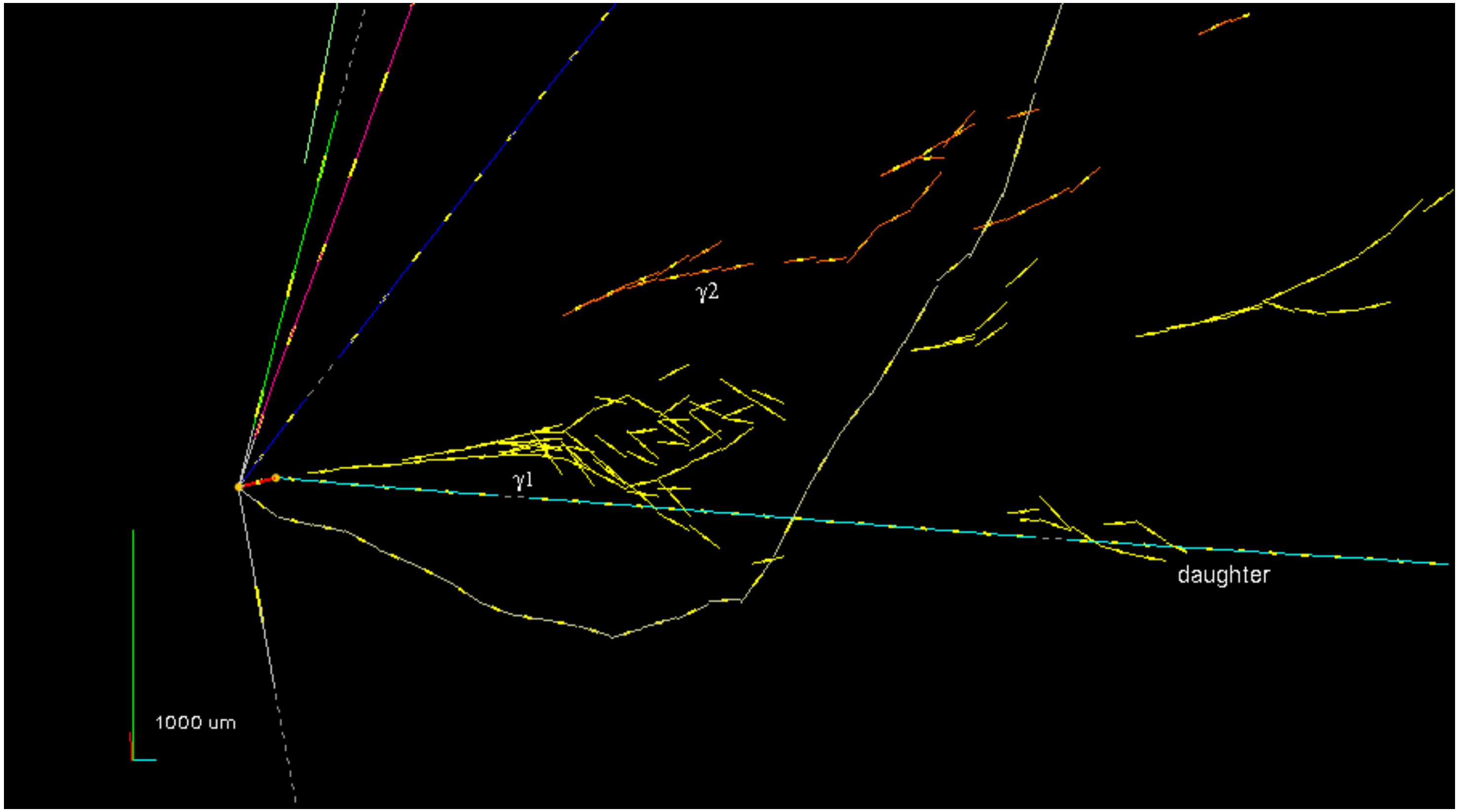
Results of the OPERA experiment

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

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS (Pontecorvo-Maki-Nakagawa-Sakata) Matrix

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

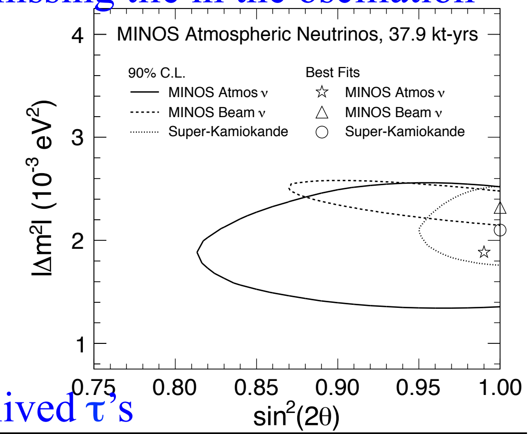
"Atmospheric" terms — Reactor experiments — "Solar" terms

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

OPERA

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.

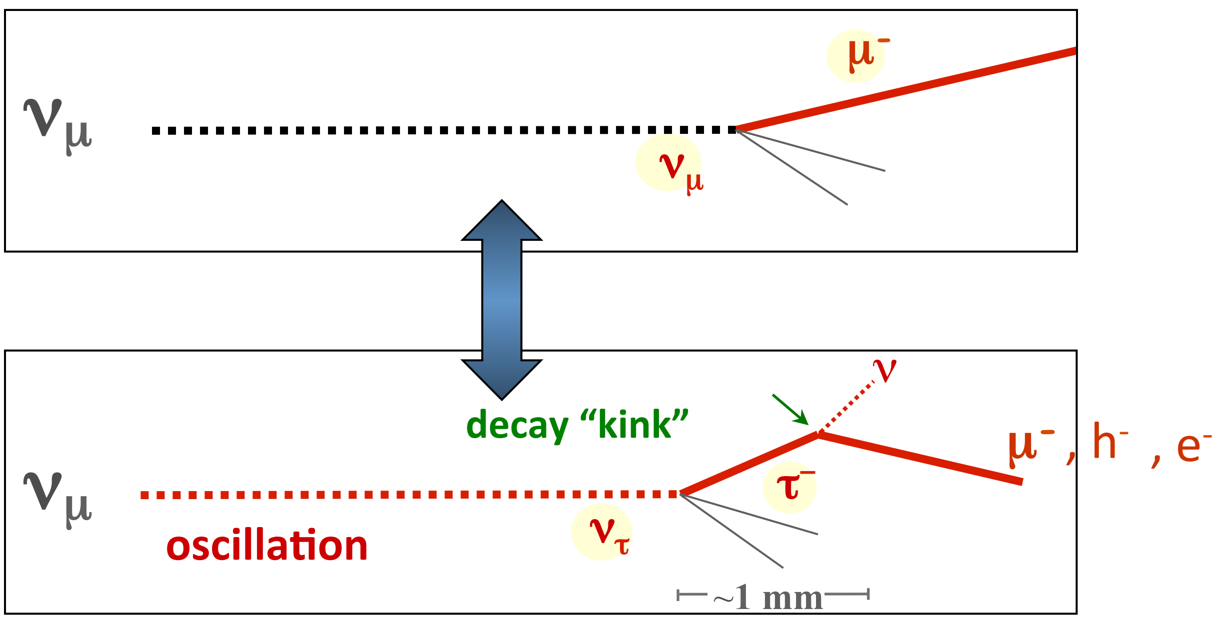


The PMNS 3-flavor oscillation formalism predicts:

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

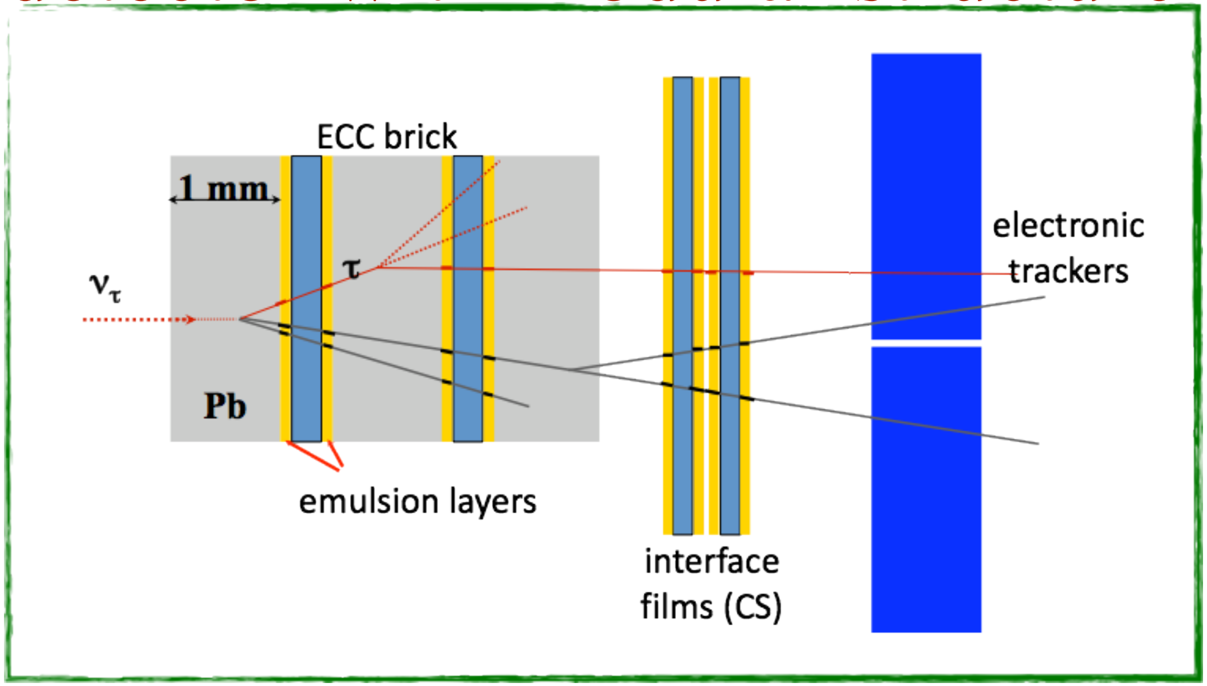
Requirements:

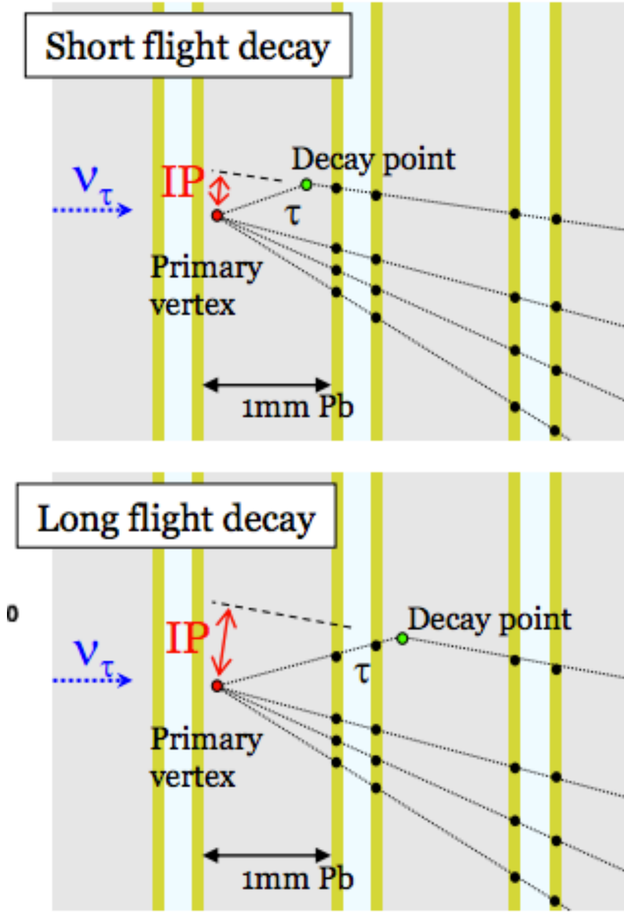
1) long baseline, 2) high neutrino energy, 3) high intensity beam, 4) detect short lived τ's



plus 3-prong decay modes

THE PRINCIPLE: hybrid detector with modular structure





- Massive active target (1.25 kton) with micrometric space resolution
- Detect τ-lepton production and decay
- Underground location (10^6 reduction of cosmic ray flux)
- Electronic detectors to provide the "time stamp", preselect the interaction brick and reconstruct muon charge/momentum

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

THE OPERA COLLABORATION

140 physicists, 28 institutions in 11 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

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

Japan
Aichi
Toho
Kobe
Nagoya
Utsunomiya

Korea
Jinju

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

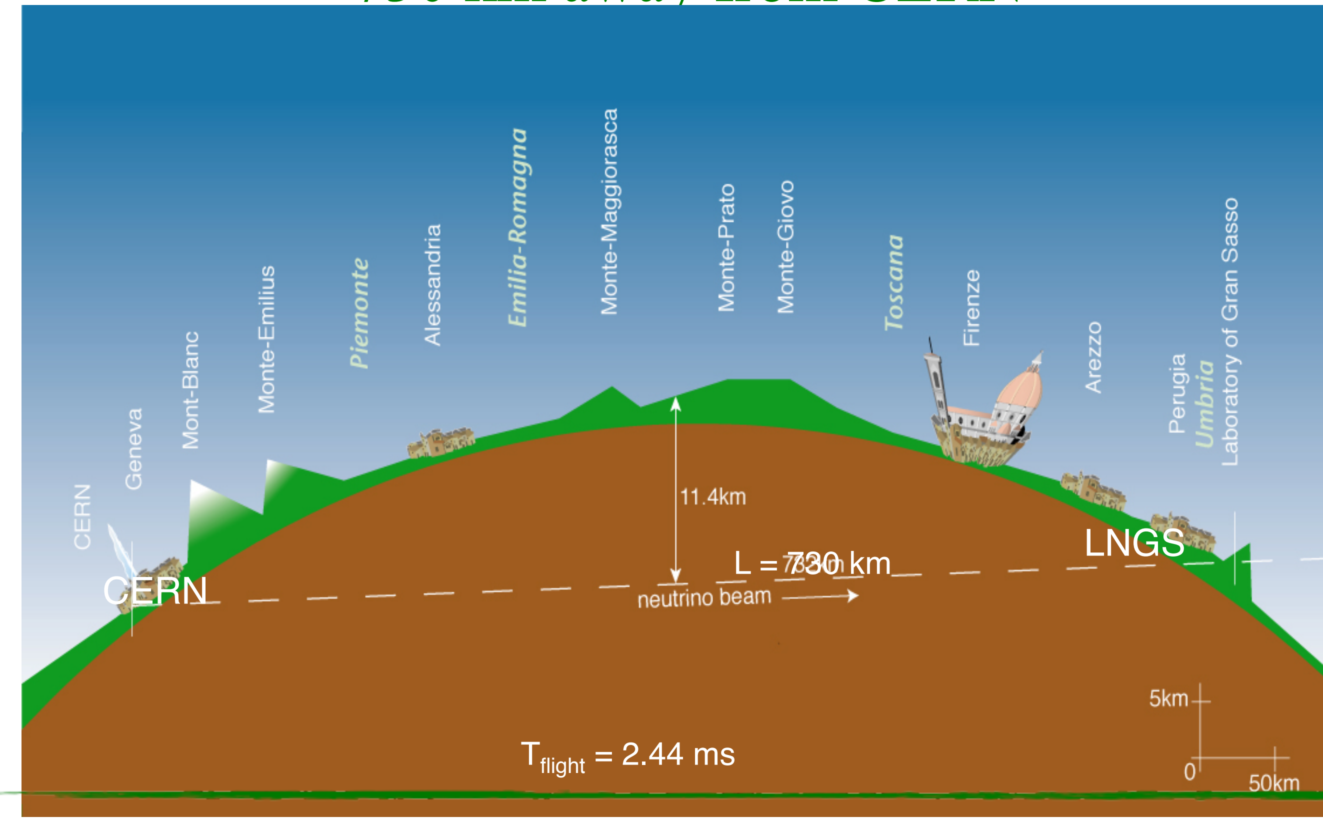
Switzerland
Bern

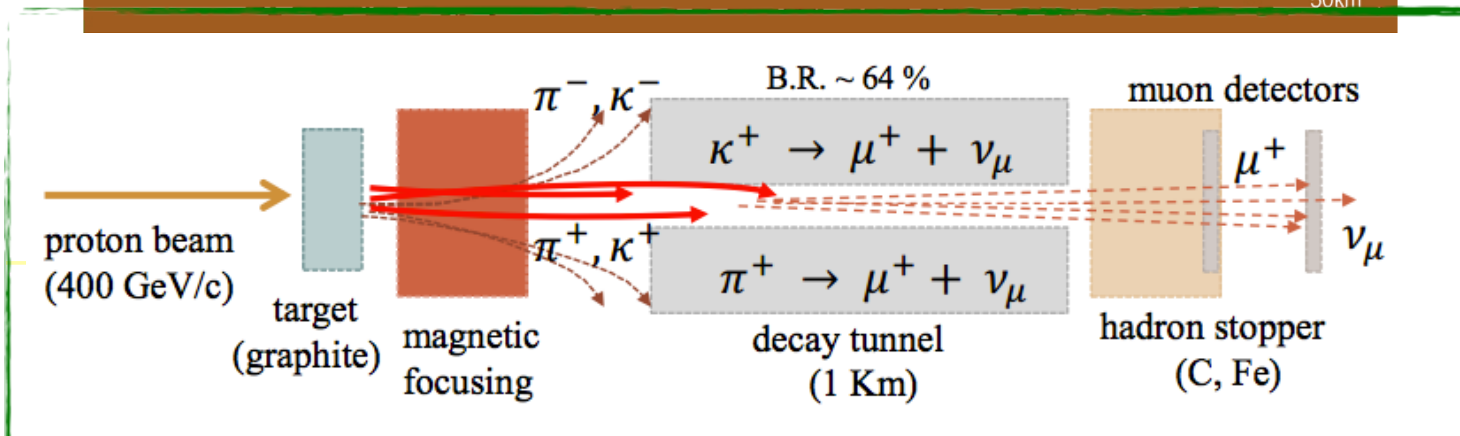
Turkey
METU, Ankara

http://operaweb.lngs.infn.it

CNGS BEAM AND LNGS

CNGS beam: tuned for τ-appearance at LNGS 730 km away from CERN



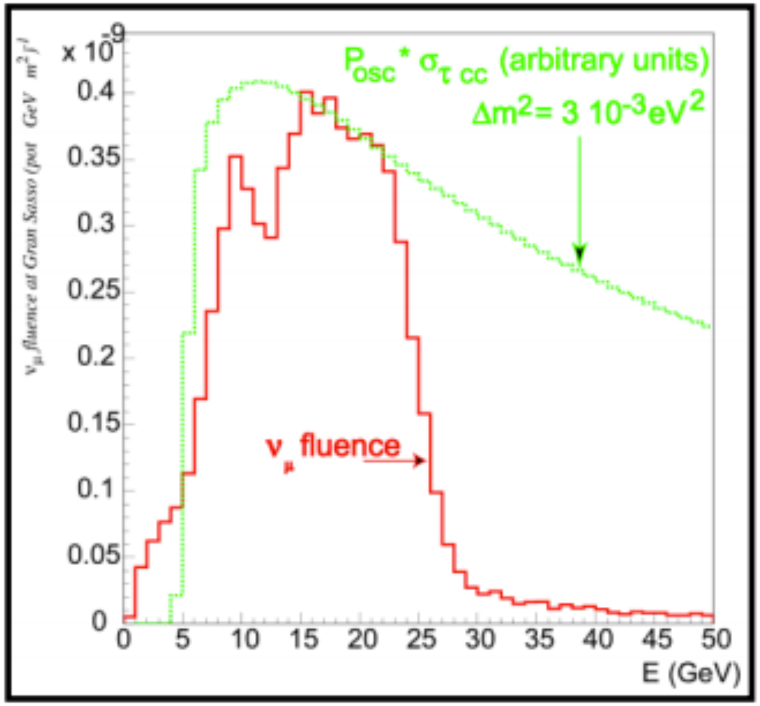


Neutrino Beam Parameters

Beam parameters

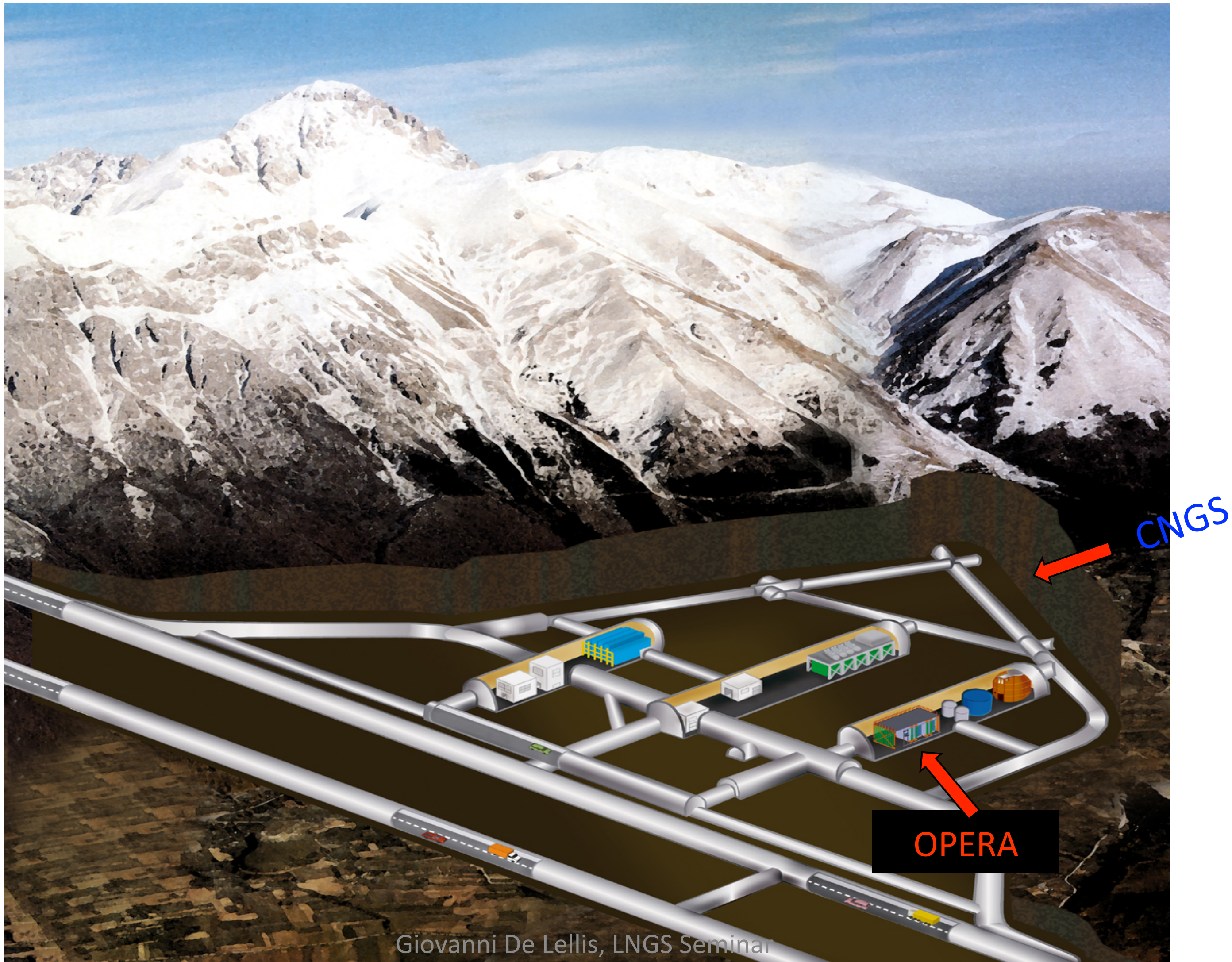
$<E\nu_\mu>$ (GeV)	17
$(\nu_e+\overline{\nu}_e)/\nu_\mu$	0.9% *
$\overline{\nu}_\mu/\nu_\mu$	2.0% *
ν_τ prompt	Negligible

* Interaction rate at LNGS

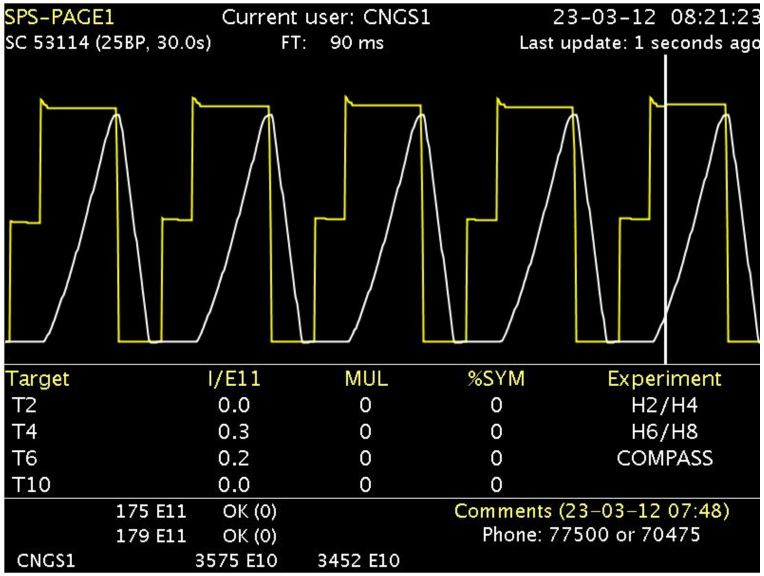


LNGS of INFN, the world largest underground physics laboratory:

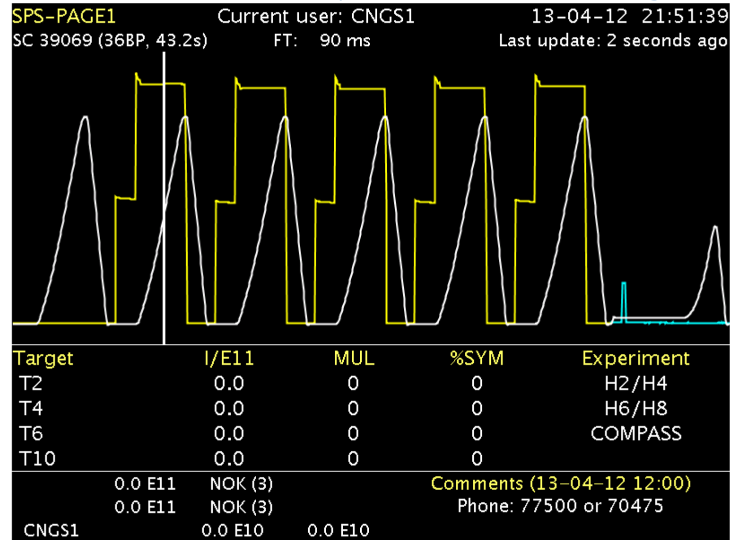
~180'000 m^3 caverns' volume, ~3'100 m.w.e. overburden, ~1 cosmic μ / (m^2 x hour), experimental infrastructure. Suitable to host detector and related facilities, caverns oriented towards CERN.



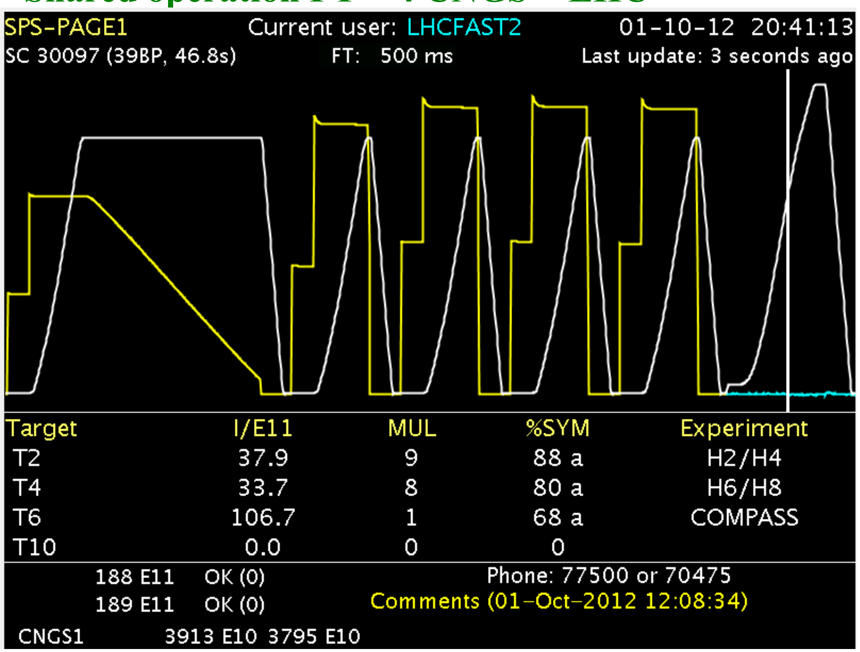
CNGS beam structure



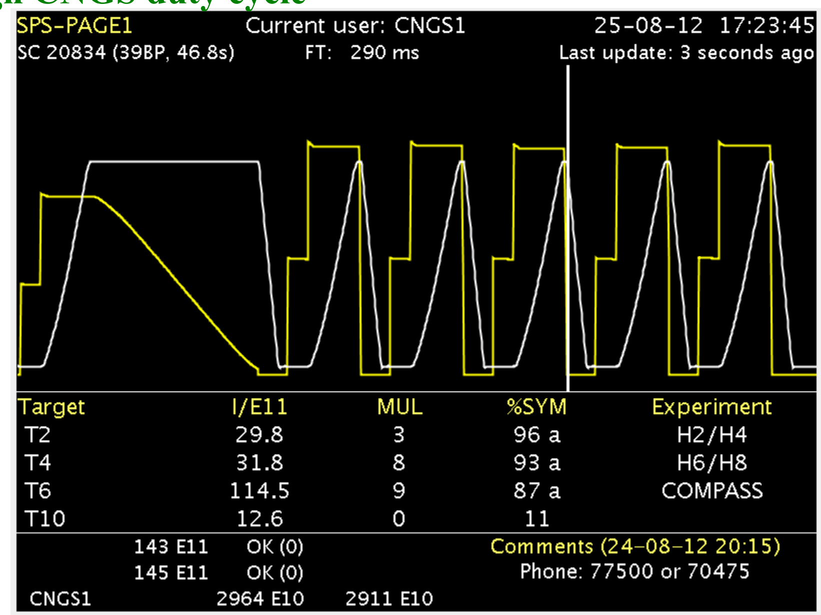
Dedicated mode or 5 cycles + LHC (during filling)



Shared operation FT + 4 CNGS + LHC

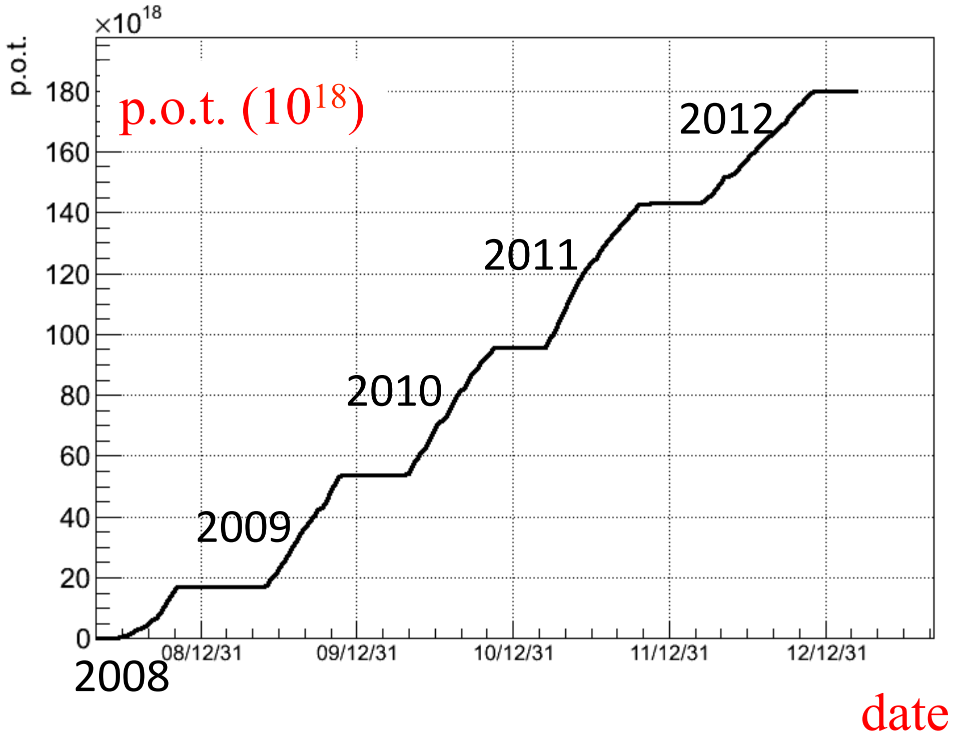


Shared operation no LHC filling (5 CNGS+ FT)
High CNGS duty cycle



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
Total	**965**	**17.97**



Record performances in 2011

Overall 20% less than the proposal value (22.5)

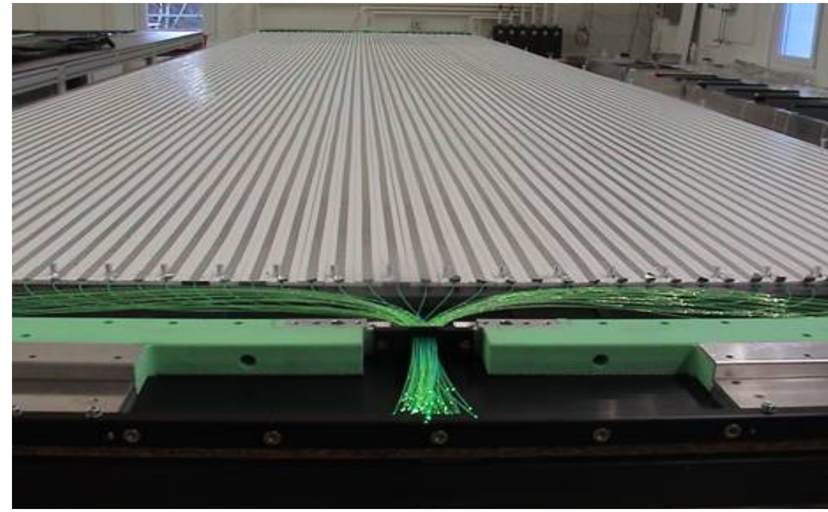
DETECTORS AND FACILITIES
in operation:

A very complex experiment…

Two target super-modules, each with an iron spectrometer for muon detection (BG rejection and tau → muon decay channel)

SCINTILLATOR STRIPS TARGET TRACKER AND BRICK TRAYS

mechanical structure:
brick trays: only 0.5% of target mass

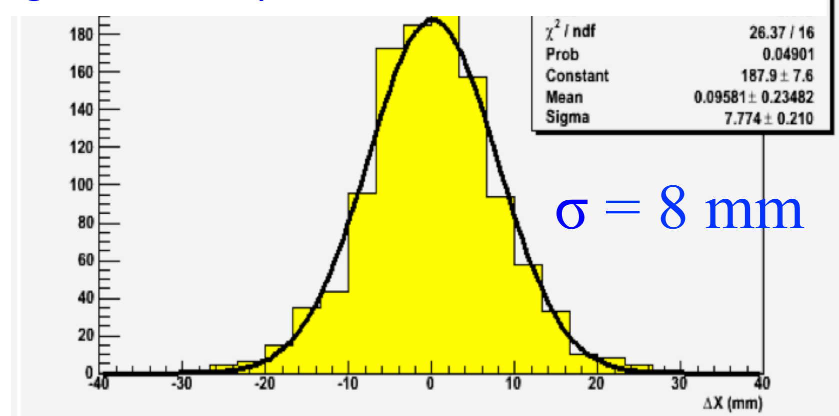


> 5 p.e. for a m.i.p.

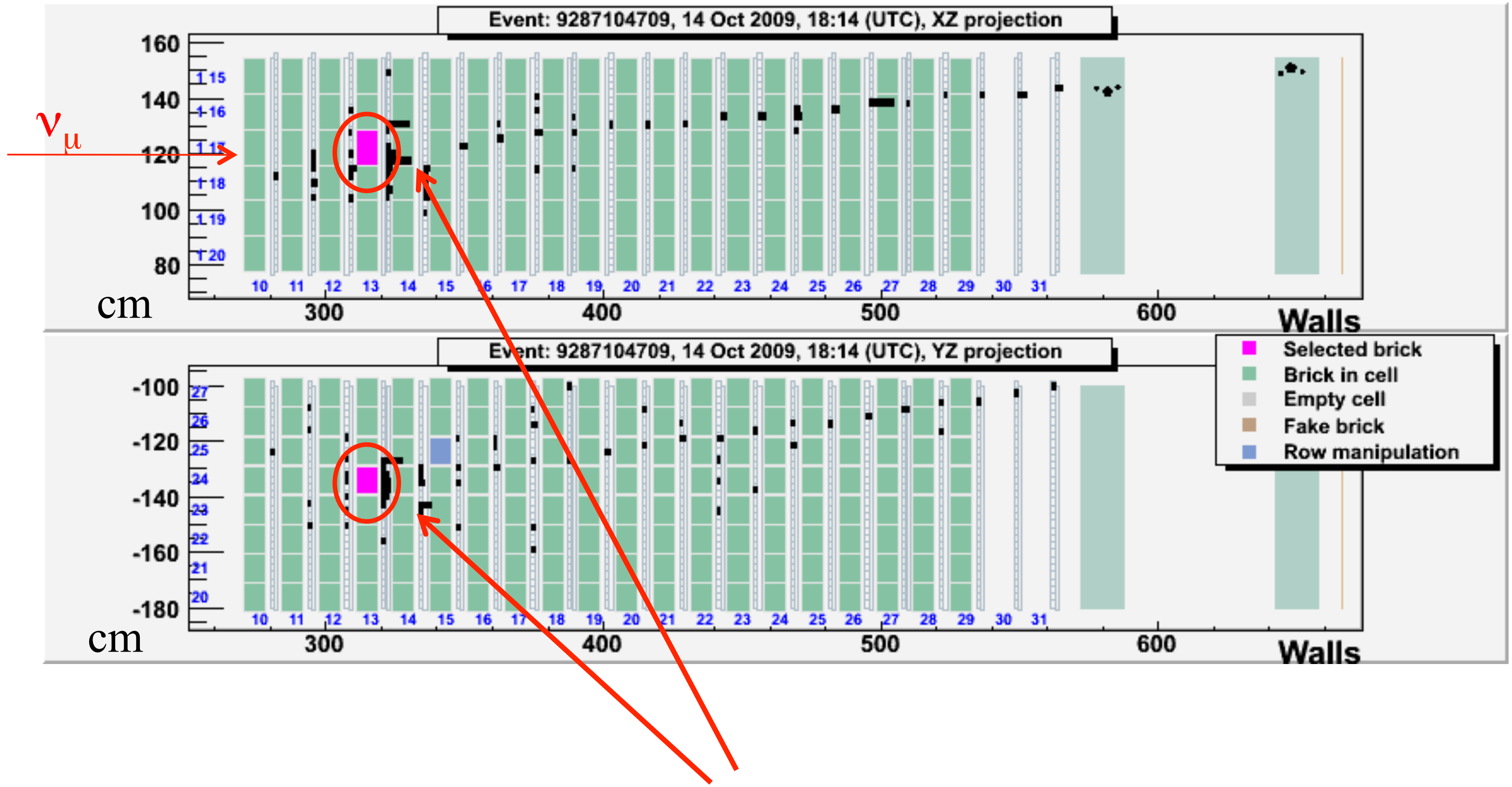
~ 99% detection efficiency ⇒ trigger

position accuracy: ~ 8 mm

angular accuracy: ~ 15 mrad

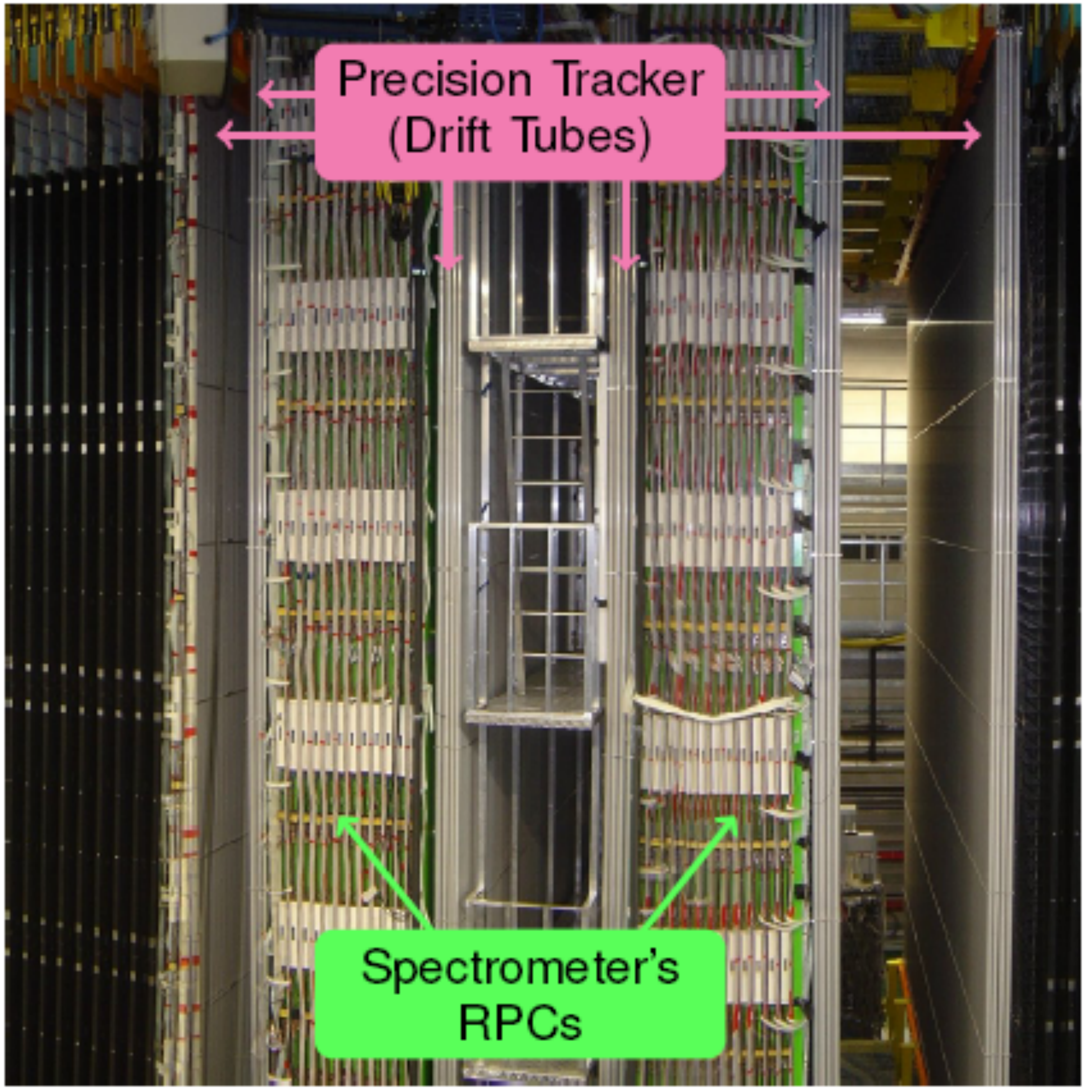


Identification of the interaction brick: iterative process (1.6 bricks involved in the analysis of one event)



Brick identified (top and side view)

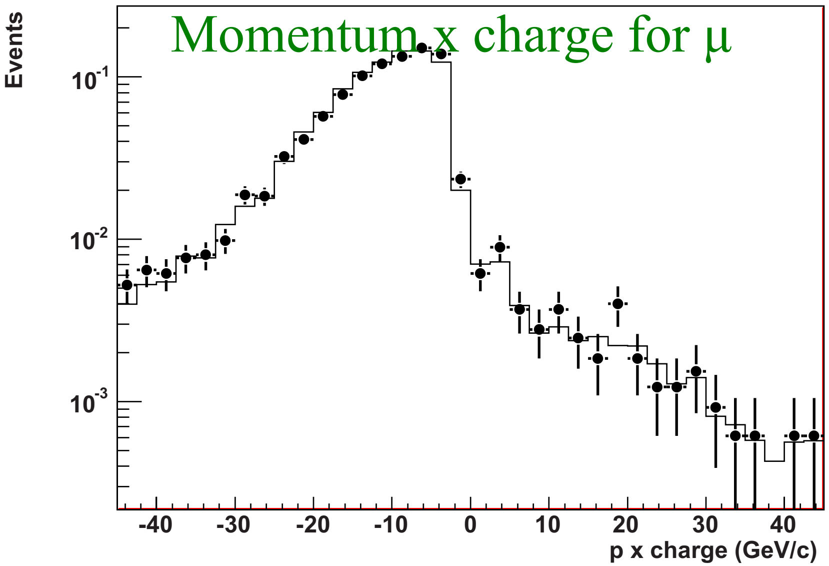
THE MAGNETIC SPECTROMETERS

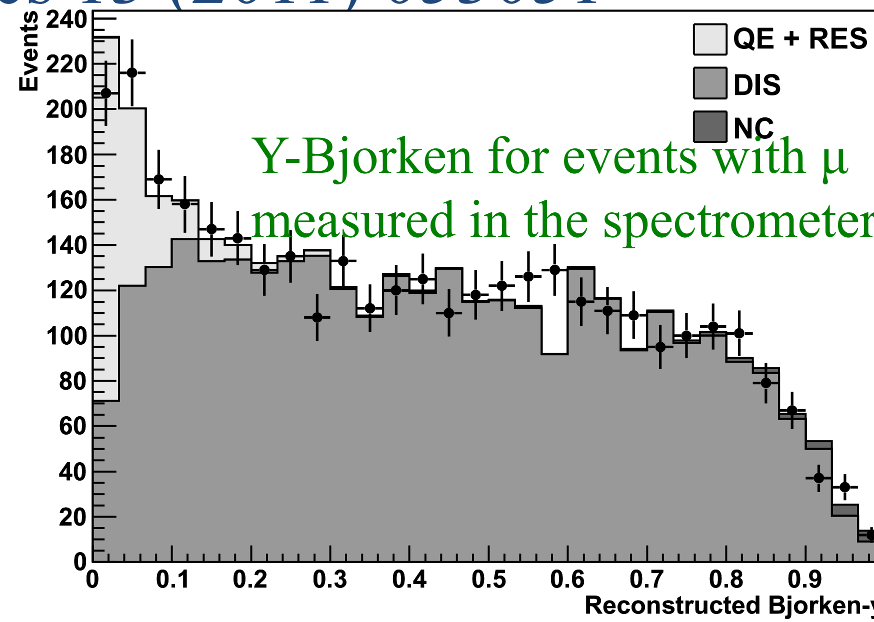


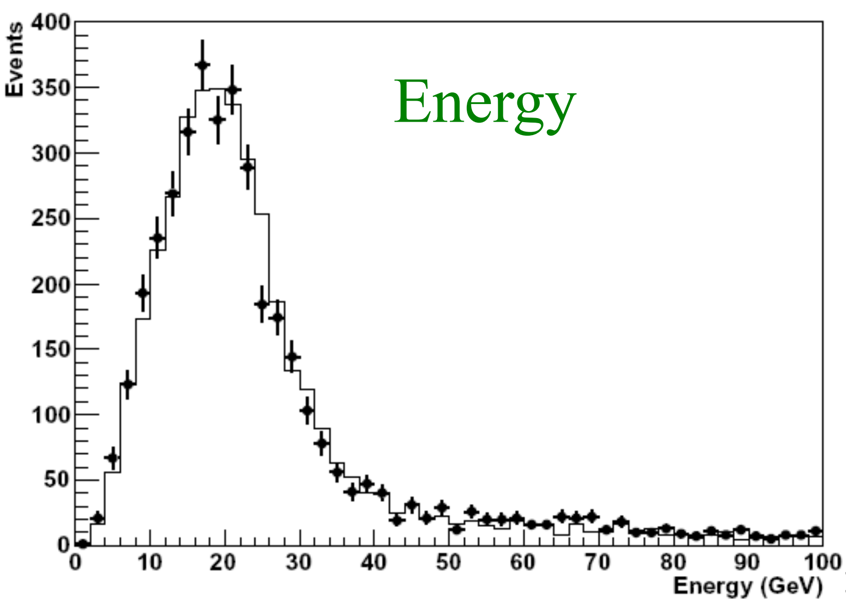
- 1.55 T magnetic field bending particles in the horizontal plane
- 24 slabs of magnetized iron interleaved with 24 RPC planes
- 6 drift tube stations for precision measurement of the angular deflection
- momentum resolution: 20% below 30 GeV

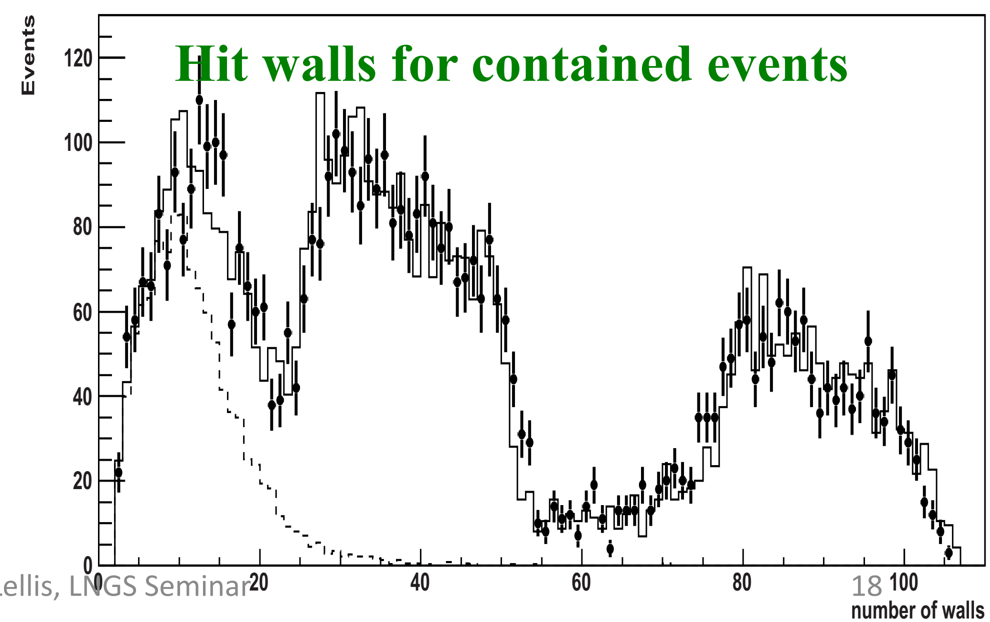
Performances of the electronic detector

New Journal of Physics 13 (2011) 053051

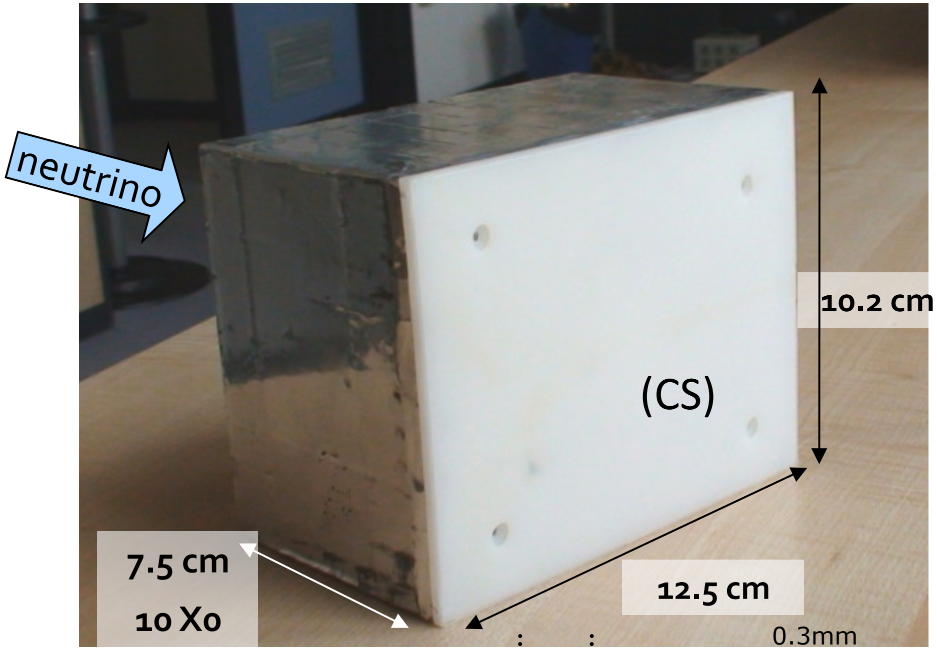


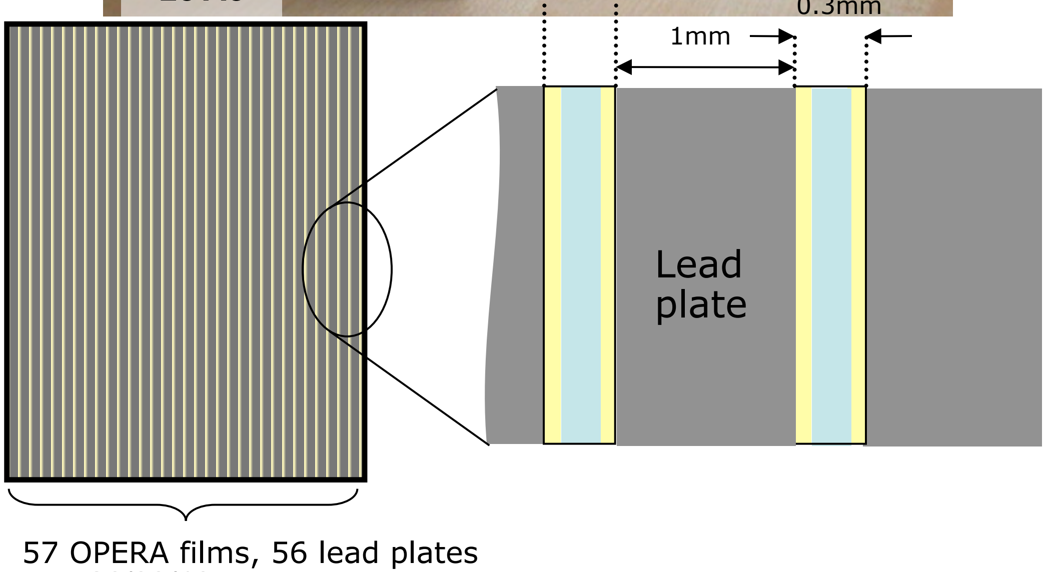


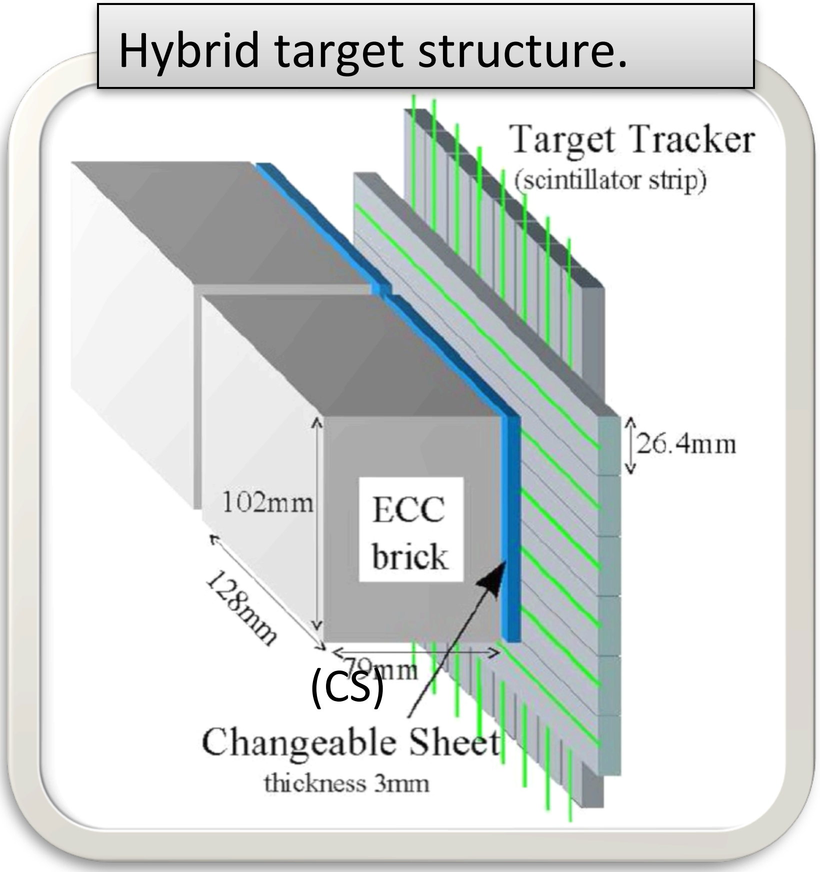




The heart of the experiment: THE ECC TARGET BRICKS







The OPERA target consists of 150’000 ECC bricks.

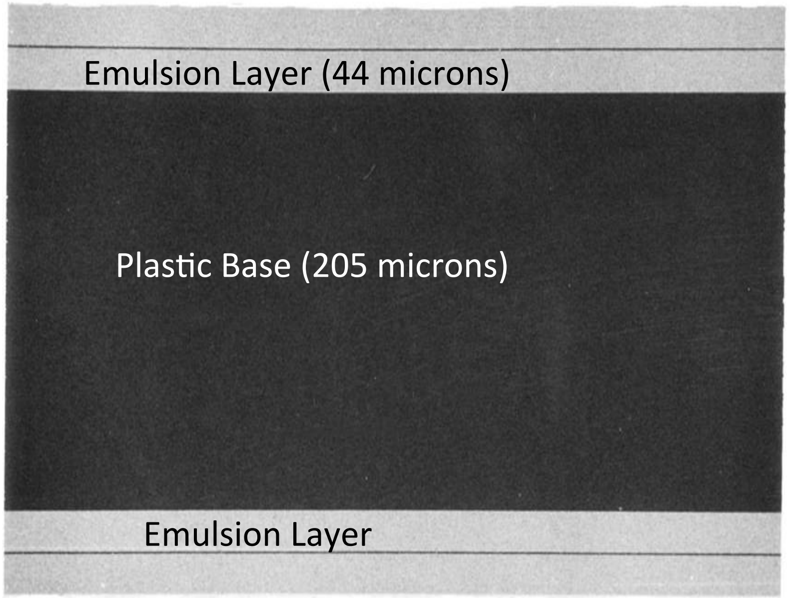
Total 105’000 m^2 of lead surface

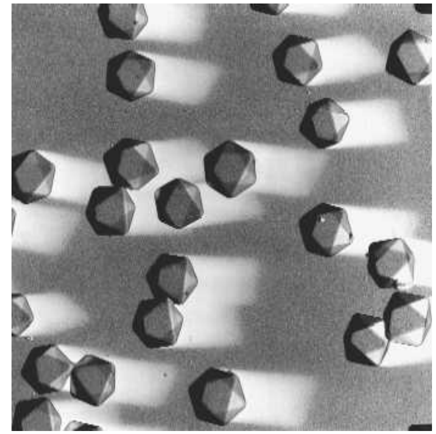
and 111’000 m^2 of film surface

(~ 9 million films)

Total target mass: 1.25 kton

INDUSTRIAL EMULSION FILMS BY *FUJI FILM*





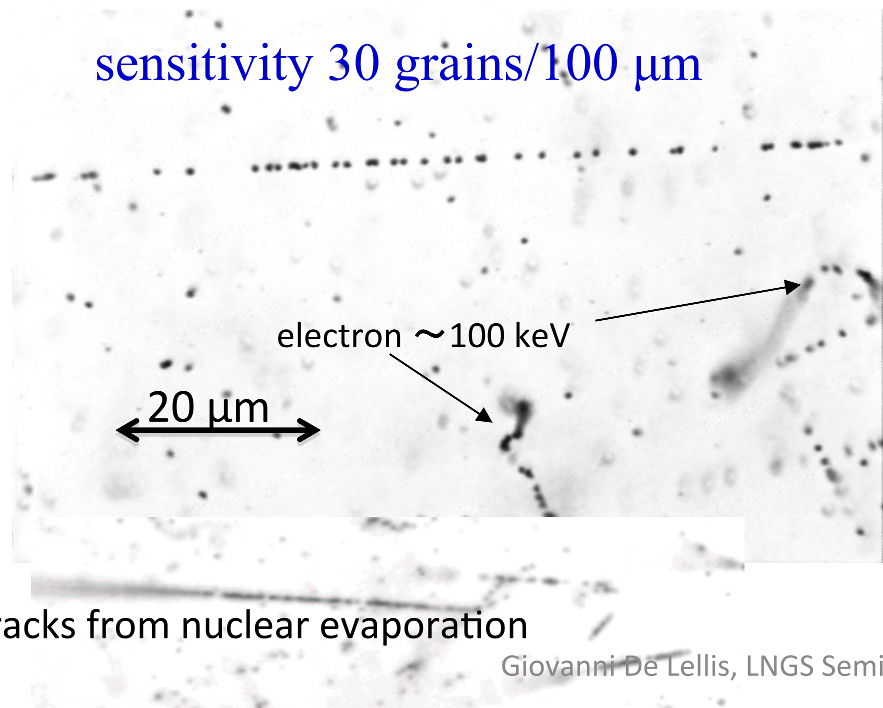
basic detector: AgBr crystal,

size = 0.2 micron

detection eff.= 0.16/crystal

10^{13} "detectors" per film

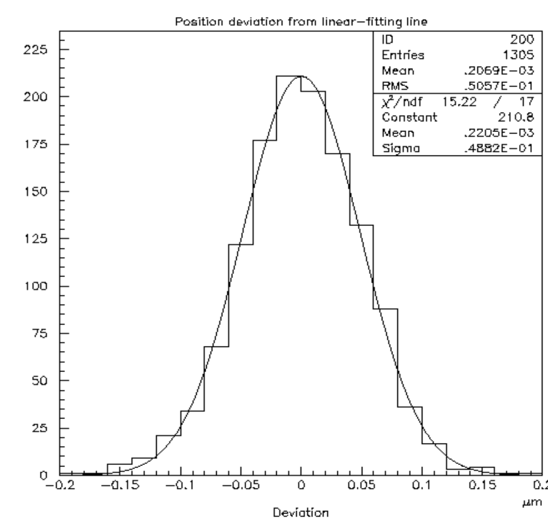
mip



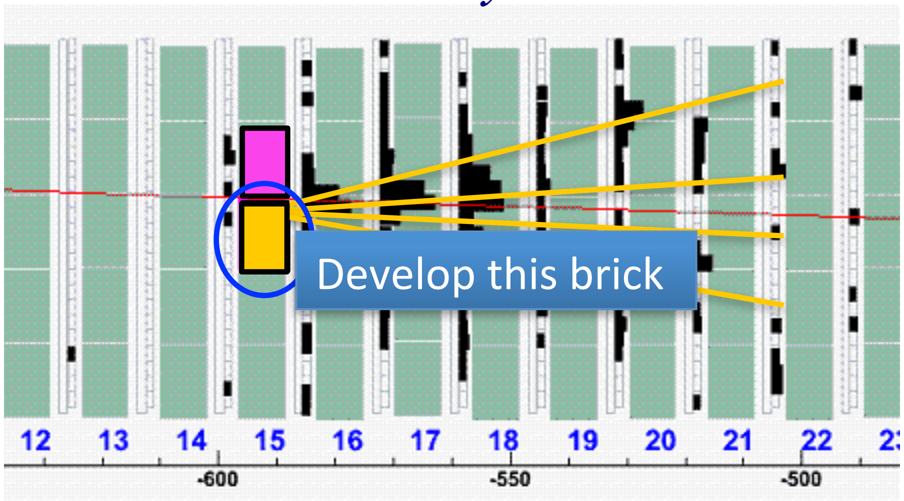
high dE/dx tracks from nuclear evaporation

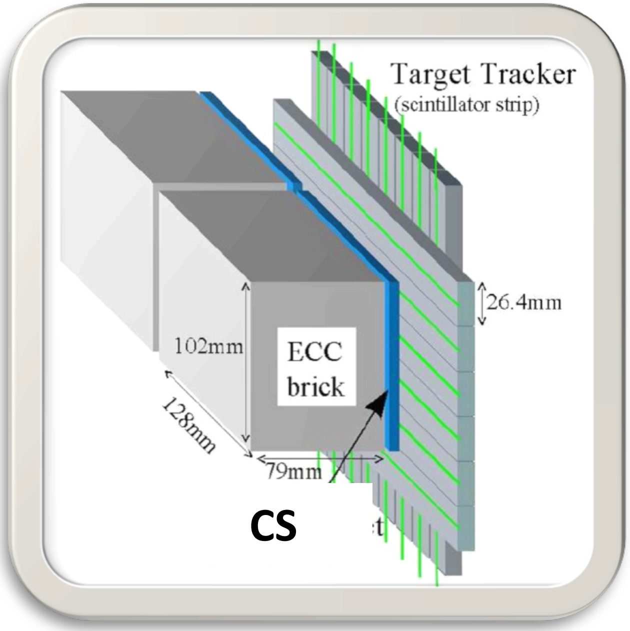
intrinsic resolution: 50 nm

deviation from linear-fit line. (2D)

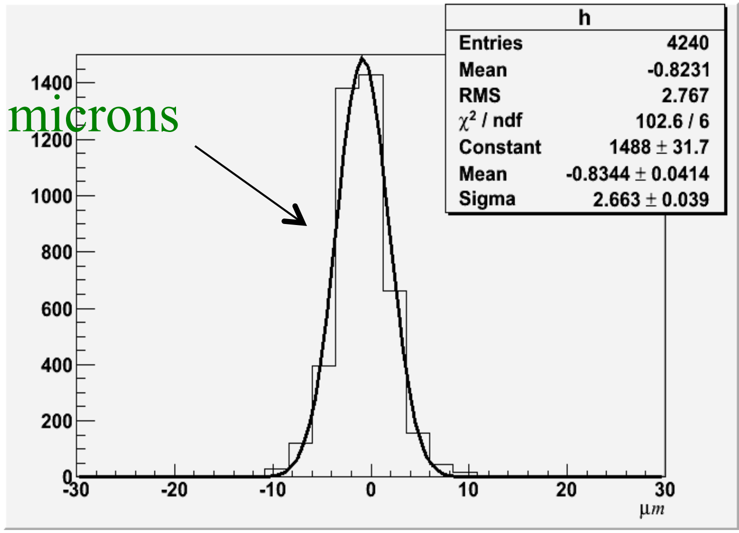


Brick validation by the interface film analysis



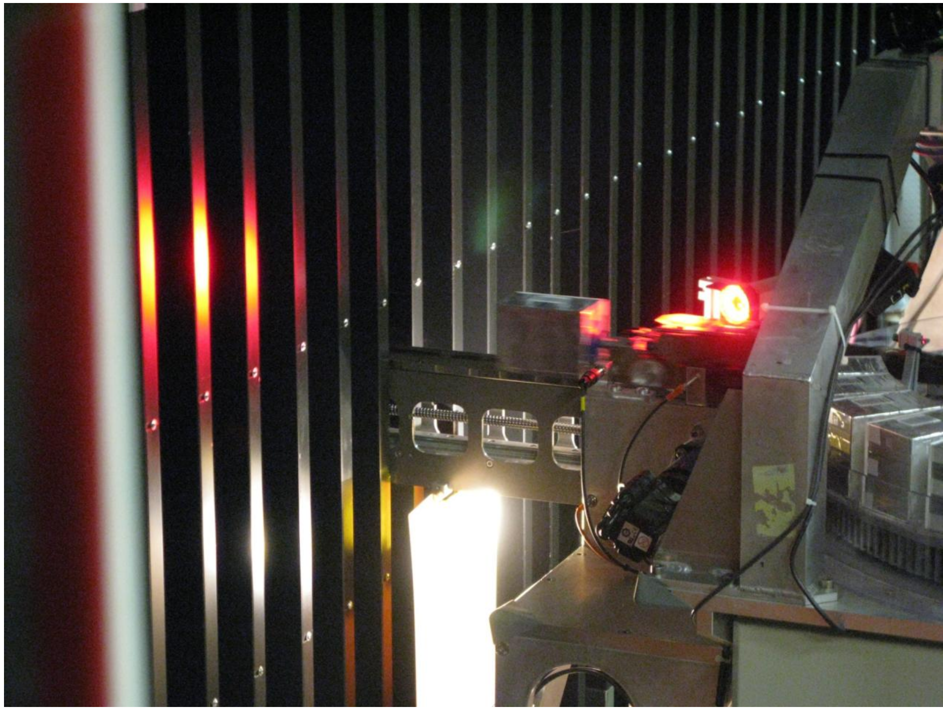


CS doublet alignment by Compton electrons: 2.5 microns



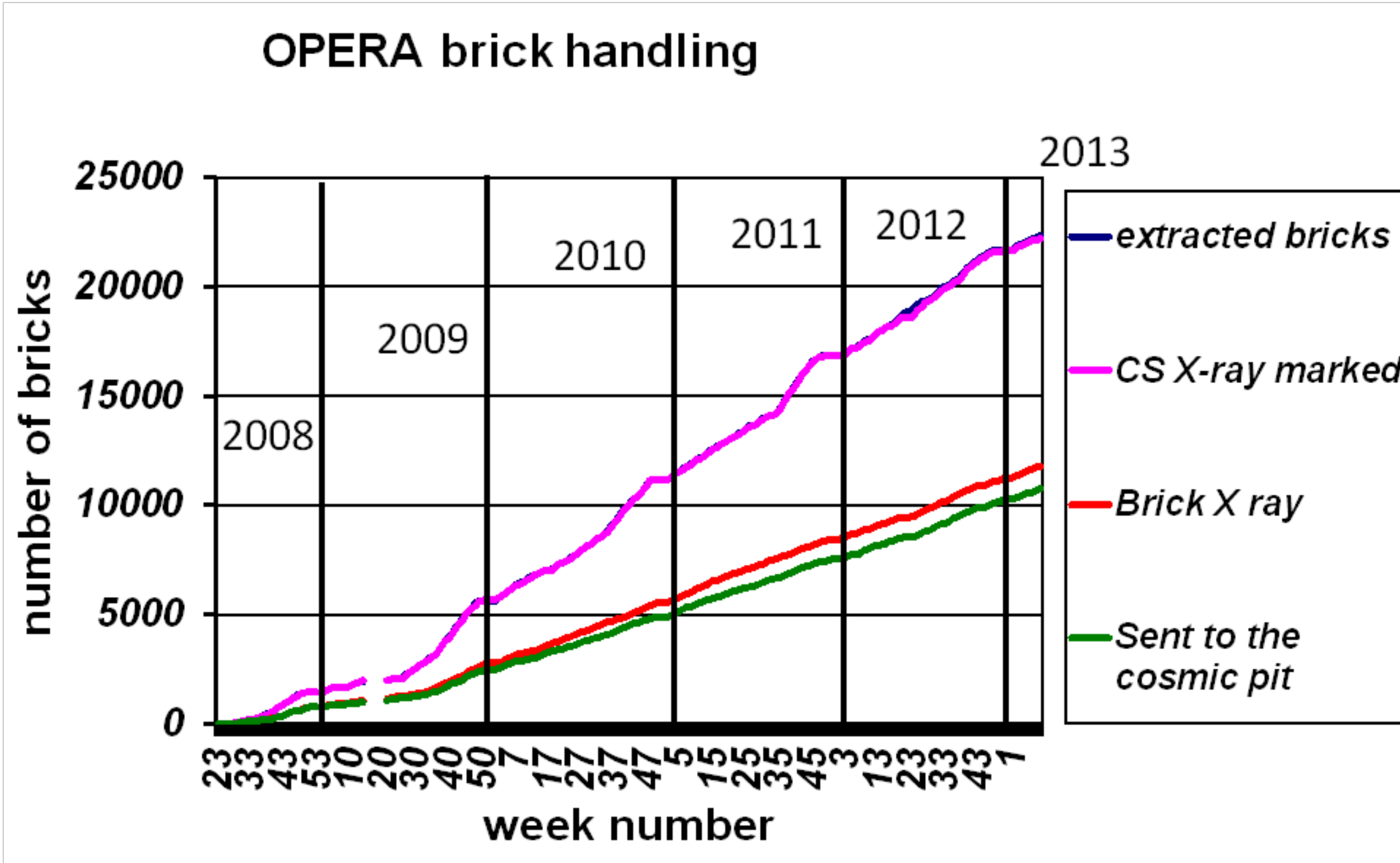
So far 2'000'000 cm^2 of CS surface have been analysed in OPERA

BRICK MANIPULATOR SYSTEM (BMS)



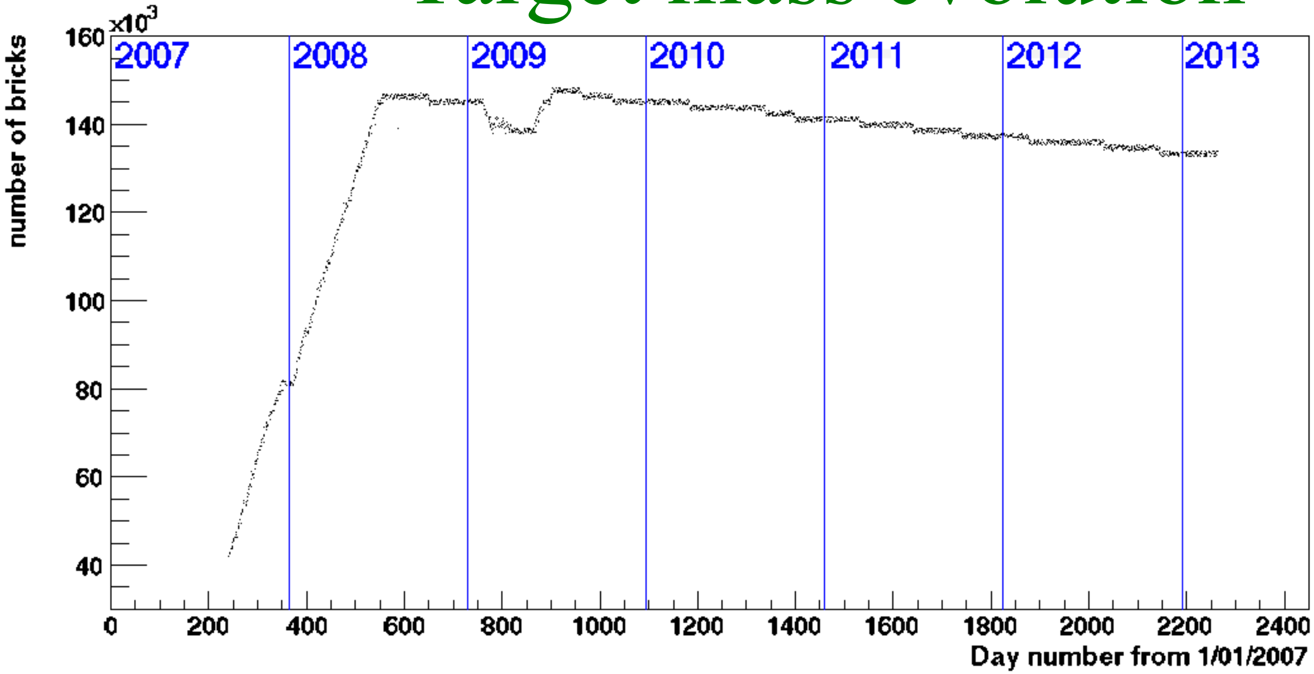
Extraction of "hit" bricks in parallel with CNGS data taking (quasi-online):

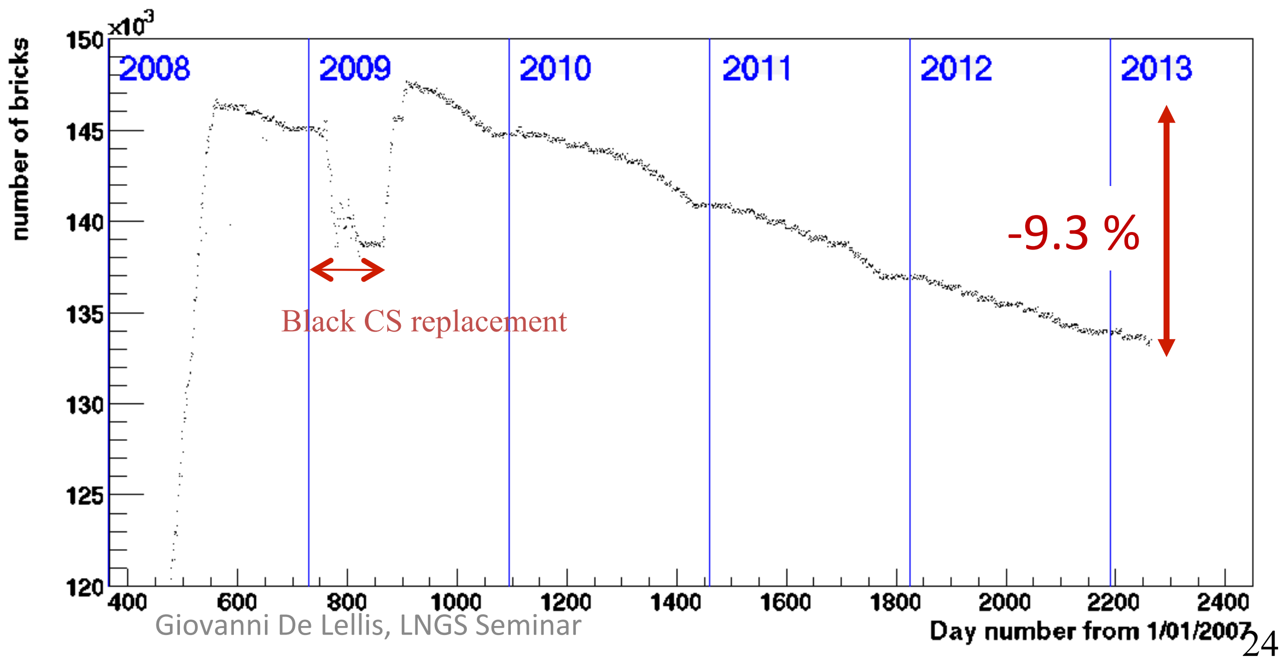
- initially used to fill the brick target (two twin devices at either detector sides)
- fully automatic extraction of up to 50 bricks/day (neutrino interactions)



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

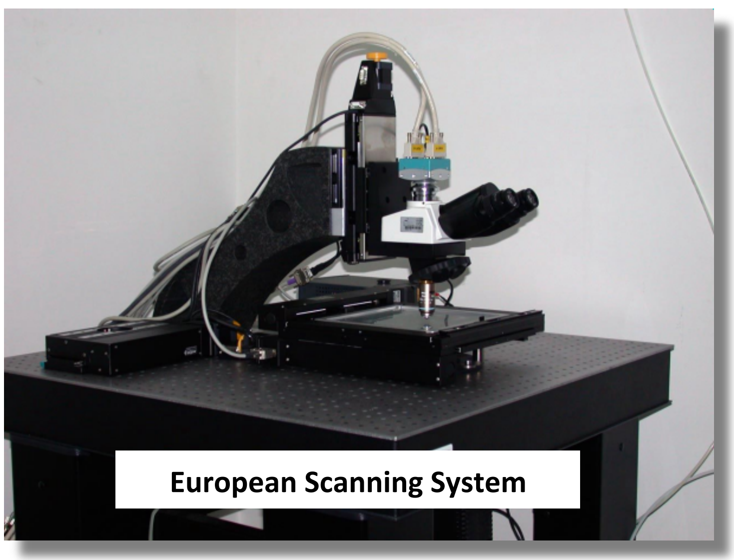
FILM DEVELOPMENT FACILITY

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

Scanning of Changeable Sheets: several tasks accomplished

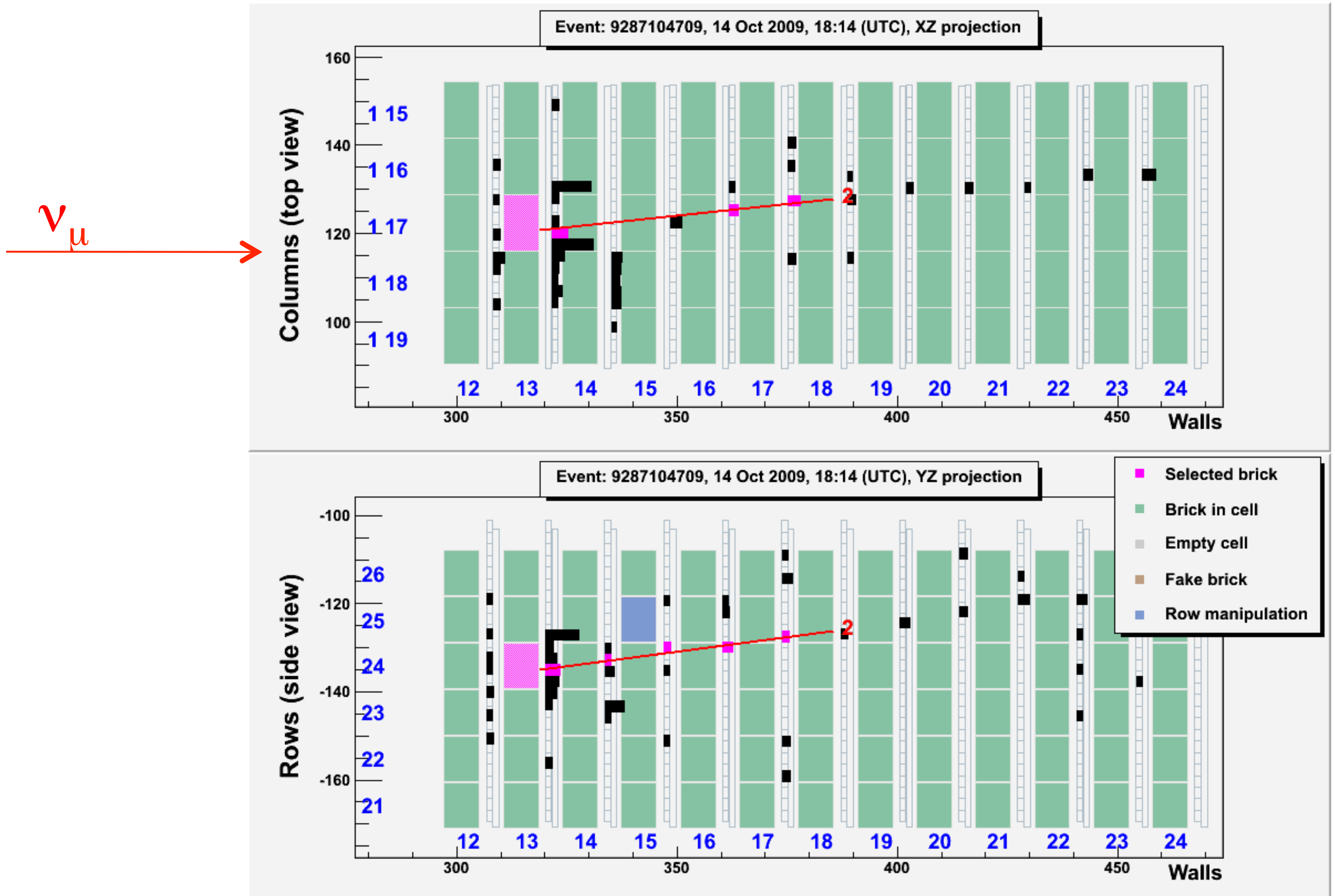
LNGS: 10 microscopes, 200 cm^2/h

Nagoya: 5 S-UTS, 220 cm^2/h

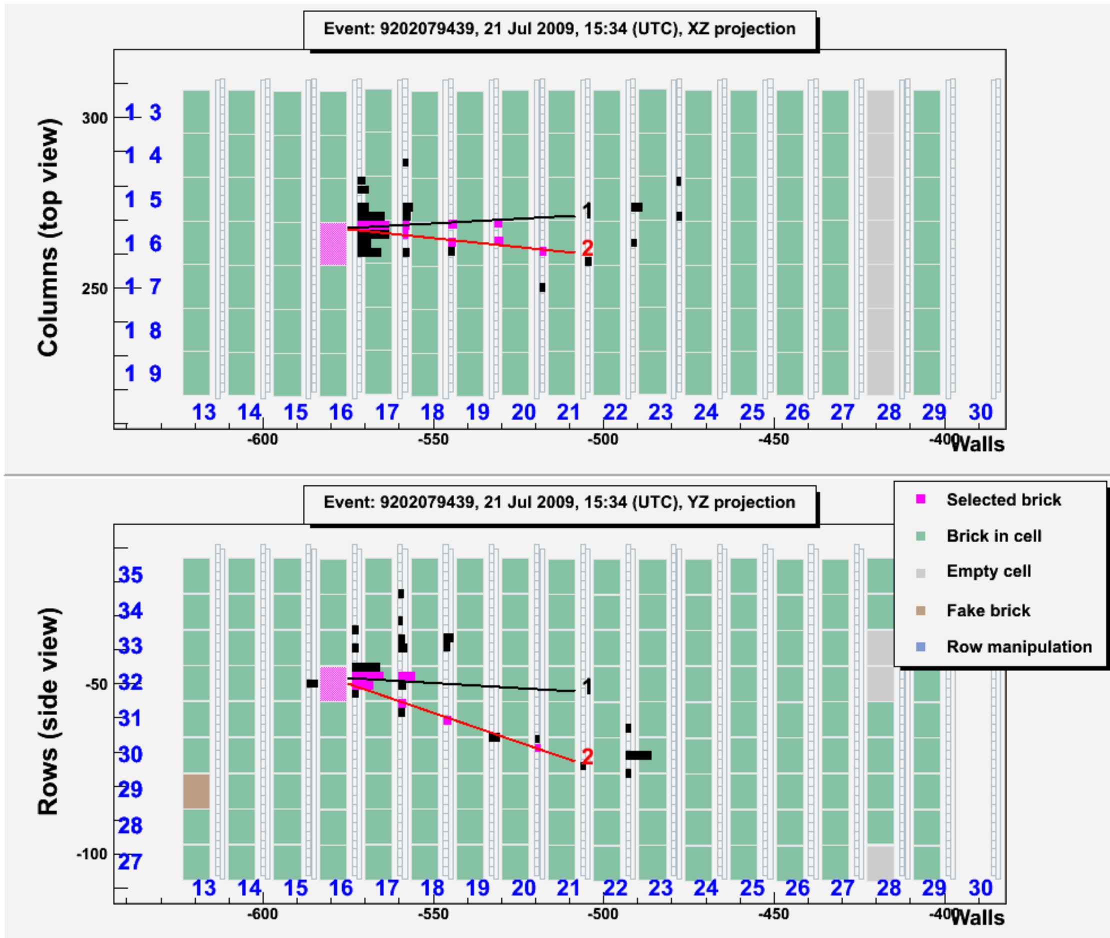


Interface emulsion films: high signal/noise ratio for event trigger and scanning time reduction

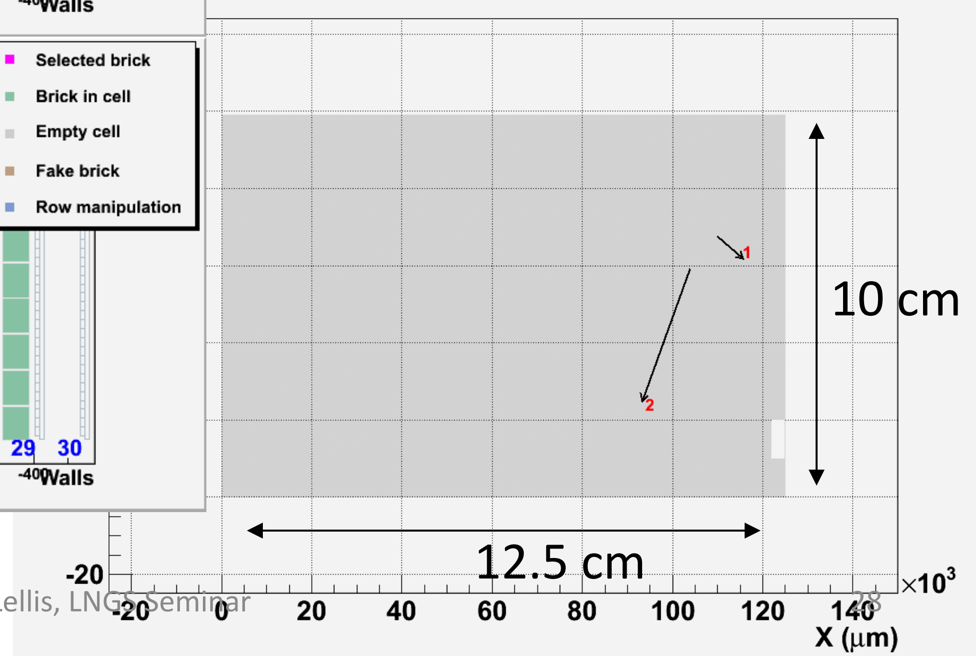
CC interaction: μ track in interface films



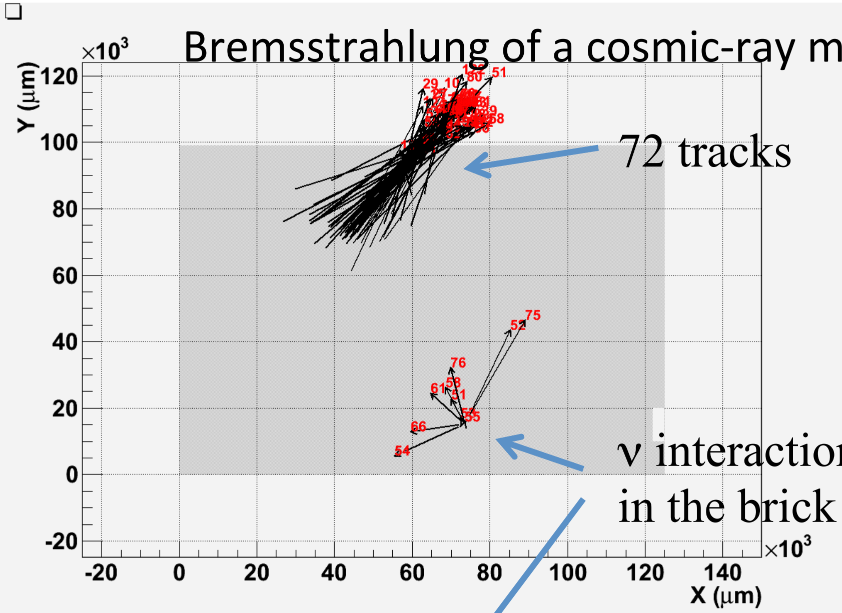
Validation of events without μ in the final state

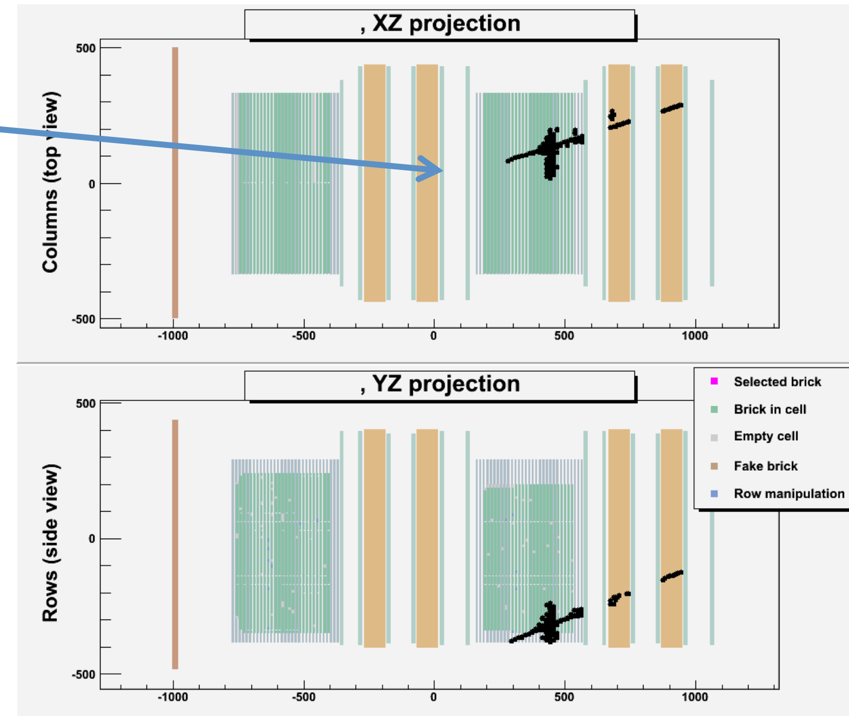


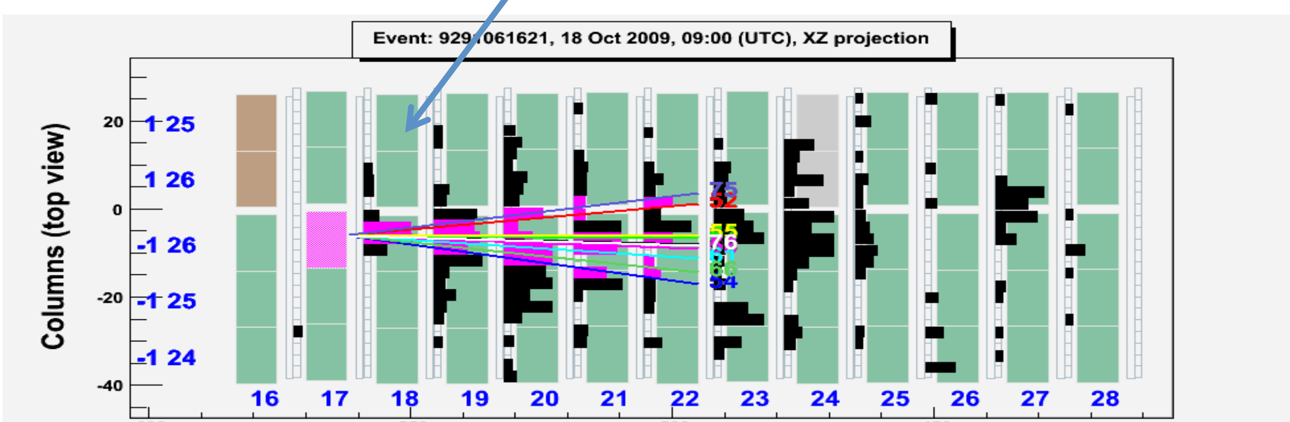
CS tracks: the arrow length is proportional to its slope

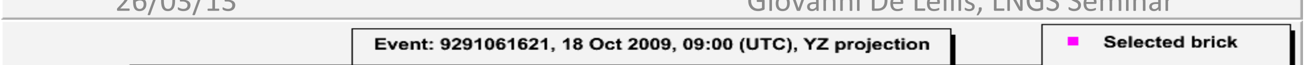


Identification of cosmic ray μ and muons from ν interactions upstream: important to keep the TT running during the shutdown

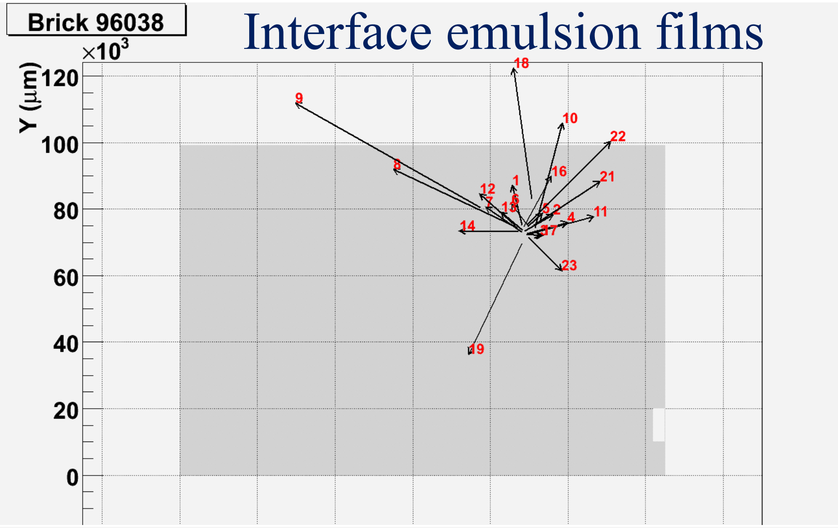


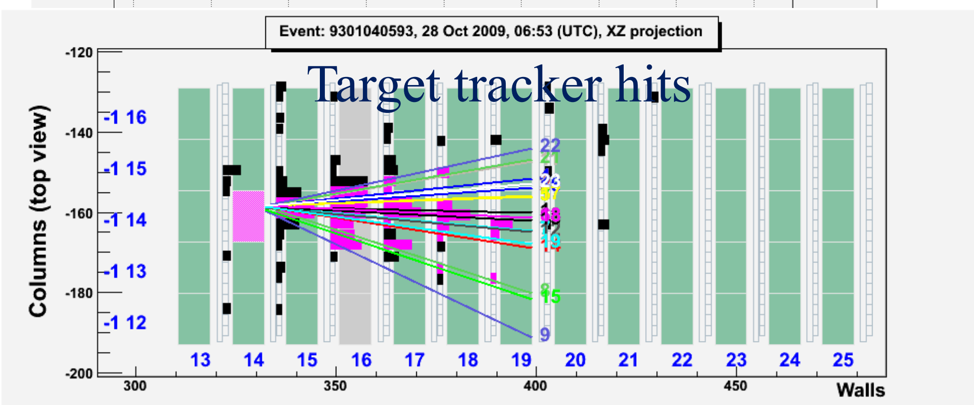


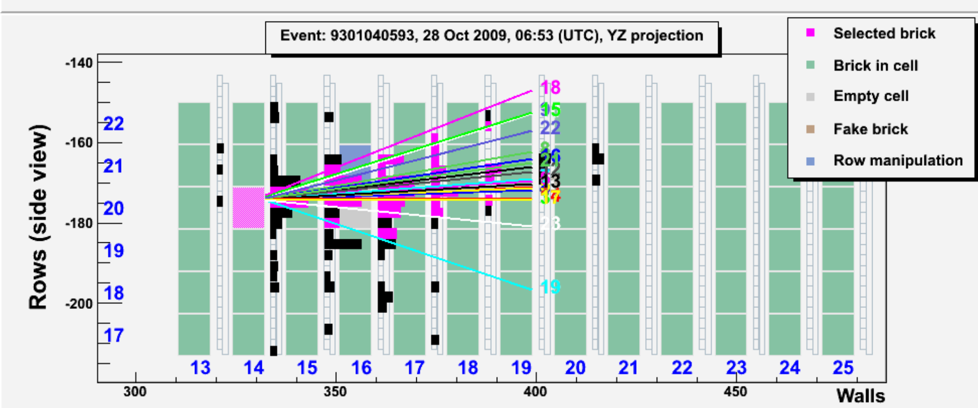


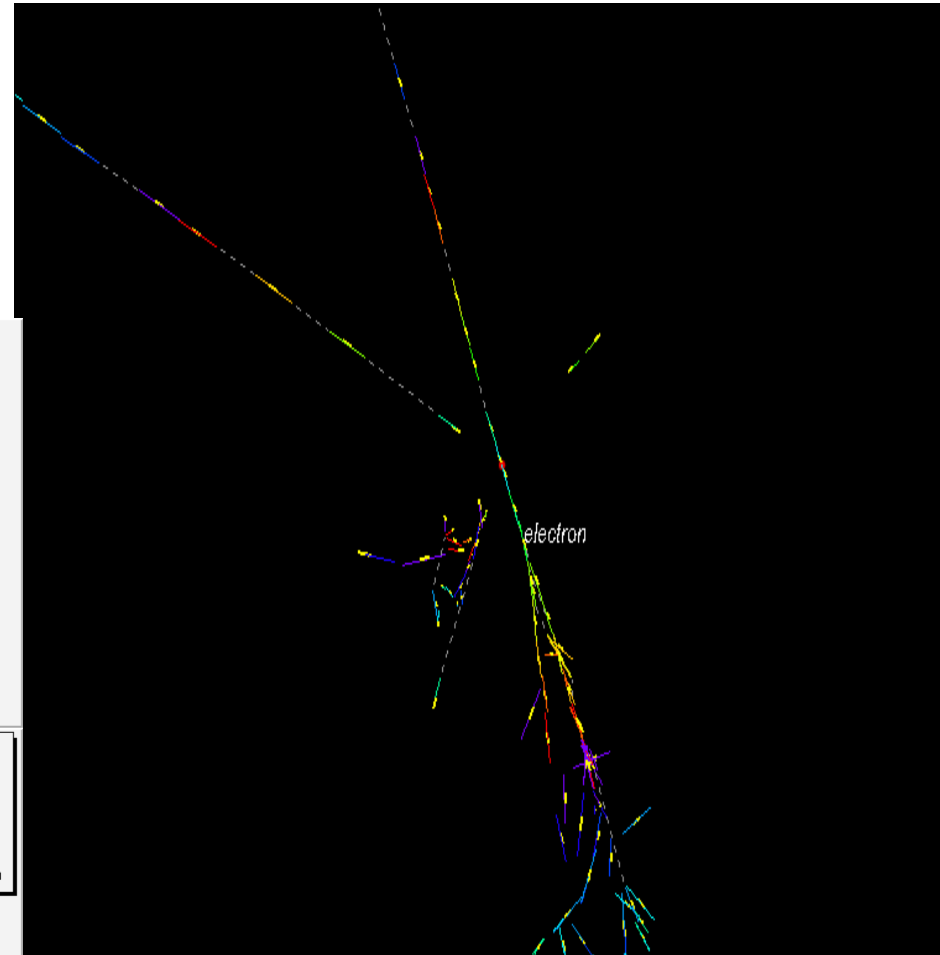


Electron shower pre-selection







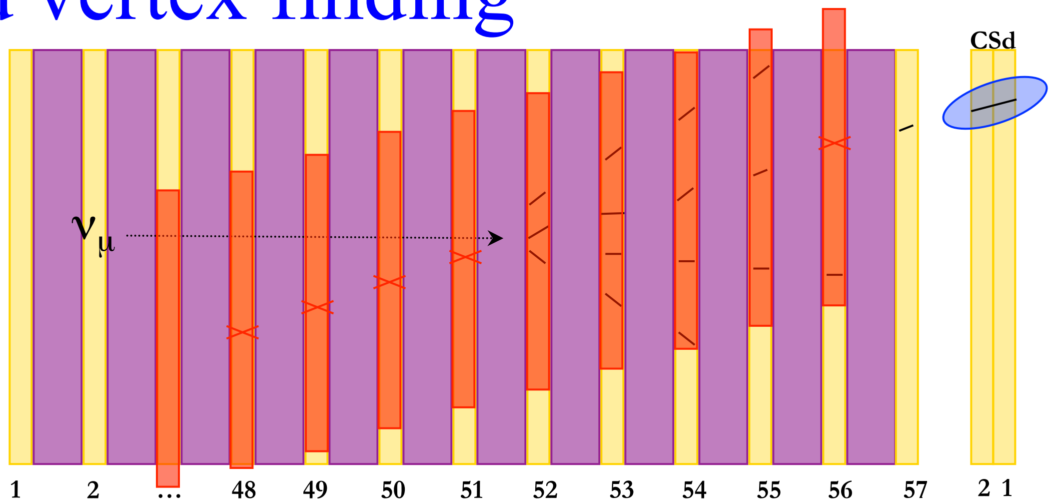


One of the electron neutrinos located as seen after the brick analysis

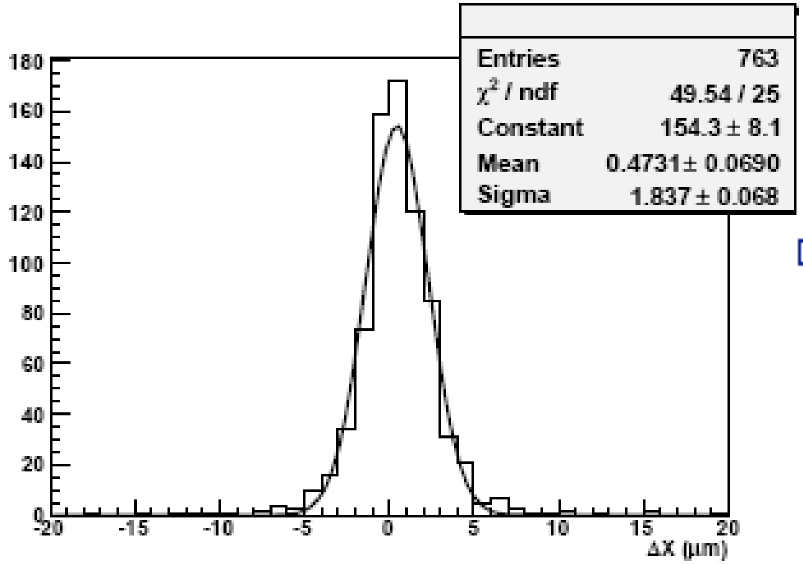
Track follow-up and vertex finding

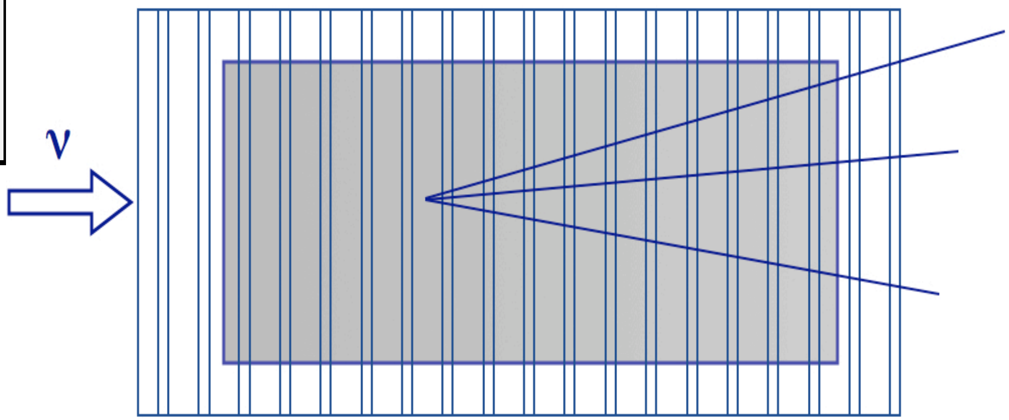
Track follow-up film by film:

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



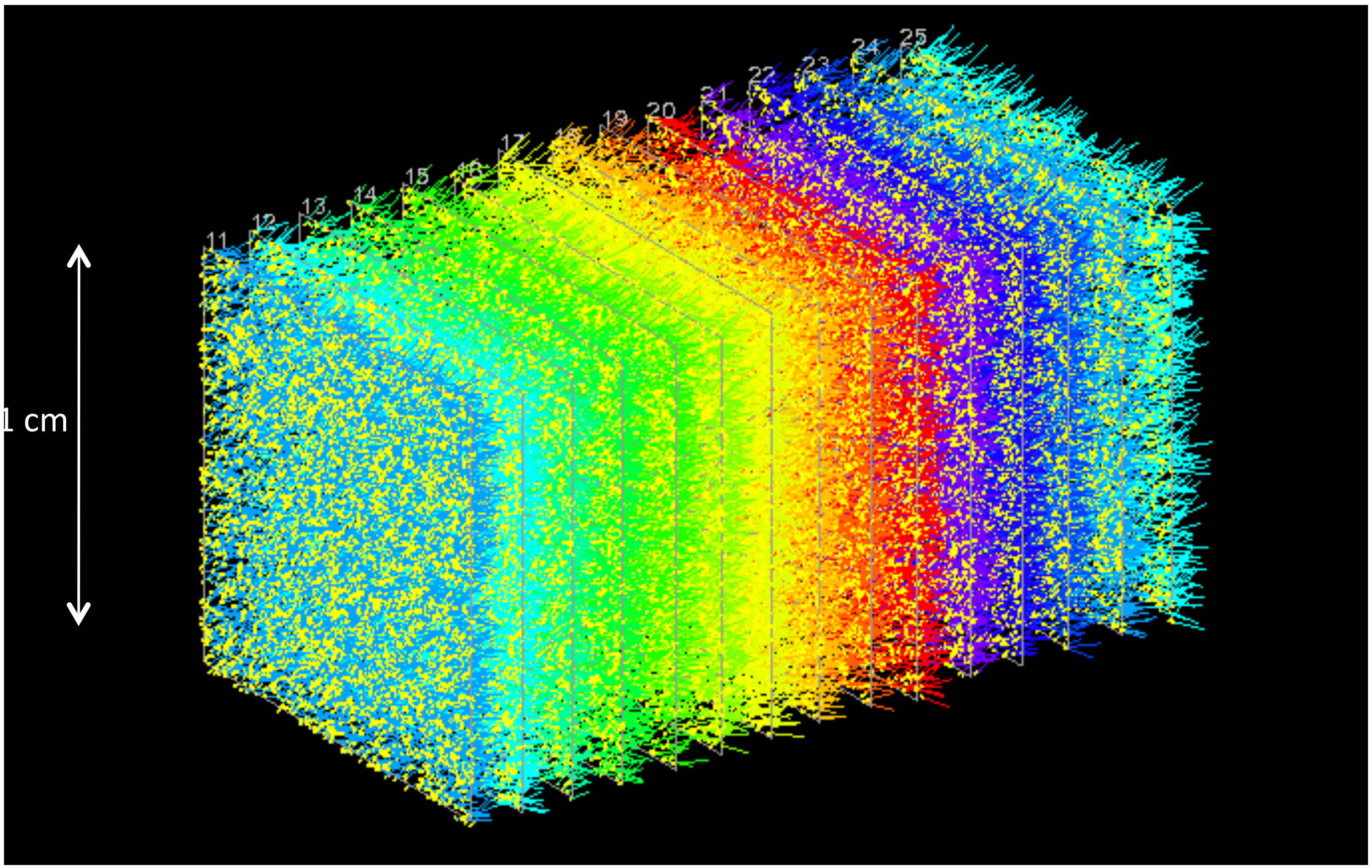
σ ~2 μm



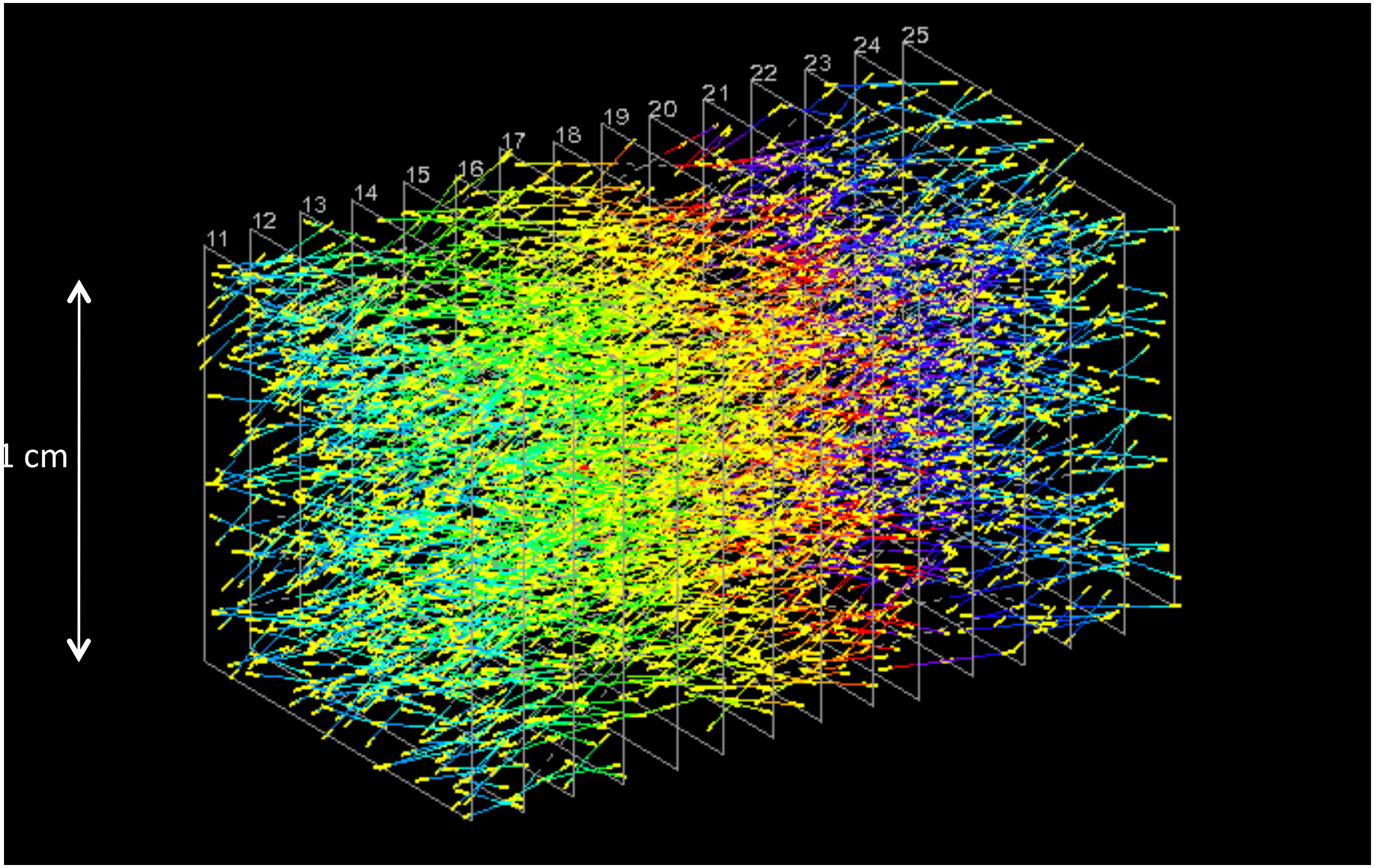


Volume scanning (~2 cm^3) around the stopping point

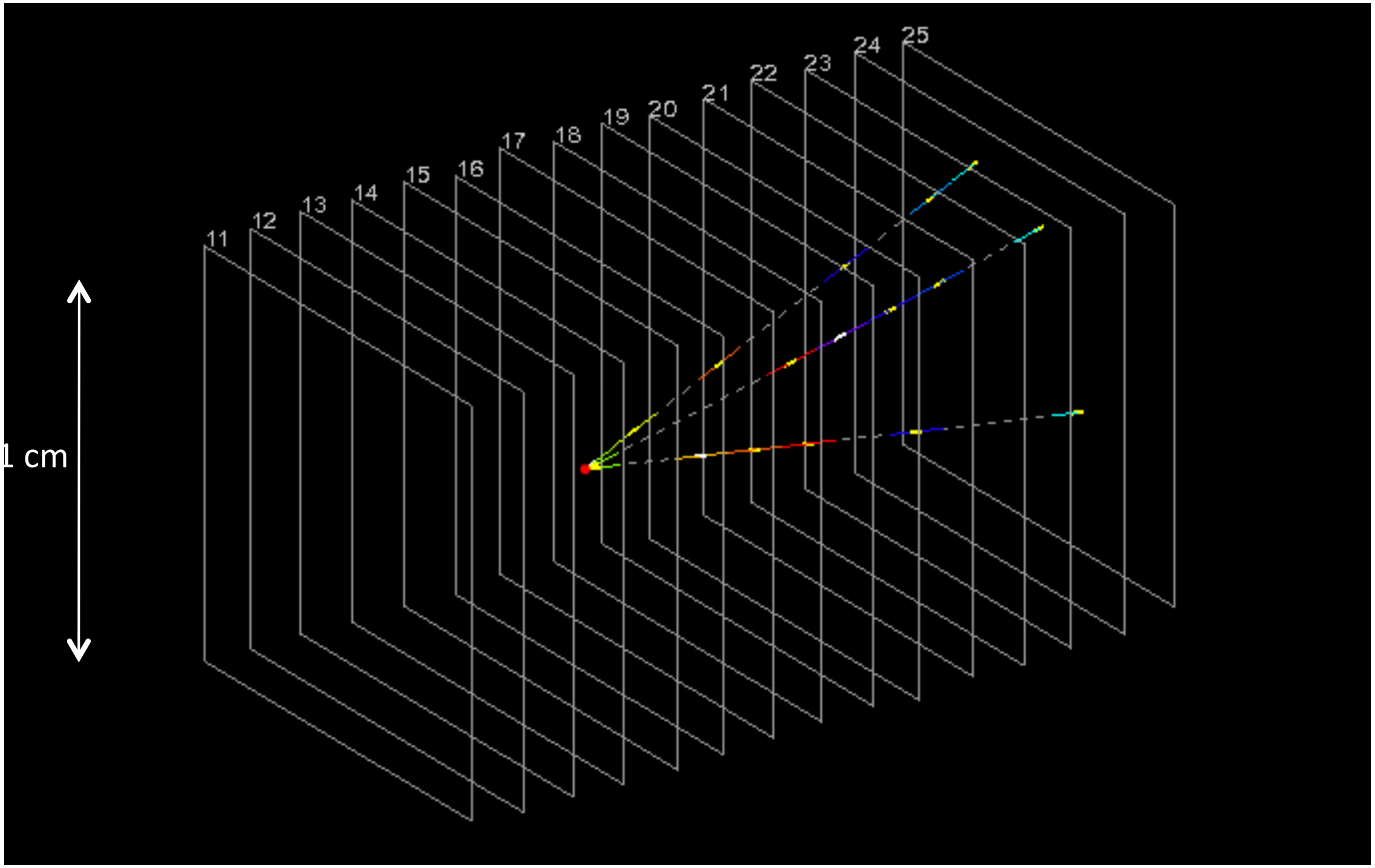
Located neutrino interaction
Volume (~2 cm^3) around the stopping point



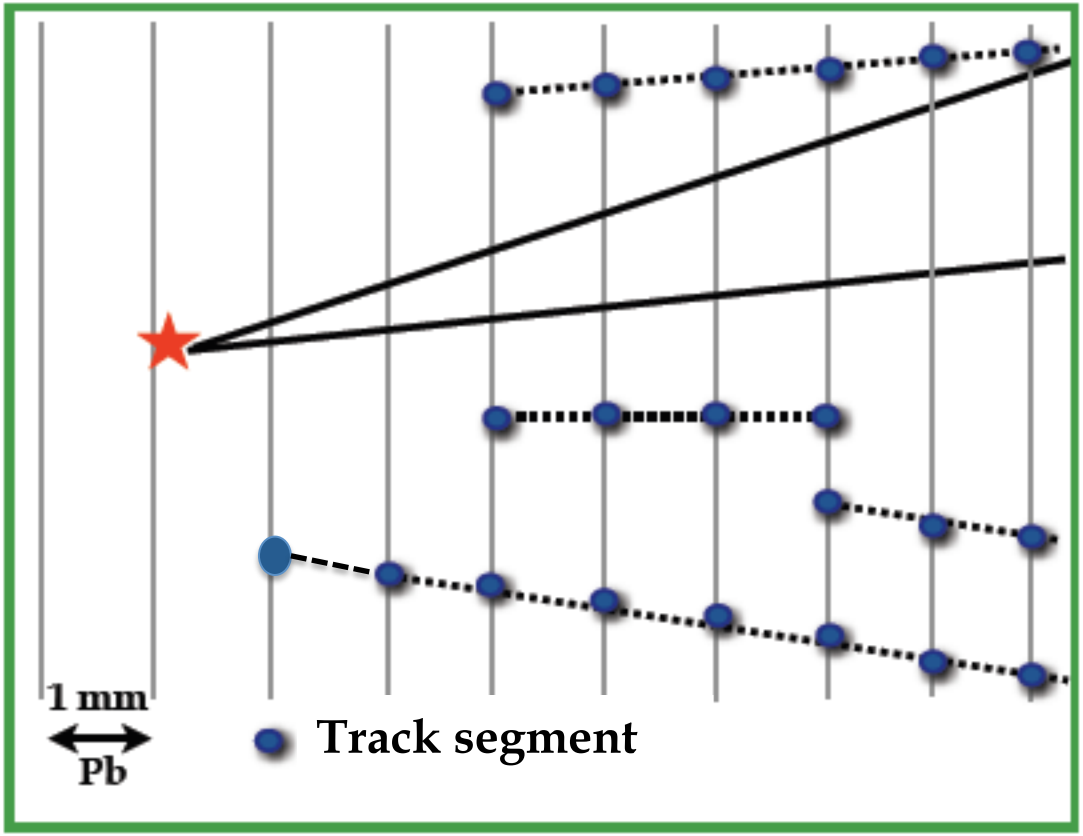
Located neutrino interaction: film to film connection



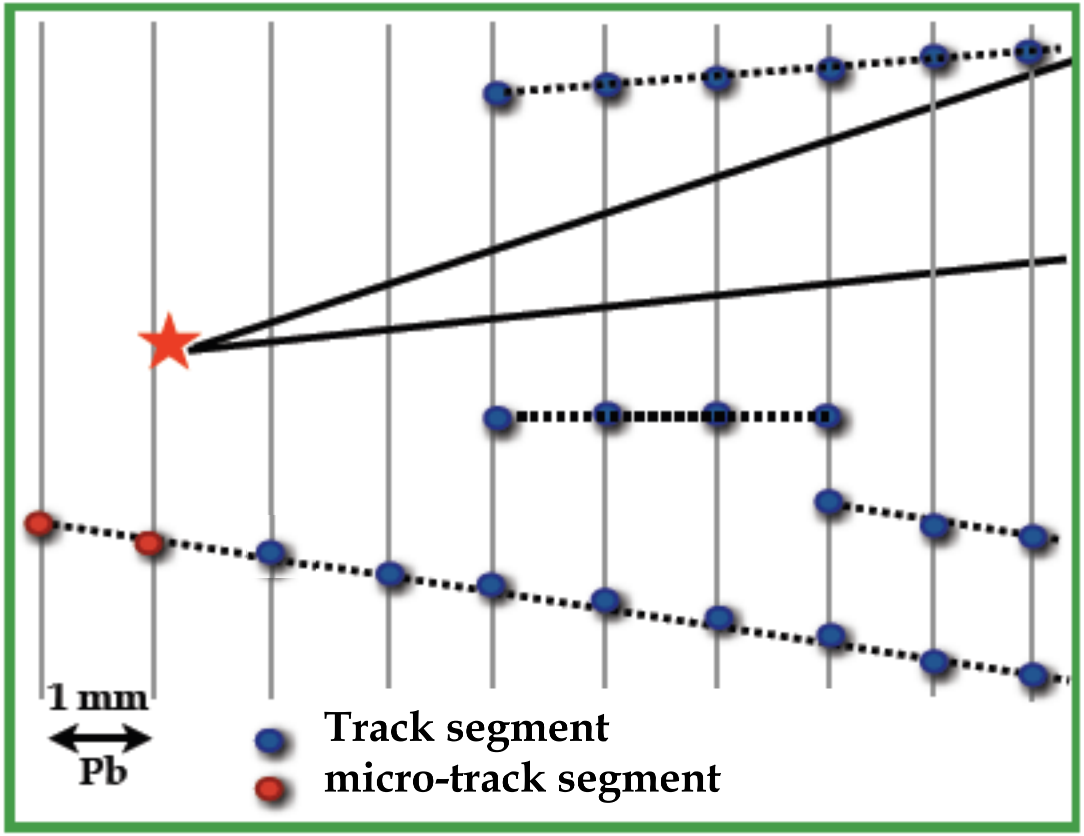
Located neutrino interaction



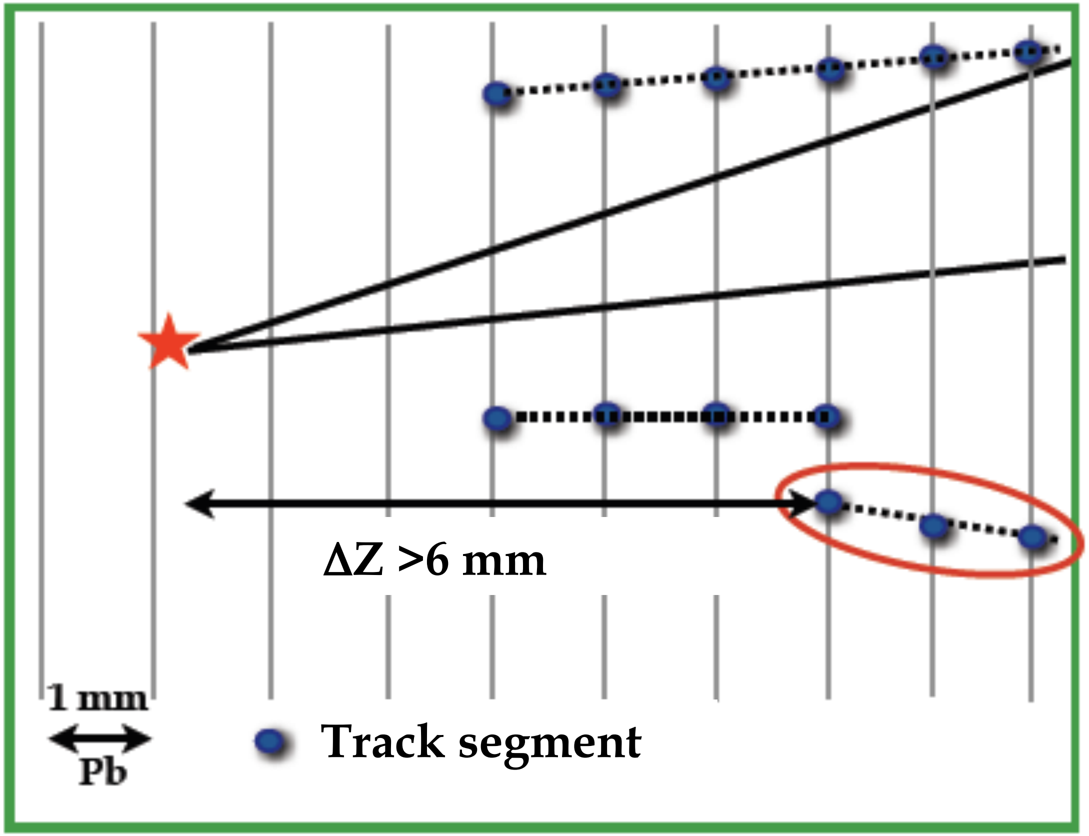
Improved decay search procedure



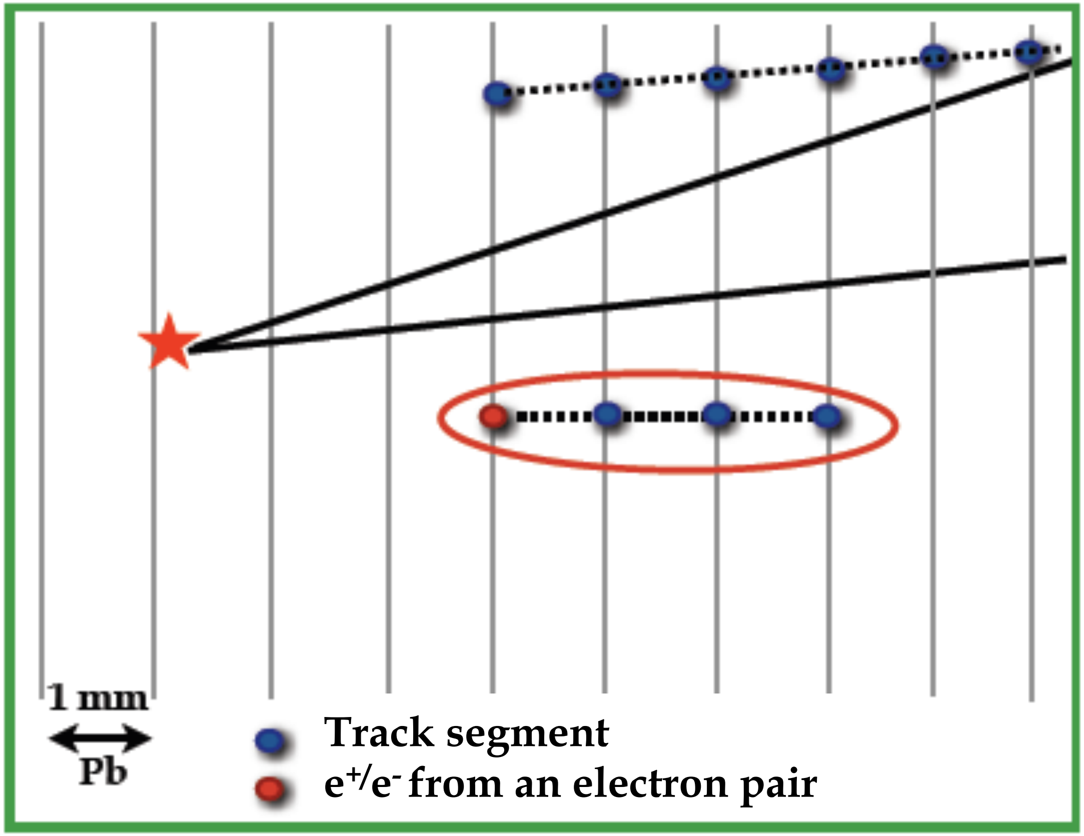
Decay search: penetrating tracks discarded



Decay search: track selection

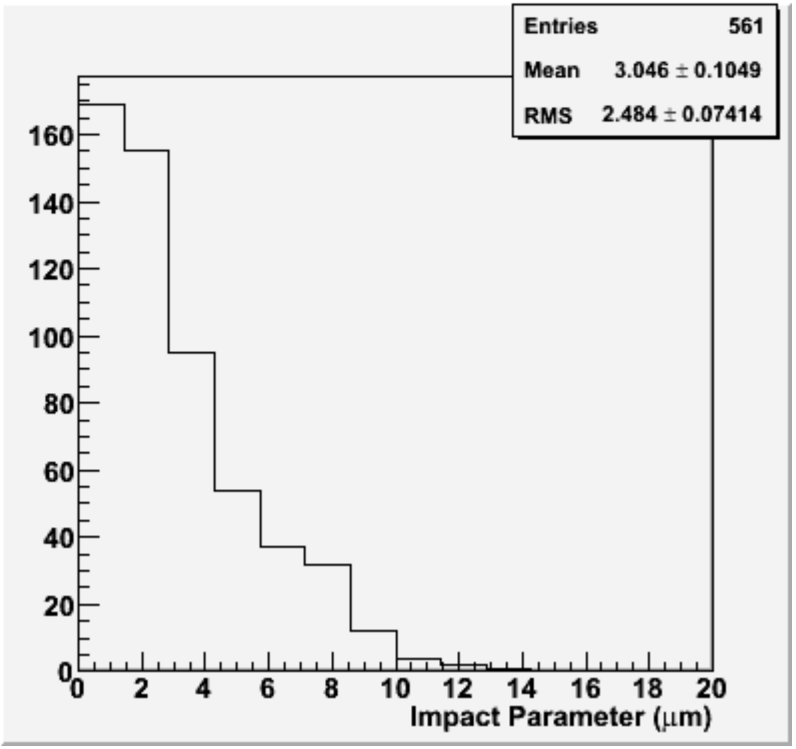


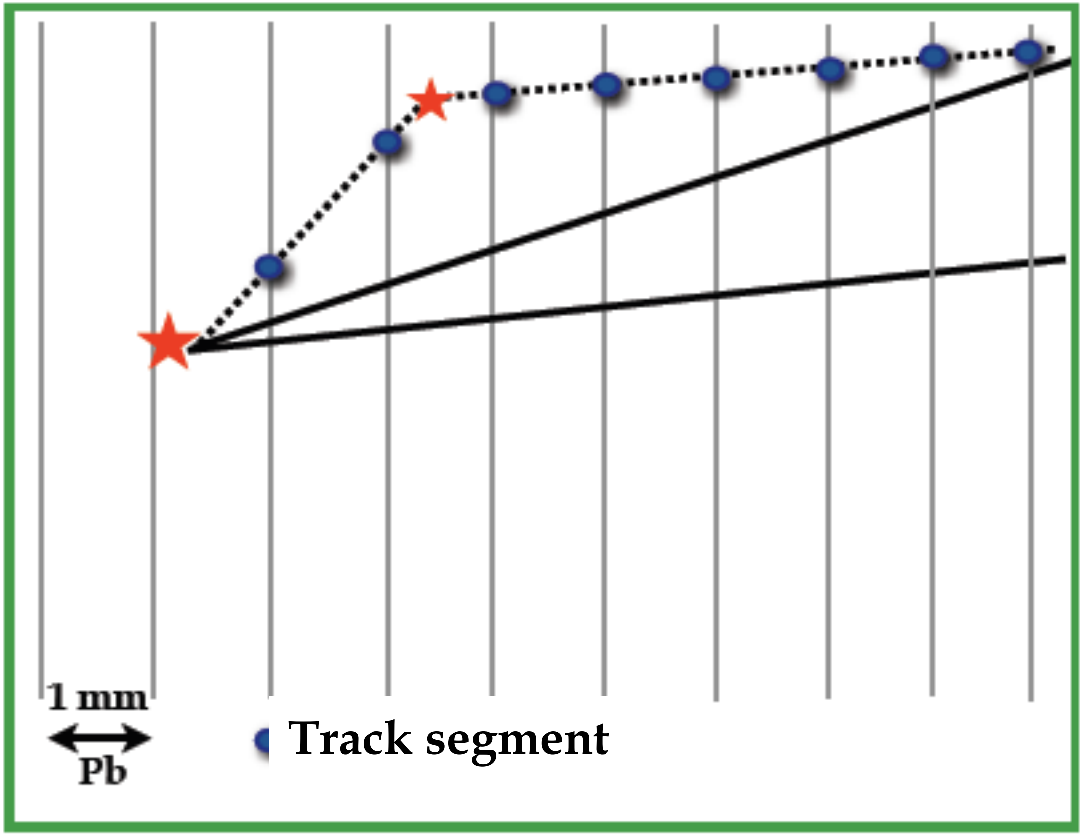
Decay search: electron pair



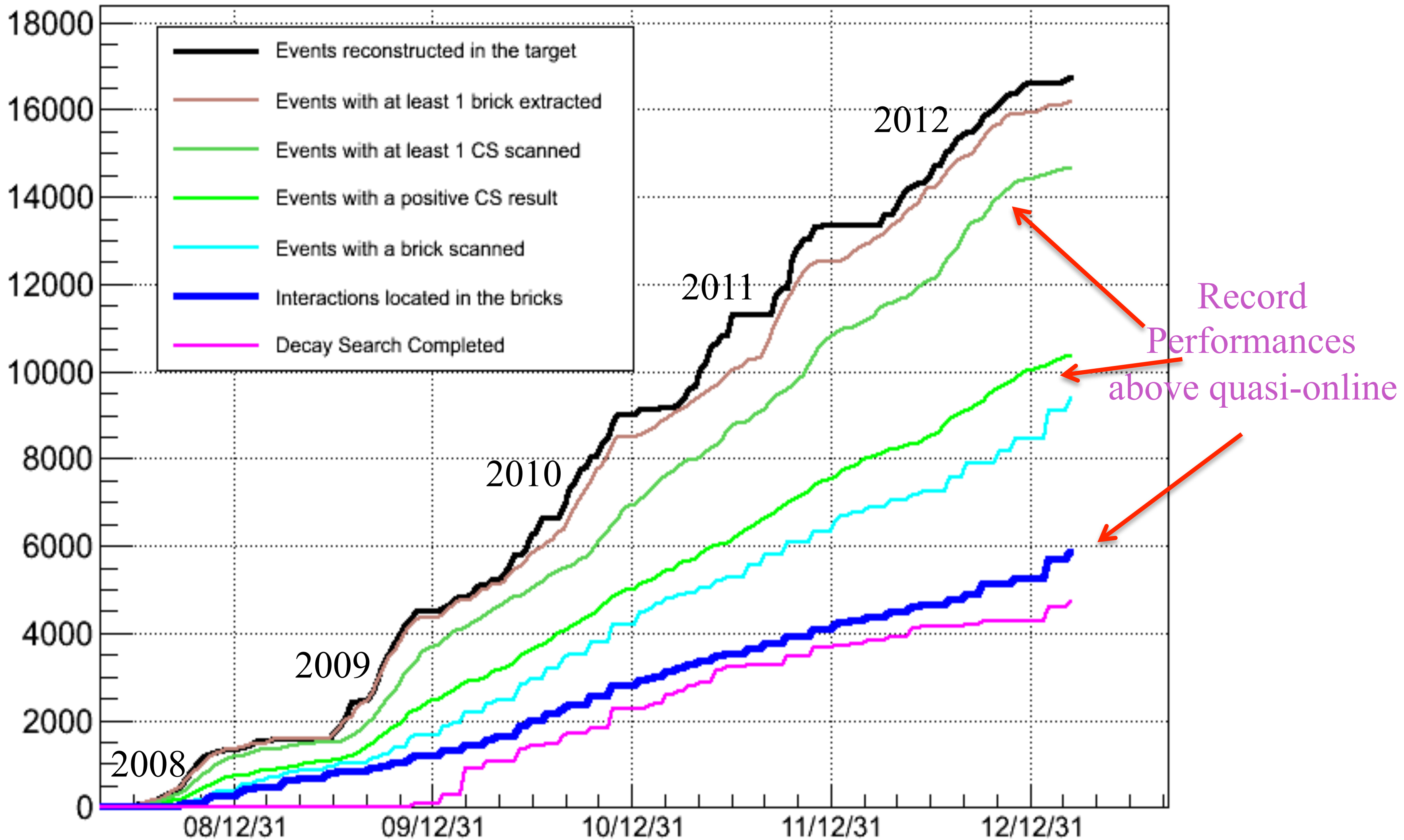
Decay search: kink topology detected

Impact parameter distribution of tracks associated to primary vertices





Status of data analysis



5844 located interactions

4725 decay search

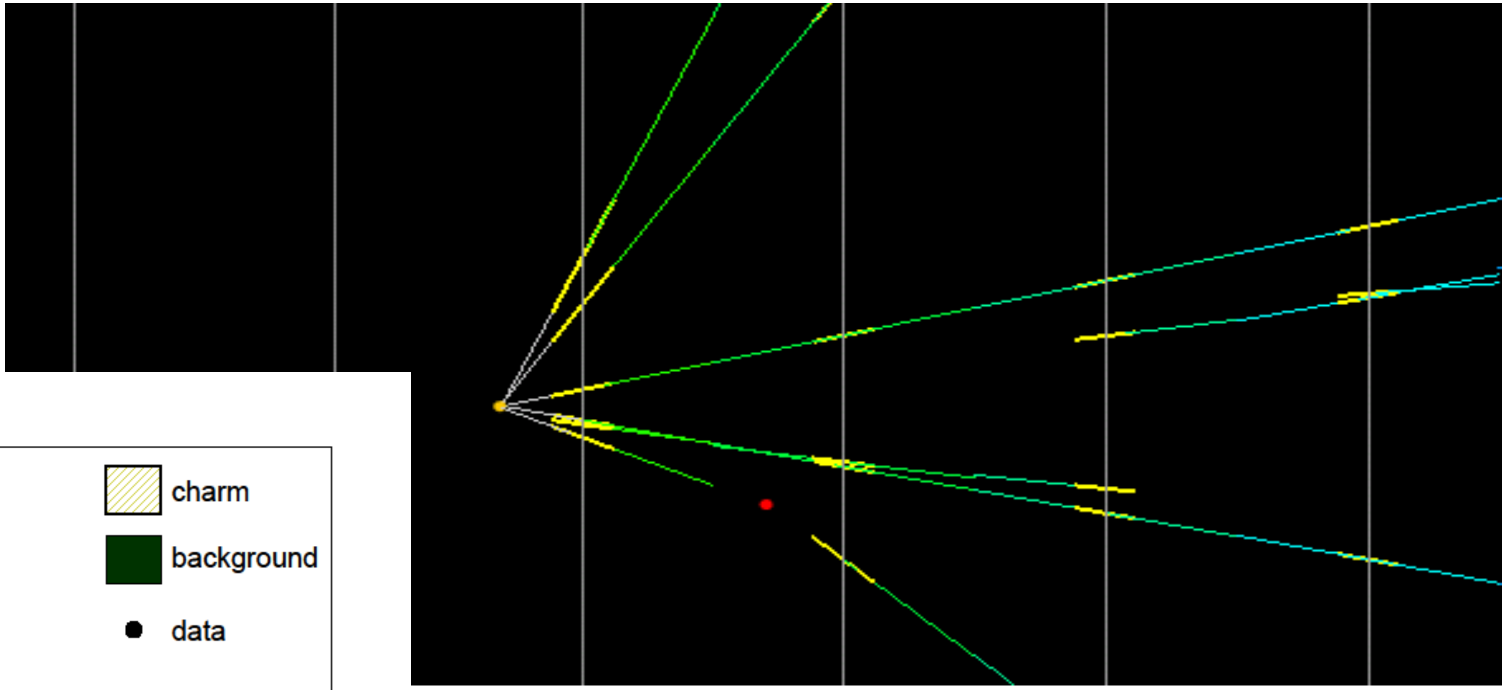
2008-2009 completed

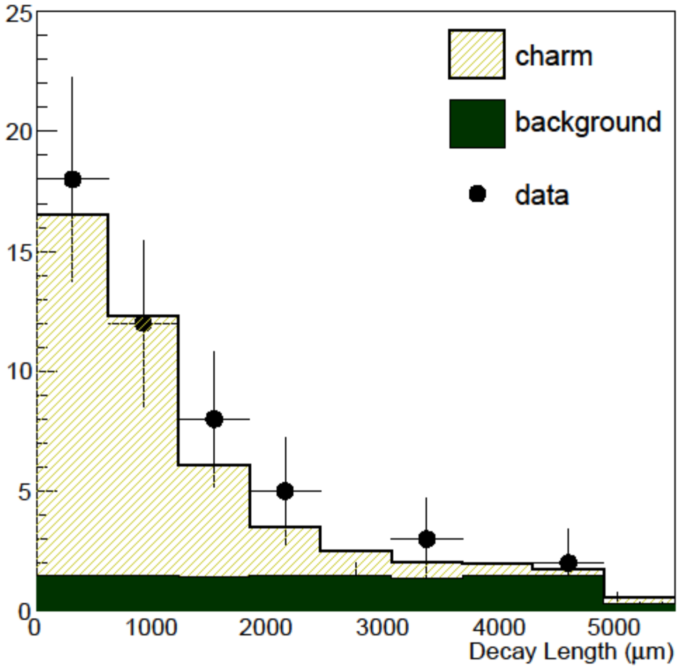
2010 to 2012 ongoing

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



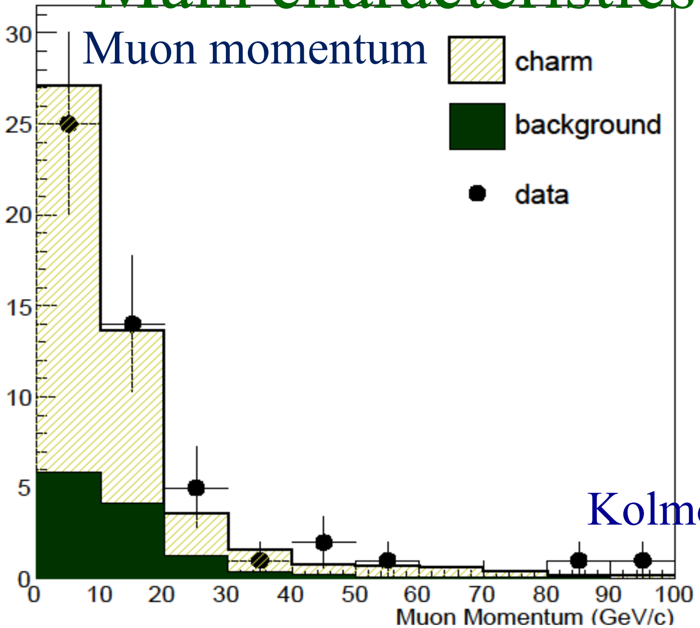


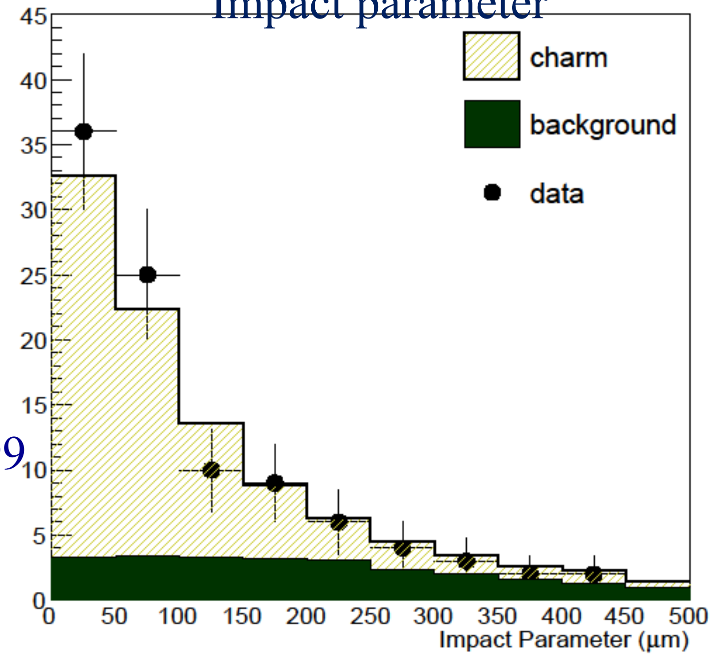
Charm yield from the analysis of 2008÷2010 data

	charm	background	expected	data
1 prong	20.5 ± 9.1	9 ± 3	29.5 ± 9.6	19
2 prong	14.9 ± 3.6	3.8 ± 1.1	18.7 ± 3.8	22
3 prong	4.6 ± 2.0	1.0 ± 0.3	5.6 ± 2.0	5
4 prong	0.8 ± 0.4	-	0.8 ± 0.4	4
All	**40.8±9.8**	**13.8±3.2**	**55±10**	**50**

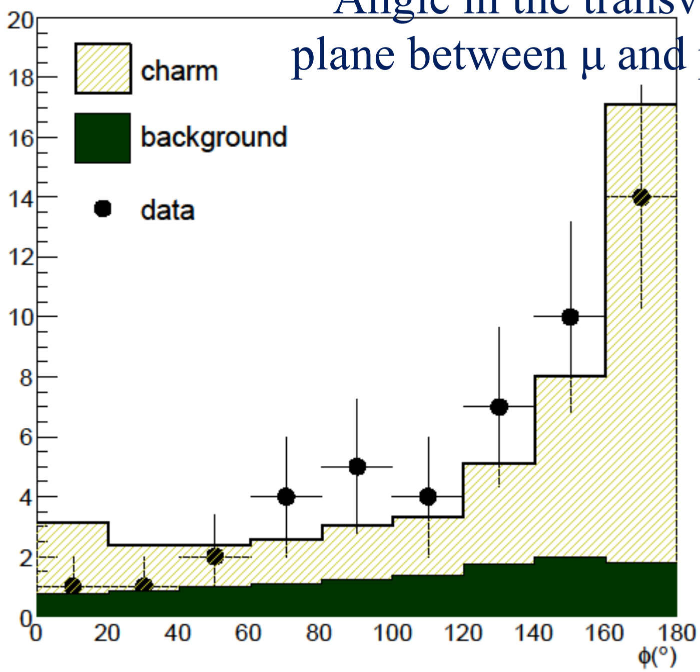
Background, mostly from hadronic interactions
(contribution from strange particle decay)

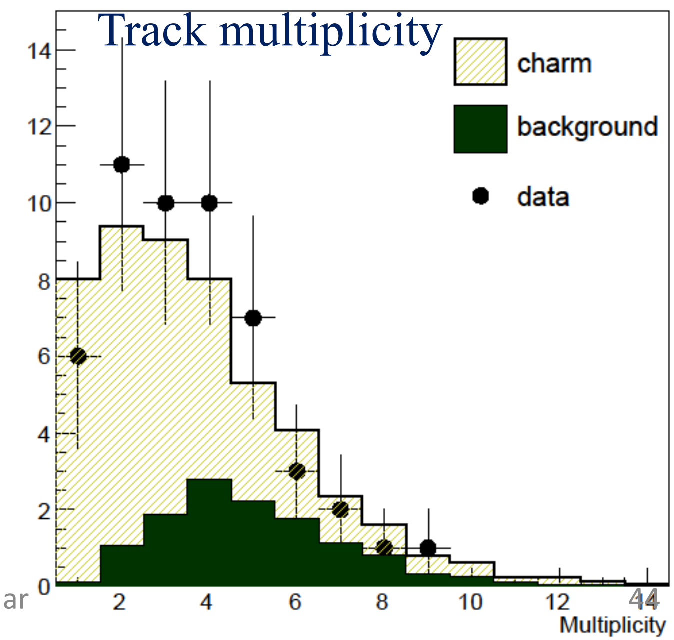
Main characteristics of the charm candidate events





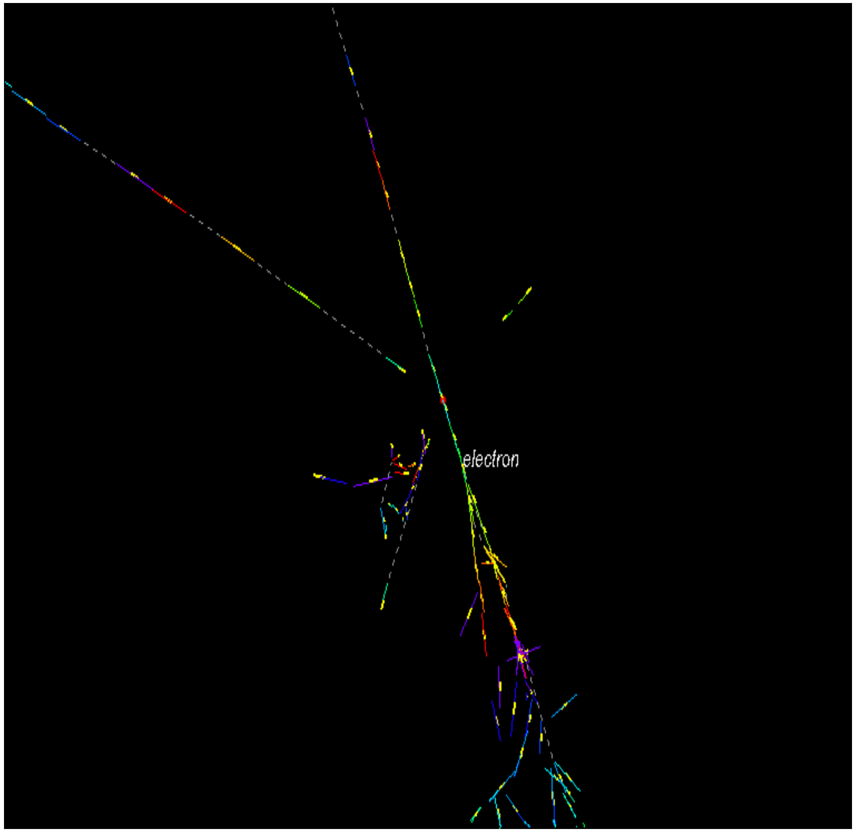
Kolmogorov test ≥ 0.99
all plots



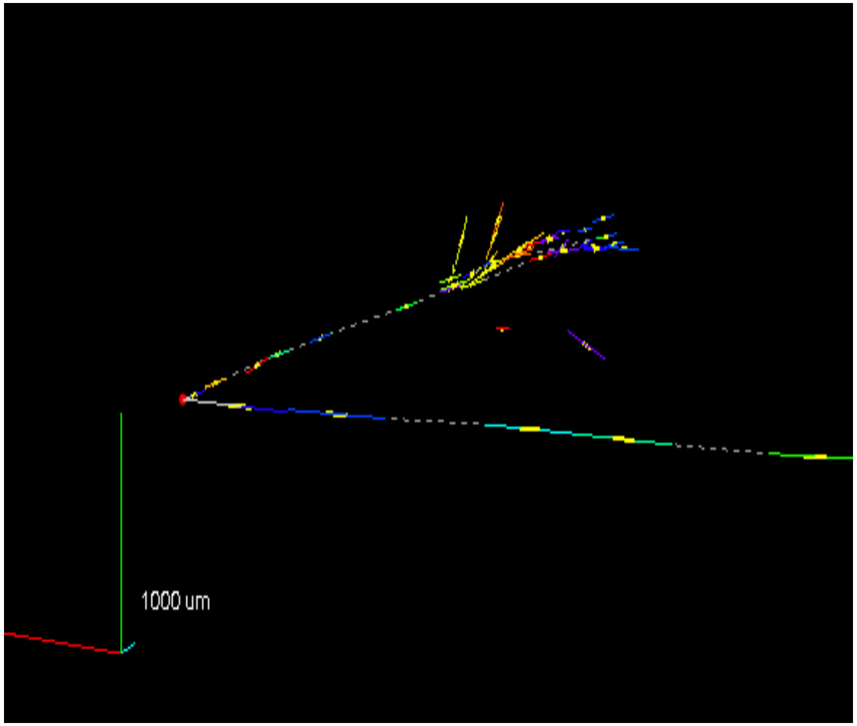


Physics results

$\nu_\mu \rightarrow \nu_e$ analysis

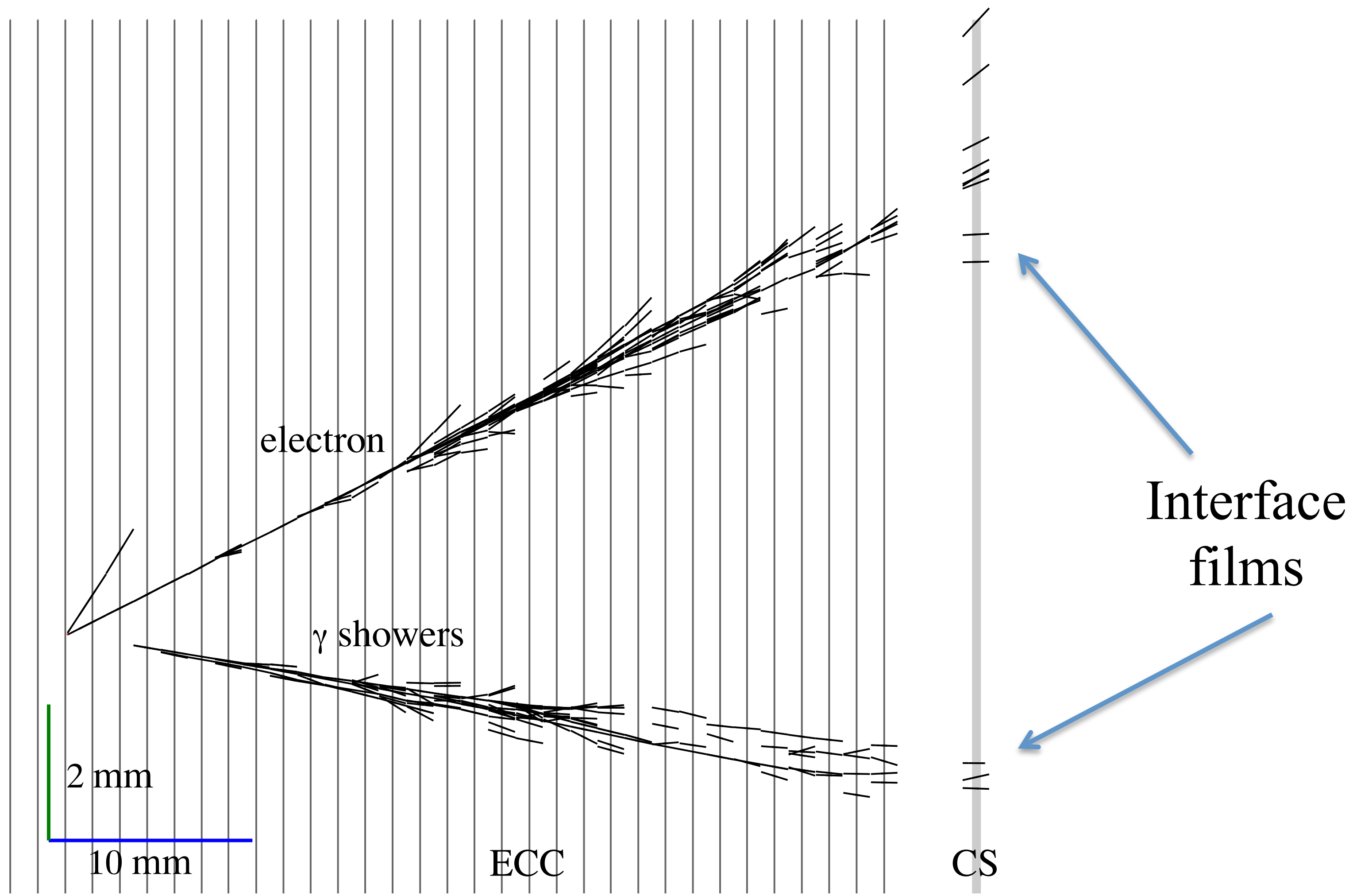


4.1 GeV electron



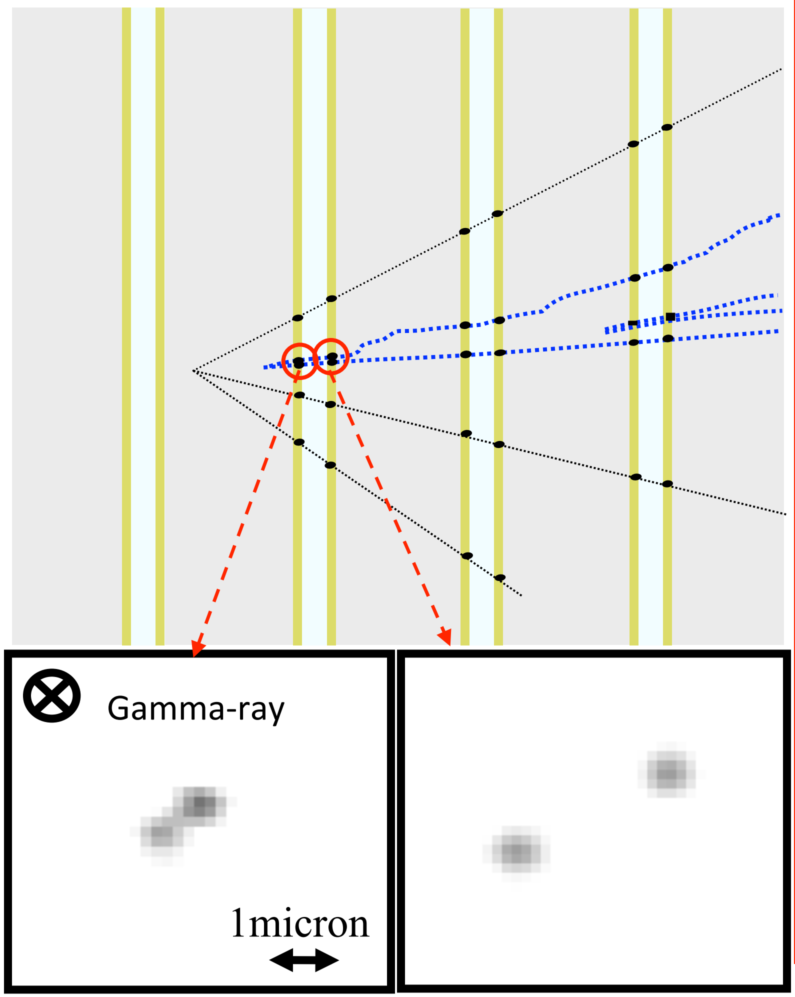
≈ 30 events found in the analyzed sample

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

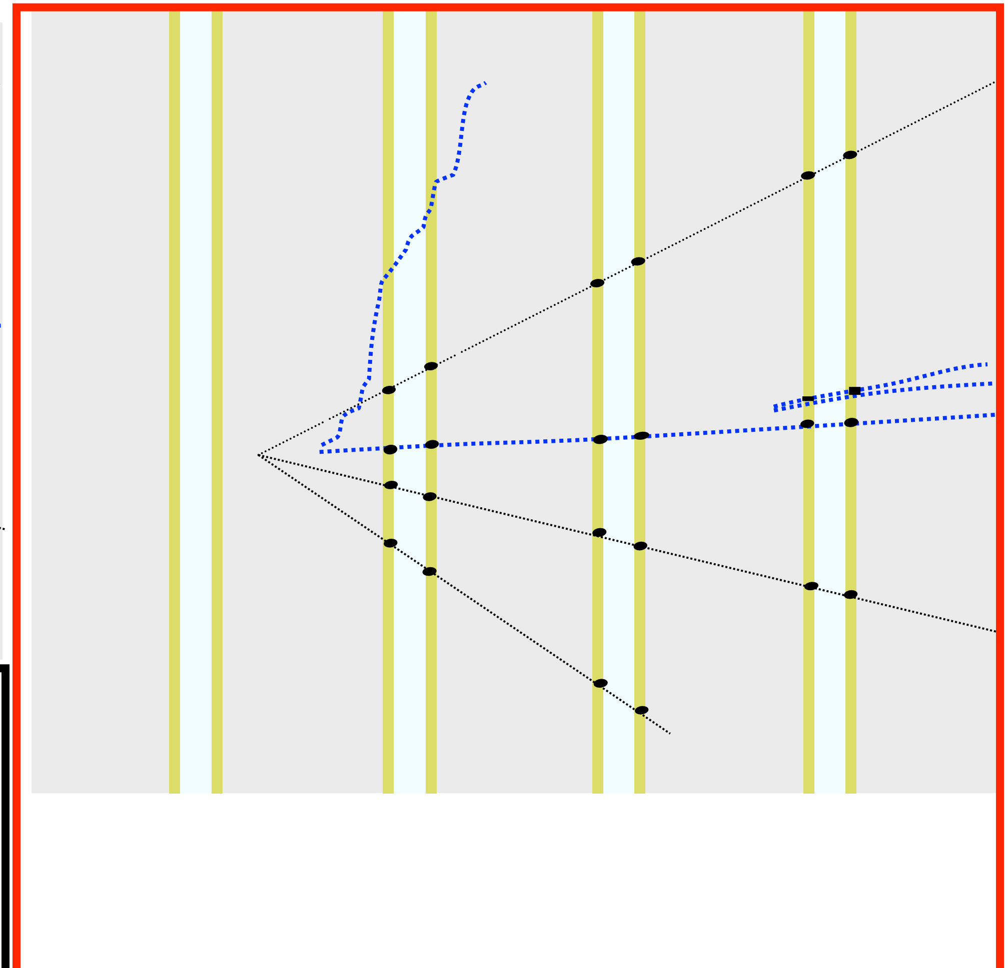


19 candidates found in a sample of 505 neutrino interactions without muon

Background from ν_μNC ($\pi^0 \to \gamma\gamma$)

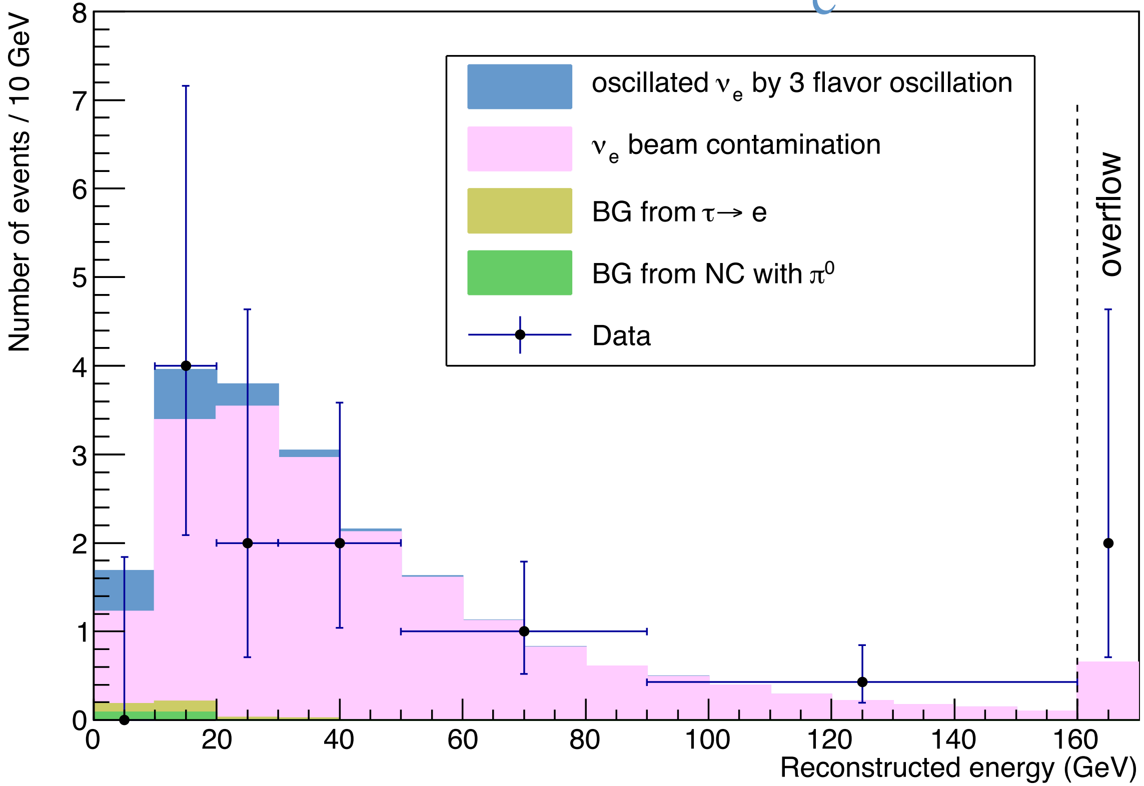


A close-up of an electron pair



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

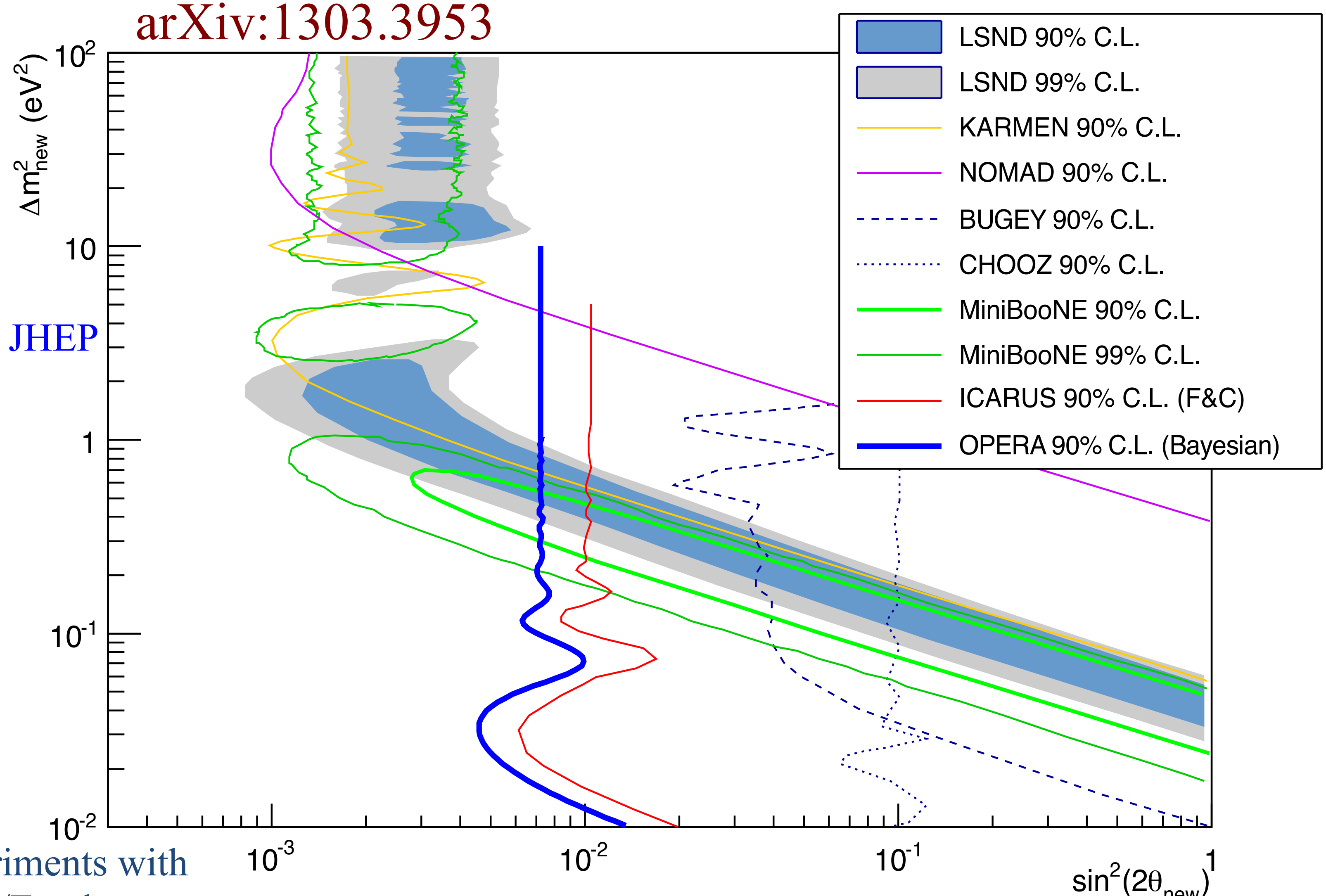
Energy cut to increase the S/N

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 $\sin^2(2\theta_{new})$ - Δm^2_{new} plane

arXiv:1303.3953

Submitted to JHEP



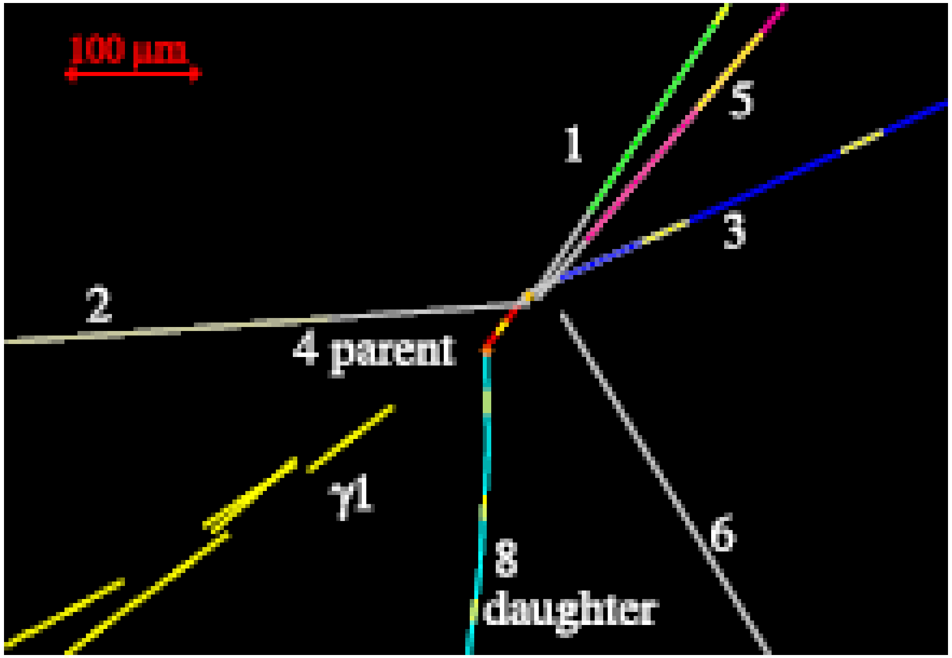
Caveat: experiments with different L/E values

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

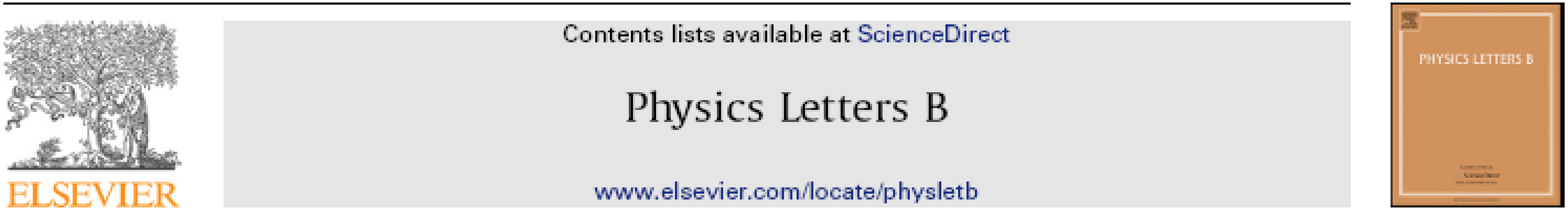
- 2008-2009 run analysis
- Conservative approach: get confidence on the detector performances before applying any kinematical cut
- No kinematical cut
- Slower analysis speed (signal/noise not optimal)
- Good data/MC agreement

The first ν_τ "appearance" candidate (2010)

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

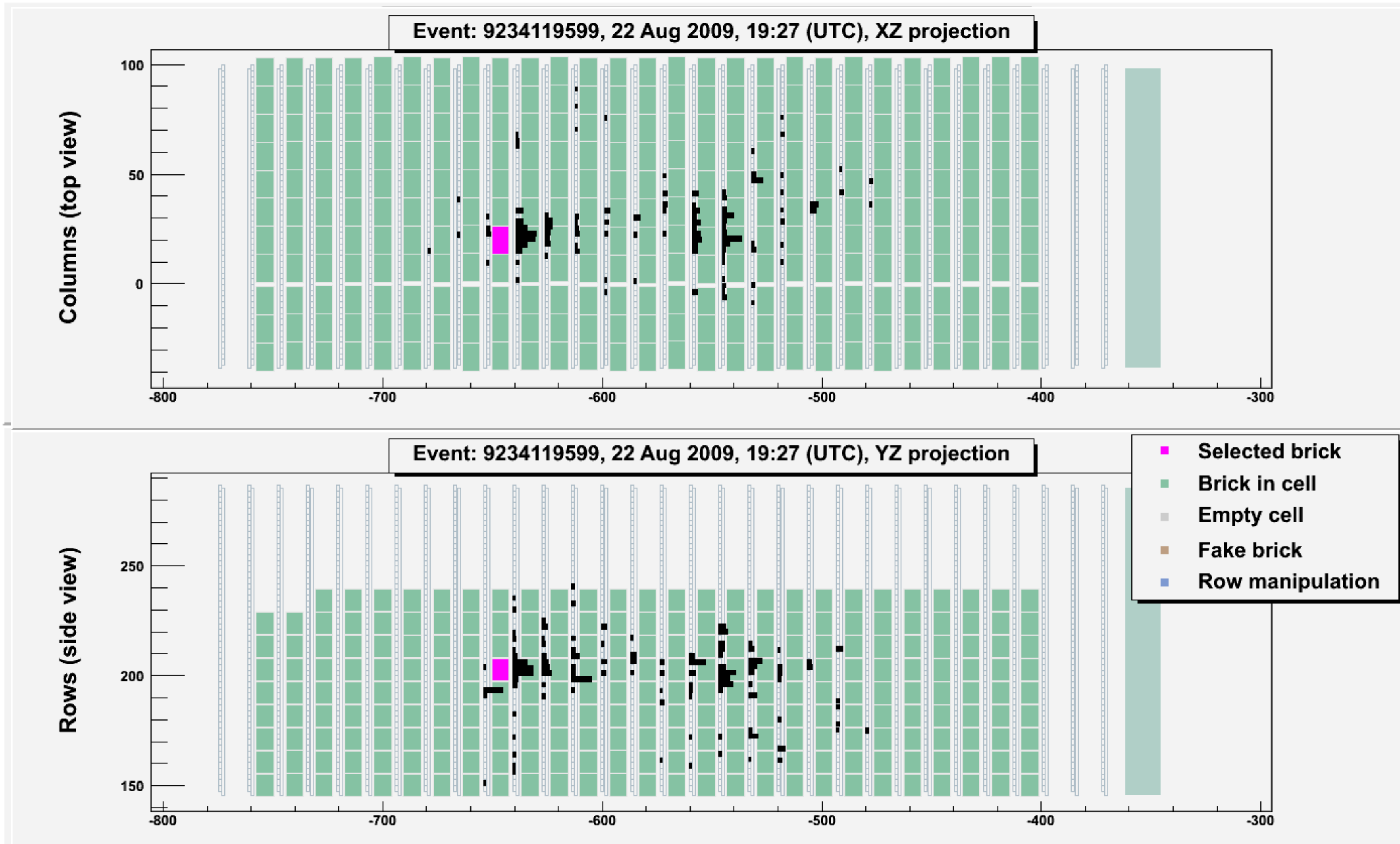


Physics Letters B 691 (2010) 138–145

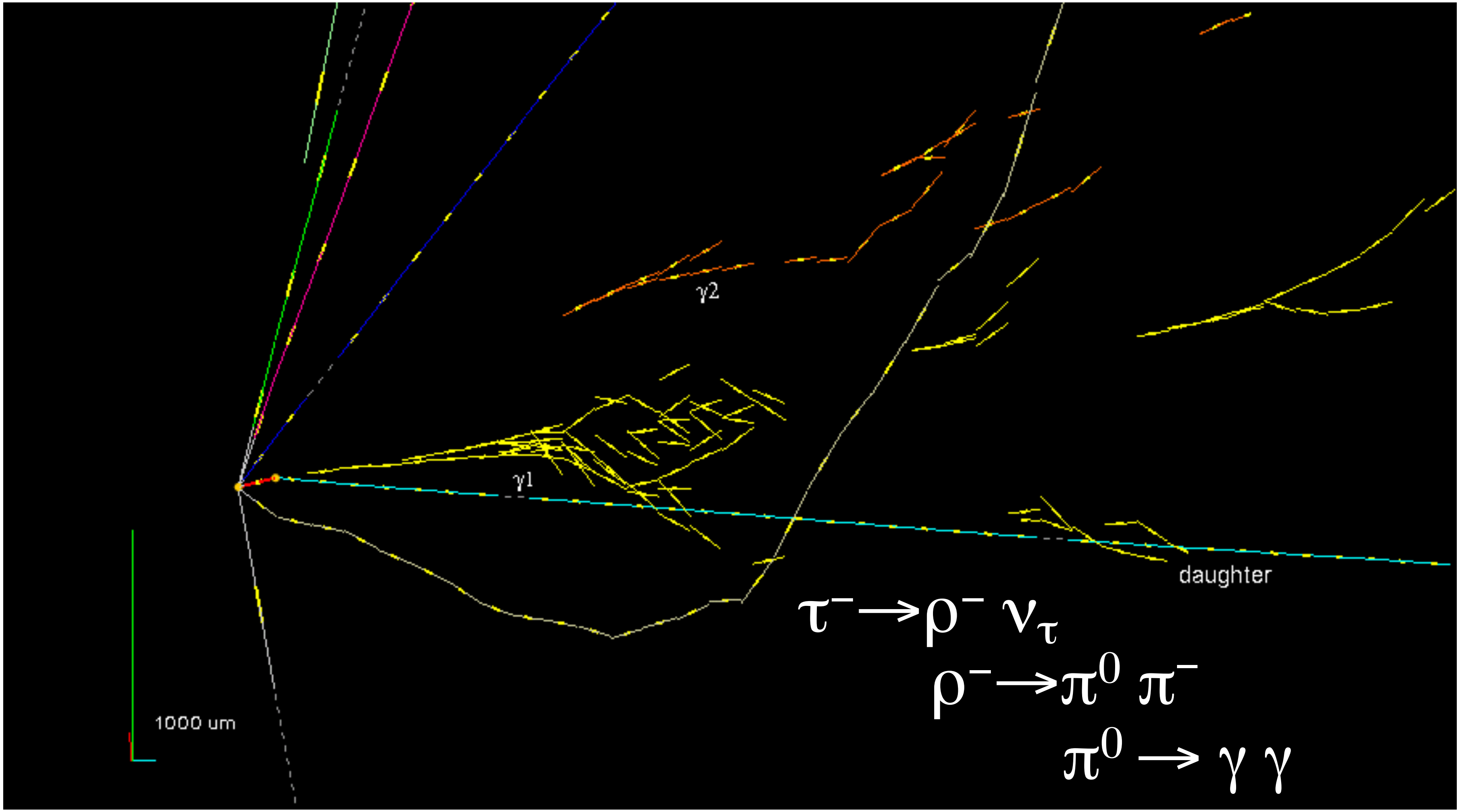


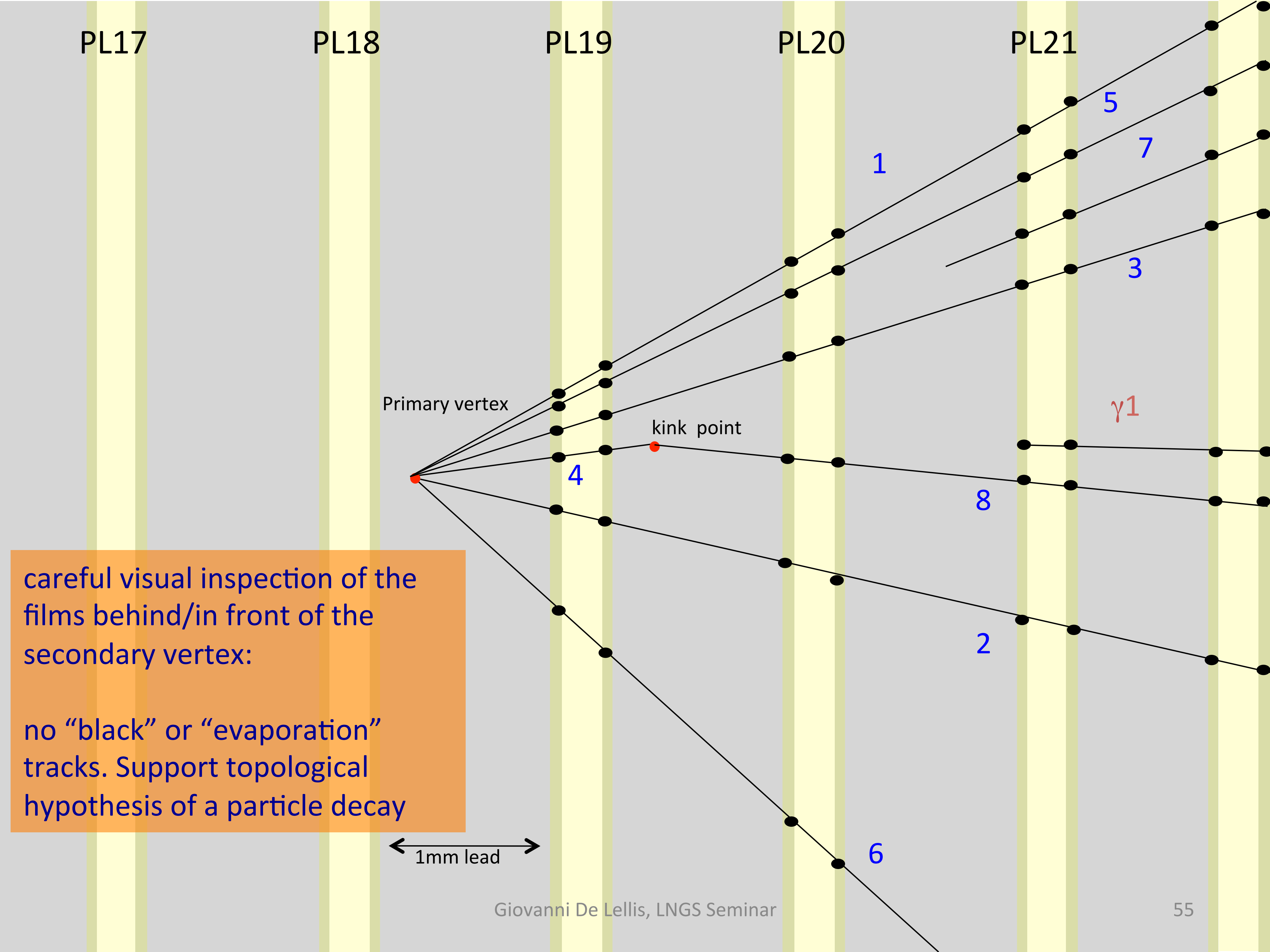
Observation of a first ν_τ candidate event in the OPERA experiment in the CNGS beam

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



Event reconstruction in the brick





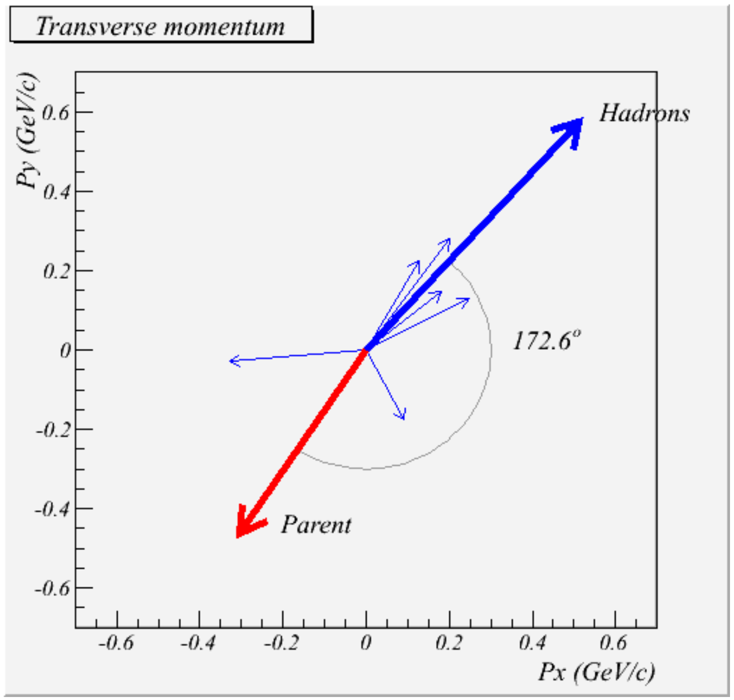
careful visual inspection of the films behind/in front of the secondary vertex:

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

Kinematical variables

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

- γ1 and γ2 both attached to 2^{ry} vertex

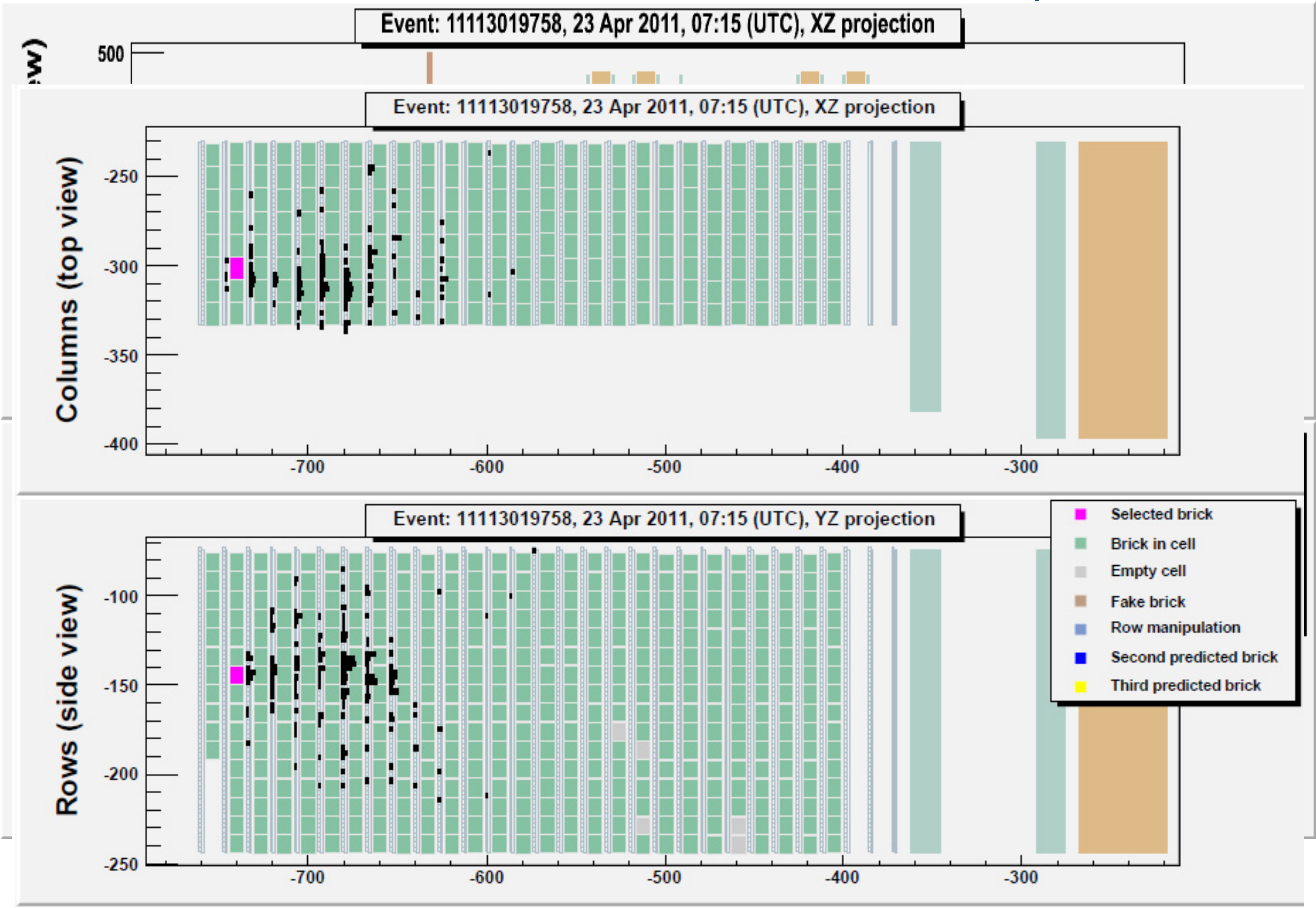


VARIABLE	AVERAGE
kink (mrad)	**41 ± 2**
decay length (μm)	**1335 ± 35**
P daughter (GeV/c)	**12^{+6}_{-3}**
Pt (MeV/c)	**470^{+240}_{-120}**
missing Pt (MeV/c)	**570^{+320}_{-170}**
ϕ (deg)	**173 ± 2**

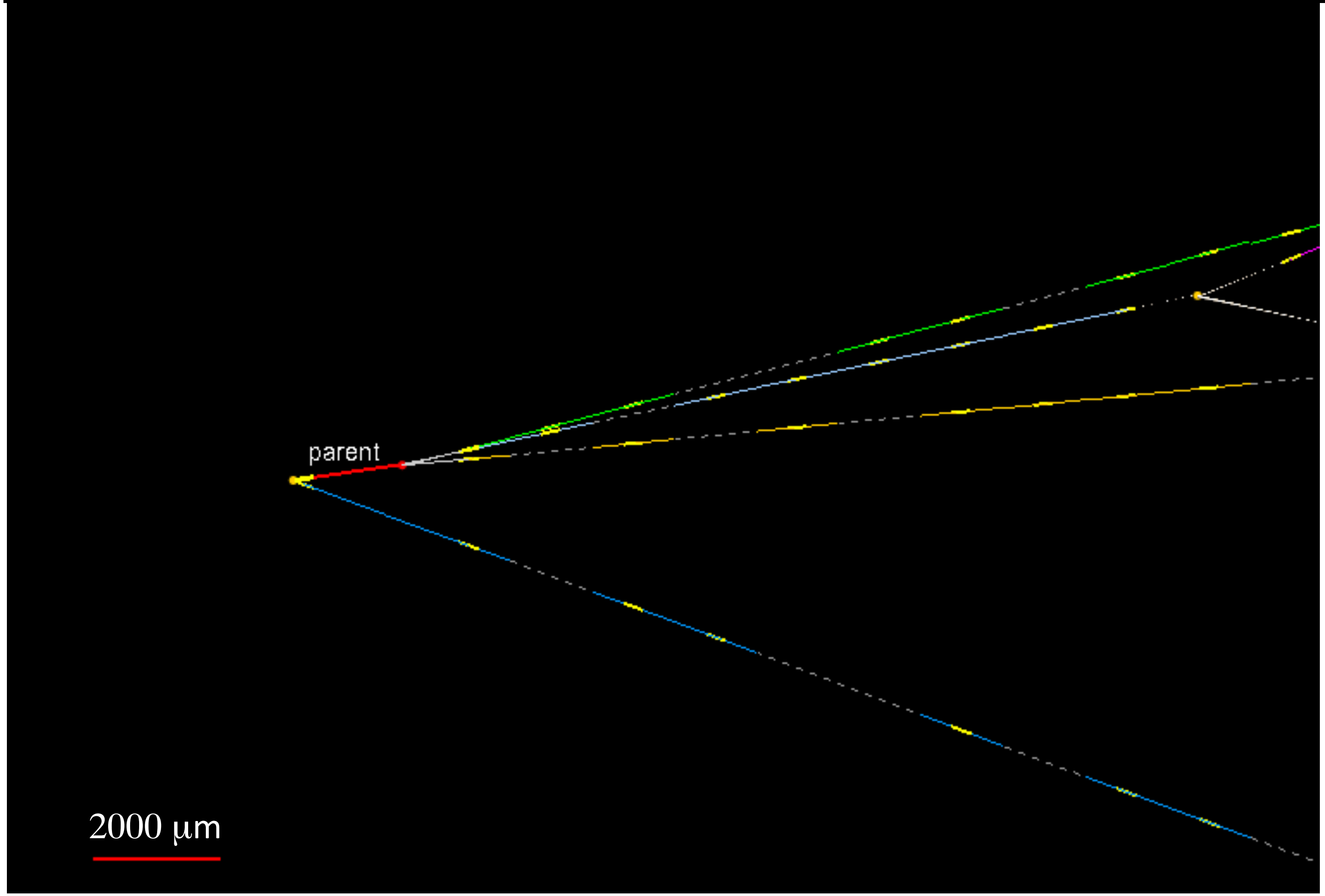
Strategy for the 2010÷2012 runs

- 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: 1μ sample for 2010 run, for 2011 run stick to 0μ sample only, 2012 not yet analysed

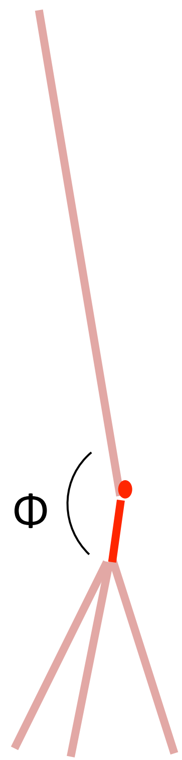
Second neutrino tau candidate event taken on 23rd April 2011



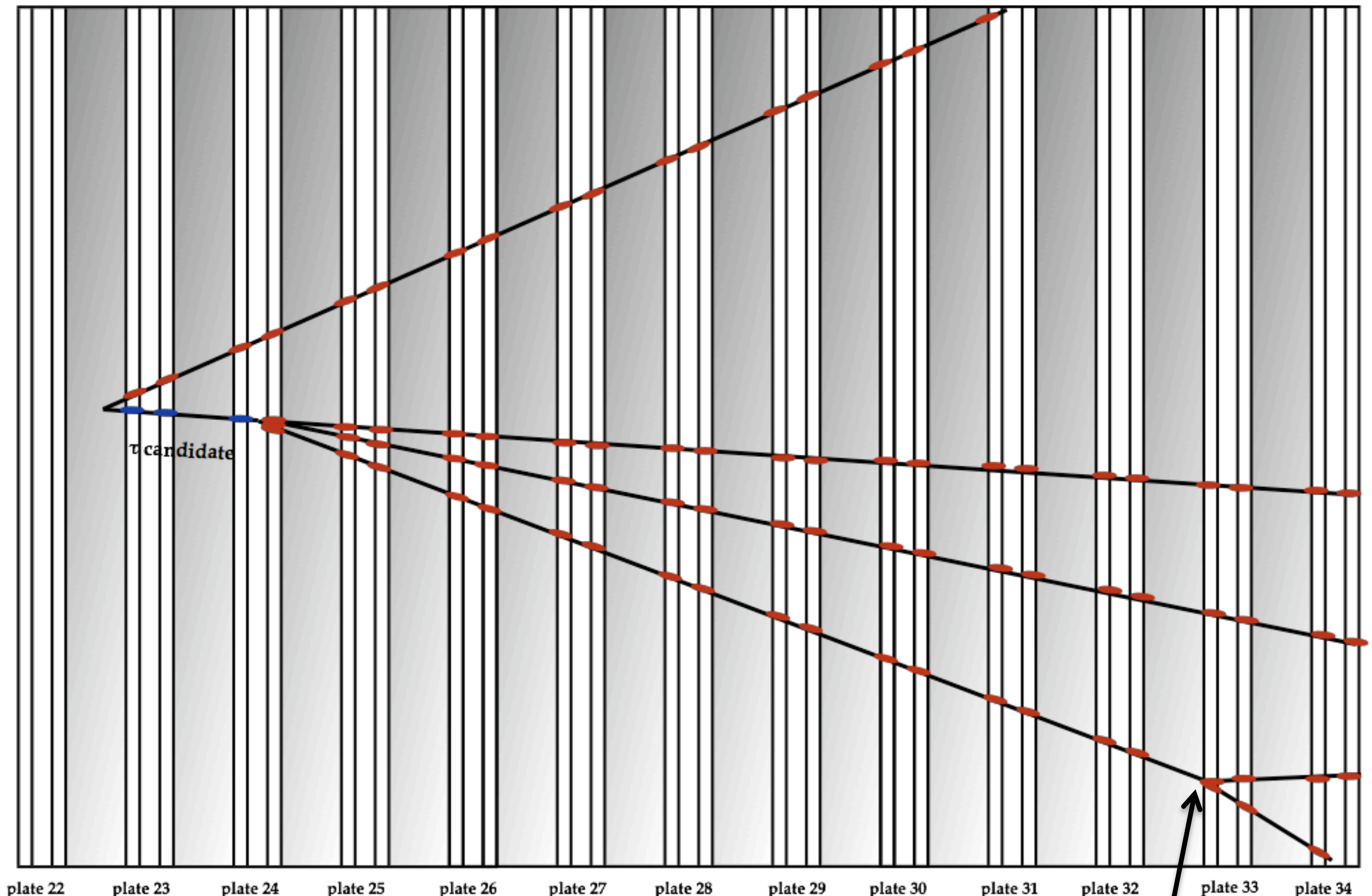
Second ν_τ Candidate Event



Schematics of the event

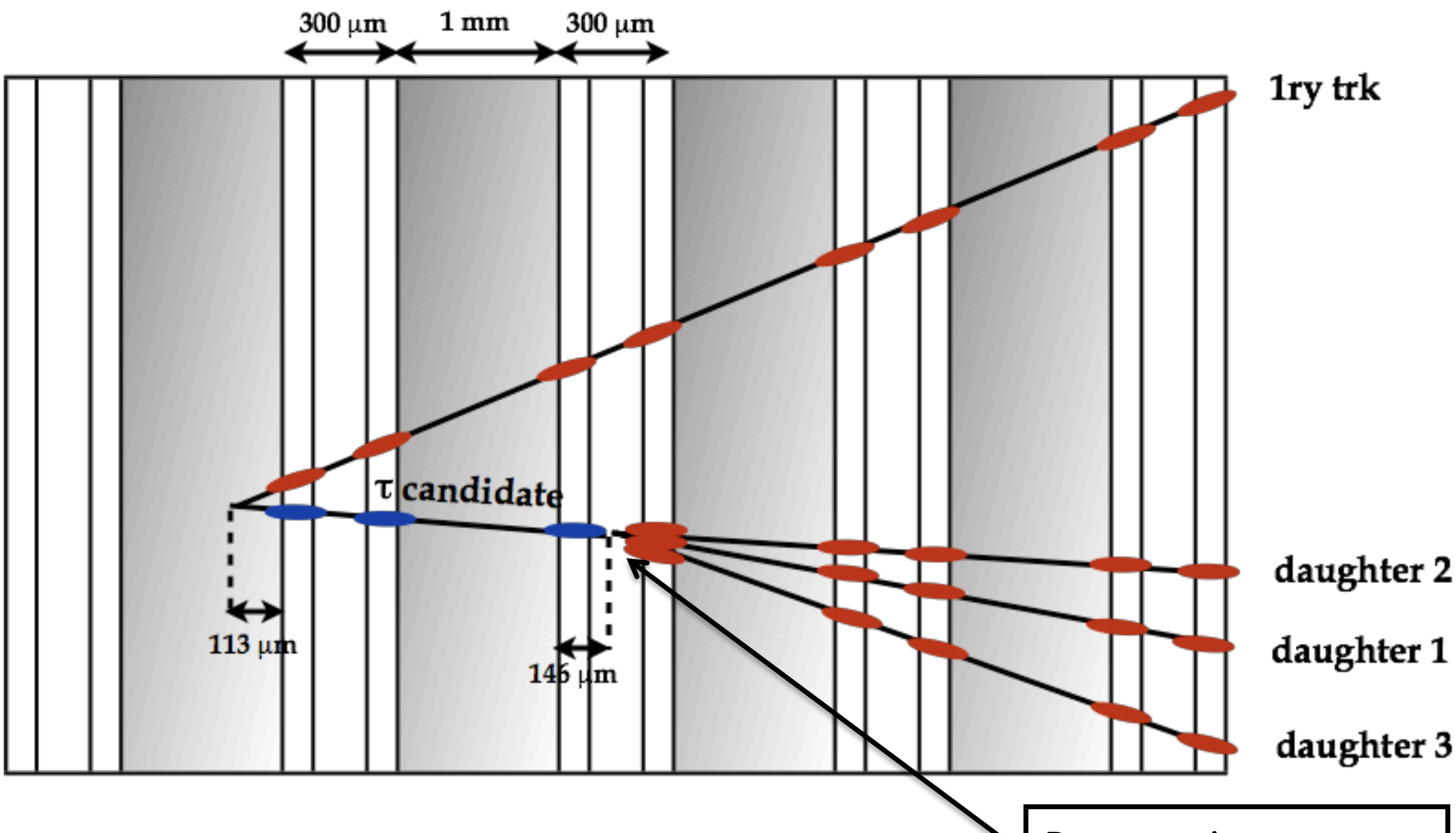


Beam View
Φ=167°



Secondary Interaction
<u>In Emulsion</u>
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

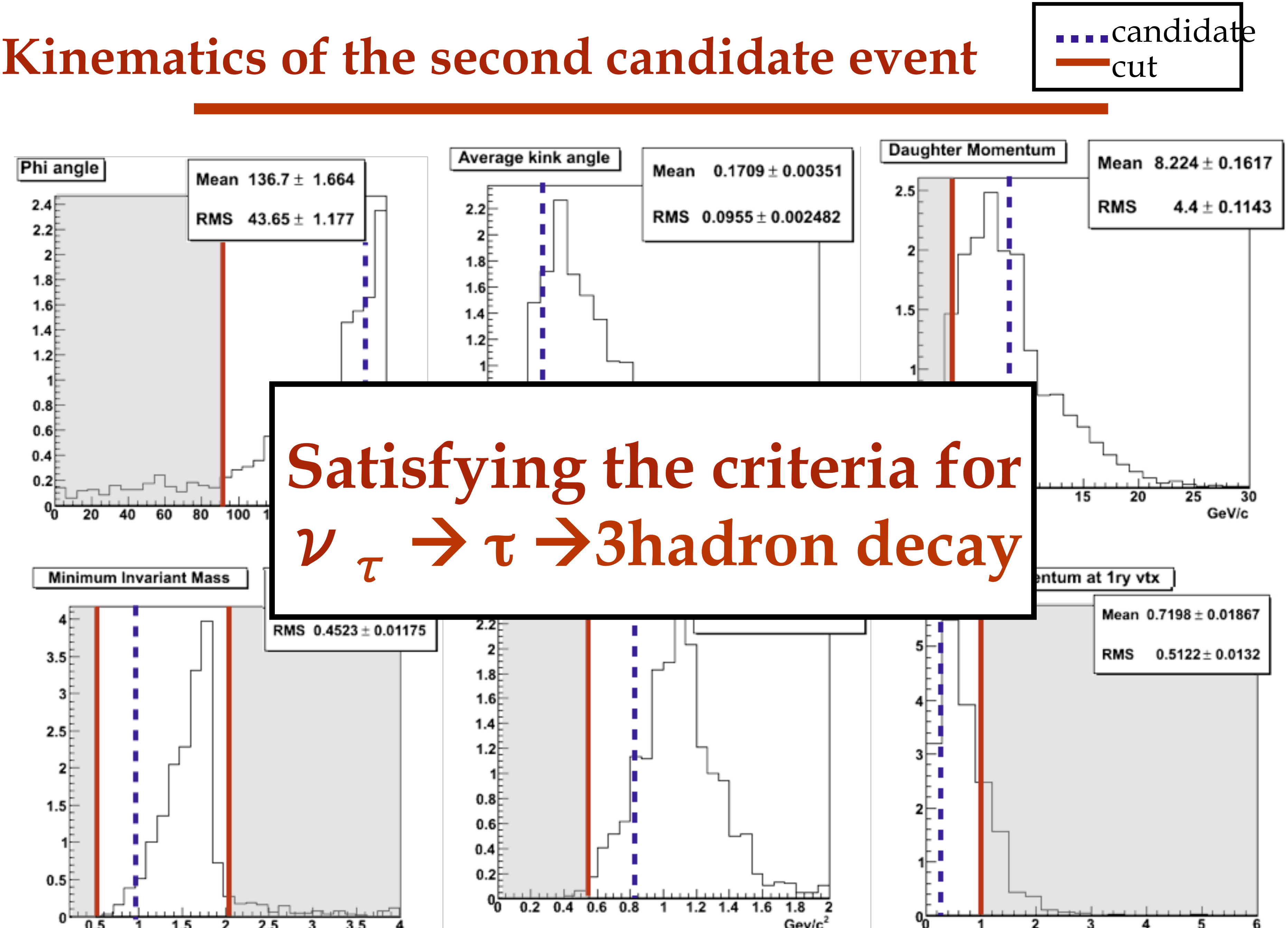
Track#	Momentum (1σ interval) [GeV/c]	Particle ID	Method / Comments
Primary	2.8 (2.1-3.5)	Hadron	• Momentum-Range Consistency Check Stops after 2 brick walls. Incompatible with muon (26÷44 brick walls)
d1	6.6 (5.2 - 8.6)	Hadron	• Momentum-Range Consistency Check
d2	1.3 (1.1 -1.5)	Hadron	• Momentum-Range 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/c²]	0.5 < < 2.0	0.96±0.13
Invariant mass [GeV/c²]	0.5 < < 2.0	0.80±0.12
Transverse Momentum at 1ry vtx [GeV/c]	< 1.0	0.31±0.11

Kinematics of the second candidate event

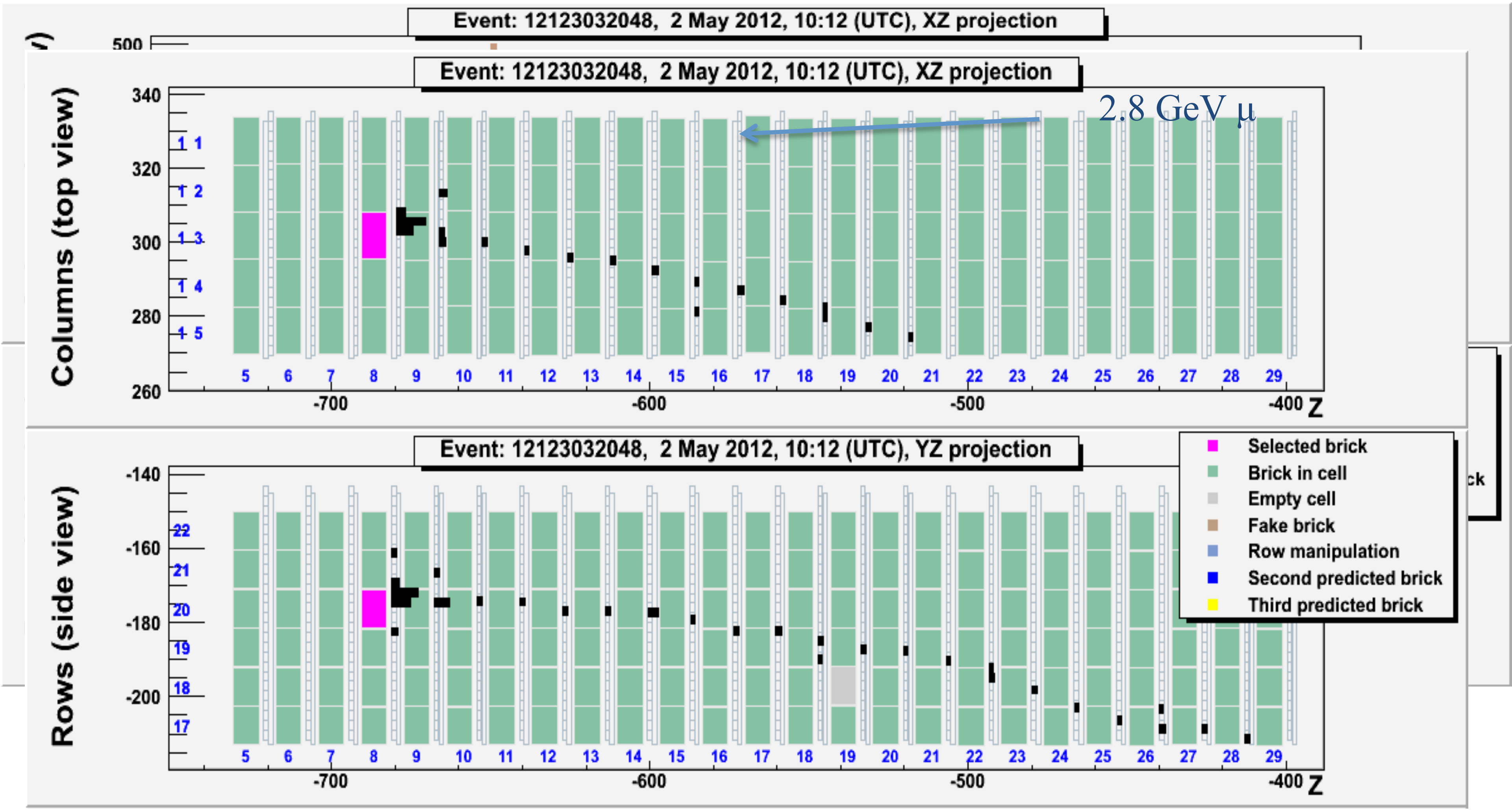


Satisfying the criteria for $\nu_\tau \rightarrow \tau \rightarrow$ 3hadron decay

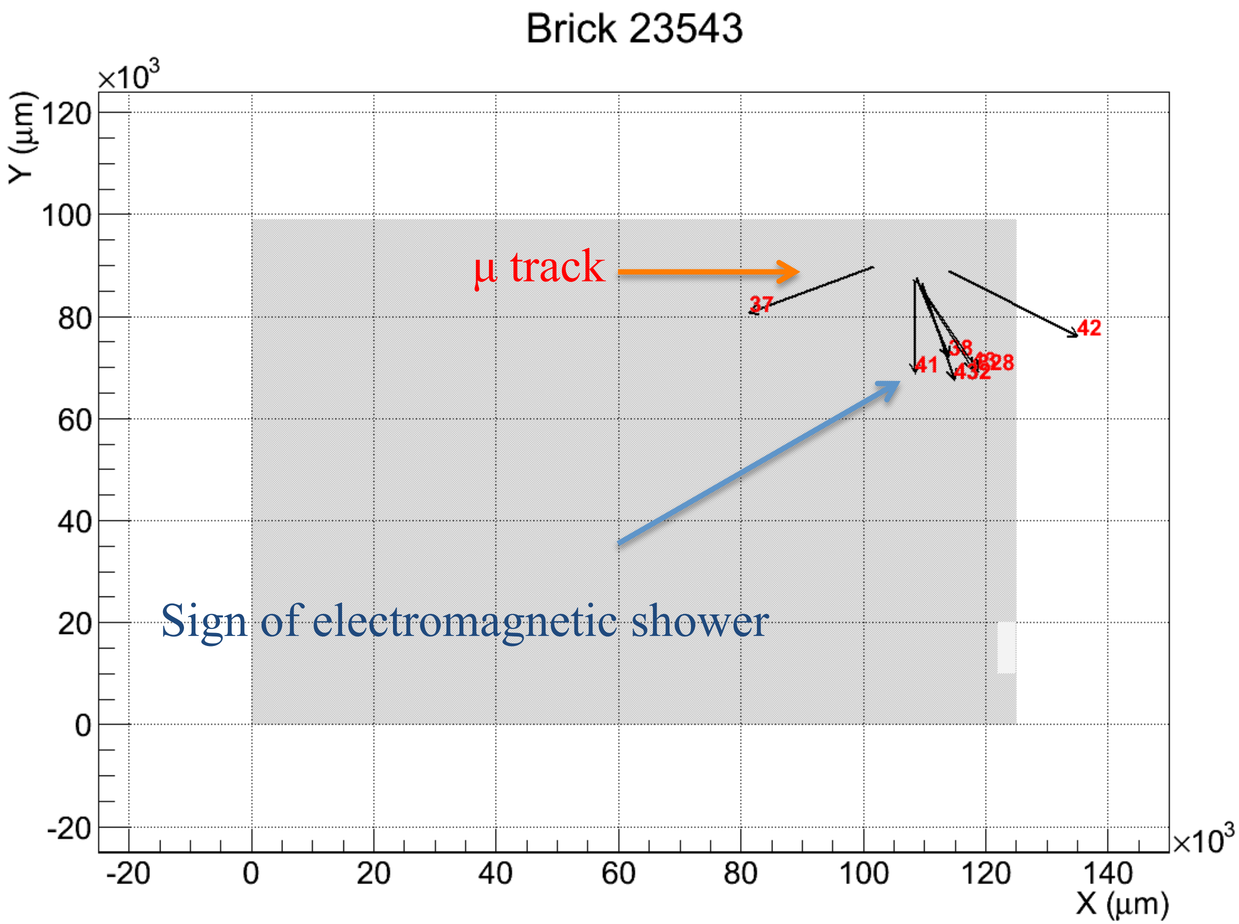
After 2012 Summer conferences

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

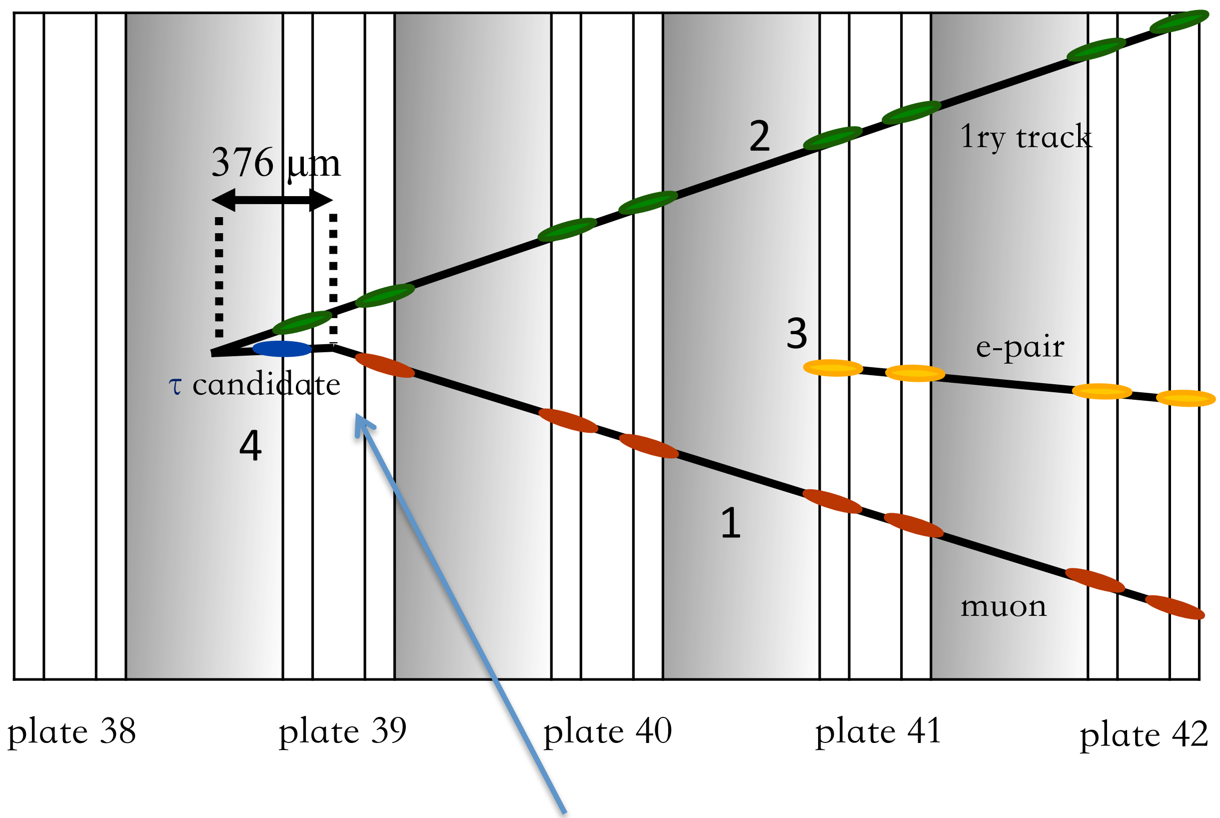
Third tau neutrino event taken on May 2nd 2012



Analysis of the interface films



τ→μ candidate
brick analysis and decay search



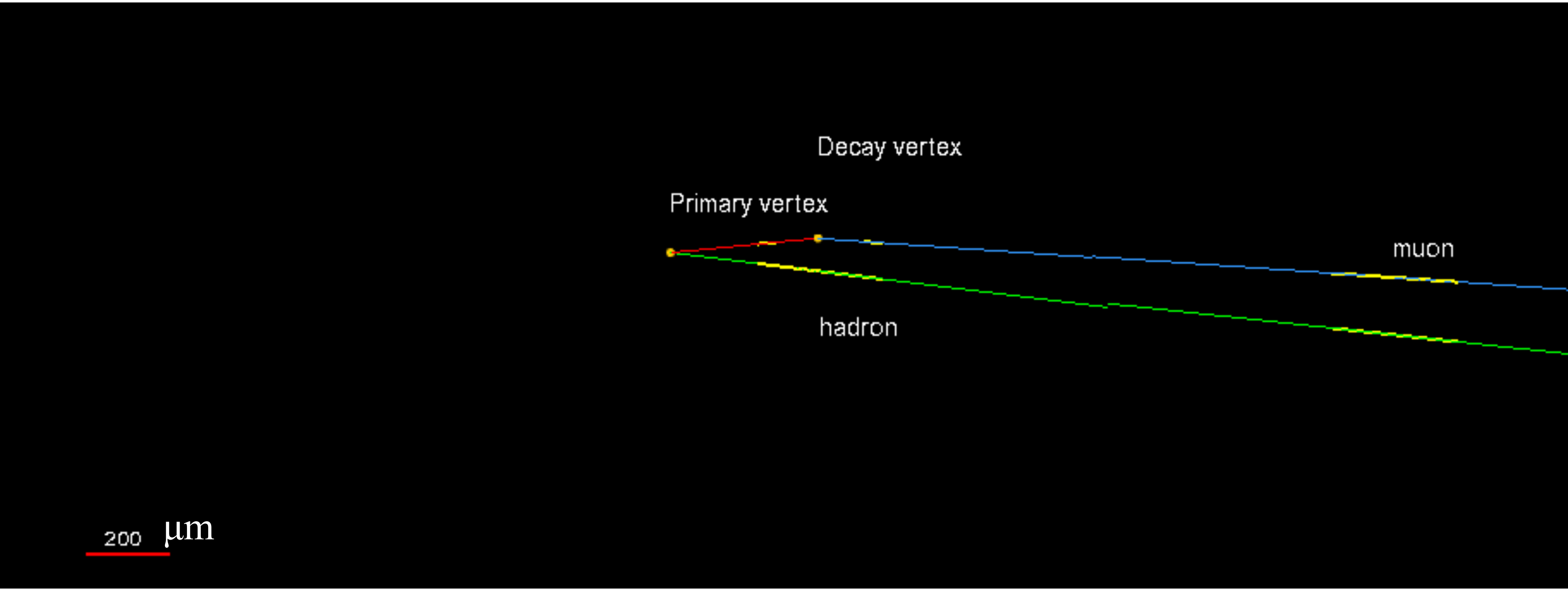
Decay in the plastic base

$\tau \rightarrow \mu$ candidate

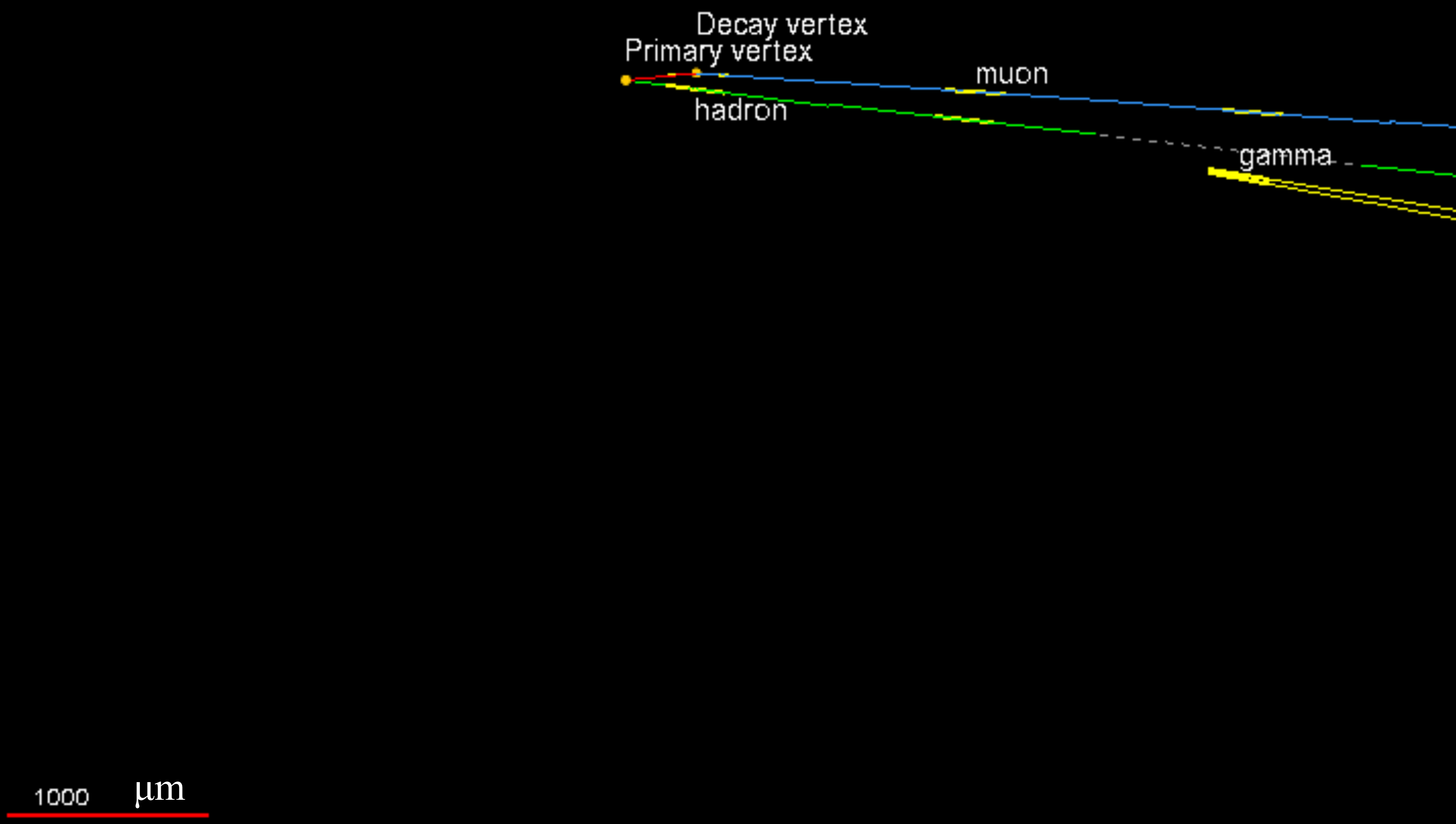
μm

2

Third tau neutrino event
$\tau \rightarrow \mu$



Third tau neutrino event
$\tau \rightarrow \mu$



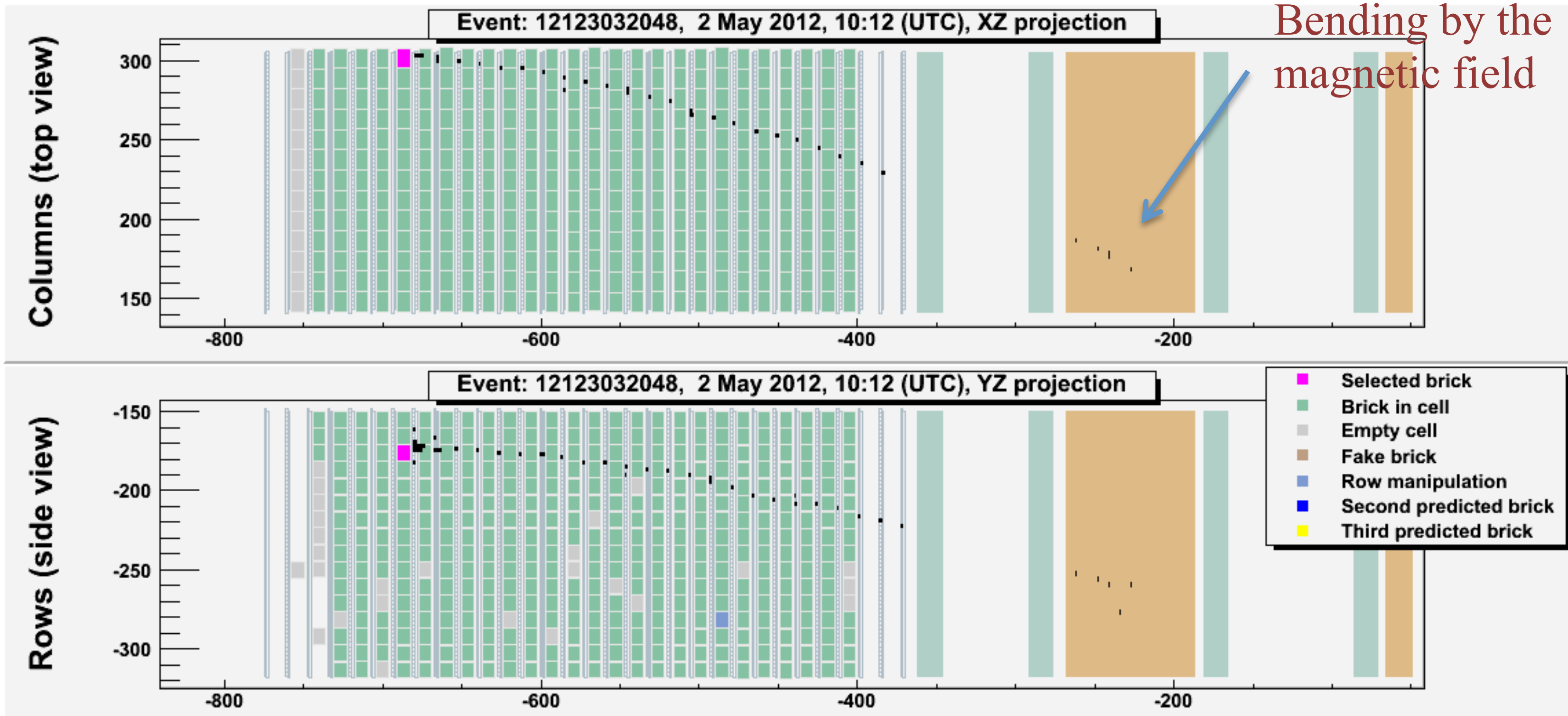
Event tracks' features

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	

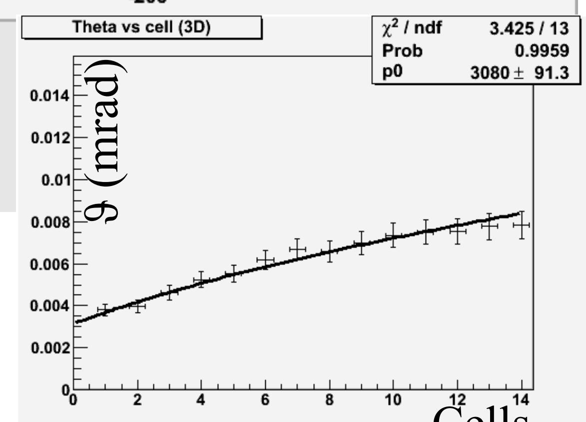
γ attachment

	$\delta\theta_{RMS}$ (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



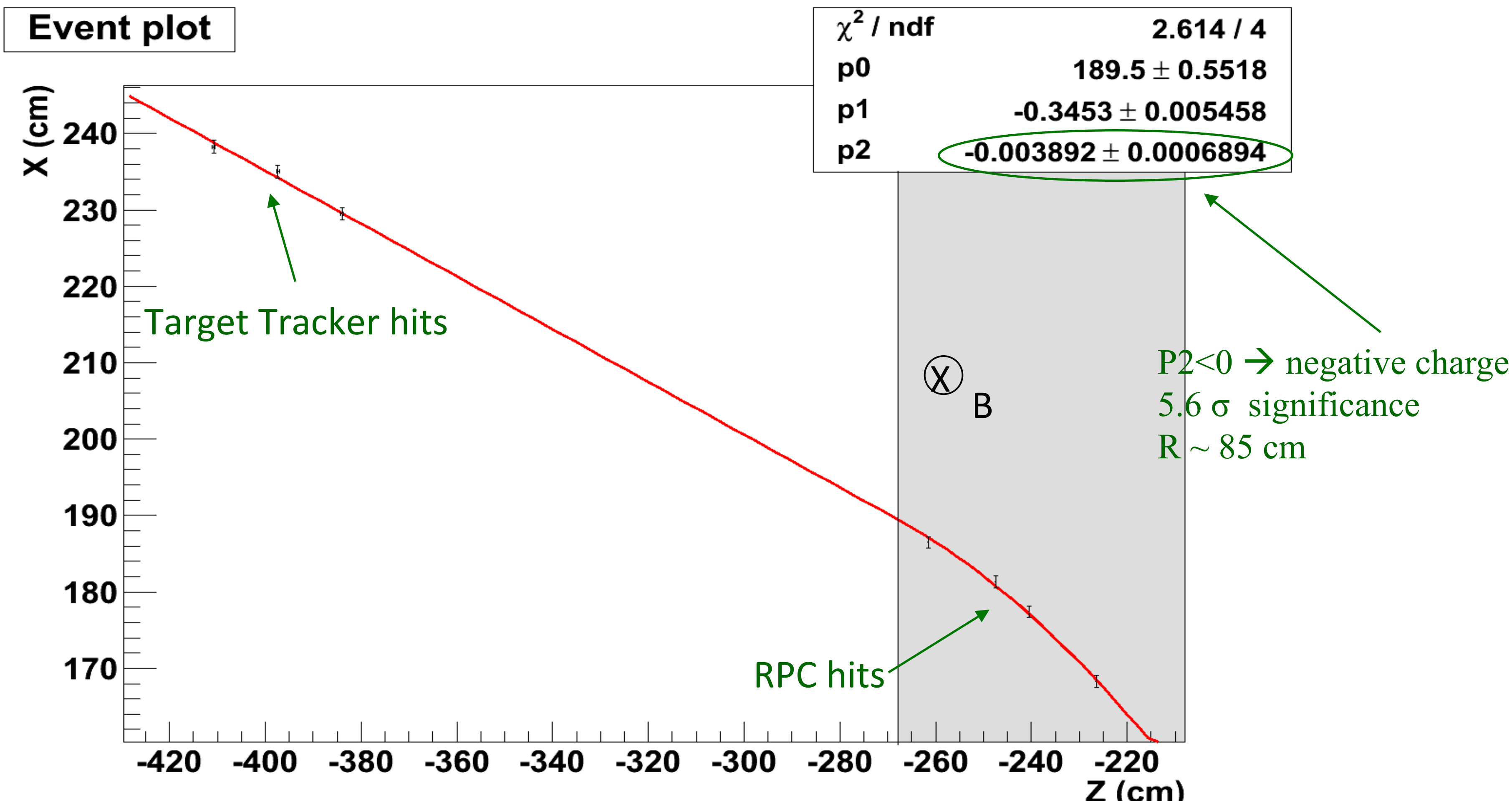
Charge determination of the muon

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

Fit function:

$X(z) = p0 + p1 \times (z-z0) + p2 \times (z-z0)^2$ for z>z0, start of magnetized region

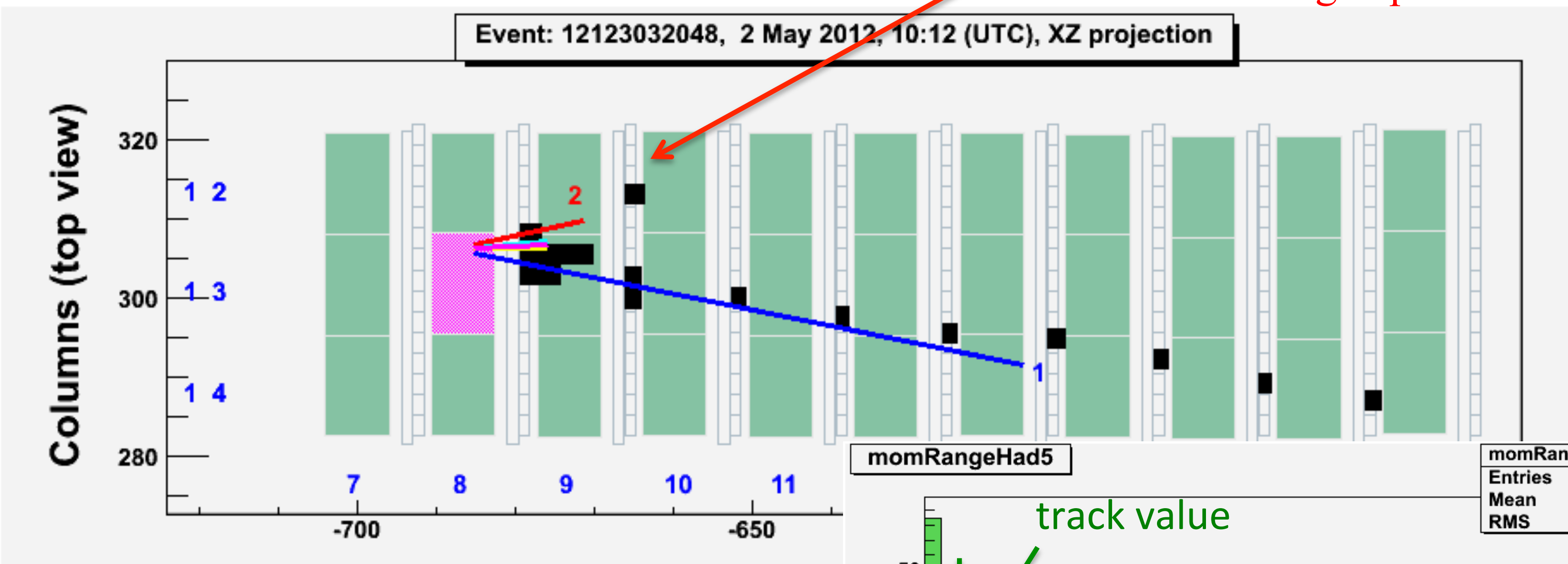
$X(z) = p0 + p1 \times (z-z0)$ for z<z0



P-value = 0.063% (probability to reconstruct a μ^+ stopping in the 7th iron layer with p2 < -0.00389 cm^{-1})

Track follow down to assess the nature of track 2

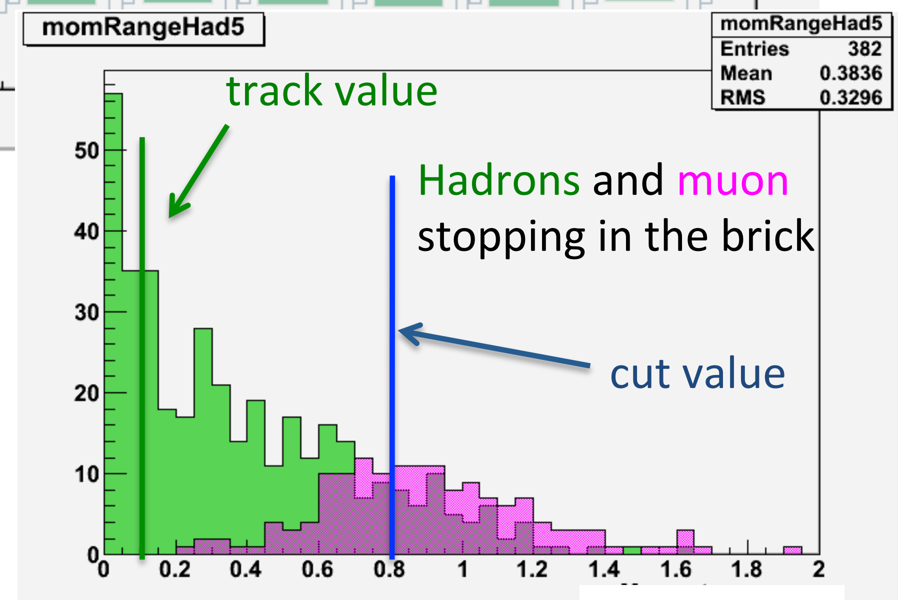
Track 2 interacting in the downstream brick without visible charged particles



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

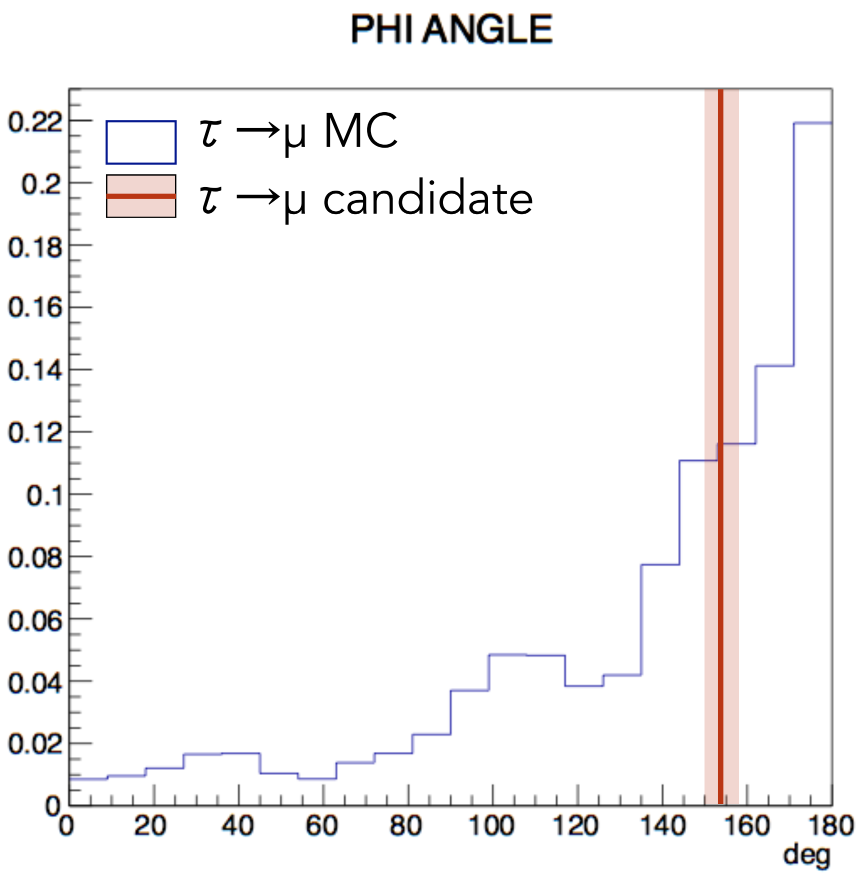
$$D = \frac{L}{R_{lead}(p)} \frac{\rho_{lead}}{\rho_{average}}$$

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



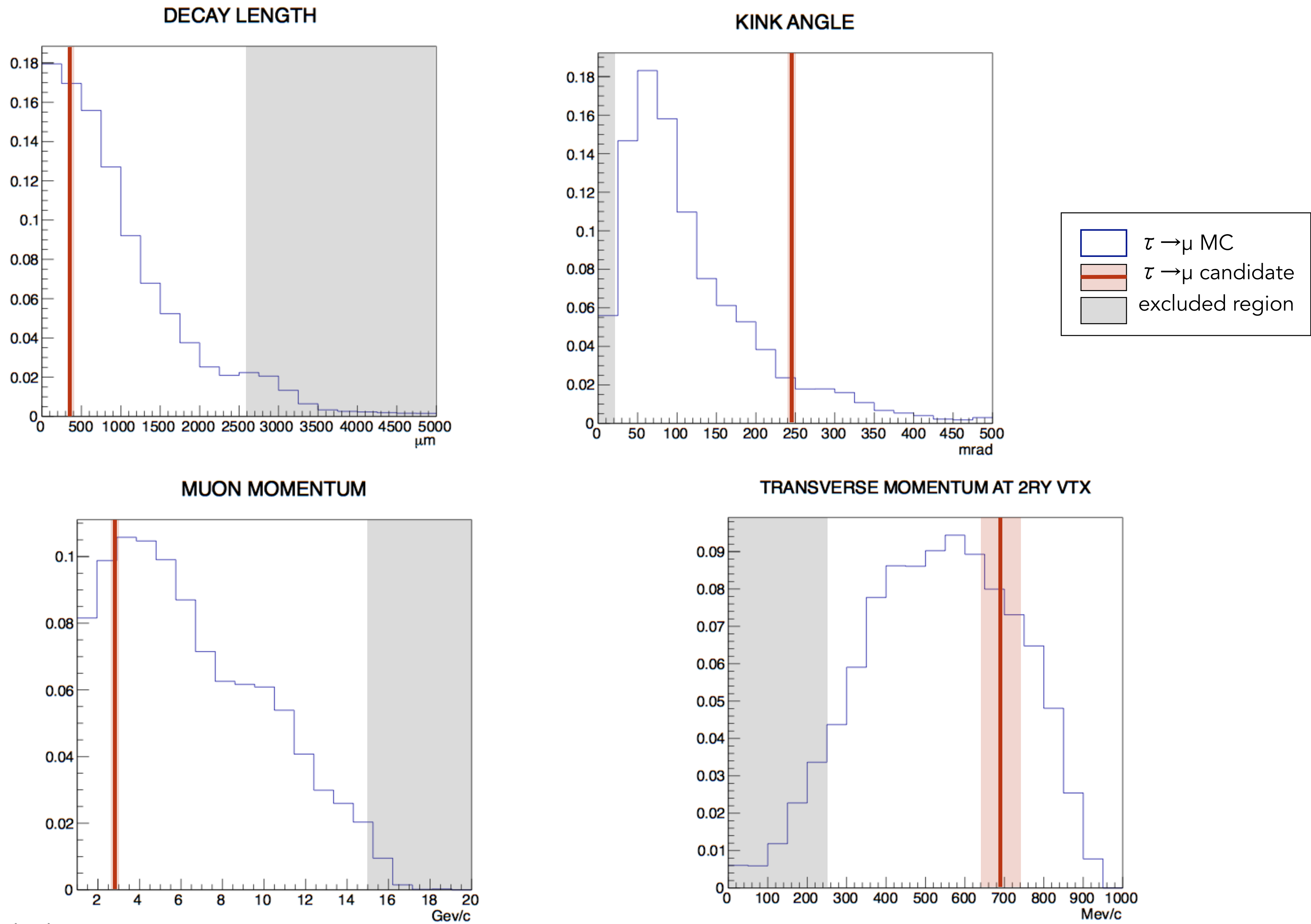
D variable

Kinematical variables



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

Kinematical variables. All cuts passed: τ →μ candidate



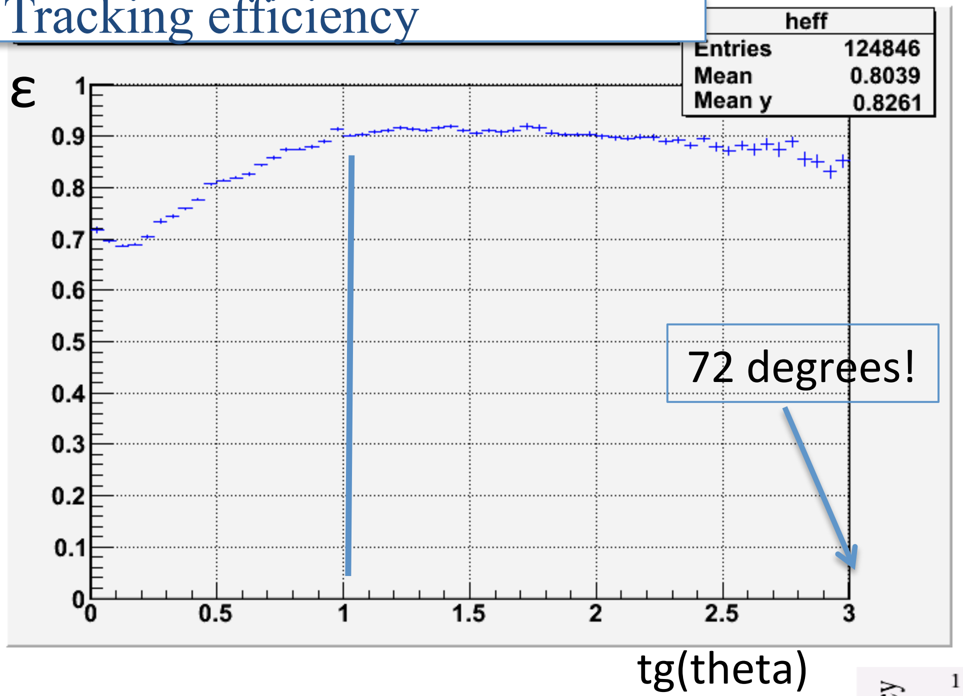
Background studies

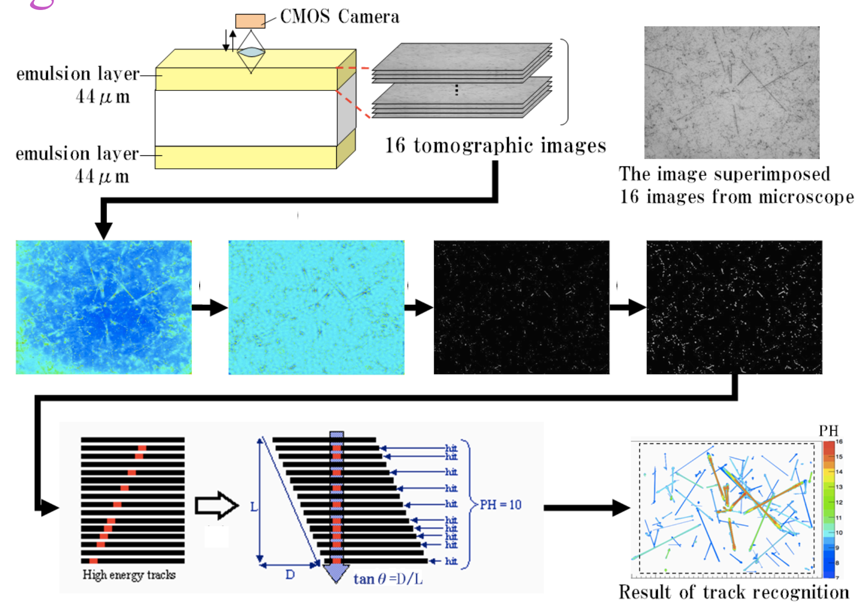
Improvements on the background rejection: large angle track detection

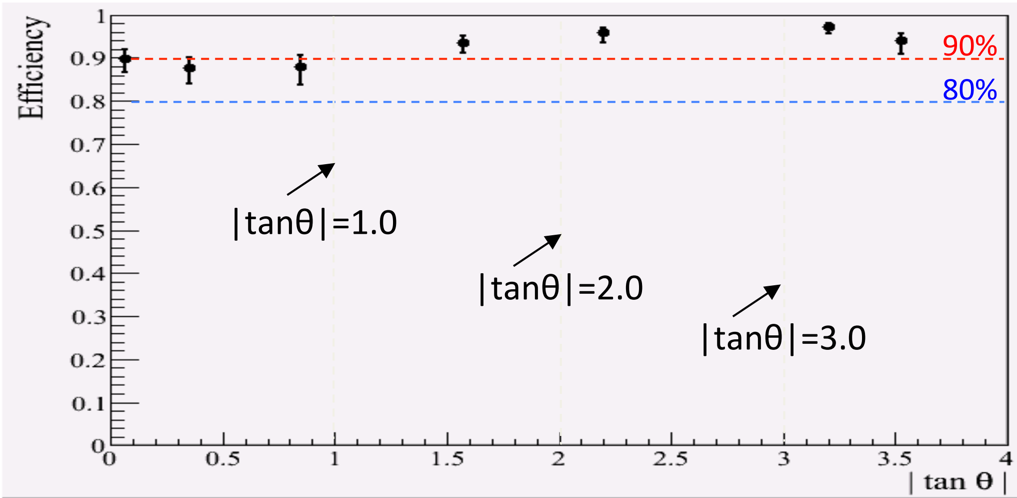
Undetected soft and large angle muons are the source of charm background

Detection of particles and nuclear fragments in hadronic interactions

Tracking efficiency





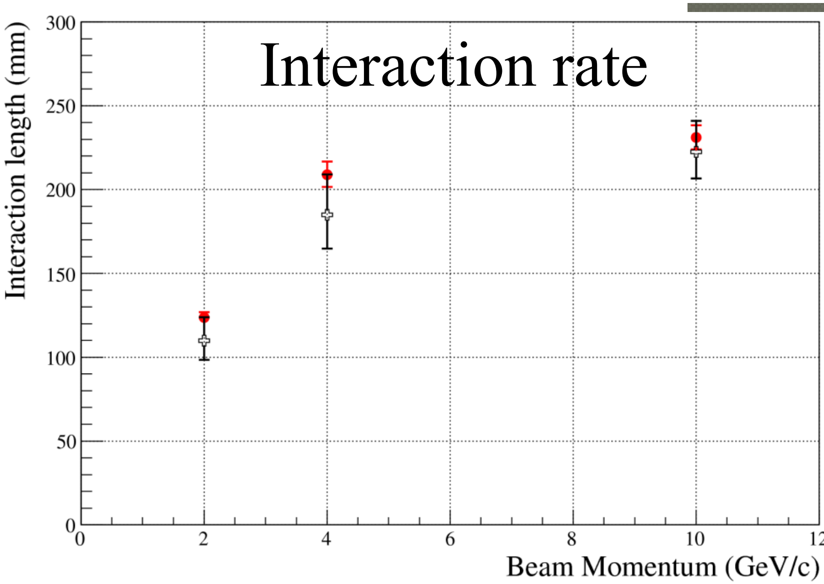


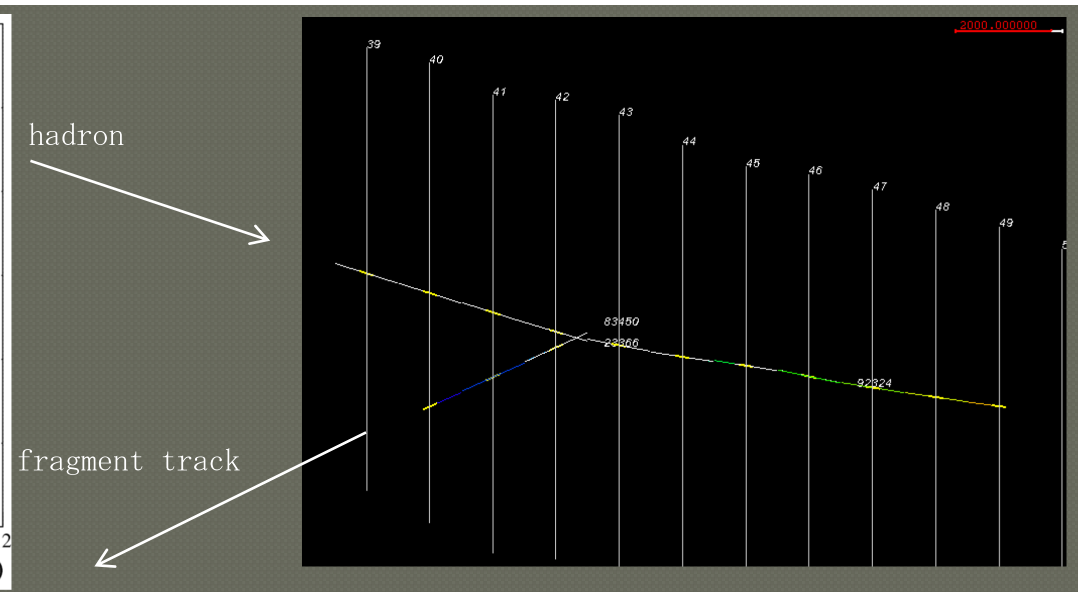
Two different approaches get comparable results

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



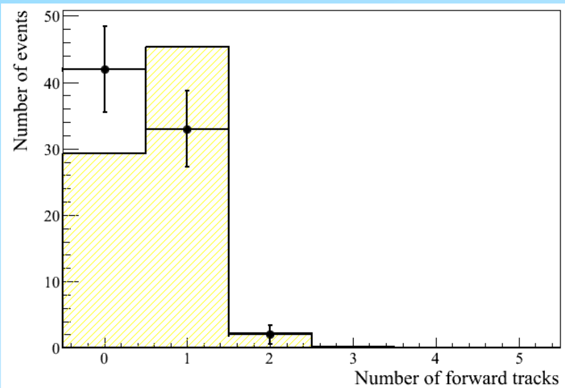


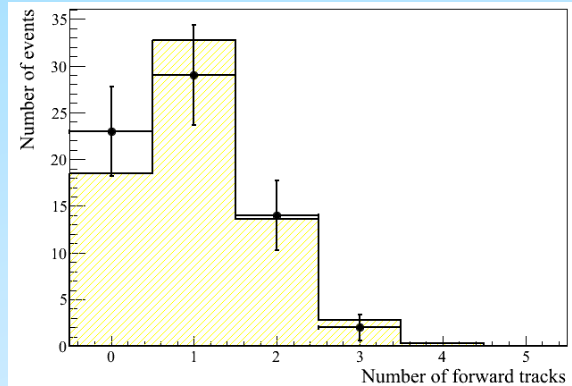
Black : π^- beam data
Red : MC (FLUKA) simulation

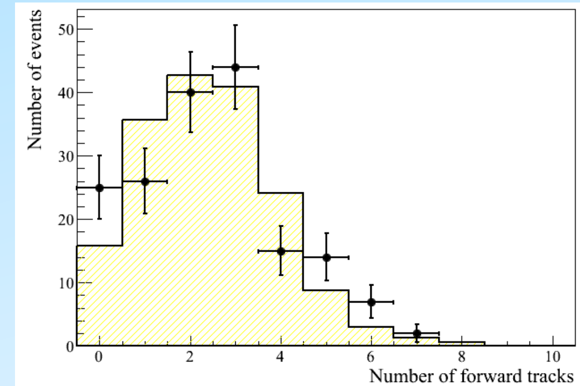
Secondary track emission

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

Multiplicity

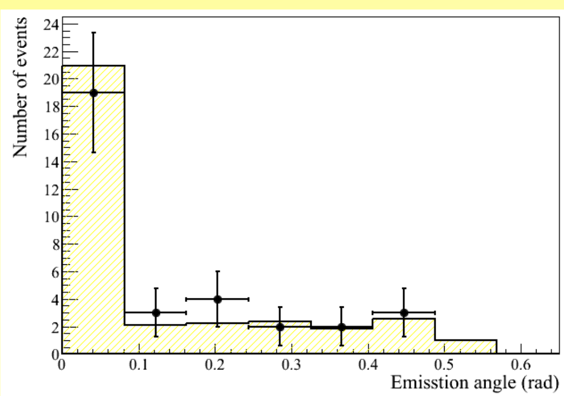


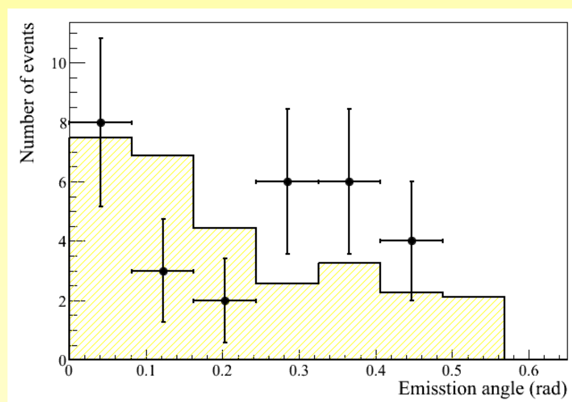


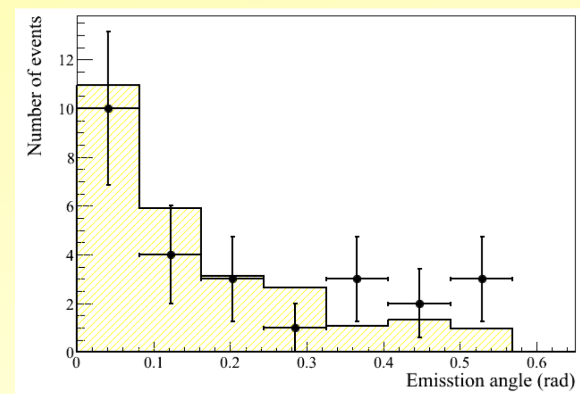


Error bars : Experimental data
Histogram : Simulated data

Kink angle (1-prong)

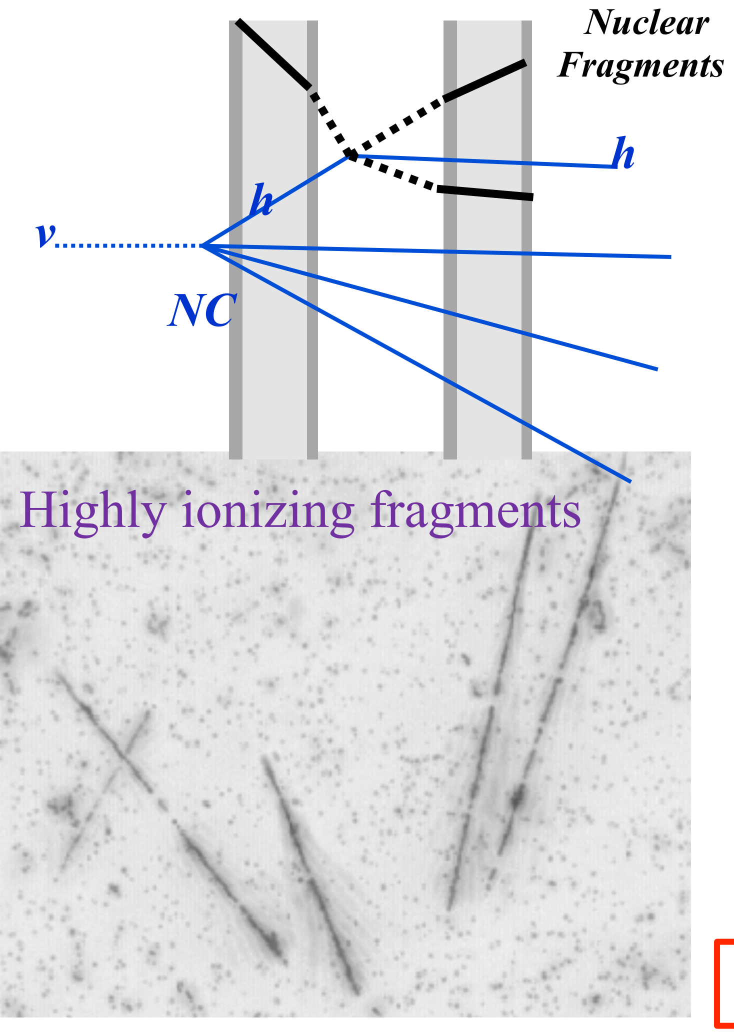


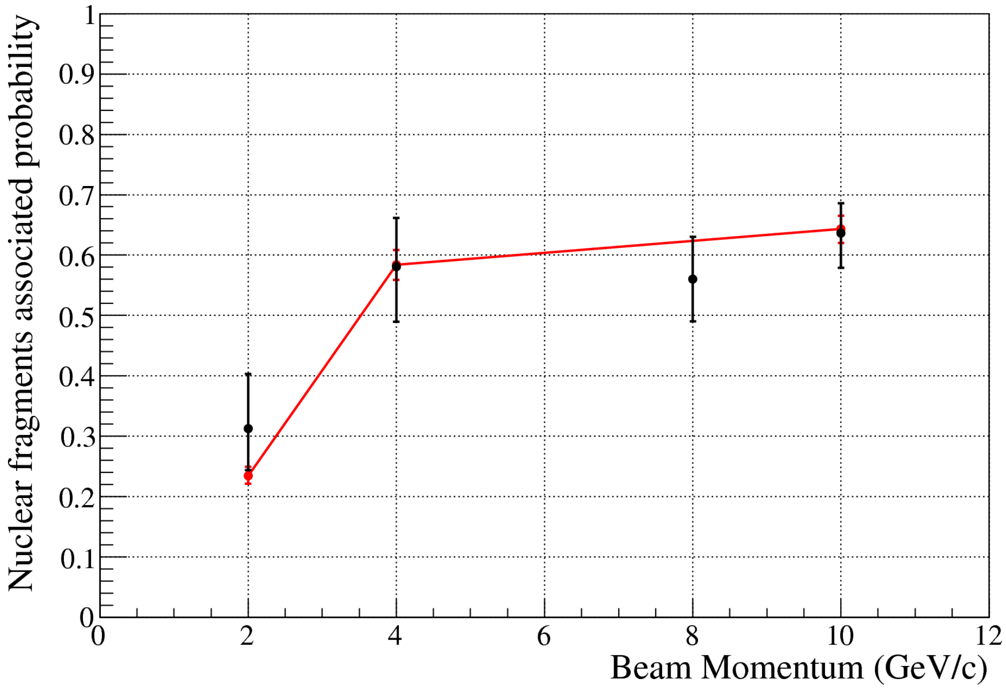




Good agreement within the statistical error: systematic error reduced to 30%

Nuclear fragments emission probability





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

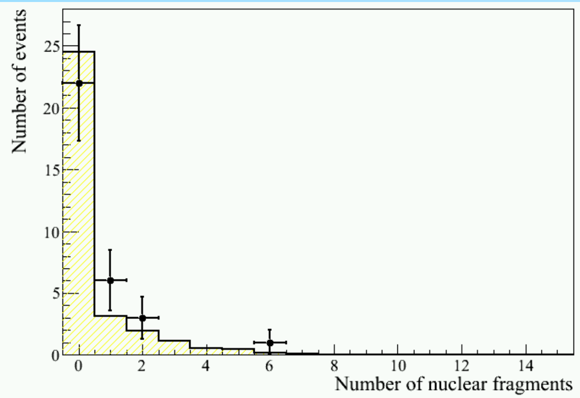
It provides additional background reduction.

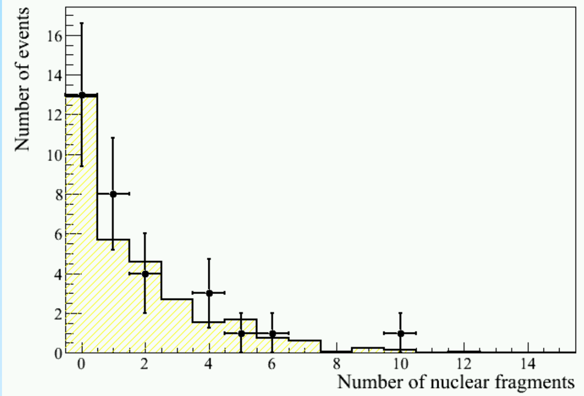
Nuclear fragments in 1 and 3 prong interactions

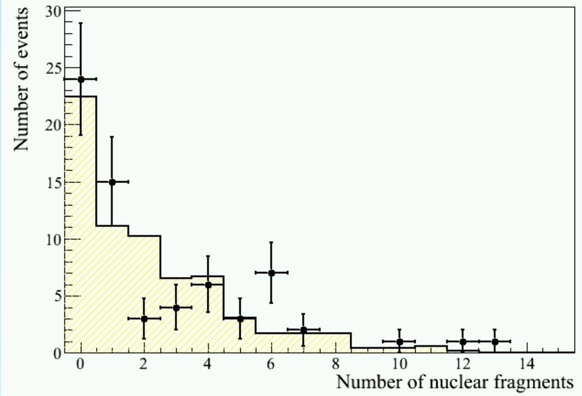
2GeV/c | 4GeV/c | 10GeV/c

Multiplicity

MC: $\beta < 0.7$

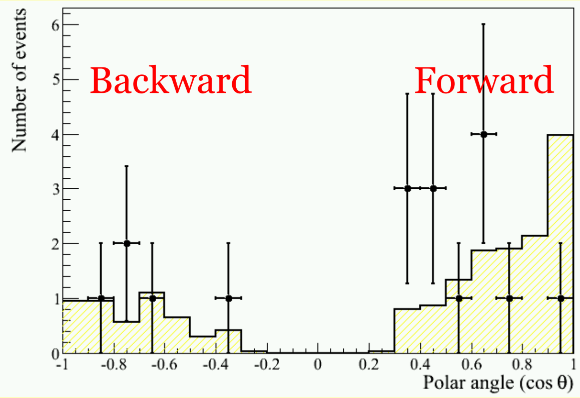


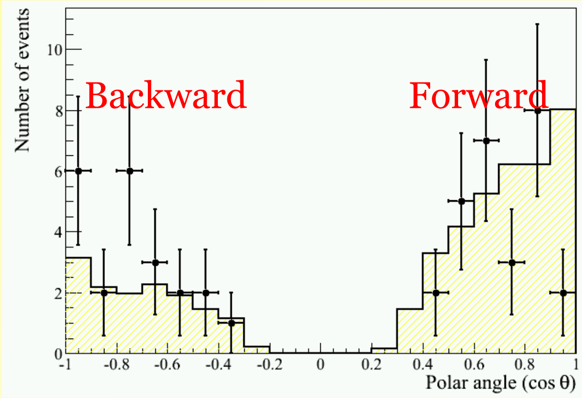


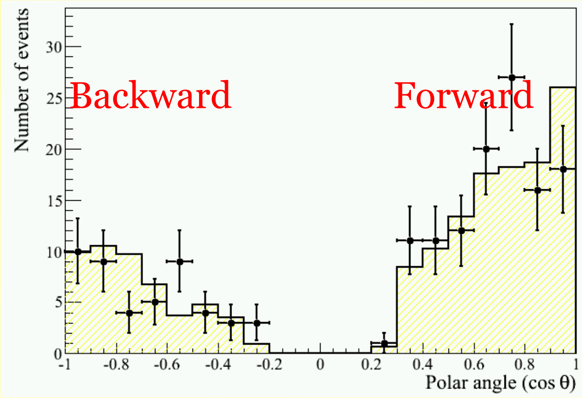


Error bars : experiment
Histogram : simulation

Emission angle(cos θ)

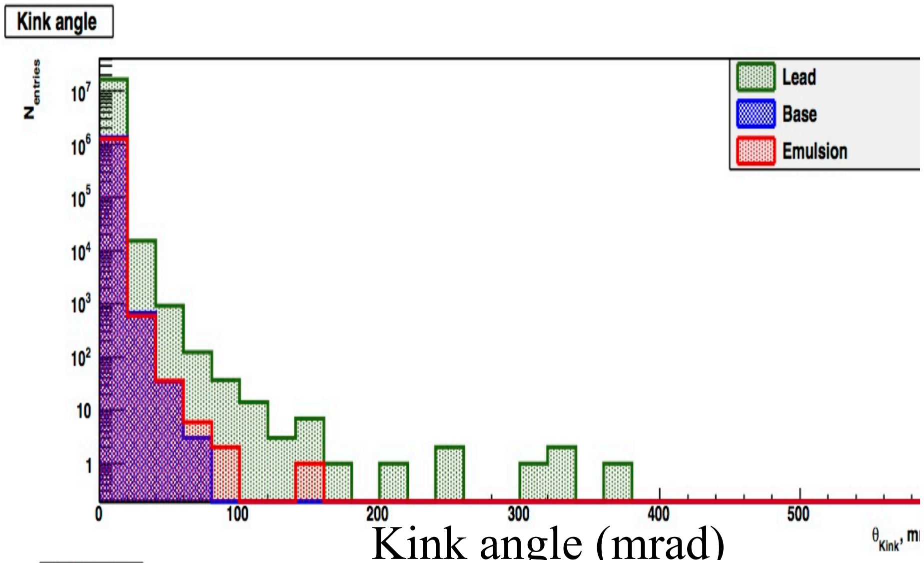


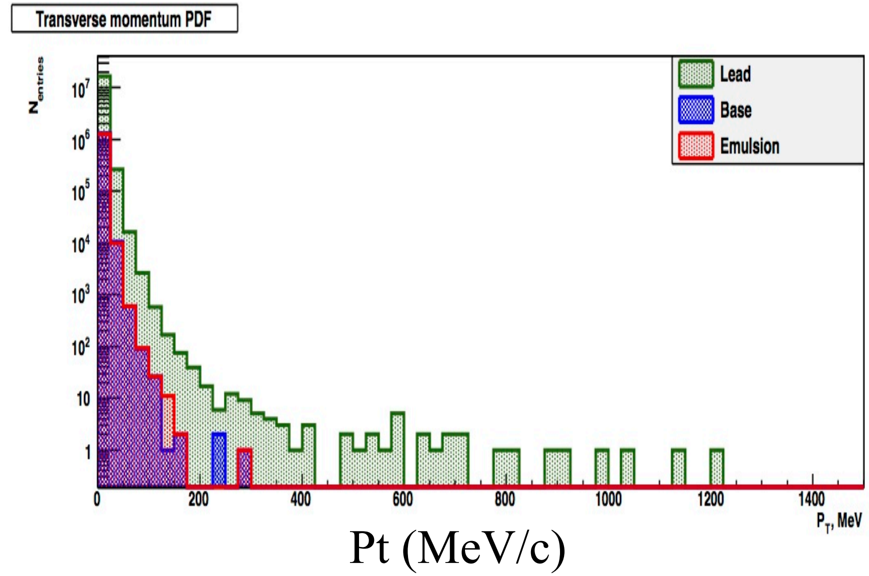


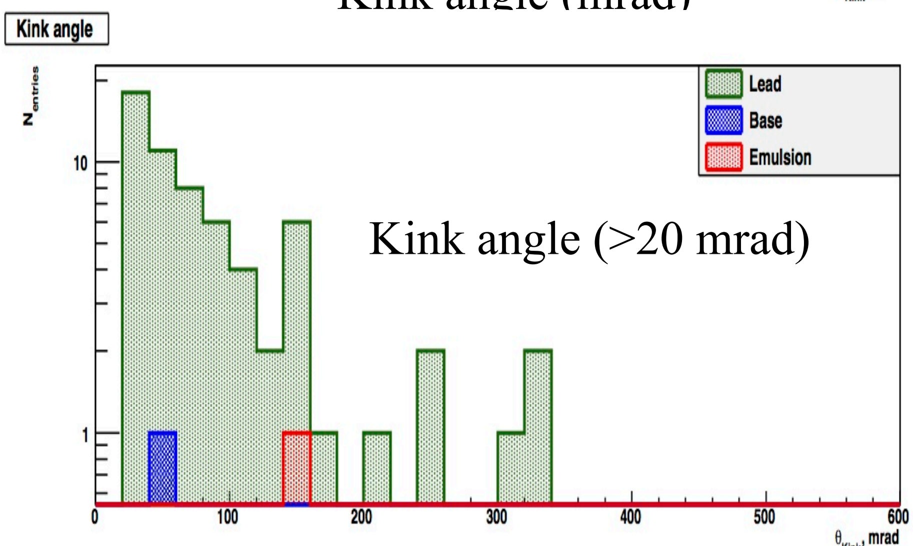


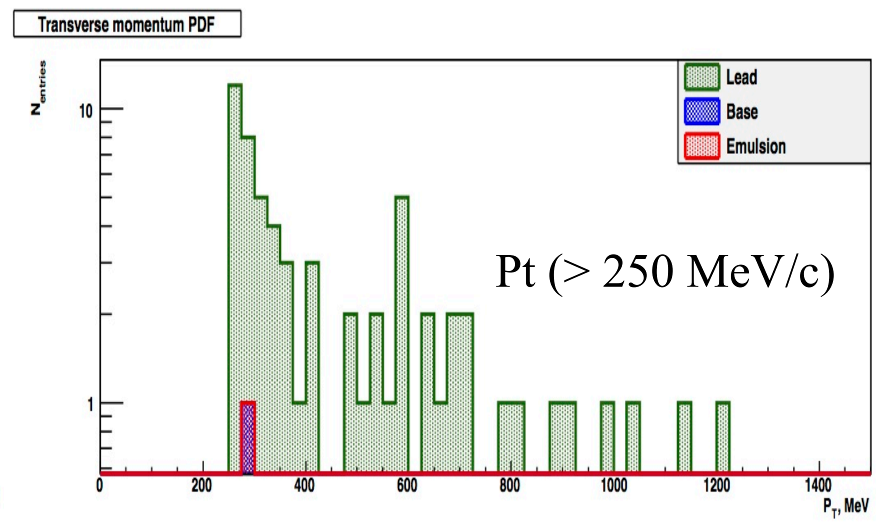
Agreement within the statistical error: systematic error is 10%.

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
Sample analysed for Summer 2012 conferences

Summer conferences

	Signal	Background	Charm	μ scattering	had int
$\tau \rightarrow h$	0.66	0.045	0.029		0.016
$\tau \rightarrow 3h$	0.61	0.090	0.087		0.003
$\tau \rightarrow \mu$	0.34	0.017	0.005	0.012	
$\tau \rightarrow e$	0.49	0.065	0.065		
total	2.10	**0.217**	0.186	0.012	0.019

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

Pvalue = $P_0 = 3.819 \times 10^{-3}$

Probability to be explained by background = 0.0134

This corresponds to 2.2 σ significance of non-null observation

Statistical considerations
Extended sample to muonic interactions

Extended sample

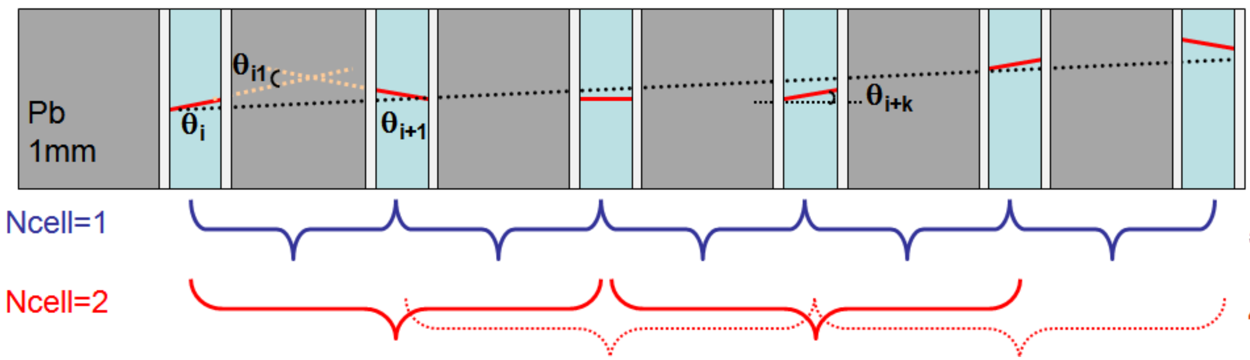
	Signal	Background	Charm	μ scattering	had int
$\tau \rightarrow h$	0.66	0.045	0.029		0.016
$\tau \rightarrow 3h$	0.61	0.090	0.087		0.003
$\tau \rightarrow \mu$	0.56	0.026	0.0084	0.018	
$\tau \rightarrow e$	0.49	0.065	0.065		
total	2.32	**0.226**	0.19	0.018	0.019

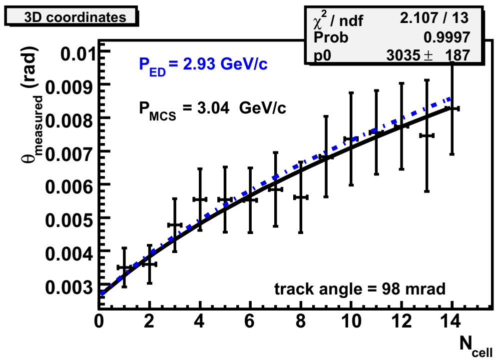
3 observed events in the $\tau \rightarrow h$ and $\tau \rightarrow 3h$ and $\tau \rightarrow \mu$ channels
Pvalue = P_0 = 1.125×10^{-4}
Probability to be explained by background = $7.29\ 10^{-4}$
This corresponds to 3.2 σ significance of non-null observation

Exploit kinematical characteristics of the events: likelihood analysis

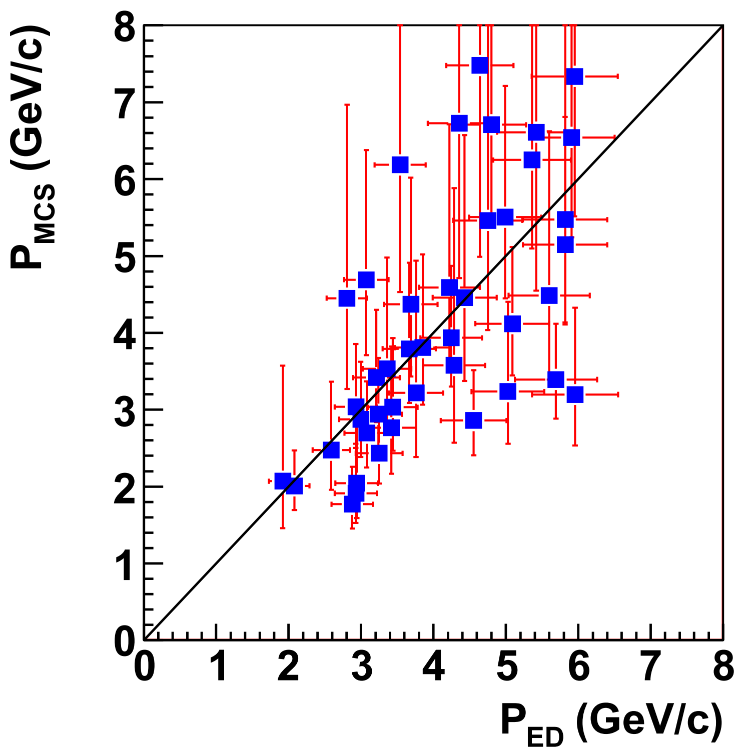
Data/MC agreement for relevant variables

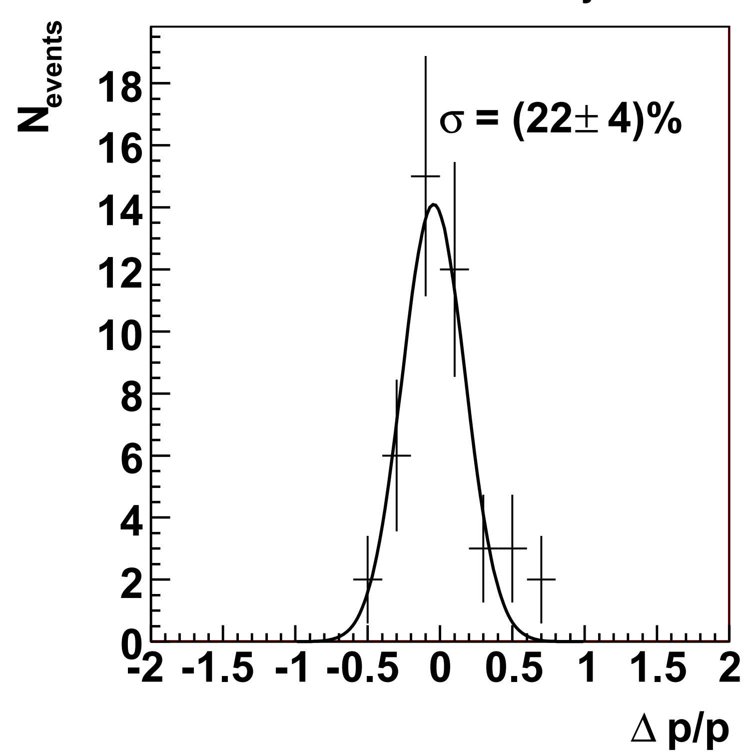
Momentum measurement by multiple Coulomb scattering for identified μ in the 2÷6 GeV range



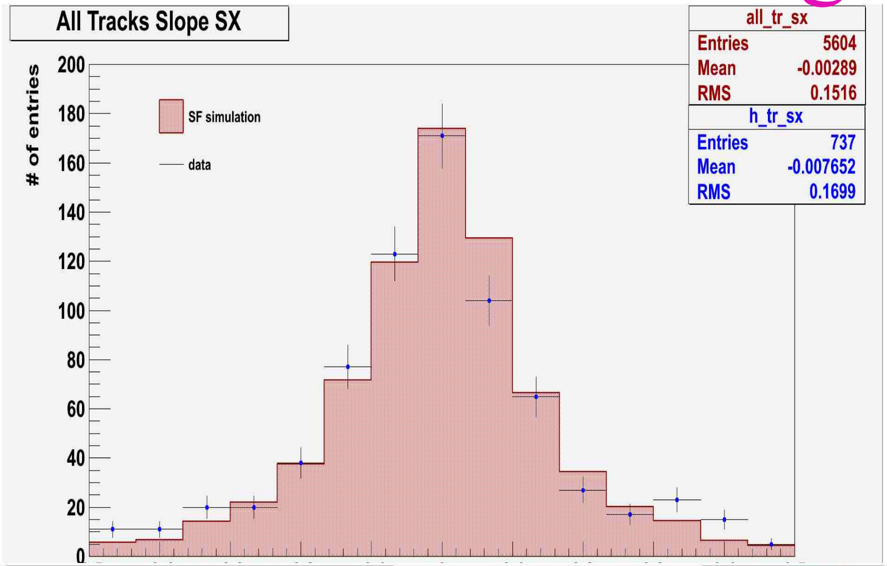


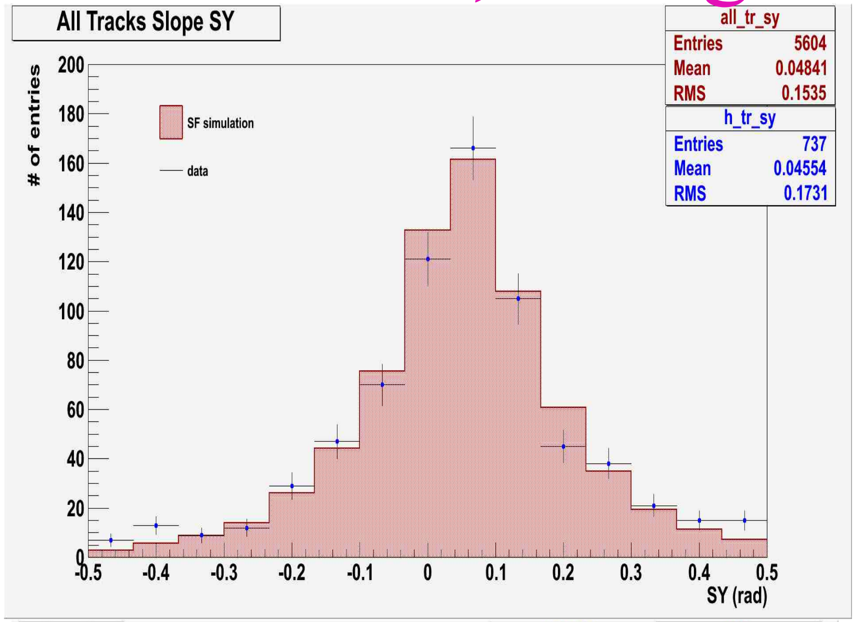
2012 New J. Phys. 14 013026

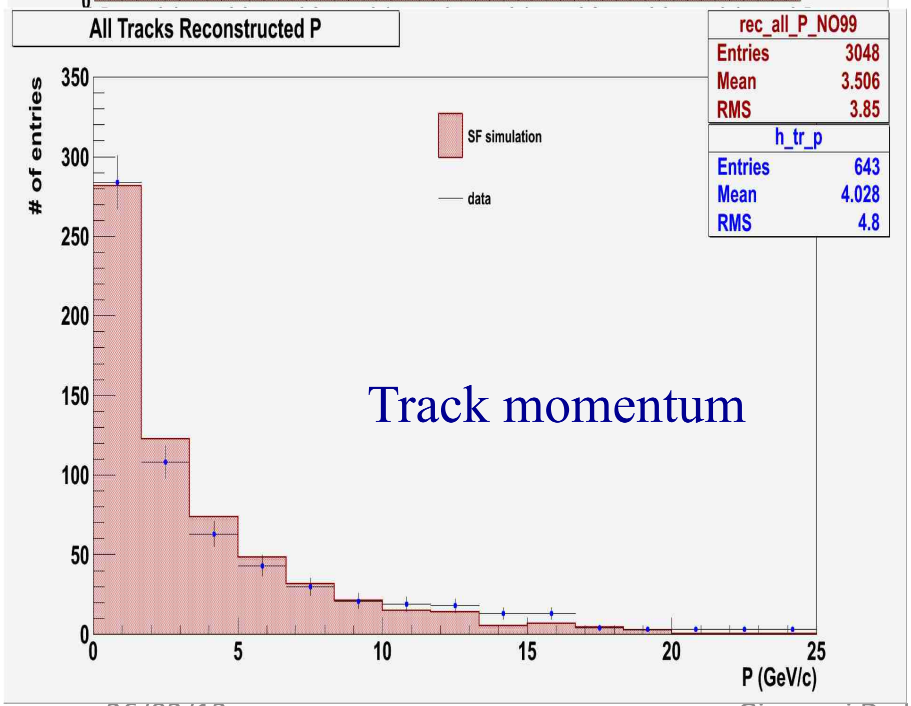


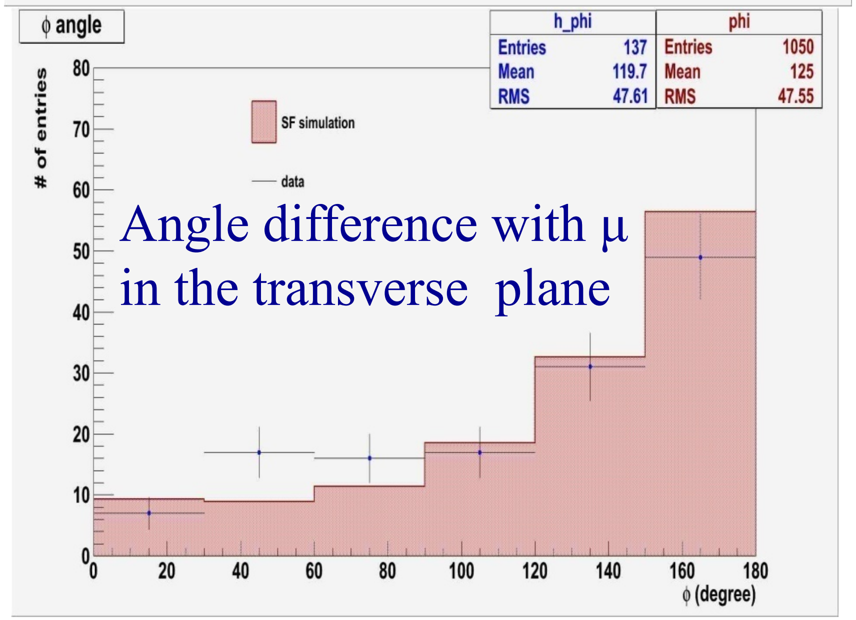


Track emission angles, momentum, Φ angle



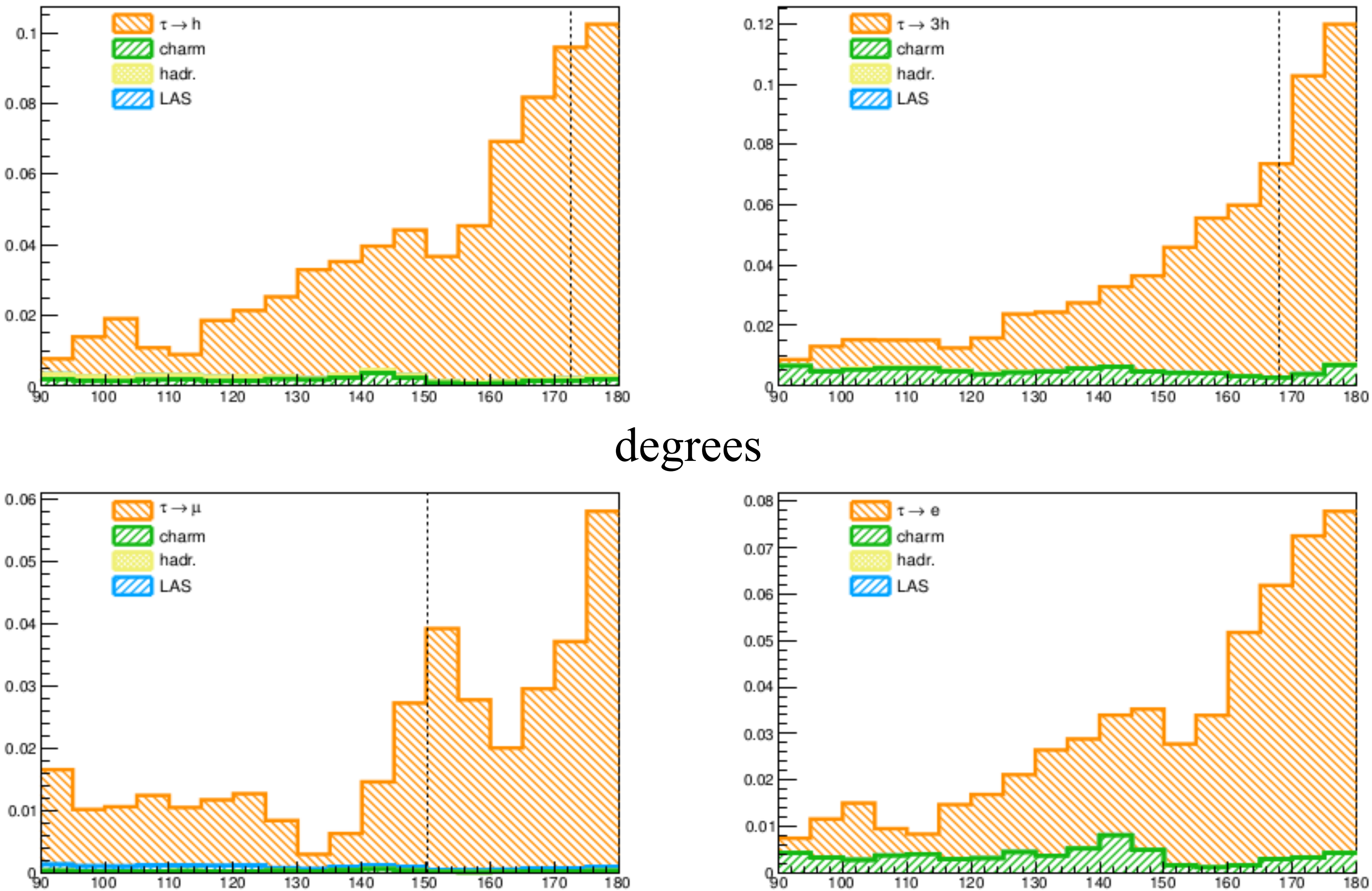




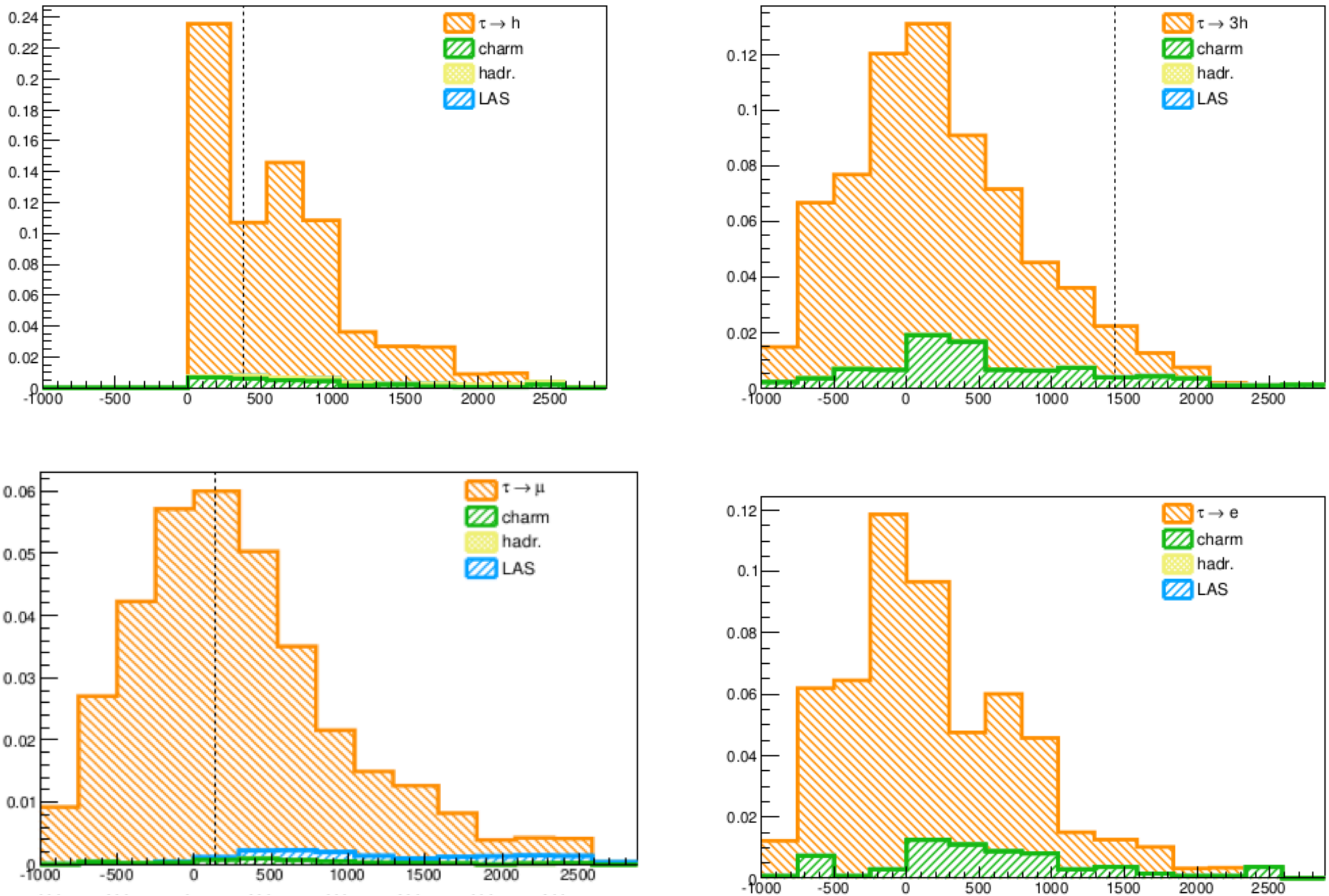


Statistical analysis

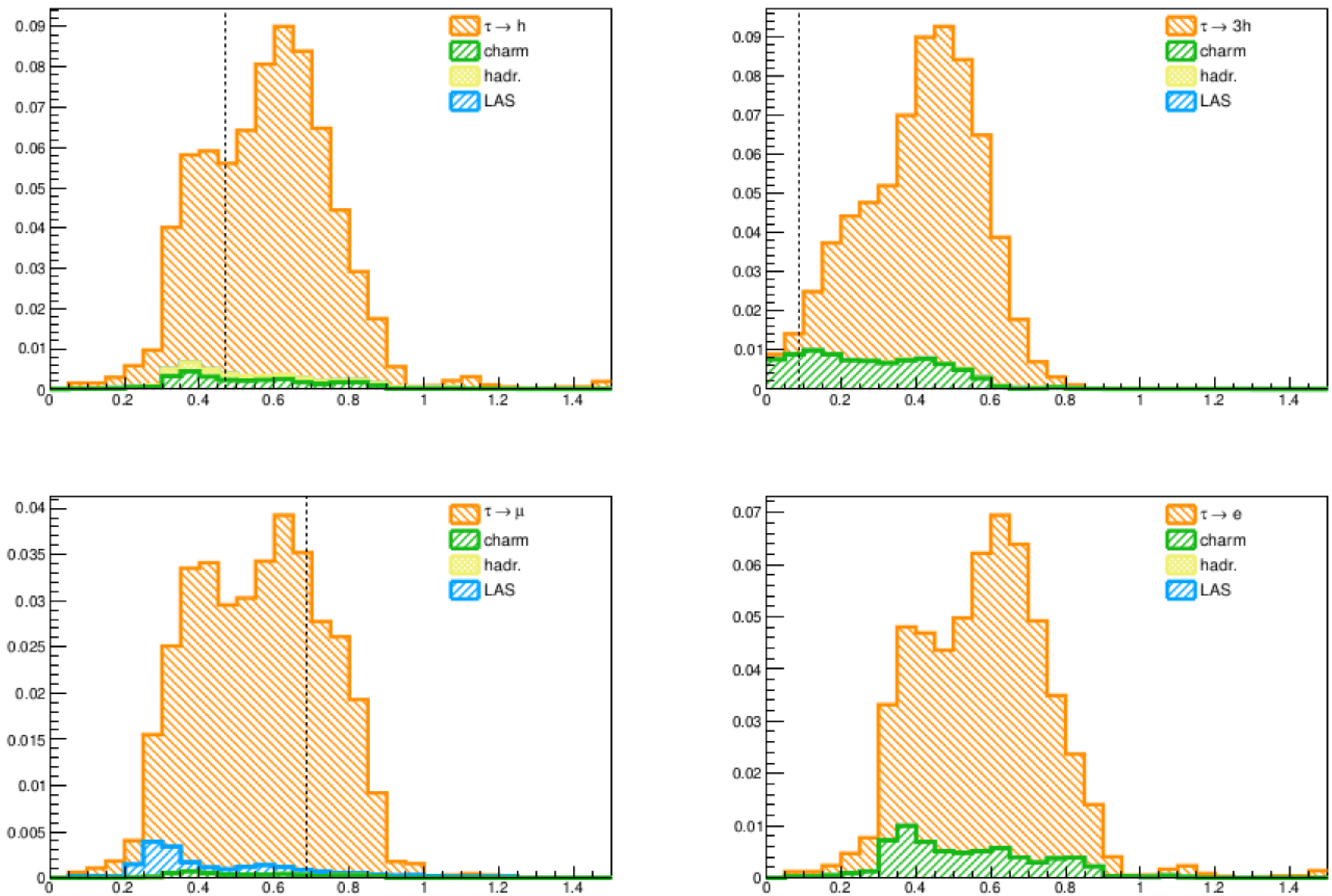
Angle between the parent particle and the hadron jet in the transverse plane
discard the largest φ track unless it is identified as hadron



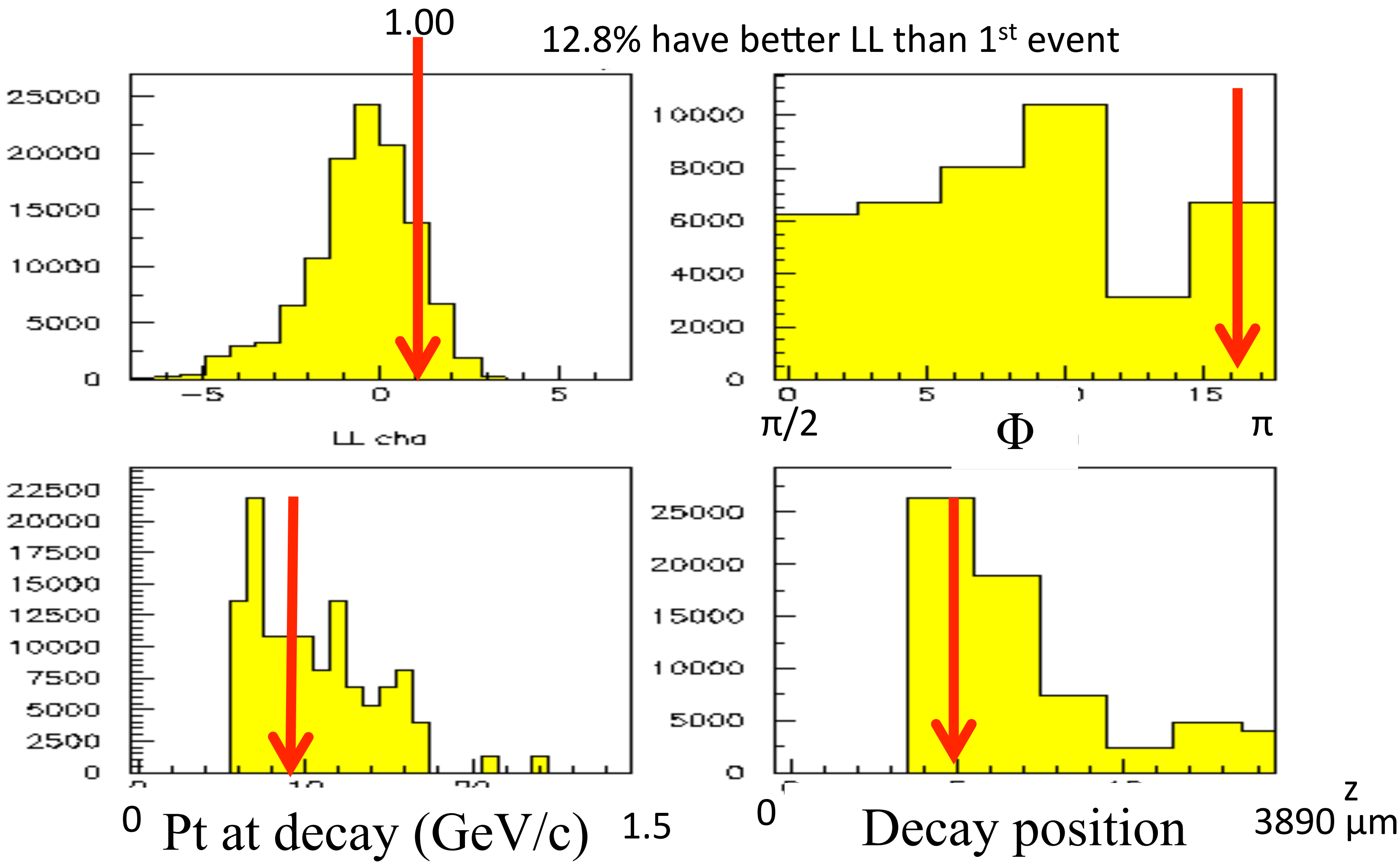
Decay position (micron)



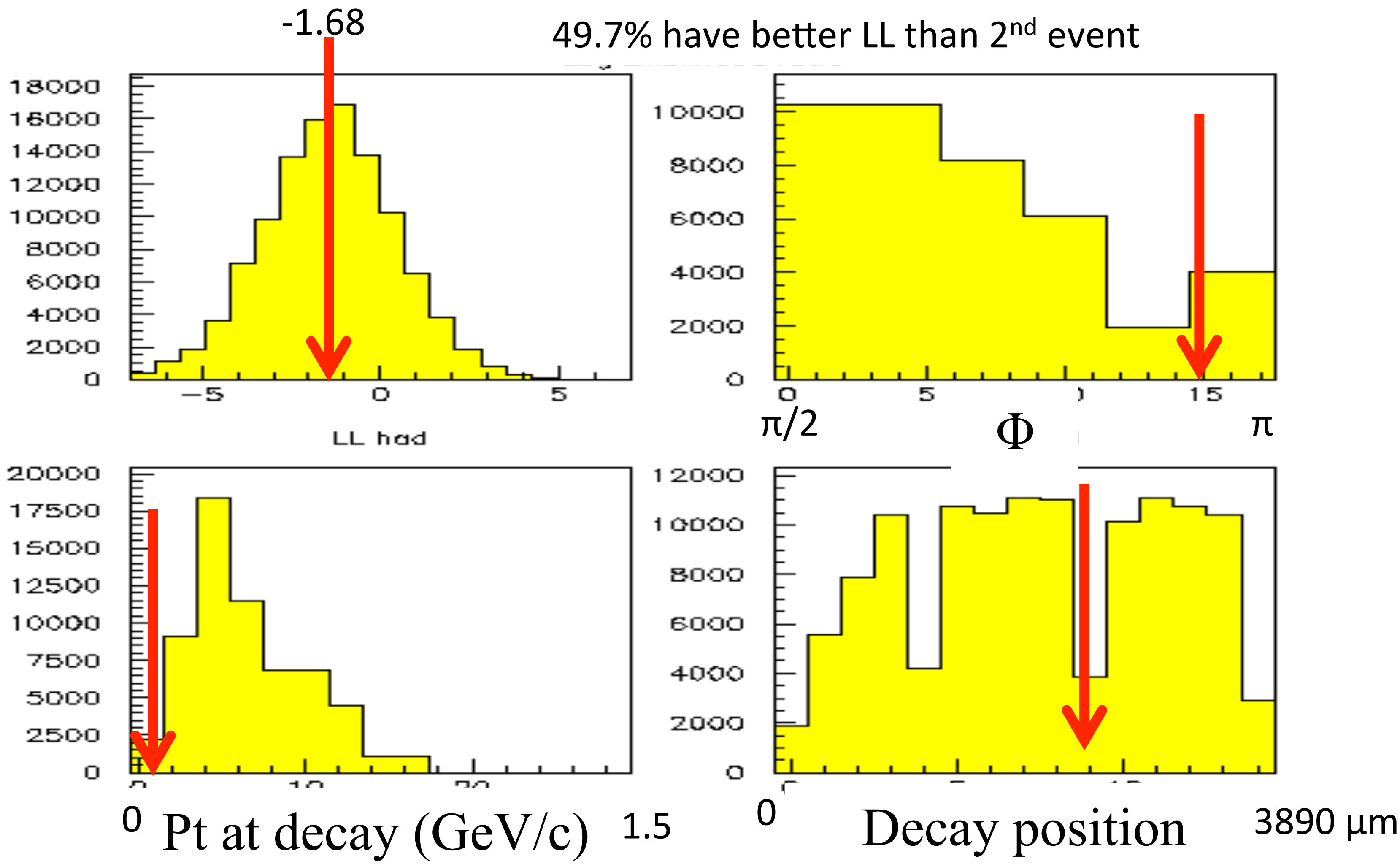
Transverse momentum at secondary vertex(GeV/c)



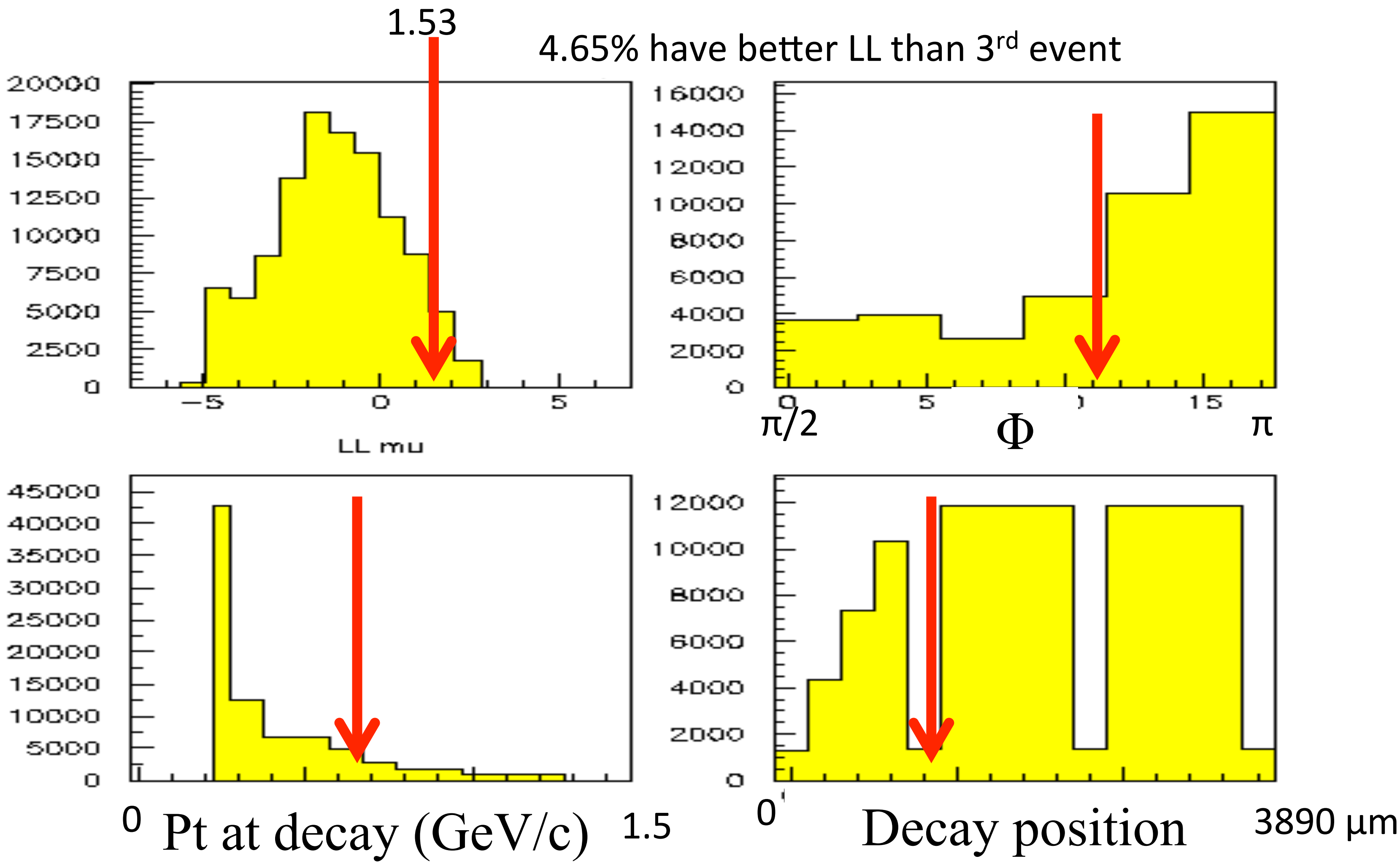
LL analysis of first event: e.g. charm



LL analysis of second event: e.g. hadron scattering



LL analysis of third event: e.g. μ scattering



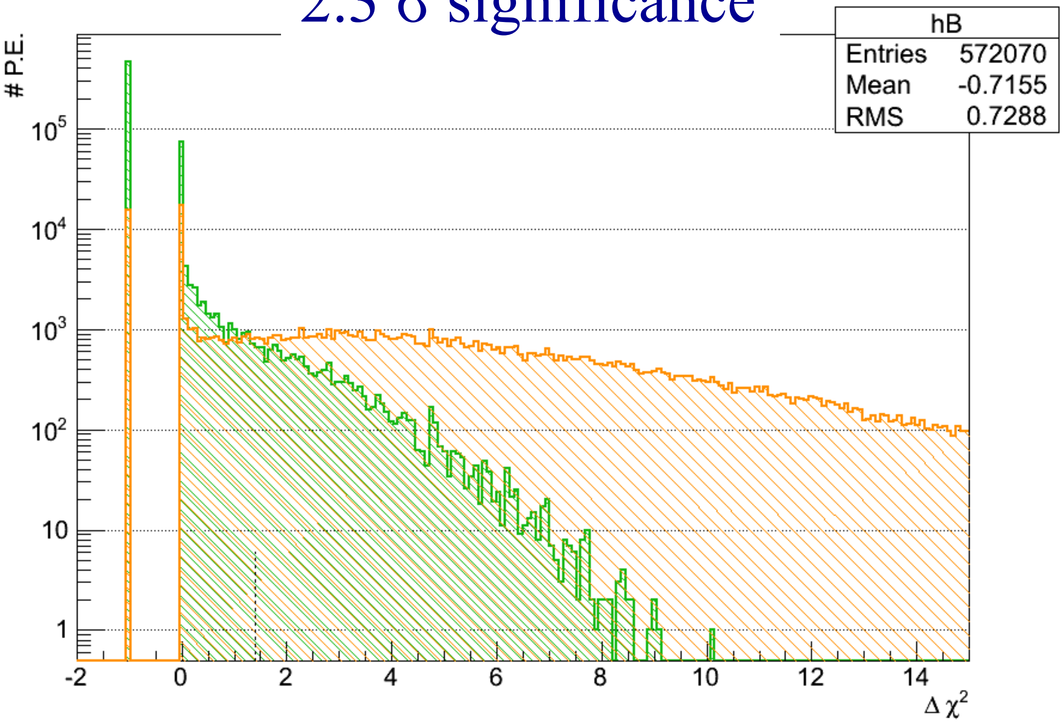
Statistical considerations sample analysed for 2012 Summer conferences

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

Summer 2012 conferences

	Signal	Background
$\tau \rightarrow h$	0.66	0.045
$\tau \rightarrow 3h$	0.61	0.090
$\tau \rightarrow \mu$	0.34	0.017
$\tau \rightarrow e$	0.49	0.065
total	2.10	**0.217**

2.3 σ significance

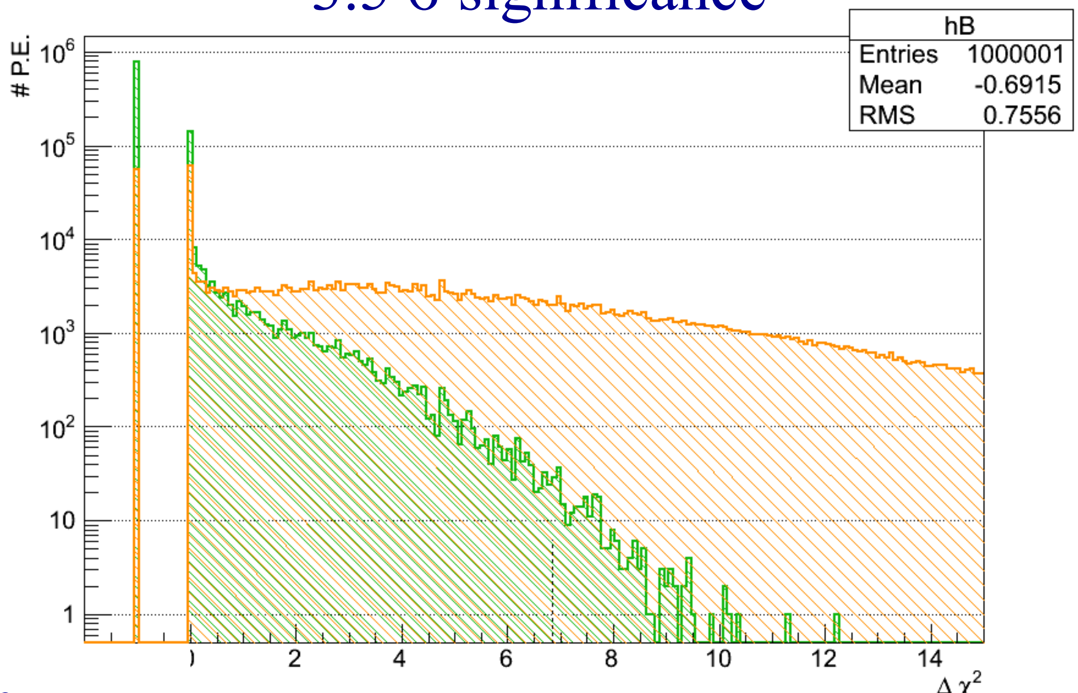


Statistical considerations
Extended sample to muonic interactions

Extended sample

	Signal	Backgrou
τ→ h	0.66	0.045
τ → 3h	0.61	0.090
τ → μ	0.56	0.026
τ → e	0.49	0.065
total	2.32	**0.226**

3.5 σ significance



3.8 σ significance with independent analysis

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

- *Three events reported in an extended sample*
- *Conservative background evaluation*
- *Significance of 3.2σ with simple counting method*
- *With a first likelihood approach, 3.5σ level*
- *4σ observation within reach in 2013*

Thank you for your attention