New results of the OPERA experiment

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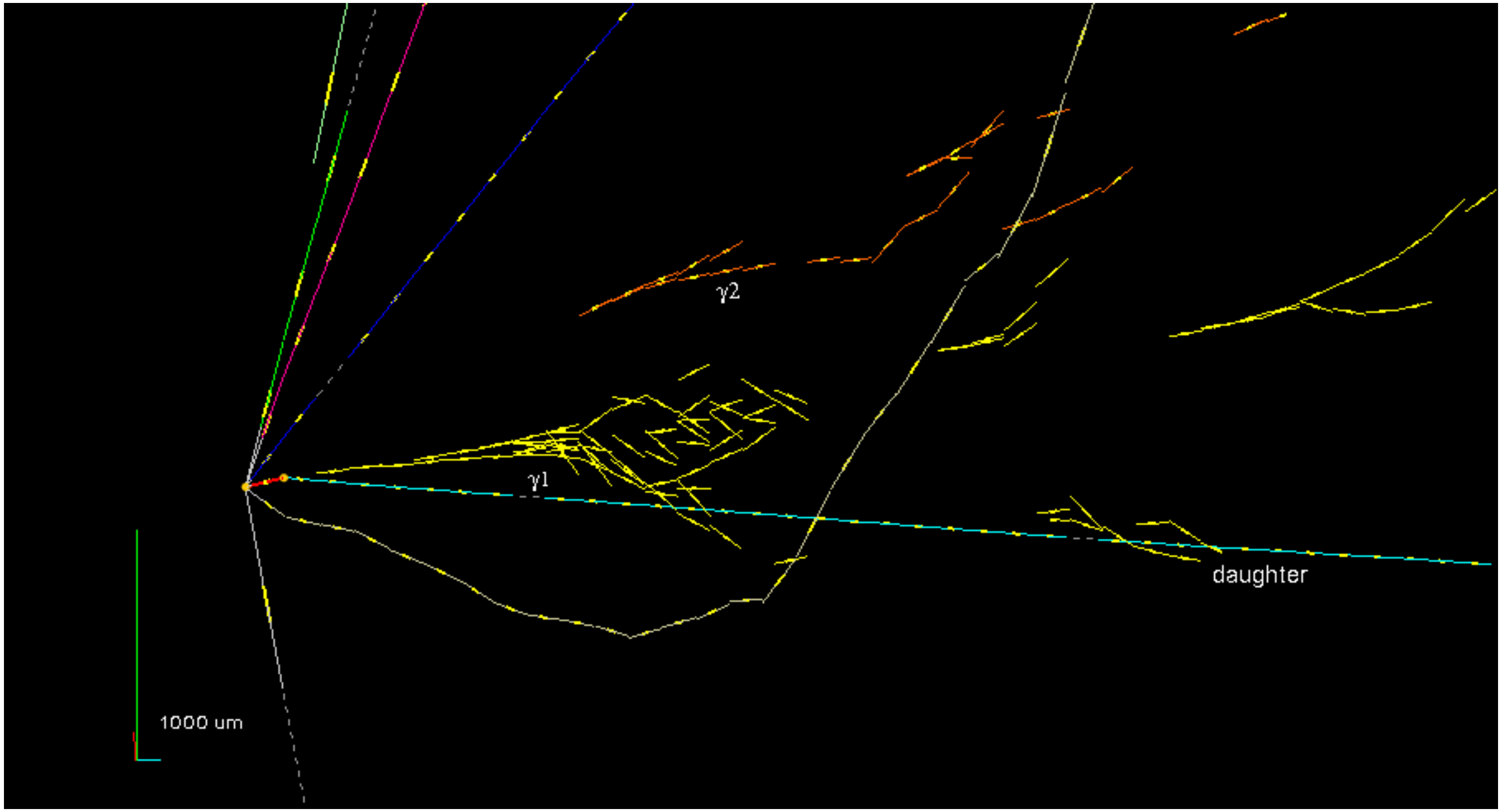
University "Federico II" and INFN Napoli

On behalf of the OPERA Collaboration



Outline Of The Talk

- The OPERA experiment and its detector
- The analysis chain
- Oscillation physics
- Background studies
- Significance of the results

Physics: From Neutrino Mixing To Oscillations

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

3x3 Unitary Mixing Matrix

PMNS (Pontecorvo-Maki-Nakagawa-Sakata) Matrix

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

Amospheric ν, SuperK, K2K, MINOS, T2K

OPERA

Chooz, Daya Bay, RENO, T2K, MINOS, NOvA. …

Solar ν, Borex, SuperK, SNO, KamLAND, …

$\Delta m^2_{32} = (2.44 \pm 0.06)\ 10^{-3}\ eV^2$ $\theta_{32} = (45.8 \pm 3.2)°$	$\theta_{13} = (8.88 \pm 0.39)°$	$\Delta m^2_{21} = (7.53 \pm 0.18)\ 10^{-5}\ eV^2$ $\theta_{12} = (33.4 \pm 0.85)°$

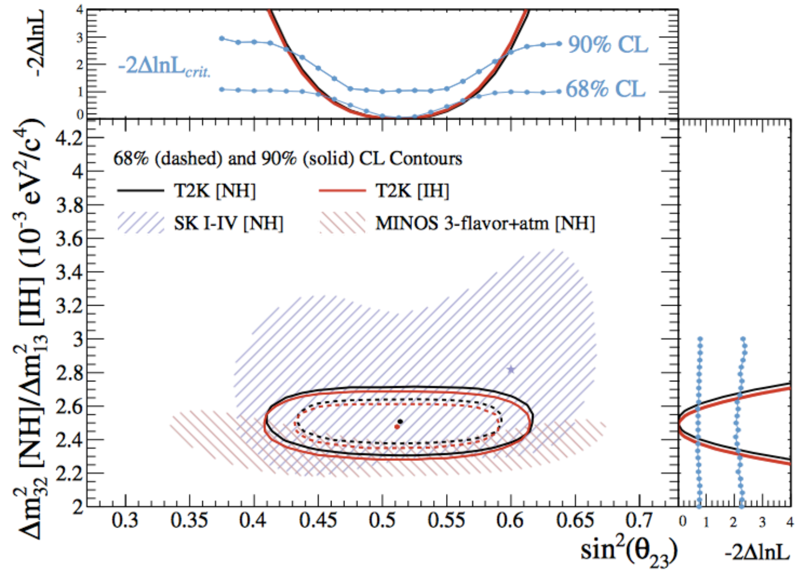
PDG 2014

THE OPERA EXPERIMENT

First direct detection of $\nu_\mu \rightarrow \nu_\tau$ 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



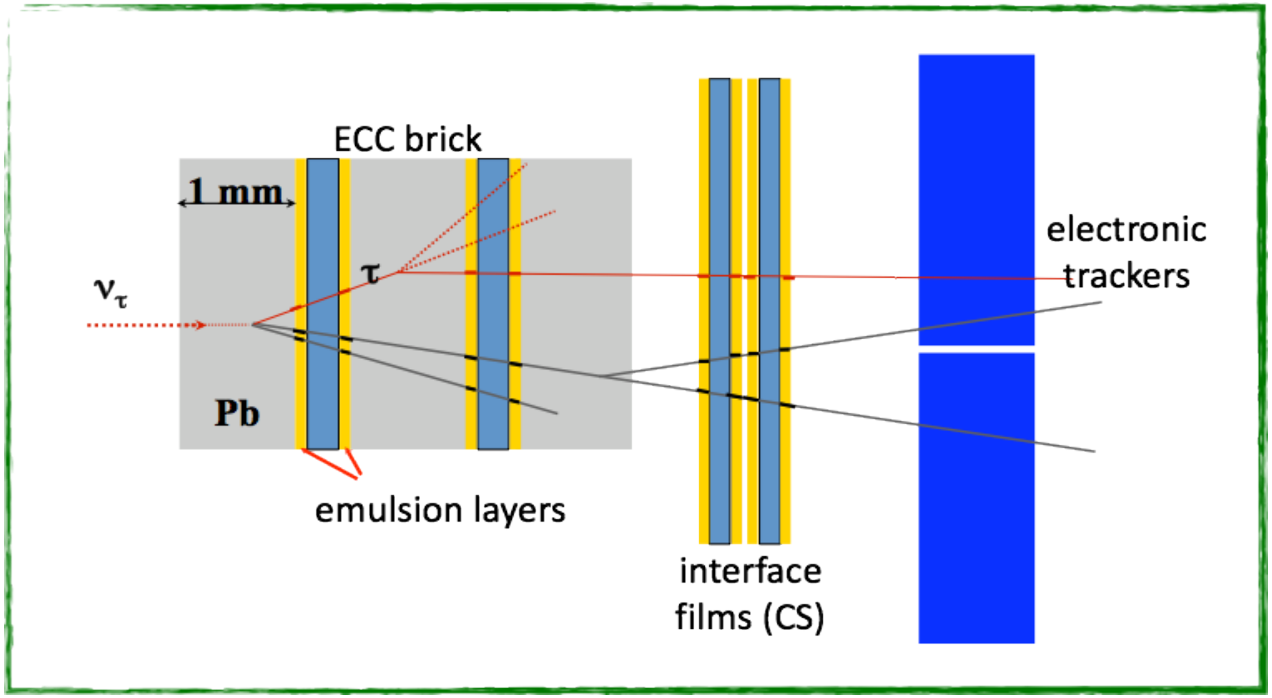
PRL 112 (2014) 181801

The PMNS 3-flavor oscillation formalism predicts:

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

Requirements:
1) Long baseline
2) High energy neutrinos
3) High intensity beam
4) Detect short lived τ leptons

The Principle:
Hybrid Detector With Modular Structure



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

- Small neutrino cross-section and beam divergence: massive active target (~ 1.2 kton)
- Detect τ-lepton production and decay: micrometric space resolution
- Underground location (10^6 reduction of cosmic ray flux)
- Electronic detectors to provide the"time stamp", preselect the interaction brick and reconstruct μ charge/momentum

THE OPERA COLLABORATION

140 physicists, 26 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,
LNGS
Naples
Padova
Rome
Salerno

Japan
Aichi
Toho
Kobe
Nagoya
Nihon

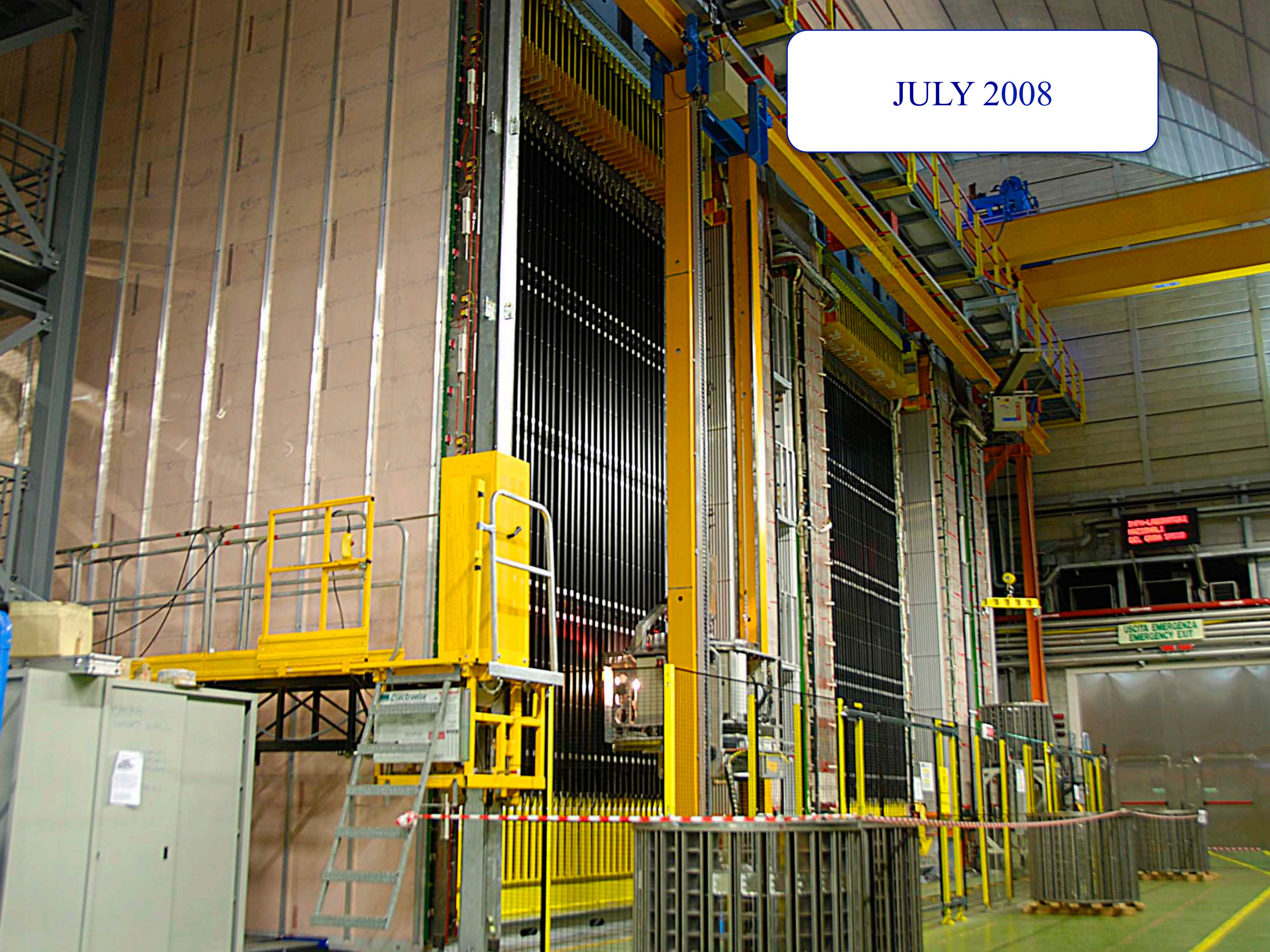
Korea
Jinju

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

Switzerland
Bern

Turkey
METU, Ankara

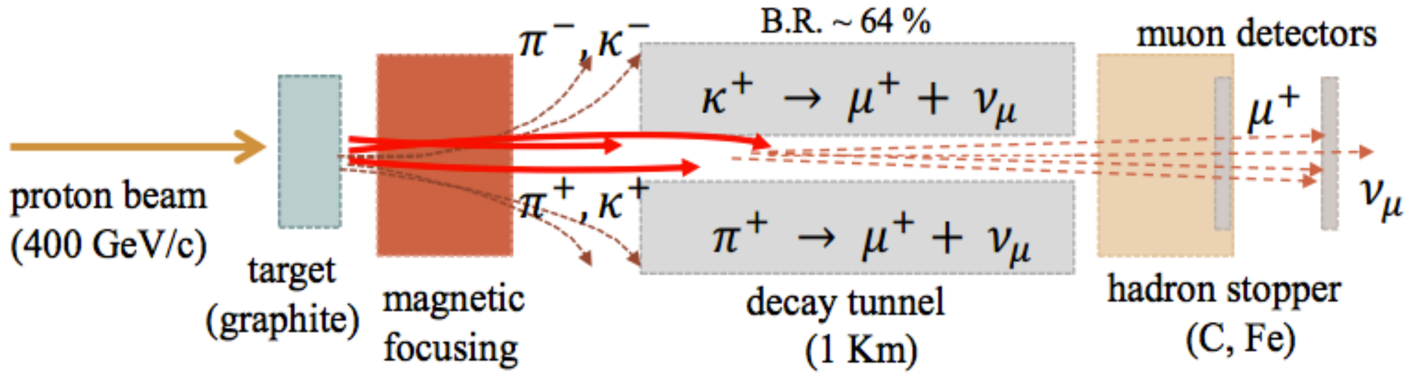
http://operaweb.lngs.infn.it


JULY 2008
USCITA EMERGENZA
EMERGENCY EXIT

CNGS Beam And LNGS Site

CNGS Beam

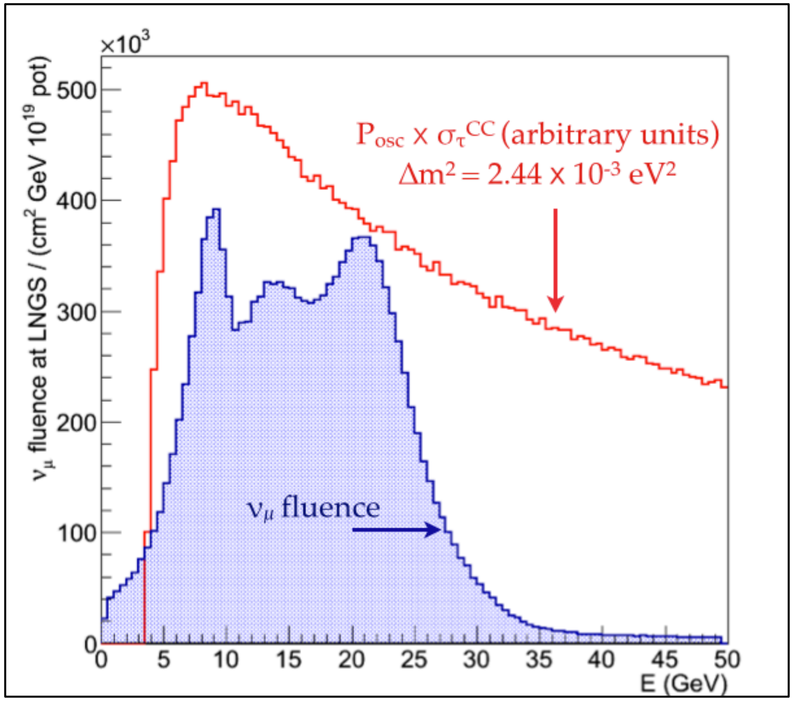
Tuned for ν_τ-appearance at LNGS



CNGS ν beam

$<E\nu_\mu>$ (GeV)	17
$(\bar{\nu}_e+\nu_e)/\nu_\mu$	0.8% *
$\bar{\nu}_\mu/\nu_\mu$	2.0% *
ν_τ prompt	Negligible *

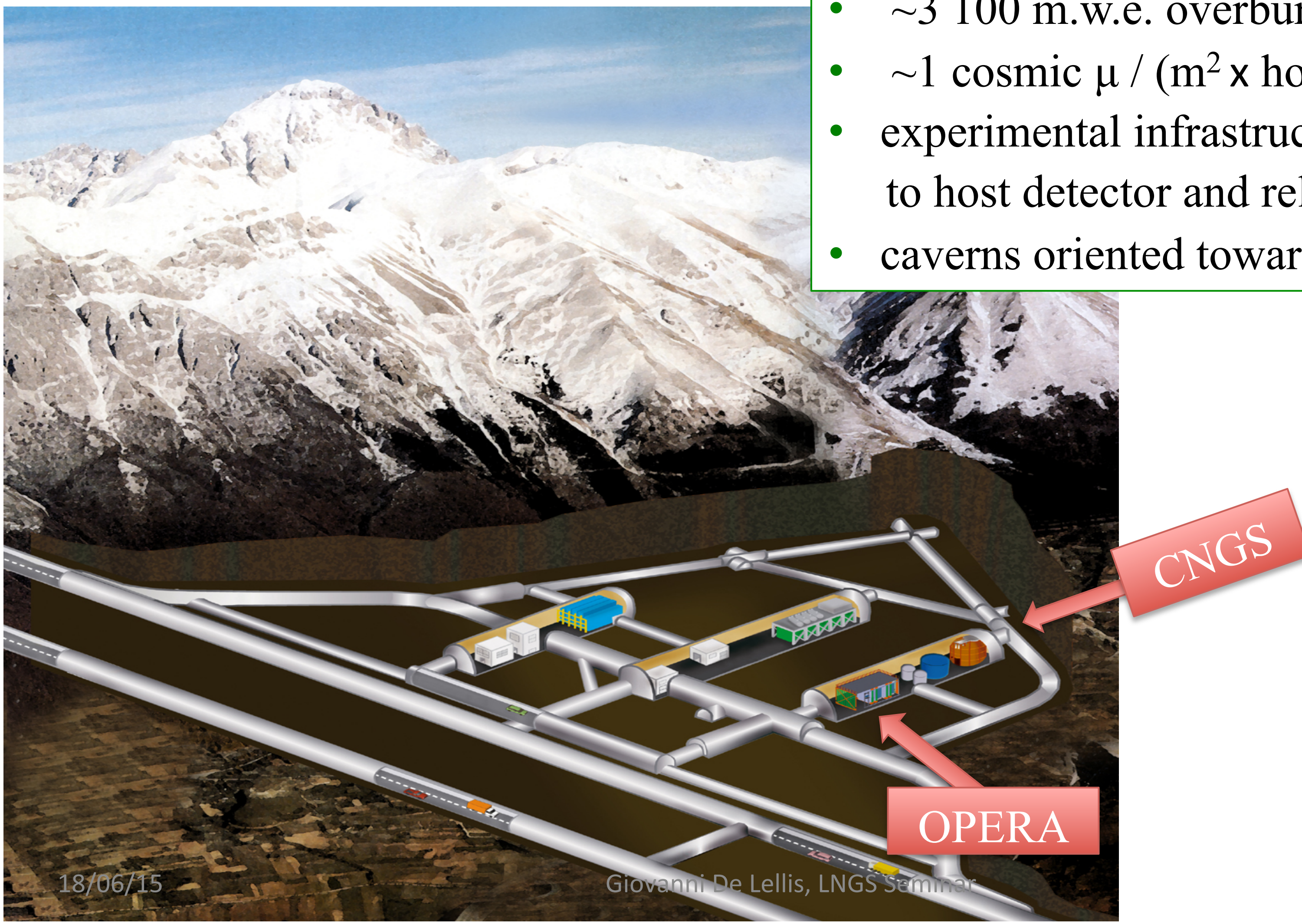
* Interaction rate at LNGS



LNGS OF INFN

The world largest underground physics laboratory

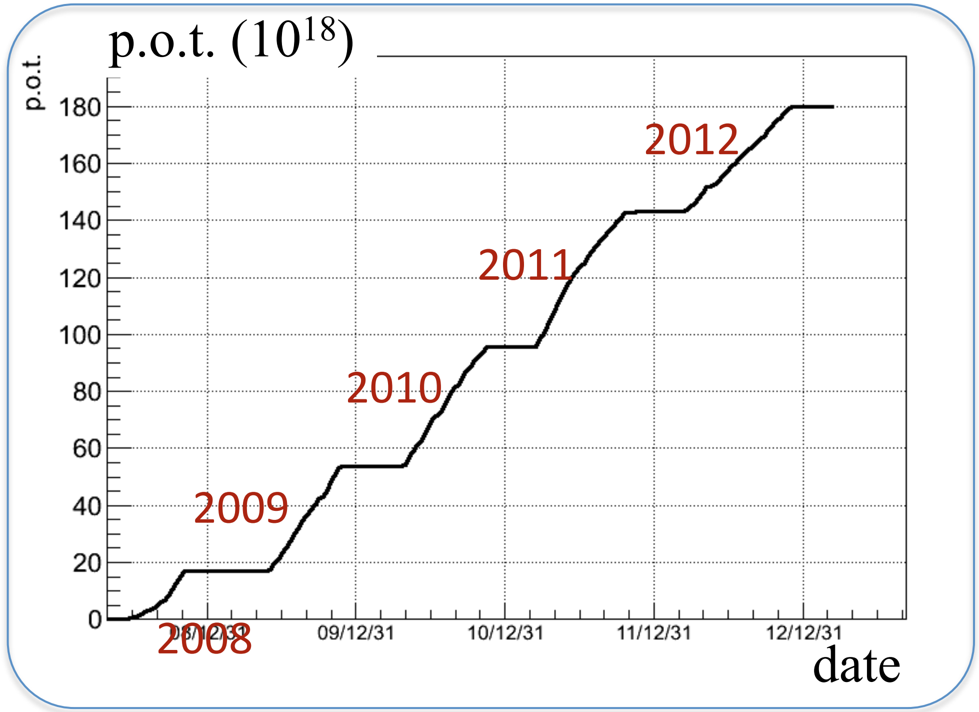
- ~180 000 m^3 caverns' volume
- ~3 100 m.w.e. overburden
- ~1 cosmic μ / (m^2 x hour)
- experimental infrastructure suitable to host detector and related facilities
- caverns oriented towards CERN



CNGS Performances

Along 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)

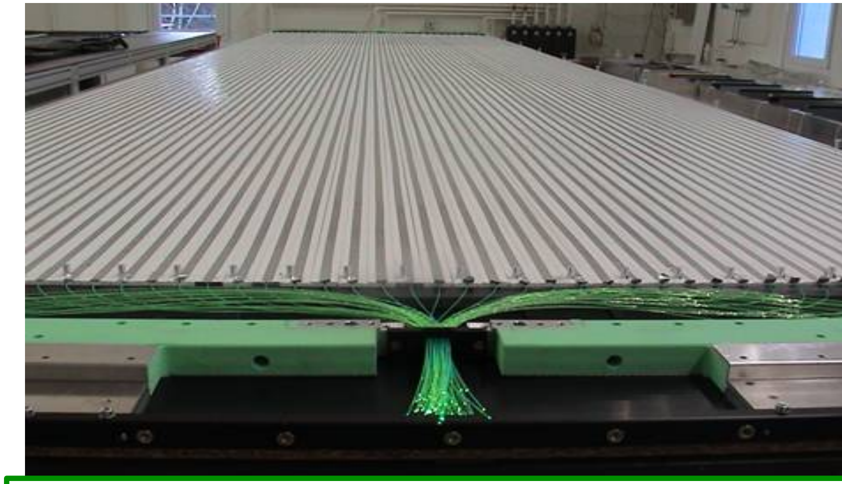
Detectors And Facilities In Operation:

A Very Complex Experiment…

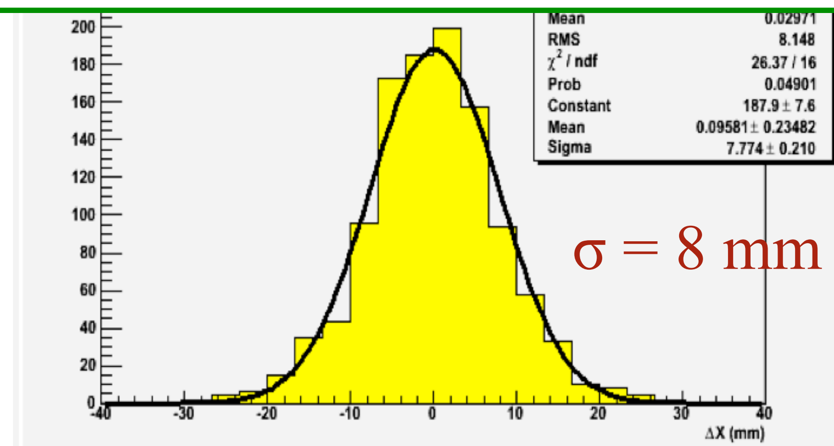
Two target super-modules, each with an iron spectrometer for muon detection
JINST 4 (2009) P04018

SCINTILLATOR STRIPS TARGET TRACKER AND BRICK TRAYS

NIM A577 (2007) 523

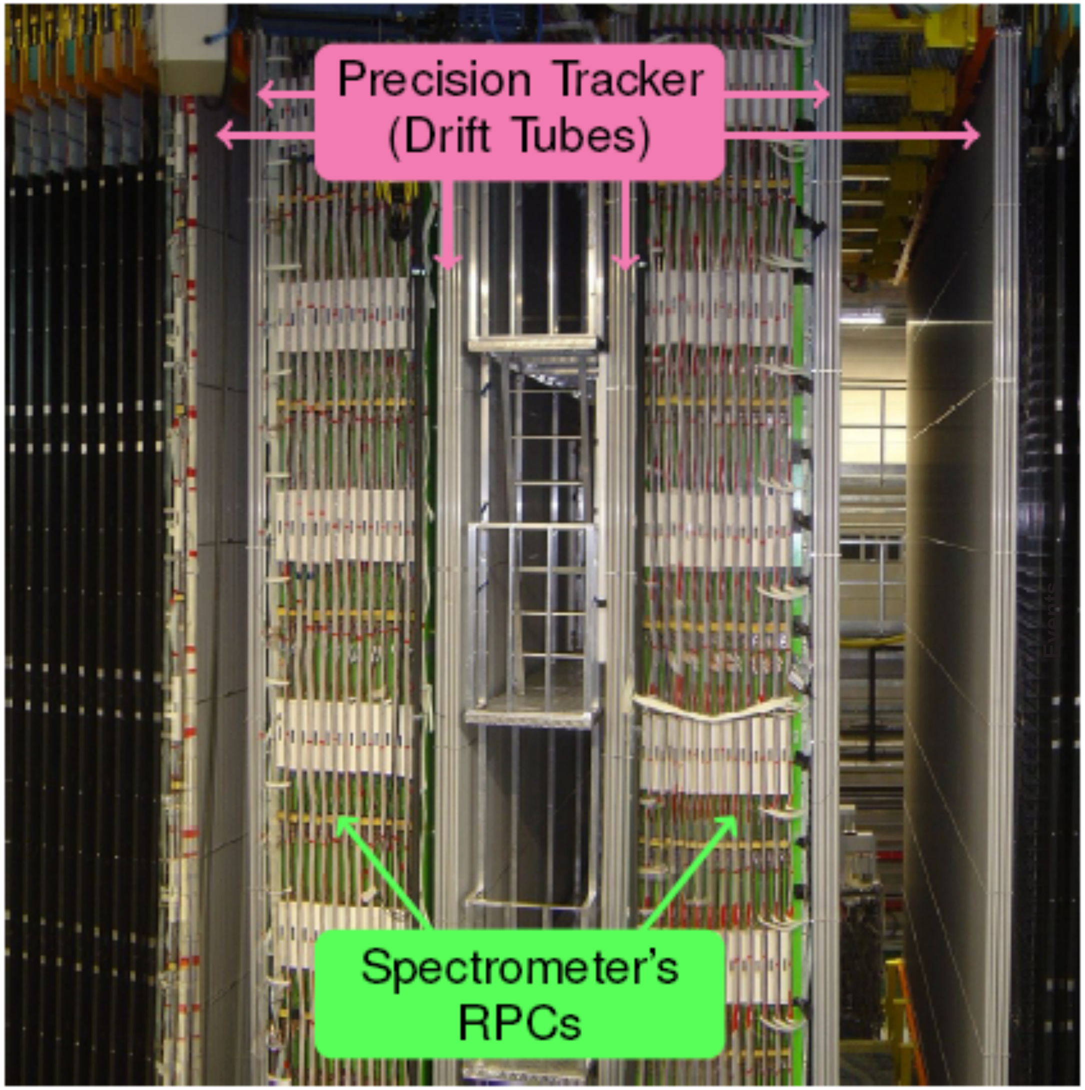


- > 5 p.e. for a m.i.p.
- ~ 99% detection efficiency ⇒ trigger
- position accuracy: ~ 8 mm
- angular accuracy: ~ 15 mrad



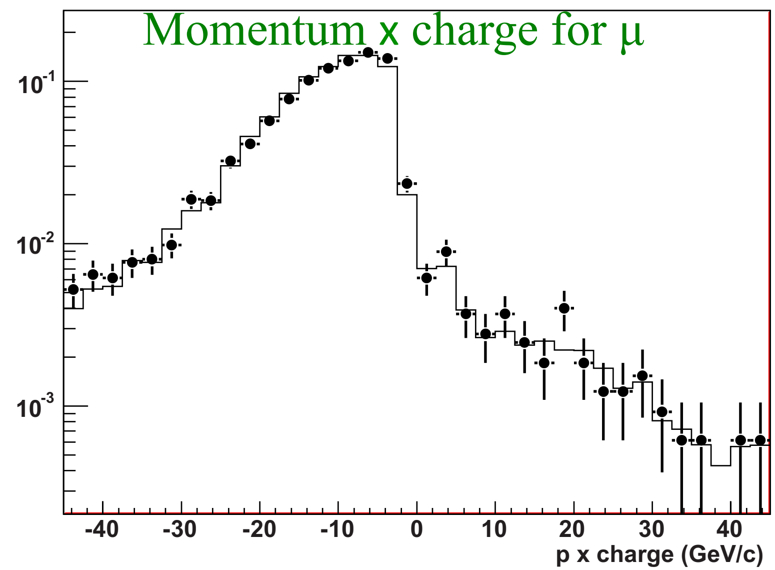
mechanical structure:
brick trays, only 0.5% of target mass

THE MAGNETIC SPECTROMETER



NIM A602 (2009) 631-634

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



New Journal of Physics 13 (2011) 053051

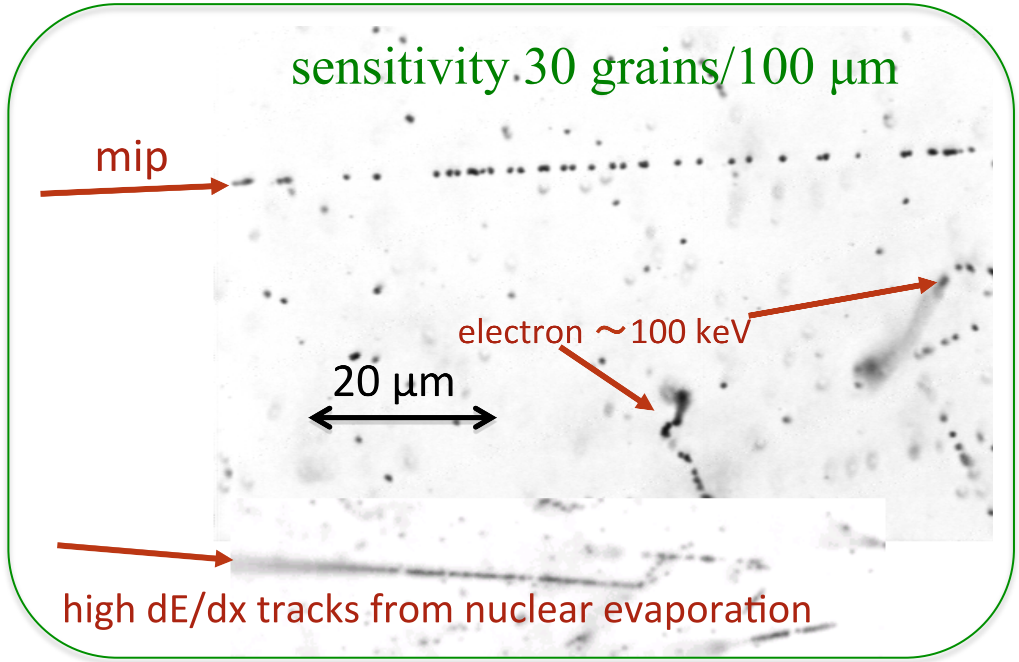
THE ECC TARGET BRICKS

The heart of the experiment

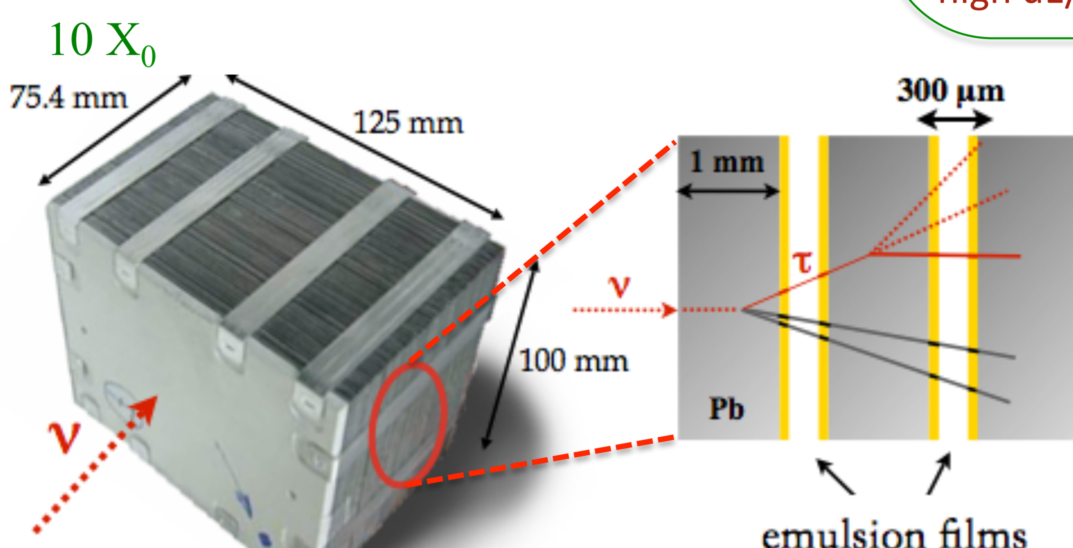
<u>Emulsion Cloud Chamber</u>

ECC

- passive material → lead
  (massive target)
- tracking device → nuclear emulsions
  (high resolution)

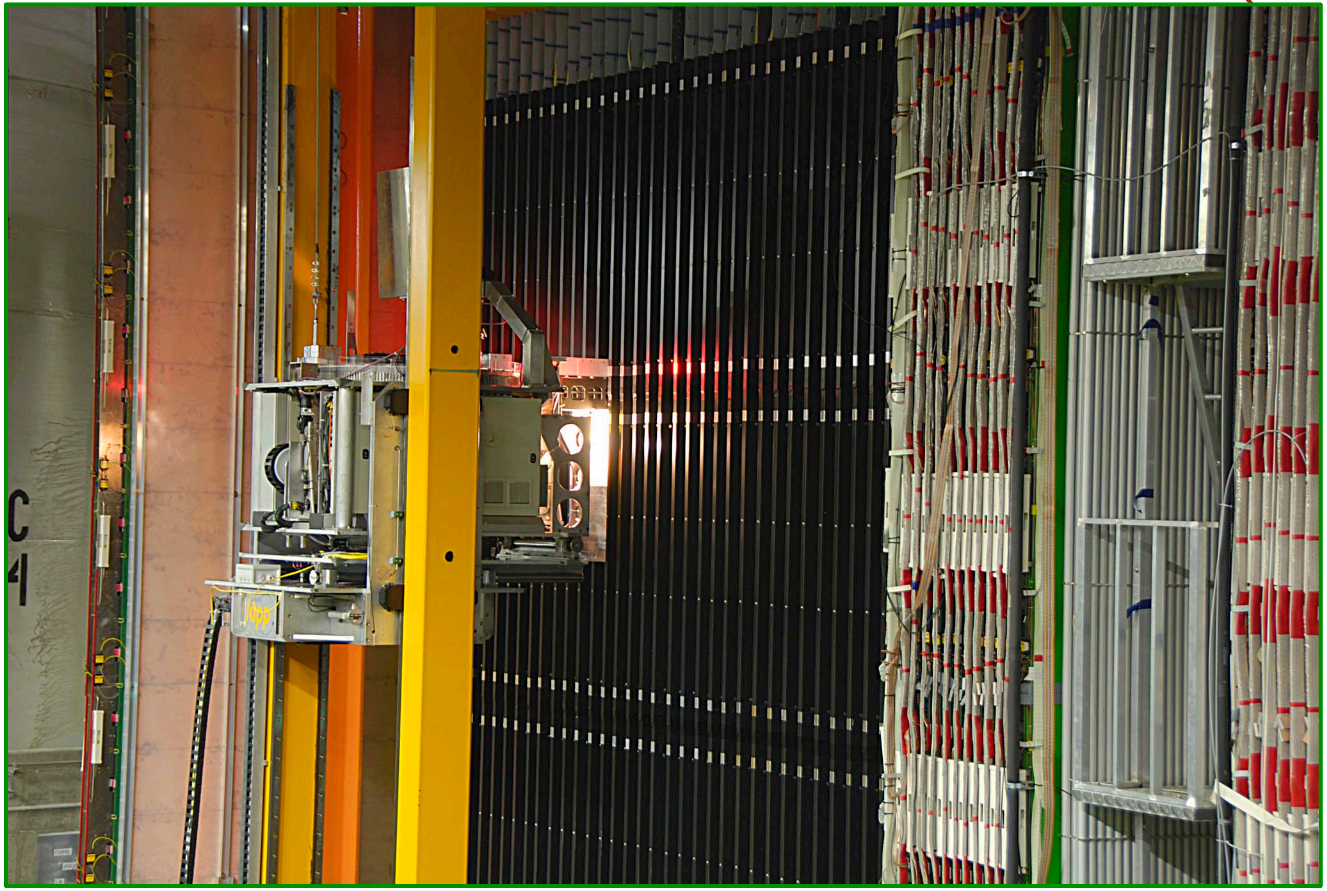


NIM A556 (2006) 80-86



- The OPERA target consists of 150’000 ECC bricks
- Total lead surface: 105’000 m^2
- Total film surface: 110’000 m^2 (~ 9 million films)
- Total target mass ~ 1.2 kton

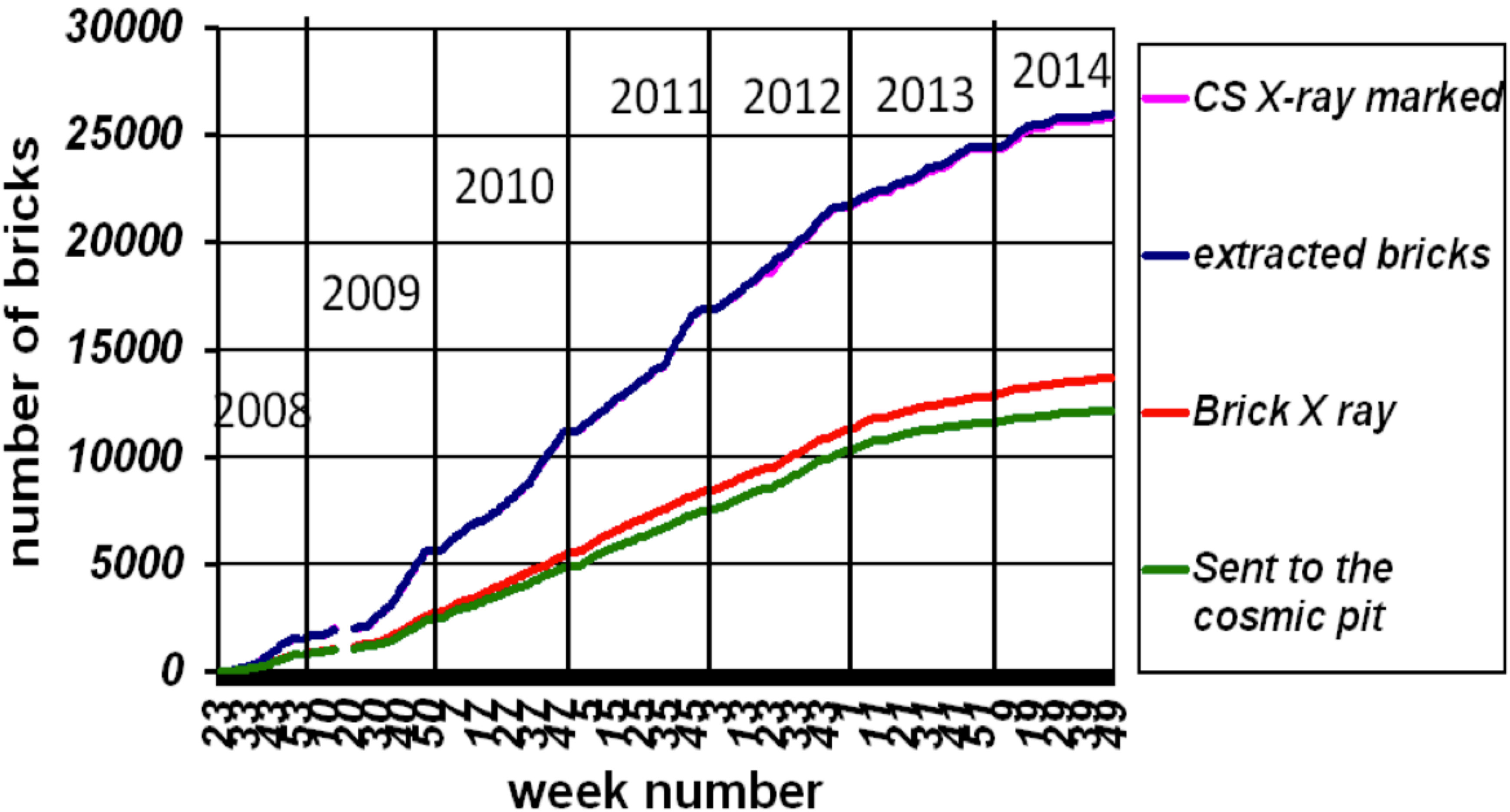
Brick Manipulator System (BMS)



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

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

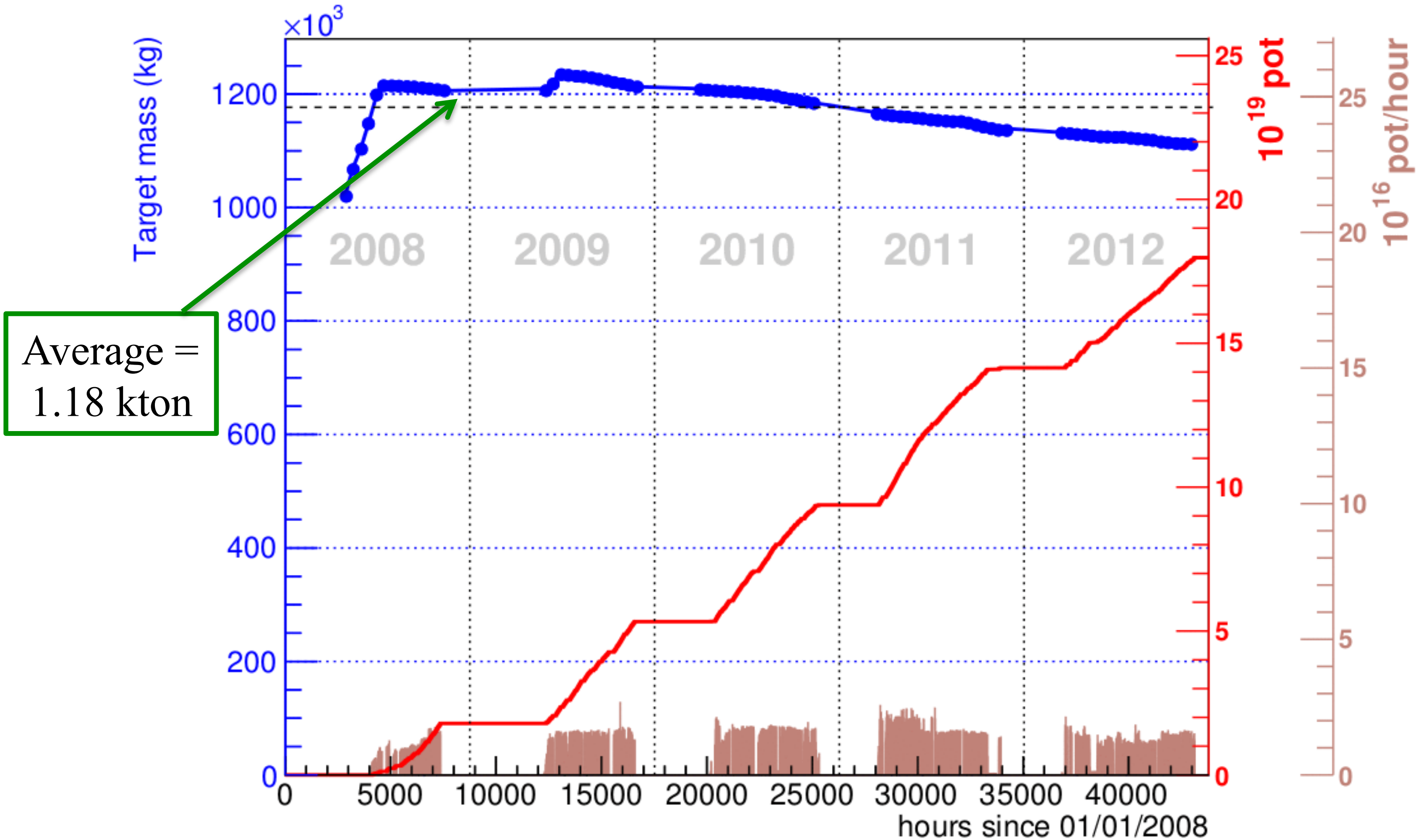
OPERA Brick Handling



26115 bricks manipulated for event analysis

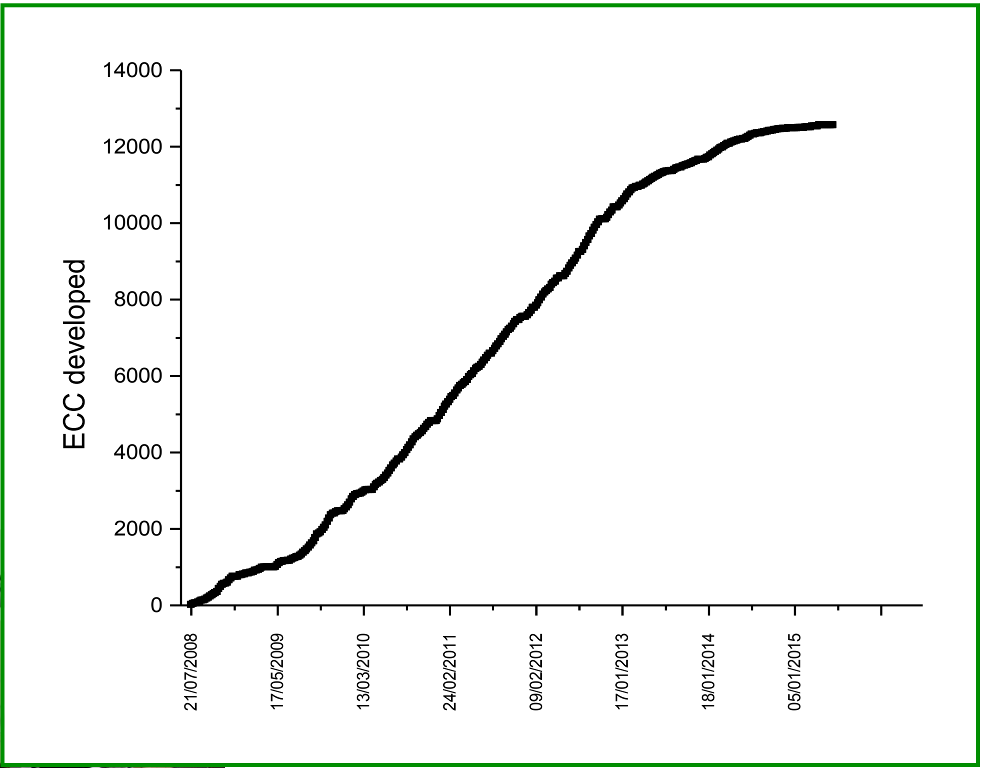
Each platform run for more than 200 km vertically and 125 km horizontally

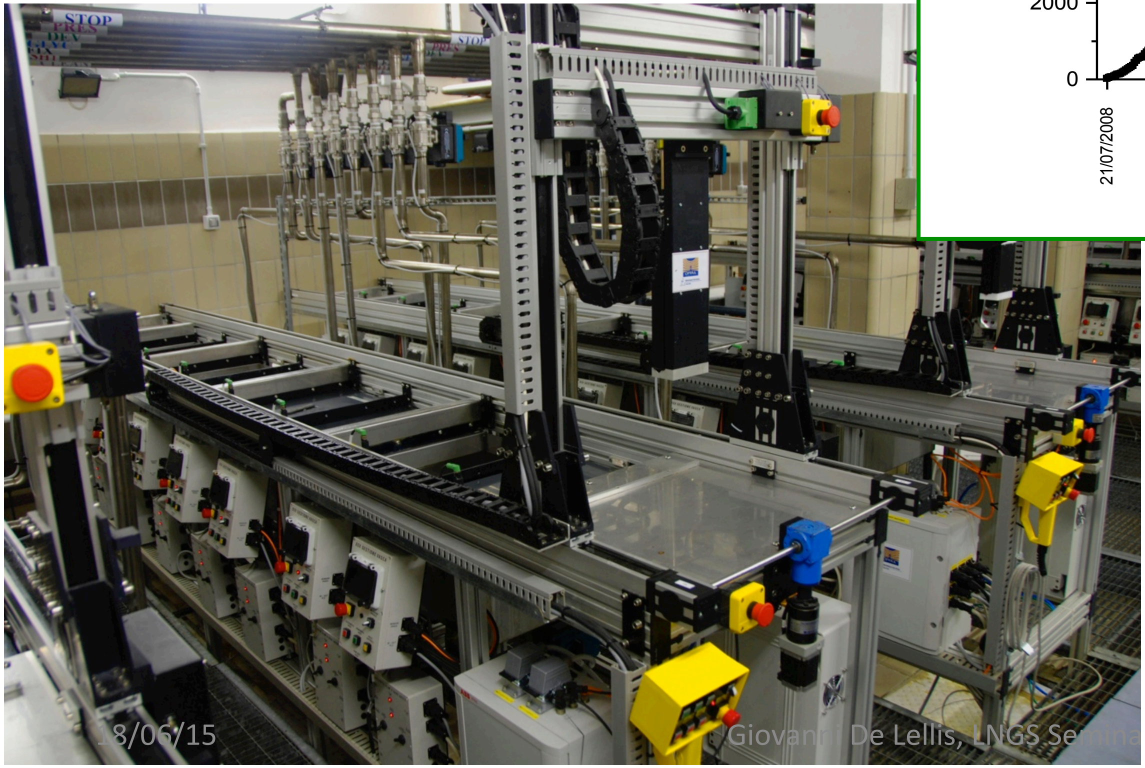
Target Mass Evolution During Runs



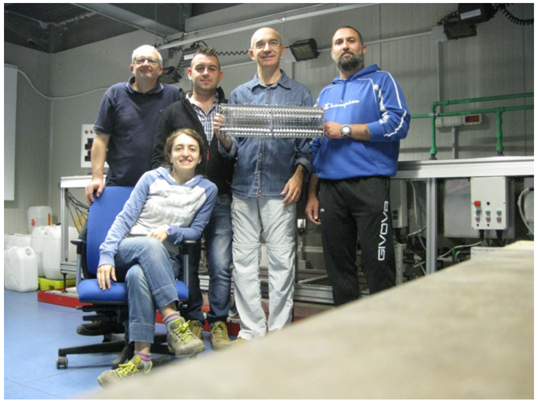
Film Development Facility

- 6 automated lines running in parallel in a dark room
- additional facility underground for CS films

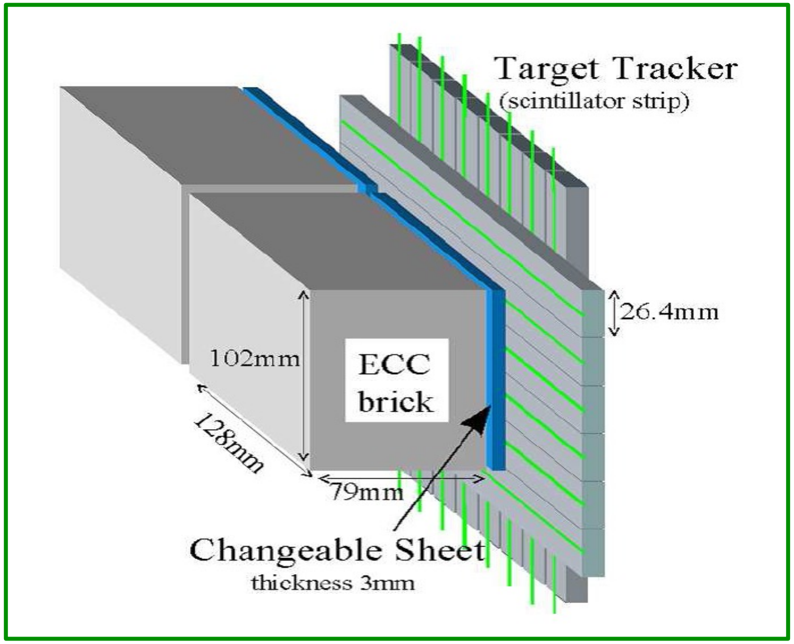


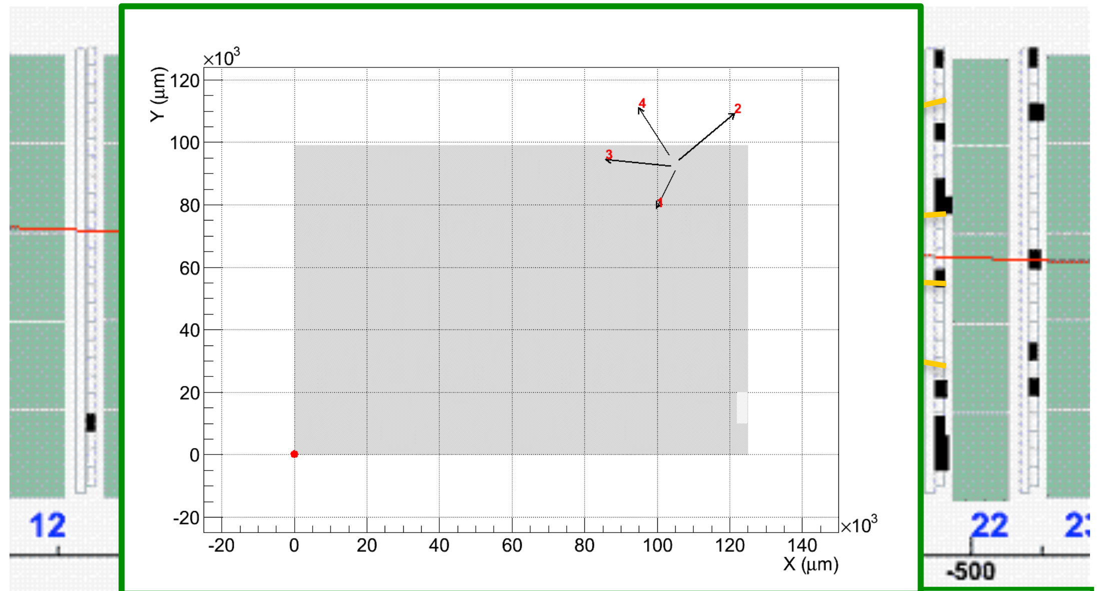


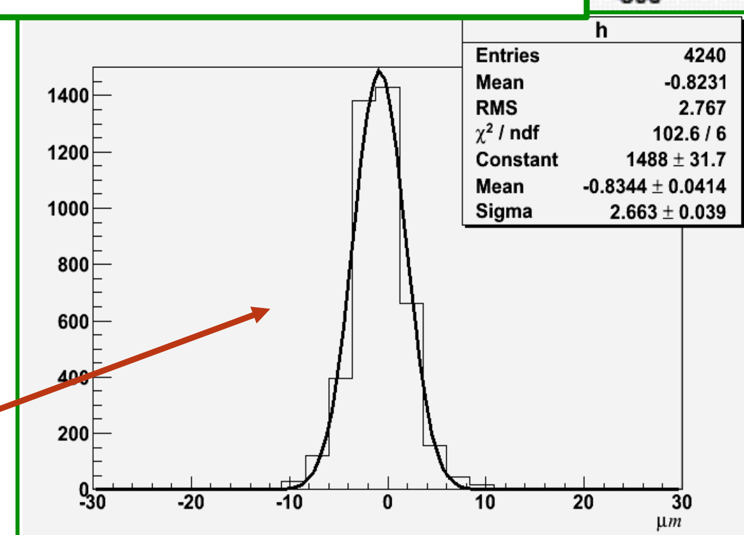
~12500 bricks developed
~ 9300 m^2



Interface Films
for the brick validation







Two interface (changeable, CS) films packed in a detachable box, glued downstream of each brick

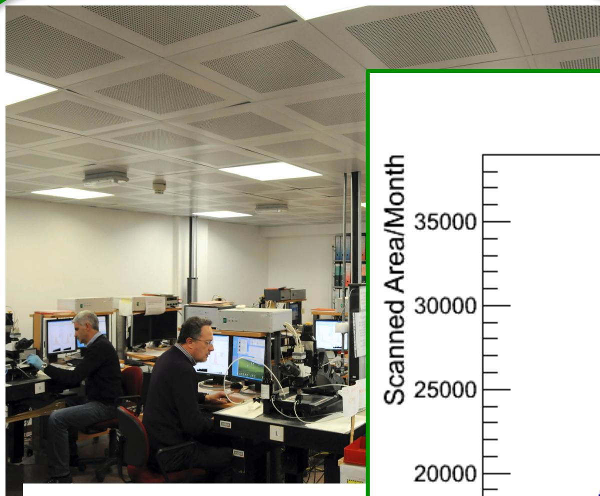
Alignment of CS films by Compton electrons: 2.5 μm

JINST 3 (2008) P07005

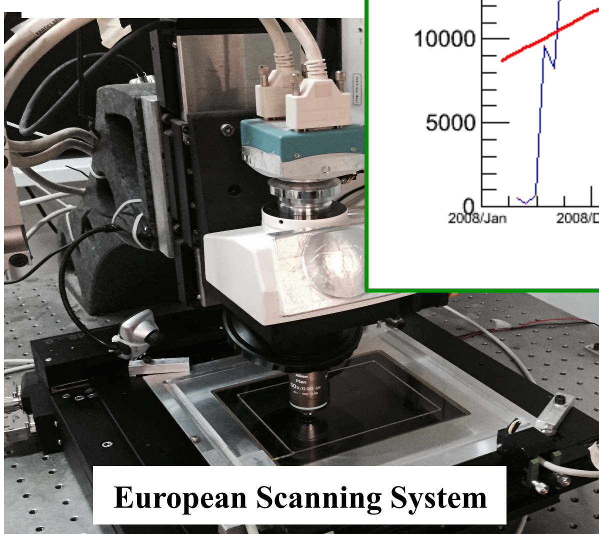
So far ~ 3’110’000 cm² of CS surface analysed

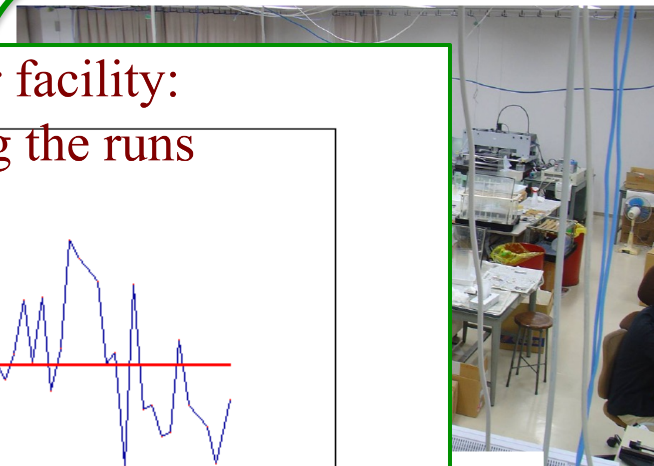
Scanning Of Changeable Sheets

Two large facilities

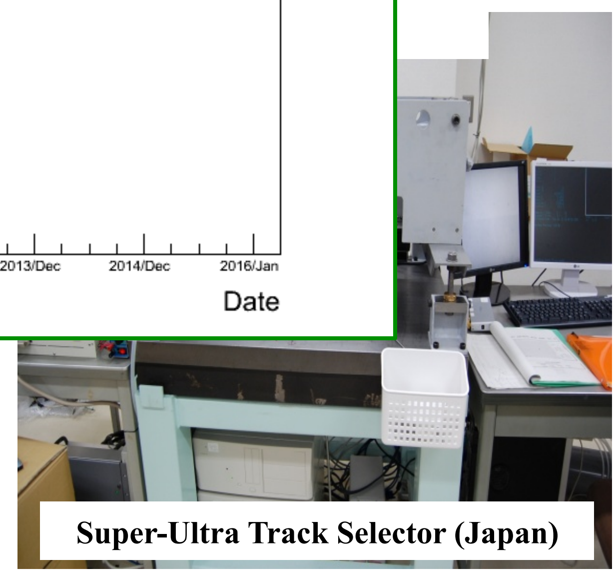


LNGS: 12 micr
240 cm²

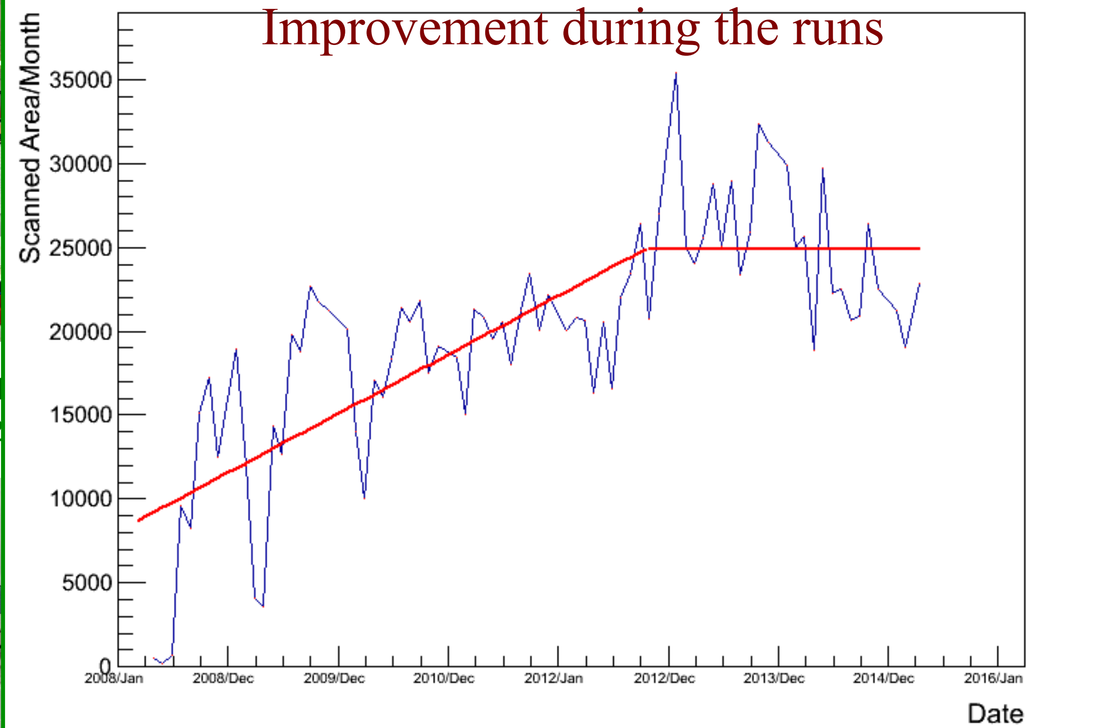




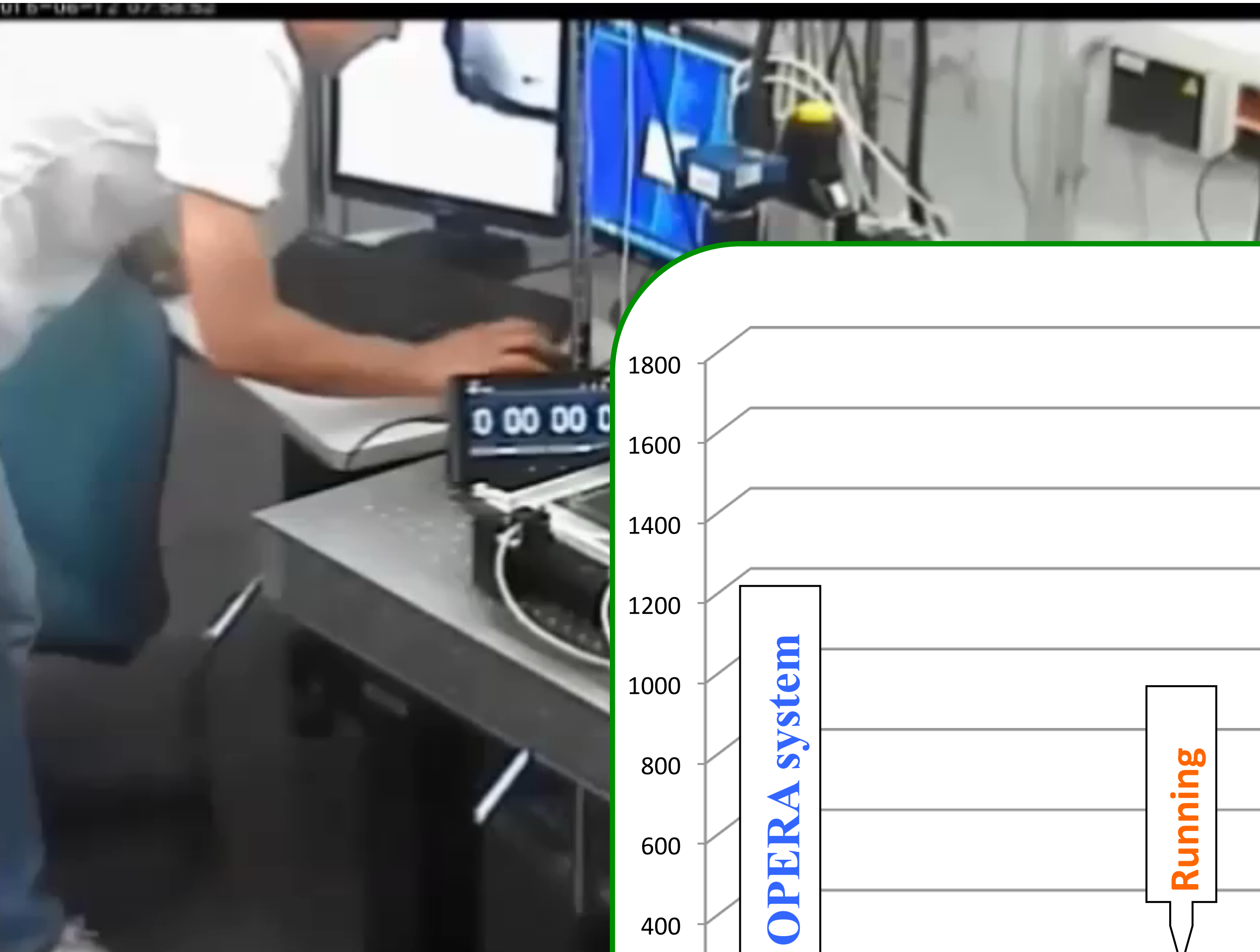
TS,

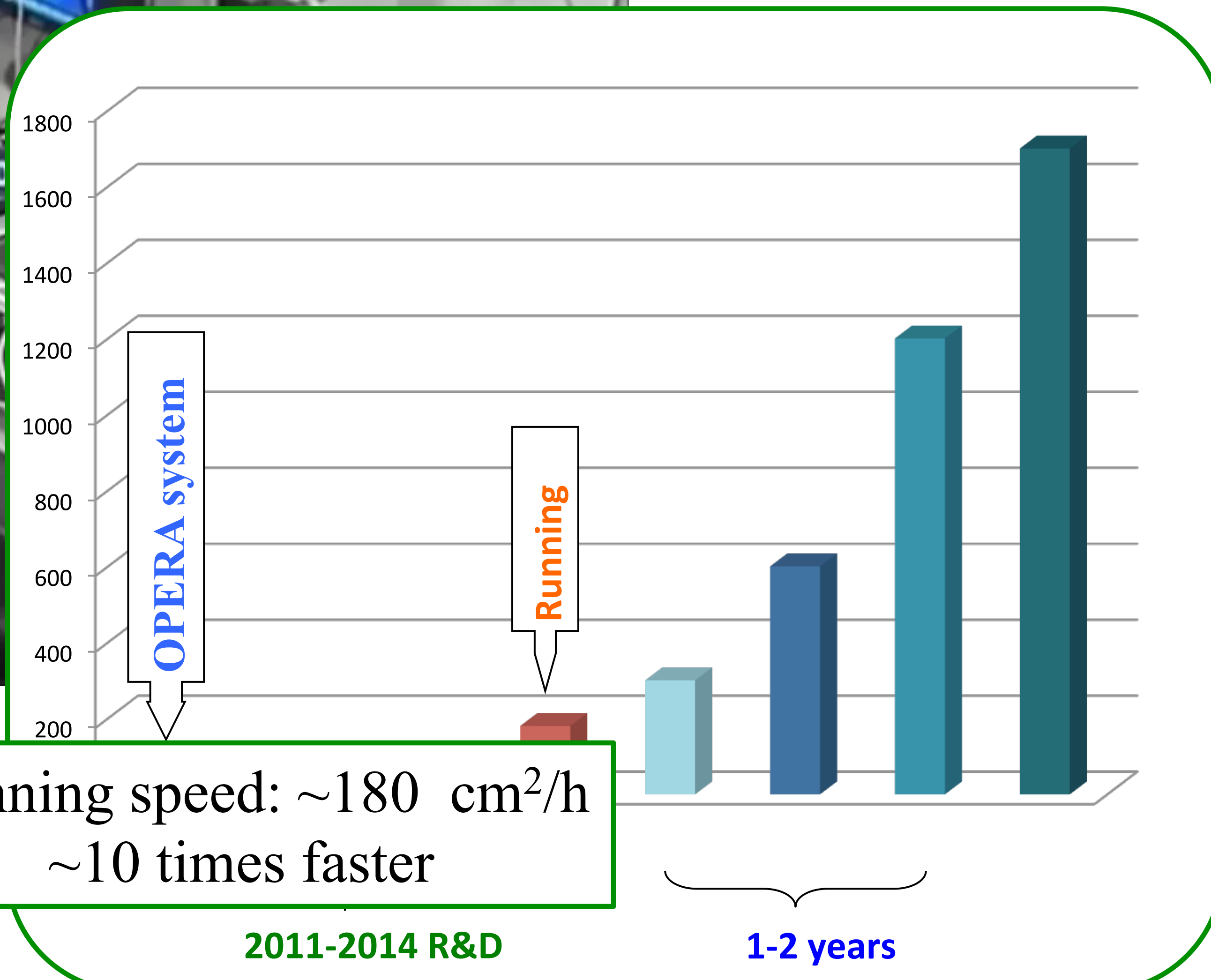


Scanning speed per facility:
Improvement during the runs



Improvements In The Scanning System



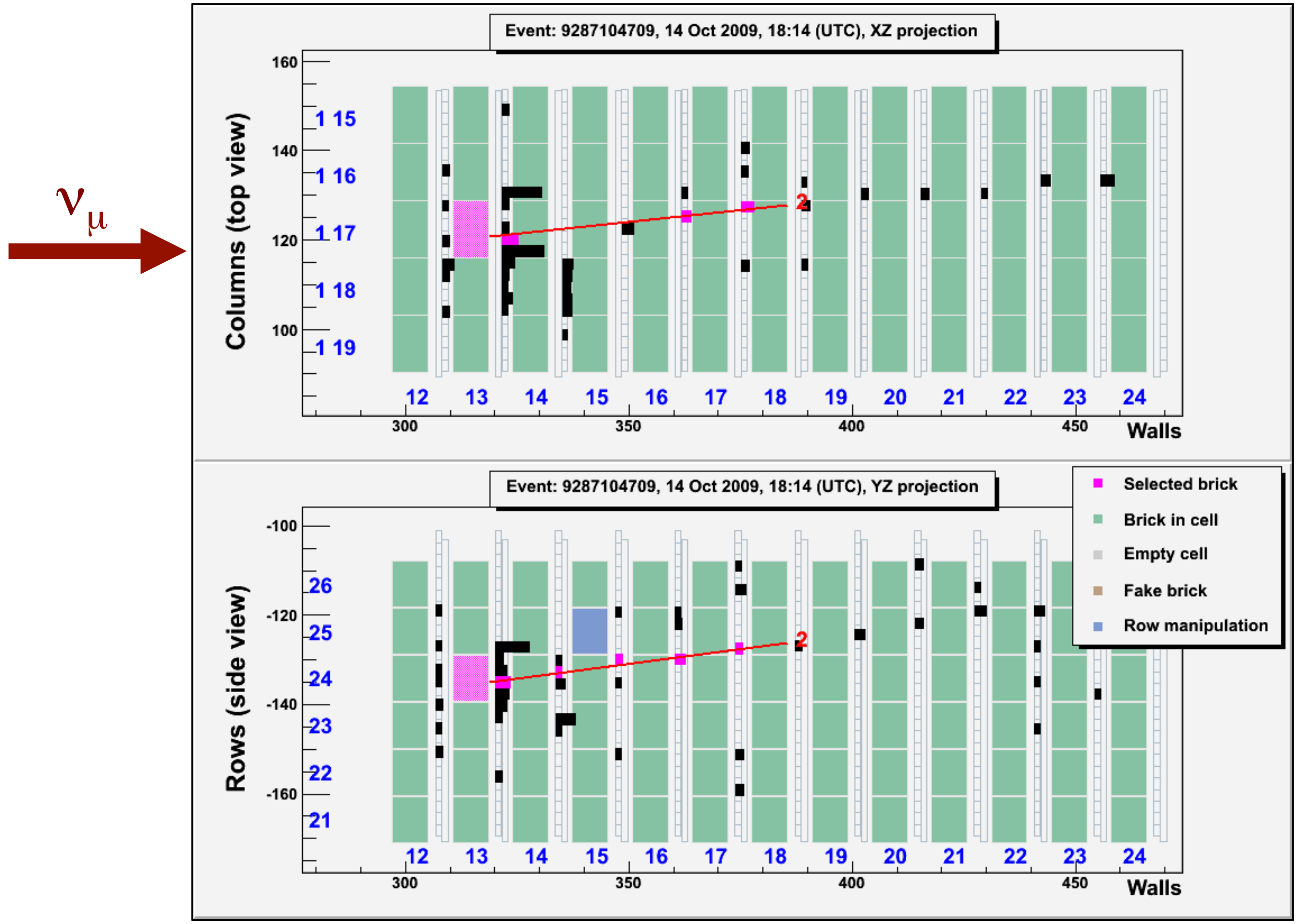


Scanning speed: ~180 cm^2/h
~10 times faster

INTERFACE EMULSION FILMS

High signal/noise ratio for event trigger and scanning time reduction

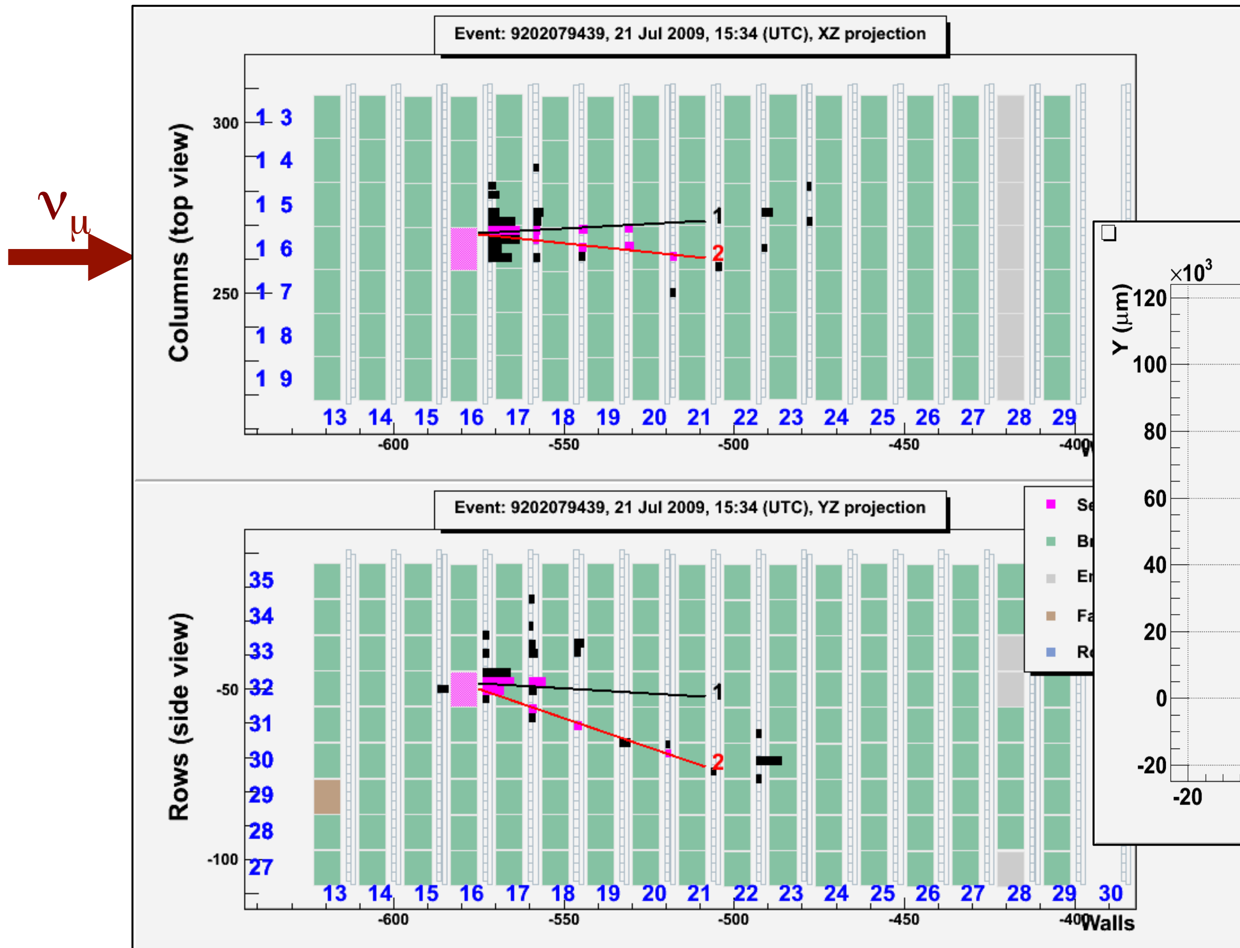
ν_μ^{CC} interaction: muon track reconstruction in interface films

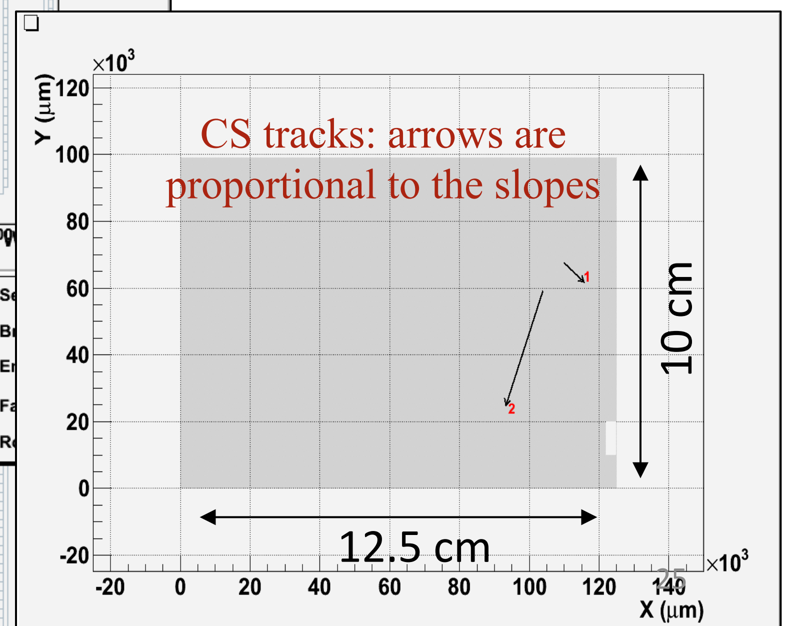


INTERFACE EMULSION FILMS

Validation of events without a μ in the final state

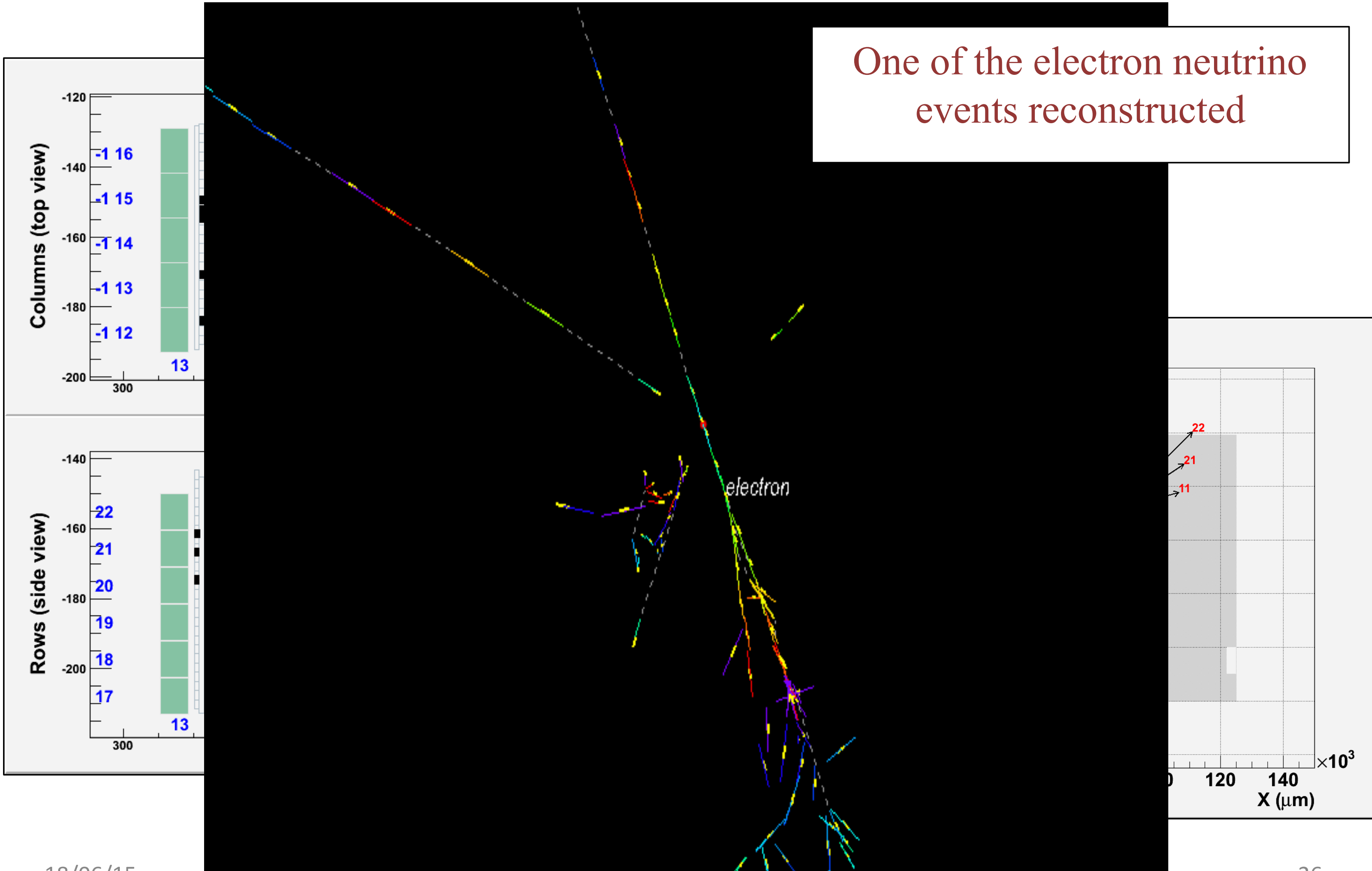
ν_μ^{NC} interaction: convergence pattern in interface films





INTERFACE EMULSION FILMS

Electron shower pre-selection

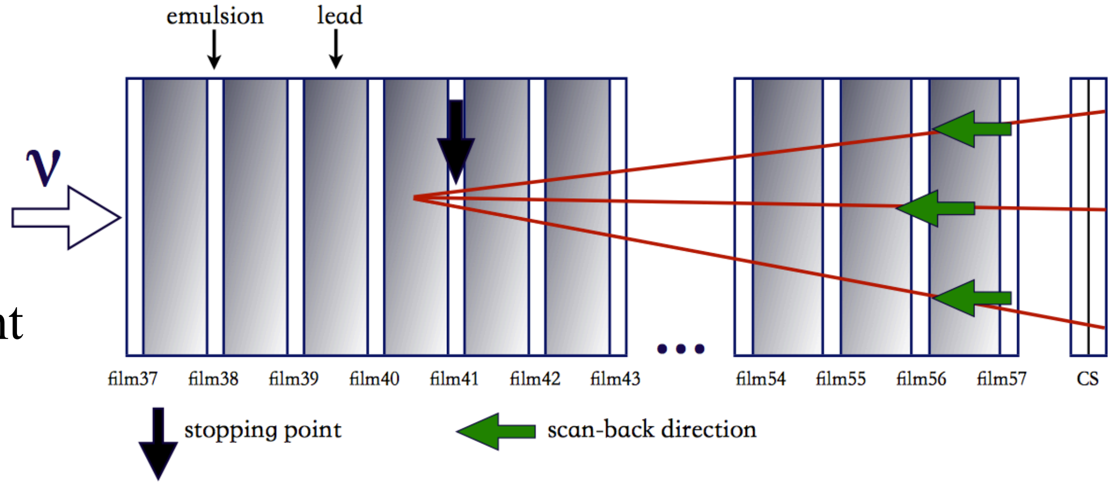


One of the electron neutrino events reconstructed

Track Follow-Up And Vertex Finding

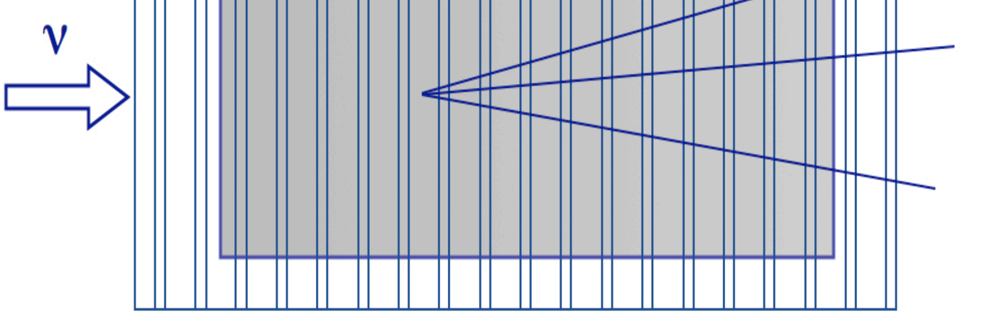
Track follow-up film by film:

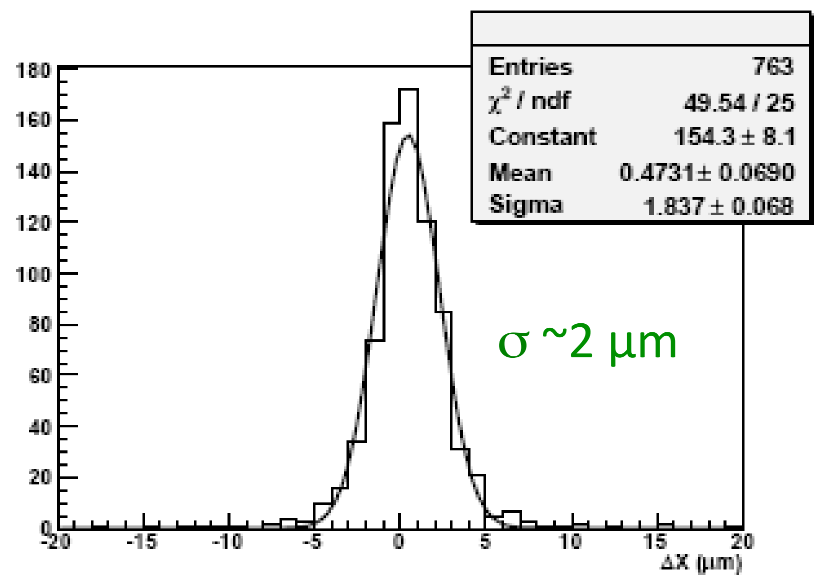
- Brick exposure at the surface laboratory to cosmic-rays for alignment
- Definition of the stopping point



Volume scan:

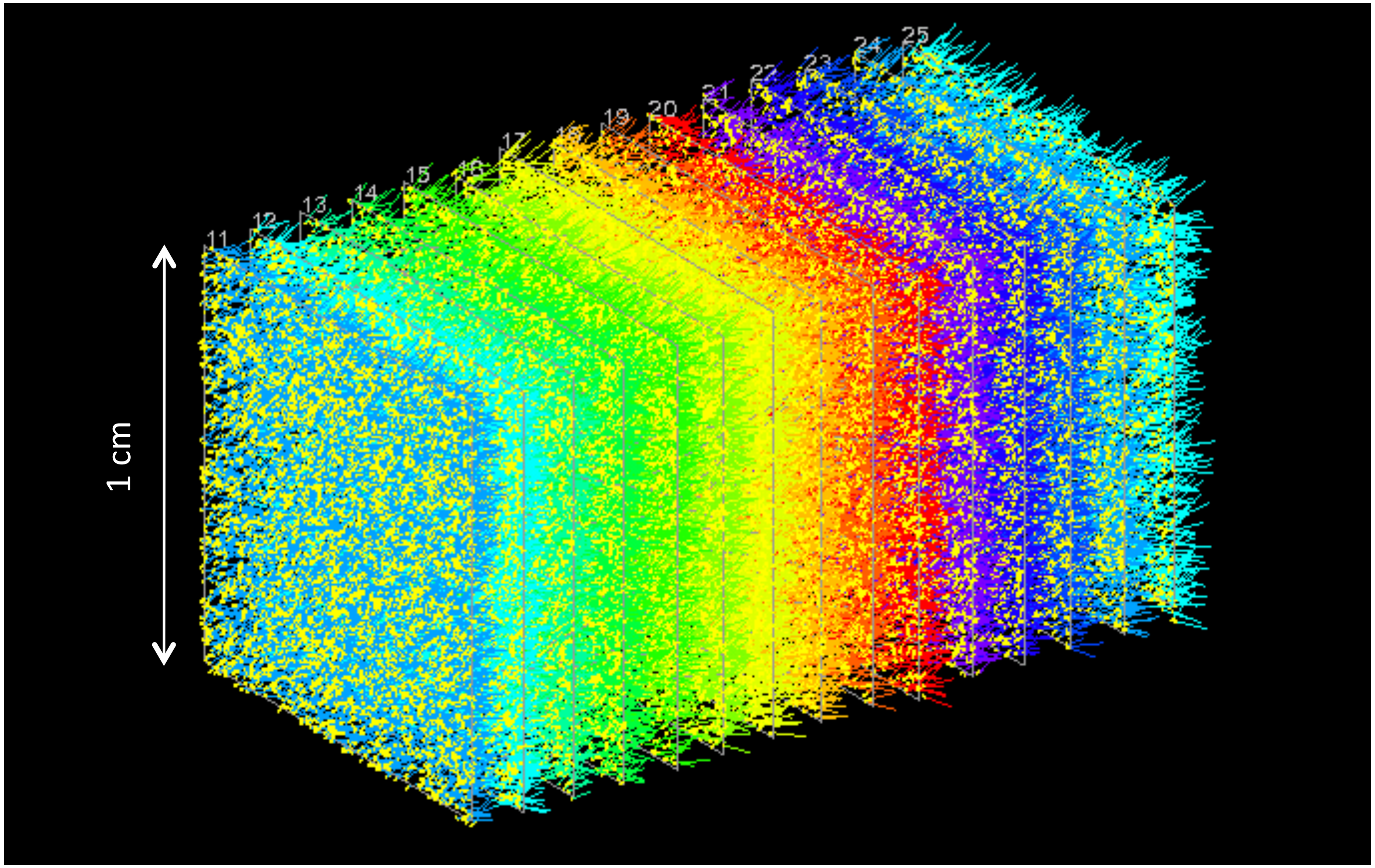
- ~2 cm^3 around the stopping point





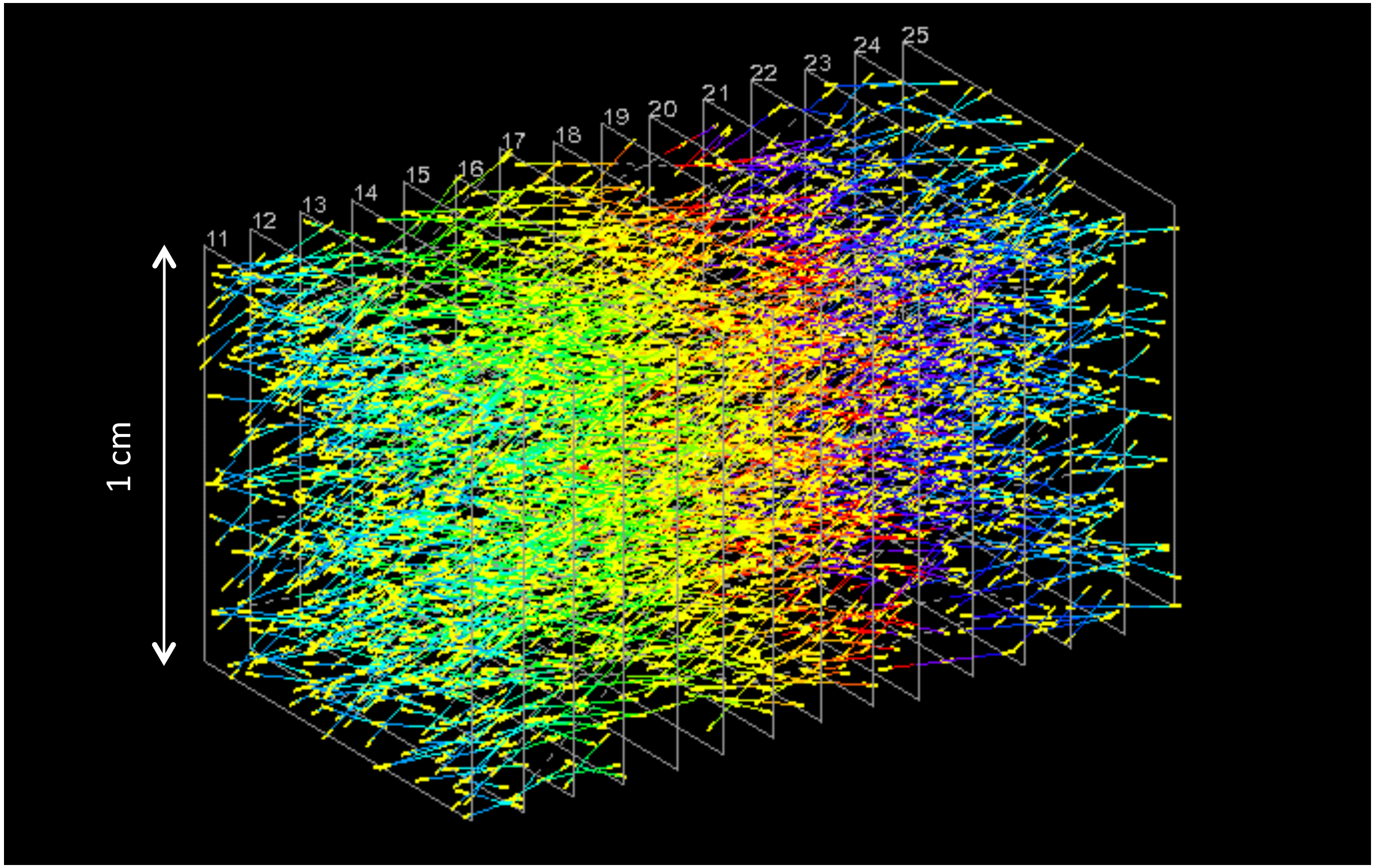
Located Neutrino Interaction

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

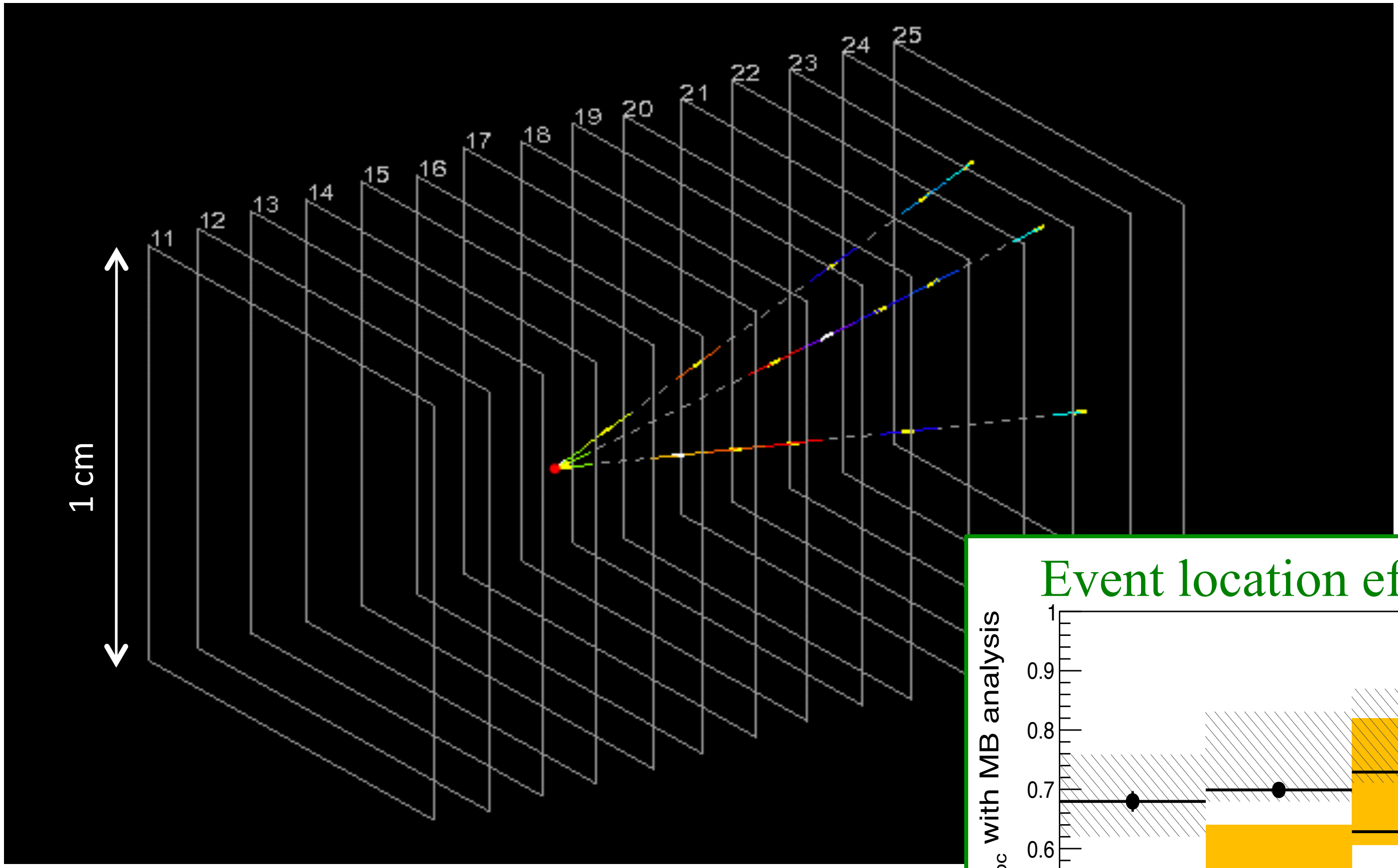


LOCATED NEUTRINO INTERACTION

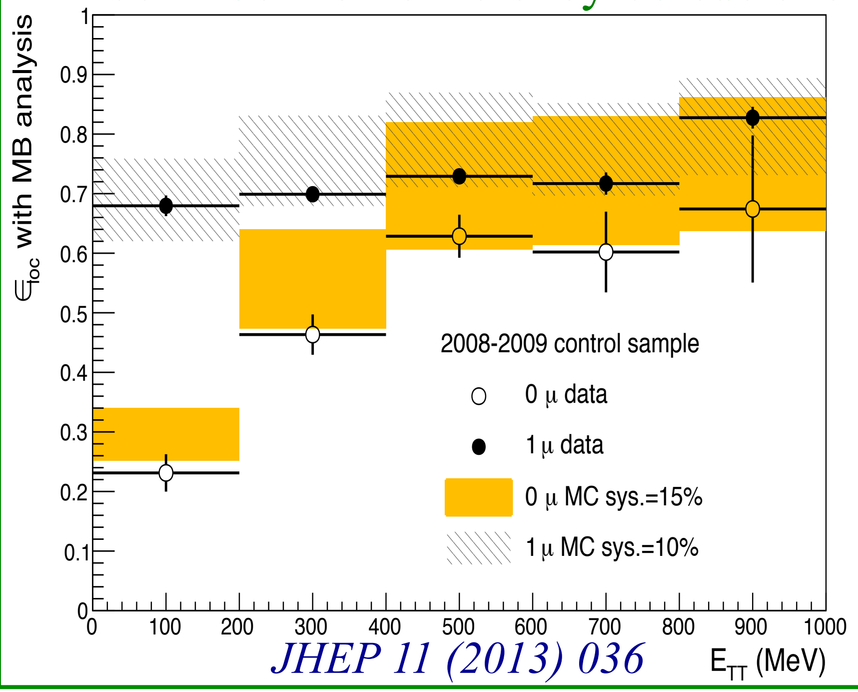
Film to film connection



LOCATED NEUTRINO INTERACTION



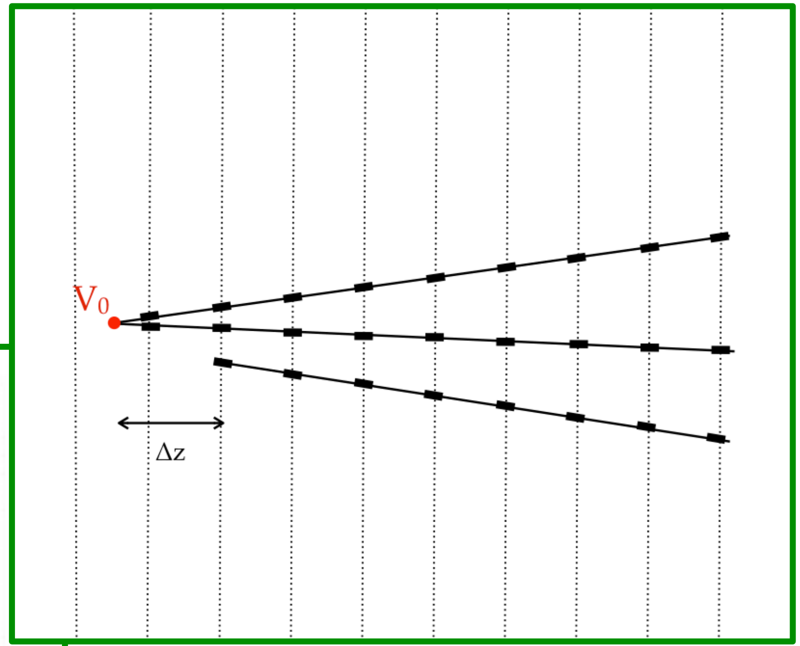
Event location efficiency versus energy

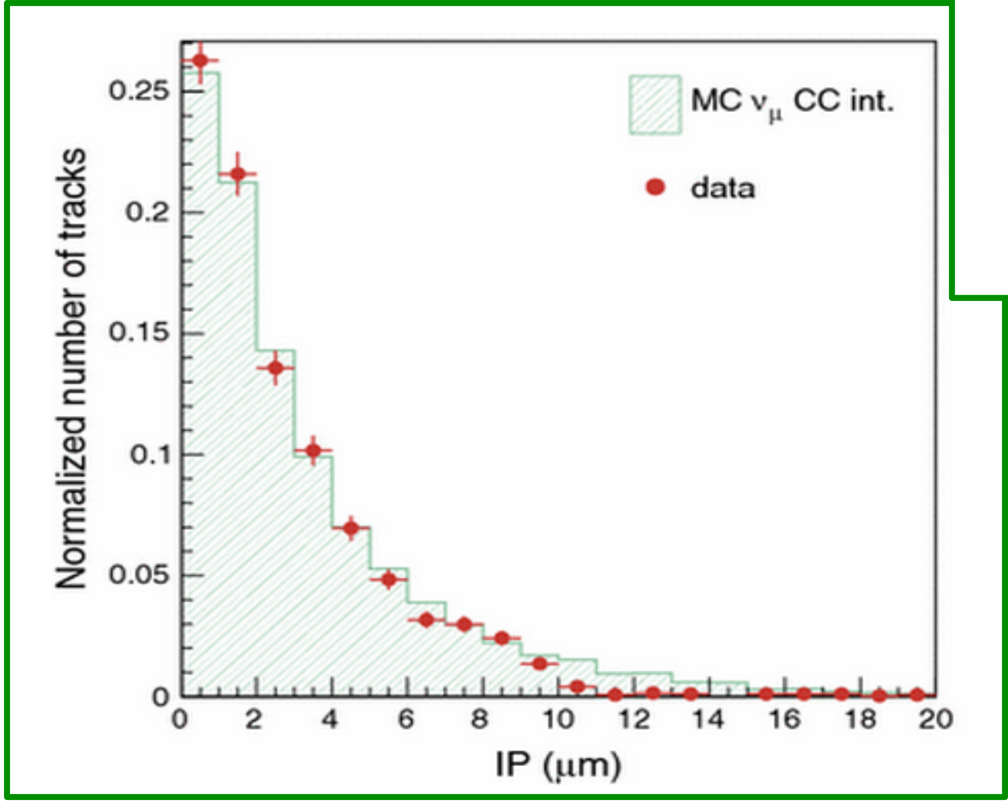


JHEP 11 (2013) 036

DECAY SEARCH

- **Primary vertex definition**
  - inspection of segments on the vertex plate
  - impact parameter <10 (5+0.01 Δz) μm,
    if Δz<(≥)500 μm

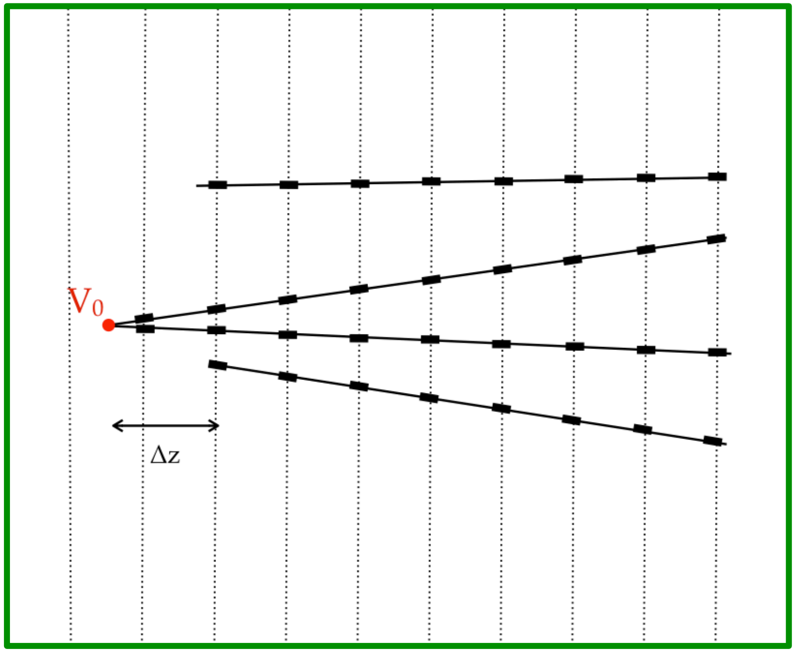




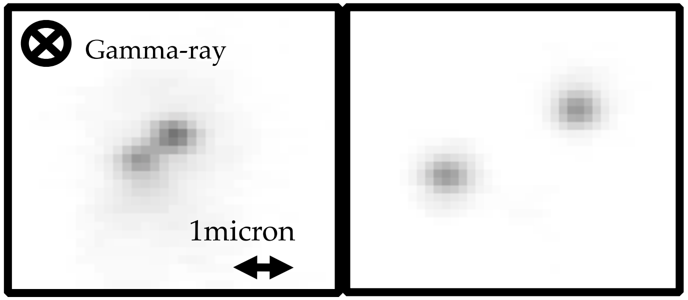
Decay Search

- **Primary vertex definition**
  - inspection of segments on the vertex plate
  - impact parameter <10 (5+0.01 Δz) µm,

    if $\Delta z<(\geq)500$ µm



- **Extra-track search**
  - selection of tracks reconstructed in the volume but not attached to primary vertex
  - identification of e^+e^- pairs by visual inspection

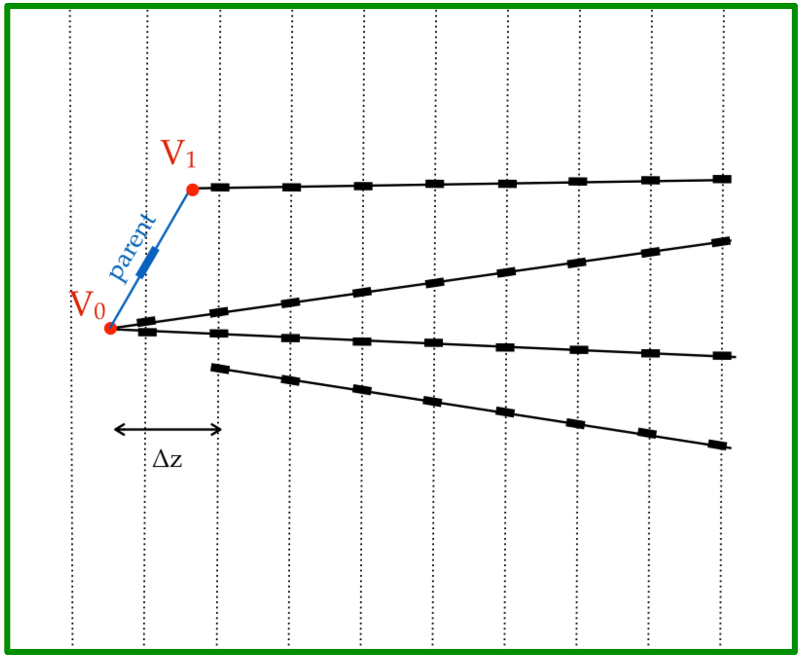


A close-up of an electron pair

DECAY SEARCH

- **Primary vertex definition**
  - inspection of segments on the vertex plate
  - impact parameter <10 (5+0.01 Δz) μm,

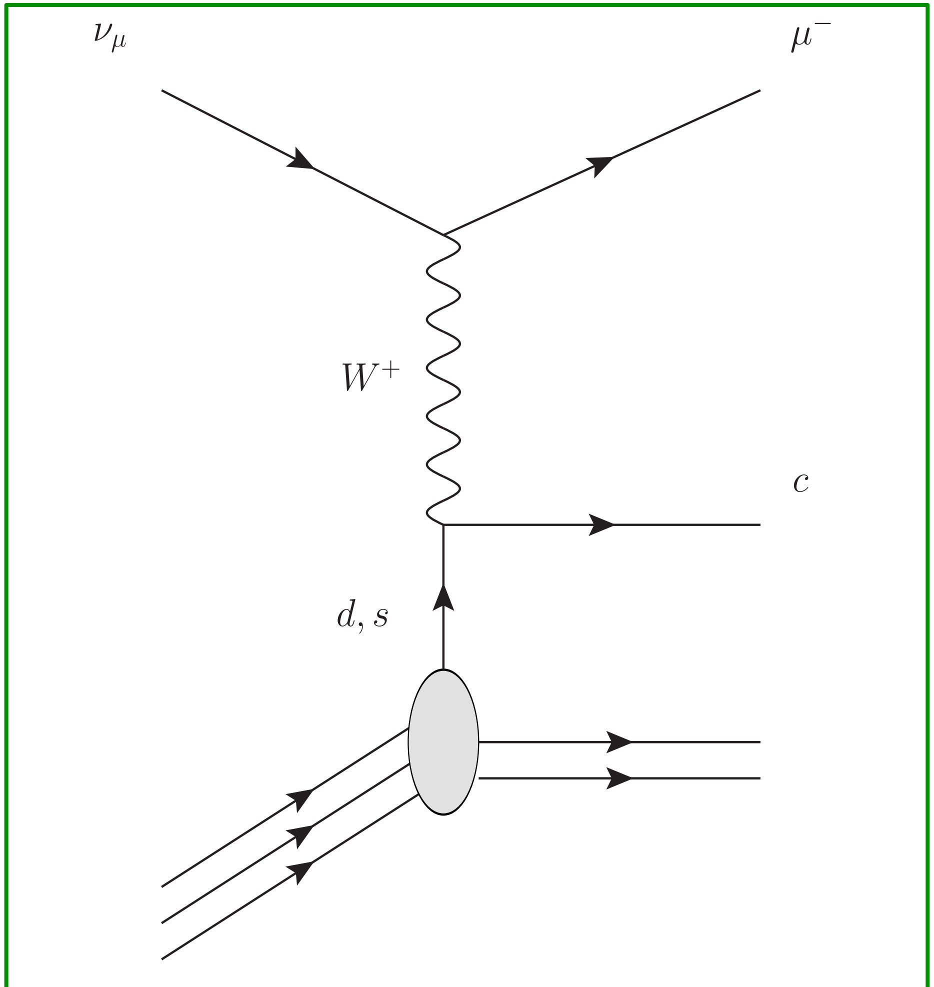
    if $\Delta z<(\geq)500$ μm



- **Extra-track search**
  - selection of tracks reconstructed in the volume but not attached to primary vertex
  - identification of e^+e^- pairs by visual inspection
- **In-track search**
  - search for small kinks along the tracks attached to the primary vertex
- **Parent search**
  - search for a track connecting the selected extra-track and the primary vertex

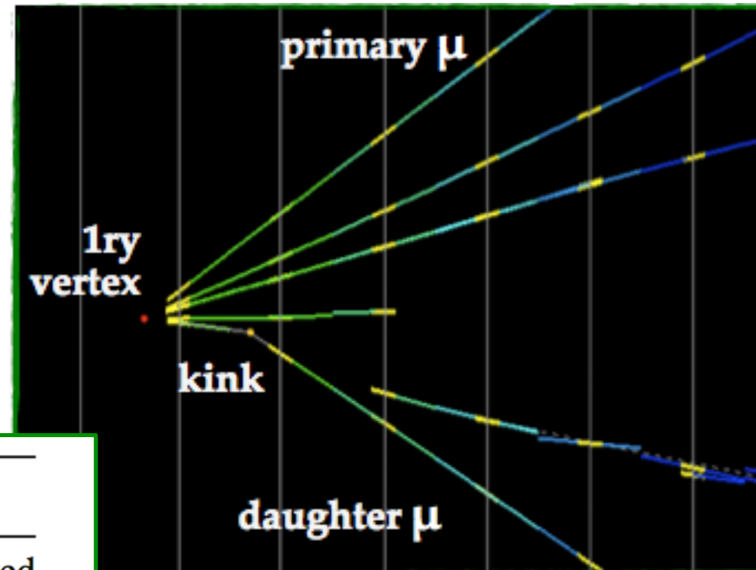
Charmed Hadron Production

control sample for the τ search
to check the efficiency → signal expectation



CHARMED HADRON PRODUCTION

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



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

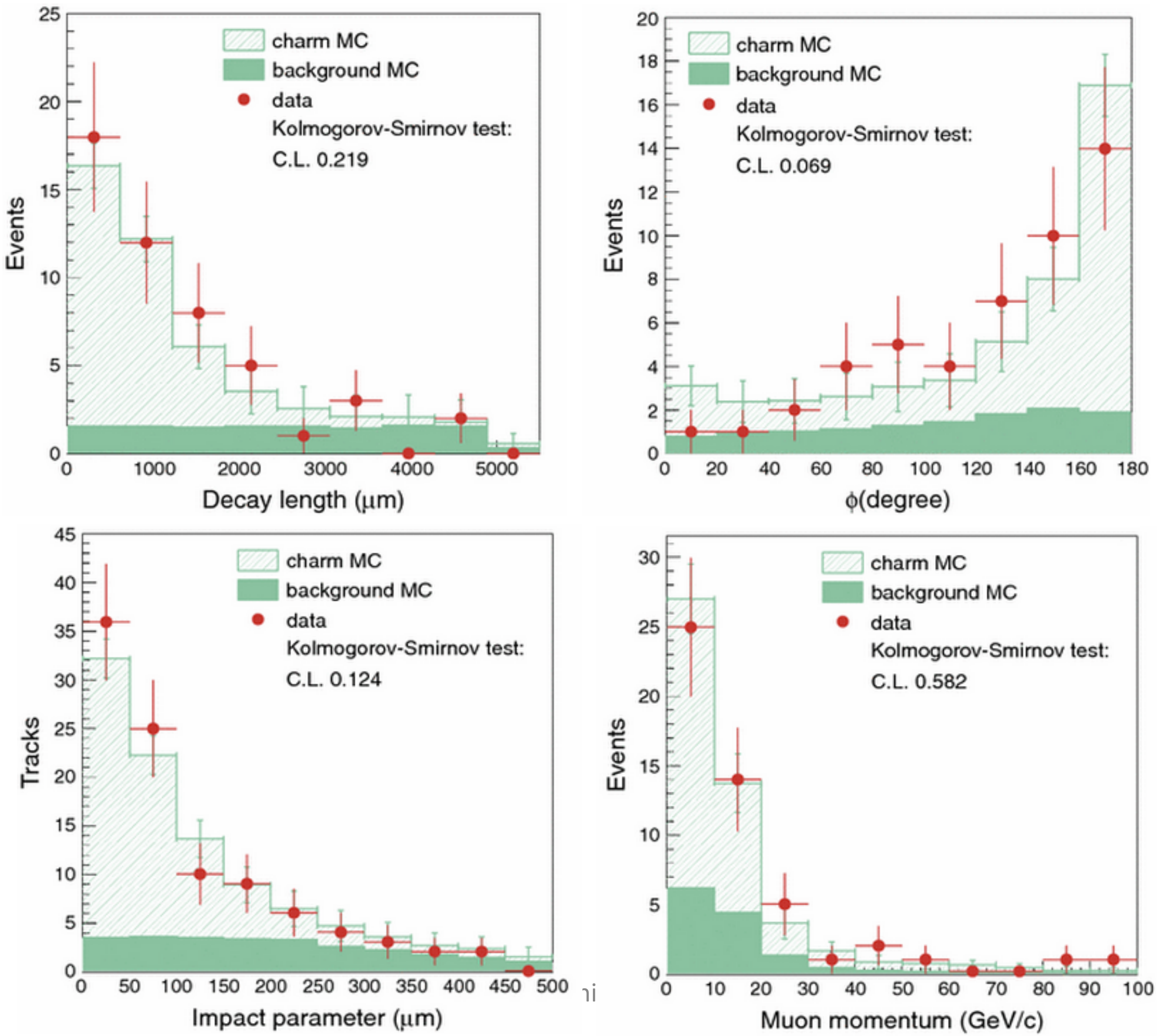
Eur. Phys. J. C74 (2014) 2986

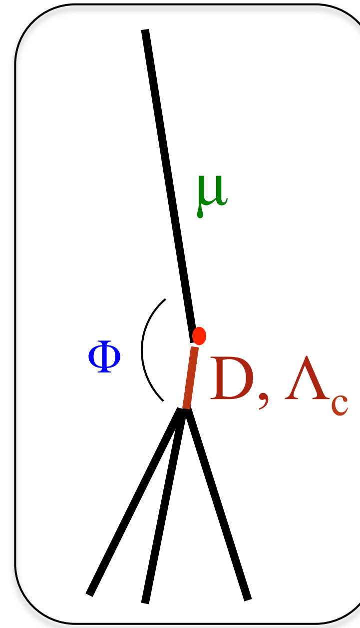
Background from hadronic interactions (87%) and strange particle decays (13%)

Good agreement between data and expectations ~10%

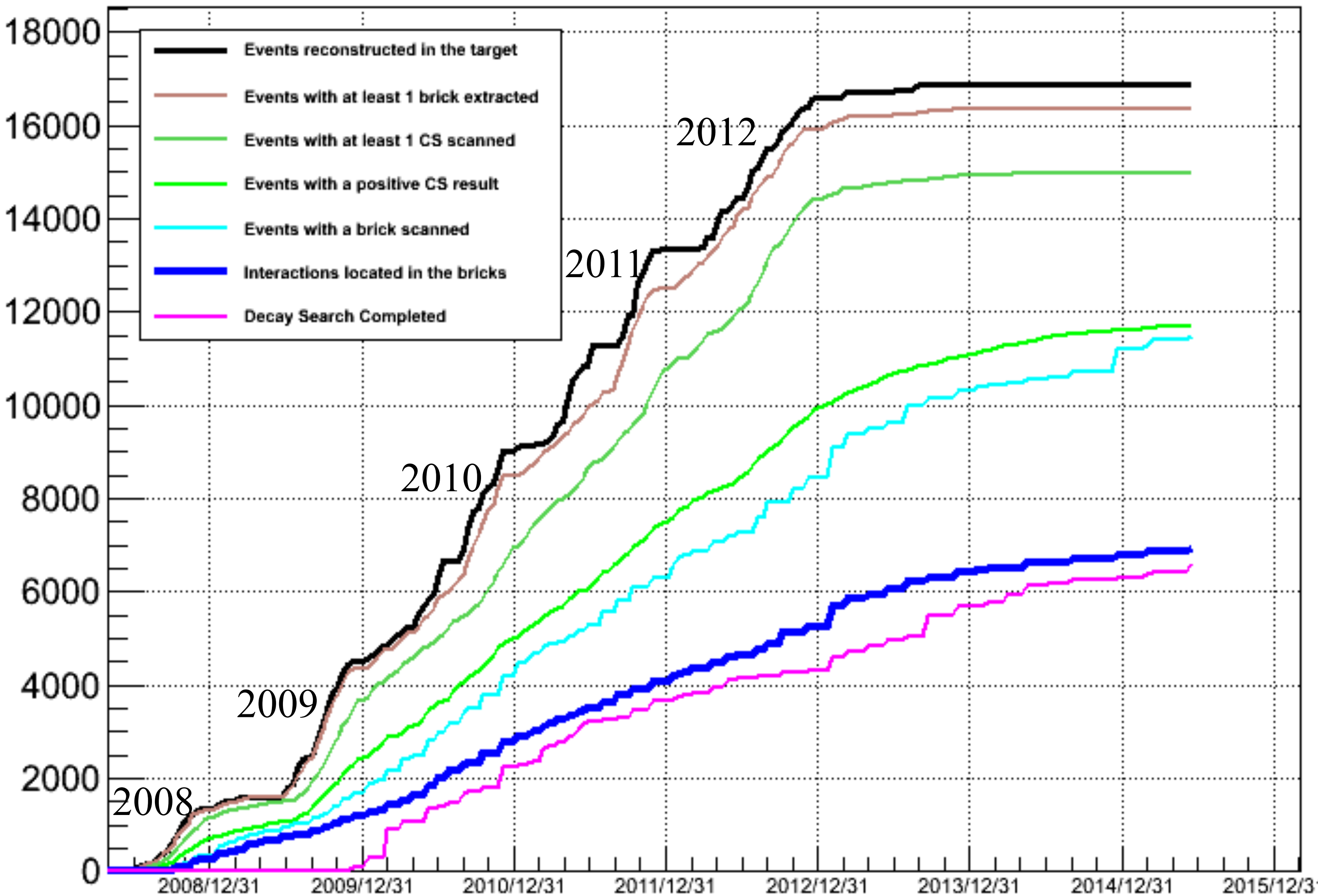
KINEMATICAL VARIABLES

Fair agreement between data and Monte Carlo *Eur. Phys. J. C74 (2014) 2986*





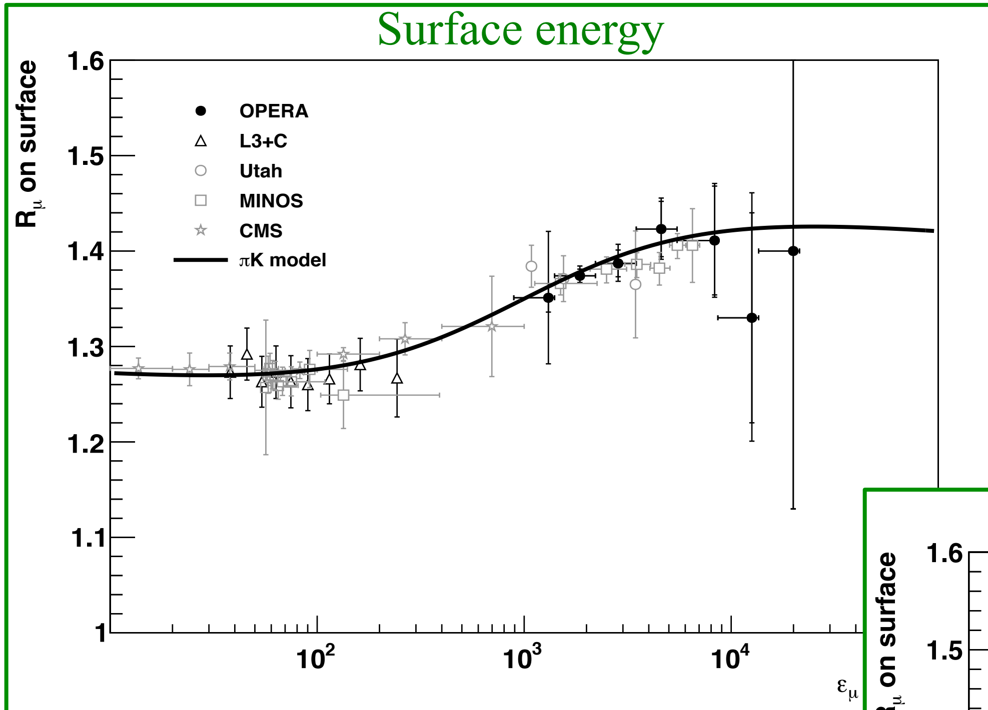
Status Of Data Analysis



6932 located interactions

6612 decay search

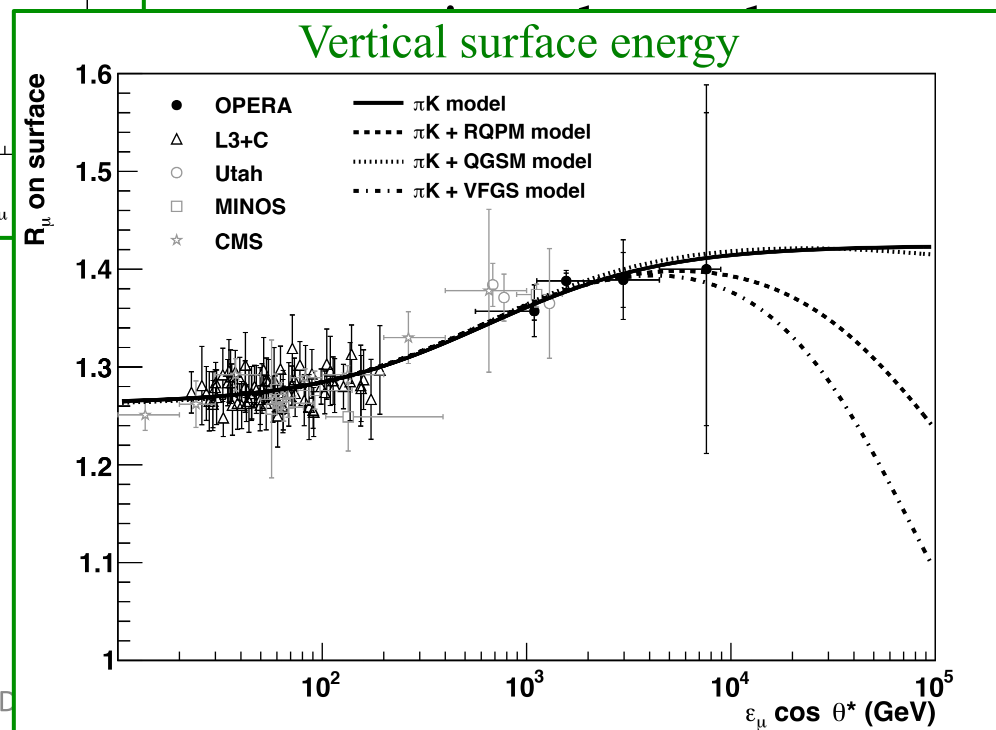
Cosmic-Ray Physics



Measurement of TeV atmospheric muon charge ratio

Eur. Phys. J. C74 (2014) 2933

$$R_\mu \equiv N_{\mu^+}/N_{\mu^-}$$

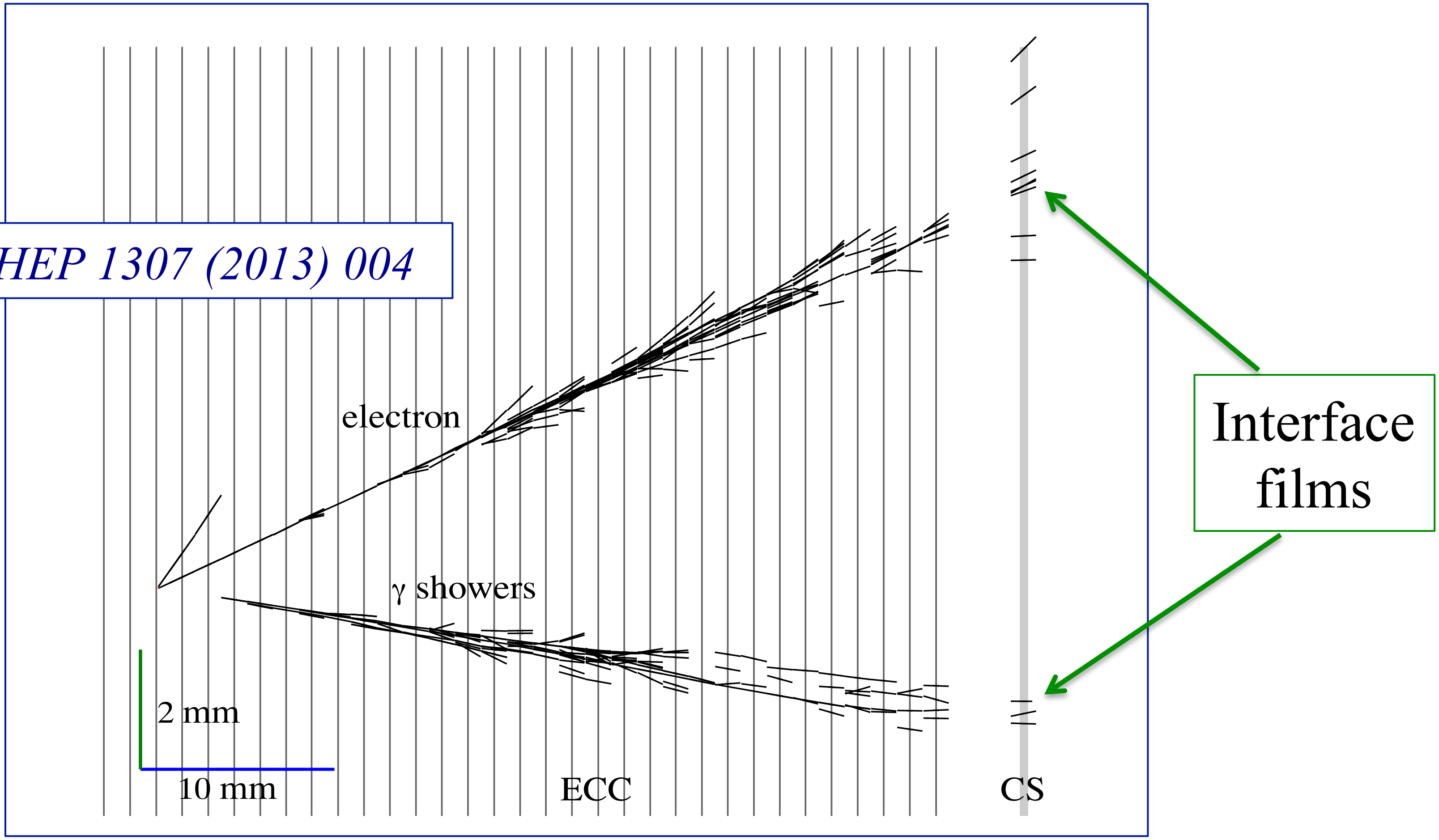


Oscillation physics

$\nu_\mu \rightarrow \nu_e$ Analysis with 2008/2009 data

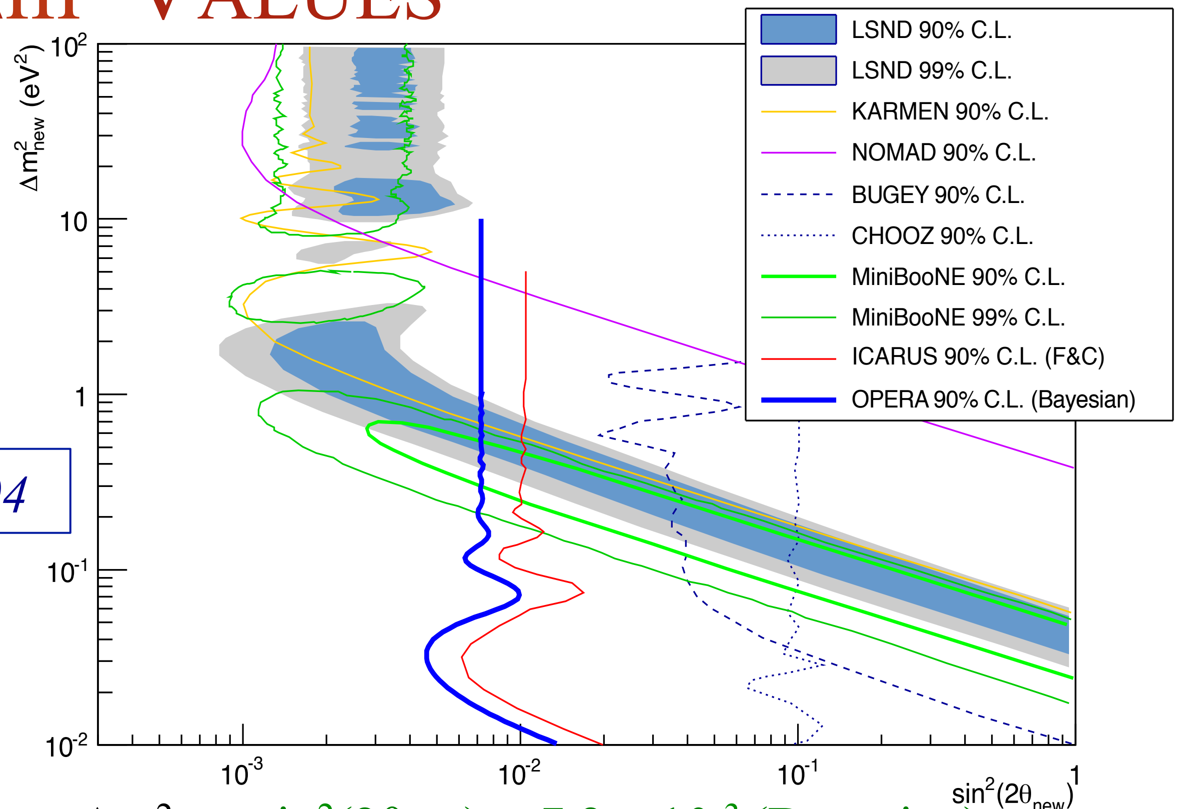
one of the ν_e events with a π^0 as seen in the brick

JHEP 1307 (2013) 004



Analysis based on 19 observed candidates (4 with E < 20 GeV)

SEARCH FOR NON-STANDARD OSCILLATIONS AT LARGE Δm^2 VALUES



JHEP 1307 (2013) 004

Caveat: experiments at different L/E

OPERA limit at large Δm^2: $\sin^2(2\theta_{new}) < 7.2 \times 10^{-3}$ (Bayesian)

ICARUS limit at large Δm^2: $\sin^2(2\theta_{new}) < 6.8 \times 10^{-3}$ (F&C) EPJ C73 (2013) 2599

Current sample extended with more than twice candidates:

So far 49 observed candidates

9 with E < 20 GeV

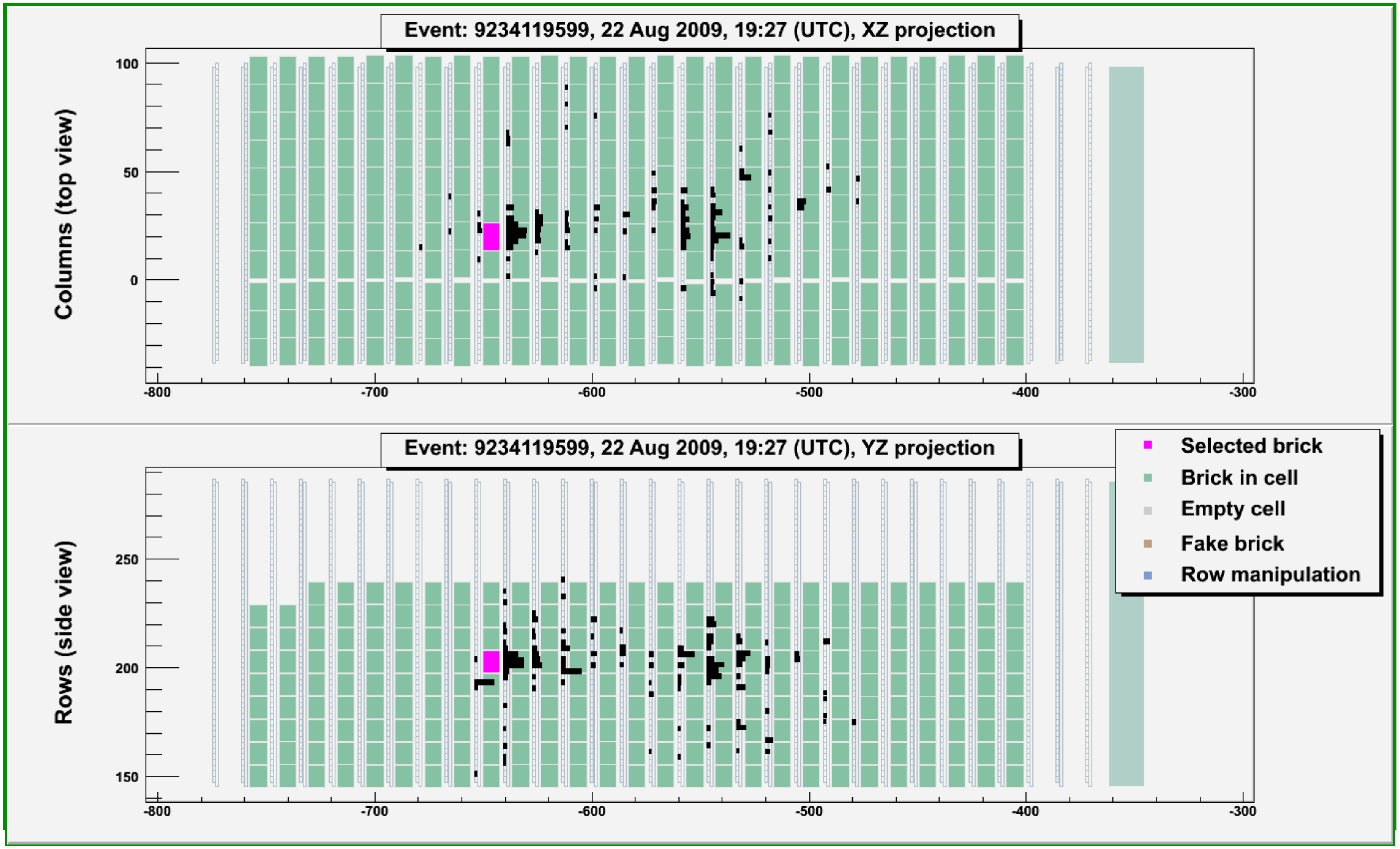
New paper in preparation

$\nu_\mu \rightarrow \nu_\tau$ Analysis Strategy

- 2008-2009 runs
  - No kinematical selection: get confidence on the detector performances before applying any kinematical cut
  - Slower analysis speed (signal/noise not optimal)
  - Kinematical selection applied for the candidate selection, coherently for all runs
  - Good data/MC agreement shown
- 2010-2012 runs
  - $P\mu < 15$ GeV/c, to suppress charm background
  - Prioritise the analysis of the most probable brick in the probability map: optimal ratio between efficiency and analysis time
  - Analyse the other bricks in the probability map

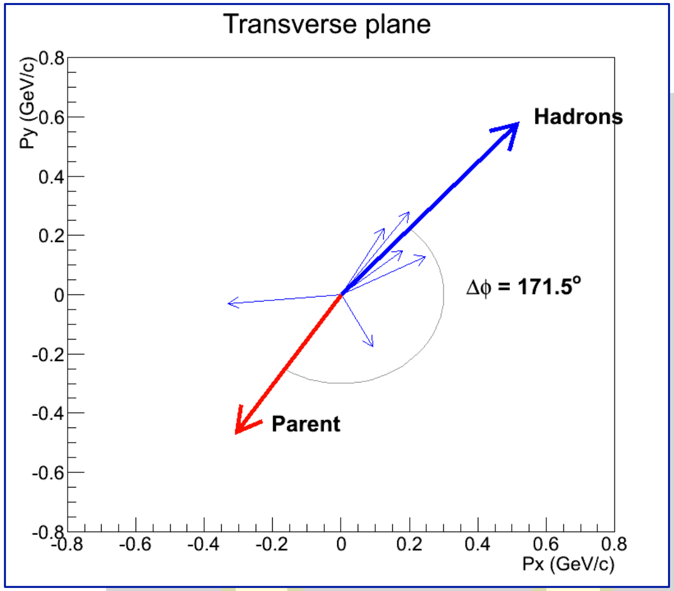
THE FIRST ν_τ CANDIDATE

As seen by the electronic detectors …

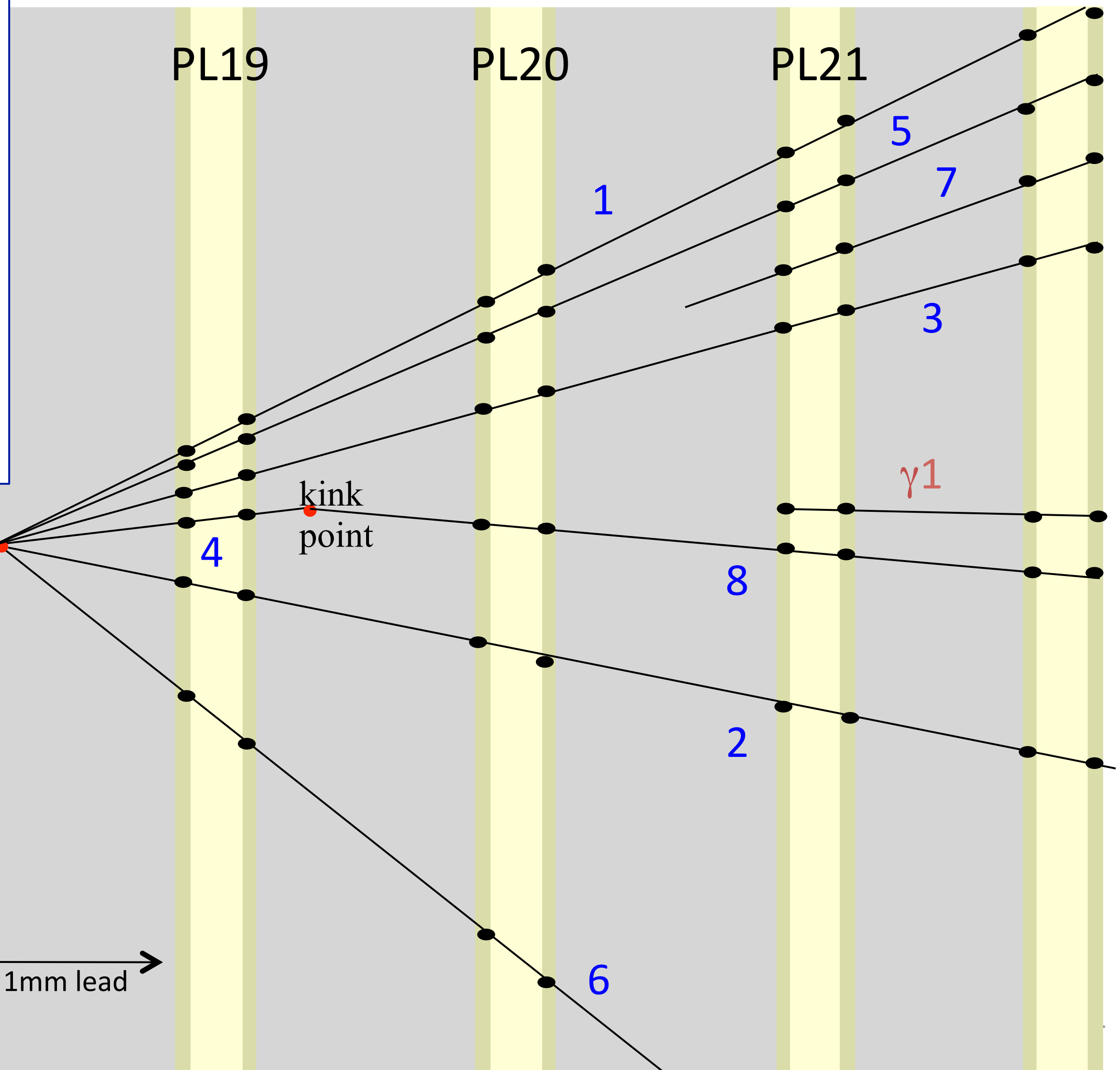


Physics Letters B691 (2010) 138

The First ν_τ Candidate

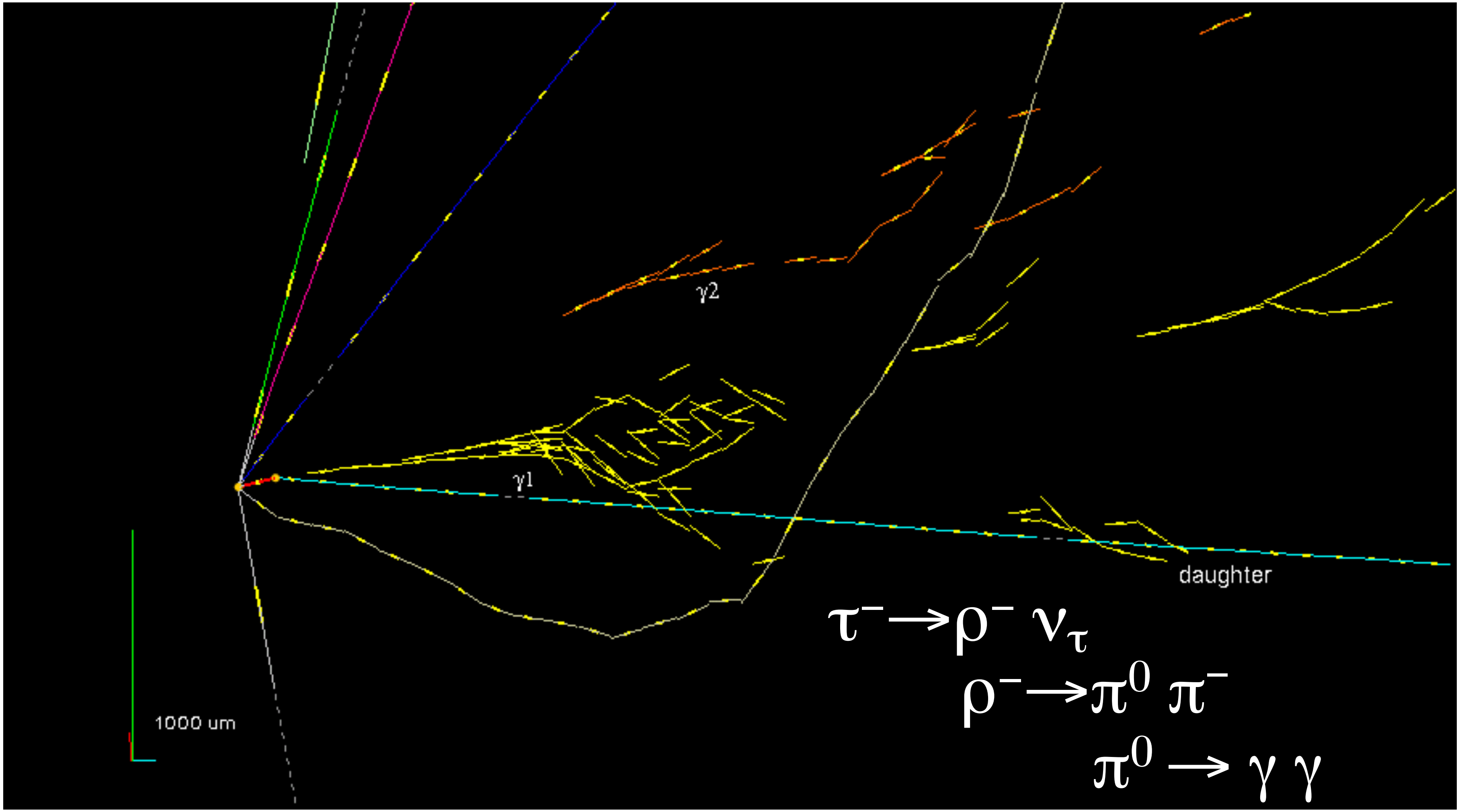


… and in the brick



THE FIRST ν_τ CANDIDATE

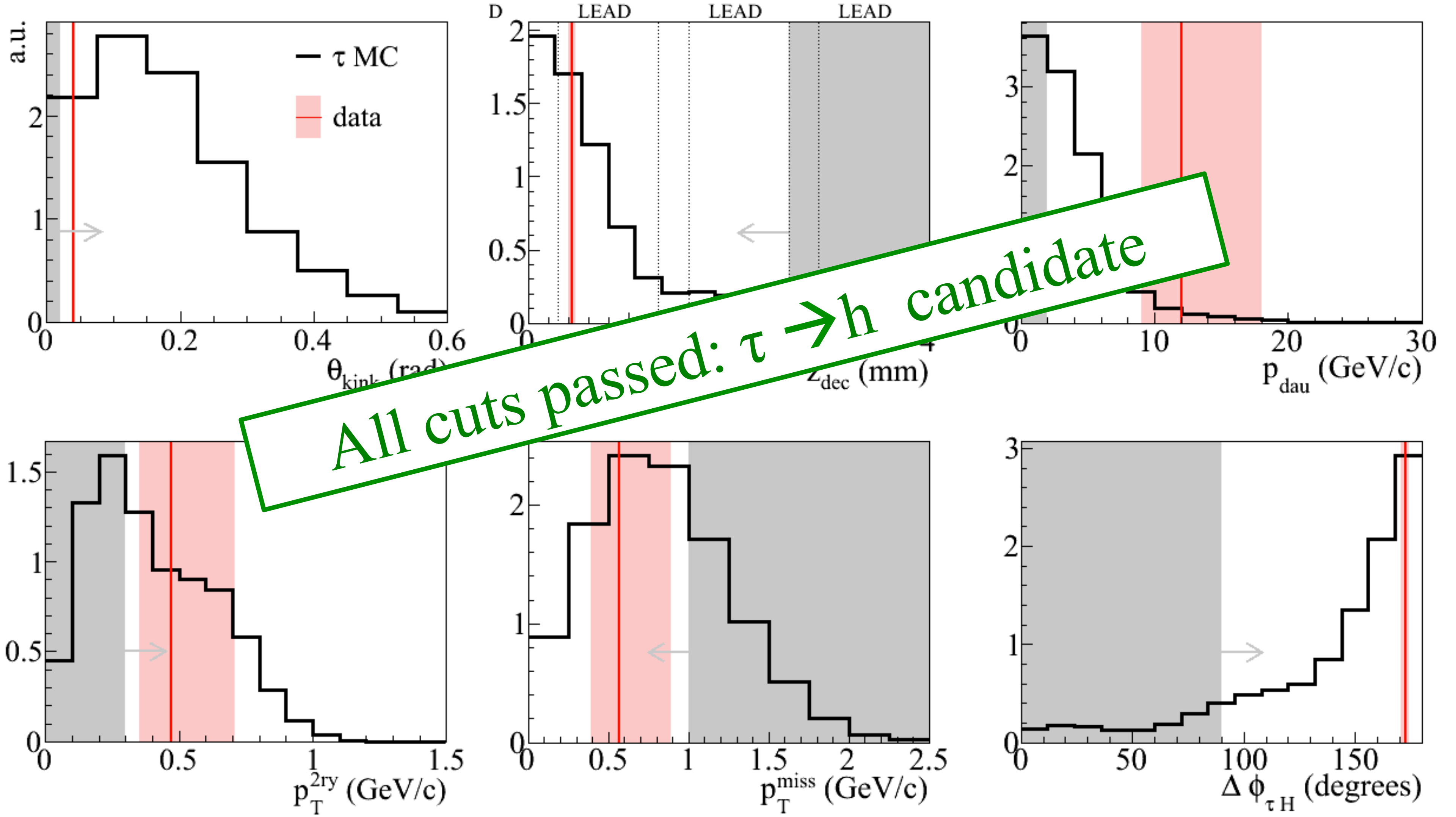
… and in the brick



Physics Letters B691 (2010) 138

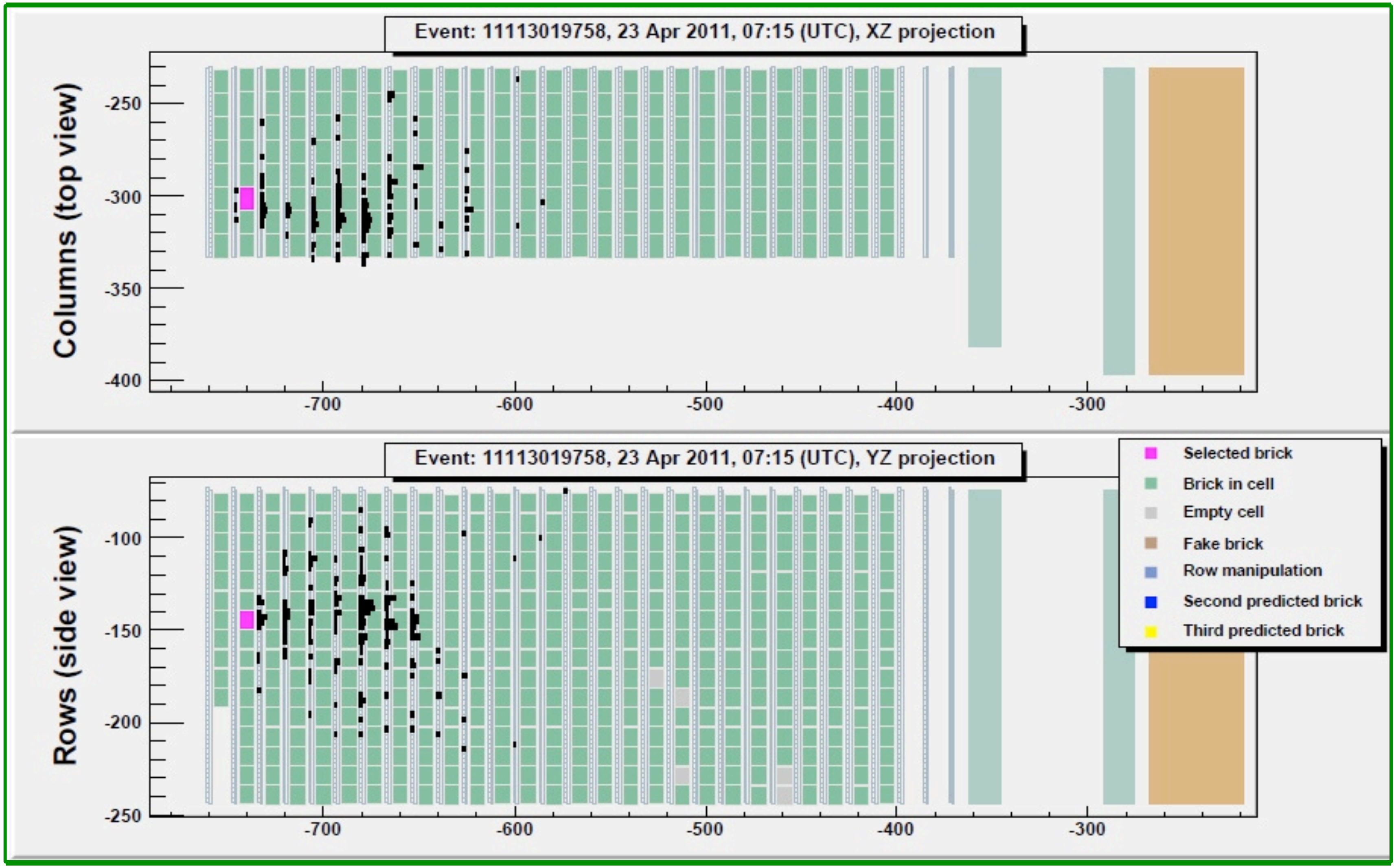
The First ν_τ Candidate

Kinematical selection



THE SECOND ν_τ CANDIDATE

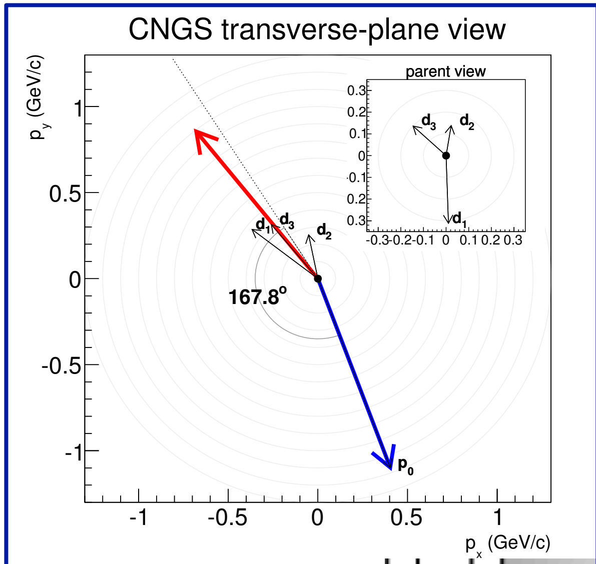
As seen by the electronic detectors …

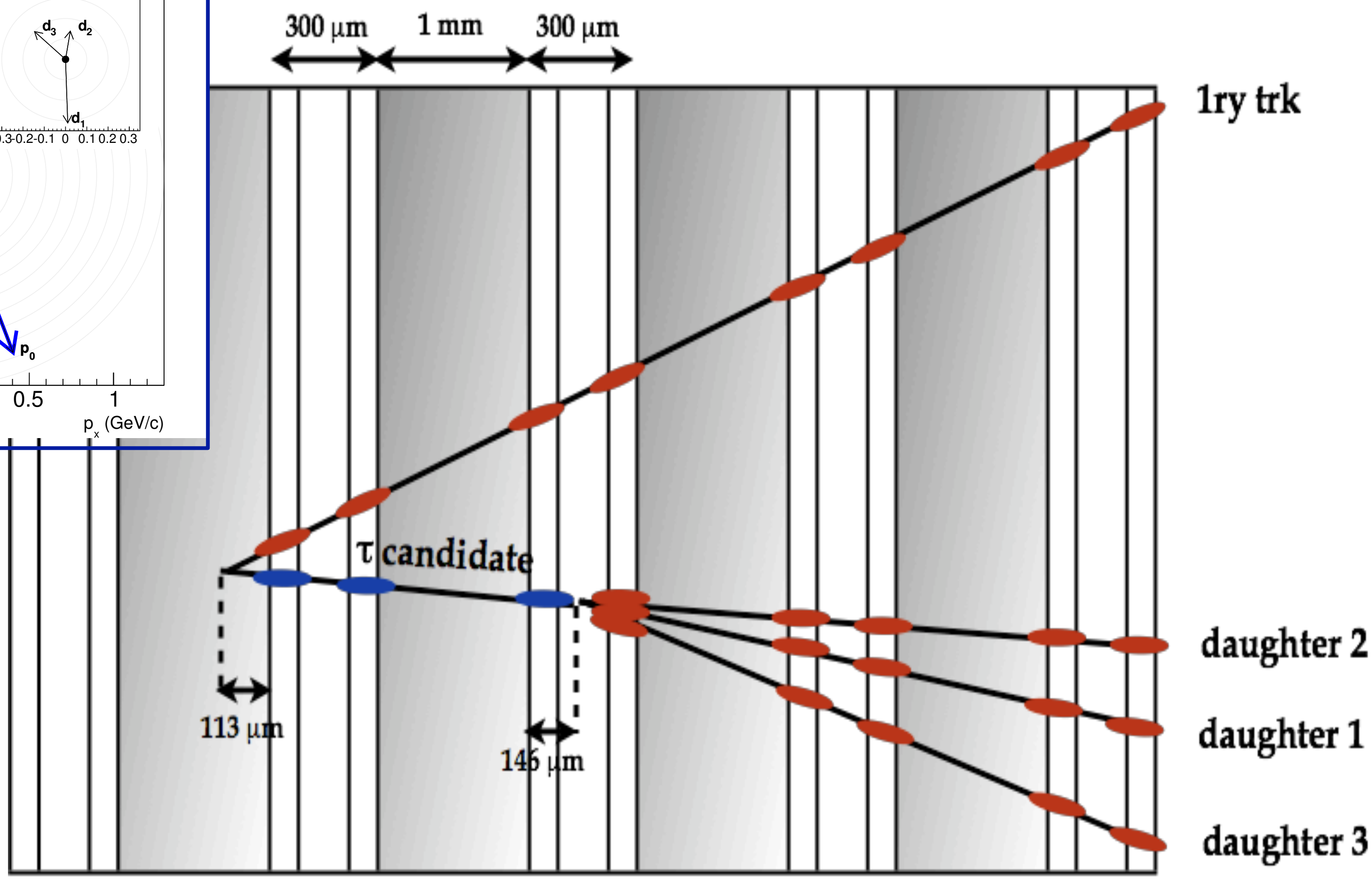


Journal of High Energy Physics 11 (2013) 036

THE SECOND ν_τ CANDIDATE

… and in the brick

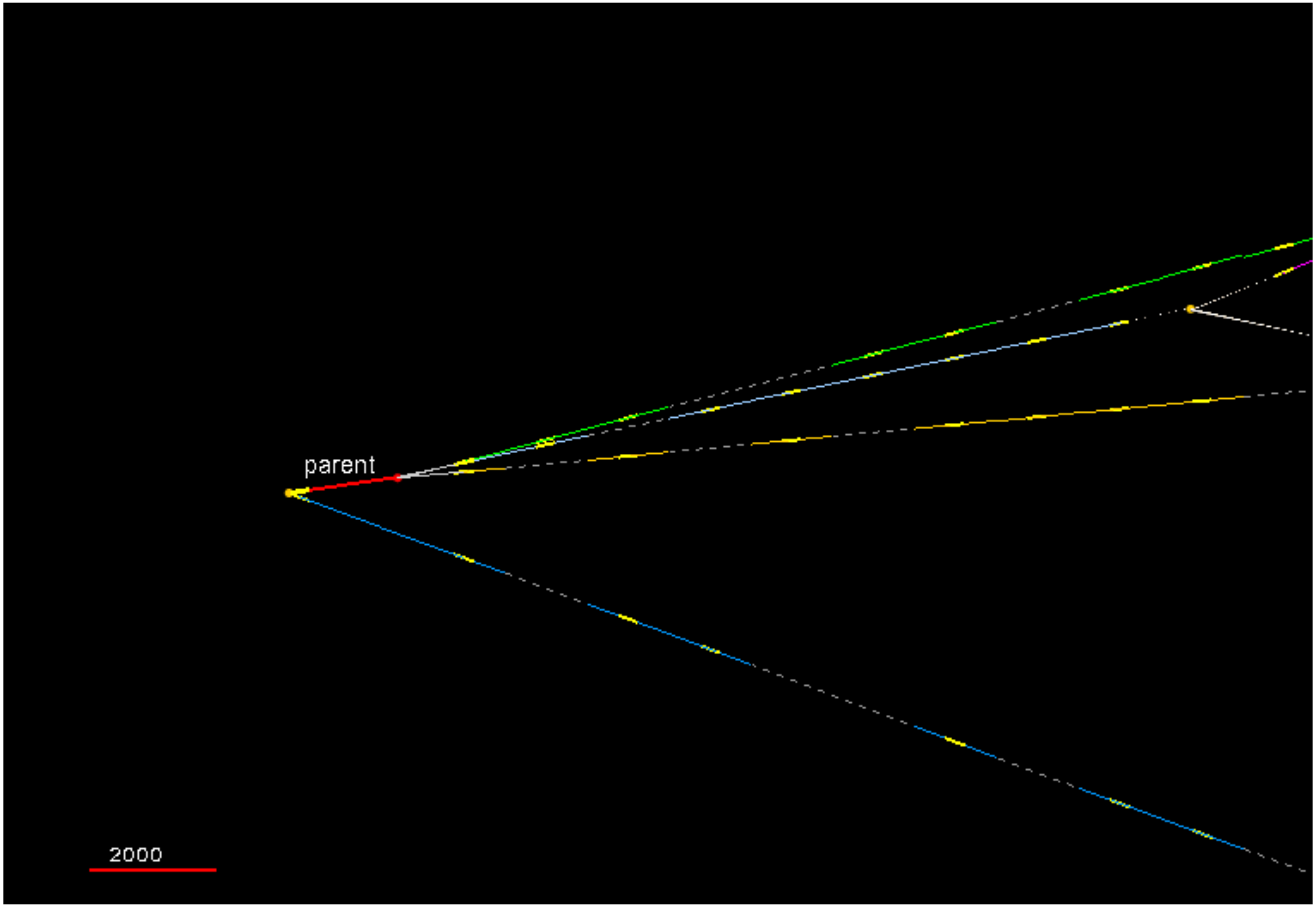




Journal of High Energy Physics 11 (2013) 036

THE SECOND ν_τ CANDIDATE

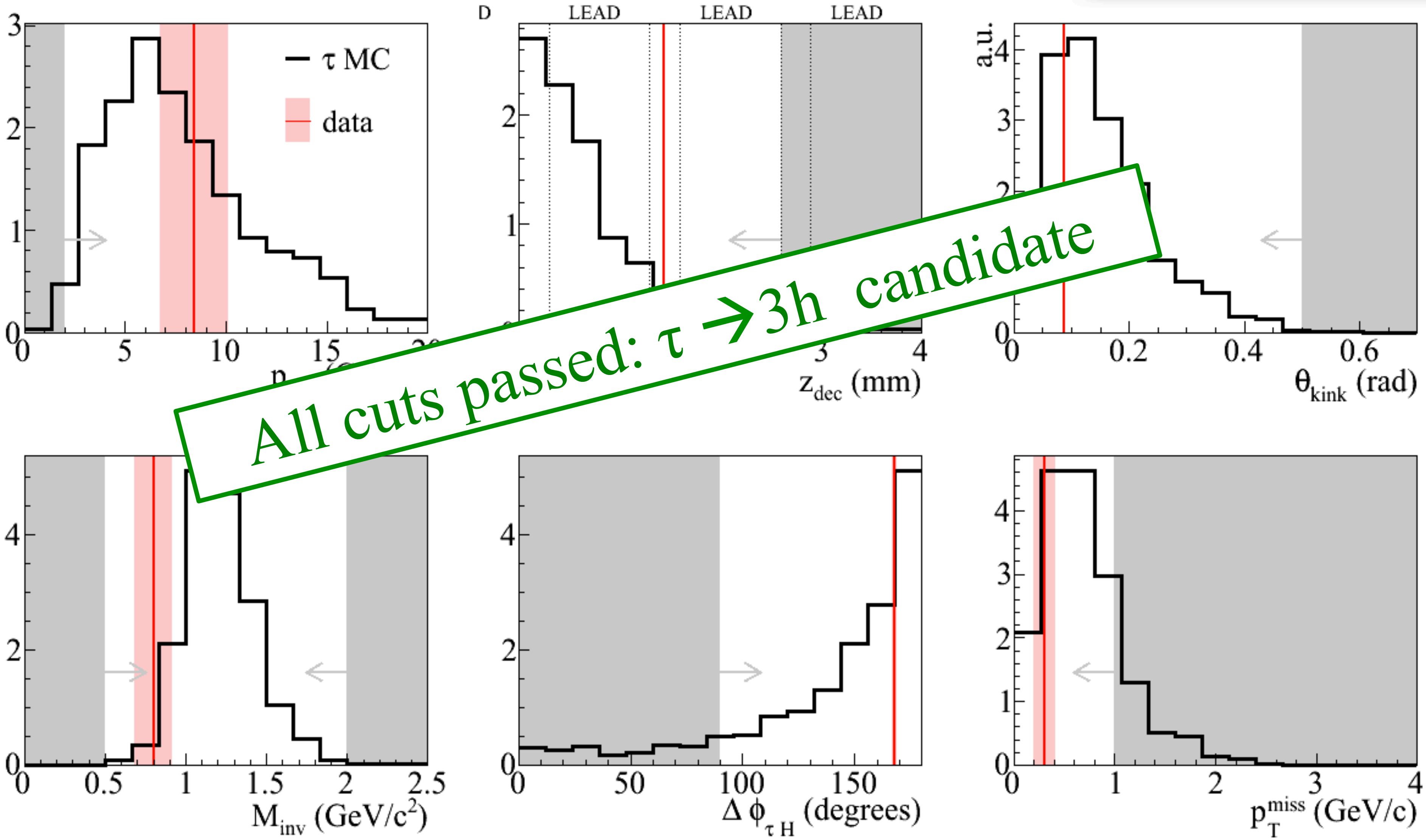
… and in the brick



Journal of High Energy Physics 11 (2013) 036

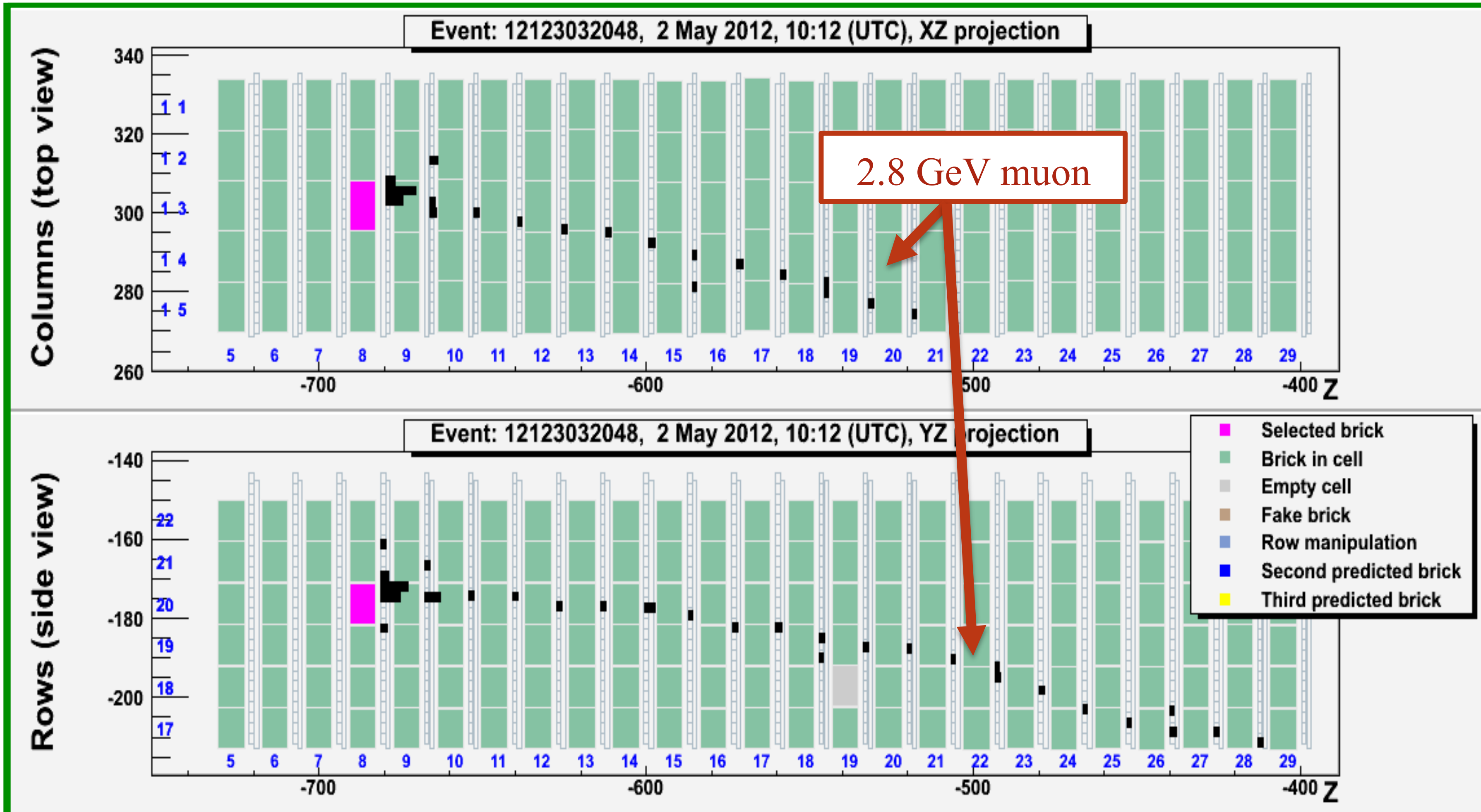
THE SECOND ν_τ CANDIDATE

Kinematical selection



THE THIRD ν_τ CANDIDATE

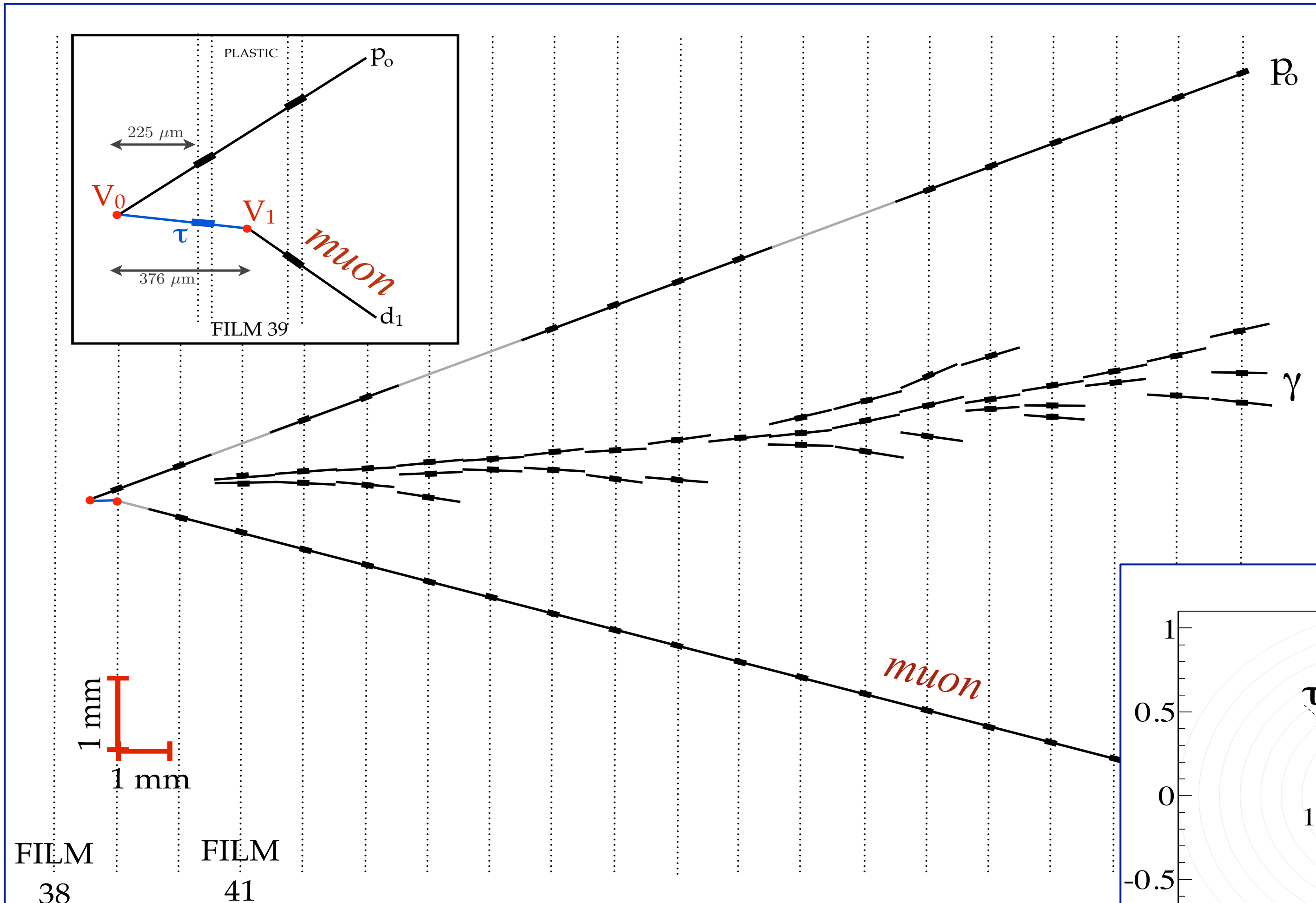
As seen by the electronic detectors …

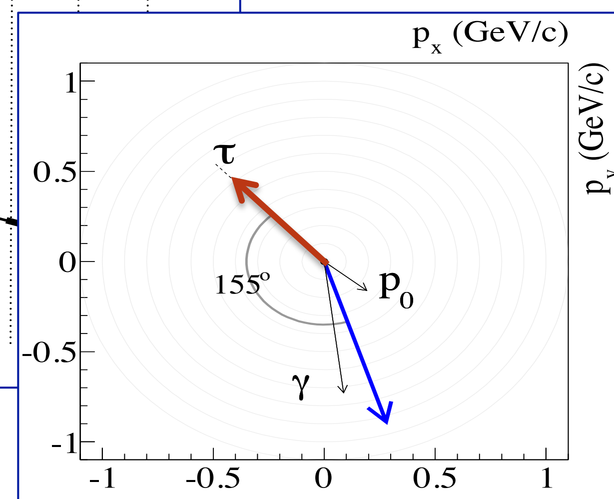


Phys. Rev. D 89 (2014) 051102(R)

THE THIRD ν_τ CANDIDATE

… and in the brick

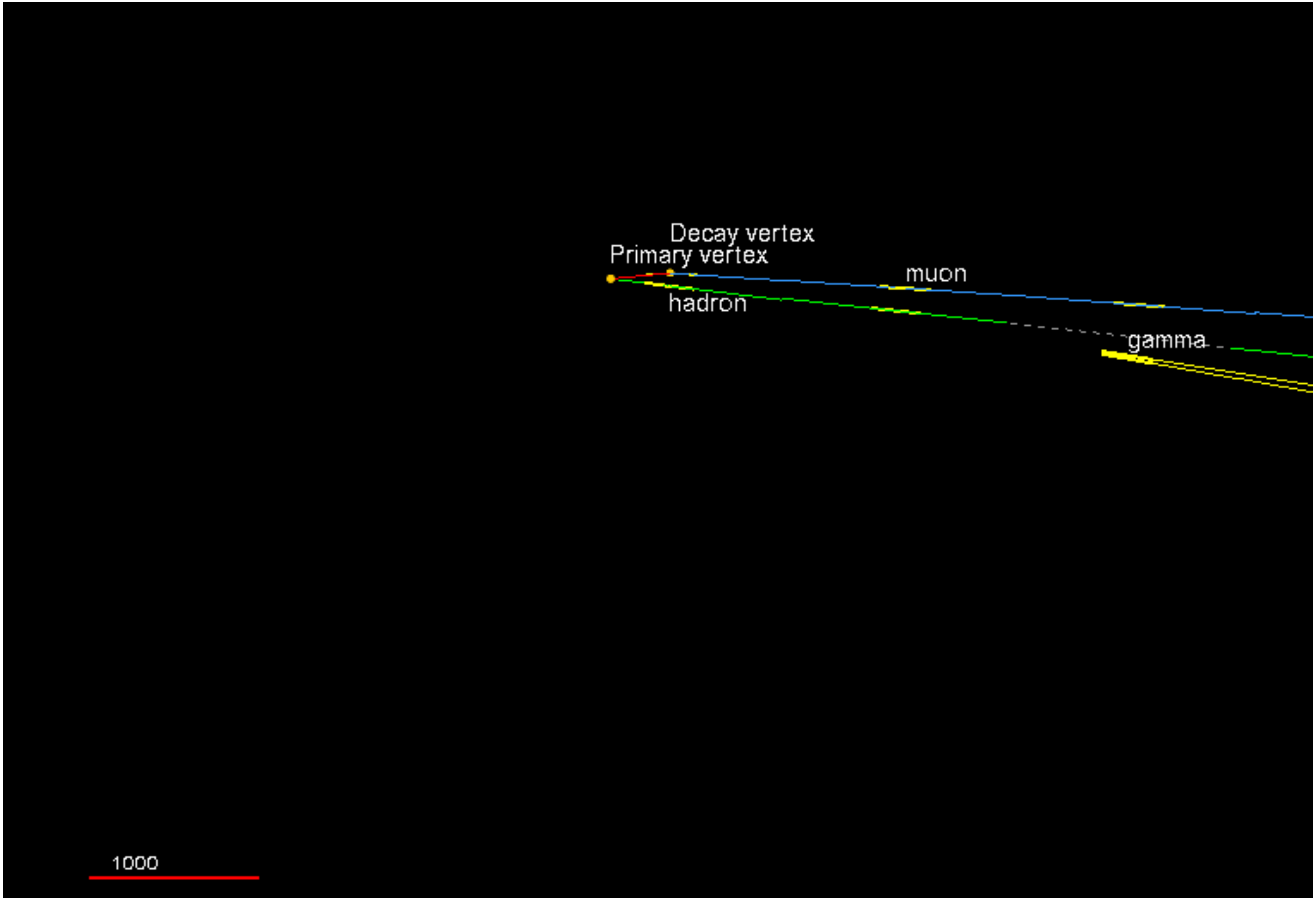




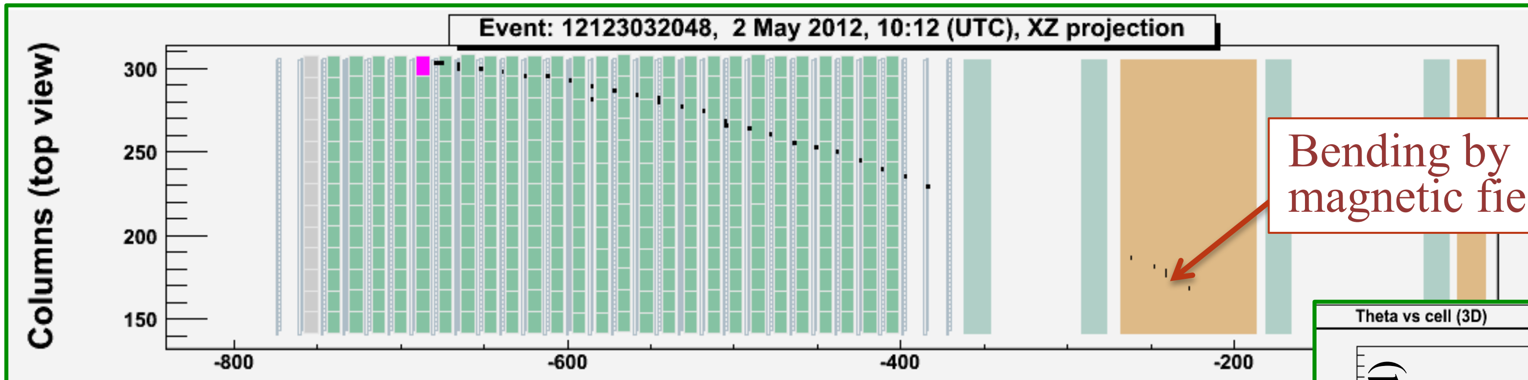
Phys. Rev. D 89 (2014) 051102(R)

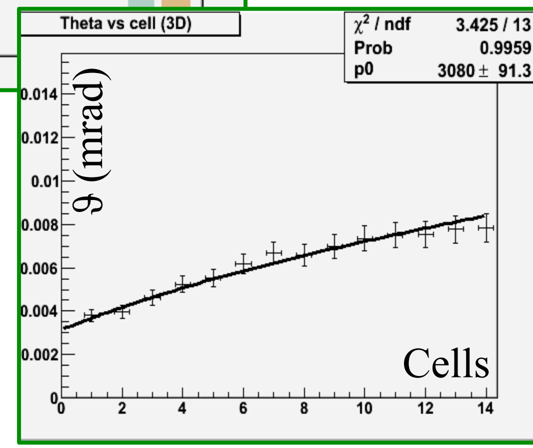
The Third ν_τ Candidate

… and in the brick



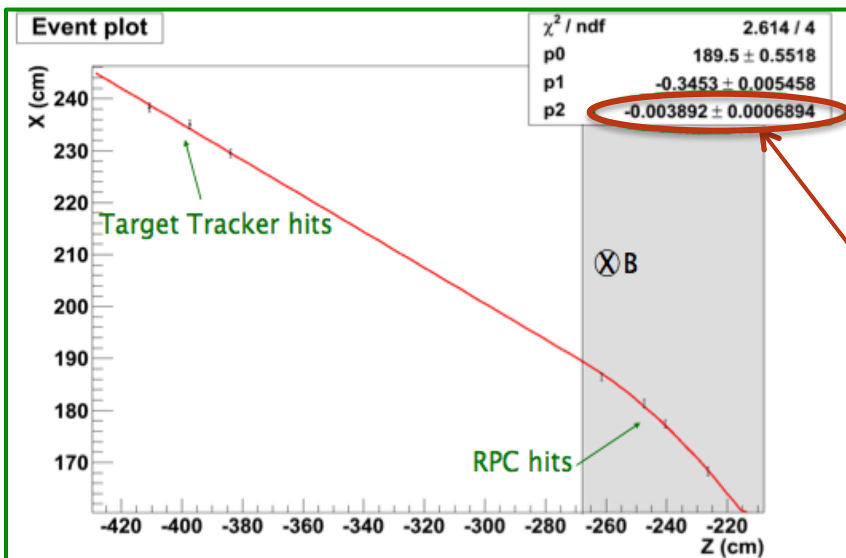
Muon Charge And Momentum





Momentum measurement

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

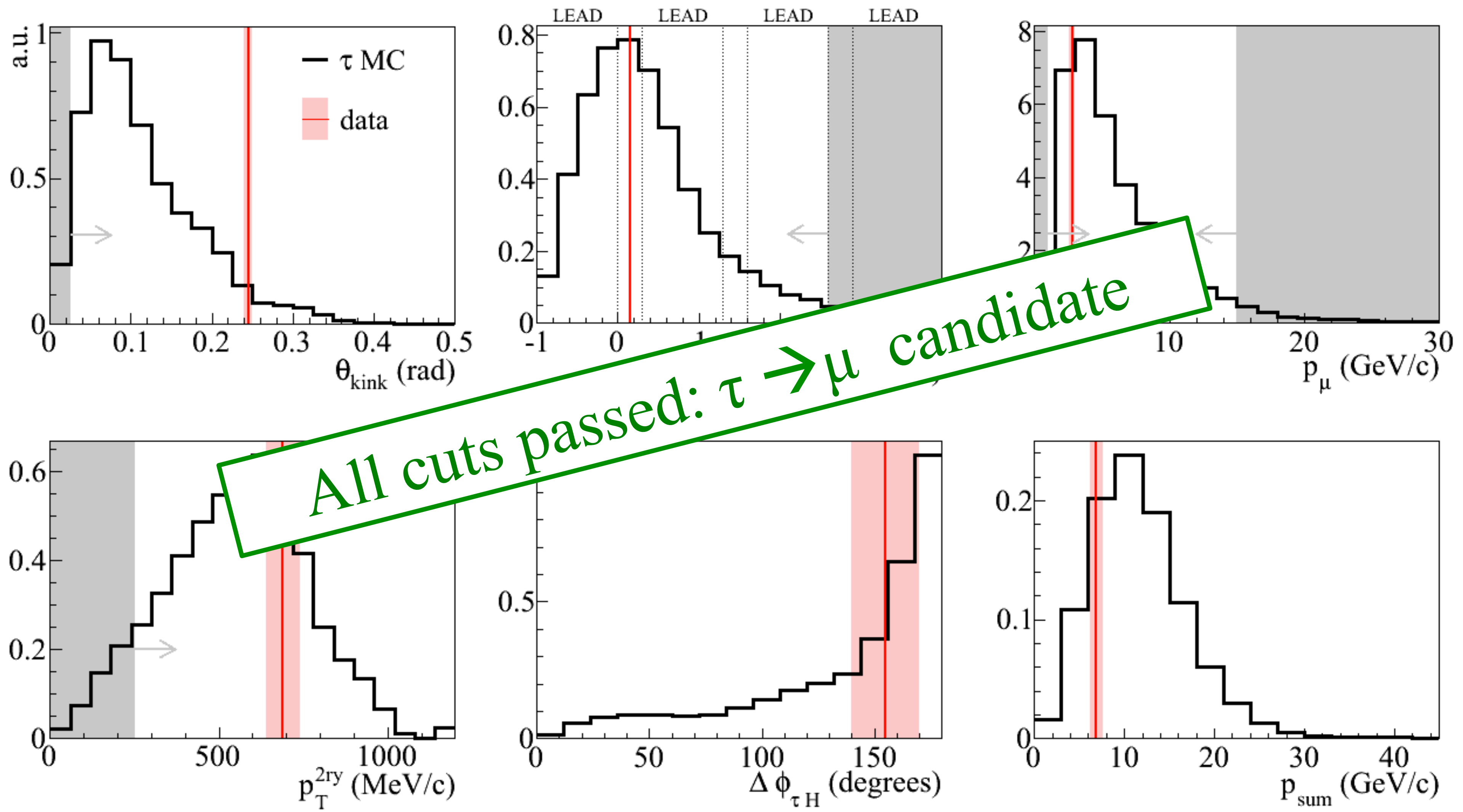


- Parabolic fit with p_2 as quadratic term coefficient in the magnetized region
- Linear fit in the non-magnetized region

p_2<0 → negative charge
5.6 σ significance
R ~ 85 cm

The Third ν_τ Candidate

Kinematical selection

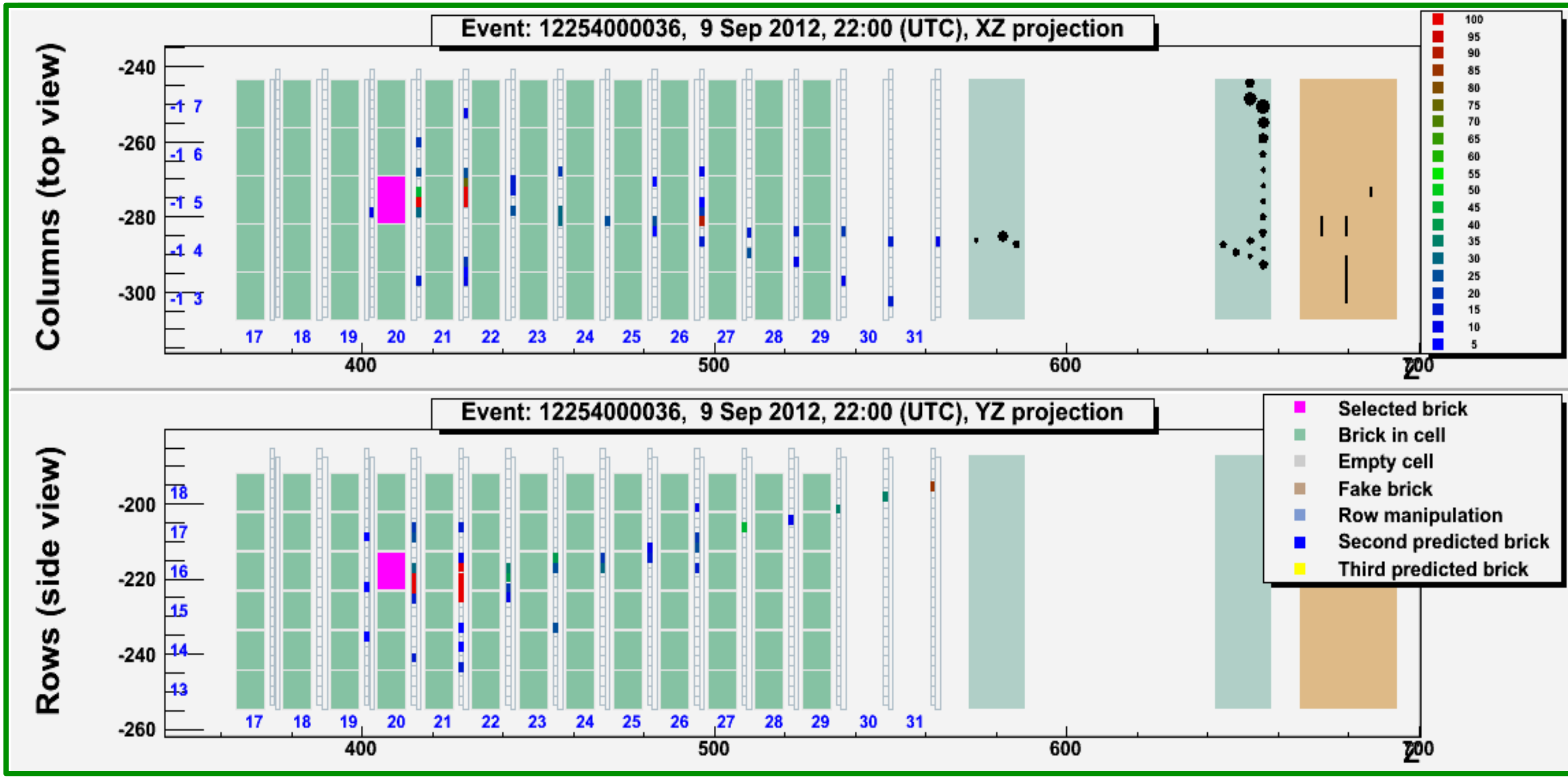


Phys. Rev. D 89 (2014) 051102(R)

Evidence for the ν_τ appearance

THE FOURTH ν_τ CANDIDATE

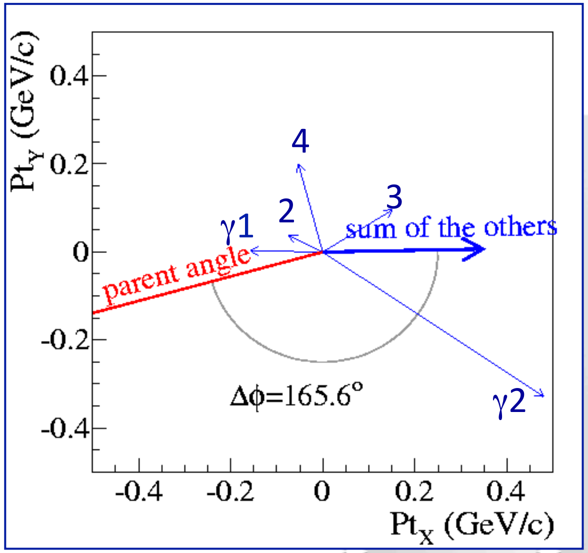
As seen by the electronic detectors …

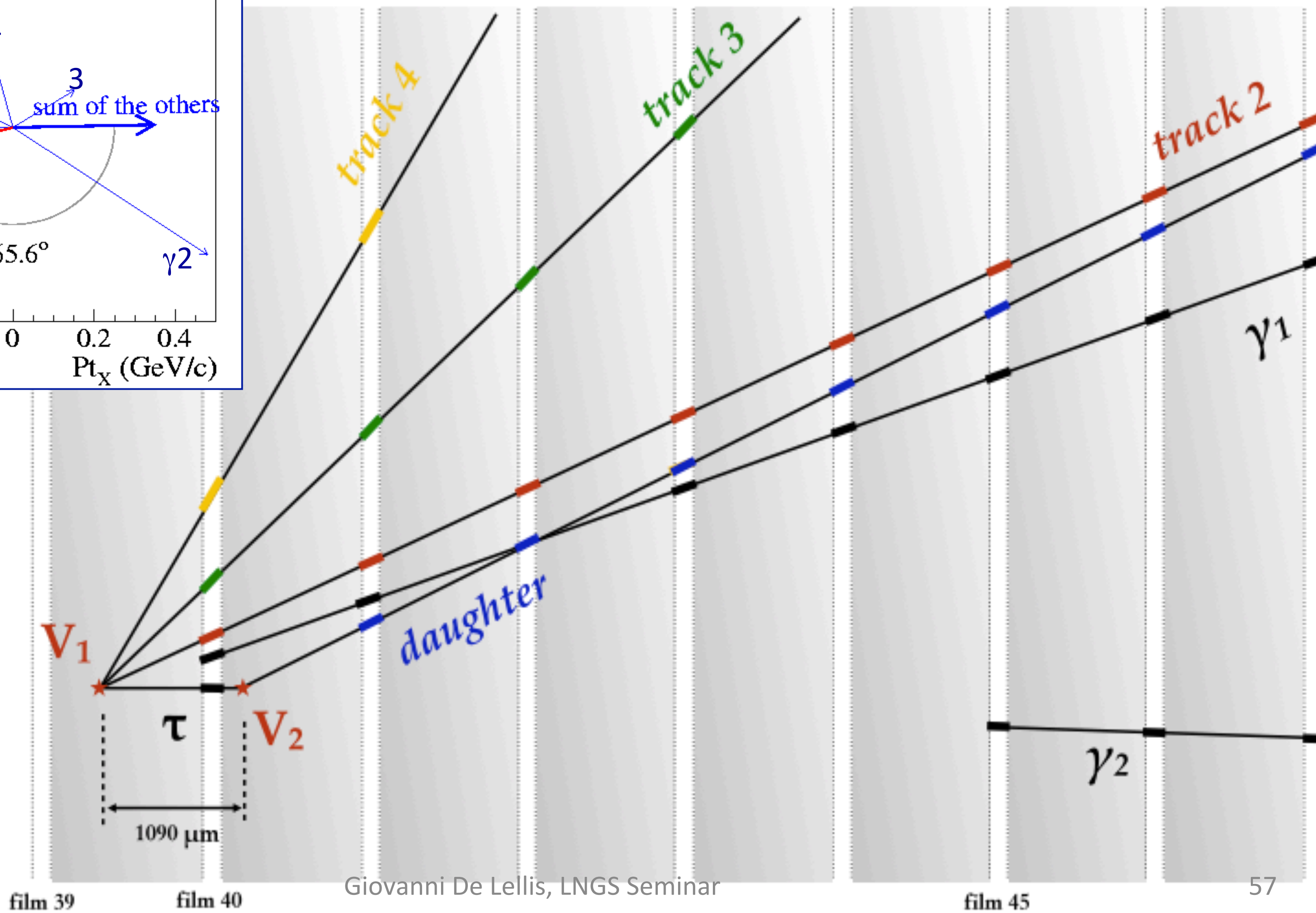


PTEP 10 (2014) 101C01

The Fourth ν_τ Candidate

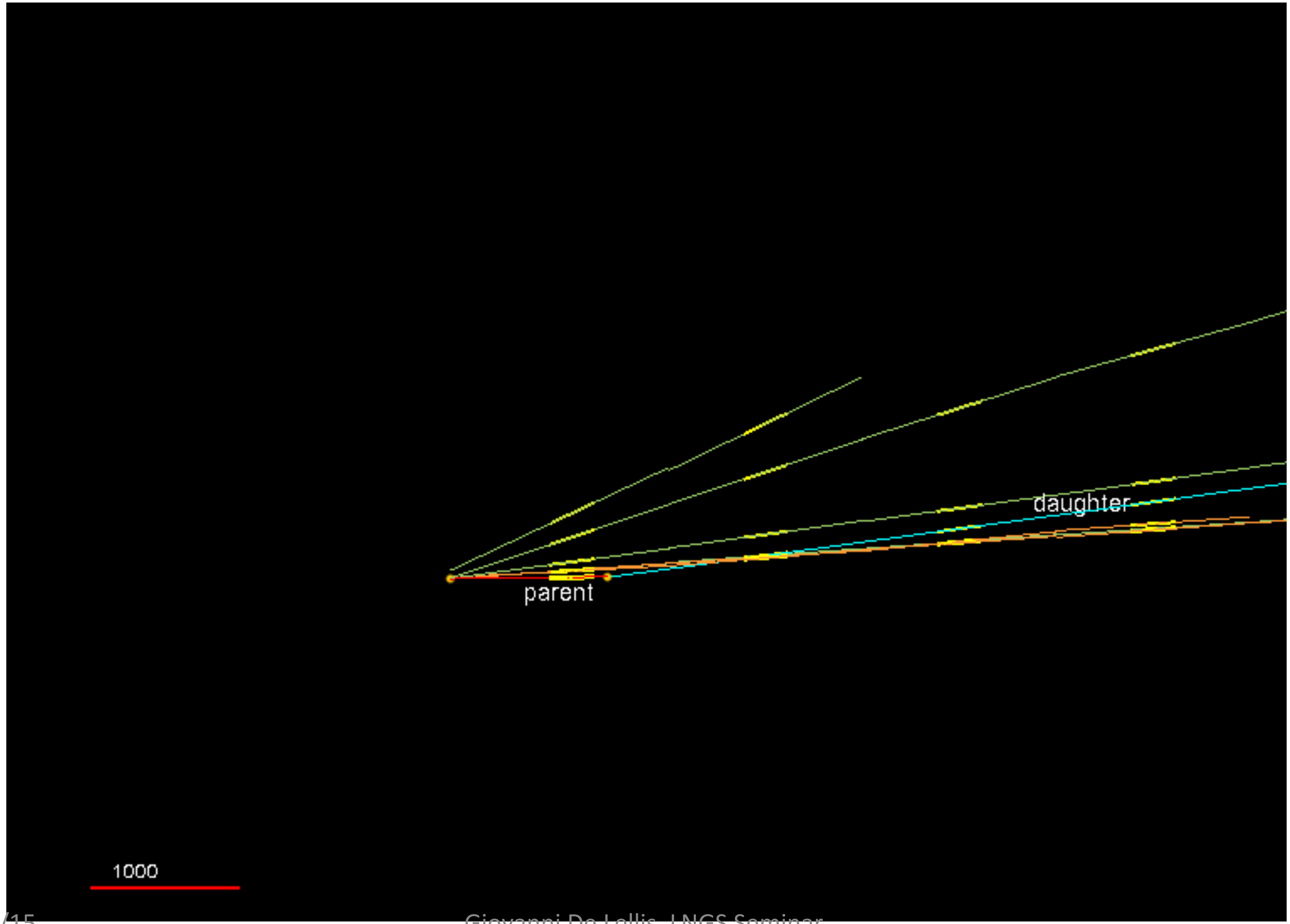
… and in the brick





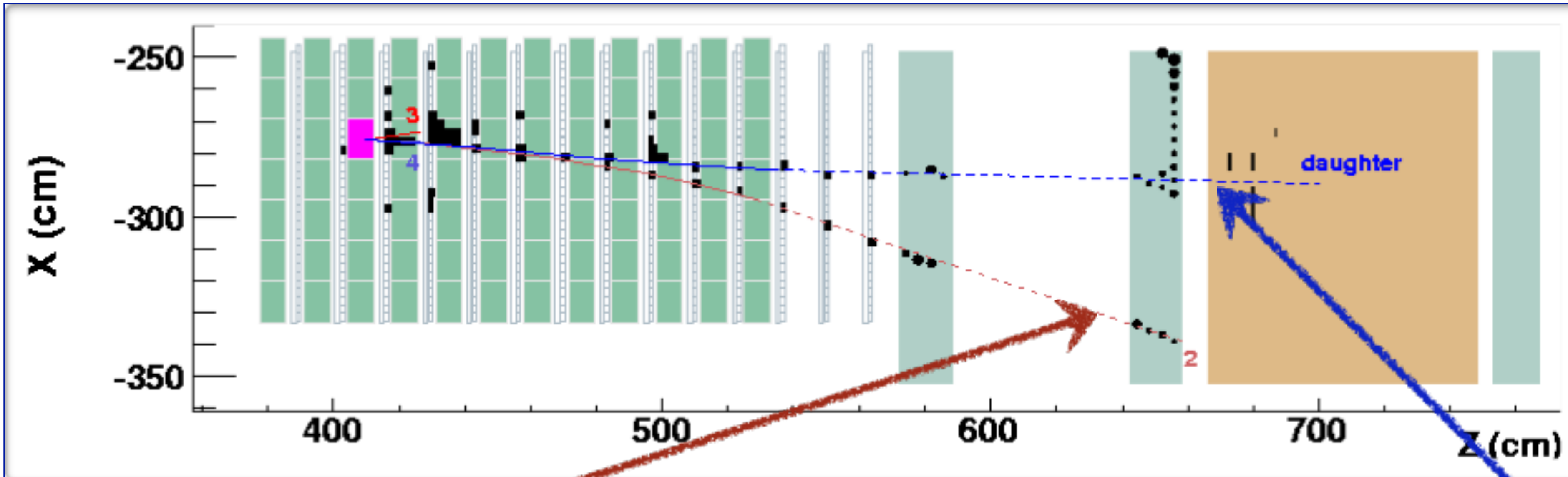
THE FORTH ν_τ CANDIDATE

… and in the brick



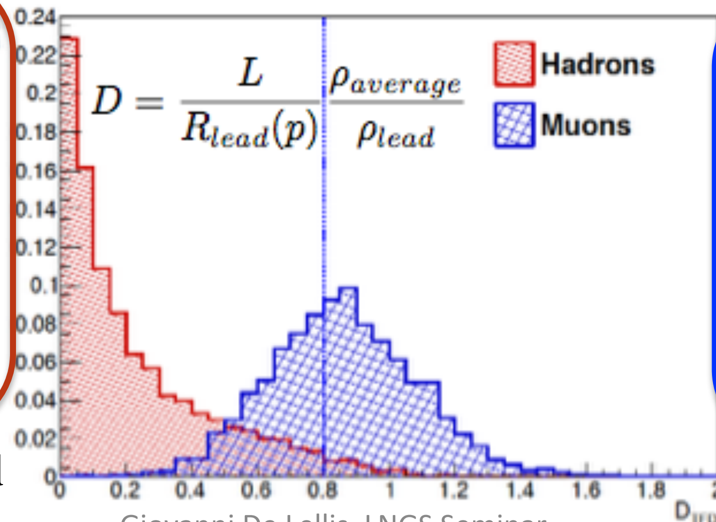
Particle ID: Track Follow-Down

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



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

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



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

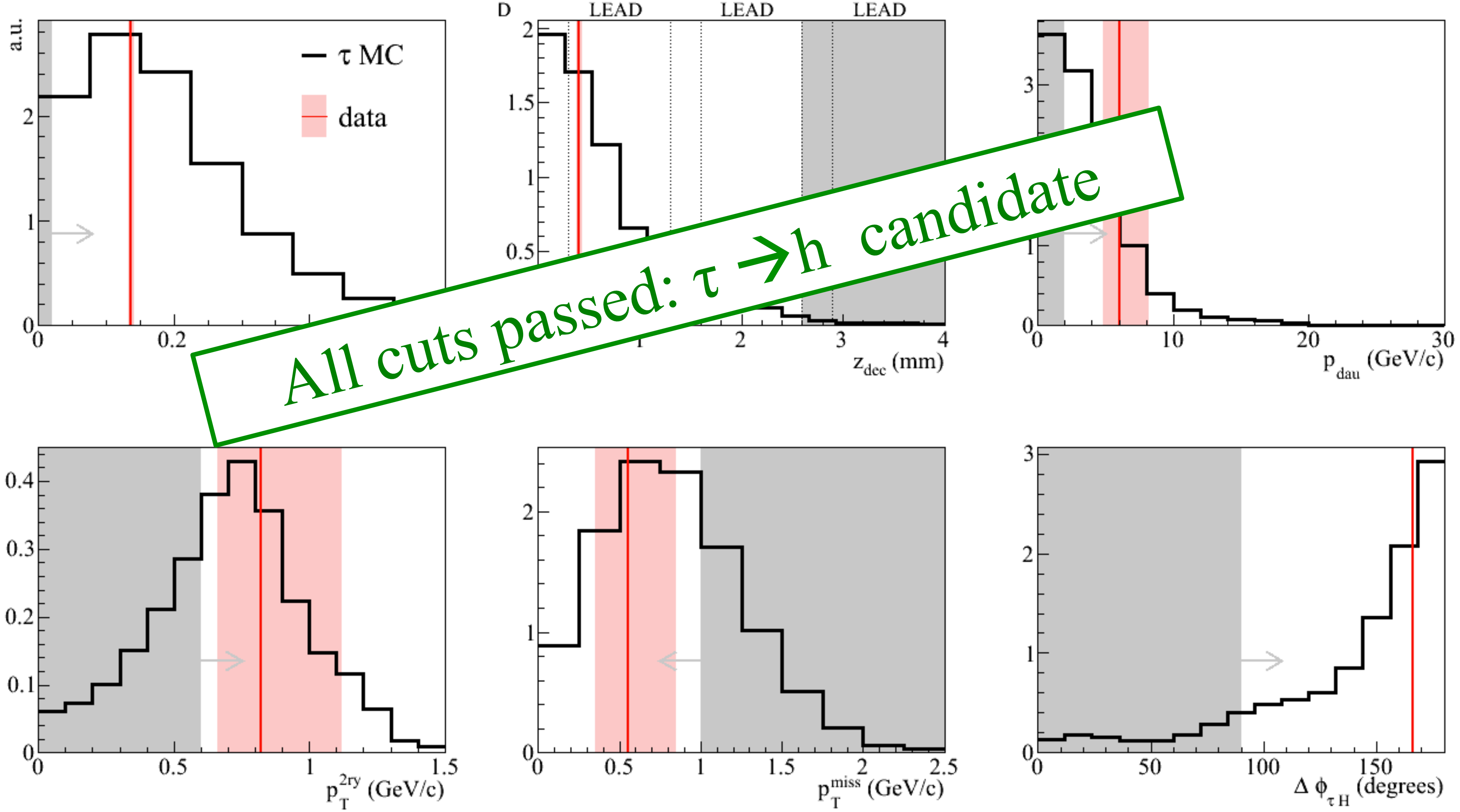
$$D = 0.18 \pm 0.04$$

Charm background hypothesis rejected

Hadronic decay channel

THE FOURTH ν_τ CANDIDATE

Kinematical variables



PTEP 10 (2014) 101C01: Observation of ν_τ appearance

BY PRODUCT ANALYSIS

STERILE NEUTRINOS

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

~standard oscillation   exotic oscillation

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

interference term

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

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

After maximising over C^2

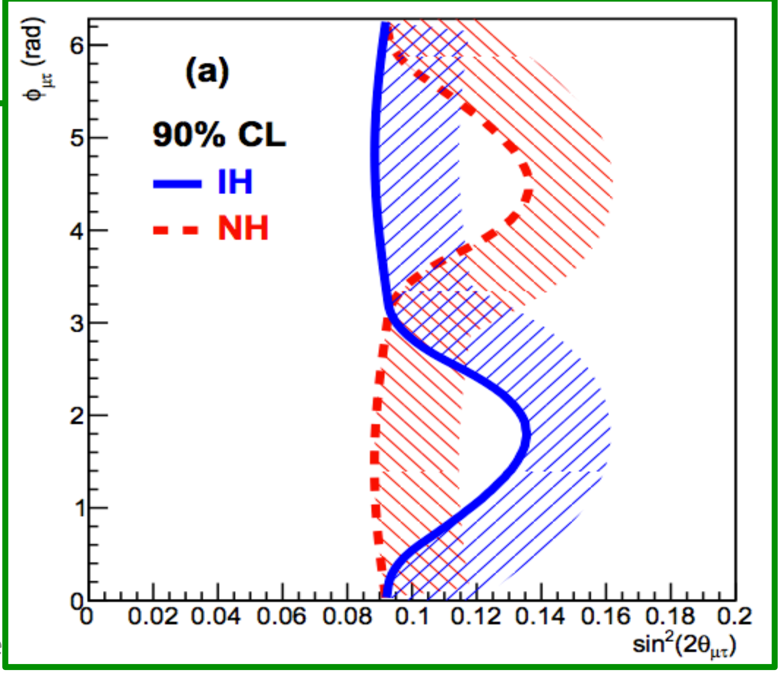
$$\tilde{L}(\phi_{\mu\tau}, sin^2 2\theta_{\mu\tau})$$

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

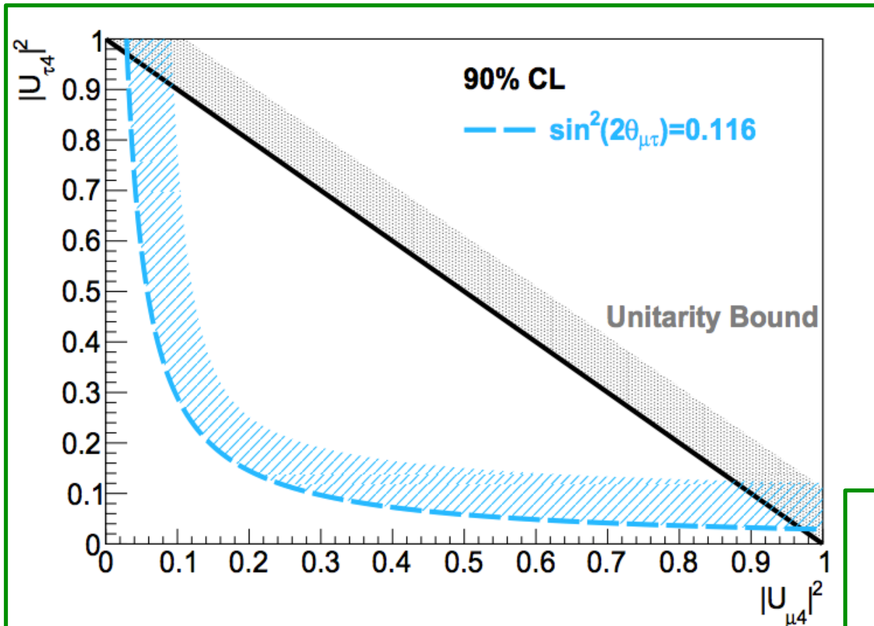
$$C = 2 \mid U_{\mu 3} U^*_{\tau 3} \mid,$$

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

JHEP_074P_0315 (2015)
ArXiv:1503.01876



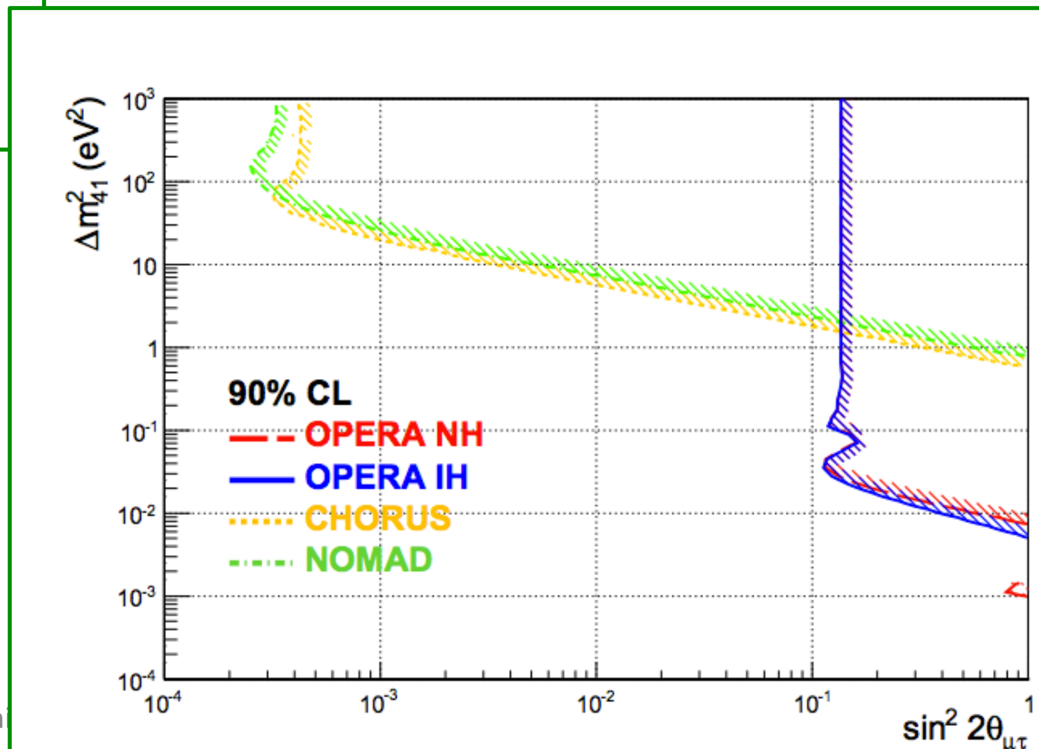
Sterile Neutrinos



Effective mixing:

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

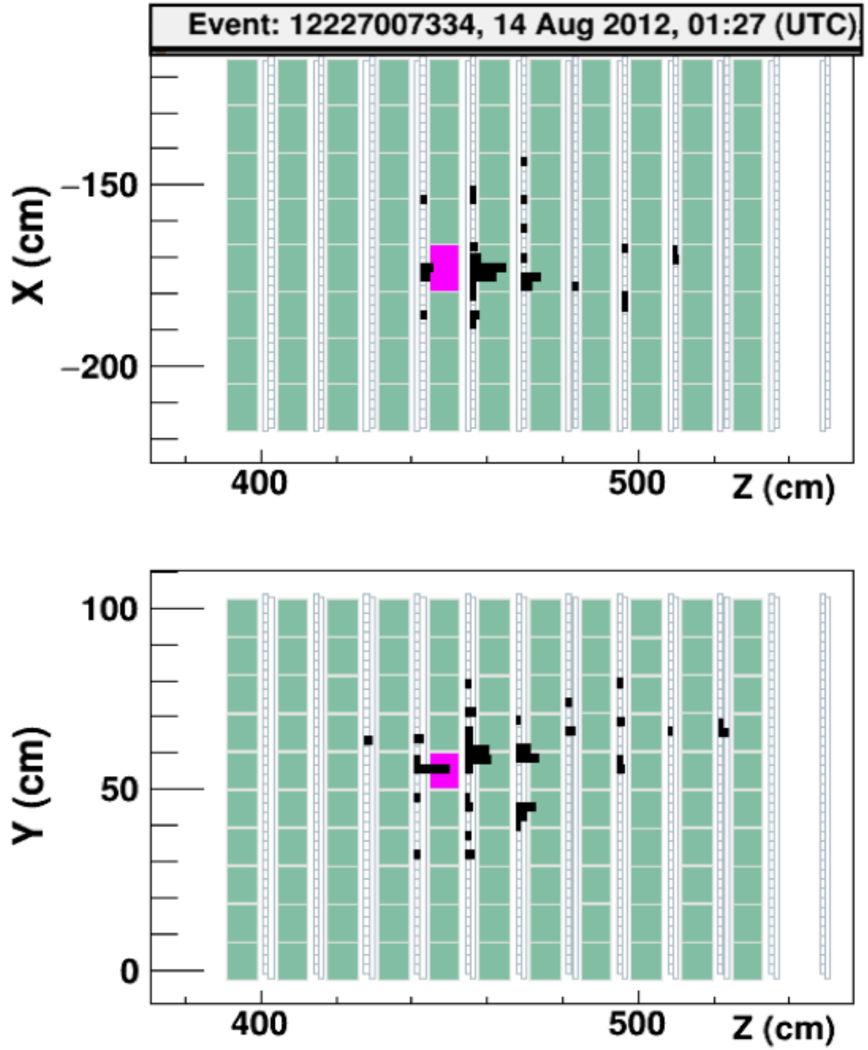
JHEP_074P_0315 (2015)
ArXiv:1503.01876



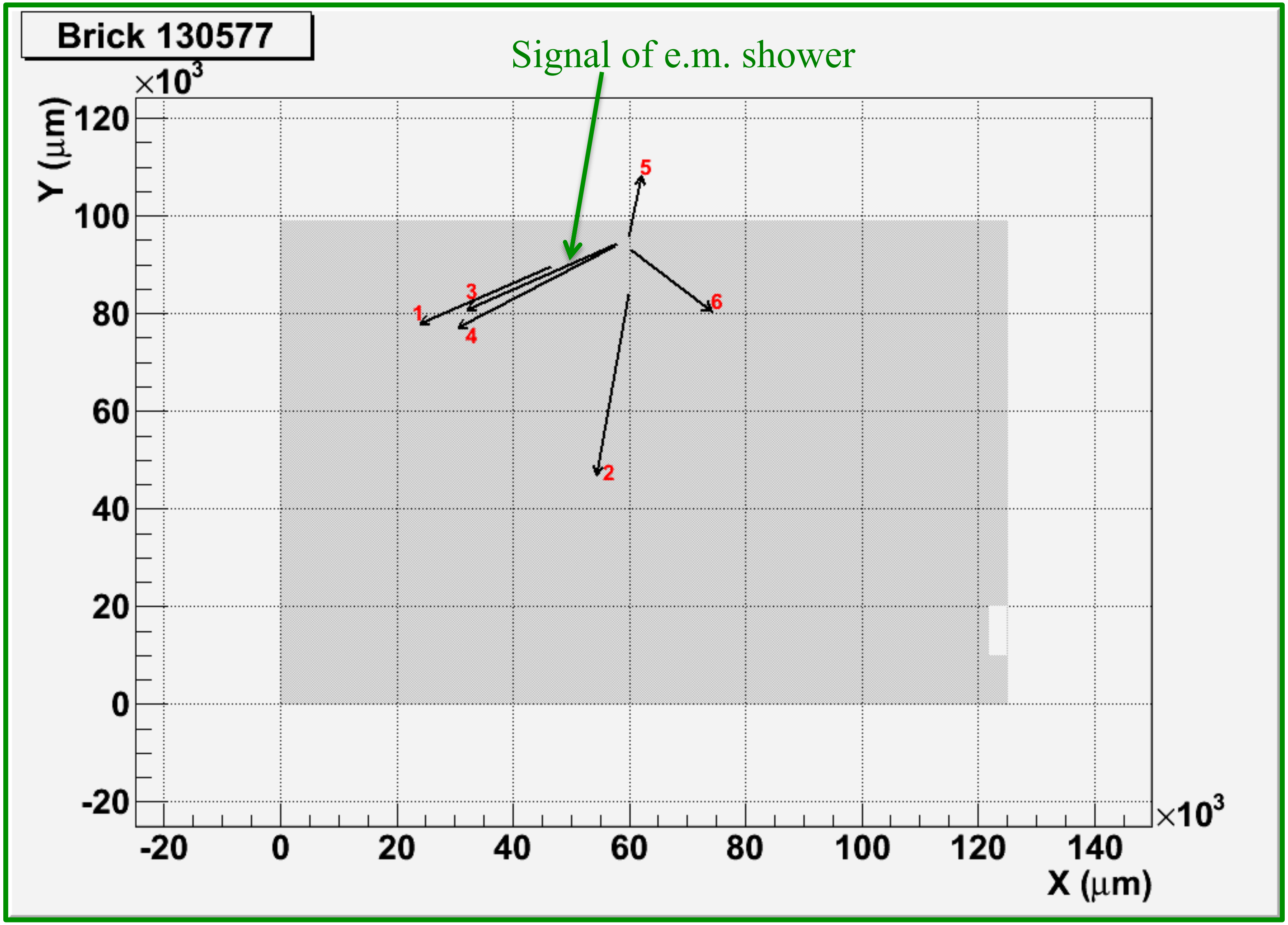
Completing The Analysis Of The Two Most Probable Bricks

The Fifth ν_τ Candidate

As seen by the electronic detectors …

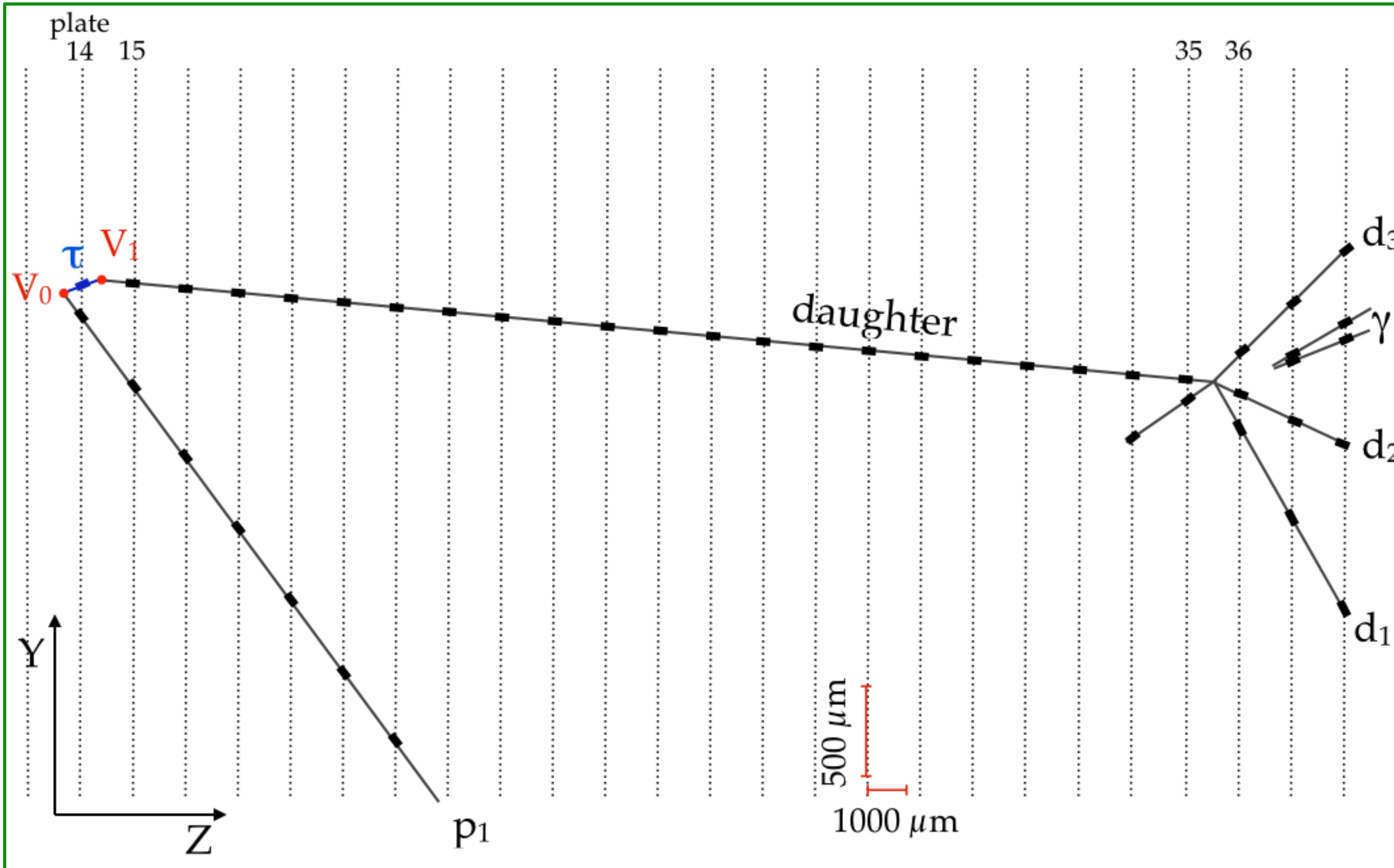


Analysis Of Interface Emulsion Films



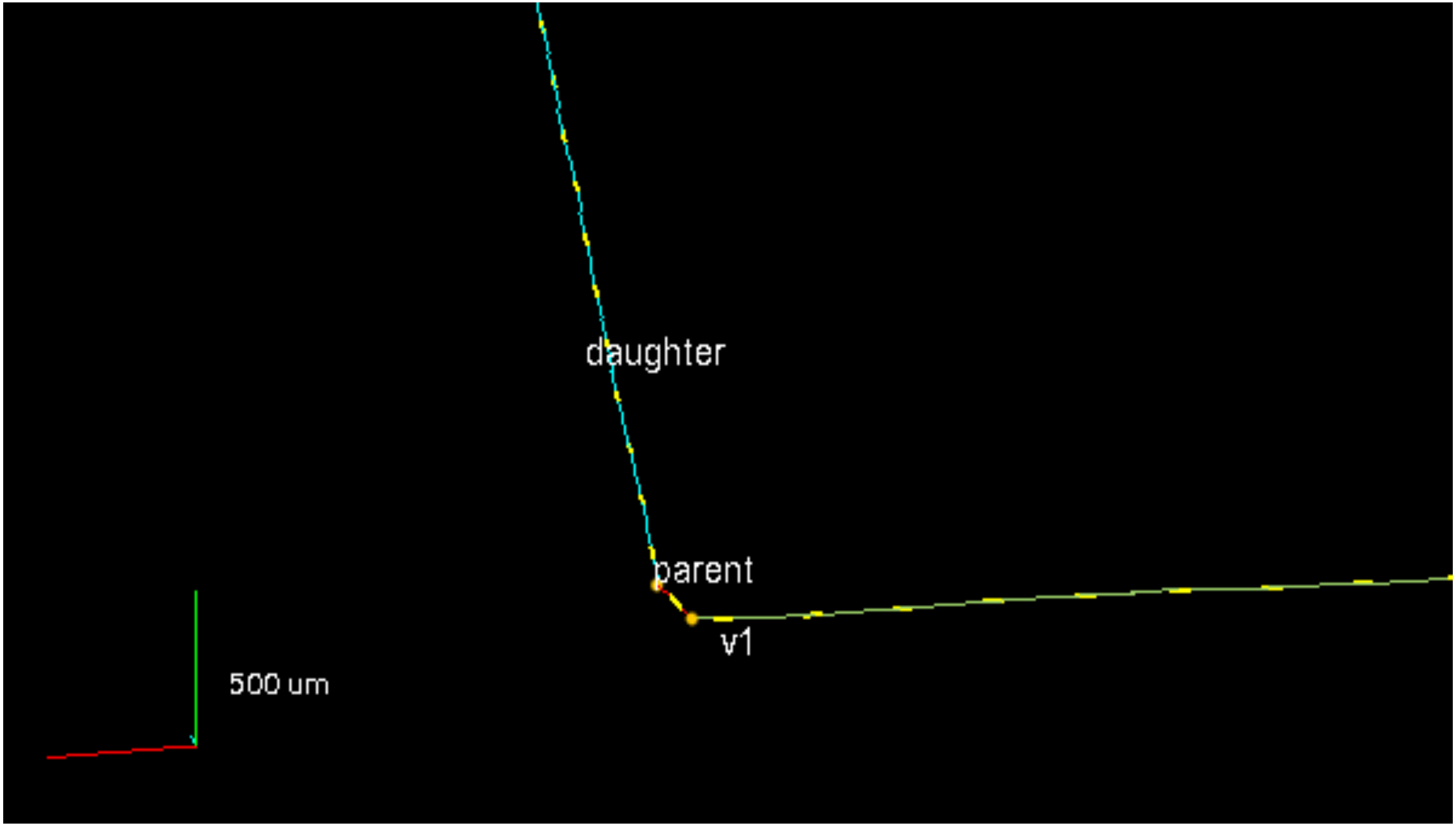
THE FIFTH ν_τ CANDIDATE

… and in the brick



THE FIFTH ν_τ CANDIDATE

… and in the brick



Search For Nuclear Fragments

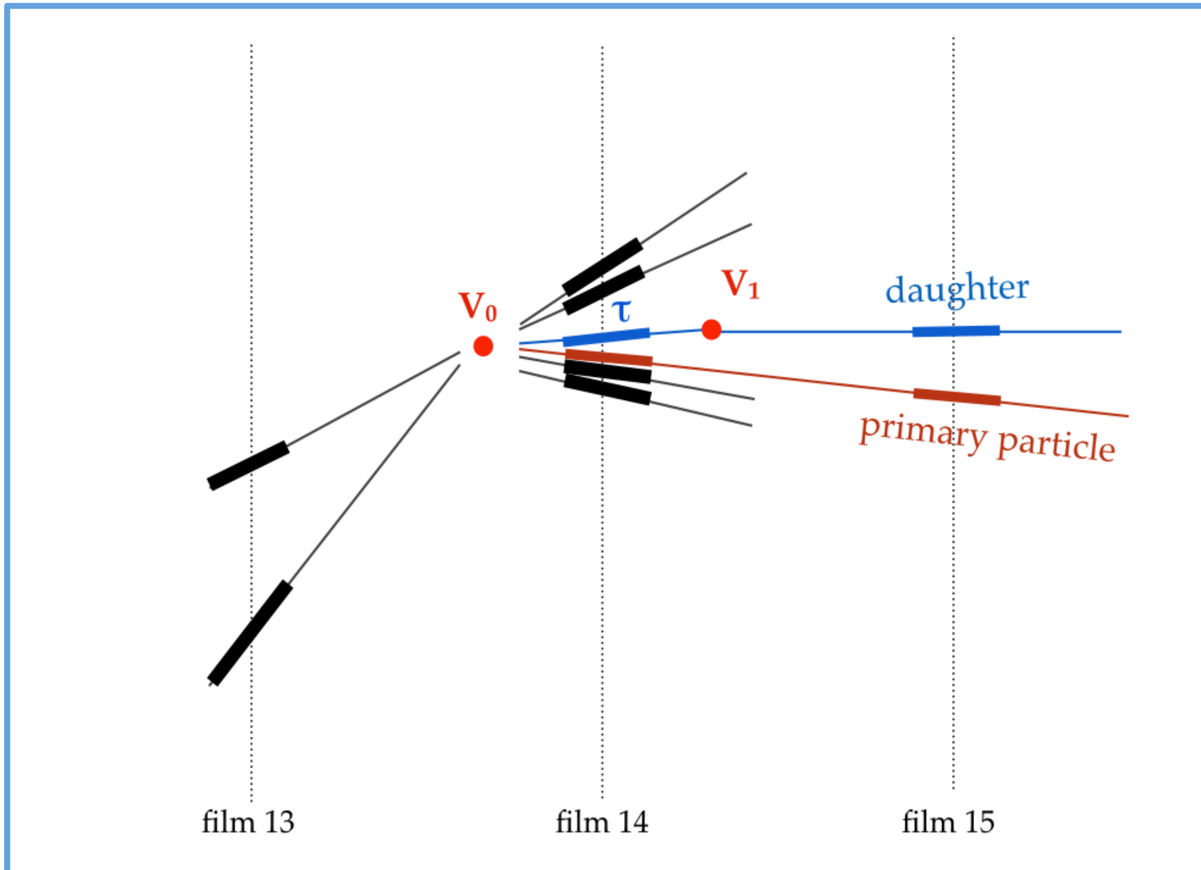
Search for nuclear fragments in an extended angular range **$|\tan\theta| \leq 3$**

Primary vertex

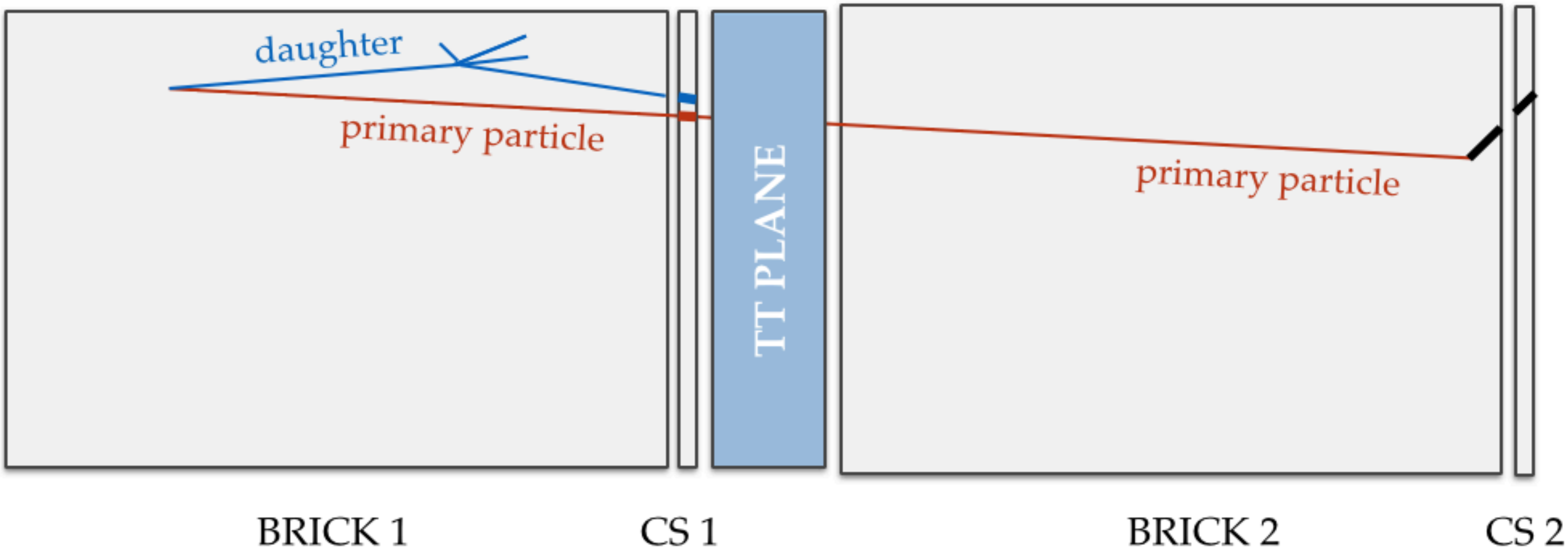
6 nuclear fragments found

Secondary vertex

None



Particle Identification



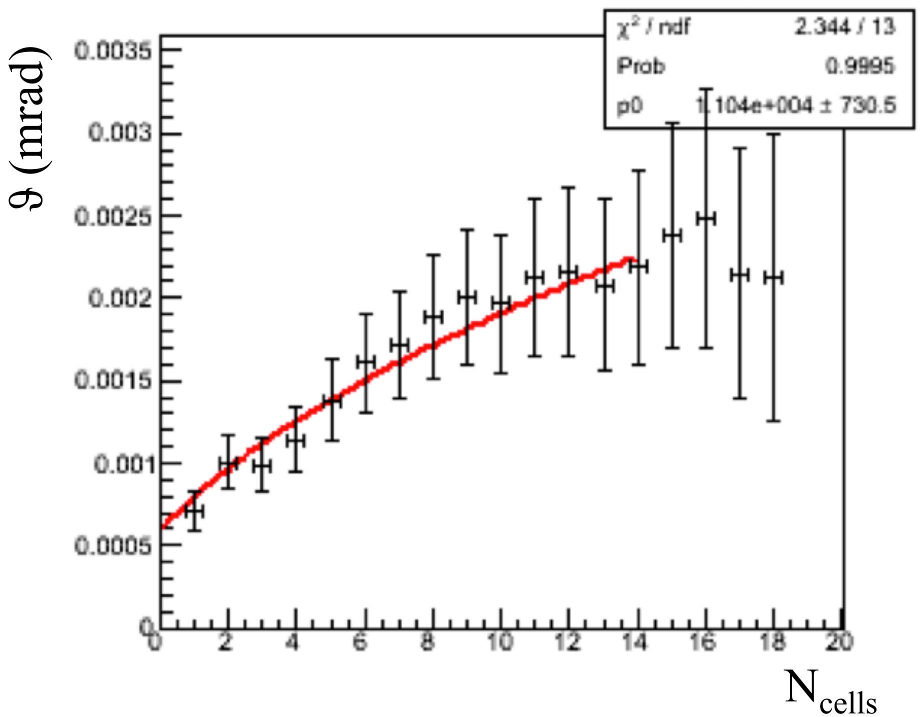
Primary particle
Followed in the downstream brick
Hadronic re-interaction: 1 visible particle
→ **Charm hypothesis discarded**

Daughter
Hadronic re-interaction in the first brick
→ **Hadronic decay channel**

MOMENTUM MEASUREMENT

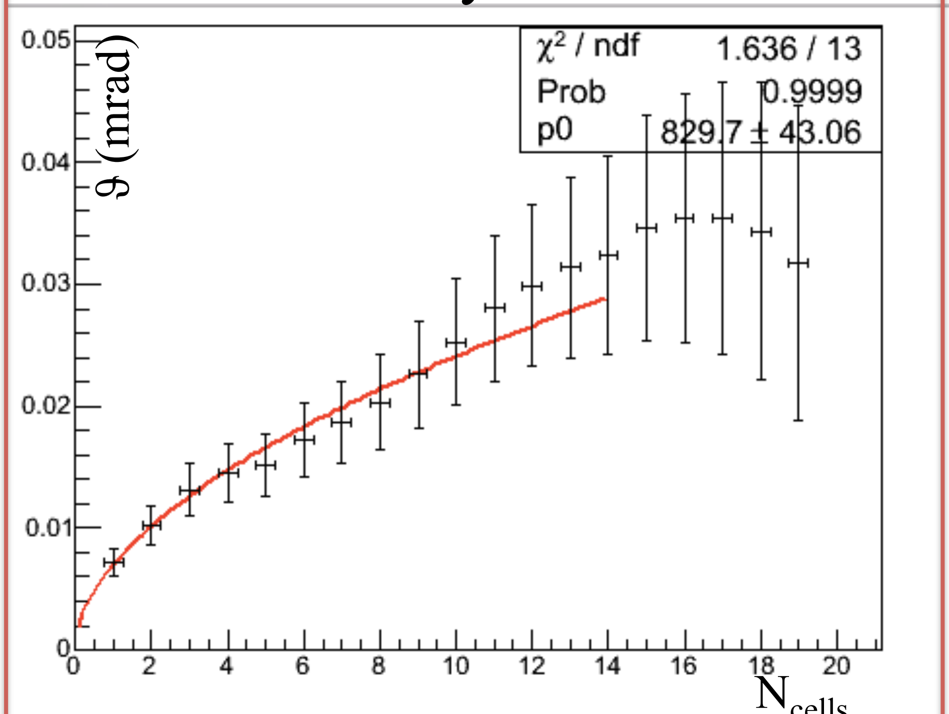
MCS method in the first brick

Daughter track



$P_{daughter} = 11.0\ [7.1, 24.9]$ GeV/c

Primary track

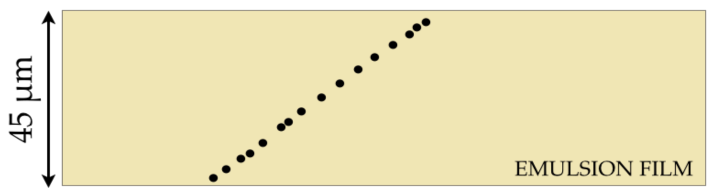


$\beta P_{1ry} = 0.8\ [0.6, 1.1]$ GeV/c

PRIMARY PARTICLE IDENTIFICATION

Grain counting method

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



MCS method in the first brick

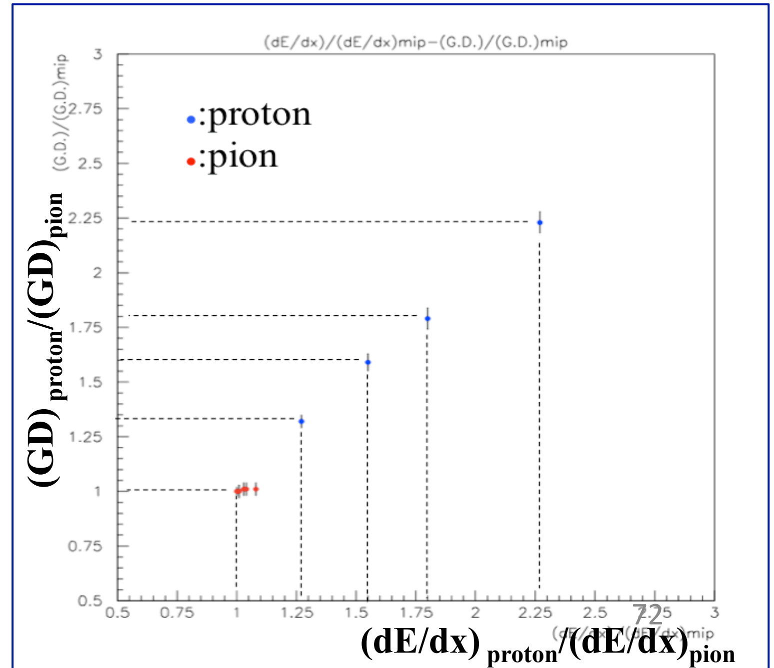
$\beta P_{1ry} = 0.8\ [0.6, 1.1]$ GeV/c

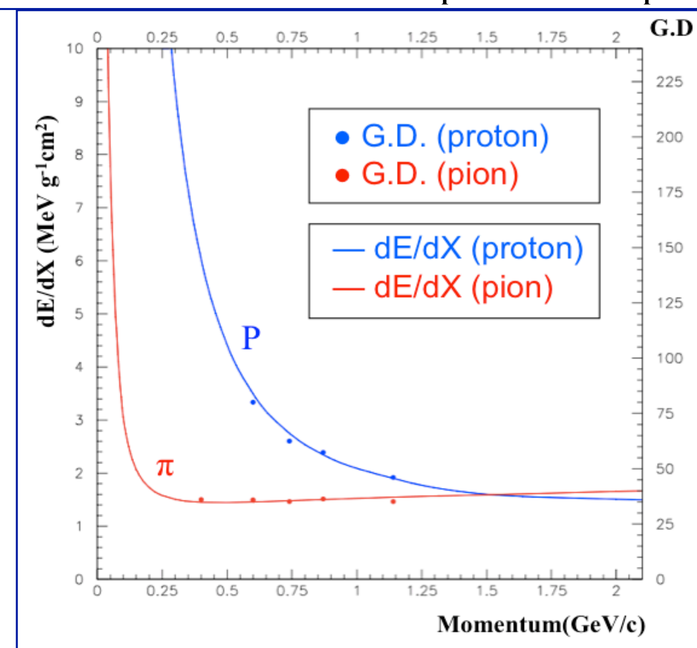
$$GD_{1ry}/GD_{\pi} = 1.45 \pm 0.06$$

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

Consistent with proton hypothesis

p = (1.0±0.2) GeV/c





THE FIFTH ν_τ CANDIDATE

Measurements performed in two different laboratories for independent cross-check

		LAB 1		LAB 2		Mean	
	ID	Slopes	p (GeV/c)	Slopes	p (GeV/c)	Slopes	p (GeV/c)
1ry	τ	0.067, 0.056	-	0.075, 0.059	-	0.071, 0.058	-
	p1	-0.268,-0.086	pβ 0.74 [0.67, 0.82]	-0.270, -0.081	pβ 0.8 [0.6, 1.1]	-0.269, -0.084	1.0 [0.8, 1.2]
2ry	daughter	-0.018, 0.057	10.3 [6.1, 33.5]	-0.016, 0.062	11.0 [7.1, 24.9]	-0.017, 0.060	10.7 [6.9, 24.4]
Interaction of the daughter track	d1	-0.096,-0.331		-0.079,-0.337			
	d2	-0.140, 0.177		-0.125, 0.163			
	d3	0.273, 0.300		0.278, 0.285			
	fragment	-0.600, 0.200		-0.651, 0.225			
	γ	-0.119,-0.024		-0.106,-0.034			

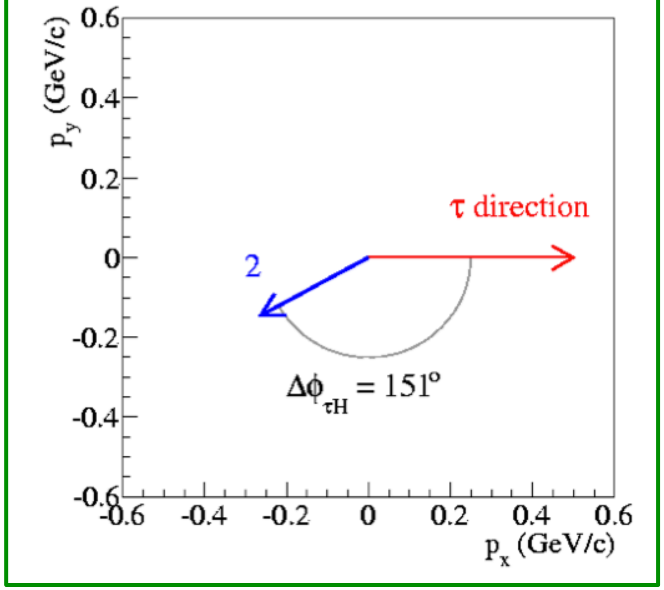
Compatible results

The Fifth ν_τ Candidate

Kinematical variables

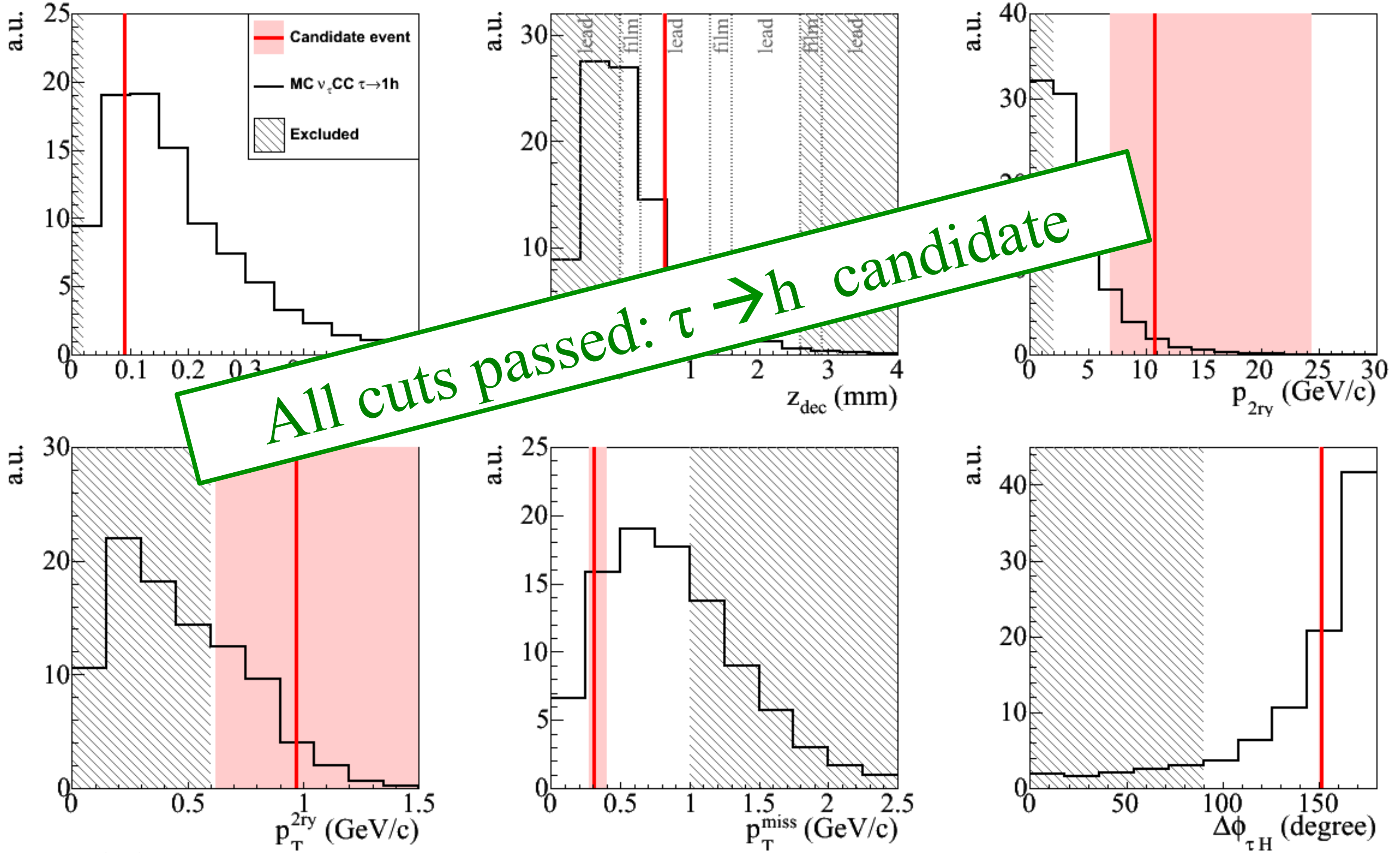
Parameter	Measured value	Selection Criteria
$\Delta\phi_{\tau H}$ (^{o})	151 ± 1	>90
p_T^{miss} (GeV/c)	0.3 ± 0.1	<1
θ_{kink} (mrad)	90 ± 2	>20
z_{dec} (μm)	634 ± 30	[44, 2600]
p^{2ry} (GeV/c)	11^{+14}_{-4}	>2
p_T^{2ry} (GeV/c)	$1.0^{+1.2}_{-0.4}$	>0.6 (no γ attached)

Flight length
960±30 μm



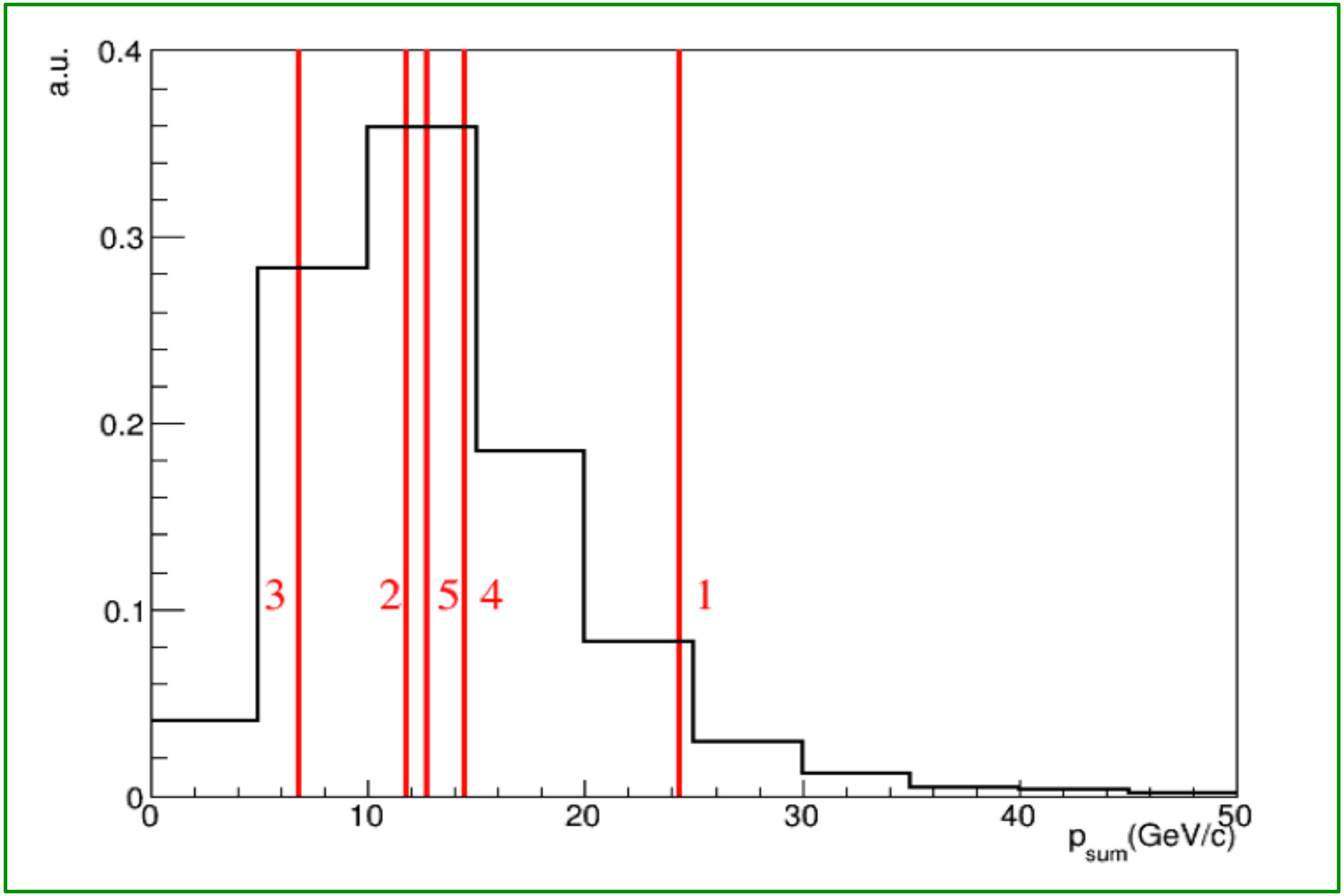
THE FIFTH ν_τ CANDIDATE

Kinematical variables



Visible Energy Of All The Candidates

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

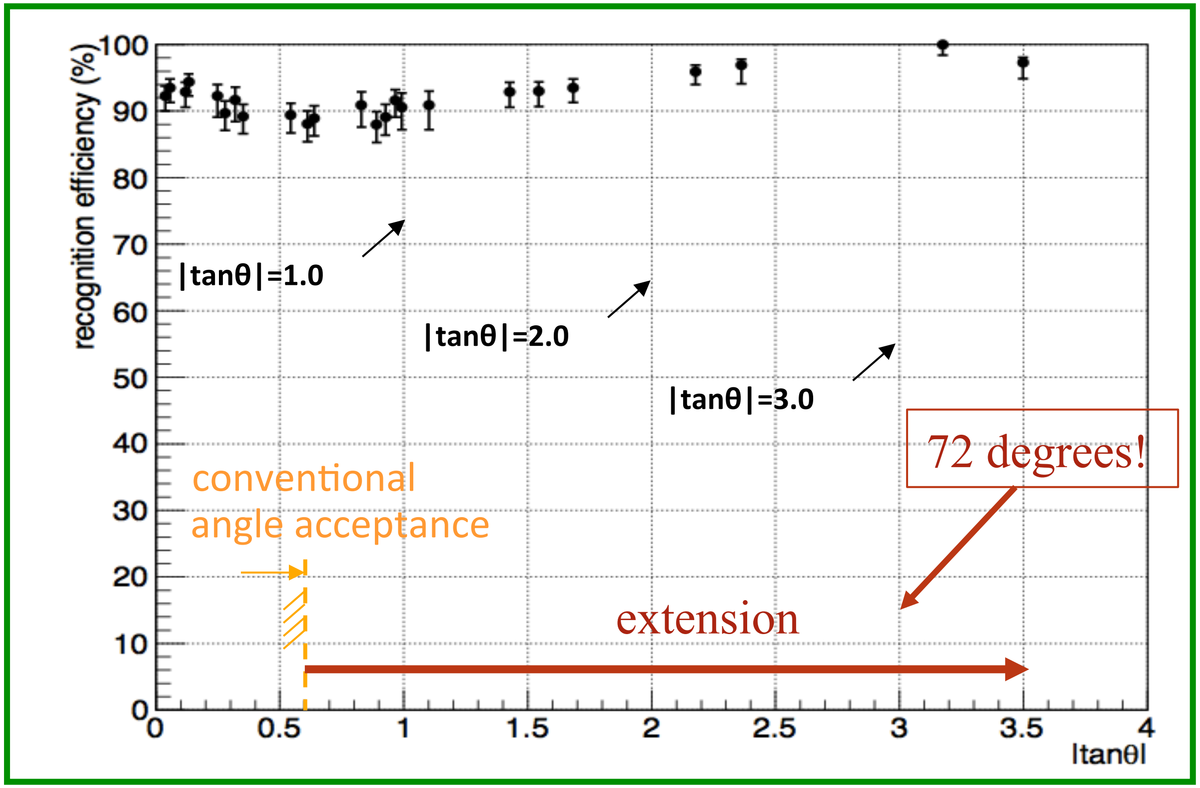


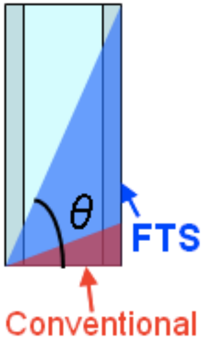
BACKGROUND STUDIES

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





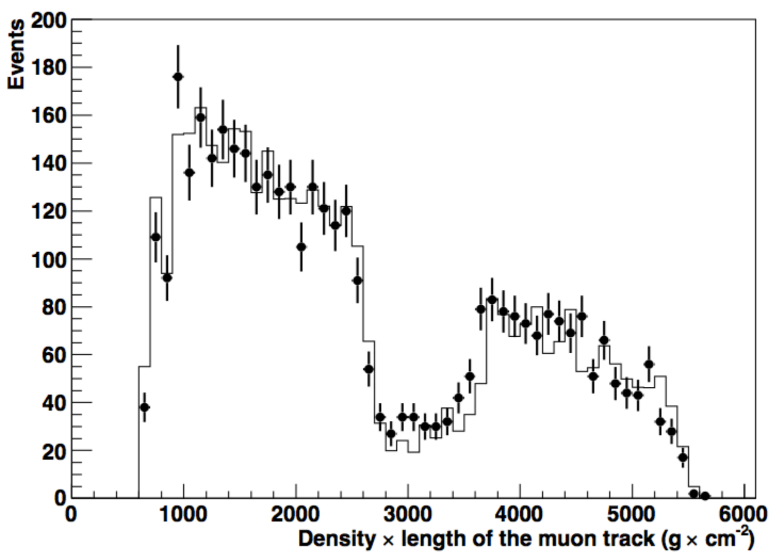
JINST 9 (2014) P12017

Charmed Particles Production

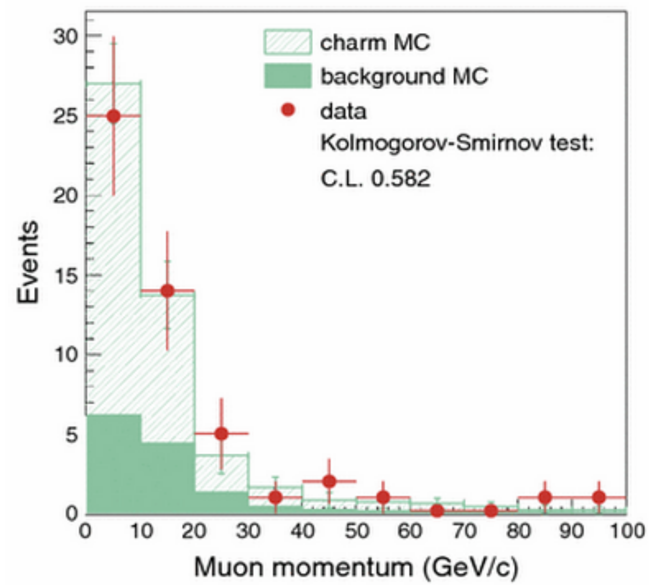
- Lifetimes and masses similar to the τ
- Background when the primary muon is not identified

ν_μ^{CC} interactions with charm quark production derived from CHORUS measurements
New J. Phys. 13 (2011) 093002

$$\frac{\sigma(\nu_\mu N \to \mu^- C X)}{\sigma(\nu_\mu N \to \mu^- X)} = (4.38 \pm 0.26)\%$$



New J. Phys. 13 (2011) 053051



Eur. Phys. J. C74 (2014) 2986

Good agreement in normalization and shape for the relevant kinematical variables in the charm detection and muon identification
Constrain the background within 20%

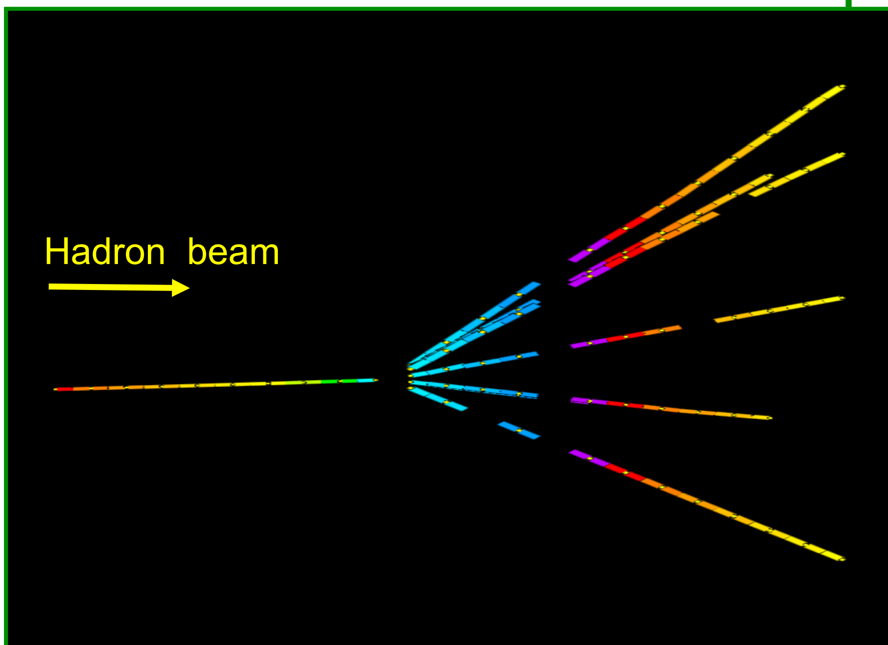
BACKGROUND STUDIES: HADRONIC INTERACTIONS

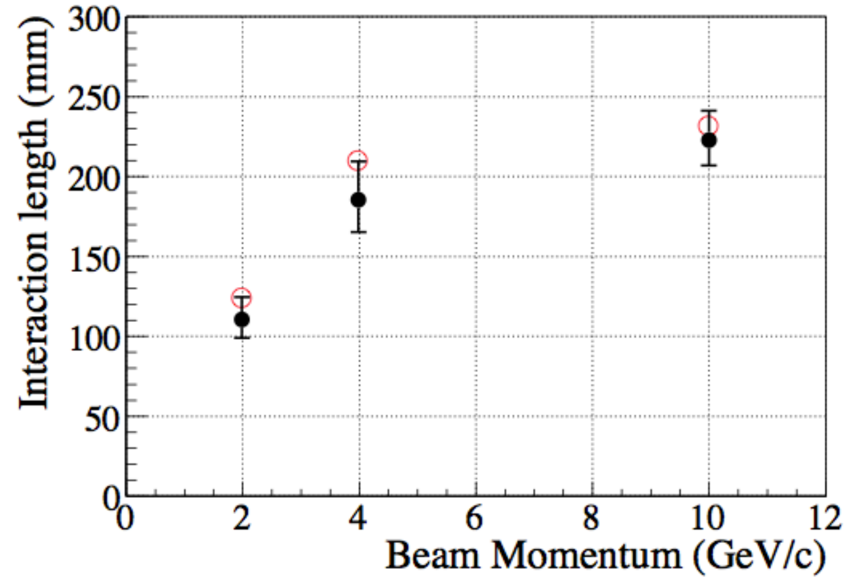
Comparison of large data sample (π^- beam test at CERN) with Fluka simulation

→ check the agreement and estimate the systematic uncertainty

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

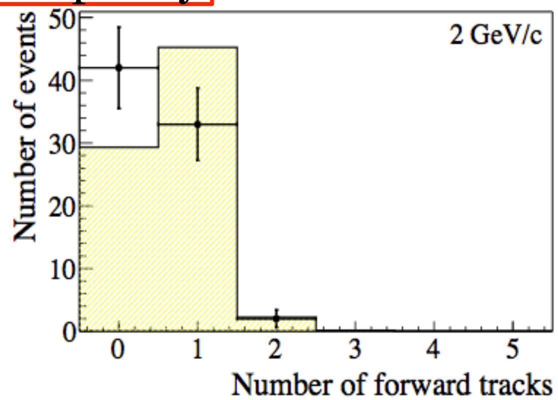
Red : MC (FLUKA) simulation

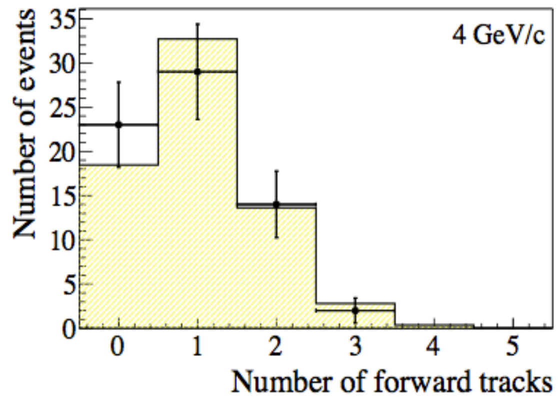
PTEP 9 (2014) 093C01

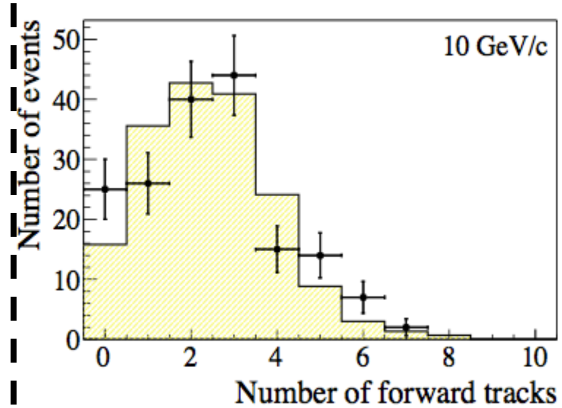
SECONDARY TRACK EMISSION

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

Multiplicity

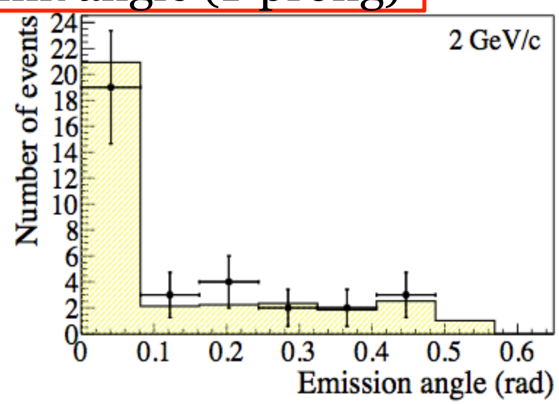


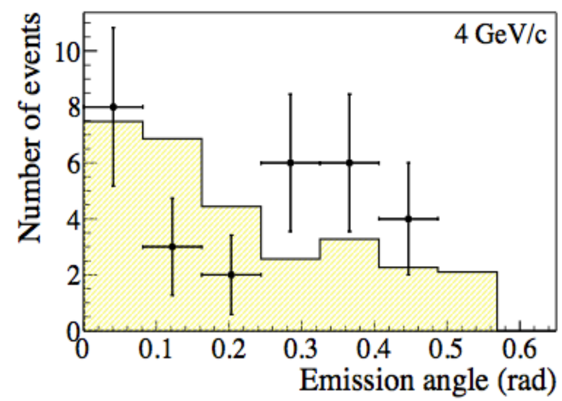


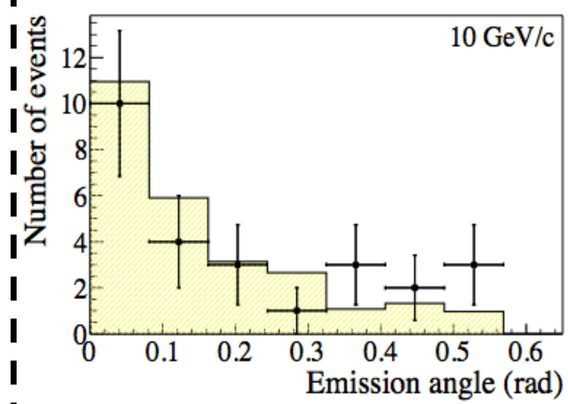


Error bars : Experimental data
Histogram : Simulated data

Kink angle (1-prong)

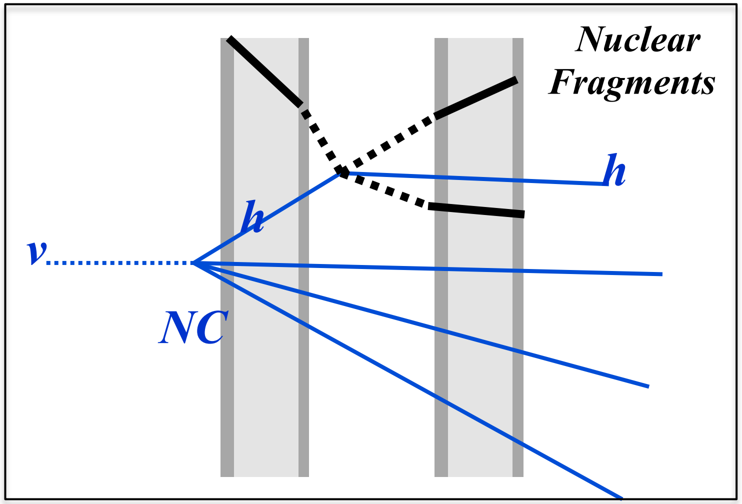




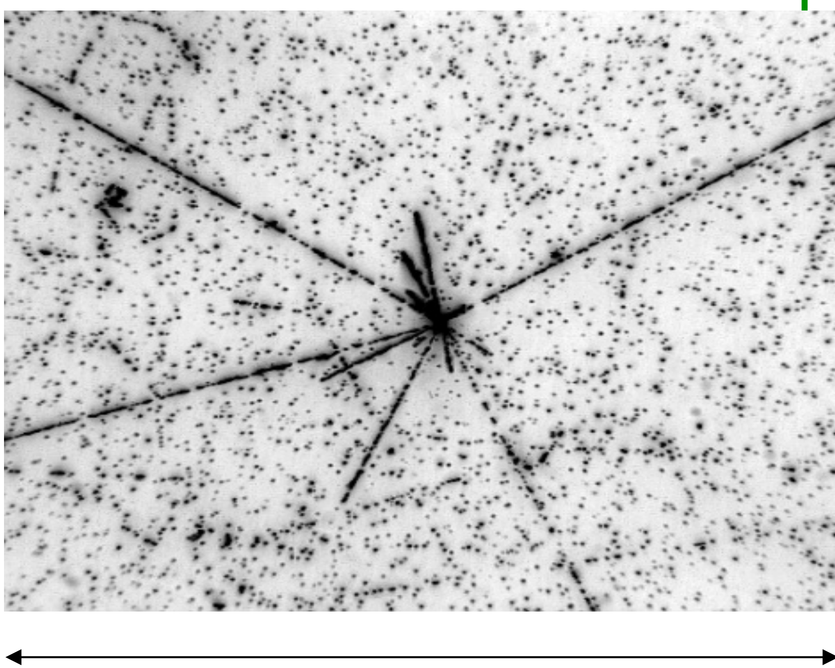


Good agreement within the statistical error: systematic error ~ 30%

Nuclear Fragments Emission Probability

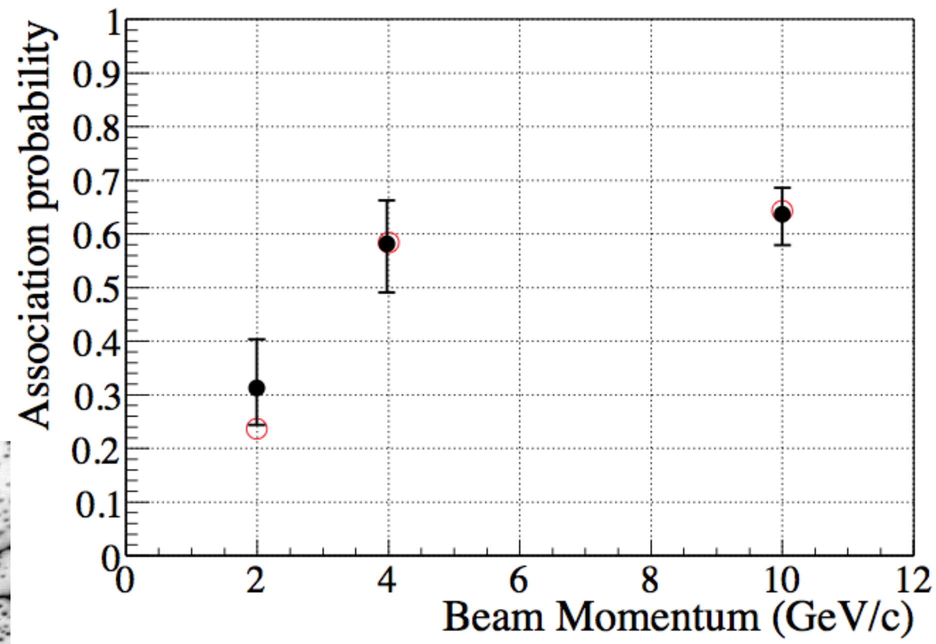


Highly ionizing fragments



150 µm

Additional background reduction



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

PTEP 9 (2014) 093C01

Nuclear Fragments In 1 And 3 Prong Interactions

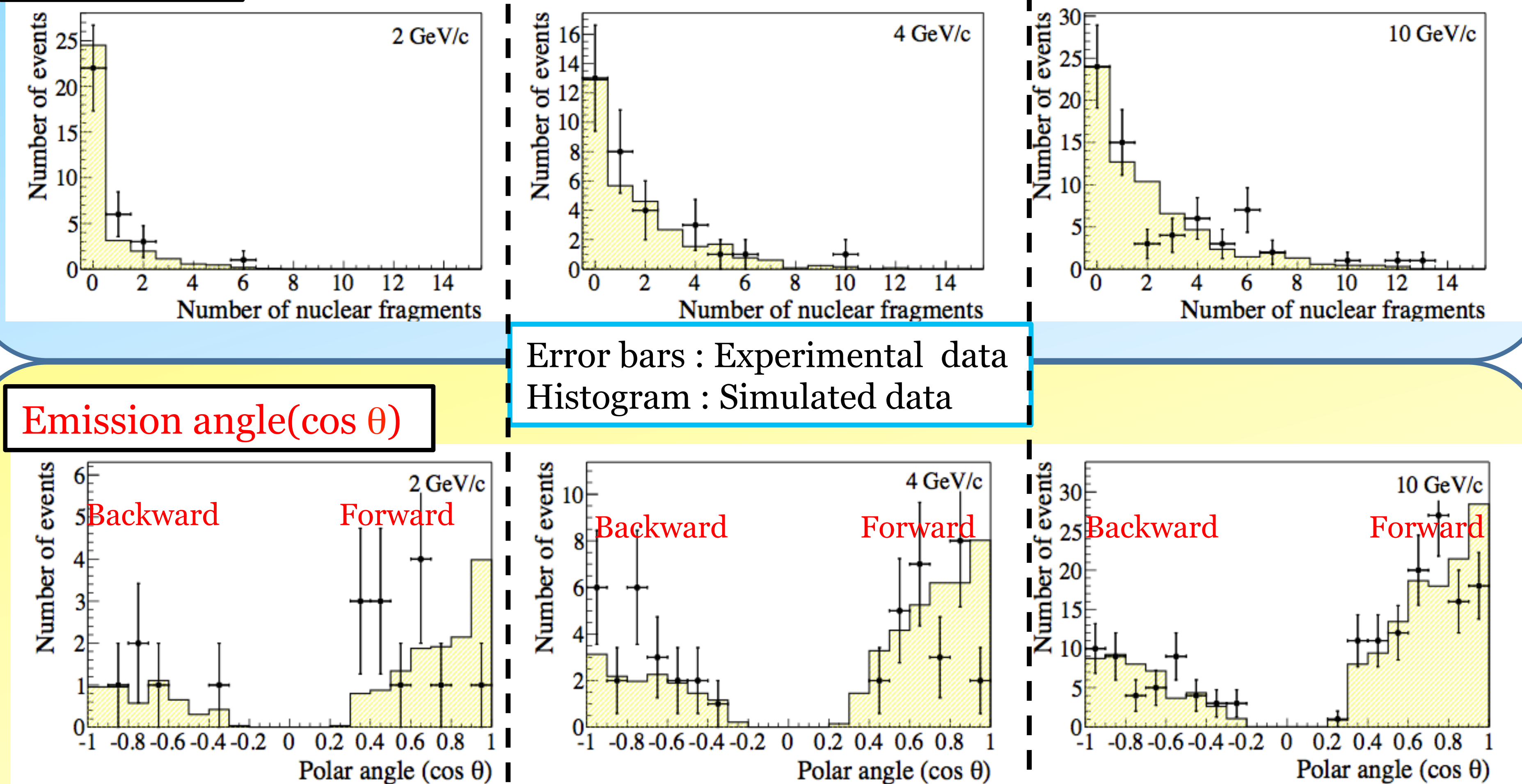
2GeV/c | 4GeV/c | 10GeV/c

Multiplicity

MC: β < 0.7

Error bars : Experimental data
Histogram : Simulated data

Emission angle(cos θ)



Agreement within the statistical error: systematic error is 10%

LARGE ANGLE μ SCATTERING

New estimate based on GEANT4
- Simulation modified by introducing form factors (FF) for Lead
(Saxon-Woods parameterization)

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

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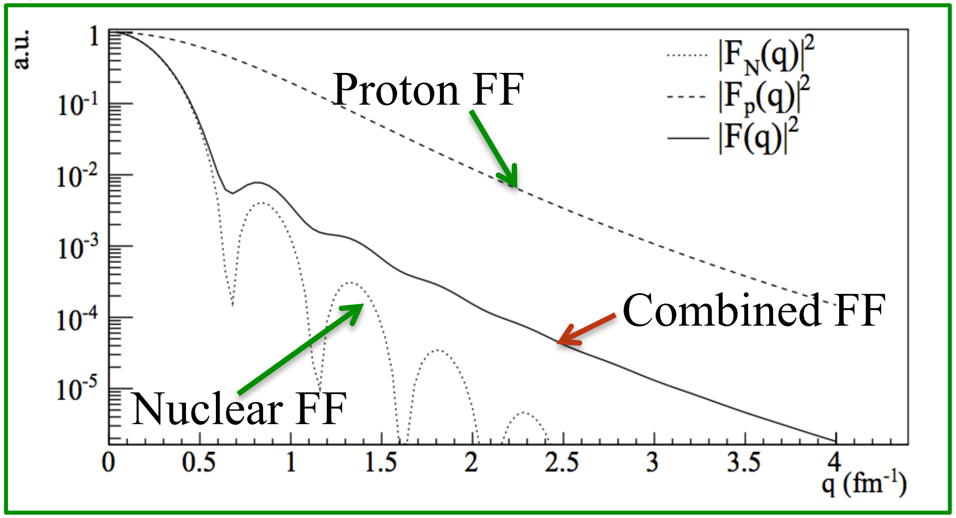
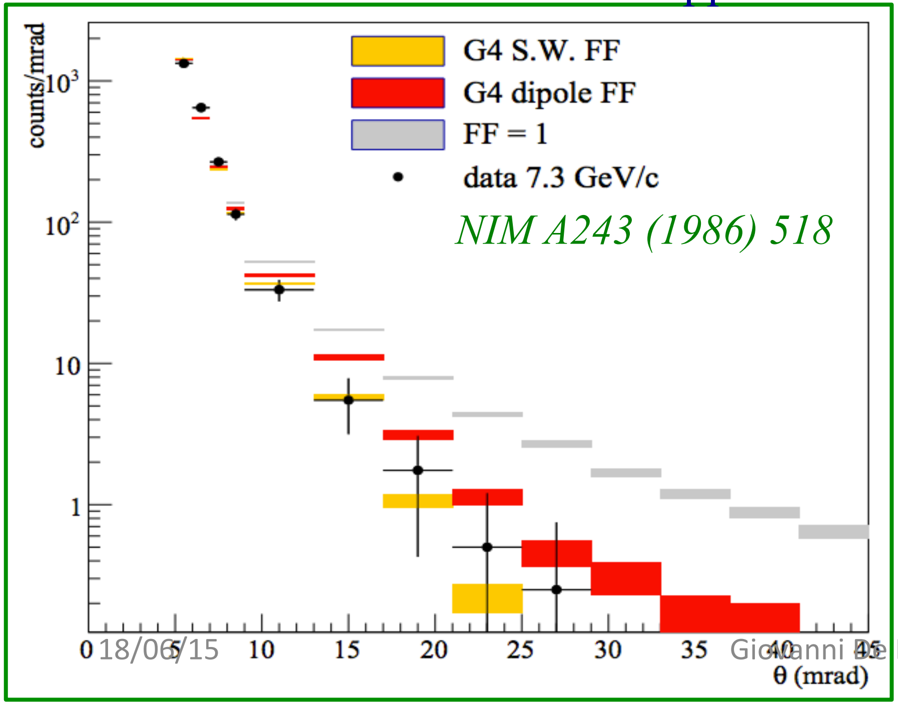
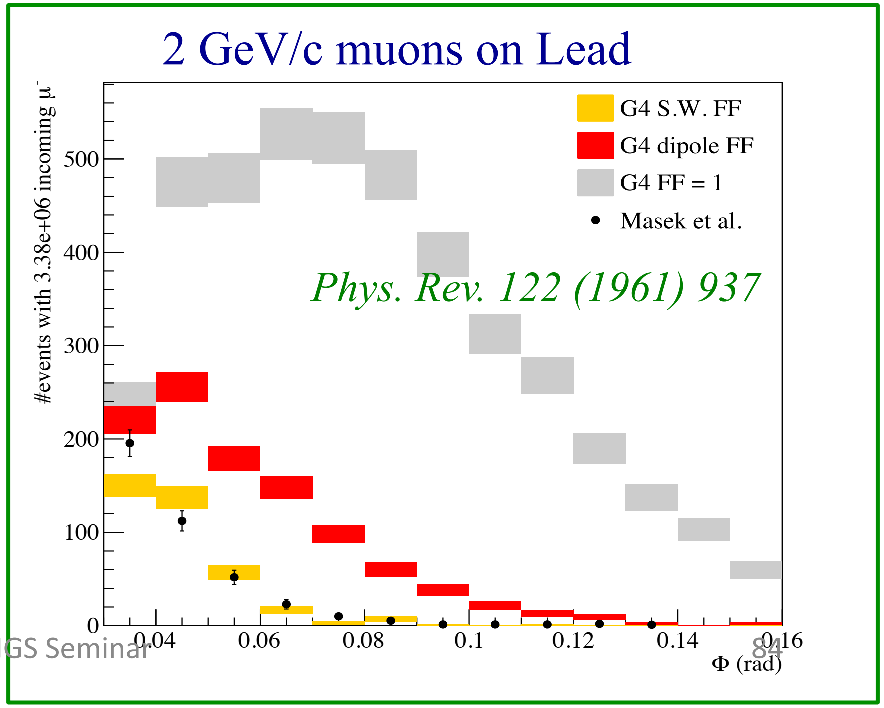


MC predictions compared to available data

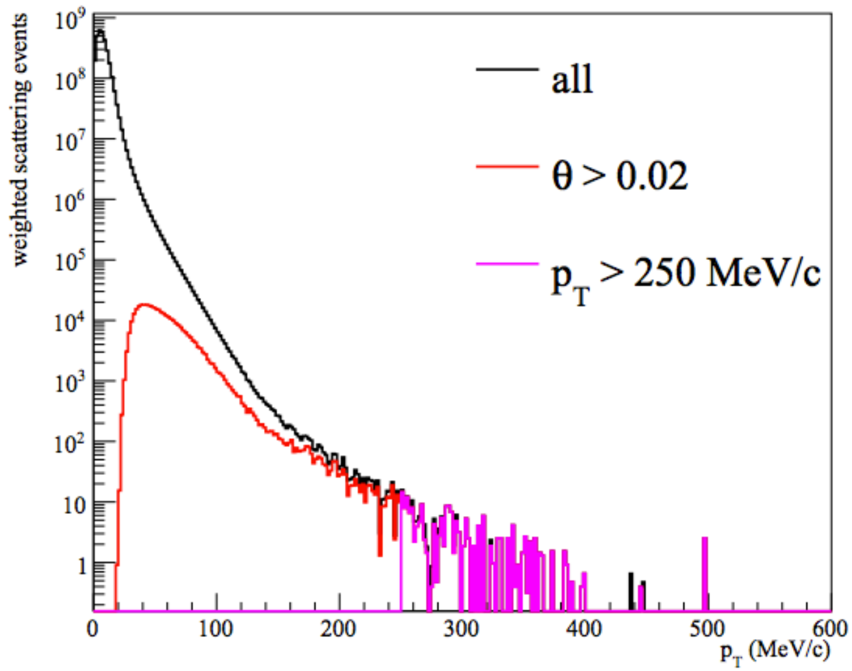
7.3 GeV/c muons on Copper



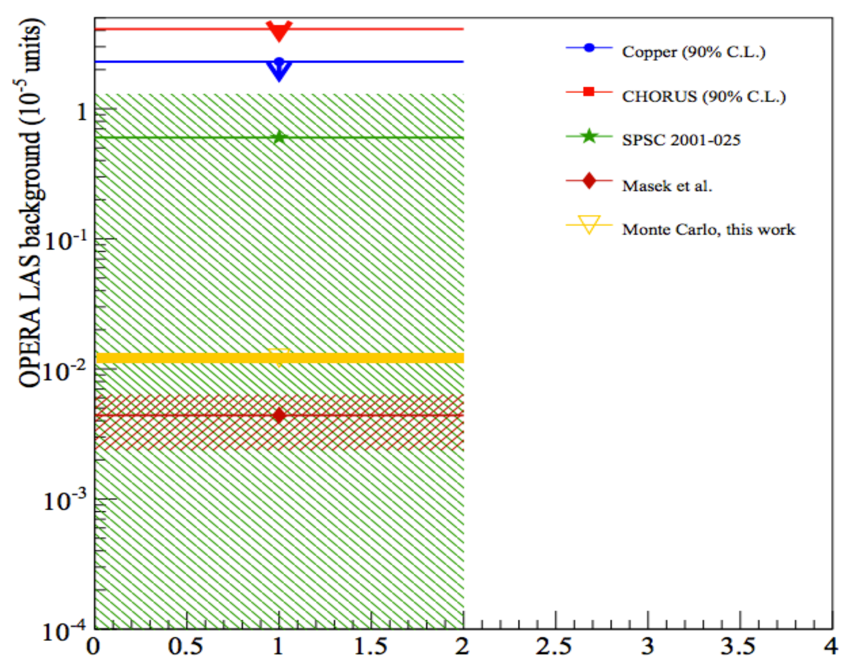


LARGE ANGLE μ SCATTERING

CNGS ν_μ CC muons on Lead $1 < p_\mu < 15$ GeV/c



Main background in the τ →μ decay channel when using upper limits in the past



LAS background estimation

$$(1.2 \pm 0.1) \times 10^{-7}/\nu_\mu^{CC}$$

well below the values considered so far

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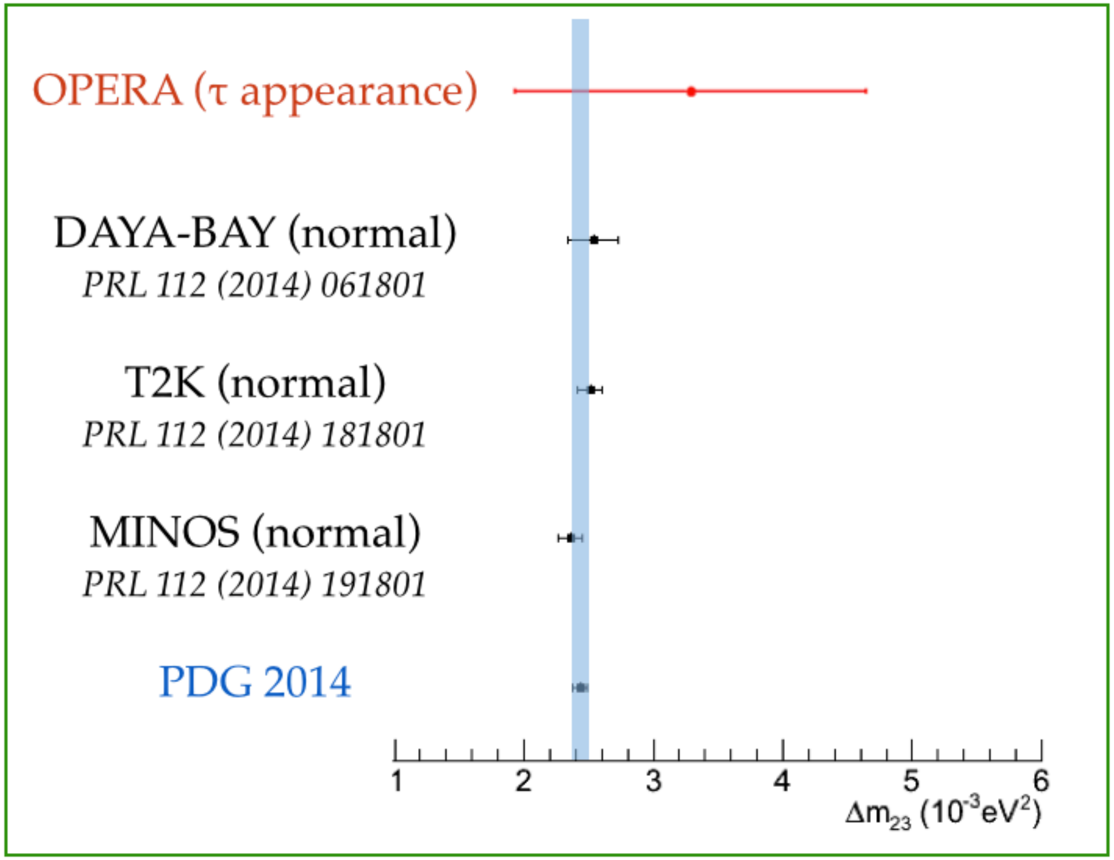
Final Results

Δm^2_{23} ESTIMATION

90% C.L. intervals on Δm^2_{23} by Feldman & Cousins method
$[2.0 – 4.7] \times 10^{-3}$ eV^2
(assuming full mixing)



Statistical Considerations

Channel	Expected background				Expected signal	Observed
	Charm	Had. re-interac.	Large μ-scat.	Total		
$\tau \to 1h$	0.017 ± 0.003	0.022 ± 0.006	–	0.04 ± 0.01	0.52 ± 0.10	3
$\tau \to 3h$	0.17 ± 0.03	0.003 ± 0.001	–	0.17 ± 0.03	0.73 ± 0.14	1
$\tau \to \mu$	0.004 ± 0.001	–	0.0002 ± 0.0001	0.004 ± 0.001	0.61 ± 0.12	1
$\tau \to e$	0.03 ± 0.01	–	–	0.03 ± 0.01	0.78 ± 0.16	0
Total	0.22 ± 0.04	0.02 ± 0.01	0.0002 ± 0.0001	0.25 ± 0.05	2.64 ± 0.53	5

$$\Delta m^2 = 2.44 \cdot 10^{-3}\ \mathrm{eV}^2$$

Two statistical methods:

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

5 observed events with 0.25 background events expected

Probability to be explained by background $\begin{cases} \text{Fisher} = 1.10 \times 10^{-7} \\ \text{Profile likelihood} = 1.07 \times 10^{-7} \end{cases}$

This corresponds to 5.1 σ significance of non-null observation

$$P(n \geq 5 \mid \mu = 2.9) = 16.6\ \%$$
$$P^{\dagger} = 6.4\%$$

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

Discovery of ν_τ Appearance In The CNGS Neutrino BEAM

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

Outlook

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

ACKNOWLEDGEMENTS

The OPERA Collaboration is very much indebted to:

- The LNGS/INFN hosting laboratory
- CERN and the CNGS beam team
- Funding agencies
- All industrial partners and suppliers
- Our technical collaborators, engineers and undergraduate students

THANK YOU FOR YOUR ATTENTION