

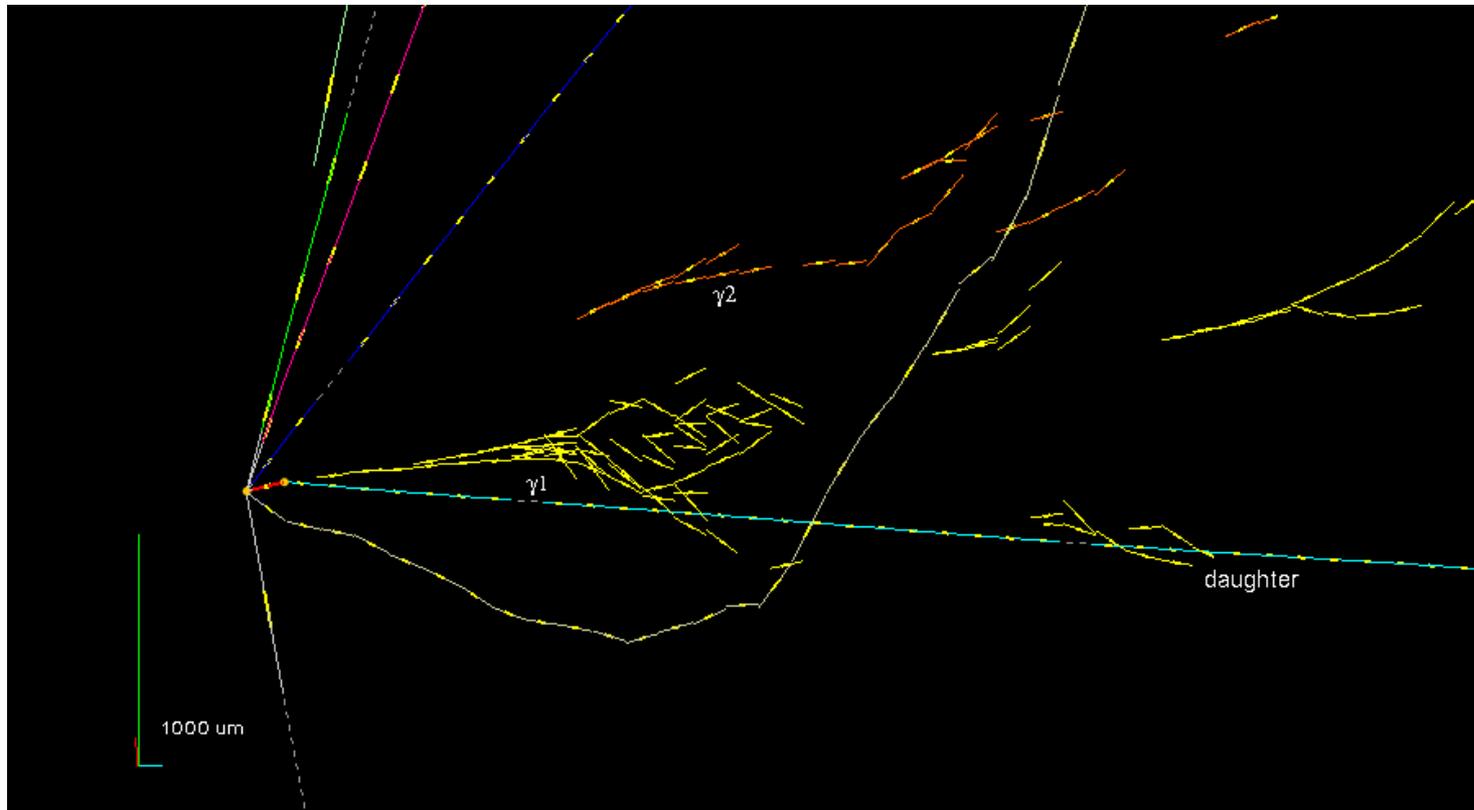


# Results of the OPERA experiment

*Giovanni De Lellis*

*University "Federico II" and INFN Napoli*

*On behalf of the OPERA Collaboration*



# *Outline of the talk*

- *The OPERA experiment and its detector*
- *The analysis chain*
- *Charmed hadron production*
- *Oscillation physics results*
- *Background studies*
- *Significance*

# PHYSICS: from neutrino mixing to oscillations

## 3x3 Unitary Mixing Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

## PMNS (Pontecorvo-Maki-Nakagawa-Sakata) Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

“Atmospheric” terms

Reactor experiments

“Solar” terms



OPERA

$$c_{ij} = \cos\theta_{ij}, \quad s_{ij} = \sin\theta_{ij}$$

# OPERA: first direct detection of neutrino oscillations in appearance mode

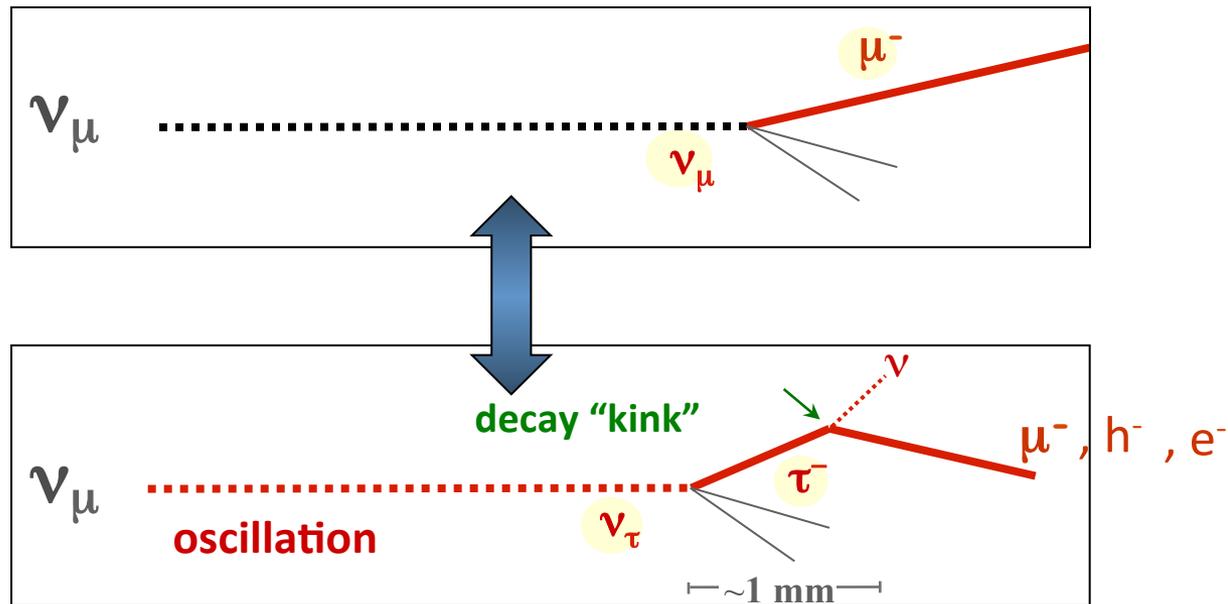
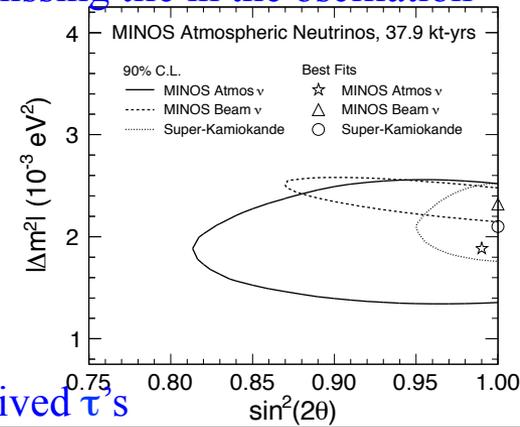
following the Super-Kamiokande (Macro and Soudan-2) discovery of oscillations with atmospheric neutrinos and the confirmation with solar neutrinos and accelerator beams. An important, missing tile in the oscillation picture.

The PMNS 3-flavor oscillation formalism predicts:

$$P(\nu_\mu \rightarrow \nu_\tau) \sim \sin^2 2\theta_{23} \cos^4 \theta_{13} \sin^2(\Delta m^2_{23} L / 4E)$$

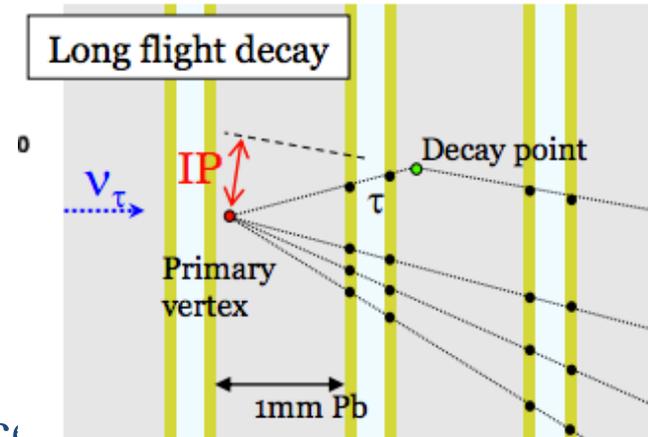
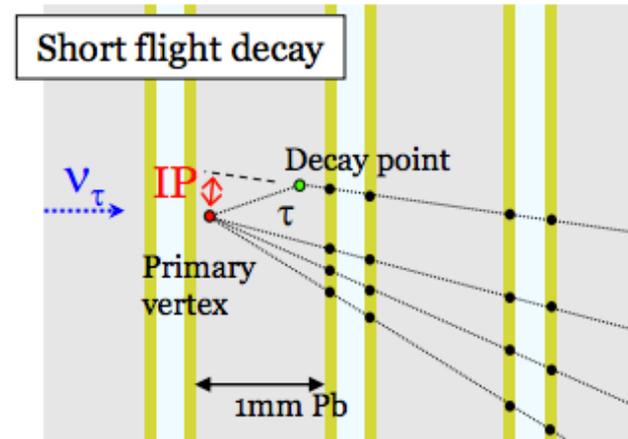
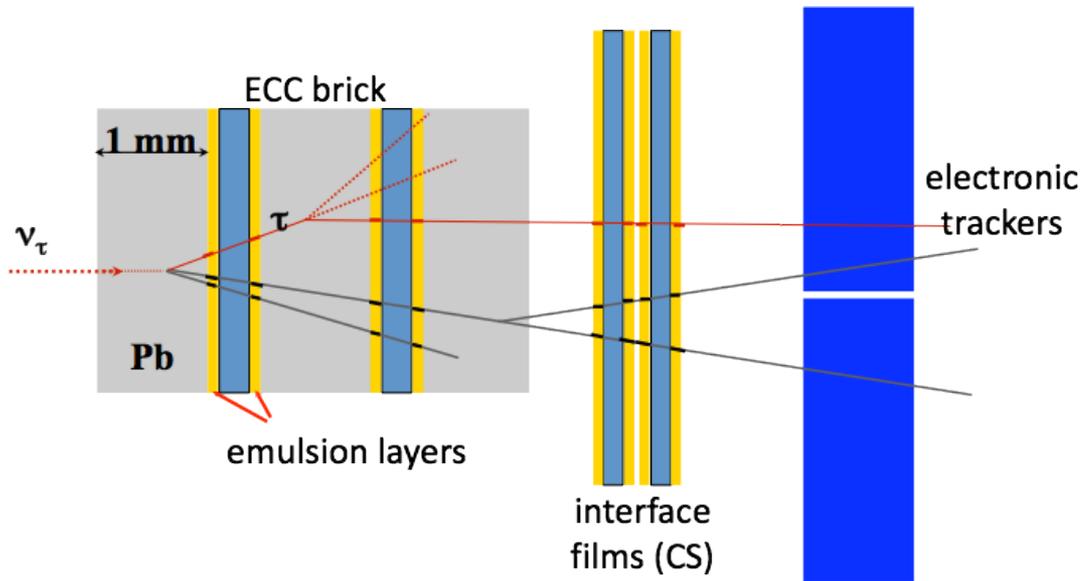
Requirements:

- 1) long baseline, 2) high neutrino energy, 3) high intensity beam, 4) detect short lived  $\tau$ 's



plus 3-prong decay modes

# THE PRINCIPLE: hybrid detector with modular structure



- Massive active target ( $\sim 1.2$  kton) with micrometric space resolution
- Detect  $\tau$ -lepton production and decay
- Electronic detectors to provide the “time stamp”, preselect the interaction brick and reconstruct  $\mu$  charge/momentum
- Underground location ( $10^6$  reduction of cosmic ray flux)

$\tau$ DECAY CHANNEL	BR (%)
$\tau \rightarrow \mu$	17.7
$\tau \rightarrow e$	17.8
$\tau \rightarrow h$	49.5
$\tau \rightarrow 3h$	15.0 <sup>5</sup>

# THE OPERA COLLABORATION

140 physicists, 28 institutions in 11 countries

**Belgium**  
IIHE-ULB Brussels



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



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



**Croatia**  
IRB Zagreb



**France**  
LAPP Annecy  
IPHC Strasbourg



**Switzerland**  
Bern



**Germany**  
Hamburg



**Japan**  
Aichi  
Toho  
Kobe  
Nagoya  
Utsunomiya



**Turkey**  
METU, Ankara



**Israel**  
Technion Haifa



**Korea**  
Jinju

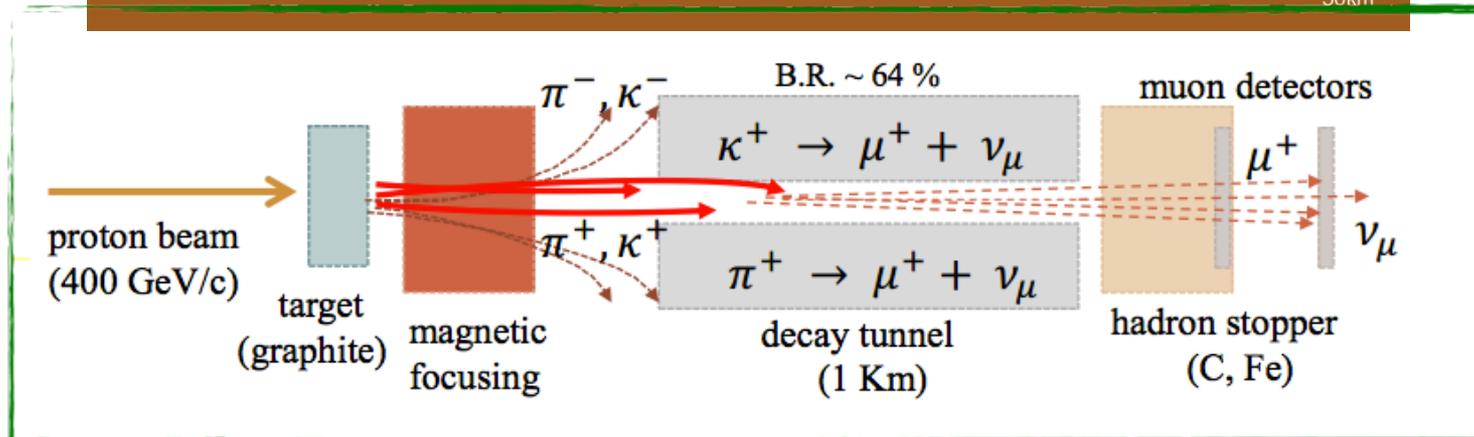
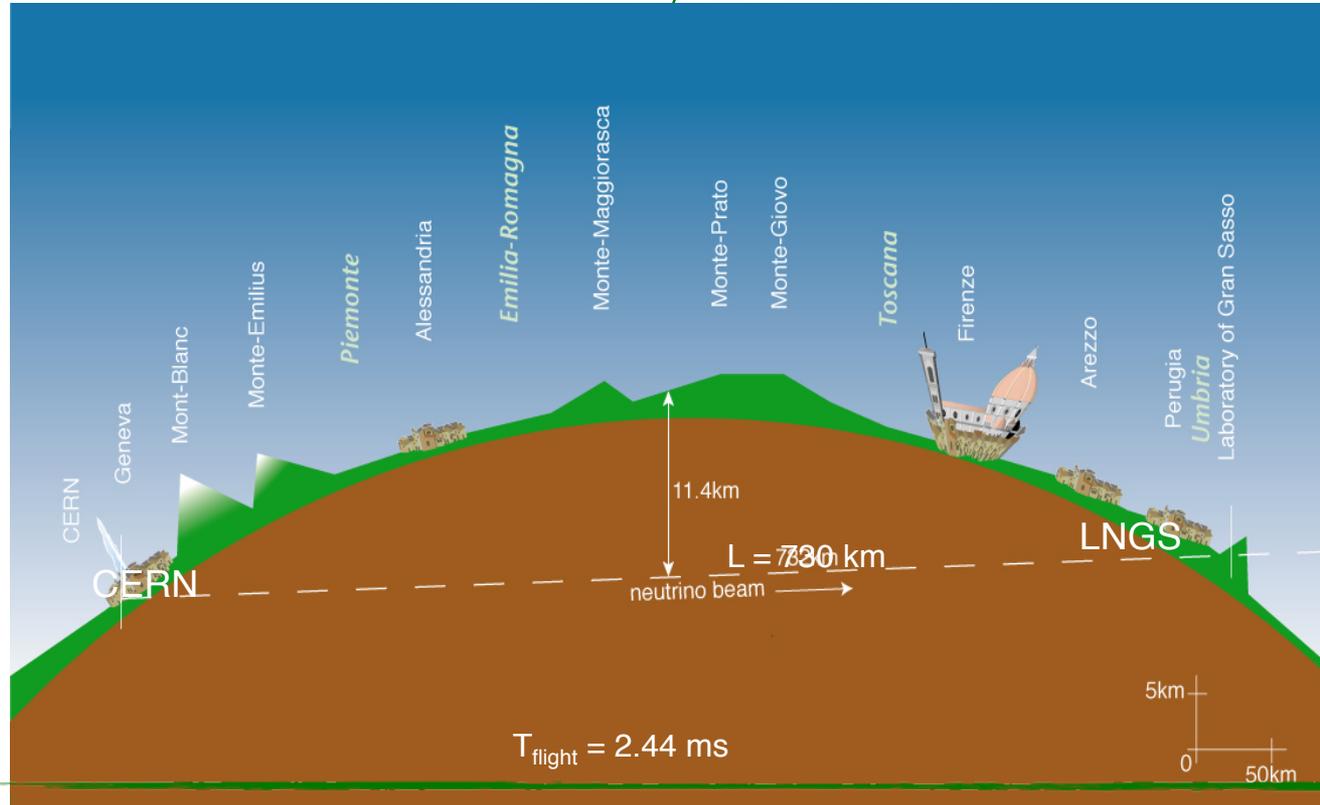


<http://operaweb.lngs.infn.it>

# *CNGS BEAM AND LNGS*

# CNGS beam: tuned for $\tau$ -appearance at LNGS

## 730 km away from CERN

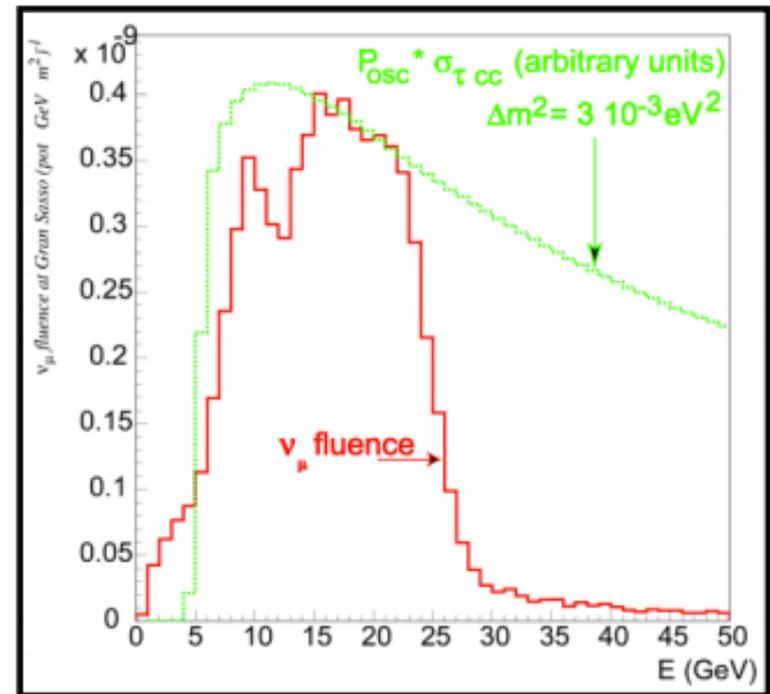


# Neutrino Beam Parameters

## Beam parameters

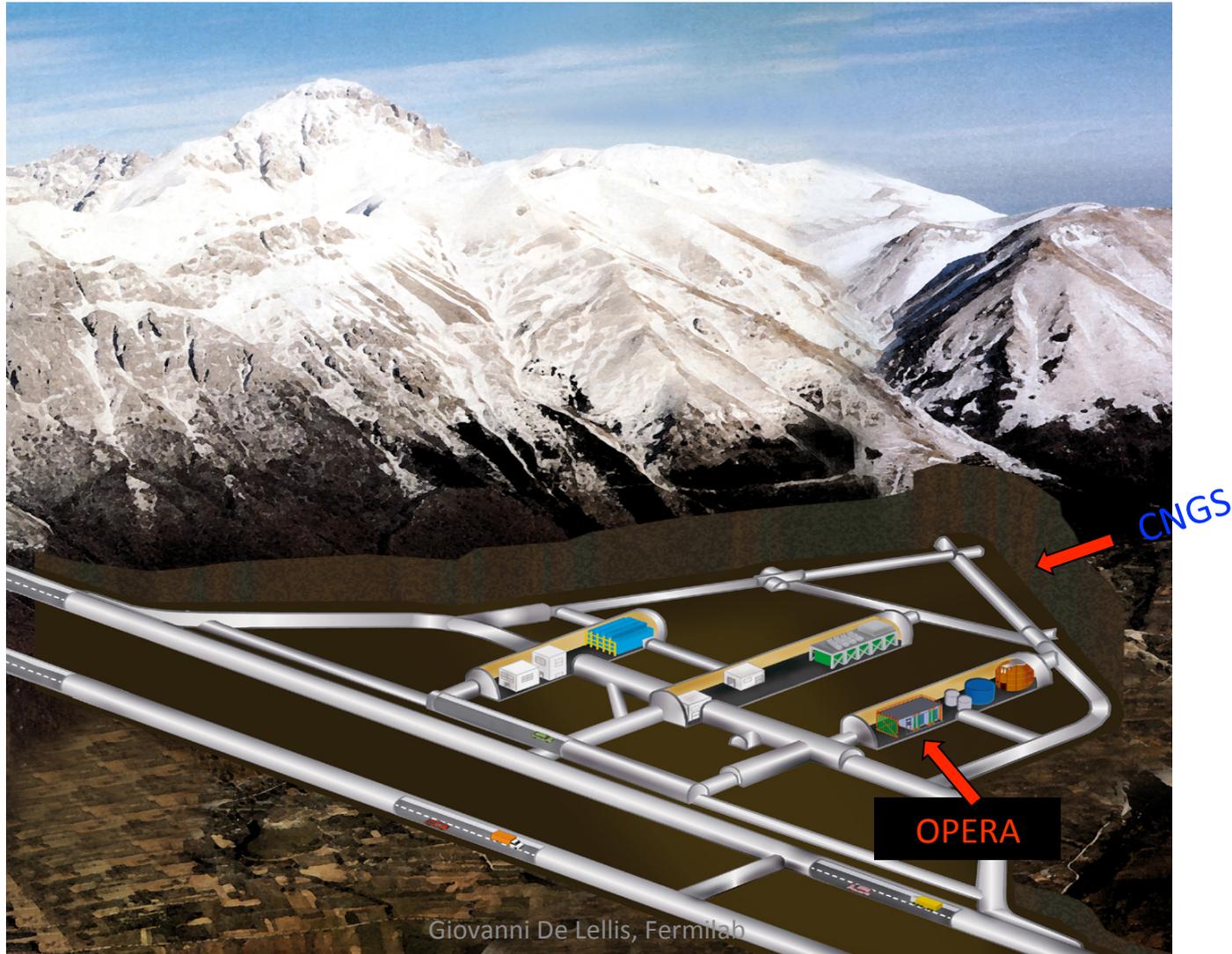
$\langle E\nu_\mu \rangle$ (GeV)	17
$(\nu_e + \bar{\nu}_e) / \nu_\mu$	0.9% *
$\bar{\nu}_\mu / \nu_\mu$	2.0% *
$\nu_\tau$ prompt	Negligible

\* Interaction rate at LNGS

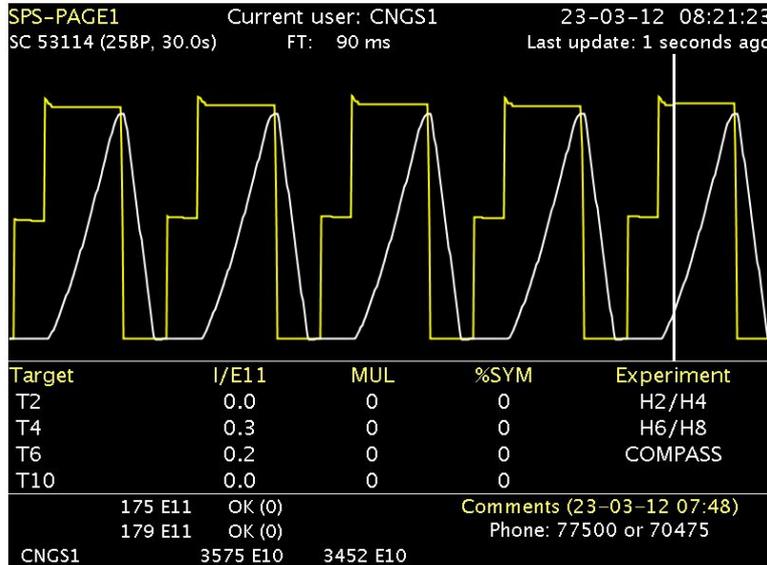


# LNGS of INFN, the world largest underground physics laboratory:

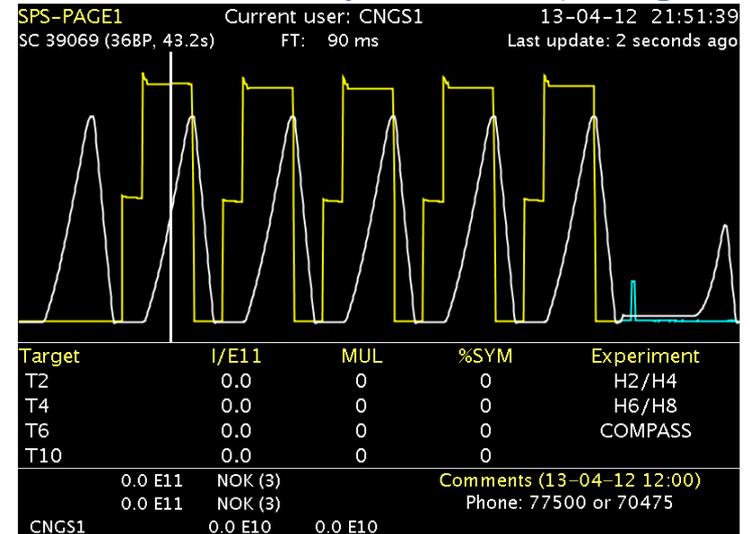
~180'000 m<sup>3</sup> caverns' volume, ~3'100 m.w.e. overburden, ~1 cosmic  $\mu$  / (m<sup>2</sup> x hour), experimental infrastructure. Suitable to host detector and related facilities, caverns oriented towards CERN.



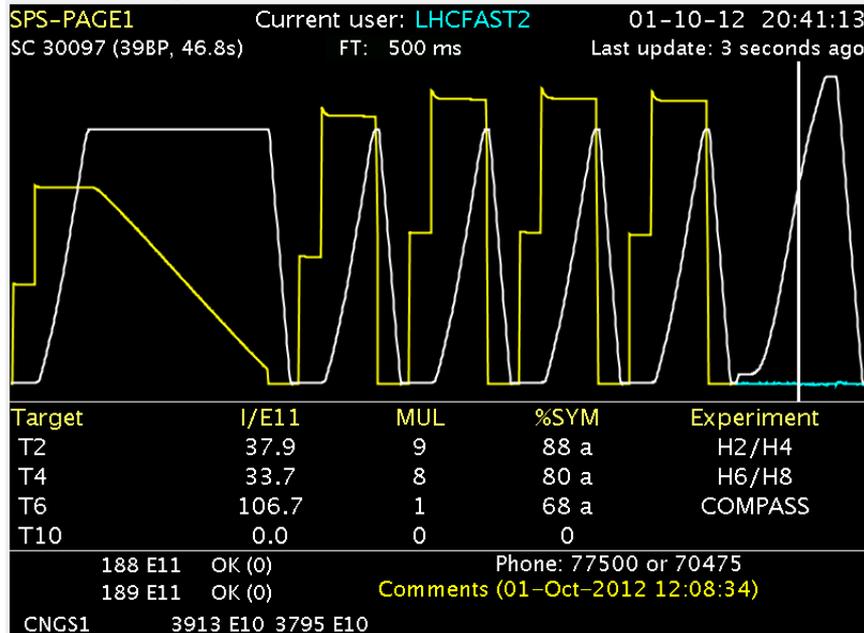
# CNGS beam structure



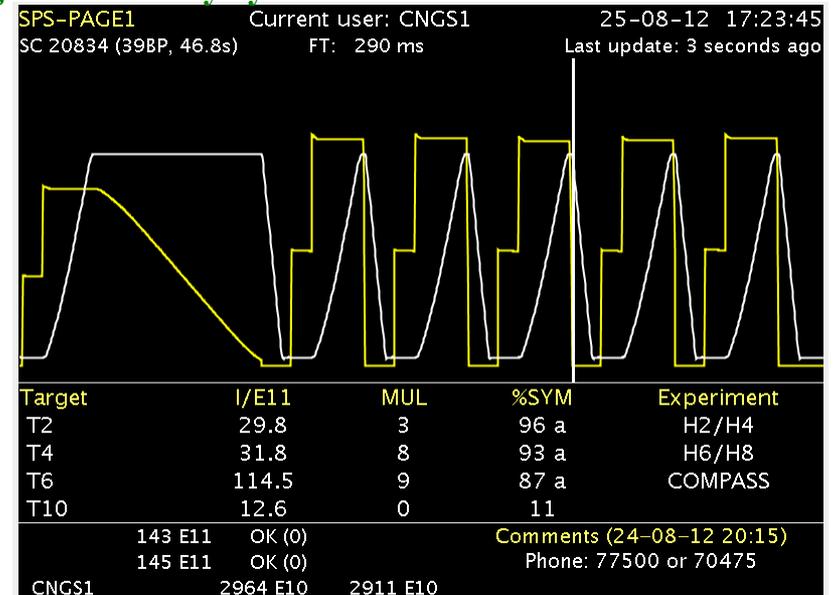
Dedicated mode or 5 cycles + LHC (during filling)



Shared operation FT + 4 CNGS + LHC

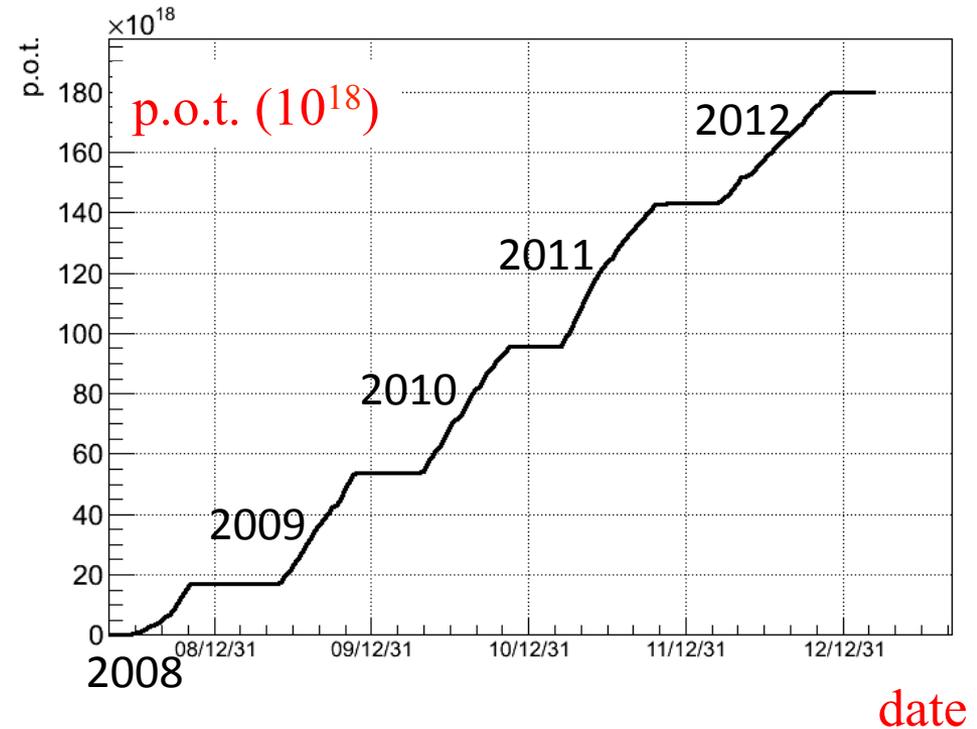


Shared operation no LHC filling (5 CNGS+ FT)  
 High CNGS duty cycle



# Final performances of the CNGS beam after five years (2008 ÷ 2012) of data taking

Year	Beam days	P.O.T. ( $10^{19}$ )
2008	123	1.74
2009	155	3.53
2010	187	4.09
2011	243	4.75
2012	257	3.86
<b>Total</b>	<b>965</b>	<b>17.97</b>



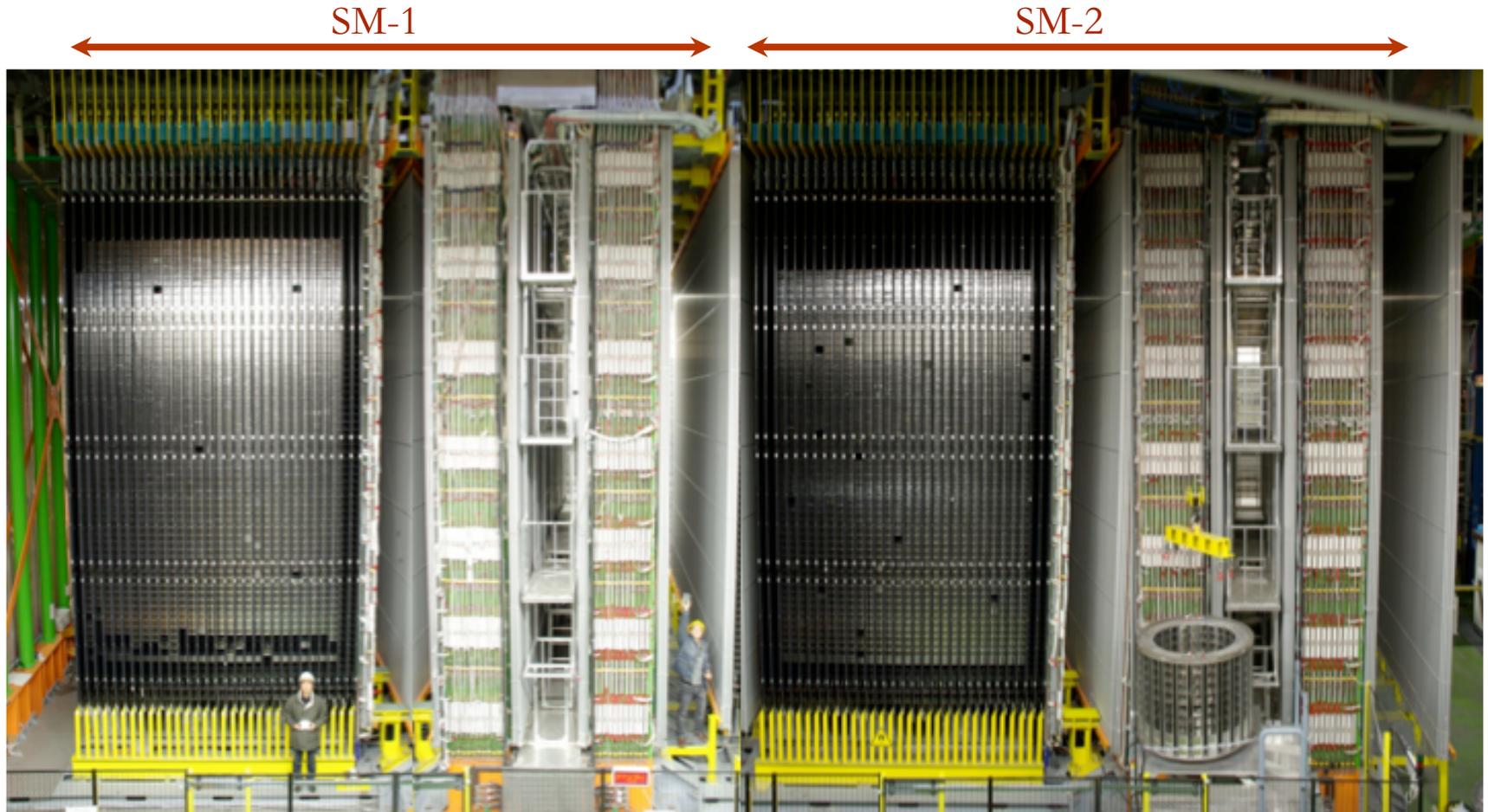
Record performances in 2011

Overall 20% less than the proposal value (22.5)

*DETECTORS AND FACILITIES  
in operation:*

*A very complex experiment...*

# THE DETECTOR



SM-1

SM-2

Target

brick walls+ Target Tracker

Spectrometer

RPC+Drift Tubes

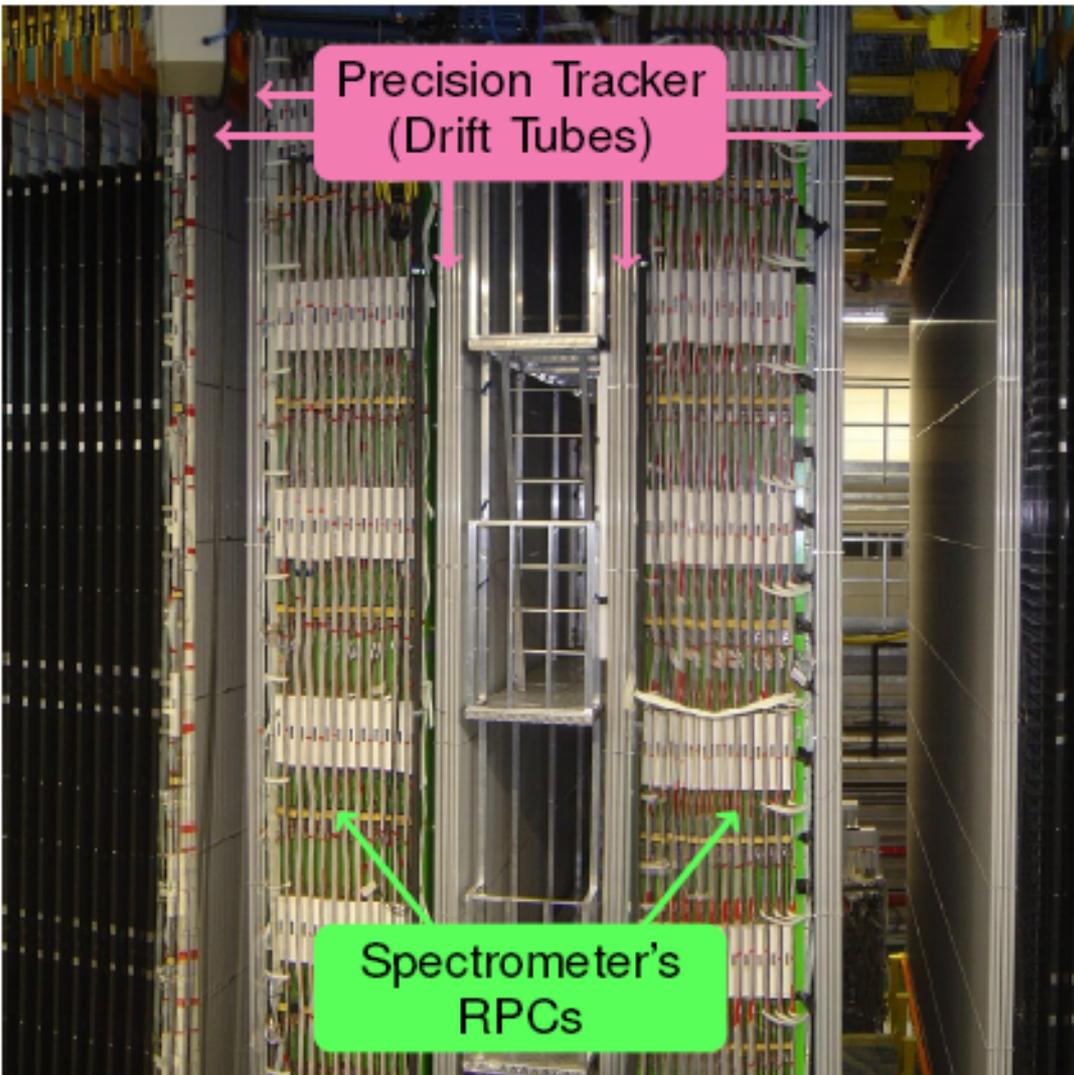
Target

brick walls+ Target Tracker

Spectrometer

RPC+Drift Tubes

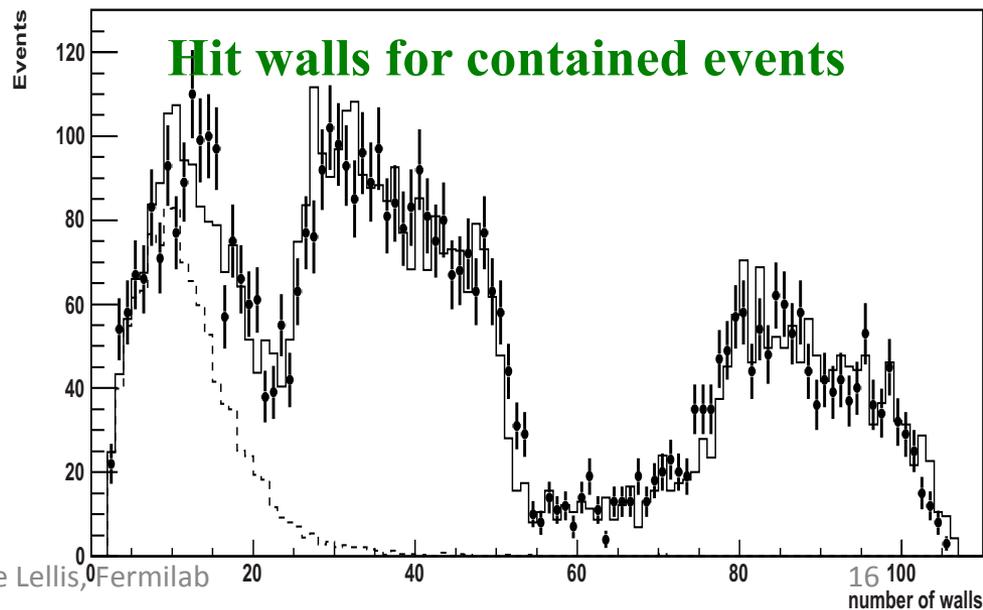
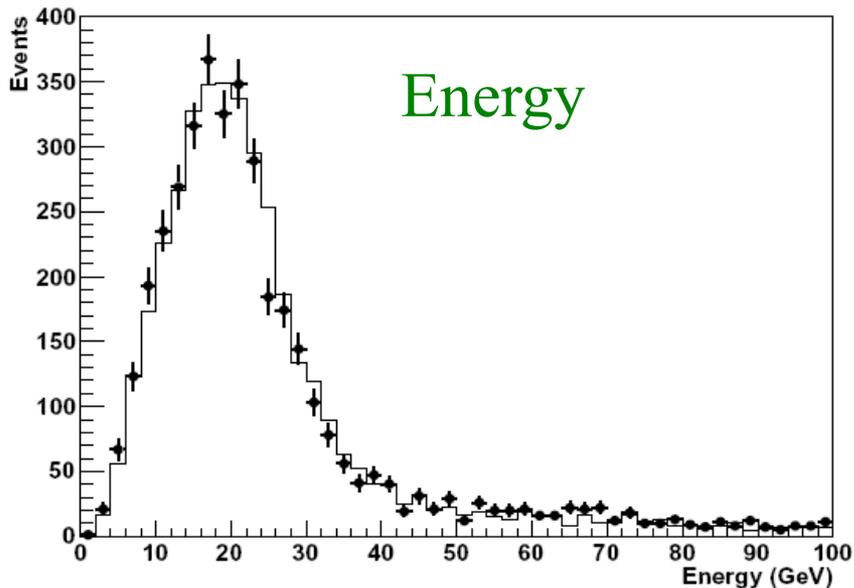
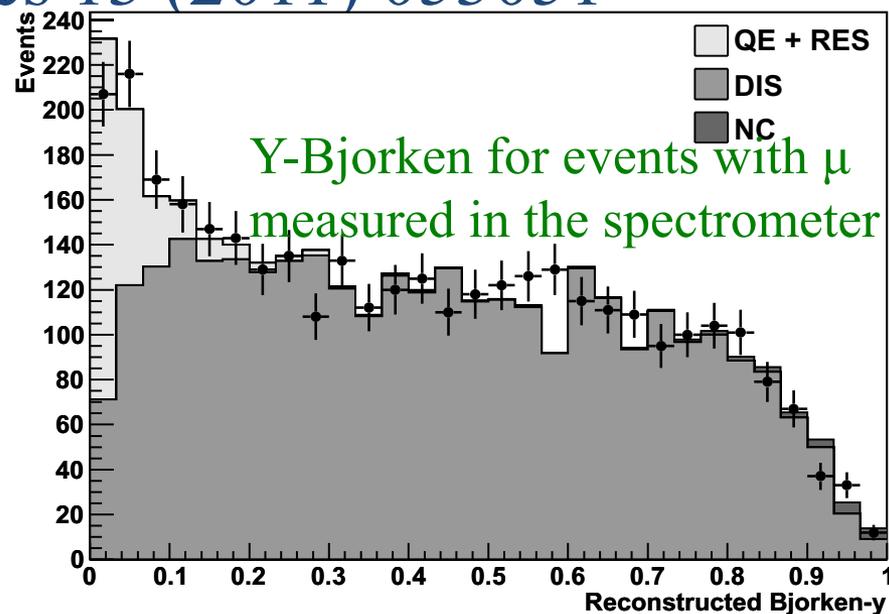
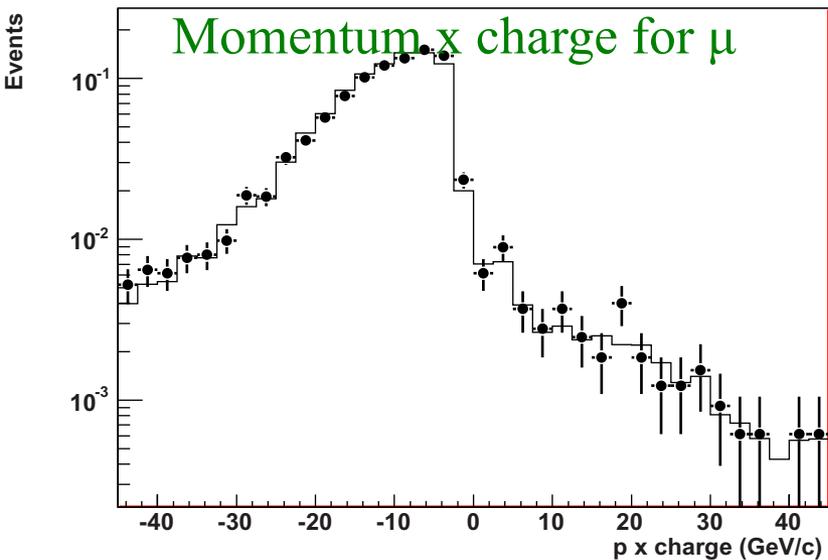
# THE MAGNETIC SPECTROMETERS



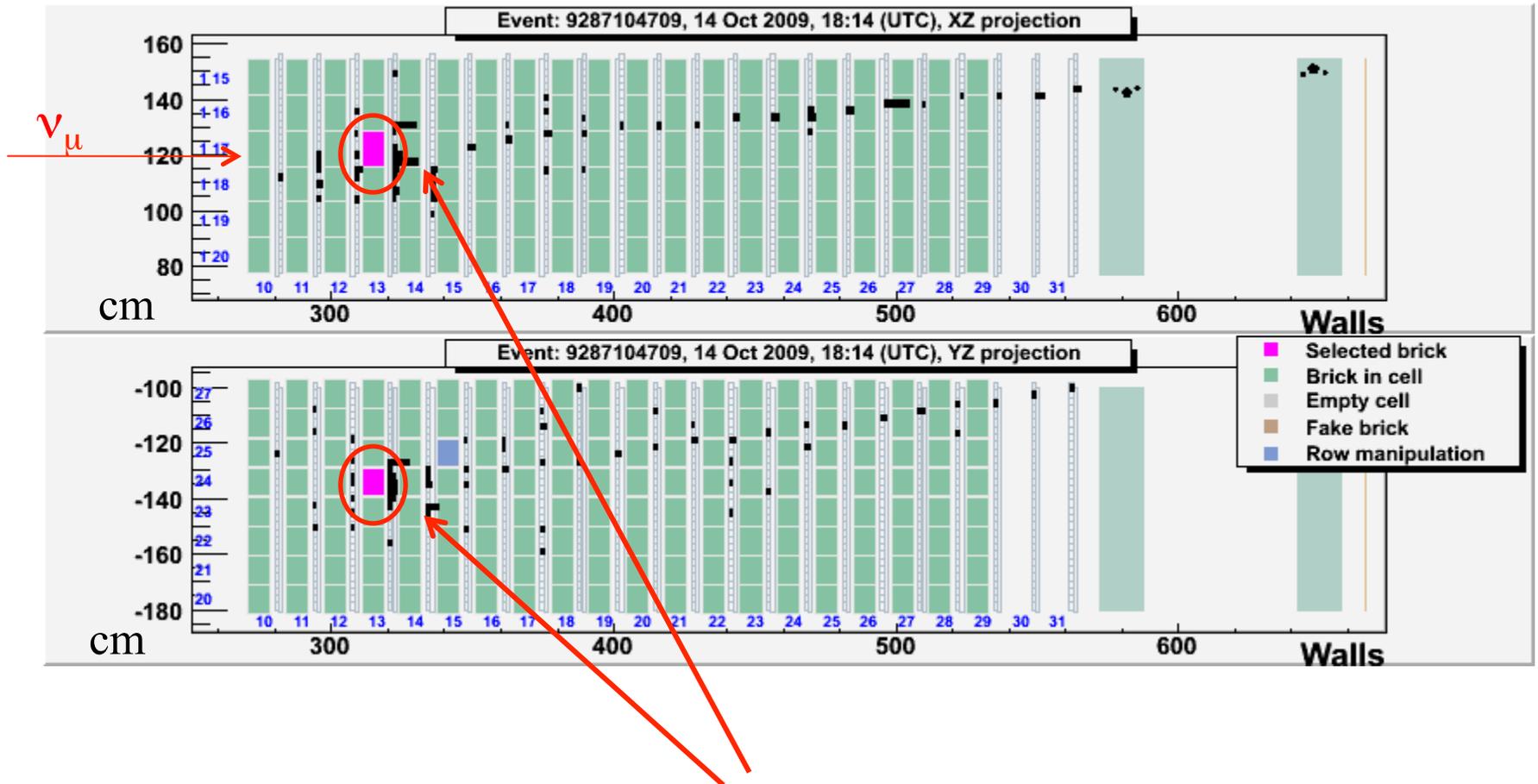
- 1.55 T magnetic field bending particles in the horizontal plane
- 24 slabs of magnetized iron interleaved with 24 RPC planes
- 6 drift tube stations for precision measurement of the angular deflection
- momentum resolution: 20% below 30 GeV/c

# Performances of the electronic detector

New Journal of Physics 13 (2011) 053051

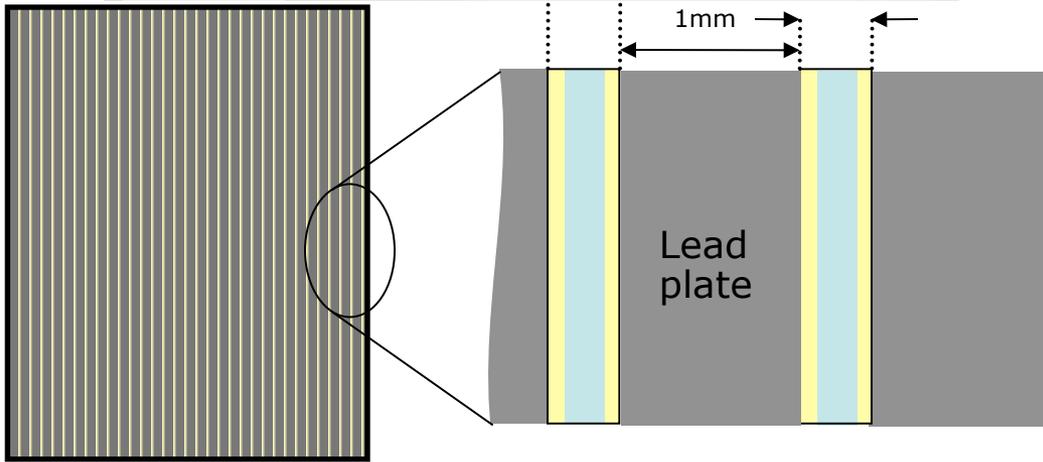
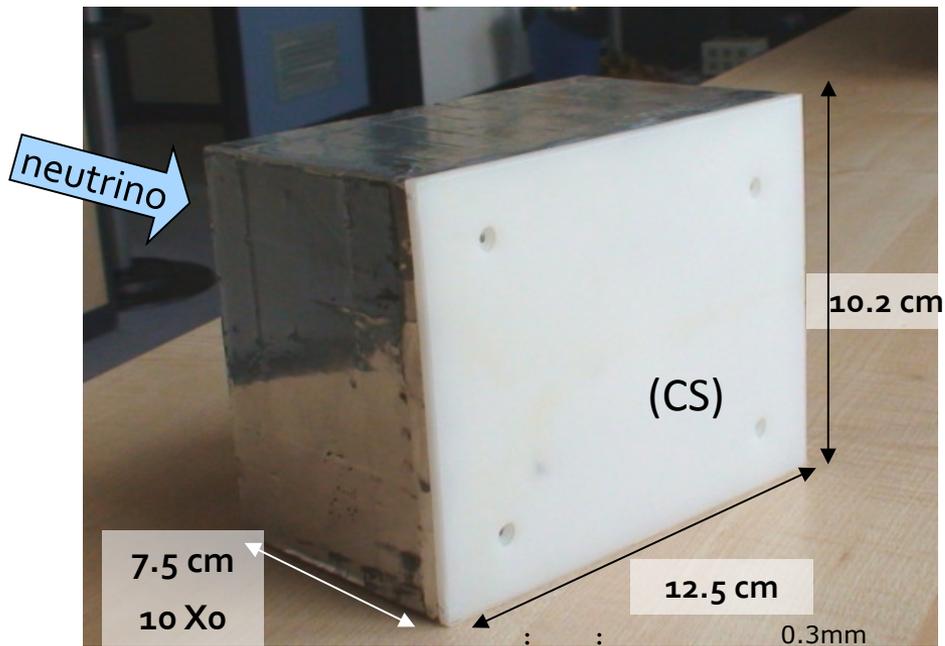


# Identification of the interaction brick: iterative process (~1.6 bricks involved in the analysis of one event)



Brick identified (top and side view)

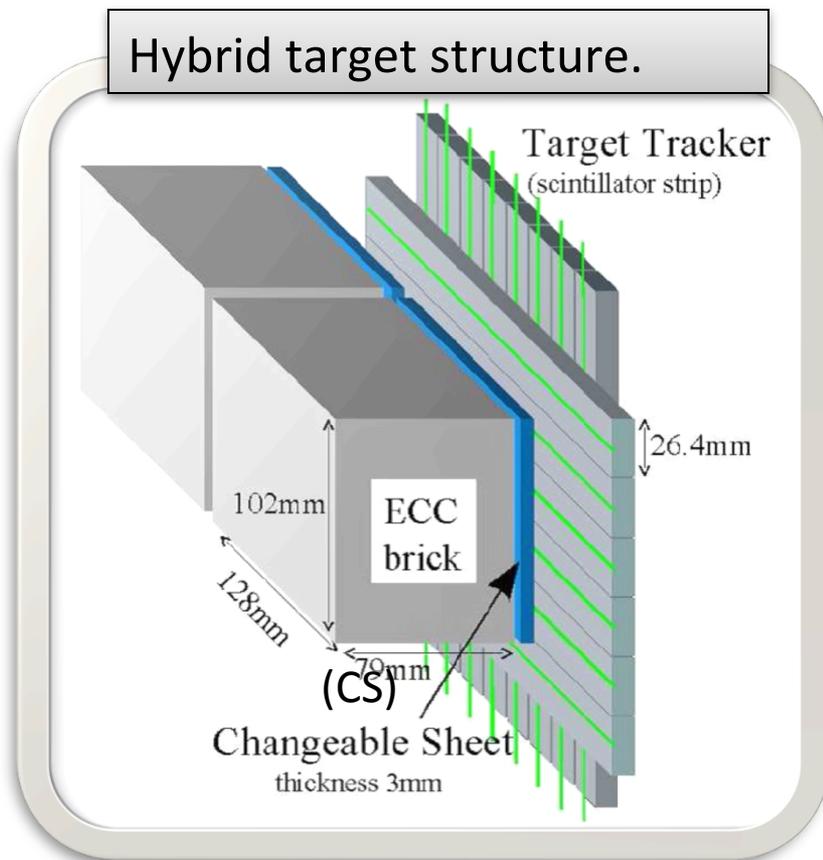
# The heart of the experiment: THE ECC TARGET BRICKS



57 OPERA films, 56 lead plates

14/06/13

## Hybrid target structure.

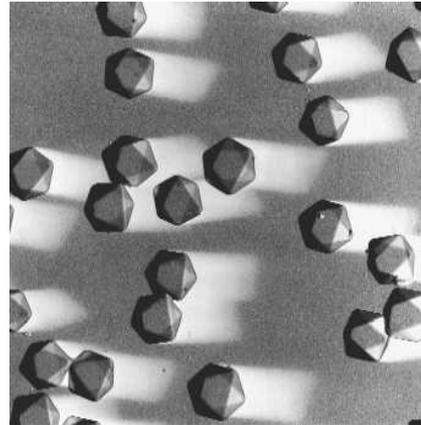
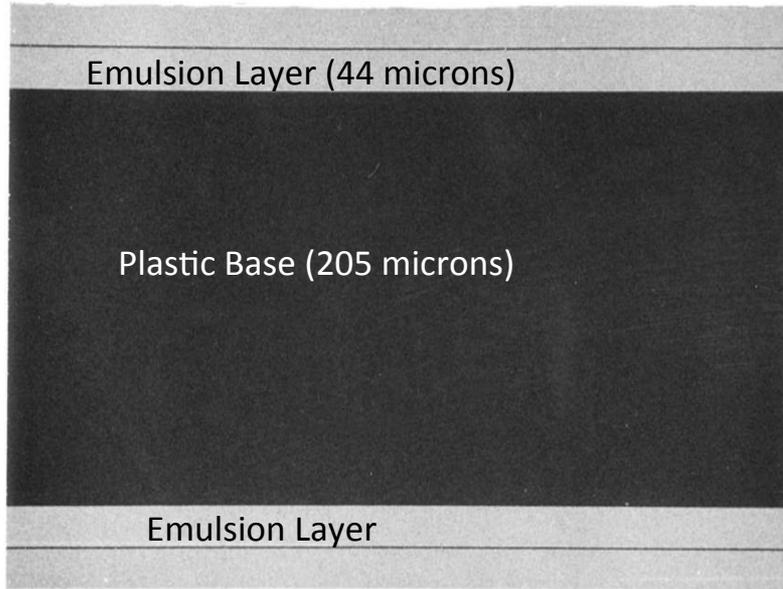


The OPERA target consists of 150'000 ECC bricks.

Total 105'000 m<sup>2</sup> of lead surface  
and 111'000 m<sup>2</sup> of film surface  
(~ 9 million films)

Total target mass: ~1.2 kton

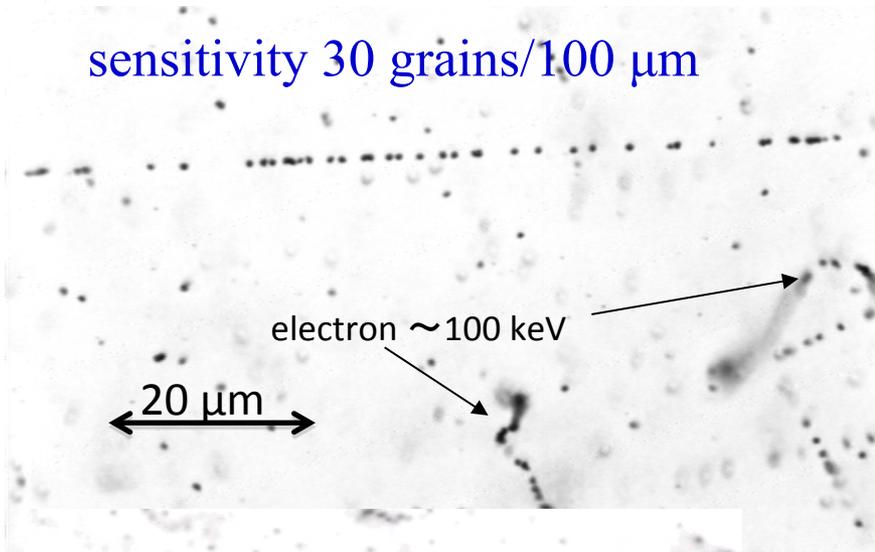
# INDUSTRIAL EMULSION FILMS BY FUJI FILM



**basic detector: AgBr crystal,**  
 size = 0.2 micron  
 detection eff. = 0.16/crystal  
 **$10^{13}$  “detectors” per film**

sensitivity 30 grains/100  $\mu\text{m}$

mip  $\rightarrow$



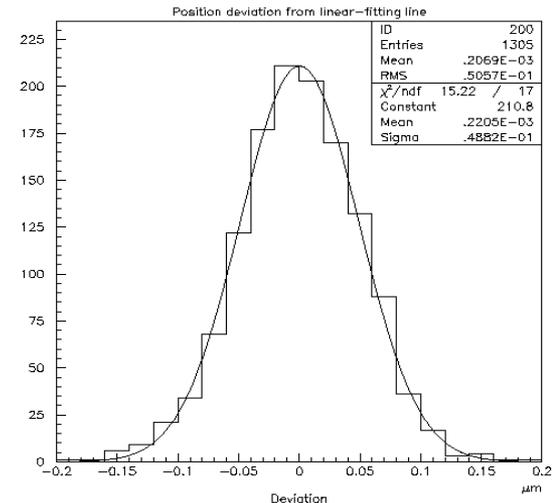
high dE/dx tracks from nuclear evaporation

14/06/13

Giovanni De Lellis, Fermilab

intrinsic resolution: 50 nm

deviation from linear-fit line. (2D)



# BRICK MANIPULATOR SYSTEM (BMS)

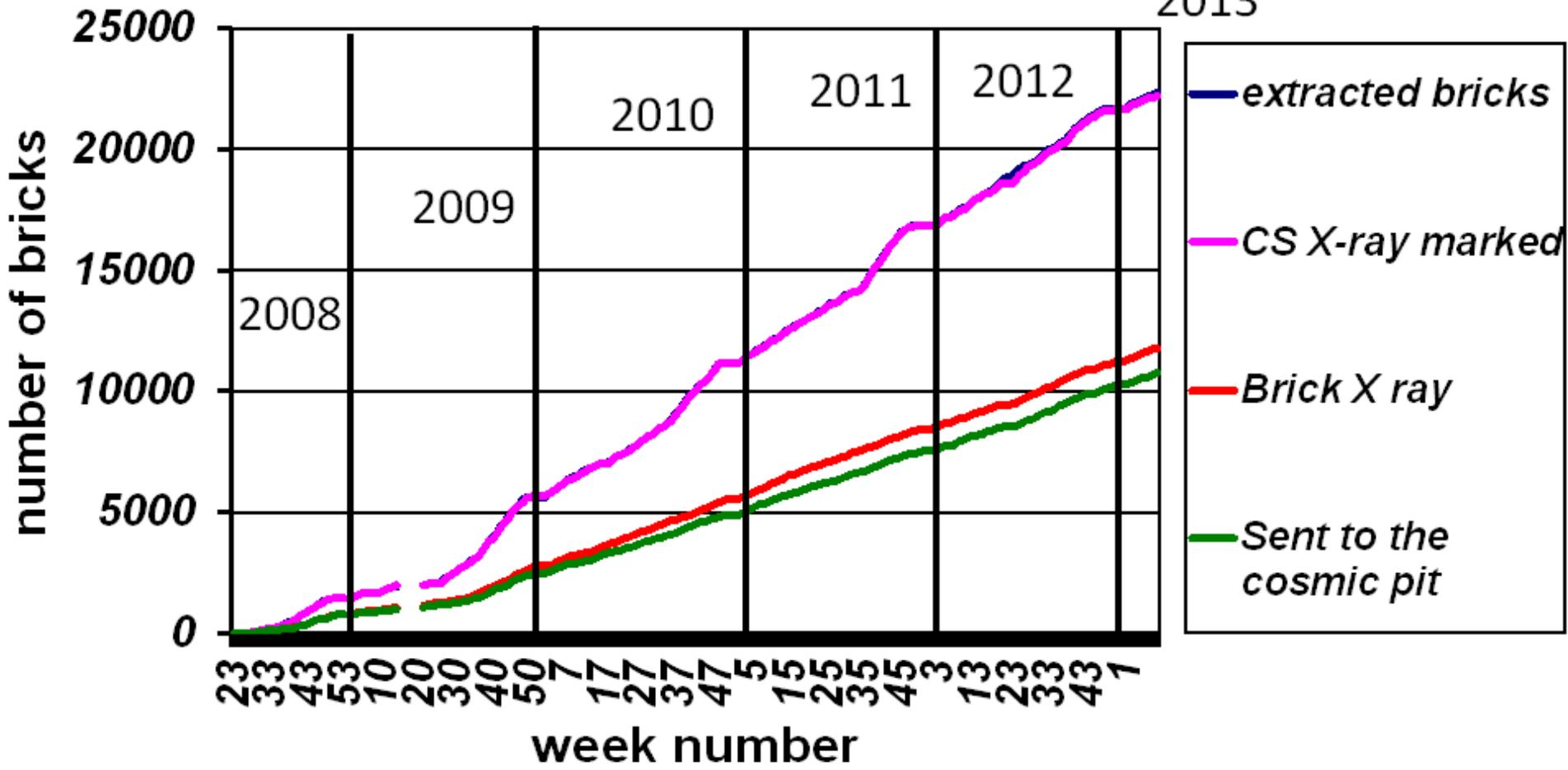


Extraction of “hit” bricks in parallel with CNGS data taking (quasi-online):

- initially used to fill the brick target (two twin devices at either detector sides)
- fully automatic extraction of up to 50 bricks/day (neutrino interactions)

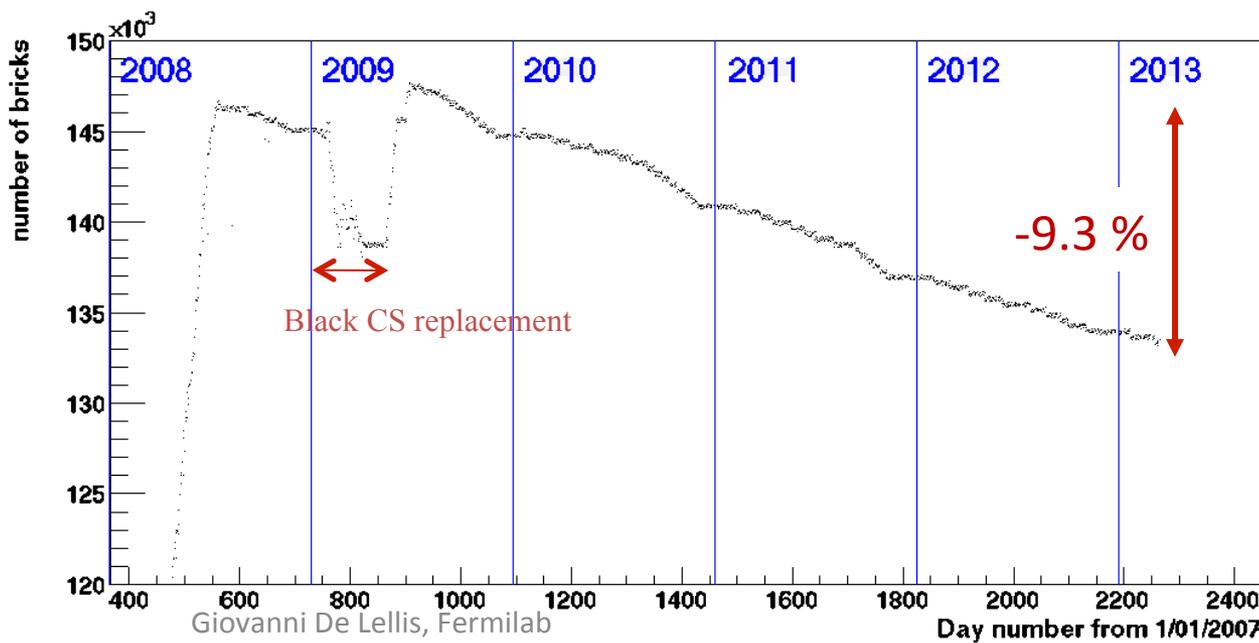
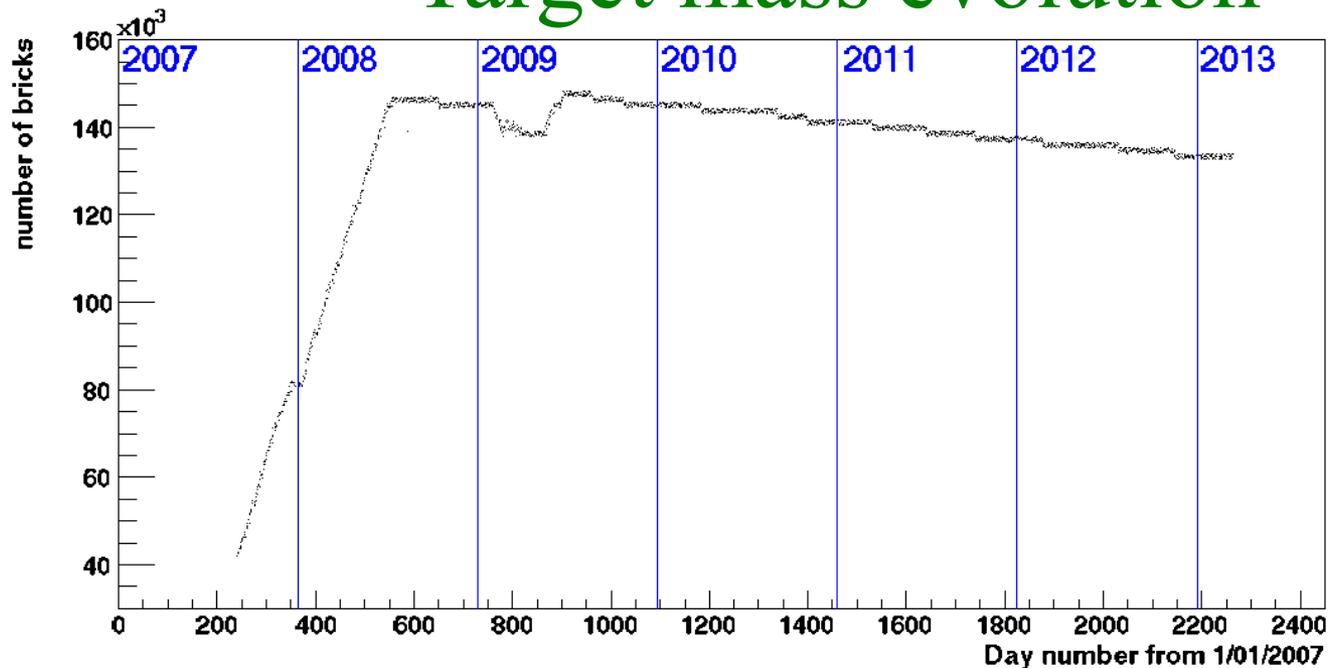
# OPERA brick handling

2013



More than 20000 bricks manipulated for event analysis

# Target mass evolution



date	bricks
16/07/08	146398
24/06/09	147292
31/05/12	135606
13/03/13	133425

Target loss ~ 112 tons

# FILM DEVELOPMENT FACILITY



- 5 automated lines running in parallel, in a dark room
- additional facility underground for Changeable Sheet films

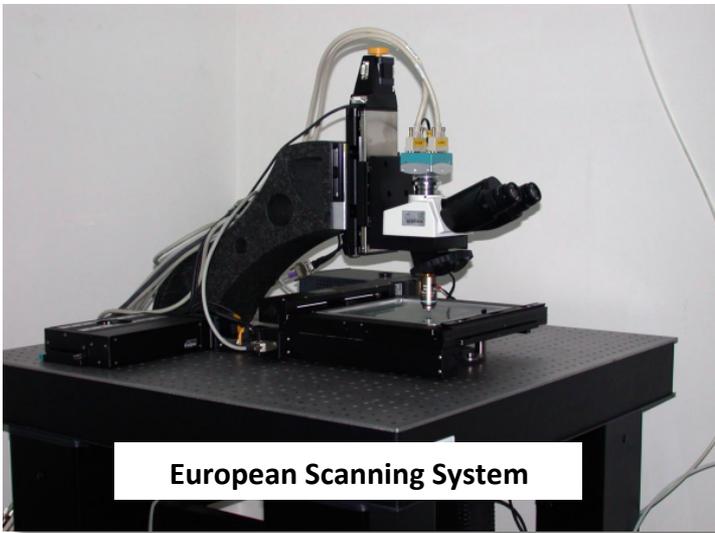
# Scanning of Changeable Sheets: several tasks accomplished



LNGS: 10 microscopes, 200 cm<sup>2</sup>/h



Nagoya: 5 S-UTS, 220 cm<sup>2</sup>/h

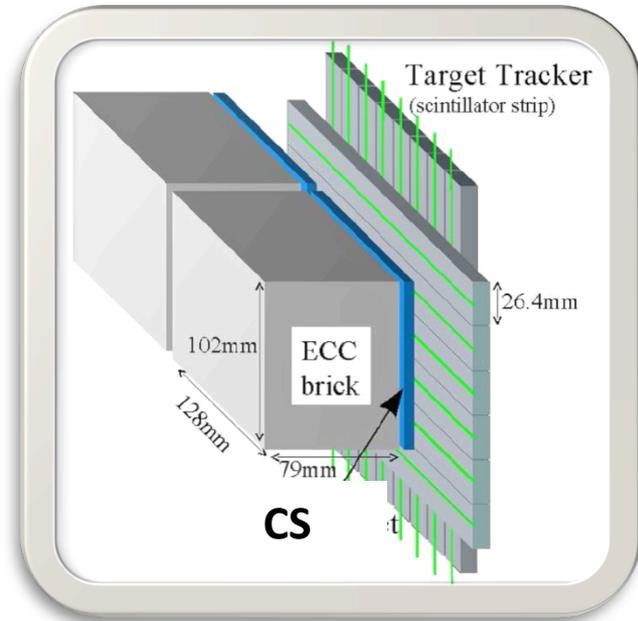
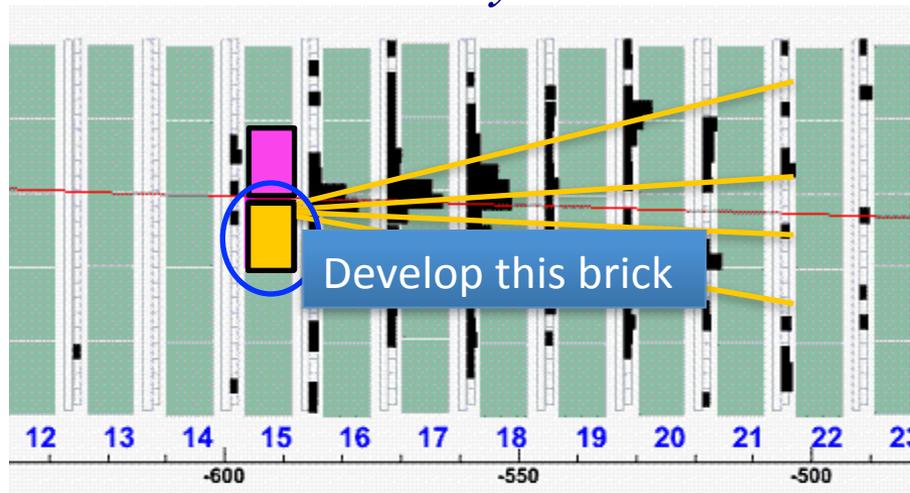


European Scanning System

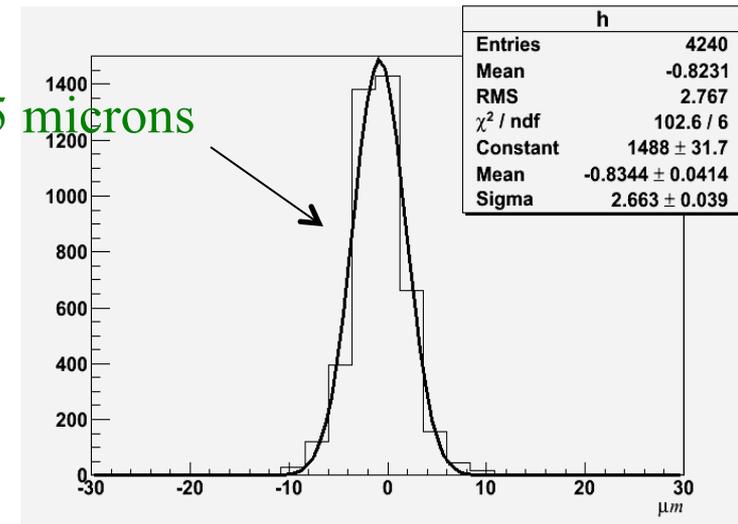


Super-UltraTrack Selector (Japan)

# Brick validation by the interface film analysis



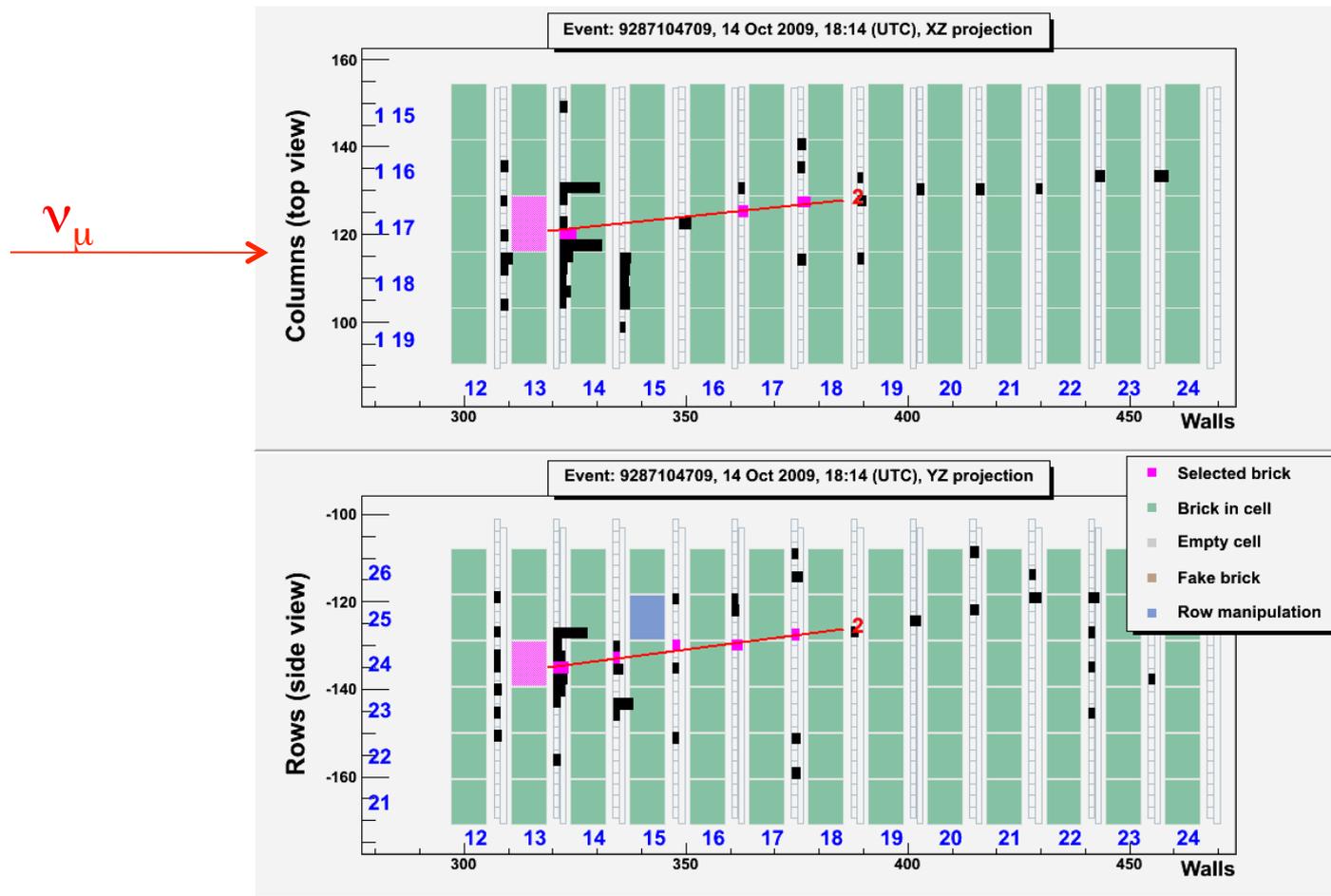
CS doublet alignment by Compton electrons: 2.5 microns



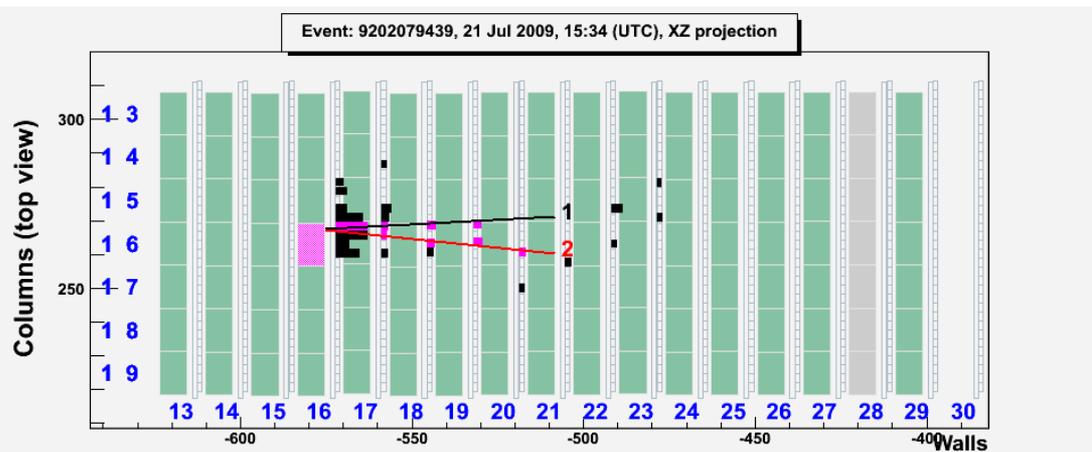
So far 2'000'000 cm<sup>2</sup> of CS surface have been analysed in OPERA

# Interface emulsion films: high signal/noise ratio for event trigger and scanning time reduction

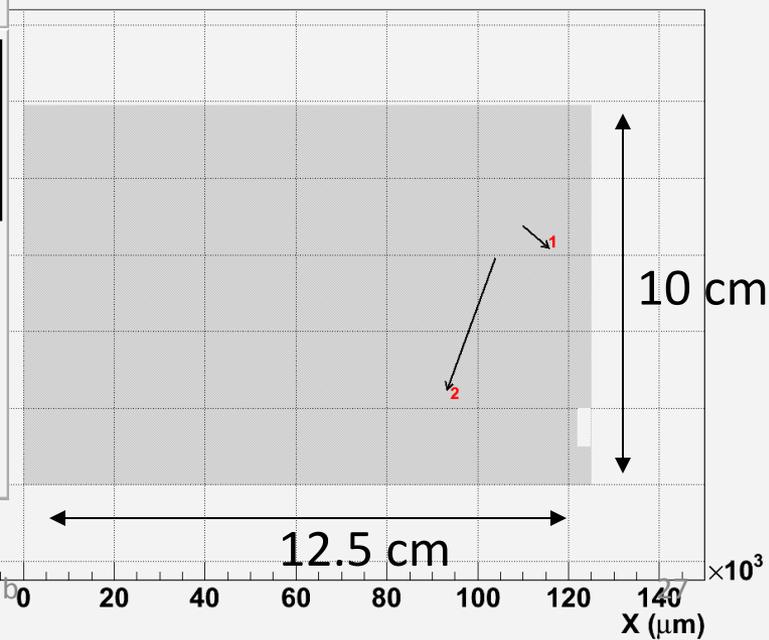
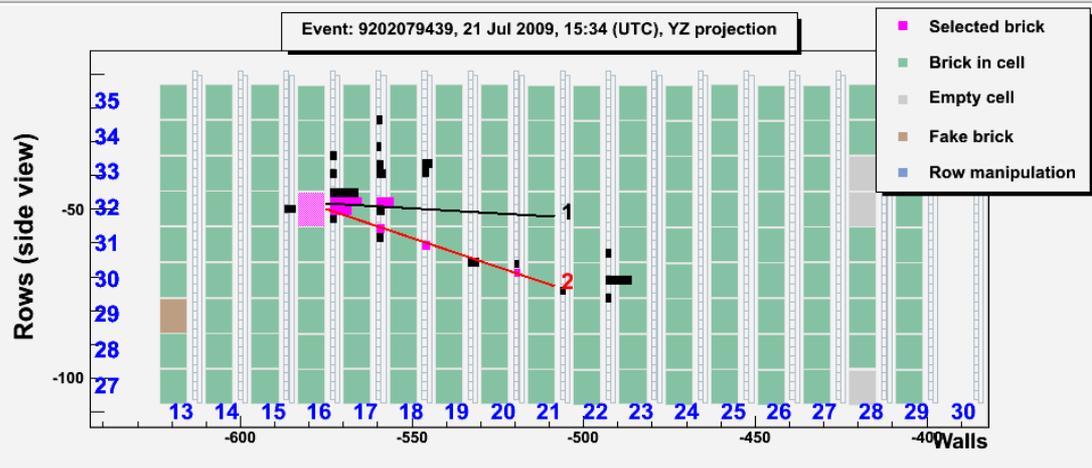
## CC interaction: $\mu$ track in interface films



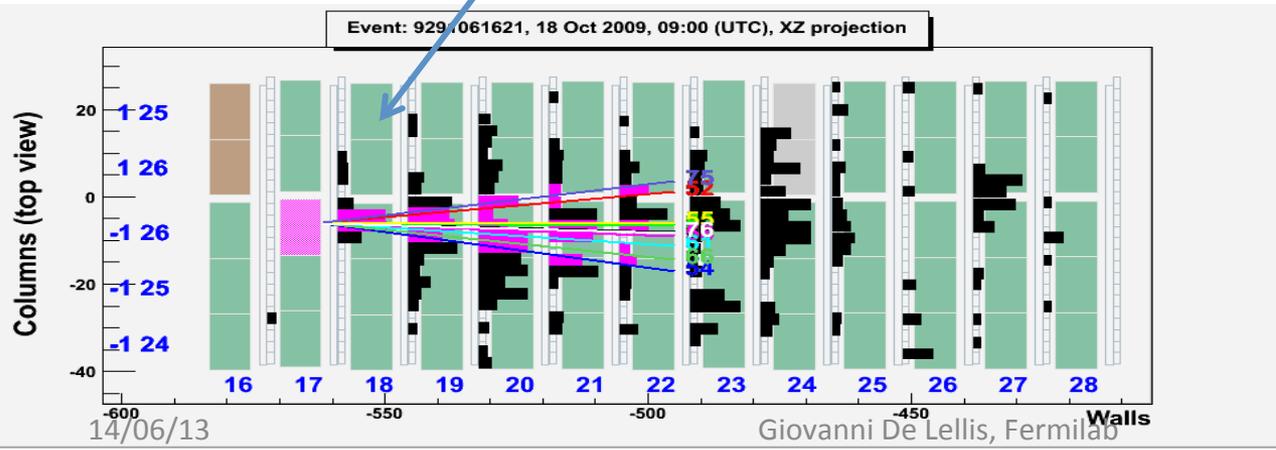
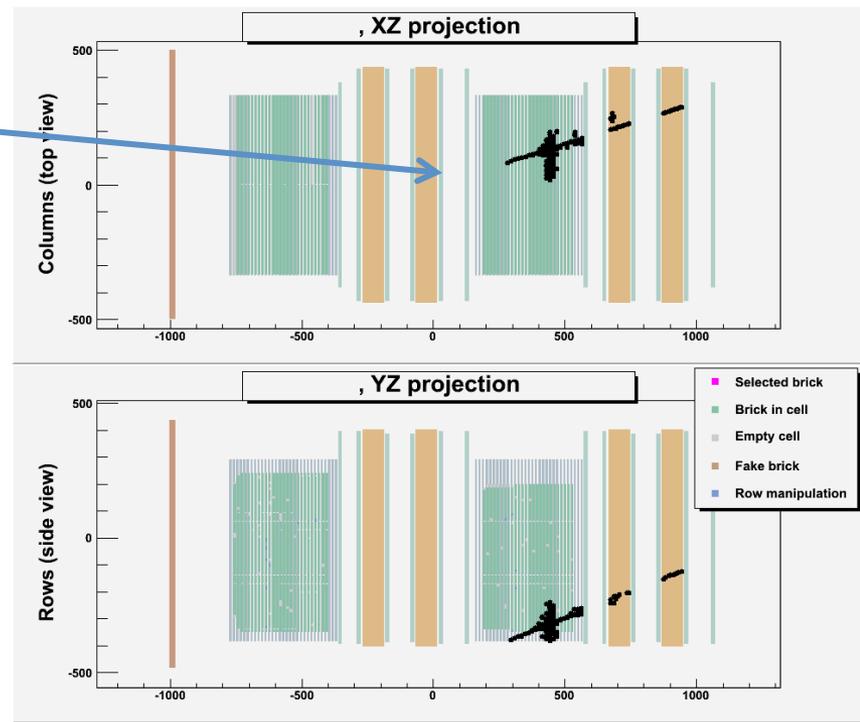
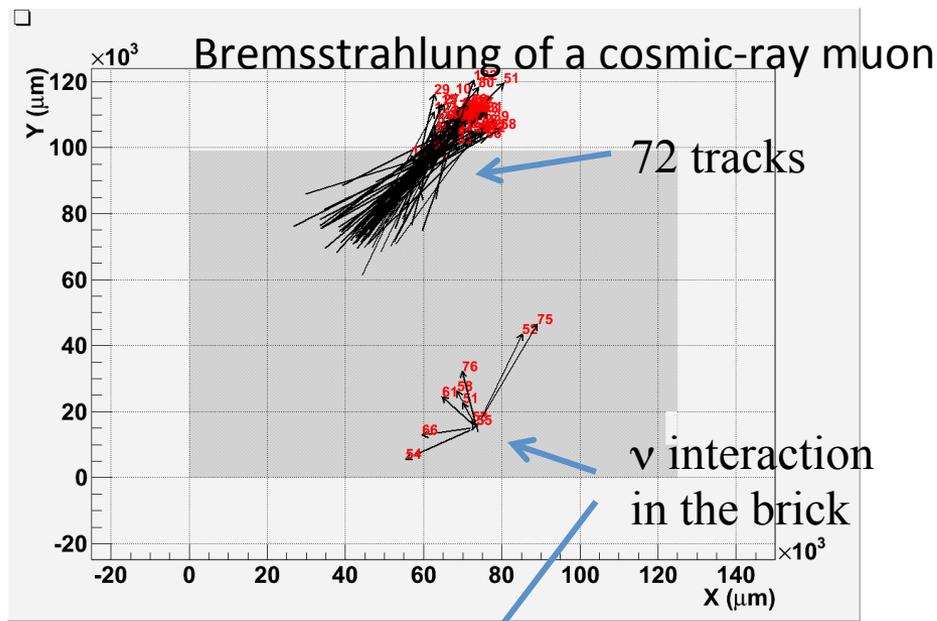
# Validation of events without $\mu$ in the final state by interface emulsion films

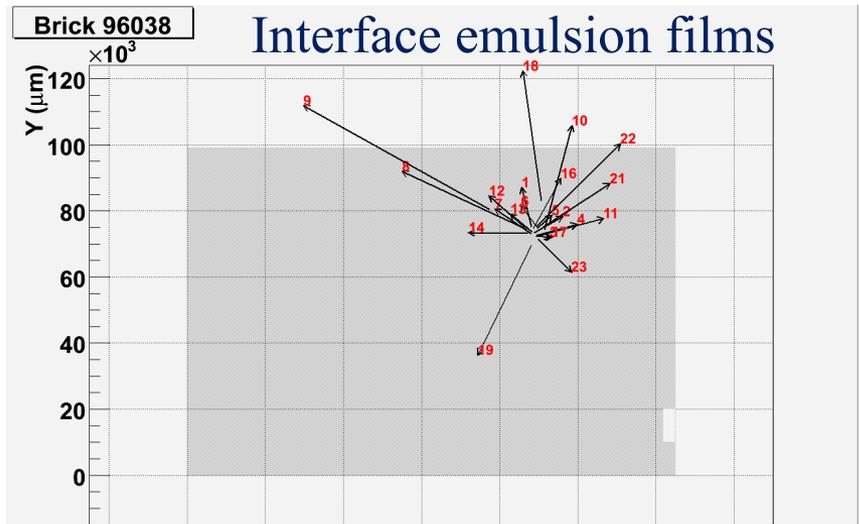


CS tracks: the arrow length is proportional to its slope

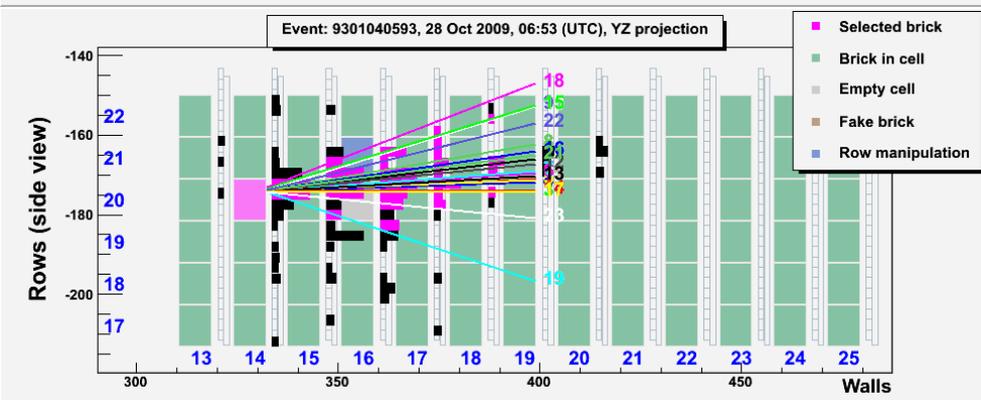
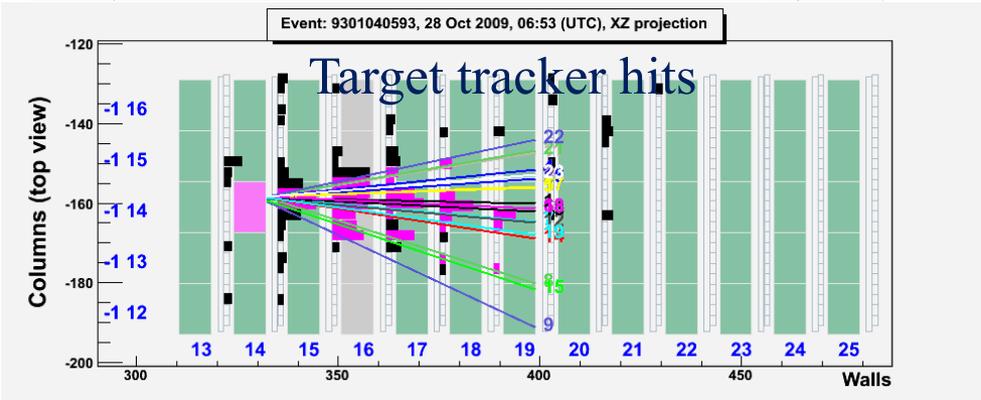
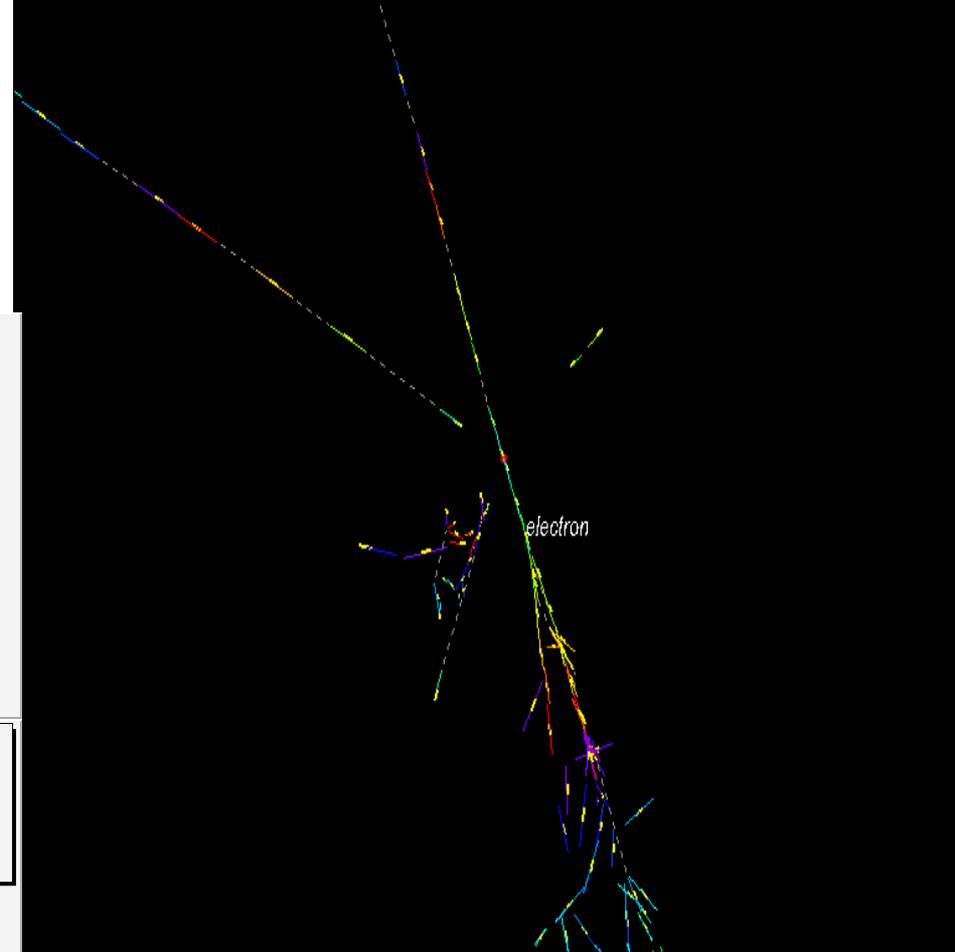


# Identification of cosmic ray $\mu$ and muons from $\nu$ interactions upstream: TT running also during the shutdown





# Electron shower pre-selection

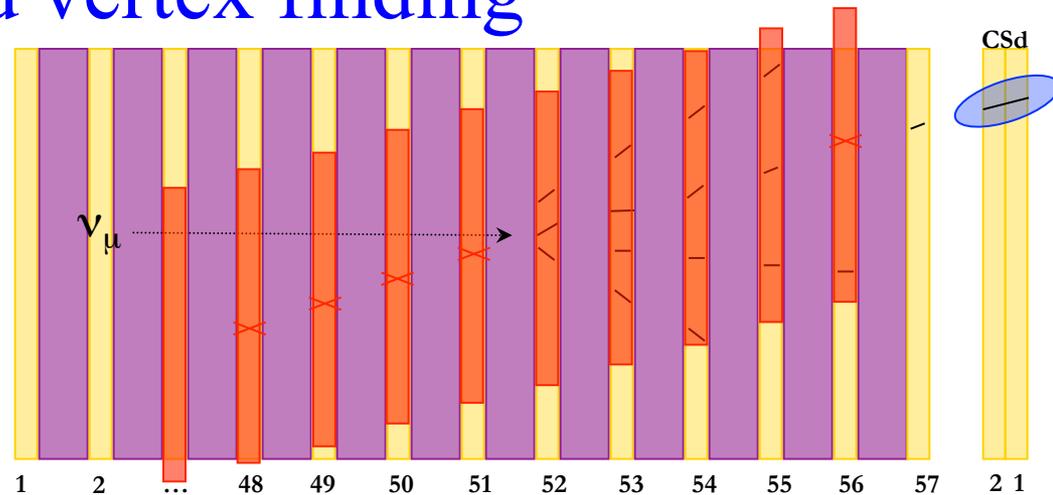


One of the electron neutrinos located as seen after the brick analysis

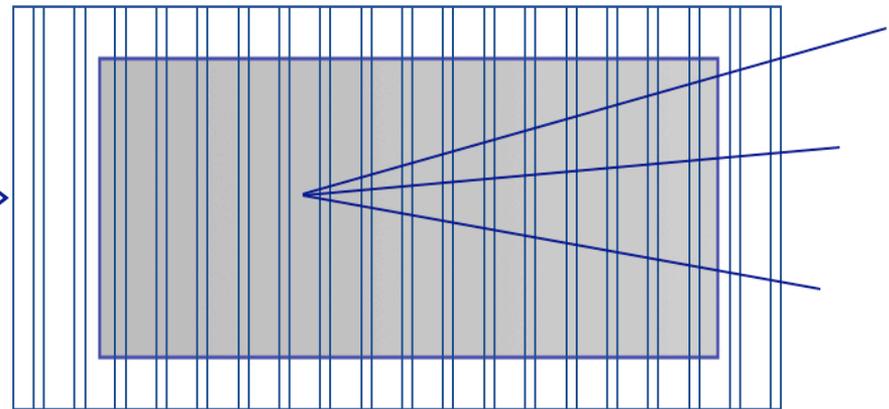
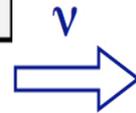
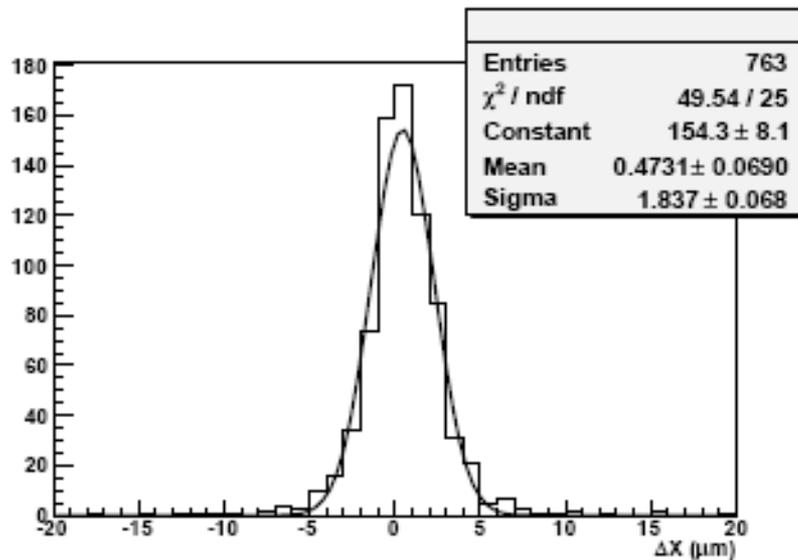
# Track follow-up and vertex finding

## Track follow-up film by film:

- alignment using cosmic ray tracks
- definition of the stopping point



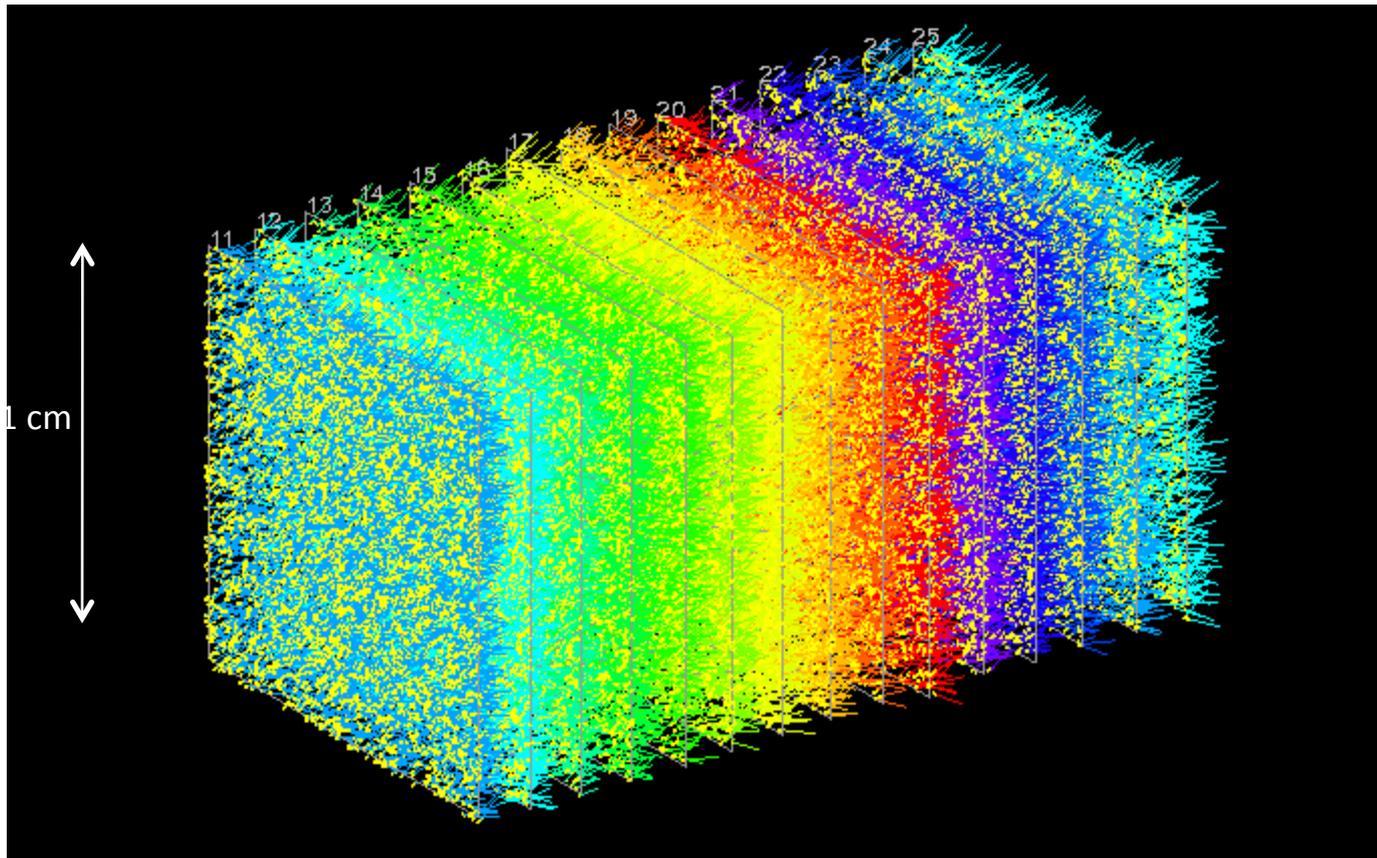
$\sigma \sim 2 \mu\text{m}$



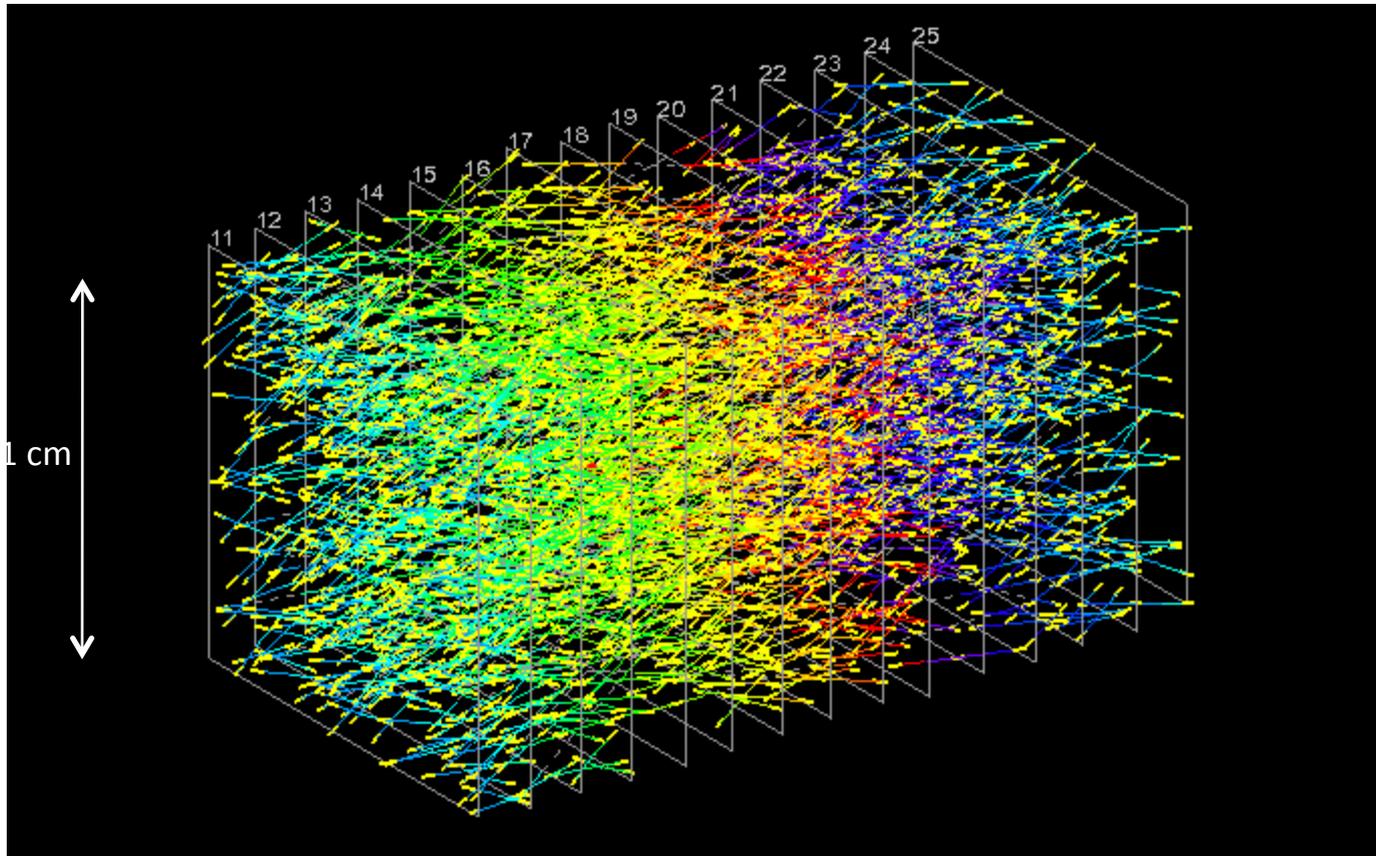
Volume scanning ( $\sim 2 \text{ cm}^3$ ) around the stopping point

# Located neutrino interaction

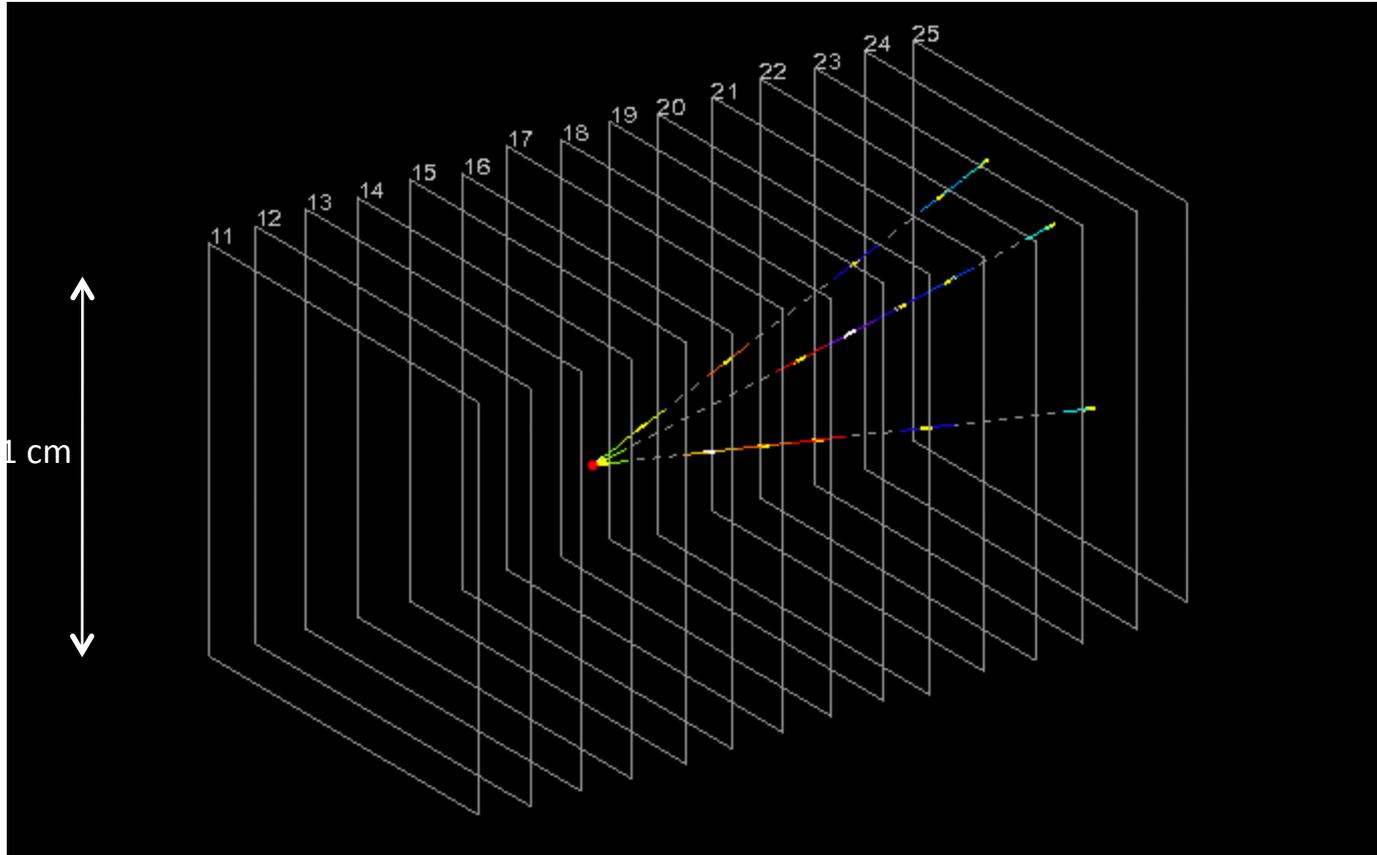
Volume ( $\sim 2 \text{ cm}^3$ ) around the stopping point



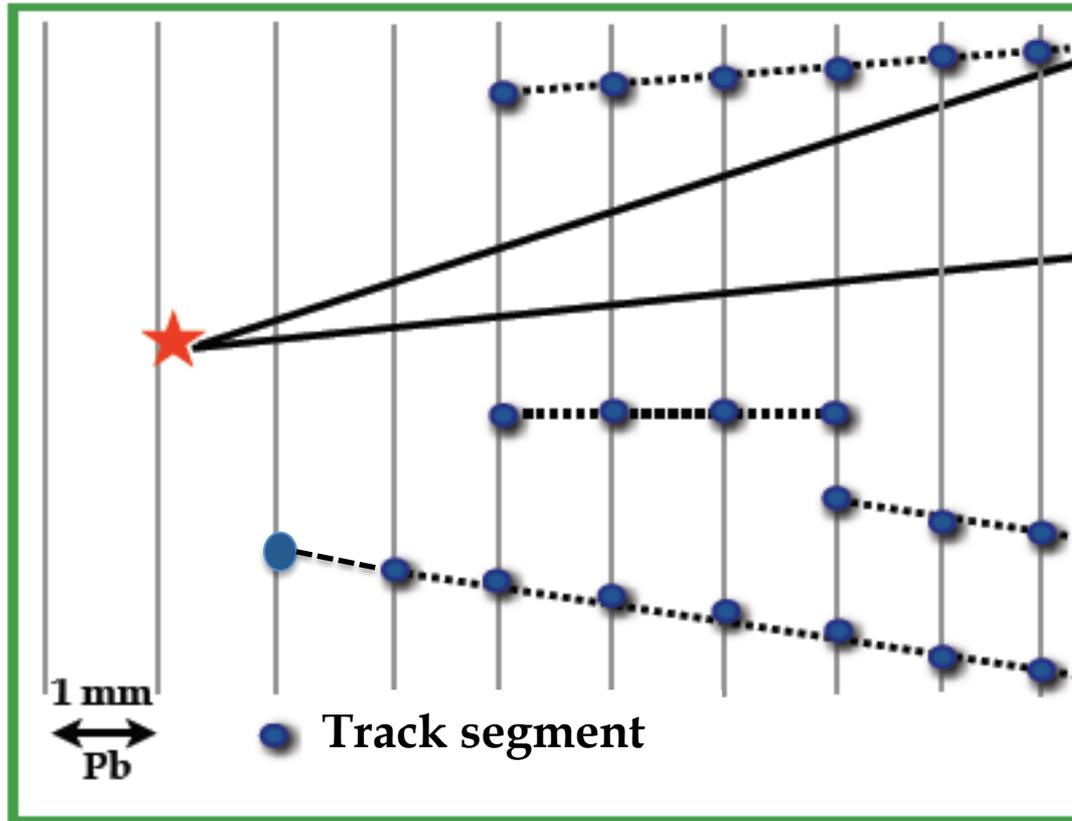
# Located neutrino interaction: film to film connection



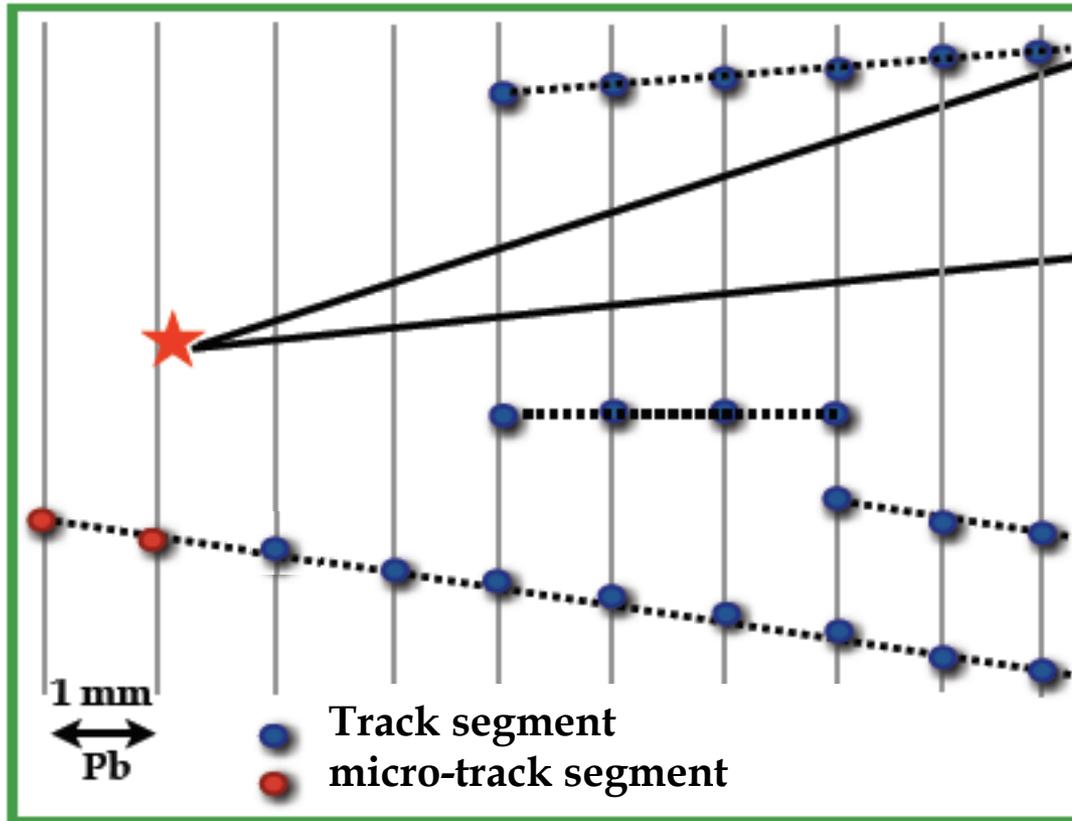
# Located neutrino interaction



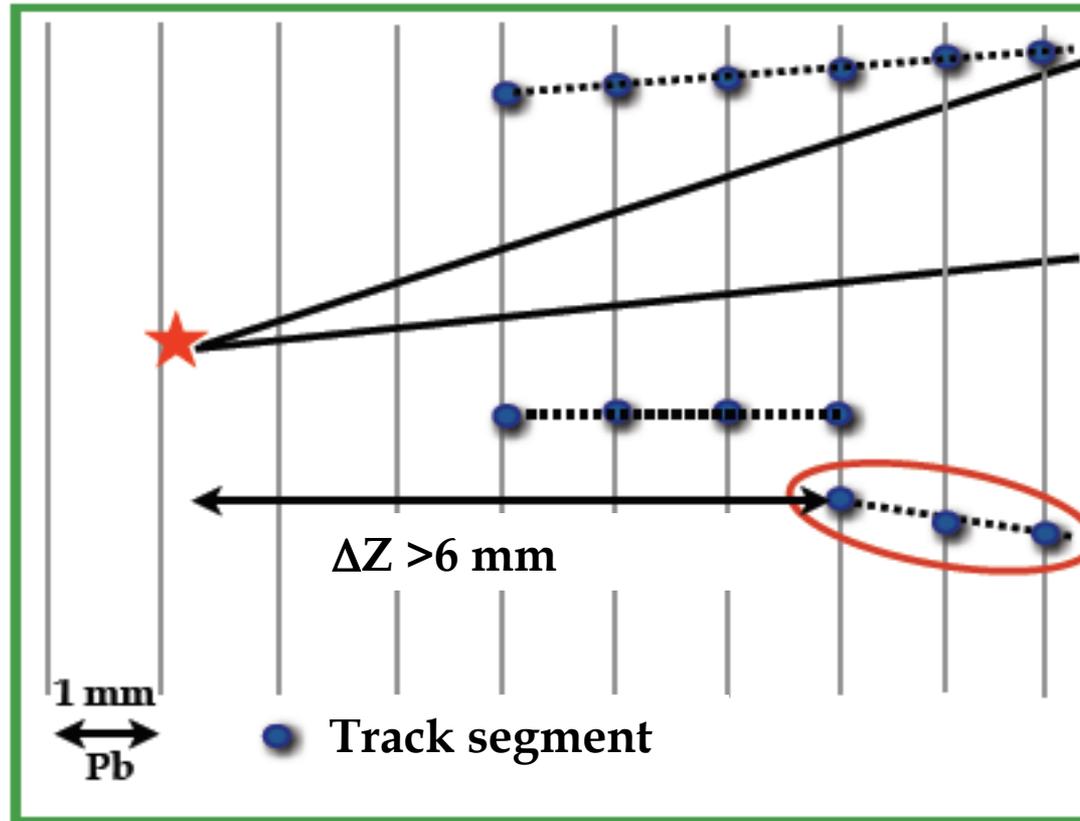
# Decay search procedure



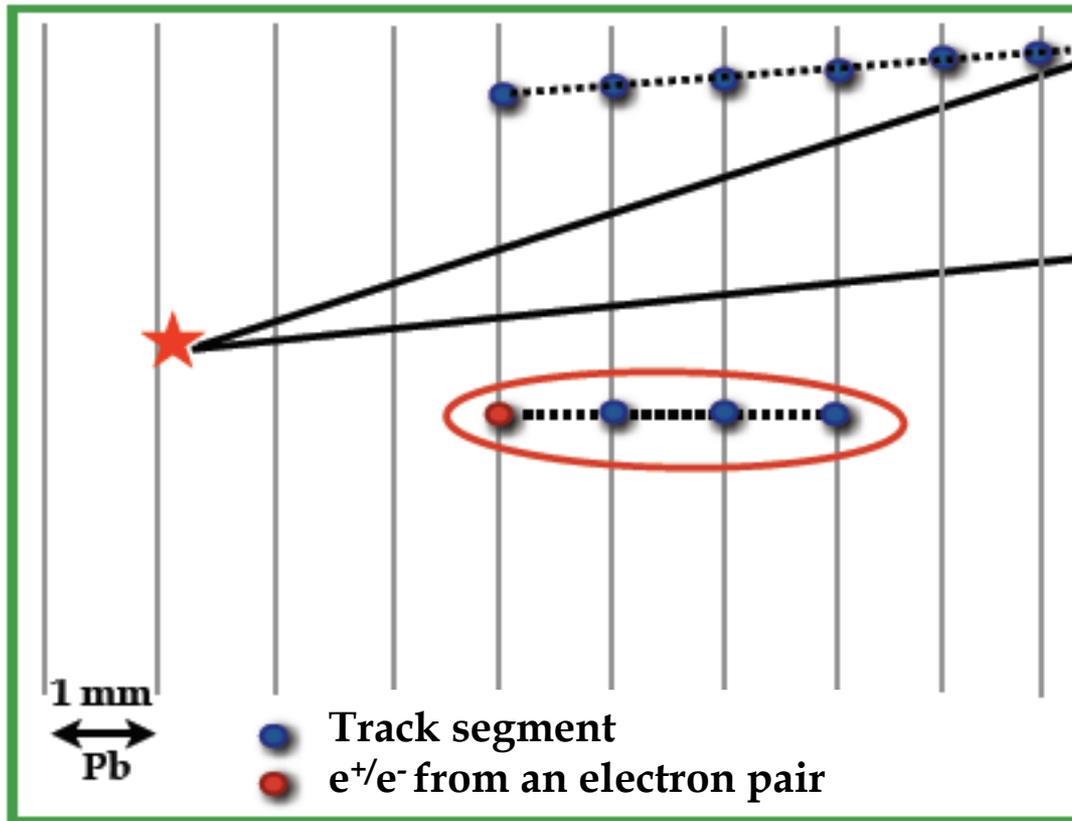
# Decay search: penetrating tracks discarded



# Decay search: track selection

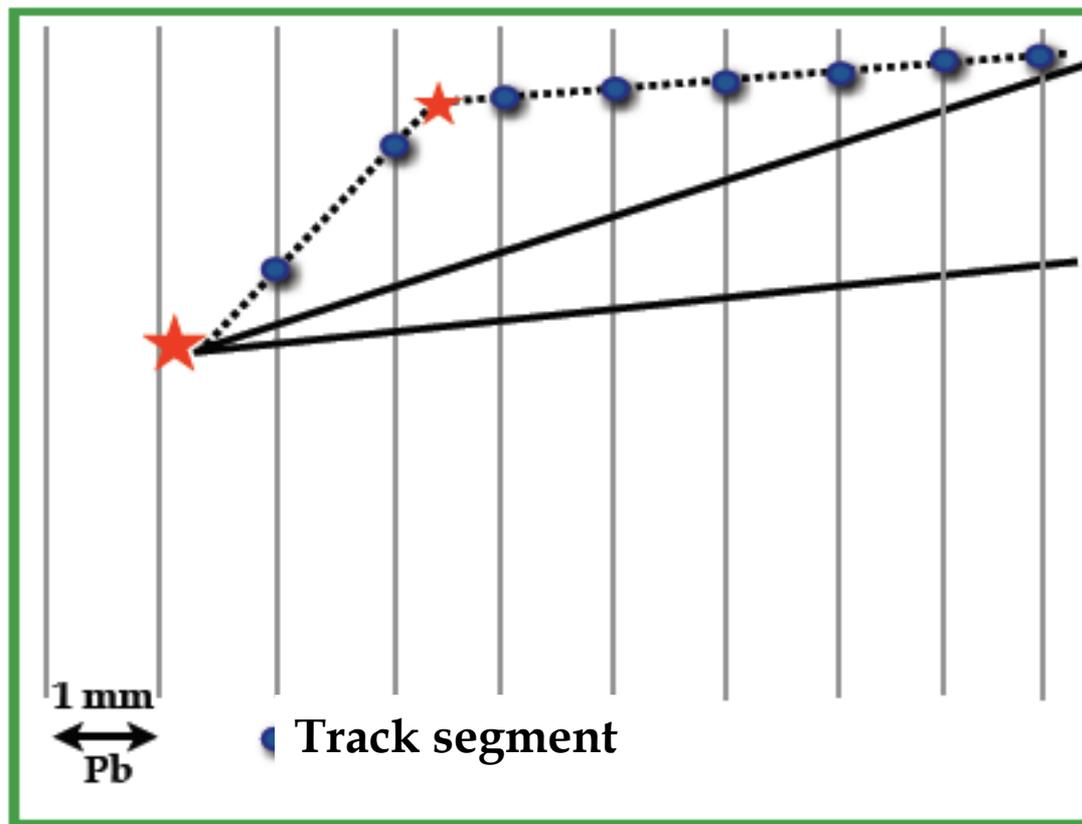
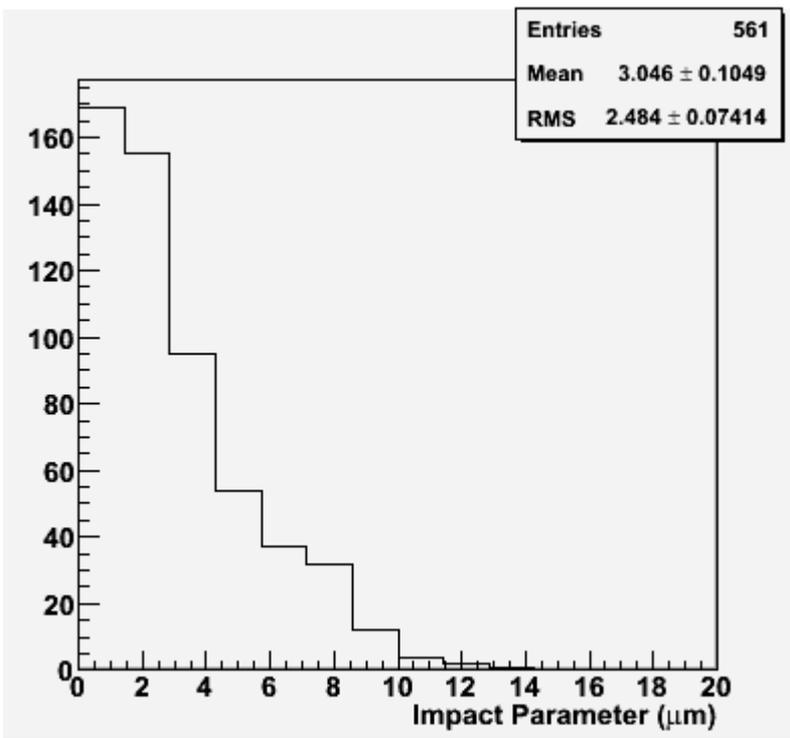


# Decay search: electron pair

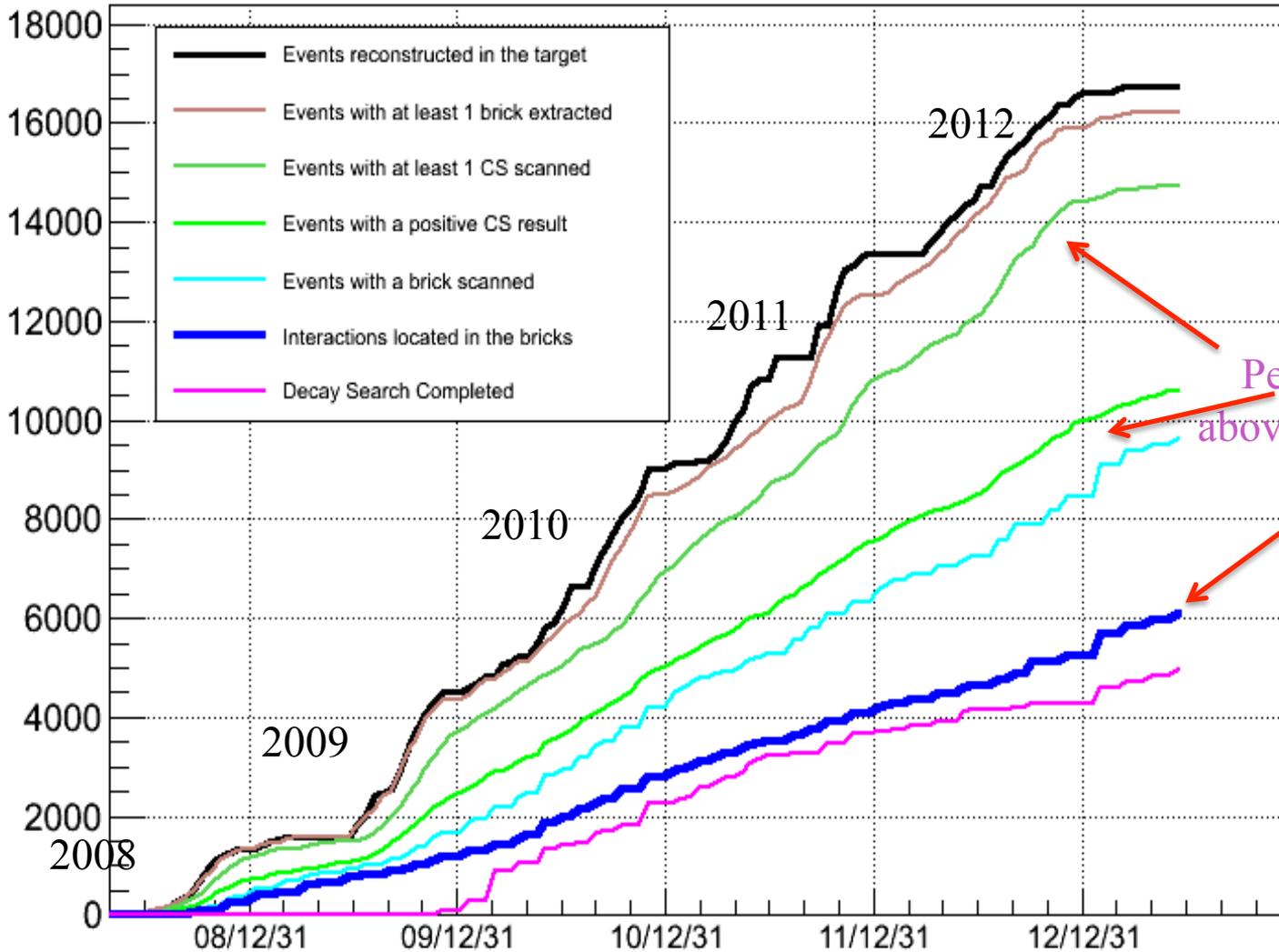


# Decay search: kink topology detected

Impact parameter distribution of tracks associated to primary vertices



# Status of data analysis



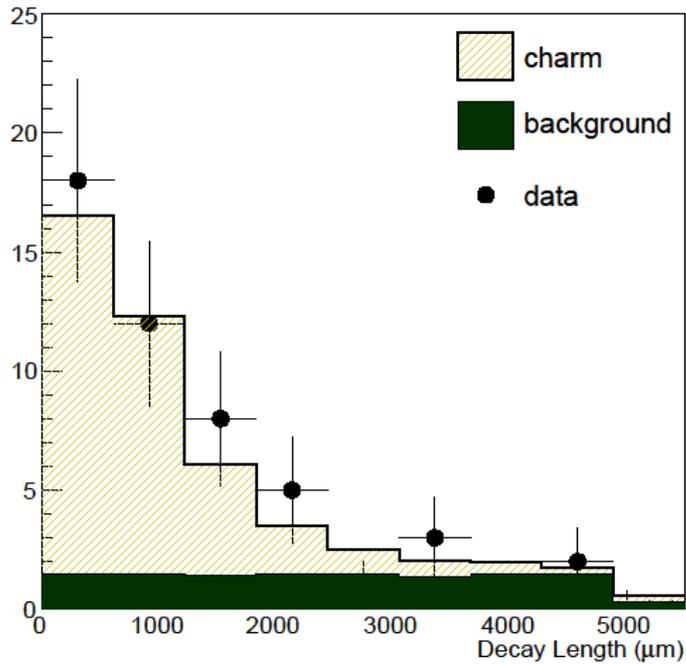
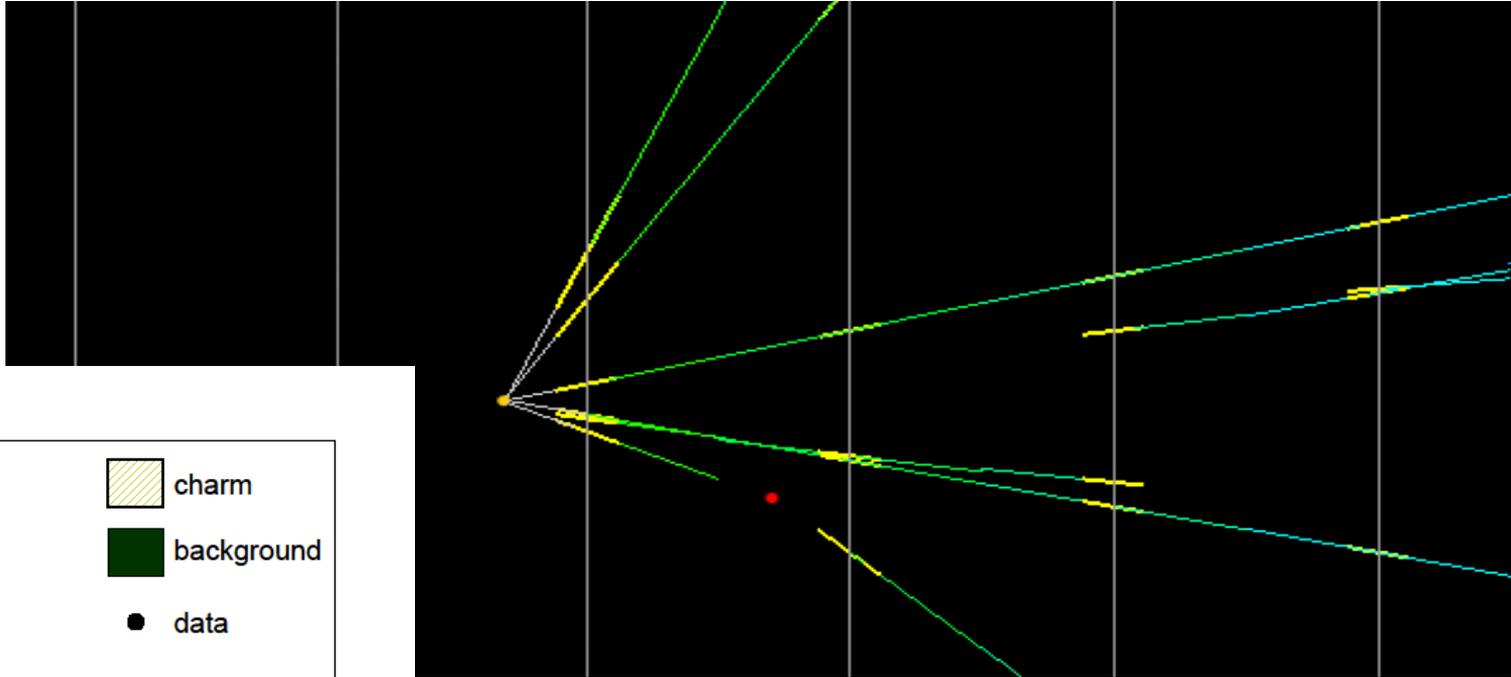
6067 located interactions

4969 decay search

2008-2009 completed  
2010 to 2012 ongoing  
with optimized strategy

*Charmed hadron production:  
an application of the decay search  
a control sample for  $\tau$*

# *Charm sample: same topology but muon at interaction vertex*

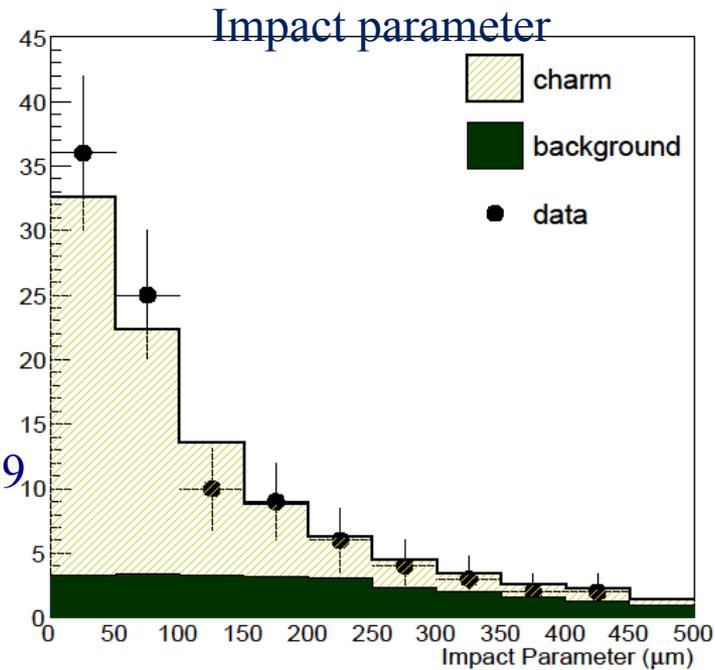
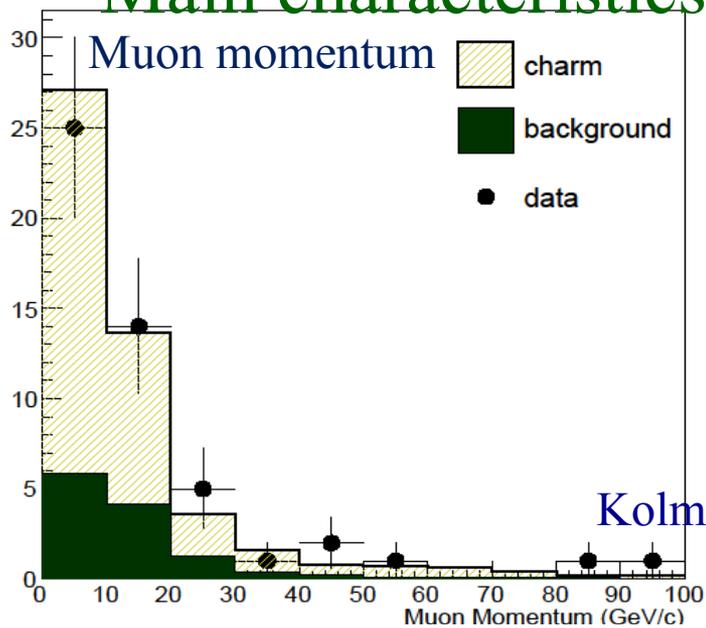


# *Charm yield from the analysis of 2008÷2010 data*

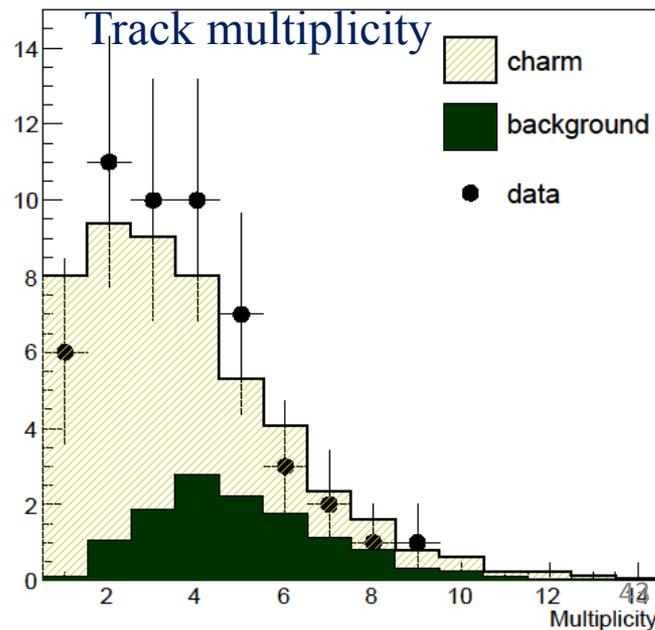
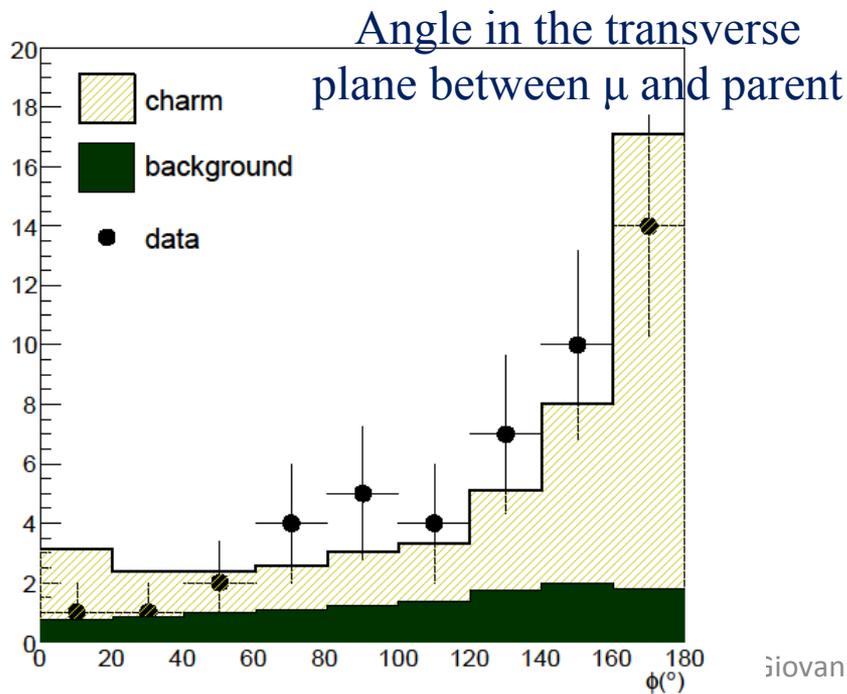
	charm	background	expected	data
1 prong	$20 \pm 3$	$9 \pm 3$	$29 \pm 4$	19
2 prong	$15 \pm 2$	$3.8 \pm 1.1$	$19 \pm 2$	22
3 prong	$5 \pm 1$	$1.0 \pm 0.3$	$6 \pm 1$	5
4 prong	$0.8 \pm 0.2$	-	$0.8 \pm 0.2$	4
All	<b><math>41 \pm 4</math></b>	<b><math>14 \pm 3</math></b>	<b><math>55 \pm 5</math></b>	<b>50</b>

Background, mostly from hadronic interactions  
(contribution from strange particle decay)

# Main characteristics of charm candidate events

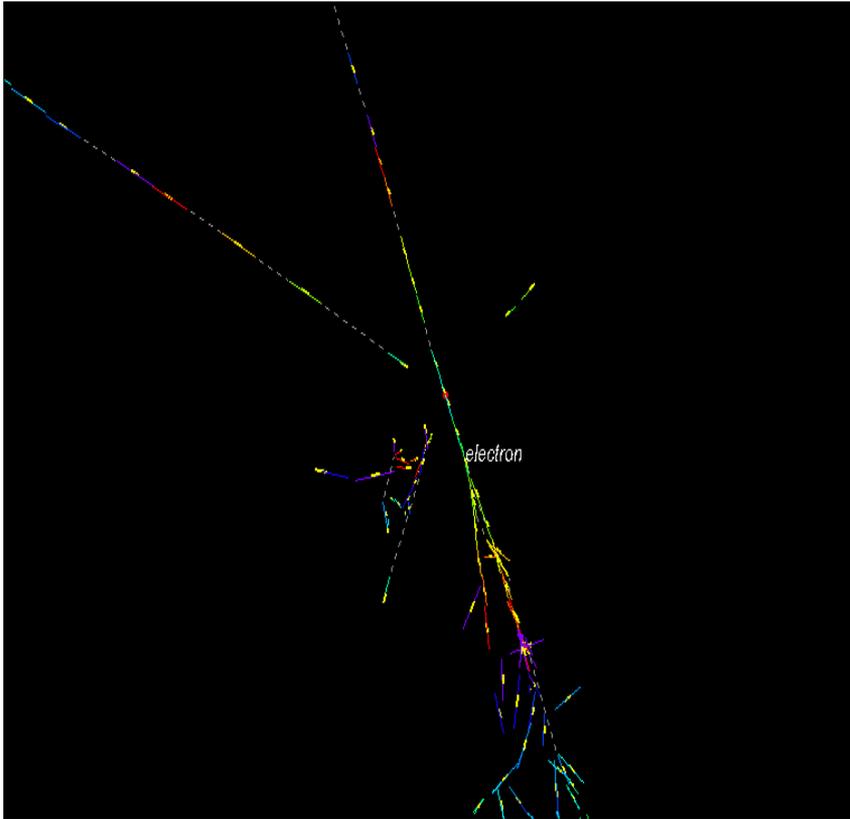


Kolmogorov test  $\geq 0.99$   
all plots

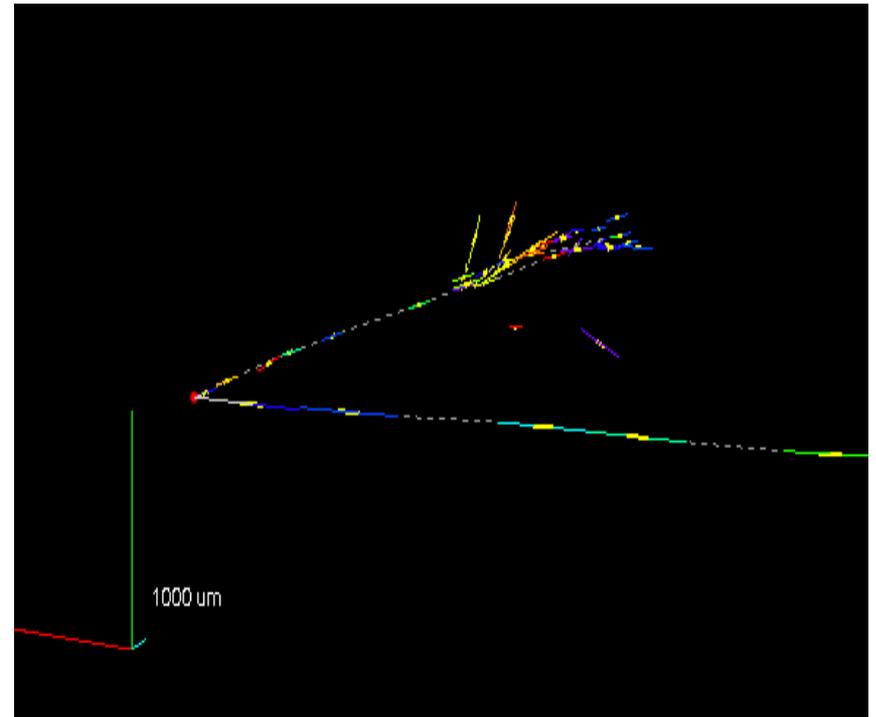


# *Physics results*

# $\nu_{\mu} \rightarrow \nu_e$ analysis

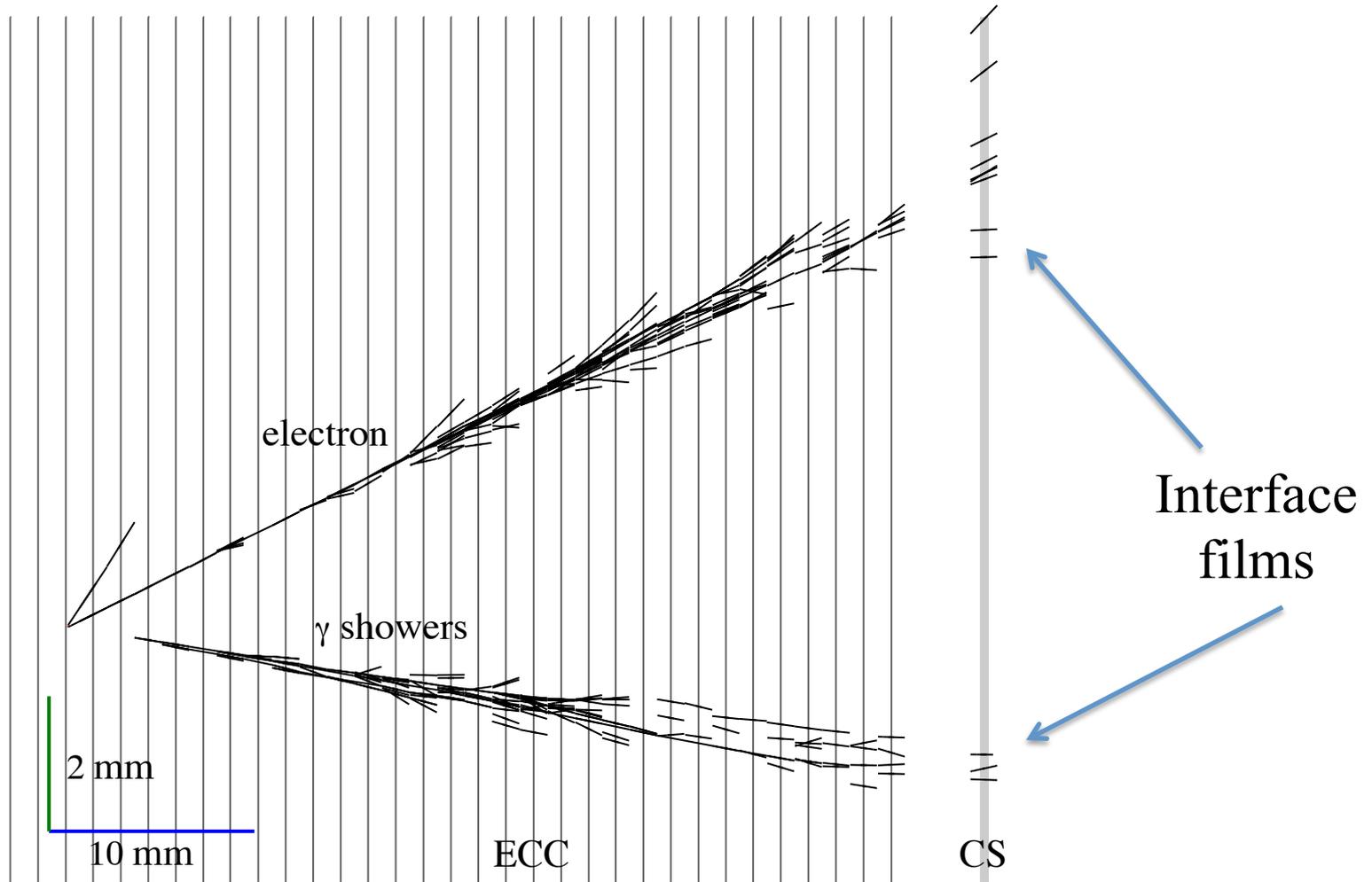


4.1 GeV electron



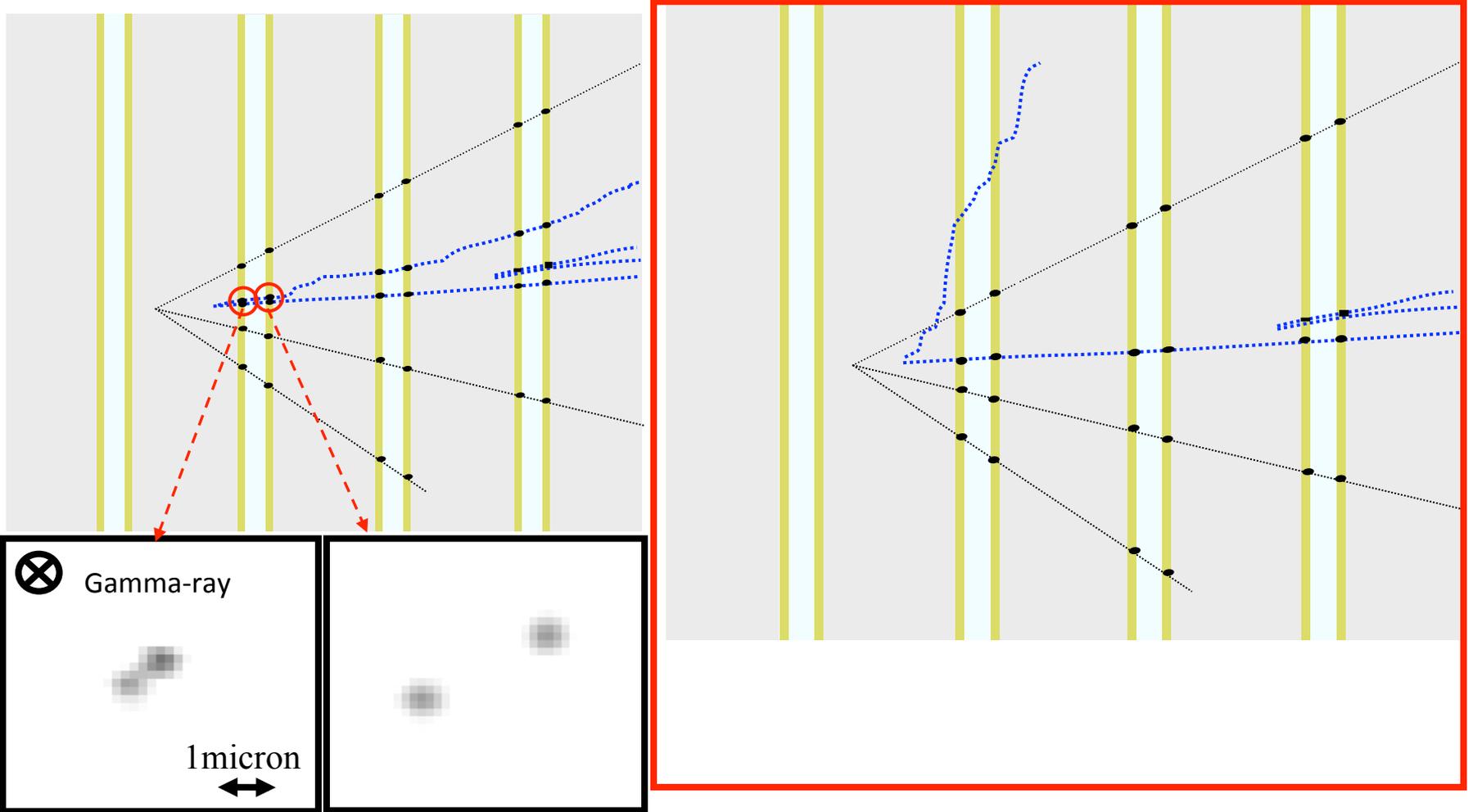
32 events found in the analyzed sample

# Electron neutrino search in 2008 and 2009 runs: one of the $\nu_e$ events with a $\pi^0$ as seen in the brick



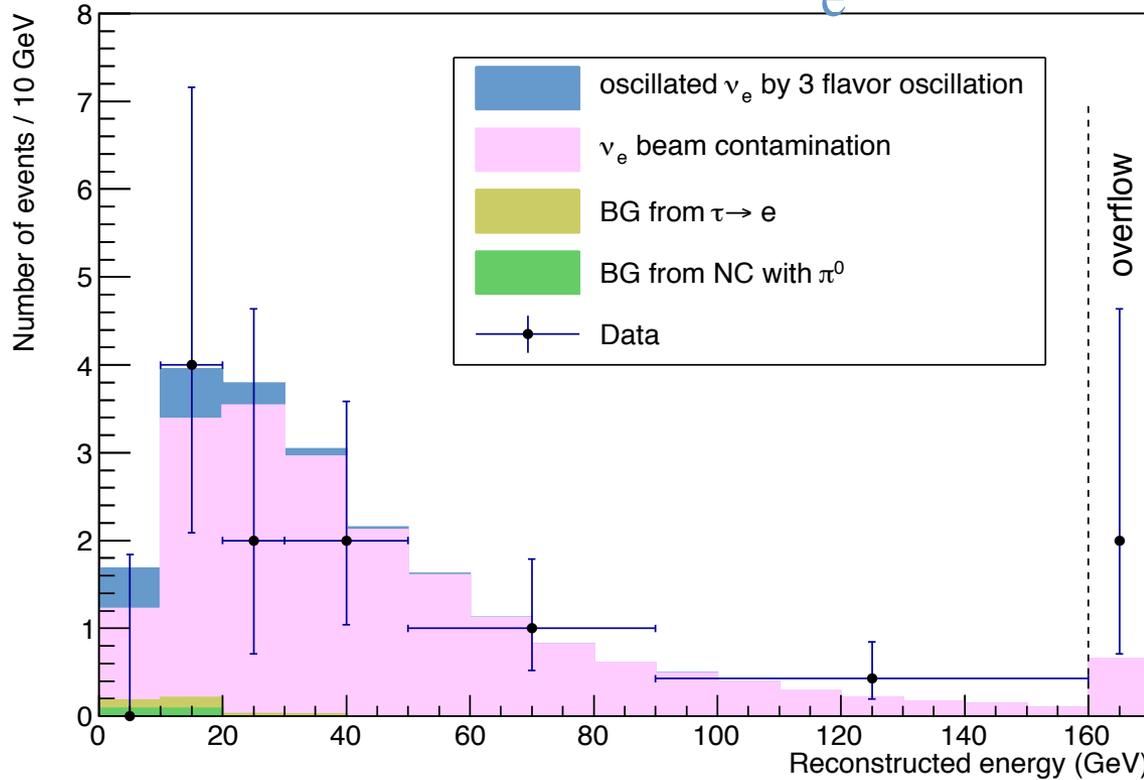
19 candidates found in a sample of 505 neutrino interactions without muon

# Background from $\nu_\mu\text{NC}$ ( $\pi^0 \rightarrow \gamma\gamma$ )



BG: 0.17 events (less than 1%)

# Energy distribution of the 19 $\nu_e$ candidates



Energy cut		20 GeV	30 GeV	No cut
BG common to both analyses	BG (a) from $\pi^0$	0.2	0.2	0.2
	BG (b) from $\tau \rightarrow e$	0.2	0.3	0.3
	$\nu_e$ beam contamination	4.2	7.7	19.4
Total expected BG in 3-flavour oscillation analysis		4.6	8.2	19.8
BG to non-standard oscillation analysis only	$\nu_e$ via 3-flavour oscillation	1.0	1.3	1.4
Total expected BG in non-standard oscillation analysis		5.6	9.4	21.3
Data		4	6	19

Observation compatible with background-only hypothesis:  
 $19.8 \pm 2.8$  (syst) events

3 flavour analysis

Energy cut to increase the S/N

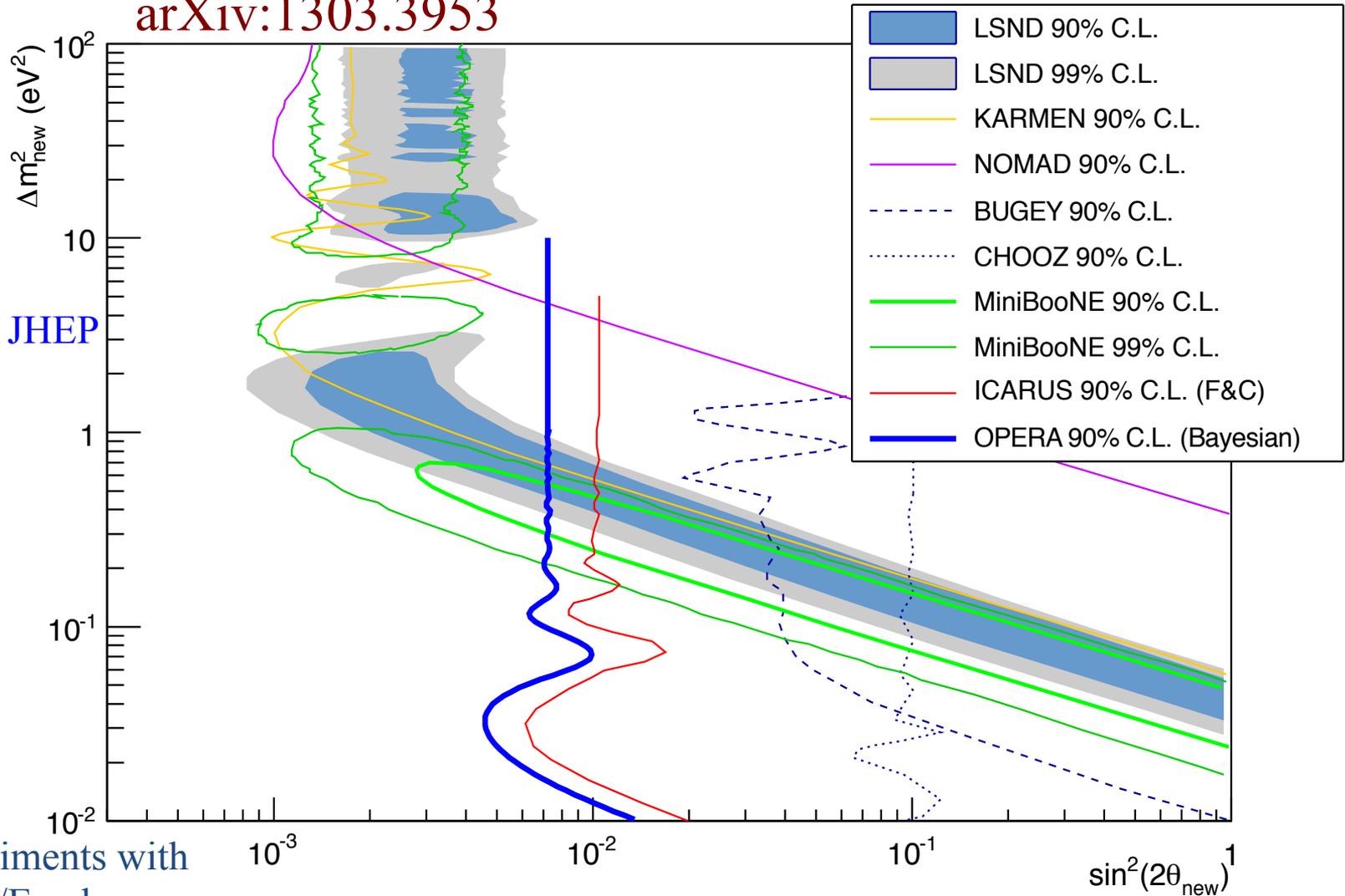
4 observed events

4.6 expected

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

# Search for non-standard oscillations at large $\Delta m^2$ values: exclusion plot in the $\sin^2(2\theta_{\text{new}})$ - $\Delta m^2_{\text{new}}$ plane

arXiv:1303.3953



To appear on JHEP

Caveat: experiments with  
different L/E values

# $\nu_{\mu} \rightarrow \nu_{\tau}$ analysis

- 2008-2009 run analysis
- Conservative approach: get confidence on the detector performances before applying any kinematical cut
- No kinematical cut
- Slower analysis speed (signal/noise not optimal)
- Good data/MC agreement

# The first $\nu_\tau$ “appearance” candidate (2010)

Candidate  
 $\nu_\tau$  interaction  
and  $\tau$  decay from  
 $\nu_\mu \rightarrow \nu_\tau$  oscillation



Physics Letters B 691 (2010) 138–145



Contents lists available at [ScienceDirect](http://ScienceDirect)

Physics Letters B

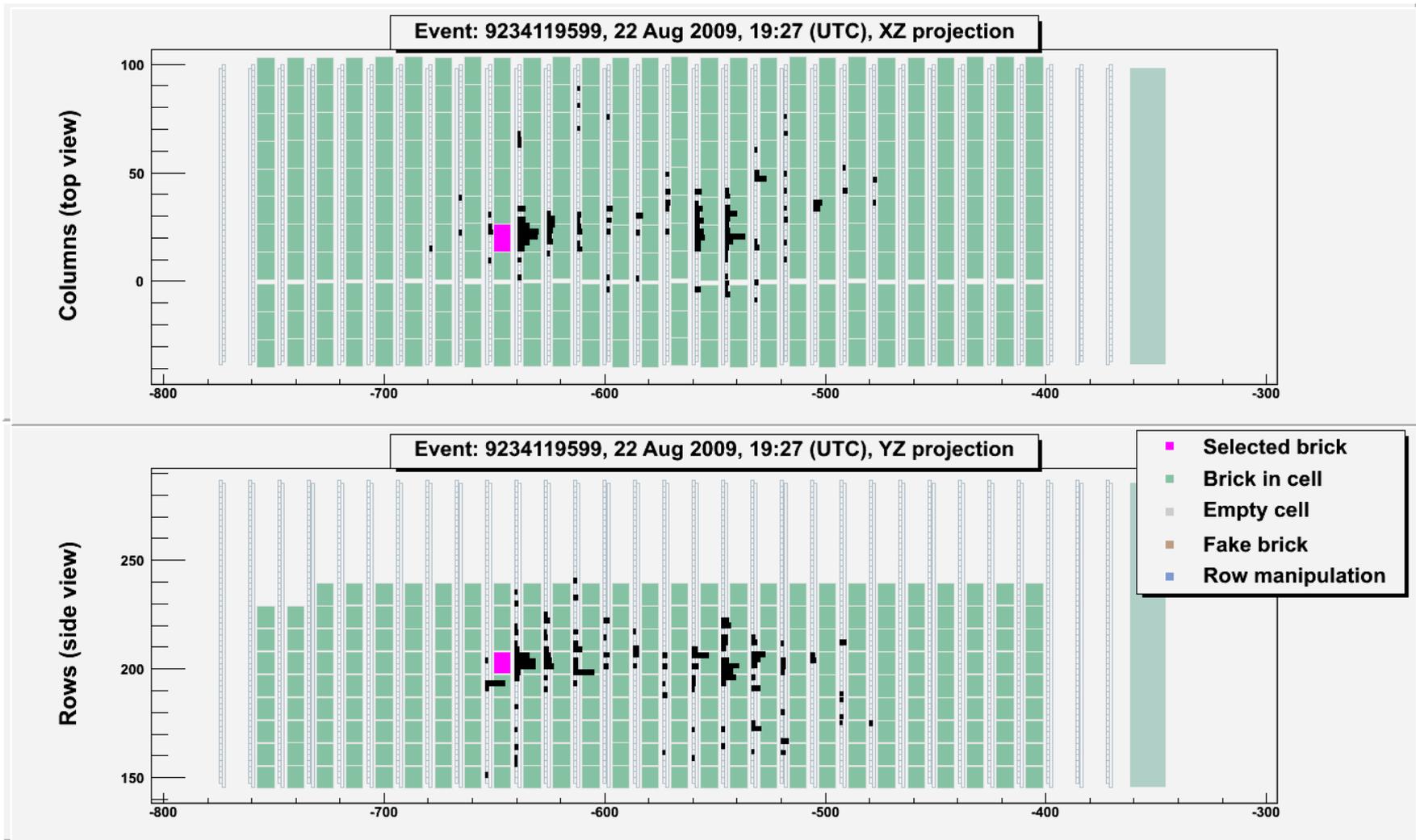
[www.elsevier.com/locate/physletb](http://www.elsevier.com/locate/physletb)



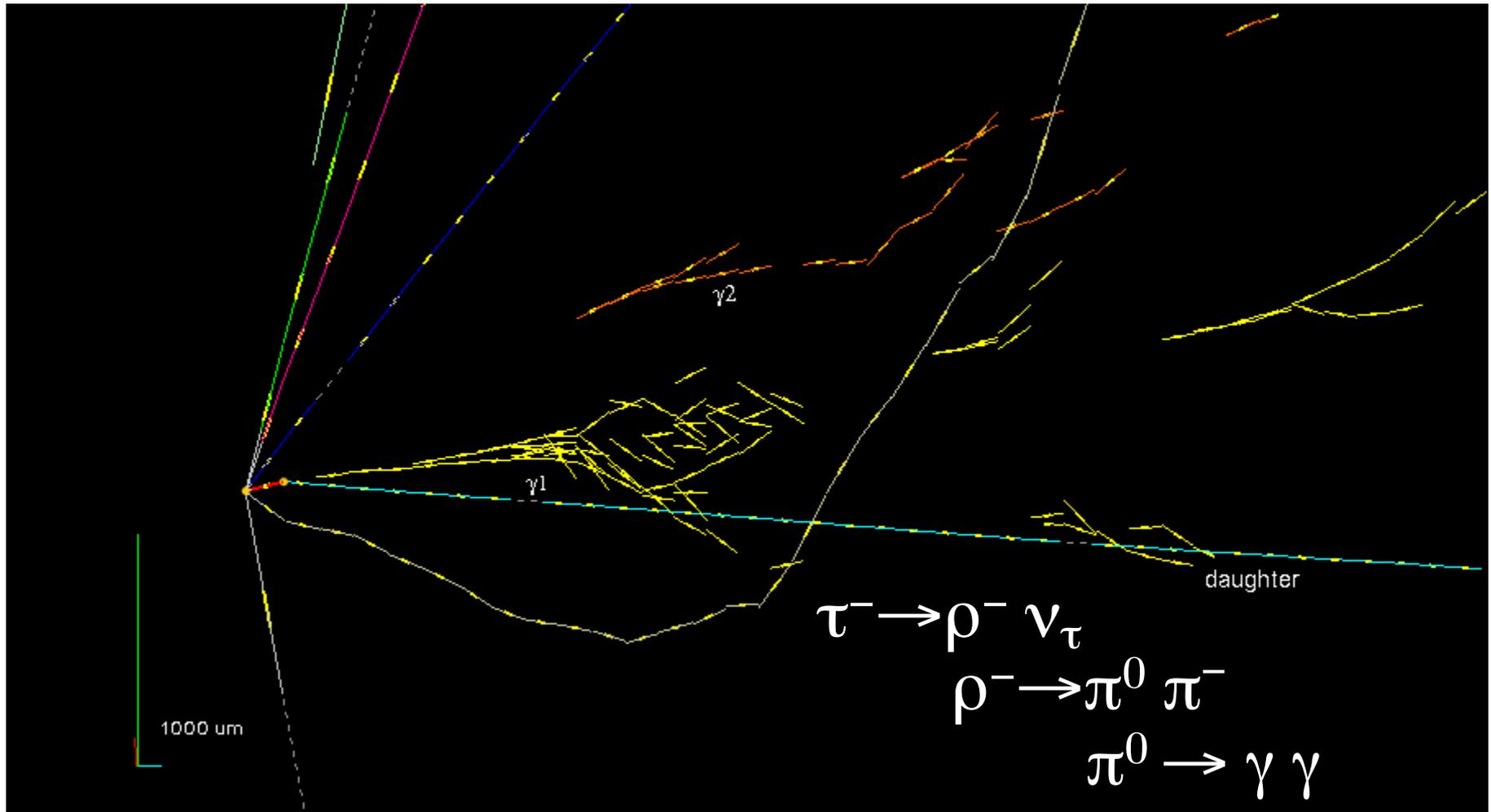
Observation of a first  $\nu_\tau$  candidate event in the OPERA experiment  
in the CNGS beam

# First tau neutrino candidate event

## Muonless event 9234119599, taken on 22<sup>nd</sup> August 2009 (as seen by the electronic detectors)



# Event reconstruction in the brick



PL17

PL18

PL19

PL20

PL21

Primary vertex

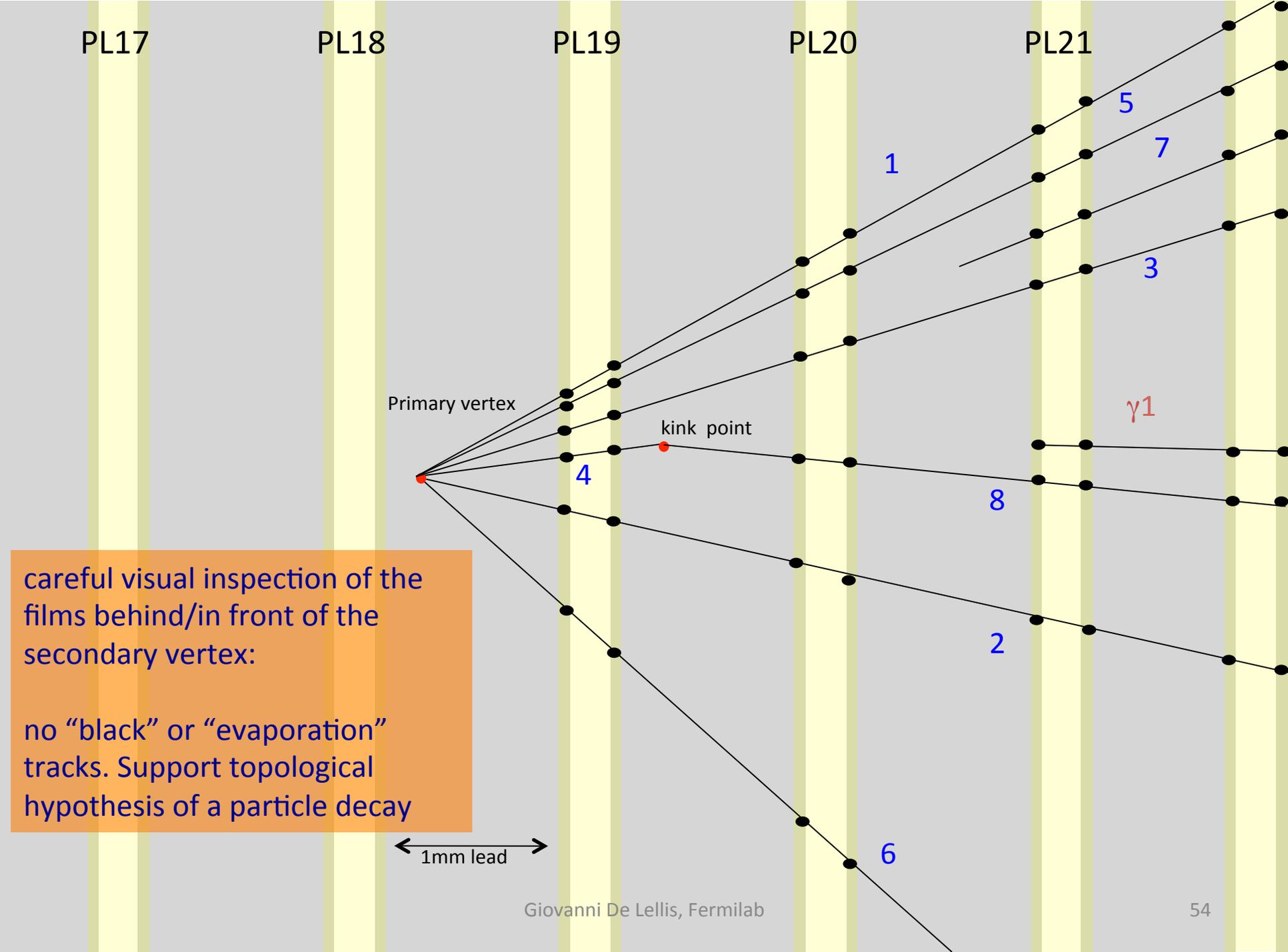
kink point

$\gamma 1$

careful visual inspection of the films behind/in front of the secondary vertex:

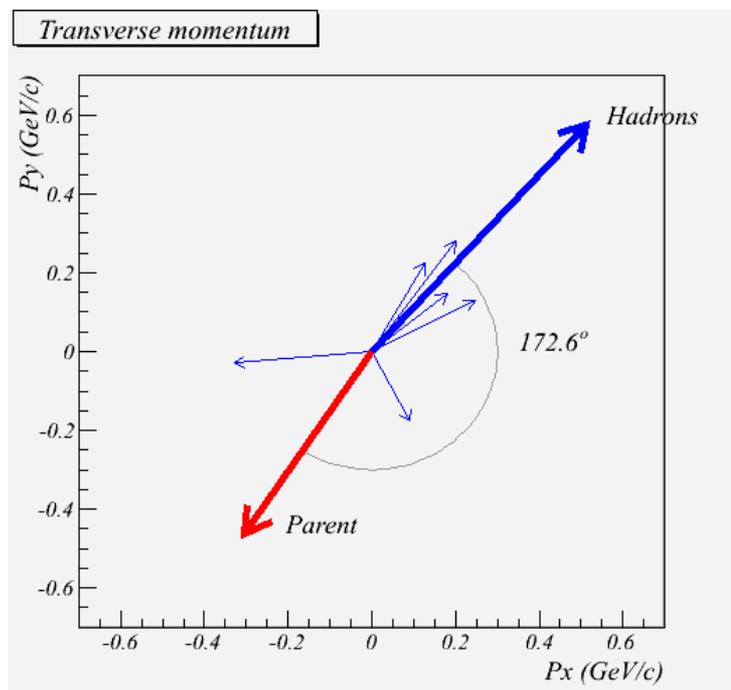
no "black" or "evaporation" tracks. Support topological hypothesis of a particle decay

← 1mm lead →



# Kinematical variables

- Kinematical variables are computed by averaging the two independent sets of measurements

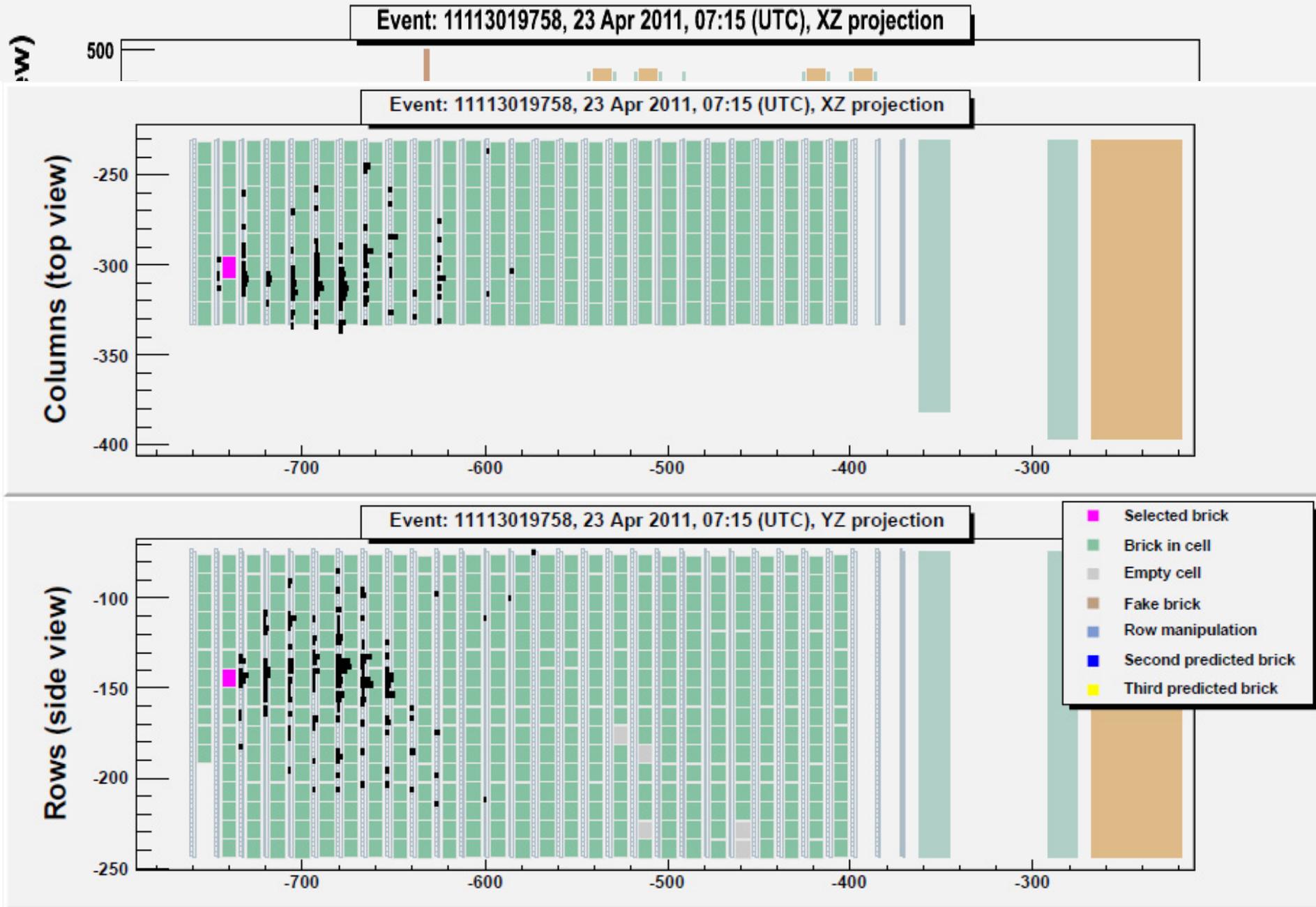


VARIABLE	AVERAGE
kink (mrad)	$41 \pm 2$
decay length ( $\mu\text{m}$ )	$1335 \pm 35$
P daughter (GeV/c)	$12^{+6}_{-3}$
Pt (MeV/c)	$470^{+240}_{-120}$
missing Pt (MeV/c)	$570^{+320}_{-170}$
$\phi$ (deg)	$173 \pm 2$

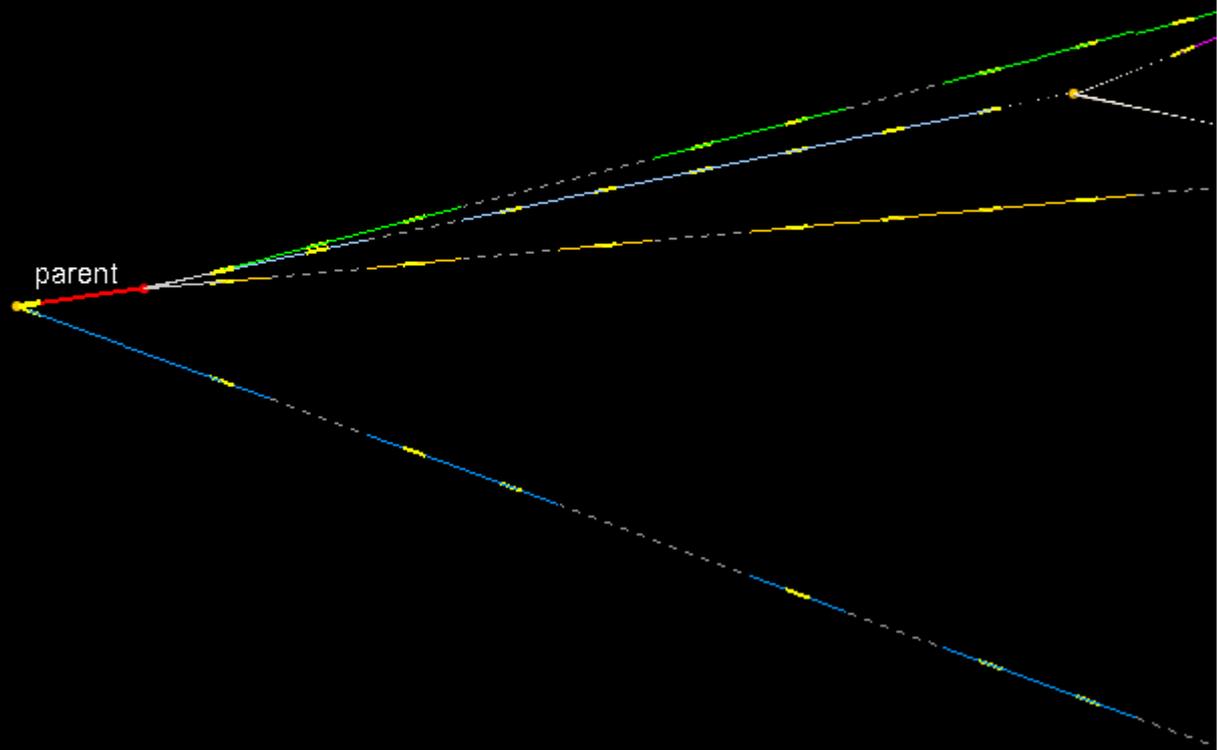
# Strategy for the 2010÷2012 runs

- Apply kinematical selection
- 15 GeV  $\mu$  momentum cut (upper bound)
- Anticipate the analysis of the most probable brick for all the events before moving to the second (and further ones): optimal ratio between efficiency and analysis time
- Anticipate the analysis of  $0\mu$  events (events without any  $\mu$  in the final state)
- In view of 2012 Summer conferences:  $0\mu$  and  $1\mu$  sample for 2010 run, for 2011 run stick to  $0\mu$  sample only, 2012 not yet analysed

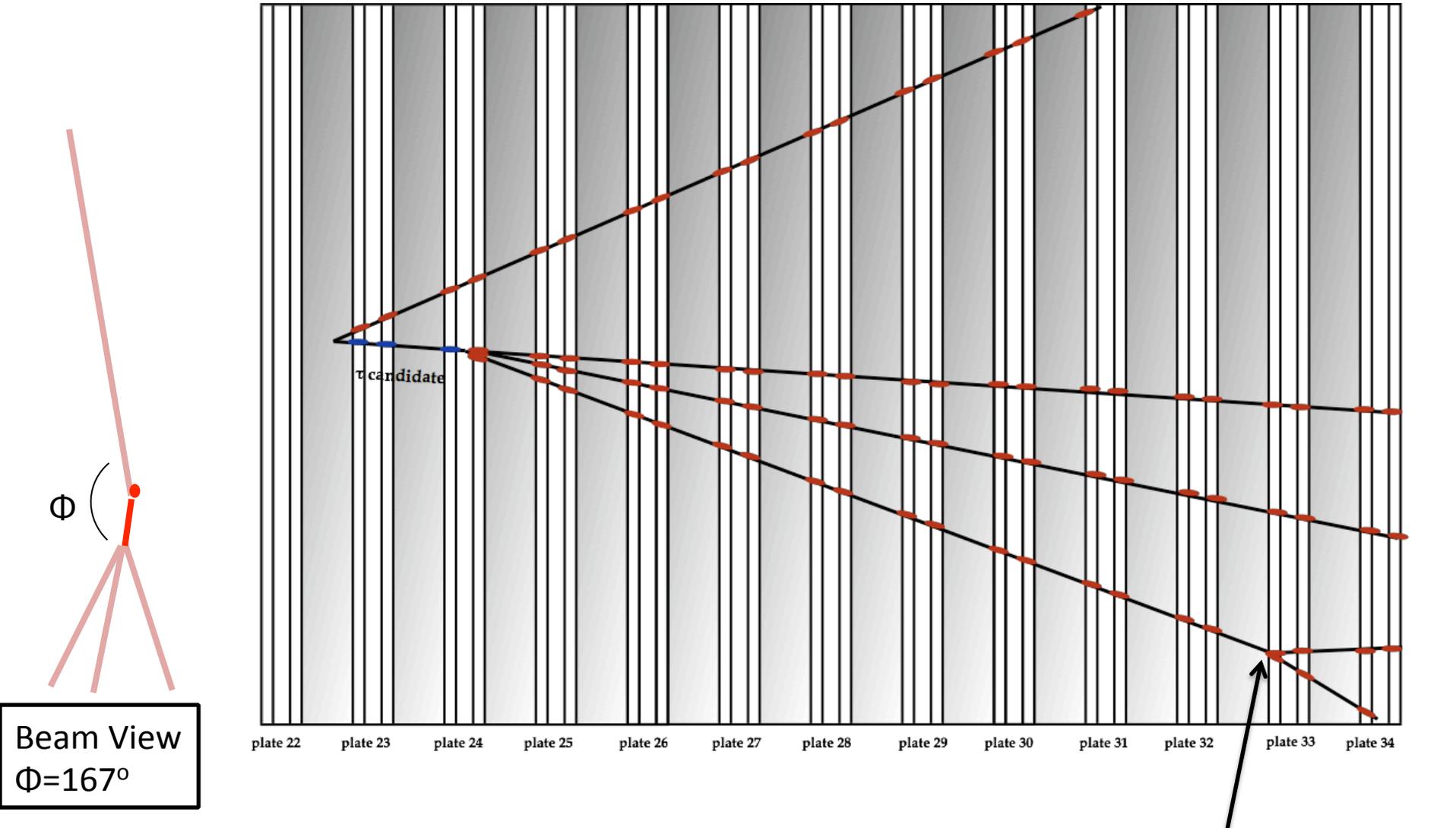
# Second neutrino tau candidate event taken on 23<sup>rd</sup> April 2011



# Second $\nu_\tau$ Candidate Event

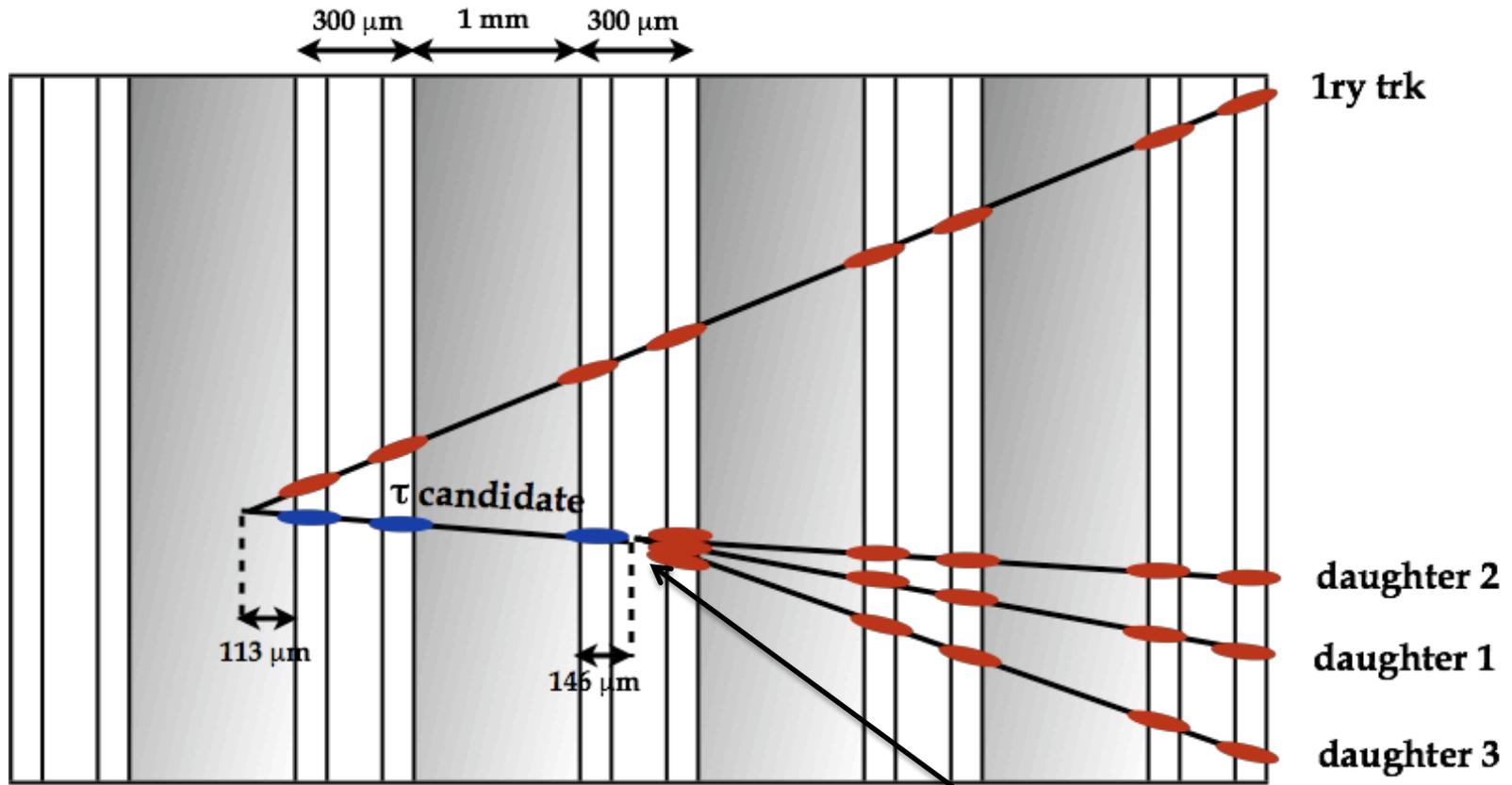


# Schematics of the event



Secondary Interaction  
In Emulsion  
With four Nuclear fragments

# Zoom of the primary interaction and decay region



Decay point  
**In Plastic Base**  
No Nuclear fragment  
Flight length 1.54mm

# Momentum measurement and particle identification of event tracks

Track#	Momentum ( $1\sigma$ interval) [ GeV/c]	Particle ID	Method / Comments
<b>Primary</b>	<b>2.8</b> (2.1-3.5)	<b>Hadron</b>	<ul style="list-style-type: none"><li>• <b>Momentum-Range Consistency Check</b></li><li><b>Stops after 2 brick walls.</b></li><li><b>Incompatible with muon</b> ( 26÷44 brick walls)</li></ul>
<b>d1</b>	<b>6.6</b> (5.2 - 8.6)	<b>Hadron</b>	<ul style="list-style-type: none"><li>• <b>Momentum-Range Consistency Check</b></li></ul>
<b>d2</b>	<b>1.3</b> (1.1 -1.5)	<b>Hadron</b>	<ul style="list-style-type: none"><li>• <b>Momentum-Range Consistency Check</b></li></ul>
<b>d3</b>	<b>2.0</b> (1.4 - 2.9)	<b>Hadron</b>	<b>Interaction in the Brick</b> <b>@ 1.3cm downstream</b>

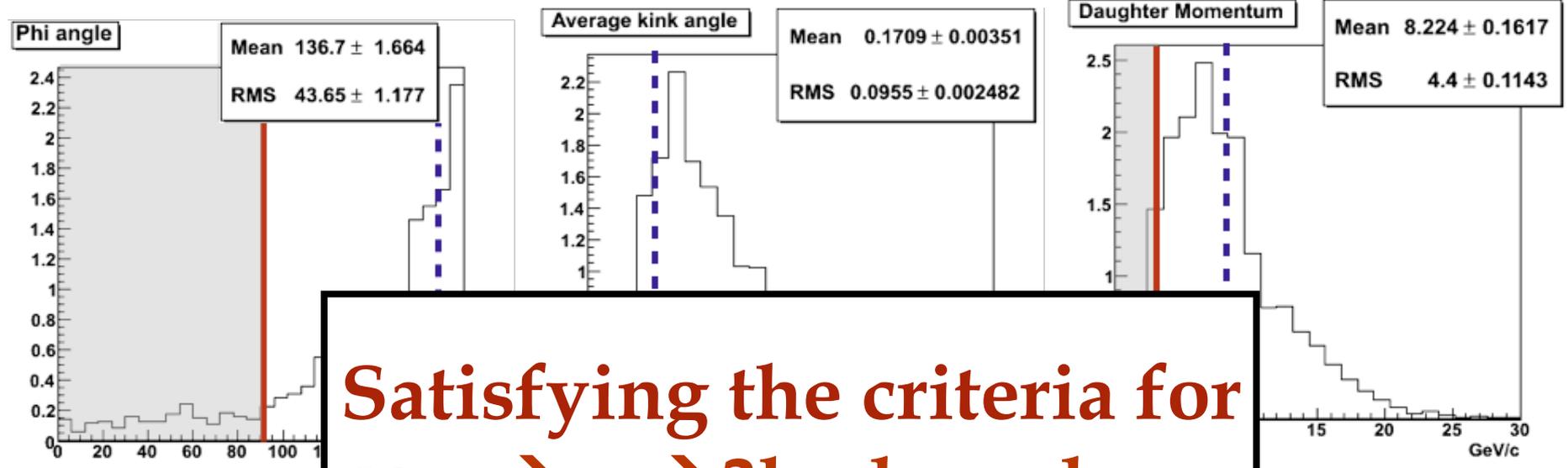
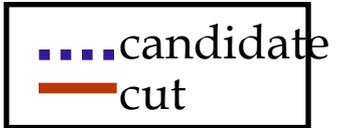
**Independent momentum measurements carried out in two labs**

# Kinematics of the second Candidate Event

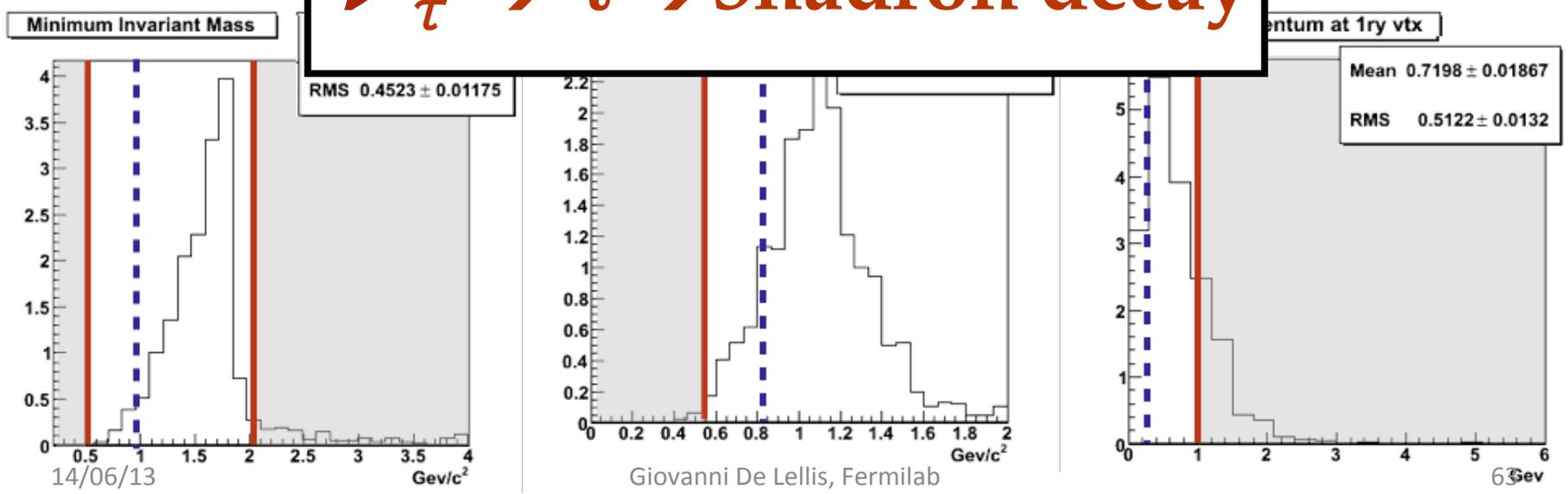
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	Cut	Value
$\phi$ (Tau - Hadron) [degree]	>90	167.8 $\pm$ 1.1
average kink angle [mrad]	< 500	87.4 $\pm$ 1.5
Total momentum at 2ry vtx [GeV/c]	> 3.0	8.4 $\pm$ 1.7
Min Invariant mass [GeV/c <sup>2</sup> ]	0.5 < < 2.0	0.96 $\pm$ 0.13
Invariant mass [GeV/c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

# Kinematics of the second candidate event



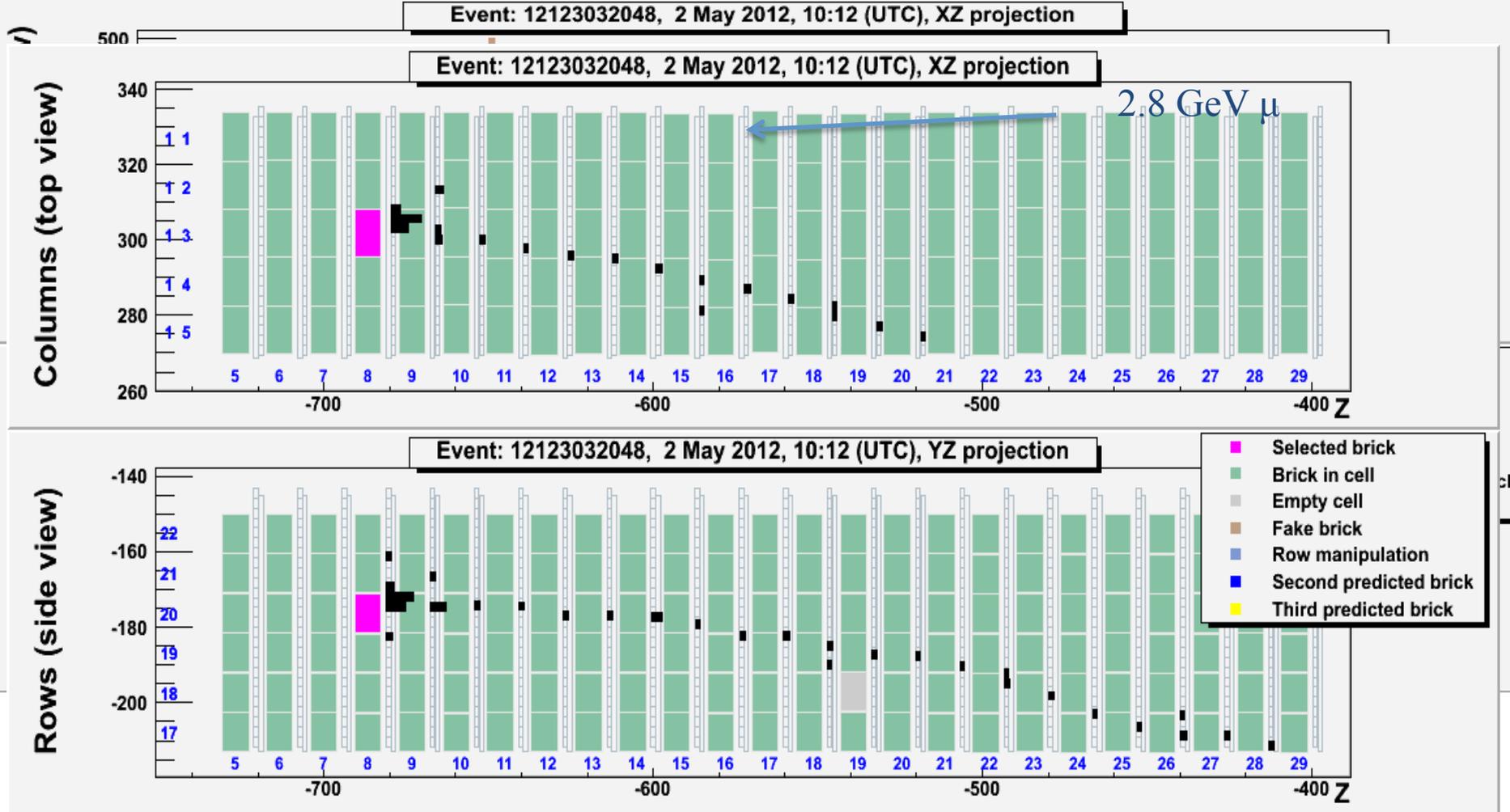
Satisfying the criteria for  $\nu_\tau \rightarrow \tau \rightarrow 3\text{hadron decay}$



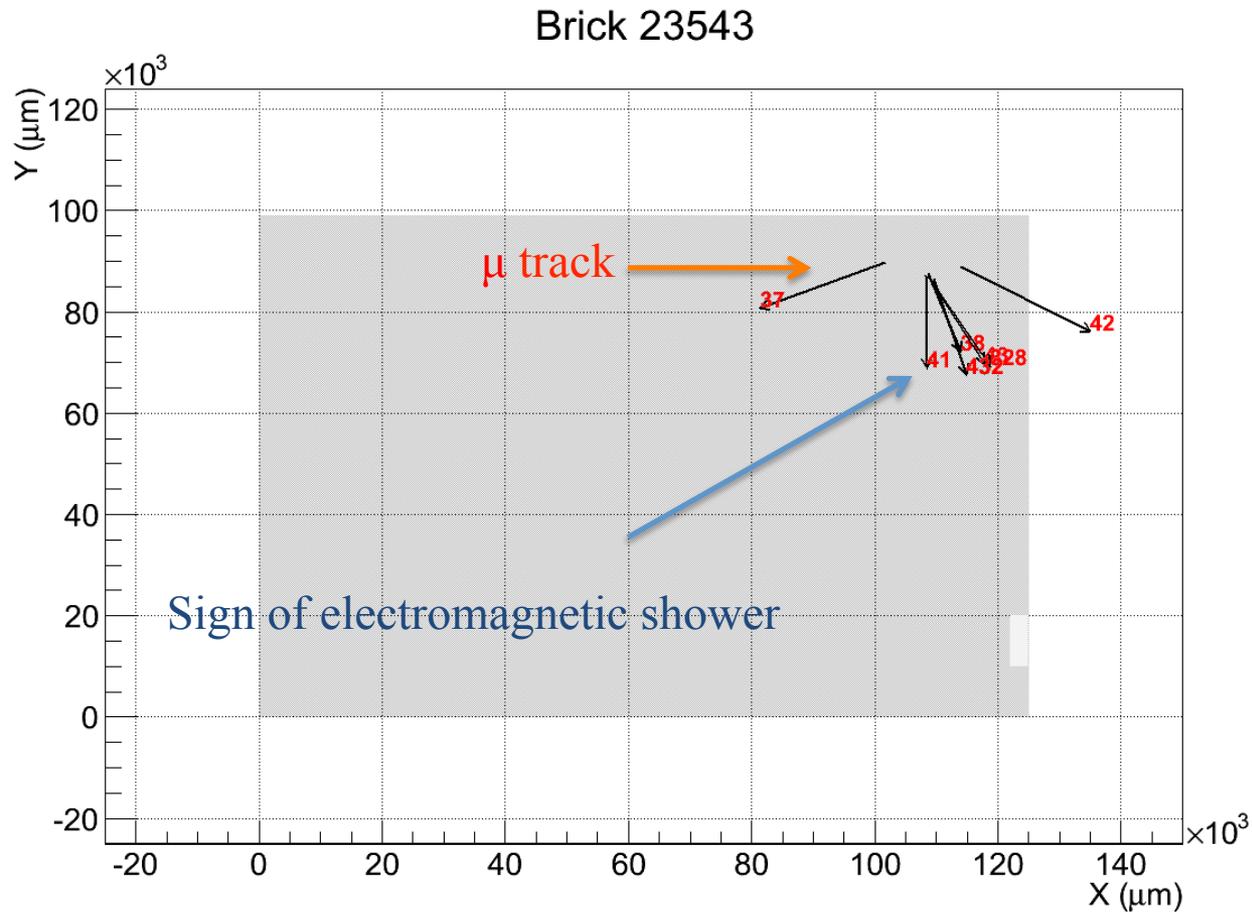
# *After 2012 Summer conferences*

- *Extension of the analysed sample to events with one  $\mu$  in the final state*

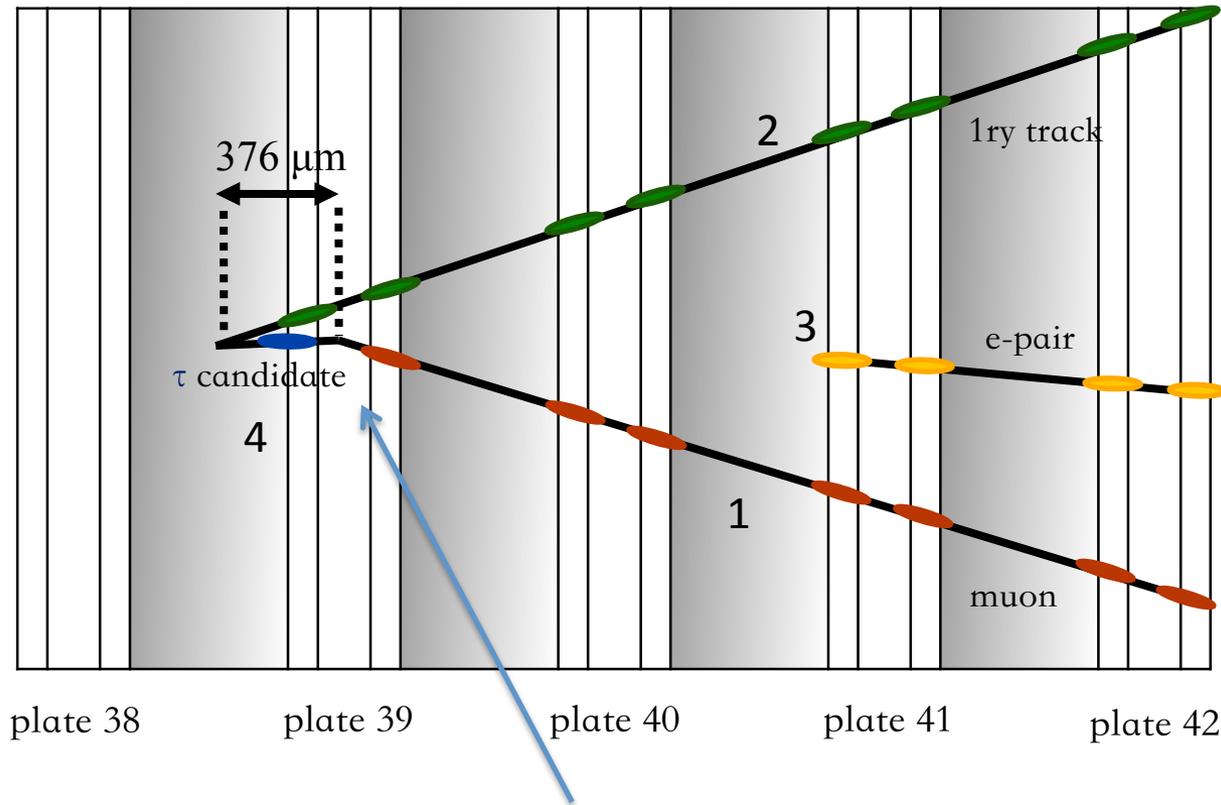
# Third tau neutrino event taken on May 2<sup>nd</sup> 2012



# Analysis of the interface films



# $\tau \rightarrow \mu$ candidate brick analysis and decay search



Decay in the plastic base

# $\tau \rightarrow \mu$ candidate

$\mu m$

# Third tau neutrino event

$$\tau \rightarrow \mu$$



1000  $\mu\text{m}$

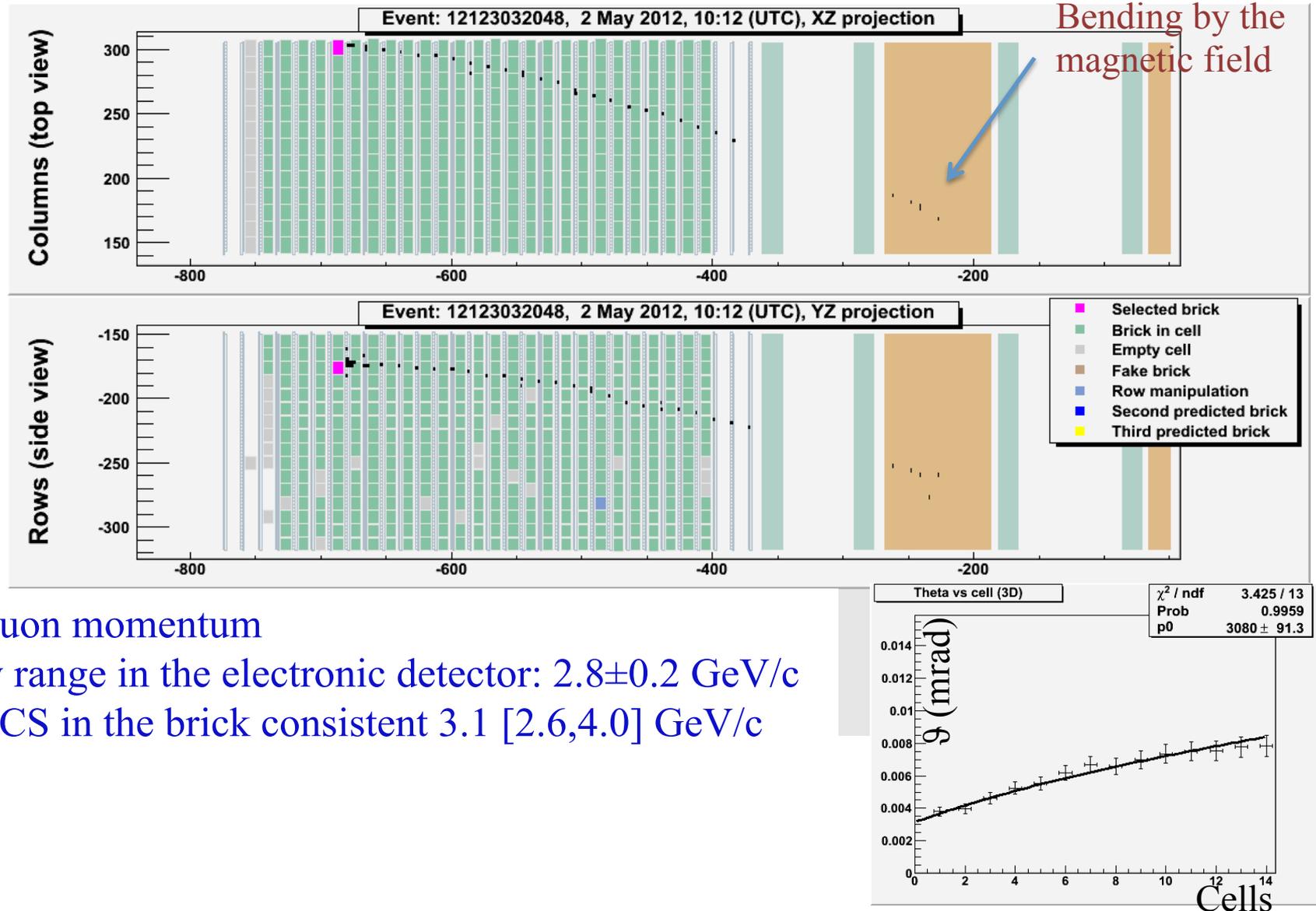
# Event tracks' features

TRACK NUMBER	PID	MEASUREMENT 1			MEASUREMENT 2		
		$\Theta_X$	$\Theta_Y$	P (GeV/c)	$\Theta_X$	$\Theta_Y$	P (GeV/c)
1 DAUGHTER	MUON	-0.217	-0.069	3.1 [2.6,4.0]MCS	-0.223	-0.069	2.8±0.2 Range (TT+RPC)
2	HADRON Range	0.203	-0.125	0.85 [0.70,1.10]	0.205	-0.115	0.96 [0.76,1.22]
3	PHOTON	0.024	-0.155	2.64 [1.9,4.3]	0.029	-0.160	3.24 [2.52,4.55]
4 PARENT	TAU	-0.040	0.098		-0.035	0.096	

## *$\gamma$ attachment*

	$\delta\theta_{\text{RMS}}$ (mrad)	DZ (mm)	Measured IP ( $\mu\text{m}$ )	IP resolution ( $\mu\text{m}$ )	ATTACHMENT
1ry vertex	6	3.1	18.2	13.6	<b>OK</b>
2ry vertex	6	2.8	68.7	12.2	<b>EXCLUDED</b>

# Muon charge and momentum reconstruction



Muon momentum

by range in the electronic detector:  $2.8 \pm 0.2$  GeV/c

MCS in the brick consistent  $3.1$  [2.6,4.0] GeV/c

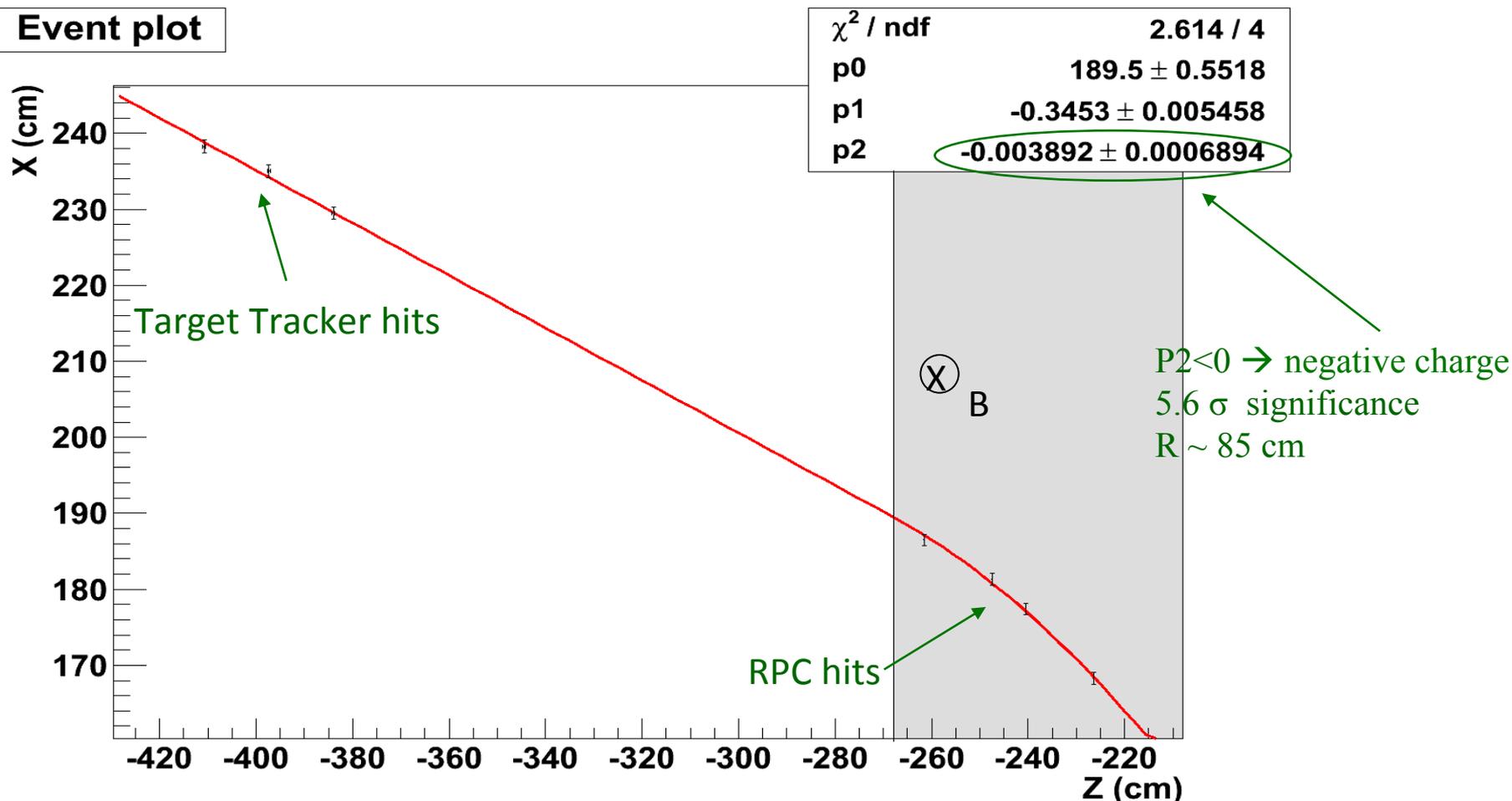
# Charge determination of the muon

Charge measurement based on TT and RPC hits when no hits in drift tubes

Fit function:

$$X(z) = p_0 + p_1 \times (z-z_0) + p_2 \times (z-z_0)^2 \quad \text{for } z > z_0, \text{ start of magnetized region}$$
$$X(z) = p_0 + p_1 \times (z-z_0) \quad \text{for } z < z_0$$

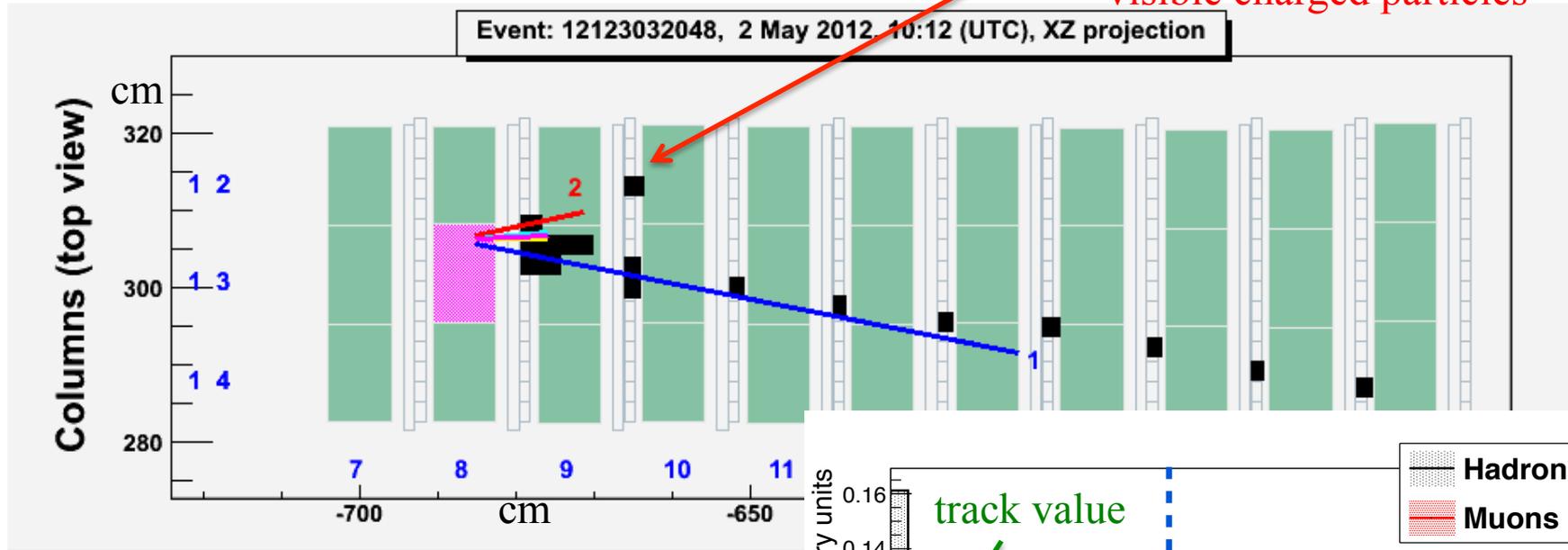
Event plot



P-value = 0.063% (probability to reconstruct a  $\mu^+$  stopping in the 7<sup>th</sup> iron layer with  $p_2 < -0.00389 \text{ cm}^{-1}$ )

# Track follow down to assess the nature of track 2

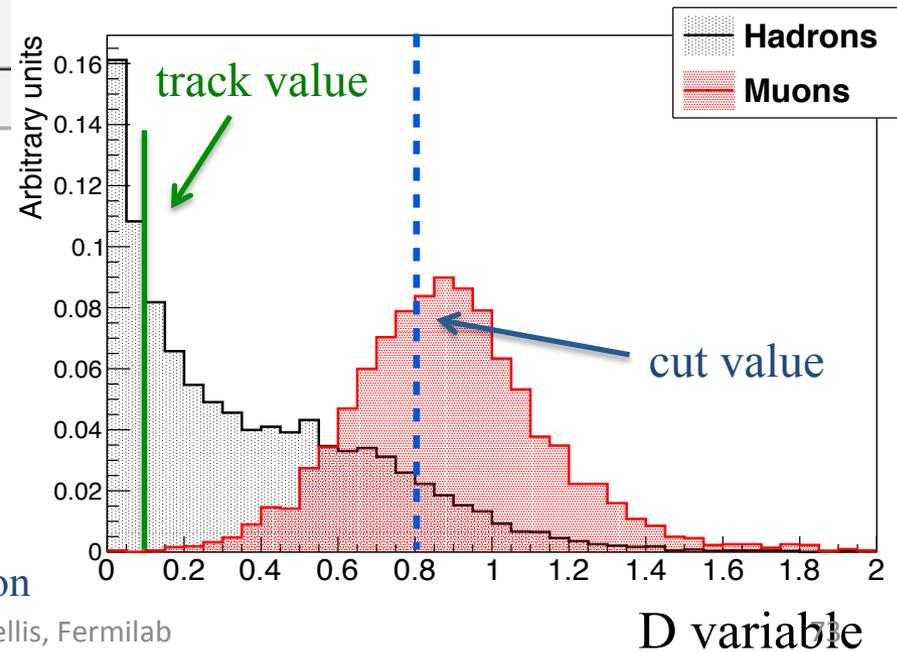
Track 2 interacting in the downstream brick without visible charged particles



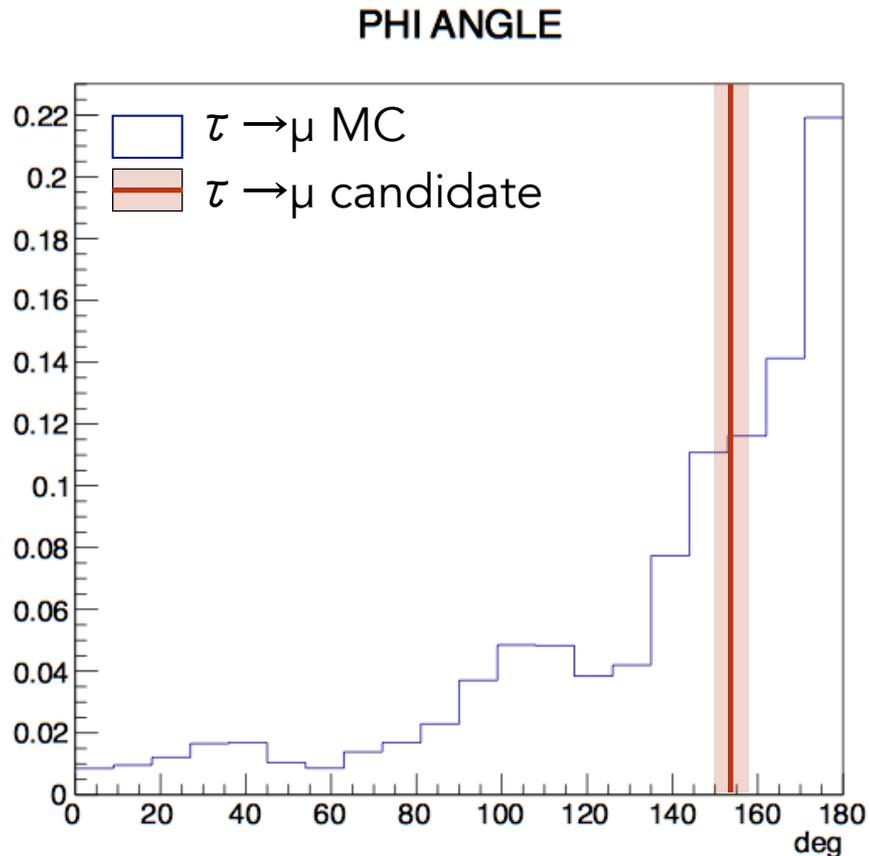
Momentum/range inconsistent with  $\mu$  hypothesis  
0.9 GeV/4 cm Lead

$$D = \frac{L}{R_{lead}(p)} \frac{\rho_{lead}}{\rho_{average}}$$

$L$  = track length  
 $R_{lead} = \mu$  range  
 $\rho_{average}$  = average density  
 $\rho_{lead}$  = lead density  
 $p$  = momentum in emulsion



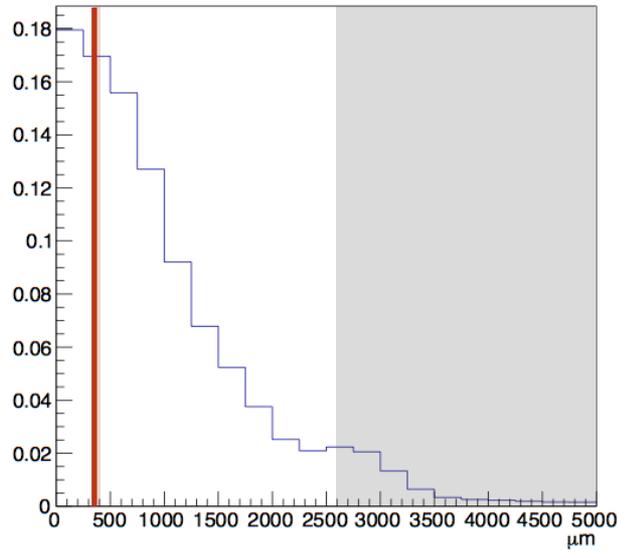
# Kinematical variables



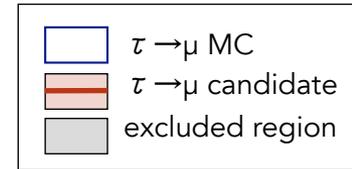
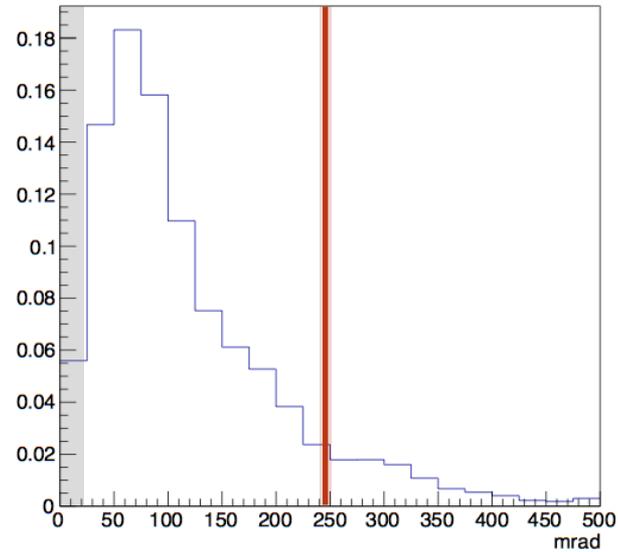
<b>VARIABLE</b>	<b>AVERAGE</b>
Kink angle (mrad)	<b><math>245 \pm 5</math></b>
decay length ( $\mu\text{m}$ )	<b><math>376 \pm 10</math></b>
$P_\mu$ (GeV/c)	<b><math>2.8 \pm 0.2</math></b>
Pt (MeV/c)	<b><math>690 \pm 50</math></b>
$\phi$ (degrees)	<b><math>154.5 \pm 1.5</math></b>

# Kinematical variables. All cuts passed: $\tau \rightarrow \mu$ candidate

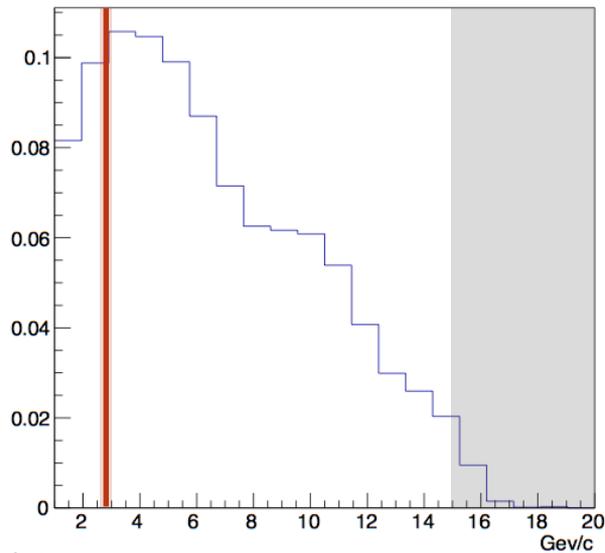
DECAY LENGTH



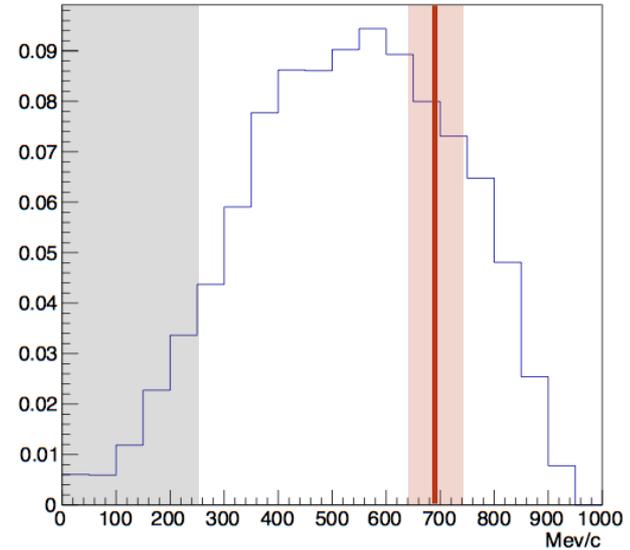
KINK ANGLE



MUON MOMENTUM



TRANSVERSE MOMENTUM AT 2RY VTX



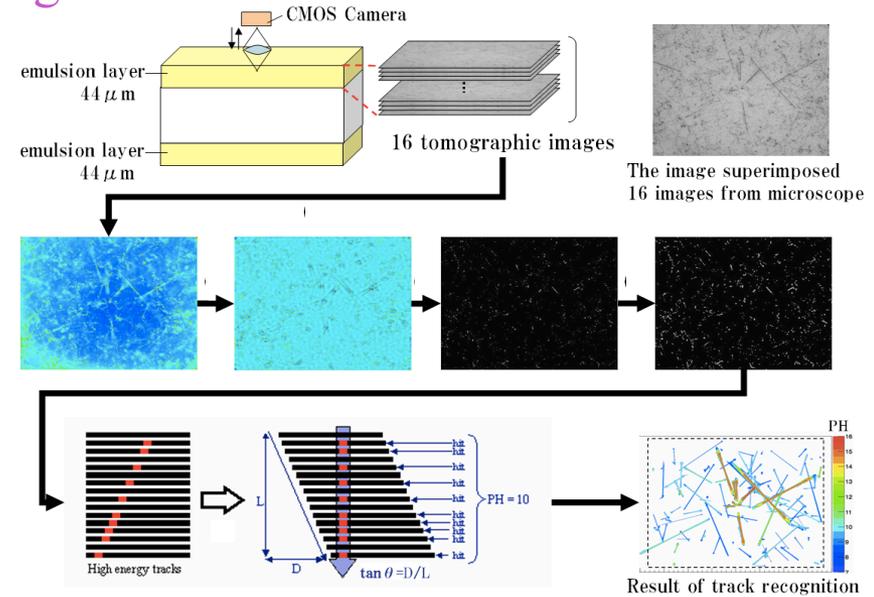
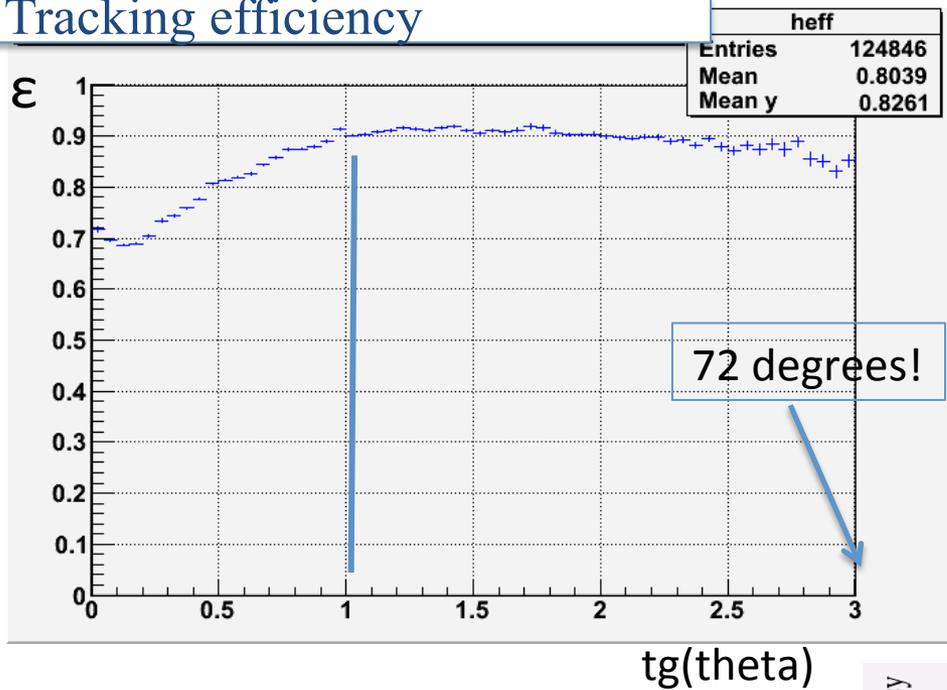
# *Background studies*

# Improvements on the background rejection: large angle track detection

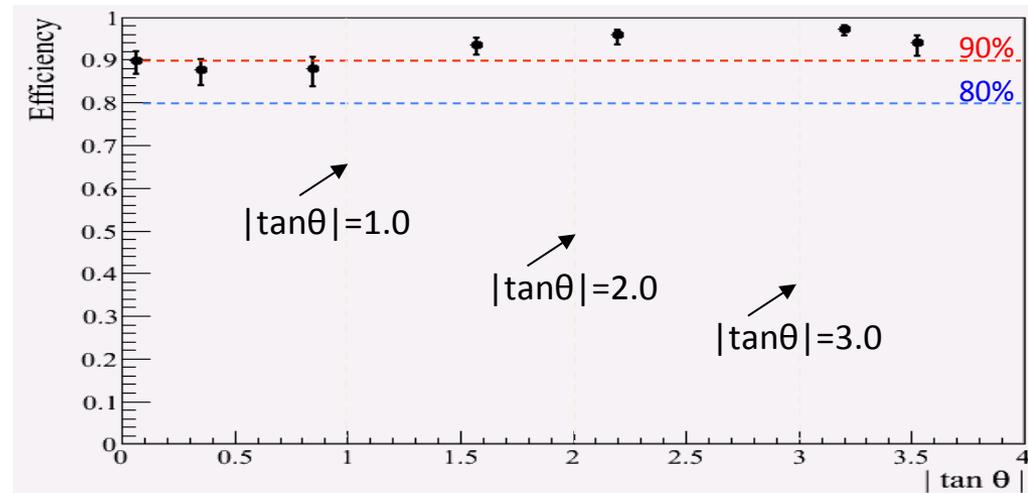
Undetected soft and large angle muons are the source of charm background

Detection of particles and nuclear fragments in hadronic interactions

## Tracking efficiency



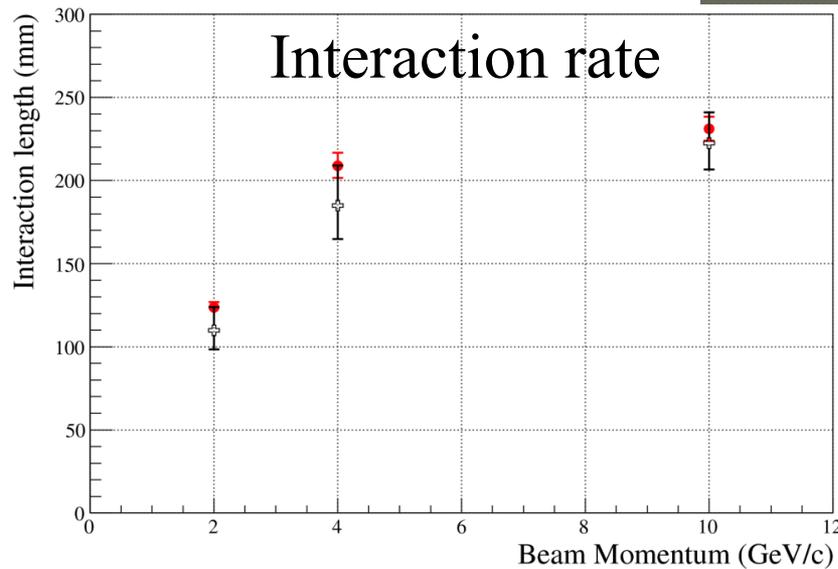
Two different approaches get comparable results



# Background studies: hadronic interactions

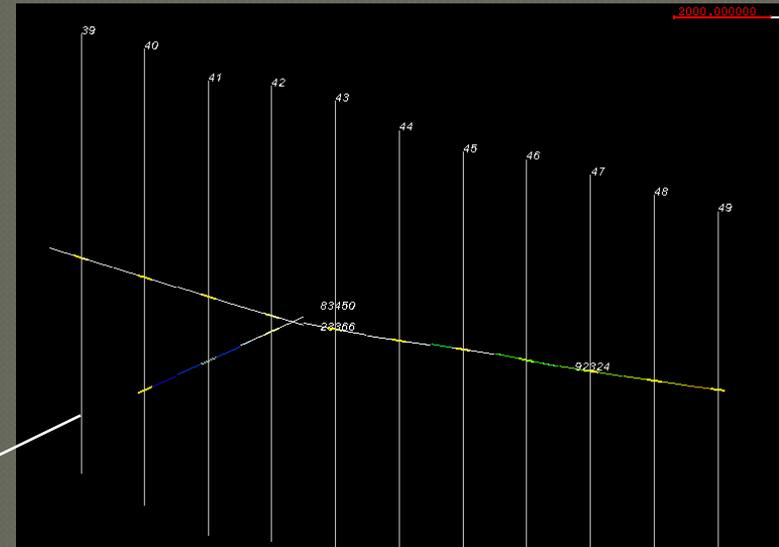
Comparison of large data sample ( $\pi^-$  beam test at CERN) with Fluka simulation: check the agreement and estimate the systematic error of simulation

Track length analysed in the brick: 2 GeV/c : 8.5 m, 4 GeV/c : 12.6 m, 10 GeV/c : 38.5 m



hadron

fragment track



Black :  $\pi^-$  beam data  
Red : MC (FLUKA) simulation

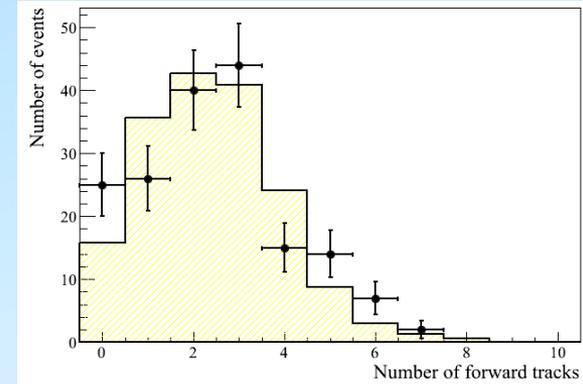
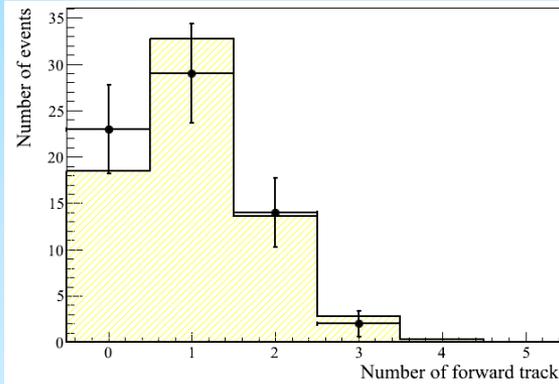
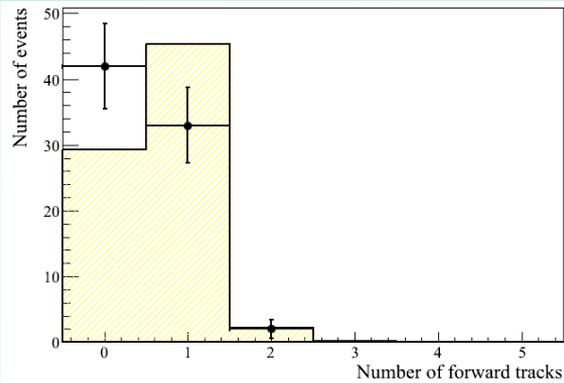
# Secondary track emission

2GeV/c

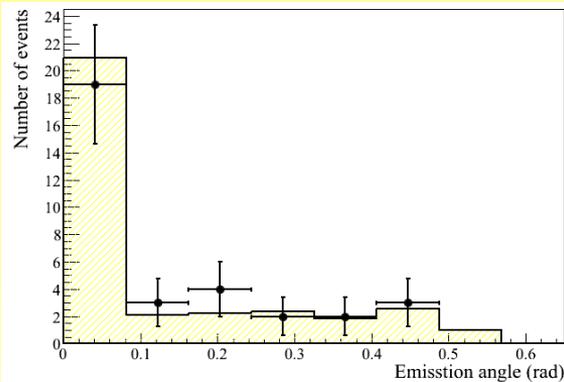
4GeV/c

10GeV/c

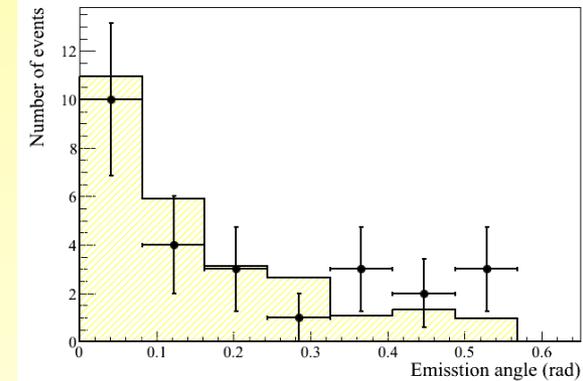
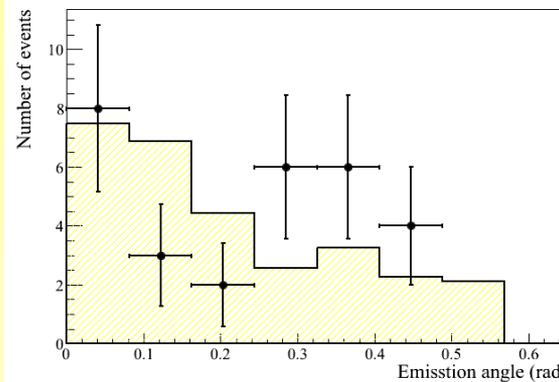
Multiplicity



Kink angle (1-prong)



Error bars : Experimental data  
Histogram : Simulated data



Good agreement within the statistical error: systematic error reduced to 30%



# Nuclear fragments in 1 and 3 prong interactions

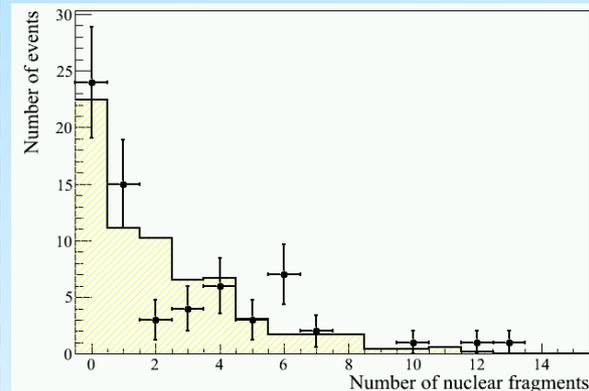
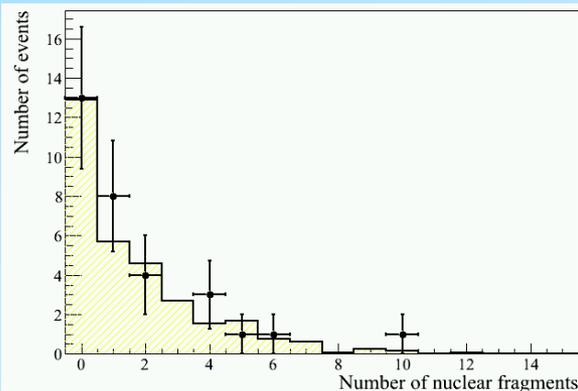
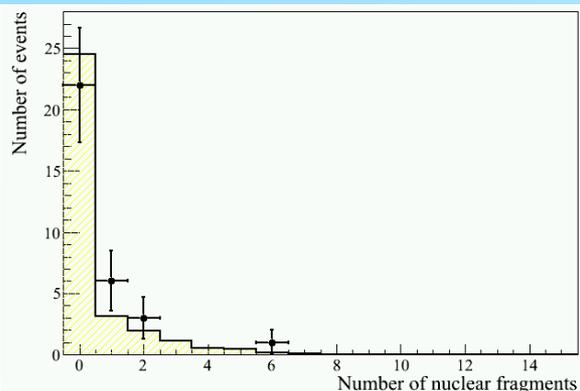
2GeV/c

4GeV/c

10GeV/c

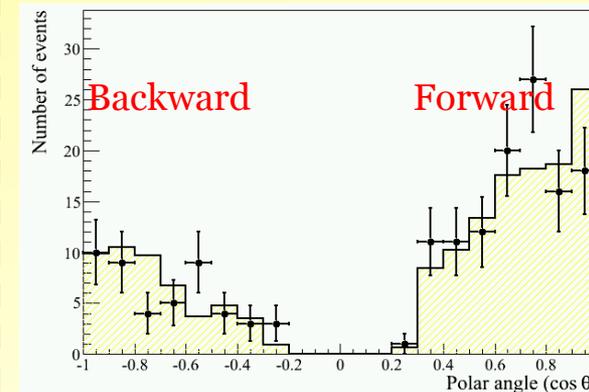
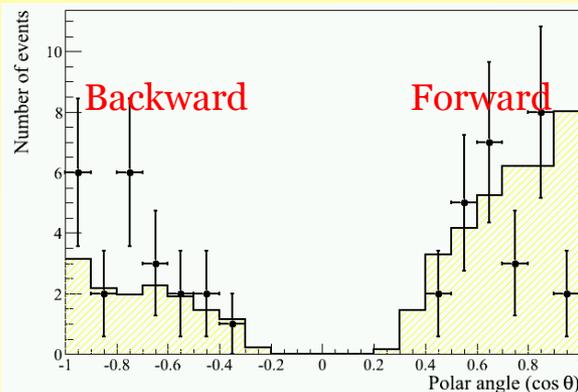
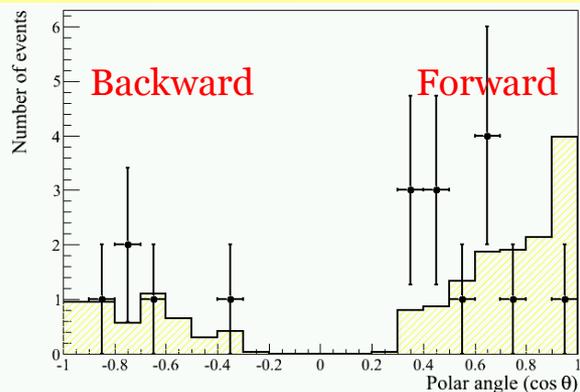
Multiplicity

MC:  $\beta < 0.7$



Emission angle( $\cos \theta$ )

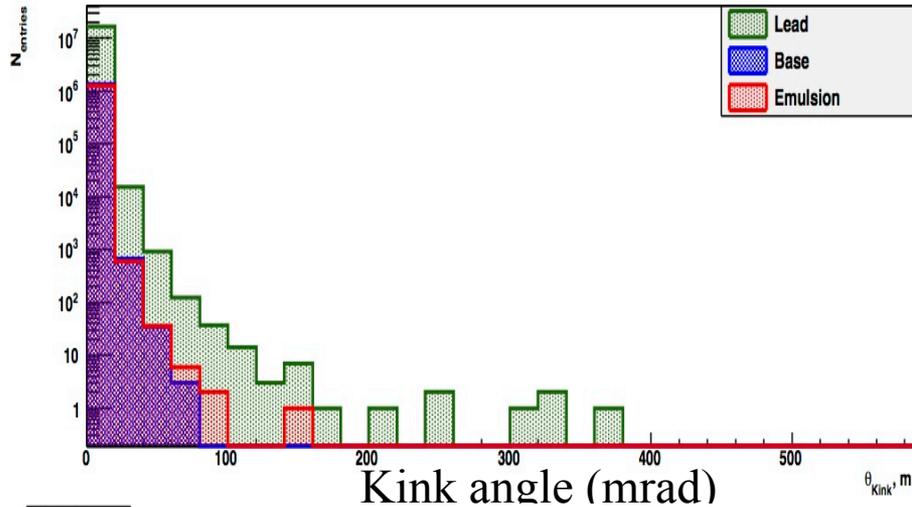
Error bars : experiment  
Histogram : simulation



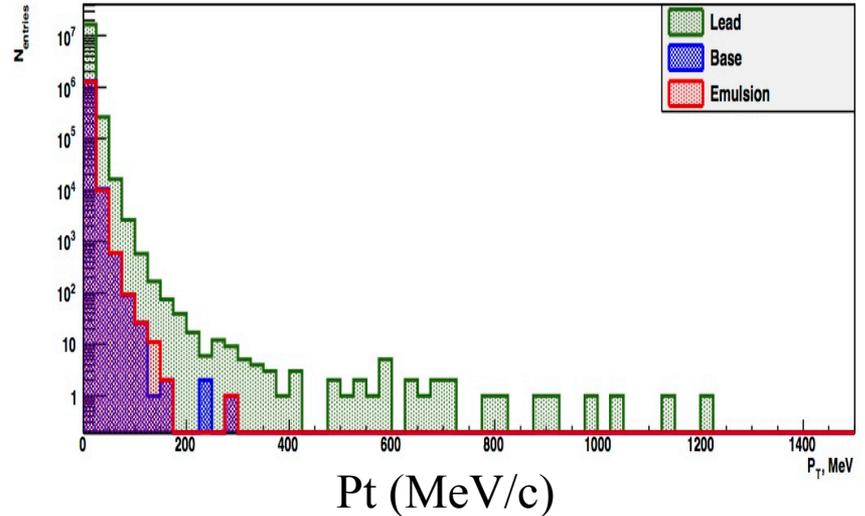
Agreement within the statistical error: systematic error is 10%.

# Large angle muon scattering

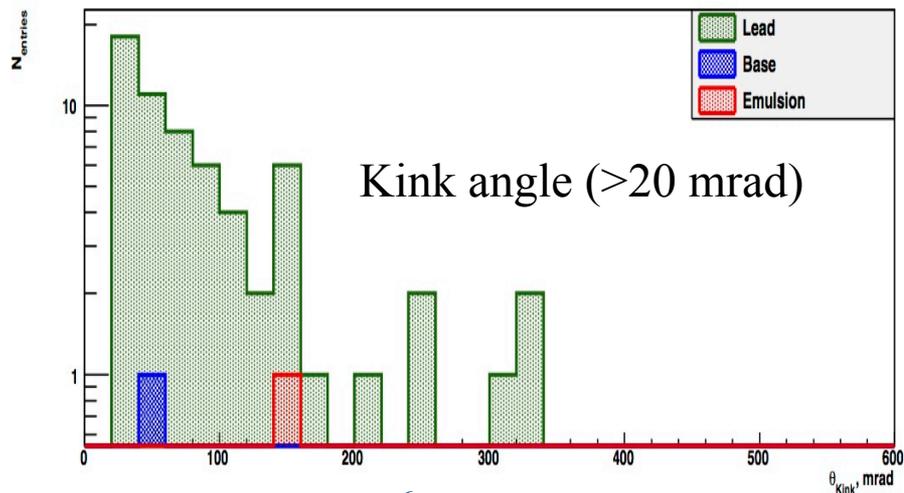
Kink angle



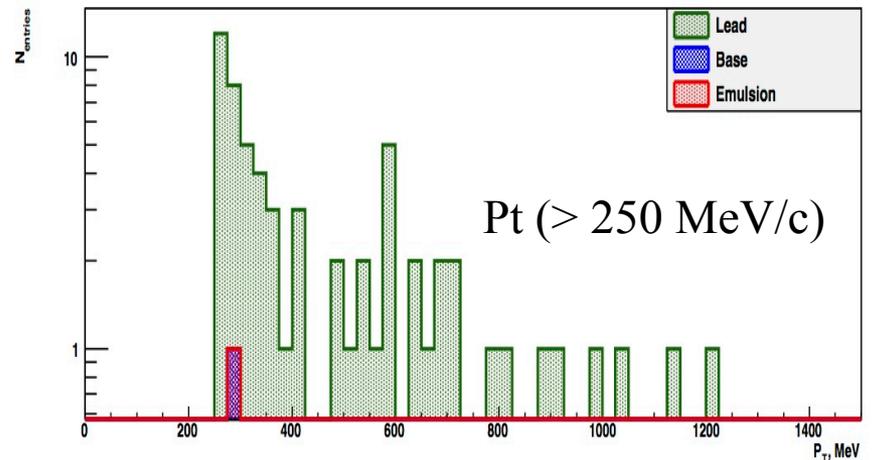
Transverse momentum PDF



Kink angle



Transverse momentum PDF



Rate in lead ( $10^{-6}$ ) and less in emulsion/base ( $10^{-8}$  to  $10^{-7}$ ). No measurements except an upper limit: S.A. Akimenko et al., NIM A423 (1986) 518 ( $< 10^{-5}$  in lead).  $10^{-5}$  rate used

Plan to revise this number by an experimental measurement with emulsion

# *Statistical considerations*

## *Extended sample to muonic interactions*

Extended sample

	Signal	Background	Charm	$\mu$ scattering	had int
$\tau \rightarrow h$	0.66	0.045	0.029		0.016
$\tau \rightarrow 3h$	0.51	0.090	0.087		0.003
$\tau \rightarrow \mu$	0.56	0.026	0.0084	0.018	
$\tau \rightarrow e$	0.49	0.065	0.065		
total	2.22	0.226	0.19	0.018	0.019

3 observed events in the  $\tau \rightarrow h$ ,  $\tau \rightarrow 3h$  and  $\tau \rightarrow \mu$  channels

$P_{\text{value}} = P_0 = 1.125 \times 10^{-4}$

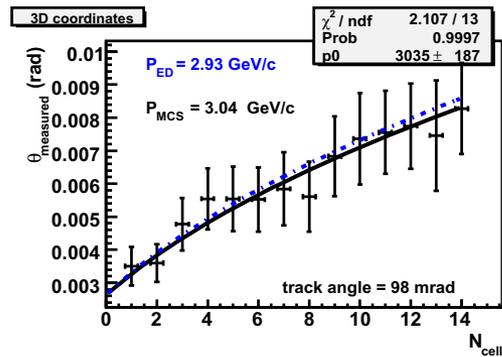
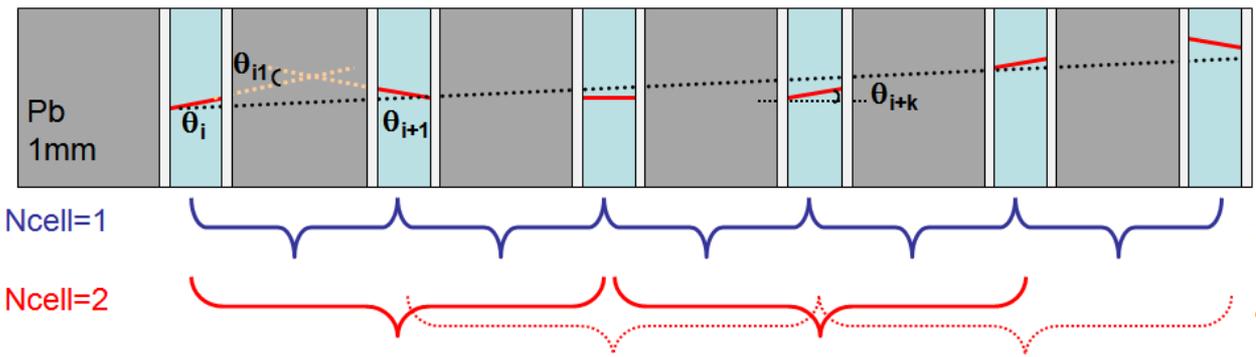
Probability to be explained by background =  $7.29 \times 10^{-4}$

This corresponds to  $3.2 \sigma$  significance of non-null observation

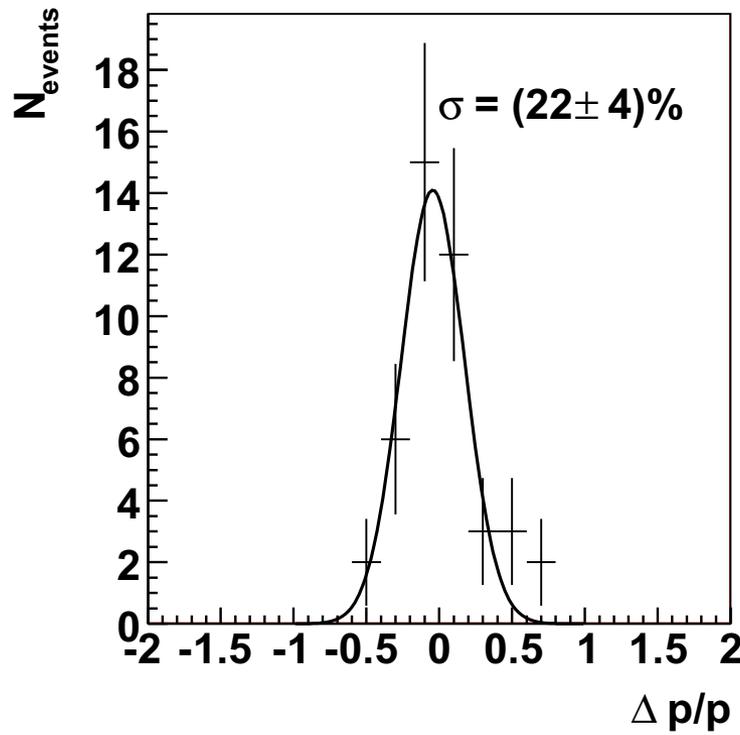
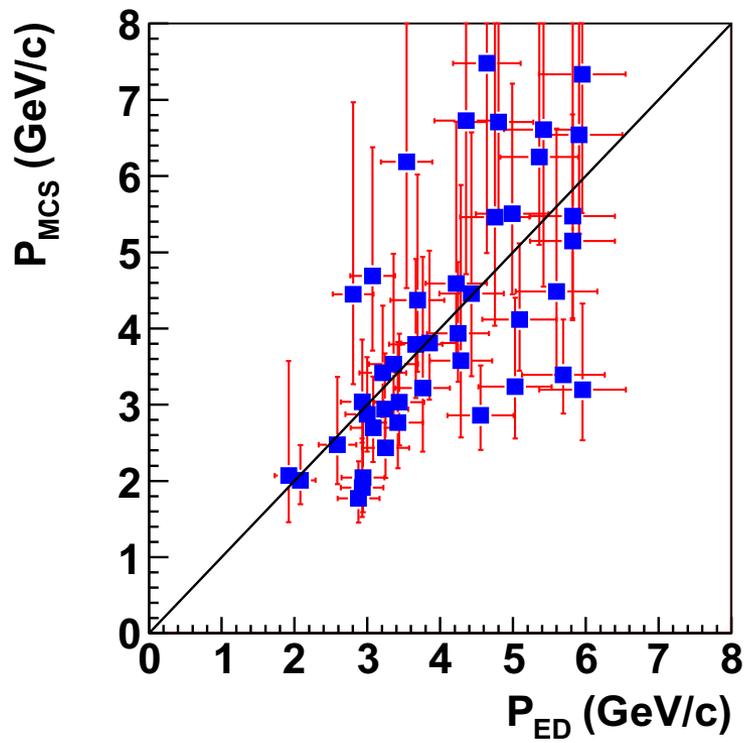
*Exploit kinematical characteristics  
of the events: likelihood analysis*

*Data/MC agreement for relevant  
variables*

# Momentum measurement by multiple Coulomb scattering for identified $\mu$ in the 2-6 GeV range

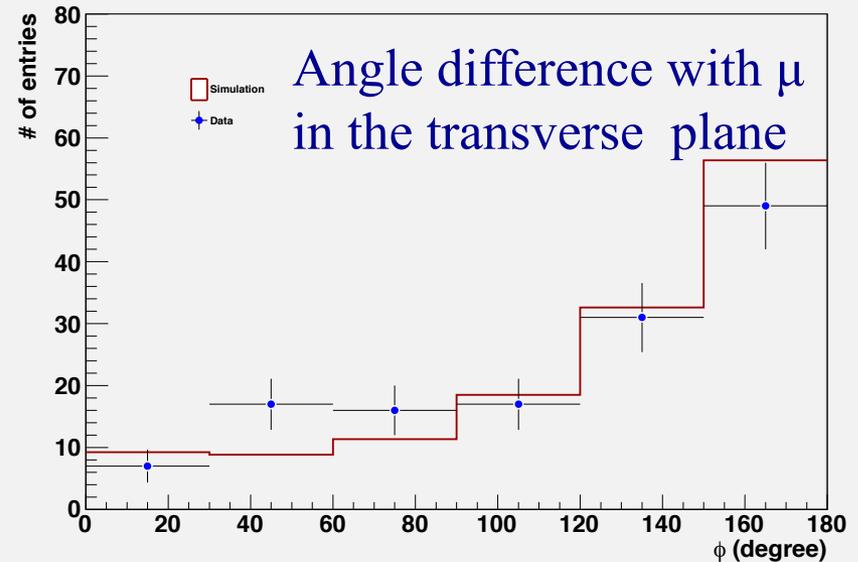
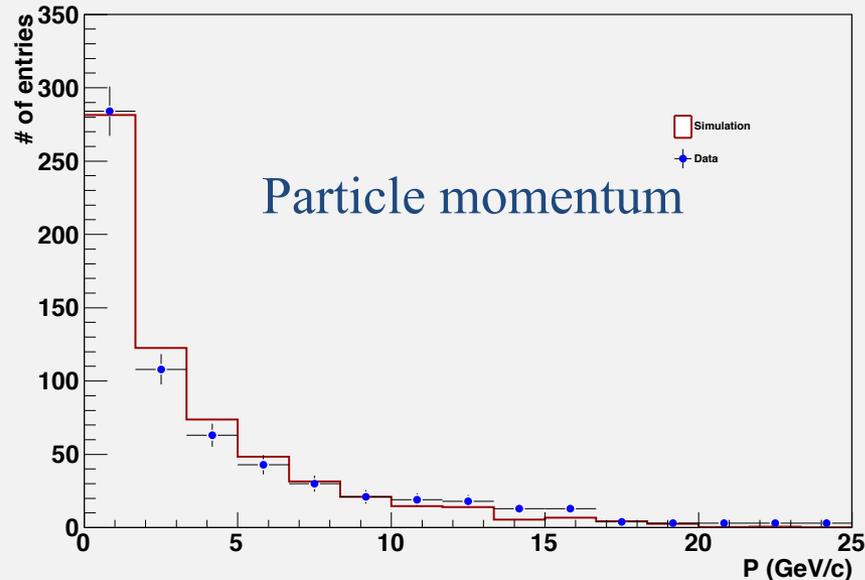
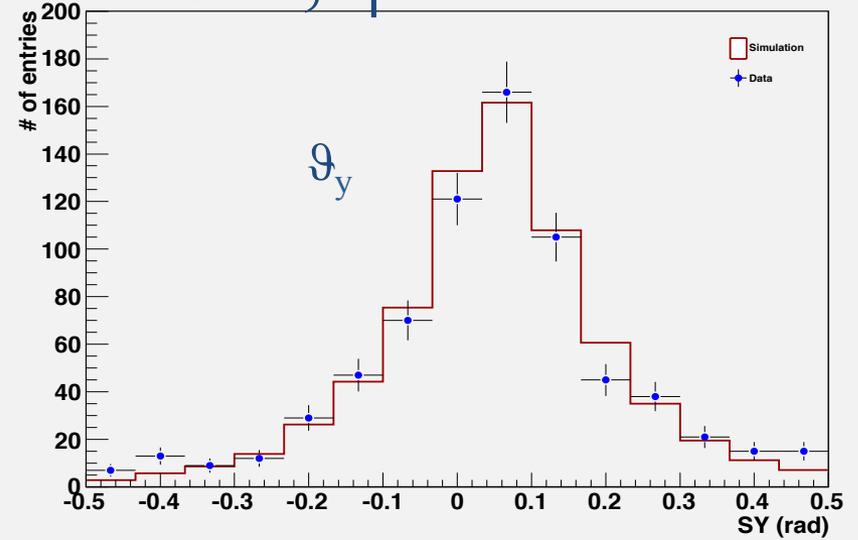
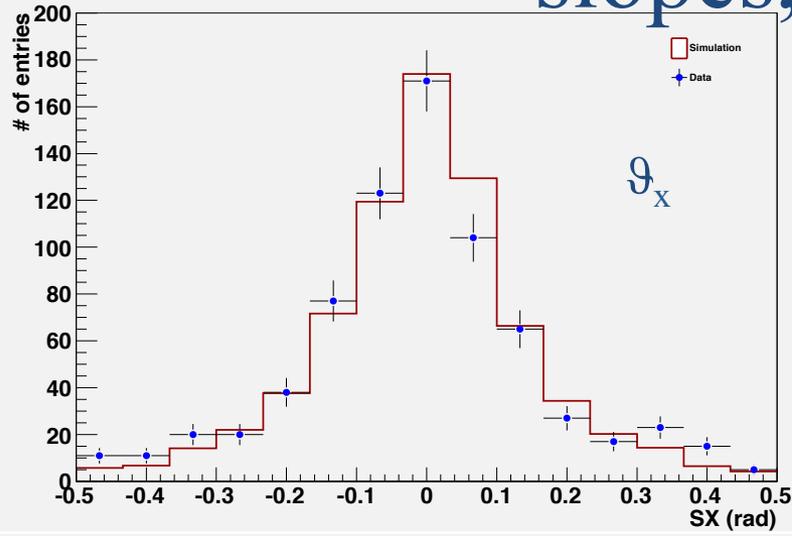


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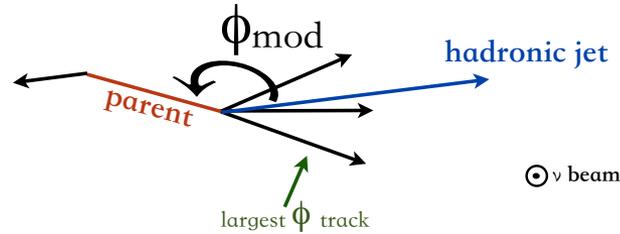


# Data/MC agreement for the relevant variables:

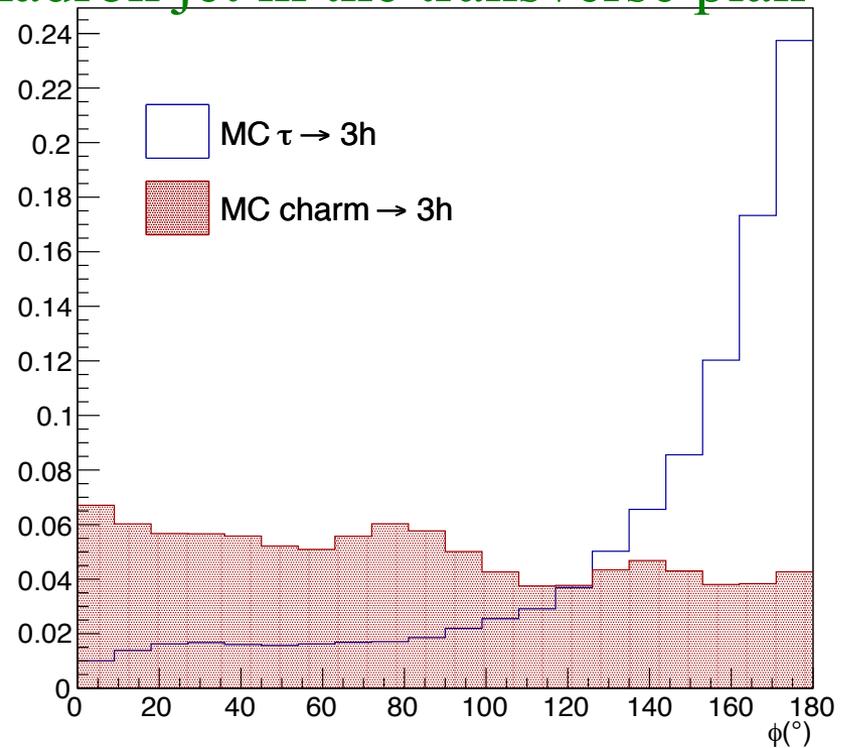
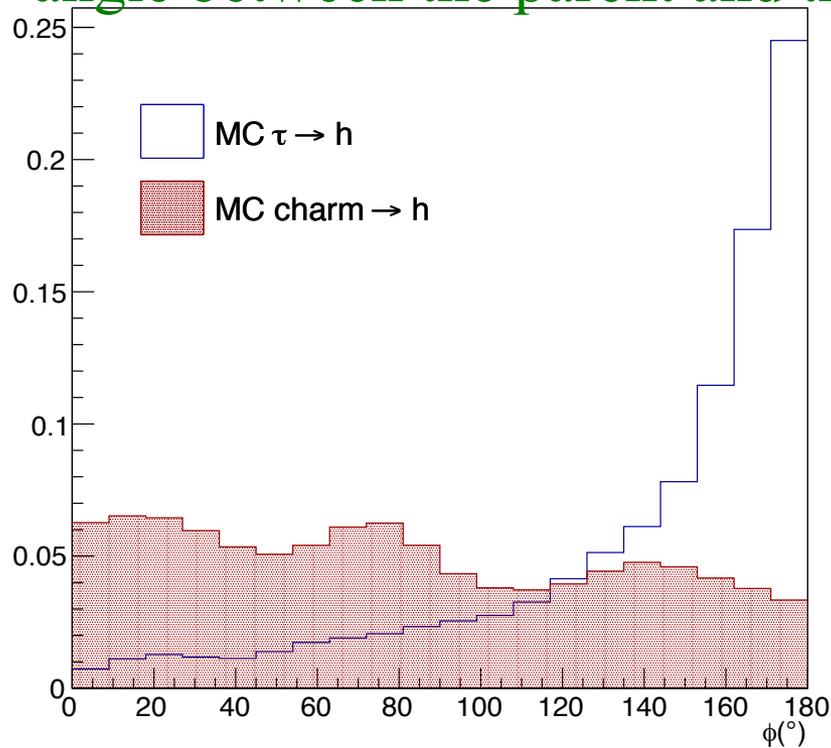
## slopes, momentum, $\phi$



# Likelihood analysis: one of the discriminating variables



angle between the parent and the hadronic jet in the transverse plane



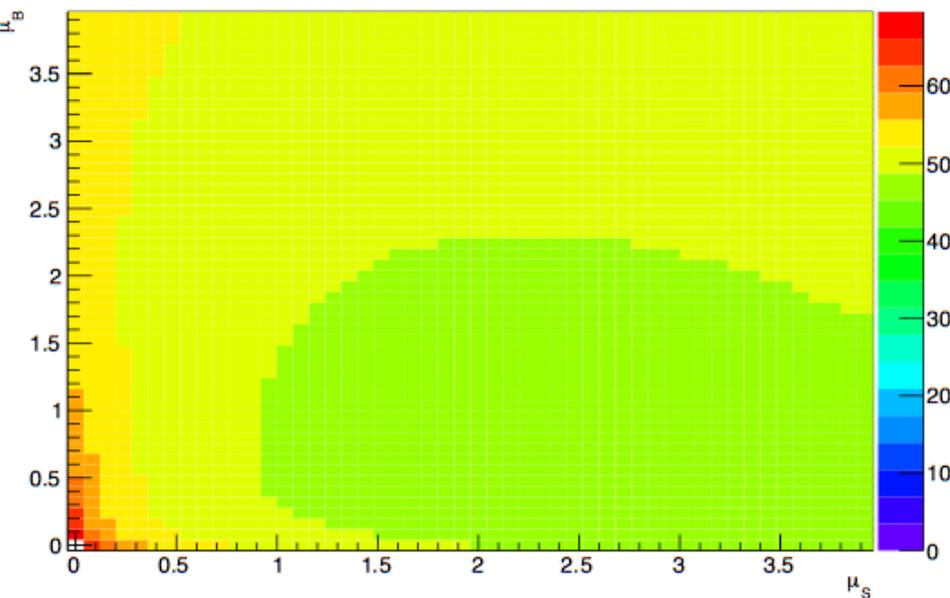
# Statistical considerations

Combining different channels: Likelihood based method, see e.g.  
G. Cowan et al., Eur. Phys. J. C71 (2011) 1554

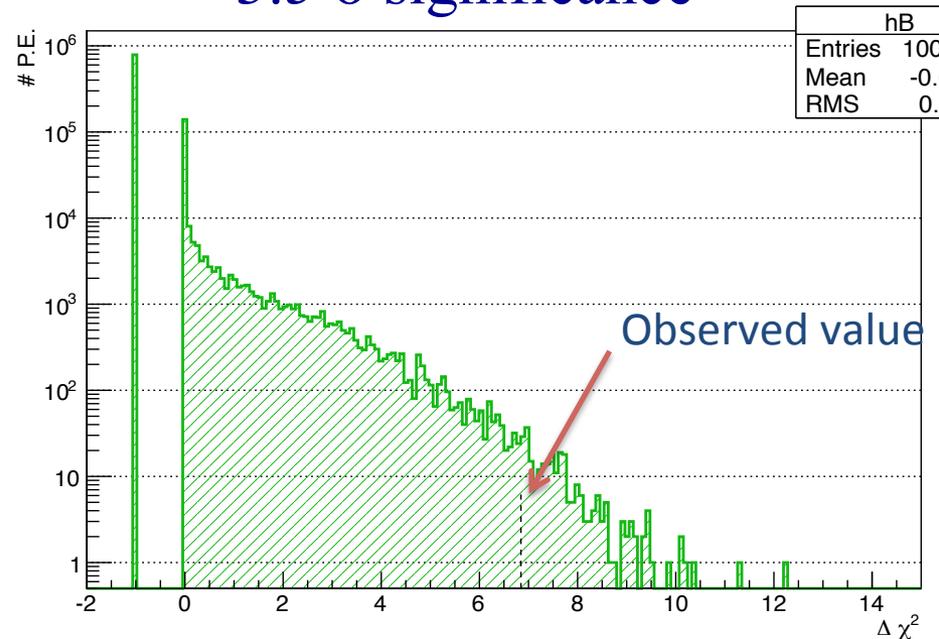
$$f^{S+B}(s, b, x) = \frac{sf_S(x) + bf_B(x)}{s + b} \quad \mathcal{L}(s, b) = \frac{(s + b)^n e^{-(s+b)}}{n!} \prod_{c=1}^4 \prod_{i=0}^{n_c} \prod_{v=1}^{n_v} f_{v,c}^{S+B}(s, b, x_v)$$

$$LR = -2 \ln \frac{\mathcal{L}(0, b)}{\mathcal{L}(s, b)}$$

-2lnL



3.5  $\sigma$  significance



# *Evidence for $\nu_{\mu} \rightarrow \nu_{\tau}$ in appearance mode*

- *Three events reported*
- *Conservative background evaluation*
- *Significance of  $3.2\sigma$  with simple counting method*
- *With a first likelihood approach,  $3.5\sigma$  level*
- *$4\sigma$  observation within reach*

Thank you for your attention