

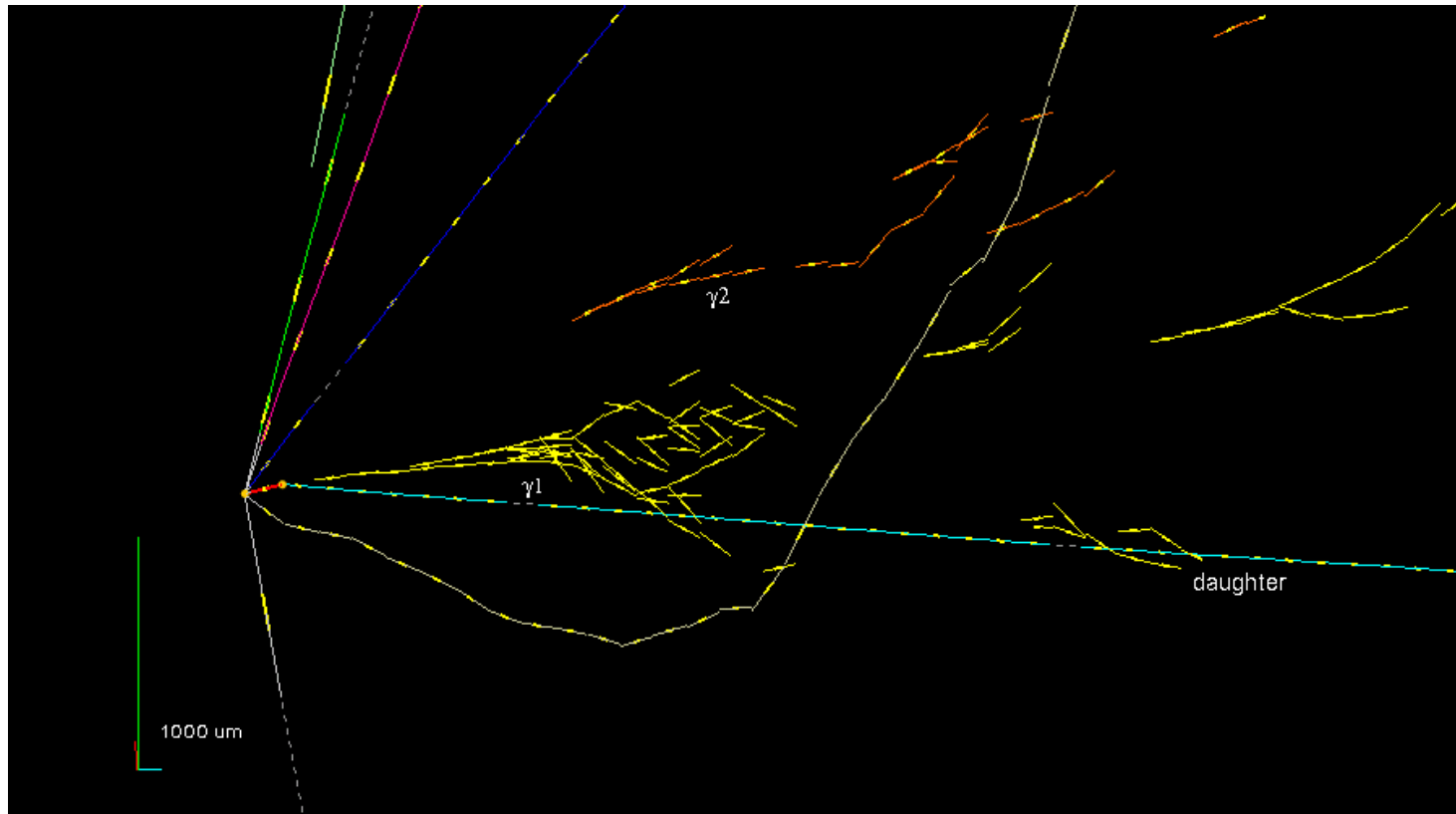


Results of the OPERA experiment

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

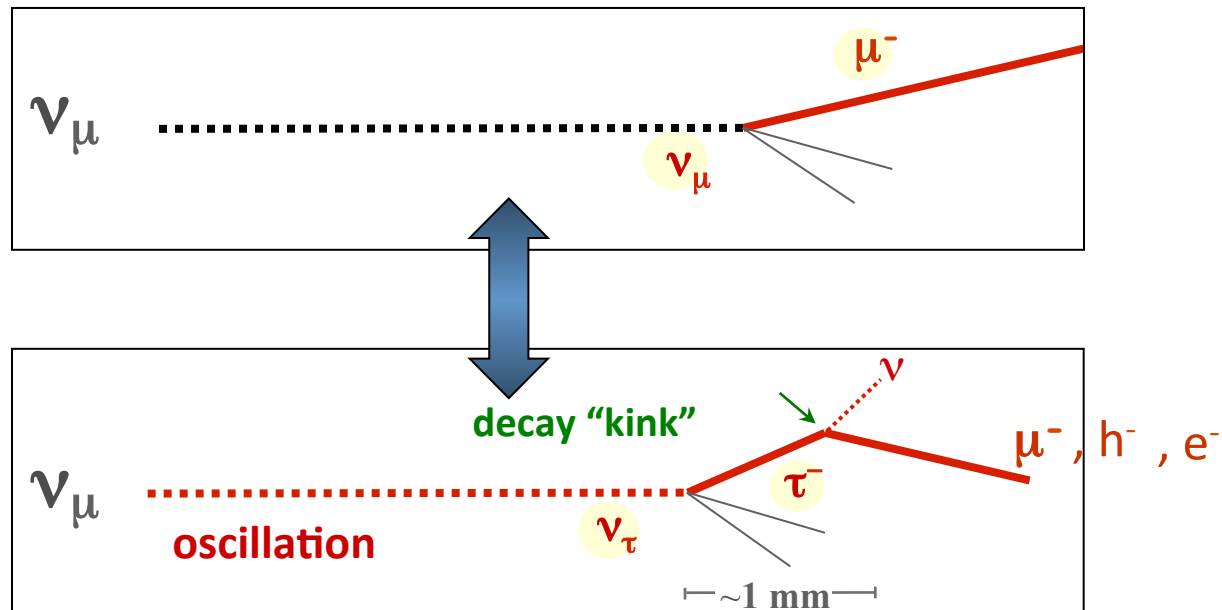
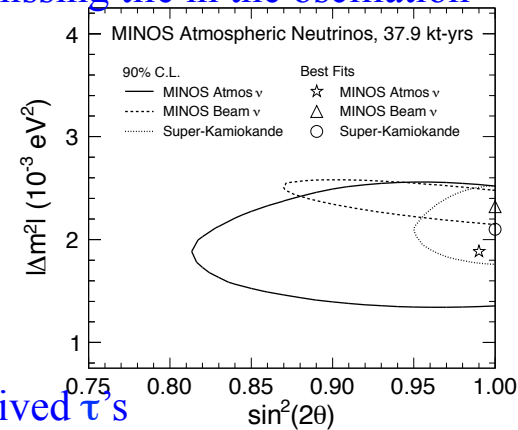
following the Super-Kamiokande (Macro and Soudan-2) discovery of oscillations with atmospheric neutrinos and the confirmation with solar neutrinos and accelerator beams. An important, missing tile in the oscillation picture.

The PMNS 3-flavor oscillation formalism predicts:

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

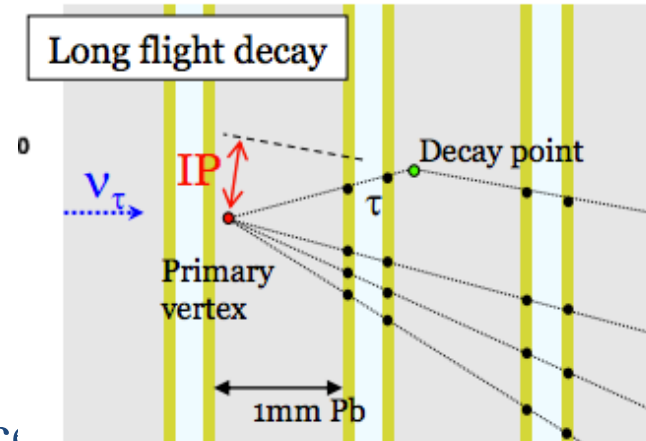
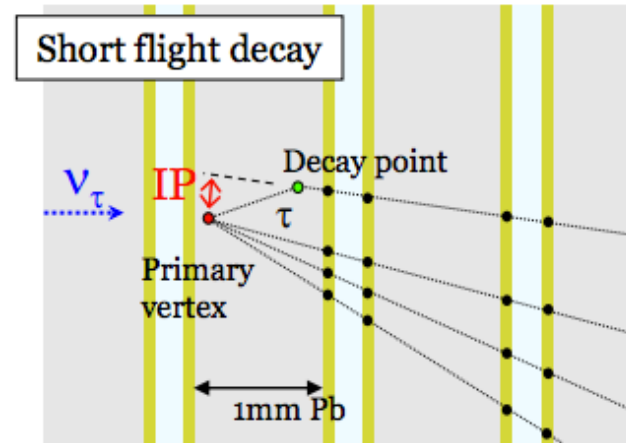
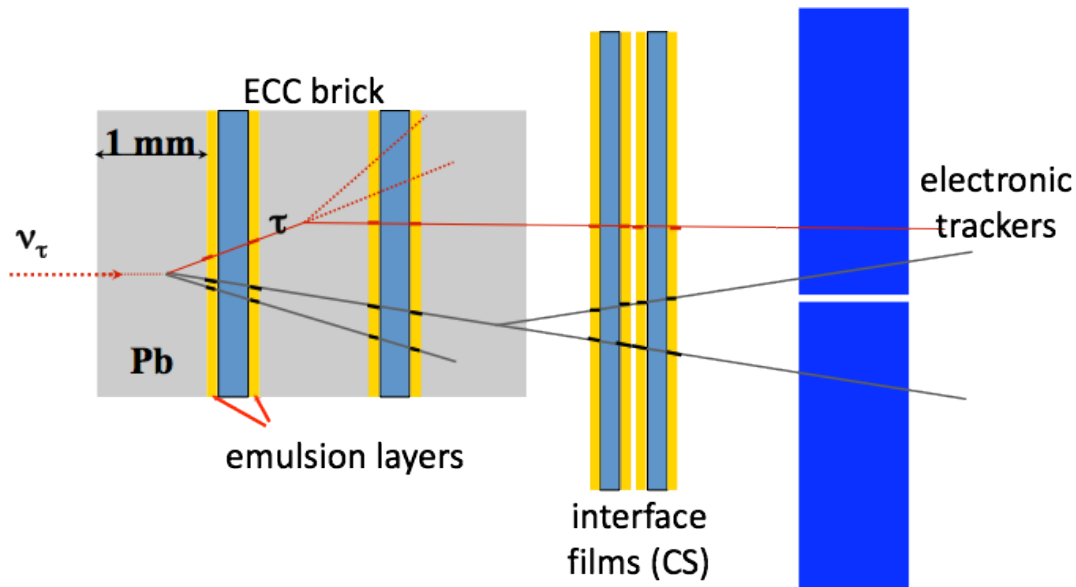
Requirements:

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



plus 3-prong decay modes

THE PRINCIPLE: hybrid detector with modular structure



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

τ DECAY CHANNEL	BR (%)
$\tau \rightarrow \mu$	17.7
$\tau \rightarrow e$	17.8
$\tau \rightarrow h$	49.5
$\tau \rightarrow 3h$	15.0 ⁵

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

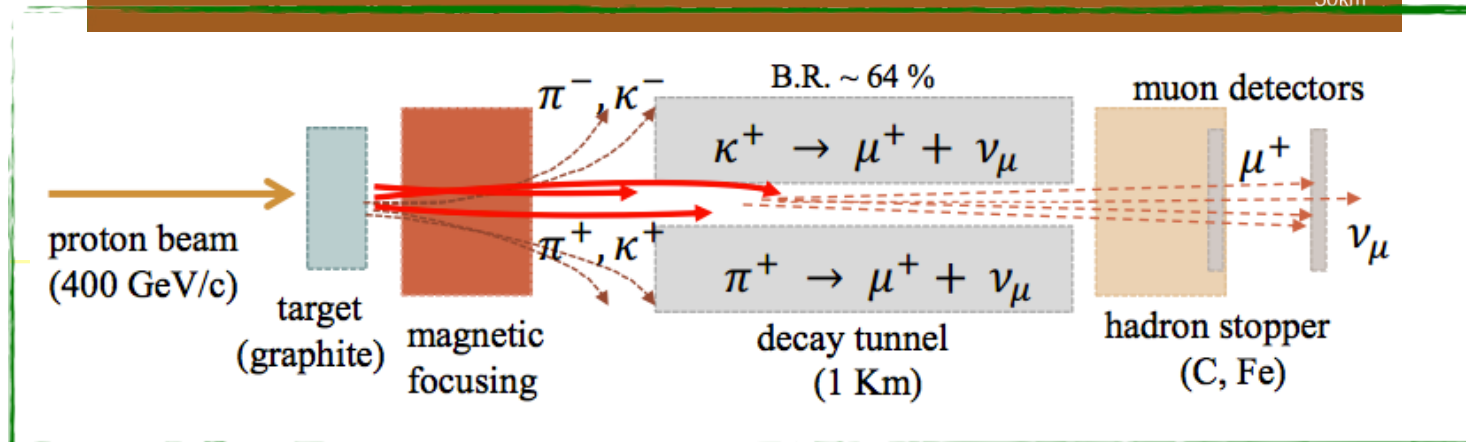
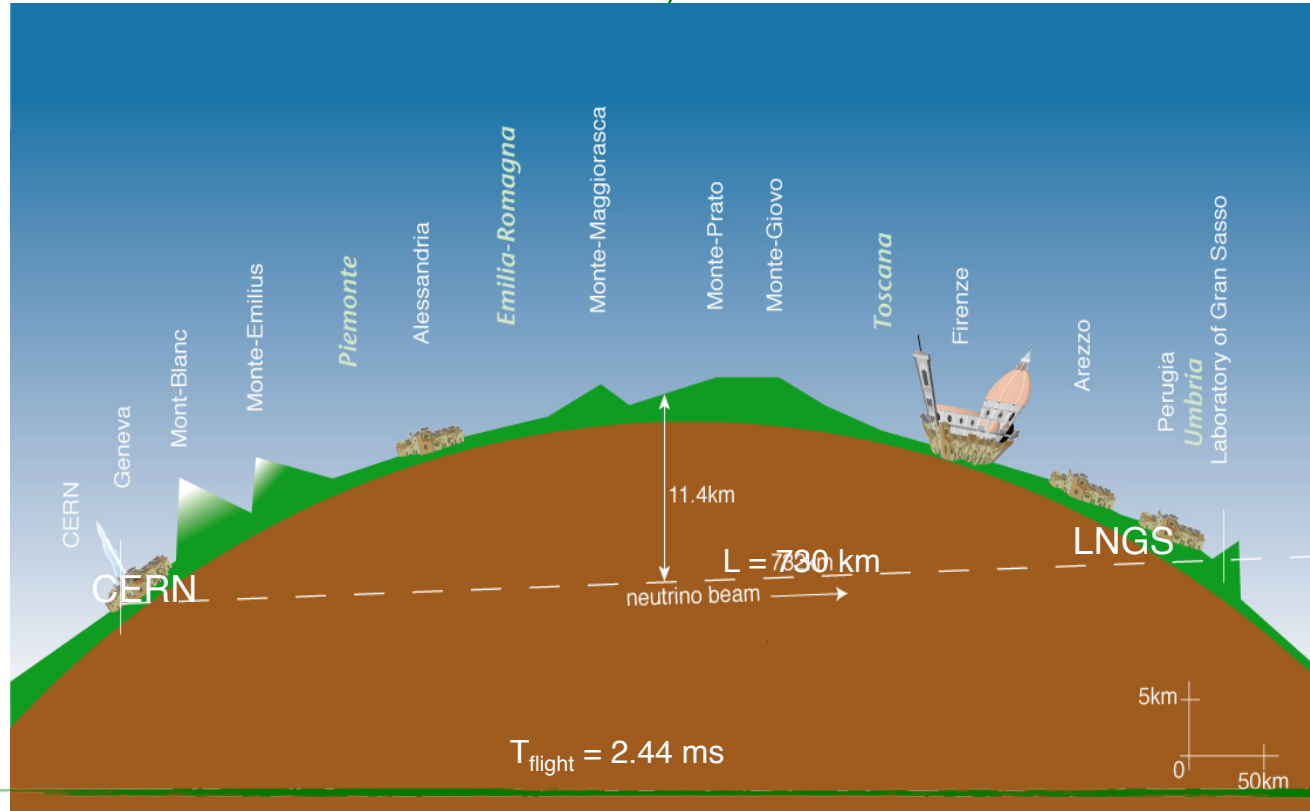


<http://operaweb.lngs.infn.it>

CNGS BEAM AND LNGS

CNGS beam: tuned for τ -appearance at LNGS

730 km away from CERN

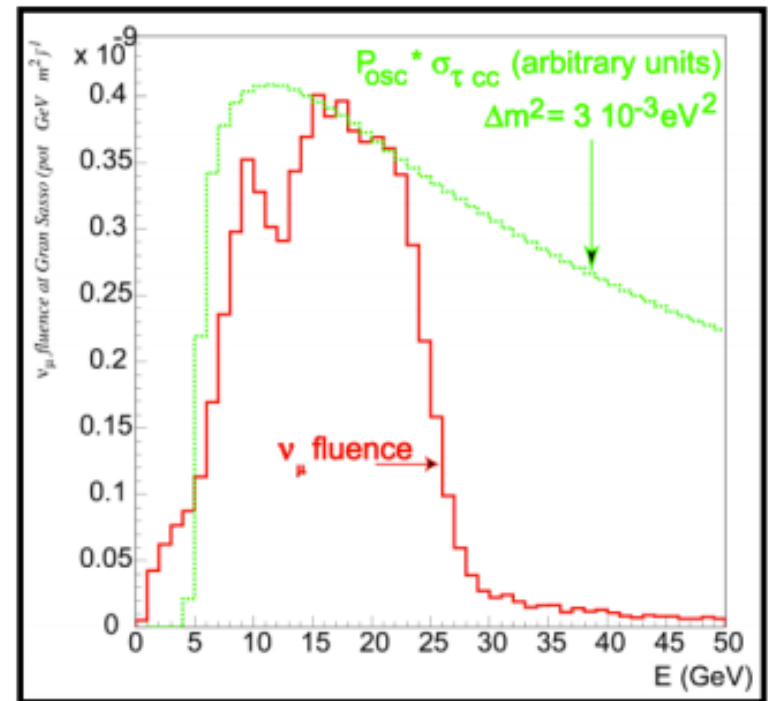


Neutrino Beam Parameters

Beam parameters

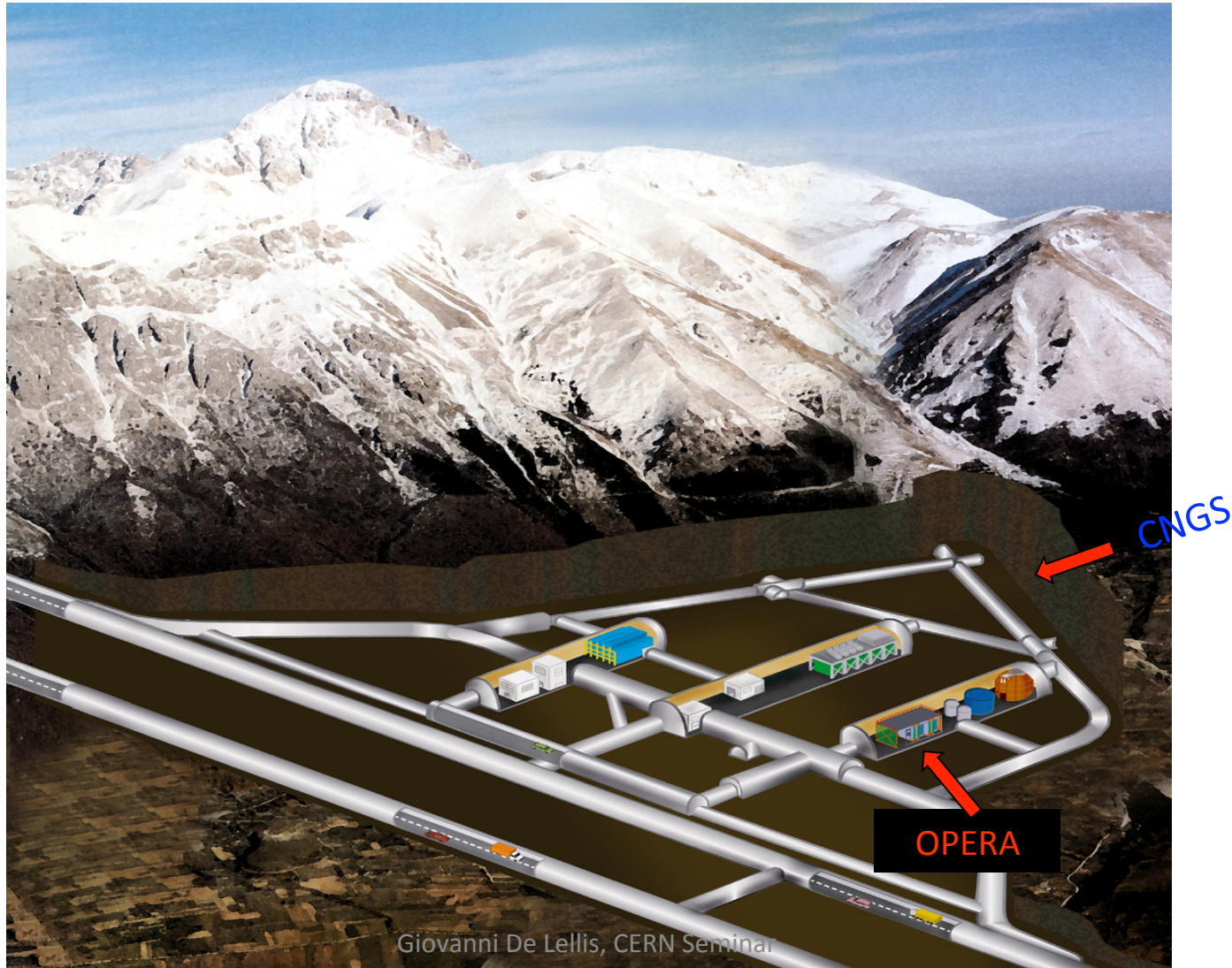
$\langle E\nu_\mu \rangle$ (GeV)	17
$(\nu_e + \bar{\nu}_e) / \nu_\mu$	0.9% *
$\bar{\nu}_\mu / \nu_\mu$	2.0% *
ν_τ prompt	Negligible

* Interaction rate at LNGS

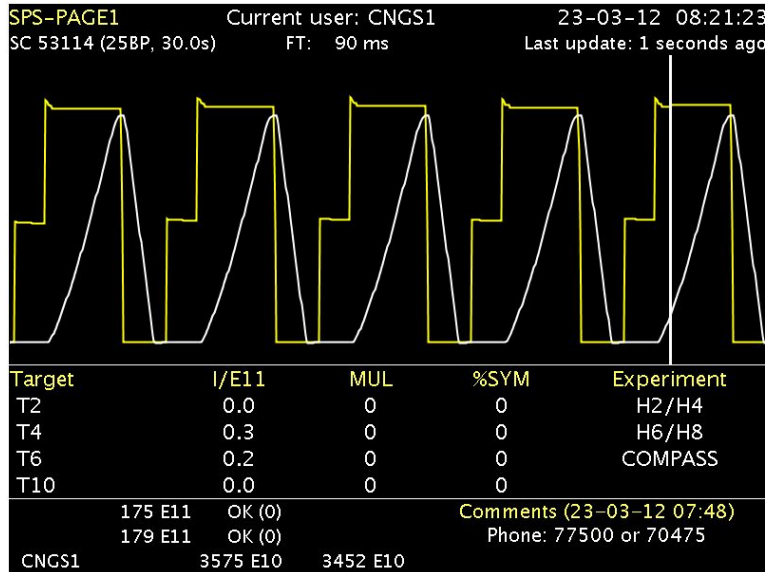


LNGS of INFN, the world largest underground physics laboratory:

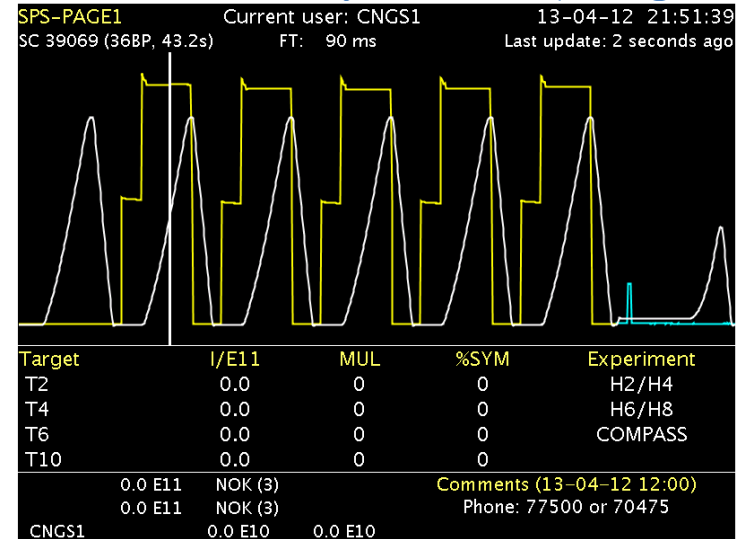
~180'000 m³ caverns' volume, ~3'100 m.w.e. overburden, ~1 cosmic μ / (m² x hour), experimental infrastructure. Suitable to host detector and related facilities, caverns oriented towards CERN.



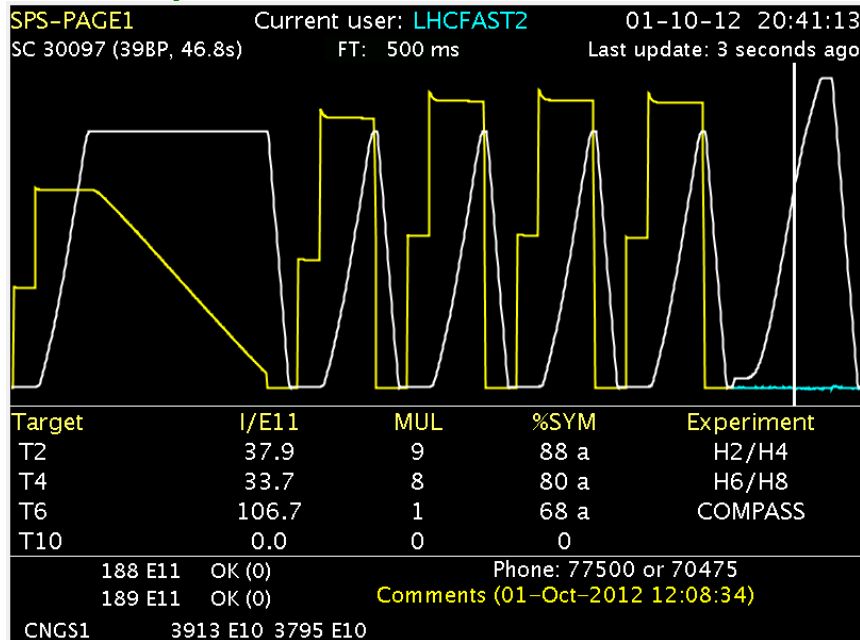
CNGS beam structure



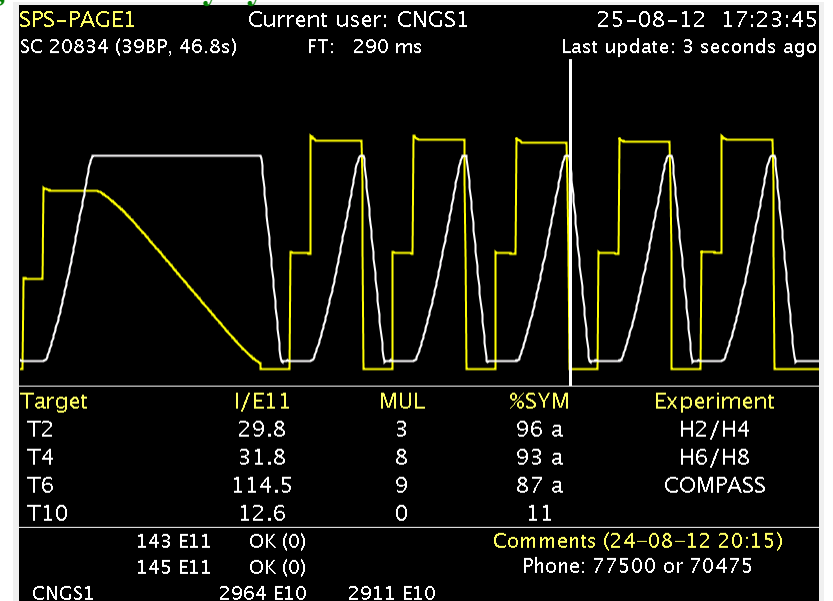
Dedicated mode or 5 cycles + LHC (during filling)



Shared operation FT + 4 CNGS + LHC

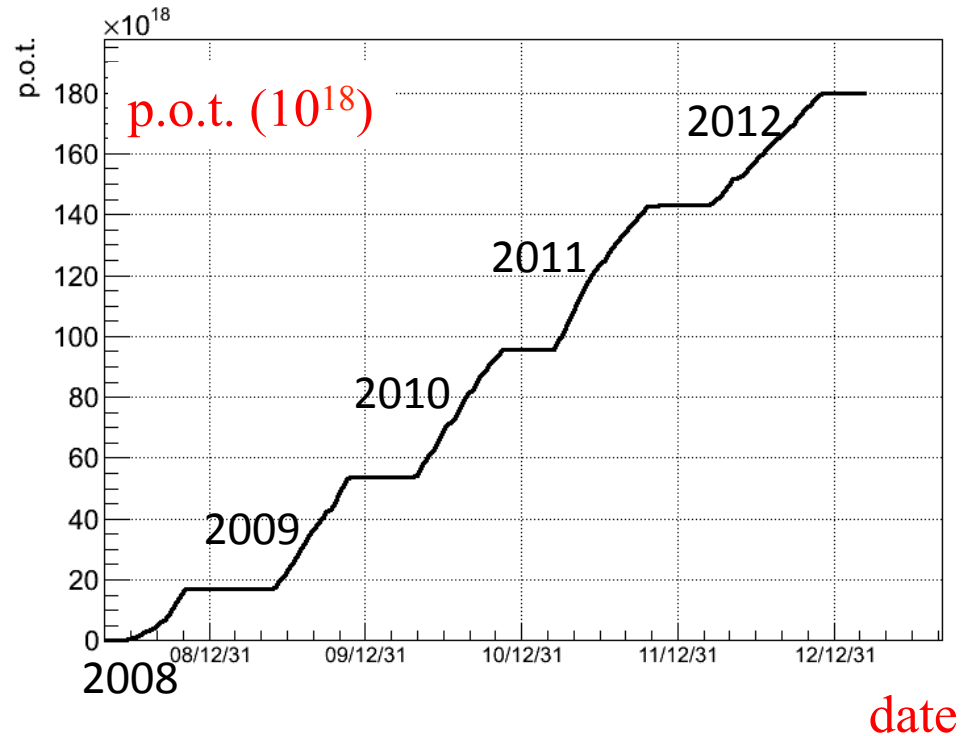


Shared operation no LHC filling (5 CNGS+ FT) High CNGS duty cycle



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
20010	187	4.09
2011	243	4.75
2012	257	3.86
Total	965	17.97



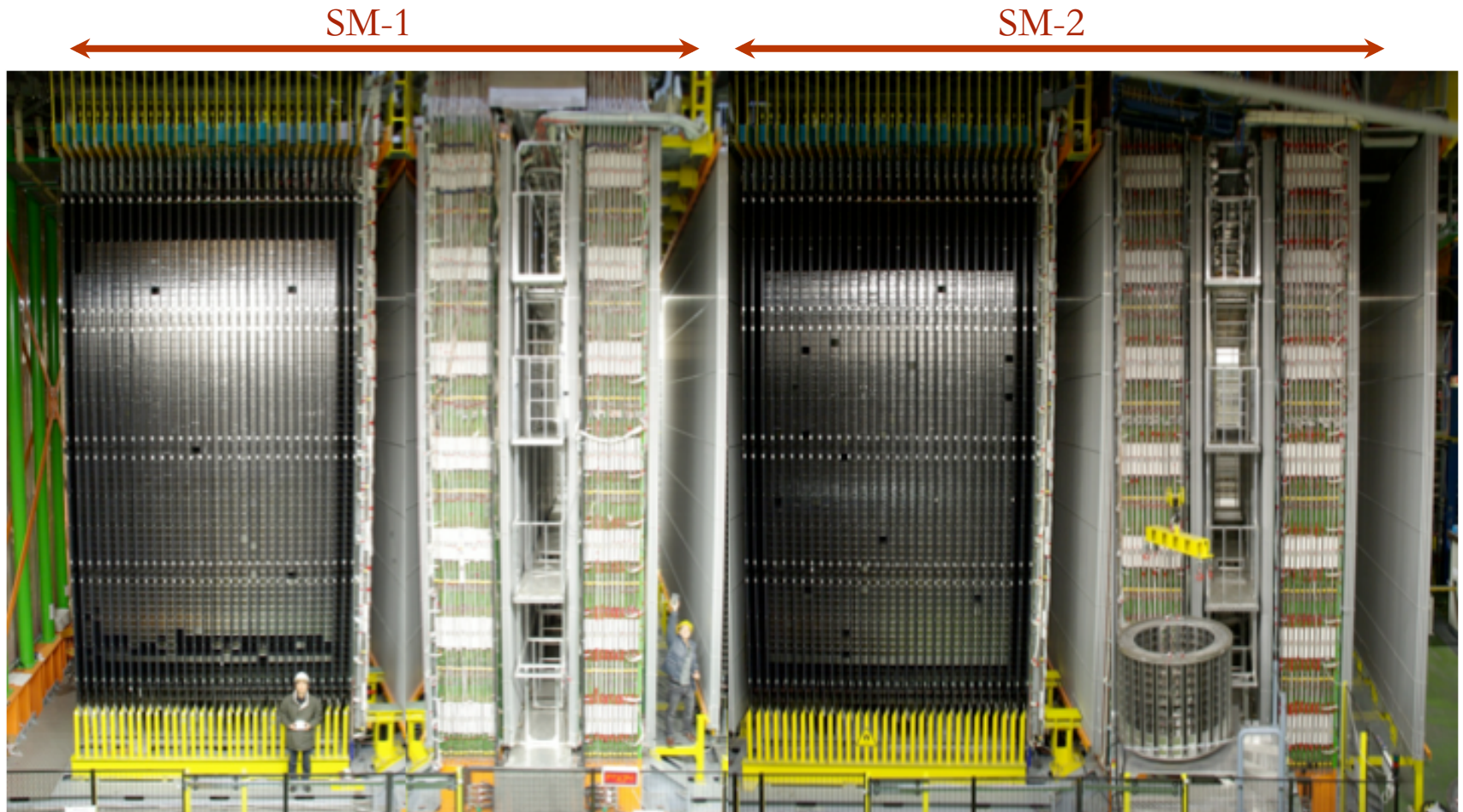
Record performances in 2011

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

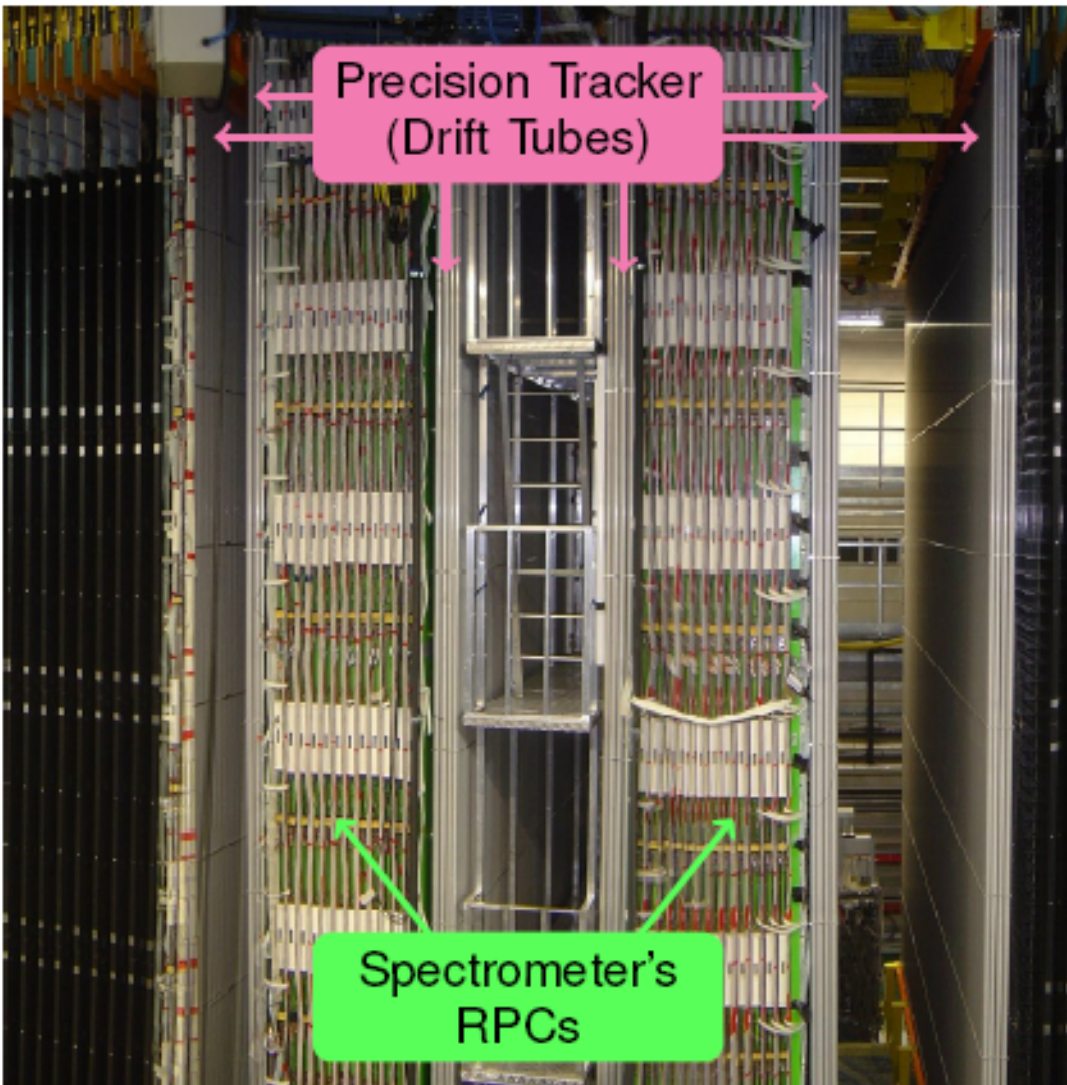
Target

brick walls+ Target Tracker

Spectrometer

RPC+Drift Tubes

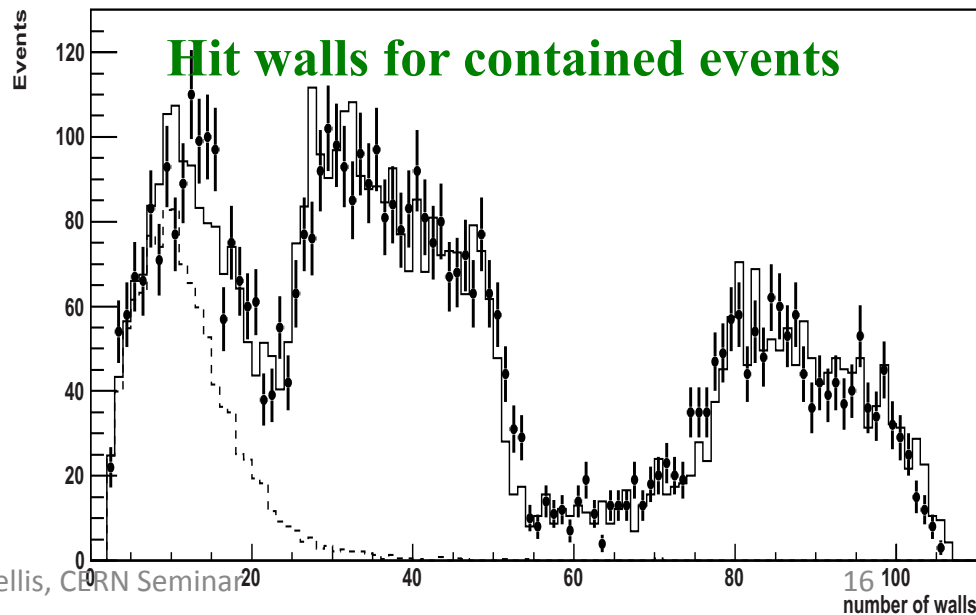
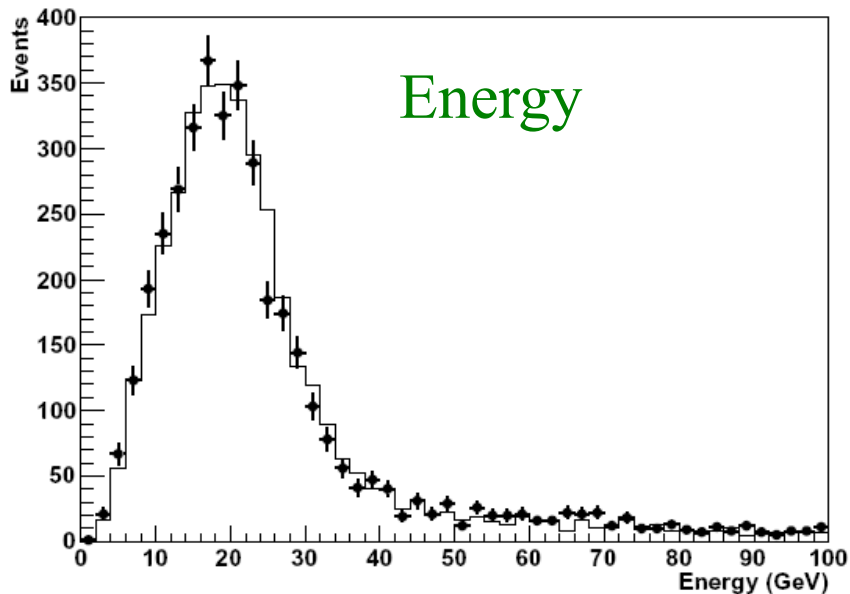
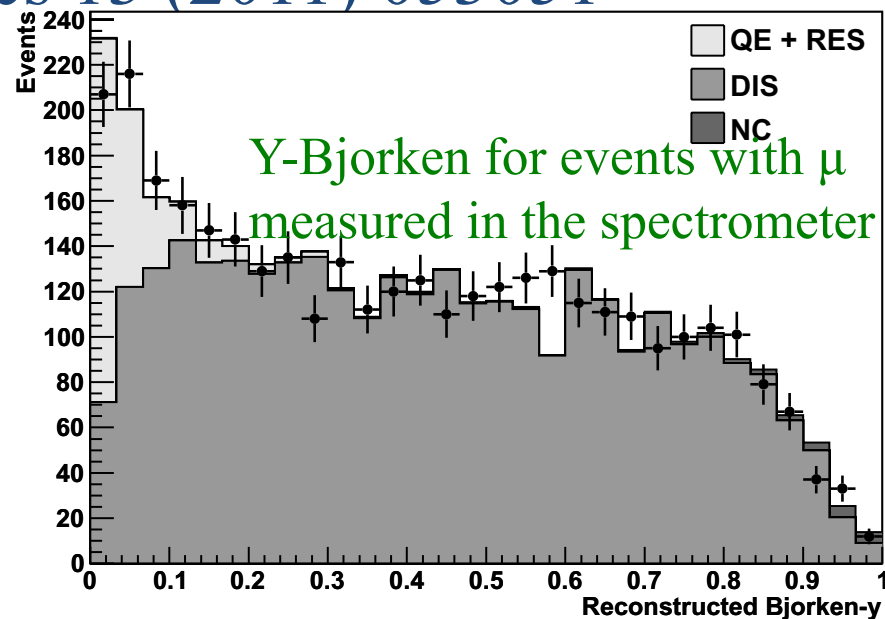
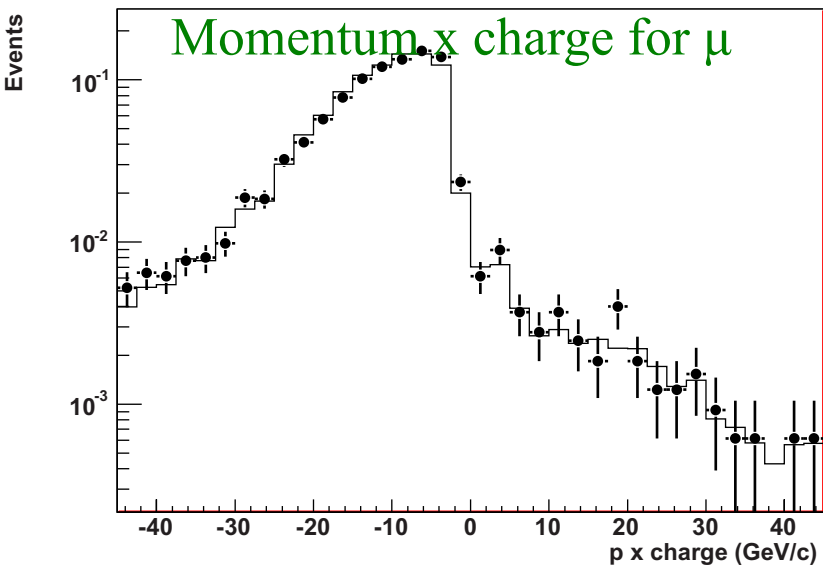
THE MAGNETIC SPECTROMETERS



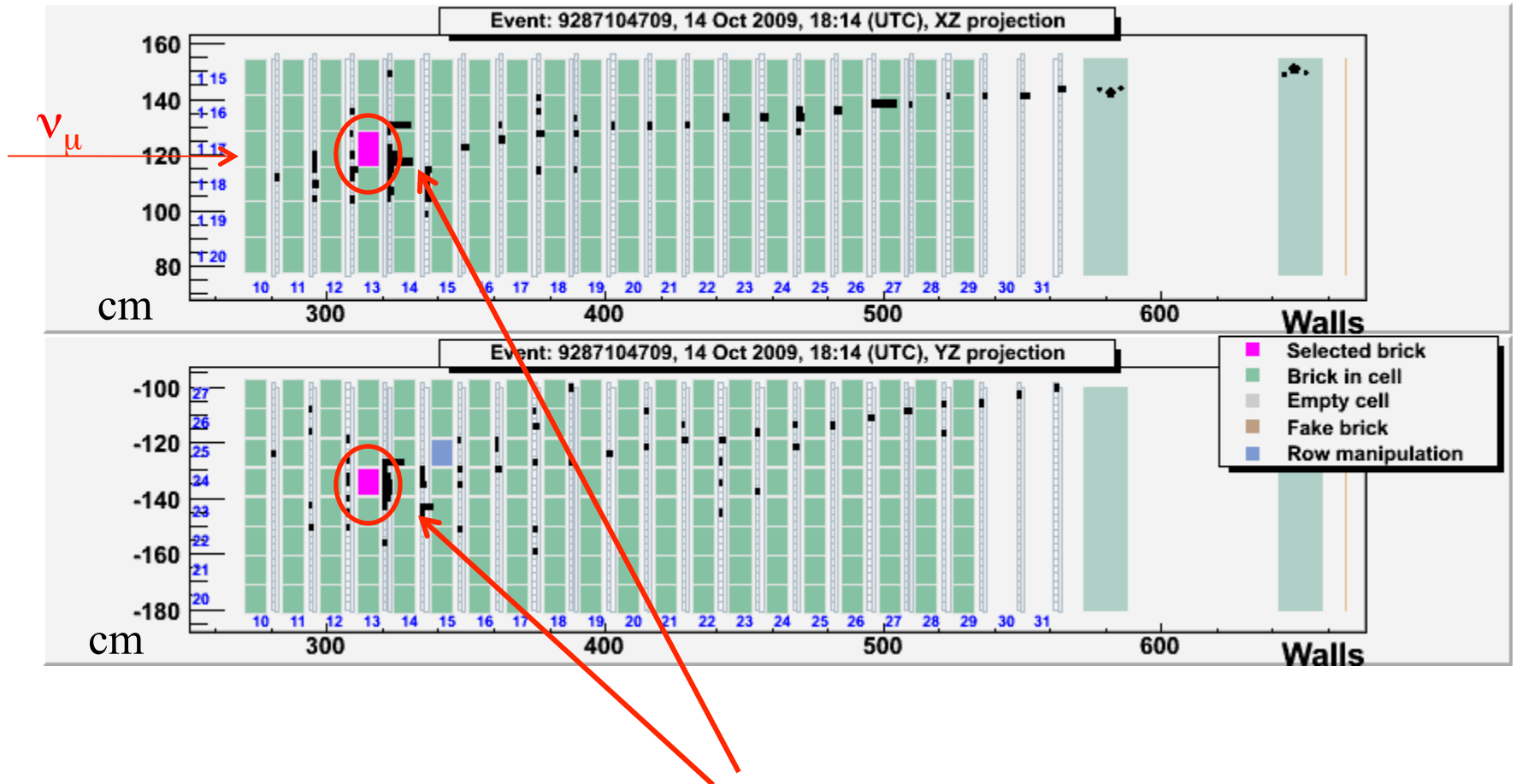
- 1.55 T magnetic field bending particles in the horizontal plane
- 24 slabs of magnetized iron interleaved with 24 RPC planes
- 6 drift tube stations for precision measurement of the angular deflection
- momentum resolution:
20% below 30 GeV/c

Performances of the electronic detector

New Journal of Physics 13 (2011) 053051

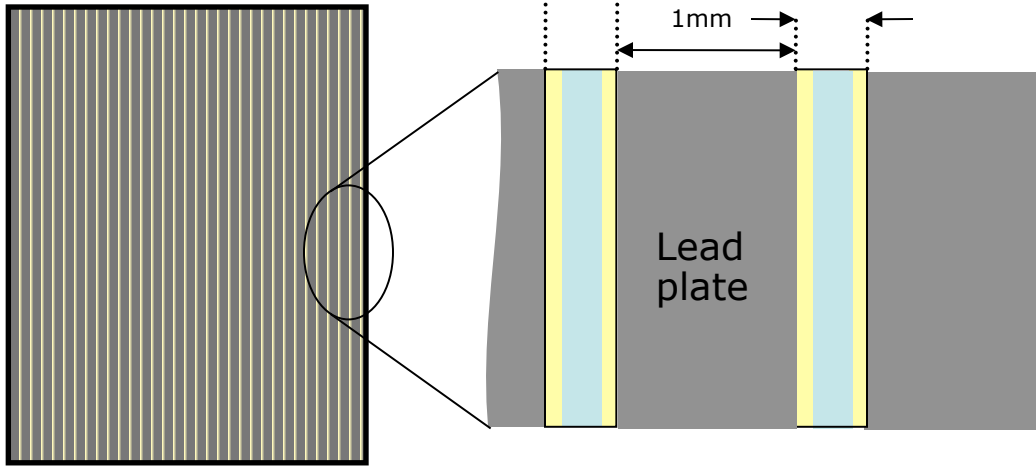
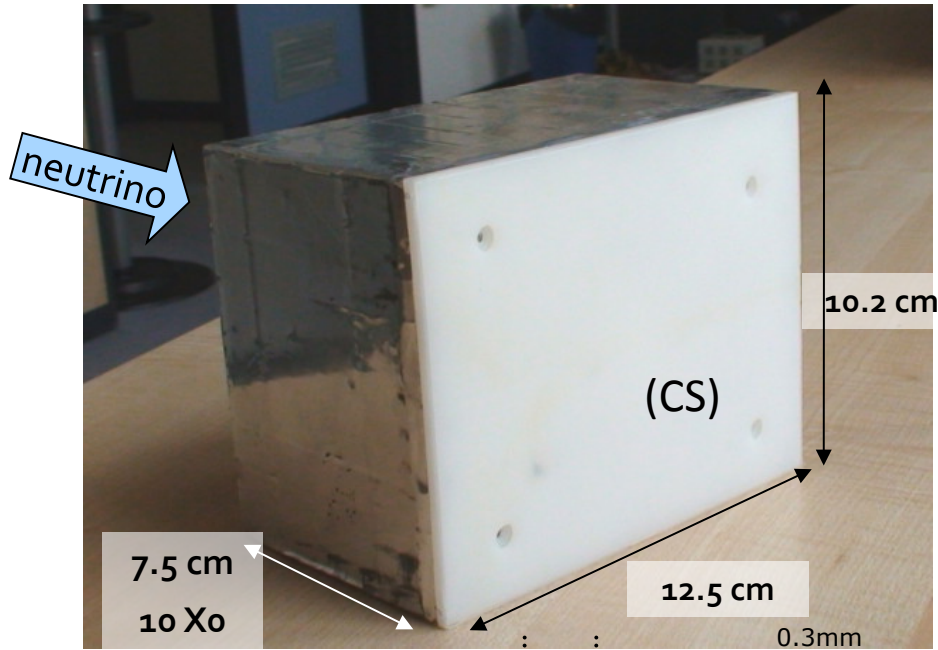


Identification of the interaction brick: iterative process (~1.6 bricks involved in the analysis of one event)



Brick identified (top and side view)

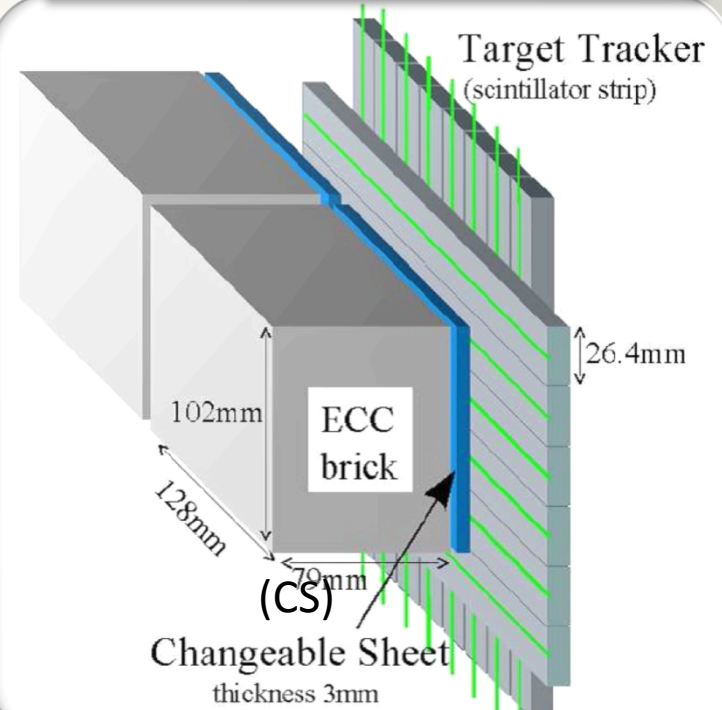
The heart of the experiment: THE ECC TARGET BRICKS



57 OPERA films, 56 lead plates

11/06/13

Hybrid target structure.

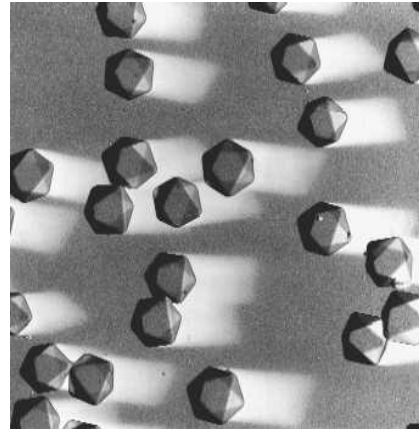
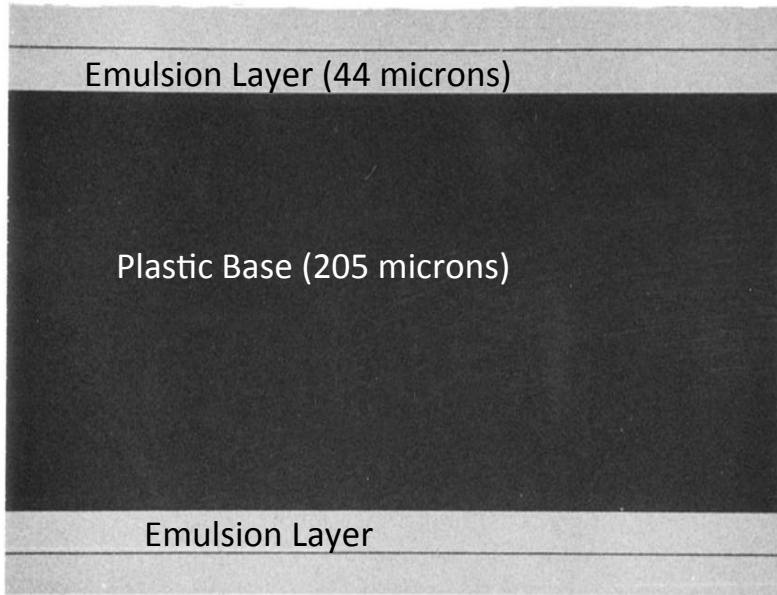


The OPERA target consists of 150'000 ECC bricks.

Total 105'000 m² of lead surface
and 111'000 m² of film surface
(~ 9 million films)

Total target mass: ~1.2 kton

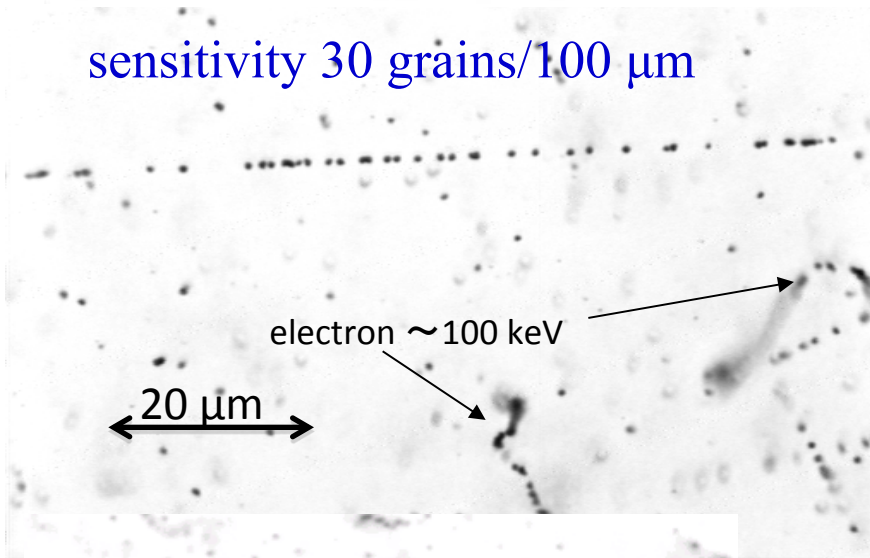
INDUSTRIAL EMULSION FILMS BY FUJI FILM



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

sensitivity 30 grains/100 μm

mip \rightarrow



electron ~ 100 keV

20 μm

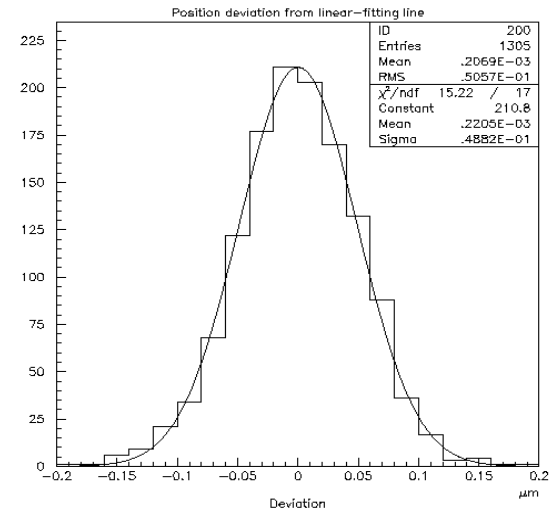
high dE/dx tracks from nuclear evaporation

11/06/13

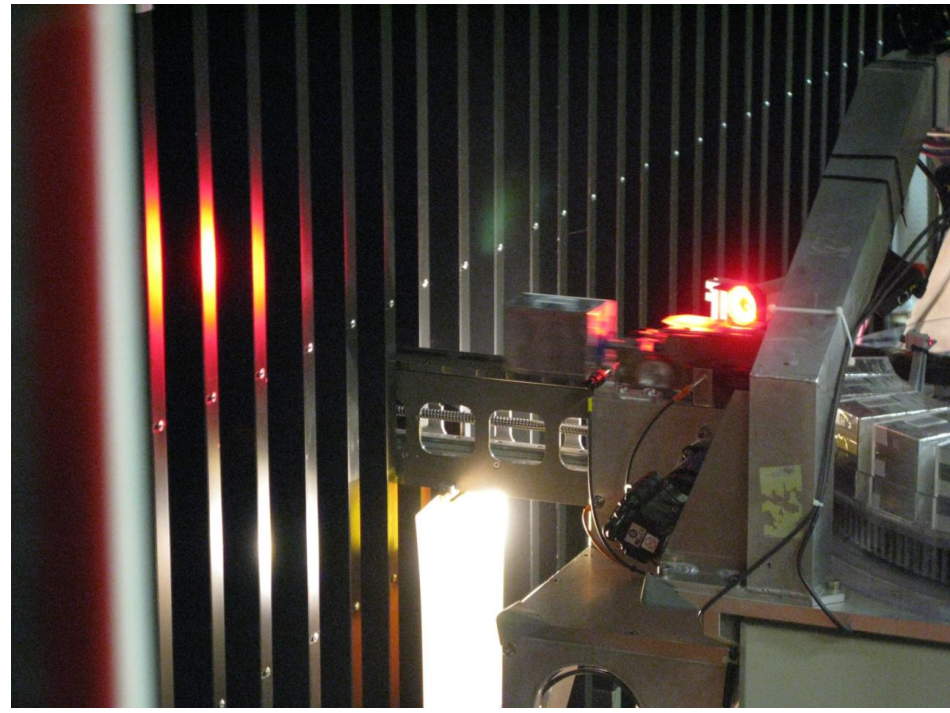
Giovanni De Lellis, CERN Seminar

intrinsic resolution: 50 nm

deviation from linear-fit line. (2D)



BRICK MANIPULATOR SYSTEM (BMS)

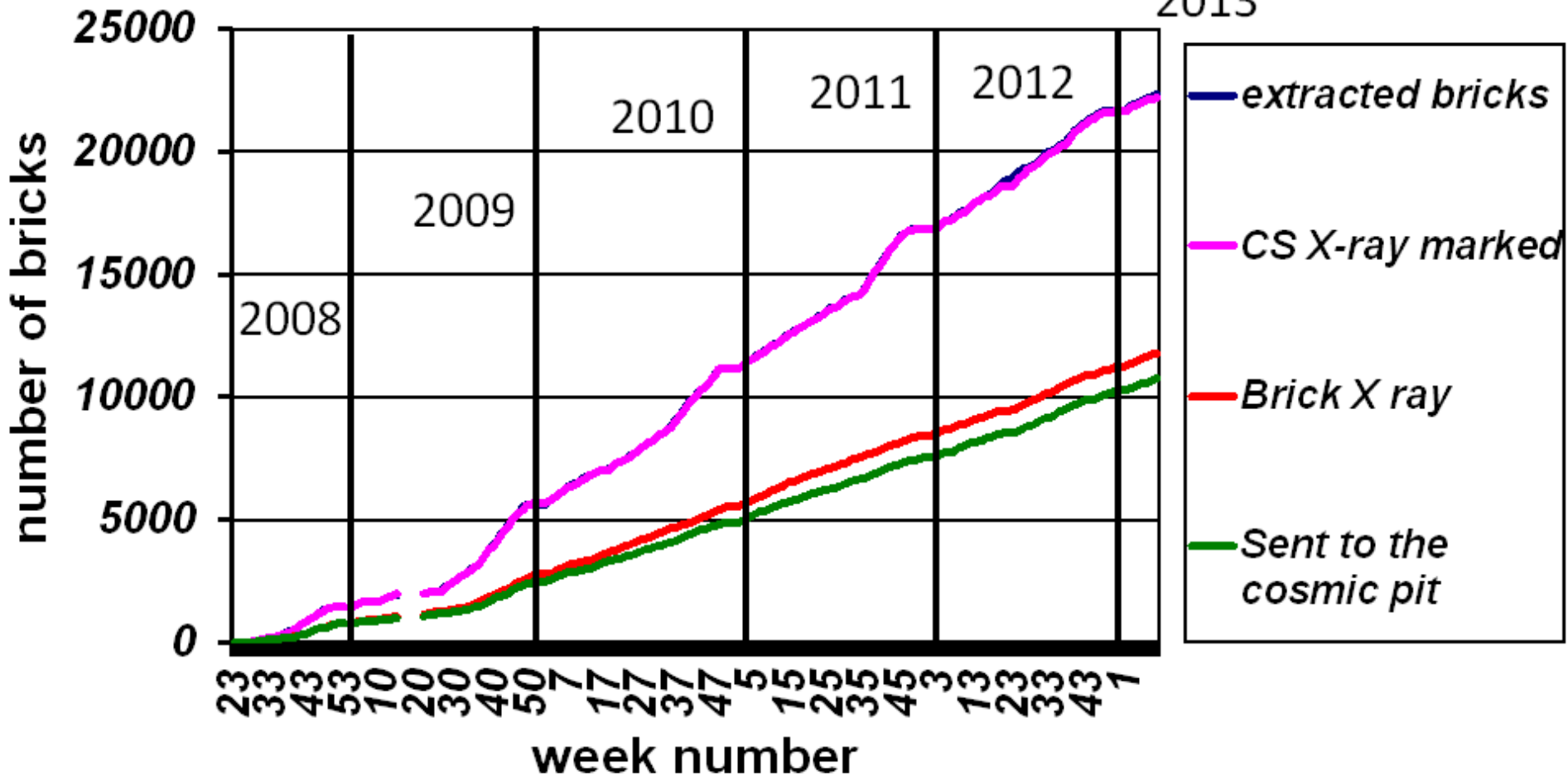


Extraction of “hit” bricks in parallel with CNGS data taking (quasi-online):

- 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)

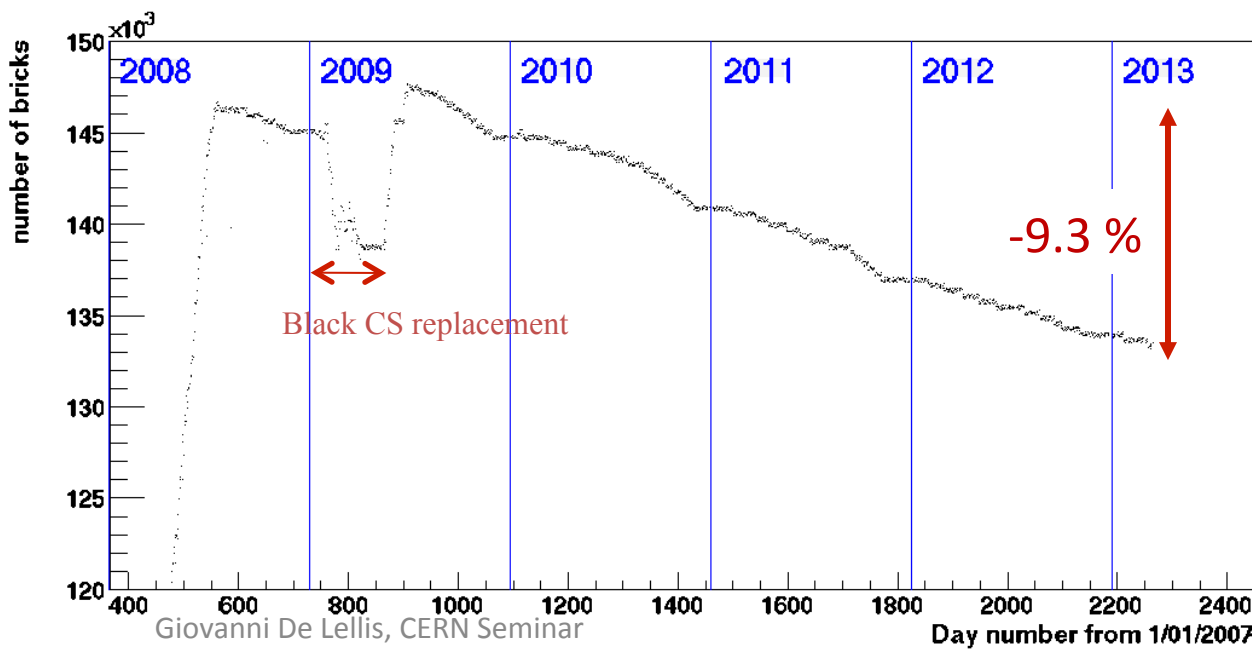
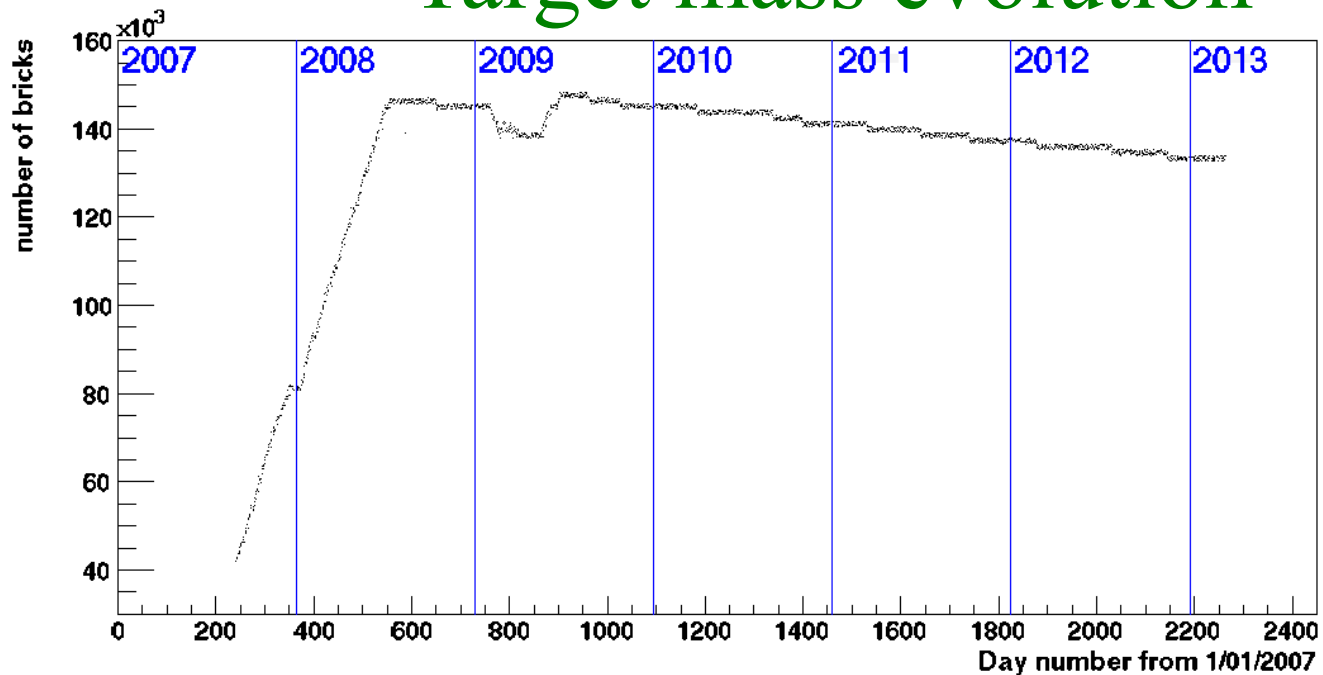
OPERA brick handling

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

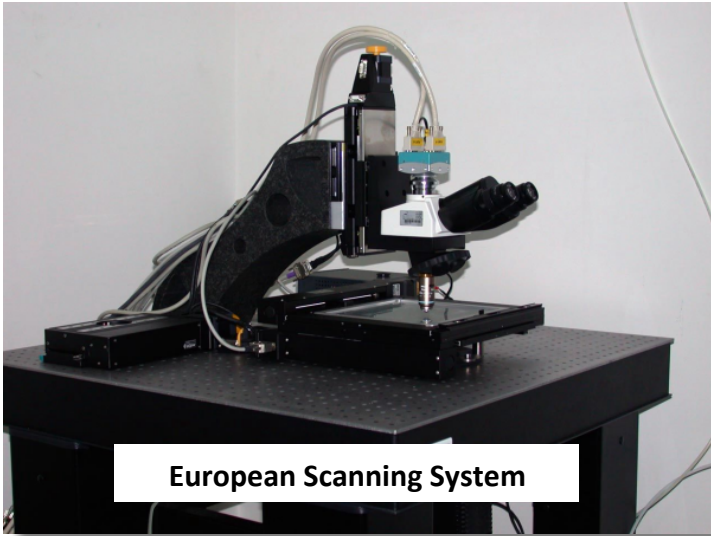
Scanning of Changeable Sheets: several tasks accomplished



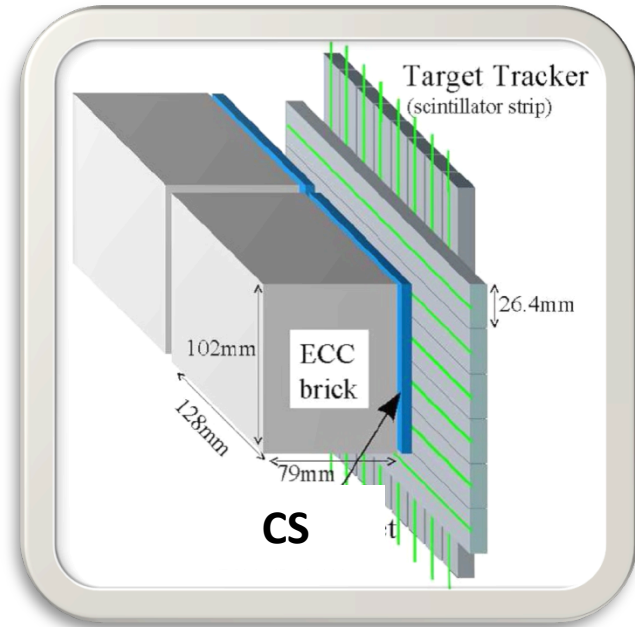
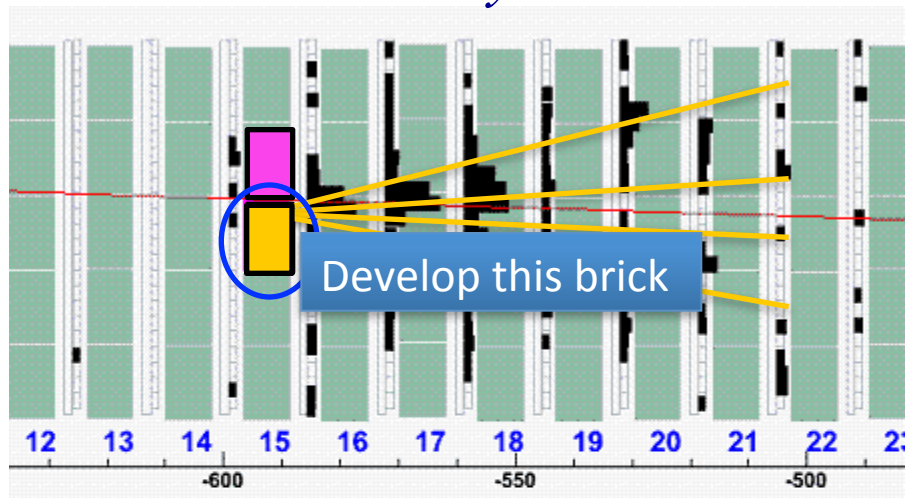
LNGS: 10 microscopes, 200 cm²/h



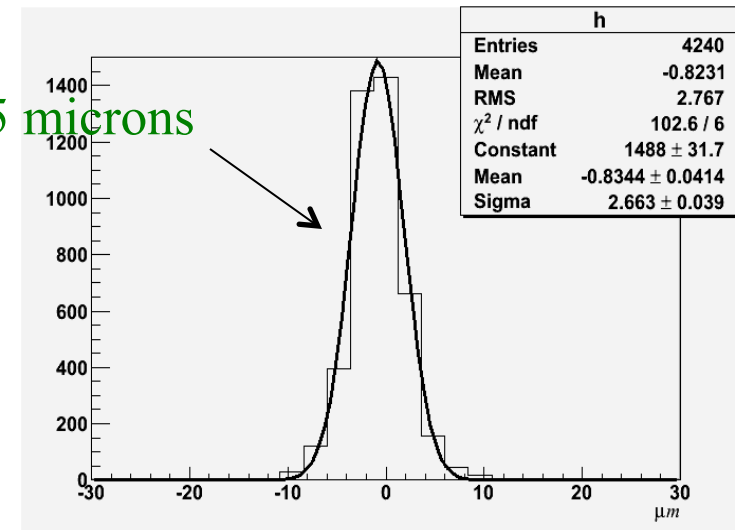
Nagoya: 5 S-UTS, 220 cm²/h



Brick validation by the interface film analysis



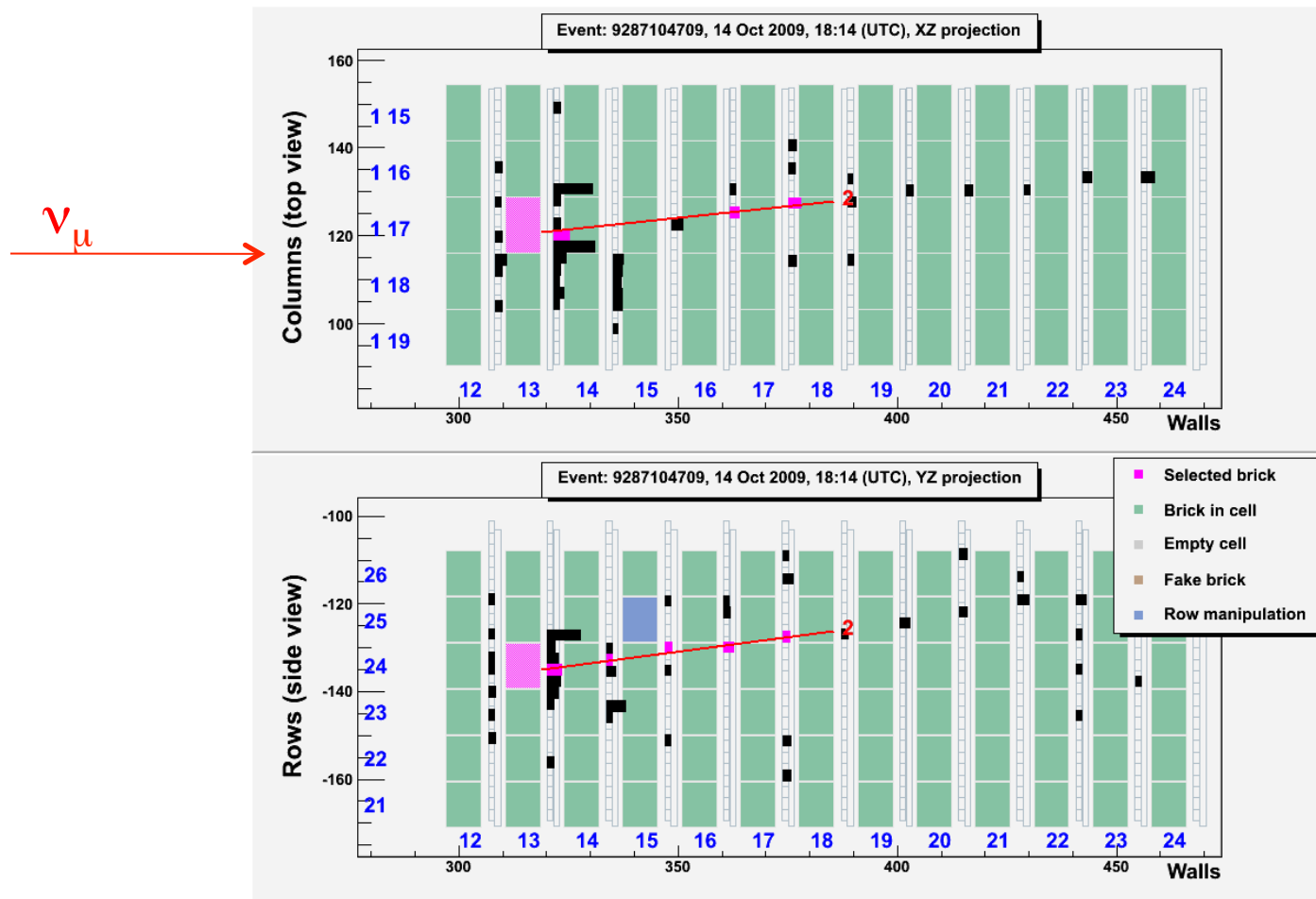
CS doublet alignment by Compton electrons: 2.5 microns



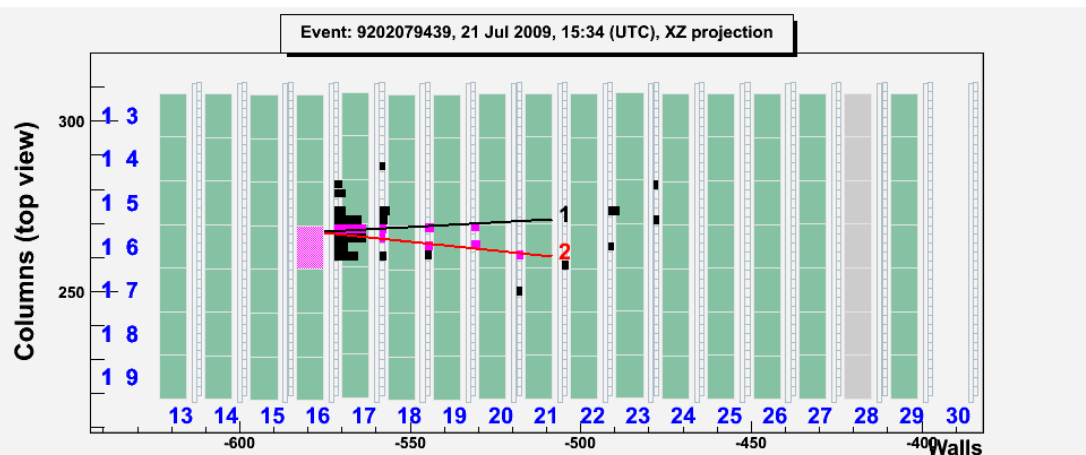
So far 2'000'000 cm² of CS surface have been analysed in OPERA

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

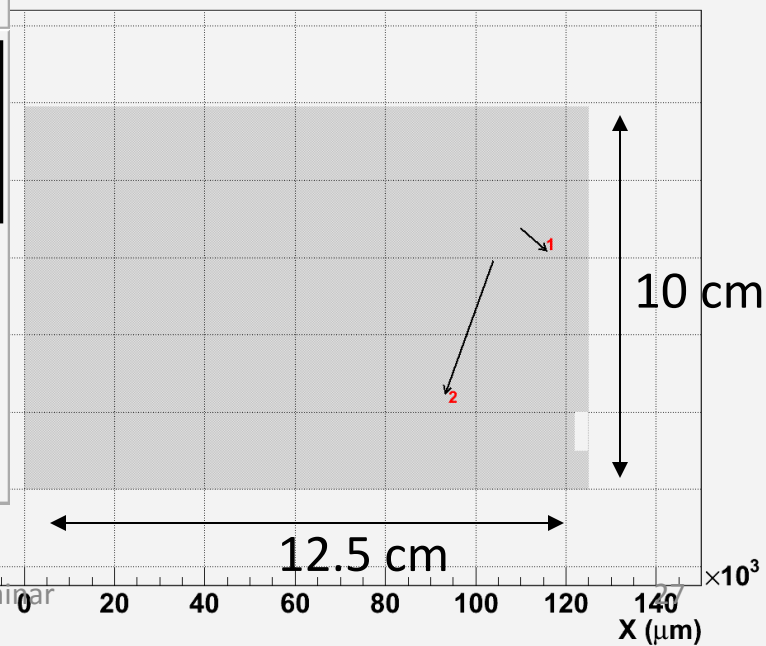
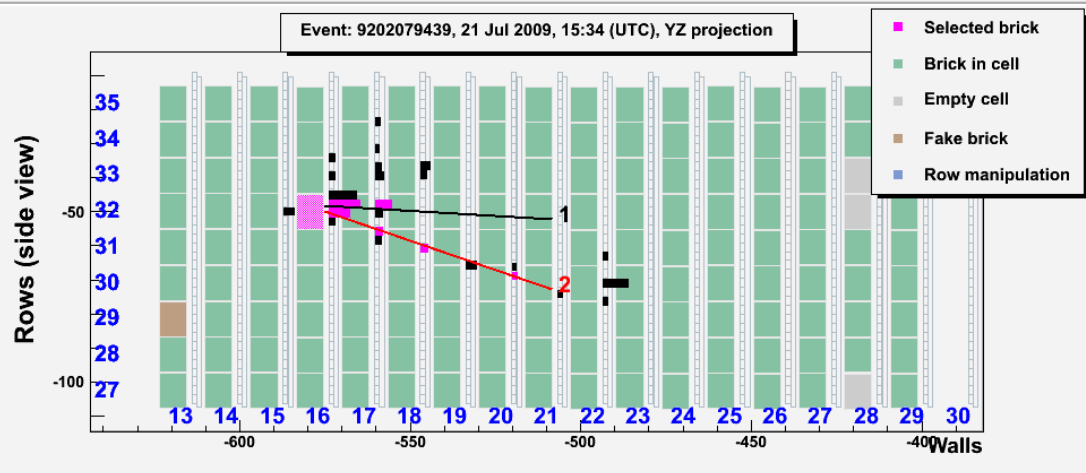
CC interaction: μ track in interface films



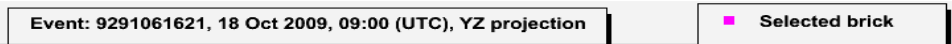
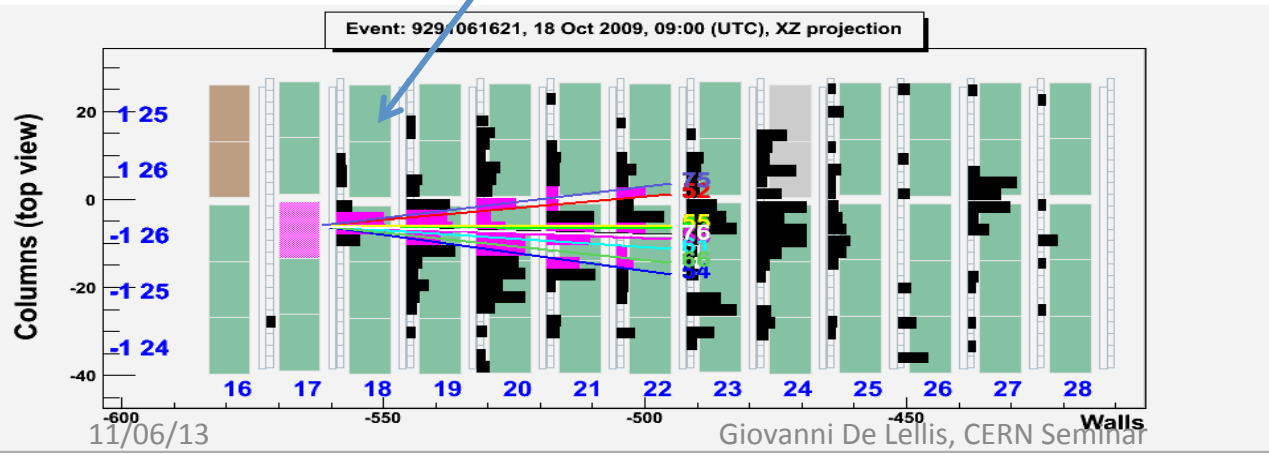
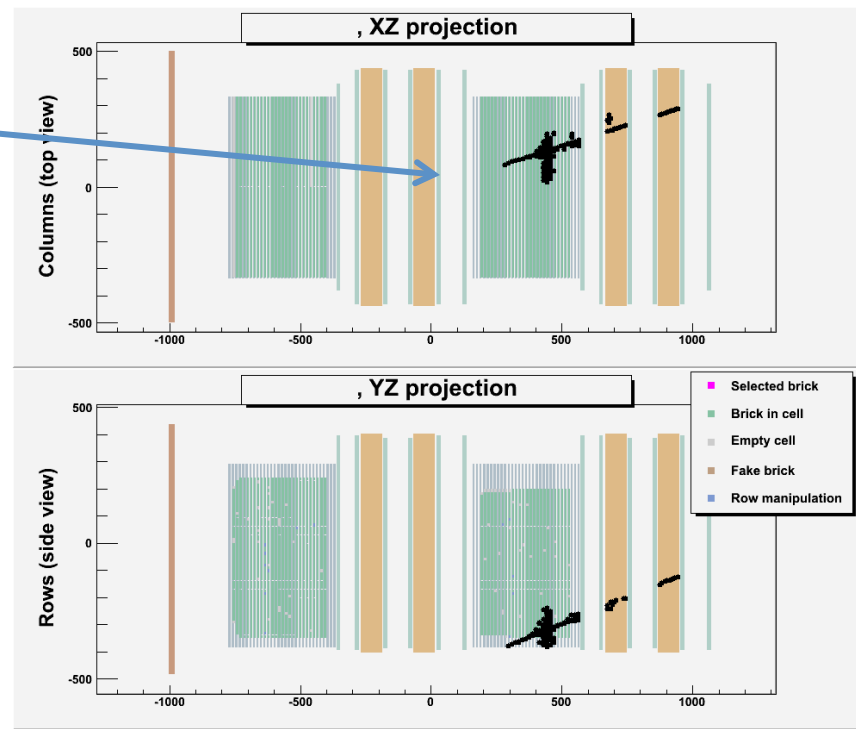
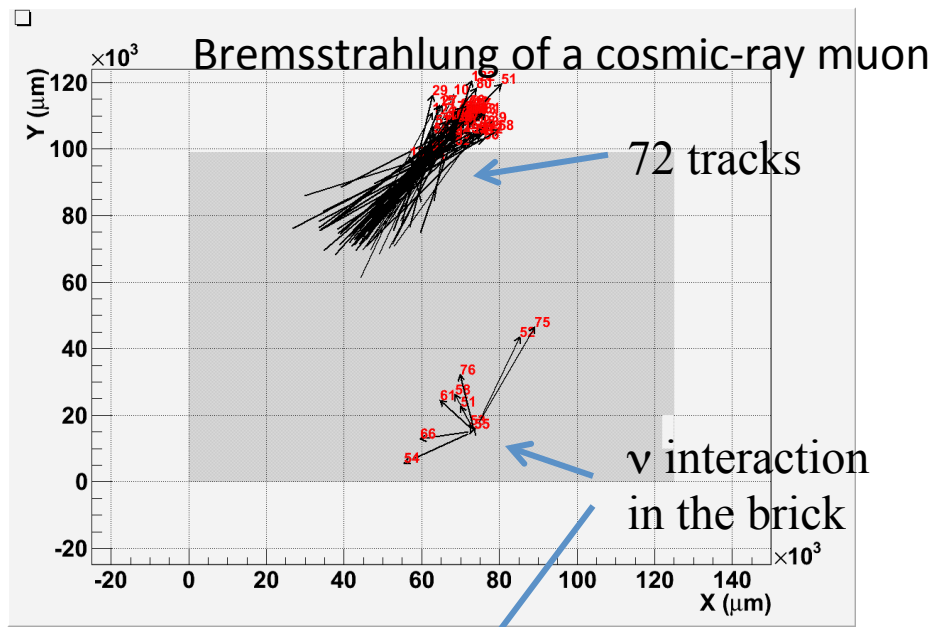
Validation of events without μ in the final state by interface emulsion films

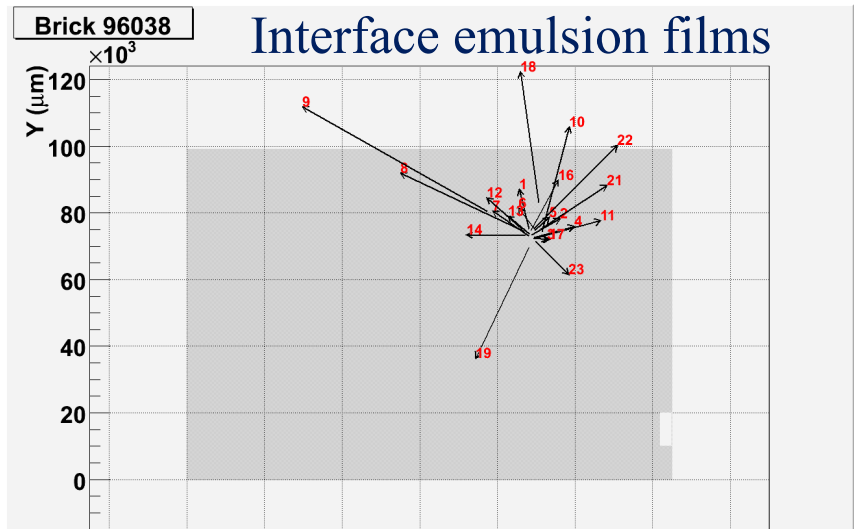


CS tracks: the arrow length is proportional to its slope

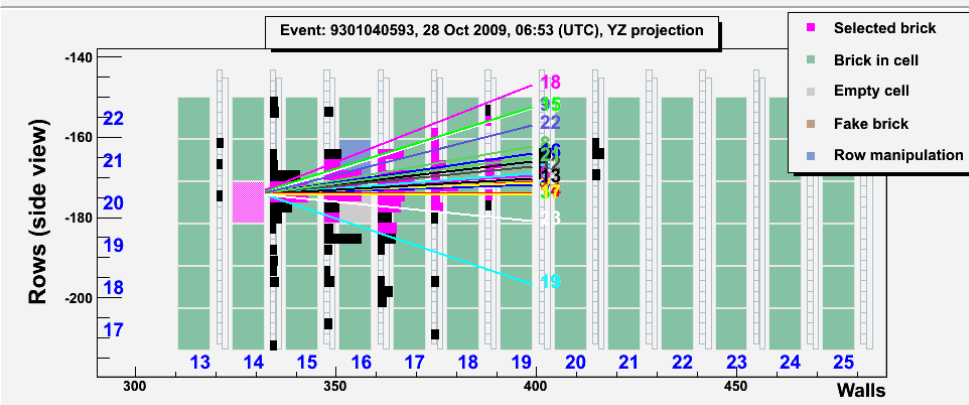
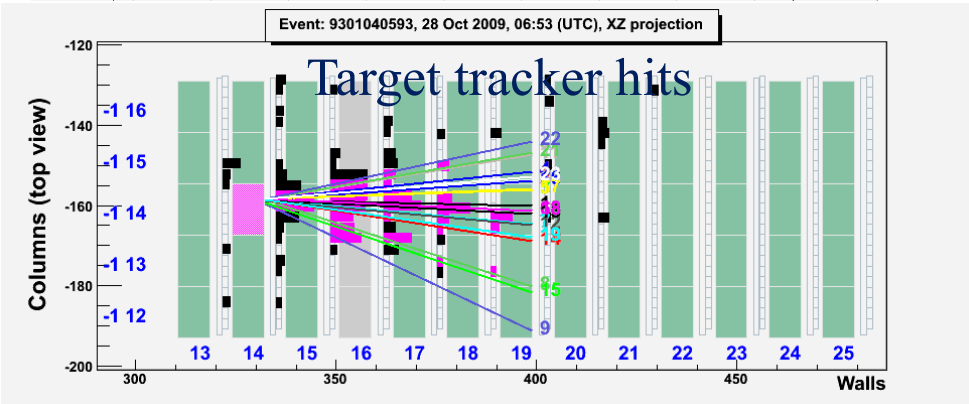
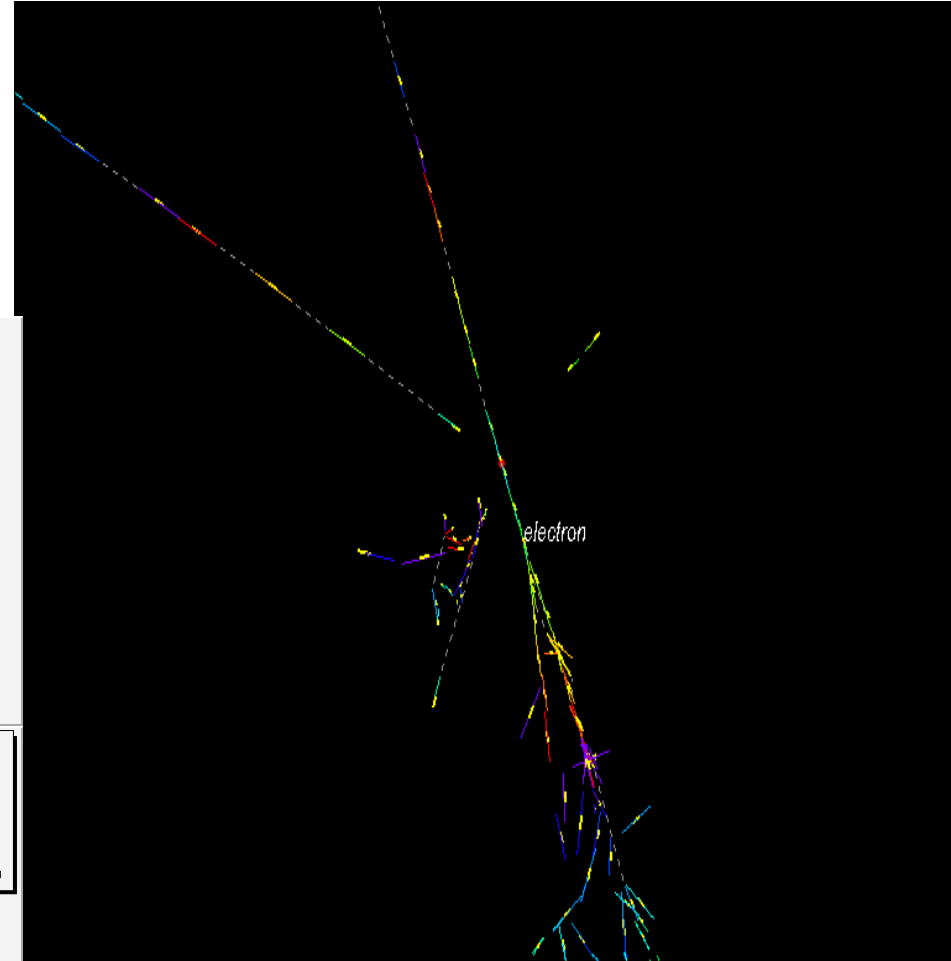


Identification of cosmic ray μ and muons from ν interactions upstream: TT running also during the shutdown





Electron shower pre-selection

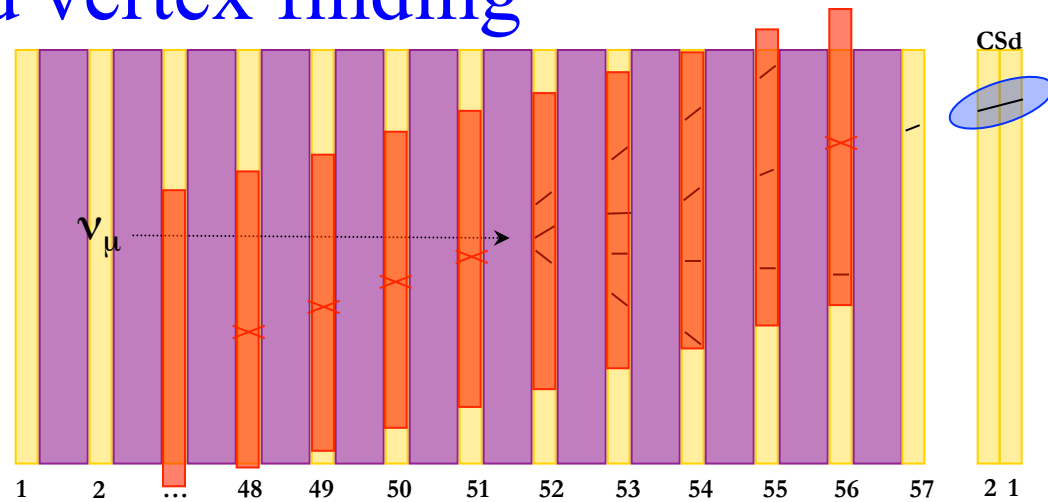


One of the electron neutrinos located as seen after the brick analysis

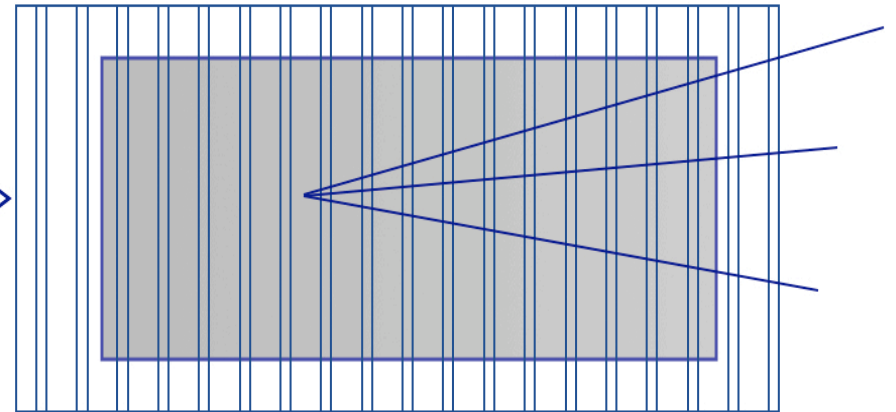
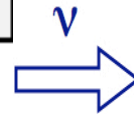
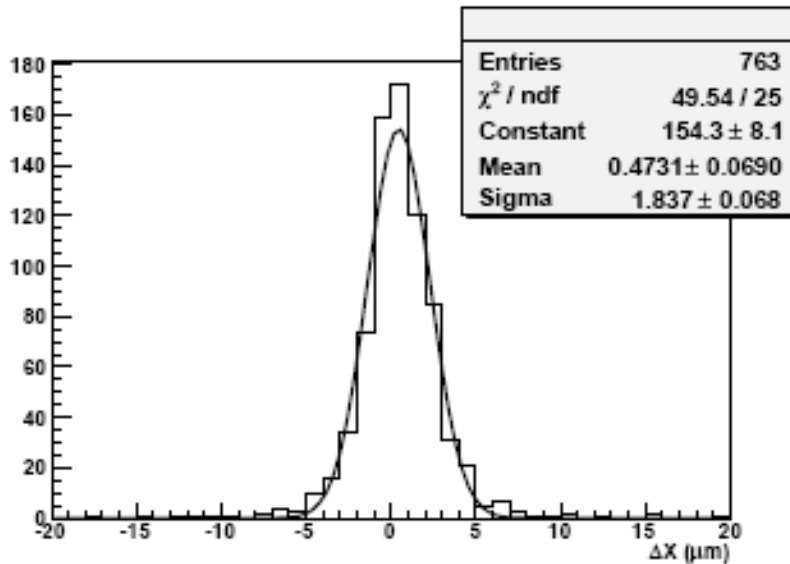
Track follow-up and vertex finding

Track follow-up film by film:

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



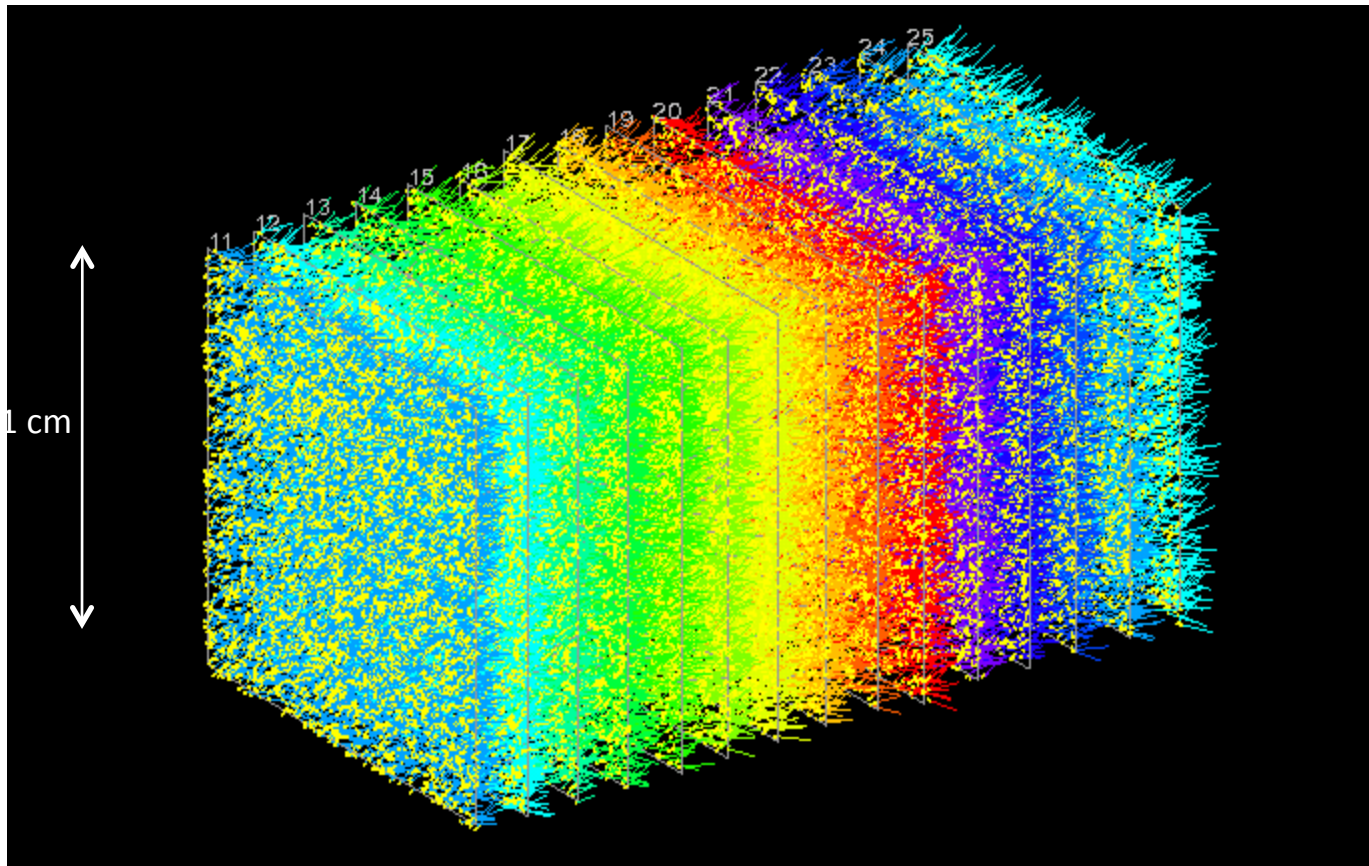
$\sigma \sim 2 \mu\text{m}$



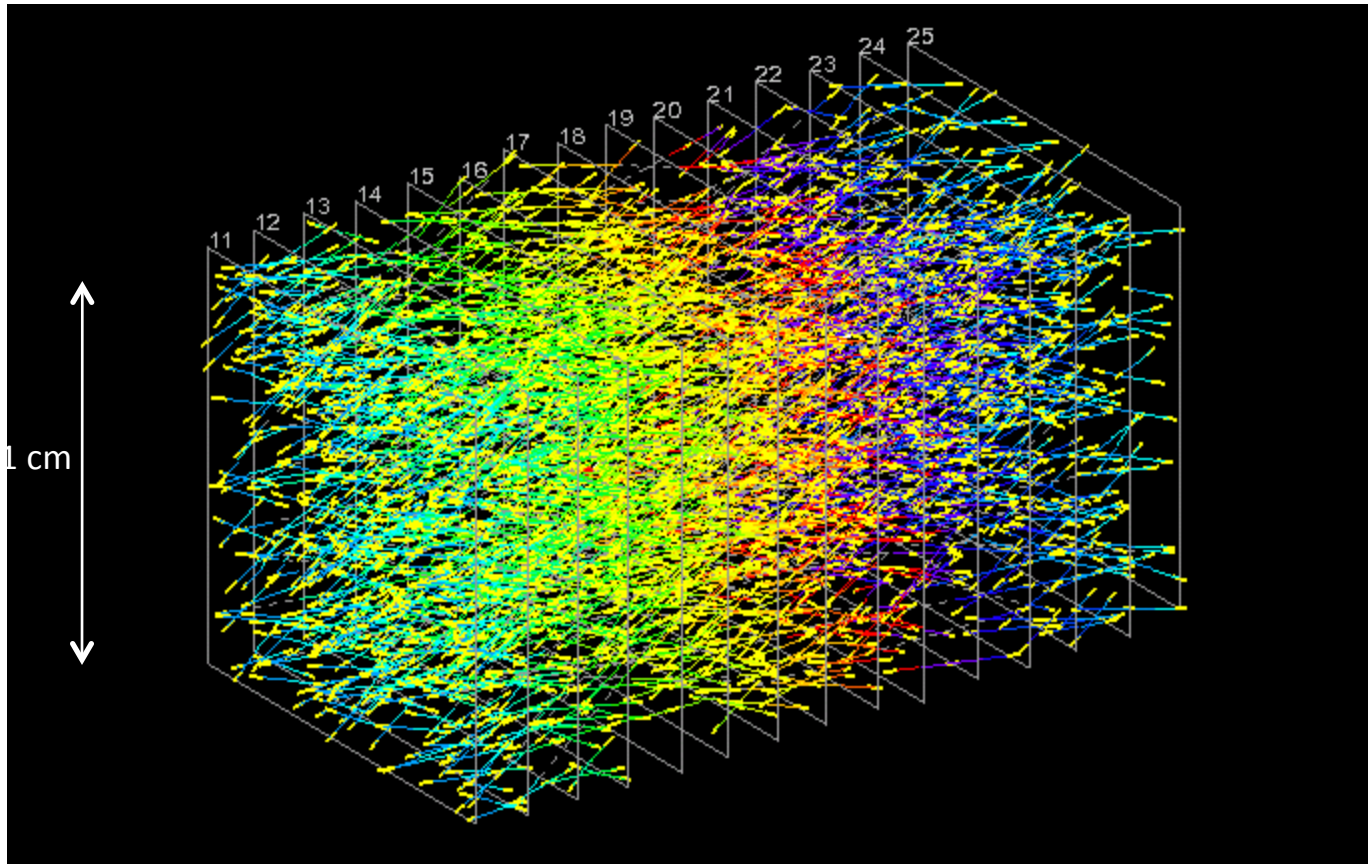
Volume scanning ($\sim 2 \text{ cm}^3$) around the stopping point

Located neutrino interaction

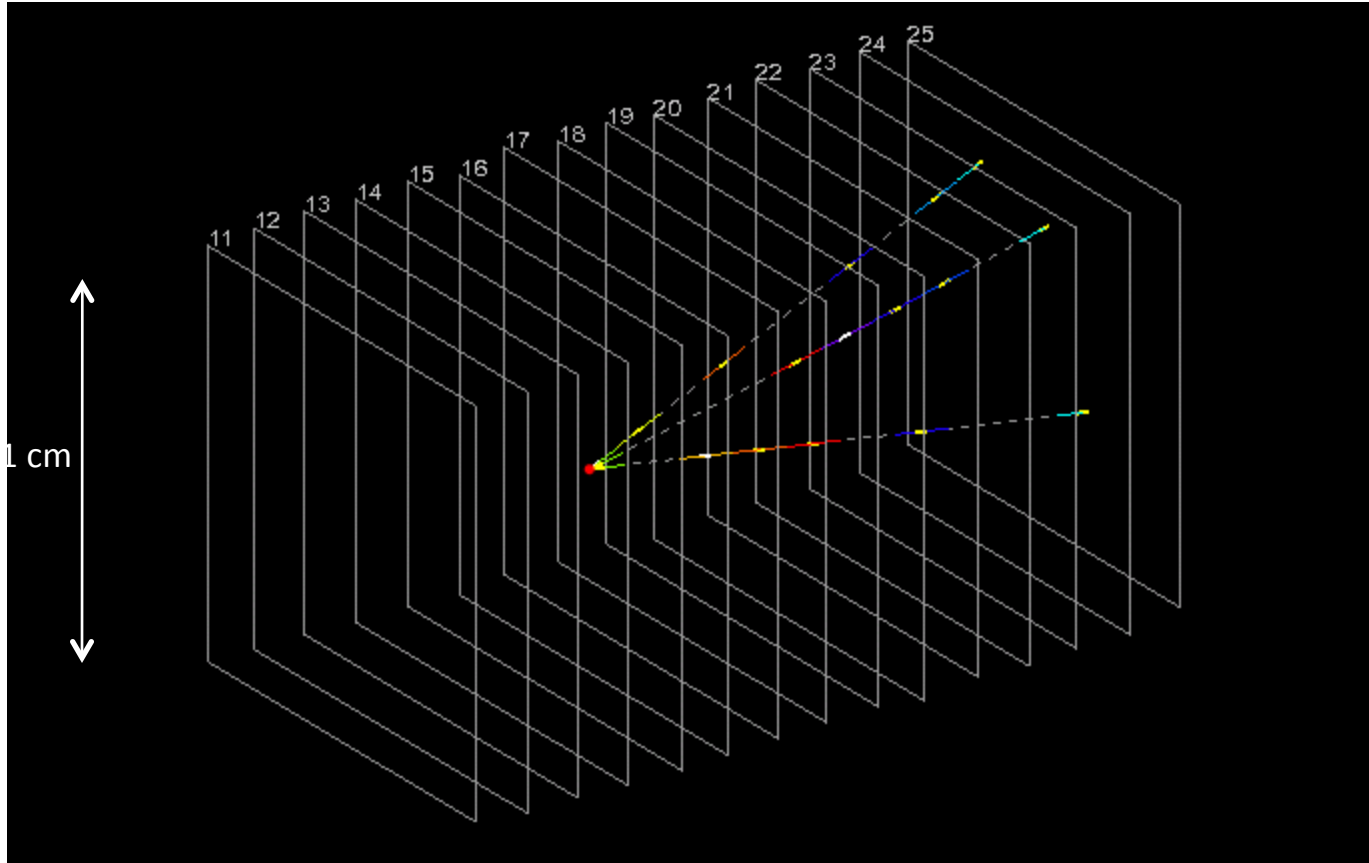
Volume ($\sim 2 \text{ cm}^3$) around the stopping point



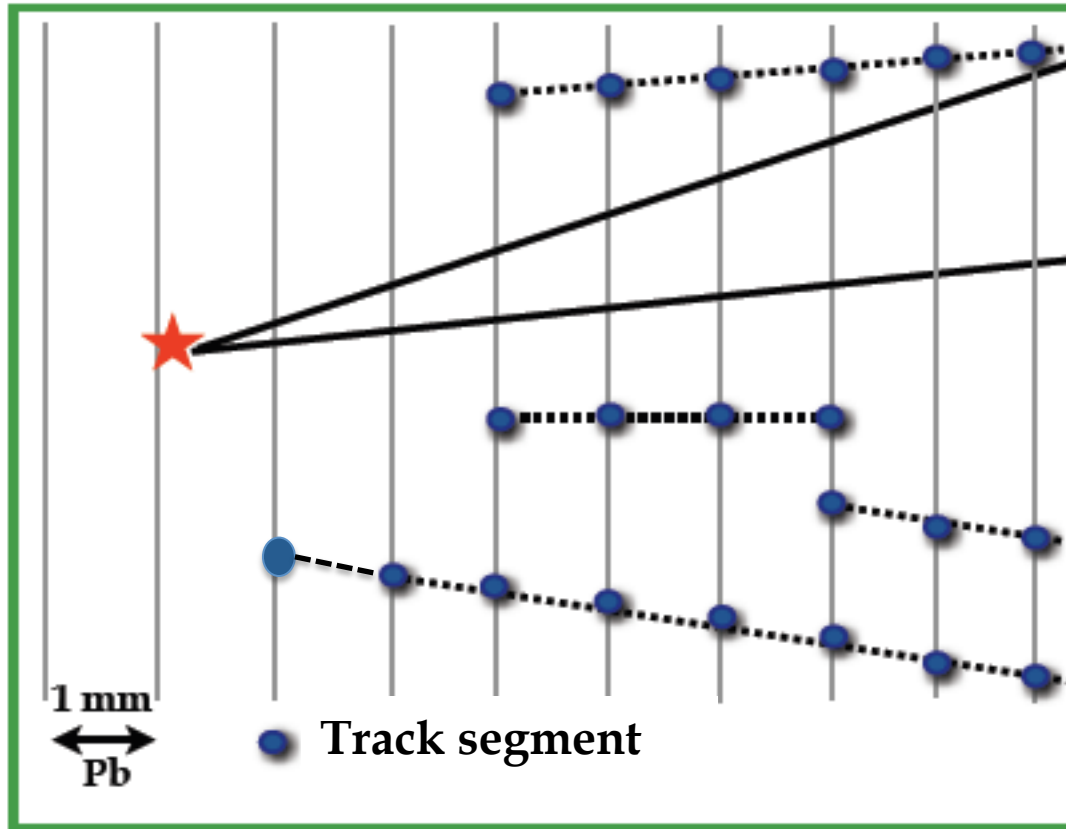
Located neutrino interaction: film to film connection



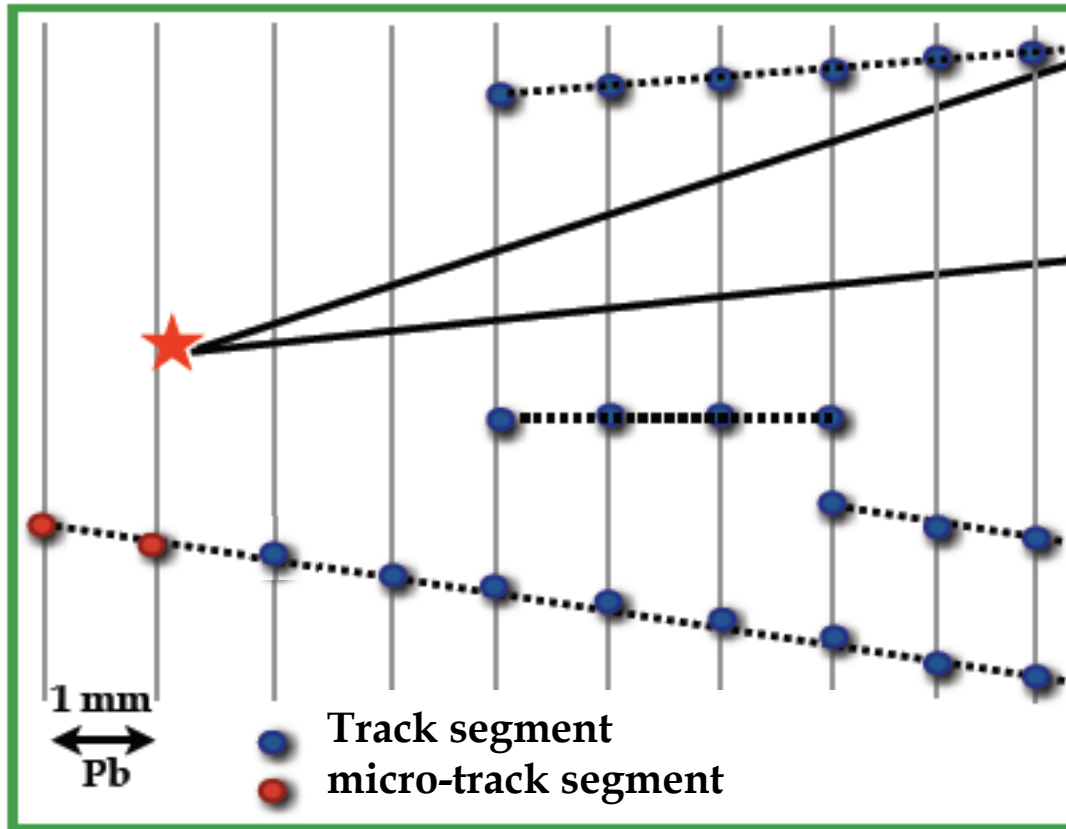
Located neutrino interaction



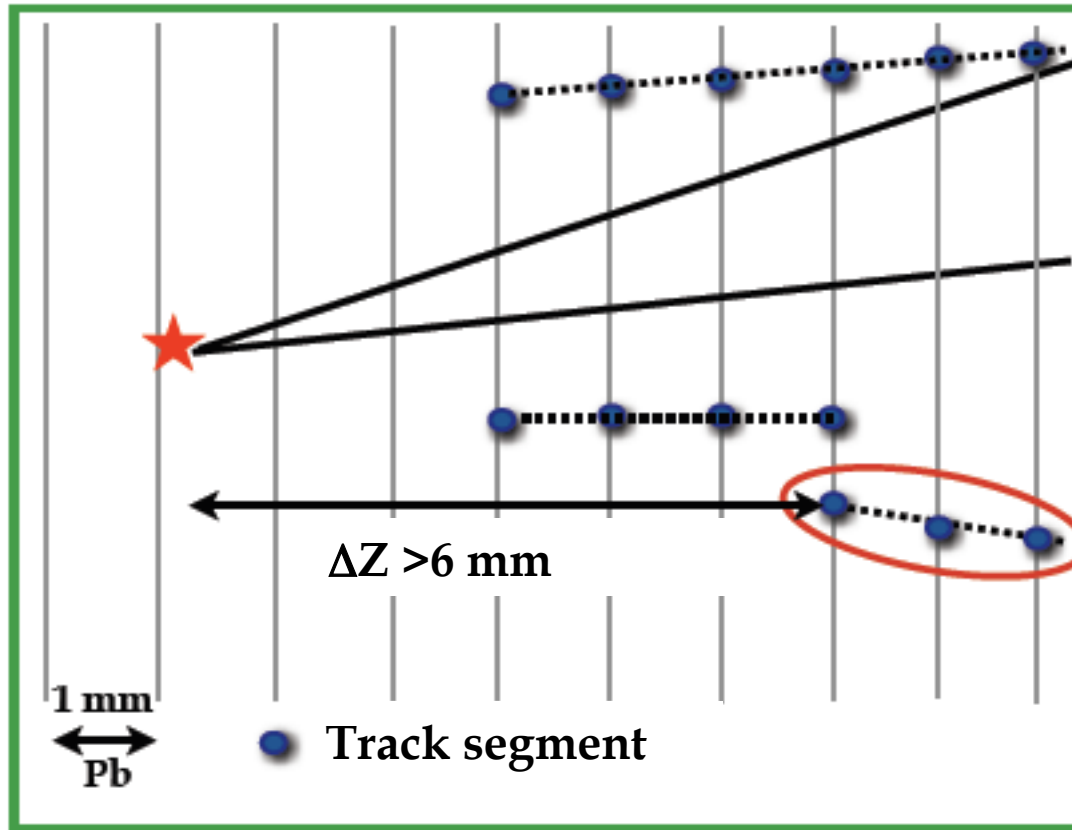
Decay search procedure



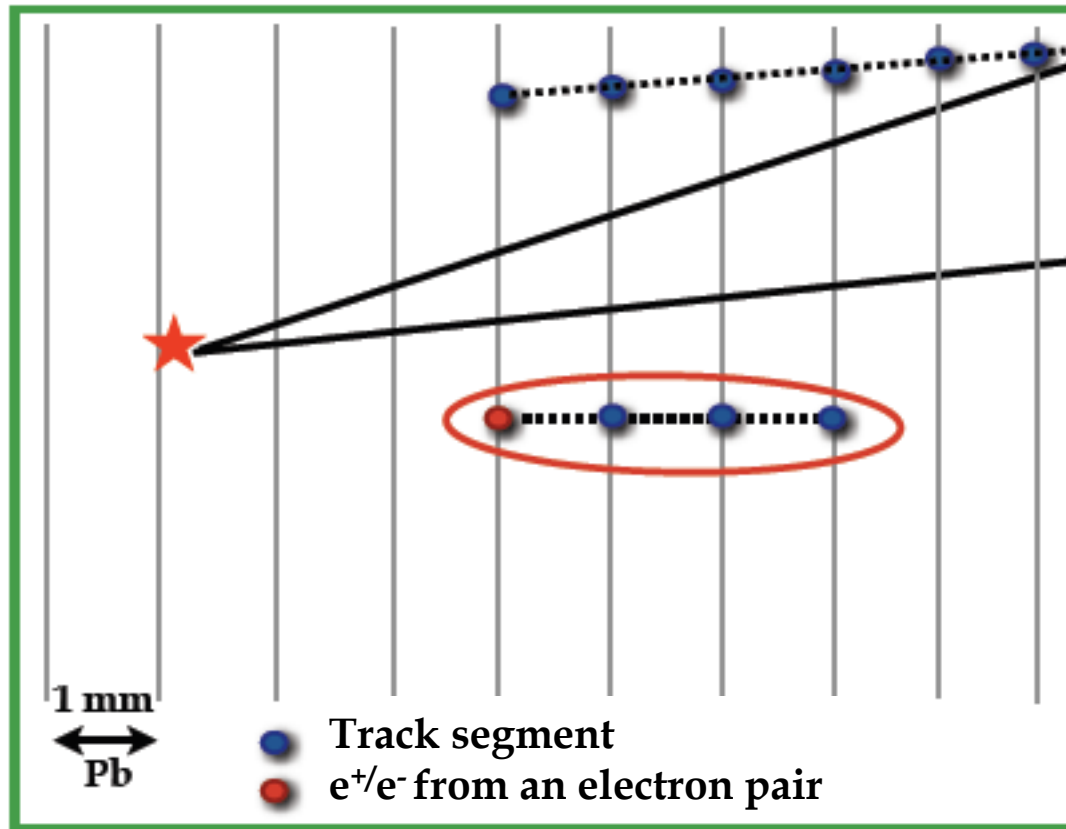
Decay search: penetrating tracks discarded



Decay search: track selection

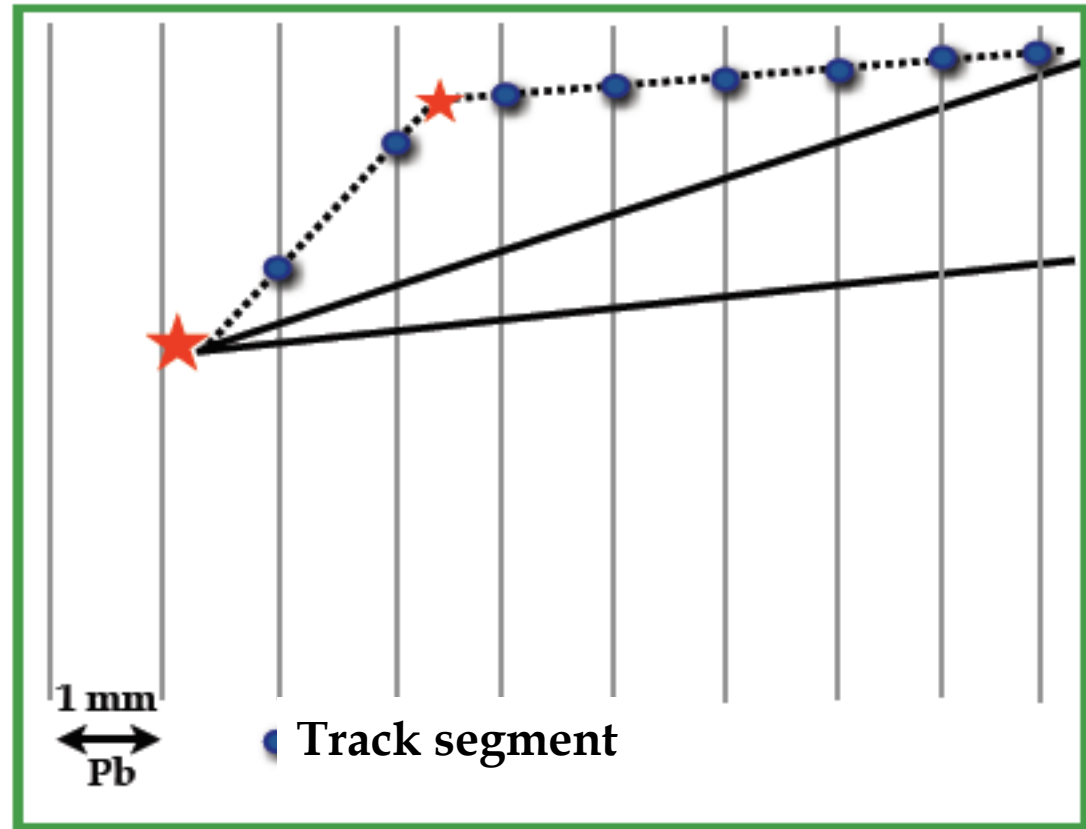
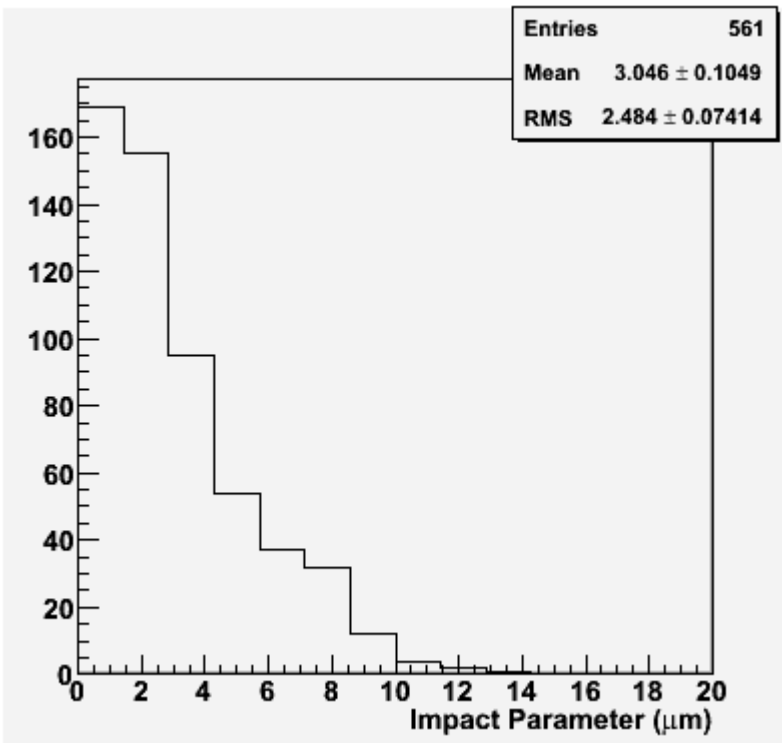


Decay search: electron pair

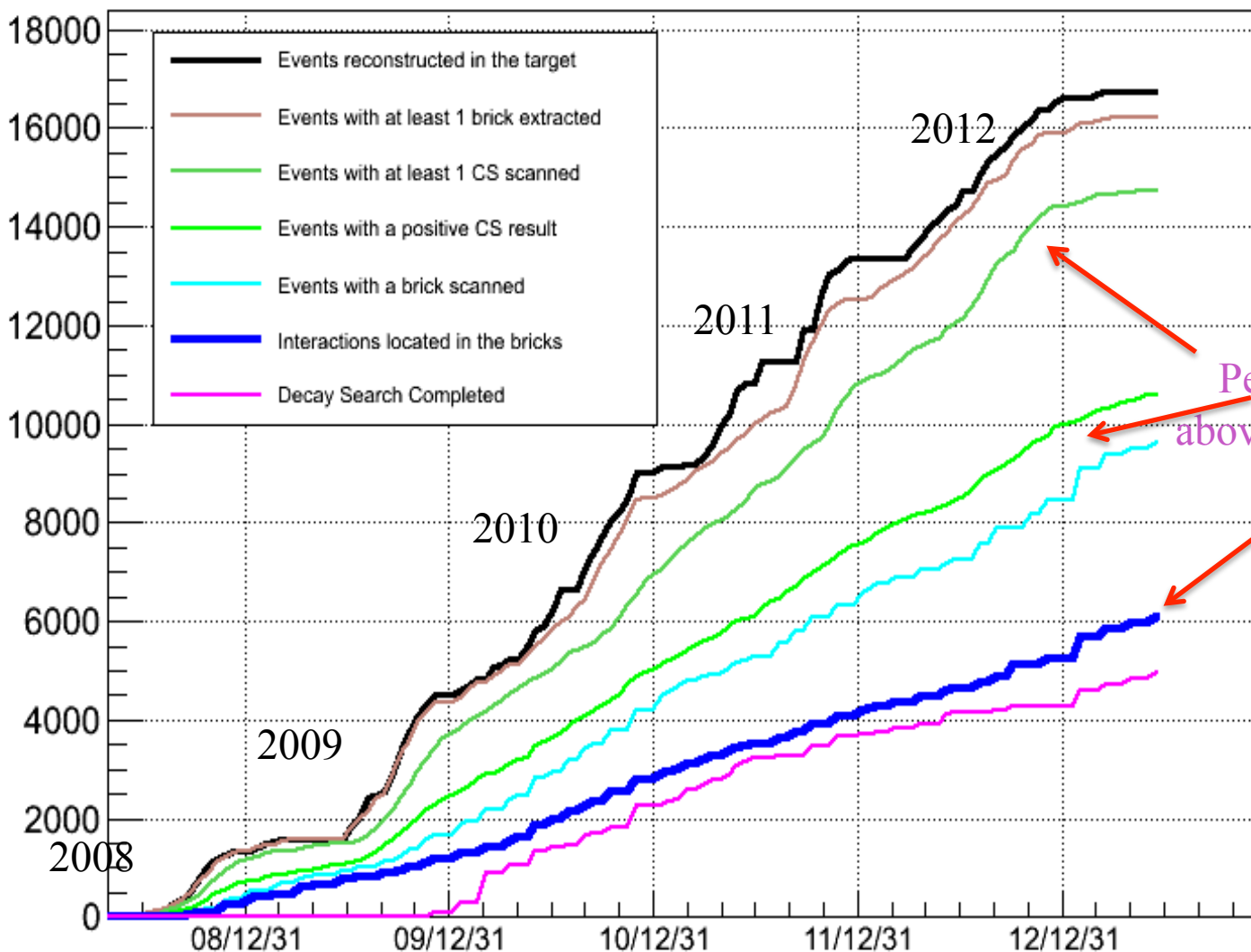


Decay search: kink topology detected

Impact parameter distribution of tracks associated to primary vertices



Status of data analysis



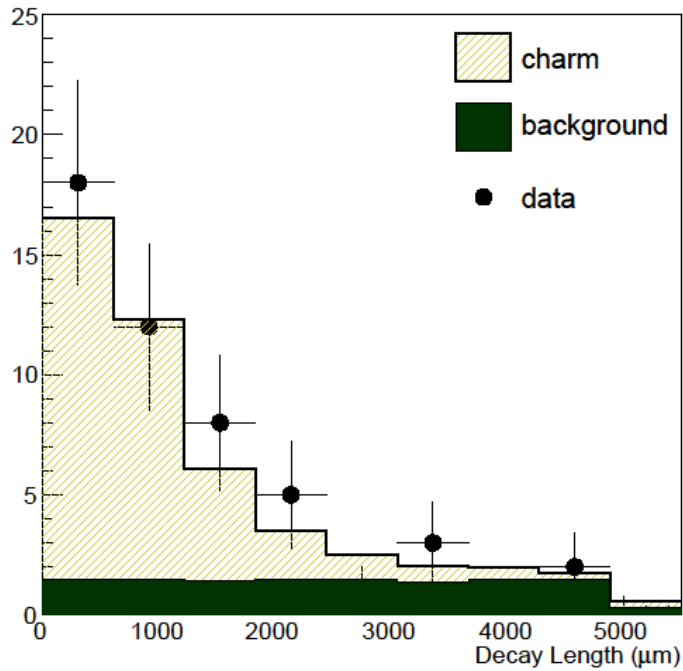
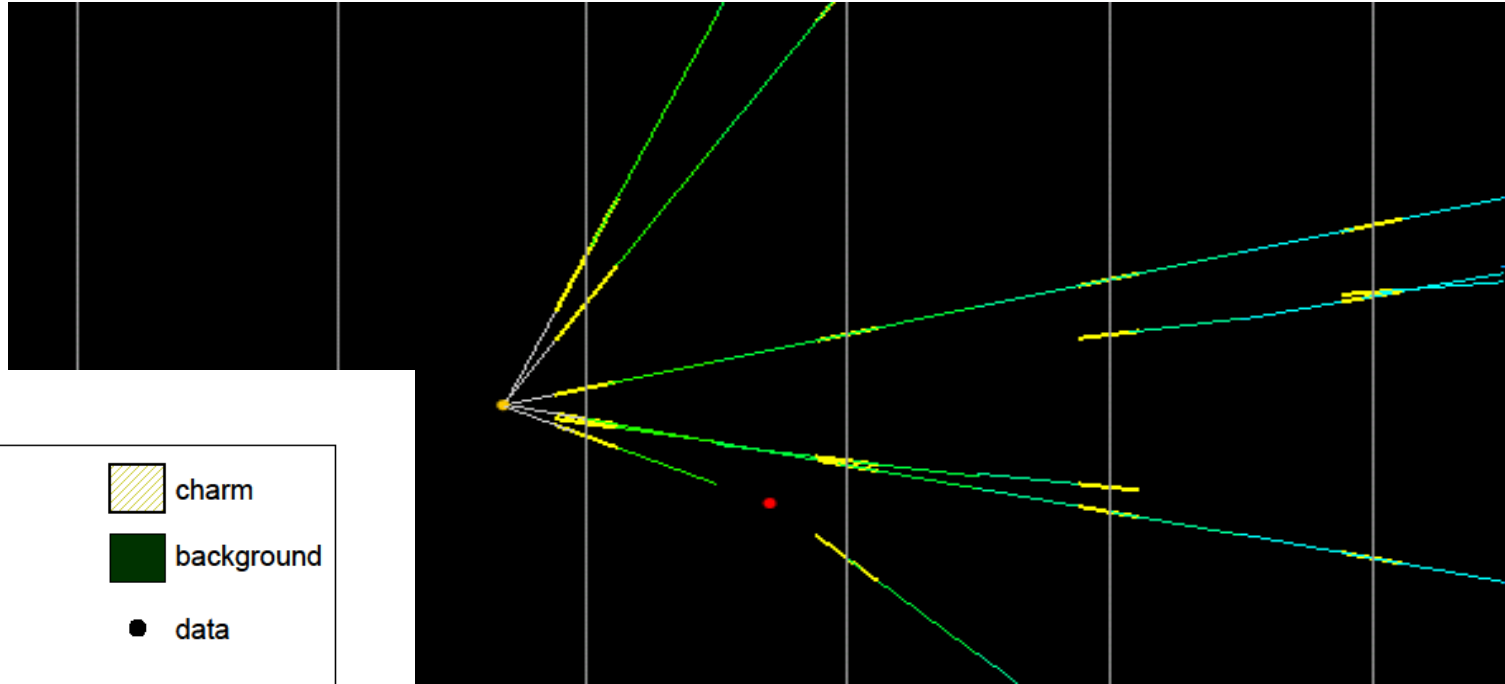
6067 located interactions

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 τ*

Charm sample: same topology but muon at interaction vertex

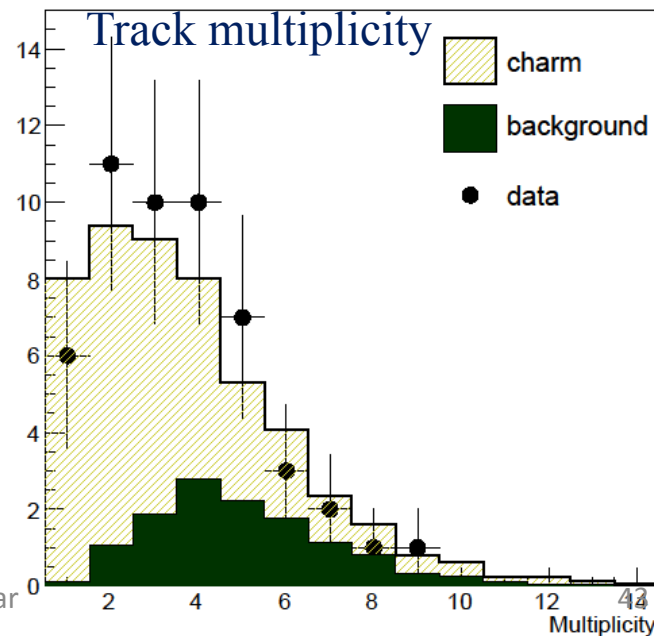
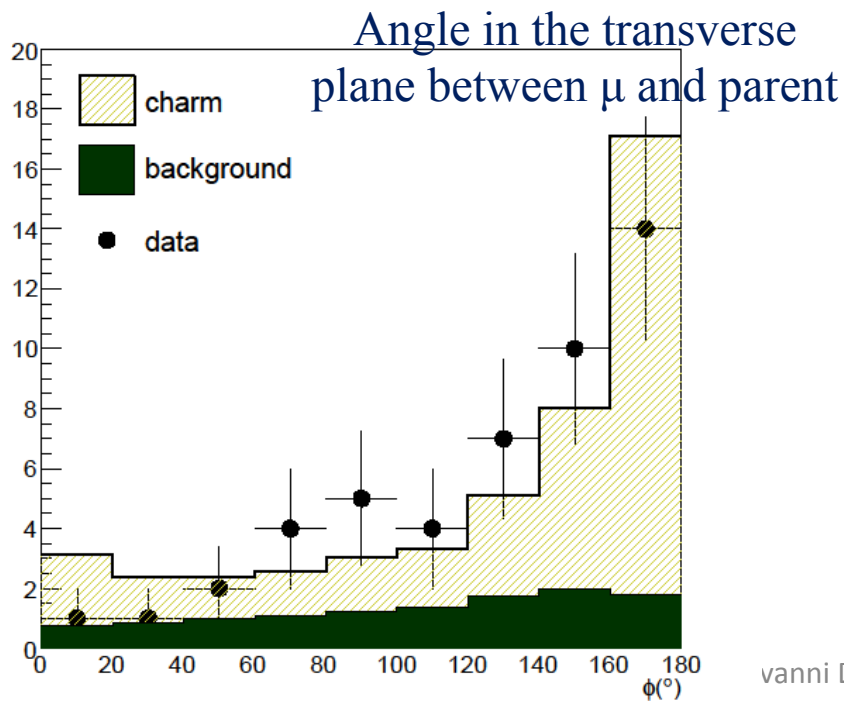
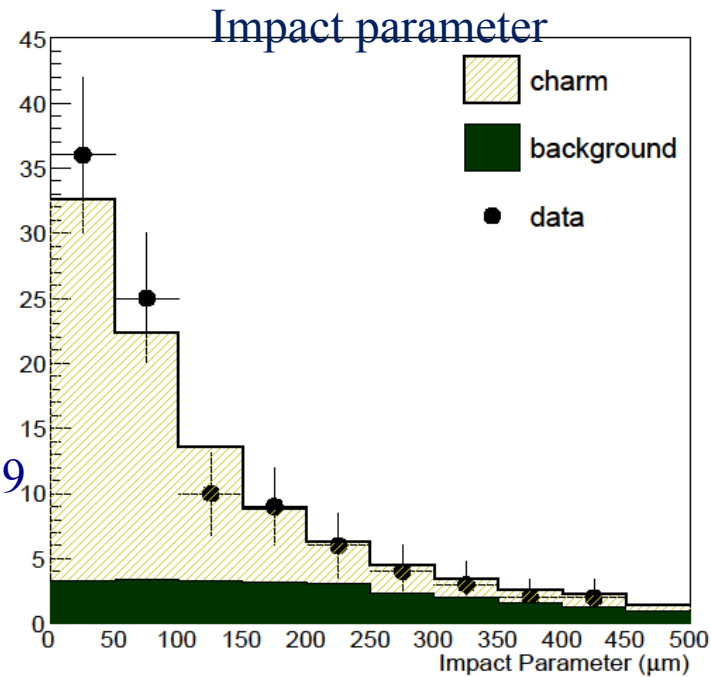
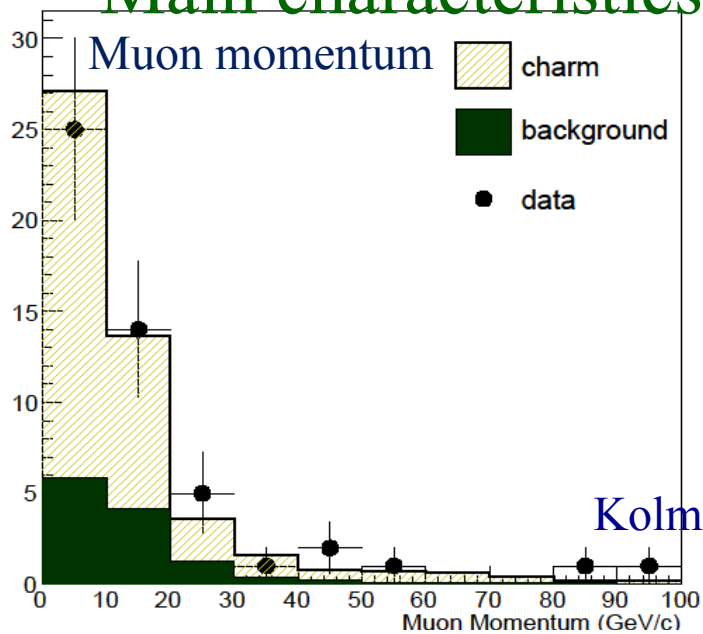


Charm yield from the analysis of 2008÷2010 data

	charm	background	expected	data
1 prong	20 ± 3	9 ± 3	29 ± 4	19
2 prong	15 ± 2	3.8 ± 1.1	19 ± 2	22
3 prong	5 ± 1	1.0 ± 0.3	6 ± 1	5
4 prong	0.8 ± 0.2	-	0.8 ± 0.2	4
All	41 ± 4	14 ± 3	55 ± 5	50

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

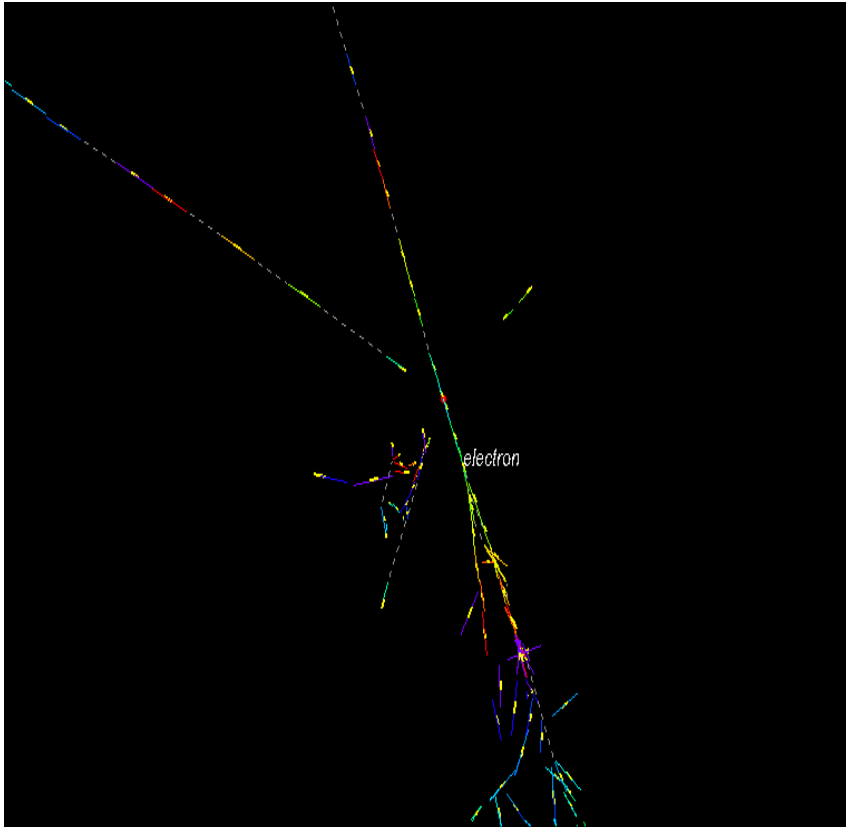
Main characteristics of charm candidate events



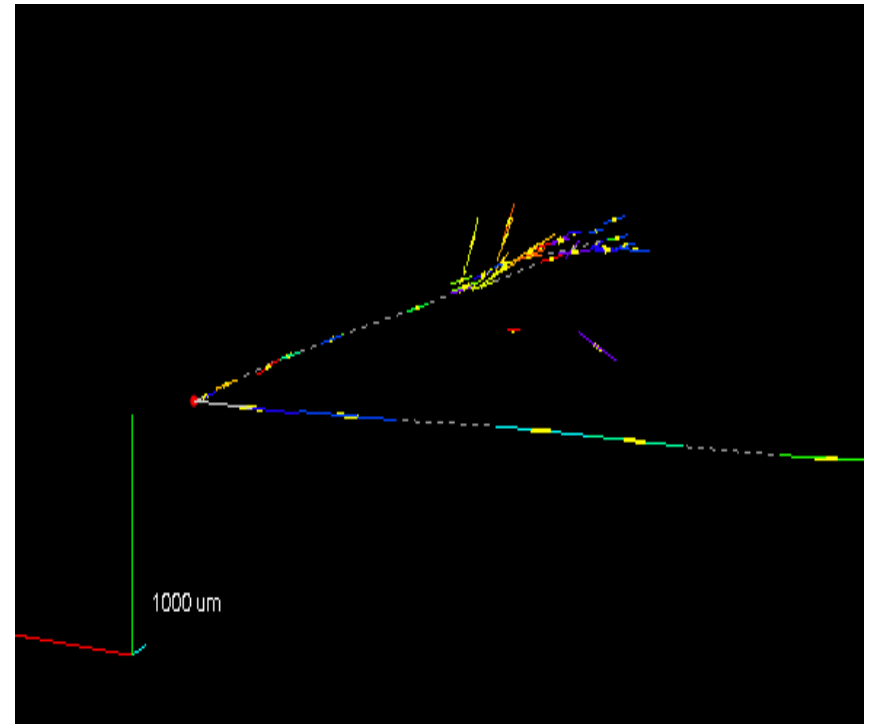
Kolmogorov test ≥ 0.99
all plots

Physics results

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

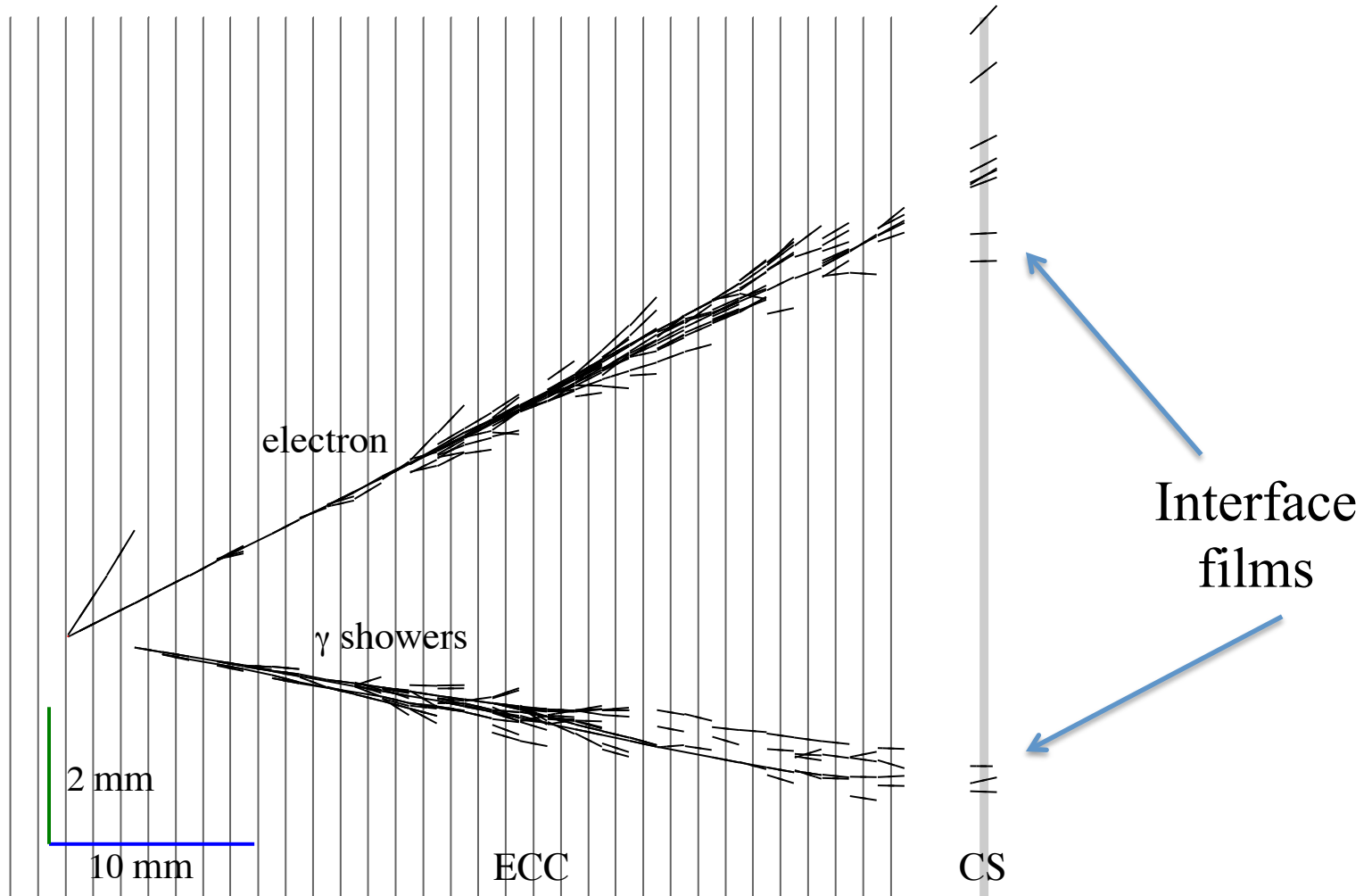


4.1 GeV electron



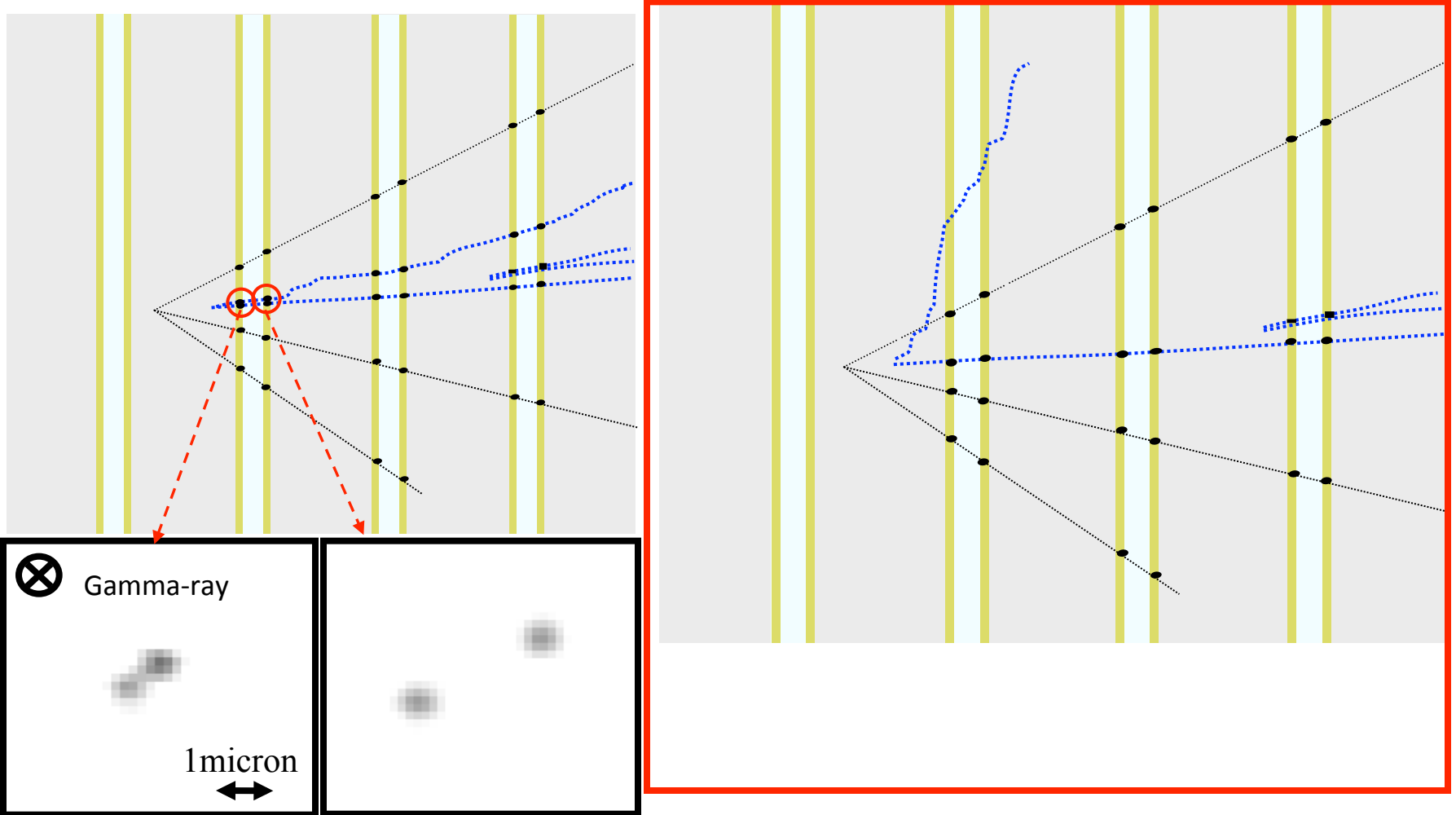
32 events found in the analyzed sample

Electron neutrino search in 2008 and 2009 runs: one of the ν_e events with a π^0 as seen in the brick



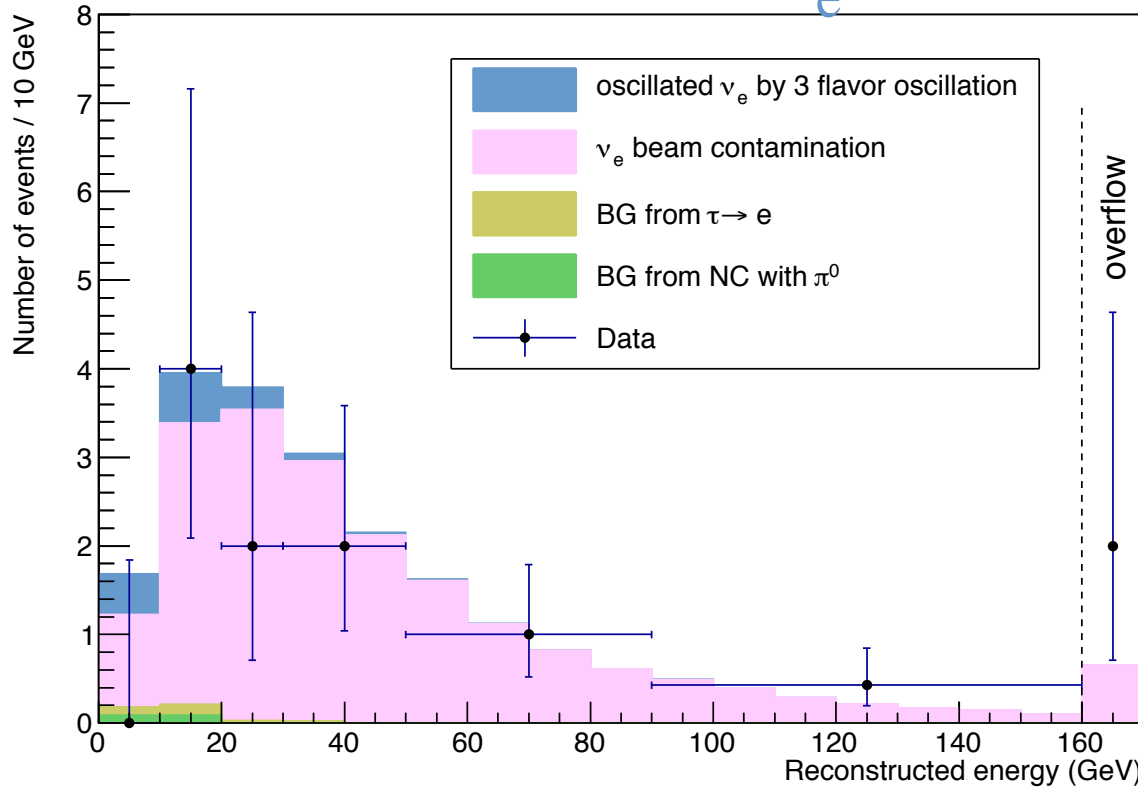
19 candidates found in a sample of 505 neutrino interactions without muon

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



BG: 0.17 events (less than 1%)

Energy distribution of the 19 ν_e candidates



Energy cut		20 GeV	30 GeV	No cut
BG common to both analyses	BG (a) from π^0	0.2	0.2	0.2
	BG (b) from $\tau \rightarrow e$	0.2	0.3	0.3
	ν_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	ν_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 ± 2.8 (syst) events

3 flavour analysis

Energy cut to increase the S/N

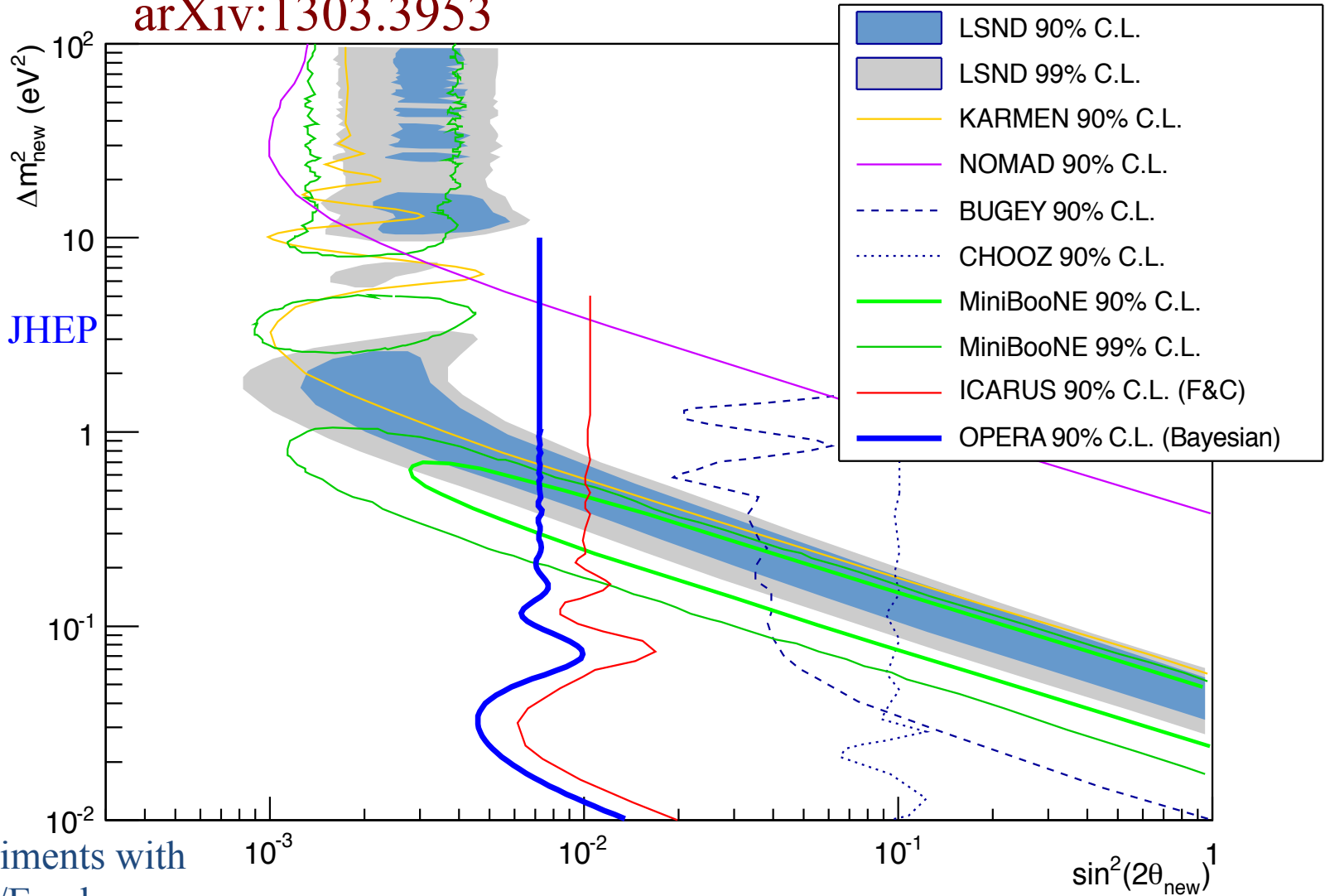
4 observed events

4.6 expected

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

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

arXiv:1303.3953



To appear on JHEP

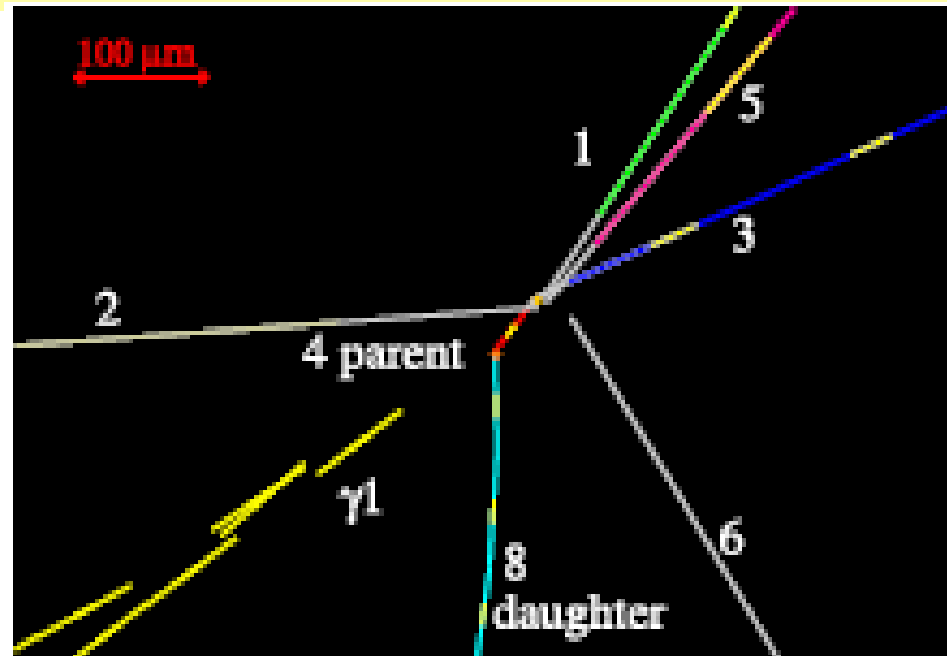
Caveat: experiments with
different L/E values

$\nu_{\mu} \rightarrow \nu_{\tau}$ 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 ν_τ “appearance” candidate (2010)

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



Physics Letters B 691 (2010) 138–145



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Physics Letters B

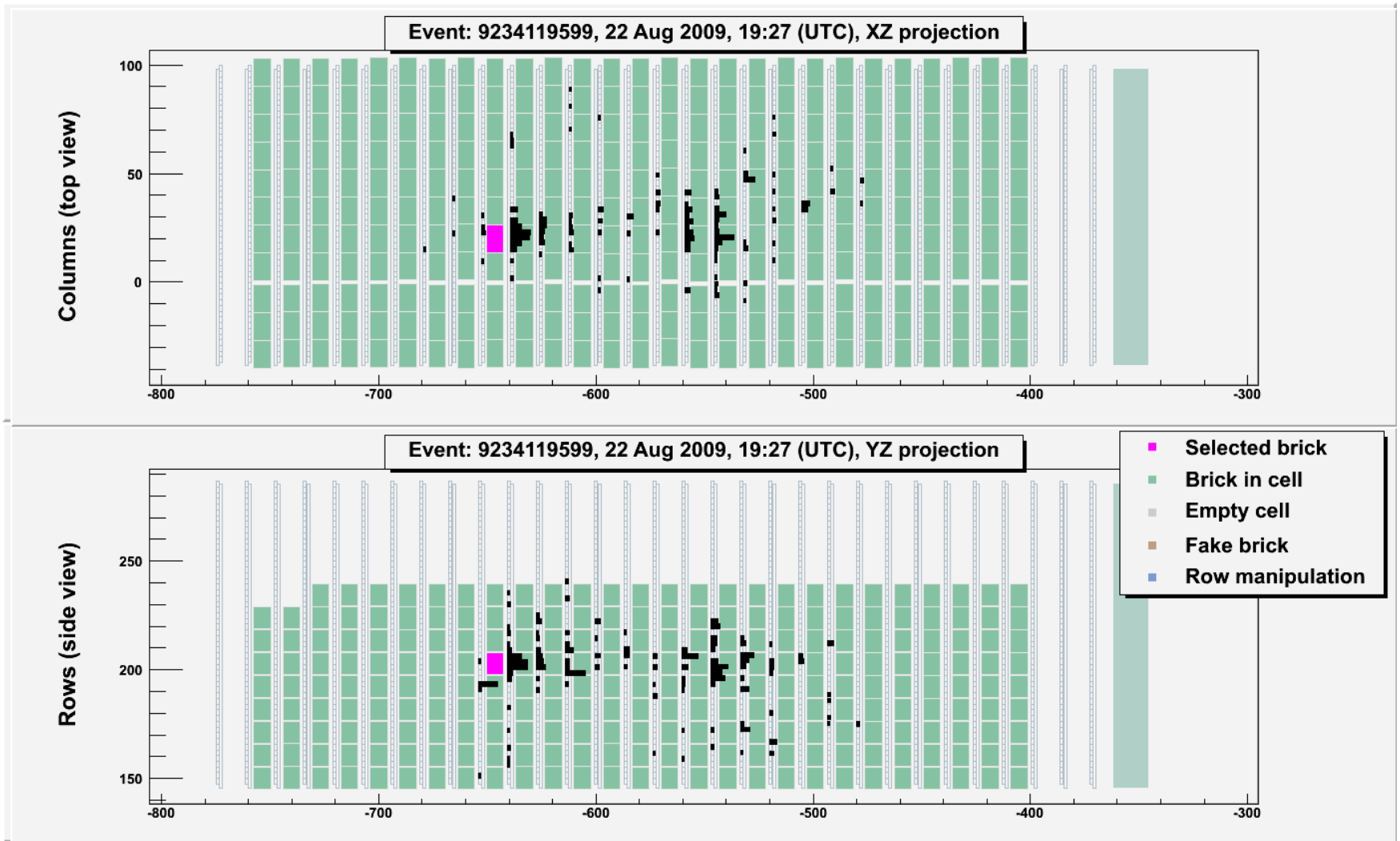
www.elsevier.com/locate/physletb



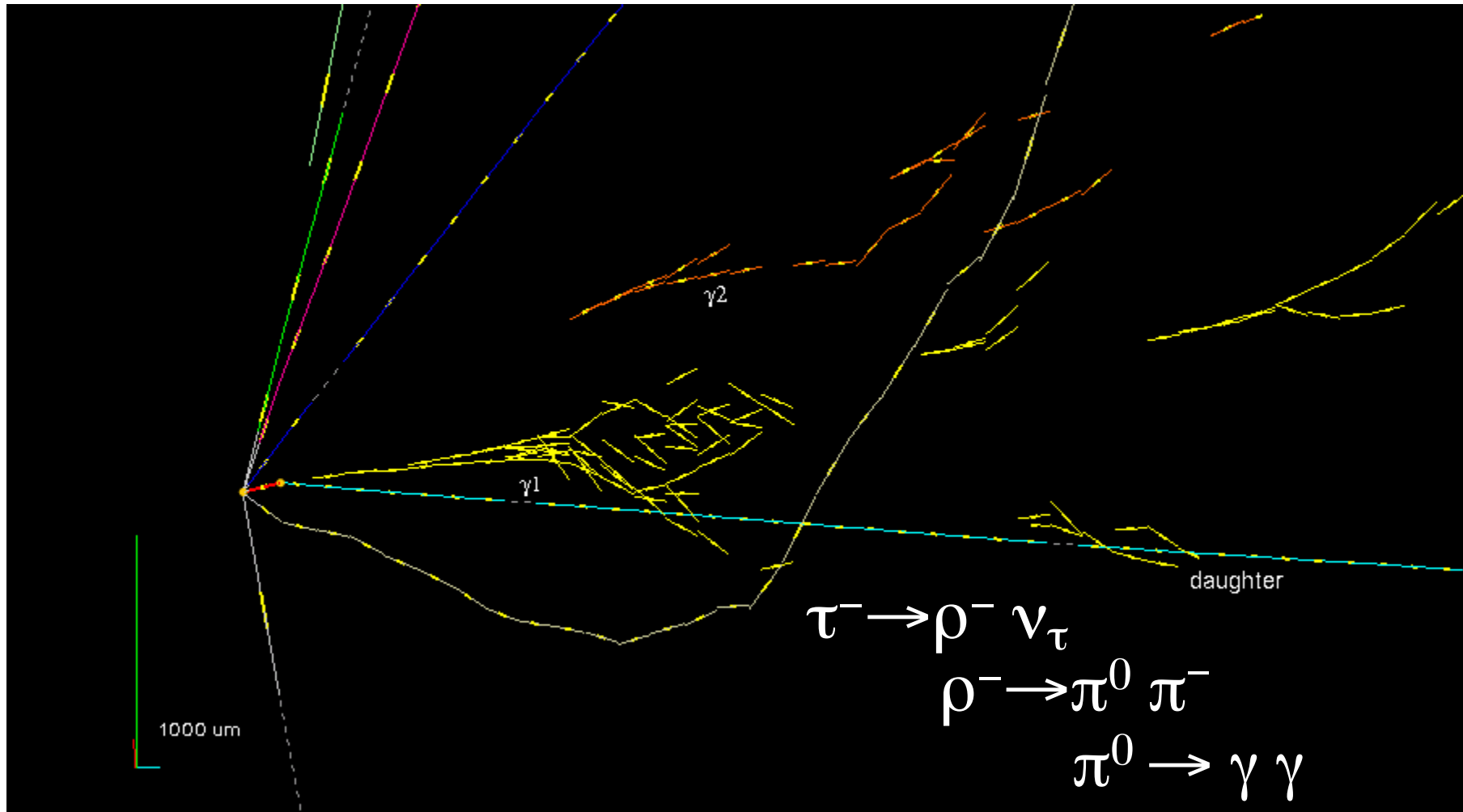
Observation of a first ν_τ candidate event in the OPERA experiment
in the CNGS beam

First tau neutrino candidate event

Muonless event 9234119599, taken on 22nd August 2009 (as seen by the electronic detectors)



Event reconstruction in the brick



PL17

PL18

PL19

PL20

PL21

Primary vertex

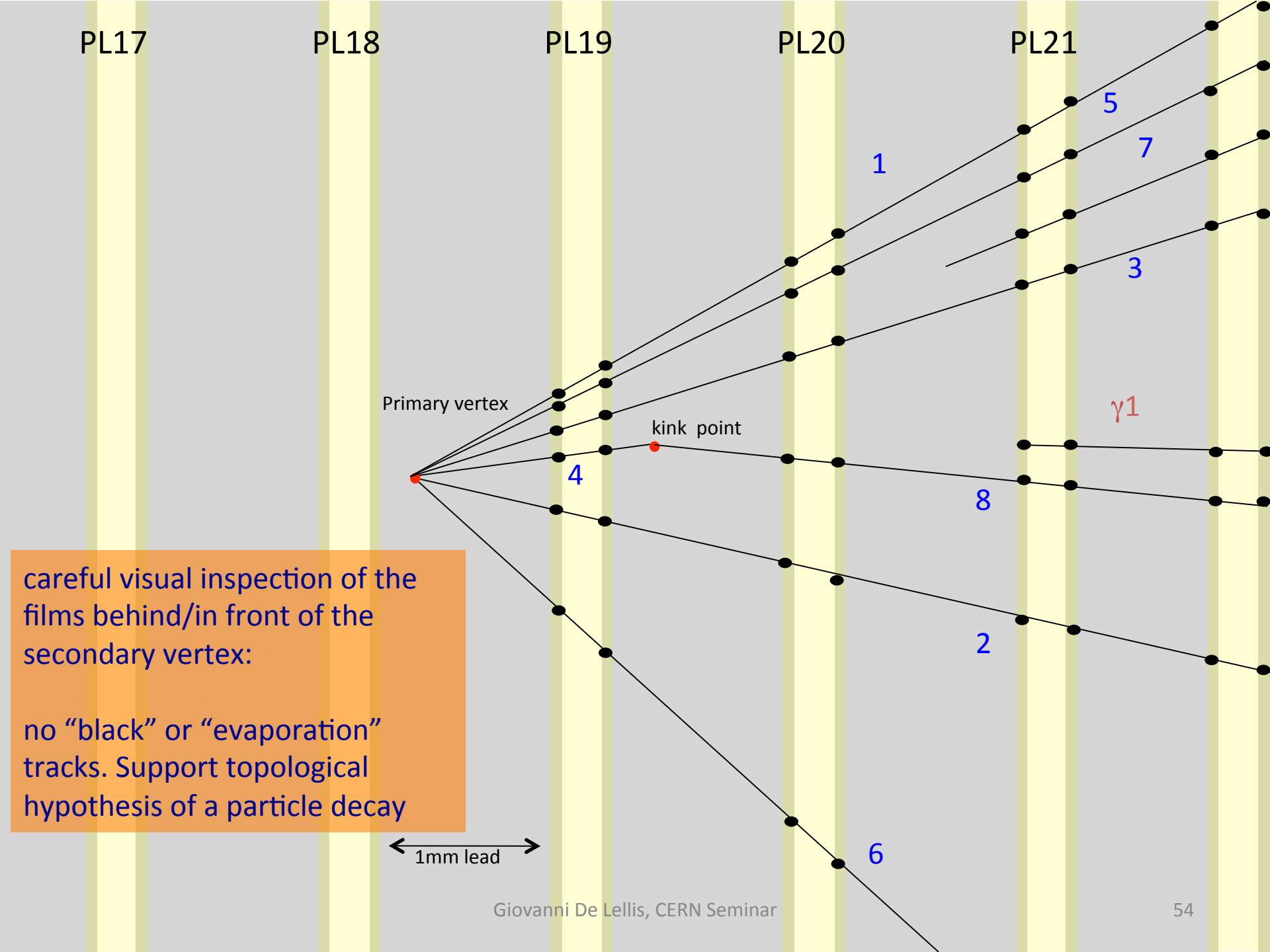
kink point

$\gamma 1$

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

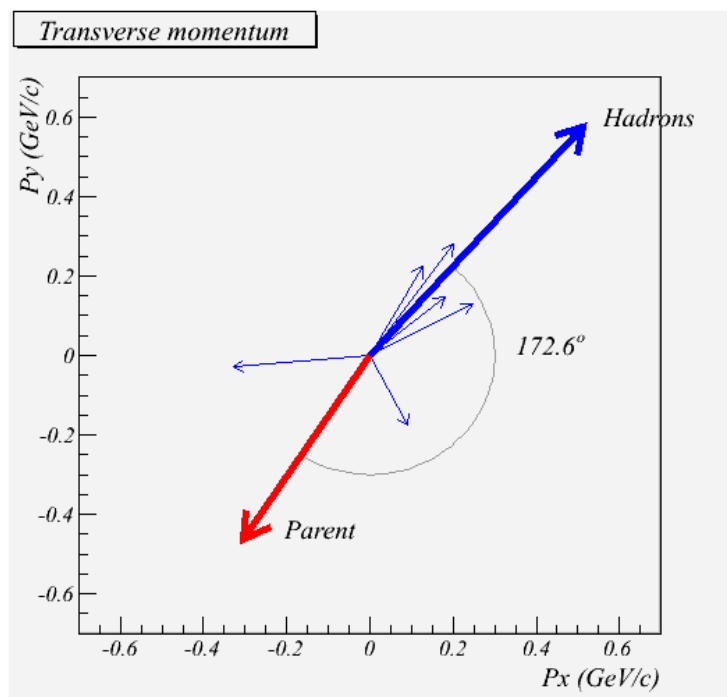
no "black" or "evaporation" tracks. Support topological hypothesis of a particle decay

← 1mm lead →



Kinematical variables

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

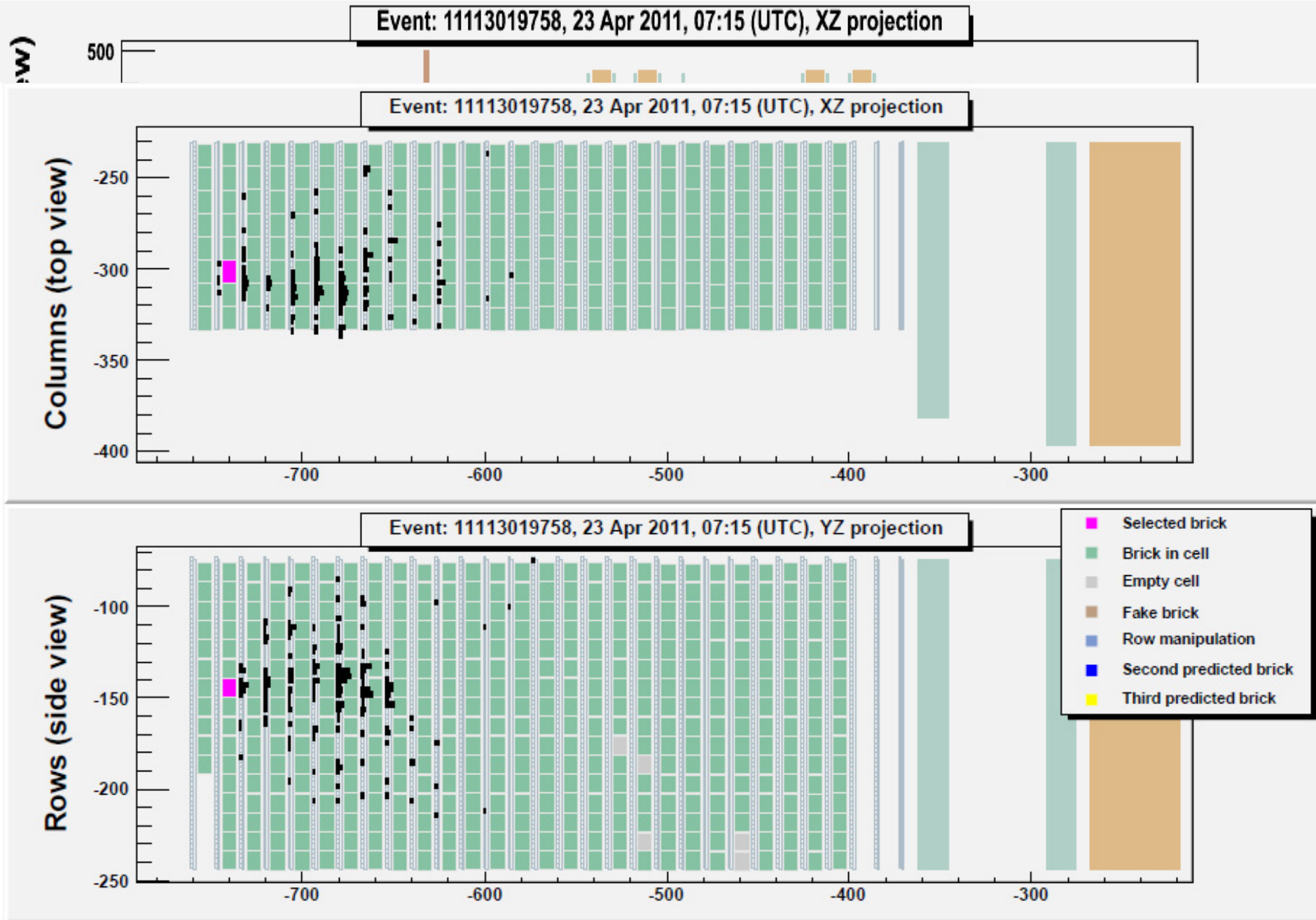


VARIABLE	AVERAGE
kink (mrad)	41 ± 2
decay length (μm)	1335 ± 35
P daughter (GeV/c)	12^{+6}_{-3}
Pt (MeV/c)	470^{+240}_{-120}
missing Pt (MeV/c)	570^{+320}_{-170}
ϕ (deg)	173 ± 2

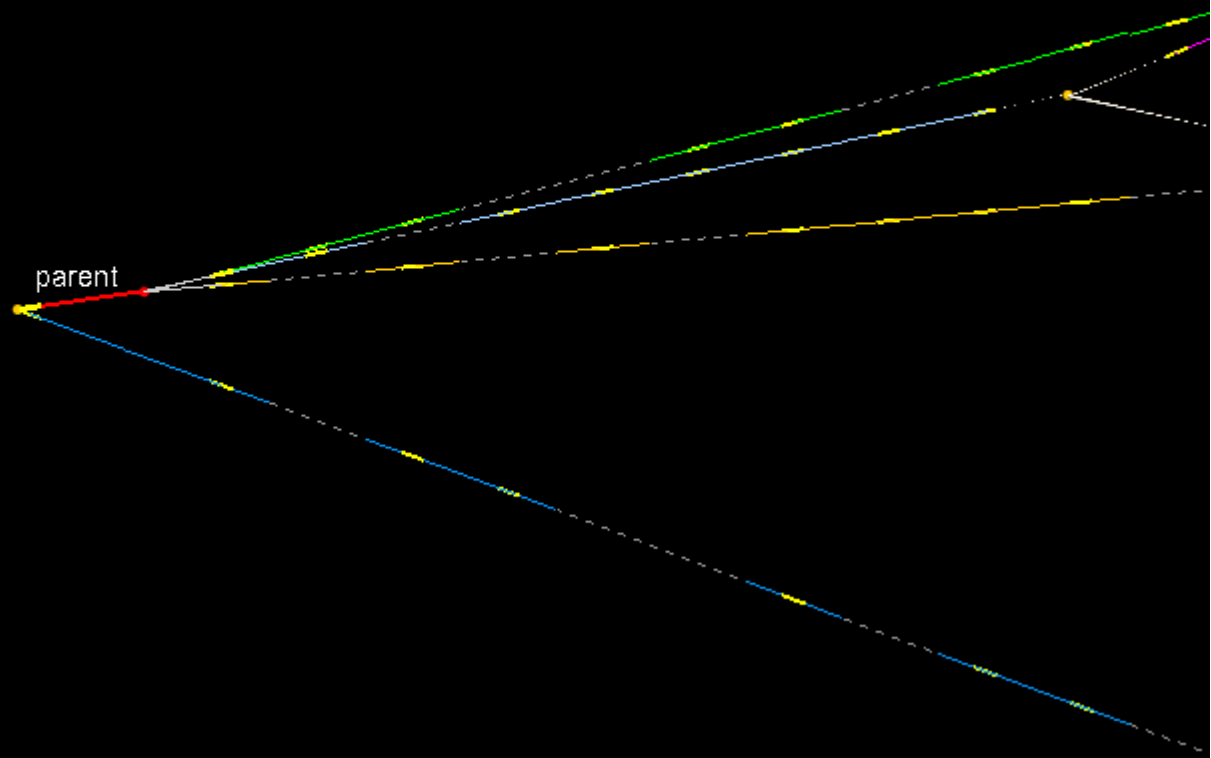
Strategy for the 2010÷2012 runs

- Apply kinematical selection
- 15 GeV μ 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 0μ events (events without any μ in the final state)
- In view of 2012 Summer conferences: 0μ and 1μ sample for 2010 run, for 2011 run stick to 0μ sample only, 2012 not yet analysed

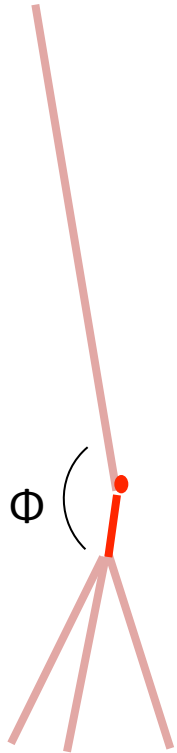
Second neutrino tau candidate event taken on 23rd April 2011



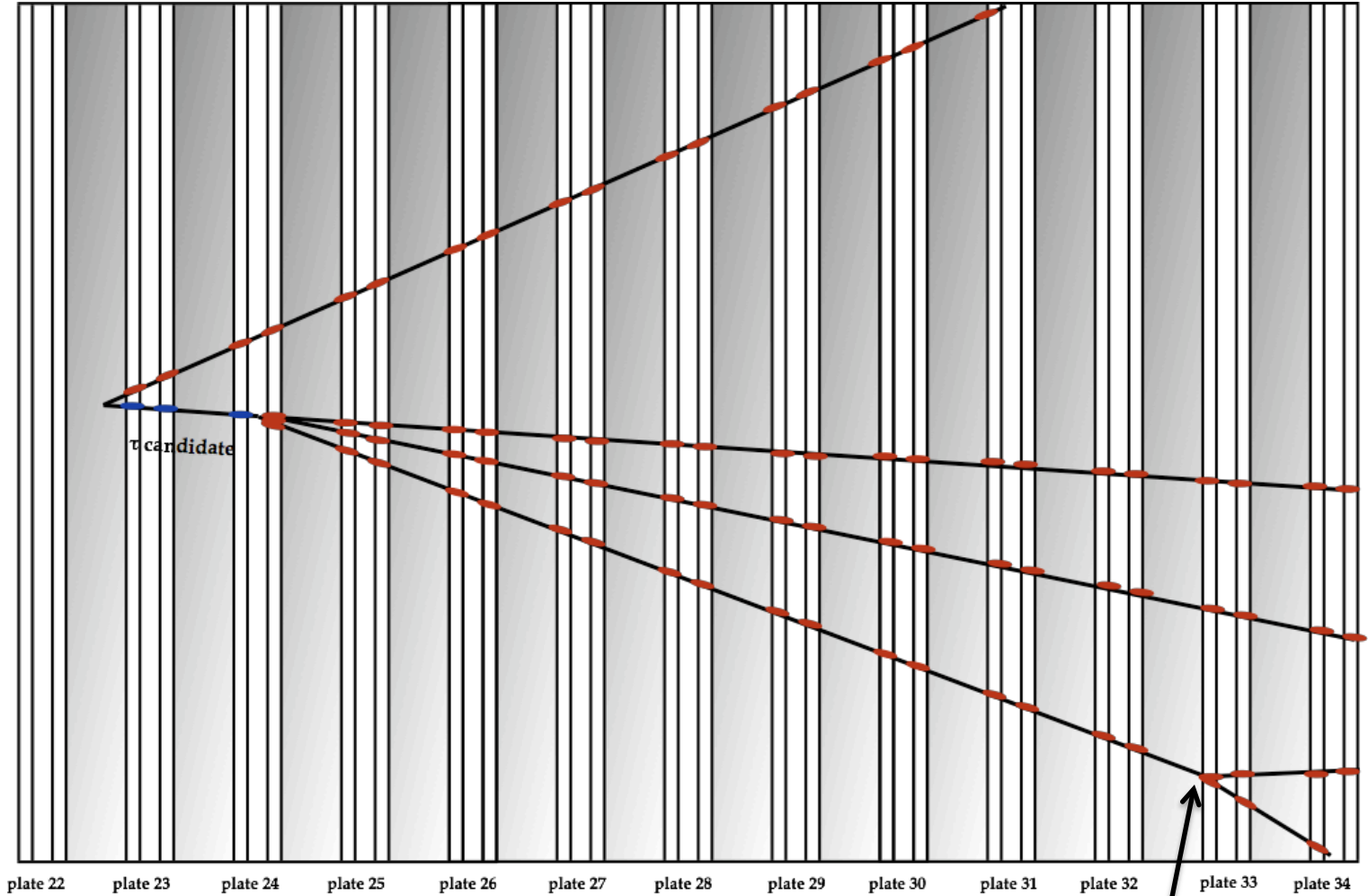
Second ν_τ Candidate Event



Schematics of the event

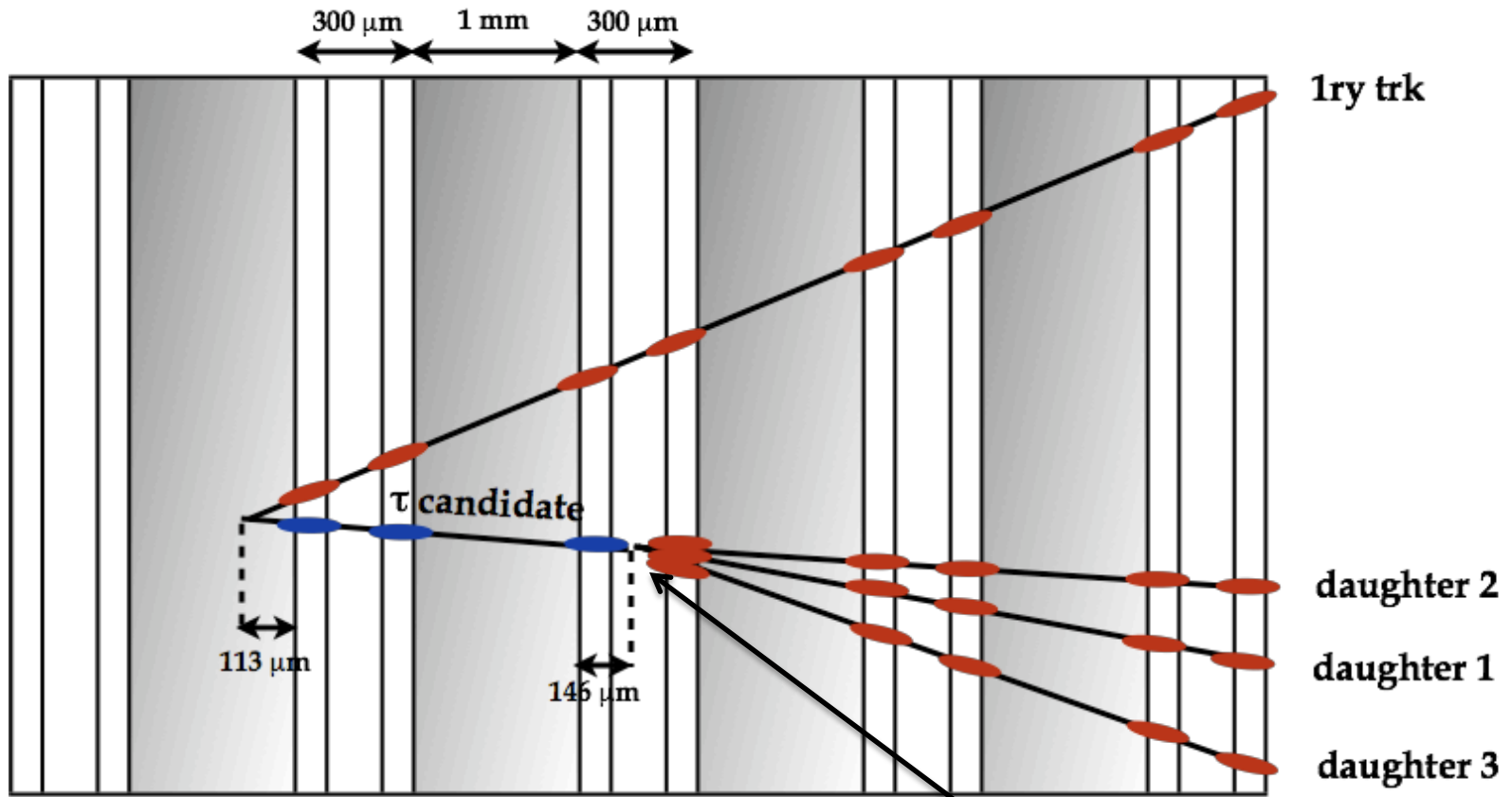


Beam View
 $\Phi=167^\circ$



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

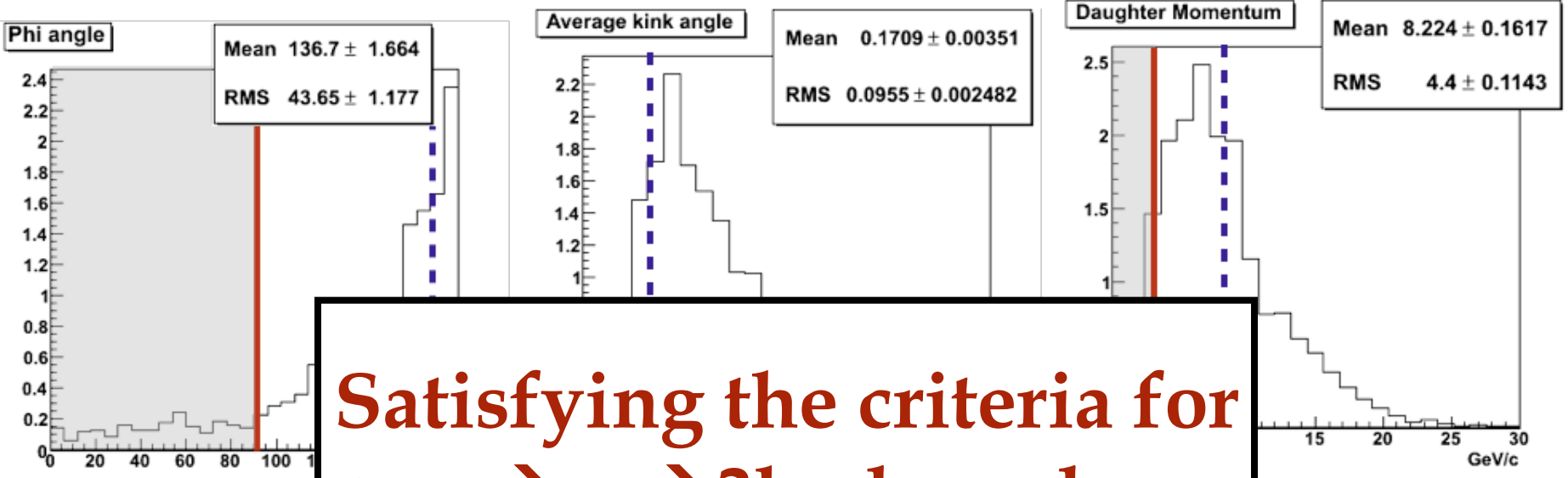
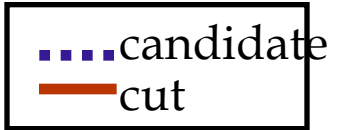
Track#	Momentum (1σ interval) [GeV/c]	Particle ID	Method / Comments
Primary	2.8 (2.1-3.5)	Hadron	<ul style="list-style-type: none"> • Momentum-Range Consistency Check Stops after 2 brick walls. Incompatible with muon (26÷44 brick walls)
d1	6.6 (5.2 - 8.6)	Hadron	<ul style="list-style-type: none"> • Momentum-Range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

Independent momentum measurements carried out in two labs

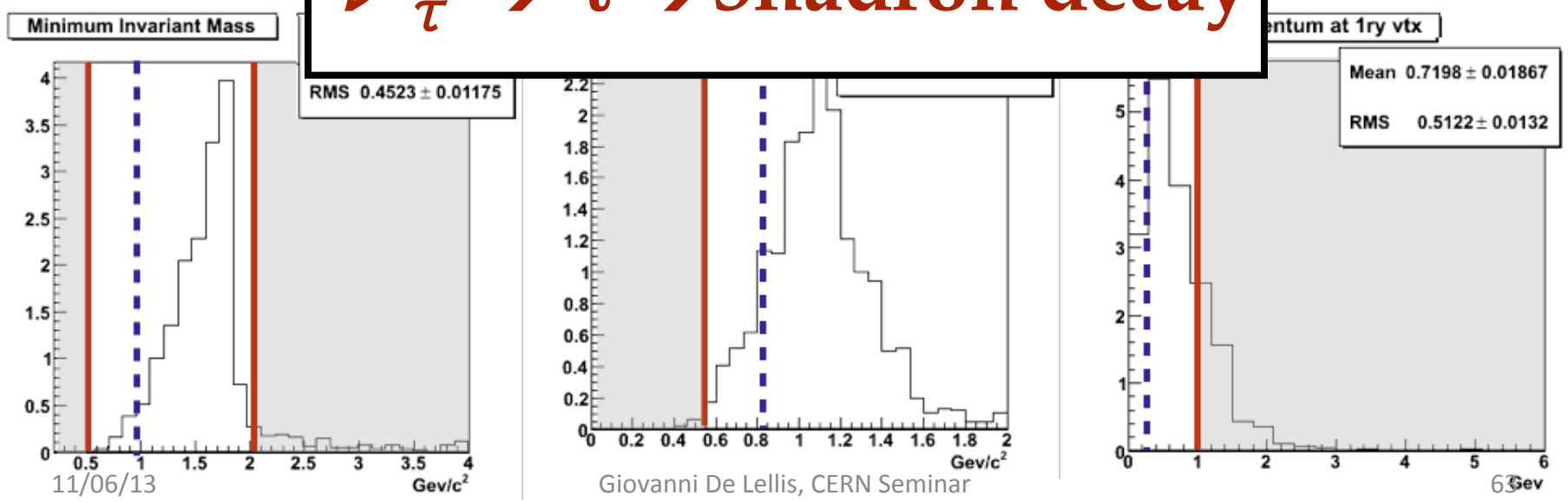
Kinematics of the second Candidate Event

	Cut	Value
ϕ (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/c ²]	0.5 < < 2.0	0.96±0.13
Invariant mass [GeV/c ²]	0.5 < < 2.0	0.80±0.12
Transverse Momentum at 1ry vtx [GeV/c]	< 1.0	0.31±0.11

Kinematics of the second candidate event



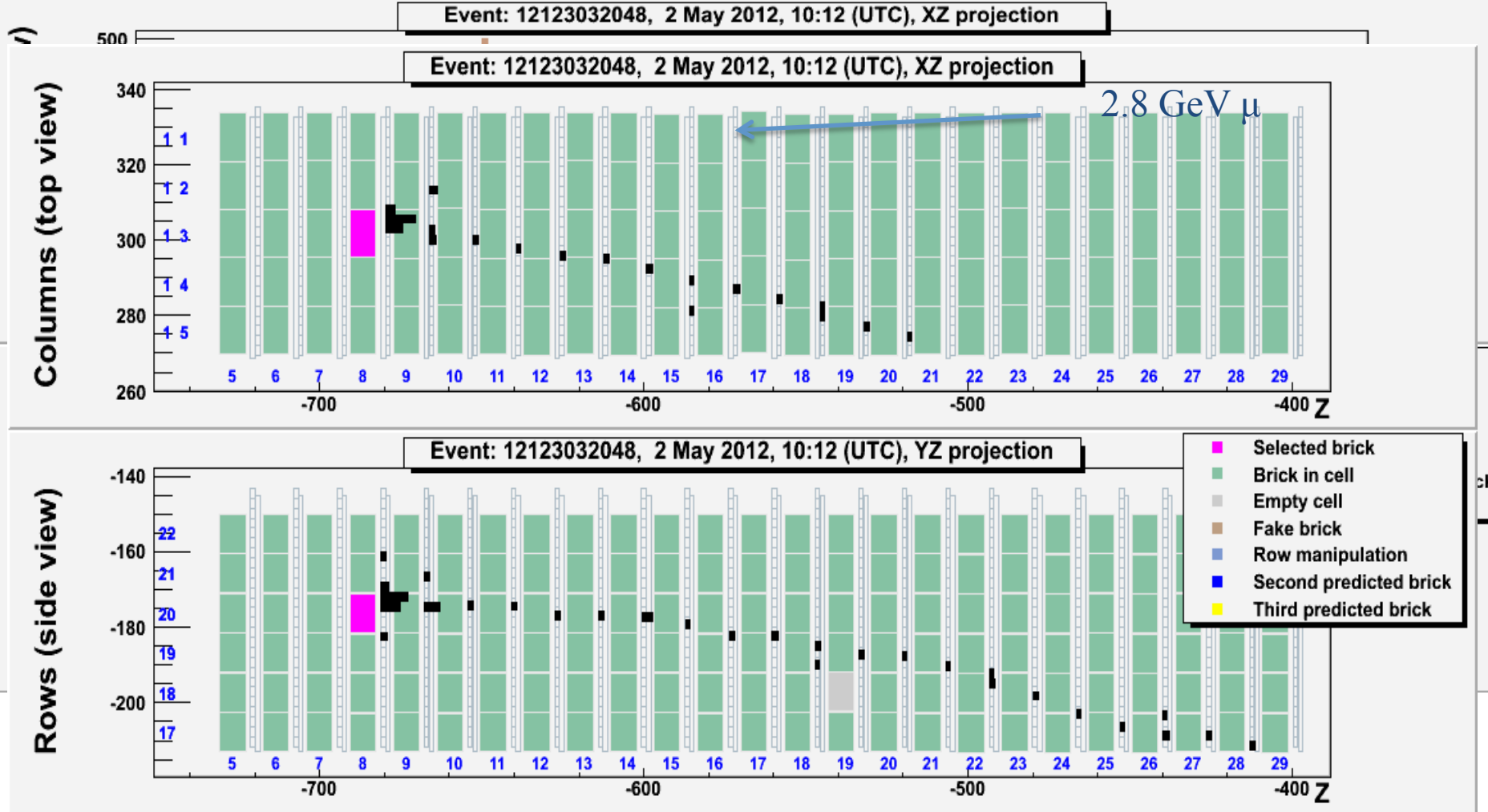
Satisfying the criteria for $\nu_\tau \rightarrow \tau \rightarrow 3\text{hadron decay}$



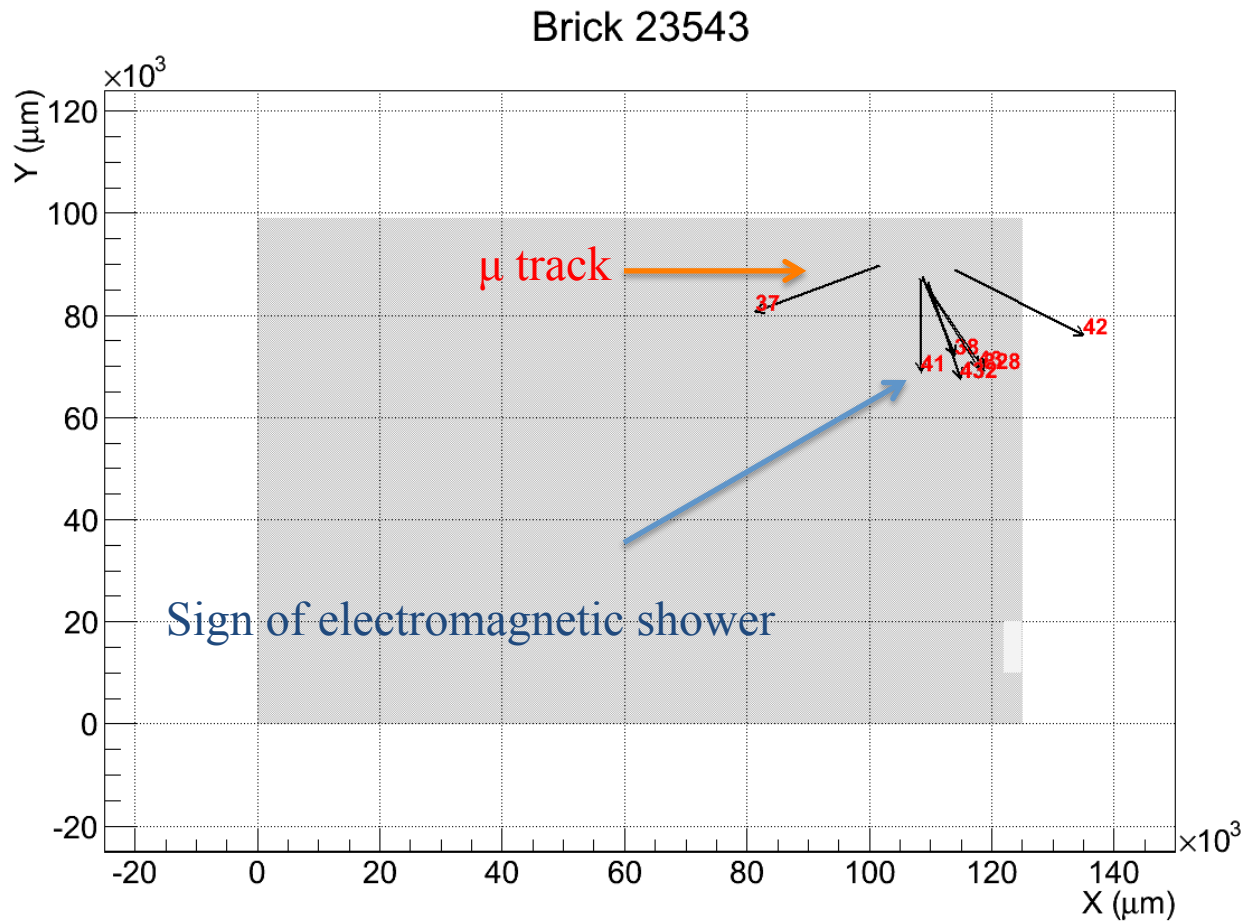
After 2012 Summer conferences

- *Extension of the analysed sample to events with one μ in the final state*

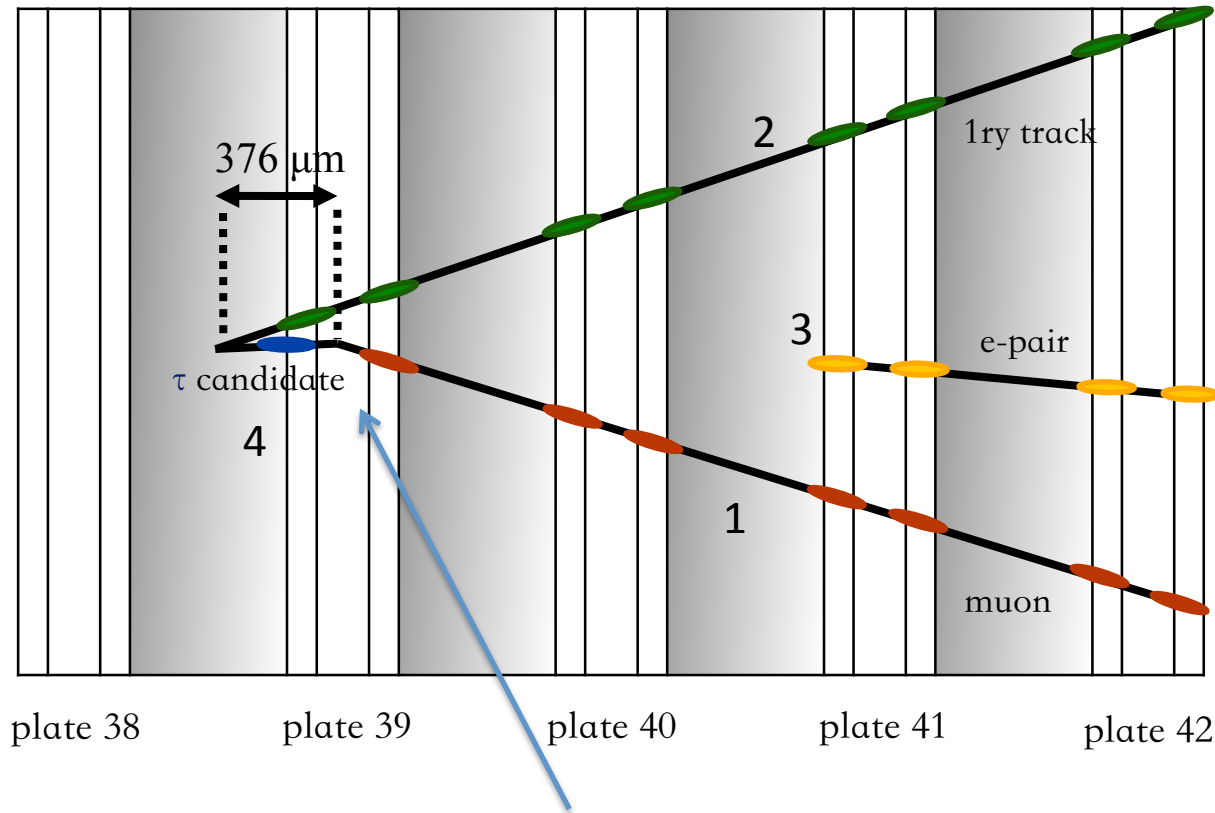
Third tau neutrino event taken on May 2nd 2012



Analysis of the interface films



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



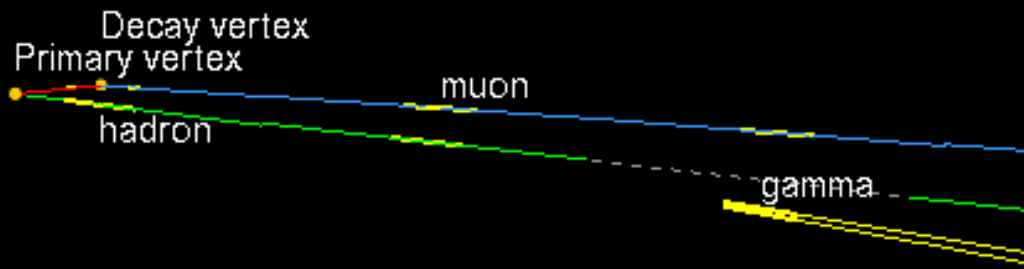
Decay in the plastic base

$\tau \rightarrow \mu$ candidate

μm

Third tau neutrino event

$$\tau \rightarrow \mu$$



1000 μm

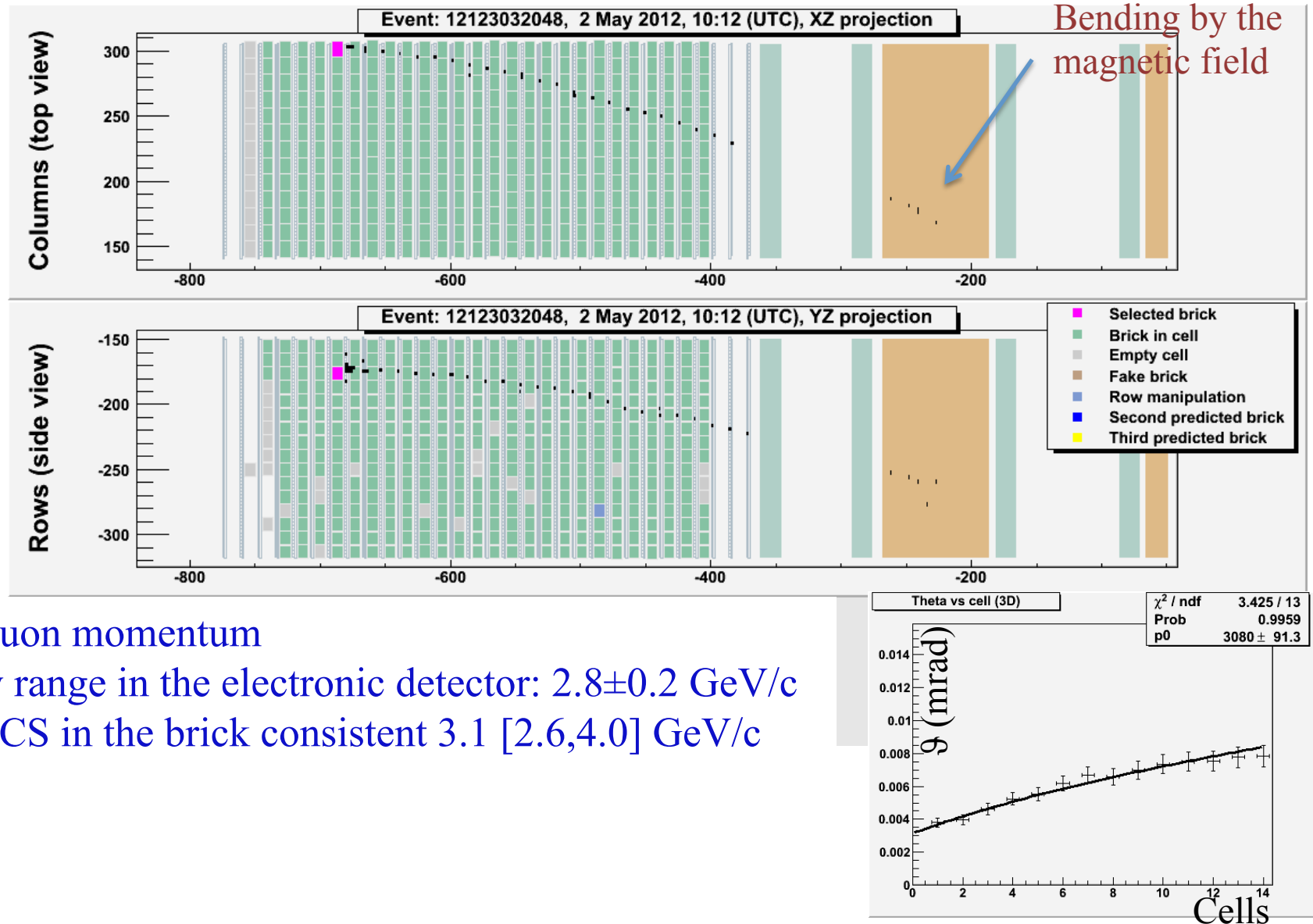
Event tracks' features

TRACK NUMBER	PID	MEASUREMENT 1			MEASUREMENT 2		
		Θ_X	Θ_Y	P (GeV/c)	Θ_X	Θ_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	

γ attachment

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

Muon charge and momentum reconstruction



Muon momentum

by range in the electronic detector: 2.8 ± 0.2 GeV/c

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

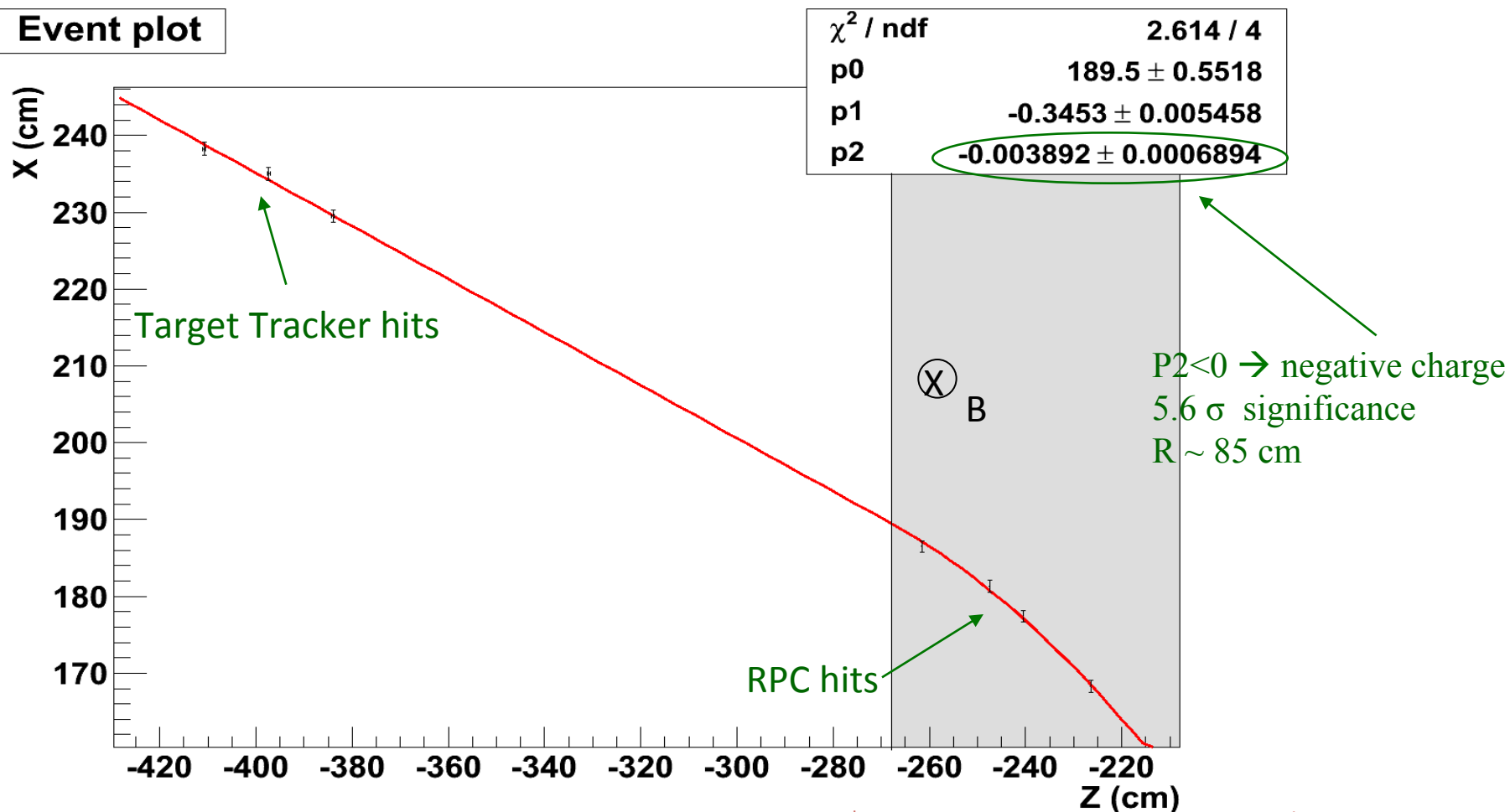
Charge determination of the muon

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

Fit function:

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

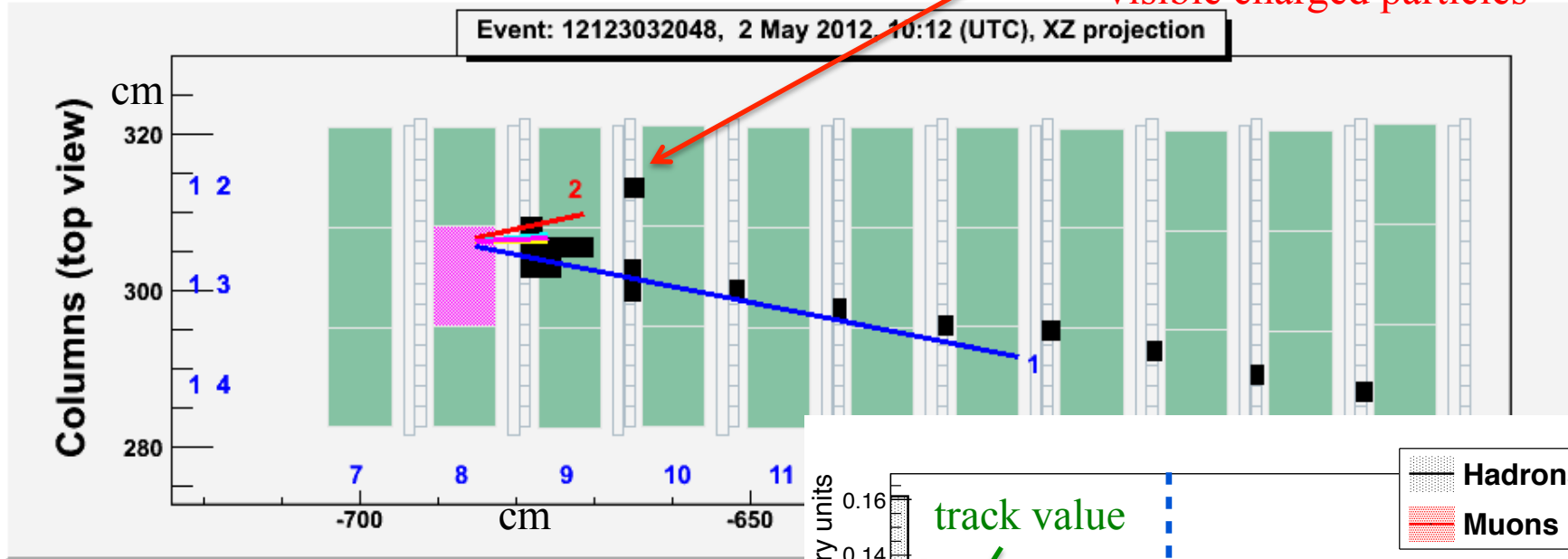
Event plot



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

Track follow down to assess the nature of track 2

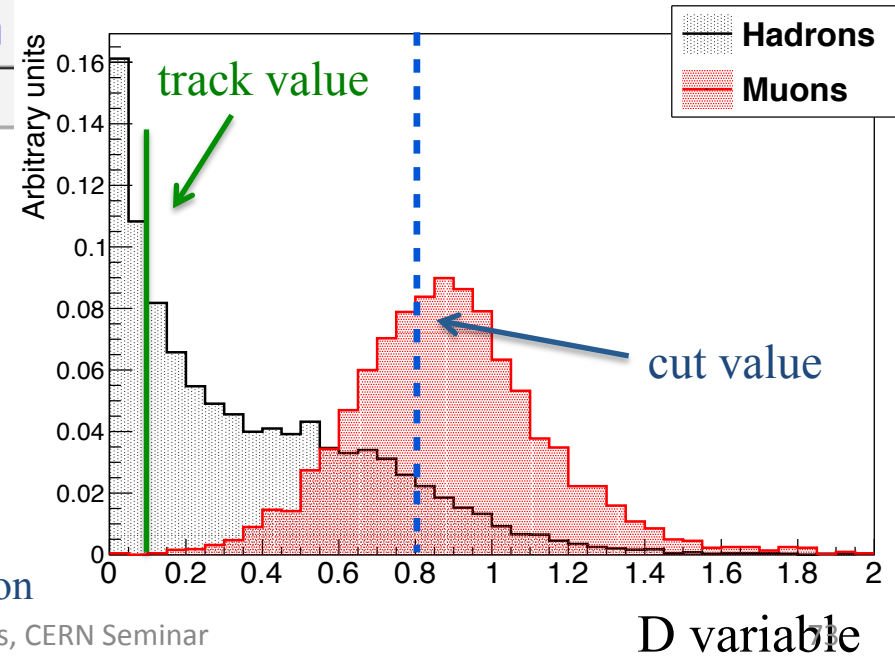
Track 2 interacting in the downstream brick without visible charged particles



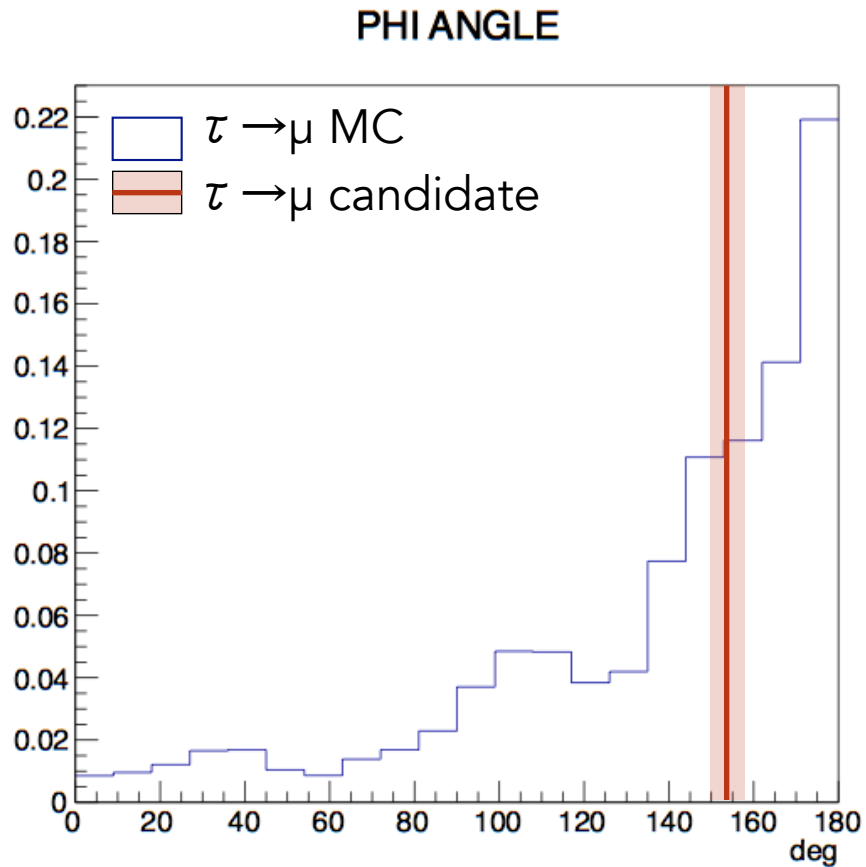
Momentum/range inconsistent with μ hypothesis
0.9 GeV/4 cm Lead

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

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

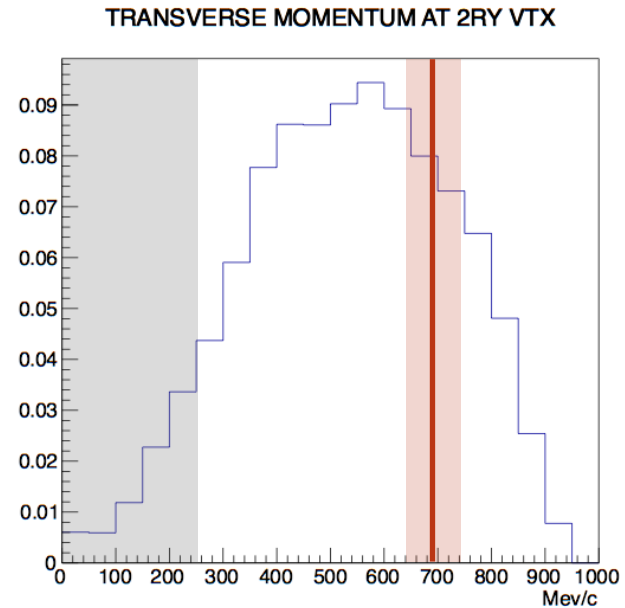
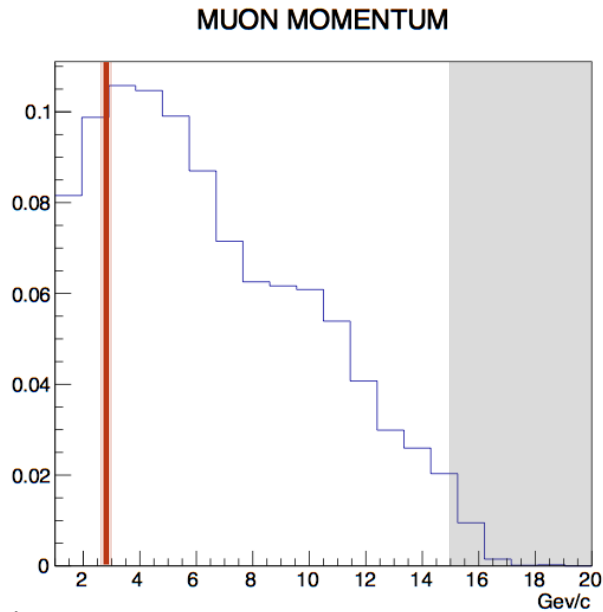
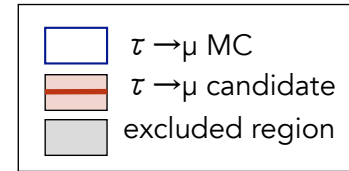
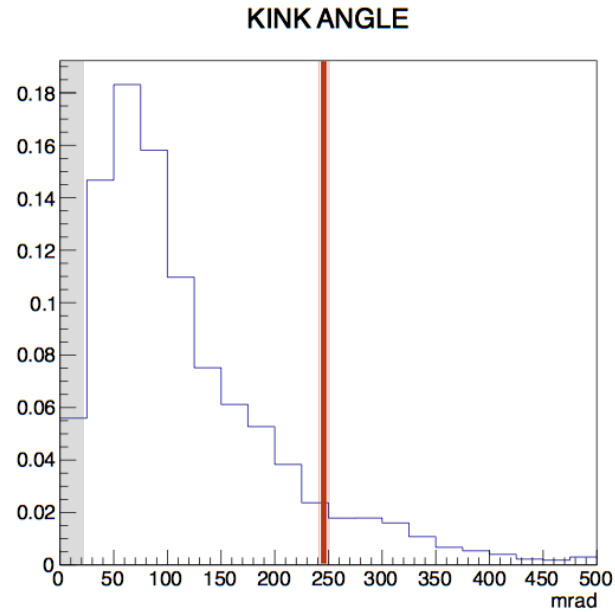
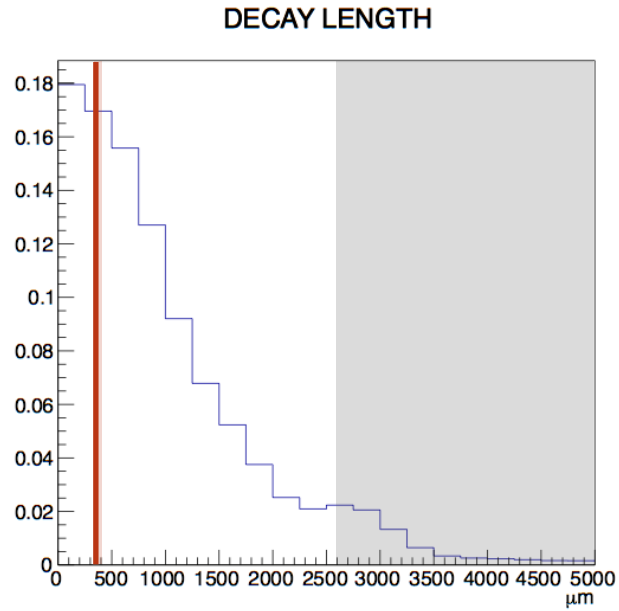


Kinematical variables



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

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



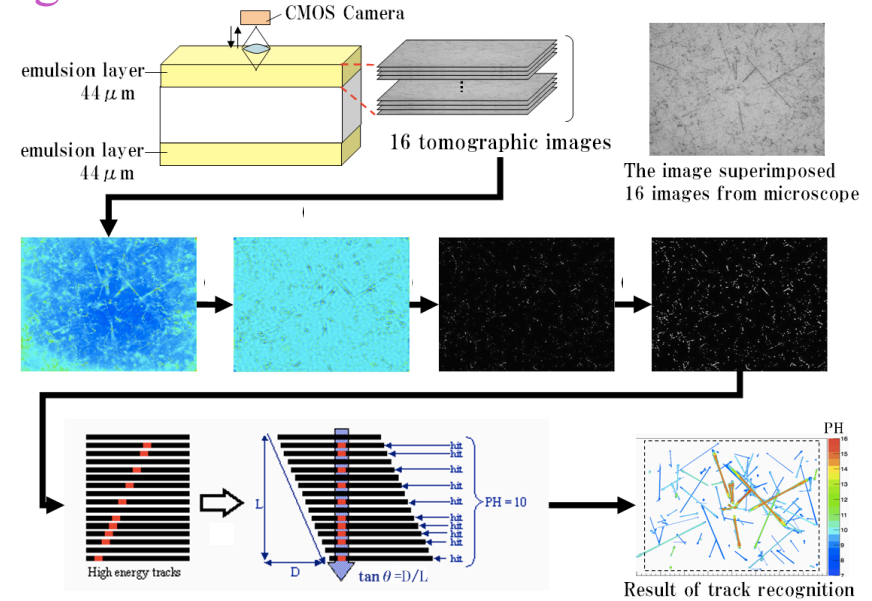
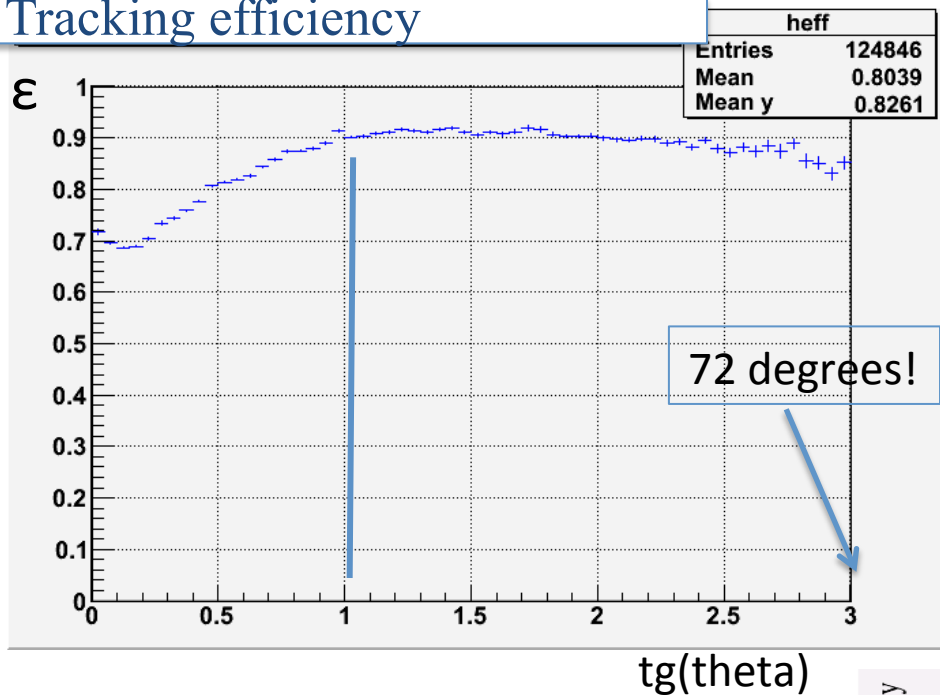
Background studies

Improvements on the background rejection: large angle track detection

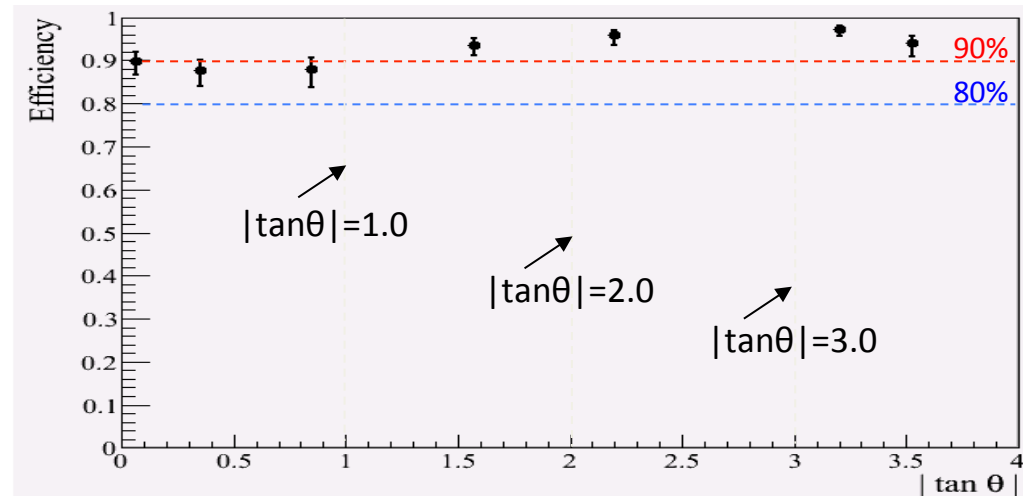
Undetected soft and large angle muons are the source of charm background

Detection of particles and nuclear fragments in hadronic interactions

Tracking efficiency



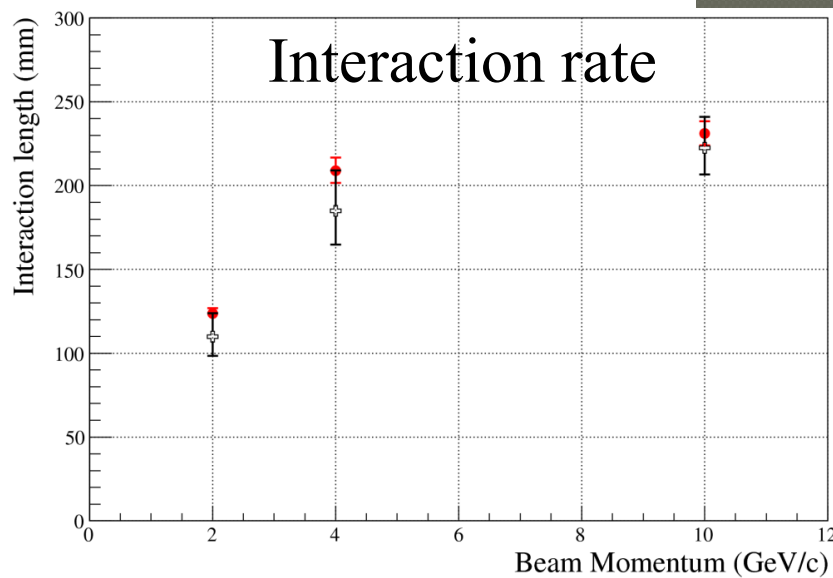
Two different approaches get comparable results



Background studies: hadronic interactions

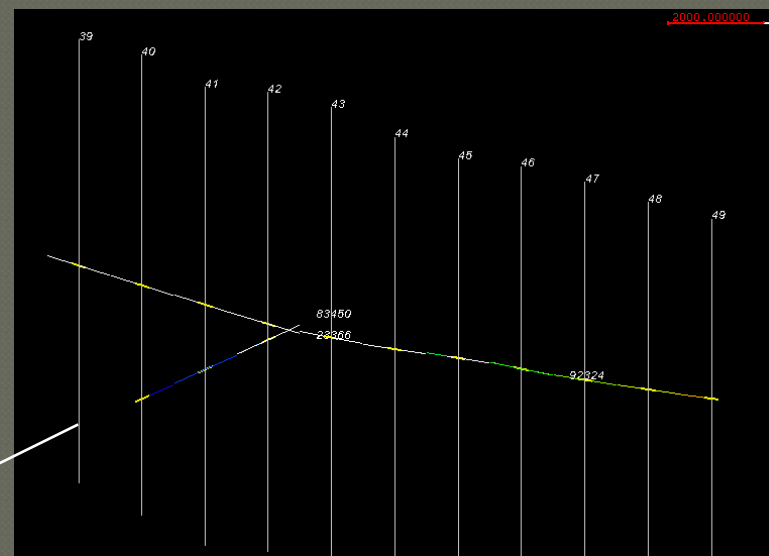
Comparison of large data sample (π^- beam test at CERN) with Fluka simulation: check the agreement and estimate the systematic error of simulation

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 : π^- beam data

Red : MC (FLUKA) simulation

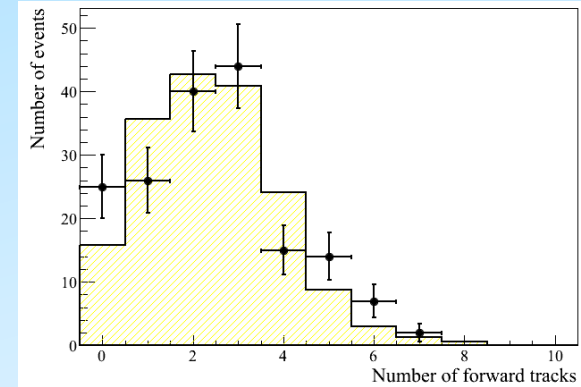
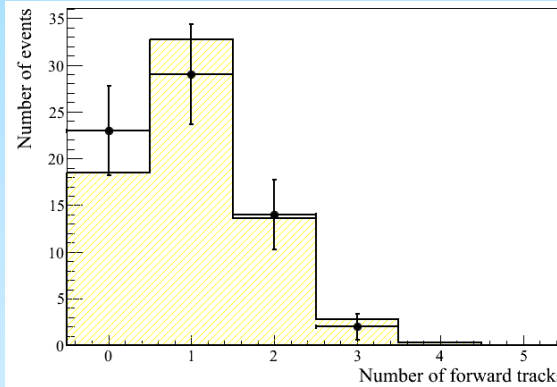
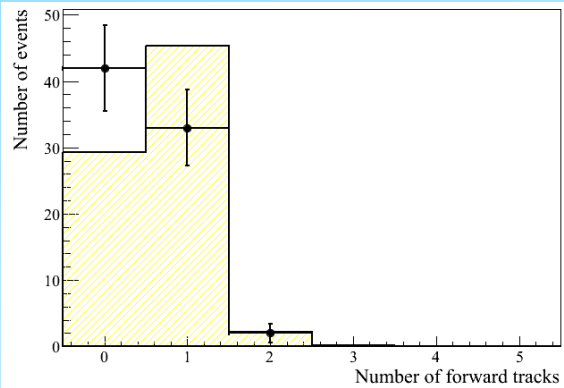
Secondary track emission

2GeV/c

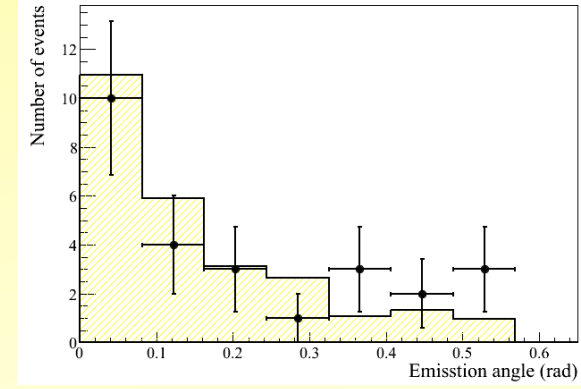
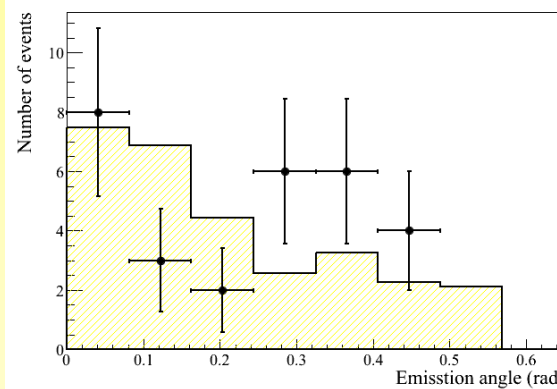
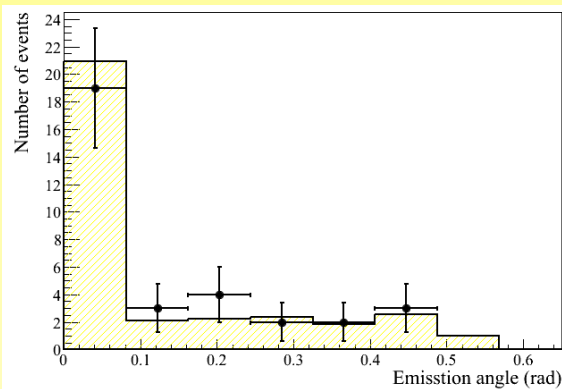
4GeV/c

10GeV/c

Multiplicity



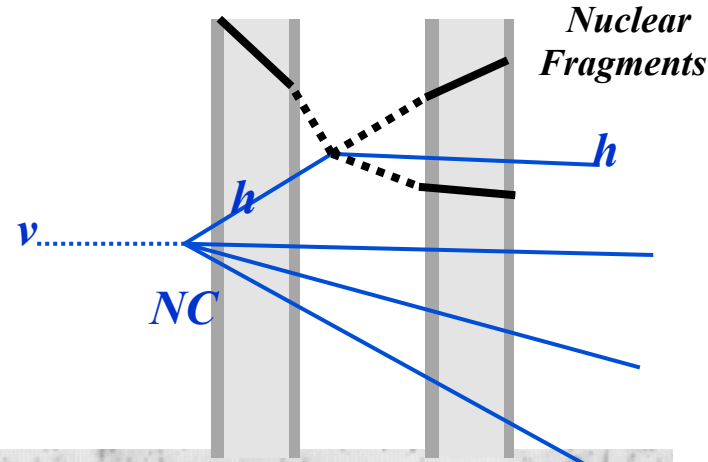
Kink angle (1-prong)



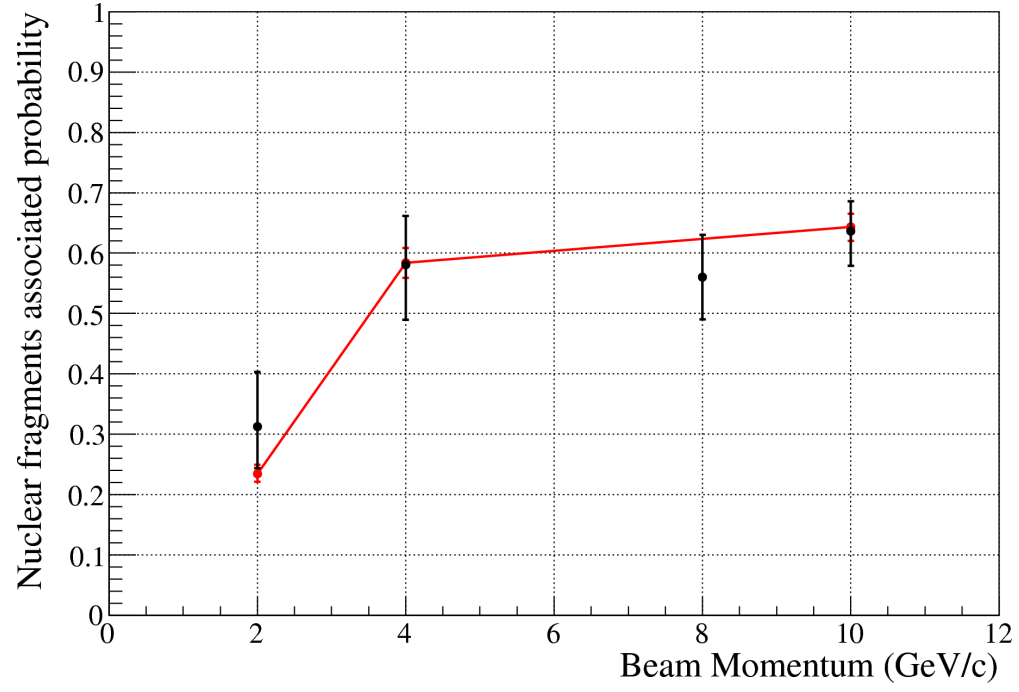
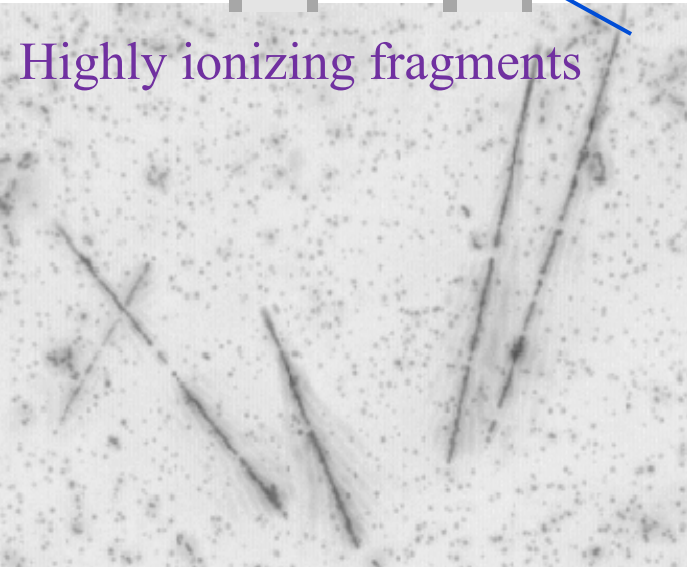
Error bars : Experimental data
Histogram : Simulated data

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

Nuclear fragments emission probability



Highly ionizing fragments



Black : experimental data
Red : simulated data ($\beta = p/E = 0.7$)

It provides additional background reduction.

Nuclear fragments in 1 and 3 prong interactions

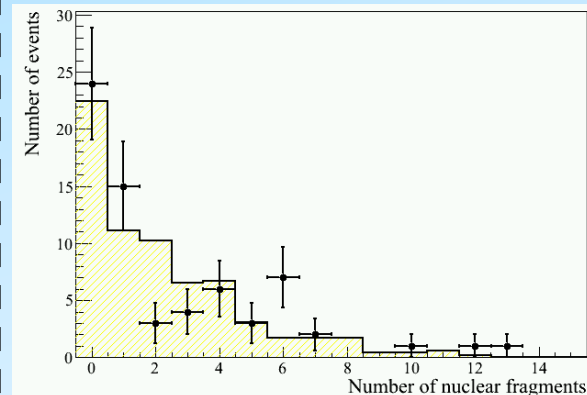
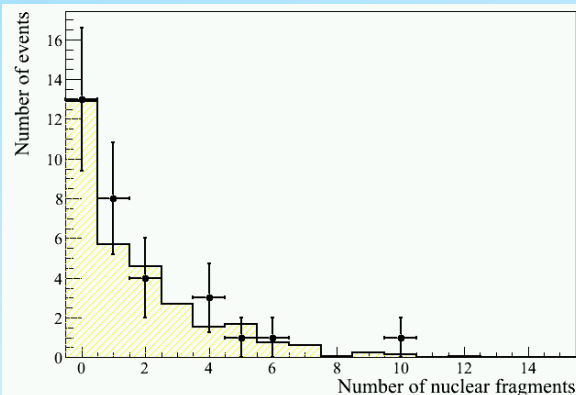
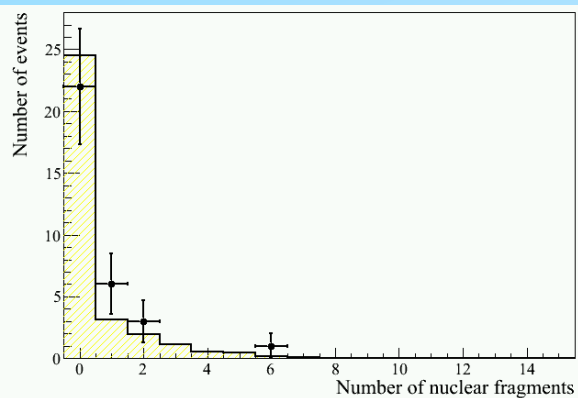
2GeV/c

4GeV/c

10GeV/c

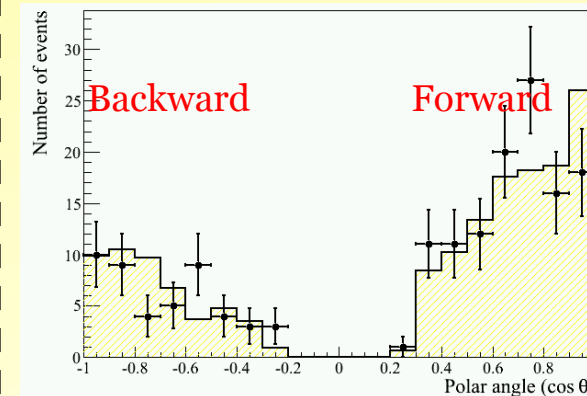
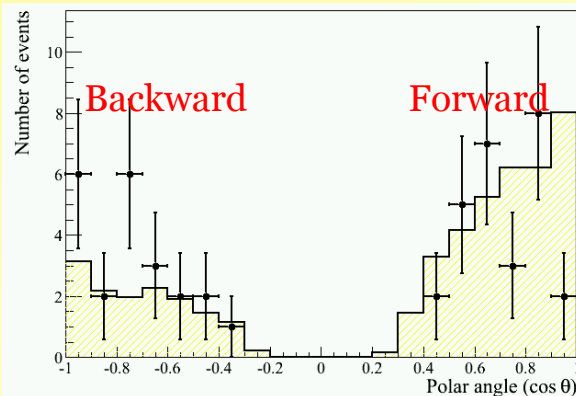
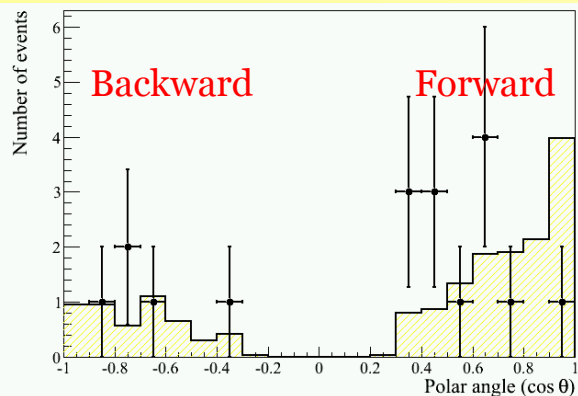
Multiplicity

MC: $\beta < 0.7$



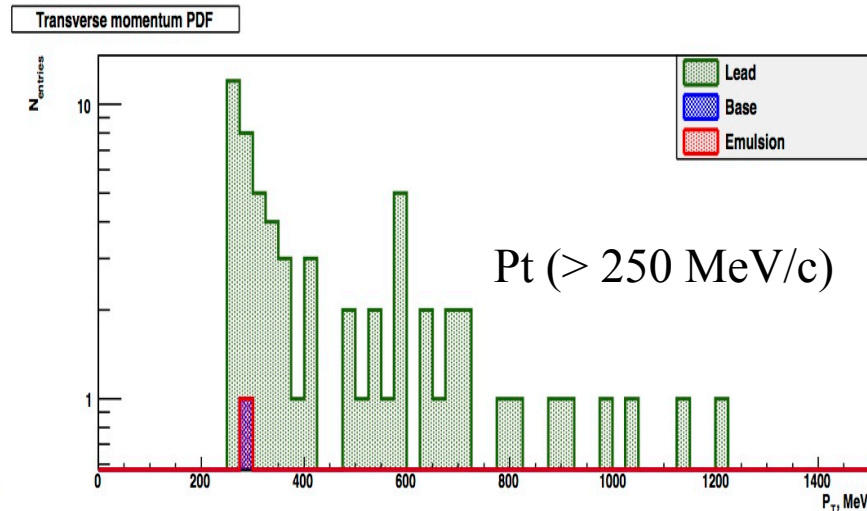
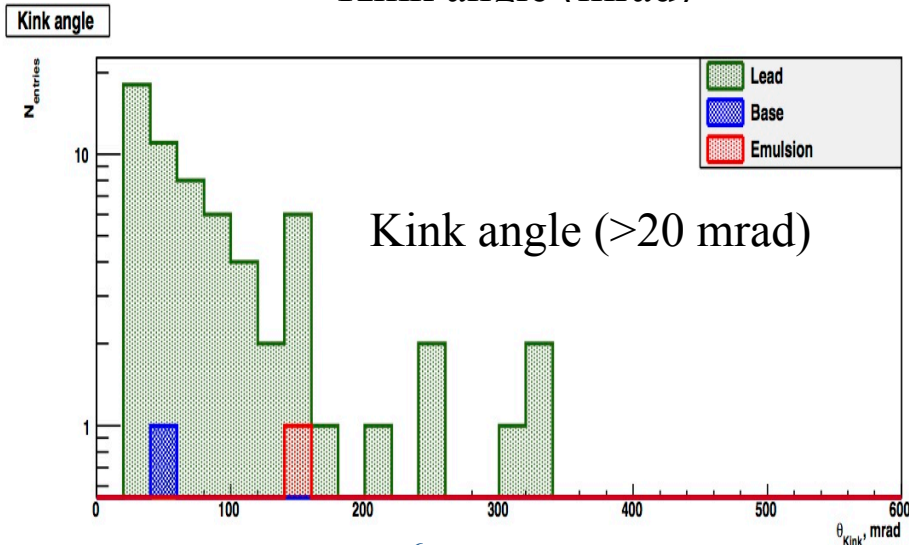
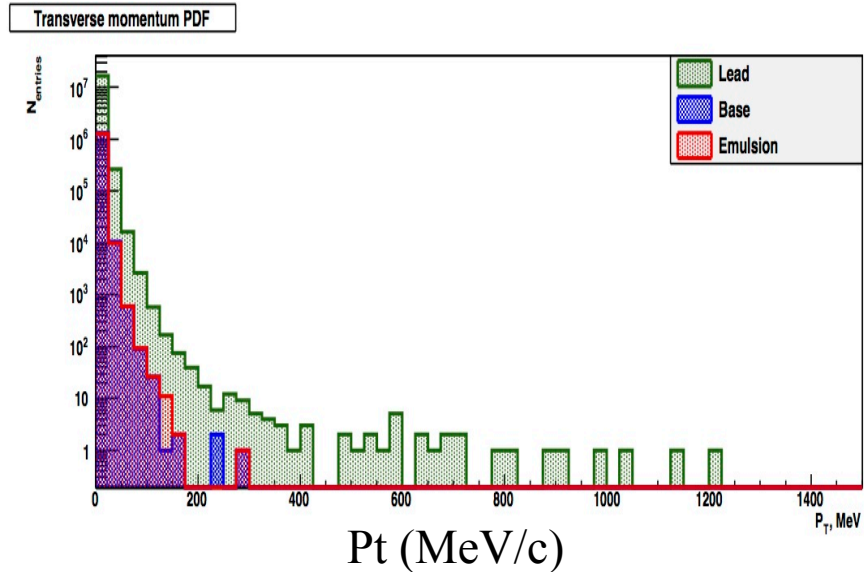
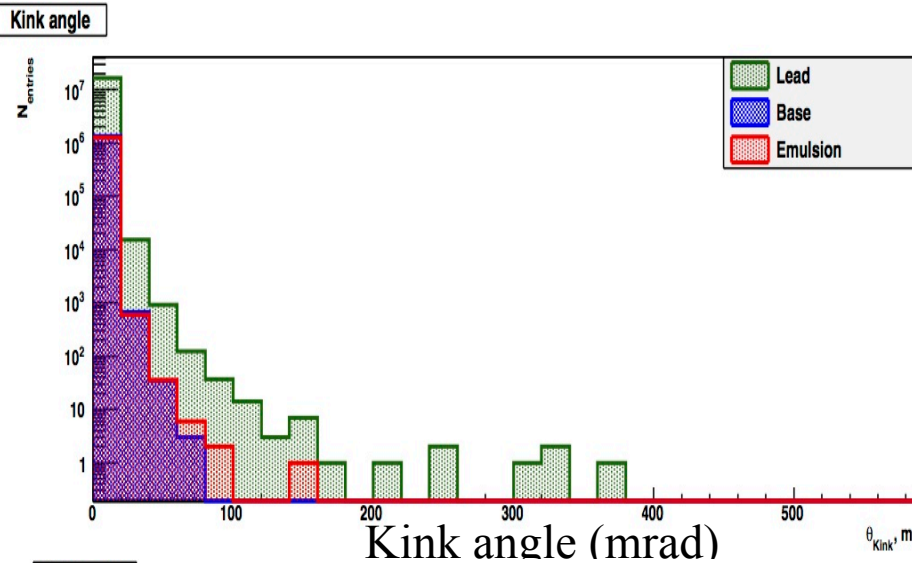
Emission angle($\cos \theta$)

Error bars : experiment
Histogram : simulation



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

Large angle muon scattering



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	μ 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

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

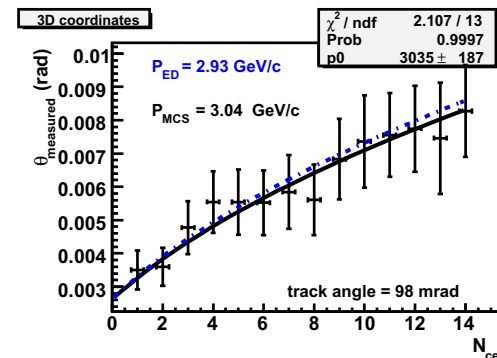
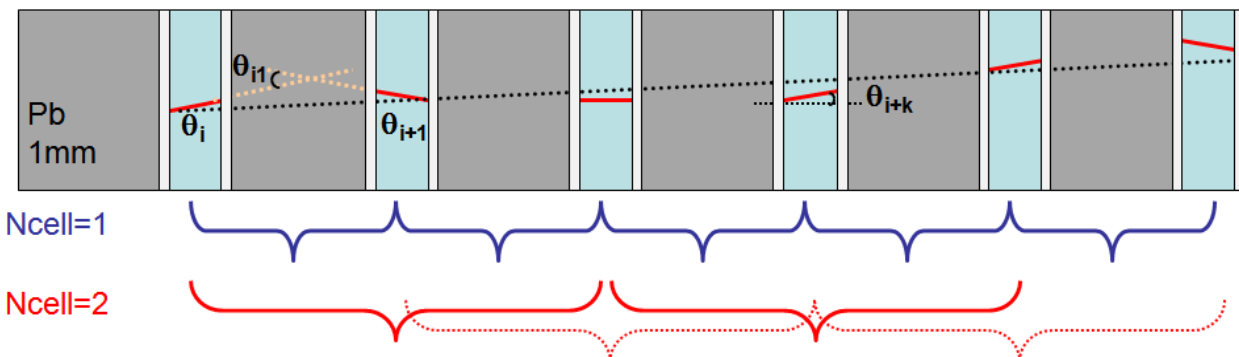
Probability to be explained by background = 7.29×10^{-4}

This corresponds to 3.2σ significance of non-null observation

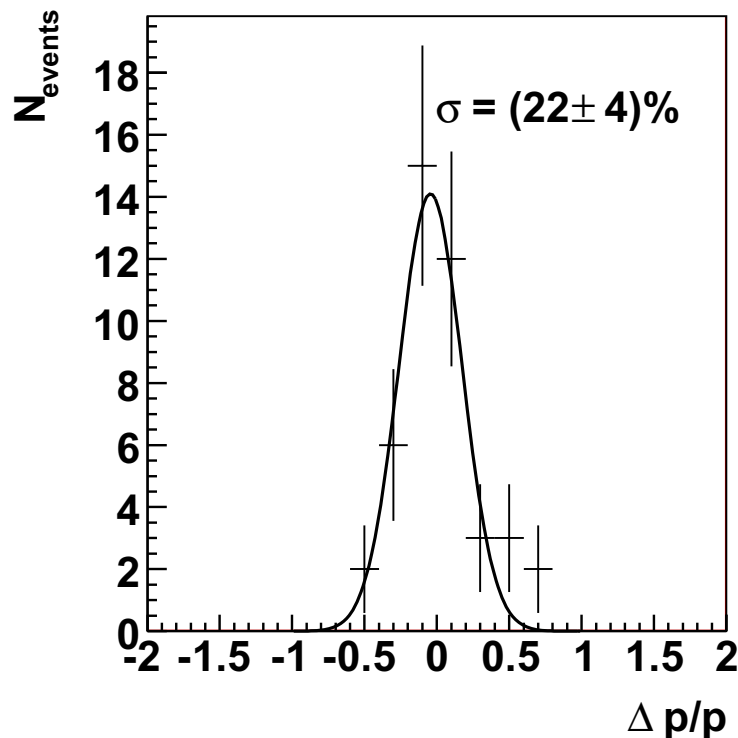
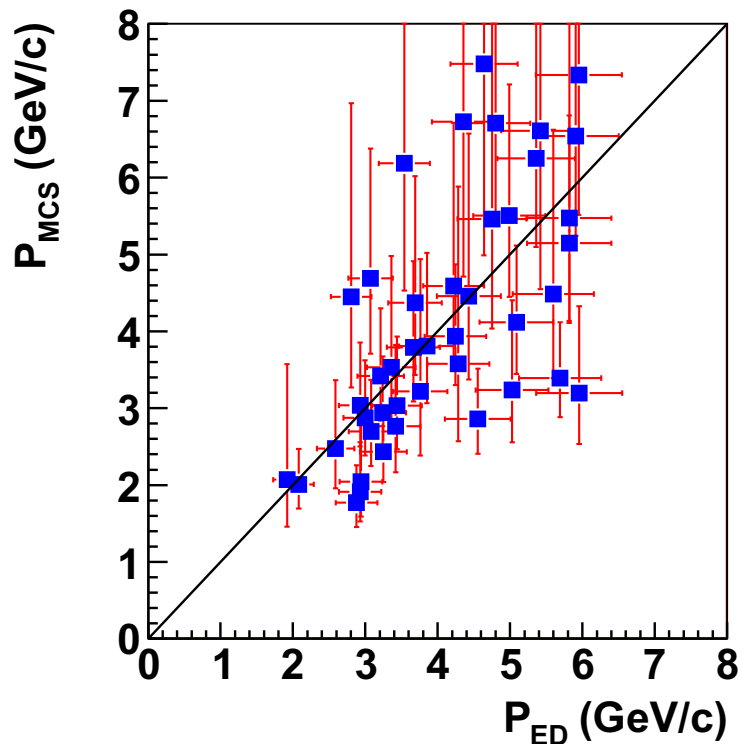
*Exploit kinematical characteristics
of the events: likelihood analysis*

*Data/MC agreement for relevant
variables*

Momentum measurement by multiple Coulomb scattering for identified μ in the 2-6 GeV range

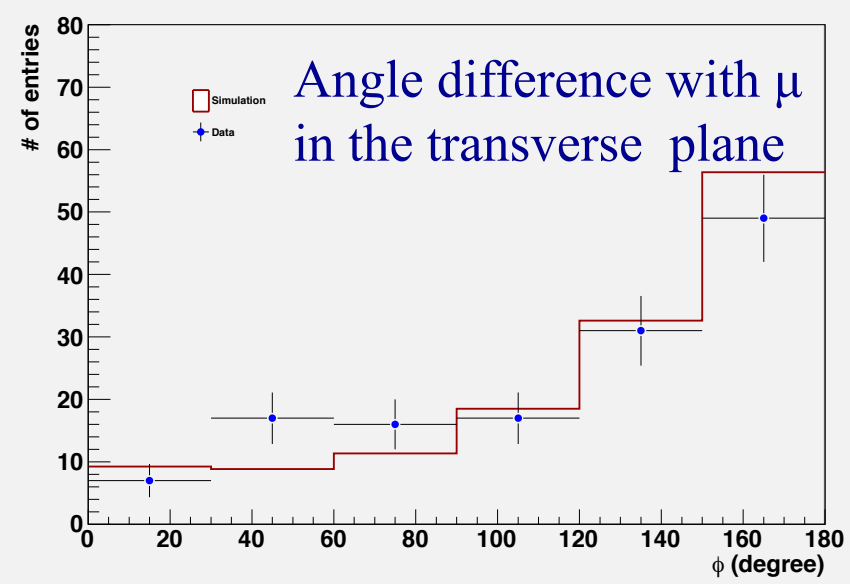
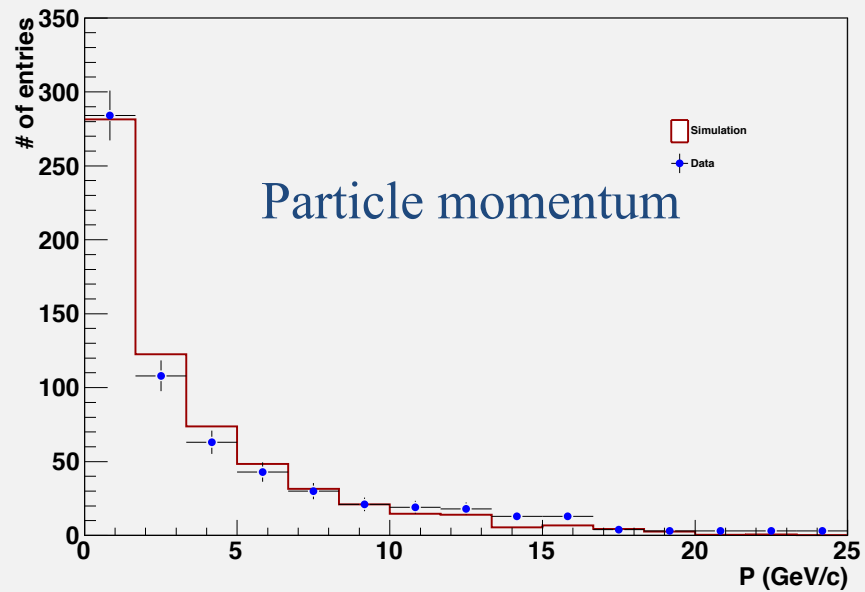
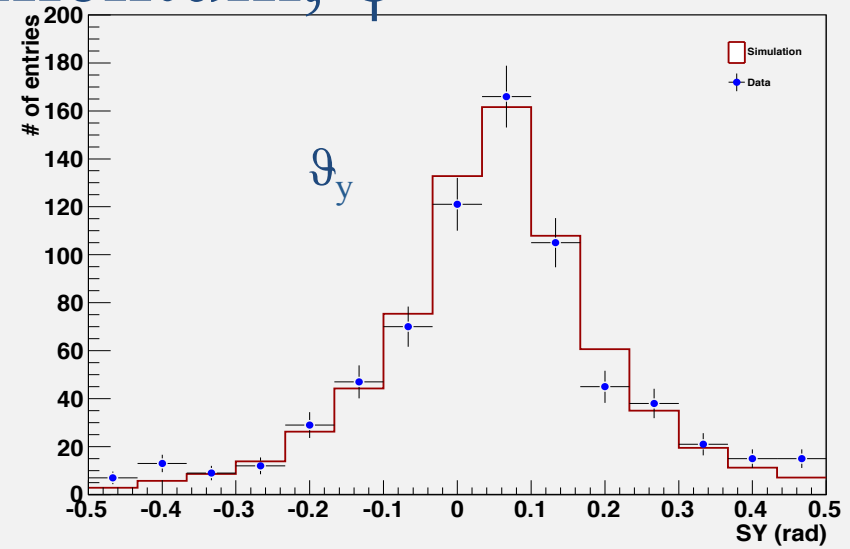
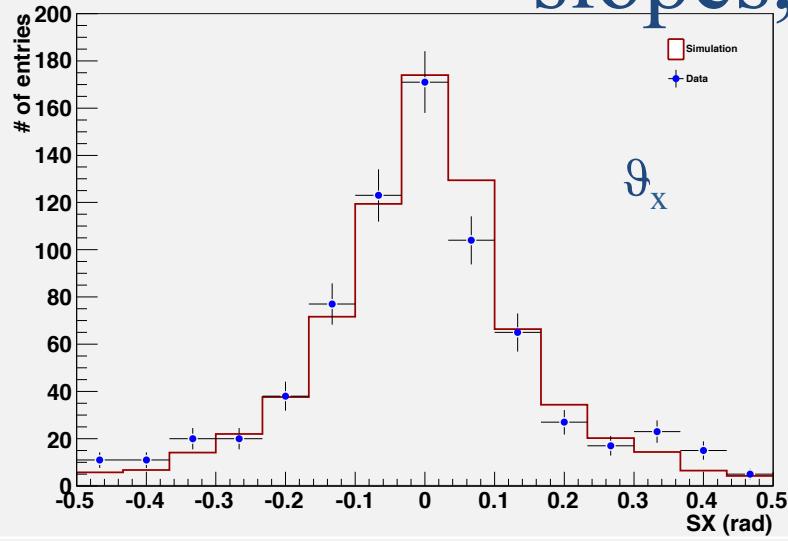


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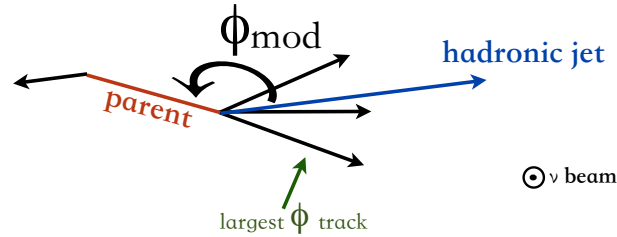


Data/MC agreement for the relevant variables:

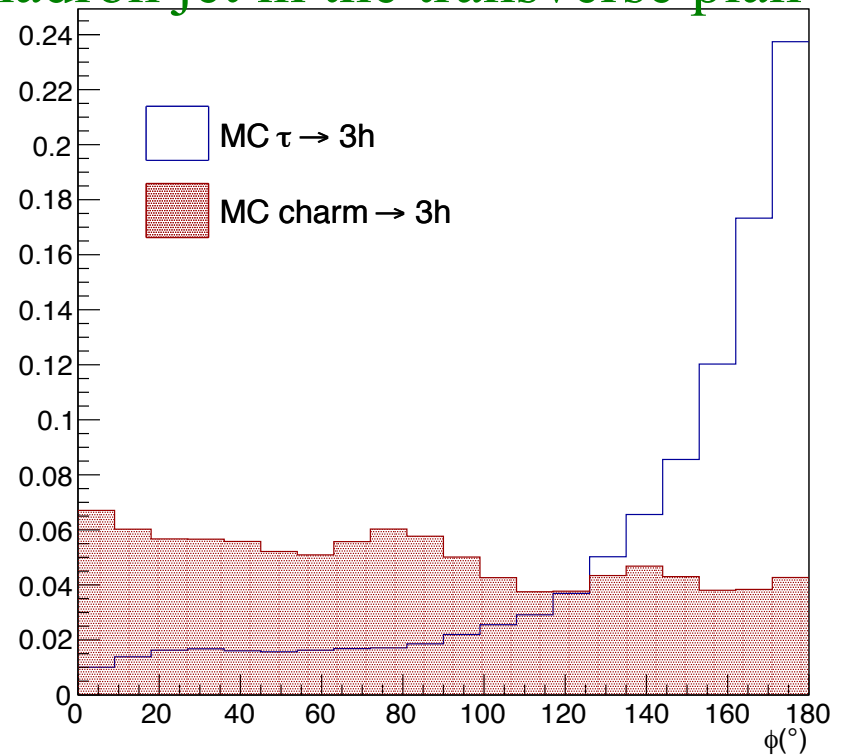
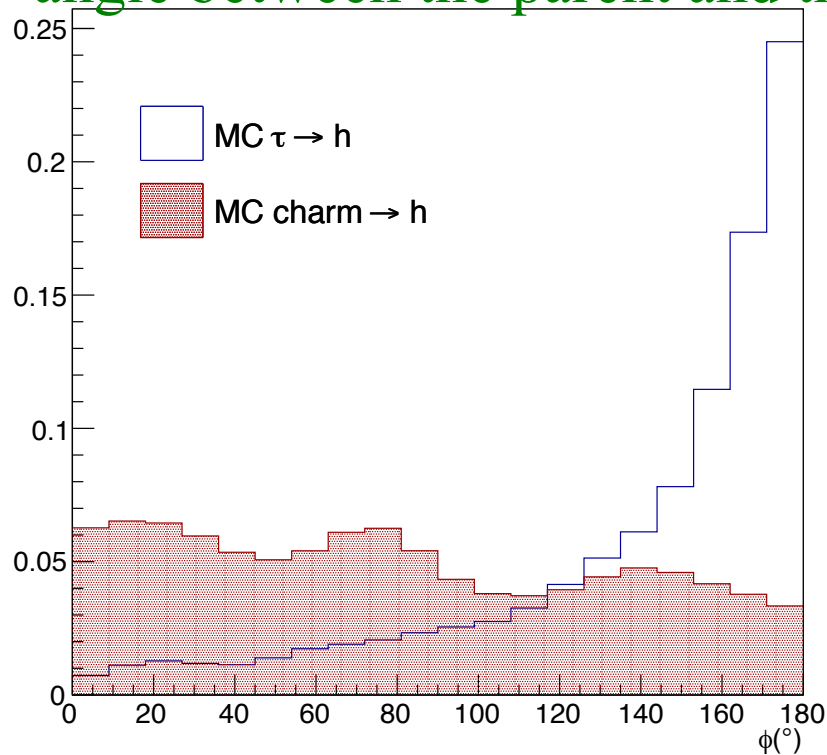
slopes, momentum, ϕ



Likelihood analysis: one of the discriminating variables



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



(a) $\tau \rightarrow h$

(b) $\tau \rightarrow 3h$

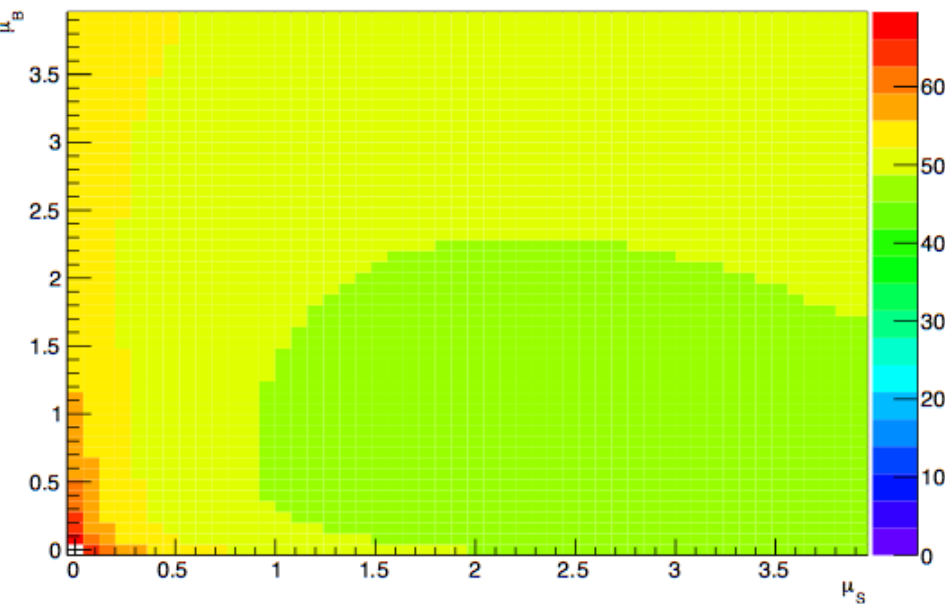
Statistical considerations

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

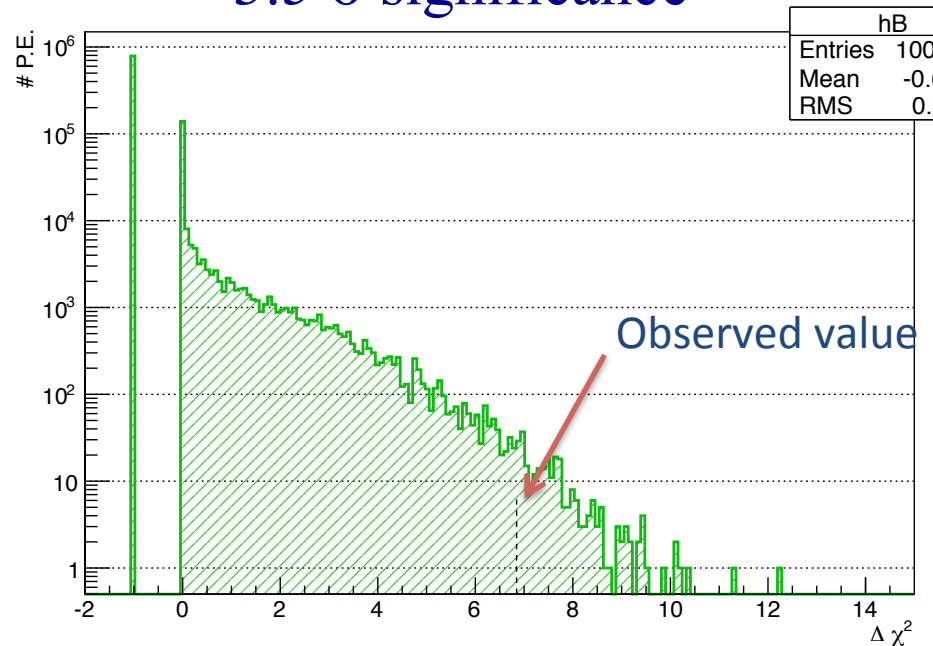
$$f^{S+B}(s, b, x) = \frac{sf_S(x) + bf_B(x)}{s + b} \quad \mathcal{L}(s, b) = \frac{(s + b)^n e^{-(s+b)}}{n!} \prod_{c=1}^4 \prod_{i=0}^{n_c} \prod_{v=1}^{n_v} f_{v,c}^{S+B}(s, b, x_v)$$

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

-2lnL



3.5 σ significance



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

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

Thank you for your attention