MORE RESULTS FROM THE OPERA EXPERIMENT

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on behalf of the OPERA Collaboration

PANIC 2017
Beijing - Sep 1, 2017

THE OPERA COLLABORATION

26 institutions in 11 countries

Belgium
ULB Brussels

Korea
Jinju

Russia
INR RAS Moscow
LPI RAS Moscow
SINP MSU Moscow
JINR Dubna

Switzerland
Bern

Italy
Bari
Bologna
LNF
LNGS
Naples
Padova
Rome
Salerno

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg

Germany
Hamburg

Japan
Aichi
Kobe
Nagoya
Toho
Nihon

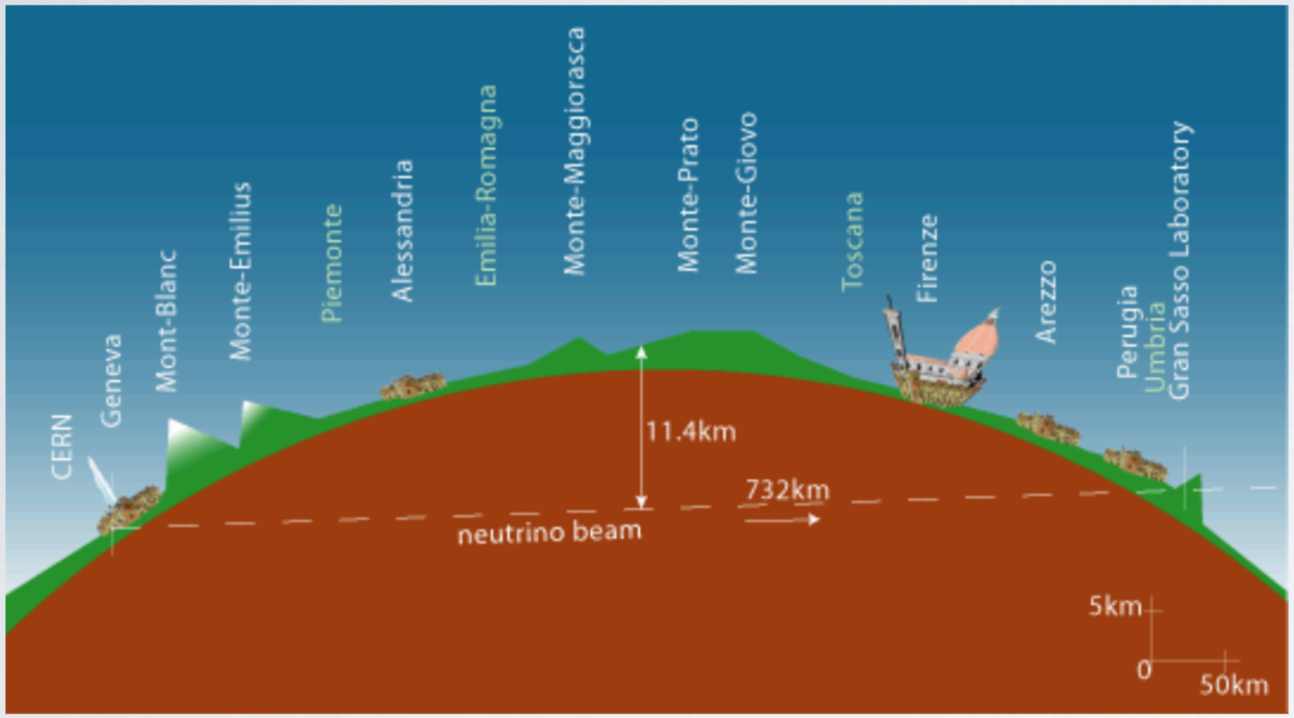
Turkey
METU Ankara

Israel
Technion Haifa

http://operaweb.lngs.infn.it

THE OPERA EXPERIMENT

Oscillation Project with Emulsion tRacking Apparatus



Long baseline (730 km from CERN to LNGS) neutrino oscillation experiment in the CERN Neutrino to Gran Sasso (CNGS) ν_μ beam

Main goal:
Direct detection of $\nu_\mu \rightarrow \nu_\tau$ oscillations in APPEARANCE mode

OPERA Requires:
Long baseline for oscillation at the atmospheric scale
High energy beam for τ production
High beam intensity and massive target for statistics
Micrometric accuracy and resolution to identify short lived τ's

Beam parameters

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

Interaction rates*

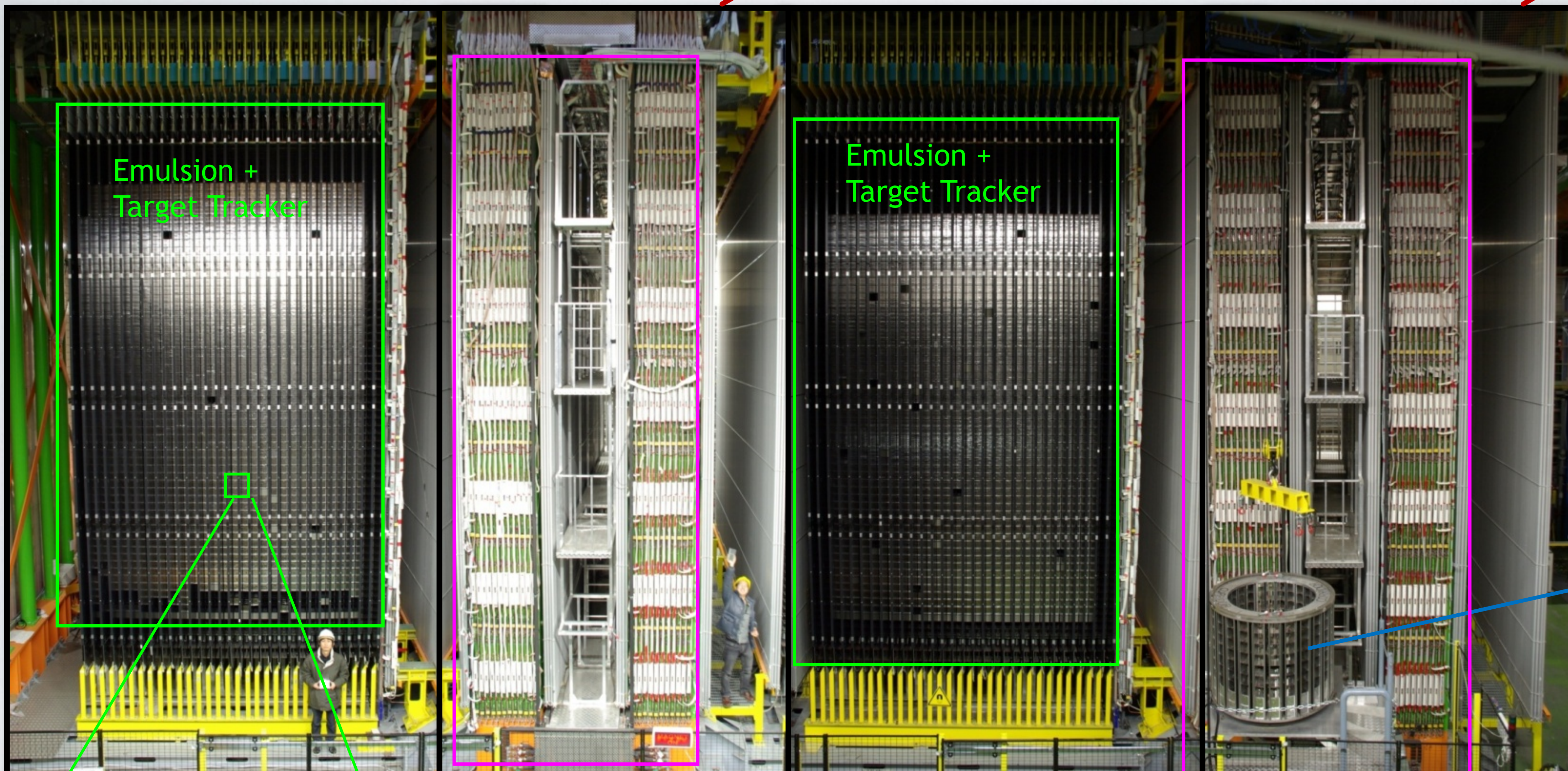
$\bar{\nu}_\mu/\nu_\mu$	CC	2.1 %
ν_e/ν_μ	CC	0.89 %
$\bar{\nu}_e/\nu_\mu$	CC	0.06 %
ν_τ/ν_μ	CC	$< 10^{-4}$ %

* Interaction rate at LNGS

THE OPERA DETECTOR

Super Module 1

Super Module 2



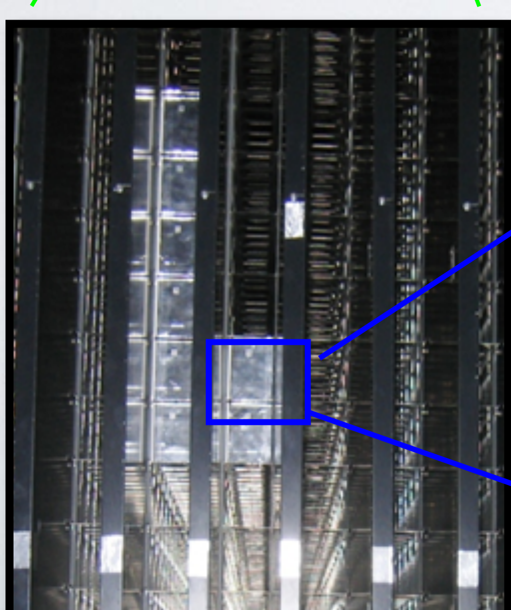
Muon spectrometer

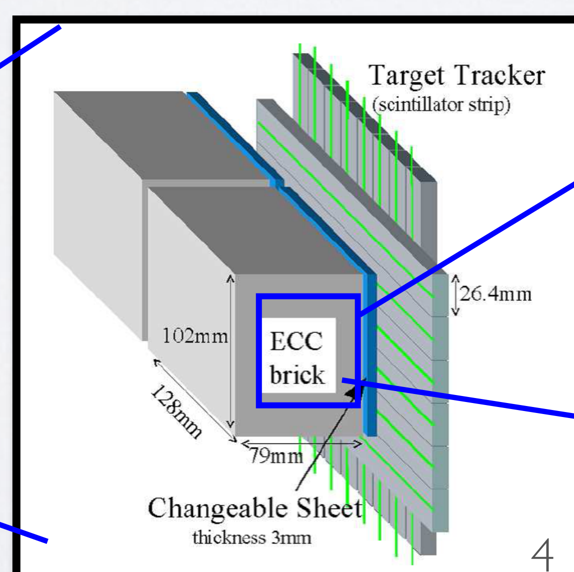
Muon spectrometer

2 supermodules,
31 walls,
150,000 bricks

Target mass:
1.25 kton

Brick Manipulator System

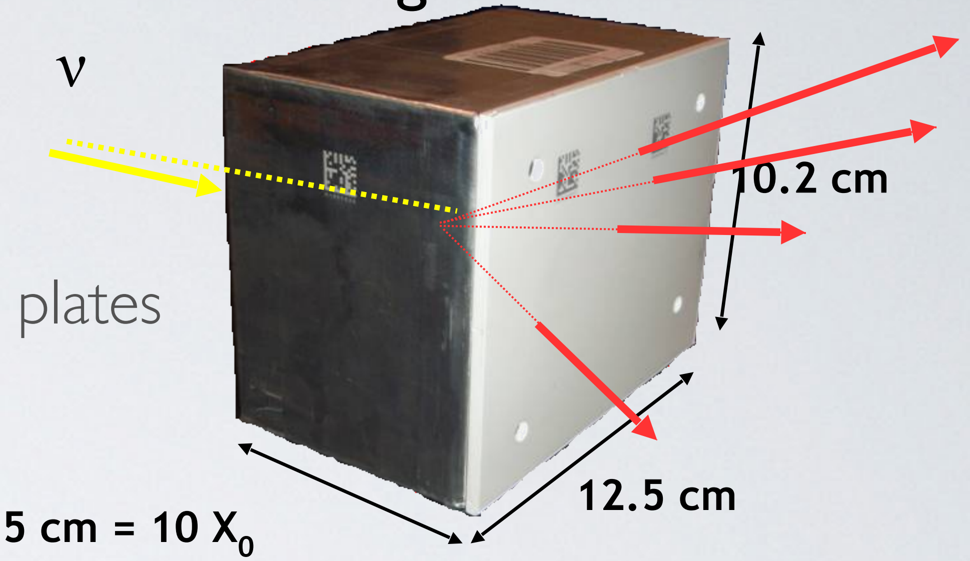


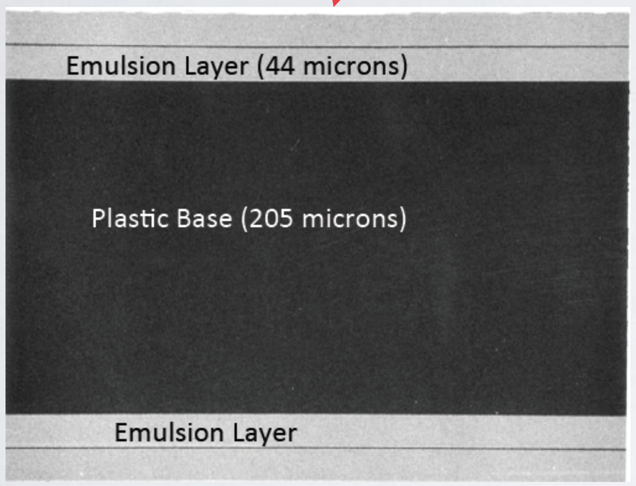


57 emulsion films
56 Pb plate

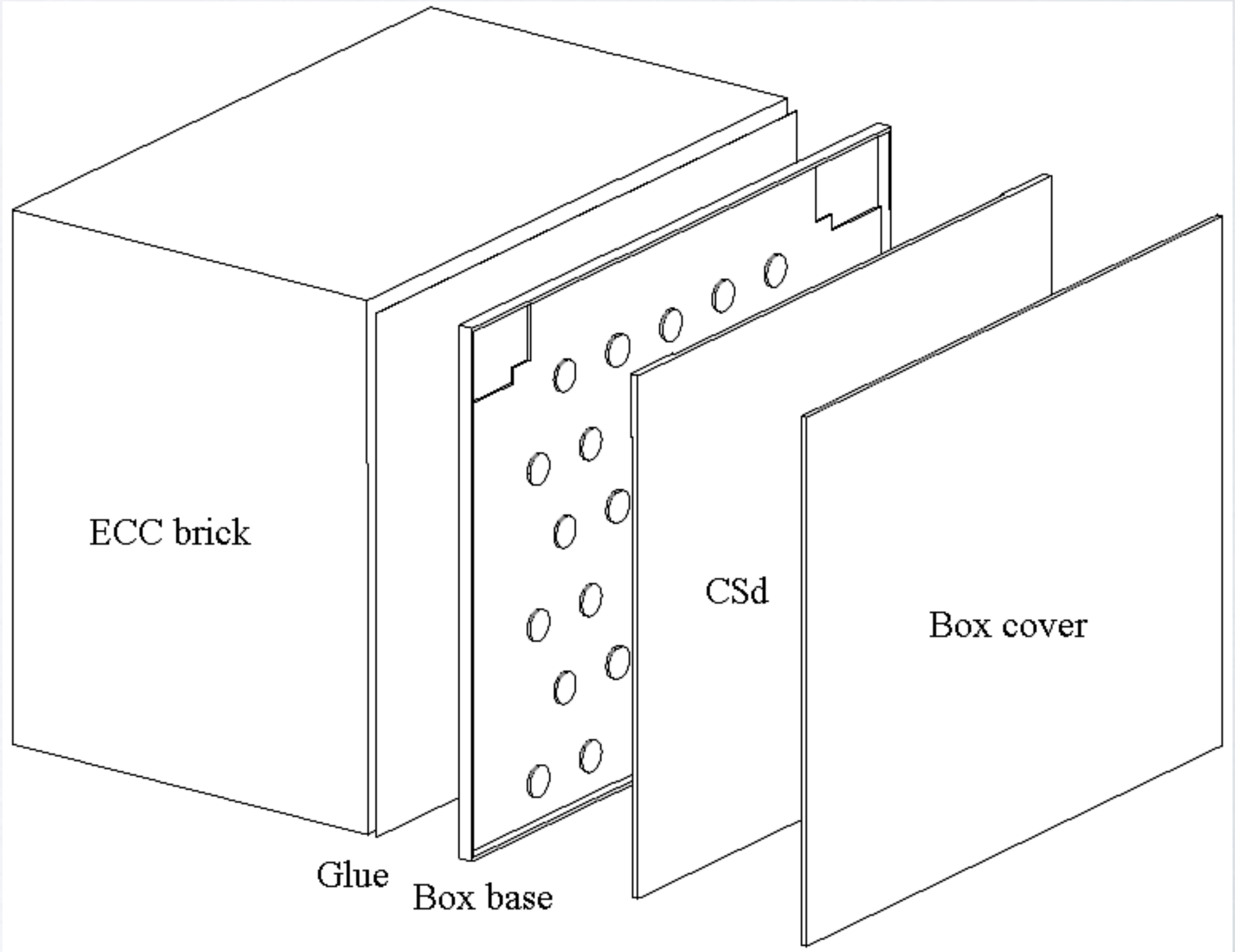
EMULSION CLOUD CHAMBER

- ECC brick = OPERA target of emulsion-lead layers
  - High resolution and large mass in a modular way
- The brick is the basic component
  - 57 nuclear emulsion films interleaved with 1 mm thick lead plates
  - a box with a removable pair of films Changeable Sheets



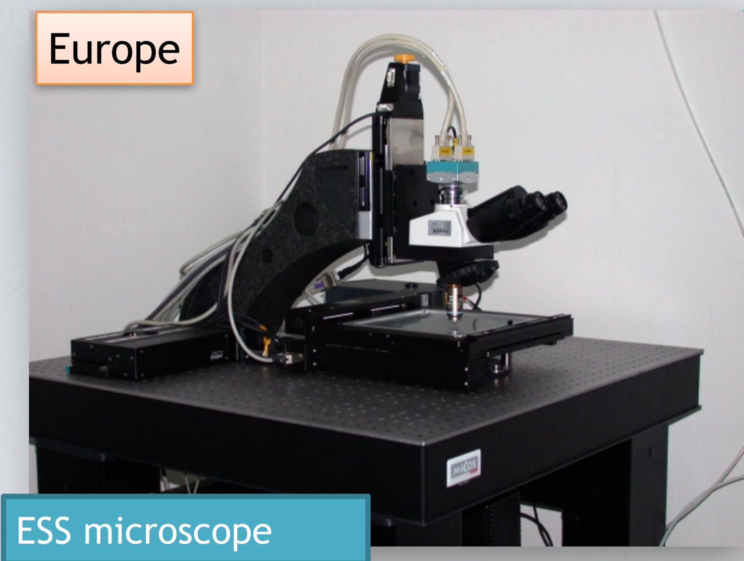


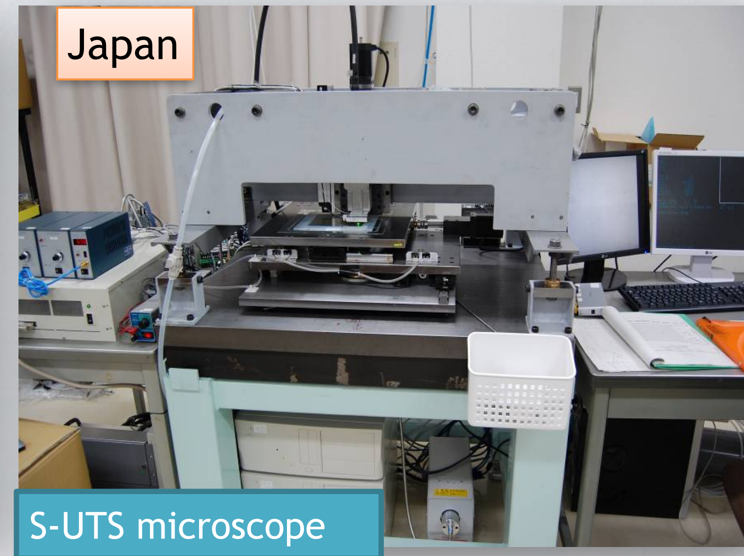
Track reconstruction accuracy in emulsions:
$\Delta x \approx 1\ \mu m$
$\Delta\theta \approx 1$ mrad



The "BRICK":
- neutrino vertex reconstruction
- search for decay topologies
- electron ID and momentum measurement

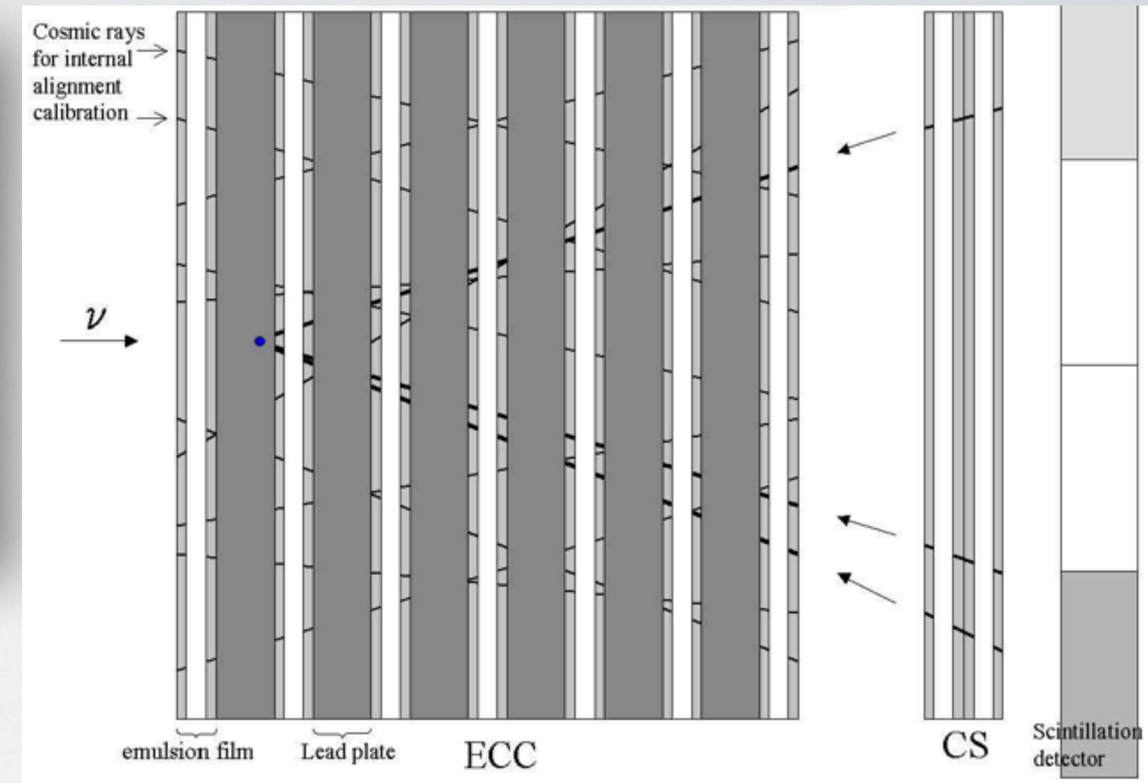
EVENT ANALYSIS

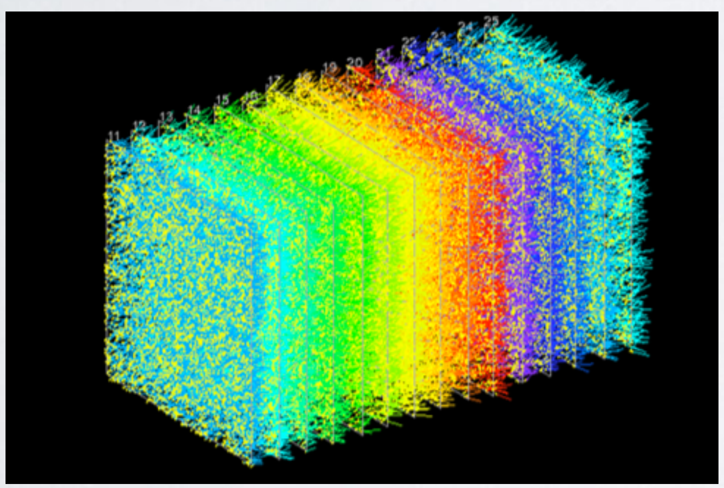




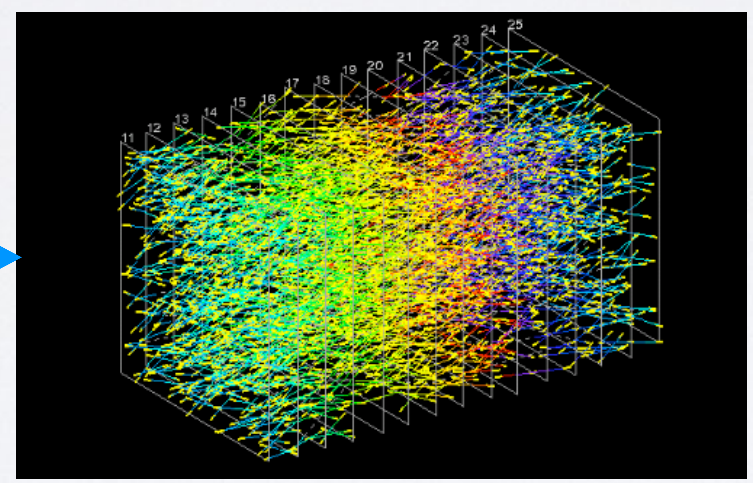
High speed scanning systems
20-75cm^2/h

Vertex finding

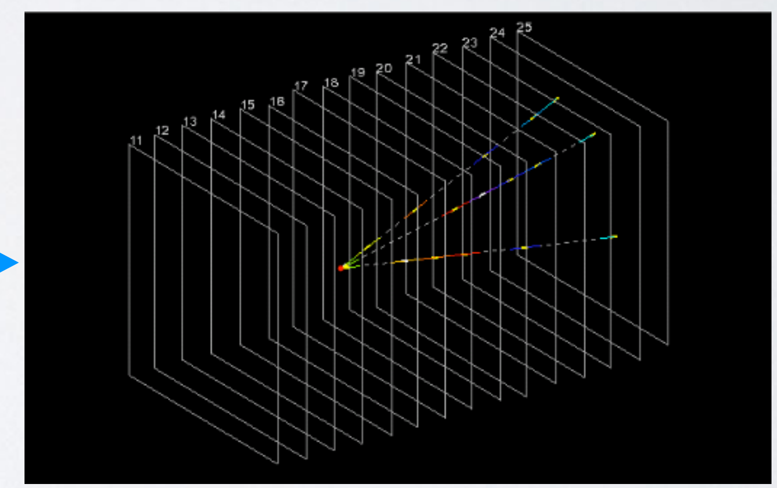




1.Scan 15 emulsion films
around stopping plate

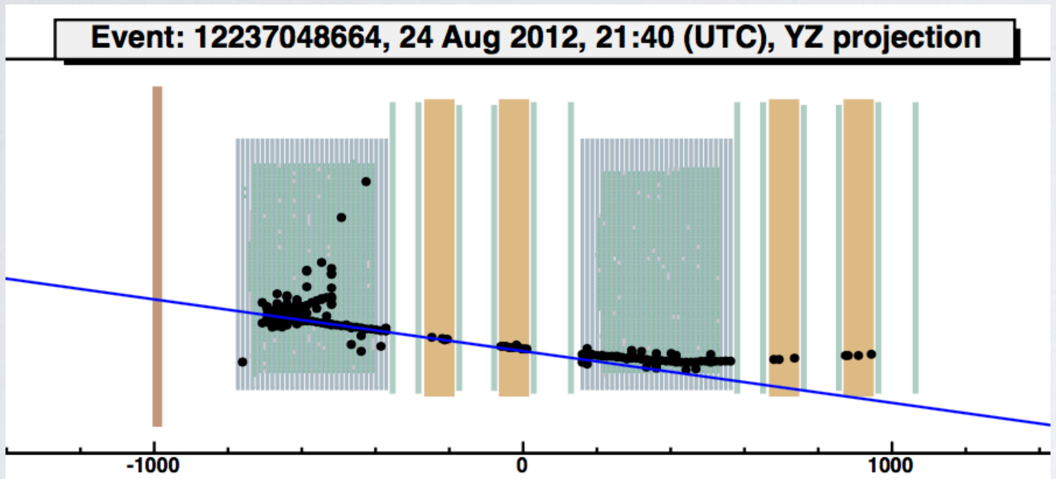


2.Track follow-up
to eliminate the background tracks

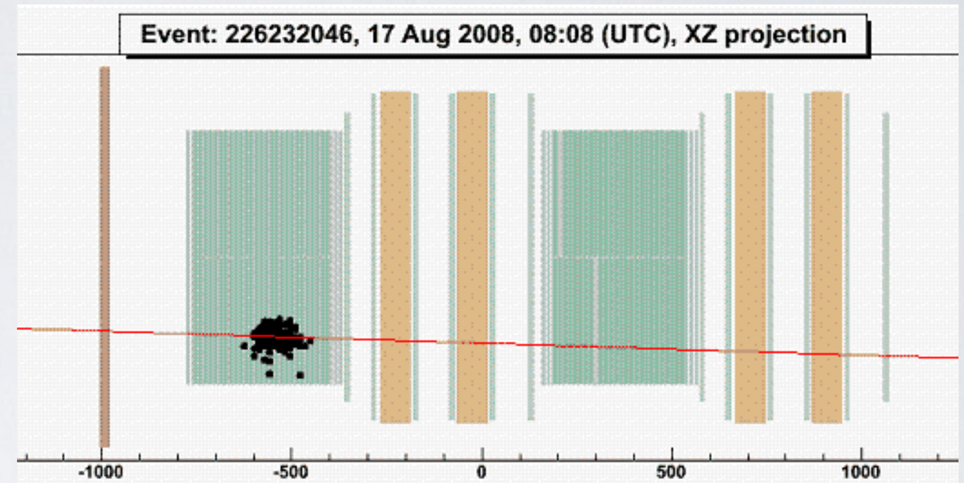


3.Find stopping point
Search vertex topology

ν_τ INTERACTION DETECTION

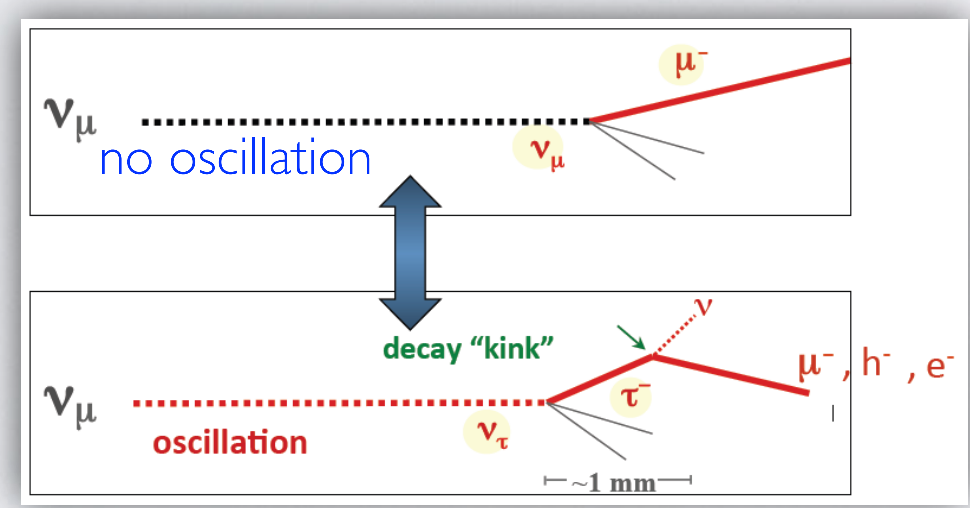


ν_μ CC like event



ν_μ NC like event

Signal



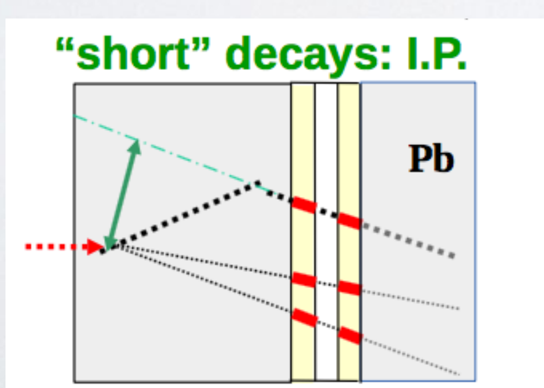
Muon attached to primary vertex

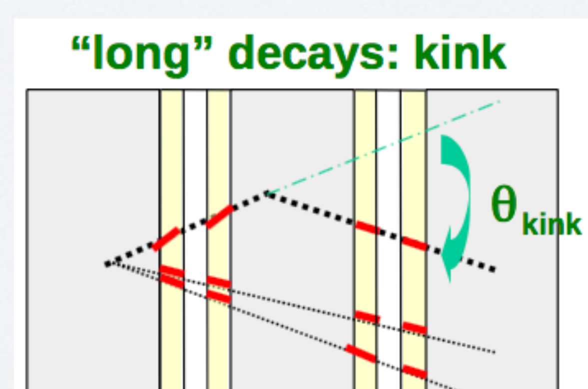
No muon attached to primary vertex

kink

multi-prong

τ Decay Channel	BR(%)
$\tau \to h$	49.5
$\tau \to \mu$	17.7
$\tau \to e$	17.8
$\tau \to 3h$	15.0

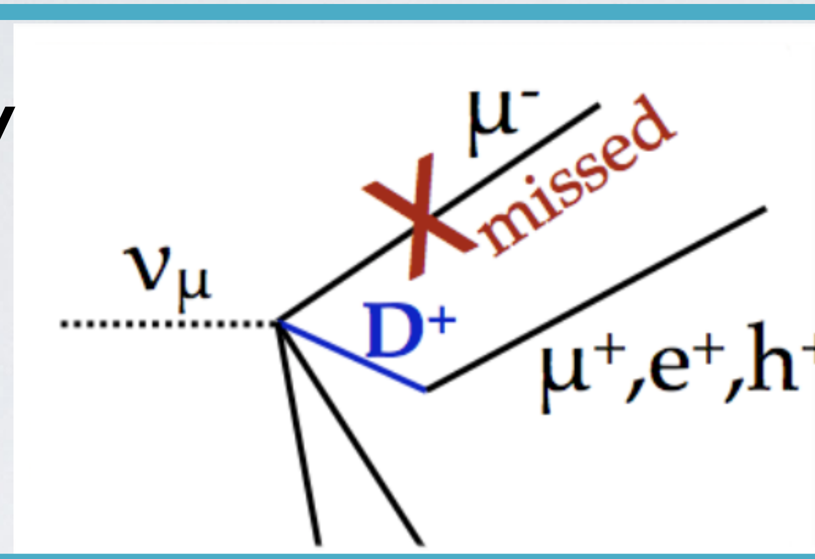




BACKGROUND SOURCES

In order of decreasing relevance

Charmed hadron decay with missed muon at primary vertex

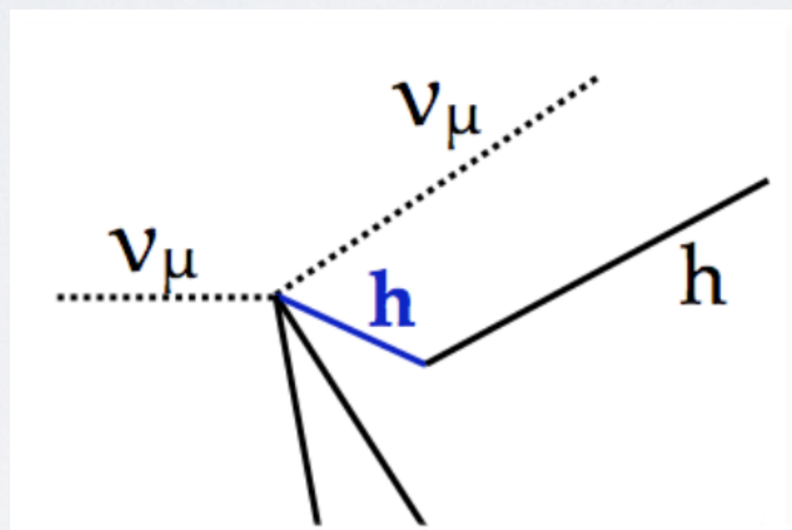


MC tuned on CHORUS data

Reduced by Track Follow- down procedure

Eur. Phys.J. C74 (2014) 2986

Hadronic re-interactions

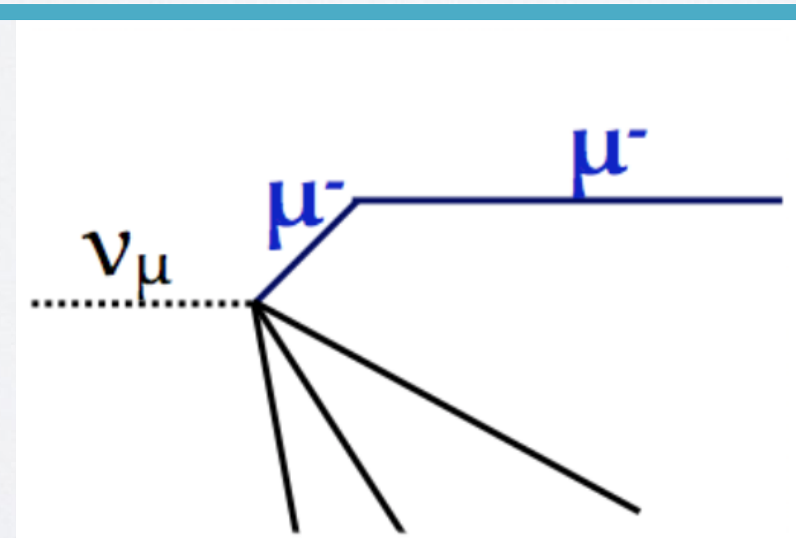


FLUKA + test beam data

Reduced by large angle scanning and nuclear fragment search

PTEP9 (2014) 093C01

Large angle muon scattering



MC tuned on old measurements on lead form factor

IEEE Transactions on Nuclear Science Vol. 62, 5, 2015

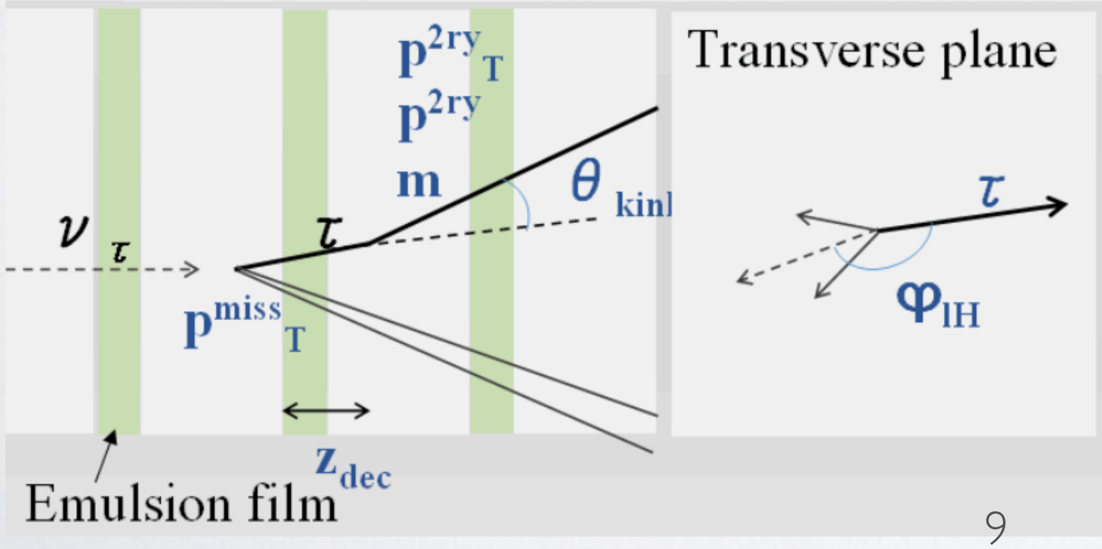
ν_τ KINEMATICAL SELECTION

Kinematical selection

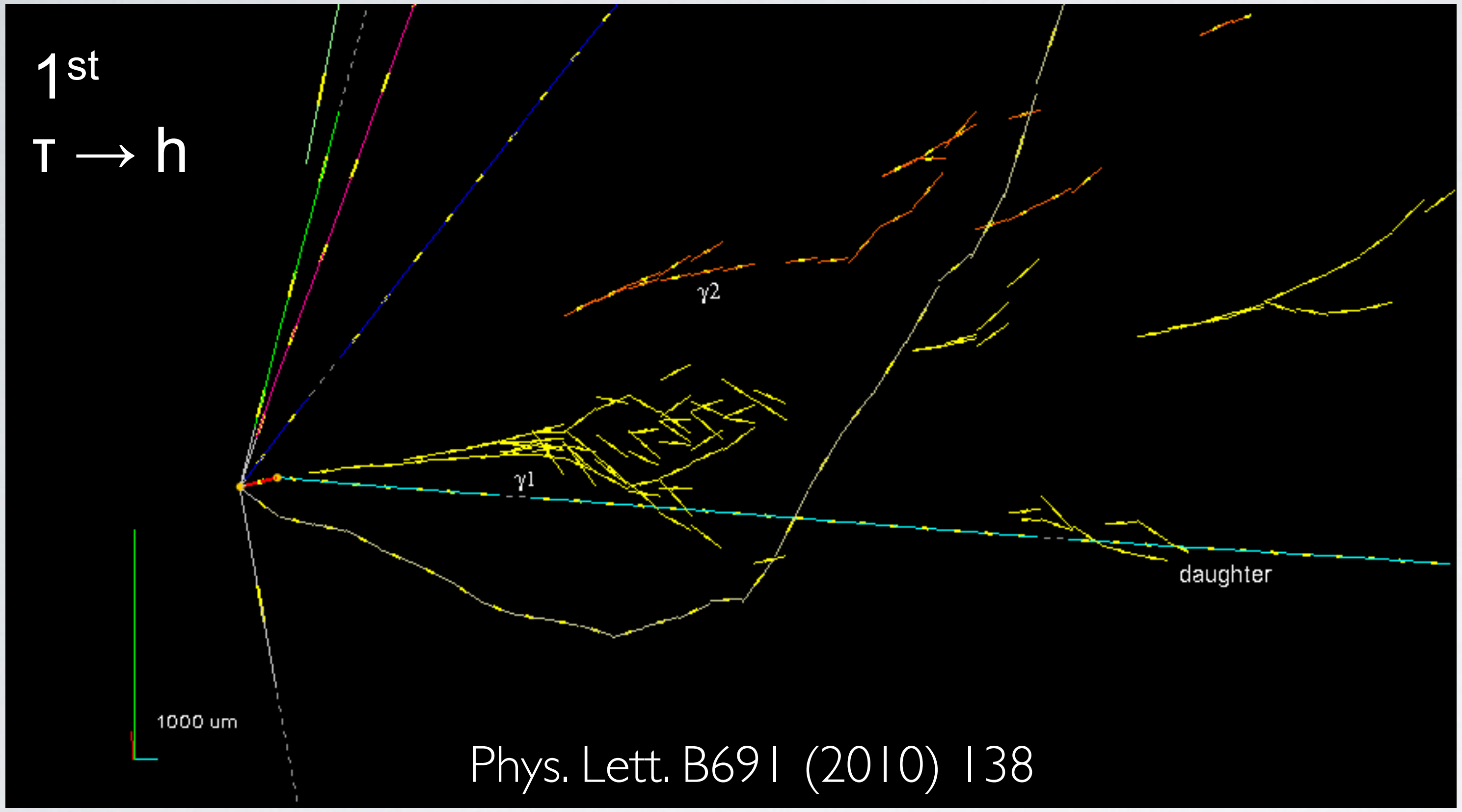
variable	$\tau \to 1h$	$\tau \to 3h$	$\tau \to \mu$	$\tau \to e$
lepton-tag		No μ or e at the primary vertex		
z_{dec} (μm)	$[44, 2600]$	< 2600	$[44, 2600]$	< 2600
p_T^{miss} (GeV/c)	$< 1^\star$	$< 1^\star$	/	/
ϕ_{lH} (rad)	$> \pi/2^\star$	$> \pi/2^\star$	/	/
p_T^{2ry} (GeV/c)	$> 0.6(0.3)^*$	/	> 0.25	> 0.1
p^{2ry} (GeV/c)	> 2	> 3	> 1 and < 15	> 1 and < 15
θ_{kink} (mrad)	> 20	< 500	> 20	> 20
m, m_{min} (GeV/c^2)	/	> 0.5 and < 2	/	/

p_T ^{miss} : vectorial sum of the transverse momenta of primaries (except the parent) and daughters wrt beam direction

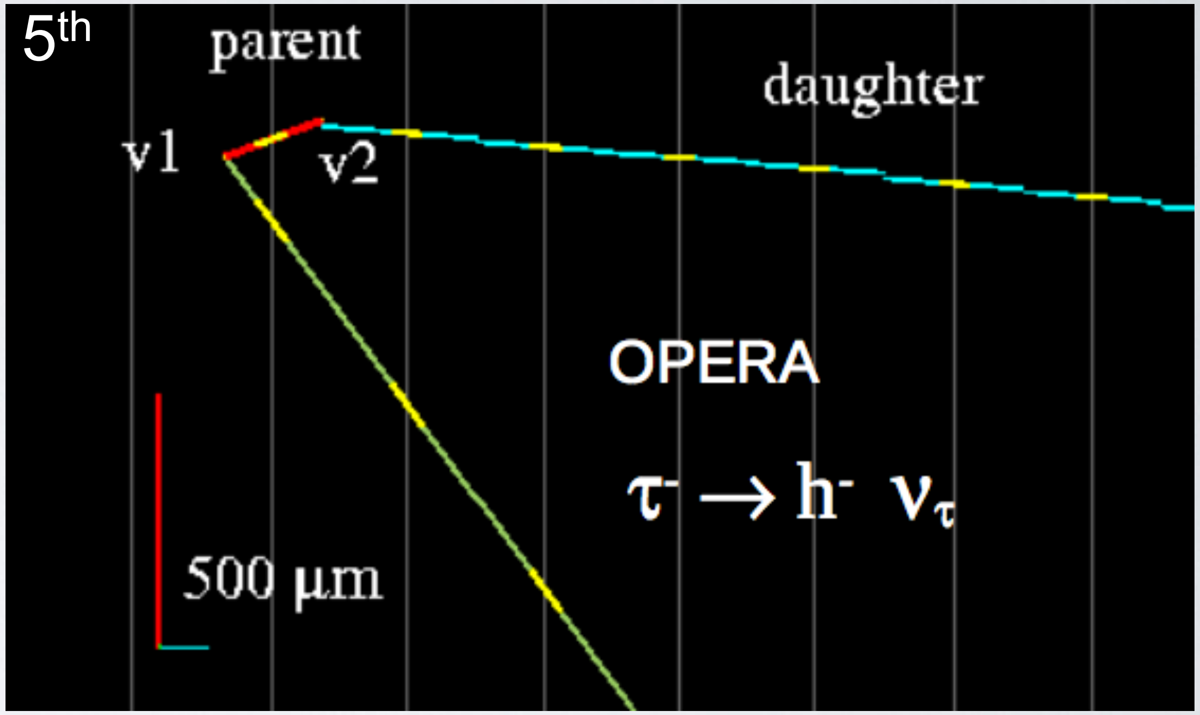
p_T ^{2ry} :the transverse momentum of the daughter wrt the parent direction.



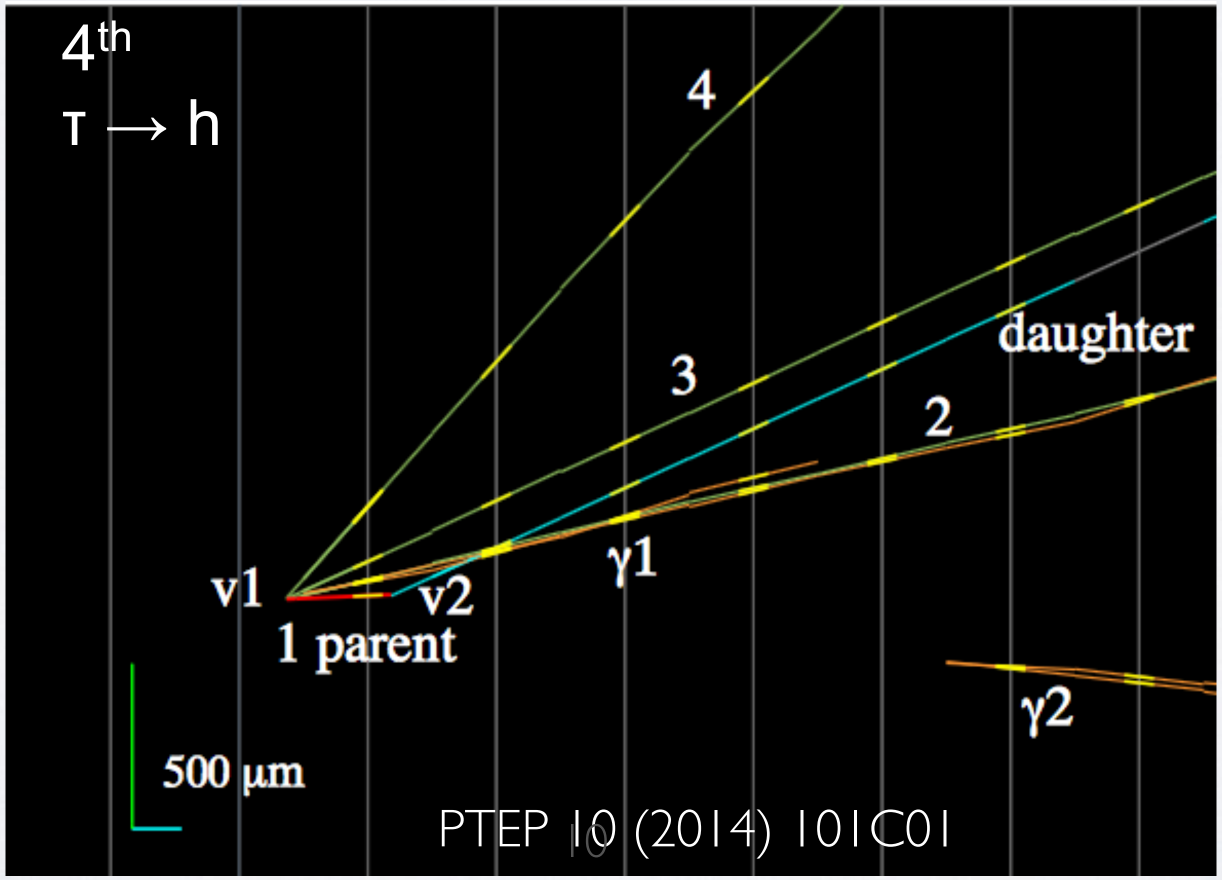
ν_τ CANDIDATE EVENTS



Phys. Lett. B691 (2010) 138

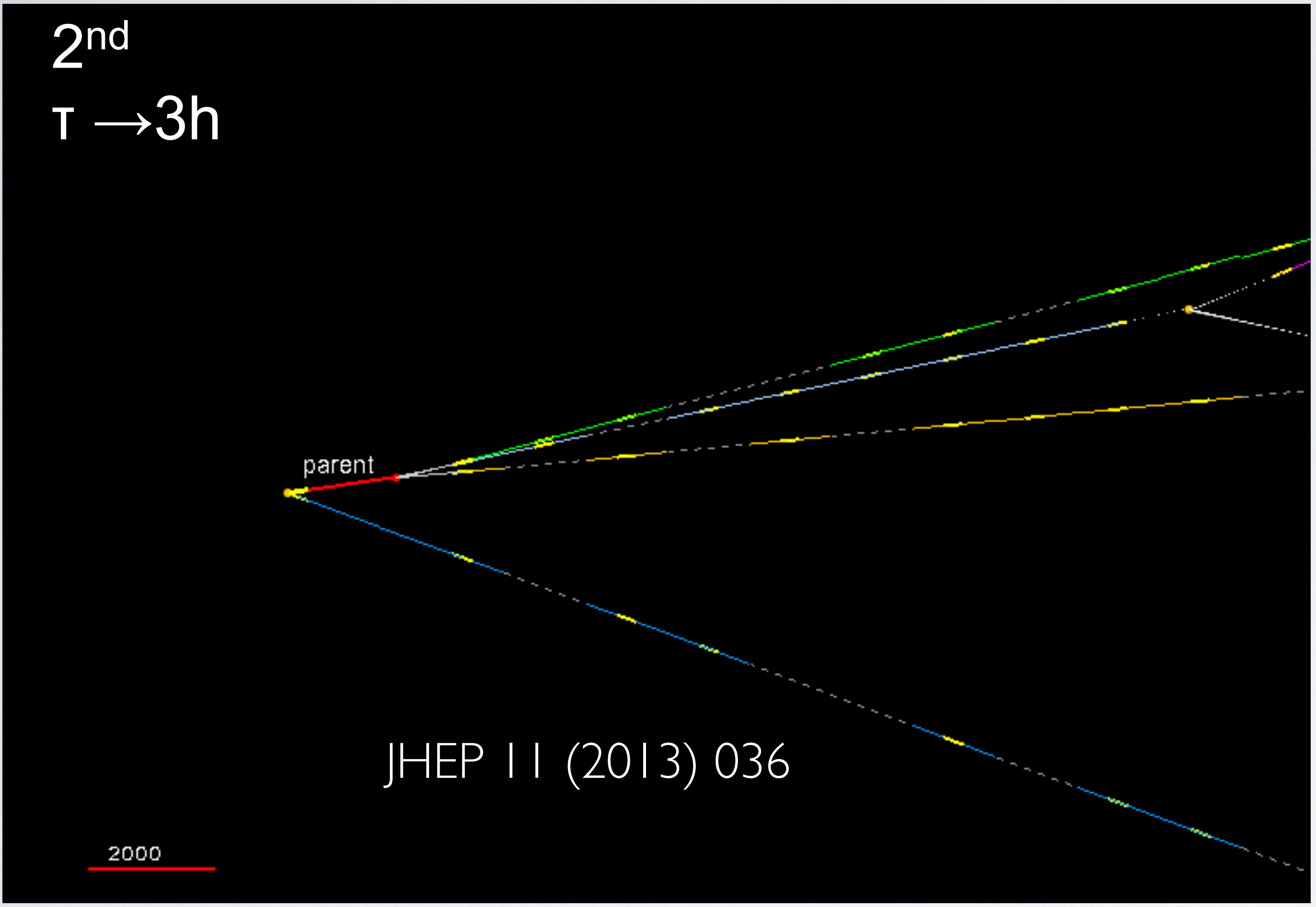


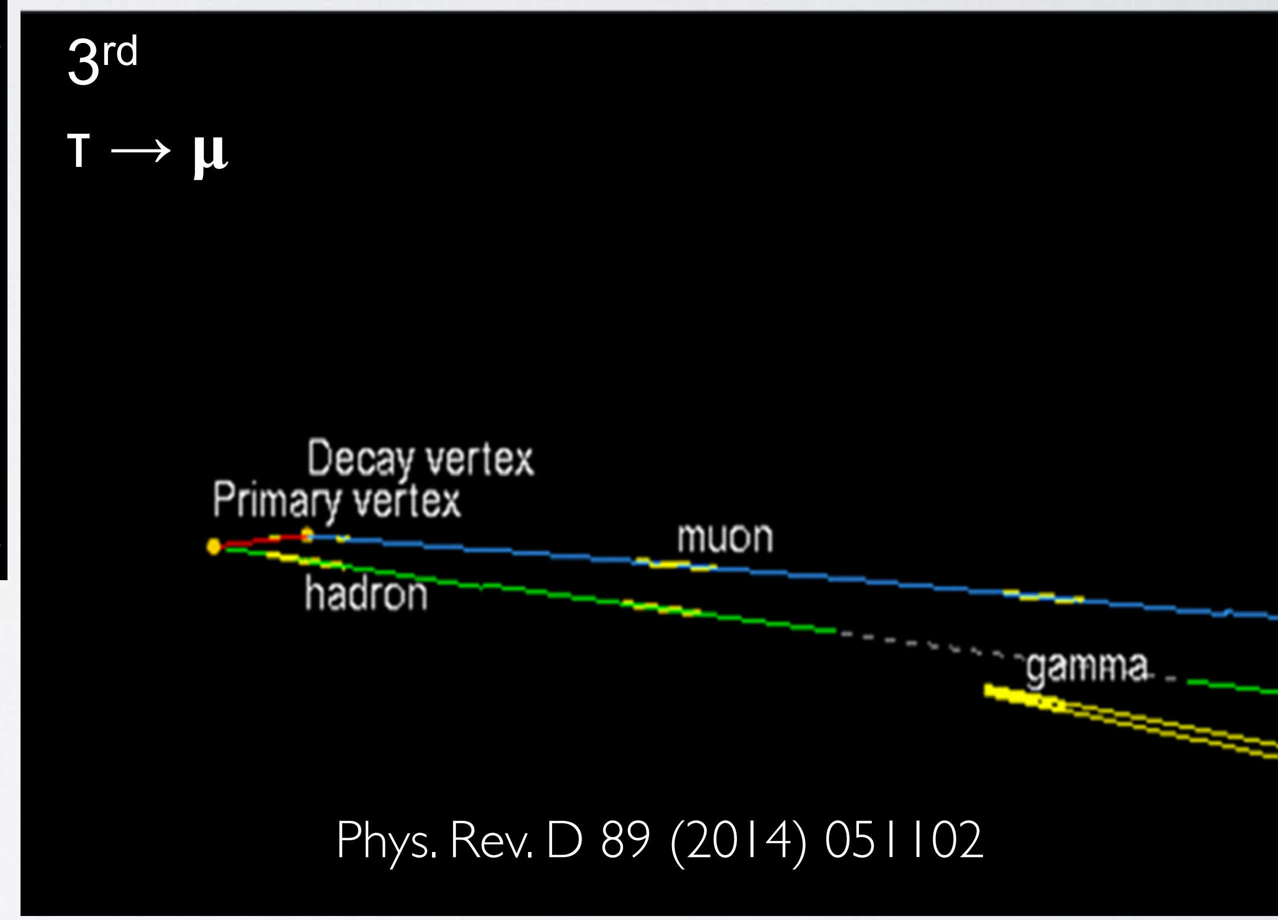
Phys. Rev. Lett. 115, 121802 (2015)



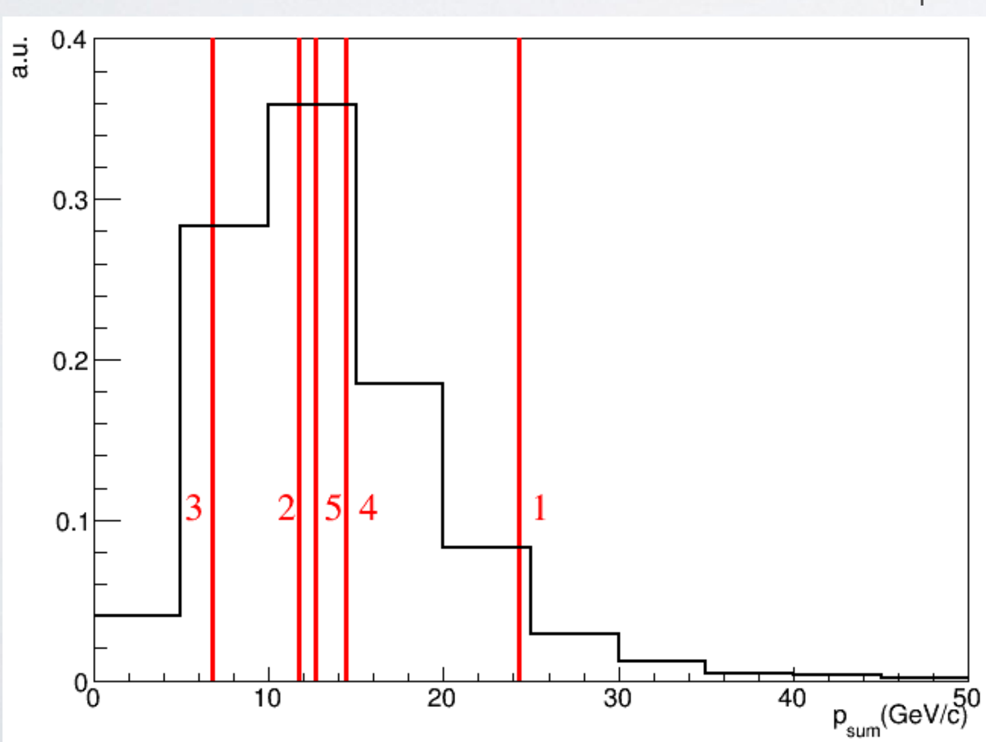
PTEP 10 (2014) 101C01

ν_τ CANDIDATE EVENTS





P_{sum} : scalar sum of the measured momentum of all particles



DISCOVERY OF $\nu_\mu \rightarrow \nu_\tau$ APPEARANCE IN THE CNGS BEAM

Exposure	17.97×10^{19} p.o.t.
Interactions in the target	19505

Decay Channel	**Signal Expectation** $\Delta m^2 = 2.44 \times 10^{-3}\ eV^2$	**Total Background**	**Observed**
$\tau \rightarrow 1h$	0.52 ± 0.10	0.04 ± 0.01	3
$\tau \rightarrow 3h$	0.73 ± 0.14	0.17 ± 0.03	1
$\tau \rightarrow \mu$	0.61 ± 0.12	0.004 ± 0.001	1
$\tau \rightarrow e$	0.78 ± 0.16	0.03 ± 0.01	0
Total	**2.64 ± 0.53**	**0.25 ± 0.05**	**5**

Probability of a background fluctuation $= 1.1 \times 10^{-7}$

No oscillation hypothesis excluded at **5.1 σ**

Physics Review Letters 115 (2015) 121802

Δm^2_{23} AND ν_τ CROSS-SECTION MEASUREMENT

New strategy is defined in order to increase the number of ν_τ candidates.

NEW Minimum bias selection:

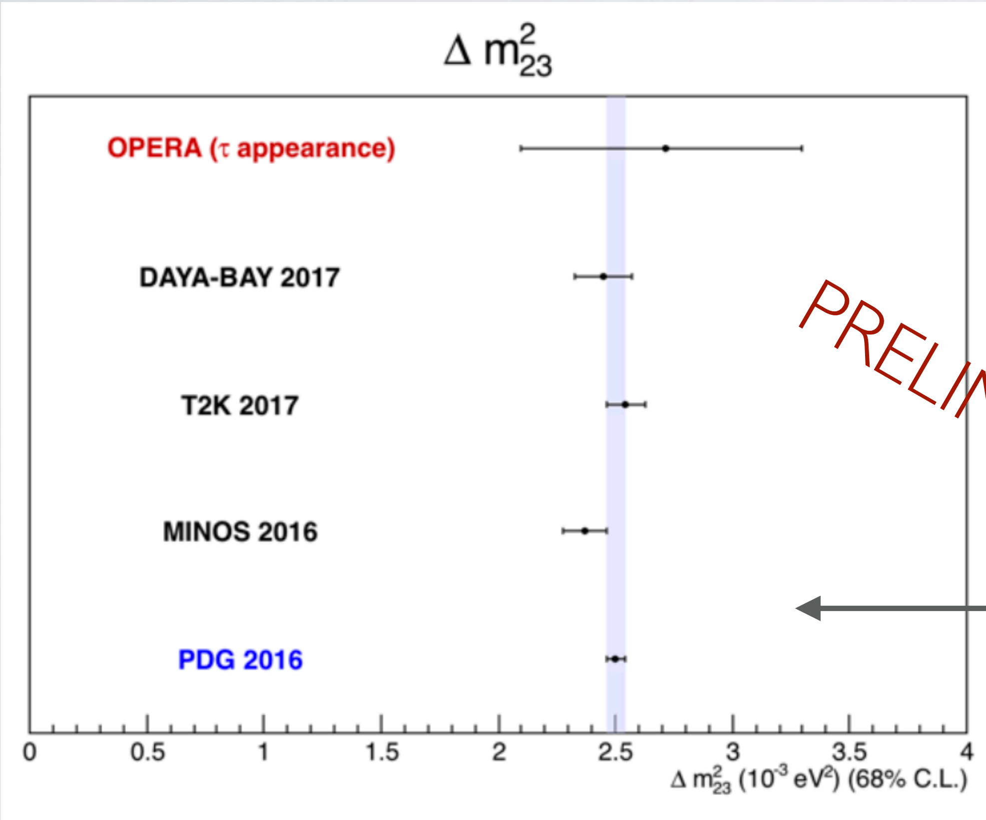
Variable	$\tau \to 1h$	$\tau \to 3h$	$\tau \to \mu$	$\tau \to e$
z_{dec} (μm)	<2600	<2600	<2600	<2600
θ_{kink} (rad)	>0.02	>0.02	>0.02	>0.02
p_{2ry} (GeV/c)	>1	>1	>1	>1
p^T_{2ry} (GeV/c)	>0.15	/	>0.1	>0.1

New strategy:

- Minimum bias kinematical cuts
- Multivariate analysis: *Boosted Decision Tree*
- *S/B reduced from 10 to 3*

Channel	Expected Background				Exp. Signal	Observed
	Charm	Had. re-interaction	Large μ-scat.	Total		
$\tau \to 1h$	0.15 ± 0.03	1.28 ± 0.38	–	1.43 ± 0.41	2.96 ± 0.59	6
$\tau \to 3h$	0.44 ± 0.09	0.09 ± 0.03	–	0.53 ± 0.12	1.83 ± 0.37	3
$\tau \to \mu$	0.008 ± 0.002	–	0.02 ± 0.008	0.03 ± 0.01	1.15 ± 0.23	1
$\tau \to e$	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

Δm^2_{23} AND ν_τ CROSS-SECTION MEASUREMENT



Δm^2_{23} evaluated using Feldman-Cousins method

Expected Signal	Expected Background	Observed ν_τ	Δm^2_{23} $(10^{-3}$ eV$^2)$
6.8	2.0	10	2.7 ± 0.6 68% C.L

PRELIMINARY

Agreement with *PDG 2016* value within 1σ

ν_τ cross-section

$$\sigma_{\nu_\tau} = \sigma^0_{\nu_\tau} E K(E)$$

Until now, ν_τ cross section measured only by DONuT

DONuT could not distinguish ν_τ from anti-ν_τ

$$\sigma^0_{\nu_\tau+\bar{\nu}_\tau} = 0.72 \pm 0.24 \pm 0.36 x 10^{-38} cm^2 GeV^{-1}$$

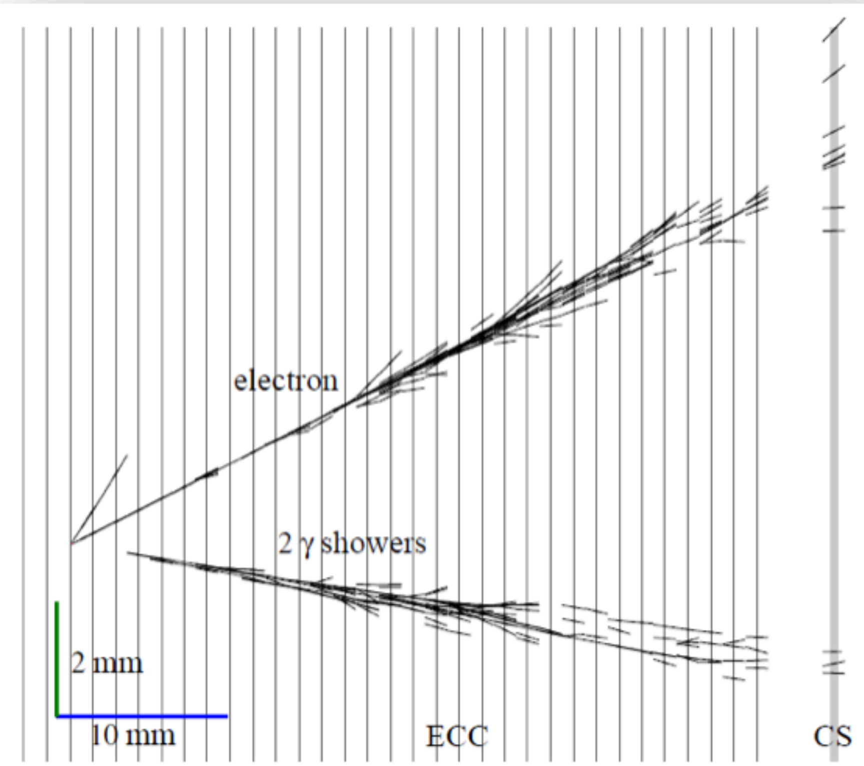
PRELIMINARY

OPERA: the first measurement with ν_τ only

Δm^2_{23} $(10^{-3}$ eV$^2)$	Expected Signal	Expected Background	Observed ν_τ	$\sigma^0_{\nu_\tau}$ $(10^{-39}$cm^{2}GeV$^{-1})$
2.5	6.8	2.0	10	8^{+4}_{-3}

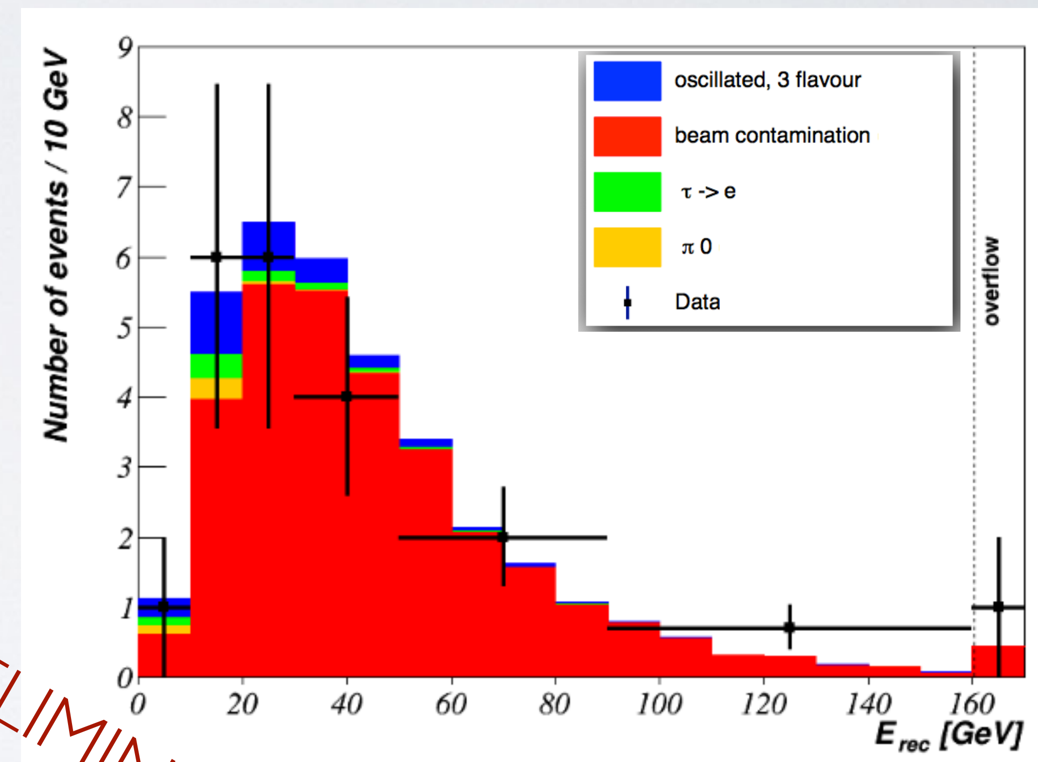
Agreement with the SM value $6.7 \times 10^{-39}\ cm^2 GeV^{-1}$ within 1σ

$\nu_\mu \rightarrow \nu_e$ OSCILLATIONS



Display of the reconstructed emulsion tracks of one of the ν_e candidate events.
Two tracks are observed at the neutrino interaction vertex.
One of the two generates an electromagnetic shower and is identified as an electron.

Reconstructed energy of the ν_e events



PRELIMINARY

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(1.27\Delta m^2_{23} L / E)$$

Observed ν_e events: 35

Expected number of events:

from ν_e beam contamination: 31 ± 3

from background $\tau \rightarrow e$: 0.8 ± 0.2

from background π^0 mis-id : 0.5 ± 0.5

from $\nu_\mu \rightarrow \nu_e$ oscillation: 2.7 ± 0.3

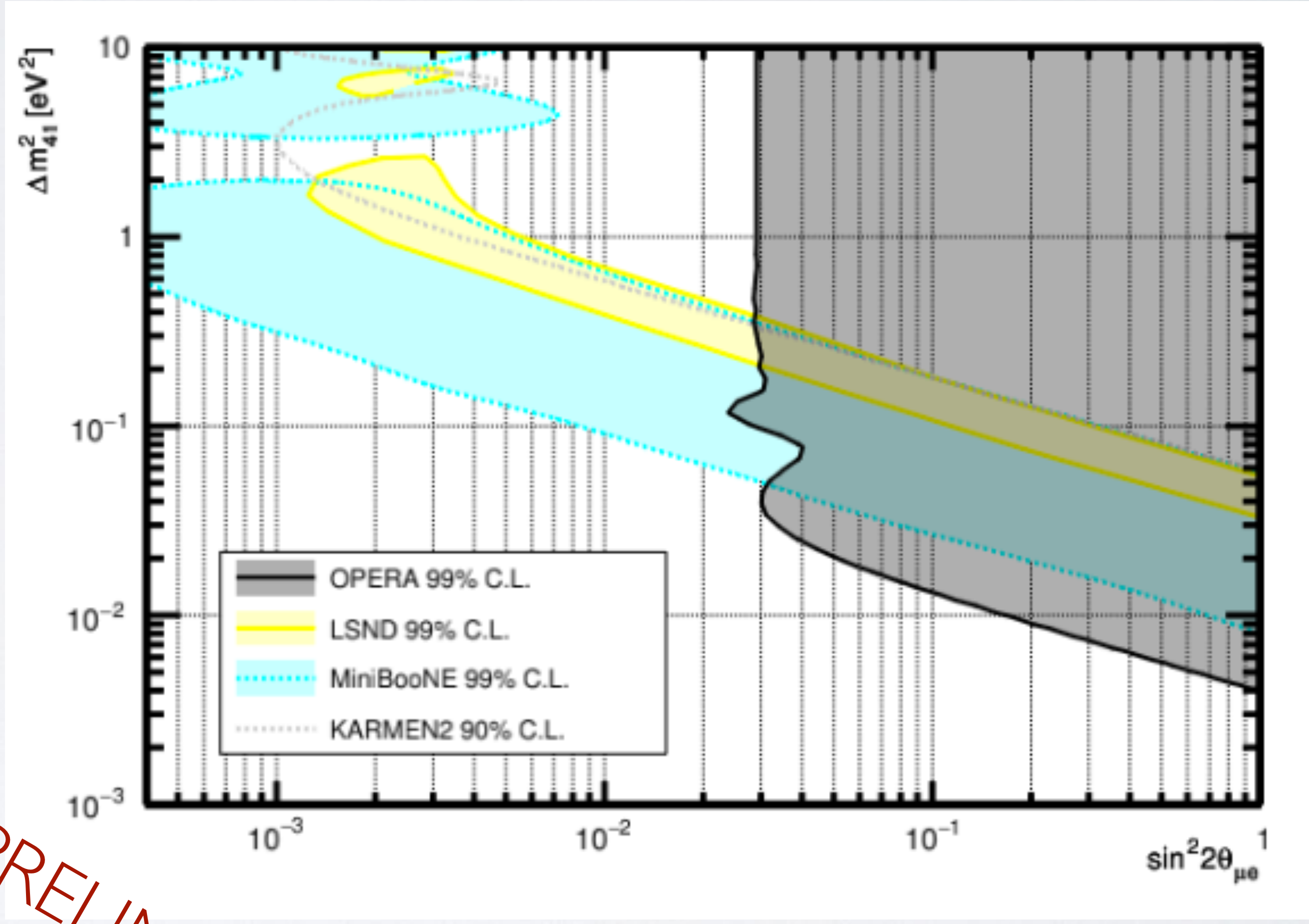
The total number of expected events is 35 ± 3 compatible with the observed event.
Allowing $\sin^2(2\theta_{13})$ to vary, we can set an upper limit of 0.22 at 90% C.L.

$\nu_\mu \rightarrow \nu_e$ IN 3+1 MODEL

ν_e data is used to set limits
on the oscillations parameters
in presence of a fourth sterile neutrino.

$$\sin^2(2\nu_{\mu e}) = 4|U_{\mu 4}|^2 |U_{e4}|^2$$

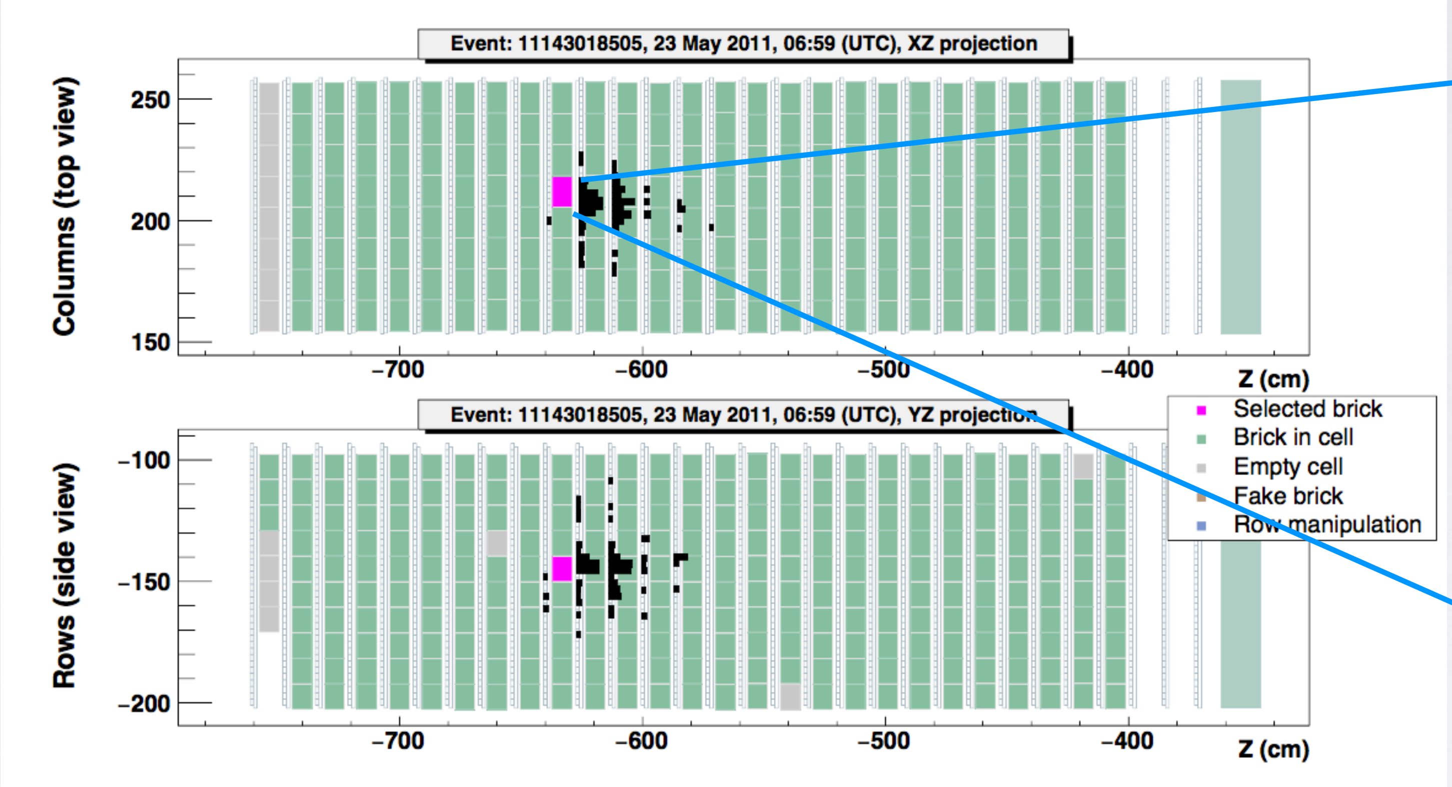
The exclusion plot for the parameters of the oscillation parameters in 3+1 scheme

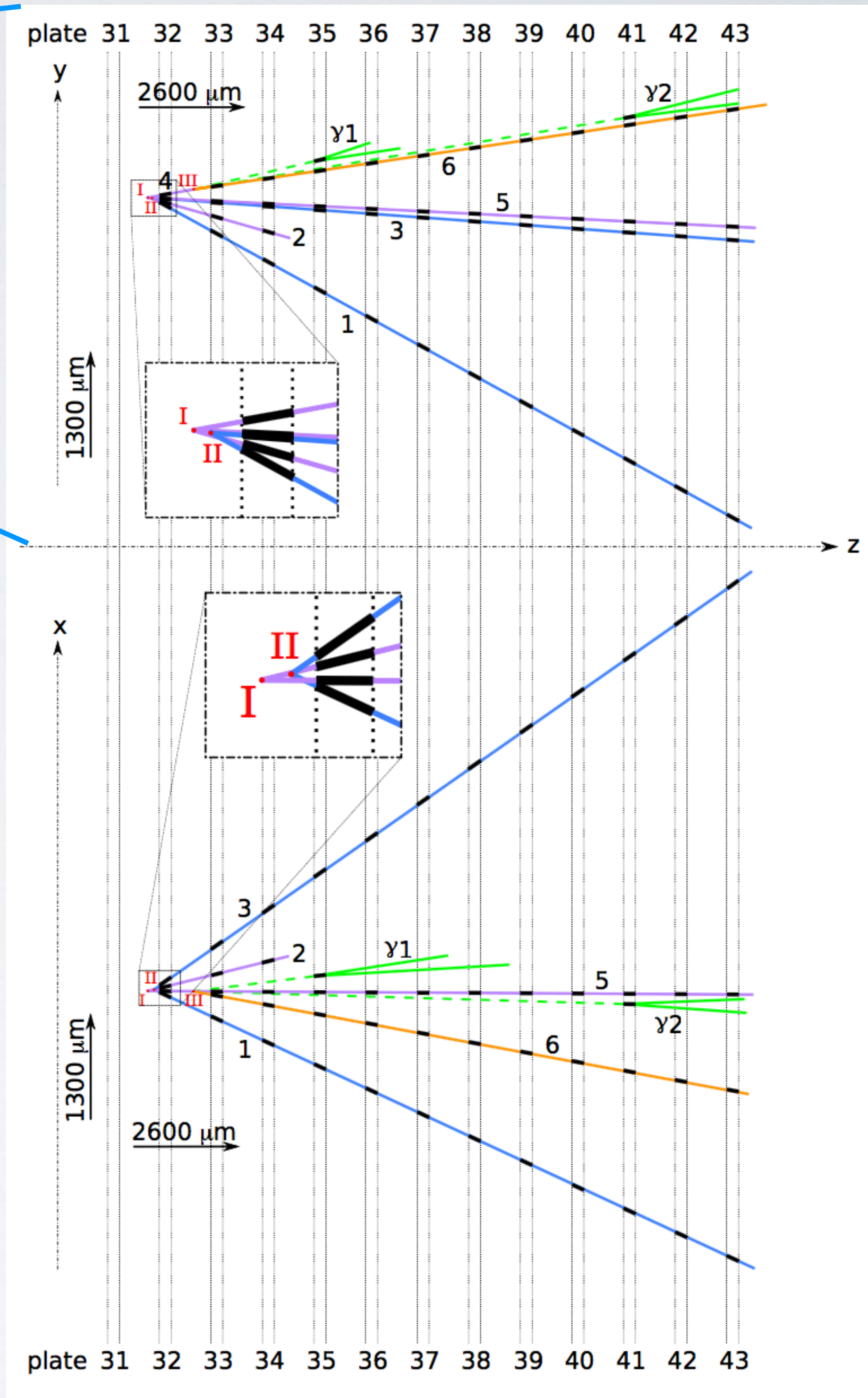


PRELIMINARY

An upper limit on the $\sin^2(2\theta_{\mu e})$=0.019 can be set at large Δm_{41}> 0.1 eV^2.

AN EVENT WITH 2 SECONDARY VERTICES





Muonless event

A primary and two secondary vertices found in emulsion

Electromagnetic activity (γ's) at the kink point.

Flight lengths:

II: 103 μm

III: 1160 μm

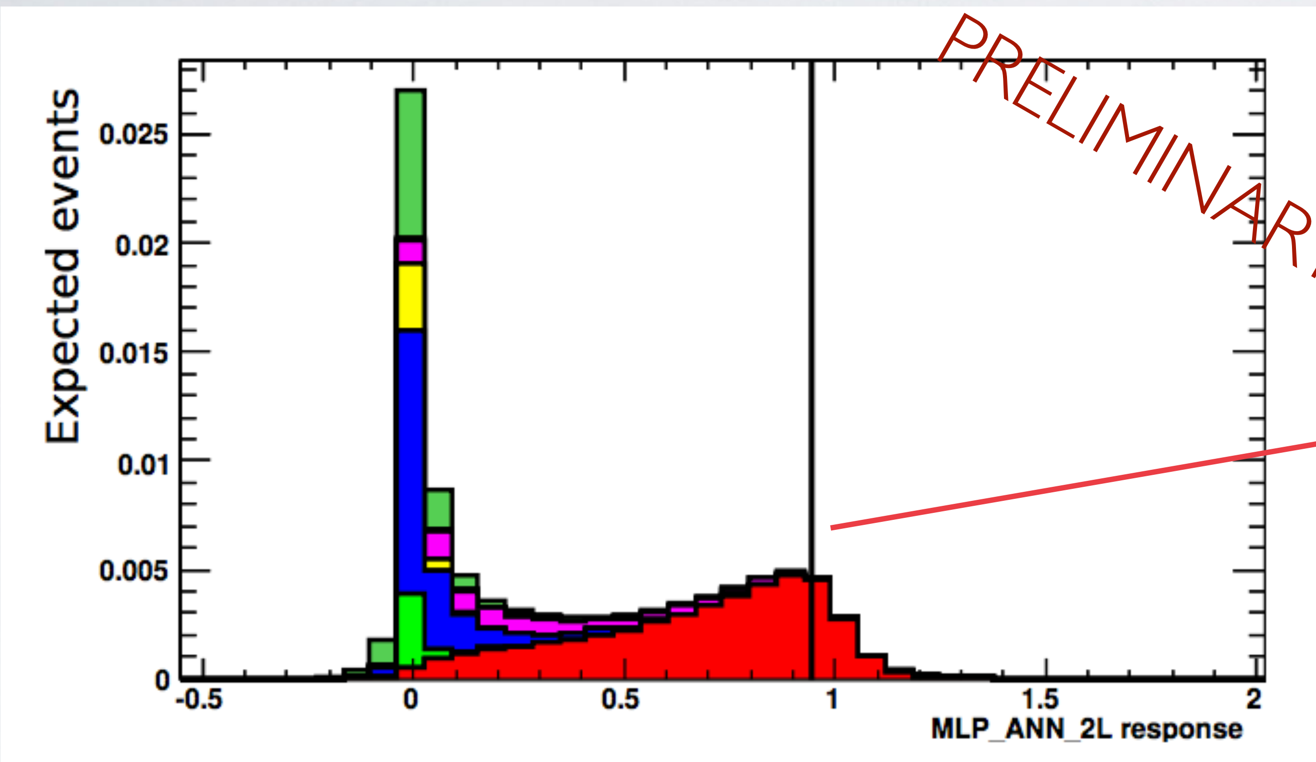
Vertex ID	Parent	Daughters	x (μm)	y (μm)	z (μm)
I (primary)	-	2, 4, 5, neutral	15077.0	59157.9	-33081.8
II (secondary)	neutral	1, 3	15085.9	59149.9	-32979.2
III (kink)	4	6	15073.9	59262.4	-31926.4

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]

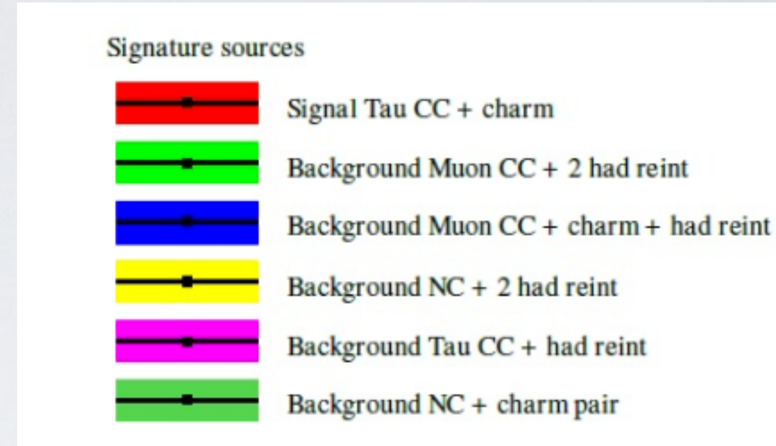
Invariant masses at both secondary vertices larger than 1 GeV.

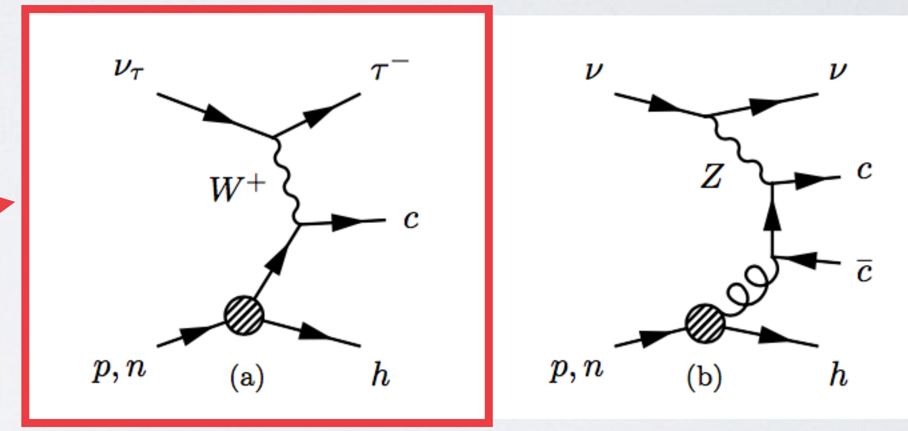
AN EVENT WITH 2 SECONDARY VERTICES

Dedicated simulations and Artificial Neural Networks (ANN) analysis performed to distinguish between possible interpretations .



PRELIMINARY





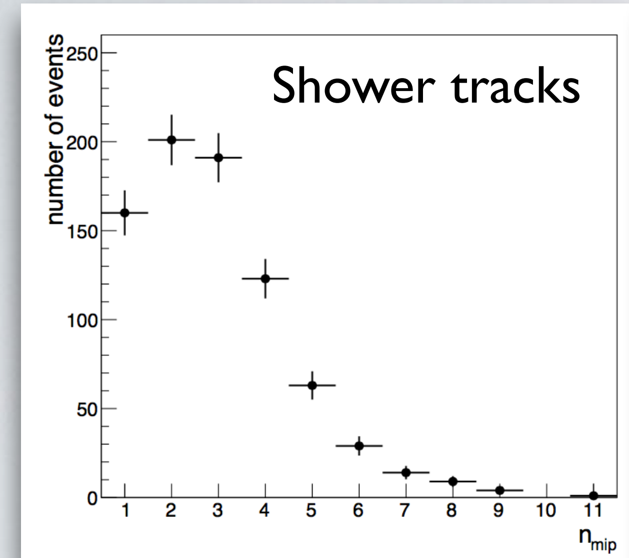
The most likely interpretation vertex II is originated by a charm decay and vertex III by tau decay into an hadron.

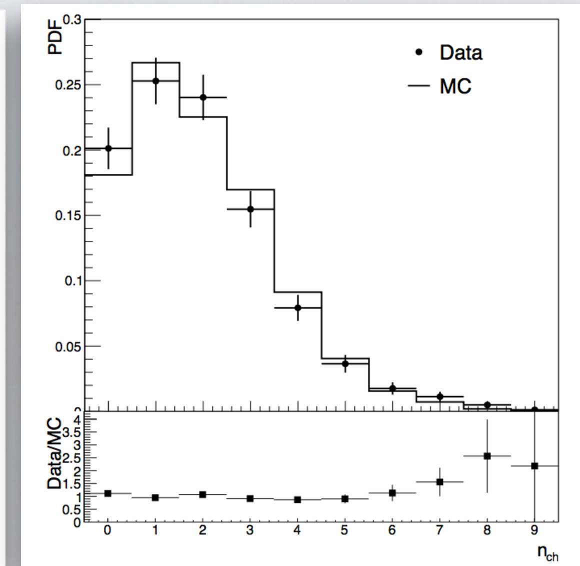
Sample	Expected events (10^{-3})
ν_τ CC + charm	44.5 ± 0.1
ν NC + $c\bar{c}$ pair	12.59 ± 0.02
ν_μ CC + two 2ry	4.0 ± 0.5
ν_μ CC + charm + 2ry	20.5 ± 0.5
ν NC + two 2ry	3.8 ± 0.3
ν_τ CC +2ry	9.0 ± 0.1
Total	94.4

PRELIMINARY

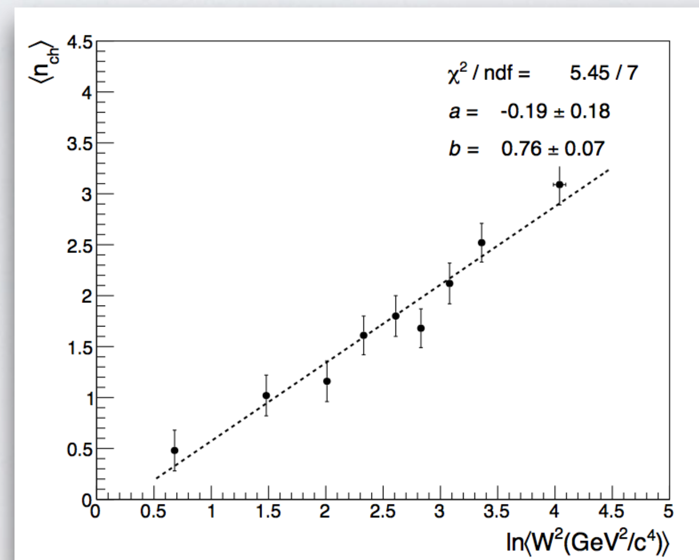
Event classified as a ν_τ CC interaction with charm production with a significance of **3.5 σ**

STUDY OF CHARGED PARTICLE MULTIPLICITY DISTRIBUTIONS





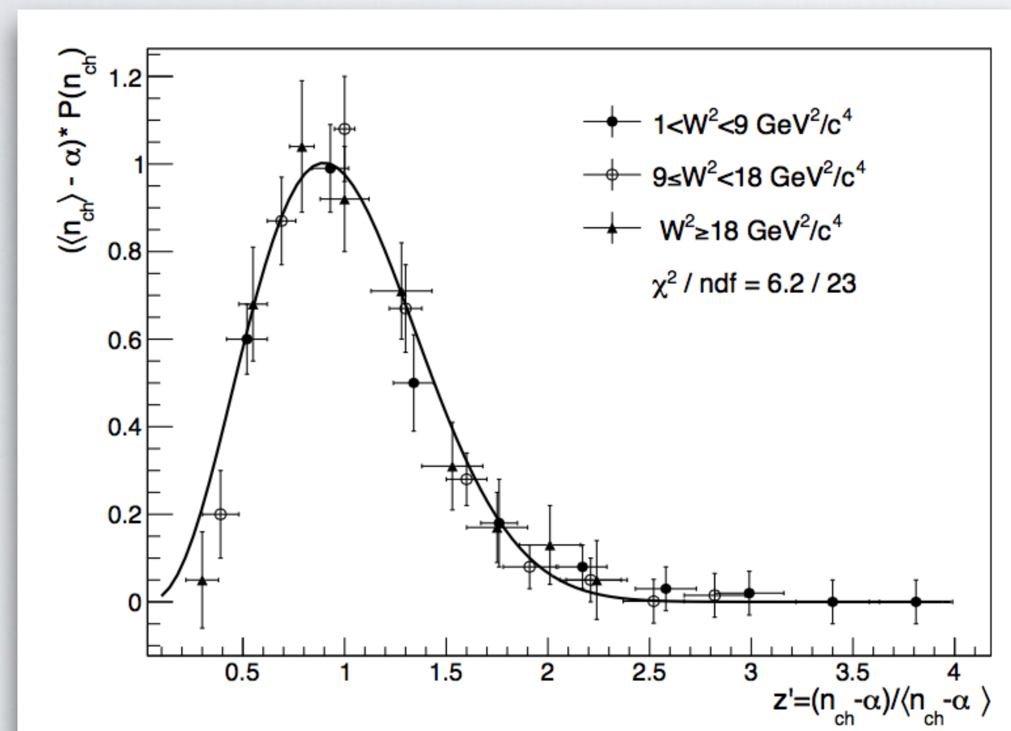
The multiplicity distribution of charged hadrons is an important characteristic of the hadronic final states in hard scattering processes. Since it reflects the dynamics of the interaction.



$\langle n_{ch} \rangle = a + b \ln W^2$

The data is well described by

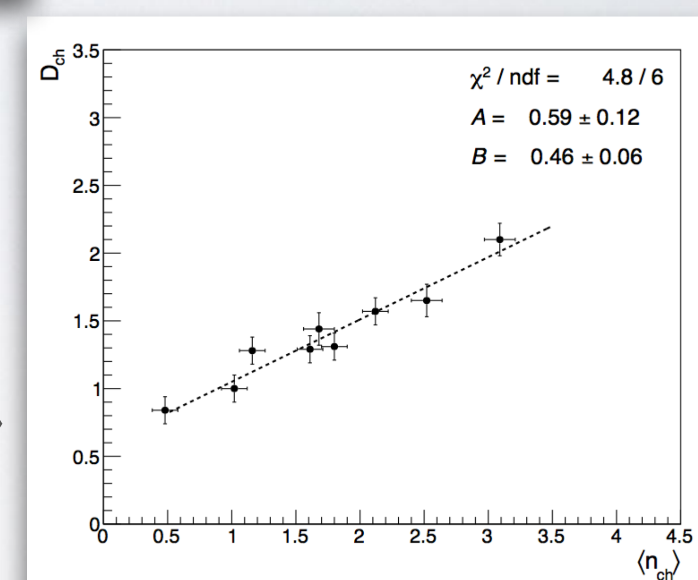
a linear function in lnW^2



Fit function

$$\Psi(z') = (A(z')^3 + B(z')^7)e^{-(Cz' + D(z')^3)}$$

$D_{ch} = A + B \langle n_{ch} \rangle$



Approximate KNO scaling is valid for the charged hadrons multiplicity Data shows good agreement with approximate KNO scaling

Useful to improve models of particle production which are used in Monte Carlo (MC) event generators.

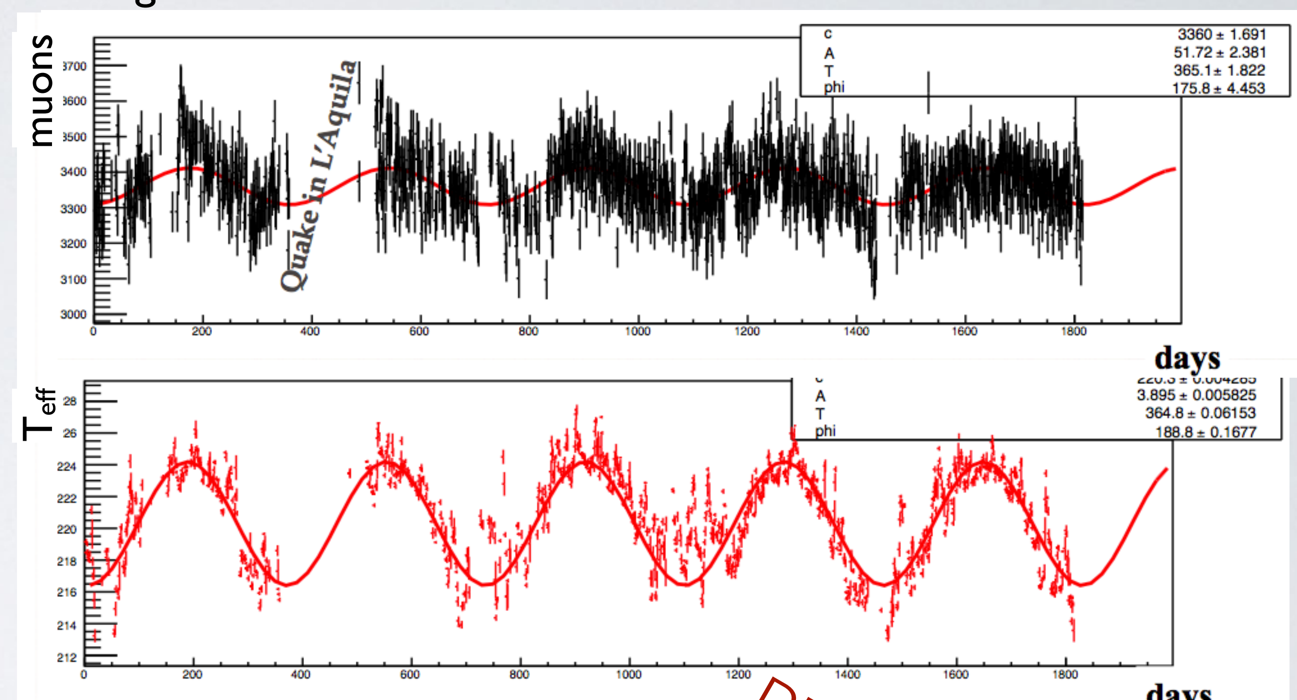
http://arxiv.org/abs/1706.07930 Submitted to EPJ C

ANNUAL MODULATION OF ATMOSPHERIC MUONS

The Gran Sasso underground lab: 1400 m of rock (~3800 m w.e.) shielding.

Cosmic ray flux reduced by a factor of 10^6 w.r.t. surface.

COMPLETE OPERA DATA SET: 2008-2012



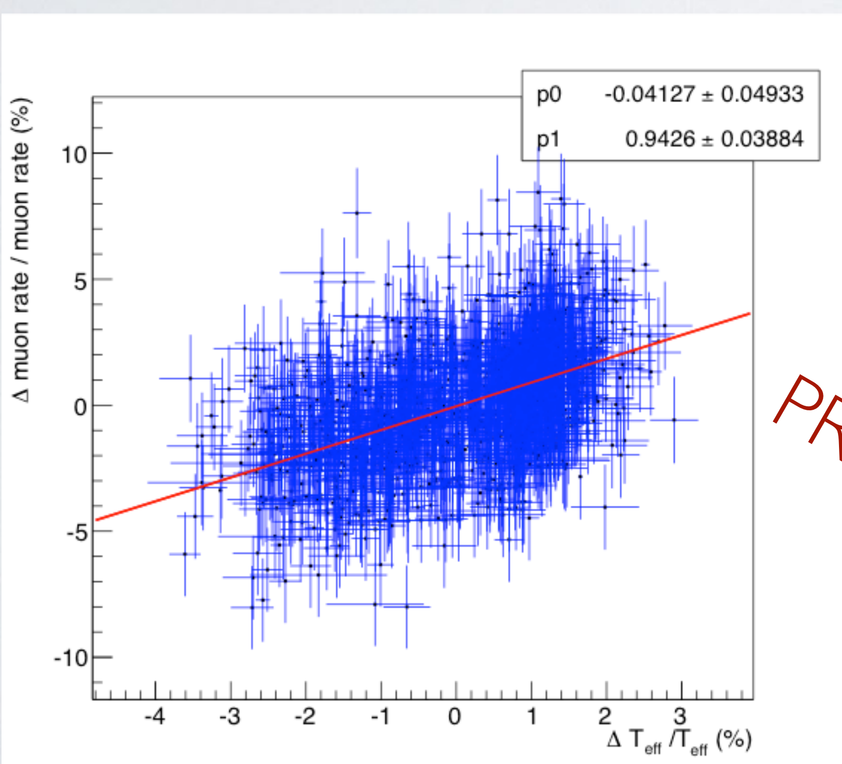
Atmospheric temperature increase → density decrease → increase the pion decay rate → muon rate increase

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

T =365±2

t_0 =176±4

PRELIMINARY



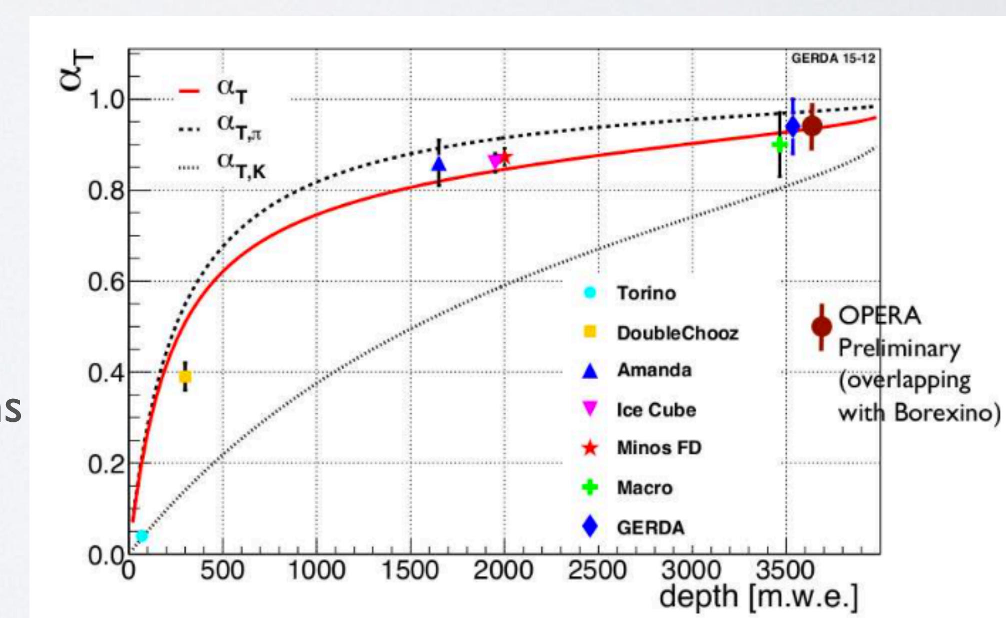
Correlation between relative variations in the muon rate and the effective temperature:

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

$\boldsymbol{\alpha}_T$ =0.94±0.04

PRELIMINARY

In agreement with predictions for LNGS site and with other experiments



CONCLUSIONS

- 5 ν_τ events found with 0.25 background.

⇒ Discovery of ν_τ appearance in the CNGS neutrino beam: 5.1σ

- Minimum bias analysis to increase the number of ν_τ candidate.

⇒ measurement of Δm^2_{23}. Preliminary results in agreement with PDG2016 at 1σ

⇒ ν_τ cross section (first measurement with ν_τ only)

- $\nu_\mu \rightarrow \nu_e$ oscillations: number of observed events in agreement with expected background and the standard oscillation signal
- Sterile neutrino constraints from $\nu_\mu \rightarrow \nu_e$ oscillations in the 3+1 flavour model

Non-oscillation Physics:

- Study of the multiplicity distribution of charged hadron particles in neutrino-lead interactions to improve models of particle production which are used in Monte Carlo (MC) event generators.

- Analysis of the annual modulation of atmospheric muons.

Thank you for your kind attention