Electroweak Precision with Muon Collider Neutrinos

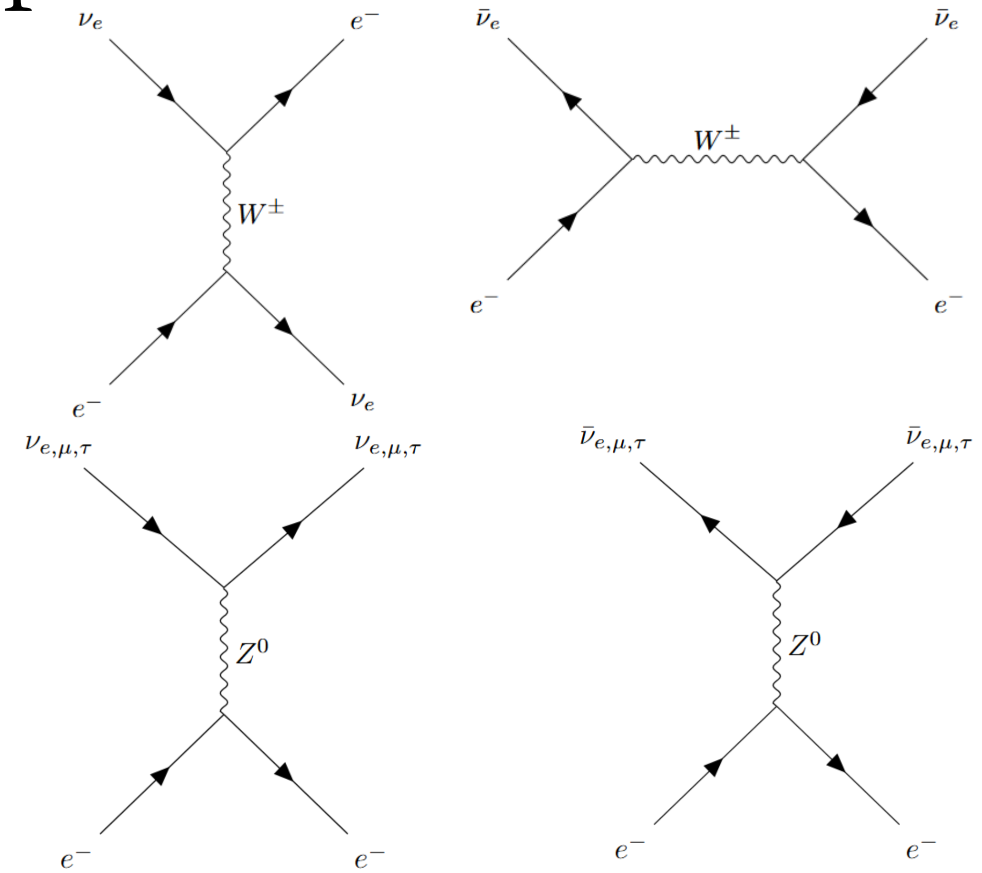
André de Gouvêa, Adrian Thompson

2505.00152

CETUP 2025

July 10, 2025

EνES as a Neutrino Microscope



Elastic neutrino-electron scattering (EνES)

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

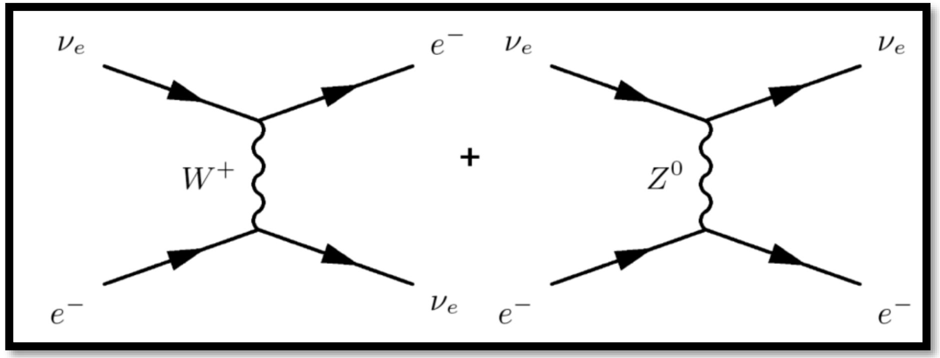
$$g^f_L = T^f_3 - Q^f sin^2\theta_W \qquad g^f_R = -Q^f sin^2\theta_W$$

Bardin, Bilenky, Pontecorvo `70
't Hooft `71
Chen, Lee `72
Sehgal `74

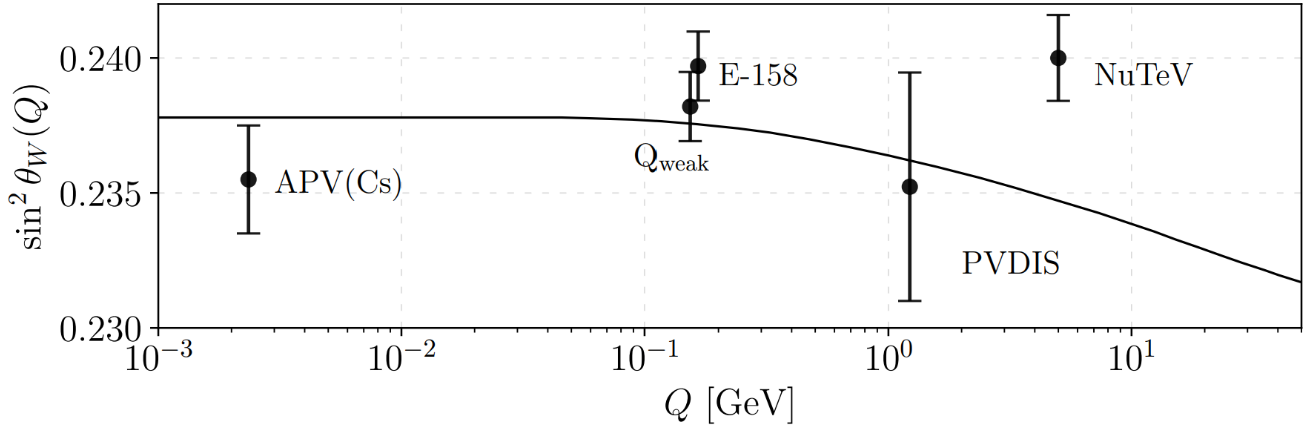
Probes of the Weak Mixing Angle

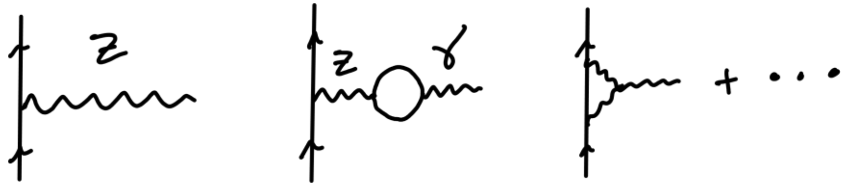
$$A_\mu = B^0_\mu \cos\theta_W + W^0_\mu \sin\theta_W$$

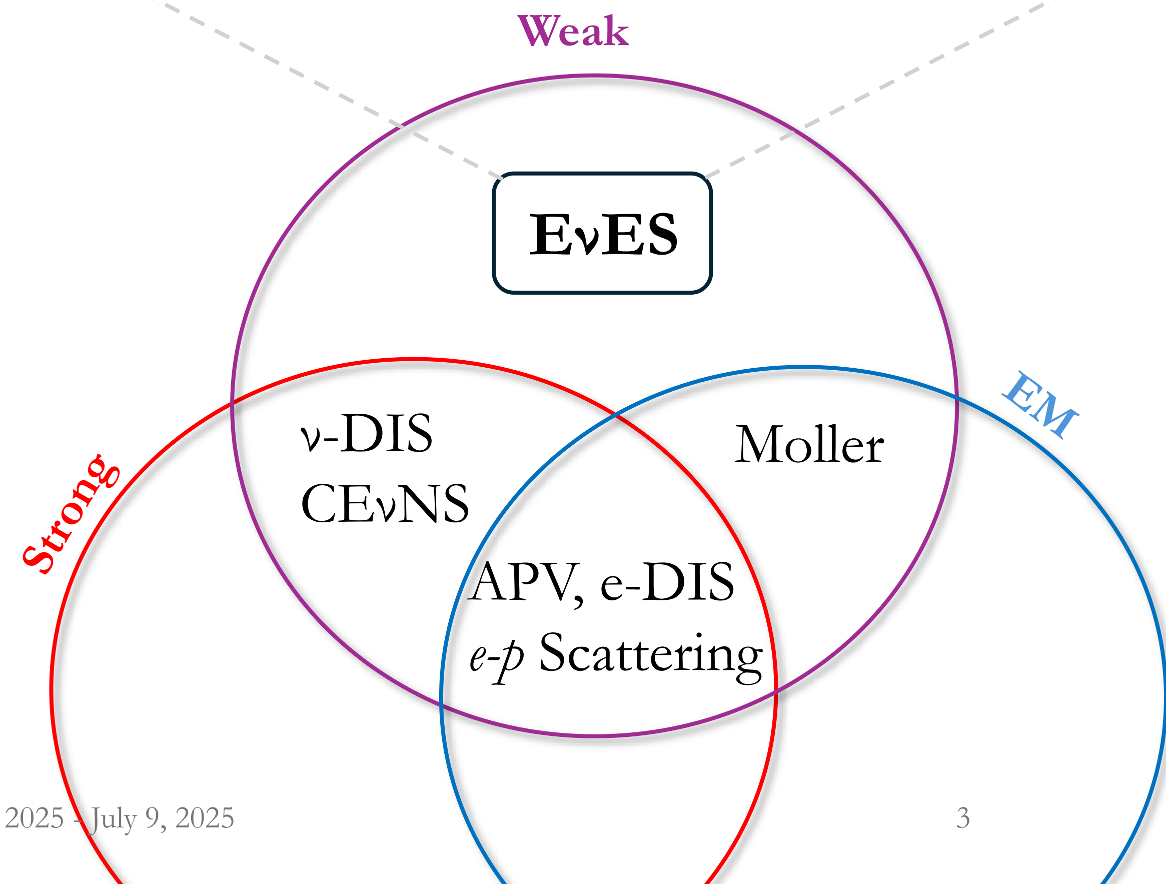
$$Z_\mu = W^0_\mu \cos\theta_W - B^0_\mu \sin\theta_W .$$



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







Muon Decay

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

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

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

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

Elastic Neutrino-Elastic Scattering (EνES)

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

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

Exclusively weak process at tree level

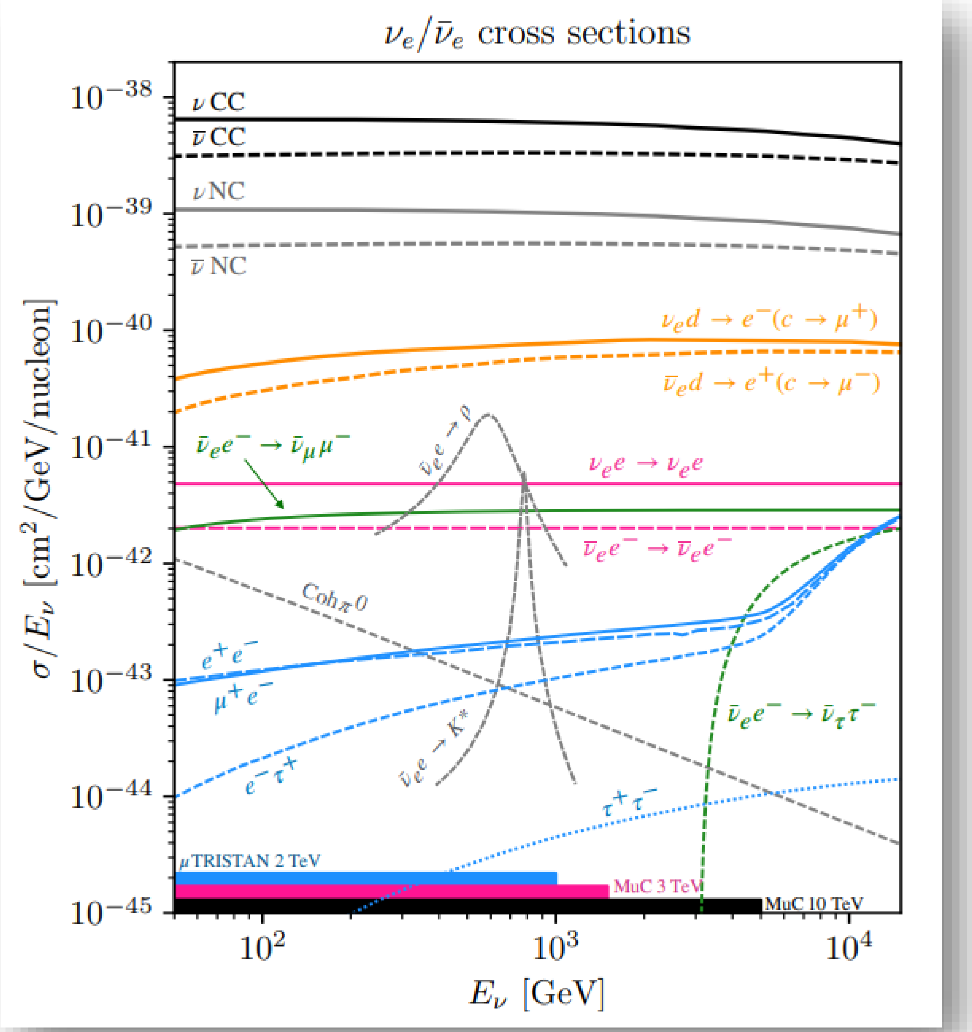
TeV-scale Muon Colliders and Neutrino Factories

Several designs and inspiring neutrino factory concepts:

- NuSOnG [0803.0354]
- IMCC Report [2407.12450], [2504.21417]
- MAP [0711.4275]
- μTRISTAN [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.)

See also nuSTORM [2505.06137]

The “Neutrino Slice”



The Neutrino Slice at Muon Colliders

Luc Bojorquez-Lopez,[1,*] Matheus Hostert,[1,†] Carlos A. Argüelles,[1,‡] and Zhen Liu[2,§]

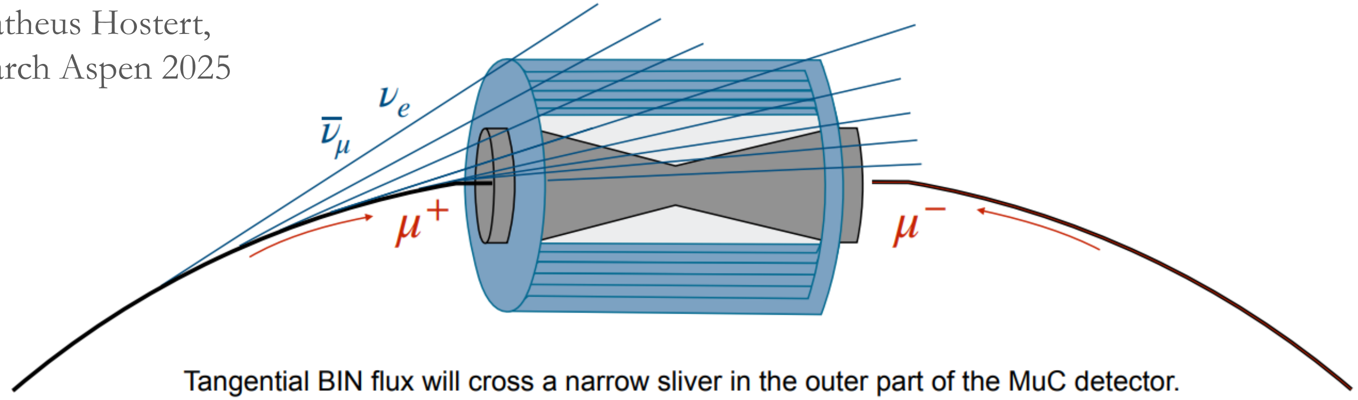
[1] *Department of Physics & Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA 02138, USA*

[2] *School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA*

(Dated: December 19, 2024)

Neutrino rates are sizeable! [2412.14115]

Matheus Hostert, March Aspen 2025



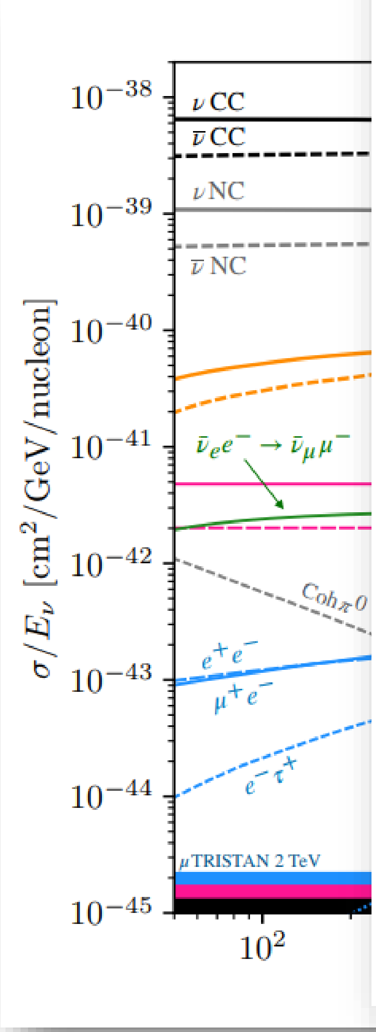
Tangential BIN flux will cross a narrow sliver in the outer part of the MuC detector.

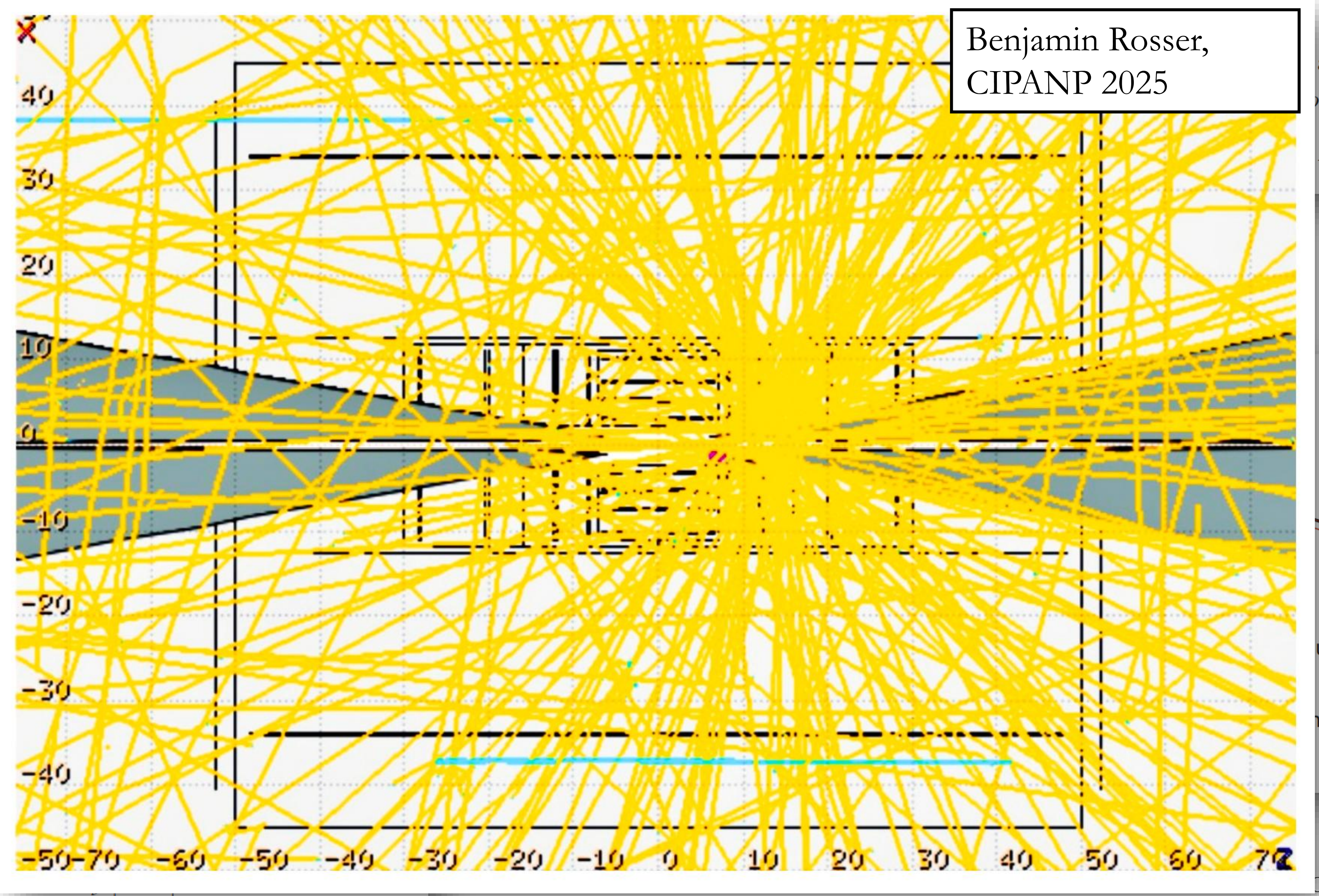
BIN interactions in this “**neutrino slice**” will be abundant and produce high energy particles

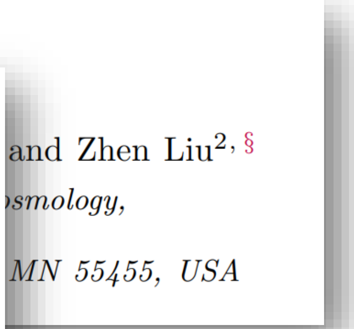
$$\sigma_\nu \sim G_F^2 m_p E_\nu$$

MAIA detector concept: [2502.00181]

The “N



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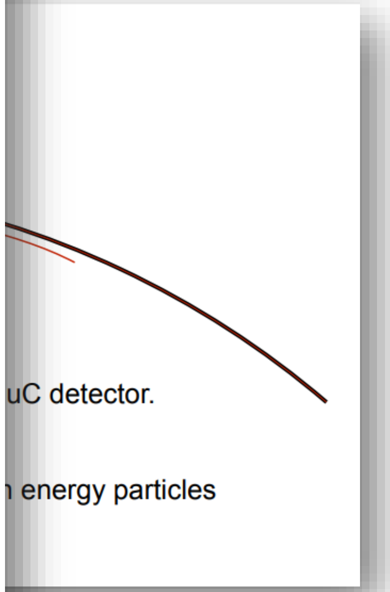
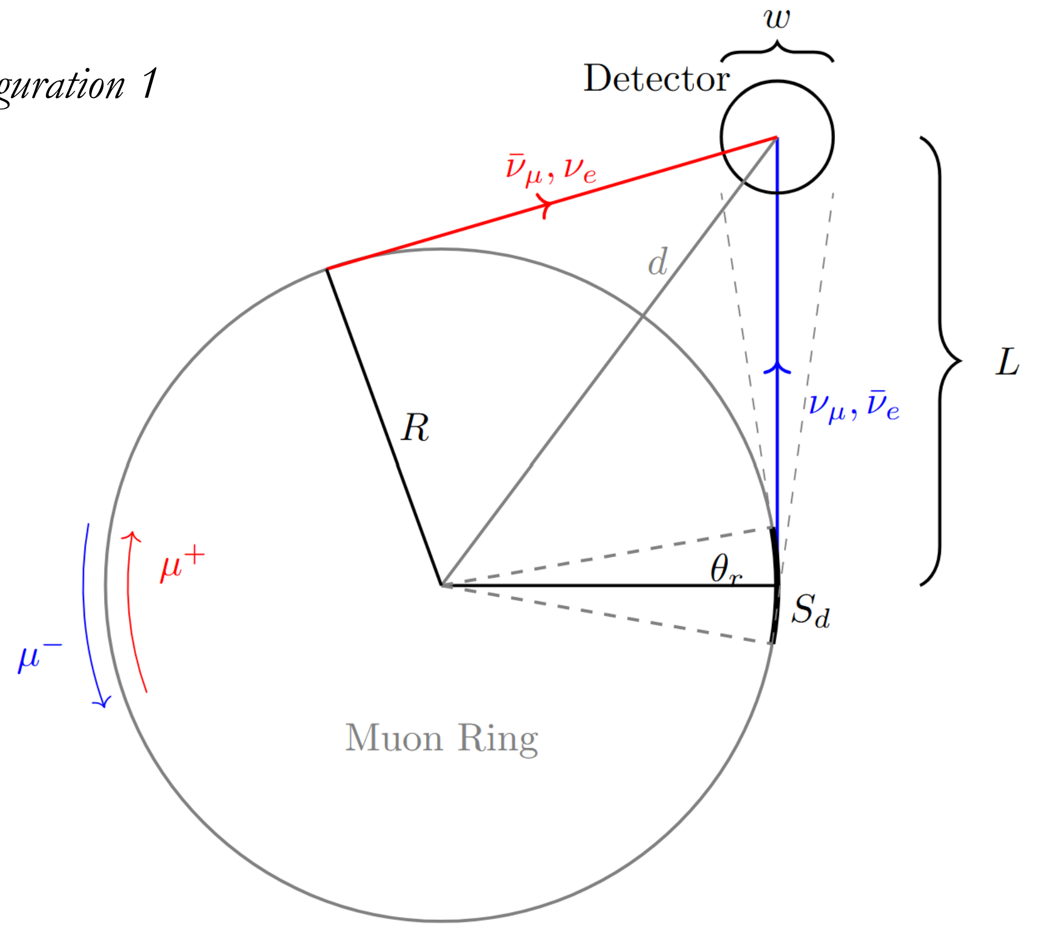


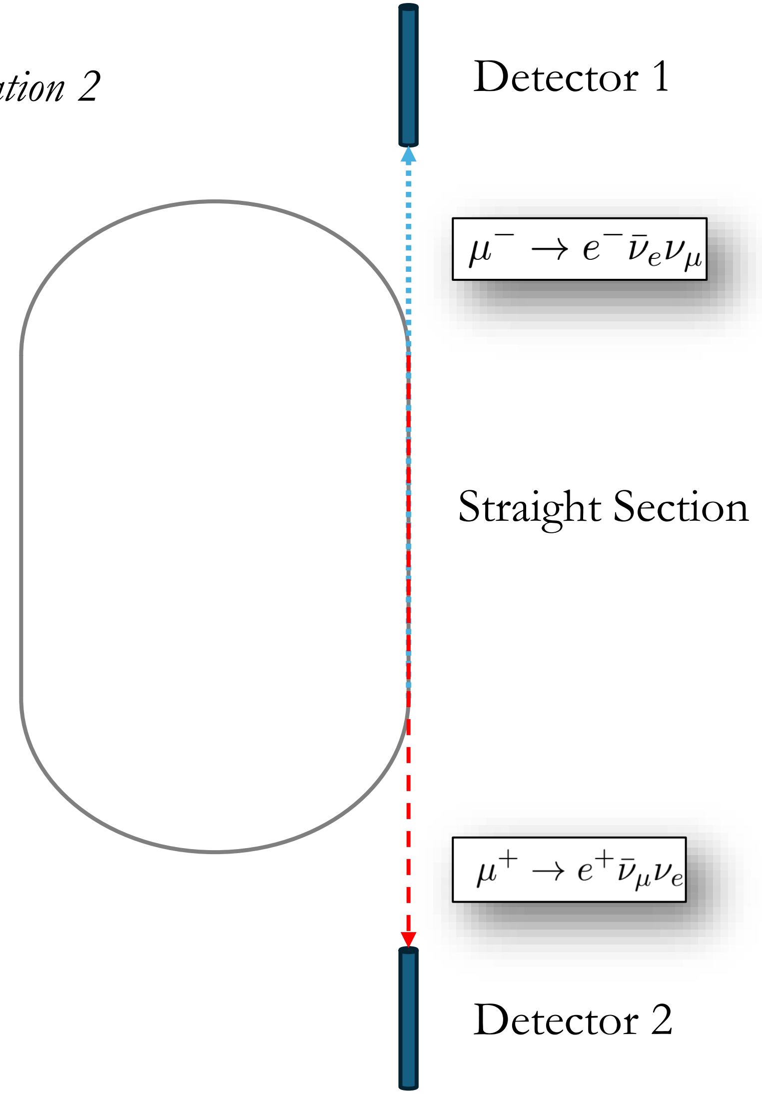
oncept: [2502.00181]

Bird's Eye View

Configuration 1

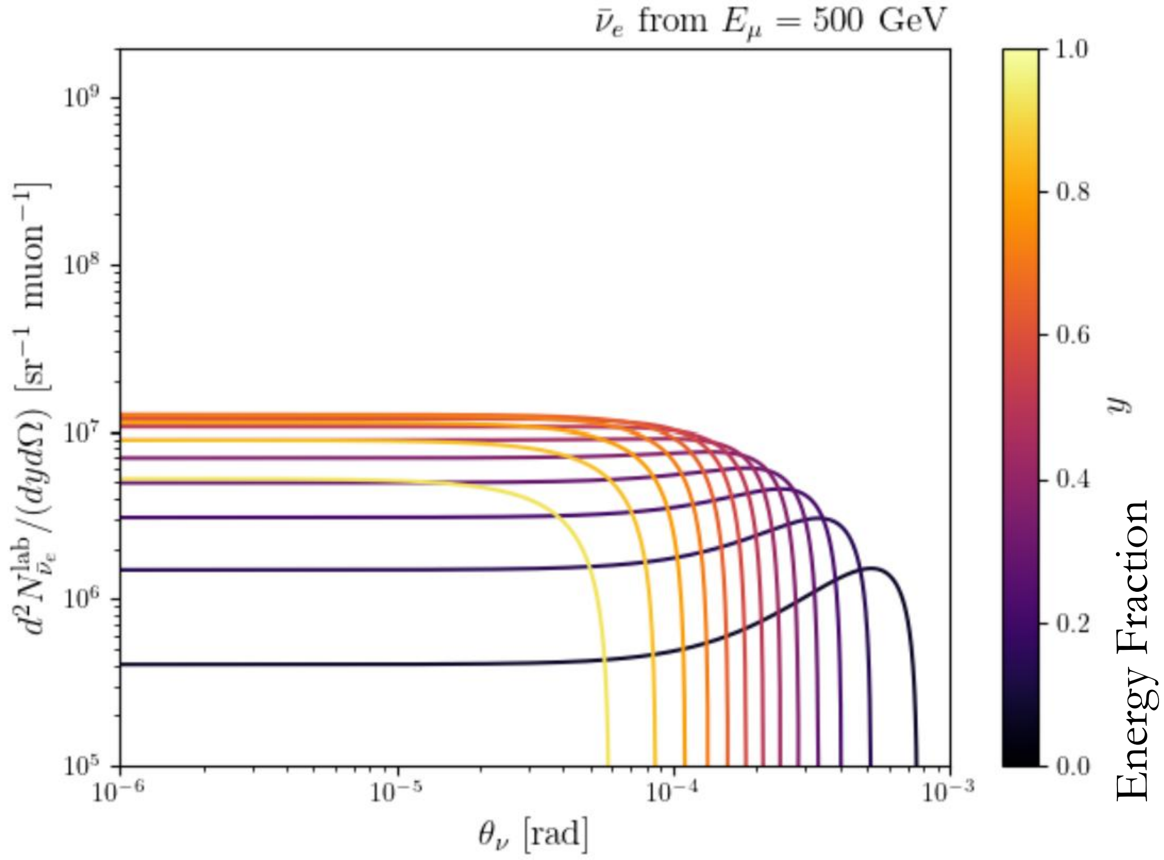


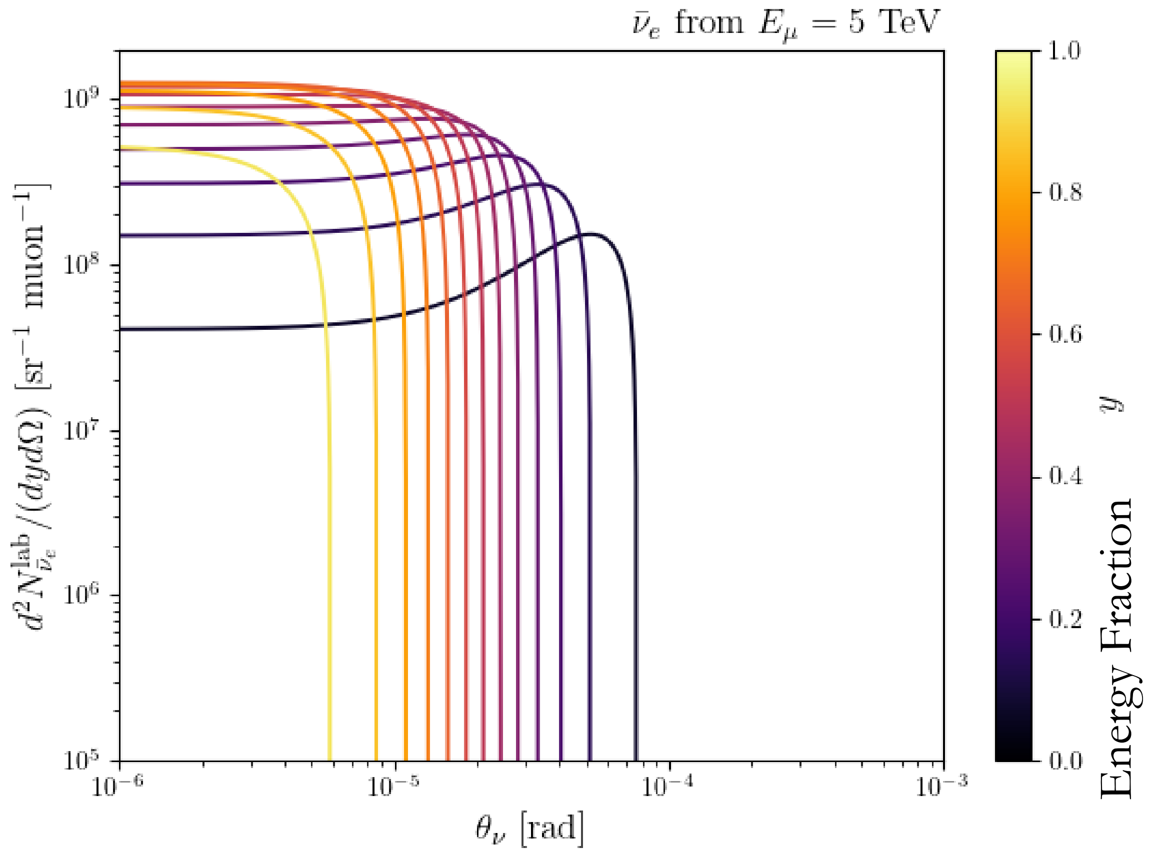
Configuration 2



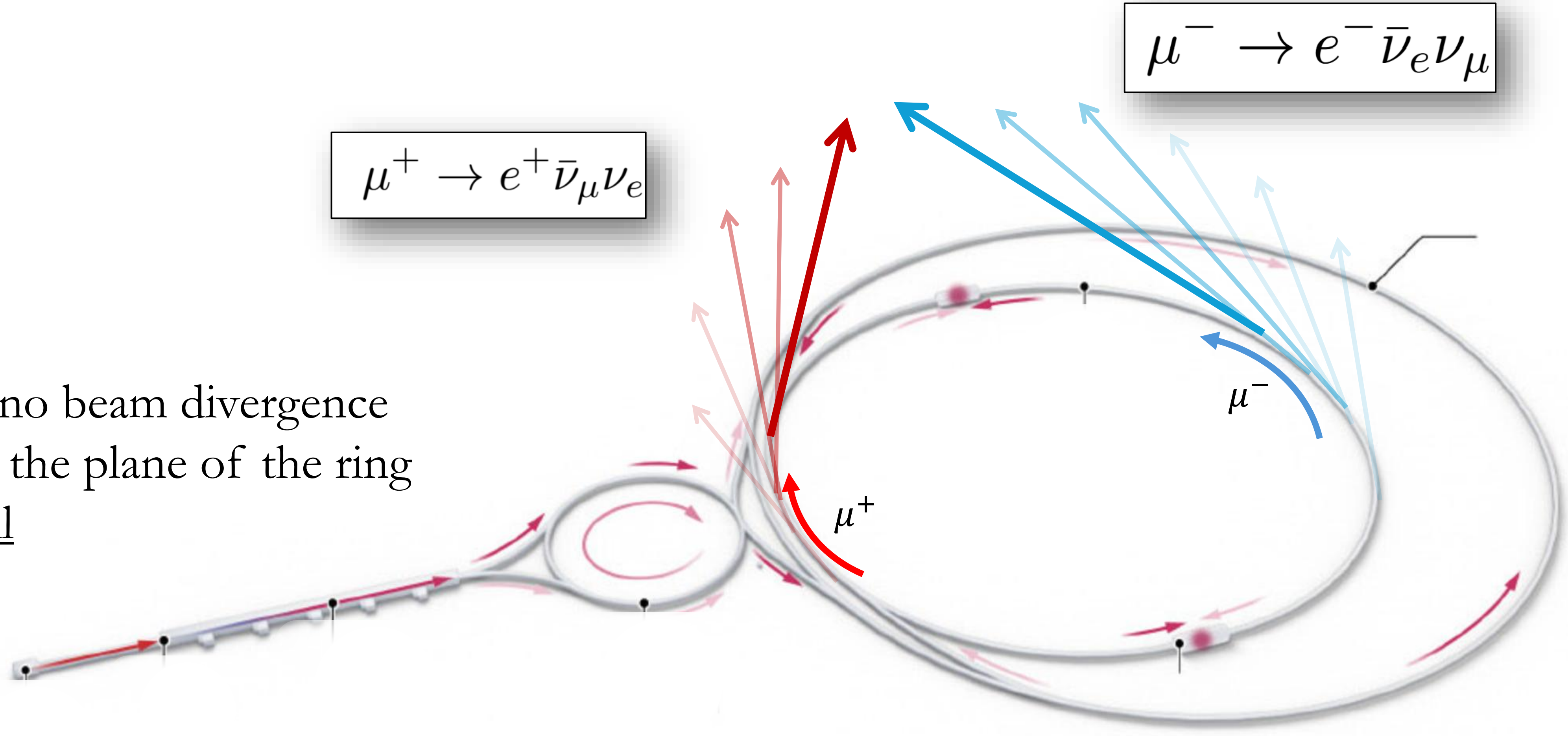
Neutrino Fluxes from Muon Decay in the Lab Frame

Neutrino beam divergence out of the plane of the ring is <u>small</u>





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



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A. FISHER/*SCIENCE*

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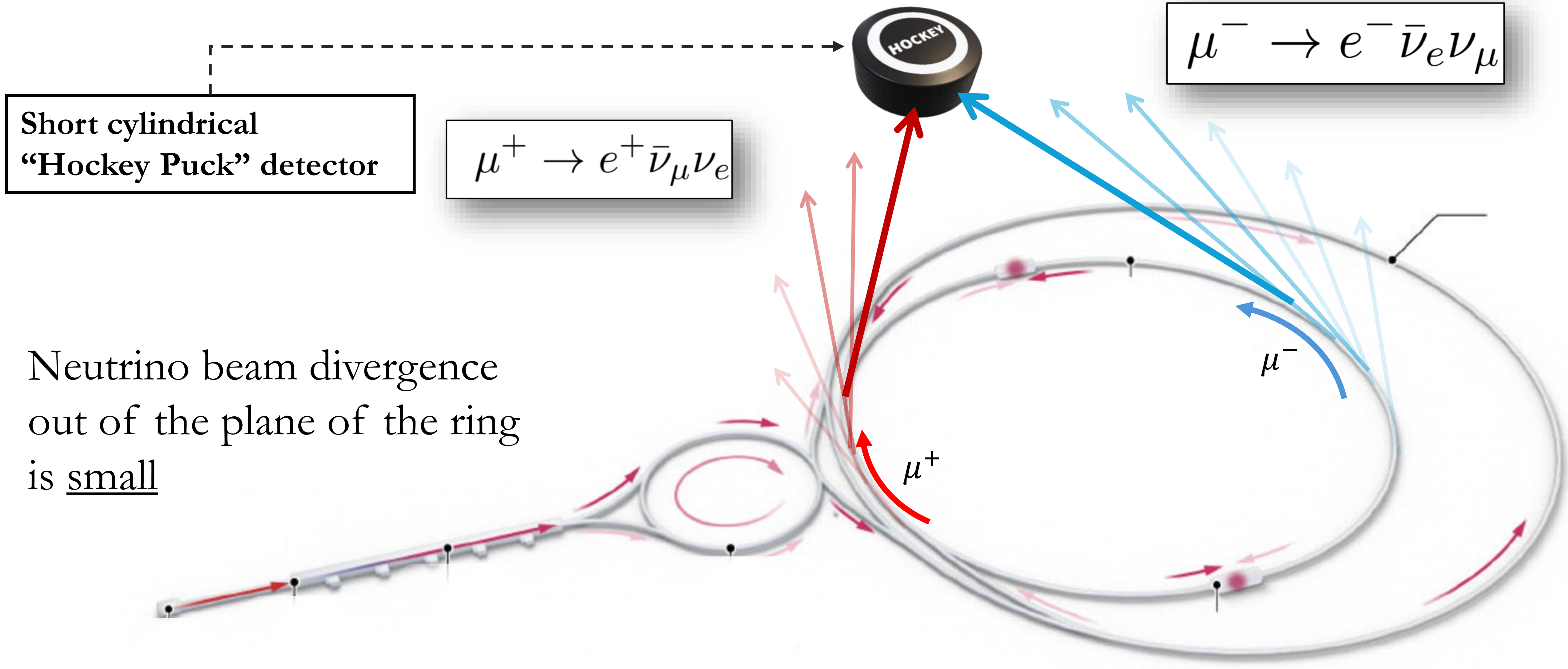
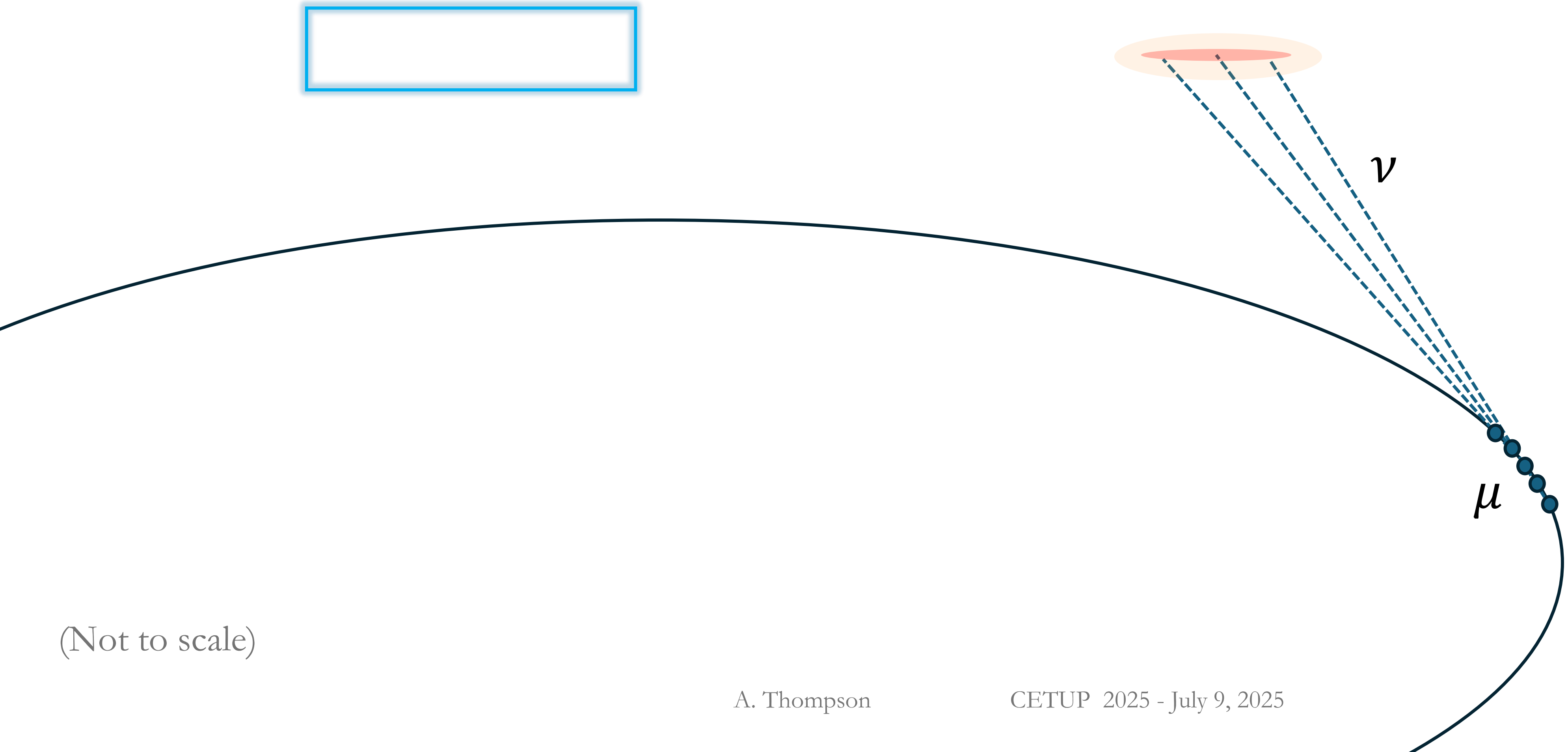


A. FISHER/*SCIENCE*

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

The (Terrestrial) Neutrino Lighthouse: Timing



(Not to scale)

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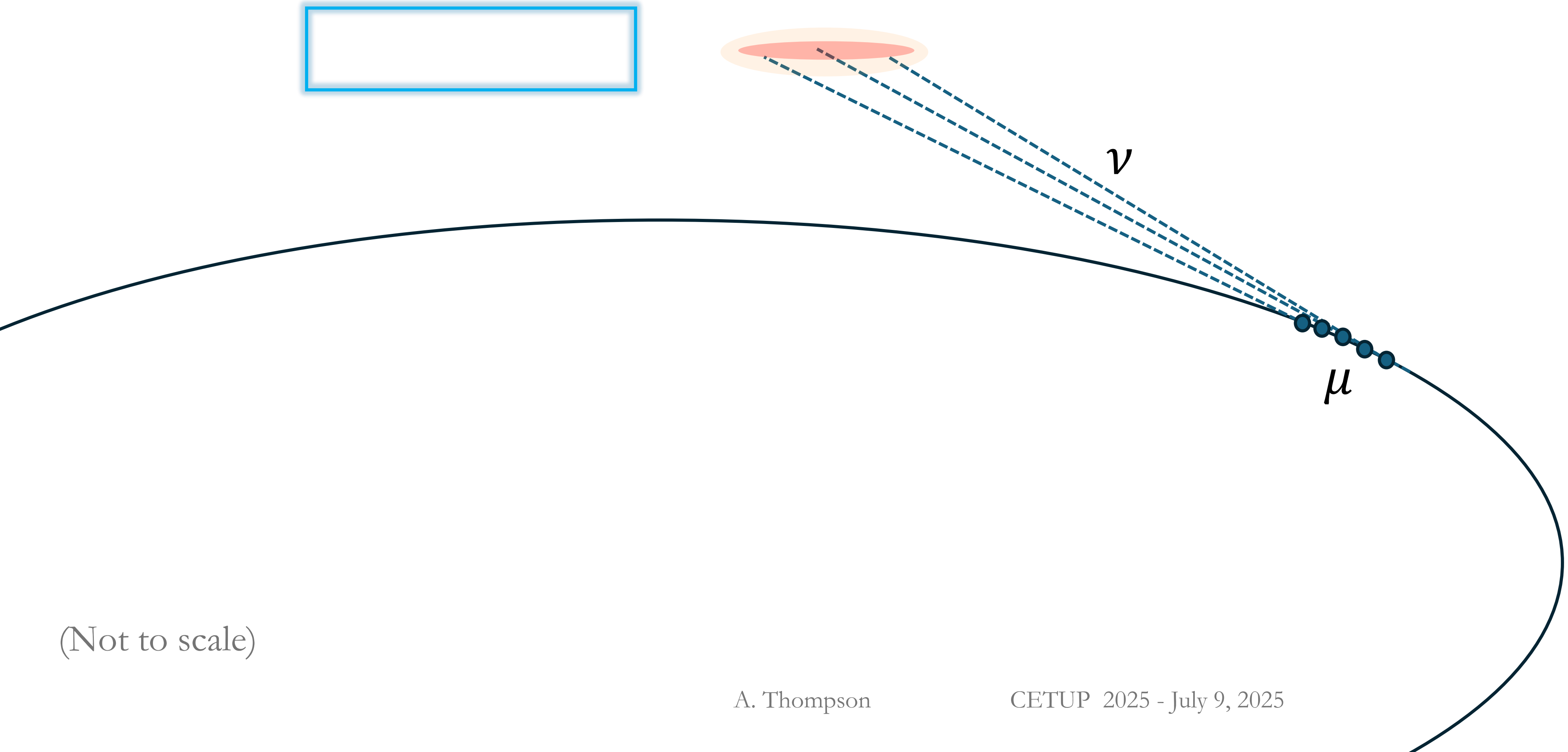

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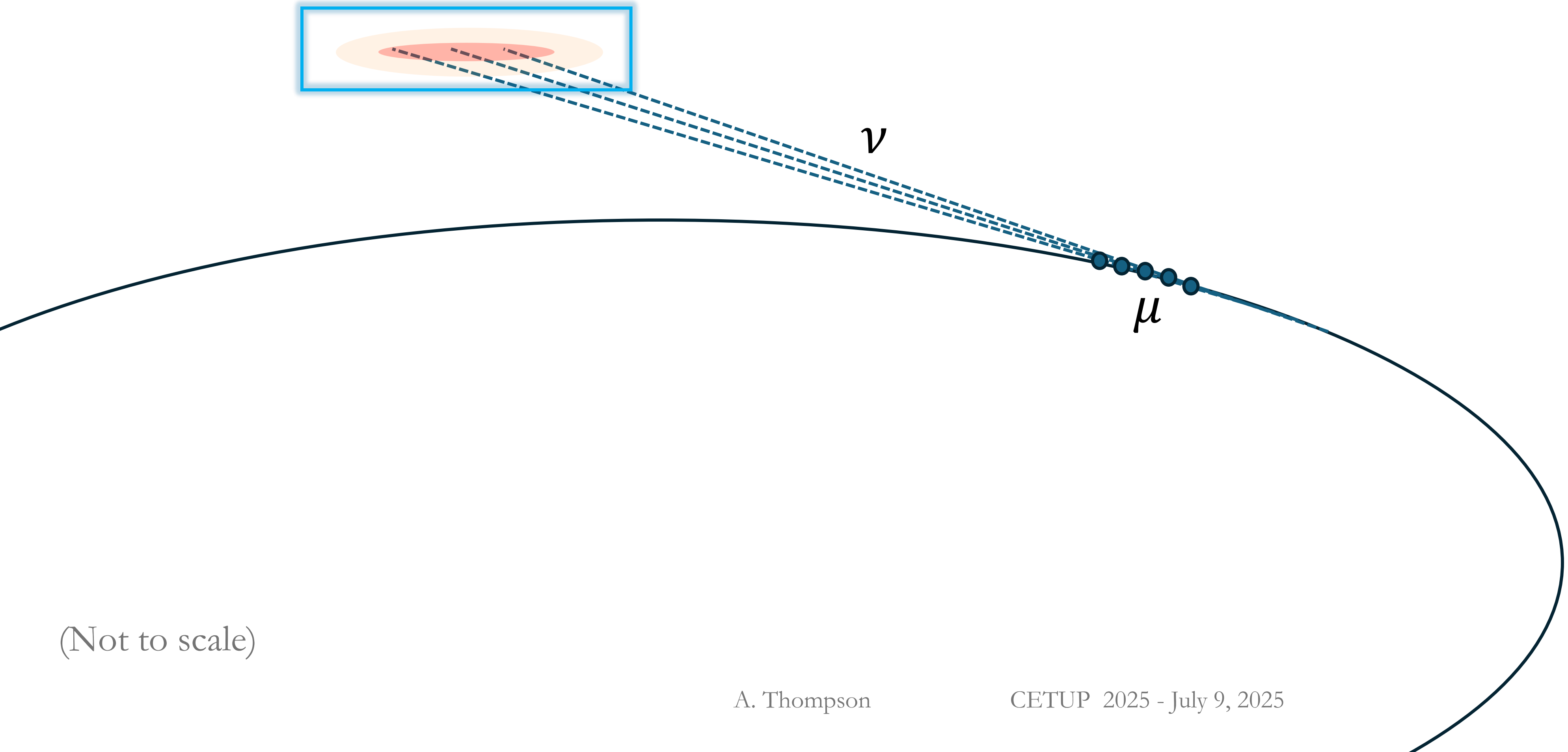


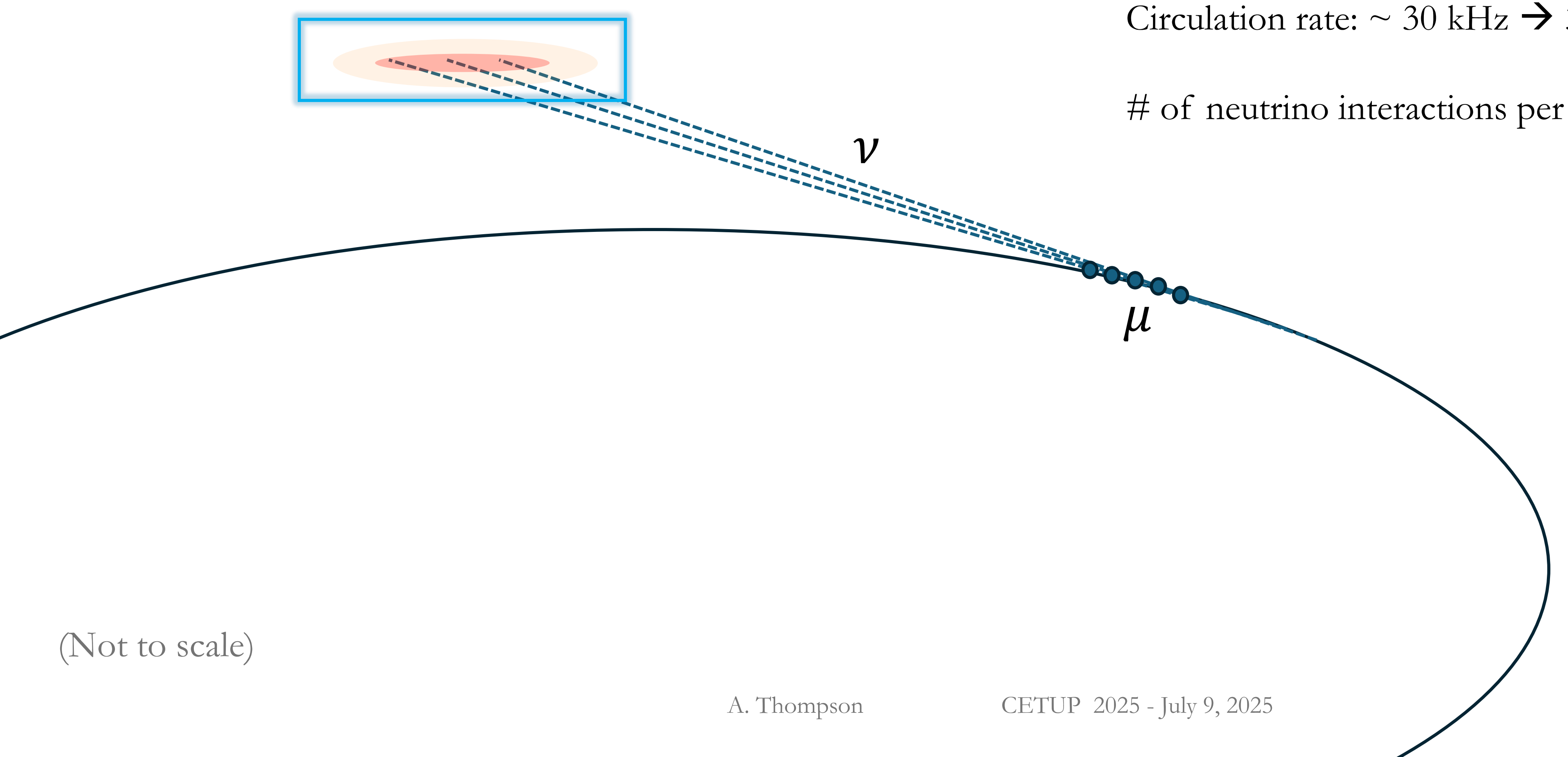
(Not to scale)

The (Terrestrial) Neutrino Lighthouse: Timing

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

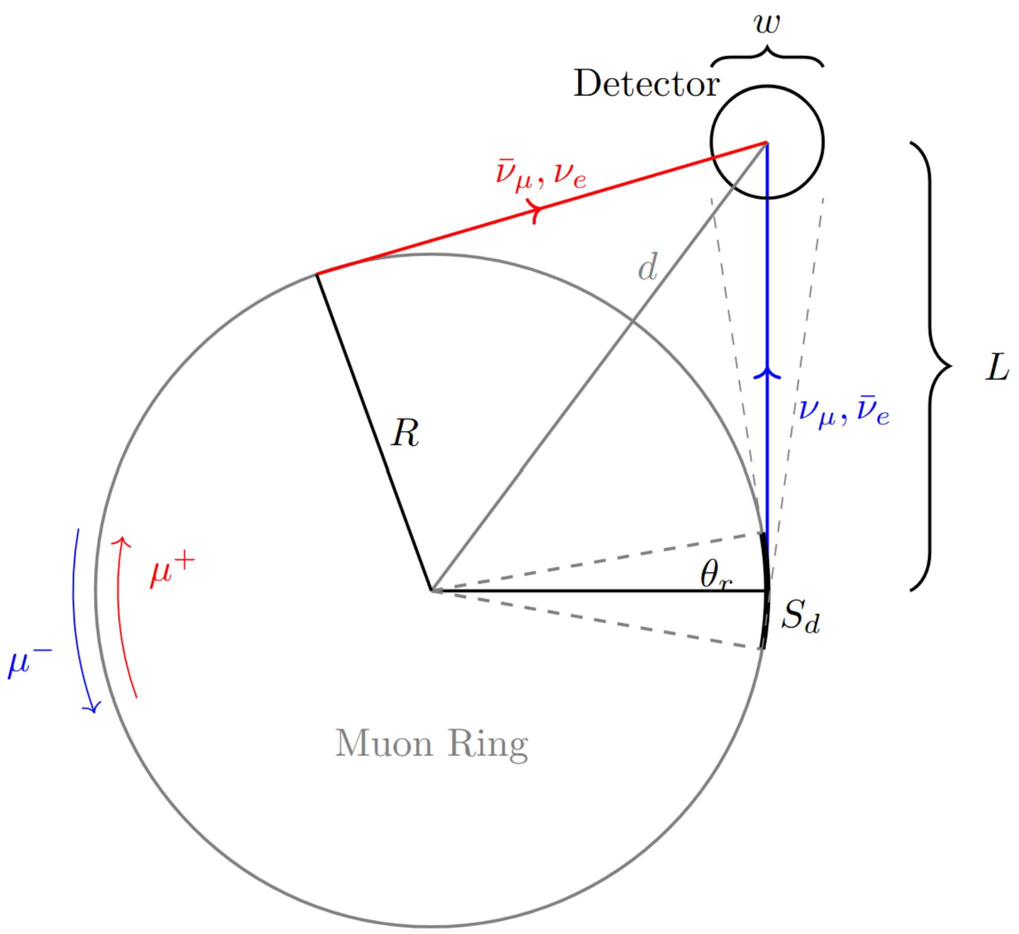
Circulation rate: ~ 30 kHz → 30 µs

# of neutrino interactions per bunch crossing: < 1



(Not to scale)

Bird's Eye View



(Not to scale)

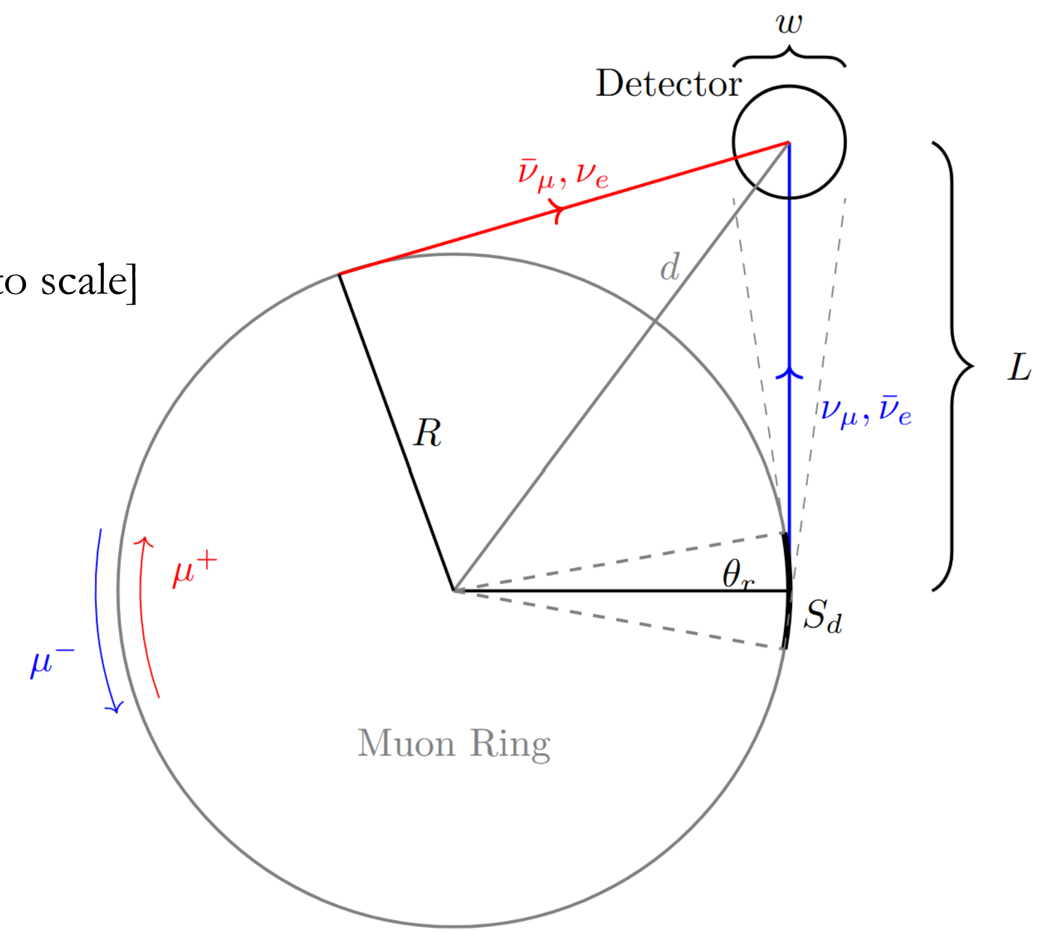
From geometry, the acceptance is:

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

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

Bird's Eye View

[not to scale]



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

Example Assumptions:

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

~9×10^{19} muons per year in the ring:

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

EνES 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:

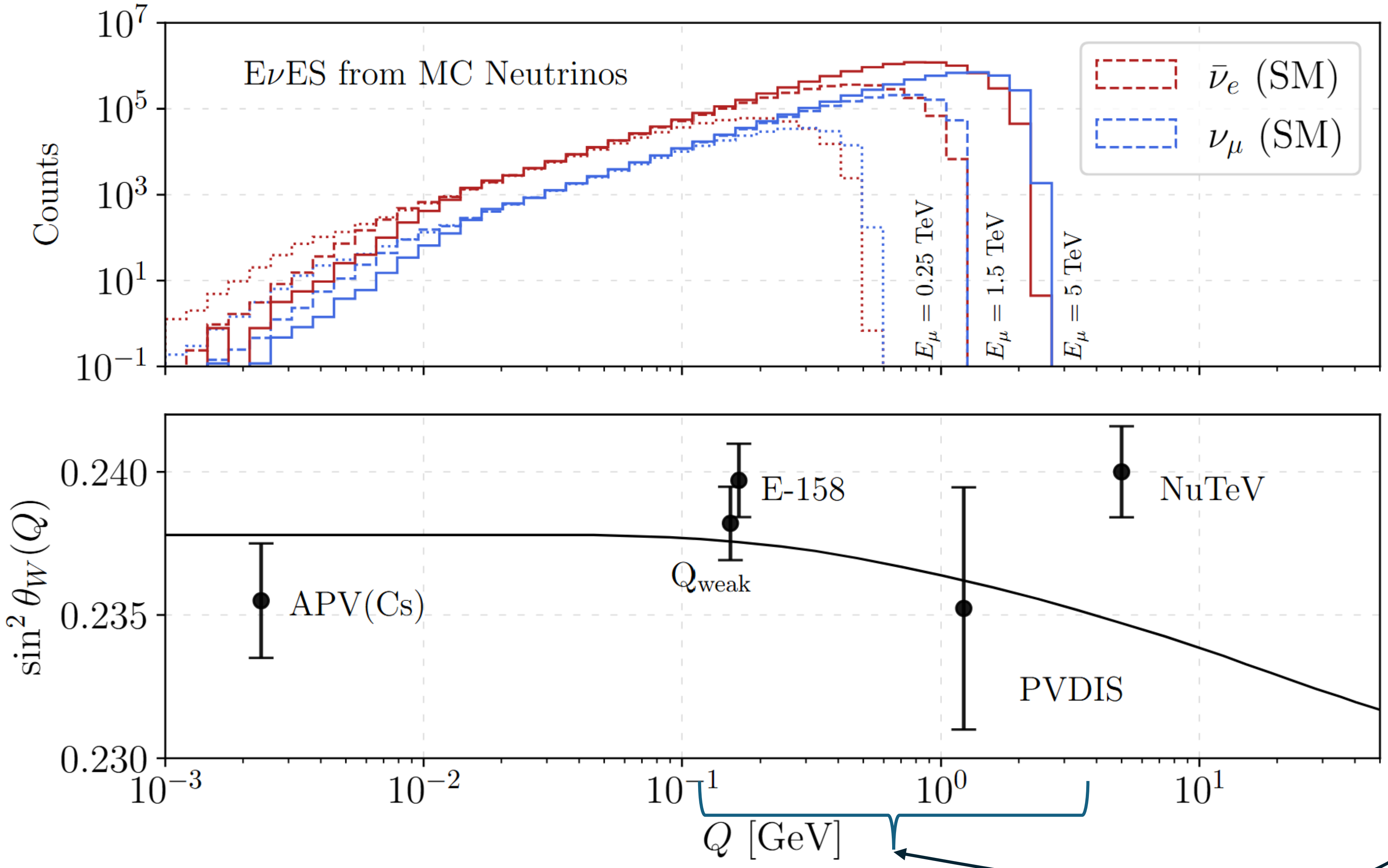
$$g_L \equiv 2g_L^\nu g_L^{e^-} = \sin^2\theta_W - \frac{1}{2}$$

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

Integrate over the EνES 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 $sin^2\theta_W$

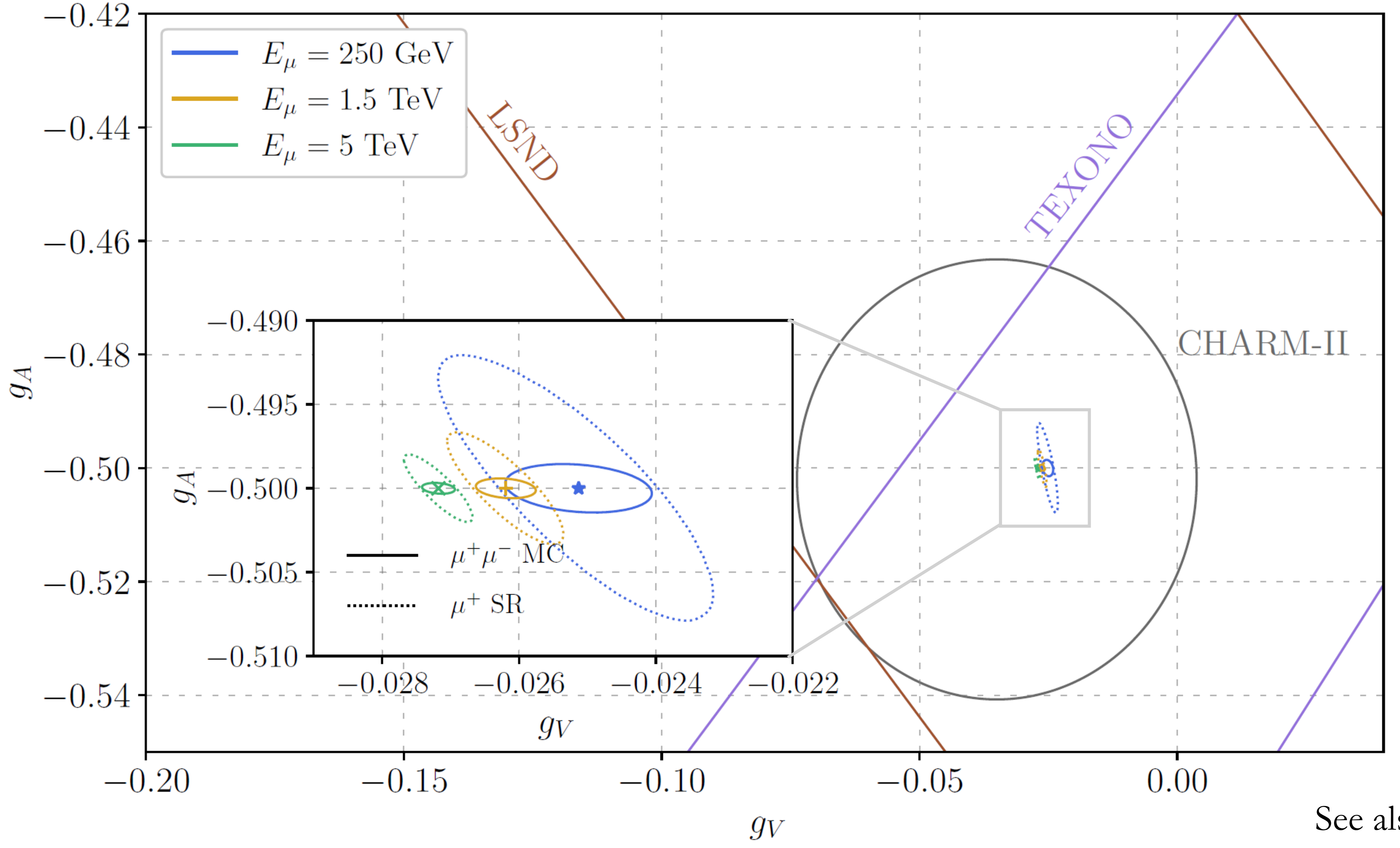


$$Q = \sqrt{2\, m_e E_r}$$

As the muon beam energy reaches ~TeV scales, we access:

- "shoulder" of the running momentum-dependence of the WMA
- NuTeV anomaly region

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 ~0.05% precision at the E_μ=5 TeV machine

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

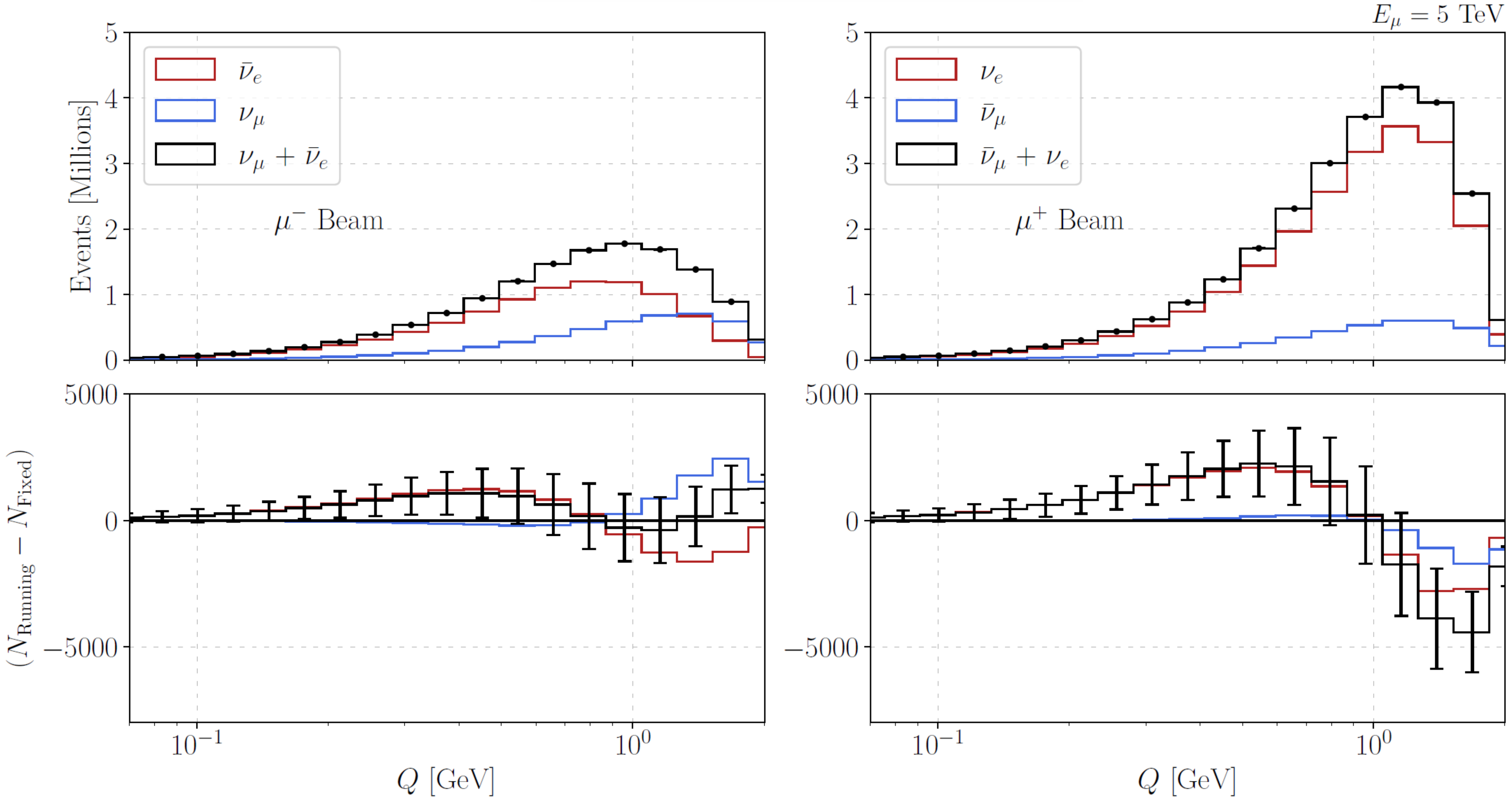
Does $sin^2\theta_W$ run?

$$g_L \to g_L(Q) = \sin^2\theta_W(Q) - \frac{1}{2}$$
$$g_R \to g_R(Q) = \sin^2\theta_W(Q)\,.$$

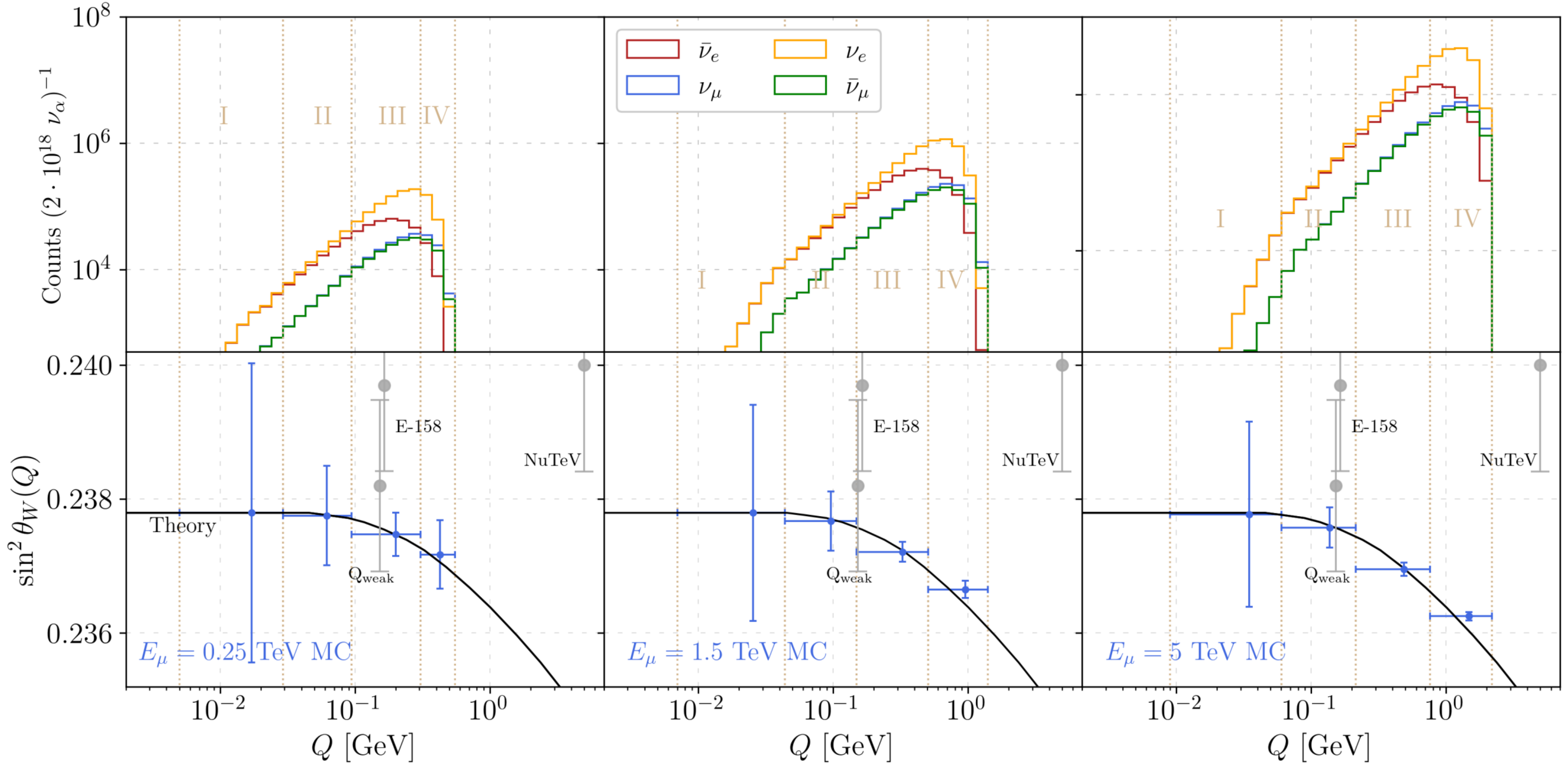
$$sin^2\theta_W(Q^2) = \kappa(Q^2,\mu)\, sin^2\theta_W(\mu)$$

Czarnecki, Marciano [0003049]

Kumar, Mantry, Marciano, Souder [1302.6263]



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



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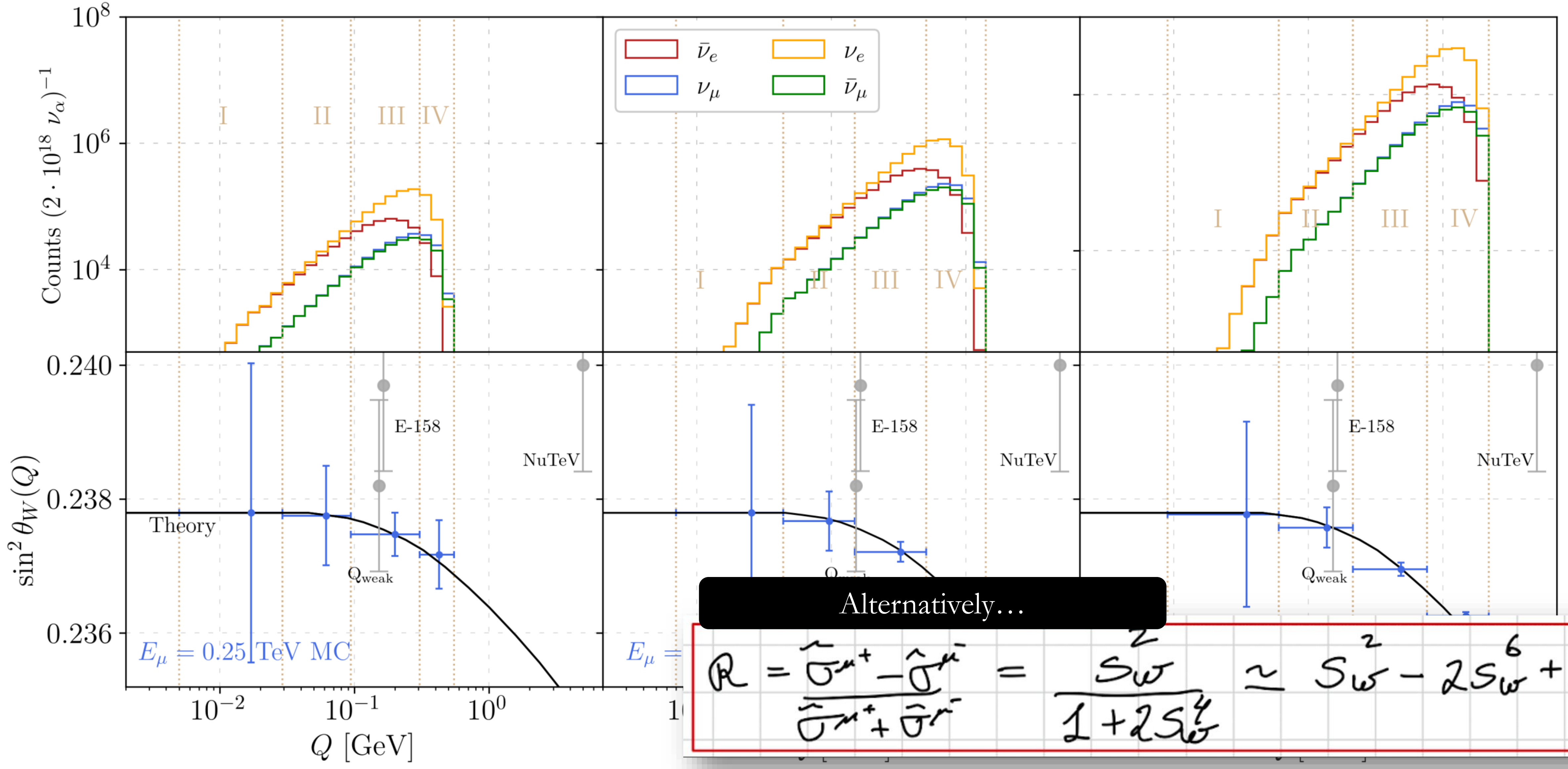
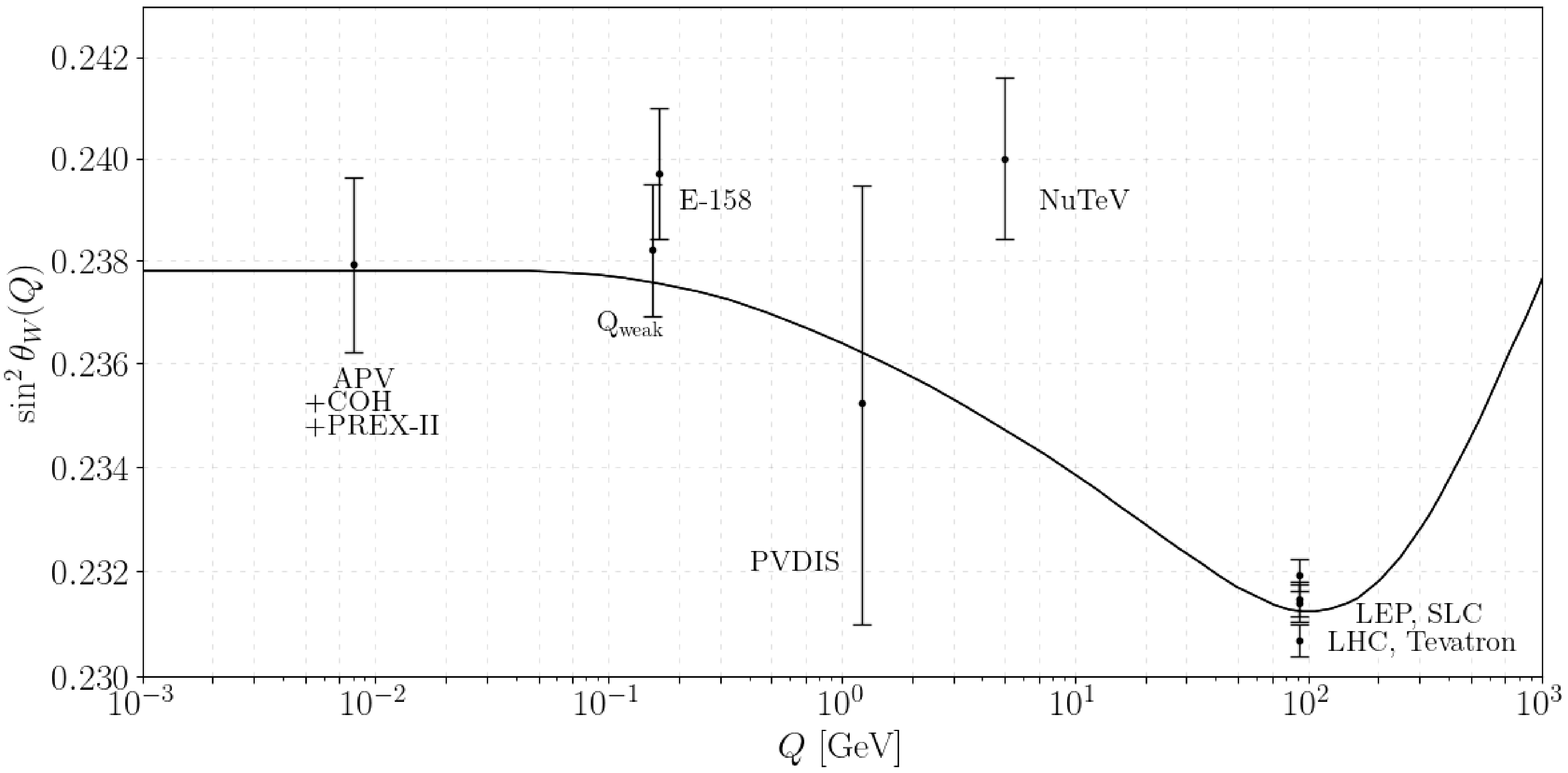


Alternatively…

$$R = \frac{\hat{\sigma}^{\mu^+} - \hat{\sigma}^{\mu^-}}{\hat{\sigma}^{\mu^+} + \hat{\sigma}^{\mu^-}} = \frac{s_w^2}{1+2s_w^4} \simeq s_w^2 - 2s_w^6 + \ldots$$

per M. Hostert

The Landscape of Weak Mixing Measurements



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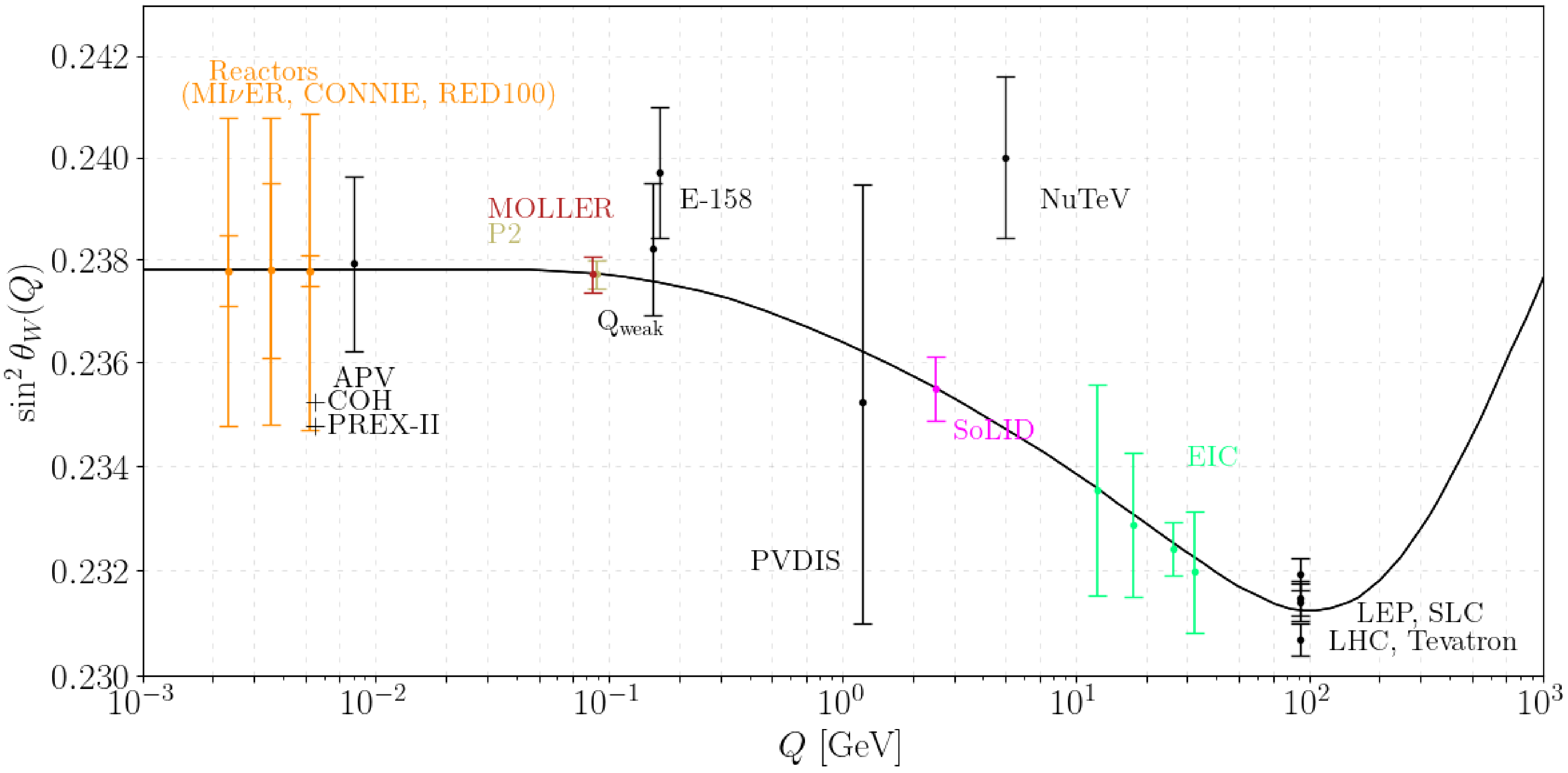

Reactors [1806.01310]
COHERENT + APV + PREX-II
[2405.09416]

EIC [2204.07557]

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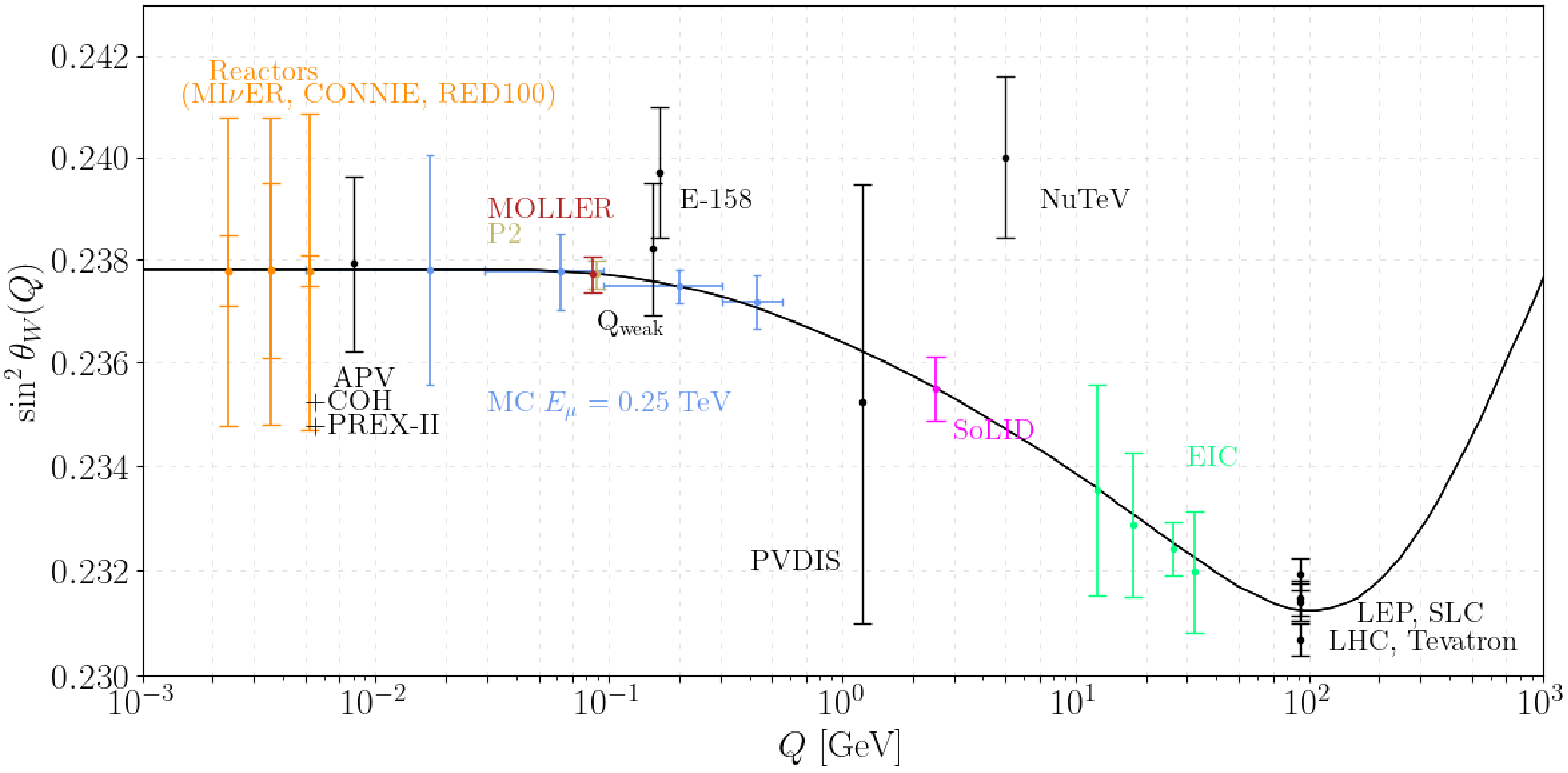

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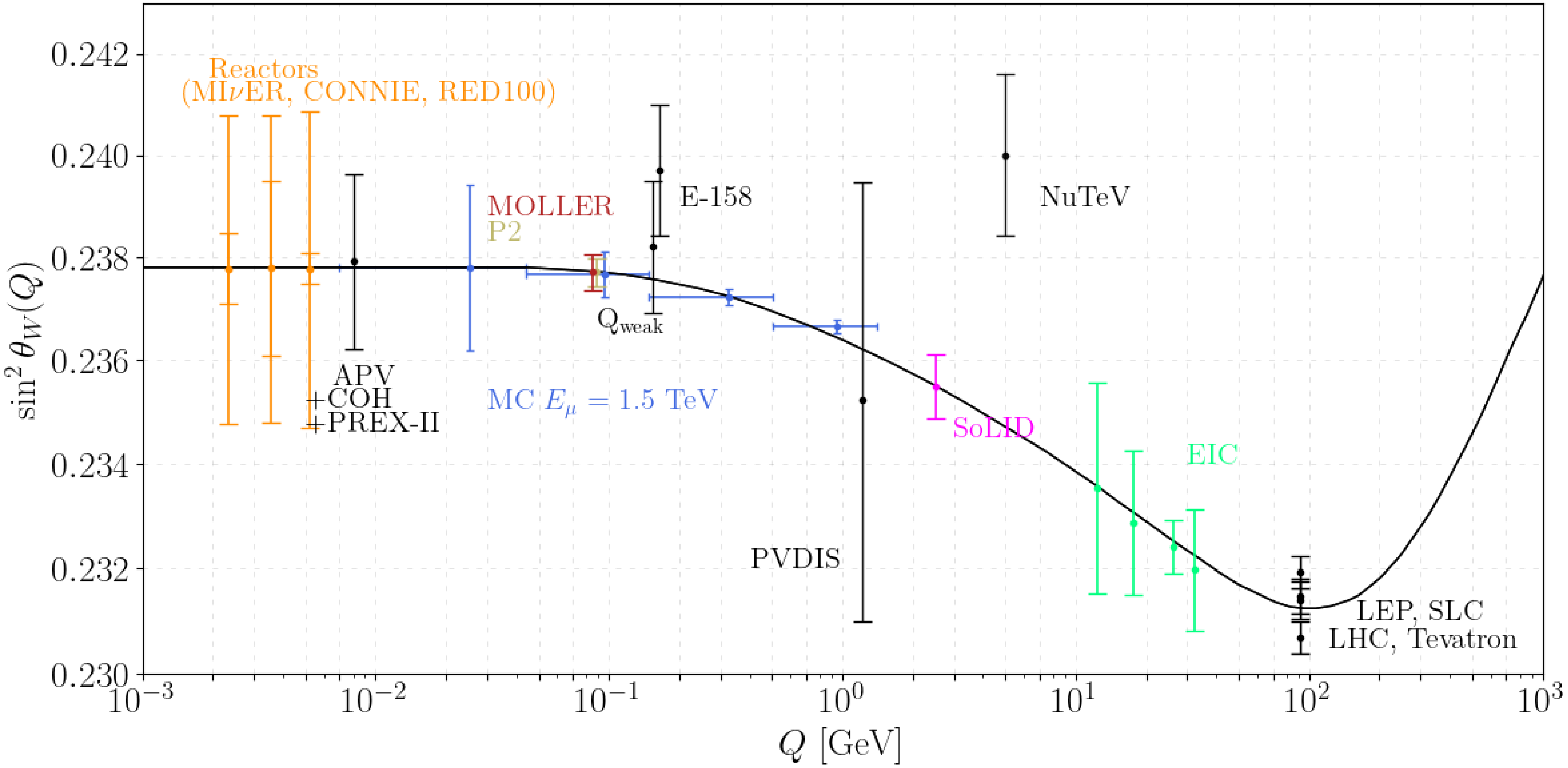

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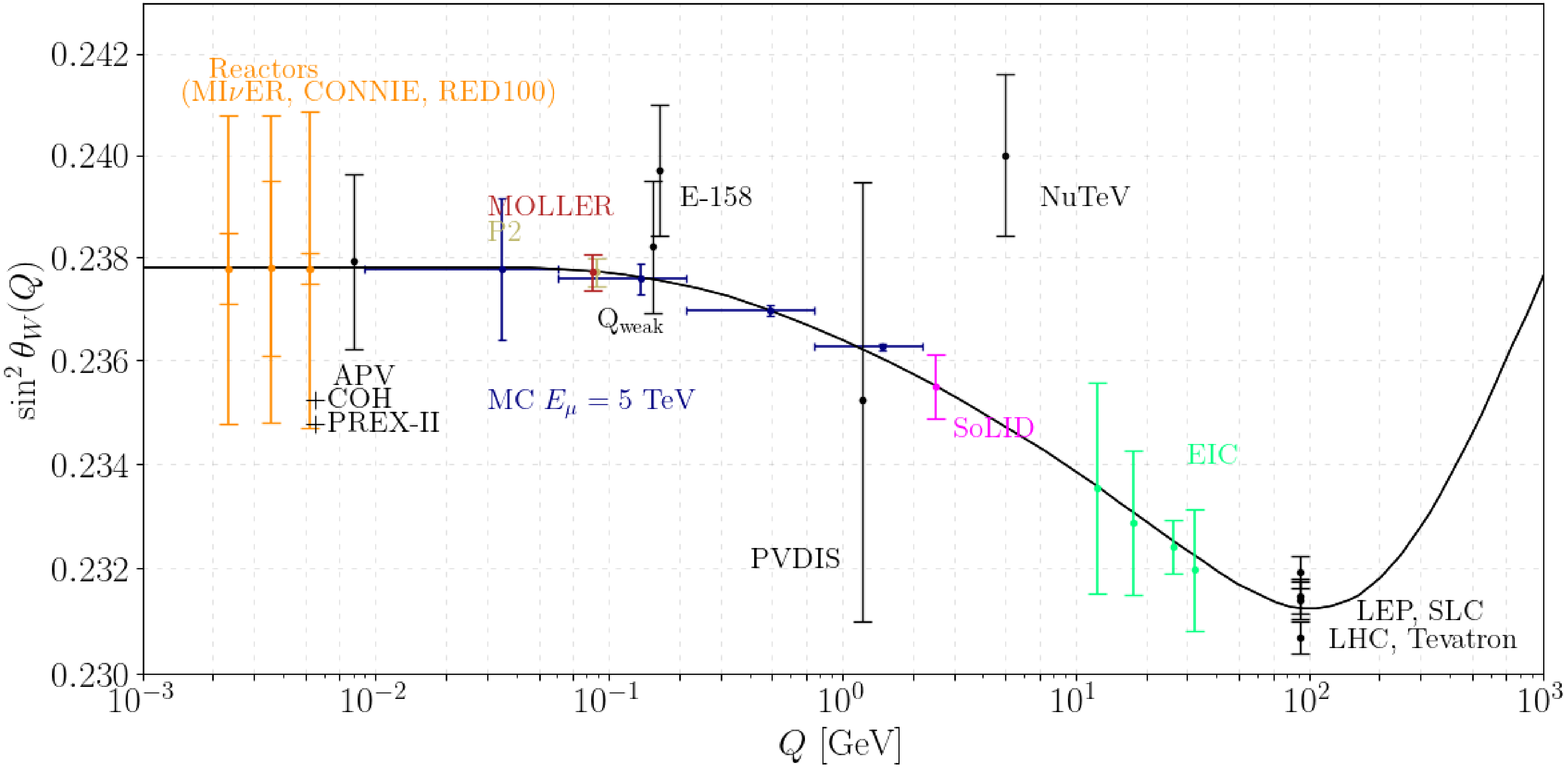

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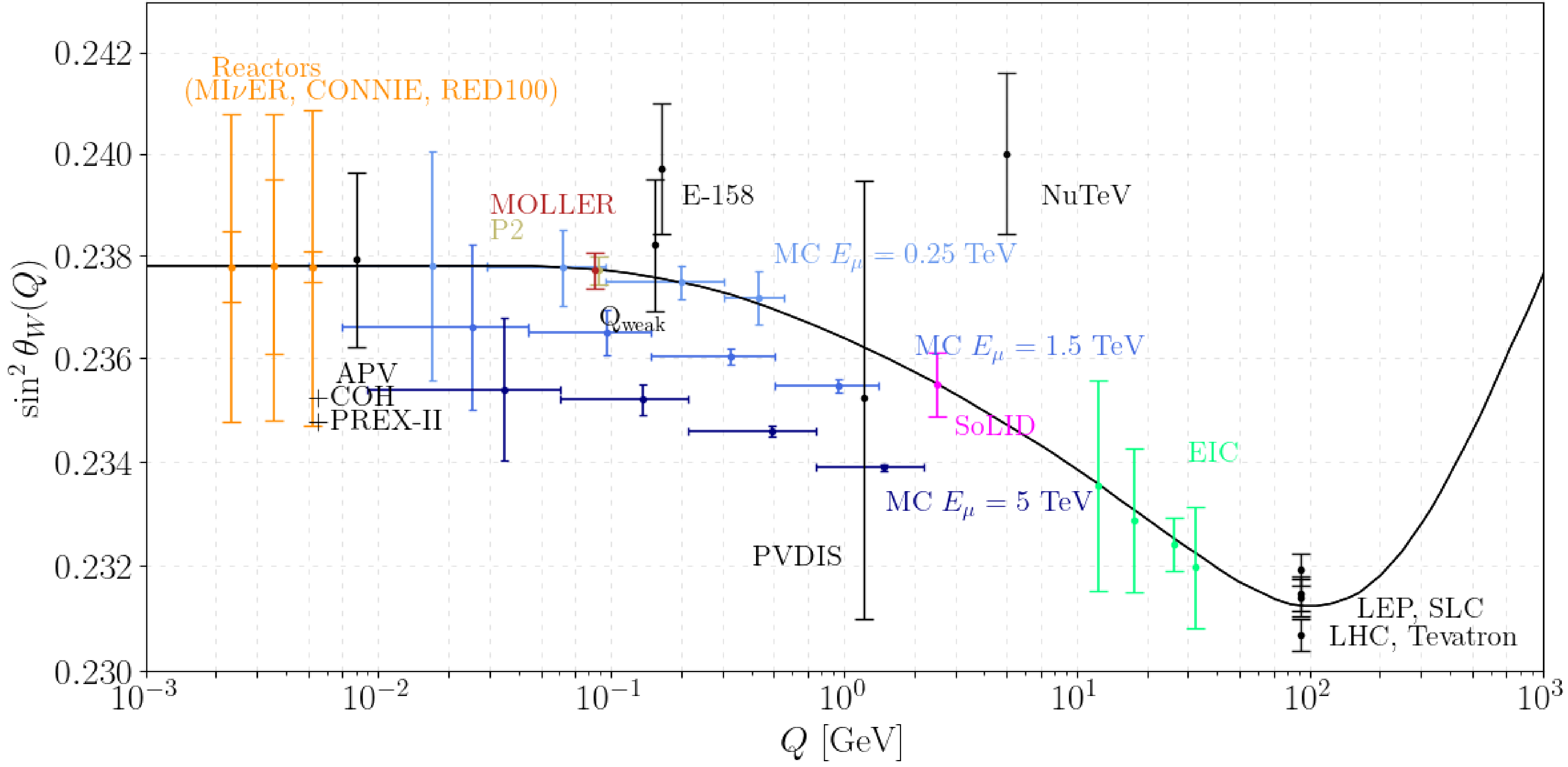

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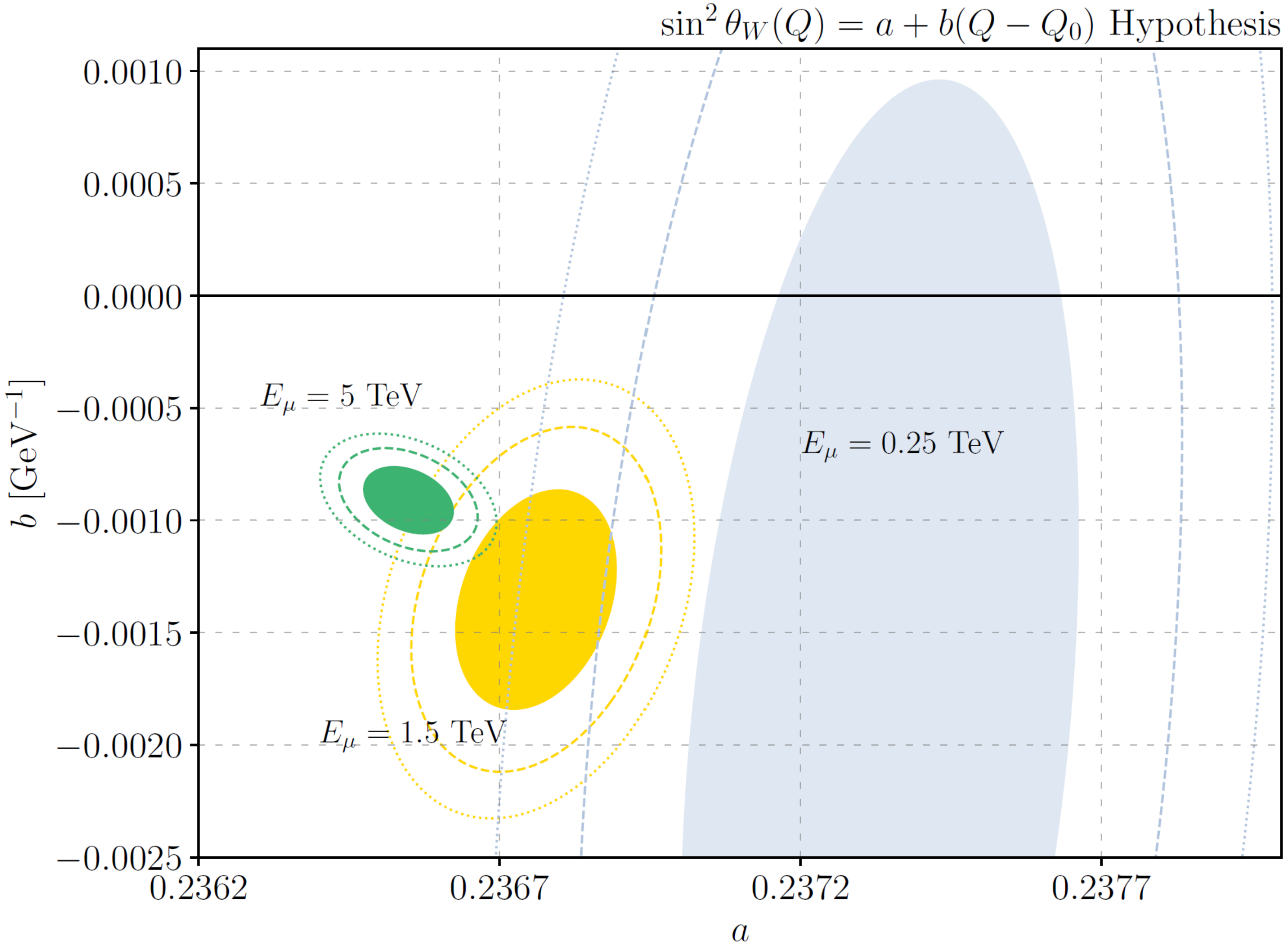
Method II: Affine running hypothesis



Null hypothesis:
EvES spectra with Q-dependent weak mixing angle

Test Hypothesis:

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

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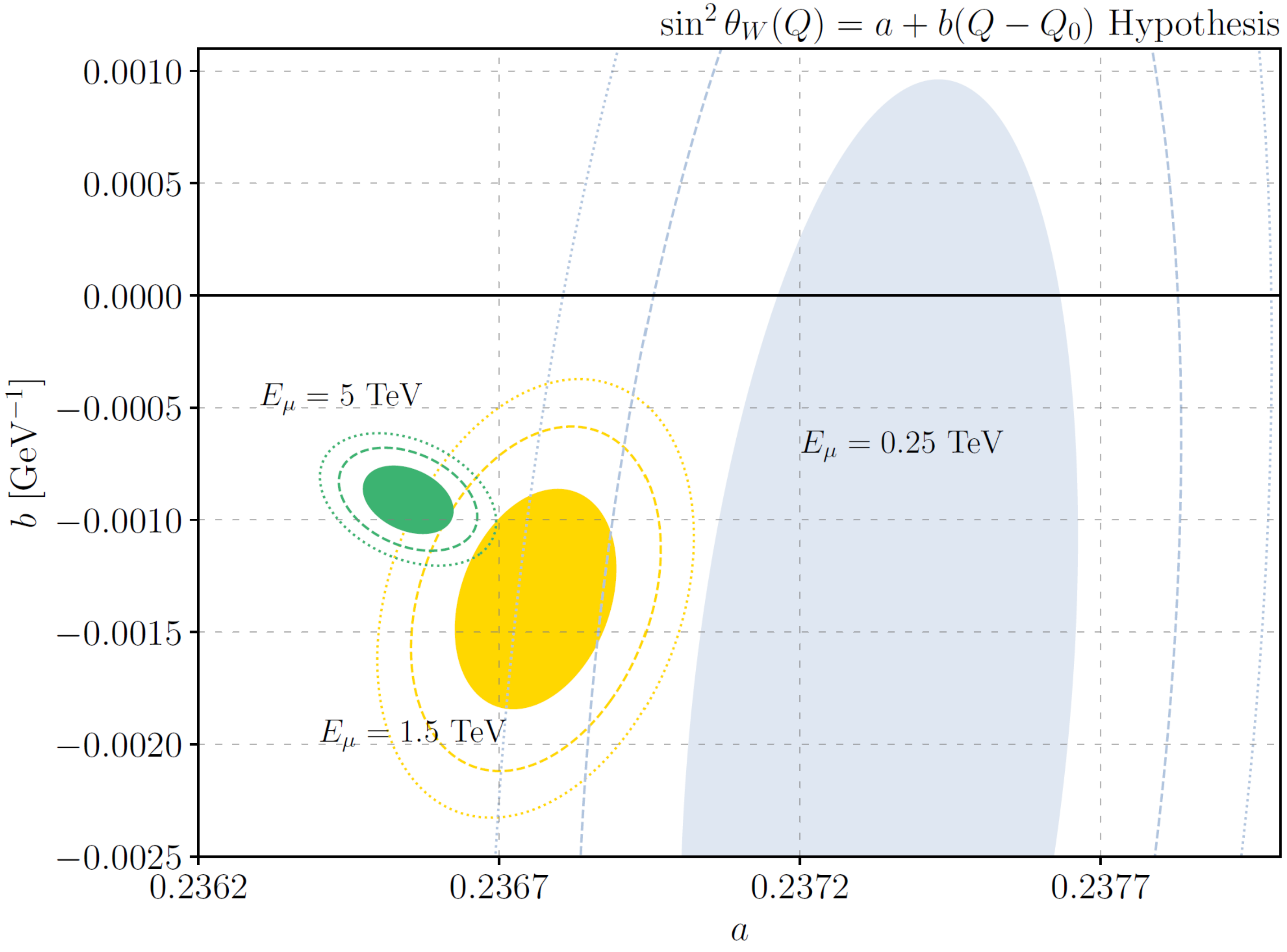

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EvES spectra with Q-dependent weak mixing angle

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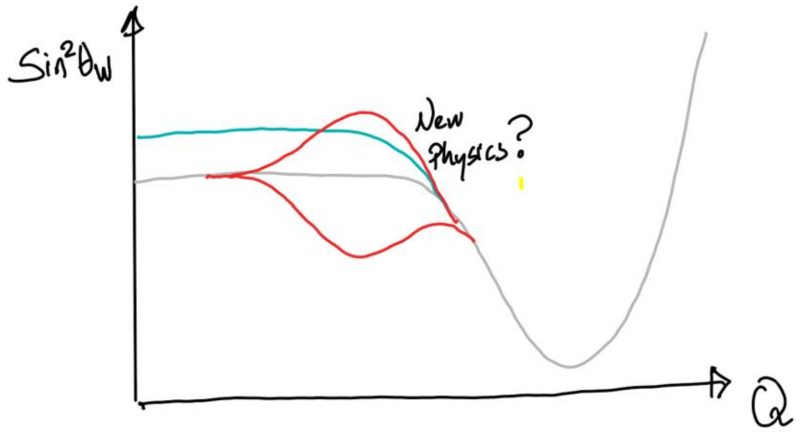


Marciano, Sirlin ‘81
Singer ‘82
Davoudiasl, Lee, Marciano *et al* (2014)

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 → degeneracy breaking of weak couplings
  - Inverse Tau/Muon Decay (QEvES) → Charged lepton flavor violation
  - CC/NC DIS → checking the NuTeV channels
- Neutrino scattering at NLO: full radiative correction picture

Backup Deck

Flavor non-universal Weak Couplings of the Neutrinos

Null hypothesis:

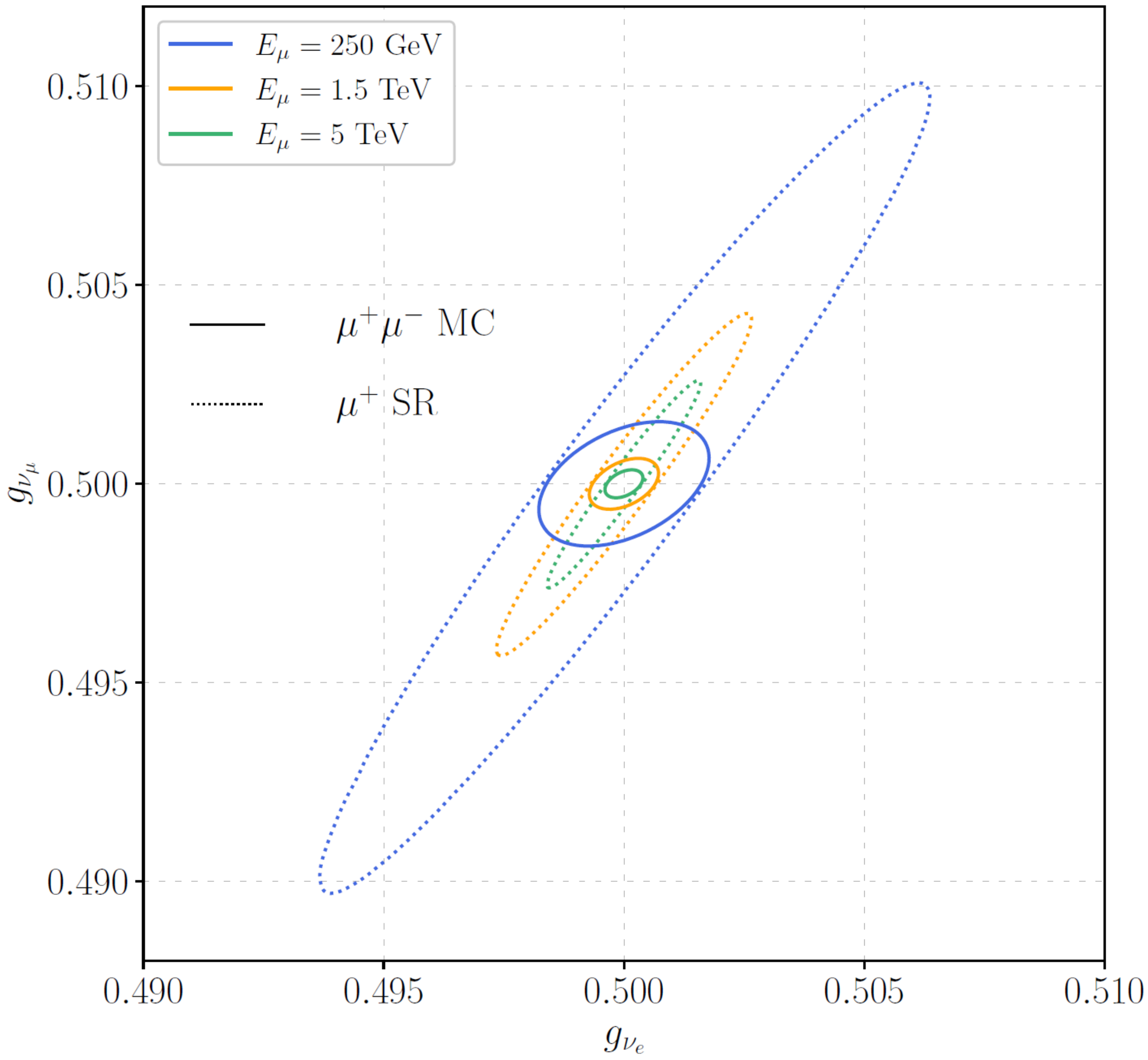
Background-free EvES spectra with fixed

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

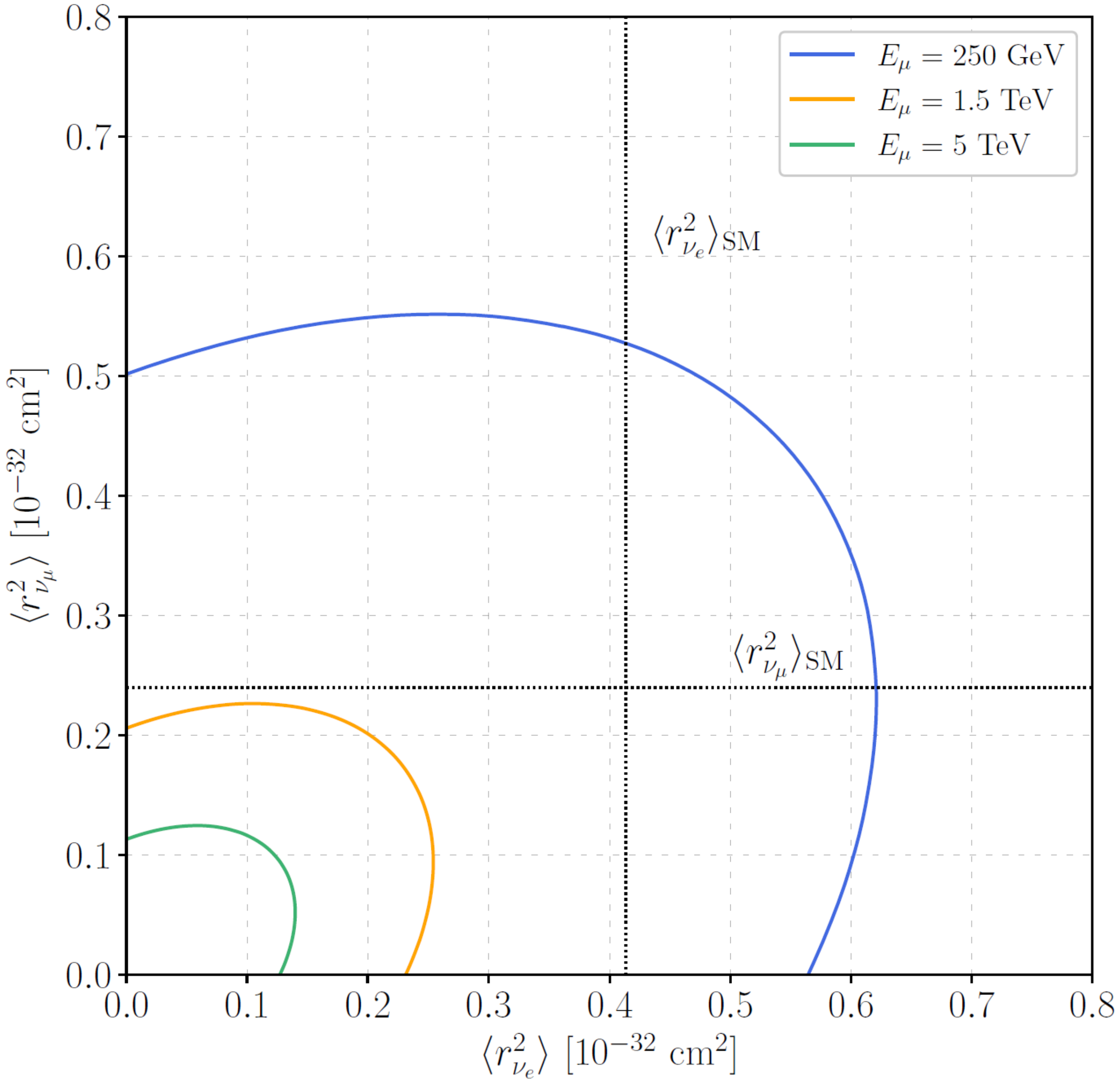
for each E_μ benchmark

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

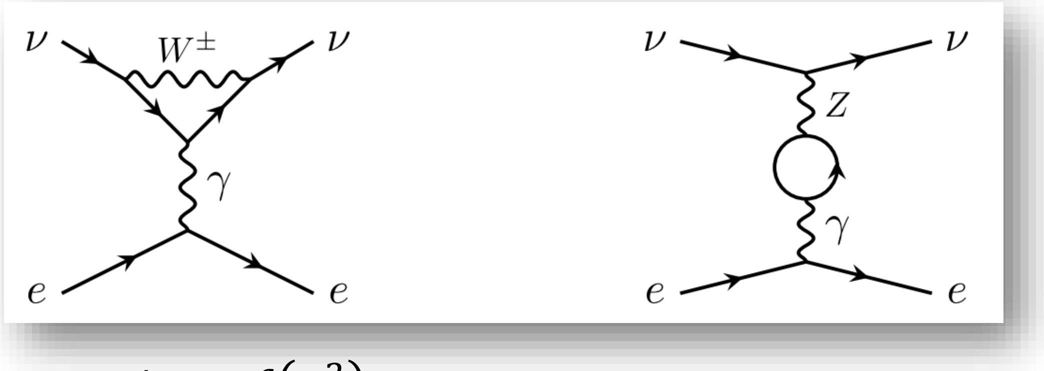
$$g_L \equiv 2g_L^{\nu_\mu} g_L^{e^-} \,, \quad g_R \equiv 2g_L^{\nu_\mu} g_R^{e^-}$$



Neutrino Charge Radius



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



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

[2410.00107]

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

See e.g., Giunti, Studenikin [0812.3646]
Abraham, Foroughi-Abari, Kling, Tsai, [2301.10254]
Brdar, Ferreira-Leite, Parker, Xu, [2410.00107]

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
  - → ~30 events / second
- CC and NC scattering have high hadronic activity
- Need good timing resolution!

First test: Weak Couplings g_V, g_A

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

Bin over electron recoil energy

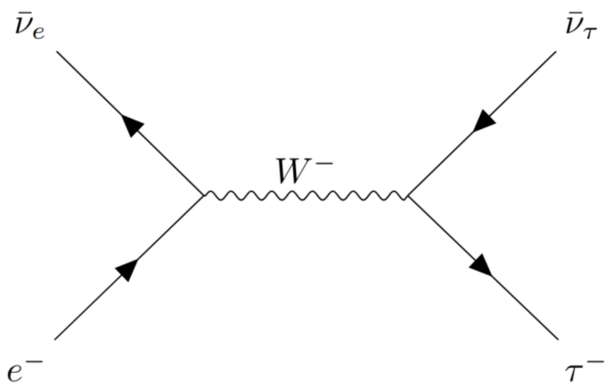
$$\chi^2_{\rm MC} \equiv \chi^2_{\mu^+} + \chi^2_{\mu^-}$$

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

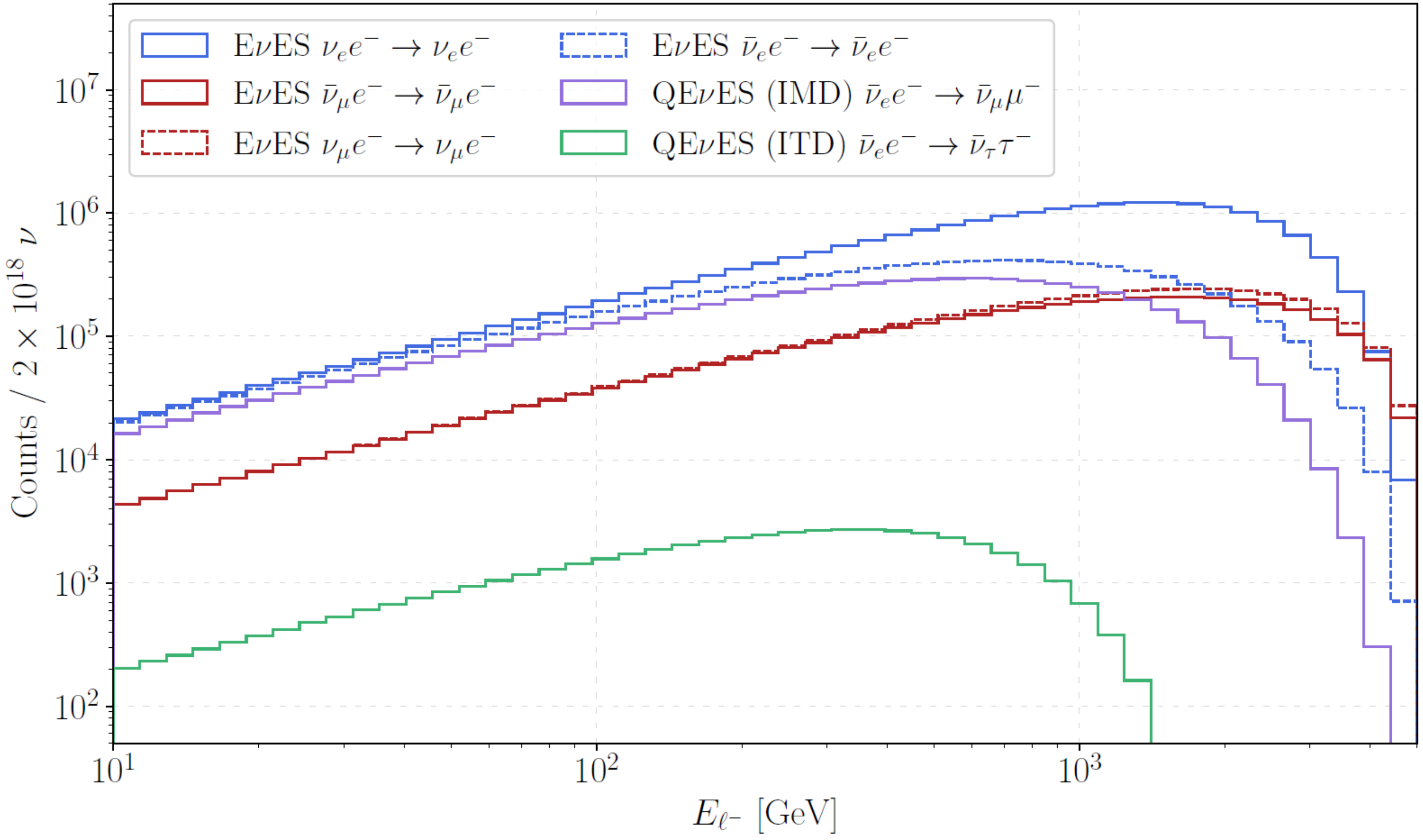
$$g_V^{\rm null} = -\frac{1}{2} + 2\sin^2\theta_W(\langle Q \rangle)$$
$$g_A^{\rm null} = -\frac{1}{2}\,.$$

QEvES / "Induced Lepton Decay"

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

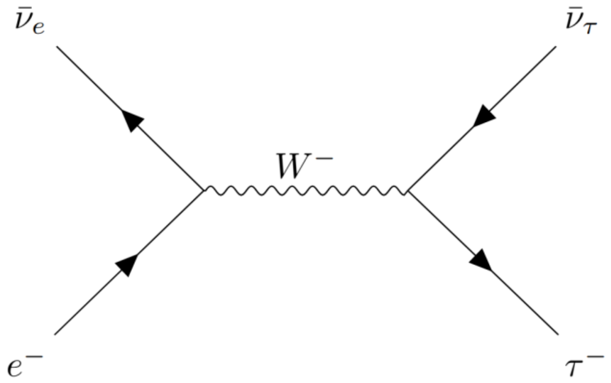


~ 10^4 τ's in the detector from ITD!



QEνES / "Induced Lepton Decay"

$\bar{\nu}_e + e \to \bar{\nu}_l + l \qquad (\mathrm{l} = \mu \text{ or } \tau)$



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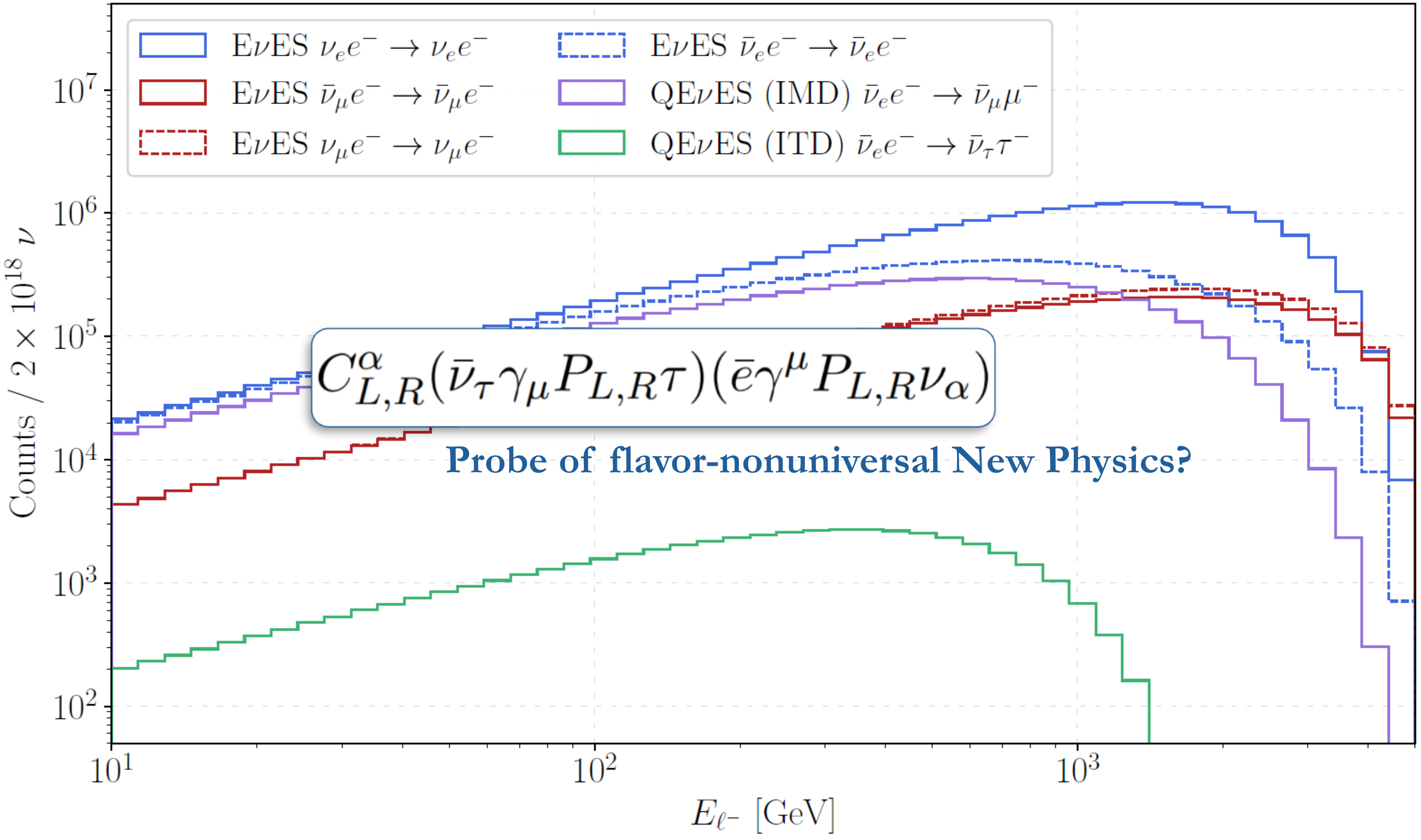
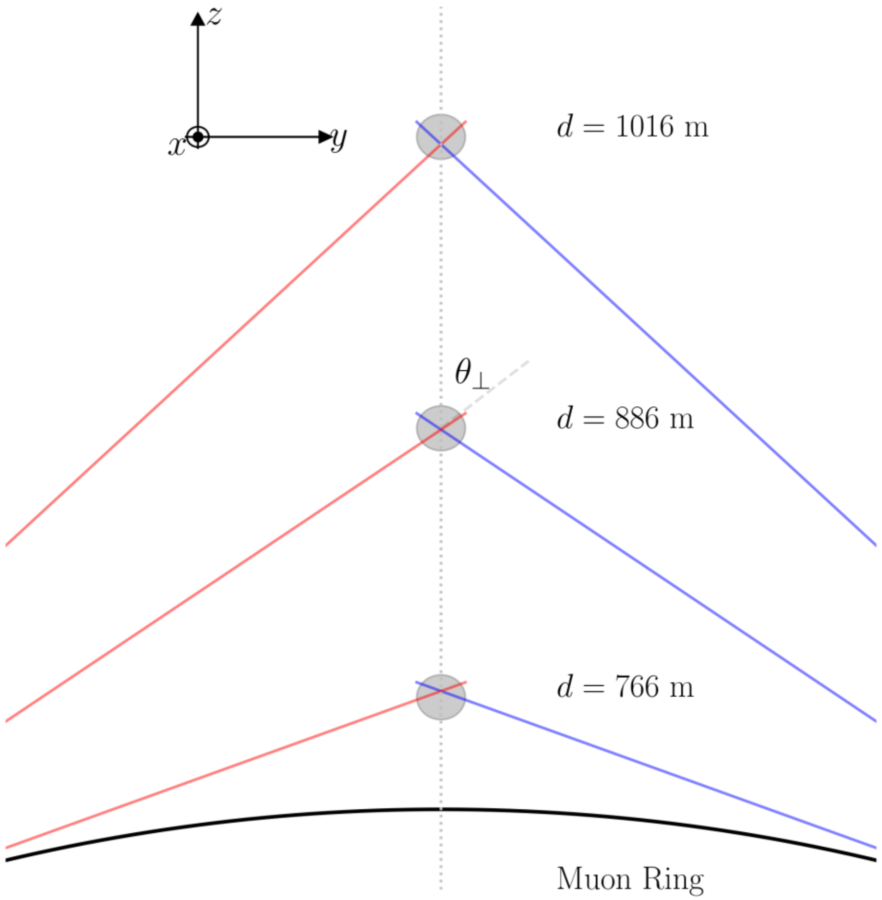
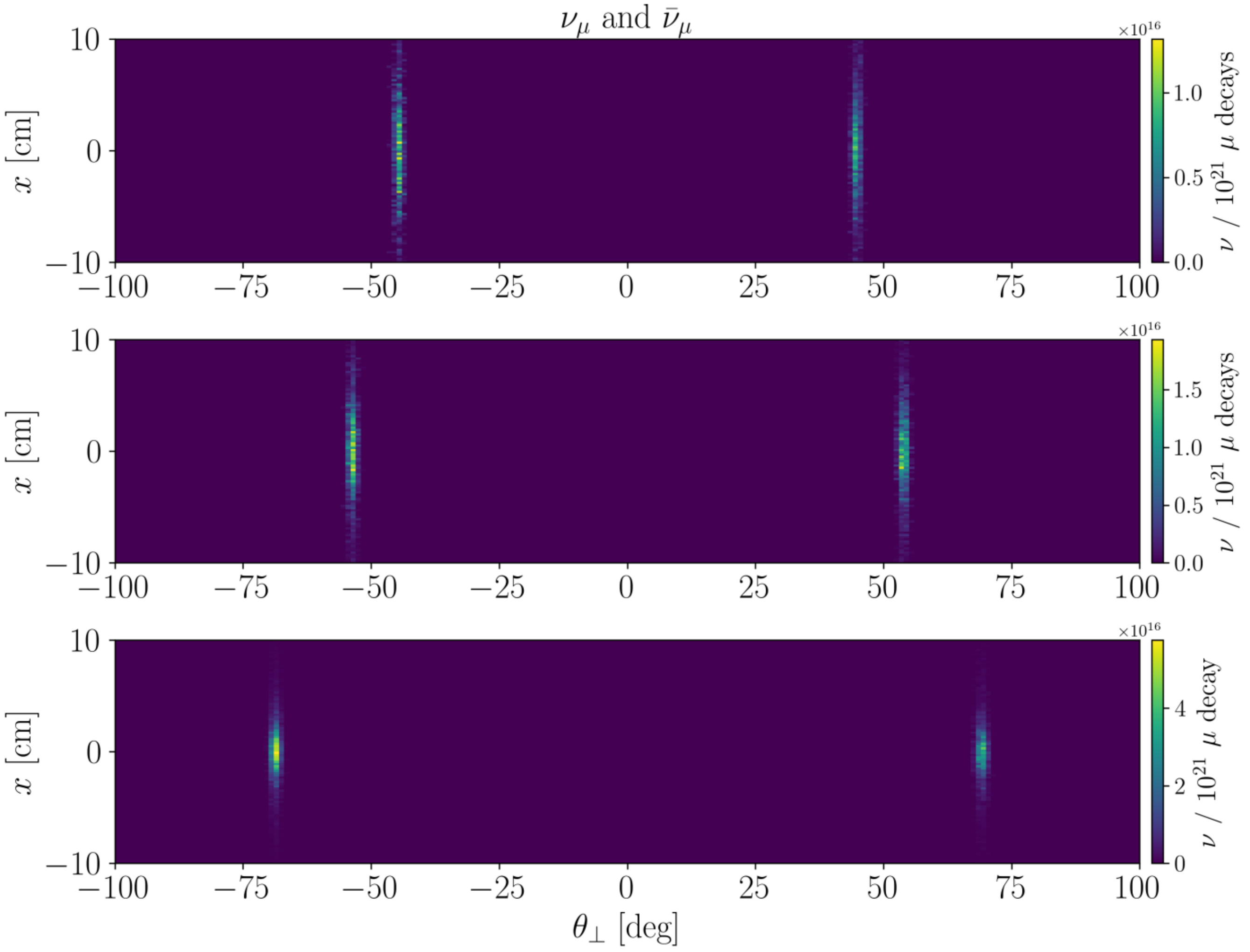


$$C^{\alpha}_{L,R}(\bar{\nu}_\tau \gamma_\mu P_{L,R} \tau)(\bar{e}\gamma^\mu P_{L,R} \nu_\alpha)$$

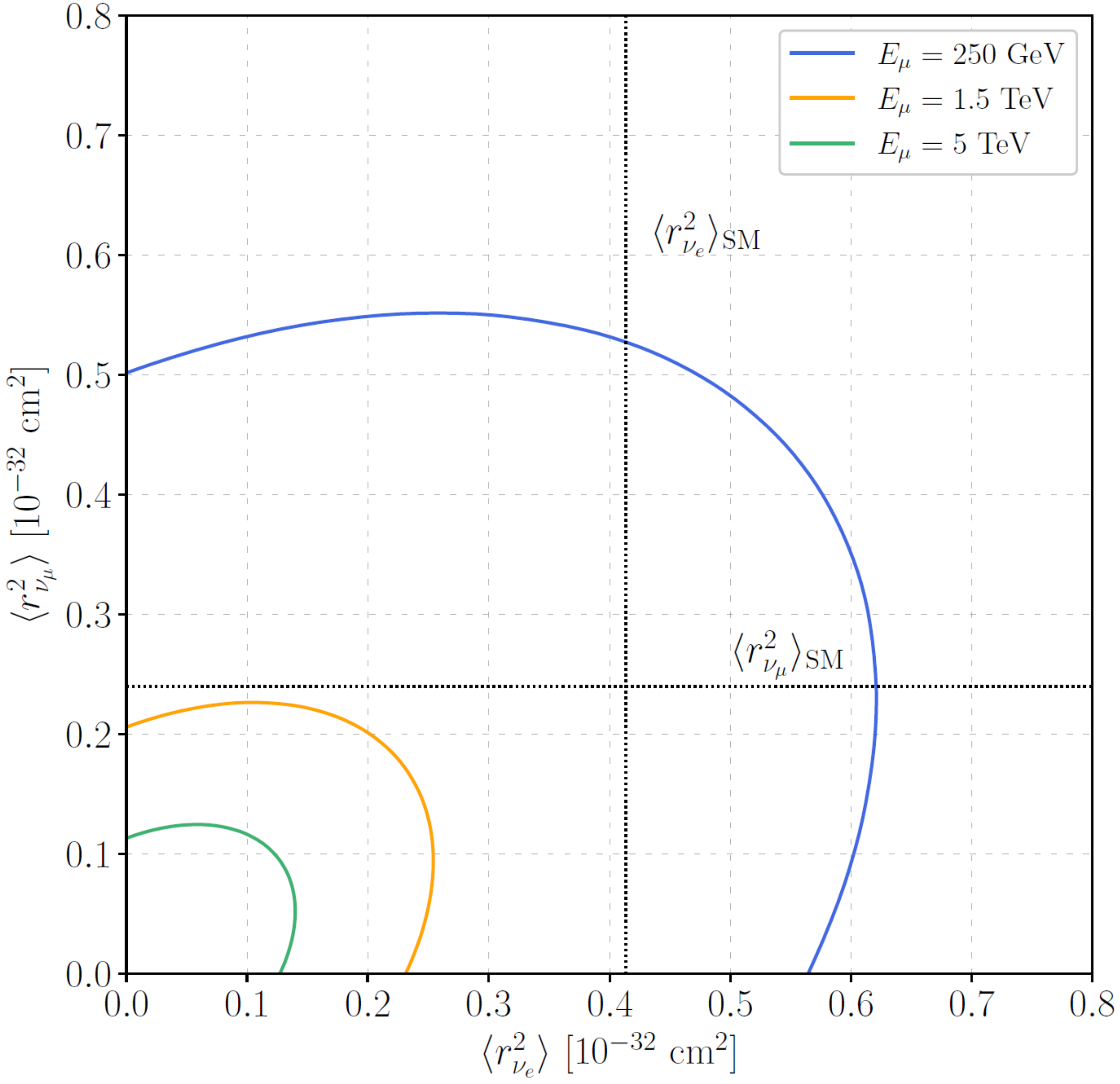
Probe of flavor-nonuniversal New Physics?

Neutrino Beamspot Geometry





4.5 km circumference



Neutrino Charge Radius

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

$$\langle r^2 \rangle \equiv 6 \frac{d f_Q\left(q^2\right)}{dq^2}\Bigg|_{q^2=0}$$

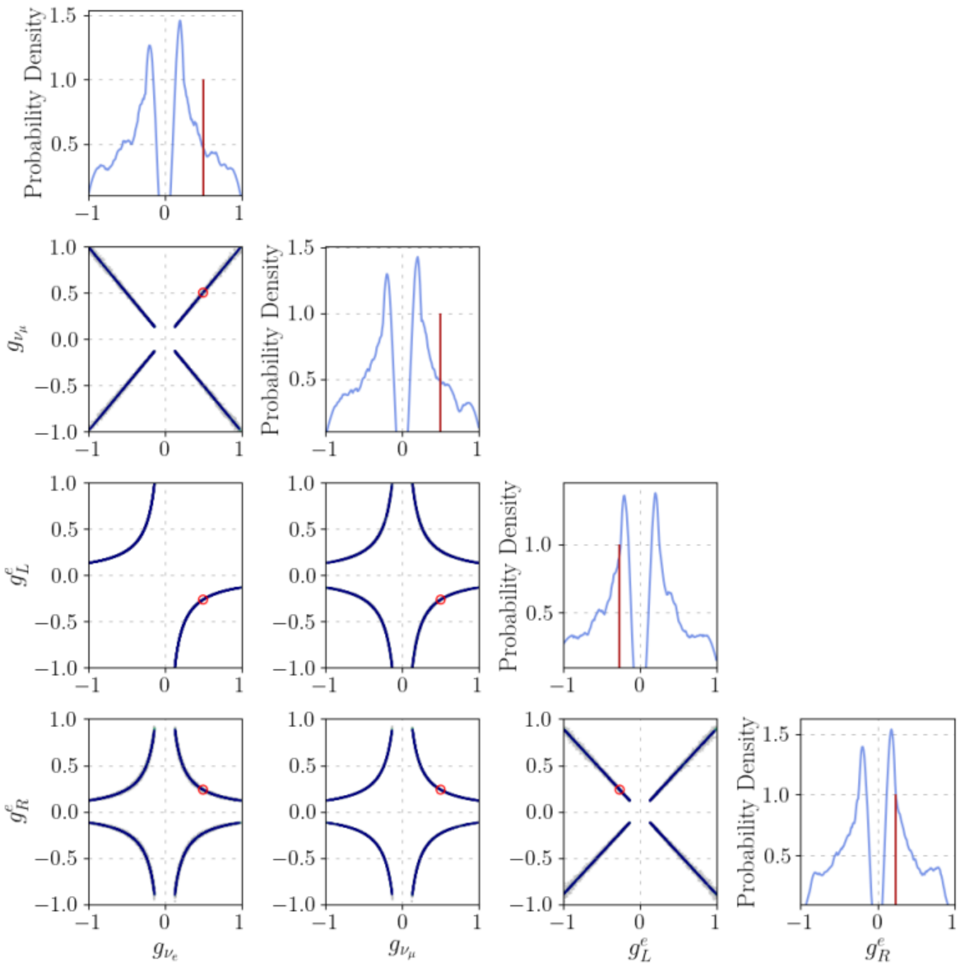
$$g_{L,R} \rightarrow g_{L,R} + \frac{1}{3} m_W^2 \langle r^2_{\nu_\alpha} \rangle \sin^2\theta_W$$

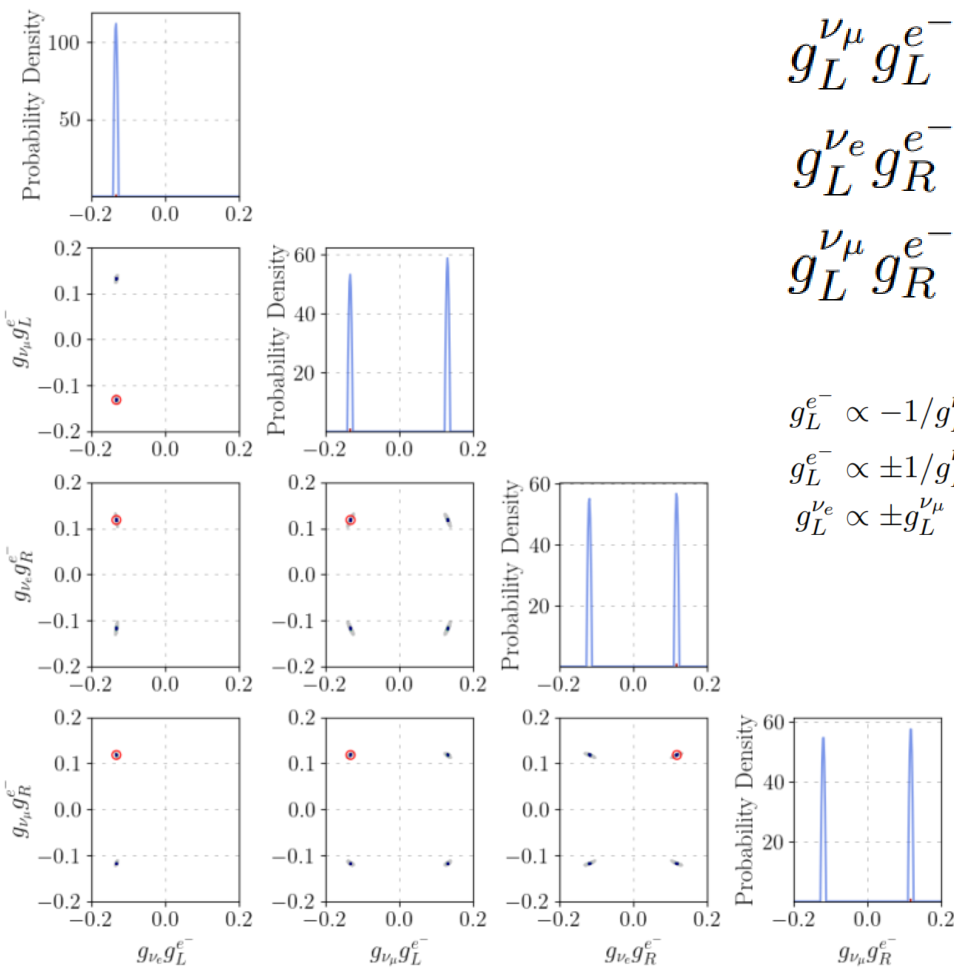
SM prediction ≅

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

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



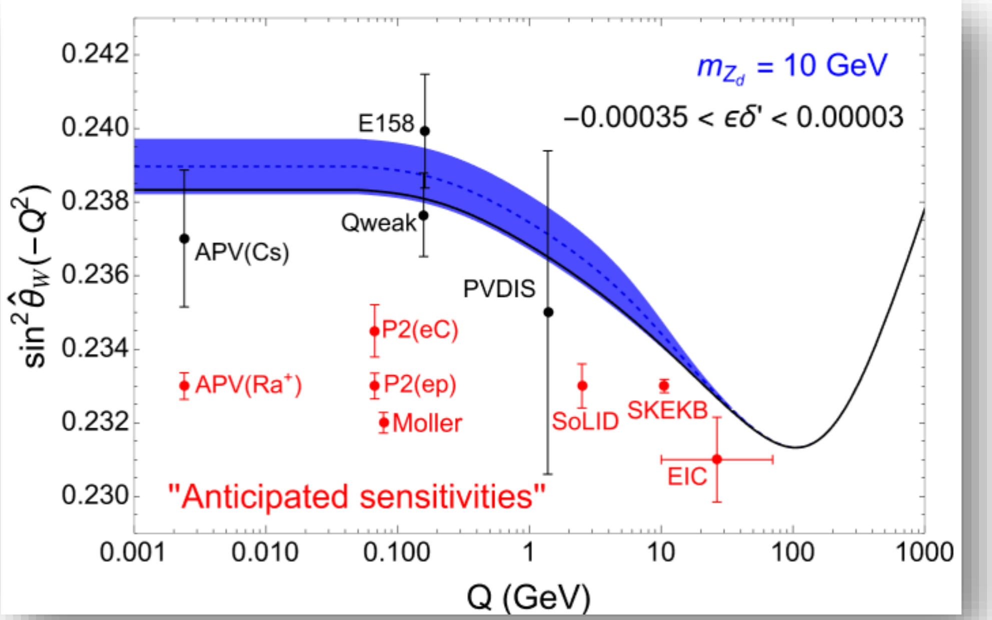


$$g_L^{\nu_e} g_L^{e^-} = -a$$
$$g_L^{\nu_\mu} g_L^{e^-} = \pm b$$
$$g_L^{\nu_e} g_R^{e^-} = \pm c$$
$$g_L^{\nu_\mu} g_R^{e^-} = \pm d$$

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

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

Hunting for New Gauge forces in the running



Davoudiasl *et al* 2309.04060

Extra $U(1)_d$ + extended scalar sector to control the U(1) breaking

→ Kinetic mixing + Z mass mixing induces shifts in the weak mixing angle running