INTRO TO MASSIVE NEUTRINOS IN 2022

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4th World Summit on Exploring the Dark Side of the Universe

Nov 8, 2022, La Réunion, France

OUTLINE

- Status of 3ν global description
- Explorations beyond 3ν's: NSI, Z's, steriles…

Global fit to neutrino oscillation data

HIDDeN

Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

http://www.nu-fit.org

Neutrinos in the Standard Model

The SM is a gauge theory based on the symmetry group

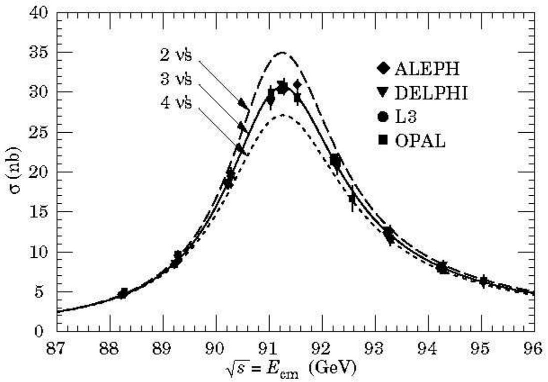
$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

With three generation of fermions

$(1,2)_{-\frac{1}{2}}$	$(3,2)_{\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	b^i_R

There is no ν_R

Three and only three



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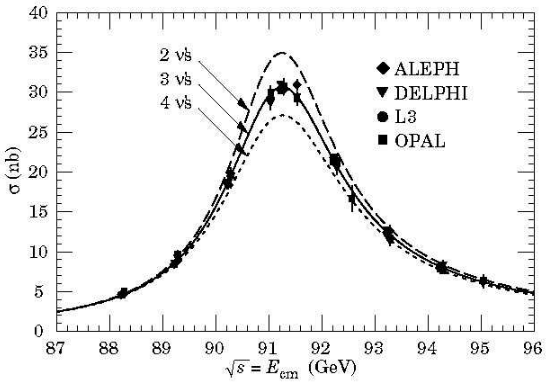

There is no ν_R

$\Downarrow$

Accidental global symmetry: $B \times L_e \times L_\mu \times L_\tau$ (hence $L = L_e + L_\mu + L_\tau$)

$\Downarrow$

ν *strictly* massless

- We have observed with high (or good) precision:
  - ∗ Atmospheric ν_μ & $\bar{\nu}_\mu$ disappear most likely to ν_τ (**SK**,MINOS, **ICECUBE**)
  - ∗ Accel. ν_μ & $\bar{\nu}_\mu$ disappear at $L \sim 300/800$ Km (K2K, **T2K, MINOS, NOνA**)
  - ∗ Some accelerator ν_μ appear as ν_e at $L \sim 300/800$ Km (**T2K**, MINOS,NOνA)
  - ∗ Solar ν_e convert to ν_μ/ν_τ (Cl, Ga, **SK, SNO, Borexino**)
  - ∗ Reactor $\overline{\nu_e}$ disappear at $L \sim 200$ Km (**KamLAND**)
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  What BSM? Not in this talk apologies (some back-up slides at the end)

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- Today the *starting* path:

Precise determination of the low energy parametrization

The New Minimal Standard Model

- Minimal Extension to allow for LFV ⇒ give Mass to the Neutrino

  $*$ Introduce ν_R AND impose L conservation ⇒ Dirac $\nu \neq \nu^c$:

$$\mathcal{L} = \mathcal{L}_{SM} - M_\nu \overline{\nu_L} \nu_R + h.c.$$

  $*$ NOT impose L conservation ⇒ Majorana $\nu = \nu^c$

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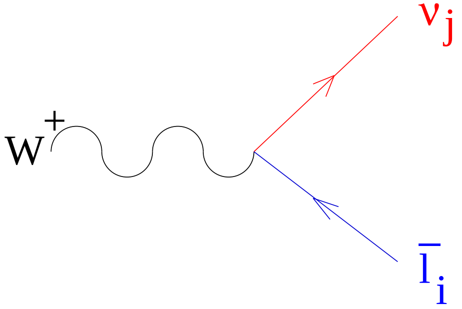
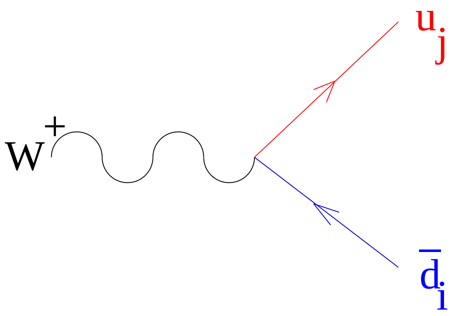
- Charged current interactions of leptons are not diagonal (as quark's but $U_{\rm LEP}$ $3 \times N$)

$$\frac{g}{\sqrt{2}} W^+_\mu \sum_{ij} \left(U^{ij}_{\rm LEP}\, \overline{\ell^i}\, \gamma^\mu\, L\, \nu^j \; + \; U^{ij}_{\rm CKM}\, \overline{U^i}\, \gamma^\mu\, L\, D^j \right) \; + \; h.c.$$





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⇒ Flavour Oscillations:

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{j \neq i}^{n} {\rm Re}[U^\star_{\alpha i} U_{\beta i} U_{\alpha j} U^\star_{\beta j}] \sin^2 \left(\frac{\Delta_{ij}}{2} \right) + 2 \sum_{j \neq i} {\rm Im}[U^\star_{\alpha i} U_{\beta i} U_{\alpha j} U^\star_{\beta j}] \sin \left(\Delta_{ij} \right)$$

$$\frac{\Delta_{ij}}{2} = \frac{(E_i - E_j) L}{2} = 1.27 \frac{(m_i^2 - m_j^2)}{{\rm eV}^2} \frac{L/E}{\rm Km/GeV}$$

No information on ν mass scale nor Majorana versus Dirac

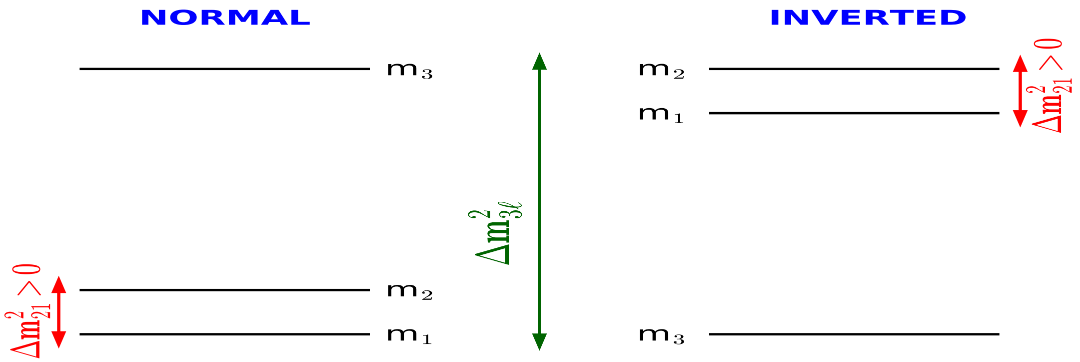
(talks B. Lenhert, P-J. Chiu on $0\nu\beta\beta$, T. Lassere on Katrin, P. Vielzeuf in m_ν in Cosmo)

3ν Flavour Parameters

- For **for 3 ν's** : 3 Mixing angles + 1 Dirac Phase + 2 Majorana Phases

$$U_{\rm LEP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta_{\rm cp}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{\rm cp}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \xcancel{\begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}$$

- Convention: $0 \leq \theta_{ij} \leq 90^\circ$ $\quad 0 \leq \delta \leq 360^\circ$ $\quad \Rightarrow$ 2 Orderings



$\Delta m^2_{21} > 0$ by convention

$$\Delta m^2_{3\ell} = \begin{cases} \Delta m^2_{31} > 0 \text{ for NO} \\ \Delta m^2_{32} < 0 \text{ for IO} \end{cases}$$

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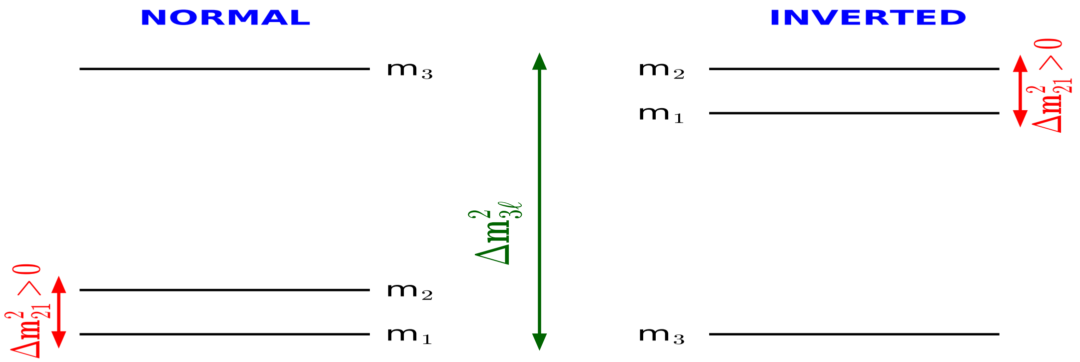

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Experiment	Dominant Dependence	Important Dependence
Solar Experiments	θ_{12}	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12} , θ_{13}
Reactor MBL (Daya Bay, Reno, D-Chooz)	θ_{13} $\Delta m^2_{3\ell}$	
Atmospheric Experiments (SK,IC)		θ_{23}, $\Delta m^2_{3\ell}$, θ_{13} ,$\delta_{\rm cp}$
Acc LBL ν_μ Disapp (Minos,T2K,NOvA)	$\Delta m^2_{3\ell}$ θ_{23}	
Acc LBL ν_e App (Minos,T2K,NOvA)	$\delta_{\rm cp}$	θ_{13}, θ_{23}

Flavour Osc in Vaccum vs Transitions in Matter

- In Vaccum

  when osc between 2-ν dominates:

$$P_{\alpha\alpha} = 1 - P_{\alpha\neq\beta} \quad \text{Disappear}$$

$$P_{\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(1.27\frac{\Delta m^2 L}{E}\right) \quad \text{Appear}$$

$\Rightarrow$ No information on Ordering of states (i.e sign(Δm^2)) nor octact of θ

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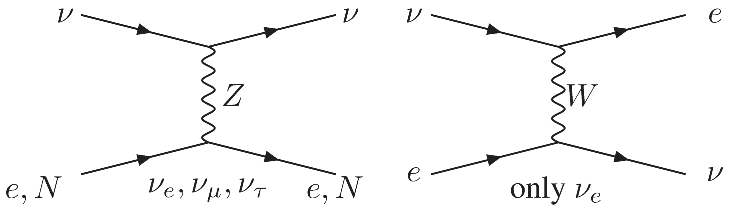
- If ν cross matter regions (Sun, Earth...) it interacts *coherently*
  - And Different flavours
    have different interactions :



$\Rightarrow$ Effective potential in ν evolution : $V_e \neq V_{\mu,\tau} \Rightarrow \Delta V^\nu = -\Delta V^{\bar\nu} = \sqrt{2}G_F N_e$

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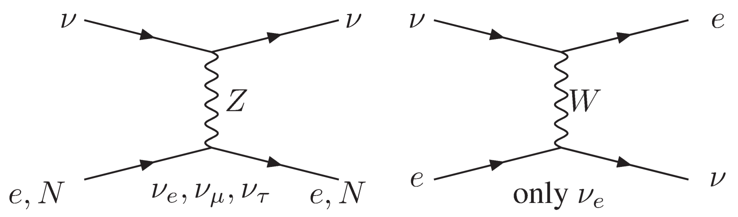

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$$\Delta m^2_{\rm mat} = \sqrt{(\Delta m^2 \cos 2\theta - 2E\Delta V)^2 + (\Delta m^2 \sin 2\theta)^2}$$

$$\sin(2\theta_m) = \frac{\Delta m^2 \sin(2\theta)}{\Delta m^2_{\rm mat}}$$

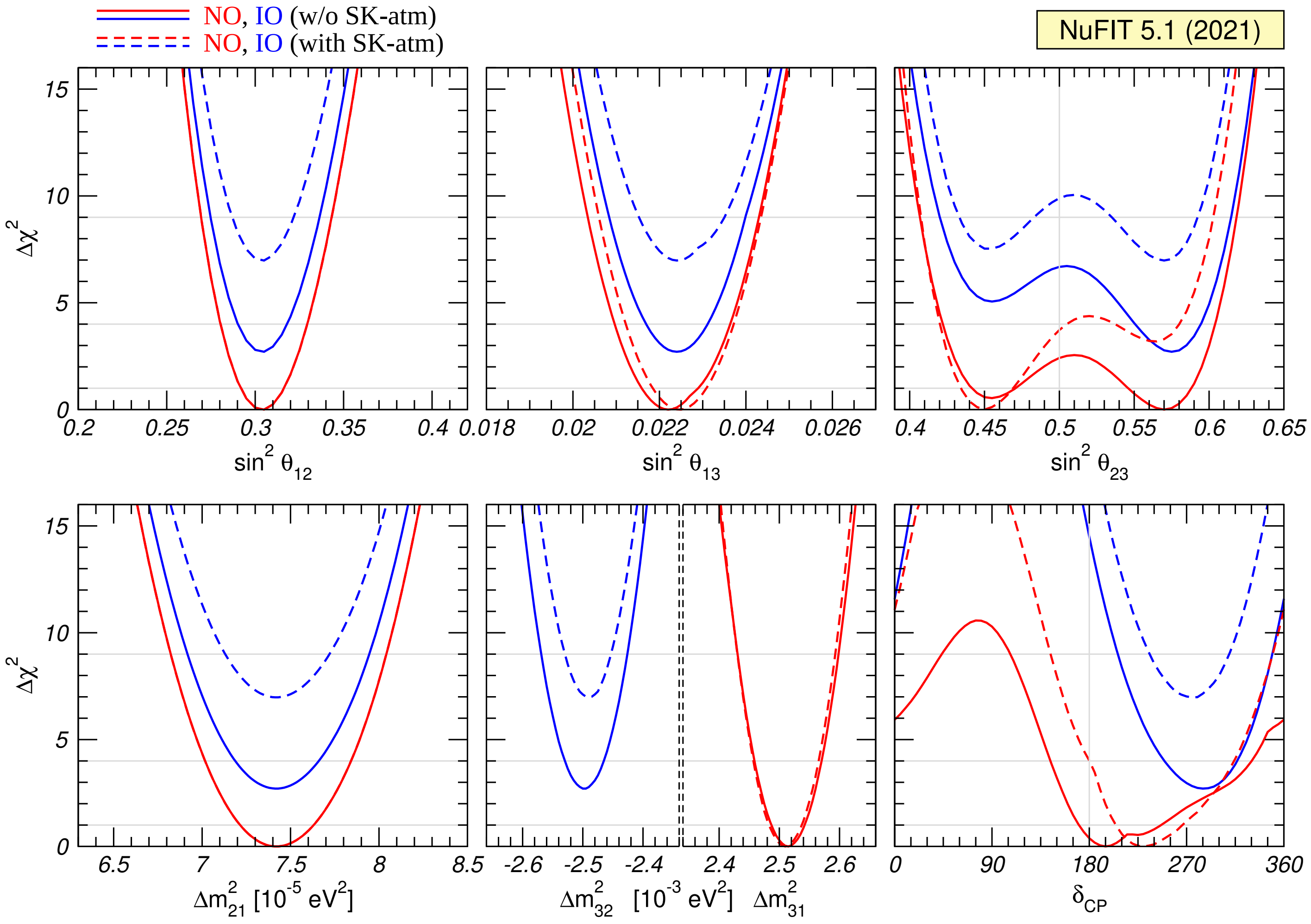
$\Rightarrow$ For solar $\nu's$ in adiabatic regime
Dependence on θ_{12} octant

$\Rightarrow$ In LBL terrestrial experiments
Dependence on sign of $\Delta m^2_{3\ell}$

Summary: Global 3 ν Flavour Parameters

Global 6-parameter fit http://www.nu-fit.org

Esteban, G-G, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792], G-G, Maltoni, Schwetz, 2111.03086



SK-atm $\equiv$ χ^2 table from SK1-4 for 372 kton-years

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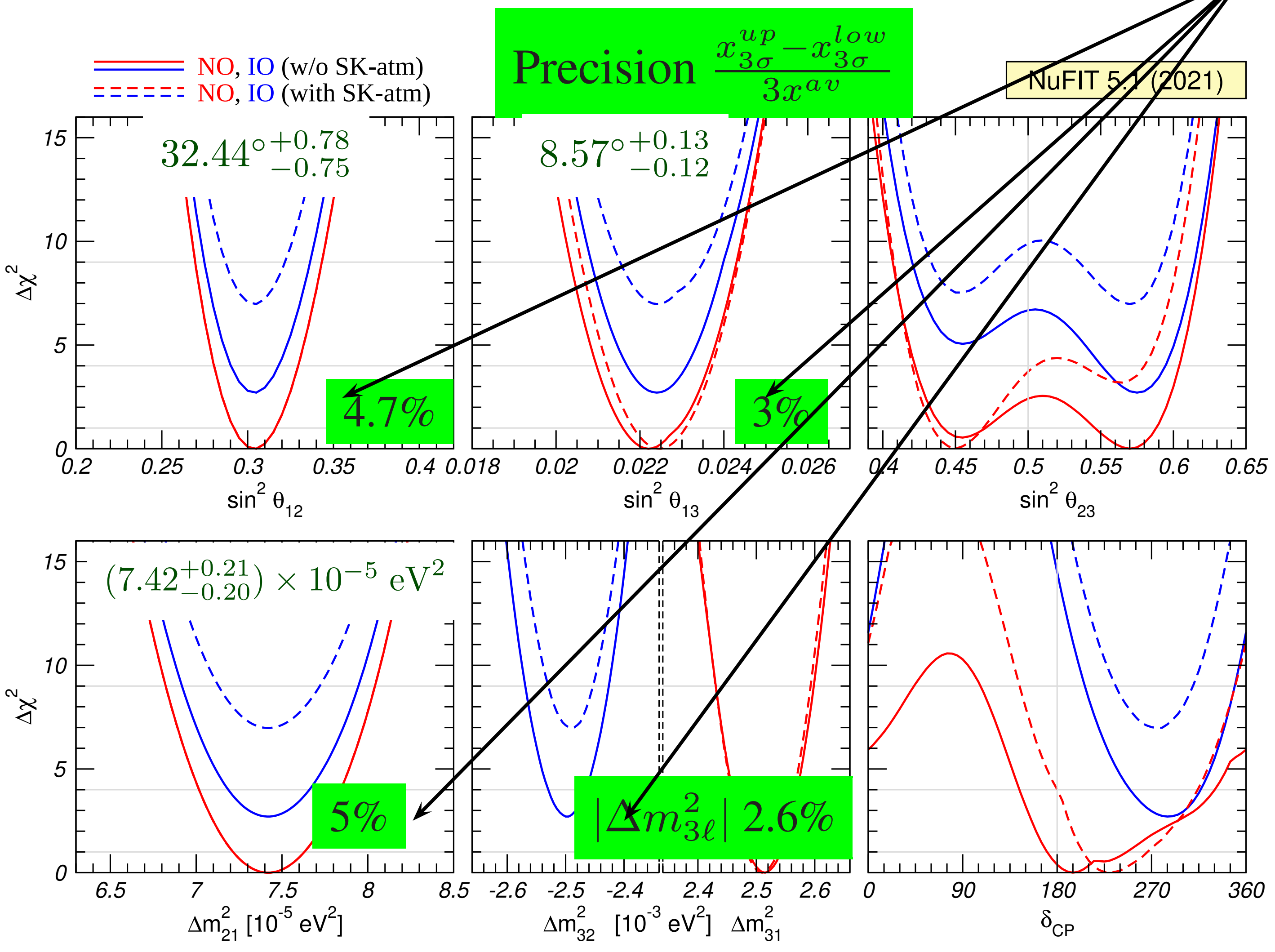

Precision $\frac{x^{up}_{3\sigma}-x^{low}_{3\sigma}}{3x^{av}}$

$32.44^{\circ}{}^{+0.78}_{-0.75}$

4.7%

$8.57^{\circ}{}^{+0.13}_{-0.12}$

3%

$(7.42^{+0.21}_{-0.20}) \times 10^{-5}\ \mathrm{eV}^2$

5%

$|\Delta m^2_{3\ell}|$ 2.6%

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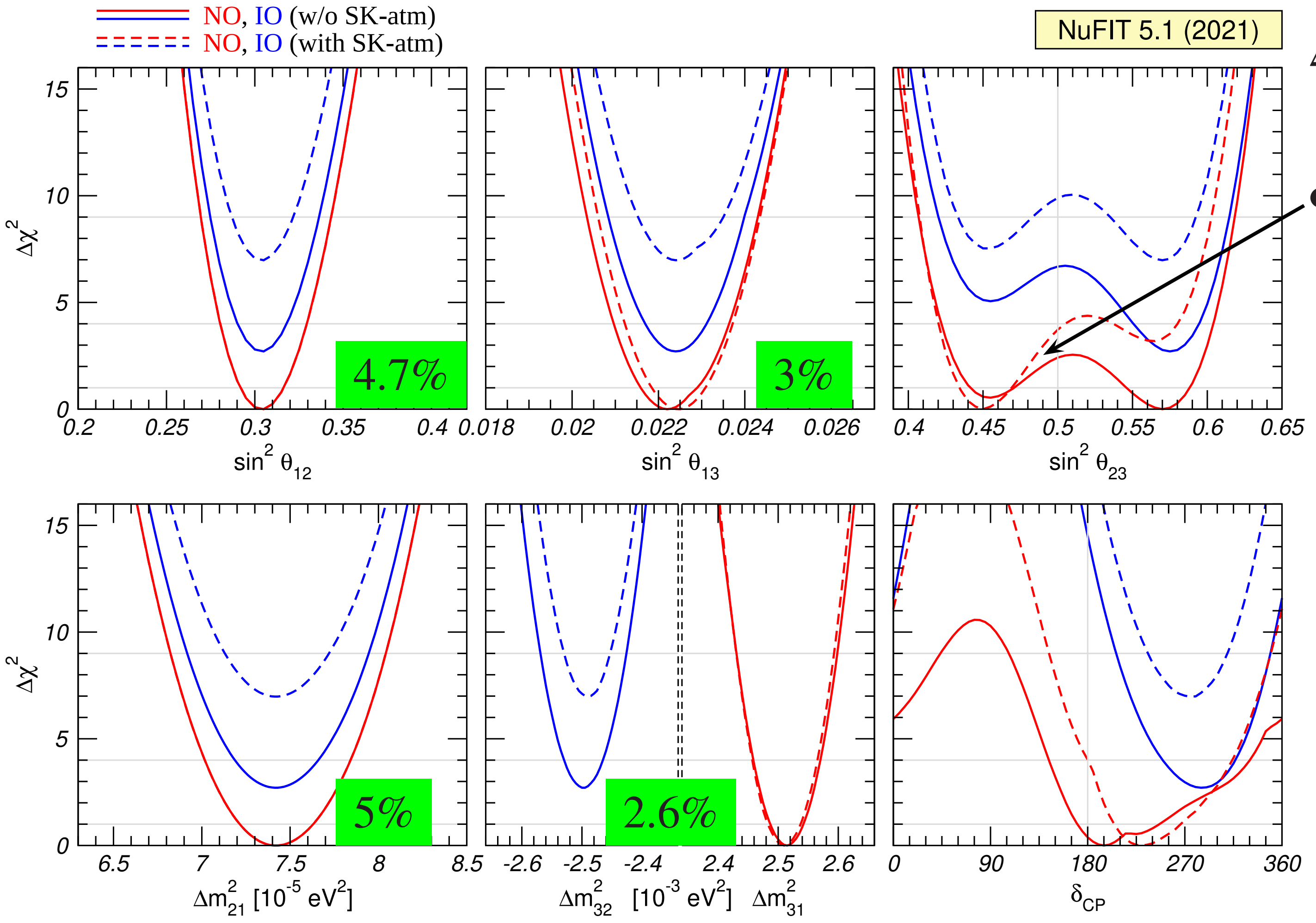

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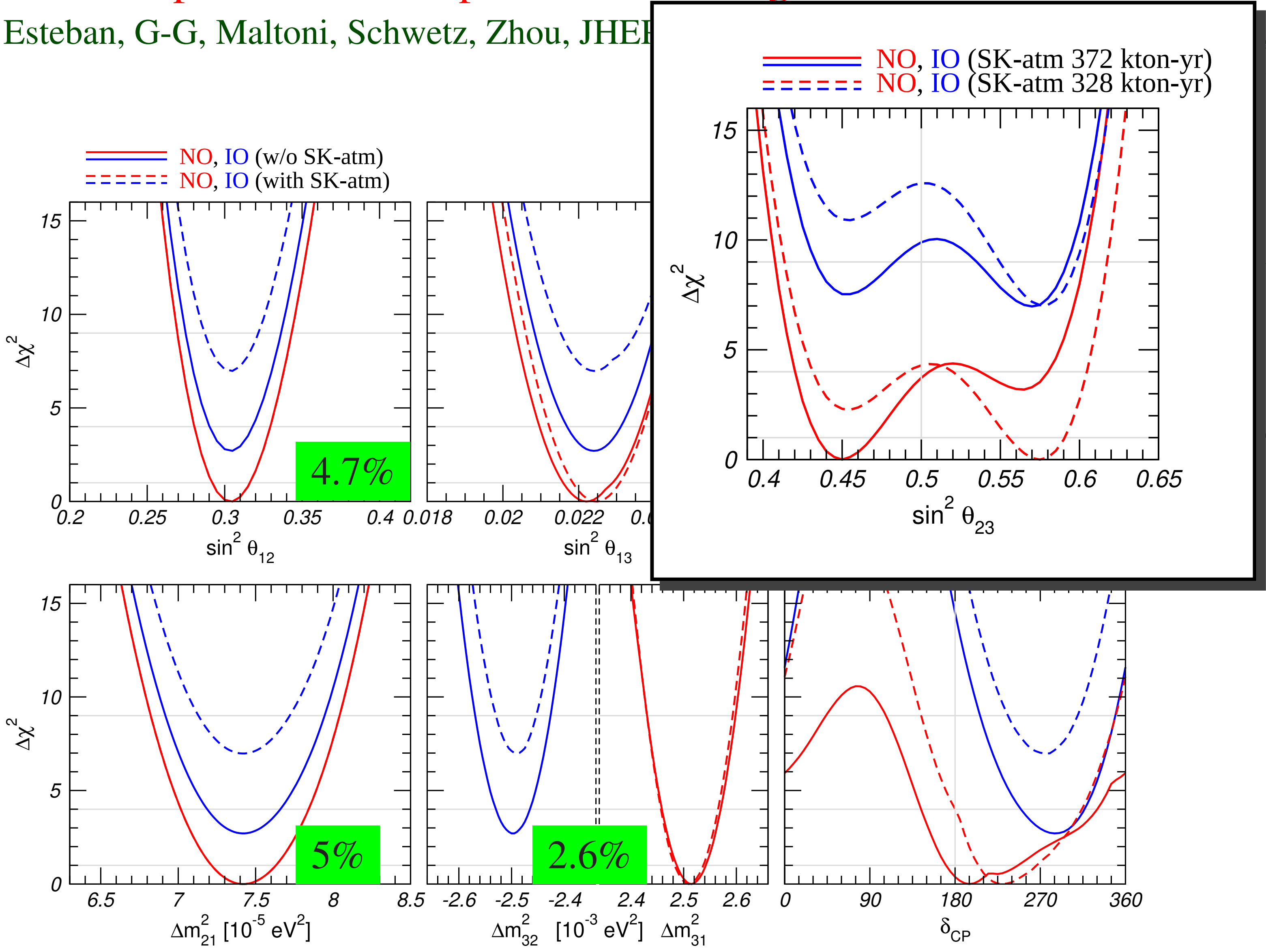

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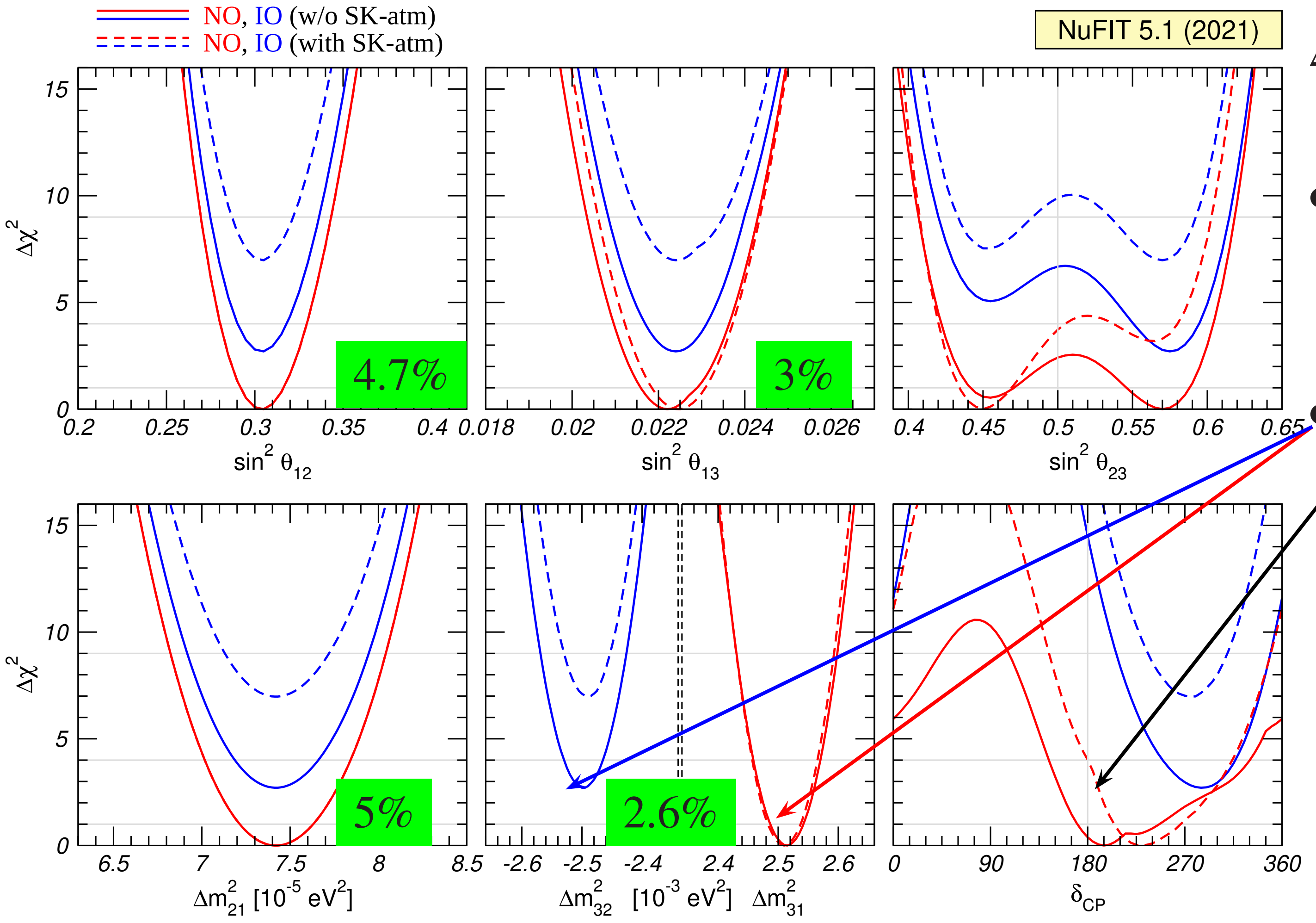
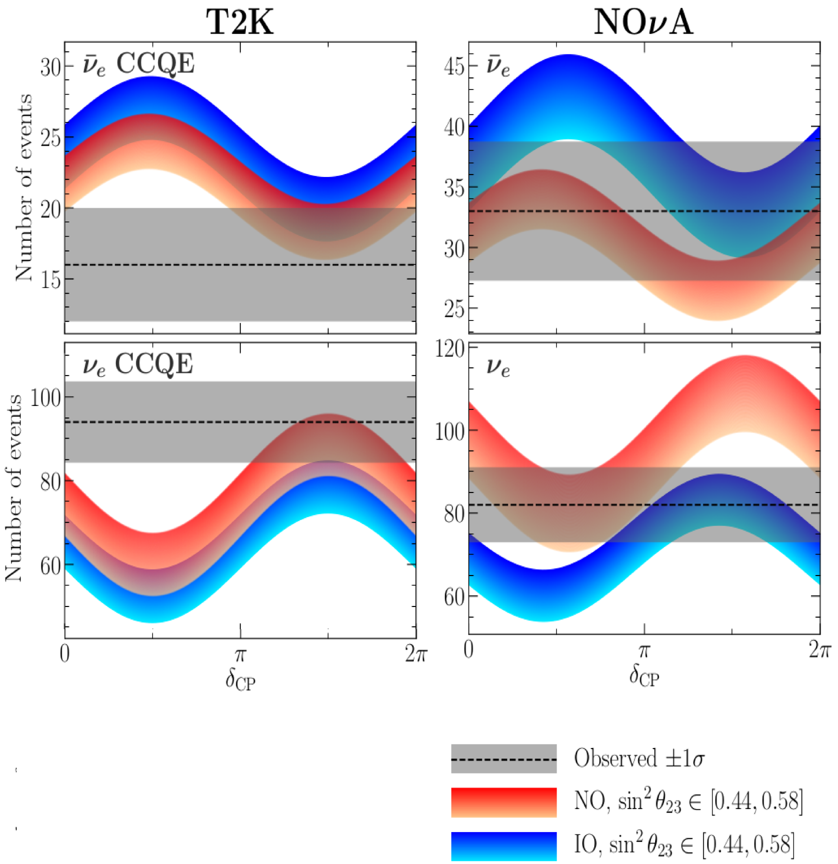
- Ordering NO or IO?

  CPV?:



CPV and MO in LBL

ν_e and $\overline{\nu}_e$ apperance events



Each T2K and NOνA favour NO

But tension in values of δ_{CP} in NO

⇒ IO best fit in LBL combination

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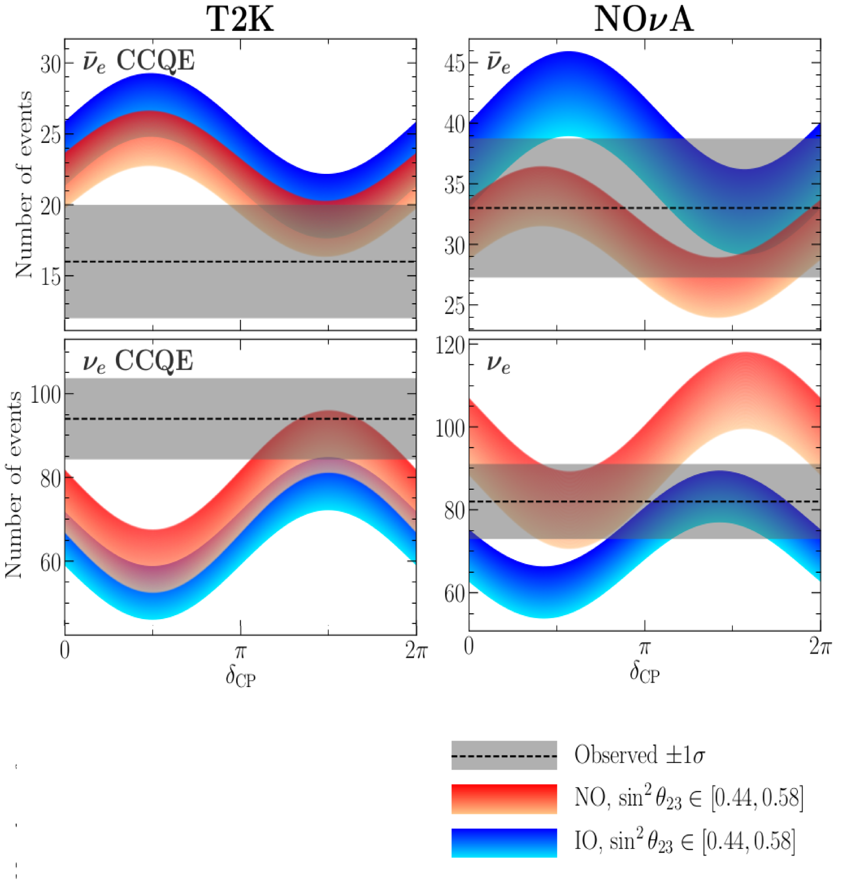

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CPV and MO in LBL+Reactors

At LBL determined in ν_μ and $\overline{\nu}_\mu$ disapp

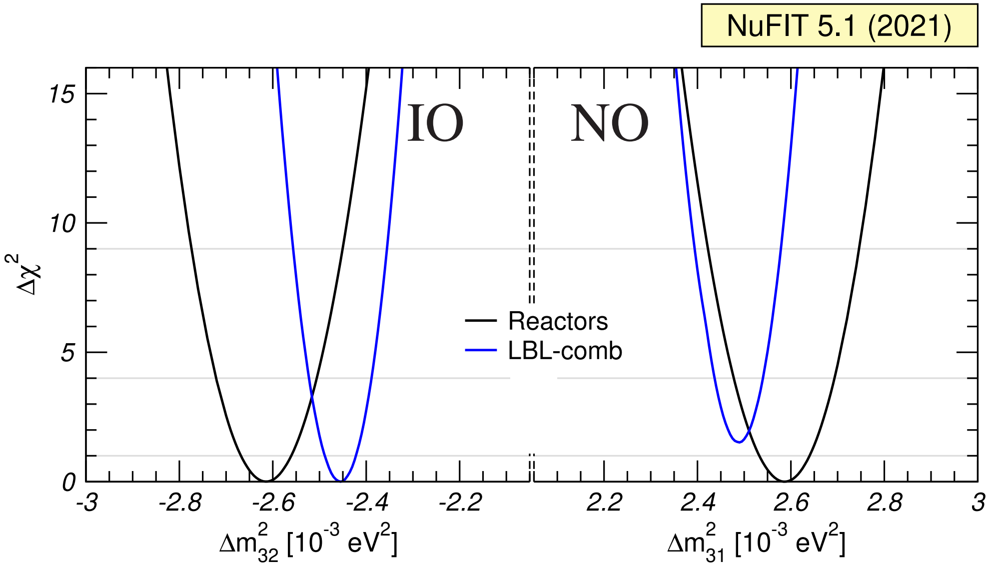
$$\Delta m^2_{\mu\mu} \simeq \Delta m^2_{3l} + \begin{matrix} c^2_{12}\Delta m^2_{21} & \text{NO} \\ s^2_{12}\Delta m^2_{21} & \text{IO} \end{matrix} + \ldots$$

At reactors Daya-Bay, Reno in $\bar{\nu}_e$ disapp

$$\Delta m^2_{ee} \simeq \Delta m^2_{3l} + \begin{matrix} s^2_{12}\Delta m^2_{21} & \text{NO} \\ c^2_{12}\Delta m^2_{21} & \text{IO} \end{matrix}$$

Nunokawa,Parke,Zukanovich (2005)

⇒ Contribution to MO from combination



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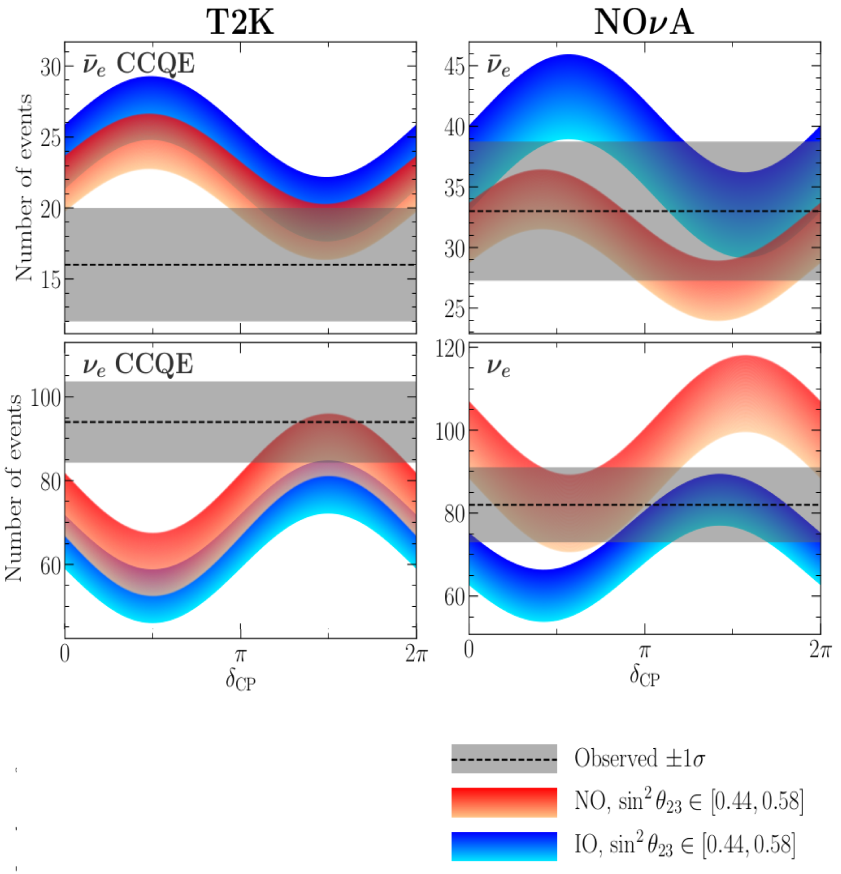

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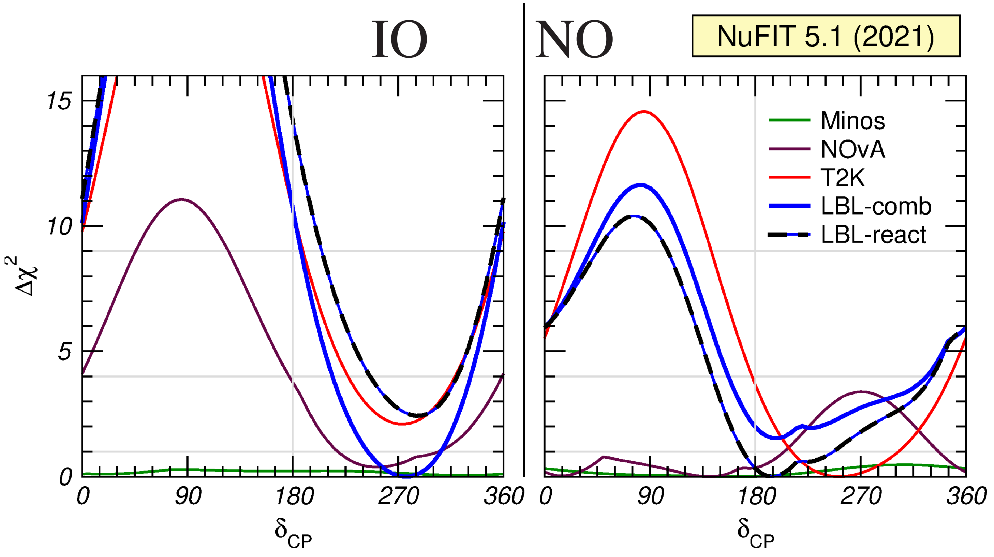
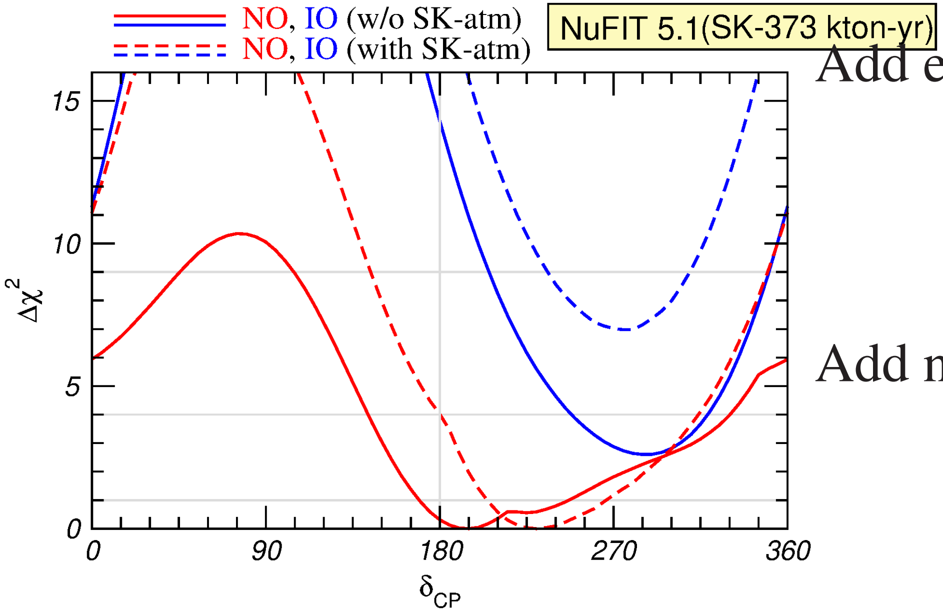


- in NO: b.f $\delta_{\rm CP} = 195°$ $\Rightarrow$ CPC allowed at 0.6 σ
- in IO: b.f $\delta_{\rm CP} \sim 270°$ $\Rightarrow$ CPC disfav. at 3 σ

Ordering & CPV including ATM

ATM results added to global fit using SK χ^2 tables

- NUFIT 5.0: included SK I-IV 328 kton-years table
- NUFIT 5.1: include SK I-IV 372.8 kton-years table



Add either SK-atm table⇒ favouring of NO:

$$\Delta\chi^2_{\mathrm{NO-IO,w/o\ SK-atm}} = 2.7$$
$$\Delta\chi^2_{\mathrm{NO-IO,with\ SK-atm}} = 7.1$$

Add new table ⇒ slight increase of significance of CPV in NO

w/o SK-Atm b.f $\delta_{\mathrm{CP}} = 195^\circ$ CPC at 0.6σ

with SK-Atm: b.f $\delta_{\mathrm{CP}} = 230^\circ$ CPC at 2σ

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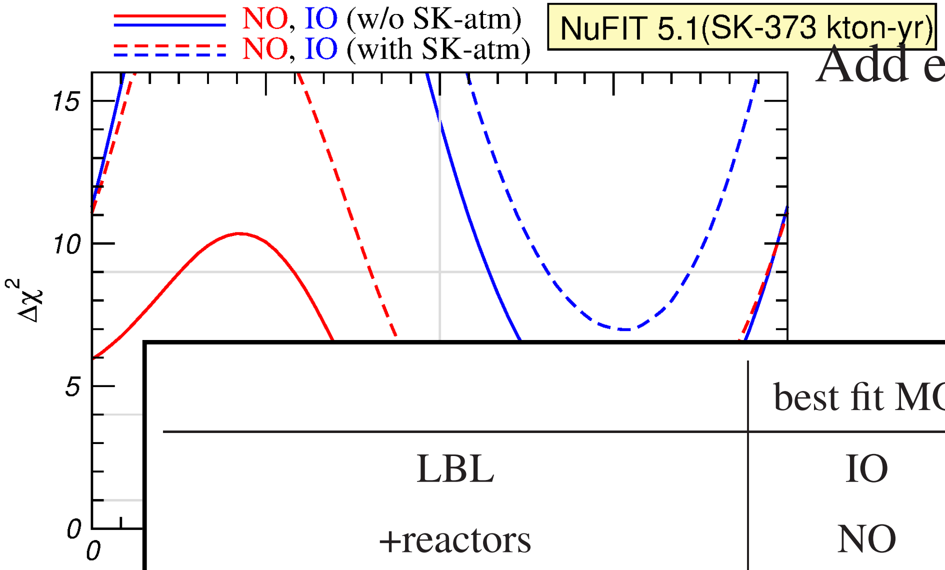

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	best fit MO	$\Delta\chi^2$(MO)	best fit $\delta_{\rm CP}$	$\Delta\chi^2$(CPC)	oct.θ_{23}	$\Delta\chi^2$(oct)
LBL	IO	1.5	275°	2.0	2nd	2.2
+reactors	NO	2.7	195°	0.4	2nd	0.5
+ SK-Atm 328 kt-y (NuFIT 5.0)	NO	7.1	197°	0.5	2nd	2.5
+ SK-Atm 373 kt-y (NuFIT 5.1)	NO	7.0	230°	4.0	1st	3.2

Confirmed Low Energy Picture: Some Open Avenues

- Present 3ν picture:
  - Robustly determined: θ_{12}, θ_{13}, Δm^2_{21}, $|\Delta m^2_{3\ell}|$
  - Mass ordering, θ_{23} Octant, CPV: depend on subdominant 3ν-effects

    ⇒ definitive answer will likely require new experiments (More on next talks)
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  - – Only model independent probe of m_ν: β-decay (Talk by T. Lassere)
  - – Dirac or Majorana?: *anxiously* waiting for ν-less $\beta\beta$ decay (Talks by Lenhert, Chiu)
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- Other NP at play in present 3ν picture?
- Only three light states?

NC-Non Standard ν Interactions in ν-OSC

Including non-standard neutrino NC interactions with fermion f

$$\mathcal{L}_{\rm NSI}^{\rm NC} = -2\sqrt{2}G_F \varepsilon_{\alpha\beta}^{fP} (\bar\nu_\alpha \gamma^\mu L \nu_\beta)(\bar f \gamma_\mu P f)\,, \qquad P = L, R$$

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$$H_{\rm mat} = \sqrt{2}G_F N_e(r)\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \sqrt{2}G_F N_e(r)\begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix}$$

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⇒ Parameters degeneracies

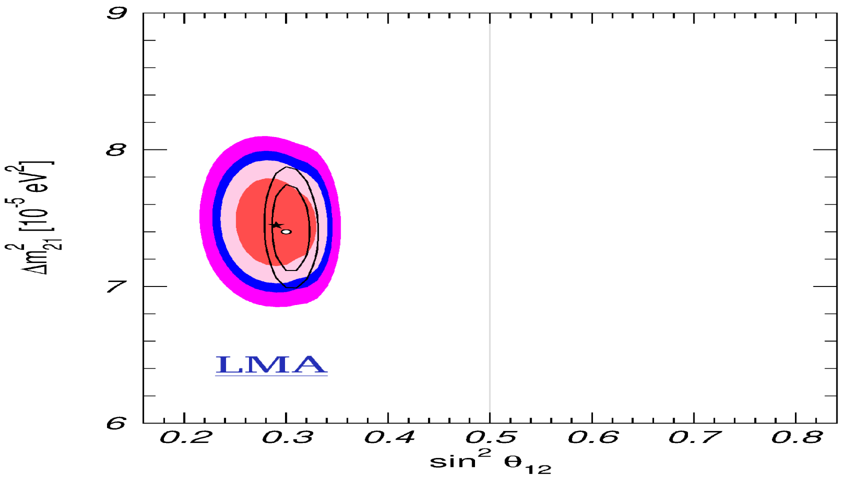
In particular $H \to -H^*$ ⇒ same Probabilities ⇒ invariance under simultaneously:

$$\begin{aligned} &\theta_{12} \leftrightarrow \tfrac{\pi}{2} - \theta_{12}\,, & &(\varepsilon_{ee} - \varepsilon_{\mu\mu}) \to -(\varepsilon_{ee} - \varepsilon_{\mu\mu}) - 2\,, \\ &\Delta m^2_{31} \to -\Delta m^2_{32}\,, & &(\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}) \to -(\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu})\,, \\ &\delta \to \pi - \delta\,, & &\varepsilon_{\alpha\beta} \to -\varepsilon^*_{\alpha\beta} \qquad (\alpha \neq \beta)\,, \end{aligned}$$

⇒ Degeneracies in θ_{12} octant and mass ordering

NSI: Bounds/Degeneracies from/in Oscillation data

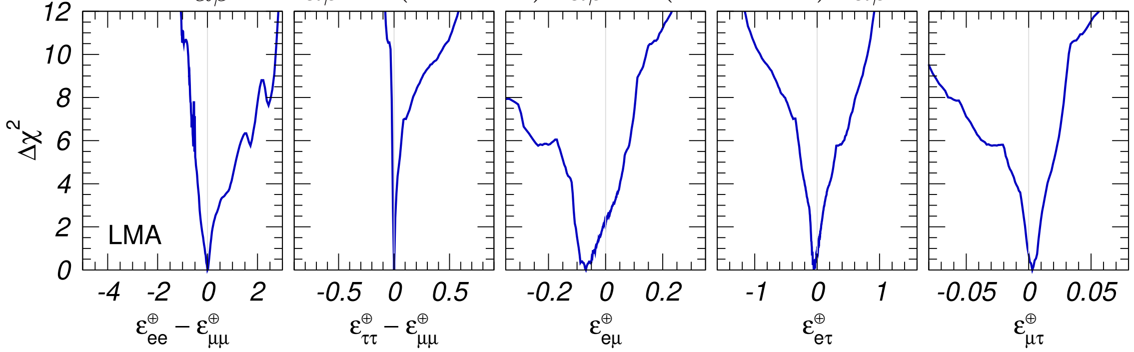
Esteban *etal* JHEP'18[1805.04530] Coloma, Esteban, MCGG, Maltoni, JHEP'19[1911.09109] (updated 2020)



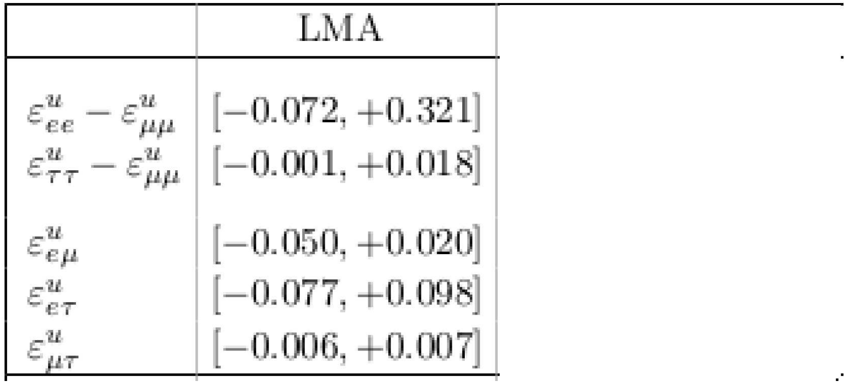
- Standard Fit $\equiv$ LMA $\Rightarrow$ Bounds $\mathcal{O}(1\% - 10\%)$

  $\Rightarrow$ Maximum effect at LBL experiments:

$$\varepsilon^{\oplus}_{\alpha\beta} = \varepsilon^{e}_{\alpha\beta} + \left(2 + Y^{\oplus}_{n}\right)\varepsilon^{u}_{\alpha\beta} + \left(1 + 2Y^{\oplus}_{n}\right)\varepsilon^{d}_{\alpha\beta}$$



$\Rightarrow$ To be considered in effects/sensitivity studies at DUNE, HK. . . (tables available)



	LMA
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$[-0.072, +0.321]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$[-0.001, +0.018]$
$\varepsilon^u_{e\mu}$	$[-0.050, +0.020]$
$\varepsilon^u_{e\tau}$	$[-0.077, +0.098]$
$\varepsilon^u_{\mu\tau}$	$[-0.006, +0.007]$

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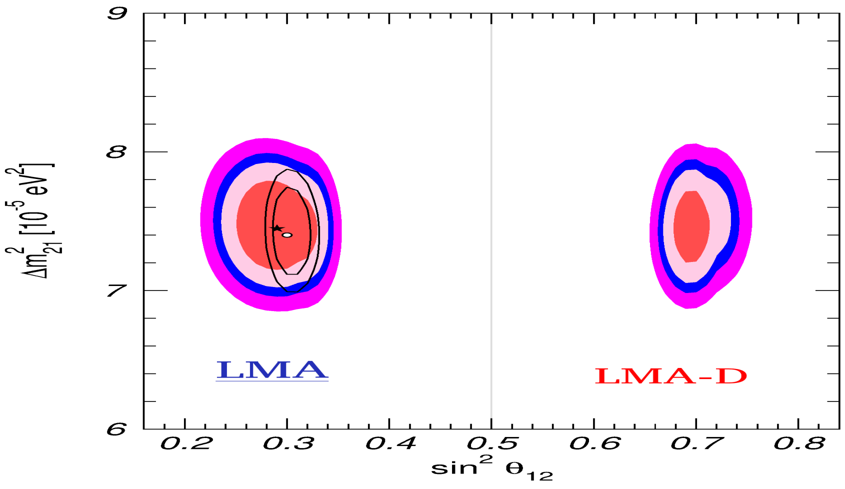

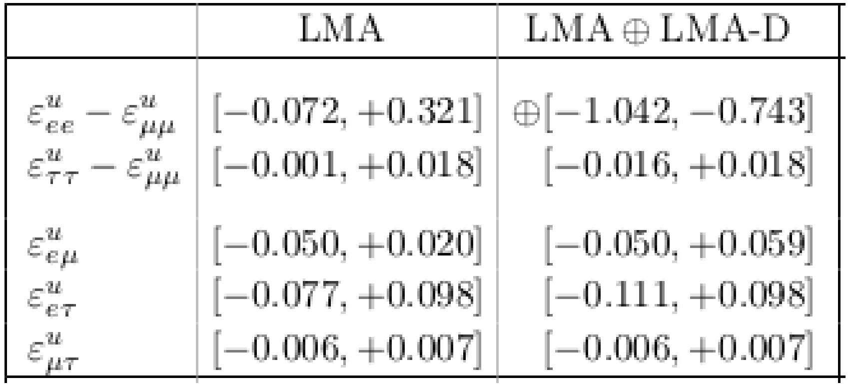

	LMA	LMA $\oplus$ LMA-D
$\varepsilon^u_{ee}-\varepsilon^u_{\mu\mu}$	$[-0.072, +0.321]$	$\oplus[-1.042, -0.743]$
$\varepsilon^u_{\tau\tau}-\varepsilon^u_{\mu\mu}$	$[-0.001, +0.018]$	$[-0.016, +0.018]$
$\varepsilon^u_{e\mu}$	$[-0.050, +0.020]$	$[-0.050, +0.059]$
$\varepsilon^u_{e\tau}$	$[-0.077, +0.098]$	$[-0.111, +0.098]$
$\varepsilon^u_{\mu\tau}$	$[-0.006, +0.007]$	$[-0.006, +0.007]$

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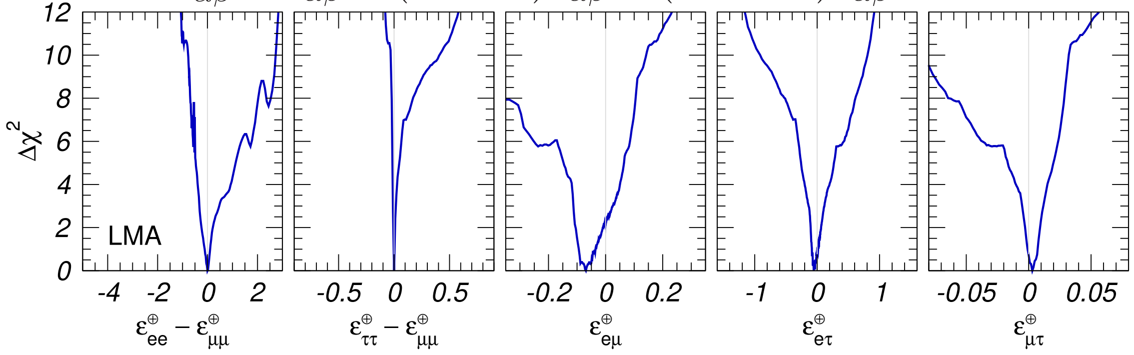


  $\Rightarrow$ To be considered in effects/sensitivity studies at DUNE, HK. . . (tables available)

- Degenerate solution $\equiv$LMA-D

  Miranda,Tortola, Valle, hep-ph/0406280

  $\Rightarrow \theta_{12} \leftrightarrow \frac{\pi}{2} - \theta_{12} \quad \& \quad (\varepsilon_{ee} - \varepsilon_{\mu\mu}) \rightarrow -(\varepsilon_{ee} - \varepsilon_{\mu\mu}) - 2$

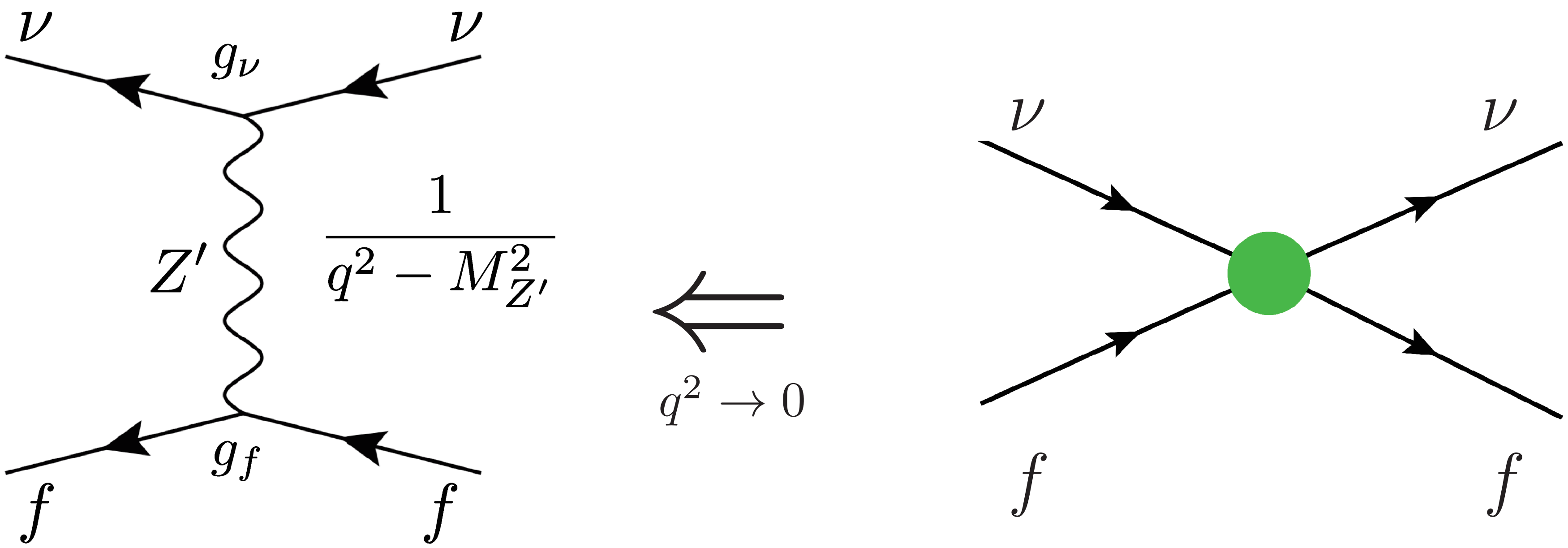
  $\Rightarrow$ Requires NSI $\sim G_F$ (light mediators?)

  Farzan 1505.06906, and Shoemaker 1512.09147

Oscillation bounds on Z’/Dark Photons

Coloma, MCGG, Maltoni, JHEP’21 [2009.14220]

Interpreting



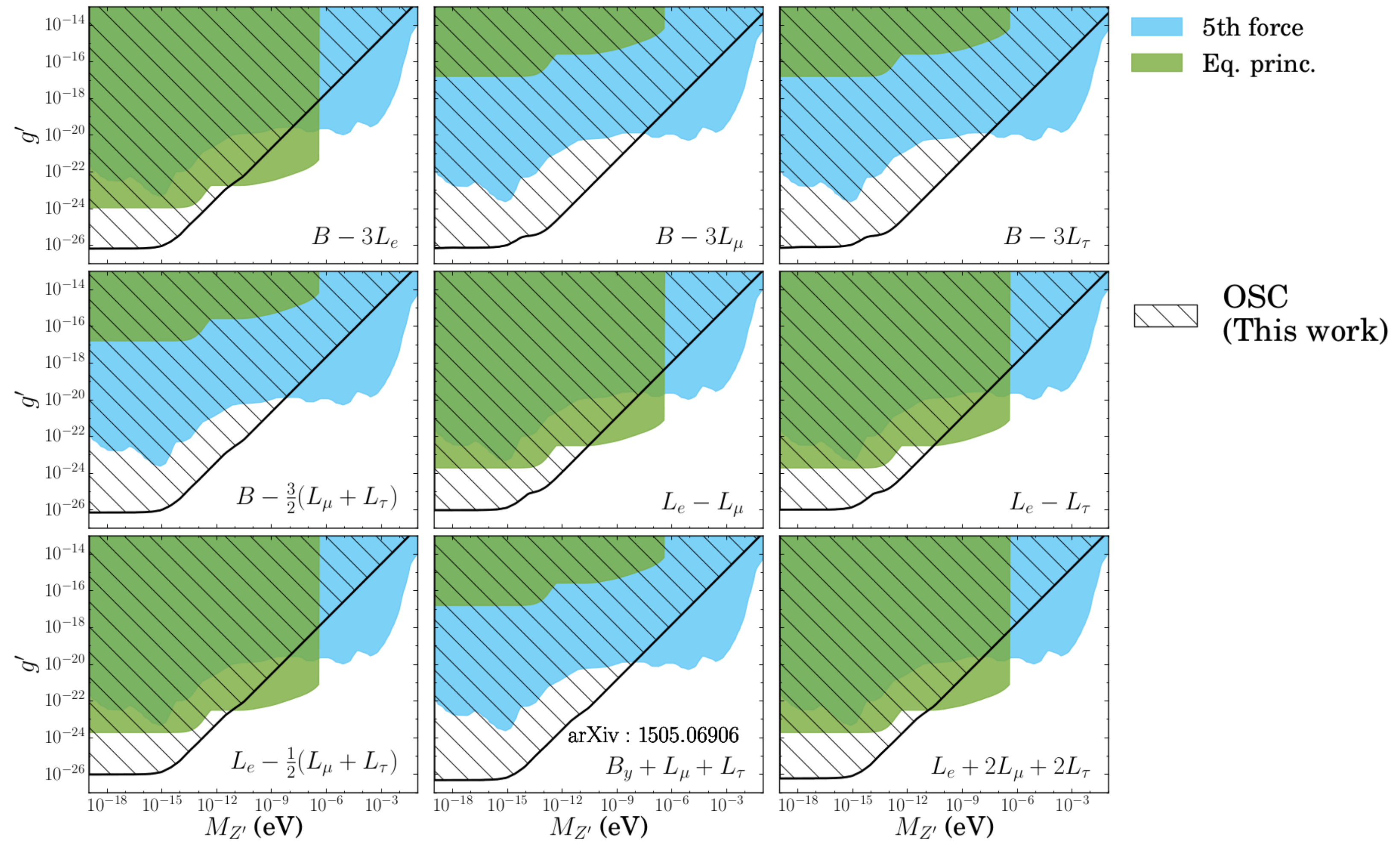
$$\frac{1}{q^2 - M_{Z'}^2} \Longleftarrow \quad q^2 \to 0$$

$$\frac{g'^2}{M_{Z'}^2}\, q'_f\, q'_\nu \qquad \Leftarrow \qquad \epsilon^f_{\alpha\beta}$$

Z'/Dark-photon: Bounds from ν Oscillations

Coloma, MCGG, Maltoni, JHEP'21 [2009.14220]

Very light ($M' \lesssim \mathcal{O}(\text{eV})$) mediator $\Rightarrow$ Long Range Force to Contact Interaction in H_{mat}

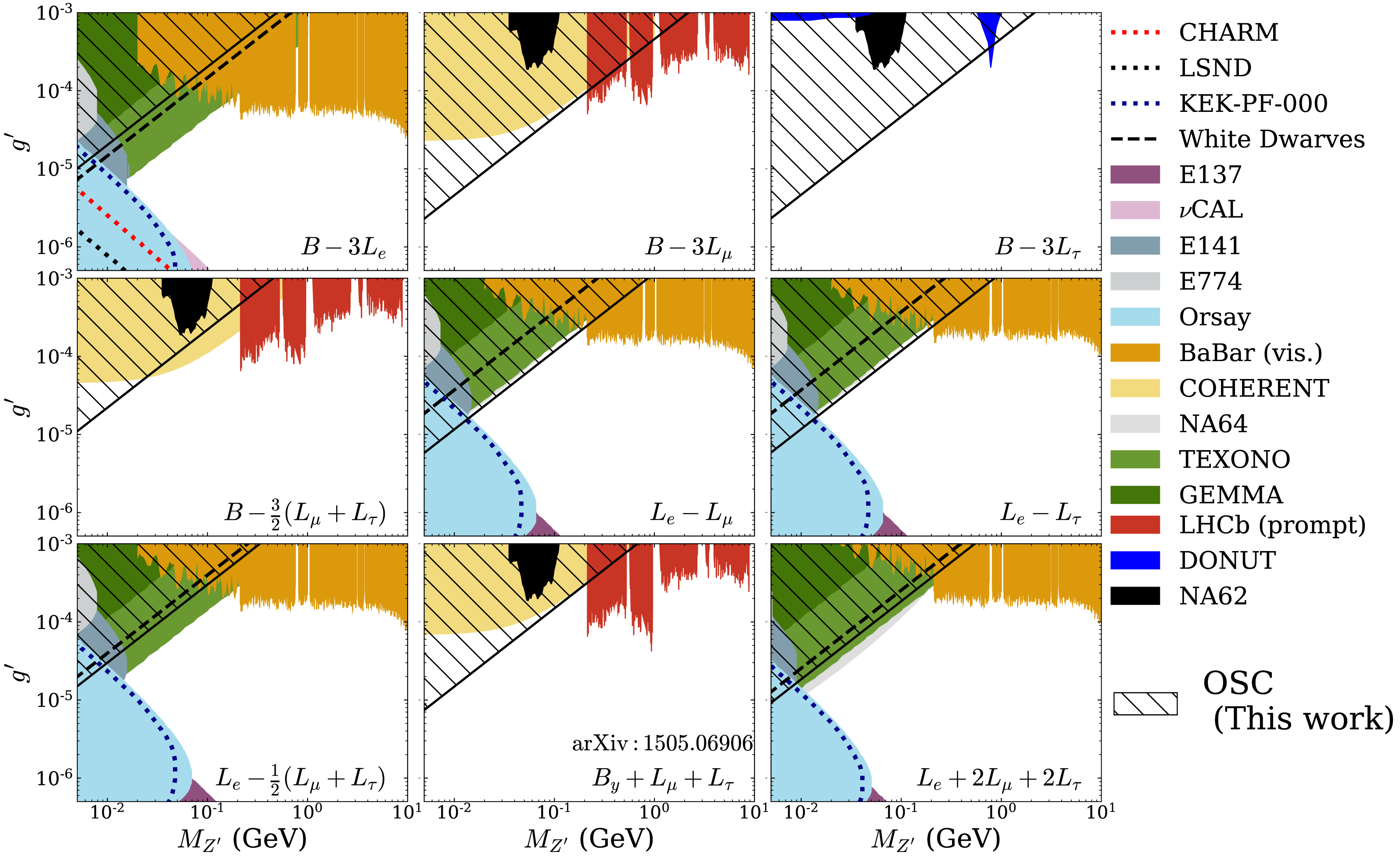


$\Rightarrow$ Bounds from Oscillations stronger than 5th force and VEP experiments

Z' Models: ν Oscillations Bounds

Coloma, MCGG, Maltoni ArXiv:2009.14220

$M_{Z'} \gtrsim \mathcal{O}(\text{MeV}) \Rightarrow$ Contact Interaction in $H_{\rm mat}$



$\Rightarrow$ Bounds from Oscillations stronger than scattering bounds on some models

Beyond 3ν's: Light Sterile Neutrinos

LSND &MiniBoone

$\bar\nu_\mu \to \bar\nu_e$ & $\nu_\mu \to \nu_e$ at SBL

Gallium Anomaly

Acero etal, 0711.4222;Giunti, Laveder,1006.3244

$$\nu_e + {}^{71}\text{Ga} \to {}^{71}\text{Ge} + e^-$$

Rate lower than expected

Explained as ν_e disappearance

Reactor Anomaly

Huber, 1106.068,Mention *etal* ,1101.2755

2011 reactor flux calculation $\Rightarrow$

Deficit in $R = \frac{\text{data}}{\text{predict}}$ at $L \lesssim 100$ m

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lez-Garcia 25-22-a

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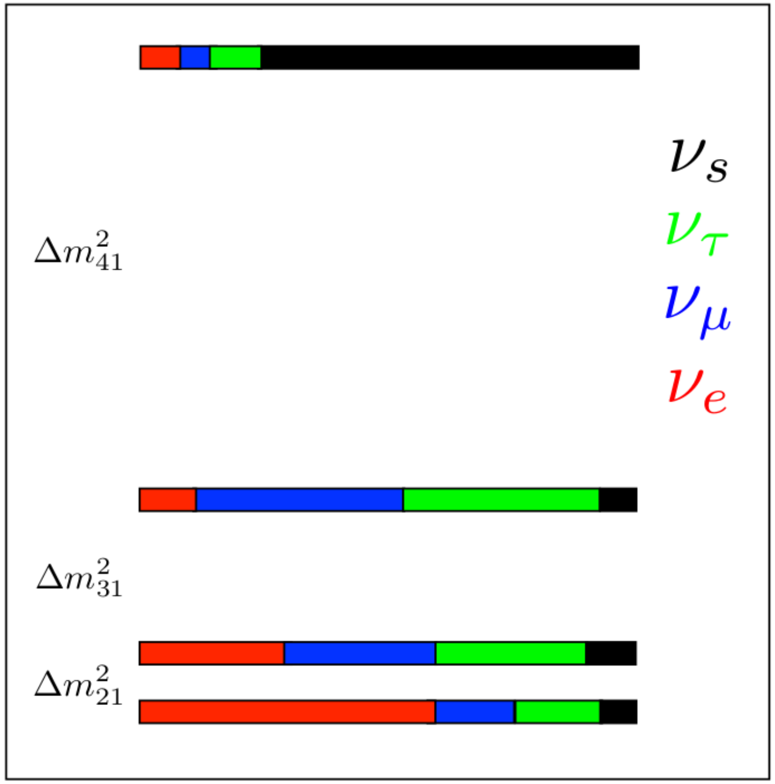
s $\bar{\nu}_e$ disappearance

Oscillation Interpretation Requires $\Delta m^2 \sim \text{eV}^2$

⇒ new (sterile) ν's



G. Palowski Talk on SBL experiments

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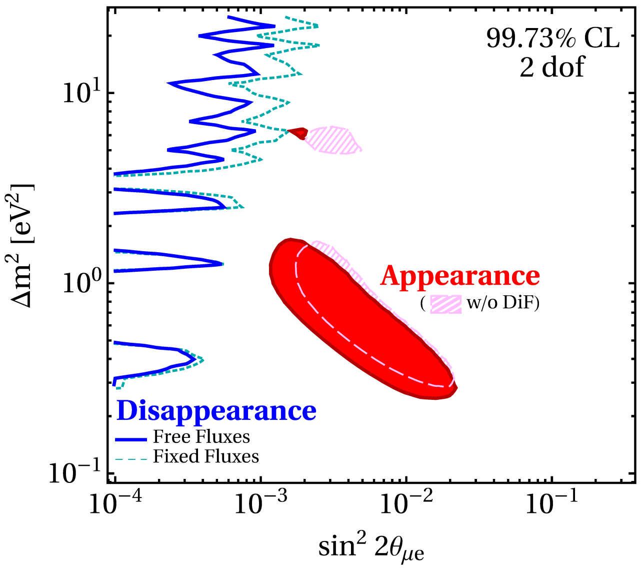
Strong tension with

non-obervation of ν_μ dissap



Dentler etal, 1803.10661

Purely sterile oscillation

robustly disfavoured

additional SM or NP effects?

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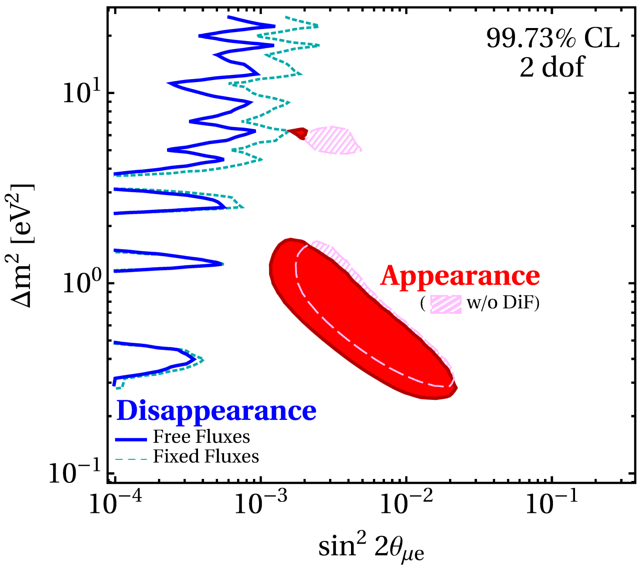

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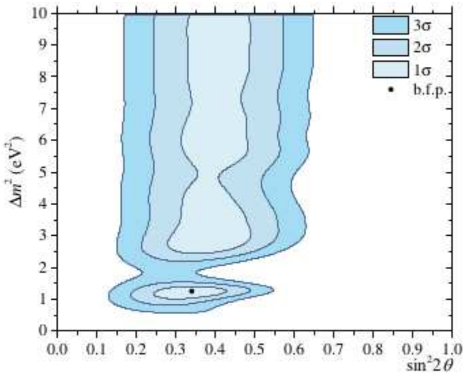
Confirming results from BEST

2109.11482



Requires large mixings

Ruled out/tension by solar $\nu' s$

Goldhagen etal 2109.14898

Berryman etal 2111.12530

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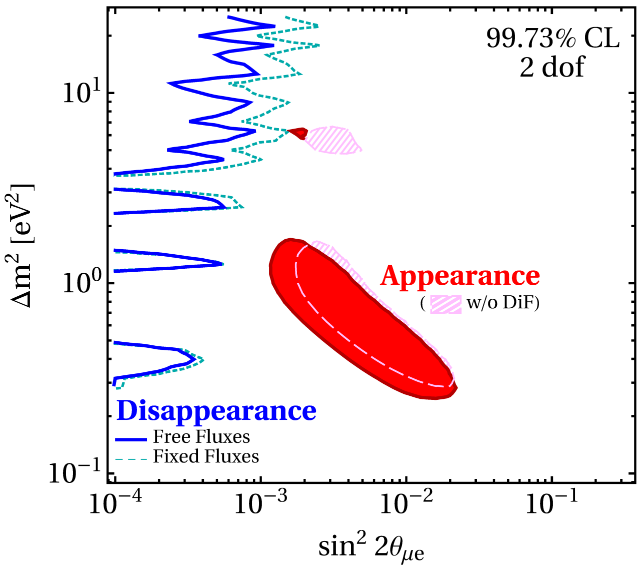

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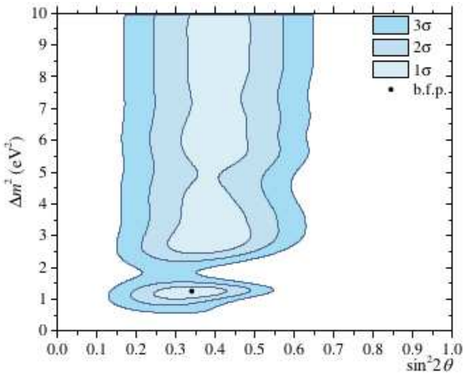

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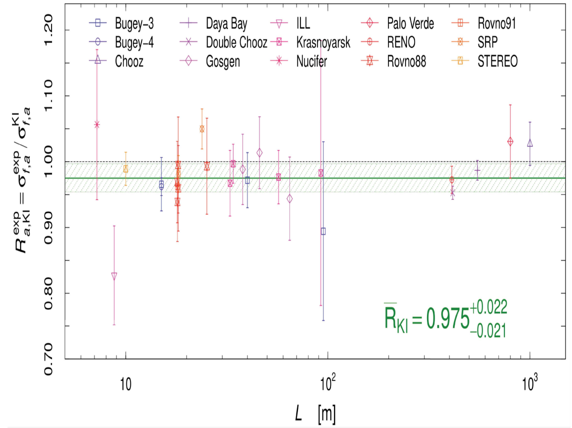
2022 with updated inputs (^{235}U)

Berryman Huber, 2005.01756
Kipeikin etal, 2103.01486
Giunti etal, 2110.06820

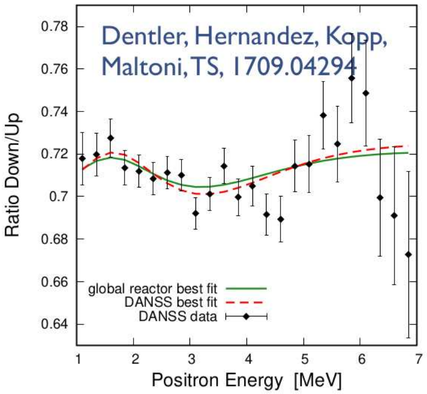


(Fig from Giunti etal, 2110.06820)

Anomaly $\sim 1\,\sigma$

with new fluxes

Recent relative spectral measurments

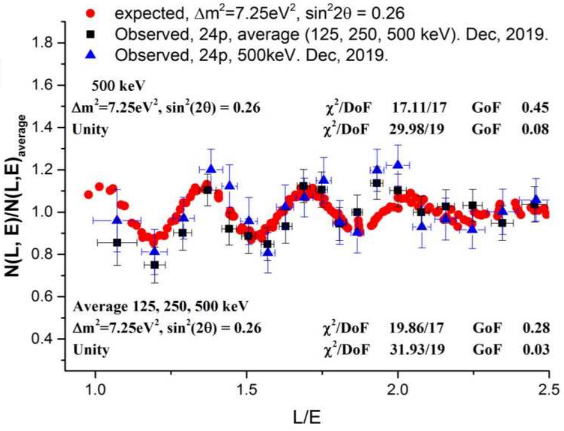

Dentler, Hernandez, Kopp, Maltoni, TS, 1709.04294

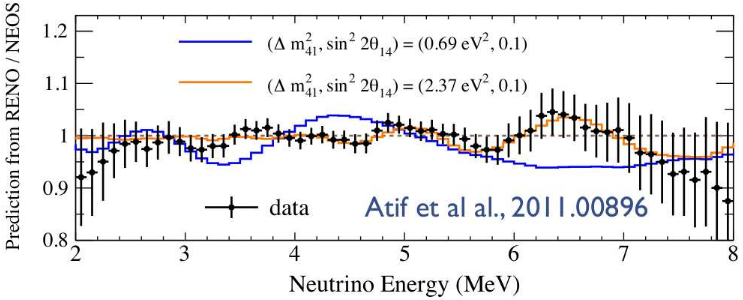
DANSS: relative spectra @ L = 10.7 and 12.7 m
prev. ~ 2σ hint decr. ~1.5σ
DANSS talk @ ICHEP20 (update at EPS-HEP21)

segmented detectors:
STEREO [arXiv:1912.06582]
L = 9 to 11 m $\Delta\chi^2$(no osc) ≈ 9
PROSPECT [arXiv:2006.11210]
L = 6.7 to 9.2 m

Neutrino4: segmented detector, L = 6.25 to 11.9 m, 216 bins in L/E „3σ“ indication

Neutrino4 2005.05301




Atif et al al., 2011.00896

NEOS: spectrum at L = 24 m, relative to RENO (or DayaBay) near detectors: $\Delta\chi^2$(no osc) = 11.7

Spectral ratios at different baselines ⇒ Independent of flux normalizations.

But low statistical significance (Wilk's theorem fails) Berryman, etal 2111.12530
MC estimation of prob distribution ⇒ no significant indication of ν_s oscillations

Summary

- Updated 3ν fit
  - Robust determination of θ_{12}, θ_{13}, Δm^2_{21}, $|\Delta m^2_{3\ell}|$
  - Mass ordering, θ_{23} Octant, CPV depend on subdominant 3ν-effects

    $\Rightarrow$ interplay of LBL/reactor/ATM results

    $\Rightarrow$ not statistically significant yet

    $\Rightarrow$ definitive answer will likely require new experiments
- Non Standard interactions
  - No hint in present experiments $\Rightarrow$ bounds on effects at future experiments
  - But degenerate solution Dark-LMA not excluded
  - Bounds on flavoured dark-photon/Z’ models
- Sterile neutrinos
  - Reactor anomaly seems to be disappearing
  - Explaining LSND/MiniBooNE requires more than just sterile neutrinos
  - Gallium anomaly sterile osc interpretation in conflict with solar and reactor data

BACK-UP SLIDES

Summary: Global 3 ν Flavour Parameters

Evolution of global 3 flavour fit

Gonzalez-Garcia, Maltoni, TS [arXiv:2111.03086]

	2012	2014	2016	2018	2021	
	NuFIT 1.0	NuFIT 2.0	NuFIT 3.0	NuFIT 4.0	NuFIT 5.1	
θ_{12}	15%	14%	14%	14%	14%	**1.07**
θ_{13}	30%	15%	11%	8.9%	9.0%	**3.3**
θ_{23}	43%	32%	32%	27%	27%	**1.6**
Δm^2_{21}	14%	14%	14%	16%	16%	**0.88**
$\lvert\Delta m^2_{3\ell}\rvert$	17%	11%	9%	7.8%	6.7% [6.5%]	**2.5**
δ_{CP}	100%	100%	100%	100% [92%]	100% [83%]	**1 [1.2]**
$\Delta\chi^2_{\text{IO-NO}}$	±0.5	-0.97	$+0.83$	$+4.7$ [$+9.3$]	$+2.6$ [$+7.0$]	

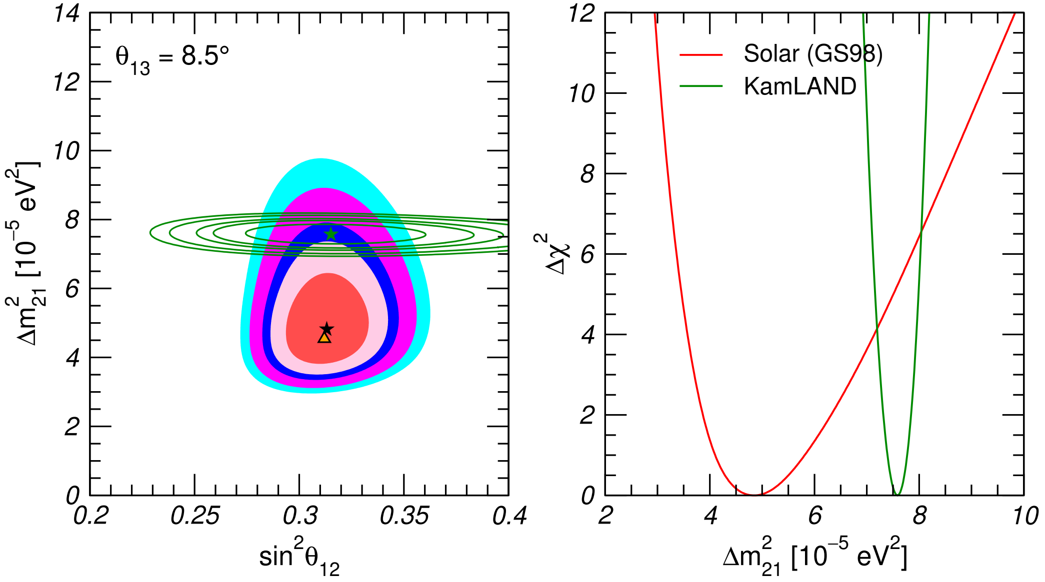
w/o [w] SK atm data

relat. precision at 3σ : $\frac{2(x^+ - x^-)}{(x^+ + x^-)}$

improvement factor from 2012 to 2021

- Last decade: after including $\theta_{13} \simeq 9^\circ$ the comparison of KamLAND vs Solar

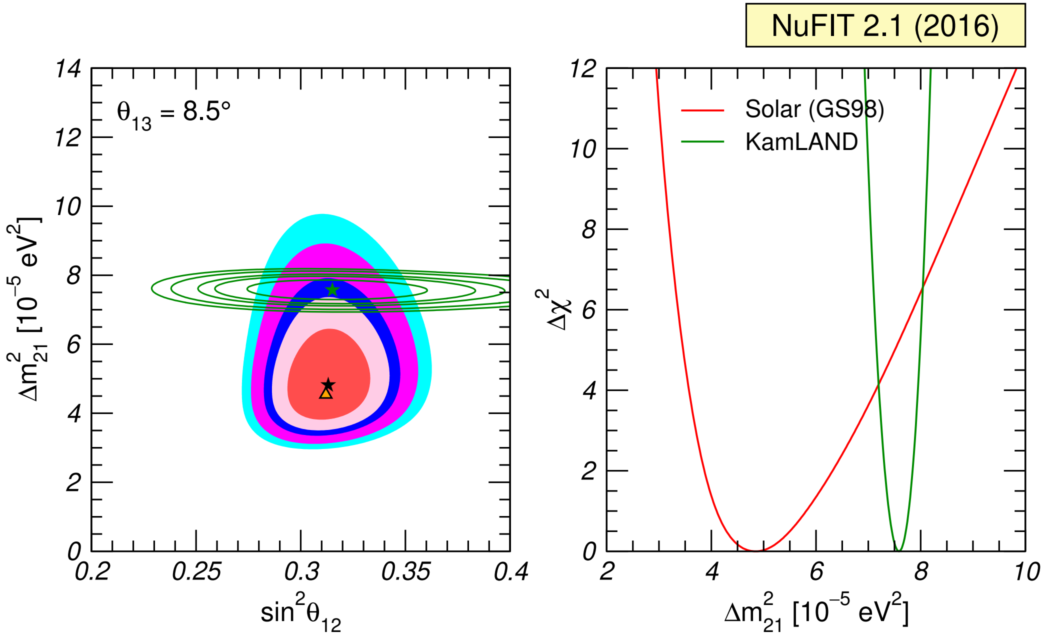
NuFIT 2.1 (2016)



θ_{12} better than 1σ agreement

But $\sim 2\sigma$ tension on Δm^2_{12}

- Last decade: after including $\theta_{13} \simeq 9^\circ$ the comparison of KamLAND vs Solar



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"too large" of Day/Night at SK

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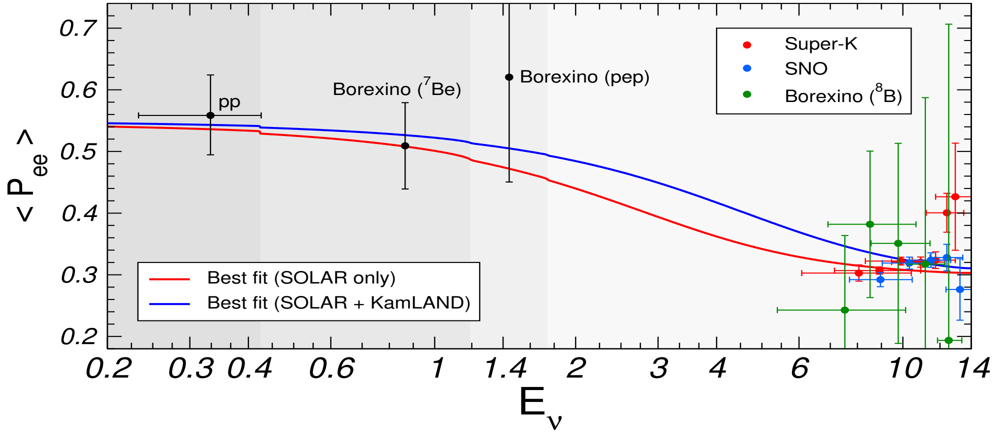

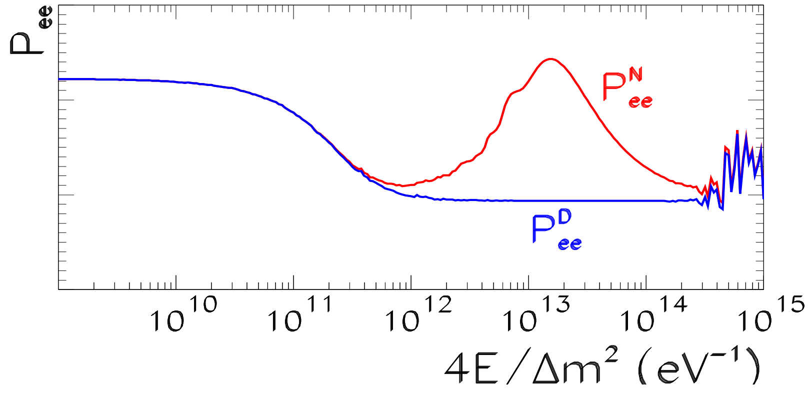

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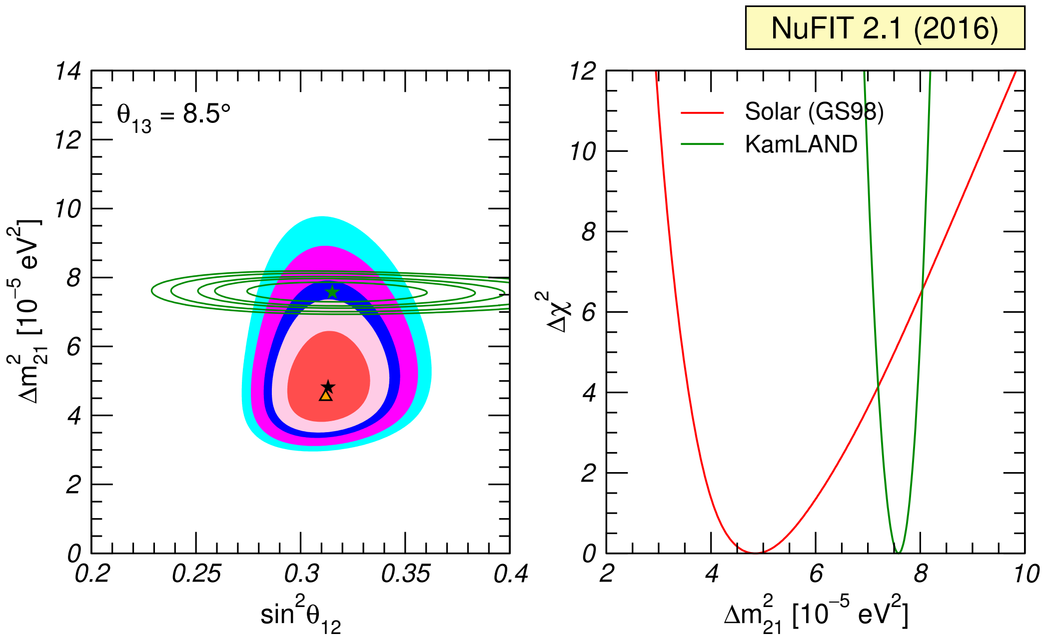

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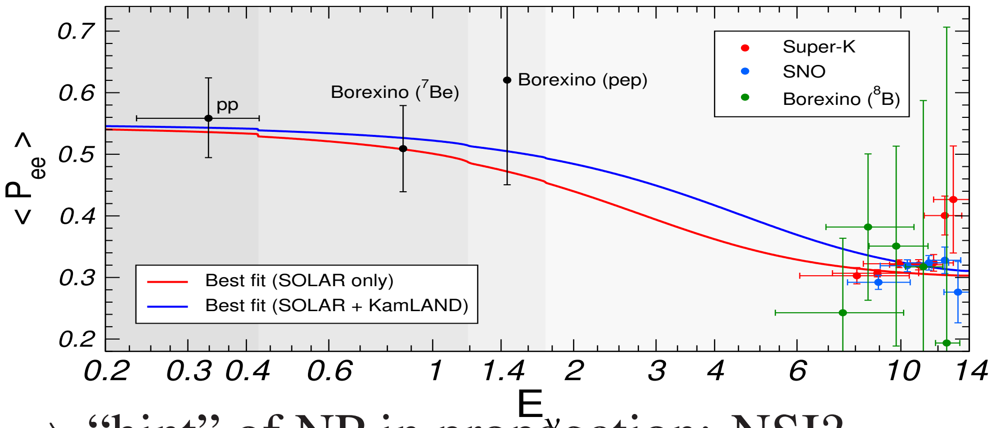

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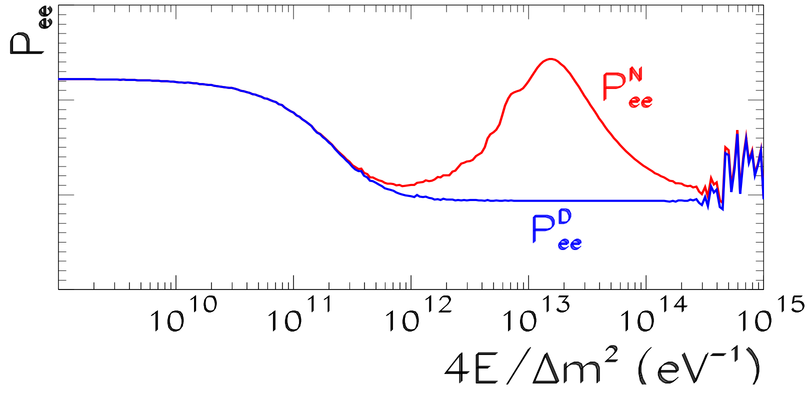
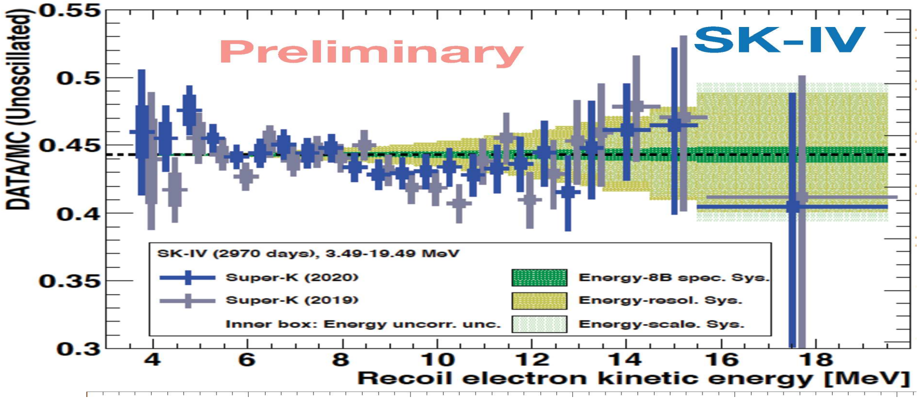


$\Rightarrow$ "hint" of NP in propagation: NSI?

- AFTER NU2020: With SK4 2970 days data

Slightly more pronounced low-E turn-up



Smaller of Day/Night at

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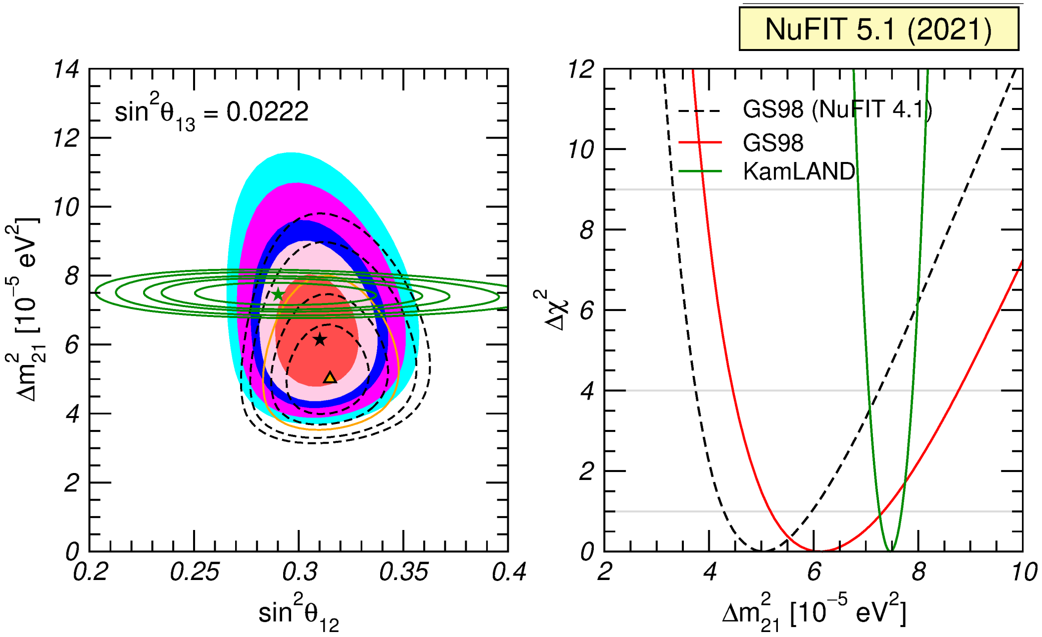
$$A_{\mathrm{D/N,SK4-2970}} = [-2.1 \pm 1.1]\%$$

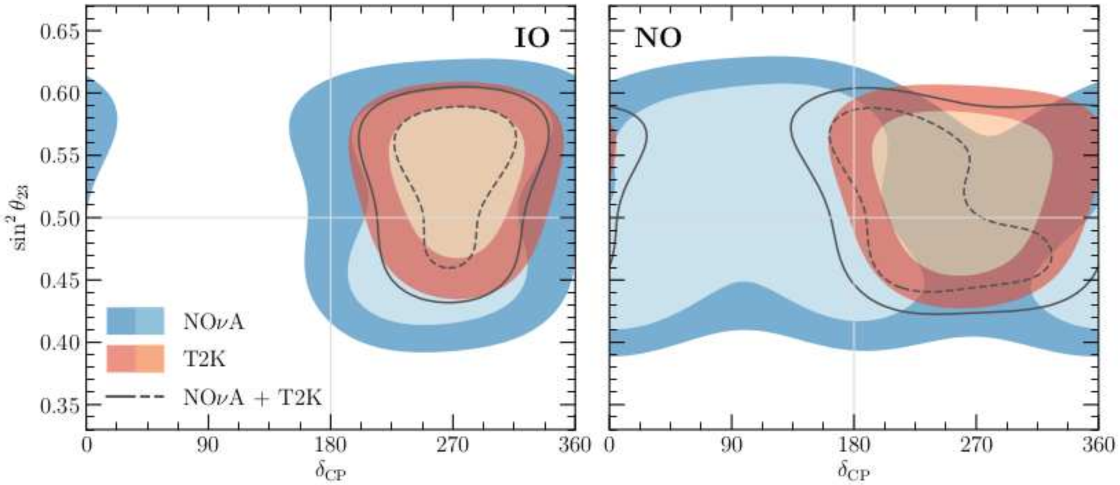
- In NuFIT 5.1



$\Rightarrow$ Agreement of Δm^2_{21} between solar and KamLAND at 1 σ

Compatibility T2K/NOνA

- 1 and 2 σ (2dof) allowed regions (for $s^2_{13} = 0.0224$, marg over $|\Delta m^2_{3\ell}|$)



$\Rightarrow$ Better agreement in IO but NO 1σ regions “touch”

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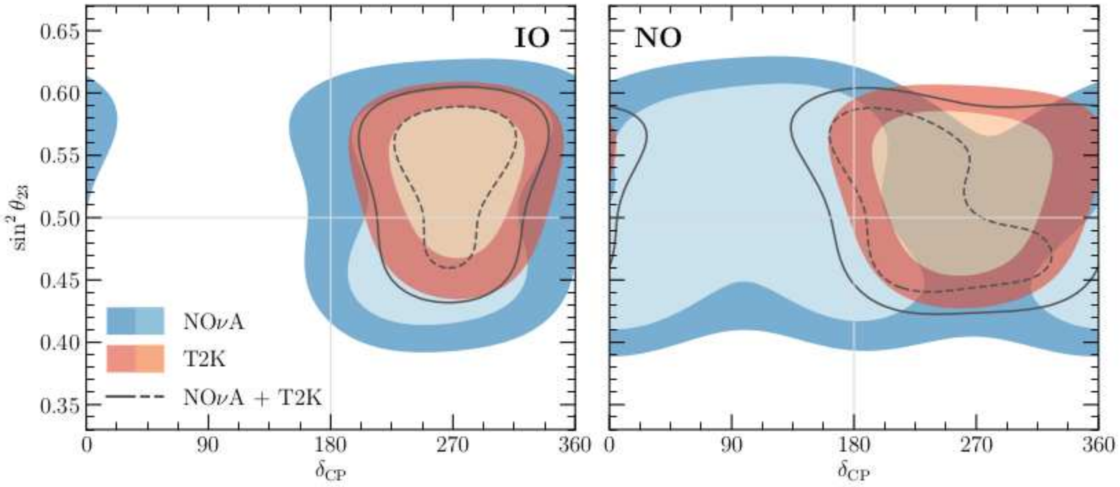

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- Parameter goodness-of-fit (PG) test:

	normal ordering			inverted ordering		
	$\chi^2_{\rm PG}/n$	p-value	#σ	$\chi^2_{\rm PG}/n$	p-value	#σ
T2K vs NOvA (θ_{13} free)	6.7/4	0.15	1.4σ	3.6/4	0.46	0.7σ
T2K vs NOvA (θ_{13} fix)	6.5/3	0.088	1.7σ	2.8/3	0.42	0.8σ

No significant
incompatibility

Δm^2_{3l} in LBL & Reactors

- At LBL determined in ν_μ and $\bar\nu_\mu$ disapperance spectrum

$$\Delta m^2_{\mu\mu} \simeq \Delta m^2_{3l} + \begin{matrix} c^2_{12}\Delta m^2_{21} & \text{NO} \\ s^2_{12}\Delta m^2_{21} & \text{IO} \end{matrix} + \ldots$$

- At MBL Reactors (Daya-Bay, Reno, D-Chooz) determined in $\bar\nu_e$ disapp spectrum

$$\Delta m^2_{ee} \simeq \Delta m^2_{3l} + \begin{matrix} s^2_{12}\Delta m^2_{21} & \text{NO} \\ c^2_{12}\Delta m^2_{21} & \text{IO} \end{matrix}$$

Nunokawa,Parke,Zukanovich (2005)

⇒ Contribution to NO/IO from combination of LBL with reactor data

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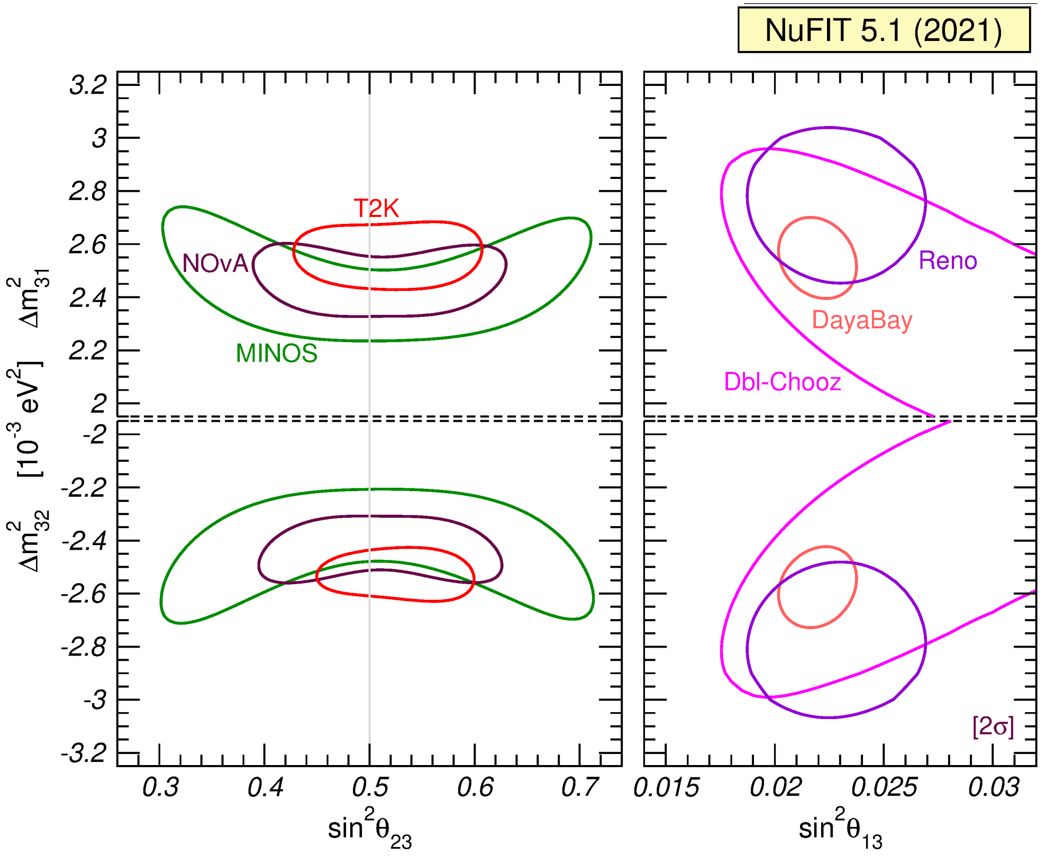
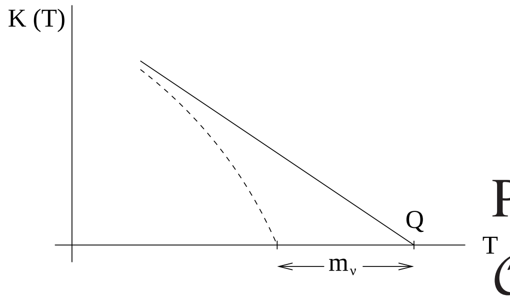


Neutrino Mass Scale

Concha Gonzalez-Garcia 25-32

Single β decay : Pure kinematics, Dirac or Majorana ν's, only model independent

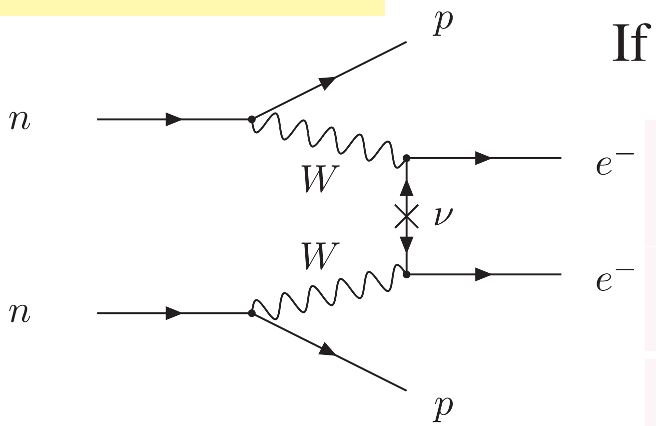


$$m_{\nu_e}^2 = \sum m_j^2 |U_{ej}|^2 = \begin{cases} \text{NO}: \ m_\ell^2 + \Delta m_{21}^2 c_{13}^2 s_{12}^2 + \Delta m_{31}^2 s_{13}^2 \\ \text{IO}: \ m_\ell^2 + \Delta m_{21}^2 c_{13}^2 s_{12}^2 - \Delta m_{31}^2 c_{13}^2 \end{cases}$$

Present bound: $m_{\nu_e} \leq 2.0$ eV (95% CL Mainz&Troisk exp)

$\mathcal{O}$(eV) bound from Katrin Talk by Lassere

ν-less Double-β decay: $\Leftrightarrow$ Majorana $\nu' s$



If m_ν only source of ΔL $\quad T_{1/2}^{0\nu} = \dfrac{m_e}{G_{0\nu}\, M_{\text{nucl}}^2\, m_{ee}^2}$

$$m_{ee} = |\sum U_{ej}^2 m_j|$$

$$= \left| c_{13}^2 c_{12}^2 m_1\, e^{i\eta_1} + c_{13}^2 s_{12}^2 m_2\, e^{i\eta_2} + s_{13}^2 m_3\, e^{-i\delta_{CP}} \right|$$

$$= f(m_\ell, \text{order}, \text{maj phases})$$

Present Bounds: $m_{ee} < 0.06$–0.76 eV

Talks by Lenhert, Chiu

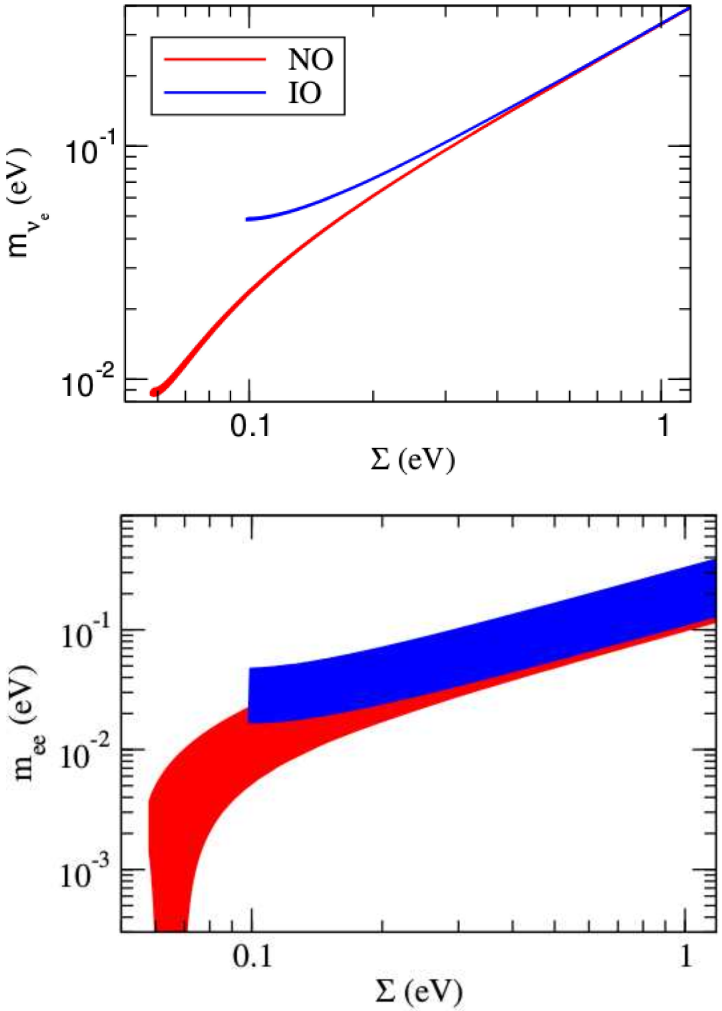
COSMO for Dirac or Majorana
m_ν affect growth of structures

$$\sum m_i = \begin{cases} \text{NO}: \ \sqrt{m_\ell^2} + \sqrt{\Delta m_{21}^2 + m_\ell^2} + \sqrt{\Delta m_{31}^2 + m_\ell^2} \\ \text{IO} \ \ \sqrt{m_\ell^2} + \sqrt{-\Delta m_{31}^2 - \Delta m_{21}^2 - m_\ell^2} + \sqrt{-\Delta m_{31}^2 - m_\ell^2} \end{cases}$$

Neutrino Mass Scale: The Cosmo-Lab Connection

Global oscillation analysis⇒ Correlations m_{ν_e}, m_{ee} and $\sum m_\nu$(Fogli *et al* (04))

NuFIT 4.1 (2019)



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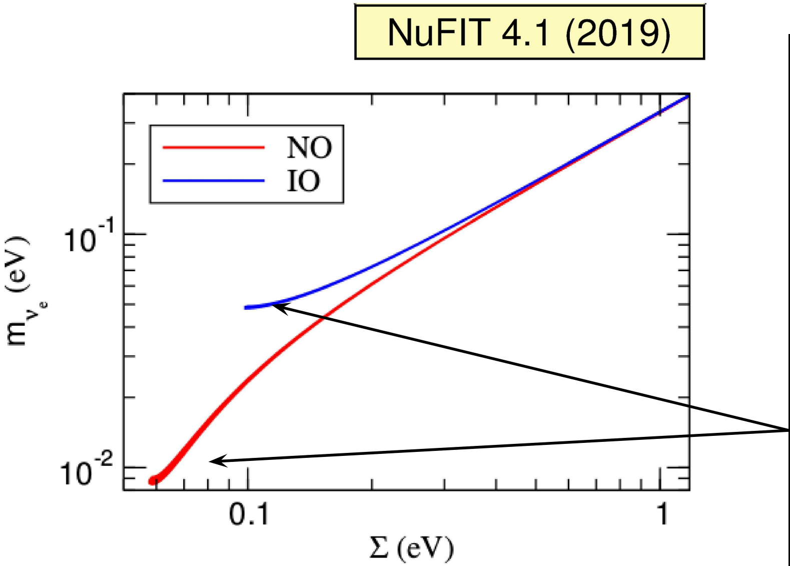

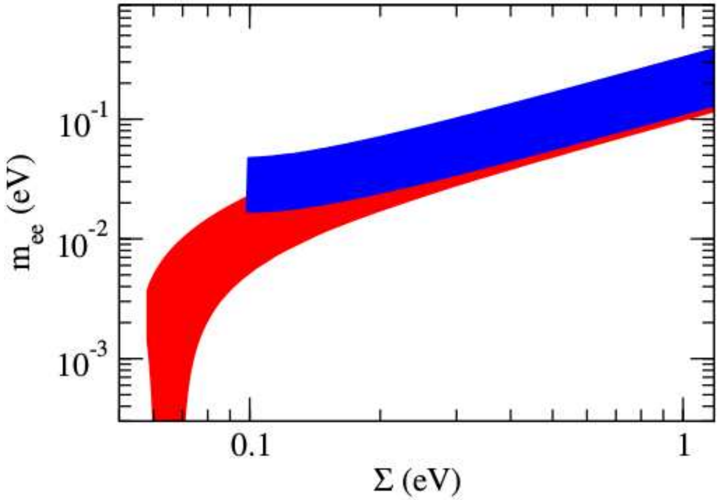

Lower bound on $\sum m_i$ depends on ordering

Precision determination/bound of $\sum m_i$ can give information on ordering ?

Hannestad, Schwetz 1606.04691, Simpson etal 1703.03425, Capozzi etal 1703.04471 . . .

Cosmo data will only add to N/I likelihood
when accuracy on Σm_ν better than 0.02 eV
(to see a 2σ N/I difference between 0.06 and 0.1)

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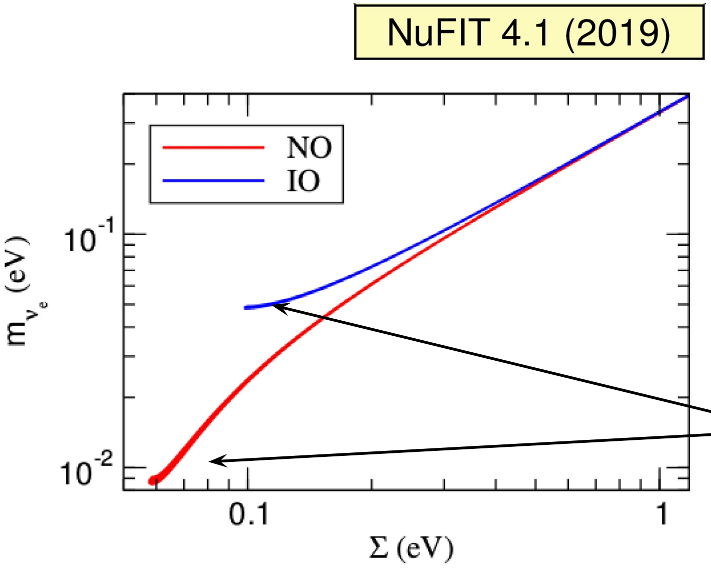

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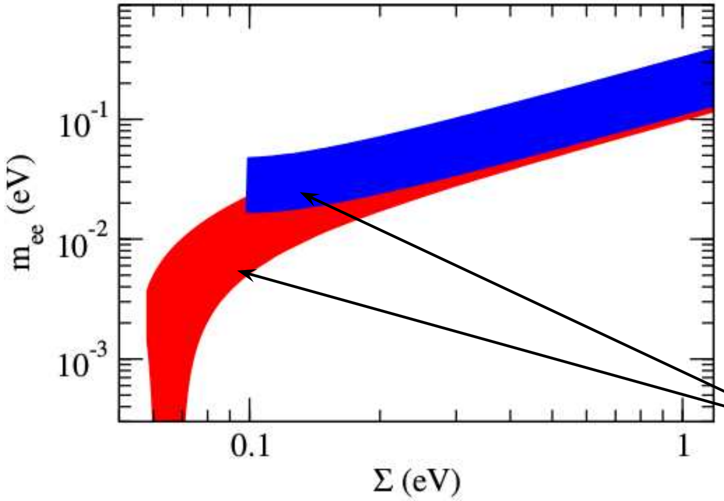

Wide band due to unknown Majorana phases ⇒ Possible Det of Maj phases?

Bottom-up: Light ν from *Generic* New Physics

If SM is an effective low energy theory, for $E \ll \Lambda_{\rm NP}$

– The same particle content as the SM and same pattern of symmetry breaking

– But there can be non-renormalizable (dim>4) operators

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_n \frac{1}{\Lambda_{\rm NP}^{n-4}} \mathcal{O}_n$$

First NP effect ⇒ dim=5 operator

There is only one!

$$\mathcal{L}_5 = \frac{Z^\nu_{ij}}{\Lambda_{\rm NP}} \left(\overline{L_{L,i}} \tilde{\phi}\right) \left(\tilde{\phi}^T L^C_{L,j}\right)$$

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Implications:

– It is natural that ν mass is the first evidence of NP

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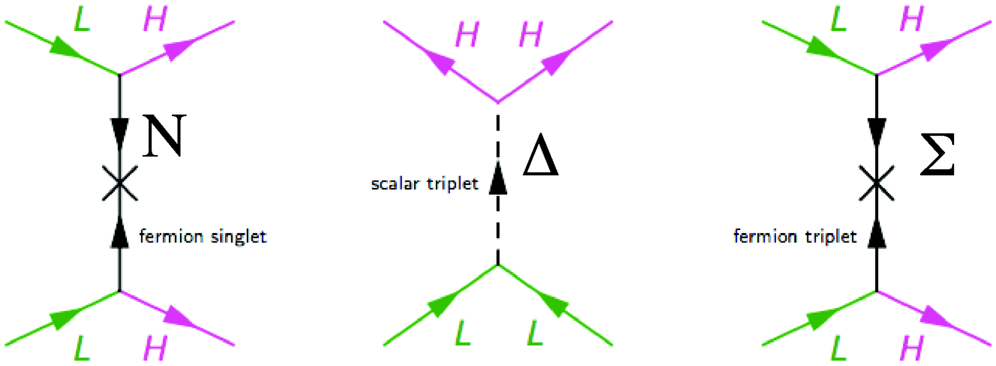
– $m_\nu > \sqrt{\Delta m^2_{\rm atm}} \sim 0.05$ eV for $Z^\nu \sim 1 \Longrightarrow \Lambda_{\rm NP} \sim 10^{15}{\rm GeV} \Longrightarrow$ $\Lambda_{\rm NP} \sim$ GUT scale

$\Rightarrow$ Leptogenesis possible

[But if $Z^\nu \sim (Y_e)^2 \Rightarrow \Lambda_{\rm NP} \sim$ TeV scale]

Model Degeneracy at Low Energy

$\mathcal{O}_5$ is generated for example by tree-level exchange of singlet ($N_i \equiv (1,1)_0$) (Type-I) or triplet fermions ($N_i \equiv \Sigma_i \equiv (1,3)_0$) (Type-III) or a scalar triplet $\Delta \equiv (1,3)_1$ (Type-II)



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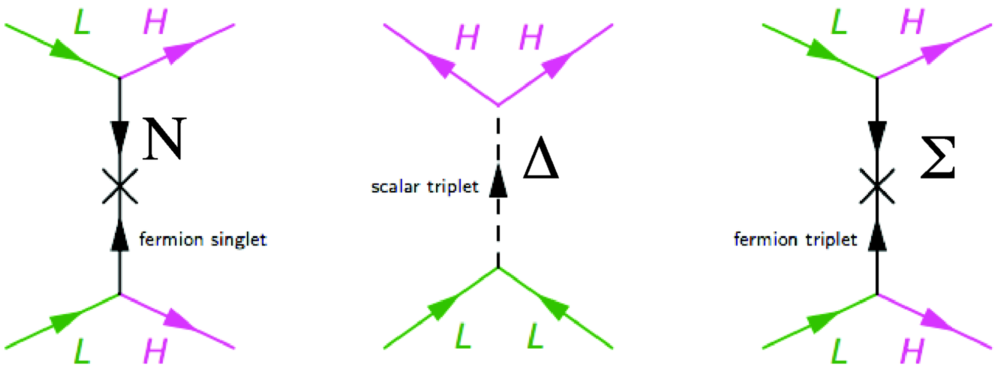

- For fermionic see-saw $-\mathcal{L}_{\rm NP} = -i\overline{N_i}\not{\partial} N_i + \frac{1}{2} M_{N_{ij}} \overline{N_i^c} N_j + \lambda^\nu_{\alpha j} \overline{L_\alpha}\tilde{\phi} N_j [.\tau]$

$$\Rightarrow \mathcal{O}_5 = \frac{(\lambda^{\nu T}\lambda^\nu)_{\alpha\beta}}{\Lambda_{\rm NP}} \left(\overline{L_\alpha}\tilde{\phi}\right)\left(\tilde{\phi}^T L^C_\beta\right) \qquad \text{with} \quad \Lambda_{\rm NP} = M_N$$

- For scalar see-saw $-\mathcal{L}_{\rm NP} = f_{\Delta_{\alpha\beta}} \overline{L_\alpha}\,\Delta\, L^C_\beta + M^2_\Delta\,|\Delta|^2 + \kappa\,\phi^T\,\Delta^\dagger\,\phi\ \ldots$

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Very different physics, but same ν parameters: How to proceed?

Model Degeneracy at Low Energy

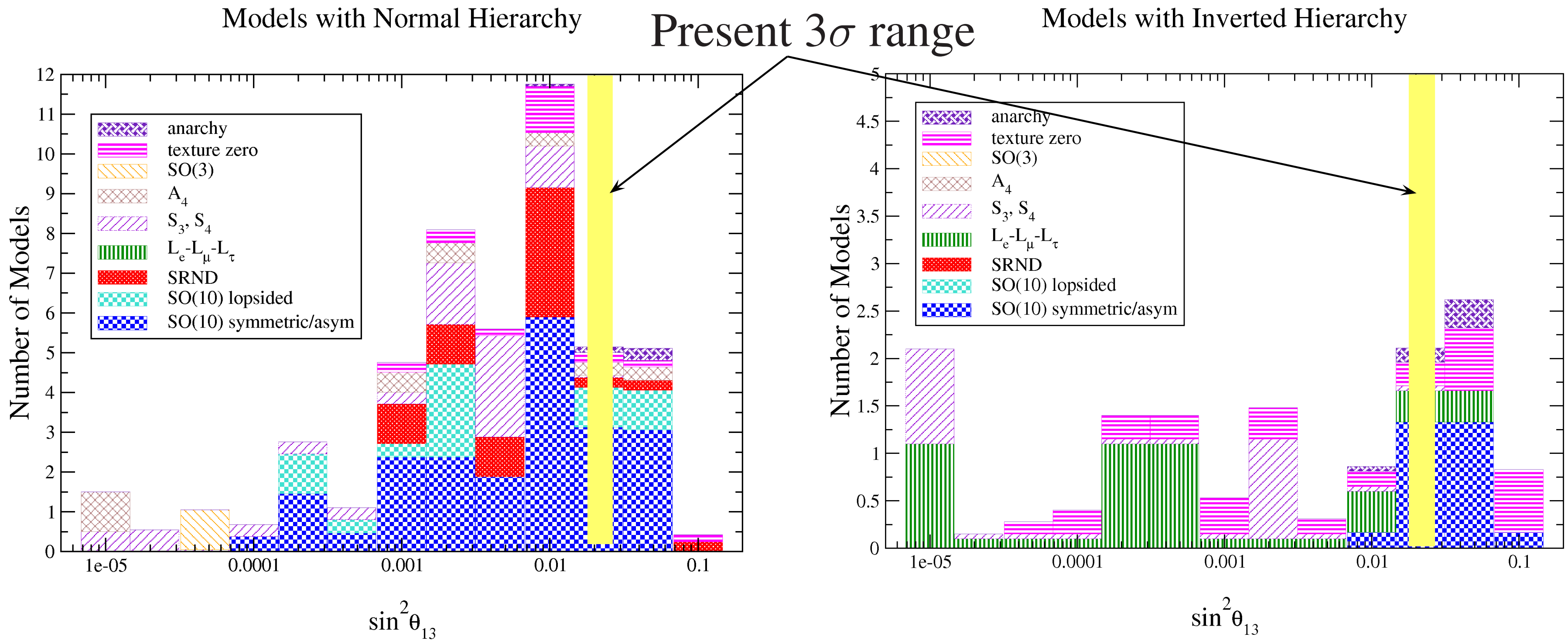
Same $\mathcal{O}_5$ can be generated by very different High Energy physics

Very different physics, but same ν parameters: How to proceed?

– Top-down: Assume some specific model and work out the relations

Modeling Lepton Flavour: 2006 to 2022

- Survey of 63 ν mass models in 2006 (Albright, M-C Chen,hep-ph/0608136)



– Determination of θ_{13} has given us important handle in flavour modeling

– Next *frontier* is the ordering

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– Hope/Wait for additional information from charged LFV, collider signals …

Connection to LFV & Collider Signatures?

- ν oscillation $\Rightarrow$ Lepton Flavour is not conserved

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  So may be

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  New Physics scale Λ_{LN} responsible for the small m_ν from

  New Physics scale Λ_{LF} ($\ll \Lambda_{LN}$) controlling of LFV

- Collider signatures if heavy state mass $M \sim \Lambda_{LN} \sim \text{TeV}$ and/or $M \sim \Lambda_{LF} \sim \text{TeV}$

  If $M \sim \Lambda_{LF} \sim \text{TeV}$ ($\ll \Lambda_{LN}$) motivation of light ν OK

  Furthermore if $c_{6,i} \propto c_5{}^{\text{some power}} \Rightarrow$ LFV and coll signals directly related to M_ν

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Minimal Lepton Flavour Violation

Cirigliano, Grinstein, Isidori, Wise(05); Davidson, Palorini (06); Gavela, Hambye, Hernandez,Hernandez (09)
Alonso, Isidori, Merlo, Munoz, Nardi(11)

MLFV & Collider Signatures

Gonzalez-Garcia 25-40

- Minimal Flavour Violation Hypothesis: Chivukula, Georgi (87) Buras, Gambino, Gorbahn, Jager, Silvestrini,(01) d'Ambrosio, Giudice, Isidori, Strumia (02)

  Yukawas are the only source of flavour violation in and beyond SM

  Very predictive and successful to explain quark flavour data

  For leptons more subtle since BSM fields are required to generate majorana M_ν

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- Scalar (Type-II) see-saw is MLFV

$$c_{5,\alpha\beta} = f_{\Delta\,\alpha\beta}\frac{\mu}{M_\Delta} \qquad c_{6,\alpha\beta\gamma\rho} = f^\dagger_{\Delta\,\alpha\beta} f_{\Delta\,\gamma\rho}$$

- If $M_\Delta \lesssim$ TeV

$\Rightarrow$ Production of triplet scalars: $H^{\pm\pm}\ H^{\pm}$, A_0, H_0

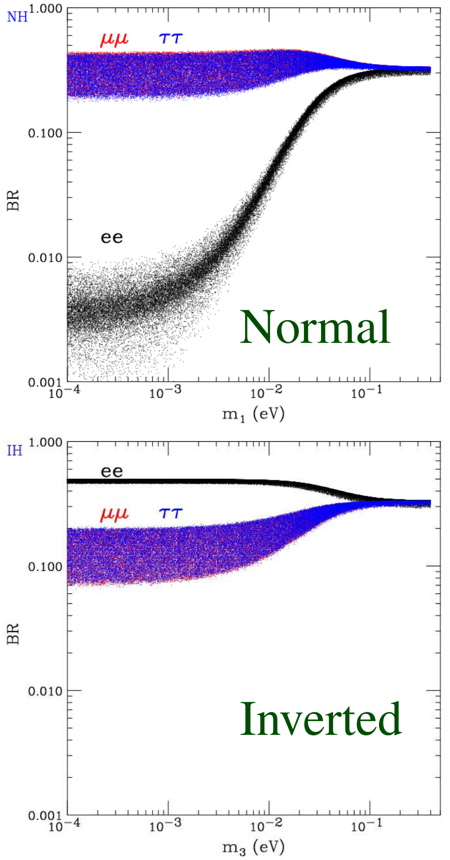
Striking Signatures

$$pp \to H^{++}H^{--}$$

$$pp \to H^{++}H^{-}$$

$\Rightarrow \quad H^{\pm\pm} l_i^\pm l_j^\pm,\ H^\pm \to l_i^\pm \nu_j$

predicted by neutrino parameters



Akeroyd *et al*, Chao *et al*, Fileviez *et al*,
Garayoa *et al*, Han *et al*, Kadastik *et al* . . .

MLFV & Collider Signatures

- MLFV Fermionic (I or III) Inverse see-saw

  Gavela, Hambye, Hernandez,Hernandez (09)

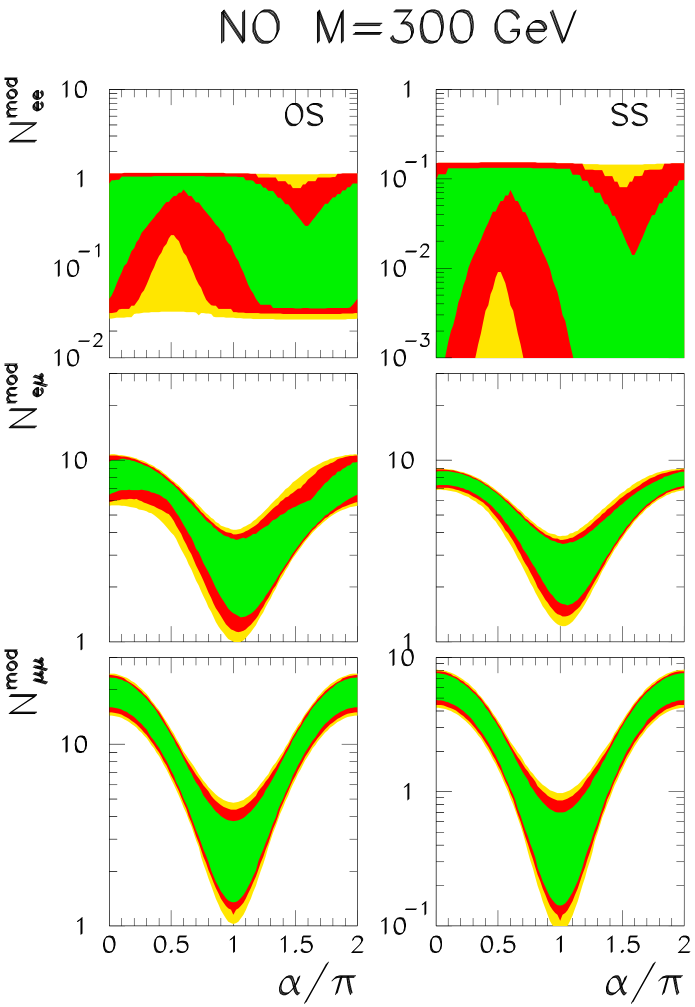
  → one massless ν & one CP phase α

  → Yukawas $\lambda_{\alpha N}$ determined by ν parameters

- At LHC:
  - Type-I unobservable but Type-III observable

    $$pp \to F(\to \ell_\alpha X)F'(\to \ell_\beta X')$$

  - Rates predictable in terms of ν parameters
  - Unambiguous constraints from existing data
  - Best with final state flavour and charge info



Rosa-Agostinho,Eboli, MCGG 1708.08456

Beyond 3ν's: Light Sterile Neutrinos

- Several Observations which can be Interpreted as Oscillations with $\Delta m^2 \sim \text{eV}^2$

LSND &MiniBoone

LSND 2001:

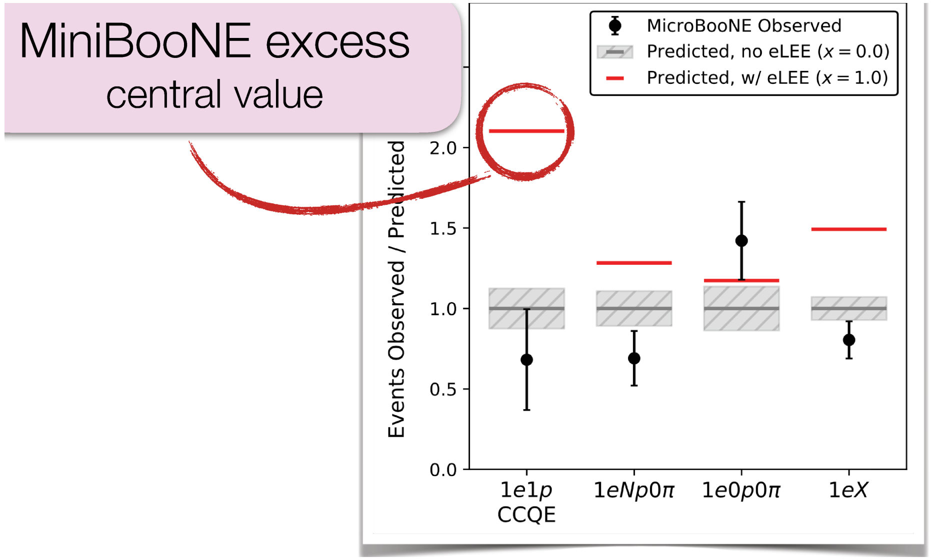
Signal $\nu_\mu \to \nu_e$ (3.8 σ)

MiniBooNE 2020:

$\bar\nu_\mu \to \bar\nu_e$ & $\nu_\mu \to \nu_e$

(639 $\pm$ 132.8 events)

MicroBooNE 2021/2022:



MiniBooNE excess central value

No support for excess ν_e interpretation in MiniBooNE

(Fig from Kopp's ν2022 talk)

MicroBooNE Coll.

2110.14054

Z' Models: Viable models for LMA-D

Coloma, MCGG, Maltoni,JHEP'21 [2009.14220]