LINEA 1 : Oscillazioni di Neutrini

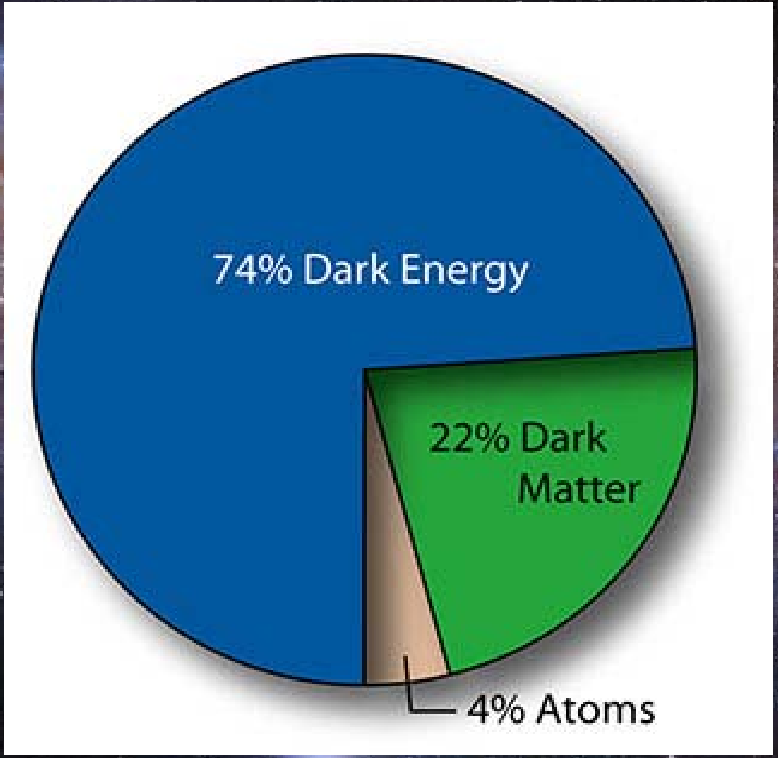
Marco Laveder

Frascati, 16 aprile 2012

BEYOND STANDARD MODEL : spin 0 composite particle

massive Majorana neutrinos

massive Dirac neutrinos

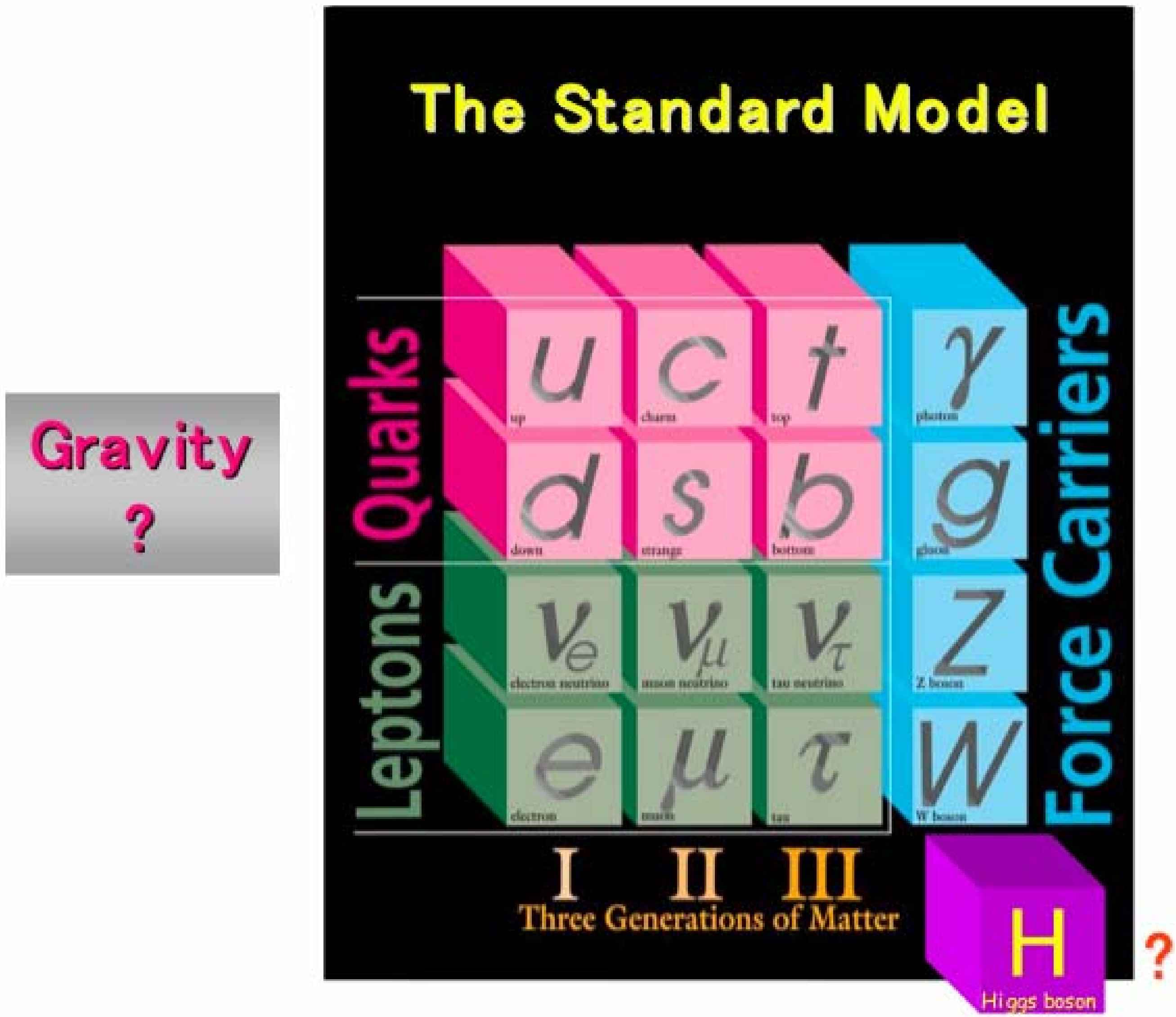


STANDARD MODEL : SM HIGGS BOSON

massless neutrinos


Il nuovo
cannocchiale !

Neutrinos: active

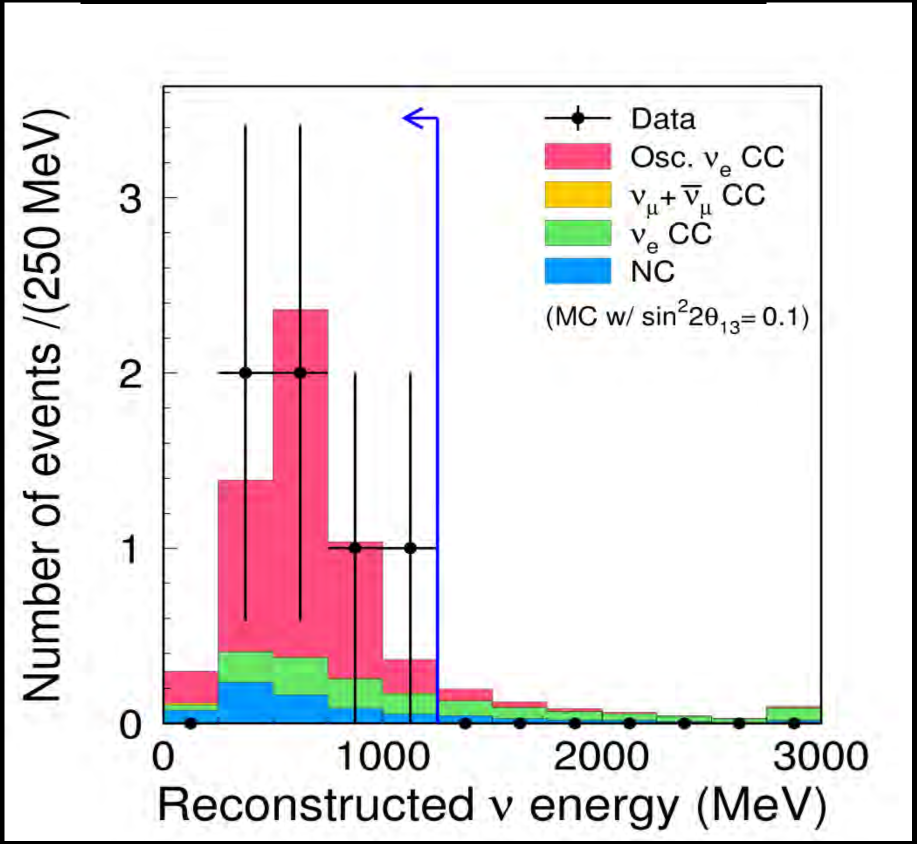


Gravity
?
The Standard Model
Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Leptons
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
e
electron
μ
muon
τ
tau
Force Carriers
γ
photon
g
gluon
Z
Z boson
W
W boson
I II III
Three Generations of Matter
H
Higgs boson
?

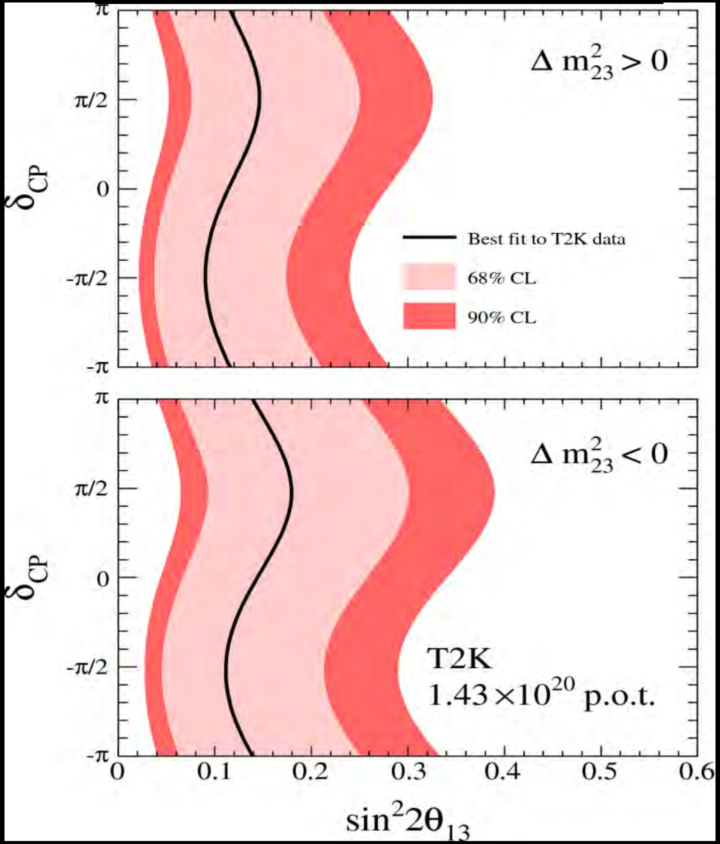
$\nu_\mu \rightarrow \nu_e$ Result

Phys. Rev. Lett. 107:041801, (2011)

Reconstructed ν_e energy



68%/90% CL region

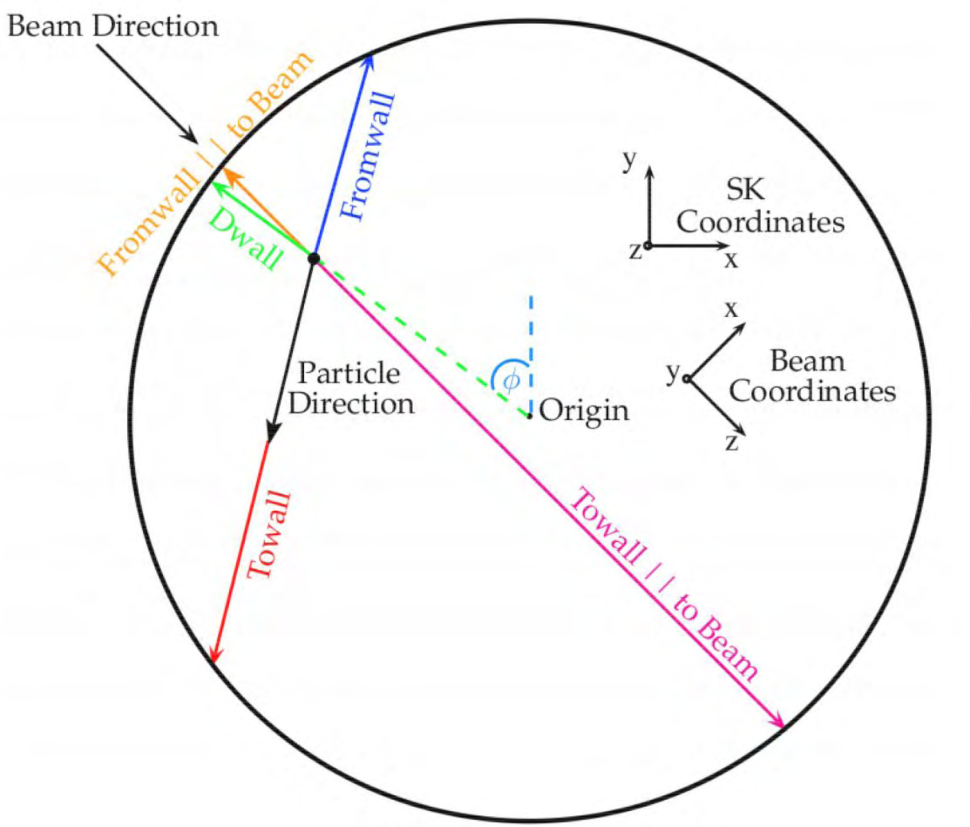


Expected 1.5 ±0.3 BG and observed 6 event. θ_{13} = 0 probability is only 0.7%.

$0.03 < \sin^2 2\theta_{13} < 0.28$(normal)
$0.04 < \sin^2 2\theta_{13} < 0.34$(inverted)

We observed the indication of $\theta_{13} \neq 0$

Probability to observe the vertex distribution



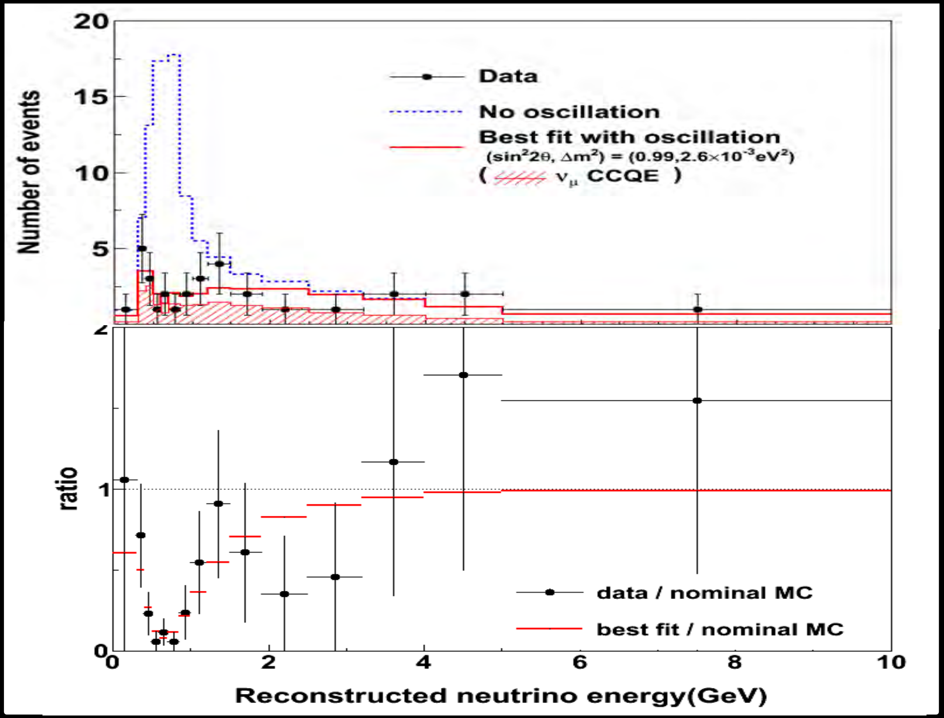
Probability From Toy-MC		
Distribution	7 FC Events	6 FCFV Events
Dwall	22.6%	3.7%
Towall	7.2%	1.9%
Fromwall	22.8%	5.8%
R^2	10.9%	3.1%
Z	38.8%	68.3%
ϕ	28.5%	11.0%

Probability From Toy-MC		
Distribution	7 FC Events	6 FCFV Events
Towall || *to Beam*	5.1%	1.1%
Fromwall || *to Beam*	1.4%	0.14%
x	32.0%	51.4%
y	42.5%	72.7%
z	5.2%	0.65%

$\nu_\mu \rightarrow \nu_x$ Result

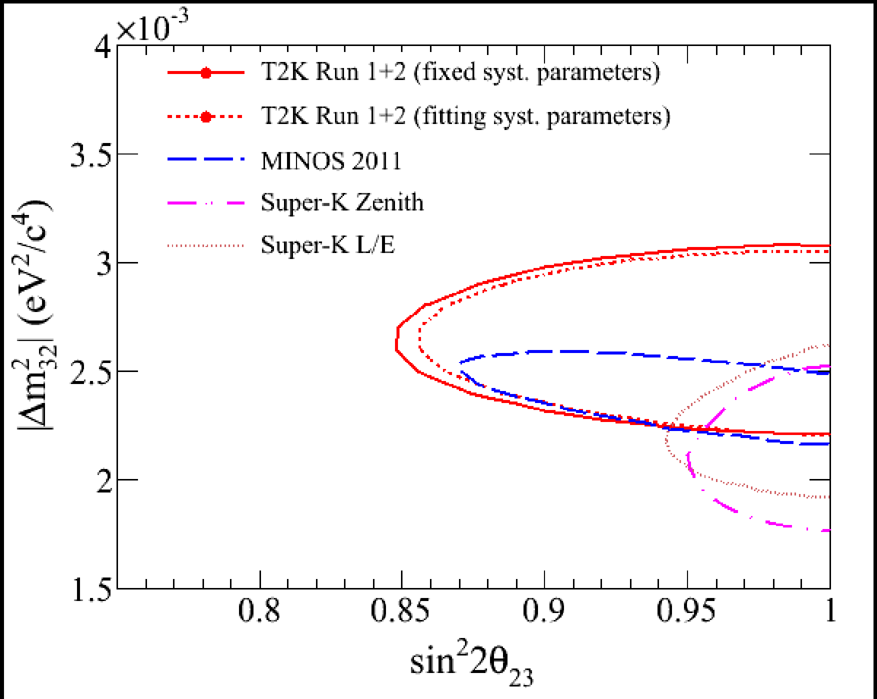
Phys. Rev. D 85, 031103(R)

Reconstructed ν_μ energy



Clear oscillation pattern is observed with off-axis beam

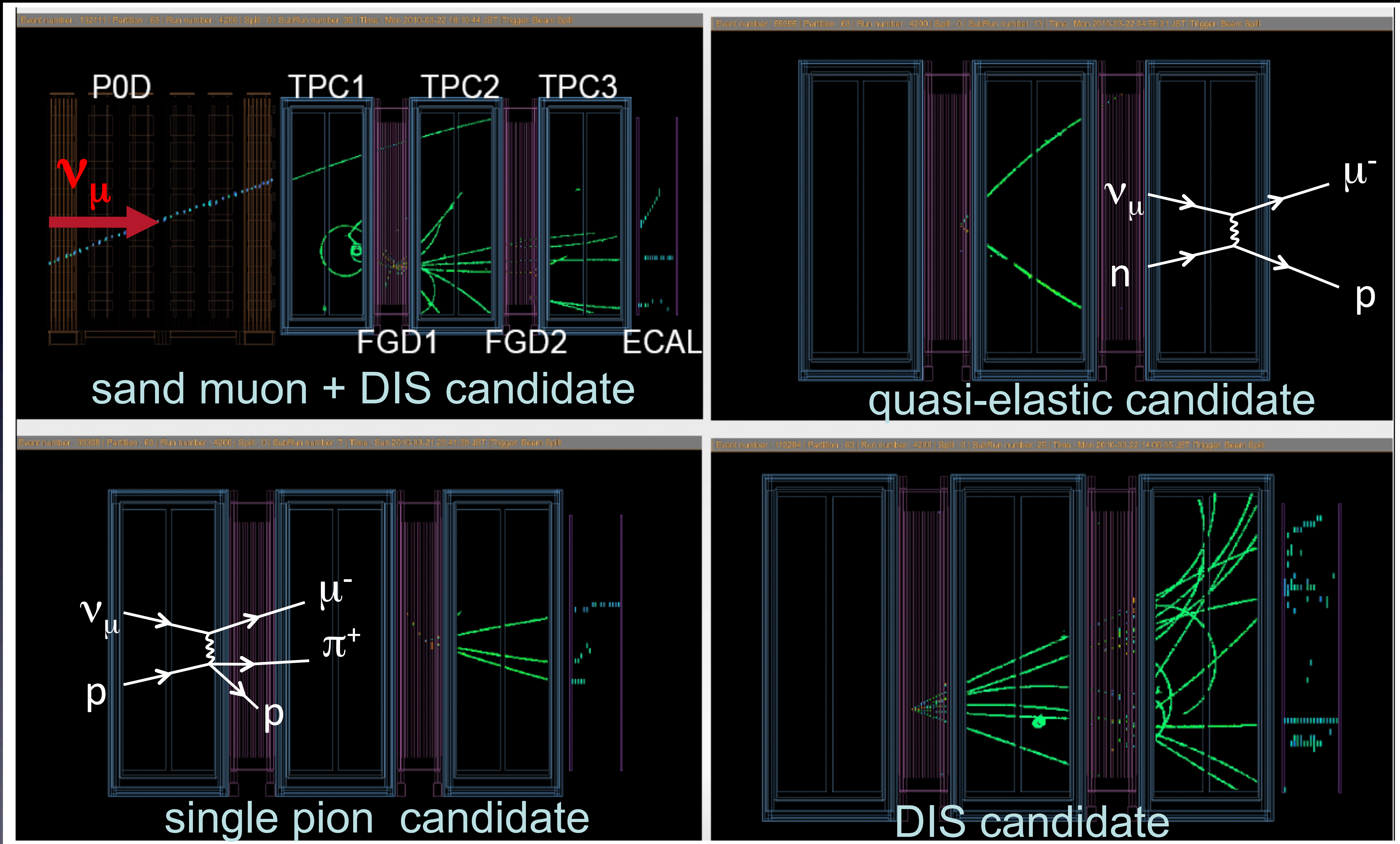
90% CL region



90% CL boundary includes $(1.0, 3.1\text{x}10^{-3}\text{eV}^2)$, $(0.84, 2.65\text{x}10^{-3}\text{eV}^2)$ and $(1.0, 2.2\text{x}10^{-3}\text{eV}^2)$

First observation of ν_μ disappearance using off-axis beam.

ND280 off-axis event gallery

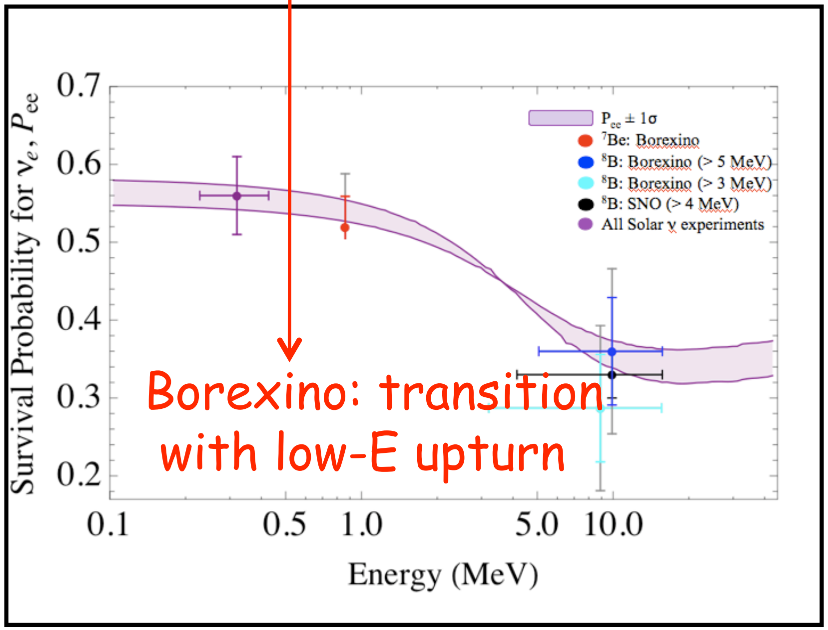


Vacuum frequency $\delta m^2/2E$ (unknown sign) interferes with ν_e interaction energy $\sqrt{2}G_F N_e$ (known sign) in solar matter: MSW

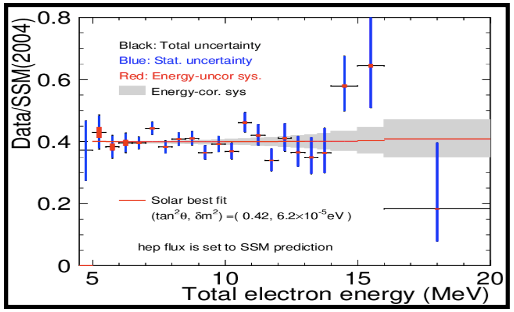
→ Get (ν_1, ν_2) hierarchy: state with largest ν_e component is the lightest of the two – conventionally, ν_1

Main features of matter effects: established

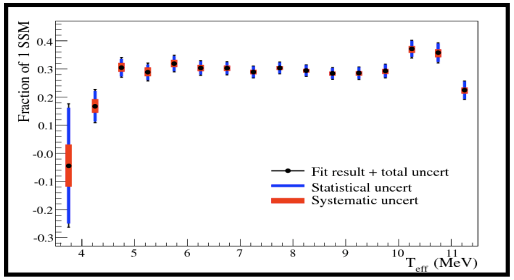
Spectral details: need higher stat, lower E



Borexino: transition with low-E upturn



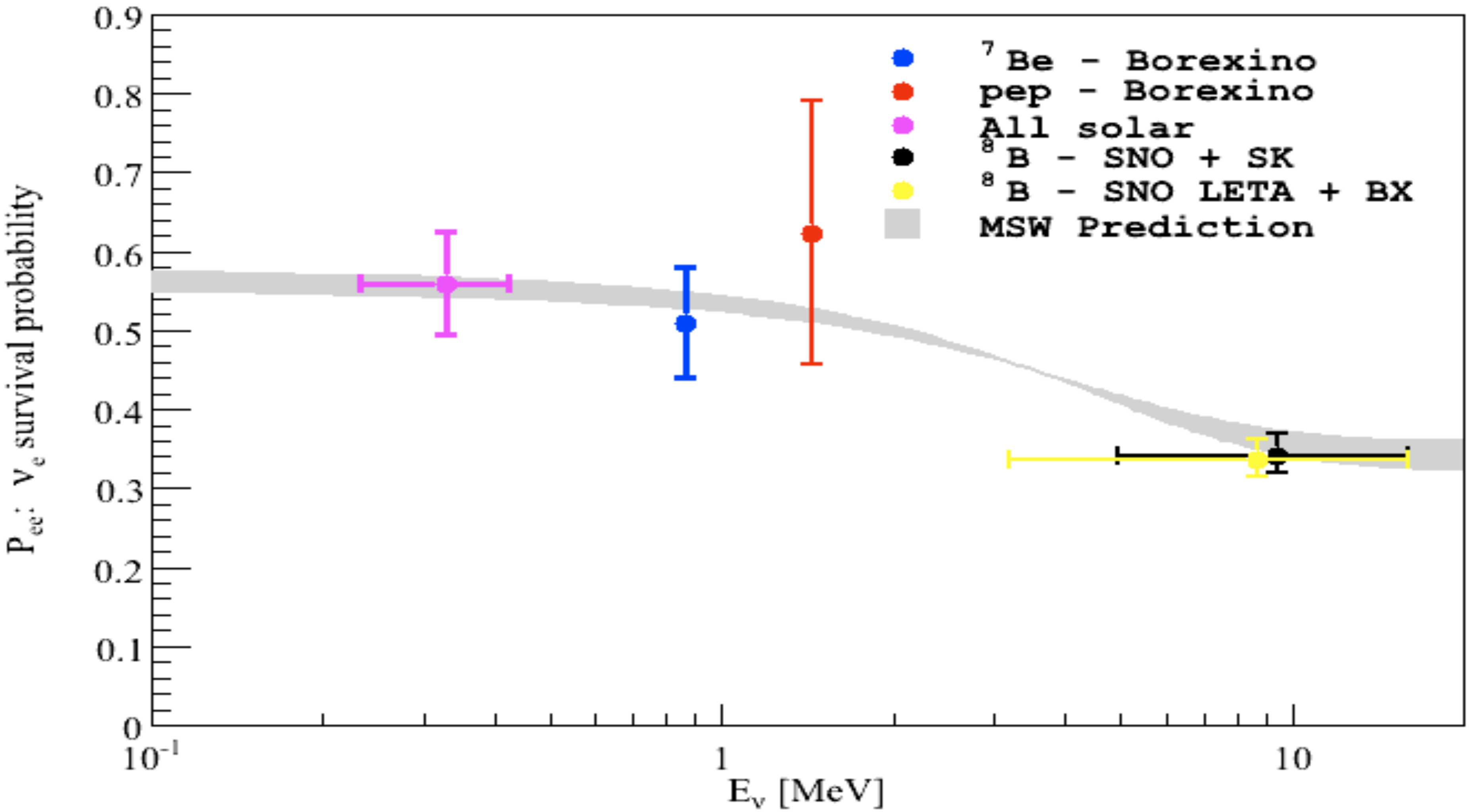
SK: ~flat



SNO: ~downturn

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

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



What can we learn from solar neutrinos (1) ?

Astrophysics: resolving "metallicity problem"

metallicity
abundance of the elements above He

New 3D Standard Solar Models -> lower metallicity -> discrepancy with helioseismology…
where is the problem?

Sources	$\Phi(\nu\ \sec^{-1}\ cm^{2})$ *high-metallicity*	$\Phi(\nu\ \sec^{-1}\ cm^{2})$ *low-metallicity*	Difference %
pp	$5.98(1\pm0.006)\times10^{10}$	$6.03(1\pm0.006)\times10^{10}$	0.8
pep	$1.44(1\pm0.012)\times10^{8}$	$1.47(1\pm0.012)\times10^{8}$	2.0
hep	$8.04(1\pm0.300)\times10^{3}$	$8.31(1\pm0.300)\times10^{3}$	3.3
^{7}Be	$5.00(1\pm0.070)\times10^{9}$	$4.56(1\pm0.070)\times10^{9}$	9.4
^{8}B	$5.58(1\pm0.140)\times10^{6}$	$4.59(1\pm0.140)\times10^{6}$	19.8
^{13}N	$2.96(1\pm0.140)\times10^{8}$	$2.17(1\pm0.140)\times10^{8}$	31.6
^{15}O	$2.23(1\pm0.150)\times10^{8}$	$1.56(1\pm0.150)\times10^{8}$	33.5
^{17}F	$5.52(1\pm0.170)\times10^{6}$	$3.40(1\pm0.160)\times10^{6}$	53.0

Solar neutrino fluxes depend on metallicity!

- **Solar Model:** Serenelli, Haxton and Pena-Garay arXiV:1104.1639
- **High metallicity GS98** = Grevesse et al. *S. Sci. Rev. 85,161 ('98);*
- ***Low metallicity AGS09*** = *Asplund, et al,* A.R.A.&A. 47(2009)481;

Implications of the ^{7}Be measurement

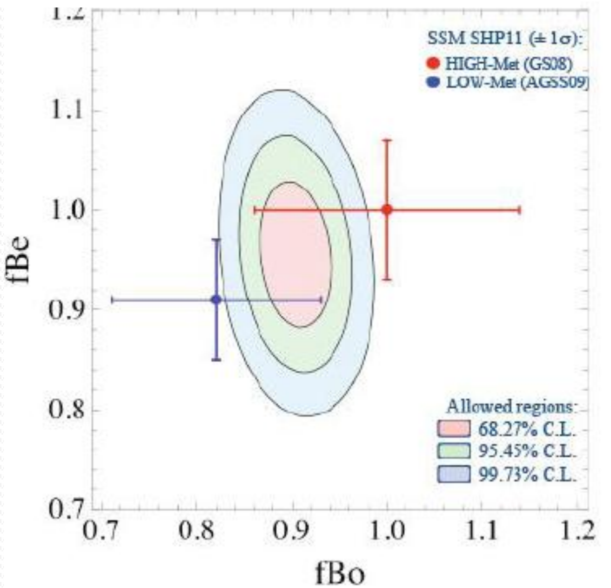
- comparing to non-oscillated SSM : **no oscillation excluded @ 5.0 σ**

(electron equivalent flux (862 keV line): **(2.78 ± 0.13) x 10^{9} cm^{-2} s^{-1})**

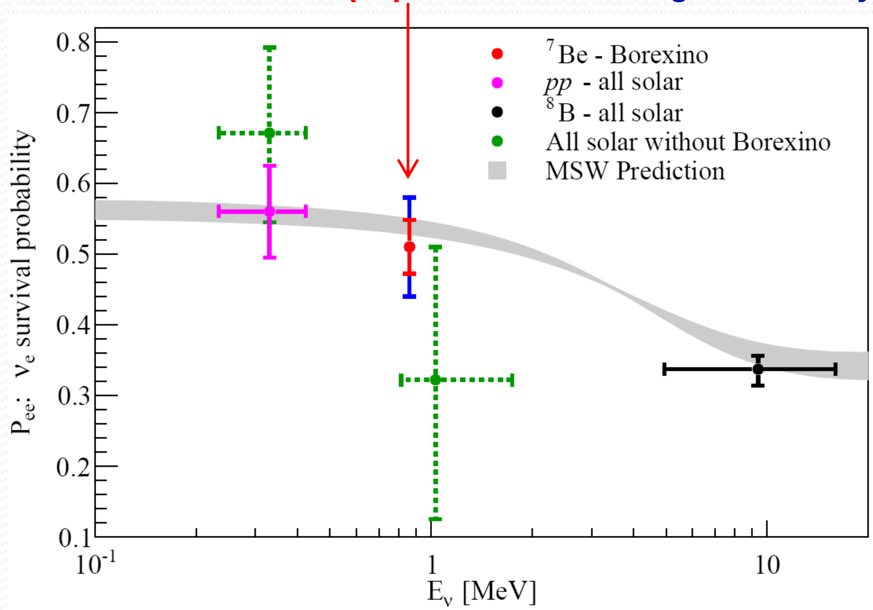
- assuming MSW-LMA: f (7Be) = measured flux / SSM = 0.97 + 0.09
- **including all solar experiments + luminosity constrain:**

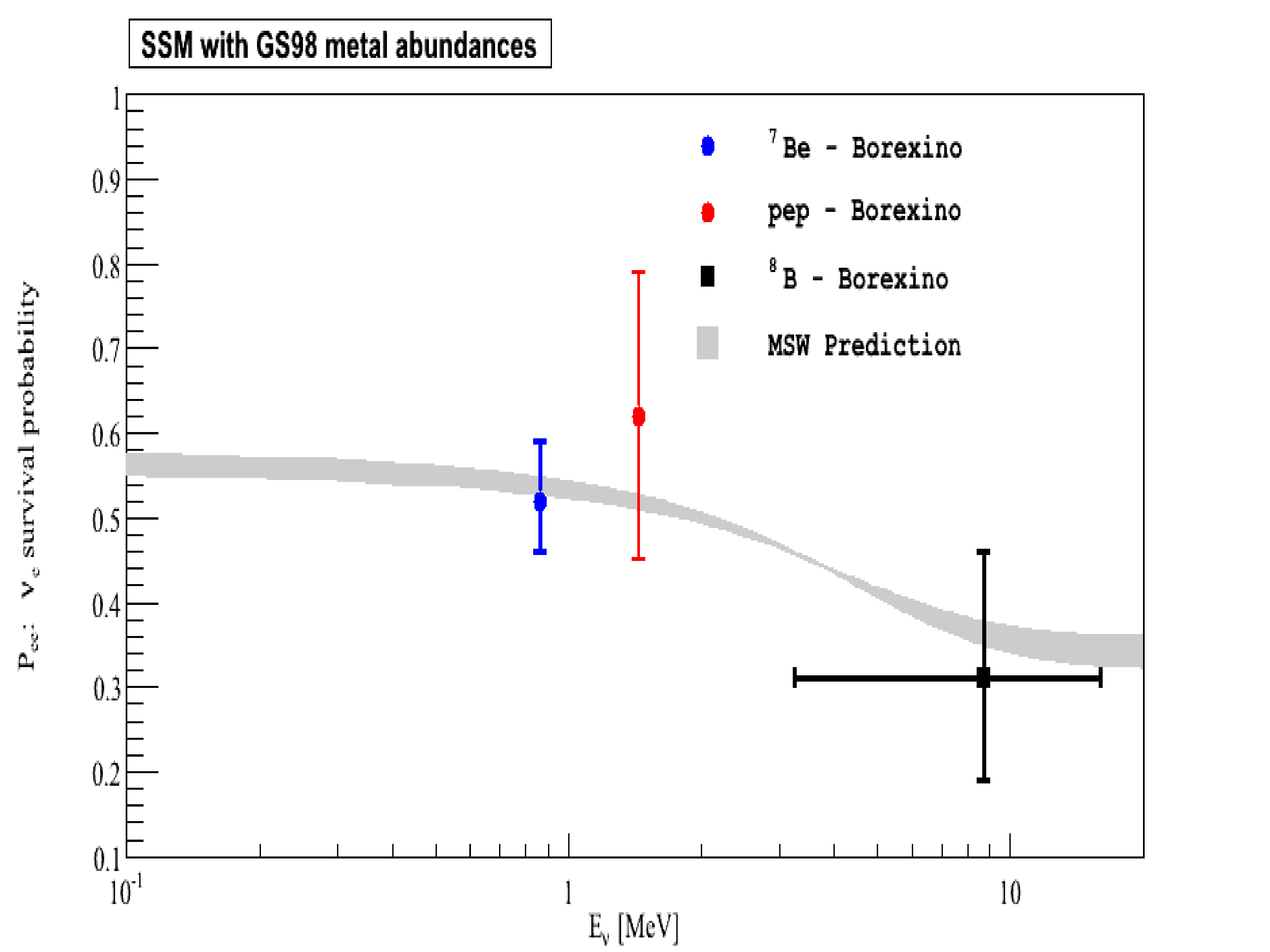
$$f_{pp} = 1.013^{+0.003}_{-0.010}$$
$$f_{CNO} < 2.5 \text{ at } 95\% \text{ C.L.}$$

no power to resolve low/high metallicity problem

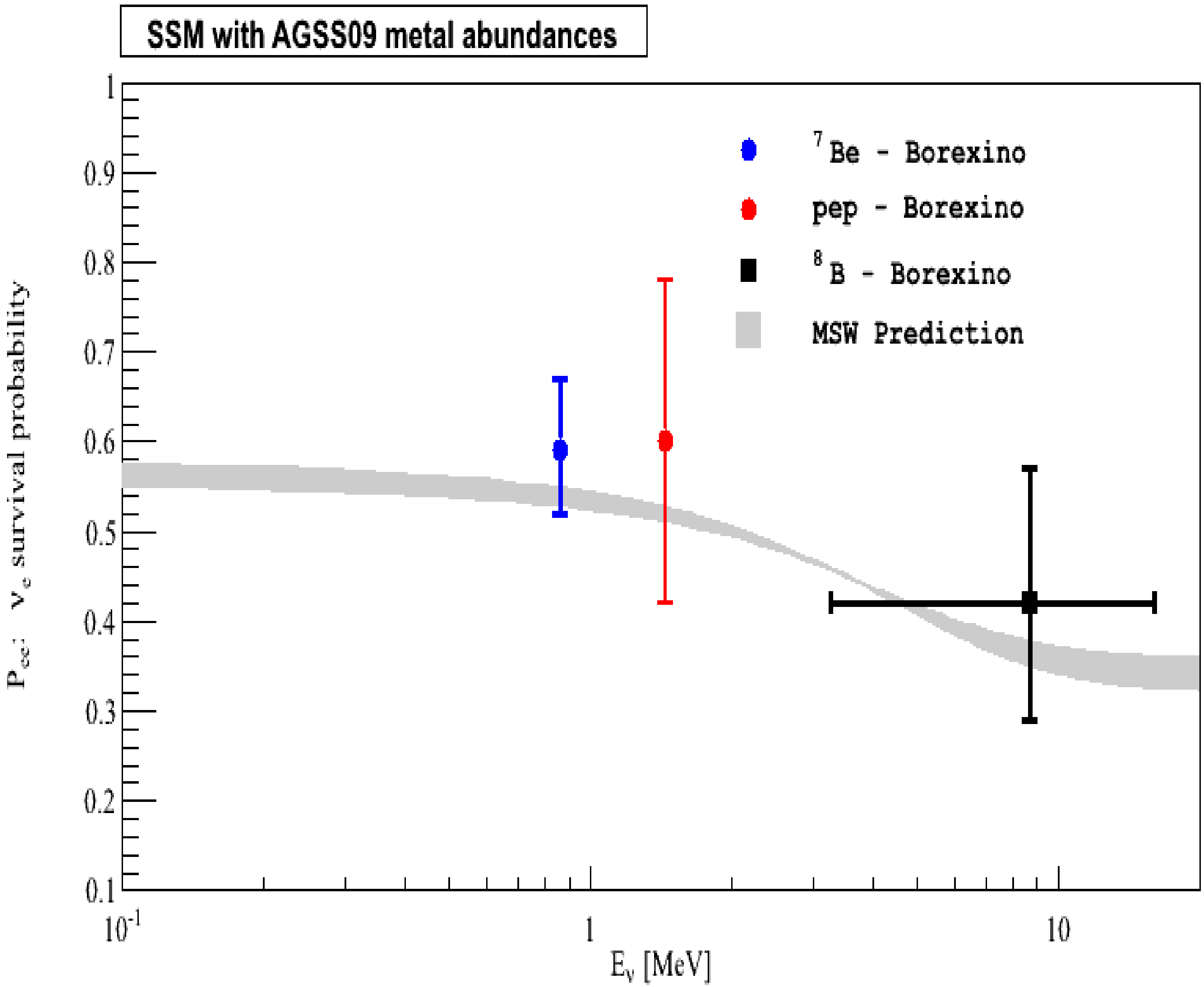


Pee = 0.51 + 0.07(experiment + SSM high metalilcity);



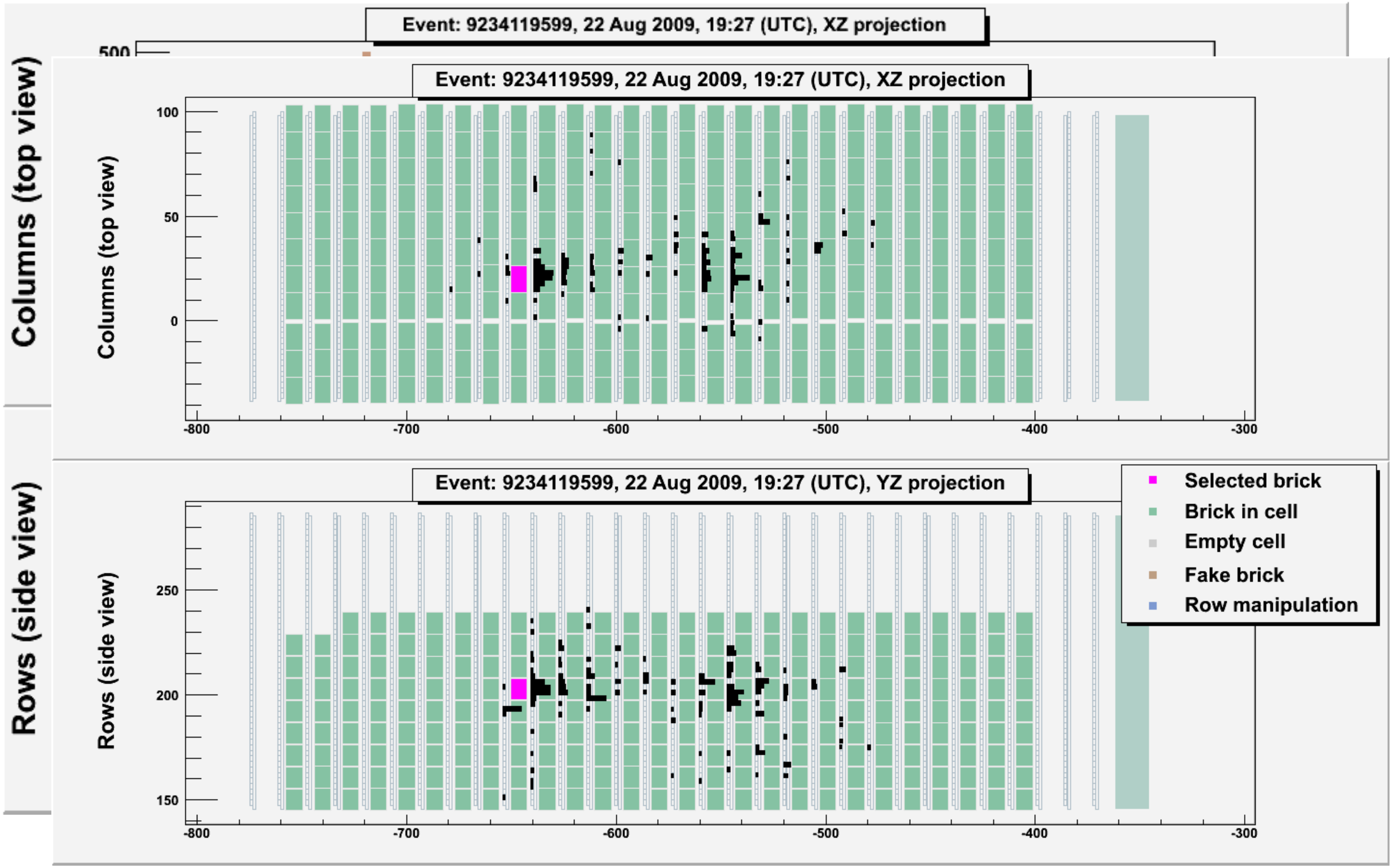


SSM with GS98 metal abundances
^{7}Be - Borexino
pep - Borexino
^{8}B - Borexino
MSW Prediction
P_{ee}: ν_e survival probability
E_ν [MeV]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
10^{-1}
1
10


SSM with AGSS09 metal abundances
^{7}Be - Borexino
pep - Borexino
^{8}B - Borexino
MSW Prediction
P_{ee}: ν_e survival probability
E_ν [MeV]
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
10^{-1}
1
10

The first ν_τ candidate event

Phys. Lett. B 691 (2010) 138



- 2008-2009 data analysis completed (arXiv:1107.2594v1) Acc. by New Journ. of Phys.
  - 4.8×10^{19} pot, 34% of available sample, 2.6 × more statistics w.r.t. τ candidate publication
  - 2738 fully analysed events (decay search). **No new τ**

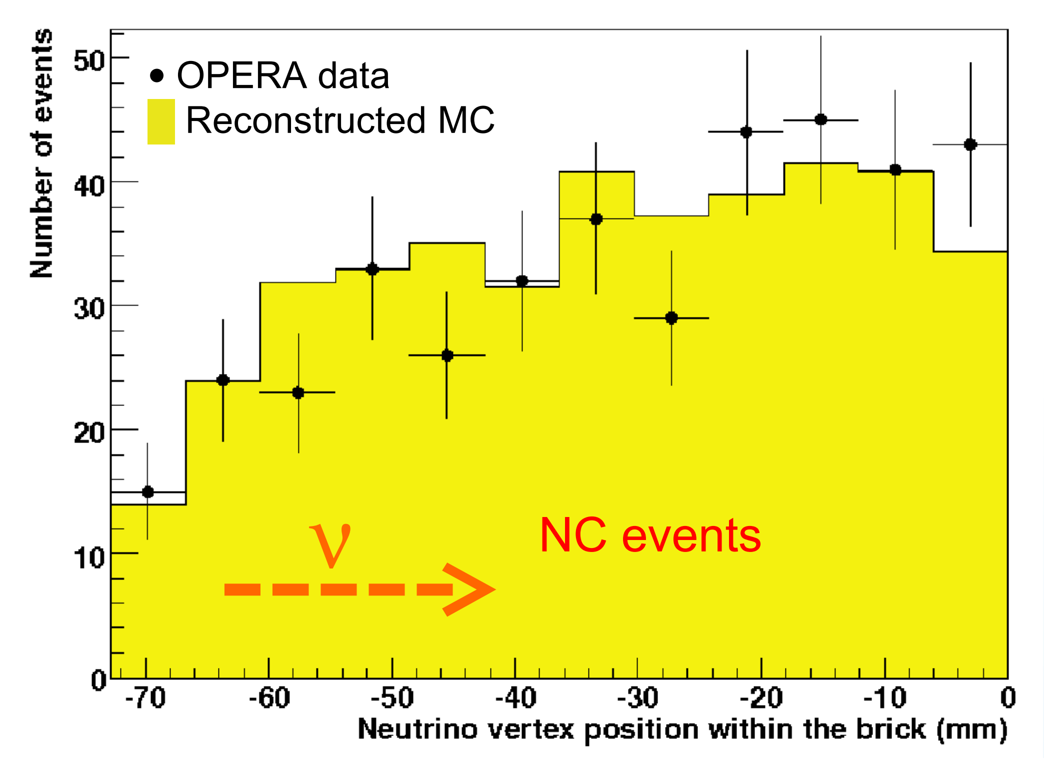
- Analysis improvements

1) Search of highly ionizing tracks in hadronic interactions (↓ bckg for $\tau \rightarrow h$)

2) Follow down of vertex tracks in the emulsion → p-range correlations → increased μ-ID efficiency →
↓ charm background
↓ hadronic bckg from ν_μ^{CC} with μ misID

3) Implementation of state-of-the art charm cross section from CHORUS (↑ σ)

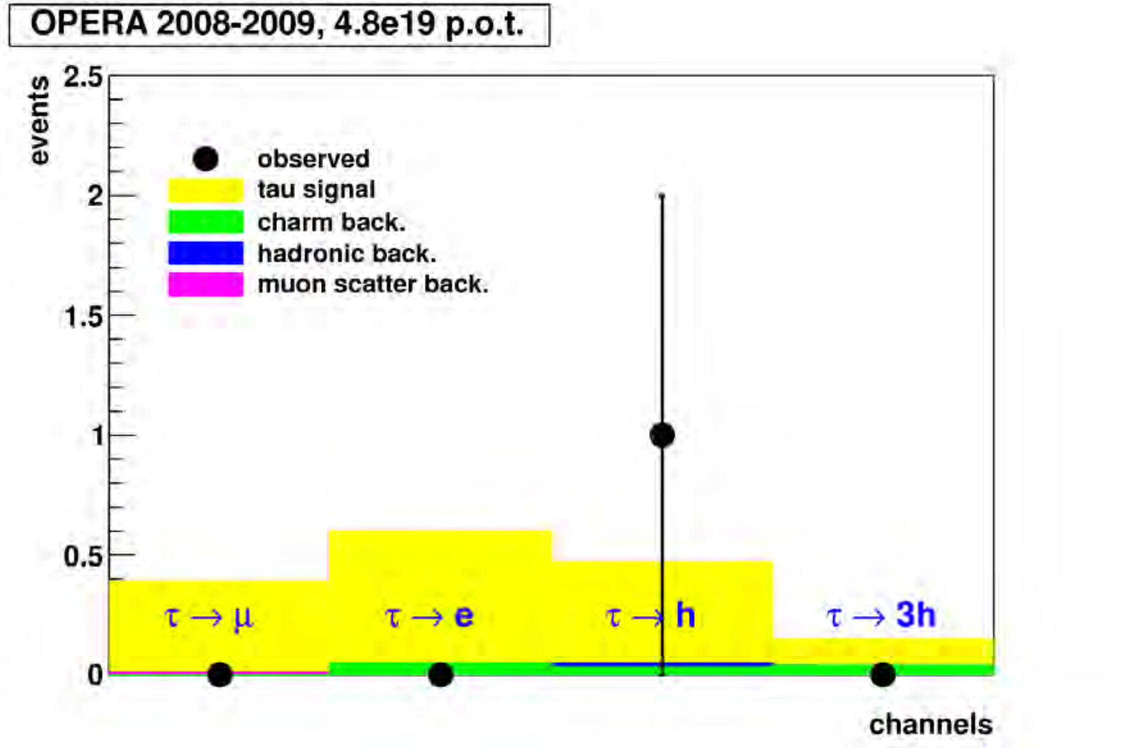
Full simulation chain with reconstruction in the emulsions



Statistics update and analysis improvements

Including all the improvements in the analysis

Decay channel	Expected signal events $\Delta m^2 = 2.5 \times 10^{-3}\ eV^2$	
	22.5 10^{19} p.o.t.	4.8 10^{19} p.o.t. (analysed)
$\tau \to \mu$	1.79	0.39
$\tau \to e$	2.89	0.63
$\tau \to h$	2.25	0.49
$\tau \to 3h$	0.71	0.15
Total	7.63	1.65



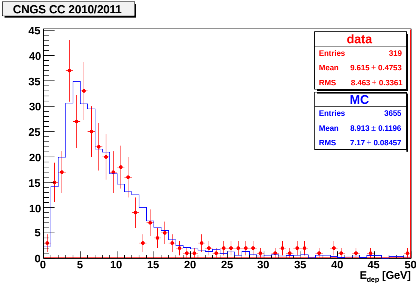
- In the analyzed sample (92% of 08/09 data)
- one ν_τ observed in the $\tau \to h$ channel compatible with the expectation of 1.65
- Expected background in $\tau \to h$: 0.05 ± 0.01 events
- Total background (considering all channels): 0.16 ± 0.03 events
- $\tau \to \mu$ is the cleanest channel

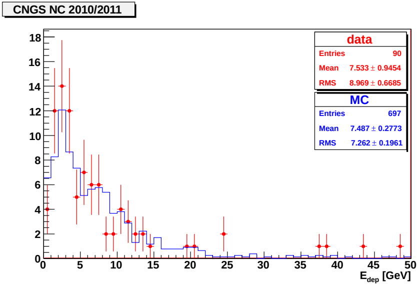
Updated S/B expectations

CNGS neutrino run in 2010-2011

	2010		2011	
Event Type	**Collected**	**Expected**	**Collected**	**Expected**
ν_μ CC	114	129	247	273
ν_μ NC	46	42	71	90
ν_e CC	1	1	-	-
$\nu XC^\star$	7	-	37	-
Total	167	171	355	363

$\star$ Events at edges, with μ track too short to be visually recognized: futher analysis needed.



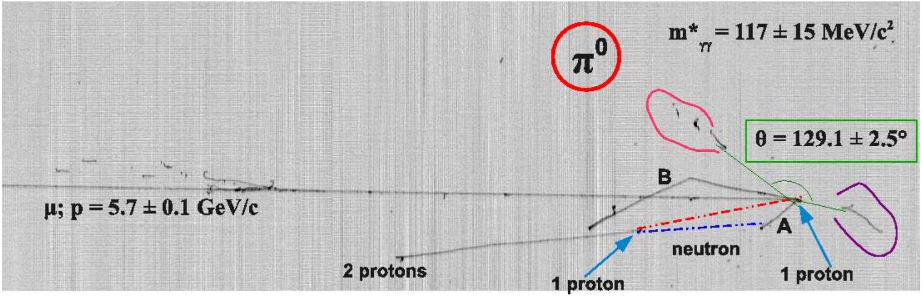


$CNGS\ CC\ \nu_\mu$ interaction

$E_{deptot} = 3.23 \pm 0.54$ GeV

1. $p_T = 78$ MeV/c
   $P_{tot} = 7$ GeV/c
2. $p_T = 154$ MeV/c
   $P_{tot} = 6.5$GeV/c

TRACK	E [MeV]	p [MeV/c]	range [cm]
A (π)	62 ± 5	145 ± 7	18
A (π)	337 ± 32	455 ± 32	18
B (π)	429 ± 36	550 ± 38	92



dE/dx for the first part of the cascades: 1.99 MeV/cm, 2.1 MeV/cm.
Conversion distances: 14.6*cm*, 61.4*cm*.

$$U^{\mathrm{D}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\vartheta_{23} \simeq \vartheta_{\mathrm{ATM}}$ $\qquad$ $\vartheta_{12} \simeq \vartheta_{\mathrm{SOL}}$

$$\Delta m^2_{21} = \left(7.65^{+0.23}_{-0.20}\right) \times 10^{-5}\,\mathrm{eV}^2 \qquad |\Delta m^2_{31}| = \left(2.40^{+0.12}_{-0.11}\right) \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2\vartheta_{12} = 0.304^{+0.022}_{-0.016} \qquad \sin^2\vartheta_{23} = 0.50^{+0.07}_{-0.06}$$

[Schwetz, Tortola, Valle, arXiv:1108.1376]

6 days ago: $\boxed{\sin^2\vartheta_{13} = 0.023 \pm 0.004}$ [Daya Bay, arXiv:1203.1669]

Previous indications of $\sin^2\vartheta_{13} > 0$: [T2K, arXiv:1106.2822], [MINOS, arXiv:1108.0015], [Double Chooz, arXiv:1112.6353]

$\vartheta_{13} \neq 0 \Longrightarrow$ CP violation, matter effects, mass hierarchy

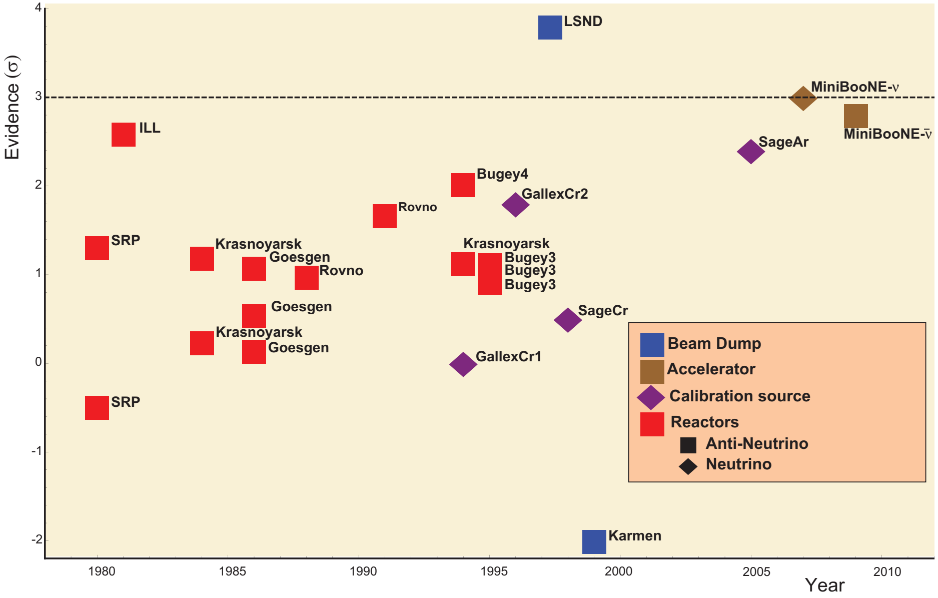
EPILOGUE

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

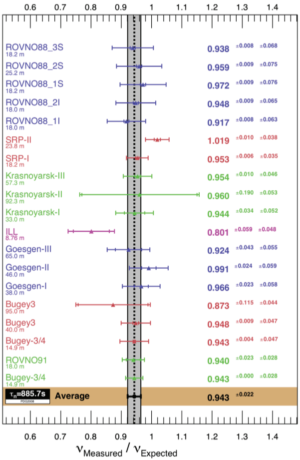
Thank you for your attention

Neutrinos: sterile

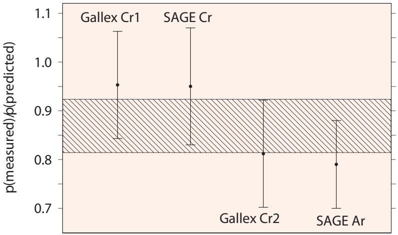
A long standing set of anomalies



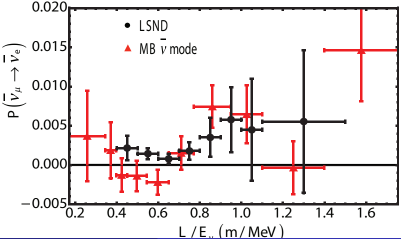
Reactors



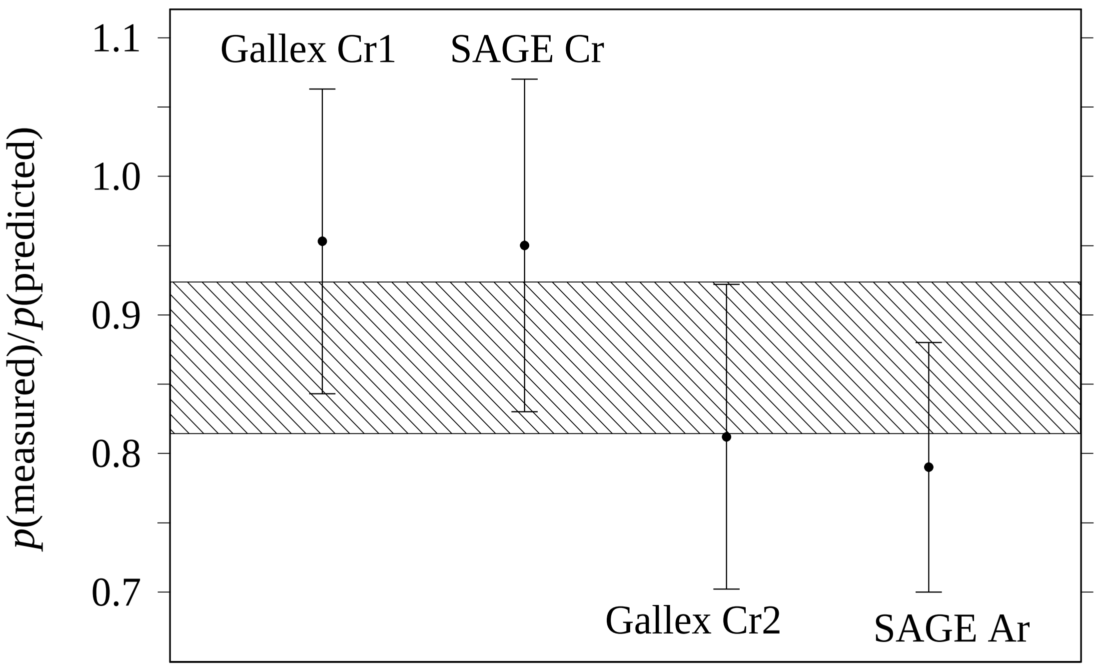
Sources



Accelerators



ν_e Disappearance in Gallium radioactive source experiments



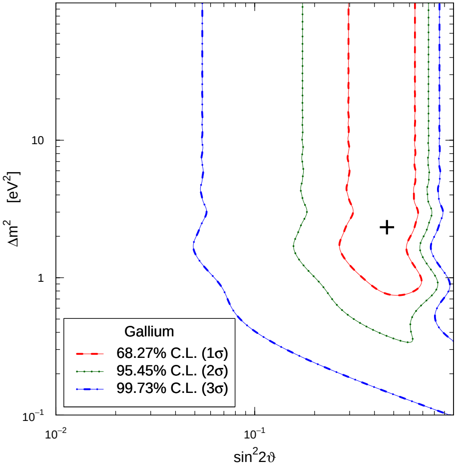
$R \equiv$ wheighted average value of the ratio of measured and predicted ^{71}Ge production rates (p) :

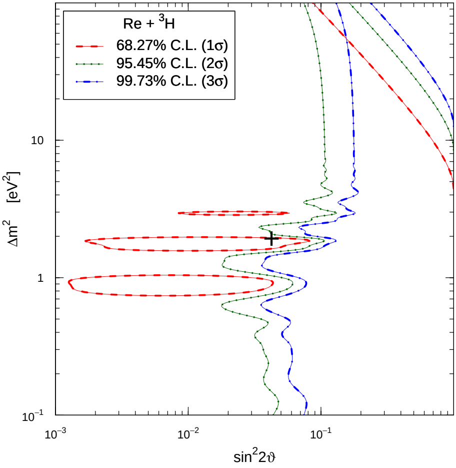
$$R \equiv \frac{\mathrm{p(measured)}}{\mathrm{p(predicted)}} = 0.87 \pm 0.05$$

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]

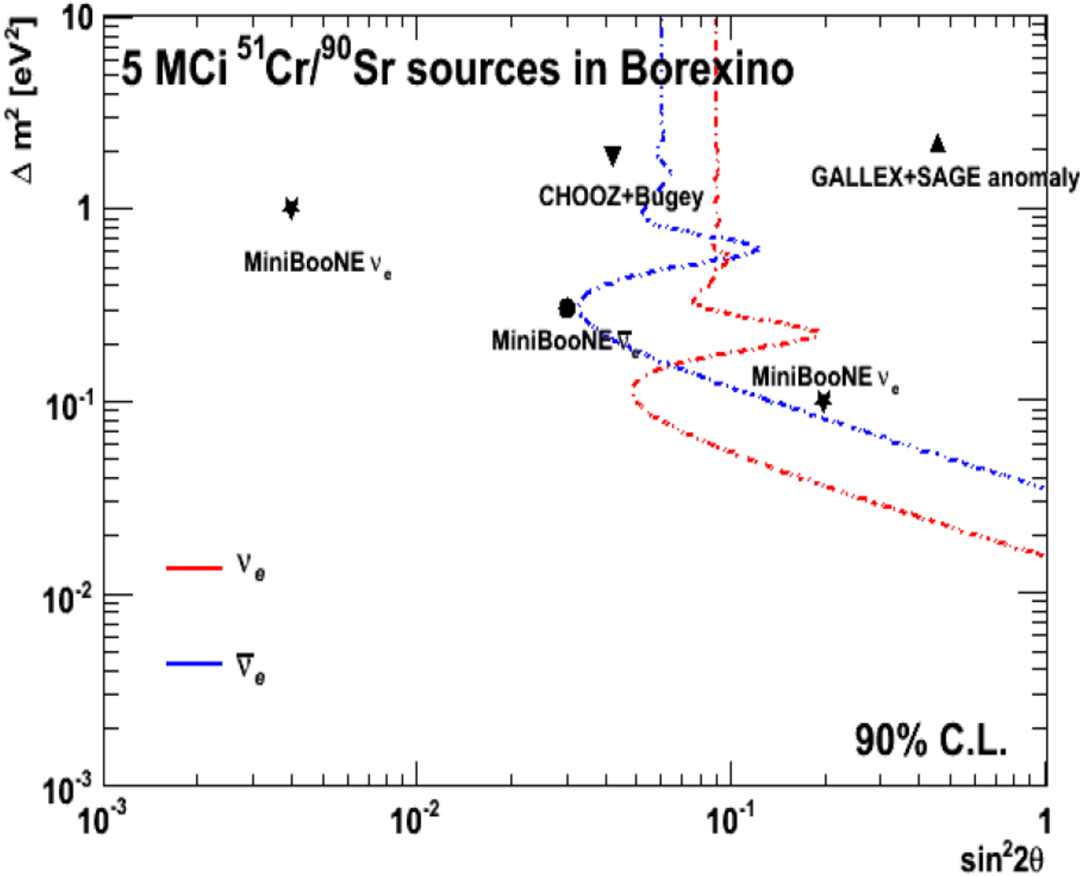
$\Delta m^2_{\mathrm{SBL}} \gtrsim 1\,\mathrm{eV}^2$ is OK, but $\sin^2 2\vartheta_{\nu} > \sin^2 2\vartheta_{\bar{\nu}}$

Parameter Goodness of Fit = 0.2%

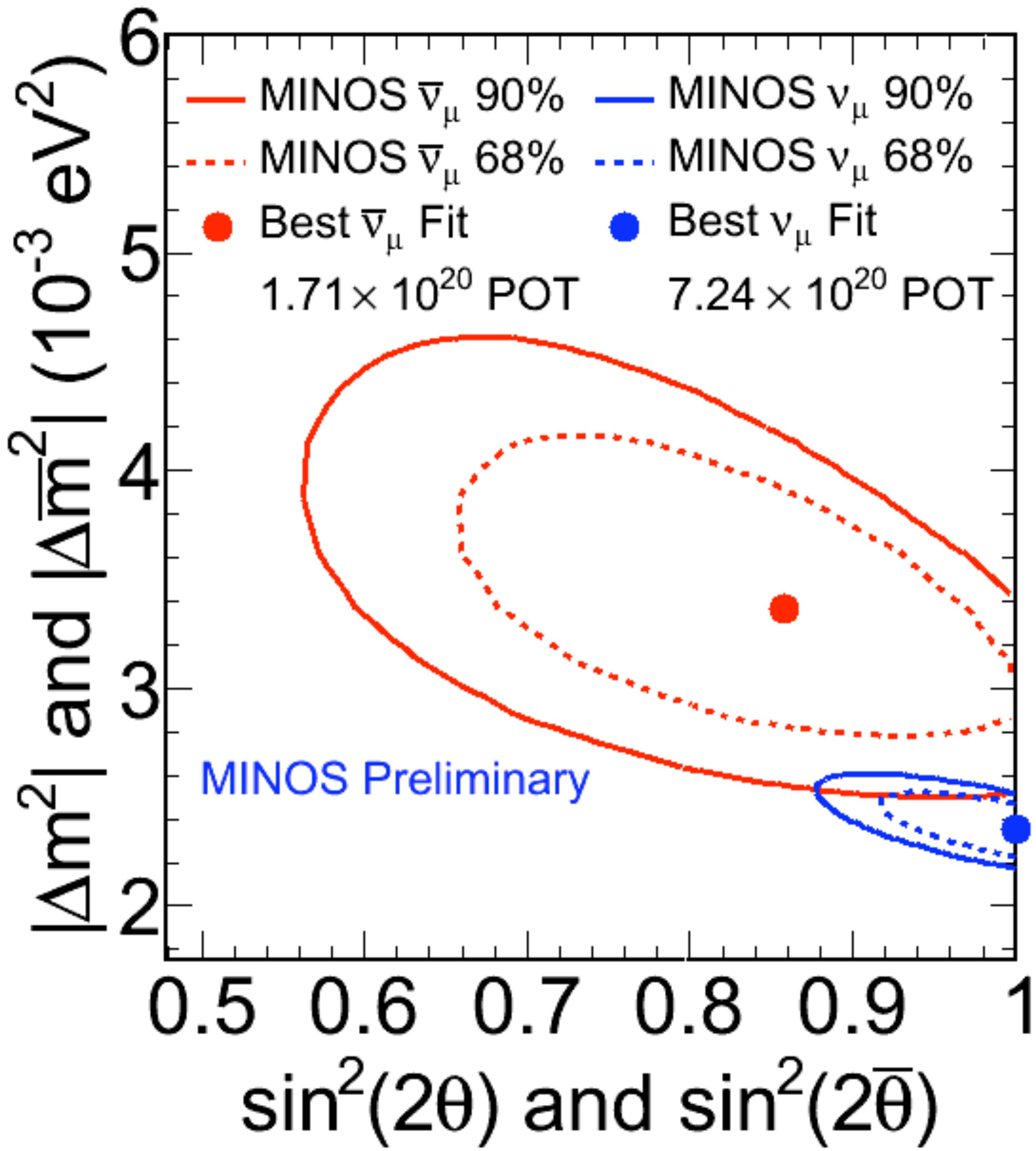
CPT violation? [Giunti, Laveder, PRD 82 (2010) 113009, arXiv:1008.4750]

Borexino test exp

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



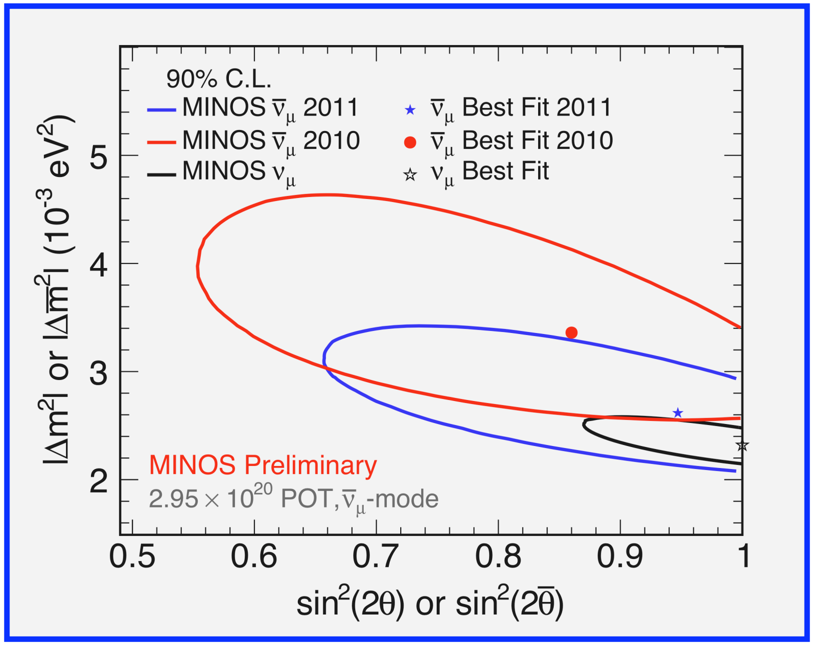
[A. Ianni, Private Communication]



- 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

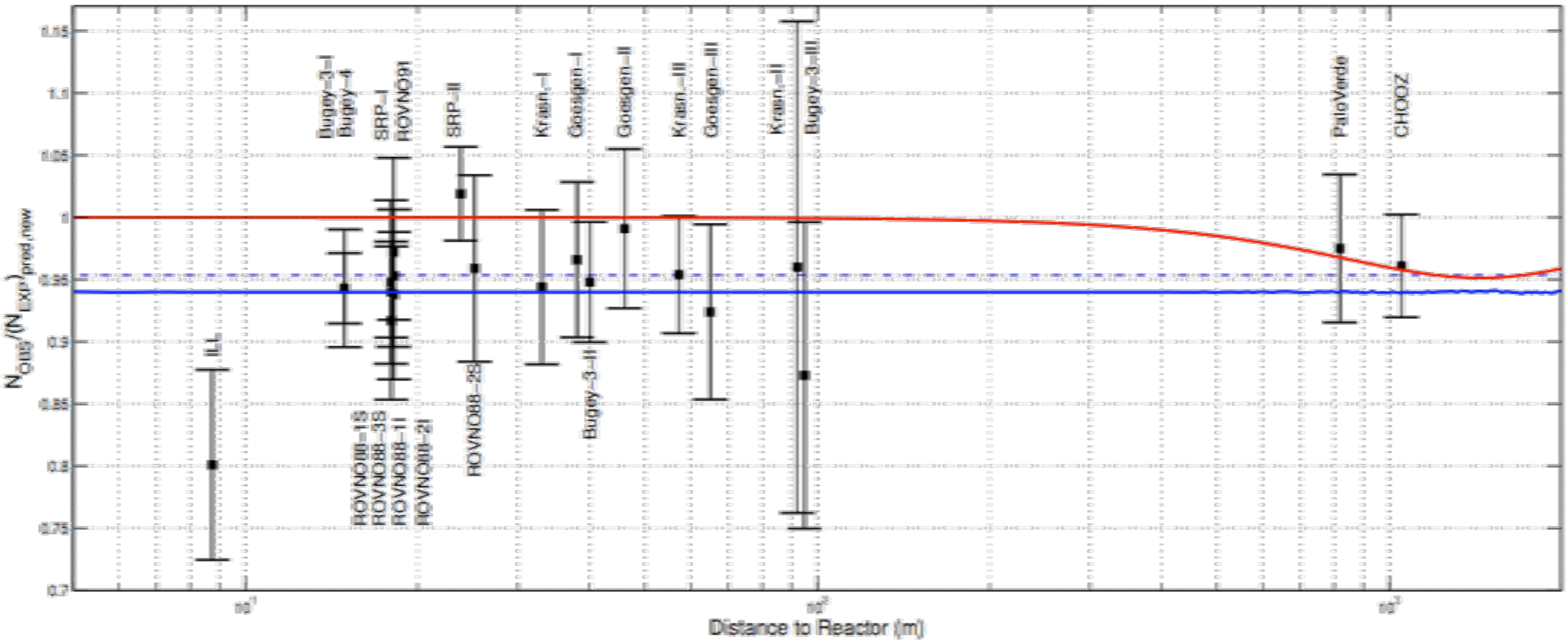
Footnote:

MINOS neutrino/antineutrino anomaly…



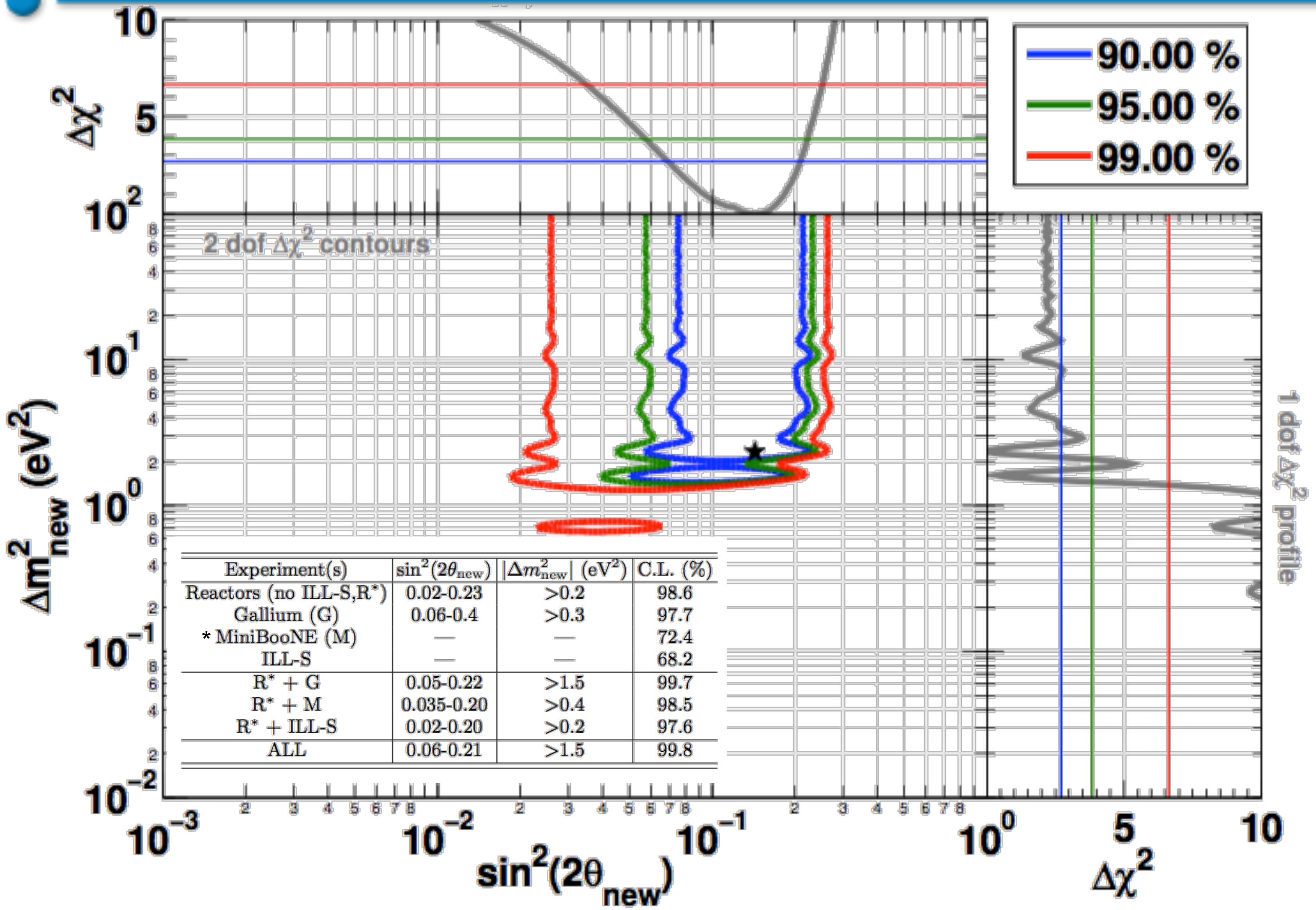
…does not show up in 2011 data!

The Reactor Antineutrino Anomaly and implications



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

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



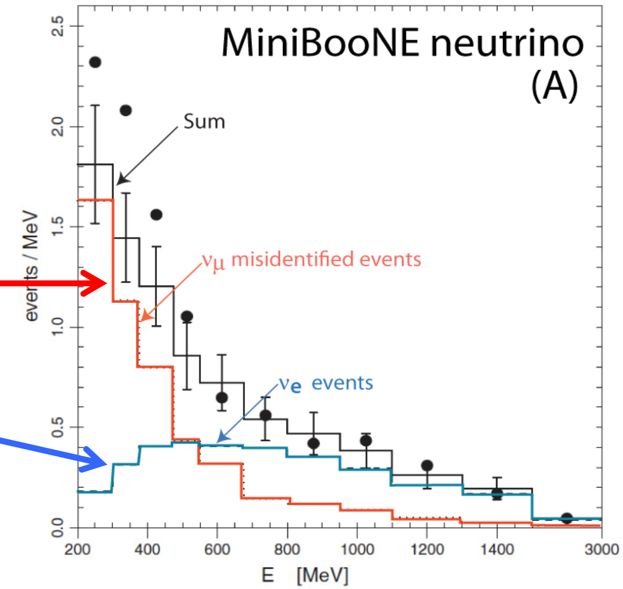
Experiment(s)	$\sin^2(2\theta_{new})$	$\lvert\Delta m^2_{new}\rvert$ (eV^2)	C.L. (%)
Reactors (no ILL-S,R*)	0.02-0.23	>0.2	98.6
Gallium (G)	0.06-0.4	>0.3	97.7
* MiniBooNE (M)	—	—	72.4
ILL-S	—	—	68.2
R* + G	0.05-0.22	>1.5	99.7
R* + M	0.035-0.20	>0.4	98.5
R* + ILL-S	0.02-0.20	>0.2	97.6
ALL	0.06-0.21	>1.5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

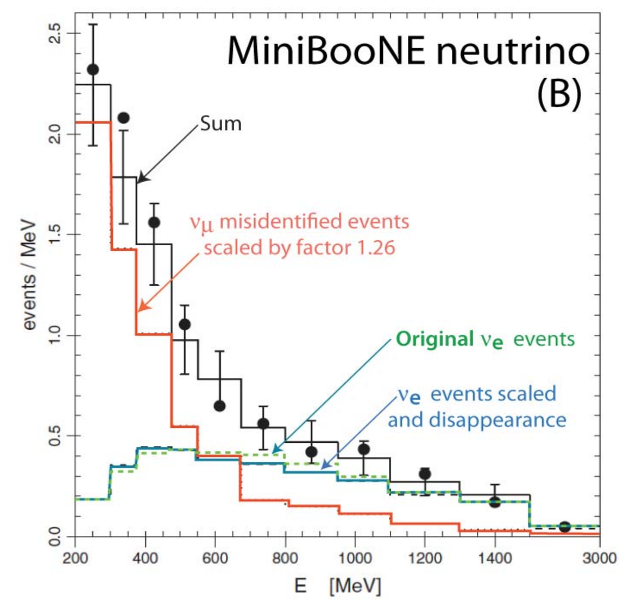
The no-oscillation hypothesis is disfavored at 99.8% CL

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

The neutrino run

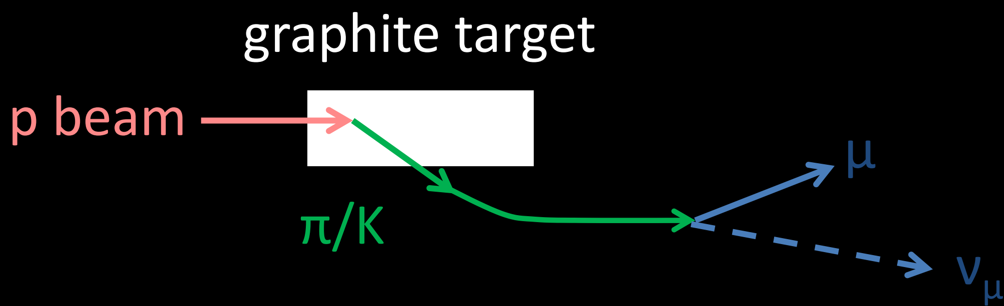
- (A) electron-like neutrino data. Comparison between the data (black dots) and the calculated distributions due to misidentified ν_μ events (red) and genuine ν_e events (blue). The sum is indicated in black. One notices an anomaly at low energies, which is incompatible with LNSD predictions.
- (B) according 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.





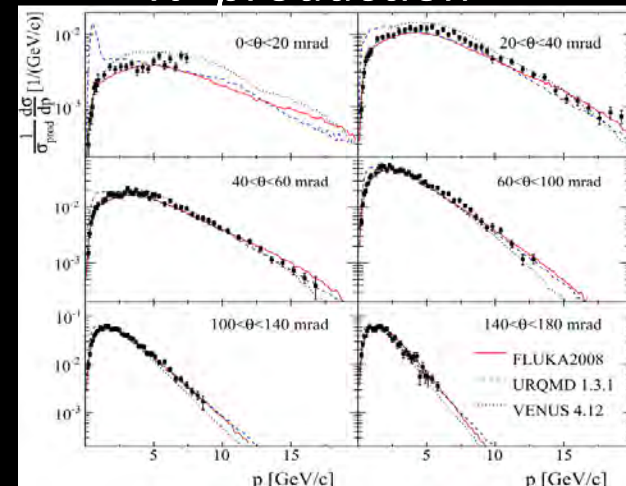
Estimation/Measurement of Neutrino Flux

Estimation of neutrino flux



The estimation is based on the measurement of π/K production in p+Carbon(target) interactions in the NA61 experiment (5-10% errors)

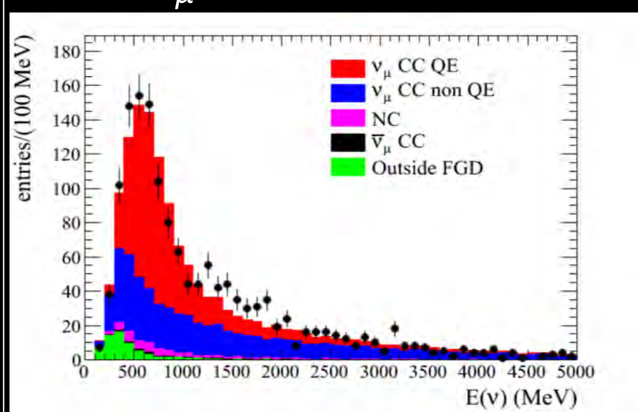
π^+ production



Phys. Rev. C84:034604 (2011)

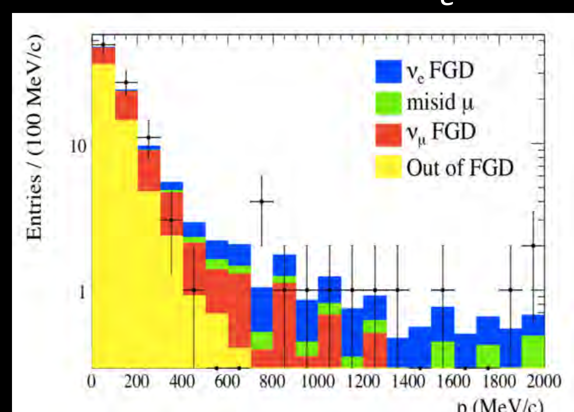
ND280 measurements

ν_μ energy spectrum



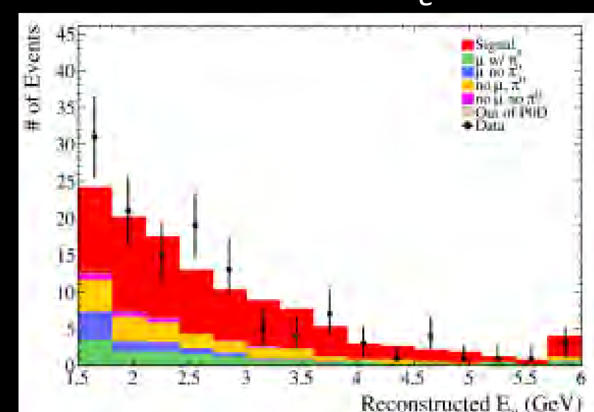
Data/MC = 1.036±0.028(stat.) +0.044-0.037(syst.) ±0.39(phys.)

e momentum with ν_e selection



Data/MC =0.6 ±0.4(stat.)±0.2(syst.)

Recon. $E\nu_e$



Data/MC =1.19 ±0.15(stat.)±0.26(syst.)

Intermezzo sulla fisica di Majorana

Natura del neutrino

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

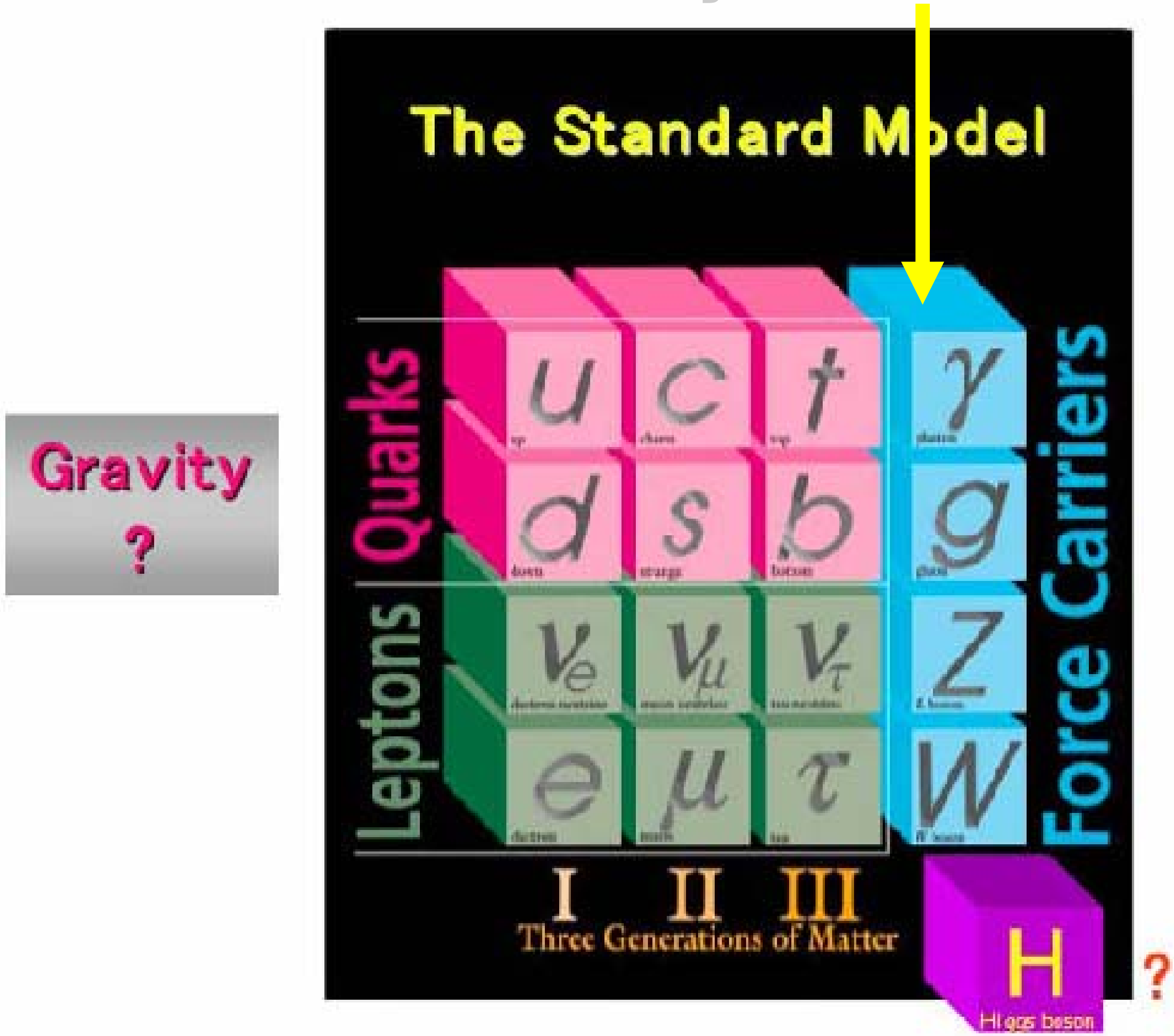
TEORIA SIMMETRICA DELL'ELETTRONE E DEL POSITRONE

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



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

TEORIA SIMMETRICA DELL' ELETTRONE E DEL POSITRONE

Nota di ETTORE MAJORANA

$$H = \sum_{\gamma} c\sqrt{m^2c^2 + h^2\gamma^2} \sum_{r=1}^{2} \left[n_r(\gamma) - \frac{1}{2} \right], \tag{22}$$

Queste formole sono completamente analoghe, salvo la diversa statistica, a quelle che si ottengono dalla quantizzazione delle equazioni di Maxwell. In luogo di quanti immateriali si hanno particelle con una massa di riposo finita e anche esse con due possibilità di polarizzazione. Anche qui *come nel caso della radiazione*, sono presenti i mezzi quanti di riposo della energia e della quantità di moto, salvo che il loro segno è opposto in apparente relazione con la diversa statistica. Essi non costituiscono pertanto una difficoltà specifica e allo stato attuale della teoria debbono anche qui essere considerati come semplici costanti addittive prive di significato.

TEORIA RELATIVISTICA DI PARTICELLE CON MOMENTO INTRINSECO ARBITRARIO

Nota di ETTORE MAJORANA

(1932)

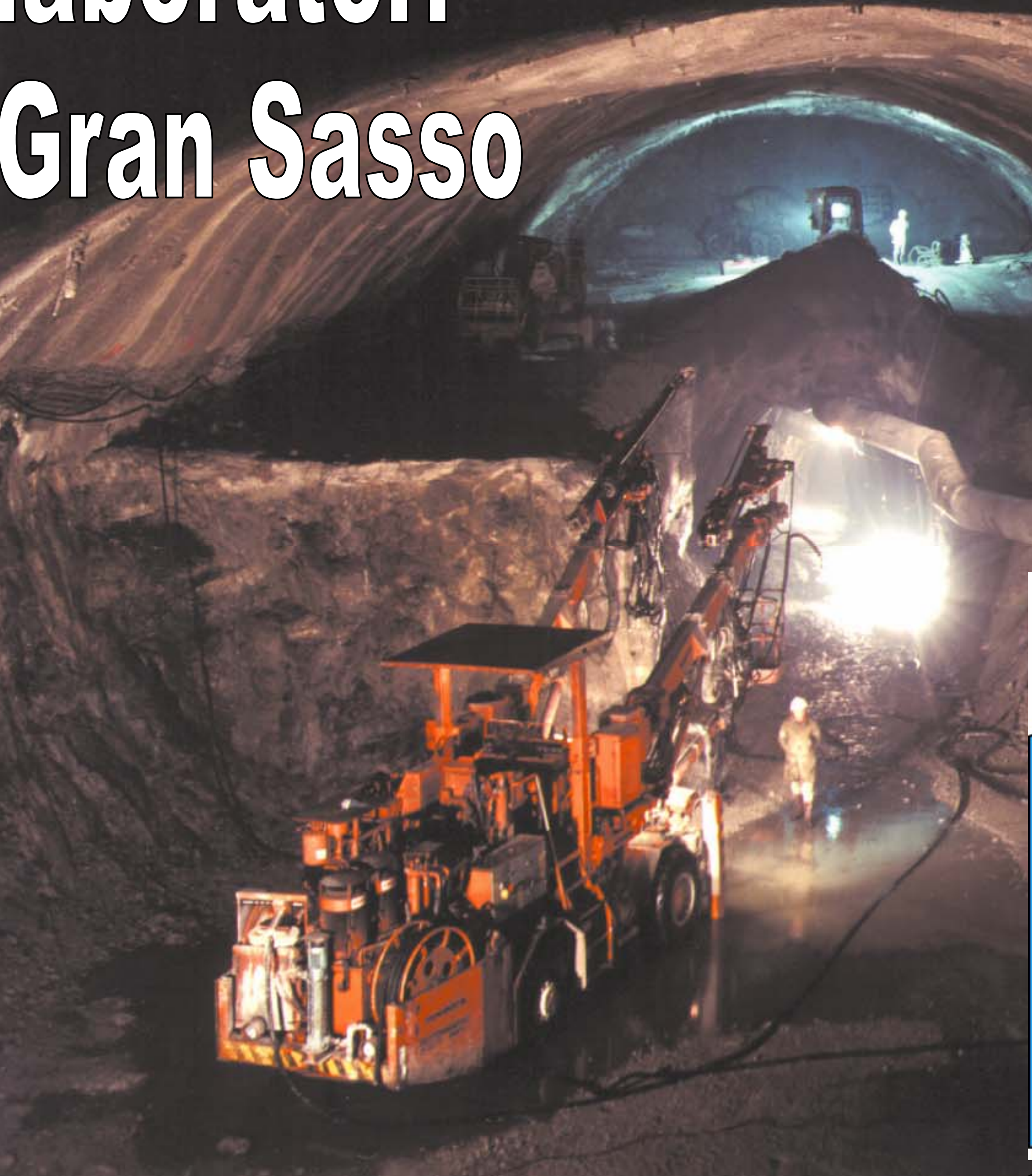
Sunto. - *L'autore stabilisce equazioni d'onda lineari nell'energia e relativisticamente invarianti per particelle aventi momento angolare intrinseco comunque prefissato.*

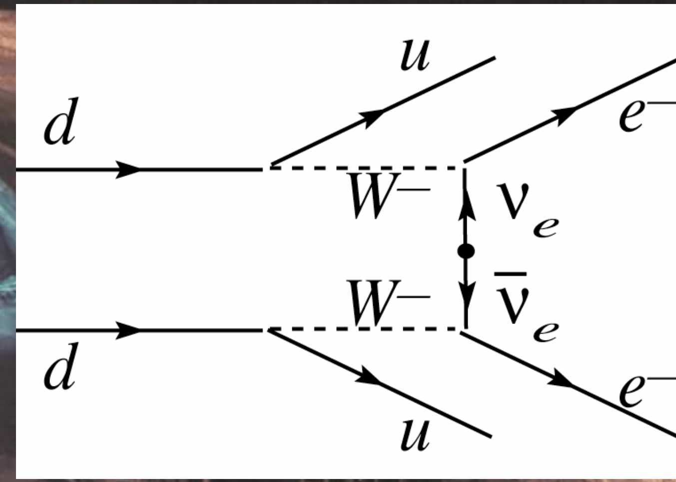
Quando si cercano le soluzioni di (16) corrispondenti a onde piane con massa positiva si trovano tutte quelle che derivano per trasformazione relativistica dalle onde di momento nullo. Per queste l'energia è data da

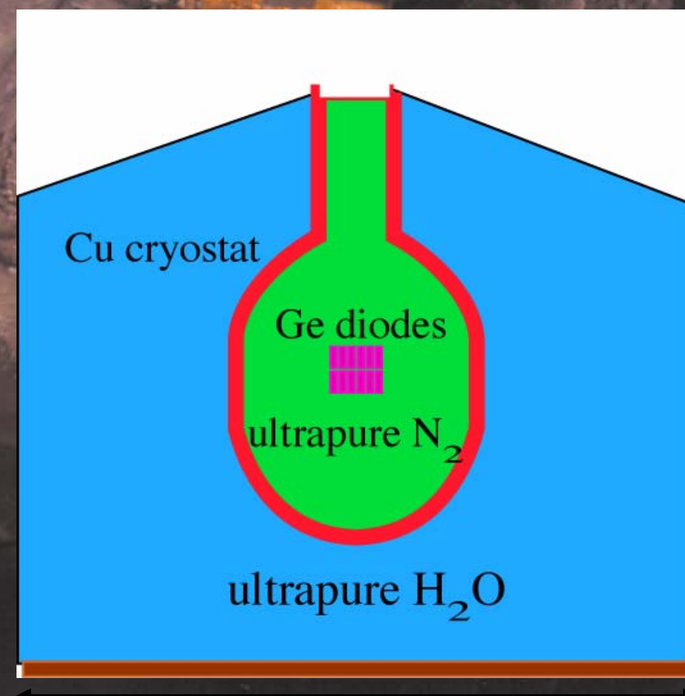
$$W_0 = \frac{mc^2}{j + \frac{1}{2}} \tag{18}$$

Massa dell' "Higgs" (J=0) = 3 volte la massa del bosone Z(J=1) → 273 GeV !!!

laboratori Gran Sasso



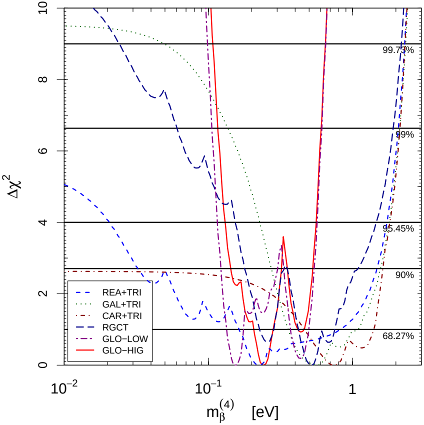




Testable Implications

[Giunti, Laveder, PLB 706 (2011) 200, arXiv:1111.1069]

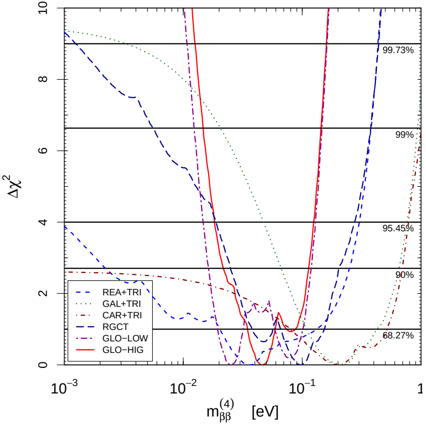
β Decay



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

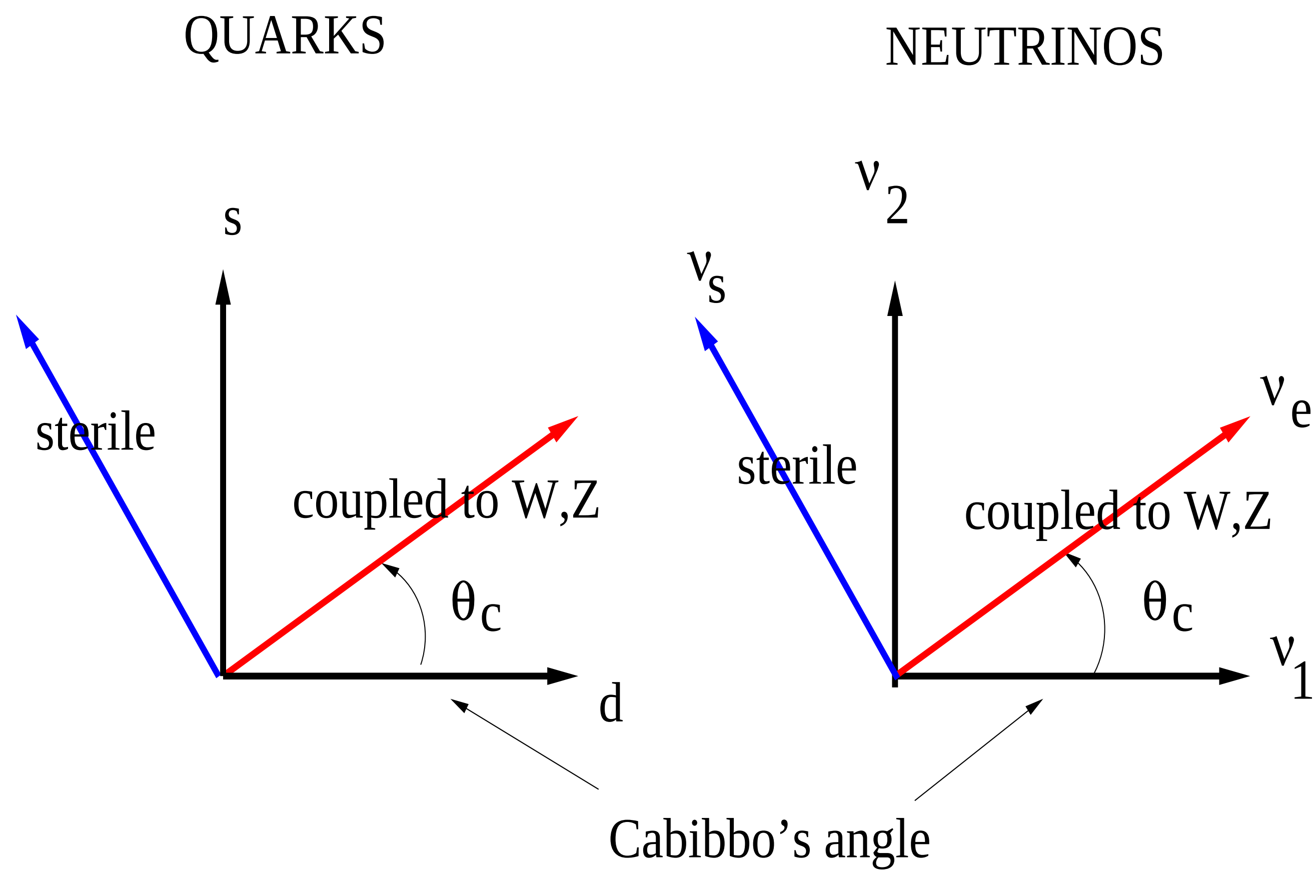
$$m_\beta^{(4)} = |U_{e4}| \sqrt{\Delta m^2_{41}}$$

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



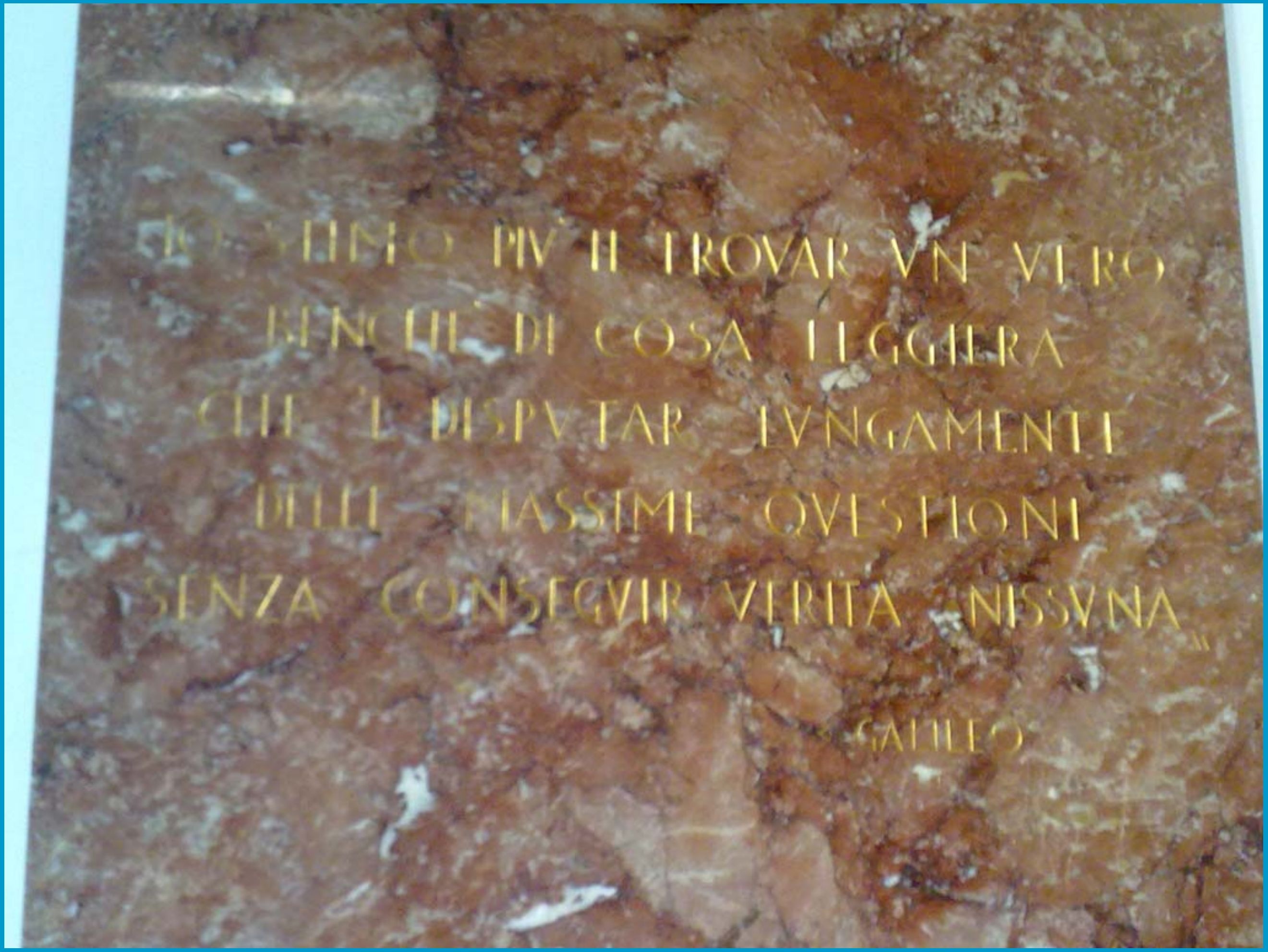
$$m_{\beta\beta} = \left|\sum_k U_{ek}^2 \, m_k\right|$$

$$m_{\beta\beta}^{(4)} = |U_{e4}|^2 \sqrt{\Delta m^2_{41}}$$



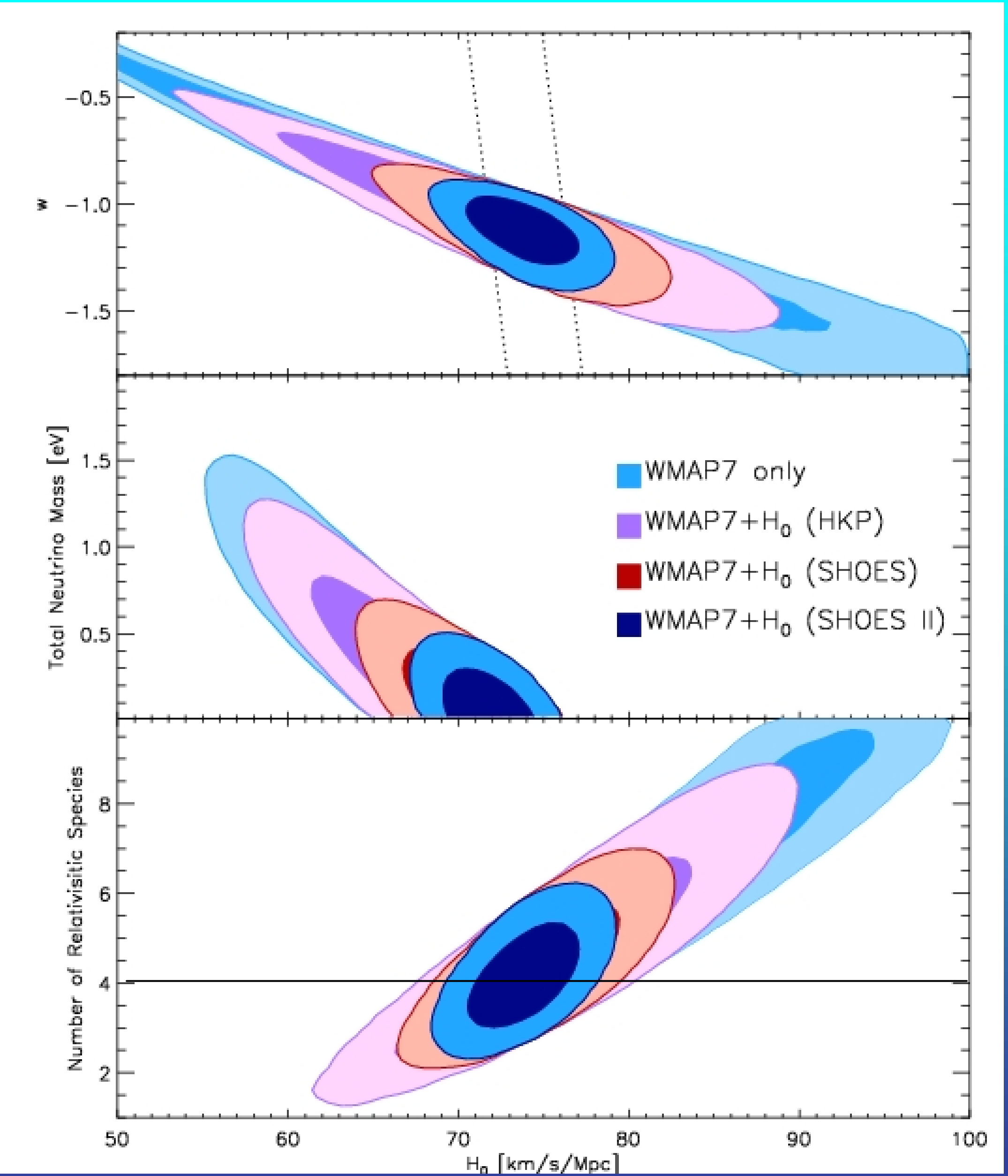
COMPLEMENTARITY relation :

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



Quale relazione tra il Neutrino di Majorana e la Dark Matter ?

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



Sciencexpress

Signatures of Majorana Fermions in Hybrid Superconductor-Semiconductor Nanowire Devices

V. Mourik,[1*] K. Zuo,[1*] S. M. Frolov,[1] S. R. Plissard,[2] E. P. A. M. Bakkers,[1,2] L. P. Kouwenhoven[1]†

[1]Kavli Institute of Nanoscience, Delft University of Technology, 2600 GA Delft, Netherlands.

[2]Department of Applied Physics, Eindhoven University of Technology, 5600 MB Eindhoven, Netherlands.

*These authors contributed equally to this work.

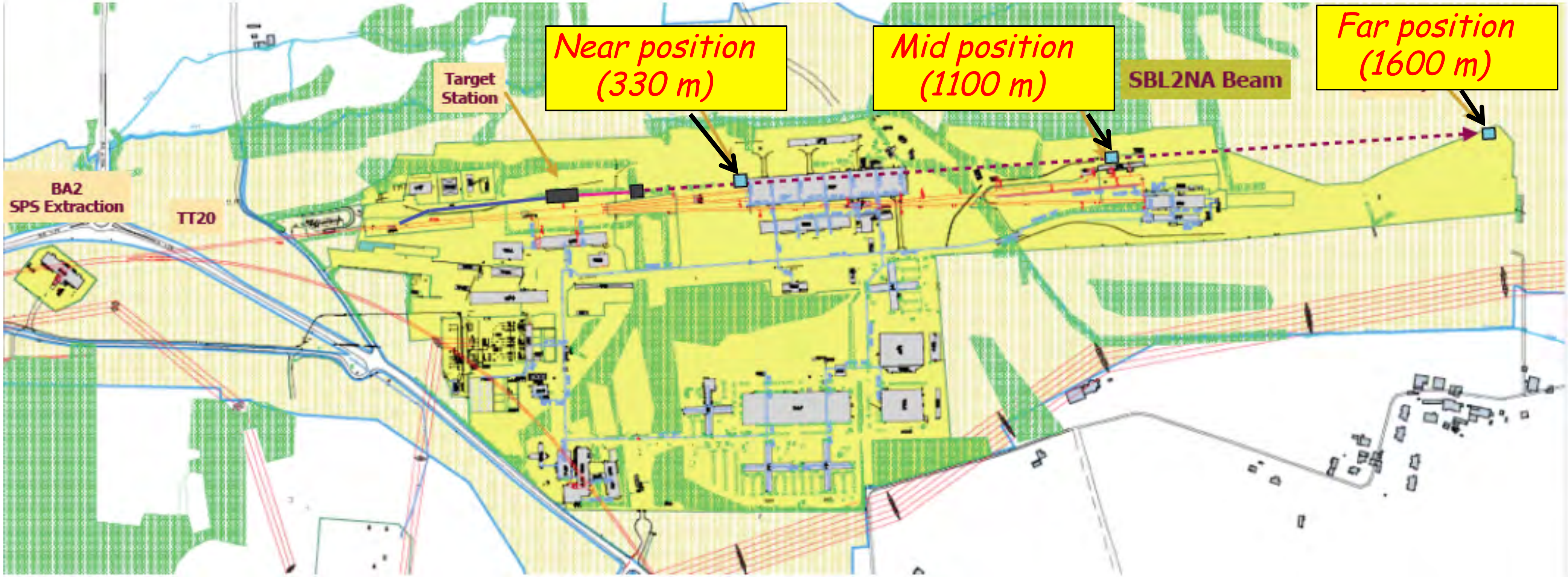
†To whom correspondence should be addressed. E-mail: l.p.kouwenhoven@tudelft.nl

Majorana fermions are particles identical to their own antiparticles. They have been theoretically predicted to exist in topological superconductors. We report electrical measurements on InSb nanowires contacted with one normal (Au) and one superconducting electrode (NbTiN). Gate voltages vary electron density and define a tunnel barrier between normal and superconducting contacts. In the presence of magnetic fields of order 100 mT we observe bound, mid-gap states at zero bias voltage. These bound states remain fixed to zero bias even when magnetic fields and gate voltages are changed over considerable ranges. Our observations support the hypothesis of Majorana fermions in nanowires coupled to superconductors.

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

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

New Neutrino Facility in the CERN North Area

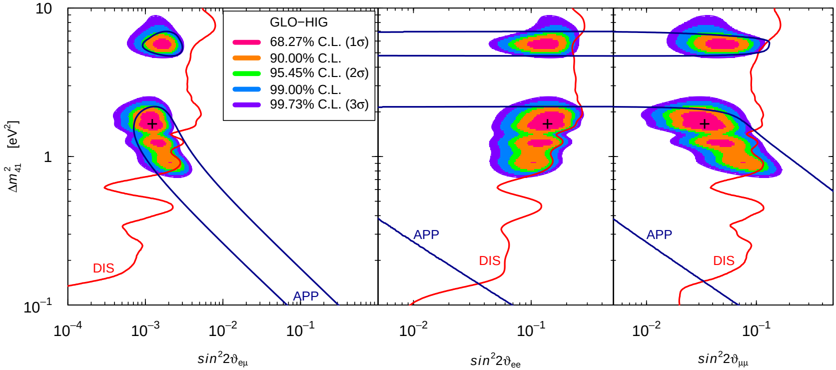


100 GeV primary beam fast extracted from SPS; target station next to TCC2; decay pipe l =100m, ø = 3m; beam dump: 15m of Fe with graphite core, followed by μ stations.
Neutrino beam angle: pointing upwards; at -3m in the far detector ~5mrad slope.

Global 3+1 Fit of SBL Data

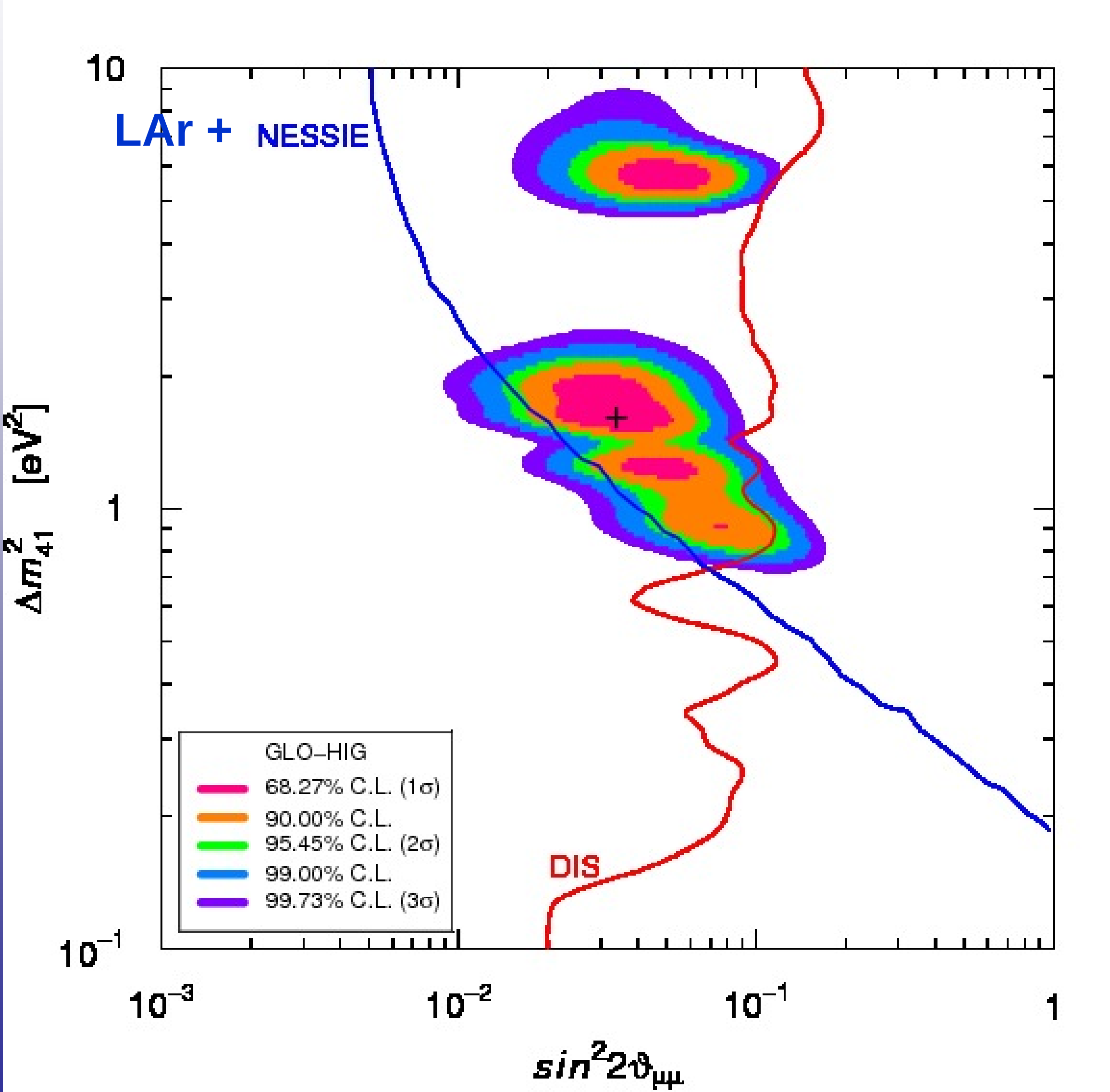
[Giunti, Laveder, arXiv:1109.4033, arXiv:1111.1069]

- Simplest scheme beyond standard three-neutrino mixing which can partially explain the data.
- It corresponds to the natural addition of one new entity (a sterile neutrino) to explain a new effect (short-baseline oscillations).



Best fit: $\Delta m^2_{41} \approx 1.6\,\text{eV}^2 \quad \Longrightarrow \quad m_4 \approx 1.3\,\text{eV}$

LAr + NESSiE ν_μ disappearance

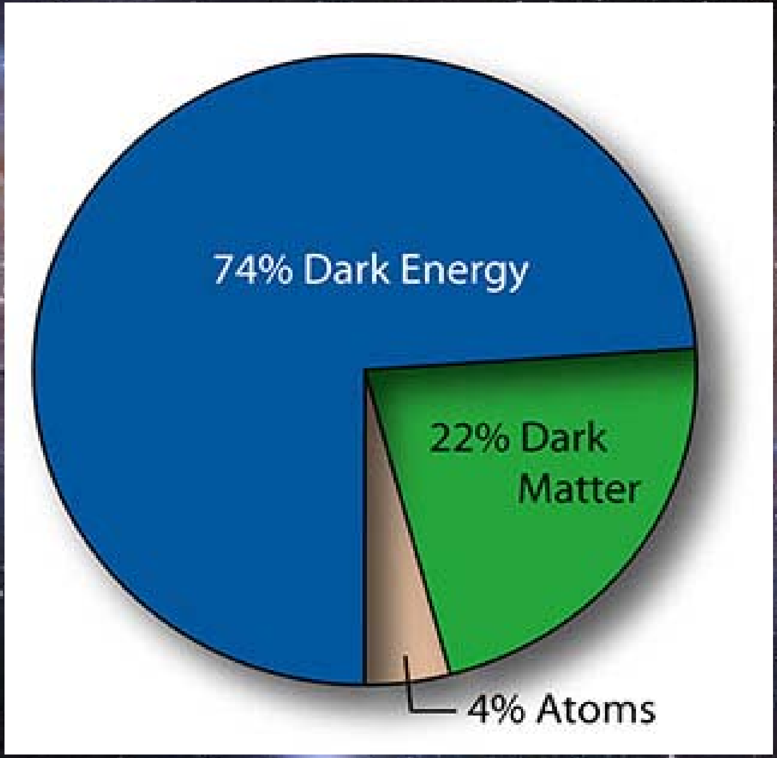


GRAZIE Milla !!!

BEYOND STANDARD MODEL : spin 0 composite particle

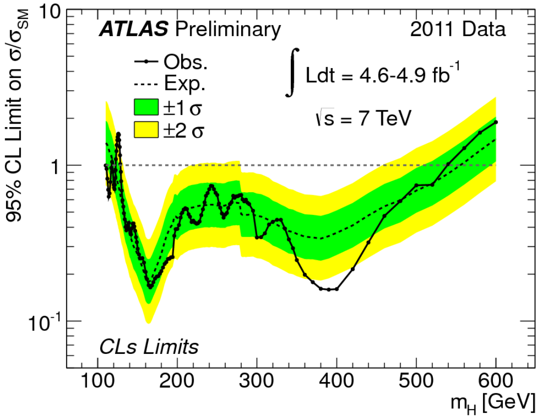
massive Majorana neutrinos

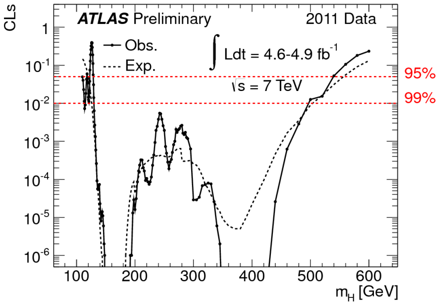
massive Dirac neutrinos



STANDARD MODEL : SM HIGGS BOSON

massless neutrinos

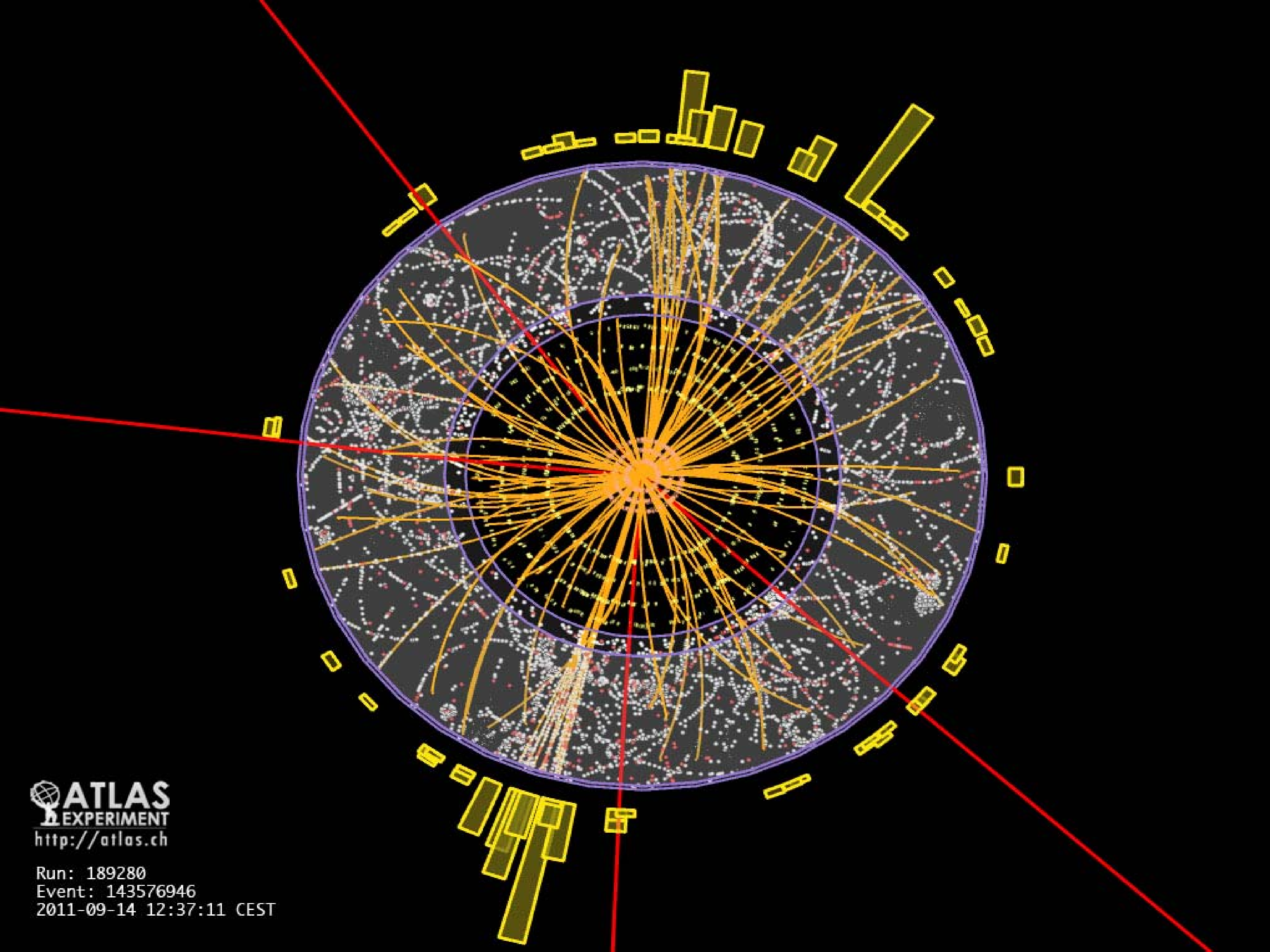




Expected exclusion at 95% CL: 120-555 GeV

Observed exclusion at 95% CL: 110-117.5, 118.5-122.5, 129-539 GeV

Observed exclusion at 99% CL: 130-486 GeV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