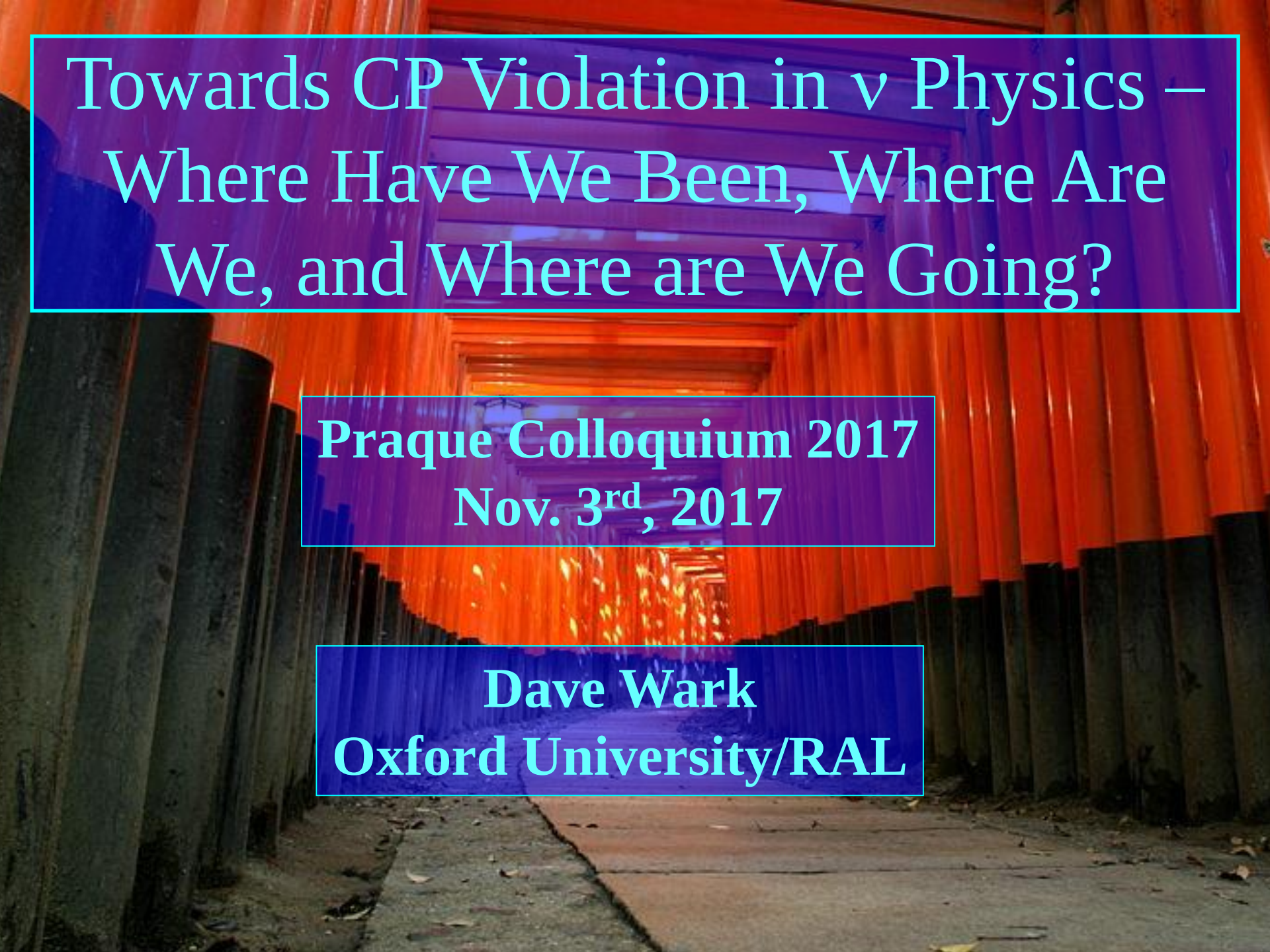


Towards CP Violation in ν Physics – Where Have We Been, Where Are We, and Where are We Going?

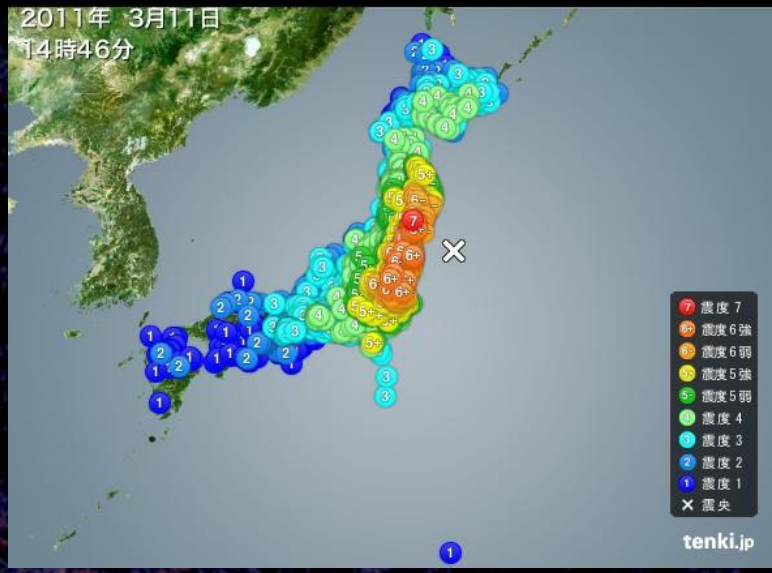
Praque Colloquium 2017
Nov. 3rd, 2017

Dave Wark
Oxford University/RAL

Where have we come during the Prague Colloquia?

- This is the 4th Praque Colloquium in the "Towards CP Violation in ν Physics" series.
- The first was in 2011, then 2013 and 2015.
- Where were we in 2011?

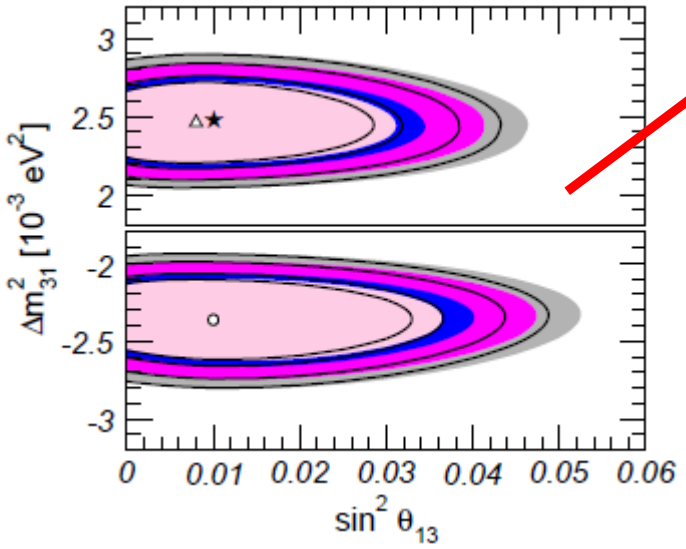
5/11, 14:46, all
Hell broke loose...

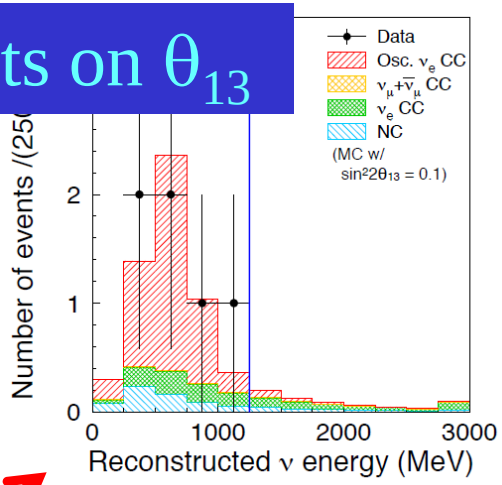


The outside world was giving us issues. . .

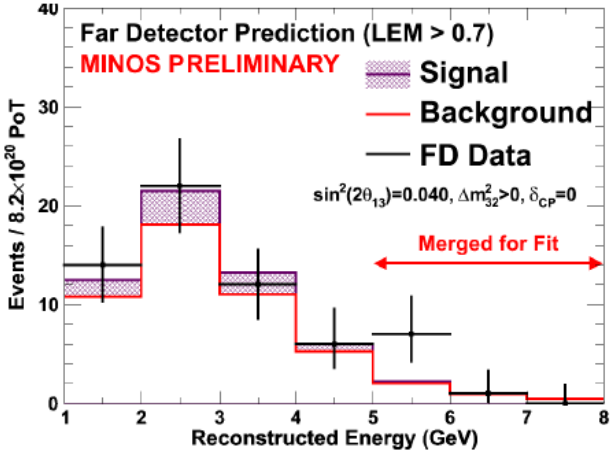
No CP info, just hints on θ_{13}

What about θ_{13}?





T2K (2.5σ)



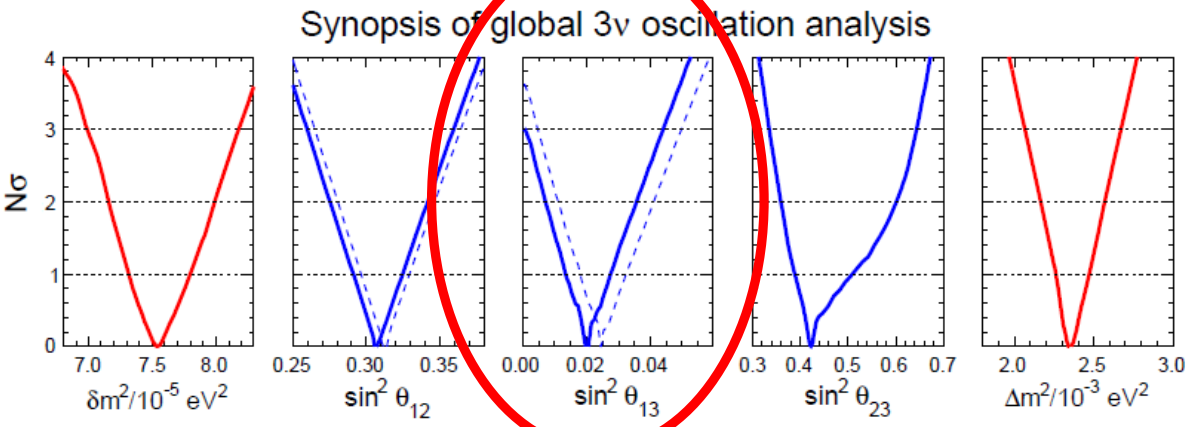
MINOS (1.7σ)

ν_e appearance, $\theta_{13} > 0$?

Interesting hints that $\theta_{13} > 0$, but clearly more data needed.

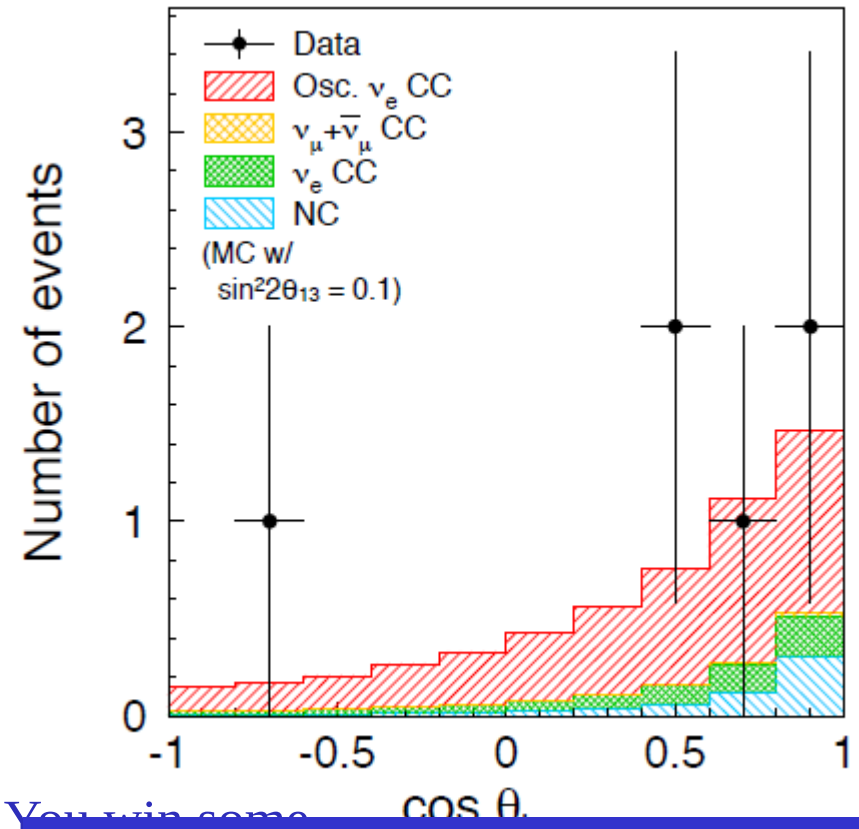
Evidence of $\theta_{13} > 0$ from global neutrino data analysis

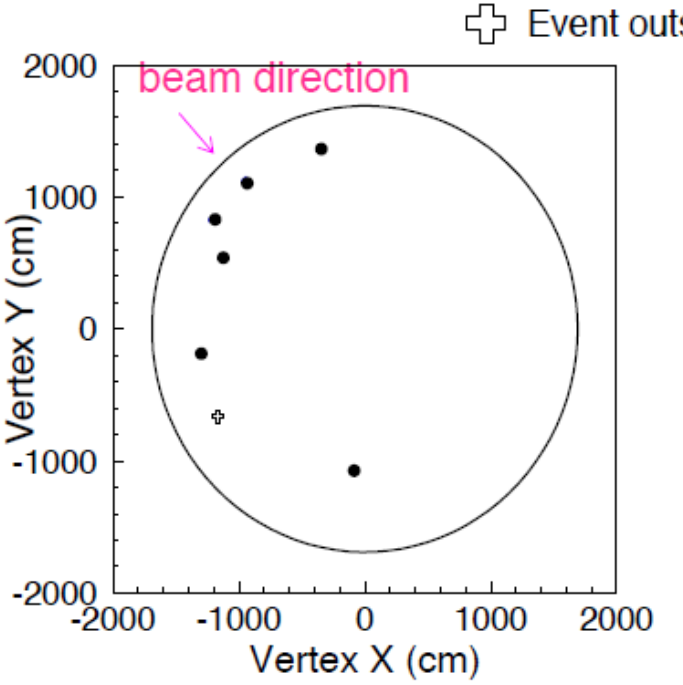
G.L. Fogli,[1,2] E. Lisi,[2] A. Marrone,[1,2] A. Palazzo,[3] and A.M. Rotunno[1]



arXiv:1106.6028v1 [hep-ph] 29 Jun 2011

Check many distributions....

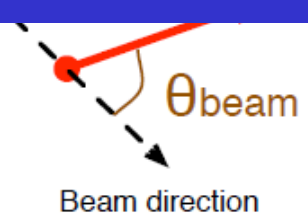


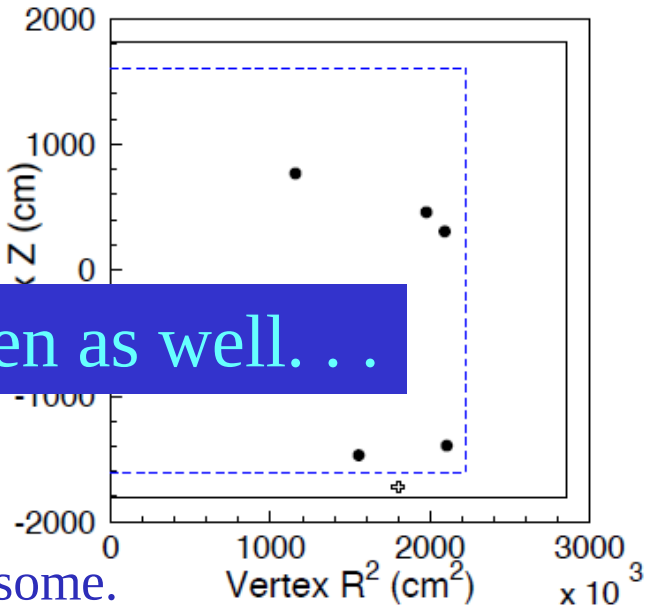


No excess outside FV or in OD,
but KS prob. for R^2 is ~3%

You win some.

We had our statistical oddities then as well. . .





You lose some.

We had theorists leading us (astray?).

An incremental approach to CP ?

- **Excitement ➡ H. Murayama presented his (anarchical) prediction for mixing angles θ_{12},θ_{23},θ_{13} which hinted at a large θ_{13}**

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\frac{\Delta m^2_{12} L}{4E} \sin\frac{\Delta m^2_{13} L}{4E} \sin\frac{\Delta m^2_{23} L}{4E}$$

all parameters turned out to be favorable !!!

- **What about δ_{CP} ?**
  - ➡ the favorable values δ_{CP}=90, 270° are still allowed. Will Nature be kind again ?
  - ➡ if so, one could find evidence for CP violation in the lepton sector early on
  - ➡ if not, we can upgrade the sensitivity by increasing the far detector mass and/or beam power

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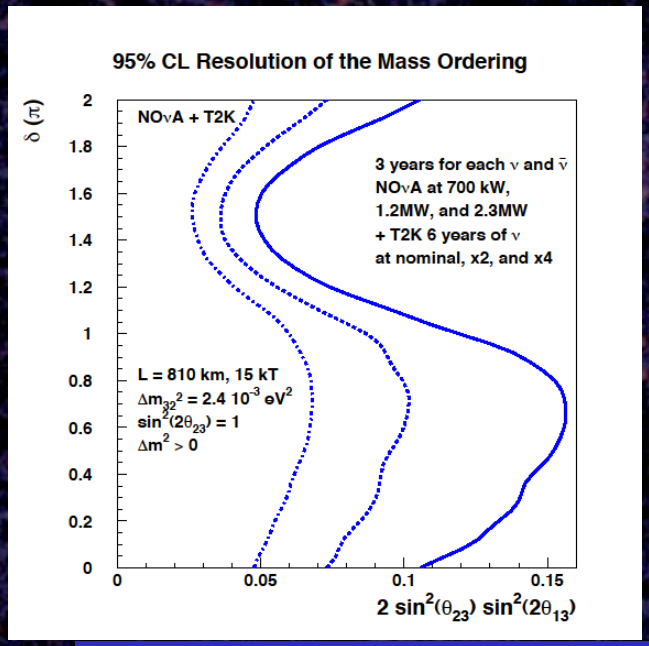
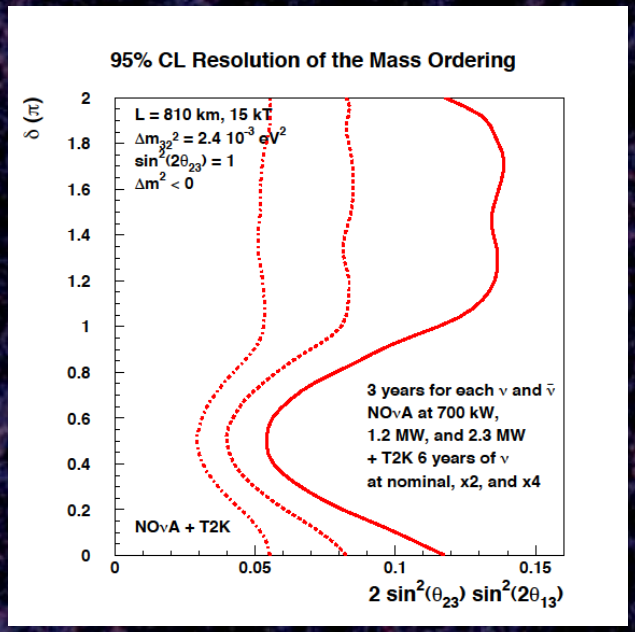
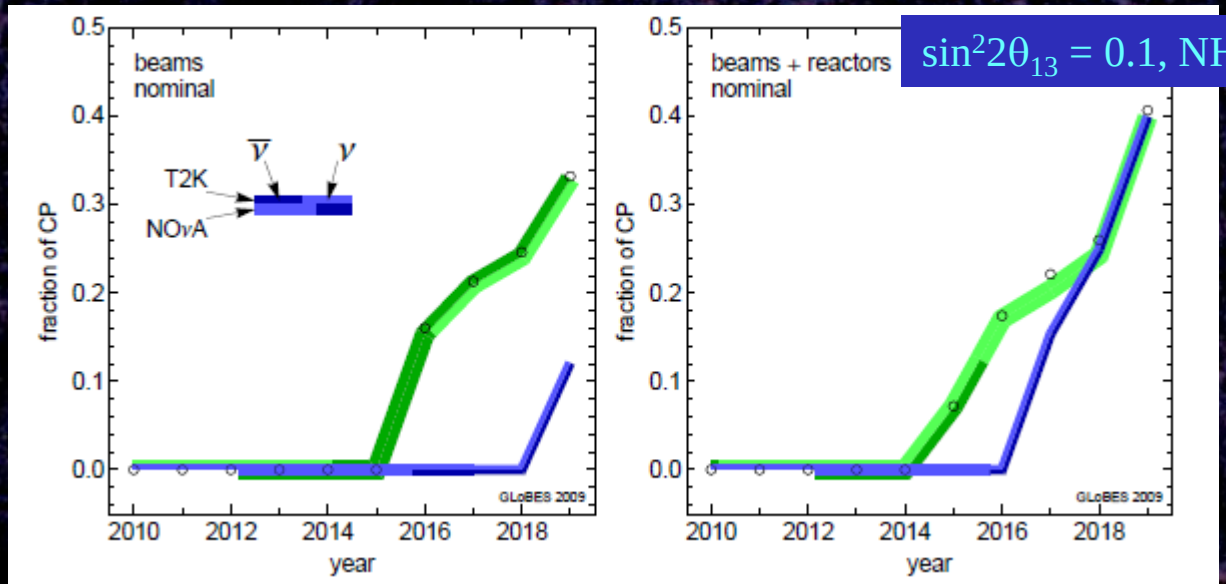
What will existing experiments yield?





Even some 90% CP violation sensitivity...



arXiv:0907.1896v1 [hep-ph] 10 Jul 2009

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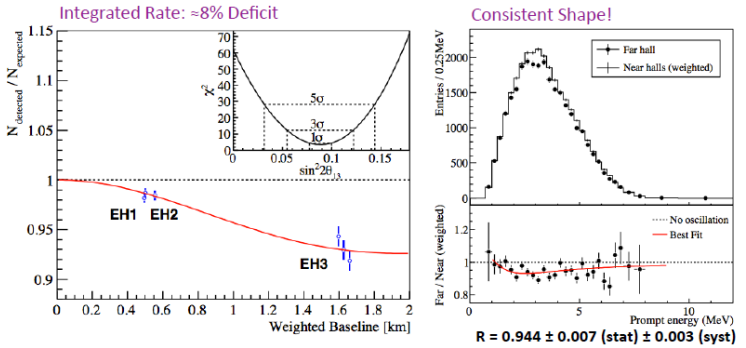
The Triumph of the Reactors!

Daya Bay

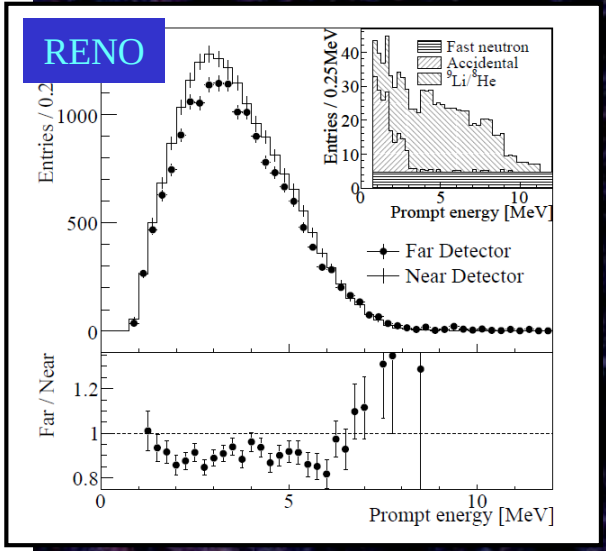
Daya Bay Observes Non-Zero Theta13

$\sin^2 2\theta_{13} = 0.089 \pm 0.010\ (\text{stat}) \pm 0.005\ (\text{syst})$



- standard χ^2 approach.
- far vs. near relative measurement (absolute rate is not constrained).
- consistent results obtained by independent analyses, different reactor flux models.

RENO



Semi-Double-Chooz

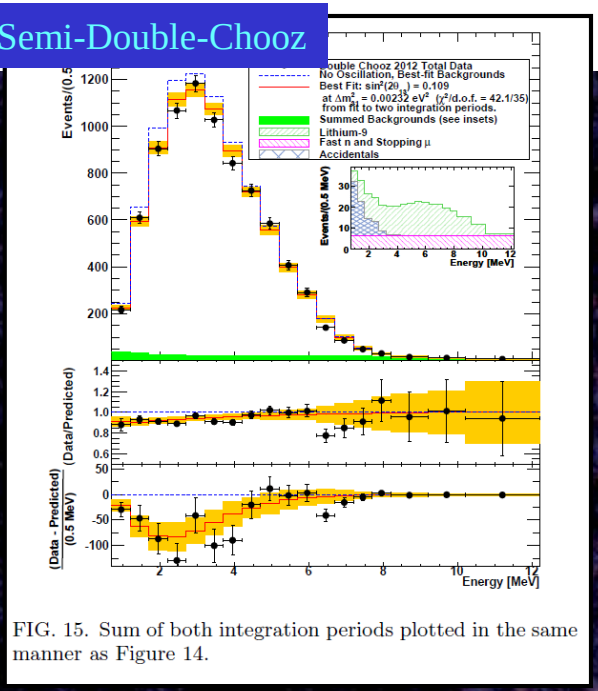
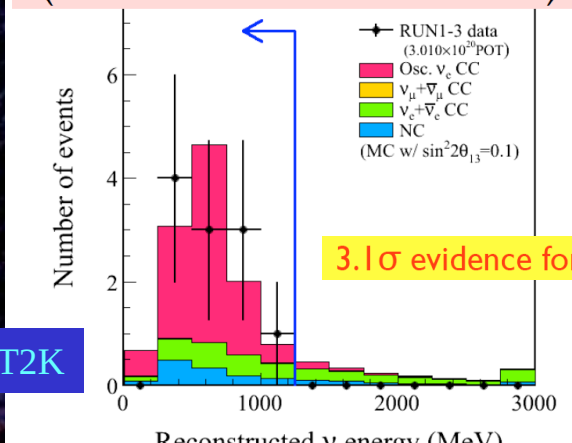


FIG. 15. Sum of both integration periods plotted in the same manner as Figure 14.

Hints of appearance had become evidence. . .

11 νe candidates observed!!
(3.3±0.4 if $\sin^2 2\theta_{13}=0$ → 3.1σ)



3.1σ evidence for ν_e appearance

T2K

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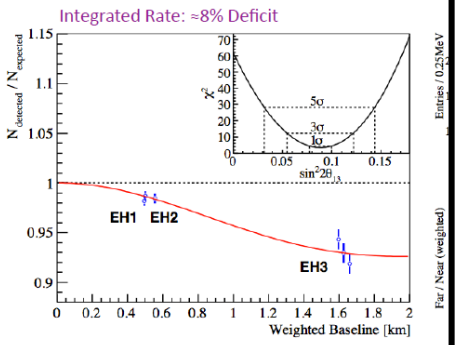
Daya Bay Observes Non-

$\sin^2 2\theta_{13} = 0.089 \pm 0.010$ (st



- standard χ^2 approach.
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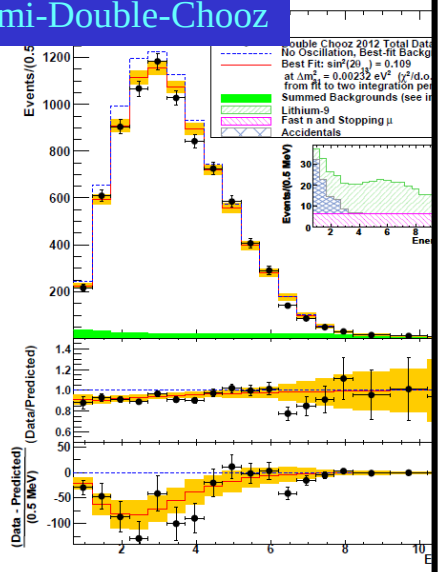
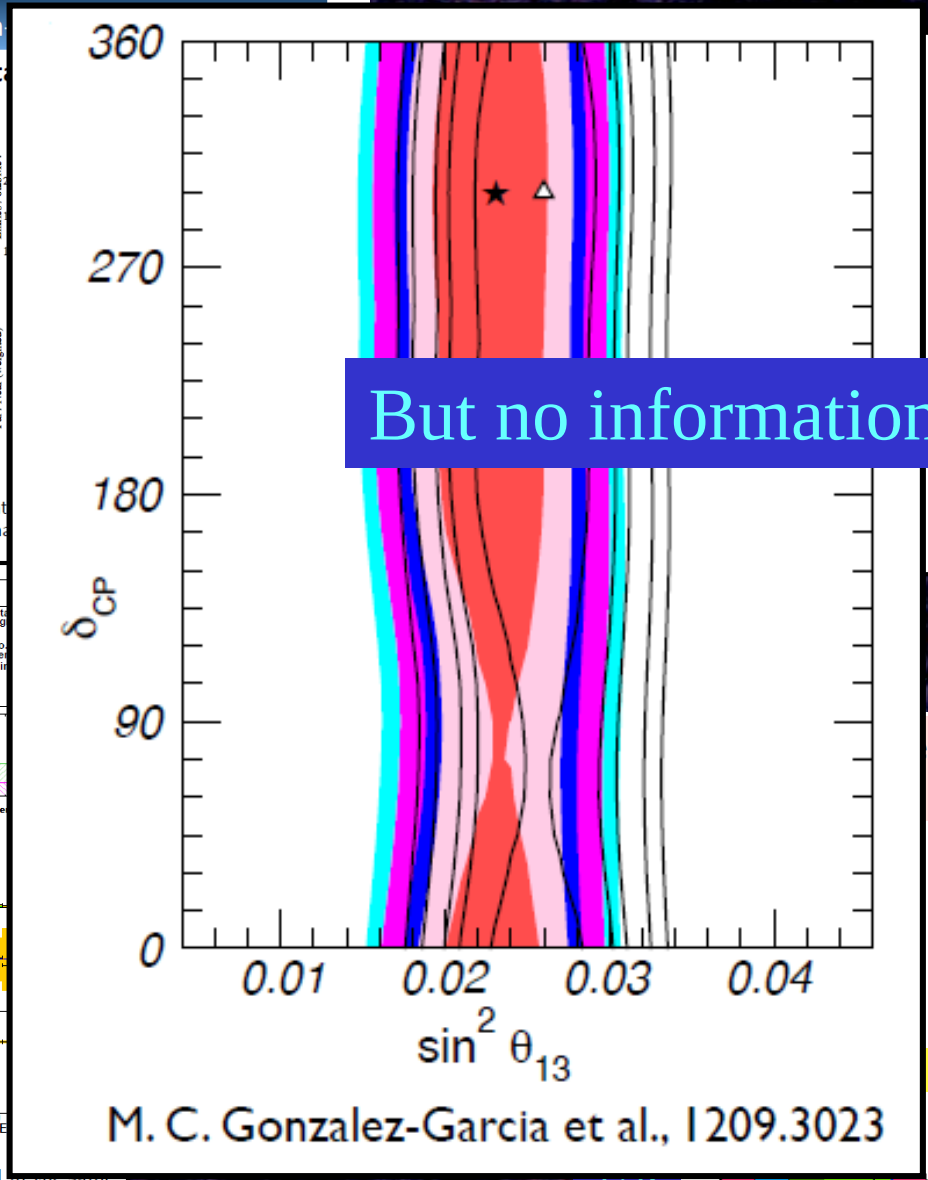


FIG. 15. Sum of both integration periods plotted in the same manner as Figure 14.

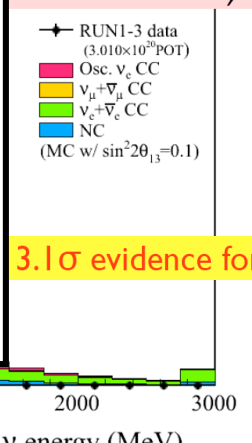


M. C. Gonzalez-Garcia et al., 1209.3023

But no information on CP!

ome evidence. . .

s observed!!
$_{13}$=0 → 3.1σ)



3.1σ evidence for ν_e appearance

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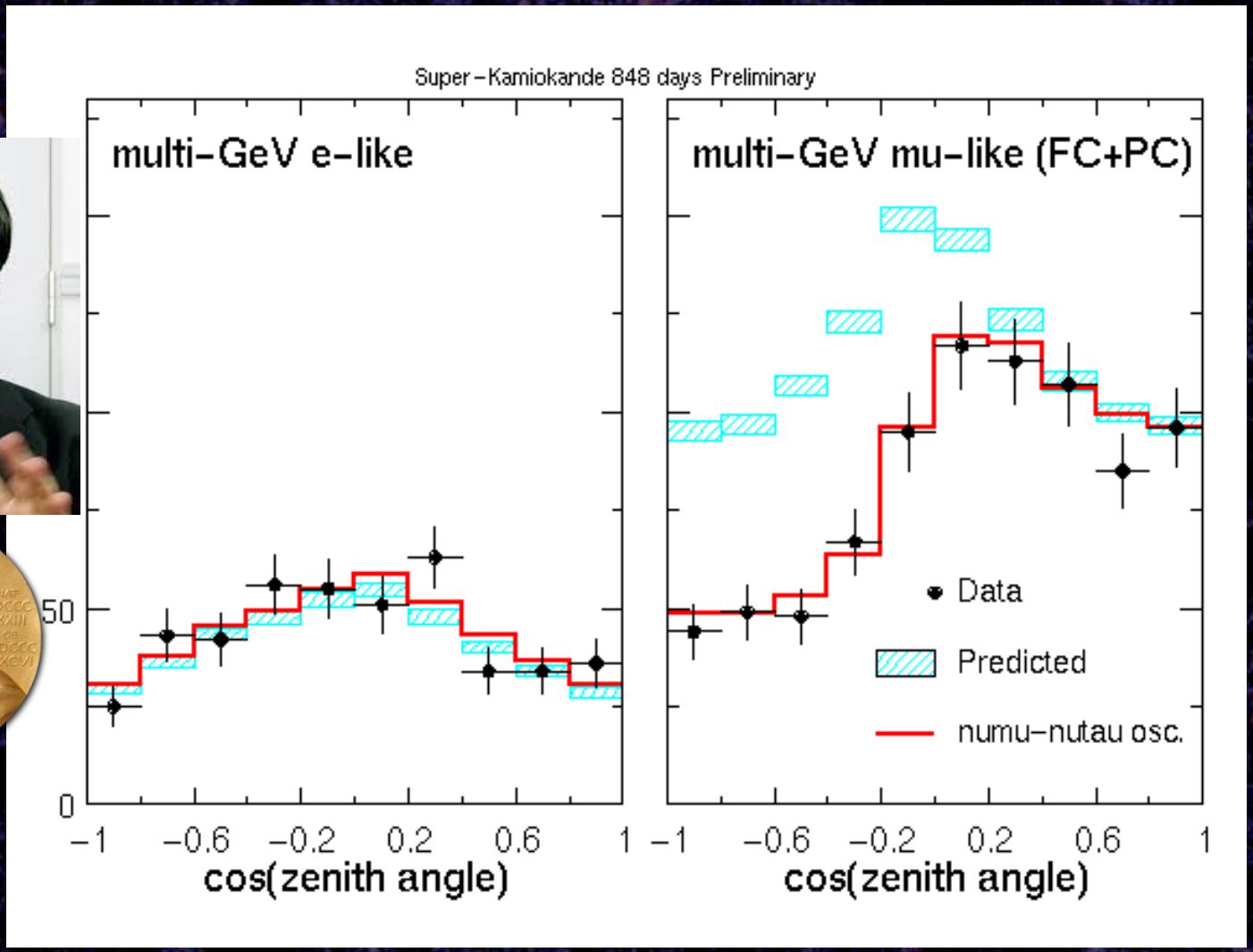
SK atmospheric ν data as a function of zenith angle



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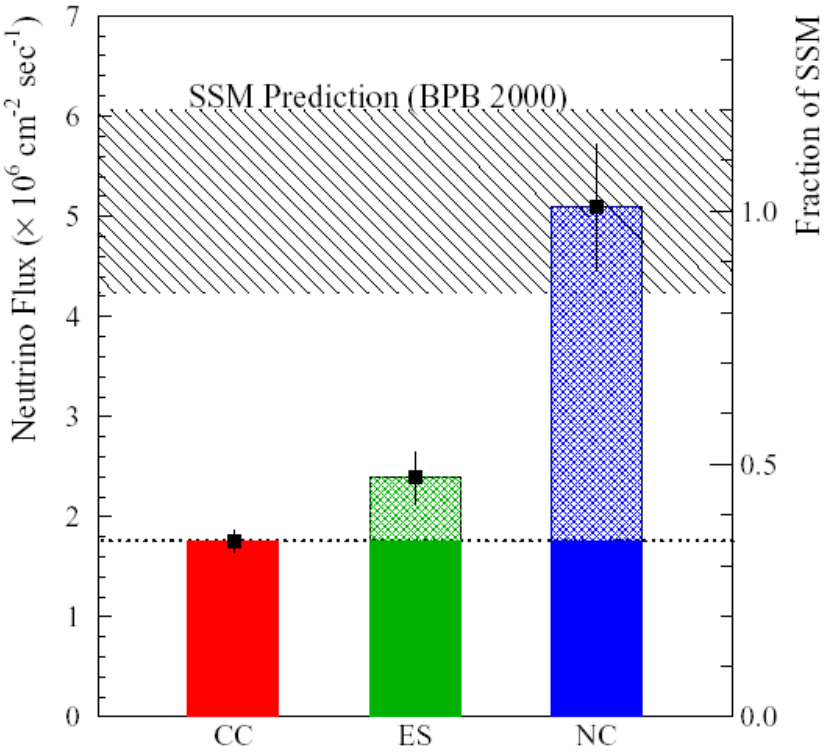
Measured SNO Fluxes



Assuming ^{8}B energy spectrum ...

Fluxes ($\times 10^6$ cm^{-2} sec^{-1})

$$\phi_{CC} = 1.76^{+0.06}_{-0.05}\ (\text{stat.}) \pm 0.09\ (\text{sys.})$$

$$\phi_{ES} = 2.39^{+0.24}_{-0.23}\ (\text{stat.}) \pm 0.12\ (\text{sys.})$$

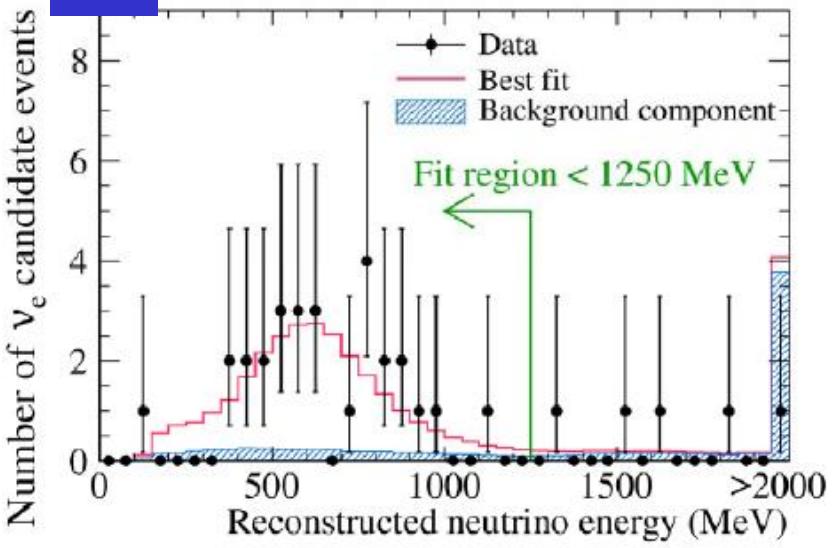
$$\phi_{NC} = 5.09^{+0.44}_{-0.43}\ (\text{stat.})^{+0.46}_{-0.43}\ (\text{sys.})$$

$$\phi_{CC} < \phi_{ES} < \phi_{NC}$$

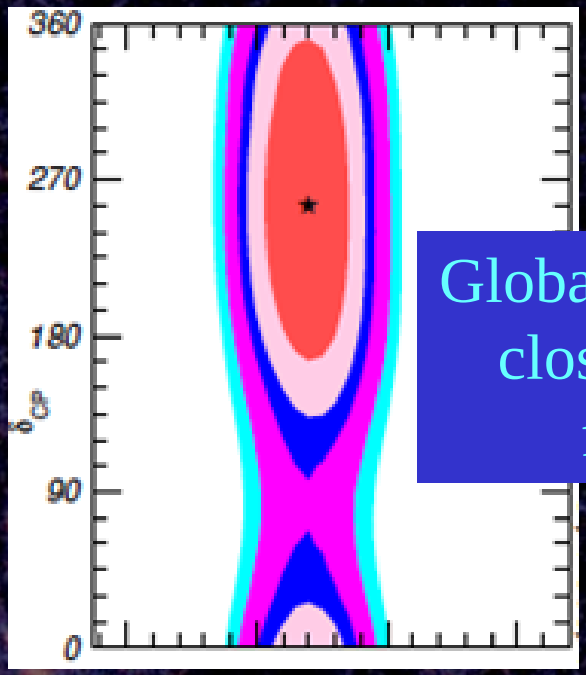
NC flux in agreement with SSM prediction!

Evidence had become Proof !

T2K



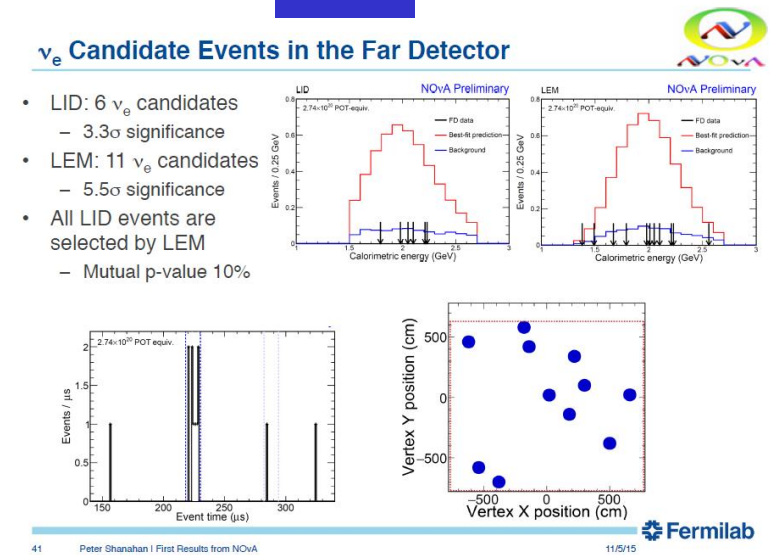
PhysRevLett.112.061802 (2014)



Global fits give first closed contours for δ_{CP}. . .

NOvA gives first results with a consistent result on appearance.

NOvA



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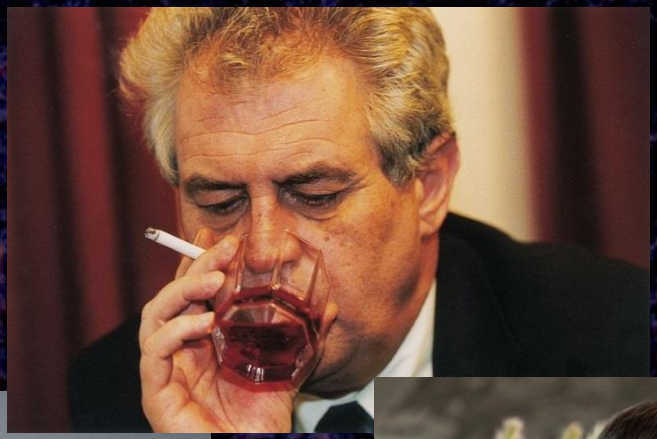
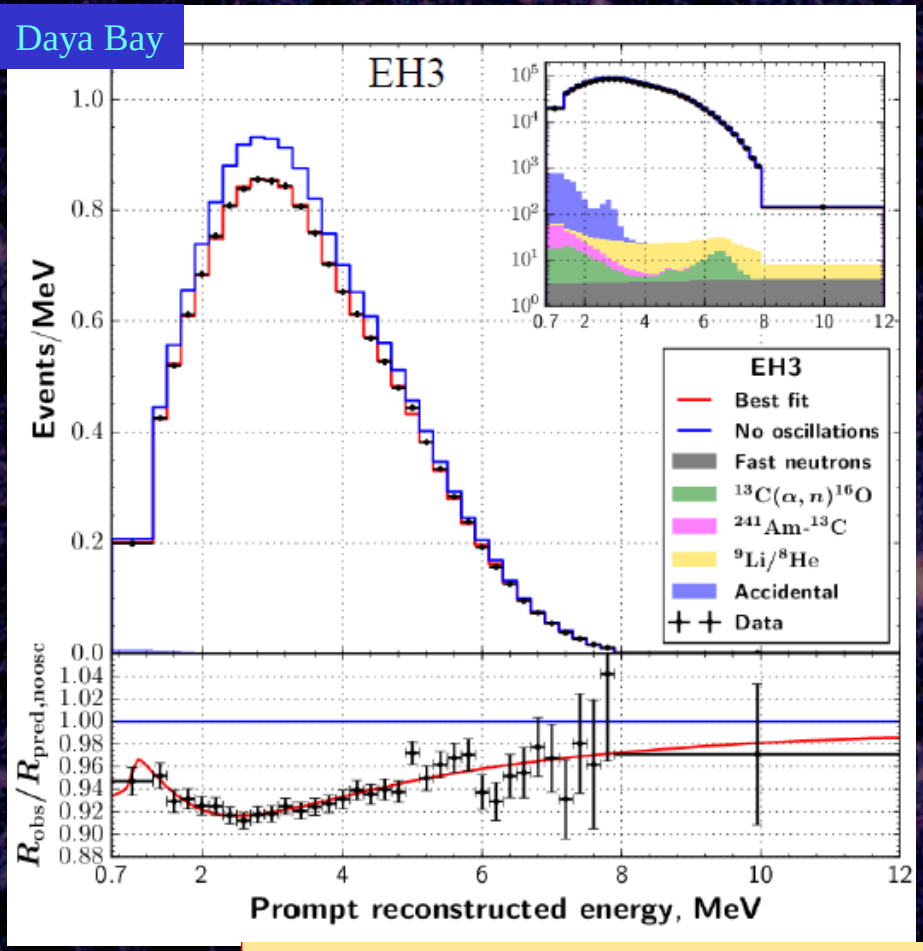
The outside world is still giving us issues. . .

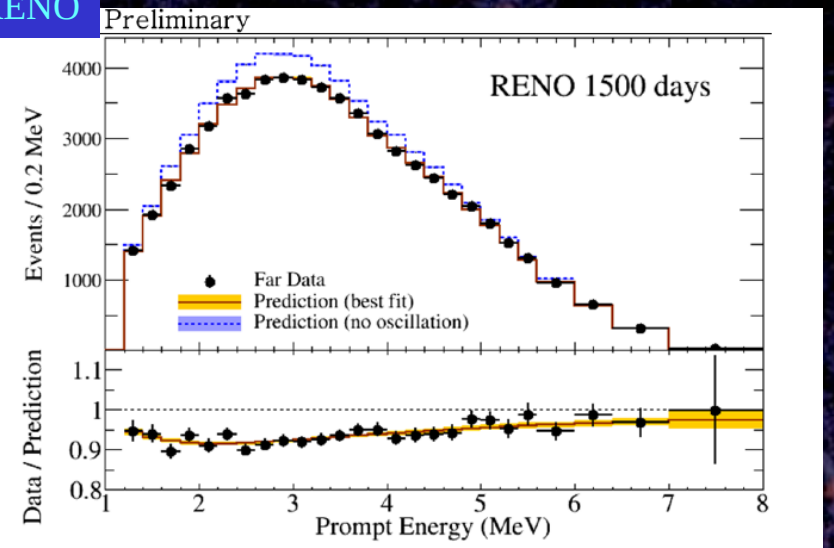


Beautiful new data from reactors. . .

Daya Bay



RENO



$\sin^2 2\theta_{13} = 0.086 \pm 0.006(\text{stat.}) \pm 0.005(\text{syst.})$ (± 9 %)

$|\Delta m^2_{ee}| = 2.61^{+0.15}_{-0.16}(\text{stat.})^{+0.09}_{-0.09}(\text{syst.})\ (\times 10^{-3}\text{eV}^2)$ (± 7 %)

$\sin^2 2\theta_{13} = [8.41 \pm 0.27(\text{stat.}) \pm 0.19(\text{syst.})] \times 10^{-2}$

$|\Delta m^2_{ee}| = [2.50 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})] \times 10^{-3}\ \text{eV}^2$

$\chi^2/\text{NDF} = 234.7/263$

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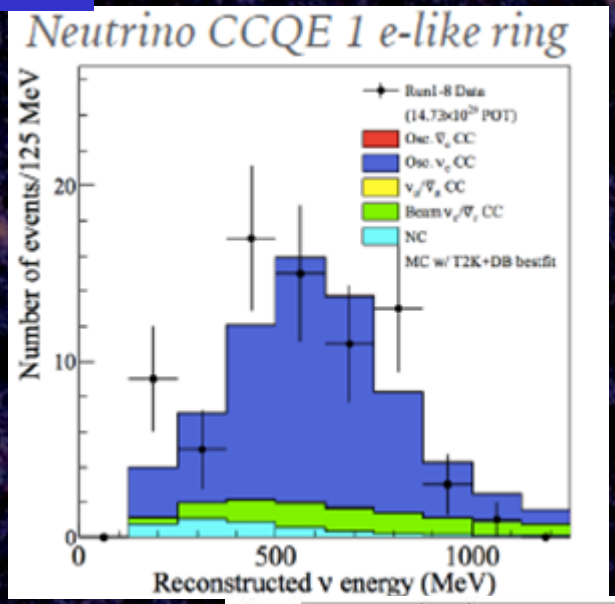
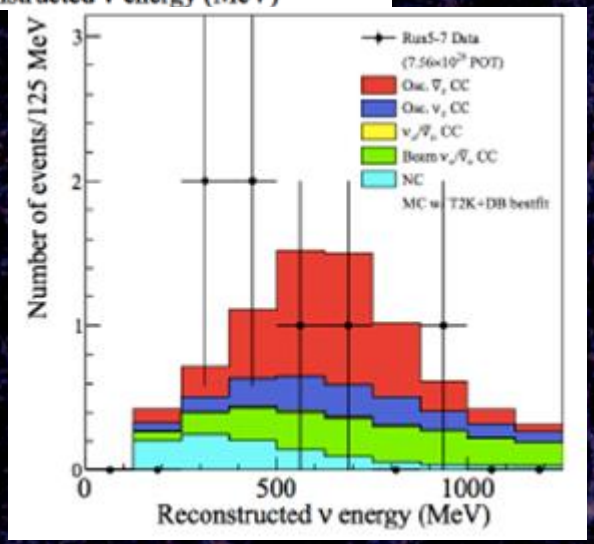
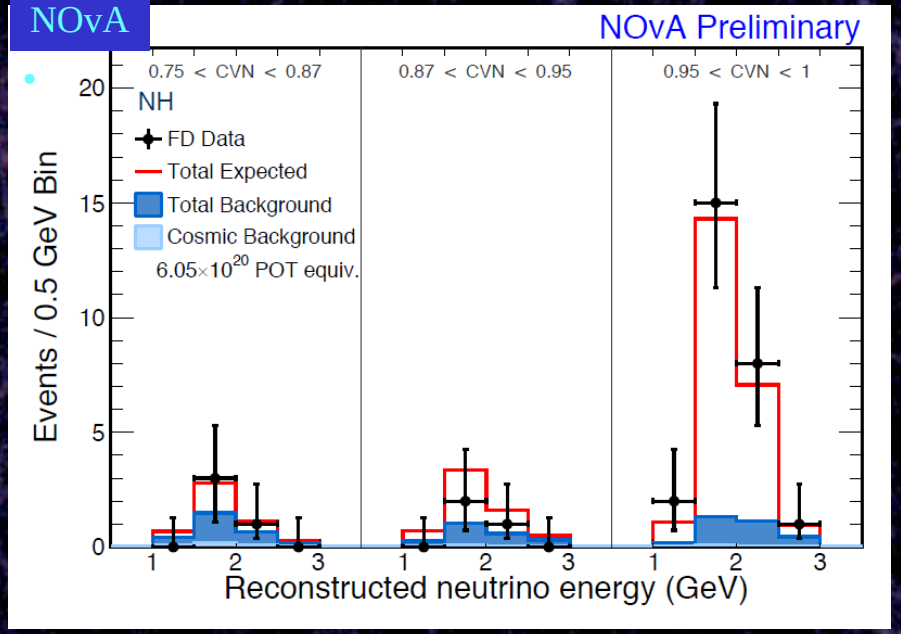
And from accelerators. .

T2K

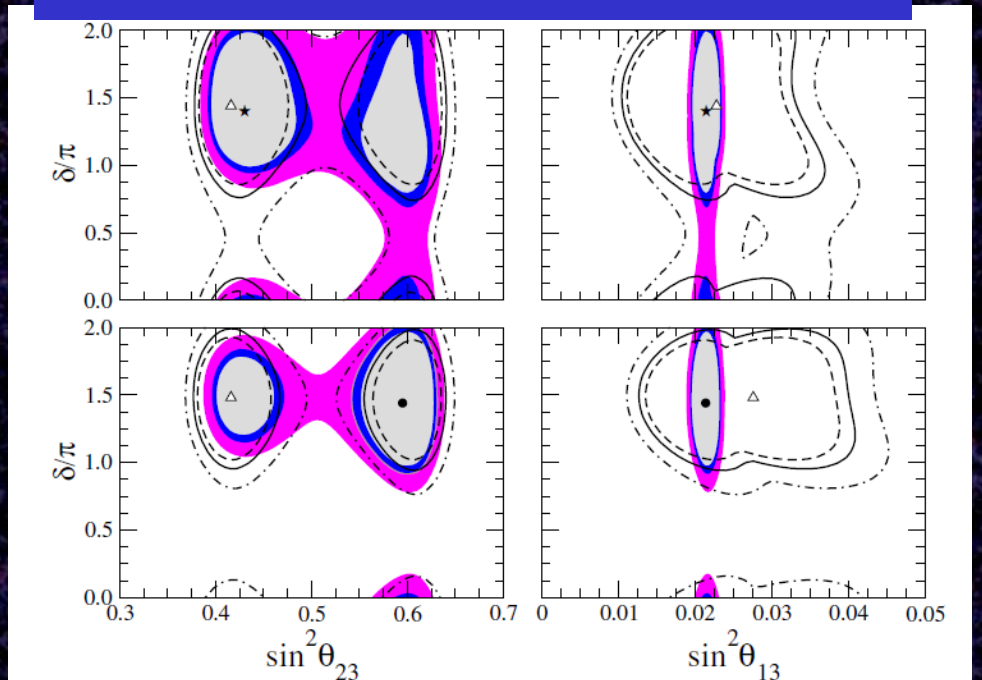




NOvA

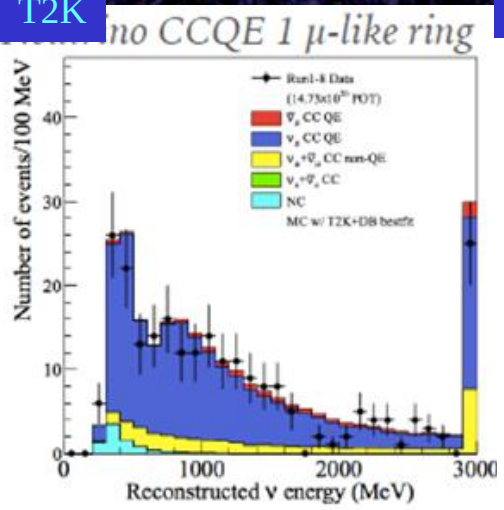


CP Conservation is disfavoured!

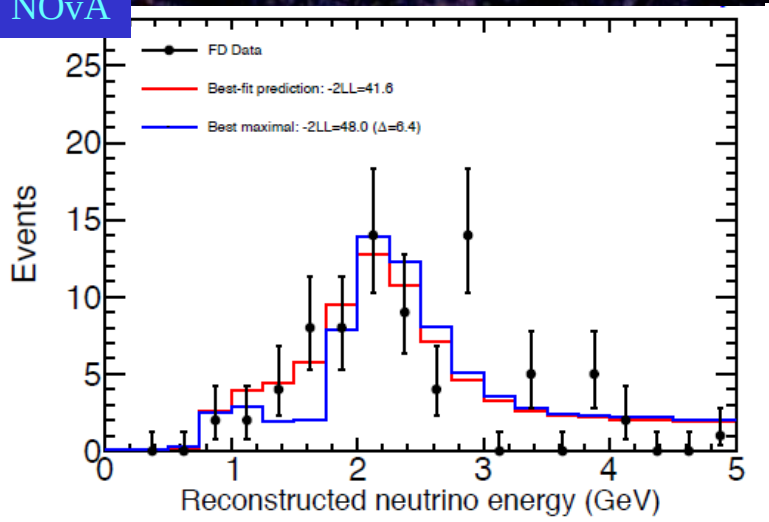


Disappearance in tension?

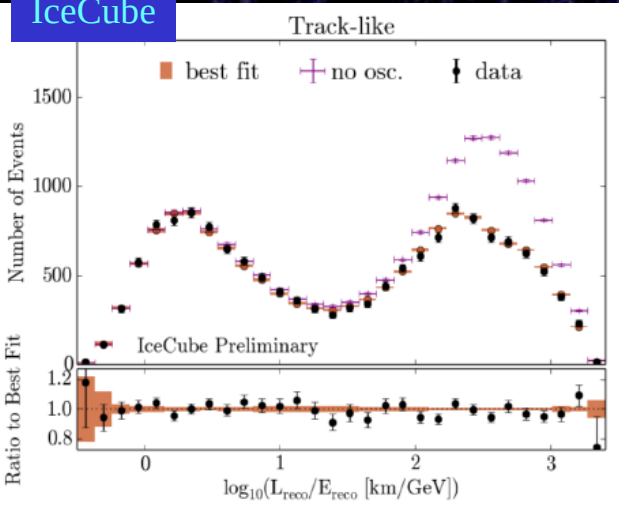
T2K

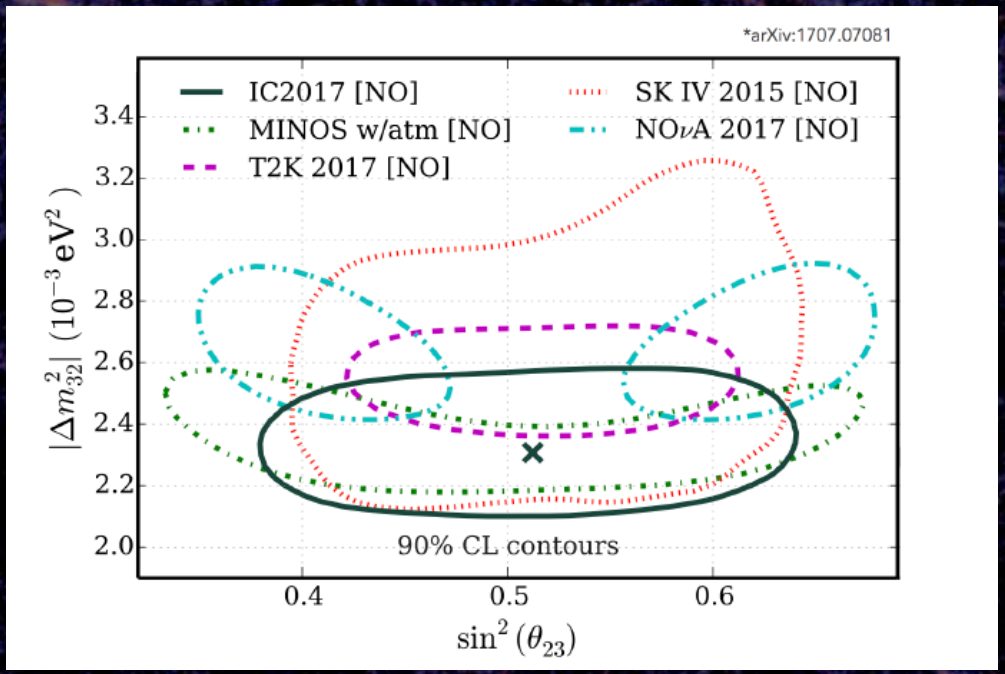


NOvA



IceCube





- Statistics?
- Neutrino Interactions?
- Detector systematics?
- New physics?

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- Where are we going?

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Oxford U./RAL

What will we have in future Prague Colloquia?

- In 2019?
  - KATRIN taking data!
  - More information about steriles from reactors and sources – DANSS!
  - More data from astrophysics.
  - More $0\nu\beta\beta$ and $2\nu\beta\beta$ decay data from SuperNEMO, GERDA, COURE, XMASS, SNO+, and others.
  - More data from T2K, NOvA, IceCube.
  - Data from the proto-DUNEs.
  - Hyper Kamiokande under construction?

What will we have in future Prague Colloquia?

- In 2021(3)?
  - JUNO taking data!
  - Data from all the FNAL SNL detectors.
  - Data from Phase 1 for IceCube.
  - More data from all the others of the above.
- In 2025(7)
  - Determination of MH by JUNO.
  - More data from all the others!
- In 2027(9)?
  - First data from DUNE.
  - First data from Hyper Kamiokande.

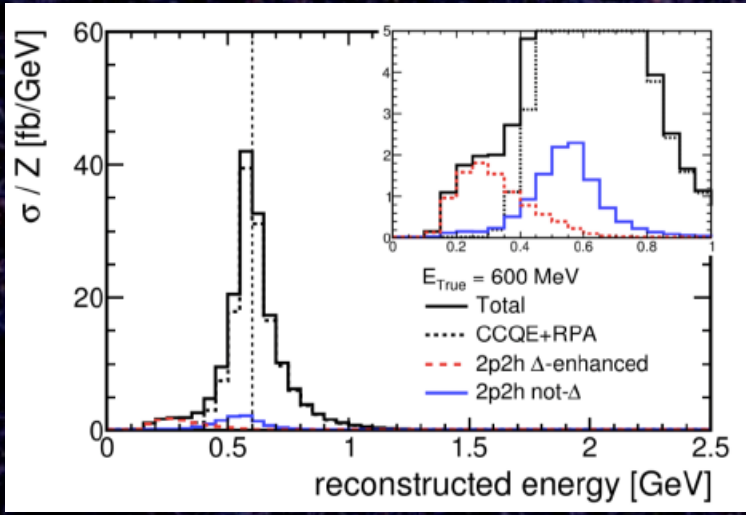
Three Issues I would like to raise (I).

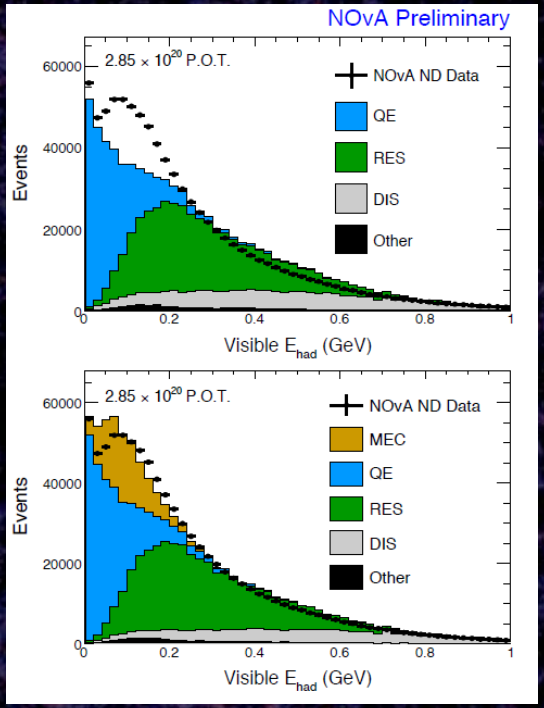
- We need help from nuclear theorists:

Effective Majorana neutrino mass contributes to 0νββ-decay rate:

$$1/\tau = G(Q^5) \cdot g_A^4 \cdot |M_{nucl}|^2 \cdot \langle m_{ee} \rangle^2$$

0νββ decay-rate	Phase space factor	Eff. ax. vec. coupling const	Matrix element	Effective Majorana Neutrino mass





- How do we get it?

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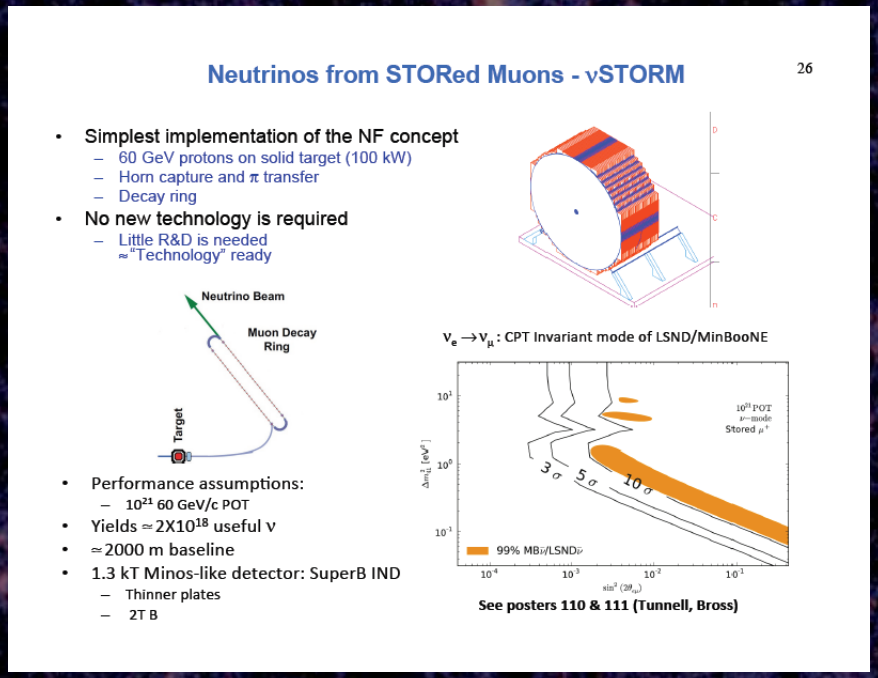
Oxford U./RAL

Three Issues I would like to raise (II).

- The CERN Strategy Process is starting again.
- We have raised the subject of NuSTORM at the colloquium before.
- If we decide we need it in 2020, it will be too late!



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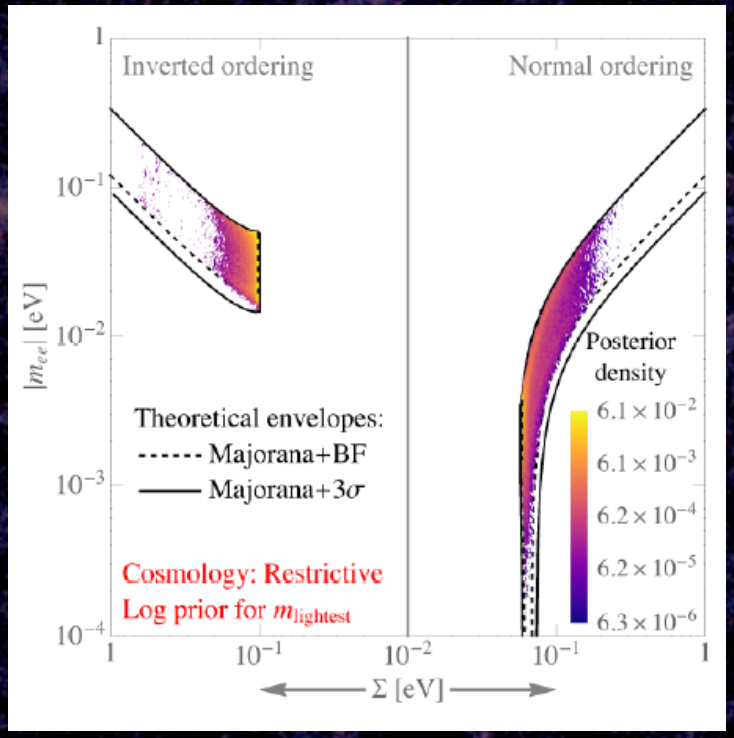
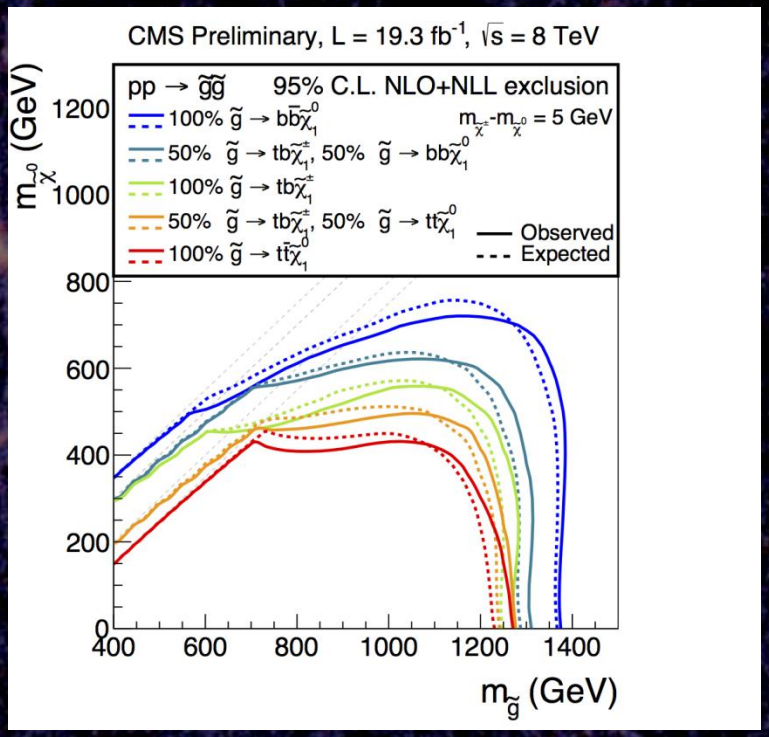
Three Issues I would like to raise (III).

- Neutrino experiments suffer from a double-standard with respect to collider experiments!



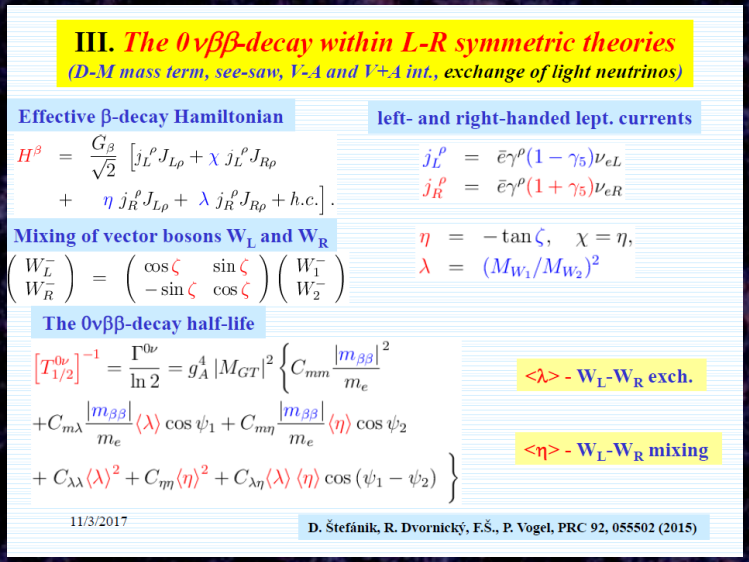


We are told we should not spend few X 10^8\$ for ton-scale ββ experiments because of this.

But we can spend few X 10^{10}\$ To run/upgrade the LHC through 2040 despite this.

Three Issues I would like to raise (III).

- We must keep pushing to find physics beyond the normal 3-ν paradigm.
- Some theorists say that neutrinos are a poor place to search, but neutrinos give surprises!
- What about the helicity problem?



Thanks to Rupert and Milos for inviting us all and for the wonderful organization…

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