ν Oscillation
(experimental review)

FFP2014 @ Marseille
July 2014

Anatael Cabrera

CNRS / IN2P3 @ APC (Paris)
Solar Neutrino Anomaly
(deficit of solar-ν_ν_e's)

Atmospheric Neutrino Anomaly
(deficit of atmospheric-ν_ν_μ's)

⟹ both manifestations (or facets) of the one phenomenon Neutrino Oscillations

major implications to ν's phenomenology…

• ν's are massive ⟹ like other fermions [⟹ why so light?]
• mixing in leptonic sector ⟹ more symmetrical quark-lepton behaviour
  ⟹ why so similar/different? [this talk: only status]

[→ Valle’s]
basic neutrino oscillations...
neutrino oscillations experimental manifestation...

Let’s take $\nu_\mu$ (a popular example) to start with…

observation: both disappearance (long ago) & appearance (July 2013) have been seen

all observations (many!) follow well one model: 3$\nu$ oscillation
ingredients for neutrino oscillations...

Non-degenerate mass spectrum $(\Delta m^2)$  \[ \oplus \]
Mixing in the leptonic sector $(\theta)$  \[ = \]
Oscillation Probability $P(f(\theta, \Delta m^2))$

Quantum interference (macroscopic)

$U_{\text{PMNS}}$ matrix (à la CKM)

$\nu_\alpha$ (start with) & $\nu_\beta$ (none at first)

\[ P = \sin^2(2\theta) \frac{\sin^2 \frac{\Delta m^2 L}{4E_\nu}}{4E_\nu} \]
Anatael Cabrera (CNRS-IN2P3 & APC)

“mixing”: a common phenomenon...

\[ \nu_\alpha = 0.5 \cdot \nu_1 + 0.5 \cdot \nu_2 \]
$\Delta m_{31}^2$

$\Delta m_{31}^2$

$\Delta m_{21}^2$

$U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}$

$\begin{pmatrix}
\begin{pmatrix}
0 & e^{-i\delta} & s_{13} \\
0 & 1 & 0 \\
-e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\end{pmatrix}$

$\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}$

$P(\nu_e \rightarrow \nu_x)$

$P(\nu_e \rightarrow \nu_e) \& P(\nu_\mu \rightarrow \nu_e)$

Effective decoupling of "solar" & "atmospheric" \(\rightarrow\) a consequence of:

- $\delta m^2$ (order $10^{-5}$eV$^2$) versus $\Delta m^2$ (order $10^{-3}$eV$^2$)
- $\theta_{13}$ being small (relative to very large $\theta_{12}$ and $\theta_{23}$)

$(\nu_e, \nu_\mu, \nu_\tau)^T = U(\nu_1, \nu_2, \nu_3)^T$, where $U_{\text{PMNS}}$ looks like

Anatael Cabrera (CNRS-IN2P3 & APC)
experimental considerations...
ingredients for neutrino oscillations…

\[ P = \sin^2(2\theta) \sin^2 \frac{\Delta m^2 L}{4E_\nu} \]

Experimental setup

\[ P(L_0, \Delta E) \rightarrow f(\theta, \Delta m^2) \]

- (typically) fixed \( L_0 \) (error \( \geq 0.1\% \) reactors/beams)
- energy spectrum \( \Delta E \) (a range of phase-space)

\[ \rightarrow \text{oscillation flux modulation} \rightarrow \text{need} \sigma \text{ knowledge} \]

Theory

experiment

rate only

rate & shape (if resolution)
the latest KamLAND’s $P(\nu_e \rightarrow \nu_e)$…

(to me) the most beautiful E/L so far…?
the \((\theta, \Delta m^2)\) plane solution...

“atmospheric” solution
- maximal mixing \((\theta_{23})\)?
  - \(\theta_{23}\) octant ambiguity
- \(\pm \Delta m^2 \sim 2 \times 10^{-3} \text{eV}^2\)
  - no sign information (vacuum oscillation)
  - \(\rightarrow\) Mass Hierarchy

“solar” solution
- large mixing \((\theta_{12})\)
- \(\delta m^2 \sim 7 \times 10^{-5} \text{eV}^2\)
  - sign information (oscillation inside Sun)

several “anomalies”
- LSND \(\oplus\) MiniBooNE \(\oplus\) Cr \(\oplus\) reactor
- \(3\nu\) (coupled to \(Z\)) \(\rightarrow\) two \(\Delta m^2\)'s possible
  - \(\rightarrow\) \(\nu\) (sterile) needed (?)
- but not fully coherent picture across all data
  - \[\text{see Palazzo's talk}\]
experimental limitations...

- **E/L unique signature of ν-oscillations...**
  - a must for disappearance experiment (so far, less important for appearance)
  - high precision parametrisation of ν-oscillations → parameter space plane ($\theta, \Delta m^2$)

- **neutrino sources...**
  - defines Energy(ν) (to set E/L ratio → defines L, if possibly constraint)
    - low cross-section ($\sim 10^{-42}$ cm$^2$) → increases linearly with energy
  - defines type of ν to be detected (CC interactions) → ν(e) and/or ν(μ±) [rarely ν(τ)]
    - e± and μ-/+ (>few 100’s MeV) are easy to identify (expensive: optimal detector for all)

- **detection limitations...**
  - detector are simple/coarse (source is far → large statistics implies large detectors)
    - limited energy (E) resolution → good calorimetry (containment) and interaction type
    - limited baseline (L) resolution → ν production point (typically weak-decays rest/fly)?
  - **PID challenging** (sign too) → only μ's can be PID-ed regularly (current technology)

- **high precision (expensive) trick...**
  - several detectors (~identical) → **reduction source/detection systematics** (no cancellation)
  - (example) **up to % systematics** ($\theta_{13}$ reactor experiments, like Double Chooz)

Anatael Cabrera (CNRS-IN2P3 & APC)
experimental status…
(as of Neutrino 2014 @ Boston)
review disclaimer...

- summarise results as of Nu2014 (June) ⊕ ICHEP14 (July)
- review will be biassed to novelties (less historical perspective)

  → complementary to Palazzo and others (@FFP14) talks

(apologies in advance if I missed anything  → please do not hesitate to comment/correct)
No $\sigma$ ranges for single parameters (all data included):

TABLE I: Results of the global 3$\nu$ oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3$\sigma$ ranges for the 3$\nu$ mass-mixing parameters. See also Fig. 3 for a graphical representation of the results. We remind that $\Delta m^2$ is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH. The CP violating phase is taken in the (cyclic) interval $\delta/\pi \in [0, 2]$. The overall $\chi^2$ difference between IH and NH is insignificant ($\Delta\chi^2_{I-N} = +0.3$).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best fit</th>
<th>1$\sigma$ range</th>
<th>2$\sigma$ range</th>
<th>3$\sigma$ range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta m^2/10^{-5}$ eV$^2$ (NH or IH)</td>
<td>7.54</td>
<td>7.32 – 7.80</td>
<td>7.15 – 8.00</td>
<td>6.99 – 8.18</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}/10^{-1}$ (NH or IH)</td>
<td>3.08</td>
<td>2.91 – 3.25</td>
<td>2.75 – 3.42</td>
<td>2.59 – 3.59</td>
</tr>
<tr>
<td>$\Delta m^2/10^{-3}$ eV$^2$ (NH)</td>
<td>2.44</td>
<td>2.38 – 2.52</td>
<td>2.30 – 2.59</td>
<td>2.22 – 2.66</td>
</tr>
<tr>
<td>$\Delta m^2/10^{-3}$ eV$^2$ (IH)</td>
<td>2.40</td>
<td>2.33 – 2.47</td>
<td>2.25 – 2.54</td>
<td>2.17 – 2.61</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}/10^{-2}$ (NH)</td>
<td>2.34</td>
<td>2.16 – 2.56</td>
<td>1.97 – 2.76</td>
<td>1.77 – 2.97</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}/10^{-2}$ (IH)</td>
<td>2.39</td>
<td>2.18 – 2.60</td>
<td>1.98 – 2.80</td>
<td>1.78 – 3.00</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}/10^{-1}$ (NH)</td>
<td>4.25</td>
<td>3.98 – 4.54</td>
<td>3.76 – 5.06</td>
<td>3.57 – 6.41</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}/10^{-1}$ (IH)</td>
<td>4.37</td>
<td>4.08 – 5.16</td>
<td>3.84 – 6.37</td>
<td>3.63 – 6.59</td>
</tr>
<tr>
<td>$\delta/\pi$ (NH)</td>
<td>1.39</td>
<td>1.12 – 1.72</td>
<td>0.00 – 0.11 $\oplus$ 0.88 – 2.00</td>
<td>—</td>
</tr>
<tr>
<td>$\delta/\pi$ (IH)</td>
<td>1.35</td>
<td>0.96 – 1.59</td>
<td>0.00 – 0.04 $\oplus$ 0.65 – 2.00</td>
<td>—</td>
</tr>
</tbody>
</table>

Fractional uncertainties (defined as 1/6 of 3$\sigma$ ranges):

- $\delta m^2$ : 2.6 % $\rightarrow$ reactor (KamLAND)
- $\Delta m^2$ : 3.0 % $\rightarrow$ MINOS/T2K + reactors (@Nu2014)
- $\sin^2 \theta_{12}$ : 5.4 % $\rightarrow$ Solar + SK
- $\sin^2 \theta_{13}$ : 8.5 % $\rightarrow$ reactors (@Nu2014)
- $\sin^2 \theta_{23}$ : $\sim$ 11 % $\rightarrow$ SK + T2K (@Nu2014)

a rather non-accelerator driven field…
the “solar” sector...

→ solar + reactor (KamLAND)
SK ν-monitors the Sun >12y...

SK I ~ IV combined 4504 days

Events/bin:
- Data: Data points
- Best fit: Red line
- Background: Dashed line

$^8\text{B flux}: 2.344 \pm 0.034 \times 10^6/\text{cm}^2/\text{s}$

~70k signal events are extracted

Preliminary
neutrino astrophysics (the Sun)...
Anatael Cabrera (CNRS-IN2P3 & APC)

Zenith angle distribution

$^8\text{B}$ Solar Flux $[\times 10^6/cm^2/sec]$ for SK-I, IV combined (Eth=4.5 MeV for SK-I, III, IV, 6.5 MeV for SK-II) statistic error only

- Solar best fit
  - $\sin^2\theta_{12}=0.311$
  - $\Delta m^2_{21}=4.85 \times 10^{-5} eV^2$

- Solar+KamLAND
  - $\sin^2\theta_{12}=0.308$
  - $\Delta m^2_{21}=7.50 \times 10^{-5} eV^2$

$\theta_z$ path exactly through day and night points

expected 3x (non oscillations)

preliminary
Solar neutrino oscillation parameters...

- $\sin^2 \theta_{12} = 0.312^{+0.033}_{-0.025}$
- $\Delta m^2_{21} = 7.54^{+0.19}_{-0.18}$

- $\sin^2 \theta_{12} = 0.311^{+0.014}_{-0.014}$
- $\Delta m^2_{21} = 4.85^{+1.4}_{-0.59}$

- $\sin^2 \theta_{12} = 0.308^{+0.013}_{-0.013}$
- $\Delta m^2_{21} = 7.50^{+0.19}_{-0.18}$

Same ~2σ tension with KamLAND in $\Delta m^2_{21}$

Solar + KamLAND
KamLAND
Solar

$\sin^2 \theta_{13} = 0.0242 \pm 0.0026$
Data set for global solar analysis

The most up-to-date data are used

✓ SK:
  - SK-I 1496 days, spectrum 4.5-19.5 MeV(kin.)+D/N: $E_{\text{kin}} > 4.5$ MeV
  - SK-II 791 days, spectrum 6.5-19.5 MeV(kin.)+D/N: $E_{\text{kin}} > 7.0$ MeV
  - SK-III 548 days, spectrum 4.0-19.5 MeV(kin.)+D/N: $E_{\text{kin}} > 4.5$ MeV
  - SK-IV 1669 days, spectrum 3.5-19.5 MeV(kin.)+D/N: $E_{\text{kin}} > 4.5$ MeV

✓ SNO:
  - Parameterized analysis ($c_0, c_1, c_2, a_0, a_1$) of all SNO phased. (PRC88, 025501 (2013))
    (Note: the same method is applied to both SK and SNO with $a_0$ and $a_1$ to LMA expectation.)

✓ Radiochemical: Cl, Ga


✓ KamLAND reactor: Latest (3-flavor) analysis (PRD88, 3, 033001 (2013))

✓ $^8$B spectrum: Winter 2006 (PRC73, 73, 025503 (2006))

✓ $^8$B and hep flux free, if not mentioned.
Borexino improved its (unimprovable) radio-purity $\rightarrow$ better CNO$_{\text{limit}}$ & pp flux?!
the “atmospheric” sector...

→ atmospheric beams reactors
MINOS & T2K latest results...

MINOS’ results

Three-Flavor Oscillations Best Fit

Inverted Hierarchy

\[ |\Delta m_{32}^2| = 2.37^{+0.11}_{-0.07} \times 10^{-3}\text{eV}^2 \]

\[ \sin^2 \theta_{23} = 0.43^{+0.19}_{-0.05} \]

0.36 < \sin^2 \theta_{23} < 0.65 (90% C.L.)

Normal Hierarchy

\[ |\Delta m_{32}^2| = 2.34^{+0.09}_{-0.09} \times 10^{-3}\text{eV}^2 \]

\[ \sin^2 \theta_{23} = 0.43^{+0.16}_{-0.04} \]

0.37 < \sin^2 \theta_{23} < 0.64 (90% C.L.)

T2K’s results

<table>
<thead>
<tr>
<th></th>
<th>Best-fit ± FC 68% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>($\Delta m^2$ units $10^{-3}\text{eV}^2$)</td>
</tr>
<tr>
<td>NH</td>
<td></td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.514$^{+0.055}_{-0.056}$</td>
</tr>
<tr>
<td>$\Delta m^2_{32}$</td>
<td>2.51 ± 0.10</td>
</tr>
<tr>
<td>IH</td>
<td></td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>0.511 ± 0.055</td>
</tr>
<tr>
<td>$\Delta m^2_{13}$</td>
<td>2.48 ± 0.10</td>
</tr>
</tbody>
</table>
SK@Nu2014: not dominant...

- most precise $\theta_{23} \rightarrow$ T2K (dominated by SK for decades)
- most precise $\Delta m^2_{\mu\mu} \rightarrow$ MINOS still (T2K very close)
**dominant $\nu_\tau$ appearance...**

**Data sample:**
- 2008/09: 398 (0$\mu$ events) + 1553 (1$\mu$ events)
- 2010/11/12: 582 (0$\mu$ events) + 2153 (1$\mu$ events)

The expected signal and background is normalized to the number of located events

$$n^0_{\mu}(\nu_\tau^{CC}) = \frac{\langle \sigma(\nu_\tau\nu_\tau^{CC}) \rangle}{\langle \sigma(\nu_\mu\nu_\nu^{CC}) \rangle} \frac{\langle \epsilon_{\nu_\mu}(\nu_\tau^{CC}) \rangle}{\langle \epsilon_{\nu_\mu}(\nu_\nu^{CC}) \rangle} n^0_{\mu} \rightarrow \alpha = \frac{NC}{CC}$$

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Expected signal $\Delta m_{32}^2 = 2.32$ meV$^2$</th>
<th>Total background</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow \mu$</td>
<td>$0.4 \pm 0.08$</td>
<td>$0.033 \pm 0.006$</td>
<td>2</td>
</tr>
<tr>
<td>$\tau \rightarrow 3\mu$</td>
<td>$0.57 \pm 0.11$</td>
<td>$0.155 \pm 0.03$</td>
<td>1</td>
</tr>
<tr>
<td>$\tau \rightarrow 1\mu$</td>
<td>$0.52 \pm 0.1$</td>
<td>$0.018 \pm 0.007$</td>
<td>1</td>
</tr>
<tr>
<td>$\tau \rightarrow e$</td>
<td>$0.61 \pm 0.12$</td>
<td>$0.027 \pm 0.005$</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$2.1 \pm 0.42$</td>
<td>$0.23 \pm 0.04$</td>
<td>4</td>
</tr>
</tbody>
</table>

**Two statistical methods:**
- Fisher combination of single channel p-value
- Likelihood ratio
  - p-value = $1.03 \times 10^{-5}$ of no oscillation

**No oscillation excluded at 4.2 $\sigma$ CL**

**Evidence for $\nu_\tau$ Appearance at Super-K**

- Search for events consistent with hadronic decays of $\tau$ leptons
  - Multi-ring e-like events, mostly DIS interactions
- Negligible primary $\nu_\tau$ flux so $\nu_\tau$ must be oscillation-induced: **upward-going**
- Event selection performed by neural network
  - Total efficiency of 60%

$$Data = \alpha(\gamma) \times bkg + \beta(\gamma) \times signal$$

Result: $0.94 \pm 0.02, 1.10 \pm 0.05, 1.42 \pm 0.35$

This corresponds to $180.1 \pm 44.3$ (stat) + 17.8-15.2 (sys) events, a $3.8 \sigma$ excess (Expected 2.7 $\sigma$ significance)

**OPERA searches: 4.2$\sigma$ excess**
(beam $\rightarrow$ event-by-event ID)

**SK searches: 3.8$\sigma$ excess**
(atmospheric $\rightarrow$ statistical excess)
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normal hierarchy</th>
<th>Inverted hierarchy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Best fit</td>
<td>68% CI</td>
</tr>
<tr>
<td>$\sin^2(\theta_{23})$</td>
<td>0.512</td>
<td>0.422 – 0.600</td>
</tr>
<tr>
<td>$\Delta m^2_{32}$ (10^3 eV^2)</td>
<td>2.684</td>
<td>2.503 - 2.877</td>
</tr>
</tbody>
</table>

5293 events selected (2011-2014)
$\chi^2 = 45.5 / 56$ dof
No preference for NH vs IH
1σ preference matter/vacuum
the "\( \theta_{13} \)" sector...

→ only reactor (likely for long)
latest $\theta_{13}$ results...

fantastic progress since late 2011 (first result since CHOOZ)

critical redundancy (% errors) $\rightarrow$ only reactor experiments will set future $\theta_{13}$
most precise $\theta_{13}$ vs $\Delta m^2_{ee}$ (Daya Bay)...

$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\text{eV}^2$$

$$\chi^2/NDF = 134.7/146$$
Double Chooz (latest May 2014)  
\(~3.0\sigma\) (~17k events @ FD)

RENO (June 2014)  
\(~3.6\sigma\) (~500k events @ ND)

Daya Bay (July 2014)  
\(~4\sigma\) (~300k events @ 3xNDs)
$>4\text{MeV}$ affecting ND and FD differently?

**Daya Bay** (July 2014 and previous publications)
- assumes ND and FD same
- not fully demonstrated $\rightarrow$ reported @ ICHEP14
- impact to $\theta_{13}$? [less via R+S]

**RENO** (PRL 2012)
- not reported issue: show rough ratio
- strange behaviour $[4,6]\text{MeV}$ (unexplained)
- impact to $\theta_{13}$? [use rate-only analysis]

**what’s going on?**
(\text{DC} \text{ will have ND this summer} \rightarrow \text{independent insight})
hints on $\delta_{\text{CP}} \ldots$

$\rightarrow$ beams (so far only)
T2K Joint $\nu_\mu + \nu_e$ Analysis: Constraints on $\delta_{CP}$

Likelihood ratio fit to both $\nu_\mu + \nu_e$ event samples

Plot includes constraint from reactor experiments as given by PDG 2013.

T2K has a slight hint for the normal hierarchy with a value of $\delta_{CP}$ of $-\pi/2$.
sensitivity $\leq 3\sigma$’s
[solid/dashed: 68%/90% CL]

T2K: 8% of data now
(100% by late 2020)
$\implies$ may NOvA make first?

dependence on $\sin^2\theta_{23}$ too
(not shown)

reactor input is critical for
pinning possible observation
of $\delta_{CP} \rightarrow$ reactor
combination is envisaged
atmospheric mass hierarchy... 

→ atmospheric ⊕ beams ⊕ reactors

[see Palazzo’s talk]
global analysis vs experiment’s analysis…

- experimental analyses (experimentalists)…
  (+) most representative precision (full account for systematics → covariant matrices)
  (-) limited to a few observables (hard to include other experiments input)
  (-) often limited to $2\nu$s framework → today’s precision (general) demands $3\nu$s scenario
    - less “natural” (so far) for experimentalist to handle

- global analyses (mainly phenomenologists/theorists)…
  use all published world data (watch out if unpublished!) → deeper insight + coherence/tension
  - over-constraint $3\nu$ scenario (anything else?) + exotic scenarios [NSI, $\nu$(sterile), etc]
  (+) several groups performing → cross-checks (handle data similarly, but not always)
  (-) less complete systematic error accounting
    - (not their fault) experimentalist not always provide full systematic knowledge and/or MC
  (+) a few successes: $\theta_{13}$ [Fogli et al.], maybe CPV? [see Palazzo’s talk]

- future (almost present)…
  - experiment’s analyses going more global (SK, T2K, etc) → need $3\nu$s scenario (accurate external input)
  - hard to go backwards in time → old experiment, not all info at hand
    - report better results ASAP (publications, data-releases, etc)
• facts (so far) about $\nu$-oscillations knowledge…
  • (high precision parametrisation) **disappearance experiments dominated**
  • **non-accelerator field dominated** (reactors, atmospheric, solar, etc)
    • (exception) unique access to $\delta$(CP) via $\nu$(e) appearance [with $\nu$(\mu) beam]
    • every data critical $\rightarrow$ over-constraining $3\nu$ model $\oplus$ exotic scenarios [→ Palazzo’s]
  • phenomenon well known (high precision) $\rightarrow$ do (astro)physics! [→ Volpe’s & Halzen’s]

• remaining questions main observables…
  • **maximal $\theta_{23}$?** [octant ambiguity]
  • (atmospheric) **Mass Hierarchy** (MH) $\rightarrow$ interplay with $2\beta\nu_0$ [→ Sarazin's]
  • $\delta$(CP), (Lepto-genesis? not enough in quark sector) [→ Sarkar's + di Bari’s]

• highlight on forthcoming experiments (not exhaustive list)…
  • (now) **Double Chooz $\oplus$ Daya Bay $\oplus$ RENO** $\rightarrow$ $\theta_{13}, \Delta m^2_{31}$
  • (now) **T2K (~8%) $\oplus$ NOvA (~0%)** $\rightarrow$ $\theta_{23}, \Delta m^2_{23}$, MH (shallow matter effects), $\delta$(CP)
  • (~2020!) **JUNO** (or alike) $\rightarrow$ $\theta_{12}, \Delta m^2_{31}, \delta m^2$ and MH (no matter effects) [→ Baussan's]
  • (~2020?) **ORCA/PINGU** $\rightarrow$ $\theta_{23}, \Delta m^2_{23}$, MH (deep matter effects) [→ Coyle's]
  • (~202X?) **LBNE/O** (or alike) $\rightarrow$ $\theta_{23}, \Delta m^2_{23}$, MH (shallow matter effects), $\delta$(CP)

• still BIG questions: $\mathbf{U}^{PMNS}$ [3x3 unitary? maximal mixing?], $\mathbf{m}(\nu)$ [why so small?], RH-$\nu$’s [exist?]