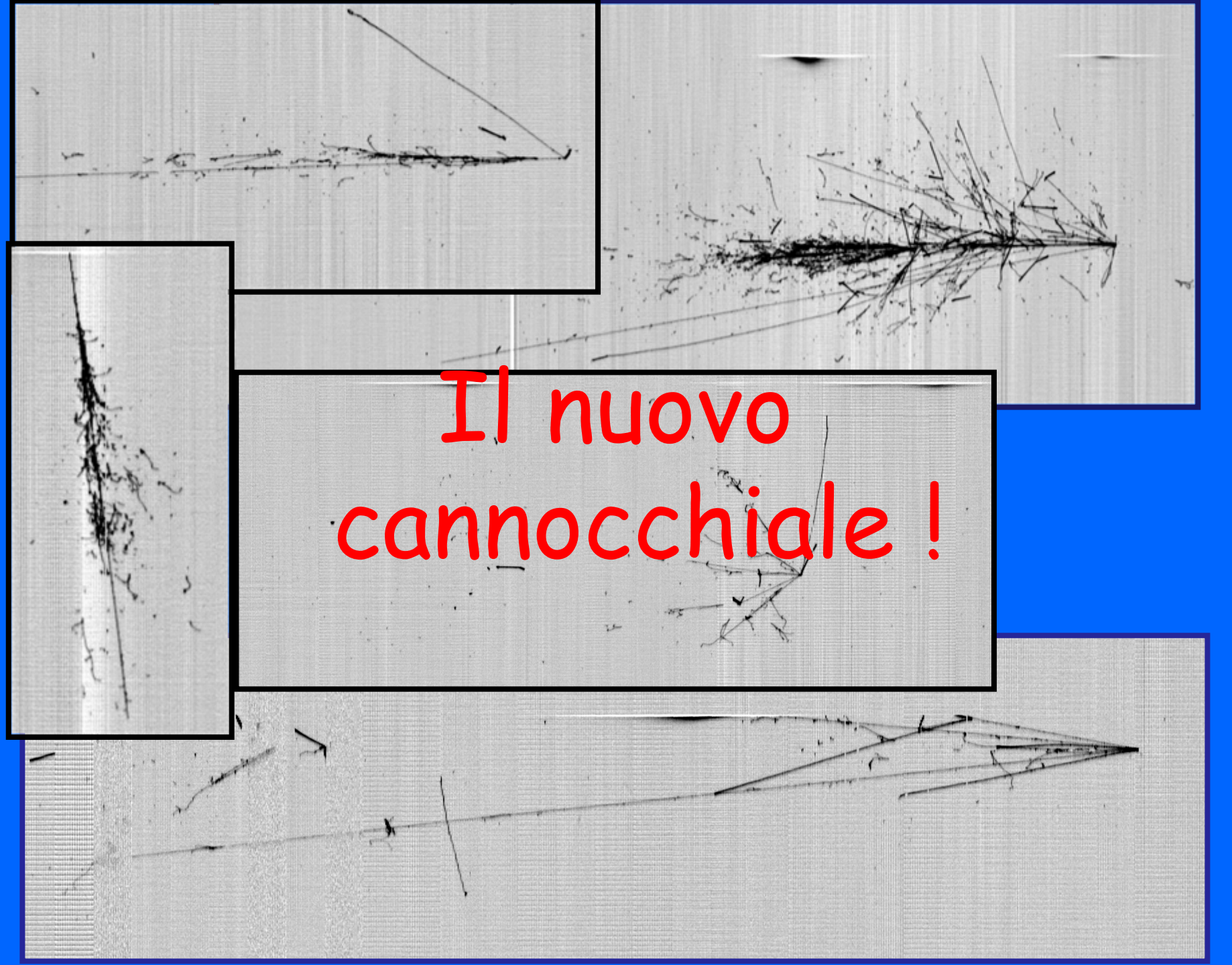
Neutrinos: active, sterile or tachionic ?

M.Laveder (Univ. of Padua & INFN-PD)

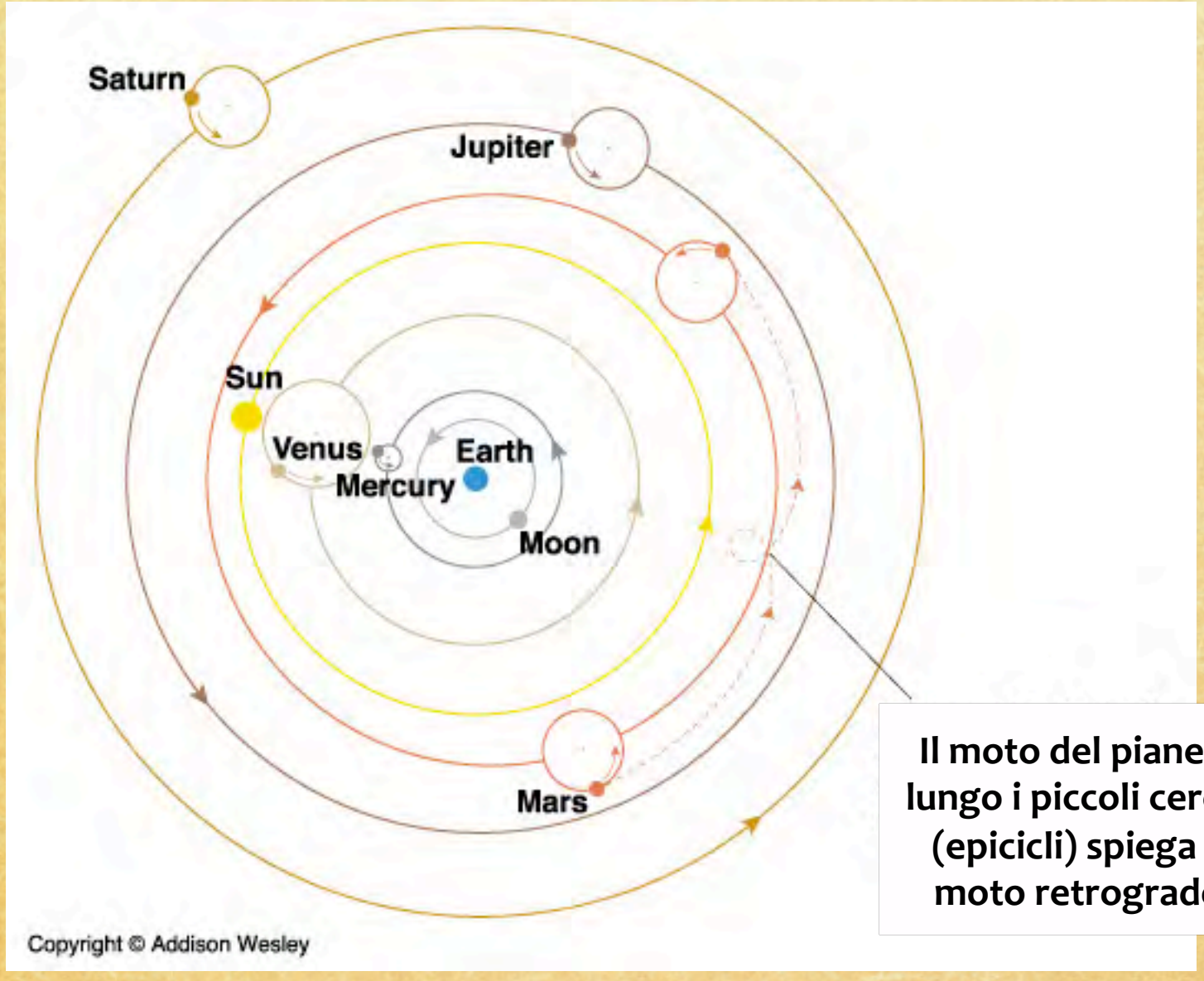
Turin – 6/12/2011

Il cannocchiale di Galileo sembra infrangere le incorruttibili sfere e rimuovere l'orizzonte


Il nuovo
cannocchiale !

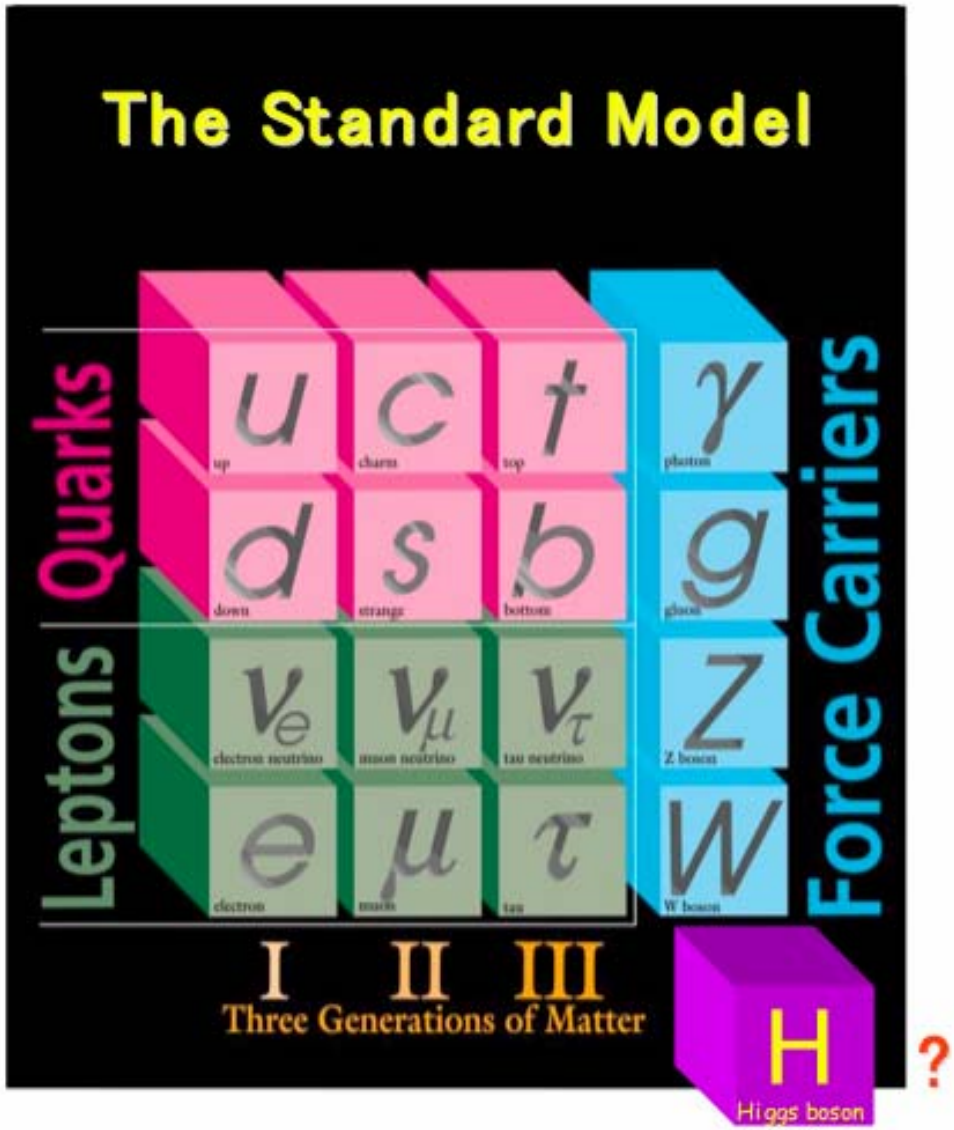
Neutrinos: active

La soluzione Tolemaica



Il moto del pianeta lungo i piccoli cerchi (epicicli) spiega il moto retrogrado

Gravity
?


The Standard Model
Quarks
Leptons
Force Carriers
u
up
c
charm
t
top
γ
photon
d
down
s
strange
b
bottom
g
gluon
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Z
Z boson
e
electron
μ
muon
τ
tau
W
W boson
I
II
III
Three Generations of Matter
H
Higgs boson
?

Matrice di mixing dei neutrini

Neutrinos
$$U_{MNSP} \sim \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Quarks
$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.005 \\ 0.2 & 1 & 0.04 \\ 0.005 & 0.04 & 1 \end{pmatrix}$$

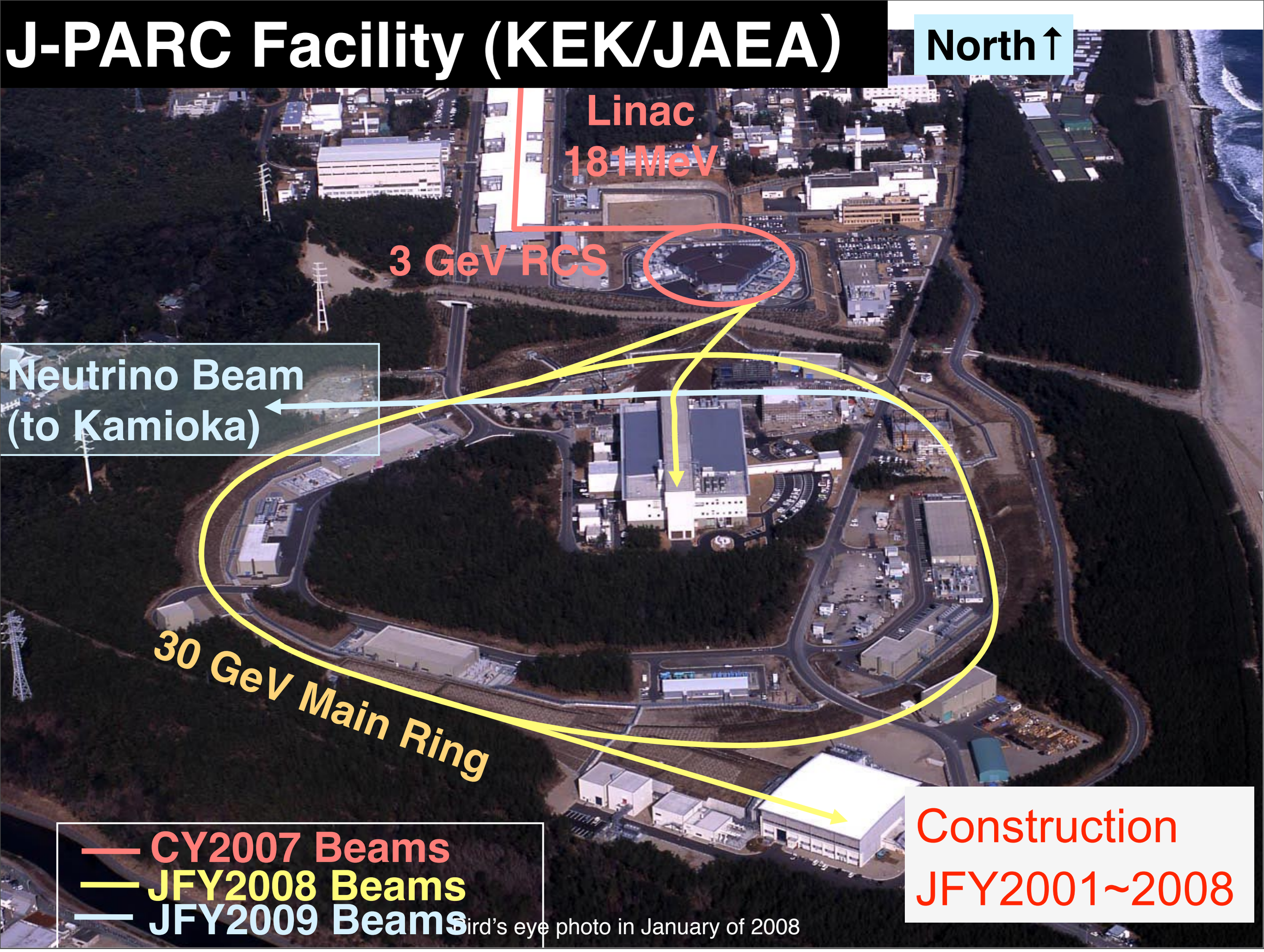
La matrice di mixing dei neutrini U_{MNSP} è molto diversa dalla matrice di mixing dei quark U_{CKM}

$$U_{MNSP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

Neutrini Atmosferici — Unknown — Neutrini Solari

$\theta_{13} \to 0 \quad \Rightarrow \quad$ La matrice 3x3 di mixing diventa il prodotto di due matrici 2x2.
La conoscenza di θ_{13} prelude ad ogni futura ricerca di violazione di CP leptonica.

J-PARC Facility (KEK/JAEA)

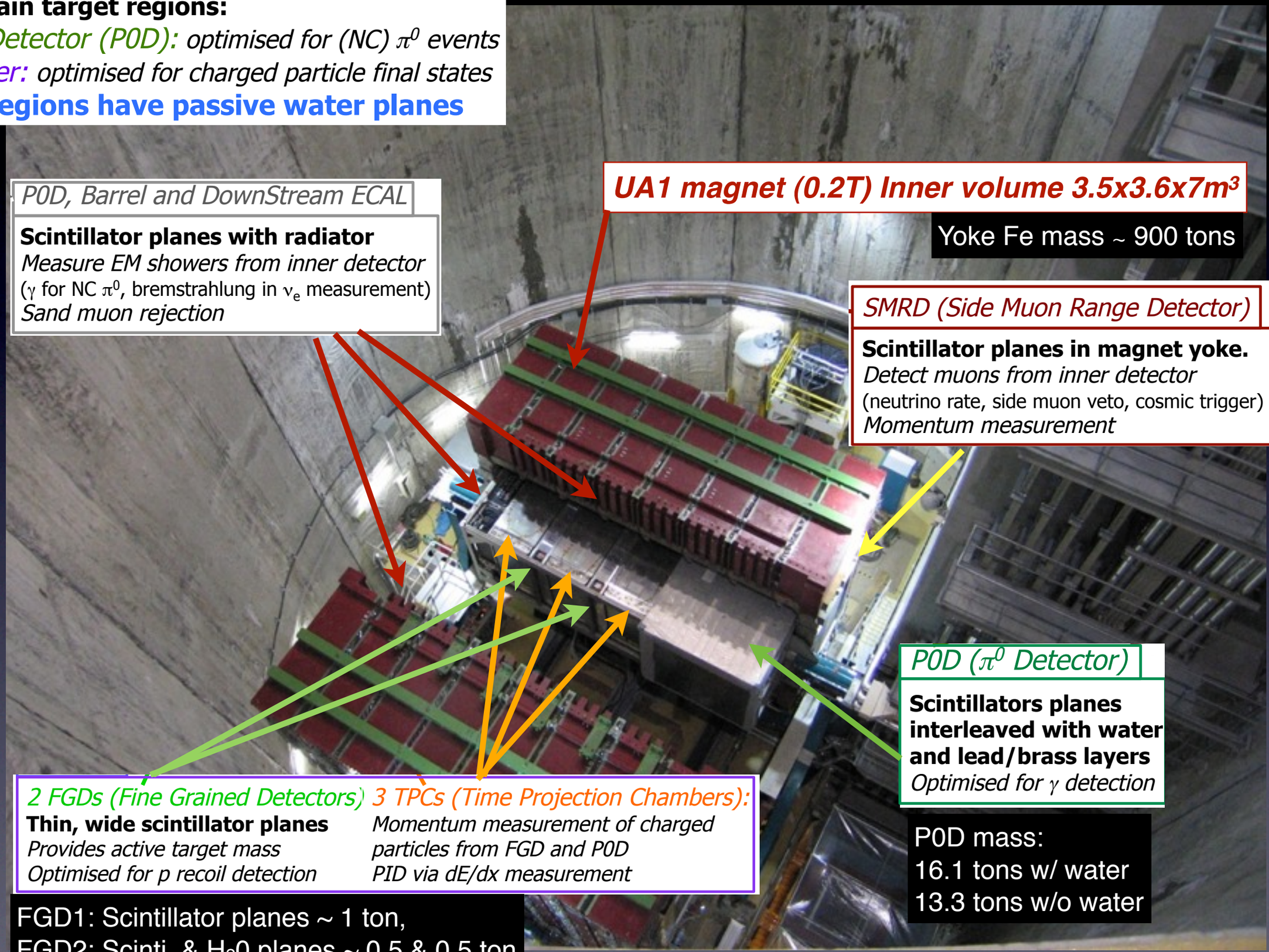


Bird's eye photo in January of 2008

ND280 off-axis detector overview

Two main target regions:
- *Pi-0 Detector (P0D):* optimised for (NC) π^0 events
- *Tracker:* optimised for charged particle final states

Both regions have passive water planes



P0D, Barrel and DownStream ECAL

Scintillator planes with radiator
Measure EM showers from inner detector
(γ for NC π^0, bremstrahlung in ν_e measurement)
Sand muon rejection

UA1 magnet (0.2T) Inner volume 3.5x3.6x7m³

Yoke Fe mass ~ 900 tons

SMRD (Side Muon Range Detector)

Scintillator planes in magnet yoke.
Detect muons from inner detector
(neutrino rate, side muon veto, cosmic trigger)
Momentum measurement

P0D (π^0 Detector)

Scintillators planes interleaved with water and lead/brass layers
Optimised for γ detection

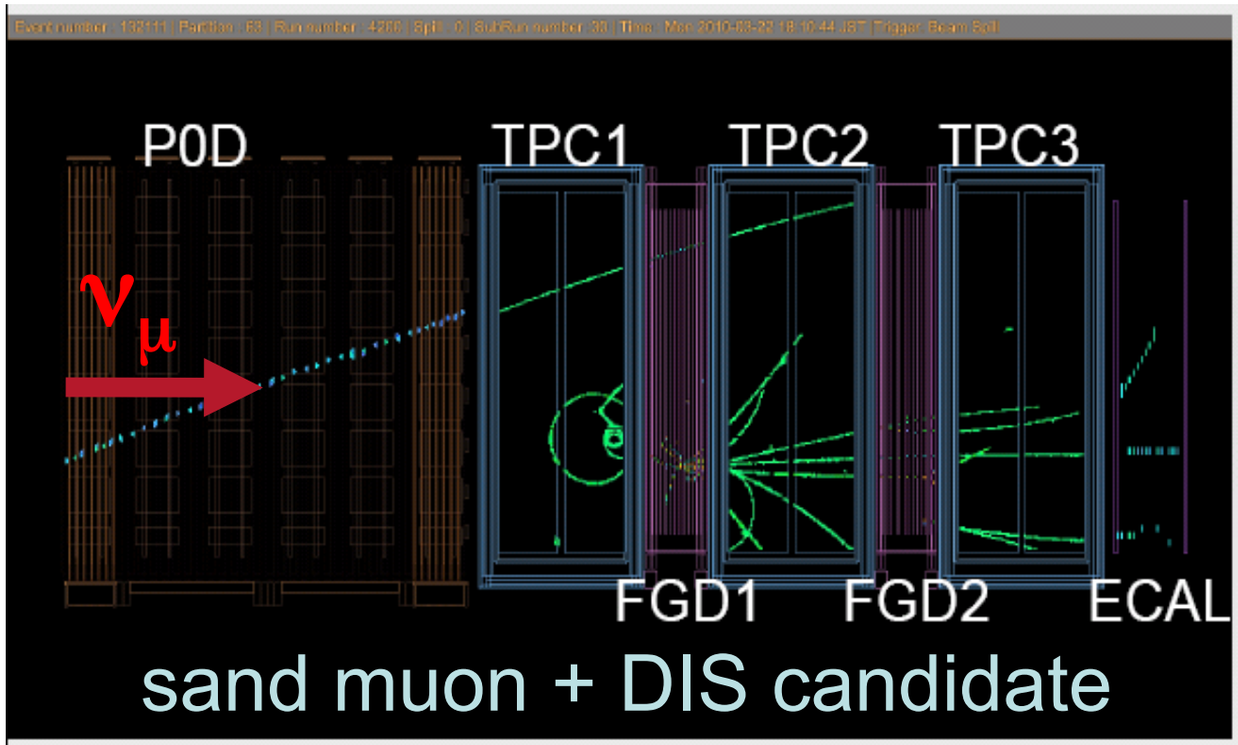
P0D mass:
16.1 tons w/ water
13.3 tons w/o water

2 FGDs (Fine Grained Detectors):
Thin, wide scintillator planes
Provides active target mass
Optimised for p recoil detection

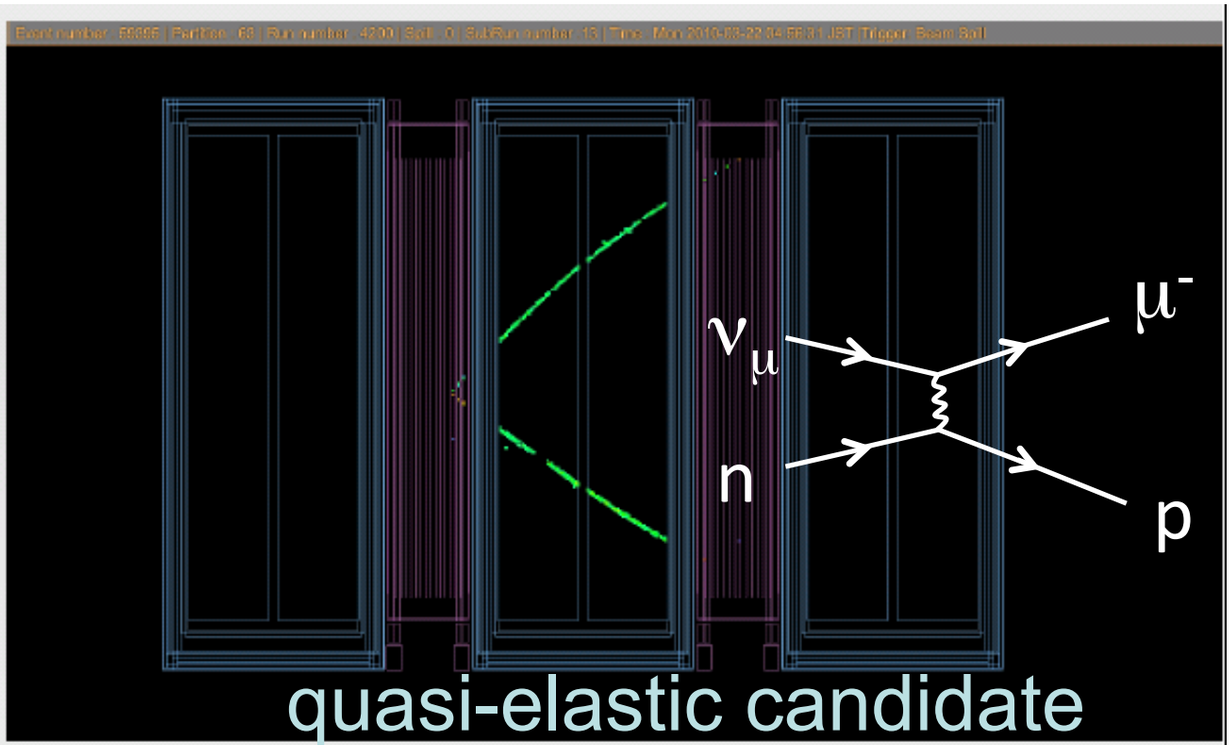
3 TPCs (Time Projection Chambers):
Momentum measurement of charged particles from FGD and P0D
PID via dE/dx measurement

FGD1: Scintillator planes ~ 1 ton,
FGD2: Scinti. & H_20 planes ~ 0.5 & 0.5 ton

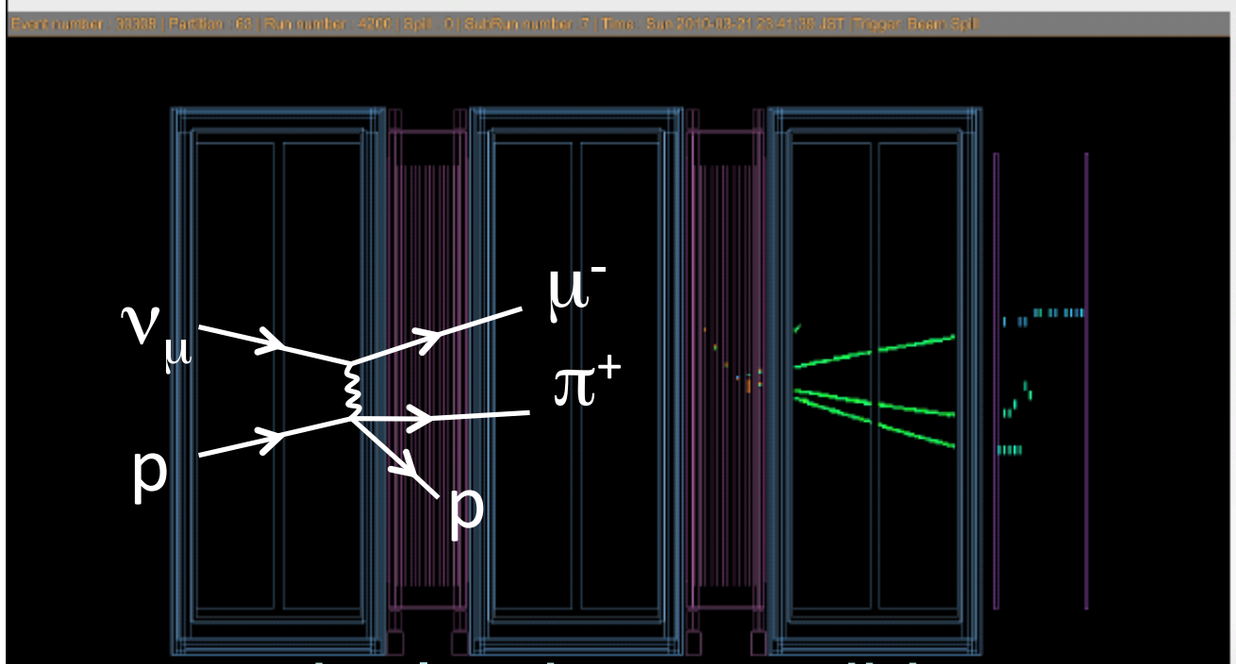
ND280 off-axis event gallery



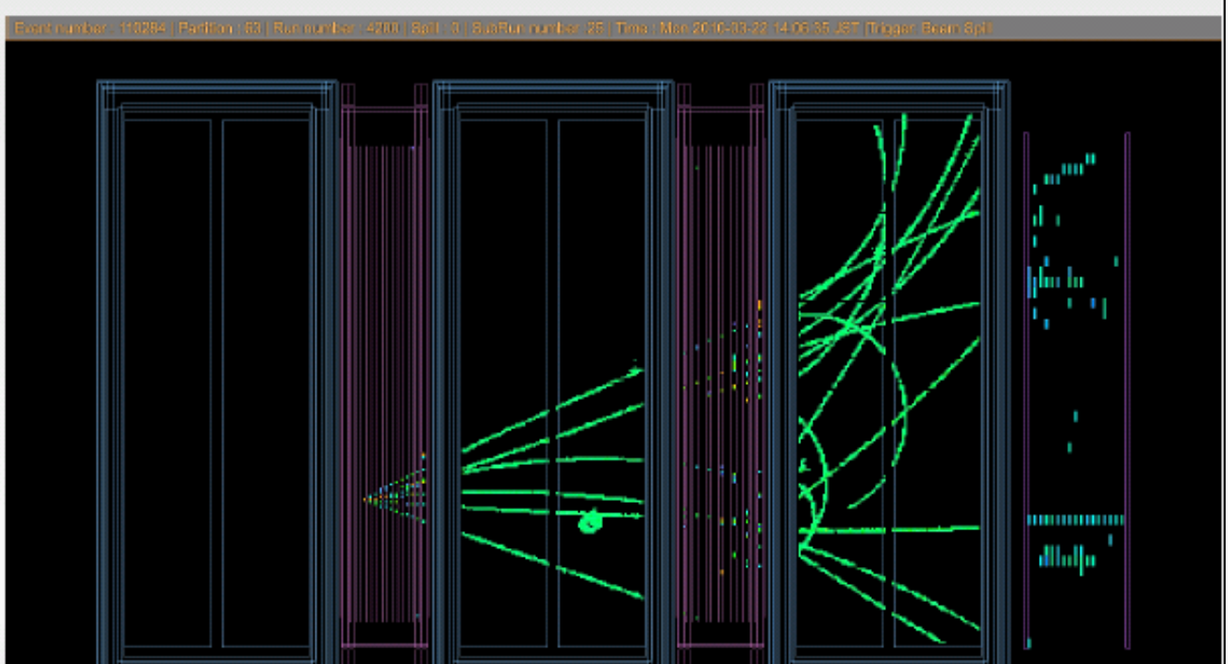
sand muon + DIS candidate



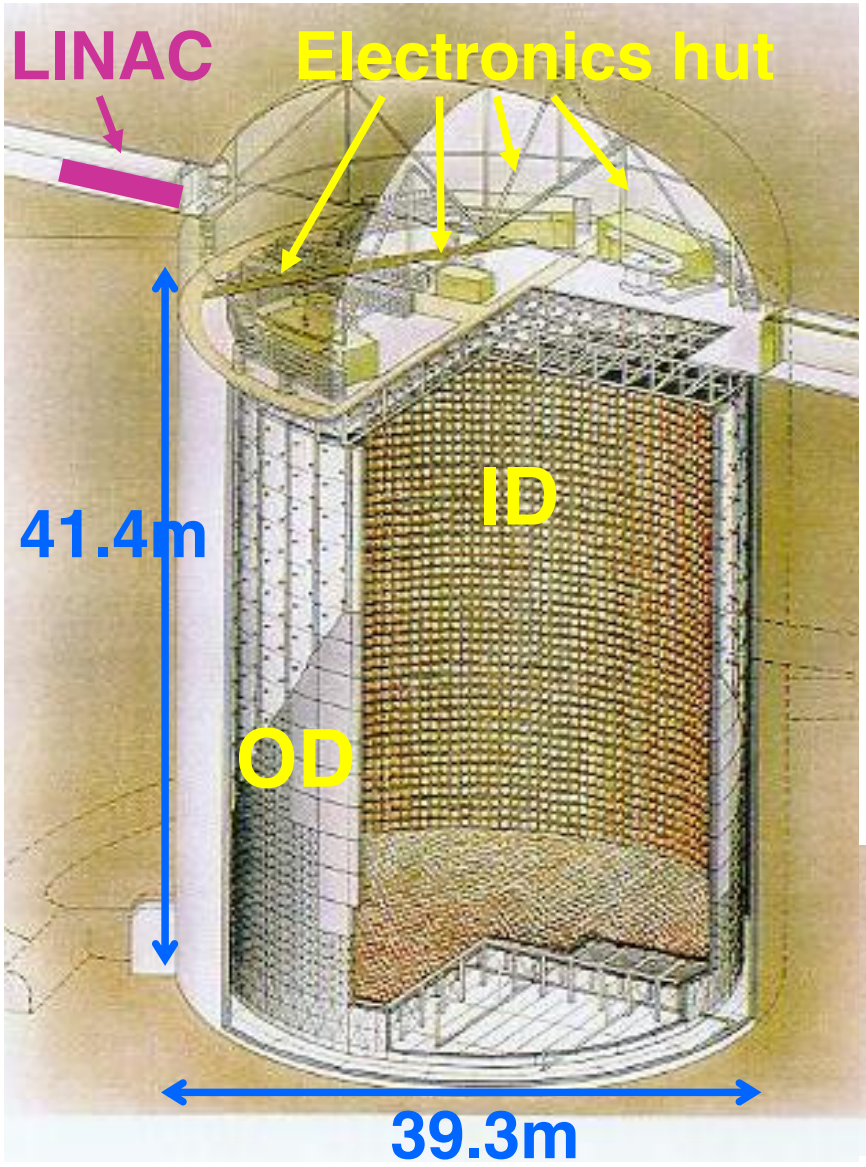
quasi-elastic candidate



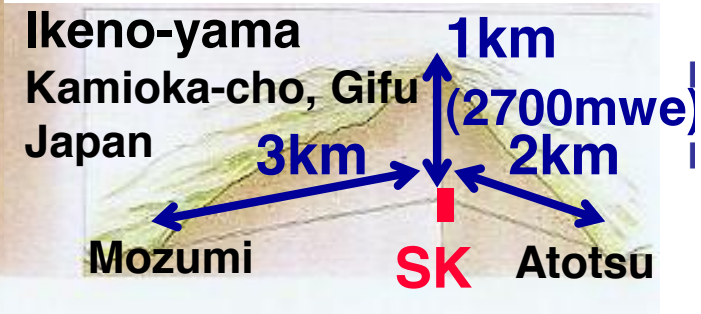
single pion candidate


DIS candidate

Far detector (Super-K)

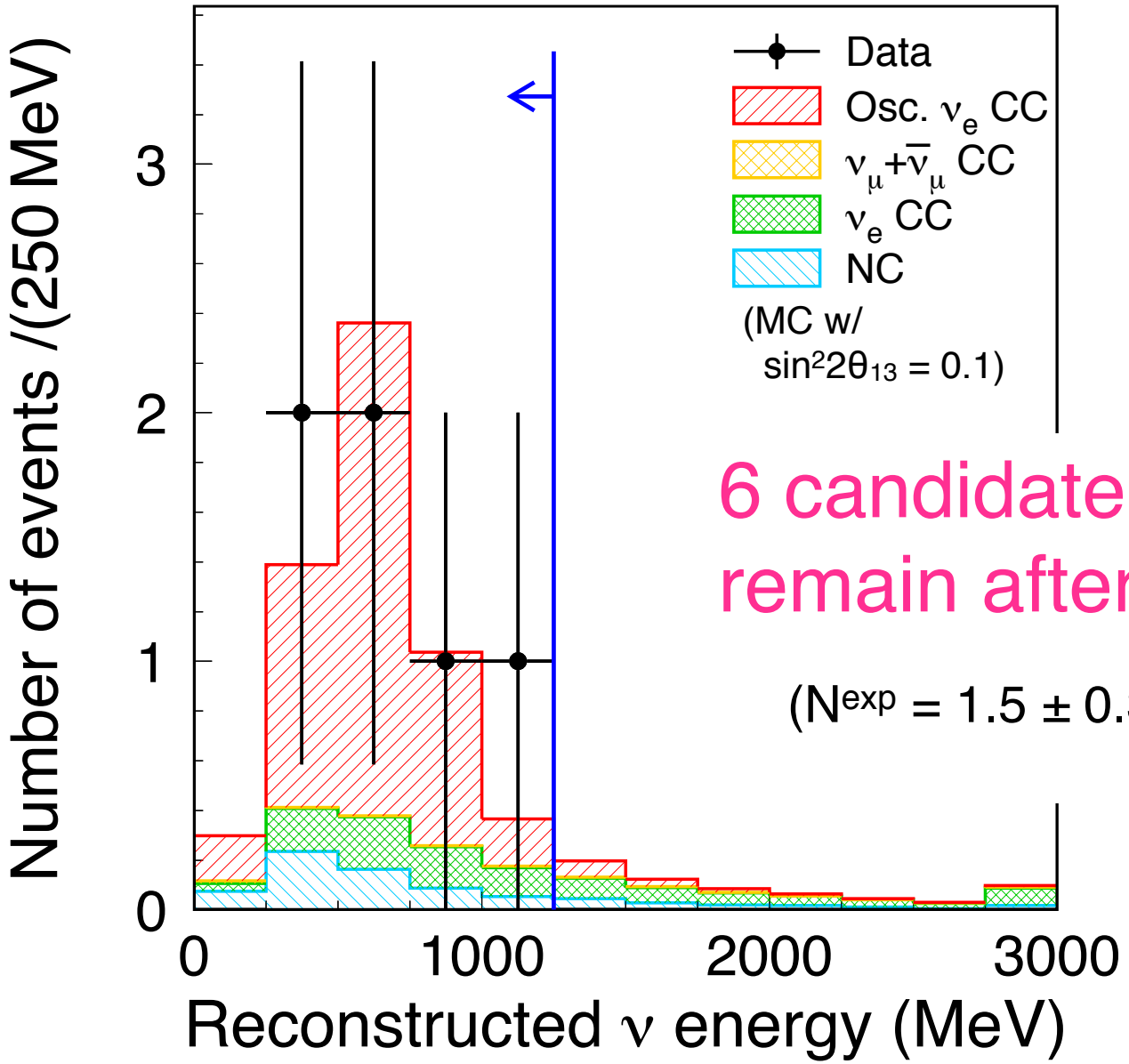


- Stable operation since April 1996
- Water Cherenkov detector w/ fiducial volume 22.5kton
- Dead-time less DAQ system (2008~)
- Detector performance is well-matched at sub GeV
  - Excellent performance for single particle event
  - Good e-like(shower ring) / μ-like separation *(next page)*



~11000 x 20inch PMTs (inner detector, ID)

Reconstructed ν energy cut (E_{rec} < 1250 MeV) : *Final cut*



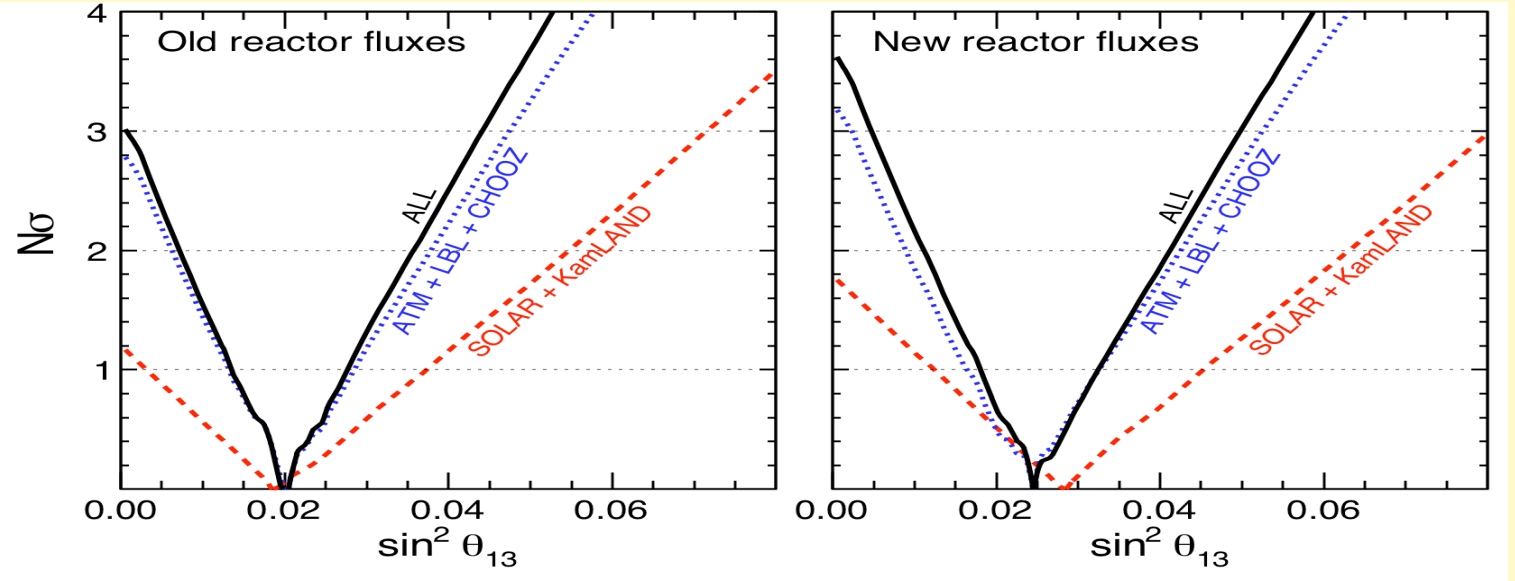
6 candidate events remain after all cuts !!

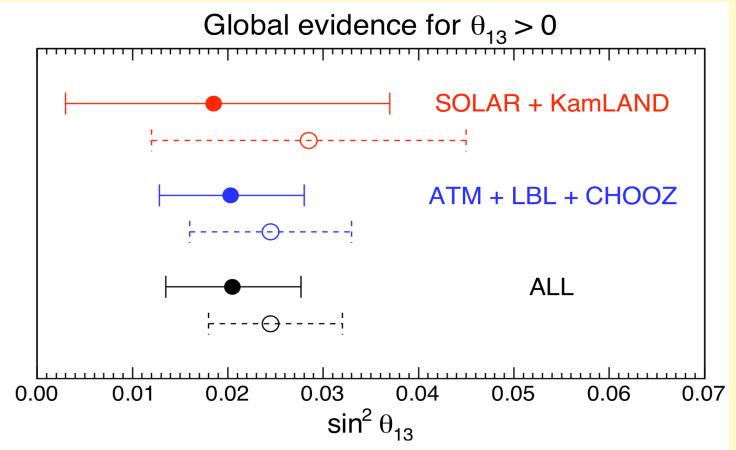
(N^{exp} = 1.5 ± 0.3 at $\sin^2 2\theta_{13}$=0)

June 2011 breakthrough: new T2K and MINOS appearance results!

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

[Fogli, EL, Marrone, Palazzo, Rotunno, arXiv:1106.6028]





Statist. significance >3σ

$\sin^2\theta_{13}=$

0.021±0.007 (old fluxes)

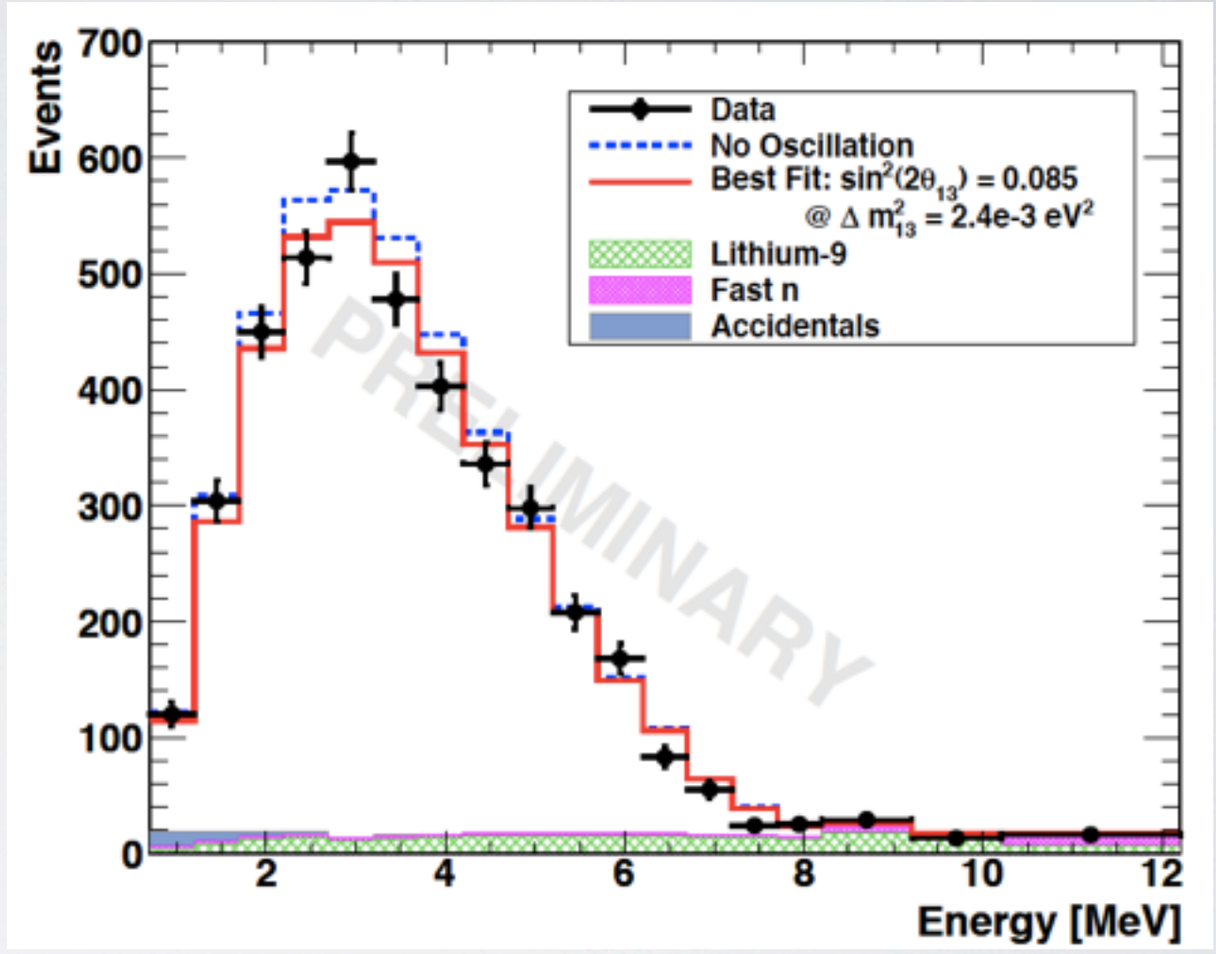
0.025±0.007 (new fluxes)

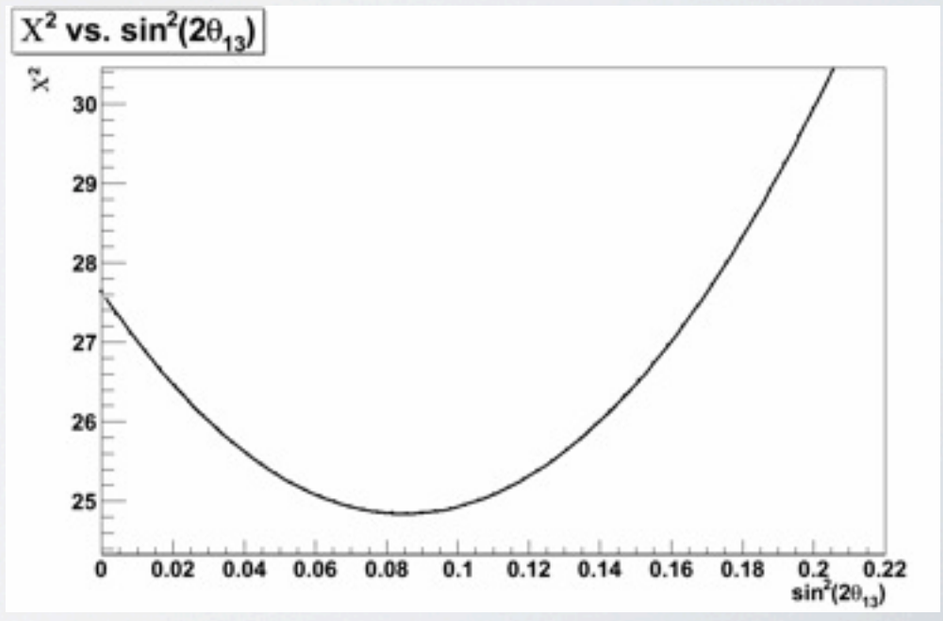
θ13 Preliminary Results

First neutrino oscillation data release of DC at LowNu11 @ Seoul (Korea)

Far detector data only

No-Oscillation:
reactor flux prediction





Rate + Shape Analysis:
$\sin^2(2\theta_{13}) = 0.085 \pm 0.029(\text{stat}) \pm 0.042(\text{syst})$

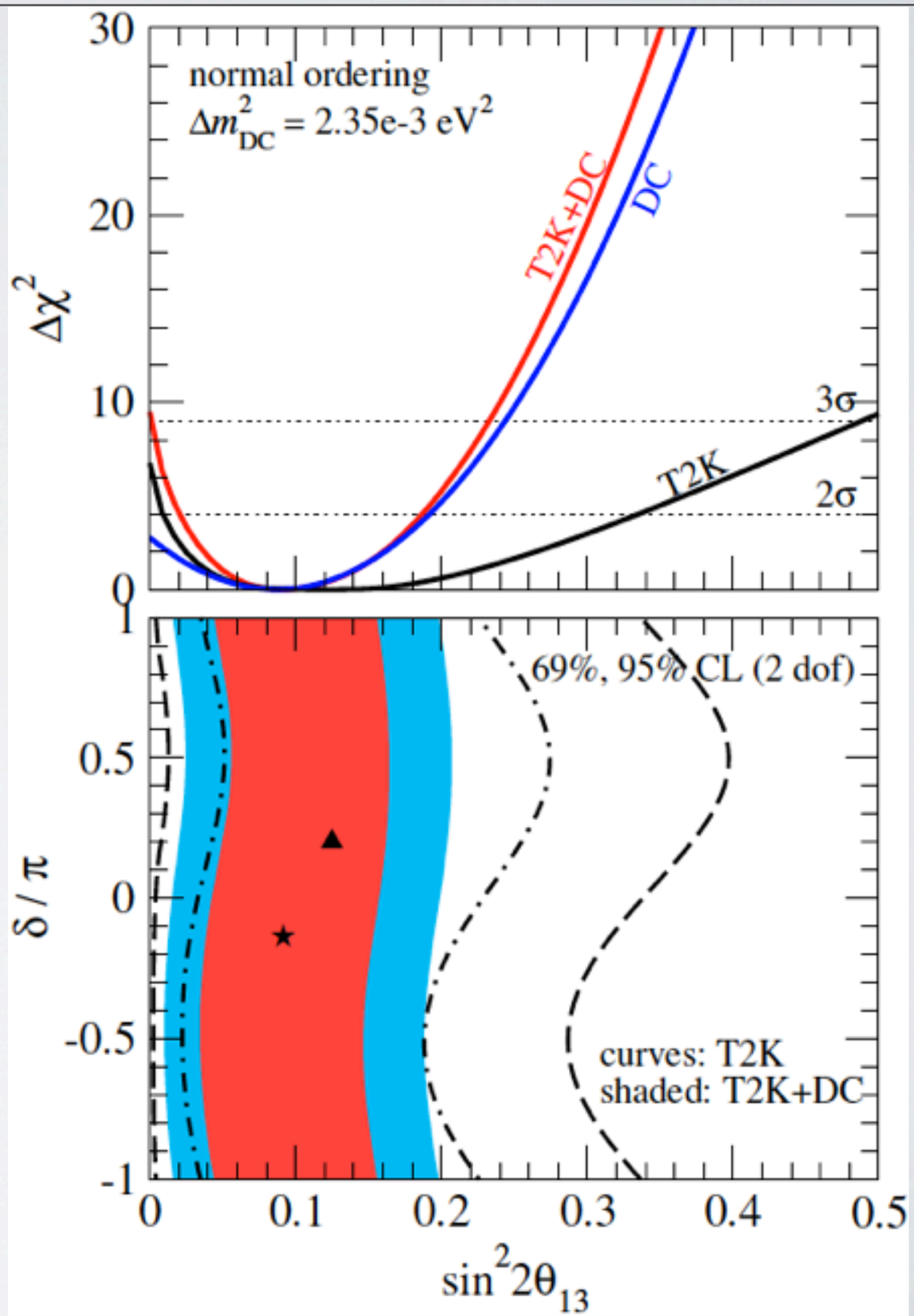
Rate Only:
$\sin^2(2\theta_{13}) = 0.093 \pm 0.029(\text{stat}) \pm 0.073(\text{syst})$

Global θ_{13} Hunt

DC results consistent with T2K results

Major impact in $\theta 13$ knowledge today by DC

Combined effect: $\sin^2(2\theta_{13})$ >0 @ 3σ



Words of caution, from someone we all miss:

"Half of all 3σ results are wrong."

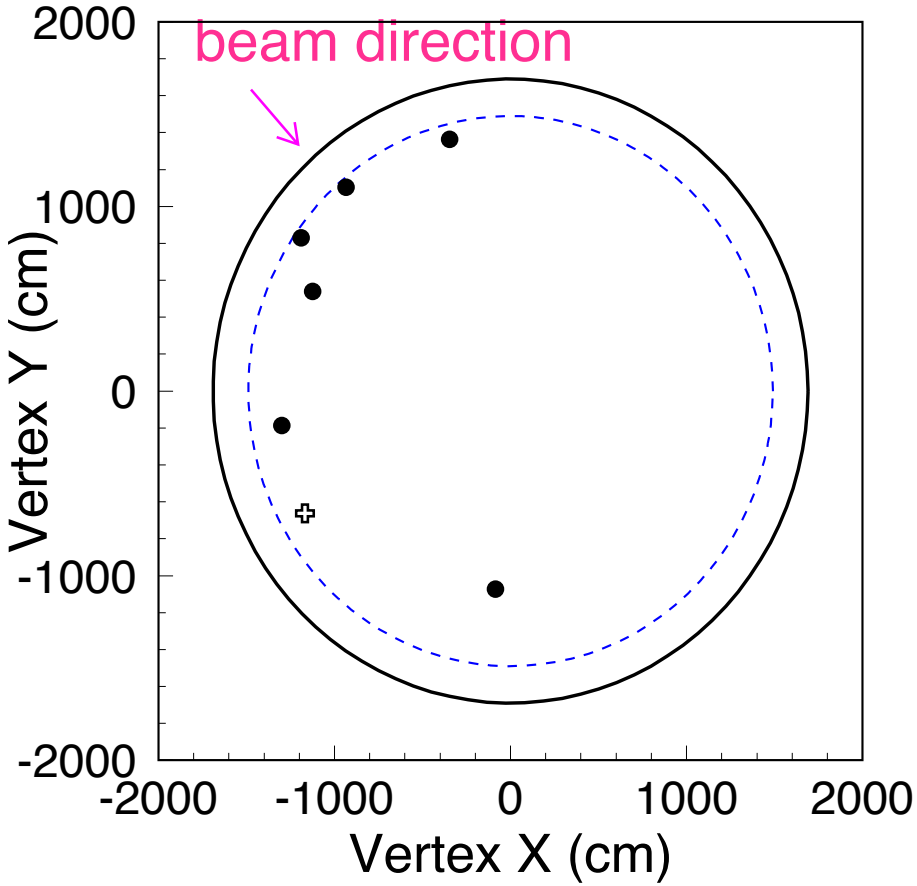
J.N. Bahcall

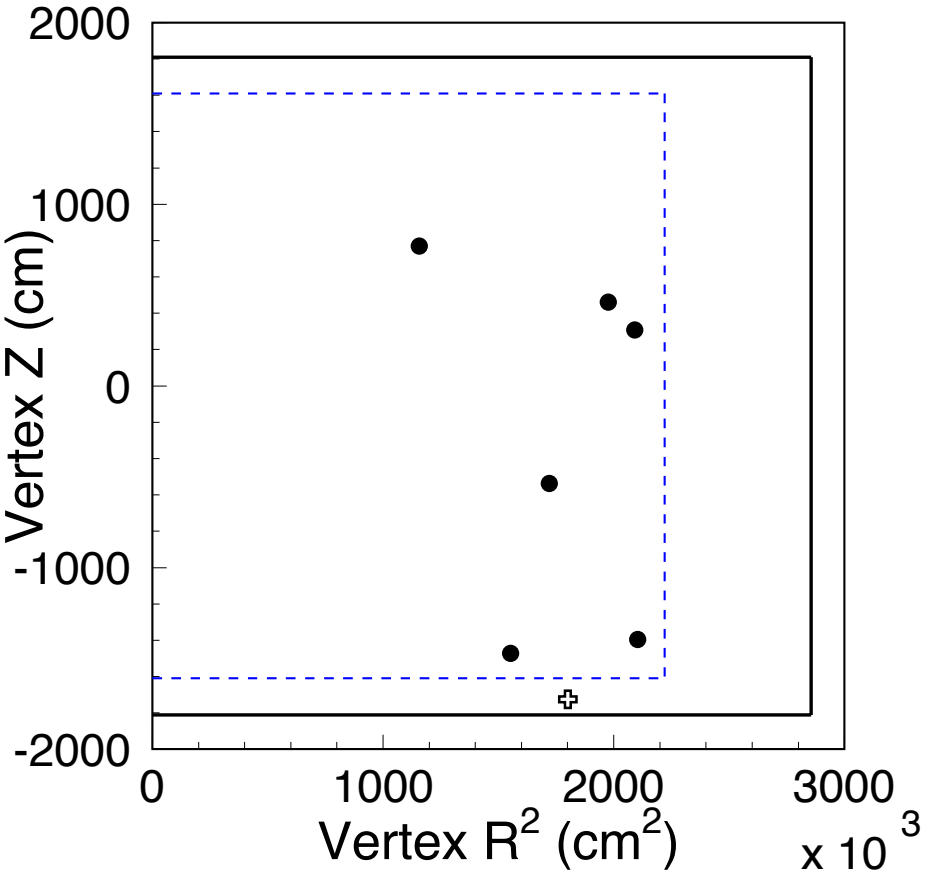
No doubt: we need further experimental tests of $\theta_{13}>0$ and, in particular, at least a single result at >3σ level !

But, it would be very surprising if the current evidence were just due to a conspiracy of fluctuations in rather different categories of neutrino oscillation experiments.

In planning future ν beams/detectors, useful to consider the likely possibility that **$\sin^2\theta_{13}\sim 0.02$**

Vertex distribution of ν_e candidate events





Event outside FV

These events are clustered at large R

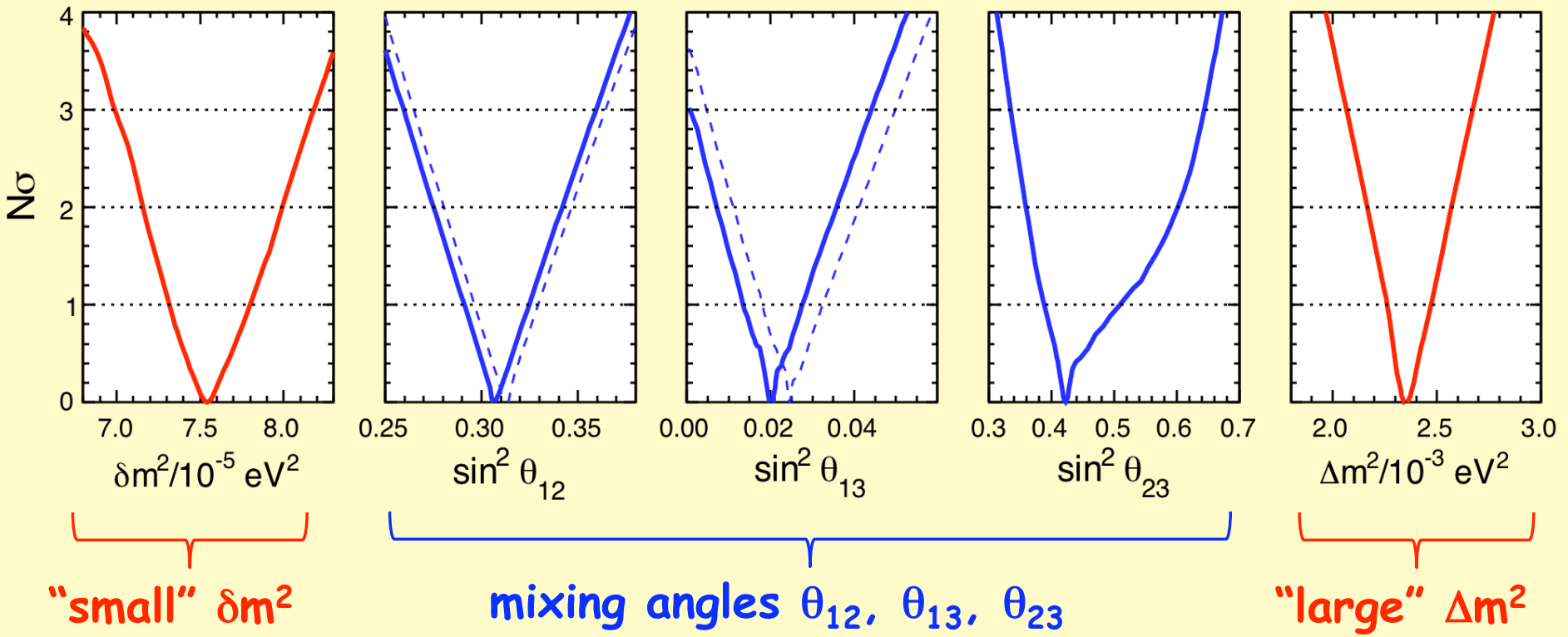
→ Perform several checks. for example

* Check distribution of events outside FV → no indication of BG contamination
* Check distribution of OD events → no indication of BG contamination
* K.S. test on the R^2 distribution yields a p-value of 0.03

Status of 3ν oscillation parameters, circa 2011

Results of recent global data analysis in terms of $N\sigma = \sqrt{\Delta\chi^2}$

(the more linear and symmetric, the more gaussian errors)



G.L.Fogli, E.L., A.Marrone, A.Rotunno (Univ. & INFN, Bari), **A. Palazzo** (TUM, Munich)

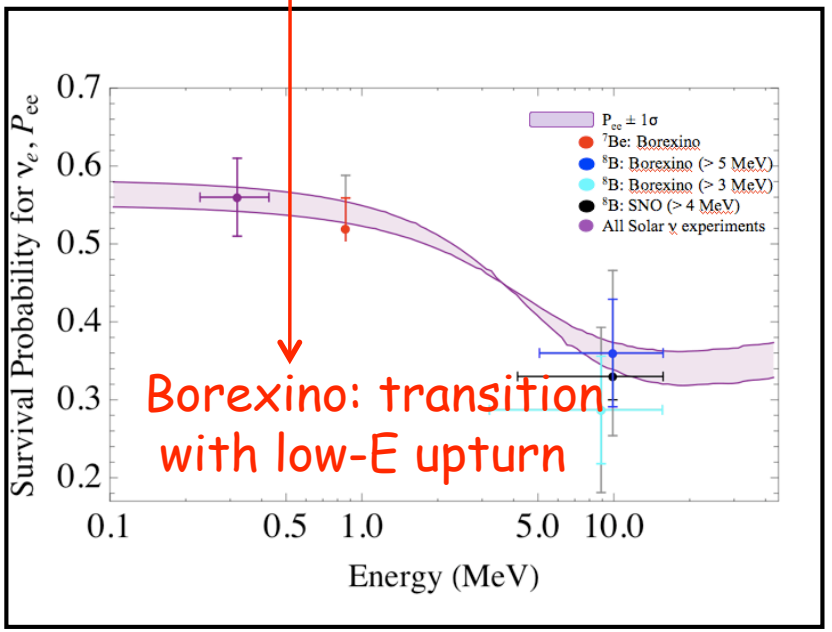
"Evidence of $\theta_{13}>0$ from global neutrino data analysis", arXiv:1106.6028v2

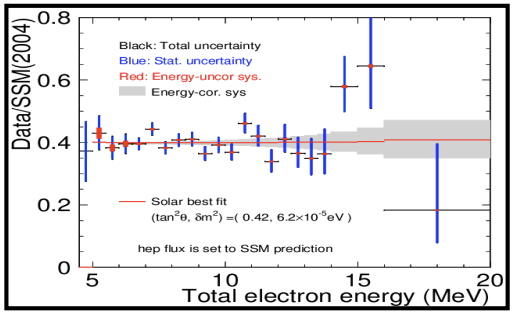
Vacuum frequency $\delta m^2/2E$ (unknown sign) interferes with ν_e interaction energy $\sqrt{2}G_F N_e$ (known sign) in solar matter: MSW

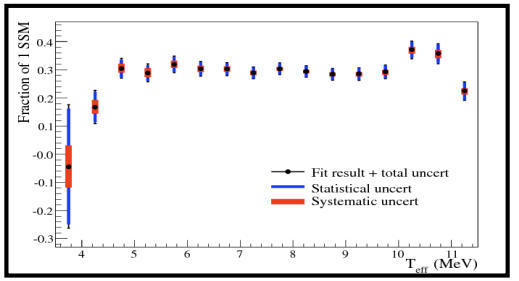
→ Get (ν_1, ν_2) hierarchy: state with largest ν_e component is the lightest of the two – conventionally, ν_1

Main features of matter effects: established

Spectral details: need higher stat, lower E







SK: ~flat

SNO: ~downturn

Here at TAUP 2011: Final SNO data analysis and first Borexino pep flux data!

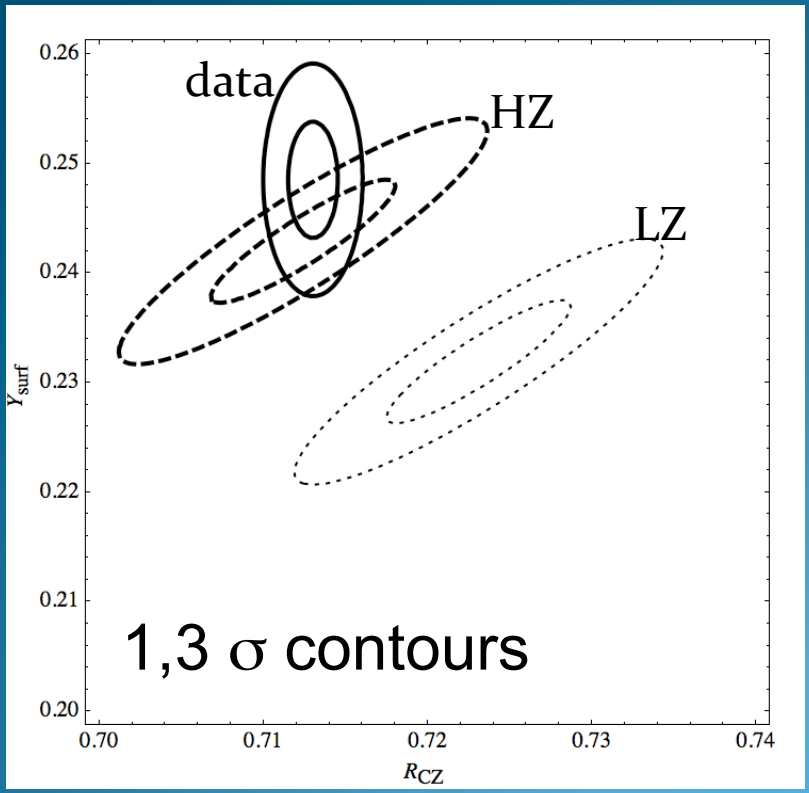
Development of the SSM after 2004: impact on neutrino fluxes

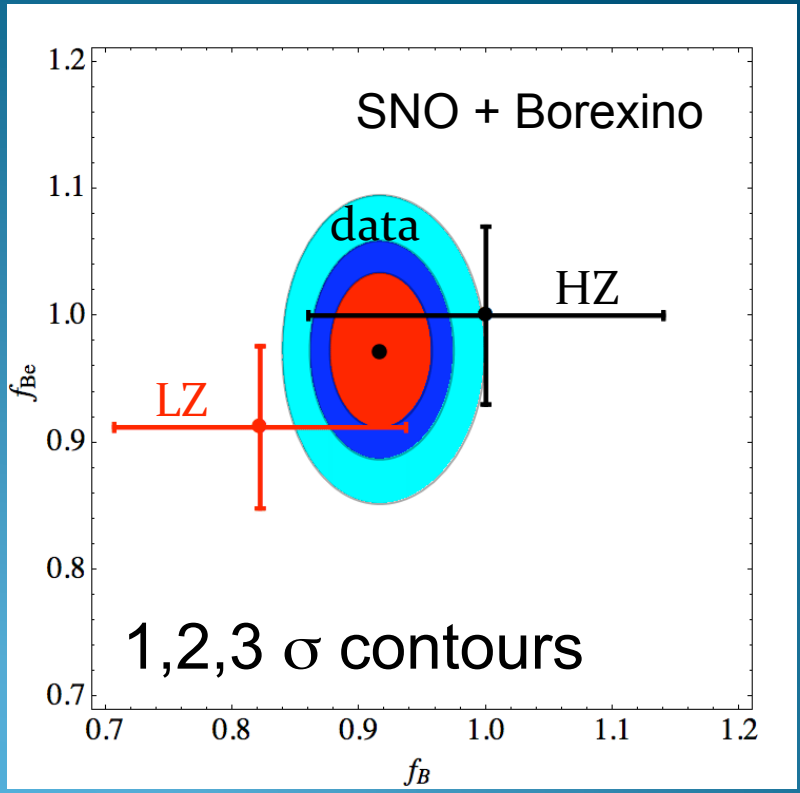
Model	pp $\times 10^{10}$	pep $\times 10^{8}$	^{7}Be $\times 10^{9}$	^{8}B $\times 10^{6}$	^{13}N $\times 10^{8}$	^{15}O $\times 10^{8}$	^{17}F $\times 10^{6}$	Y_{surf}	R_{CZ}/R_{Sun}
BS04	5.94	1.40	4.88	5.87	5.62	4.90	6.01	0.0169	0.7148
BS04(^{14}N)	5.99	1.42	4.89	5.83	3.11	2.38	5.97	0.0170	0.7153
BS05 (OP,GS98)	5.99	1.42	4.84	5.69	3.07	2.33	5.84	0.0170	0.7138
BS05(OP, AGS05)	6.06	1.45	4.34	4.51	2.01	1.45	3.25	0.0126	0.7280
BPSH2011 GS98 [AGSS09]	5.98 [6.03]	1.44 [1.47]	5.00 [4.56]	5.58 [4.59]	2.96 [2.17]	2.23 [1.56]	5.52 [3.40]	0.0170 [0.0134]	0.7124 [0.7231]

1. BS04(^{14}N) accounts for new $S_{1,14}$ for $^{14}N(p,\gamma)^{15}O$ [A. Formicola et al 2004]
2. BS05(OP,GS98) accounts for new opacities
3. BS05(OP,AGS05) accounts for new calculations of surface abundances: **Z/X ~ 0.023 -> ~ 0.018**

Solar Standard Model metallicity problem

- Borexino and SNO solar neutrino measurement of ^{7}Be and ^{8}B

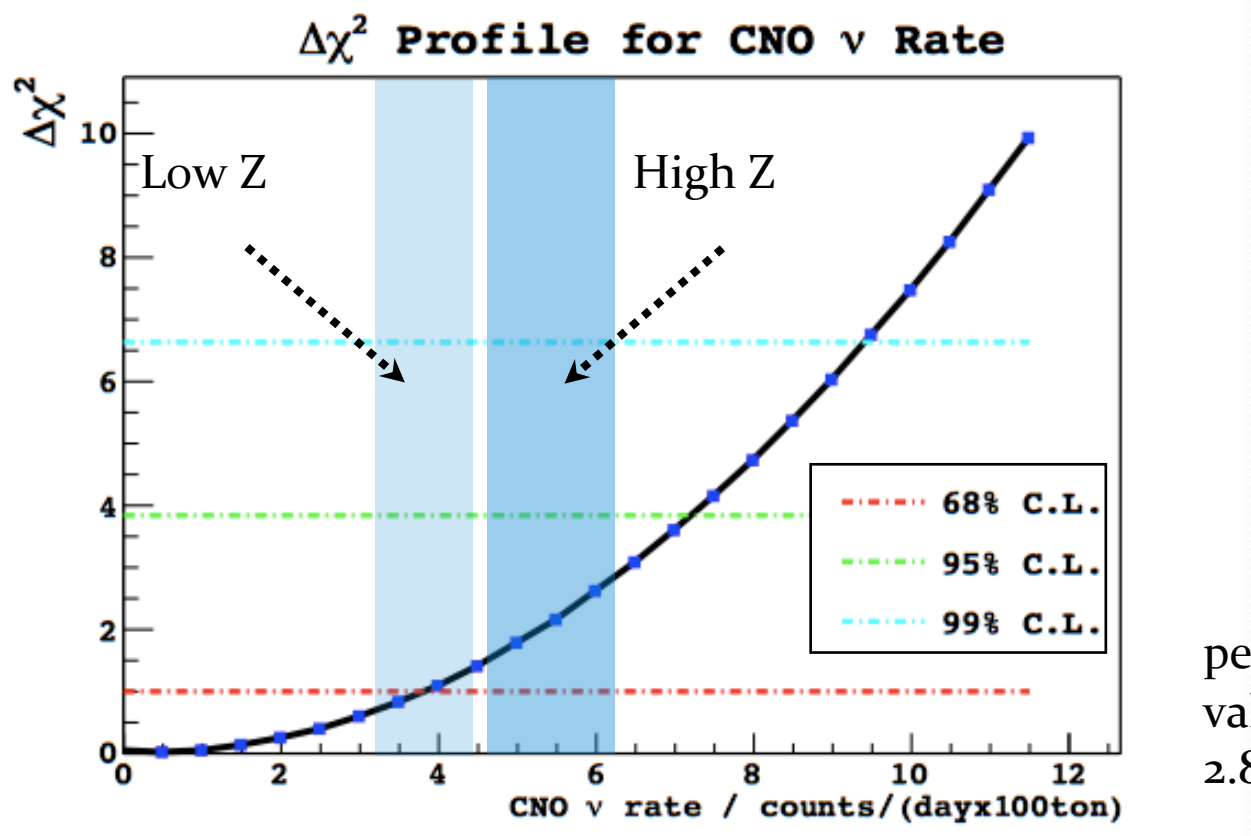




CNO to probe metallicity problem

	CNO FLUX (10^8 cm^{-2} s^{-1})
HIGH Z SSM	5.24 ± 0.84
LOW Z SSM	3.76 ± 0.60
$\Delta\Phi$	28%

CNO interaction rate

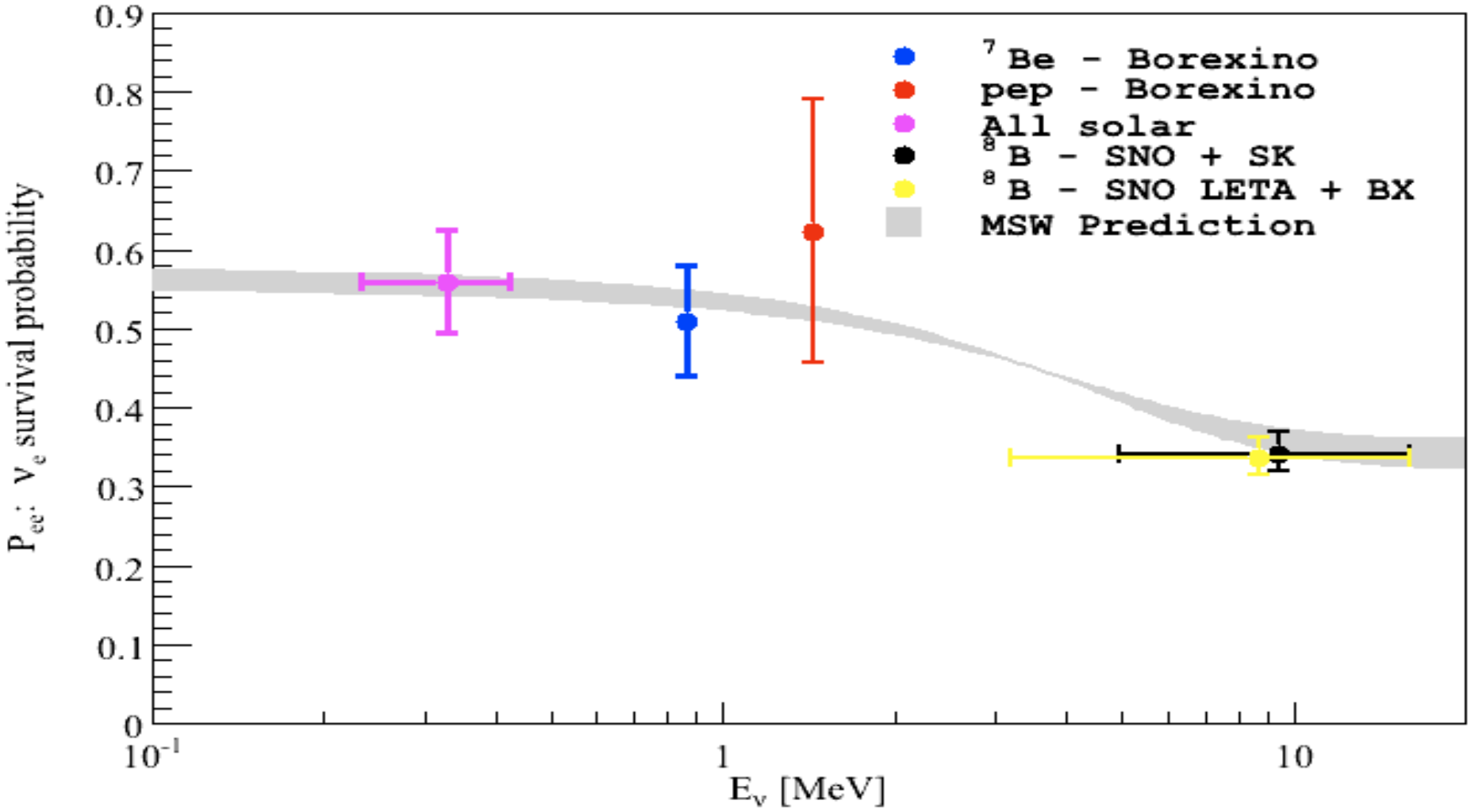


Upper limit
(95% C.L.)
<7.7 counts/day/100ton

pep fixed at SSM predicted value:
2.8 counts/day/100ton

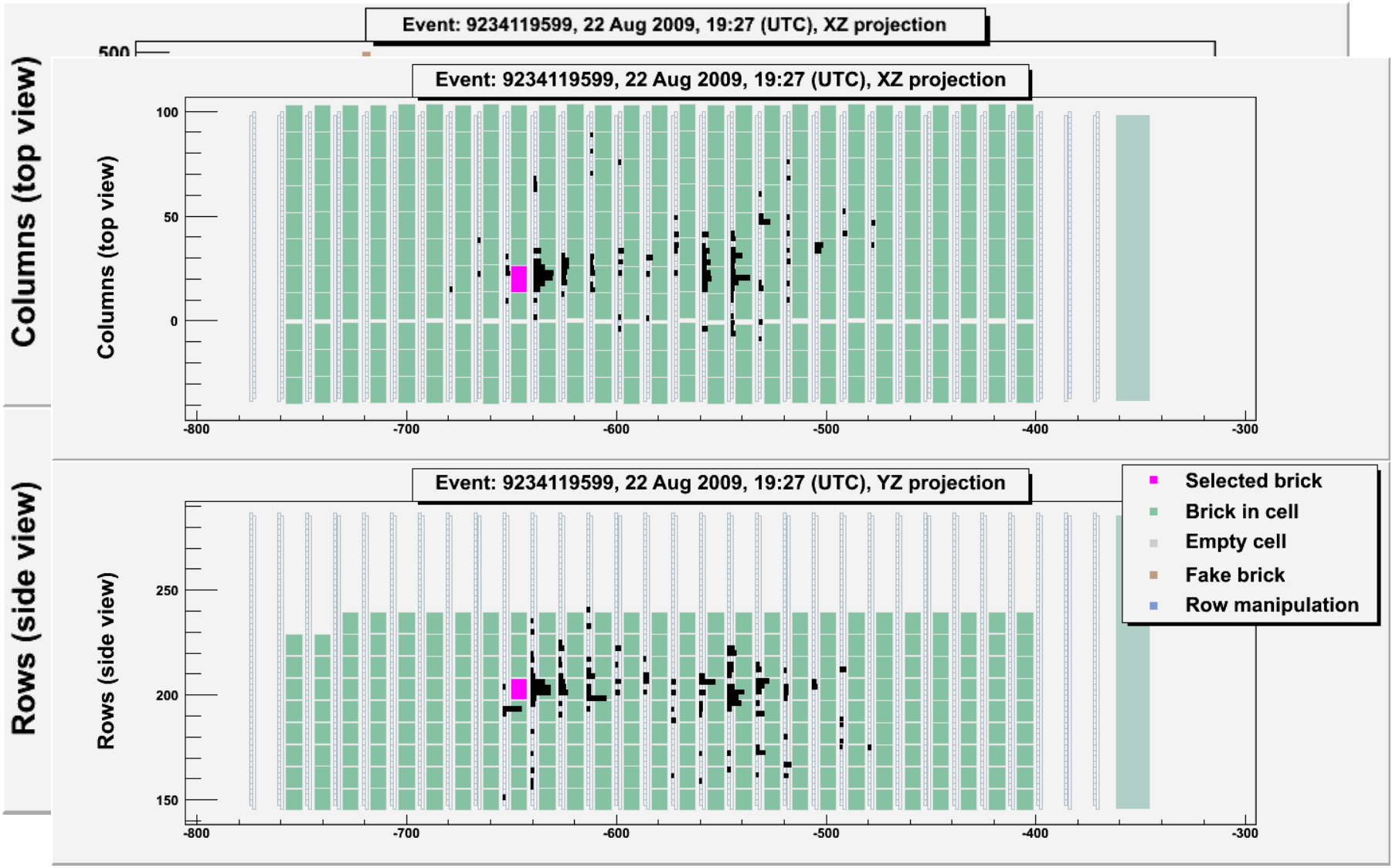
Assuming MSW-LMA

Solar neutrinos survival probability: after Borexino including pep ν_e's



The first ν_τ candidate event

Phys. Lett. B 691 (2010) 138



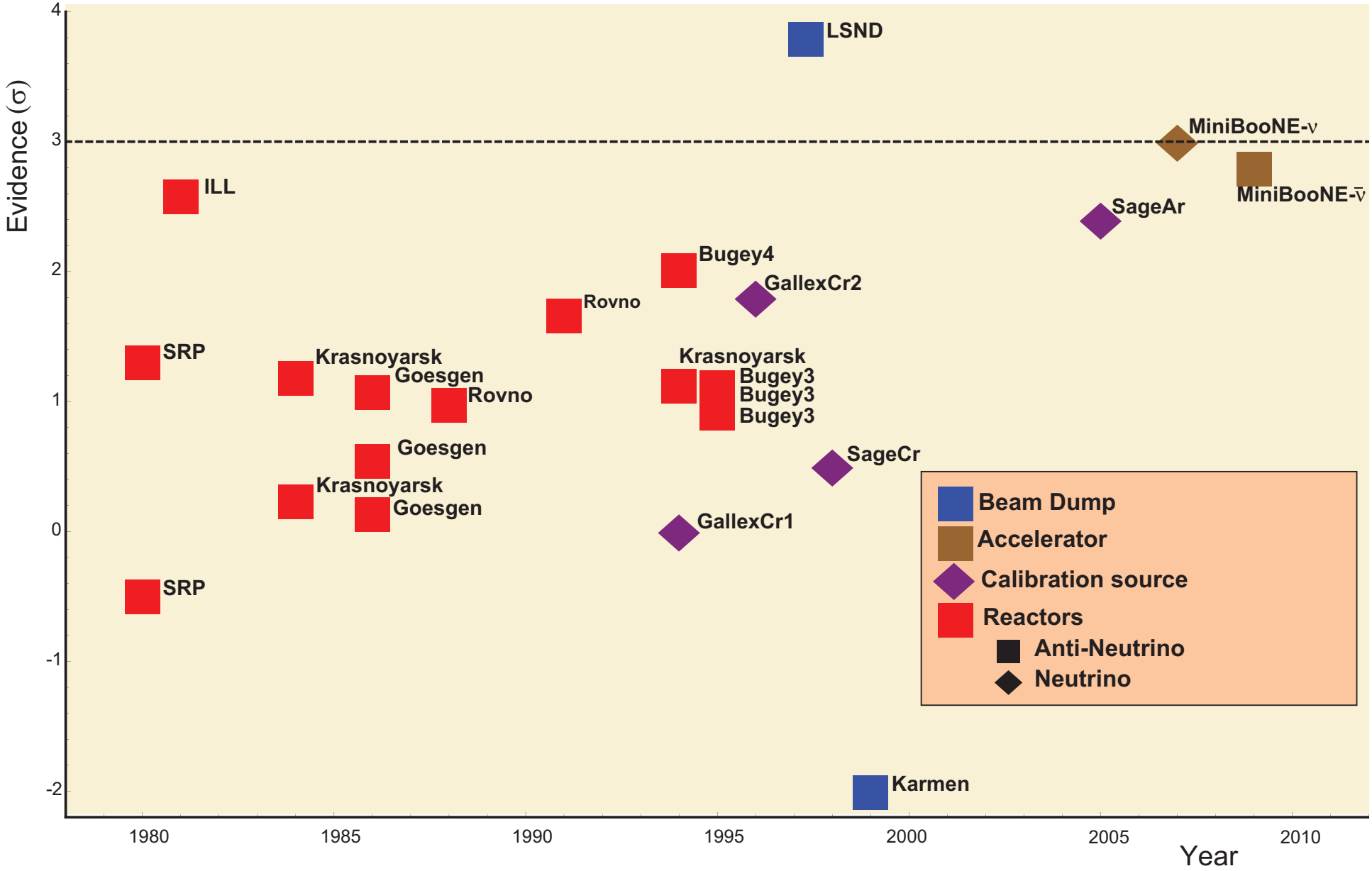
EPILOGUE

Three (ν) gondolas are safe in the harbor…
…but that's not what they are made for.
New gondolas might join, and all lead us towards new (physics) horizons

Thank you for your attention

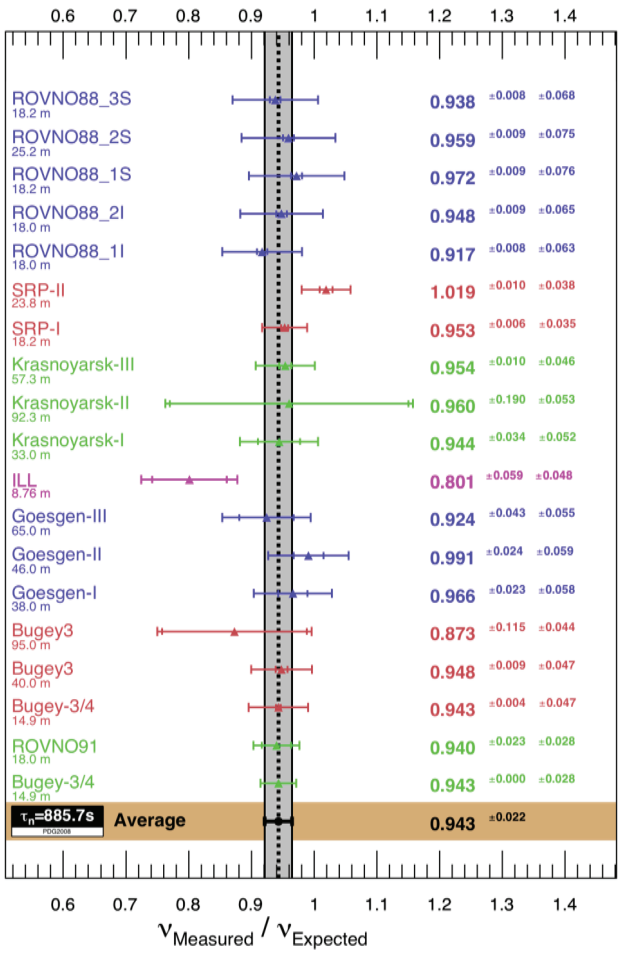
Neutrinos: sterile

A long standing set of anomalies

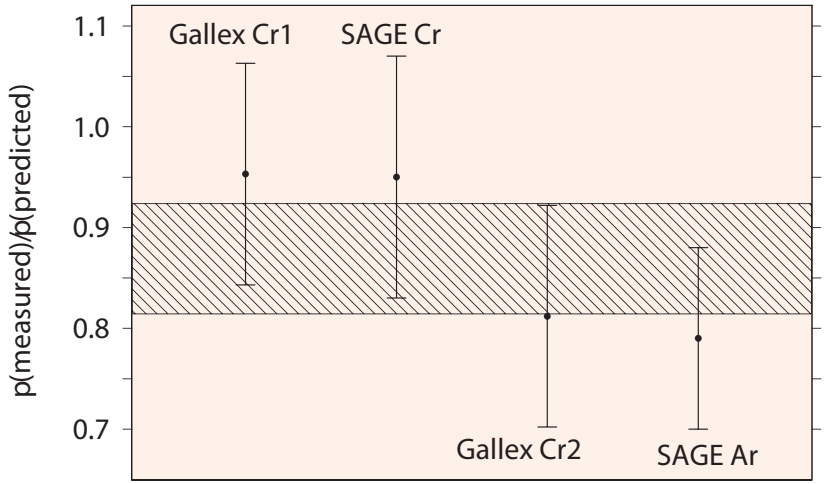


Summarizing

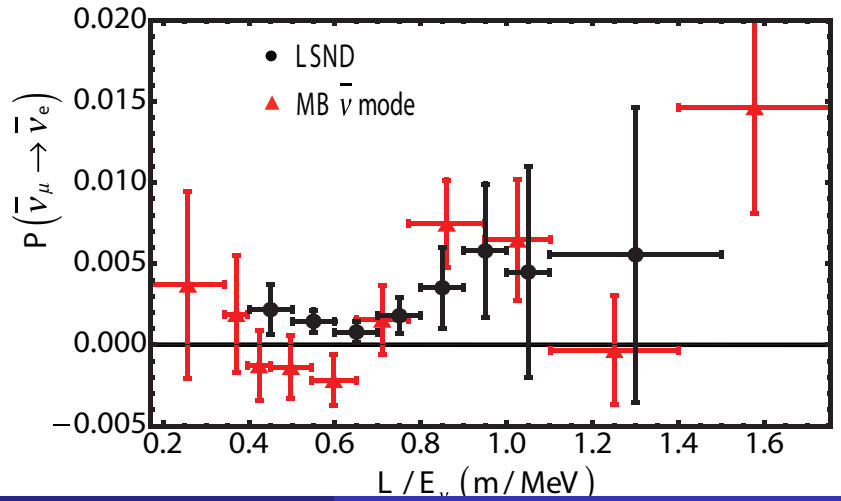
Reactors



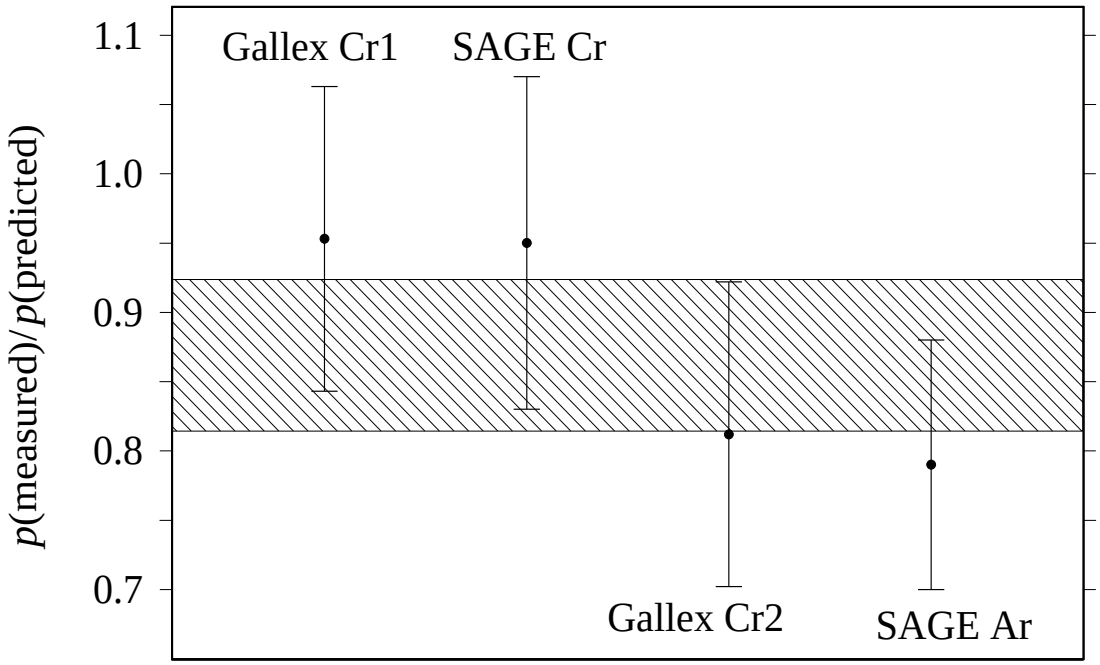
Sources



Accelerators



ν_e Disappearance in Gallium radioactive source experiments



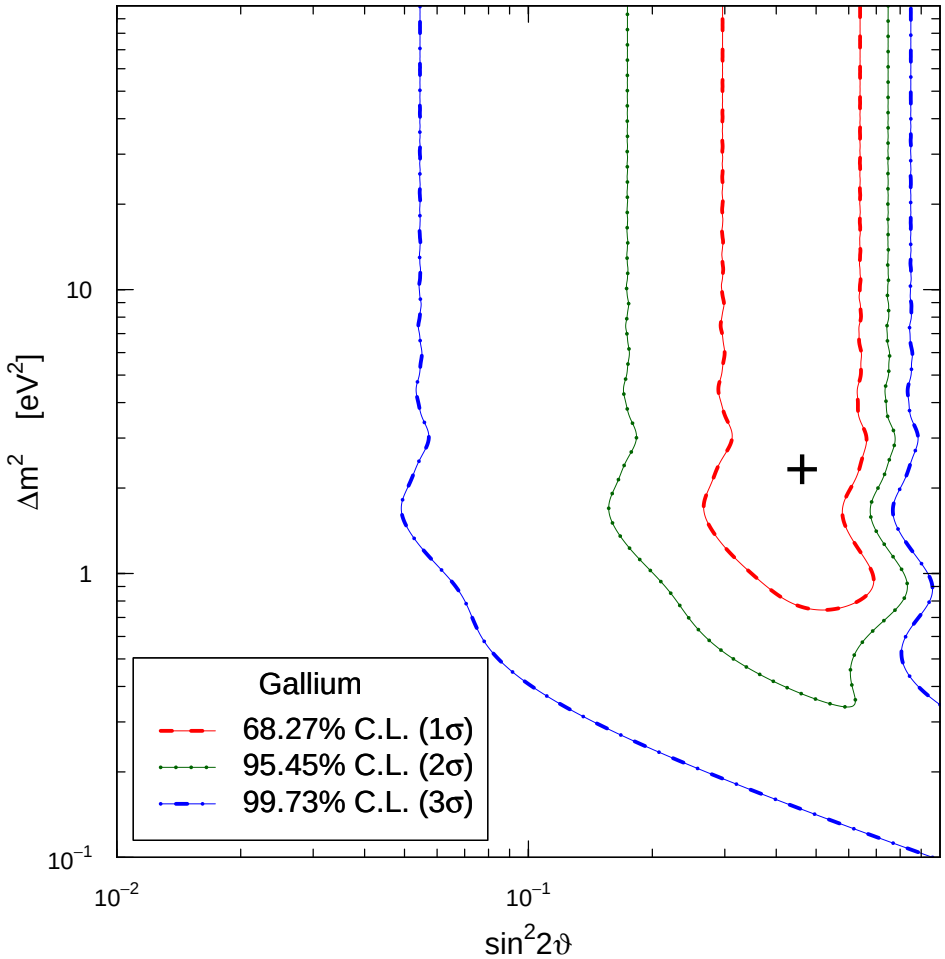
$R \equiv$ wheighted average value of the ratio of measured and predicted ^{71}Ge production rates (p) :

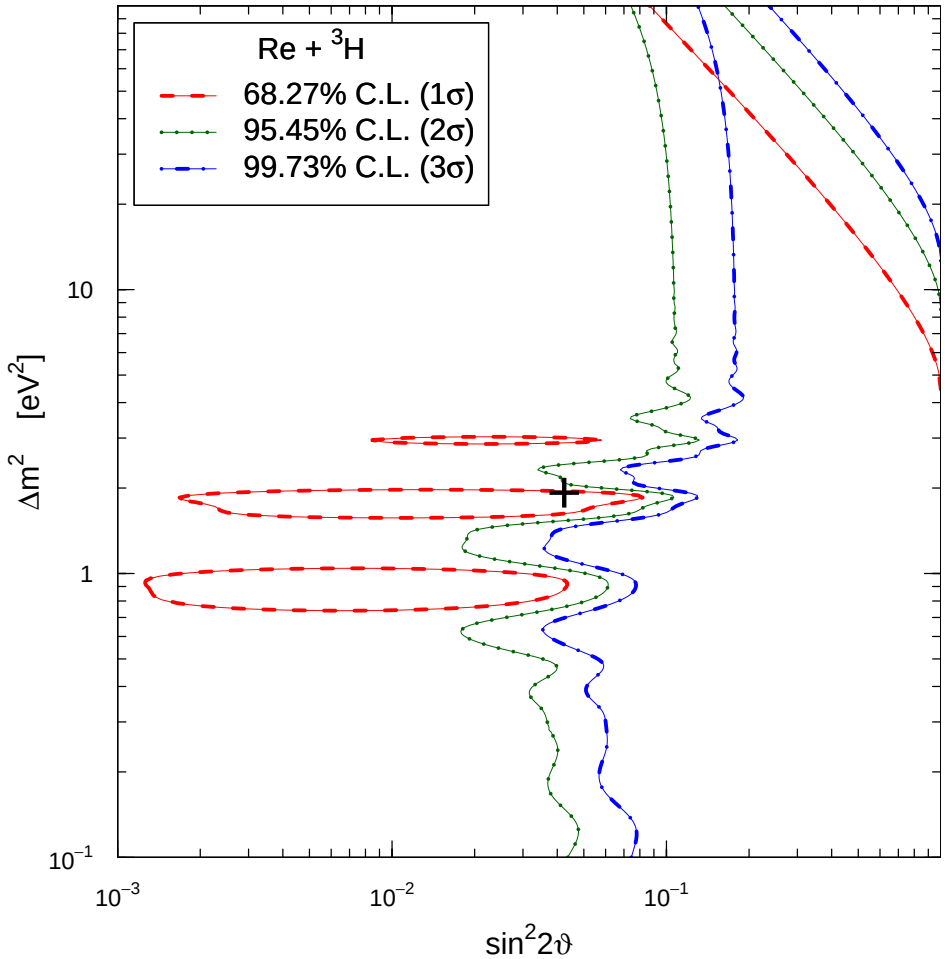
$$R \equiv \frac{\mathrm{p(measured)}}{\mathrm{p(predicted)}} = 0.87 \pm 0.05$$

arXiv:0901.2200[nucl-ex]

Ga radioactive source exp. results may be interpreted as an indication of the disappearance of ν_e due to active-sterile oscillations!

hep-ph/0610352 Carlo Giunti & ML





[Giunti, Laveder, arXiv:1006.3244]

[Giunti, Laveder, PRD 82 (2010) 053005, arXiv:1005.4599]

$\Delta m^2_{\rm SBL} \gtrsim 1\,{\rm eV}^2$ is OK, but $\sin^2 2\vartheta_\nu > \sin^2 2\vartheta_{\bar\nu}$

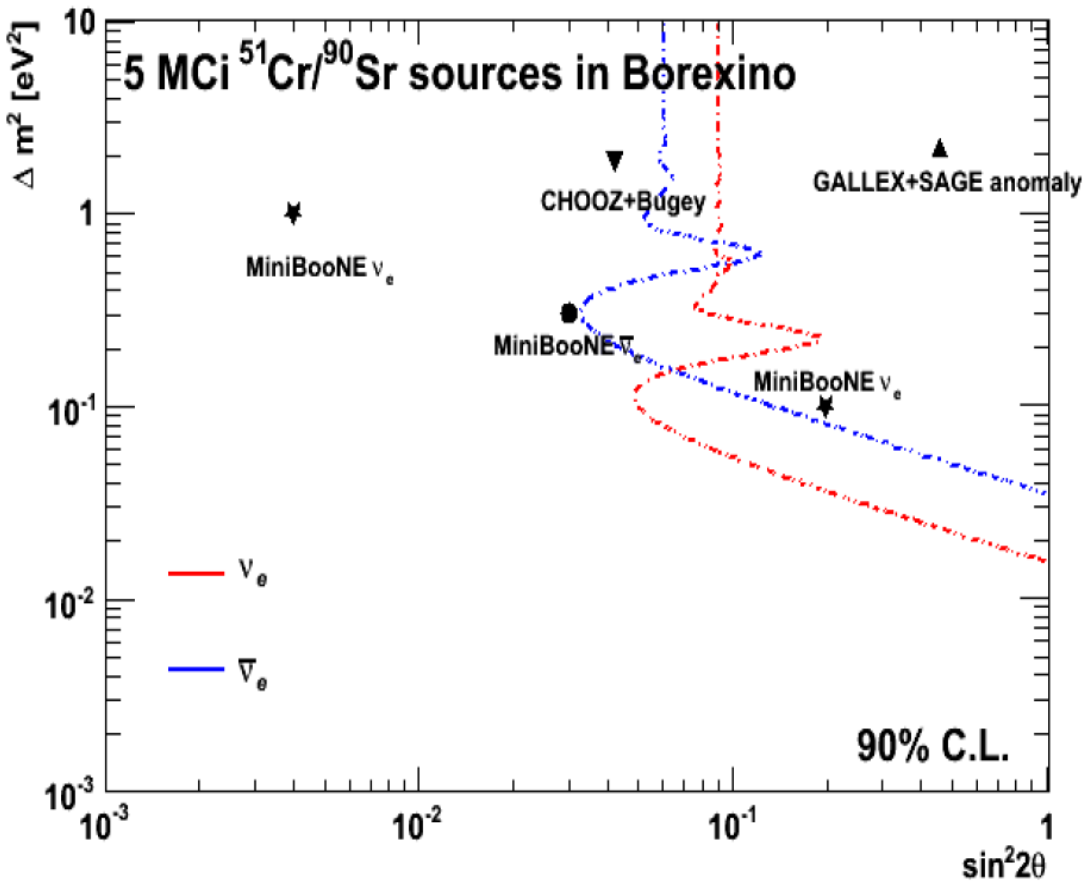
Parameter Goodness of Fit = 0.2%

CPT violation? [Giunti, Laveder, PRD 82 (2010) 113009, arXiv:1008.4750]

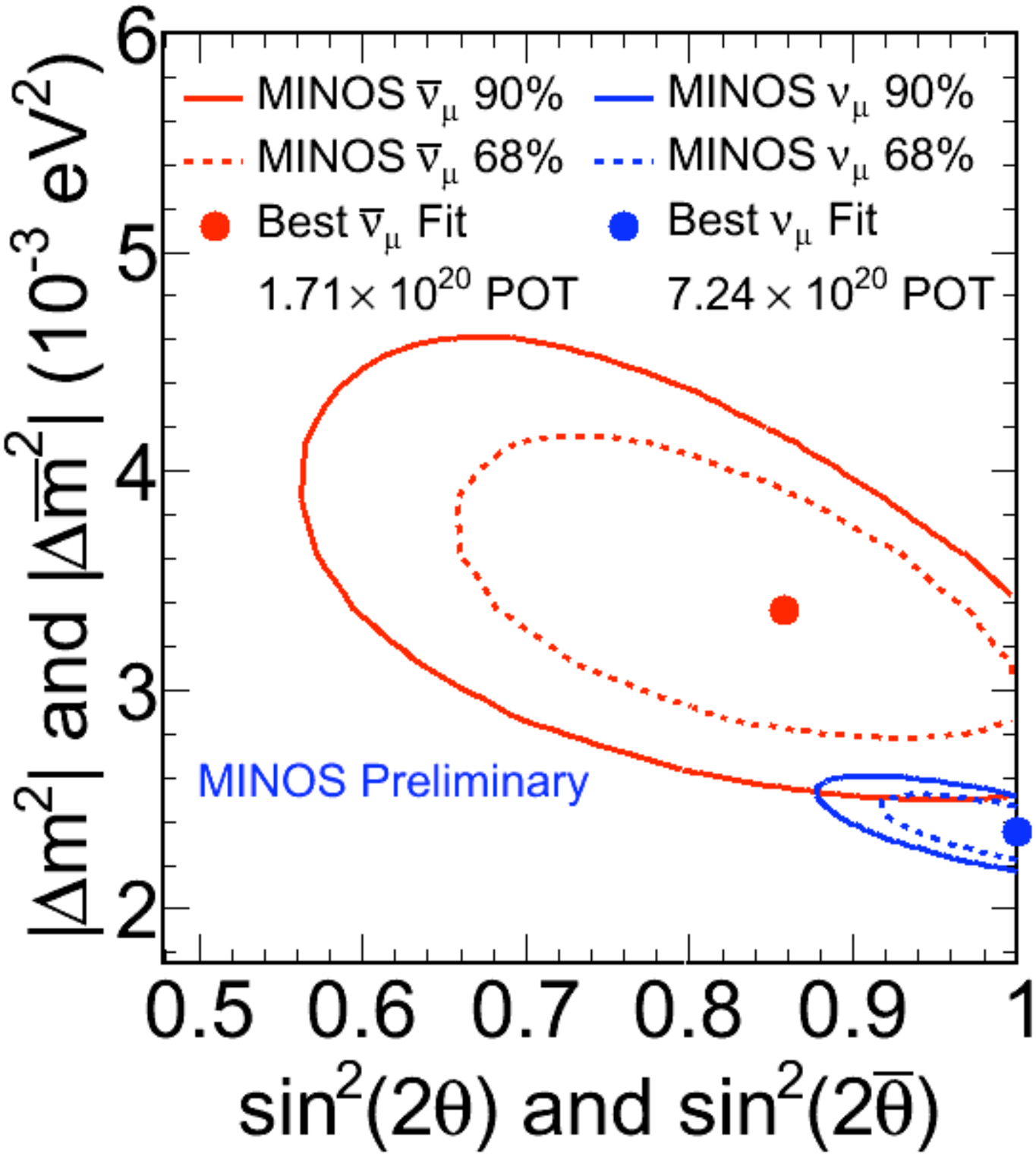
Borexino test exp

- Borexino:

[Ianni, Montanino, Scioscia, EPJC 8 (1999) 609, arXiv:hep-ex/9901012]



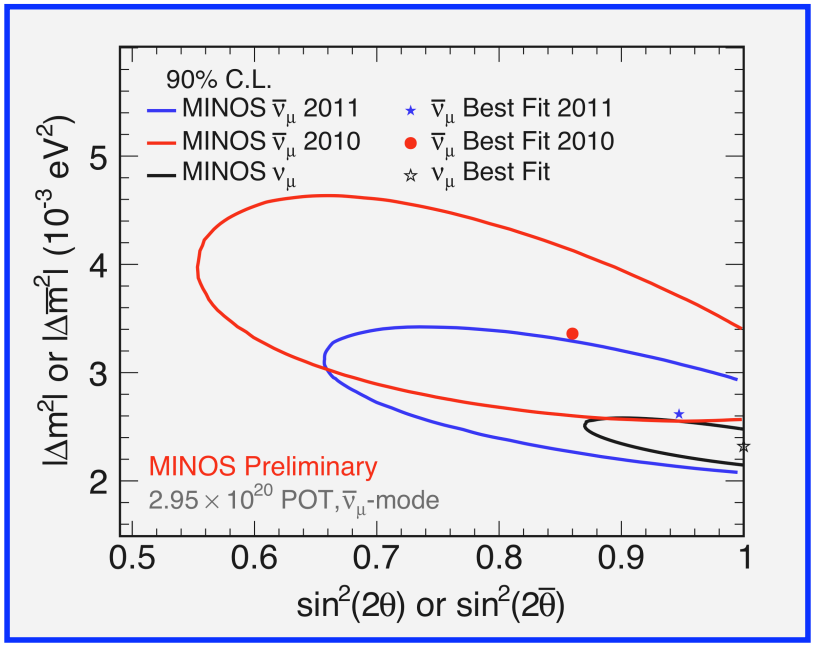
[A. Ianni, Private Communication]



- Interesting Tension (2.3σ difference)
- Plan to have at least double current data set by this Summer.
  - Data taking interrupted by target failure on Feb. 26
  - Plan to have new target in April

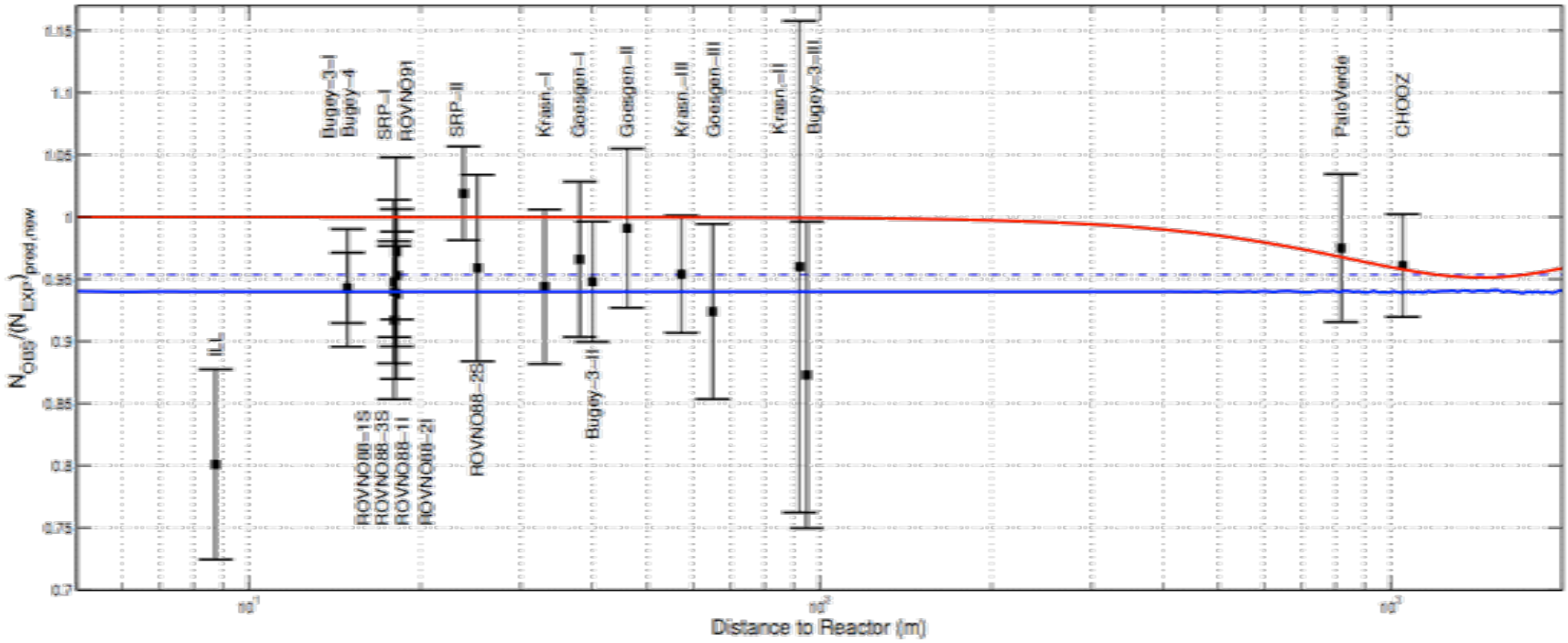
Footnote:

MINOS neutrino/antineutrino anomaly…



…does not show up in 2011 data!

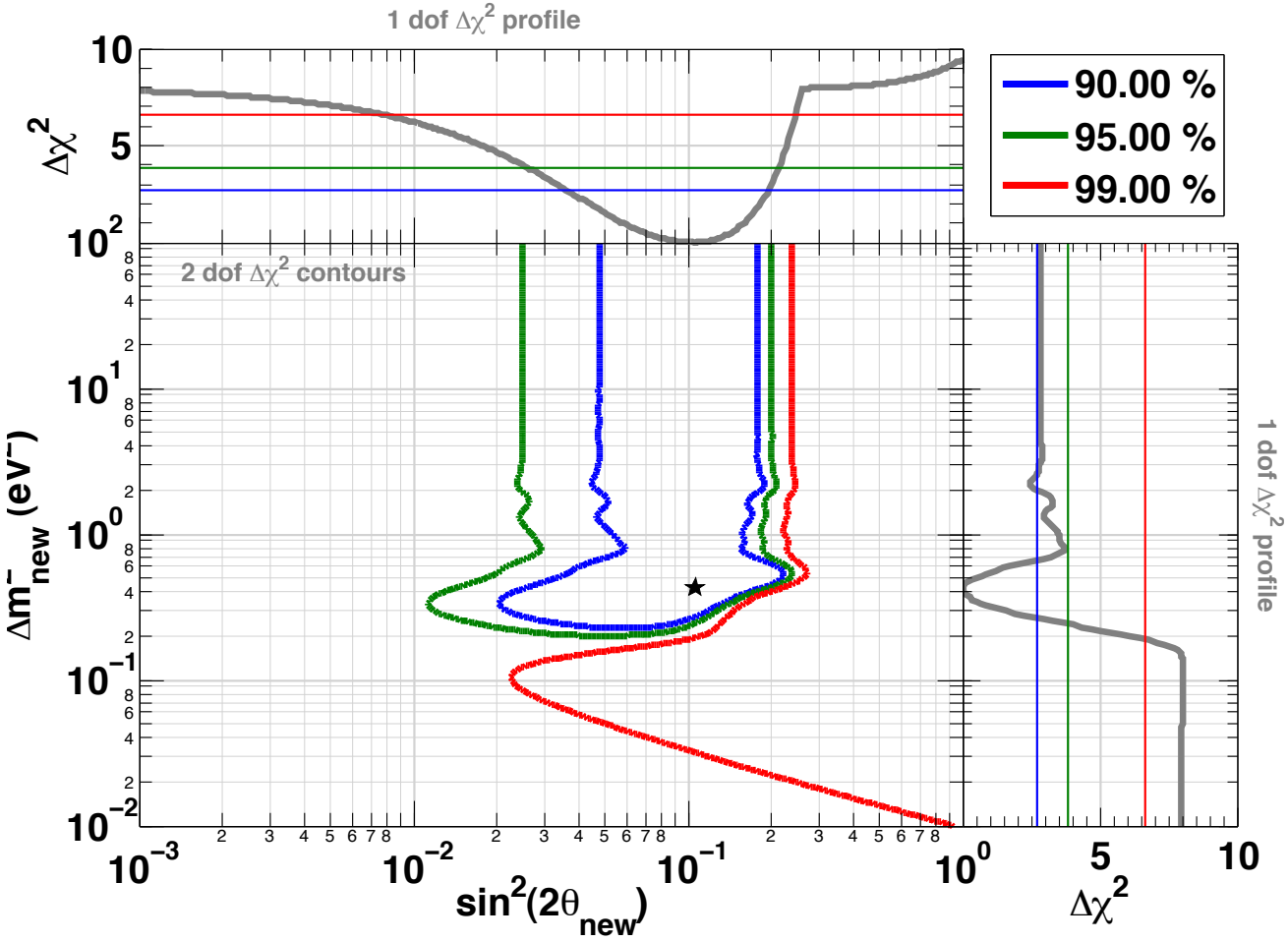
The Reactor Antineutrino Anomaly and implications



Th. Lasserre (CEA-Saclay, Irfu SPP & APC)

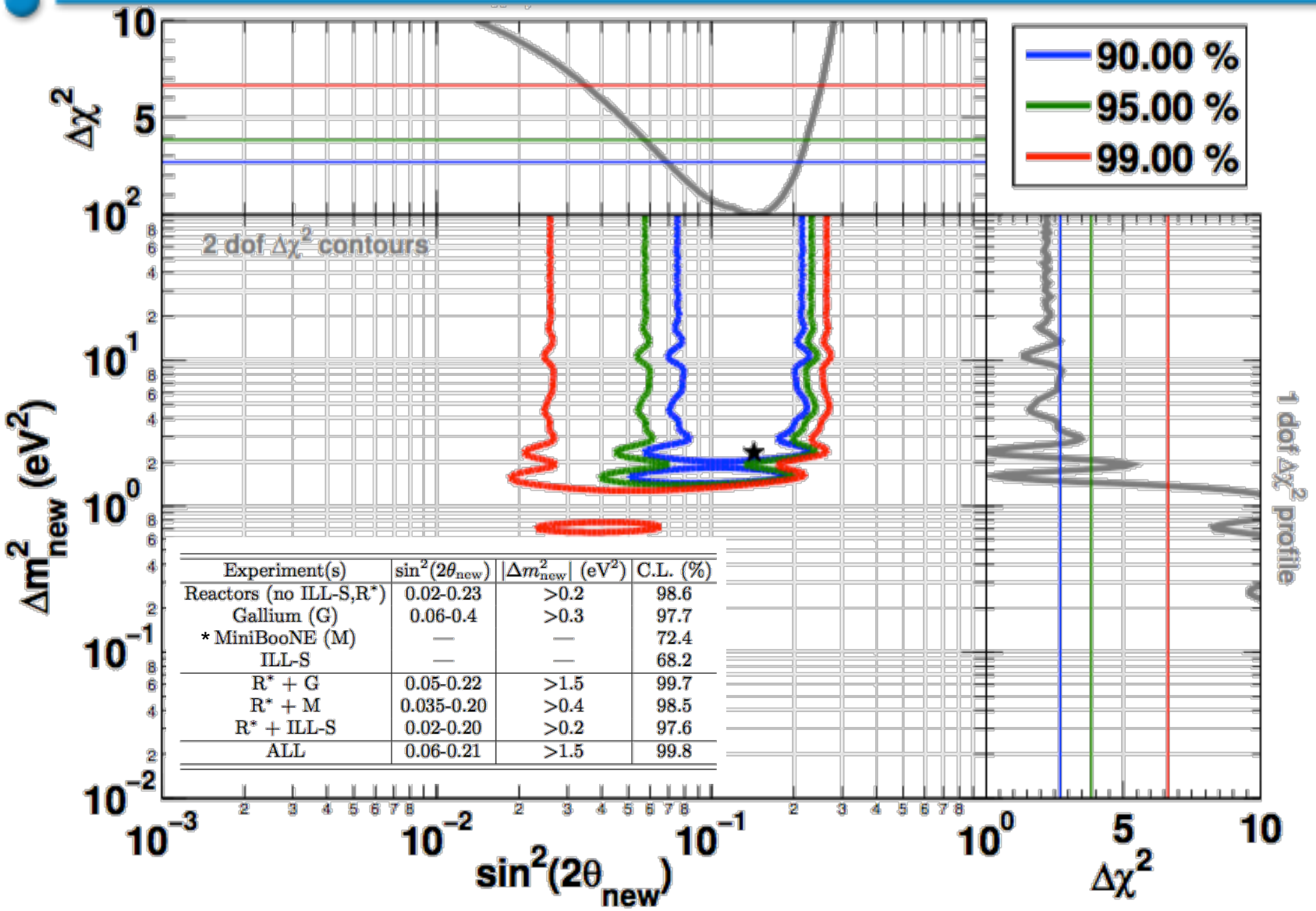
The 4th neutrino hypothesis

- Combine all rate measurements, no spectral-shape information
- Fit to anti-ν_e disappearance hypothesis



- Absence of oscillations disfavored at 98.6% C.L.

Putting it all together: reactor rates + shape + Gallium + (MB)



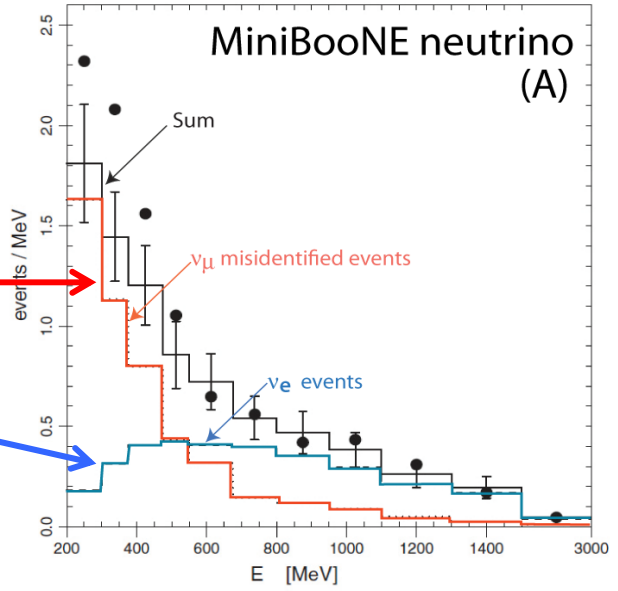
Experiment(s)	$\sin^2(2\theta_{new})$	$\lvert\Delta m^2_{new}\rvert$ (eV^2)	C.L. (%)
Reactors (no ILL-S,R*)	0.02-0.23	>0.2	98.6
Gallium (G)	0.06-0.4	>0.3	97.7
* MiniBooNE (M)	—	—	72.4
ILL-S	—	—	68.2
R* + G	0.05-0.22	>1.5	99.7
R* + M	0.035-0.20	>0.4	98.5
R* + ILL-S	0.02-0.20	>0.2	97.6
ALL	0.06-0.21	>1.5	99.8

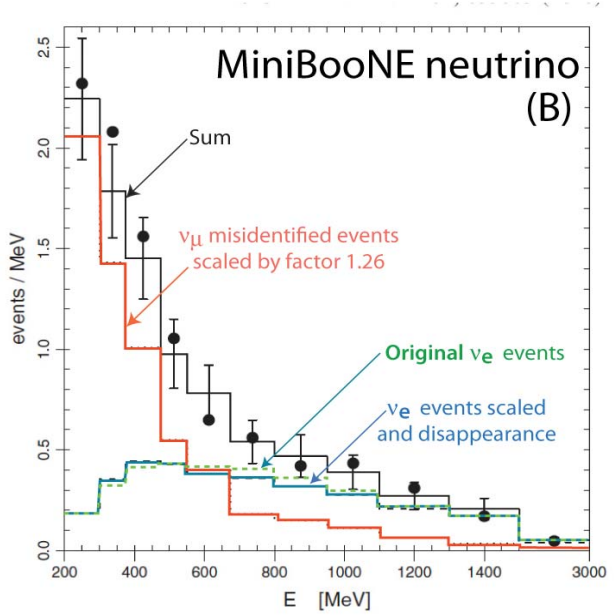
The no-oscillation hypothesis is disfavored at 99.8% CL

* Miniboone re-analysis of : C. Giunti, M. Laveder, Phys. Rev. D82 (2010) 053005

The neutrino run

- (A) electron-like neutrino data. Comparison between the data (black dots) and the calculated distributions due to misidentified ν_μ events (red) and genuine ν_e events (blue). The sum is indicated in black. One notices an anomaly at low energies, which is incompatible with LNSD predictions.
- (B) according to Giunti & Laveder scaling of the events is applied with a factor 1.26, within the permitted uncertainty of F = 1.24 ±0.21 and gives an acceptable fit to the data. The ν_e with and without scaling and disappearance are also shown.





Intermezzo sulla fisica di Majorana

Natura del neutrino

Nuovo Cimento **14** (1937) 171-184

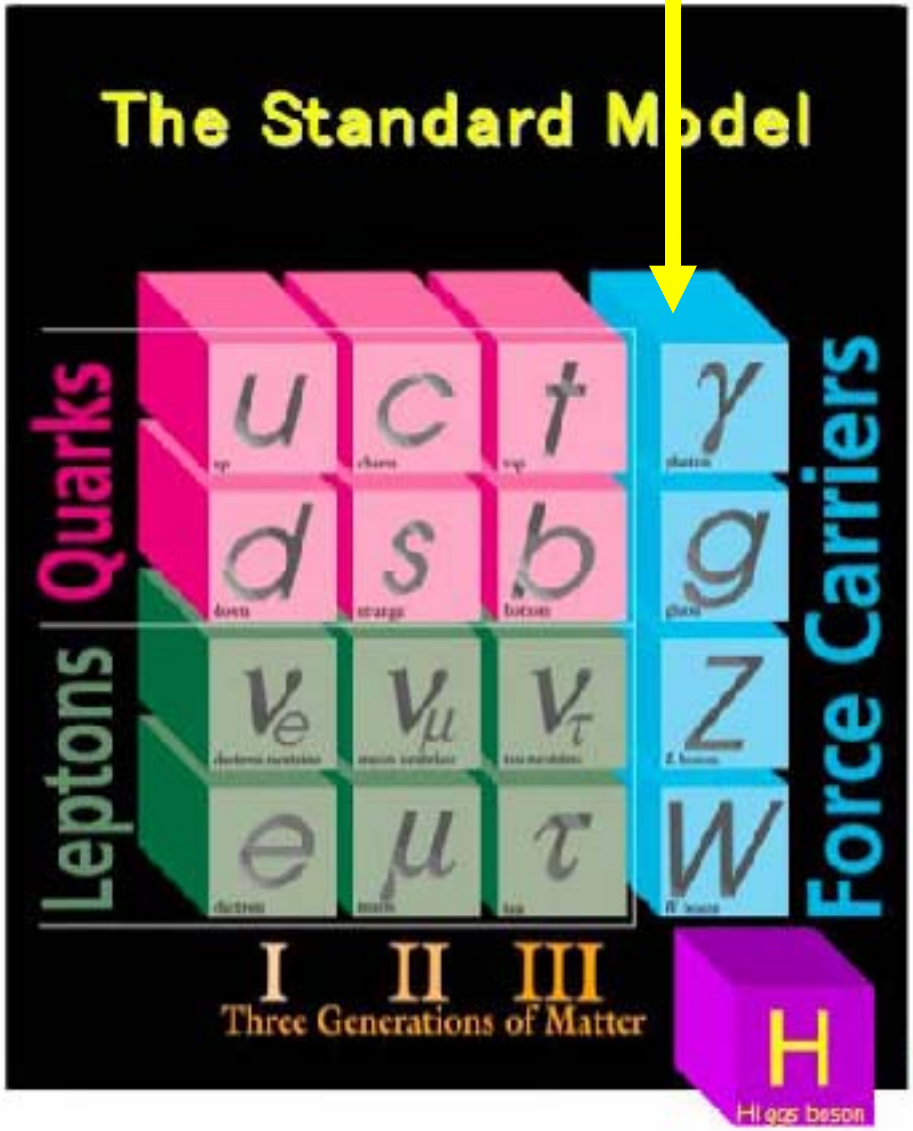
TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

Nota di ETTORE MAJORANA

Sunto. - *Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell'elettrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di* DIRAC *ne risulta alquanto modificato e non vi è più luogo a parlare di stati di energia negativa; nè a presumere per ogni altro tipo di particelle, particolarmente neutre, l'esistenza di « antiparticelle » corrispondenti ai « vuoti » di energia negativa.*

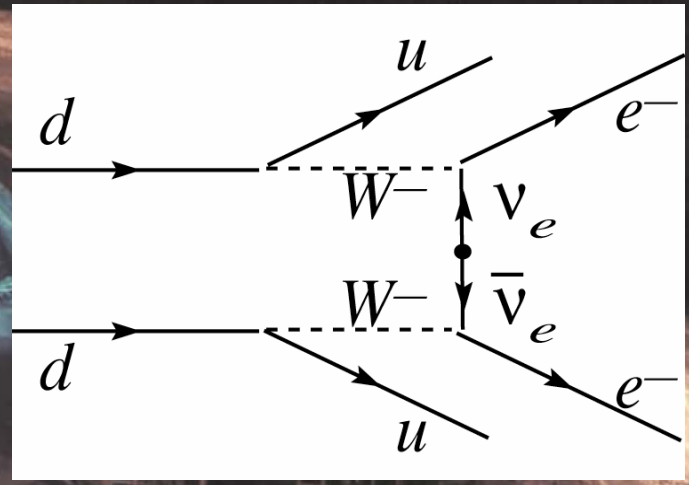
We show that it is possible to achieve complete formal symmetrization in the electron and positron quantum theory by means of a new quantization process. The meaning of Dirac equations is somewhat modified and it is no more necessary to speak of negative-energy states; nor to assume, for any other type of particles, especially neutral ones, the existence of antiparticles, corresponding to the "holes" of negative energy.

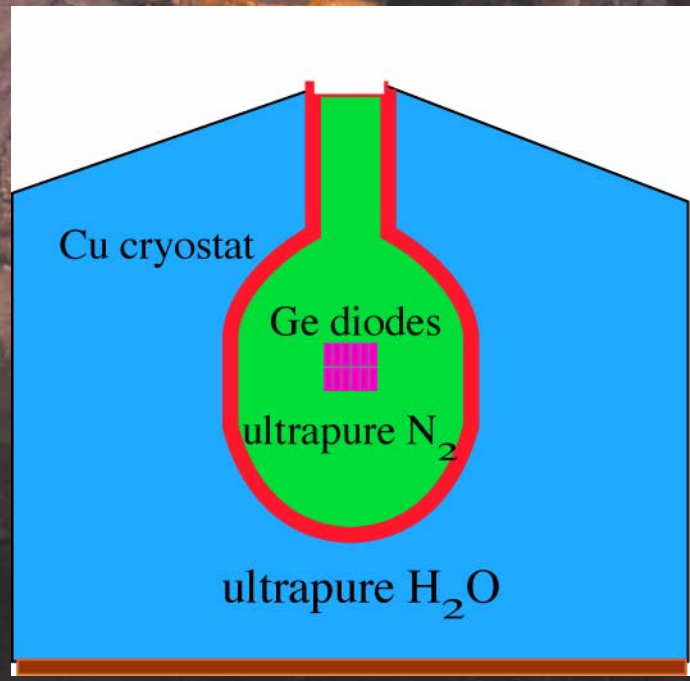
Majorana Neutrino



Gravity
?

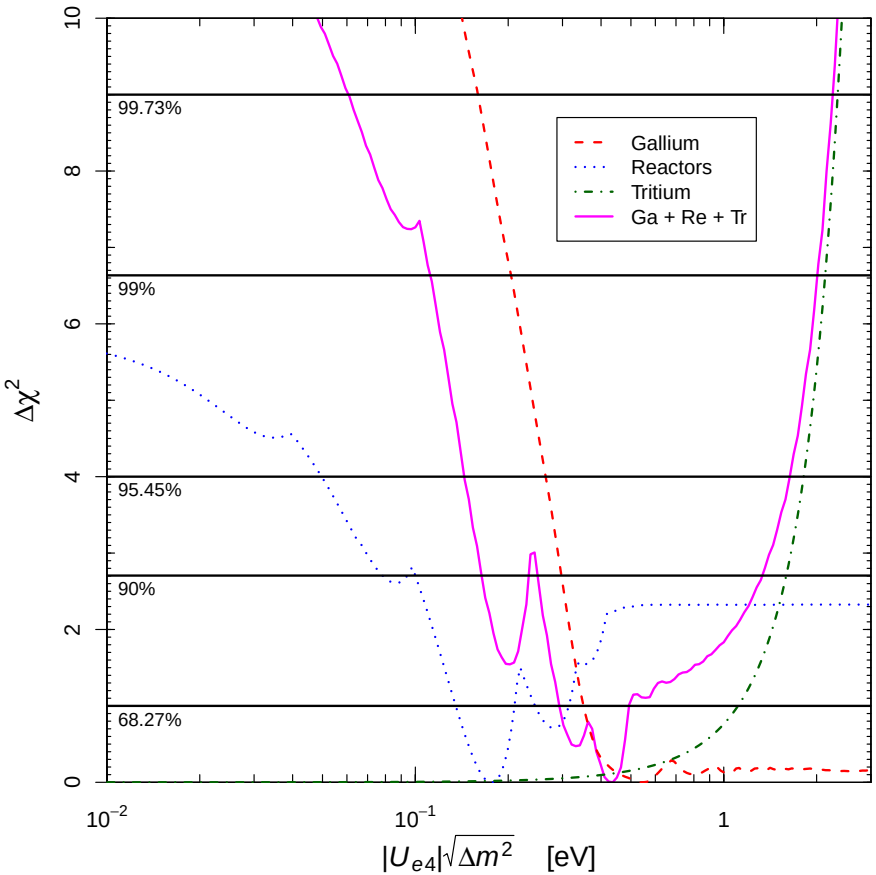
laboratori Gran Sasso





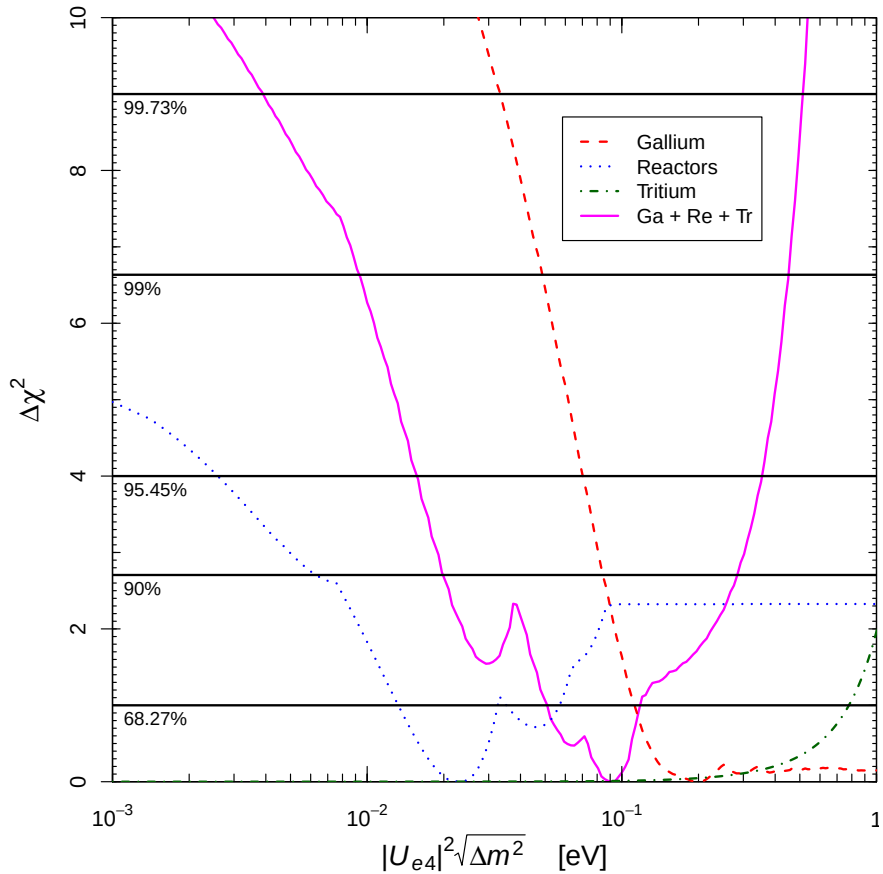
Implications of Gallium and Reactor Anomalies

β Decay



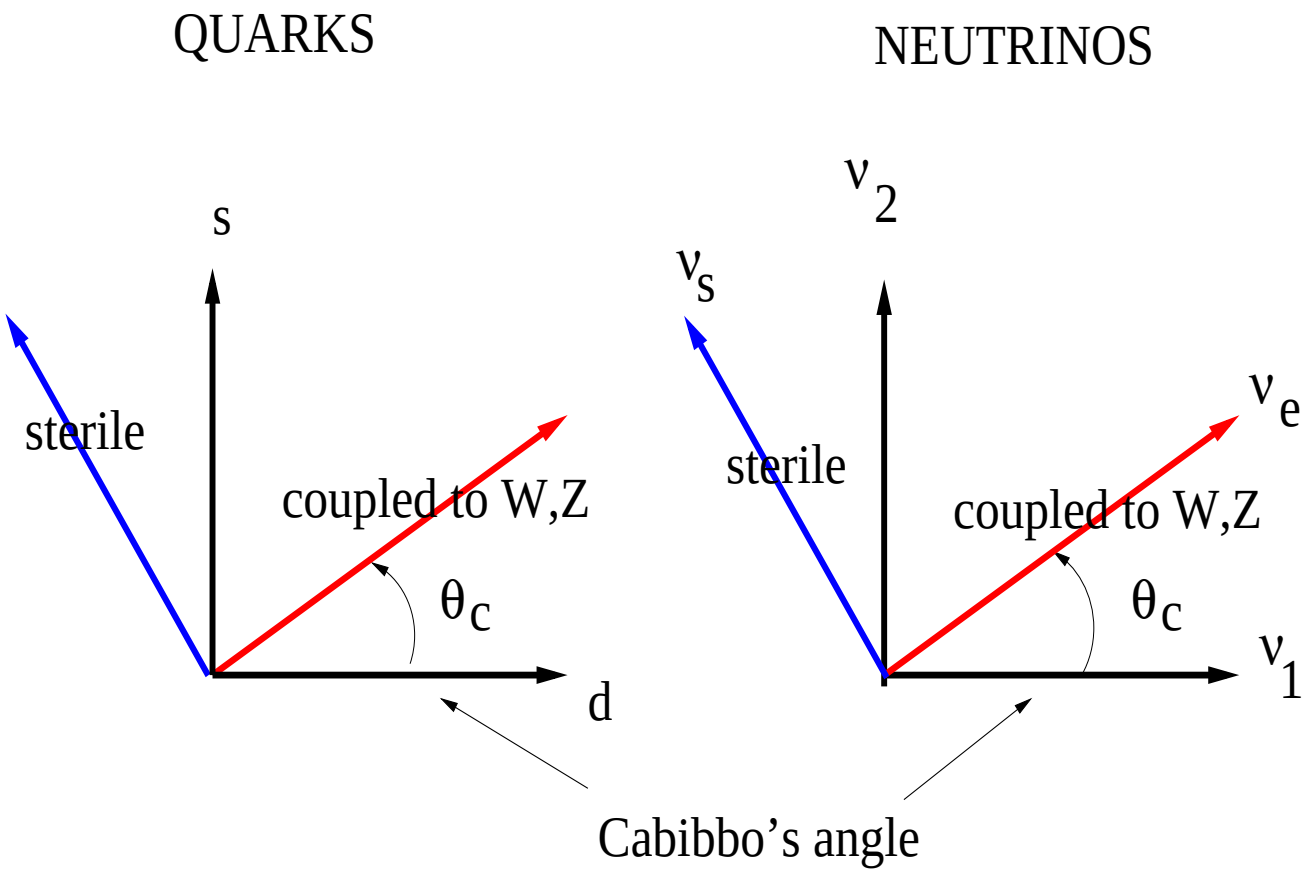
$$m_\beta^2 = \sum_k |U_{ek}|^2 m_k^2$$

$(\beta\beta)_{0\nu}$ Decay



$$m_{\beta\beta} = \left| \sum_k U_{ek}^2 \, m_k \right|$$

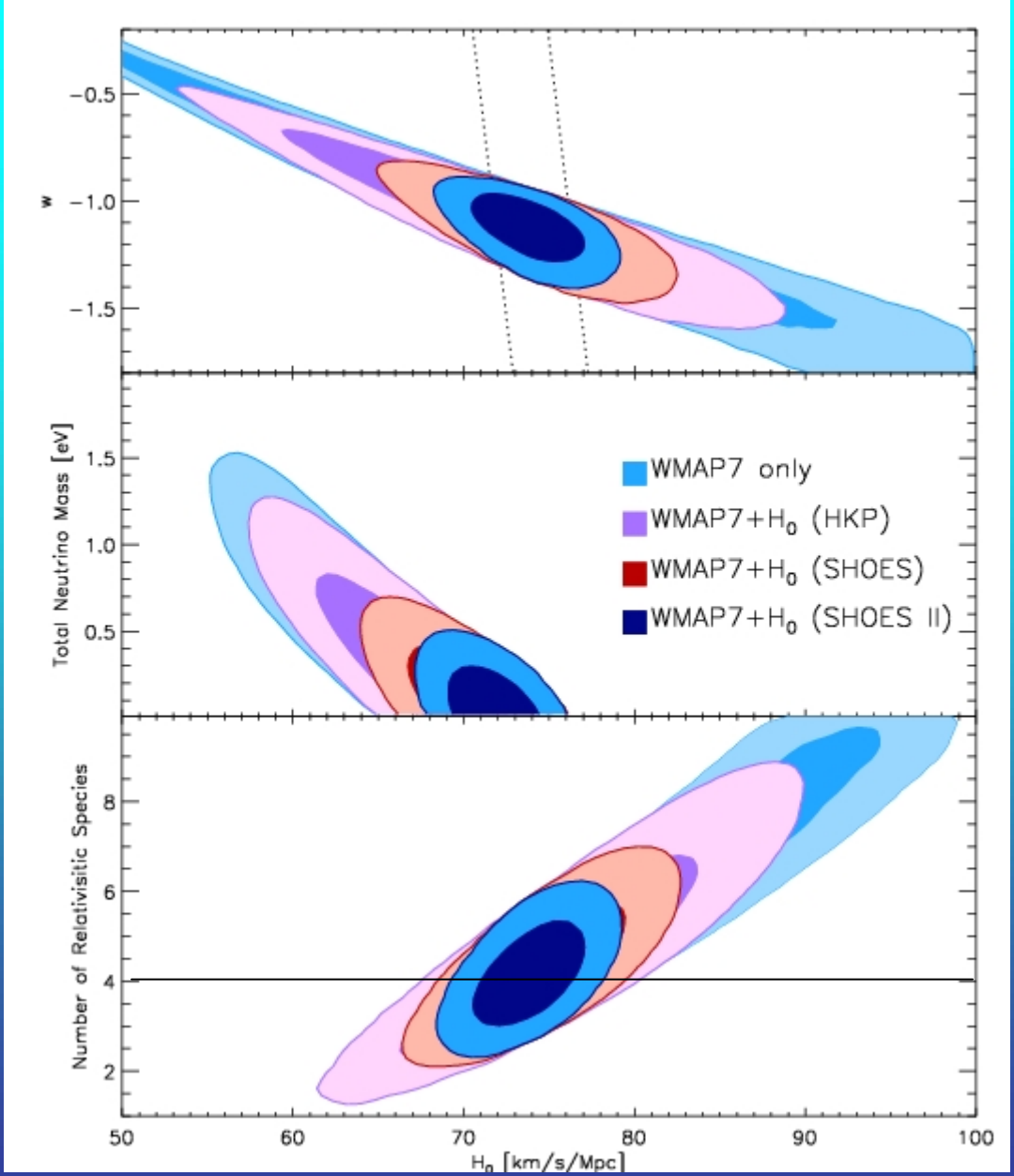
[Giunti, Laveder, In Preparation]



COMPLEMENTARITY relation :

$$\theta_{12} \sim 32^o \qquad \theta_{es} \sim 13^o \qquad \theta_{12} + \theta_{es} = 45^o$$

A.G. Riess et al. astro-ph 1103.2976



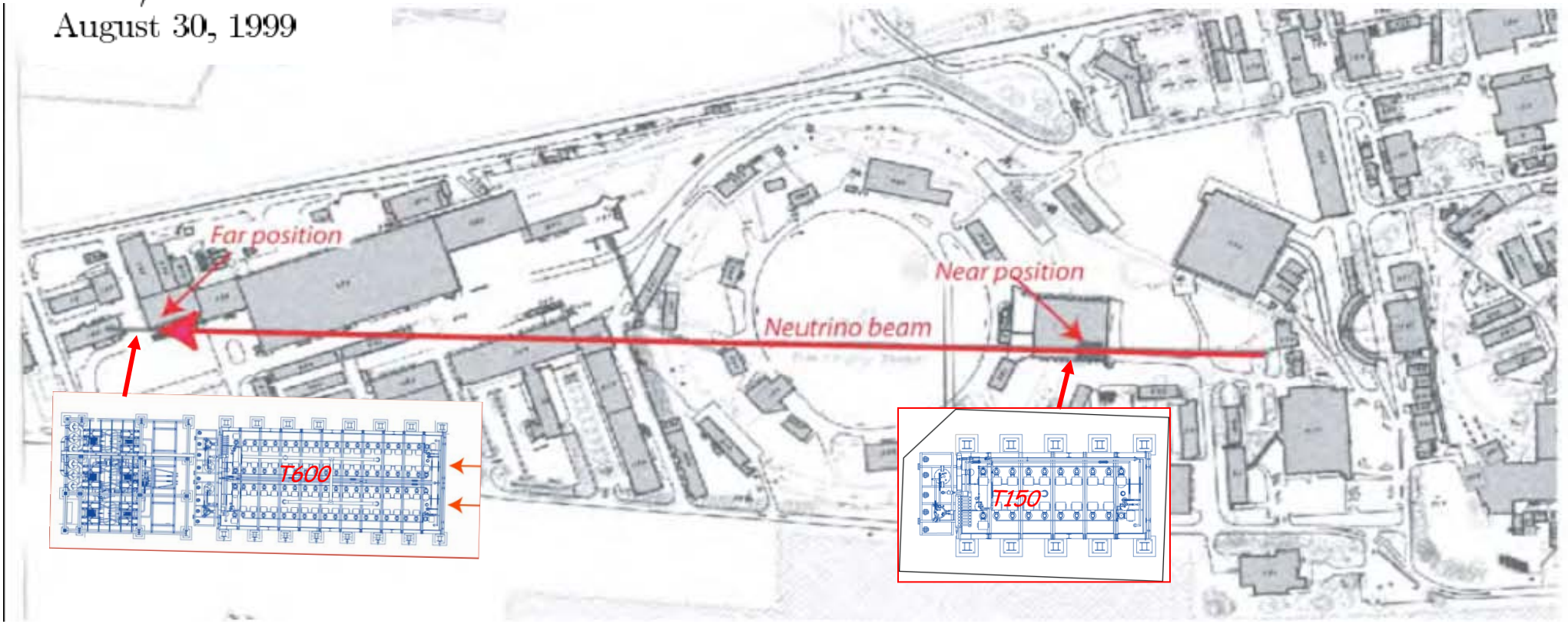
... if they are roses they'll flower...

... A BRIGHT FUTURE for Majorana ν physics !!!

Two detectors at the CERN-PS neutrino beam

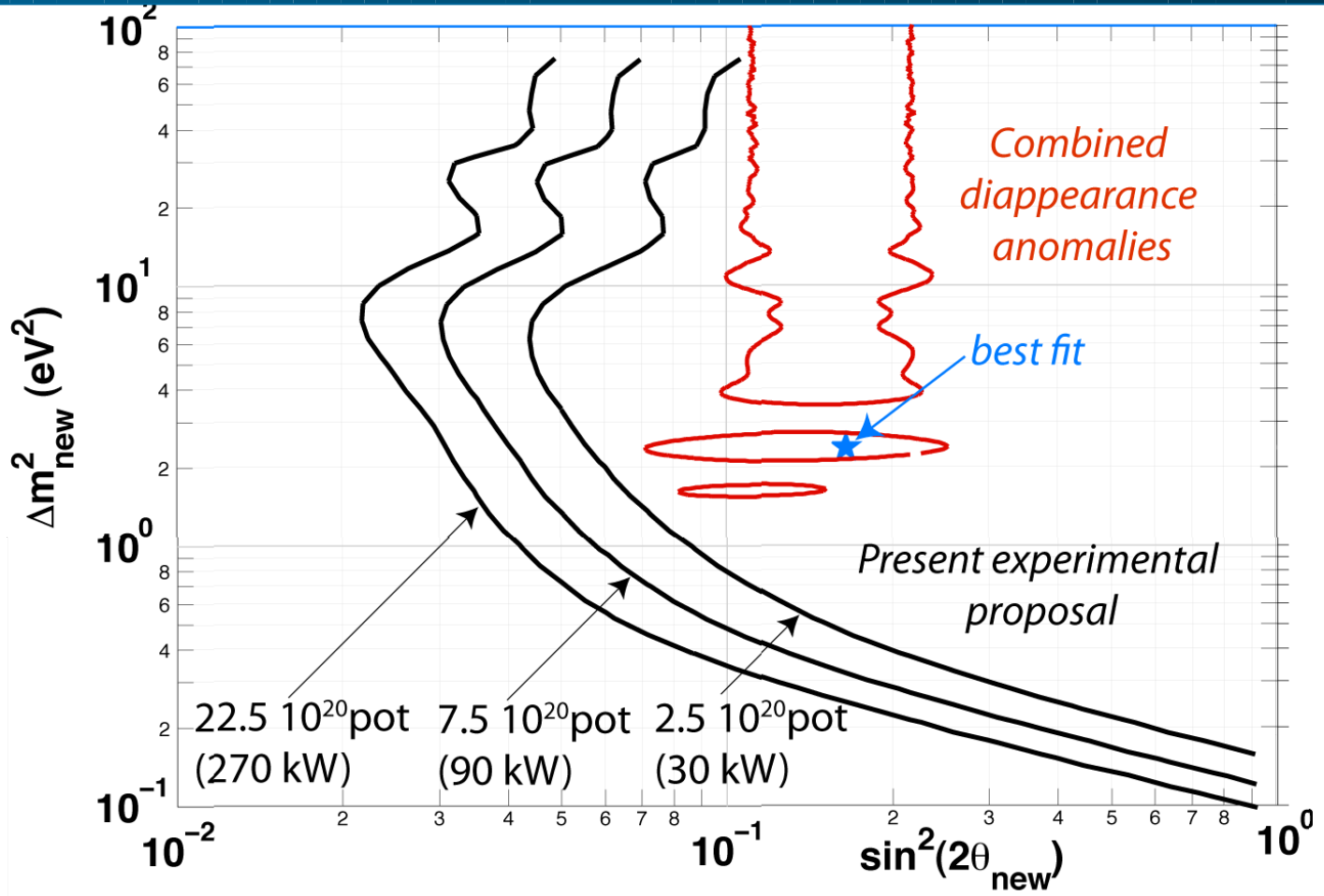
CERN-SPSC/99-26
SPSC/P311
August 30, 1999

SEARCH FOR $\nu_\mu \rightarrow \nu_e$ OSCILLATION AT THE CERN PS



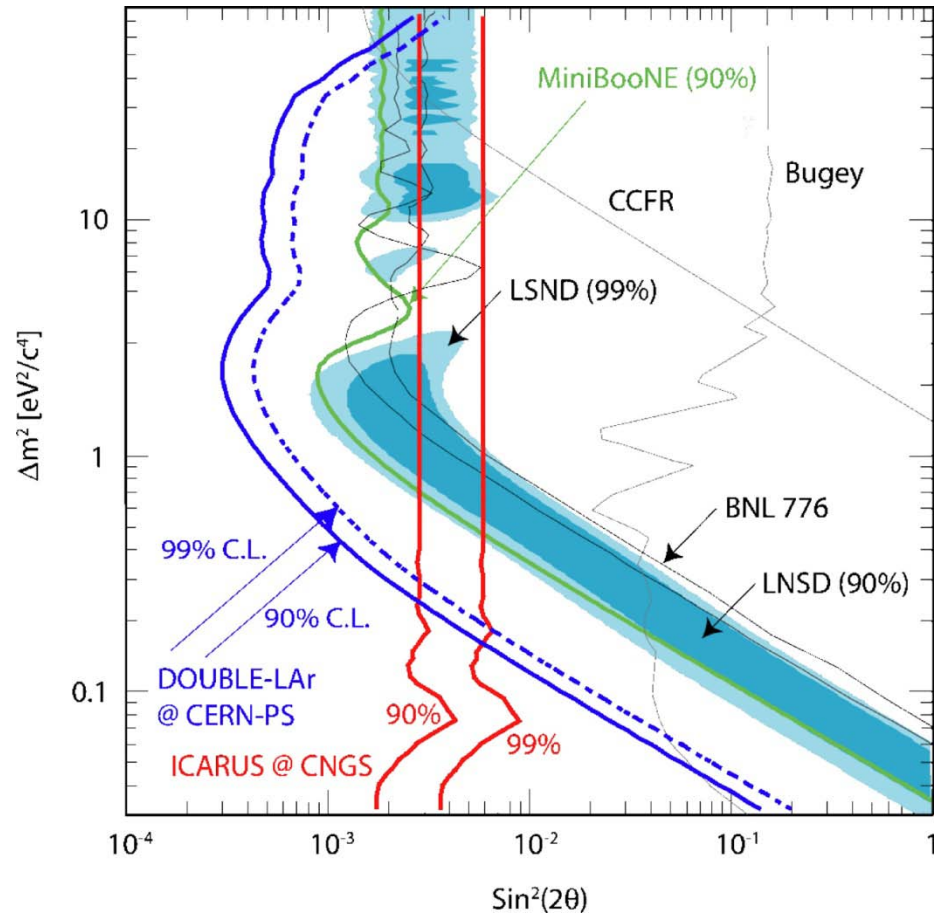
Two positions are foreseen for the detection of the neutrinos
The far (T600) location at 850 m from the target: L/E ~ 1 km/GeV;
The new location at a distance of 127 m from the target: L/E 0.15 km/GeV

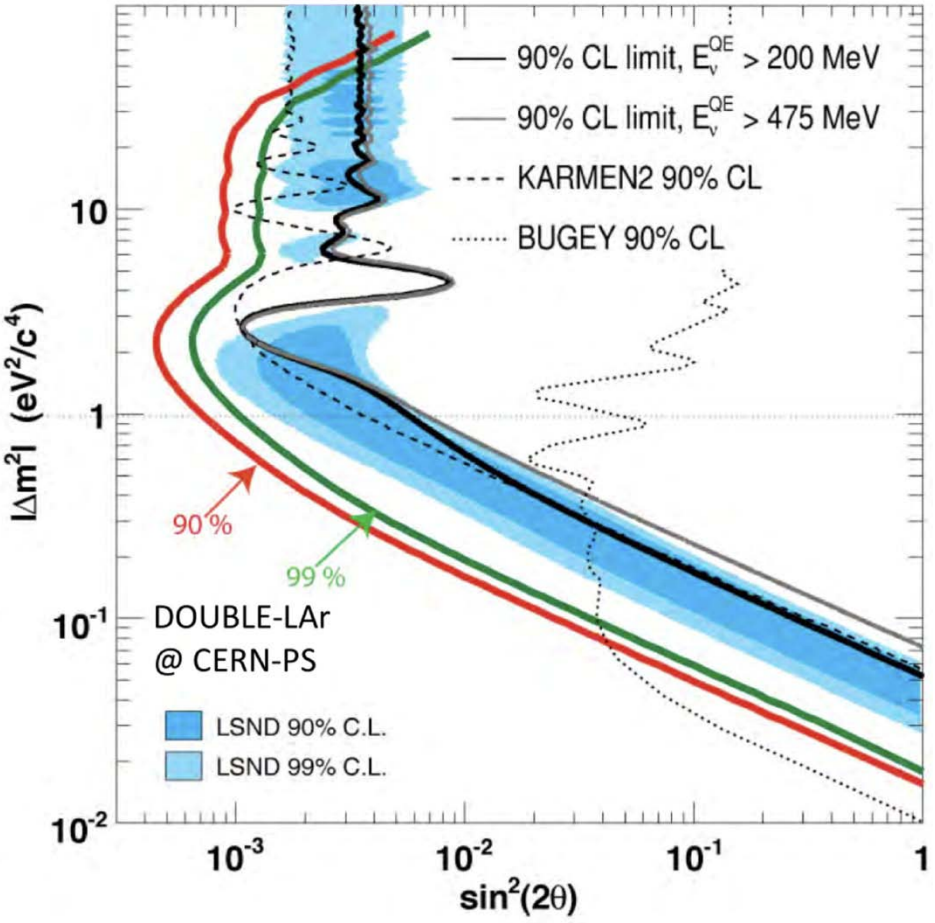
Sensitivity to disappearance anomaly



- Sensitivities (90% CL) in the $\sin^2(2\theta_{new})$ vs. Δm^2_{new} for an integrated intensity of (a) at the 30 kWatt beam intensity of the previous CERN/PS experiments, (b) the newly planned 90 kWatt neutrino beam and (c) a 270 kWatt curve. They are compared (in red) with the "anomalies" of the reactor + Gallex and Sage experiments. A 1% overall and 3% bin-to-bin systematic uncertainty is included (for 100 MeV bins).

Comparing sensitivities *(arXiv:0909.0355)*





Expected sensitivity for the proposed experiment exposed at the CERN-PS neutrino beam (left) for 2.5 10^{20} pot and twice as much for anti-neutrino (right) . The LSND allowed region is fully explored both for neutrinos. The expectations from one year of at LNGS are also shown.

The detector layout at FAR/NEAR sites

Liquid Argon is the best option for ν measurements in the PS beam energy range (electronic bubble chamber):

- *full measurement of ν interactions*
- *electron π^0 discrimination at 10^{-3} level*
- *NC rejection at 10^{-3} with 90% ν_e identification efficiency*

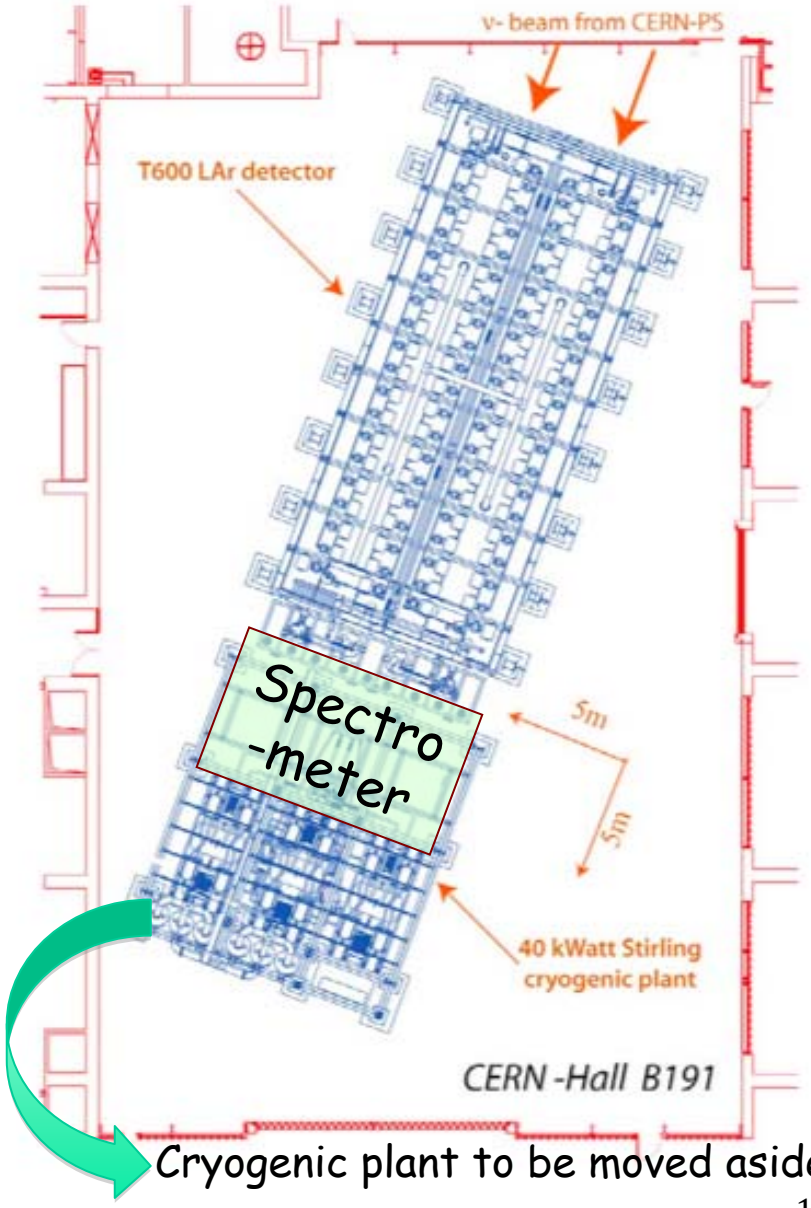
Memorandum to SPSC, 09/03/2011

Spectrometer is essential to allow

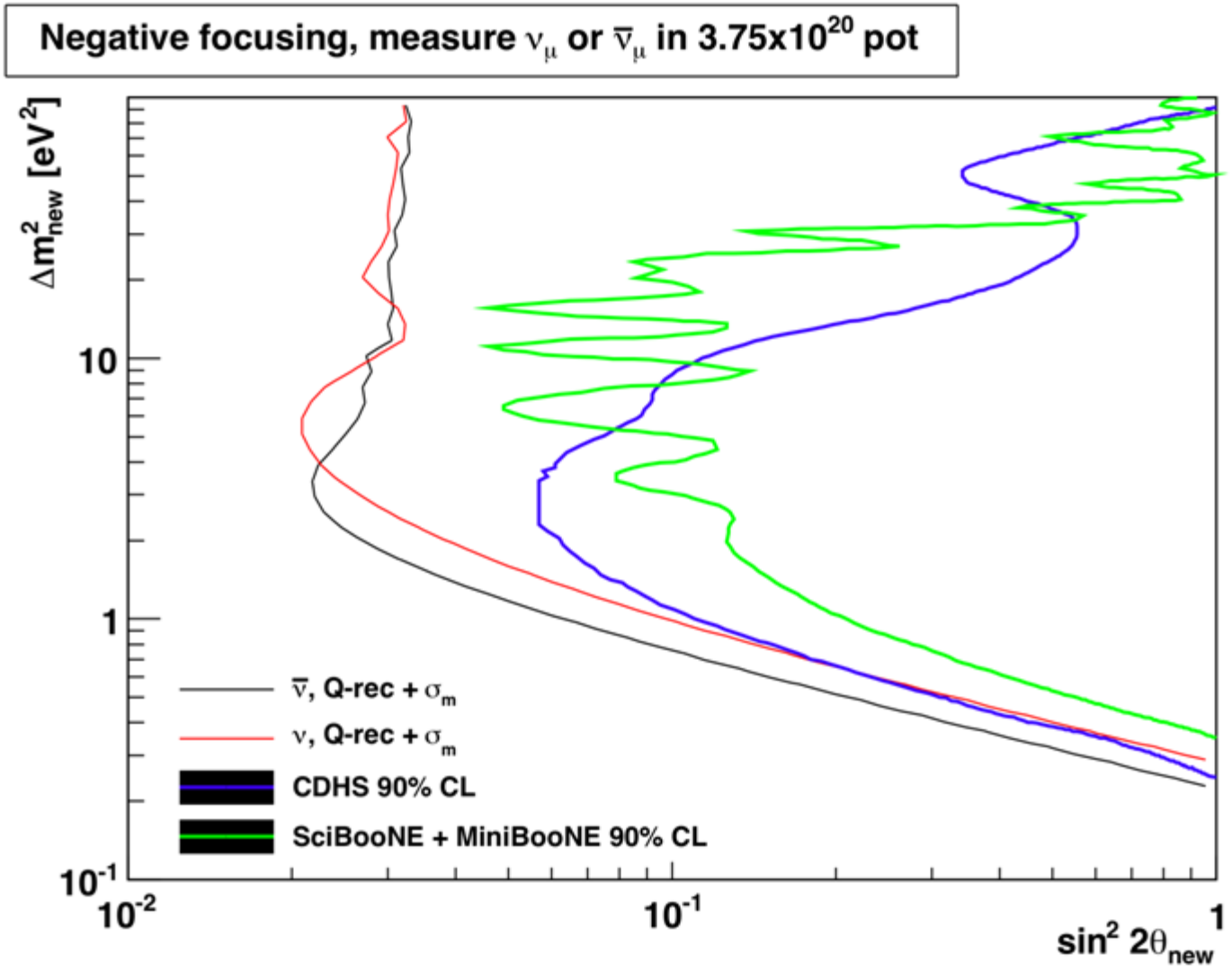
- *full Charge ID*
- *systematics control*
- *clean separation nu and anti-nu*

NESSiE proposal (t.b.s.)

Identical LAr-TPC + spectrometer combination at near site.



Our Goal

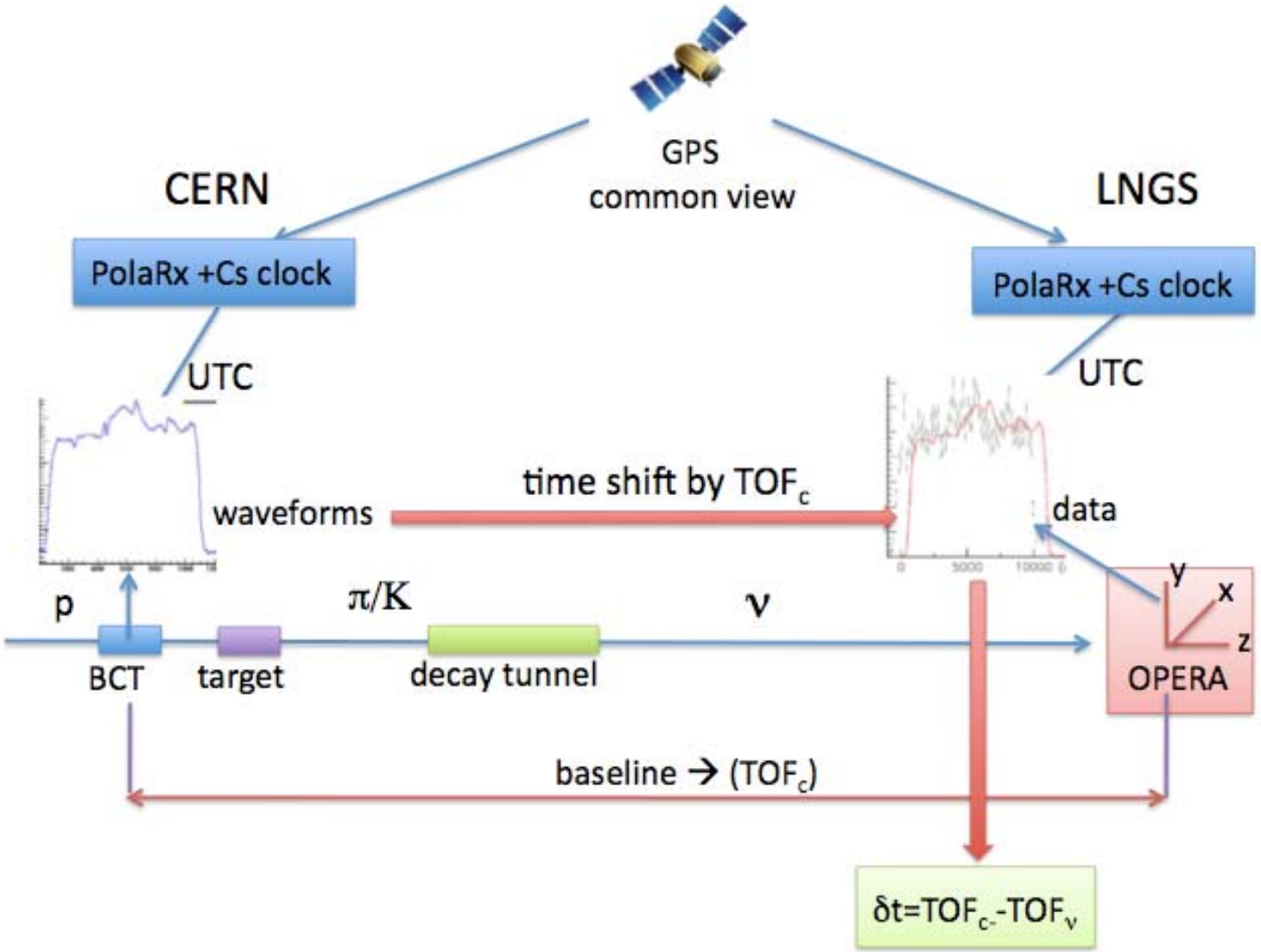


1 day run enough to test the CDHS limit !

(full simulation AND reconstruction)

Neutrinos: tachionic ?

Summary of the principle for the TOF measurement



Results

For CNGS ν_μ beam, <E> = 17 GeV:

$\delta t = TOF_c - TOF_\nu =$

$(1043.4 \pm 7.8\ (stat.))\ ns - 985.6\ ns = (57.8 \pm 7.8\ (stat.)\ ^{+8.3}_{-5.9}(sys.))\ ns$

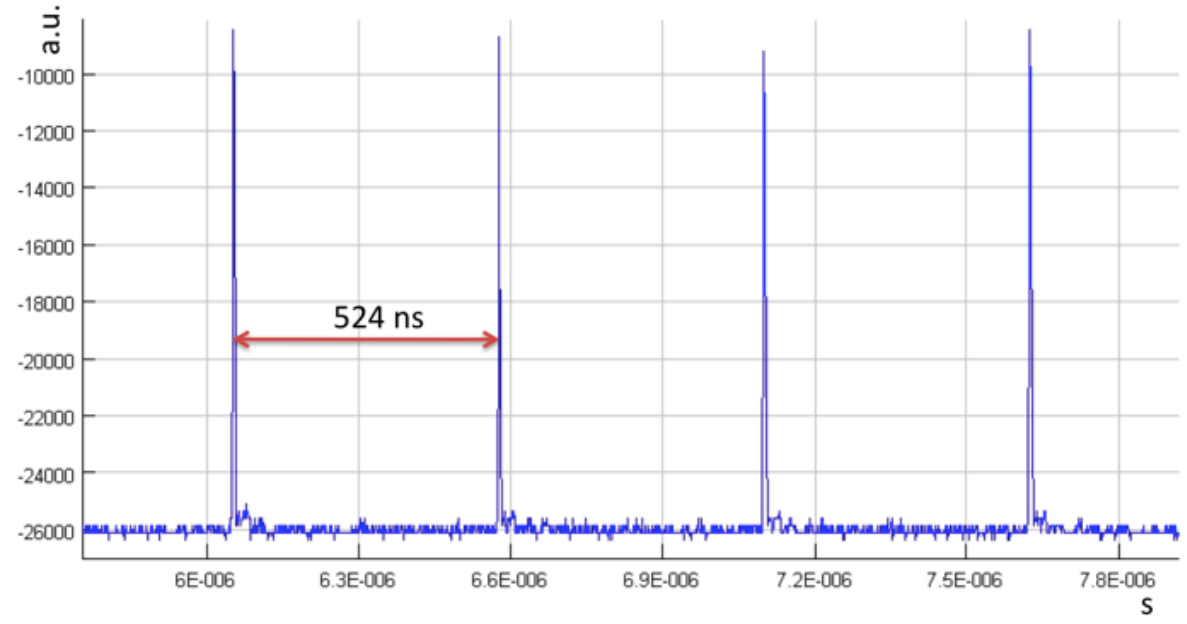
relative difference of neutrino velocity w.r.t. *c*:

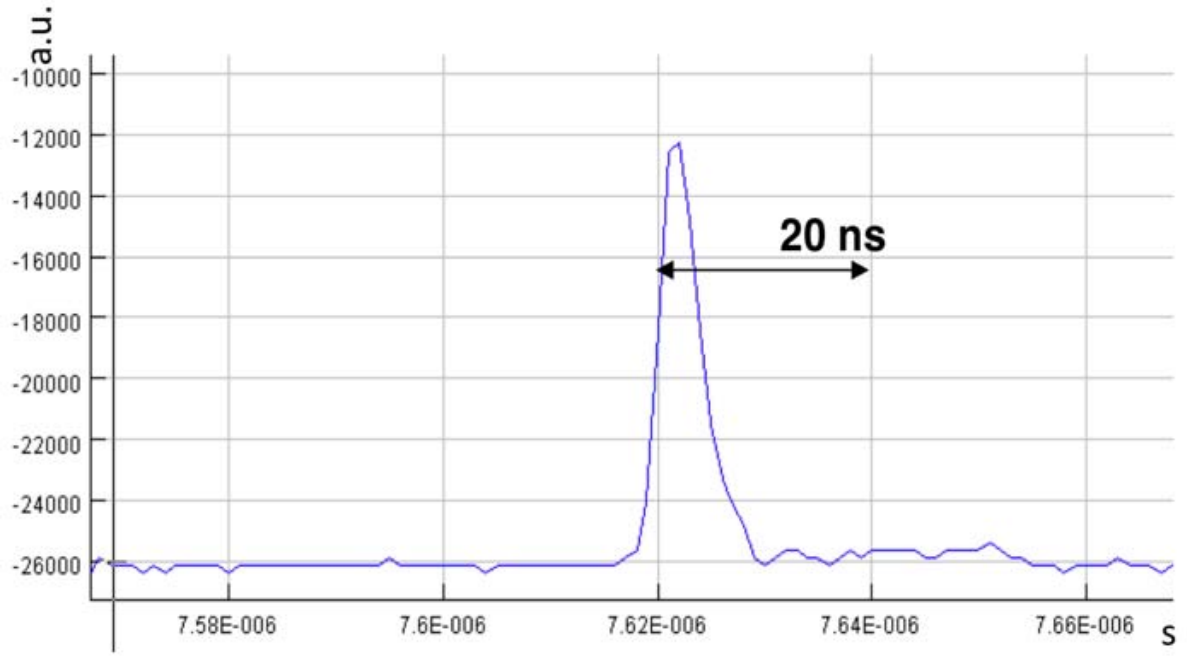
$(v-c)/c = \delta t\ /(TOF_c - \delta t) = (2.37 \pm 0.32\ (stat.)\ ^{+0.34}_{-0.24}(sys.)) \times 10^{-5}$

(730085 m used as neutrino baseline from parent mesons average decay point)

6.2 σ significance

Short-bunch wide-spacing neutrino beam





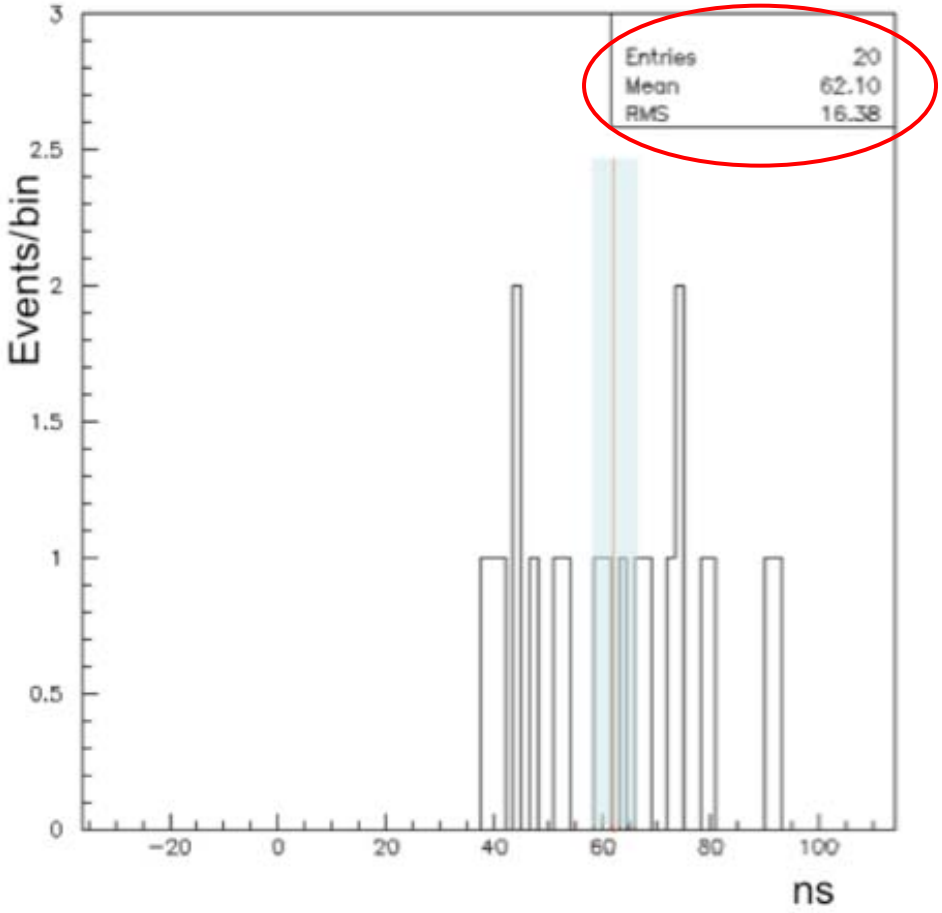
4×10^{16} pot accumulated

Proton bunch-length 3ns

35 beam-related events

20 events selected

Results with the bunched-beam



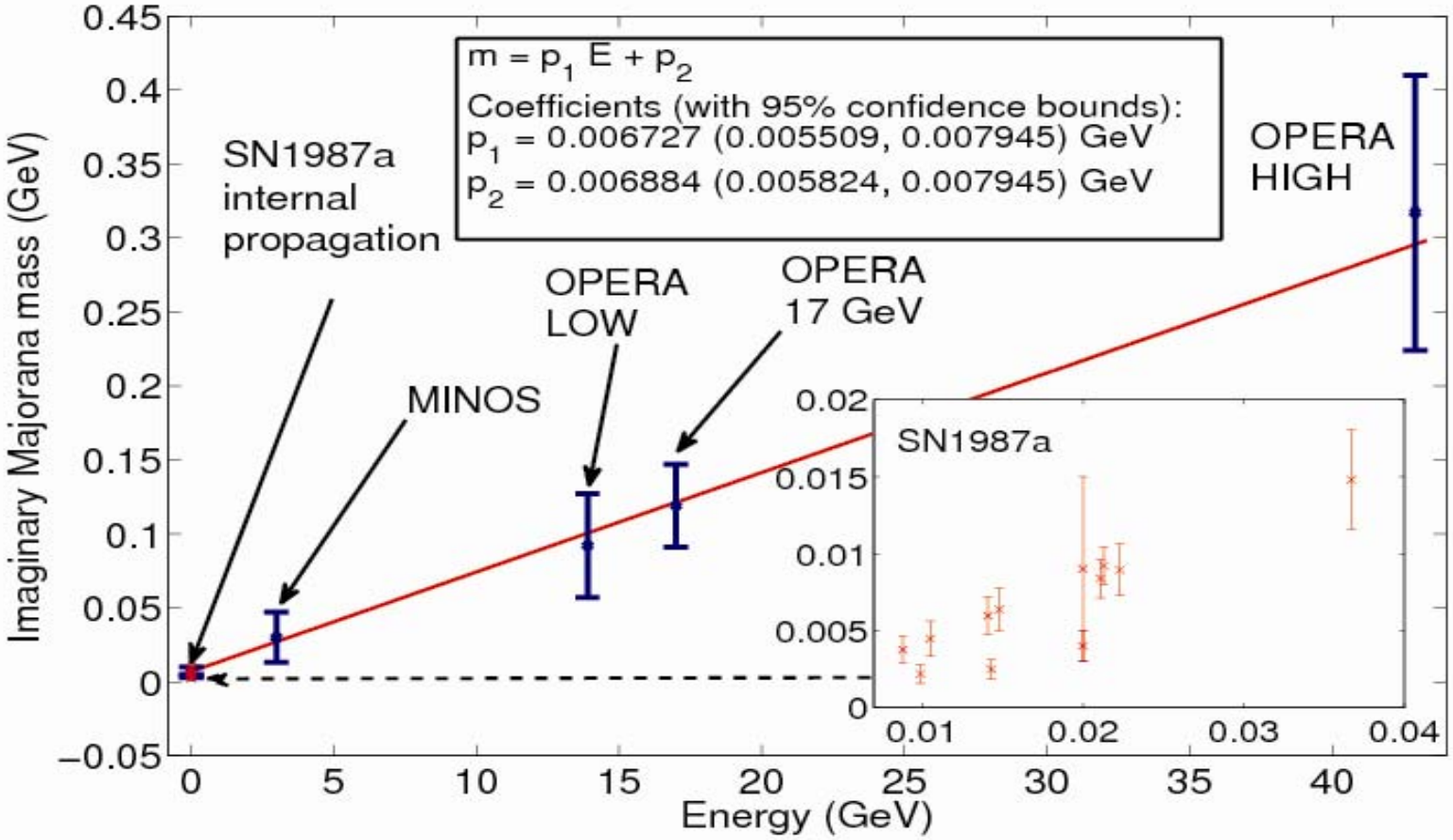
$\delta t = 62.1 \pm 3.7$ (stat.)

The systematic uncertainties are equal or smaller than those affecting the result with the nominal CNGS beam

These result excludes biases affecting the PDF based analysis

Imaginary mass in matter ?

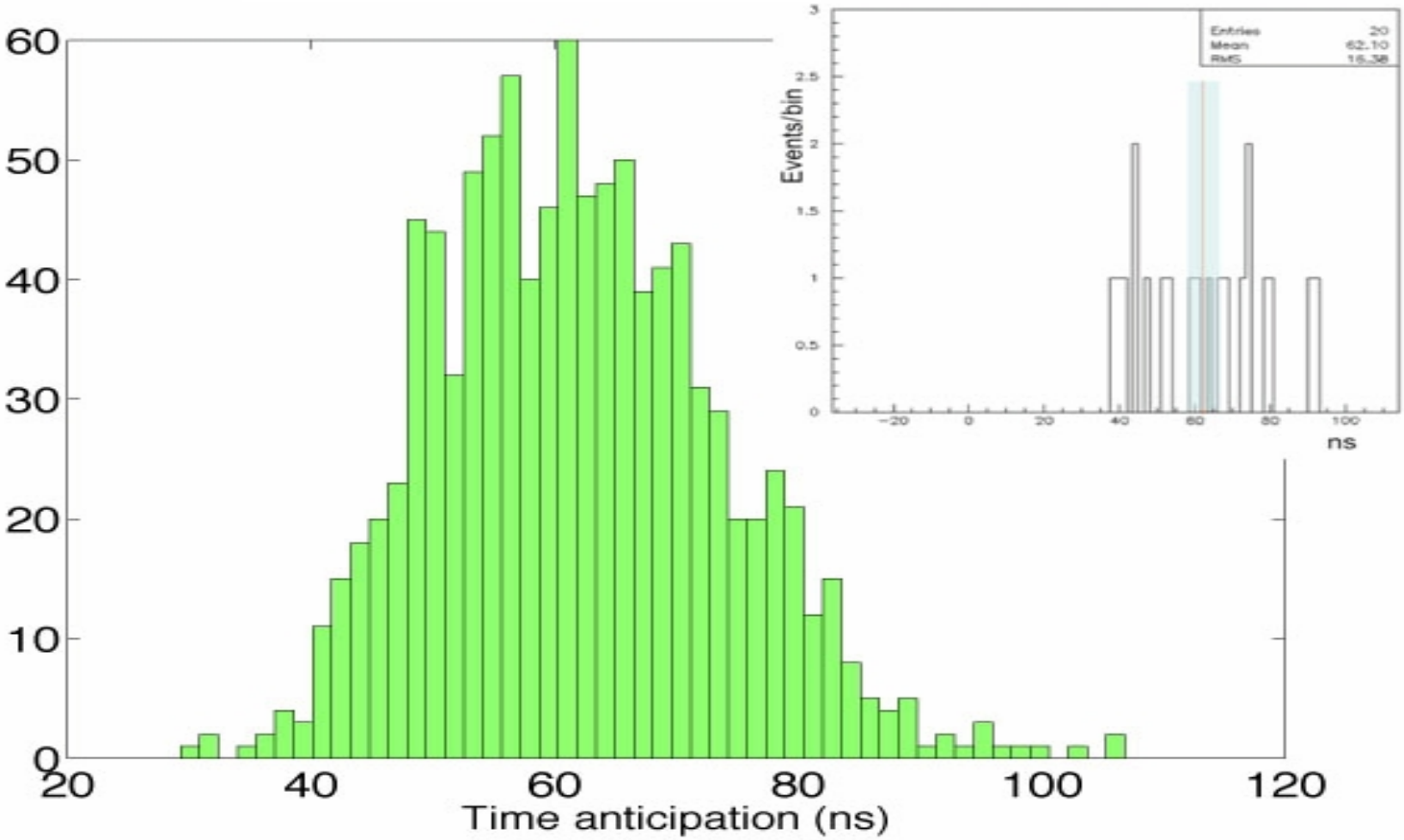
F.Tamburini & ML 1109.5445



$M = im$ $\quad M^2 = 2\,E^2\,\Delta T/T_0$

Excellent data vs MC agreement !

F.Tamburini & ML 1111.4441



$M = im \quad m=p_1E+p_2 \qquad \Delta T = \frac{1}{2}\, T_0\, M^2/E^2$

GRAZIE Milla !!!