Non-Standard neutrino Interactions and CEνNS

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IFIC, UV/CSIC

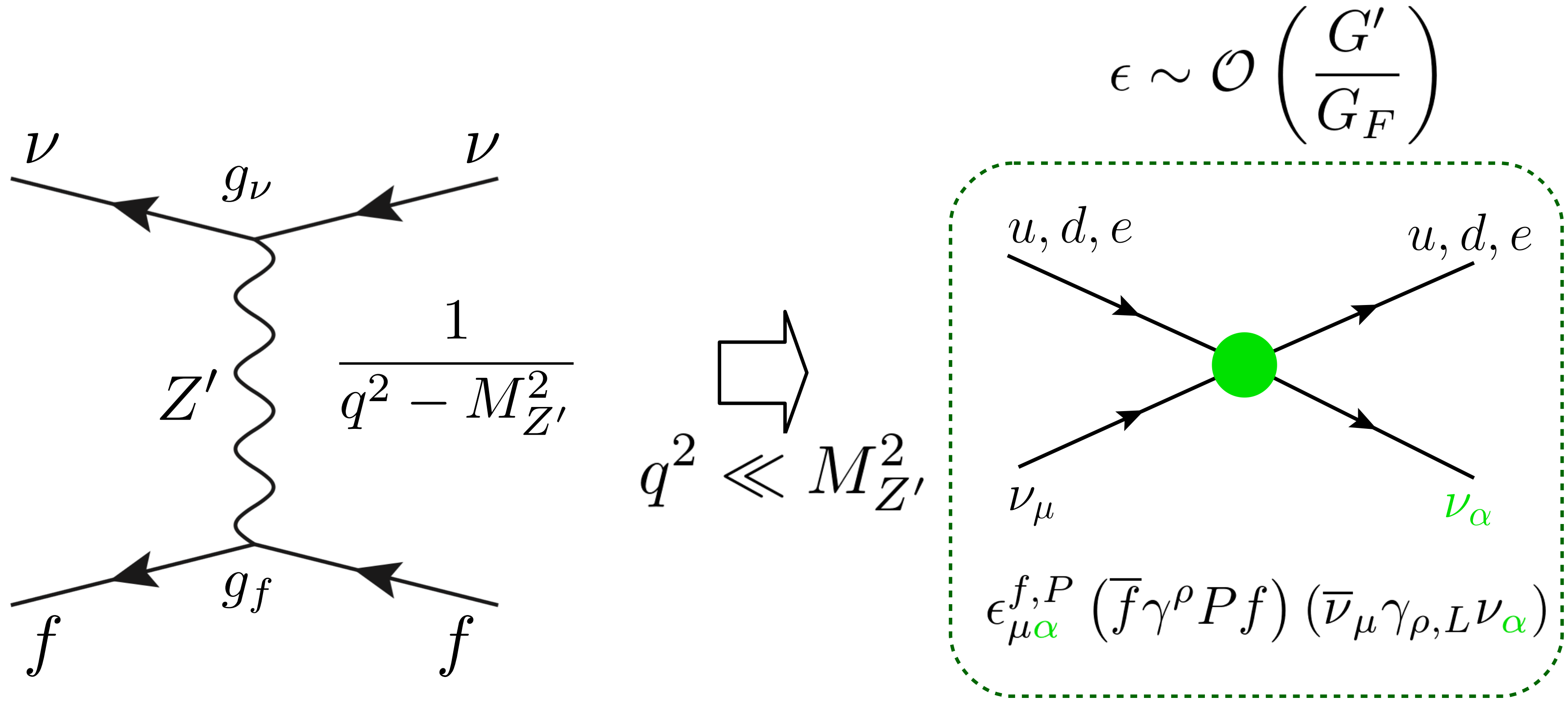
Based on:
Coloma, Gonzalez-Garcia, Maltoni, Schwetz, 1708.02899
Baxter et al, 1911.00762
and Coloma, Esteban, Gonzalez-Garcia, Maltoni, 1911.xxxxx

Magnificent CEnuNS workshop
Chapel Hill, Nov 9th 2019

Outline

- Introduction, NSI in oscillations
- NSI in CEνNS
- Updates using timing and energy information
- Outlook

Introduction



$$\frac{1}{q^2 - M_{Z'}^2}$$

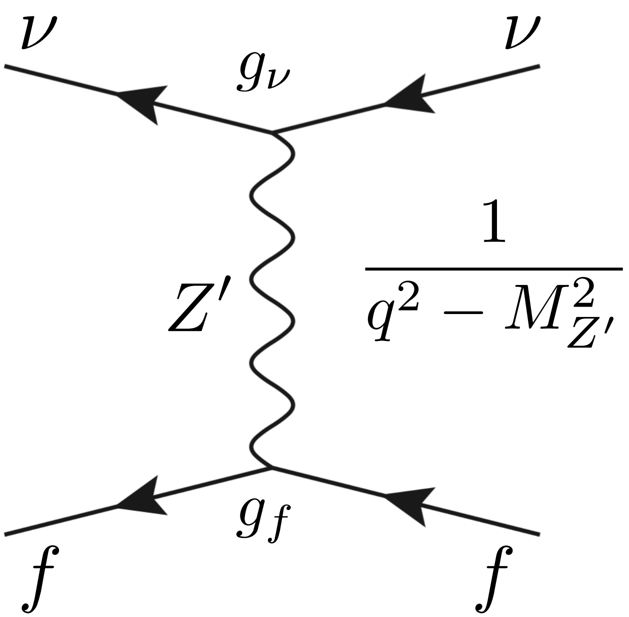
$$q^2 \ll M_{Z'}^2$$

$$\epsilon \sim \mathcal{O}\left(\frac{G'}{G_F}\right)$$

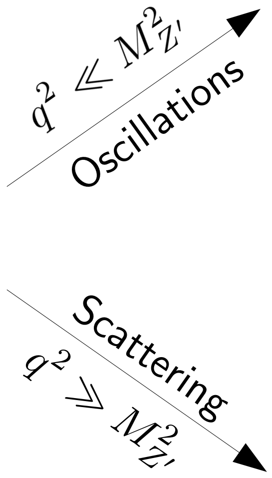
$$\epsilon_{\mu\alpha}^{f,P}\left(\overline{f}\gamma^\rho P f\right)\left(\overline{\nu}_\mu \gamma_{\rho,L}\nu_\alpha\right)$$

→ Only NSI with quarks in this talk, and only neutral-current

Heavy vs light NSI mediators



$$\frac{1}{q^2 - M_{Z'}^2}$$



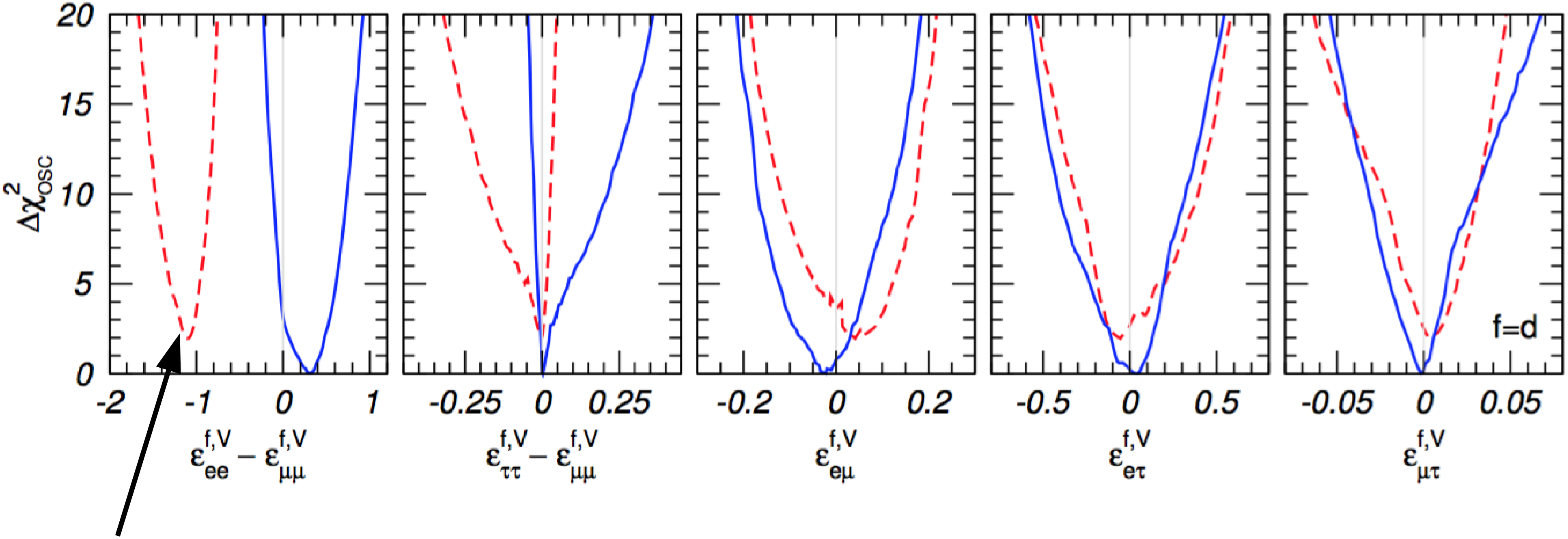
$$\sigma \propto \epsilon \sim \frac{g_f g_\nu}{M_{Z'}^2}$$

$$\sigma \propto \frac{g_f g_\nu}{q^2} \sim \epsilon \frac{M_{Z'}^2}{q^2}$$

→ We can distinguish between two classes of NSI models: “heavy” mediators (above 1 GeV) and “light” mediators (above 10 MeV)

NSI in oscillations

Figure from Gonzalez-Garcia and Maltoni, 1307.3092
See also Esteban et al, 1805.04530



LMA-dark
solution

Miranda, Tortola, Valle,
hep-ph/0406280

$$V_{\rm mat} = \sqrt{2} G_F N_e(x) \begin{pmatrix} 1 + (\epsilon_{ee} - \epsilon_{\mu\mu}) & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & 0 & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & (\epsilon_{\tau\tau} - \epsilon_{\mu\mu}) \end{pmatrix}$$

Generalized mass ordering degeneracy

$$H \to -H^*$$

$$\boxed{\begin{array}{l} \Delta m^2_{31} \to -\Delta m^2_{31} + \Delta m^2_{21} \\ \sin\theta_{12} \leftrightarrow \cos\theta_{12} \\ \delta \to \pi - \delta \\ \hdashline \epsilon_{ee} - \epsilon_{\mu\mu} \to -(\epsilon_{ee} - \epsilon_{\mu\mu}) - 2 \\ \epsilon_{\tau\tau} - \epsilon_{\mu\mu} \to -(\epsilon_{\tau\tau} - \epsilon_{\mu\mu}) \\ \epsilon_{\alpha\beta} \to -\epsilon^*_{\alpha\beta} \quad (\alpha \neq \beta) \end{array}}$$

The oscillation pattern is invariant under transformations that change the Hamiltonian as H → -H*

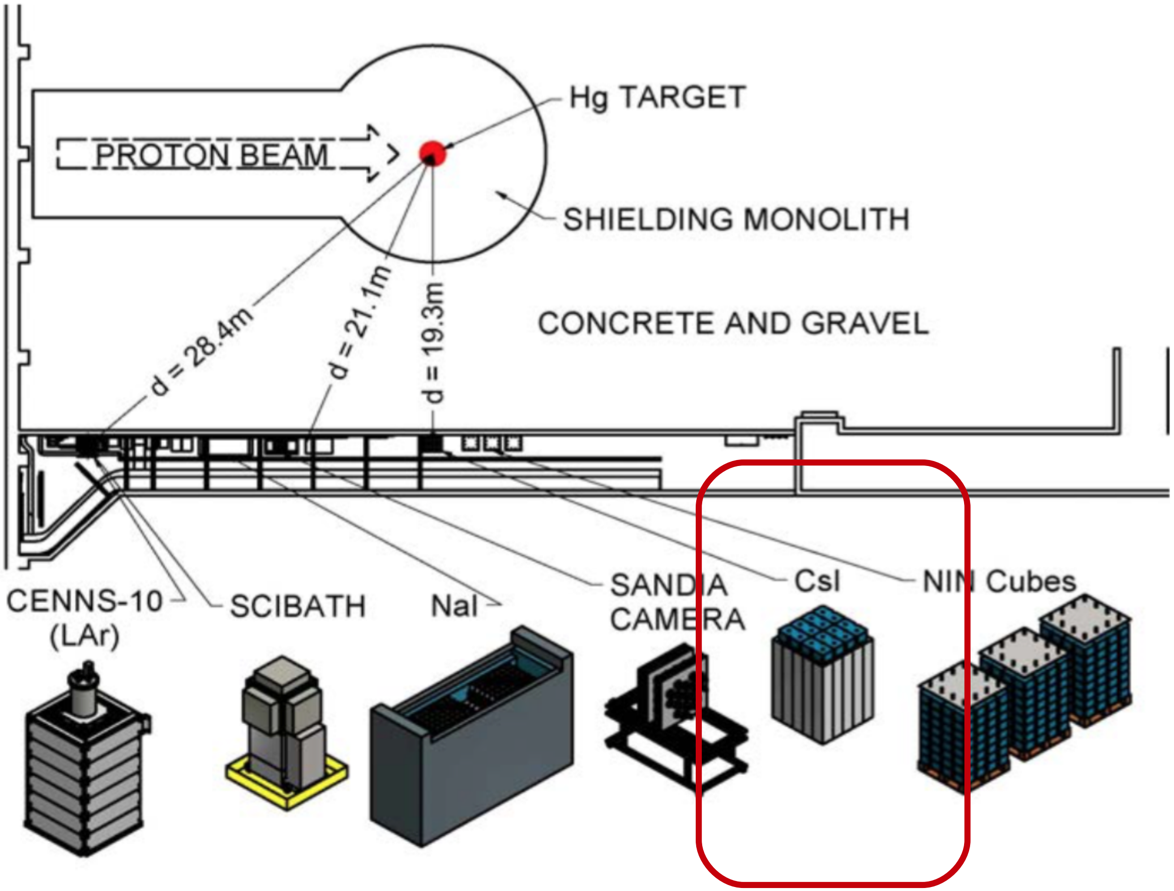
PC and Schwetz, 1604.05772
Bakhti and Farzan, 1403.0744
Gonzalez-Garcia and Maltoni, 1307.3092

At a given experiment, this is exact

NSI in coherent scattering

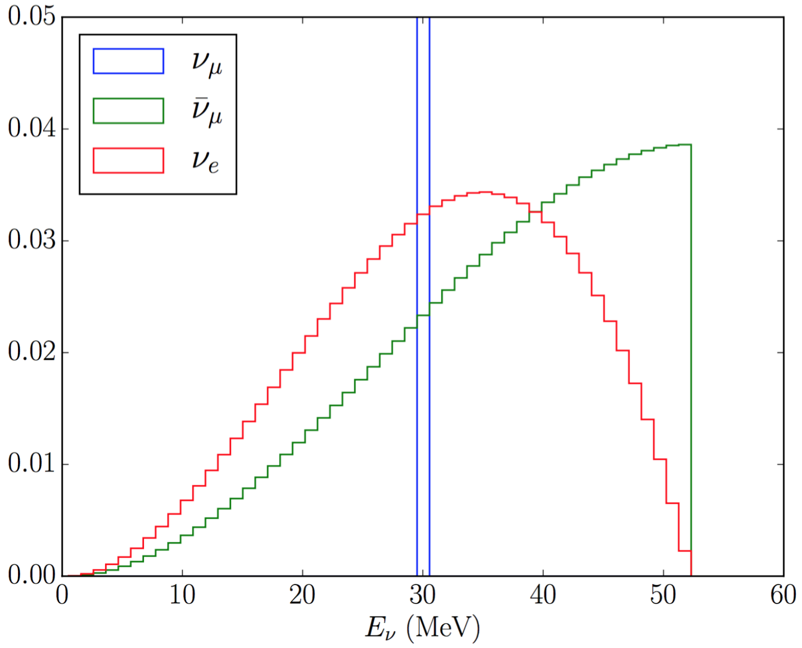
COHERENT

The Spallation Neutron Source generates the most intense pulsed neutron beam in the world, produced by the interactions of 1 GeV protons striking a mercury target



$$\pi^+ \to \mu^+ \nu_\mu$$

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

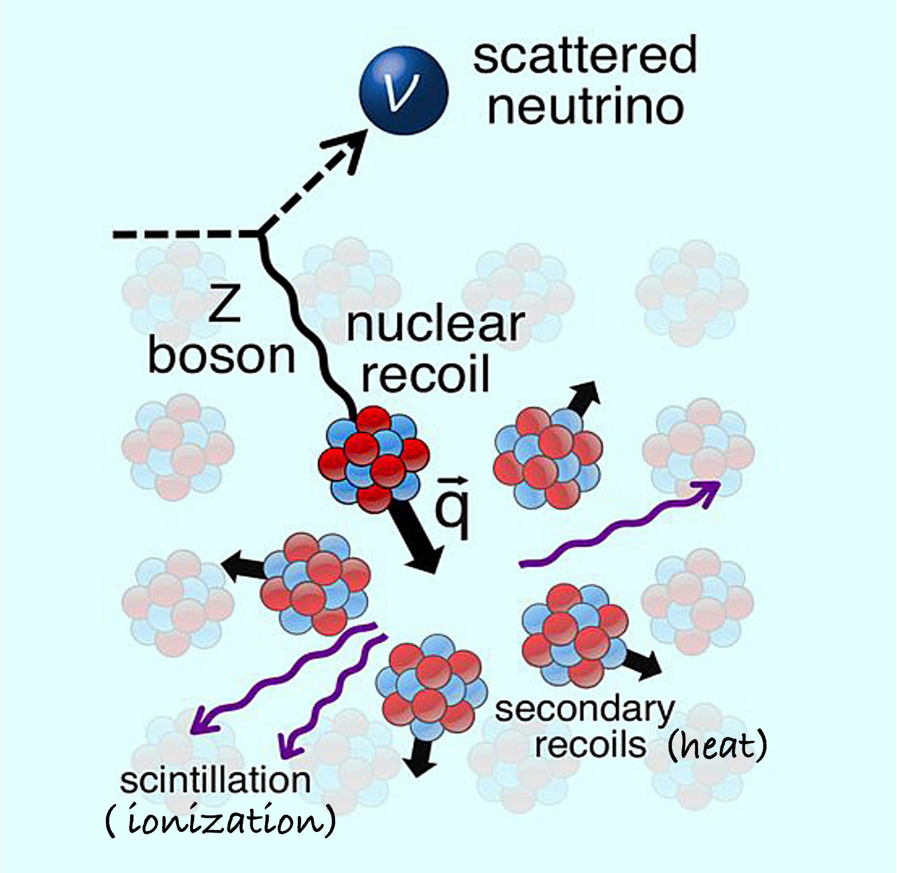


COHERENTresults: 1708.01294, 1909.05913

Coherent elastic scattering on nuclei

$$\frac{d\sigma}{dE_r} = \frac{G_F^2}{2\pi}\frac{\mathcal{Q}^2}{4}F^2(2ME_r)M\left(2 - \frac{ME_r}{E_\nu^2}\right)$$

$$\frac{\mathcal{Q}^2}{4} = \left[Zg_p^V + Ng_n^V\right]^2$$



For neutrinos at/below 50 MeV, coherence condition(q < 1/R) satisfied for a medium size nucleus (Ar, Ge, ... Cs, Xe)

Although predicted in 1974, it has not been observed until 2017!

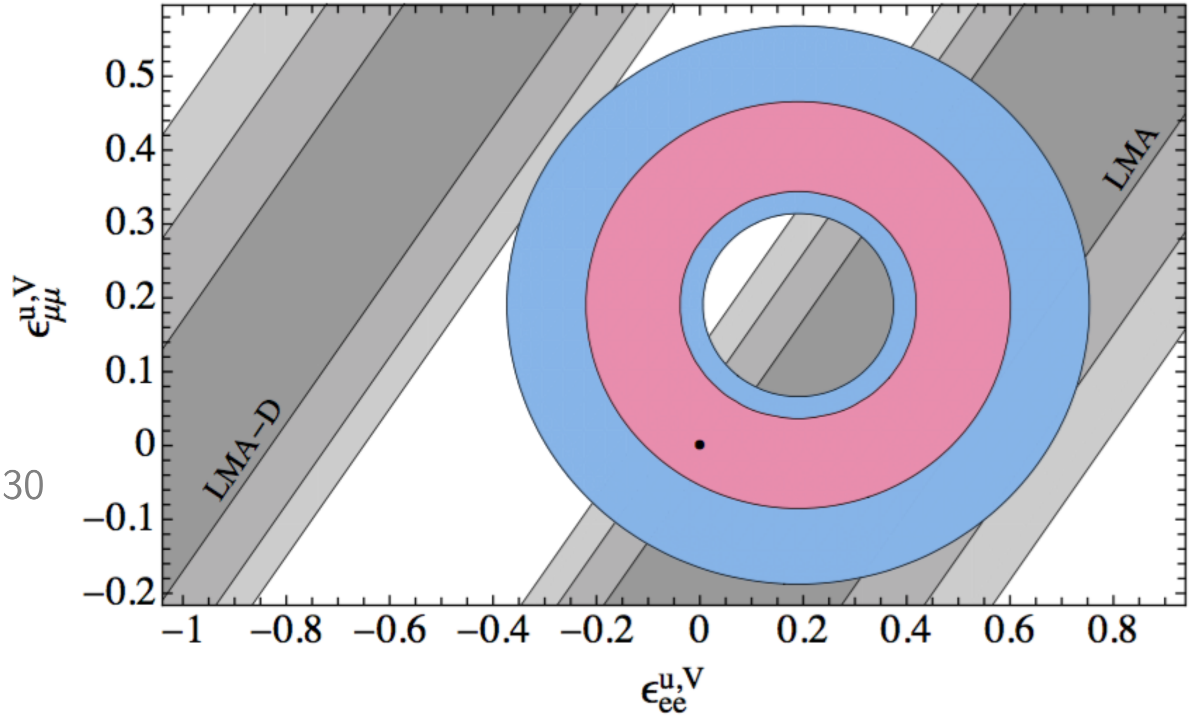
Freedman et al, PRD9 (1974) 1389

CEvNS in presence of NSI

$$\frac{\mathcal{Q}^2}{4} \rightarrow \quad \frac{\mathcal{Q}^2_\alpha(\varepsilon)}{4} = \left[Z(g_p^V + 2\epsilon^{u,V}_{\alpha\alpha} + \epsilon^{d,V}_{\alpha\alpha}) + N(g_n^V + \epsilon^{u,V}_{\alpha\alpha} + 2\epsilon^{d,V}_{\alpha\alpha})\right]^2 +$$

$$+ \sum_{\beta\neq\alpha} \left[Z(2\epsilon^{u,V}_{\alpha\beta} + \epsilon^{d,V}_{\alpha\beta}) + N(\epsilon^{u,V}_{\alpha\beta} + 2\epsilon^{d,V}_{\alpha\beta})\right]^2$$

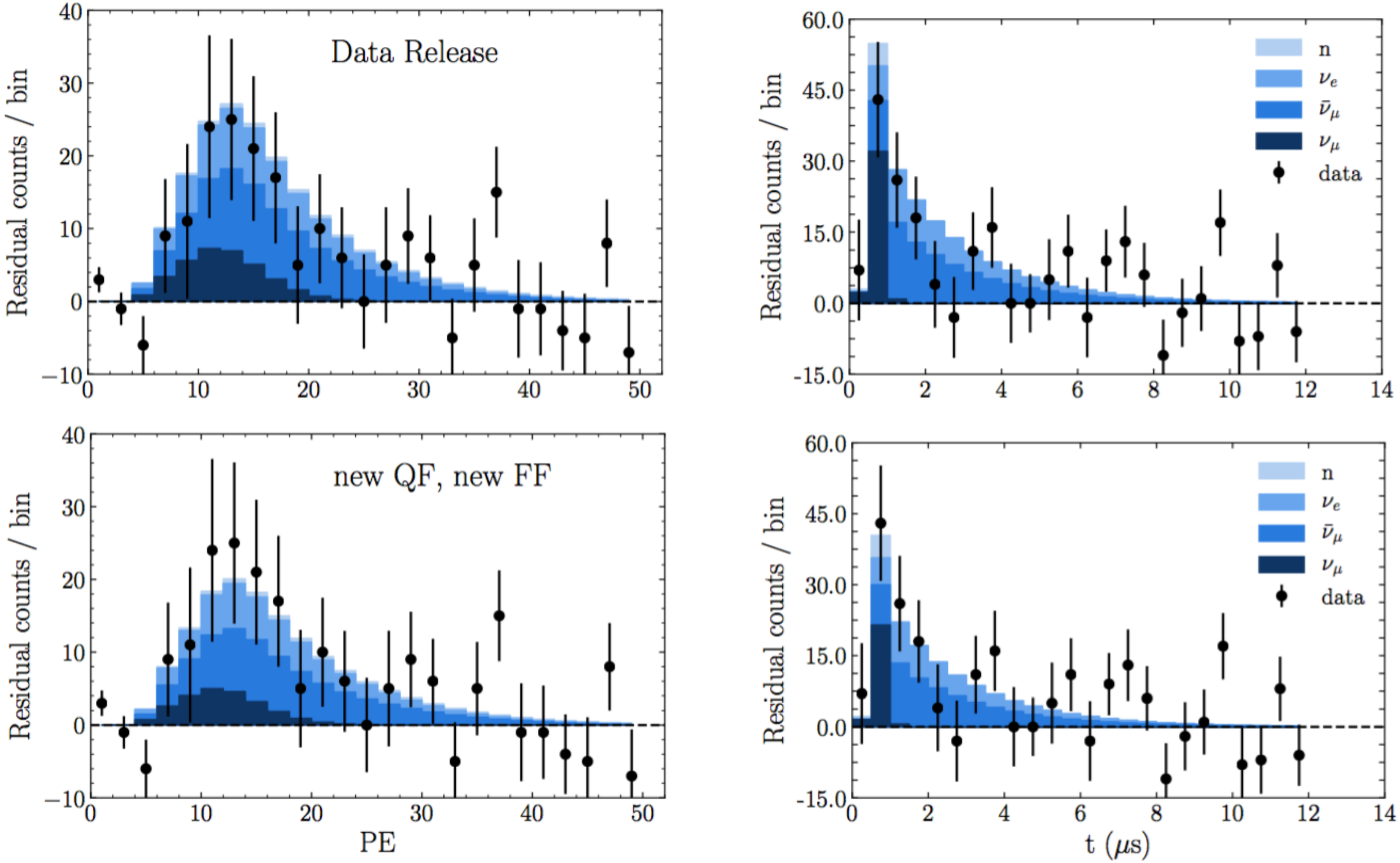
Coloma, Gonzalez-Garcia, Maltoni, Schwetz, 1708.02899



See also, e.g.: Esteban et al, 1805.04530
Cadeddu et al, 1908.06045
Kahn and Rodejohann, 1907.12444
Papoulias, 1907.11644

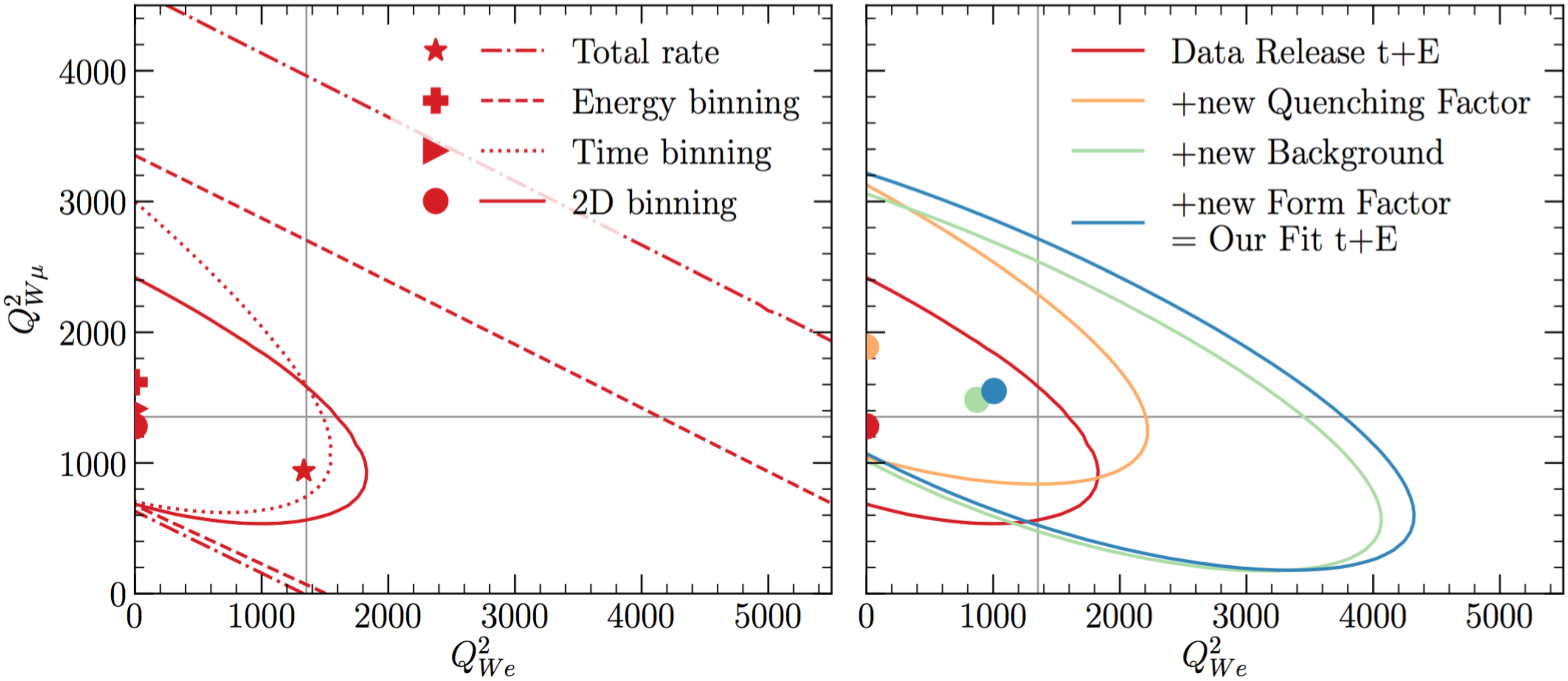
Updates with timing information

Predicted events in 2D



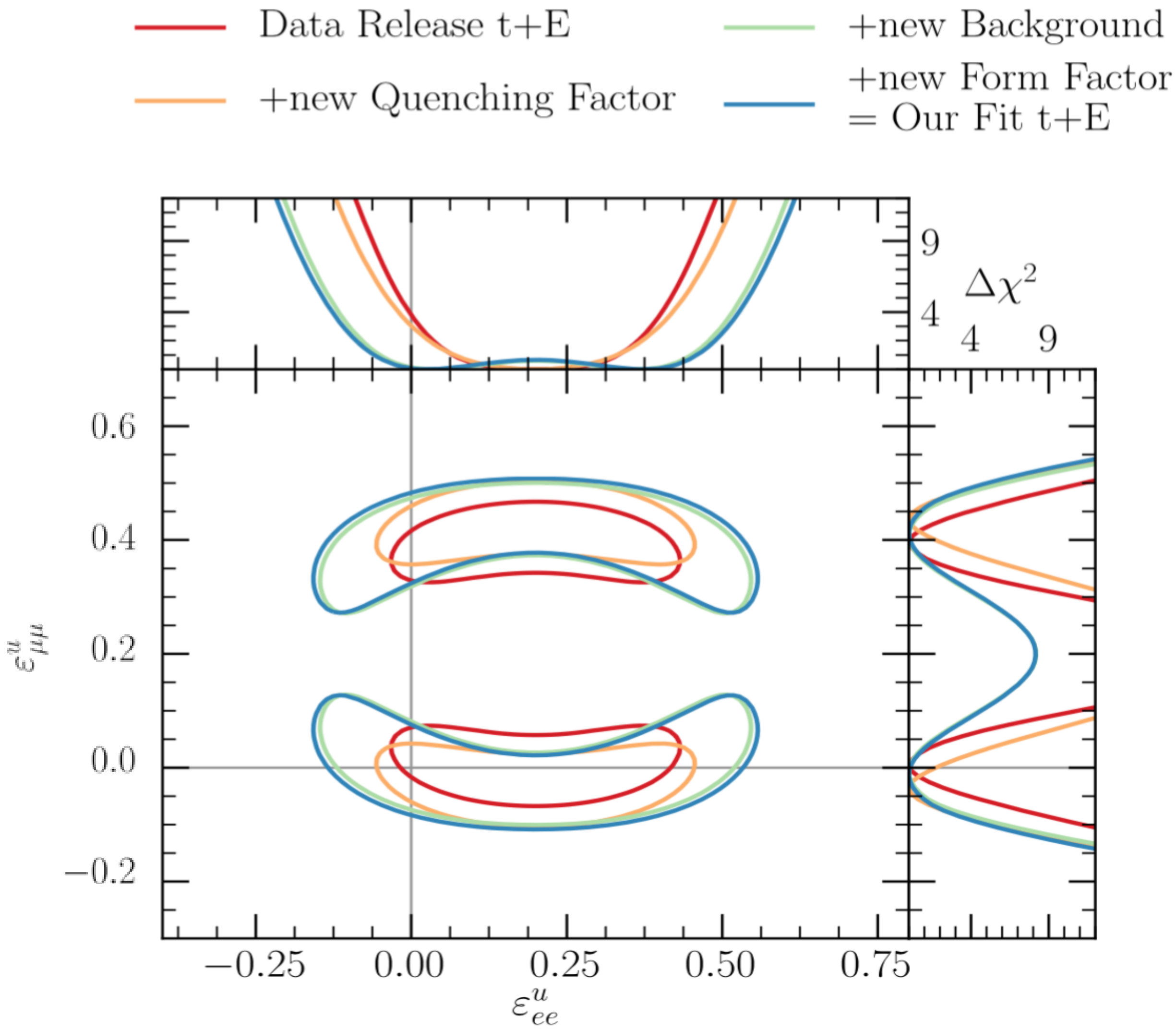
Coloma, Esteban, Gonzalez-Garcia, Maltoni, 1911.xxxxx

Updated results



Coloma, Esteban, Gonzalez-Garcia, Maltoni, 1911.xxxxx

Impact of QF, FF, and bg



Coloma, Esteban, Gonzalez-Garcia, Maltoni, 1911.xxxxx

Arbitrary NSI with quarks

Let's focus on NSI with quarks only:

$$\mathcal{O}_{\alpha\beta}^{\mathrm{NSI}} = -2\sqrt{2}G_F \sum_{q,P} \epsilon_{\alpha\beta}^{qP} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{q}\gamma_\mu P q)$$

Assuming* that $\epsilon_{\alpha\beta}^{q,P} = \xi^{q,P}(\eta)\epsilon_{\alpha\beta}^{\eta}$

then:

$$\mathcal{O}_{\alpha\beta}^{\mathrm{NSI}} = -2\sqrt{2}G_F \epsilon_{\alpha\beta}^{\eta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) \sum_{q,P} \xi^{q,P} (\bar{q}\gamma_\mu P q)$$

where η determines the ratio between the strength of the coupling between up and down quarks

*Remember: $\epsilon^f \sim \frac{g_f g_\nu}{M_{Z'}^2}$

Arbitrary NSI models

In oscillations, we are sensitive to combinations of NSI with different quarks:

$$\epsilon(x) = \epsilon^{\eta}\left(\xi^{p}(\eta) + Y_n(x)\xi^{n}(\eta)\right)$$

While in COHERENT, with a CsI target:

$$\epsilon^{\mathrm{coh}} = \epsilon^{\eta}\left(\xi^{p}(\eta) + Y_n^{\mathrm{CsI}}\xi^{n}(\eta)\right)$$

In our parametrization, we choose:

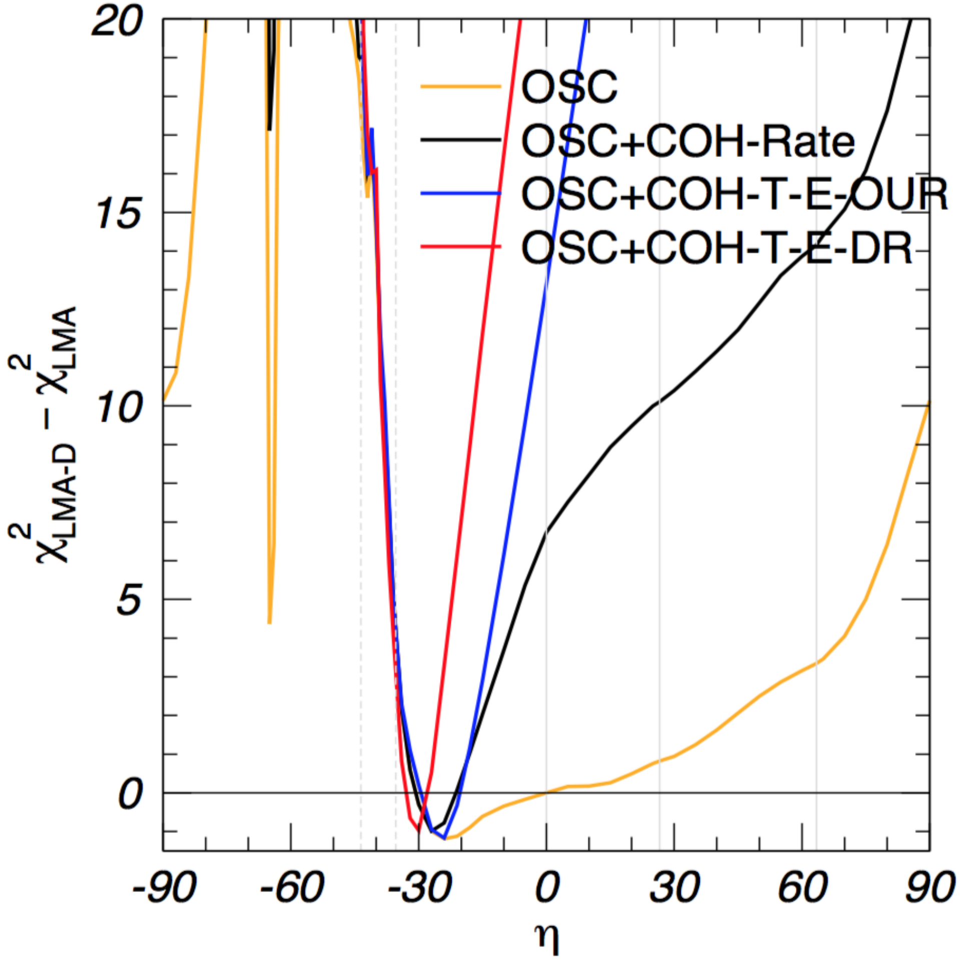
$$\xi^{p}(\eta) = \sqrt{5}\cos\eta$$

$$\xi^{n}(\eta) = \sqrt{5}\sin\eta$$

$\eta = 0 \Rightarrow$ NSI with p only

$\eta = 90^{\circ} \Rightarrow$ NSI with n only

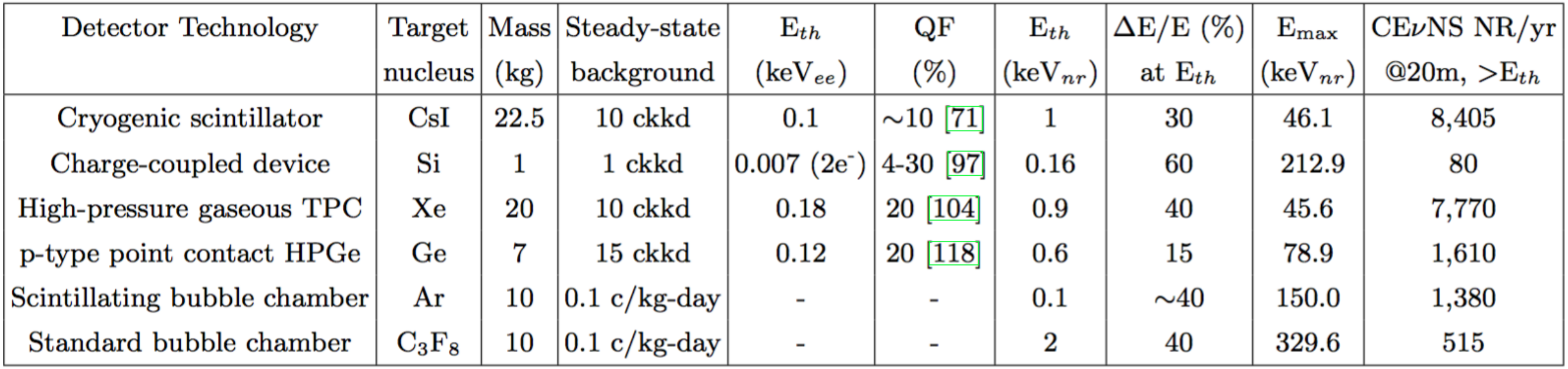
Rejection of LMA-Dark solution



Coloma, Esteban, Gonzalez-Garcia, Maltoni, 1911.xxxxx
(see also Esteban et al 1805.04530)

Looking ahead...

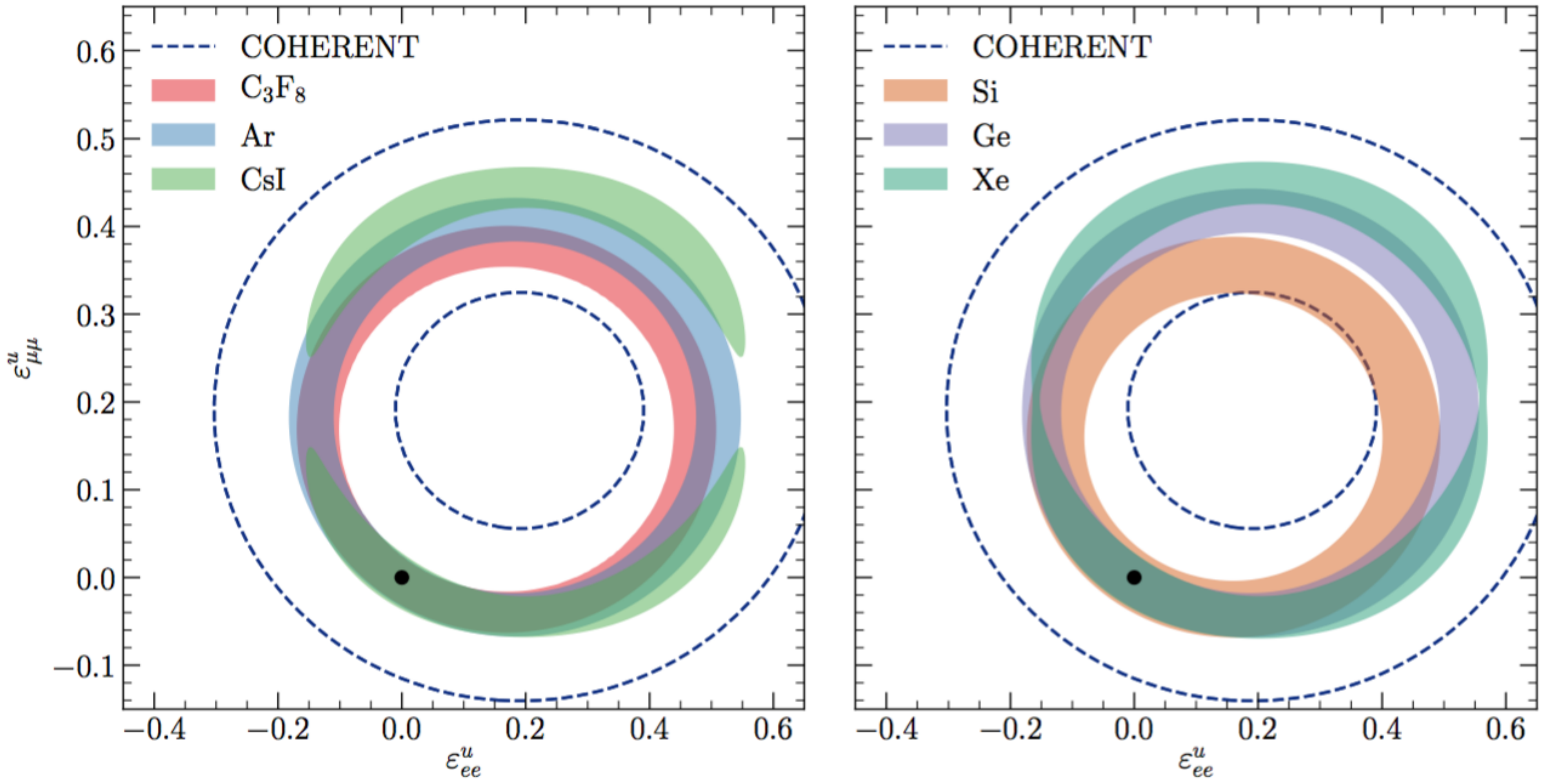
Low threshold detectors



Detector Technology	Target nucleus	Mass (kg)	Steady-state background	E_{th} (keV_{ee})	QF (%)	E_{th} (keV_{nr})	$\Delta E/E$ (%) at E_{th}	E_{max} (keV_{nr})	CEνNS NR/yr @20m, $>E_{th}$
Cryogenic scintillator	CsI	22.5	10 ckkd	0.1	∼10 [71]	1	30	46.1	8,405
Charge-coupled device	Si	1	1 ckkd	0.007 ($2e^-$)	4-30 [97]	0.16	60	212.9	80
High-pressure gaseous TPC	Xe	20	10 ckkd	0.18	20 [104]	0.9	40	45.6	7,770
p-type point contact HPGe	Ge	7	15 ckkd	0.12	20 [118]	0.6	15	78.9	1,610
Scintillating bubble chamber	Ar	10	0.1 c/kg-day	-	-	0.1	∼40	150.0	1,380
Standard bubble chamber	C_3F_8	10	0.1 c/kg-day	-	-	2	40	329.6	515

Baxter et al, 1911.00762

European Spallation Source



Baxter et al, 1911.00762

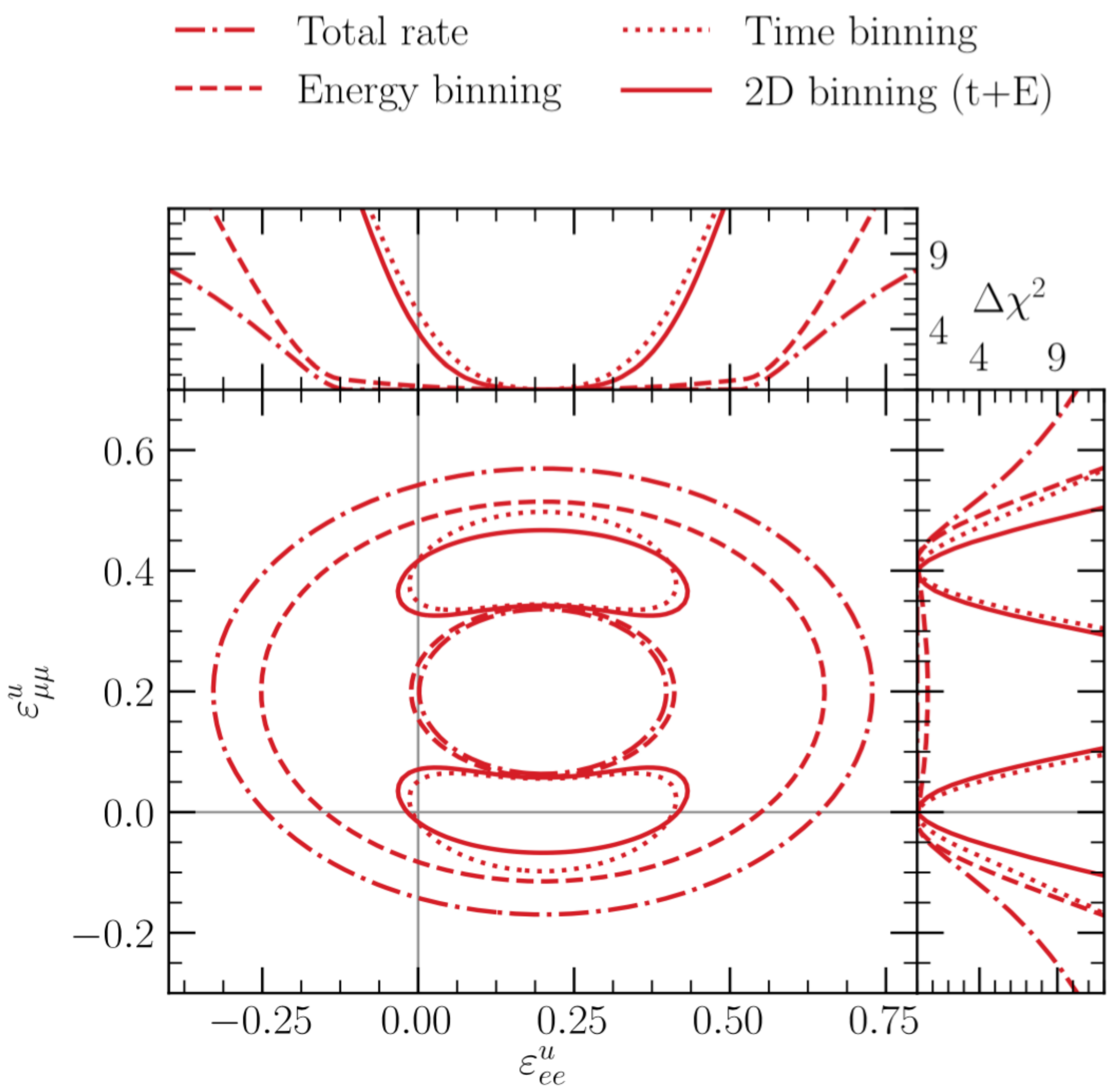
Summary

- New physics may be weakly interacting, and hiding at low scales
- COHERENT is already probing new part of parameter space allowed for NSI:
  - LMA dark is already ruled out for a large number of NSI models
  - The addition of timing data is crucial to get the full potential of the measurement
- Future data: exciting prospects at both SNS and ESS!

Thank you!!

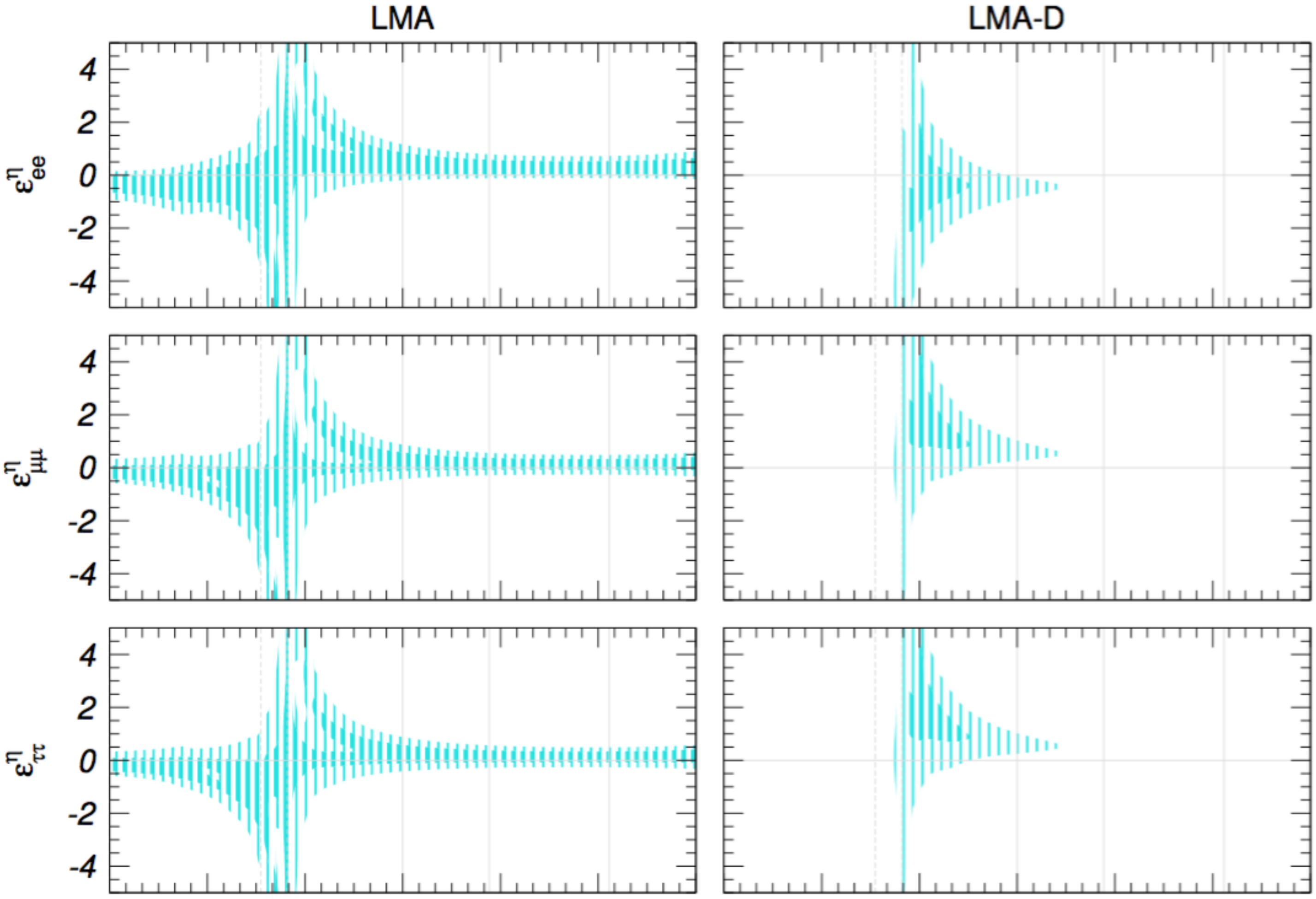
Backup slides

Impact of timing info



Coloma, Esteban, Gonzalez-Garcia, Maltoni, 1911.xxxxx

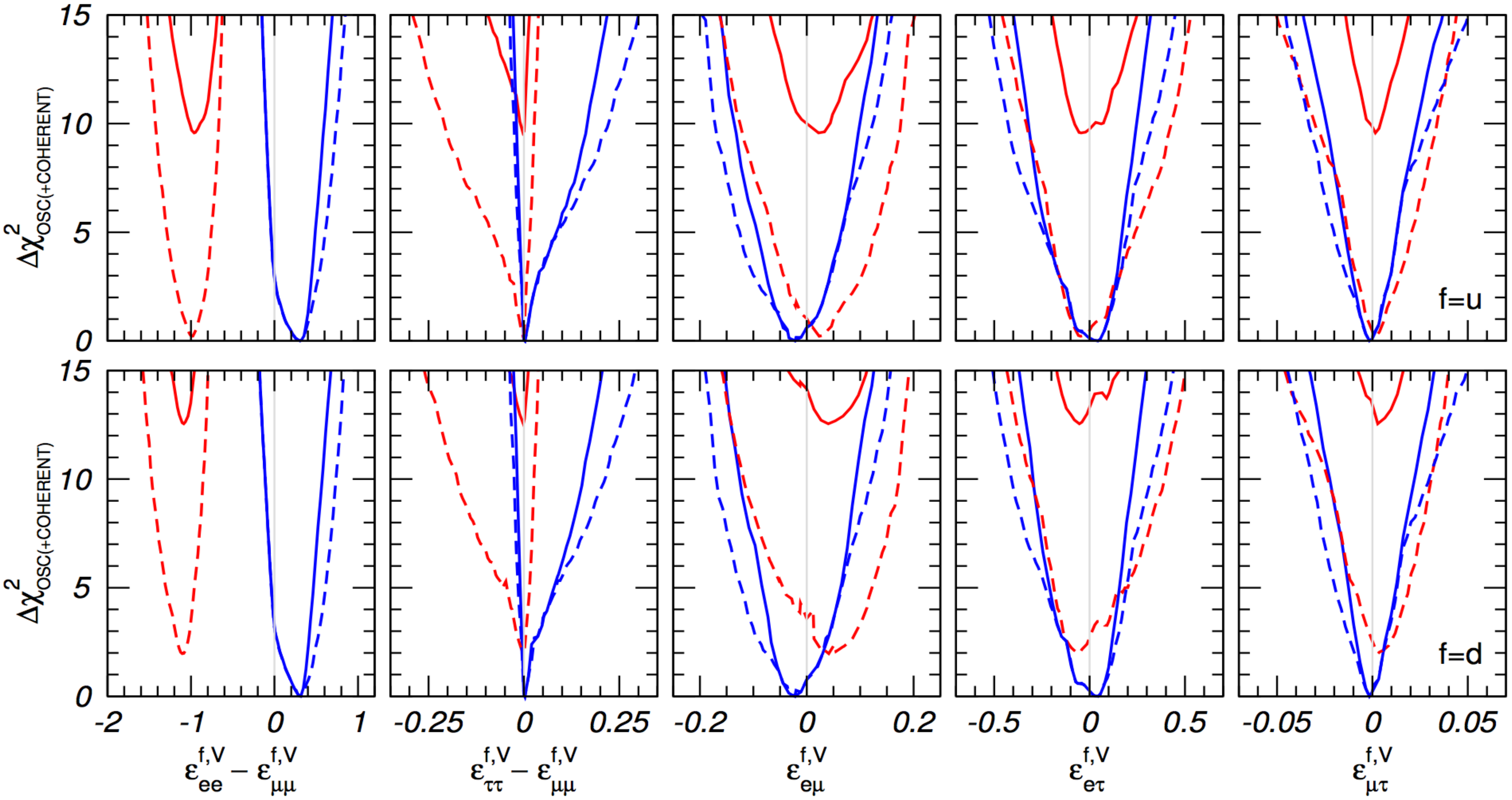
Arbitrary NSI models



Esteban et al, 1805.04530

Combination with oscillation data

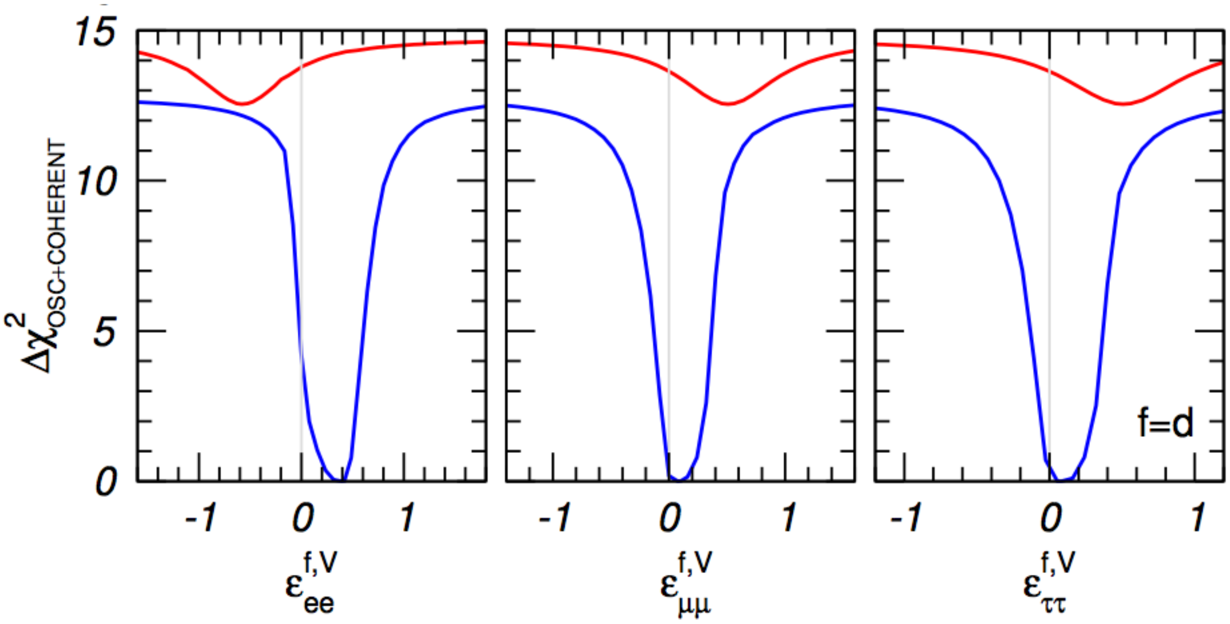
Dashed = oscillations only; Solid = oscillations + COHERENT



PC, Gonzalez-Garcia, Maltoni and Schwetz, 1708.02899
(see also Esteban et al, 1805.04530)

Combination with oscillation data

The combination allows to obtain independent bounds for all diagonal couplings at the 90% CL:

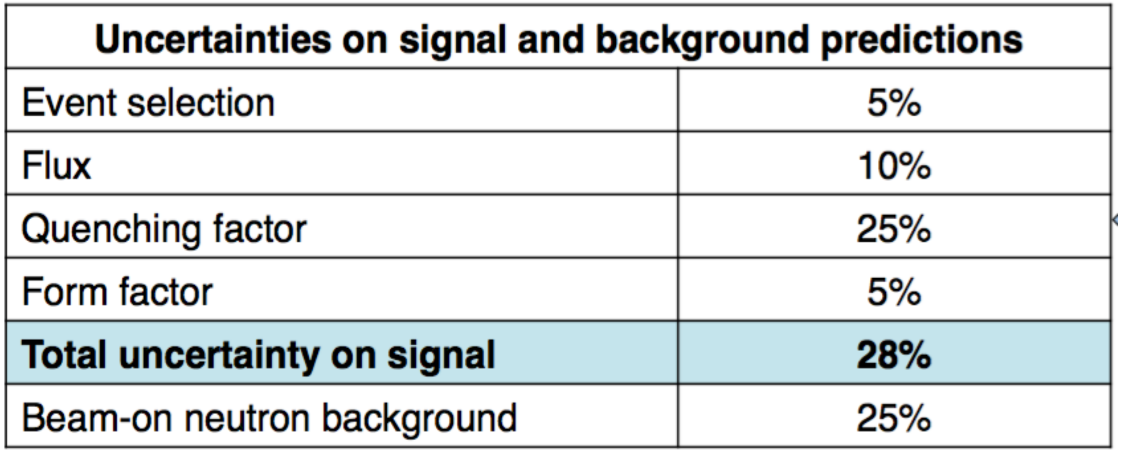


	$f=u$	$f=d$
$\epsilon^{f,V}_{ee}$	$[0.028, 0.60]$	$[0.030, 0.55]$
$\epsilon^{f,V}_{\mu\mu}$	$[-0.088, 0.37]$	$[-0.075, 0.33]$
$\epsilon^{f,V}_{\tau\tau}$	$[-0.090, 0.38]$	$[-0.075, 0.33]$
$\epsilon^{f,V}_{e\mu}$	$[-0.073, 0.044]$	$[-0.07, 0.04]$
$\epsilon^{f,V}_{e\tau}$	$[-0.15, 0.13]$	$[-0.13, 0.12]$
$\epsilon^{f,V}_{\mu\tau}$	$[-0.01, 0.009]$	$[-0.009, 0.008]$

PC, Gonzalez-Garcia, Maltoni and Schwetz, 1708.02899
(see also Esteban et al, 1805.04530)

First analysis

Two-dimensional (E, timing) likelihood used: $t < 6$ microsec, $6 < \#$ of PE < 30



Uncertainties on signal and background predictions	
Event selection	5%
Flux	10%
Quenching factor	25%
Form factor	5%
Total uncertainty on signal	**28%**
Beam-on neutron background	25%

Note: discrepancies found between different measurements on quenching, so they chose to use a conservative 25% error

COHERENT coll., 1708.01294
Scholberg's talk

The SNS as a neutrino source

Some key features of the SNS source:

- Protons are pulsed in short bunches (700 ns) with 60 Hz repetition rate → Extremely good background rejection
- Proton energies are very low (around a GeV) → Reduced production of heavier mesons and DIF
- Very intense source!! 5e20 PoT/day (Production yield: 0.08 pions/proton) → To beat the small detector size and cross section