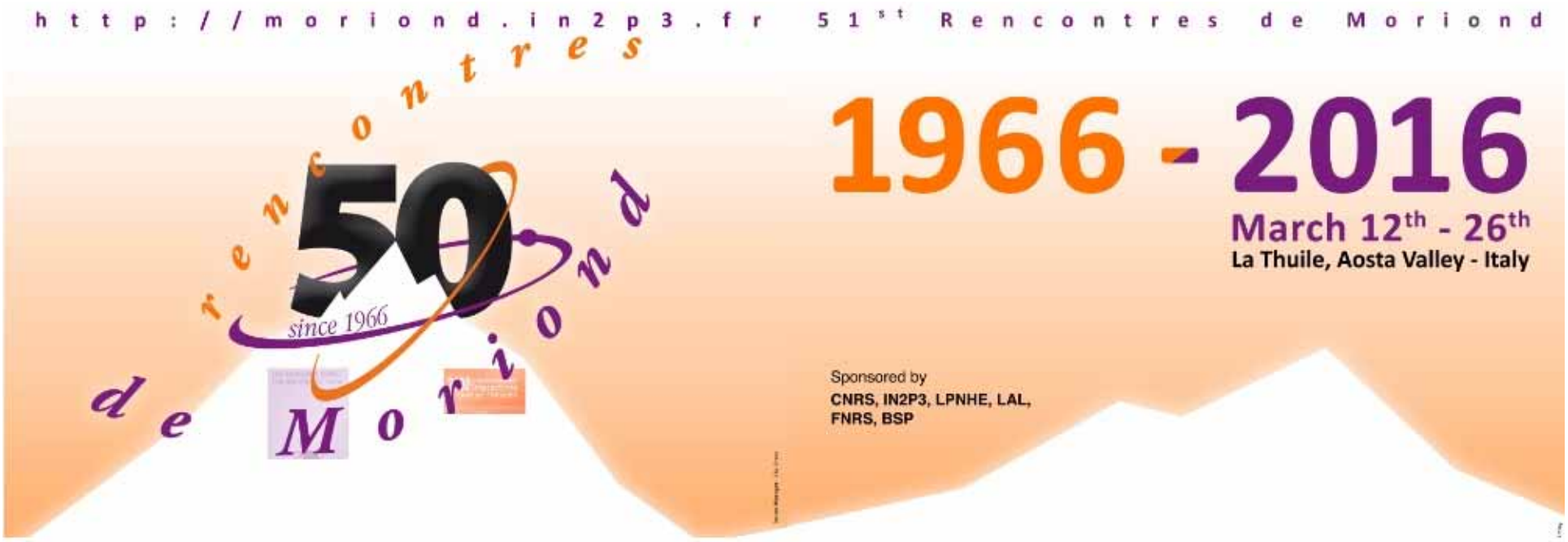


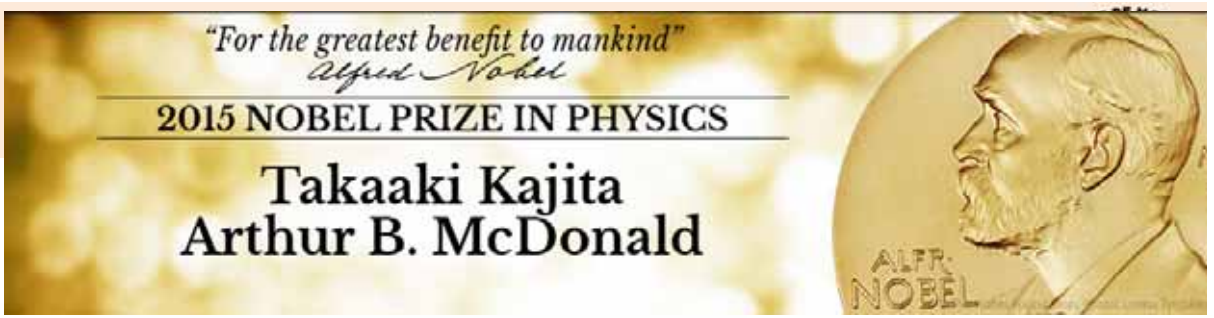
Results from OPERA

Alessandra Pastore
Bari University & INFN Bari, ITALY

on behalf of the OPERA Collaboration

26 institutions
140 physicists

2015



"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Scientific Background on the Nobel Prize in Physics 2015

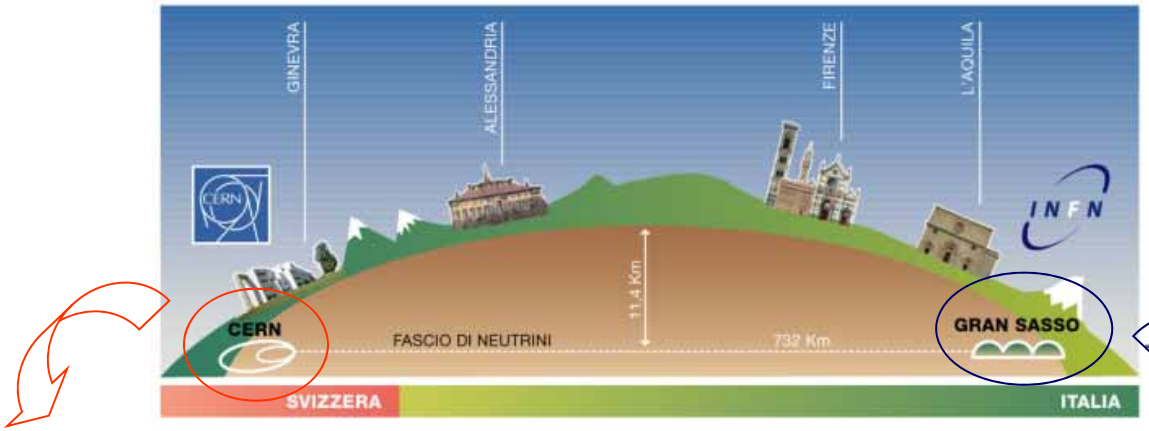
NEUTRINO OSCILLATIONS

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, 121802 (2015)]***

Outline

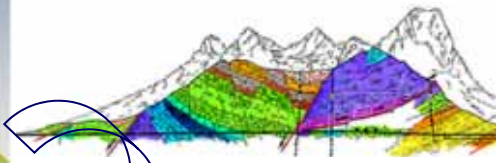
- *the OPERA way to 'appearance'*
- *status of the experiment*
- *Oscillation physics results*

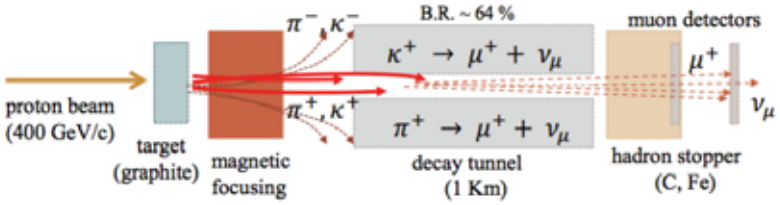
The Oscillation Project with Emulsion tRacking Apparatus



Laboratori Nazionali del Gran Sasso (Italy)

- 1400 m rock overburden
- cosmic μ reduction ~ 10^6 (1μ /m^2/h)
- low radioactivity rock

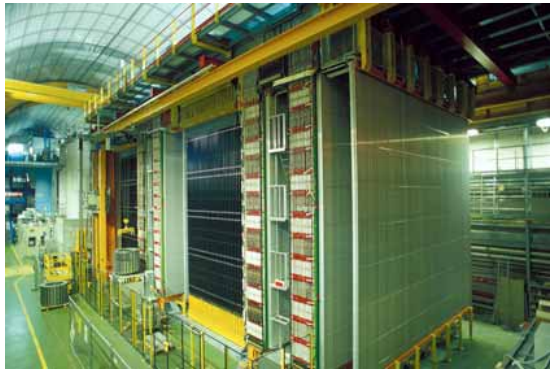




Cern Neutrinos to Gran Sasso beam

- conventional high energy ν_μ beam

732 km



Hybrid OPERA detector
- large target mass (1.25 kton)
- submicron resolution

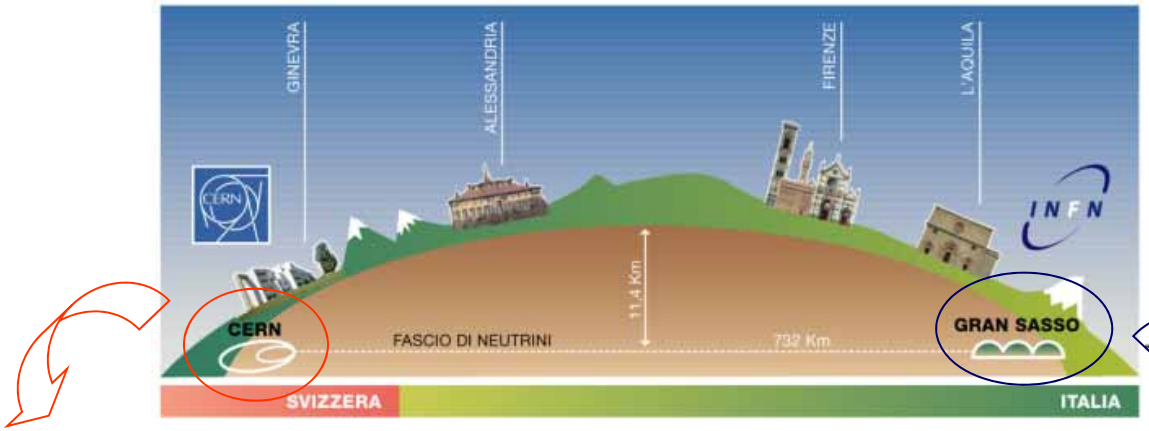
The Oscillation Project with Emulsion tRacking Apparatus

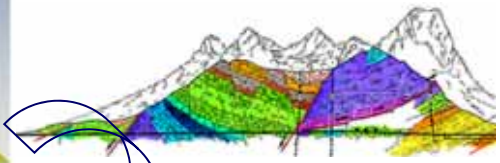
Laboratori Nazionali del Gran Sasso (Italy)

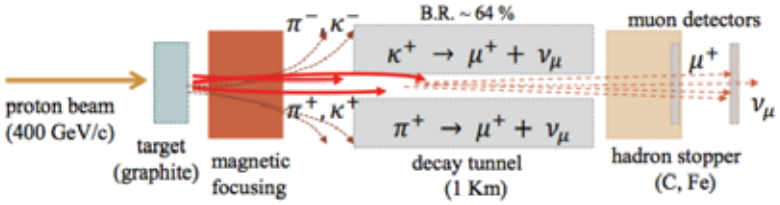
- 1400 m rock overburden

- cosmic μ reduction ~ 10^6 ($1\mu/m^2/h$)

- low radioactivity rock

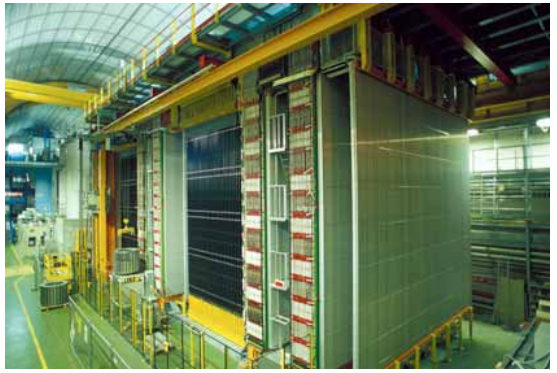






Cern Neutrinos to Gran Sasso beam

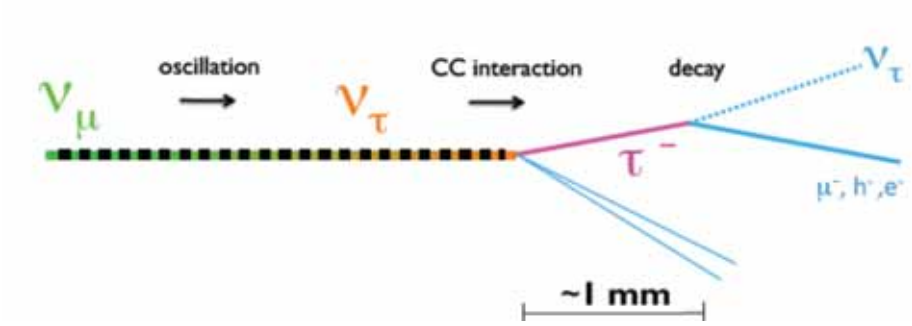
732 km



Hybrid OPERA detector

Direct observation of ν_τ appearance from ν_μ oscillation at atmospheric scale

the OPERA way to 'appearance'



τ decay channel	B.R. (%)
τ → μ	17.7
τ → e	17.8
τ → h	49.5
τ → 3h	15.0

Based on event-by-event separation of ν_τ CC interactions from dominant ν_μ interactions by direct observation of τ lepton decay.

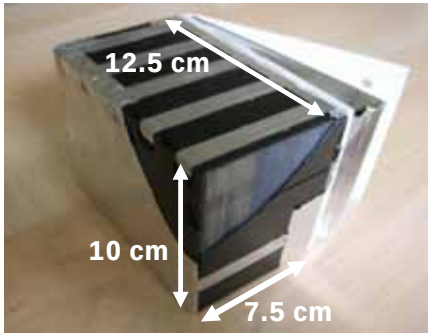
Requirements:

- Large target mass
- Micrometric resolution to observe τ decay *kink*

→ Nuclear emulsions

- High muon identification efficiency to reduce charm background; event region pre-selection

→Electronic detectors



Target segmented into basic units called bricks.
Brick: sandwich of 57 emulsion films interleaved with 1mm-thick lead plates

Total target mass ~ 1.25 kt
(about 150000 bricks)

The OPERA detector@LNGS

Veto
(RPC)

High precision tracker
- drift tubes

Dipole magnet
- 1.53 *T*
- RPC planes

muon spectrometer (8×10 m^2)

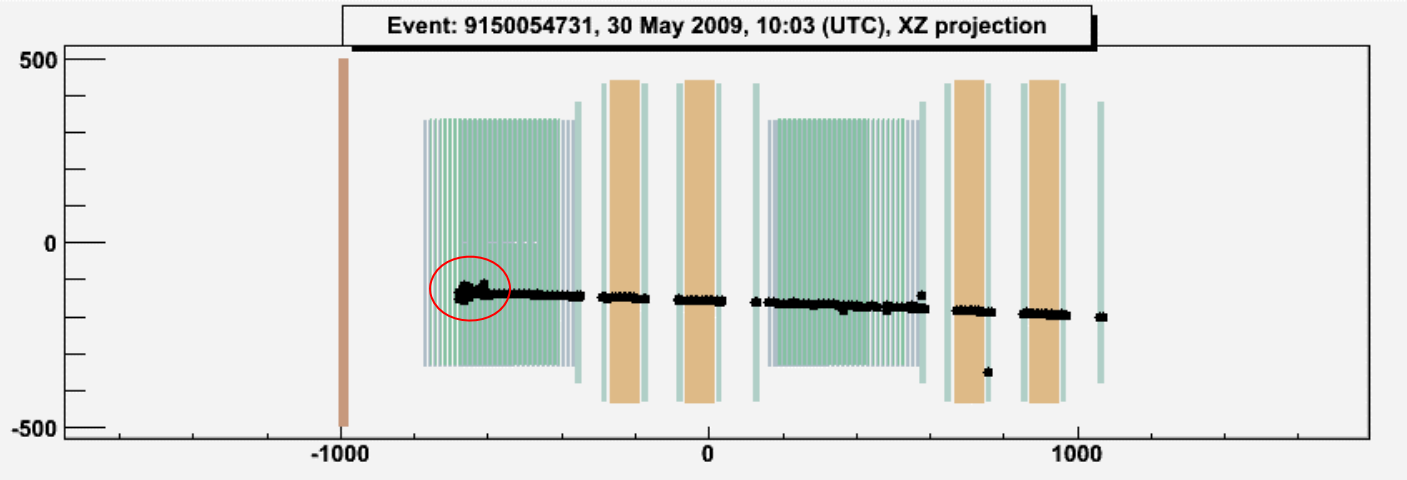
Brick walls + Target Tracker (6.7m)^2

- brick/SM: ~75000
  Mass/SM 0.625 kt

- Target tracker :
  31 doublets of planes per SM (XY)
  (256 plastic scintillator strips per plane + WLS fibres+ multi-anodes PMT)
  for trigger, brick selection and calorimetry

[JINST 4 (2009) P04018]

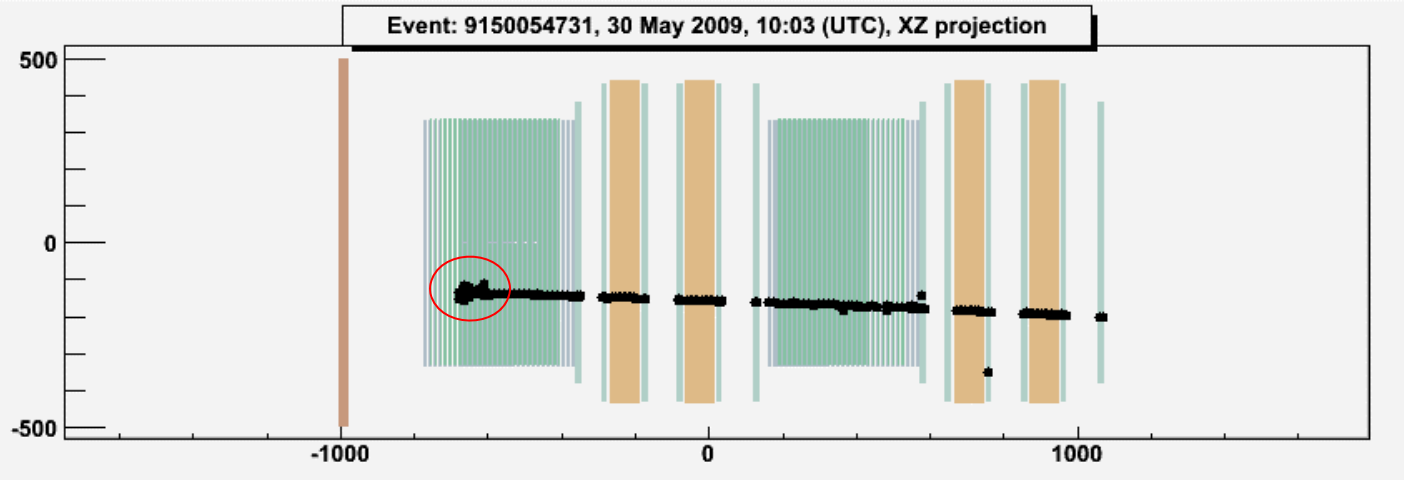
Detection of ν interactions in the target



- on-line analysis of electronic data

[2009 JINST 4 P04018]

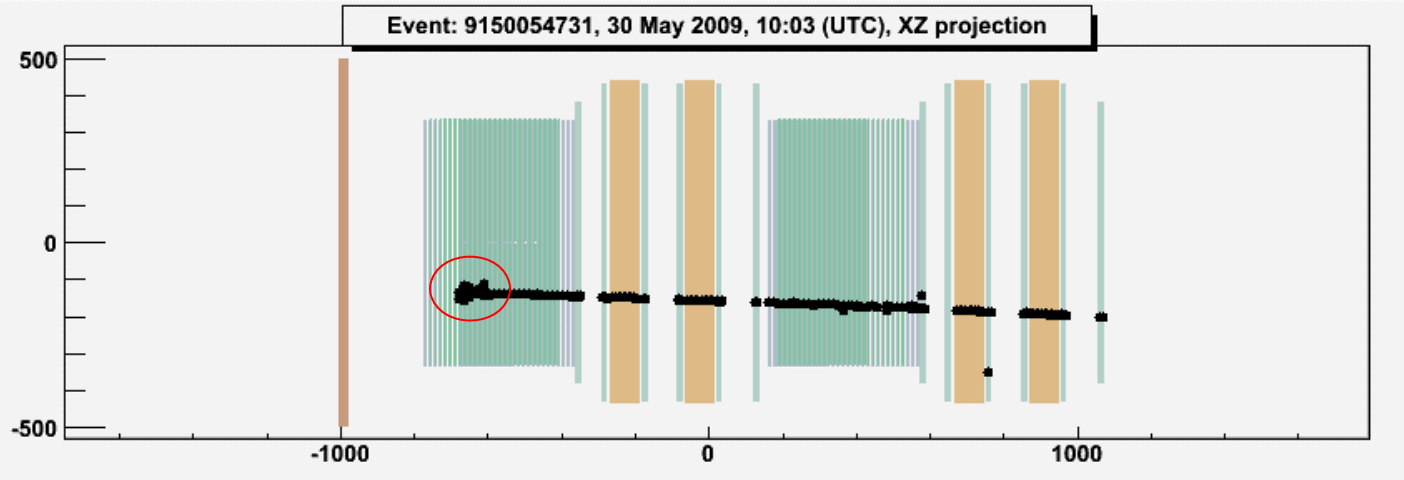
Detection of ν interactions in the target



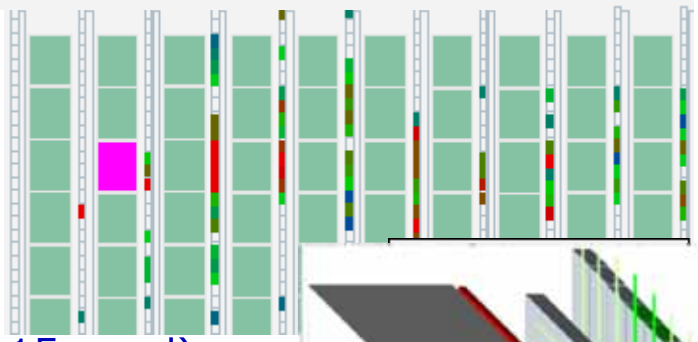
- on-line analysis of electronic data
- brick finding algorithm for events on time with the beam

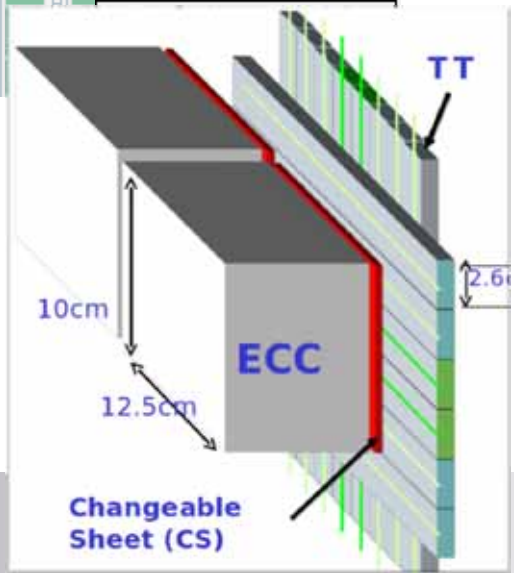
[2009 JINST 4 P04018]

Detection of ν interactions in the target



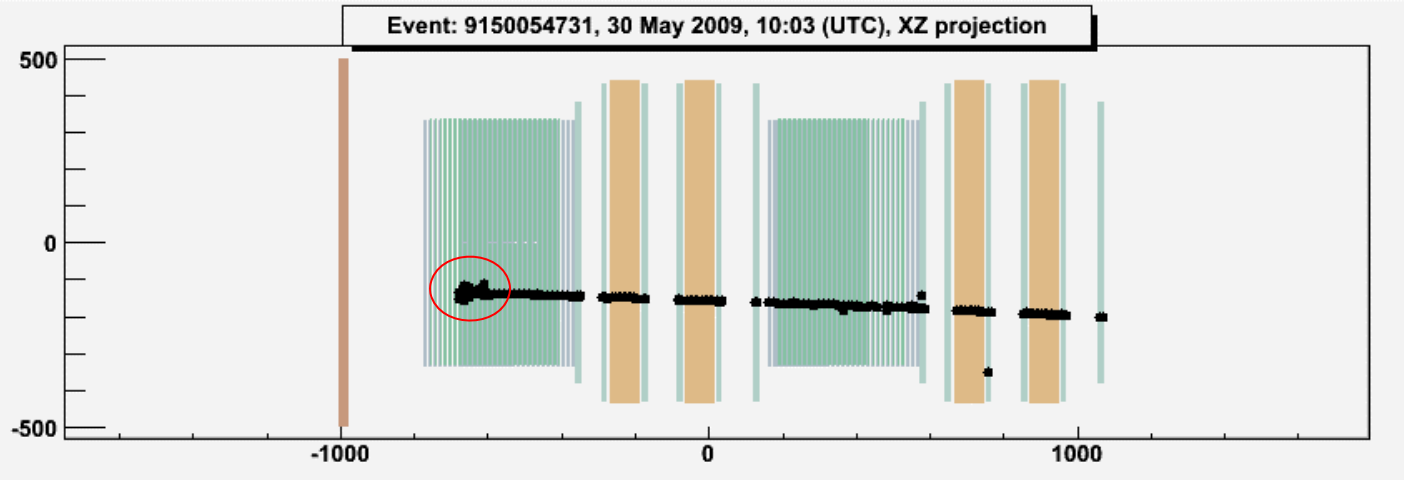
- on-line analysis of electronic data
- brick finding algorithm for events on time with the beam
- remove brick and scan CS: the interface between brick and TT ($\sigma_{pos} \approx 8$ mm, $\sigma_{\theta} \approx 15$ mrad)



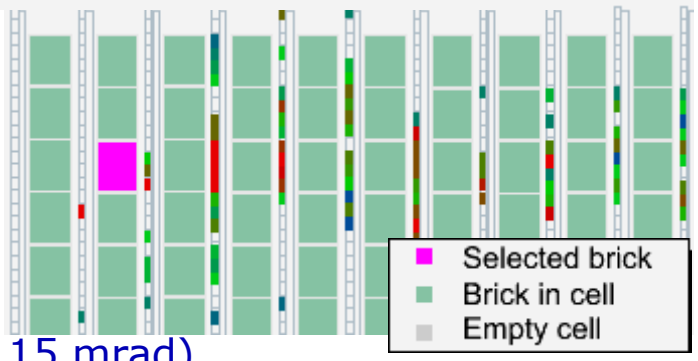


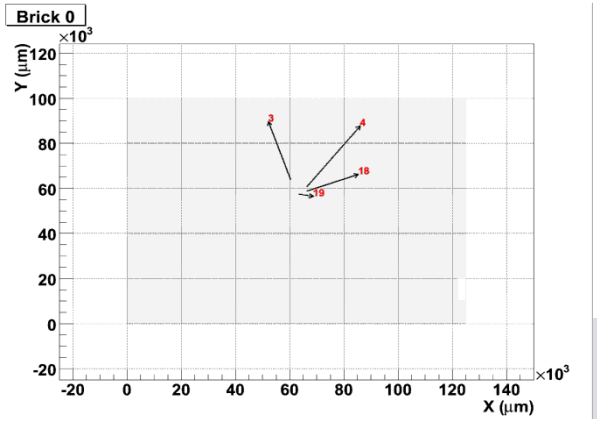
[2009 JINST 4 P04018]

Detection of ν interactions in the target



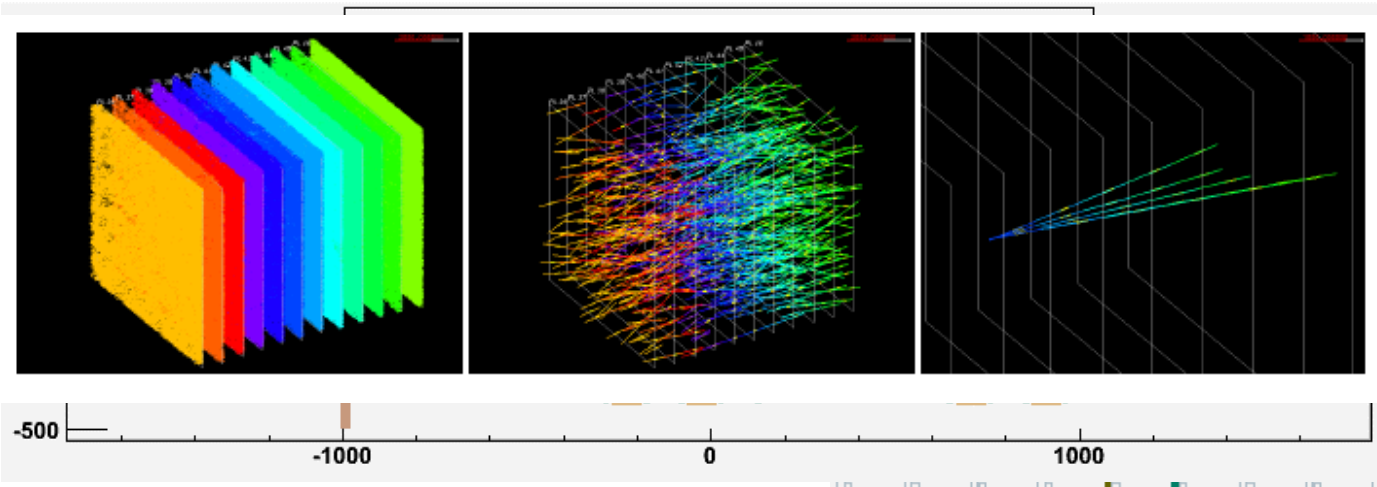
- on-line analysis of electronic data
- brick finding algorithm for events on time with the beam
- remove brick and scan CS: the interface between brick and TT ($\sigma_{pos} \approx 8$ mm, $\sigma_{\theta} \approx 15$ mrad)
- confirmation of the extracted brick



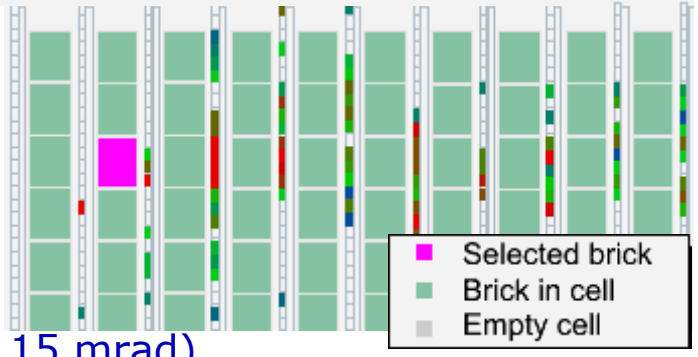


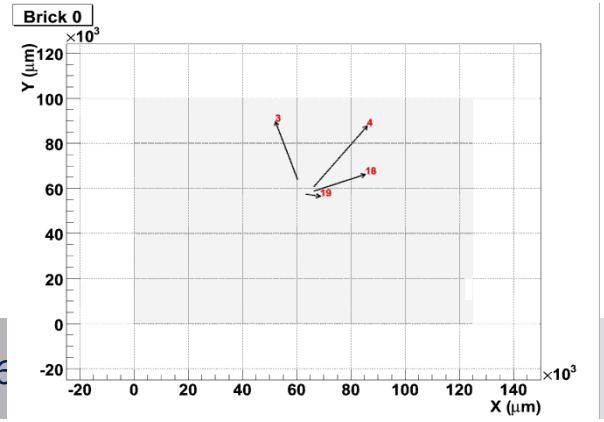
[2009 JINST 4 P04018]

Detection of ν interactions in the target



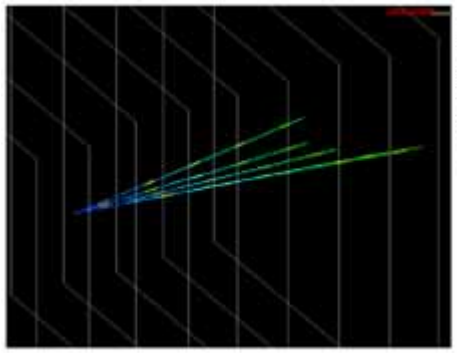
- on-line analysis of electronic data
- brick finding algorithm for events on time with the beam
- remove brick and scan CS: the interface between brick and TT ($\sigma_{pos} \approx 8$ mm, $\sigma_\theta \approx 15$ mrad)
- confirmation of the extracted brick
- development of the brick to be sent in a scanning Lab for '*CS to brick connection*' ($\sigma_{pos} \approx 70$ μm, $\sigma_\theta \approx 8$ mrad), event location, decay search studies, etc ..

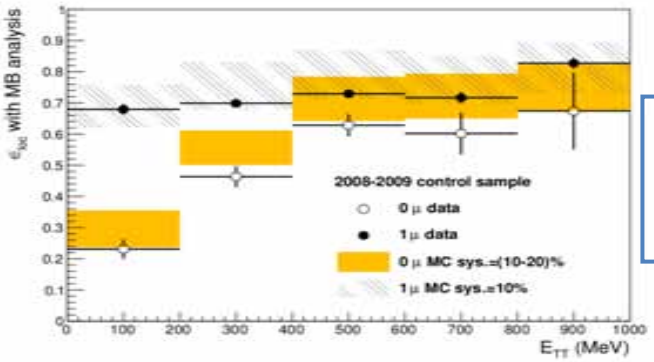




[2009 JINST 4 P04018]

Detection of decay topologies in a brick





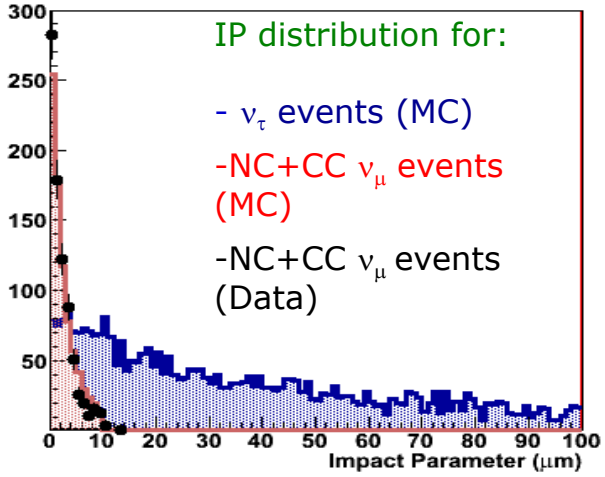
[JHEP 11 (2013) 036]

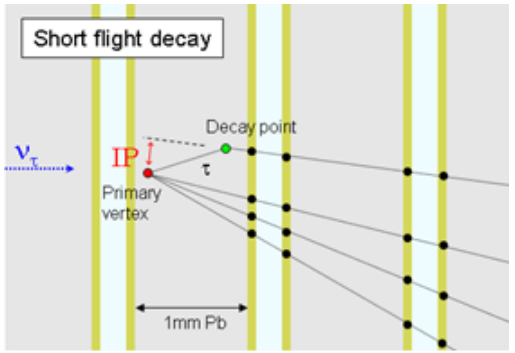
location efficiency data/MC comparison as a function of the visible energy in TT

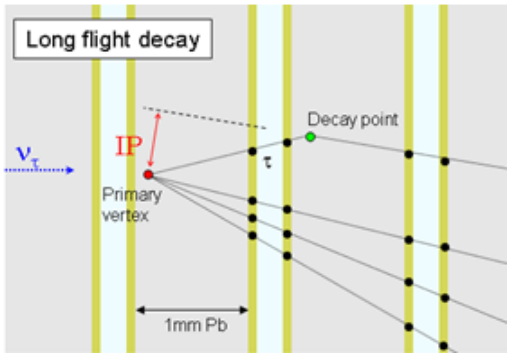
Decay search procedure based on

- impact parameter (IP) evaluation
- small kink angle search
- extra-tracks search

[Eur.Phys.J. C74 (2014) 2986]





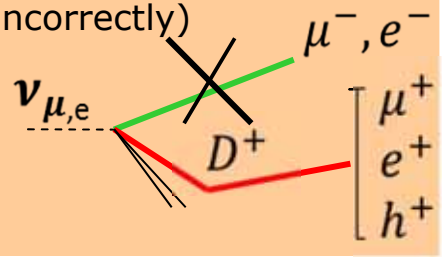


Background sources

*In **red** some improvements relative to previous analyses…*

In order of decreasing importance

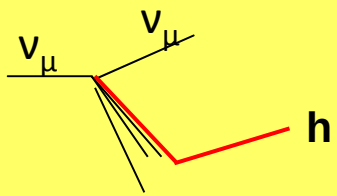
CC with charm production (all channels)
If primary lepton is not identified and the daughter charge is not (or incorrectly) measured



MC tuned on CHORUS data (cross section and fragmentation functions), validated with measured OPERA charm events.
(54±4 expected, 50 observed)

Reduced by "track follow down" procedure and large angle scanning
[Eur.Phys.J. C74 (2014) 2986]

Hadronic interactions
Background for τ → h

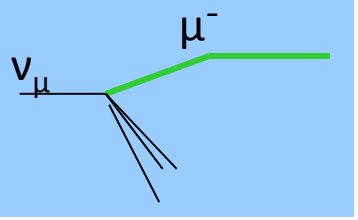


FLUKA + pion test beam data

Reduced by large angle scanning and nuclear fragment search

[PTEP9 (2014) 093C01]

Large-angle muon scattering
Background for τ → μ



Simulation study (updated lead form factor) benchmarked with available data

Reduction of a factor ~ 100 wrt to previous estimation

[Trans.of Nuclear Science, Vol.62, No.5 (2015)]

Status of the experiment

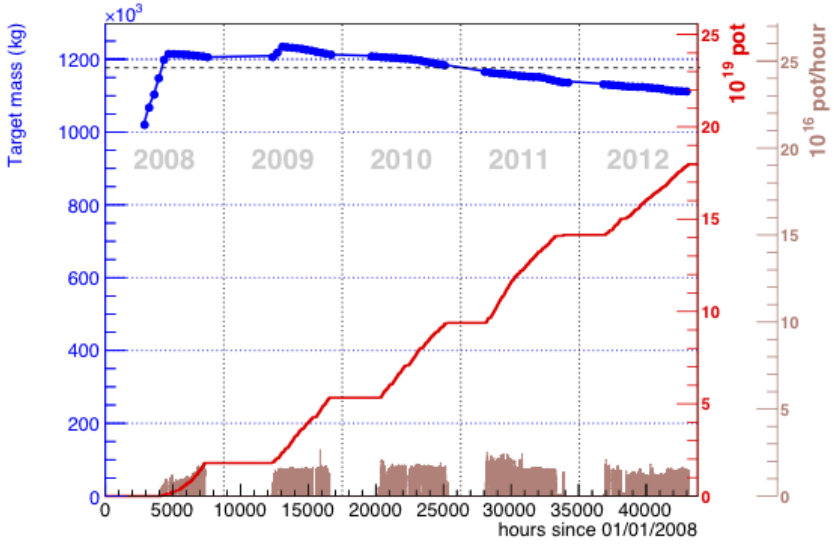
Status of the experiment

CNGS run	beam days	# p.o.t.*
2008	123	1.74 x 10^{19}
2009	155	3.53 x 10^{19}
2010	187	4.09 x 10^{19}
2011	243	4.75 x 10^{19}
2012	257	3.86 x 10^{19}
tot	965	17.97 x 10^{19}

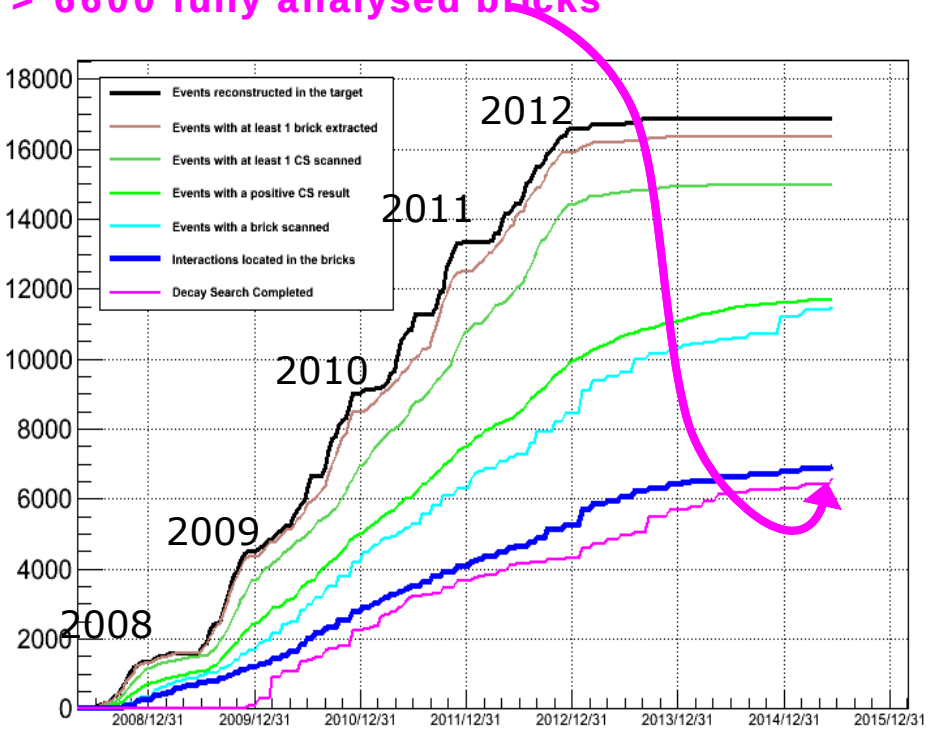
* nominal value: 4.5 10^{19} pot/year

Status of data analysis

- **150'000** ECC bricks. Total 105'000 m^2 of lead surface and 111'000 m^2 of film surface (**~ 9 million films**)
- About **26115** bricks manipulated for event analysis
- So far **3110000 cm²** of **CS** surface analysed
- **~12500** developed **bricks** (~ 9300 m^2)



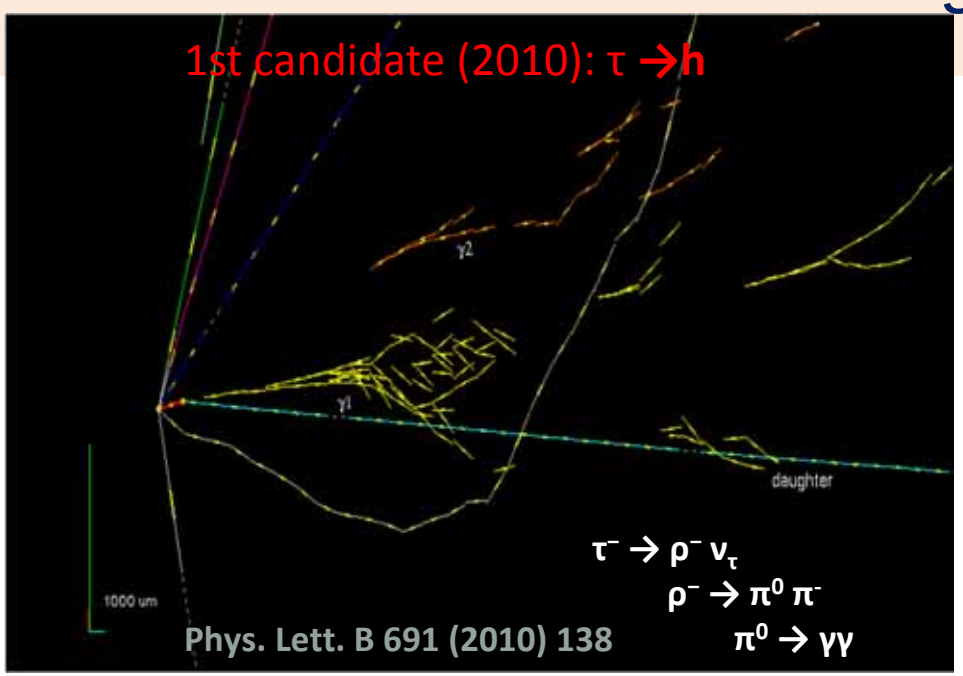
> 6600 fully analysed bricks



Fully analysed events	**> 6600**
ν_τ candidate events	**5**

OPERA candidate event gallery

1st candidate (2010): τ →h



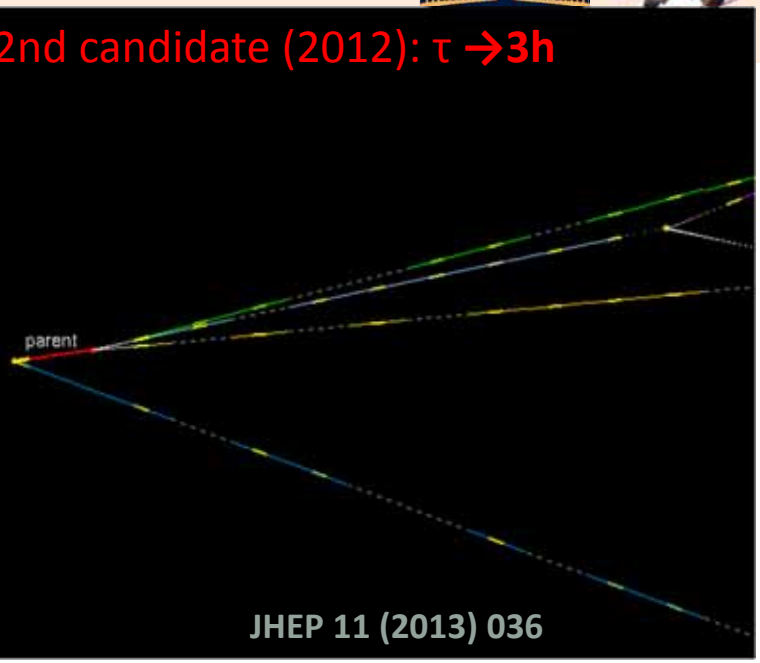
$\tau^- \rightarrow \rho^- \nu_\tau$

$\rho^- \rightarrow \pi^0 \pi^-$

$\pi^0 \rightarrow \gamma\gamma$

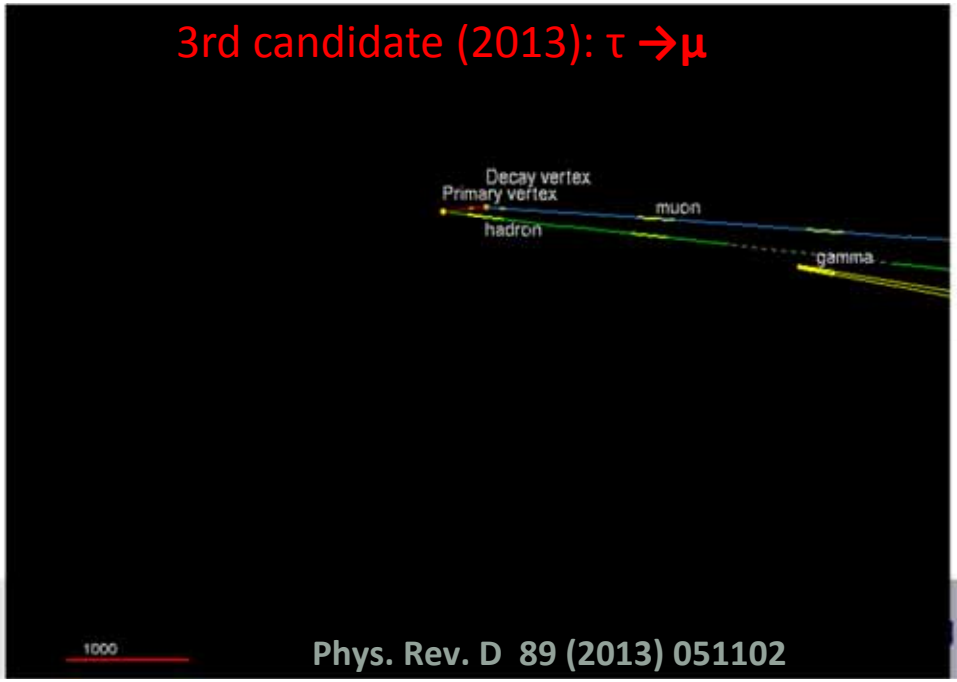
Phys. Lett. B 691 (2010) 138

2nd candidate (2012): τ →3h



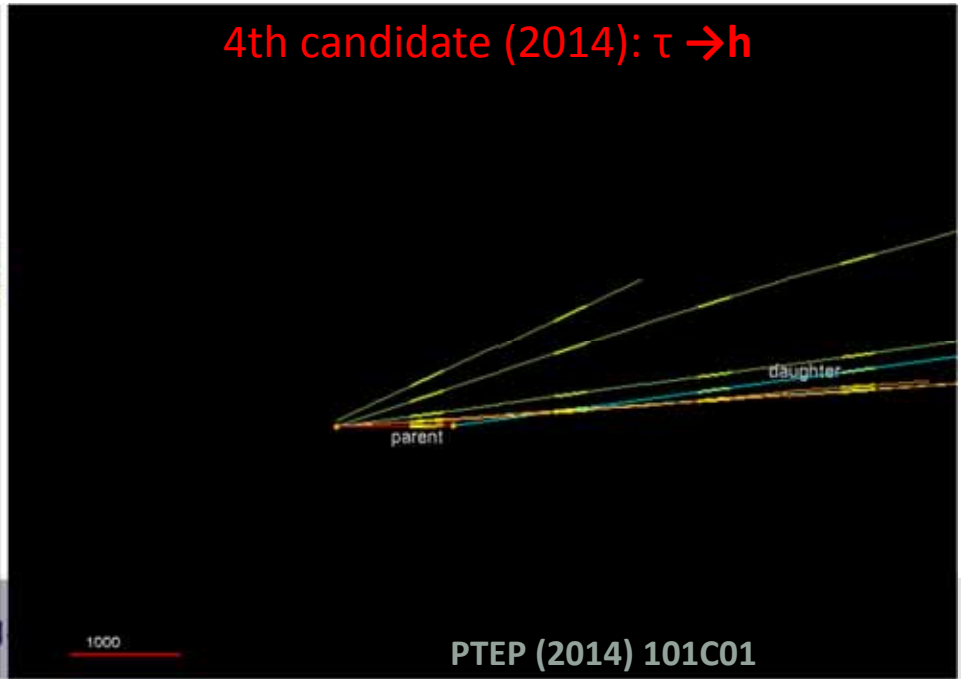
JHEP 11 (2013) 036

3rd candidate (2013): τ →μ



Phys. Rev. D 89 (2013) 051102

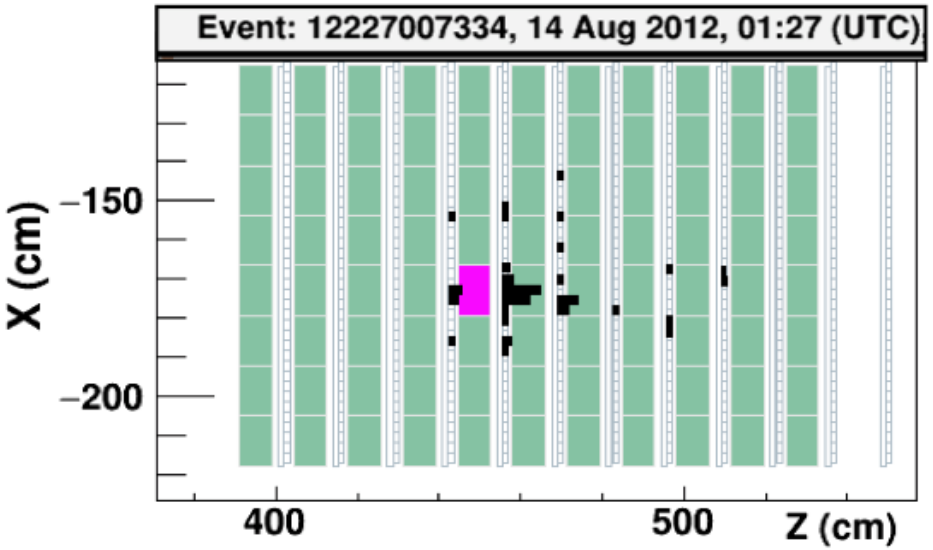
4th candidate (2014): τ →h



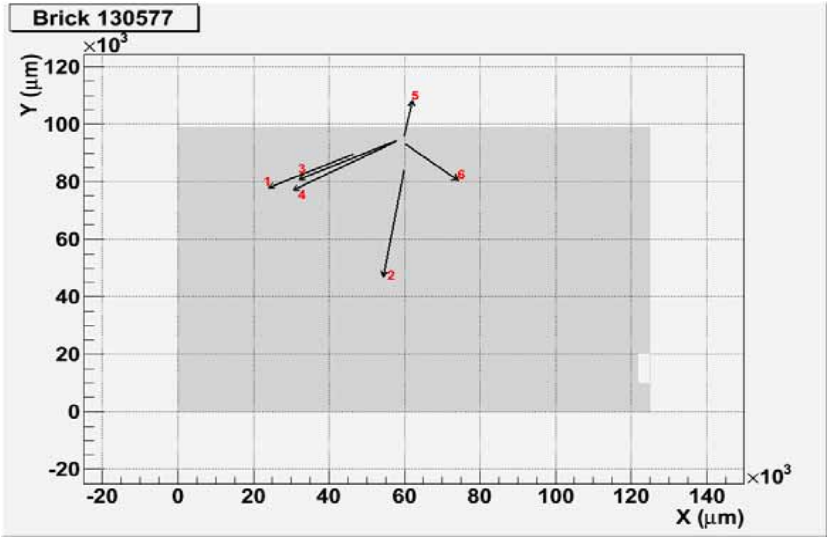
PTEP (2014) 101C01

The 5th candidate event (2015): τ→h

..seen by the electronic detectors…

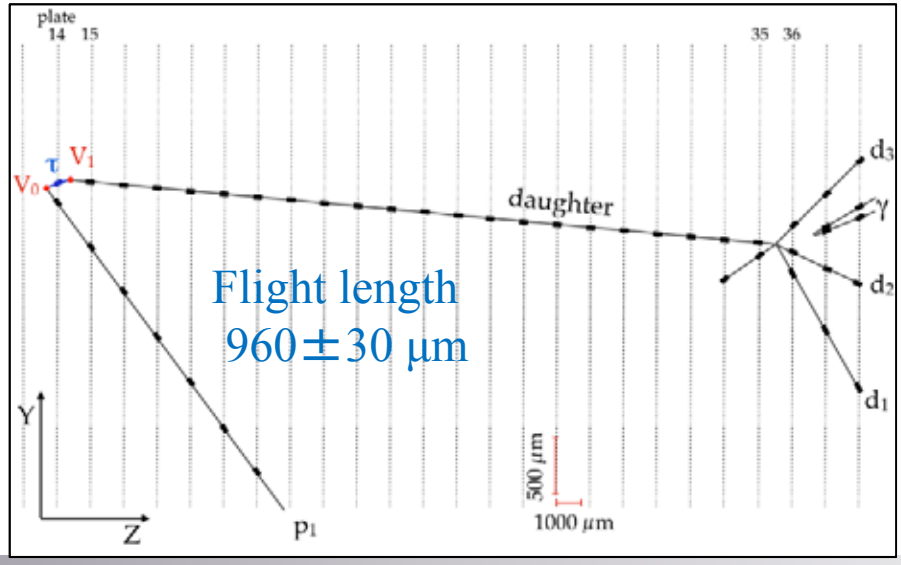


.. and in the brick



Kinematical variables

Parameter	Measured value	Selection Criteria
$\Delta\phi_{\tau H}$ $(^o)$	151 ± 1	>90
p_T^{miss} (GeV/c)	0.3 ± 0.1	<1
θ_{kink} (mrad)	90 ± 2	>20
z_{dec} (μm)	634 ± 30	$[44, 2600]$
p^{2ry} (GeV/c)	11^{+14}_{-4}	>2
p_T^{2ry} (GeV/c)	$1.0^{+1.2}_{-0.4}$	>0.6 (no γ attached)



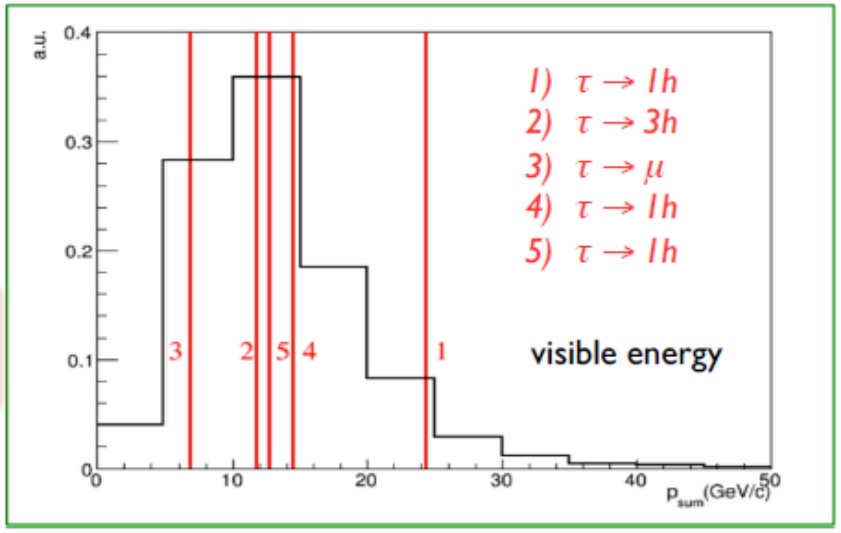
[PRL 115, 121802 (2015)]

Discovery of the appearance of ν_τ in the CNGS beam

$\Delta m^2 = 2.44*10^{-3}$ eV^2

Channel	Expected background				Expected signal	Observed
	Charm	Had. re-interac.	Large μ-scat.	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

5 observed events with 0.25 background events expected



Probability to be explained by background

Two statistical methods:
- Fisher combination of single channel p-values
- Profile likelihood ratio

P-value : 1.10×10^{-7}

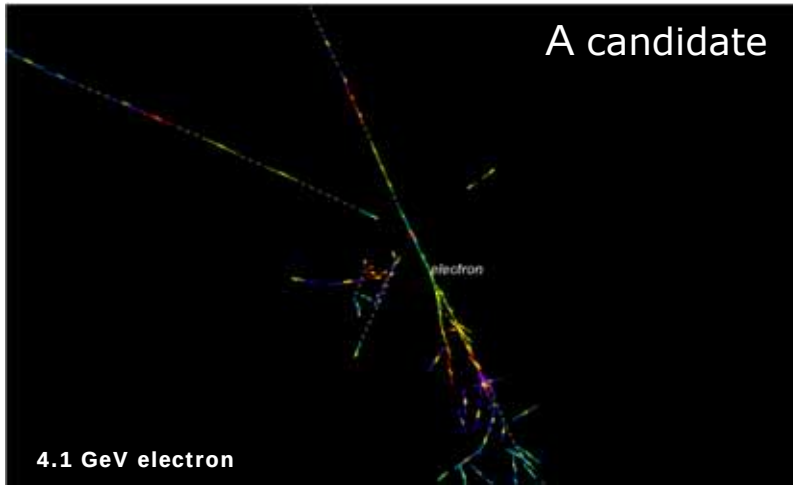
Exclusion of background only hypothesis: 5.1 σ

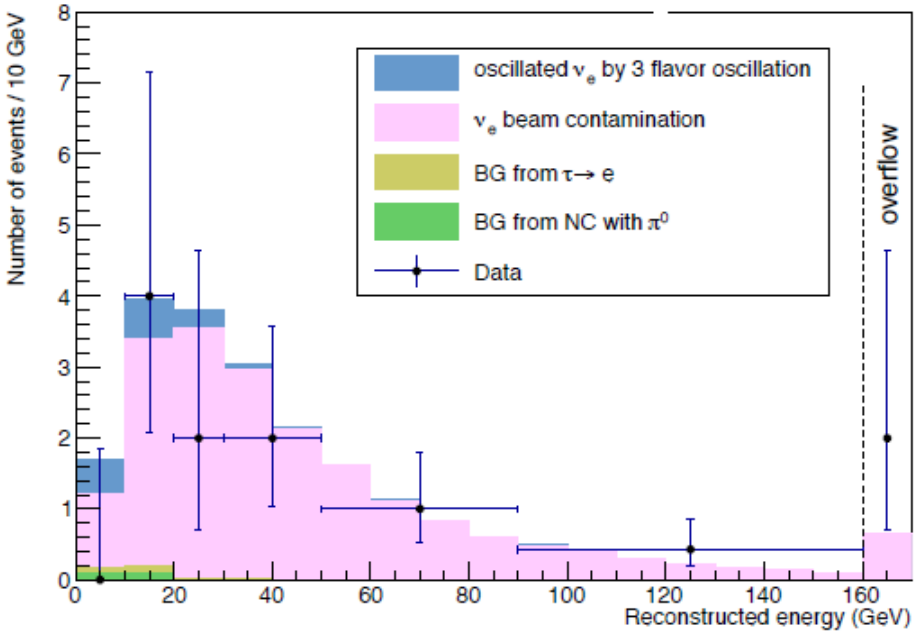
[PRL 115, 121802 (2015)]

Subdominant $\nu_\mu \rightarrow \nu_e$ channel

[JHEP 1307 (2013)] 004]

0μ-like interactions: 505
(≈half of the final sample)





2008/2009		E < 20 GeV
ν_e cand	19	4
background	19.8±2.8 (syst)	4.6

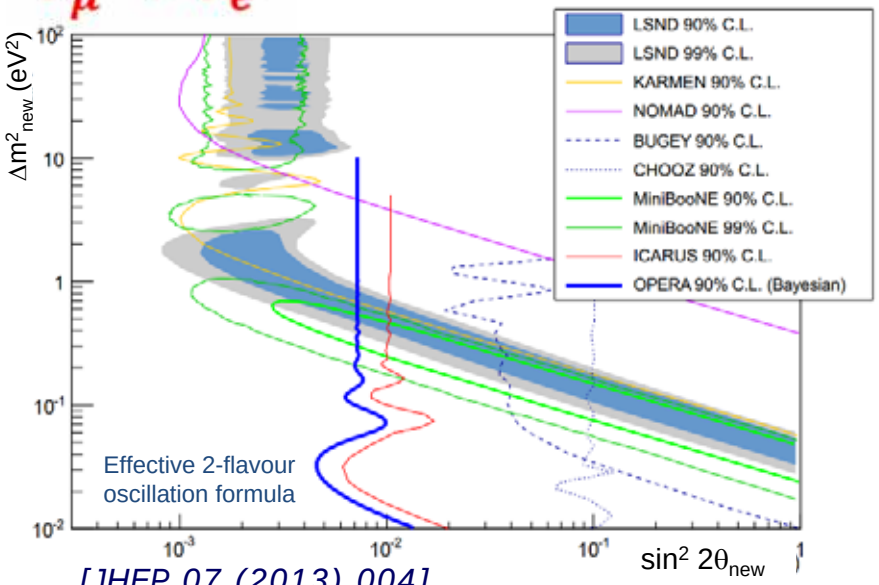
$\sin^2(2\theta_{13}) < 0.44$ (90% C.L.)

New analysis with more than twice candidates (so far 52, 9 with E<20 GeV) on going

Testing the sterile neutrino hypothesis

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

$\nu_\mu \rightarrow \nu_e$



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Caveat: experiments at different L/E

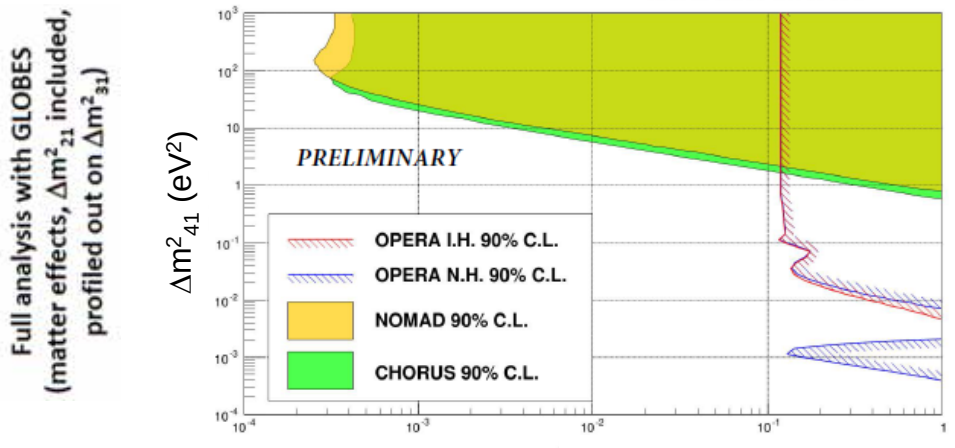
OPERA limit at large Δm^2:

$\sin^2(2\theta_{new}) < 7.2 \times 10^{-3}$ (Bayesian)

bounds set in the large Δm^2 region → full data set analysis update on-going

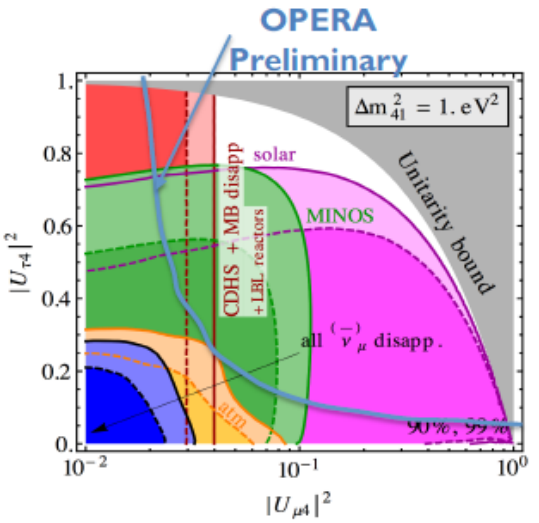
$\nu_\mu \rightarrow \nu_\tau$

$\Delta m^2_{41} < 0$ (disfavoured by cosmological limits on Σm_ν) gives similar results with hierarchies inverted



- 90% C.L. exclusion region on Δm^2_{41} lowered down to 10^{-2} eV^2 for $\sin^2 2\theta_{\mu\tau} > 0.5$
- At large Δm^2_{41}: $\sin^2 2\theta_{\mu\tau} < 0.119$

first limits from direct measurement of ν_τ



Conclusions ..

- OPERA ran on the CNGS neutrino beam from 2008 to December 2012, $1.8*10^{20}$ pot collected in total
- detector successfully measuring ν_μ , ν_e , ν_τ interactions
- 5 tau neutrino candidates observed, with a 5.1 σ significance

→ *discovery of tau neutrino appearance in a muon neutrino beam*

- subdominant $\nu_\mu \rightarrow \nu_e$ oscillation analysis extension to the full data sample under way
- firsts limits on a sterile neutrino state in an appearance search, complementary approach relative to disappearance experiments

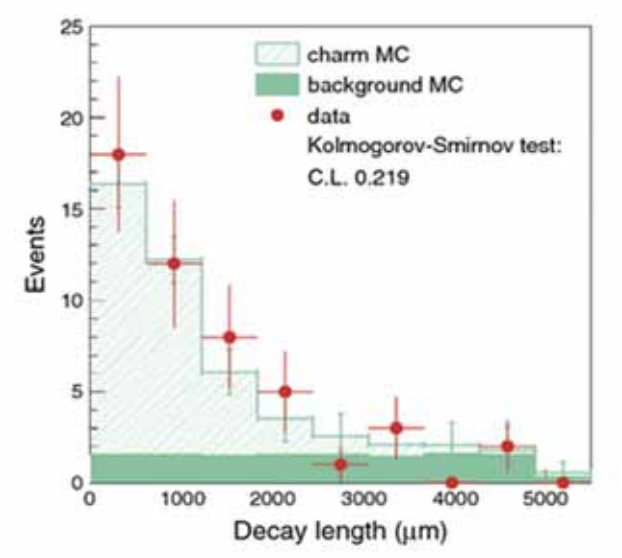
.. and prospects

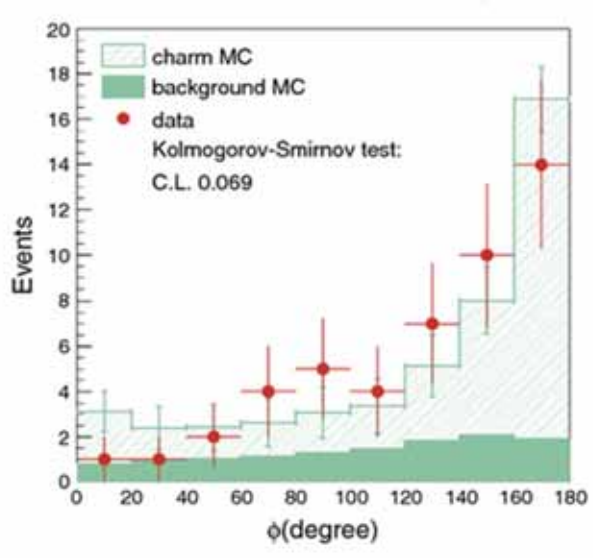
- Multi-brick analysis under completion
- Re-analysis of the full data sample with a likelihood approach and looser (kinematical) selection criteria

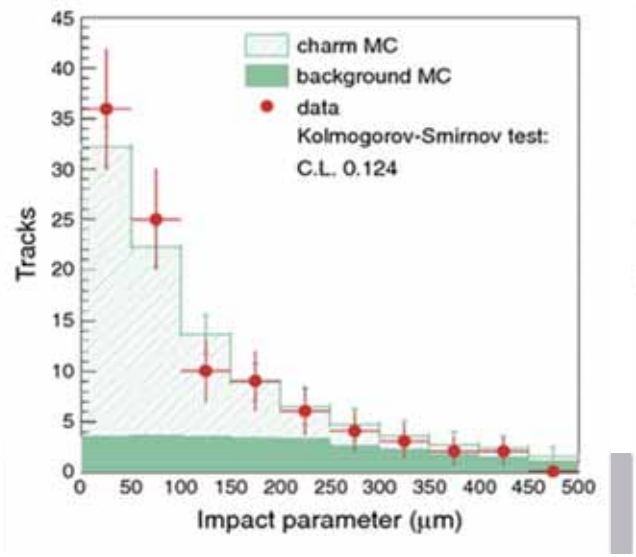
Backup

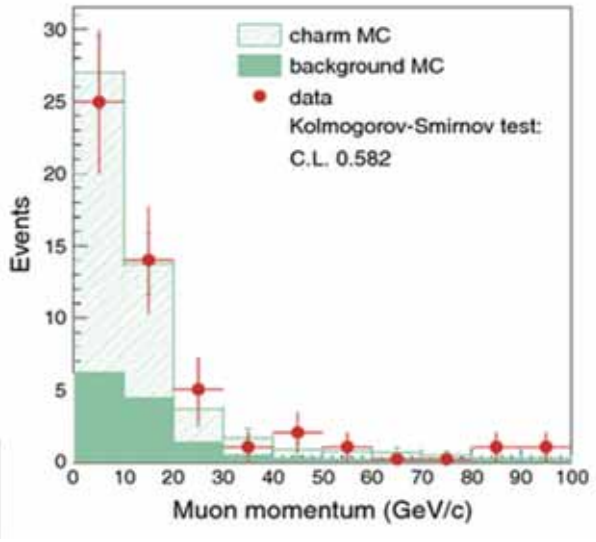
CNGS charm events sample

Test for: reconstruction efficiencies, description of kinematical variables, charm background.

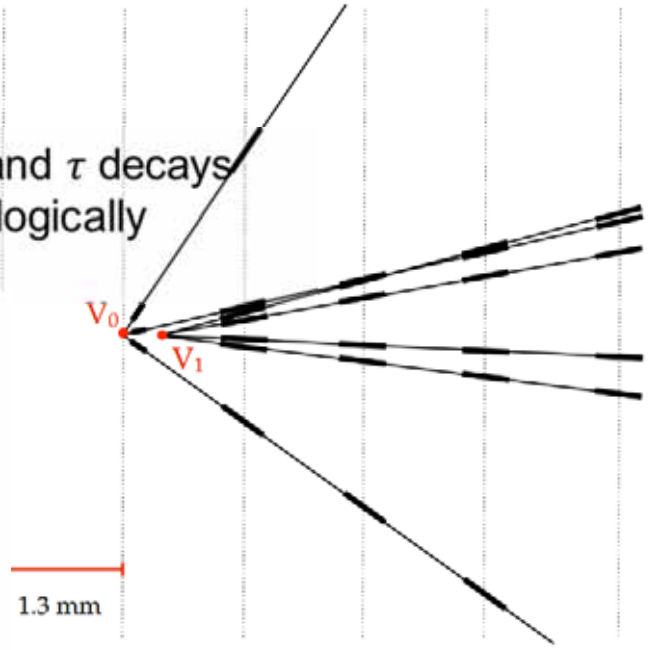


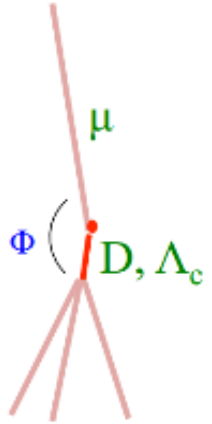






Charm and τ decays are topologically Similar





54 ± 4 expected
50 observed

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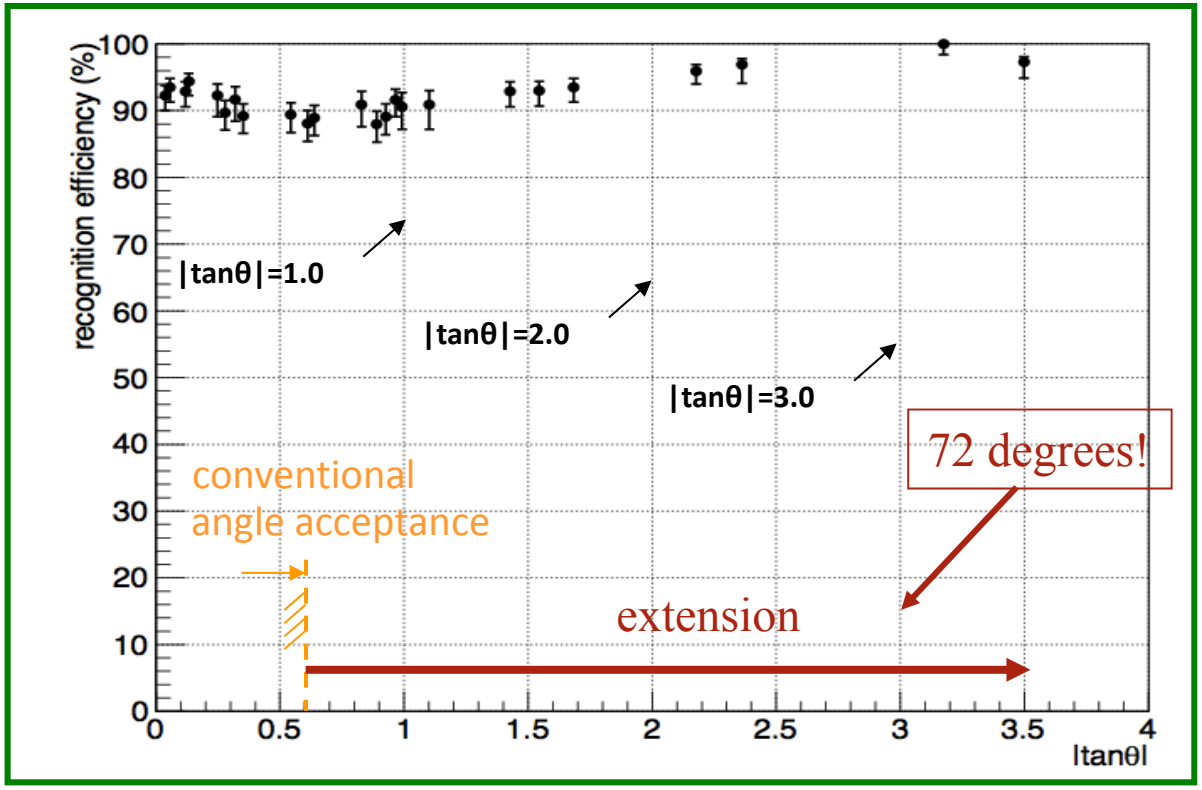
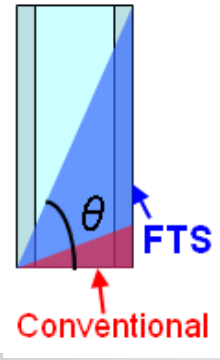
Improvements on the background rejection

Large angle track detection

Undetected soft and large angle muons are the source of charm background
Detection of particles and nuclear fragments in hadronic interactions

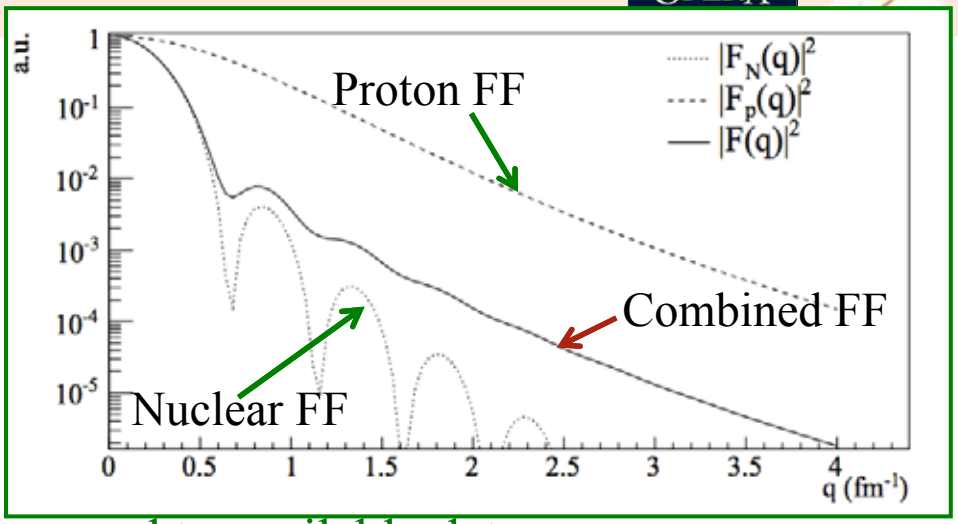




LAS

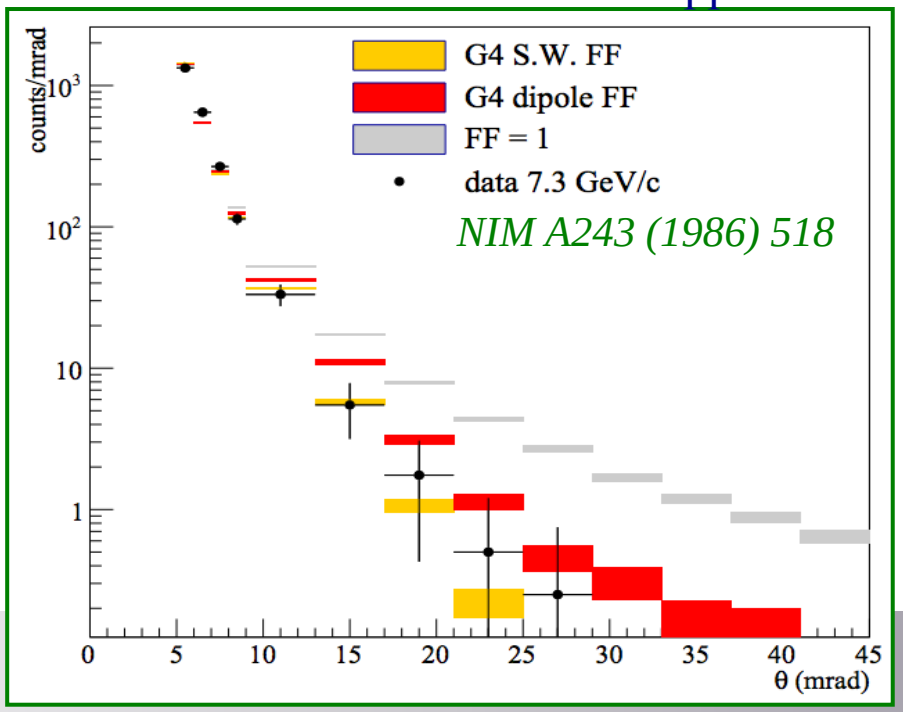
New estimate based on GEANT4
- Simulation modified by introducing form factors (FF) for Lead
(Saxon-Woods parameterization)

$$\rho_{SW}(r) = \rho_0 \left(1 + e^{\frac{r-b}{a}}\right)^{-1}$$

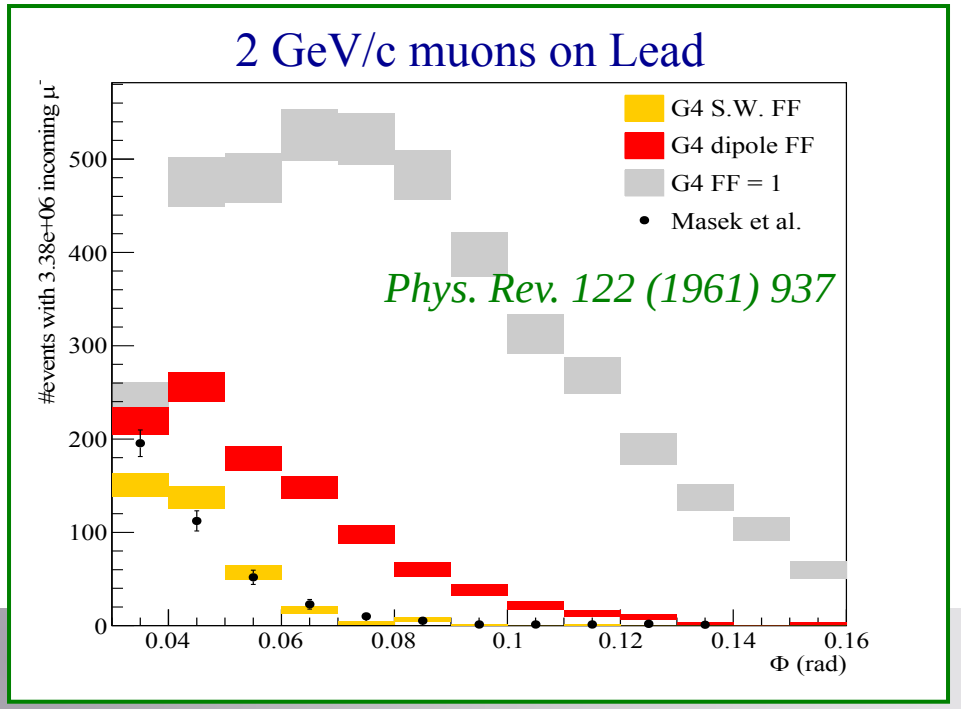


MC predictions compared to available data

7.3 GeV/c muons on Copper



2 GeV/c muons on Lead

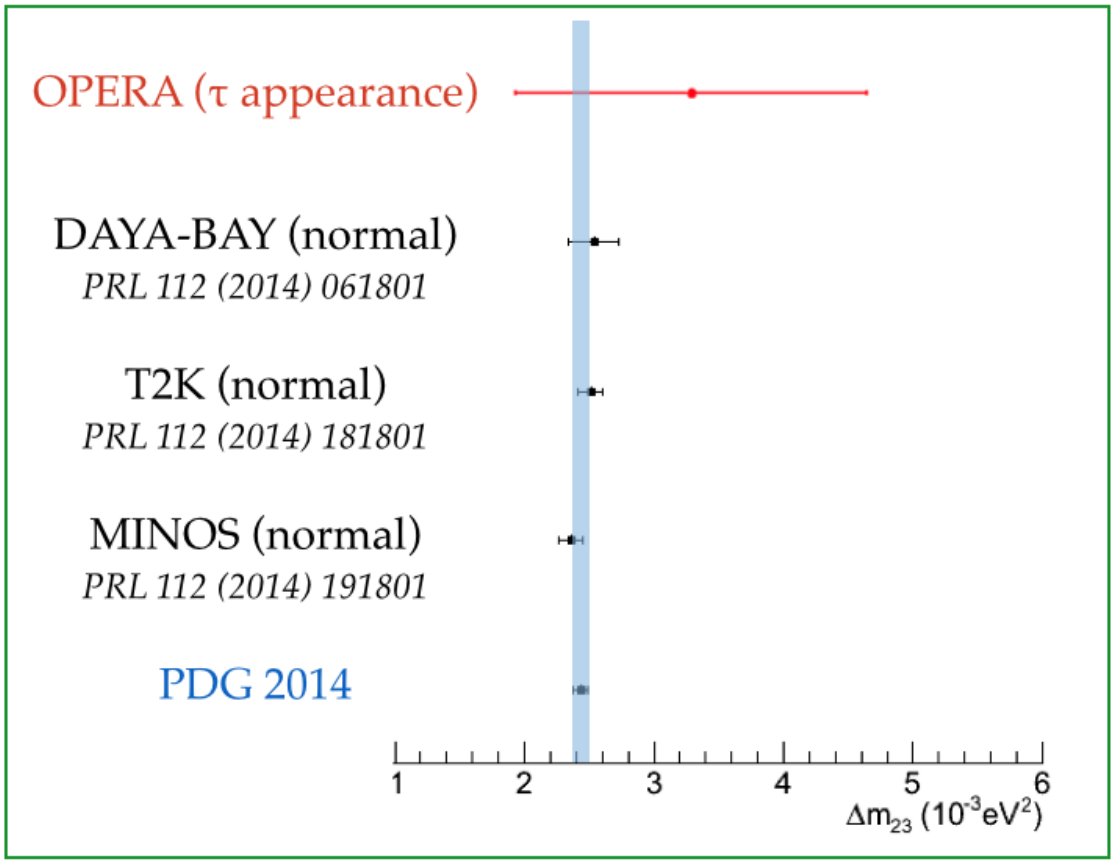


Δm^2_{23} estimation

90% C.L. intervals on Δm^2_{23} by Feldman & Cousins method

$[2.0 – 4.7] \times 10^{-3}$ eV^2

(assuming full mixing)



Kinematical cuts for ν_τ selection

Event kinematics reconstructed using:

• momentum measurement by Multiple Coulomb Scattering in lead (20-30% resolution) [***New J.Phys. 14 (2012) 013026***]

• e.m. shower energy measurement using calorimetric techniques (brick thickness 10 X_0)

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	/	/