ν_e Appearance at OPERA

Electromagnetic Shower Energy Estimation

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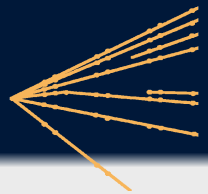
DPG Frühjahrstagung 2014, Mainz



The OPERA Experiment

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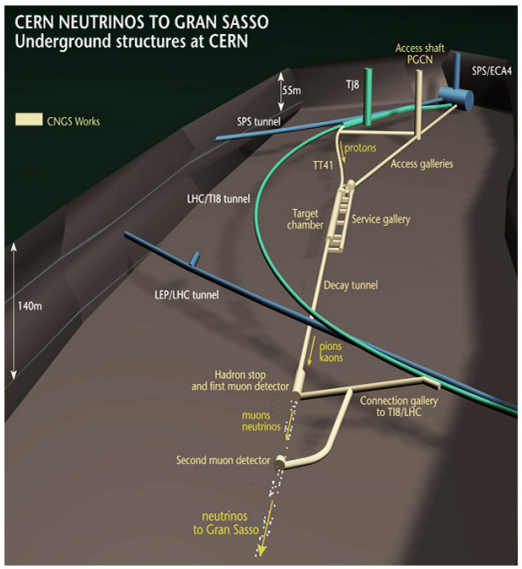
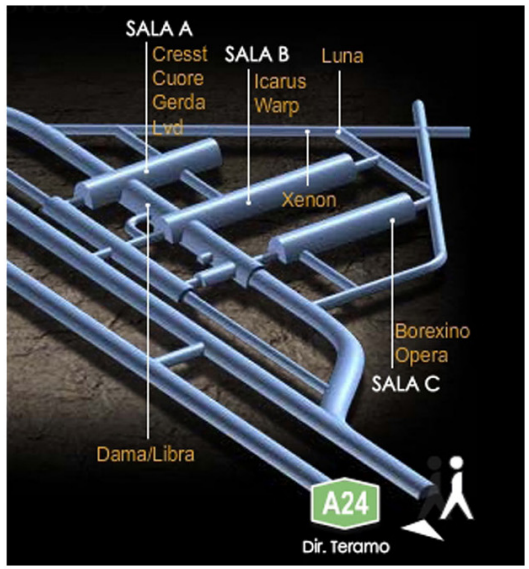
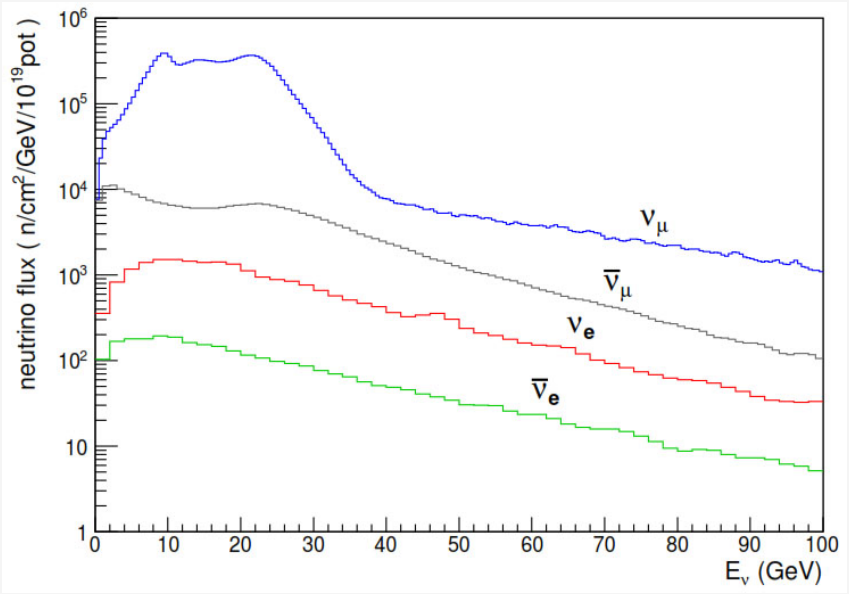
OPERA: Oscillation Project with Emulsion Tracking Apparatus





- **Appearance search:** Direct observation of $\nu_\mu \rightarrow \nu_\tau$ oscillations
  (detection of τ production & decay)
- **ν beam:** High-intensity & high-energy long-baseline ν_μ beam
  (CERN $\rightarrow$ LNGS: $\sim 730\,\mathrm{km}$)
- **Detector:** Large target mass ($\sim 1.25\,\mathrm{kt}$), high precision ($\mathcal{O}(\mu\mathrm{m})$)
- **Location:** **L**aboratori **N**azionali del **G**ran **S**asso (LNGS)
  ($1\,400\,\mathrm{m}$ rock coverage, $3\,800\,\mathrm{m}\,w.e.$)

The CNGS Neutrino Beam



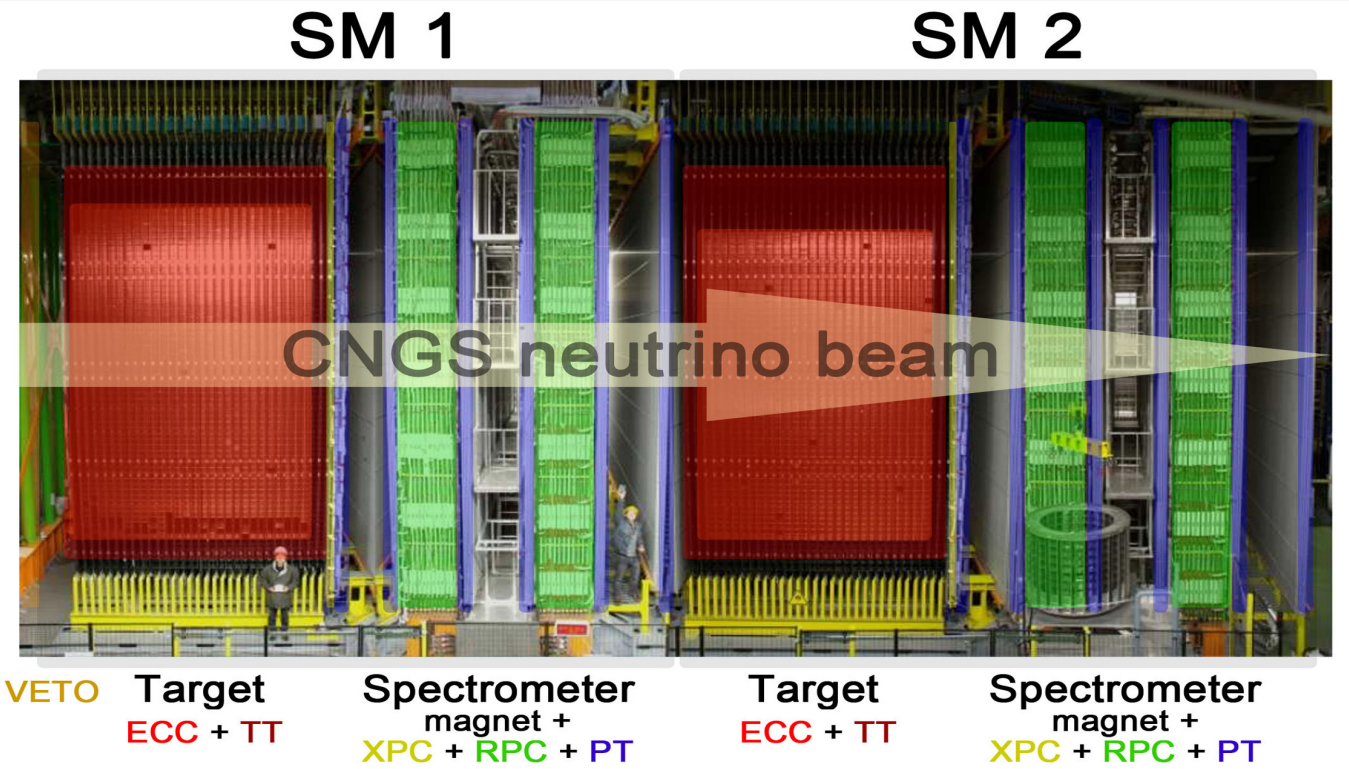
$\langle E_p \rangle$		400 GeV
$\langle E_\nu \rangle$		17 GeV

$\overline{\nu}_\mu/\nu_\mu$	CC	2.1 %
ν_e/ν_μ	CC	0.88 %
$\overline{\nu}_e/\nu_\mu$	CC	0.05 %
ν_τ/ν_μ	CC	$< 10^{-4}$ %

$\nu_\mu \rightarrow \nu_e$ oscillation search:

- Intrinsic ν_e beam contamination
- No OPERA near detector
  - ▷ Reliable MC required (interaction rates & detector efficiencies)

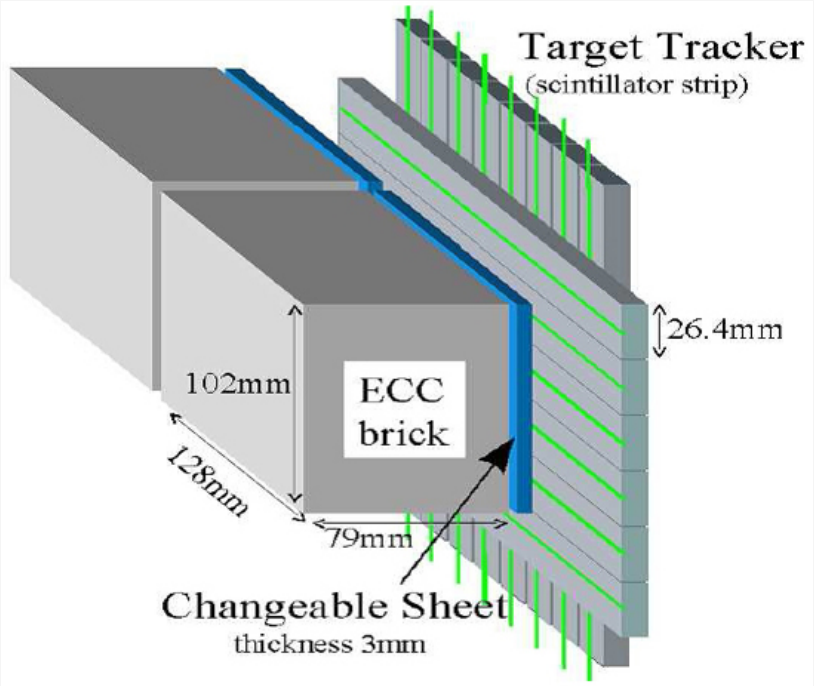
The OPERA Detector

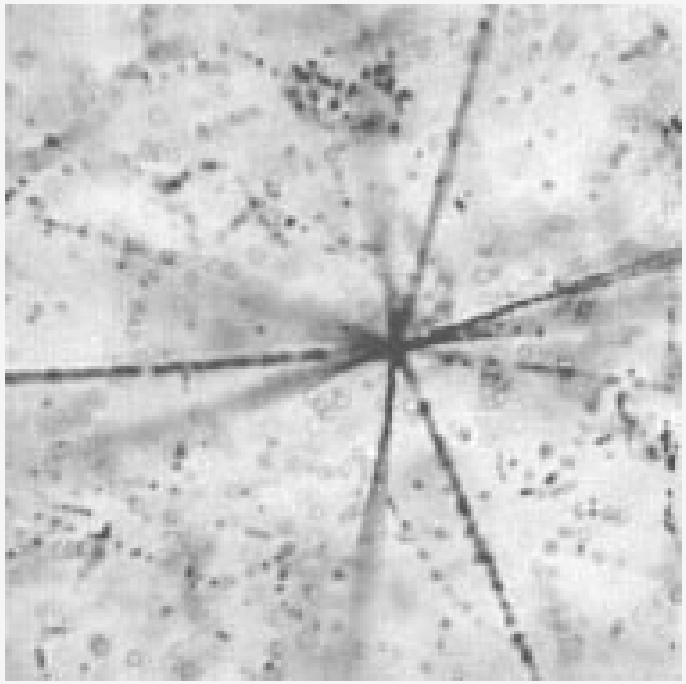


The OPERA hybrid detector

- **Electronic Detector (ED):** TT (scintillator), PT (drift tubes), RPC & XPC & VETO (RPC)
- **Emulsion Cloud Chamber (ECC) detectors:** $\sim$ 150 000 bricks

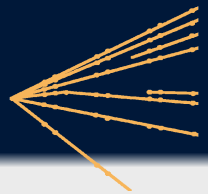
The OPERA Detector





Target area:

- **Emulsion Cloud Chamber (ECC) bricks:** 57×2 AgBr nuclear emulsions on plastic bases, 56 lead plates ($\sim 10\,X_0$)
- **Changeable Sheets (CS):** 2 extra emulsion sheets (per brick)
- **Target Tracker (TT):** 31 walls of plastic scintillator strips (per SM)

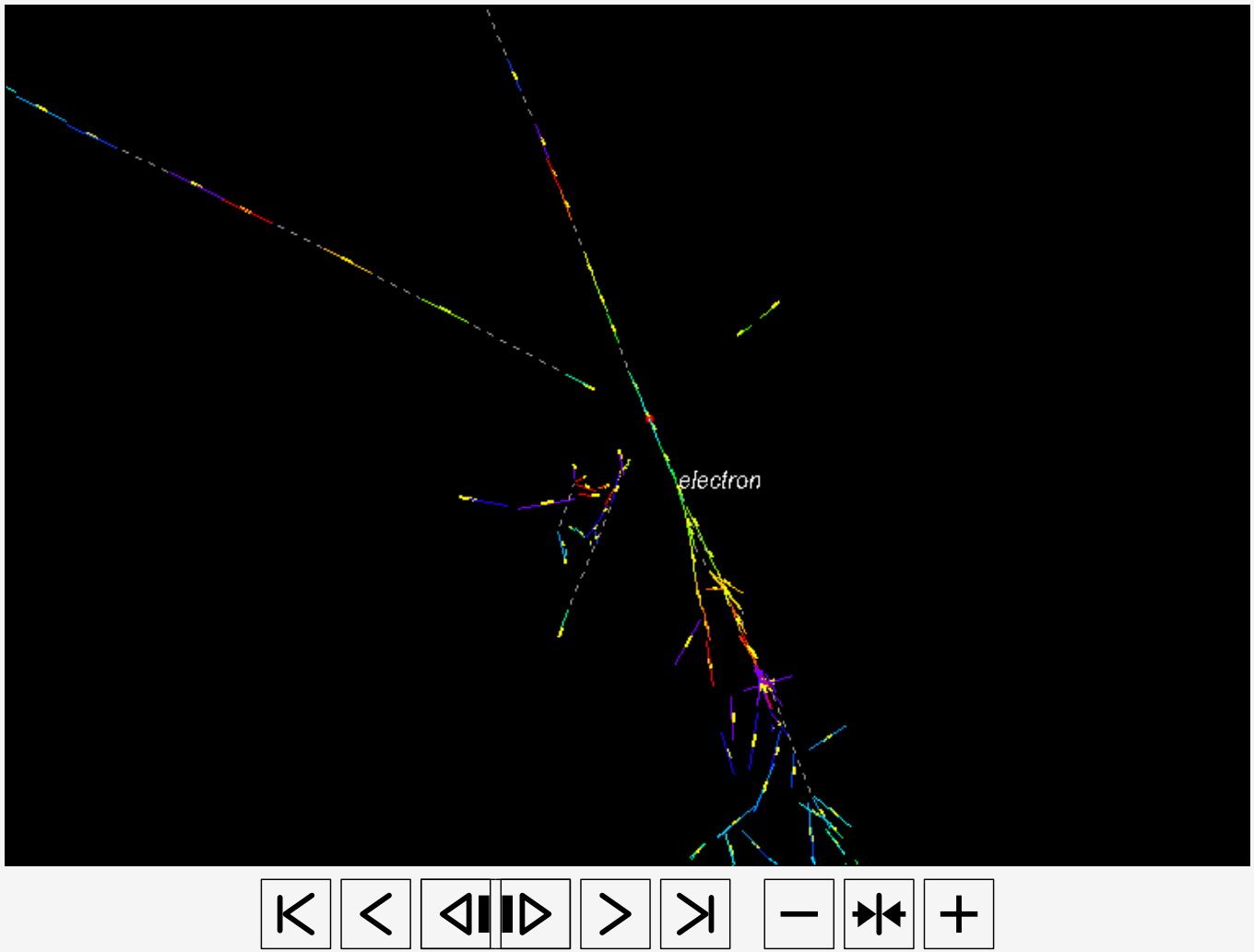


$$\nu_\mu \rightarrow \nu_e$$

Oscillation Search

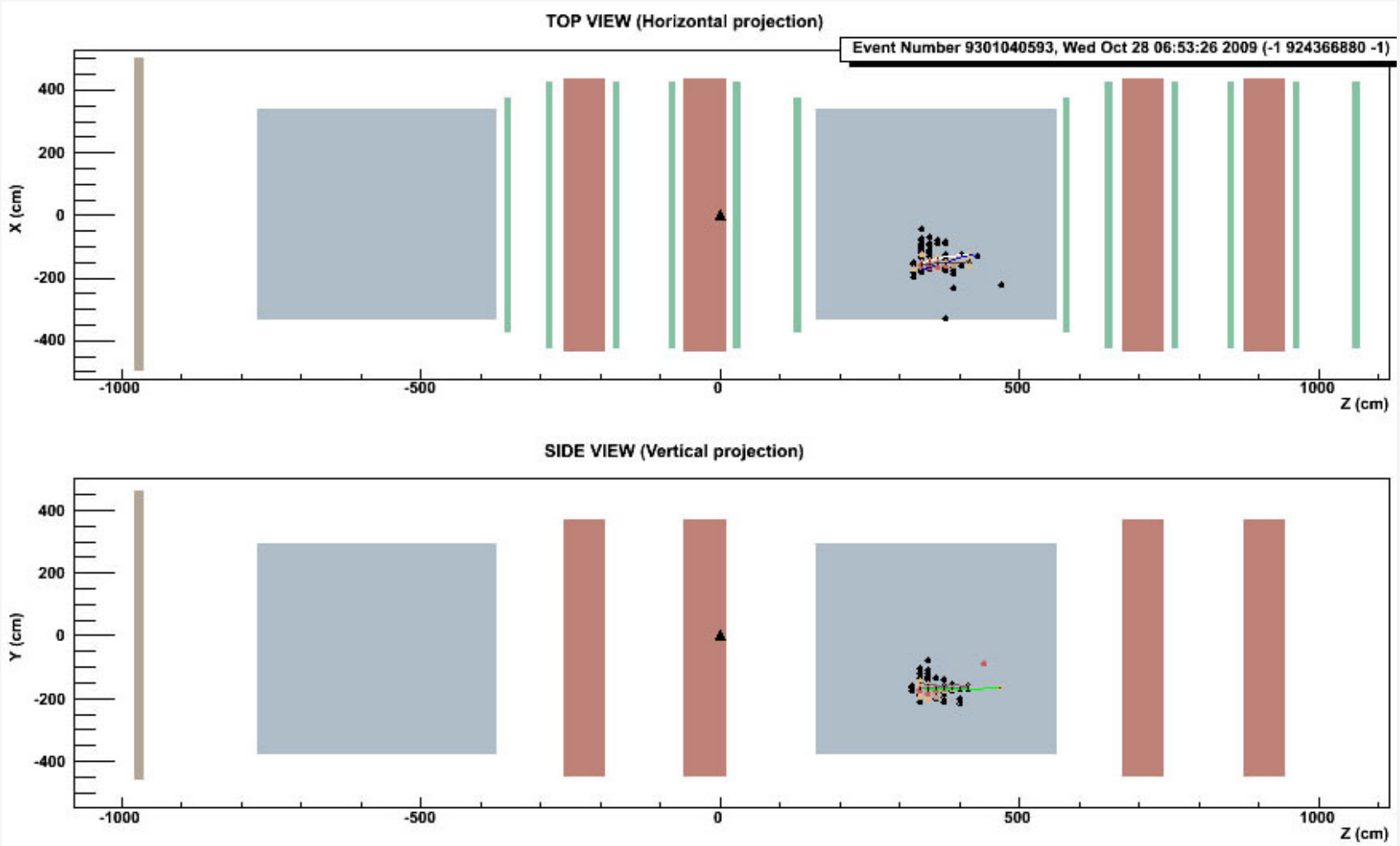
A ν_e Event

ECC reconstruction: Event 9301040593



A ν_e Event

ED reconstruction: Event 9301040593

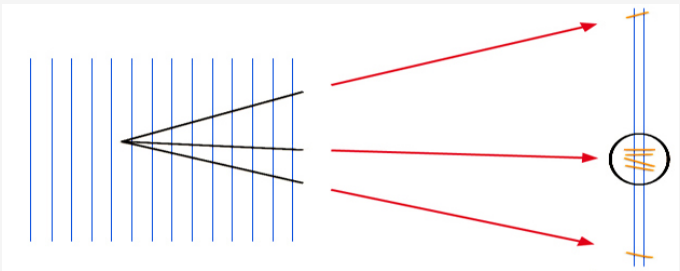


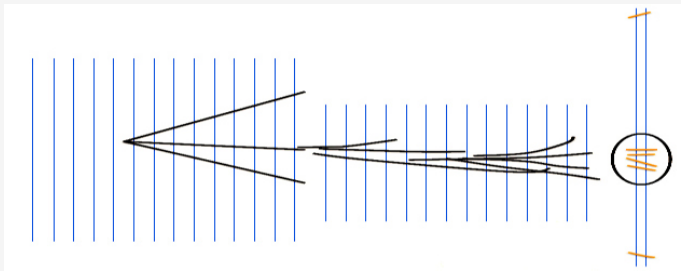
Systematic ν_e Event Selection

General event selection:

- **ED:** NC-like events, TT predictions for large-area CS scan
- **ECC:** Scan-back of CS tracks, ν interaction vertex search

CS *em* shower hints:





- Interpolation of 1ry vertex tracks to CS
- ▷ Expanded scan volume, analysis of downstream bricks

Backgrounds:

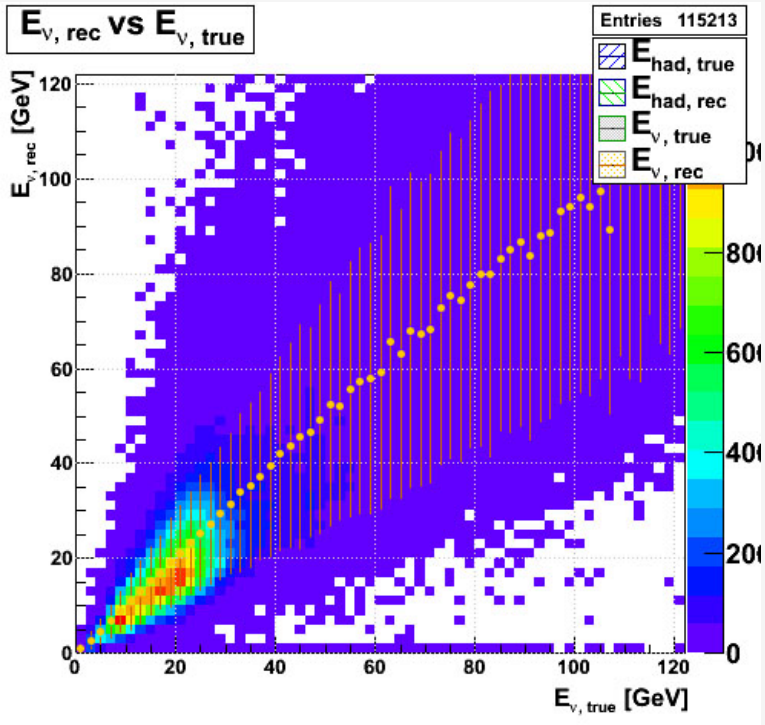
- ν_e from intrinsic beam contamination
- e^+e^- from π^0 decays misidentified as single-e
- ν_τ CC interactions with $\tau \rightarrow e$

ν_e Energy Reconstruction

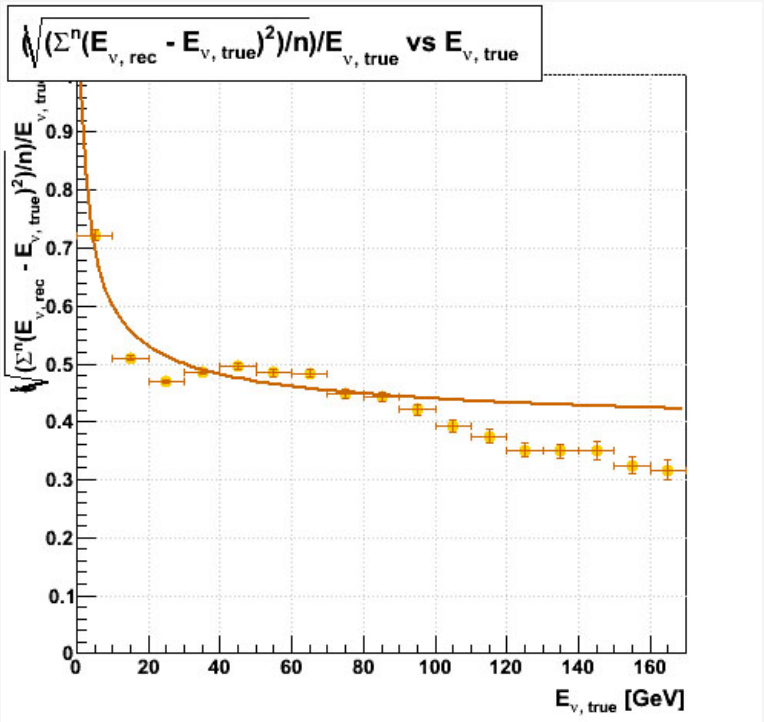
Energy reconstruction in the ED:

- Reconstructed energy deposition in the TT
- Calibration obtained using MC

$E_{\nu,rec}$ vs $E_{\nu,rec}$:

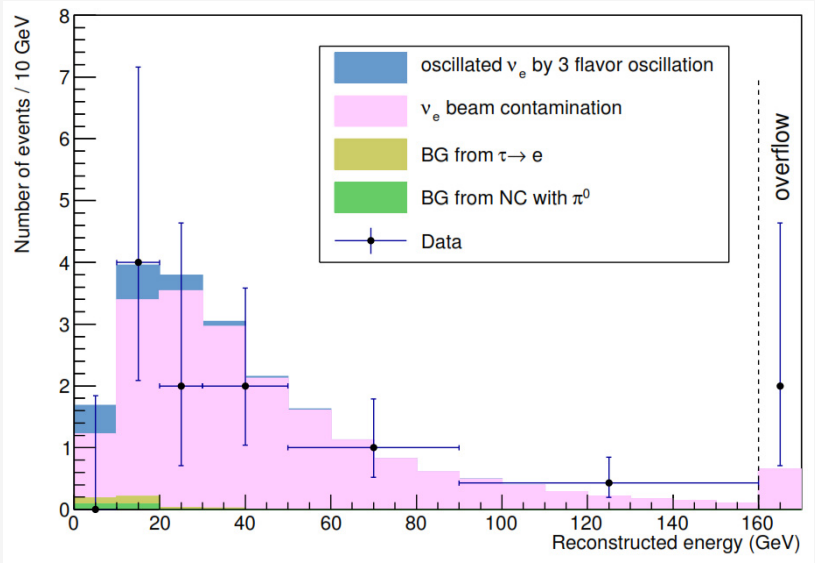


Energy resolution $\frac{\Delta E}{E}$:



ν_e Energy Reconstruction

Energy reconstruction: 2008 + 2009 ν_e **candidate events**



Cuts on $E_{\nu,rec}$: Separation of signal & background

Energy cut		20 GeV	30 GeV	No cut
BG common to both analyses	BG (a) from π^0	0.2	0.2	0.2
	BG (b) from $\tau \to e$	0.2	0.3	0.3
	ν_e beam contamination	4.2	7.7	19.4
Total expected BG in 3-flavour oscillation analysis		4.6	8.2	19.8
BG to non-standard oscillation analysis only	ν_e via 3-flavour oscillation	1.0	1.3	1.4
Total expected BG in non-standard oscillation analysis		5.6	9.4	21.3
Data		4	6	19

Assumptions:

- $\sin^2(2\theta_{13}) = 0.098$
- $\sin^2(2\theta_{23}) = 1$
- $\Delta m^2_{32} = \Delta m^2_{31} = 2.32 \times 10^{-3}\,\mathrm{eV}^2$
- $\delta_{CP} = 0$
- No matter effects

Oscillation Analysis: 3-Flavour

2008 + 2009 data sample:

- 5255 ν CC interactions $(5.25 \times 10^{19}\,\text{p.o.t.})$
  - ▷ ν_e **candidates:** 19 events

Separation of beam contamination and oscillated ν_e:

- ν **energy cut:** $E_{\nu,rec} < 20\,\text{GeV}$
  - ▷ **Expected BG:** 4.6 events
  - ▷ **Expected signal:** 1.0 events
  - ▷ **Remaining ν_e candidates:** 4 events

Compatible with no-oscillation hypothesis:

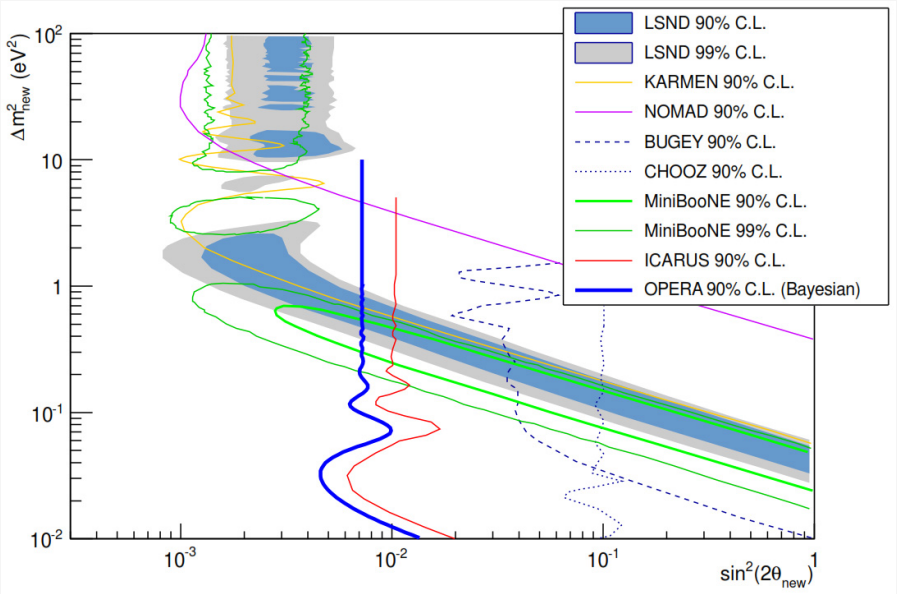
- $\sin^2(2\theta_{13}) < 0.44$ (90% C.L.)

Oscillation Analysis: Non-Standard

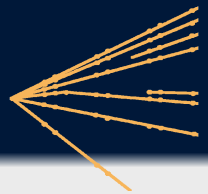
Separation of BG and oscillated ν_e:

- **ν energy cut:** $E_{\nu,rec} < 30\,\mathrm{GeV}$
- ▷ **Expected BG:** 9.4 events
- ▷ **Remaining ν_e candidates:** 6 events

$$P_{\nu_\mu \to \nu_e} = \sin^2(2\theta_{new}) \cdot \sin^2(1.27 \cdot \Delta m^2_{new} L[\mathrm{km}]/E[\mathrm{GeV}])$$



Bayesian Analysis: $\sin^2(2\theta_{new}) < 7.2 \times 10^{-3}$ for $\Delta m^2_{new} > 0.1\,\mathrm{eV}^2$ (90% C.L.)



Conclusion & Outlook

Conclusion

Conclusion: $\nu_\mu \rightarrow \nu_e$ **oscillation search** (2008 + 2009 **data**)

- **Confirmed ν_e candidate events:** 19
- **Compatible with 3-flavour no-oscillation hypothesis:**

  $\sin^2(2\theta_{13}) < 0.44$ (90% C.L.)
- **New limits on non-standard oscillation analysis:**

  $\sin^2(2\theta_{new}) < 7.2 \times 10^{-3}$ for $\Delta m^2_{new} > 0.1\,\mathrm{eV}^2$ (90% C.L.)

Outlook: $\nu_\mu \rightarrow \nu_e$ **oscillation search** (2008 – 2012 **data**)

- **Analysis of full data sample:**
  - ▷ Statistics ×3.4
- **Improvement of energy estimation, decrease of uncertainties:**
  - ▷ **ED:** Extension of energy estimation to RPC data, event-by-event energy calibration
  - ▷ **ECC:** *em* shower energy estimation

Thank you for your attention!

The OPERA Collaboration

11 countries, 29 institutes, $\sim$ 150 physicists:

Belgium:
- IIHE-ULB Brussels

Croatia:
- IRB Zagreb

France:
- LAPP Annecy
- IPHC Strasbourg

Germany:
- Hamburg University

Israel:
- Technion Haifa

Italy:
- INFN-LNGS Assergi
- University & INFN Bari
- University & INFN Bologna
- University & INFN-LNF Frascati
- University & INFN l'Aquila
- University & INFN Naples
- Univeristy & INFN Padova
- University & INFN Rome
- University & INFN Salerno

Japan:
- University Aichi
- University Toho
- University Kobe
- University Nagoya
- University Utsunomiya

Korea:
- University Jinju

Russia:
- JINR Dubna
- ITEP Moscow
- INR-RAS Moscow
- LPI-RAS Moscow
- SINP-MSU Moscow

Switzerland:
- LHEP Bern
- ETH Zurich

Turkey:
- METU Ankara

OPERA Publications

- N. Agafonova *et al.* [OPERA Collaboration], *Search for $\nu_\mu \to \nu_e$ oscillations with the OPERA experiment in the CNGS beam*, JHEP **1307** (2013) 004
- N. Agafonova *et al.* [OPERA Collaboration], *Study of neutrino interactions with the electronic detectors of the OPERA experiment*, New J. Phys. **13** (2011) 053051
- N. Agafonova *et al.* [OPERA Collaboration], *The detection of neutrino interactions in the emulsion/lead target of the OPERA experiment*, JINST **4** (2009) P06020
- R. Acquafredda *et al.* [OPERA Collaboration], *The OPERA experiment in the CERN to Gran Sasso neutrino beam*, JINST **4** (2009) P04018
- A. Anokhina *et al.* [OPERA Collaboration], *Emulsion sheet doublets as interface trackers for the OPERA experiment*, JINST **3** (2008) P07005
- *CNGS neutrino flux calculations webpage*, http://www.mi.infn.it/ psala/Icarus/cngs.html