Search for $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode in the OPERA experiment

Umut KOSE

on behalf of the OPERA Collaboration

Dipartimento di Fisica Galileo Galilei
INFN-PADOVA

XXV Rencontres de Physique de la Vallee d'Aoste, La Thuile, Aosta Valley, Italy, February 27, March5 2011.

The OPERA Collaboration

180 physicists, 32 institutions in 12 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

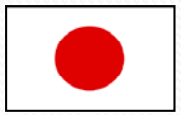
France
LAPP Annecy
IPHC Strasbourg
IPNL Lyon

Germany
Hamburg
Münster

Israel
Technion Haifa

Italy
Bari
Bologna
LNF Frascati
L'Aquila,
LNGS
Naples
Padova
Rome
Salerno

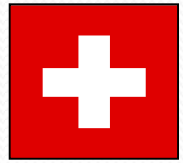
Japan
Aichi
Toho
Kobe
Nagoya
Utsunomiya



Korea
Jinju

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

Switzerland
Bern
ETH Zurich



Tunisia
CNSTN Tunis

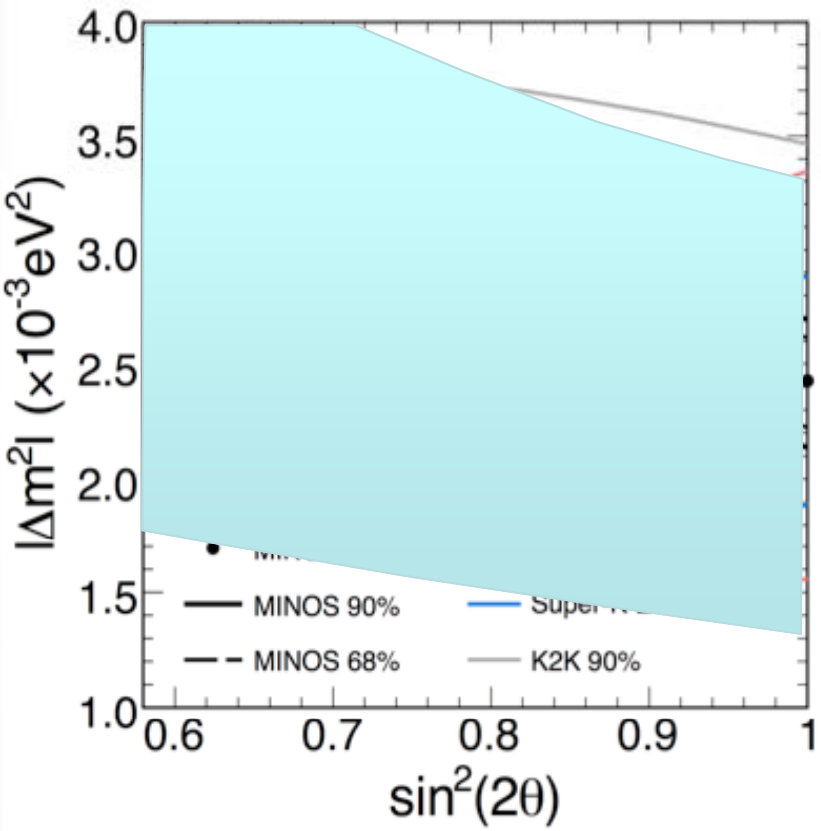
Turkey
METU Ankara

http://operaweb.lngs.infn.it/scientists/?lang=en

Oscillation Project with Emulsion-tRacking Apparatus

Aiming at the first direct detection of neutrino oscillations in appearance mode where is identified by the charged lepton created in its CC interaction.

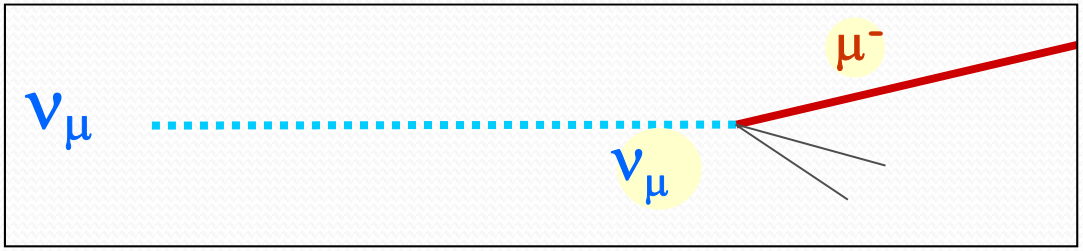
Oscillation parameters in the atmospheric neutrino sector



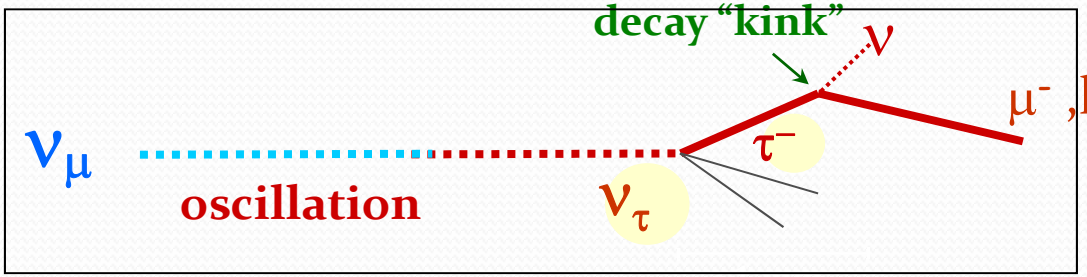
Full mixing and $\Delta m^2_{23} \sim 2.4 \times 10^{-3}$ eV^2

The light blue band indicates the OPERA allowed region (90% CL) for the above parameter values for 22.5×10^{19} pot

Direct detection of $\nu_\mu \rightarrow \nu_\tau$ appearance signal

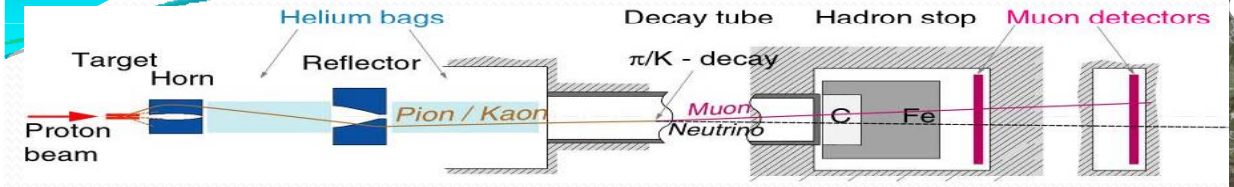


The challenge is to identify ν_τ interactions from ν_μ interactions.



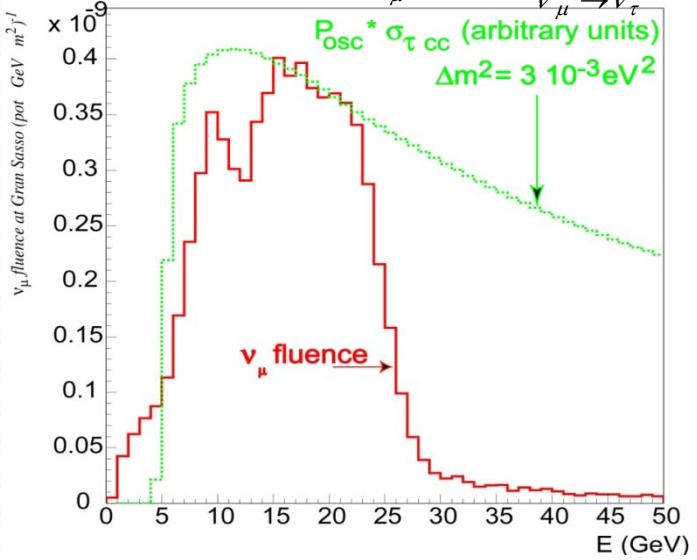
Requirements **:** *high neutrino energy & intensity & long base line & large target mass & sub-micron resolution &detect short lived τ's*

CNGS neutrino beam



CNGS beam optimized to study ν_τ appearance by τ detection

$$N_\tau = N_A M_D \int \phi_{\nu_\mu}(E) P_{\nu_\mu \to \nu_\tau}(E) \sigma_{\nu_\tau}{}^{CC}(E) \varepsilon(E) dE$$



< Eν>	17 GeV
L	730 km
$(\nu_e + \bar{\nu}_e) / \nu_\mu$	0.87 % *
$\bar{\nu}_\mu / \nu_\mu$	2.1 % *
ν_τ prompt	Negligible *

* Interaction rate at LNGS

Expected interactions for 22.5 x 10¹⁹ pot (4.5 x 10¹⁹ pot nominal pot in 5 years):

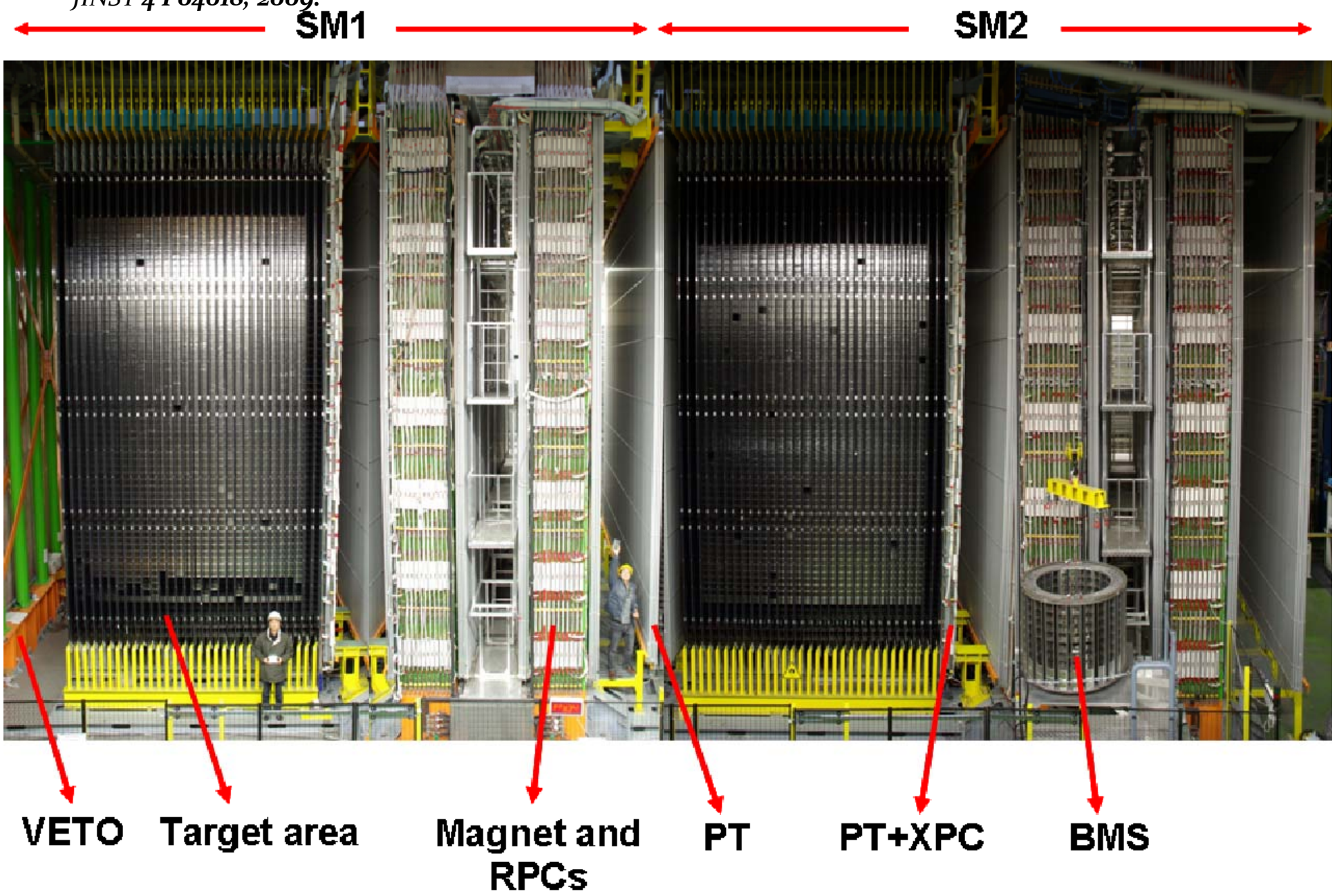
~ 24300 ν_μ CC + NC

~ 115 ν_τ CC ($\Delta m^2 = 2.5 \times 10^{-3}$ eV²)

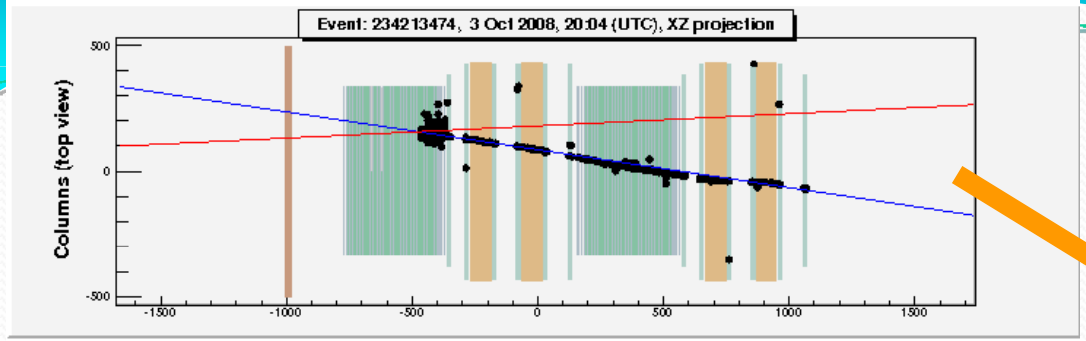
~ 10 tau decays are expected to be observed (BG<1)

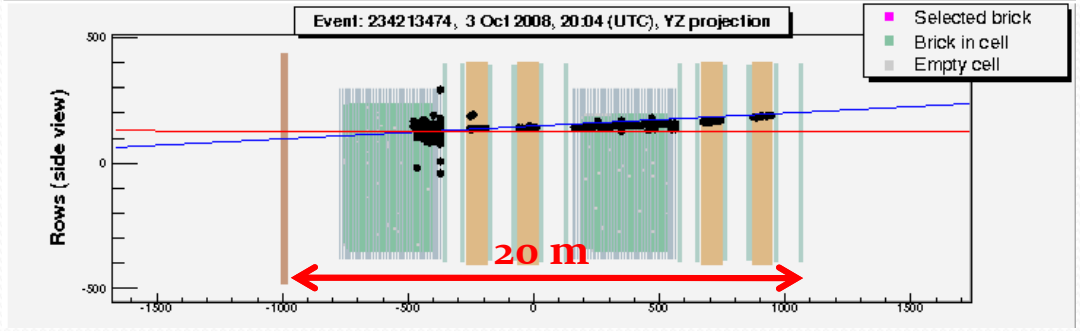
OPERA detector*

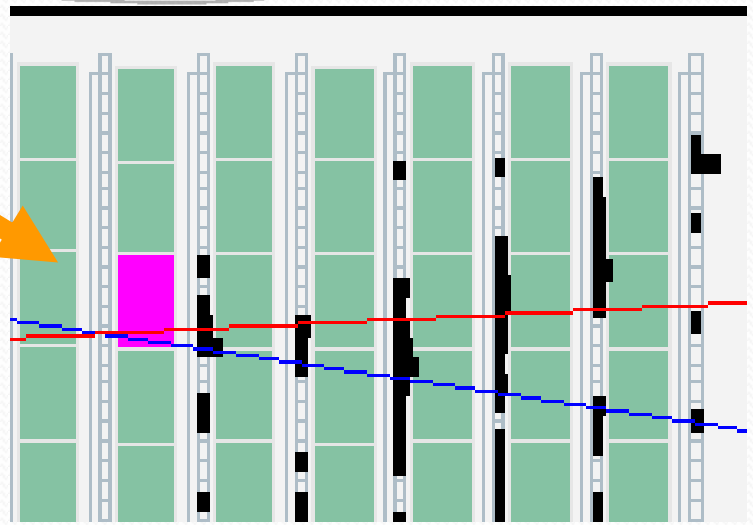
*JINST 4 P04018, 2009.

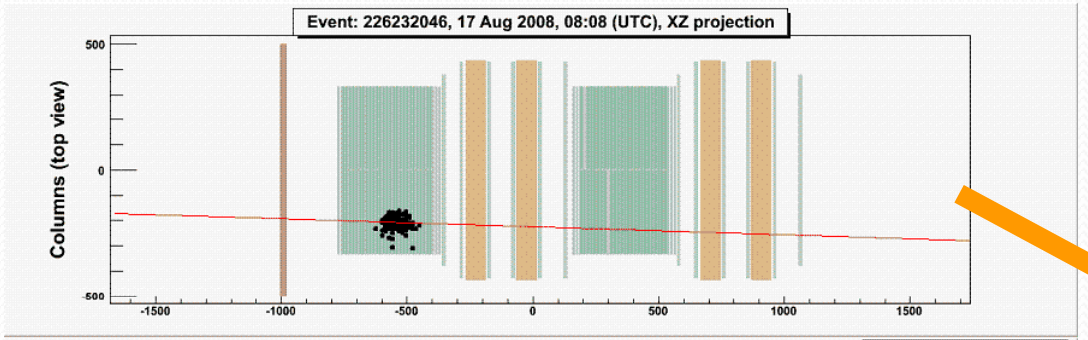


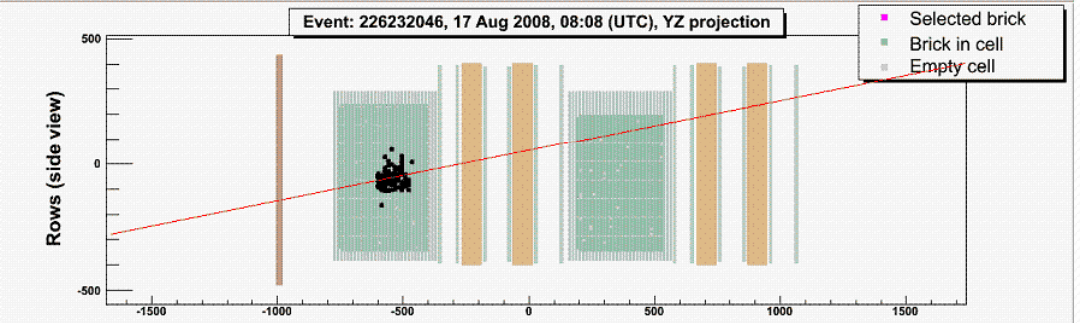
Typical ν_μ CC-like and NC-like events

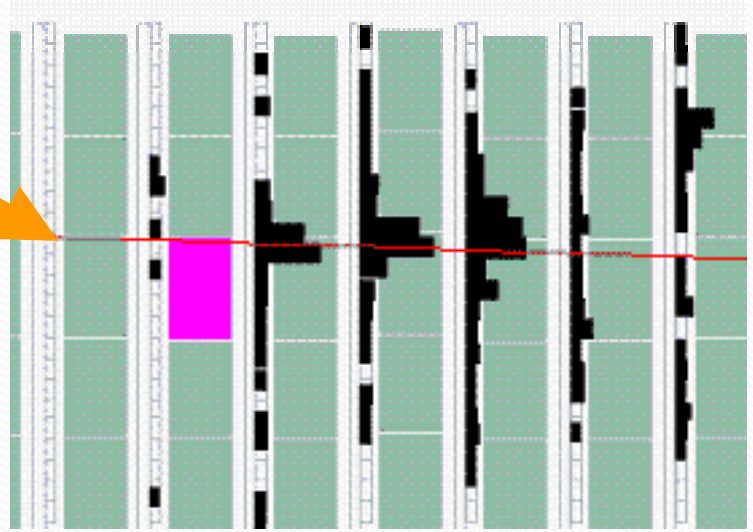








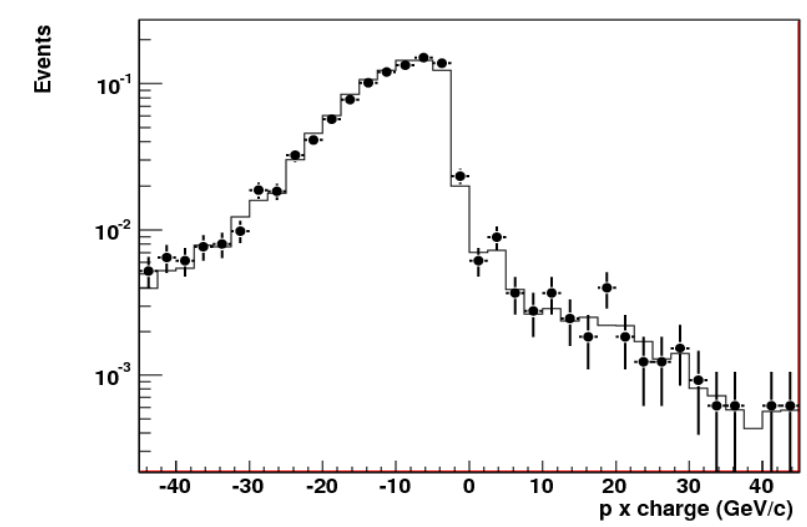


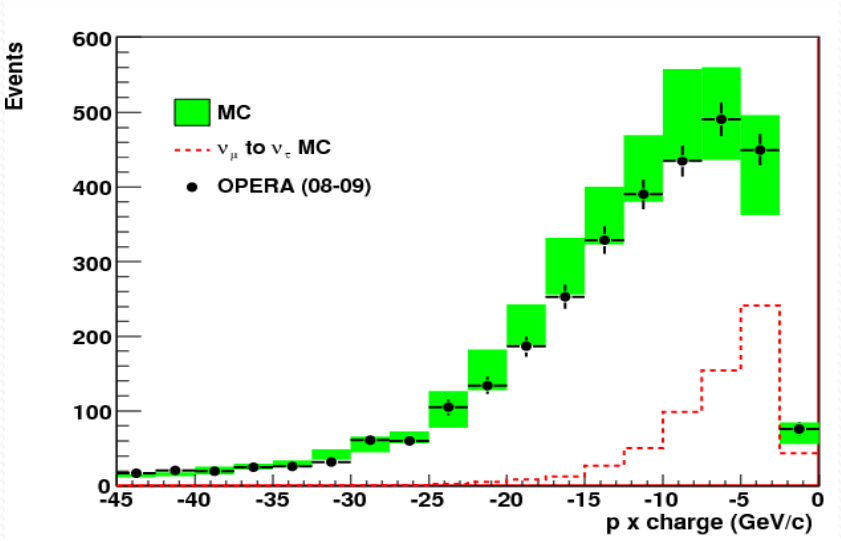


OPERA Detector performance*

* hep-ex 1102.1882v1 Submitted to New Journal of Physics

Muon momentum*charge





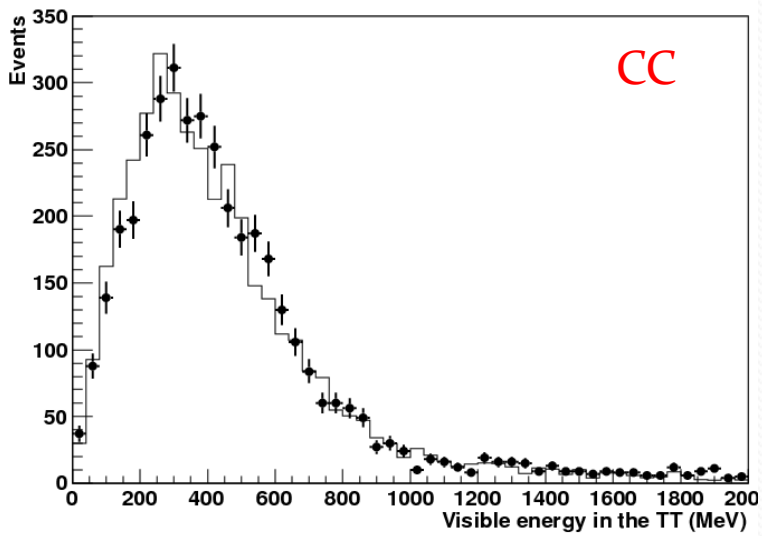
The overall efficiency ** for CC events > 97.5%

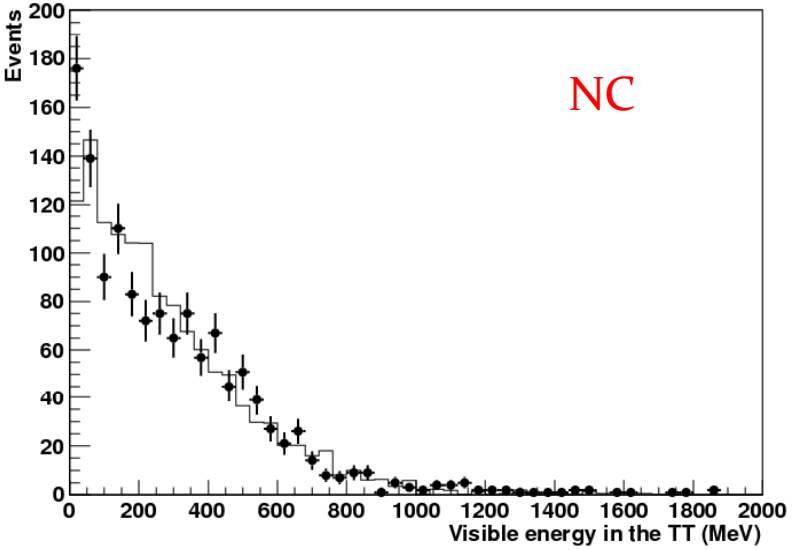
Charge id efficiency** above **96%** for **45GeV/c > |P| >2.5GeV/c

Momentum resolution** as computed from MC is about **10%** at **2.5GeV/c** and **20%** at **25GeV/c** and **transverse spatial resolution** is better than **1mm.

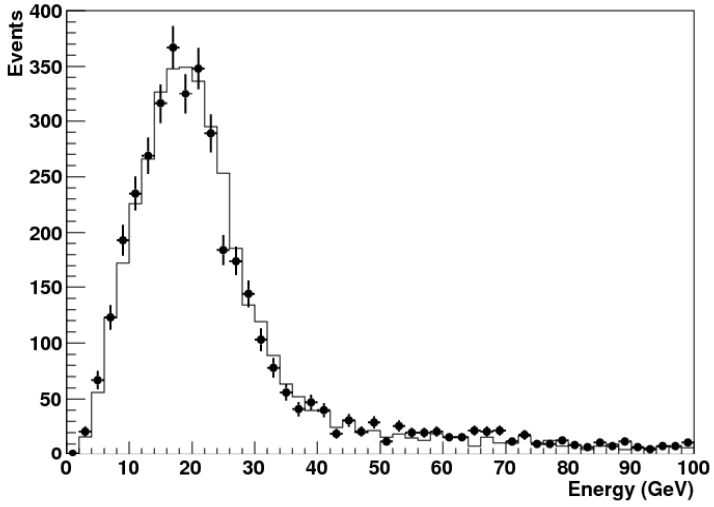
**Trigger efficiency + reconstruction efficiency*

Performance : Energy deposit in the Target Tracker





Total reconstructed energy



For energy above 200MeV in a good agreement. Investigating the energy deposition in the low energy region.

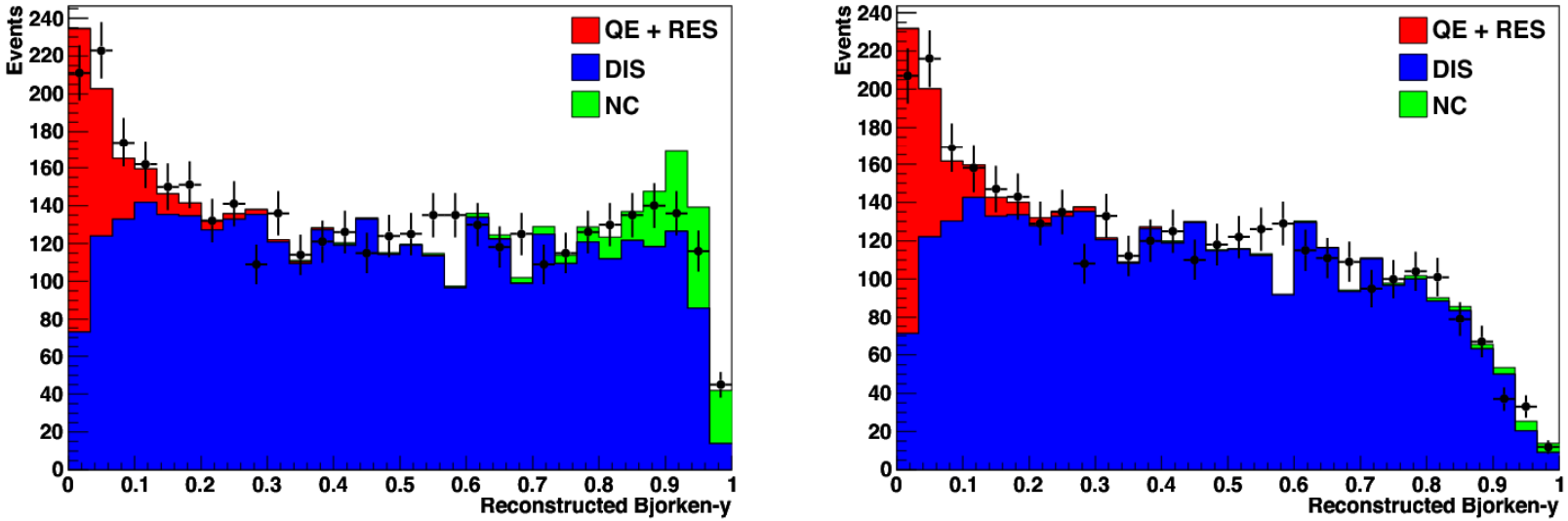
dE/E** is between (20-40)% for the **energy range (5-40)GeV/c2

Performance :

Bjorken-y variable:

$$y = 1 - \frac{E_\mu}{E_{\nu_\mu}} = \frac{E_{had}}{E_\mu + E_{had}}$$

connects muon momentum measurement with calorimetric measurement of all the hadrons

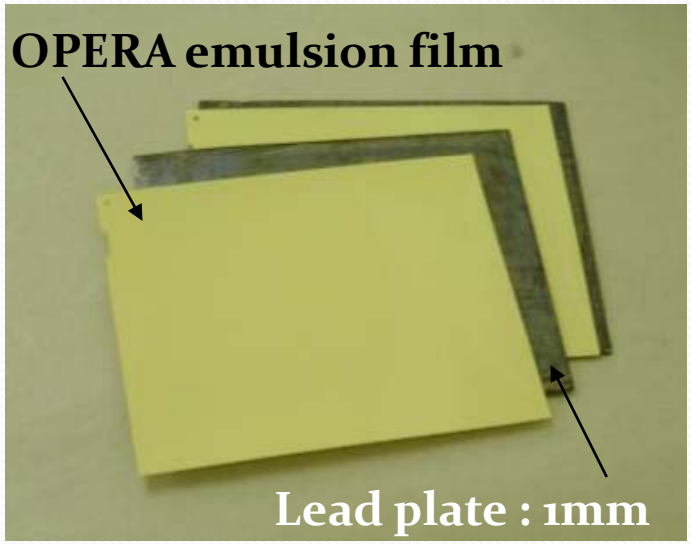


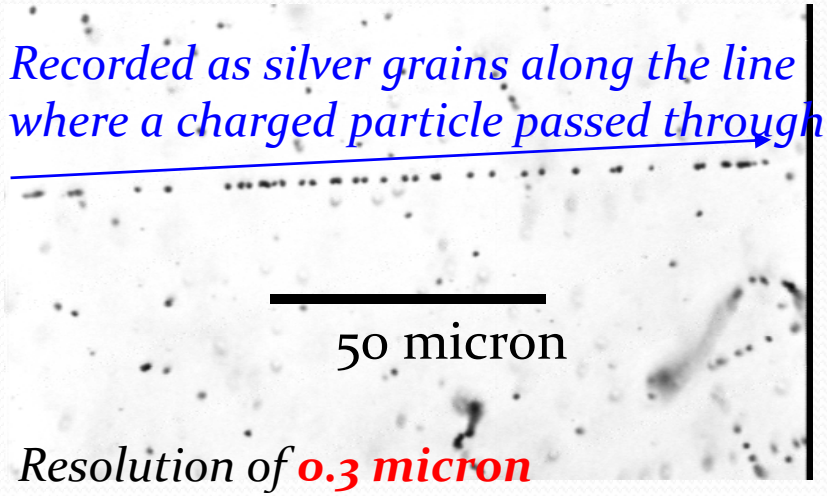
Left: events selected just with muon ID NC background **5.2%**

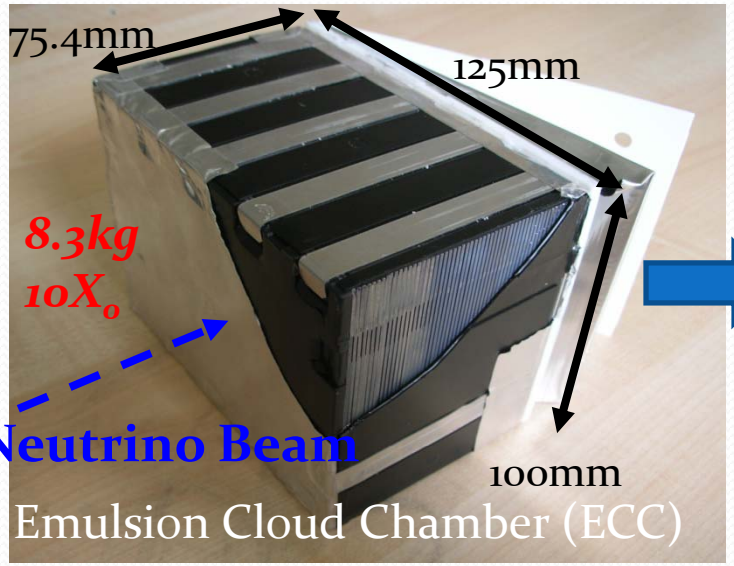
Right: muon ID + bending in spectrometer NC background **0.8%**

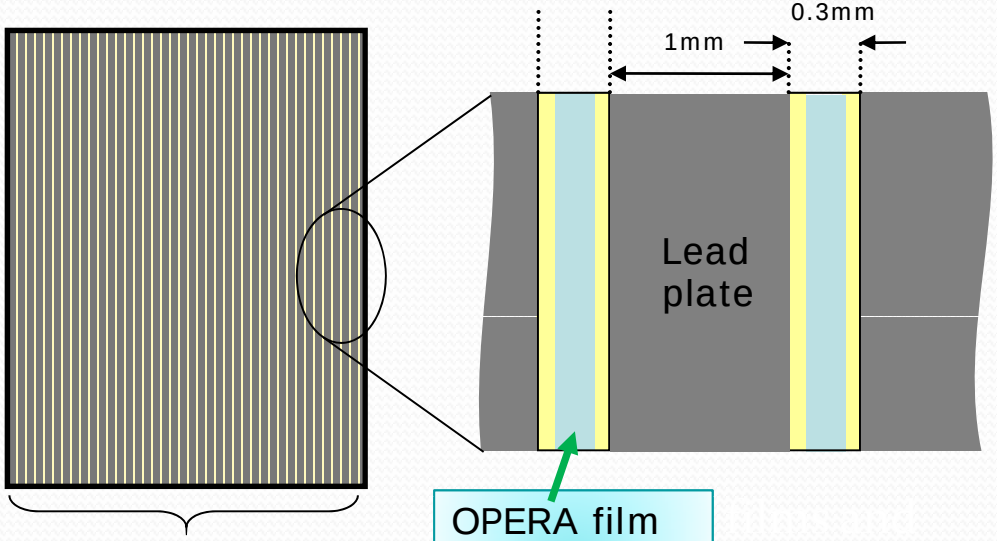
The resolution is good enough to clearly see QE peak.
NC background could be eliminated by requiring momentum measurement in the spectrometer.

The OPERA target : Emulsion Cloud Chamber







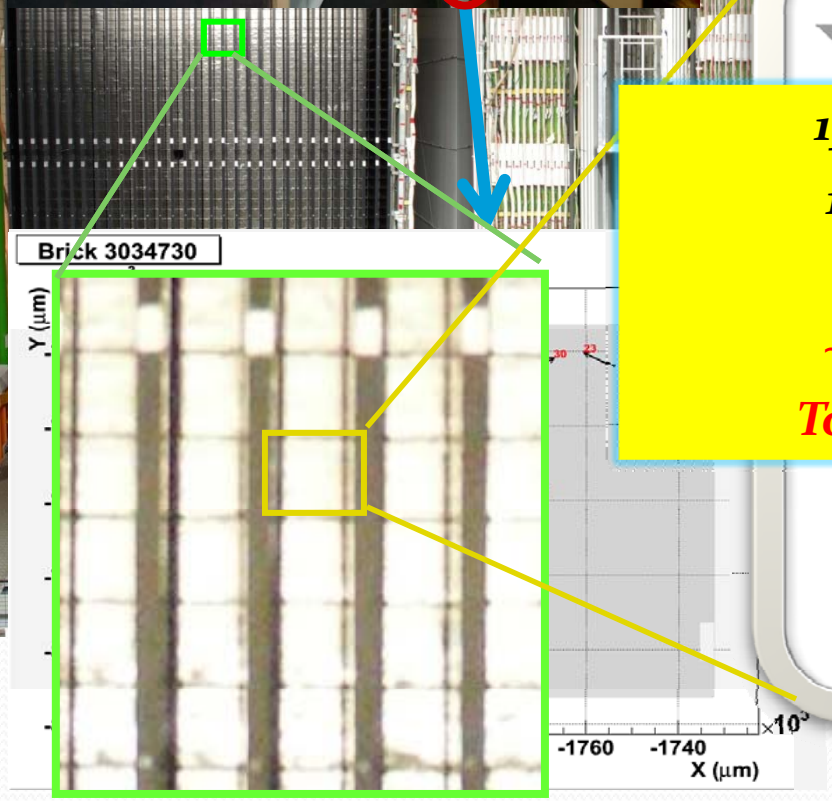


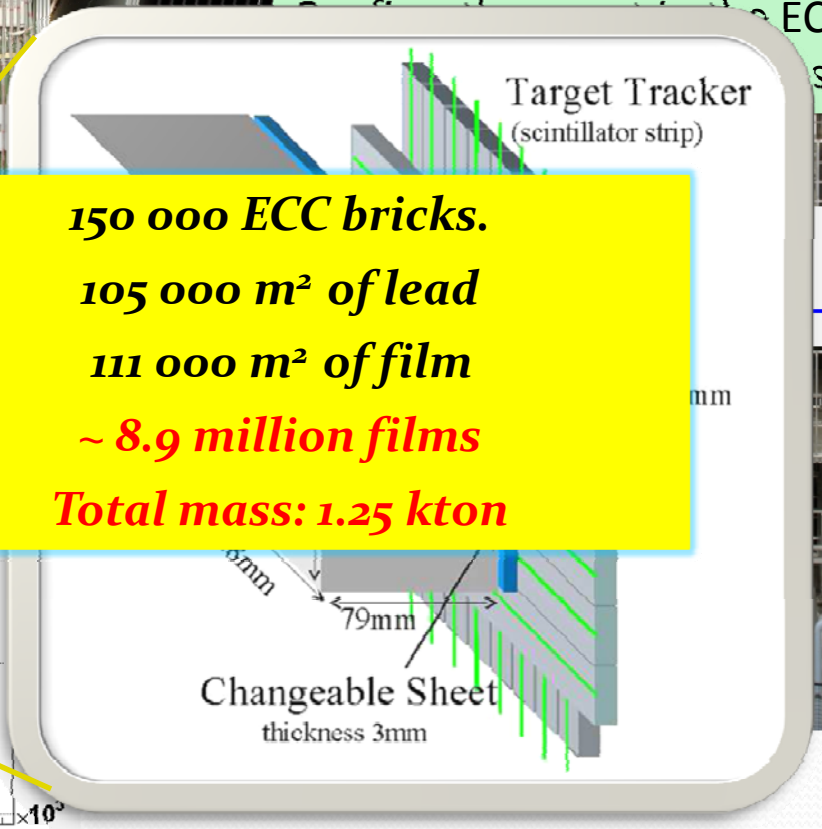
57 films interleaved by 1 mm thick lead plates

2 emulsion layers (44 μm thick) poured on a 205 μm plastic base

OPERA as hybrid detector

Extract ECC brick and CS, scan CS.
ECC brick.
scanning labs.





150 000 ECC bricks.

105 000 m² of lead

111 000 m² of film

~ 8.9 million films

Total mass: 1.25 kton

Emulsion scanning

Parallel ECC brick analysis in ~ 10 labs.

CS Scan & analysis

→ *NAGOYA : LNGS = 50:50*

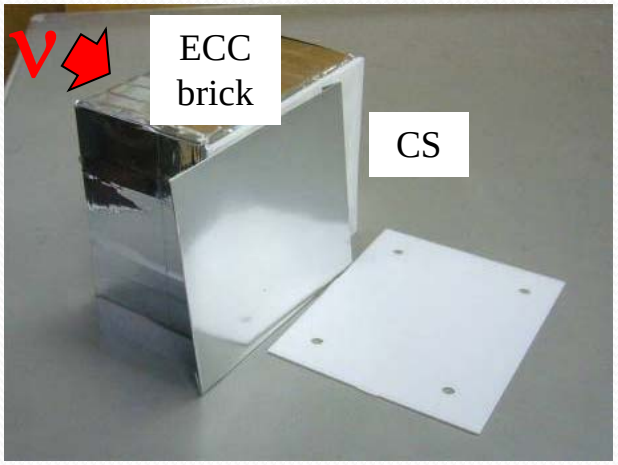
ECC brick Scan & analysis

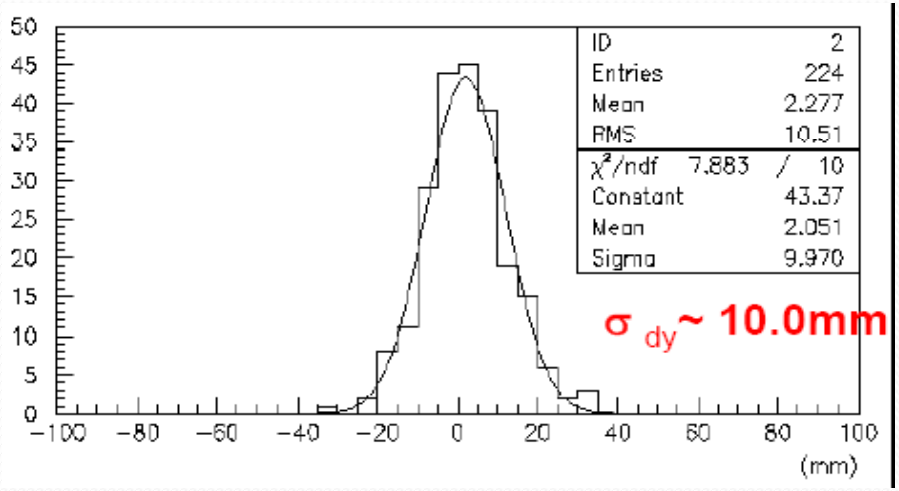
→ *NAGOYA : EU = 50:50*

CS Scanning Stations

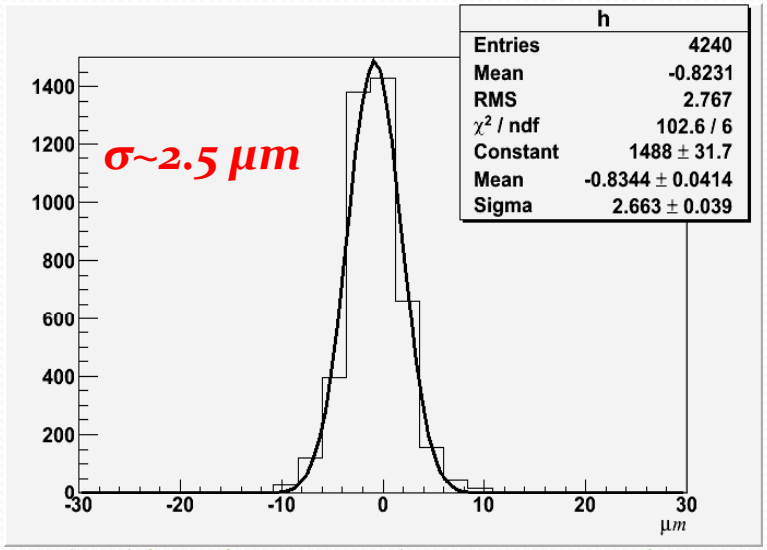
The Changeable Sheets (CS)

- the interface between Electronic Detector and ECC brick

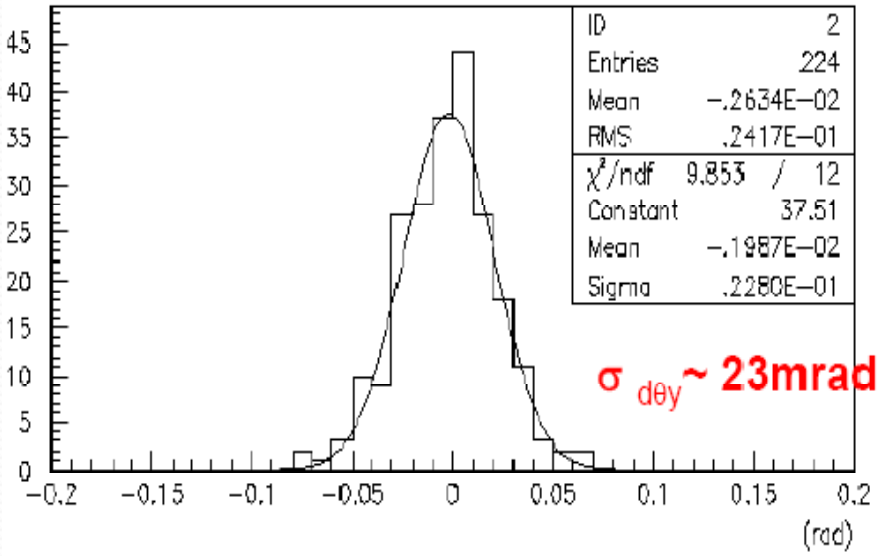




Position accuracy of the electronic predictions

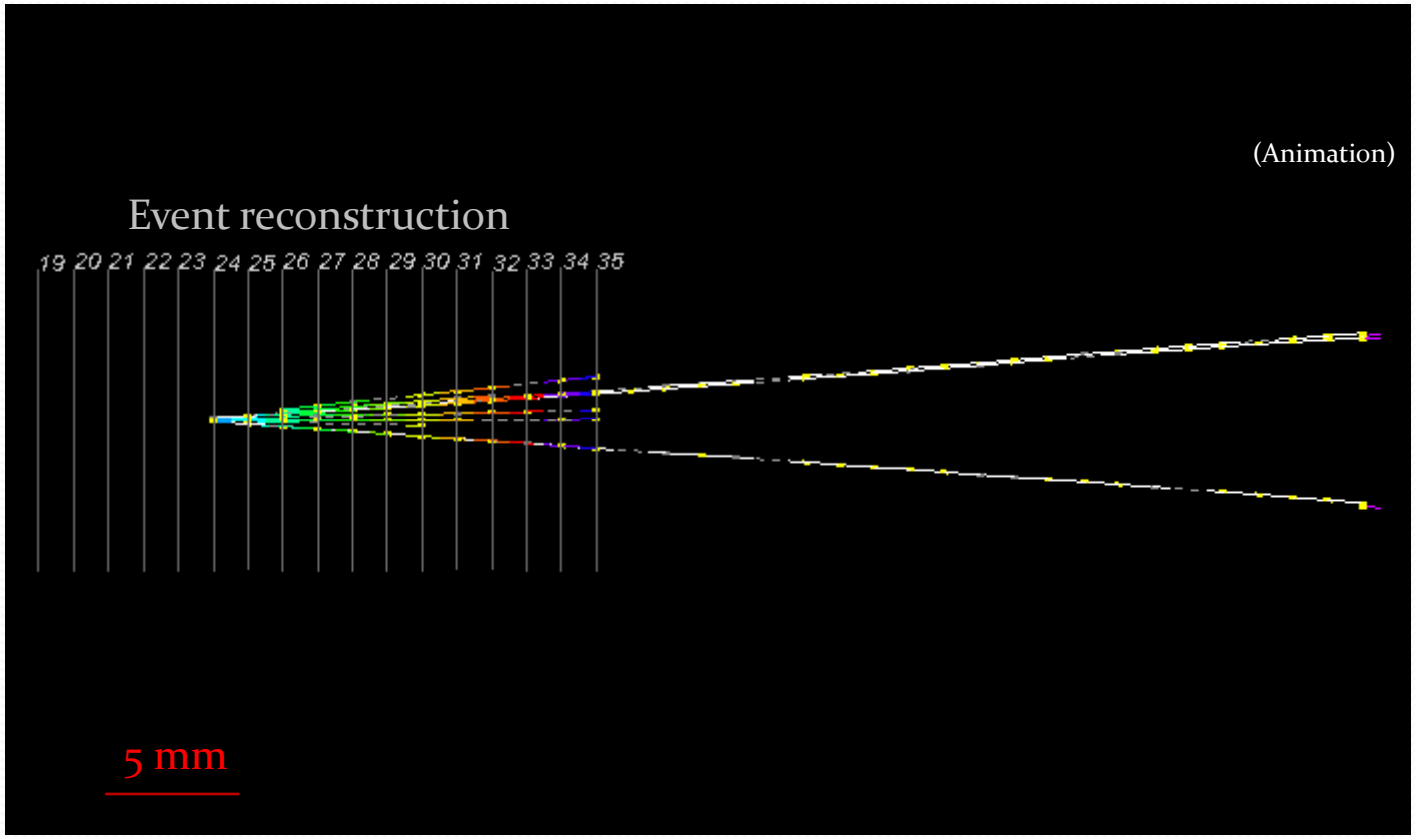


CS doublet alignment by Compton electrons



Angular accuracy of the electronic predictions

Event analysis in ECC brick



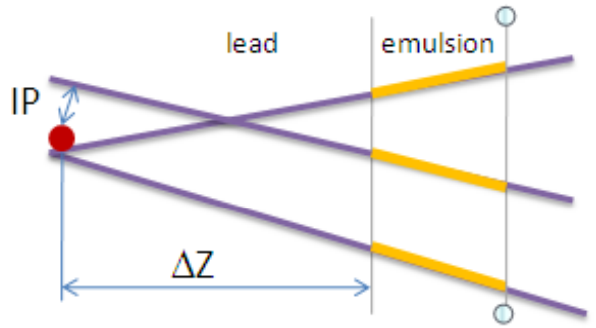
Emulsion gives 3D vector data, with a few micron precision of the vertex accuracy.

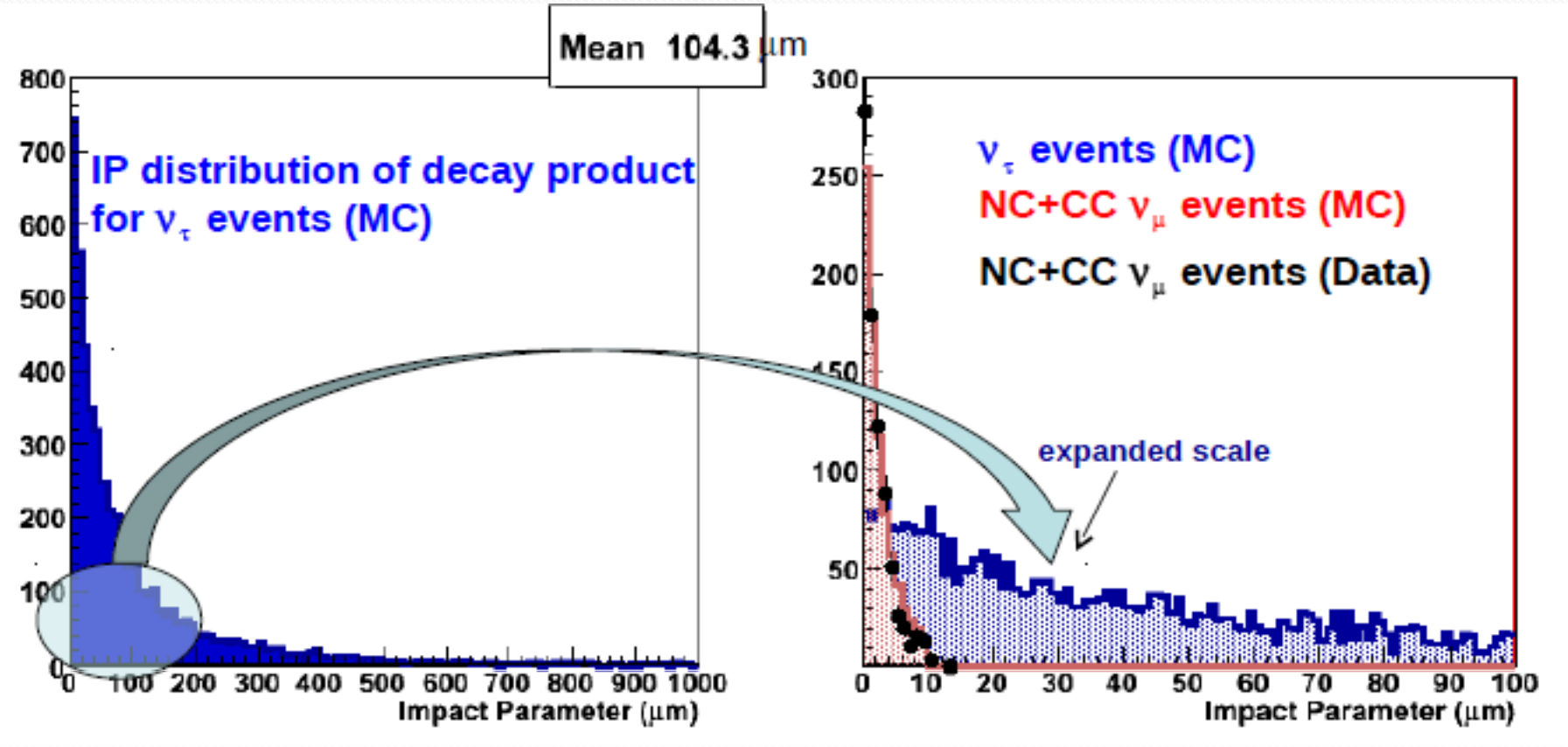
The frames correspond to scanning area. Yellow short lines are measured tracks. Other colored lines are interpolation or extrapolation.

Performance of ECC brick

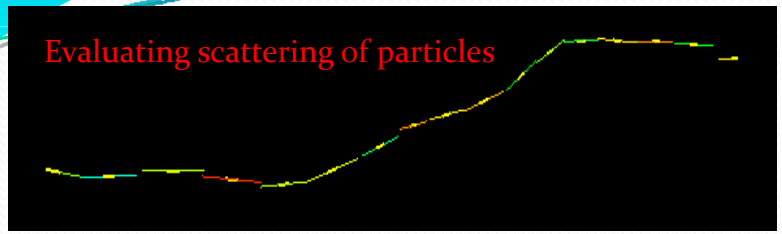
Impact Parameter (IP) measurement:

The IP evaluation is a crucial point to detect decay topology.

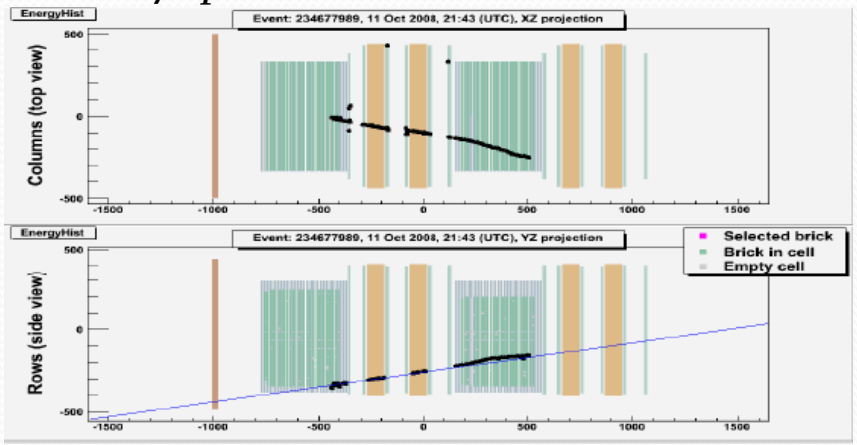




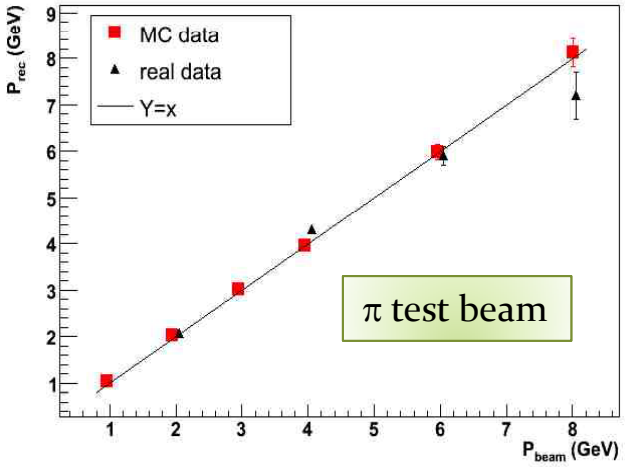
Momentum measurement by MCS

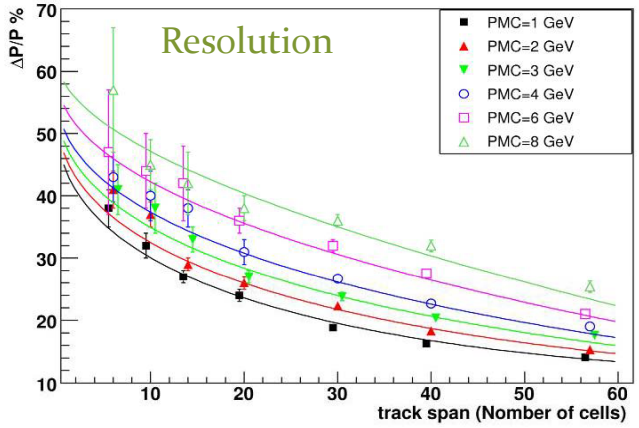


$$\theta_0 = \frac{13.6MeV}{\beta cp}\sqrt{x/X_0}\left[1+0.038\ln(x/X_0)\right]$$

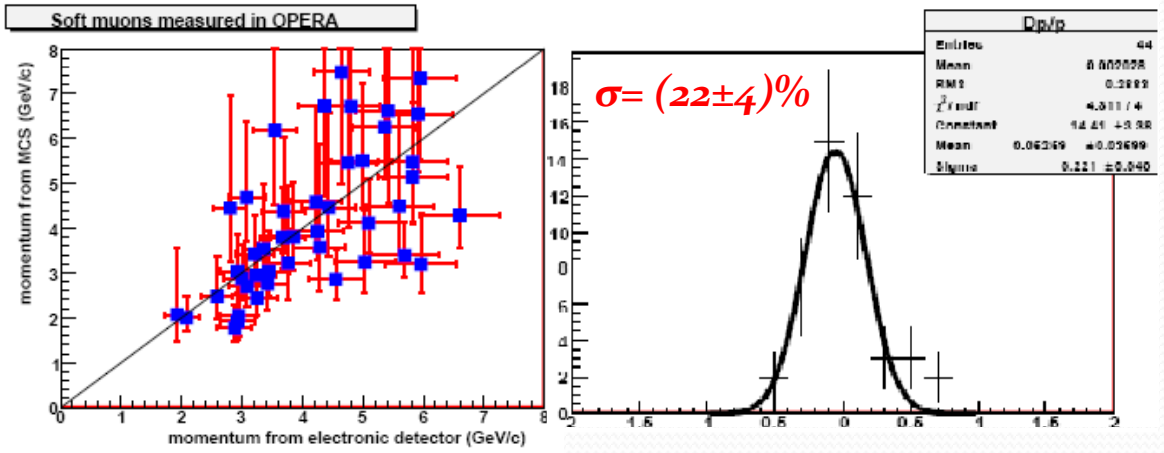


Linearity of momentum center

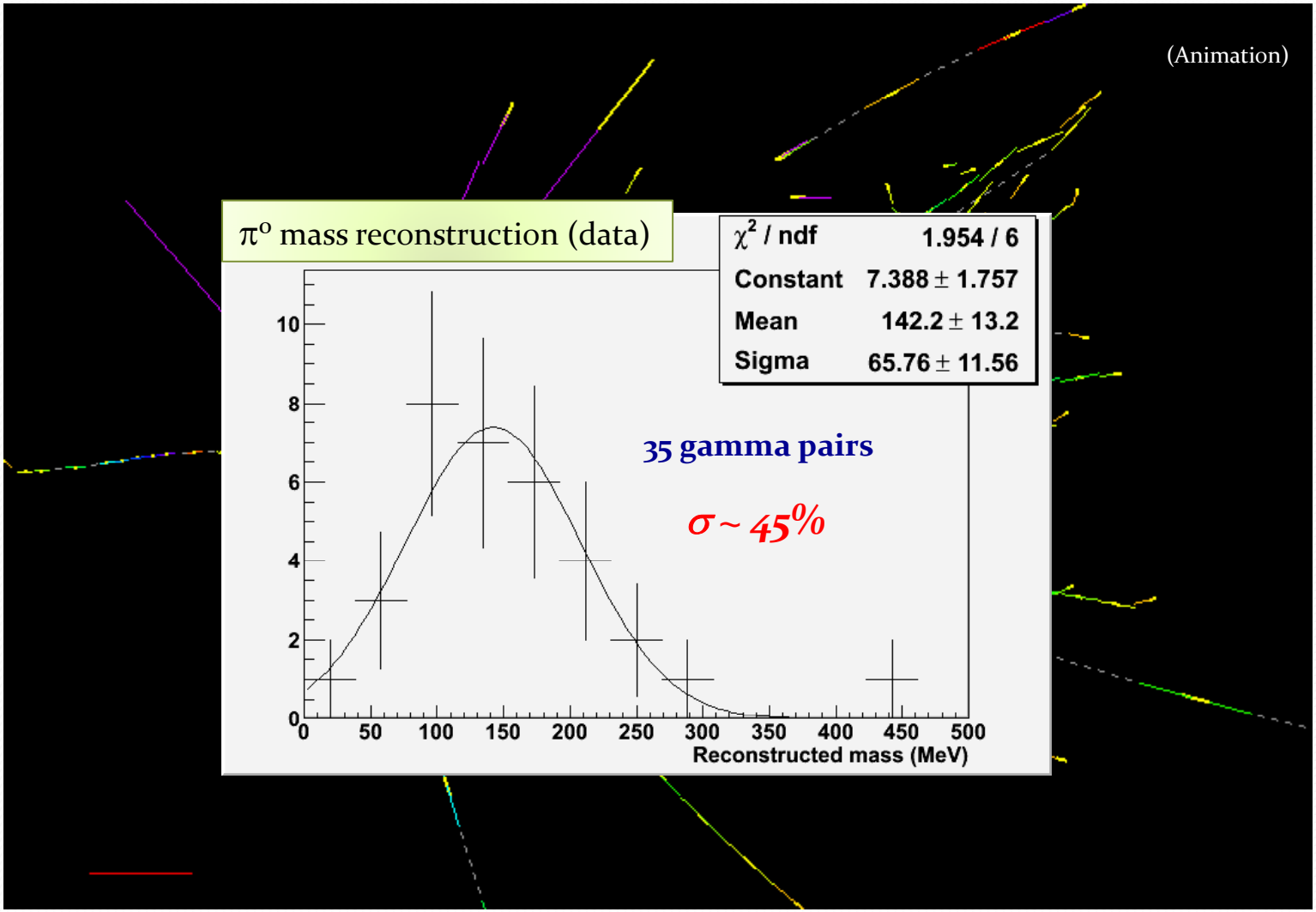




soft muons in the bricks

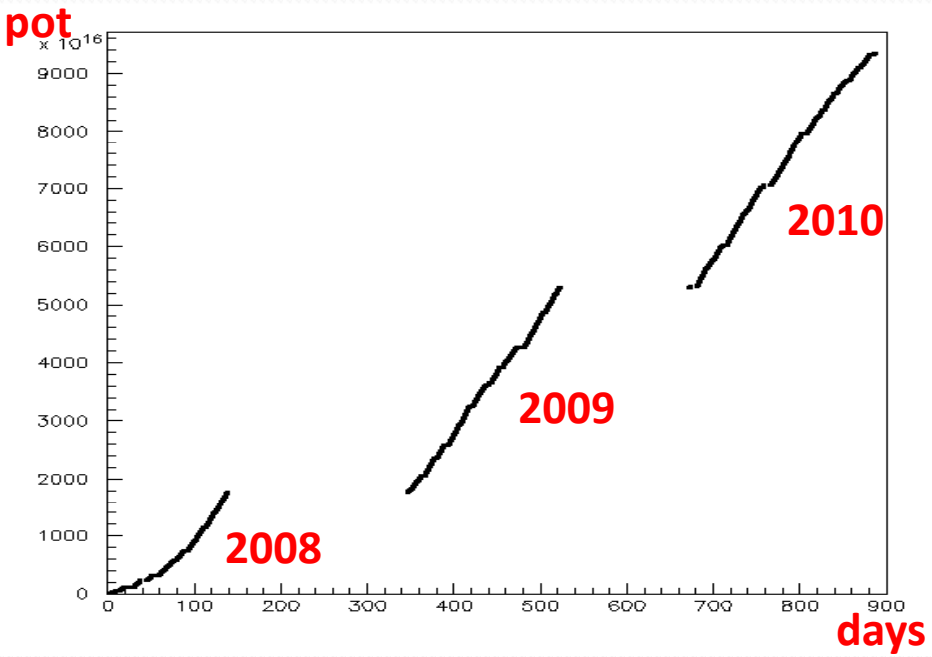


Gamma reconstruction analysis in ECC brick



CNGS physics runs

year	beam days	protons on target	SPS eff.	events in the bricks	run
2008	123	1.78×10^{19}	61%	1698	Physics runs
2009	155	3.52×10^{19}	70%	3693	Physics runs
2010	187	4.04×10^{19}	81%	4248	Physics runs

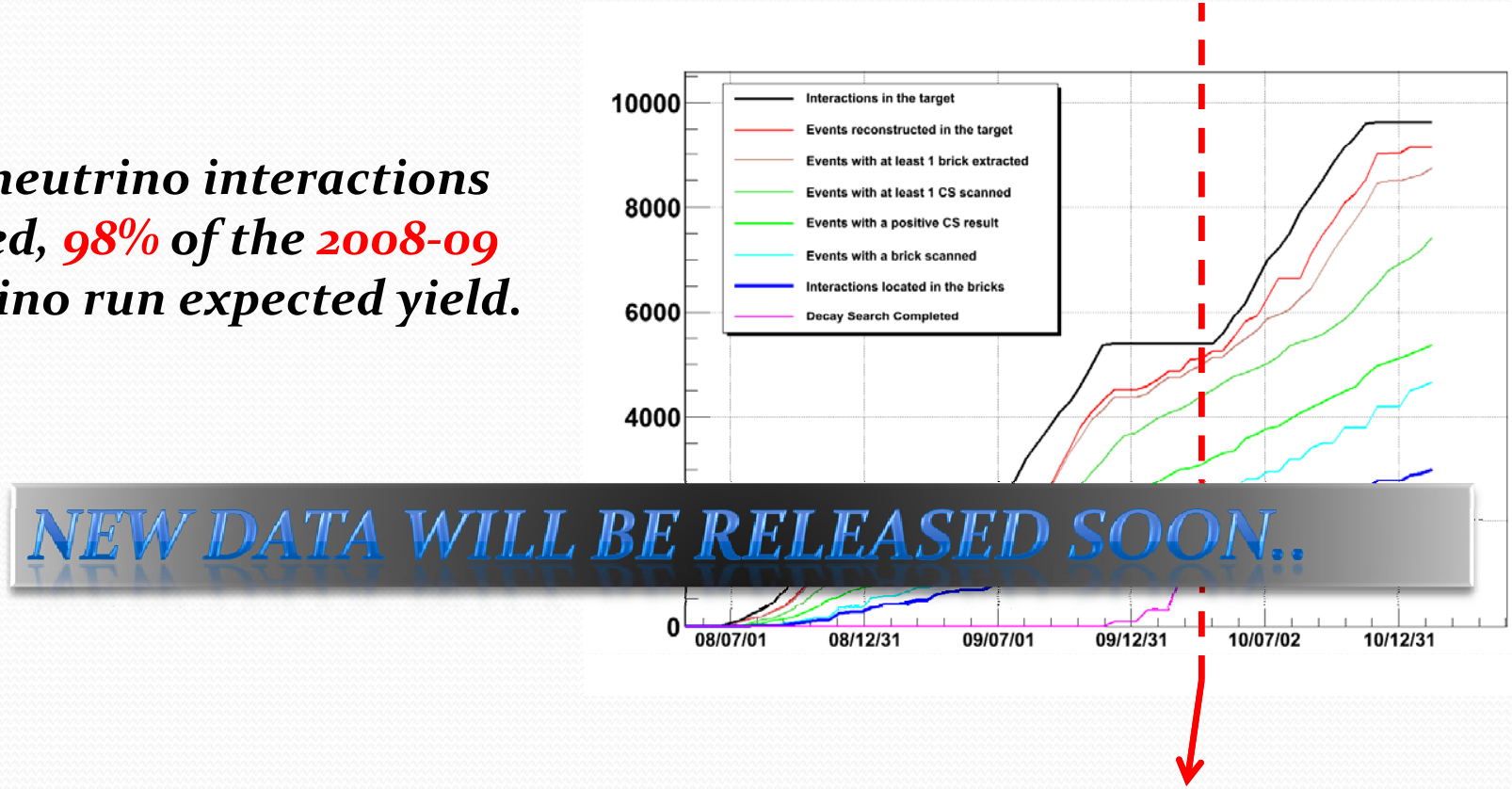


In total 9639 events collected (within 1σ w.r.t. expectation from pot)

➔ 2.1 nominal years in 3 years

Analysis status in ECC brick

3006 neutrino interactions located, 98% of the 2008-09 neutrino run expected yield.



The first results was opened and published at June 2010*.

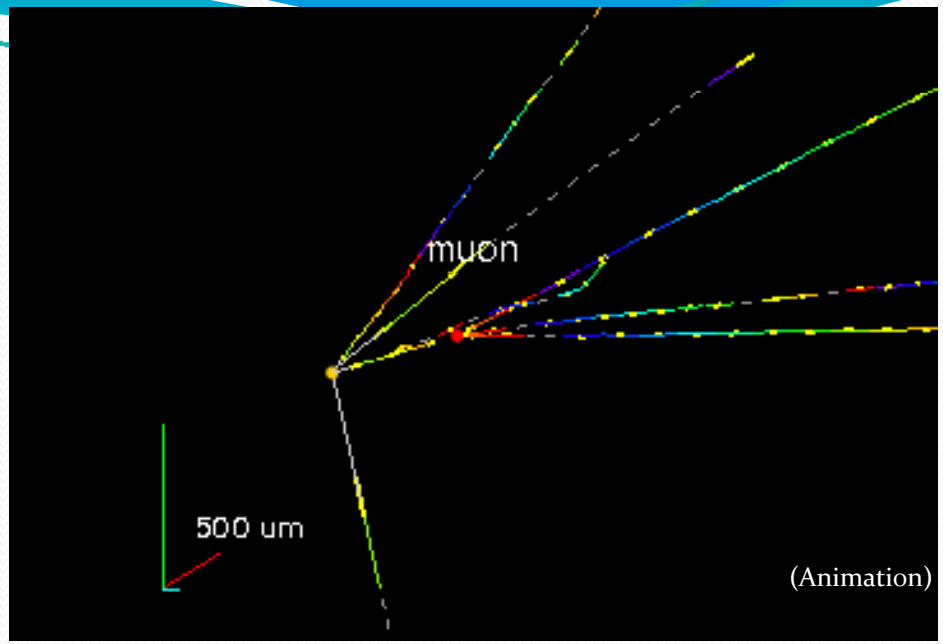
*Phys.Lett.B691:138-145,2010

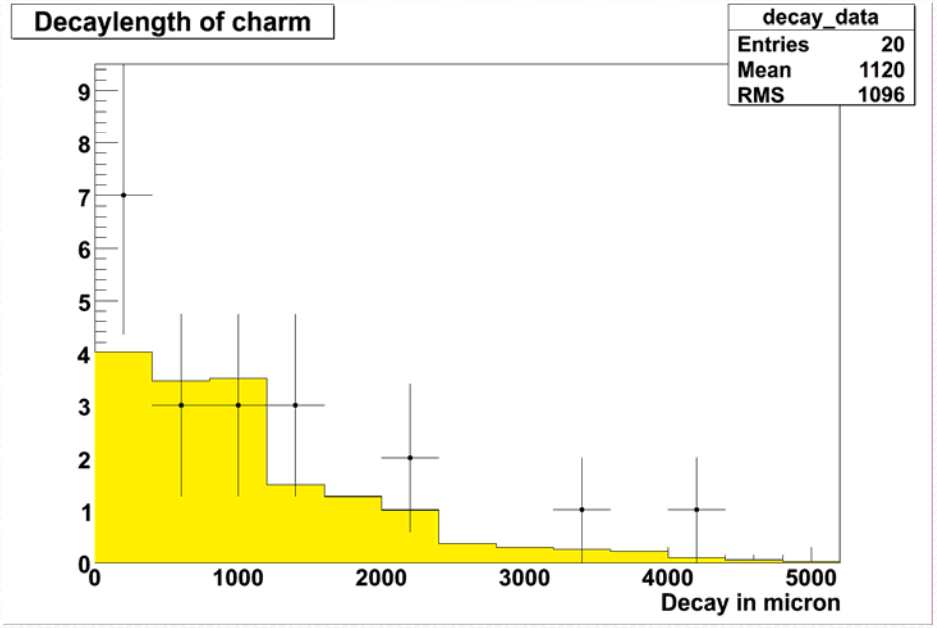
Charm candidate events

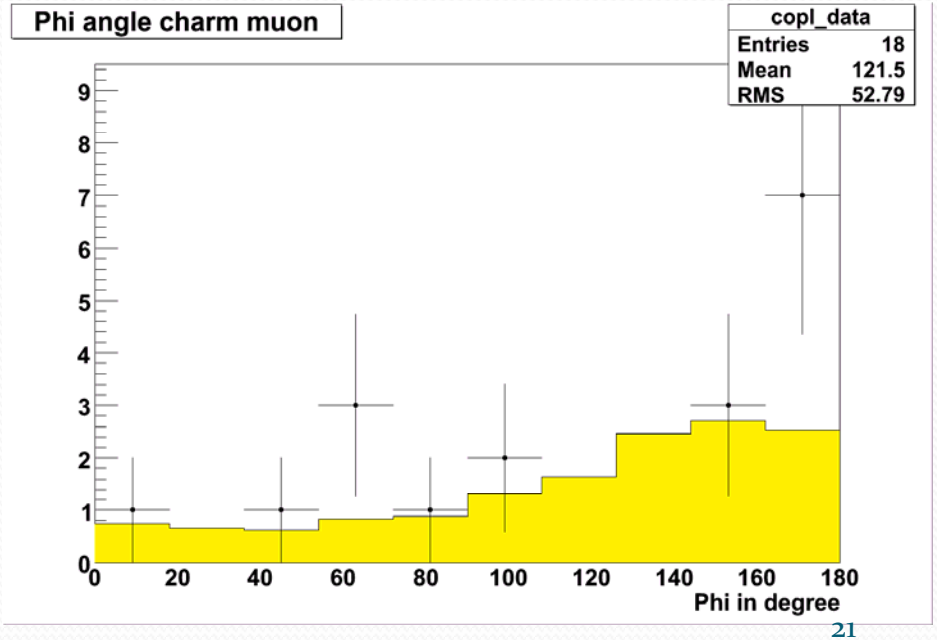
- proof of the τ efficiency -

On the published data sample

- ***20 charm events*** selected
  (3 events with 1-prong kink topology)
- ***Expected: 16.0 ± 2.9***
  (0.80 ± 0.22 with kink)
- ***~ 2 BG events*** expected







The first ν_τ candidate event was found

Physics Letters B 691 (2010) 138–145

Contents lists available at ScienceDirect

Physics Letters B

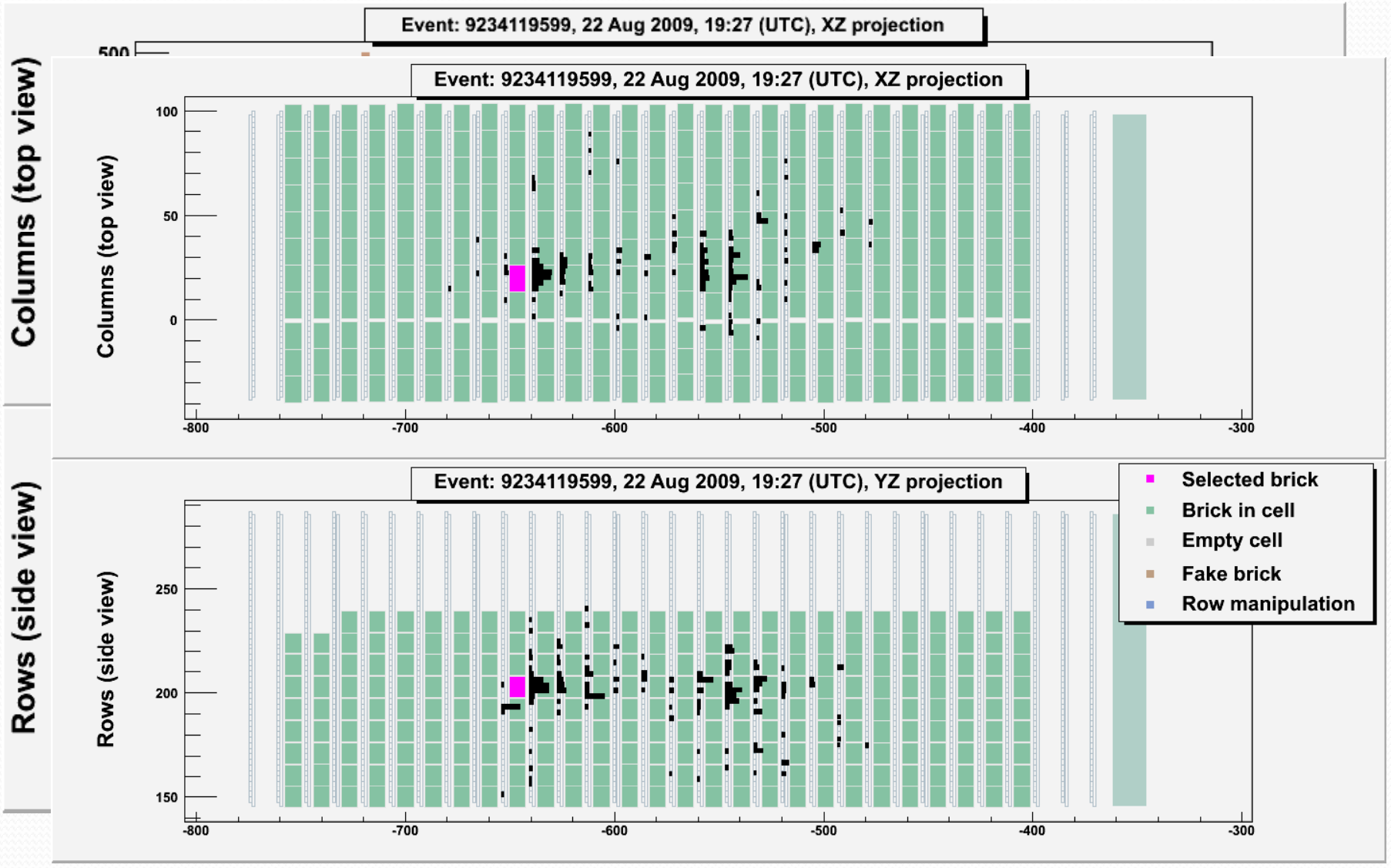
www.elsevier.com/locate/physletb

Observation of a first ν_τ candidate event in the OPERA experiment in the CNGS beam

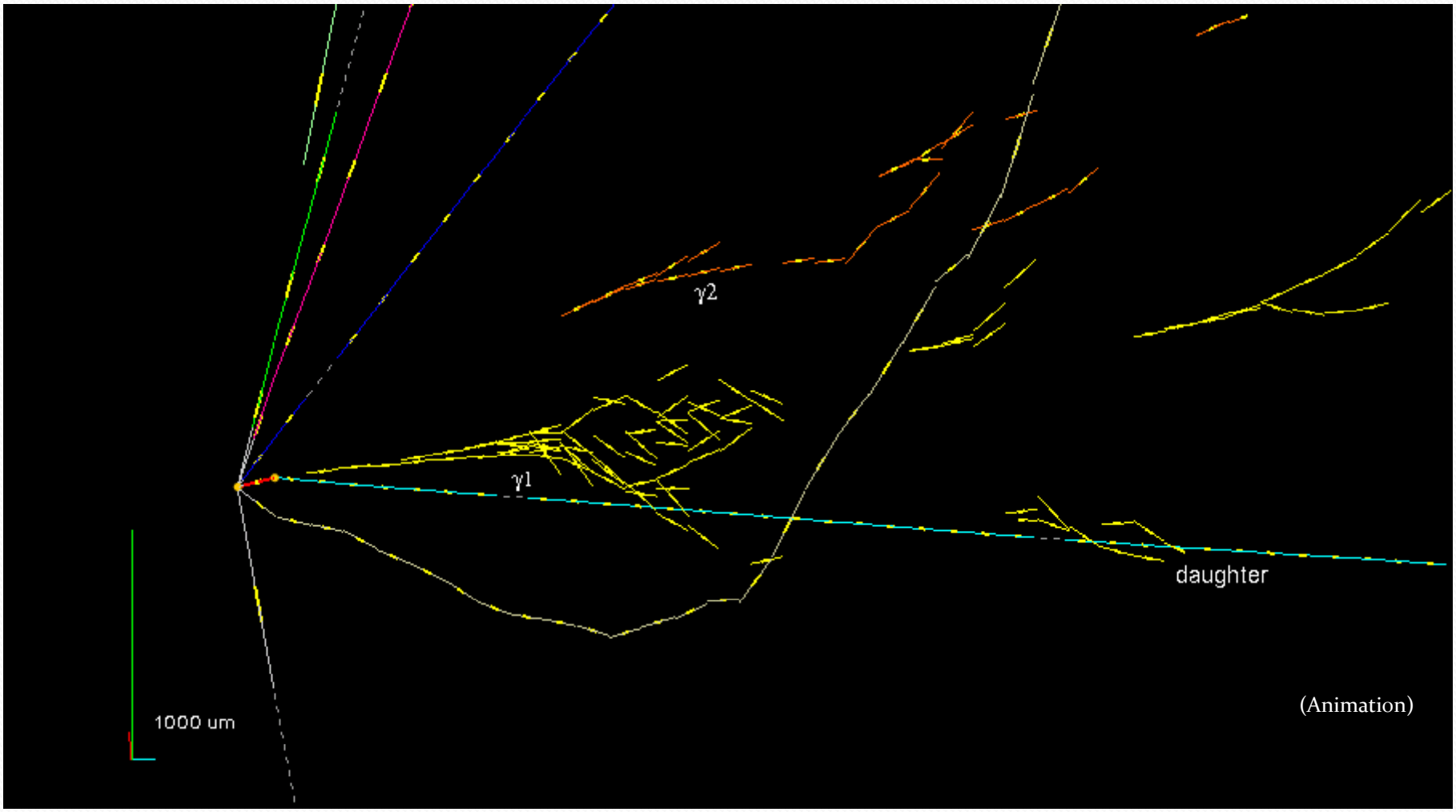
Event number 9234119599,
taken on 22 August 2009, 19:27 (UTC)

This result was opened at June/2010.

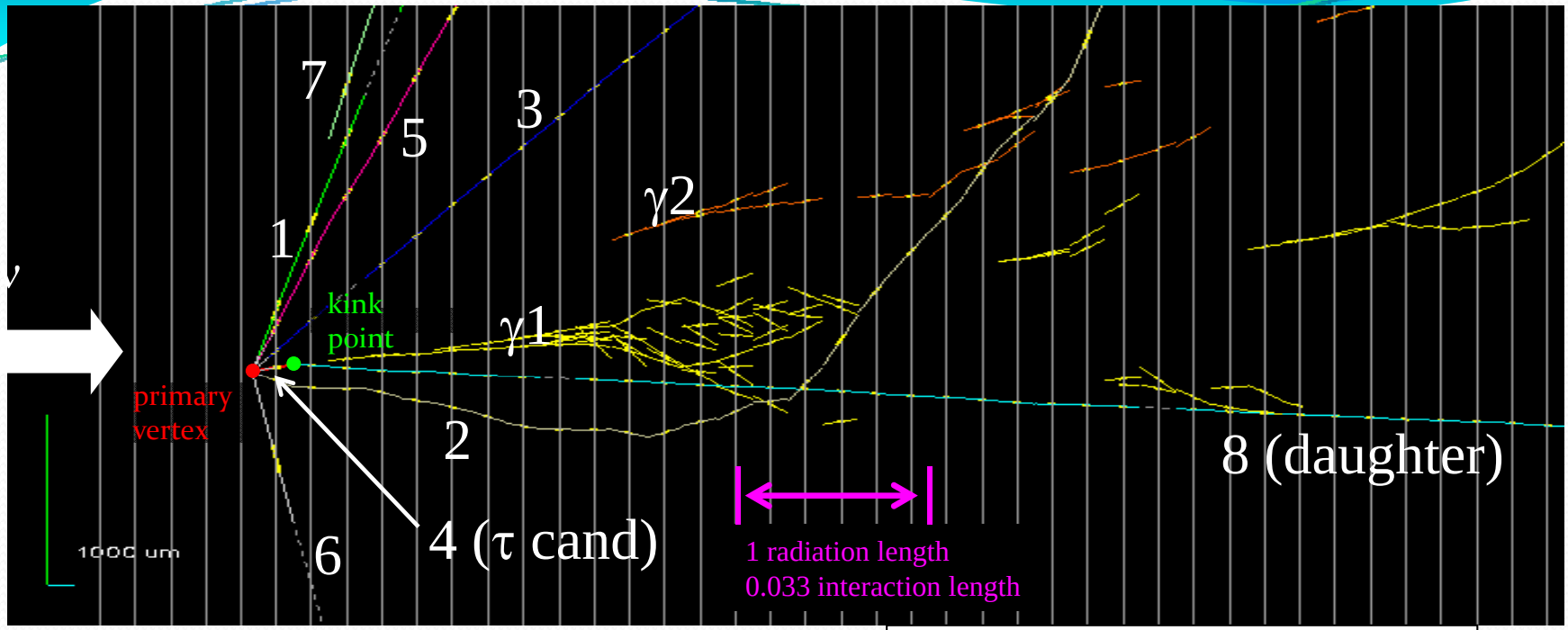
The ν_τ candidate event as seen by the electronic detectors...



...and as seen in emulsion

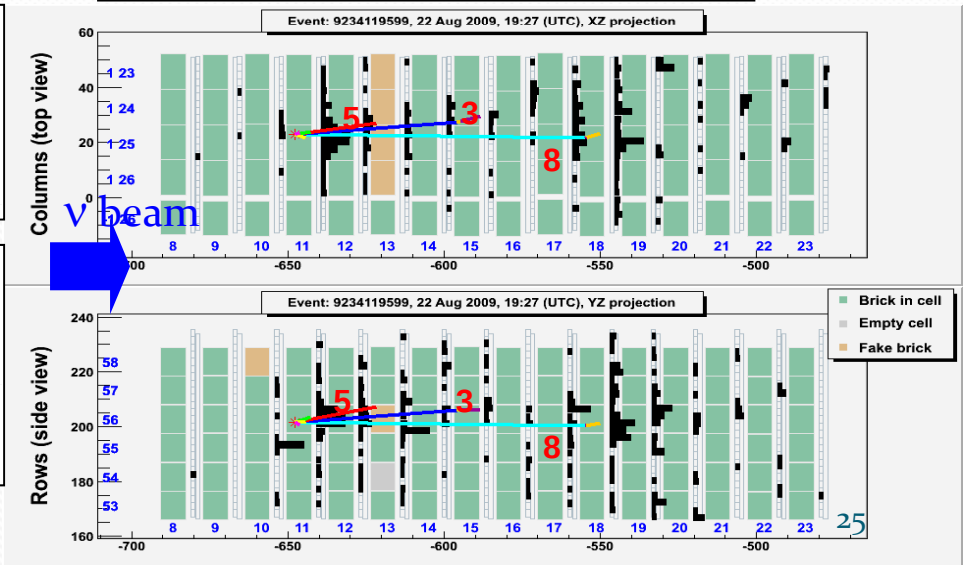


Event topological features (Side view)



track #	tan θ_x	tan θ_y	pβ [GeV/c]	
1	0.176	0.363	$0.78^{+0.13}_{-0.10}$	top view
2	-0.650	0.000	$0.32^{+0.31}_{-0.11}$	
3	0.108	0.113	$1.97^{+0.33}_{-0.25}$	
4（parent）	-0.027	0.022		
5	0.157	0.267	$1.30^{+0.22}_{-0.16}$	side view
6	0.334	-0.584	$0.36^{+0.18}_{-0.09}$	
7(from neutral track)	0.438	0.419	$0.49^{+0.29}_{--0.13}$	
8（daughter）	-0.007	-0.014	12^{+6}_{-3}	

The viewer of scintillation Target Tracker



γ attachment to the vertices

Pointing resolution (1σ) for a given gamma: function of scattering and distance

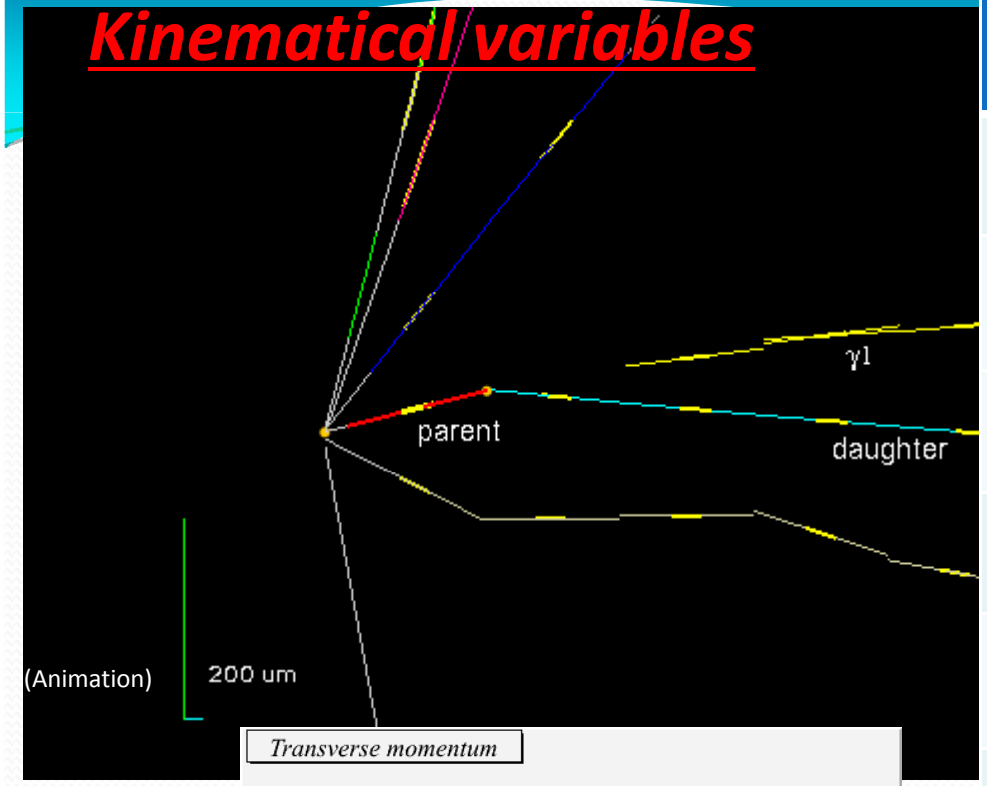
	Distance from 2ry vertex (mm)	IP to 1ry vertex (μm) <resolution>	IP to 2ry vertex (μm) <resolution>	Prob. of attach. to 1ry vtx*	Prob. of attach. to 2ry vtx*	Attachment hypothesis
γ1	2.2	45.0 <11>	**7.5** <7>	$<10^{-3}$	**0.32**	**2ry vertex**
γ2	12.6	85.6 <56>	**22** <50>	0.10	**0.82**	**2ry vertex** (favored)

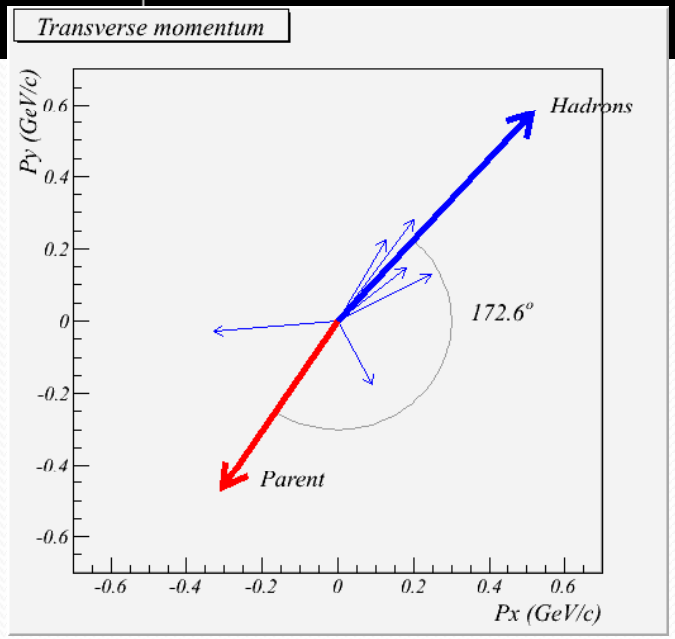
* probability to find an IP larger than the observed one

	Energy (GeV)
γ 1	5.6 ± 1.0 ± 1.7
γ 2	1.2 ± 0.4 ± 0.4

γ1 + γ2	π (8) + γ1 + γ2
120 ± 20 ± 35 MeV	$640\ ^{+125}_{-80}\ ^{+100}_{-90}$ MeV

Kinematicdl variables





VARIABLE	Measured	Selection criteria
Kink (mrad)	**41 ± 2**	**>20**
Decay length (μm)	**1335 ± 35**	**Within 2 plates**
P daughter (GeV/c)	**$12\ ^{+6}_{-3}$**	**>2**
Pt daughter (MeV/c)	**$470\ ^{+230}_{-120}$**	**>300 (γ attached)**
Missing Pt (MeV/c)	**$570\ ^{+320}_{-170}$**	**<1000**
ϕ (deg)	**173 ± 2**	**>90**

Background sources

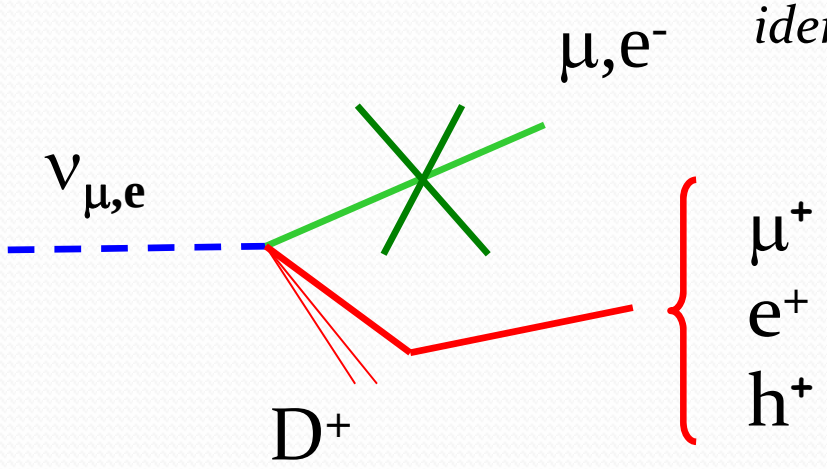
- Prompt ν_τ ~ 10^{-7}/CC
- Decay of charmed particles produced in ν_e interactions ~ 10^{-6}/CC
- Double charm production ~ 10^{-6}/CC

Main backgrounds:

- Decay of charmed particles produced in ν_μ interactions (CC & NC) ~ 10^{-5}/CC
- Hadronic interactions (CC & NC) ~ 10^{-5}/CC

Charm background

Primary lepton not identified



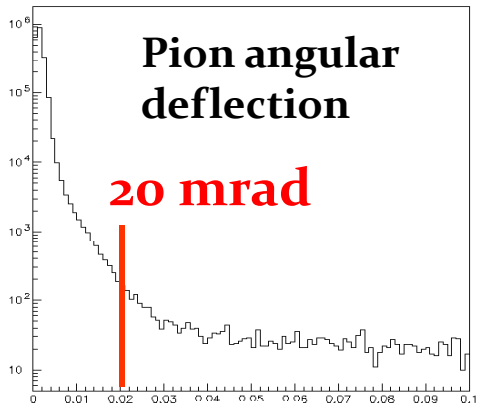
- *This background can be suppressed by identifying the primary lepton → ~ 96% muon ID*

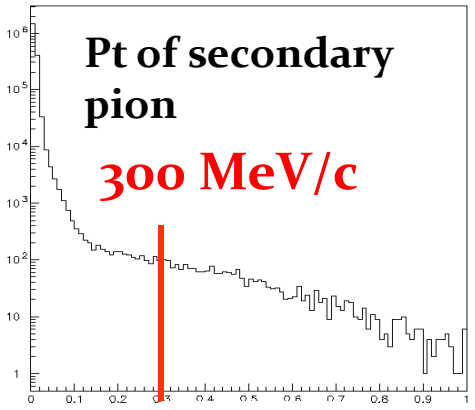
- *For the 1-prong hadronic channel* **0.007±0.004 (syst.)** *background events are expected for the analyzed statistics*

Simulation of the hadronic interaction BG

• *160 million events (0.5-15 GeV/c) of $\pi^+, \pi^-, K^+, K^-, p$ impinging 1 mm of lead, equivalent to 160 km of hadronic track length produced with FLUKA*

Typical Monte Carlo scattering distributions for 5 GeV π^+

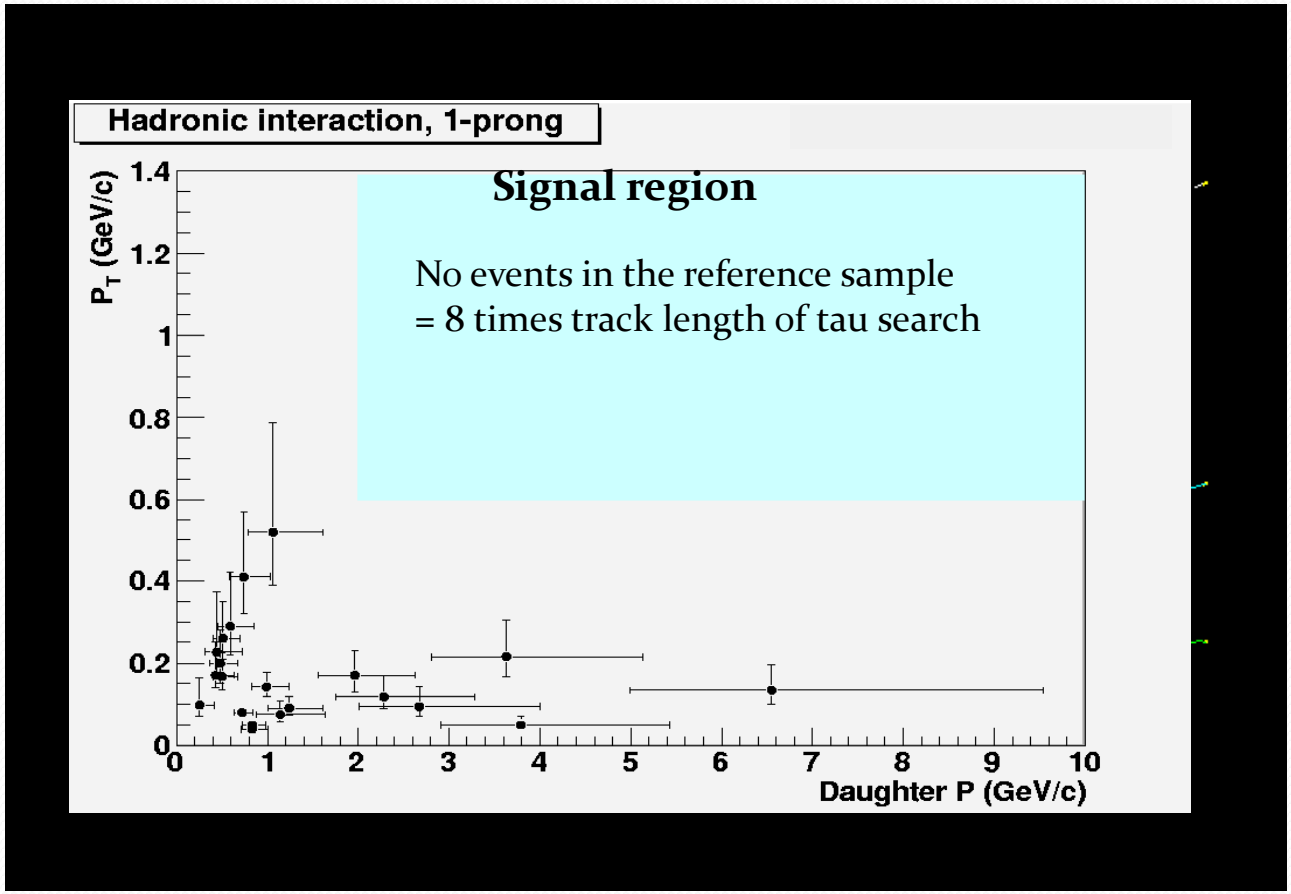




kink probability integrated over the ν_μ NC hadronic spectrum after 2 mm Pb and taking in to account the cuts on the event global kinematics:

$(3.8 \pm 0.2) \times 10^{-5}$ kinks/NC

Hadronic interaction background study in OPERA data



- *Search for "decay-like" interactions track far away from the primary vertex*
- *no background-like interaction has been found in the signal region*

90% CL upper limit of ***1.54 x 10^{-3} kinks/NC event***

Statistical significance

We observe 1 event in the 1-prong hadron τ decay channel, with a background expectation of:

0.007 events (charm)

0.011 events (hadronic interactions)

events 1-prong hadron:

0.018 ± 0.007 (syst)

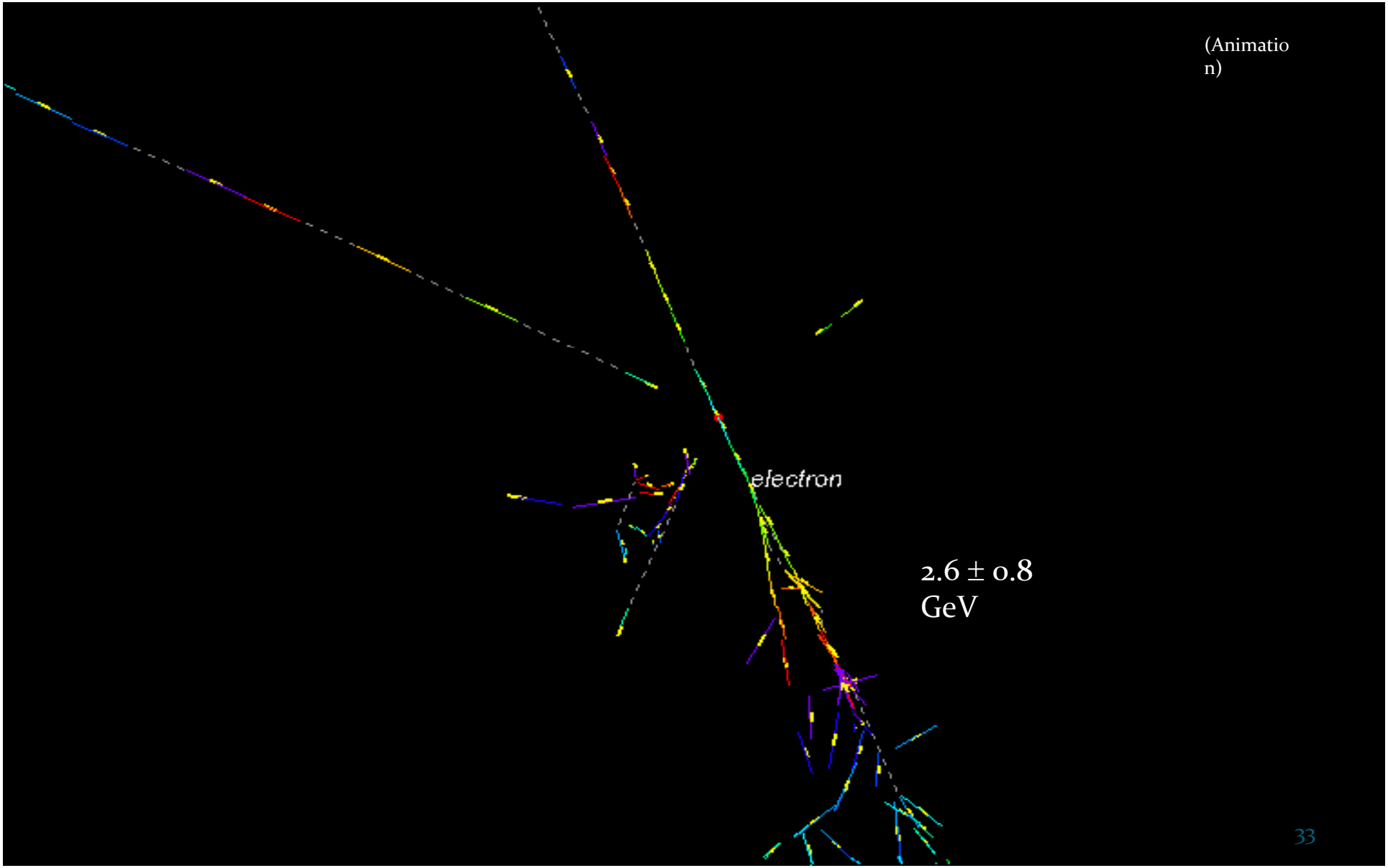
all decay modes: *1-prong hadron, 3-prongs + 1-prong μ + 1-prong e:*

0.045 ± 0.020 (syst) *events total BG*

Channel	Probability to observe 1 event due to BG	Statistical significance (σ)
1-prong hadron	1.8 %	2.36
all decay mode	4.5 %	2.01

ν_e events

13 ν_e candidate events have been observed.



Summary

- *The OPERA experiment is aimed at the discovery of neutrino oscillations in direct appearance mode through the study of the $\nu_\mu - \nu_\tau$ channel.*

- *A subsample of 2008-2009 data taking corresponding to 1.85×10^{19} pot (20% of the available statistics) have been opened and published on June 2010.*
  - *Decay topologies due to charmed particles have been observed in good agreement with expectations, as well as several events induced by ν_e present as a contamination in the ν_μ beam.*
  - *One muon-less event candidate for the τ ➔ 1-prong hadron decay topology has been detected (0.54 ±0.13(syst.)expected).*
- *By considering 1-prong hadron channel, the statistical significance on the measurement of a first ν_τ candidate event is 2.36 σ.*

Outlook

- *In 2008 – 2010, data has been taken corresponding to 2.1 nominal years.*
  In 2010, beam intensity has reached 90% nominal and SPS efficiency 81%.

- *Analysis on 2008+2009 full sample will be released soon.*

- *Analysis of 2010 events is being performed in parallel.*

- ***Next CNGS run will in 2011 and 2012.***

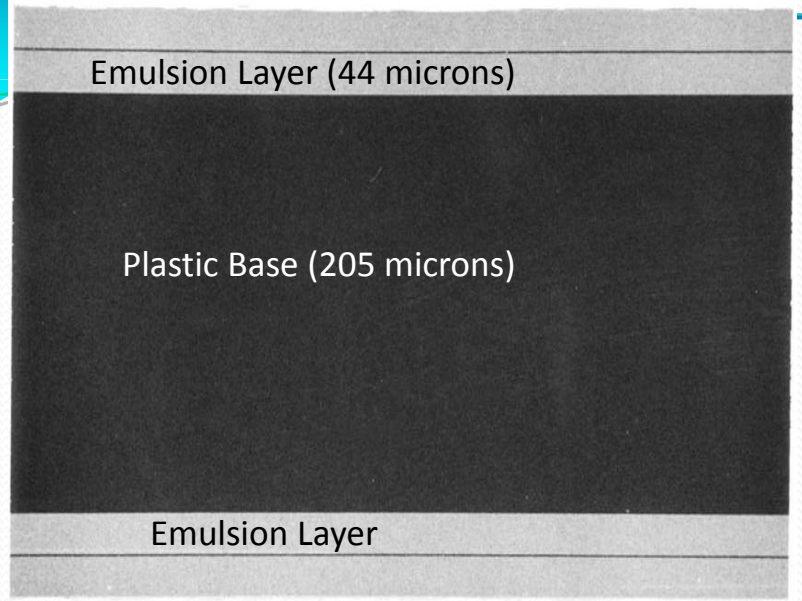
- ***From 18th of March 2011, CNGS run will start with 6 extra weeks of beam in dedicated mode . It will correspond to 1.2 nominal years if CNGS and OPERA efficiencies are at the 2010 level.***

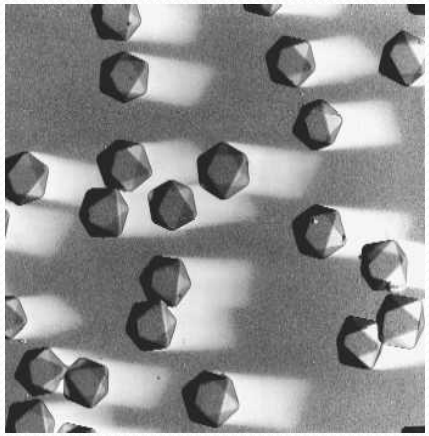
- ***If 2012 run is like 2011: data on ~ 19.9×10^19 POT or ~ 88% of Proposal beam intensity will be collected.***

Thank you for your attention!

BACKUP

INDUSTRIAL EMULSION FILMS BY *FUJI FILM*





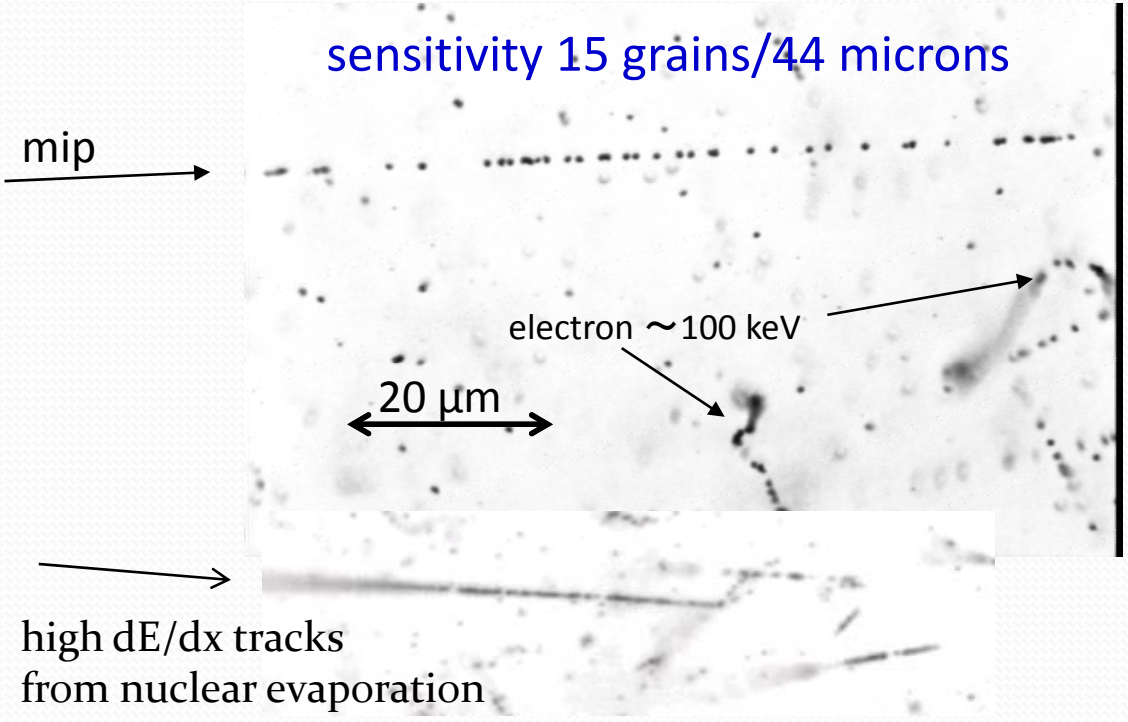
basic detector: AgBr crystal,

size = 0.2 micron

detection eff.= 0.16/crystal

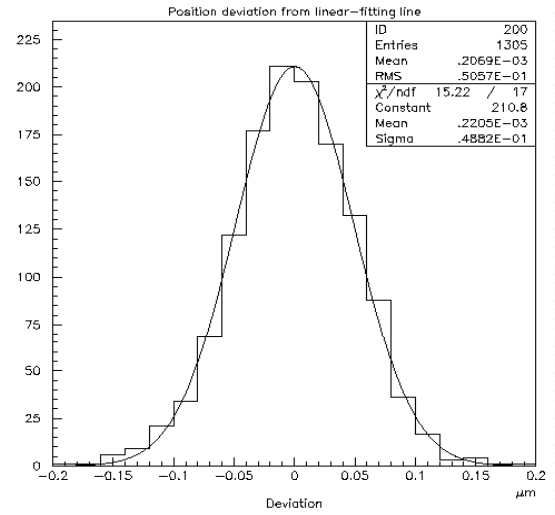
10^{13} "detectors" per film

sensitivity 15 grains/44 microns



intrinsic resolution: 50 nm

deviation from linear-fit line. (2D)



39

OPERA expected performance (Proposal)

τ decay channel	B.R. (%)	Signal $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2	Background
$\tau \rightarrow \mu$	17.7	2.9	0.17
$\tau \rightarrow e$	17.8	3.5	0.17
$\tau \rightarrow h$	49.5	3.1	0.24
$\tau \rightarrow 3h$	15.0	0.9	0.17
Total		10.4	0.75

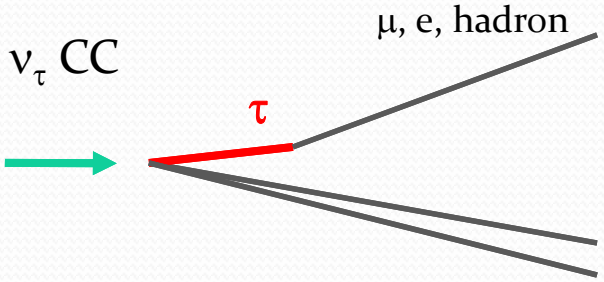
Main background sources:

- Production and decay of charmed particles
- Hadron reinteractions
- Large angle muon scattering

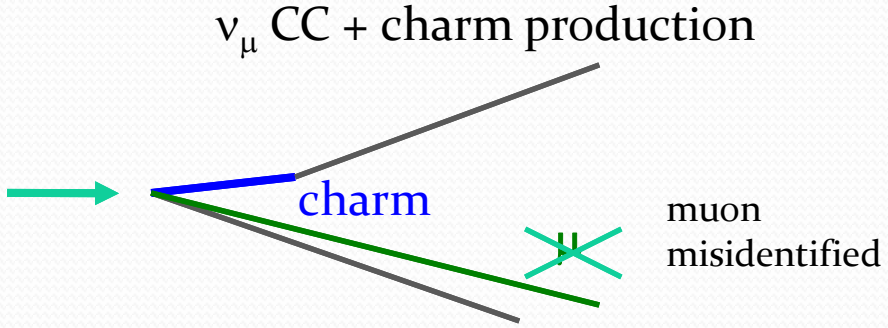
Assume 22.5 x 10^{19} pot

Example: charm BG to tau decays

Signal



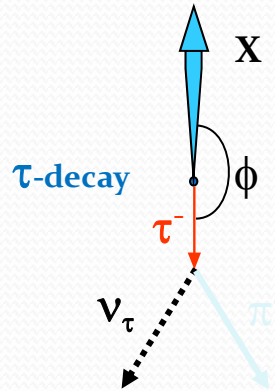
Background



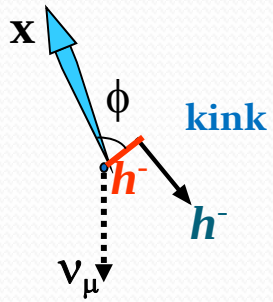
Nominal selection criteria for hadron kink topology

- *Kink occurring within 2 lead plates downstream of the primary vertex*
- *Kink angle larger than 20 mrad*
- *Daughter momentum higher than 2 GeV/c*
- *Decay P_t higher than 600 MeV/c,*
  300 MeV/c if ≥ 1 γ pointing to the decay vertex
- *Missing P_t at primary vertex lower than 1 GeV/c*
- *Azimuth angle between the primary hadron shower momentum direction and the parent track direction larger than π/2 rad*

Signal : ϕ =180°



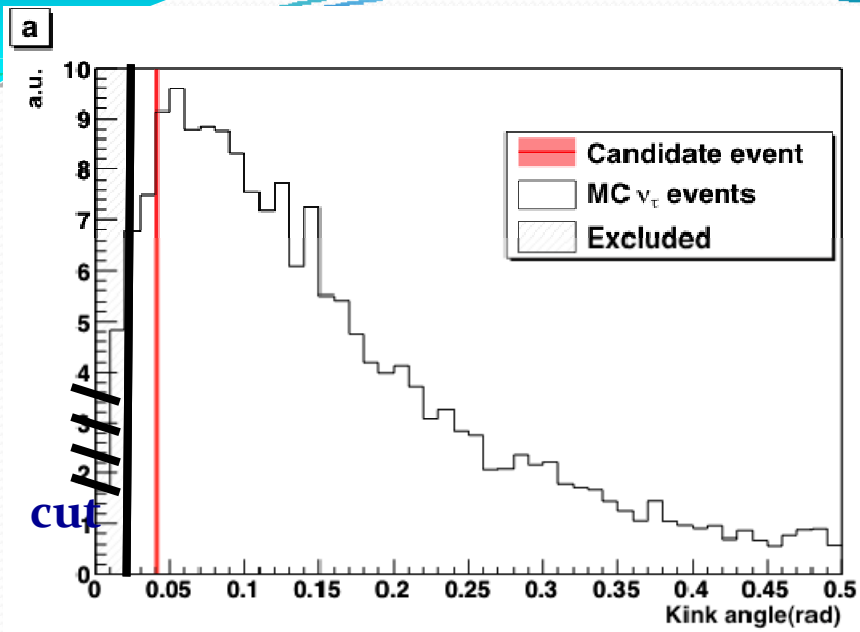
$$\nu_\tau + N \rightarrow \tau^- + X$$



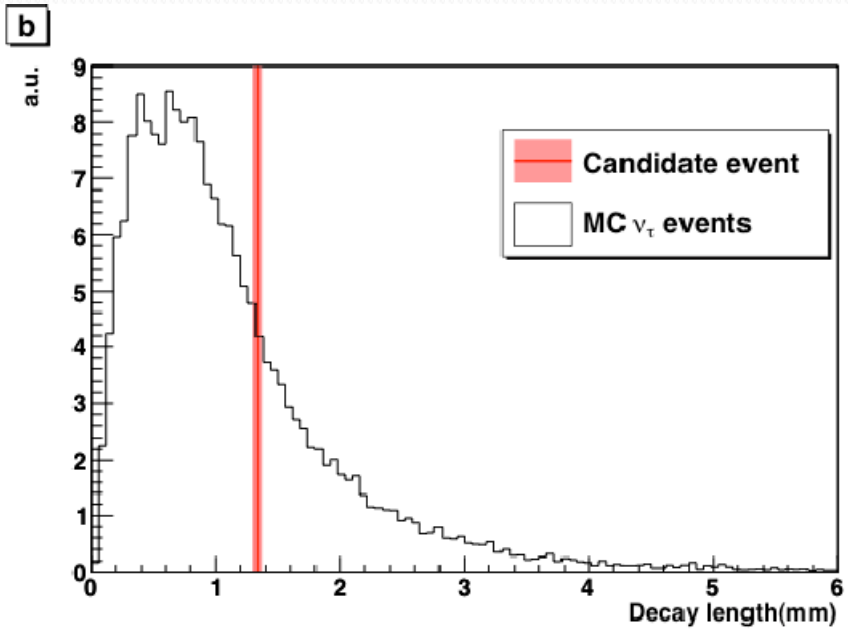
BG: small ϕ

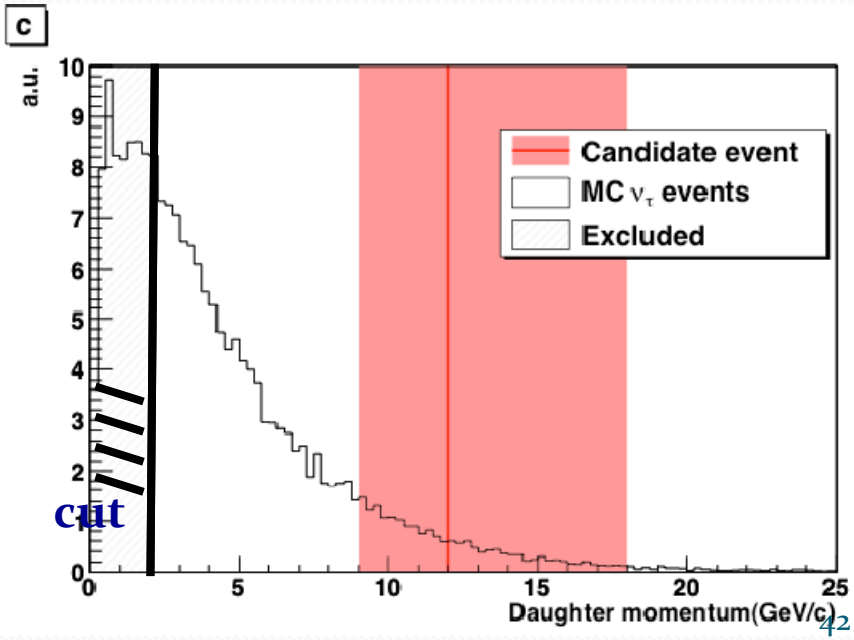
$$\nu_\mu + N \rightarrow \nu_\mu + h^\pm + X$$

Features of the decay topology



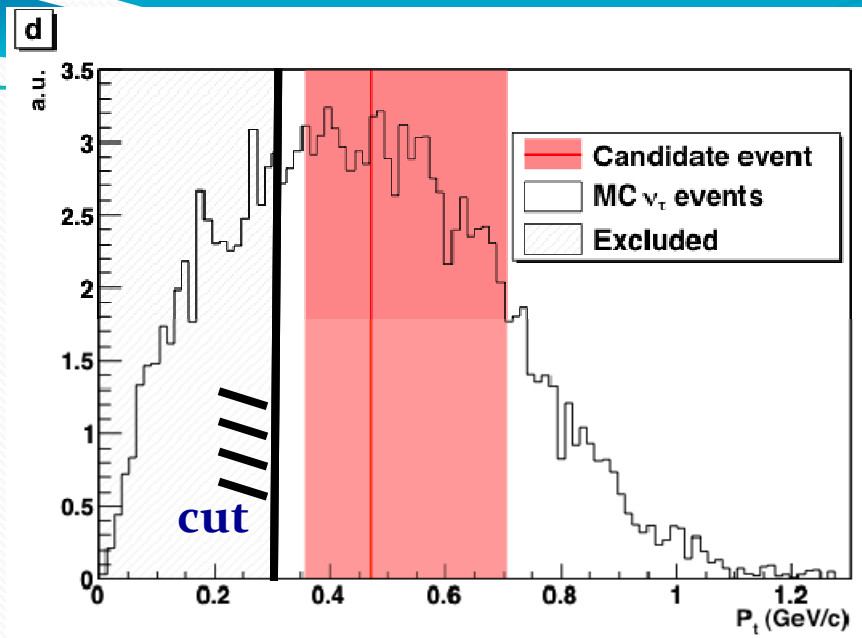
red bands: values for the "interesting" event with uncertainties



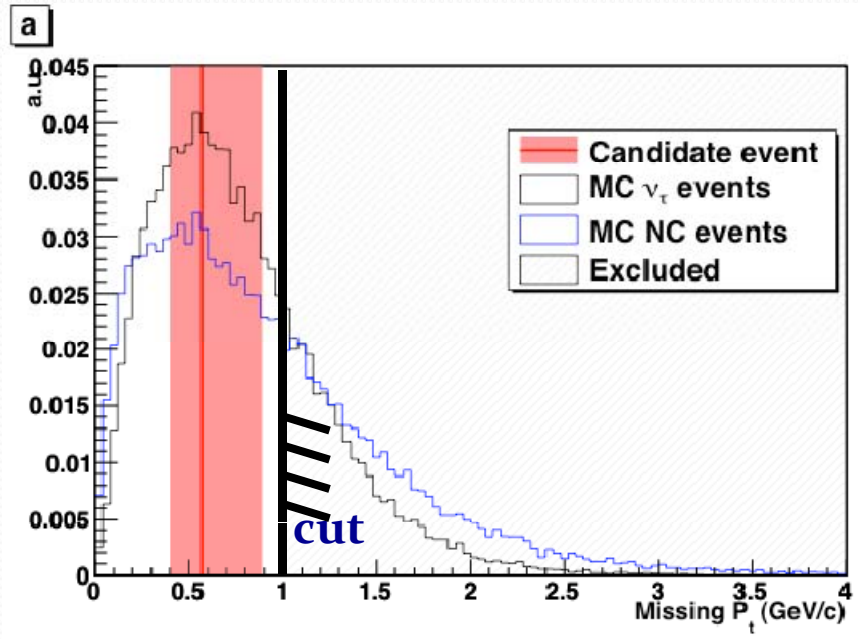


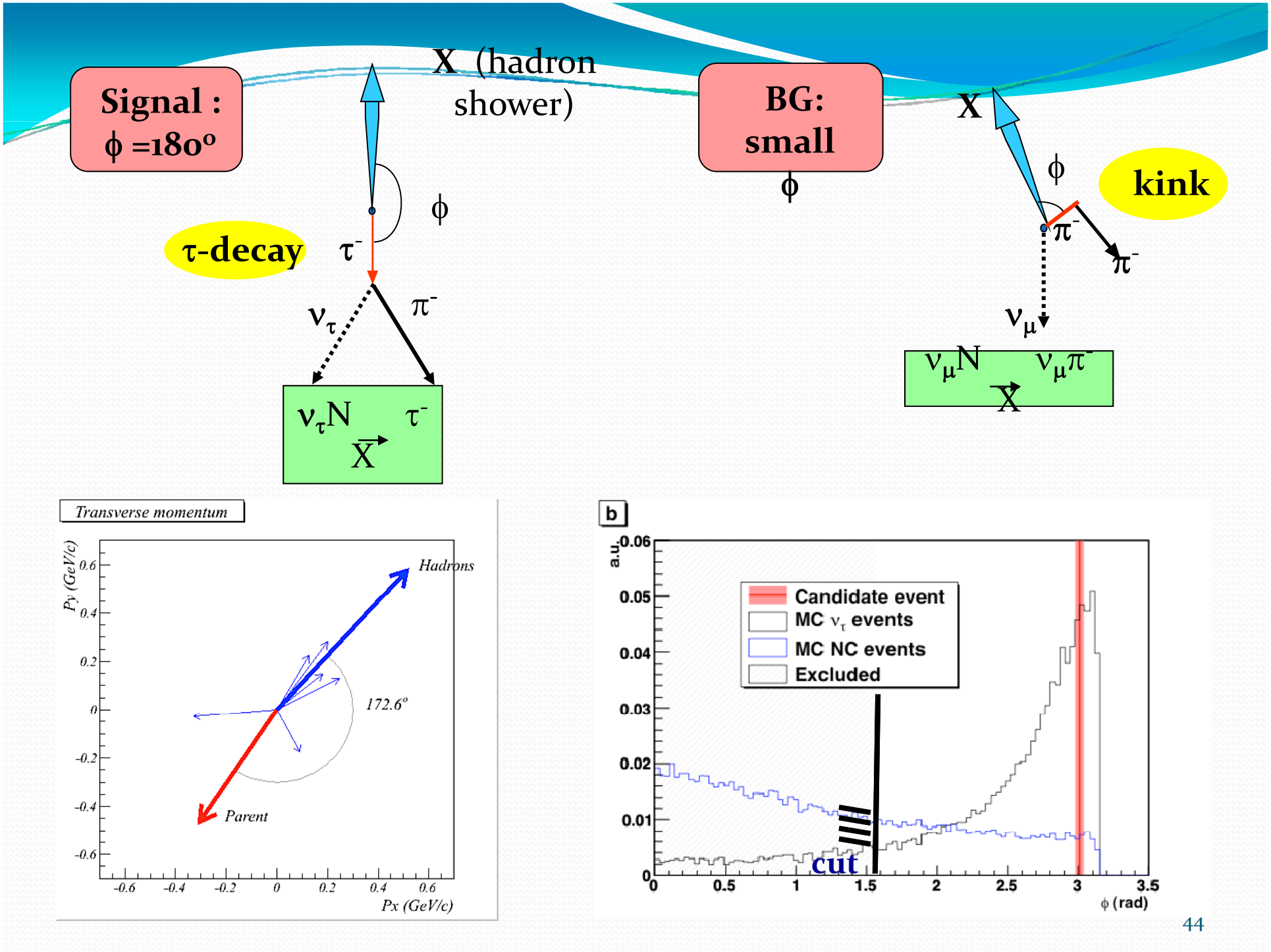
Kinematical cuts

Reject hadron interactions with small P_t at secondary vertex



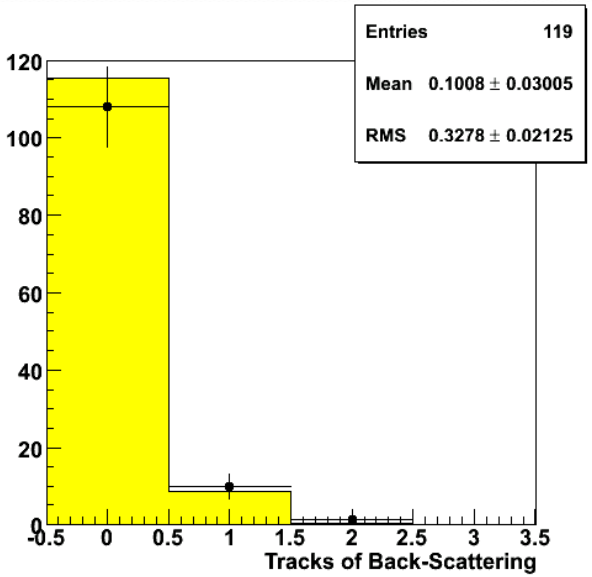
Reject NC events with larger missing P_t at primary vertex

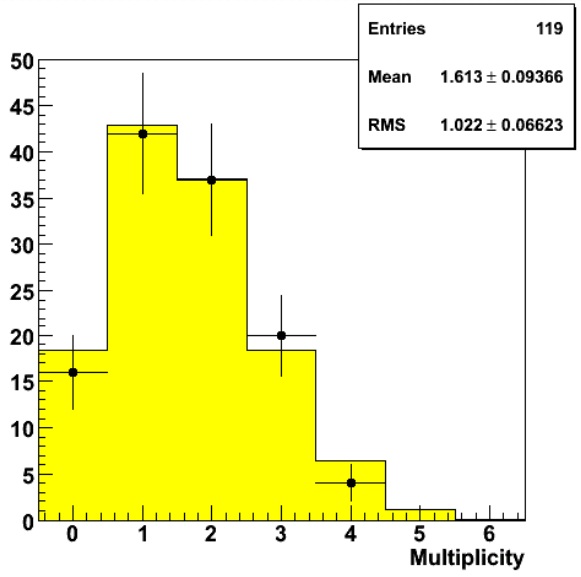


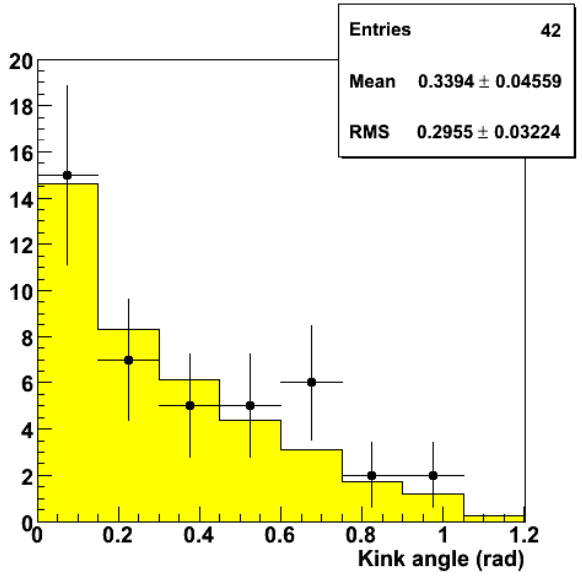

Signal :
ϕ =180°
X (hadron shower)
ϕ
τ-decay
τ⁻
ν_τ
π⁻
ν_τN
τ⁻
X
BG:
small
ϕ
X
ϕ
kink
π⁻
π⁻
ν_μ
ν_μN
ν_μπ⁻
X
Transverse momentum
Py (GeV/c)
Px (GeV/c)
Hadrons
172.6°
Parent
b
a.u.
Candidate event
MC ν_τ events
MC NC events
Excluded
cut
ϕ (rad)

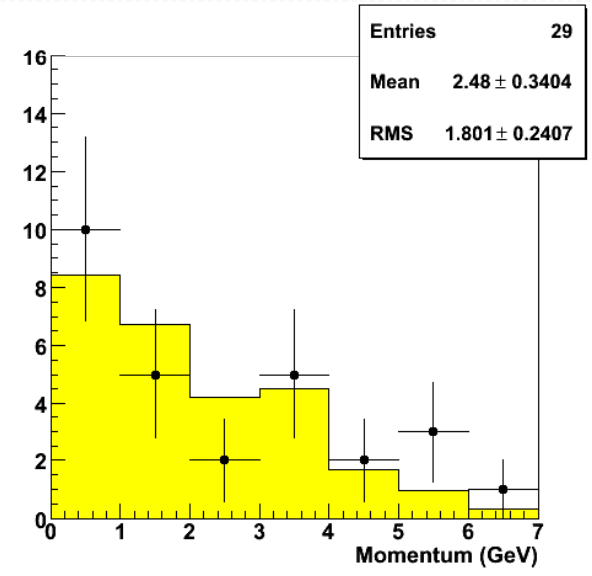
DATA/MC comparison: good agreement in normalization and shape

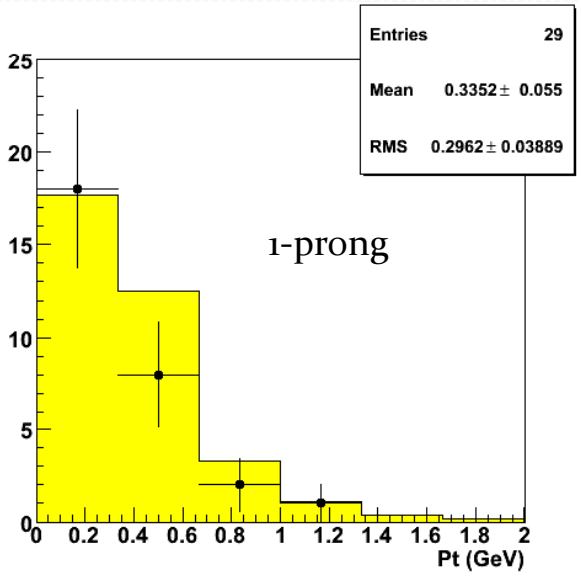
Beam test 4 GeV pion 18 times track length (20m) of tau search.

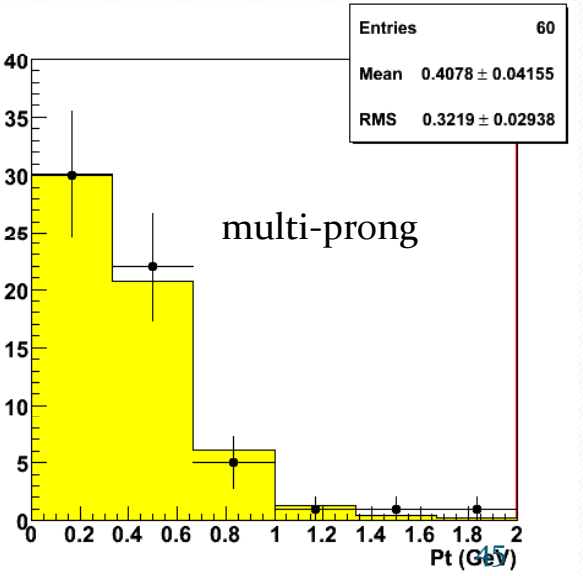






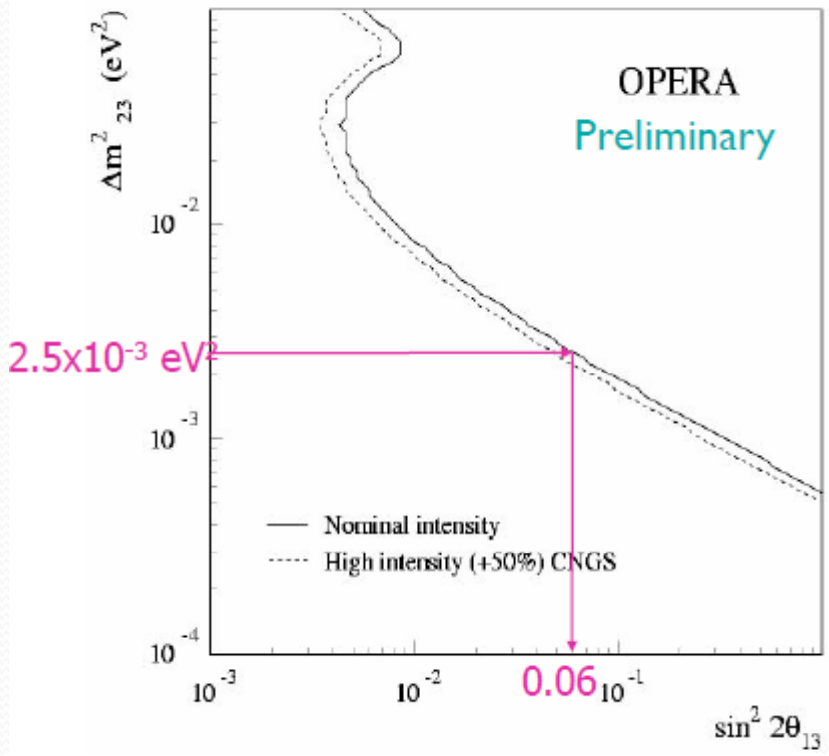






Sensitivity to Θ_{13}

Simultaneous fit on:
E_e, missing p_T and visible energy



full mixing, 5 years run @ 4.5×10^{19} pot / year

Θ_{13} (deg)	Signal $\nu_\mu \to \nu_e$	Background			
		$\tau \to e$	ν_μCC	ν_μNC	ν_eCC beam
9	9.3	4.5	1.0	5.2	18
7	5.8	4.5	1.0	5.2	18
5	3.0	4.5	1.0	5.2	18

Limits at 90% CL for
$\Delta m^2 = 2.5\times10^{-3}$ eV^2 full mixing

	$\sin^2 2\Theta_{13}$	Θ_{13}
CHOOZ	<0.14	11°
OPERA	<0.06	7.1°