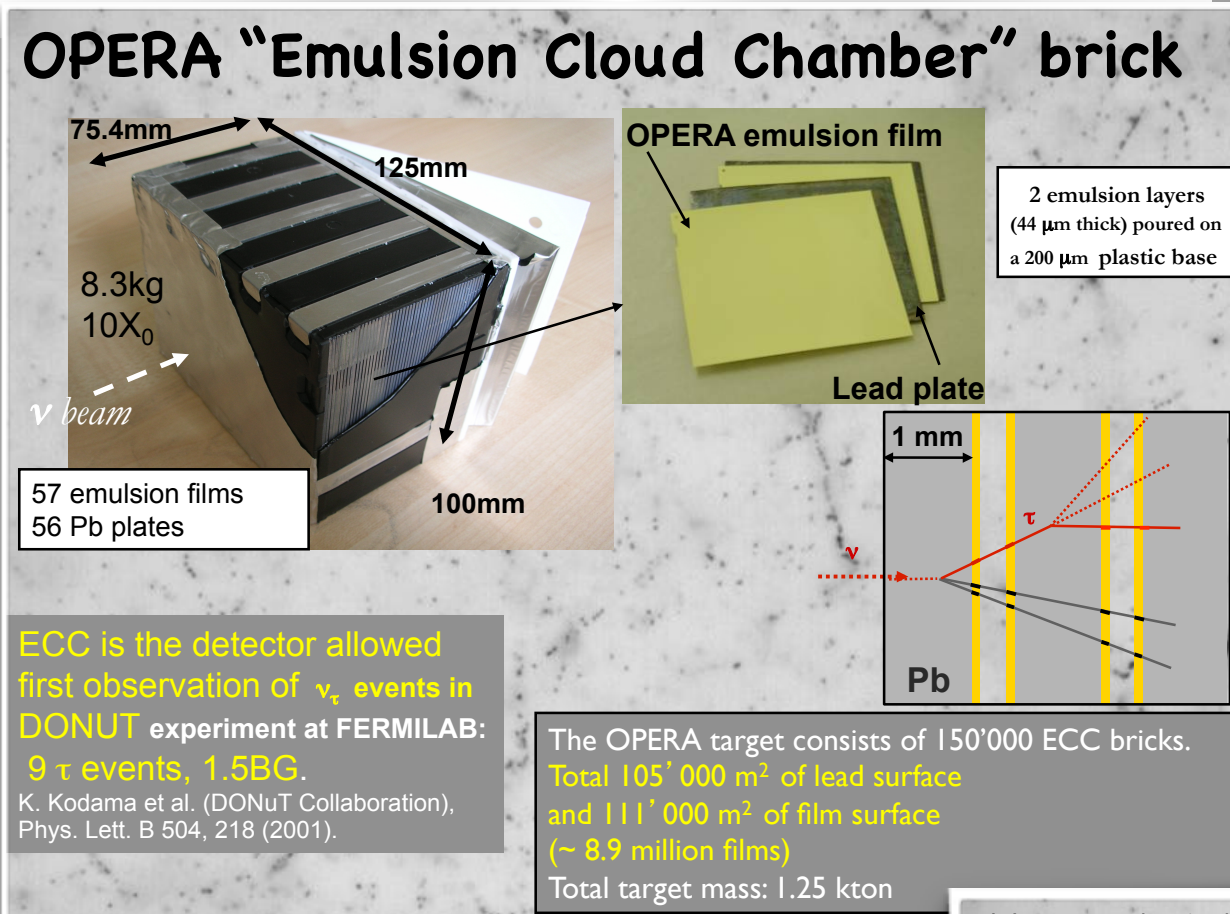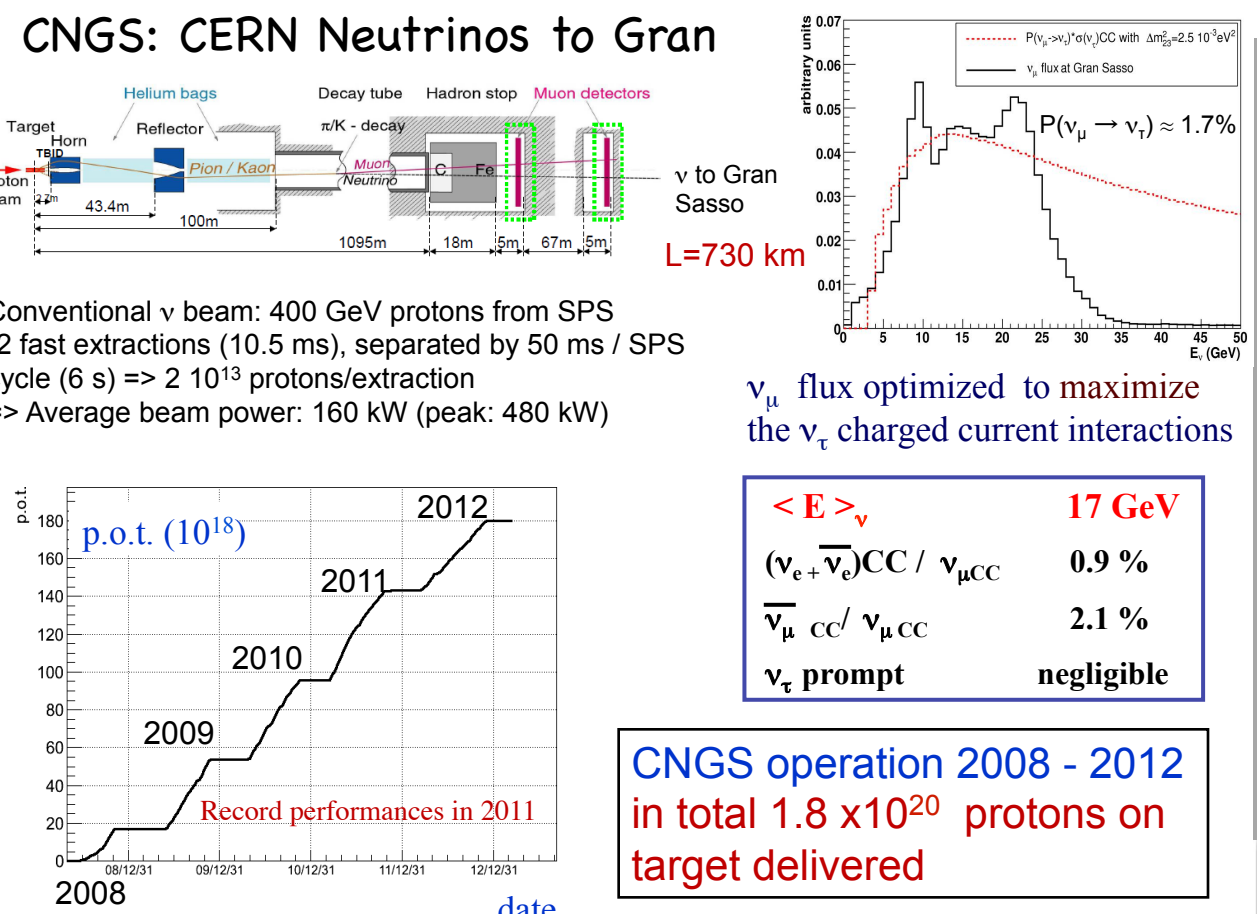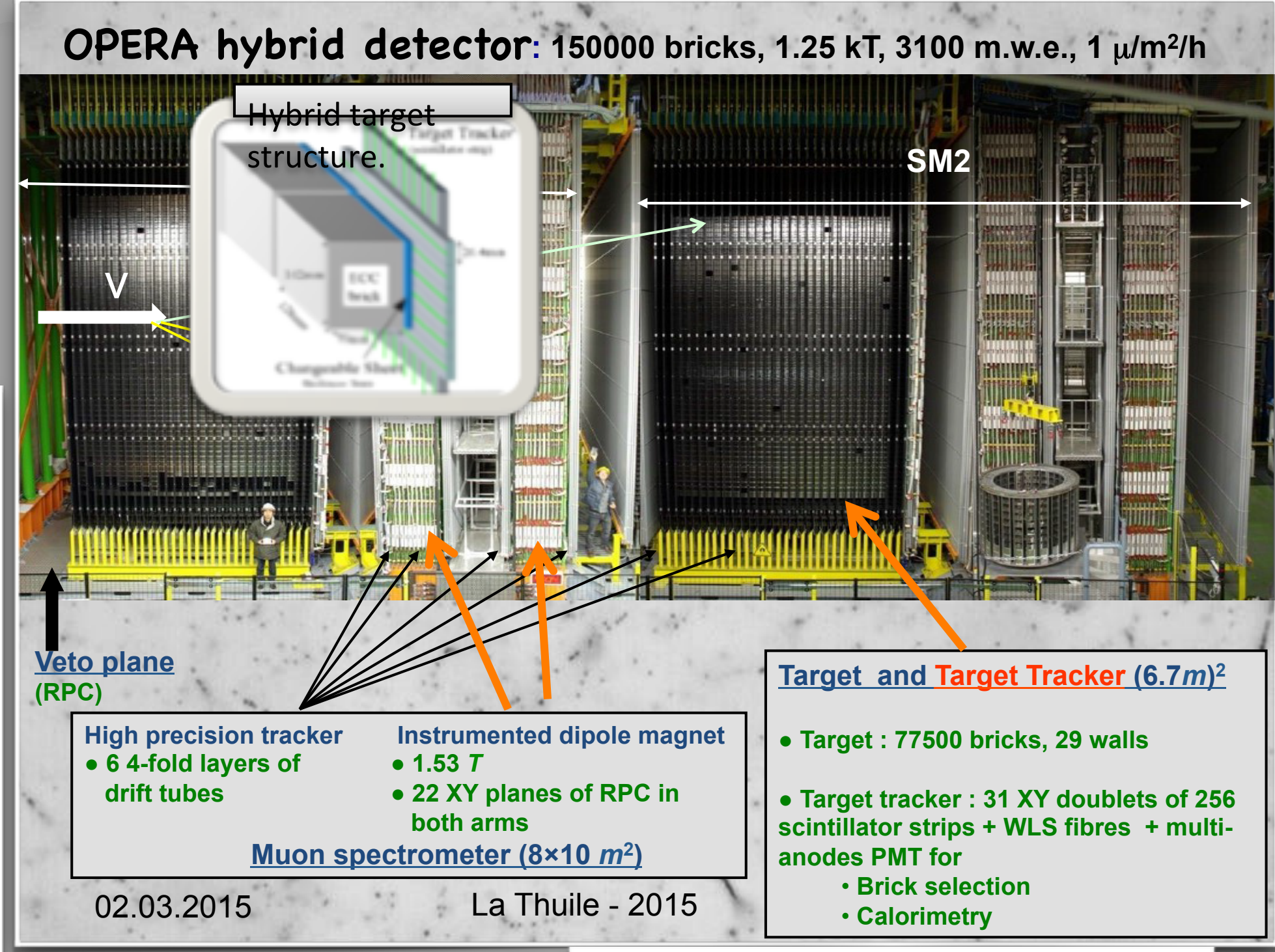# MORE RESULTS FROM THE OPERA EXPERIMENT

Yury Gornushkin (JINR, Russia) *(gornushk@yandex.ru)* on behalf of the OPERA Collaboration

OPERA

The OPERA experiment was proposed in 1998 to prove oscillations of muon neutrinos to tau neutrinos (as explanation of the observed atmospheric neutrinos anomaly) through direct detection of the appearance of tau neutrinos in the CNGS muon neutrino beam as a result of the oscillations. The OPERA hybrid detector consisted of the target part made of 150000 lead-nuclear emulsion bricks, where neutrino interaction occurred, and the electronic detectors: Target Tracker (TT), which provided the real time trigger for the events recording and the event vertex location at the brick level, and magnetic spectrometers to identify muons and to measure their momentum.

OPERA hybrid detector: 150000 bricks, 1.25 kT, 3100 m.w.e., 1 μ/m²/h

Hybrid target structure.

SM2

ν

Veto plane (RPC)

High precision tracker
- 6 4-fold layers of drift tubes

Instrumented dipole magnet
- 1.53 T
- 22 XY planes of RPC in both arms

Muon spectrometer (8×10 m^2)

02.03.2015 — La Thuile - 2015

Target and Target Tracker (6.7 m^2)
- Target : 77500 bricks, 29 walls
- Target tracker: 31 XY doublets of 256 scintillator strips + WLS fibres + multi-anodes PMT for
  - Brick selection
  - Calorimetry

CNGS: CERN Neutrinos to Gran

ν to Gran Sasso
L=730 km

$P(\nu_\mu \to \nu_\tau) = 1.7\%$

Conventional ν beam: 400 GeV protons from SPS
- 2 fast extractions (10.5 ms), separated by 50 ms / SPS cycle (6 s) => 2 10¹³ protons/extraction
=> Average beam power: 160 kW (peak: 480 kW)

ν_μ flux optimized to maximize the ν_τ charged current interactions

$<E>$	17 GeV
$(\nu_e + \overline{\nu}_e)CC / \nu_\mu CC$	0.9 %
$\overline{\nu}_\mu cc / \nu_\mu CC$	2.1 %
ν_τ prompt	negligible

CNGS operation 2008 - 2012
in total 1.8 ×10²⁰ protons on target delivered

p.o.t. (10¹⁸) 2012 2011 2010 2009 2008
Record performances in 2011
date

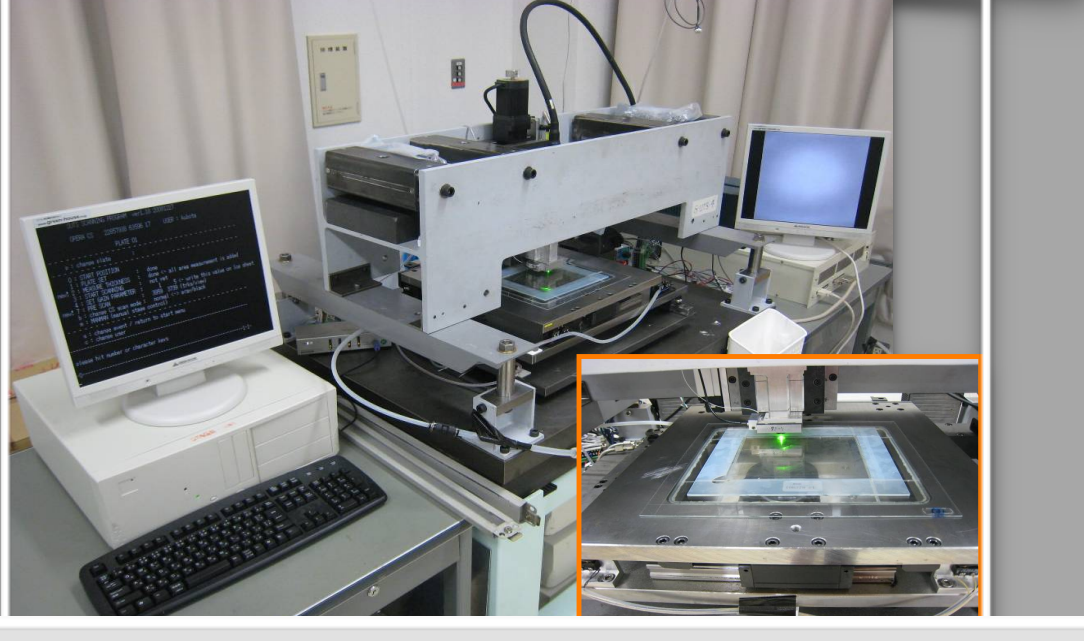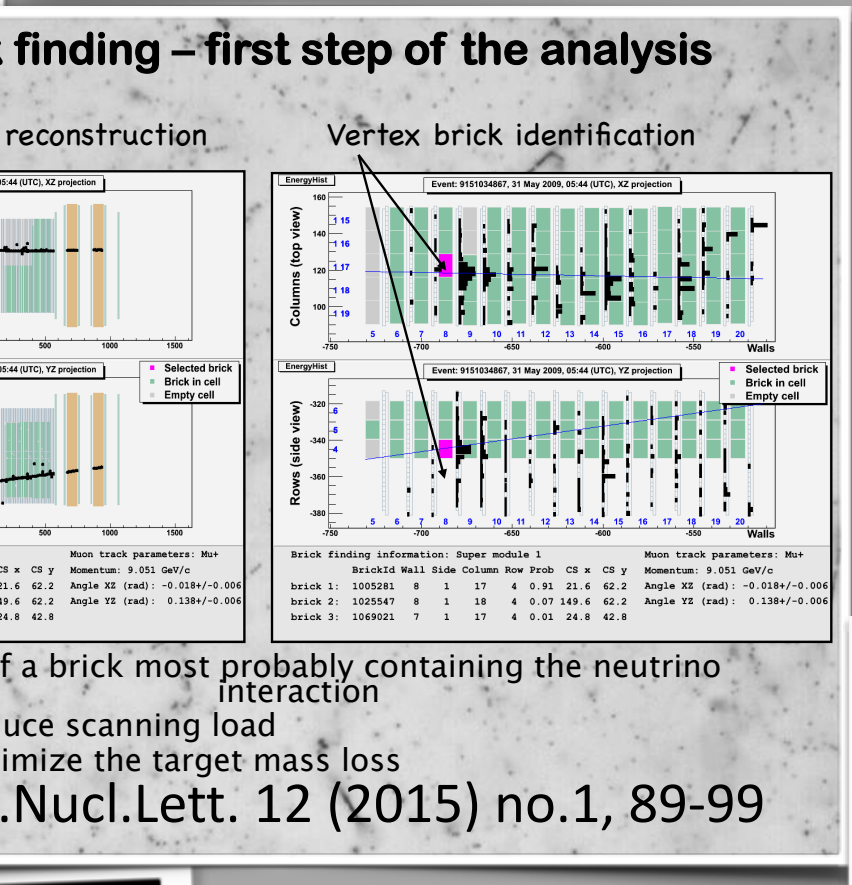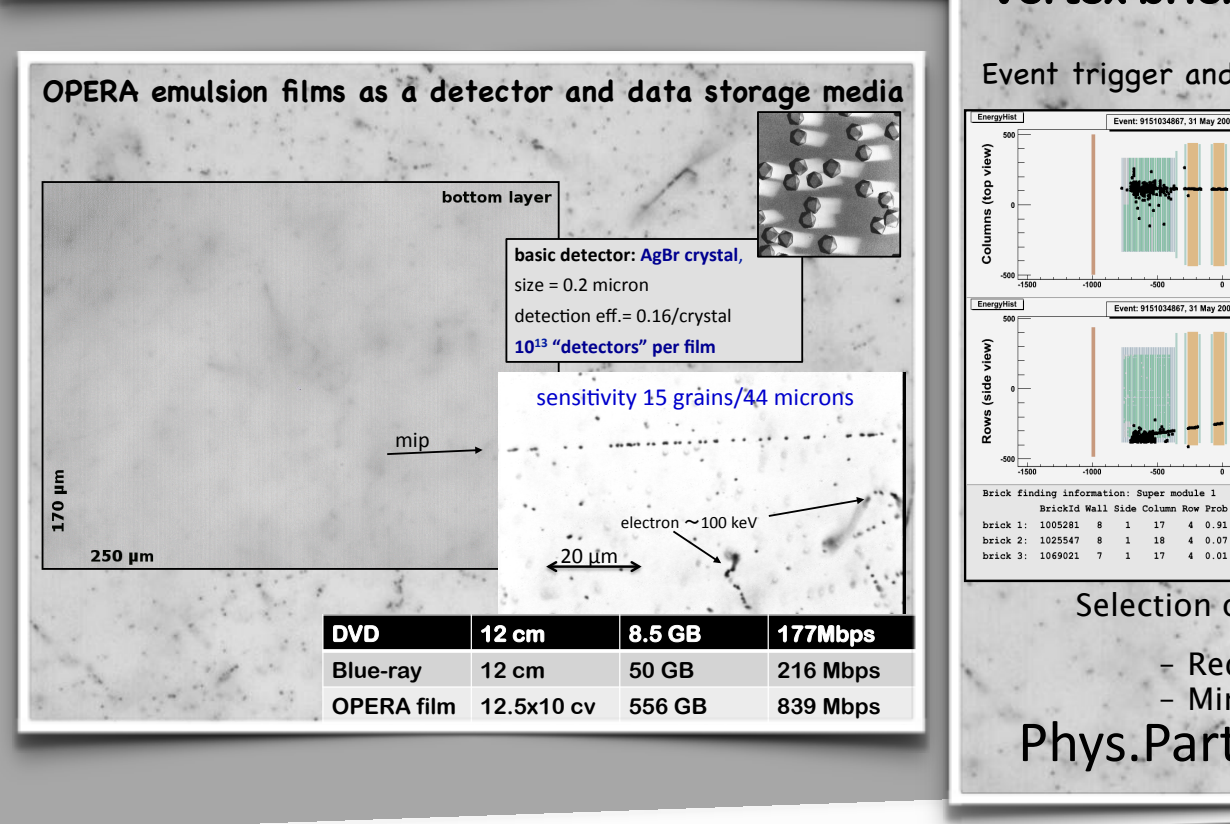| Year	Protons on target	SPS Eff.	Beam days	ν interactions
2008	1.74x10¹⁹	61%	123	1931
2009	3.53x10¹⁹	73%	155	4005
2010	4.09x10¹⁹	80%	187	4515
2011	4.75x10¹⁹	79%	243	5131
2012	3.86x10¹⁹	82%	257	3923

20% less than the experiment proposal value (22.5x10¹⁹ p.o.t.)
$\varepsilon_{trigger}$ = 99%
- 106 422 on time events recorded
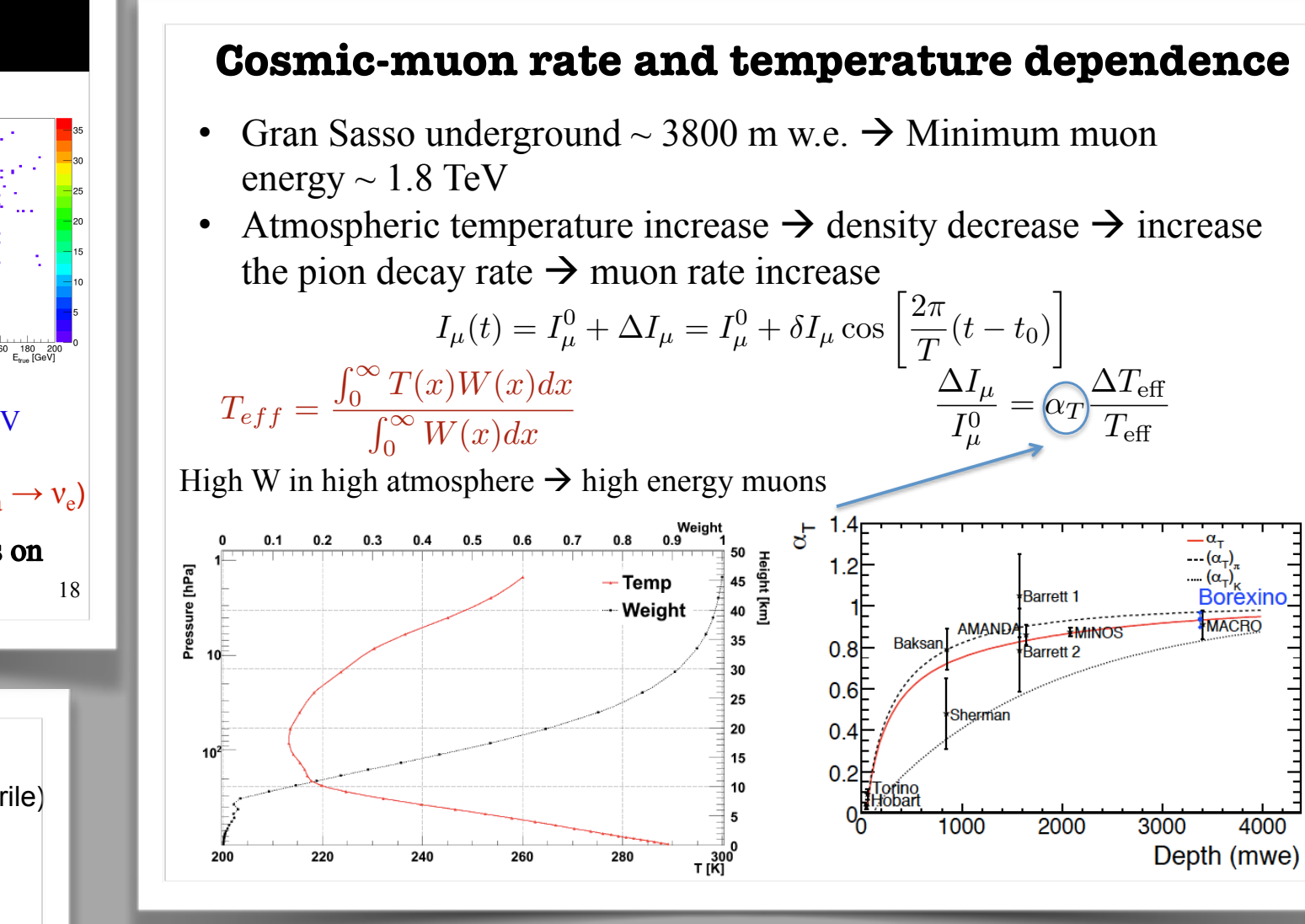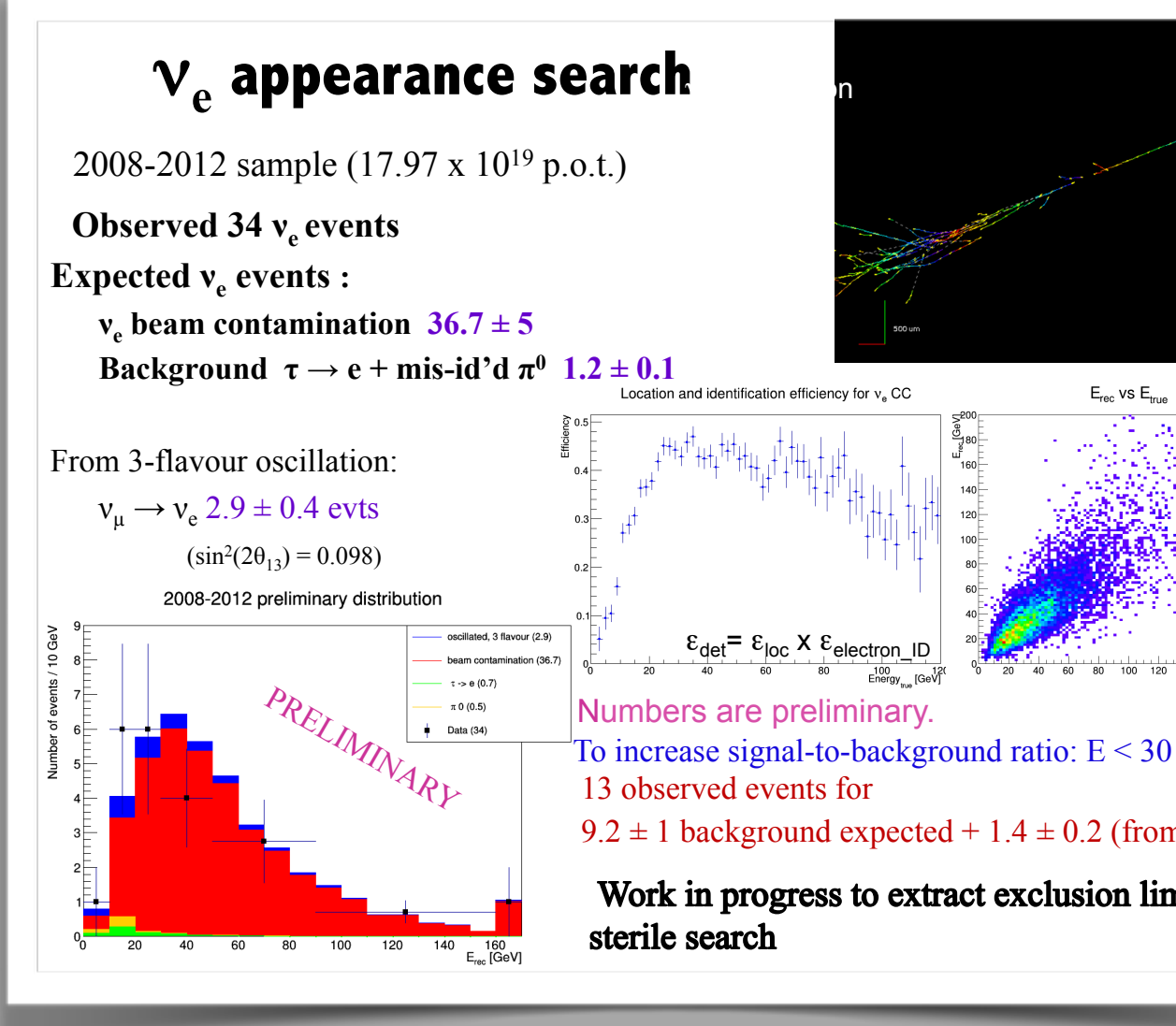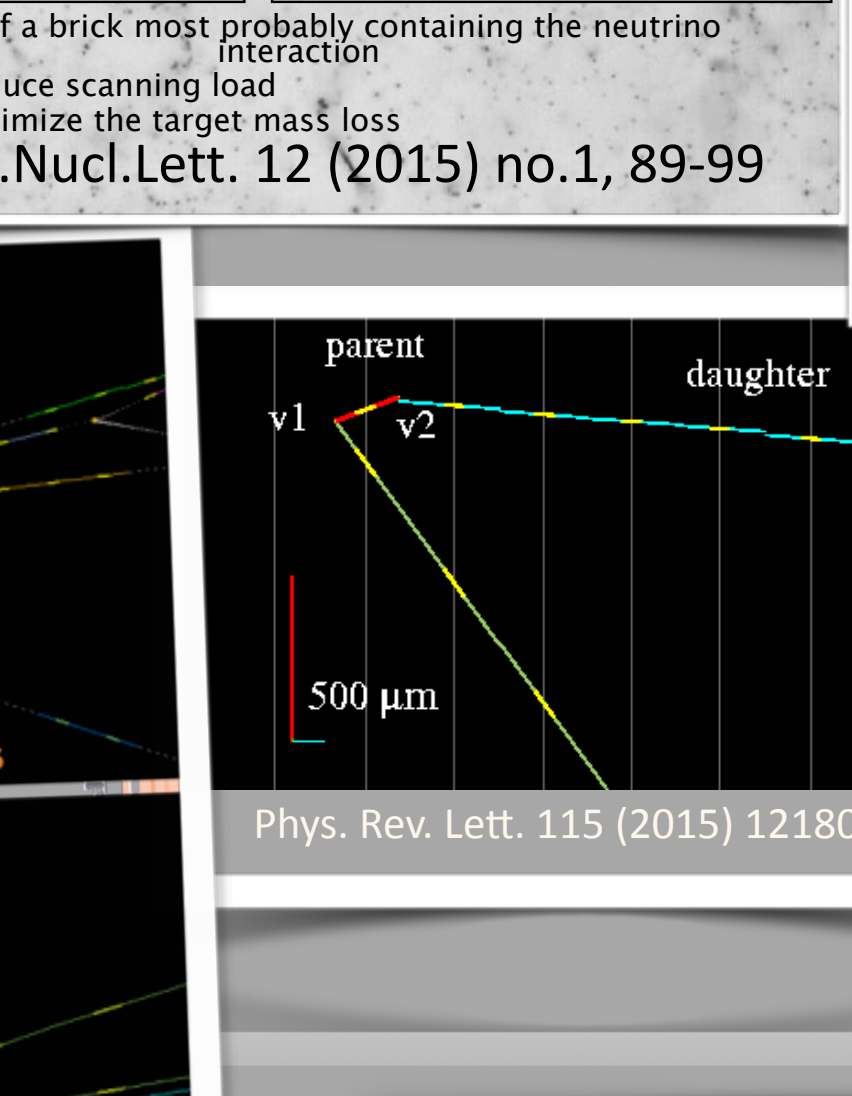- 60% are external rock events
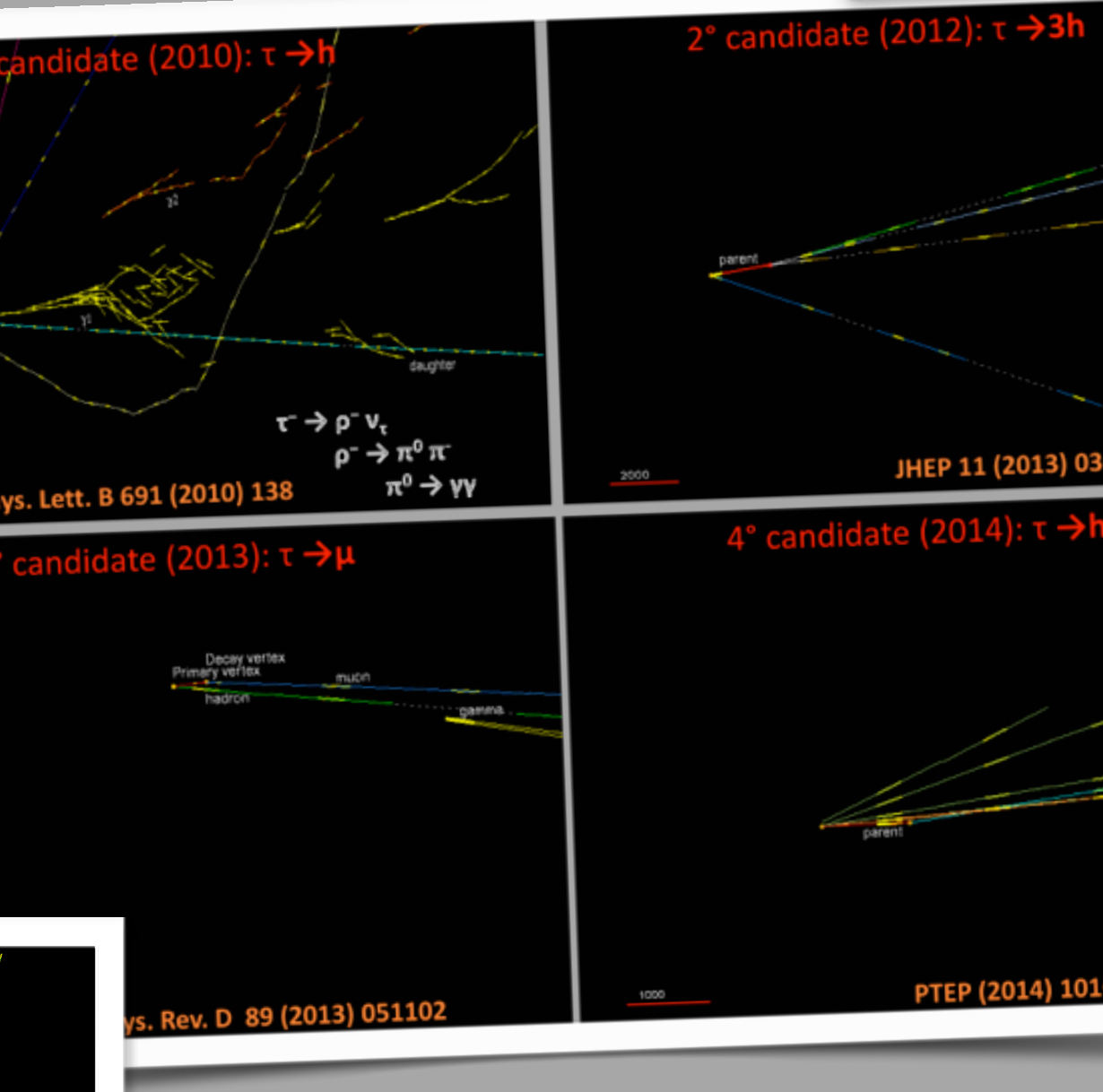- 20% are spectrometer interactions

19505 recorded ν interactions in the OPERA target 83% are reconstructed in the target

Event classification	Performed analysis	# of Decay Searched events
0μ	1ˢᵗ+2ⁿᵈ brick	1144
1μ (Pμ < 15 GeV)	1ˢᵗ+2ⁿᵈ brick	4264
All		5408

P distribution for 1 μ sample

OPERA "Emulsion Cloud Chamber" brick

75.4mm
125mm
8.3kg 10X₀
100mm
57 emulsion films
56 Pb plates

OPERA emulsion film
2 emulsion layers (44 μm thick poured on a 200 μm plastic base)
Lead plate
1 mm
Pb

ECC is the detector allowed first observation of ν_τ events in DONUT experiment at FERMILAB: 9 τ events, 1.5BG.
K. Kodama et al. (DONuT Collaboration), Phys. Lett. B 504, 218 (2001).

The OPERA target consists of 150'000 ECC bricks. Total 105' 000 m² of lead surface and 111' 000 m² of film surface (~ 8.9 million films) Total target mass: 1.25 kton

OPERA emulsion films as a detector and data storage media

basic detector: AgBr crystal
size = 0.2 micron
detection eff. = 0.16/crystal
10¹⁴ "detectors" per film
mip
sensitivity 15 grains/44 microns
electron ~ 100 keV

	12 cm	8.5 GB	177Mbps
DVD	12 cm	50 GB	216 Mbps
Blue-ray	12 cm		
OPERA film	12.5x10 cv	556 GB	839 Mbps

Vertex brick finding – first step of the analysis

Event trigger and reconstruction — Vertex brick identification

Selection of a brick most probably containing the neutrino interaction
– Reduce scanning load
– Minimize the target mass loss

Phys.Part.Nucl.Lett. 12 (2015) no.1, 89-99

Automatic scanning system as a reader
- Scanning speed/system: 75cm²/h
- High speed CCD camera (3 kHz), Piezo-controlled objective lens
- FPGA Hard-coded algorit

$\nu_\mu \to \nu_\tau$ oscillation analysis :

By proving with 5.1 sigma appearance of tau neutrinos, OPERA successfully accomplished the mission, but several analysis are still in progress and more results are coming soon.

1ˢᵗ candidate (2010): τ →h
2ˢᵗ candidate (2012): τ →3h
Phys. Lett. B 691 (2010) 138
JHEP 11 (2013) 036
3ˢᵗ candidate (2013): τ →μ
4ˢᵗ candidate (2014): τ →h
PTEP (2014) 101C01
Phys. Rev. D 89 (2013) 051102

$\tau \to \rho^- \nu_\tau$
$\rho^- \to \pi^0 \pi^-$
$\pi^0 \to \gamma\gamma$

parent — daughter
v1 v2
500 μm
Phys. Rev. Lett. 115 (2015) 121802

Background

Signal:
- τ - creation in ν_τ CC interaction
- Decay of the τ-- lepton after ~ 600 μm
- Topology: 'kink' characteristic of the tau decay (missing energy)

- ν_μ CC interactions with charm production & undetected muon(s)
- Hadronic re-interactions of secondary hadrons in lead
- Large-angle μ scattering

Estimation by MonteCarlo
Validation by OPERA data or test beam studies.

IEEE Trans.Nucl.Sci. 62 (2015) 2216, PTEP 2014 (2014) no.9, 093C01
Eur.Phys.J. C74 (2014) no.8, 2986

ν_e appearance search

2008-2012 sample (17.97 x 10¹⁹ p.o.t.)

Observed 34 ν_e events

Expected ν_e events :
- ν_e beam contamination 36.7 ± 5
- Background $\tau \to e$ + mis-id'd π^0 1.2 ± 0.1

From 3-flavour oscillation:
$\nu_\mu \to \nu_e$ 2.9 ± 0.4 evts
$(sin^2(2\theta_{13}) = 0.098)$

2008-2012 preliminary distribution

$\varepsilon_{det} = \varepsilon_{loc} \times \varepsilon_{electron\_ID}$

PRELIMINARY

Numbers are preliminary.
To increase signal-to-background ratio: E < 30 GeV
13 observed events for
9.2 ± 1 background expected + 1.4 ± 0.2 (from $\nu_\mu \to \nu_e$)

Work in progress to extract exclusion limits on sterile search

Cosmic-muon rate and temperature dependence

- Gran Sasso underground ~ 3800 m w.e. → Minimum muon energy ~ 1.8 TeV
- Atmospheric temperature increase → density decrease → increase the pion decay rate → muon rate increase

$$I_\mu(t) = I_\mu^0 + \Delta I_\mu = I_\mu^0 + \delta I_\mu \cos\left[\frac{2\pi}{T}(t-t_0)\right]$$

$$T_{eff} = \frac{\int_0^\infty T(x)W(x)dx}{\int_0^\infty W(x)dx} \qquad \frac{\Delta I_\mu}{I_\mu^0} = \alpha_T \frac{\Delta T_{eff}}{T_{eff}}$$

High W in high atmosphere → high energy muons

Temp — Weight

Baksan AMANDA MINOS MACRO Borexino Barrett 1 Barrett 2 Sherman Torino Hobart

Decay channel	Expected background				expected signal events $\Delta m^2 = 2.44 \times 10^{-3} eV^2$	Observed events
	Charm	Had. Re-interaction	Large μ scattering	Total		
$\tau \to 1h$	0.017±0.003	0.022±0.006	-	0.04±0.01	0.52±0.10	3
$\tau \to 3h$	0.17±0.03	0.003±0.001	-	0.17±0.03	0.73±0.14	1
$\tau \to \mu$	0.004±0.001	-	0.0002±0.0001	0.004±0.001	0.61±0.12	1
$\tau \to e$	0.03±0.01	-	-	0.03±0.01	0.78±0.16	0
Total	0.22±0.04	0.02±0.01	0.0002±0.0001	0.25±0.05	2.64±0.53	5

p_{sum}: scalar sum of the momenta of all particles measured in the emulsion films

1, 4, 5: τ → 1h
2: τ → 3h
3: τ → μ

Probability to be explained by background fluctuation p = 1.1x10⁻⁷

No oscillation hypothesis excluded at 5.1 σ

$\Delta m_{23}^2 = 3.3 \times 10^{-3}$ eV² with a 90% confidence interval [2.0, 5.0] x 10⁻³ eV² (assuming full mixing)

Probability of observing ≥5 candidates (2.9 S+B events expected): 17%
Frequency of configurations being less probable than the observed one: 6.4%

ν_μ disappearance

- Full data sample (2008-2012)
- Use of electronic detector data only and separation between CC and NC like events

a fit using NC-like/CC-like ratio in which all mixing parameters are fixed to the PDG values but Δm_{23}^2

NC-like/CC-like ratio vs. Eₕ
energy deposited in the scintillator planes
Data — No oscillation — Best fit

PRELIMINARY
$\chi^2/n_{d.o.f.} = 0.98$

reweighting MC according to oscillation probability and minimizing χ² between MC and data

To reduce systematic effects coming from the beam uncertainty (no near detector), NC like over CC like ratio is used

systematics under study

⇒ Preliminary measurement of Δm_{23}^2
⇒ consistent with the world average and the internal OPERA appearance results

Sterile neutrino search

appearance probability modified by one possible extra (sterile)
(3+1 scheme)

$\nu_\mu \to \nu_e$
2008+2009 data:

LSND 90% C.L.
KARMEN 90% C.L.
NOMAD 90% C.L.
BUGEY 90% C.L.
CHOOZ 90% C.L.
MiniBooNE 90% C.L. (FSLC)
ICARUS 90% C.L.
OPERA 90% C.L. (Bayesian)

JHEP07 (2013) 004
Upper limit on non standard ν oscillations
$sin^2(2\theta_{new}) < 7.2 \times 10^{-3}$ 90% CL
where $P = sin^2(2\theta_{new}) sin^2(1.27 \Delta m^2_{new} L/E)$
Analysis to be updated with full ν_e sample and 3+1framework

$\nu_\mu \to \nu_\tau$
→ Observed 5 ν_τ events with 0.25 ± 0.05 background expected

PRELIMINARY
OPERA I.H. 90% C.L.
OPERA N.H. 90% C.L.
NOMAD 90% C.L.
CHORUS 90% C.L.

- 90% CL exclusion region on Δm^2_{41} lowered down to 10⁻² eV² for $sin^2(2\theta_{μτ}) > 0.5$
- At large Δm^2_{41}: $sin^2(2\theta_{μτ}) < 0.119$ at 90% CL

Update of JHEP 1506 (2015) 069

Annual modulation of cosmic-muon rate

$\frac{\Delta I_\mu}{I_\mu^0} = (1.32 \pm 0.11)\%$
$t_0 = 216 \pm 16$

Muon rate vs temperature variations
R = 0.42

$\frac{\Delta I_\mu}{I_\mu^0} = \alpha_T \frac{\Delta T_{eff}}{T_{eff}}$
$\alpha_T = 0.93 \pm 0.06$

Temperature data by the European Center for Medium-range Weather Forecasts (ECMWF)