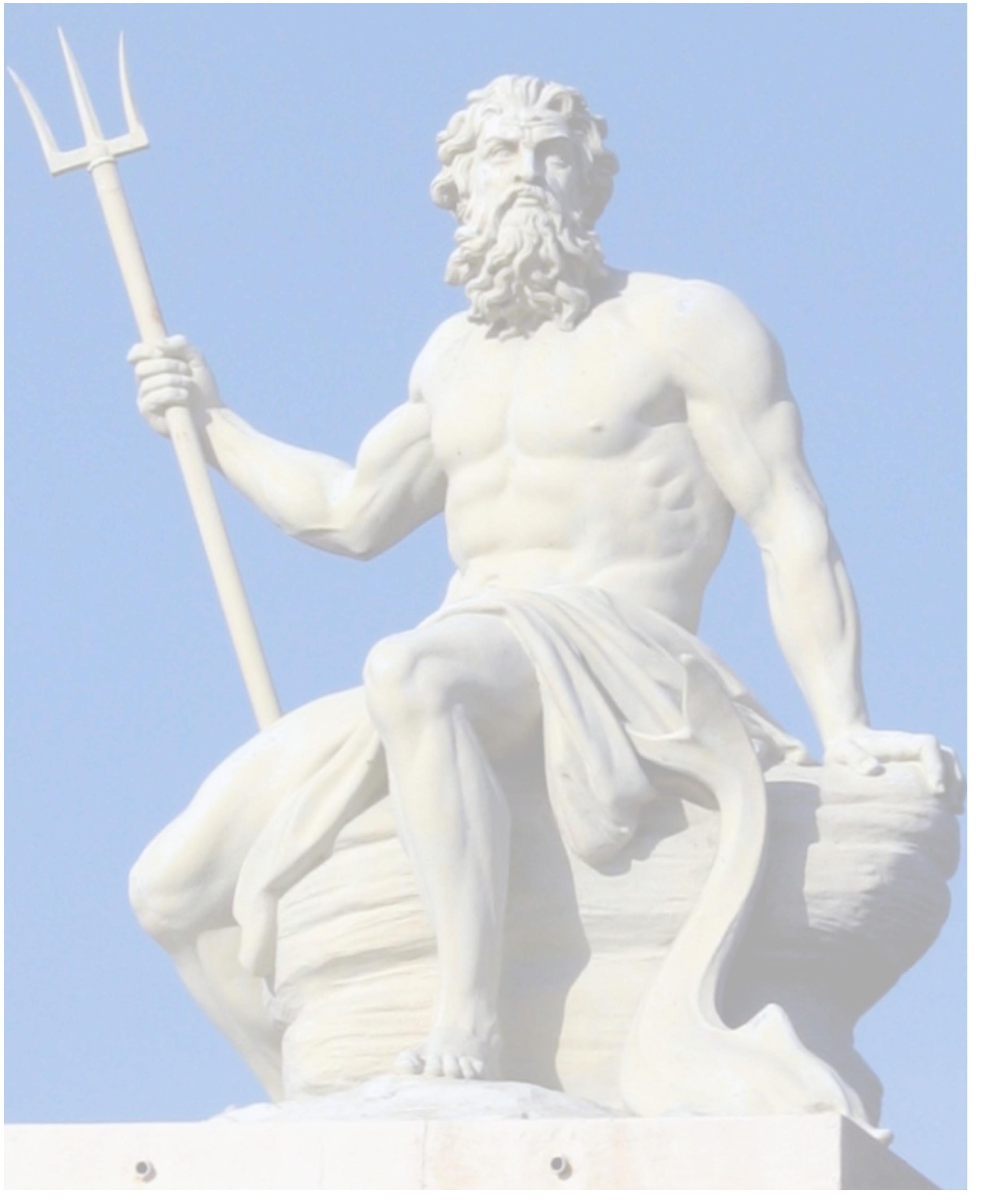
De Gouvêa, Machado, YFPG, Tabrizi
PRL125(2020) 5, 051803

Trident Inelastic Scattering

M. A. Kozhushner et. al.1962
W. Czyz et al. 1964
Lovseth et al, 1971

Production of a charged lepton pair from the inelastic neutrino scattering in the Coulomb field of the nucleus

$$\nu_\alpha + \mathscr{H} \to \nu_{\alpha\,\mathrm{or}\,\kappa(\beta)} + \ell^-_\beta + \ell^+_\kappa + \mathscr{H}$$

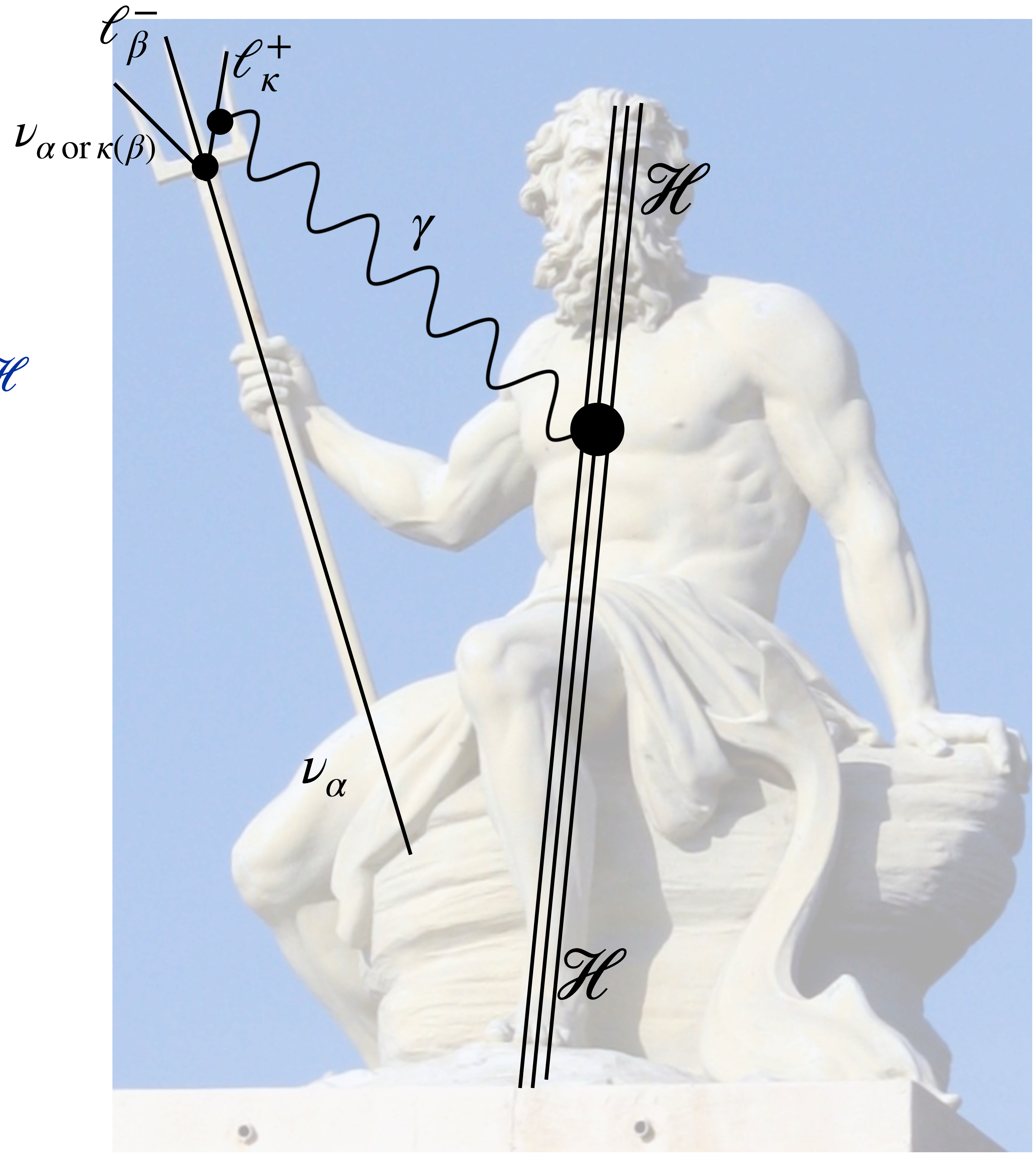


Trident Inelastic Scattering

M. A. Kozhushner et. al.1962
W. Czyz et al. 1964
Lovseth et al, 1971

Production of a charged lepton pair from the inelastic neutrino scattering in the Coulomb field of the nucleus

$$\nu_\alpha + \mathscr{H} \rightarrow \nu_{\alpha\,\mathrm{or}\,\kappa(\beta)} + \ell^-_\beta + \ell^+_\kappa + \mathscr{H}$$



Trident Inelastic Scattering

M. A. Kozhushner et. al.1962
W. Czyz et al. 1964
Lovseth et al, 1971

Production of a charged lepton pair from the inelastic neutrino scattering in the Coulomb field of the nucleus

$$\nu_\alpha + \mathscr{H} \rightarrow \nu_{\alpha\,\mathrm{or}\,\kappa(\beta)} + \ell_\beta^- + \ell_\kappa^+ + \mathscr{H}$$

$$\nu_\mu \rightarrow \nu_\mu \mu^+ \mu^-$$

CHARM II

PLB 245 (1990) 271

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

CCFR

PRL 66 (1991) 3117

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

NuTeV

Vancouver 1998, High energy physics, vol. 1

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

Neutrino trident scattering

Magill, Plestid , 1612.05642
Ballet et al., 1807.10973
Altmannshofer et al, 1912.06765

Relatively small cross section

$$\sigma_{\Psi} \approx 10^{-5} \sigma_{\rm CCQE}$$

Neutrino trident scattering

Magill, Plestid , 1612.05642
Ballet et al., 1807.10973
Altmannshofer et al, 1912.06765

Relatively small cross section

$$\sigma_\Psi \approx 10^{-5} \sigma_{\rm CCQE}$$

(Anti)Neutrino	SM Contributions
$\overset{(-)}{\nu}_\mu \mathcal{H} \to \overset{(-)}{\nu}_\mu \mu^- \mu^+ \mathcal{H}$	CC + NC
$\overset{(-)}{\nu}_\mu \mathcal{H} \to \overset{(-)}{\nu}_e e^\pm \mu^\mp \mathcal{H}$	CC
$\overset{(-)}{\nu}_\mu \mathcal{H} \to \overset{(-)}{\nu}_\mu e^- e^+ \mathcal{H}$	NC
$\overset{(-)}{\nu}_e \mathcal{H} \to \overset{(-)}{\nu}_e e^- e^+ \mathcal{H}$	CC + NC
$\overset{(-)}{\nu}_e \mathcal{H} \to \overset{(-)}{\nu}_\mu \mu^\pm e^\mp \mathcal{H}$	CC
$\overset{(-)}{\nu}_e \mathcal{H} \to \overset{(-)}{\nu}_e \mu^- \mu^+ \mathcal{H}$	NC

$$m_e, m_\mu \to 0$$

$$\sigma \sim g_V^2 + g_A^2 \qquad (\nu_\mu \; e^+ e^-)$$

$$\sigma \sim (g_V + 1)^2 + (g_A + 1)^2 \qquad (\nu_\mu \; \mu^+ \mu^-)$$

$$g_V \leftrightarrow g_A$$ → In principle, invariant under this transformation

Neutrino trident scattering

Magill, Plestid , 1612.05642
Ballet et al., 1807.10973
Altmannshofer et al, 1912.06765

Relatively small cross section

$$\sigma_\Psi \approx 10^{-5}\sigma_{\rm CCQE}$$

(Anti)Neutrino	SM Contributions
$\overset{(-)}{\nu}_\mu \mathcal{H} \to \overset{(-)}{\nu}_\mu \mu^- \mu^+ \mathcal{H}$	CC + NC
$\overset{(-)}{\nu}_\mu \mathcal{H} \to \overset{(-)}{\nu}_e e^\pm \mu^\mp \mathcal{H}$	CC
$\overset{(-)}{\nu}_\mu \mathcal{H} \to \overset{(-)}{\nu}_\mu e^- e^+ \mathcal{H}$	NC
$\overset{(-)}{\nu}_e \mathcal{H} \to \overset{(-)}{\nu}_e e^- e^+ \mathcal{H}$	CC + NC
$\overset{(-)}{\nu}_e \mathcal{H} \to \overset{(-)}{\nu}_\mu \mu^\pm e^\mp \mathcal{H}$	CC
$\overset{(-)}{\nu}_e \mathcal{H} \to \overset{(-)}{\nu}_e \mu^- \mu^+ \mathcal{H}$	NC

$$m_e, m_\mu \to 0$$

$$\sigma \sim g_V^2 + g_A^2 \qquad (\nu_\mu\ e^+ e^-)$$

$$\sigma \sim (g_V + 1)^2 + (g_A + 1)^2 \qquad (\nu_\mu\ \mu^+ \mu^-)$$

$$g_V \leftrightarrow g_A$$

In principle, invariant under this transformation

Lepton masses break this symmetry

Neutrino trident scattering

Magill, Plestid , 1612.05642
Ballet et al., 1807.10973
Altmannshofer et al, 1912.06765

Relatively small cross section

$$\sigma_\Psi \approx 10^{-5}\sigma_{\rm CCQE}$$

(Anti)Neutrino	SM Contributions
$\overset{(-)}{\nu}_\mu \mathcal{H} \to \overset{(-)}{\nu}_\mu \mu^-\mu^+ \mathcal{H}$	CC + NC
$\overset{(-)}{\nu}_\mu \mathcal{H} \to \overset{(-)}{\nu}_e e^\pm\mu^\mp \mathcal{H}$	CC
$\overset{(-)}{\nu}_\mu \mathcal{H} \to \overset{(-)}{\nu}_\mu e^-e^+ \mathcal{H}$	NC
$\overset{(-)}{\nu}_e \mathcal{H} \to \overset{(-)}{\nu}_e e^-e^+ \mathcal{H}$	CC + NC
$\overset{(-)}{\nu}_e \mathcal{H} \to \overset{(-)}{\nu}_\mu \mu^\pm e^\mp \mathcal{H}$	CC
$\overset{(-)}{\nu}_e \mathcal{H} \to \overset{(-)}{\nu}_e \mu^-\mu^+ \mathcal{H}$	NC

$$m_e, m_\mu \to 0$$

$$\sigma \sim g_V^2 + g_A^2 \qquad (\nu_\mu\, e^+e^-)$$

$$\sigma \sim (g_V+1)^2 + (g_A+1)^2 \qquad (\nu_\mu\, \mu^+\mu^-)$$

$$g_V \leftrightarrow g_A$$ → In principle, invariant under this transformation

Lepton masses break this symmetry

Backgrounds??

Ballet et al. 1807.10973 → Estimated efficiency from cuts

Rates

$$N_{\rm X}^{\psi} = {\rm Norm} \times \int dE_\nu \, \sigma_{\nu {\rm X}}(E_\nu) \frac{d\phi_\nu(E_\nu)}{dE_\nu} \epsilon(E_\nu)$$

14×10^{21}

Ballet et al., 1807.10973

$\text{Exposure} = 14 \times 10^{21}$ POT

Rates

Assuming a LAr ND for nuSTORM

$$N_{\rm X}^{\psi} = {\rm Norm} \times \int dE_\nu \, \sigma_{\nu {\rm X}}(E_\nu) \frac{d\phi_\nu(E_\nu)}{dE_\nu} \epsilon(E_\nu)$$

$$\text{Exposure [POT]} \times \frac{\text{Fiducial Detector Mass} \times {\rm N_A}}{m_{\rm T}} \left[\text{target particles}\right]$$

$$14 \times 10^{21}$$

Ballet et al., 1807.10973

$$\text{Exposure} = 14 \times 10^{21} \text{ POT}$$

Rates

Assuming a LAr ND for nuSTORM

$$N_X^{\psi} = \text{Norm} \times \int dE_\nu \, \sigma_{\nu X}(E_\nu) \frac{d\phi_\nu(E_\nu)}{dE_\nu} \epsilon(E_\nu)$$

$$\text{Exposure [POT]} \times \frac{\text{Fiducial Detector Mass} \times \text{N}_\text{A}}{m_\text{T}} \left[\text{target particles}\right]$$

Experiment	Baseline (m)	Total Exposure (POT)	Fiducial Mass (t)	E_ν (GeV)
SBND	110	6.6×10^{20}	112	$0-3$
μBooNE	470	1.32×10^{21}	89	$0-3$
ICARUS	600	6.6×10^{20}	476	$0-3$
DUNE	574	$12.81\ (12.81) \times 10^{21}$	50	$0-40$
νSTORM	50	14×10^{21}	100	$0-6$

Ballet et al., 1807.10973

$$\text{Exposure} = 14 \times 10^{21}\ \text{POT}$$

Rates for current/future NDs

Exposure = 14×10^{21} POT

Channel	SBND	μBooNE	ICARUS	DUNE ND	νSTORM ND
Total $e^{\pm}\mu^{\mp}$	10	0.7	1	2993 (2307)	3248
	1	0.1	0.1	391 (299)	
Total e^+e^-	6	0.4	0.7	1007 (800)	1792
	0.2	0.0	0.02	64 (49)	
Total $\mu^+\mu^-$	0.4	0.0	0.0	286 (210)	280
	0.3	0.0	0.0	143 (108)	

Not seen yet (Total $e^{\pm}\mu^{\mp}$)

Not seen yet (Total e^+e^-)

100 t LAr

Large contributions of diffractive events

Backgrounds?

Goal: Reach suppressions of order $\mathcal{O}(10^{-6} - 10^{-5})$

- misID
  - $\mu^+\mu^- \longrightarrow \nu_\mu CC1\pi^\pm$
  - $e^+e^- \longrightarrow NC\pi^0$
  - $e^\pm\mu^\mp \longrightarrow CC\pi^0$
  - $CC\gamma$ $\quad \nu_e CC\pi^\pm$

misID	Rate
γ as $e^\pm$	0.05
γ as e^+e^-	0.1 (w/ vertex) 1 (no vertex + overlapping)
$\pi^\pm$ as $\mu^\pm$	0.1

- No hadronic activity
- $m^2_{\mu^+\mu^-} < 0.2\ \text{GeV}^2, \Delta\theta < 20^\circ, \theta_\pm < 15^\circ$

A more careful analysis is needed

Channel	N_B^{misID}/N_{CC}	N_B^{had}/N_{CC}	N_B^{kin}/N_{CC}	ϵ_{sig}^{coh}	ϵ_{sig}^{dif} [11]
$e^\pm\mu^\mp$	$1.67\ (1.62) \times 10^{-4}$	$2.68\ (4.31) \times 10^{-5}$	$4.40\ (3.17) \times 10^{-7}$	0.61 (0.61)	0.39 (0.39)
e^+e^-	$2.83\ (4.19) \times 10^{-4}$	$1.30\ (2.41) \times 10^{-4}$	$6.54\ (14.1) \times 10^{-6}$	0.48 (0.47)	0.21 (0.21)
$\mu^+\mu^-$	$2.66\ (2.73) \times 10^{-3}$	$10.4\ (9.75) \times 10^{-4}$	$3.36\ (3.10) \times 10^{-8}$	0.66 (0.67)	0.17 (0.16)

misID — Hadronic veto — Kinematic cuts — Efficiencies after cuts

BSM in tridents

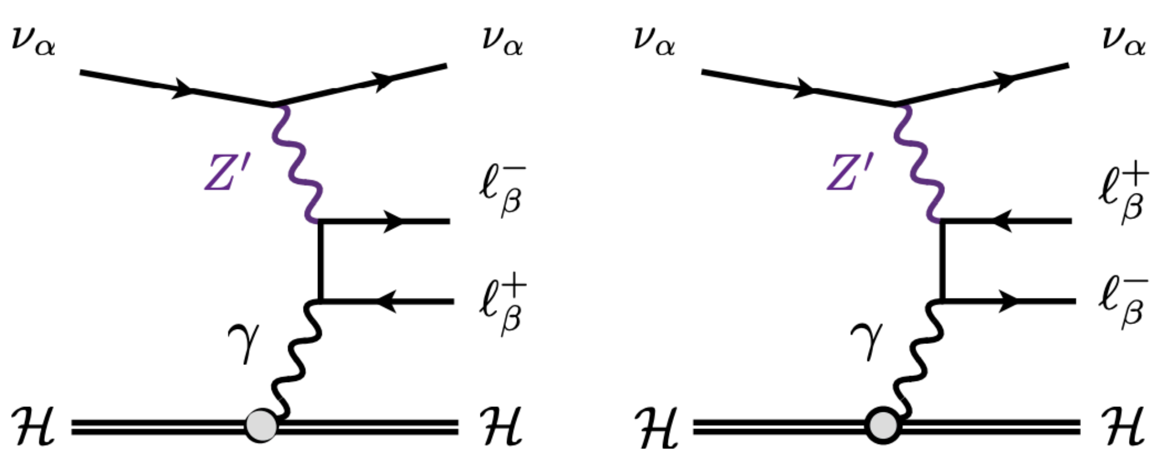
Let's consider a leptophilic Z'

Anomaly free scenarios: $L_\alpha - L_\beta$

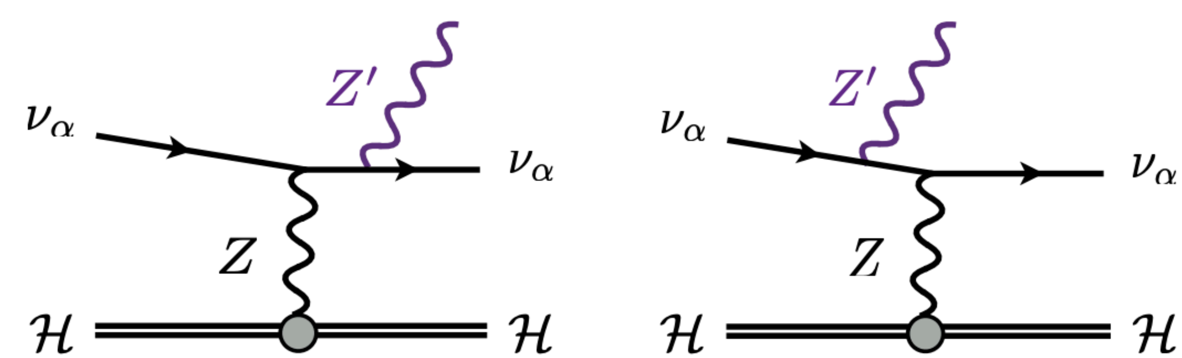
$\alpha, \beta = \{e, \mu, \tau\}$

$L_\mu - L_\alpha$ → Could solve $(g-2)_\mu$

- $\ell\ell\ell$ trident: $\mathcal{H} + \nu_\alpha \to \mathcal{H}' + \ell_\alpha^- + \ell_\beta^+ + \ell_\beta^-$
- $\nu\ell\ell$ trident: $\mathcal{H} + \nu_\alpha \to \mathcal{H} + \nu_\beta + \ell_\gamma^+ + \ell_\delta^-$
- $\nu\nu\ell$ trident: $\mathcal{H} + \nu_\alpha \to \mathcal{H}' + \ell_\alpha^- + \nu_\beta + \overline{\nu}_\beta$
- $\nu\nu\nu$ trident: $\mathcal{H} + \nu_\alpha \to \mathcal{H} + \nu_\alpha + \nu_\beta + \overline{\nu}_\beta$



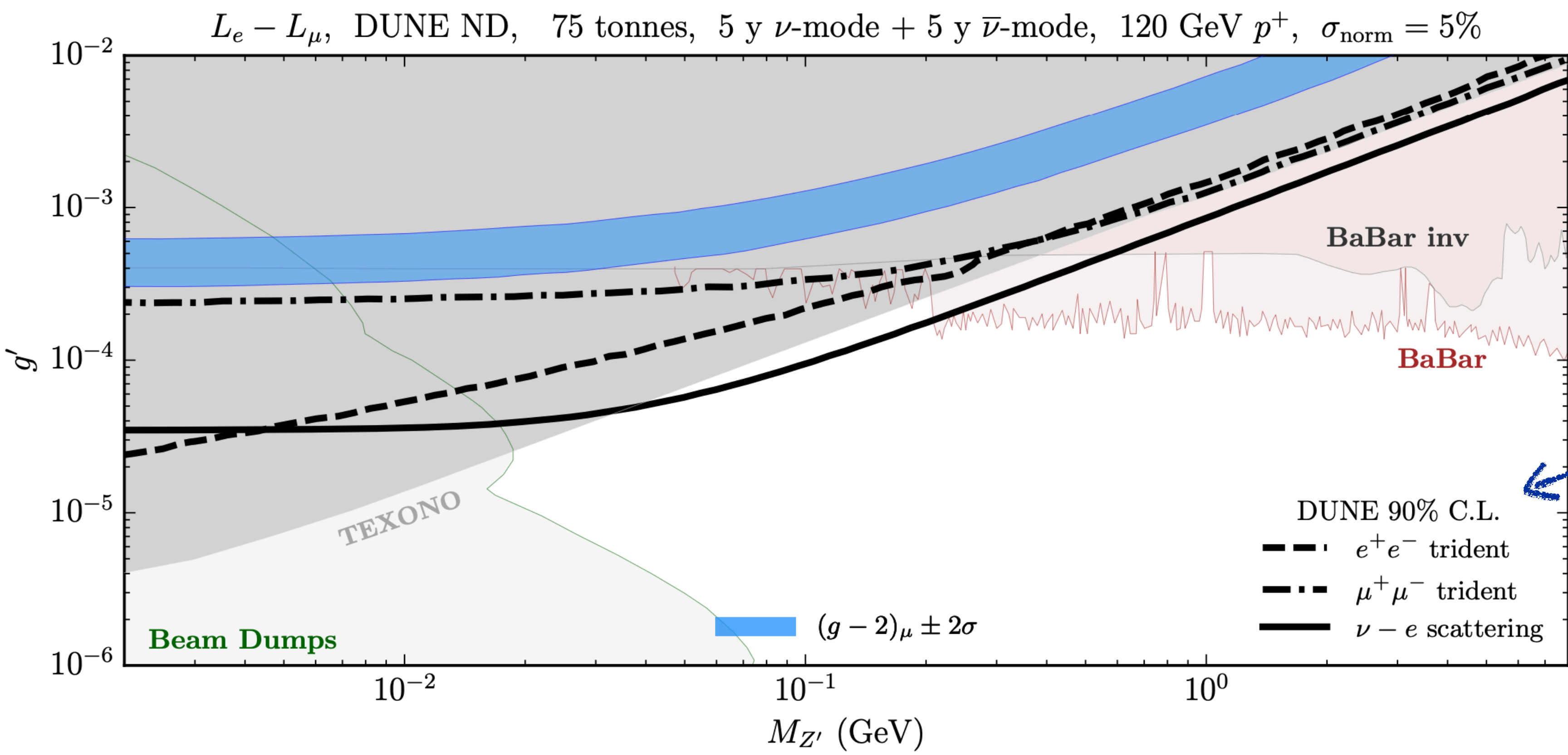
Bethe-Heitler



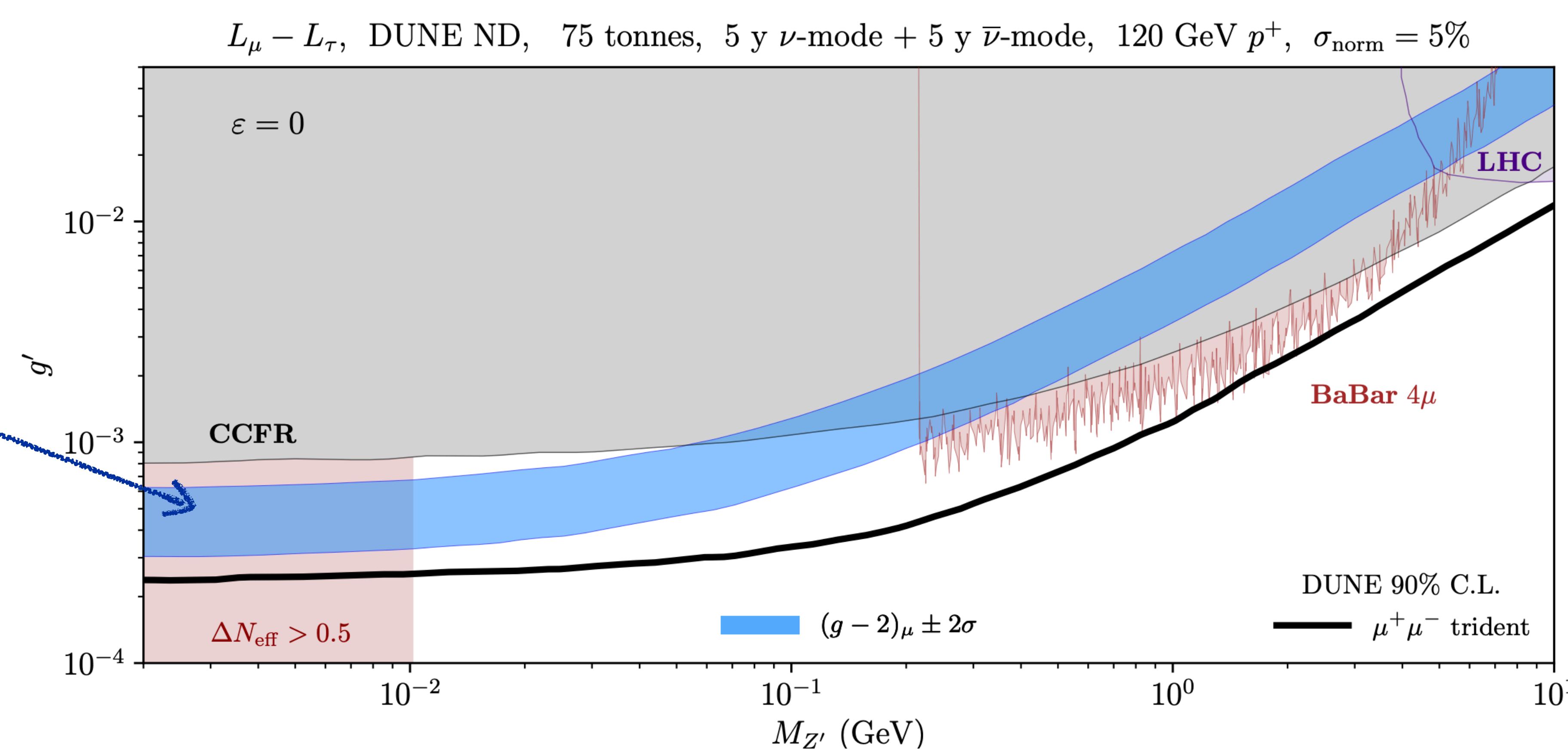
Dark-Bremsstrahlung

Ballet et al. 1902.08579

BSM in tridents



$\nu - e$ scattering can also me modified



$(g-2)_\mu$ can fully be tested

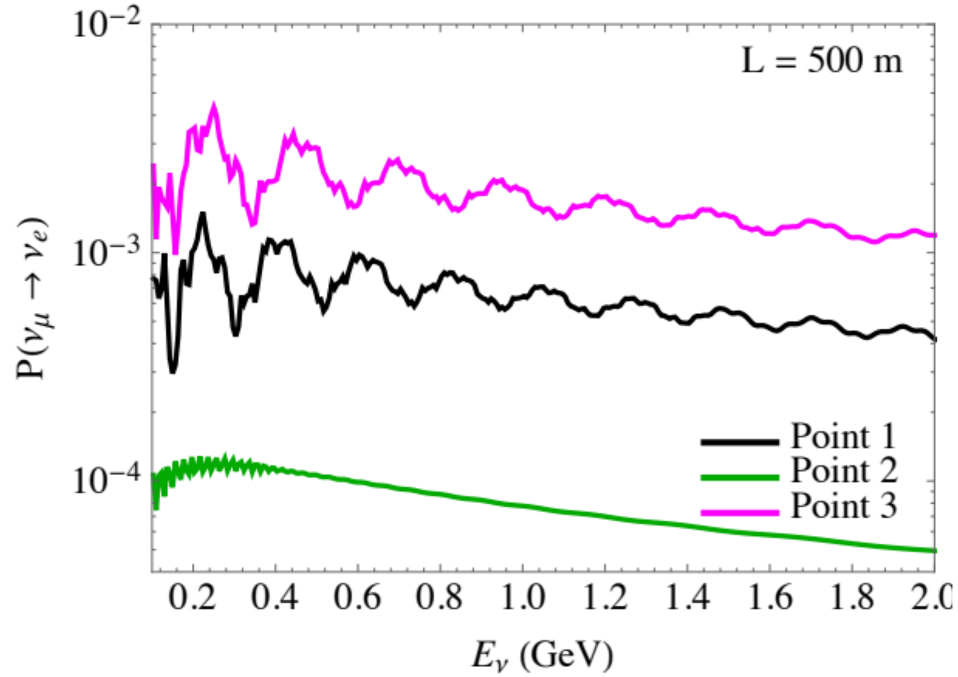
Ballet et al. 1902.08579

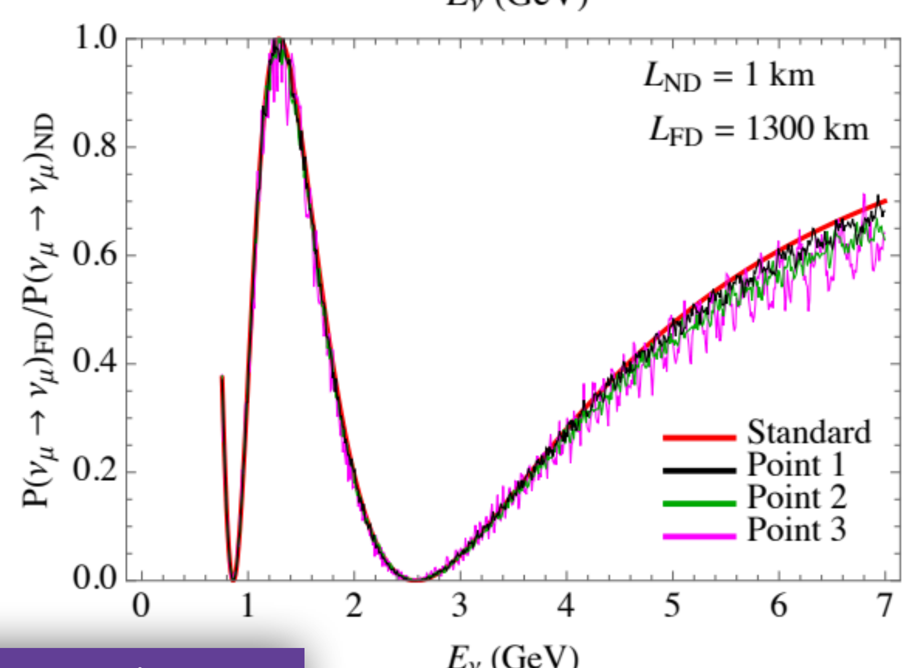
Large Extra Dimensions

Large Extra Dimensions

Weakness of Gravity might be the result of the existence of extra dimensions

$$M_4^2 = M_D^{2+n}(2\pi R)^n$$





$\{P_a, \nu_i\}$	$\frac{R}{\mathrm{eV}^{-1}}$	$c_i R$	λ^i	$\frac{m_{i,0}^2}{\mathrm{eV}^2}$	$\frac{m_{i,n'}^2}{\mathrm{eV}^2}$	$\lvert W_i^{0n'}\rvert^2$
$\{P_1, \nu_1\}$	1.9	4.24	0.42	≈ 0	9.3	$9.0 \cdot 10^{-5}$
$\{P_1, \nu_2\}$	1.9	1.19	2.0	$7.6 \cdot 10^{-5}$	0.66	0.0196
$\{P_1, \nu_3\}$	1.9	−0.037	0.66	$2.5 \cdot 10^{-3}$	0.27	0.0169
$\{P_2, \nu_1\}$	6.4	−1.1	0.27	$2.5 \cdot 10^{-3}$	0.056	$5.9 \cdot 10^{-3}$
$\{P_2, \nu_2\}$	6.4	−1.2	0.25	$2.6 \cdot 10^{-3}$	0.066	$3.8 \cdot 10^{-3}$
$\{P_2, \nu_3\}$	6.4	3.2	1.1	≈ 0	0.64	0.01
$\{P_3, \nu_1\}$	1.8	0.43	0.42	$1.9 \cdot 10^{-4}$	0.37	$4.4 \cdot 10^{-3}$
$\{P_3, \nu_2\}$	1.8	1.0	2.4	$2.6 \cdot 10^{-4}$	0.65	0.0361
$\{P_3, \nu_3\}$	1.8	0.41	1.7	$2.7 \cdot 10^{-3}$	0.37	0.0576

ADD model, hep-ph/9803315

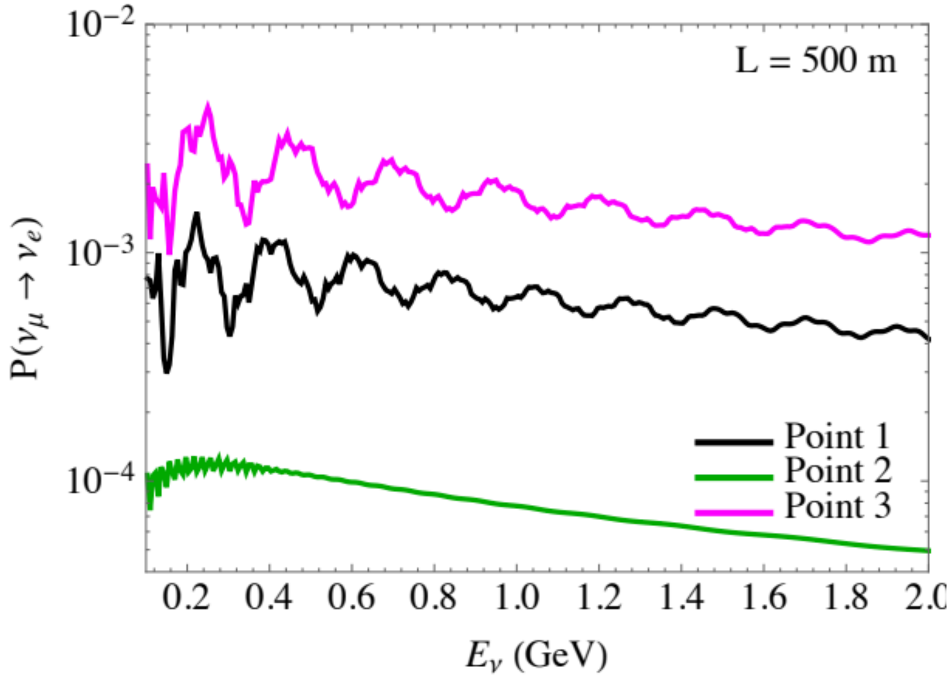
Carena et al,1708.09548

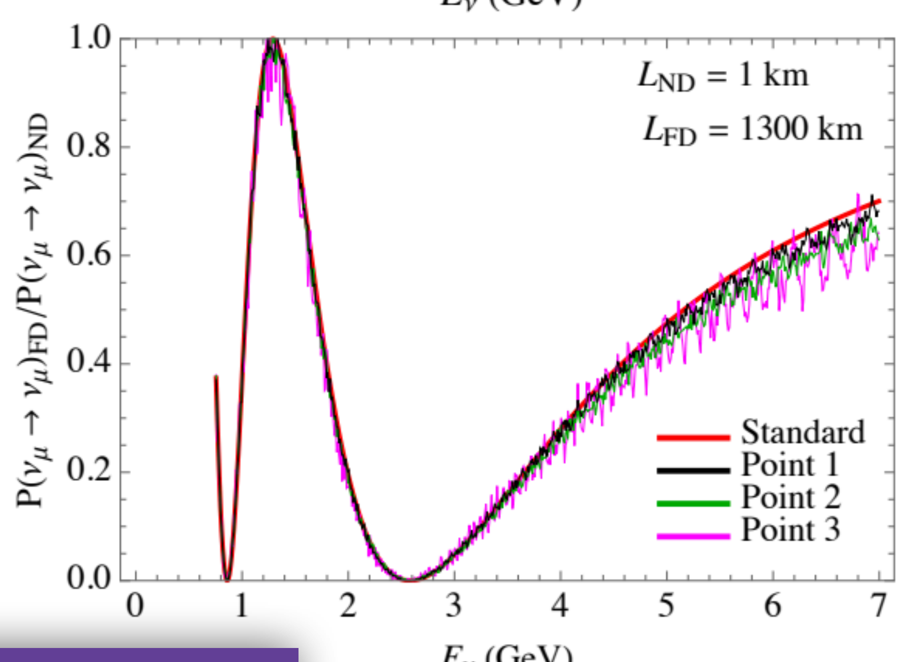
Maybe neutrino masses also "leak" through the extra dim?

A generalization of steriles

Large Extra Dimensions

Weakness of Gravity might be the result of the existence of extra dimensions





Maybe neutrino masses also "leak" through the extra dim?

Volume of extra dims

$$M_4^2 = M_D^{2+n}(2\pi R)^n$$

Gravity that we "feel"

Actual gravity

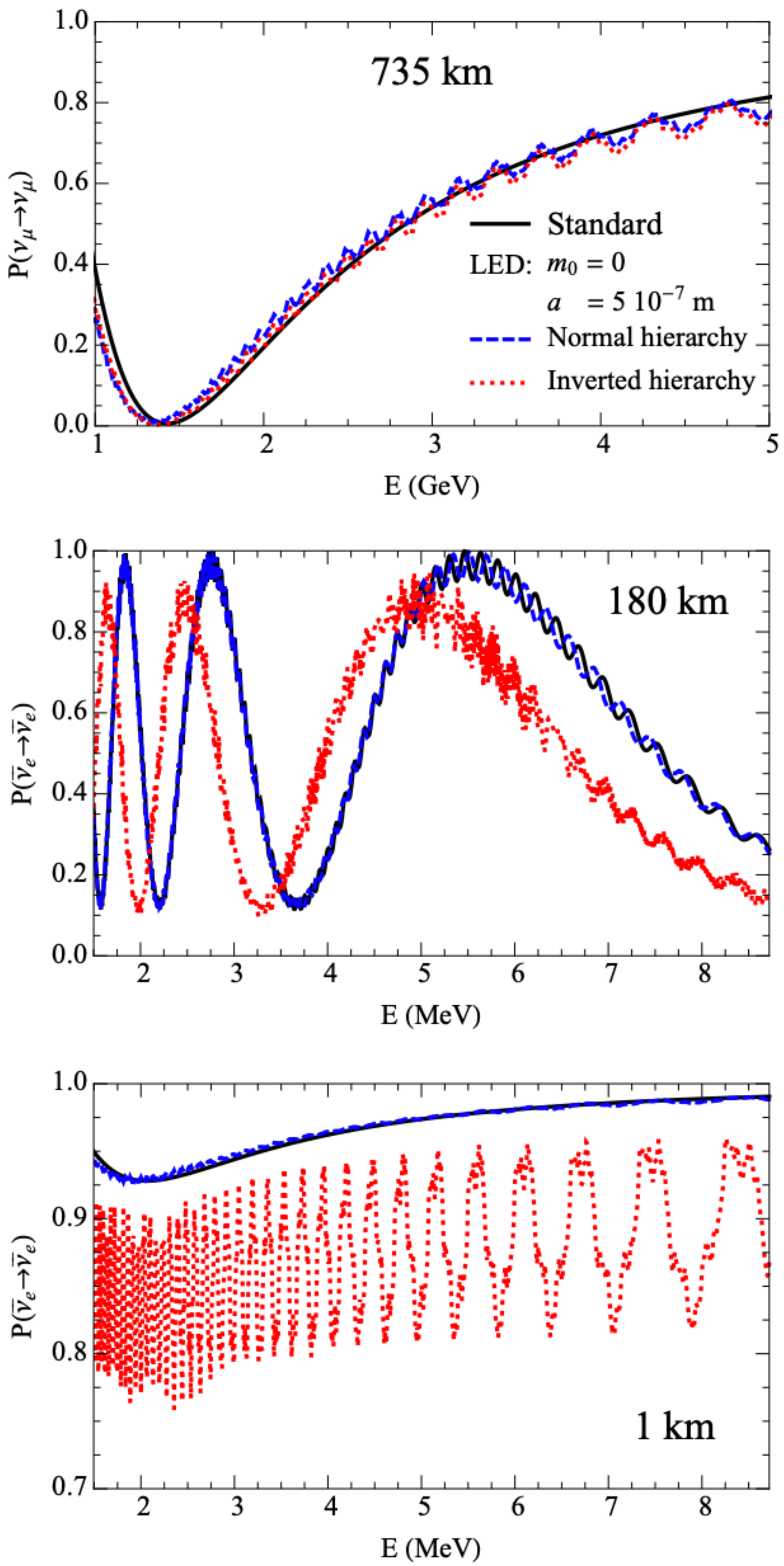
$\{P_a, \nu_i\}$	$\frac{R}{\text{eV}^{-1}}$	$c_i R$	λ^i	$\frac{m^2_{i,0}}{\text{eV}^2}$	$\frac{m^2_{i,n'}}{\text{eV}^2}$	$\lvert W_i^{0n'}\rvert^2$
$\{P_1, \nu_1\}$	1.9	4.24	0.42	≈ 0	9.3	$9.0 \cdot 10^{-5}$
$\{P_1, \nu_2\}$	1.9	1.19	2.0	$7.6 \cdot 10^{-5}$	0.66	0.0196
$\{P_1, \nu_3\}$	1.9	−0.037	0.66	$2.5 \cdot 10^{-3}$	0.27	0.0169
$\{P_2, \nu_1\}$	6.4	−1.1	0.27	$2.5 \cdot 10^{-3}$	0.056	$5.9 \cdot 10^{-3}$
$\{P_2, \nu_2\}$	6.4	−1.2	0.25	$2.6 \cdot 10^{-3}$	0.066	$3.8 \cdot 10^{-3}$
$\{P_2, \nu_3\}$	6.4	3.2	1.1	≈ 0	0.64	0.01
$\{P_3, \nu_1\}$	1.8	0.43	0.42	$1.9 \cdot 10^{-4}$	0.37	$4.4 \cdot 10^{-3}$
$\{P_3, \nu_2\}$	1.8	1.0	2.4	$2.6 \cdot 10^{-4}$	0.65	0.0361
$\{P_3, \nu_3\}$	1.8	0.41	1.7	$2.7 \cdot 10^{-3}$	0.37	0.0576

A generalization of steriles

ADD model, hep-ph/9803315

Carena et al,1708.09548

Large Extra Dimensions

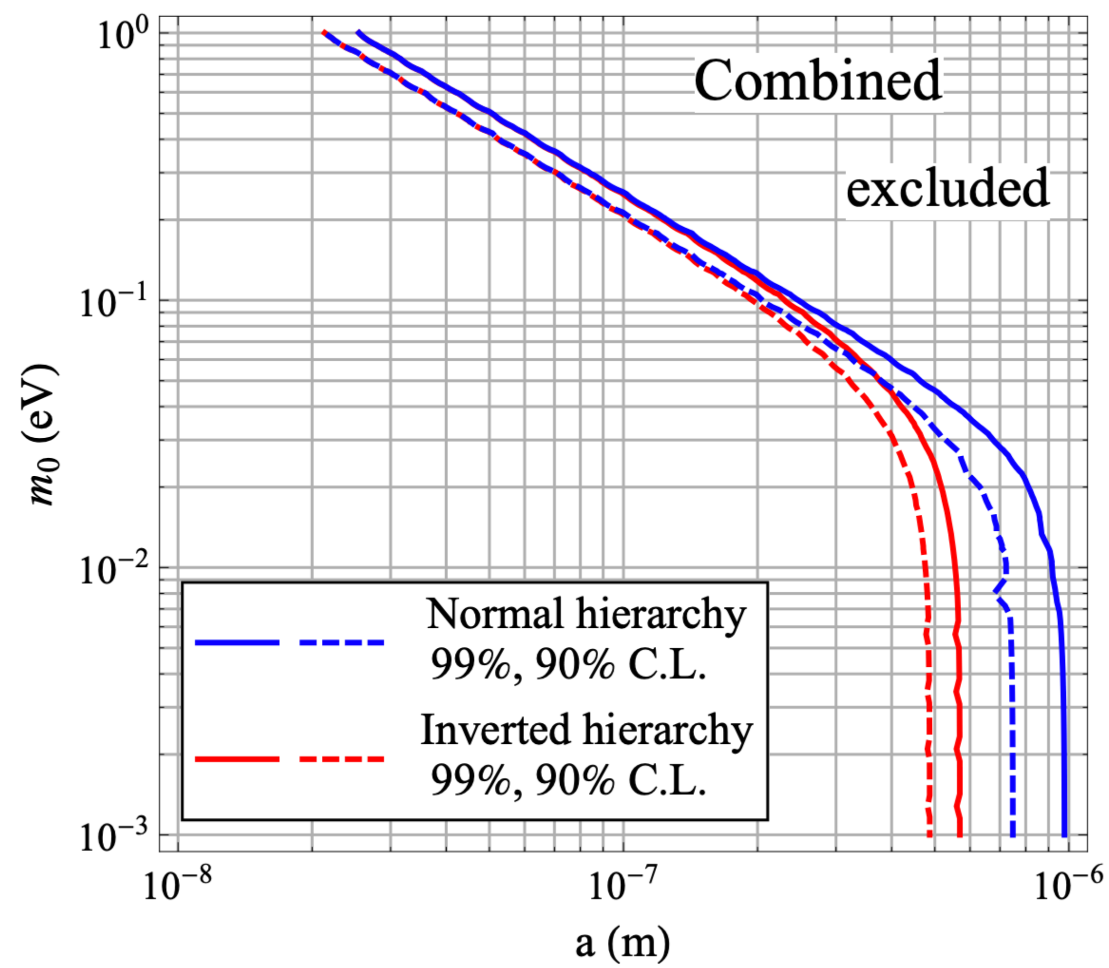


Volume of extra dims

$$M_4^2 = M_D^{2+n}(2\pi R)^n$$

Gravity that we "feel"

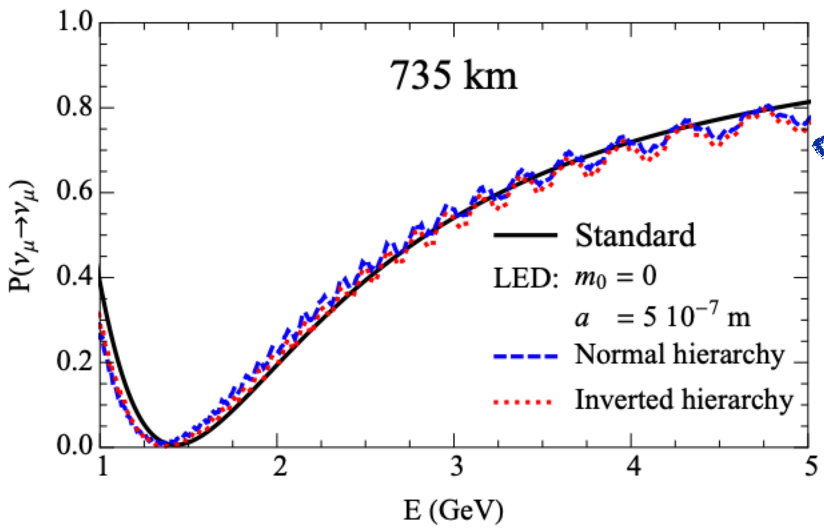
Actual gravity



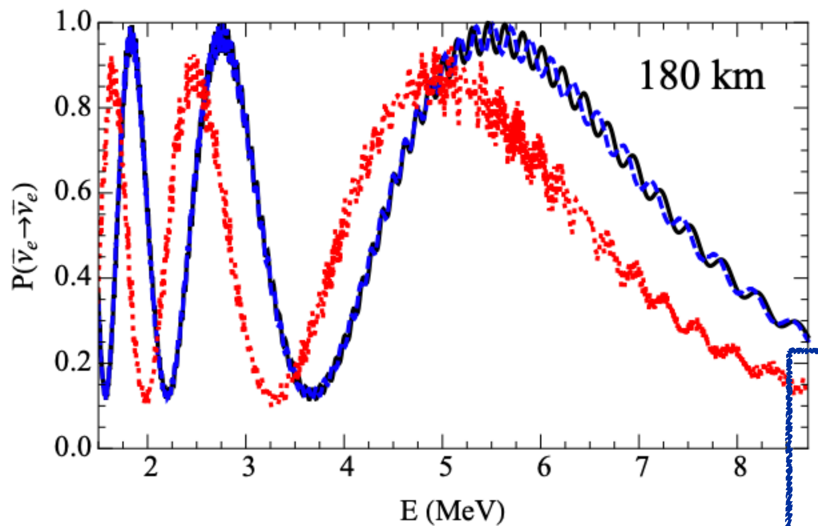
Limits from CHOOZ, Kamland, MINOS

Machado et al,1101.0003

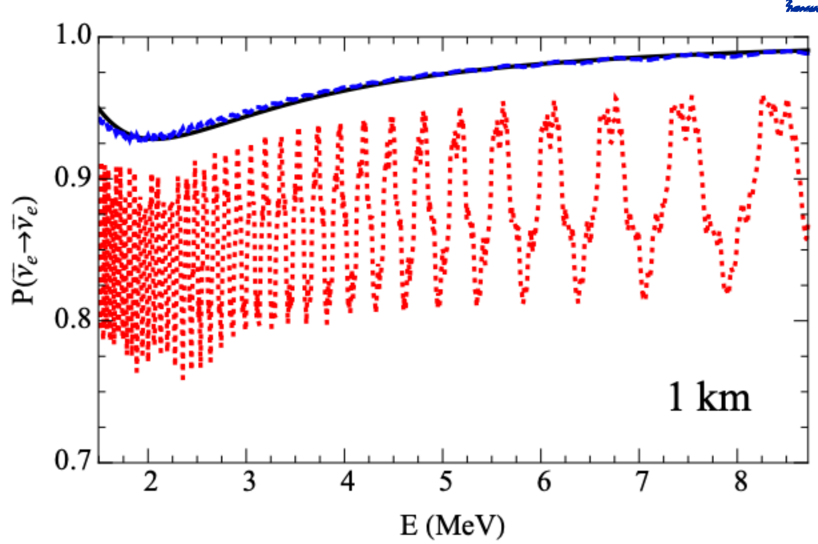
Large Extra Dimensions



Wiggles are difficult to see



Large differences between probabilities

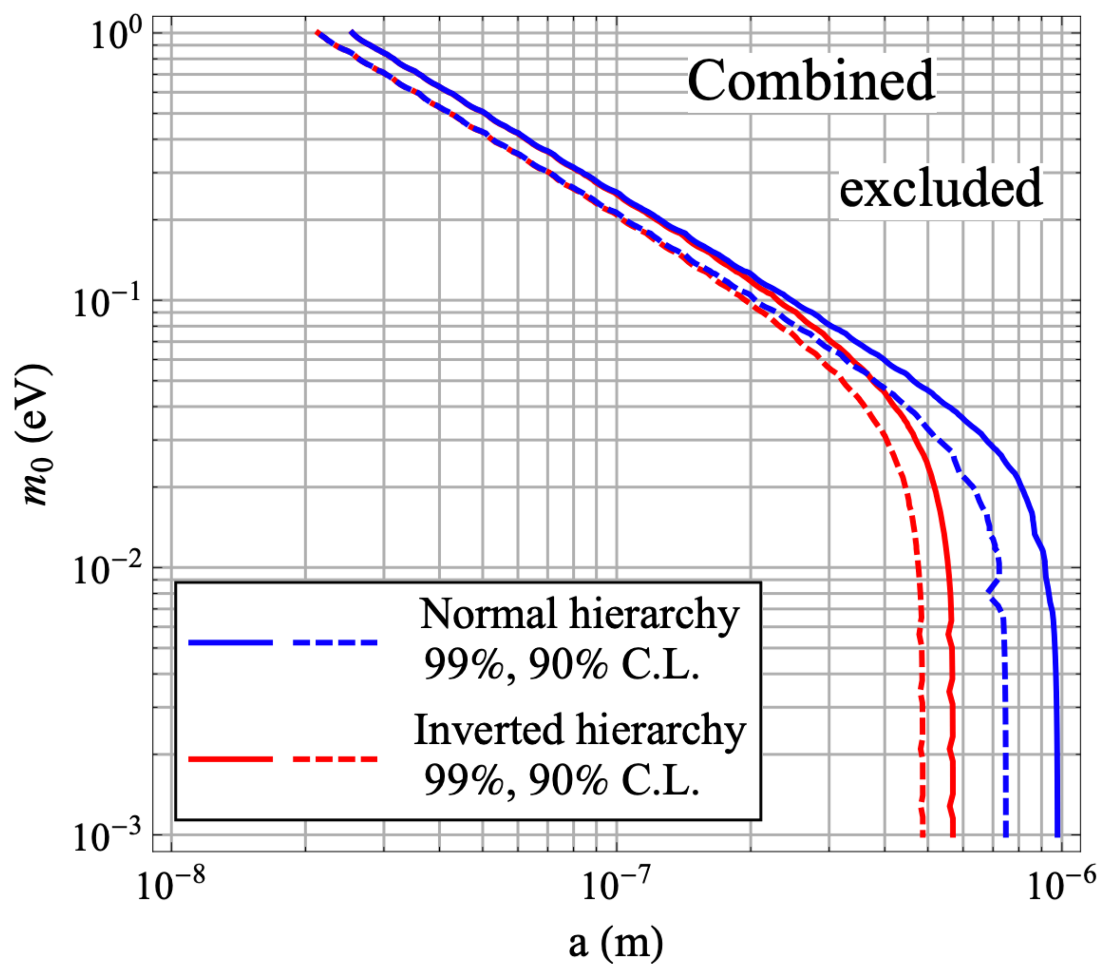


Volume of extra dims

$$M_4^2 = M_D^{2+n}(2\pi R)^n$$

Gravity that we "feel"

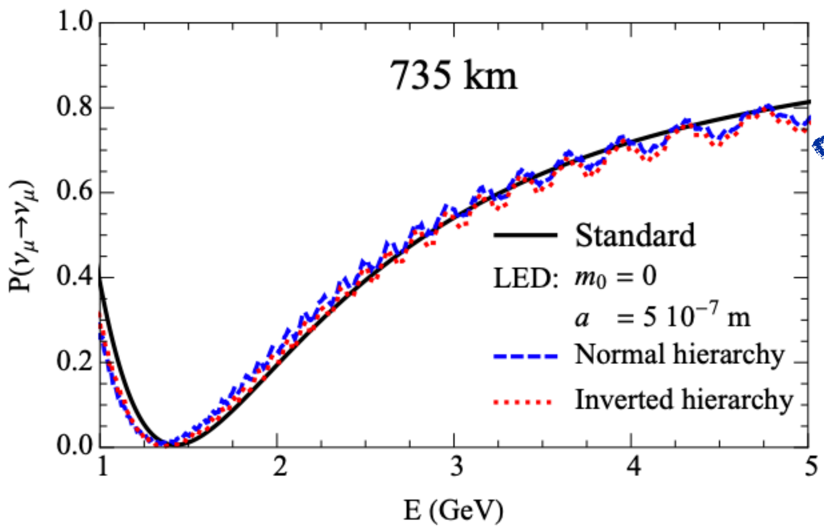
Actual gravity



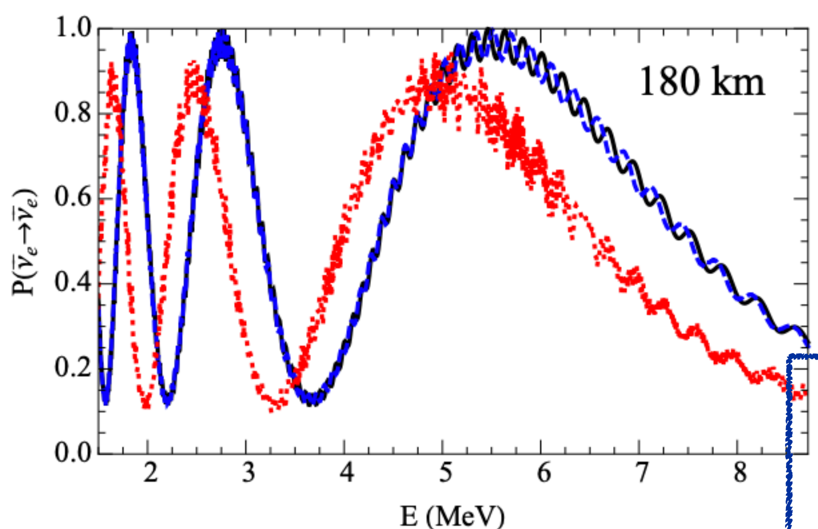
Limits from CHOOZ, Kamland, MINOS

Machado et al,1101.0003

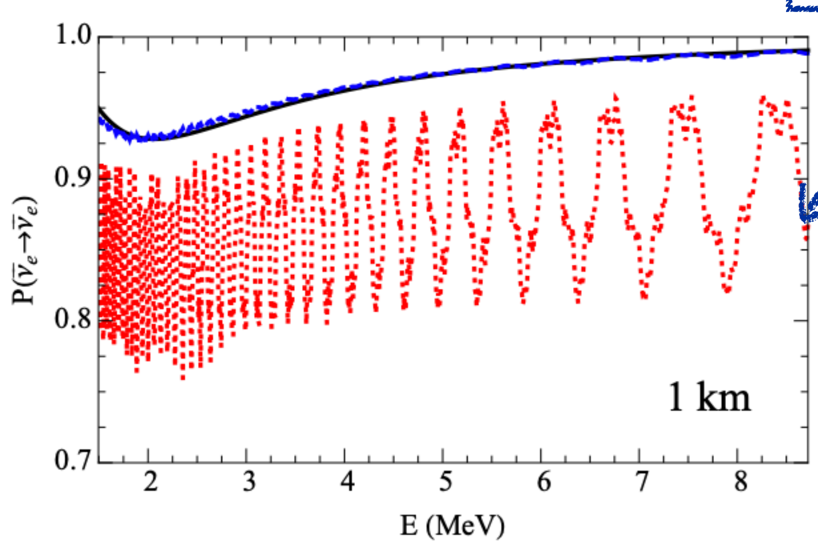
Large Extra Dimensions



Wiggles are difficult to see



Large differences between probabilities

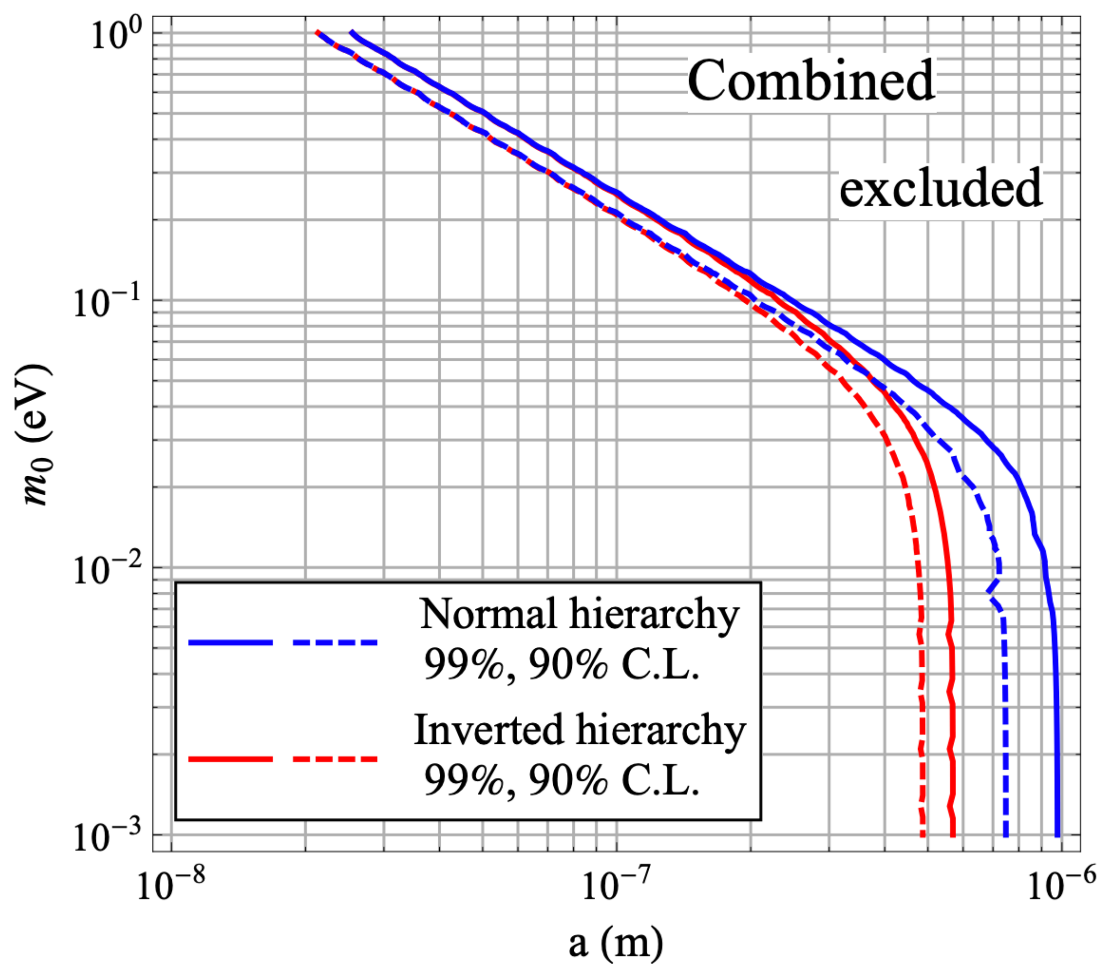


Volume of extra dims

$$M_4^2 = M_D^{2+n}(2\pi R)^n$$

Gravity that we "feel"

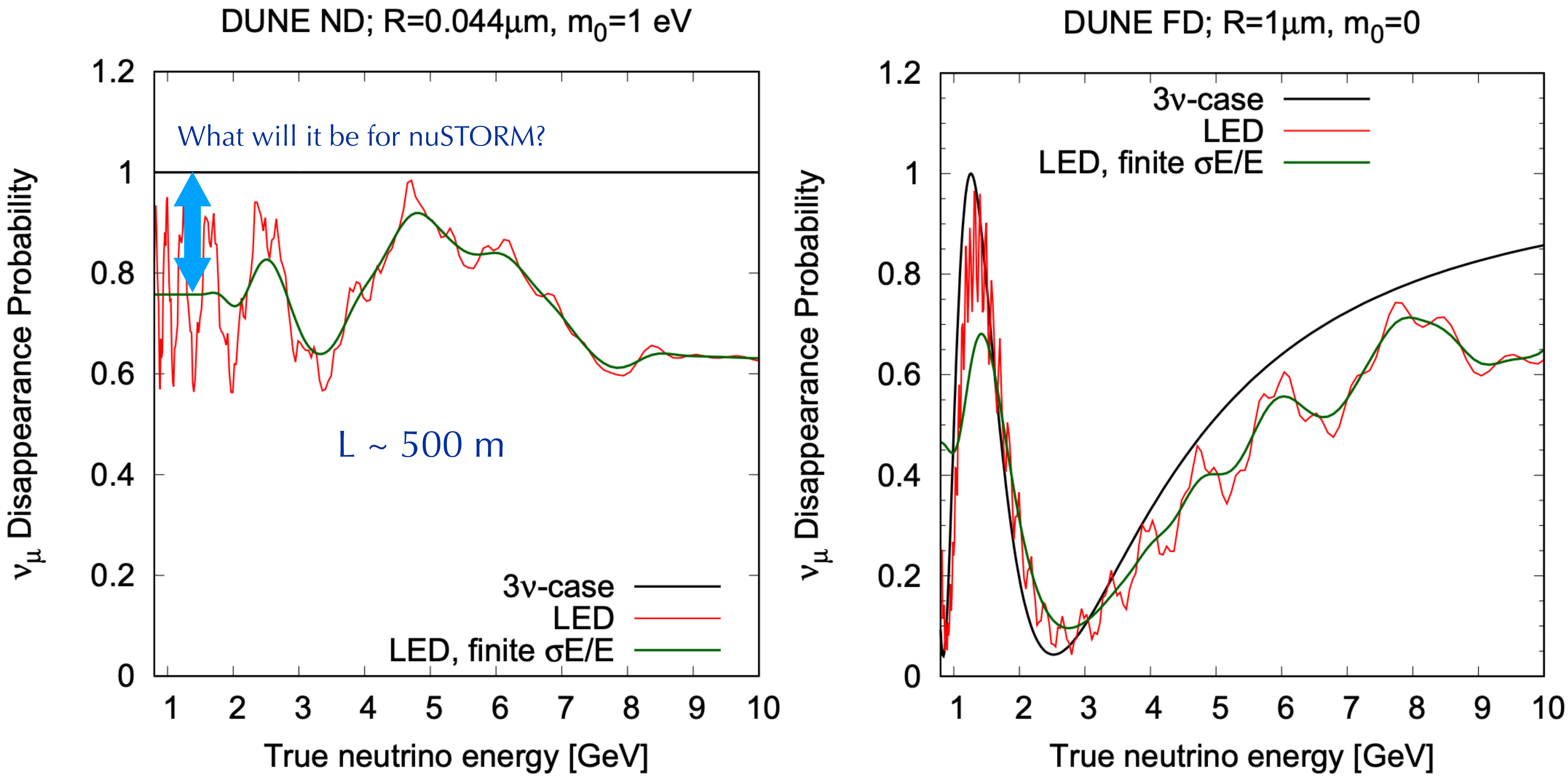
Actual gravity



Limits from CHOOZ, Kamland, MINOS

Machado et al,1101.0003

Large Extra Dimensions



nuSTORM energy range

DUNE?

SNOWMASS - LOI - 078

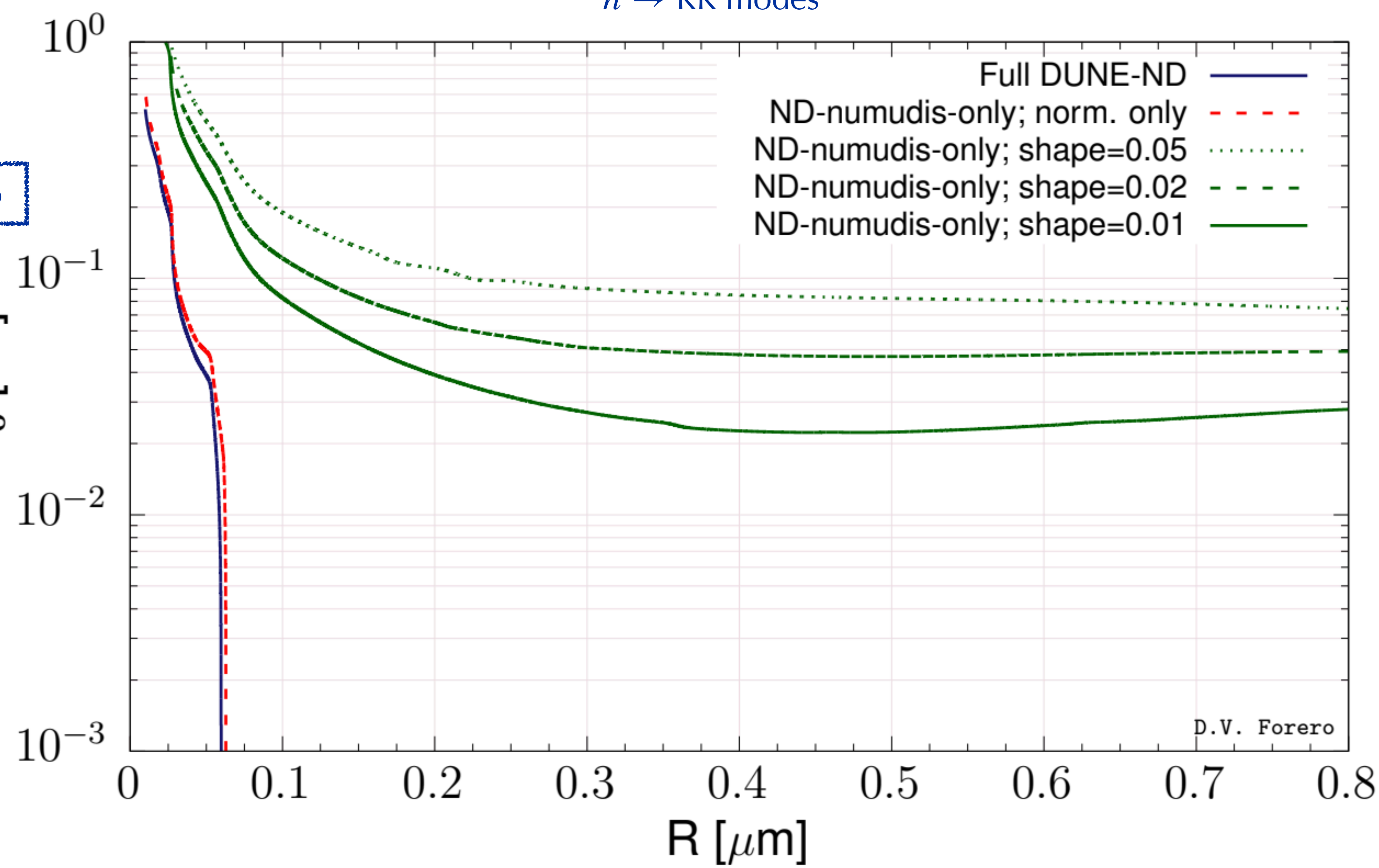
Large Extra Dimensions

$$\Delta m^2_{n1} = n^2/R^2 + 2m_0 n/R$$

$n \rightarrow$ KK modes

Highly dependent on systematics!

Lightest neutrino

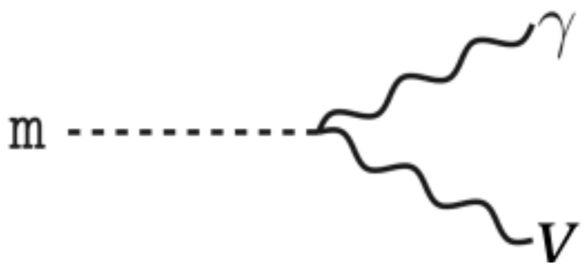


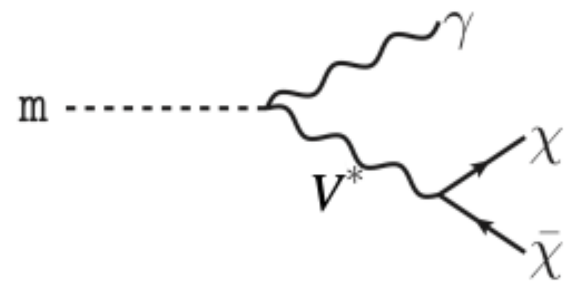
Detector distance??

Again, having a "clean" flux would help here

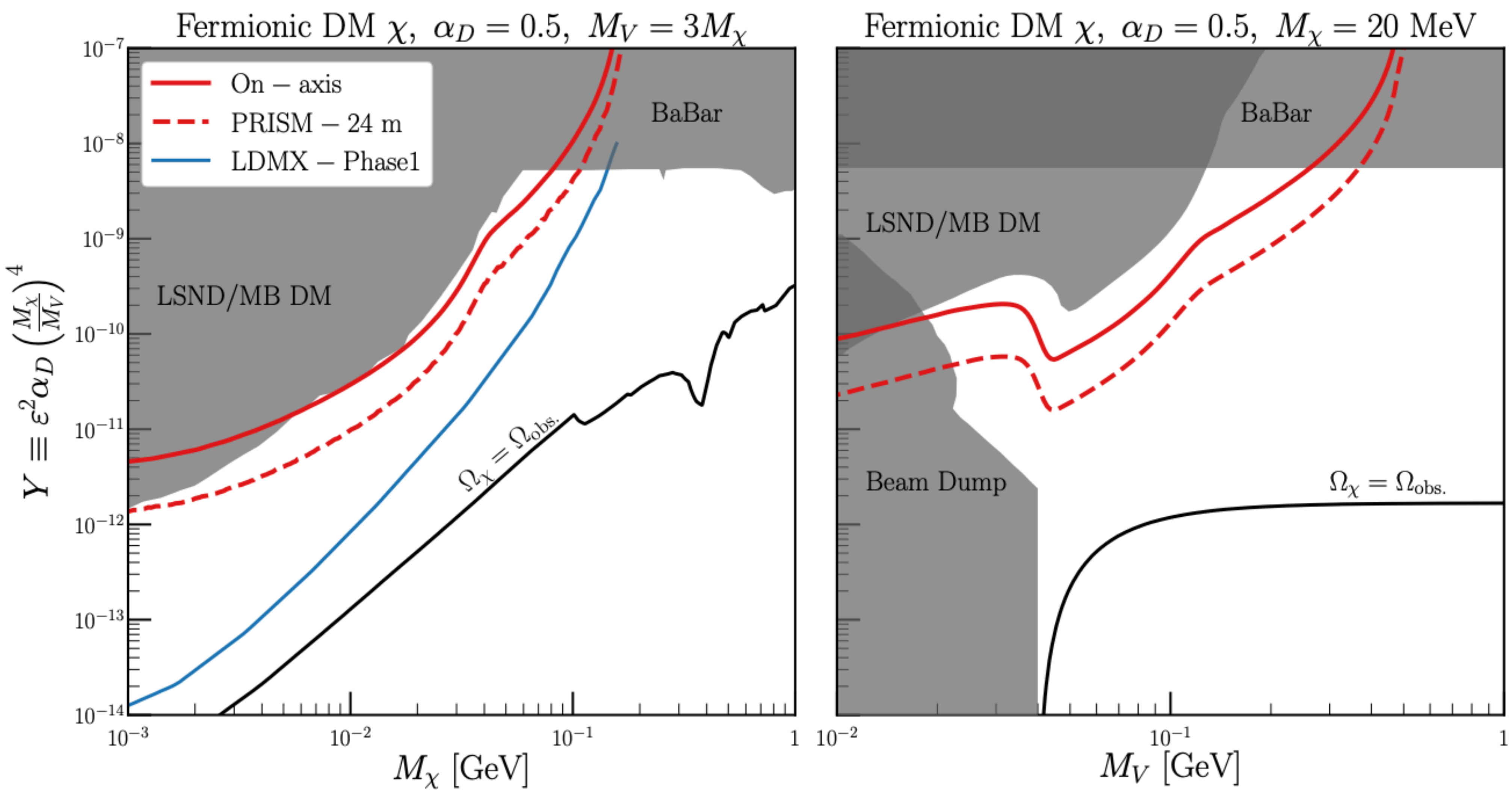
Non-neutrino BSM

Light Dark Matter?



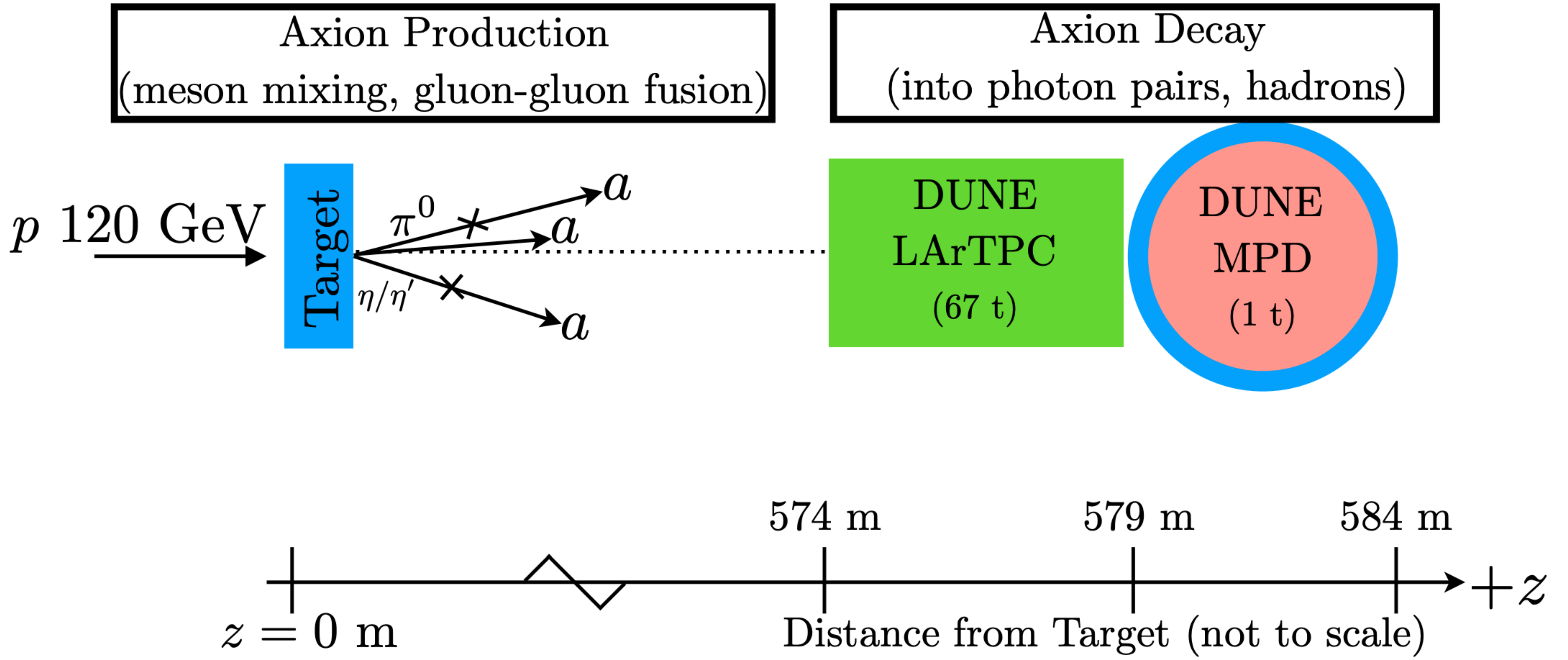


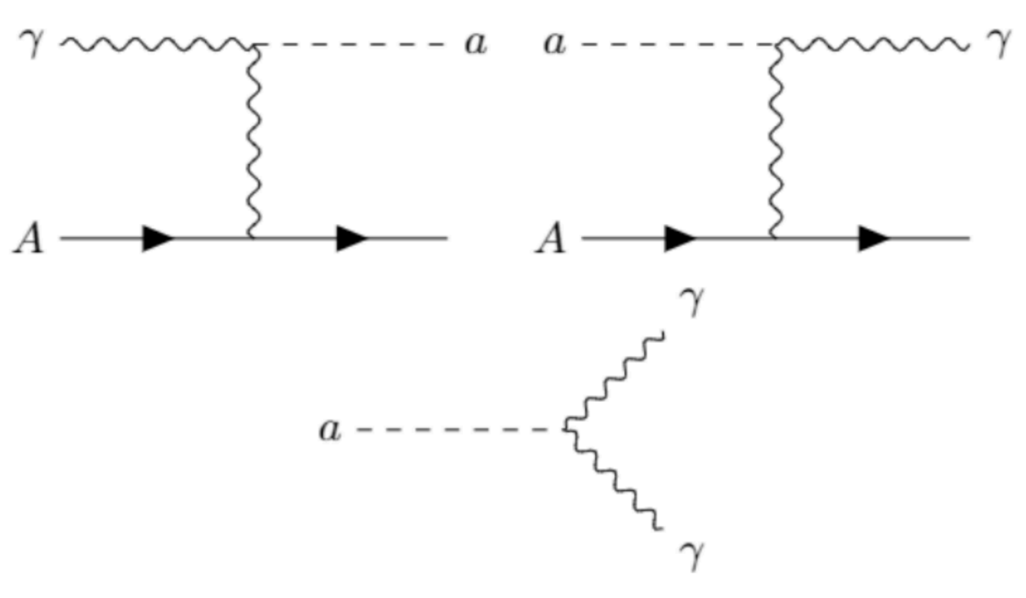
$\mathfrak{m} = \pi^0, \eta$



Additional channels?
What could nuSTORM do here?

Axions?





Photons from meson decay

What happens for nuSTORM?

Conclusions

- Unique combination of flavours should help in constraining the $g_A^{\nu e}$, $g_V^{\nu e}$ SM couplings
- There is a vast landscape of BSM models trying to explain different phenomena, like the short baseline anomalies.
- Large flux, low backgrounds and low systematics make nuSTORM the best place to constrain many possible BSM models.
- Flux time dependence?? Handle for some BSM searches??
- Other ideias???

Thanks!