More results from the OPERA experiment

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on behalf of the OPERA Collaboration

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Neutrinos 2017
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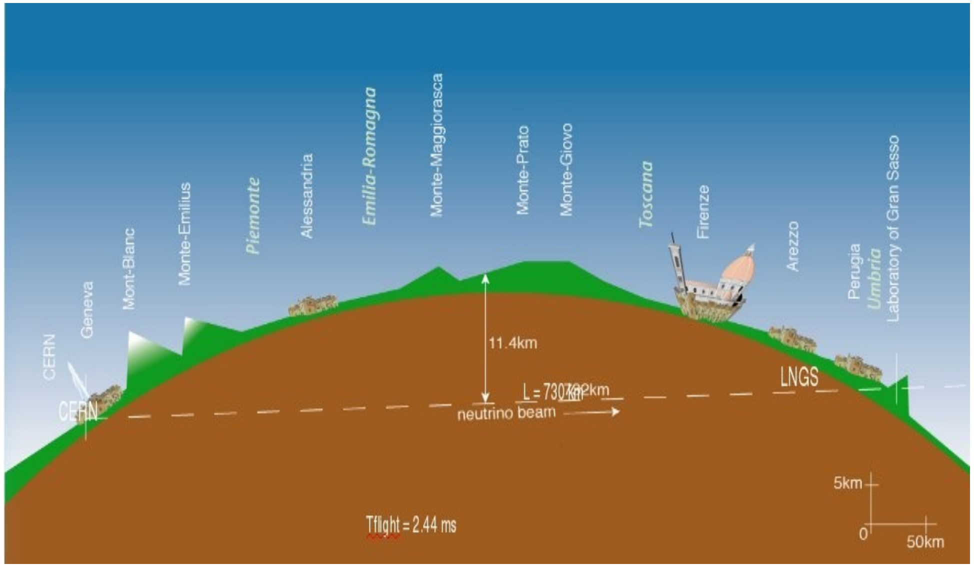
Goals of the OPERA experiment

The main goal of the OPERA experiment (Oscillation Project with Emulsion tRacking Apparatus) was an observation of the $\boldsymbol{\nu_\mu \rightarrow \nu_\tau}$ oscillations in **appearance mode** in a pure ν_μ beam through the detection of the short-lived τ leptons produced in ν_τ charged-current (CC) interactions.

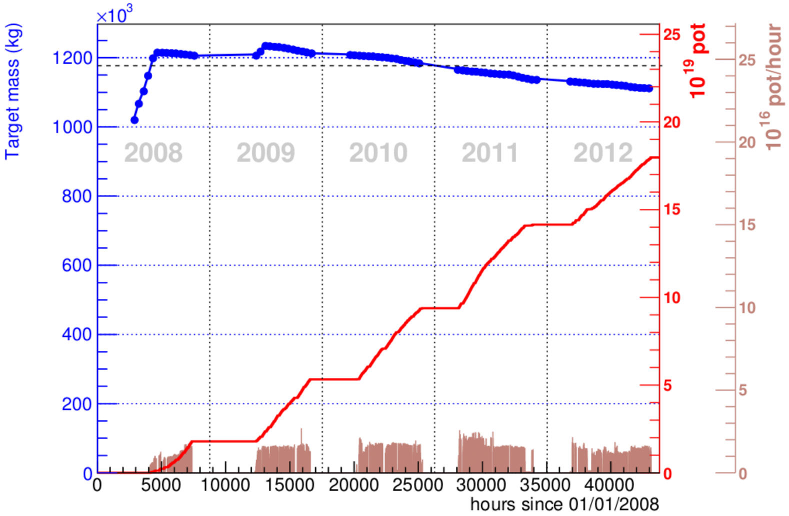
The tracking capabilities of the detector allow to expand physics program:

- **oscillation physics:** $\nu_\mu \rightarrow \nu_e$ study, sterile neutrino analysis
- **non-oscillation physics:** charged particle multiplicity analysis, cosmic-ray physics

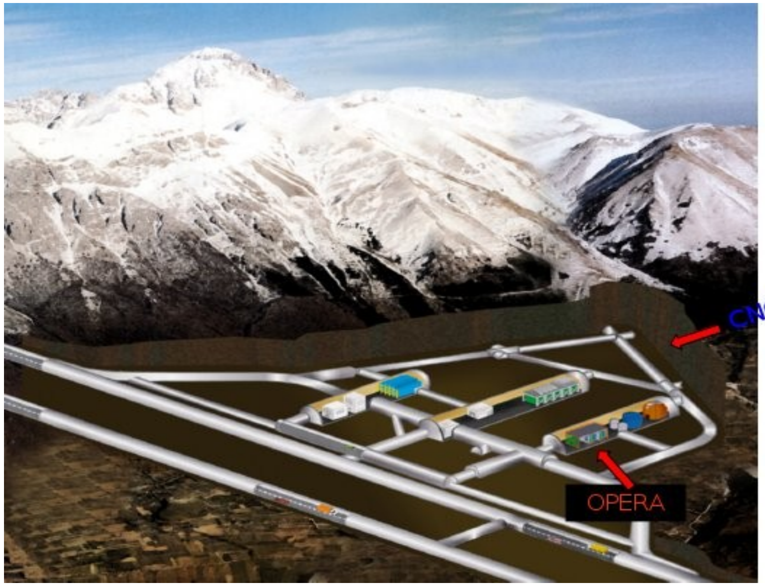


CNGS beam: CERN Neutrinos to Gran Sasso

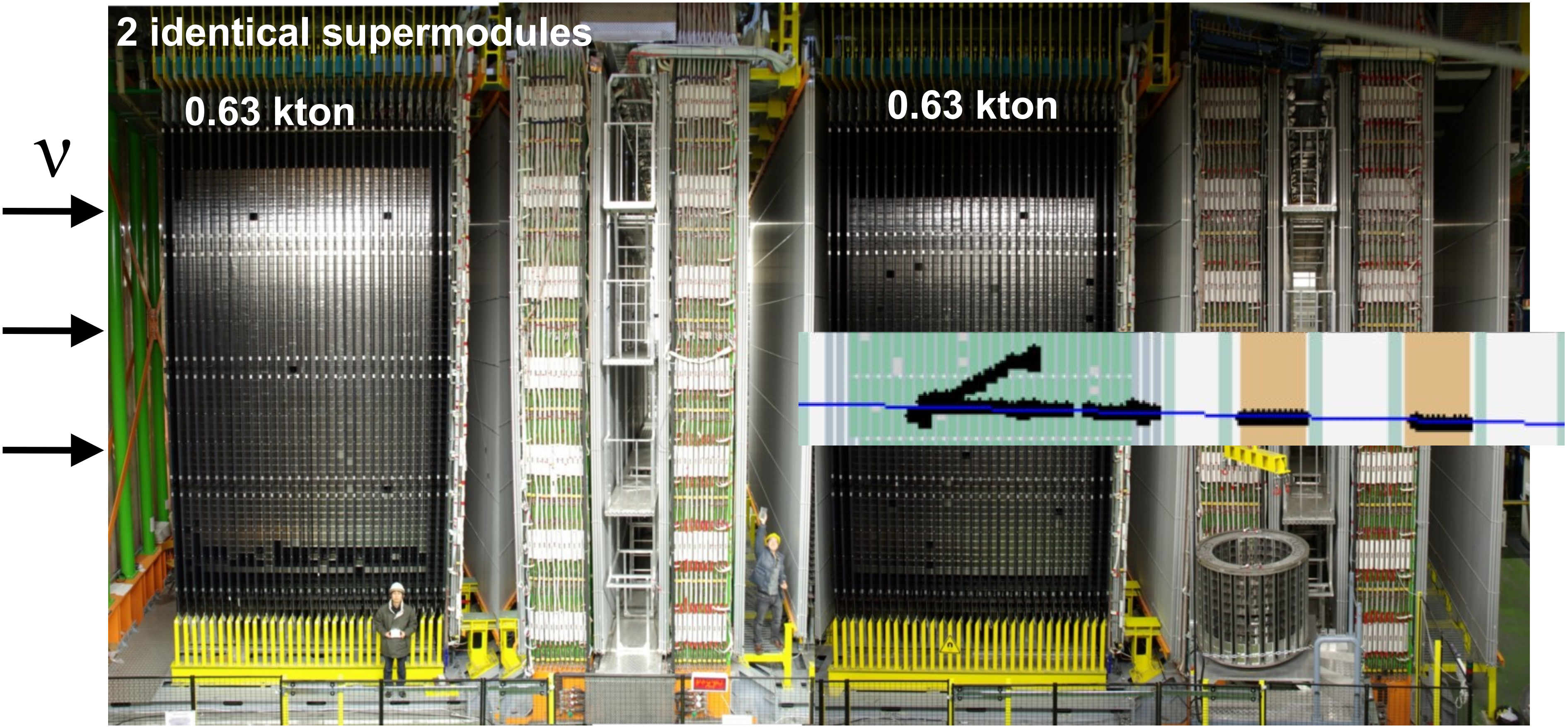
- Beam data taken during 2008-2012
- **1.8 *10^{20} p.o.t.** were collected
- 19505 ontime events were recorded
- **6785 events were located** and used for the analysis



$< E_{\nu_\mu} > (GeV)$	17
$(\nu_e + \overline{\nu_e})/\nu_\mu$	0.87%
$\overline{\nu_\mu}/\nu_\mu$	2.1%
ν_τ prompt	Negligible



OPERA detector



Target and Target Tracker (6.7m × 6.7m) ~75000 bricks

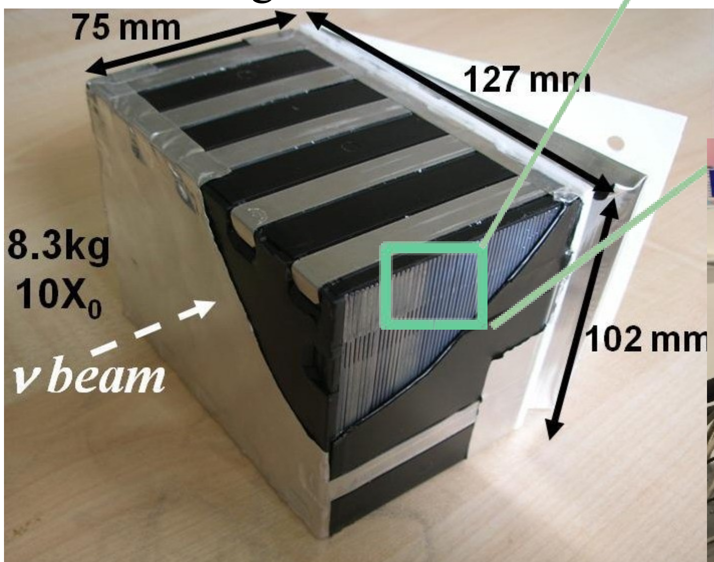
Muon spectrometer (8m×10m)

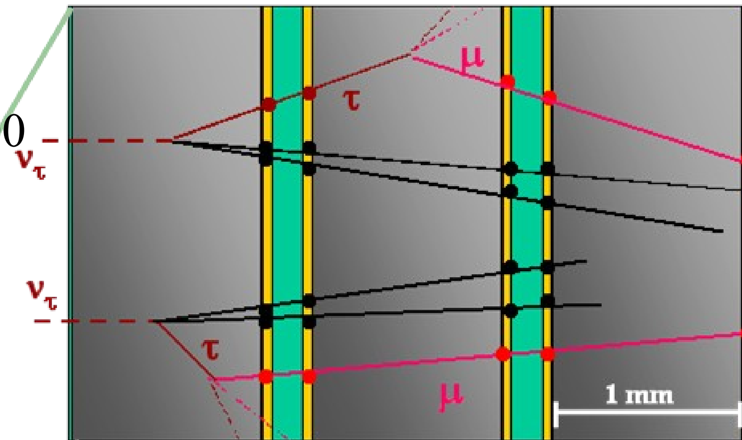
Target and Target Tracker (6.7m × 6.7m) ~75000 bricks

Brick Manipulator System

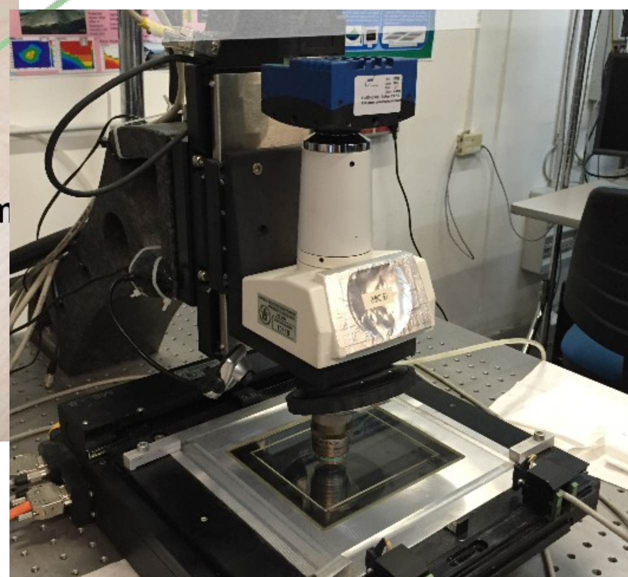
OPERA ECC (emulsion cloud chamber)

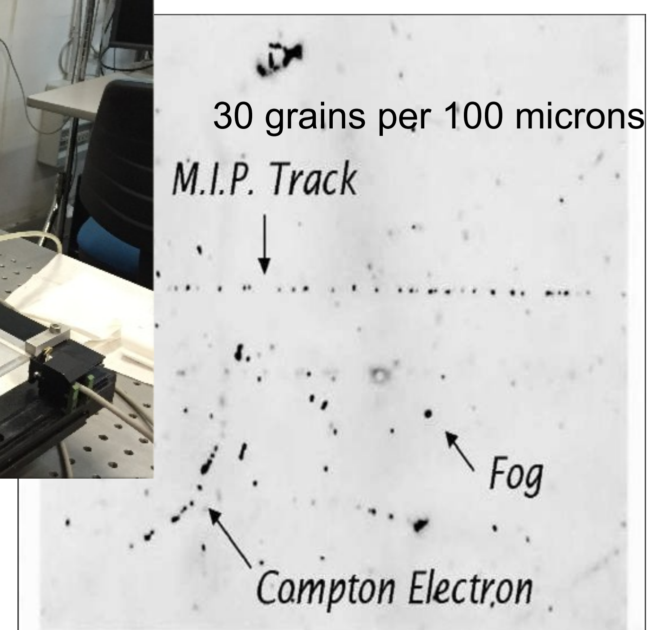
- OPERA target consisted of ~150 000 ECC bricks
- Total 111 000 m^2 of film surface (about 9 million films)
- Total target mass is about 1.2 kt





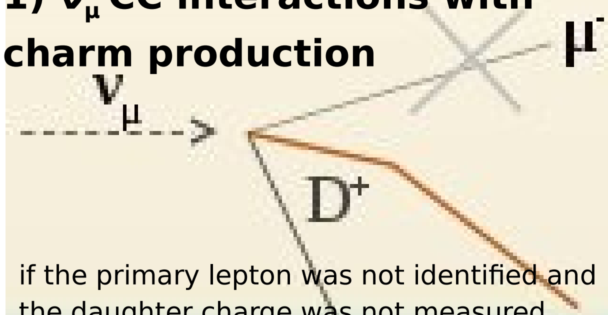
- 57 films of nuclear emulsion
- 56 lead plates (1 mm thick) - 10 X_0
- 2 Changeable Sheets
- Fast fully automated optical microscopes
- 3D track reconstruction with micrometric resolution





$\nu_\mu \rightarrow \nu_\tau$: background sources

1) ν_μ CC interactions with charm production



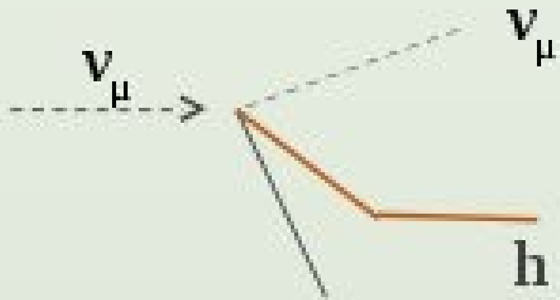
if the primary lepton was not identified and the daughter charge was not measured

Monte Carlo simulation tuned on CHORUS data

Reduced by multi-brick tracking

Eur. Phys. J C74 (2014) 2986)

2) Hadronic re-interactions

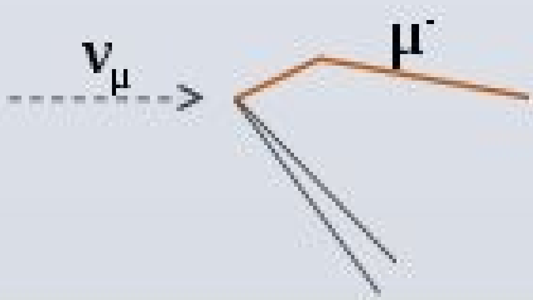


FLUKA simulation and test beam data

Reduced by nuclear fragment search and large angle scattering

PTEP9 (2014) 093C01

3) Large angle μ scattering



Estimate by implementing a proper form factor for Lead
Simulation bench-marked on experimental data

IEEE Transactions on Nucl. Sci. Vol. 62, 5, 2015

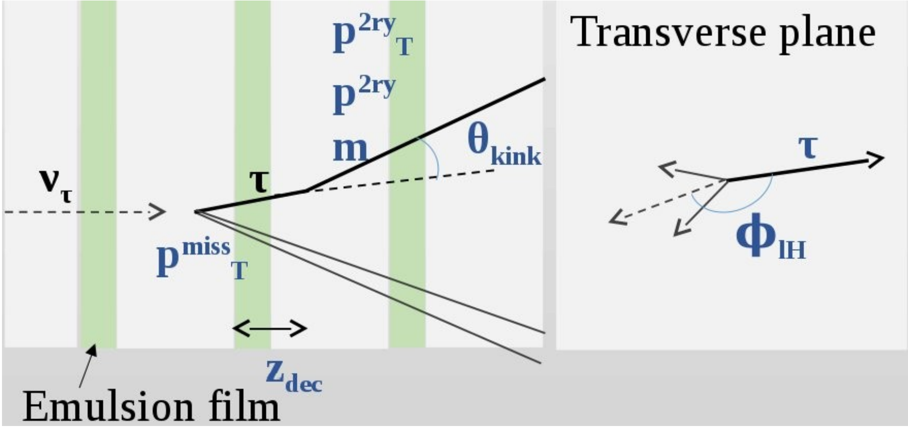
$\nu_\mu \rightarrow \nu_\tau$: kinematical selection

Cuts fixed since the beginning of the experiment

Variable	$\tau \rightarrow 1h$	$\tau \rightarrow 3h$	$\tau \rightarrow \mu$	$\tau \rightarrow e$
z_{dec} (μm)	$[44, 2600]$	<2600	$[44, 2600]$	<2600
p^T_{miss} (GeV/c)	$< 1\star$	$< 1\star$	/	/
ϕ_{lH} (rad)	$>\pi/2\star$	$>\pi/2\star$	/	/
p^T_{2ry} (GeV/c)	$>0.6\,(0.3)^*$	/	>0.25	>0.1
p_{2ry} (GeV/c)	>2	>3	$[1, 15]$	$[1, 15]$
θ_{kink} (rad)	>0.02	<0.5	>0.02	>0.02
m, m_{min} (GeV/c^2)	/	$[0.5, 2]$	/	/

Cuts marked with $\star$ are not applied for Quasi-Elastic event

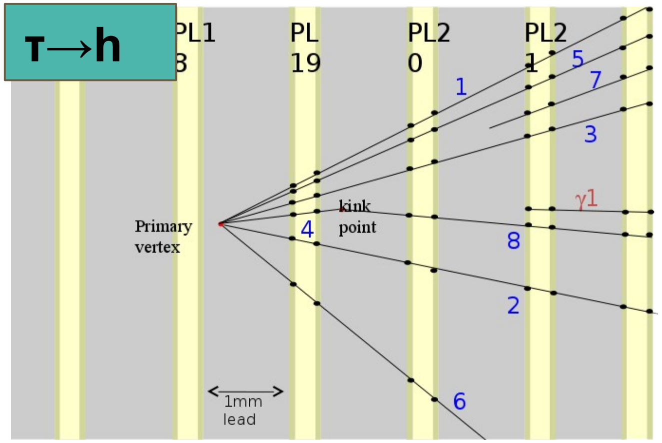
* p^T_{2ry} cut is 0.3 in the presence of γ particles associated to the decay vertex



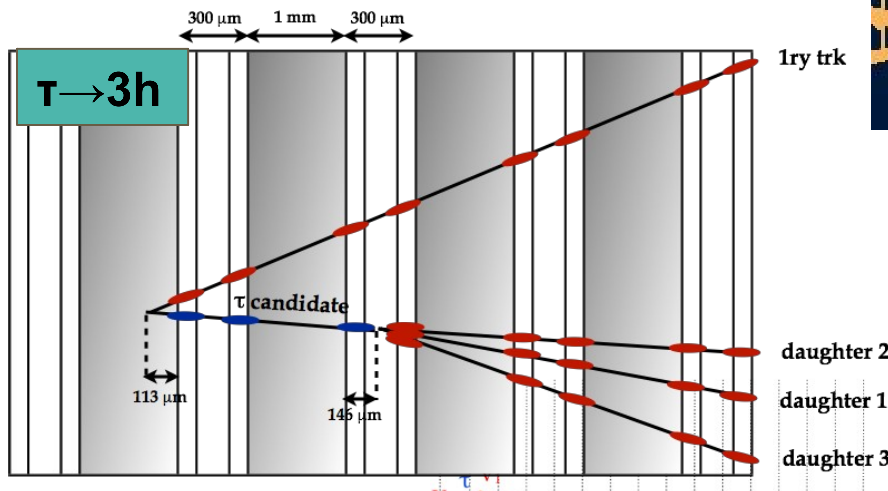
p^{miss}_T: vectorial sum of the transverse momenta of primaries (except the parent) and daughters with regard to the beam direction

p^{2ry}_T: transverse momentum of the daughter with regard to the parent direction

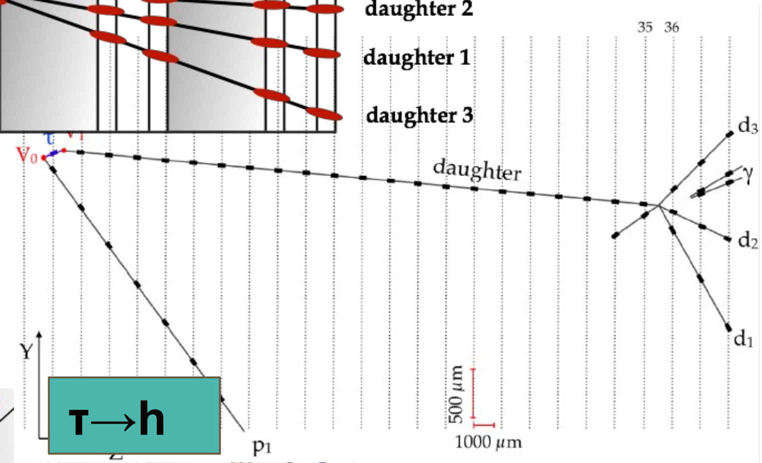
$\nu_\mu \to \nu_\tau$: 5 ν_τ candidates observed



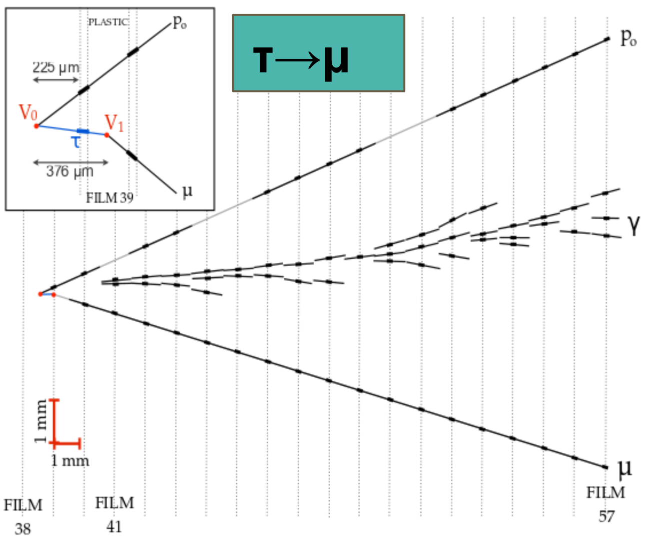
Phys. Lett. B 691 (2010) 183



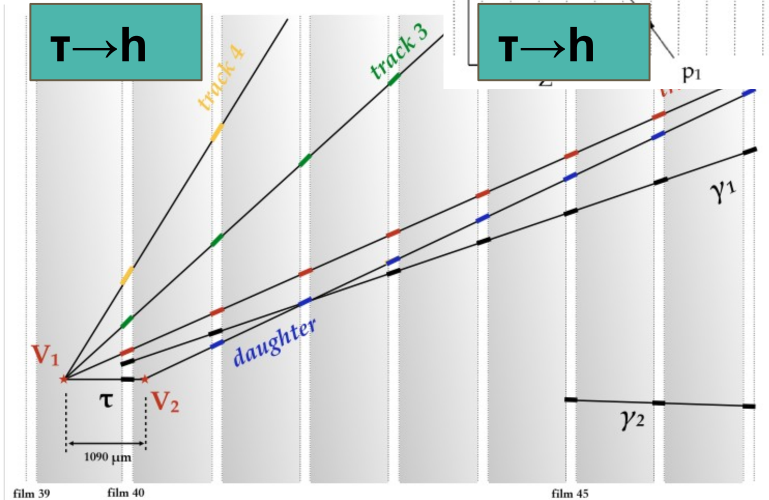
JHEP 11 (2013) 036



Phys. Rev. Lett. 115 (2015) 12, 121802



Phys. Rev/ D 89 (2014) **051102**



PTEP (2014) 10, 101C01

$\nu_\mu \rightarrow \nu_\tau$: discovery of ν_τ appearance in the CNGS beam

Channel	Expected background				Expected signal	Observed
	Charm	Had. reinterac.	Large μ scat.	Total		
$\tau \rightarrow 1h$	0.017 ± 0.003	0.022 ± 0.006		0.04 ± 0.01	0.52 ± 0.10	3
$\tau \rightarrow 3h$	0.17 ± 0.03	0.003 ± 0.001		0.17 ± 0.03	0.73 ± 0.14	1
$\tau \rightarrow \mu$	0.004 ± 0.001		0.0002 ± 0.0001	0.004 ± 0.001	0.61 ± 0.12	1
$\tau \rightarrow e$	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

Probability of the background fluctuation = $1.1 * 10^{-7}$

$\rightarrow$ absence of the signal excluded with a significance of **5.1 σ**

Scientific Background on the Nobel Prize in Physics 2015

NEUTRINO OSCILLATIONS

compiled by the Class for Physics of the Royal Swedish Academy of Sciences

Super-Kamiokande's oscillation results were later confirmed by the detectors MACRO [55] and Soudan [56], the long-baseline accelerator experiments K2K [57], MINOS [58] and T2K [59] and more recently also by the large neutrino telescopes ANTARES [60] and IceCube [61]. Appearance of tau-neutrinos in a muon-neutrino beam has been demonstrated on an event-by-event basis by the OPERA experiment in Gran Sasso, with a neutrino beam from CERN [62].

PRL 115 (2015) 121802

$\nu_\mu \rightarrow \nu_\tau$: new event analysis

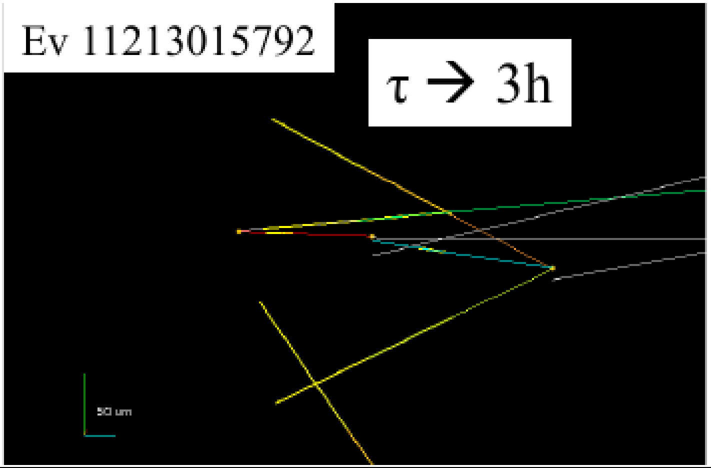
New selection strategy was defined in order to increase the number of ν_τ candidates to estimate Δm^2_{23} (first measurement in appearance mode) and ν_τ cross section with less statistical error:

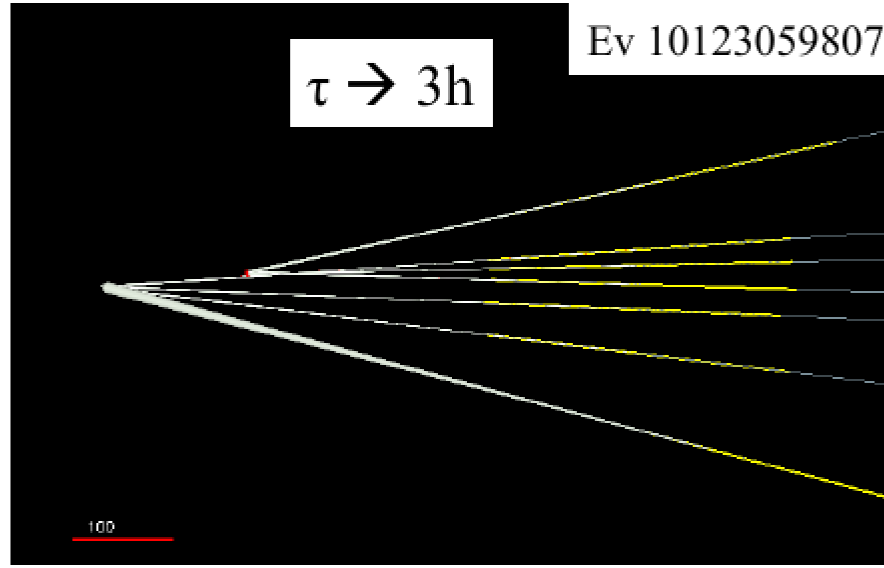
- Minimum bias kinematical cuts
- Multivariate analysis: Boosted Decision Tree

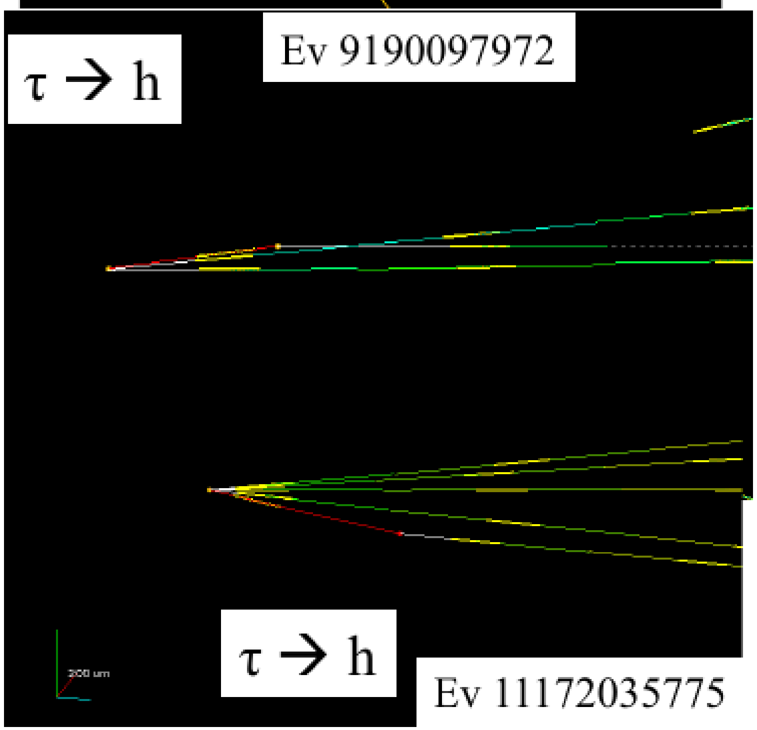
Variable	$\tau \rightarrow 1h$ PREV.	$\tau \rightarrow 1h$ NEW	$\tau \rightarrow 3h$ PREV.	$\tau \rightarrow 3h$ NEW	$\tau \rightarrow \mu$ PREV.	$\tau \rightarrow \mu$ NEW	$\tau \rightarrow e$ PREV.	$\tau \rightarrow e$ NEW
z_{dec} (μm)	$[44, 2600]$	< 2600	< 2600		$[44, 2600]$	< 2600	< 2600	
θ_{kink} (rad)	> 0.02		< 0.5	> 0.02	> 0.02		> 0.02	
p_{2ry} (GeV/c)	> 2	> 1	> 3	> 1	$[1, 15]$		$[1, 15]$	> 1
p^T_{2ry} (GeV/c)	$> 0.6\,(0.3)$	> 0.15	/		> 0.25	> 0.1	> 0.1	
p^T_{miss} (GeV/c)	$< 1\star$	/	$< 1\star$	/	/		/	
ϕ_{lH} (rad)	$> \pi/2\star$	/	$> \pi/2\star$	/	/		/	
m, m_{min} (GeV/c^2)	/		$[0.5, 2]$	/	/		/	

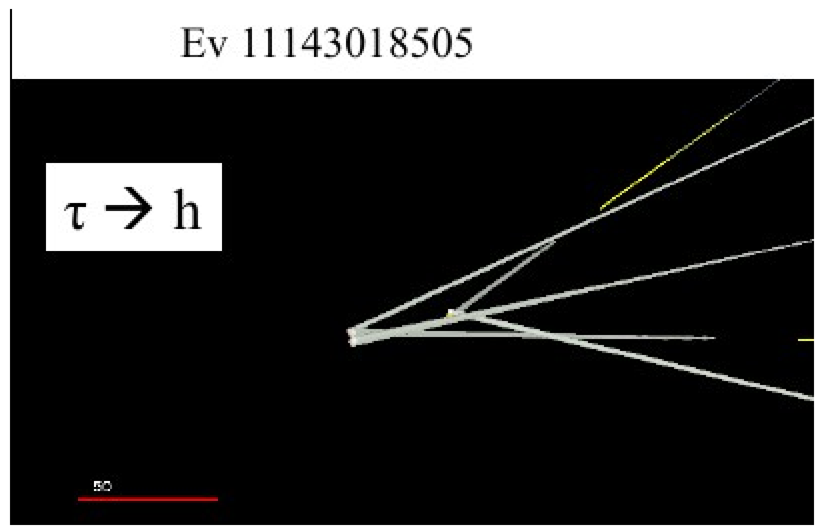
Channel	**Expected Background** Charm	Had. re-interaction	Large μ-scat.	Total	**Exp. Signal**	**Observed**
$\tau \rightarrow 1h$	0.15 ± 0.03	1.28 ± 0.38	–	1.43 ± 0.41	2.96 ± 0.59	6
$\tau \rightarrow 3h$	0.44 ± 0.09	0.09 ± 0.03	–	0.53 ± 0.12	1.83 ± 0.37	3
$\tau \rightarrow \mu$	0.008 ± 0.002	–	0.02 ± 0.008	0.03 ± 0.01	1.15 ± 0.23	1
$\tau \rightarrow e$	0.035 ± 0.007	–	–	0.03 ± 0.007	0.84 ± 0.17	0
Total	0.63 ± 0.13	1.37 ± 0.41	0.02 ± 0.008	2.0 ± 0.5	6.8 ± 1.4	10

$\nu_\mu \rightarrow \nu_\tau$: new 5 ν_τ candidates

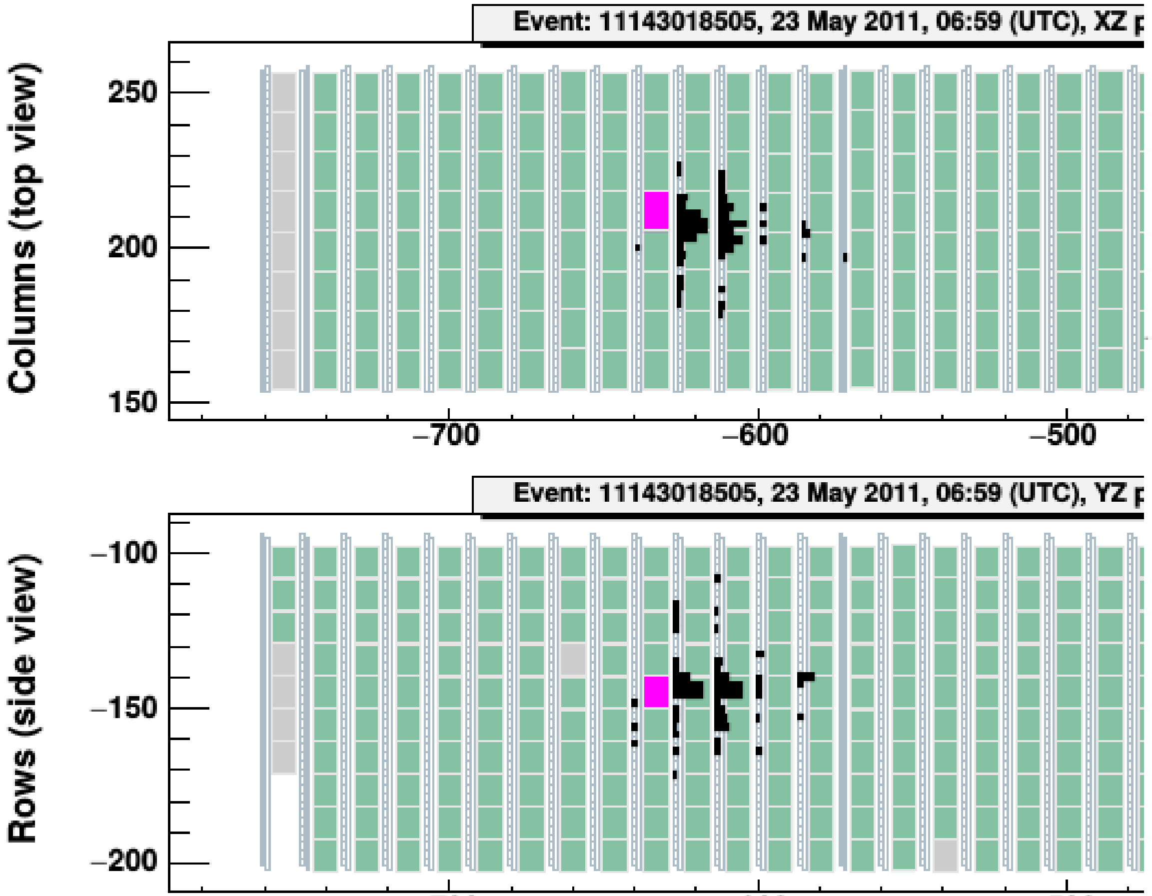


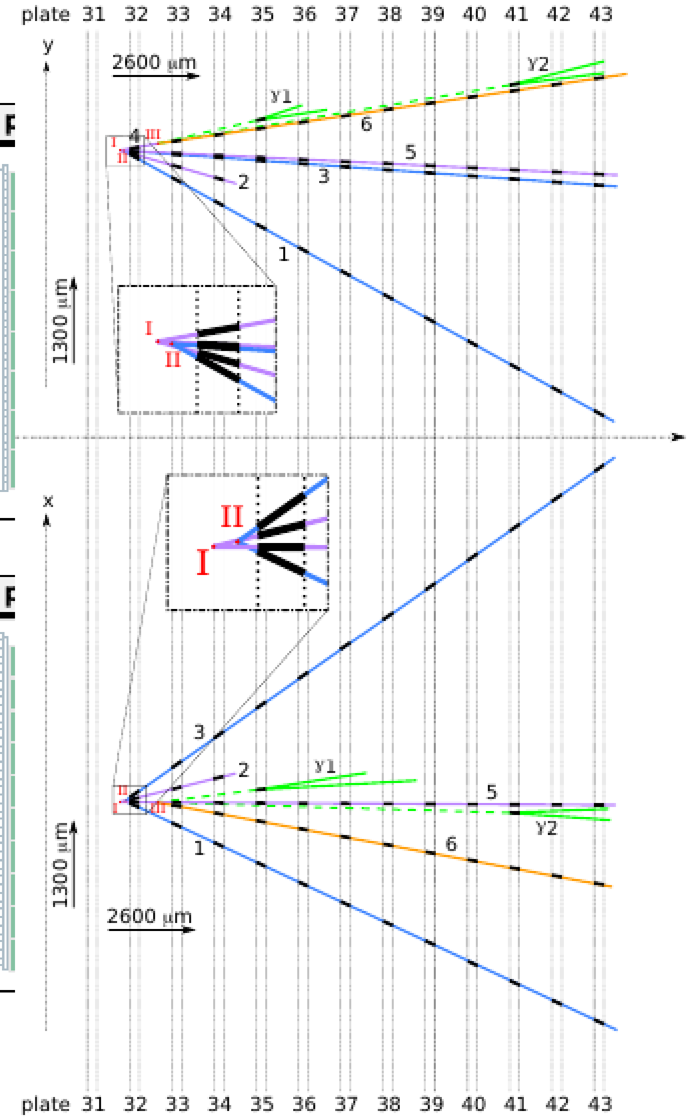






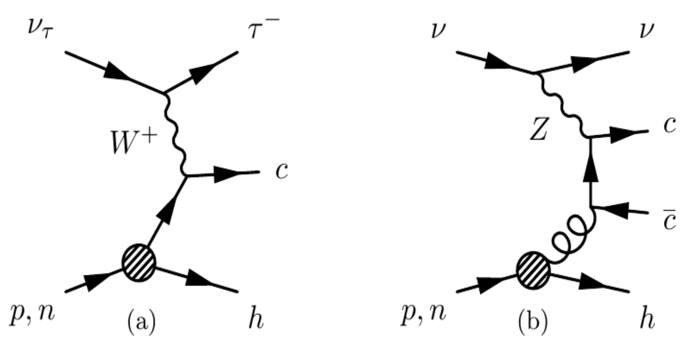
$\nu_\mu \rightarrow \nu_\tau$: an event with three vertices



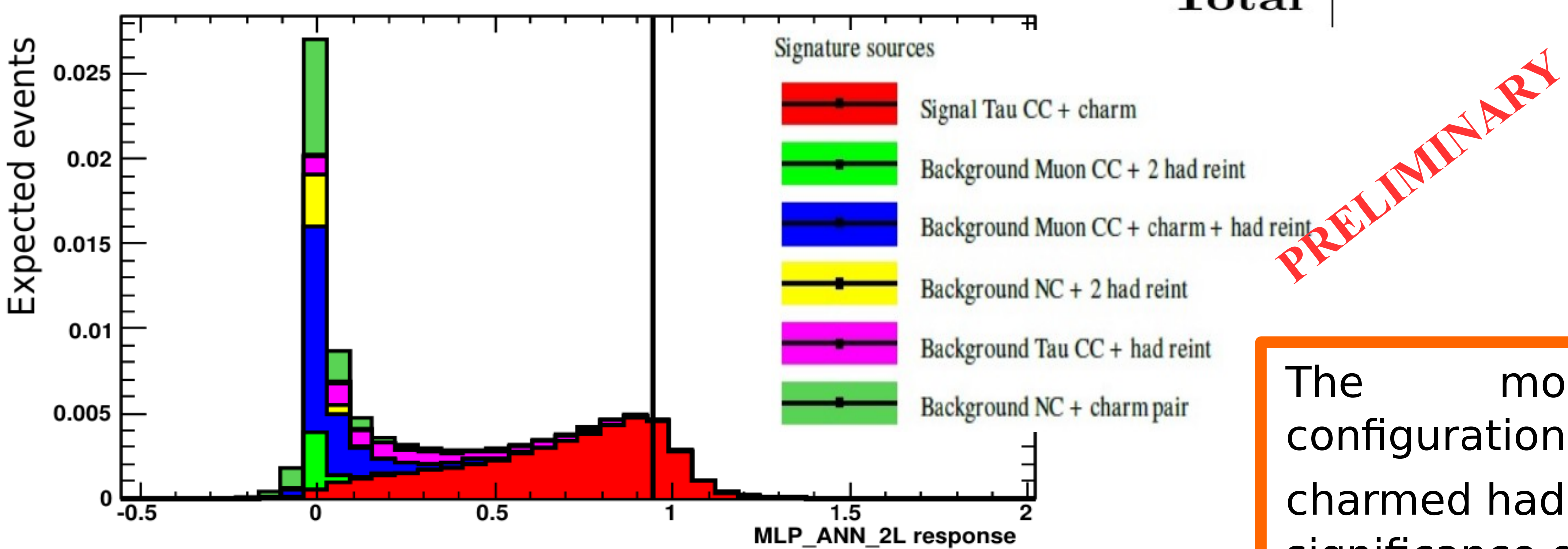


Views in electronic detectors and in the brick

$\nu_\mu \rightarrow \nu_\tau$: an event with three vertices



Sample	Expected events (10^{-3})
ν_τ CC + charm	44.5 ± 0.1
ν NC + $c\bar{c}$ pair	12.59 ± 0.02
ν_μ CC + two 2ry	4.0 ± 0.5
ν_μ CC + charm + 2ry	20.5 ± 0.5
ν NC + two 2ry	3.8 ± 0.3
ν_τ CC +2ry	9.0 ± 0.1
Total	94.4



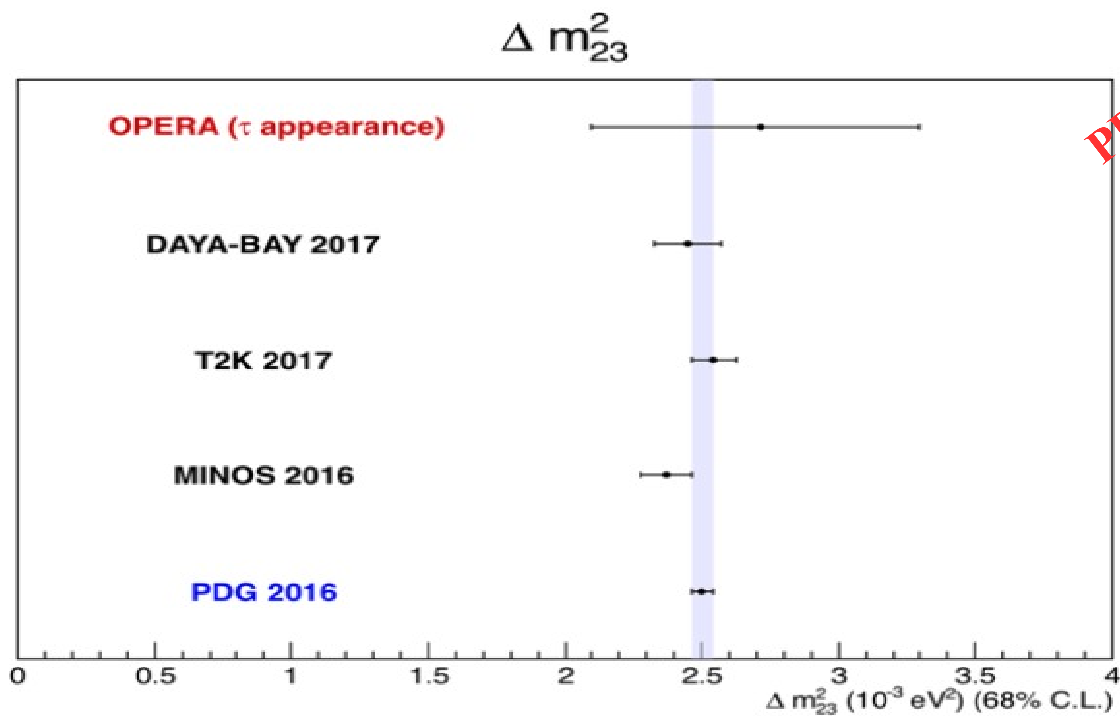
The most likely configuration is ν_τ CC with charmed hadron with significance of **3.5σ**

$\nu_\mu \to \nu_\tau$: Δm^2_{23} measurement

$$N_{\nu_\tau} \propto P(\nu_\mu \to \nu_\tau)\sigma_{\nu_\tau}$$

Expected Signal	Expected Background	Observed ν_τ	Δm^2_{23} $(10^{-3}\ \text{eV}^2)$
6.5	2.0	10	$2.8^{+0.6}_{-0.6}$ 68% C.L

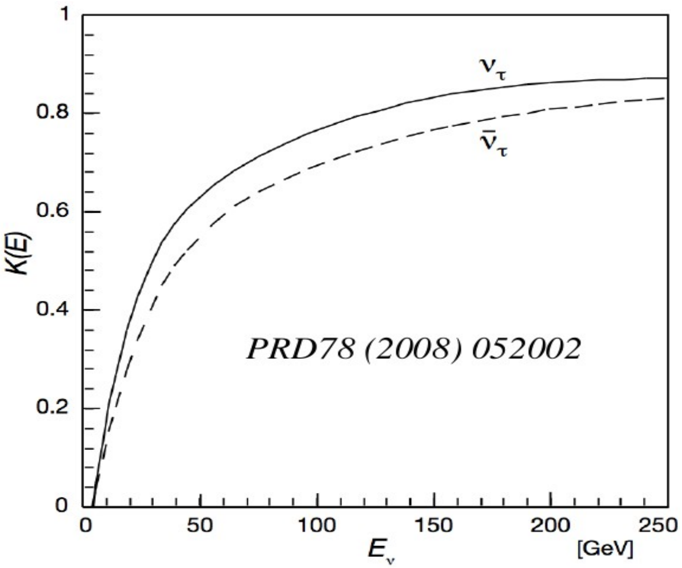
PRELIMINARY



Agreement with PDG 2016 value within 1σ

$\nu_\mu \rightarrow \nu_\tau$: ν_τ cross-section masurement

$$\sigma_{\nu_\tau} = \sigma_{\nu_\tau}^{const} E\, K(E)$$



Untill now, ν_τ cross-section was measured only by DONuT

DONuT could not distinguish ν_τ from anti-ν_τ

$$\sigma_{\nu_\tau+\overline{\nu_\tau}}^{const} = 0.72 \pm 0.24 \pm 0.36 \times 10^{-38}\, cm^2\, GV^{-1}$$

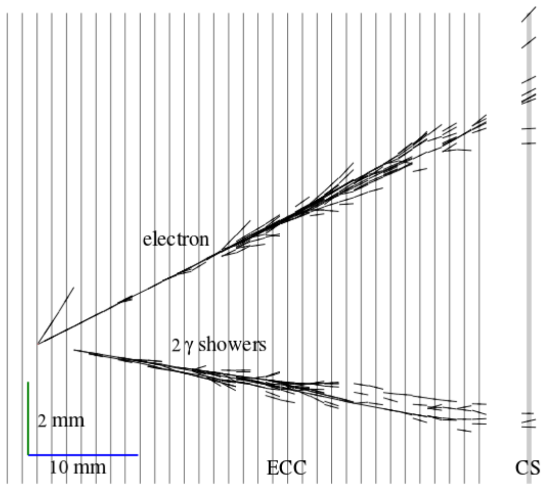
OPERA: first measurement with ν_τ only

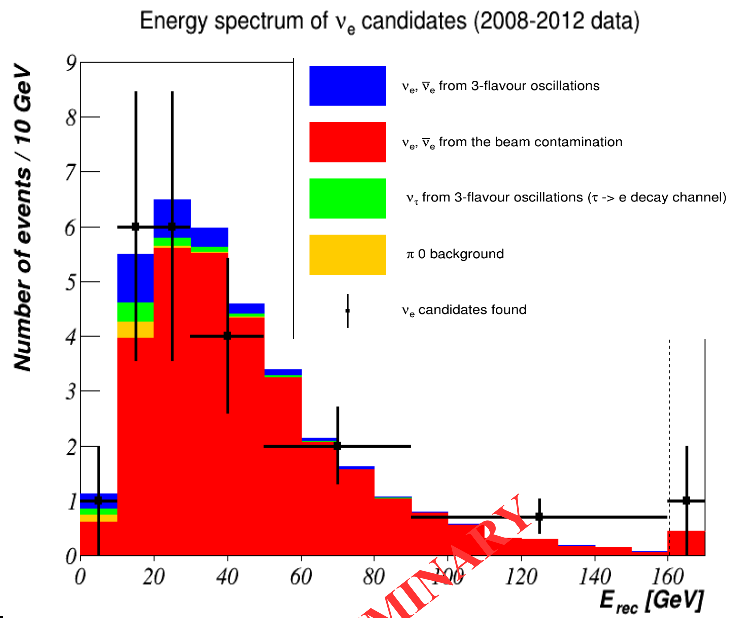
Δm^2_{23} $(10^{-3}\ \mathrm{eV}^2)$	Expected Signal	Expected Background	Observed ν_τ	$\sigma^0_{\nu_\tau}$ $(10^{-39}\mathrm{cm}^2\mathrm{GeV}^{-1})$
2.5	6.5	2.0	10	8^{+4}_{-3}

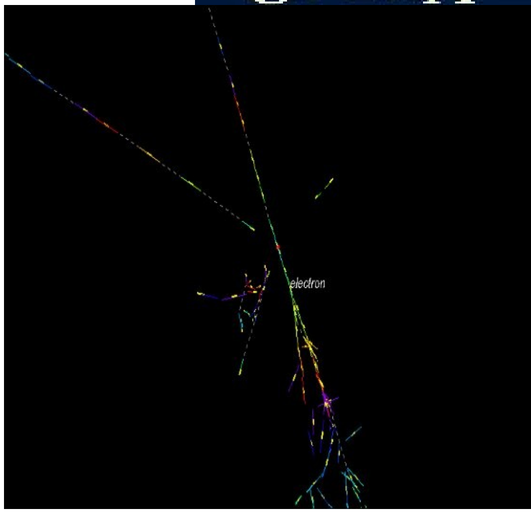
Agreement with SM value $0.67 \times 10^{-38}\, cm^2 GV^{-1}$ within 1σ

PRELIMINARY

$\nu_\mu \to \nu_e$: full data sample analysis







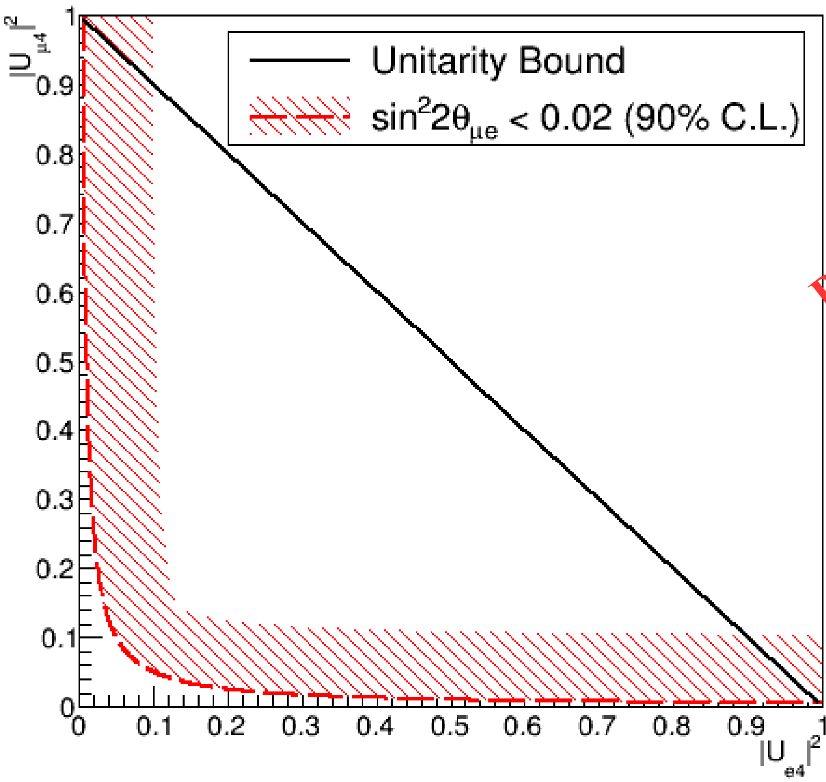
Energy cut, GeV	10	20	30	40	50	No cut
ν_e, $\bar{\nu}_e$ from the beam contamination	0.6	4.6	10.2	15.7	20.0	30.8
π^0	0.1	0.4	0.5	0.5	0.5	0.5
ν_τ from 3-flavour oscillations ($\tau \to e$ channel)	0.1	0.5	0.6	0.7	0.8	0.9
Total expected BG	0.8	5.5	11.3	16.9	21.3	32.2
ν_e, $\bar{\nu}_e$ from 3-flavour oscillations	0.3	1.1	1.8	2.3	2.4	2.7
Expected spectrum in case of 3 flavour oscillations	1.1	6.6	13.1	19.2	23.7	34.9
Data	1	7	13	19	21	35

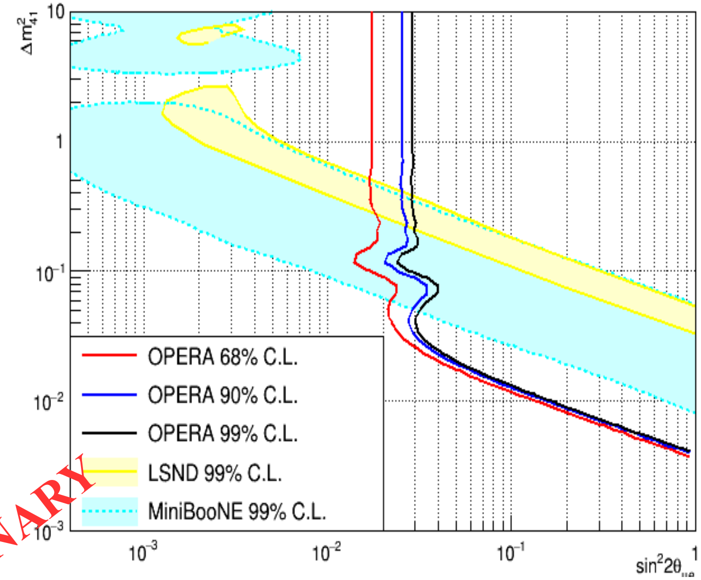
Number of observed events is in agreement with the expected background and 3 flavour oscillation signal

$\nu_\mu \rightarrow \nu_e$: sterile neutrinos in 3+1 model

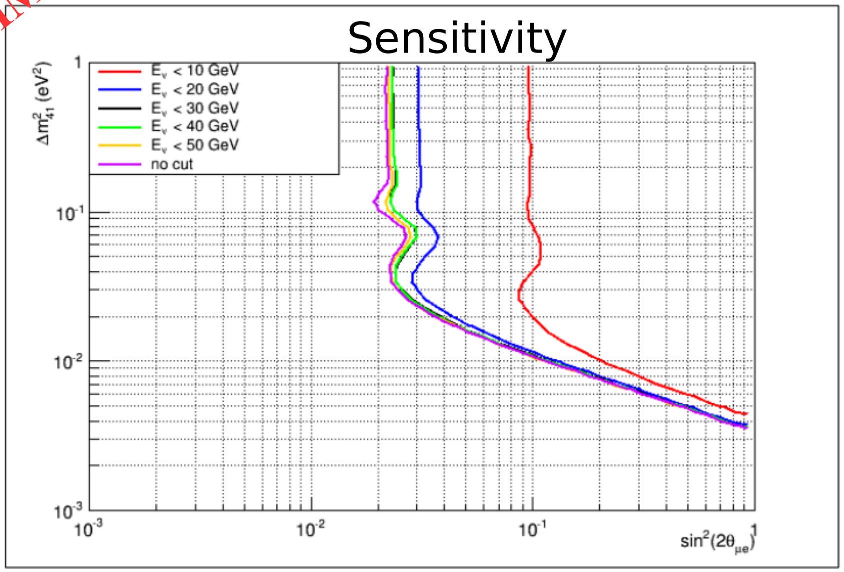
νe search results used to derive limits on the mixing parameters of a massive sterile neutrino in the 3+1 neutrino model

$$\sin^2 2\theta_{\mu e} = 4|U_{\mu 4}^2||U_{e4}^2|$$

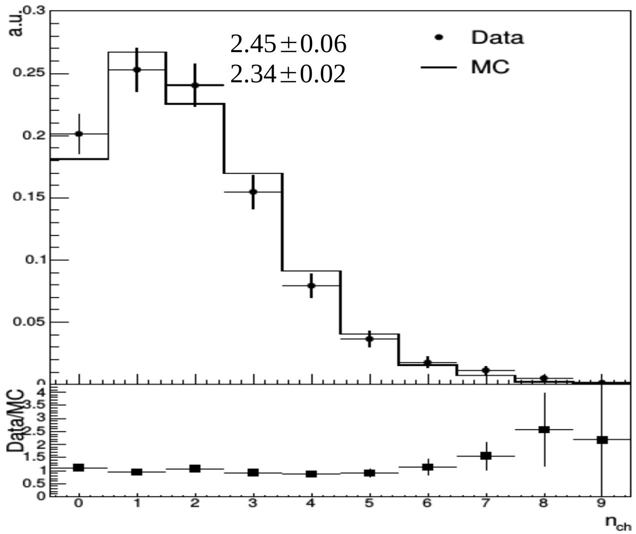




PRELIMINARY



Study of charged particles multiplicity distribution in Pb

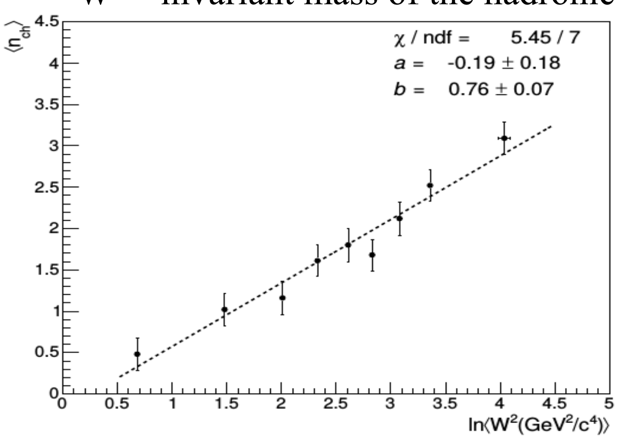


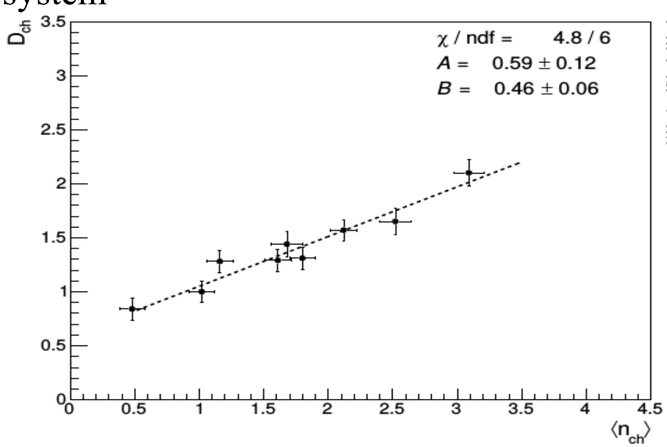
The study is aimed in tuning the models used in MC generators.

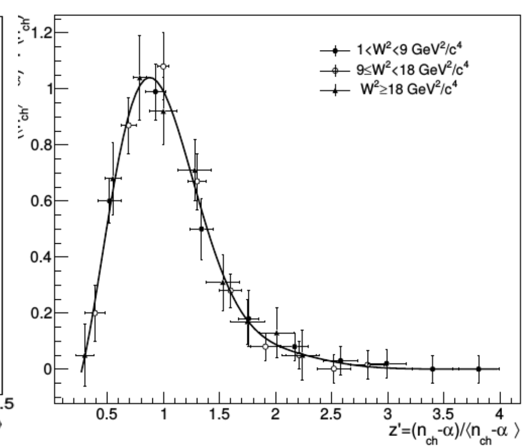
Arxiv:1706.07930

- Linear dependence: $\langle n_{ch} \rangle = a + b \ln W^2$
- Linear dependence $\langle D_{ch} \rangle = A + B \langle n_{ch} \rangle$
- Aproximate KNO (Koba, Nielsen, Olesen) scaling is valid for the charged hadrons multiplicity

- $\langle n_{ch} \rangle$ - the average multiplicity
- $\langle D_{ch} \rangle$ - dispersion of $\langle n_{ch} \rangle$
- W^2 – invariant mass of the hadronic system





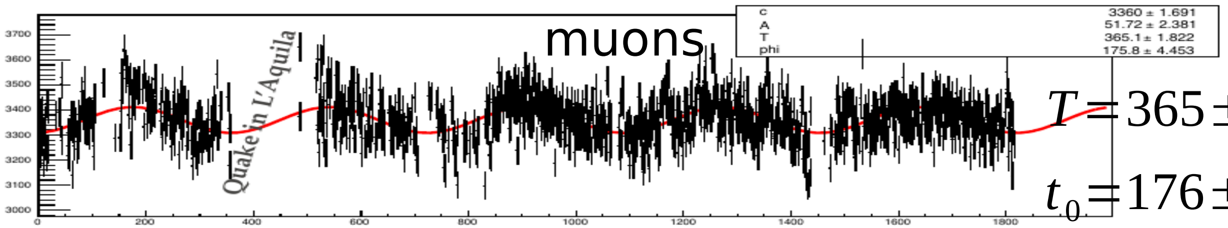


Annual modulations of atmospheric muons

Gran Sasso underground ~3800 m w.e. → Minimum muon energy ~ 1.8 TeV

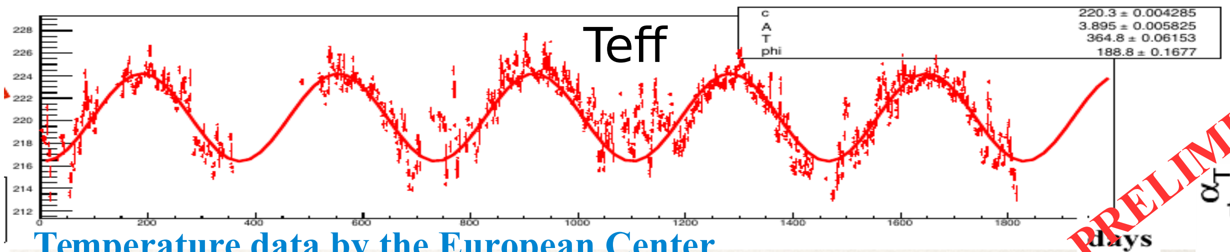
Atmospheric temperature increase → density decrease → the pion and kaon decay rate increase → muon rate increase

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

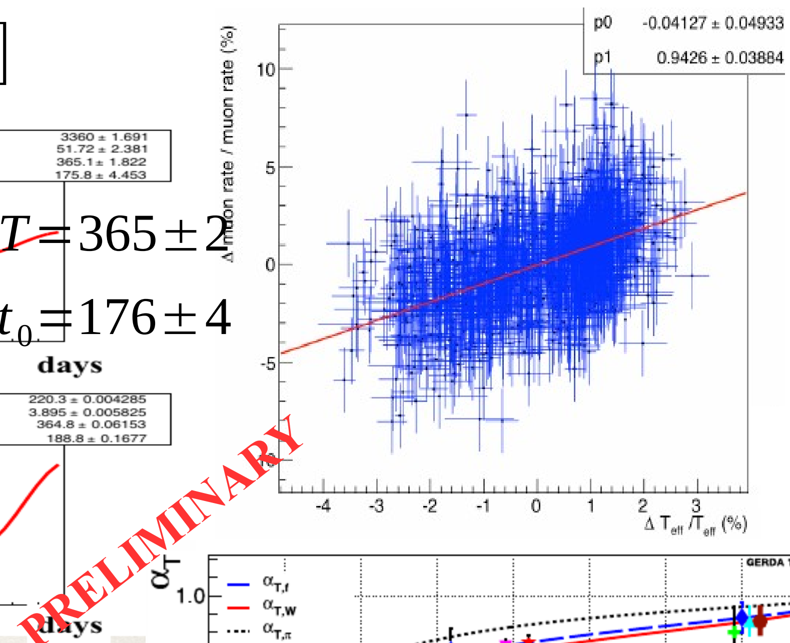


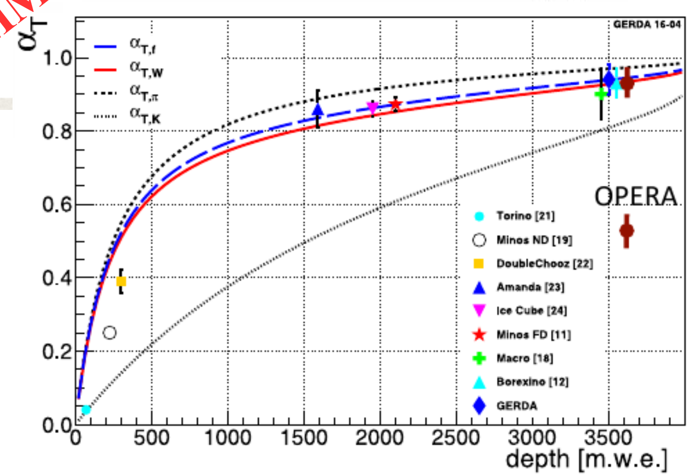
$$T = 365 \pm 2$$

$$t_0 = 176 \pm 4$$



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





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

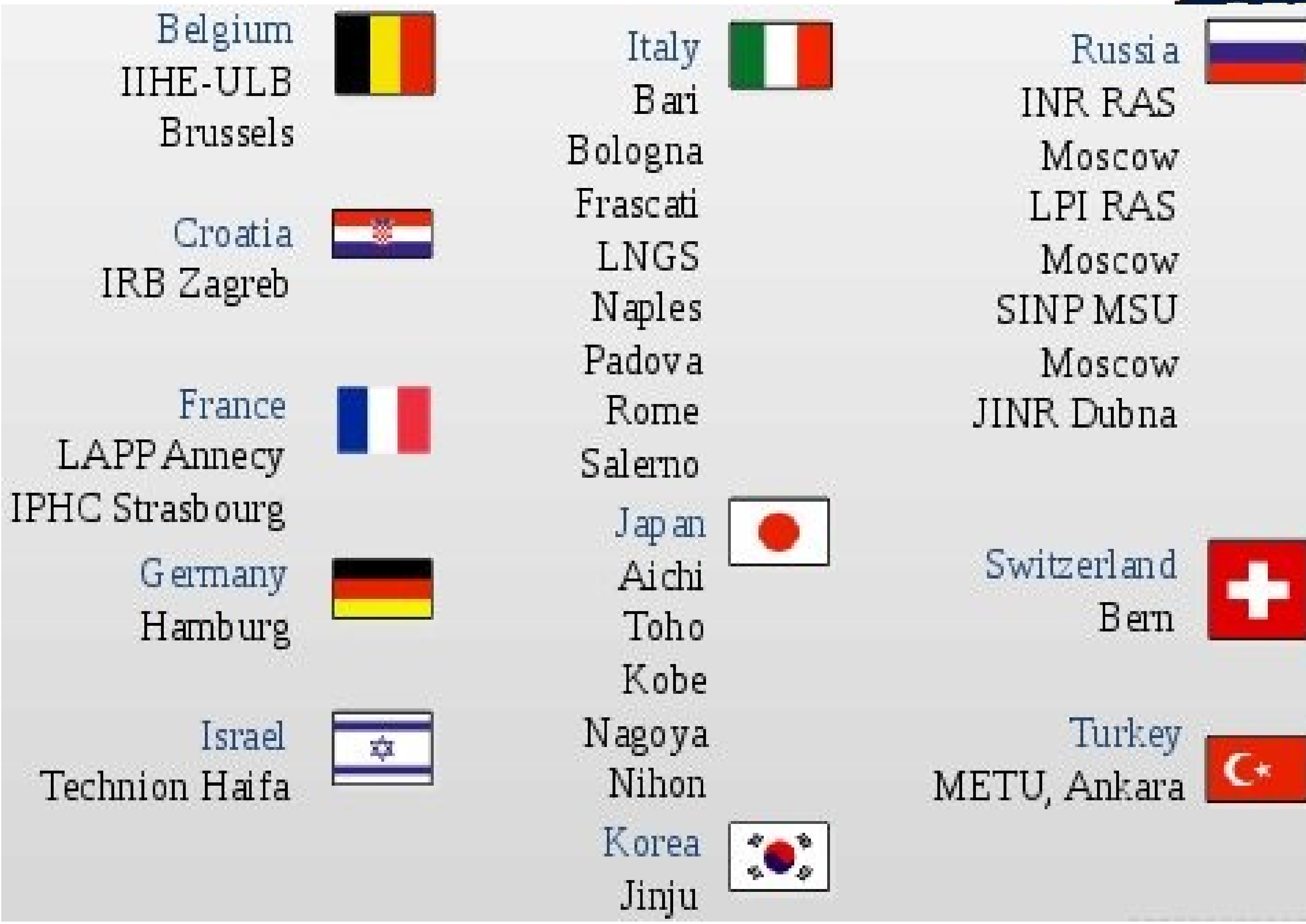
$$\frac{\Delta I_\mu}{I_\mu^0} = (1.54 \pm 0.07)\%$$

$$\alpha_T = 0.94 \pm 0.04$$

Summary

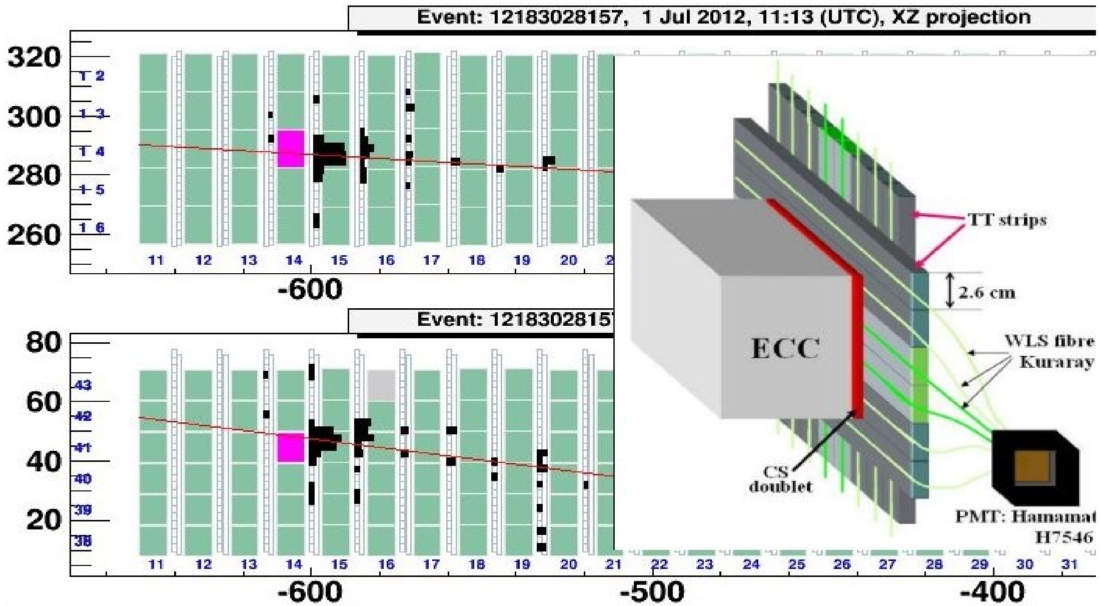
- **Discovery of $\nu_\mu \rightarrow \nu_\tau$ appearance** in the CNGS beam with 5.1σ
- Minimum bias analysis to increase the number of ν_τ candidates:
  - **Δm^2_{23} measurement (first measurement in appearance mode) and absolute measurement of ν_τ cross section (first measurement)** with less statistical uncertainties
- **$\nu_\mu \rightarrow \nu_e$ oscillation search**: number of observed candidates is in the agreement with the expected background and the standard oscillation signal
- Constraint on **sterile neutrinos** from $\nu_\mu \rightarrow \nu_e$ analysis with the 3+1 flavour model
- Study of the **charged particle multiplicity distribution** in high-energy neutrino-lead interactions
- Study of **cosmic-ray annual modulation**
- **Perspectives:** a unique feature is anability of the detector to measure all 3 neutrino flavours. Use of ν_μ disappearance and both ν_τ and ν_e appearance to constrain on the oscillation parameters with one single experiment

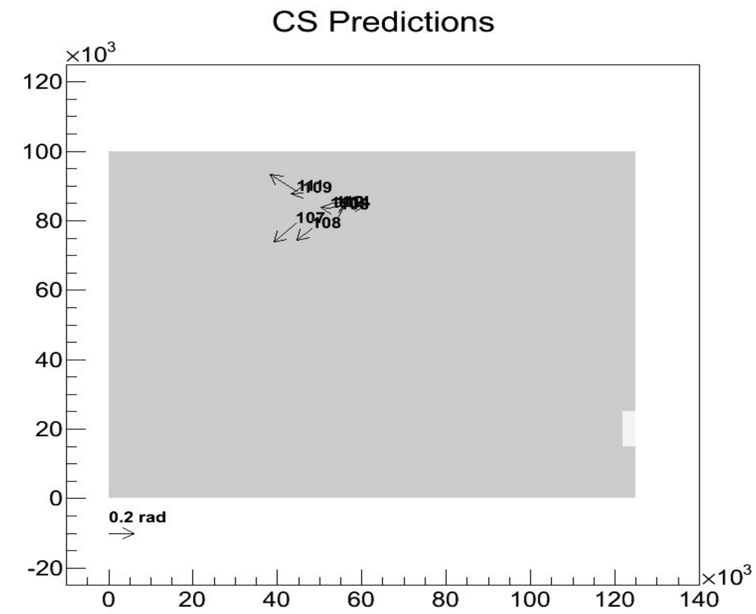
Thank you for your attention!



Backup slides

Data analysis chain

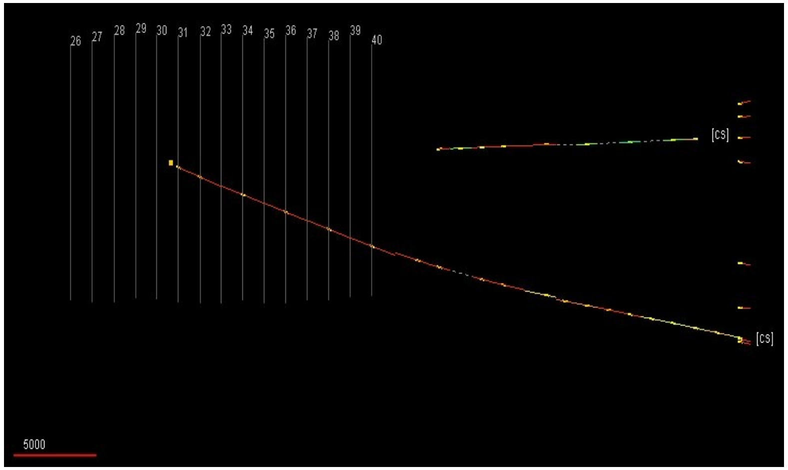


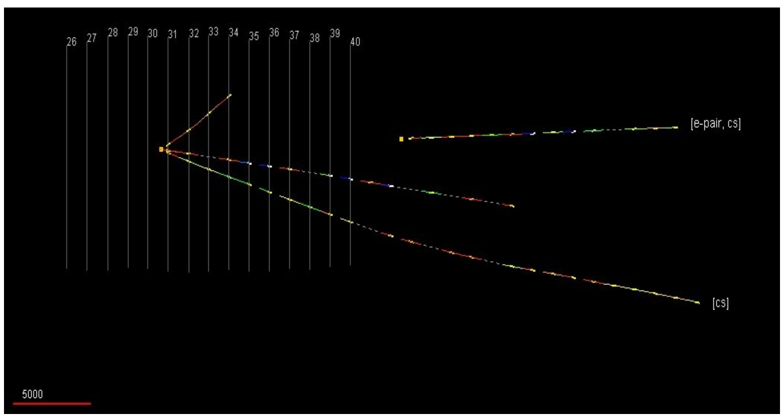


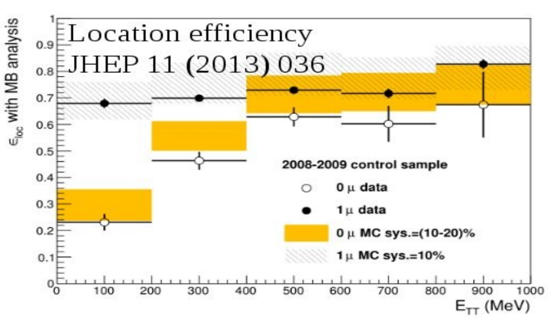
Target Tracker data is used for a prediction of the bricks which contain neutrino interactions

A large area of the corresponding changeable film is scanned
(so far 2 500 000 cm^2 of CS surface analysed)

Data analysis chain

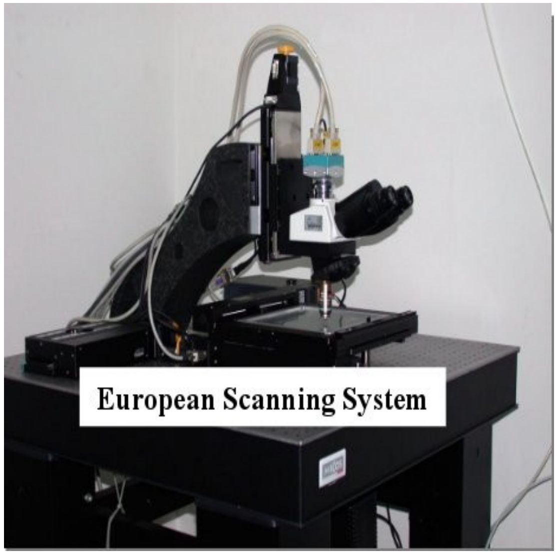






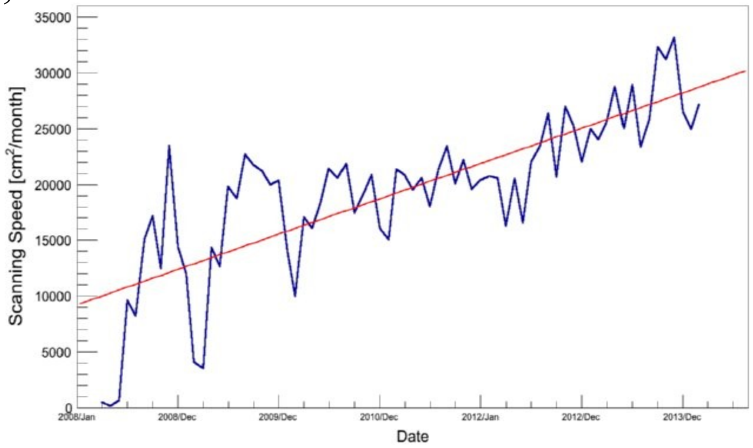
- Brick exposure at the surface laboratory to collect **cosmic-rays for alignment**
- **Scan-back:** CS-tracks are followed upstream from film to film to find the n-interaction vertex
- **Total-scan**: scanning of the 1 cm2 around the vertex in 15 plates is performed
- **Scan-forth:** improvement of the momentum measurement of the tracks
  New J. of Phys. 4 (2012) 013026
- **Decay search:** impact parameter, kink search, parent search
  Eur. Phys. J. C (2014) 74:2986

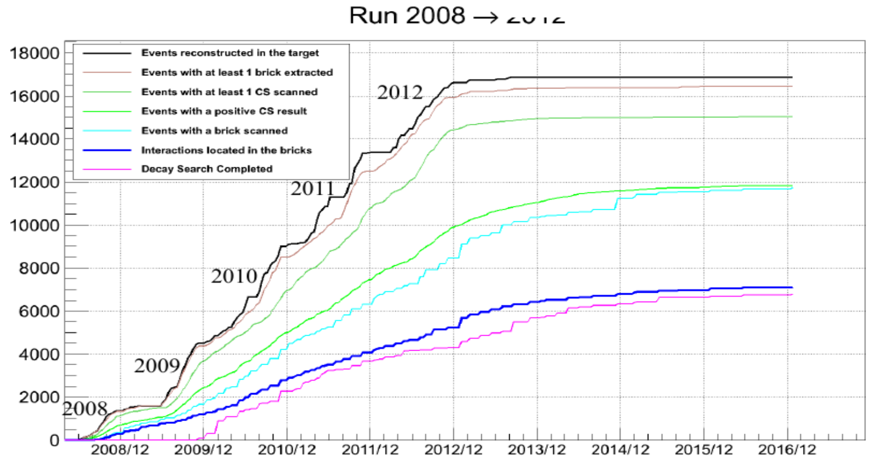
Data analys: event location



Scanning of CS: two large facilities

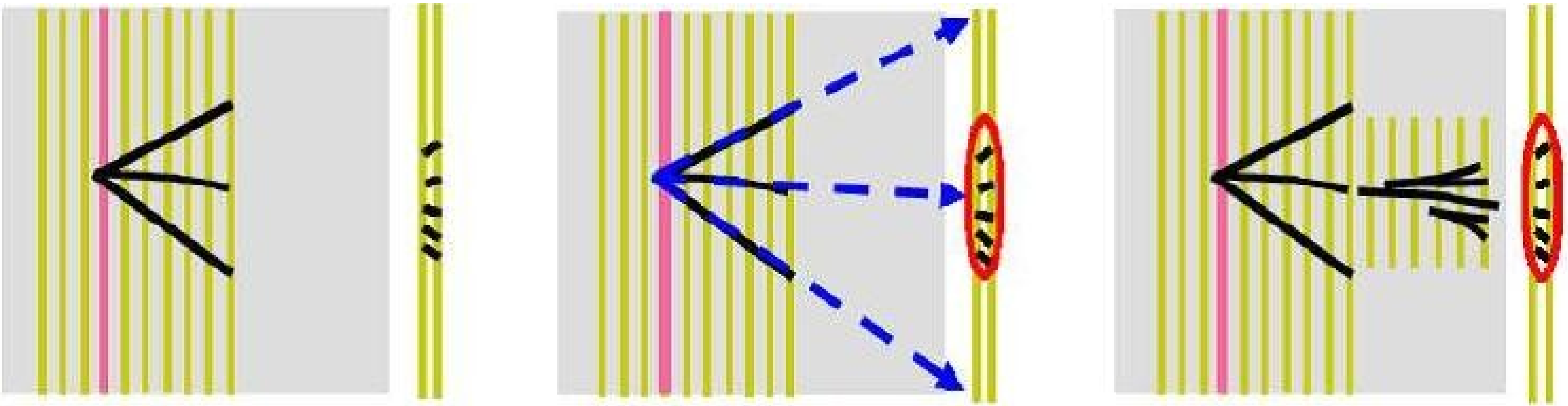
Nagoya: 5 S-UTS, 220 cm^2/h
LNGS: 10 microscopes, 200 cm^2/h





7132 located interactions
6785 decay search

Data analysis chain: ν_e search



Search for ν_e candidates **JHEP 1307 (2013) 004**

The electron identification is based on the search of associated electromagnetic shower. Primary tracks extrapolated to the changeable emulsion doublets. The tracks with angles and positions similar to projection ones are searched (150 mrad, 2 mm)

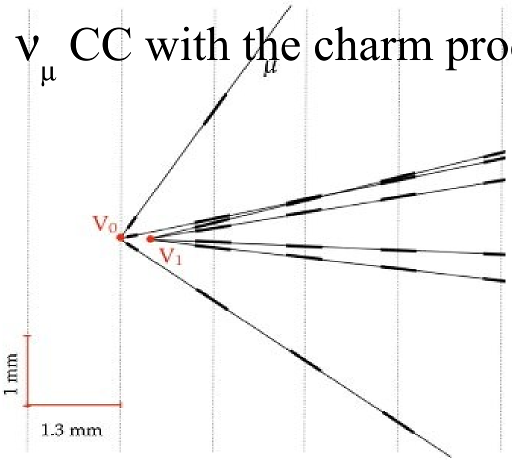
If 3 or more tracks found, an additional volume along the candidates track is scanned

Charm decay control sample for the τ decay search

Charm and τ decays have similar topologies.Good agreement between data and expectation

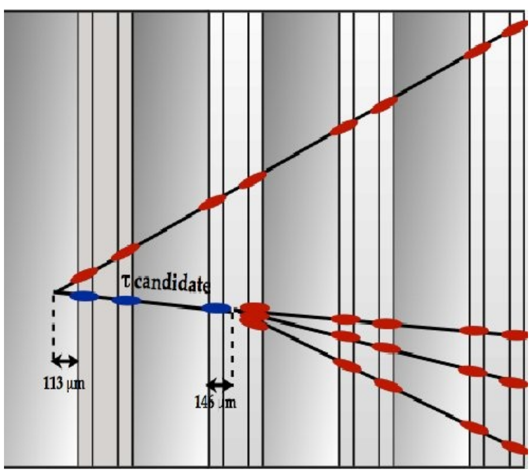
Eur Phys. J. C (2014) 74:2986

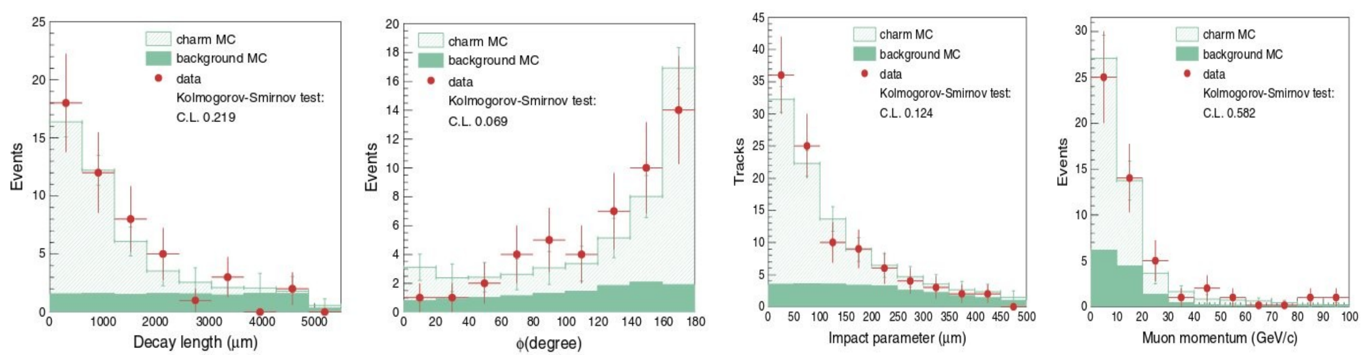
ν_μ CC with the charm production



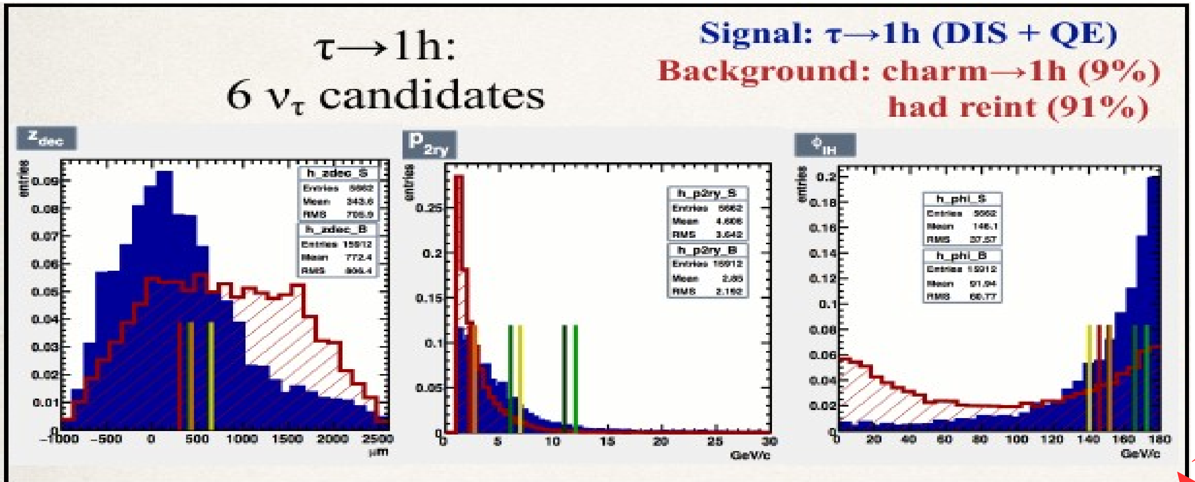
Decay topology	Events			
	Expected charm	Expected background	Expected total	Observed
1-prong	21 ± 2	9 ± 3	30 ± 4	19
2-prong	14 ± 1	4 ± 1	18 ± 1	22
3-prong	4 ± 1	1.0 ± 0.3	5 ± 1	5
4-prong	0.9 ± 0.2	-	0.9 ± 0.2	4
Total	40 ± 3	14 ± 3	54 ± 4	50

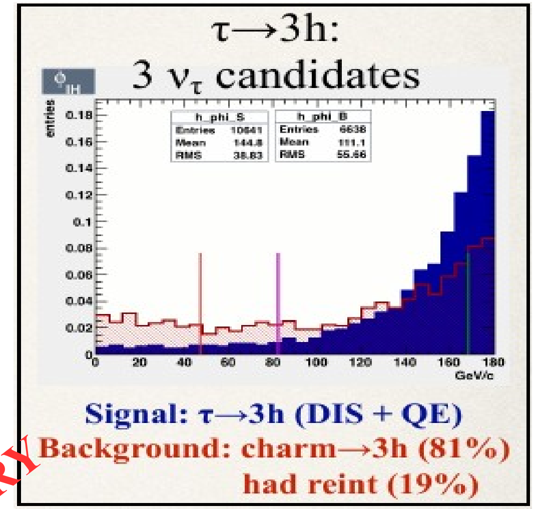
$\nu_\tau \rightarrow 3h$ candidate JHEP 11 (201



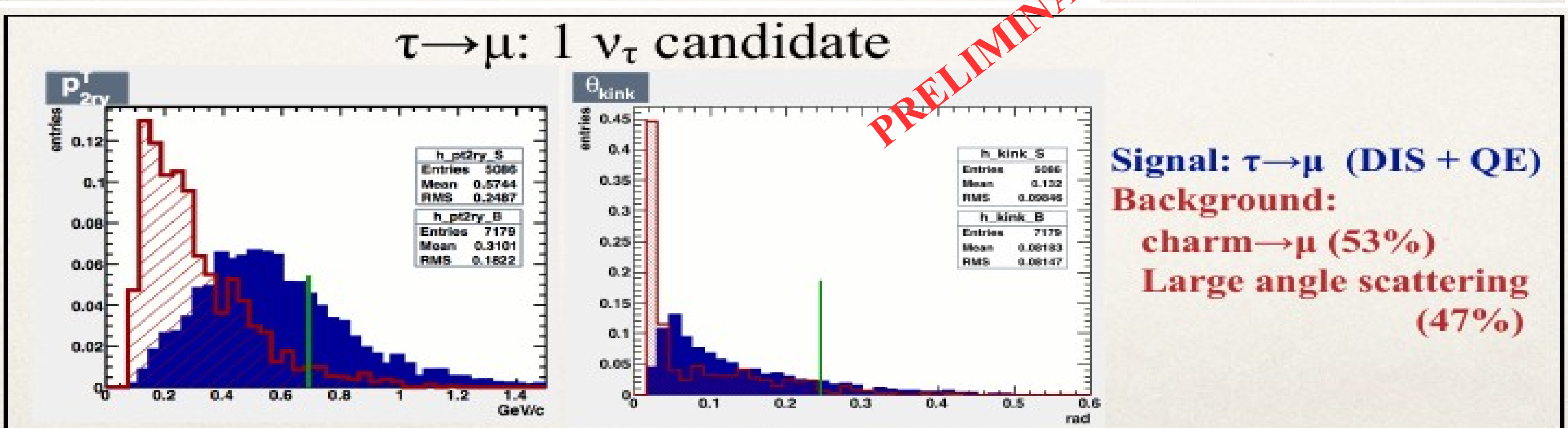


DataExample of the signal and background distribution for the most discriminating variables

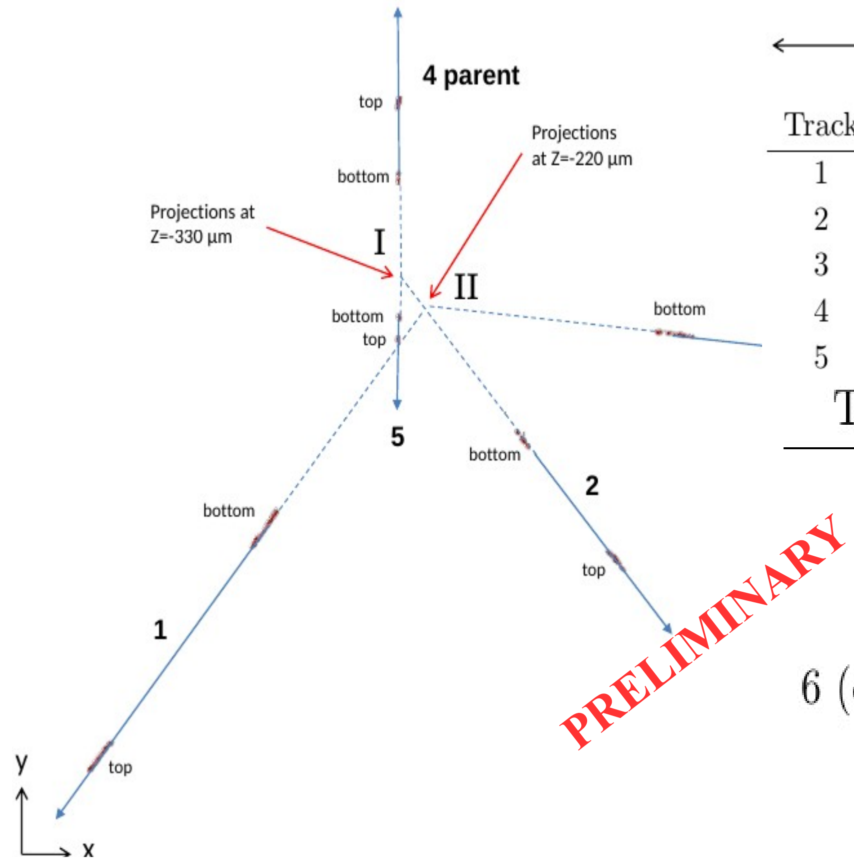




PRELIMINARY

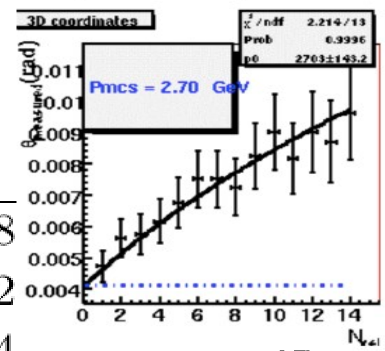


$\nu_\mu \rightarrow \nu_\tau$: an event with three vertices



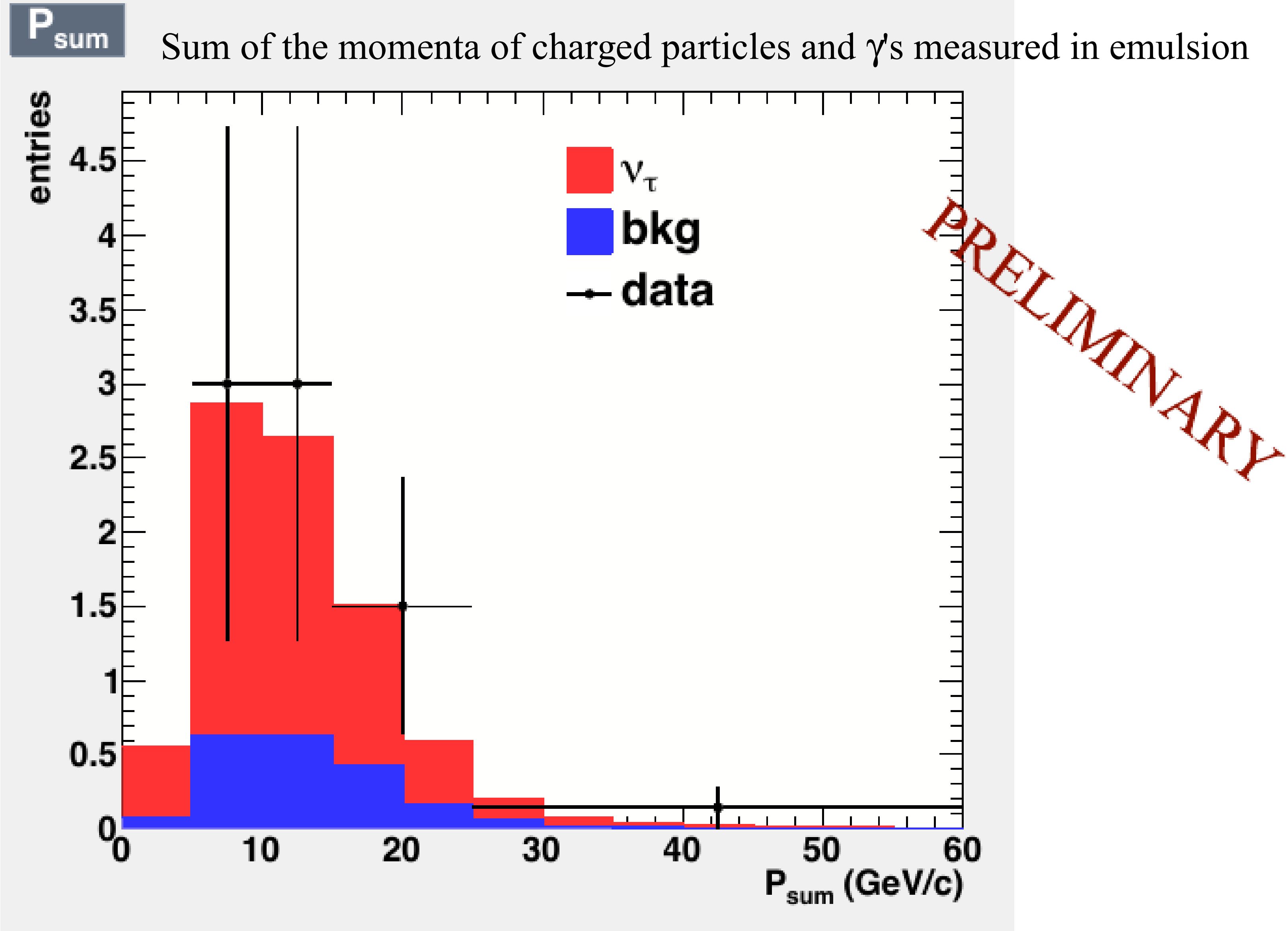
Track	θ_x (rad)	θ_y (rad)	One Vertex IP (μm) w.r.t. V_0	Two vertices IP (μm) w.r.t. V_I	w.r.t. V_{II}
1	-0.230	-0.275	8.3	36.2	0.1
2	0.121	-0.144	8.8	1.0	6.5
3	0.349	-0.036	4.8	25.9	0.1
4	-0.003	0.088	13.0	1.5	20.4
5	-0.003	-0.025	5.1	2.2	9.6

Track ID	p best fit (GeV/c)	68 % p range (GeV/c)
1	2.1	[1.6 ; 3.1]
3	4.3	[3.1 ; 7.1]
5	0.54	[0.45 ; 0.68]
6 (daughter)	2.7	[2.1 ; 3.7]



Vertex ID	Parent	Daughters	x (μm)	y (μm)	z (μm)
I (primary)	-	2, 4, 5, neutral	15077.0	59157.9	-33081.8
II (secondary)	neutral	1, 3	15085.9	59149.9	-32979.2
III (kink)	4	6	15073.9	59262.4	-31926.4

$\nu_\mu \rightarrow \nu_\tau$: visible energy of all candidates



$\nu_\mu \to \nu_e$: sterile neutrinos in 3+1 model

~standard oscillation Exotic oscillation

$$P_{\nu_\mu \to \nu_e} = C^2 \sin^2 \Delta_{31} + \sin^2 2\theta_{\mu e} \sin^2 \Delta_{41}$$

Interference term

$$\begin{aligned}
&+ 0.5\, C \sin 2\theta_{\mu e} \cos \phi_{\mu e} \sin 2\Delta_{31} \sin 2\Delta_{41} \\
&- C \sin 2\theta_{\mu e} \sin \phi_{\mu e} \sin^2 \Delta_{31} \sin 2\Delta_{41} \\
&+ 2\, C \sin 2\theta_{\mu e} \cos \phi_{\mu e} \sin^2 \Delta_{31} \sin^2 \Delta_{41} \\
&+ C \sin 2\theta_{\mu e} \sin \phi_{\mu e} \sin 2\Delta_{31} \sin^2 \Delta_{41}
\end{aligned}$$

$$C = 2|U_{\mu 3} U^*_{e3}|$$

$$\Delta_{ij} = \frac{1.27 \Delta m^2_{ij} L}{E}$$

$$\phi_{\mu e} = Arg(U_{\mu 3} U^*_{e3} U^*_{\mu 4} U_{e4})$$

$$\sin^2 2\vartheta_{\mu e} = 4|U_{\mu 4}|^2 |U_{e4}|^2$$

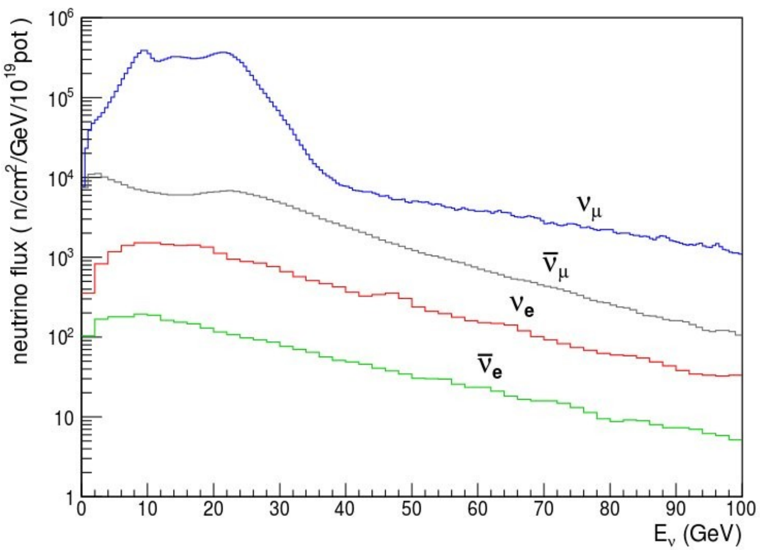
3+1 model: bounds from ne appearance with profile Likelyhood method

$$L = \prod_i Poisson(n_i; (1+k_j) \cdot u_i) \times \prod_j Gauss(k_j; 0, \sigma_j) \times Gauss(\Delta m^2_{23}; \widehat{\Delta m^2_{23}}, \sigma_{\Delta m^2_{23}})$$

With j = 1,2, $\sigma_1 = 0.2$ is applied to bin with $E_\nu < 10\ GeV$ and $\sigma_2 = 0.1$ is applied to bin with $E_\nu > 10\ GeV$.

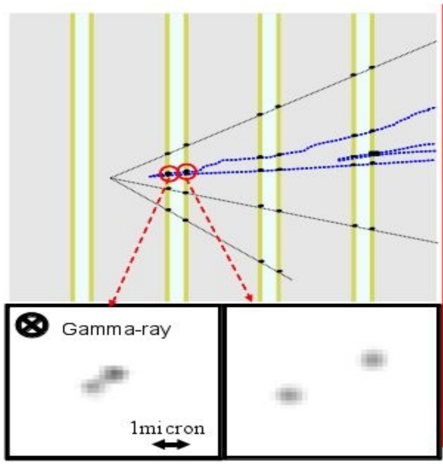
Energy distribution is used to constrain the parameter space: shape analysis

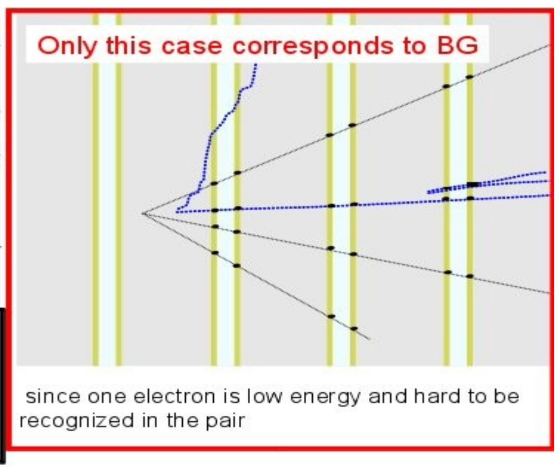
$\nu_\mu \rightarrow \nu_e$: background

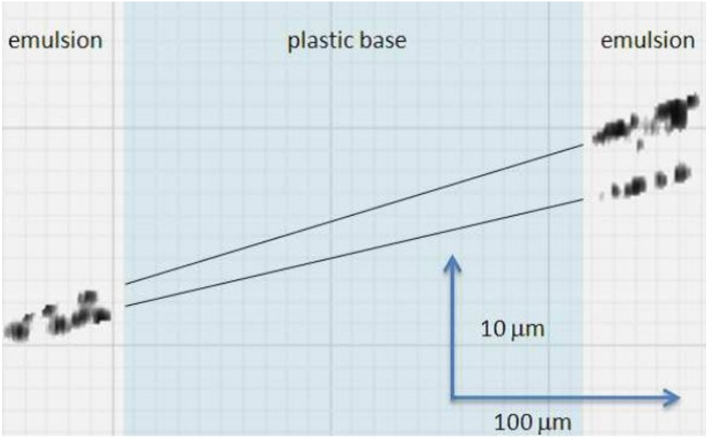


- ν_e events from intrinsic ν_e beam components
- ν_τ CC interactions with the decay of the $\tau \rightarrow e$
- π^0 misidentified as an electron in neutrino interactions without a reconstructed m

- e^+e^- can not be distinguished from a singe particle in the first 2 emulsion films after the vertex
- one pair component undetected



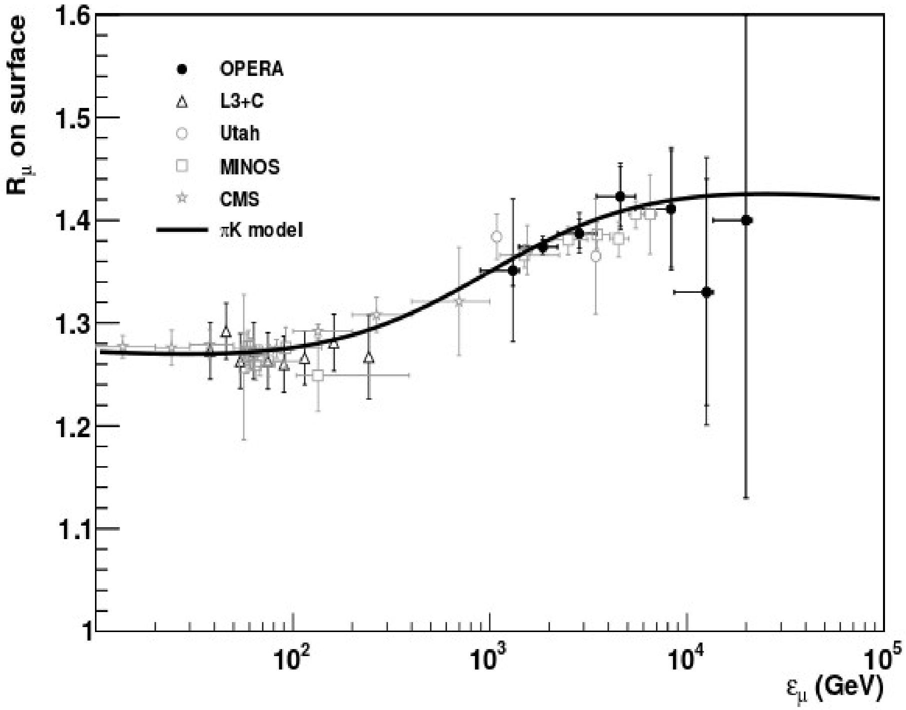




Cosmic ray physics

Measurement of TeV atmospheric muon charge ratio

Eur. Phys. J. C74 (2014) 2933



$$R_\mu \equiv N_{\mu^+}/N_{\mu^-}$$