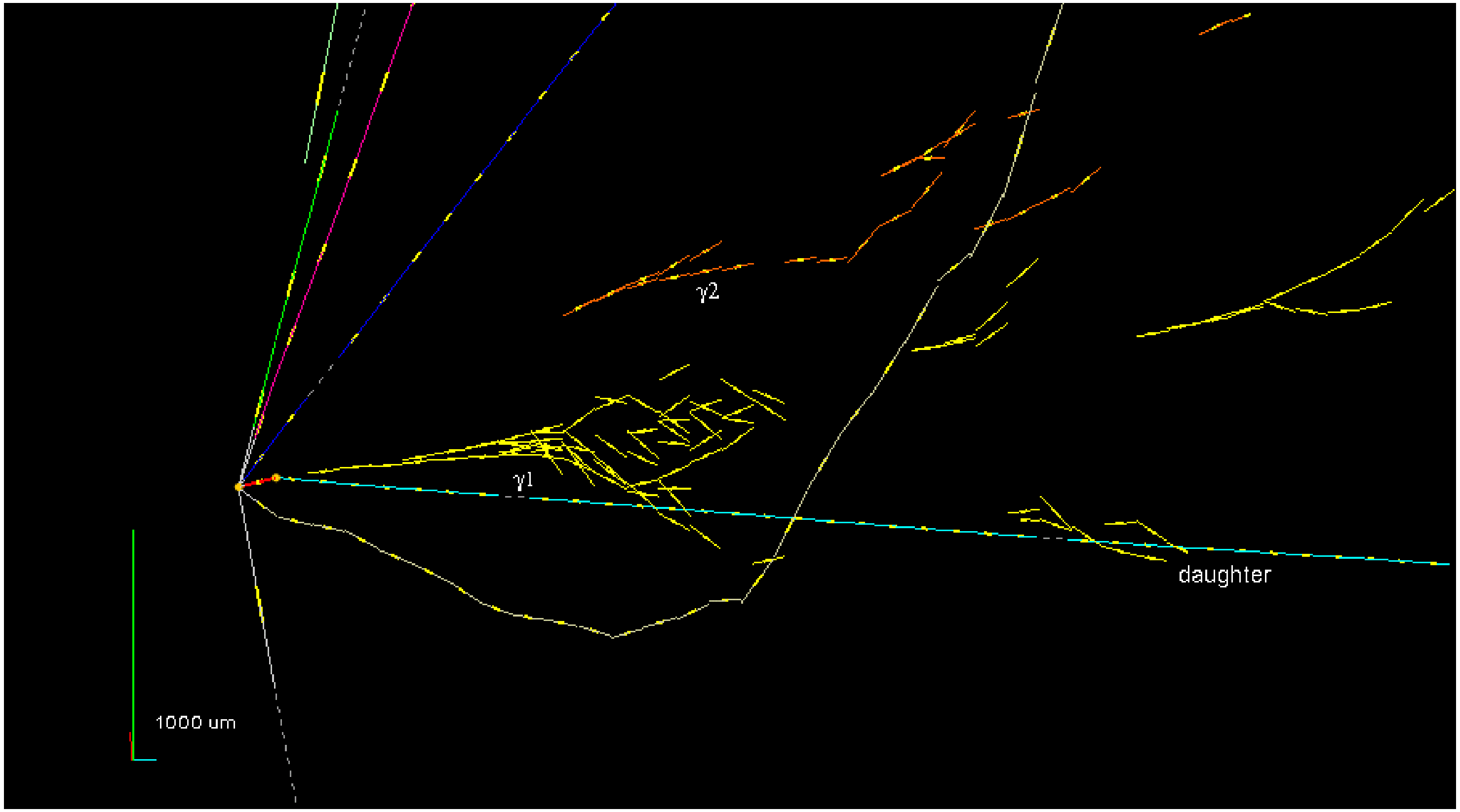
# Results of the OPERA experiment

*Giovanni De Lellis*

*University "Federico II" and INFN Napoli*

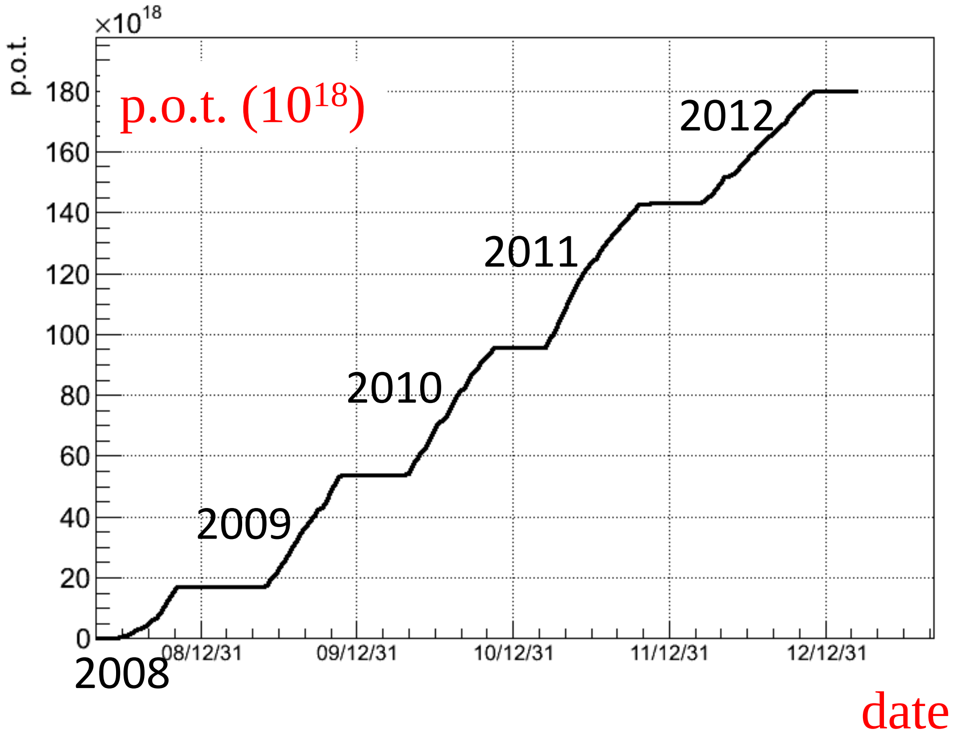
*On behalf of the OPERA Collaboration*

*For the 118$^{th}$ Meeting of the SPSC Committee*



# 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** |

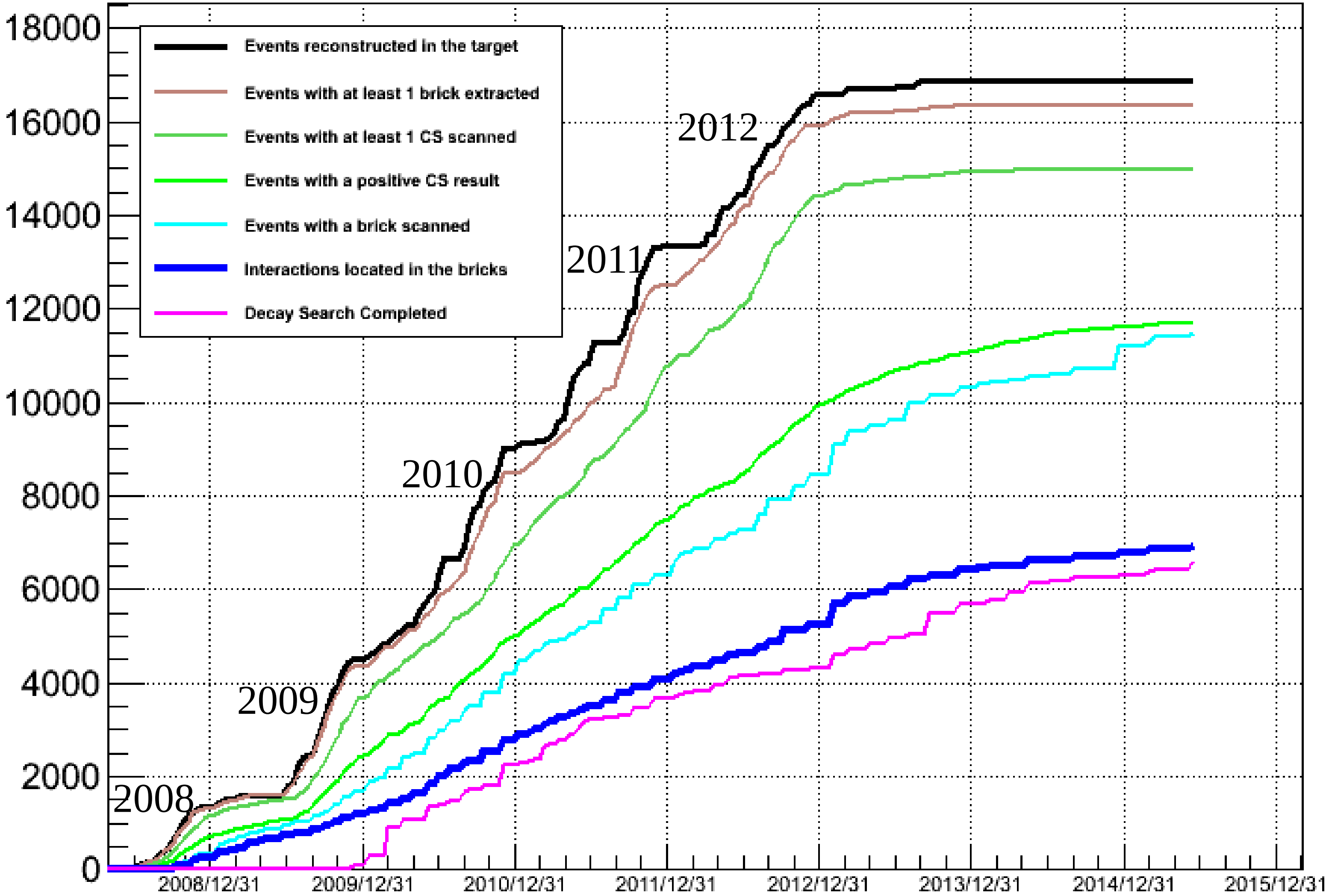



Record performances in 2011

Overall 20% less than the proposal value (22.5)

Last neutrino interaction recorded on December 3rd 2012

# Status Of Data Analysis



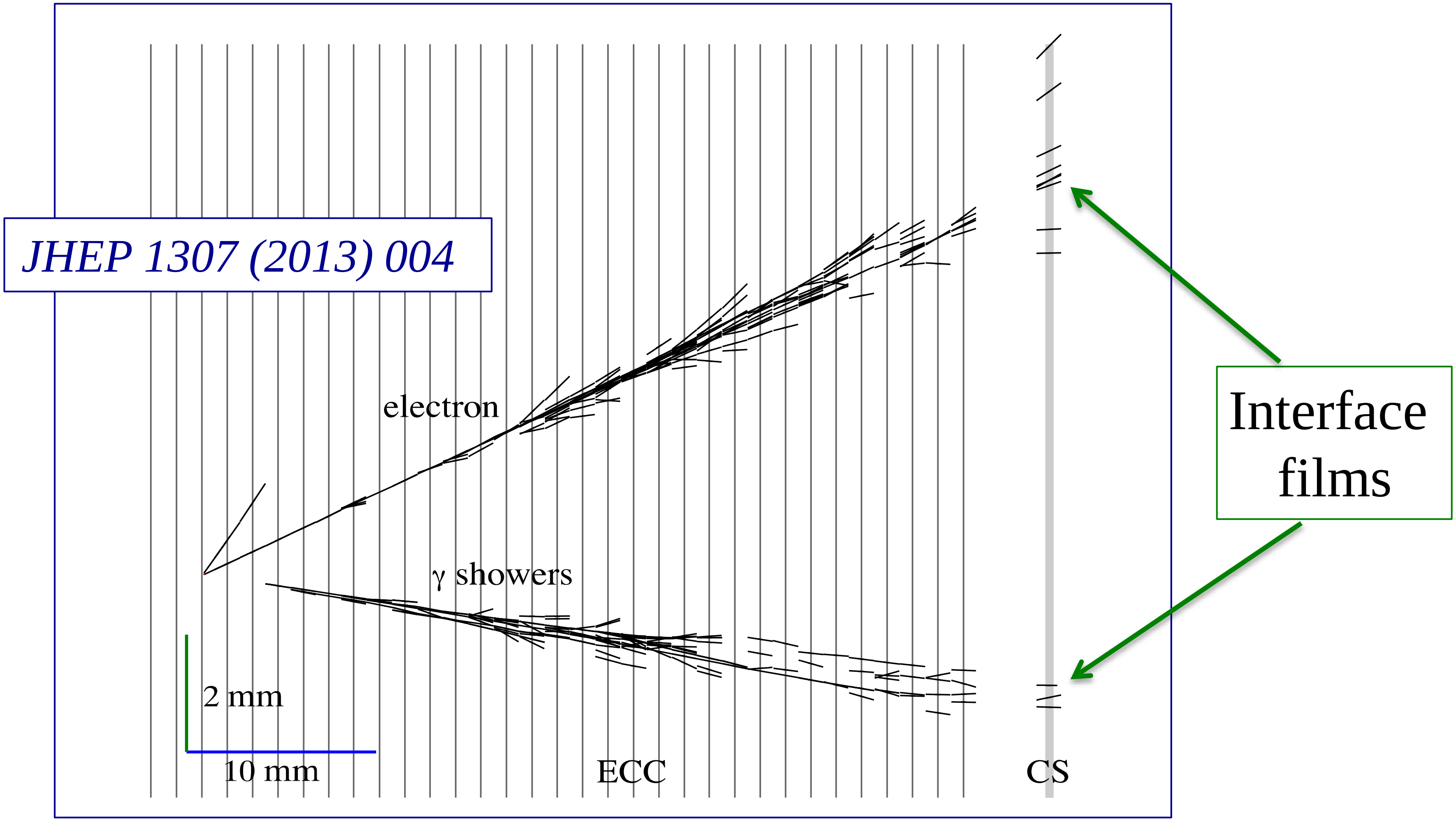

6932 located interactions

6612 decay search

# Oscillation physics

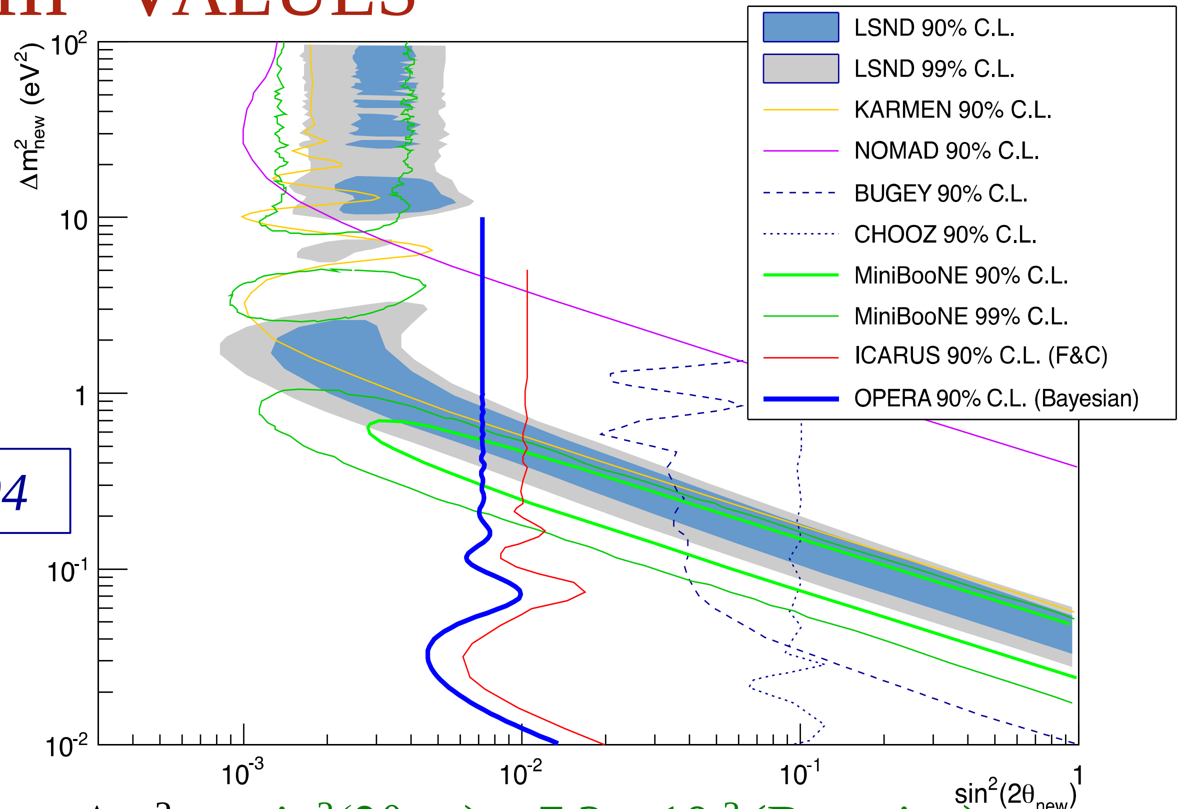
# $\nu_M \to \nu_e$ Analysis with 2008/2009 data

one of the $\nu_e$ events with a $\pi^0$ as seen in the brick




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

# Search For Non-Standard Oscillations At Large $\Delta m^2$ Values




*JHEP 1307 (2013) 004*

Caveat: experiments at different L/E

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

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

Current sample extended with more than twice candidates:

So far 50 observed candidates

10 with E < 20 GeV

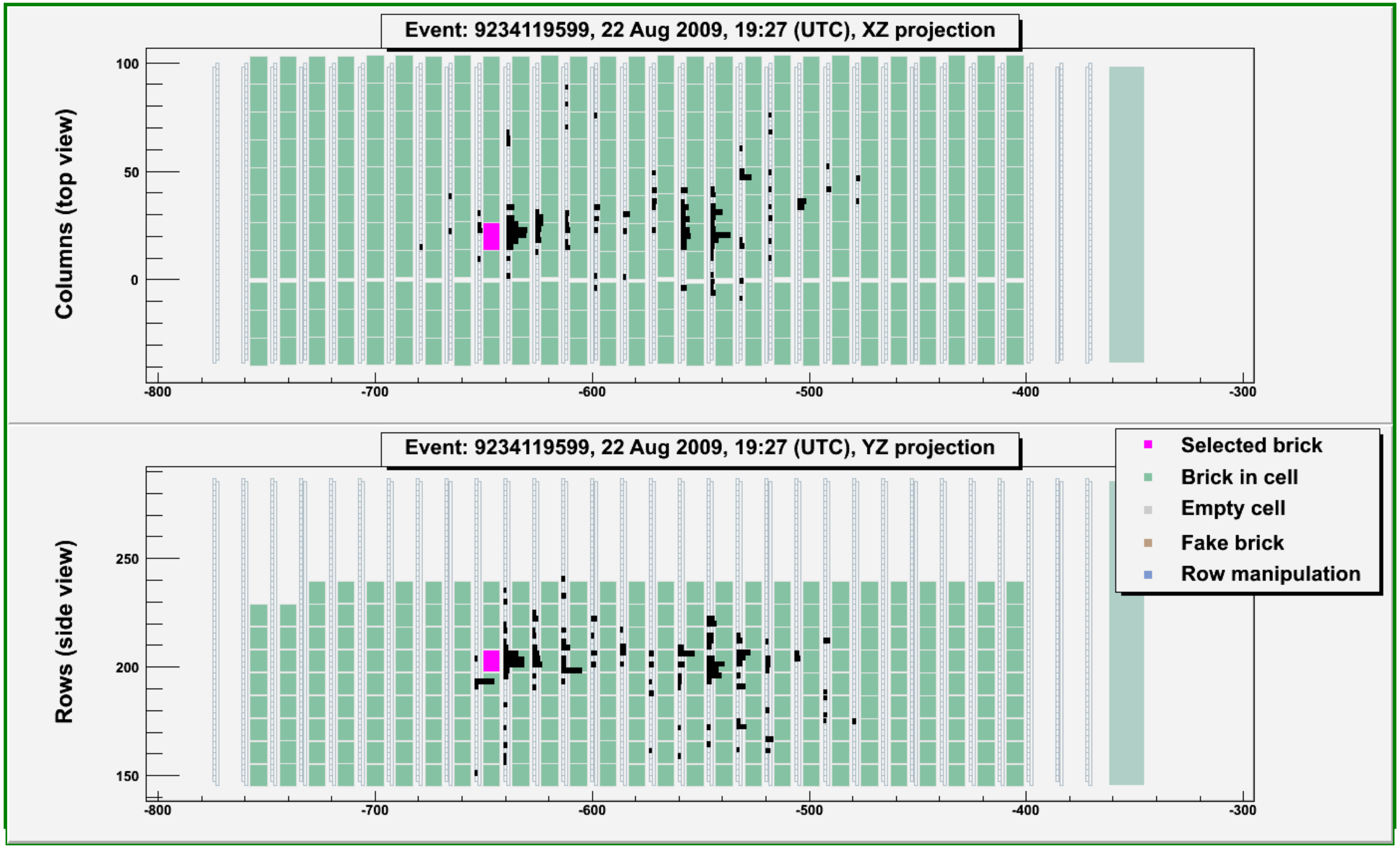
New paper in preparation

# $\nu_M \rightarrow \nu_\tau$ 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 $\nu_\tau$ Candidate

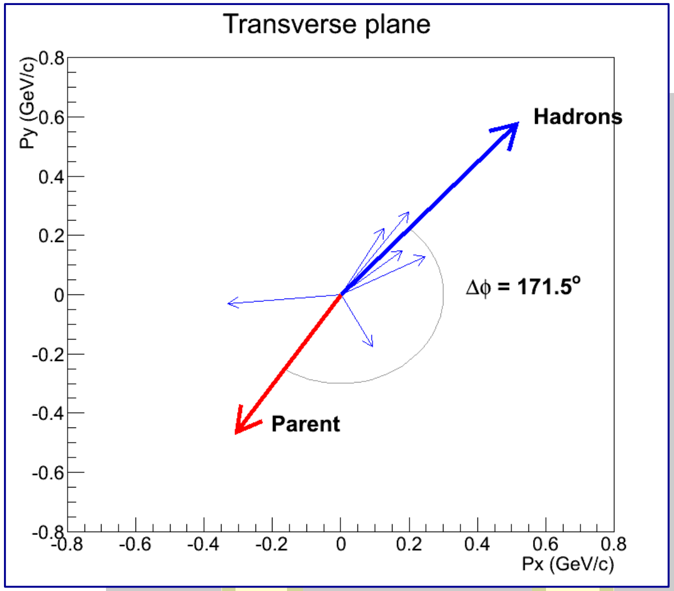
As seen by the electronic detectors …

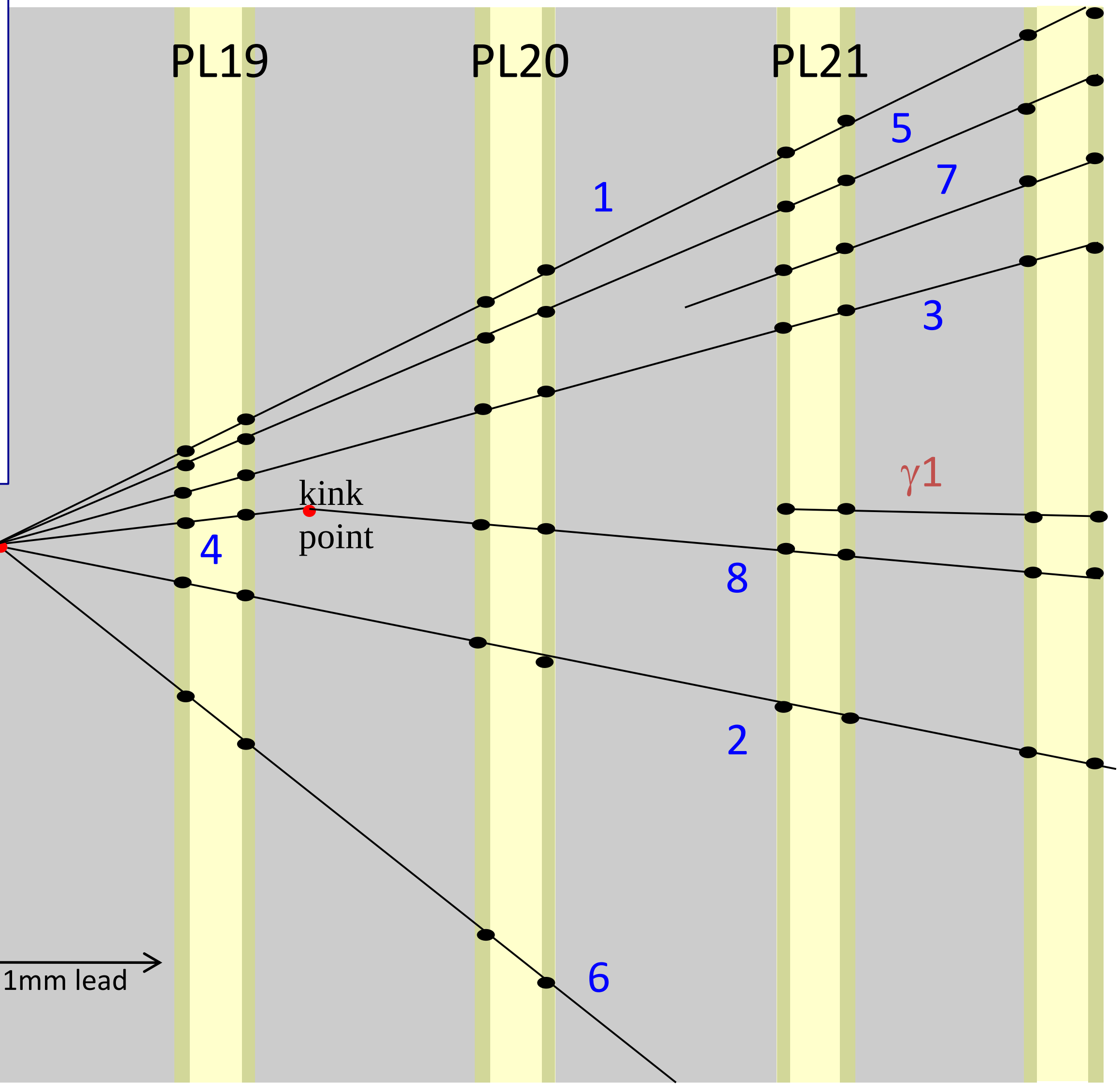



*Physics Letters B691 (2010) 138*

# THE FIRST $\nu_\tau$ CANDIDATE

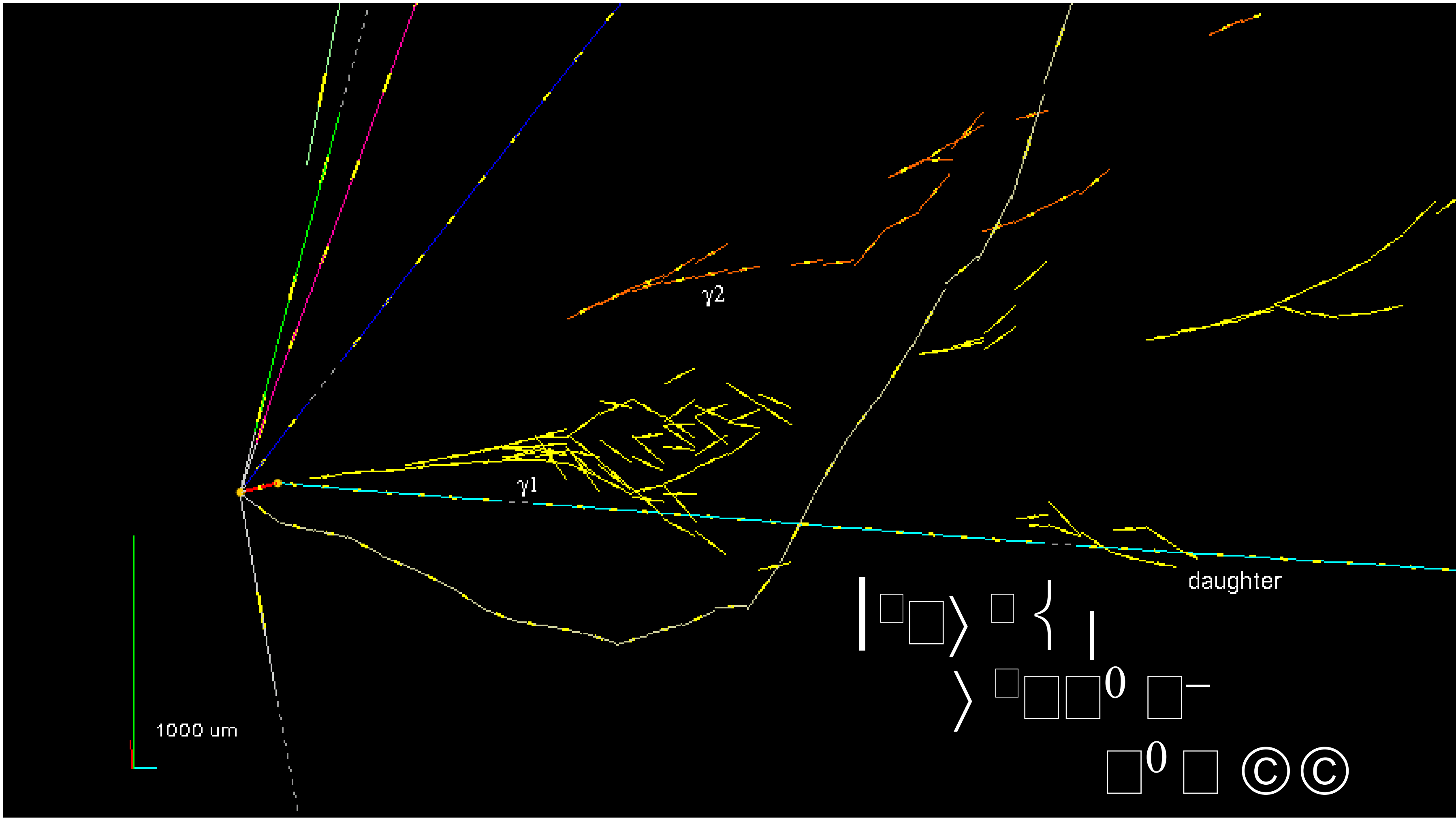
… and in the brick



# The First $\nu_\tau$ Candidate

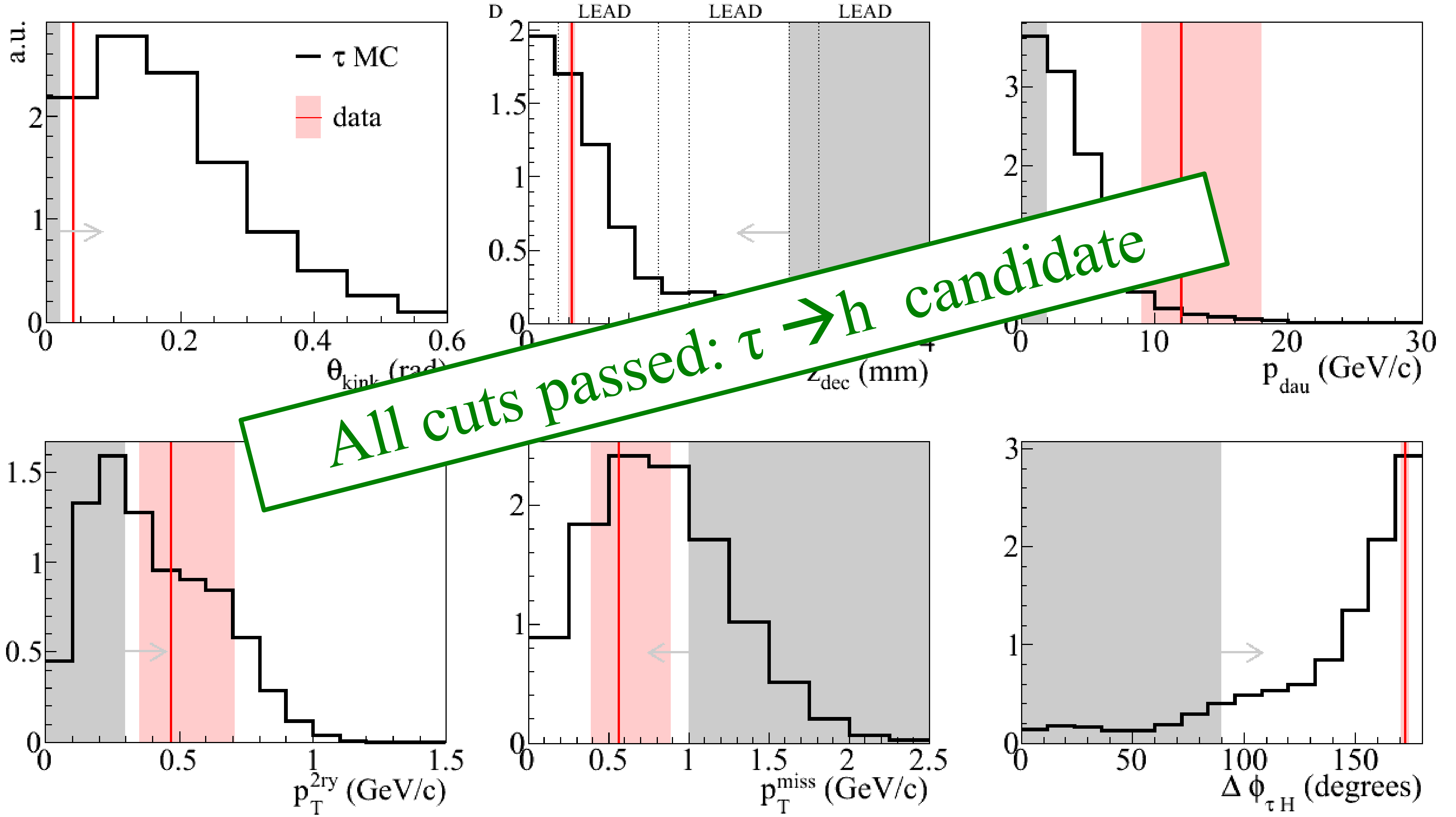
… and in the brick




*Physics Letters B691 (2010) 138*

# The First $\nu_\tau$ Candidate

Kinematical selection

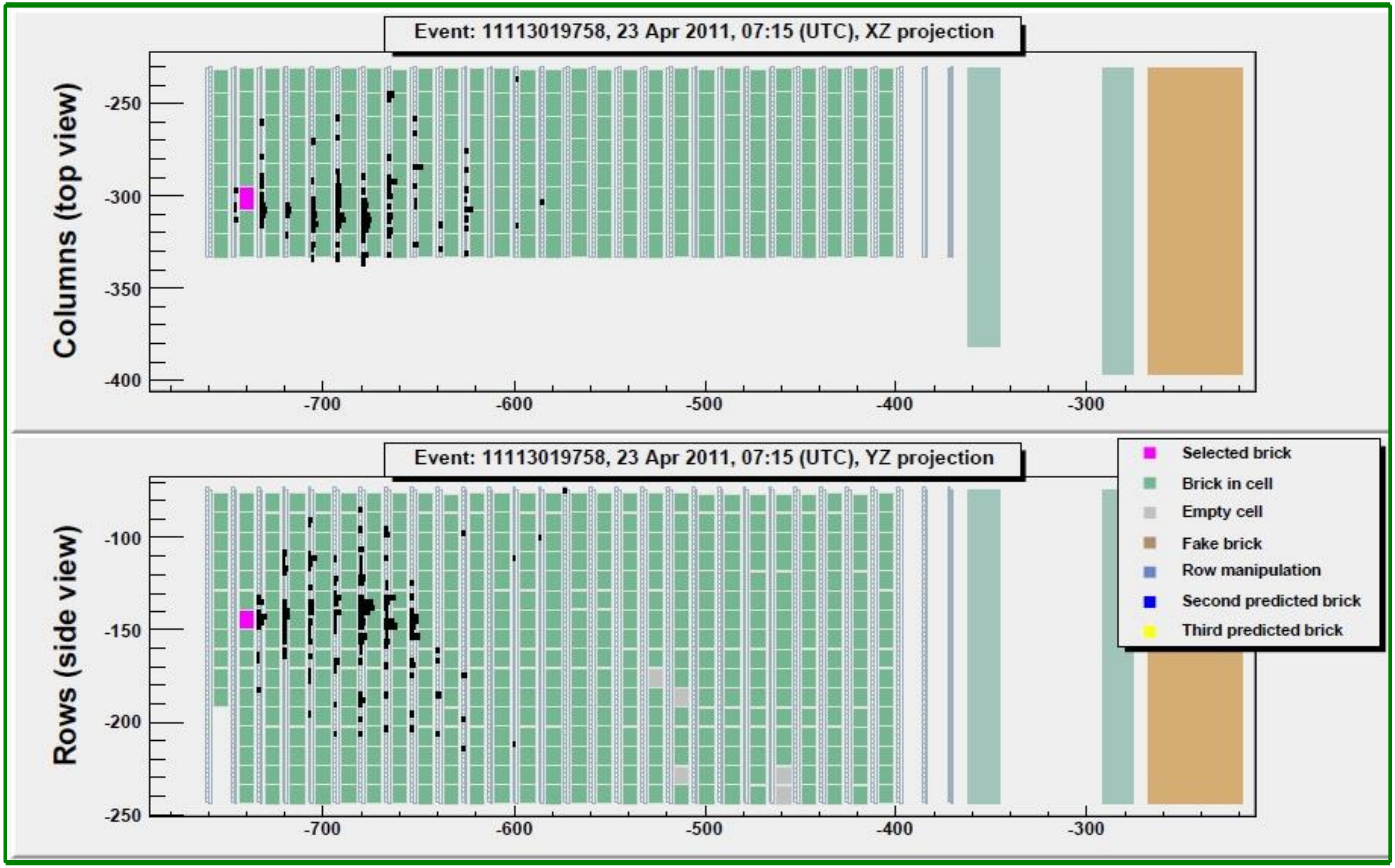





*Physics Letters B691 (2010) 138*

# THE SECOND $\nu_\tau$ CANDIDATE

As seen by the electronic detectors …

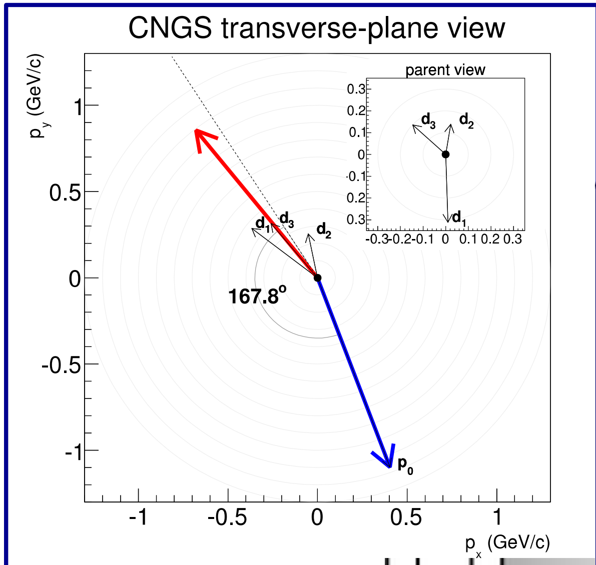


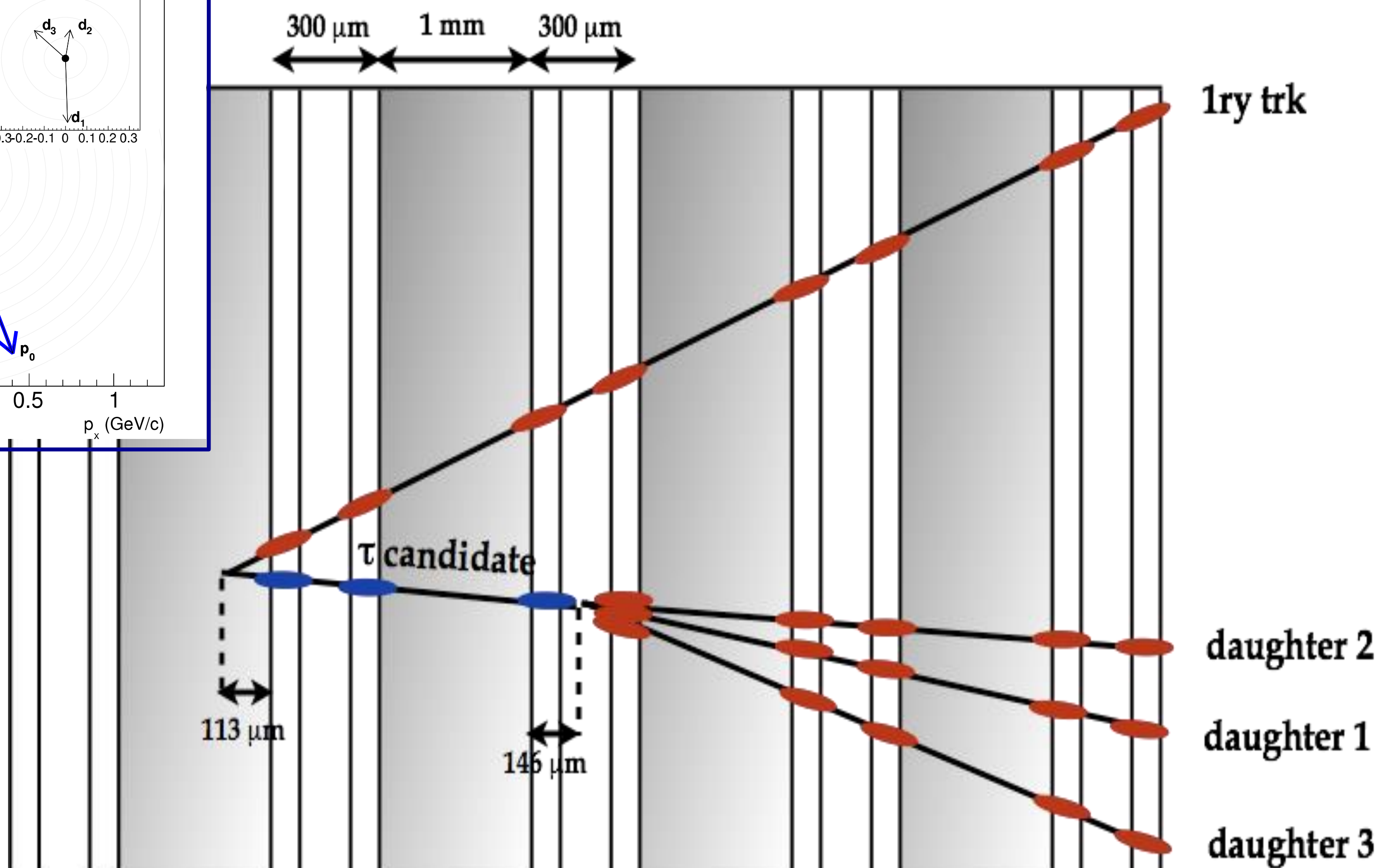



*Journal of High Energy Physics 11 (2013) 036*

# THE SECOND $\nu_\tau$ CANDIDATE

… and in the brick



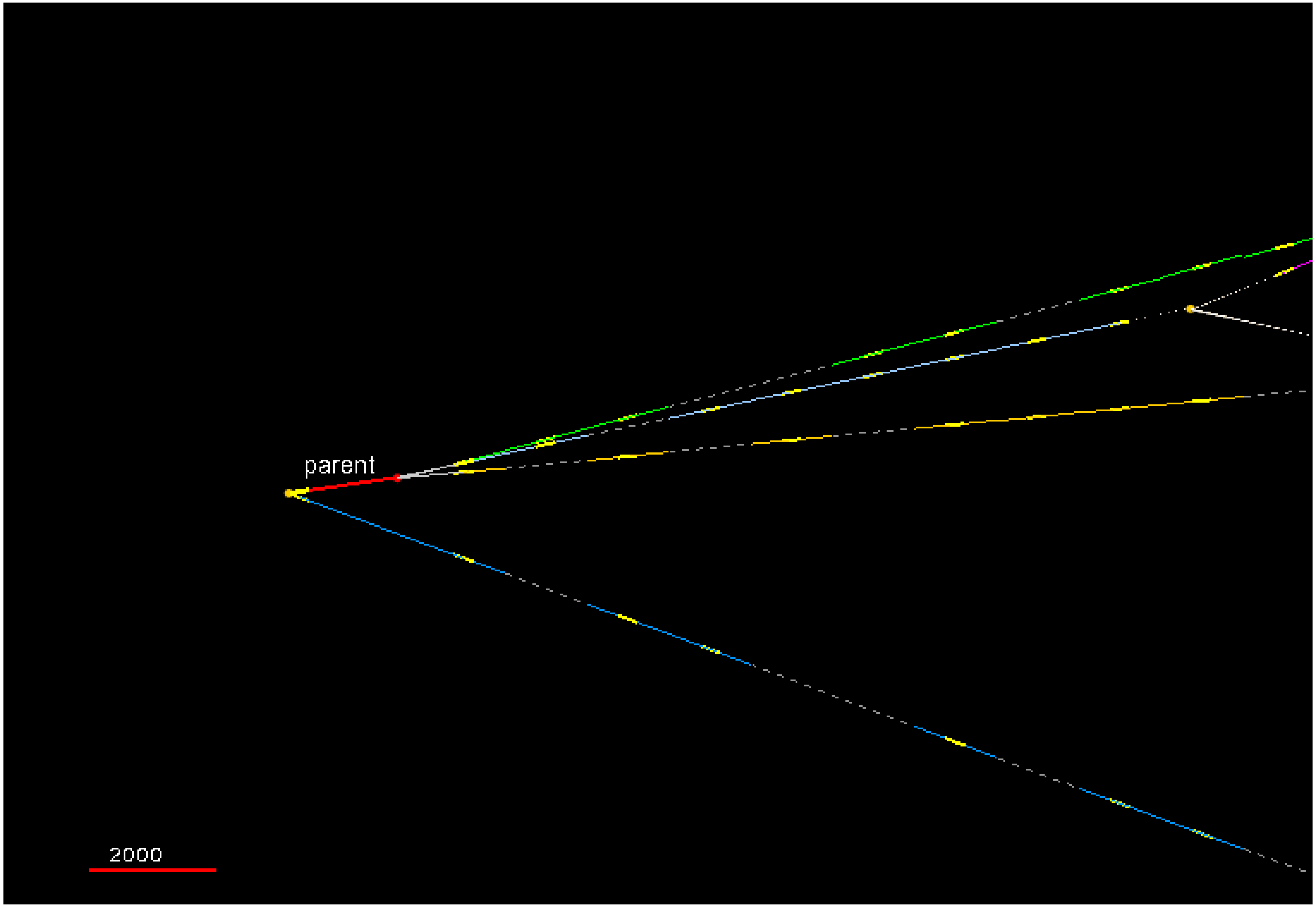






*Journal of High Energy Physics 11 (2013) 036*

# The Second $\nu_\tau$ Candidate

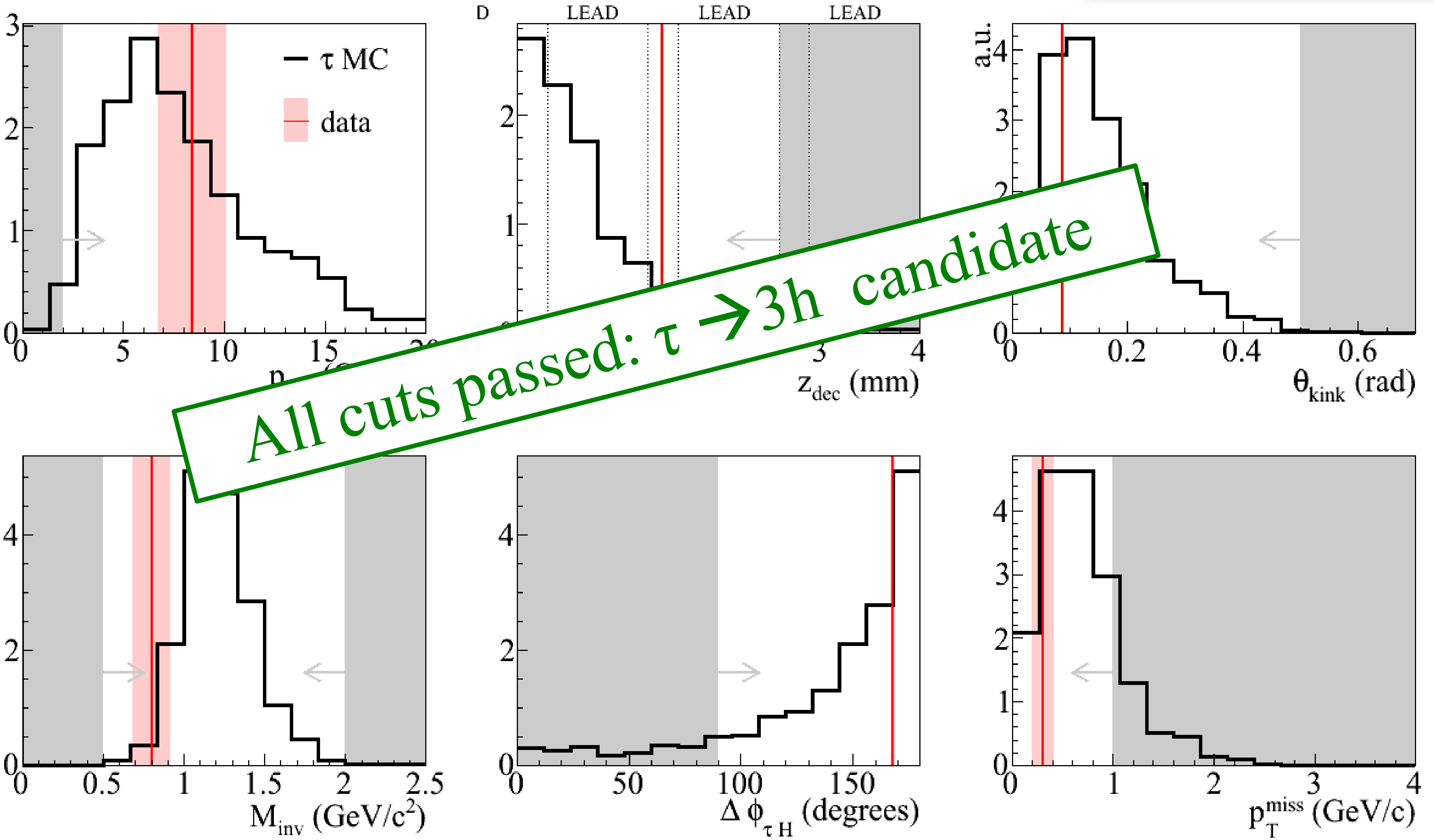
… and in the brick




Journal of High Energy Physics 11 (2013) 036

# THE SECOND $\nu_\tau$ CANDIDATE

Kinematical selection

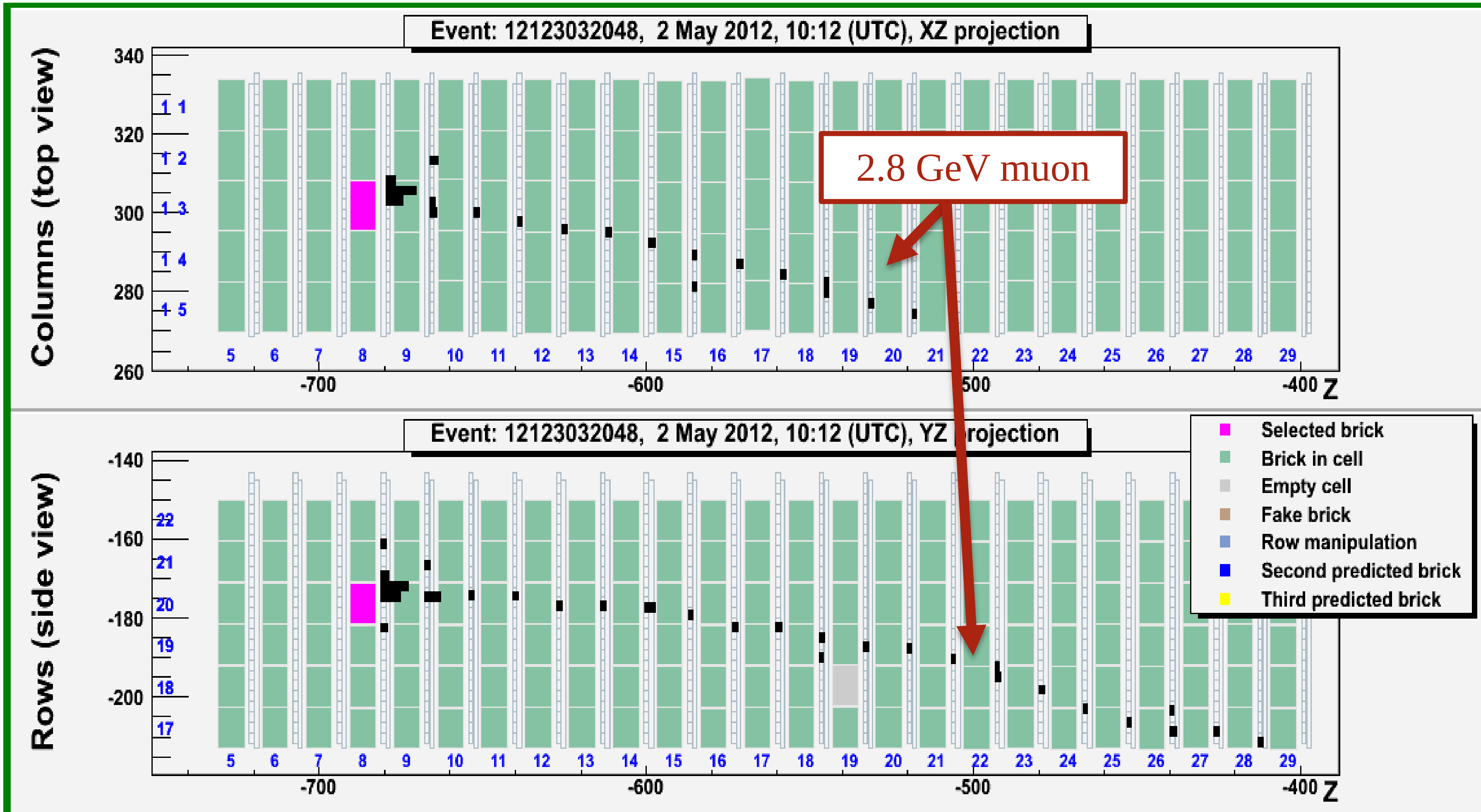





*Journal of High Energy Physics 11 (2013) 036*

# THE THIRD $\nu_\tau$ CANDIDATE

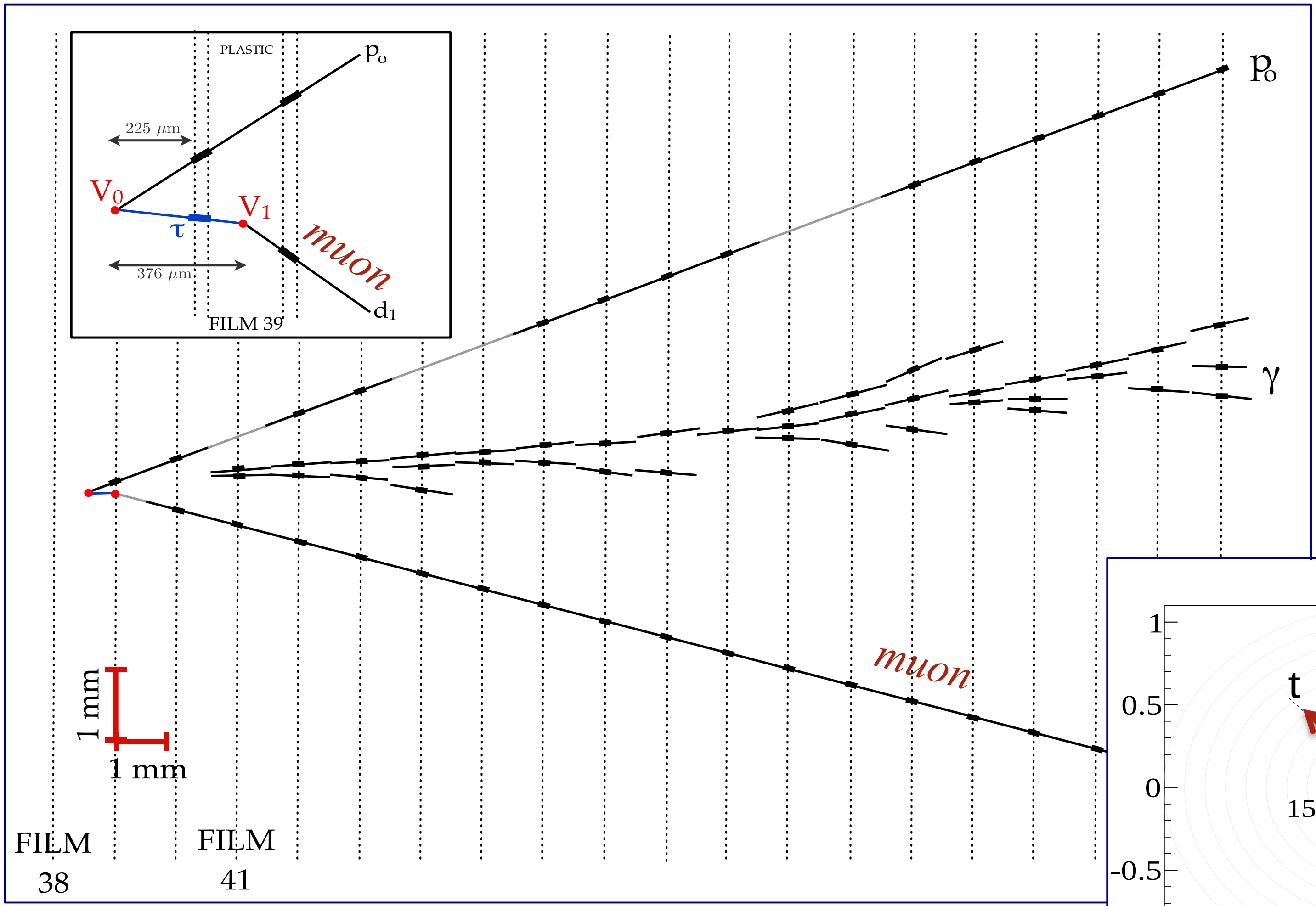
As seen by the electronic detectors …

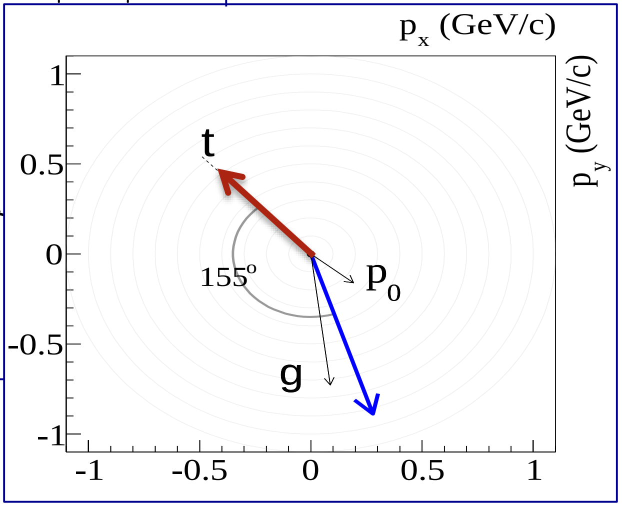



*Phys. Rev. D 89 (2014) 051102(R)*

# THE THIRD $\nu_\tau$ CANDIDATE

… and in the brick

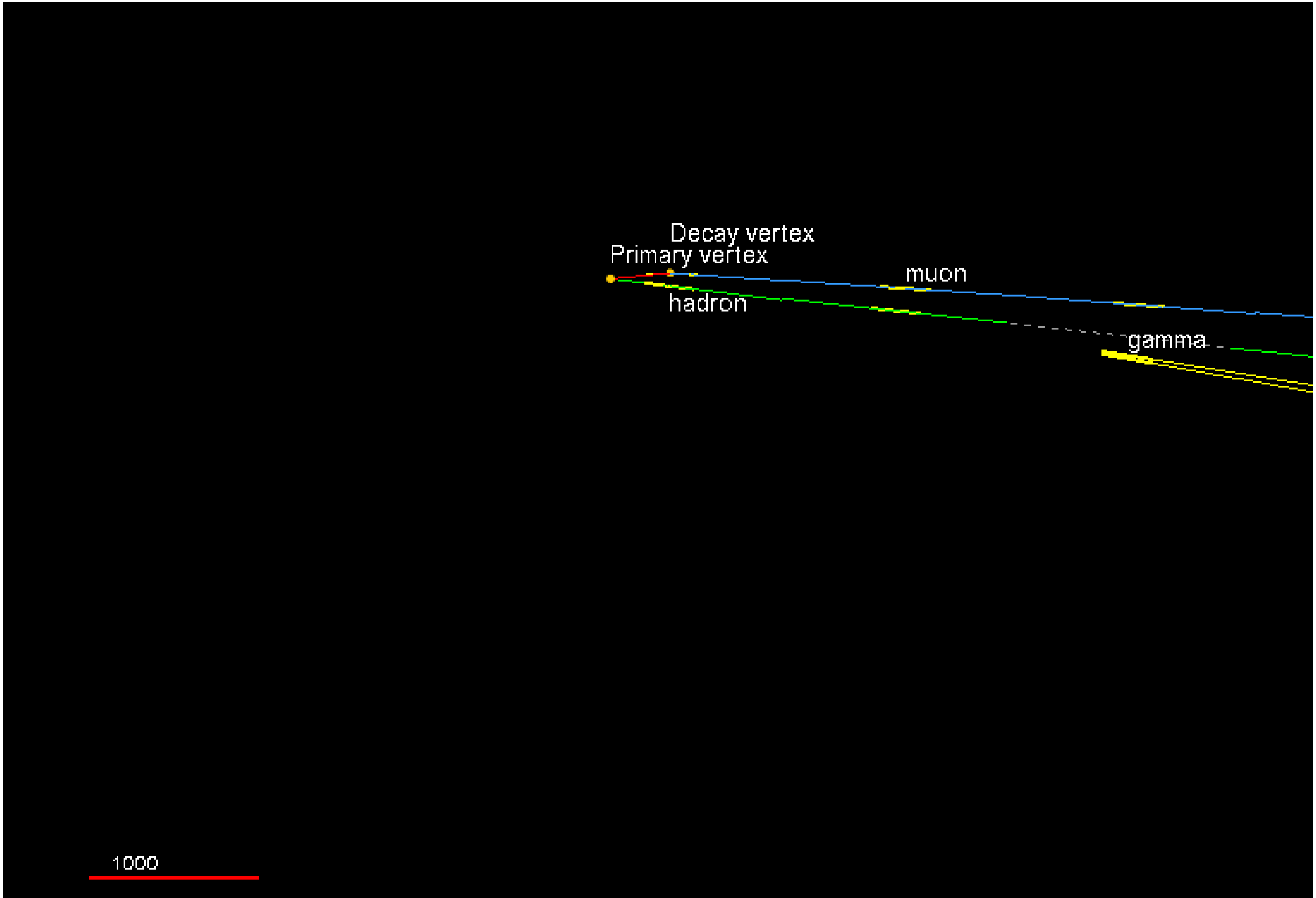


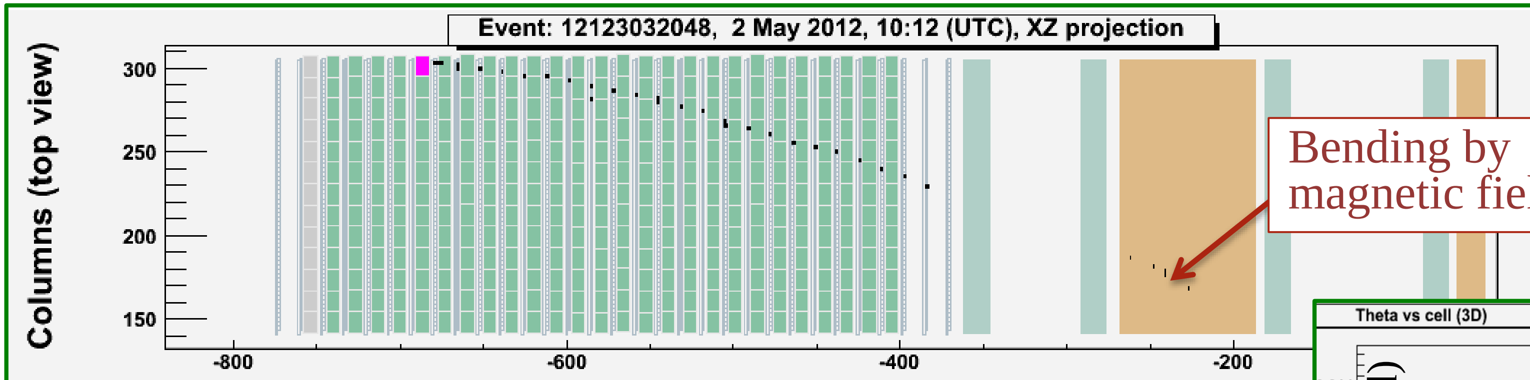

*Phys. Rev. D 89 (2014) 051102(R)*

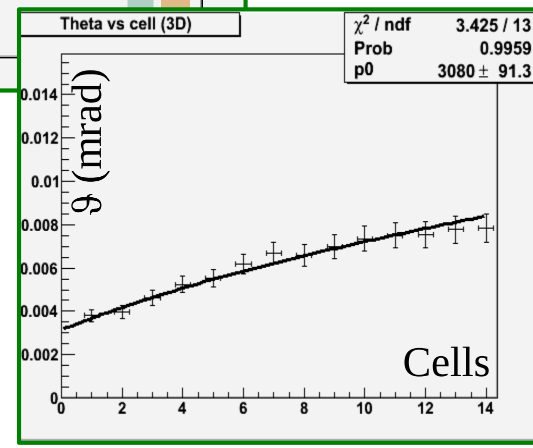
# THE THIRD $\nu_\tau$ CANDIDATE

… and in the brick



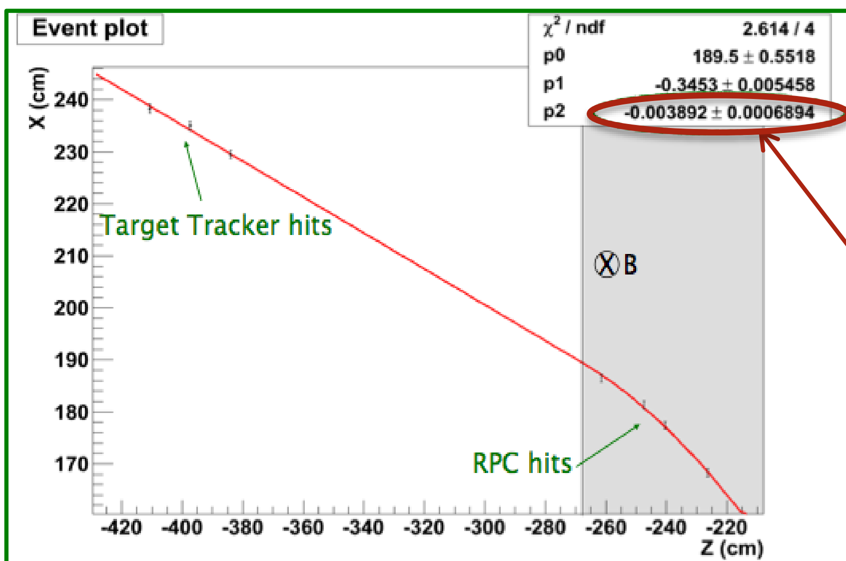
# MUON CHARGE AND MOMENTUM




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

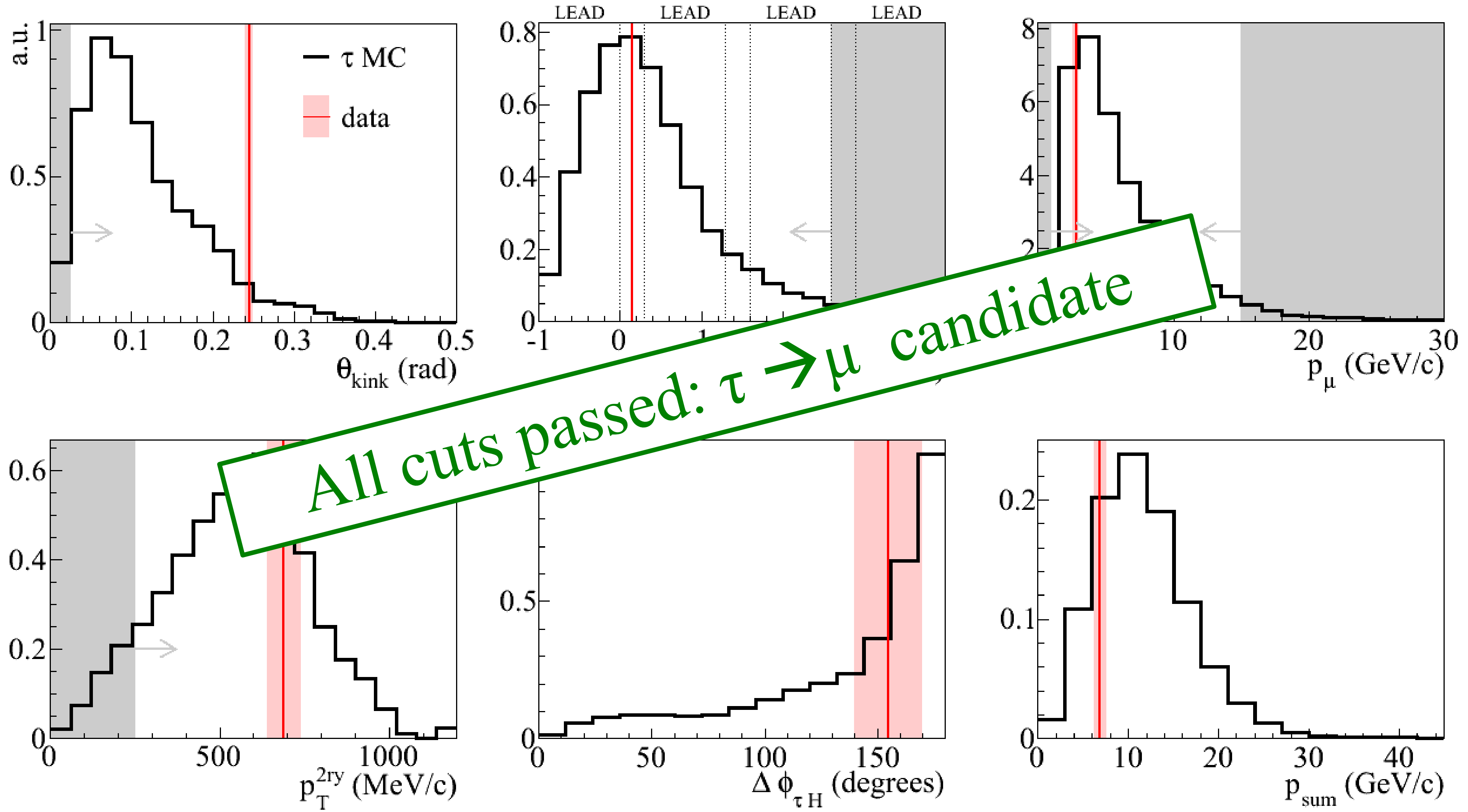



- Parabolic fit with $p_2$ as quadratic term coefficient in the magnetized region
- Linear fit in the non-magnetized region

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

# The Third $\nu_\tau$ Candidate

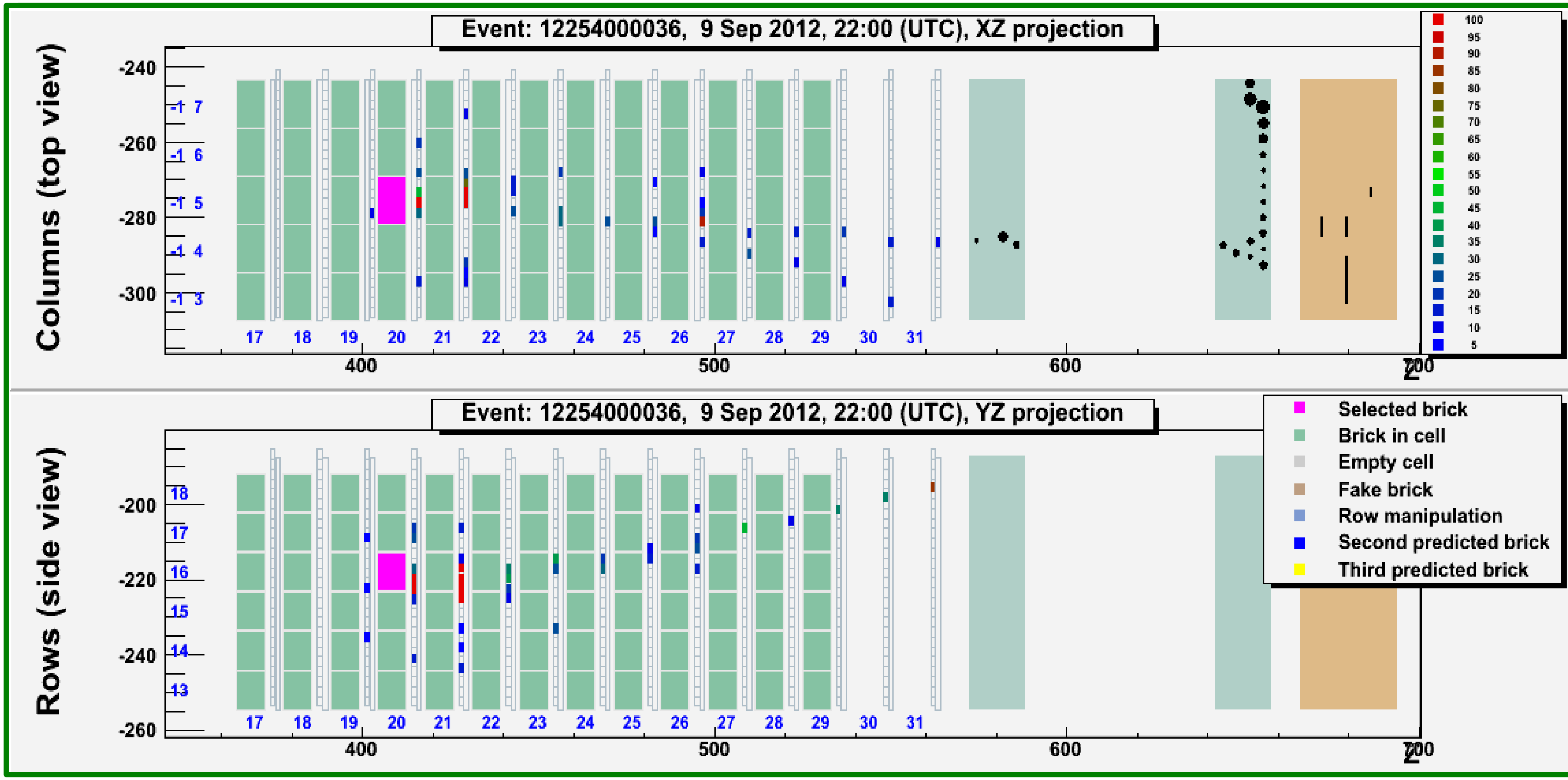
## Kinematical selection




*Phys. Rev. D 89 (2014) 051102(R)*
*Evidence for the $\nu_\tau$ appearance*

# THE FOURTH $\nu_\tau$ CANDIDATE

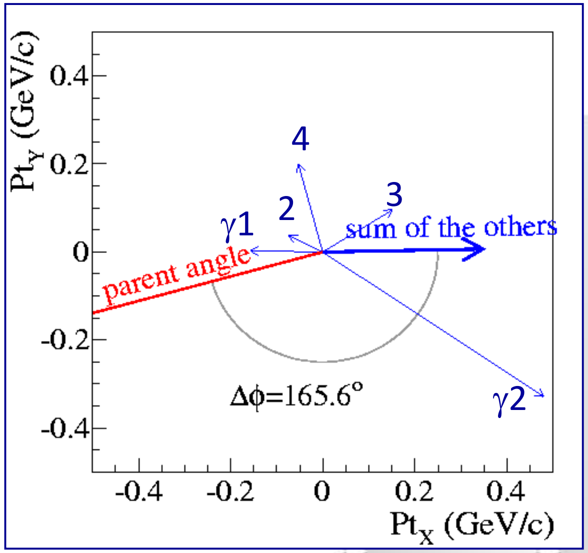
As seen by the electronic detectors …

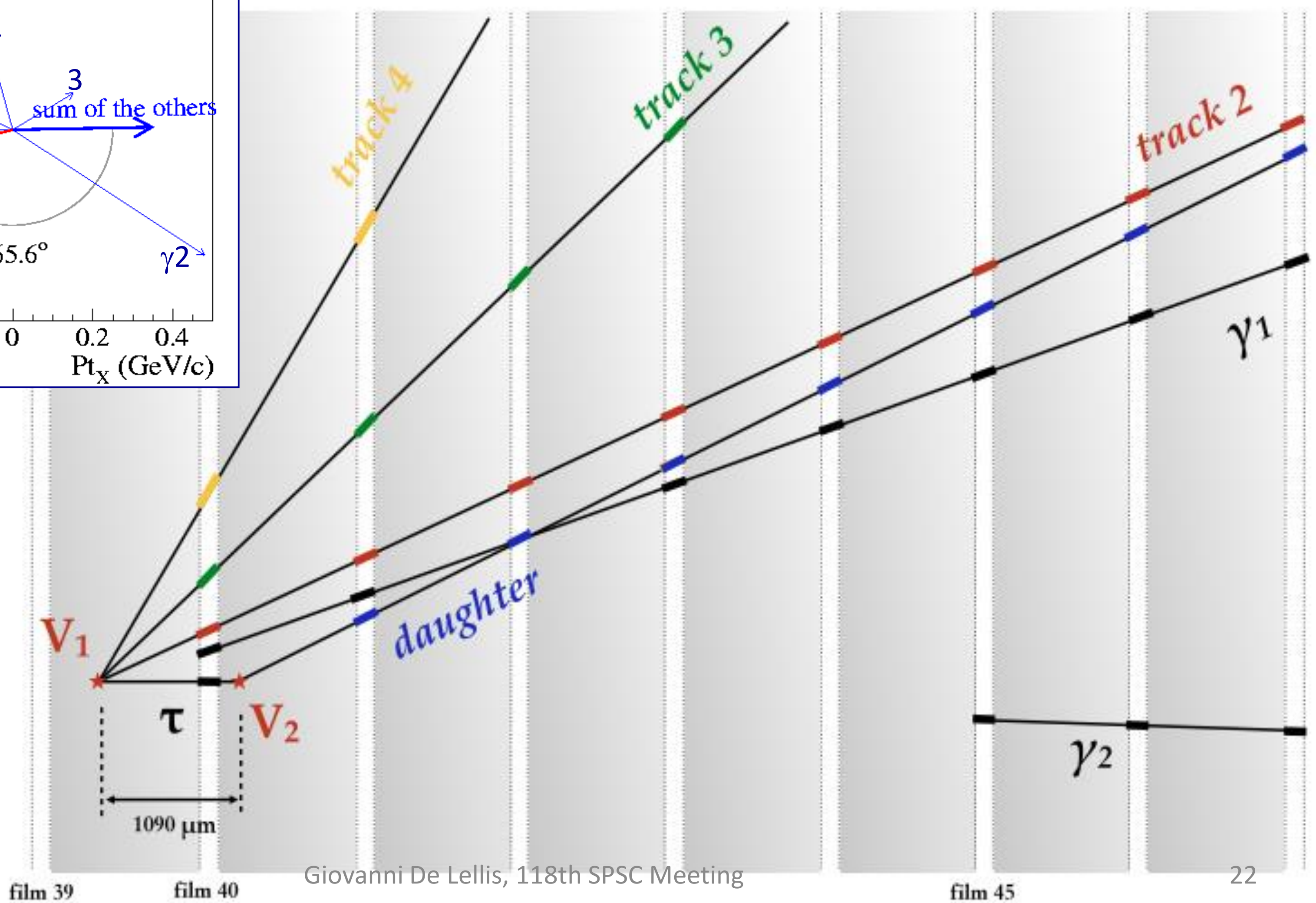



*PTEP 10 (2014) 101C01*

# THE FOURTH $\nu_\tau$ CANDIDATE

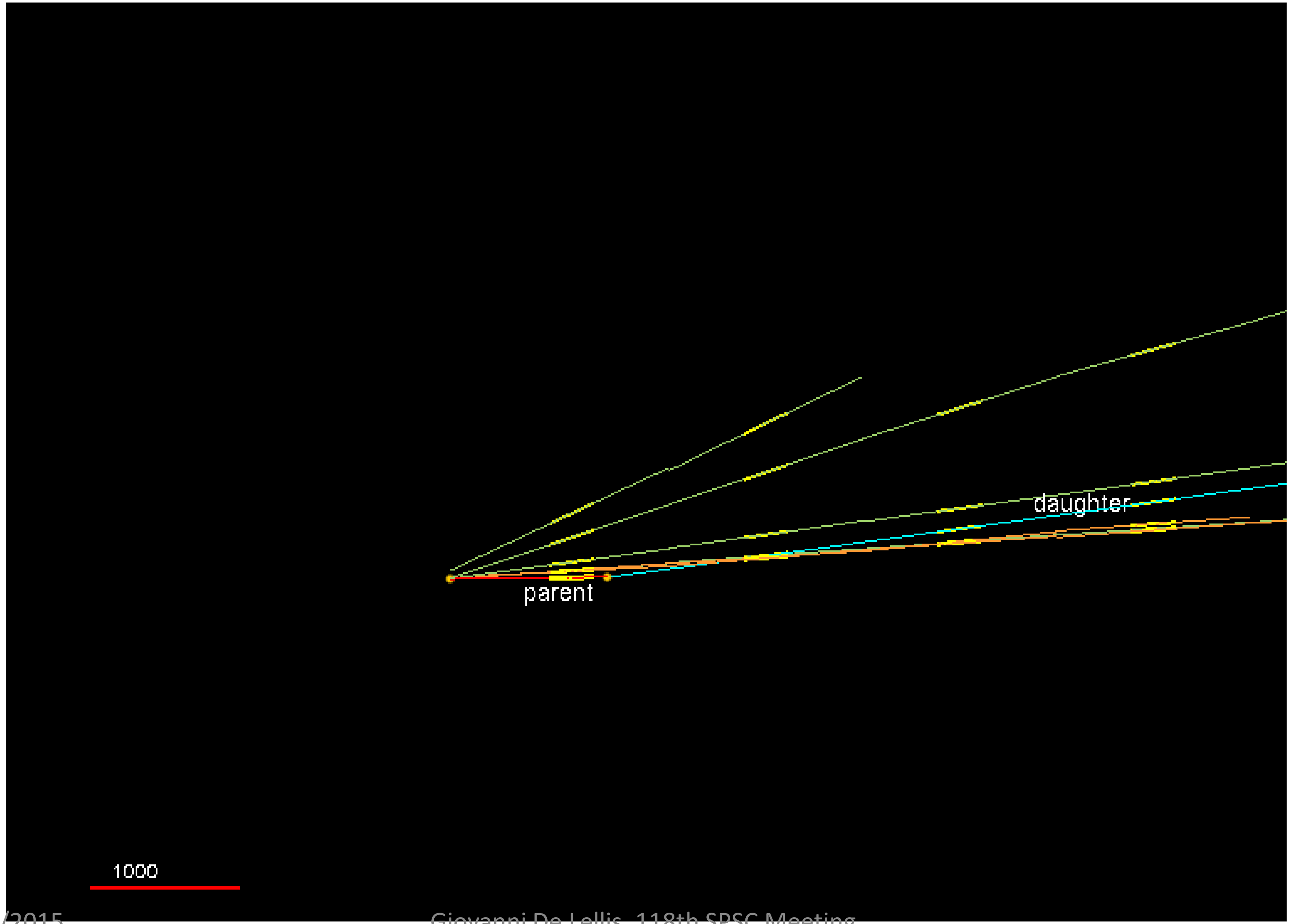
… and in the brick



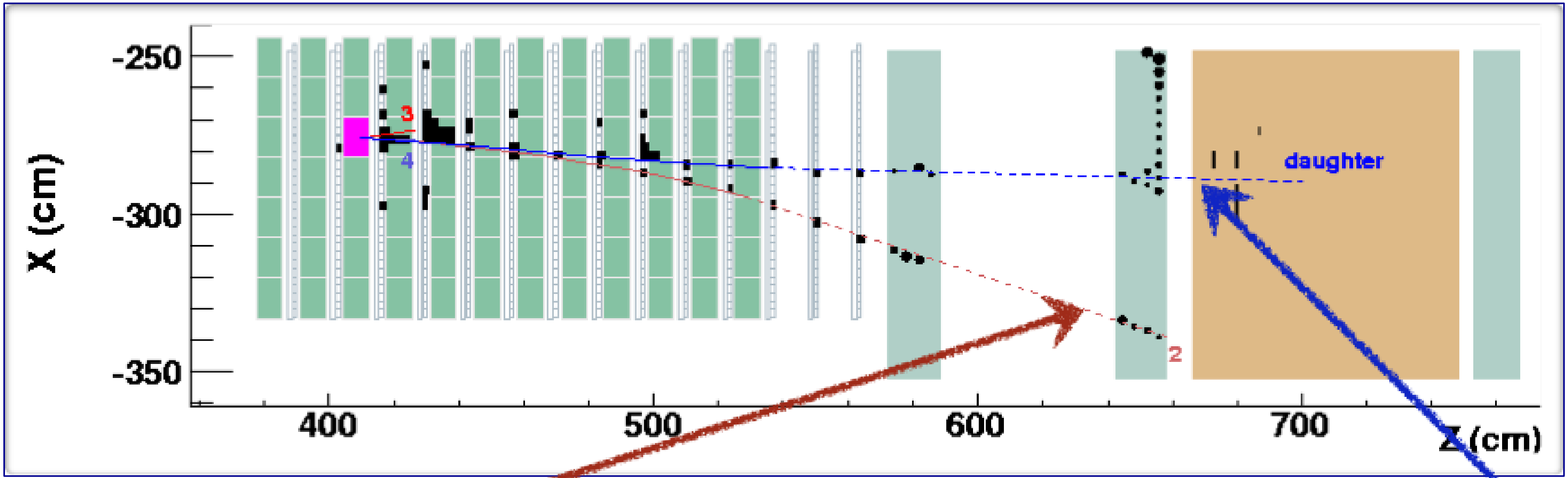
# THE FORTH $\nu_\tau$ CANDIDATE

… and in the brick



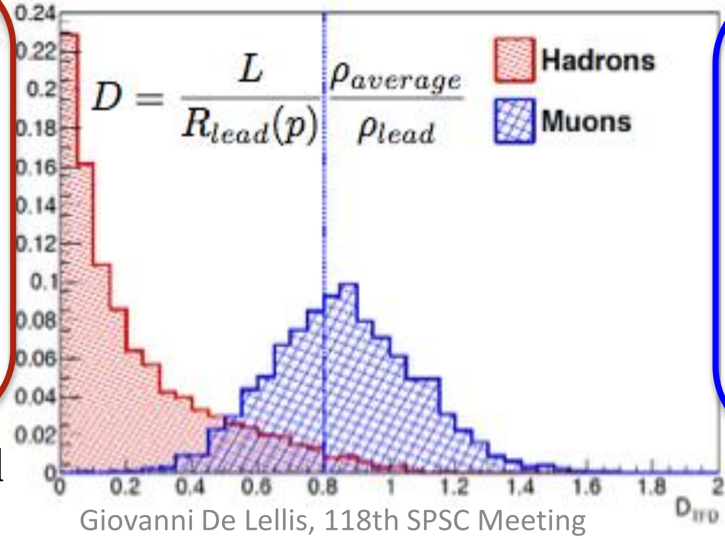
# Particle ID: Track Follow-Down

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**

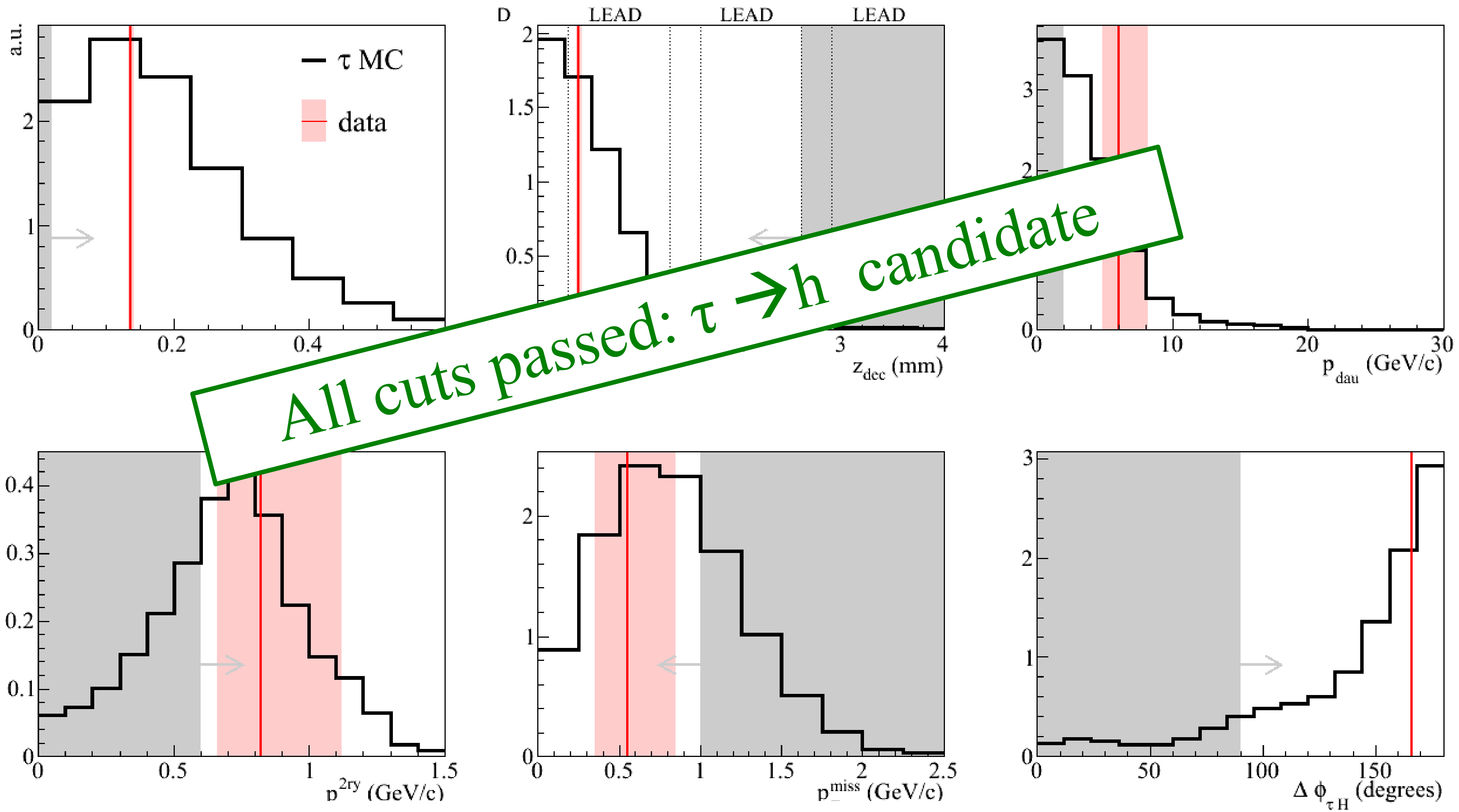
$$D = 0.18 \pm 0.04$$

**Charm background hypothesis rejected**

**Hadronic decay channel**

# THE FOURTH $\nu_\tau$ CANDIDATE

Kinematical variables




*PTEP 10 (2014) 101C01: Observation of $\nu_\tau$ appearance*

# By Product Analysis

# Sterile Neutrinos

**3+1 model:** bounds from $\nu_\tau$ 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 $C^2$*

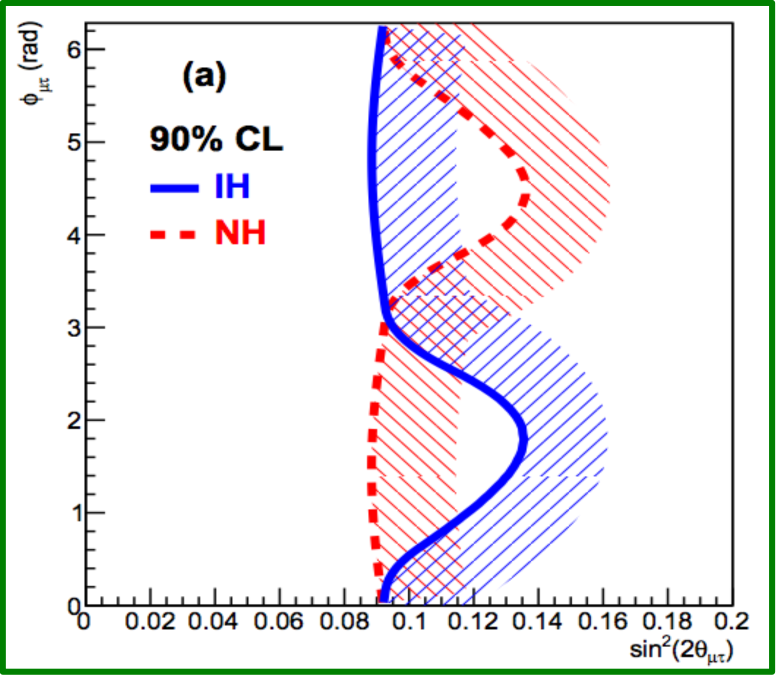
$$\tilde{L}(\phi_{\mu\tau}, sin^2 2\theta_{\mu\tau})$$

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

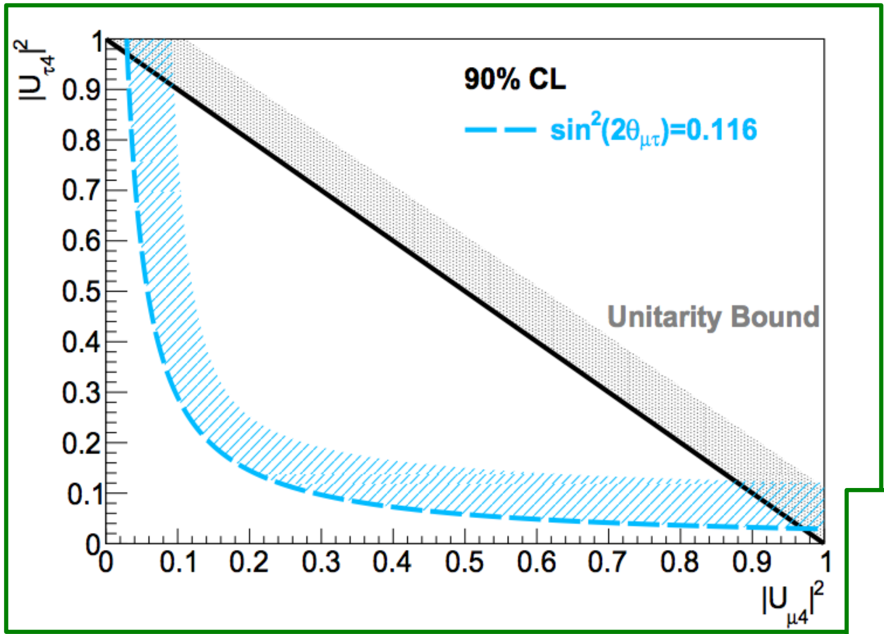
$$C = 2 \mid U_{\mu 3} U^*_{\tau 3} \mid,$$

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

*JHEP 6 (2015) 069*



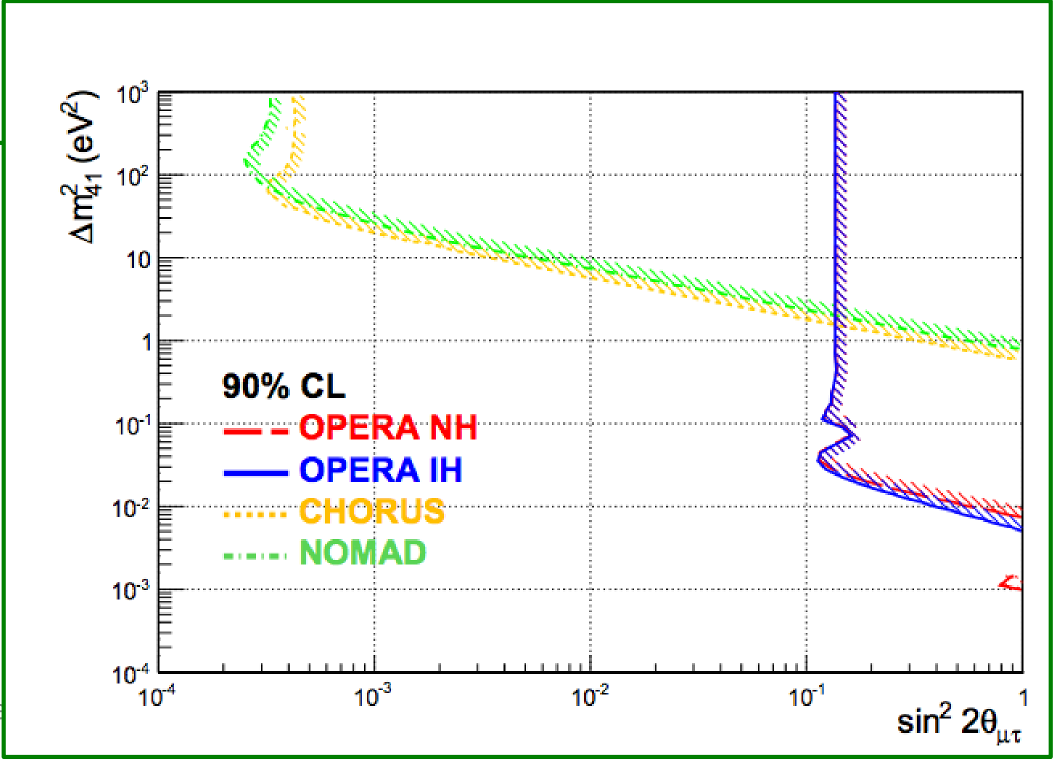
# STERILE NEUTRINOS




Effective mixing:

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

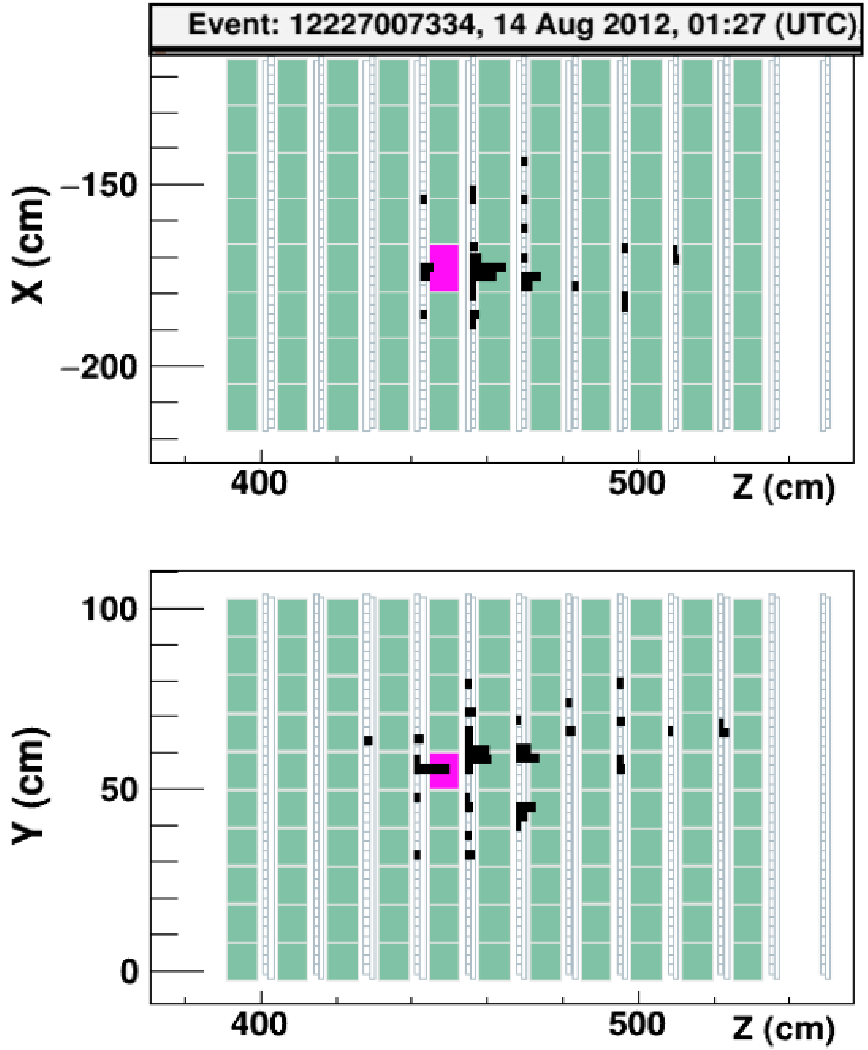
*JHEP 6 (2015) 069*



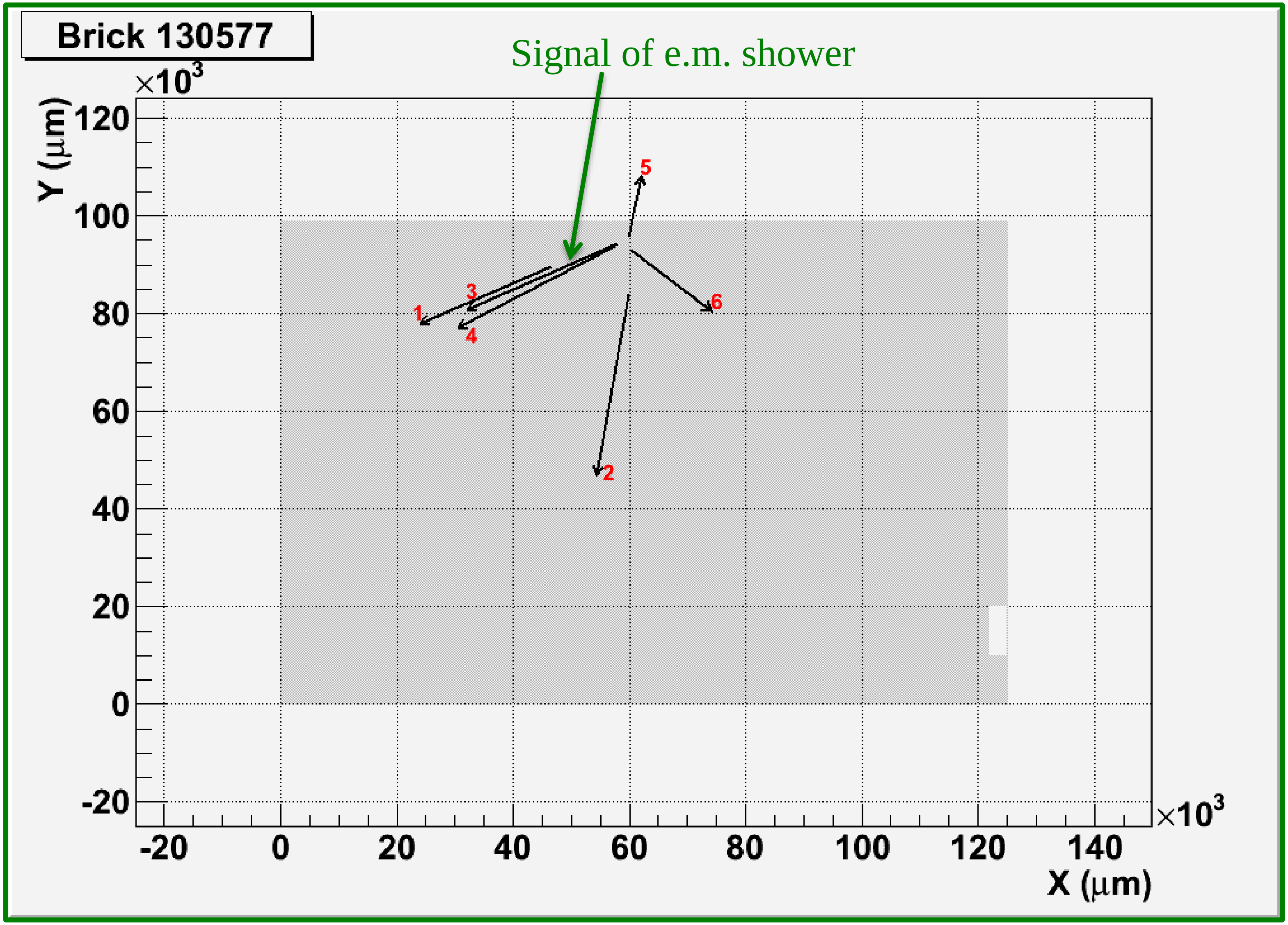
# Completing The Analysis Of The Two Most Probable Bricks

# THE FIFTH $\nu_\tau$ CANDIDATE

As seen by the electronic detectors …

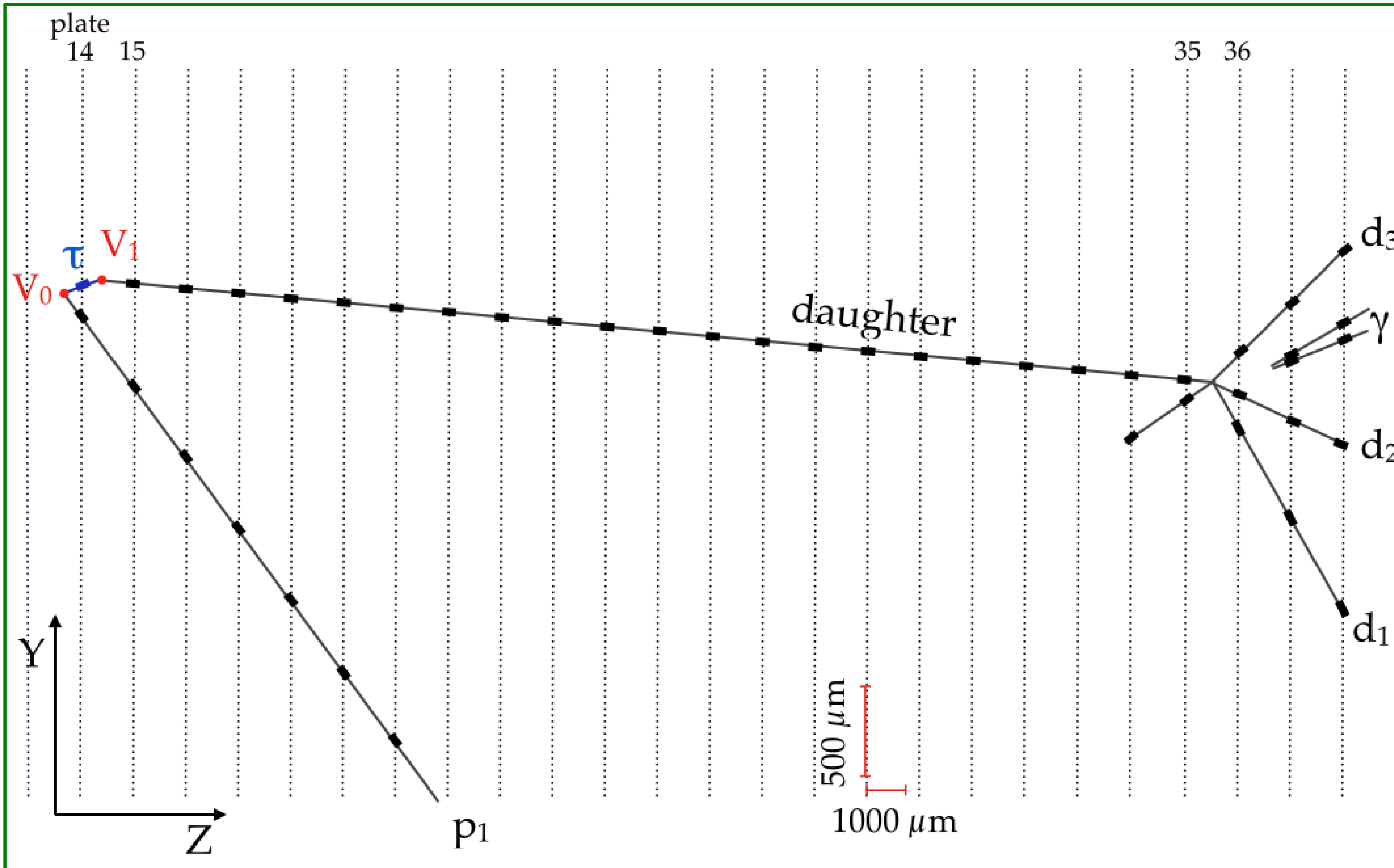


# Analysis Of Interface Emulsion Films



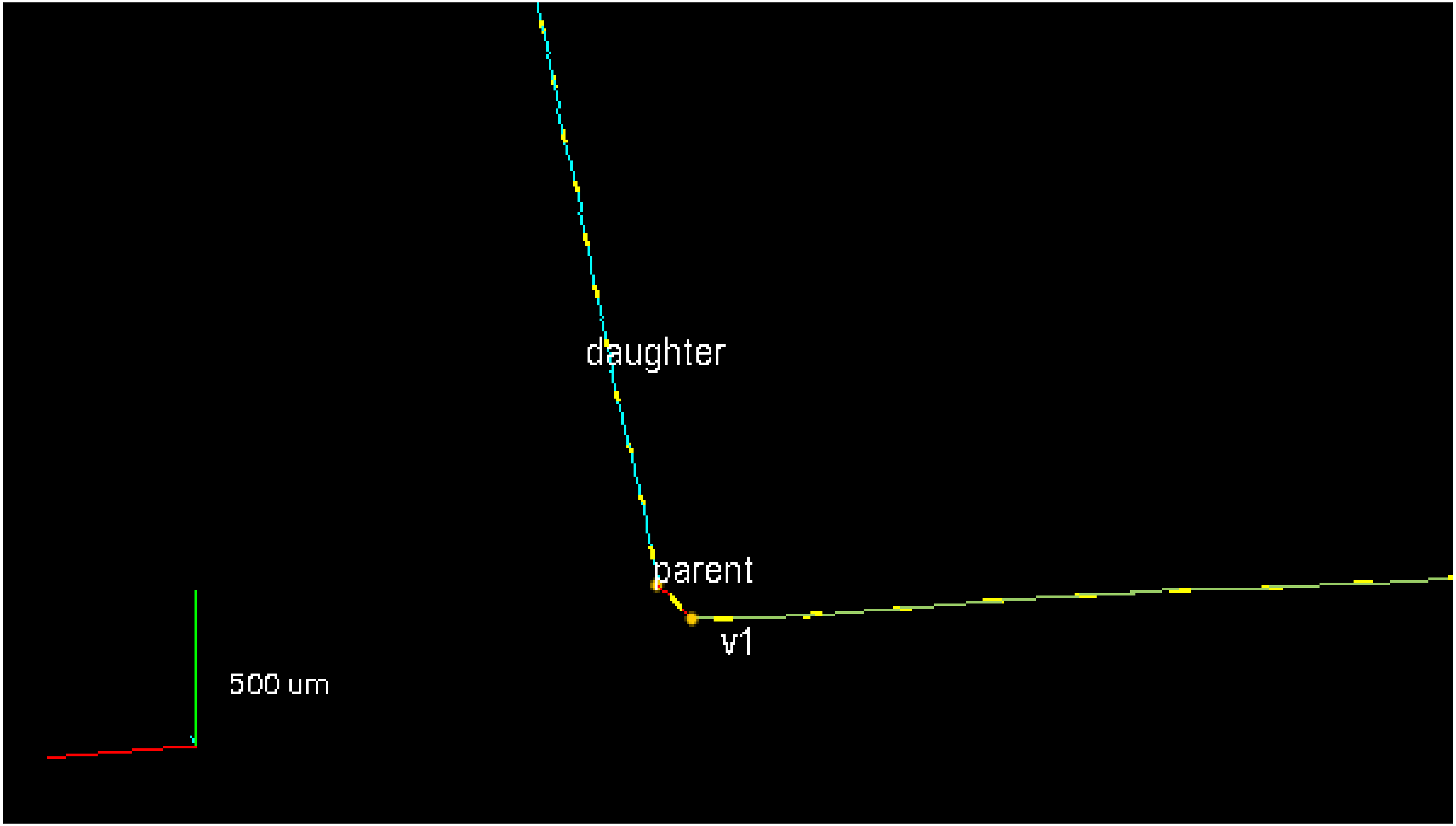
# The Fifth $\nu_\tau$ Candidate

… and in the brick



# THE FIFTH $\nu_\tau$ CANDIDATE

… and in the brick



# Search For Nuclear Fragments

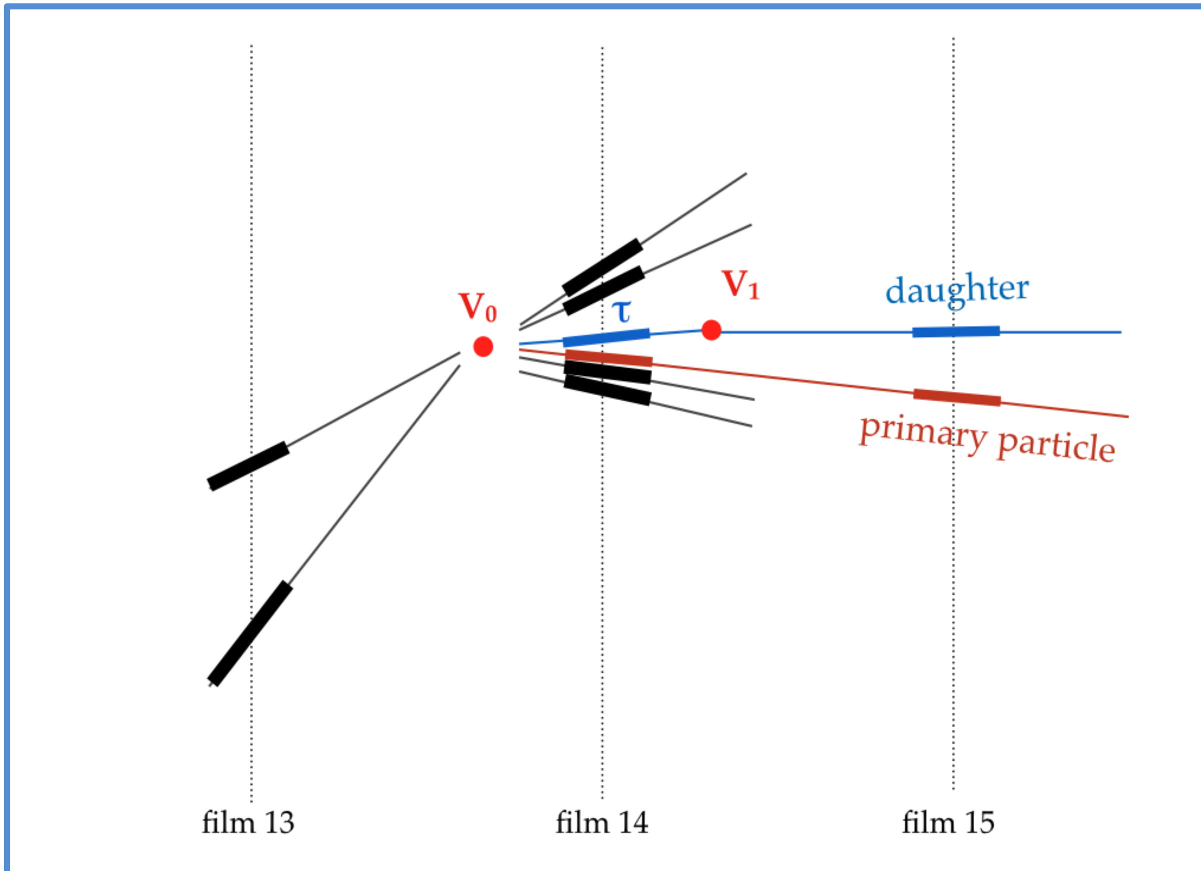
Search for nuclear fragments in an extended angular range **|tanθ|≤ 3**

Primary vertex

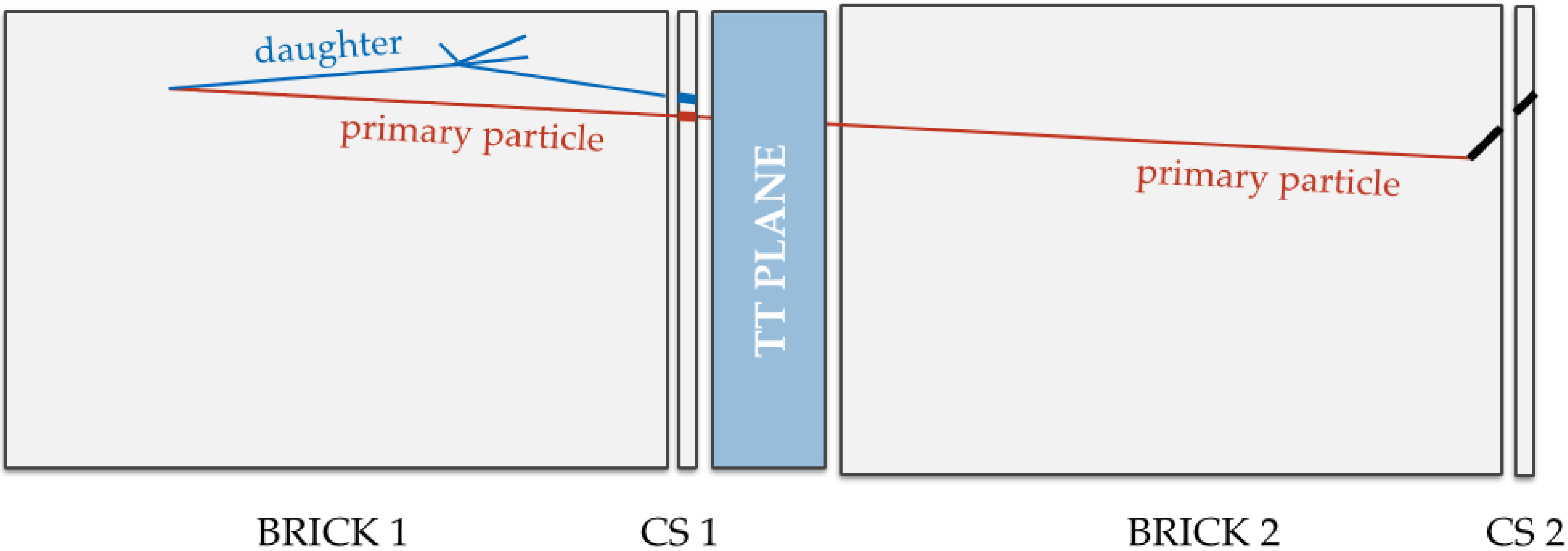
6 nuclear fragments found

Secondary vertex

None



# Particle Identification




**Primary particle**
Followed in the downstream brick
Hadronic re-interaction: 1 visible particle

→ **Charm hypothesis discarded**

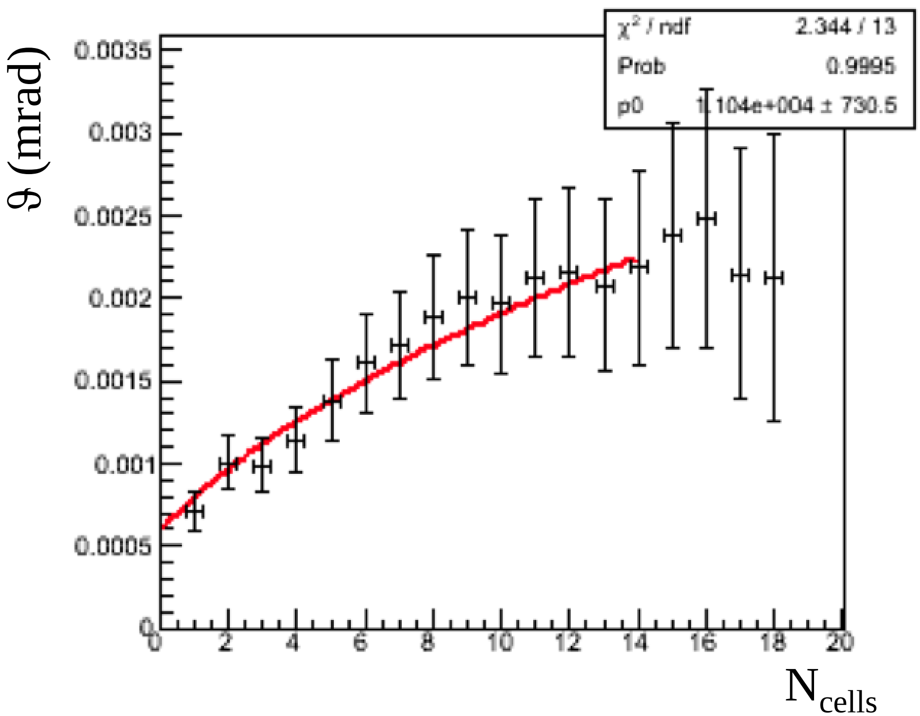
**Daughter**
Hadronic re-interaction in the first brick

→ **Hadronic decay channel**

# Momentum Measurement

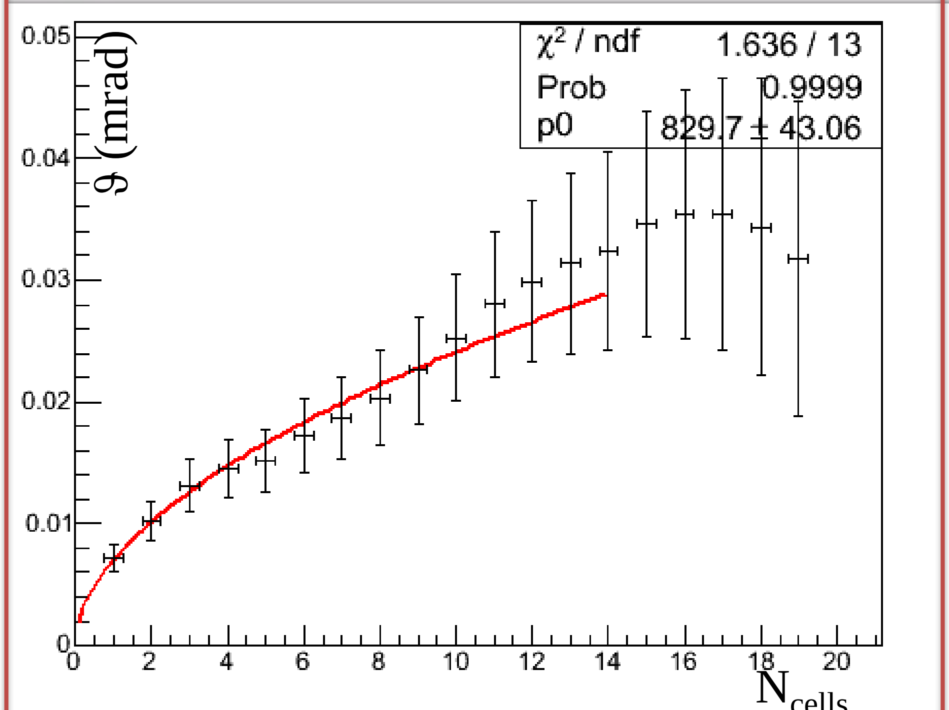
MCS method in the first brick

Daughter track




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

Primary track

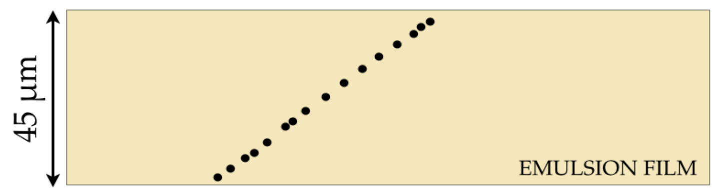



$\beta P_{1ry}$ = 0.8 [0.6, 1.1] GeV/c

# 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

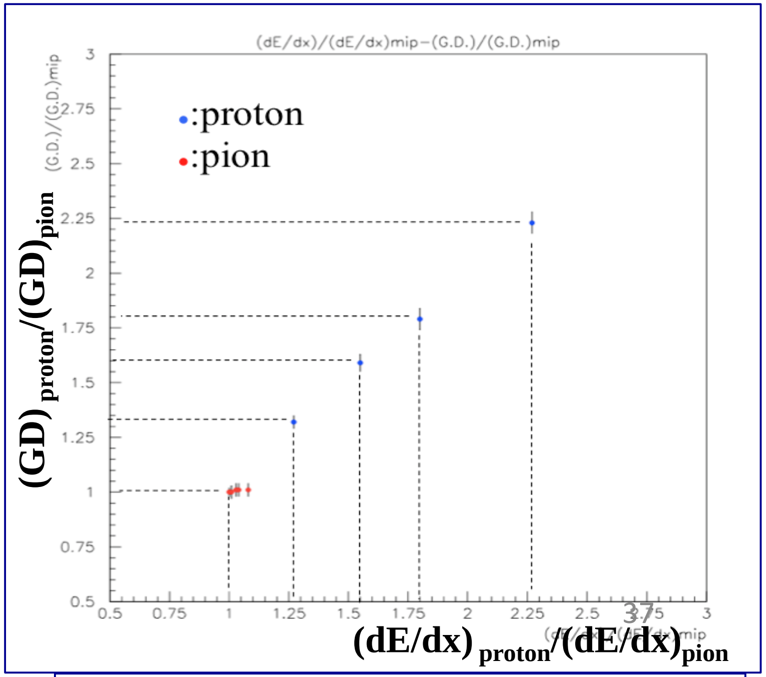
$\beta P_{1ry}$ = 0.8 [0.6, 1.1] GeV/c

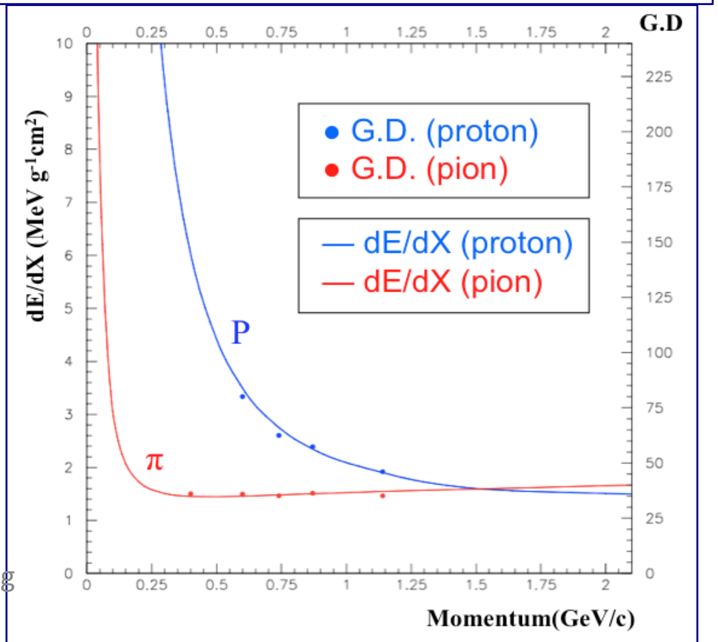
$$GD_{1ry}/GD_{\pi} = 1.45 \pm 0.06$$

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

**Consistent with proton hypothesis**

p = (1.0±0.2) GeV/c



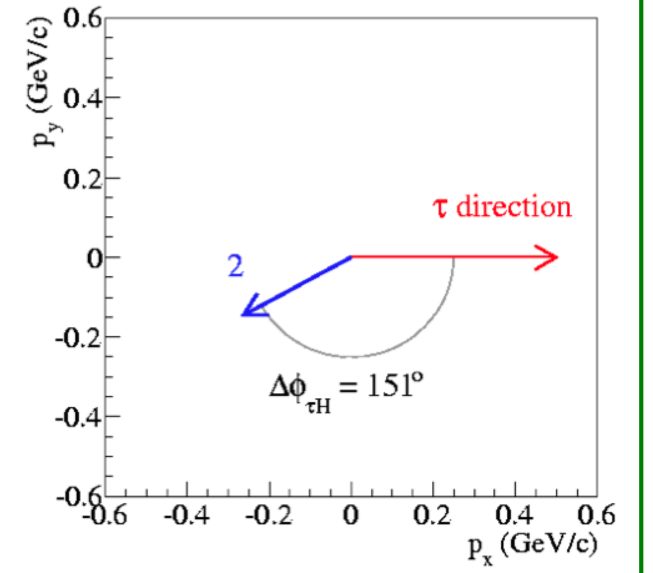



# The Fifth $\nu_\tau$ Candidate

Kinematical variables

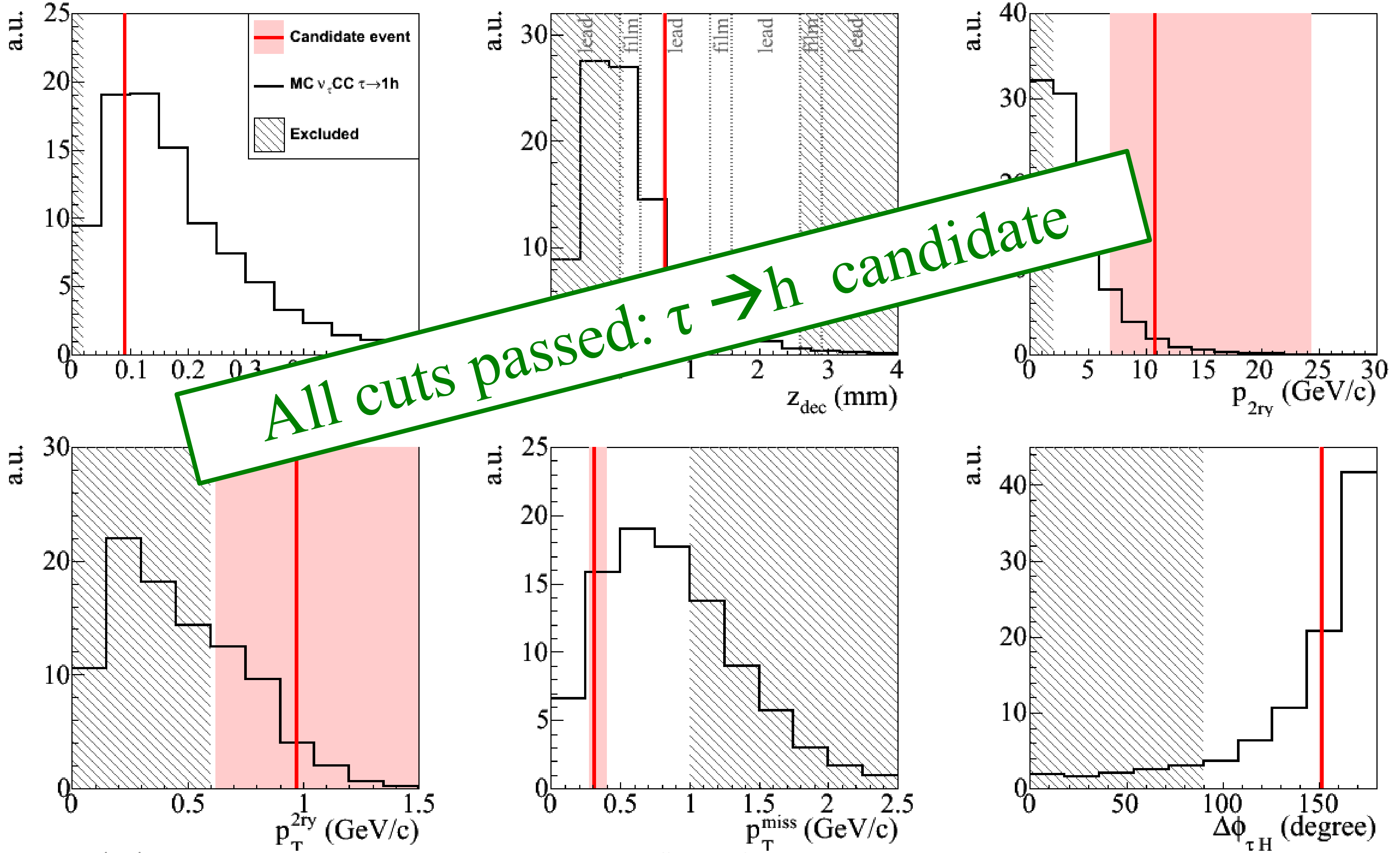
| Parameter | Measured value | Selection Criteria |
|---|---|---|
| $\Delta\phi_{\tau H}$ ($^o$) | $151\pm1$ | $>90$ |
| $p_T^{miss}$ (GeV/c) | $0.3 \pm 0.1$ | $<1$ |
| $\theta_{kink}$ (mrad) | $90 \pm 2$ | $>20$ |
| $z_{dec}$ ($\mu m$) | $634 \pm 30$ | [44, 2600] |
| $p^{2ry}$ (GeV/c) | $11^{+14}_{-4}$ | $>2$ |
| $p_T^{2ry}$ (GeV/c) | $1.0^{+1.2}_{-0.4}$ | $>0.6$ (no $\gamma$ attached) |

Flight length: $(960\pm30)\ \mu m$



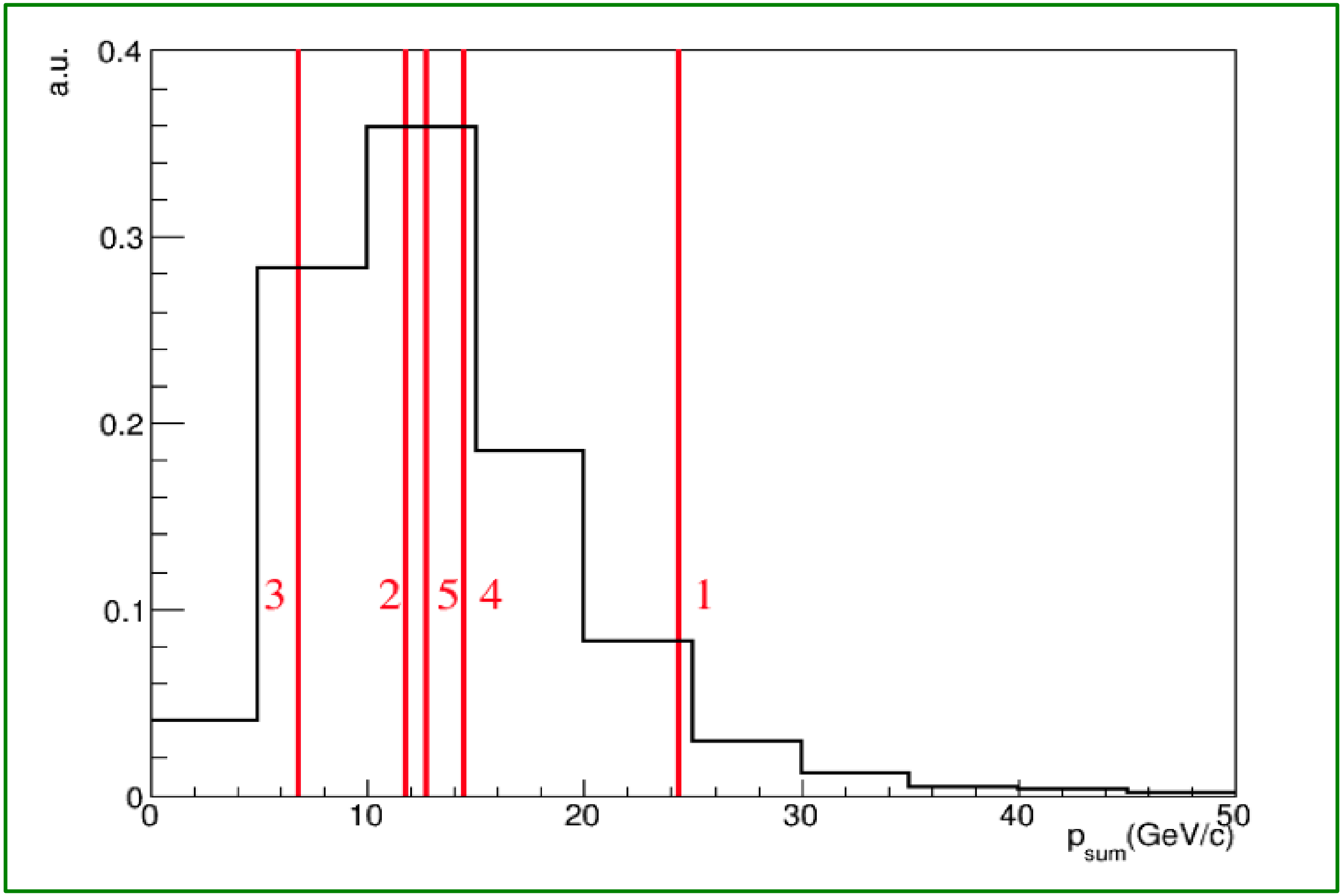
# The Fifth $\nu_\tau$ Candidate

Kinematical variables



# Visible Energy Of All The Candidates

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

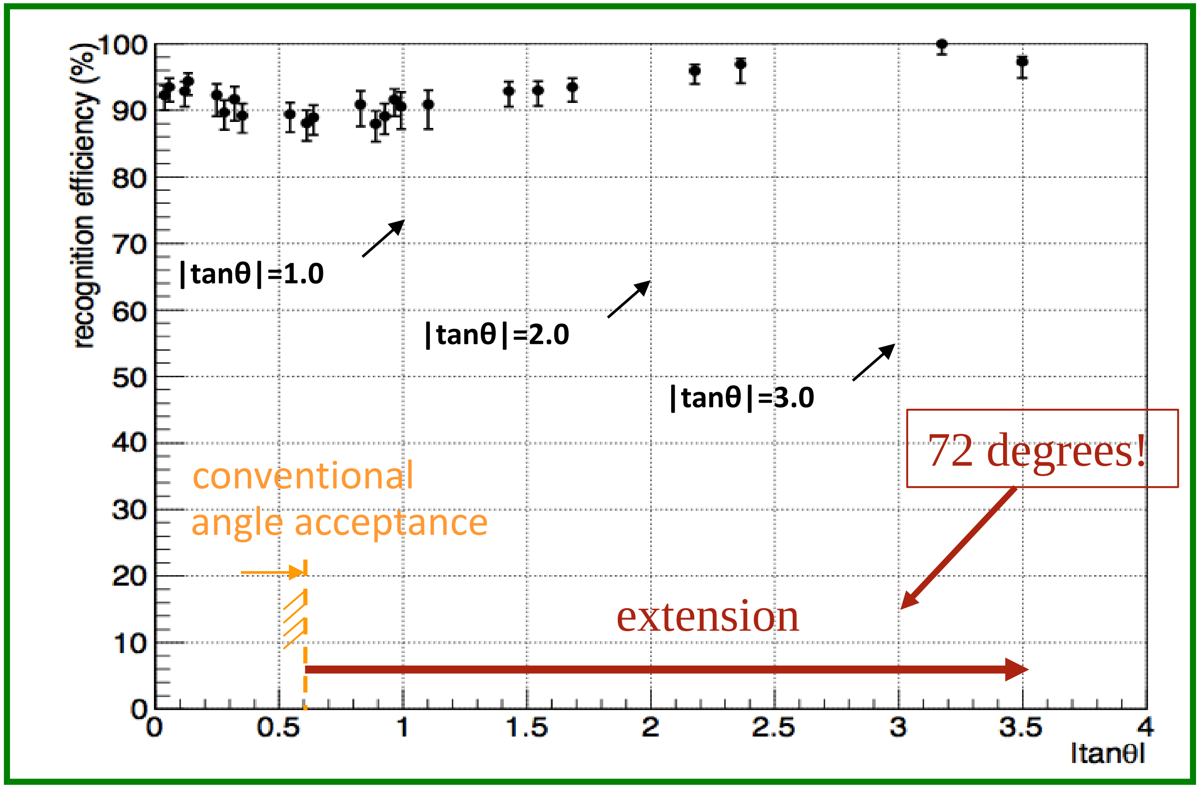


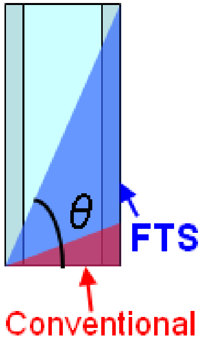
# BACKGROUND STUDIES

# 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



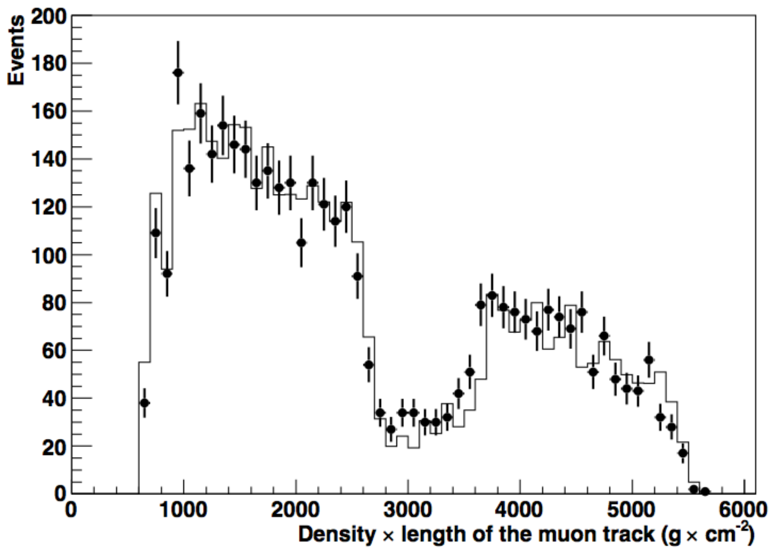

*JINST 9 (2014) P12017*

# Charmed Particles Production

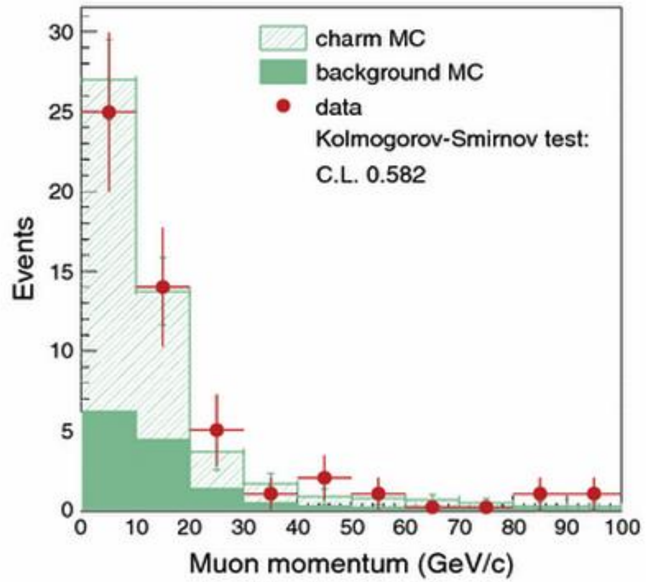
- Lifetimes and masses similar to the $\tau$
- Background when the primary muon is not identified

$\nu_\mu^{CC}$ 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*



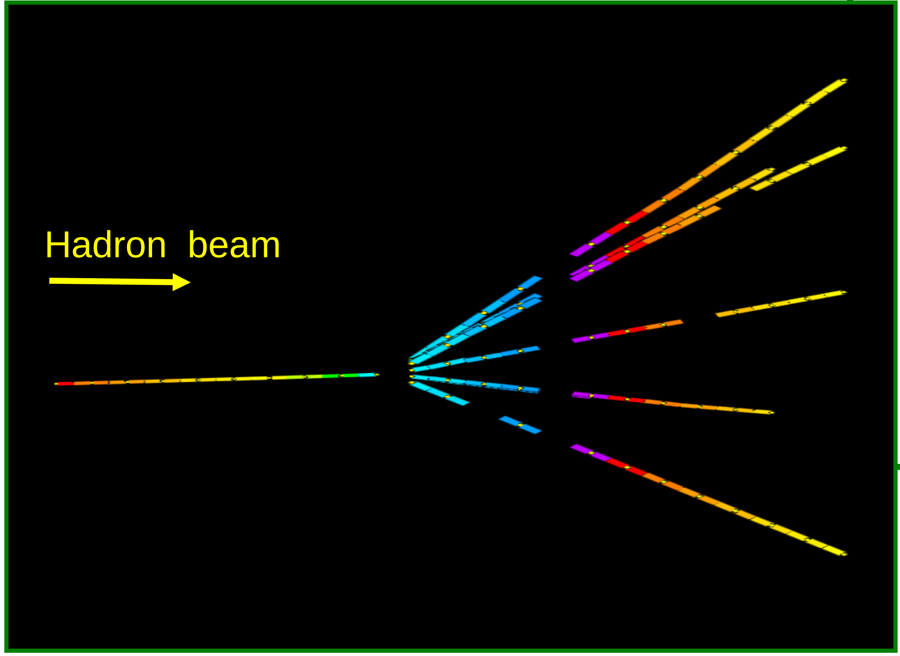

*Eur. Phys. J. C74 (2014) 2986*

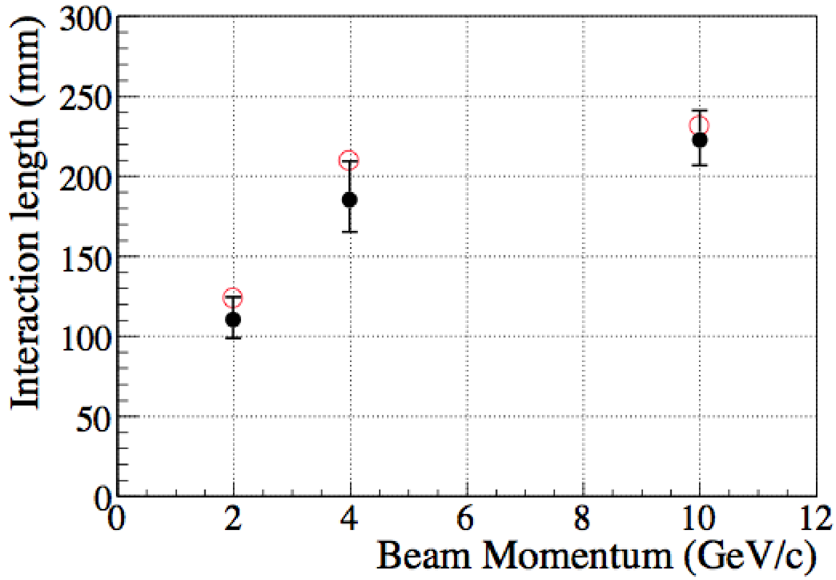
Good agreement in normalization and shape for the relevant kinematical variables in the charm detection and muon identification
Constrain the background within 20%

# Background Studies: Hadronic Interactions

Comparison of large data sample ($\pi^-$ 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



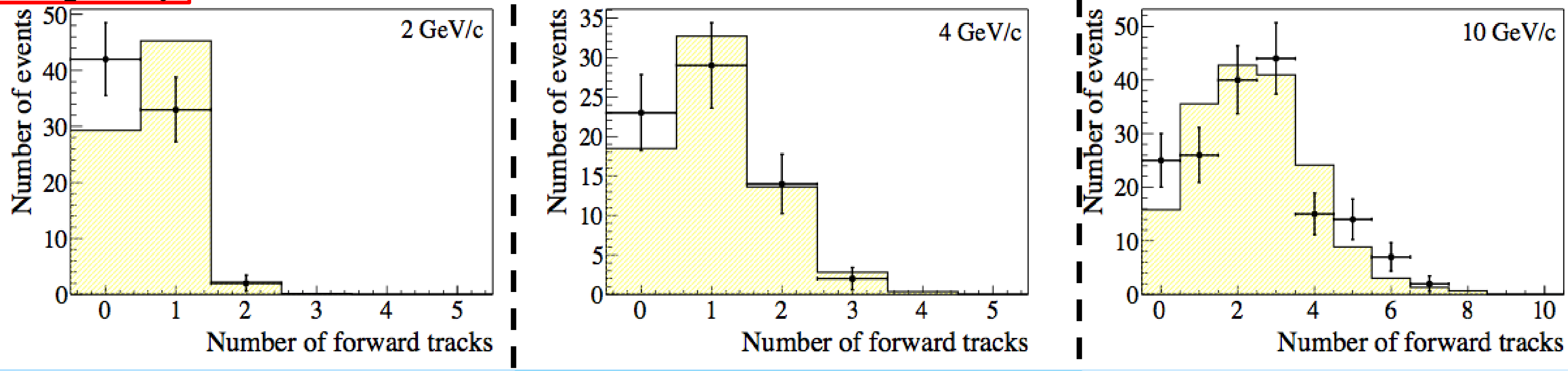

Black : $\pi^-$ beam data
Red : MC (FLUKA) simulation

*PTEP 9 (2014) 093C01*

# SECONDARY TRACK EMISSION

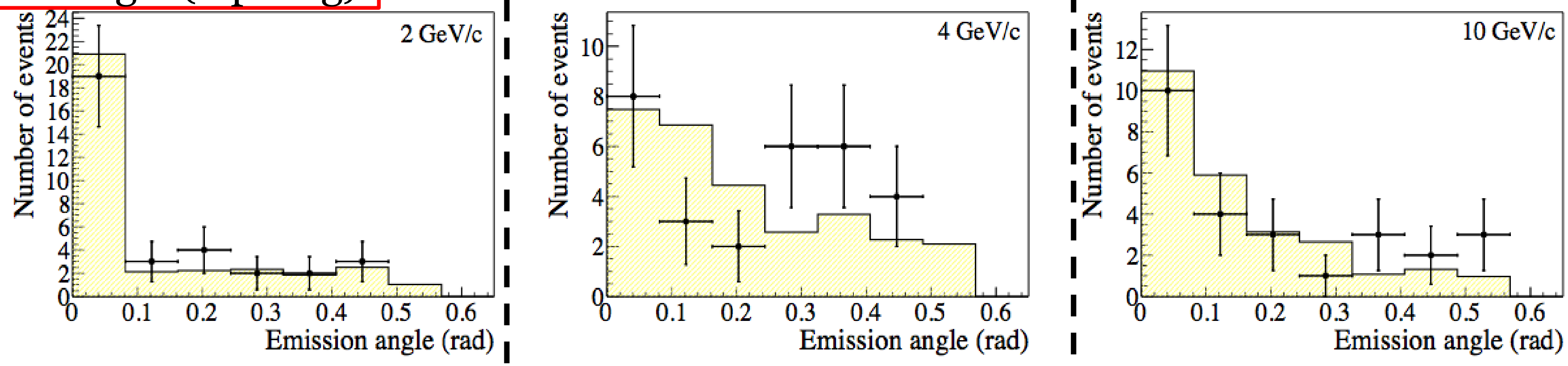
2GeV/c | 4GeV/c | 10GeV/c

Multiplicity



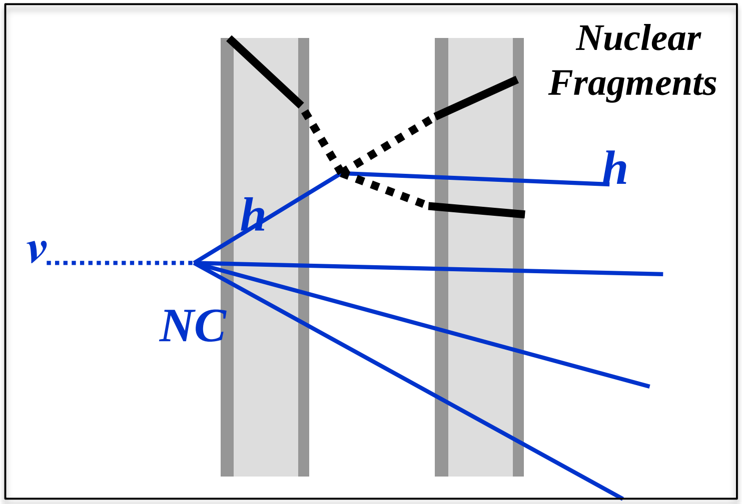

Error bars : Experimental data
Histogram : Simulated data

Kink angle (1-prong)

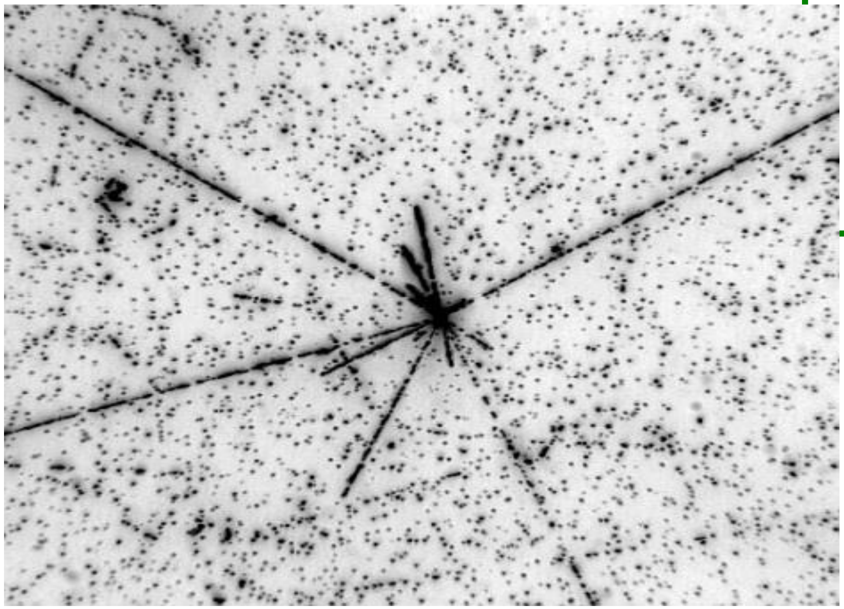



Good agreement within the statistical error: systematic error ~ 30%

# Nuclear Fragments Emission Probability

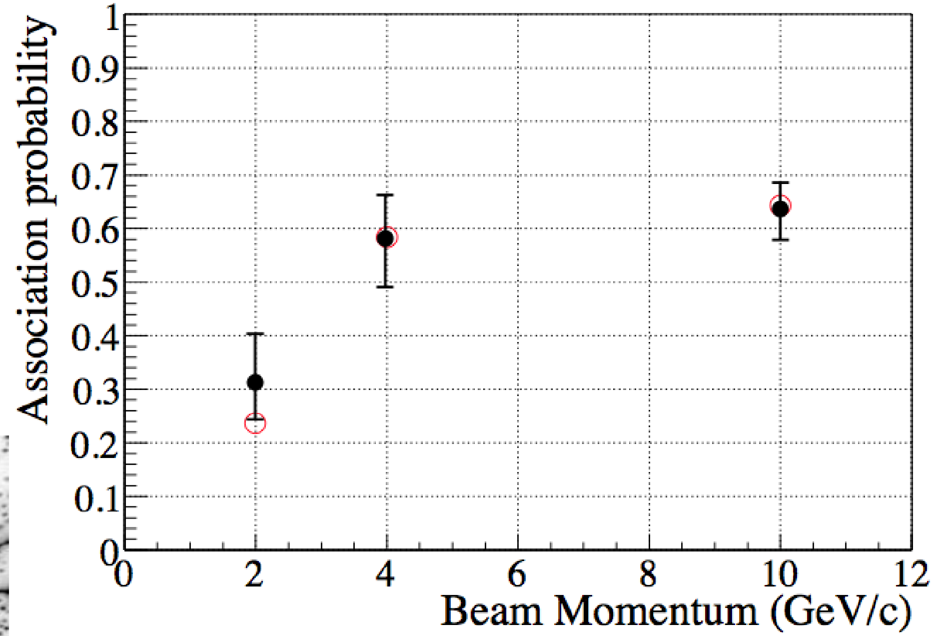



Highly ionizing fragments



150 µm

Additional background reduction




Black : experimental data

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

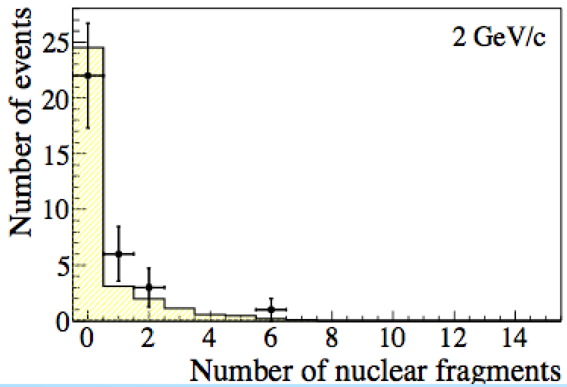
*PTEP 9 (2014) 093C01*

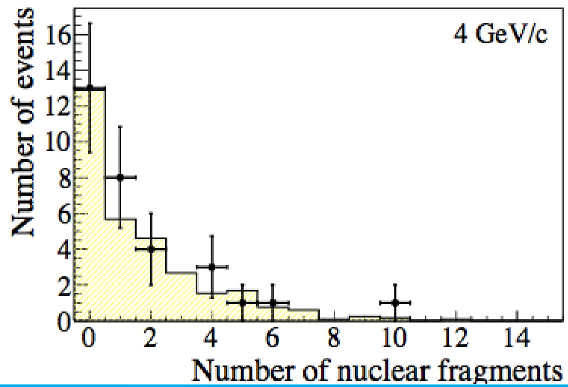
# Nuclear Fragments In 1 And 3 Prong Interactions

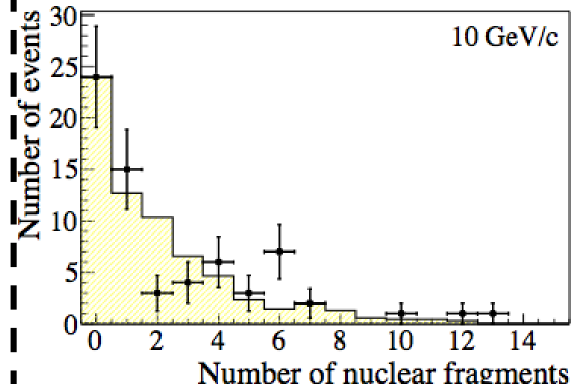
2GeV/c | 4GeV/c | 10GeV/c

## Multiplicity

MC: β < 0.7

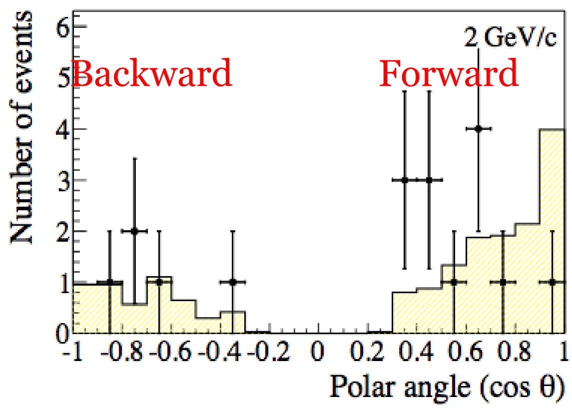


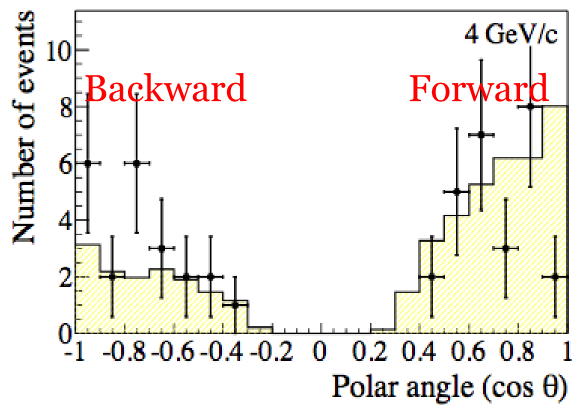



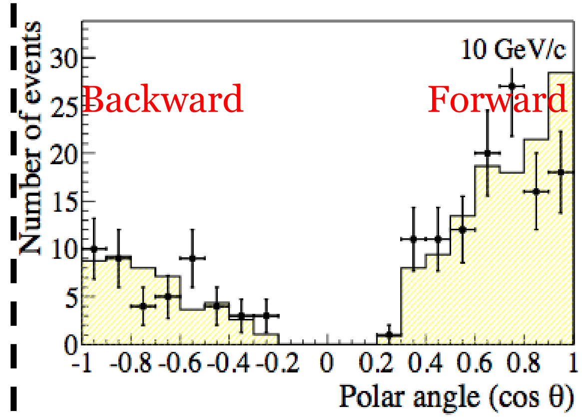




Error bars : Experimental data
Histogram : Simulated data

## 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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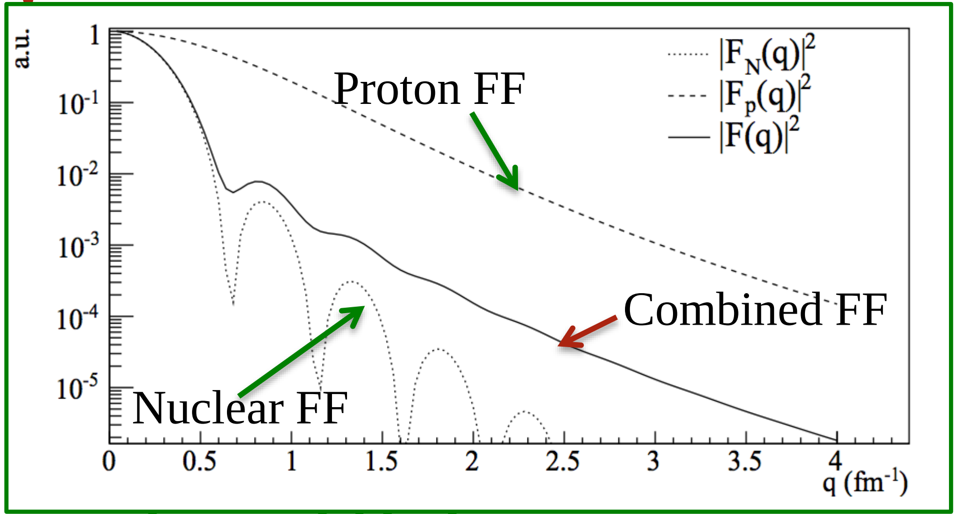
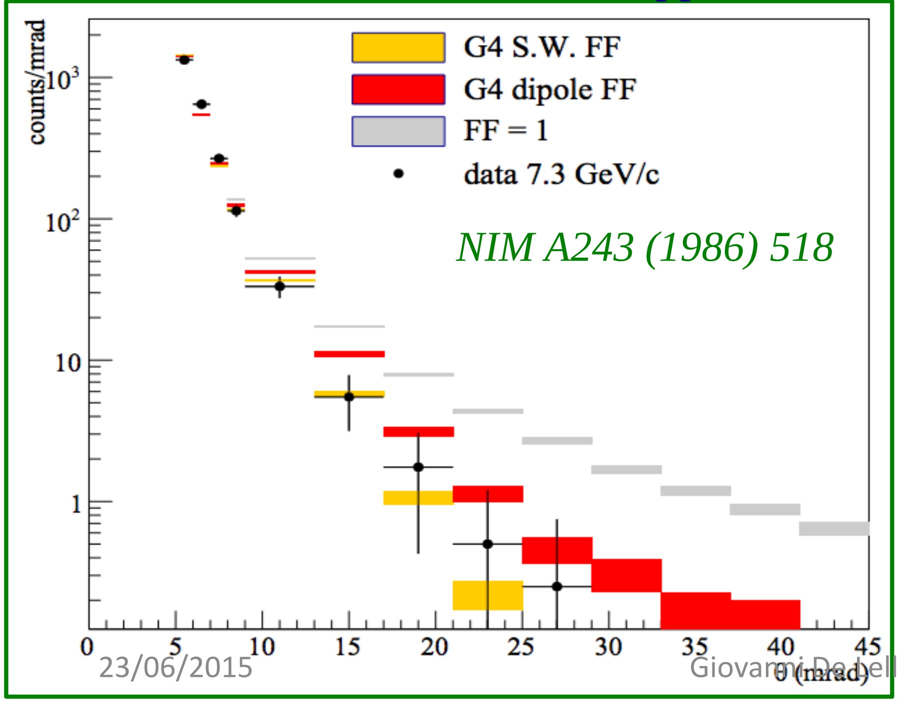


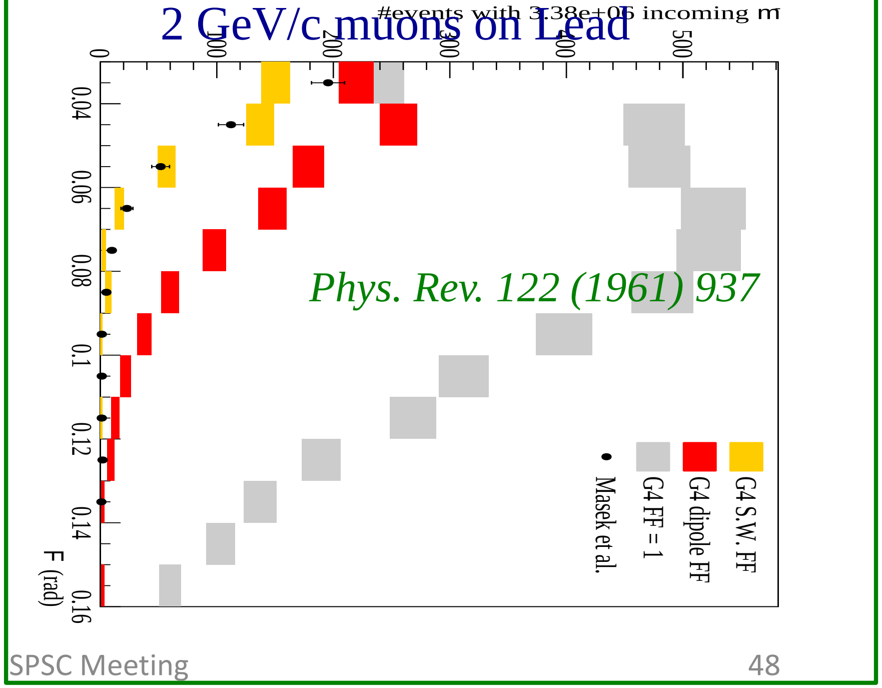

MC predictions compared to available data

7.3 GeV/c muons on Copper




*NIM A243 (1986) 518*

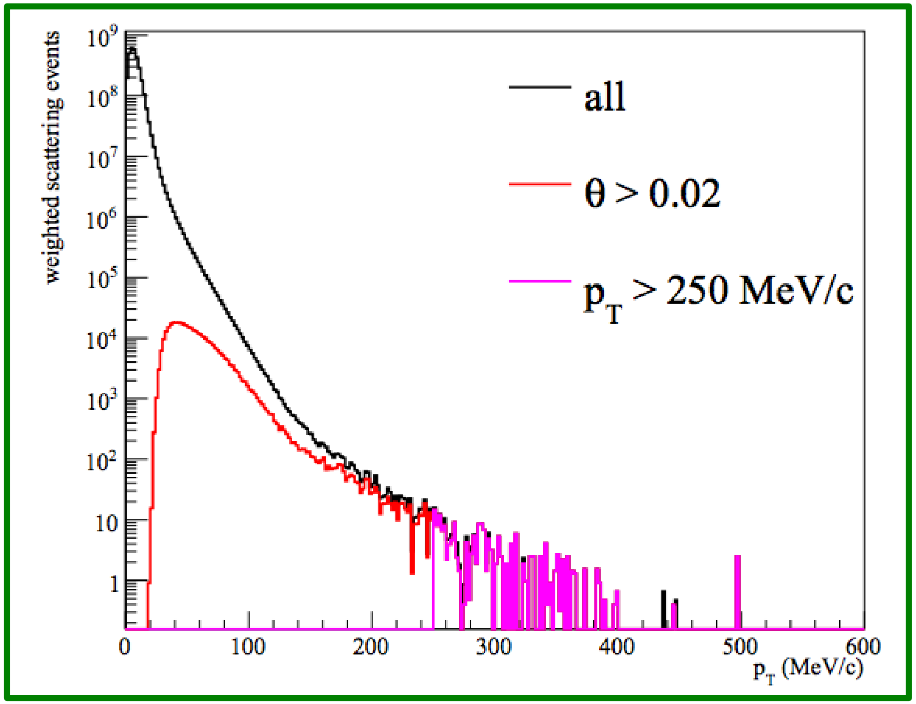
2 GeV/c muons on Lead



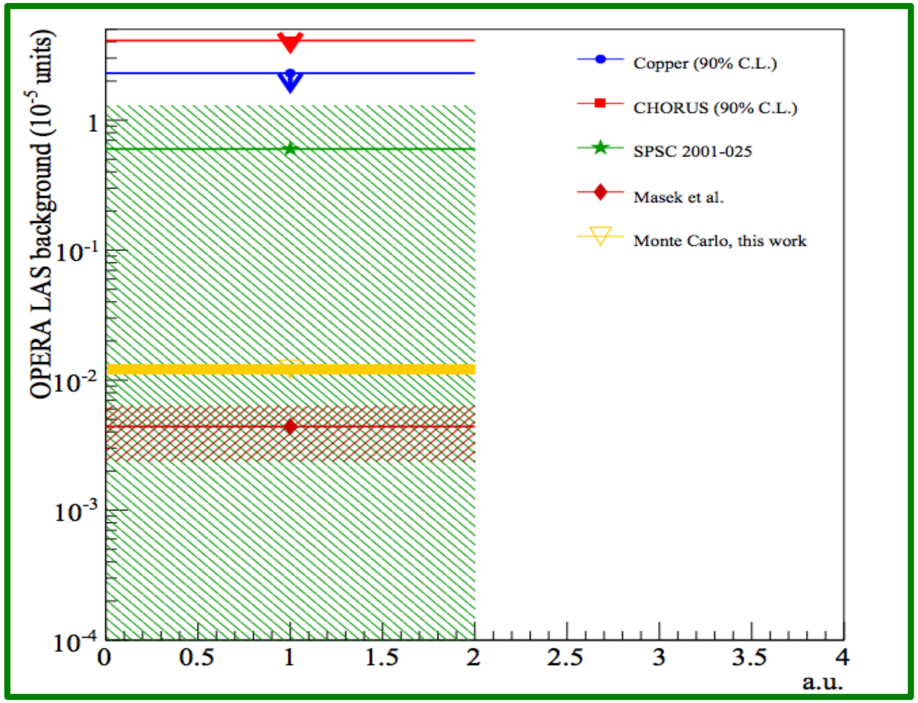

*Phys. Rev. 122 (1961) 937*

# LARGE ANGLE μ SCATTERING

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




Main background in the $\tau \rightarrow \mu$ 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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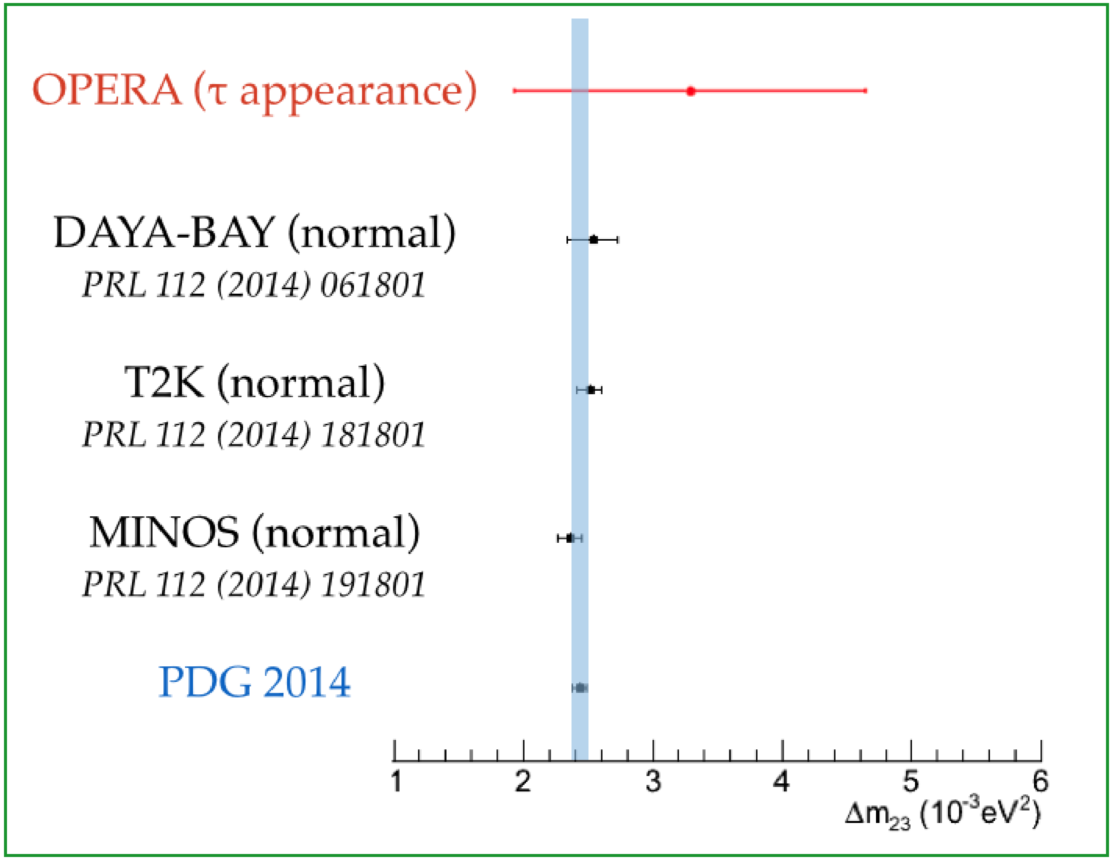
# $\Delta m^2_{23}$ ESTIMATION

90% C.L. intervals on $\Delta m^2_{23}$ 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 $\mu$-scat. | Total | | |
| $\tau \to 1h$ | $0.017 \pm 0.003$ | $0.022 \pm 0.006$ | – | $0.04 \pm 0.01$ | $0.52 \pm 0.10$ | 3 |
| $\tau \to 3h$ | $0.17 \pm 0.03$ | $0.003 \pm 0.001$ | – | $0.17 \pm 0.03$ | $0.73 \pm 0.14$ | 1 |
| $\tau \to \mu$ | $0.004 \pm 0.001$ | – | $0.0002 \pm 0.0001$ | $0.004 \pm 0.001$ | $0.61 \pm 0.12$ | 1 |
| $\tau \to e$ | $0.03 \pm 0.01$ | – | – | $0.03 \pm 0.01$ | $0.78 \pm 0.16$ | 0 |
| Total | $0.22 \pm 0.04$ | $0.02 \pm 0.01$ | $0.0002 \pm 0.0001$ | $0.25 \pm 0.05$ | $2.64 \pm 0.53$ | 5 |

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

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:
- Fisher = $1.10 \times 10^{-7}$
- Profile likelihood = $1.07 \times 10^{-7}$

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)

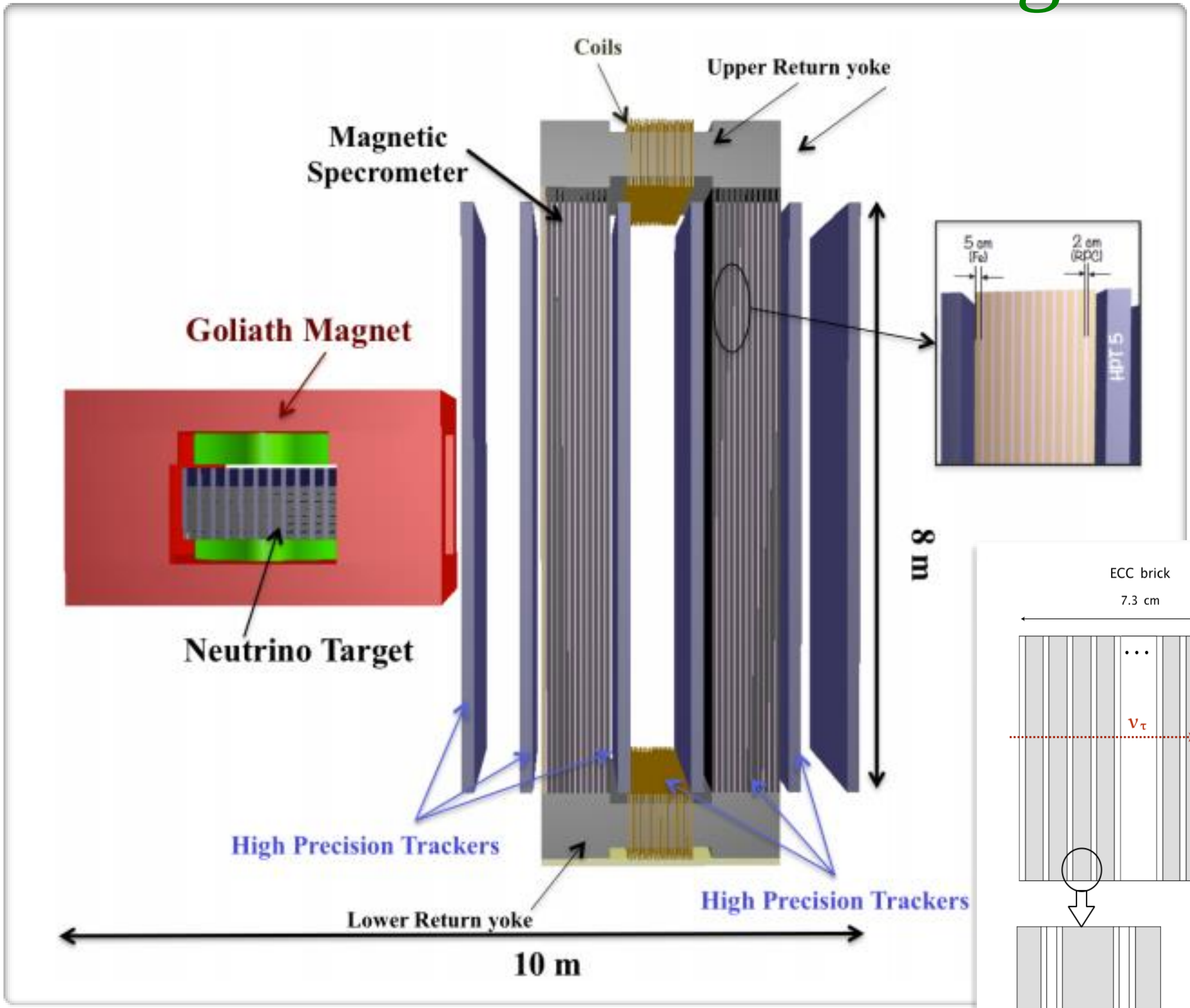
# DISCOVERY OF $\nu_\tau$ APPEARANCE IN THE CNGS NEUTRINO BEAM

- Detector successfully measuring $\nu_e$, $\nu_\mu$ and $\nu_\tau$
- Analysis of an extended data sample (+15%)
- Improved background evaluation
- Five $\nu_\tau$ candidates observed
- 5.1 $\sigma$ significance
- Mission accomplished

## OUTLOOK

- Re-analysis of the full data sample with a likelihood approach and less tight (kinematical) selection criteria
- Extend further the scanning (multi-brick)
- Constrain the oscillation parameters with $\nu_e$, $\nu_\mu$ and $\nu_\tau$ simultaneous measurements

# Know-how and technologies for SHiP




## Target structure