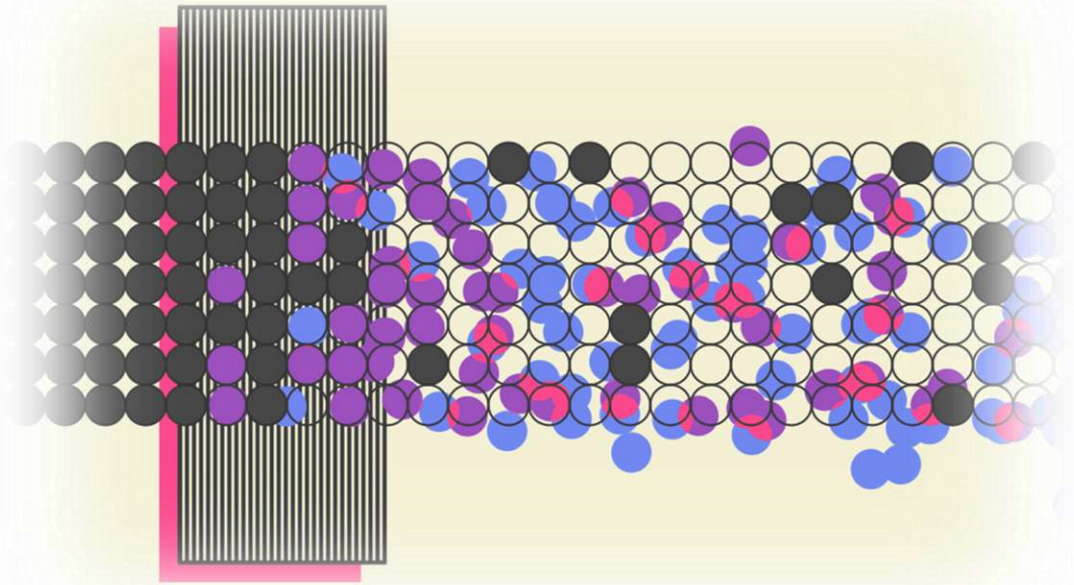


Electroweak Observables from TeV Muon Collider Neutrino Beams



André de Gouvêa, Adrian Thompson

2nd USMC Meeting – University of Chicago
August 8, 2025



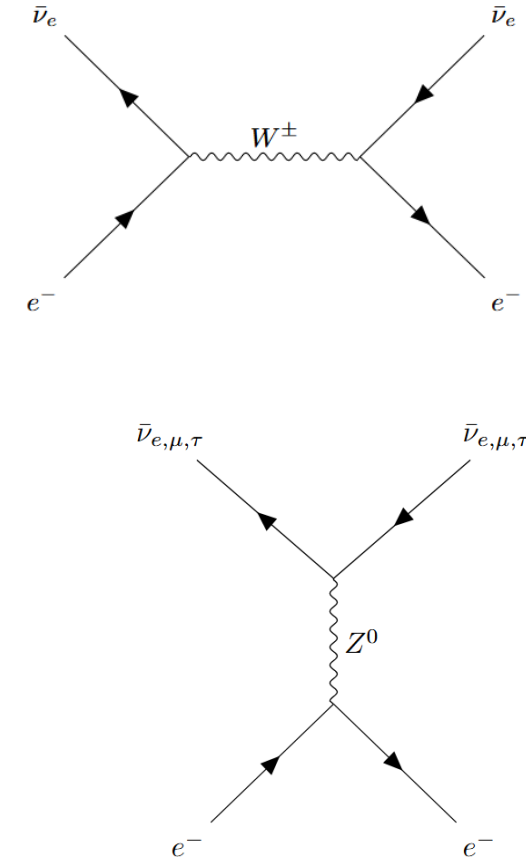
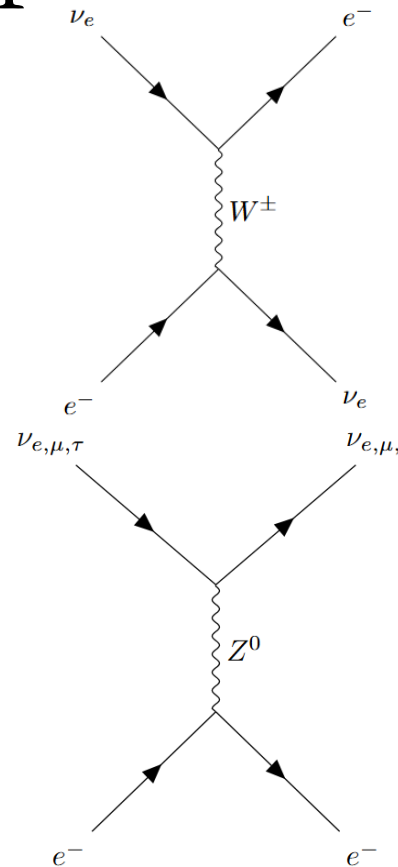
$\text{E}\nu\text{ES}$ as a Neutrino Microscope

Elastic neutrino-electron scattering ($\text{E}\nu\text{ES}$)

- Purely weak process (at tree level) only W, Z exchange
- Depends on the SM weak charges ($g_{L,R}^f$) and the weak mixing angle $\sin^2\theta_W$
- Complements other measurements of the Weak Mixing Angle

$$g_L^f = T_3^f - Q^f \sin^2\theta_W$$

$$g_R^f = -Q^f \sin^2\theta_W$$



Bardin, Bilenky, Pontecorvo '70

't Hooft '71

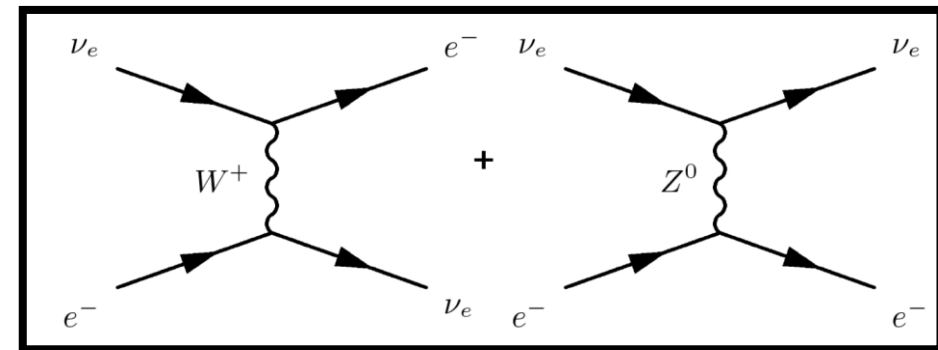
Chen, Lee '72

Sehgal '74

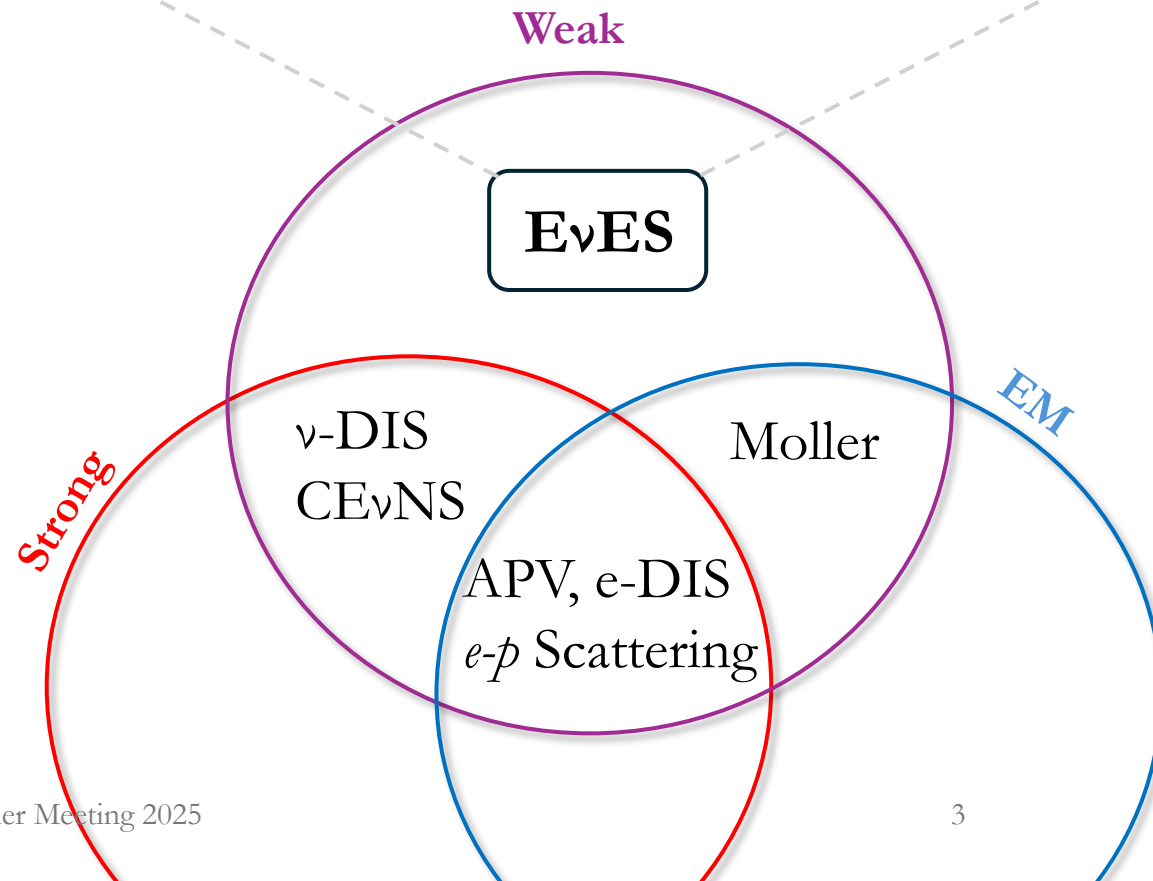
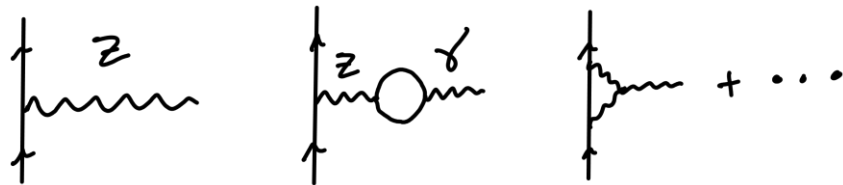
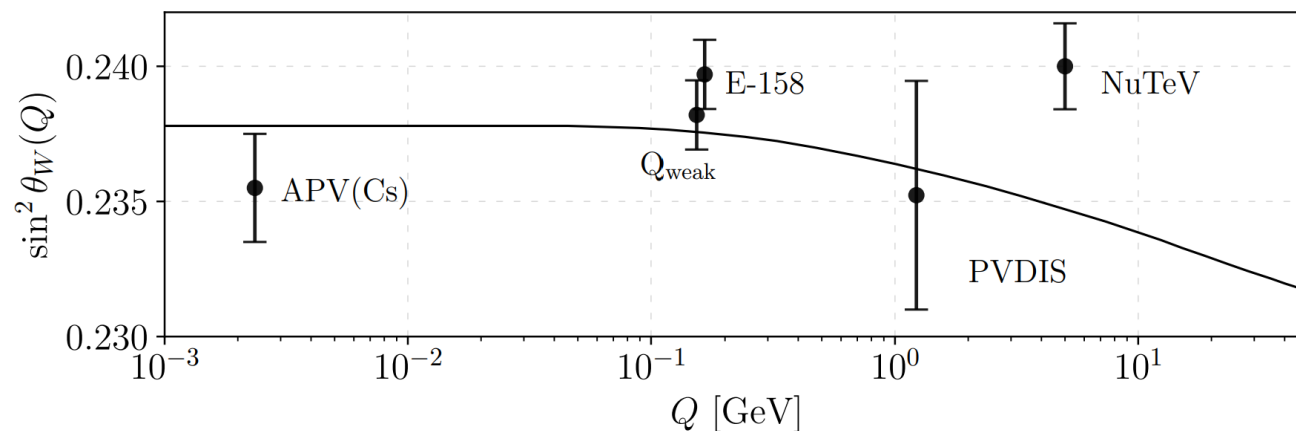
Probes of the Weak Mixing Angle

$$A_\mu = B_\mu^0 \cos \theta_W + W_\mu^0 \sin \theta_W$$

$$Z_\mu = W_\mu^0 \cos \theta_W - B_\mu^0 \sin \theta_W.$$



Renormalization Group **Running** of the Weak Mixing Angle



Muon Decay

$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

Weak charged current process,
known to 1 part in 10^6

Muon Decay

$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$$

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

Weak charged current process,
known to 1 part in 10^6

Elastic Neutrino-Elastic Scattering (EvES)

$$\nu_\alpha e^- \rightarrow \nu_\alpha e^-$$

$$\bar{\nu}_\alpha e^- \rightarrow \bar{\nu}_\alpha e^-$$

Exclusively weak process at
tree level

TeV-scale Muon Colliders and Neutrino Factories

Several designs and inspiring Nu Factory concepts:

- NuSOnG [[0803.0354](#)]
- IMCC Report [[2407.12450](#)], [[2504.21417](#)]
- MAP [[0711.4275](#)]
- μ TRISTAN [[2201.06664](#)]
- Neutrinos at a Muon Collider, 1st wave c. '97:
 - B.K. King (Charm physics, EW precision, CKM etc.)
 - Paschos (beam backgrounds, QCD)
 - Palmer, McDonald *et al* nu factory from muon storage
 - R. Mohapatra ($\nu_e - \nu_\mu$, $\nu_\mu - \nu_\tau$ oscillations, Lorentz violation)
 - Spentzouris (Charm, oscillations, CKM, etc.)

ACCELERATORS | FEATURE

CERN Courier, '99

Muon ring could act as a neutrino factory

27 June 1999

Terascale Physics Opportunities at a High Statistics, High Energy
Neutrino Scattering Experiment: NuSOnG

T. Adams⁵, P. Batra³, L. Bugel³, L. Camilleri³, J.M. Conrad³, A. de Gouvêa¹¹, P.H. Fisher⁸, J.A. Formaggio⁸, J. Jenkins¹¹, G. Karagiorgi³, T.R. Kobilarcik⁴, S. Kopp¹⁵, G. Kyle¹⁰, W.A. Loinaz¹, D.A. Mason⁴, R. Milner⁸, R. Moore⁴, J. G. Morfin⁴, M. Nakamura⁹, D. Naples¹², P. Nienaber¹³, F.I. Olness¹⁴, J.F. Owens⁵, S.F. Pate¹⁰, A. Pronin¹⁶, W.G. Seligman³, M.H. Shaevitz³, H. Schellman¹¹, I. Schienbein⁷, M.J. Syphers⁴, T.M.P. Tait^{2,11}, T. Takeuchi¹⁶, C.Y. Tan⁴, R.G. Van de Water⁶, R.K. Yamamoto⁸, J.Y. Yu¹⁴

Neutrino Physics at a Muon Collider

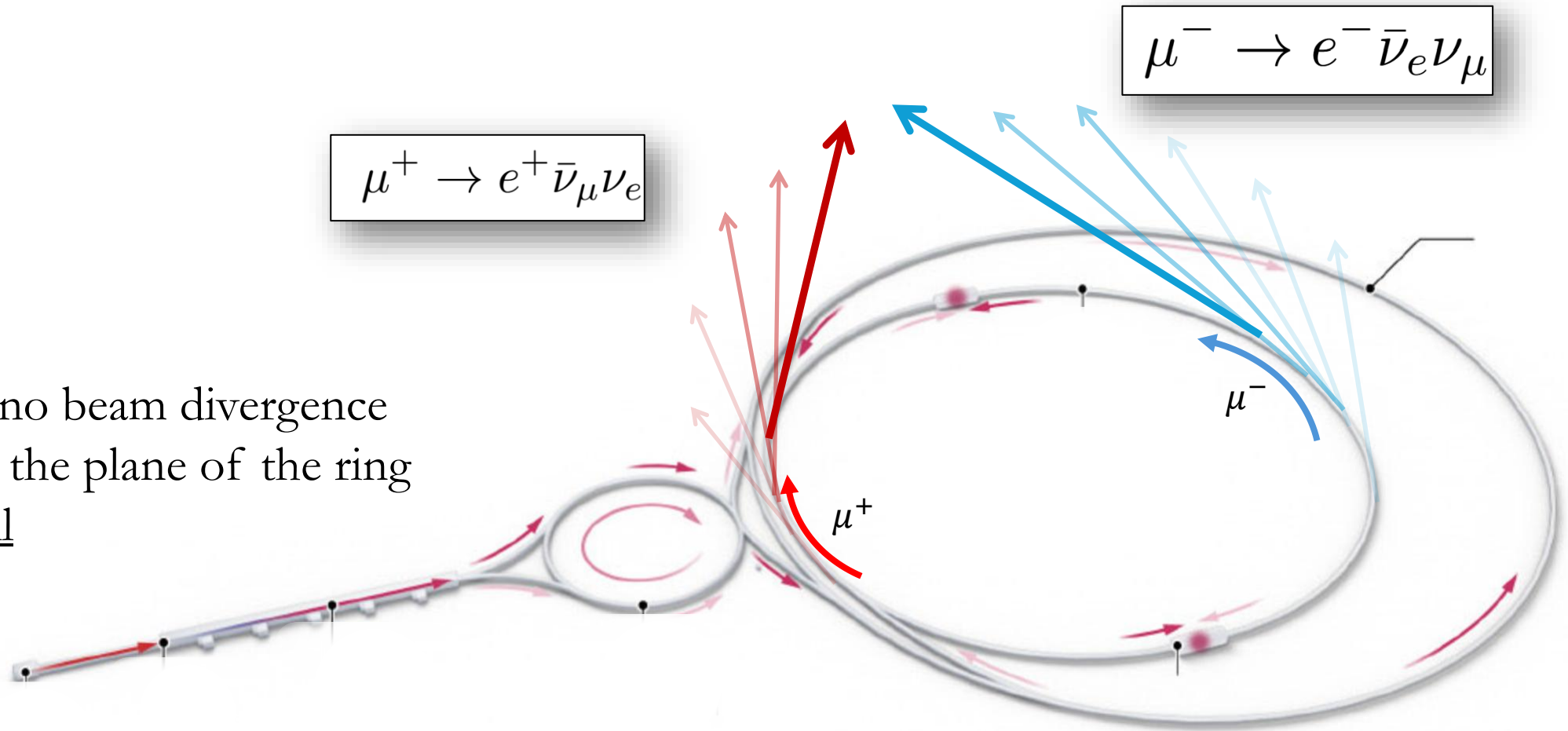
Bruce J. King

Brookhaven National Laboratory
email: bking@bnl.gov

7

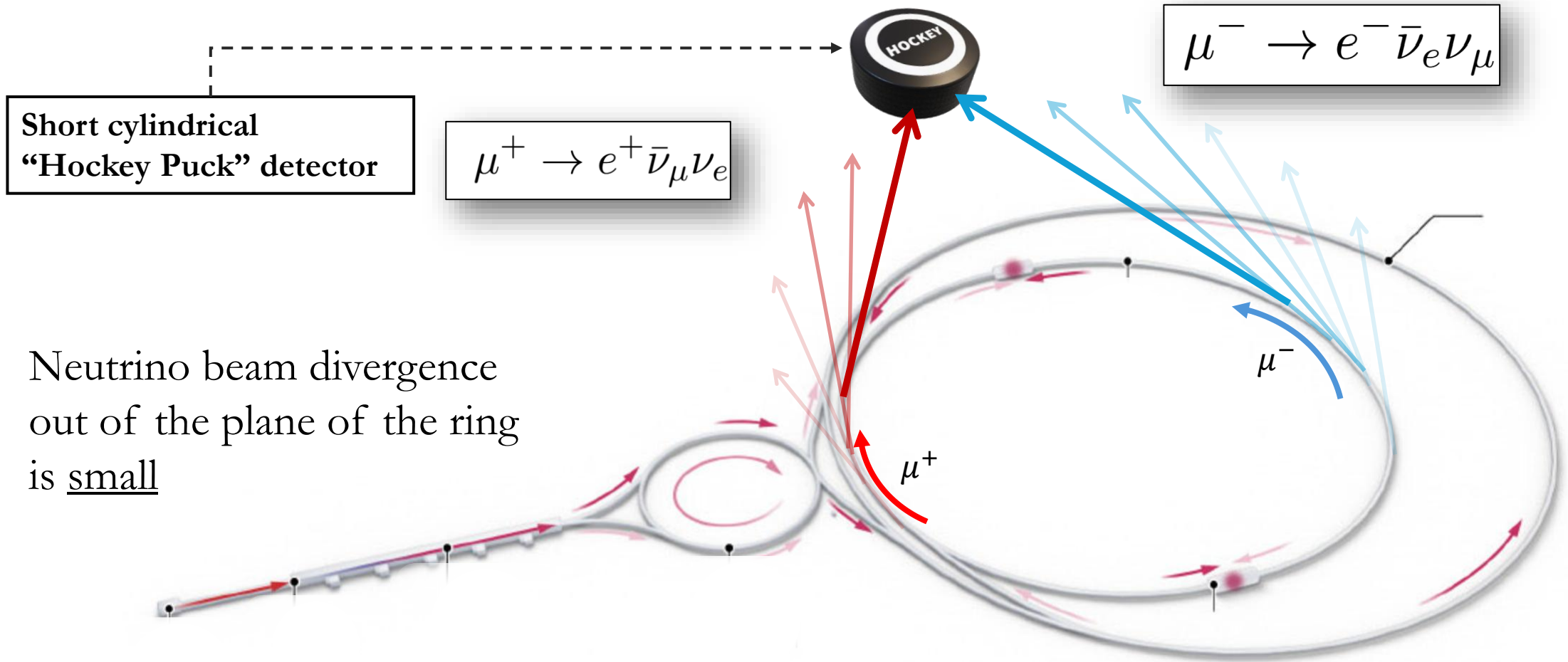
Concept: Companion Neutrino Detector Near the Muon Collider / Storage Ring

Neutrino beam divergence
out of the plane of the ring
is small



A. FISHER/SCIENCE

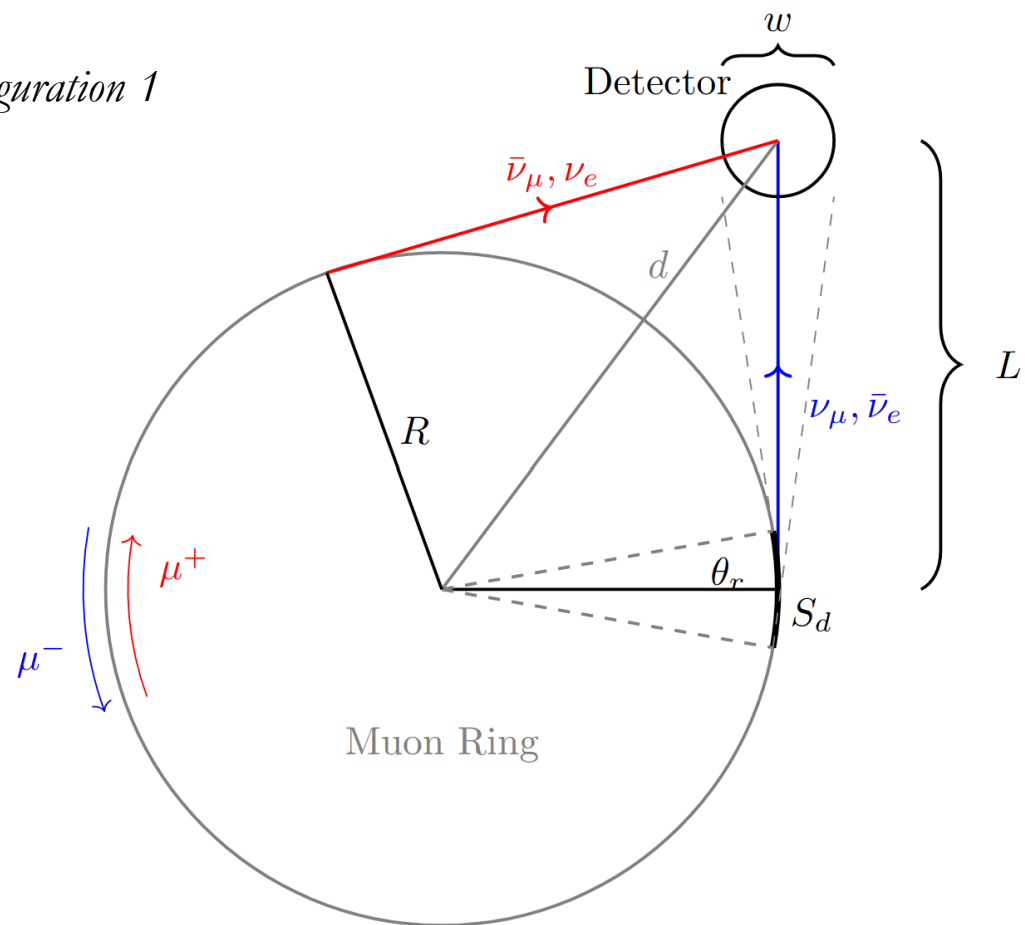
Concept: Companion Neutrino Detector Near the Muon Collider / Storage Ring



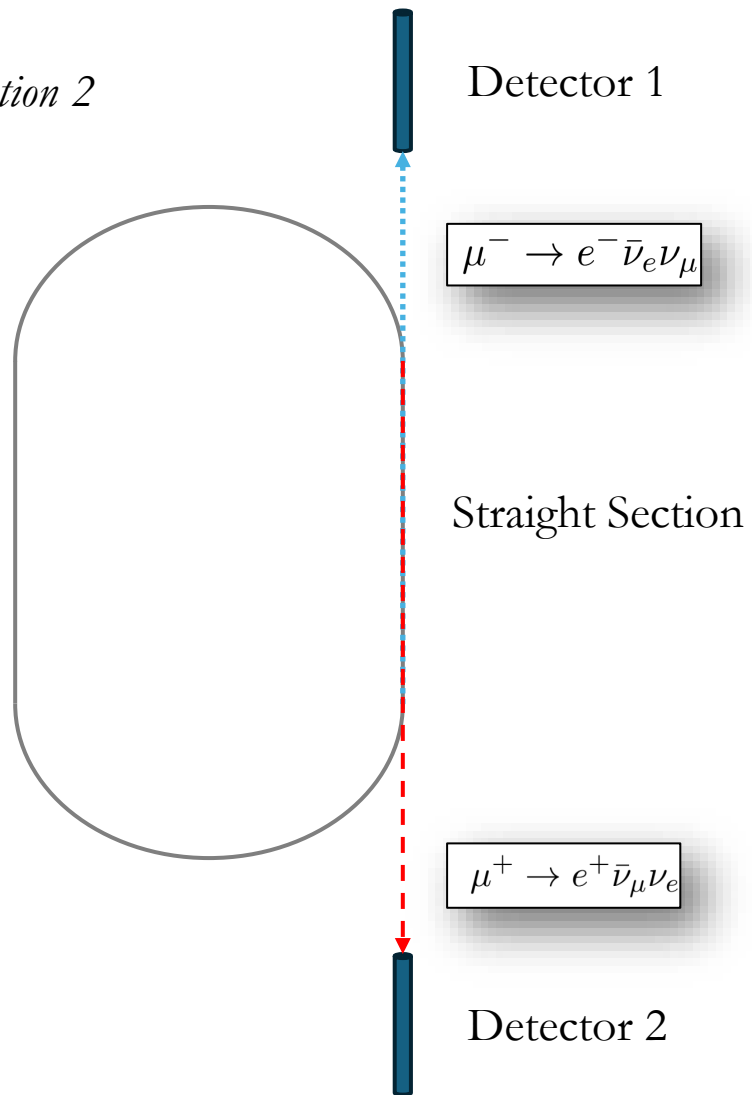
A. FISHER/SCIENCE

Bird's Eye View

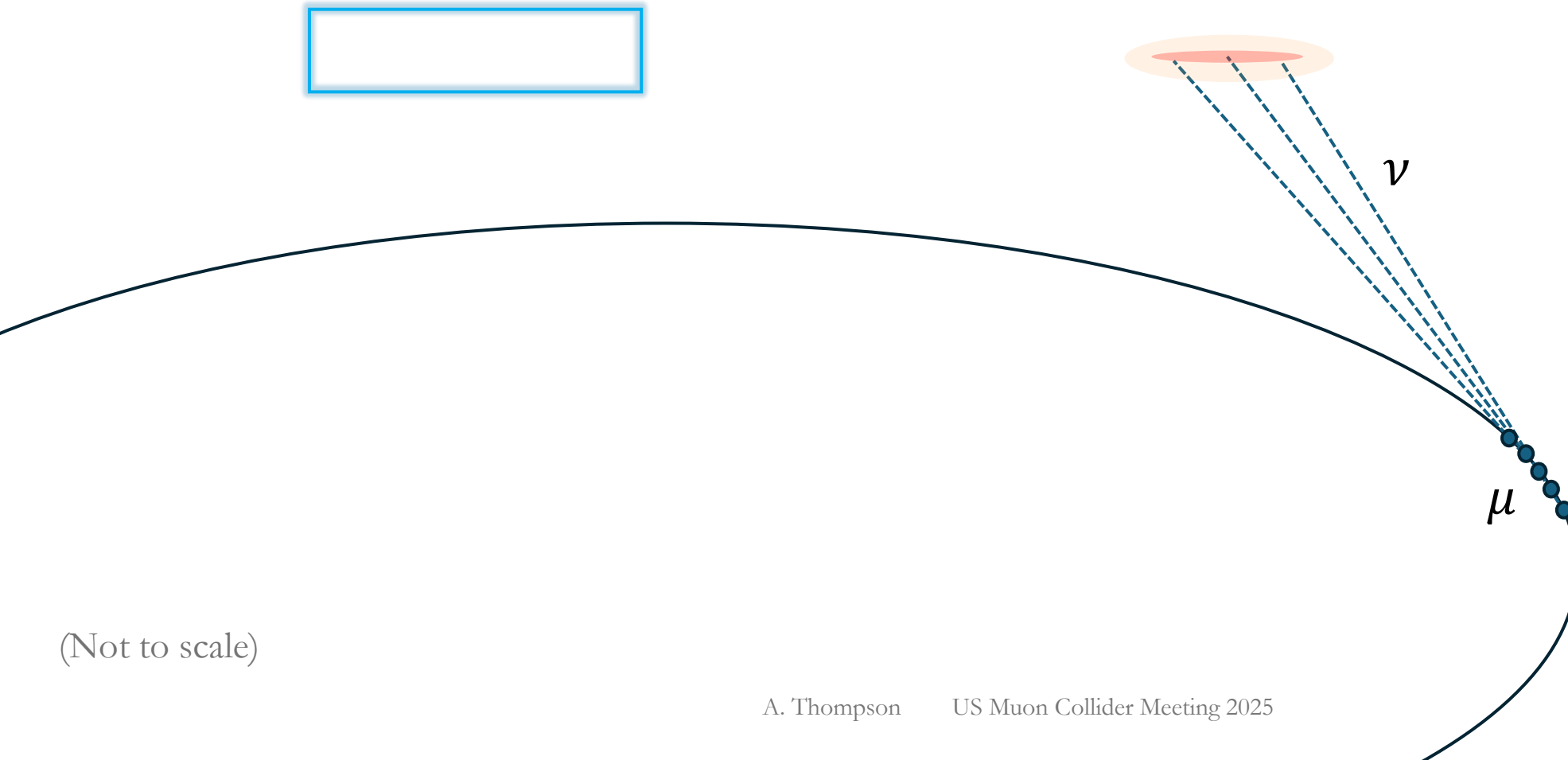
Configuration 1



Configuration 2

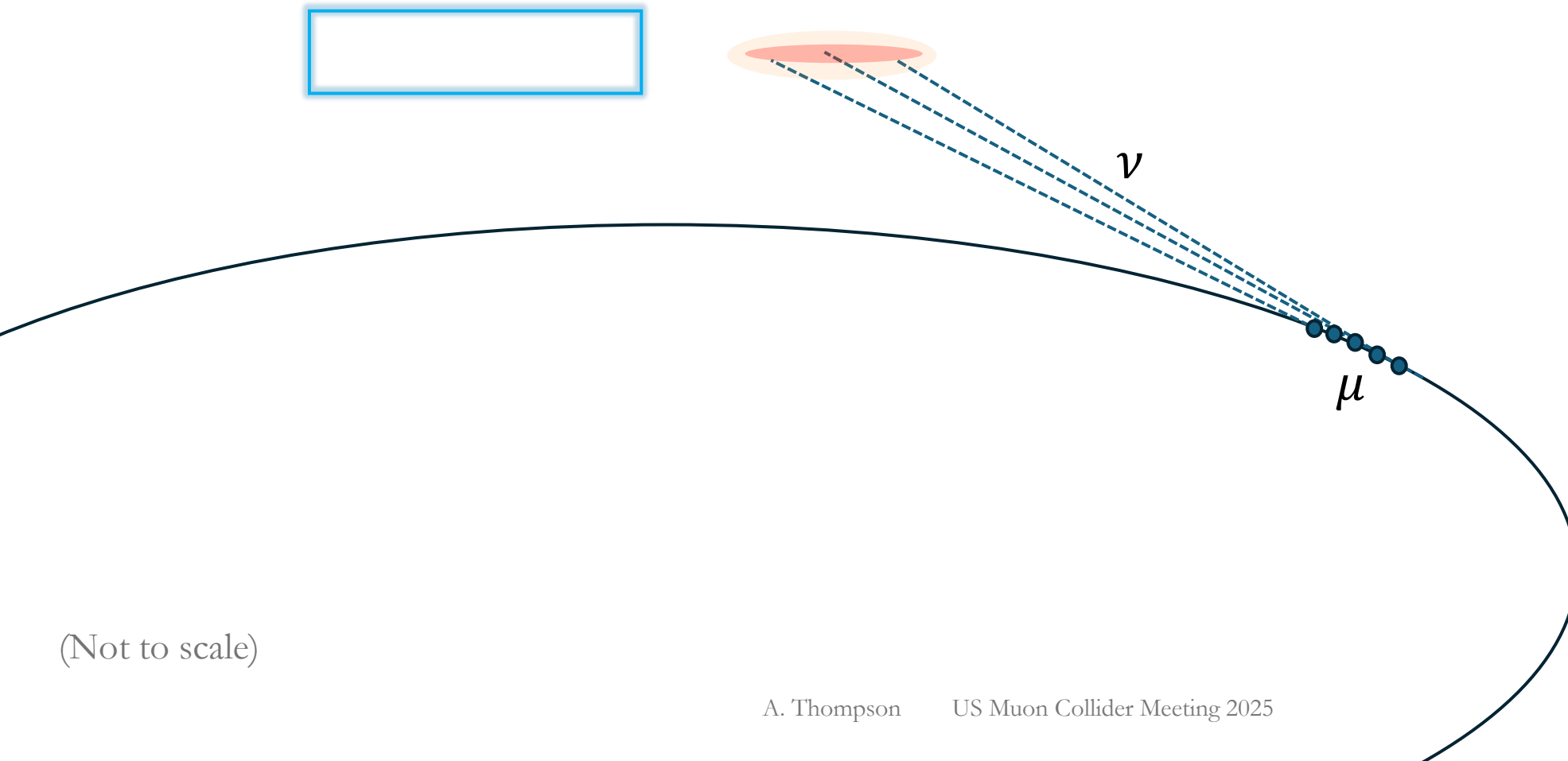


The (Terrestrial) Neutrino Lighthouse: Timing



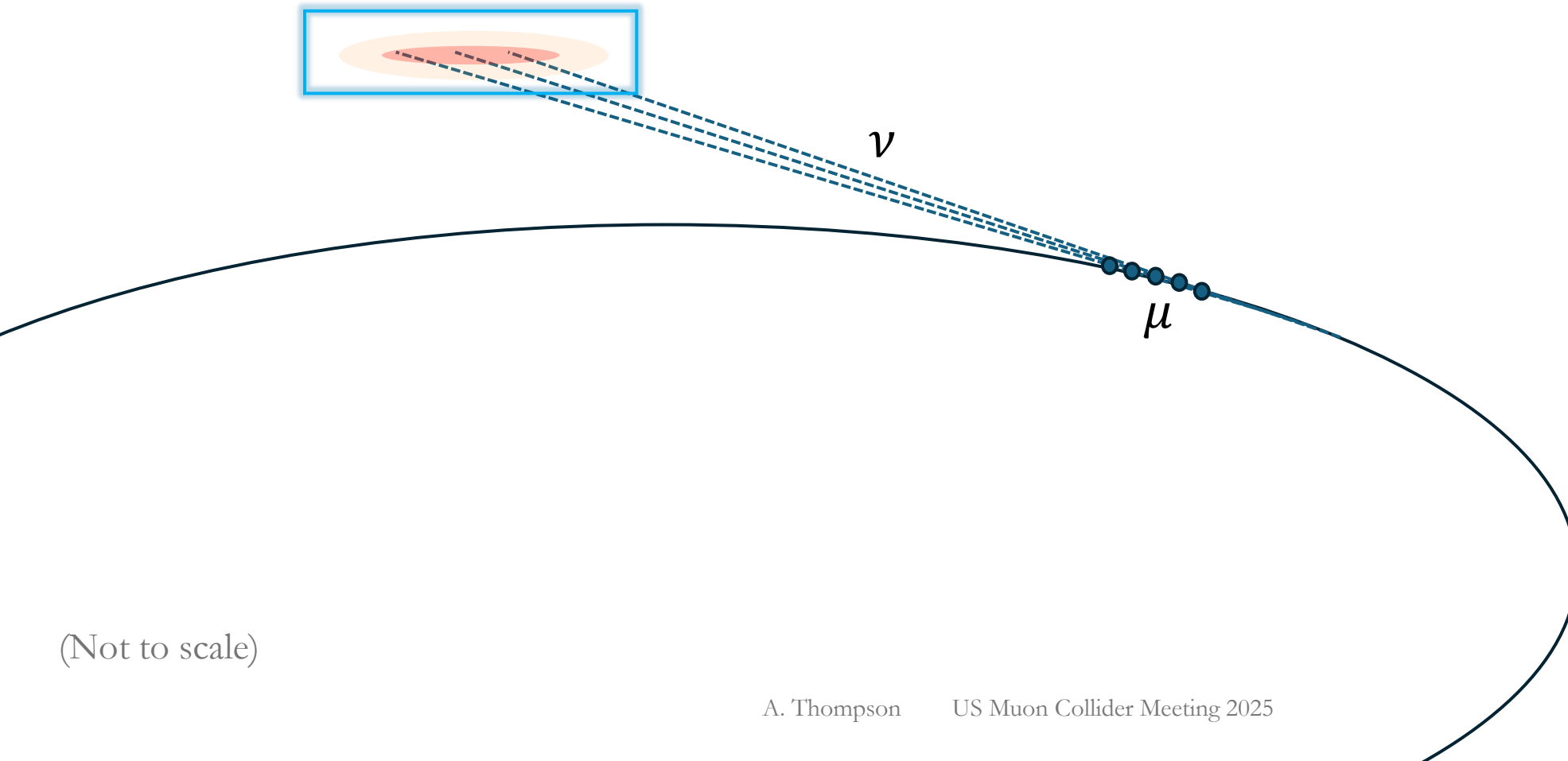
(Not to scale)

The (Terrestrial) Neutrino Lighthouse: Timing



(Not to scale)

The (Terrestrial) Neutrino Lighthouse: Timing



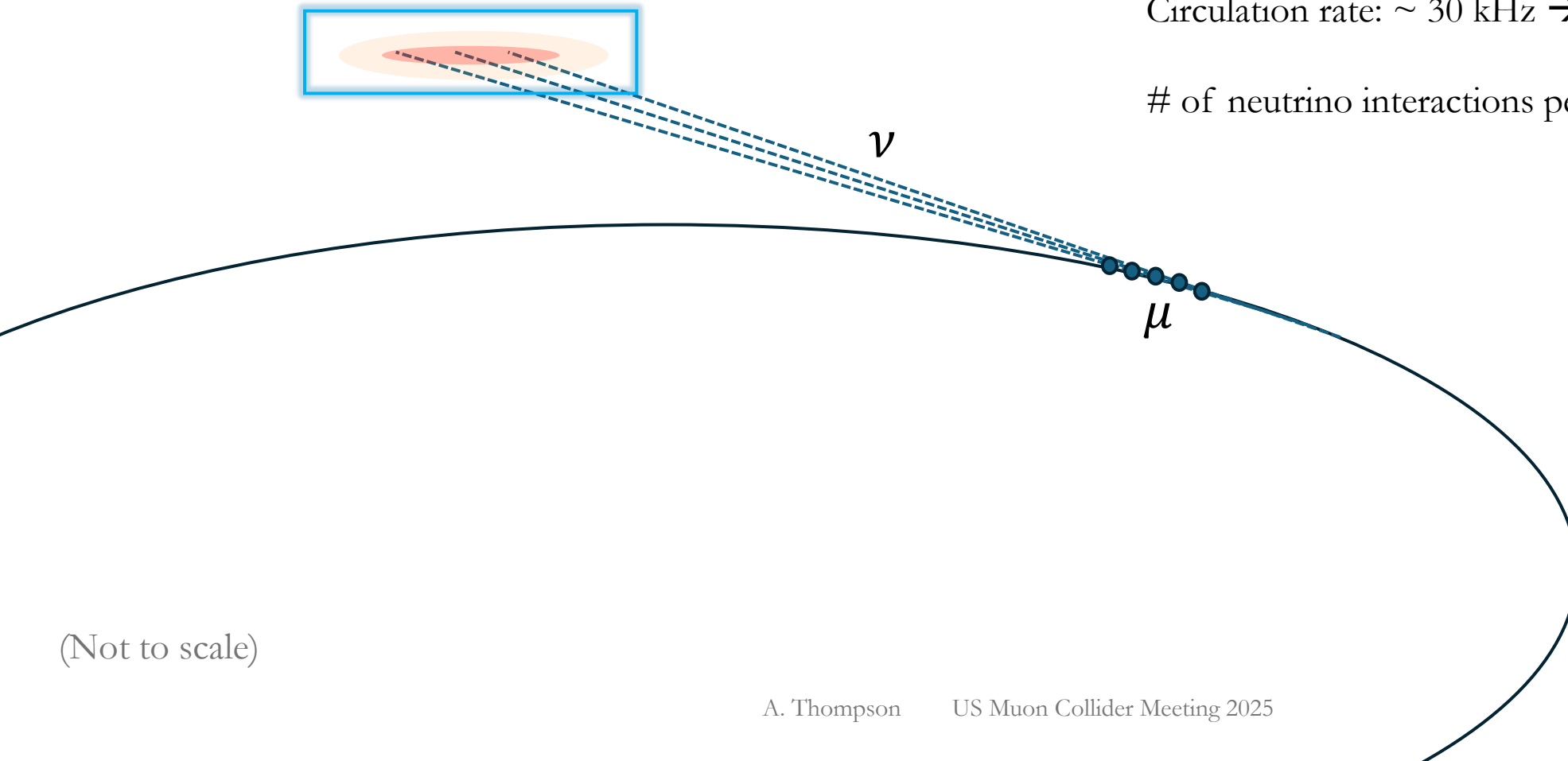
(Not to scale)

The (Terrestrial) Neutrino Lighthouse: Timing

Nominal bunch intensity: $\sim 10^{12} \mu$

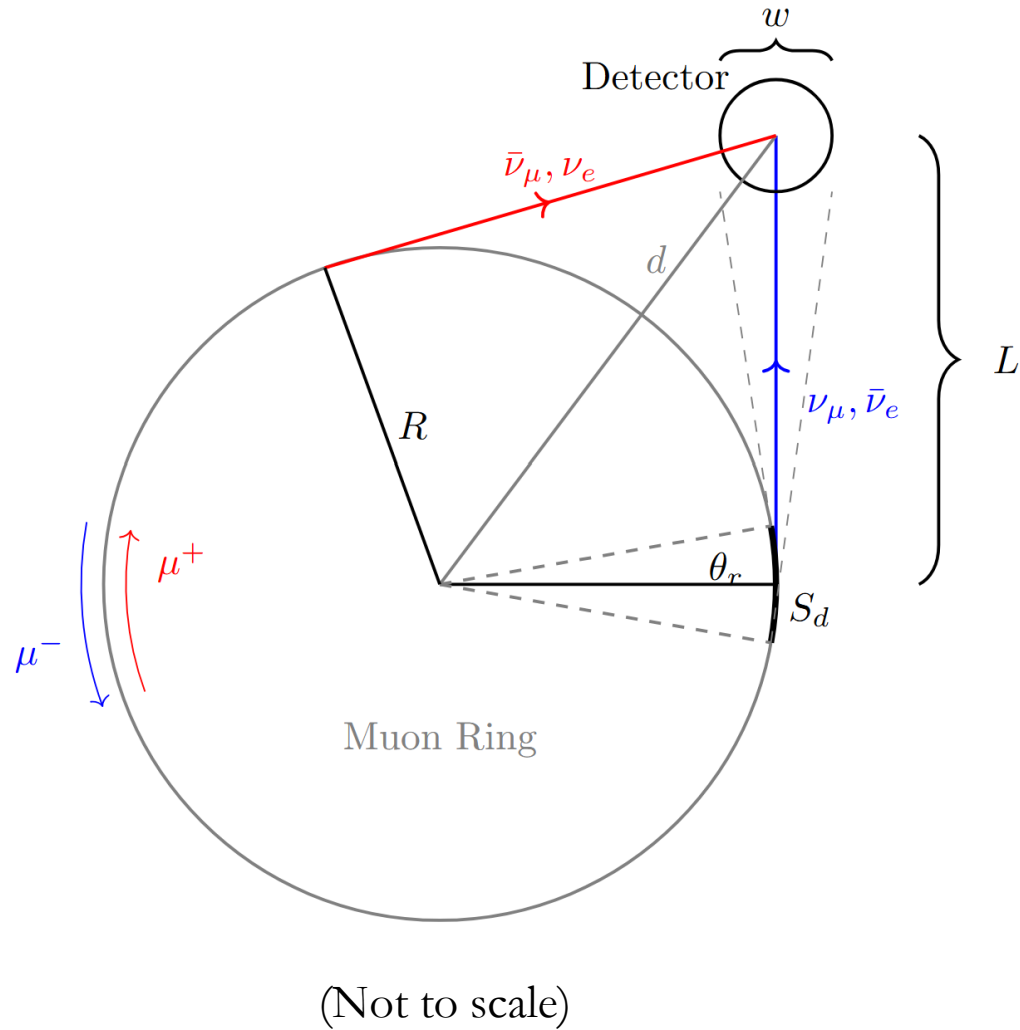
Circulation rate: $\sim 30 \text{ kHz} \rightarrow 30 \mu\text{s}$

of neutrino interactions per bunch crossing: < 1



(Not to scale)

Bird's Eye View

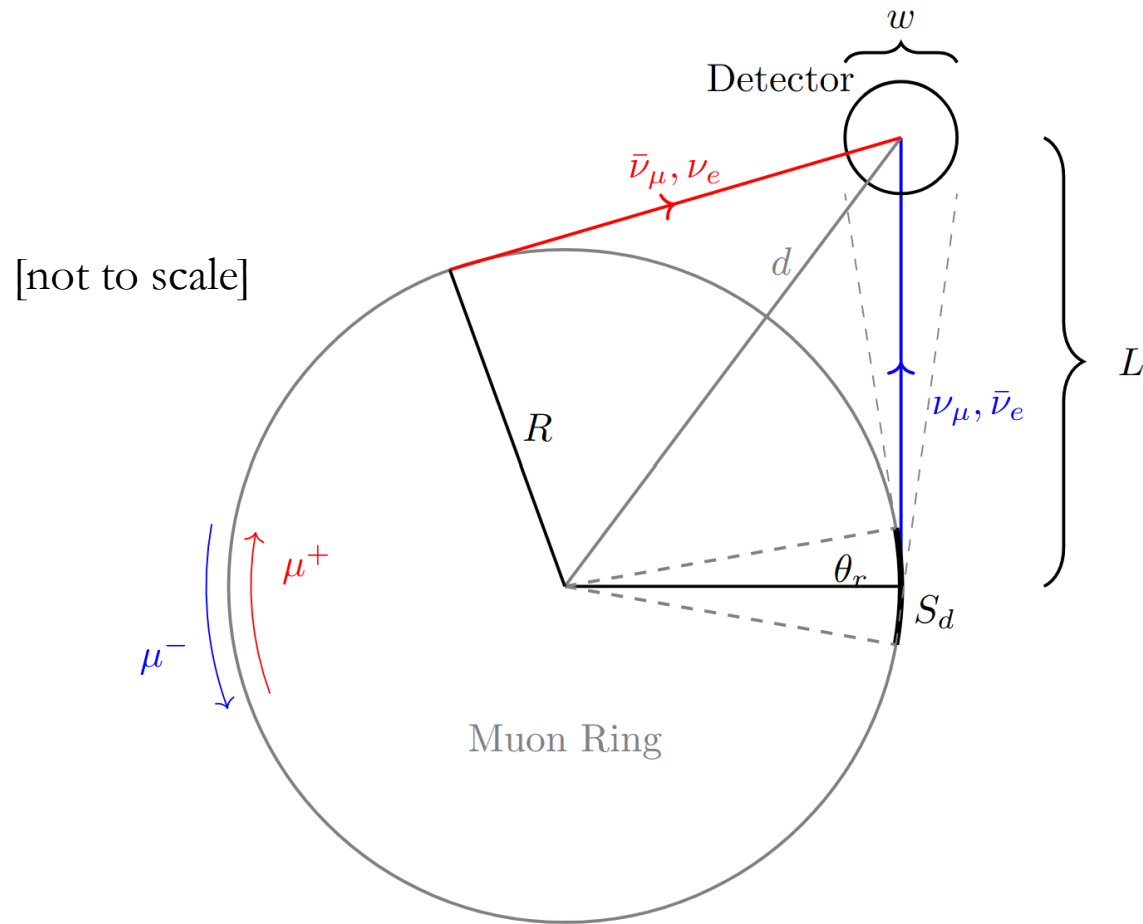


From geometry, the acceptance is:

$$F_{\mu,\text{useful}} \approx \frac{w}{2\pi d}$$

$$N_{\nu,\text{accept}} = F_{\mu,\text{useful}} N_{\mu,\text{decays}}$$

Bird's Eye View



$$F_{\mu, \text{useful}} \approx \frac{w}{2\pi d}$$

Example Assumptions:

- 10 km circumference ($R=1.6$ km)
- $d=1.7$ km
- $w=20$ m diameter
- $\rightarrow F_{\mu, \text{useful}} \approx 0.2\%$

$\sim 9 \times 10^{19}$ muons per year in the ring:

- 2×10^{18} neutrinos in detector volume / 10 years
- Consider $E_\mu = 250$ GeV, 1.5 TeV, 5 TeV
- Detector density: $\sim 10^{24}$ e- / cm^3

EvES from a High Energy Muon Decay Source

$$\frac{d\sigma_{\nu_\alpha}}{dE_r} = 2 \frac{G_F^2 m_e}{\pi} \left[(g_L + \delta_{e\alpha})^2 + (g_R)^2 \left(1 - \frac{E_r}{E_\nu}\right)^2 - (g_L + \delta_{e\alpha}) g_R \frac{m_e E_r}{E_\nu^2} \right]$$

$$\frac{d\sigma_{\bar{\nu}_\alpha}}{dE_r} = 2 \frac{G_F^2 m_e}{\pi} \left[(g_R)^2 + (g_L + \delta_{e\alpha})^2 \left(1 - \frac{E_r}{E_\nu}\right)^2 - (g_L + \delta_{e\alpha}) g_R \frac{m_e E_r}{E_\nu^2} \right]$$

Weak couplings in the SM:

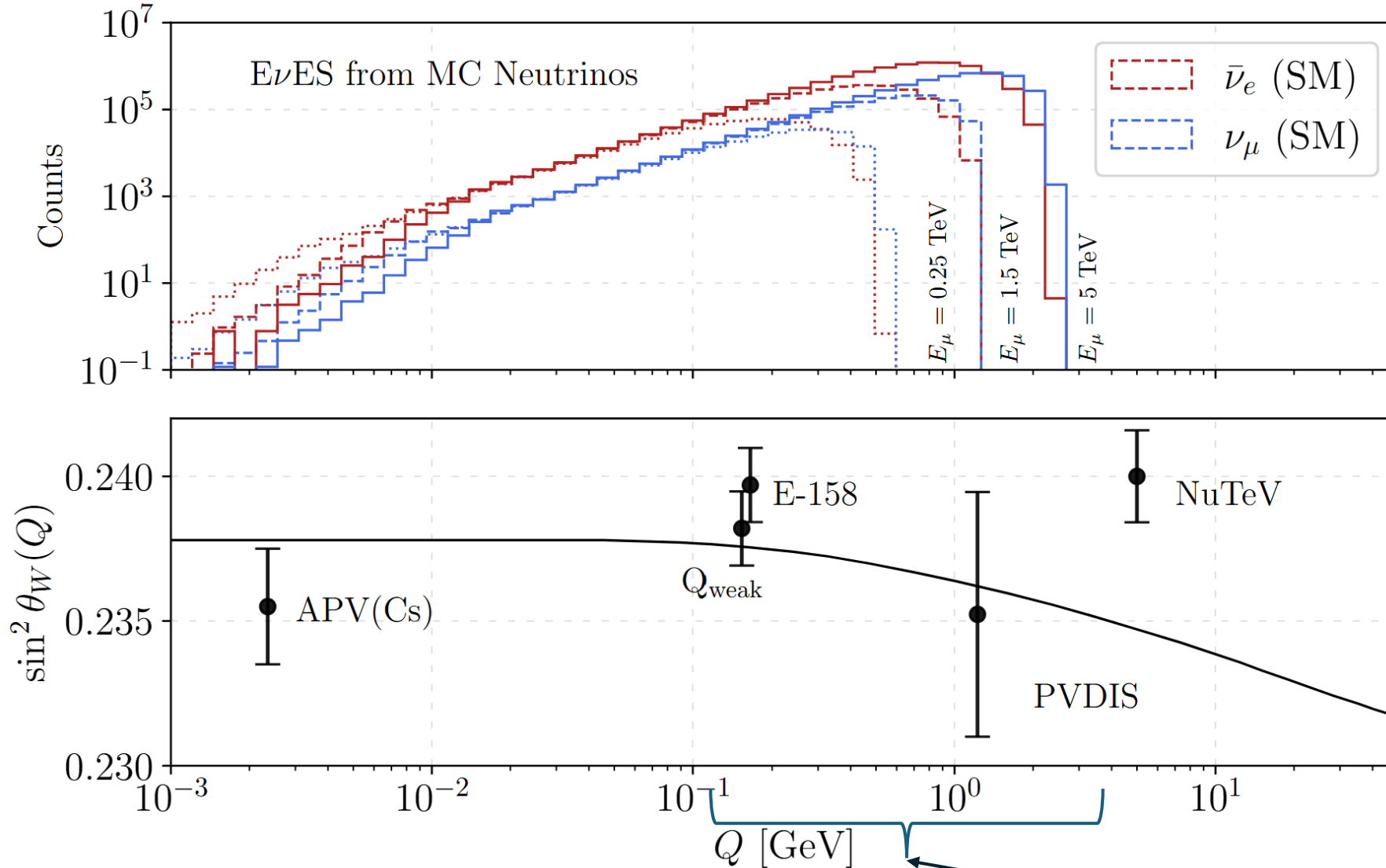
$$g_L \equiv 2g_L^\nu g_L^{e^-} = \sin^2 \theta_W - \frac{1}{2}$$

$$g_R \equiv 2g_L^\nu g_R^{e^-} = \sin^2 \theta_W$$

Integrate over the EvES cross sections for both muon decay fluxes:

$$\frac{d^2 N_{\nu_\alpha, \bar{\nu}_\alpha}}{dE_r dt} = N_\mu \times F_{\mu, \text{useful}} \times \underbrace{(n_e w)}_{\text{Det. electron density and path length}} \times \int_{y_{\min}}^1 \int_0^{2\pi} \int_{\cos \theta_{\min}}^1 \overbrace{\frac{\partial^2 N_{\nu_\alpha, \bar{\nu}_\alpha}}{\partial y \partial \Omega}}^{\text{Muon decay flux}} \underbrace{\frac{d\sigma_{\nu_\alpha, \bar{\nu}_\alpha}}{dE_r}}_{\text{EvES cross section}} d(\cos \theta) d\phi dy$$

Accessing the running of $\sin^2 \theta_W$



$$Q = \sqrt{2 m_e E_r}$$

As the muon beam energy reaches $\sim$ TeV scales, we access:

- “shoulder” of the running momentum-dependence of the WMA
- NuTeV anomaly region

First test: Weak Couplings g_V, g_A

$$\chi_{\mu^\pm}^2 = \sum_{i=1}^{N_{\text{bins}}} \frac{(s_i^{\mu^\pm} - n_i^{\mu^\pm})^2}{n_i^{\mu^\pm}}$$

Bin over electron recoil energy

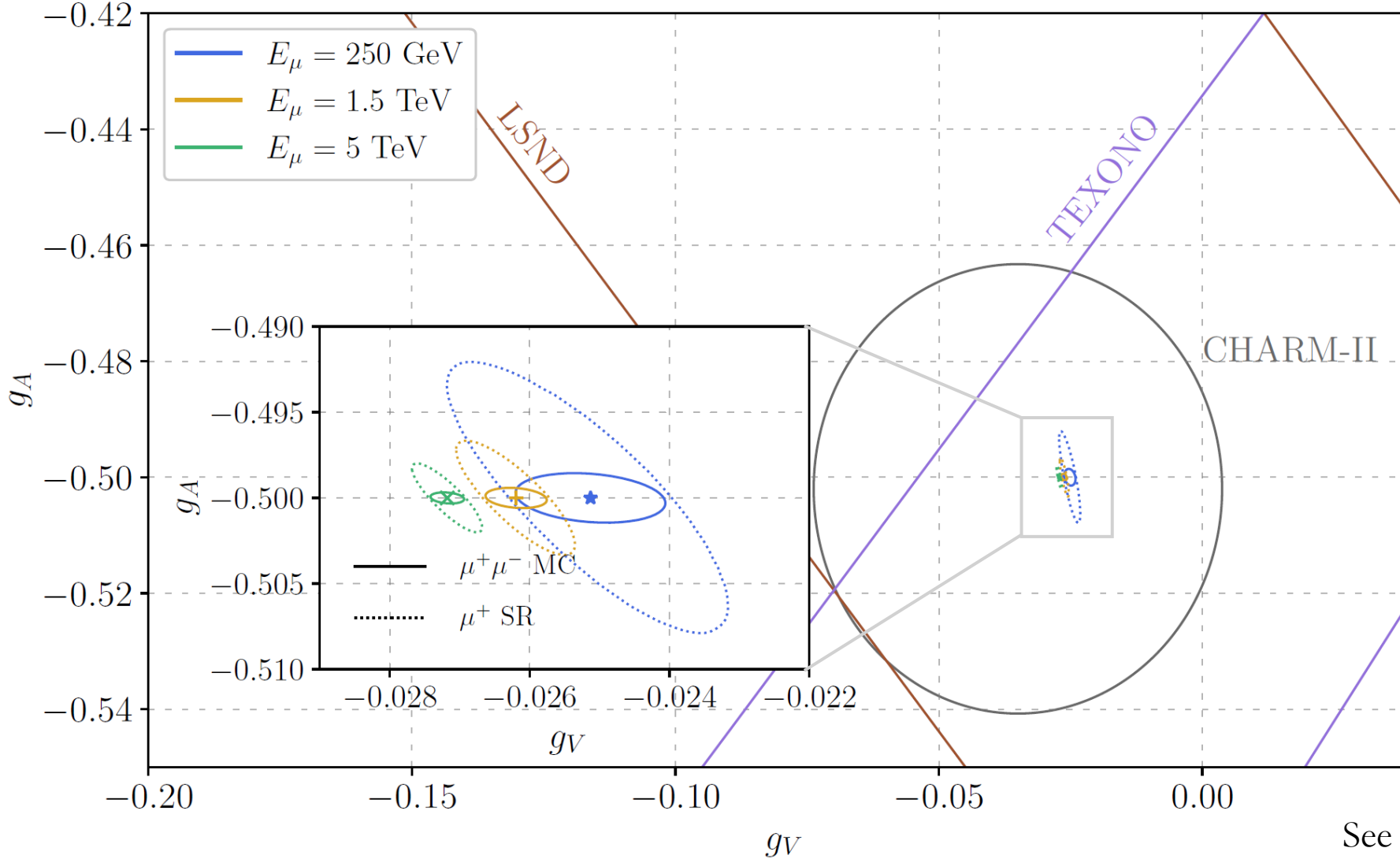
$$\chi_{\text{MC}}^2 \equiv \chi_{\mu^+}^2 + \chi_{\mu^-}^2$$

$$g_V \equiv (g_L + g_R)$$

$$g_A \equiv (g_L - g_R)$$

$$g_V^{\text{null}} = -\frac{1}{2} + 2 \sin^2 \theta_W (\langle Q \rangle)$$
$$g_A^{\text{null}} = -\frac{1}{2}.$$

Sensitivity to the Weak Couplings



Null hypothesis:

Background-free EvES
spectra with fixed
 $\sin^2\theta_W(\langle Q \rangle)$
for each E_μ benchmark

as good as $\sim 0.05\%$
precision at the $E_\mu = 5$
TeV machine

See also Corona *et al* [[2504.05272](#)]
AdG, Machado, Perez-Gonzalez, Tabrizi
[[1912.06658](#)]

Flavor non-universal Weak Couplings of the Neutrinos

Null hypothesis:

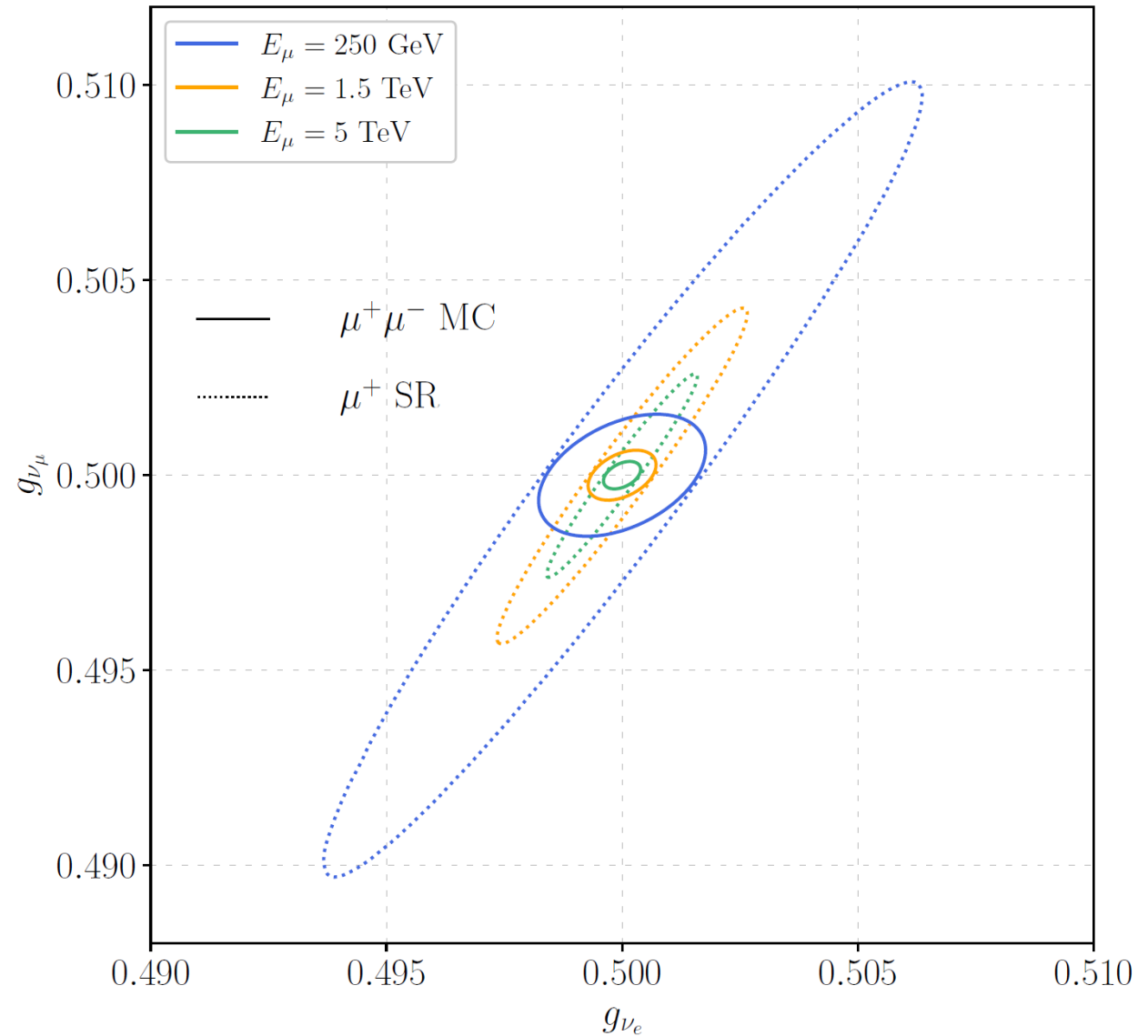
Background-free EvES spectra
with fixed

$$\sin^2 \theta_W(\langle Q \rangle)$$

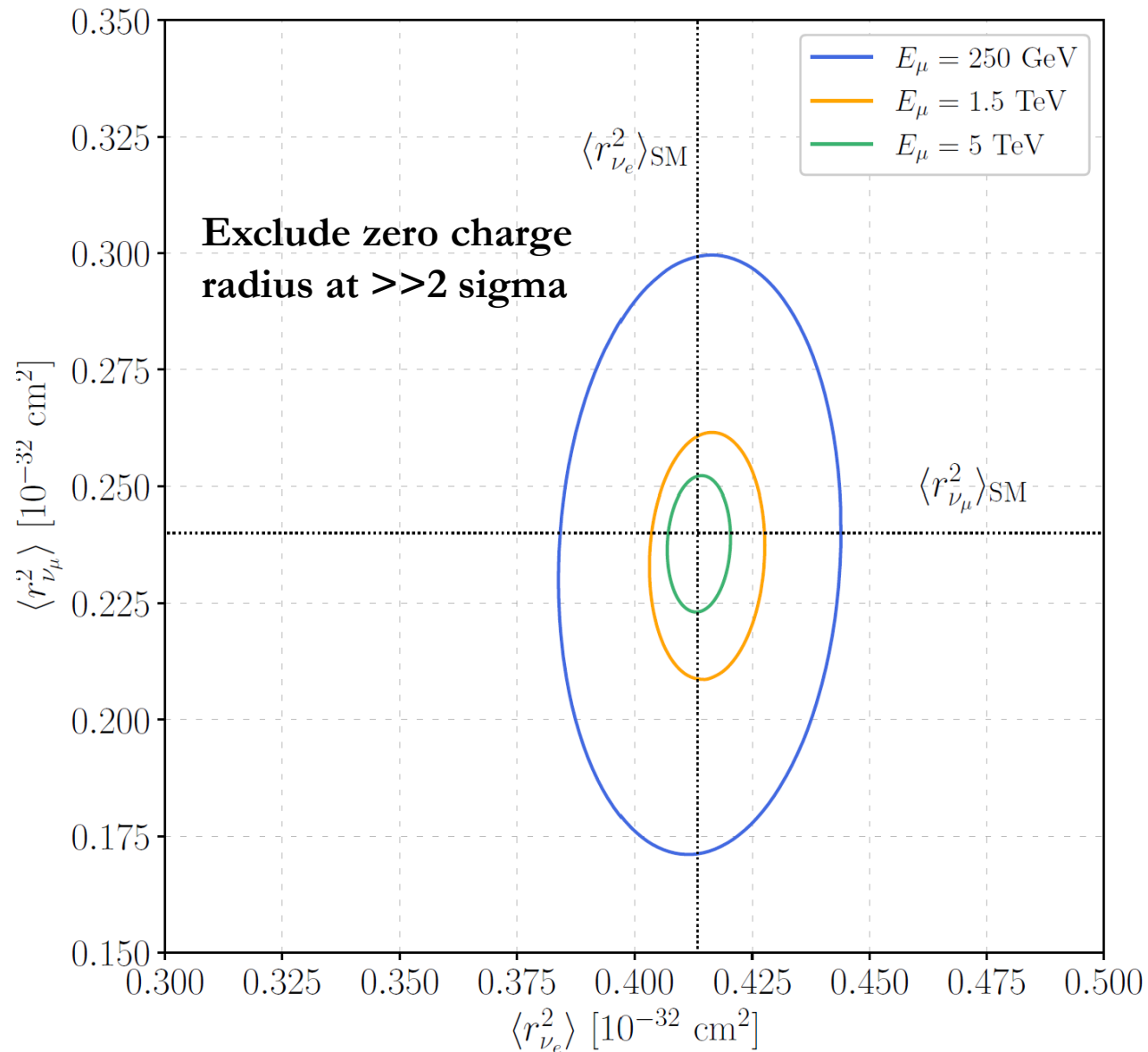
for each E_μ benchmark

$$g_L \equiv 2g_L^{\nu_e} g_L^{e^-}, \quad g_R \equiv 2g_L^{\nu_e} g_R^{e^-}$$

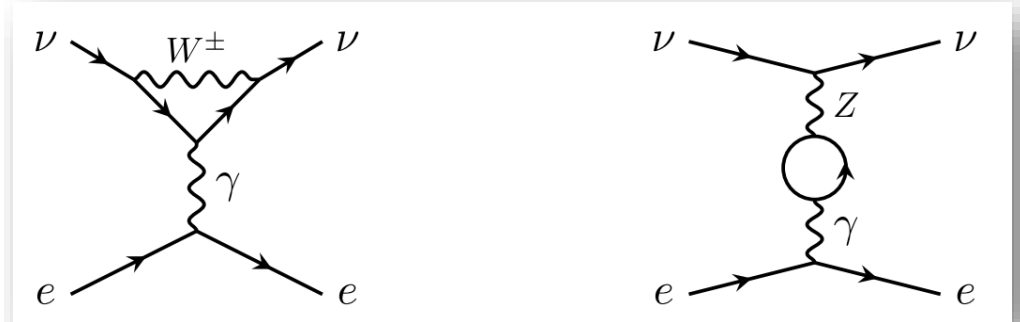
$$g_L \equiv 2g_L^{\nu_\mu} g_L^{e^-}, \quad g_R \equiv 2g_L^{\nu_\mu} g_R^{e^-}$$



Neutrino Charge Radius



$$\mathcal{L}_{\text{eff}} \supset \bar{\nu} \Lambda_\mu(q) \nu A^\mu$$



$$\Lambda_\mu = f(q^2) \gamma_\mu + \dots$$

[2410.00107]

$$g_{L,R} \rightarrow g_{L,R} + \frac{1}{3} m_W^2 \langle r_{\nu_\alpha}^2 \rangle \sin^2 \theta_W$$

See e.g., Giunti, Studenikin [0812.3646]

Abraham, Foroughi-Abari, Kling, Tsai, [2301.10254]

Brdar, Ferreira-Leite, Parker, Xu, [2410.00107]

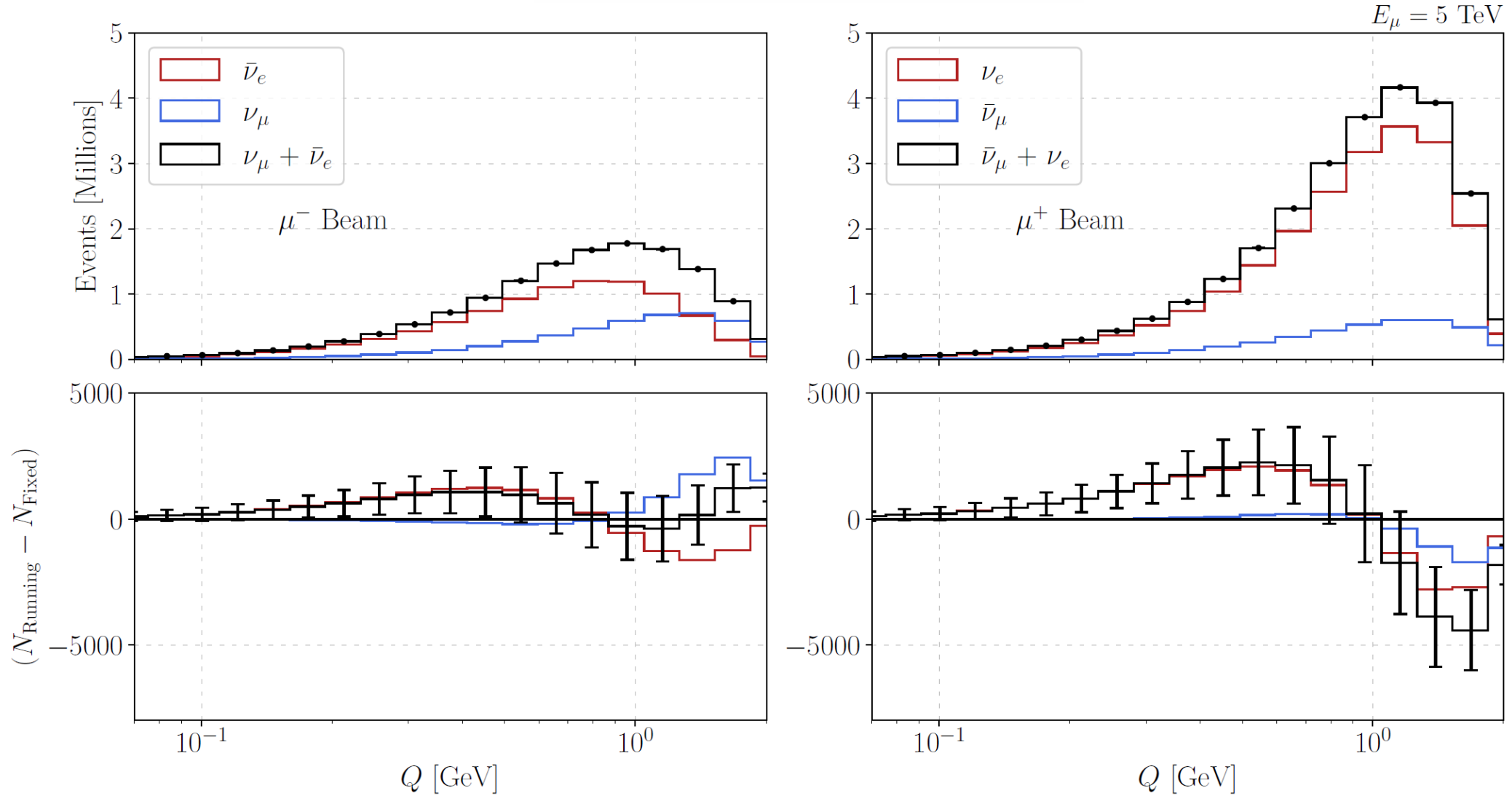
Does $\sin^2 \theta_W$ run?

$$g_L \rightarrow g_L(Q) = \sin^2 \theta_W(Q) - \frac{1}{2}$$

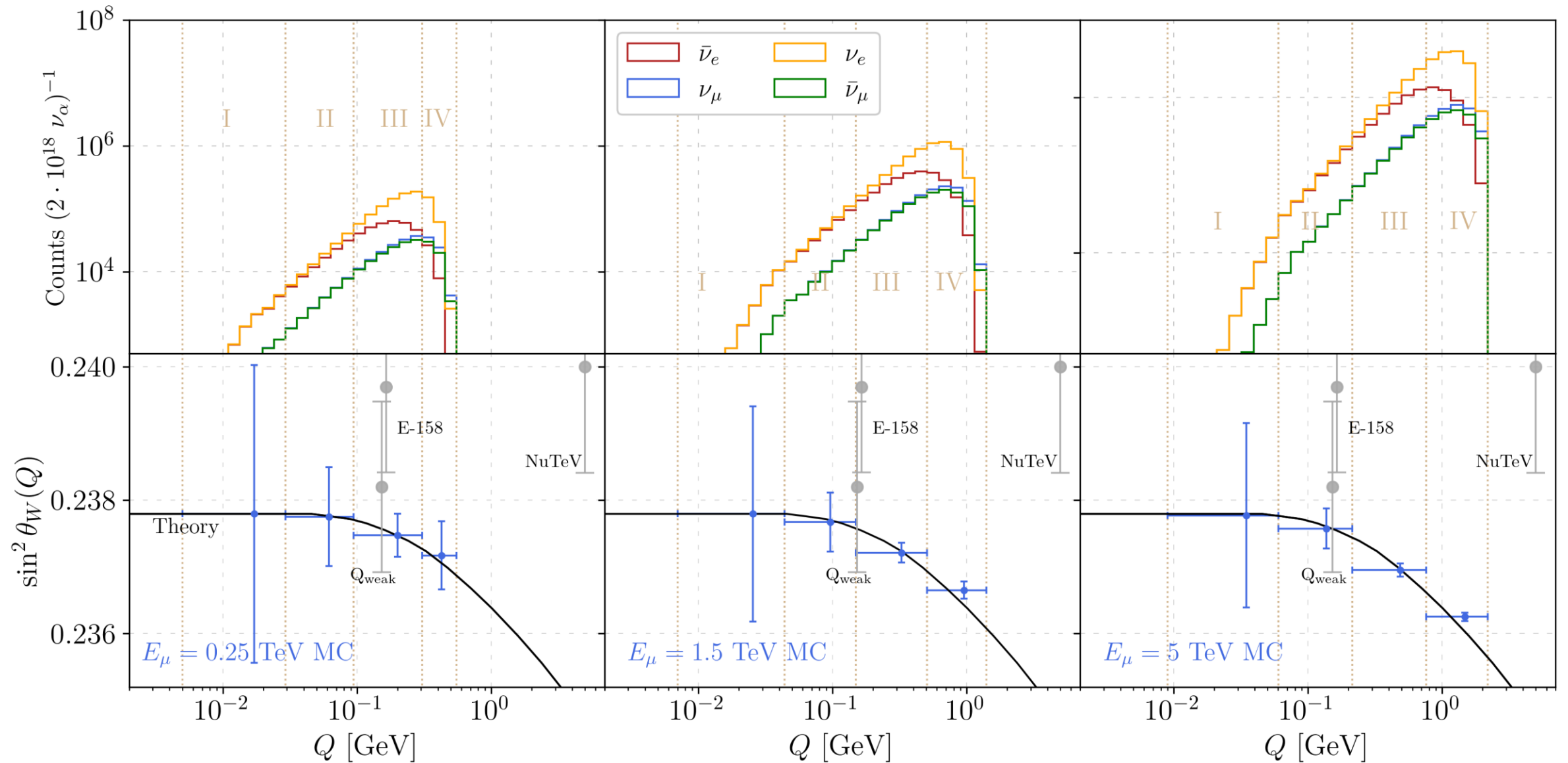
$$g_R \rightarrow g_R(Q) = \sin^2 \theta_W(Q).$$

$$\sin^2 \theta_W(Q^2) = \kappa(Q^2, \mu) \sin^2 \theta_W(\mu)$$

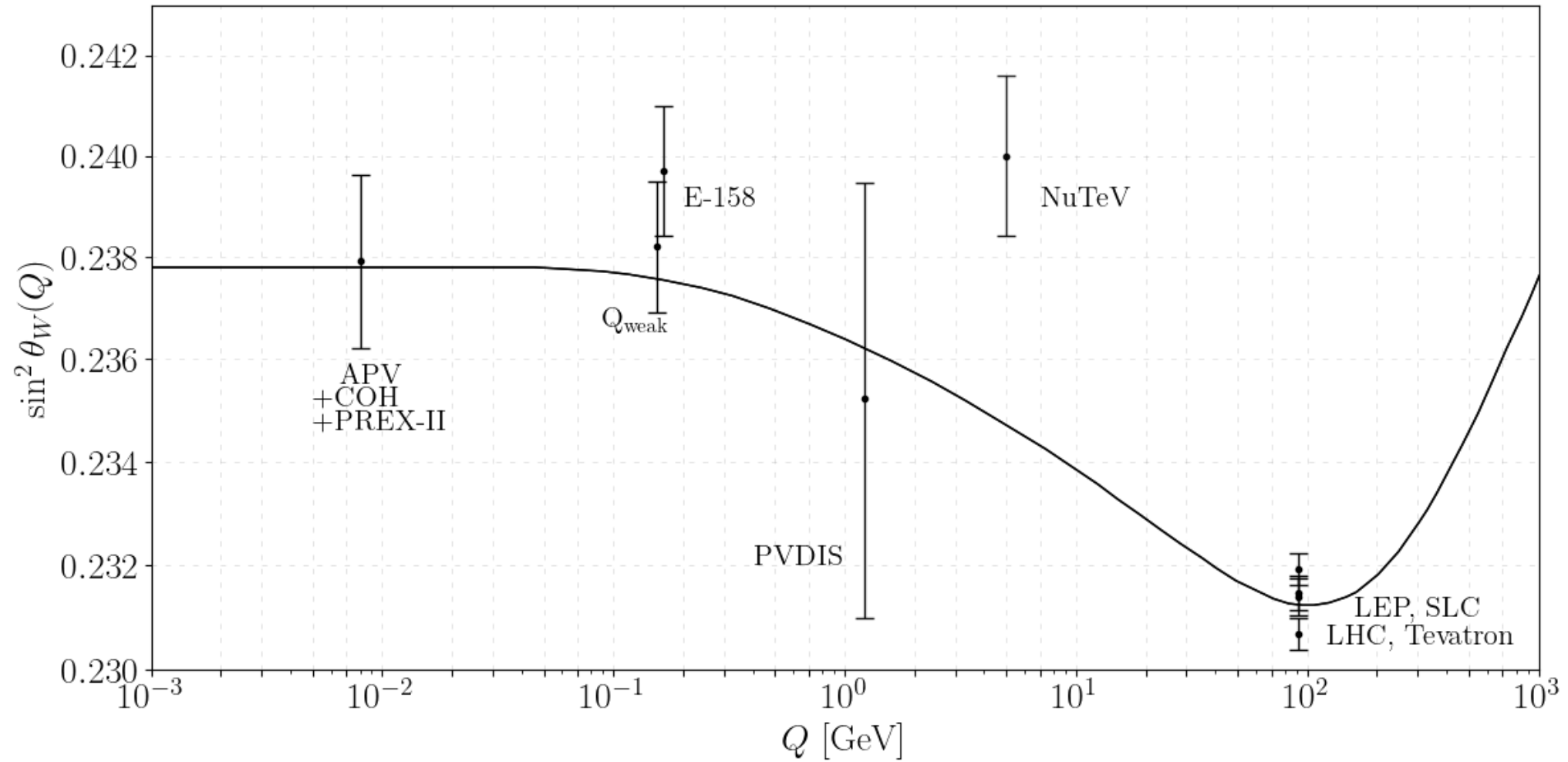
Czarnecki, Marciano [[0003049](#)]
 Kumar, Mantry, Marciano, Souder [[1302.6263](#)]



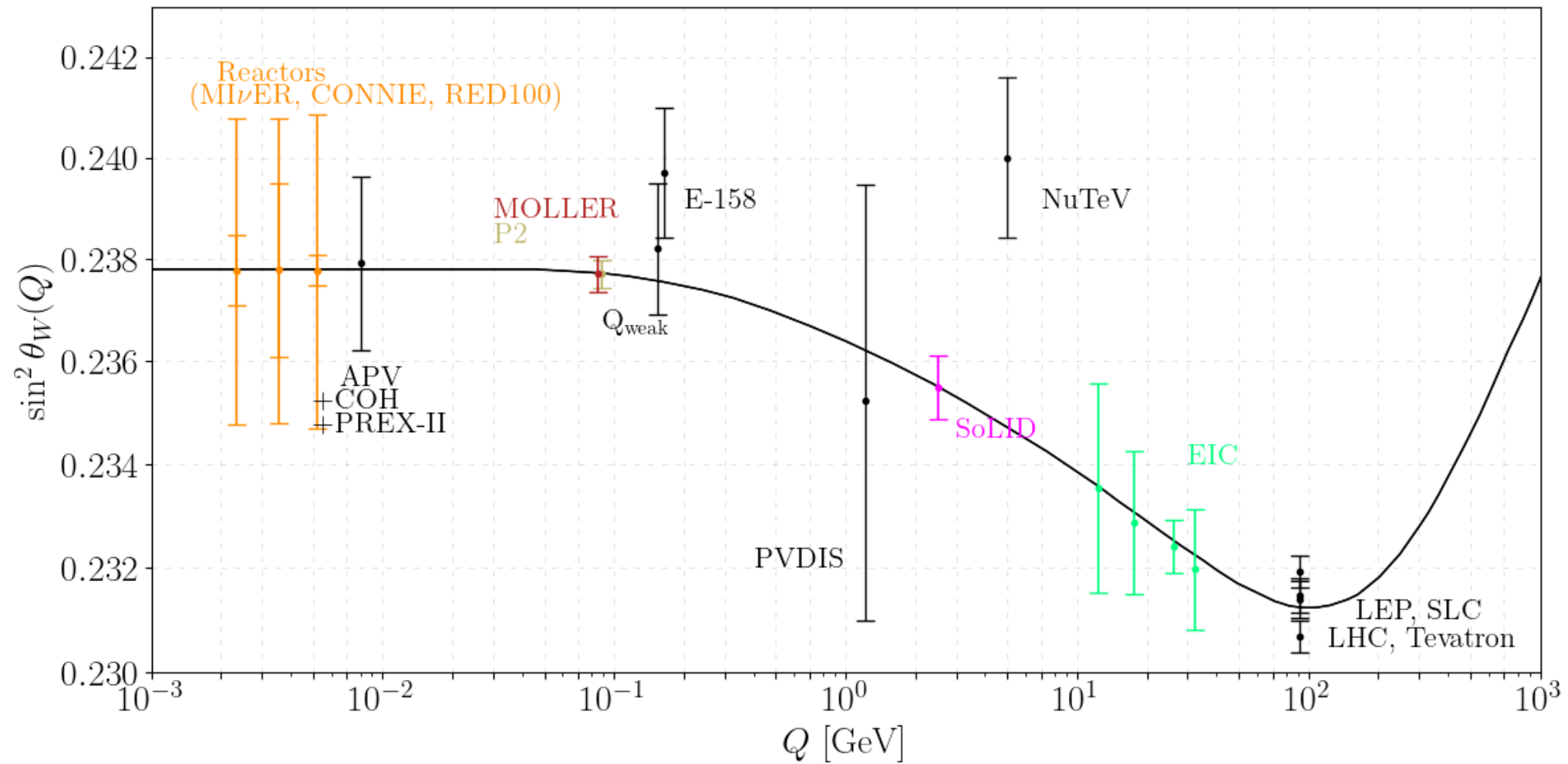
Method I: Q -binned Extraction of $\sin^2\theta_W$



The Landscape of Weak Mixing Measurements



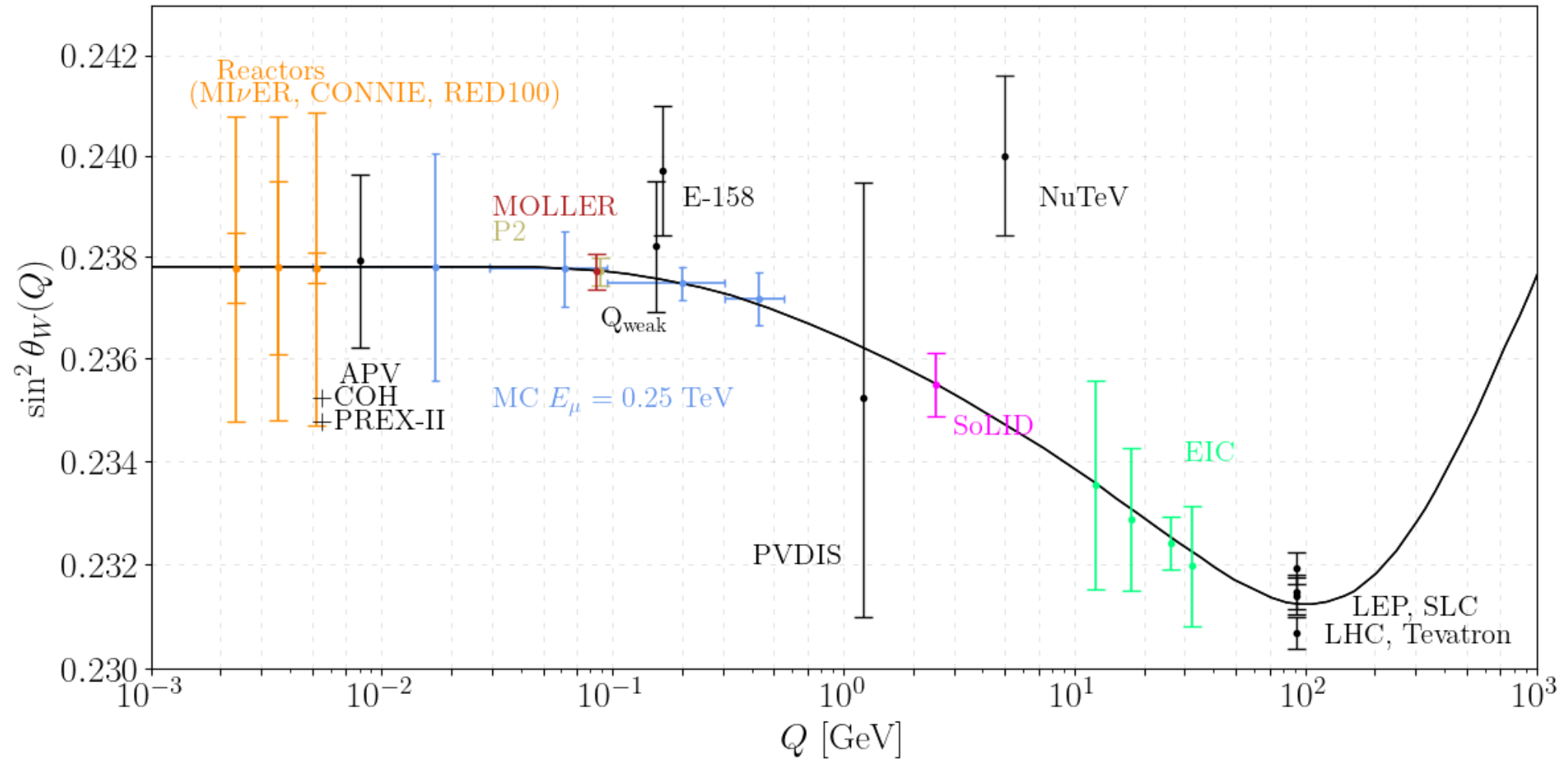
The Landscape of Weak Mixing Measurements



Reactors [[1806.01310](#)]
 COHERENT + APV + PREX-II
[\[2405.09416\]](#)

EIC [[2204.07557](#)]

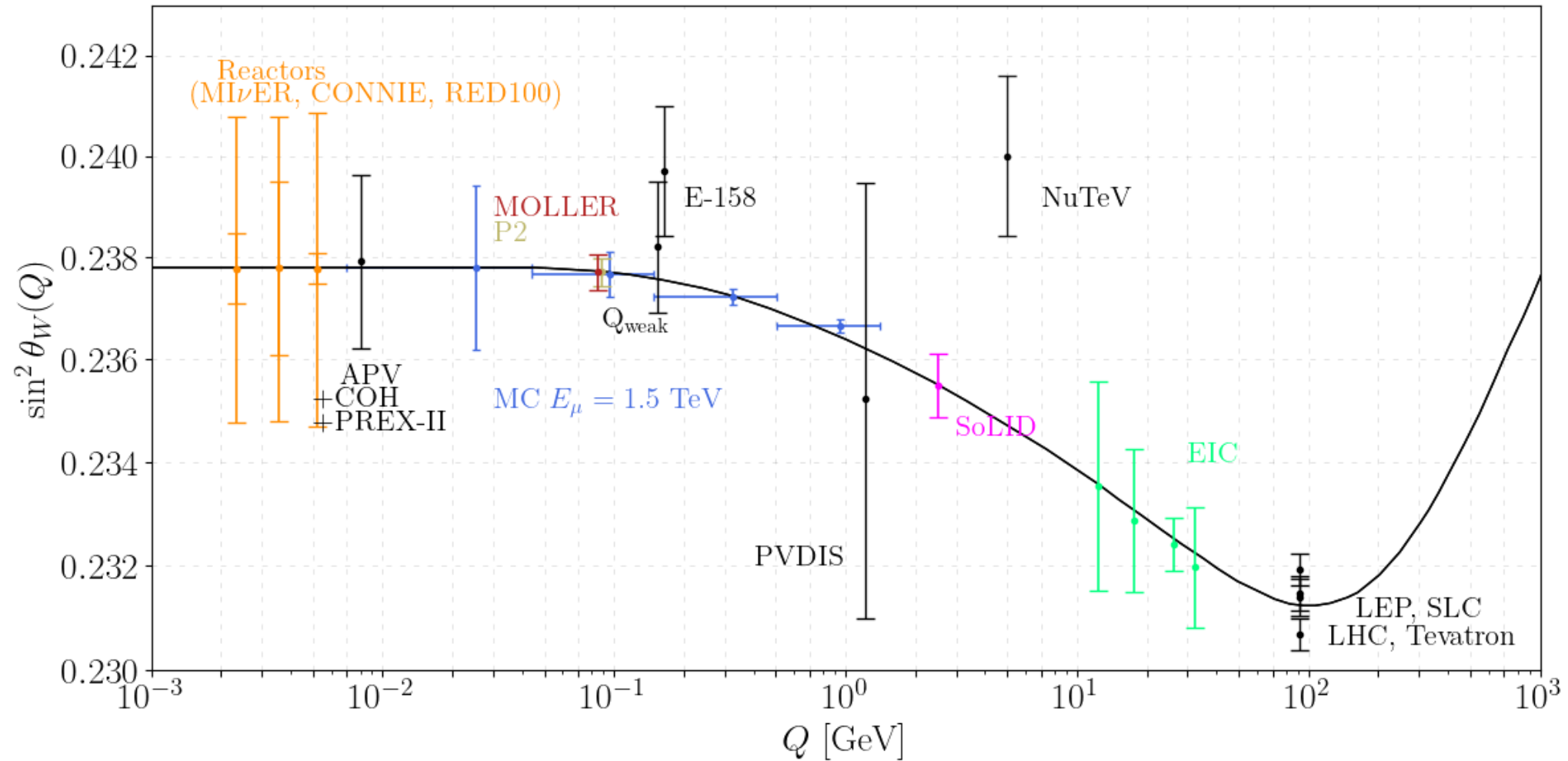
The Landscape of Weak Mixing Measurements



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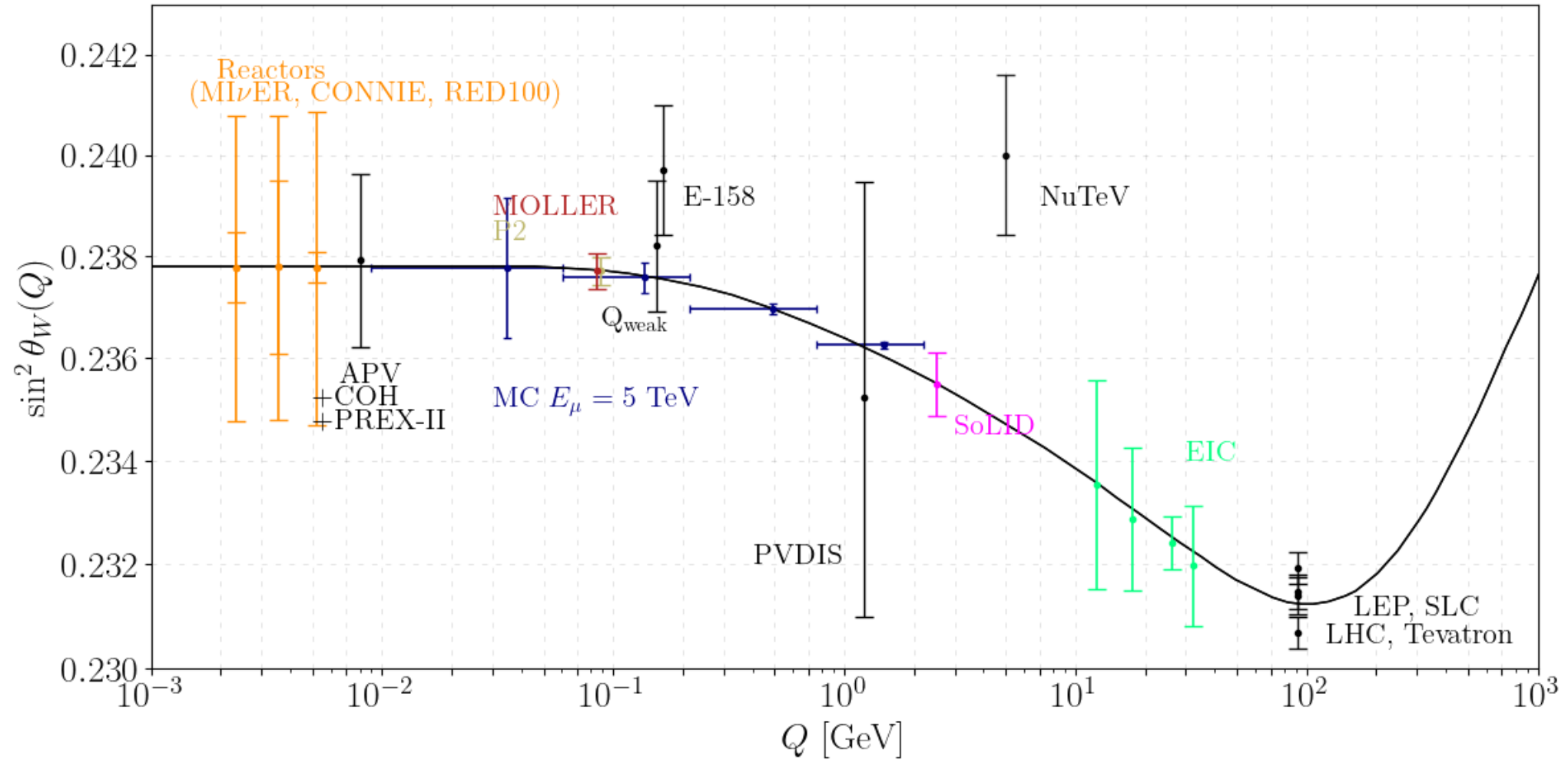
The Landscape of Weak Mixing Measurements



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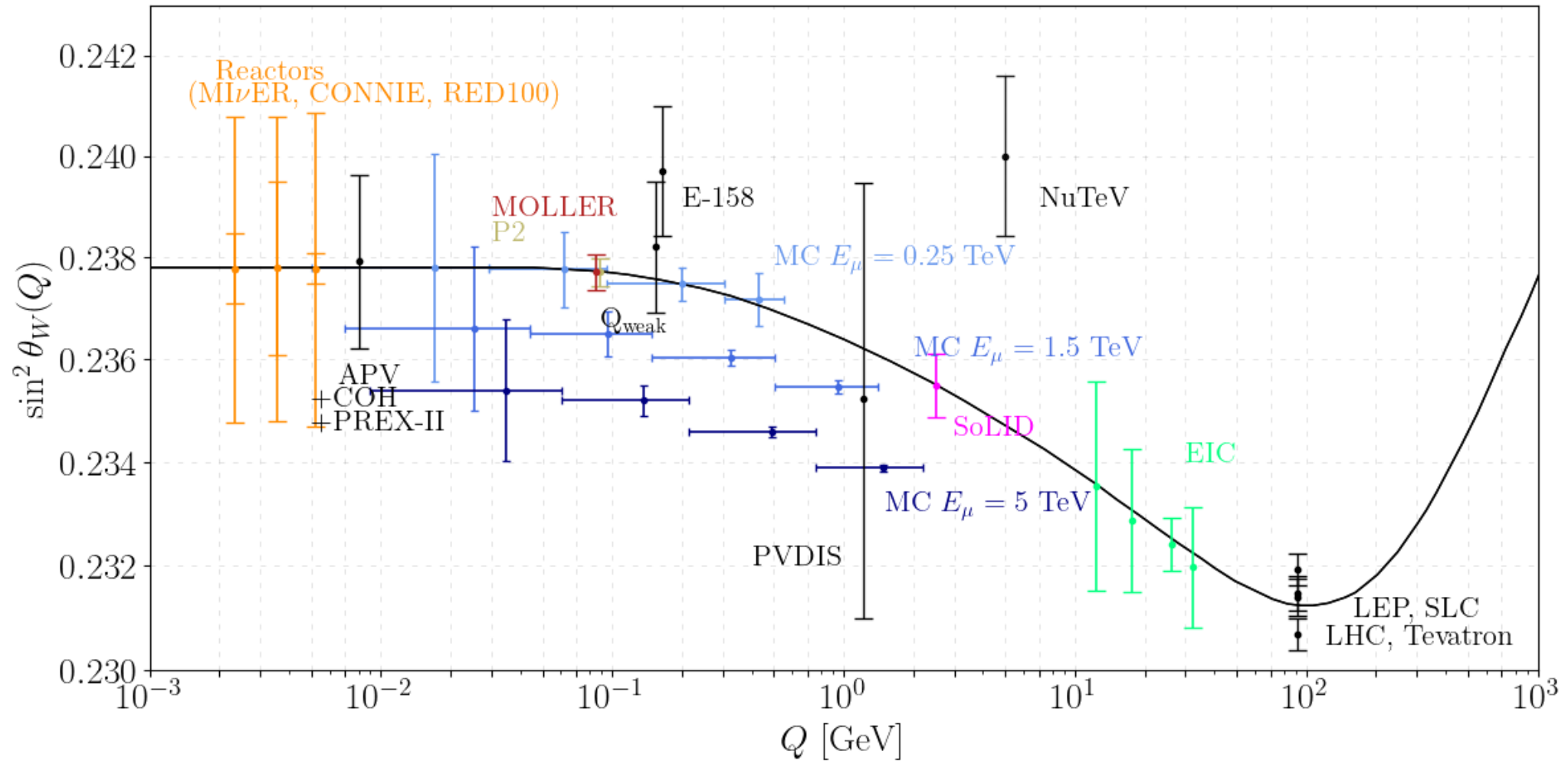
The Landscape of Weak Mixing Measurements



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The Landscape of Weak Mixing Measurements



Reactors [[1806.01310](#)]
 COHERENT + APV + PREX-II
[\[2405.09416\]](#)

EIC [[2204.07557](#)]

Takeaways and future work

- **Electroweak** observables $<1\%$ **precision** with neutrino scattering
- Equivalently, sensitivity to charge radius for muon and electron flavors
- Tests of flavor universality in the couplings

Future work:

- Beam polarization impact, profile (wigglers?)
- Detector location optimization, timing, reconstruction
- Backgrounds
- Other channels offer exciting physics targets:
 - Neutrino Tridents $\rightarrow$ degeneracy breaking of weak couplings
 - Inverse Tau/Muon Decay (QEvES) $\rightarrow$ Charged lepton flavor violation
 - CC/NC DIS $\rightarrow$ checking the NuTeV channels

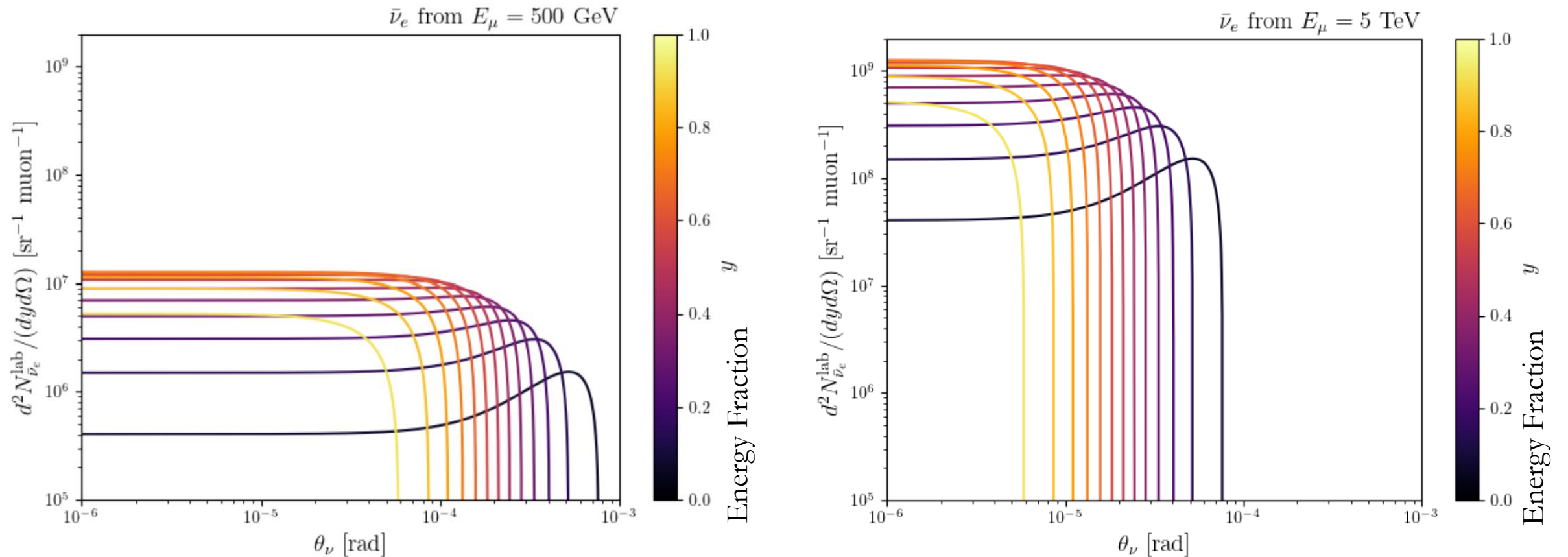
See also Matheus'
Plenary @ 4pm

See also:
Oscillations: [2502.14027](#)
Neutrino NSI [2508.00761](#)
Nu in Mu: [2410.21383](#)

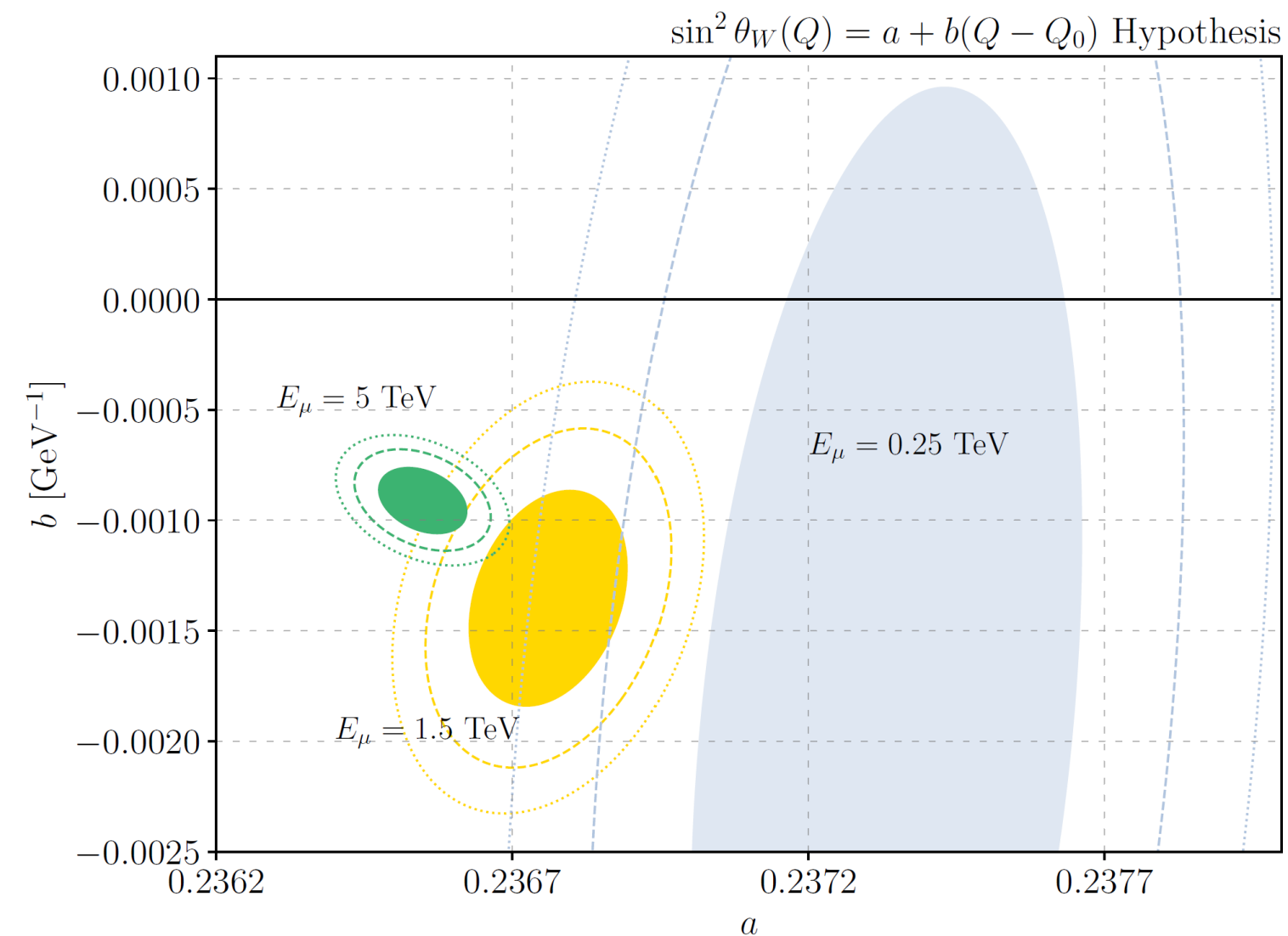
Backup Deck

Neutrino Fluxes from Muon Decay in the Lab Frame

Neutrino beam divergence out of the plane of the ring is small



Method II: Affine running hypothesis



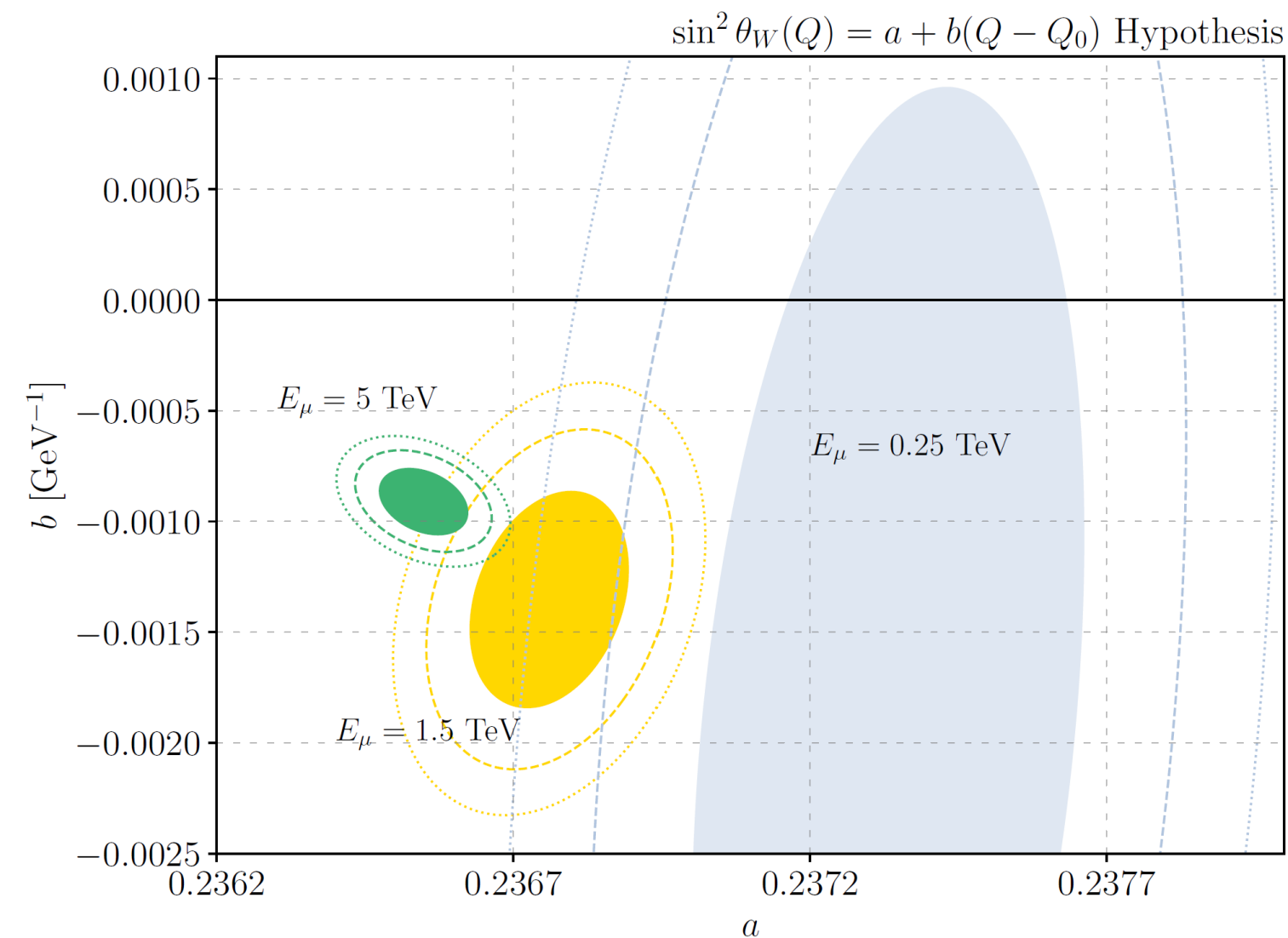
Null hypothesis:

EvES spectra with Q -dependent weak mixing angle

Test Hypothesis:

$$\sin^2 \theta_W = \sin^2 \theta_W(Q_0) + \frac{d\sin^2 \theta_W}{dQ} \Big|_{Q_0} (Q - Q_0)$$

Method II: Affine running hypothesis

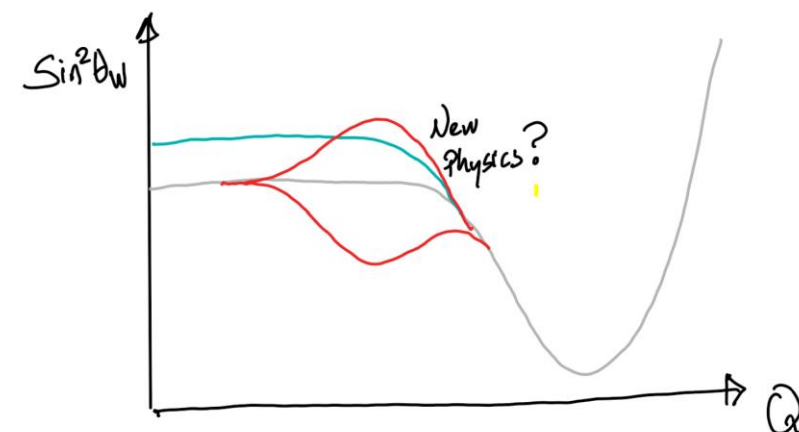


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EvES spectra with Q -dependent weak mixing angle

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$$\sin^2 \theta_W = \sin^2 \theta_W(Q_0) + \frac{d\sin^2 \theta_W}{dQ} \big|_{Q_0} (Q - Q_0)$$



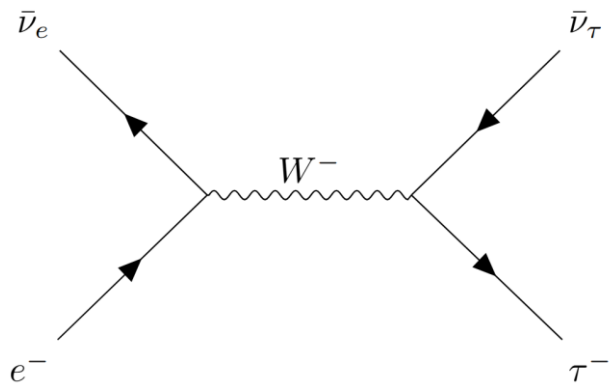
Marciano, Sirlin '81

Singer '82

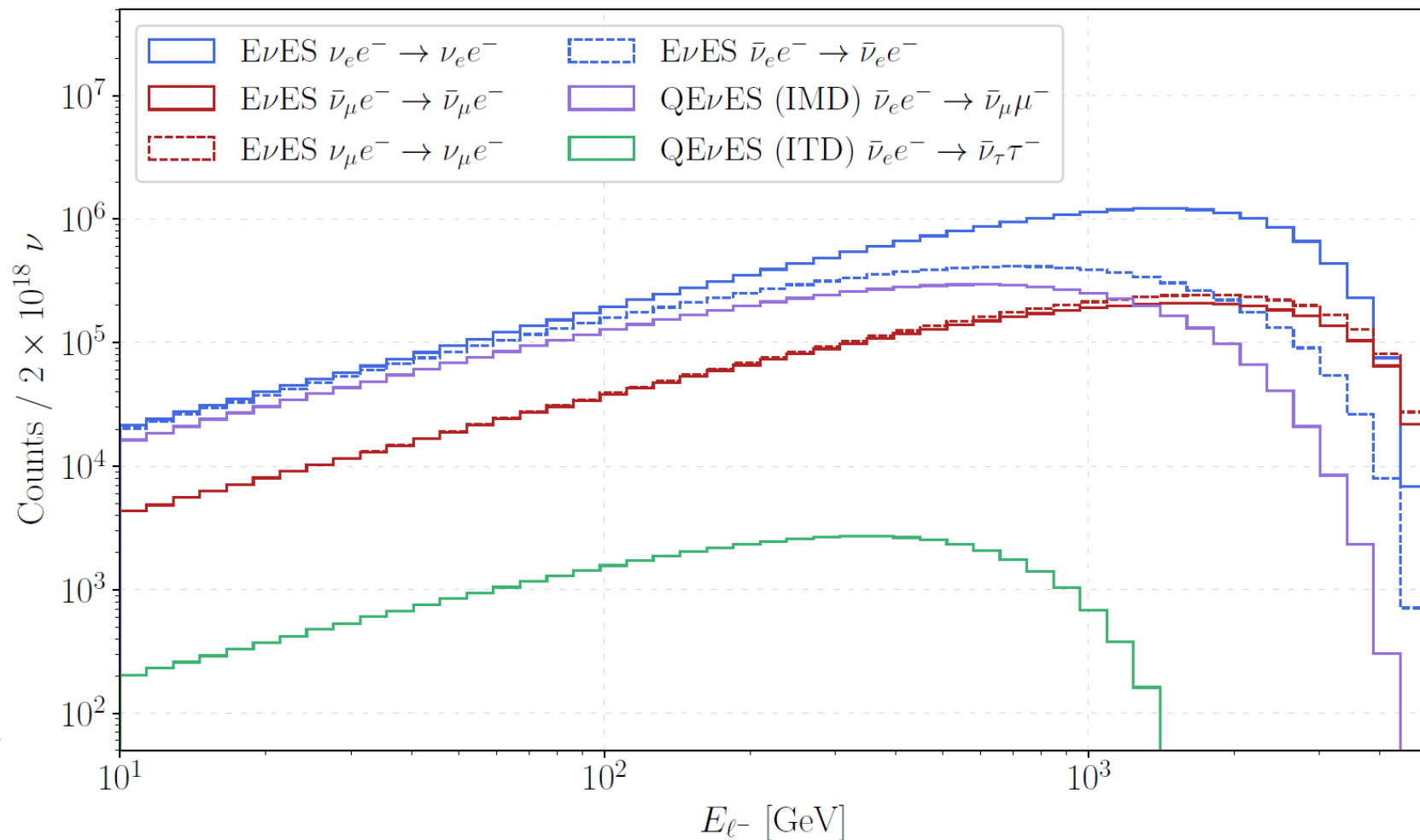
Davoudiasl, Lee, Marciano *et al* (2014)

QEvES / “Induced Lepton Decay”

$$\bar{\nu}_e + e \rightarrow \bar{\nu}_l + l \quad (l = \mu \text{ or } \tau)$$

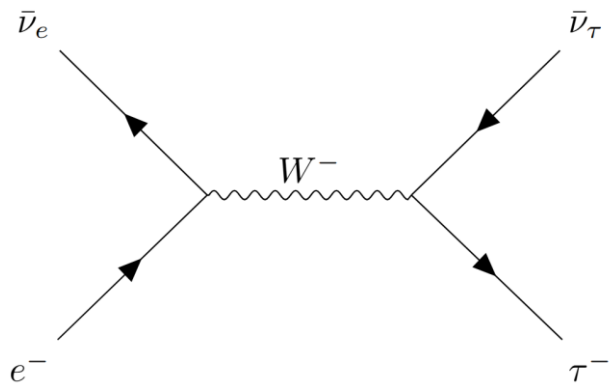


$\sim 10^4$ τ 's in the detector from ITD!

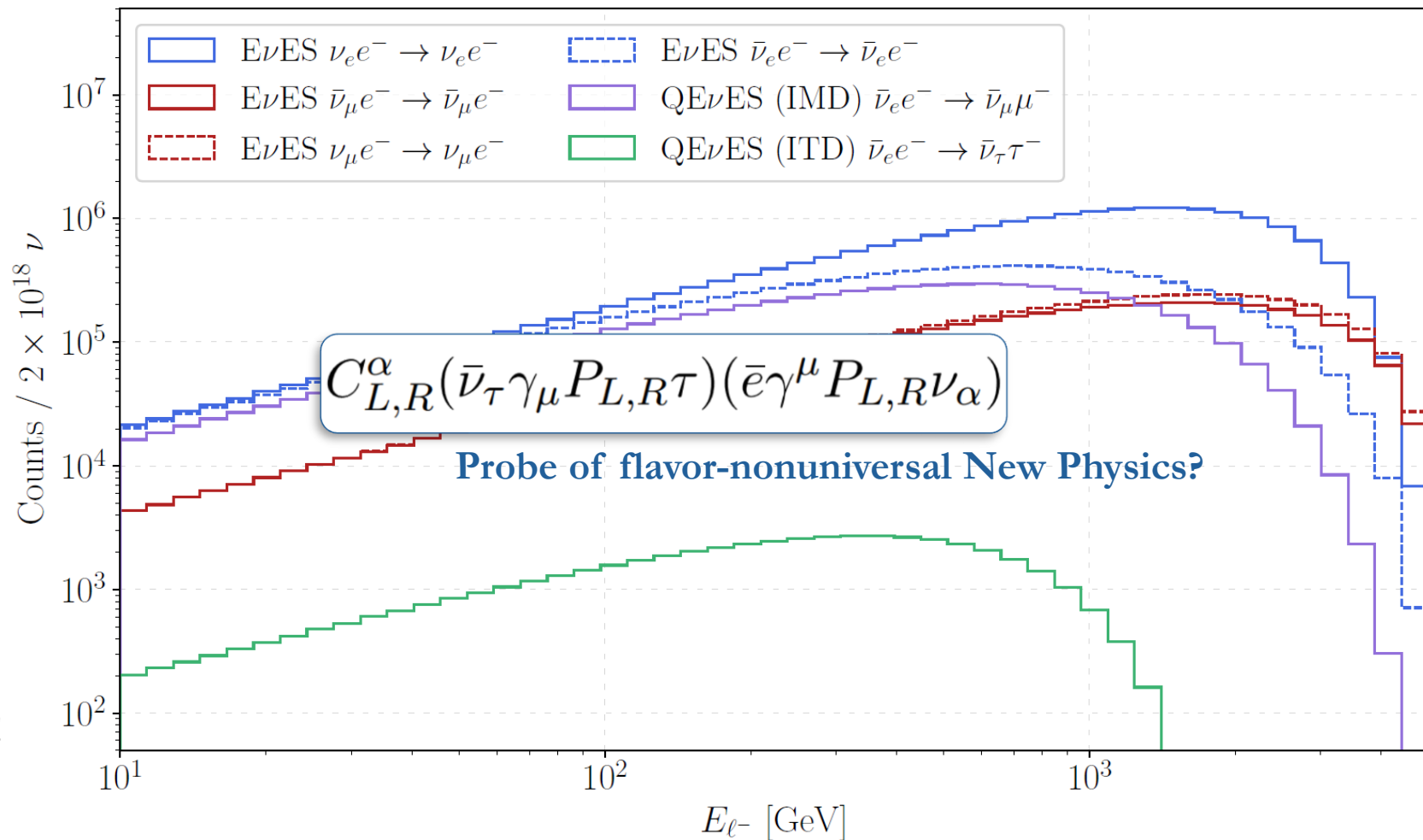


QEvES / “Induced Lepton Decay”

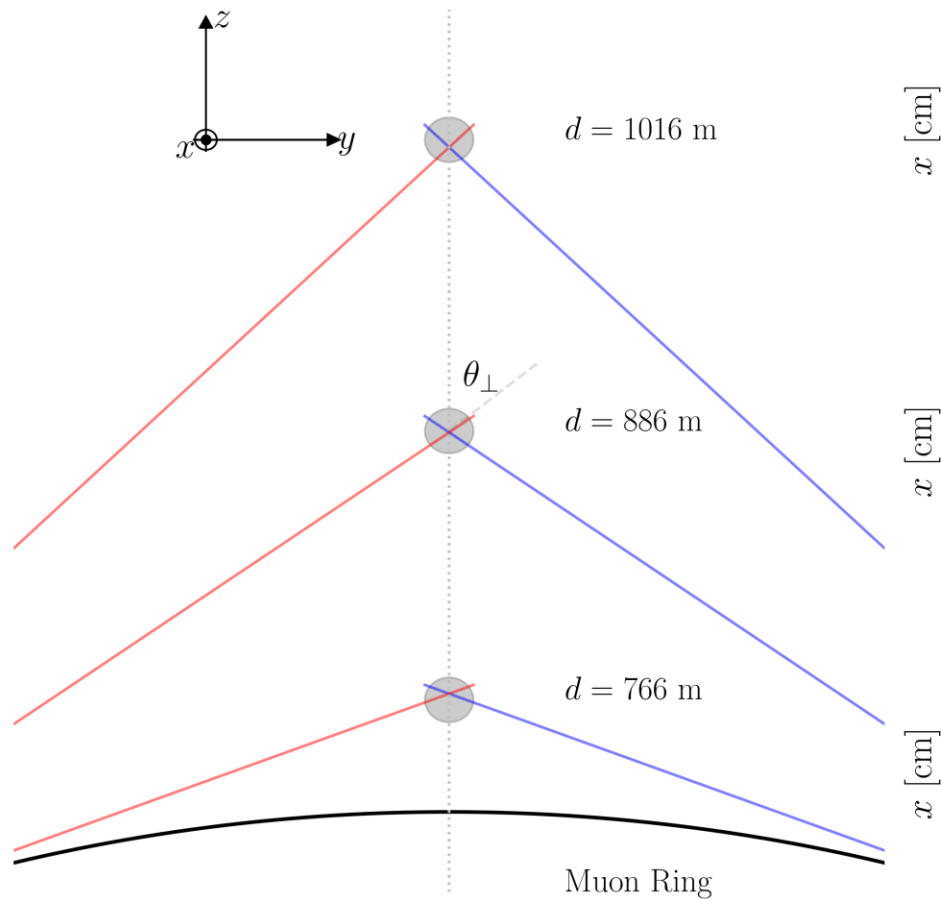
$$\bar{\nu}_e + e \rightarrow \bar{\nu}_l + l \quad (l = \mu \text{ or } \tau)$$



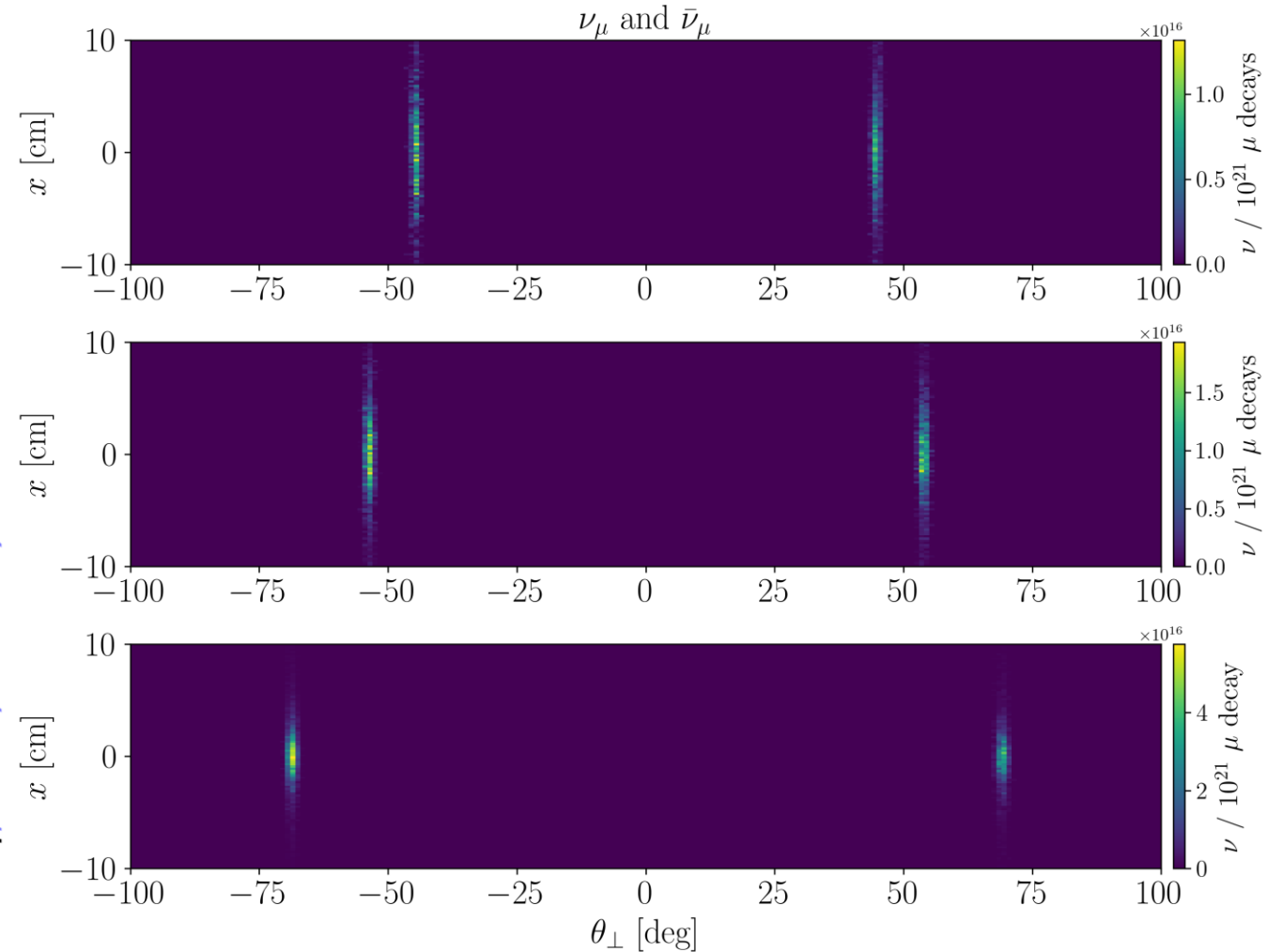
$\sim 10^4$ τ 's in the detector from ITD!



Neutrino Beamspot Geometry



4.5 km circumference



Rates and backgrounds

	$N_{\nu_\alpha}, N_{\bar{\nu}_\alpha}$	$N(\nu_\mu)$	$N(\bar{\nu}_e)$	$N(\bar{\nu}_\mu)$	$N(\nu_e)$	$\langle Q \rangle_{\mu^-, \mu^+}$ [GeV]	$\sin^2 \theta_W (\langle Q \rangle)_{\mu^-, \mu^+}$
$E_\mu = 0.25$ TeV	2×10^{18}	0.24×10^6	0.48×10^6	0.2×10^6	1.08×10^6	0.262, 0.296	0.2374, 0.2373
$E_\mu = 1.5$ TeV		1.4×10^6	2.78×10^6	1.24×10^6	6.56×10^6	0.482, 0.538	0.237, 0.2369
$E_\mu = 5$ TeV		4.64×10^6	9.28×10^6	4.2×10^6	22.0×10^6	0.879, 0.981	0.2365, 0.2364

- Tens of millions of EvES events / 10 years
 - ~ 1 event / 30 seconds
- ~ 1000 times larger CC and NC scattering rate
 - $\rightarrow \sim 30$ events / second
- CC and NC scattering have high hadronic activity
- Need good timing resolution!

Neutrino Charge Radius

$$\Lambda_\mu = f_Q(q^2) \gamma_\mu + \dots$$

$$\langle r^2 \rangle \equiv 6 \frac{d\mathbb{f}_Q(q^2)}{dq^2} \bigg|_{q^2=0}$$

$$g_{L,R} \rightarrow g_{L,R} + \frac{1}{3} m_W^2 \langle r_{\nu_\alpha}^2 \rangle \sin^2 \theta_W$$

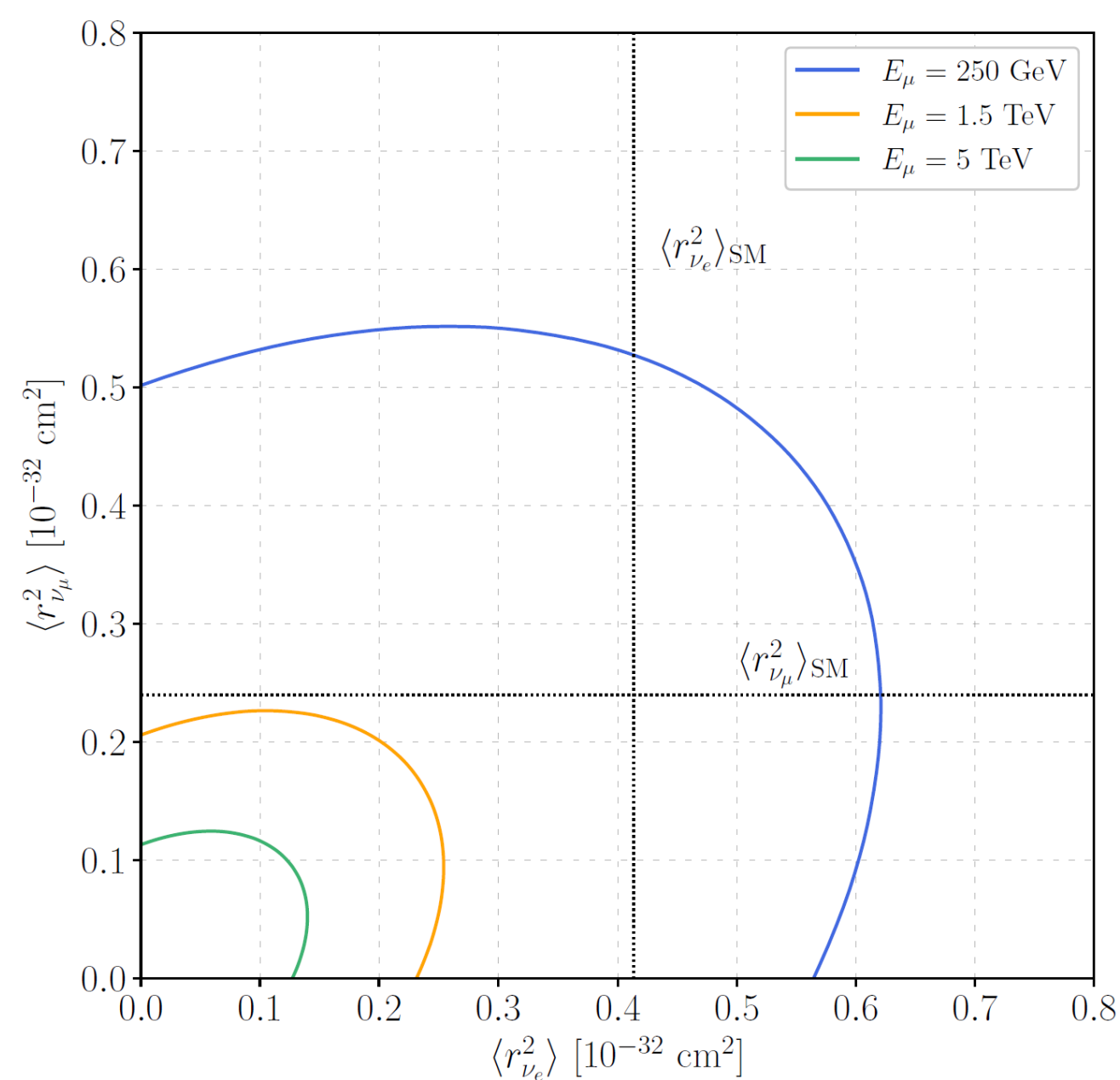
SM prediction $\cong$

$$\langle r_{\nu_\alpha}^2 \rangle_{\text{SM}} = \frac{G_F}{4\sqrt{2}\pi^2} \left(3 - 2 \log \frac{m_\alpha^2}{m_W^2} \right)$$

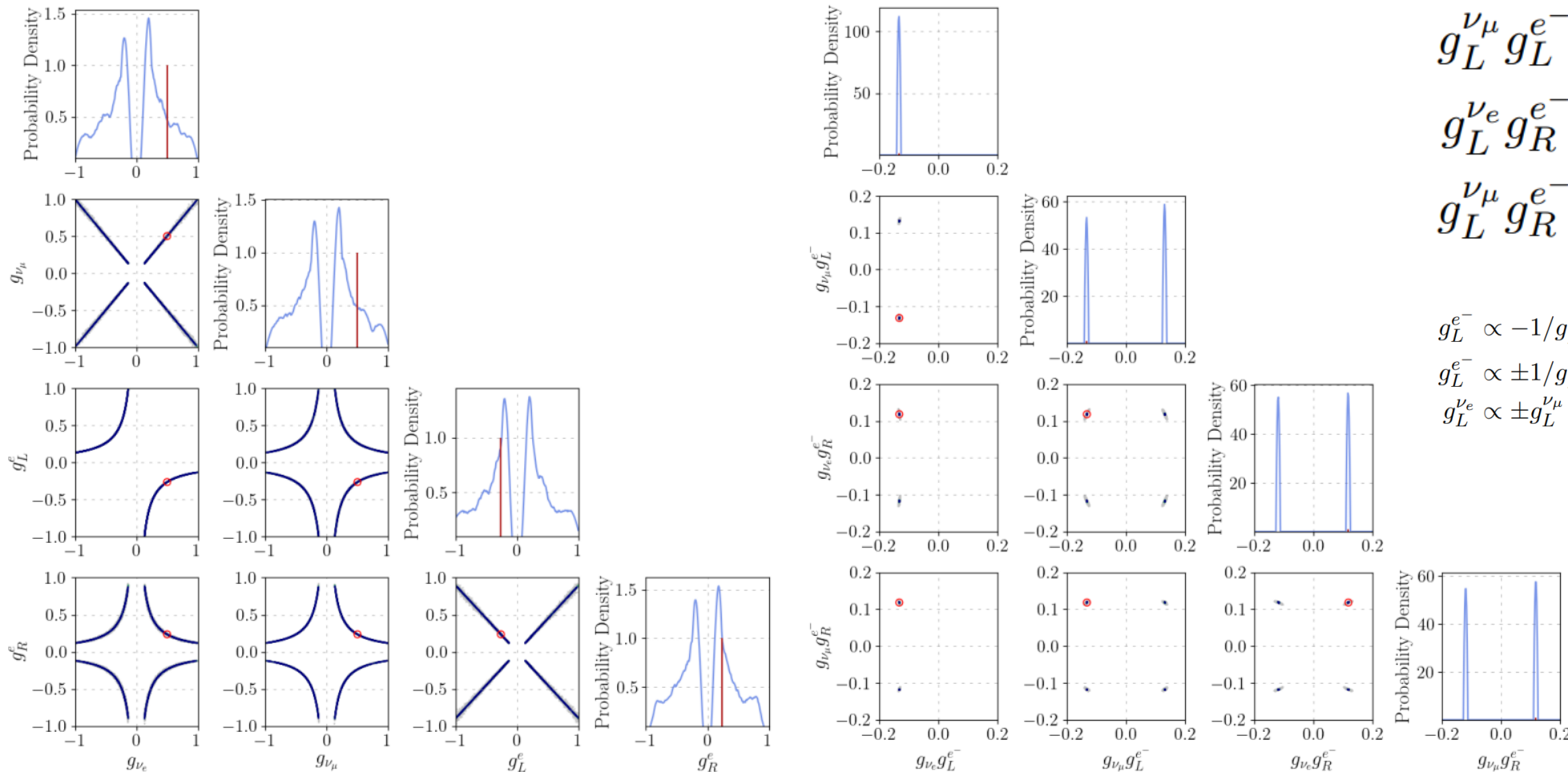
See e.g., Giunti, Studenikin [[0812.3646](#)]

Abraham, Foroughi-Abari, Kling, Tsai, [[2301.10254](#)]

Brdar, Ferreira-Leite, Parker, Xu, [[2410.00107](#)]



Degeneracies across 4 parameters



$$g_L^{\nu_e} g_L^{e^-} = -a$$

$$g_L^{\nu_\mu} g_L^{e^-} = \pm b$$

$$g_L^{\nu_e} g_R^{e^-} = \pm c$$

$$g_L^{\nu_\mu} g_R^{e^-} = \pm d$$

$$g_L^{e^-} \propto -1/g_L^{\nu_e},$$

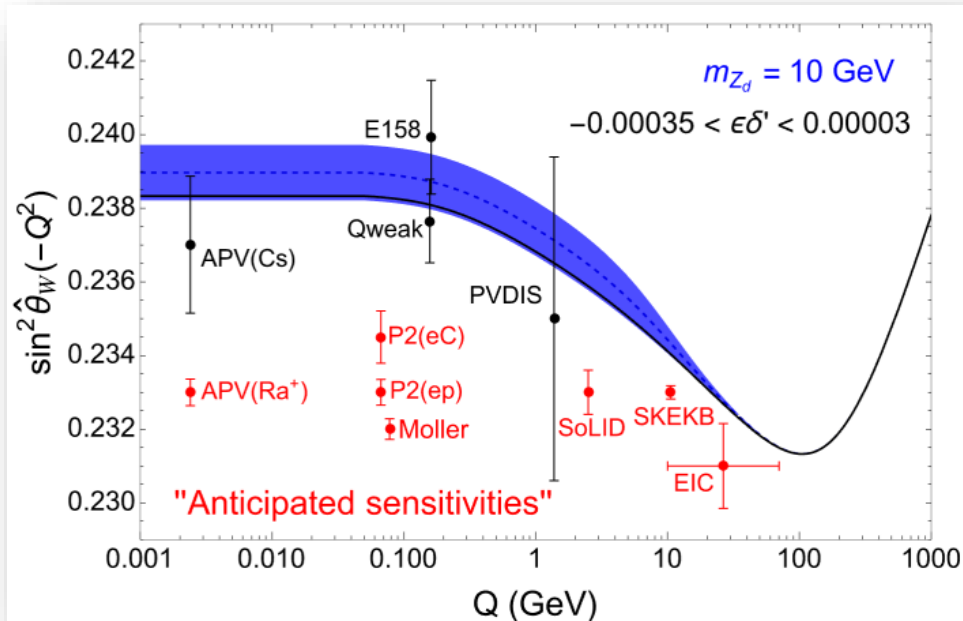
$$g_L^{e^-} \propto \pm 1/g_L^{\nu_\mu},$$

$$g_L^{\nu_e} \propto \pm g_L^{\nu_\mu}.$$

$$g_L^{e^-} \propto \pm g_R^{e^-},$$

$$g_R^{e^-} \propto \pm 1/g_L^{\nu_\mu},$$

Hunting for New Gauge forces in the running



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