cheetah oscillations

…smaller and smaller oscillations peaks
due to multispace parameters…

Neutrino Oscillations with LongBaseLine beams

(Past, Present and very near Future business)

Luca Stanco - INFN Padova

The experimental observation of neutrino oscillations

- A touch of physics
- How the recent history enlighted the path,
  opened up to new questions
  and drives us into the future
- MiniBooNE(SBL) and MINOS/OPERA(LBL)
- Expectations…

Here is our START and END point:

the lepton mixing

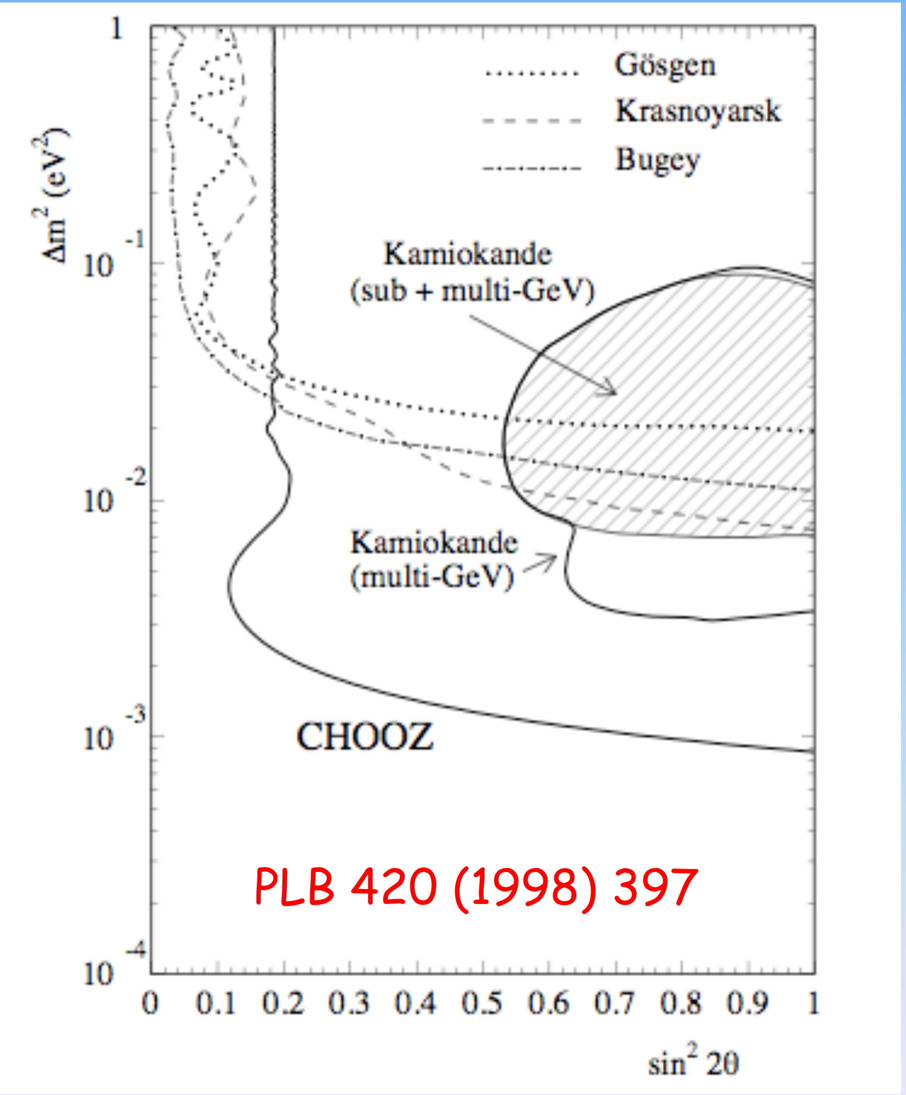
Why, how, which

In 1998 new history for neutrino begins *(as a second life)* :

- **Neutrinos oscillate*** (SK and afterwords SNO, K2K …):
  they own masses
- **Neutrinos mix themselves** (CHOOZ and afterwords KamLAND …):
  MNS matrix

* 41 years after **Pontecorvo** idea on oscillations in 1957

CHOOZ looked for $\overline{\nu_e} \rightarrow \overline{\nu_\mu}$ oscillations *(disappearance)*



Mainly after KamLAND…
re-interpretation
of Chooz result in terms of
oscillations of Mass eigenstates

$$|\nu_\ell\rangle = V^*_{\ell i}|\nu_i\rangle$$

Gauge eigenstates

Mass eigenstates

Maki-Nakagawa-Sakata
(1962)

Lepton mixing arranged (and quark mixing in 1963 by Cabibbo)

Standard parametrization of Mixing matrix via 3 Euler rotations

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

where $c_{12} = \cos\theta_{12}$ and $s_{12} = \sin\theta_{12}$.

Message: leptons and quarks mix in a similar way

BUT with 3 BIG questions :

1) Phase δ violates **CP** and
2) so phases α_1,α_2 in **Majorana** picture
3) Matrix unitarity if no **sterile** neutrino

≈≈≈Oscillations≈≈≈

$\Delta m_{12}^2=7.5*10^{-5}\ eV^2$

"solar" frequency

$$\Delta m_{ij}^2 \equiv m_j^2 - m_i^2 \qquad \varphi_{ij} \equiv \varphi_i - \varphi_j = \frac{\Delta m_{ij}^2 L}{4E} \qquad S_{ij} = \sin^2 \varphi_{ij}$$

$\Delta m_{23}^2=2.5*10^{-3}\ eV^2$

"atmospheric" frequency

consider the limit $|\Delta m_{23}^2| \gg \Delta m_{12}^2$, i.e. $S_{13} \approx S_{23}$ ➡ $P_{\rm CP} = 8J \sin^2 \varphi_{13} \sin \varphi_{12}$

$$\begin{aligned}
P(\nu_e \to \nu_\mu) &= s_{23}^2 \sin^2 2\theta_{13} S_{23} + c_{23}^2 \sin^2 2\theta_{12}\ \underline{S}_{12} + P_{\rm CP}, \\
P(\nu_e \to \nu_\tau) &= c_{23}^2 \sin^2 2\theta_{13} S_{23} + s_{23}^2 \sin^2 2\theta_{12}\ \underline{S}_{12} - P_{\rm CP}, \\
P(\nu_\mu \to \nu_\tau) &= c_{13}^4 \sin^2 2\theta_{23} S_{23} - s_{23}^2 c_{23}^2 \sin^2 2\theta_{12}\ \underline{S}_{12} + P_{\rm CP}
\end{aligned}$$

Strumia-Vissani, arXiv:hep-ph/0606054v2

SK, K2K/Minos, SNO, KamLand YES *(they see oscillations)*

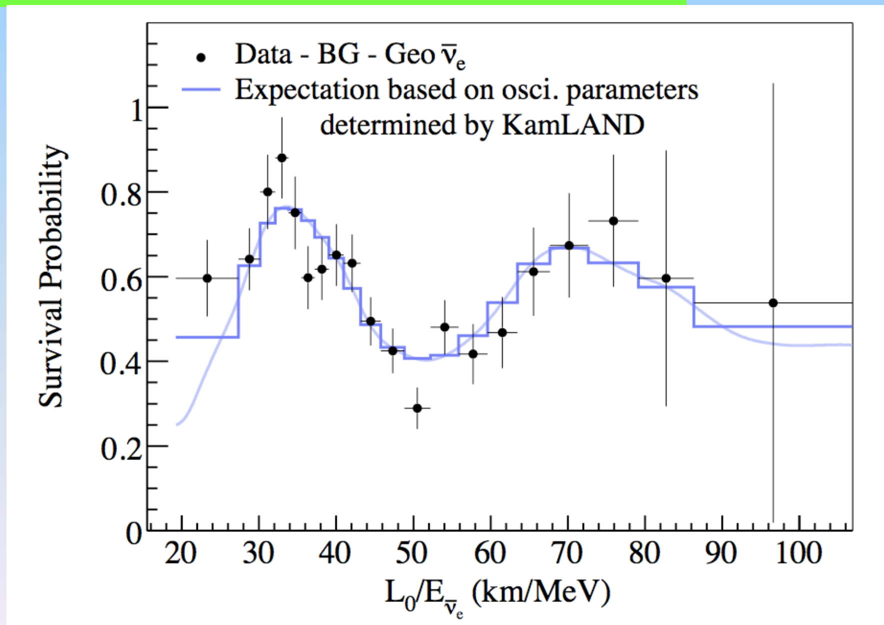
Chooz NO *: it did not see anything because $S_{12} \approx 0$ ($L \approx 1$ km) and θ_{13} too small*

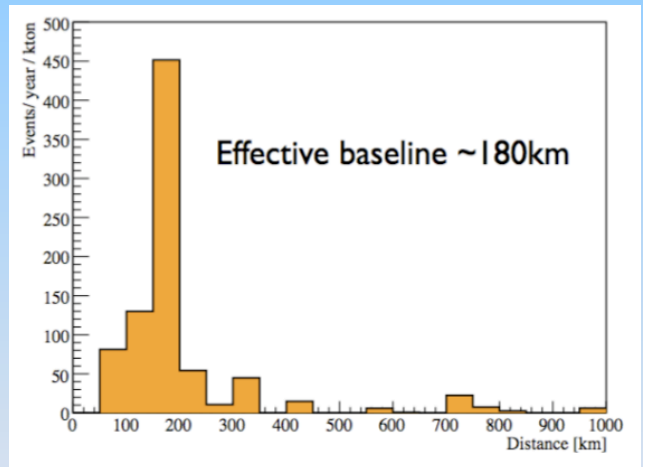
Searching of disappearance:

$$
\begin{aligned}
P(\nu_e \to \nu_e) &= 1 - \sin^2 2\theta_{13}\, S_{23} - c_{13}^4 \sin^2 2\theta_{12}\, S_{12}, \\
P(\nu_\mu \to \nu_\mu) &= 1 - 4c_{13}^2 s_{23}^2 (1 - c_{13}^2 s_{23}^2) S_{23} - c_{23}^4 \sin^2 2\theta_{12}\, \underline{S}_{12} \\
P(\nu_\tau \to \nu_\tau) &= 1 - 4c_{13}^2 c_{23}^2 (1 - c_{13}^2 c_{23}^2) S_{23} - s_{23}^4 \sin^2 2\theta_{12}\, \underline{S}_{12}
\end{aligned}
$$

θ_{13} measurements from **Reactors** suffer from Δm_{23} correlations

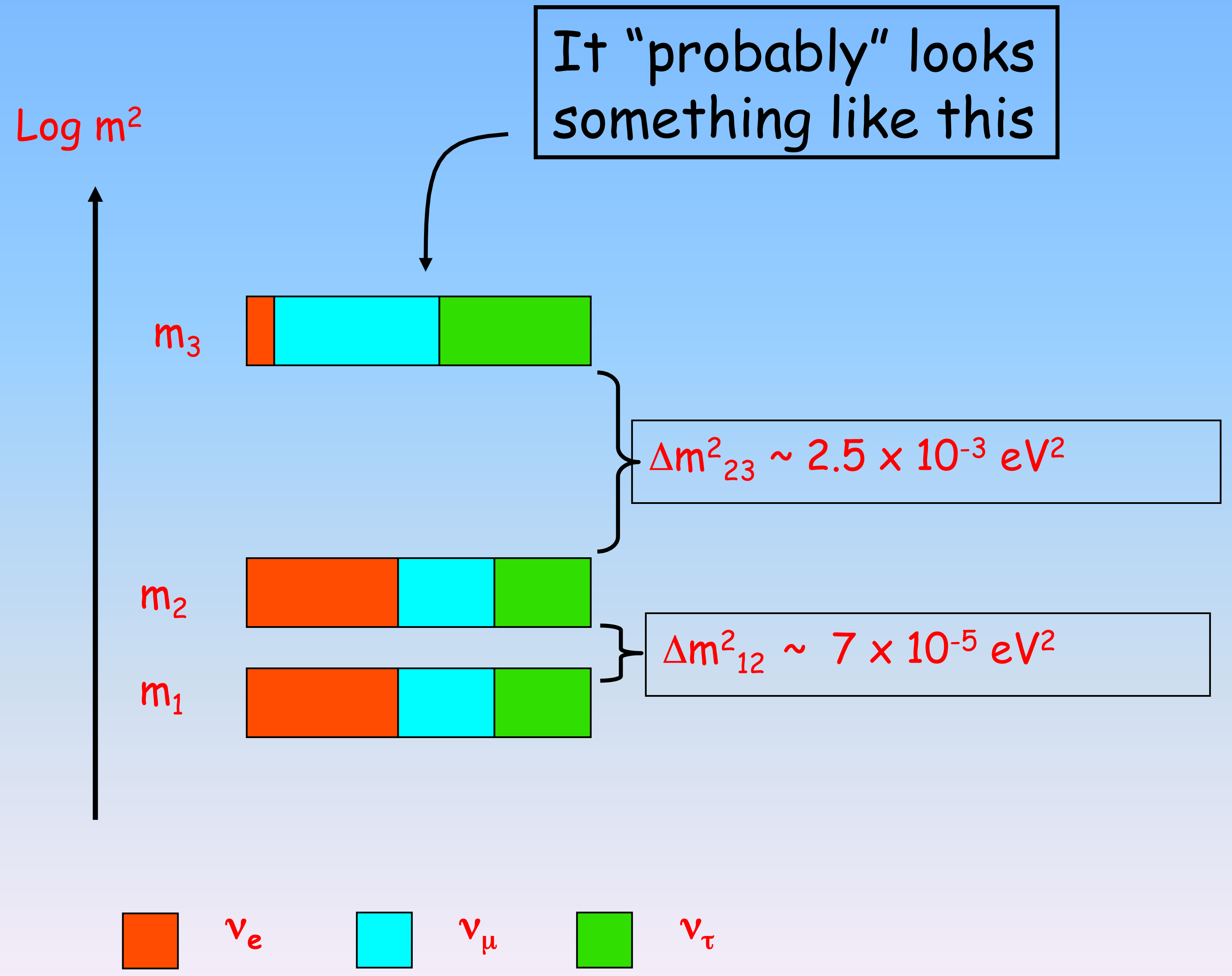
Wonderful KamLAND 2008 Results



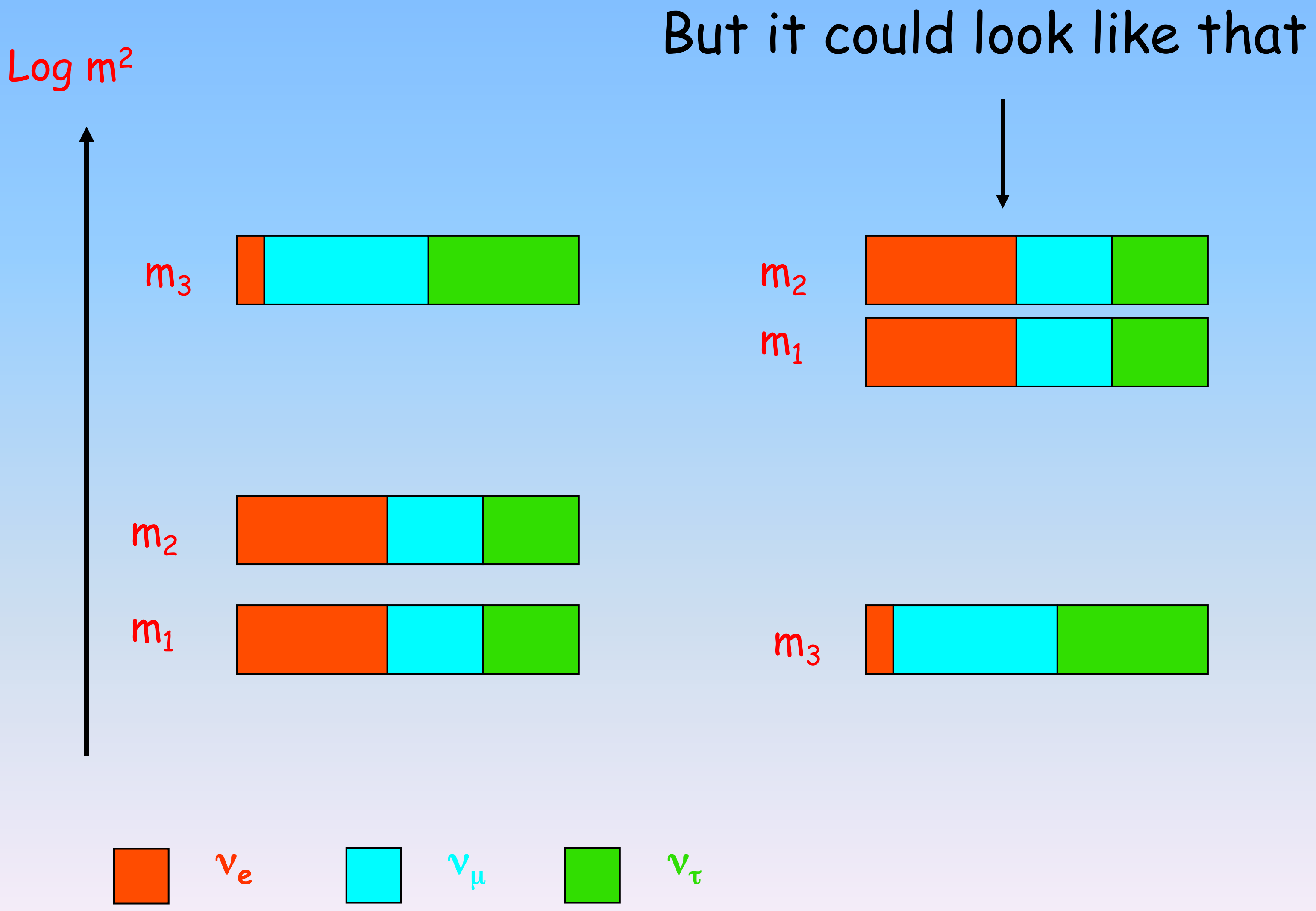


S. Abe et al., Phys. Rev. Lett. 100, 221803(2008)

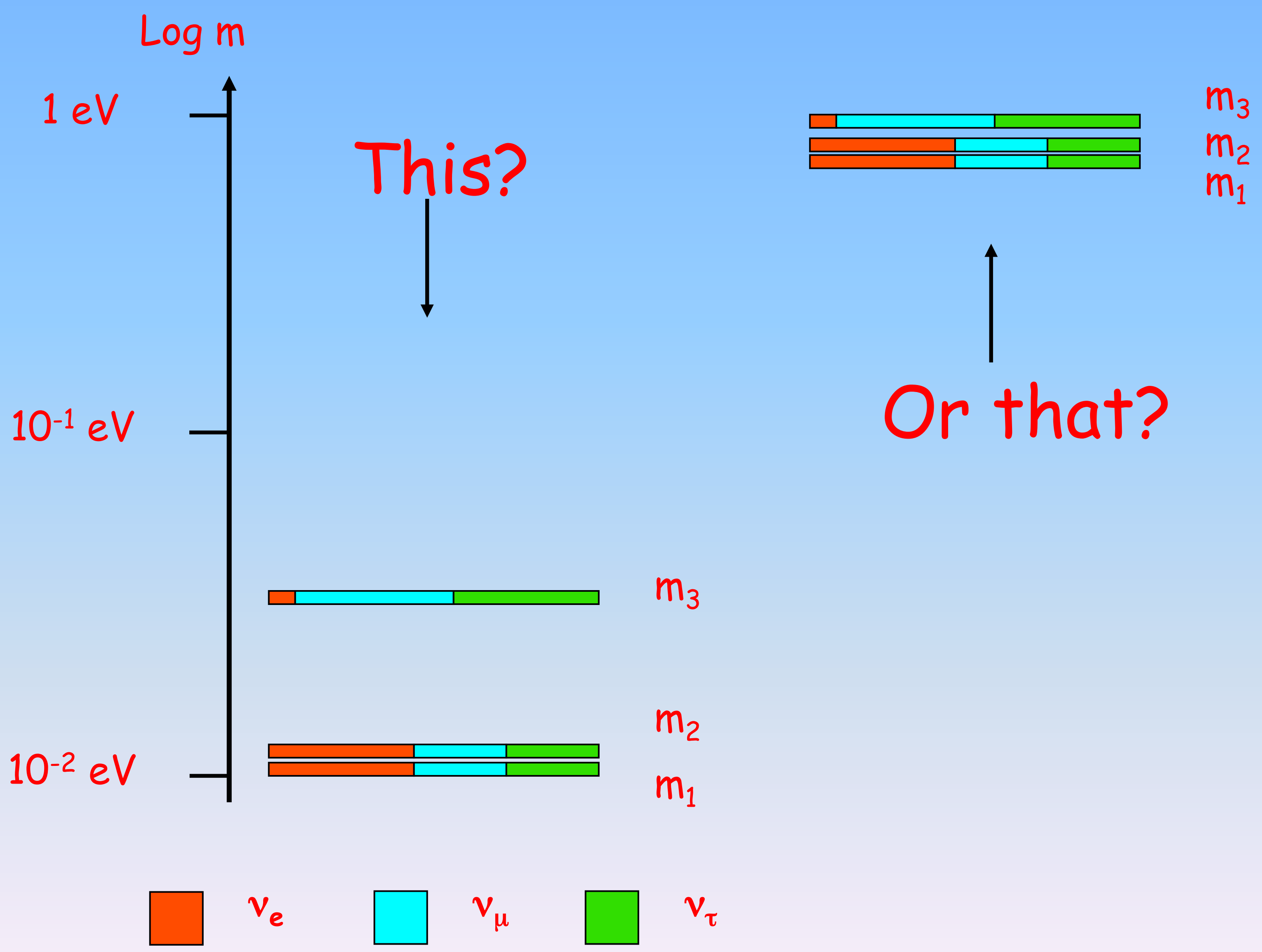
What is the pattern of neutrino masses?



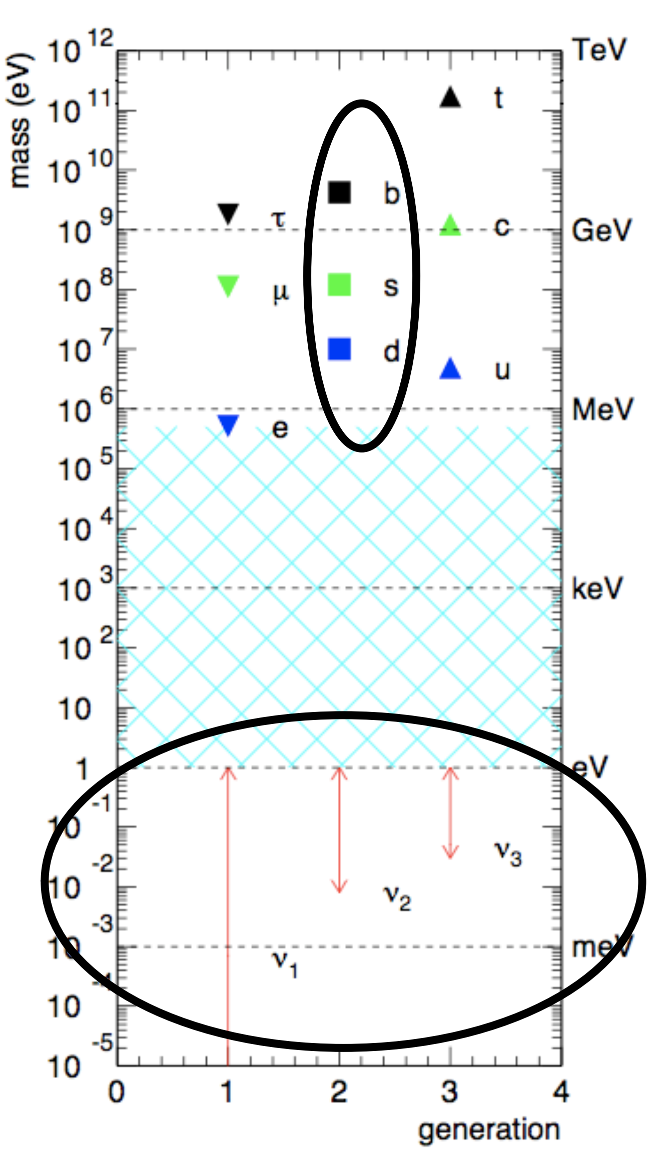
What is the pattern of neutrino masses?



Even more significant is the absolute scale.



Masses



Mixing

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

Lepton Mixing is *weird*

What does all that means ?

Is there any meaning at all ?

(more than those for cabalistes)

e.g. Quark-Lepton Complementarity:

$\theta^l_{12}+\theta^q_{12}\approx\pi/4$ and $\theta^l_{23}+\theta^q_{23}\approx\pi/4$

$U_{MNS}=U_{bm}U^+_{CKM}$ (QLC_l) or $U_{MNS}=U^+_{CKM}\,U_{bm}$ (QLC_ν)

U_{bm} stands for QL symmetry or GUT

However….

What is presently known of MNS matrix:

$\sin^2 2\theta_{23}$=1.02±0.05
$\tan^2\theta_{12}$=0.47±0.6
$\sin^2 2\theta_{13}$ from fits *(or <0.15@Δm^2_{23}=2.5*10^{-3}eV^2, 90% C.L.)* *θ_{13}<11.4^0*
$(\Delta m_{23})^2$=2.4±0.13*10^{-3}eV^2
$(\delta m_{13})^2$=7.59±0.21*10^{-5} eV^2

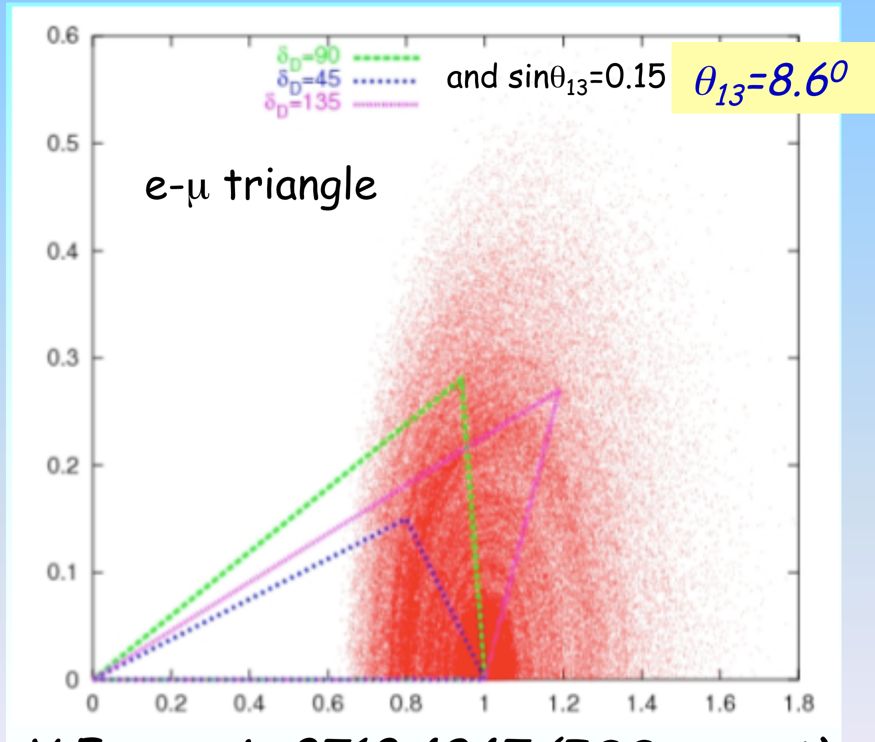
Rather poor resolutions still…

Look at unitarities of Kobayashi-Maskawa !! *(from PDG06)*

$$\sum_{i=d,s,b} |V_{ui}|^2 = 0.9992 \pm 0.0011$$

$$\sum_{i=u,c,t} |V_{id}|^2 = 1.001 \pm 0.005$$

$$\sum_{i=u,c,j=d,s,b} |V_{ij}|^2 = 2.002 \pm 0.027$$



Y Farzan in 0710.4947 (ISS report)

Message: leptons mixing matrix poorly known …

W.Buchmuller
at EPS09:
Summary talk

Status of the “Standard Models” at this EPS conference:

- Particles: wealth of data, all consistent with the SM
- Astrophysics: no phenomena which are inconsistent with conventional physics
- Cosmology: remarkably precise data, all consistent with cosmological SM

Are there hints for new physics, and if yes,
at which energy scale?

Right-handed neutrinos have been “found”;
no exotics have been found

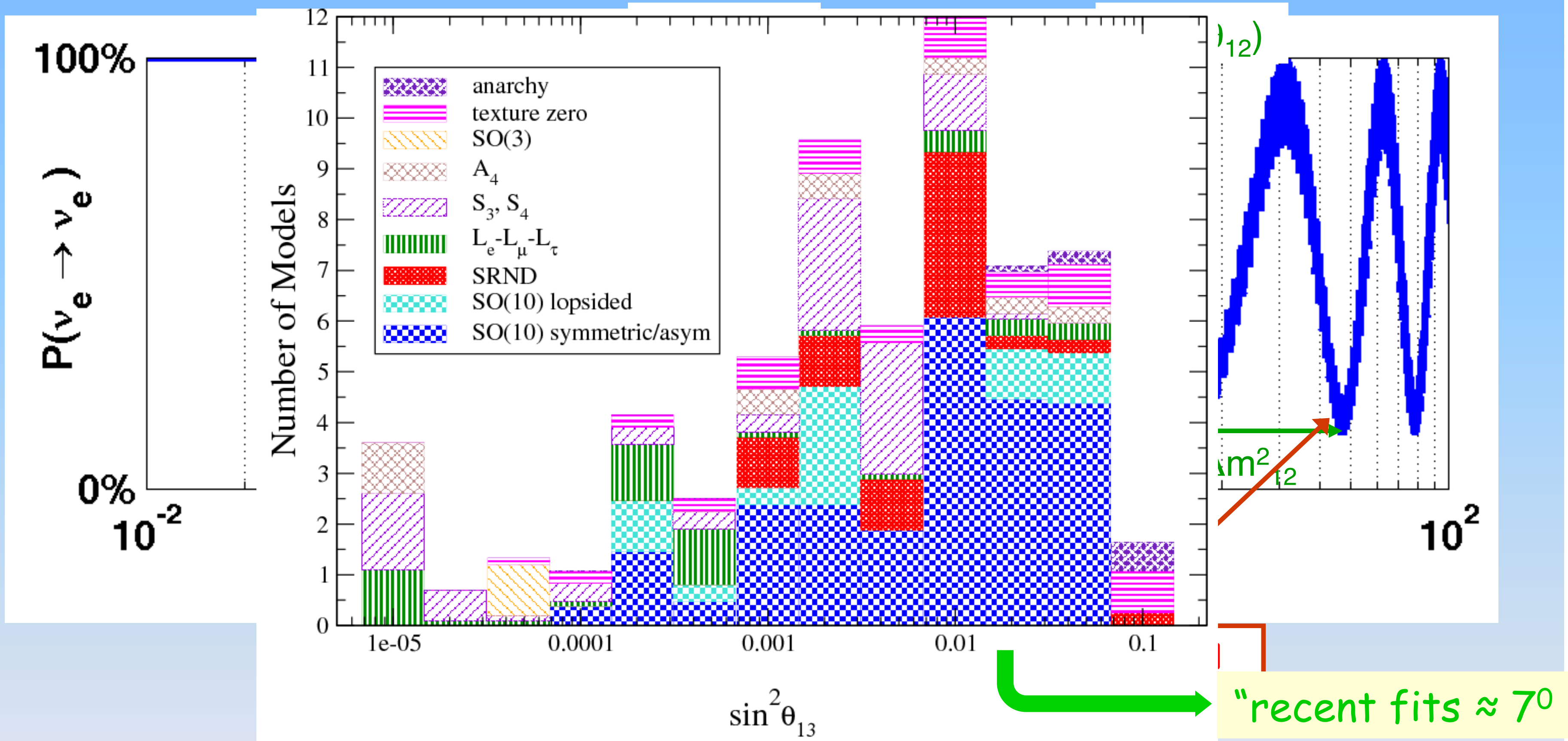
Message: be prepared to the unexpected !

Then what do we have to measure?

- Three angles (θ_{12}, θ_{13}, θ_{23})
- Two mass differences (Δm^2_{12}, Δm^2_{23})
- The sign of the mass difference Δm^2 ($\pm\Delta m^2_{23}$)
- One CP phase (δ)
- The source of atmospheric oscillations (detect τ appearan.)
- The absolute mass scale
- Are neutrino Dirac or Majorana particles (or both)?
- Are there more - sterile - neutrinos?

the BIG items can be studied with LBL experiments

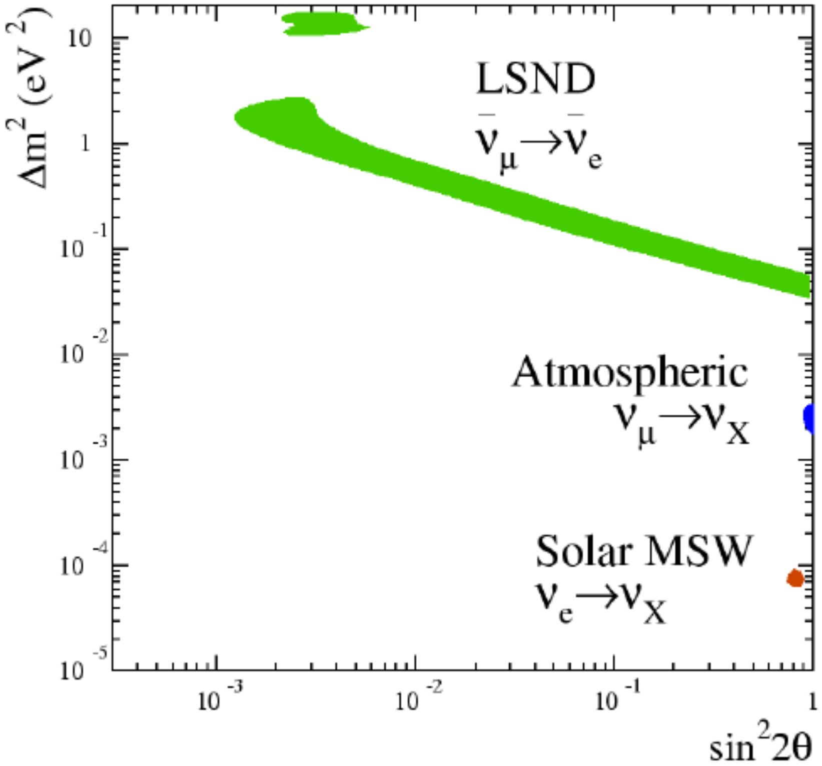
Example for 3 flavour Oscillation probability !



Imperative to measure θ_{13} !

There are also "INTERNAL" problems !

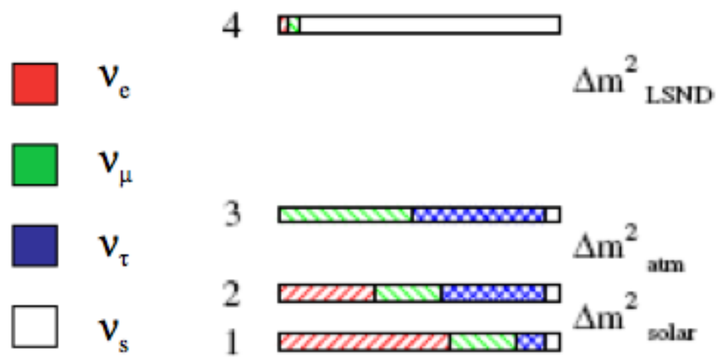
$$P_{osc} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$



A 3 neutrino picture requires

$$\Delta m_{13}^2 = \Delta m_{12}^2 + \Delta m_{23}^2$$

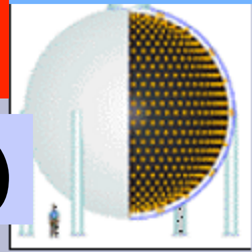
Sterile neutrino interpretations:
(3+1) scheme



The three oscillation signals cannot be reconciled without introducing Beyond Standard Model Physics

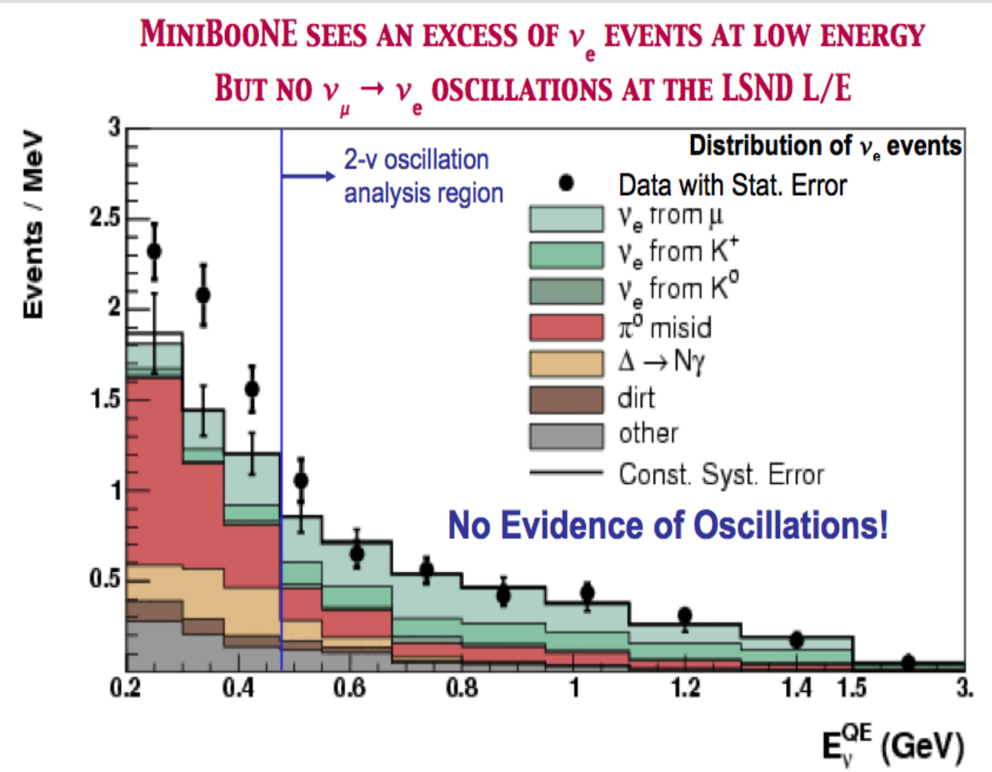
From WIN09 (Perugia, Oct.09)

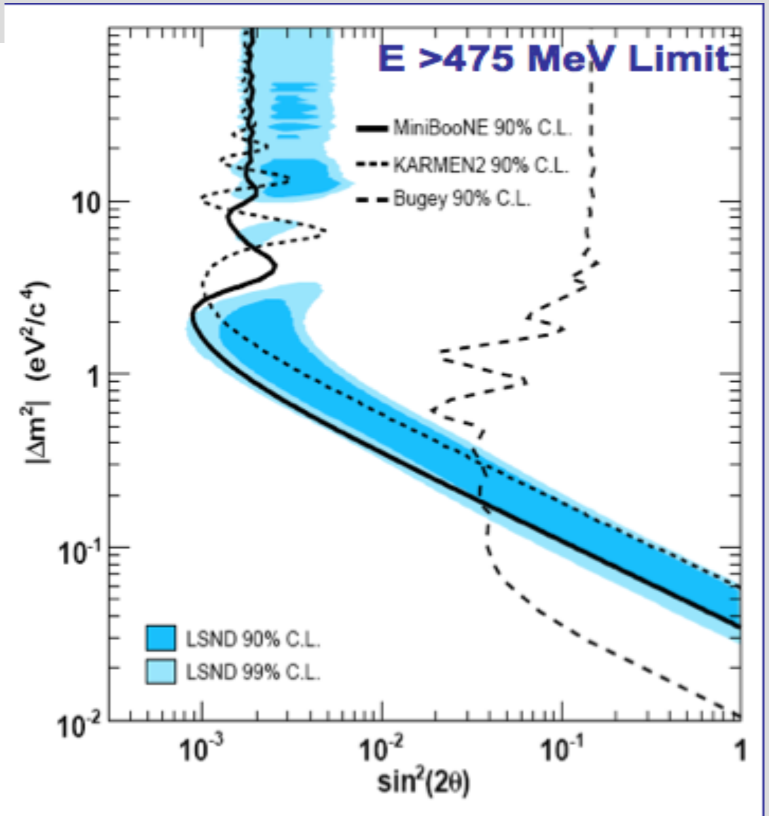
MiniBooNE



Neutrino mode result (2007/09)

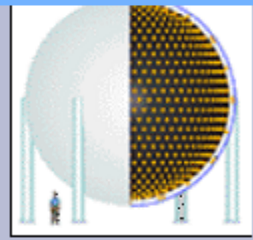
- Based on 6.46x10^20 POT
- Ruled out interpretation of LSND signal as oscillations
- Unexplained excess of events in low-energy region





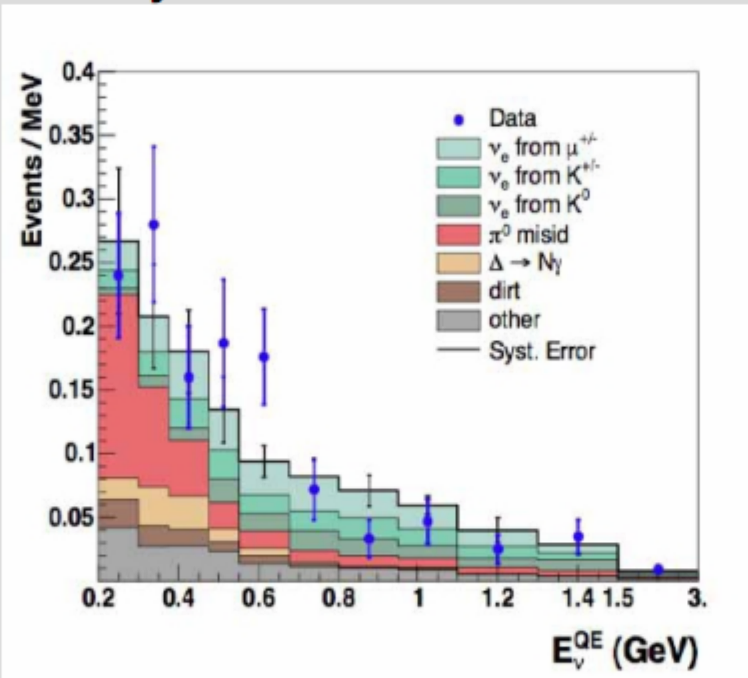
MiniBooNE

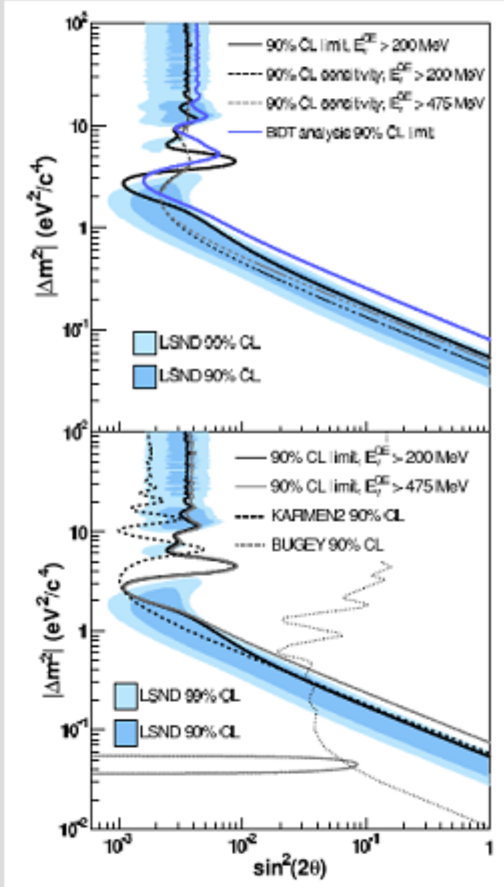
Anti-neutrino mode result (2008/2009)



(G.Karagiorgi)

- Based on 3.386E20 POT (low statistics)
- Similar backgrounds at low energy
- Same analysis chain as in neutrino mode





- no low-energy excess
- currently work on combined $\nu - \bar{\nu}$ analysis
- need more stats

arXiv:0904.1958

- MiniBooNE data are themselves not conclusive
  - No evidence for neutrino and/or anti-neutrino oscillations
  - There is an excess for low energy neutrinos that is not there for anti-neutrinos
- A 3+1 model can reconciles all *appearance* data, but not the *disappearance* once (also adding more neutrinos does not help)
- Models with sterile neutrinos and exotic physics have been therefore proposed
- **A fact: the experimental situation is confused!**
- **Can MINOS/OPERA help?**

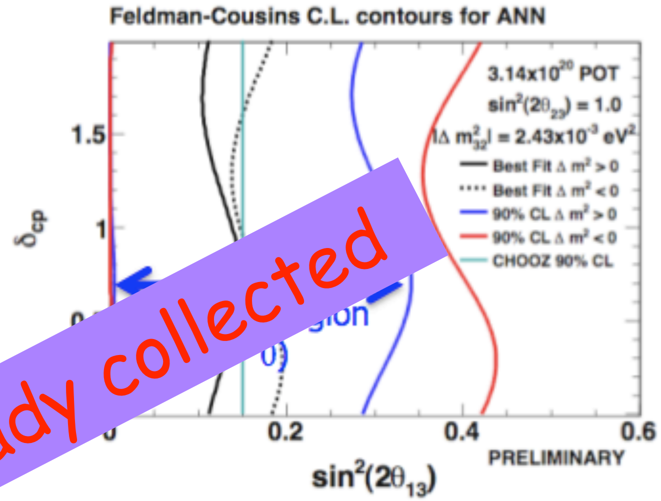
MINOS actually…

J.Evans at EPS09

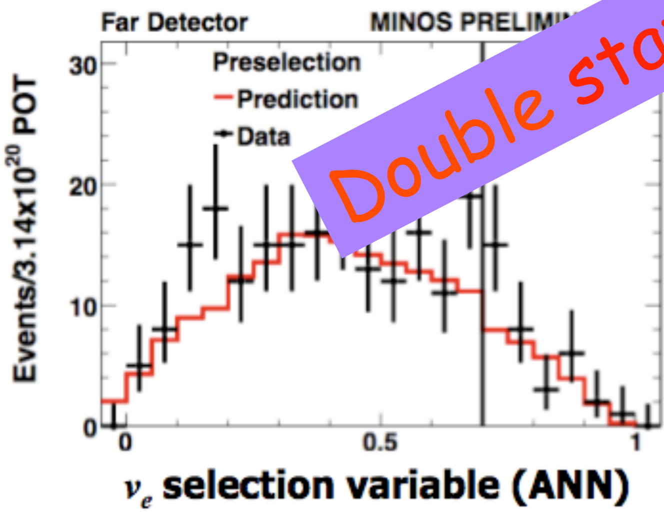
Far Detector ν_e Data

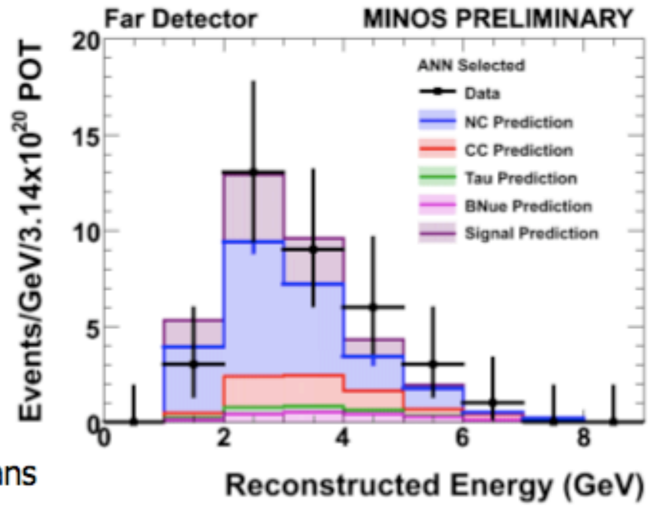
* 37 ν_e selected events seen
  - Expected background: 27 ± 5_{stat} ± 2_{syst}
  - Excess is 1.5σ

Fit to the oscillation hypothesis using Feldman-Cousins method
  - Best fit is at the Chooz limit
  - $\sin^2(2\theta_{13}) < 0.29$ (90% c.l.); $\Delta m^2>0$ $\delta_{CP}=0$
  - $\sin^2(2\theta_{13}) < 0.49$ (90% c.l.); $\Delta m^2<0$ δ…



Double stat already collected





Justin Evans 9

updated to 35 events…

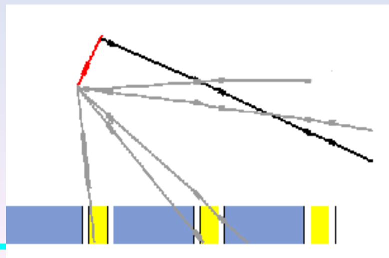
…and wait for τ appearance in OPERA !!!

1998 SK atmospheric neutrino anomaly:
deficit of ν_μ (and not ν_e) with
zenith angle dependence: **OSCILLATION !!!**

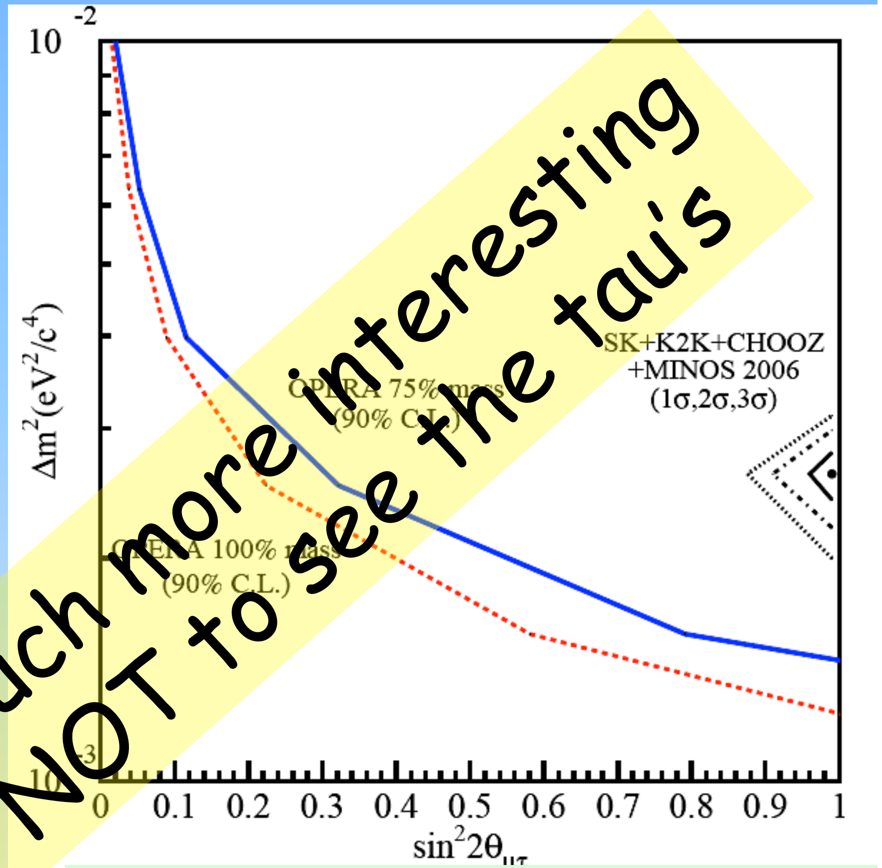
CHOOZ: final
flavour not (only) ν_e ...

1999 CNGS beam design

2000 DONUT "sees"
the ν_τ in the nuclear
emulsions

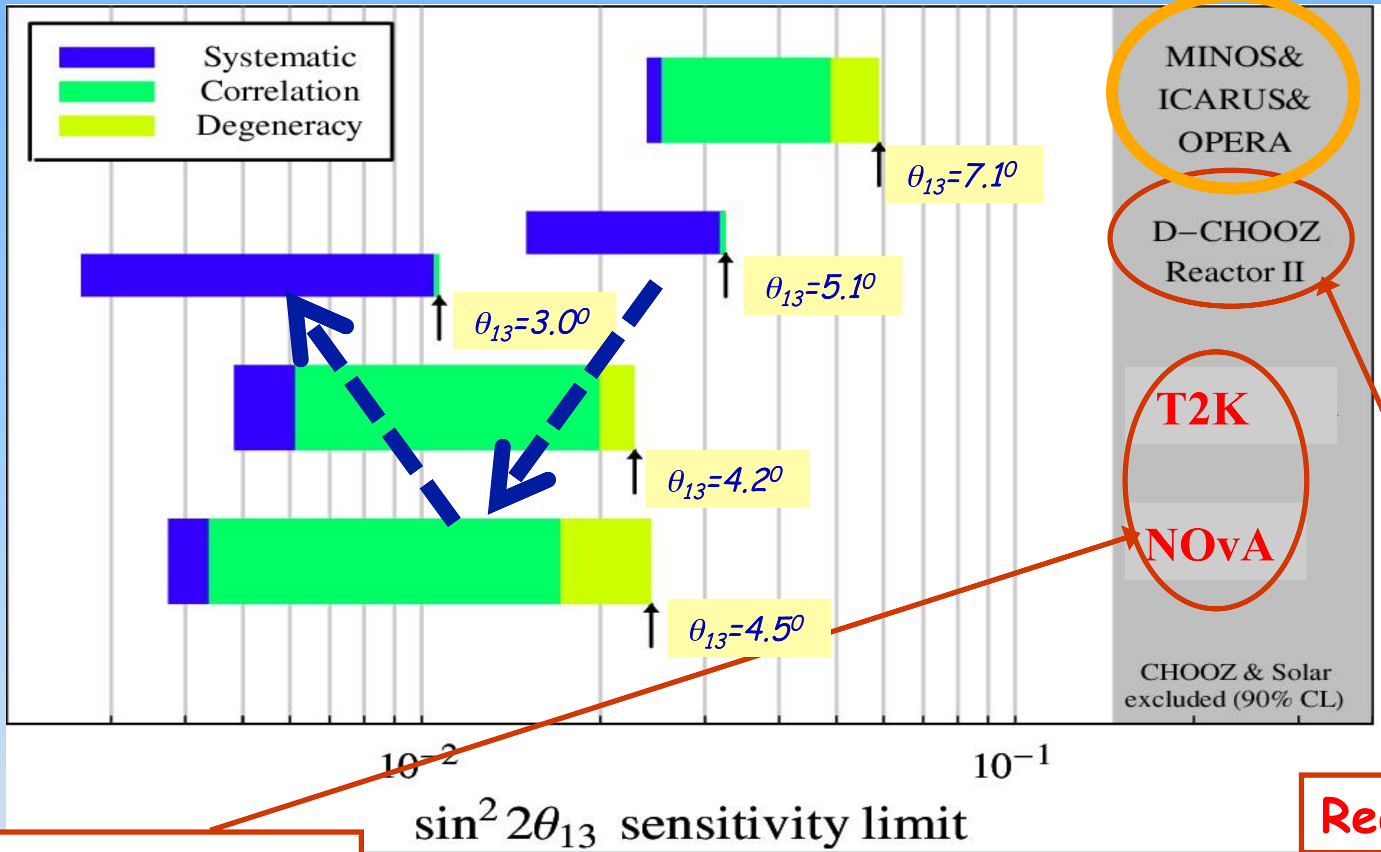


2000 OPERA proposal



provide an unambiguous evidence for $\nu_\mu \rightarrow \nu_\tau$ oscillation in the region of atmospheric neutrinos by looking for ν_τ **appearance** in a pure ν_μ beam

(almost) Near future. (almost) Assured.



Beams: may be...

Reactors

Neutrino superbeams

$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \Delta$$
$$\mp \alpha \sin 2\theta_{13} \sin \delta_{CP} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin^3 \Delta$$
$$+ \alpha \sin 2\theta_{13} \sin \delta_{CP} \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \sin^2 \Delta$$
$$+ \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta$$

$$1 - P(\overline{\nu}_e \to \overline{\nu}_e) \cong \sin^2 2\theta_{13} \sin^2 \Delta + \alpha^2 \Delta^2 \cos^4 \theta_{13} \sin^2 2\theta_{12}$$

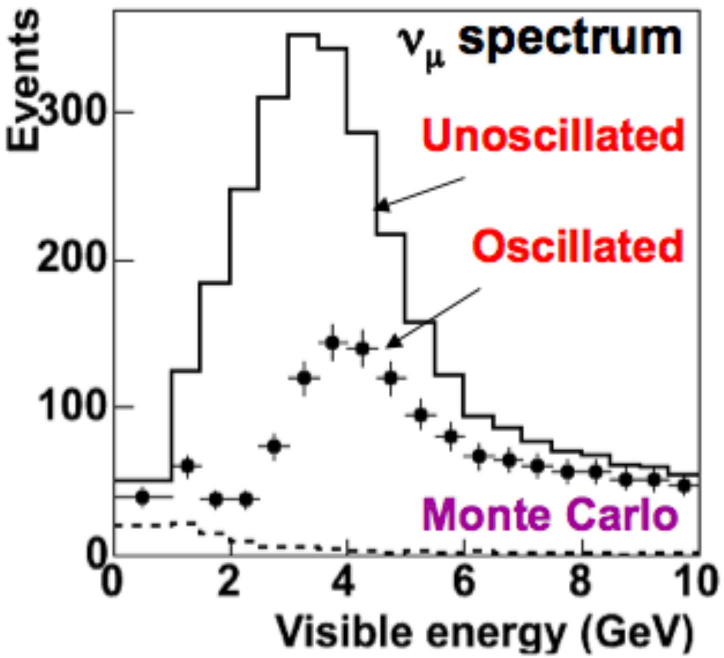
with $\quad \Delta \equiv \Delta m^2_{31} L/(4E_\nu) \qquad \alpha \equiv \Delta m^2_{21} / \Delta m^2_{31}$

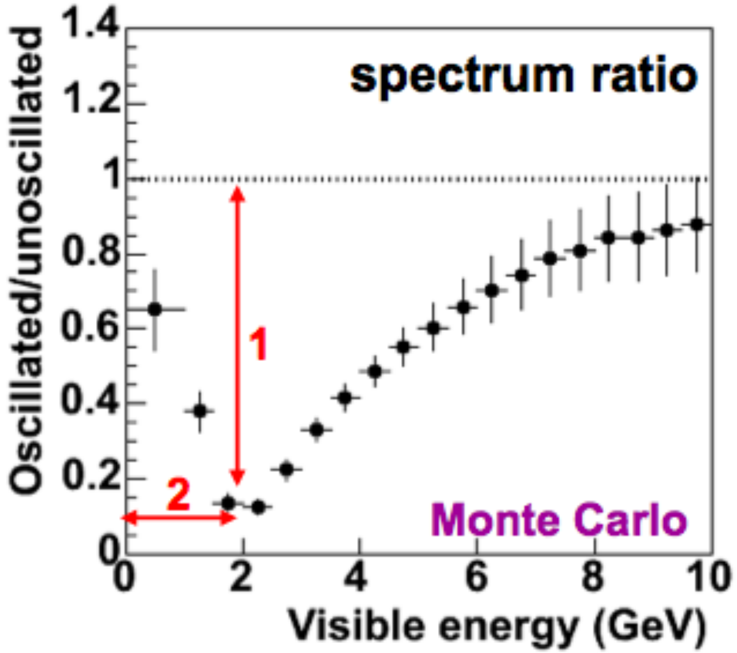
Different patterns of oscillations: synergy

The present

The MINOS way

- **Two detector experiment** to reduce systematic errors:
  - Flux, cross-section and detector uncertainties minimised
  - Measure unoscillated ν_μ spectrum at Near detector
    - extrapolate using MC
  - Compare to measured spectrum at Far detector





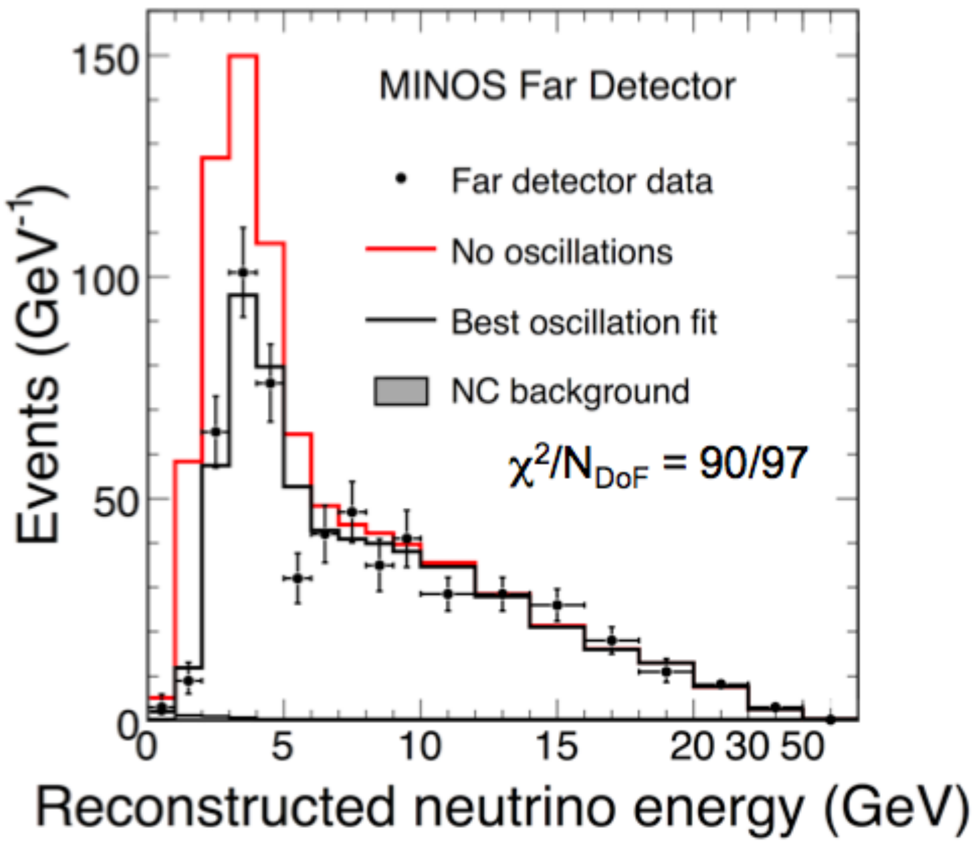
$$P(\nu_\mu \to \nu_\mu) = 1 - \underbrace{\boxed{\sin^2 2\theta}}_{1} \sin^2(1.267 \underbrace{\boxed{\Delta m^2}}_{2} L/E)$$

What MINOS observes

Far Detector ν_μ CC Data

- See strong energy dependent distortion of spectrum
- Energy spectrum fit with the oscillation hypothesis:

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$



MINOS result

Allowed Region

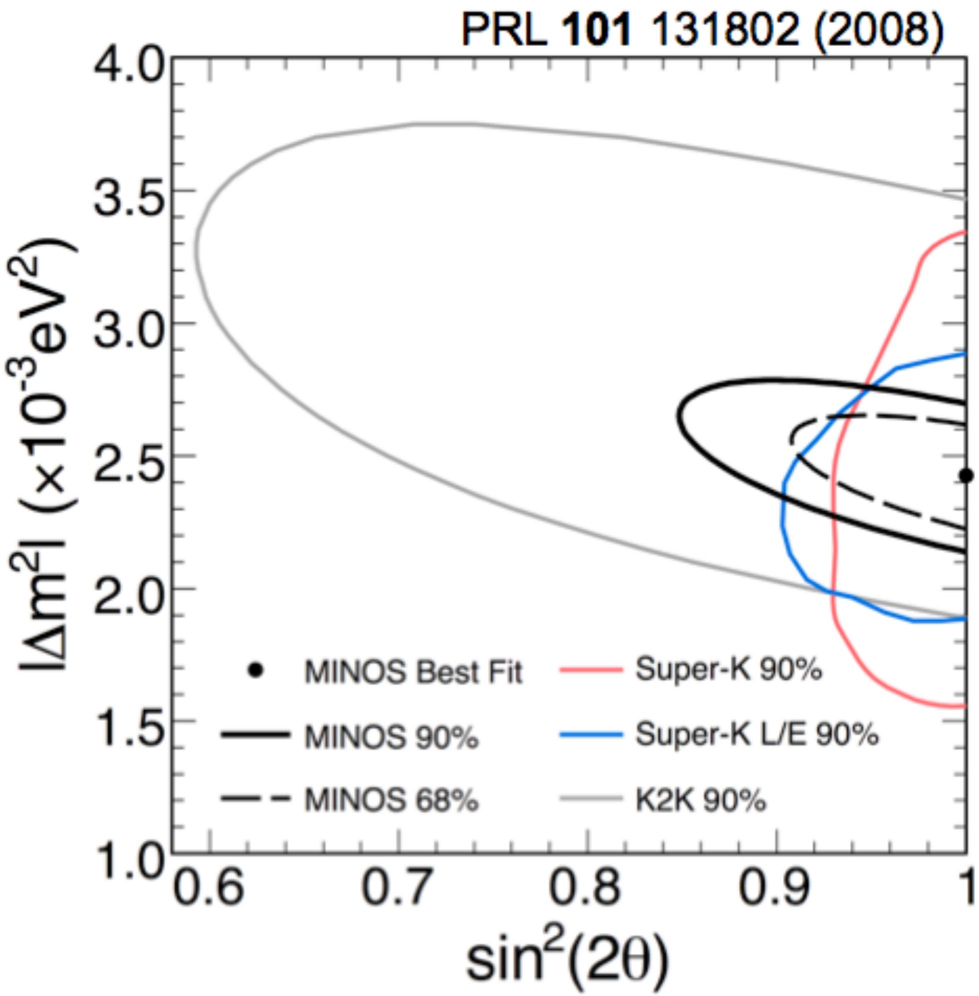
- Fit constrained to physical region and includes 3 largest systematic uncertainties
- Results:

$|\Delta m^2_{32}| = (2.43 \pm 0.13) \times 10^{-3}\ eV^2$

at 68% C.L.

$\sin^2(2\theta_{23}) > 0.90$

at 90% C.L.

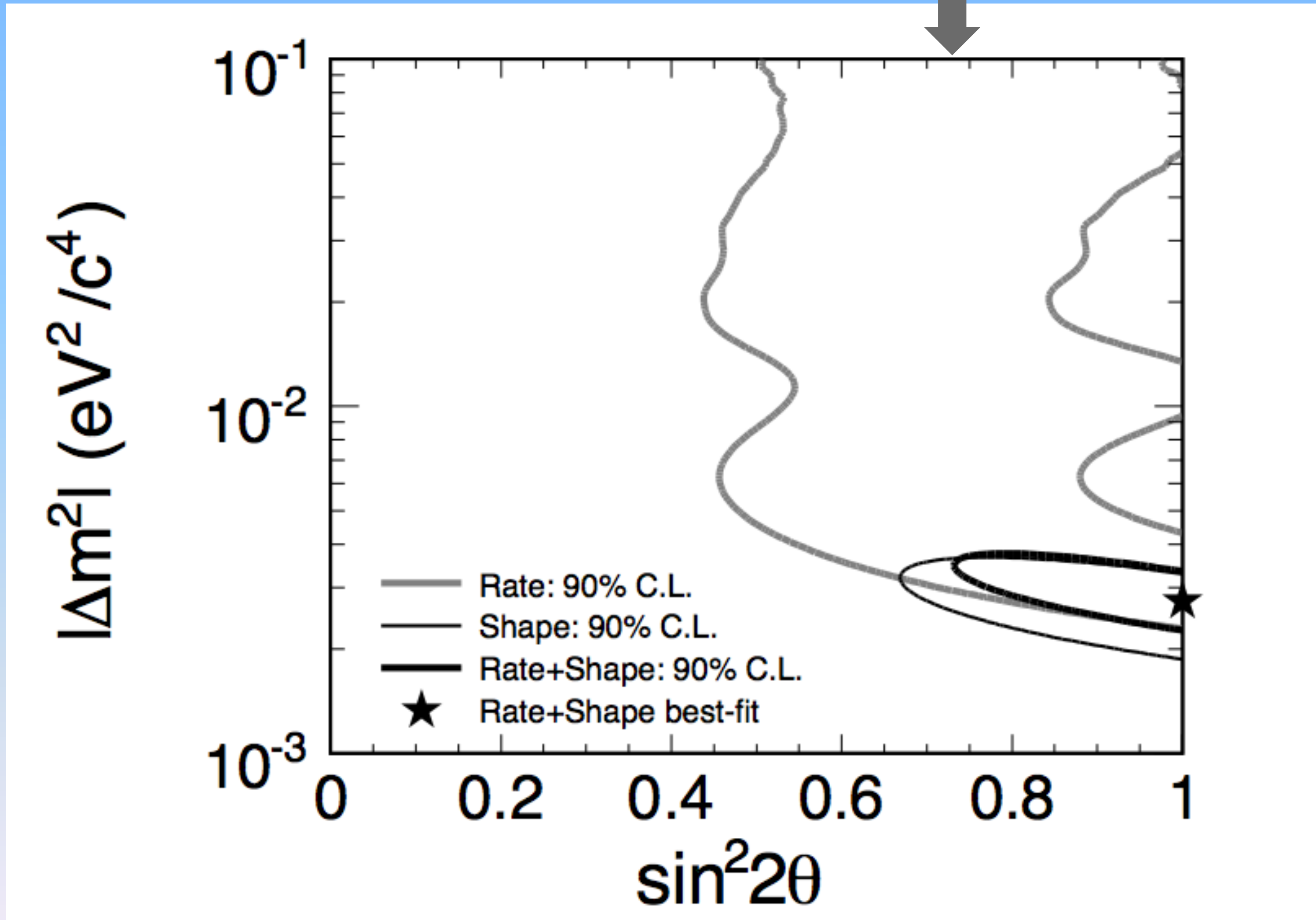


Most precise measurement of $|\Delta m^2_{32}|$ performed to date

The MINOS limitations

- disappearance only
- relatively "high" background

"RATE" gives poor information



OPERA expectations

- **Presently (assuming 22.5x10^{19}pot) OPERA expects about 15 detected τ with a background smaller than 1 event**
- **What happens whether LESS taus' are indeed observed ??**

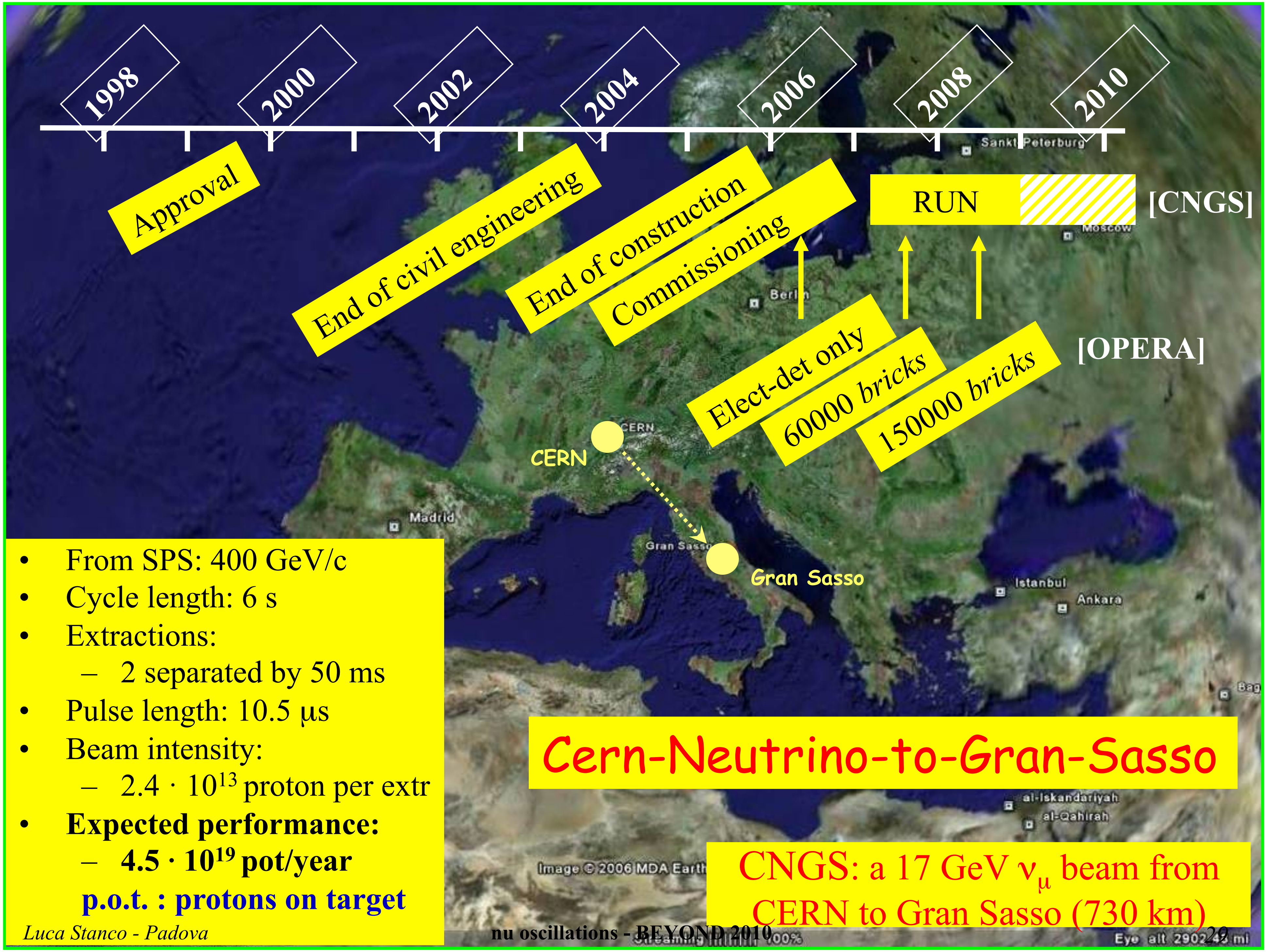
Example for 3+1 neutrinos (plus 1 sterile)

$(\theta_{13};\theta_{14};\theta_{24};\theta_{34})$	N_τ	background	$(\theta_{13};\theta_{14};\theta_{24};\theta_{34})$	N_τ	background
$(5°;5°;5°;20°)$	8.9	1.0	$(10°;5°;5°;20°)$	8.5	1.0
$(5°;5°;5°;30°)$	6.9	1.0	$(10°;5°;5°;30°)$	6.5	1.0
$(5°;5°;10°;20°)$	8.3	1.0	$(10°;5°;10°;20°)$	7.9	1.0
$(5°;5°;10°;30°)$	10.5	1.0	$(10°;5°;10°;30°)$	10.3	1.0
3 families	15.1	1.0	3 families	14.4	1.0

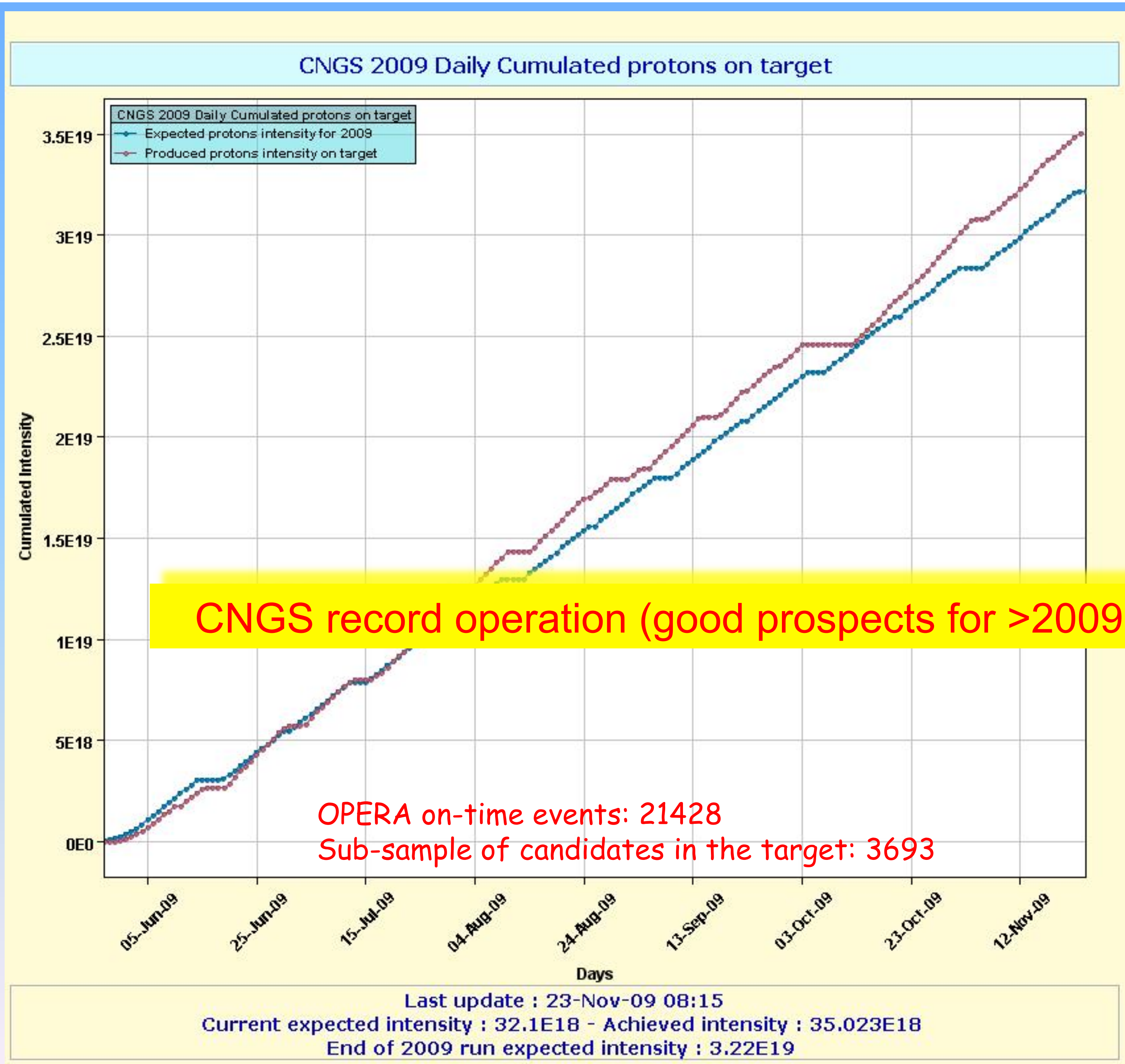
Table 1: Event rates and expected background for the $\nu_\mu \to \nu_\tau$ channel in the OPERA detector, for different values of θ_{14}, θ_{24} and θ_{34} in the (3+1) scheme. The other unknown angle, θ_{13} has been fixed to: $\theta_{13} = 5°, 10°$. The CP-violating phases are: $\delta_1 = \delta_2 = 0$; $\delta_3 = 90°$. As a reference, the expected value in the case of standard three-family oscillation (i.e., for $\theta_{i4} = 0$) is shown for maximal CP-violating phase δ. The rates are computed according to eq. (5.1).

From A.Donini et al., **JHEP 0712:013,2007**

Similarly for Non-Standard-Interac, M.Bennow et al., **Eur.Phys.J.C56:529-536,2008**


1998
2000
2002
2004
2006
2008
2010
Approval
End of civil engineering
End of construction
Commissioning
RUN
[CNGS]
Elect-det only
60000 *bricks*
150000 *bricks*
[OPERA]
CERN
Gran Sasso
Cern-Neutrino-to-Gran-Sasso
• From SPS: 400 GeV/c
• Cycle length: 6 s
• Extractions:
– 2 separated by 50 ms
• Pulse length: 10.5 μs
• Beam intensity:
– $2.4 \cdot 10^{13}$ proton per extr
• **Expected performance:**
– **$4.5 \cdot 10^{19}$ pot/year**
p.o.t. : protons on target
CNGS: a 17 GeV ν_μ beam from CERN to Gran Sasso (730 km)
Madrid
Berlin
Sankt Peterburg
Moscow
Istanbul
Ankara
al-Iskandariyah
al-Qahirah
Image © 2006 MDA EarthSat

CNGS 2009



CNGS record operation (good prospects for >2009)

OPERA on-time events: 21428
Sub-sample of candidates in the target: 3693

... for tau neutrino CC detection in OPERA

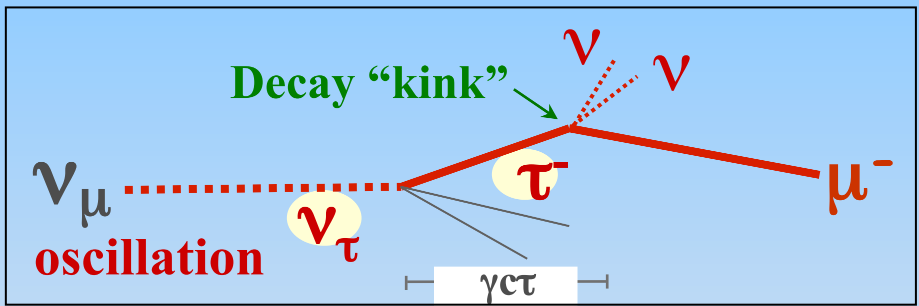
CC interaction

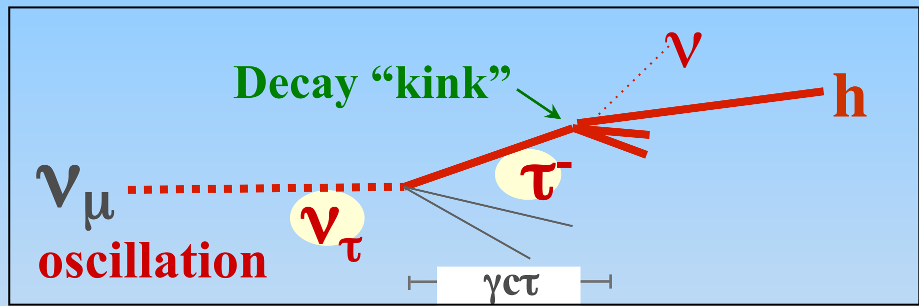
ν_μ .... $\nu_\tau + N \rightarrow \tau^- + X$

oscillation

$\tau^- \rightarrow$

$\mu^- \ \nu_\tau \ \bar{\nu}_\mu$	B. R. ~ 17%
$h^- \ \nu_\tau \ n(\pi^o)$	B. R. ~ 49%
$e^- \ \nu_\tau \ \bar{\nu}_\varepsilon$	B. R. ~ 18%
$\pi^+ \pi^- \pi^- \ \nu_\tau \ n(\pi^o)$	B. R. ~ 15%

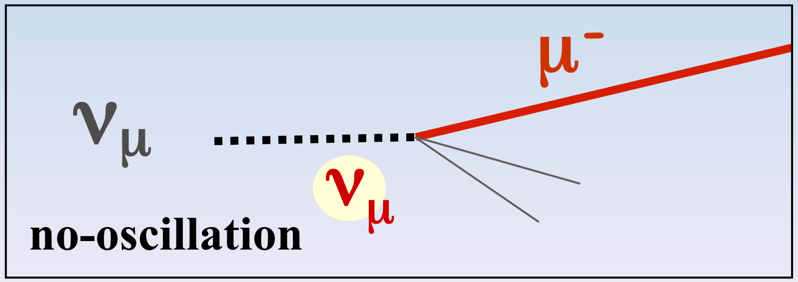


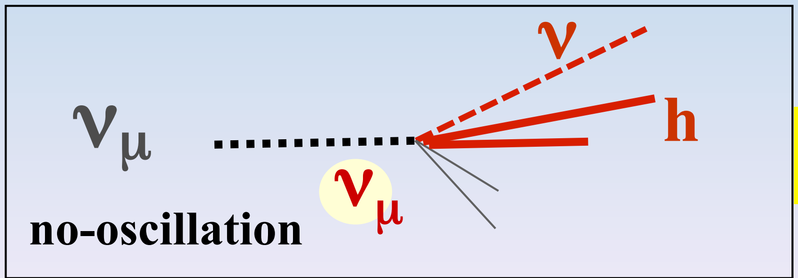


$c\tau \sim 87\ \mu m$ (≈ 600 μm of path)

(with ≈ 35% of Non-Scaling QE and 65% DIS)

CC





NC

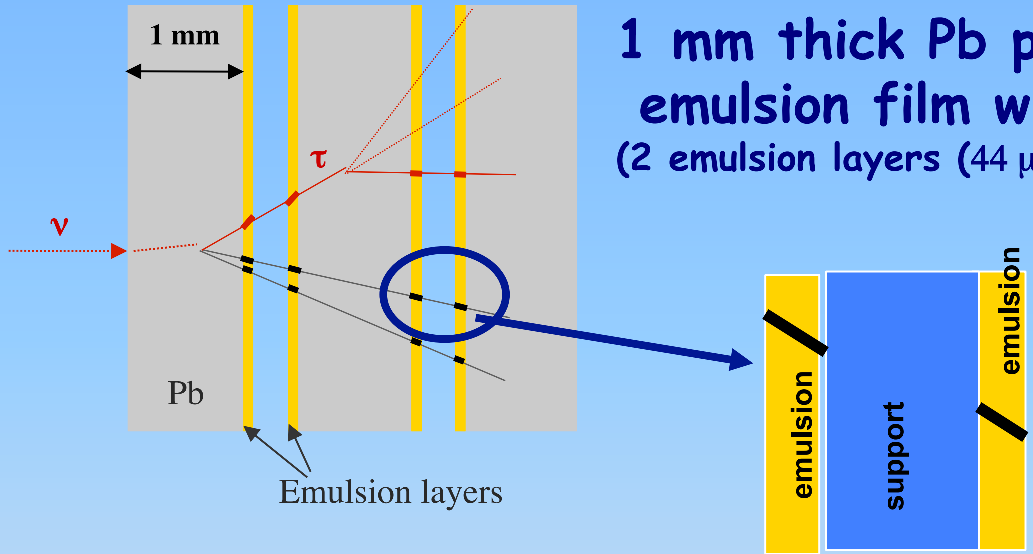
(with ≈ 11% of Non-Scaling QE and 89% DIS)

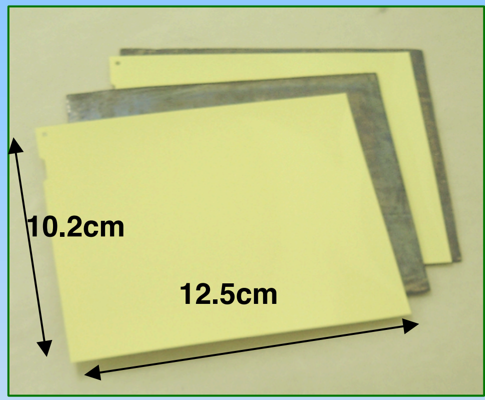
The OPERA way (the principle)

OPERA adopts the ECC concept (Emulsion Cloud Chamber):

1 mm thick Pb plate interleaved with emulsion film with 1 μm space resolution

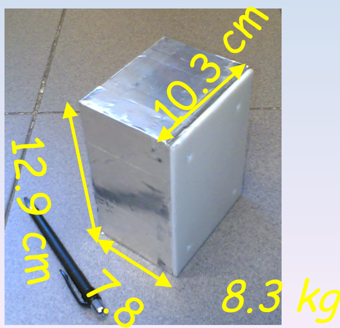
(2 emulsion layers (44 μm thick) poured on a 205 μm plastic base)





Track reconstruction accuracy inside emulsion film: $\Delta x \approx 1\ \mu m$ $\quad \Delta\theta \approx 1$ mrad

arranged in a "BRICK":
- 57 emulsion sets
- 56 Pb layers

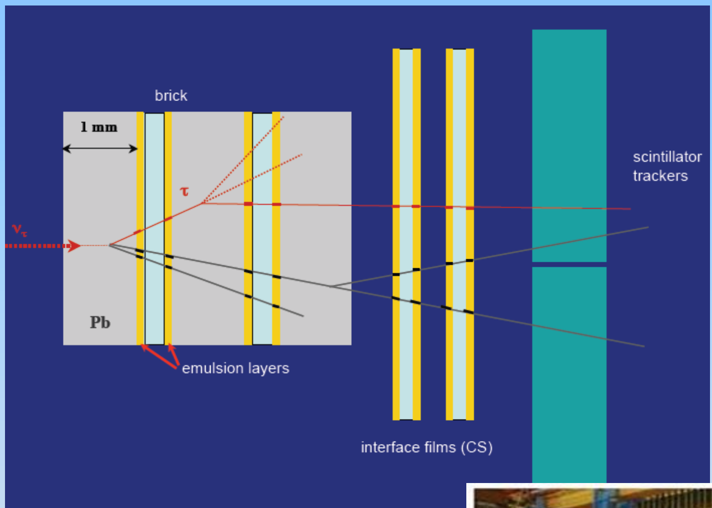


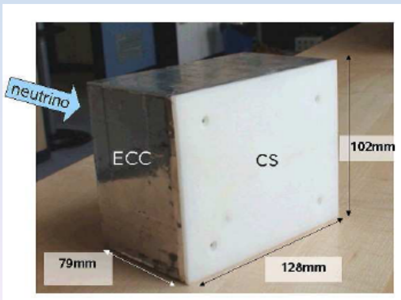
plus downstream

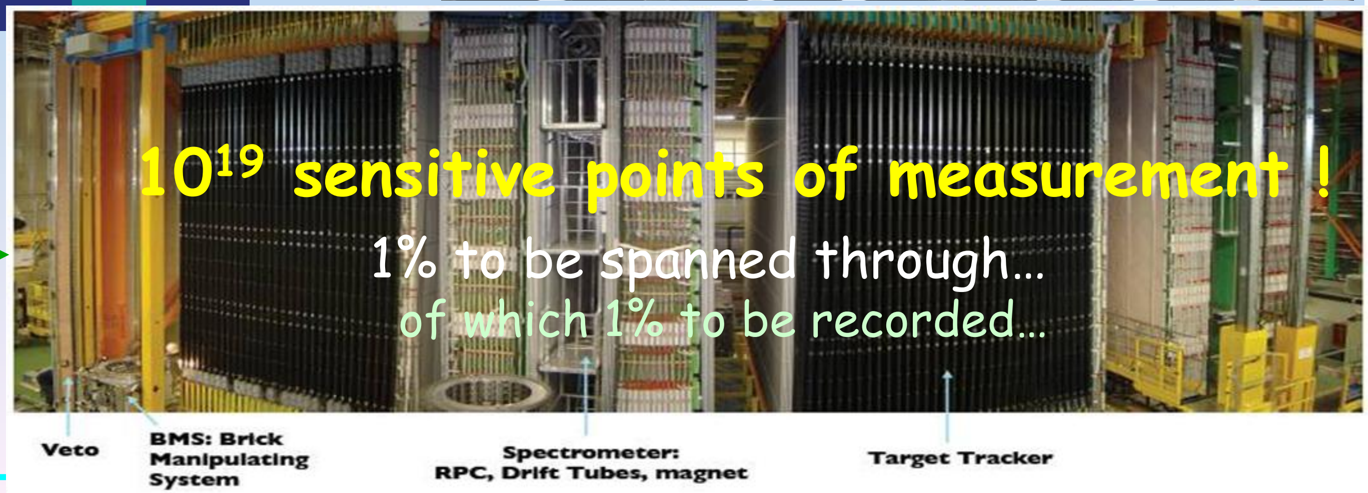
Plus 2 external emulsion sets for "interplay" with Electronics Data, arranged in a white plastic box | **CS**

The completion of the OPERA construction(*)

OPERA is based on the only proven technology (DONUT) to identify ν_τ on an event-by-event basis (nucl.emuls.&lead driven by real time detectors). It is celebrated as a **major engineering achievement** since it brought such technology to an **immense size** (1.25 kton)



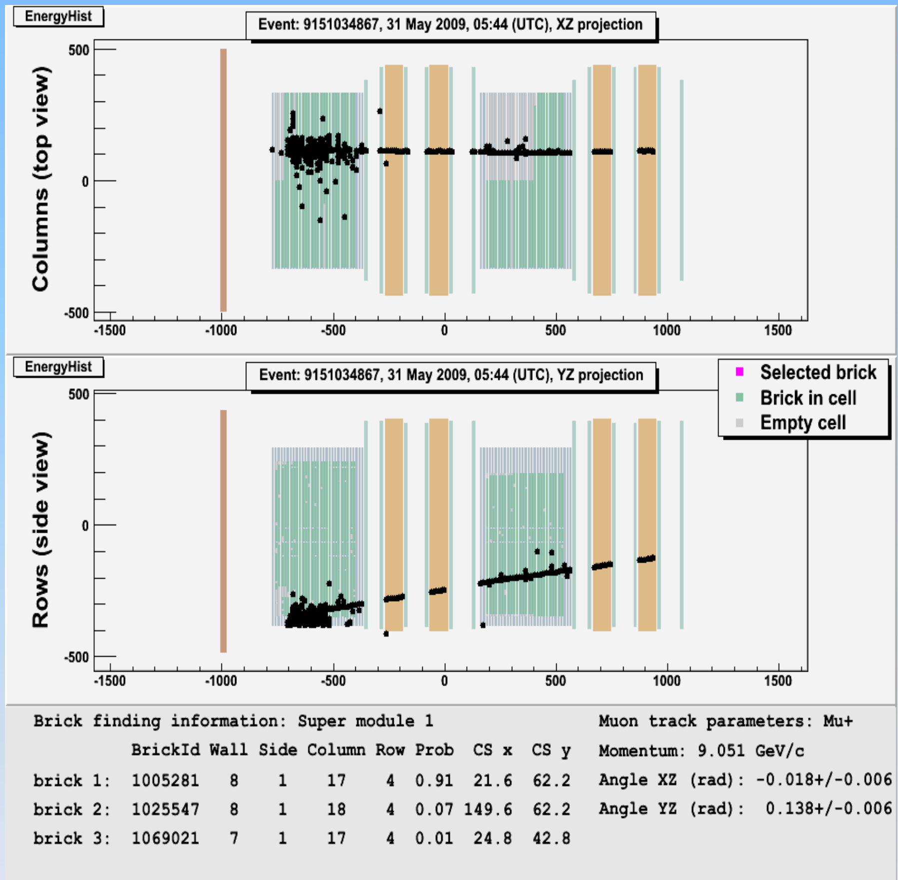




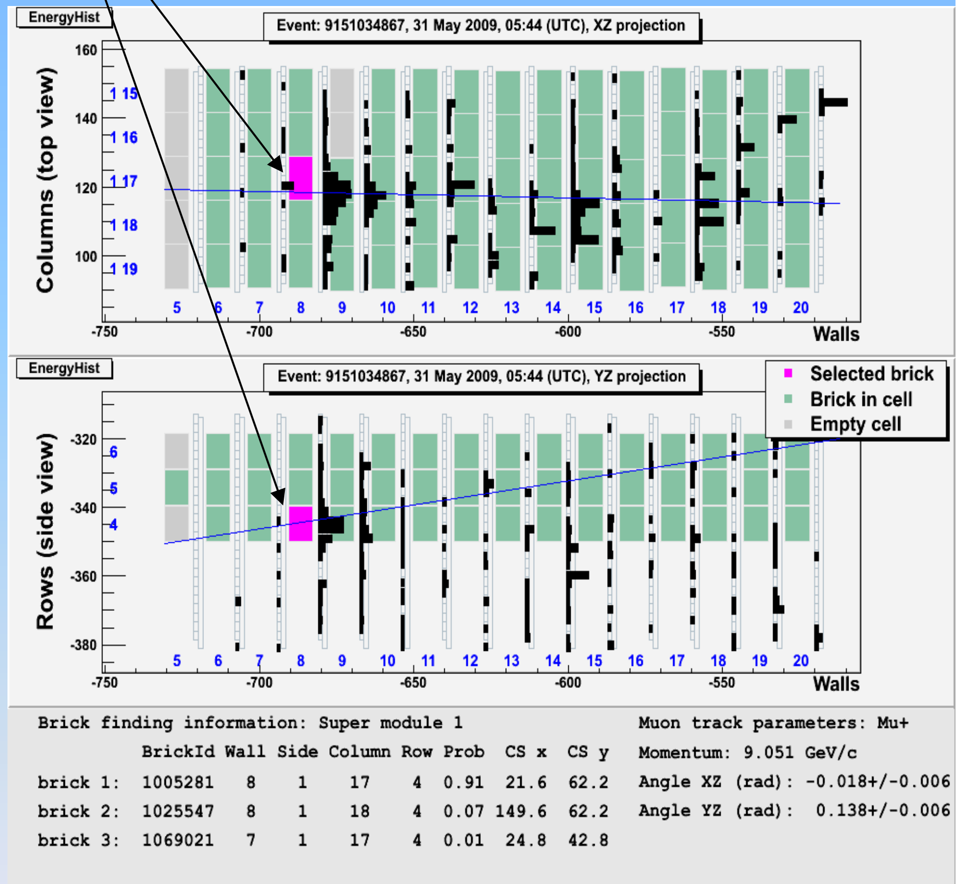
(*) R.Acquafredda et al., "The Opera experiment in the CERN to GS ν beam"; JINST, 4:P04018,2009

Event in OPERA

Event trigger and reconstruction



Brick identification

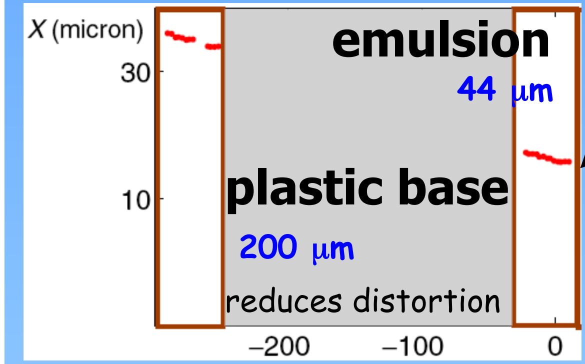


- Select the brick containing the neutrino interaction
  - Reduce the analysis time
  - Minimize the target mass loss

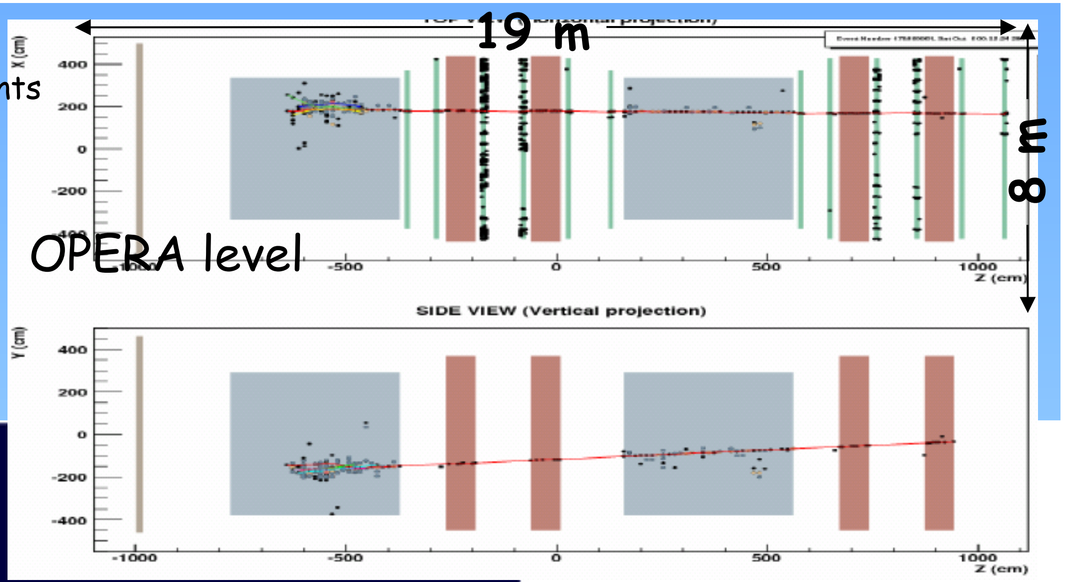
What the microscope CCD sees in one film...

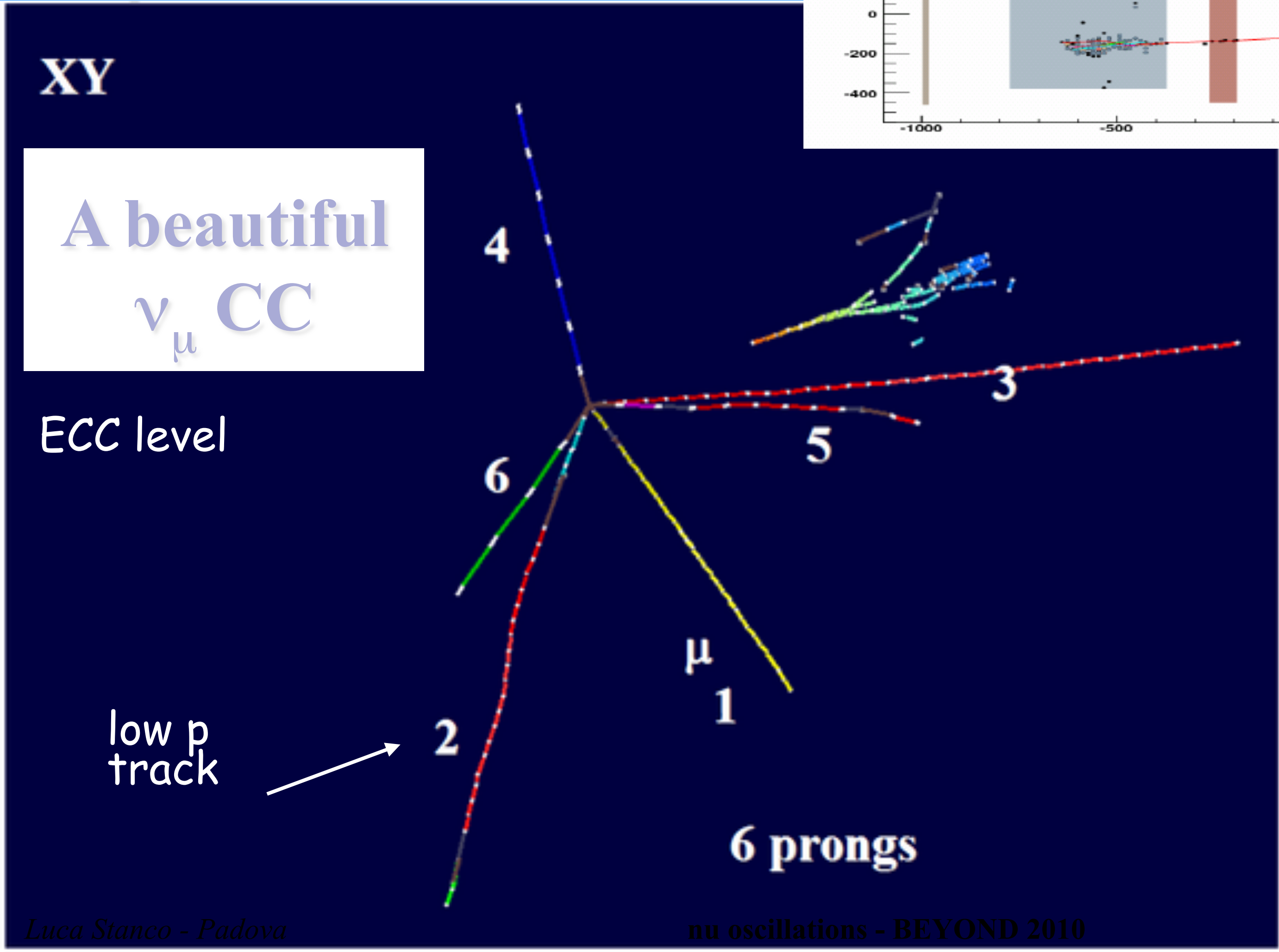
170 μm

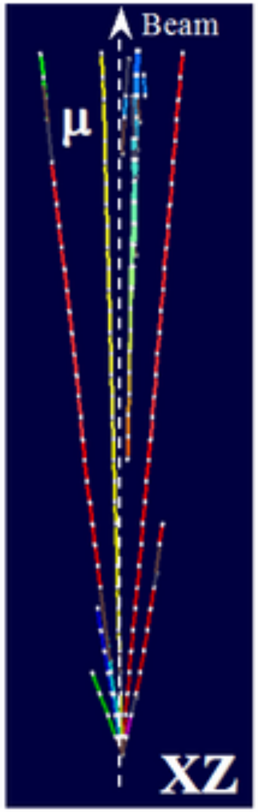
250 μm

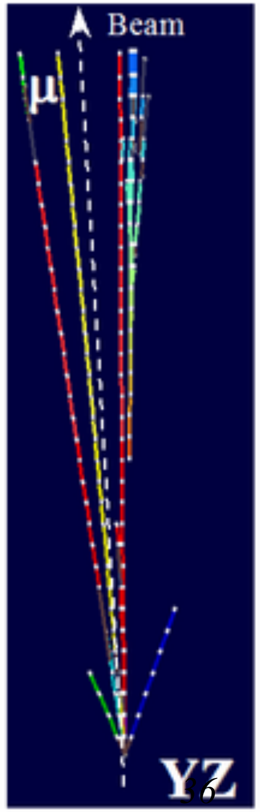


10-20 measurements per layer

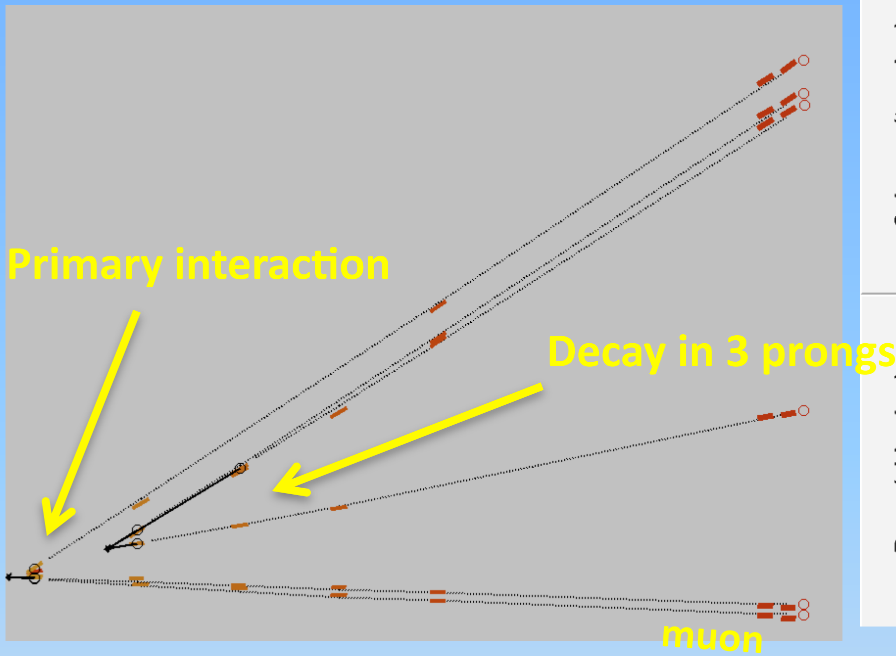


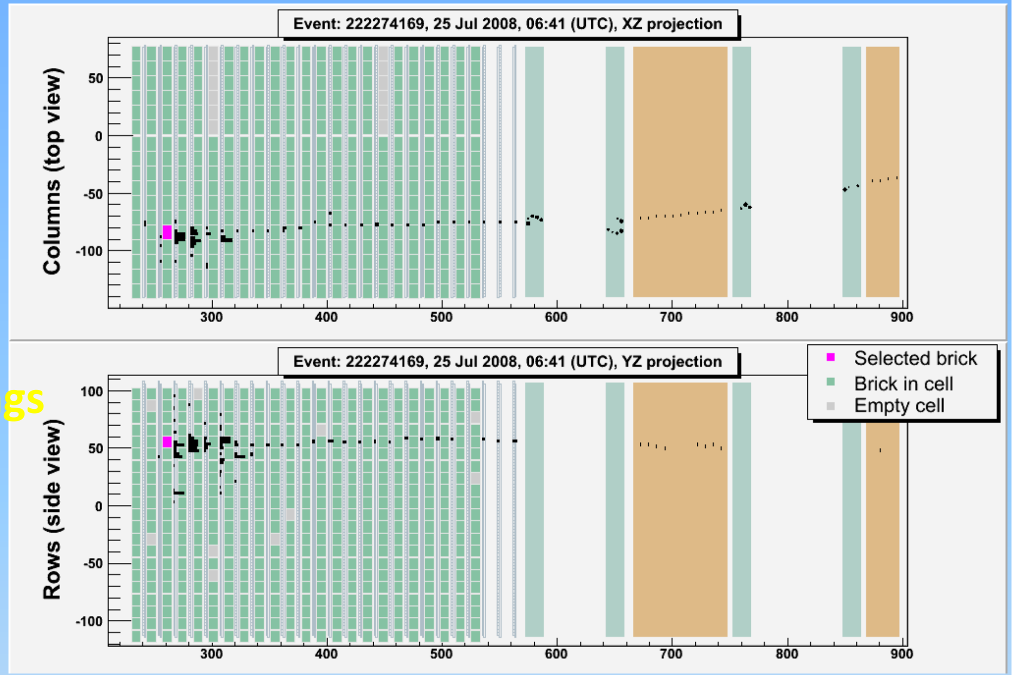


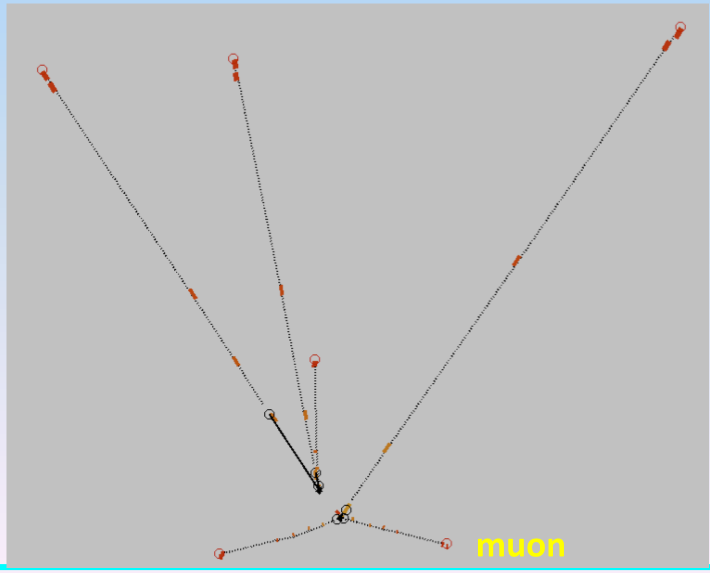




A Charm candidate Event in OPERA







Three charged prong decay

Flight length : ~1150 μm
Angle (muon – 3 prongs decay) : ~150°

Kaon decay probability : 10^{-4} %
Hadron re-interaction probability : 1×10^{-5} %

8

OPERA: tau physics search potential

Full mixing, 5 years run, 4.5×10^{19} pot/year and M_D =1.3 Kton

Efficiency before τ identification: $\varepsilon_{trigger} \times \varepsilon_{brick} \times \varepsilon_{geom} \times \varepsilon_{vertex\ location} = 99\% \times (\geq 70\%) \times 94\% \times 90\%$

τ decay channels	ε(%)	BR(%)	Signal $\Delta m^2 = 2.5\times10^{-3}$ eV^2	Signal $\Delta m^2 = 3.0\times10^{-3}$ eV^2	Background
$\tau \to \mu$	17.5	17.7	2.9	4.2	0.17
$\tau \to e$	20.8	17.8	3.5	5.0	0.17
$\tau \to h$	5.8	49.5	3.1	4.4	0.24
$\tau \to 3h$	6.3	15	0.9	1.3	0.17
ALL	$\varepsilon\times$BR=10.6%		**10.4**	**14.9**	**0.75**

Expected backgrounds:

- Charmed particles produced in ν_μ CC and NC interaction
- Hadron reinteractions in lead
- Large angle μ scattering: muons produced in ν_μ CC events
- π^0 mis-identification
- …

Occur if primary muon is not detected and possible wrong charge measurement of secondary muon. **Muon ID is very crucial issue for the experiment!**

RUN 2009 expectations

173 days
48s supercycle
75% efficiency
2.1^{E}13 pot/extraction

→3.5^{E}19 pot
→3500 events of nu interactions

Efforts needed for improving the bea
performance…

RUN 2010 expectations

(with LHC permit)

→4.5^{E}19 pot
→4500 nu interactions in OPERA bricks

With 2008-10 runs
OPERA be able to confirm
tau appearance with a
reasonable probability

OR

at a not so large probab.
to exclude tau appearance!

Conclusions

- Neutrinos mass and oscillations new history

  (many results in last 10 years but still far from settling them)
- Matrix of leptonic mixing clue issue

MNS elements: more measurements, better resolutions...

MiniBooNE/MINOS/OPERA challenges:

1) collect more statistics
2) disantagle the physics measurements !
3) find the taus ! Measure θ_{13} (if > 7^0)...
4) confirm the unexpected !

NEXT few years exciting (and unclear) !

FAR future does really exist

out of present facilities ?