ICARUS Report to the June 2011 SPS-C

Carlo Rubbia

CERN, Geneva, Switzerland
LNGS, INFN, Assergi, Italy

The present ICARUS Collaboration

M. Antonello, P. Aprili, N. Canci, C. Rubbia, E. Scantamburlo, E. Segreto, C. Vignoli
Laboratori Nazionali del Gran Sasso dell’ INFN, Assergi (AQ), Italy

B. Baibussinov, M. BaldoCeolin, S. Centro, D. Dequal, C. Farnese, A. Fava, D. Gibin, A. Guglielmi, G. Meng, F. Pietropaolo, F. Varanini, S. Ventura
Dipartimento di Fisica e INFN, Università di Padova, Via Marzolo 8, I-35131, Padova, Italy

P. Benetti, E. Calligarich, R. Dolfini, A. Gigli Berzolari, A. Menegolli, C. Montanari, A. Rappoldi, G. L. Raselli, M. Rossella
Dipartimento di Fisica Nucleare e Teorica e INFN, Università di Pavia, Via Bassi 6, I-27100, Pavia Italy

F. Carbonara, A. G. Cocco, G. Fiorillo
Dipartimento di Scienze Fisiche, INFN e Università Federico II, Napoli, Italy

A. Cesana, P. Sala, A. Scaramelli, M. Terrani
INFN, Sezione di Milano e Politecnico, Via Celoria 2, I-20123

K. Cieslik , A. Dabrowska, M. Haranczyk , D. Stefan , M. Szarska ,T. Wachala ,A. Zalewska
The Henryk Niewodniczanski, Institute of Nuclear Physics, Polish Academy of Science, Krakow, Poland

D. B. Cline, S. Otwinowski, H.-G. Wang, X. Yang
Department of Physics and Astronomy, University of California, Los Angeles, USA

A.Dermenev, S. Gninenko, M. Kirsanov
INR RAS, prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russia

A. Ferrari
CERN, Ch1211 Geneve 23, Switzerland

T. Golan , J. Sobczyk ,J. Zmuda
Institute of Theoretical Physics, Wroclaw University, Wroclaw, Poland

J. Holeczek ,J. Kisiel , I. Kochanek, S. Mania
Institute of Physics, University of Silesia, 12 Bankowa st., 40-007 Katowice, Poland

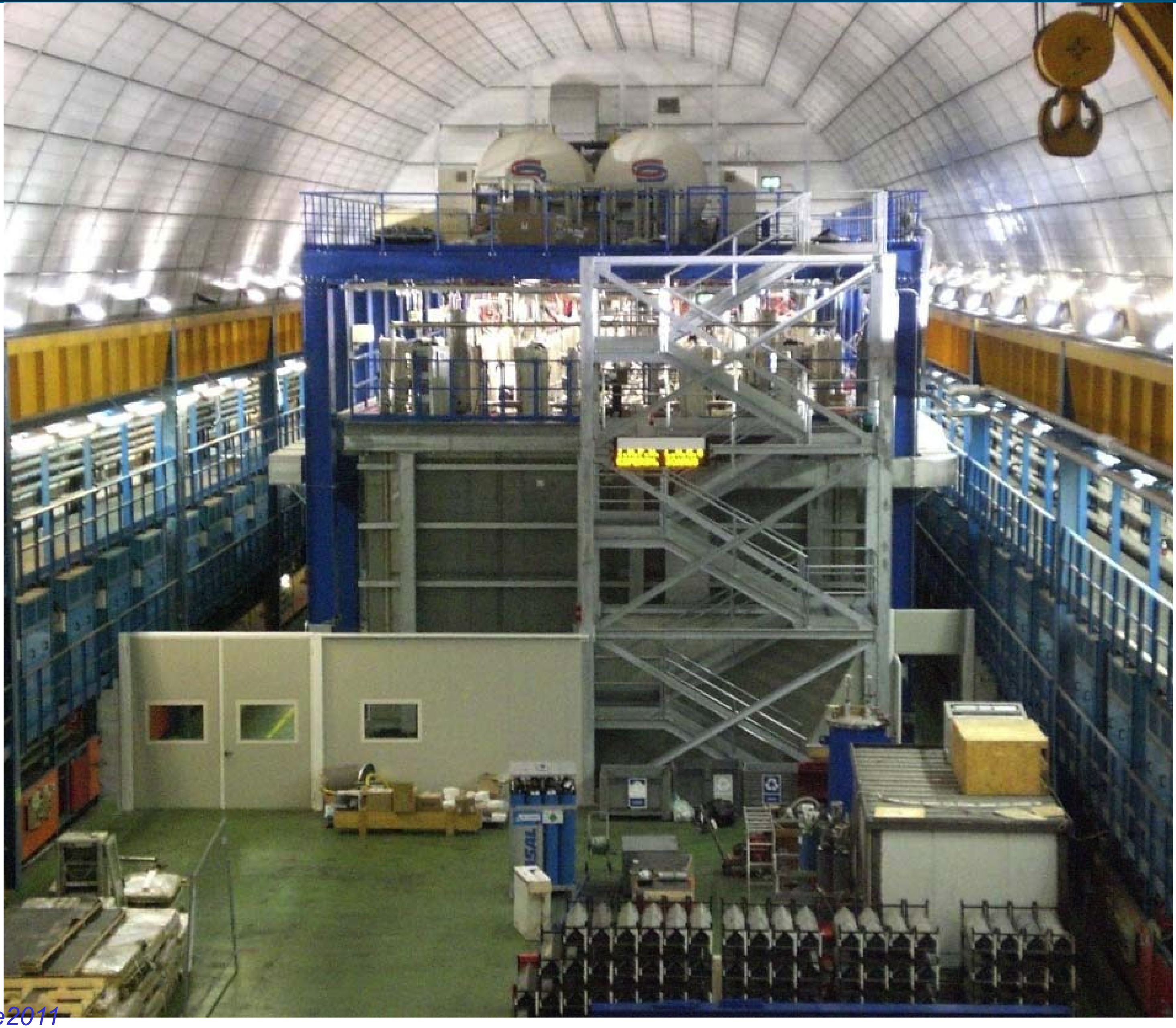
J. Lagoda , T. J. Palczewski ,P. Przewlocki ,J. Stepaniak ,R. Sulej
A. Soltan Institute for Nuclear Studies, 05-400 Swierk/Otwock, Warszawa, Poland

G. Mannocchi, L. Periale, P. Picchi,
Laboratori Nazionali di Frascati (INFN), Via Fermi 40, I-00044, Italy

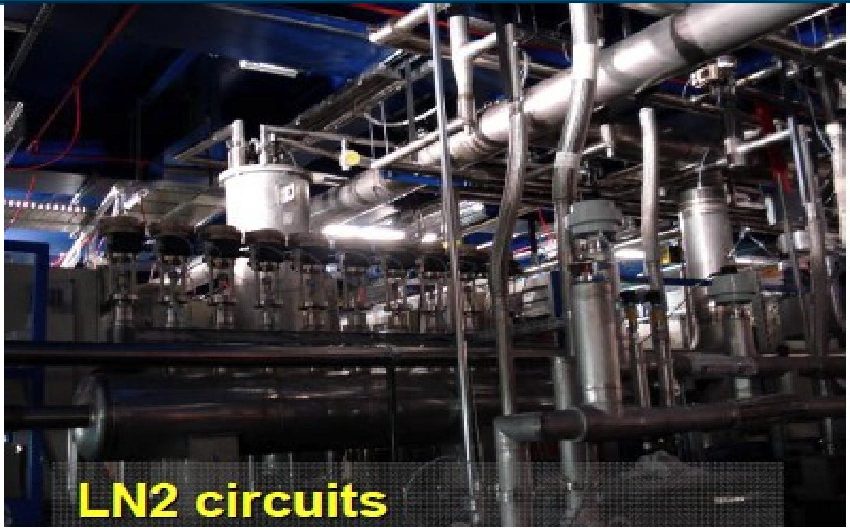
P. Plonski , K. Zaremba
Institute for Radioelectronics, Warsaw Univ. of Technology Pl. Politechniki 1, 00-661 Warsaw, Poland

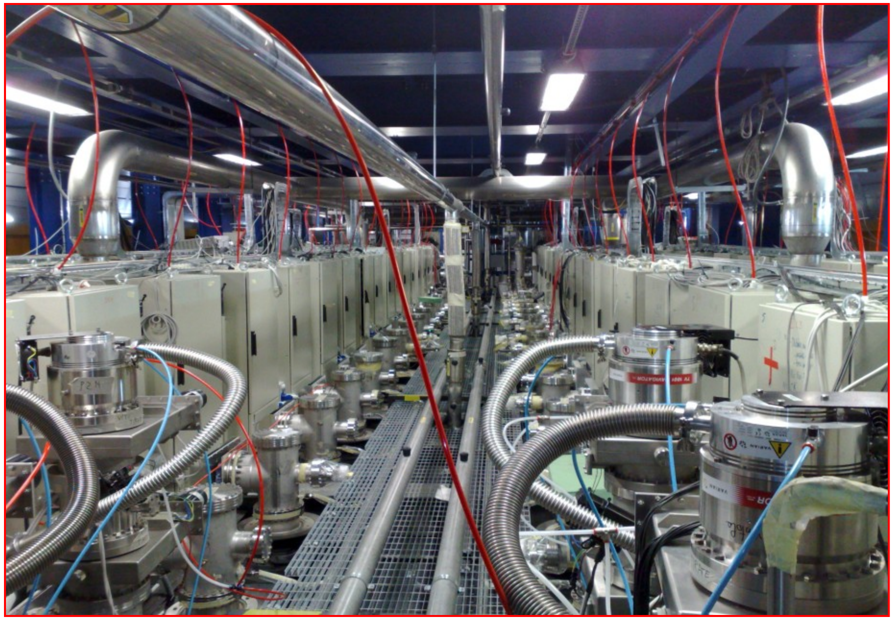
F. Sergiampietri
Dipartimento di Fisica, Università di Pisa, Largo Bruno Pontecorvo 3, I-56127, Pisa, Italy

The ICARUS detector in underground Hall B of LNGS



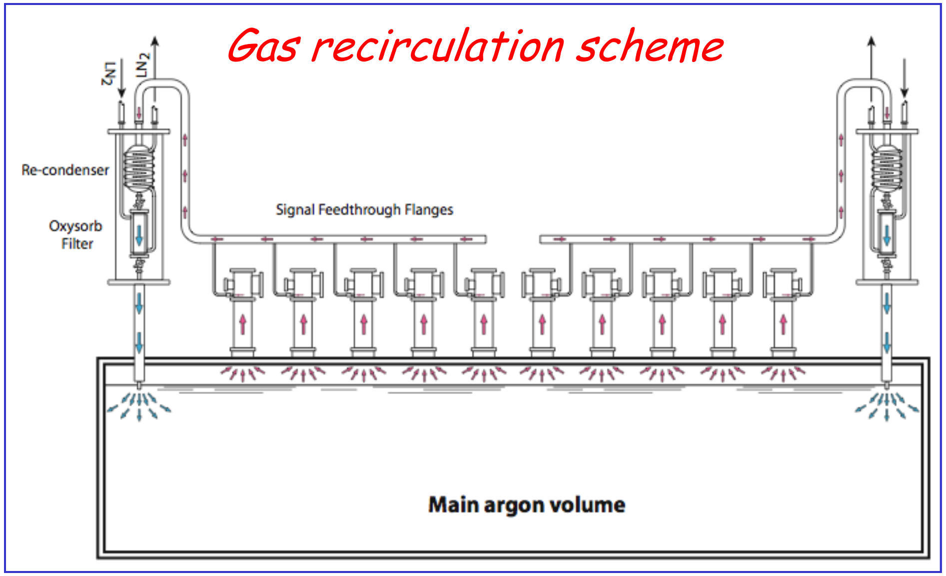
T600 in hall B (CNGS2-2010)

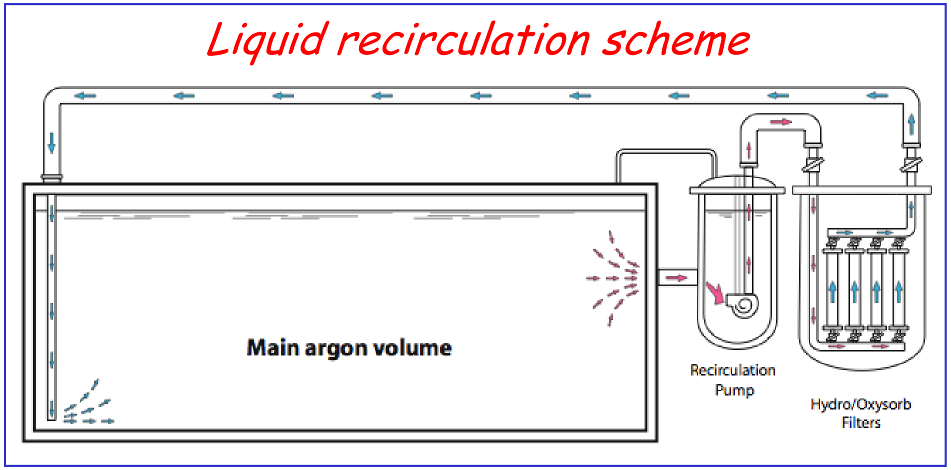




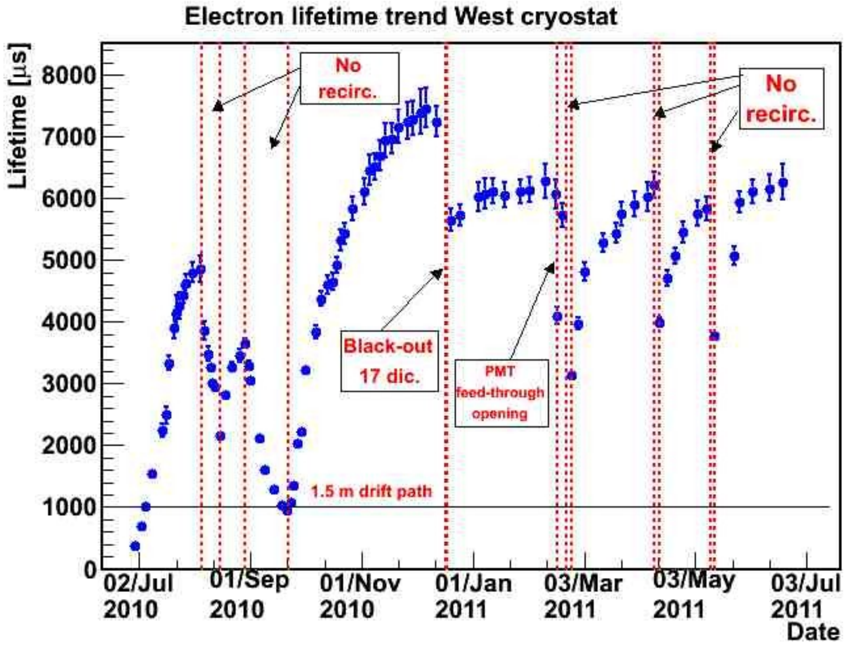
LAr Purification in T600

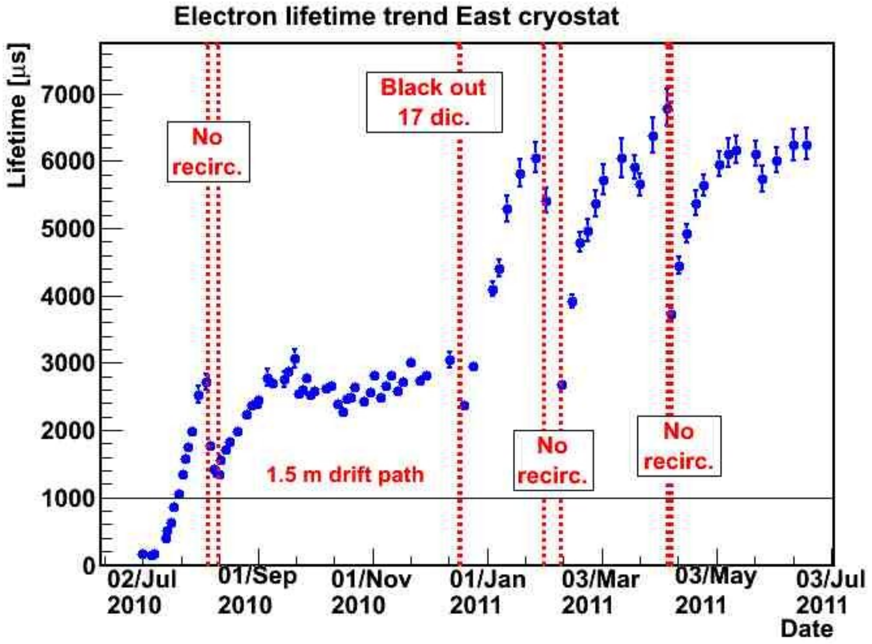
- The presence of electron trapping polar impurities attenuates the electron signal as exp(-tD/ τ ele)
- $|_{ele}$ ~ 300 ⌈s / ppb (O_2 equivalent).
- Because of temperature (87 K) most of the contaminants freeze out spontaneously. Main residuals: O_2, H_2O, CO_2.
- Recirculation/purification (100 Nm^3/h) of the gas phase (~40 Nm^3) to block the diffusion of the impurities from the hot parts of the detector and from micro-leaks on the openings (typically located on the top of the device) into the bulk liquid.
- Recirculation/purification (4 m^3/h) of the bulk liquid volume (~550 m^3) to efficiently reduce the initial impurities concentration (can be switched on/off).


Gas recirculation scheme


Liquid recirculation scheme

LAr purity time evolution





Simple model: uniform distribution of the impurities, including internal degassing, decreasing in time, constant external leak and liquid purification by recirculation.

$$dN/dt = -N/\tau_R + k + k_I \exp\left(-t/\tau_I\right)$$

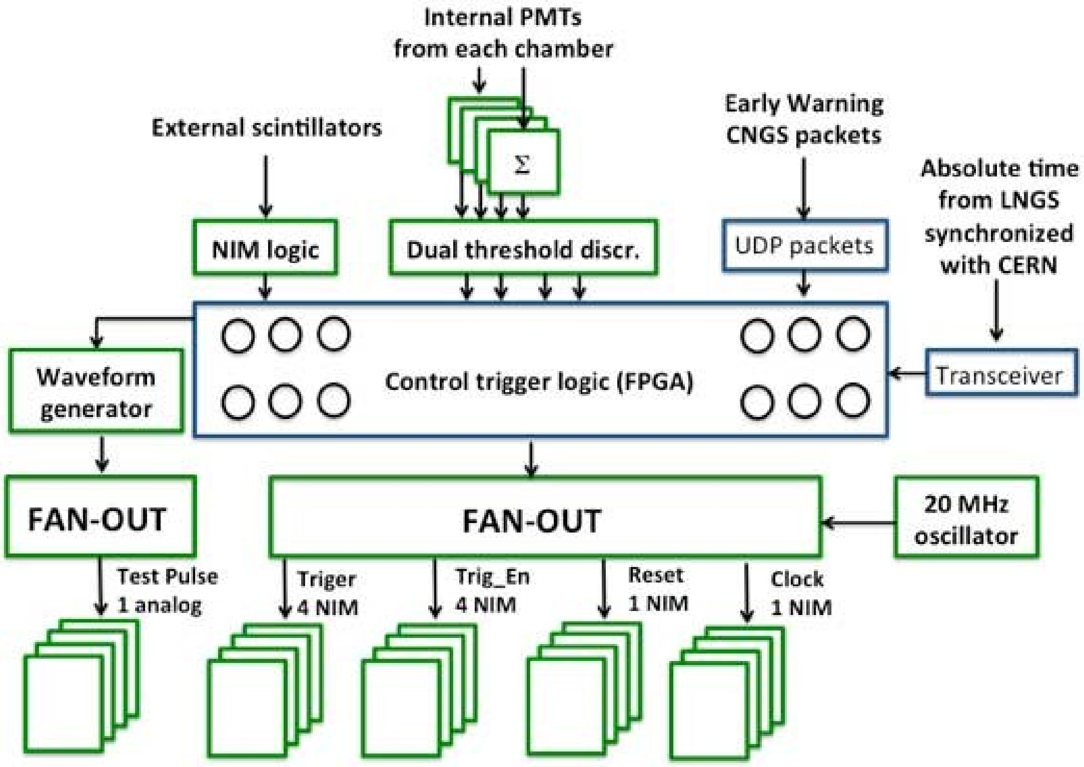
τele [ms] = 0.3 / N[ppb O2 equivalent]

τR: recirculation time for a full detector volume
kI and τI : related to the total degassing internal rate
k : related to the external leaks

τR: 2 m^3/h corresponding to ≈ 6 day cycle time

Trigger System

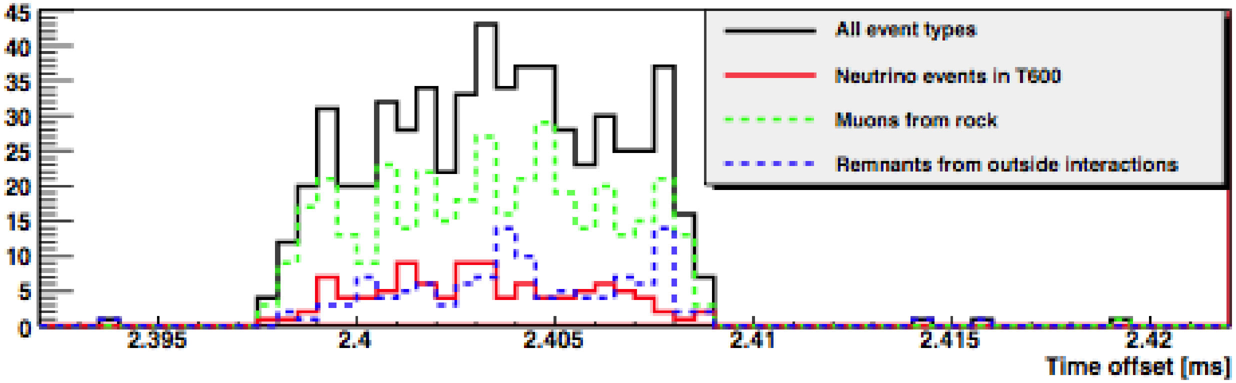
- *It handles different trigger sources: PMTs, CNGS proton extraction time and test pulses for calibration.*
- *It provides the absolute time stamp for the recorded events and the opening of the CNGS proton spill gate by means of the signal from LNGS atomic clock.*
- *It distributes the trigger signals to the electronic crates.*

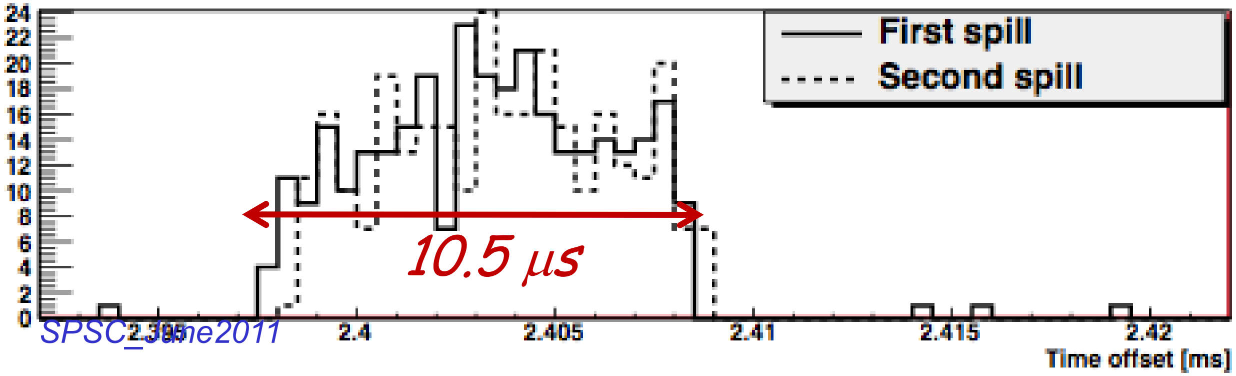


The controller crate, hosting a FPGA-board for signals processing, is interfaced to a PC for data communication and parameter setting.

CNGS trigger

- At every CNGS cycle protons are extracted in 2 spills lasting 10.5 μs each, 50 ms apart. CNGS "Early Warning" signal sent 80 ms before the proton extraction, the expected absolute time for next extraction.
- Trigger: photomultiplier signal for each chamber with low threshold discrimination at 100 phe, within 60 μs wide beam gate.
- 80 events per day are recorded with a trigger rate of about 1 mHz.

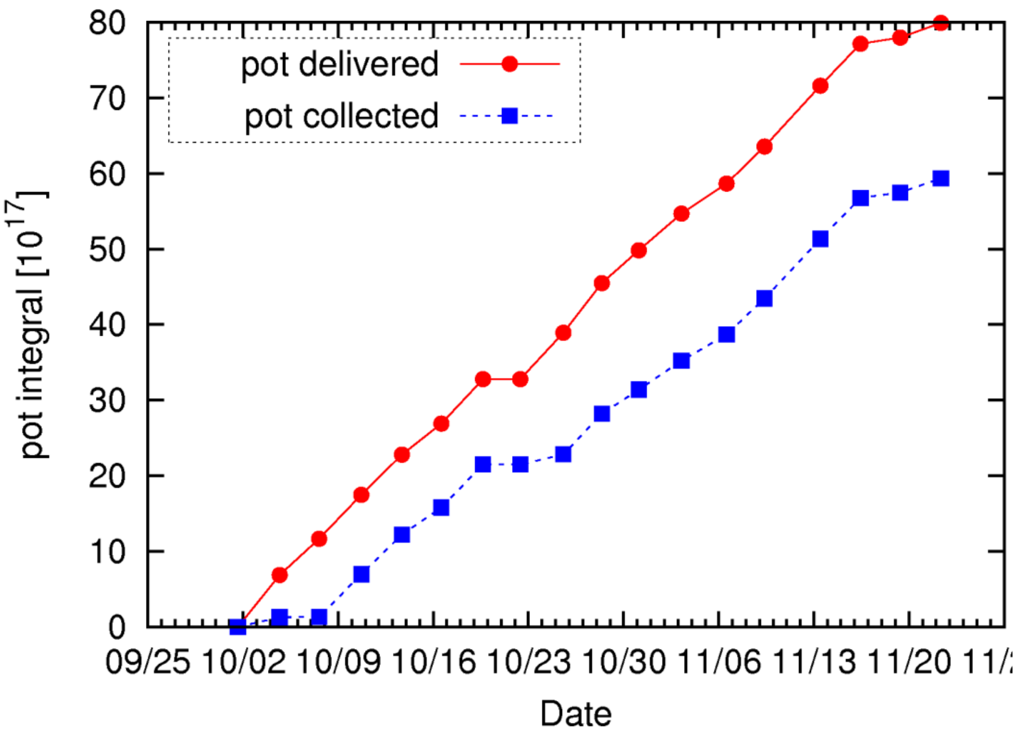


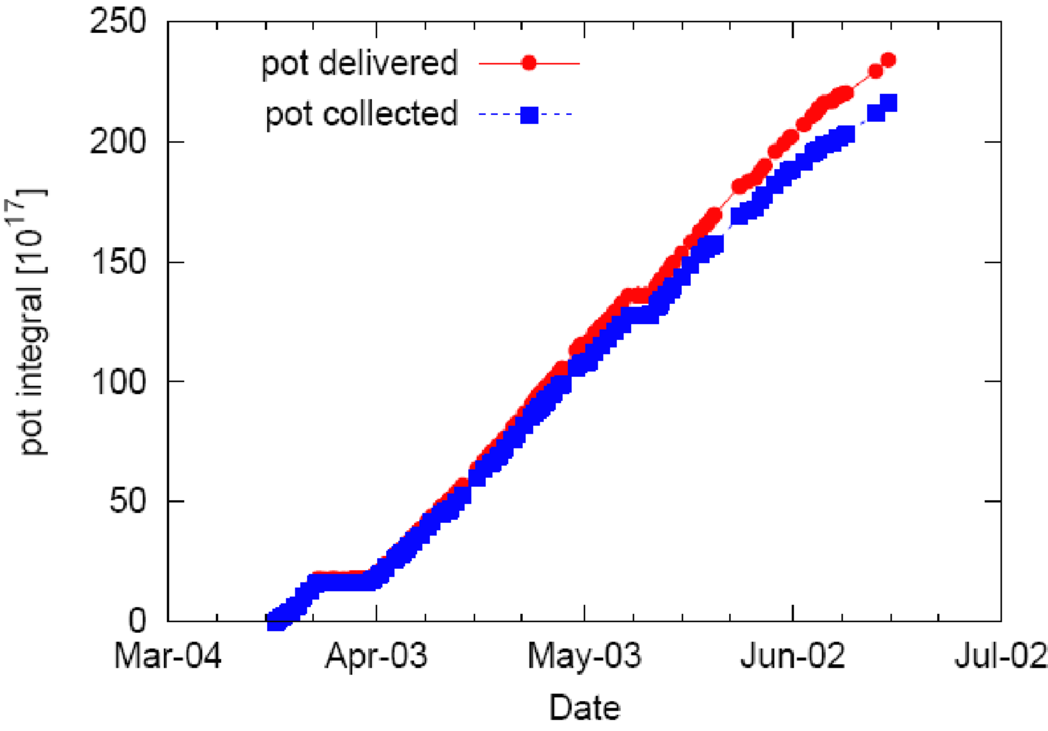


- *Offset value (2.40 ms) in agreement with ν t.o.f. (2.44 ms) with the addition of 40 μs fiber transit time from external LNGS labs to Hall B (8km).*

CNGS runs during 2010 and 2011

- ICARUS operational for CNGS from Oct. 1st - Nov. 22nd 2010.
- 8 x 10^{18} (5.8 x 10^{18}) pot delivered (collected).
- ICARUS data taking for CNGS events from 19th March 2011.
- 2.3 x 10^{19} (2.2 x 10^{19}) pot delivered (collected) up to 15th June.





Preliminary results of first CNGS 2010 run

- Full sample analyzed, i.e. $5.8 \cdot 10^{18}$ pot. Classified by visual scanning into fiducial volume of 434 t.

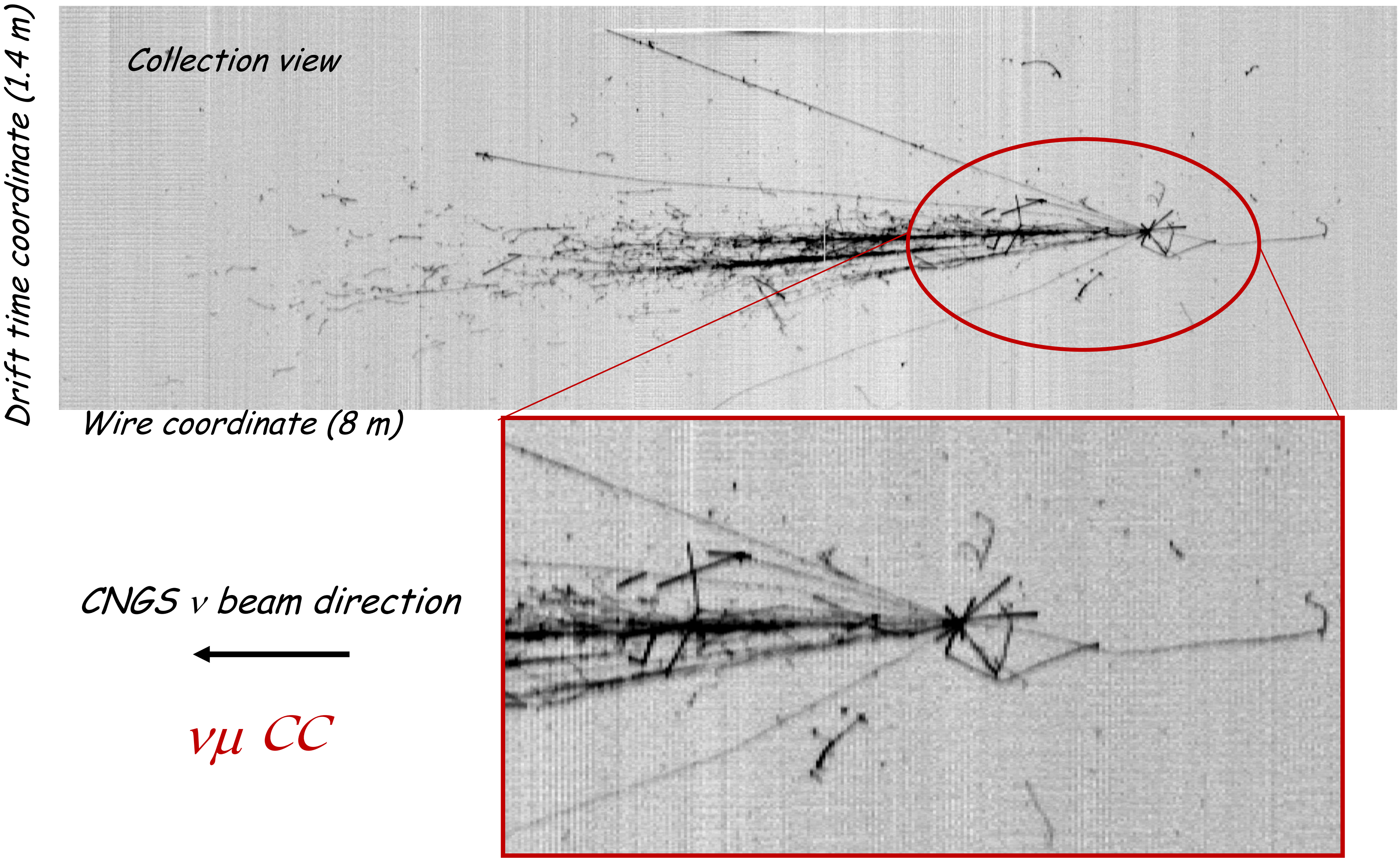
- Number of collected interactions compared with number of interactions predicted ((2.6 ν CC + 0.86 ν NC) 10^{-17}/pot), in the whole energy range up to 100 GeV, corrected by fiducial volume and DAQ dead-time.

Event type	Collected	Expected
ν_μ CC	115	129
ν NC	46	42
ν XC *	7	-
Total	169	172

** Events at edges, with μ track too short to be visually recognized: further analysis needed.*

On overall statistics in agreement with expectations.

CNGS neutrino interactions in ICARUS T600

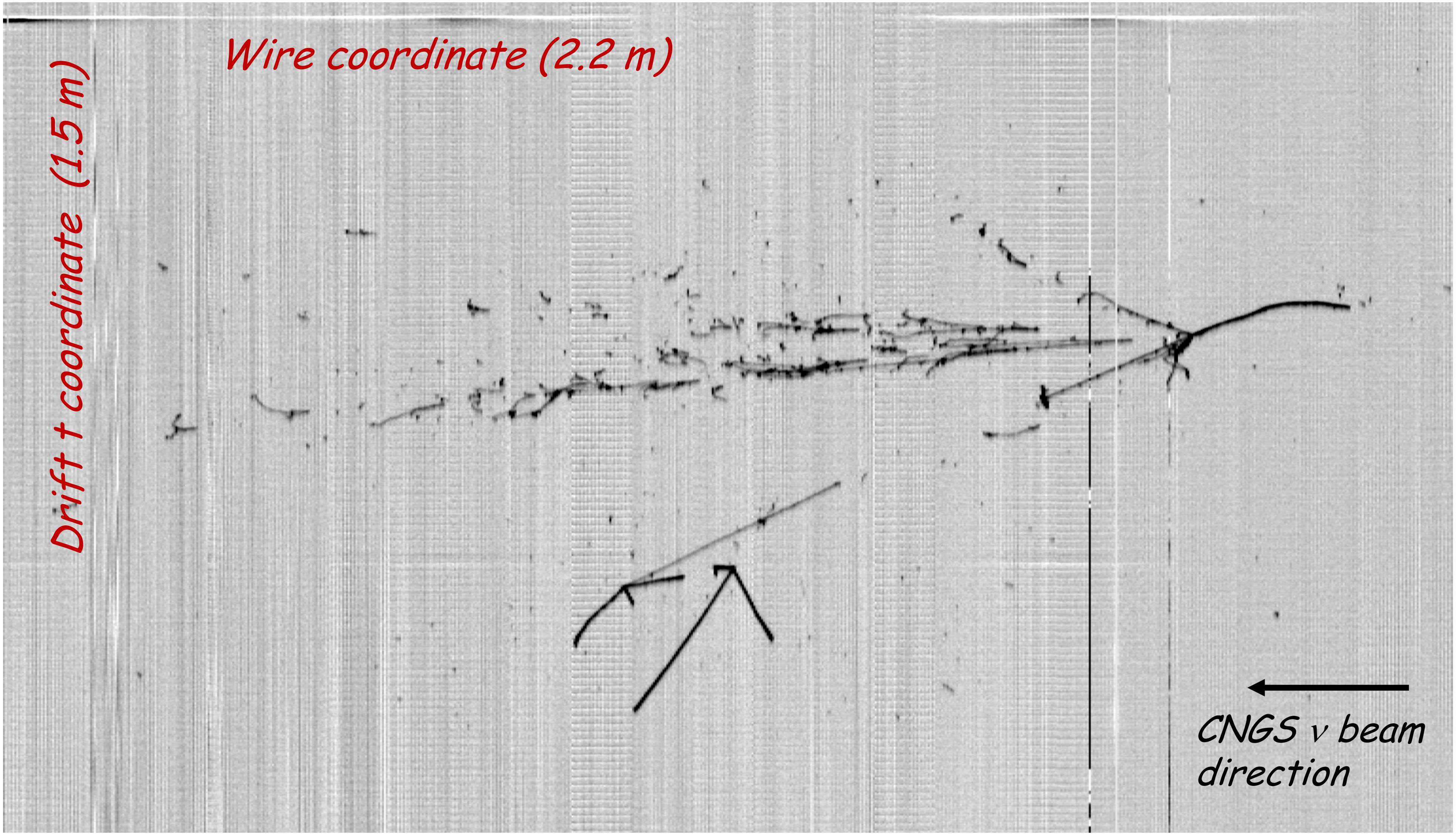


CNGS ν beam direction

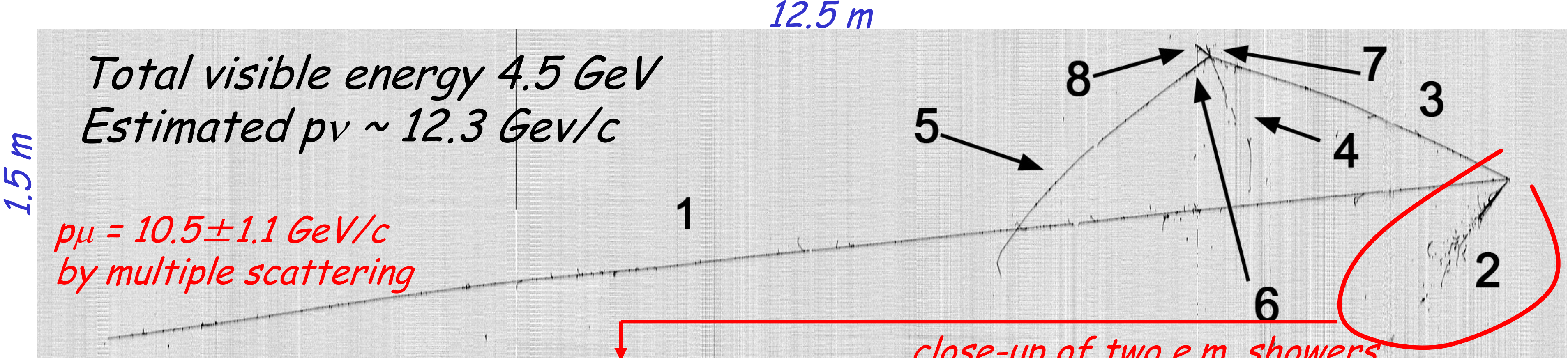
←

$\nu\mu$ CC

CNGS NC interaction



LAr-TPC: powerful technique. Run 9927 Event 572



Total visible energy 4.5 GeV
Estimated pν ~ 12.3 Gev/c

pμ = 10.5±1.1 GeV/c
by multiple scattering

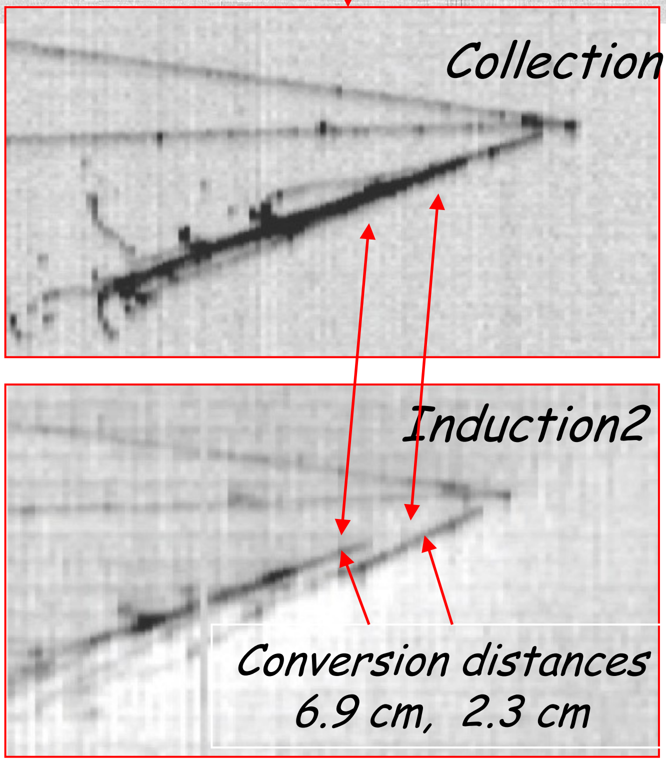
close-up of two e.m. showers

Primary vertex (A)

very long μ (1), e.m. cascade(2), pion (3).

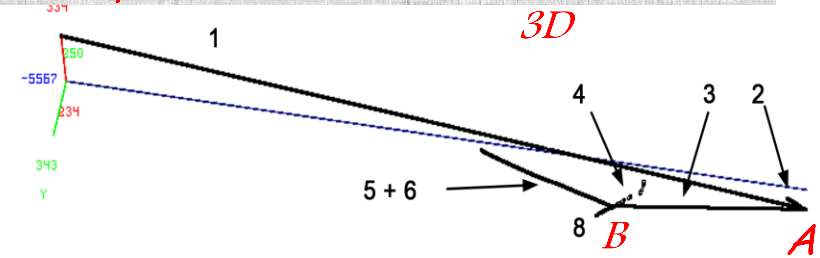
Secondary vertex (B)

The longest track (5) is a μ coming from stopping k (6).
- μ decay is observed.



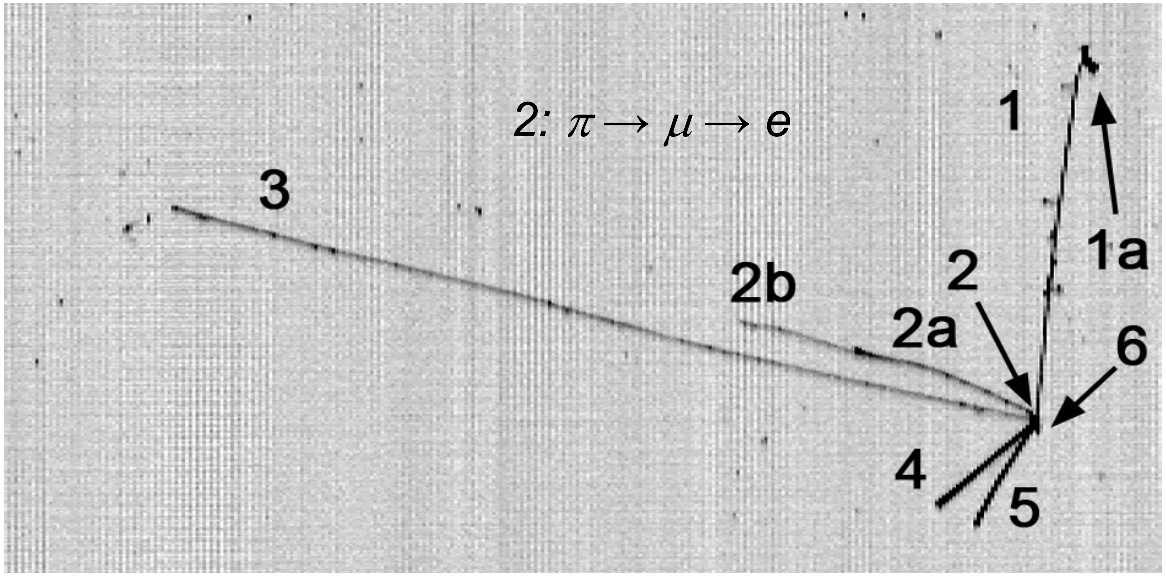
Conversion distances
6.9 cm, 2.3 cm

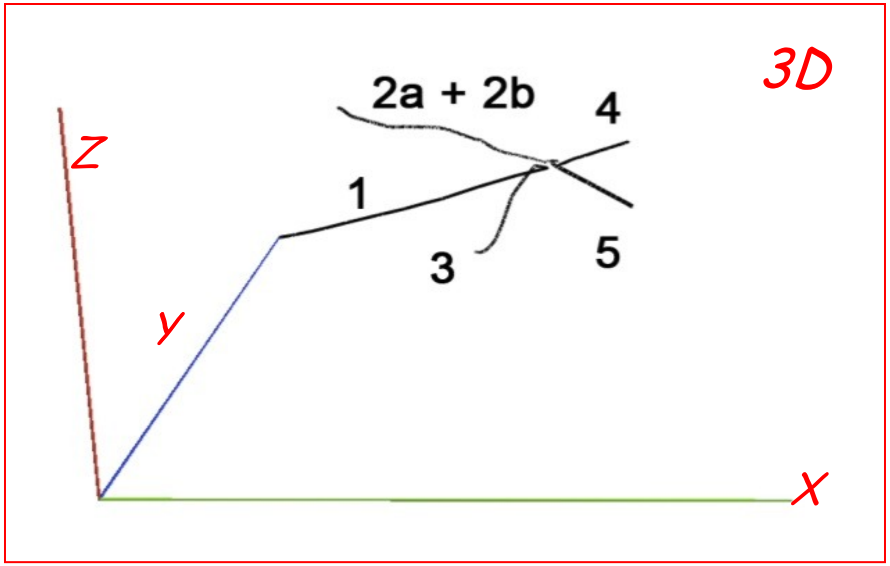
$M^*_{\gamma\gamma}$ = 125±15 MeV/c^2



Track	E_{dep}[MeV]	cosx	cosy	cosz
1 (μ)	2701.97	0.069	-0.040	-0.997
2 (π^0)	520.82	0.054	-0.420	-0.906
3 (π)	514.04	-0.001	0.137	-0.991
Sec.vtx.	797.			
4	76.99	0.009	-0.649	0.761
5 (μ)	313.9			
6 (K)	86.98	0.000	-0.239	-0.971
7	35.87	0.414	0.793	-0.446
8	283.28	-0.613	0.150	-0.776

Run 9392 Event 106

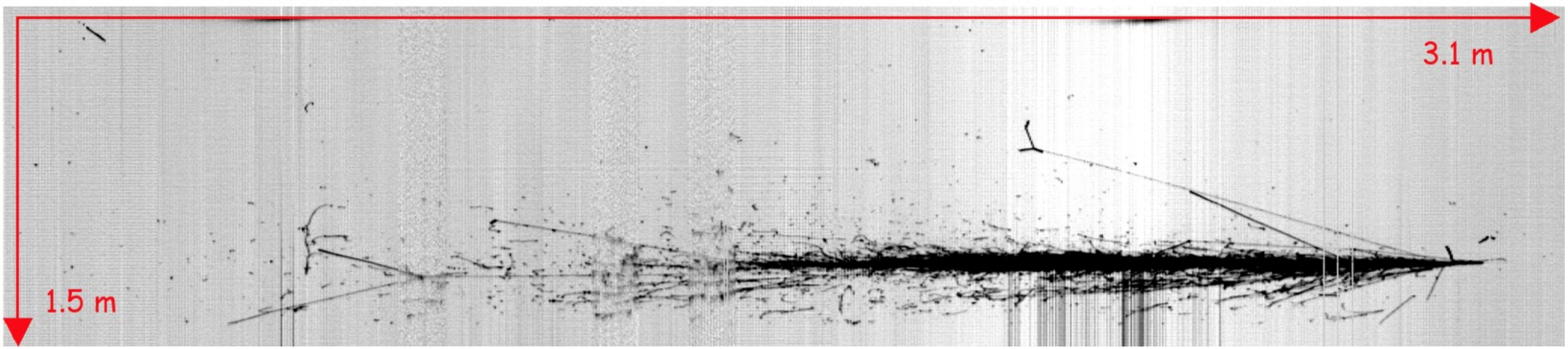




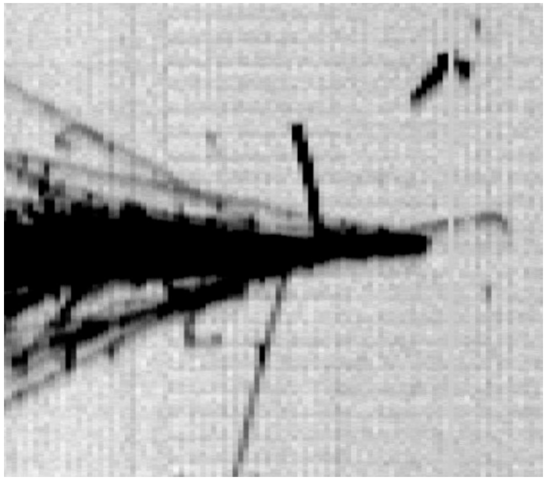
Track	E_k [MeV]	Range [cm]
1 (prob. π, decays in flight)	136.1	55.77
2 **(π)**	26	3.3
2a **(μ)**	79.1	17.8
2b **(e)**	24.1	10.4
3 **(μ)**	231.6	99.1
4 **(p)**	168	19.2
5 **(p)**	152	16.3
6 (?) (merged with vtx)		2.9

- *Total deposited energy: 887 MeV*
- *Total reconstructed momentum: 929 MeV/c at about 35° away from the CNGS beam direction*

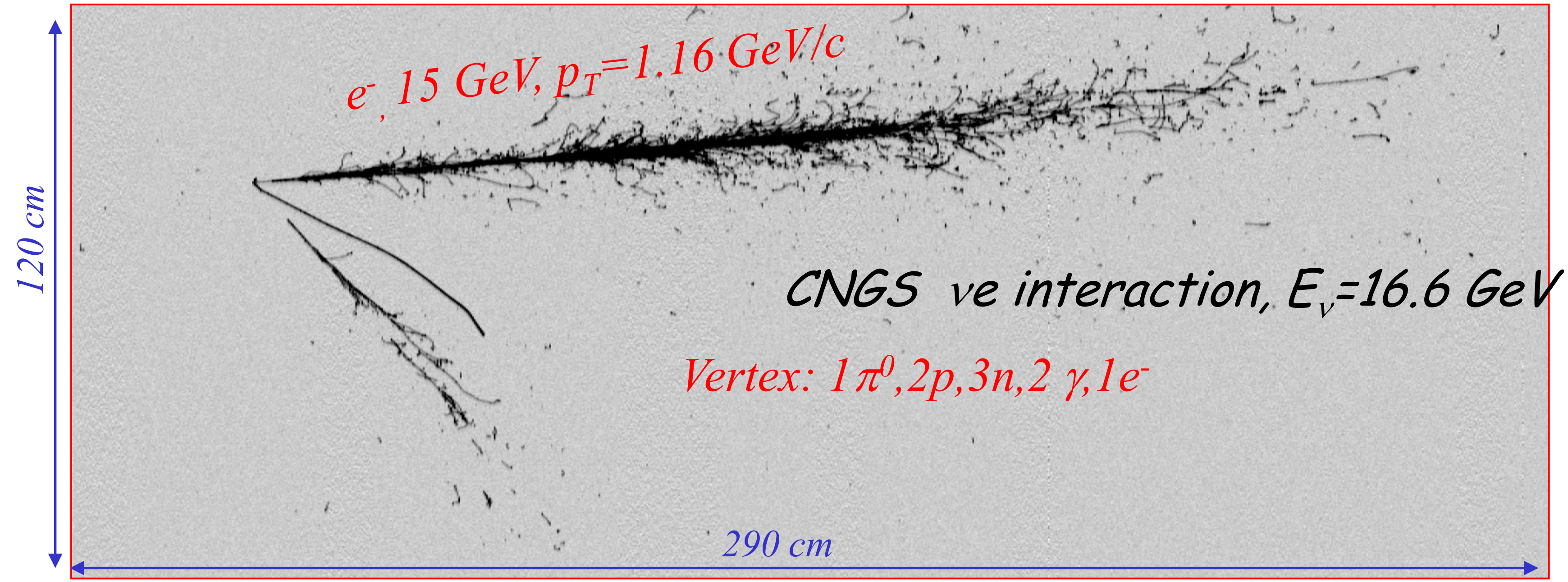
Electron event candidate

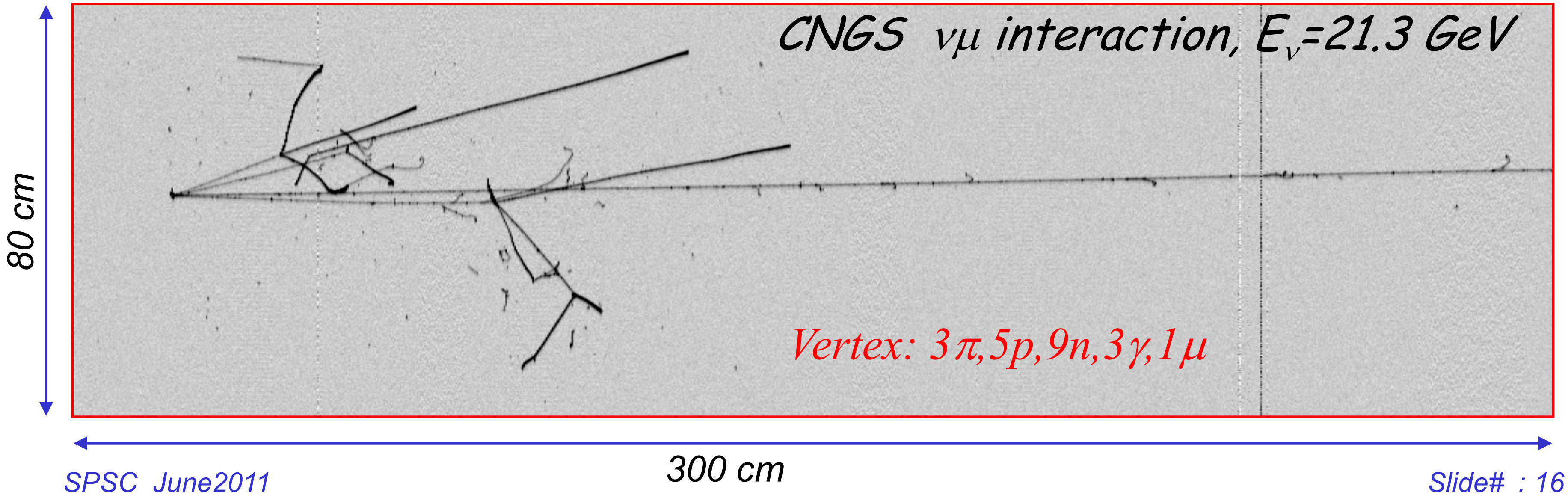


- In the 2010 analyzed sample a n_eCC candidate has been identified, presumably coming from the intrinsic ne beam contamination . This event has 45 GeV total energy with a single powerful e.m. shower at the vertex of about 37 GeV, and with a longitudinal profile peaking at the expected position (~88 cm).

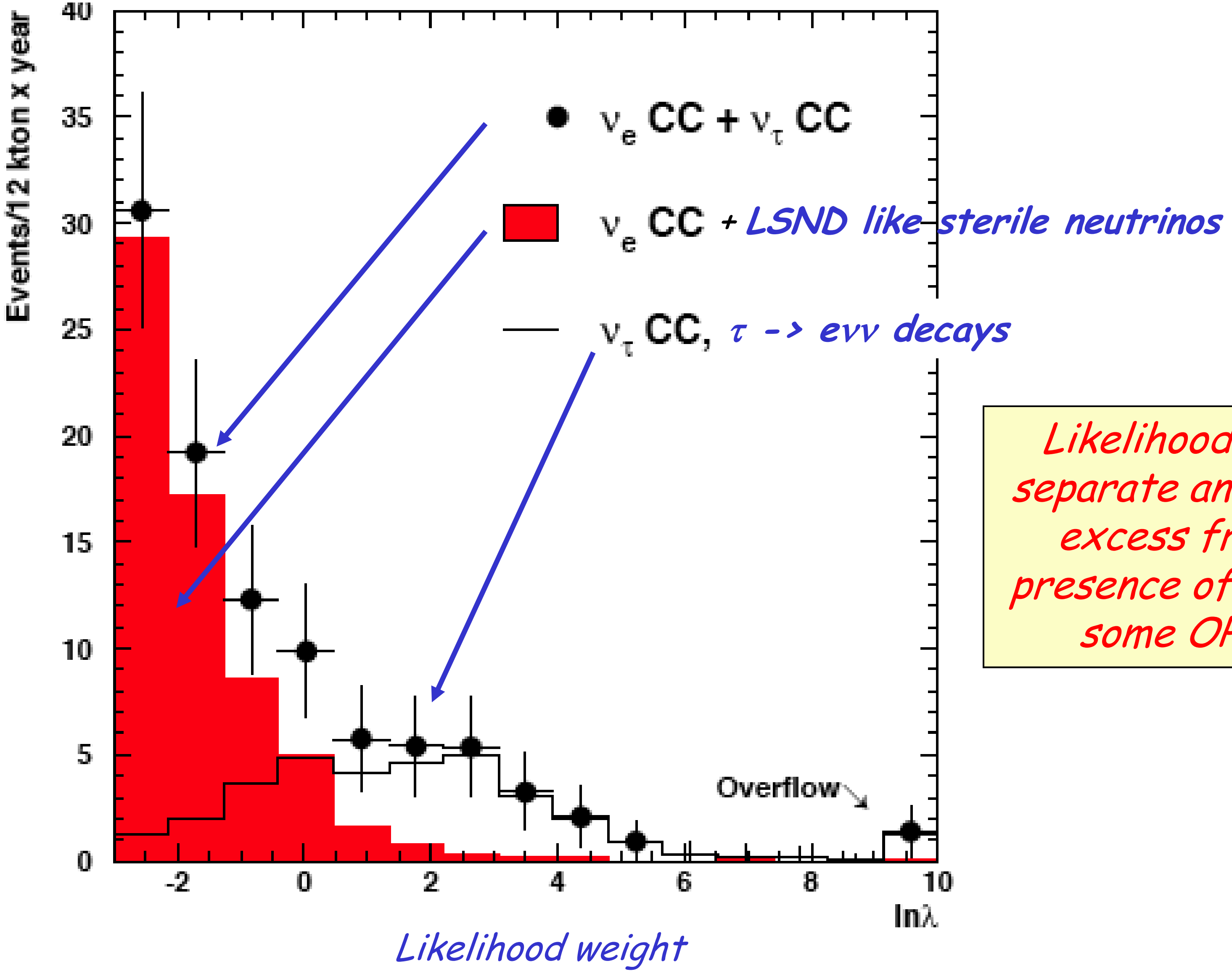


Reconstructed CC events in T600





ν–e balanced events or ν–tau decays ?



+ LSND like sterile neutrinos

$\tau \to e\nu\nu$ decays

Likelihood weight

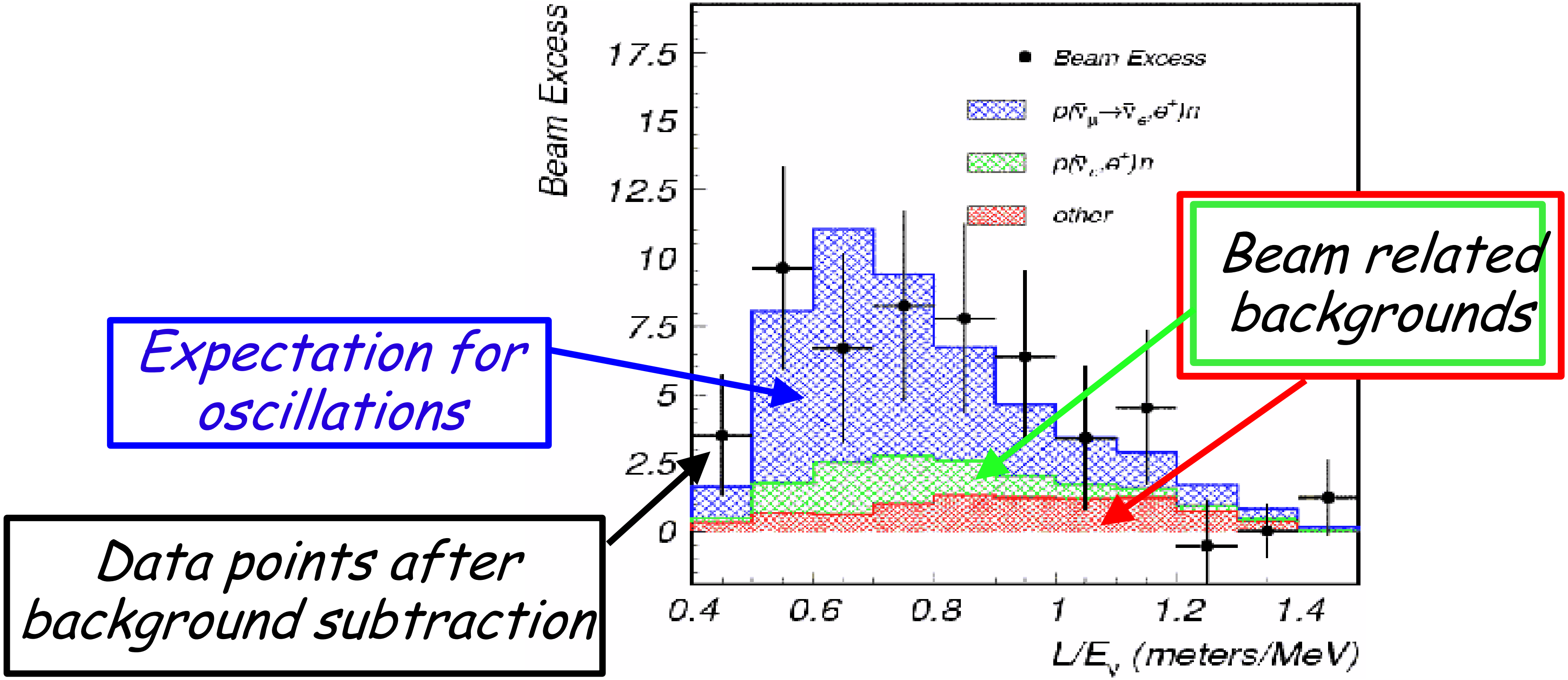
Likelihood distributions may separate an hypothetical LSND excess from the expected presence of $\tau \to \varepsilon\nu\nu$ decays i.e. some OPERA like events

Sterile neutrinos

- The possible presence of oscillations into sterile neutrinos was proposed by B. Pontecorvo, but so far without conclusion.
- Two distinct classes of anomalies have been analyzed, namely
  - the apparent *disappearance signal* in the anti-ν_e events detected from near-by nuclear reactors and from the from Mega-Curie k-capture calibration sources in the Gallium experiments to detect solar ν_e
  - observation for *excess signals* of ν_e electrons from neutrinos from particle accelerators (LNSD/MiniBooNE)
- These experiments may all point out to the possible existence of at least one fourth non standard neutrino state driving oscillations at a small distances, with typically $\Delta m^2_{new} \geq 1$ eV^2 and relatively large mixing angle with $\sin^2(2\theta_{new}) \approx 0.1$.
- The existence of additional neutrino states may be also hinted — or at least not excluded — by cosmological data

LSND: Evidence for $(\nu_\mu \rightarrow \nu_e)$

Excess of events: 87.9 ± 22.4 ± 6.0



Expectation for oscillations

Beam related backgrounds

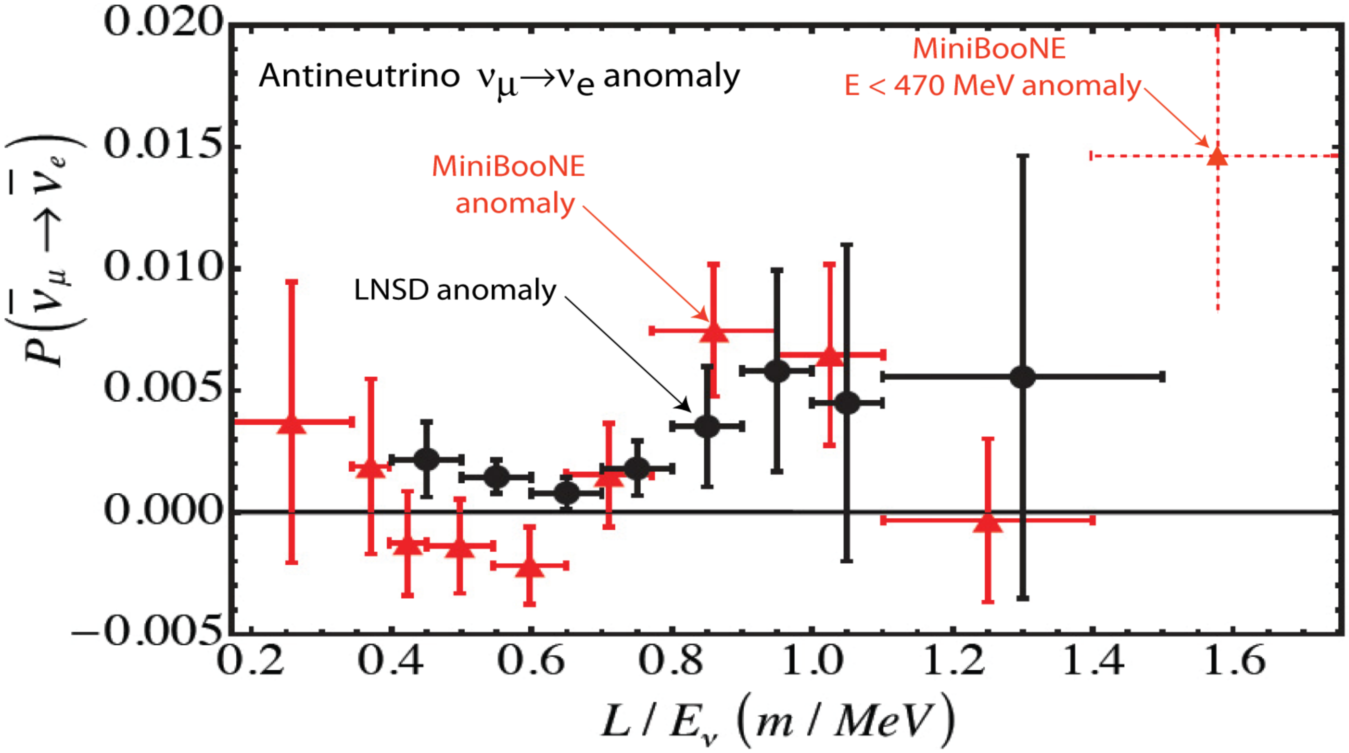
Data points after background subtraction

- *The experimental evidence is very strong, namely 3.8 s.d.*
- *The experimental result so far has not been challenged experimentally*

The LNSD like anomalies ($\nu_\mu \to \nu_e$)

- As well known, the LNSD signal with anti-neutrino oscillations from an accelerator would imply an additional mass-squared difference largely in excess of the Standard Model's values.
- The LSND signal (87.9 ± 22.4 ± 6.0) represented a 3.8 σ effect at L/E distances of about 0.5 – 1.0 m/MeV.
- The MiniBooNE experiment has used a horn focused neutrino beam from 8 GeV protons of the FNAL Booster, to verify the observation of an anti- ν_e anomaly of the LNSD experiment
- While the LSND like anomaly seems to be absent in the neutrino data, a new "anomaly" appears at much smaller values of the neutrino energy.

The MiniBooNE anti-neutrino run

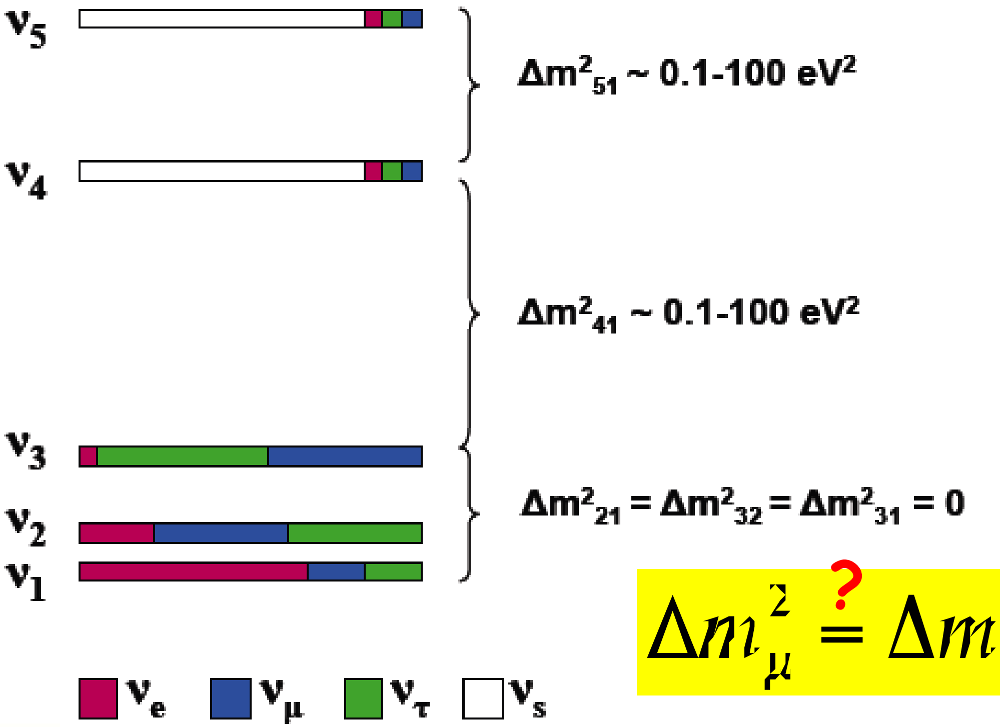


F.Mills, ICHEP, July 2010

- The more recent MiniBooNE antineutrino run has shown the direct presence of a LSND like anomaly for neutrino energies > 430 MeV. The result is compelling with respect to the ordinary two-neutrino fit, indicating a 99.4% probability for an anomalous excess in ν_e production.
- The reported effect is broadly compatible with the expectation of LNSD experiment, which, as well known, was originally dominant in the antineutrino channel.

Can the anomalies indicate a more complicated picture?

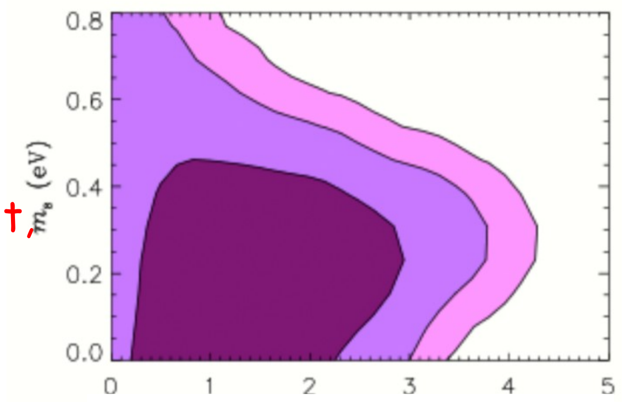
- Sterile neutrino models
- 3+2 next minimal extension to 3+1 models
- 2 independent Δm^2
- 4 mixing parameters
- 1 Dirac CP phase allowing difference between neutrinos and antineutrinos



$$\Delta m^2_\mu \overset{?}{=} \Delta m^2_{\bar{\mu}}$$

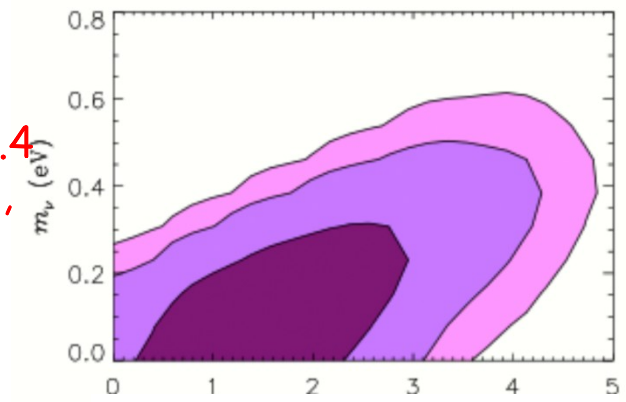
From cosmology

CMB + LSS +
ΛCDM
Ns= 1.6 ± 0.9
Hamann, Hannestad, Raffelt, Tamborra, Wong, PRL 105 (2010) 181301



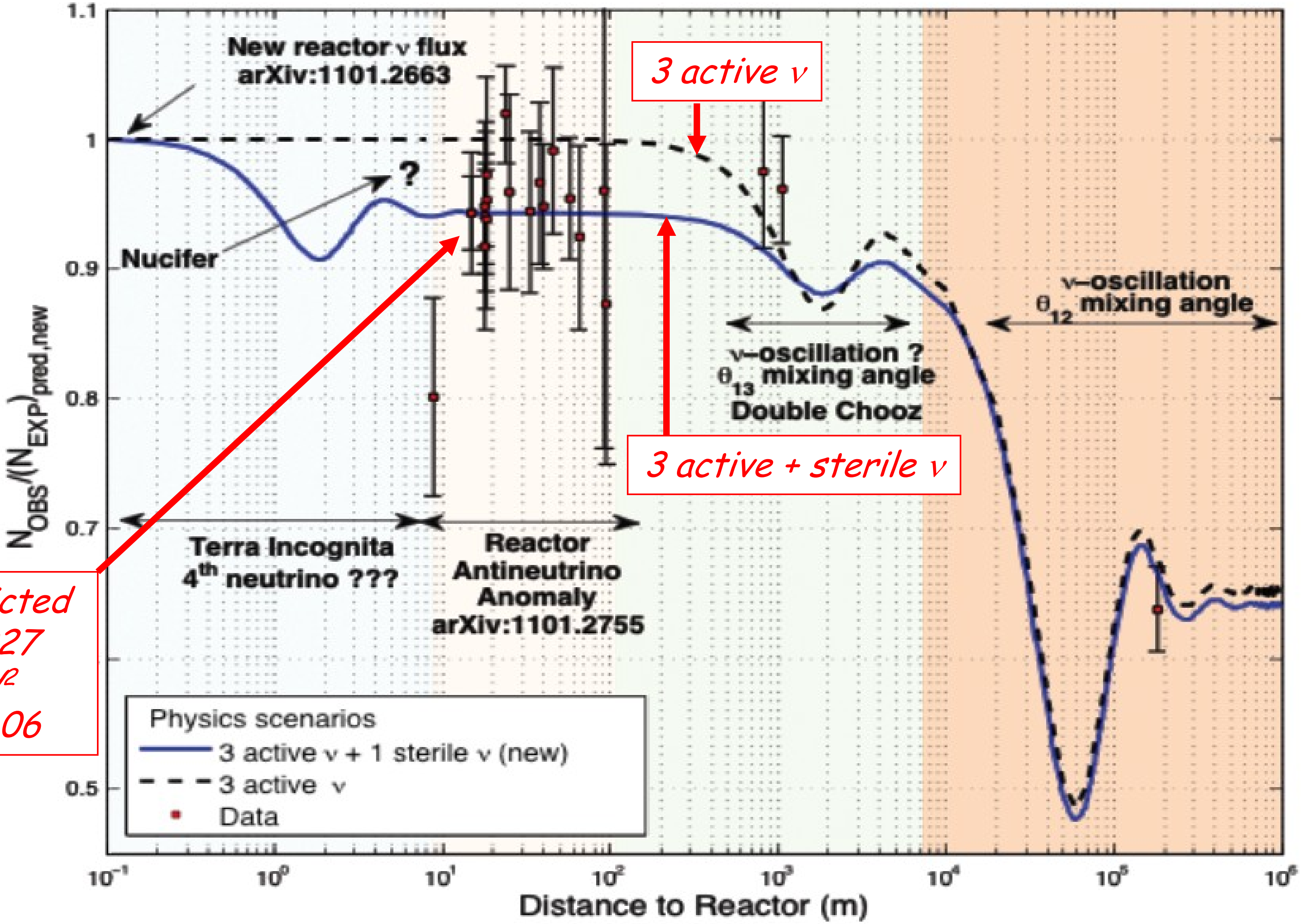
Number of sterile neutrinos

BBN:
Ns= 0.64 ± 0.4
Izotov, Thuan, ApJL 710 (2010) L67



Number of sterile neutrinos

Short baseline reactor antineutrino anomaly



3 active ν

3 active + sterile ν

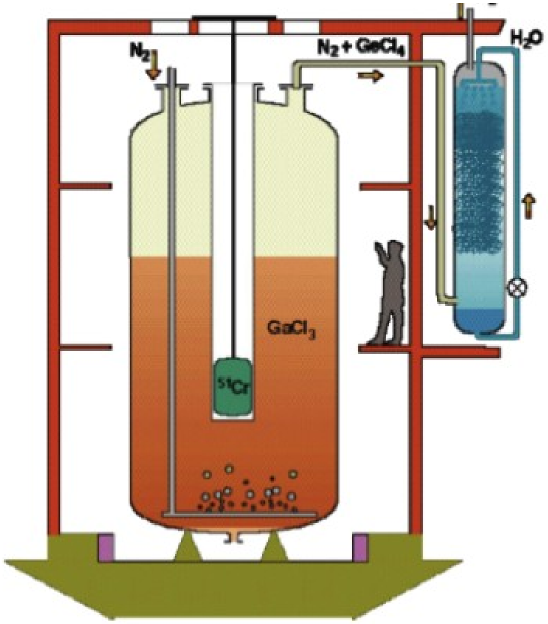
Observed/predicted
= 0.937 ± 0.027
$\Delta m^2_{new} \gg 1\ eV^2$
$\sin^2(2\theta_{new}) = 0.06$

From G. Mention et al. arXiv:1101.2755v1 [hep-ex]

The Gallium anomaly

- SAGE and GALLEX experiments recorded the calibration signal produced by intense artificial k-capture sources of ^{51}Cr and ^{37}Ar.
- The averaged result of the ratio R between the source detected and predicted neutrino rates are consistent with each other, giving R = (0.86 ± 0.05), about 2.7σ from R=1

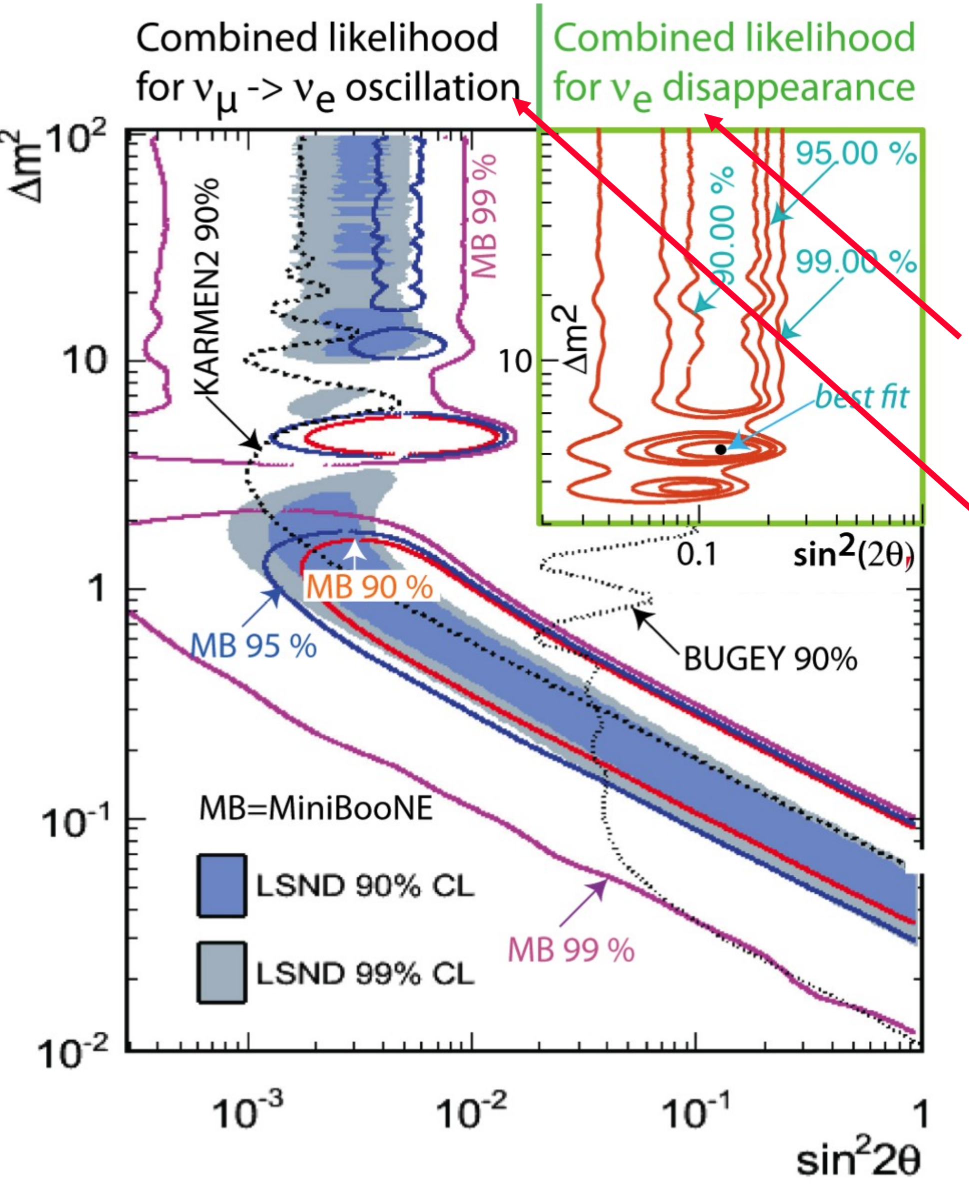
$$^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$$



30.3 tons of Gallium
in an aqueous solution : $GaCl_3$ + HCl

- These best fitted values may favour the existence of an undetected sterile neutrino with an evidence of 2.3σ and a broad range of values centred around $\Delta m^2_{new} \approx 2\ eV^2$ and $\sin^2(2\theta_{new}) \approx 0.3$.

Anomalies: an unified approach ?



Allowed regions in the plane for combined results:

the νe disappearance rate (right) (reactors and Gallium sources)

the LSND /MiniBooNE anti-νe accelerator driven anomaly (left).

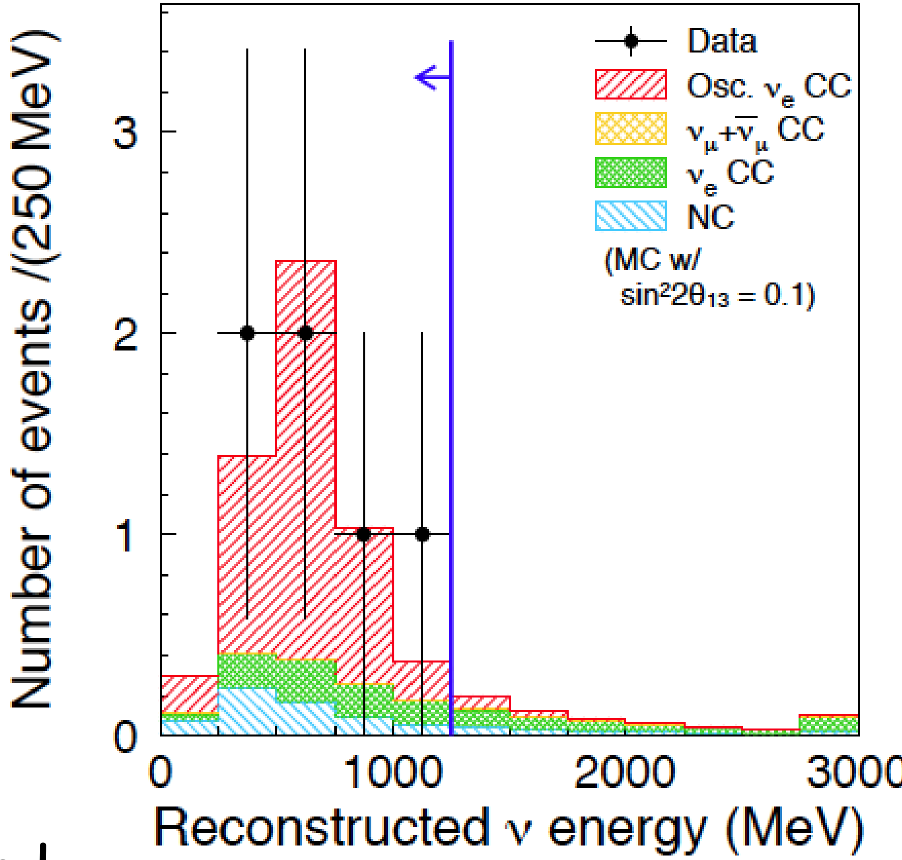
While the values of Δm^2_{new} may indeed have a common origin, the different values of $\sin^2(2\theta_{new})$ may reflect within the four neutrino hypothesis the structure of $U_{(4,k)}$ mass matrix, with k = μ and e.

T2K observation of the ν_e appearance from an initial ν_μ.

Beam ν_e background	NC background	Oscillated $\nu_\mu \rightarrow \nu_e$ (solar term)	Total
0.8	0.6	0.1	1.5

- 6 events observed for 1.5 backgr events
- Events analyzed as due to $\sin^2(2\theta_{13}) > 0$ with the result for normal (inverted) hierarchy at 90% c.l.

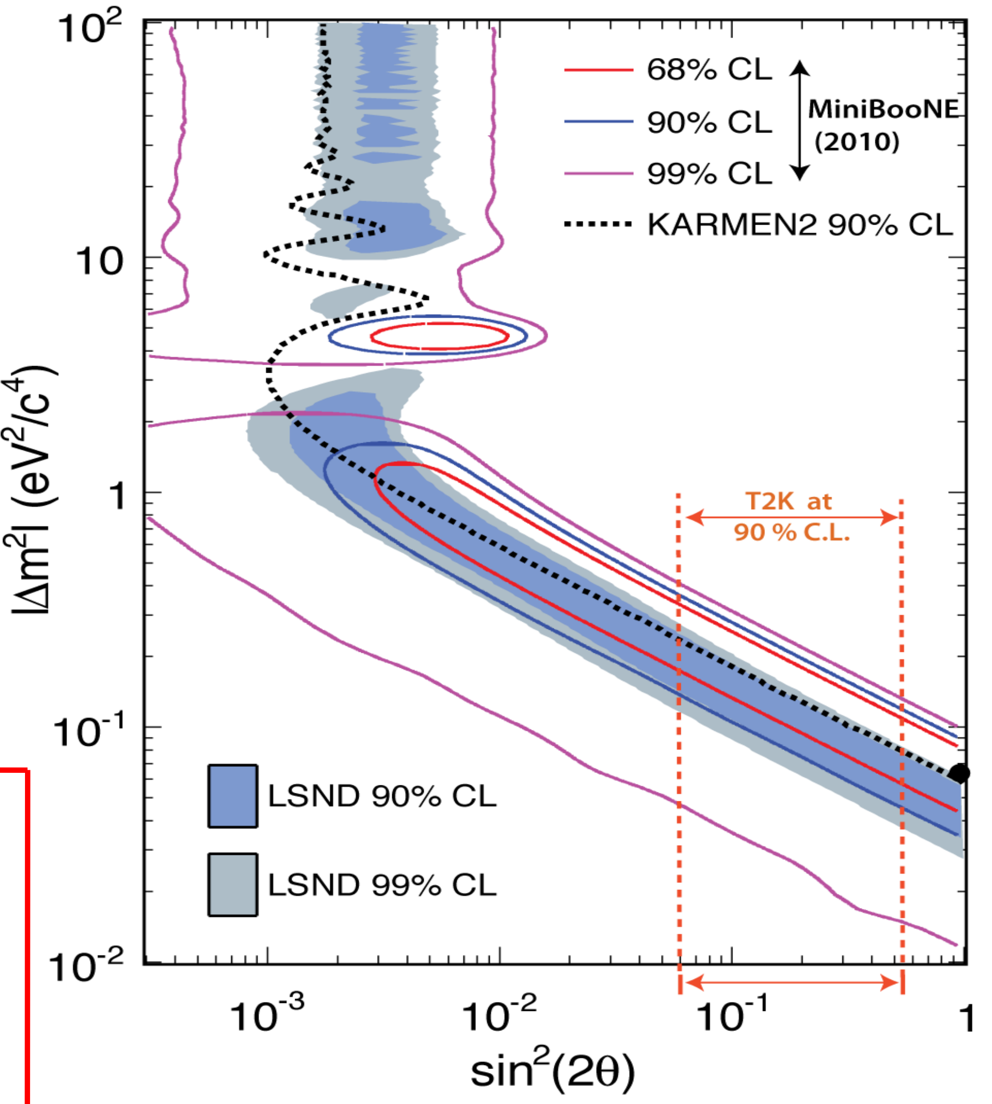
$$0.03\,(0.04) < \sin^2(2\theta_{13}) < 0.28\,(0.34)$$



- For CHOOZ, $\sin^2(2\theta_{13}) < 0.14$ at 90% c.l.
- Another possible alternative is the presence of a LSND-anomaly with sterile neutrino which could be the origin of the observed T2K signal. ICARUS at LNGS2 may statistically distinguish between the two alternatives

A sterile neutrino LNSD-like effect ?

- If the (6 -1.5) = 4.5 events of T2K experiment were <u>entirely</u> due to LNSD-like oscillations, with the ≈1500 fully contained neutrino events expected by the end of 2011 run we would record of the order of 4.5/121 x 1500 ≈ 56 oscillated events, with a intrinsic beam related ν-e background of ≈ 7.5 events.
- ICARUS is insensitive to the option $\sin^2(2\theta_{13}) > 0$ of the T2K result because of the much higher energies of the CNGS neutrino beam.



We neglect differences in the detection efficiencies for T2K and of ICARUS (66% vs ≈ 100%)

Neu-e or anti-neu-e ?

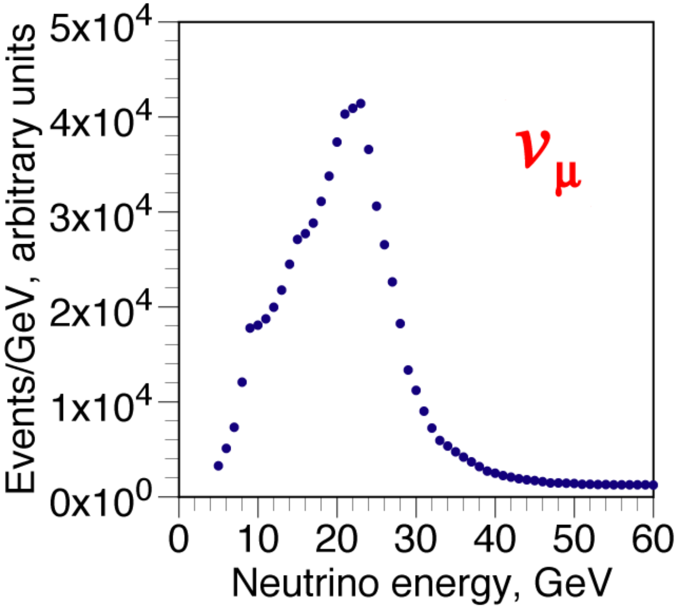
- In order to explain the claimed differences between neutrino and antineutrinos in MiniBooNE we must assume (at least !) two sterile neutrinos:

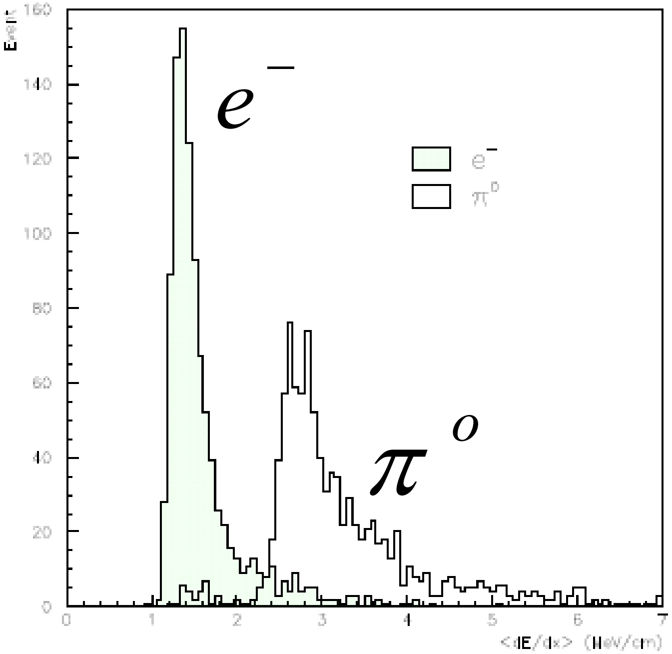
$$P(\overset{(-)}{\nu}_{\mu} \rightarrow \overset{(-)}{\nu}_{e}) = 4|U_{\mu 4}|^2|U_{e4}|^2\sin^2(\theta_{41}) + 4|U_{\mu 5}|^2|U_{e5}|^2\sin^2(\theta_{51}) +$$
$$8|U_{\mu 4}||U_{e4}||U_{\mu 5}||U_{e5}|\sin(\theta_{41})\sin(\theta_{51})\cos(\theta_{54} \pm \varphi_{45})$$

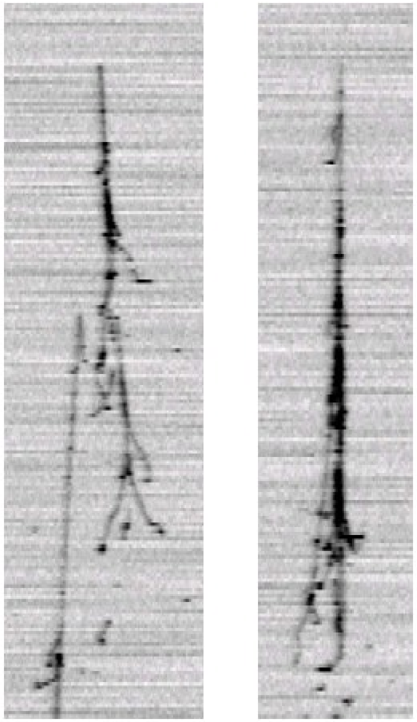
- The differences are due to the presence of the CP violating phase φ_{45} with opposite values for neu and anti-neu. *There is however a considerable "tension" amongst the over-all data.*
- It would however be appropriate to perform with ICARUS also an extended anti-neu run, where the LSND signal has been observed.
- The event rate with anti-neu is about a factor 2-3 smaller and compatibility with OPERA has to be carefully considered

Events with leading electron signature for T600.

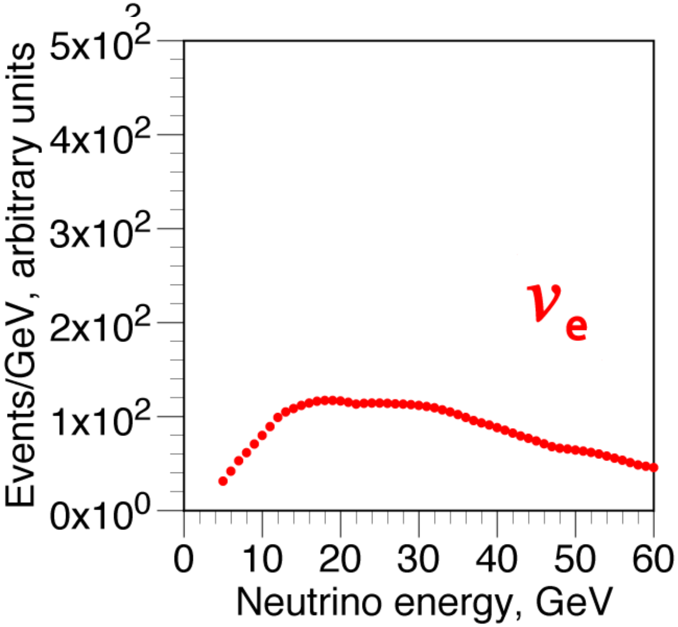
- The basic spectrum of LNGS is made of νμ, with a most probable energy in the order of 25 GeV.
- The νε spectrum has also been calculated and found to to be accurate to about 5%.
- Electron shower events are extremely well identified experimentally, because of the ionization behaviour in the first cells after the vertex.







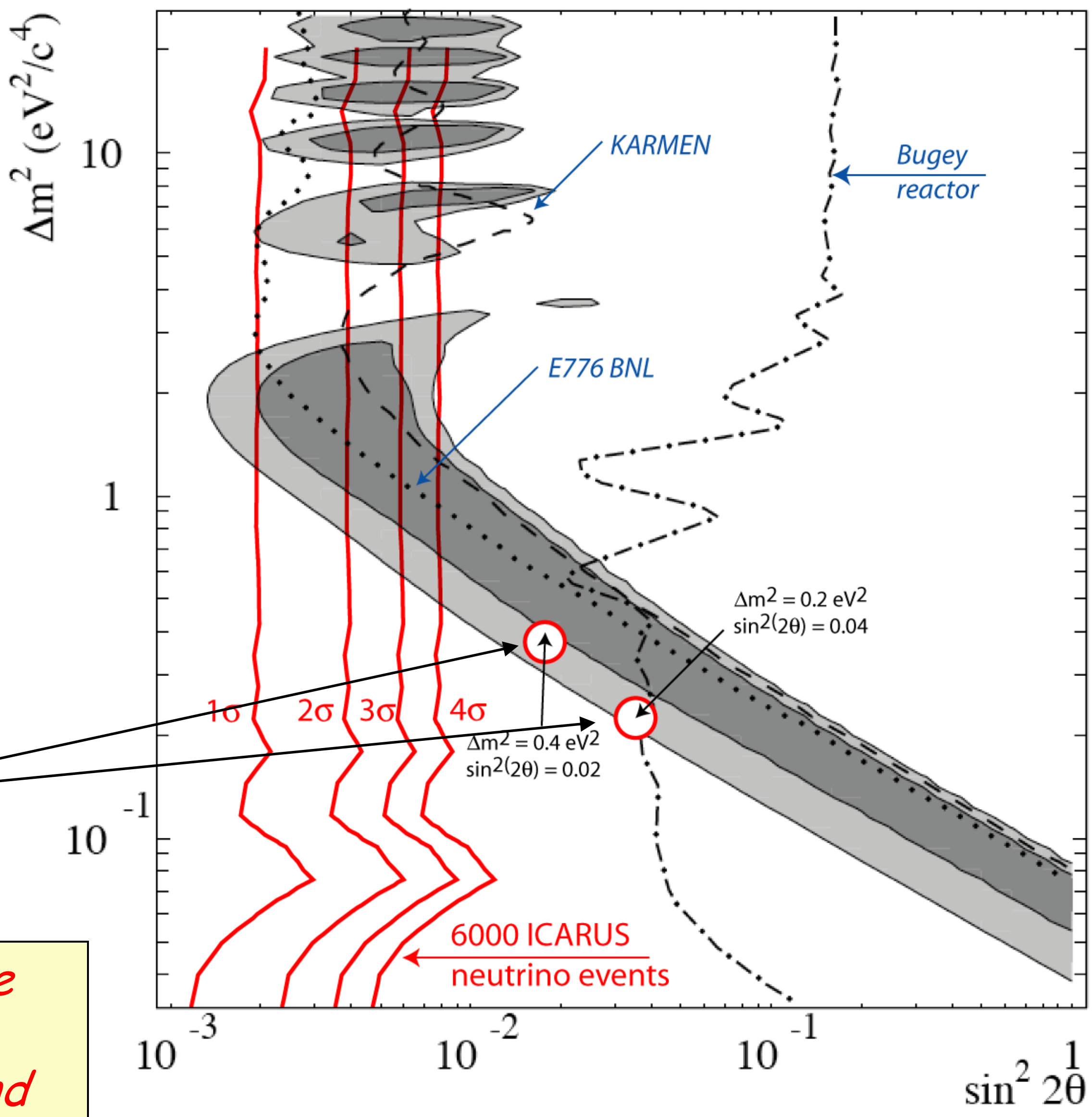
electron (right) and pion (left) in T600



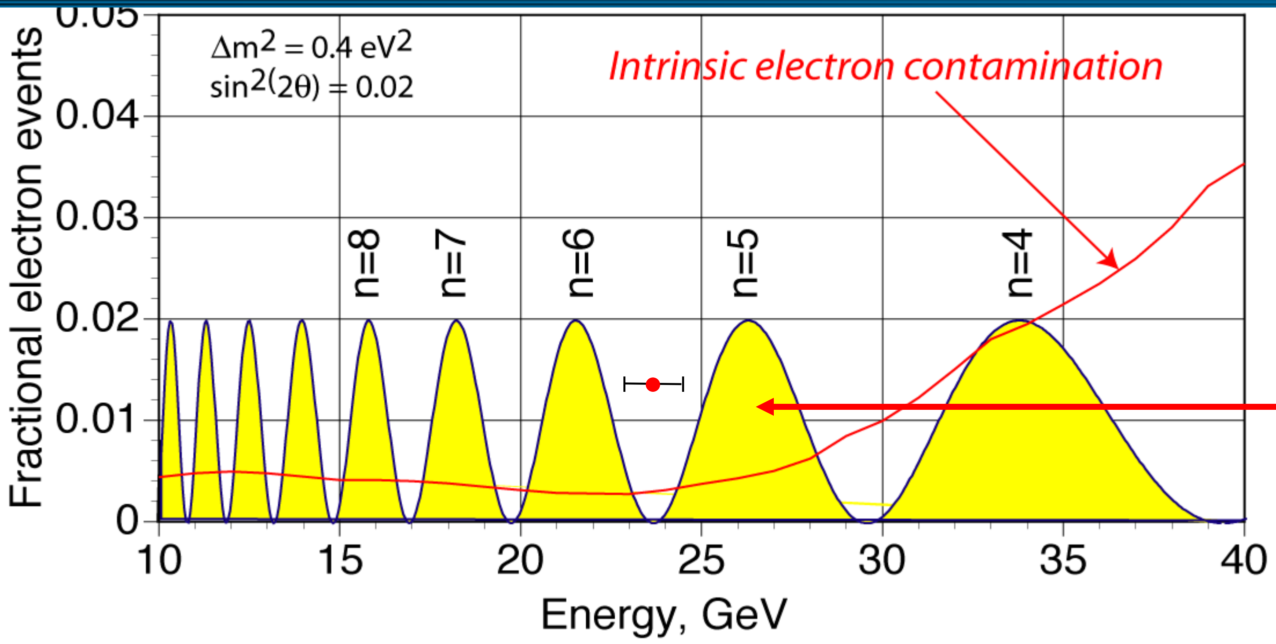
Limits at T600 with 6000 events.

- *Sensitivity region, in terms of Standard Deviations σ, for 6000 raw CNGS neutrino events. The potential signal is above the background generated by the intrinsic νe beam contamination, in the deep inelastic interval 10-30 GeV.*
- *The Δm^2 distribution extends widely beyond the LNSD and MiniBoone regions.*
- *Two indicated points are reference values of MiniBoone proposal and of previous slide*

T600 at the CNGS offers an unique possibility of searching for sterile neutrinos, largely complementary and comparable to the T2K programme.

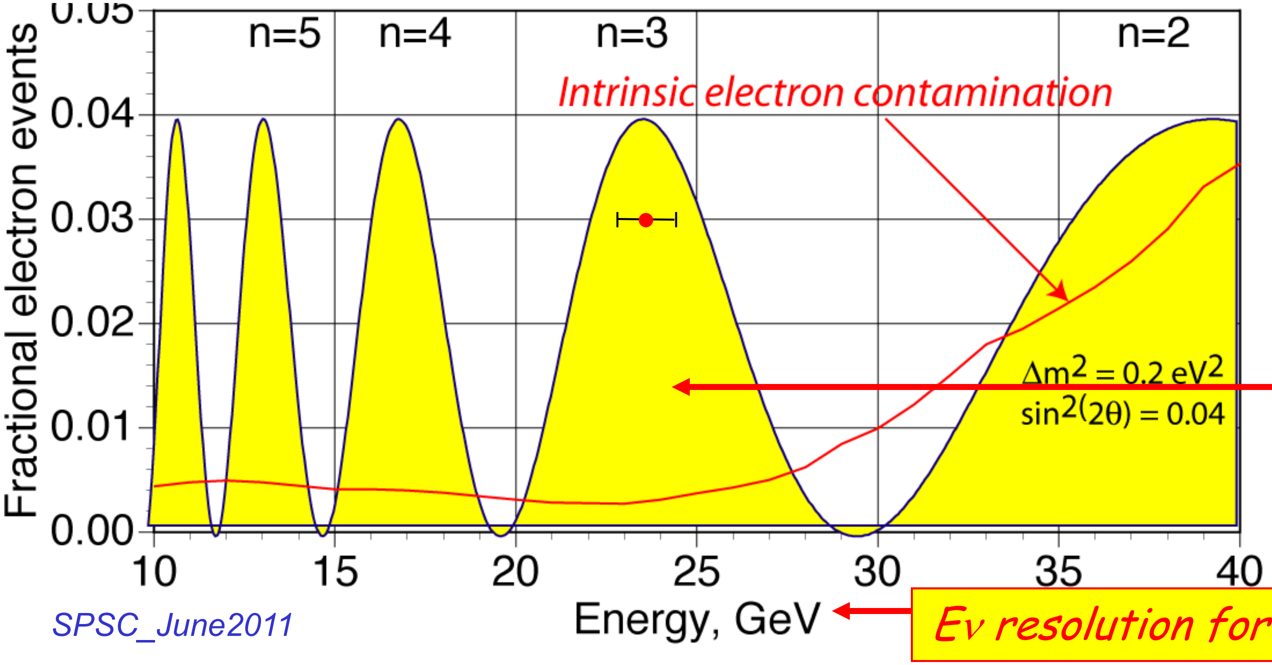


Indicative energy spectra for LSND signals



Eν:10 ÷ 30 GeV
N(νμ):4635
N(νe,beam): 18.8
N(νe,oscill): 45.5

Hypothetical sterile neutrino oscillations (LSDN) Δm² = 0.4 eV²



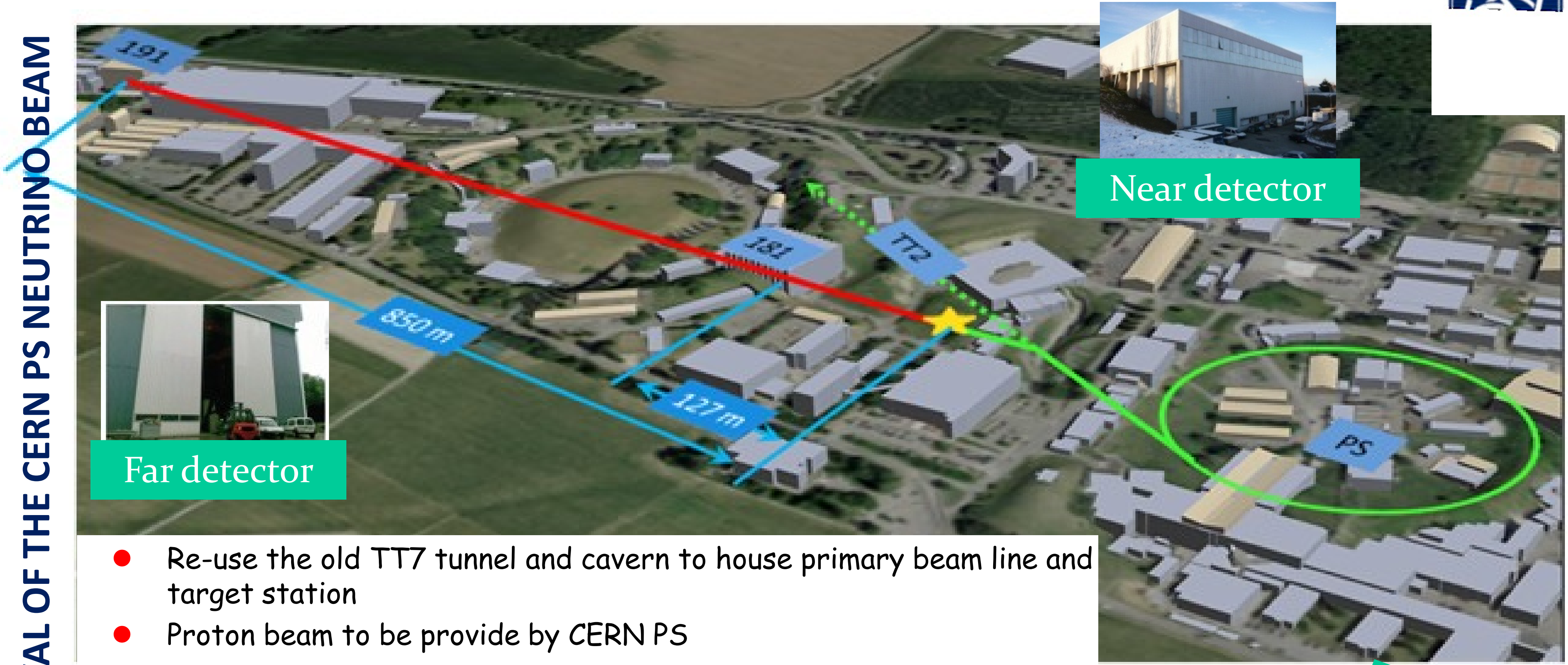
Eν:10 ÷ 30 GeV
N(νμ):4635
N(νe,beam): 18.8
N(νe,oscill): 94.9

Hypothetical sterile neutrino oscillations (LSDN) Δm² = 0.2 eV²

Eν resolution for contained events ≤ 0.17sqrt(E)

The Proposed Lay-out at CERN-PS

Rende Steerenberg, CERN Switzerland

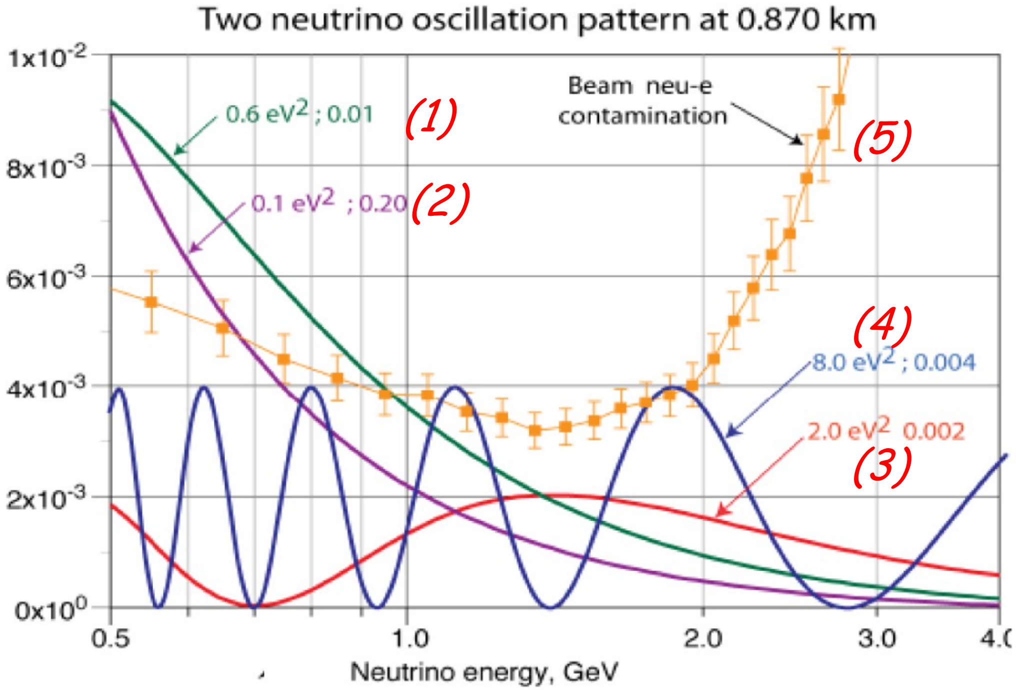


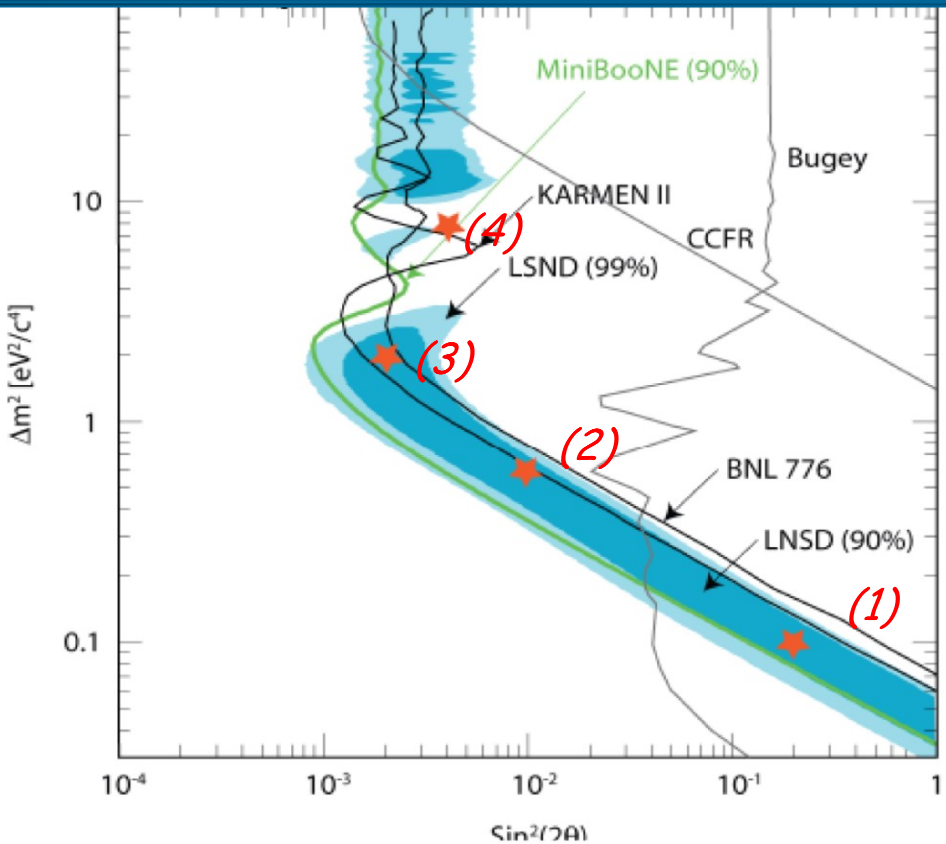
- Re-use the old TT7 tunnel and cavern to house primary beam line and target station
- Proton beam to be provide by CERN PS

- 150t liquid argon TPC near detector in building 181
- 600t liquid argon TPC far detector in building 191

T600 ICARUS detectors

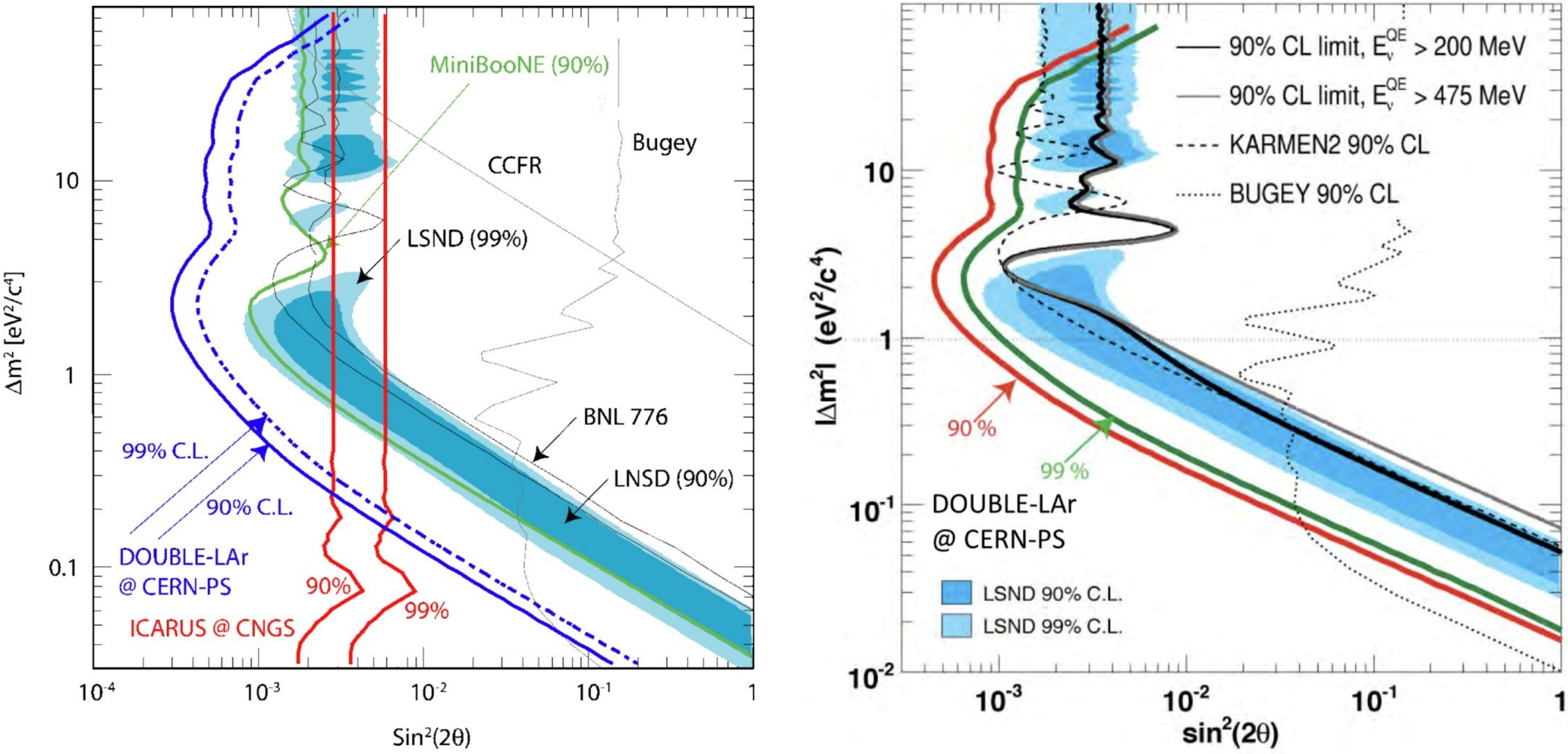
LSND direct determination of mass and mixing angle





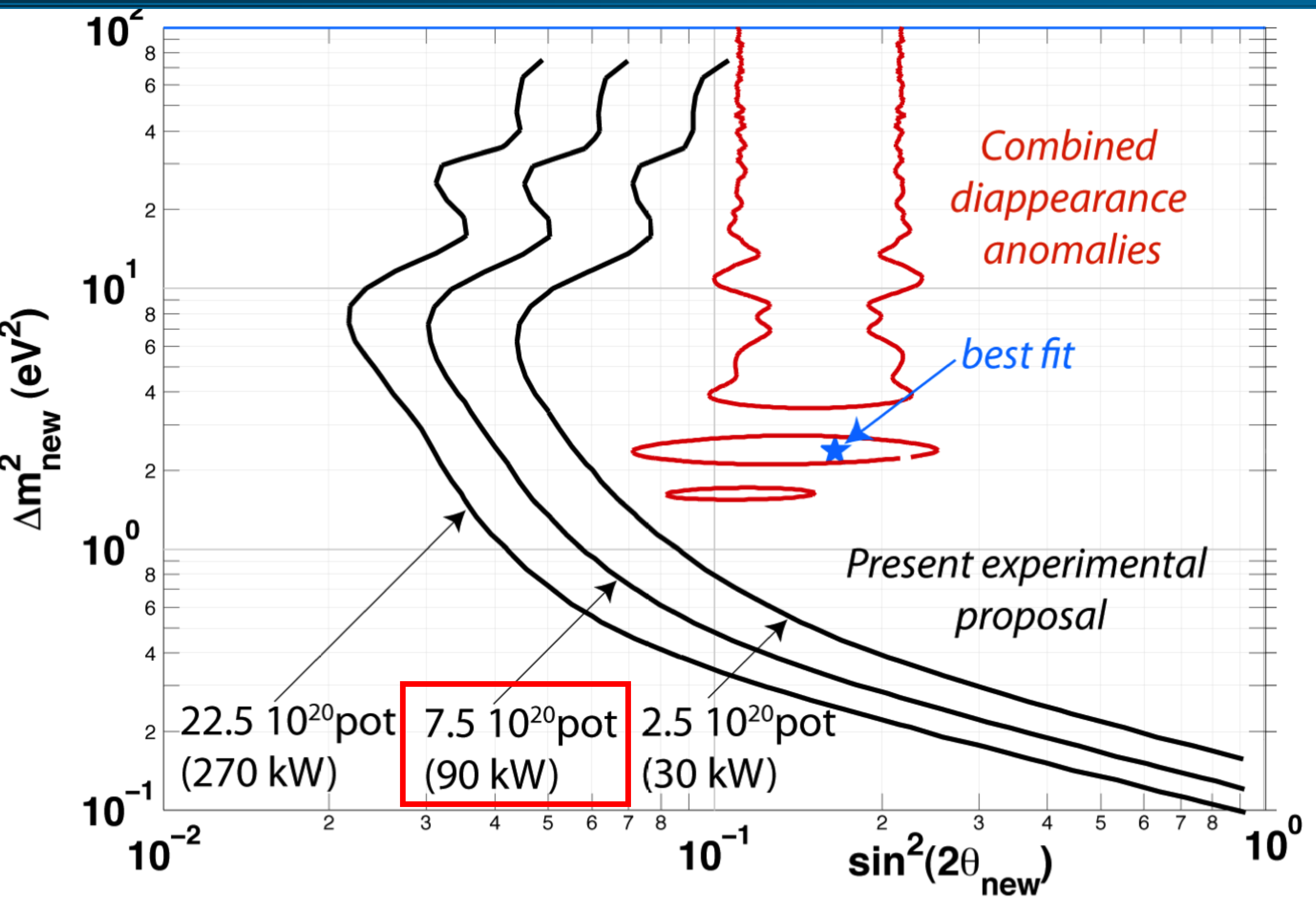
- The present method, unlike LNSD and MiniBooNE, determines both the mass difference and the value of the mixing angle.
- Very different and clearly distinguishable patterns (1-4) are possible, depending on the values in the (Δm^2 – $\sin^2 2\theta$) plane.
- The intrinsic ν −e background (5) is also shown.

Comparing LNSD like 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 and antineutrino. The expectations from one year of ν at CNGS2 are also shown.

Sensitivity to disappearance anomalies



- 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 are included (for each 100 MeV bins).

F.Mills,
July 2010

“ *** LSND effect rises from the dead… “

Thank you !