Measuring the weak mixing angle with reactor neutrino experiments

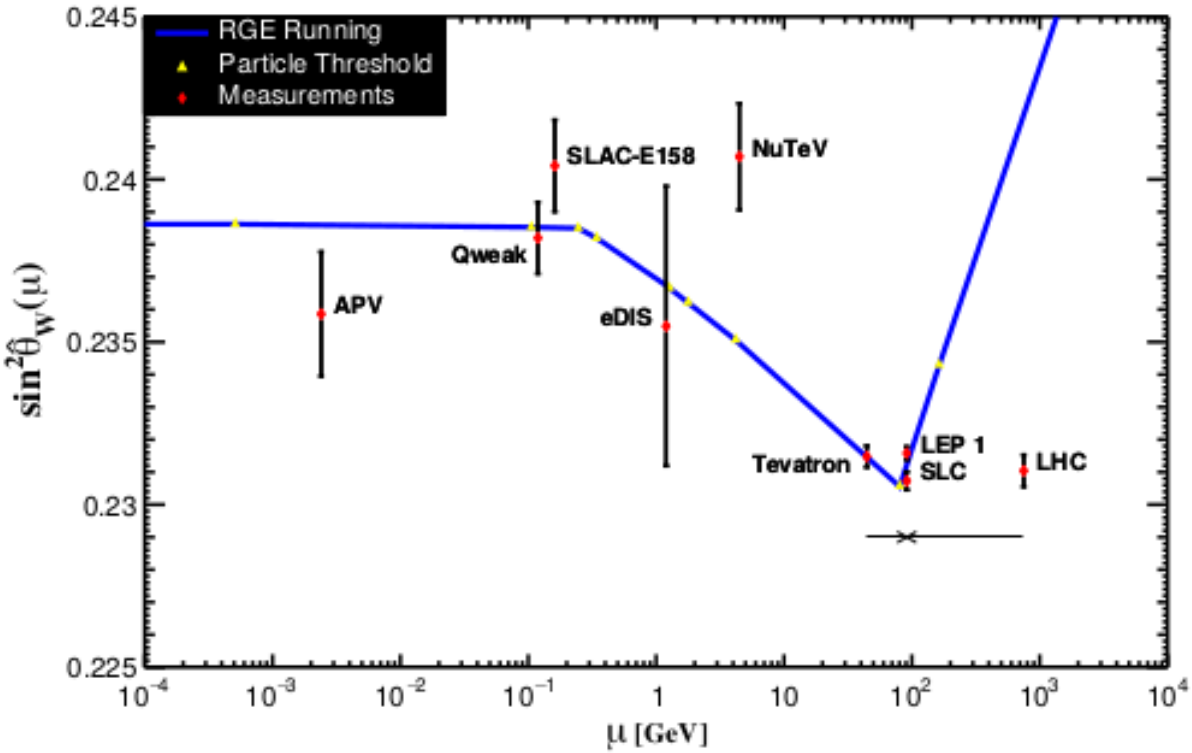
Iván Martínez Soler

Based on: G. Fernandez-Moroni, P.A.N Machado, IMS, Y.F. Perez-Gonzalez, D. Rodrigues, S. Rosauro-Alcaraz, **arXiv:2009.10741**

November 16, 2020

The weak mixing angle

The value of $\sin^2\theta_w$ depends on the energy scale



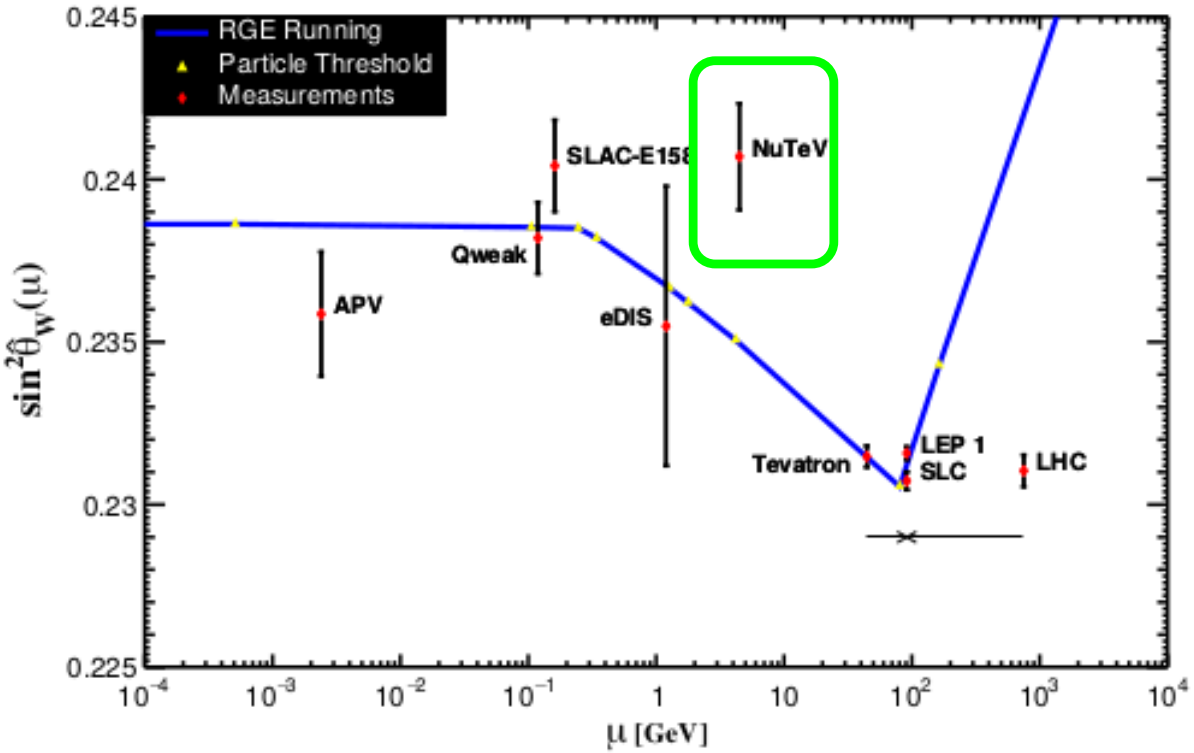
In the $\overline{MS}$ renormalization scheme

$$\sin^2\theta_w = \frac{g'^2}{g^2 + g'^2}$$

- g is the $SU(2)_L$ coupling constant
- g' is the $U(1)_Y$ coupling constant

The weak mixing angle

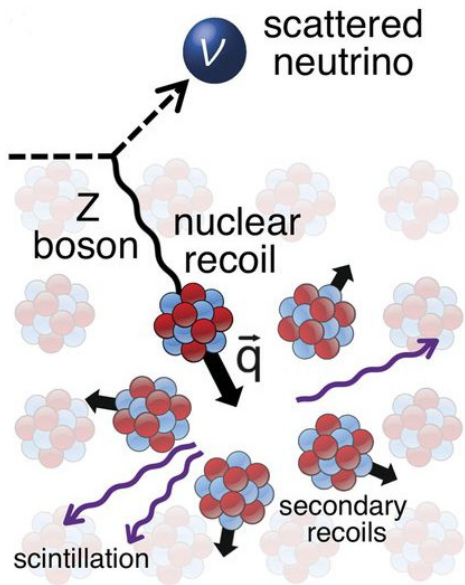
The value of $\sin^2\theta_w$ depends on the energy scale



NuTeV determined $\sin^2\theta_w$ by the Paschos-Wolfenstein ratio

$$R^- = \frac{\sigma^{NC}_{\nu N} - \sigma^{NC}_{\overline{\nu} N}}{\sigma^{CC}_{\nu N} - \sigma^{CC}_{\overline{\nu} N}}$$

Measuring $\sin^2\theta_w$ via CEvNS



$\sin^2\theta_w$ can be measured at lower energies via CEvNS

$$\frac{d\sigma^\nu}{dE_R} = [\mathcal{Q}_V^{\rm SM}]^2 \mathcal{F}^2(E_R) \frac{G_F^2 m_N}{4\pi} \left(1 - \frac{E_R}{E_\nu} + \frac{E_R^2}{2E_\nu^2} - \frac{m_N E_R}{2E_\nu^2}\right)$$

where $\mathcal{Q}_V^{\rm SM}$ is the weak charge of the nucleus

$$\mathcal{Q}_V^{\rm SM} = N - (1 - 4\sin^2\theta_W) Z$$

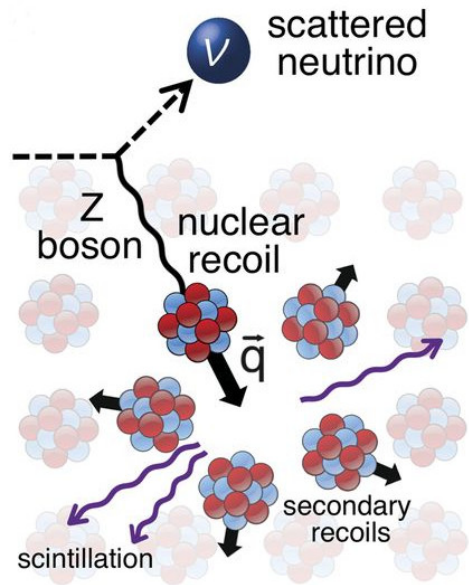
and $\mathcal{F}(E_R)$ is the form factor

$$\mathcal{F}(E_R) = 3e^{-k^2 s^2/2} \left[\sin(kr) - kr\cos(kr)\right] / (kr)^3 \qquad k \equiv \sqrt{2 m_N E_R}$$

In the limit $E_R \to 0$ $\qquad$ $\mathcal{F}(E_R) \to 1$

For radiative corrections in CEvNS see **Oleksandr Tomalak and Ryan Plestid Talk**

Measuring $\sin^2\theta_w$ via CEvNS

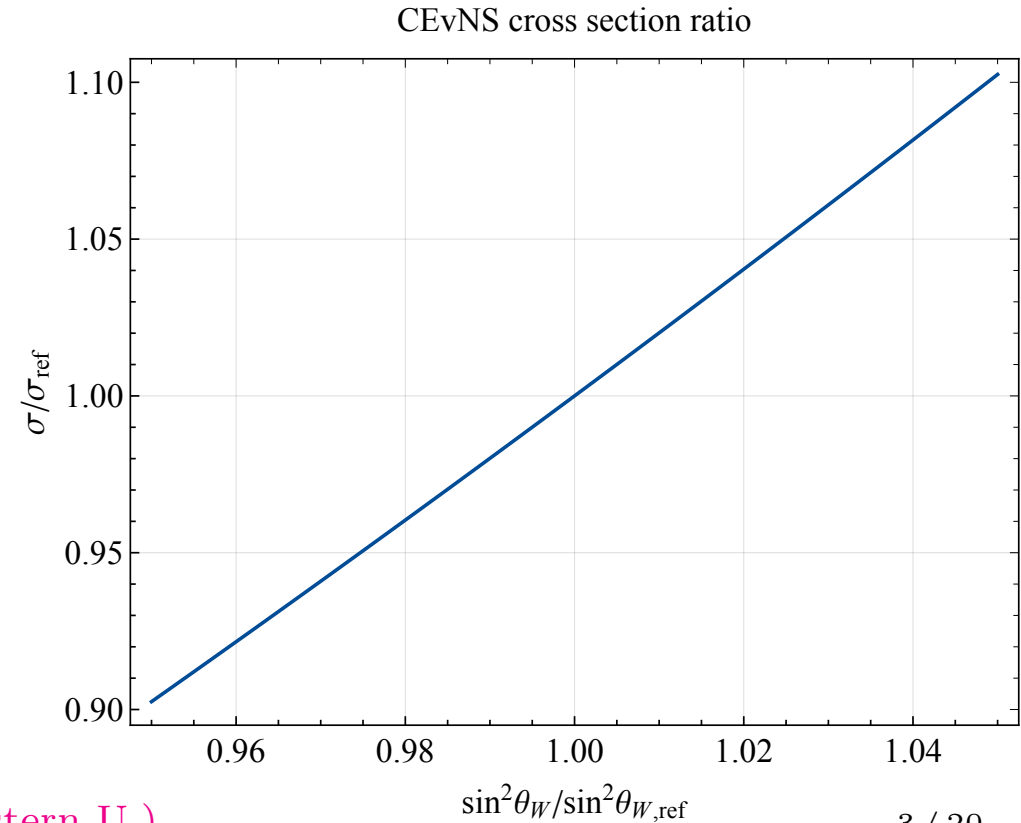


$\sin^2\theta_w$ can be measured at lower energies via CEvNS

$$\frac{d\sigma^\nu}{dE_R} = [\mathcal{Q}_V^{\rm SM}]^2 \mathcal{F}^2(E_R) \frac{G_F^2 m_N}{4\pi} \left(1 - \frac{E_R}{E_\nu} + \frac{E_R^2}{2E_\nu^2} - \frac{m_N E_R}{2E_\nu^2}\right)$$

Dependence on $\sin^2\theta_w$ via the weak charge of the nucleus

$$\mathcal{Q}_V^{\rm SM} = N - (1 - 4\sin^2\theta_W)Z$$

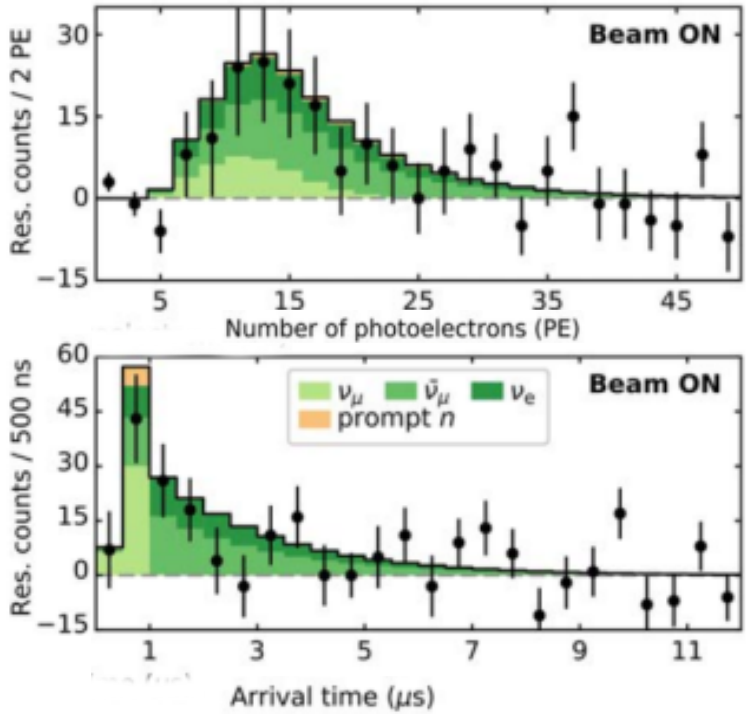


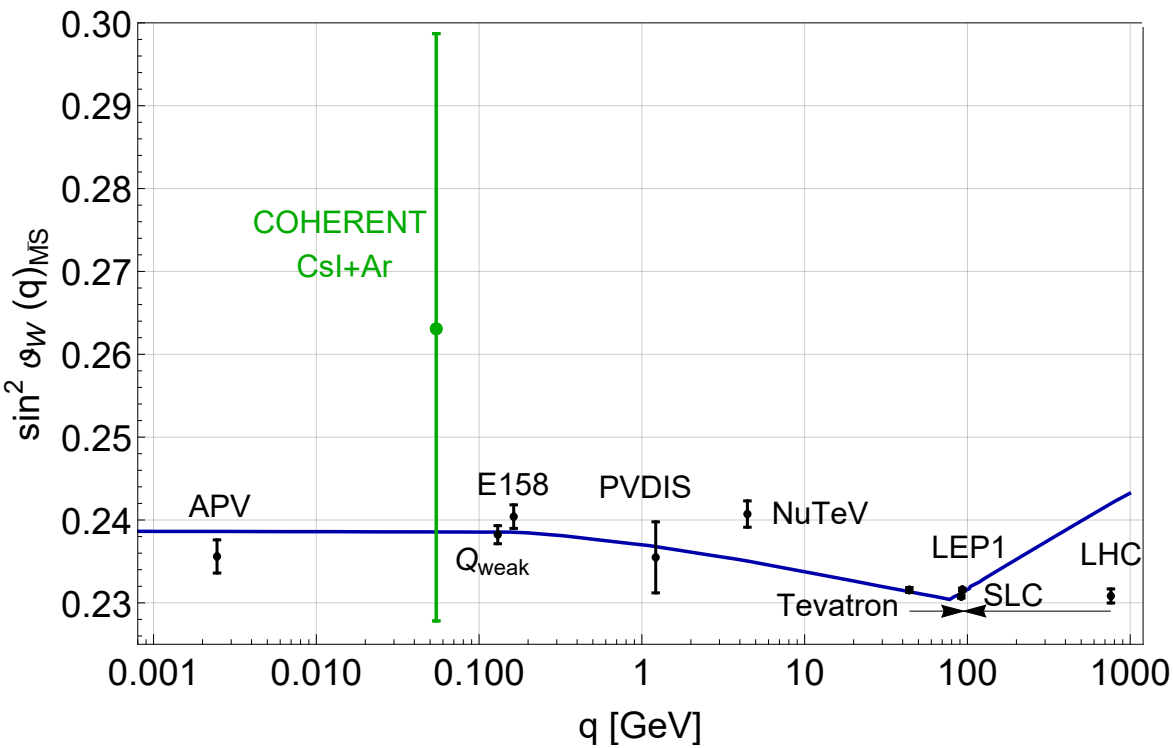
Measuring $\sin^2\theta_w$ via CEvNS

COHERENT reported the first observation of CEvNS at 6.7σ

- Neutrino flux created by pion decay at rest

$$\pi^+ \to \mu^+ \nu_\mu \qquad \mu \to e \overline{\nu}_\mu \nu_e$$





COHERENT **Science 357 (2017) 6356** (1708.01294)

Neutrino electromagntic properties from CEvNS see **Daniel Pershey and Yiyu Zhang Talk**

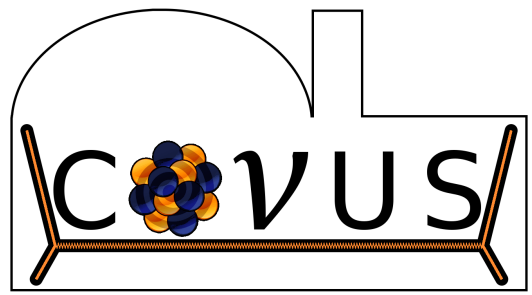
Cadeddu, Dordei, Giunti, Li, Picciau, Zhang (Phys.Rev.D 102 (2020) 1, 015030)

MINER

RICOCHET
A Coherent Neutrino Scattering Program

Where will be we able to measure CEvNS?

νGeN



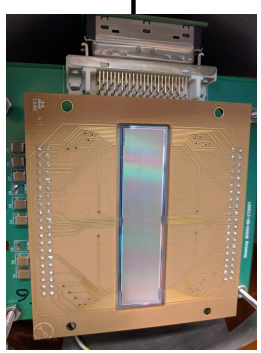
For a complete description of the Skipper CCD see **Guillermo Fernandez Moroni's Talk**

We will focus in the detection CEvNS with reactor neutrinos.

Detector benchmark configuration:

- Detector: **Skipper CCD**
- Distance: **12 m**
- Mass: **1 kg**
- Reactor Power: $\mathbf{W = 2\ GW}$ ($\sim 10^{25}\nu$/day)
- Time: **3 years**
- **Reactor-off time of 45/days per year**

12 m



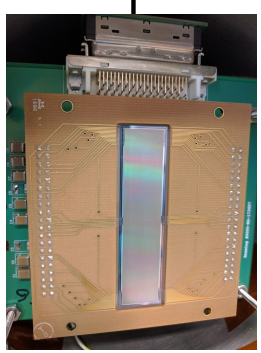
For a complete description of the Skipper CCD see **Guillermo Fernandez Moroni's Talk**

We will focus in the detection CEvNS with reactor neutrinos.

Detector benchmark configuration:

- Detector: **Skipper CCD**
- Distance: **12 m**
- Mass: **1 kg**
- Reactor Power: **W = 2 GW** ($\sim 10^{25}\nu$/day)
- Time: **3 years**
- **Reactor-off time of 45/days per year**

12 m



Backgrounds:

- **High energy photons and neutrons**
- Bkg: 10^3 events/day/kg/keV
- Flat energy spectrum

Expected event rate in vIOLETA

The expected event rate in a Skipper CCD detector

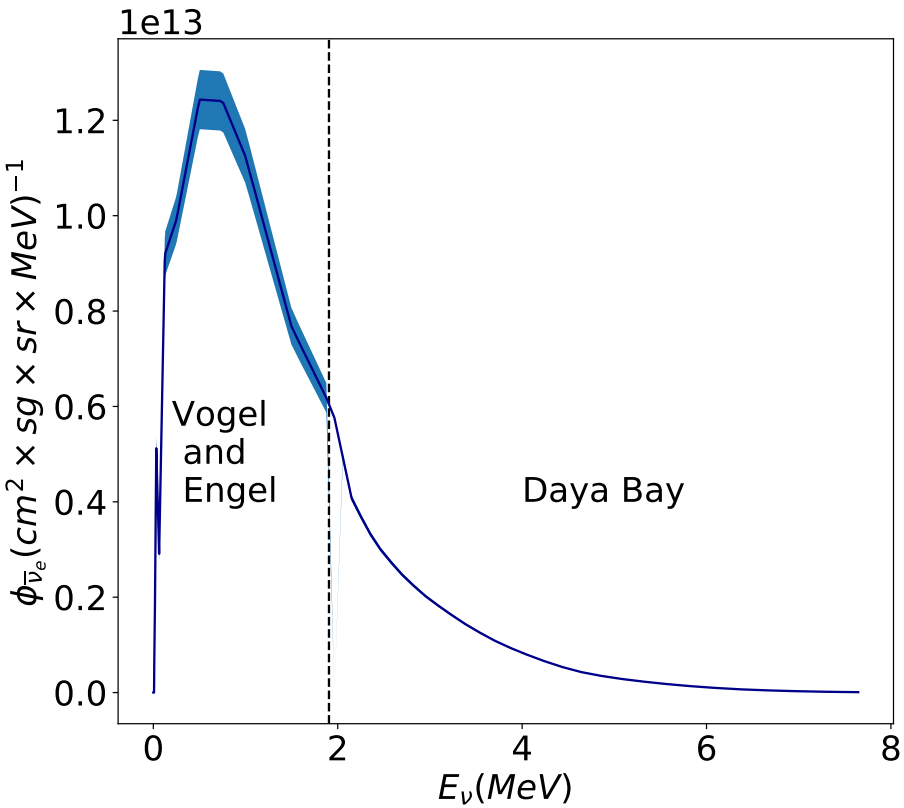
$$n_a = \frac{W}{\sum_{q'}(f_{q'}e_{q'})} \int_{\text{bin } a} dE_I \frac{1}{Q(E_I)} \left(1 - \frac{E_I}{Q(E_I)} \frac{dQ(E_I)}{dE_I}\right) \int dE_\nu \frac{d\phi_{\bar{\nu}_e}}{dE_\nu} \frac{d\sigma_{\text{CE}\nu\text{NS}}}{dE_R}\bigg|_{E_R=E_I/Q(E_I}$$

Expected event rate in vIOLETA

$$n_a = \frac{W}{\sum_{q'}(f_{q'} e_{q'})} \int_{\text{bin } a} dE_I \frac{1}{Q(E_I)} \left(1 - \frac{E_I}{Q(E_I)} \frac{dQ(E_I)}{dE_I}\right) \int dE_\nu \left(\frac{d\phi_{\bar{\nu}_e}}{dE_\nu}\right) \frac{d\sigma_{\text{CE}\nu\text{NS}}}{dE_R}\bigg|_{E_R = E_I/Q}$$

For the reactor flux we will follow a "data driven" approach:

- $\bar{\nu}_e \ni \{U^{235}, U^{238}, Pu^{239}, Pu^{241}\}$
- $E_\nu > 2$ MeV, Daya Bay flux
- $E_\nu < 2$ MeV, Vogel and Engel prediction



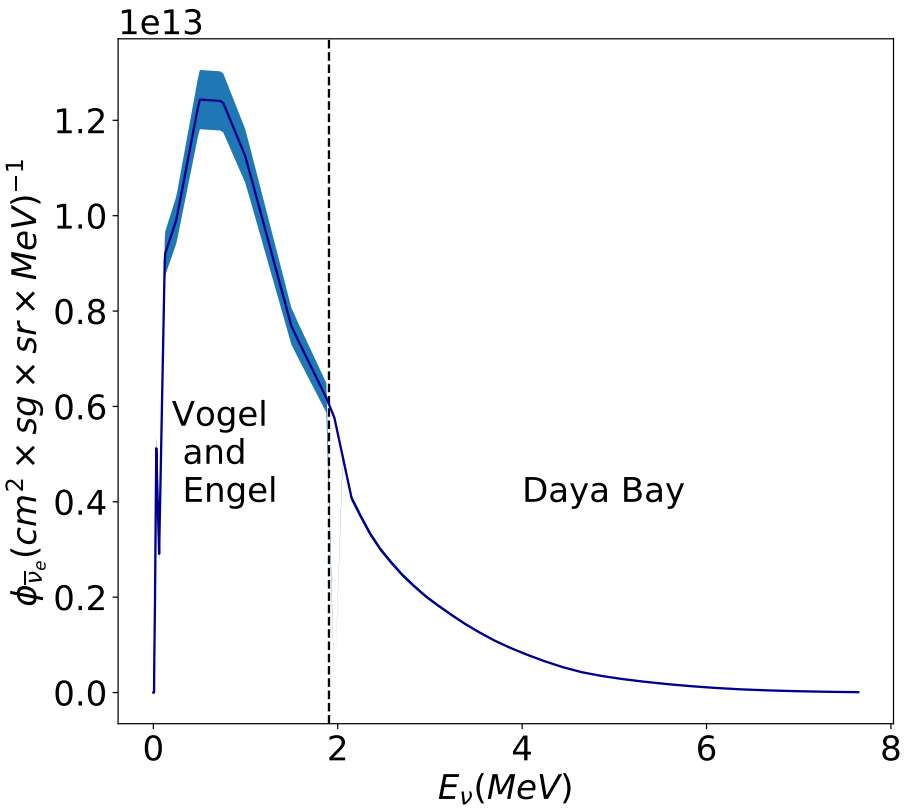
Daya Bay: Phys.Rev.Lett. 123 (2019) 11
Vogel and Engel: Phys. Rev. D39 (1989) 3378

Expected event rate in vIOLETA

$$n_a = \frac{W}{\sum_{q'}(f_{q'} e_{q'})} \int_{\text{bin } a} dE_I \frac{1}{Q(E_I)} \left(1 - \frac{E_I}{Q(E_I)} \frac{dQ(E_I)}{dE_I}\right) \int dE_\nu \left(\frac{d\phi_{\bar{\nu}_e}}{dE_\nu}\right) \frac{d\sigma_{\text{CE}\nu\text{NS}}}{dE_R}\bigg|_{E_R = E_I/Q}$$

Reactor experiments allow to explore **lower nuclear recoil energies than COHERENT**

$$E_R^{\max} = \frac{2E_\nu^2}{m_N + 2E_\nu}$$
$$\simeq 76 \text{ eV} \left(\frac{E_\nu}{\text{MeV}}\right)^2 \left(\frac{28\ m_p}{m_N}\right)$$



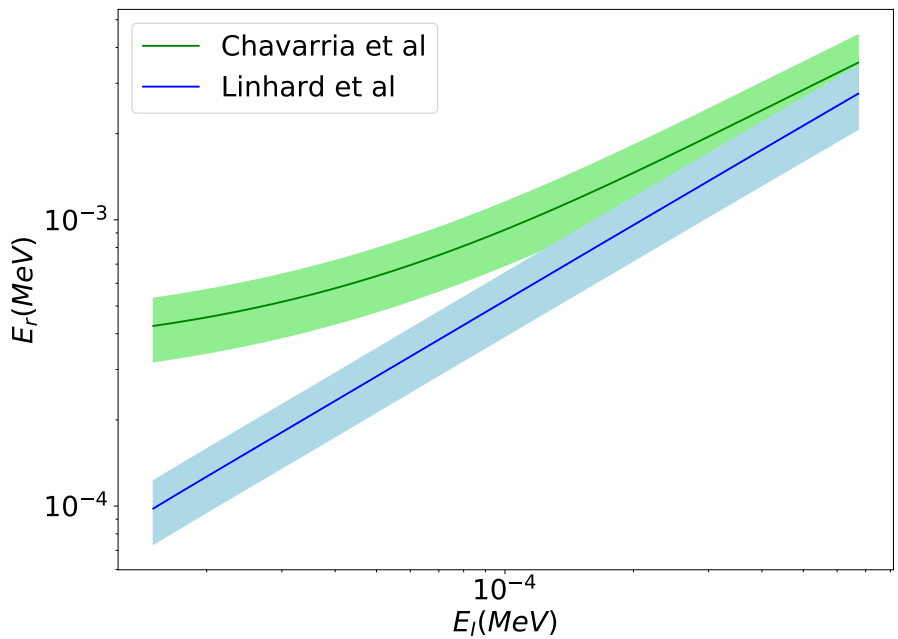
Expected event rate in vIOLETA

$$n_a = \frac{W}{\sum_{q'}(f_{q'}e_{q'})} \int_{\text{bin } a} dE_I \left(\frac{1}{Q(E_I)}\right) \left(1 - \frac{E_I}{Q(E_I)} \frac{dQ(E_I)}{dE_I}\right) \int dE_\nu \frac{d\phi_{\bar{\nu}_e}}{dE_\nu} \frac{d\sigma_{\text{CE}\nu\text{NS}}}{dE_R}\bigg|_{E_R = E_I/Q}$$

The ionization (E_I) and the recoil (E_R) energies are related by the Quenching factor

$$Q(E_I) = \frac{E_I}{E_R}$$

We will consider as a benchmark "Chavarria et al"

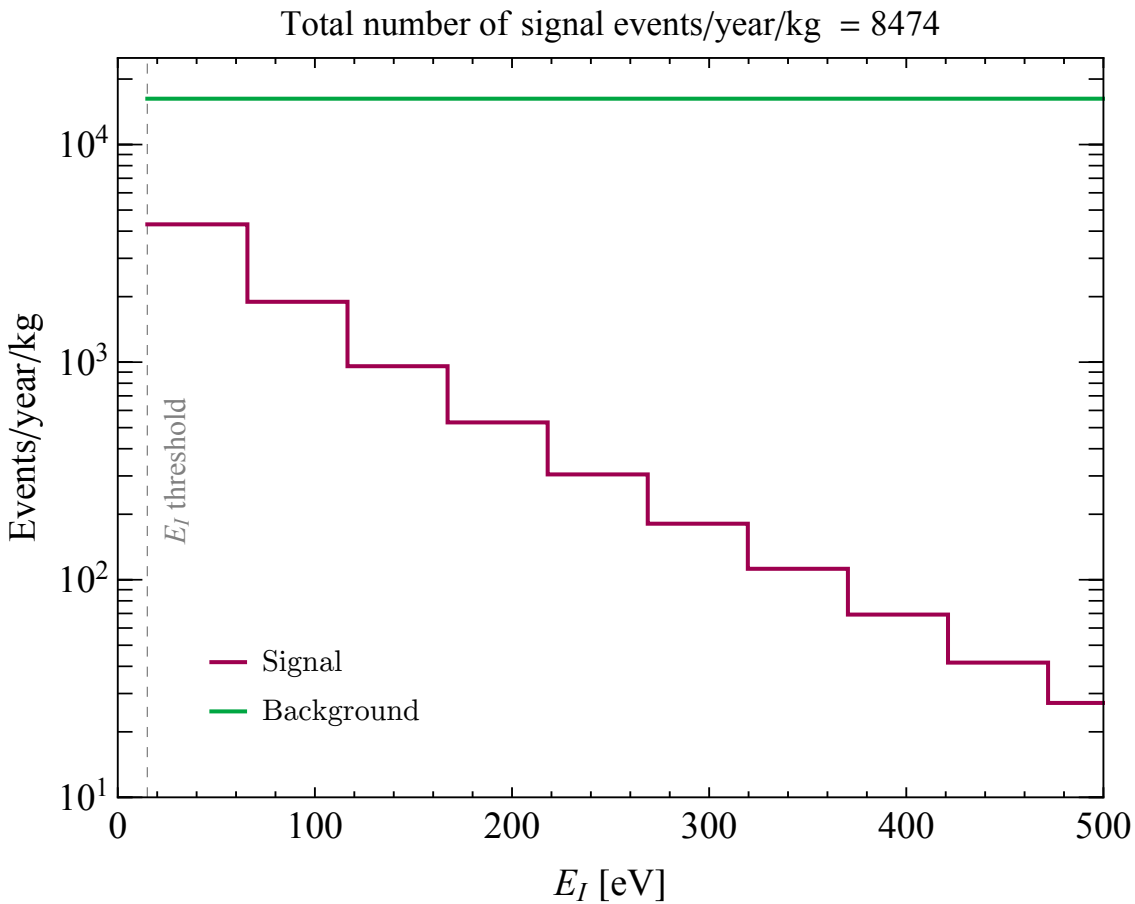


$$E_\nu^{\text{min}} = \frac{1}{2}\left(E_R + \sqrt{E_R^2 + 2E_R m_N}\right)$$
$$\simeq 1.1 \text{ MeV} \left(\frac{E_R}{100 \text{ eV}} \frac{m_N}{28 m_p}\right)^{1/2}$$

- Chavarria $\rightarrow E_\nu^{\text{min}} \sim 2$ MeV
- Lindhard $\rightarrow E_\nu^{\text{min}} \sim 1$ MeV

Expected event rate in vIOLETA

$$n_a = \frac{W}{\sum_{q'}(f_{q'}e_{q'})} \int_{\text{bin } a} dE_I \frac{1}{Q(E_I)} \left(1 - \frac{E_I}{Q(E_I)} \frac{dQ(E_I)}{dE_I}\right) \int dE_\nu \frac{d\phi_{\bar{\nu}_e}}{dE_\nu} \left.\frac{d\sigma_{\text{CE}\nu\text{NS}}}{dE_R}\right|_{E_R=E_I/Q(E_I}$$



Measuring the weak mixing angle

The sensitivity over the $\sin^2\theta_w$ is determined by the following χ^2

$$\chi^2 = (\mathbf{d}-\mathbf{t})^T \mathbf{C}^{-1} (\mathbf{d}-\mathbf{t}) + \sum_a^{\text{bins}} \underbrace{\left(\frac{\alpha_a^B}{\sigma_a^B}\right)^2}_{\text{Backg}} + \underbrace{\left(\frac{\alpha_W}{\sigma_W}\right)^2}_{\text{Power}} + \sum_q^{\text{isotopes}} \underbrace{\left(\frac{\alpha_q}{\sigma_q}\right)^2}_{\text{fission fraction}} + \underbrace{\left(\frac{\alpha_Q}{\sigma_Q}\right)^2}_{\text{Quenching}}$$

Asimov data: d ($\sin^2\theta_w = 0.238$) and t ($\sin^2\theta_w$)

$$\mathrm{t_a}, \mathrm{d_a} = \sum_{j,q} f_q n_{aj}^q + B_a$$

Covariance matrix accounting for the correlated systematics uncertainties in the **flux** and the statistical error

$$\mathbf{C}_{ab} = \sum_{ij}^{\text{energies}} \sum_{q}^{\text{isotopes}} n_{aj}^q n_{bi}^q \boxed{V_{ji}^q} + \mathrm{d}_a \delta_{ab}$$

Daya Bays flux covariance matrix

Measuring the weak mixing angle

The sensitivity over the $\sin^2\theta_w$ is determined by the following χ^2

$$\chi^2 = (\mathbf{d}-\mathbf{t})^T \mathbf{C}^{-1} (\mathbf{d}-\mathbf{t}) + \sum_{a}^{\text{bins}} \underbrace{\left(\frac{\alpha_a^B}{\sigma_a^B}\right)^2}_{\text{Backg}} + \underbrace{\left(\frac{\alpha_W}{\sigma_W}\right)^2}_{\text{Power}} + \sum_{q}^{\text{isotopes}} \underbrace{\left(\frac{\alpha_q}{\sigma_q}\right)^2}_{\text{fission fraction}} + \underbrace{\left(\frac{\alpha_Q}{\sigma_Q}\right)^2}_{\text{Quenching}}$$

- Independent normalization for each bin in the background

Uncertainties used in the analysis

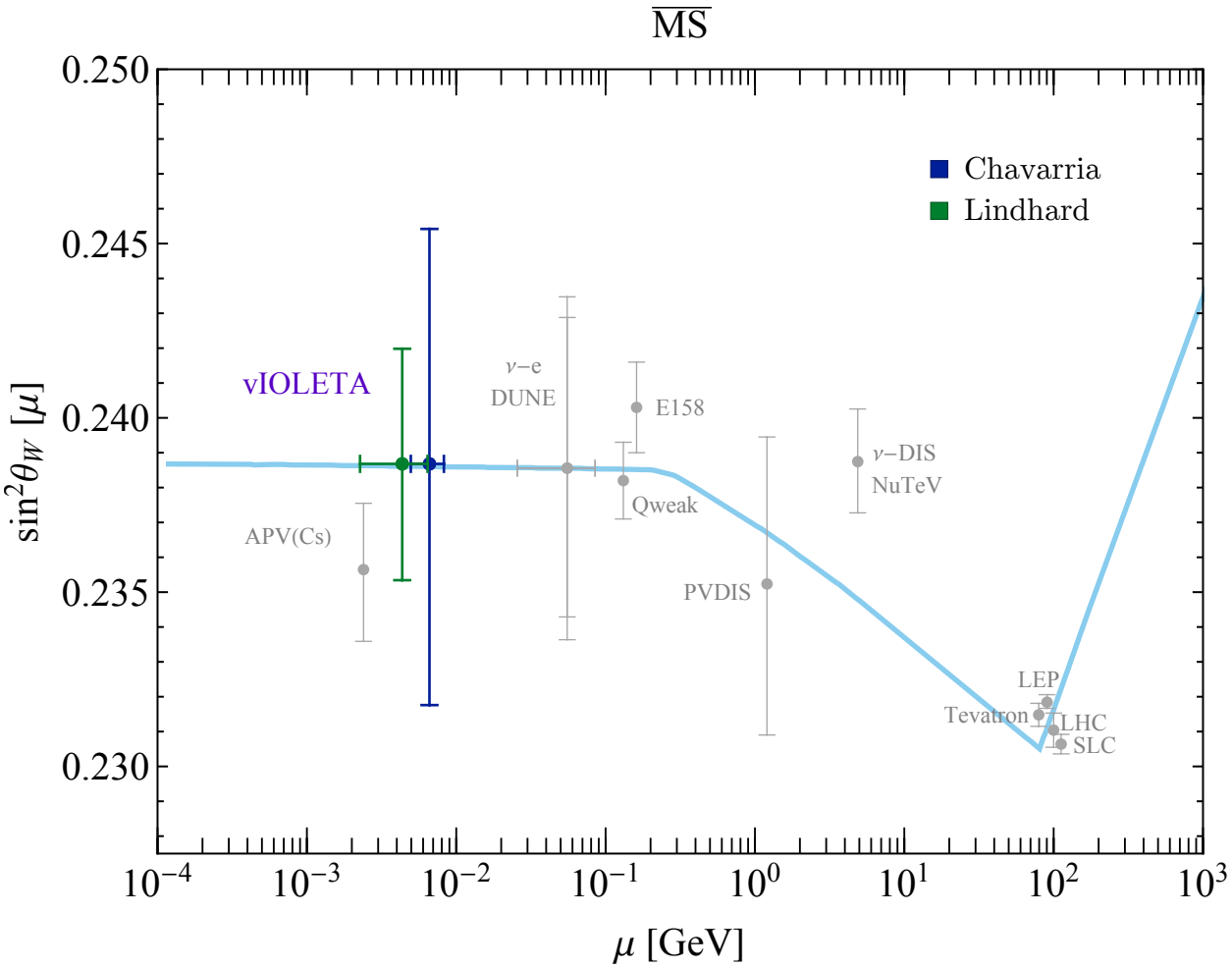
$\sigma_a^B = 1.2\%$

$\sigma_W = 0.5\%$

$\sigma_q = 5\%$

$\sigma_Q = (0-25)\%$

Measuring the weak mixing angle



DUNE can also measure $\sin^2\theta_w$ Phys.Rev.Lett. 125 (2020) 5, 051803

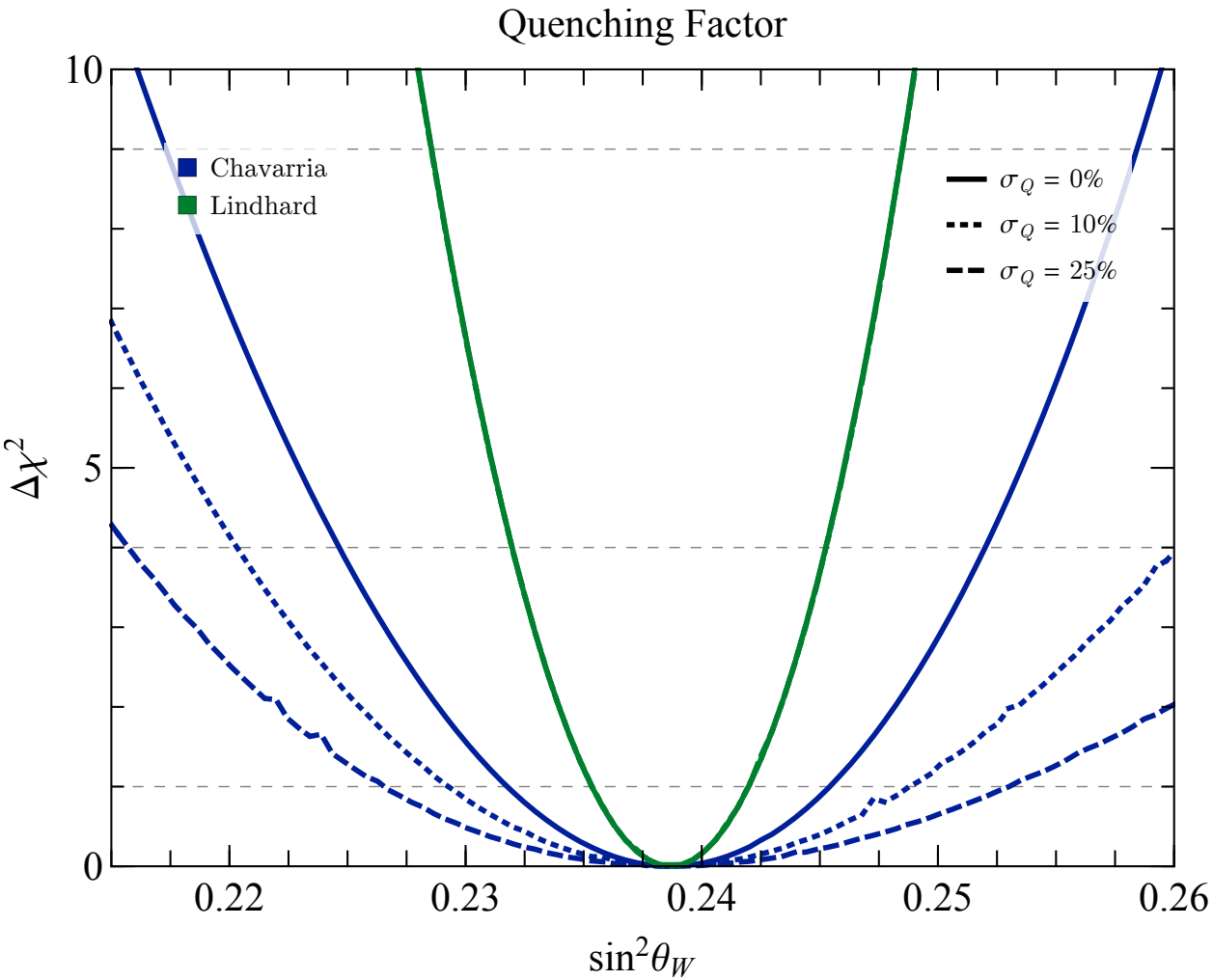
Detector configuration:

- Distance: 12 m
- Mass: 1 kg
- Reactor Power: 2 GW
- Time: 3 years
- Reactor-off: 45/days per year
- $\sigma_Q = 0\%$

$\delta \sin^2\theta_w \sim 1.4\%$ Linhard ($\langle Q^2 \rangle \sim 4.3$ MeV)
$\delta \sin^2\theta_w \sim 2.8\%$ Chavarria ($\langle Q^2 \rangle \sim 6.6$ MeV)

Measuring the weak mixing angle: Quenching factor dependence

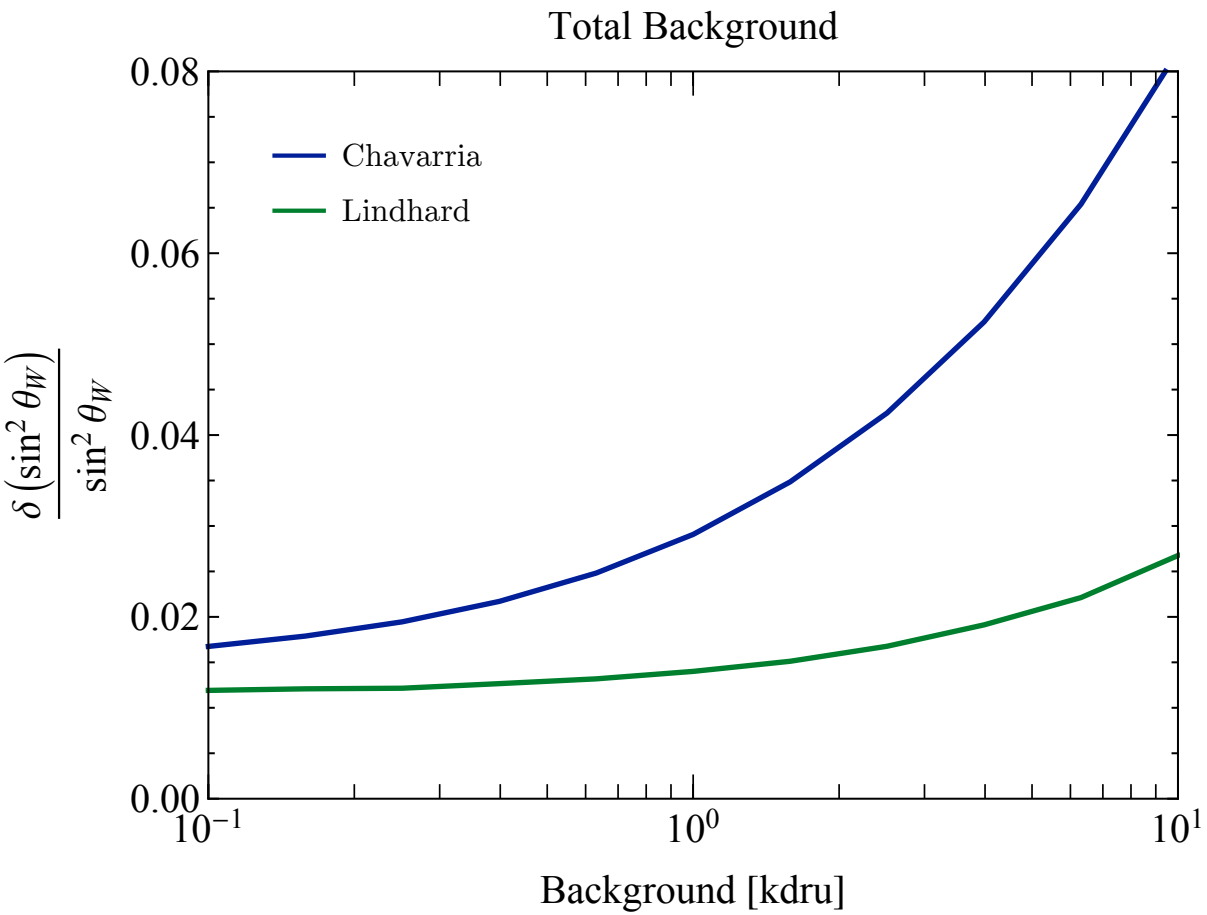
The Quenching factor uncertainty is parameterized by a normalization



$\Rightarrow$ Small dependence of Lindhard Quenching

Measuring the weak mixing angle: Background

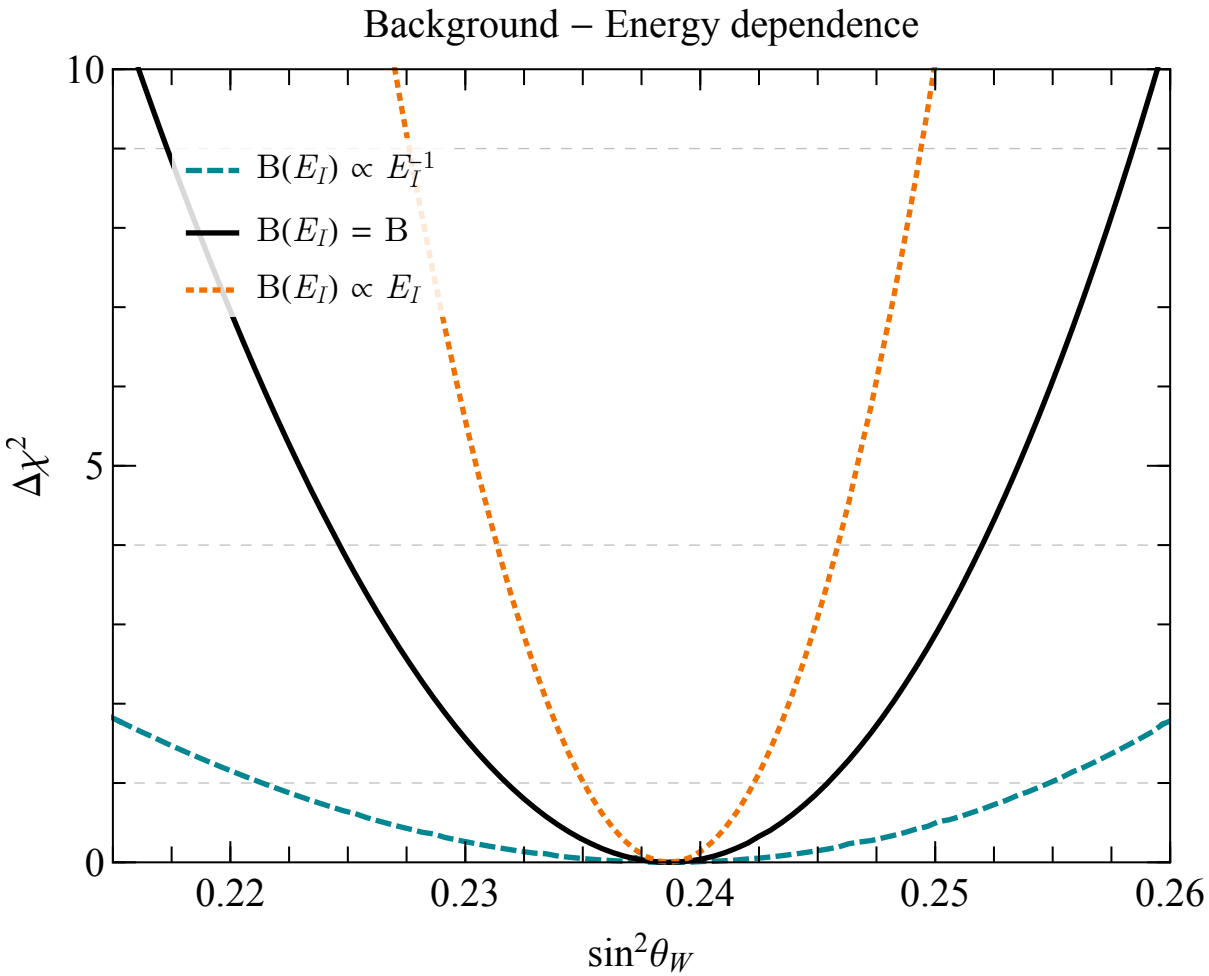
The sensitivity can be modified with the background rate



- The background is energy flat
- Larger impact for Chavarria due to the lower number of events.

Measuring the weak mixing angle: Background

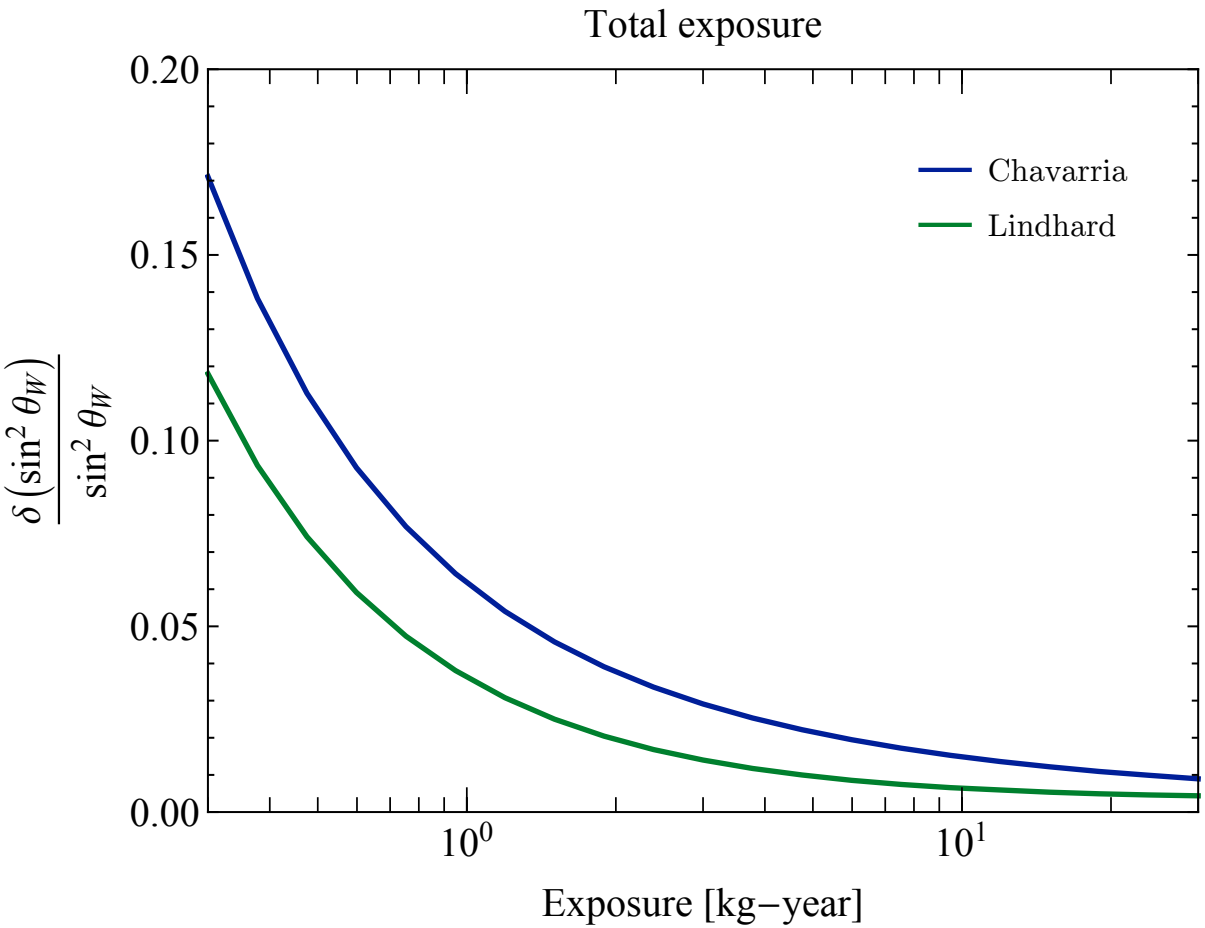
A different energy dependence of the background can also has an impact



- The background rate is 1kdru
- For Bkg $\sim E^{-1}$, the background is able to mimic the signal

Measuring the weak mixing angle: Exposure

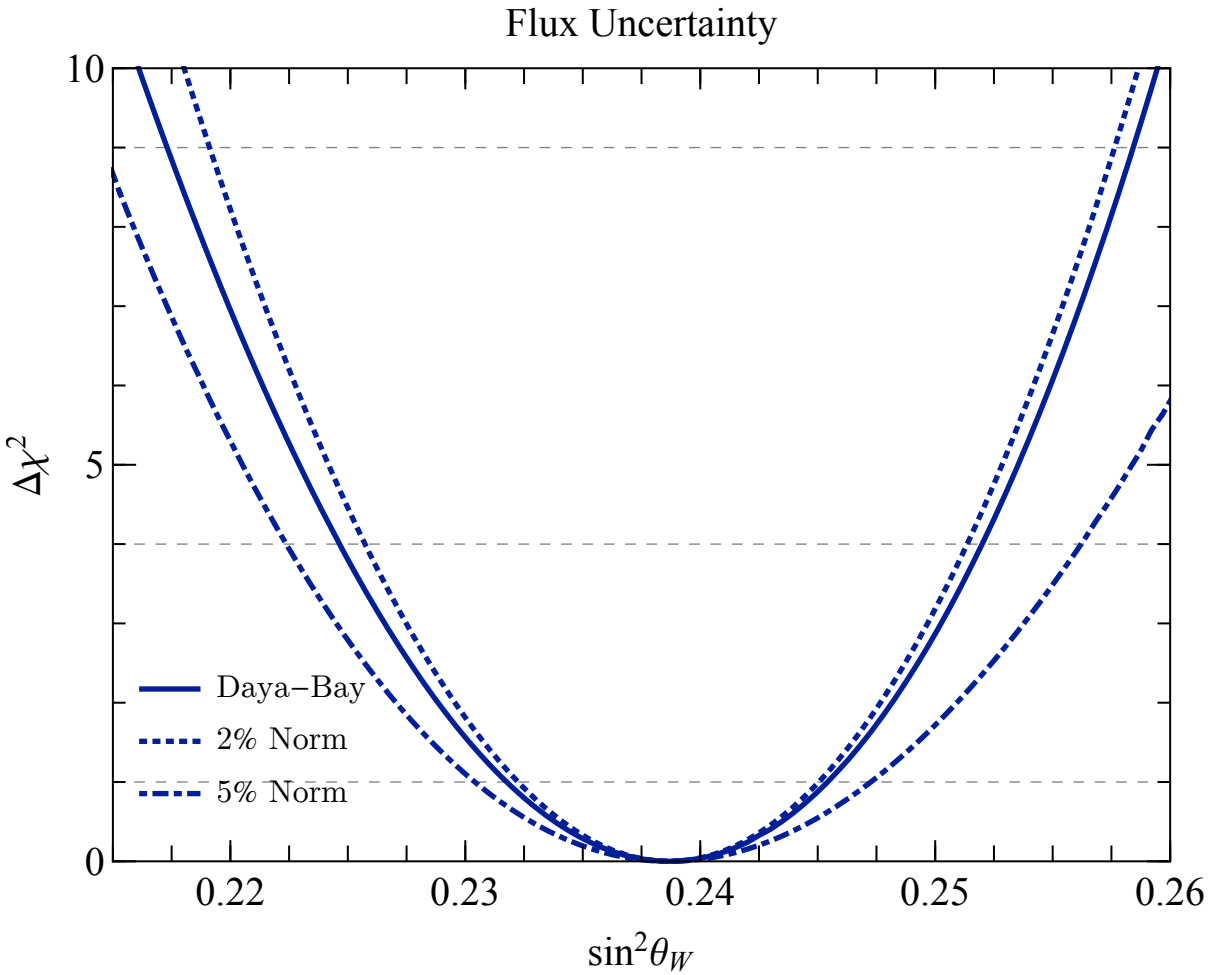
The sensitivity is not systematic limited



- The precision can be $< 1\%$ for a 10kg detector.

Measuring the weak mixing angle: Reactor flux uncertainty

The Daya Bay **covariance matrix** provides a sensitivity consistent with a **normalization uncertainty** between 2% and 5%



- The 2% and 5% normalization does not include the Daya Bay covariance matrix

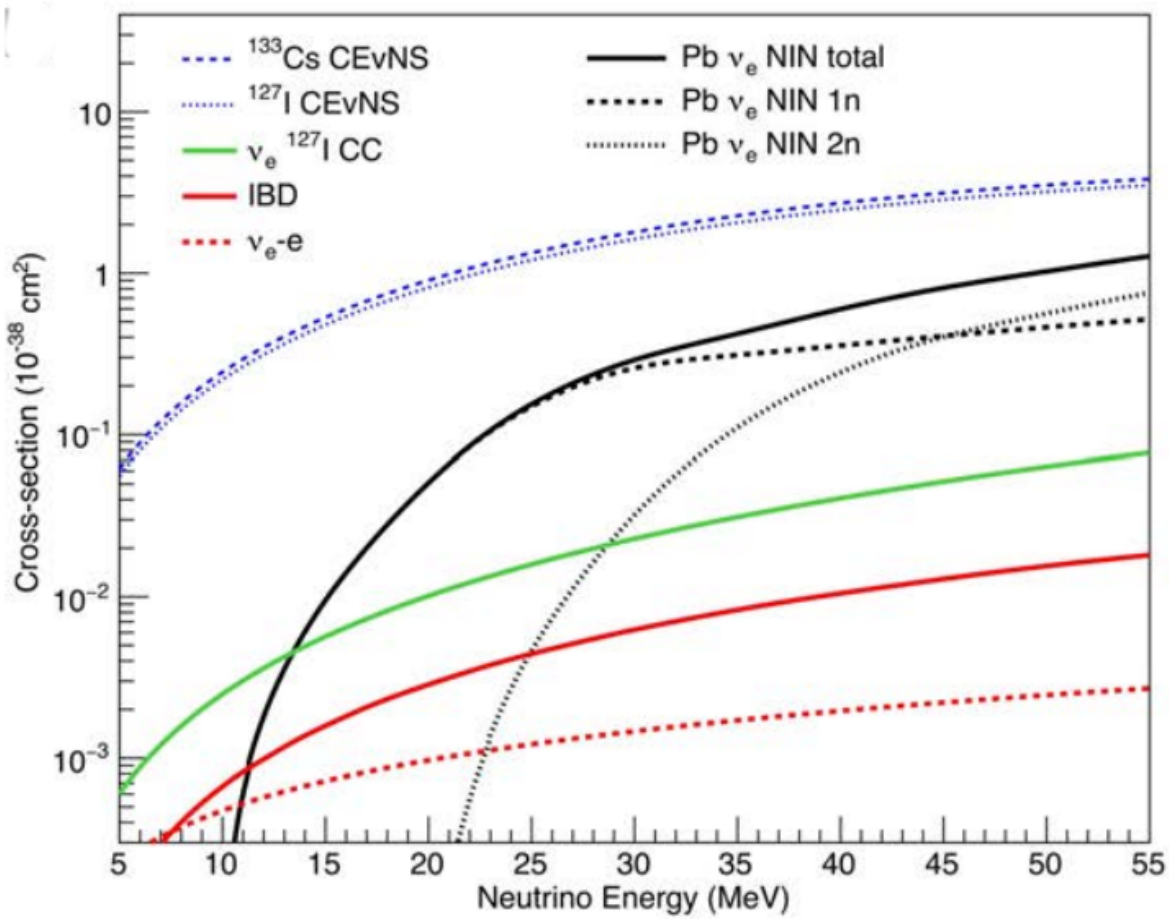
Conclusions

- We have explored the role of **CEvNS** in the measurement of the **weak mixing angle**.
- Nuclear reactors can probide a measurement of $\sin^2\theta_w$ at **very low momentum transfer** ($\sim \langle Q \rangle$ MeV).
- **vIOLETA** can measure $\delta \sin^2\theta_w \sim 2\%$
- The **Quenching factor** and the **background** are the main experimental drawbacks, we quantify their impact

Thank you!

Backup: Neutrino cross section at low energy

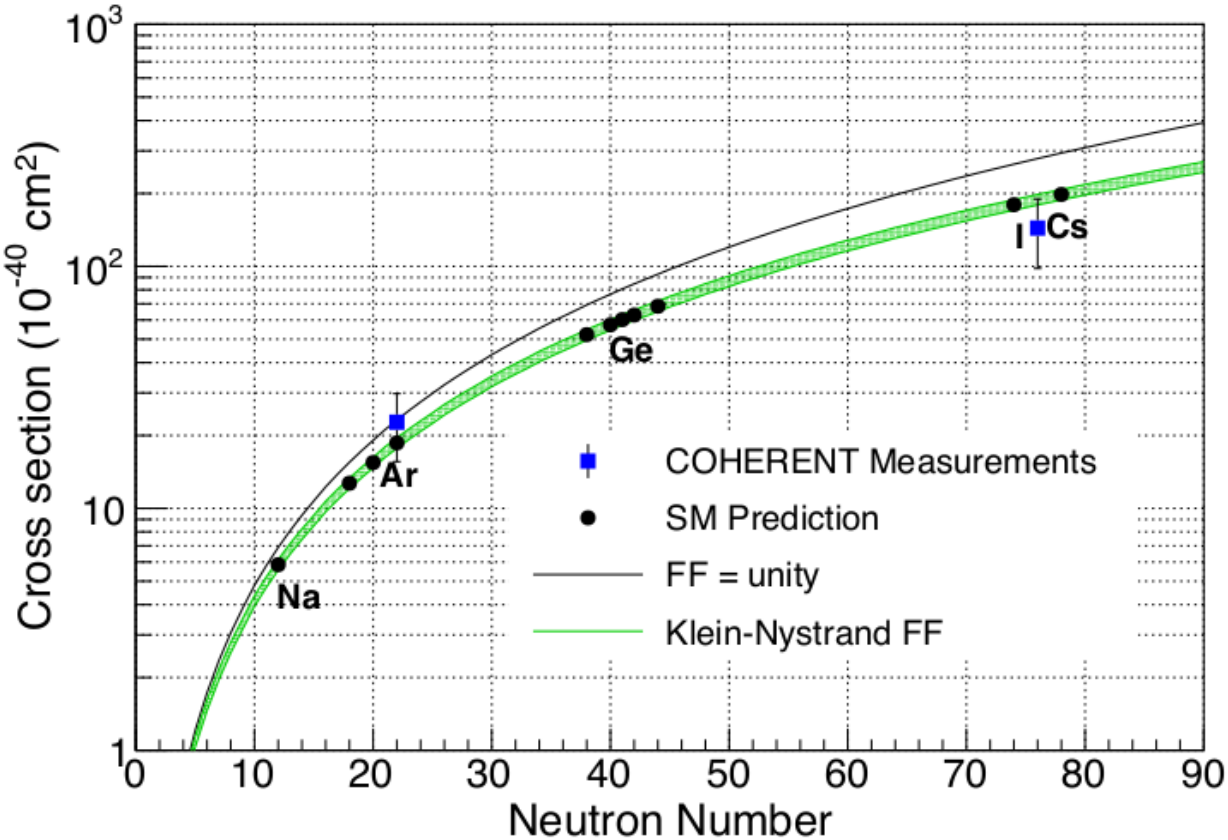
Comparison of neutrino cross section at low energy



COHERENT
Science 357 (2017) 6356
(1708.01294)

Coherent Elastic Scattering

Confirmation of N^2 dependence of the cross section



Jason Newby,
Neutrino 2020