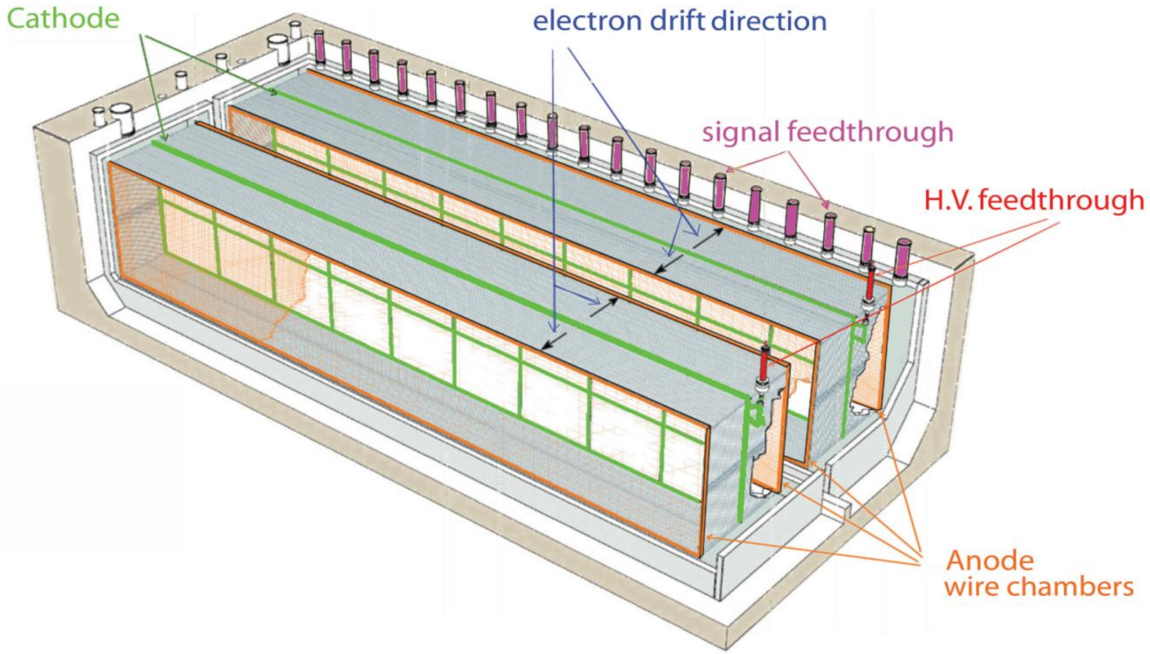
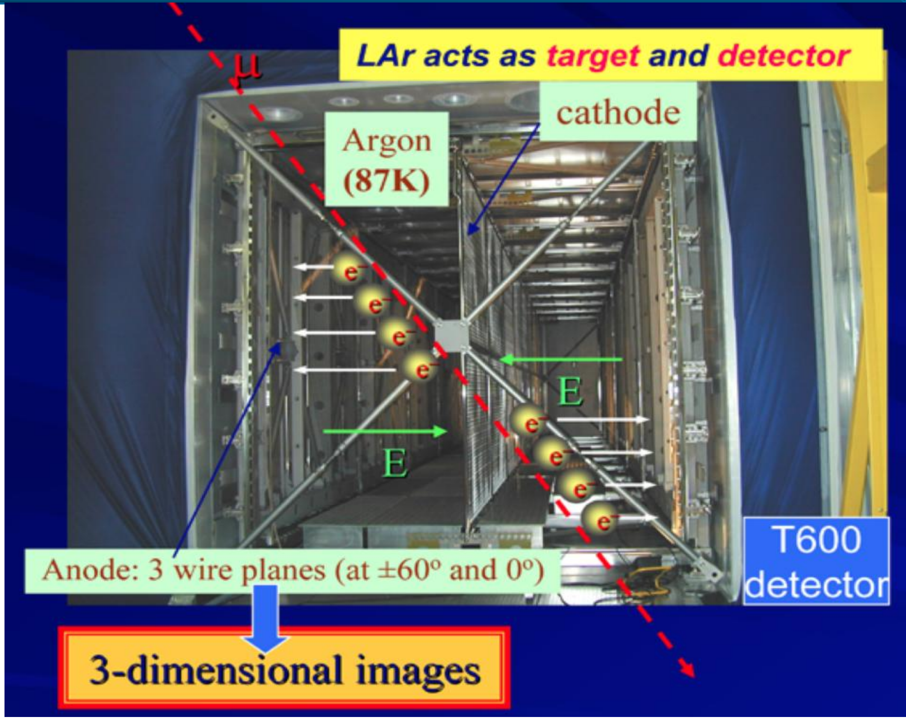
The ICARUS detector in underground Hall B of LNGS

The ICARUS T600 detector

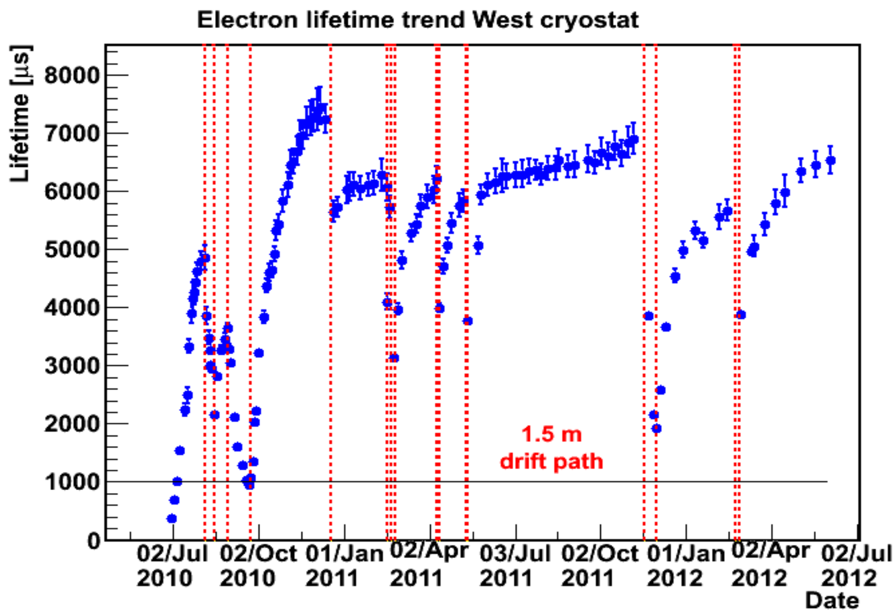


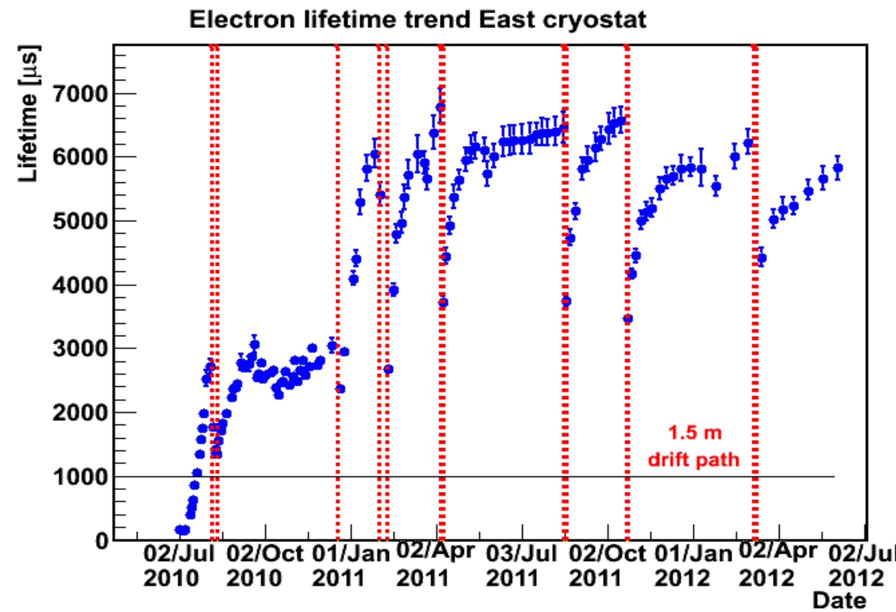


- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m (1 ms)
  - HV = -75 kV E = 0.5 kV/cm
  - v-drift = 1.55 mm/μs
- 4 wire chambers:
  - 2 chambers per module
  - 3 readout wire planes per chamber, wires at 0, ±60°
  - ≈ 54000 wires, 3 mm pitch, 3 mm plane spacing
- 20+54 PMTs , 8" Ø, for scintillation light:
  - VUV sensitive (128nm) with wave shifter (TPB)

Key feature: LAr purity from electro-negative molecules (O_2, H_2O,CO_2).
Now: 0.06 ppb (O_2 equivalent) -> 5 ms lifetime.

LAr purification





LAr continuously filtered, e^- life-time measured by charge attenuation study on cosmic μ tracks.

τ_{ele} > 5ms (~60 ppt $[O_2]_{eq}$) corresponding to a maximum charge attenuation of 17% at 1.5m

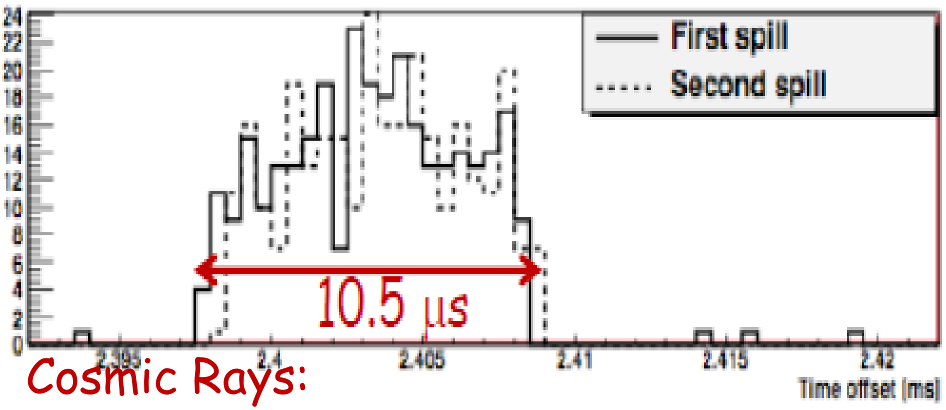
These results allow operation at larger drift distances

LAr recirculation system upgrade:

- 11 accidental stops up to now (LAr immersed pumps)
- New pumps with non-immersed motor already ordered – installation 2012. Similar pumps operating since 2010 on the LN2 circulation systems worked without any accidental stop.

ICARUS T600 trigger system

- CNGS:
  - CNGS "Early Warning" signal sent 80 ms before the SPS p extraction: allows opening a 60 ms wide gate around neutrino arrival time at LNGS.
  - PMT sum signal for each chamber in coincidence with the beam gate.



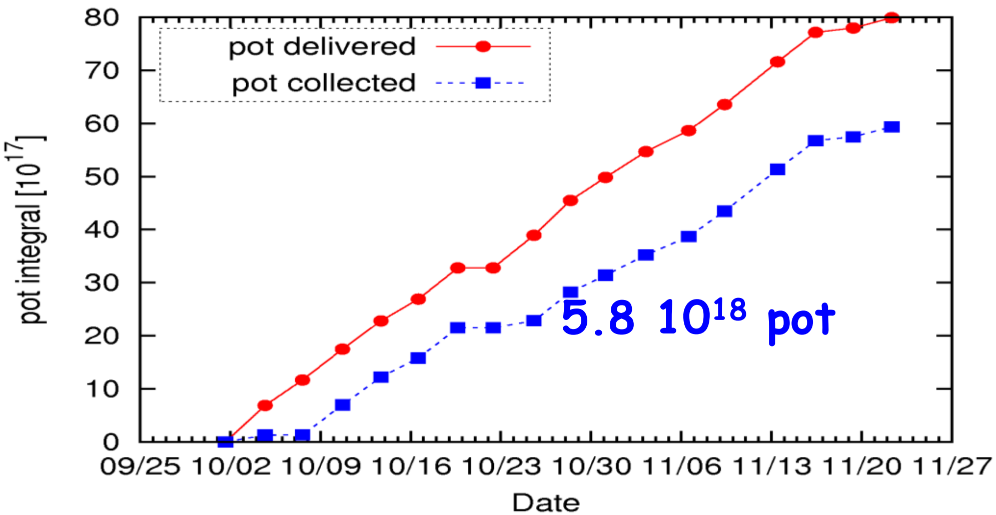
  - 2.40 ms offset value in agreement with 2.44 ms ν tof (40 µs fiber transit time from external lab to Hall B)
  - Spill duration reproduced (10.5µs), 1 mHz event rate , ≈ 80 events/day

- Cosmic Rays:
  - PMT sum signal: coincidence of two adjacent chambers (50% cathode transparency)
  - Globally 35 mHz trigger rate achieved: ~130 cosmic events/h after intervention on read-out, was 100 in 2011.
- Local trigger based on deposited charge (SuperDaedalus):
  - on-line hit-finding/zero-skipping algorithm implemented in FPGA's, used to improve trigger efficiency at low energy (below 500 MeV)

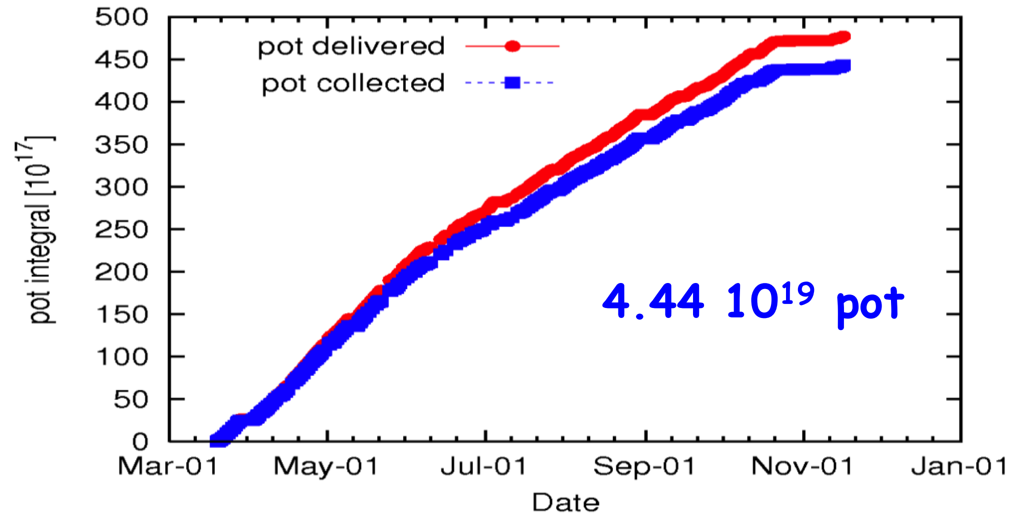
CNGS neutrino runs – summary

- **ICARUS T600 fully operational since Oct. 1st 2010**

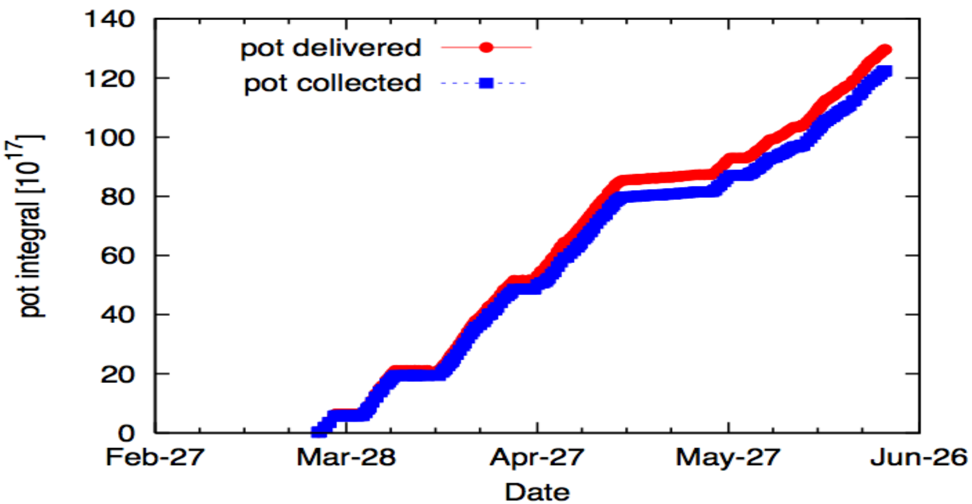
2010: Oct. 1st ÷ Nov. 22nd



2011: Mar. 19th ÷ Nov. 14th



2012: March 23rd ÷ now



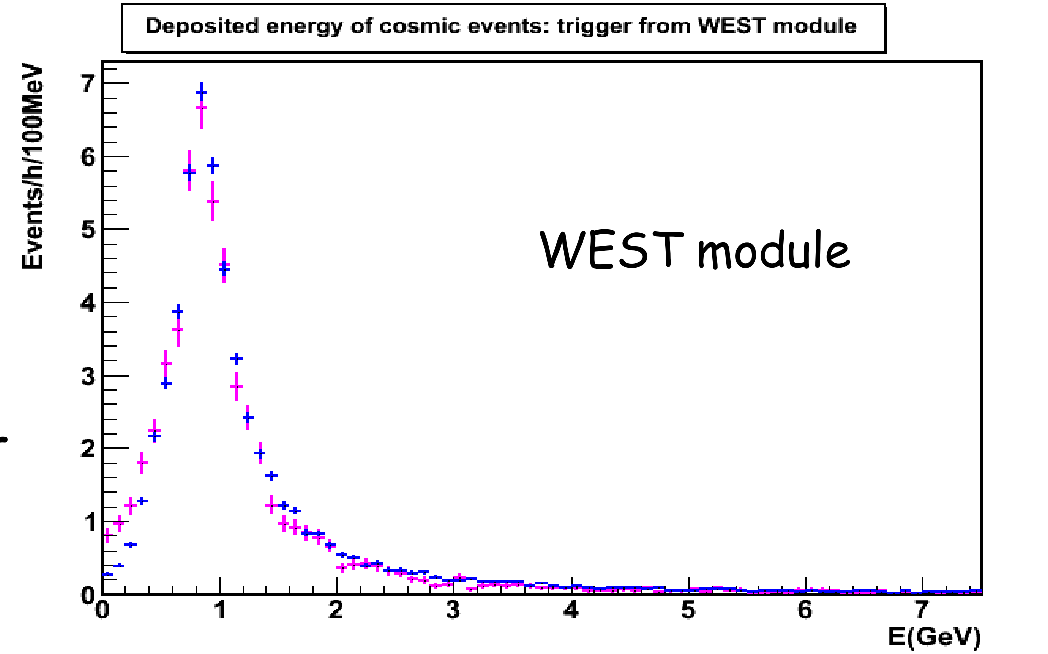
- **Detector live-time > 93%**
- November 2011 and May 2012: timing measurement with bunched beam.
- 2011 run: expected 1200 CC and 390 NC events (so far, for 2.7 10^{19} pot 925 ν interactions in 447 t fiducial volume with ~ 3% detector electronic inefficiency – DAQ crate off; 975 interactions expected from MC assuming full detector efficiency).

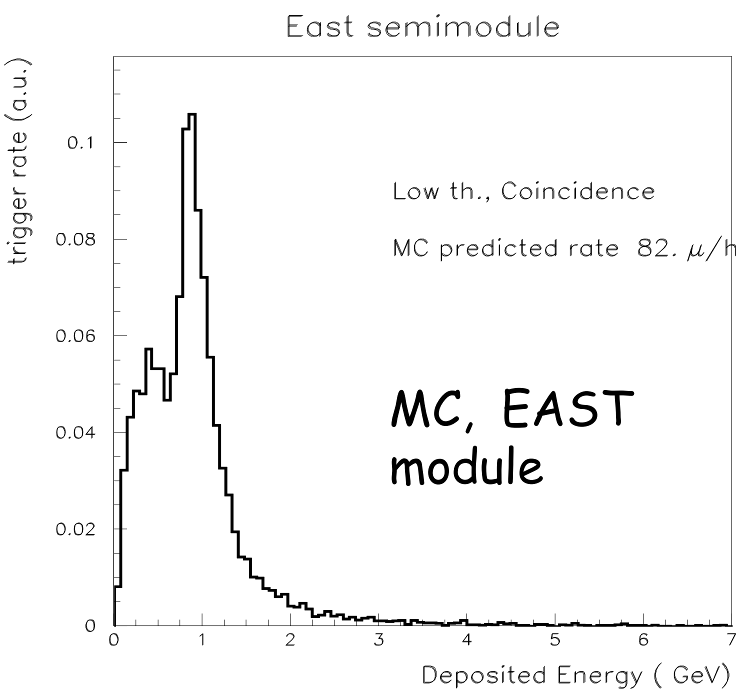
Progress on data analysis

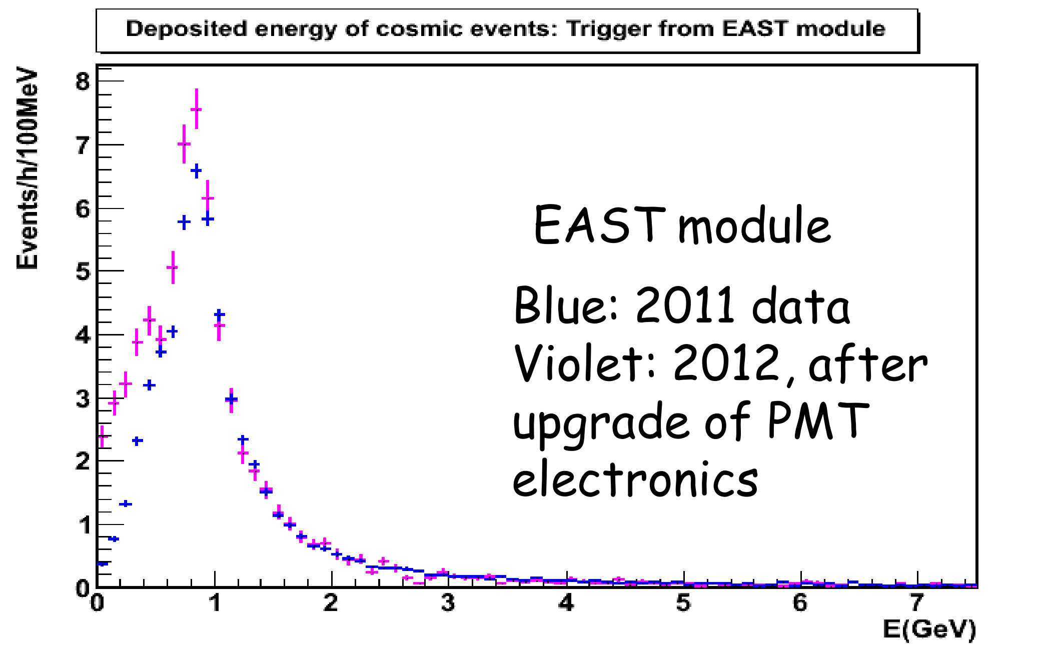
- The analysis of CNGS neutrino events is ongoing.
- First step on cosmic-ray analysis: automatic reconstruction of deposited energy from c-muons in agreement with expectations
- In parallel, optimization of analysis tools in term of performance, calibrations and event reconstruction:
  - Progresses in 3D reconstruction, leading to better performance especially for horizontal tracks
  - Momentum measurement by M.S. for escaping muons, under refinement
  - Progresses in the Particle Identification Algorithm
  - Progresses in automatic reconstruction: vertex finding, clustering, track finding
  - Developments on tools for calorimetric reconstruction

Cosmic ray muon spectrum

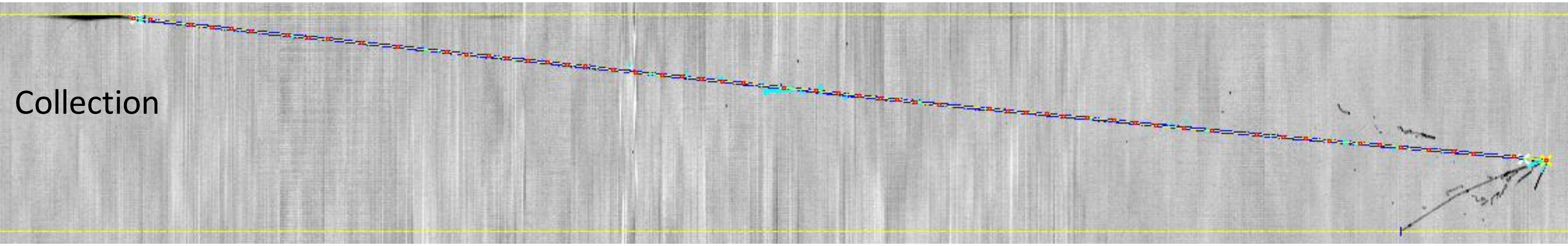
- CR data automatically filtered:
  - Skip fake triggers
  - Find "good" muons for purity
  - First reconstruction
- Good agreement of energy spectrum with MC expectation is found (MC simulation includes light collection and trigger conditions).

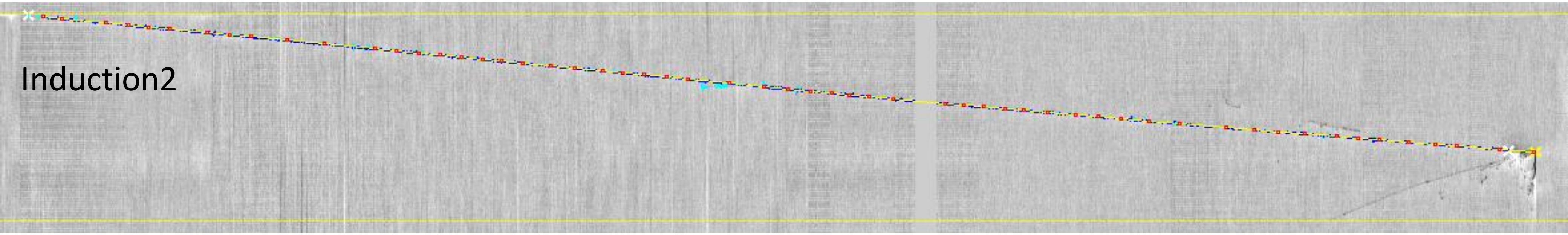




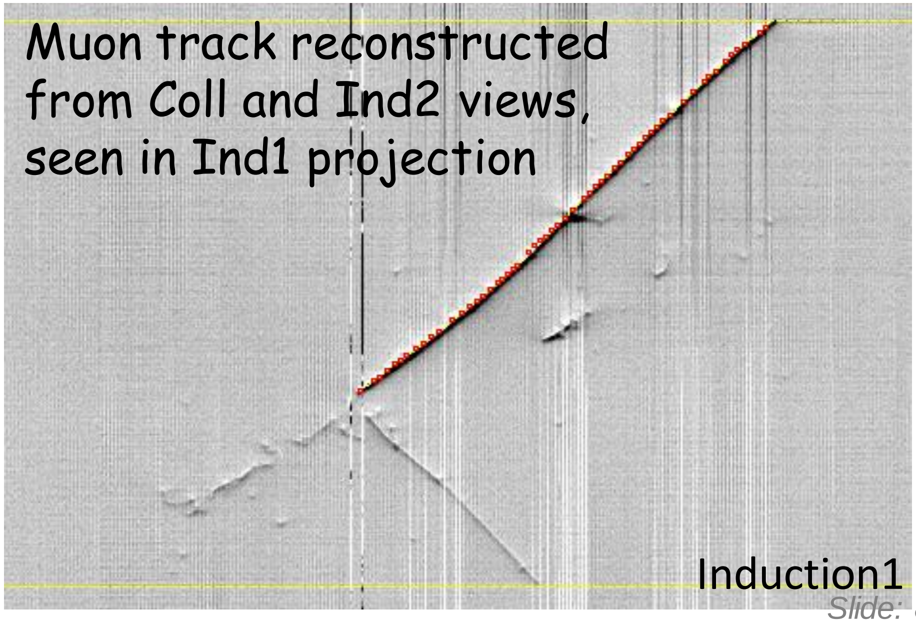


3D reconstruction



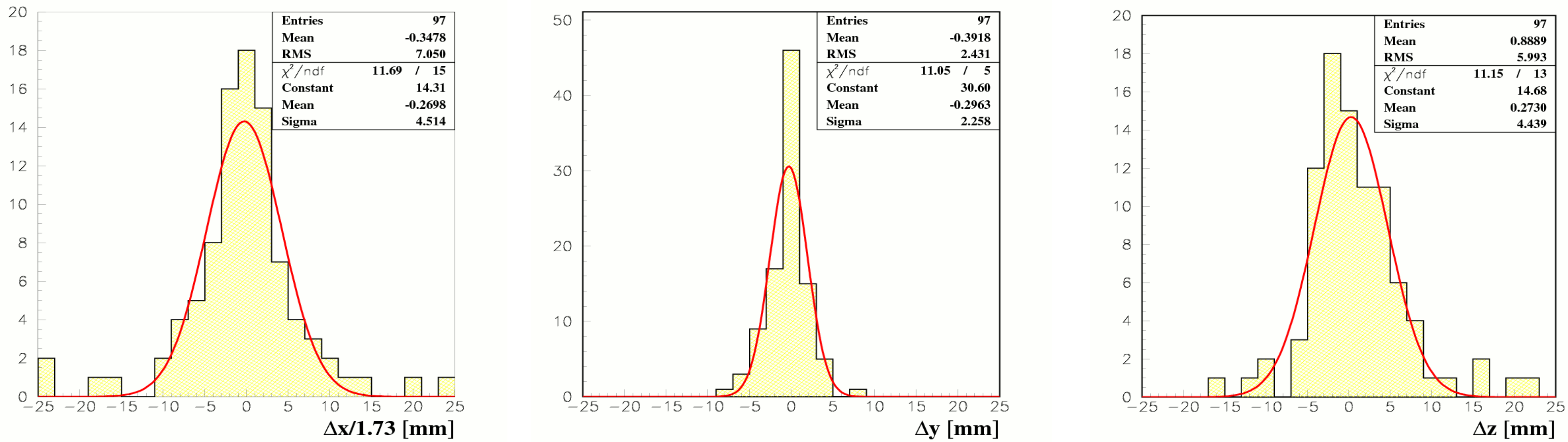


NEW: Single **3D** PLA-fit optimized to all available hits in the **2D** wire planes and all identified **3D** reference points (vertices, delta rays). **2D** hit-to-hit associations are not longer needed -> missing parts in a single view and horizontal tracks are now accepted.



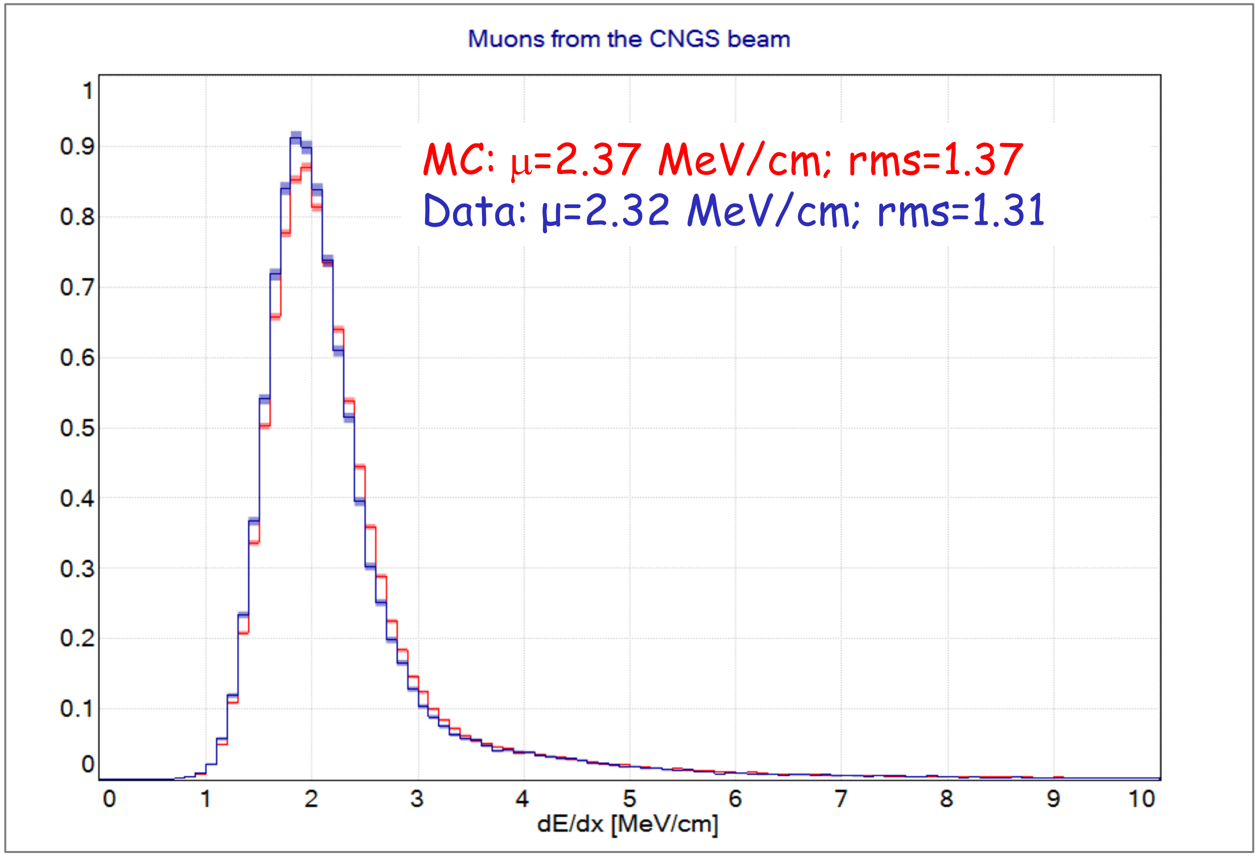
Automation of the event reconstruction

- A challenging task due to the complexity of high energy CNGS events.
- Algorithm for identification and reconstruction of the promary vertex exploits relative angular distribution of hit positions. Identified 2D vertices are merged together to recontruct 3D vertex.
- Validation with visually identified CNGS vertices. Distributions of the distance between reconstructed and visually identified vertex position.



Obtained, with real CNGS data, algorithm efficiency ~ 97%.

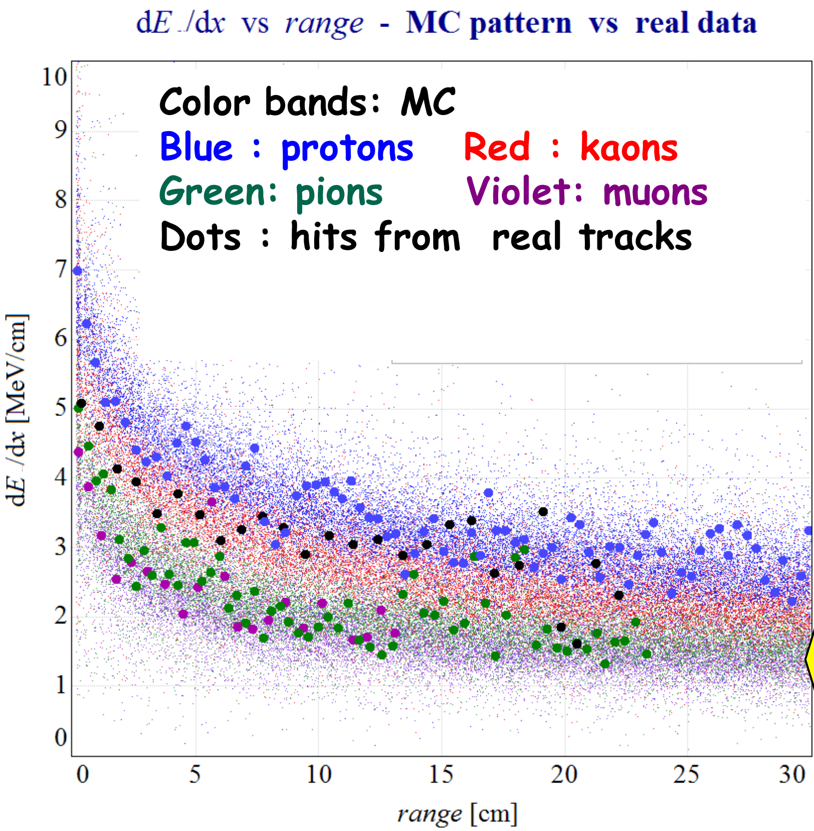
m.i.p. calibration with CNGS muons

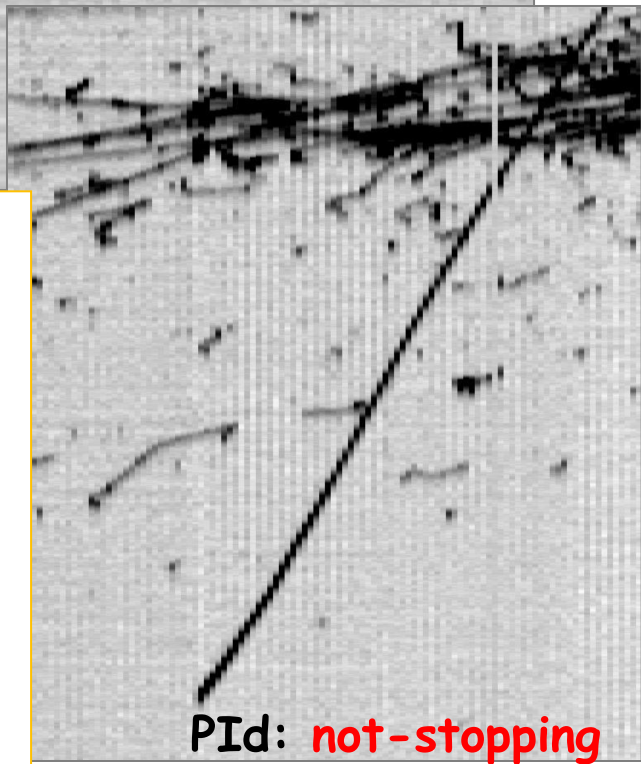


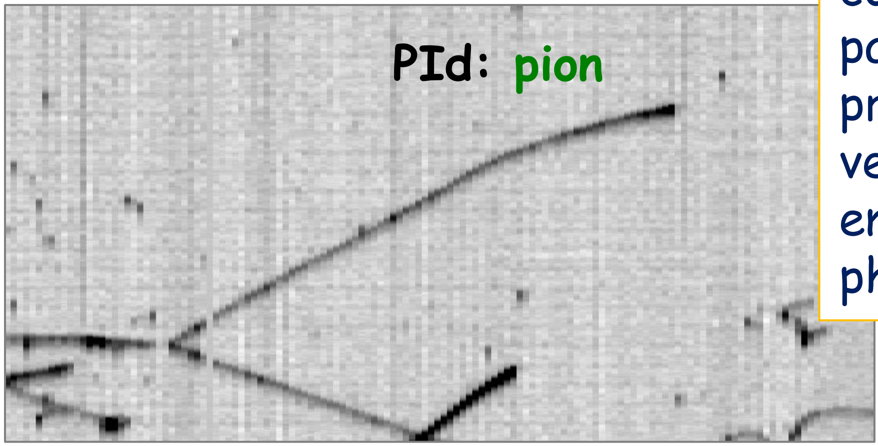
dE/dx distribution for real and MC muon tracks from CNGS events

- Tracks reconstructed in 3D. δ rays and showers rejected. Same reconstruction on MC muons with CNGS spectrum.
- Very good agreement (~ 2-3%) - residual small difference due to noise patterns and their effects on δ ray.

Calibration with stopping particles: examples



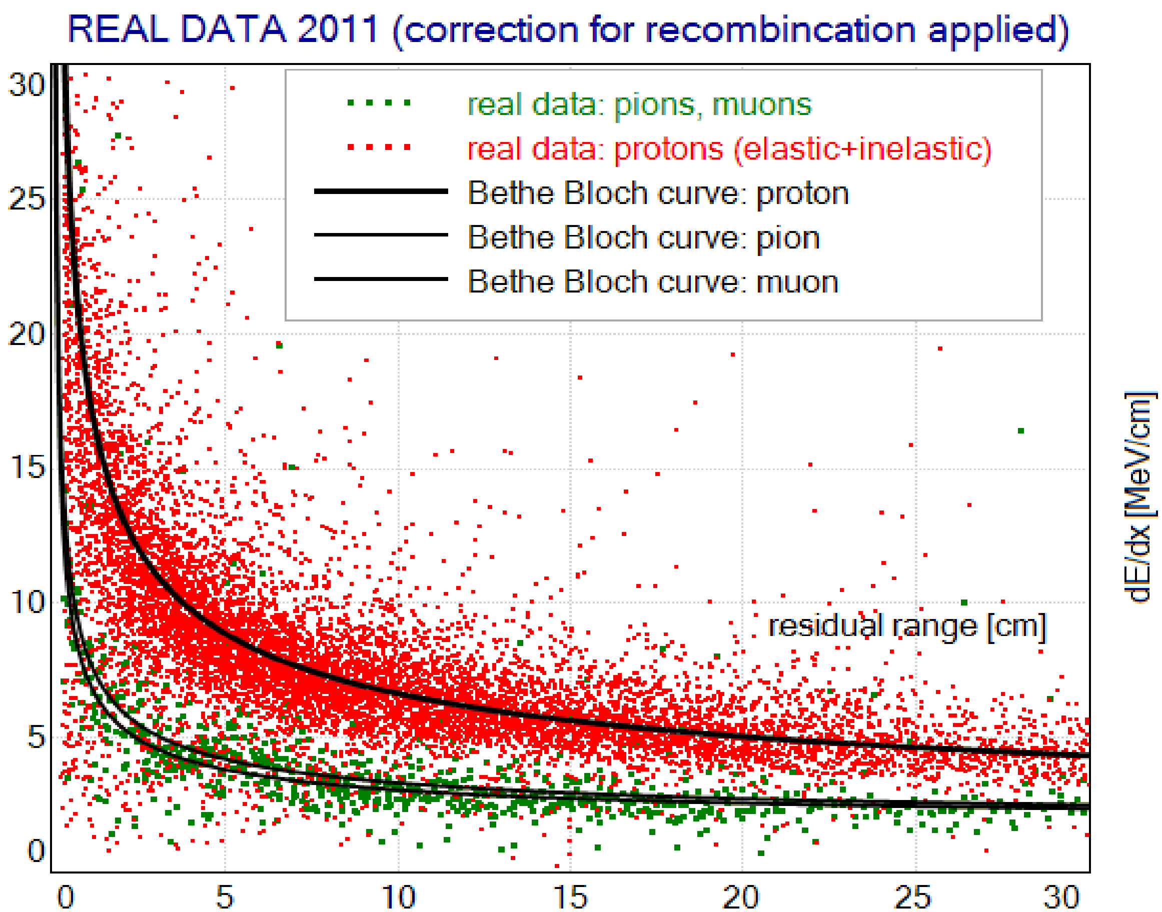




- Deposited dE/dx vs residual range
- No quenching correction
- Black dots: not consistent with any pattern, most probably protons interacting at very low energy with emission of neutrons and photons

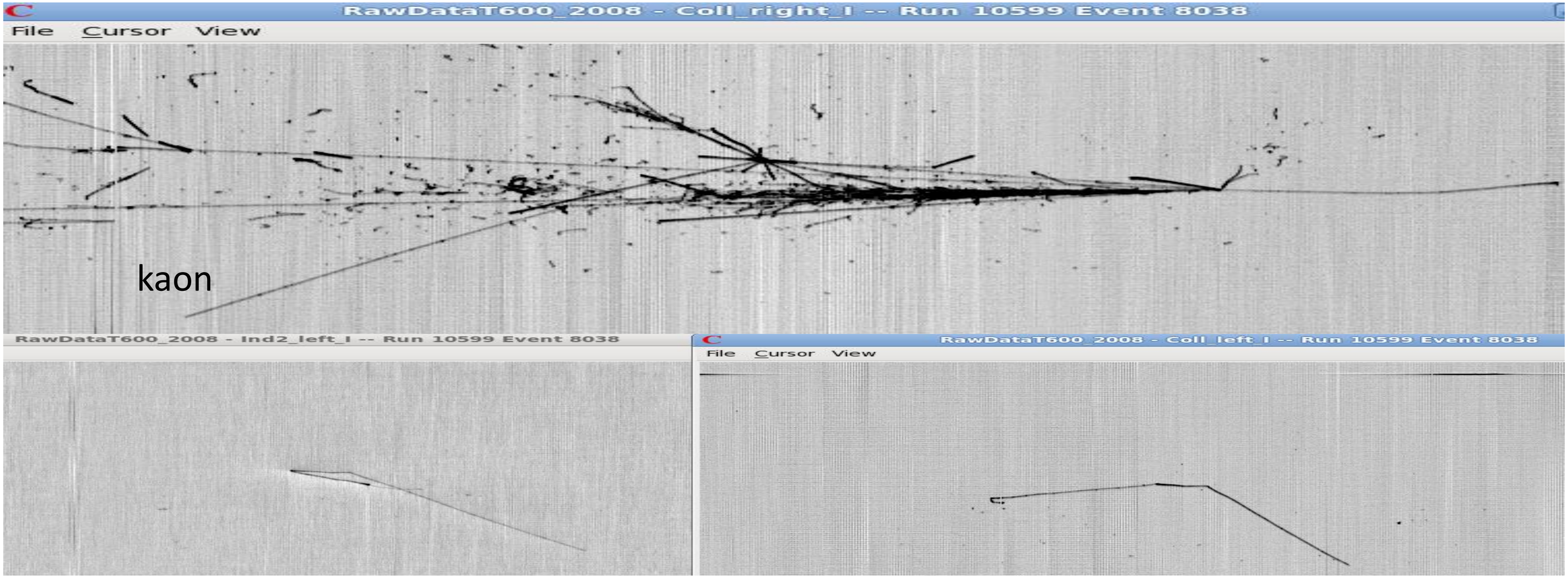
Methods for identification of non-stopping particles are under development (including quenching correction)

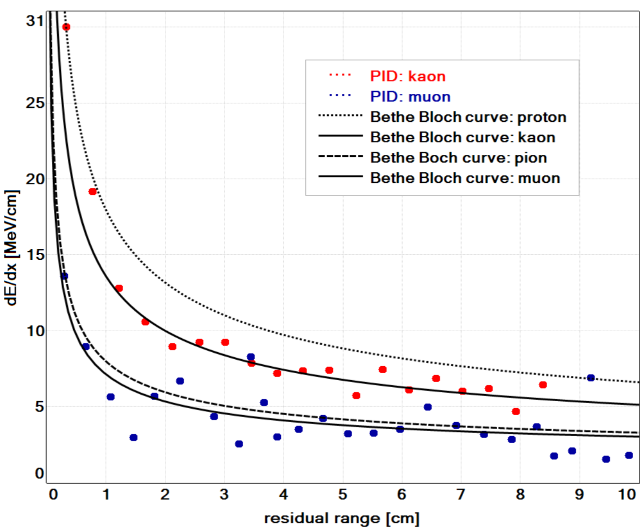
dE/dx for stopping particles



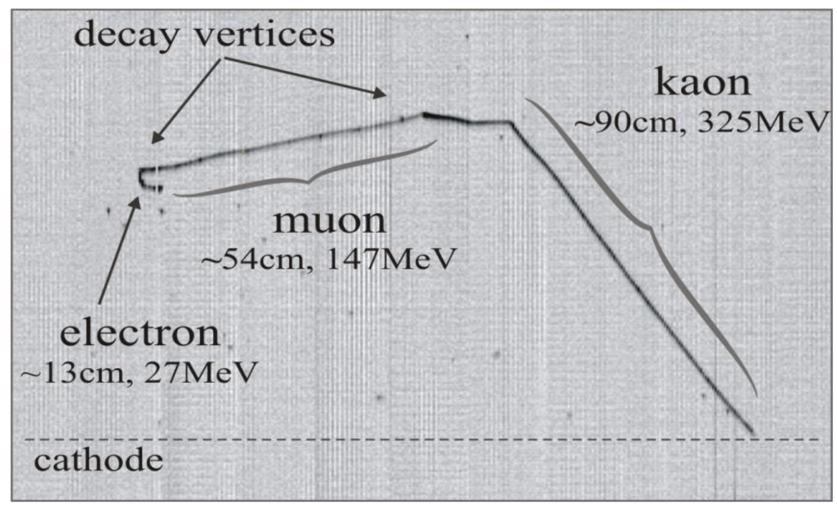
dE/dx as a function of residual range for stopping particles, 2011 data sample, quenching correction applied.

Example of data: kaon decay in a CNGS event





Corresponding PId patterns



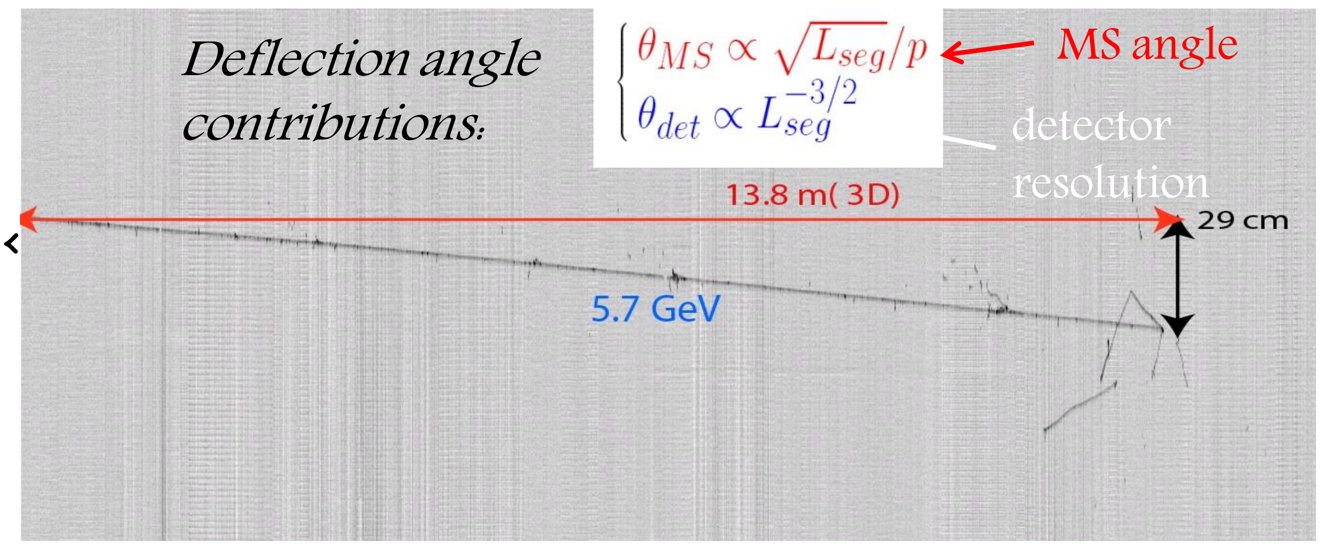
Muon momentum by multiple scattering

- Key tool to measure momentum of non-contained μ's: essential for ν_μ CC event reconstruction.

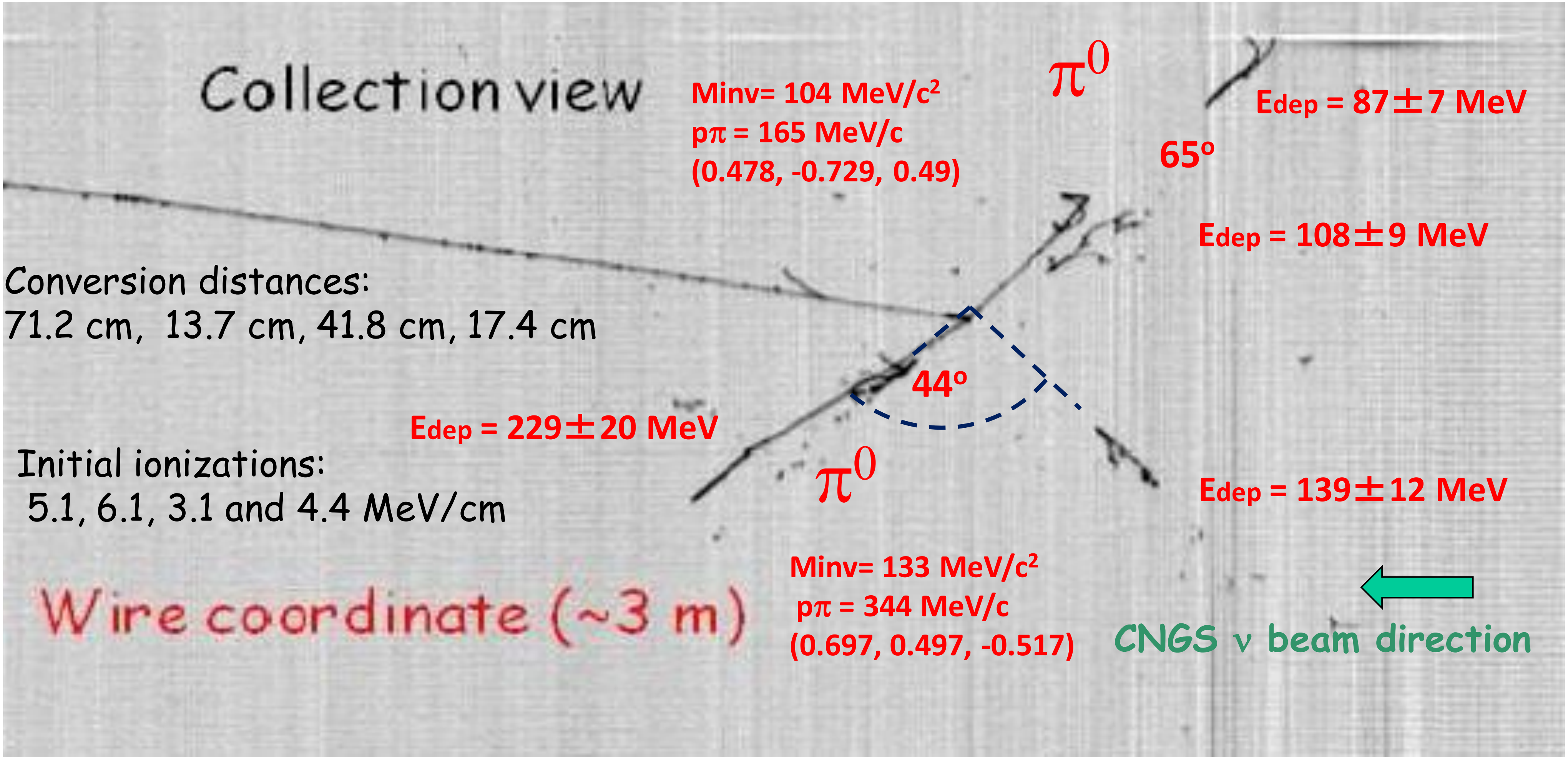
Two methods under development:

- 2D track projection in Coll. view is repeatedly segmented at various segment lengths (L_{seg}); deflection angles θ along the track are extracted by linear fit; to estimate muon momentum the distribution of $\theta(L_{seg})$ is fitted – the opimization of the track segmentation not needed. *(A.Ferrari, C.Rubbia – ICARUS TN 99)*
- Kalman fit of the segmented track; muon momentum p extracted from deflection angle θ. *(ICARUS Coll. - Eur. Phys. J C48 (2006) 667)*

- Both methods under validation
- Δp/p depends mainly on the track length: for CNGS Δp/p < 20% expected on average.



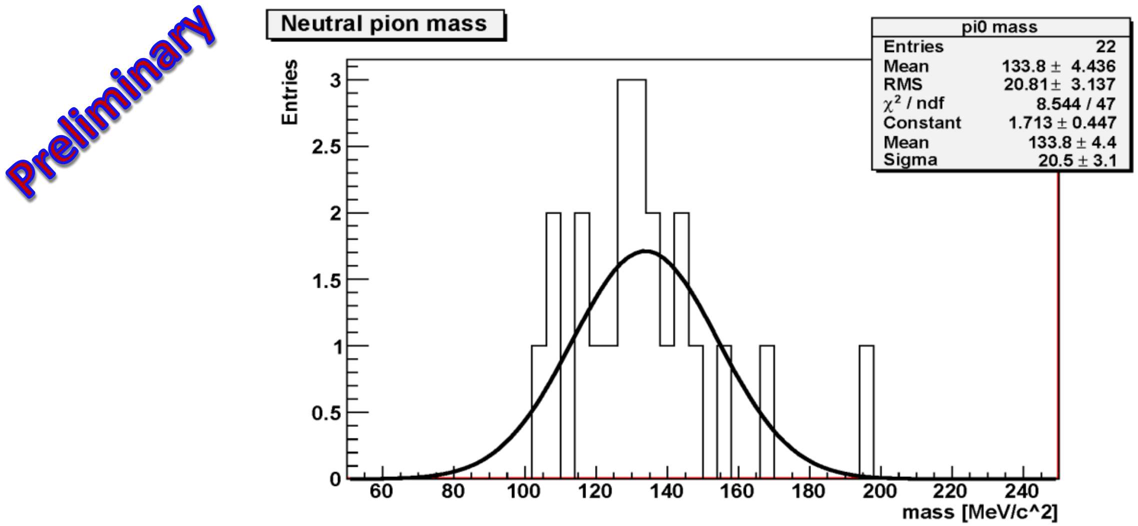
π^0 identification / reconstruction in CNGS events (1)



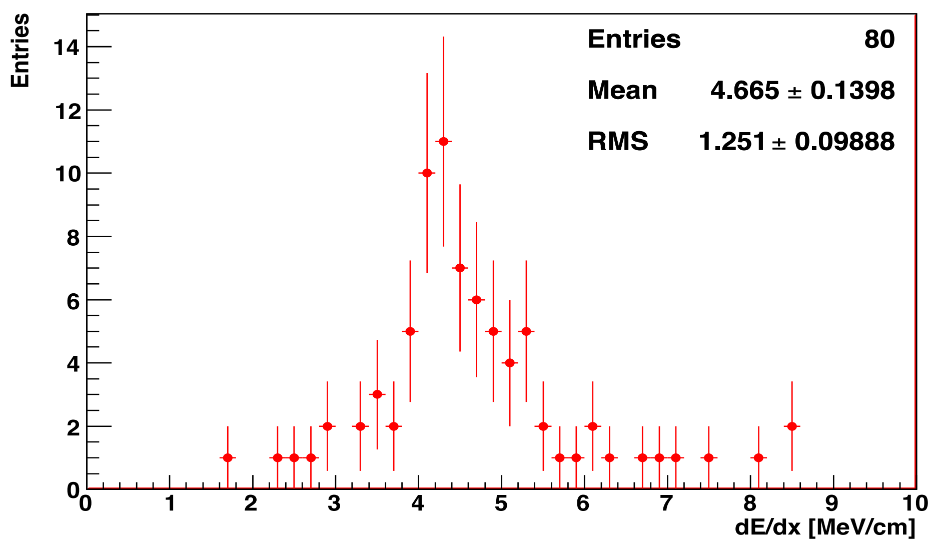
π^0 showers identified by:

- 2γ conversion separated from primary vertex
- Reconstruction of $\gamma\gamma$ invariant mass
- Ionization in the first segment of showers (1 or 2 mips)

π^0 identification / reconstruction in CNGS events (2)

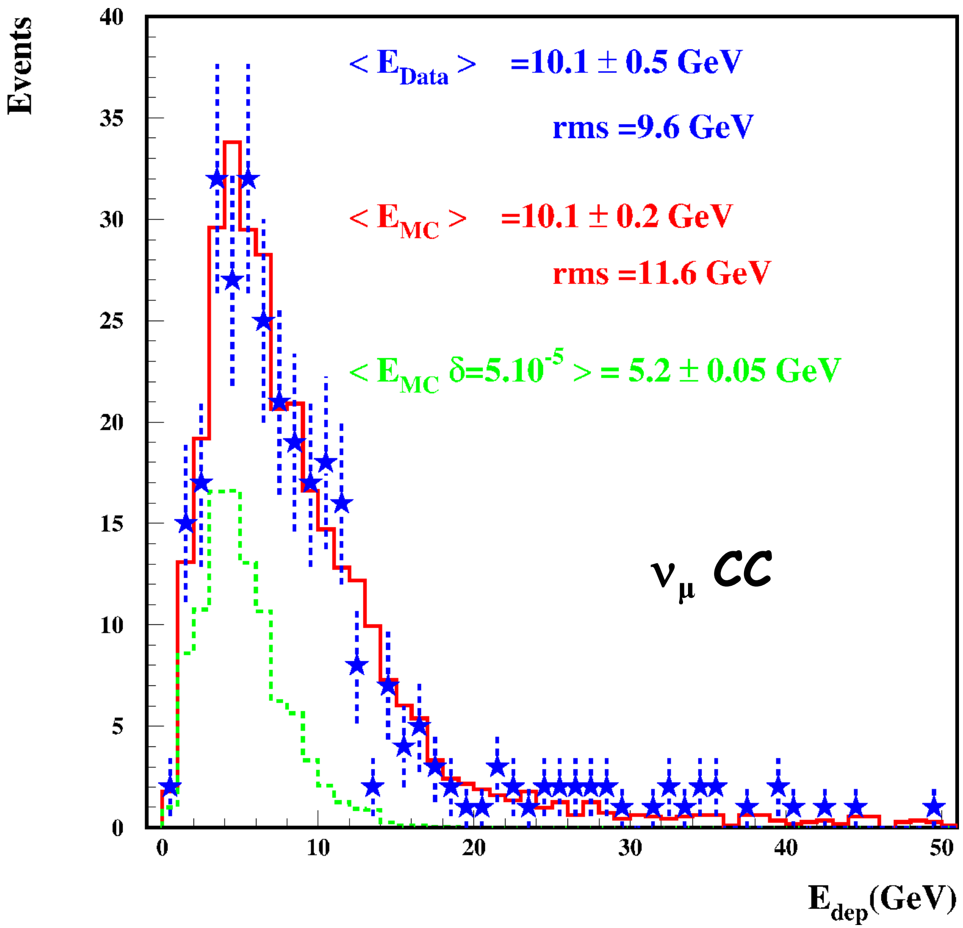


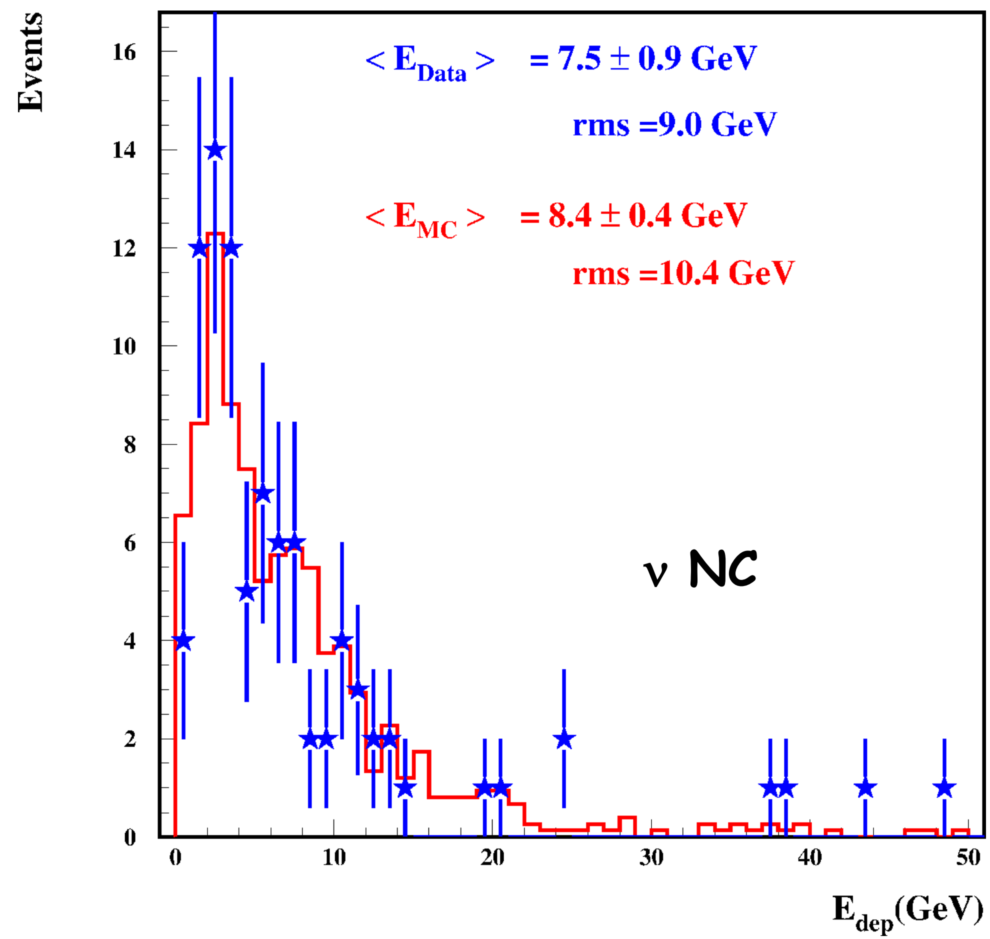
Mean: 133.8 ± 4.4(stat) ± 4 (syst) MeV/c^2
σ = 20.5 MeV



dE/dx in the first 2.5 cm of candidate photon shower

Total energy deposition in CNGS n events





- Comparison of the predicted (full MC) and detected deposited energy spectrum from NC and CC events on 2010 statistics and a subset of the 2011 statistics
- Used for the “superluminal” neutrino searches

Search for superluminal ν's radiative processes in ICARUS
Phys. Lett. B-711 (2012) 270-275

- Cohen and Glashow [Phys. Rev. Lett., 107 (2011) 181803] argued that superluminal ν should loose energy mainly via e^+e^- bremsstrahlung, on average $0.78 \cdot E_\nu$ energy loss/emission
- Full FLUKA simulation of the process kinematics, folded in the CNGS beam, studied as a function of $\delta = (v_\nu^2 - c^2)/c^2$

  For $\delta = 5\ 10^{-5}$ (OPERA first claim):

  - full ν event suppression for E > 30 GeV
  - $\sim 10^7$ e^+e^- pairs $/10^{19}$ pot/kt

- Effects searched in $6.7\ 10^{18}$ pot·kt ICARUS exposure (2010/11) to CNGS
  - No spectrum suppression found in both NC , CC data (~ 400 events)
  - No e^+e^- pair bremsstrahlung event candidate found

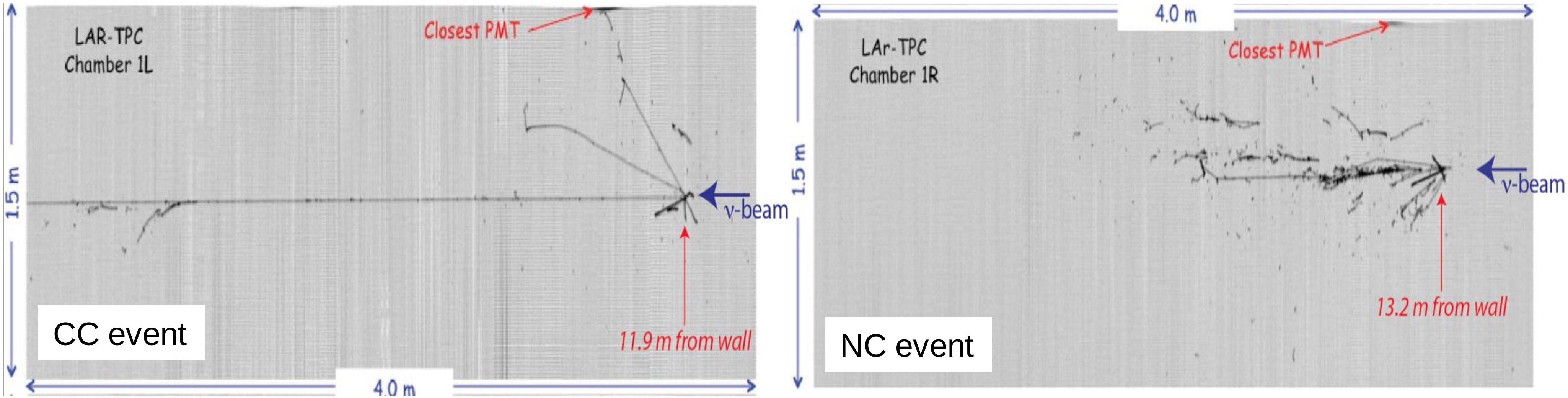
- The lack of pair in CNGS ICARUS 2010/2011 data, sets the limit:

$$\delta = (v_\nu^2 - c^2)/c^2 < 2.5\ 10^{-8}\ \ 90\%\ CL$$

- comparable to the SuperK atm. limit $\delta < 1.4\ 10^{-8}$, somewhat larger than the lower energy velocity constraint $\delta < 4\ 10^{-9}$ from SN1987A.

Neutrino time of flight with CNGS bunched beam

- 2011 low intensity bunched beam: 4 bunches/spill, 3 ns FWHM, 524 ns separation.
- ICARUS observed 7 beam-associated events, (~2.2 10^{16} pot collected): 2 CC ν_μ events, 1 NC ν event, 1 stopping + 3 crossing μ's from ν interaction in upstream rock.
- Arrival time determined using the prompt scintillation light signals (~ns resolution) and the accurate localization of each event w.r.t. PMT position.

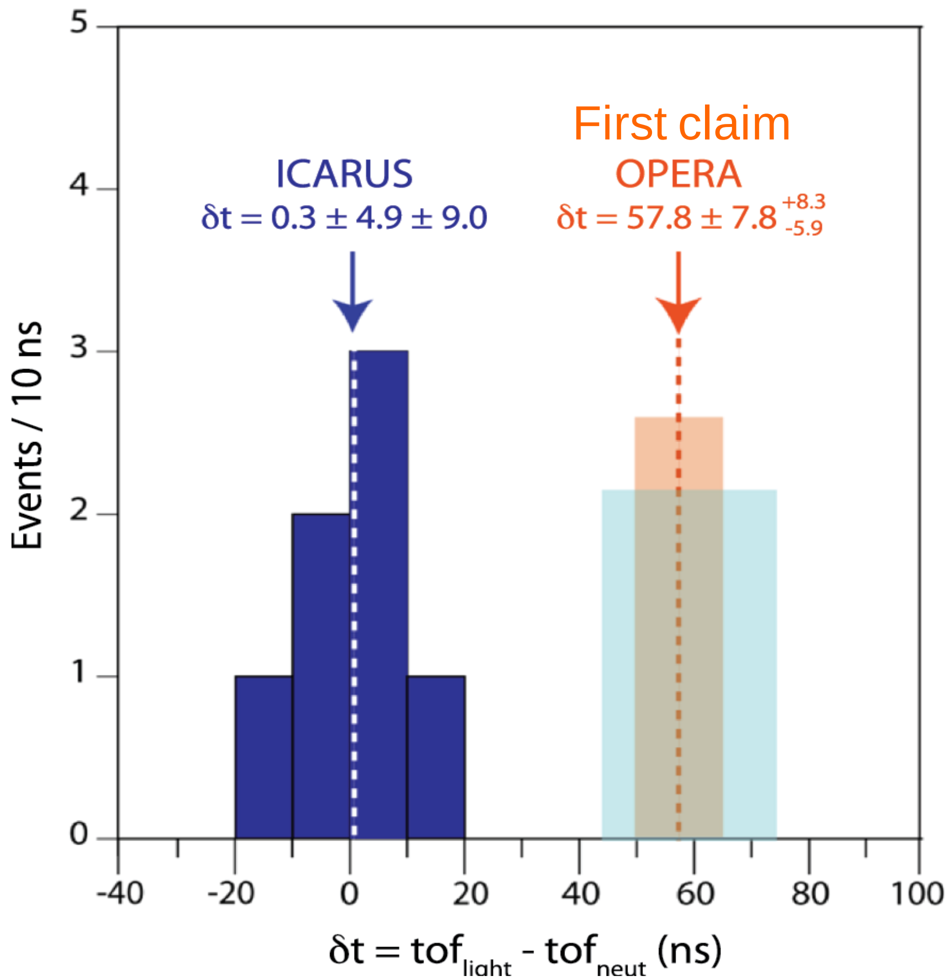


Neutrino time of flight: 2011 result

Phys. Lett. B 713 (2012) 17-22

- All fixed delays/propagation times calibrated (thanks also to LNGS and CERN)
- Baseline estimation relies on existing available geodesy data (OPERA/LNGS)
- Variable corrections to GPS from OPERA/CERN recipe

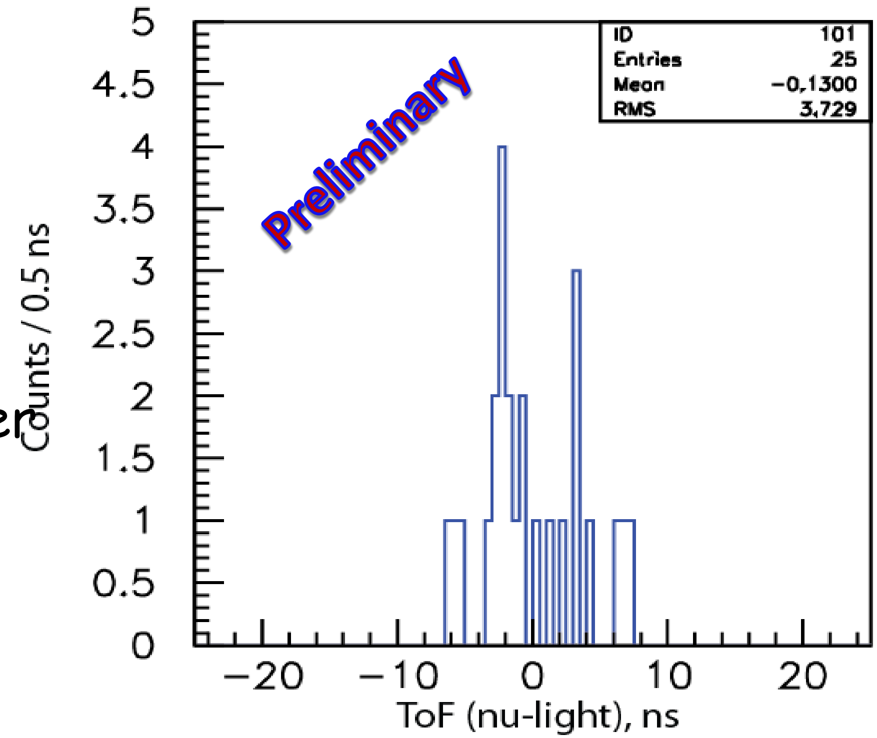
- The average δt = $tof_c - tof_\nu$ of the 7 events is + 0.3 ns with an r.m.s. of 10.5 ns; statistical error on the average = 4.9 ns; systematic error ~ 9 ns



Data taking/analysis with 2012 bunched CNGS

- New beam structure: 64 bunches, 3 ns width, 100 ns spacing.
- 2011 system + Borexino + White Rabbit (CERN synchronization system)
- Beam related events observed in ICARUS (for ~1.8 10^{17} pot):
  - 16 crossing μ's (1 stopping) from the upstream rock;
  - 7 CC ν_μ events;
  - 2 NC ν event.

- Analysis in progress:
  - **PRELIMINARY** results compatible with 2011 value: 0 to 3 ns depending on timing synchronization path;
  - distribution r.m.s: ~ 3.7 ns (10.5 in 2011)
  - Systematics corrections and offset under final evaluation (PMT-DAQ propagation chain, topological corrections, timing delay).



A proposal for short baseline neutrino "anomalies" with innovative LAr imaging detectors coupled with large muon spectrometers

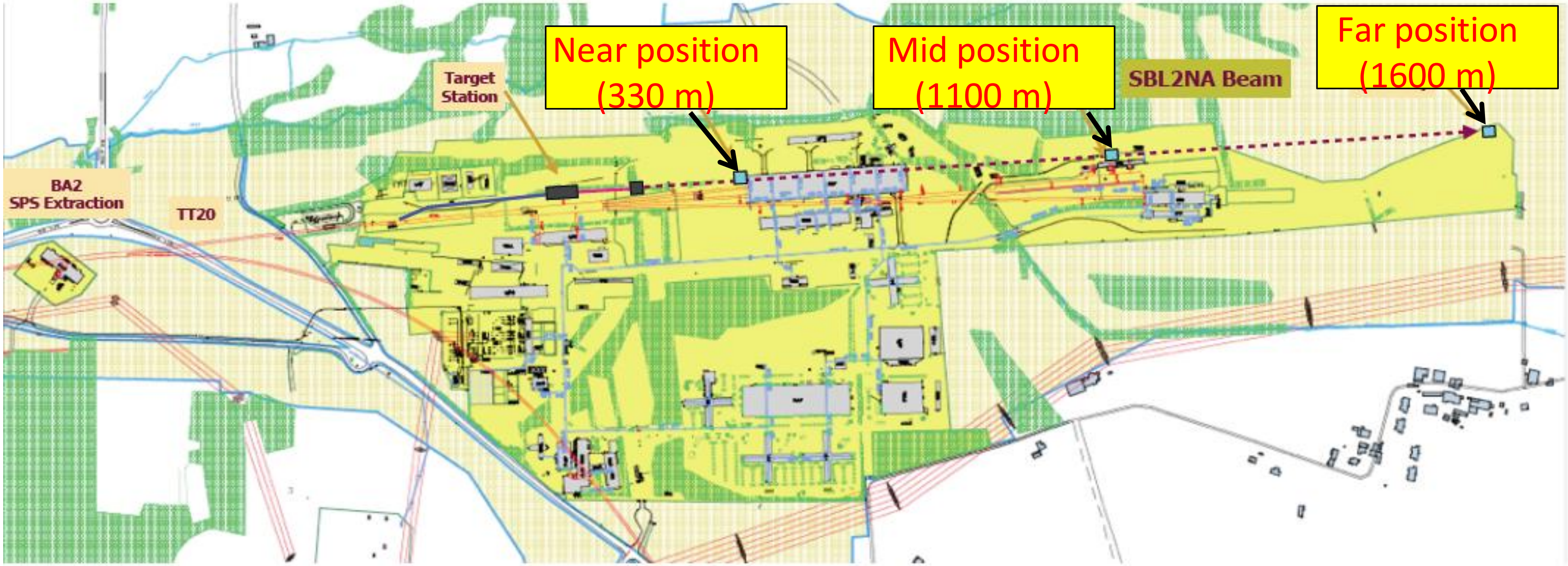
SPSC-P347

(ICARUS + NESSIE)

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 reported, although not in an entirely conclusive level, namely:
  - observation of *excess* ν_e electrons originated by initial anti-ν_μ events from accelerators (LNSD/MiniBooNE)
  - the apparent *disappearance signal* in the anti-ν_e events detected from (1) near-by nuclear reactors and (2) from Mega-Curie k-capture calibration sources in the Gallium experiments which detect solar ν_e
- 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 angles.
- The existence of additional neutrino states may be also hinted — or at least not excluded — by cosmological data

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

Neutrino and antineutrino beams, energy around 2GeV

Far detector: T600 + magnetic spectrometer

Near detector: new 150 ton Lar + magnetic spectrometer

➔Nue appearance, nue disappearance, numu disappearance, low systematic because of near-far comparison

attivita' del Gruppo di Milano 2011-2012

- Software di ricostruzione off-line: coordinamento e partecipazione allo sviluppo
- Partecipazione alla presa dati
- Supporto al Technical Coordinator (da parte di A.Scaramelli)
- Analisi dati (ongoing)
- Sviluppi futuri: partecipazione alla proposta per una ricerca di oscillazioni "alla LSND" con due rivelatori LAr TPC sul fascio del SPS al CERN

Futuro

Fine 2012 o primi mesi 2013: stop del fascio CNGS

- T600 in operazione per alcuni mesi, proton decay, atmosferici, test criogenia
- Possibilmente : fine 2013 e inizio 2014 : decommissioning, trasporto al CERN

attivita' del Gruppo di Milano 2012-2013

- 1.5 F.T.E

- Prosecuzione del coordinamento software
- Partecipazione alla presa dati T600
- Partecipazione all'analisi dati
- Confronto dati/Montecarlo e possibili sviluppi MC
- Supporto all'esperimento

- Ottimizzazione target/ottica e studi di fisica per SPS-NF
- Partecipazione decommissioning T600 -
- Supporto tecnico per eventuale spostamento T600
- Partecipazione studi di ingegneria/criogenia per nuova installazione al CERN

Anagrafica Icarus Milano

A.Cesana	100
P.R. Sala	50
A. Scaramelli	~~100~~ (age over 70)
Totale FTE:	1.5

Possibile richiesta di partecipazione di un tecnico per decommissioning

PRELIMINARE: preventivi 2012

Missioni interne (meetings nazionali, attivita' ai LNGS)	**15**
Missioni estere (meetings, coll. CERN, CNGS,SPS)	**6**
Consumo supporti per il calcolo, metabolismo	**2**
Totale	**29**

+ fondi sub-judice per SPS-NF, da quantificare in riunione 11-7

end

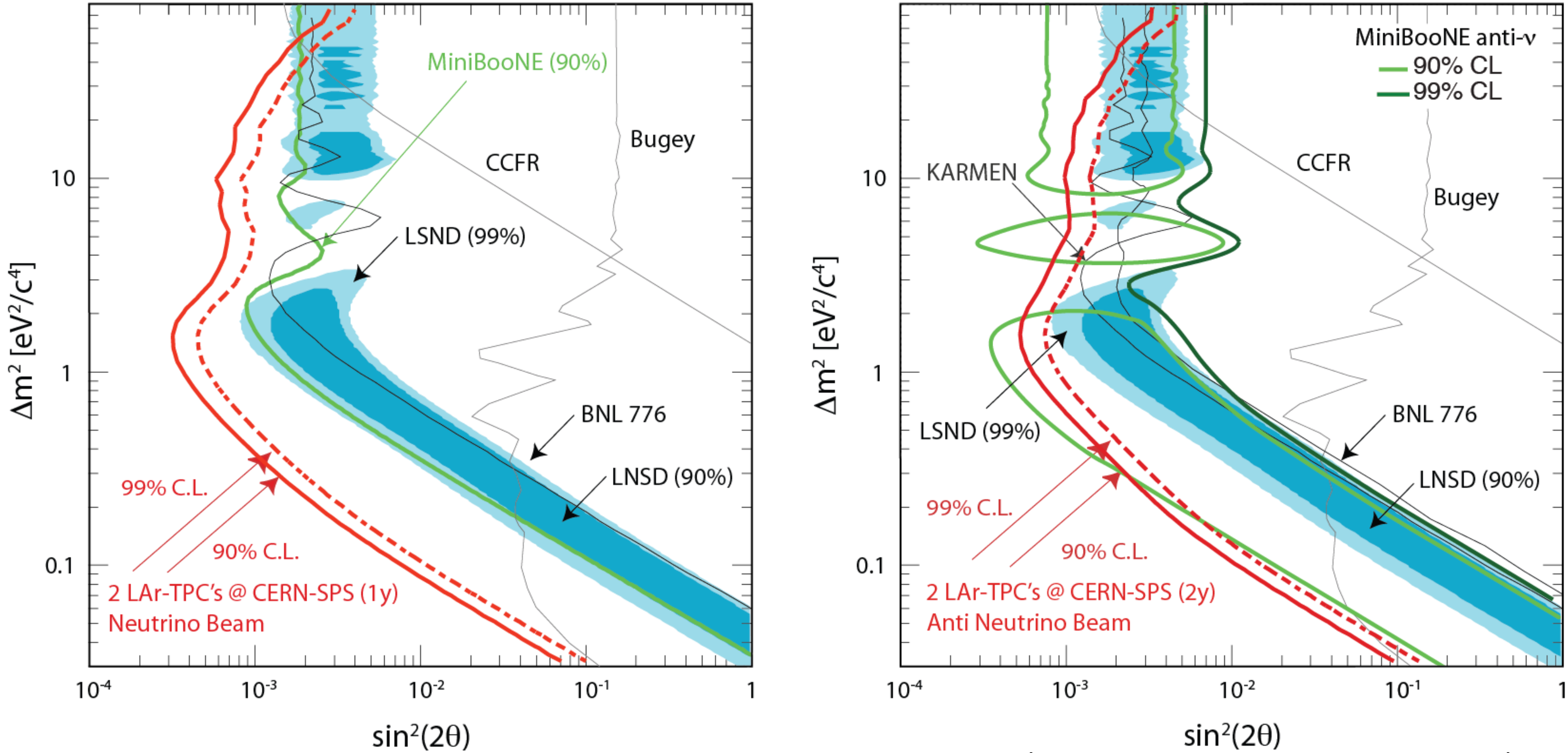
Expected signals for LSND/MiniBooNE anomalies

- Event rates for the near and far detectors given for 4.5 10^{19} pot. The oscillated signals are clustered below 3 GeV of visible energy
- Values for: $\sin^2(2\theta) = 0.002$, $\Delta m^2 = 2\ eV^2$ are reported as example

		NEAR (neg. foc.)	NEAR (pos. foc.)	FAR (neg. foc.)	FAR (pos. foc.)
produced	$\nu_e + \bar{\nu}_e$ (LAr)	35 K	54 K	4.2 K	6.4 K
produced	$\nu_\mu + \bar{\nu}_\mu$ (LAr)	2030 K	5250 K	270 K	670 K
produced	Appear. test point	590	1900	360	914
detected	ν_μ (LAr+NESSiE)	230 K	1200 K	21 K	110 K
detected	ν_μ (NESSiE)	1150 K	3600 K	94 K	280 K
detected	$\bar{\nu}_\mu$ (Lar+NESSiE)	370 K	56 K	33 K	6.9 K
detected	$\bar{\nu}_\mu$ (NESSiE)	1100 k	300 K	89 K	22 K
detected	Disappear. test point	1840	4700	1700	5000

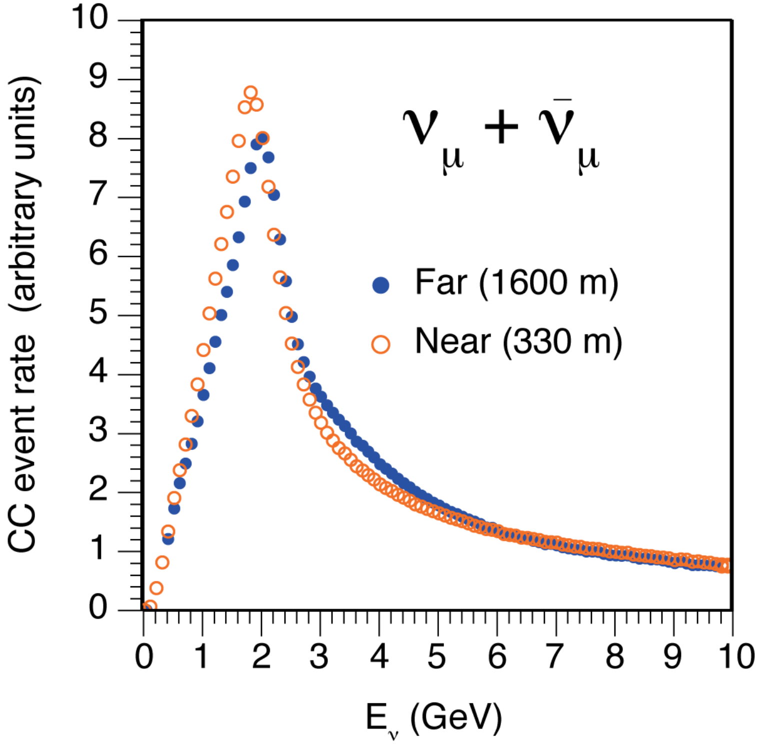
NOTE: ν "contamination" in anti-ν negative polarity beam

Comparing LSND sensitivities



Expected sensitivity for the proposed experiment: ⦃ beam (left) and anti-⦃ (right) for 4.5 10^{19} pot (1 year) and 9.0 10^{19} pot (2 years) respectively. LSND allowed region is fully explored in both cases.

Sensitivity to νμ disappearance (see NESSIE for details)



90% C.L. sensitivity for 2 years anti-ν + 1 year ν. Exclusion limits : CCFR, CDHS, SciBooNE + MiniBooNE