RESULTS FROM THE **OPERA EXPERIMENT** AT THE ***CNGS BEAM***

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on behalf of the OPERA Collaboration

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

Italy
Bari
Bologna
Frascati,
LNGS
Naples
Padova
Rome
Salerno

Japan
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Toho
Kobe
Nagoya
Nihon

Korea
Jinju

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

Switzerland
Bern

Turkey
METU, Ankara

The OPERA experiment

- Direct detection of $\nu_\mu \rightarrow \nu_\tau$ oscillations in **appearance mode**
- Long baseline (732 Km) neutrino oscillation experiment in the CNGS (Cern Neutrino to Gran Sasso) ν_μ beam

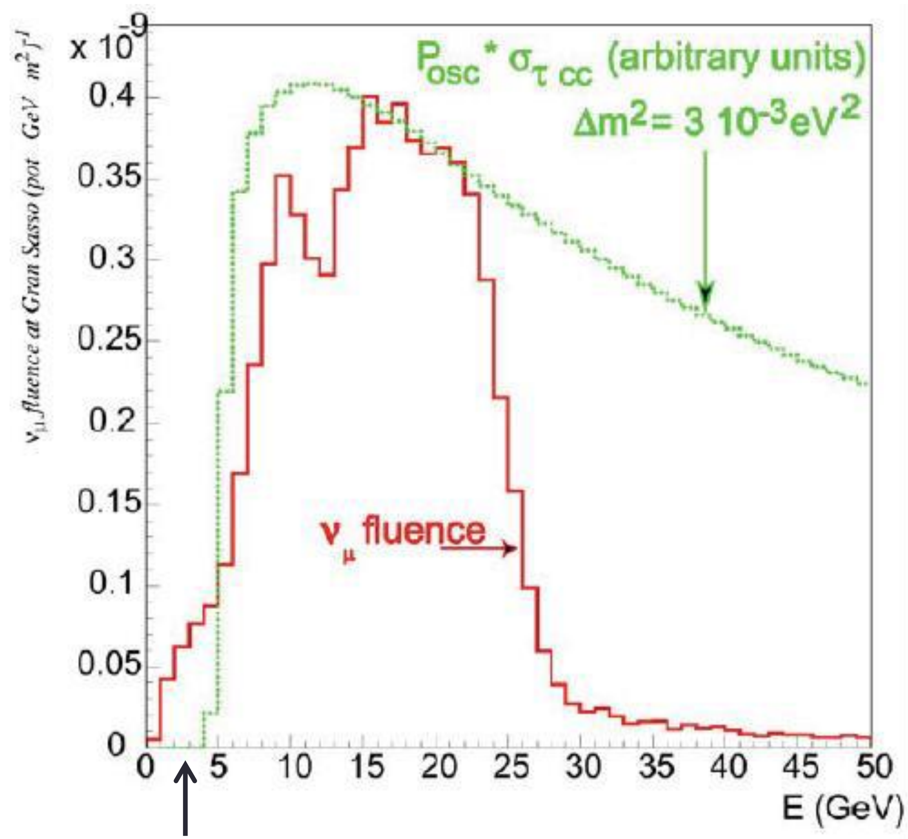
Conventional **high energy** beam optimised for ν_τ CC interactions observation

< E_ν>	**17 GeV**
L	**730 km**
(ν_e + $\overline{\nu}_e$) / ν_μ	**0.87 %**
$\overline{\nu}_\mu$ / ν_μ	**2.1 %**
ν_τ prompt	**Negligible**

Interaction rates (1.8 x 10^{20} p.o.t.):

~ 20k ν_μ CC+NC

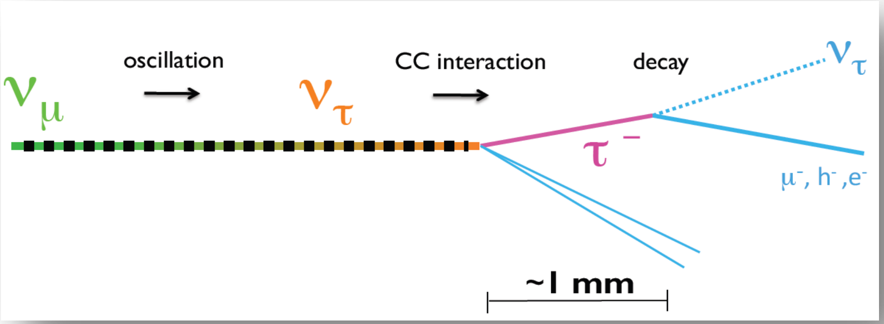
66 ν_τ CC (not efficiency corrected)



Threshold for τ production ~ 3.5 GeV.

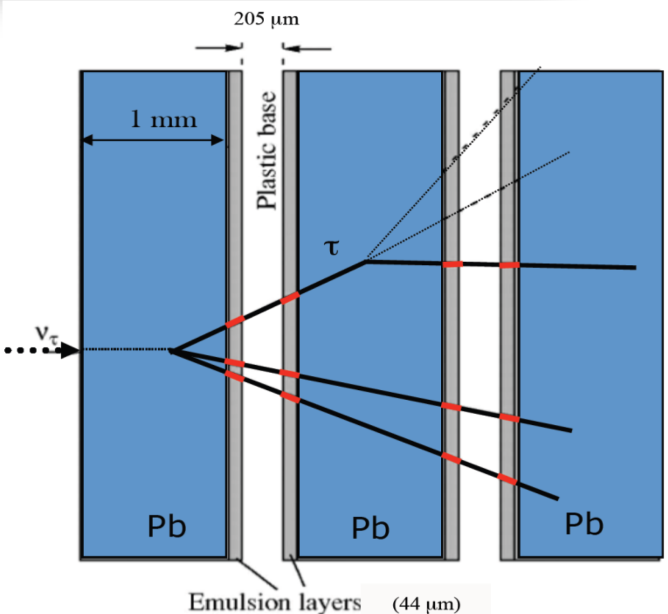
ν_τ appearance: detection principle

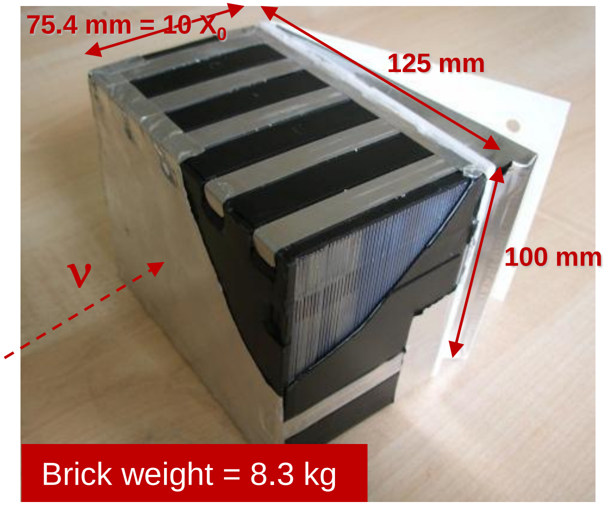
Event-by-event separation of ν_τ CC interactions from dominant ν_μ interactions by direct observation of τ lepton decay



τ decay channel	B.R (%)
$\tau \to \mu$	17.7
$\tau \to e$	17.8
$\tau \to h$	49.5
$\tau \to 3h$	15.0

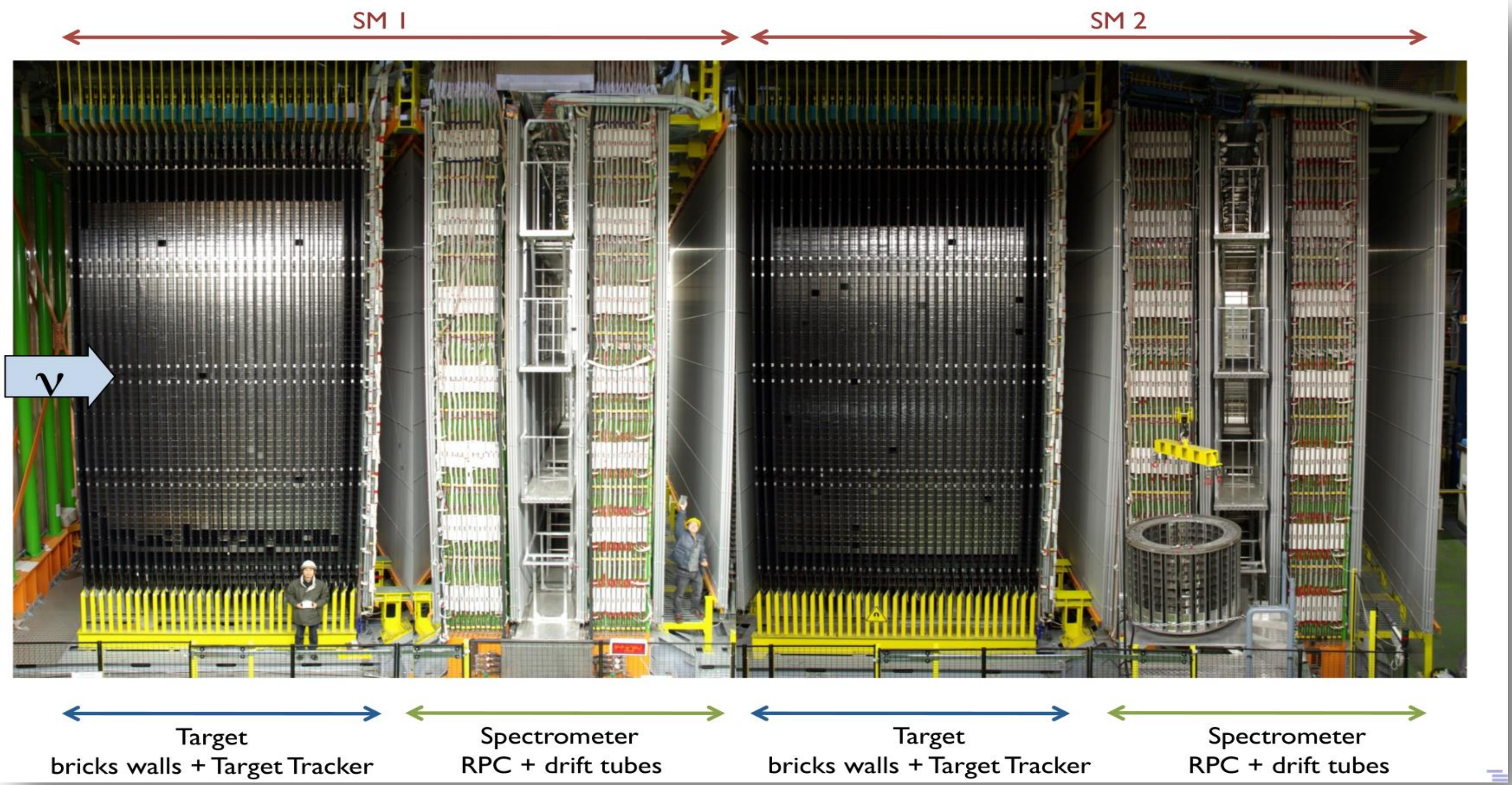
- Target mass O(kton) (low ν interaction cross-section)
- High granularity detector (τ decay detection, background rejection)





The OPERA detector

*JINST **4 (2009) P04018***



Target:

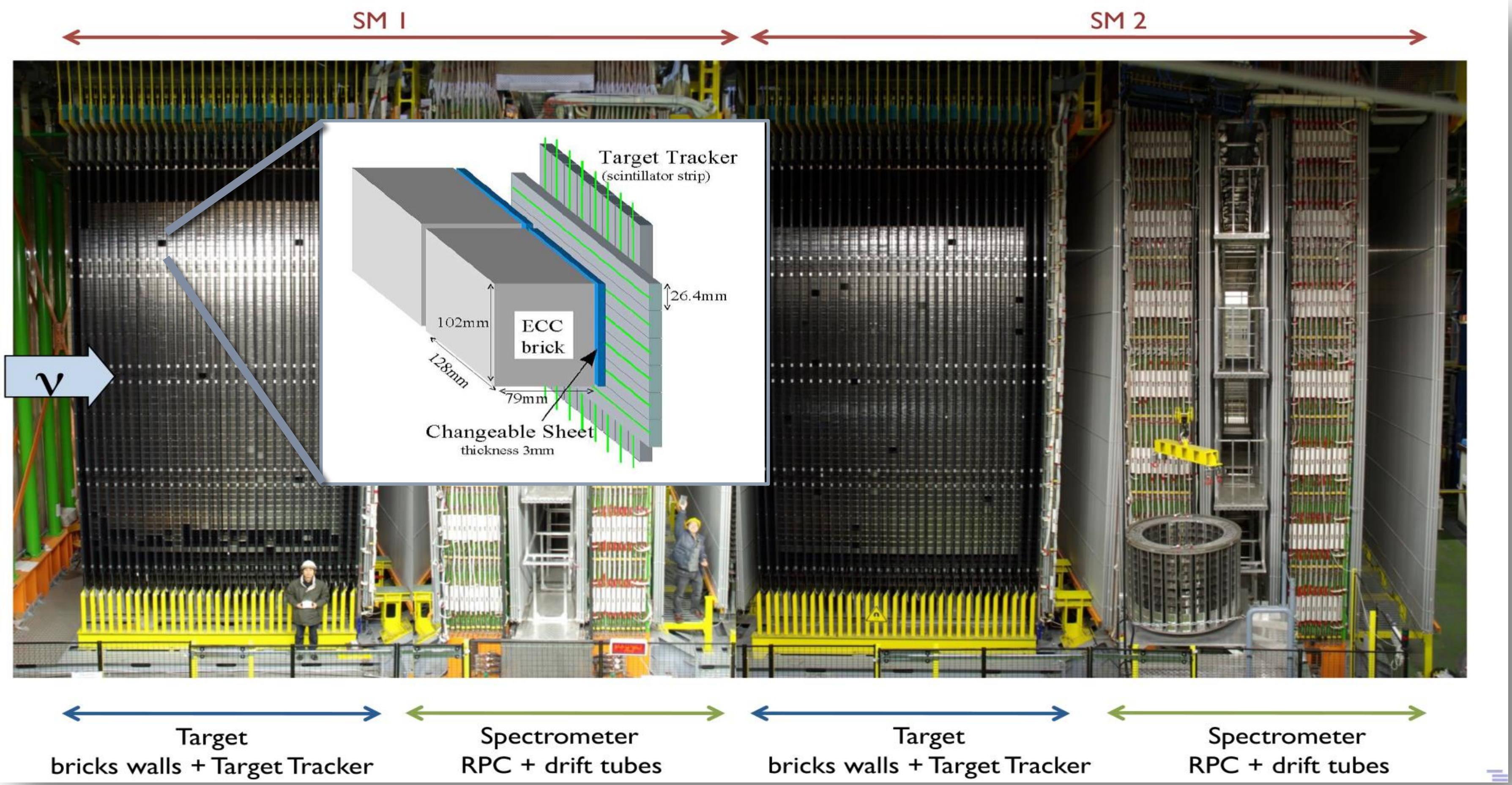
- Brick walls interleaved with plastic scintillators (TT) planes
- ~150 000 bricks
- 1.25 Kton mass

Spectrometers:

- Muon ID, momentum and charge measurement
- Track measurements are performed by RPC planes inserted in the magnet yoke (1.5 T field) and by drift tubes planes to add more precision

The OPERA detector

*JINST **4 (2009) P04018***



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- Muon ID, momentum and charge measurement
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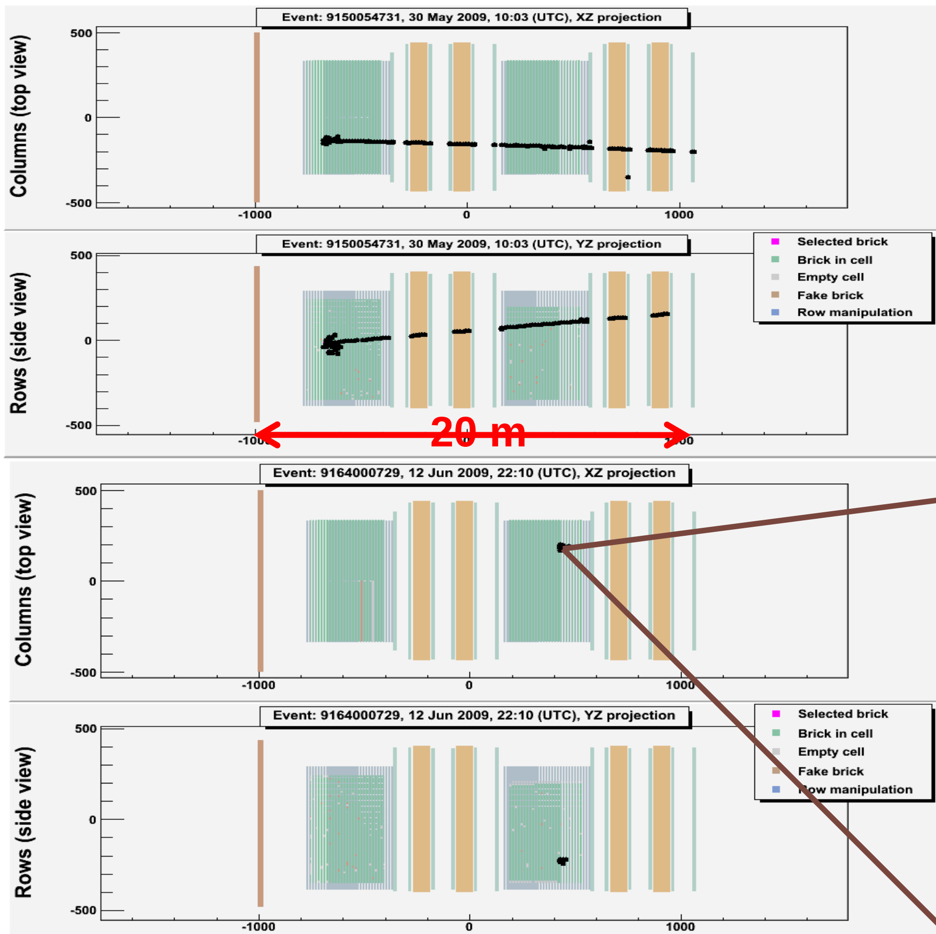
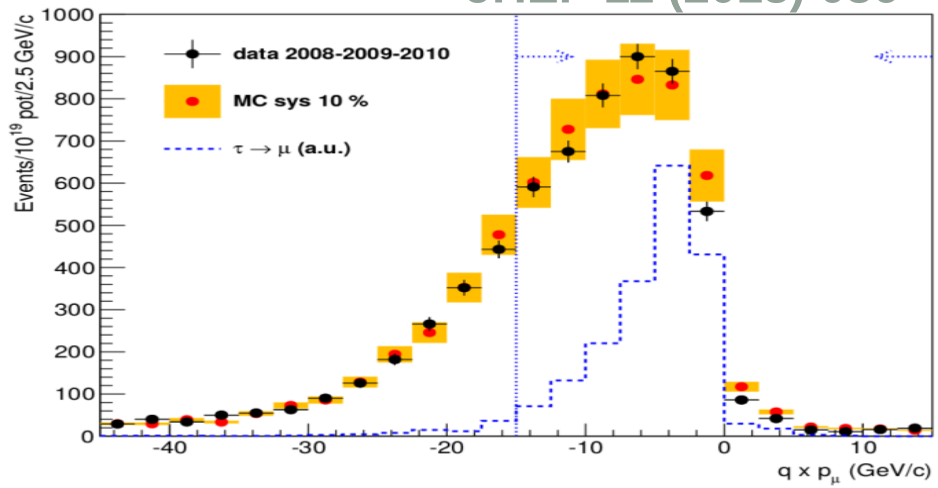
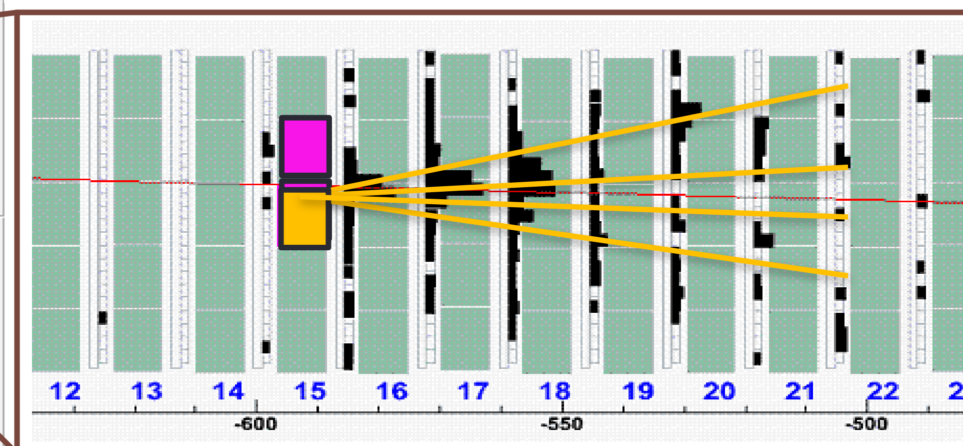
Event Reconstruction: electronic detectors

- Selection of contained and “on-time” events
- Muon reconstruction and classification as CC-like (1μ) or NC-like (0μ)
- Muon momentum and charge measurement through the spectrometer

JHEP 11 (2013) 036

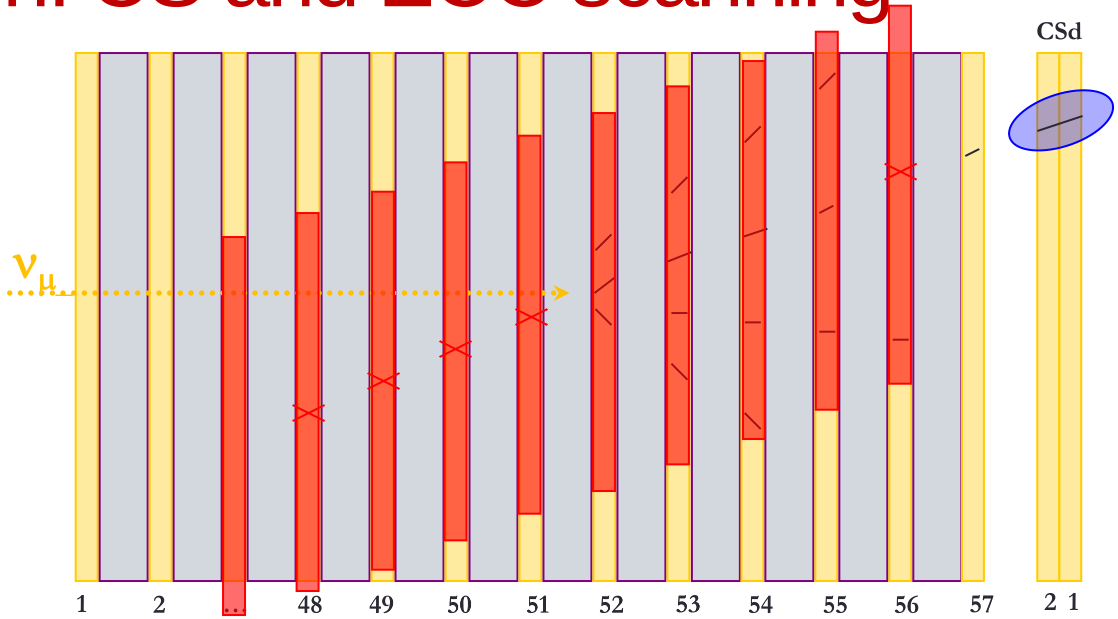




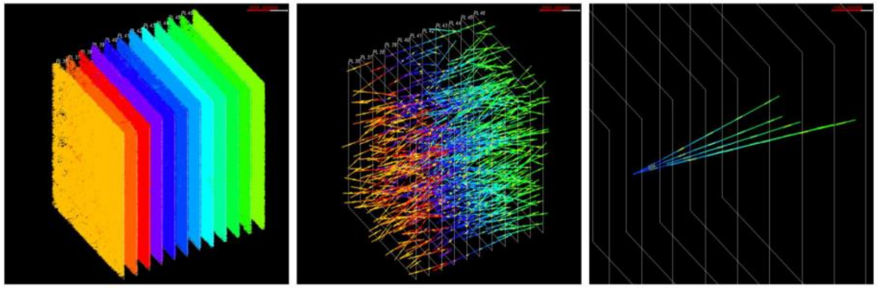


Event Reconstrution: CS and ECC scanning

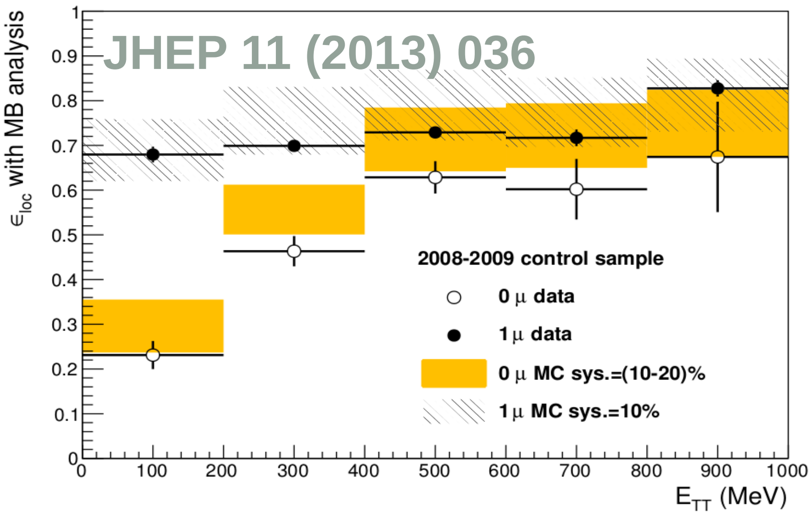
- **CS analysis**: interface between electronic detectors (σ_{pos} ~ 8 mm, σ_θ ~ 15 mrad) and emulsion
- **CS to brick connection** (σ_{pos} ~ 70 µm, σ_θ ~ 8 mrad) and **scan back**: stopping point definition
- **Volume scan**: topological vertex reconstruction and decay search



2 cm^3 volume

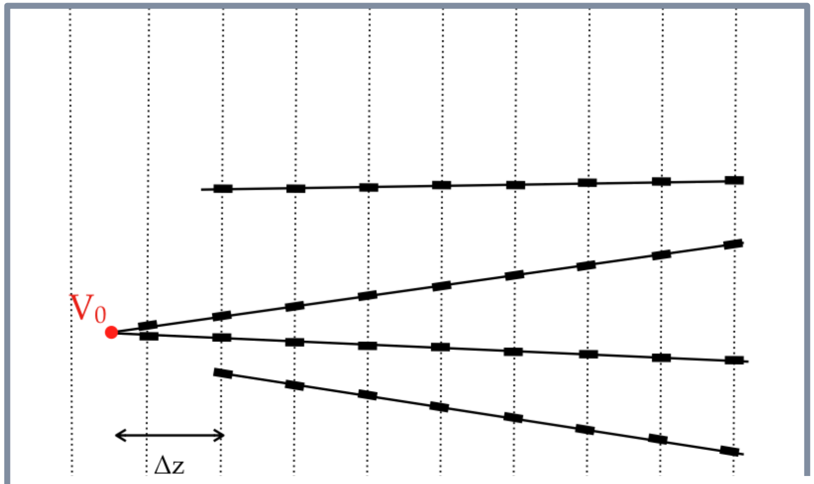


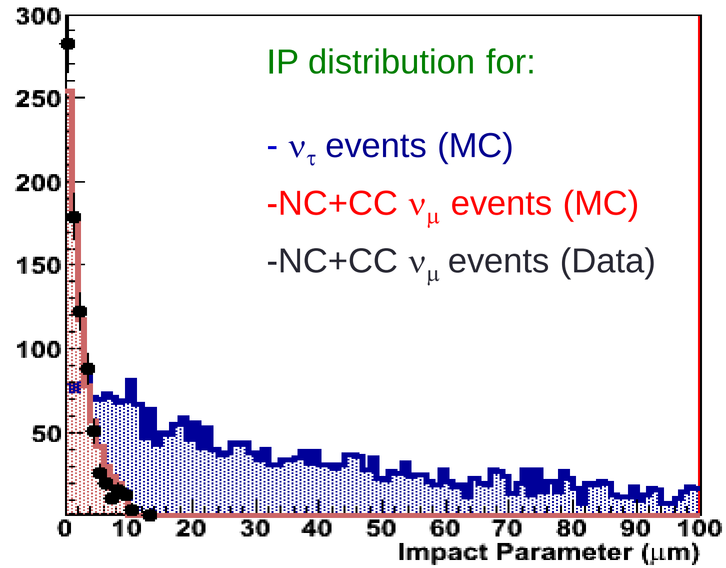
Data/MC comparison of the **location efficiency** as a function ot the visible energy in TT
Reasonable agreement



Event Reconstruction: Decay Search

- **Primary vertex definition**
  - inspection of segments on the vertex plate
  - impact parameter <10 (5+0.01 Δz) μm, if Δz<(≥)500 μm
- **Extra-track search**
  - selection of tracks reconstructed in the volume but not attached to primary vertex
  - identification of e^+e^- pairs by visual inspection





Event Reconstruction: Decay Search

- **Primary vertex definition**
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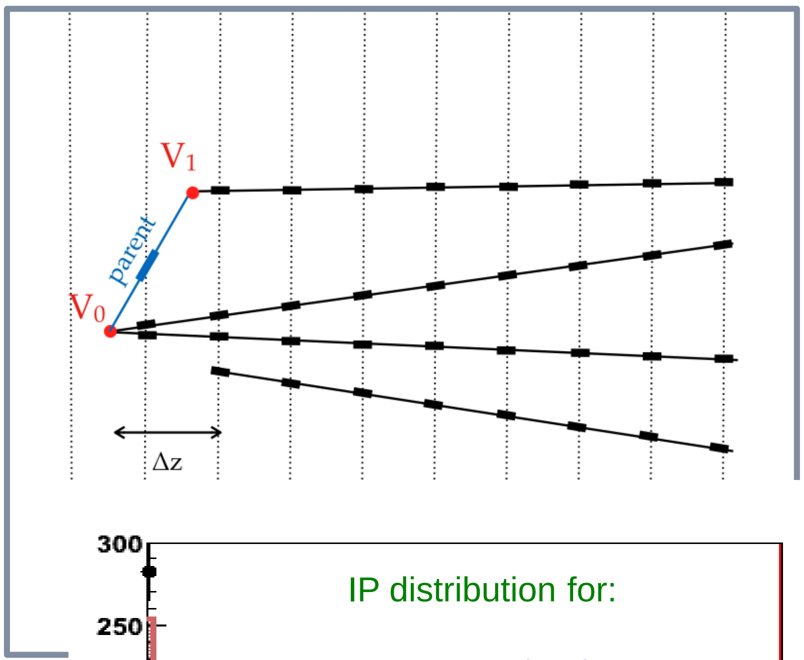
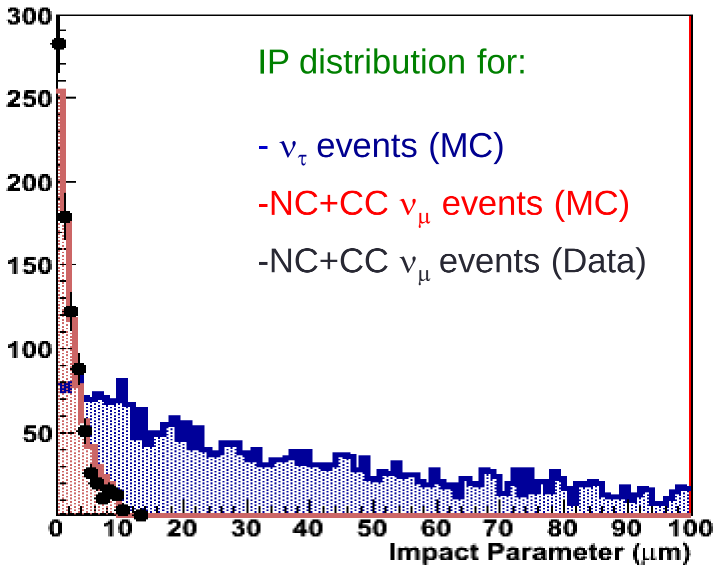
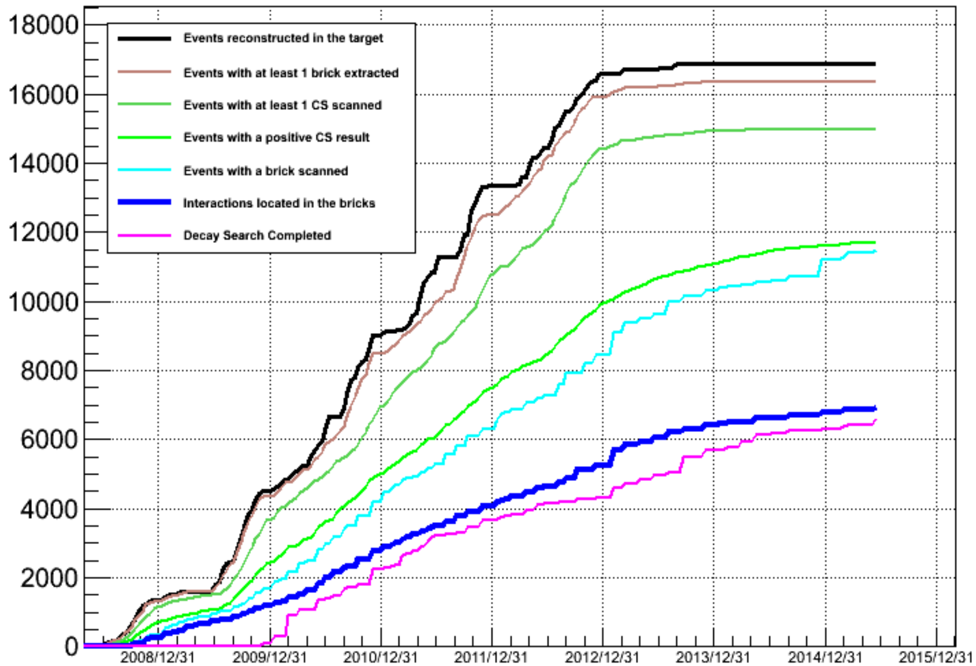
  - impact parameter <10 (5+0.01 Δz) μm, if Δz<(≥)500 μm
- **Extra-track search**
  - selection of tracks reconstructed in the volume but not attached to primary vertex
  - identification of e^+e^- pairs by visual inspection
- **In-track search**
  - search for small kinks along the tracks attached to the primary vertex
- **Parent search**
  - search for a track connecting the selected extra-track and the primary vertex





Data taking status

Run 2008 → 2012



Located neutrino interactions	6932
Fully analysed events	6612
ν_τ **candidate events**	5

Year	Days	p.o.t. (10^{19})	ν interactions
2008	123	1.74	1698
2009	155	3.53	3693
2010	187	4.09	4248
2011	243	4.75	5131
2012	257	3.86	3923
tot	**965**	**17.97**	**19505**

Overall 20% less than the proposal value (22.5)

- 150'000 ECC bricks.

Total 105'000 m^2 of lead surface and 111'000 m^2 of film surface (~ 9 million films)

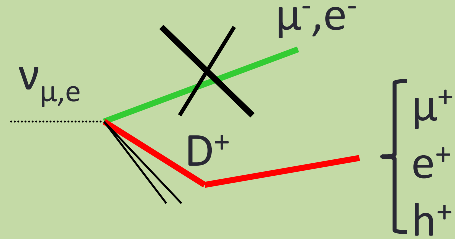
- About 26115 bricks manipulated for event analysis
- So far **3'110'000** cm^2 of CS surface analysed
- ~12500 bricks developed (~ 9300 m^2)

Background

In order of decreasing relevance

CC with charm production (all channels)

IF the primary lepton is not identified and the daughter charge is not (or incorrectly) measured

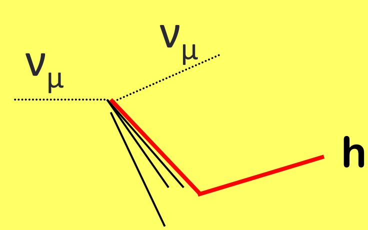


MC (using Chorus data on cross section and fragmentation functions), validated with measured OPERA charm events. (54±4 expected, 50 observed) [*Eur. Phys. J. C74 (2014) 2986*]

Reduced by "track follow down" procedure and large angle scanning

Hadronic interactions

Background for $\tau \rightarrow h$

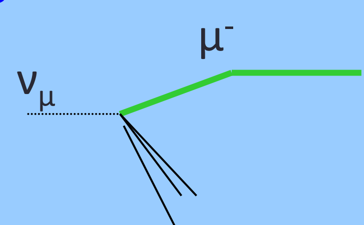


FLUKA + pion test beam data

Reduced by large angle scanning and nuclear fragment search

Large-angle muon scattering

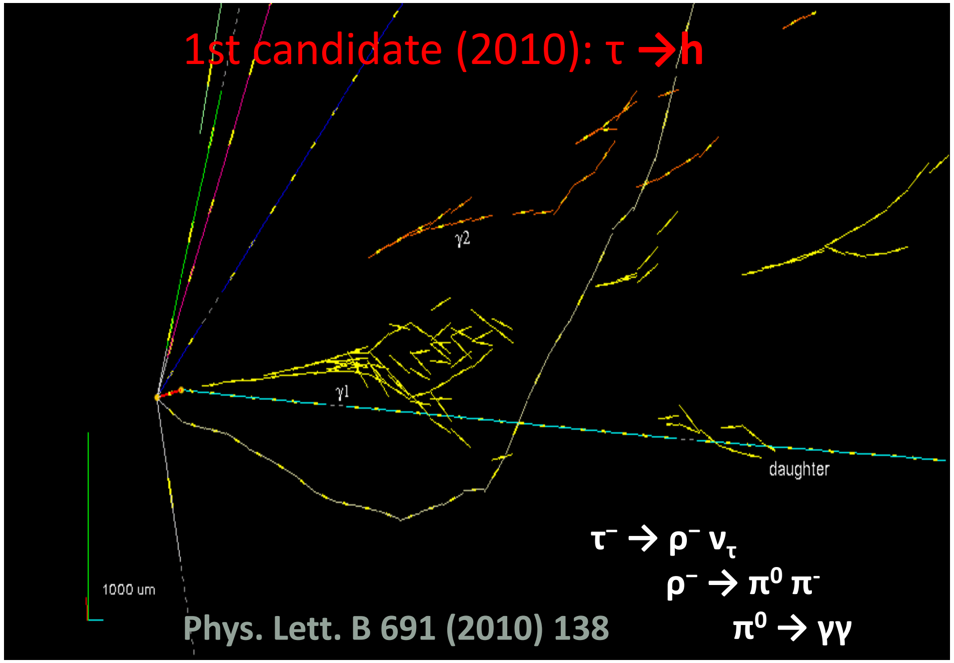
Background for $\tau \rightarrow \mu$

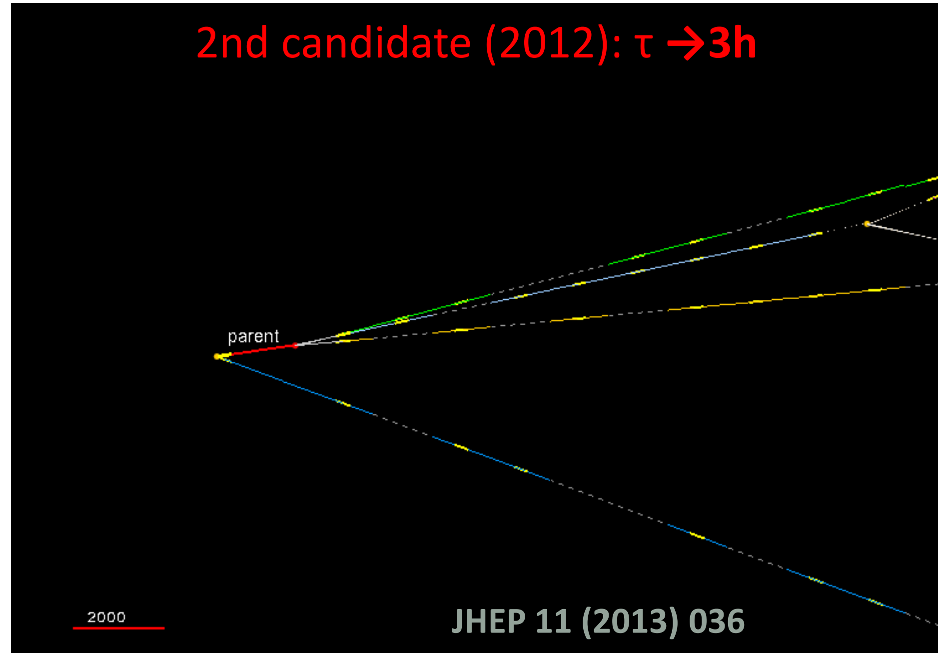


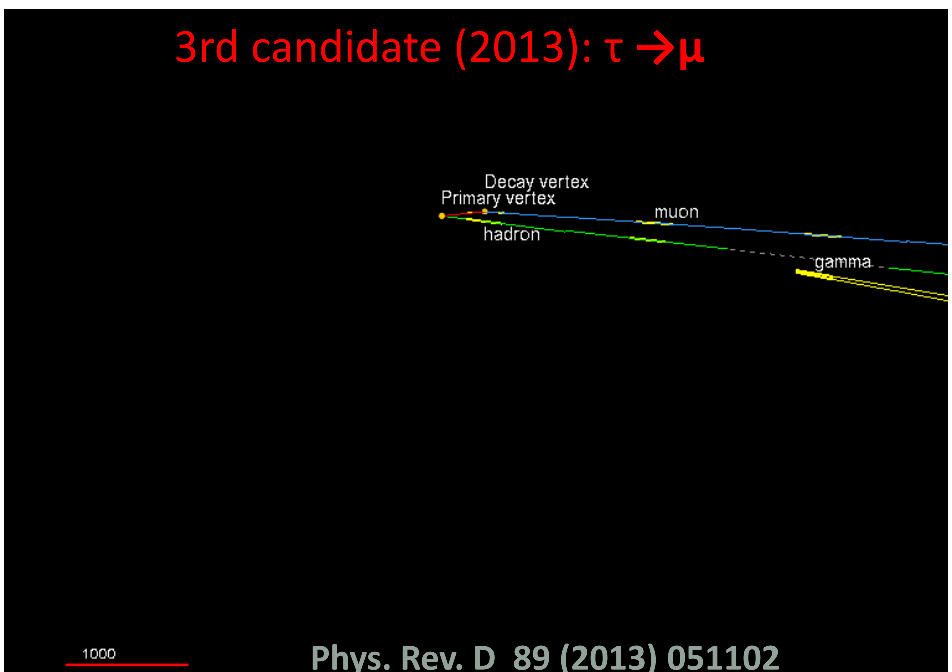
Simulation study (updated lead form factor) benchmarked with available data

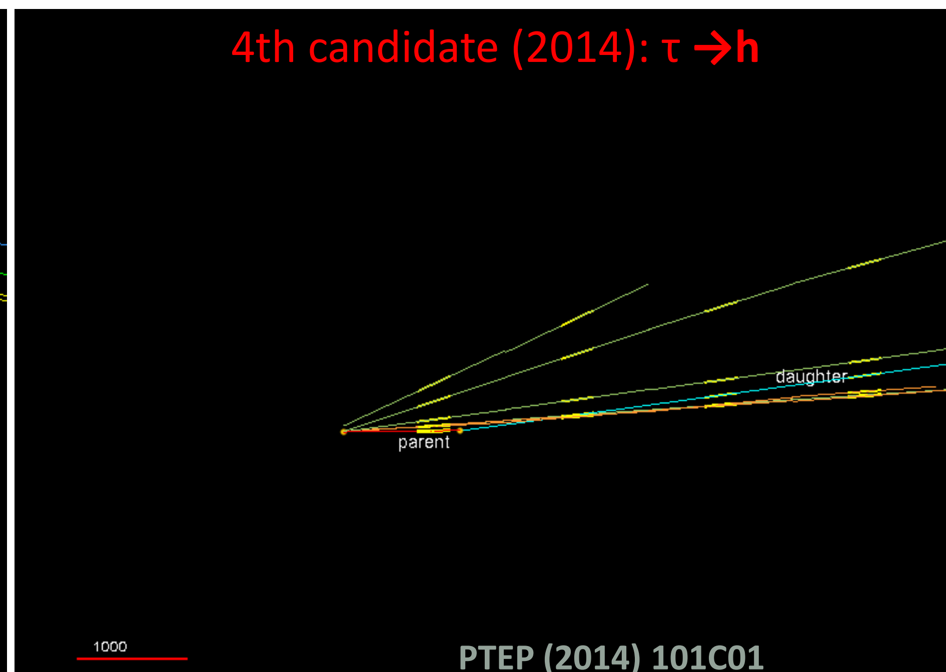
arXiv:1506.08759
accepted by Transactions of Nuclear Science

Reduction of a factor ~ 100 wrt to previous estimation

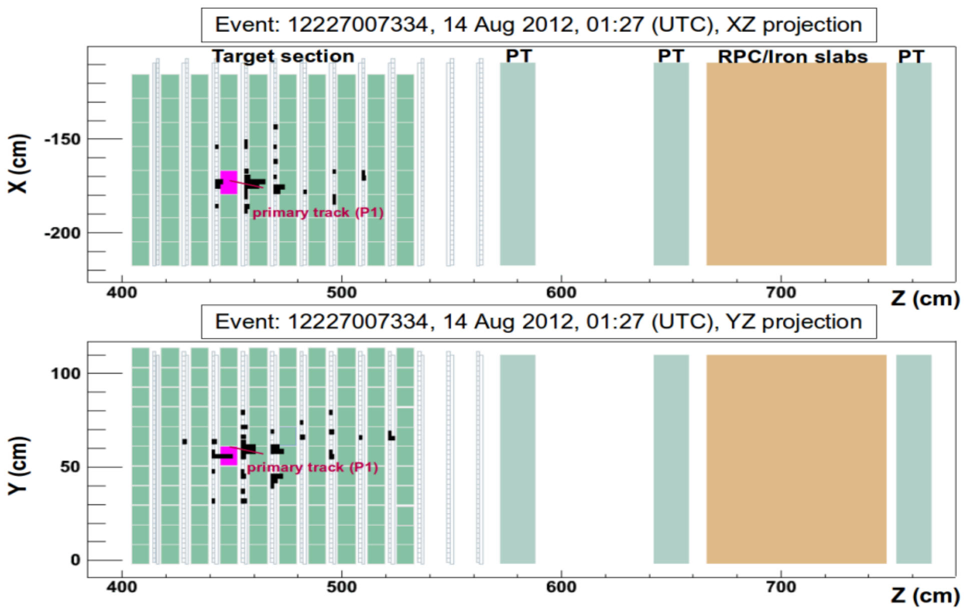

1st candidate (2010): τ →h
γ2
γ1
daughter
1000 um
τ⁻ → ρ⁻ ν_τ
ρ⁻ → π⁰ π⁻
π⁰ → γγ
Phys. Lett. B 691 (2010) 138

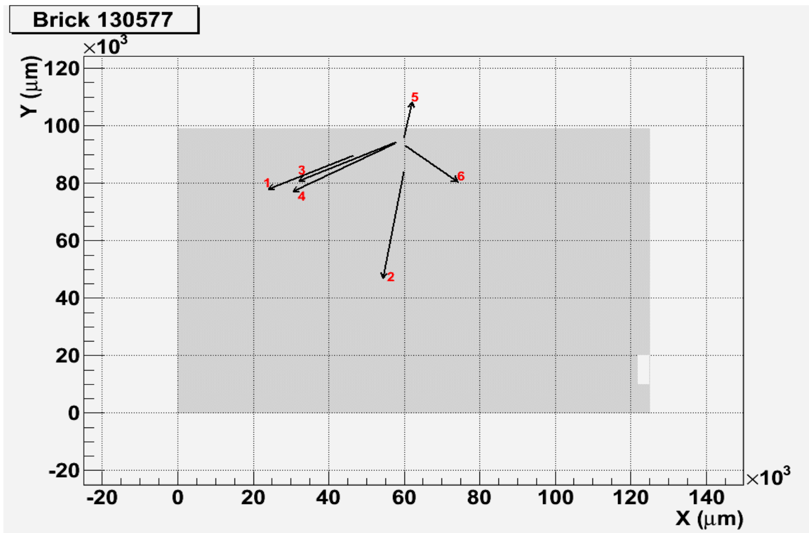

2nd candidate (2012): τ →3h
parent
2000
JHEP 11 (2013) 036

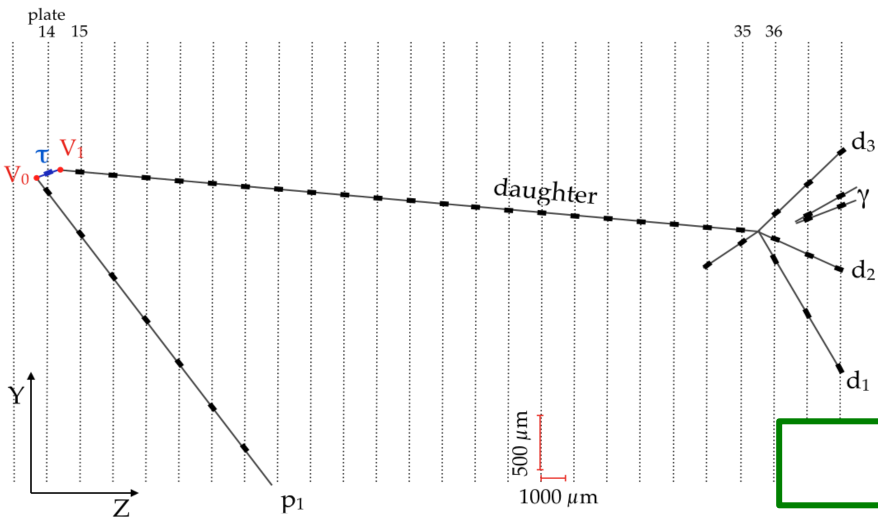

3rd candidate (2013): τ →μ
Decay vertex
Primary vertex
muon
hadron
gamma
1000
Phys. Rev. D 89 (2013) 051102


4th candidate (2014): τ →h
daughter
parent
1000
PTEP (2014) 101C01

5th ν_τ candidate event







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)

All cuts passed: τ →h candidate

Statistical Considerations

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

Two statistical methods:

- Fisher combination of single channel p-values
- Profile likelihood ratio

Probability to be explained by background { Fisher = 1.10 x 10^{-7}
Profile likelihood = 1.07 x 10^{-7}

Exclusion of null hypothesis: 5.1 σ

Marginality of the observation

$$P(n \geq 5 \mid \mu = 2.9) = 16.6\ \%$$

$$P^{\dagger} = 6.4\%$$

$P^{\dagger}$ = probability to obtain a configuration less likely than (3, 1, 1, 0)

see A. Di Crescenzo's talk

$\nu_\mu \rightarrow \nu_\tau$: effect of a sterile?

3+1 model: bounds from ν_τ appearance with profile Likelihood method

~standard oscillation — exotic oscillation

$$P_{\nu_\mu \rightarrow \nu_\tau} = C^2 \sin^2 \Delta_{31} + \sin^2 2\theta_{\mu\tau} \sin^2 \Delta_{41}$$

interference term:

$$+0.5 C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin 2\Delta_{31} \sin 2\Delta_{41}$$
$$-C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin^2 \Delta_{31} \sin 2\Delta_{41}$$
$$+2C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin^2 \Delta_{31} \sin^2 \Delta_{41}$$
$$+C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin 2\Delta_{31} \sin^2 \Delta_{41}$$

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

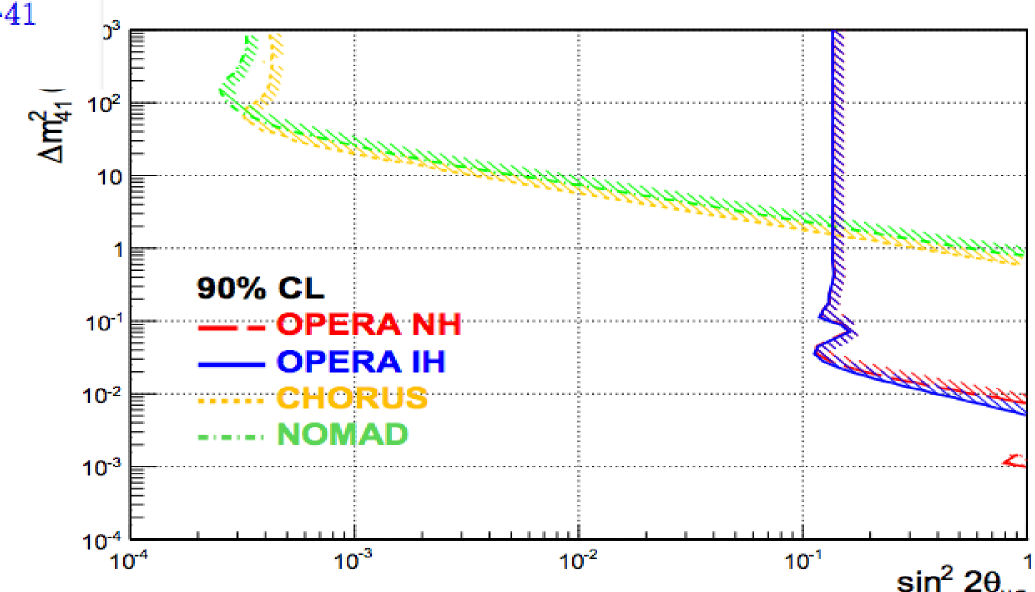
$$C = 2 \mid U_{\mu 3} U^*_{\tau 3} \mid,$$

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

$$\Delta m^2_{41} > 1\, eV^2$$

Analysis based on 4 ν_τ events

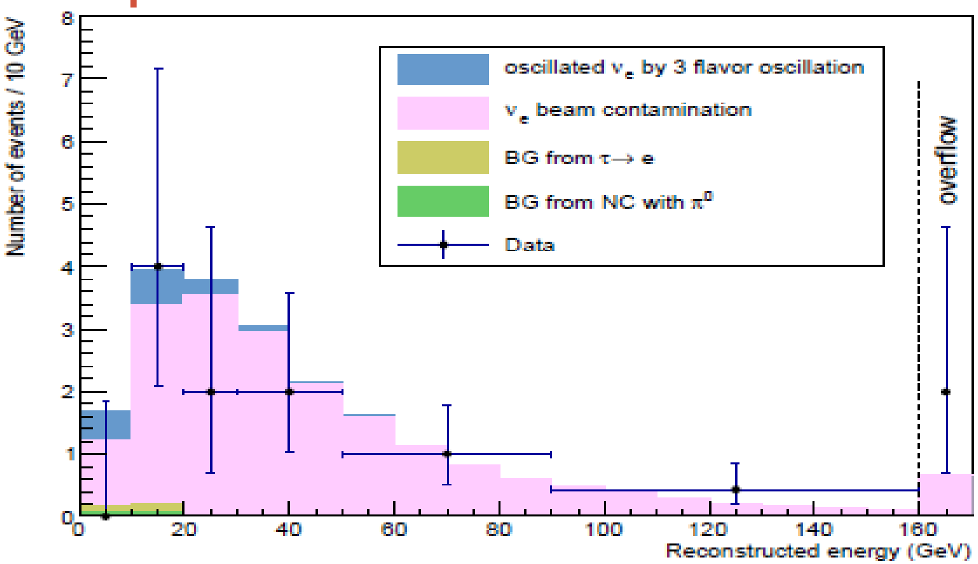
JHEP 06 (2015) 069



Effective mixing:

$$\sin^2 2\theta_{\mu\tau} = 4 \mid U_{\mu 4} \mid^2 \mid U_{\tau 4} \mid^2$$

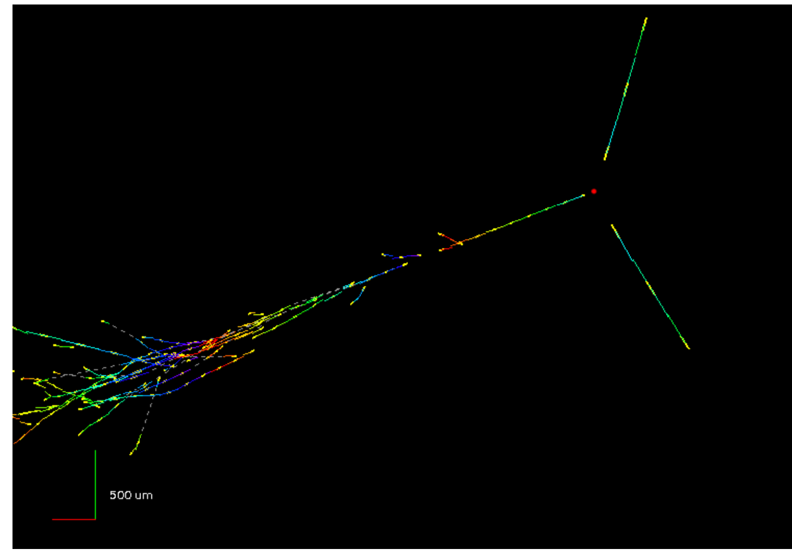
$\nu_\mu \rightarrow \nu_e$



<u>2008 → 2009 data sample</u>

19 ν_e candidates observed

19.8±2.8 (syst.) events expected from bkg



<u>Three flavour mixing analysis</u> (E_{cut} = 20 GeV):

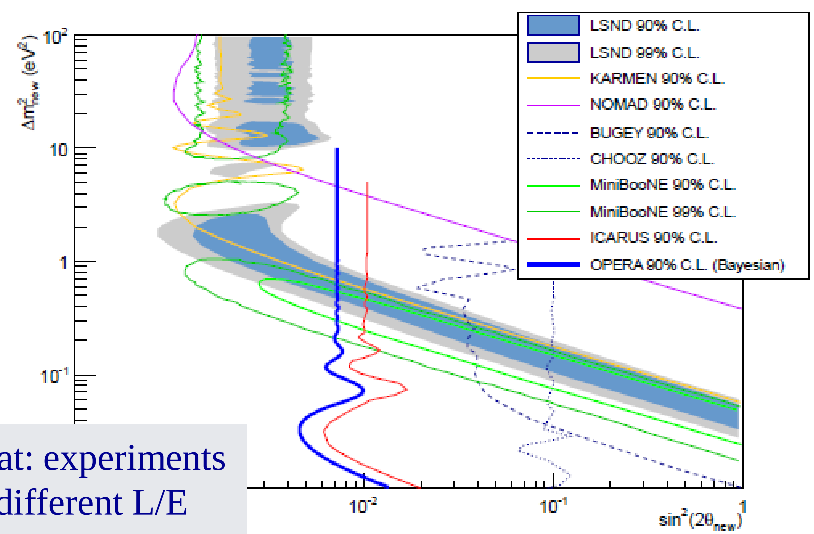
4 observed events

4.6 expected

<u>Non standard oscillations at large Δm^2</u> (E_{cut} = 30 GeV):

6 observed events

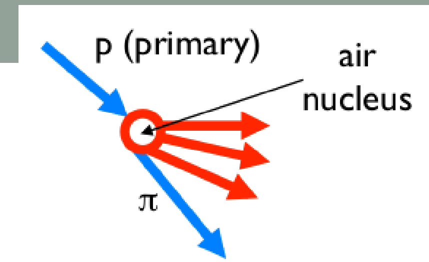
9.4 expected



Caveat: experiments at different L/E

JHEP 1307 (2013) 004

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



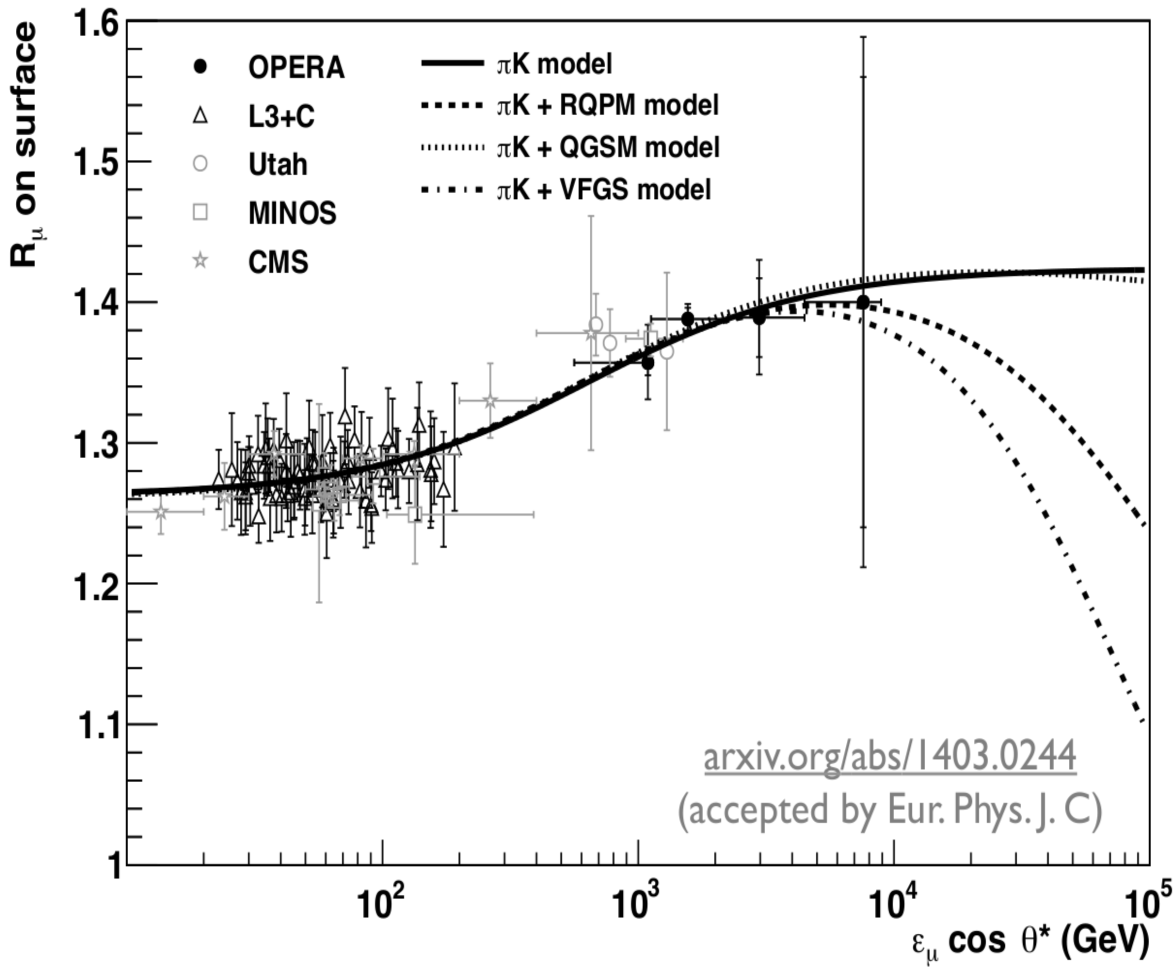
Cosmic Rays: $N_{\mu+}/N_{\mu-}$ ratio

$$\phi_{\mu^\pm} \propto \frac{a_\pi f_{\pi^\pm}}{1 + b_\pi \mathcal{E}_\mu \cos\theta/\epsilon_\pi} + R_{K\pi} \frac{a_K f_{K^\pm}}{1 + b_K \mathcal{E}_\mu \cos\theta/\epsilon_K}$$

- Highest-E region reached!
- Opposite magnet polarities runs → lower systematics
- Strong reduction of the charge ratio for multiple muon events

1-μ	1.377 ± 0.006
Multi-μ	1.098 ± 0.023

- Results compatible with a simple π-K model



Conclusions

- Detector successfully measuring ν_e , ν_μ and ν_τ
- Analysis of an extended data sample
- Improved background evaluation
- Five ν_τ candidates observed
- 5.1 σ significance

  "Discovery of tau neutrino appearance in the CNGS neutrino beam with the OPERA experiment" accepted by PRL (arXiv:1507.01417)

OUTLOOK

- Multi-brick analysis under completion
- Re-analysis of the full data sample with a likelihood approach and less tight (kinematical) selection criteria
- More to come!

OPERA taking a "selfie"... Thank you!

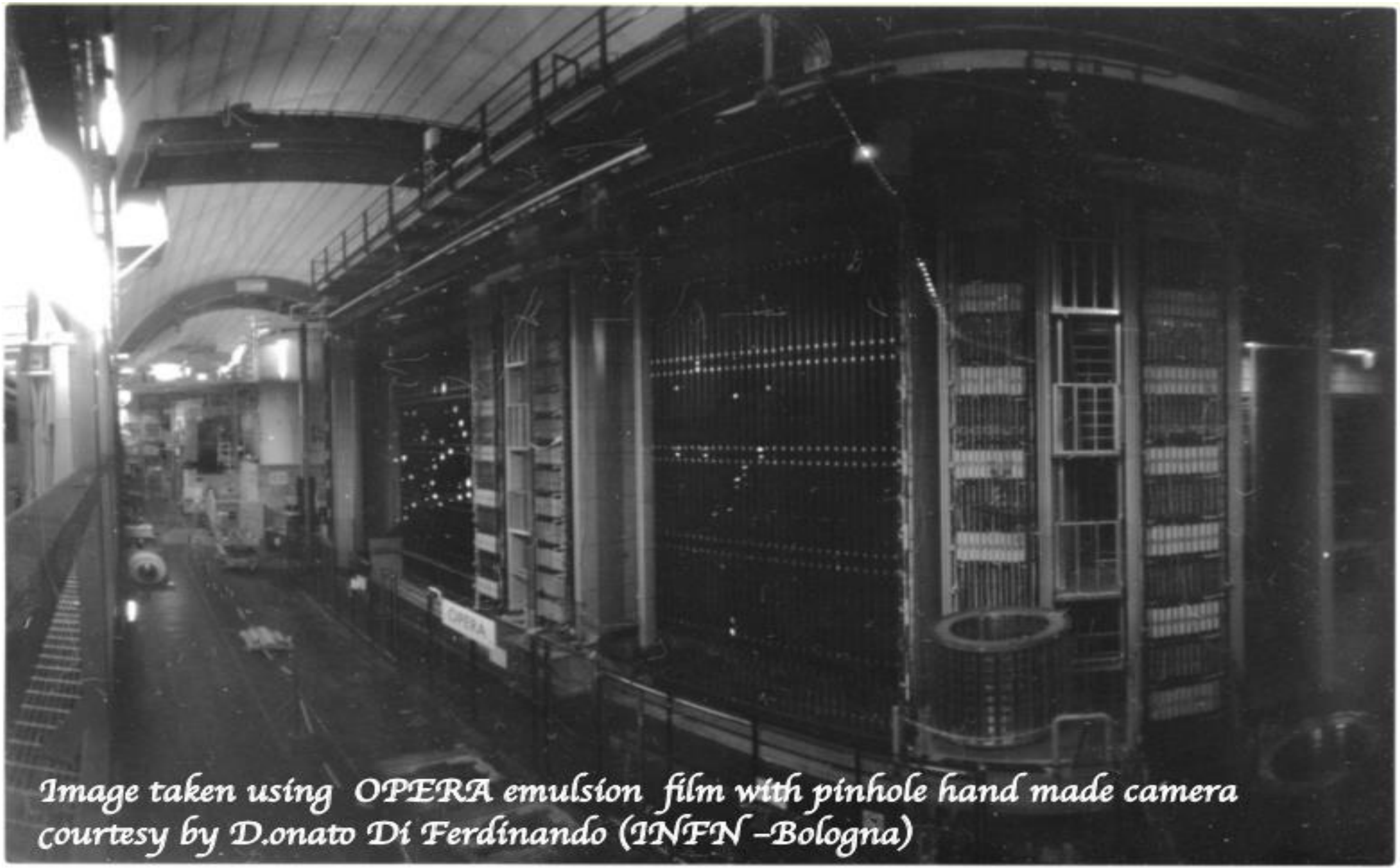
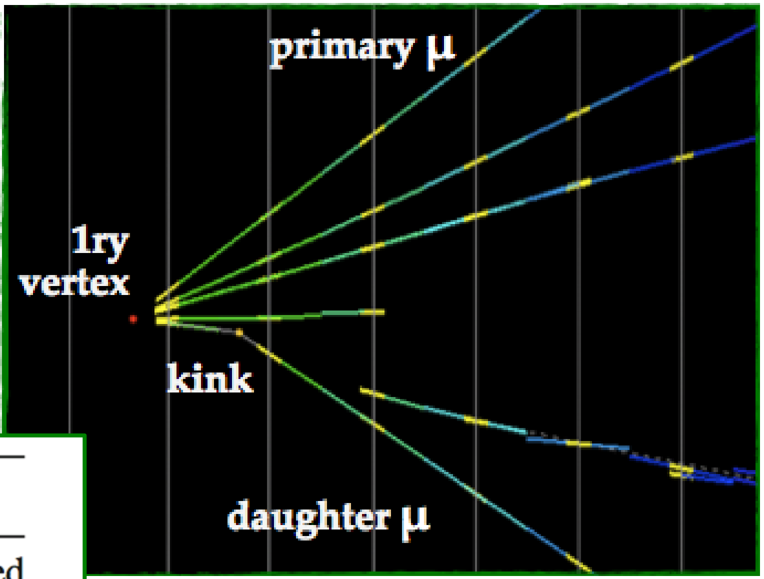


Image taken using OPERA emulsion film with pinhole hand made camera
courtesy by D.onato Di Ferdinando (INFN –Bologna)

BACKUP

CHARMED HADRON PRODUCTION

- Charm and τ decays have the same topology
- Similar lifetime and masses
- Charmed hadrons from ν_μ CC interactions
- Muon at the primary vertex
- Used as “control sample”



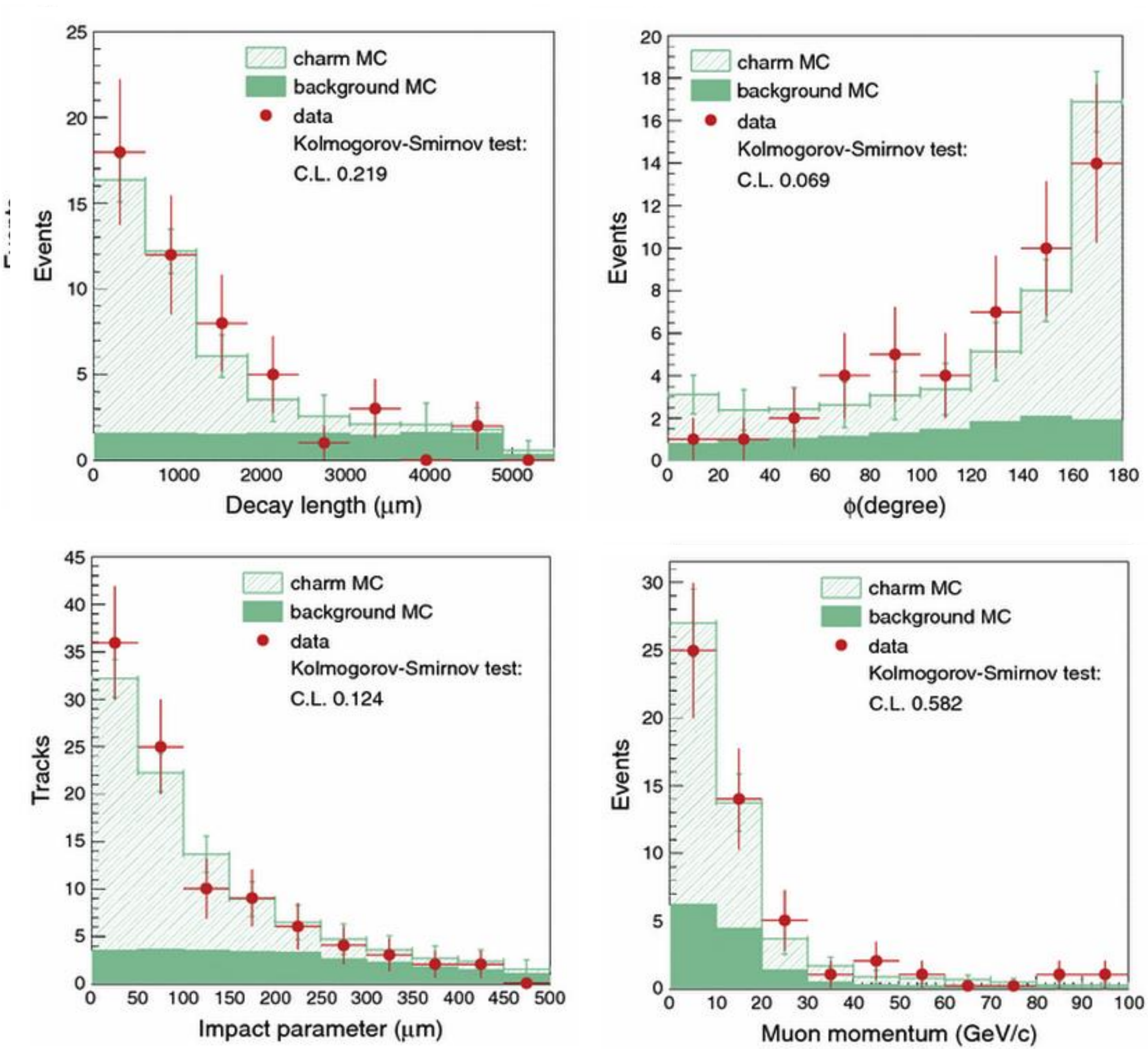
Decay topology	Events			
	Expected charm	Expected background	Expected total	Observed
1-prong	21 ± 2	9 ± 3	30 ± 4	19
2-prong	14 ± 1	4 ± 1	18 ± 1	22
3-prong	4 ± 1	1.0 ± 0.3	5 ± 1	5
4-prong	0.9 ± 0.2	–	0.9 ± 0.2	4
Total	40 ± 3	14 ± 3	54 ± 4	50

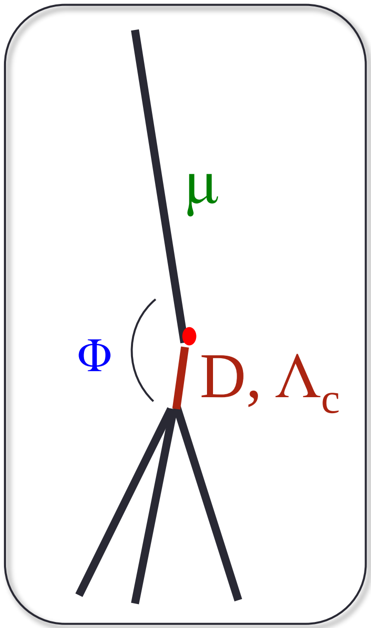
Eur. Phys. J. C74 (2014) 2986

Background from hadronic interactions (87%) and strange particle decays (13%)

Good agreement between data and expectations ~10%

KINEMATICAL VARIABLES





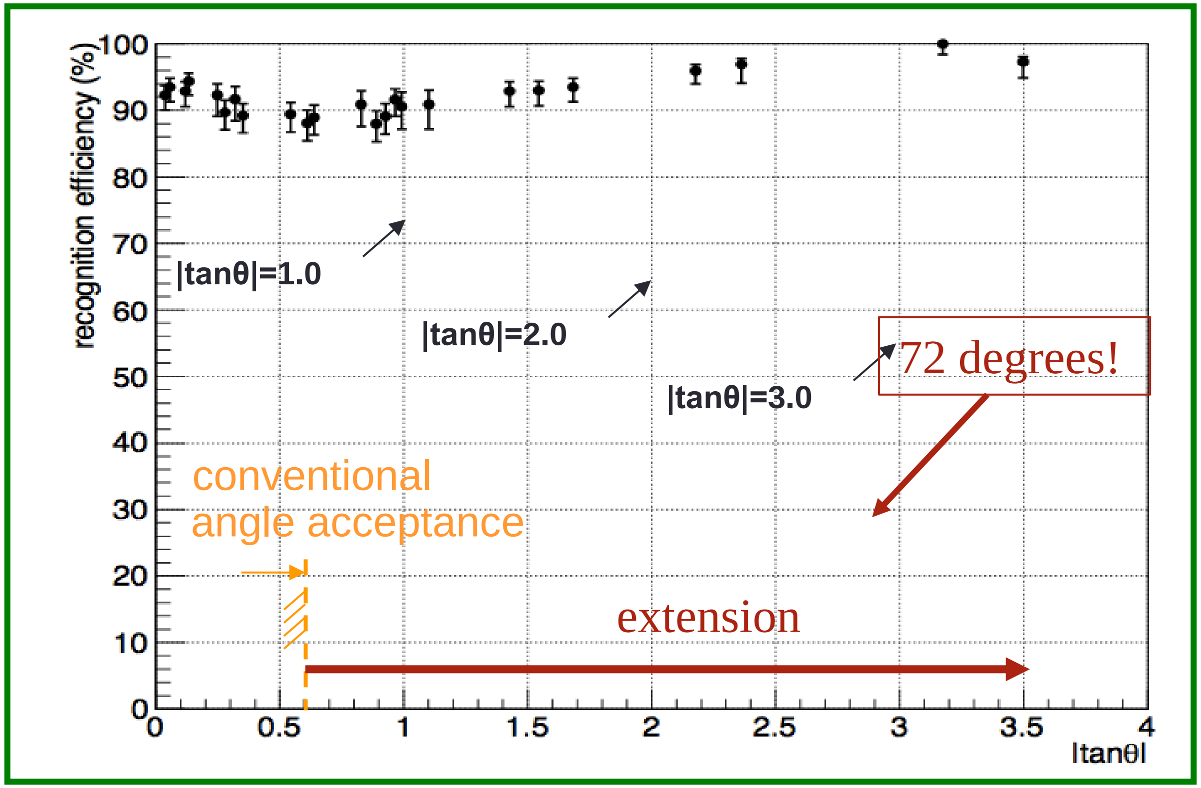
Fair agreement between data and Monte Carlo

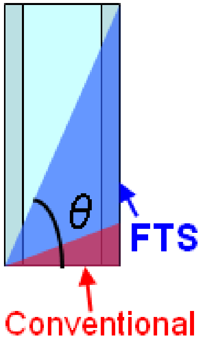
Eur. Phys. J. C74 (2014) 2986

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



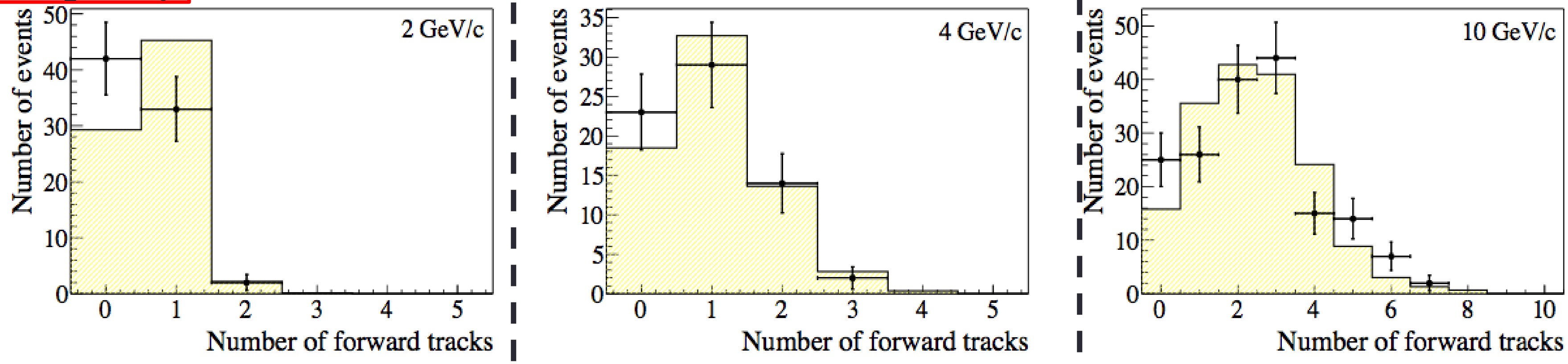


JINST 9 (2014) P12017

SECONDARY TRACK EMISSION

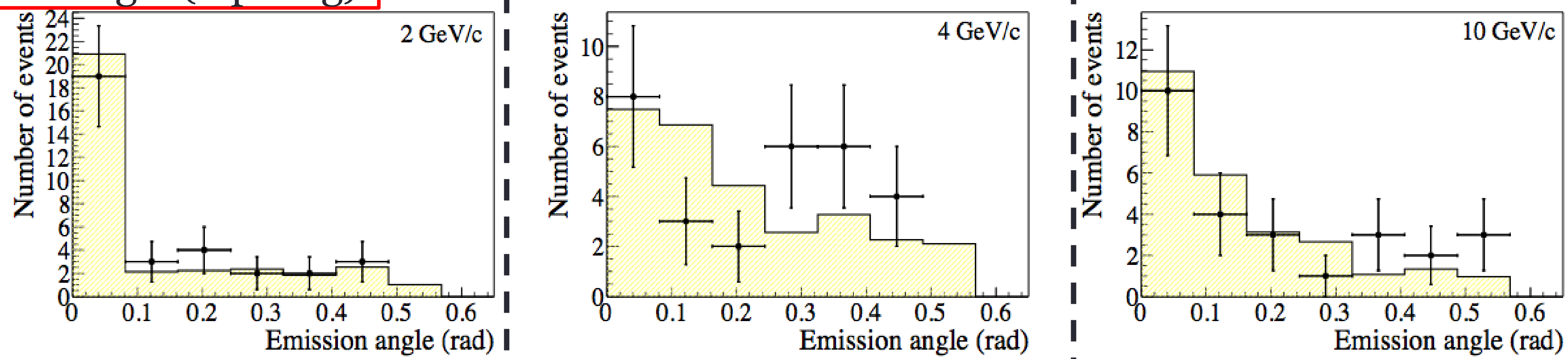
2GeV/c | 4GeV/c | 10GeV/c

Multiplicity



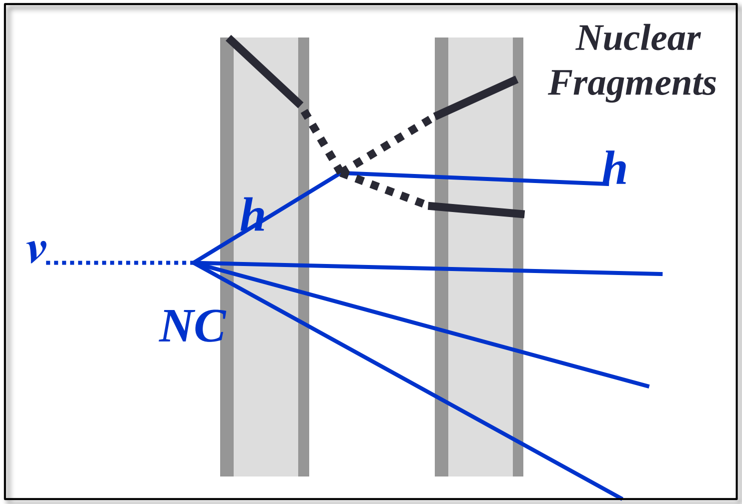
Error bars : Experimental data
Histogram : Simulated data

Kink angle (1-prong)

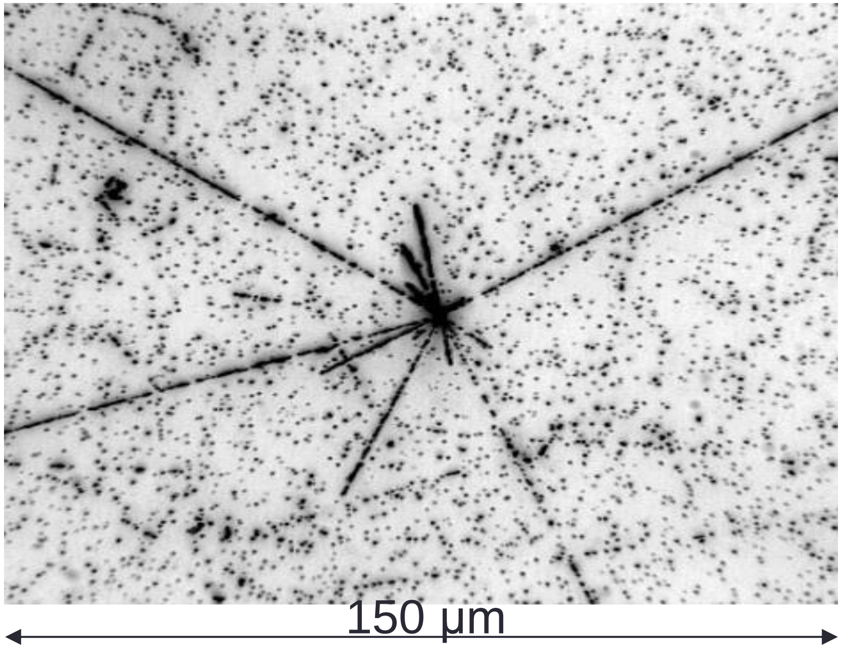


Good agreement within the statistical error: systematic error ~ 30%

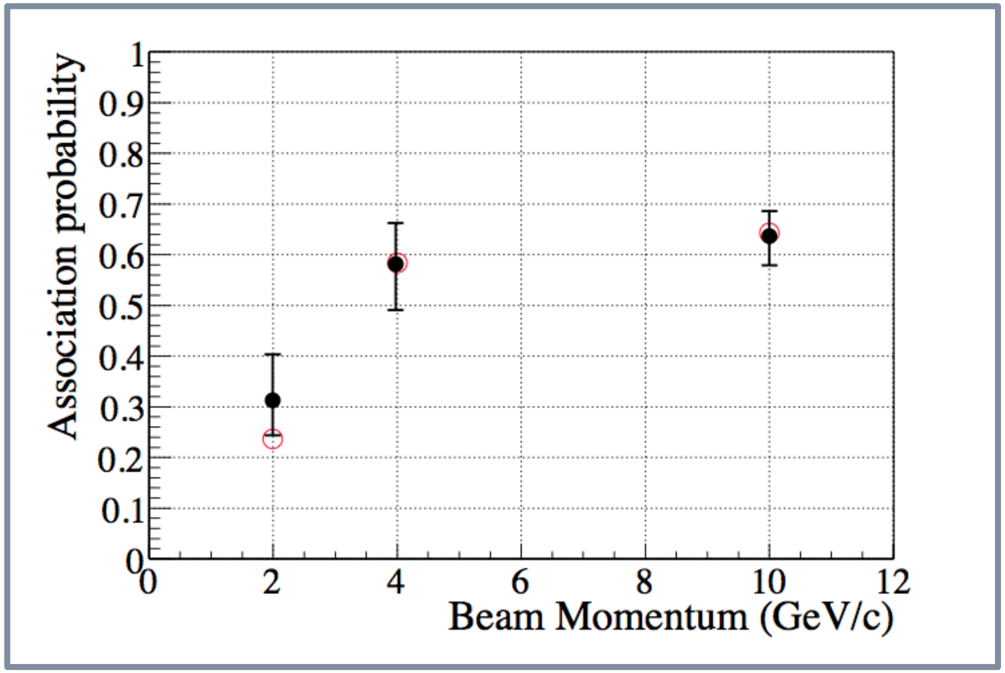
Nuclear Fragments Emission Probability



Highly ionizing fragments



Additional background reduction



Black : experimental data
Red : simulated data (β= p/E = 0.7)

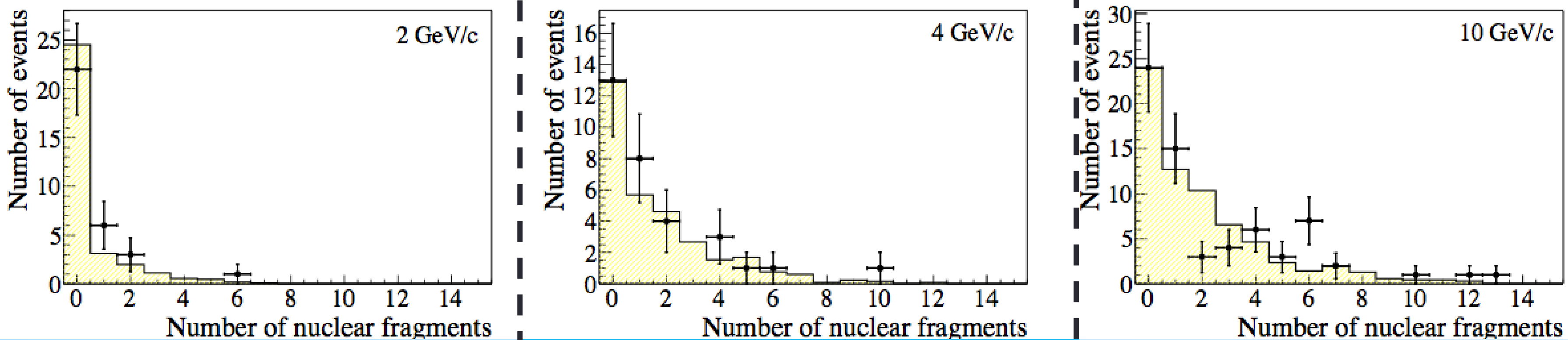
PTEP 9 (2014) 093C01

Nuclear Fragments In 1 And 3 Prong Interactions

2GeV/c | 4GeV/c | 10GeV/c

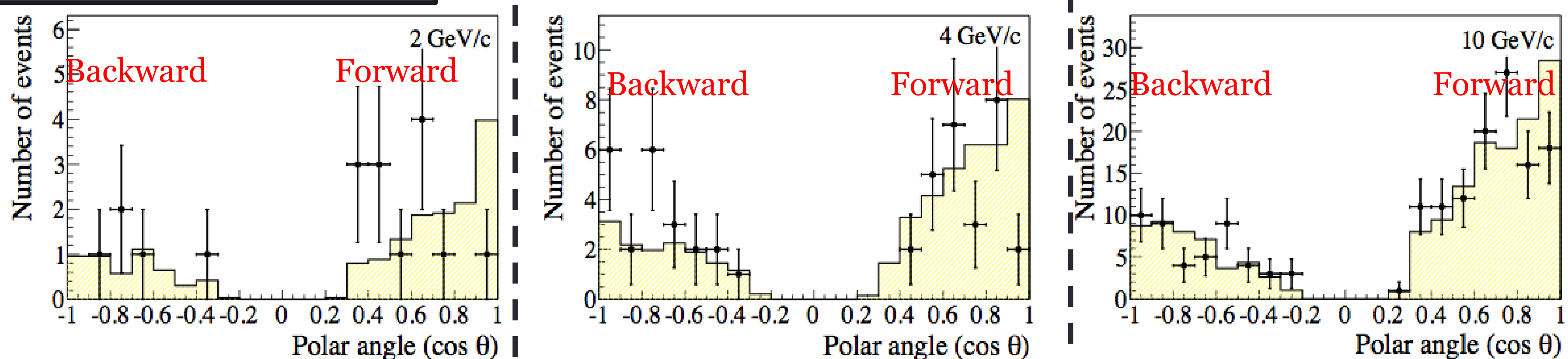
Multiplicity

MC: $\beta < 0.7$



Error bars : Experimental data
Histogram : Simulated data

Emission angle(cos θ)



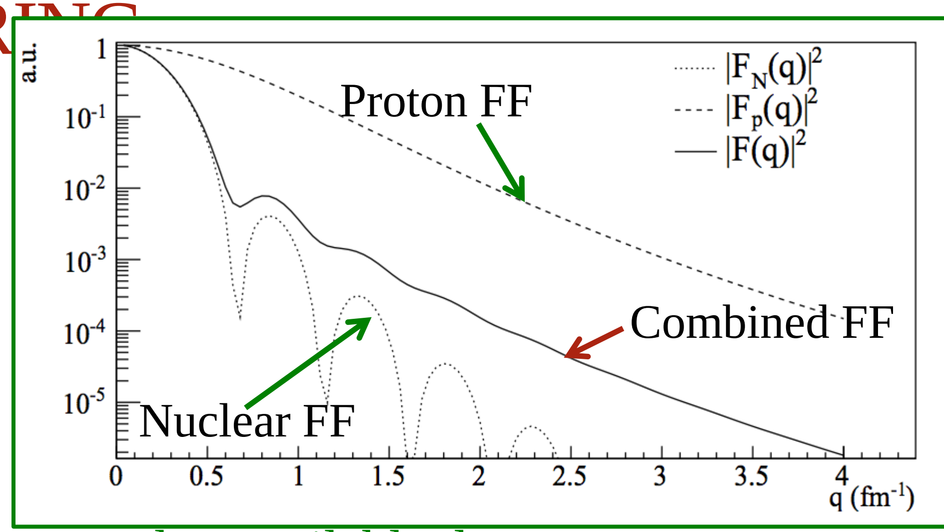
Agreement within the statistical error: systematic error is 10%

LARGE ANGLE μ SCATTERING

New estimate based on GEANT4

- Simulation modified by introducing form factors (FF) for Lead
(Saxon-Woods parameterization)

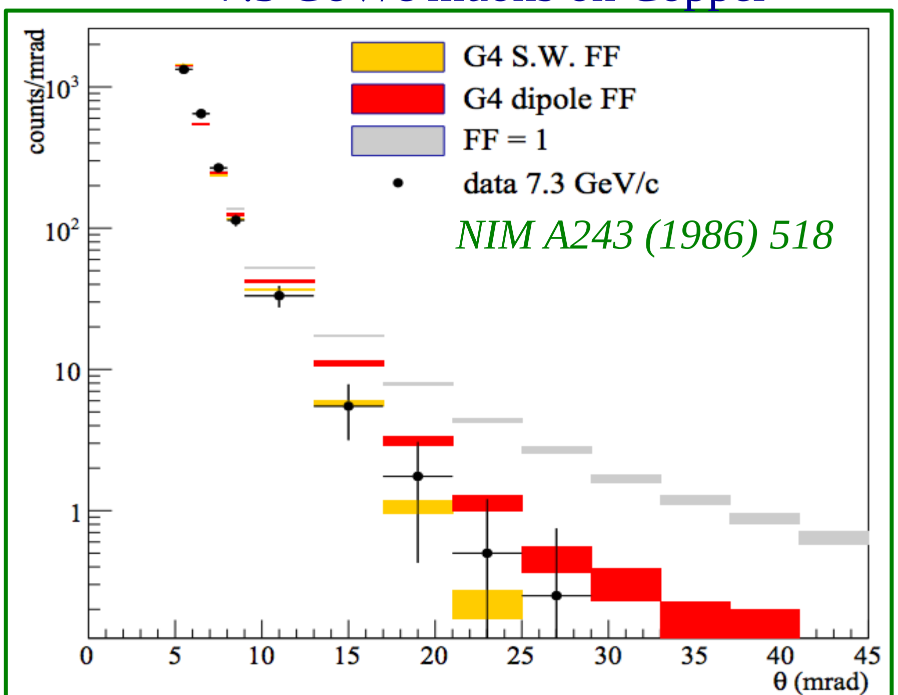
$$\rho_{SW}(r) = \rho_0 \left(1 + e^{\frac{r-b}{a}}\right)^{-1}$$

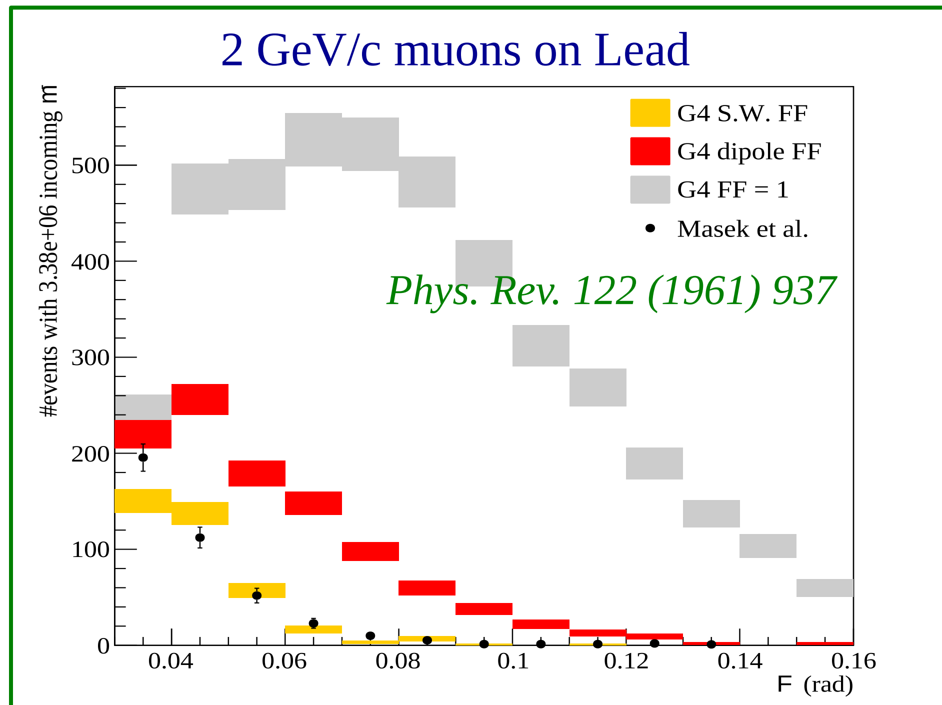


arXiv:1506.08759
accepted by Transactions of Nuclear Science

MC predictions compared to available data

7.3 GeV/c muons on Copper



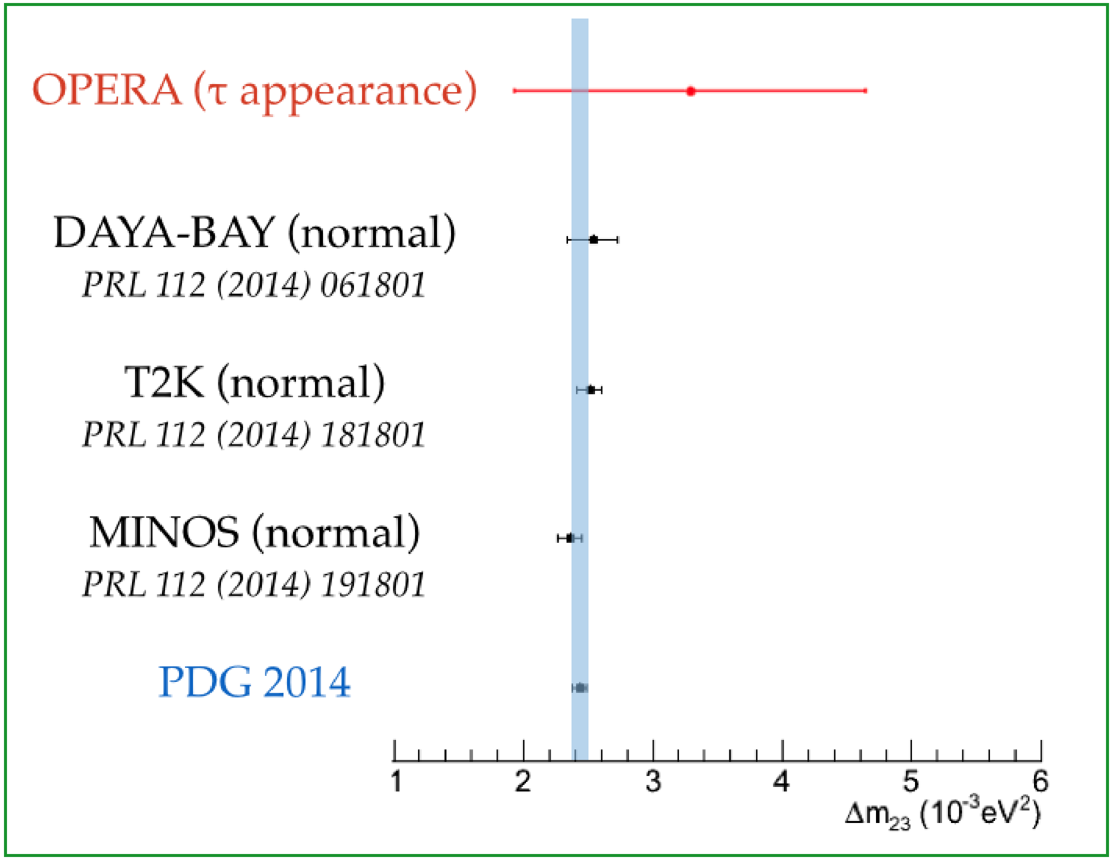


Δm^2_{23} ESTIMATION

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

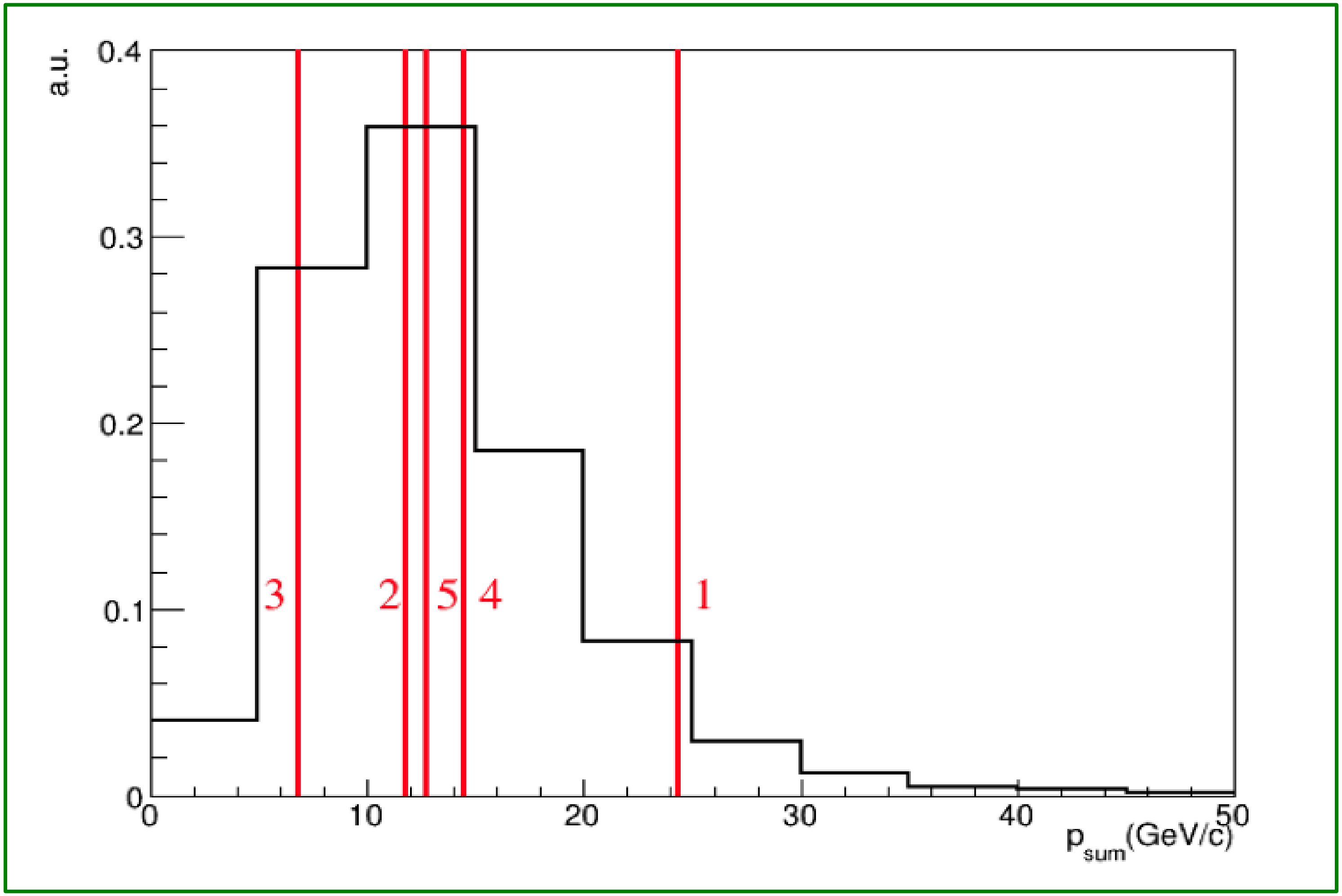
[2.0 – 4.7] x 10^{-3} eV^2

(assuming full mixing)

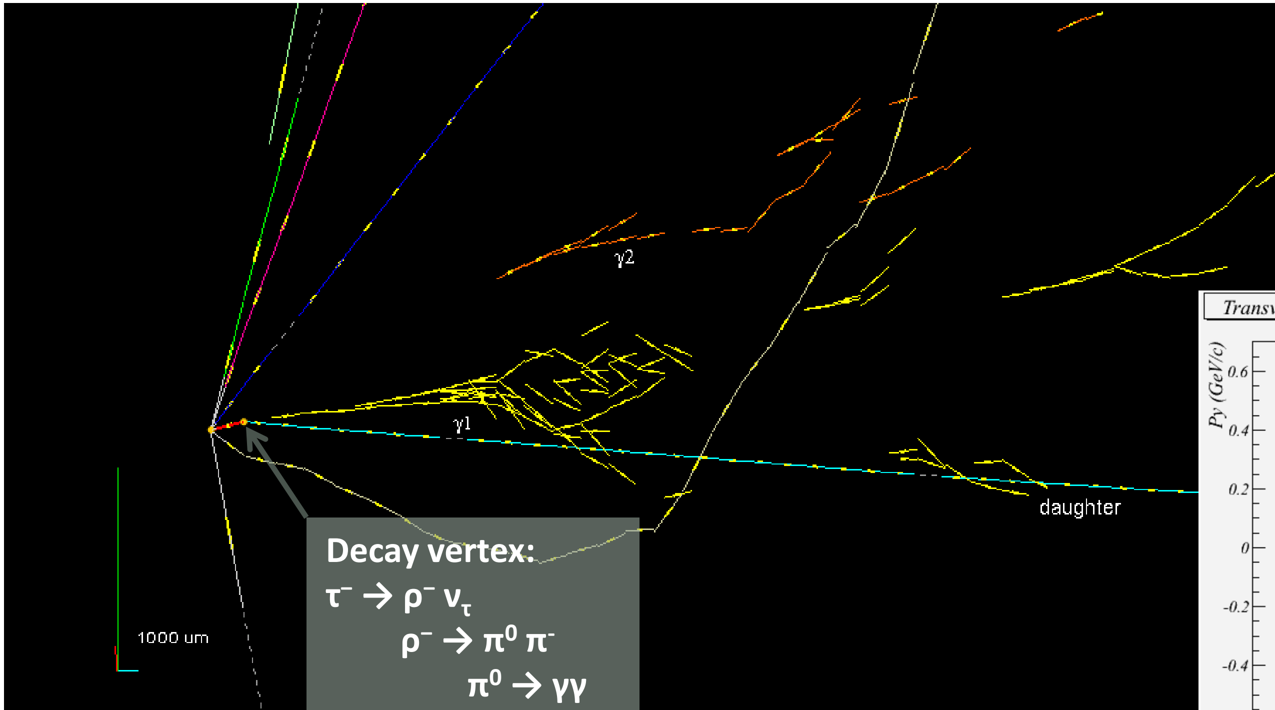


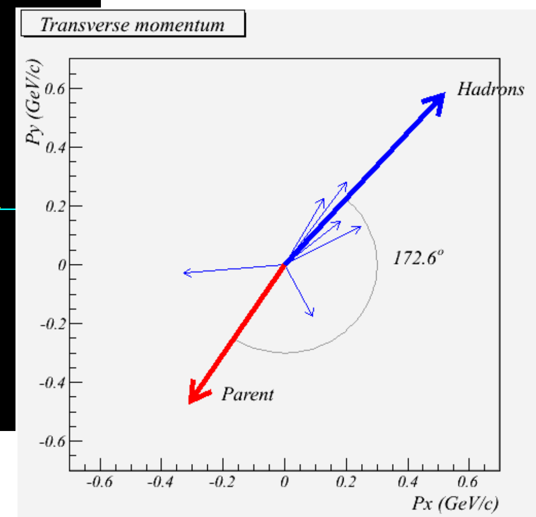
Visible Energy Of All The Candidates

Sum of the momenta of charged particles and γ's measured in emulsion



THE FIRST ν_τ CANDIDATE





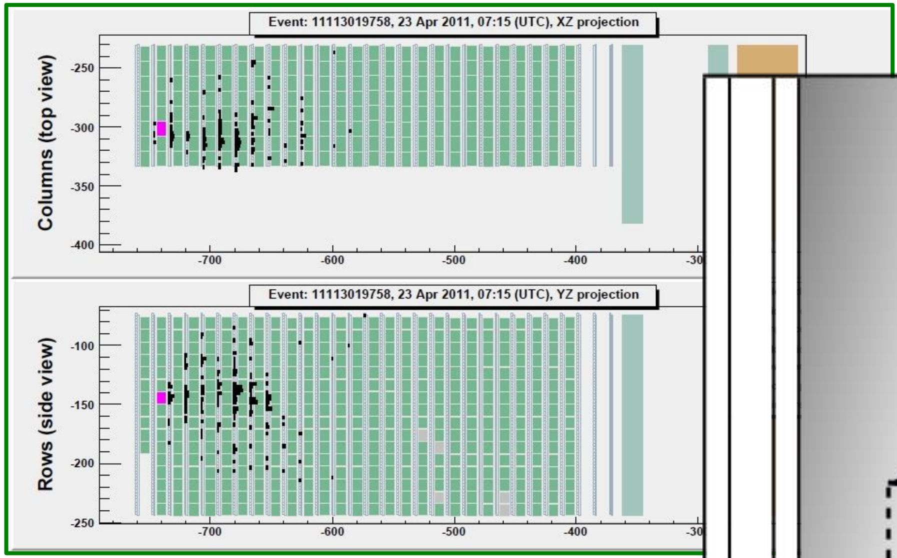
VARIABLE	AVERAGE	Selection criteria
kink (mrad)	41 ± 2	>20
decay length (µm)	1335 ± 35	within 2 lead plates
P daughter (GeV/c)	12^{+6}_{-3}	>2
Pt (MeV/c)	470^{+230}_{-120}	>300 (γ attached)
missing Pt (MeV/c)	570^{+320}_{-170}	<1000
ϕ (deg)	173 ± 2	>90

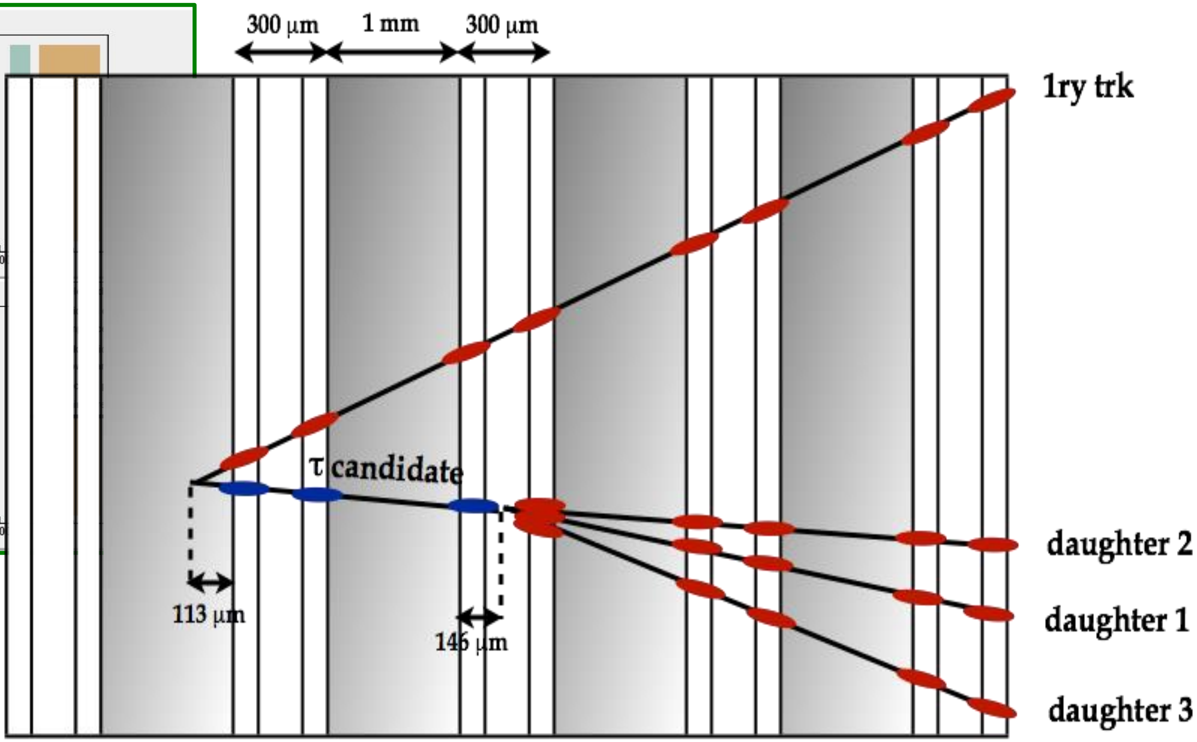
All primary tracks incompatible with muon hypothesis

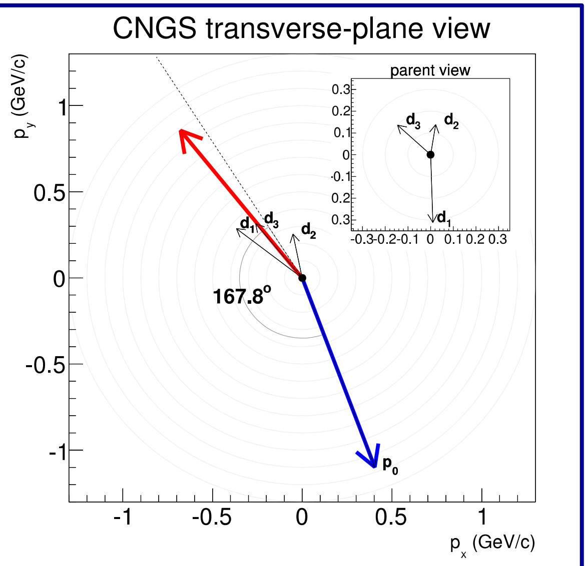
Found in 2008-2009 decay searched data, released in 2010

[Phys. Lett. B 691 (2010) 138]

THE SECOND ν_τ CANDIDATE







	Cut	Value	Error
Phi (Tau - Hadron) [degree]	>90	167.8	± 1.1
average kink angle [mrad]	< 500	87.4	± 1.5
Total momentum at 2ry vtx [GeV/c]	> 3.0	8.4	± 1.7
Min Invariant mass [GeV/c²]	0.5 < < 2.0	0.96	± 0.13
Invariant mass [GeV/c²]	0.5 < < 2.0	0.80	± 0.12
Transverse Momentum at 1ry vtx [GeV/c]	< 1.0	0.31	± 0.11

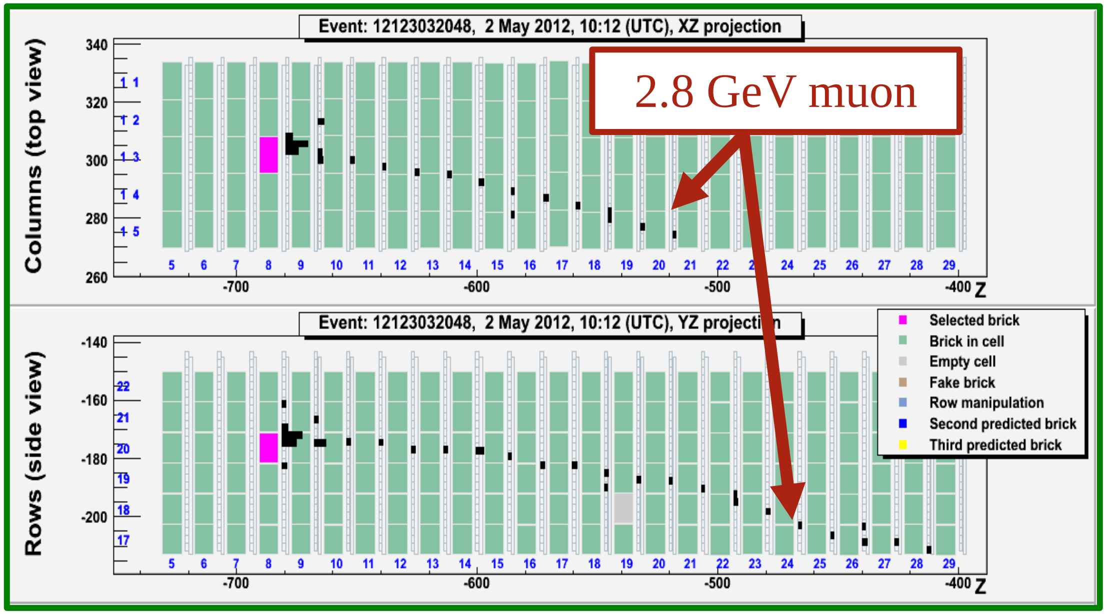
- Primary track incompatible with muon hypothesis
- All tracks identified as hadrons

Event satisfies criteria for:

$\tau \rightarrow h^+h^-h^-\nu_\tau$

THE THIRD ν_τ CANDIDATE

VARIABLE	AVERAGE
Kink angle (mrad)	245 ± 5
decay length (µm)	376 ± 10
Pµ (GeV/c)	2.8±0.2
Pt (MeV/c)	690±50
ϕ (degrees)	154.5 ± 1.5

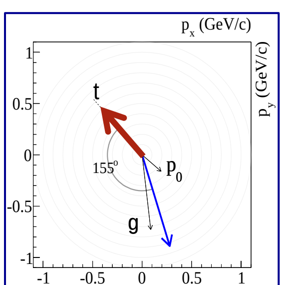


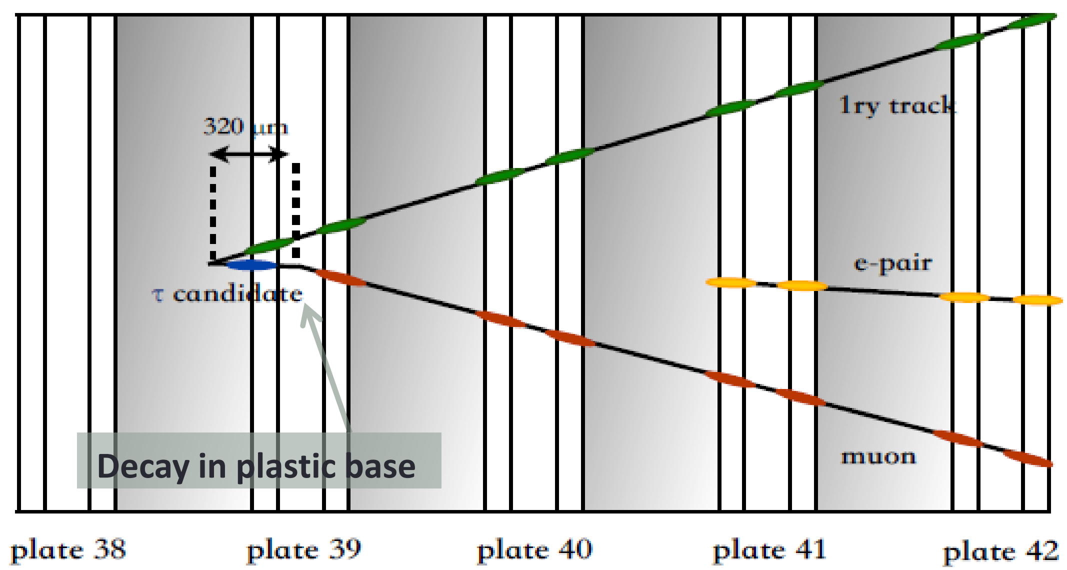
Momentum measurement

- by range in the electronic detector 2.8 ± 0.2 GeV/c
- MCS in the brick consistent $3.1^{+0.9}_{-0.5}$ GeV/c

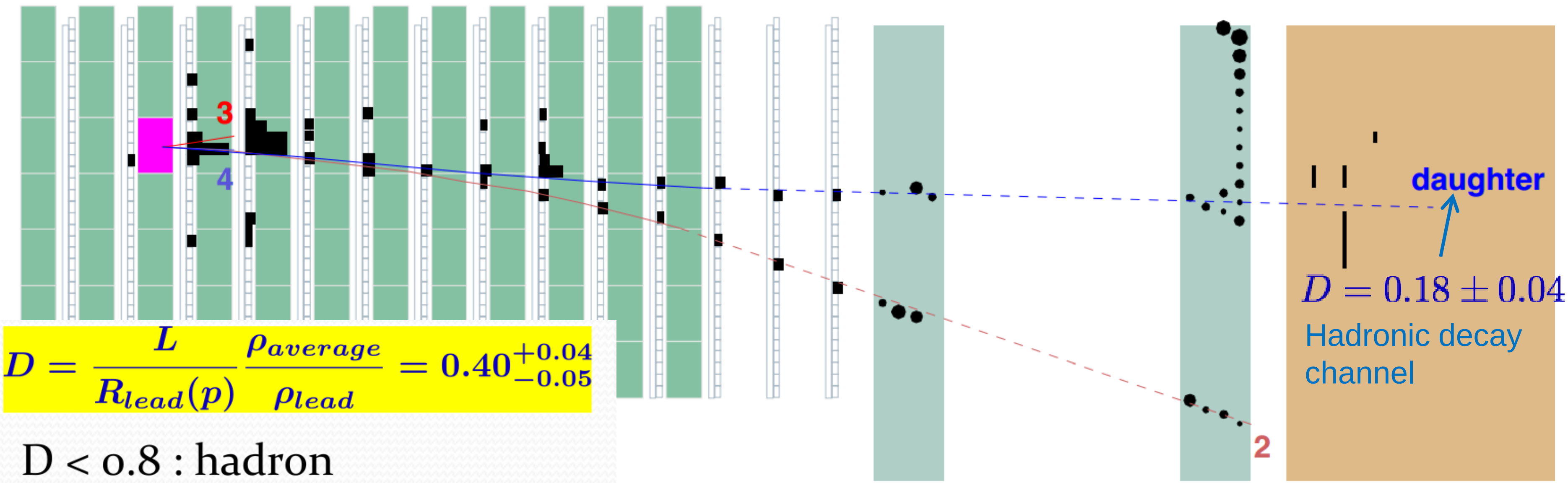
Primary track incompatible with muon hypothesis

Negative charge of the secondary muon assessed with 5.6 σ significance (by spectrometer measurement)



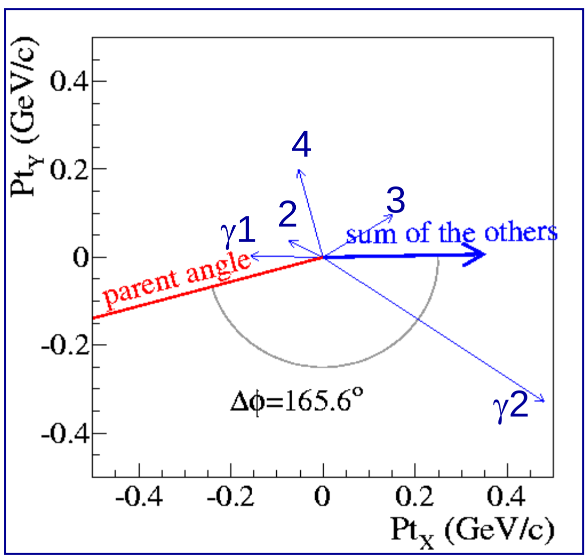


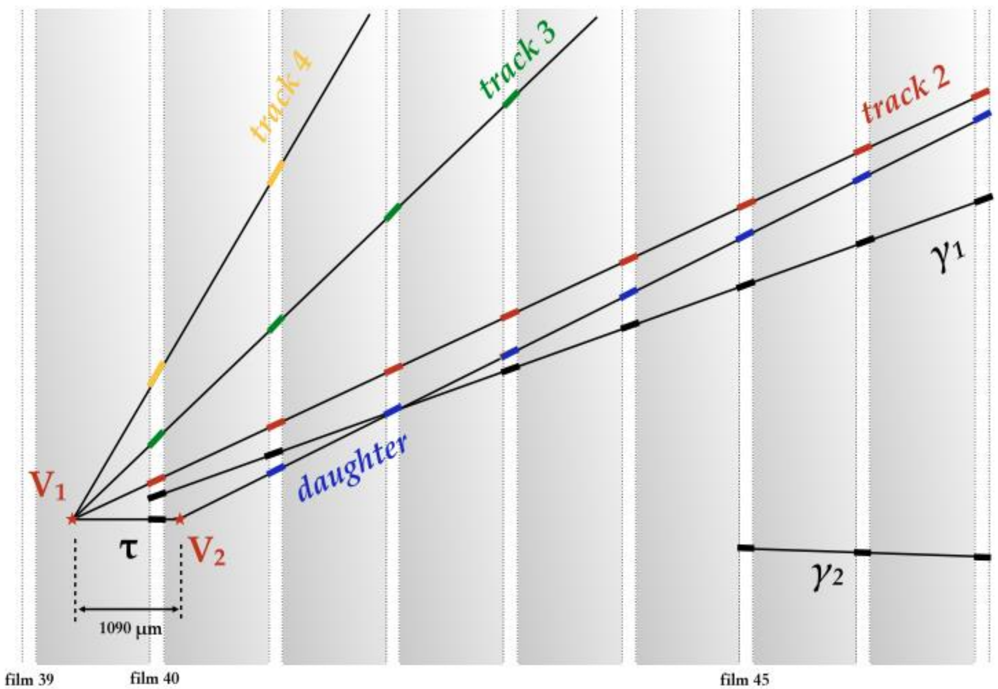
THE FOURTH ν_τ CANDIDATE



$$D = \frac{L}{R_{lead}(p)} \frac{\rho_{average}}{\rho_{lead}} = 0.40^{+0.04}_{-0.05}$$

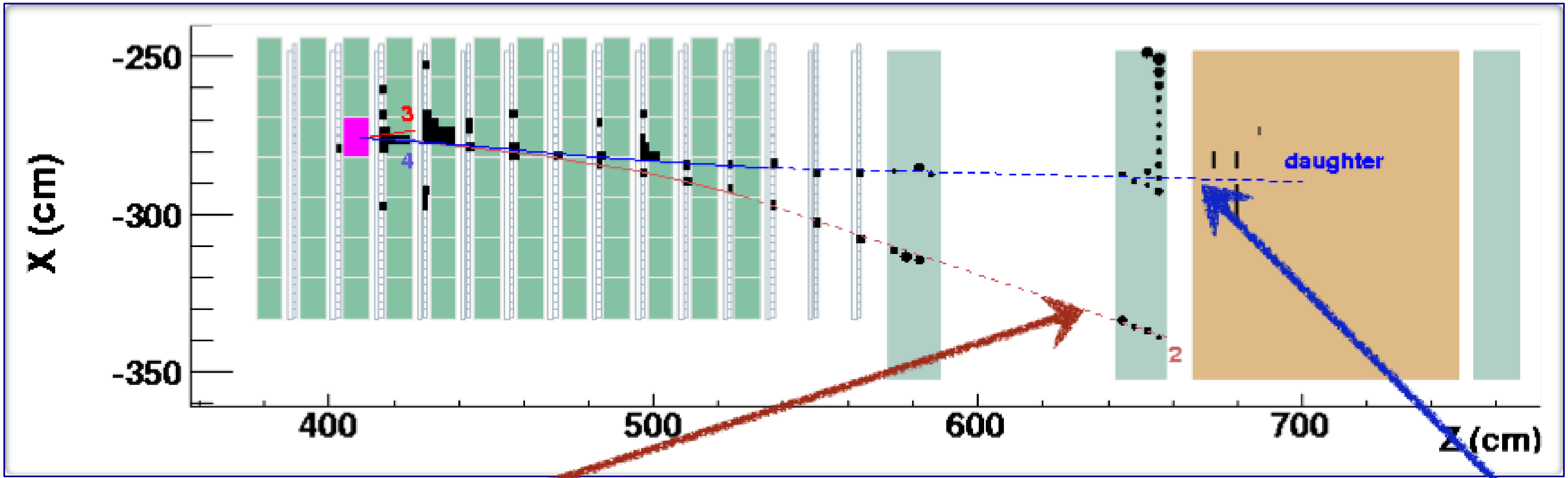
D < 0.8 : hadron





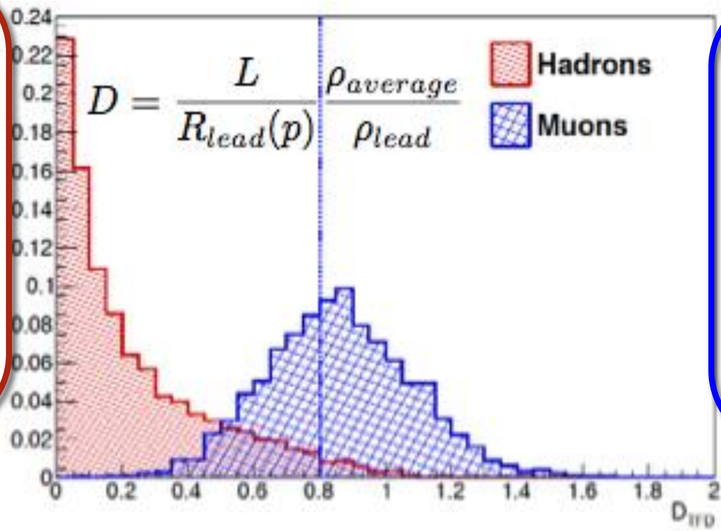
Particle ID: Track Follow-Down

A powerful tool to assess the muon-less nature of the event



Track 2 from neutrino interaction vertex
- **p = 1.9 GeV/c**
- stopping in the first iron slab of the magnet
- muon hypothesis rejected

$D = 0.40^{+0.04}_{-0.05}$



Daughter track from τ decay
- **p = 6.0 GeV/c**
- stopping in the first arm of the spectrometer
- Classified as **hadron**

$D = 0.18 \pm 0.04$

Charm background hypothesis rejected

Hadronic decay channel

The 5th ν_τ event

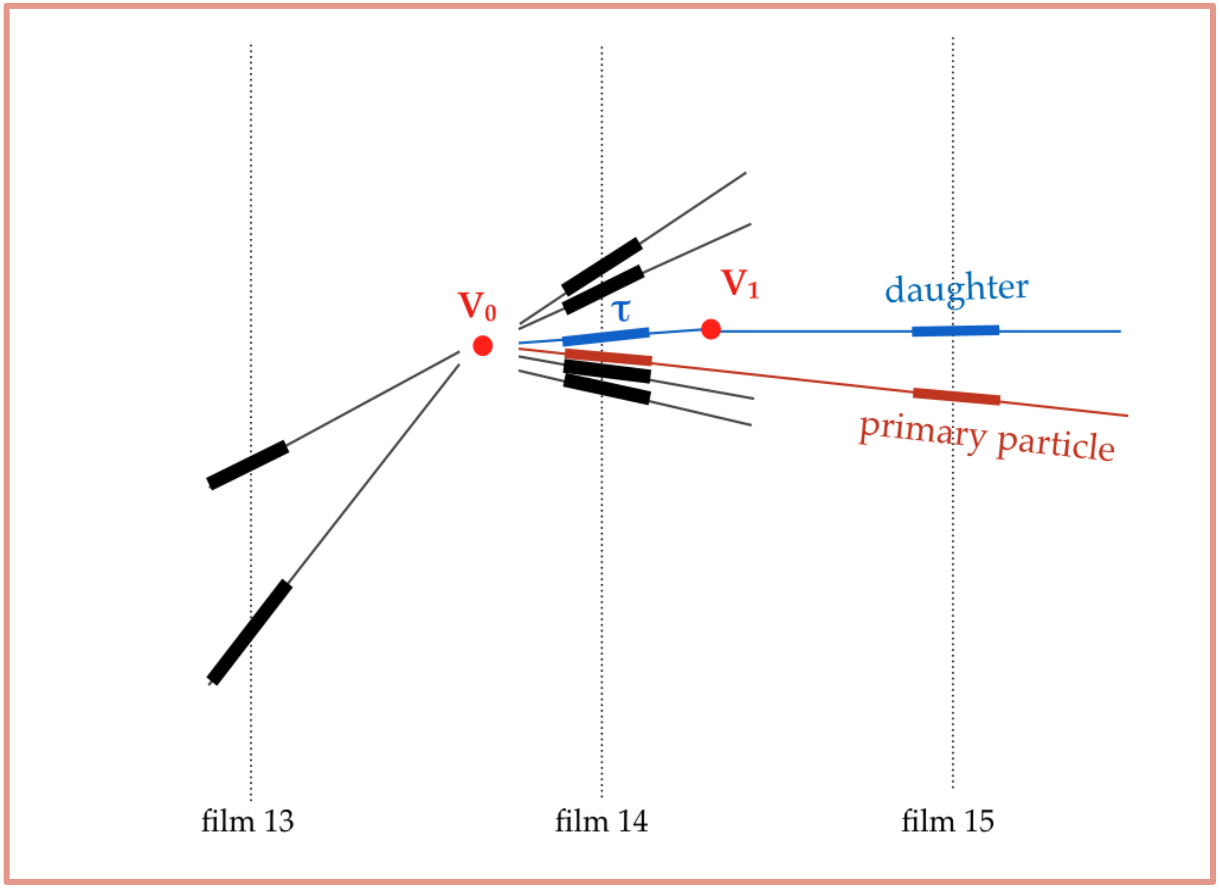
Search for nuclear fragments in an extended angular range **$|\tan\theta| \leq 3$**

Primary vertex

6 nuclear fragments found

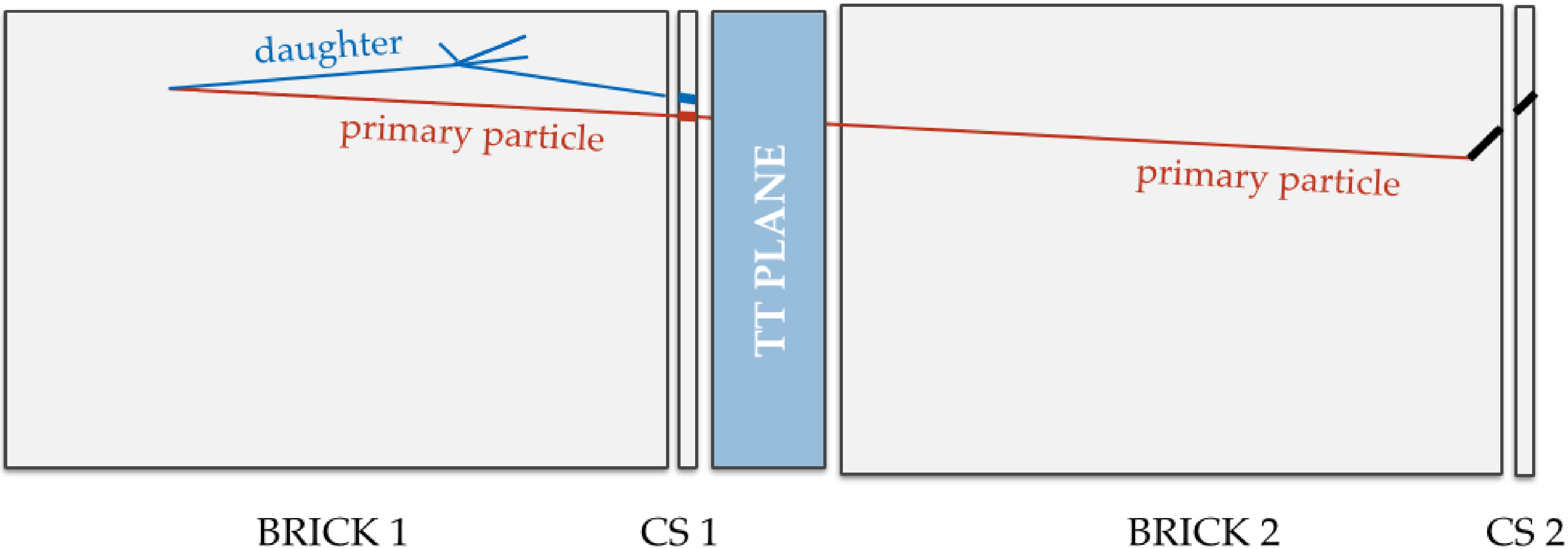
Secondary vertex

None



The 5th ν_τ event

Particle Identification



Primary particle
Followed in the downstream brick
Hadronic re-interaction: 1 visible particle

→ **Charm hypothesis discarded**

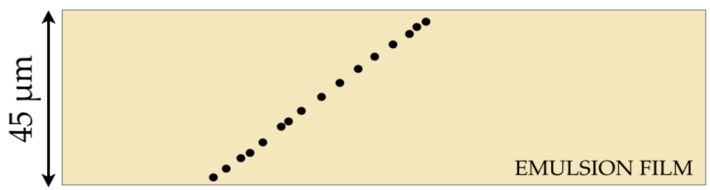
Daughter
Hadronic re-interaction in the first brick

→ **Hadronic decay channel**

The 5th ν_τ event

Grain counting method

- Count all grains along the track
- Grain density (GD) proportional to the energy deposition dE/dx



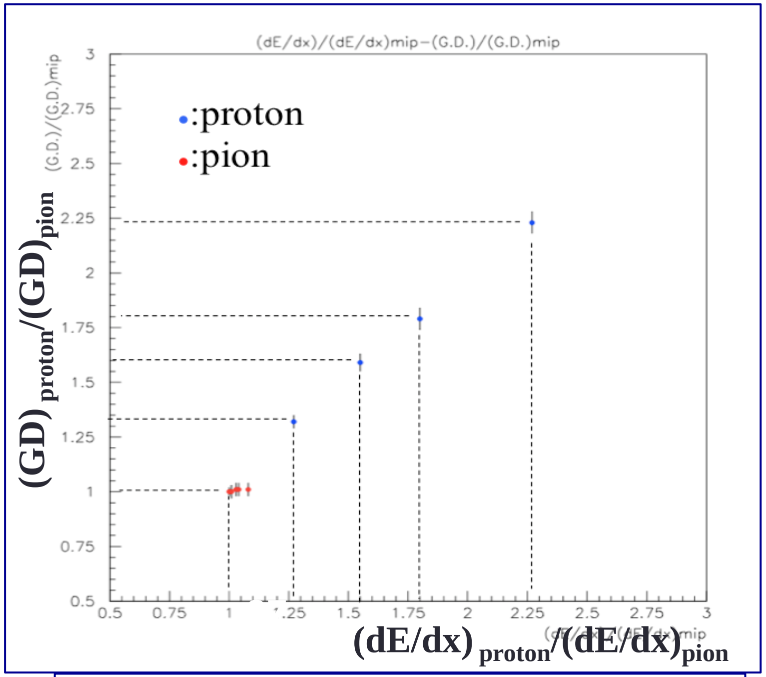
MCS method in the first brick
βP_{1ry} = 0.8 [0.6, 1.1] GeV/c

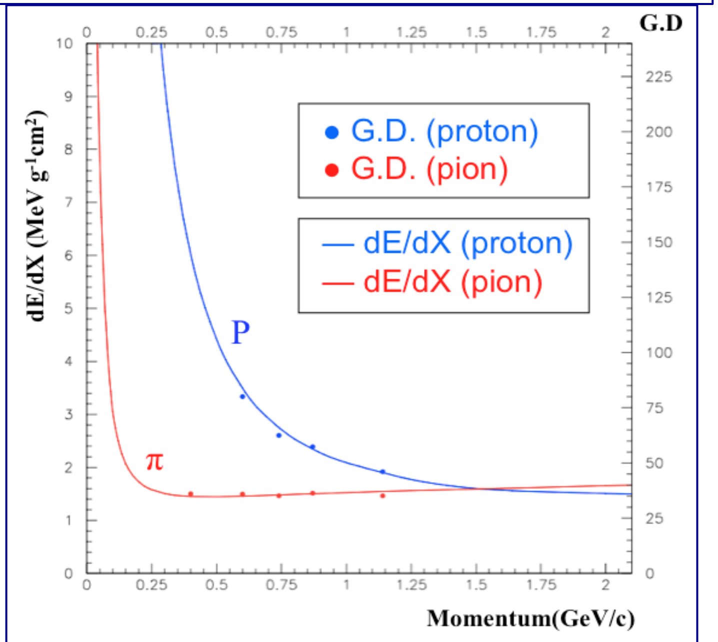
$$GD_{1ry}/GD_\pi = 1.45 \pm 0.06$$

$$(dE/dx)_{proton}/(dE/dx)_\pi = 1.38 \pm 0.14$$

Consistent with proton hypothesis

p = (1.0±0.2) GeV/c





Kinematical cuts

Kinematical cuts for ν_τ selection to increase S/B ratio

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	/	/

The atmospheric muon charge ratio

- The atmospheric muon charge ratio $R_\mu \equiv N_{\mu+}/N_{\mu-}$ is being studied and measured since many decades
  - Depends on the **chemical composition** and energy spectrum of the primary cosmic rays
  - Depends on the **hadronic interaction features**
  - At high energy, depends on the **prompt component**
- Possibility to check HE hadronic interaction models (E>1TeV) in the fragmentation region (phase space complementary to collider's one)
- Atmospheric muons are kinematically related to atmospheric neutrinos (same sources) → R_μ provides a benchmark for atmospheric ν flux computations (e.g. background for neutrino telescopes)