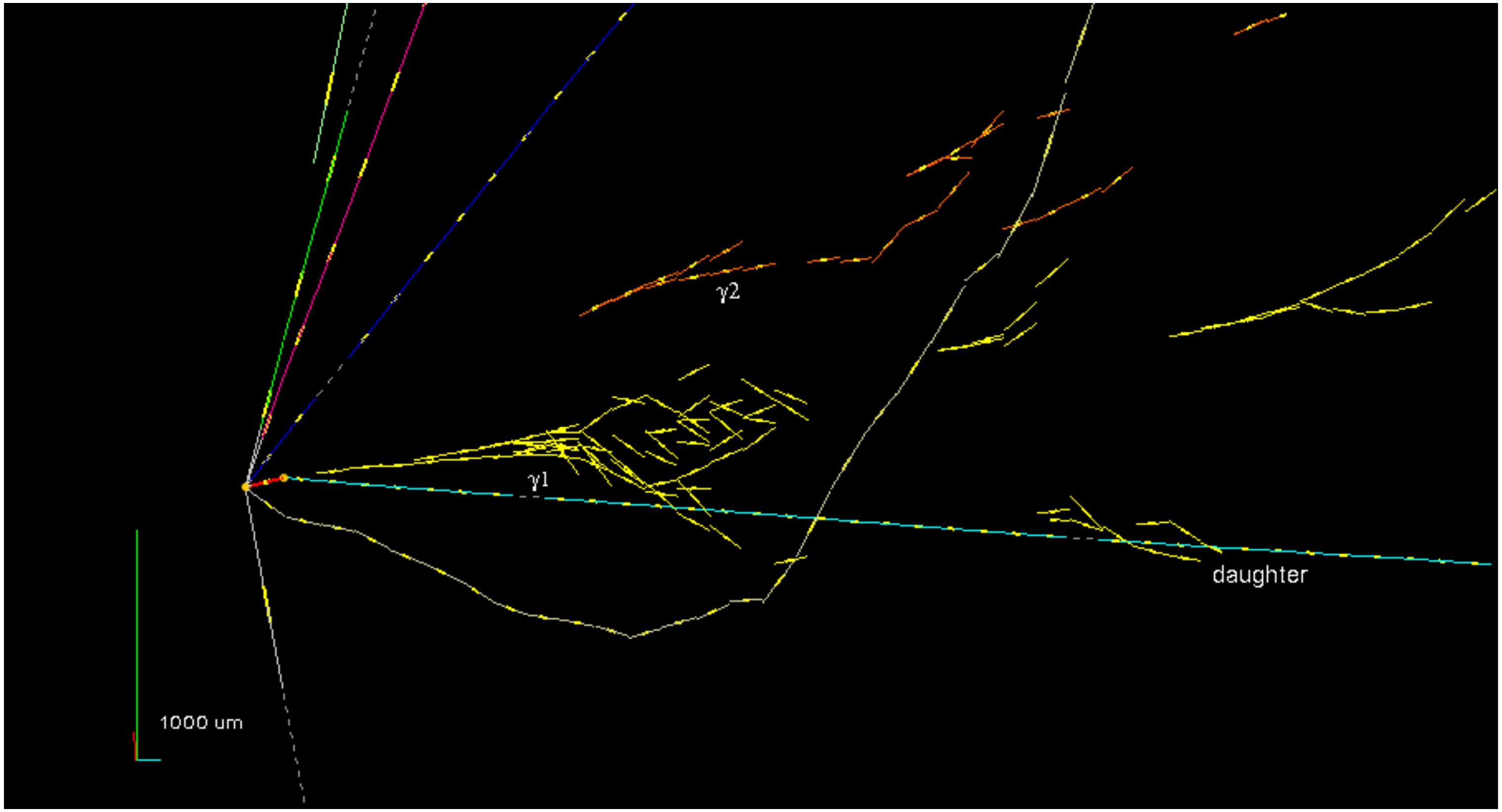
# NEUTRINO OSCILLATIONS WITH THE OPERA EXPERIMENT

Giovanni De Lellis

University "Federico II" and INFN Napoli

On behalf of the OPERA Collaboration



# Outline Of The Talk

- Motivations of the OPERA project
- The OPERA detector
- The analysis chain
- Oscillation physics
- Studies of background sources
- 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, …

$\Delta m^2_{32} = (2.44 \pm 0.06)\ 10^{-3}\ eV^2$
$\theta_{32} = (45.8 \pm 3.2)°$

$\theta_{13} = (8.88 \pm 0.39)°$

*PDG 2014*

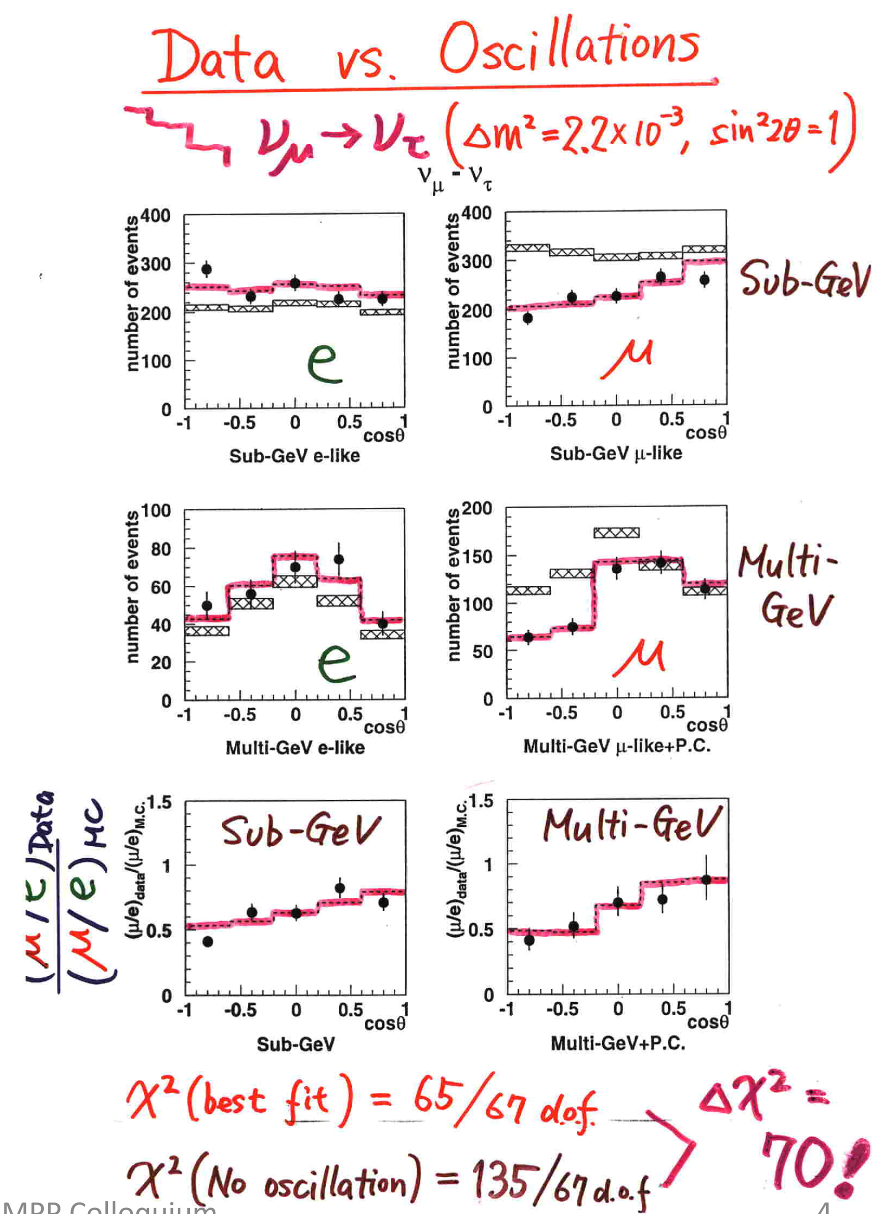
$\Delta m^2_{21} = (7.53 \pm 0.18)\ 10^{-5}\ eV^2$
$\theta_{12} = (33.4 \pm 0.85)°$

# Back to 1998: Neutrino98, Takayama, Japan

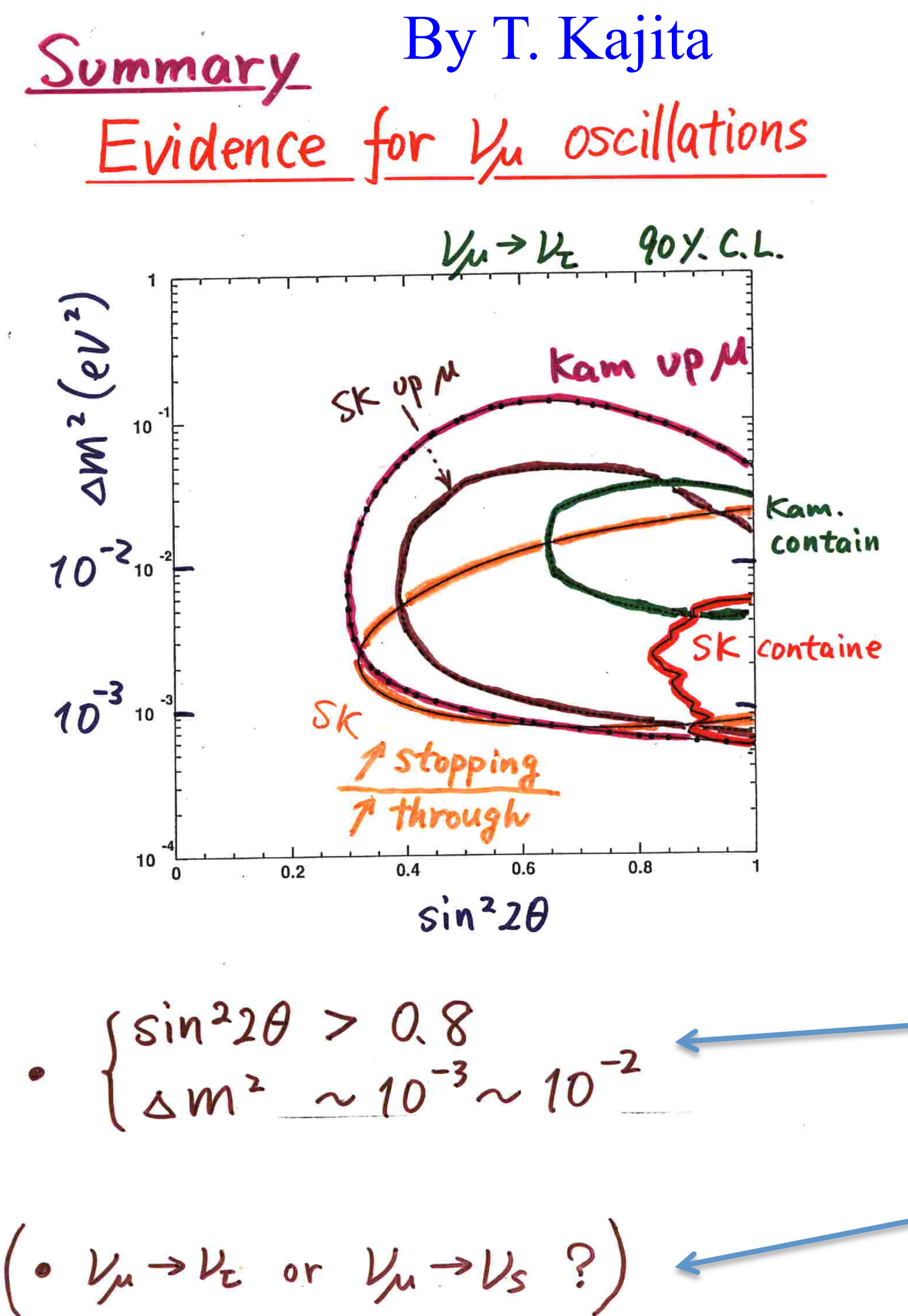
ν98, @Takayam
June 1998

Atmospheric neutrino results
from Super-Kamiokande & Kamiokand
— Evidence for $\nu_\mu$ oscillations —

T. Kajita
Kamioka observatory, Univ. of Tokyo
for the {Kamiokande / Super-Kamiokande} Collaborations

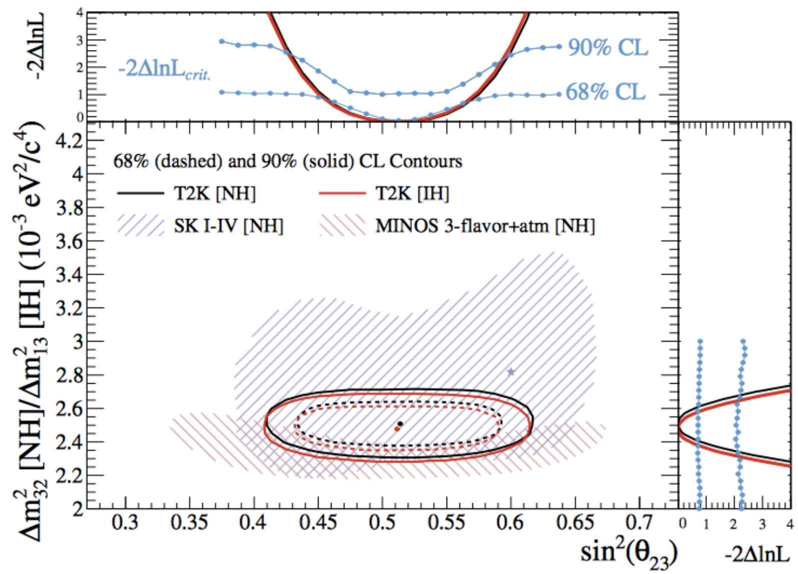



T. Kajita
Nobel Laureate 2015




# Current status

*PRL 112 (2014) 181801*




$$P = \sin^2(2\vartheta)\sin^2\left(\frac{\Delta m^2 L}{E}\right)$$

- $\nu_\tau$ not yet seen in 1998!
- First indication of $\nu_\tau$ in 2001 at Fermilab (DONUT)

# THE OPERA EXPERIMENT

## First direct detection of $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode

- Super-Kamiokande (MACRO and Soudan-2) discovery of oscillations with atmospheric neutrinos
- Later confirmation with solar neutrinos and accelerator beams — K2K, PRL 94 (2005) 081802; MINOS, PRL 97 (2006) 191801
- → An important, missing tile in the oscillation picture

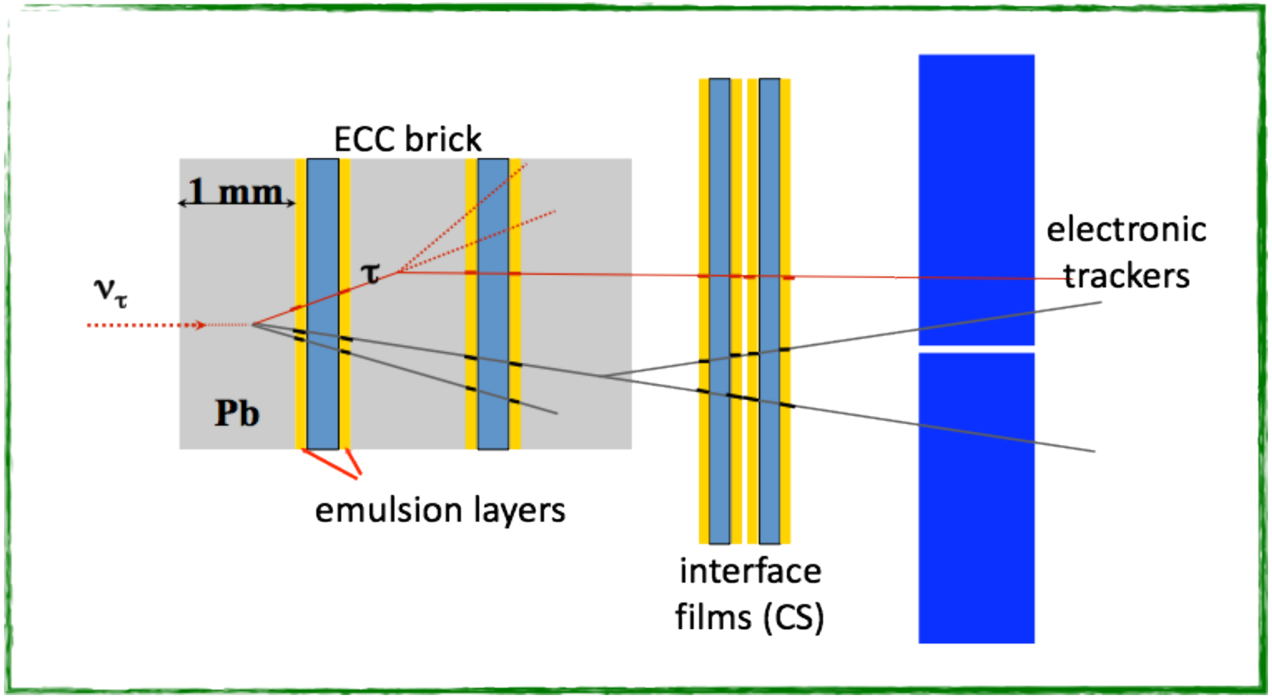
CNGS beam approved at CERN in December 1999

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 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

160 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

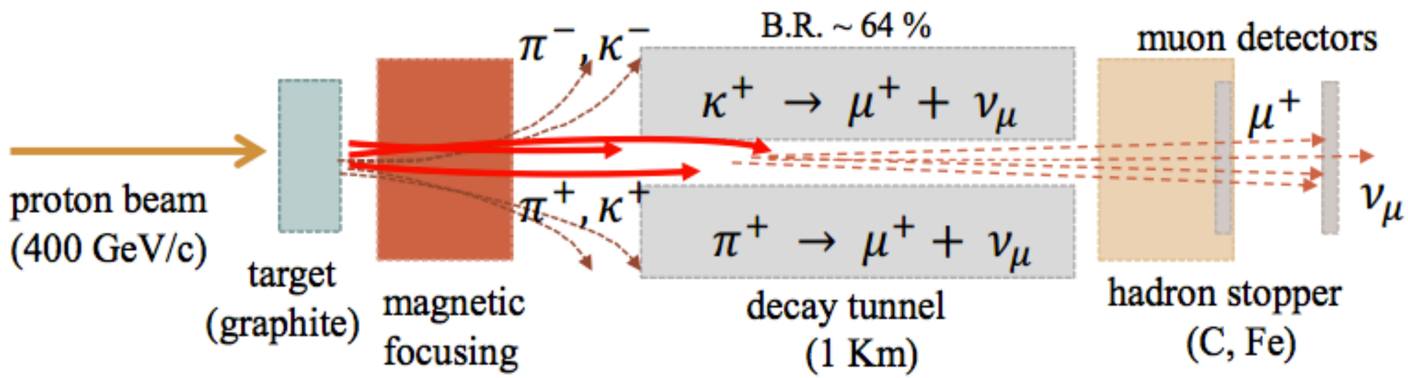
http://operaweb.lngs.infn.it

JULY 2008

# CNGS Beam And LNGS Site

# CNGS BEAM

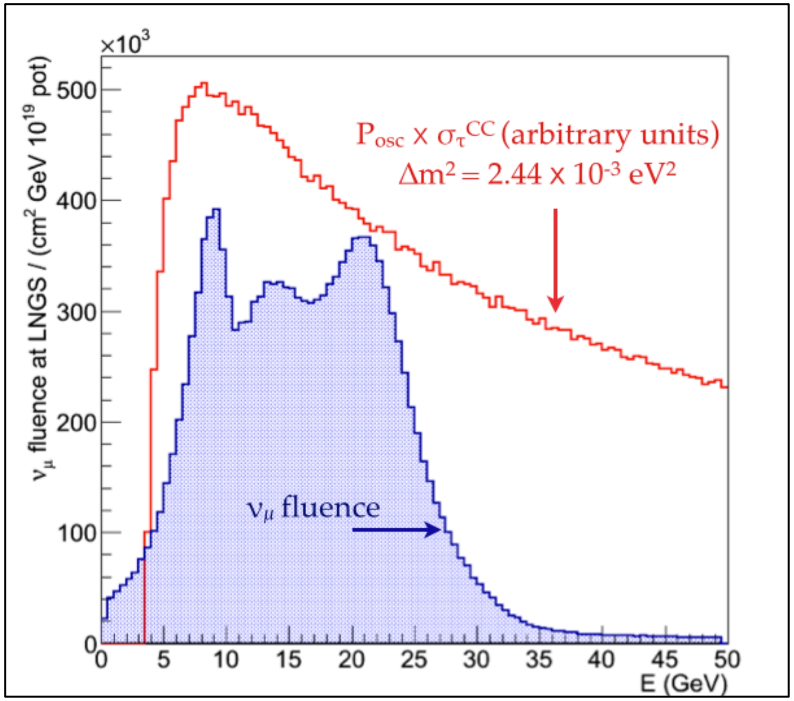
## Tuned for $\nu_\tau$-appearance at LNGS




### CNGS ν beam

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

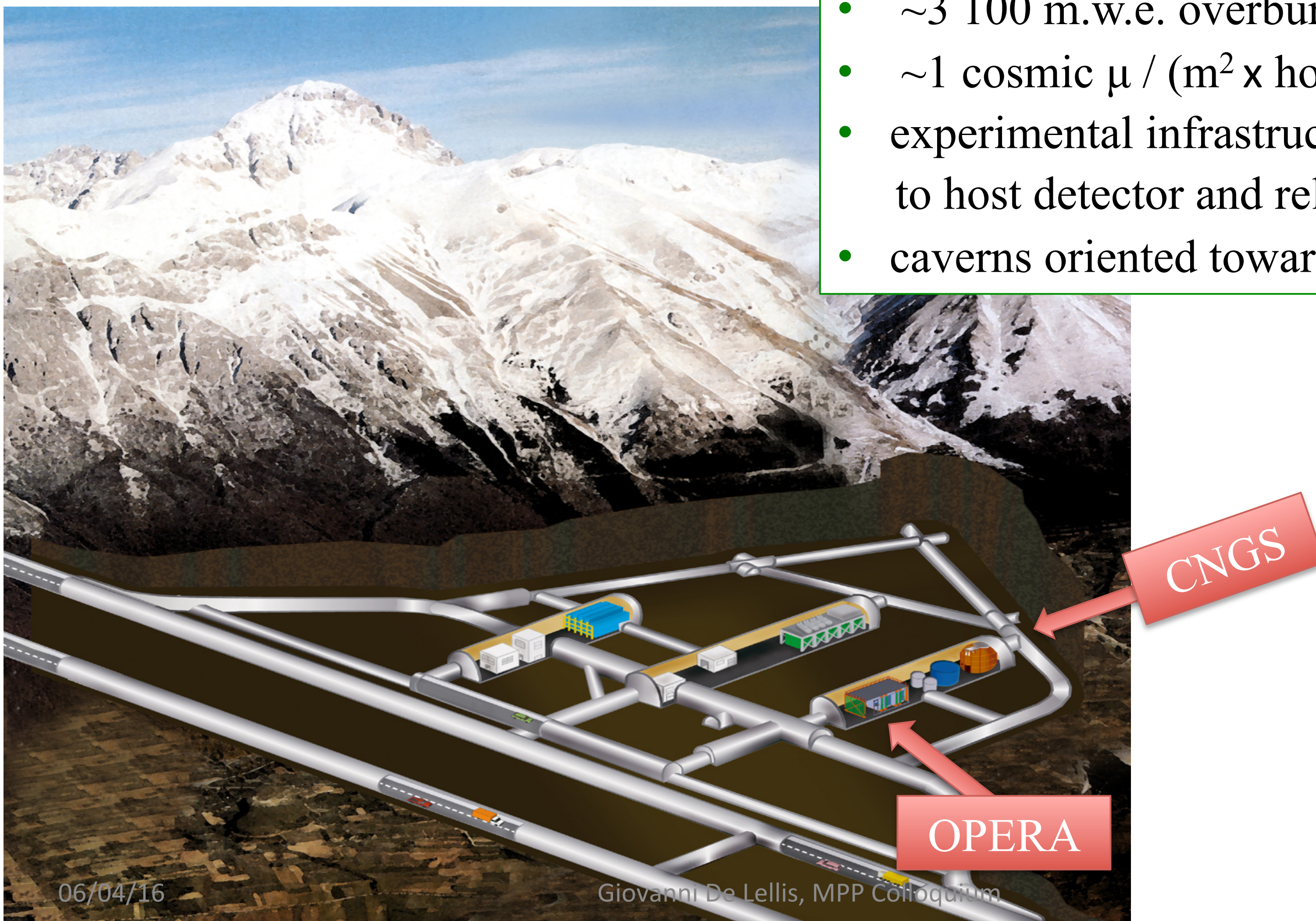
* Interaction rate at LNGS



# LNGS of INFN

## The world largest underground physics laboratory

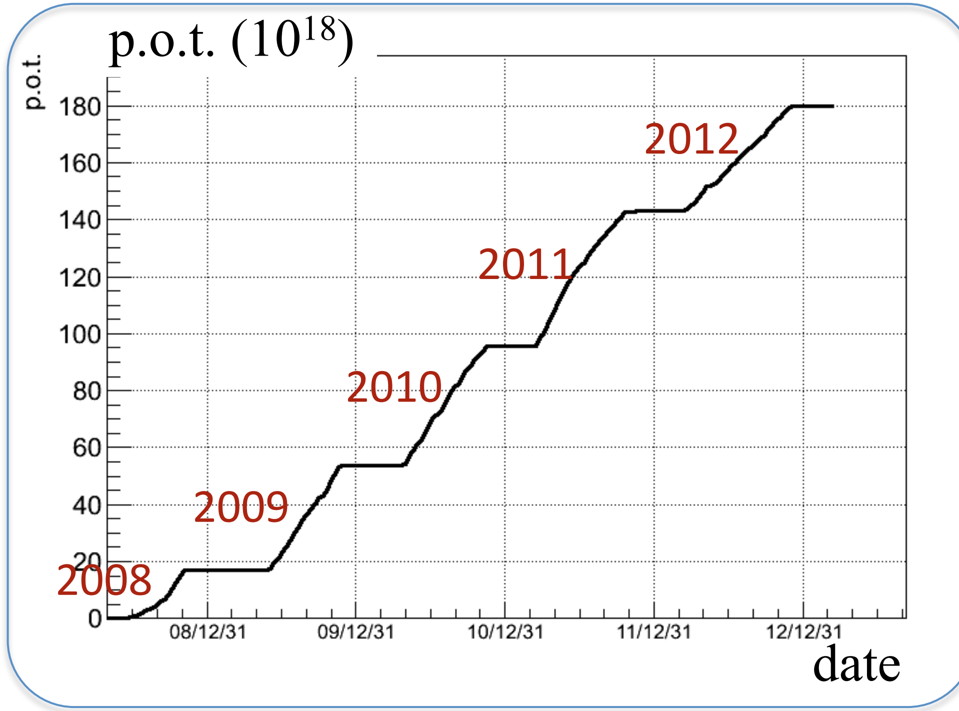
- ~180 000 $m^3$ caverns' volume
- ~3 100 m.w.e. overburden
- ~1 cosmic $\mu$ / ($m^2$ x hour)
- experimental infrastructure suitable to host detector and related facilities
- caverns oriented towards CERN



# 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

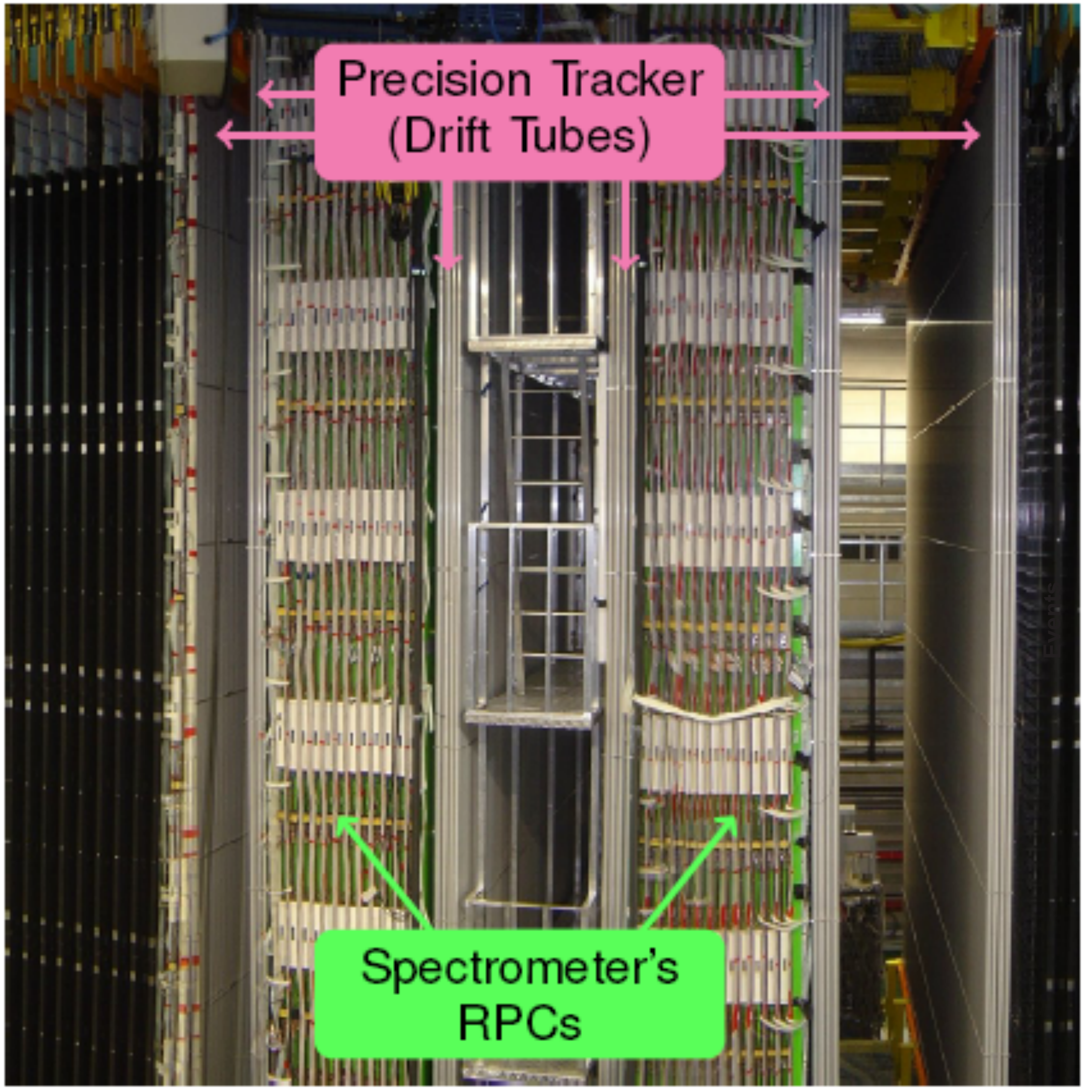
Overall 20% less than the proposal value (22.5)

# DETECTORS AND FACILITIES IN OPERATION:

# A VERY COMPLEX EXPERIMENT…

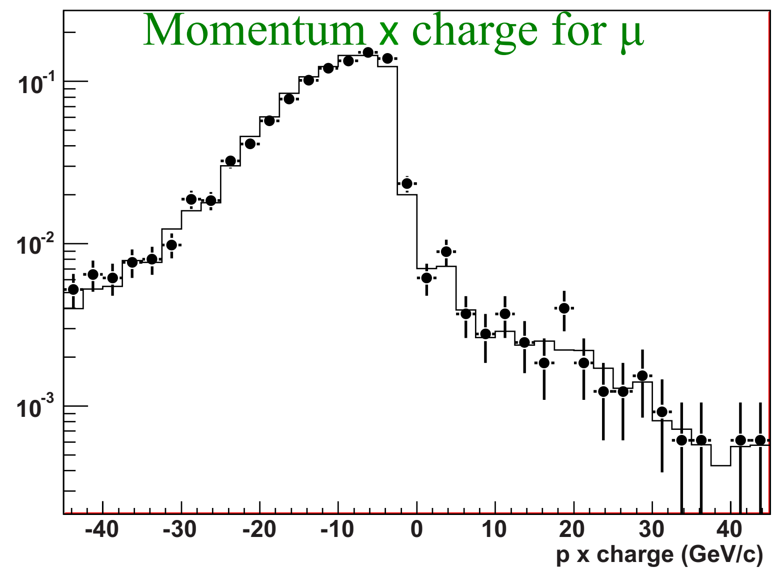
# Two target super-modules, each with an iron spectrometer for muon detection
JINST 4 (2009) P04018

# 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*

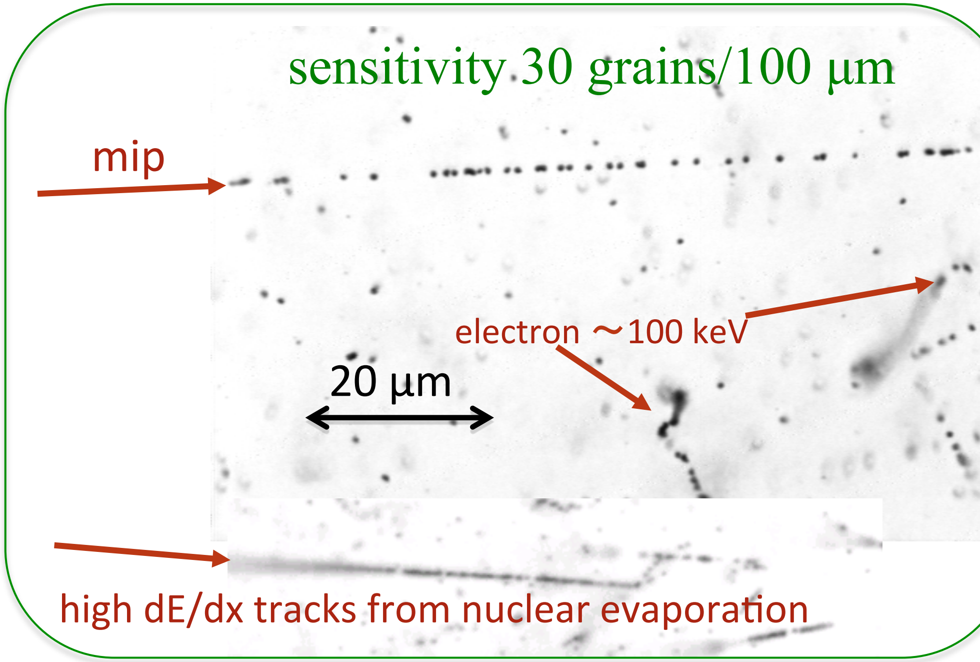
# The ECC Target Bricks

The heart of the experiment

<u>Emulsion Cloud Chamber</u>

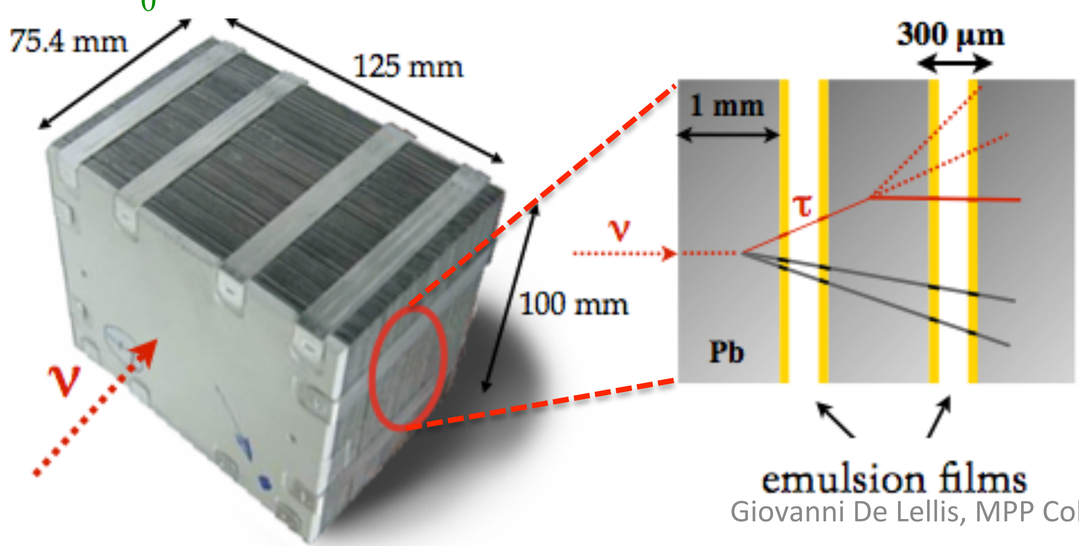
ECC

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




*NIM A556 (2006) 80-86*

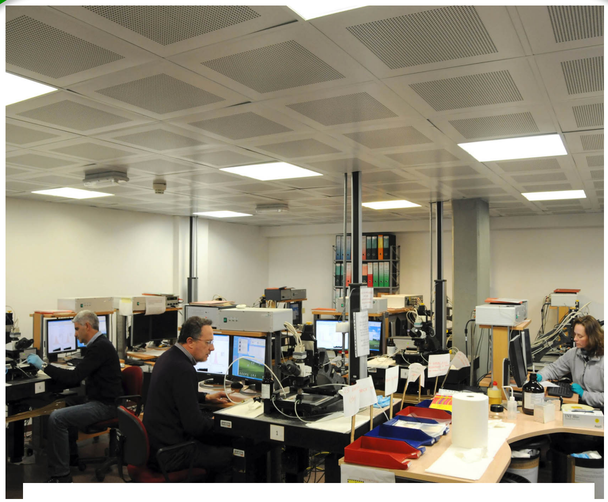
$10\ X_0$



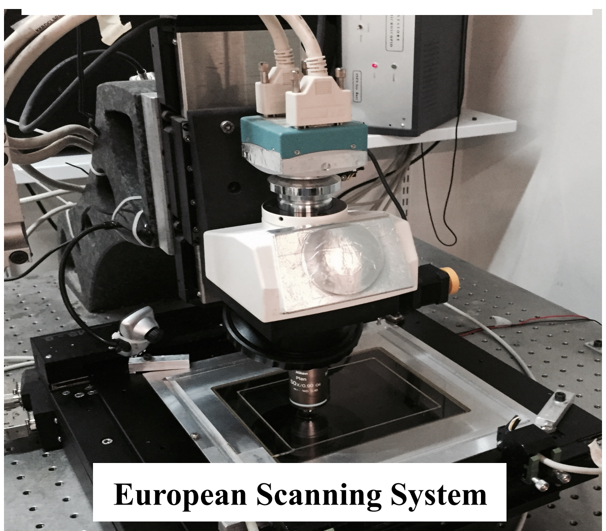

- The OPERA target consists of 150'000 ECC bricks
- Total lead surface: 105'000 m$^2$
- Total film surface: 110'000 m$^2$ (~ 9 million films)
- Total target mass ~ 1.2 kton

# SCANNING OF CHANGEABLE SHEETS

## Two large facilities

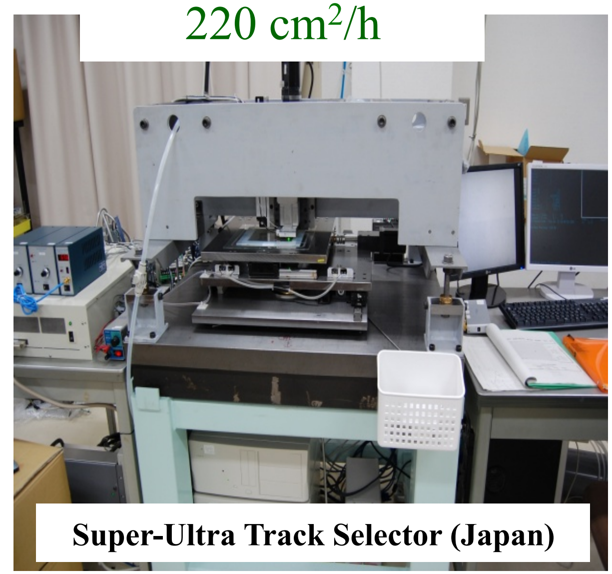


LNGS: 12 microscopes, 240 $cm^2/h$



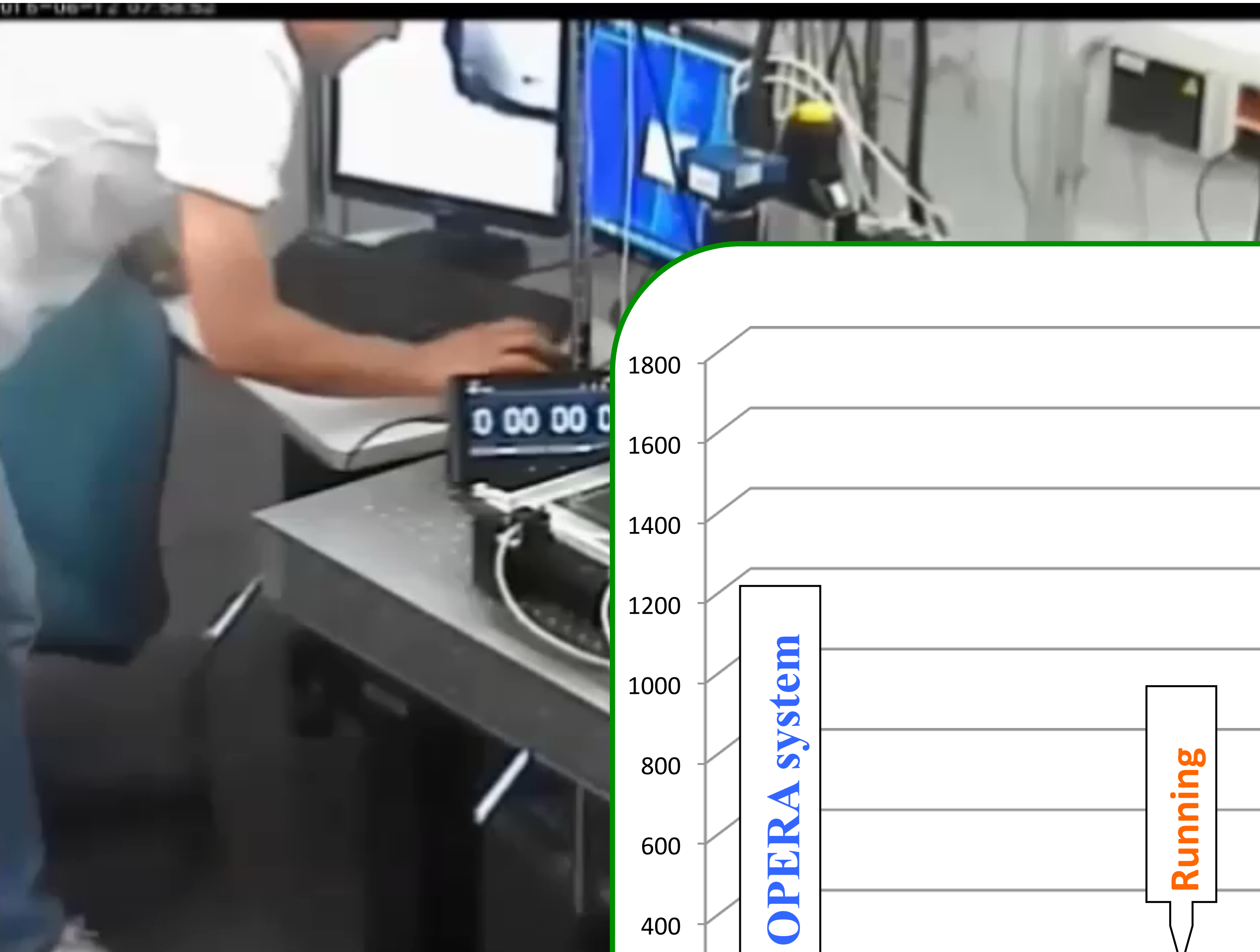
**European Scanning System**

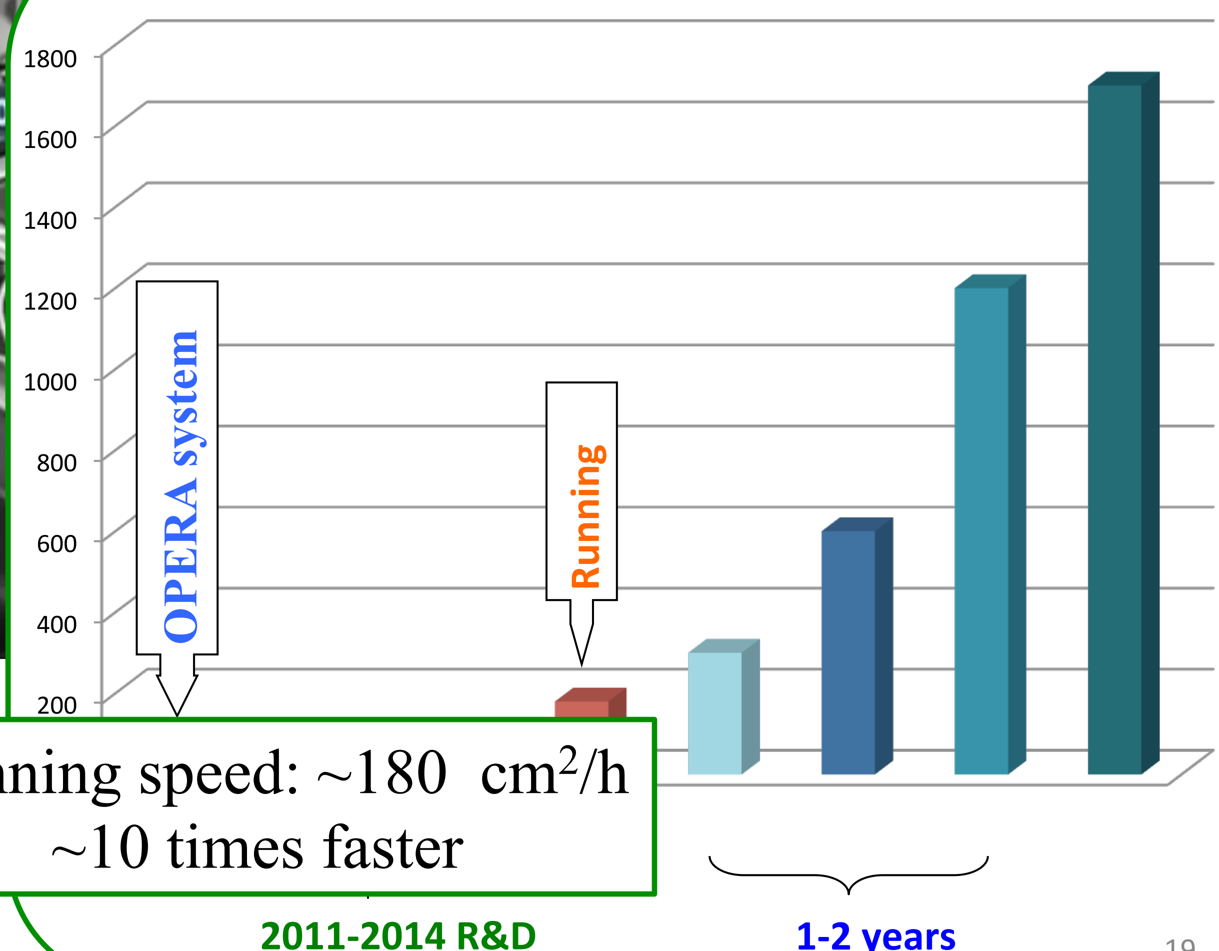
Nagoya: 5 S-UTS, 220 $cm^2/h$



**Super-Ultra Track Selector (Japan)**

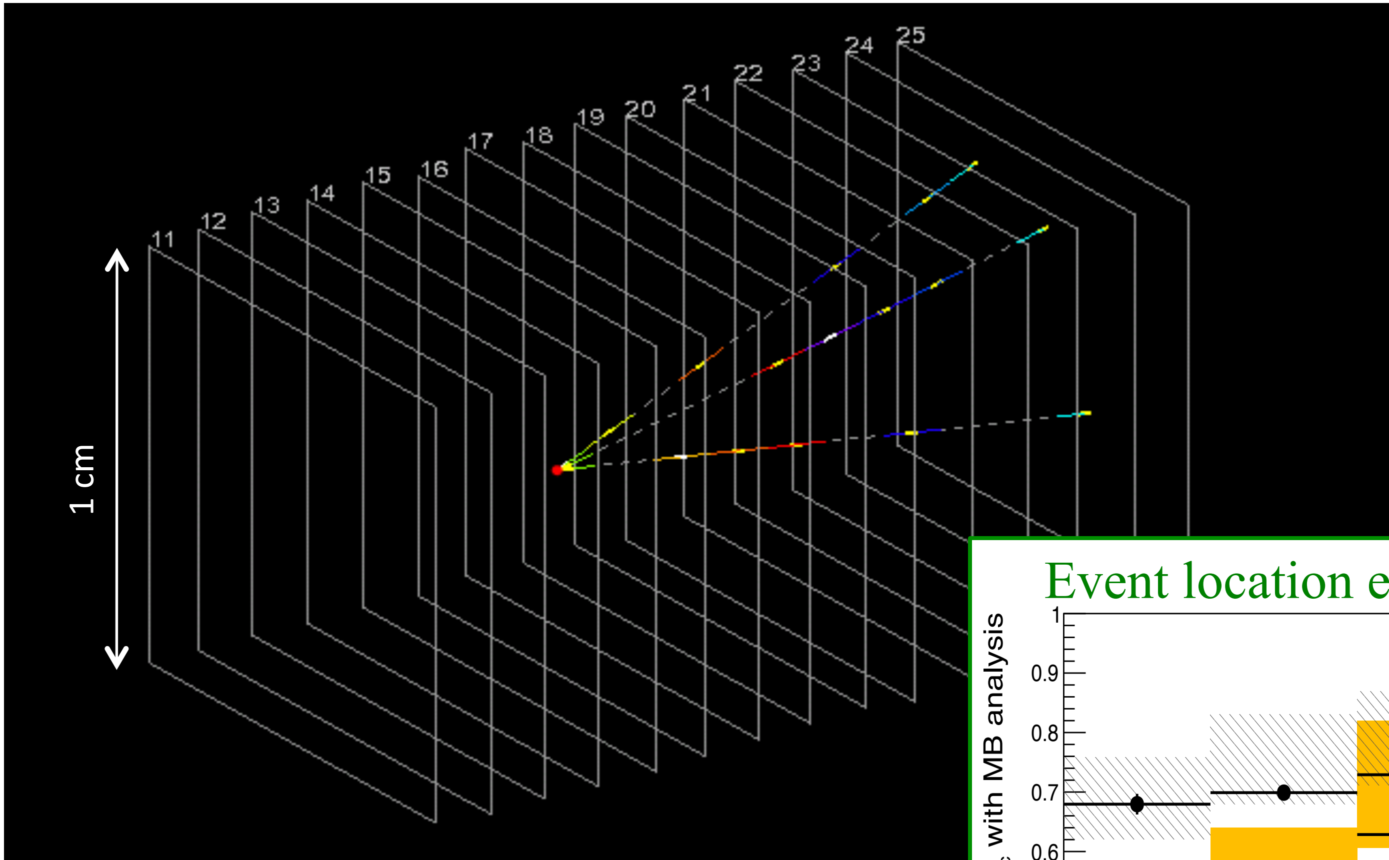
# IMPROVEMENTS IN THE SCANNING SYSTEM



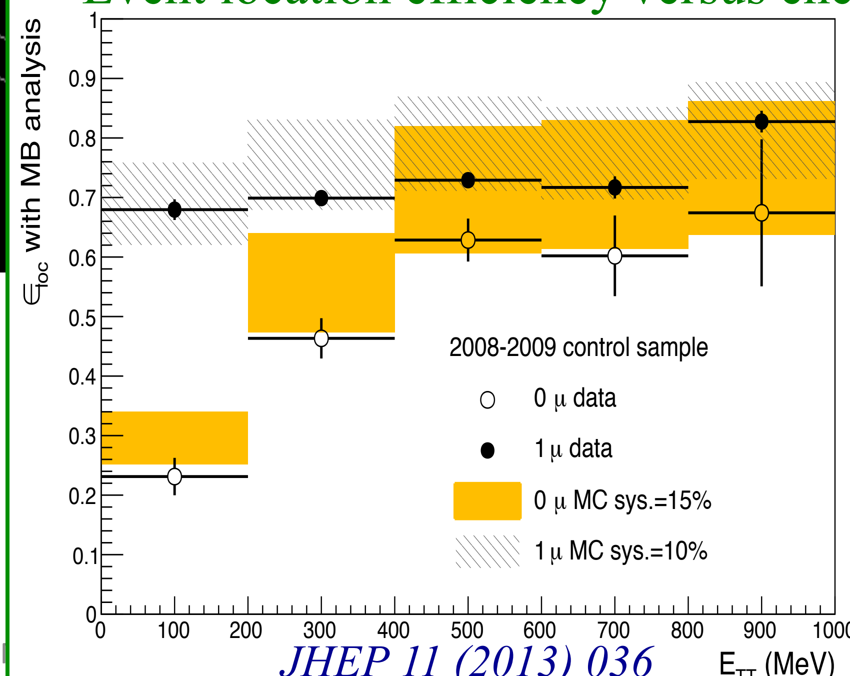



Scanning speed: ~180 $cm^2/h$
~10 times faster

# LOCATED NEUTRINO INTERACTION



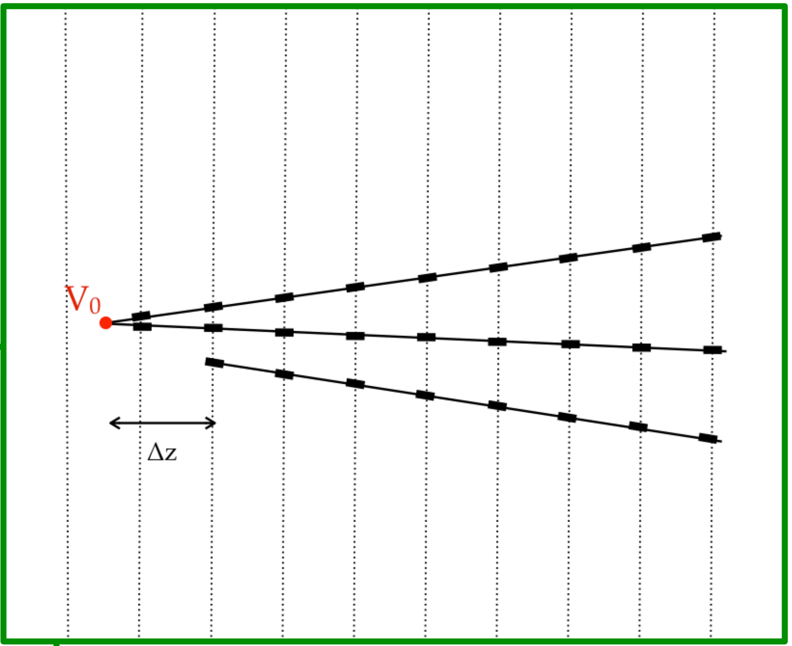

Event location efficiency versus energy

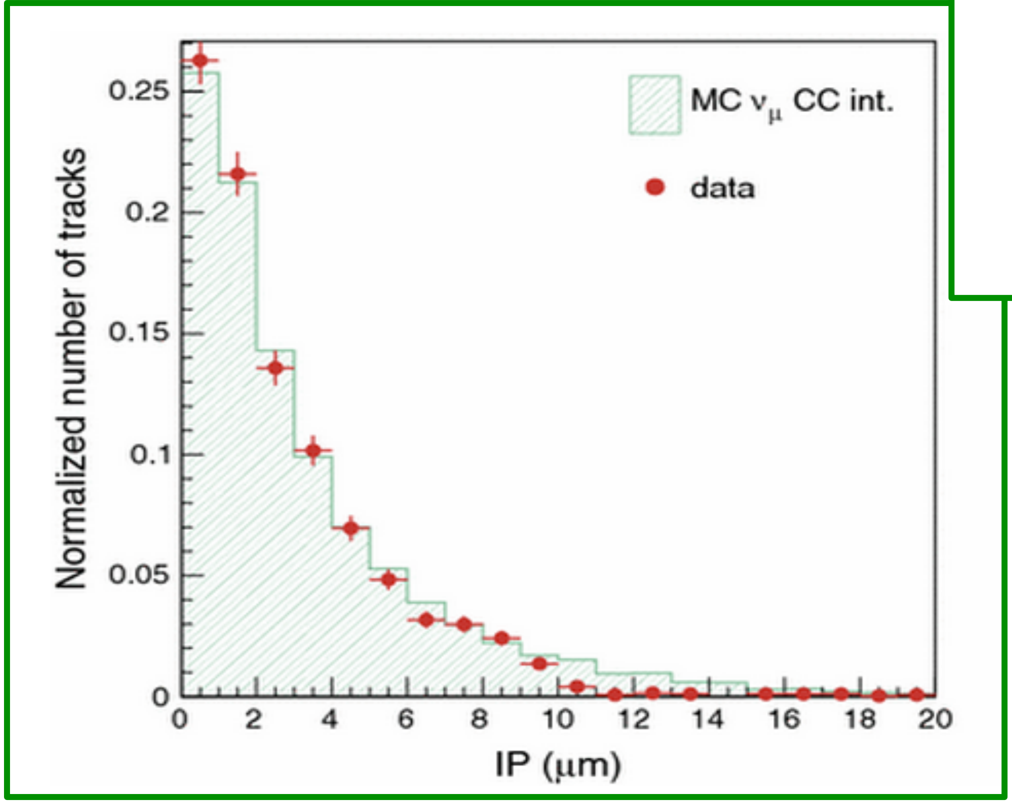



*JHEP 11 (2013) 036*

# DECAY SEARCH

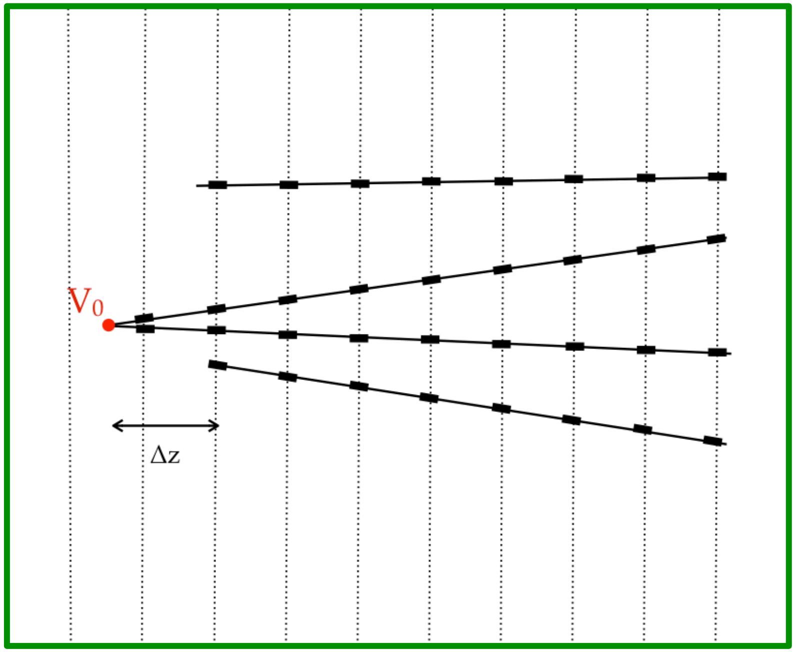
- **Primary vertex definition**
  - inspection of segments on the vertex plate
  - impact parameter <10 (5+0.01 Δz) μm, if Δz<(≥)500 μm

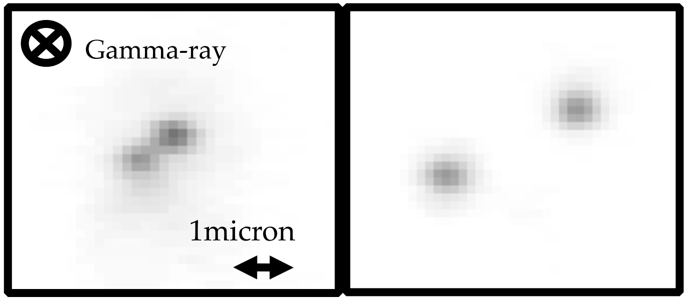


# DECAY SEARCH

- **Primary vertex definition**
  - inspection of segments on the vertex plate
  - impact parameter <10 (5+0.01 $\Delta z$) $\mu m$,
    if $\Delta z<(\geq)500$ $\mu m$
- **Extra-track search**
  - selection of tracks reconstructed in the volume but not attached to primary vertex
  - identification of $e^+e^-$ pairs by visual inspection

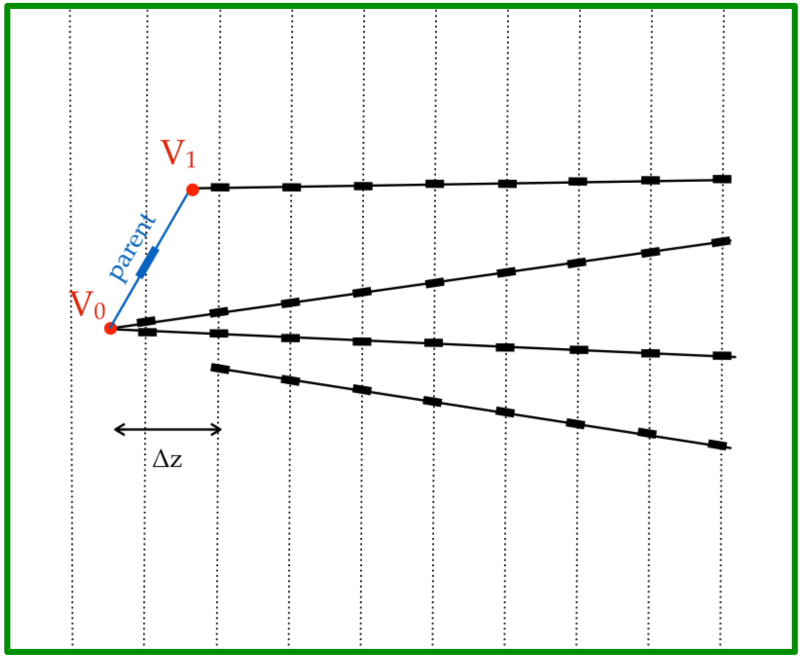



A close-up of an electron pair

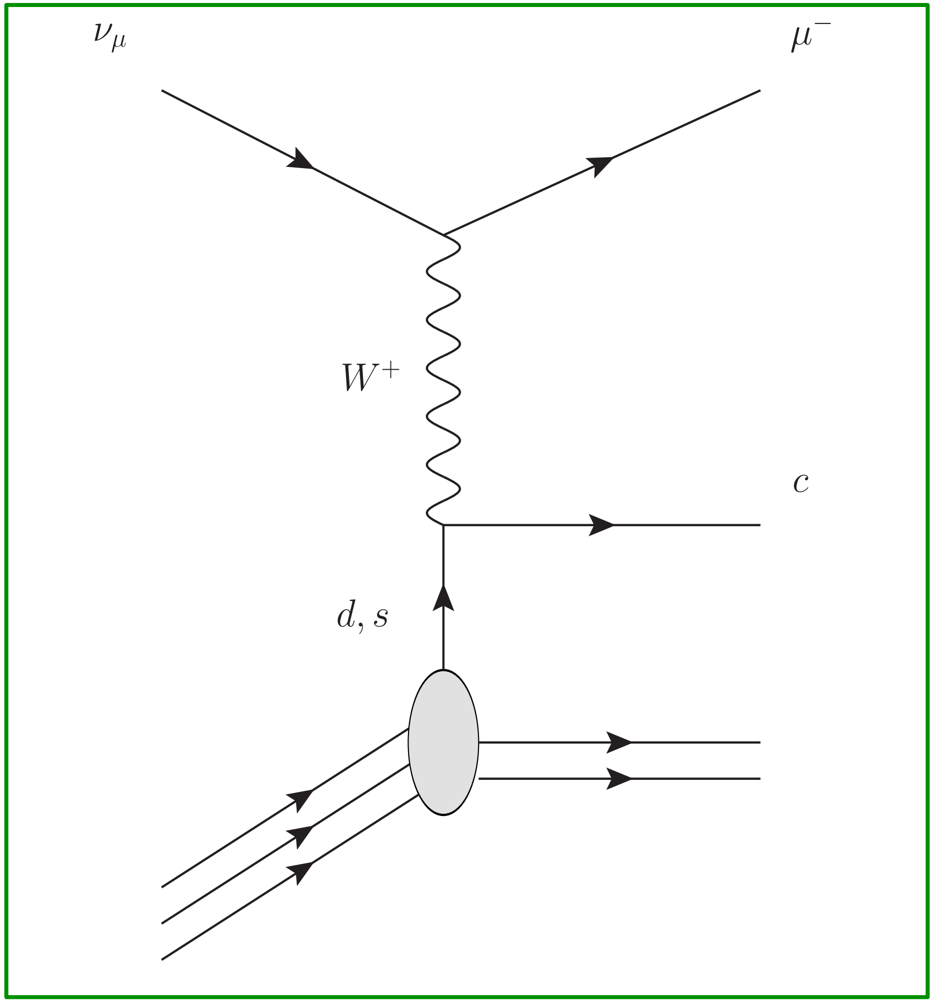
# Decay Search

- **Primary vertex definition**
  - inspection of segments on the vertex plate
  - impact parameter <10 (5+0.01 $\Delta z$) $\mu$m,
    if $\Delta z$<(≥)500 $\mu$m
- **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



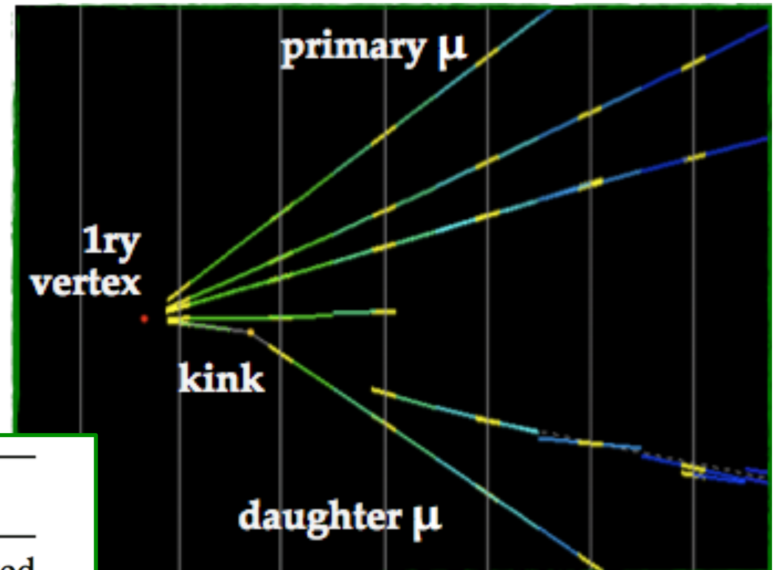
# CHARMED HADRON PRODUCTION

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 $\nu_\mu$ CC interactions
- Muon at the primary vertex
- Used as "control sample"




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

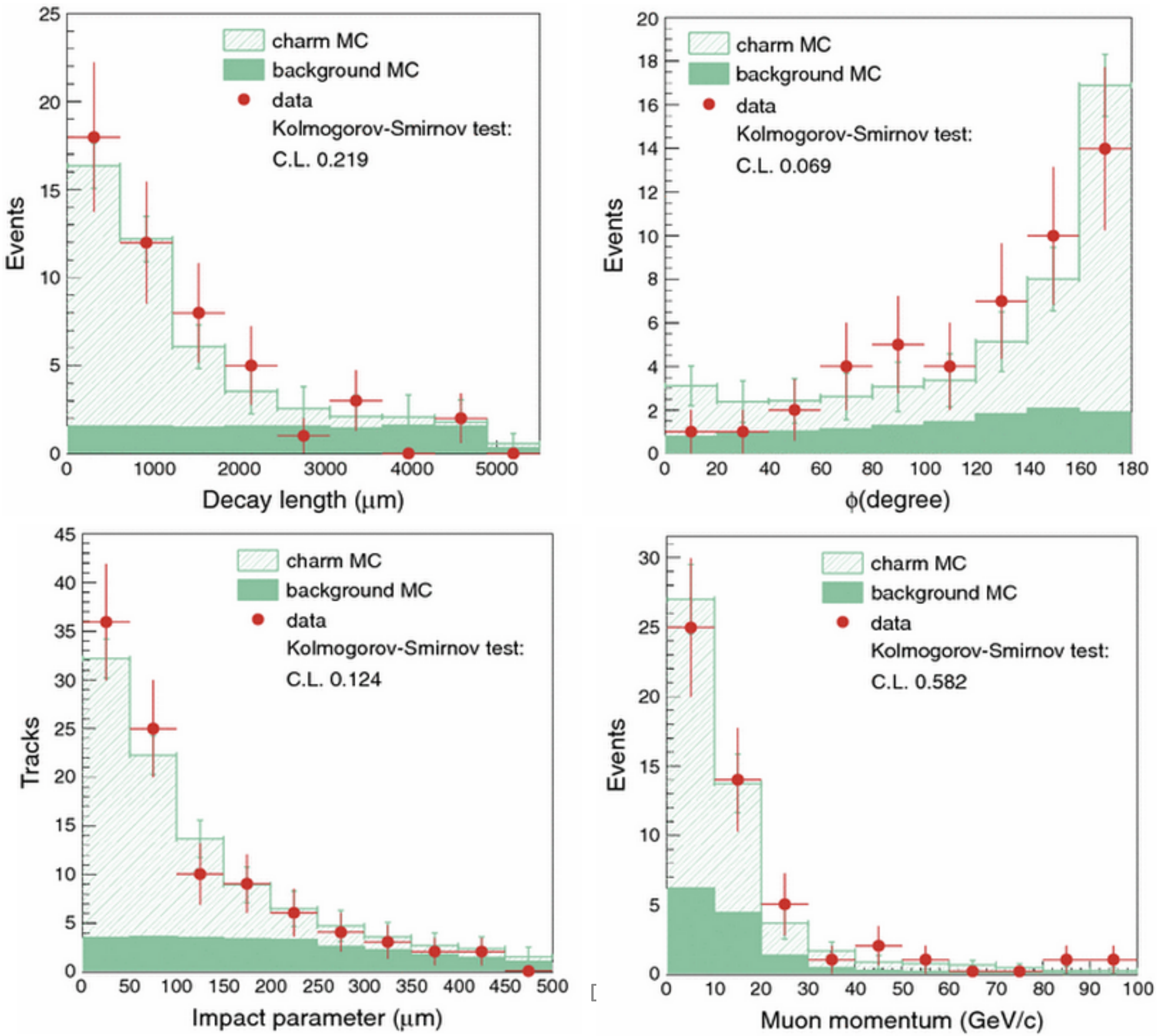
*Eur. Phys. J. C74 (2014) 2986*

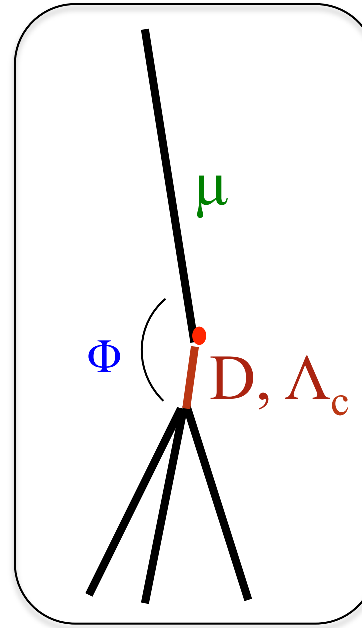
Background from hadronic interactions (87%) and strange particle decays (13%)

Good agreement between data and expectations ~10%

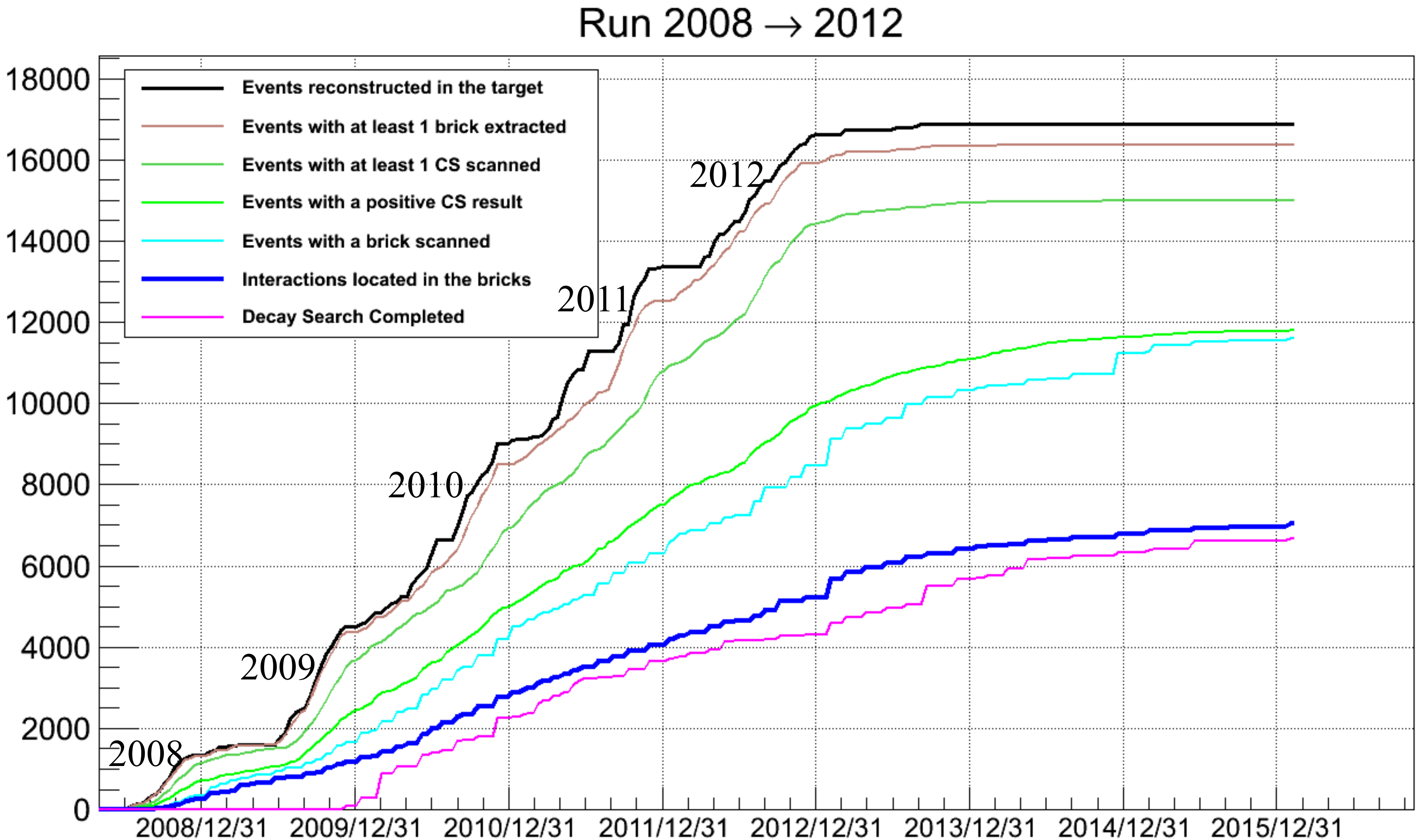
# KINEMATICAL VARIABLES

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



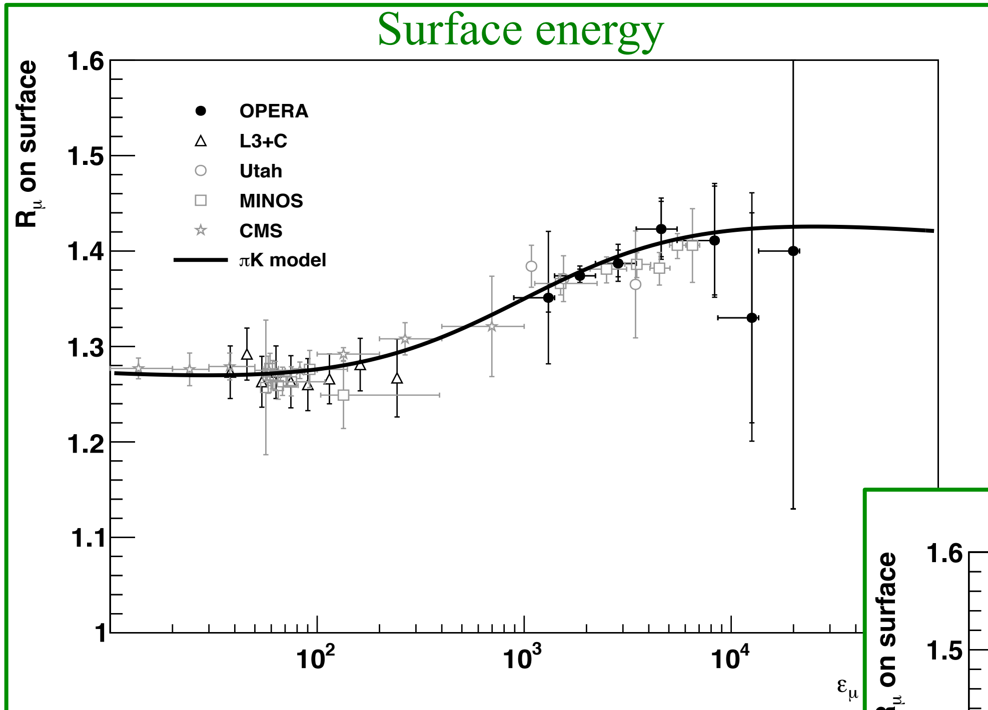
# Status Of Data Analysis




7041 located interactions

6682 decay search

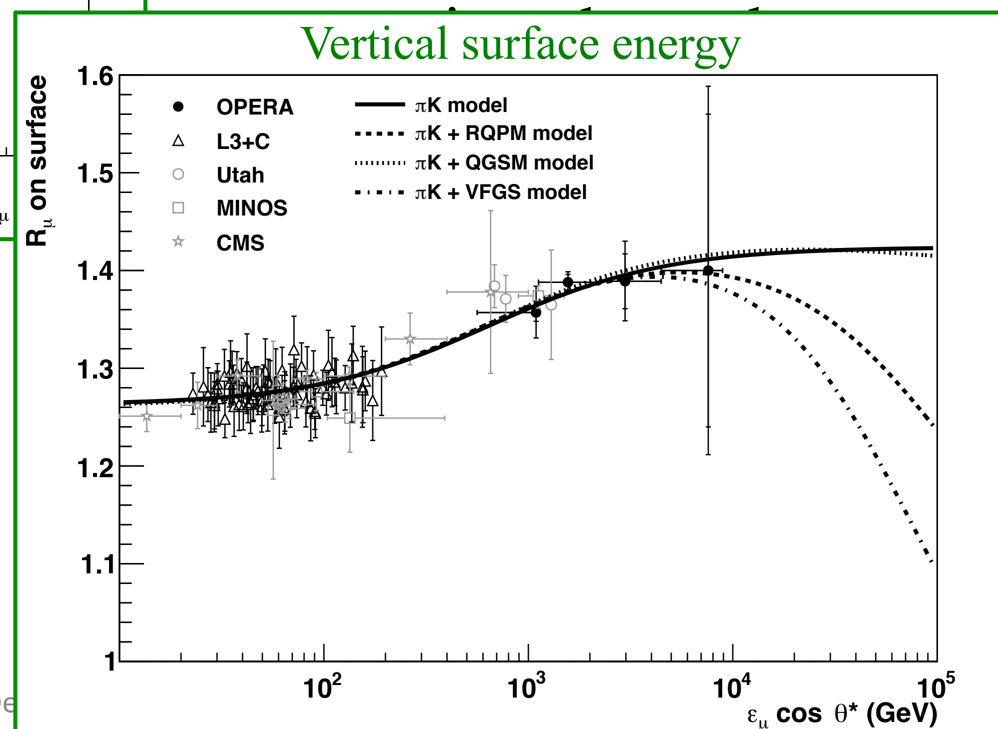
# Cosmic-Ray Physics




Measurement of TeV atmospheric muon charge ratio

*Eur. Phys. J. C74 (2014) 2933*

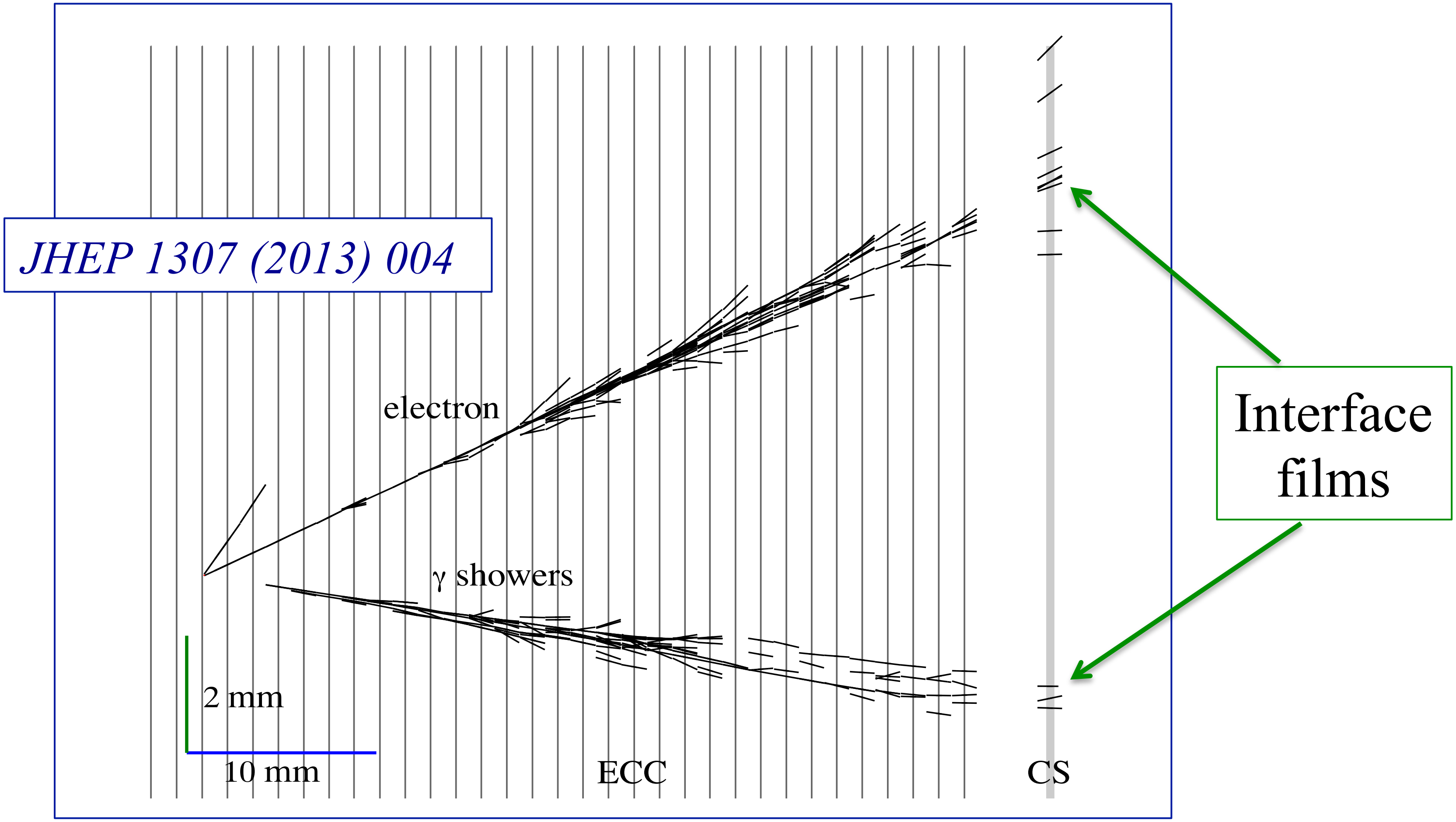
$$R_\mu \equiv N_{\mu^+}/N_{\mu^-}$$



# Oscillation physics

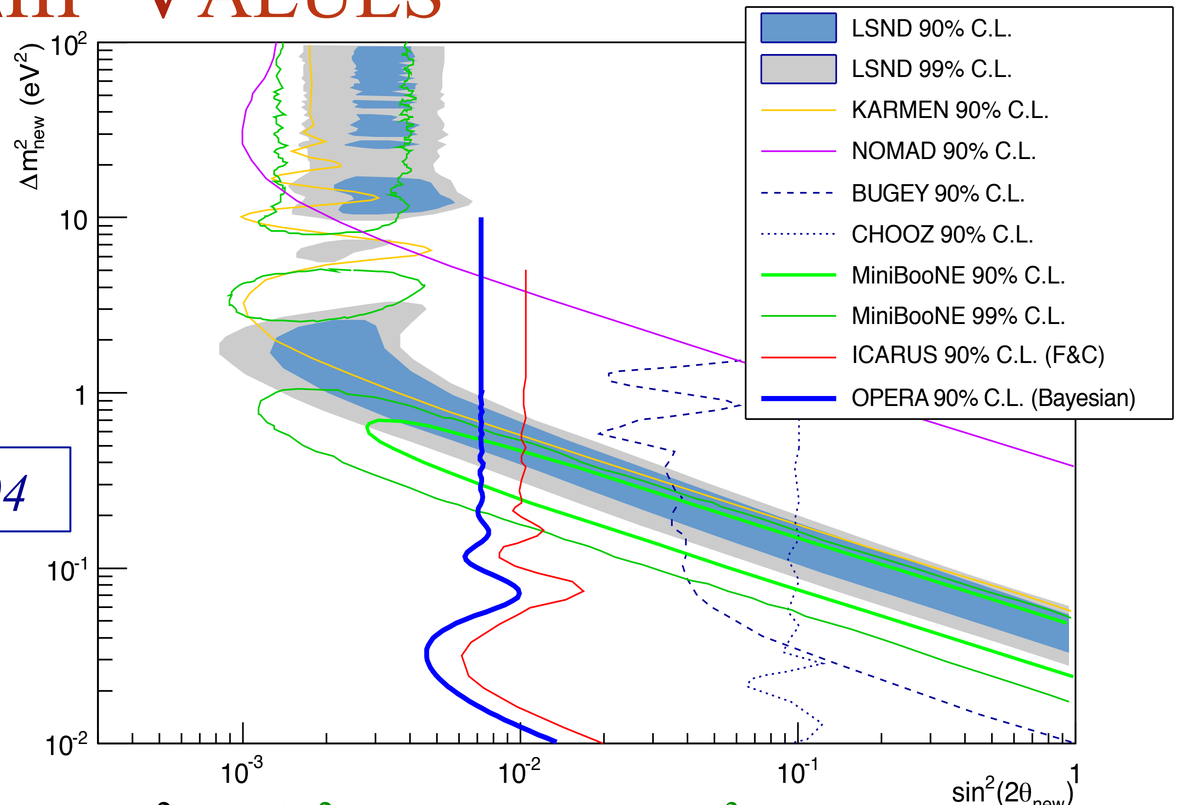
# $\nu_\mu \rightarrow \nu_e$ ANALYSIS WITH 2008/2009 DATA

one of the $\nu_e$ 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 49 observed candidates

9 with E < 20 GeV

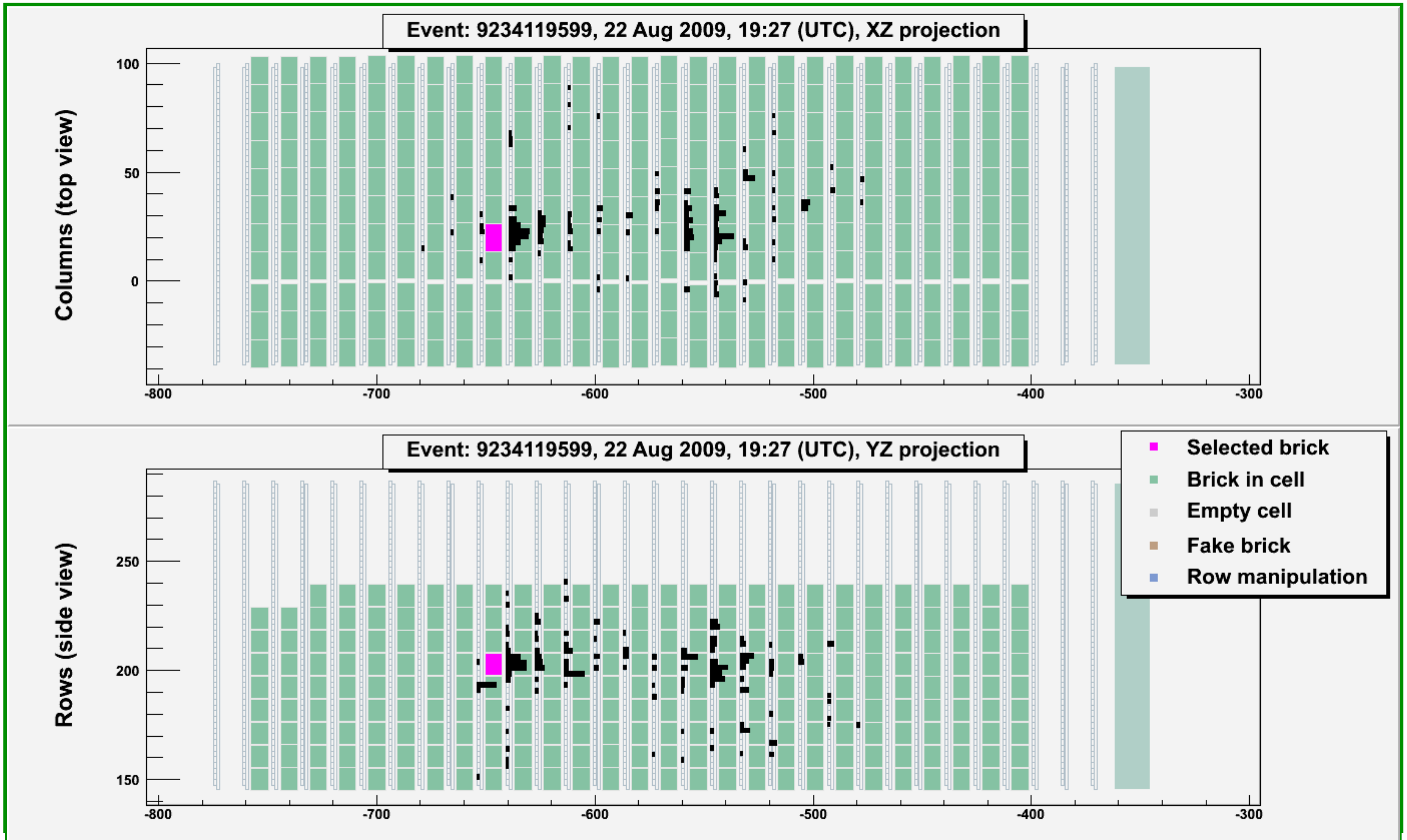
New paper in preparation

# $\nu_\mu \rightarrow \nu_\tau$ 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

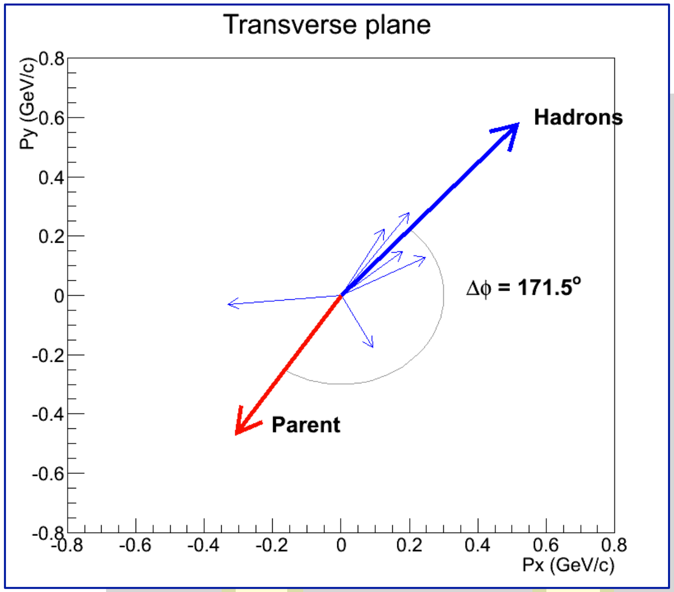
# THE FIRST $\nu_\tau$ CANDIDATE

As seen by the electronic detectors …

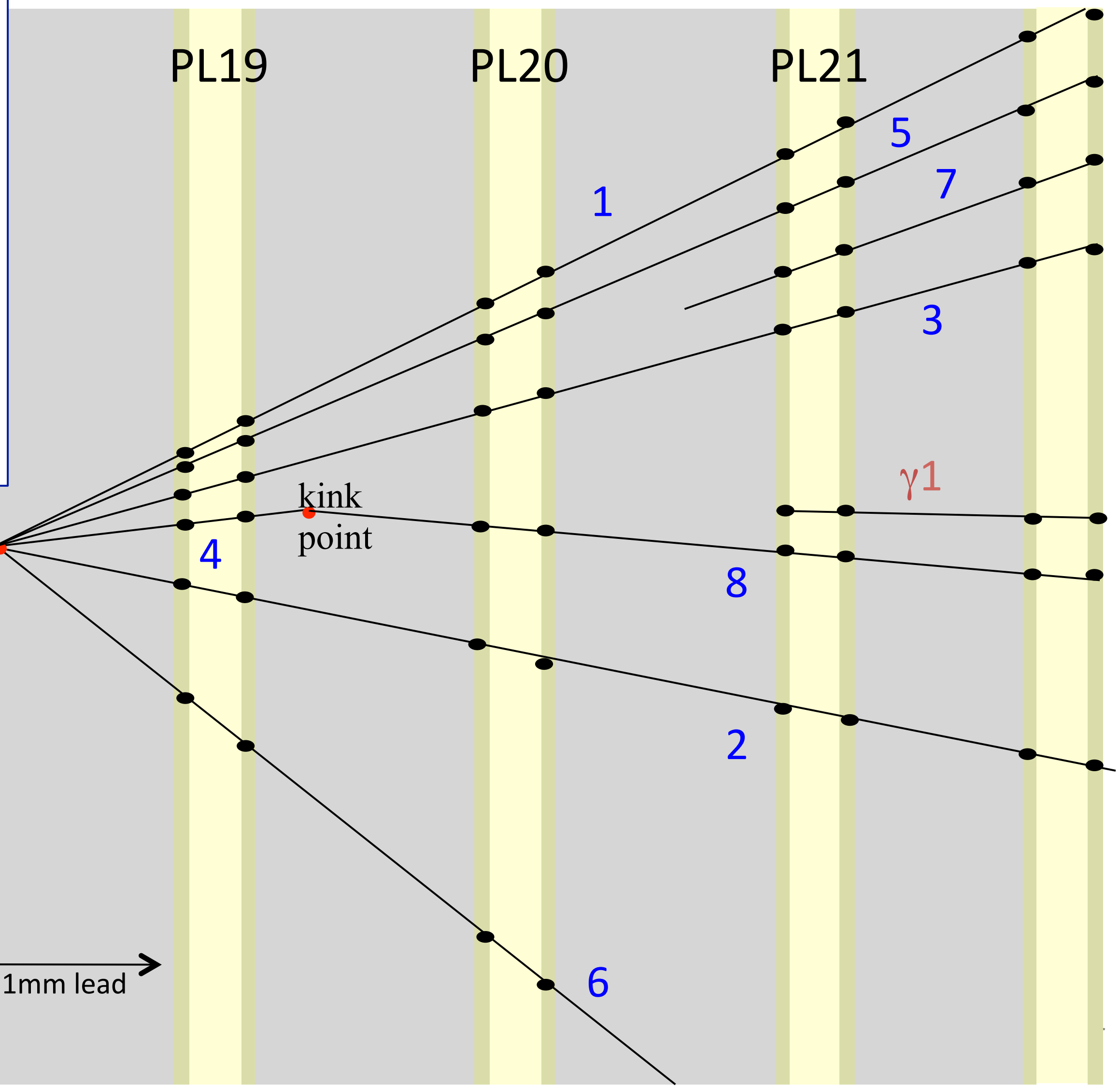



*Physics Letters B691 (2010) 138*

# The First $\nu_\tau$ Candidate

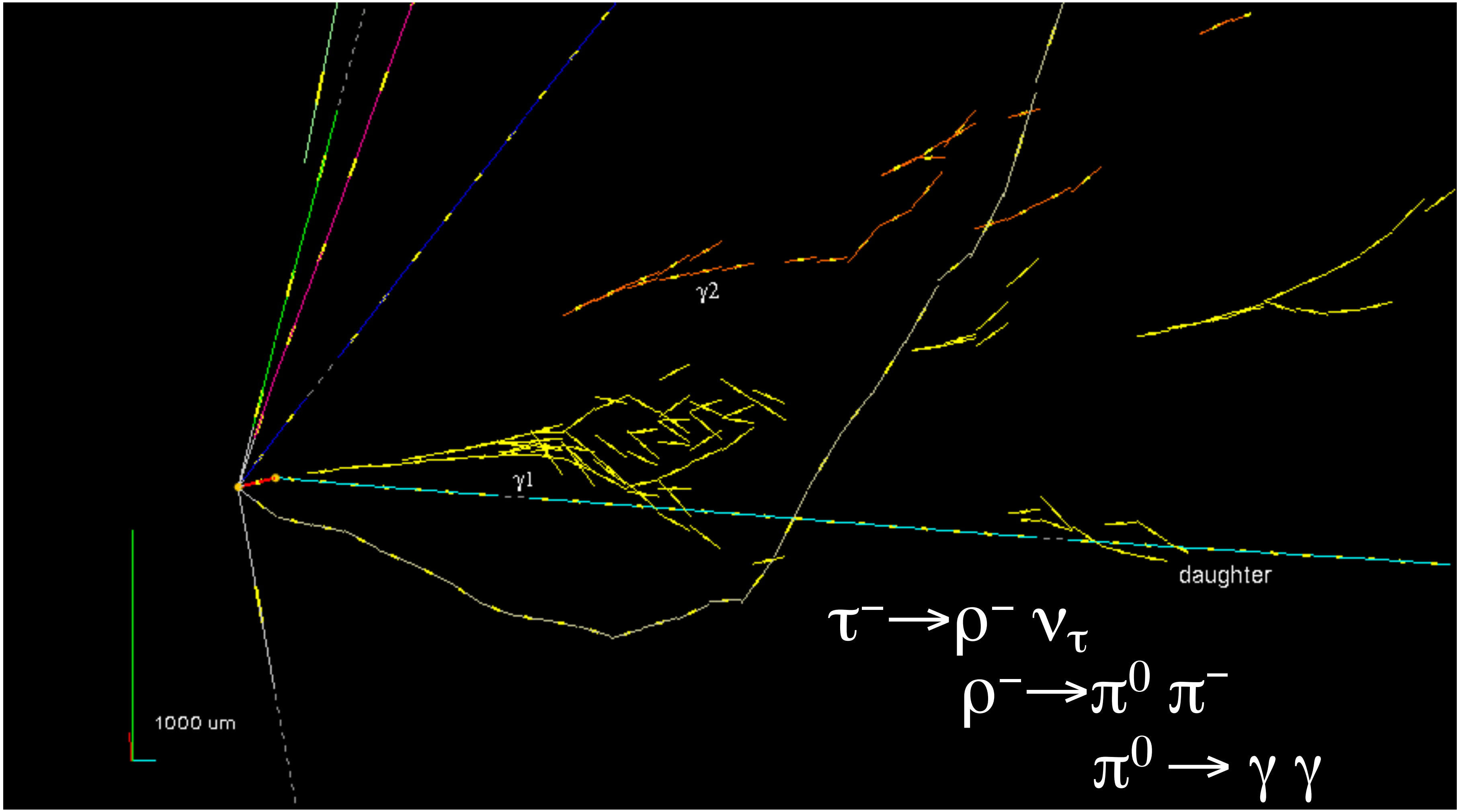



… and in the brick



# THE FIRST $\nu_\tau$ CANDIDATE

… and in the brick




$\tau^- \rightarrow \rho^- \nu_\tau$

$\rho^- \rightarrow \pi^0 \pi^-$

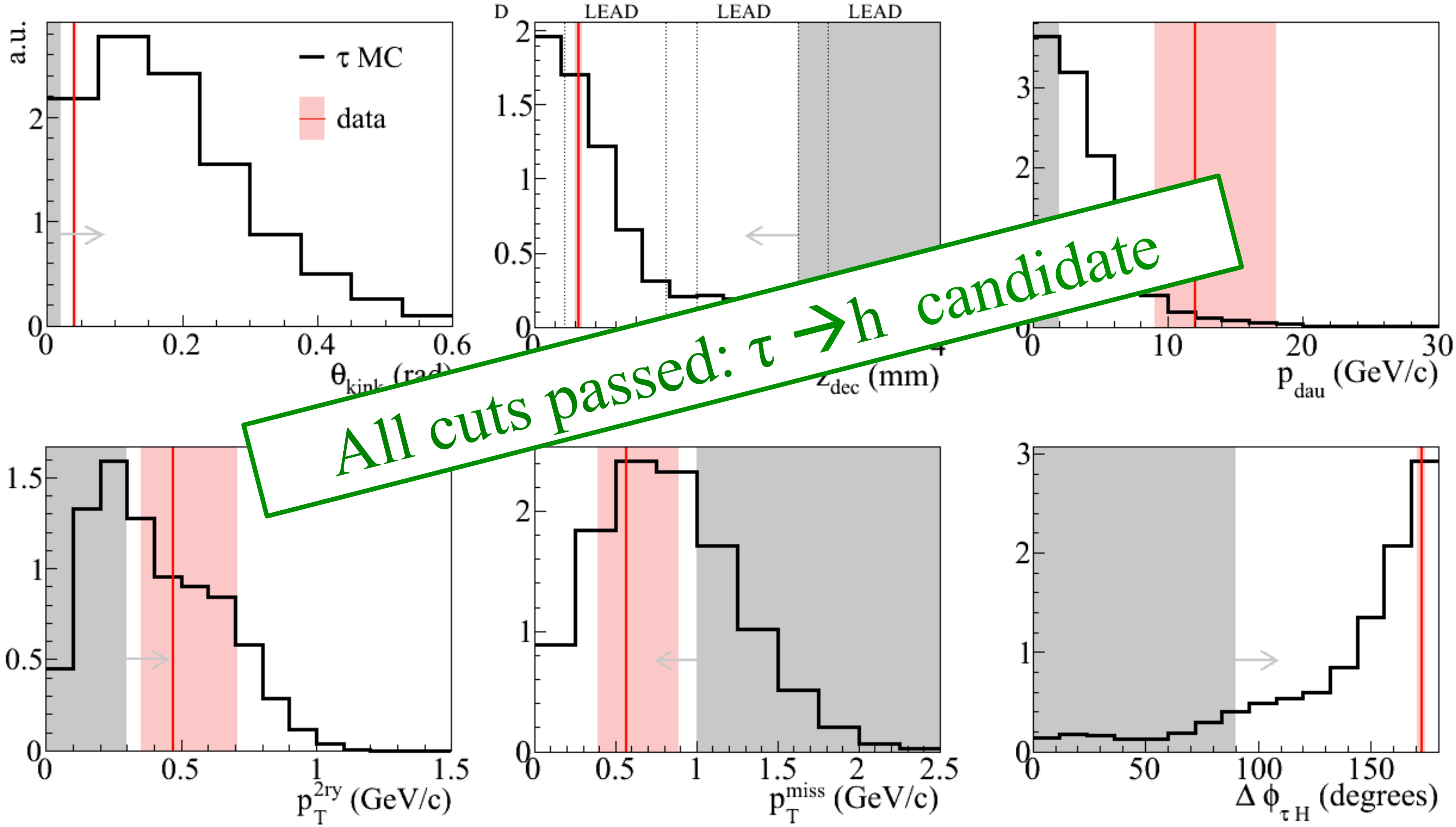
$\pi^0 \rightarrow \gamma \gamma$



*Physics Letters B691 (2010) 138*

# THE FIRST $\nu_\tau$ CANDIDATE

Kinematical selection

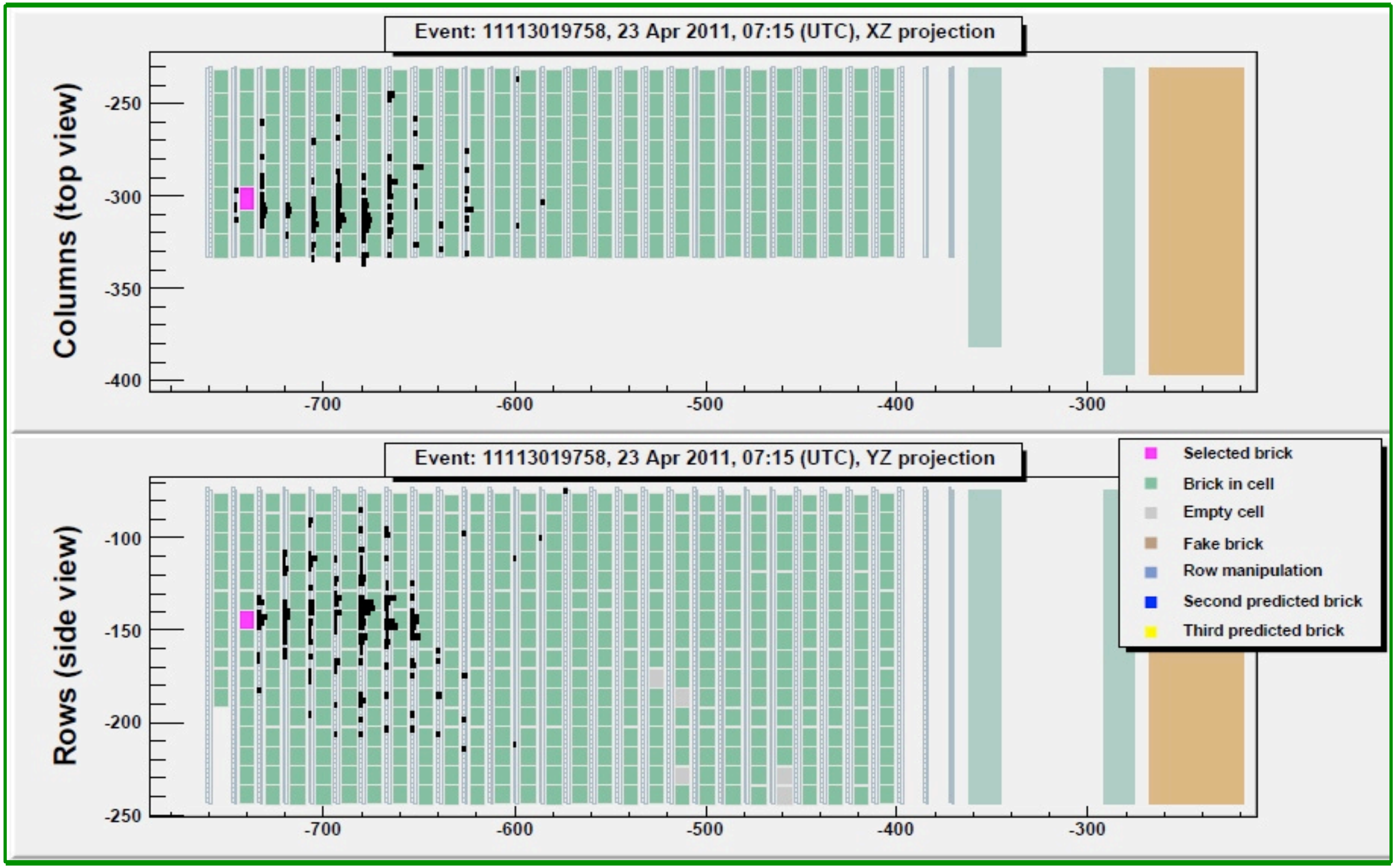





*Physics Letters B691 (2010) 138*

# THE SECOND $\nu_\tau$ CANDIDATE

As seen by the electronic detectors …

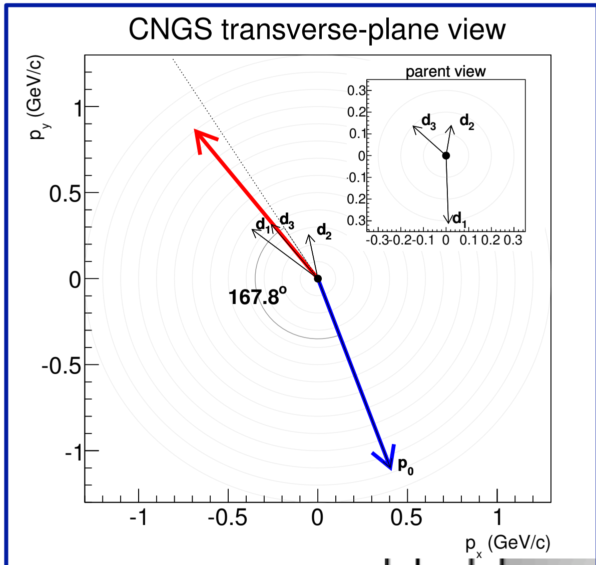


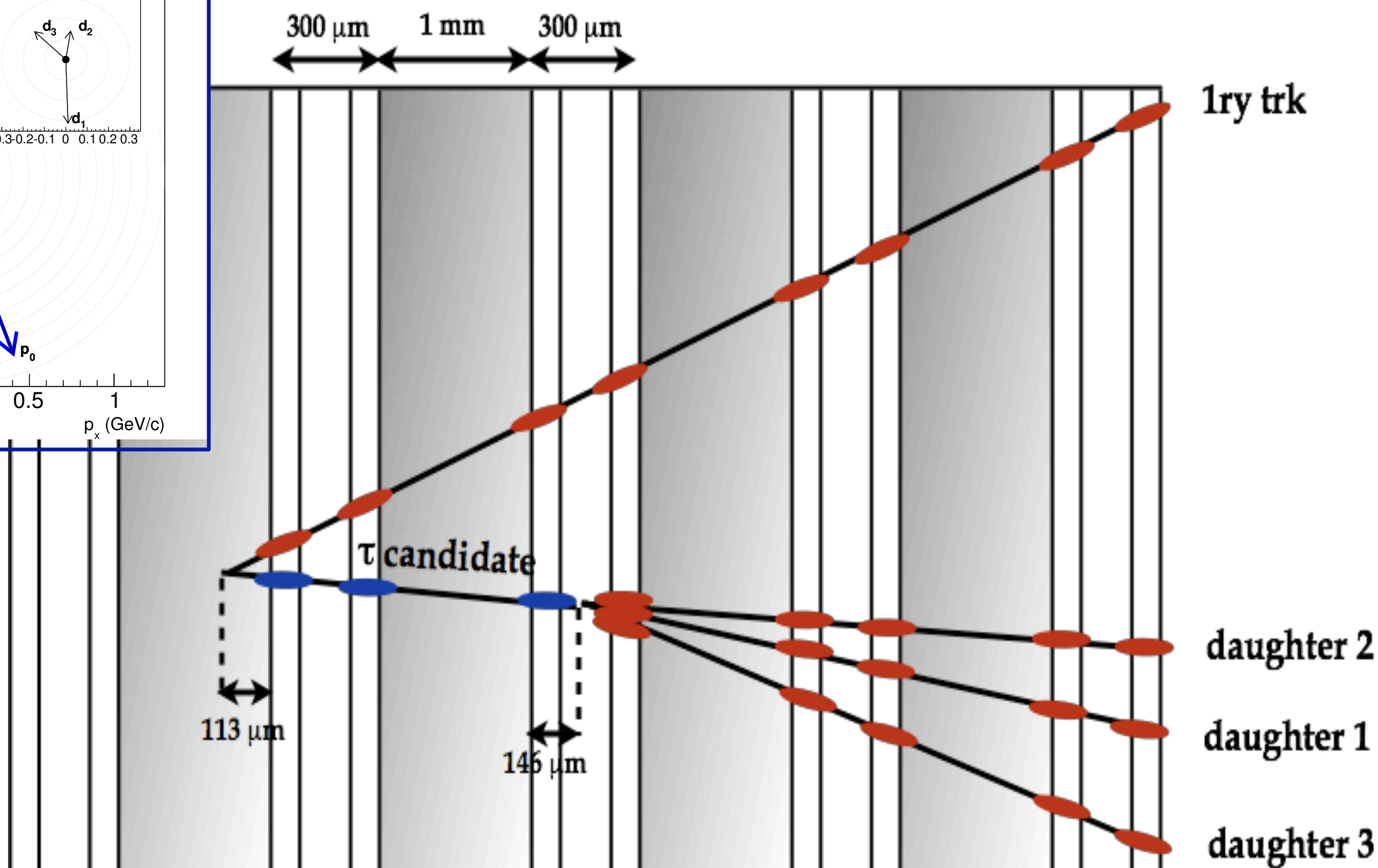



*Journal of High Energy Physics 11 (2013) 036*

# THE SECOND $\nu_\tau$ CANDIDATE

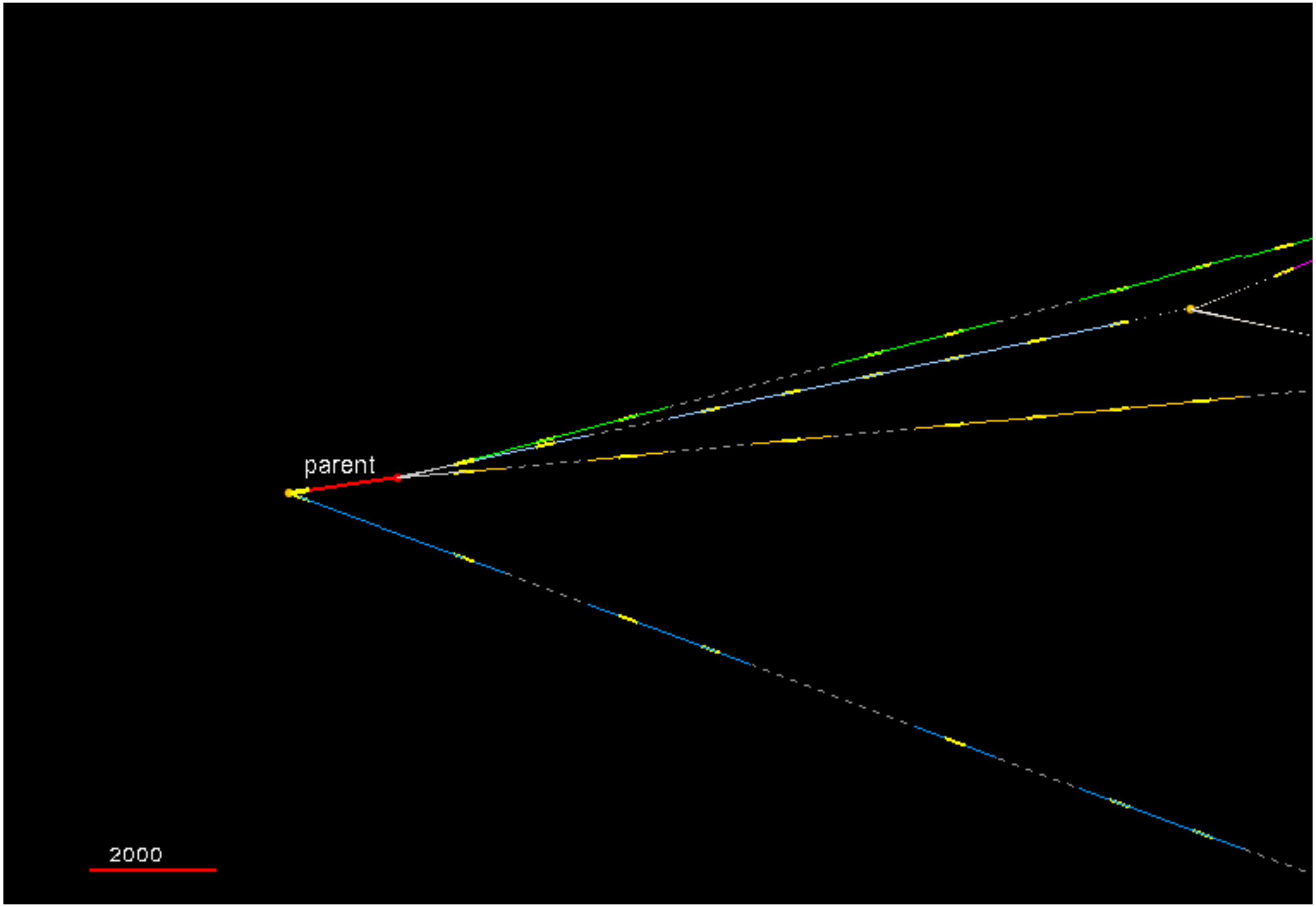
… and in the brick



# THE SECOND $\nu_\tau$ CANDIDATE

… and in the brick

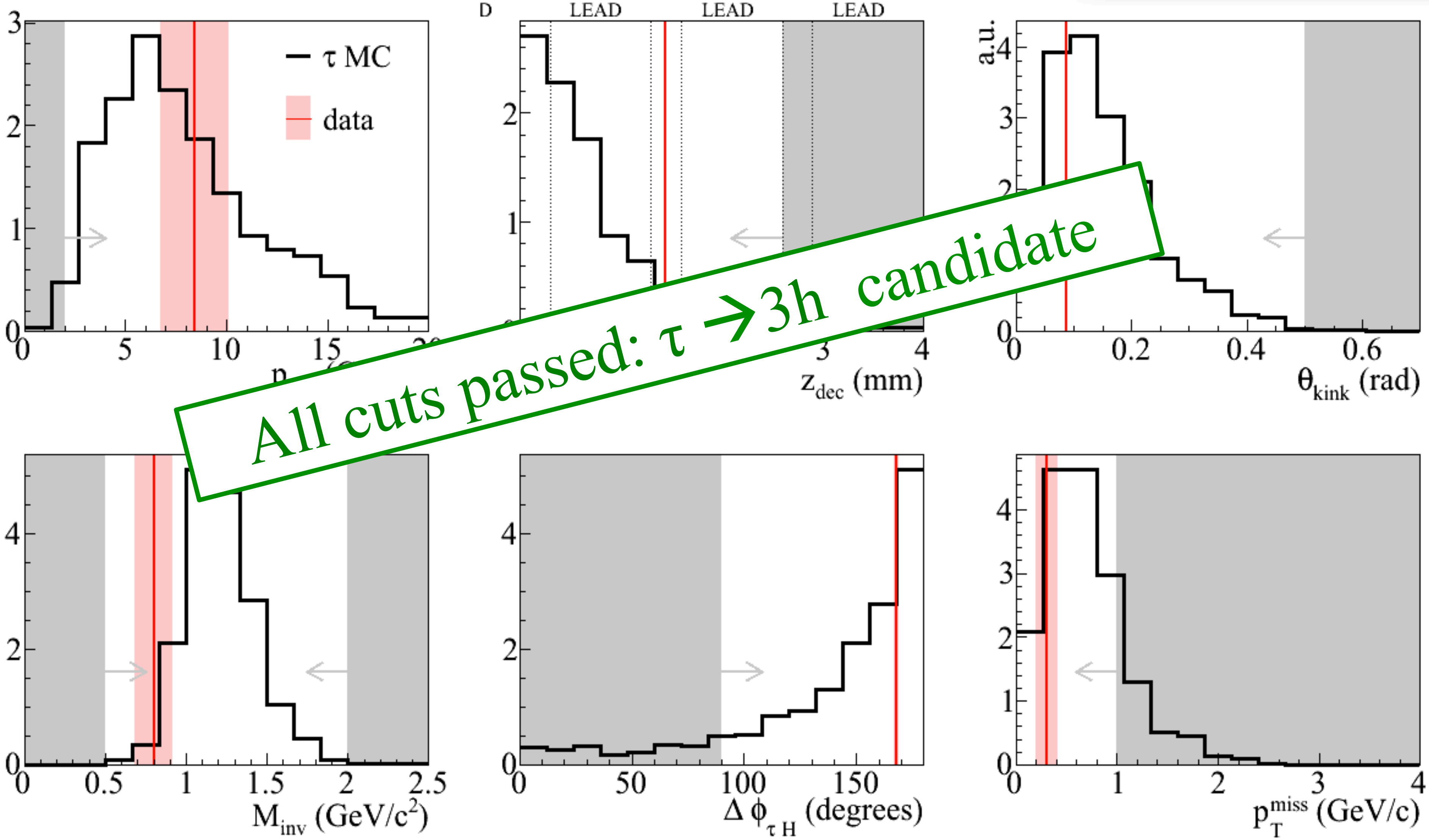





*Journal of High Energy Physics 11 (2013) 036*

# THE SECOND $\nu_\tau$ CANDIDATE

Kinematical selection

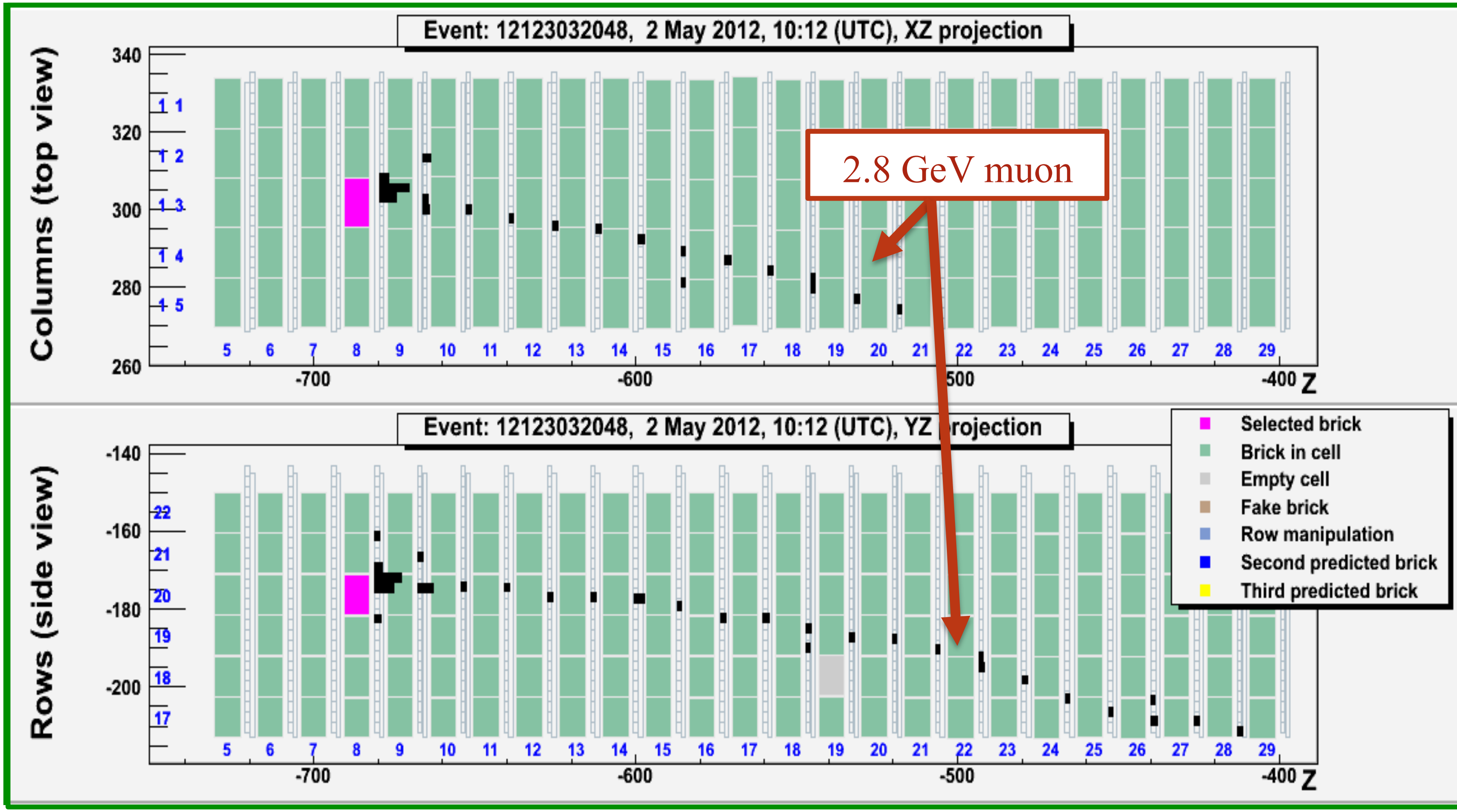





*Journal of High Energy Physics 11 (2013) 036*

# THE THIRD $\nu_\tau$ CANDIDATE

As seen by the electronic detectors …

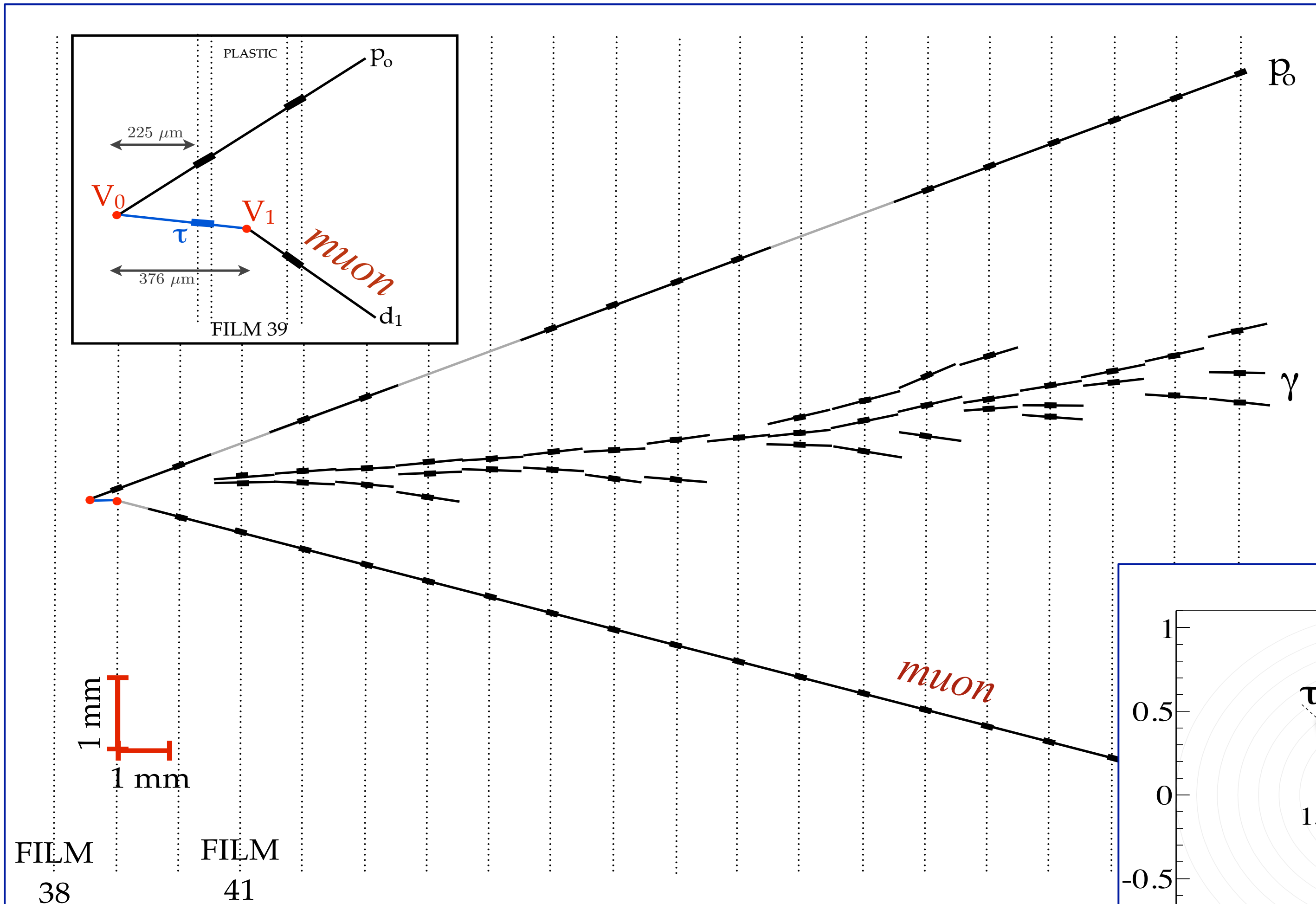


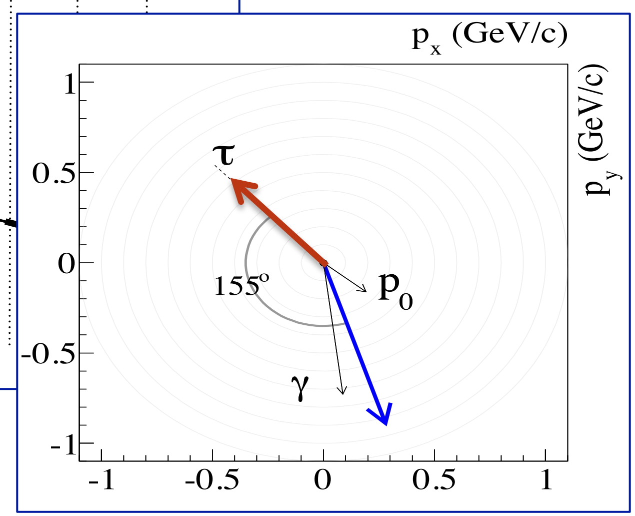



*Phys. Rev. D 89 (2014) 051102(R)*

# THE THIRD $\nu_\tau$ CANDIDATE

… and in the brick

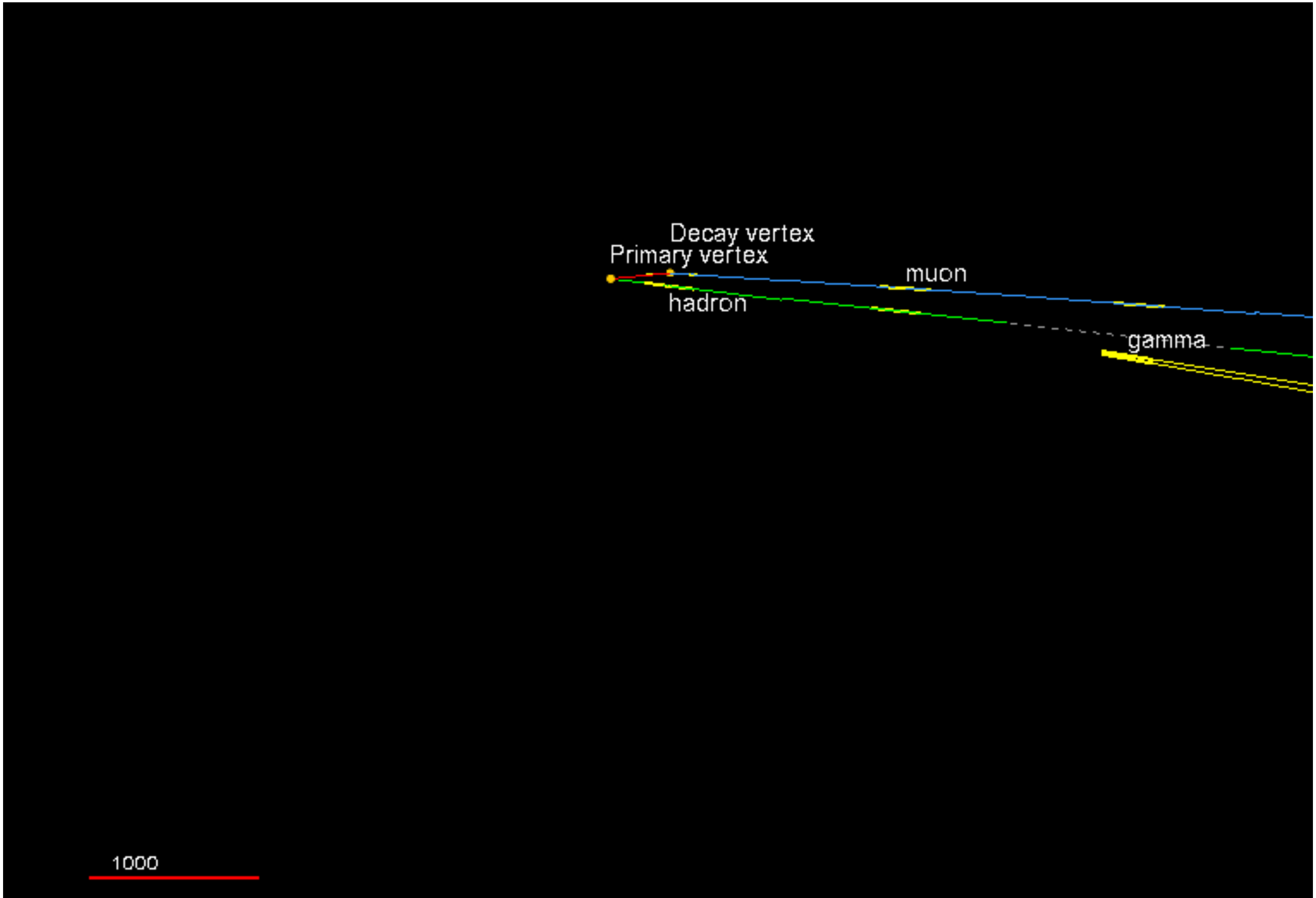


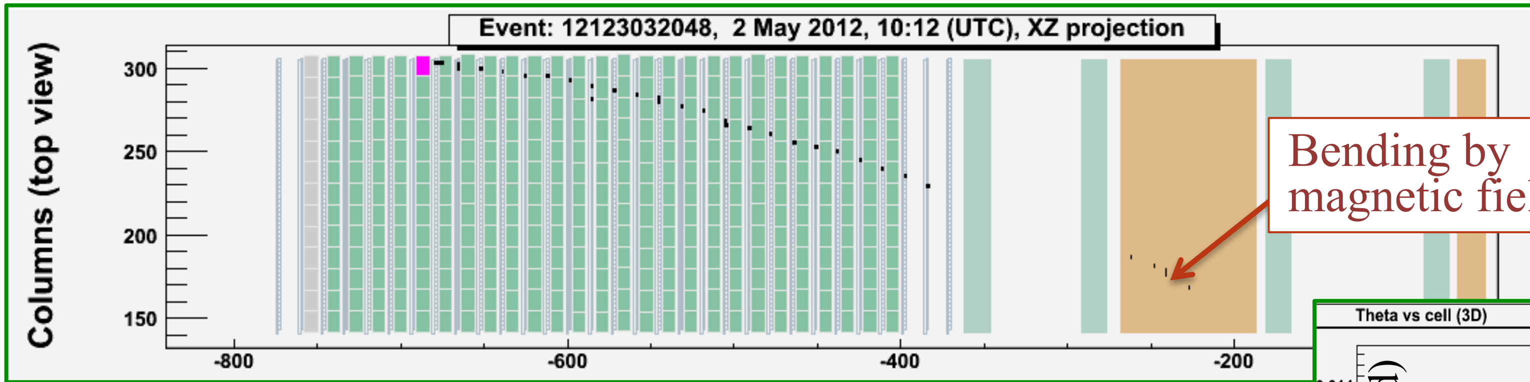

*Phys. Rev. D 89 (2014) 051102(R)*

# The Third $\nu_\tau$ Candidate

… and in the brick

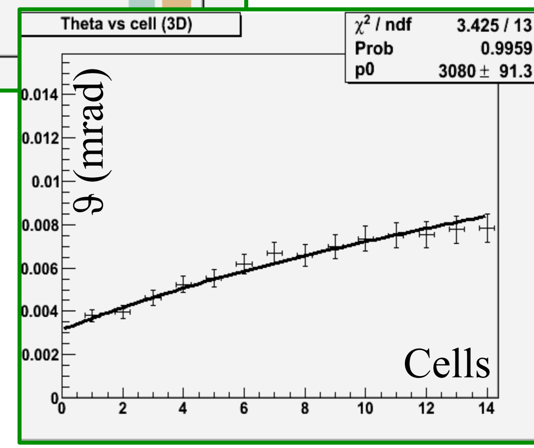


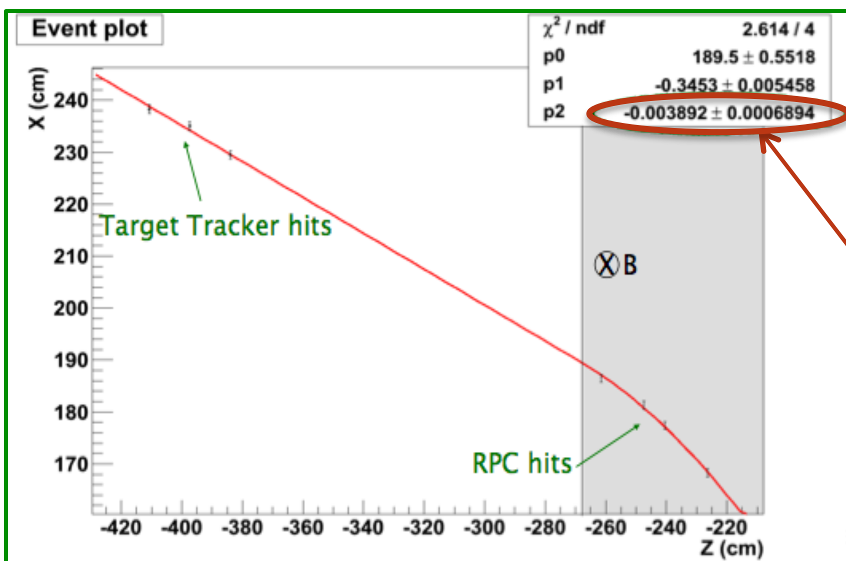
# Muon Charge And Momentum




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



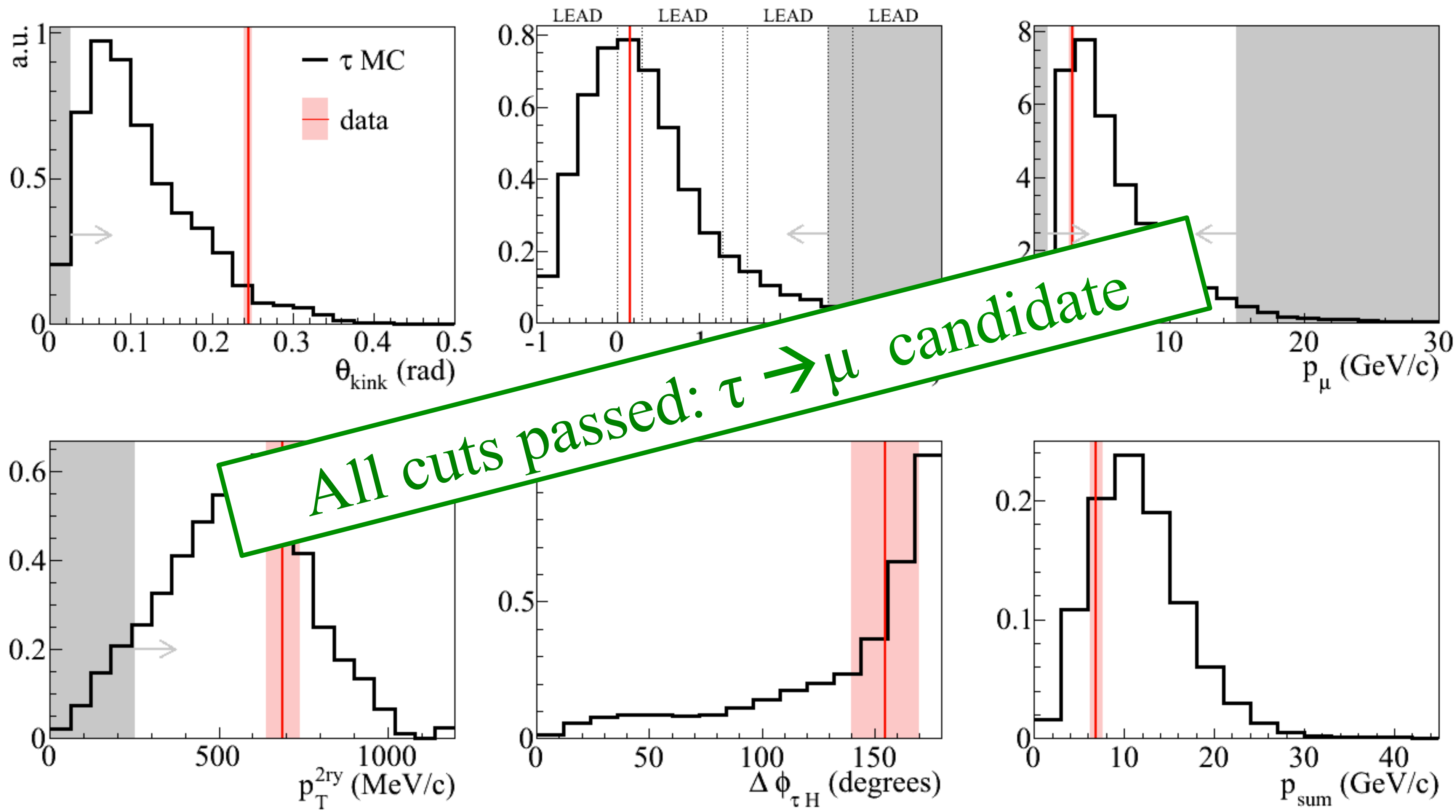




- Parabolic fit with $p_2$ as quadratic term coefficient in the magnetized region
- Linear fit in the non-magnetized region

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

# THE THIRD $\nu_\tau$ CANDIDATE

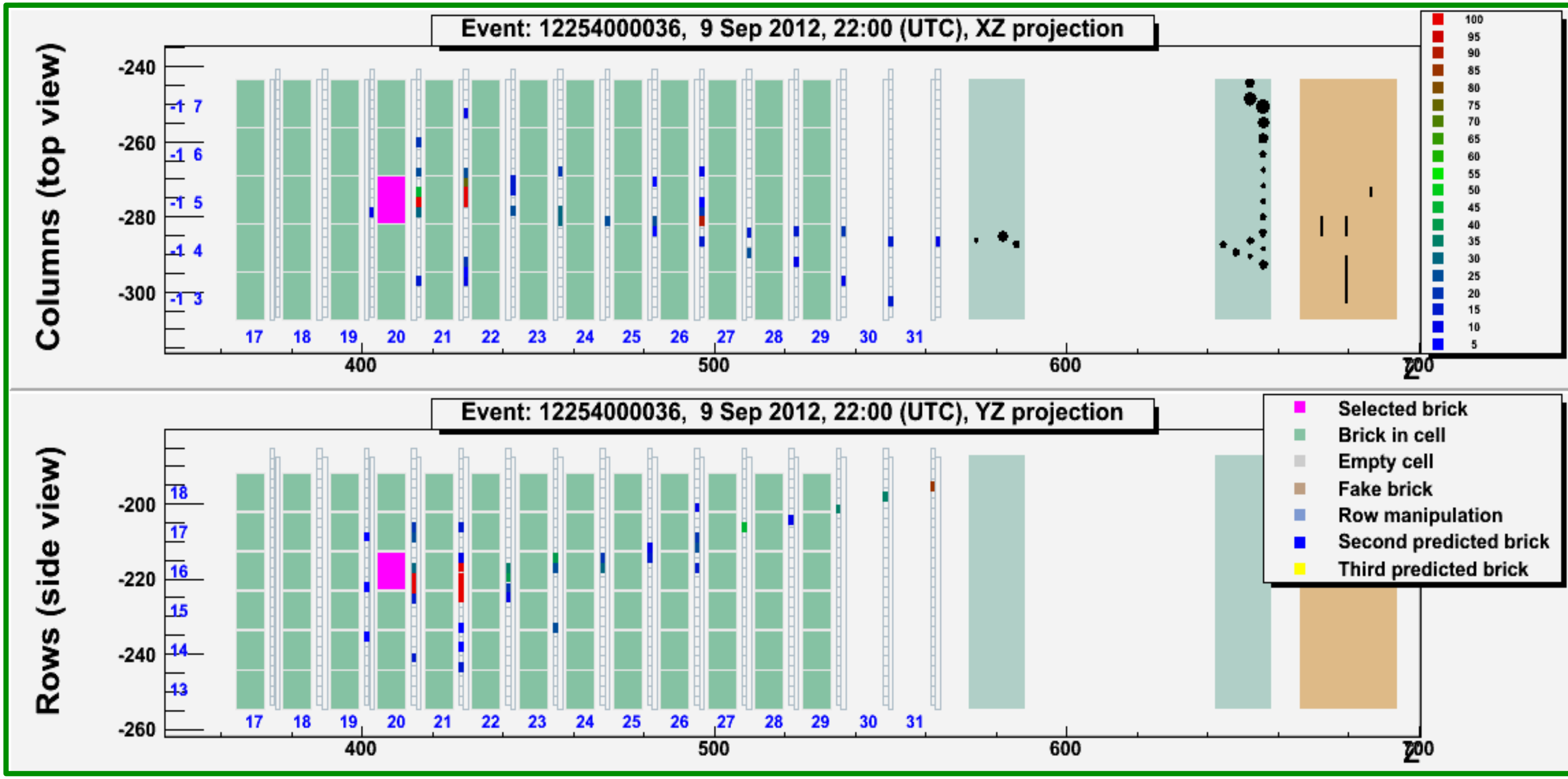
## Kinematical selection




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

# THE FOURTH $\nu_\tau$ CANDIDATE

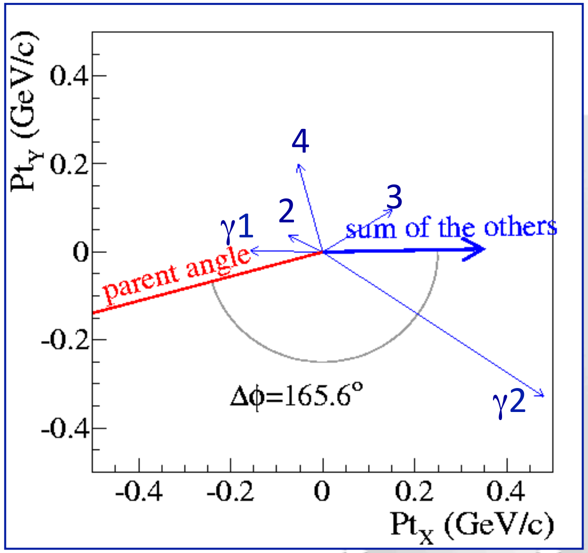
As seen by the electronic detectors …

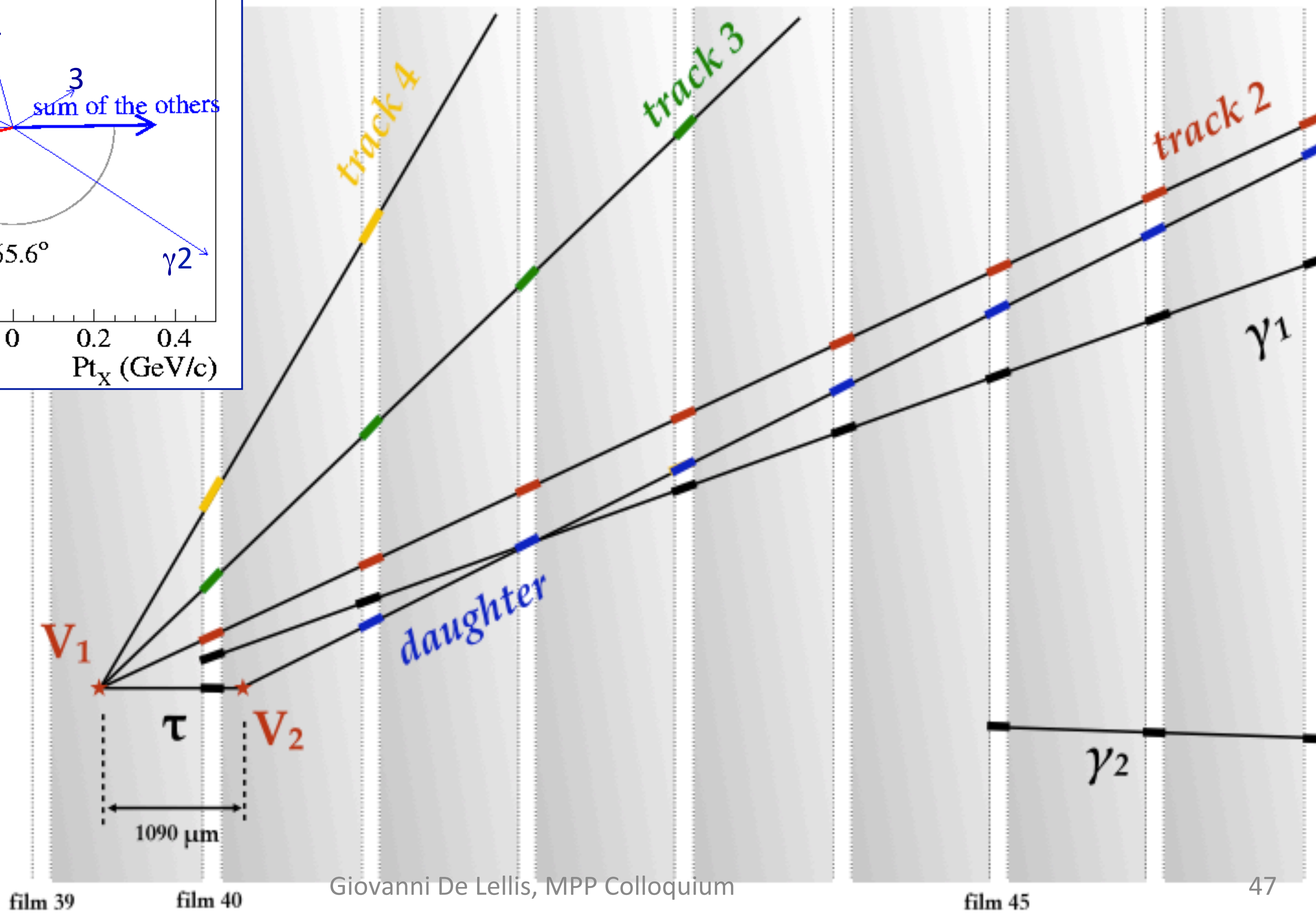



*PTEP 10 (2014) 101C01*

# THE FOURTH $\nu_\tau$ CANDIDATE

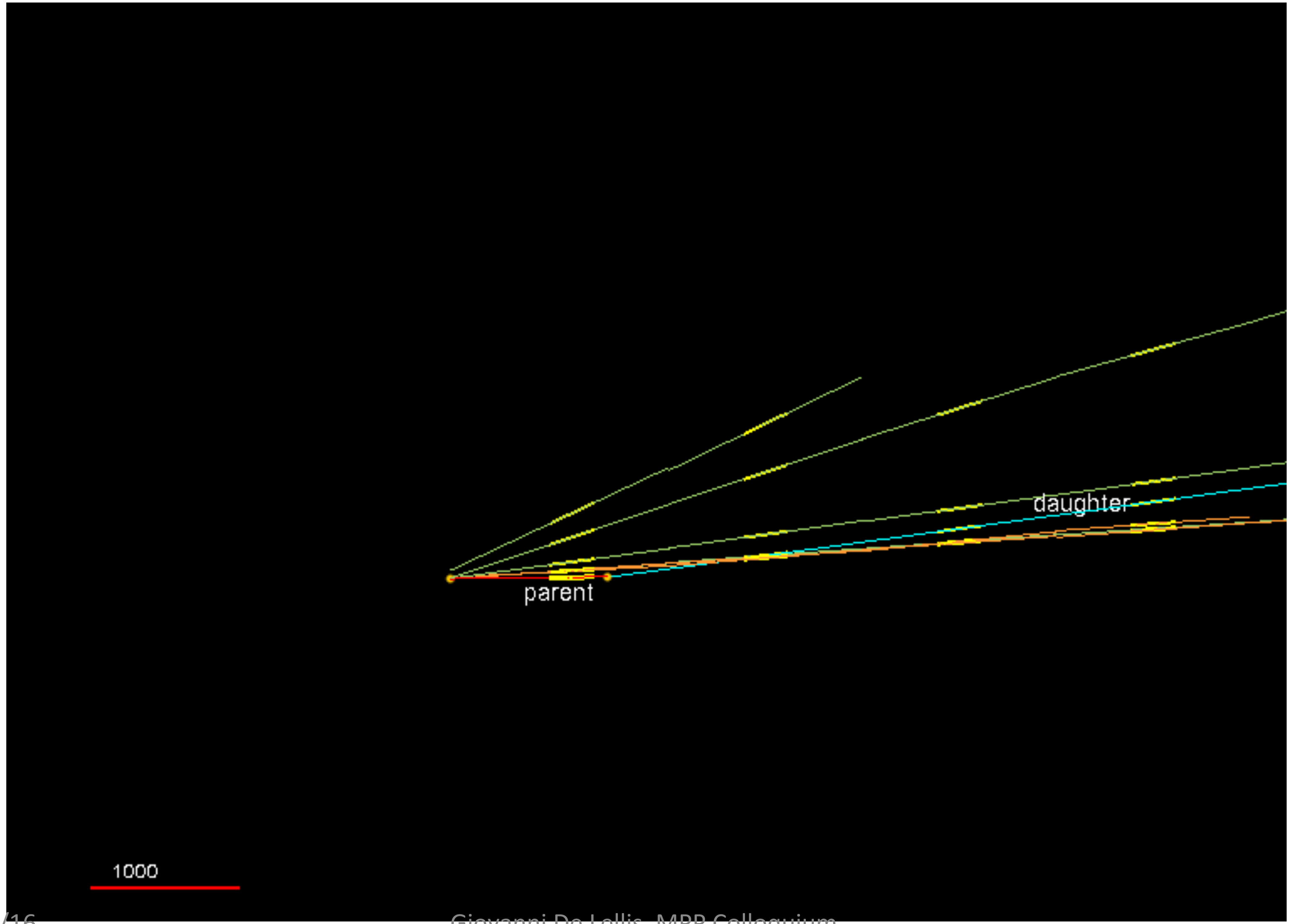
… and in the brick



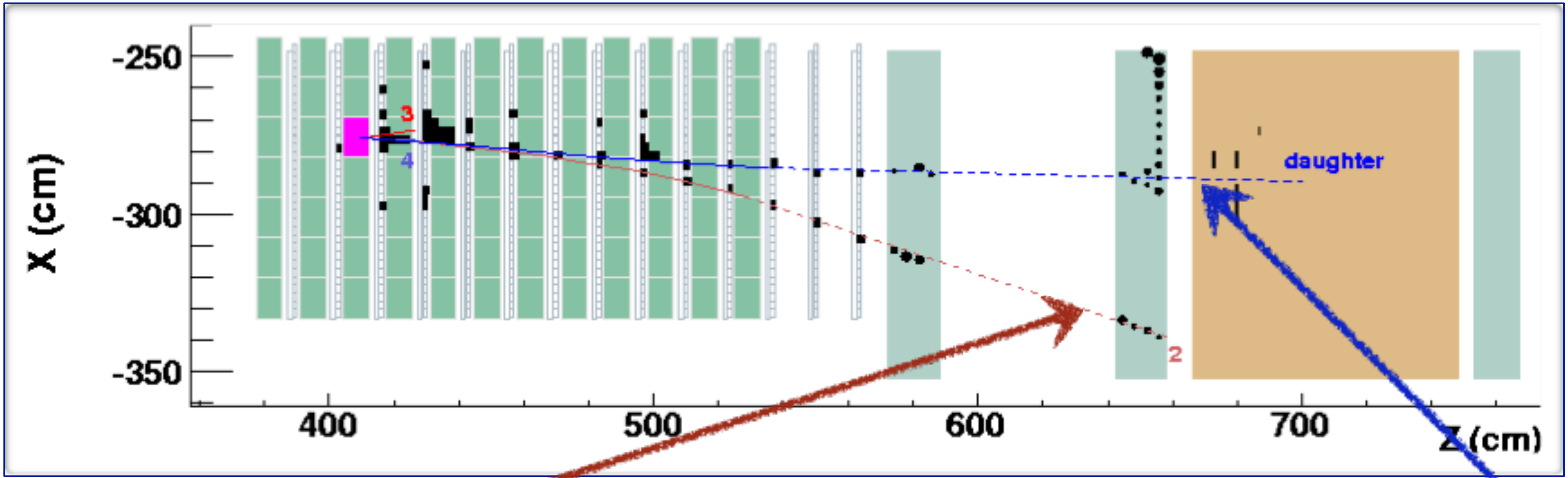
# THE FORTH $\nu_\tau$ CANDIDATE

… and in the brick



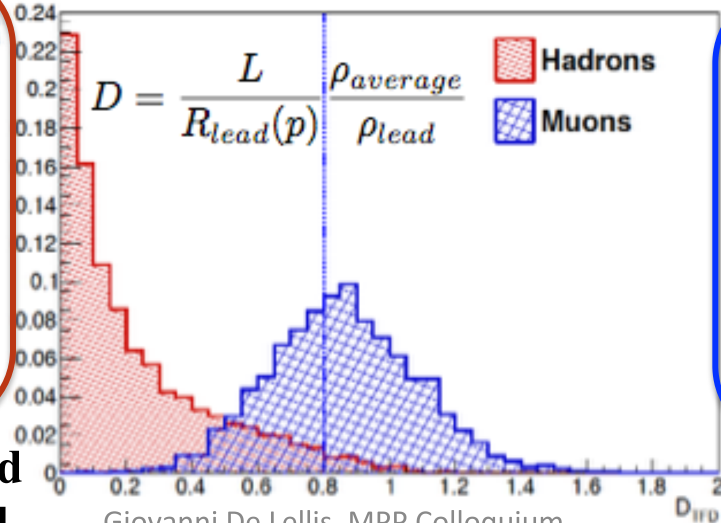
# PARTICLE ID: TRACK FOLLOW-DOWN

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**

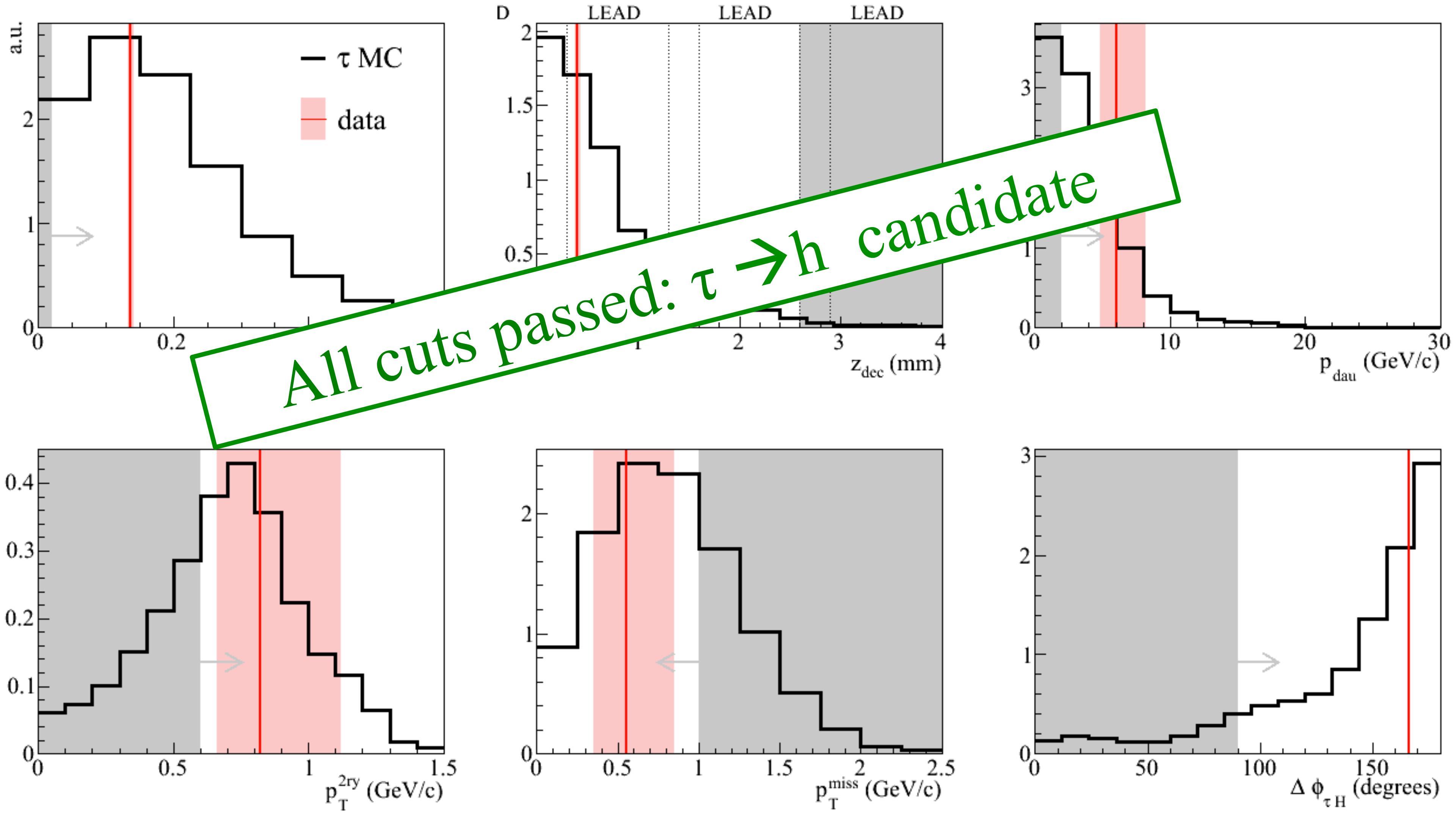
$$D = 0.18 \pm 0.04$$

**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 $C^2$*

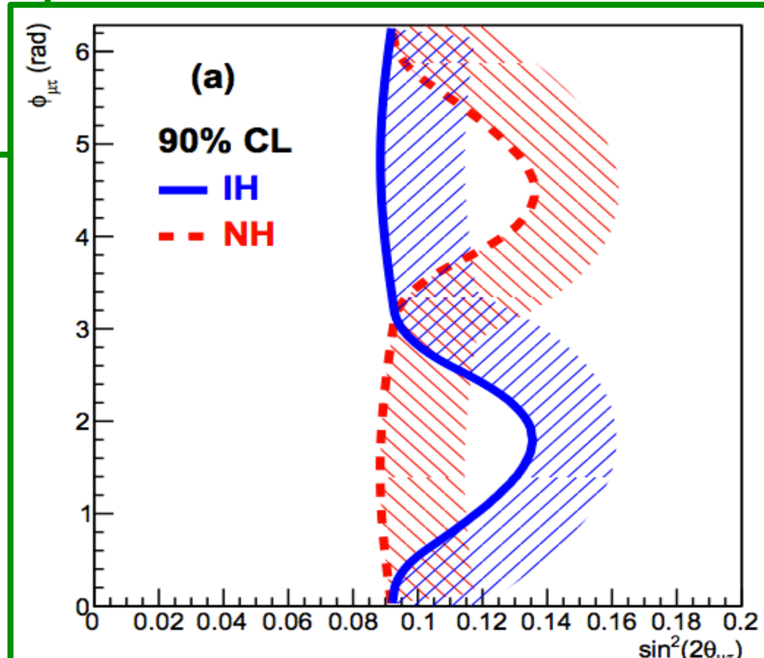
$$\tilde{L}(\phi_{\mu\tau}, sin^2 2\theta_{\mu\tau})$$

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

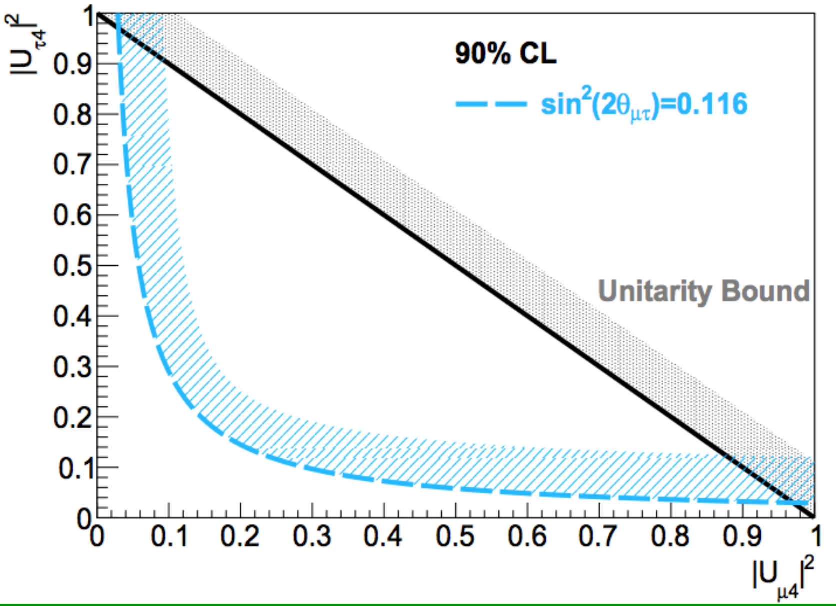
$$C = 2 \mid U_{\mu 3} U^*_{\tau 3} \mid,$$

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

*JHEP 1506 (2015) 069*

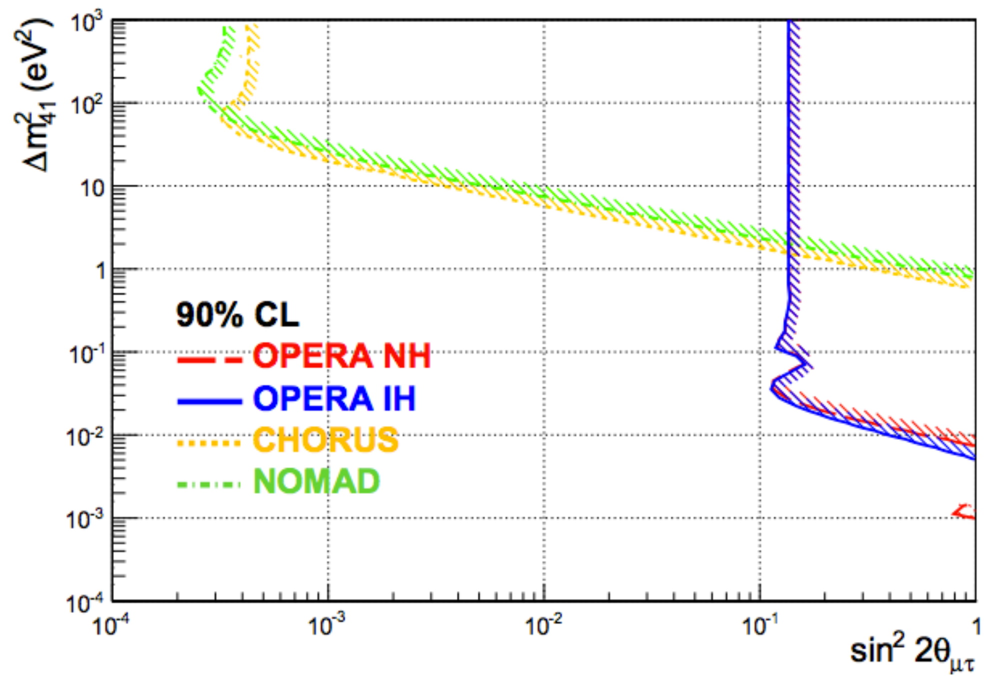


# Sterile Neutrinos




Effective mixing:

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

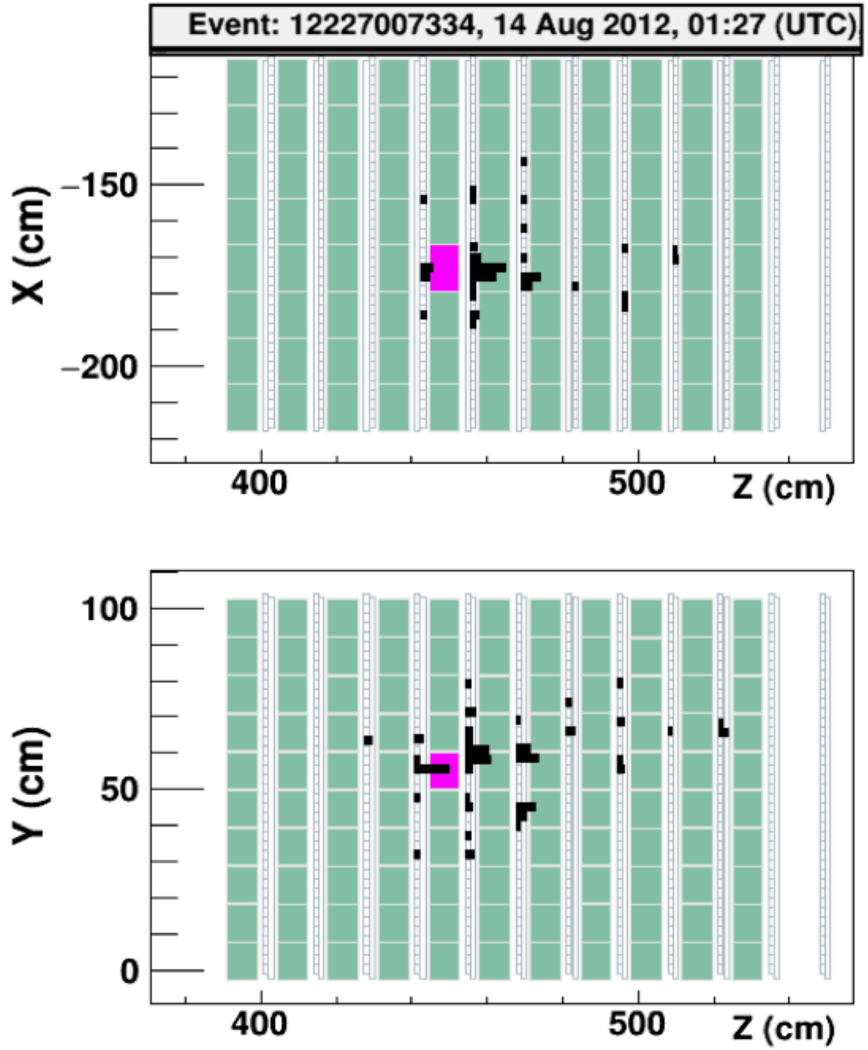



*JHEP 1506 (2015) 069*

# Completing The Analysis Of The Two Most Probable Bricks

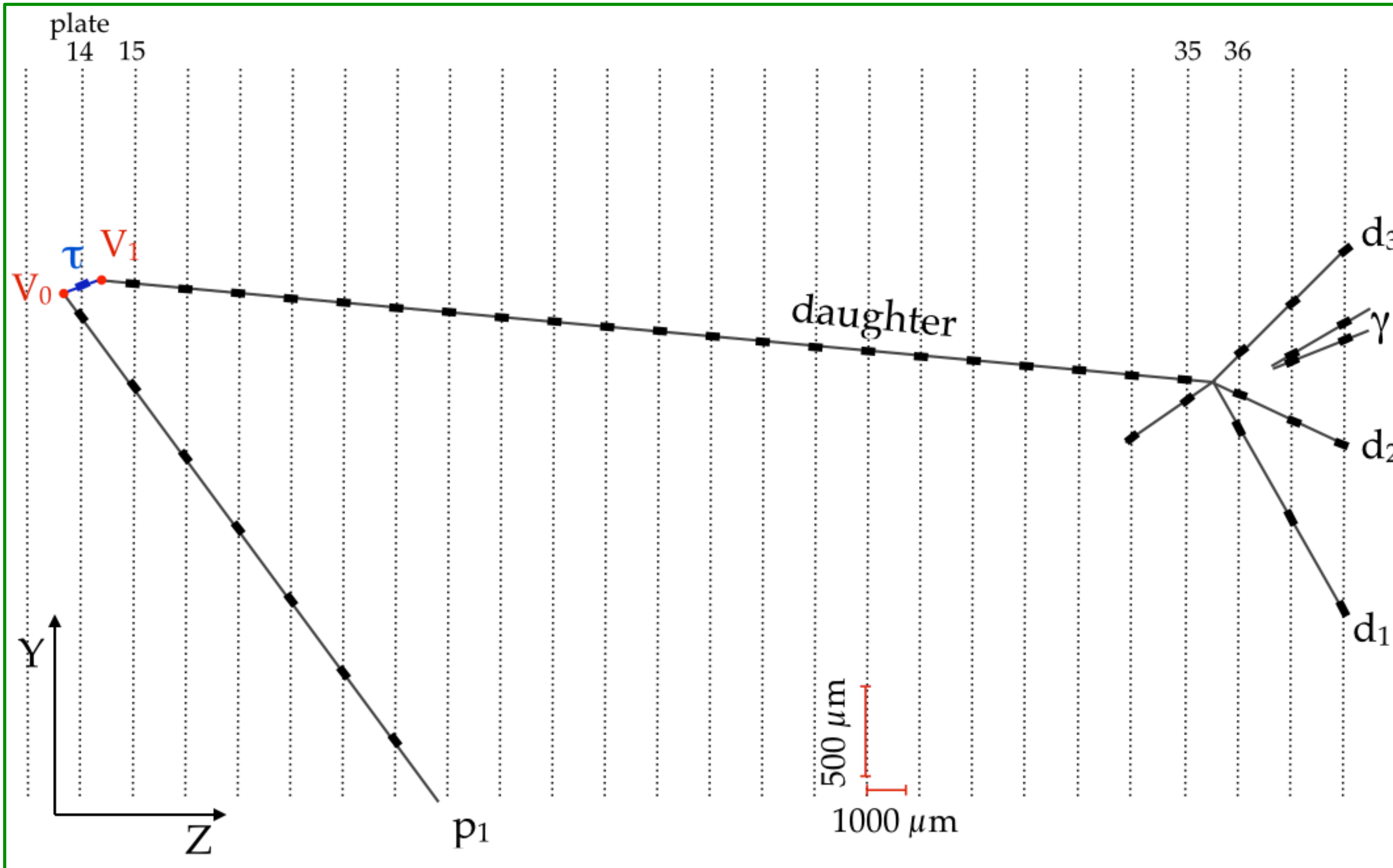
# The Fifth $\nu_\tau$ Candidate

As seen by the electronic detectors …



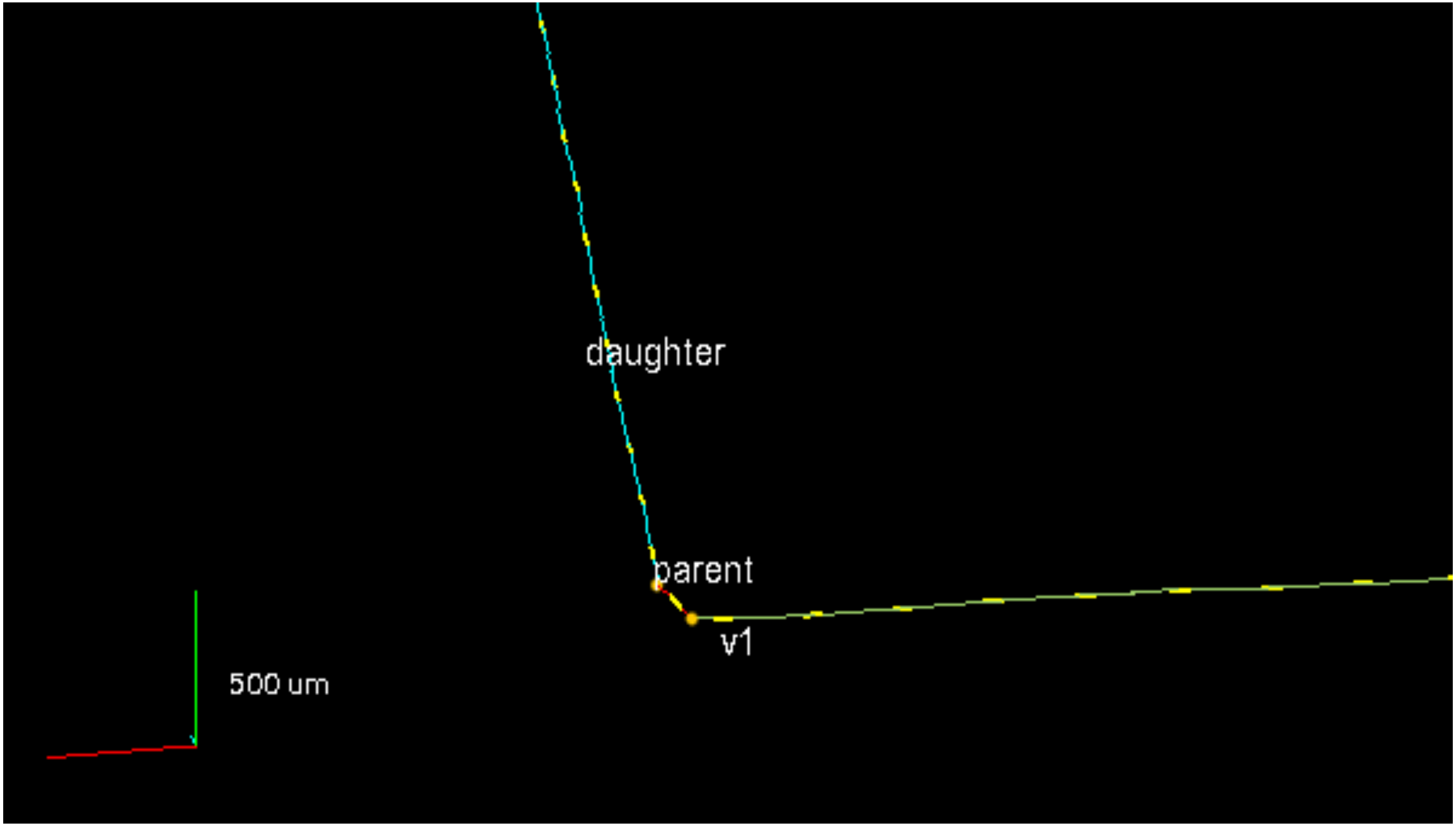
# THE FIFTH $\nu_\tau$ CANDIDATE

… and in the brick

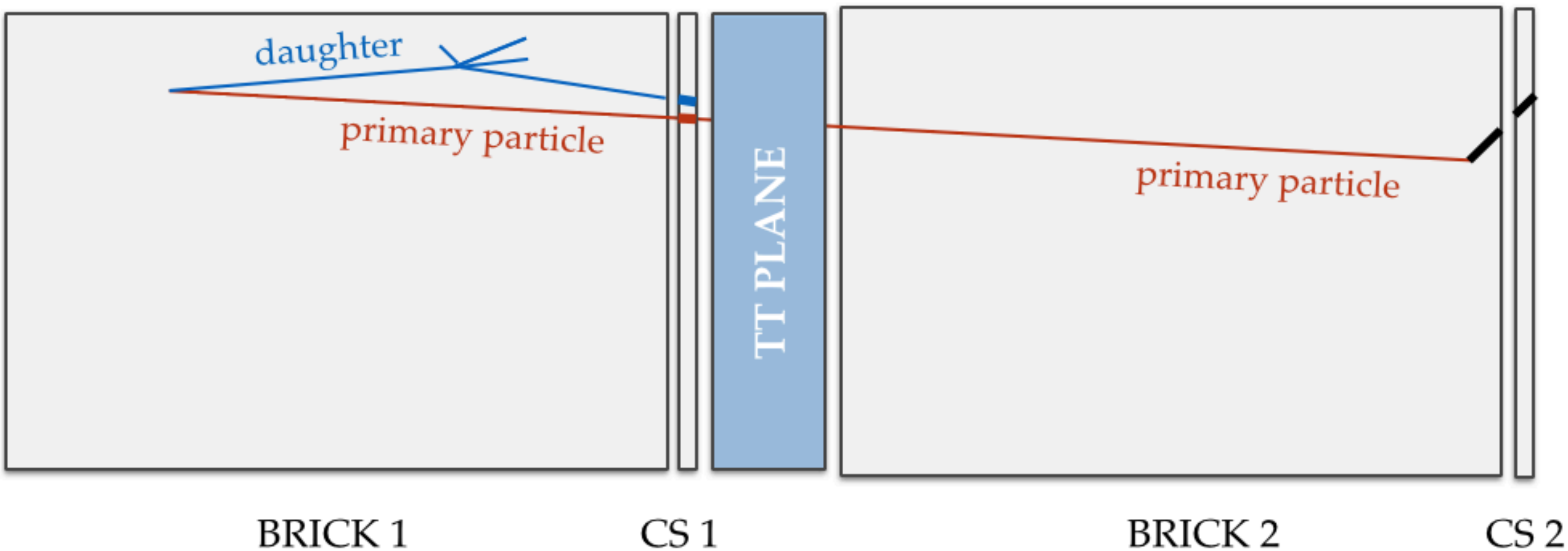


# THE FIFTH $\nu_\tau$ CANDIDATE

… and in the brick



# PARTICLE IDENTIFICATION




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

→ **Charm hypothesis discarded**

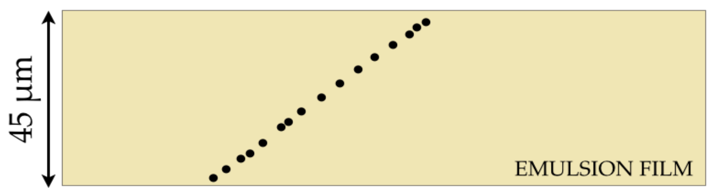
**Daughter**
Hadronic re-interaction in the first brick

→ **Hadronic decay channel**

# 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

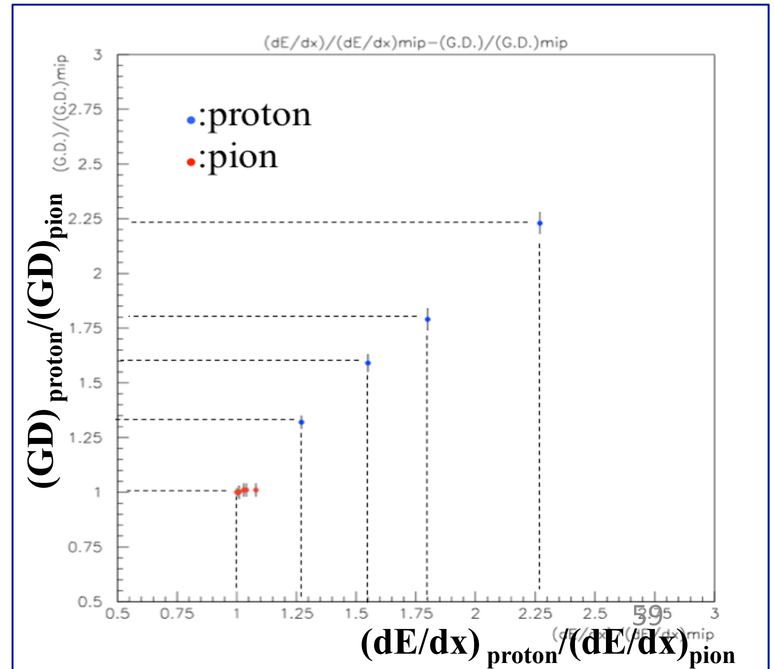
$\beta P_{1ry} = 0.8\ [0.6, 1.1]$ GeV/c

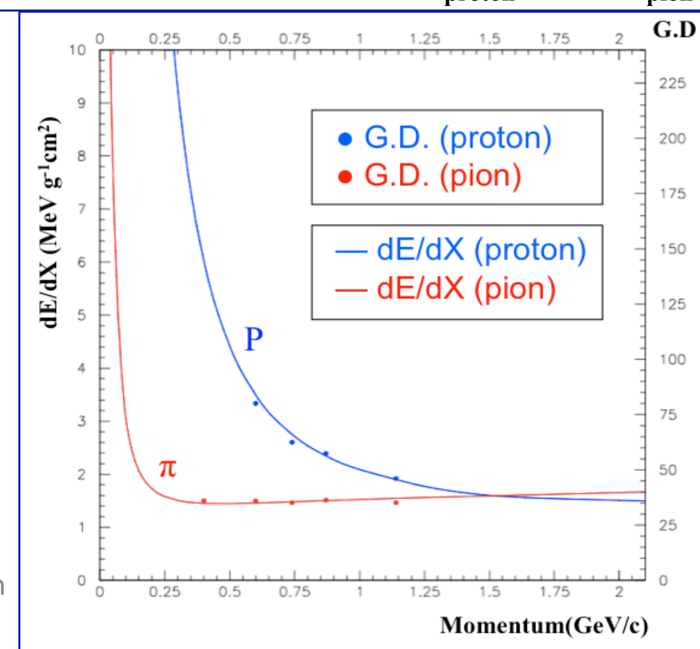
$$GD_{1ry}/GD_{\pi} = 1.45 \pm 0.06$$

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

Consistent with proton hypothesis

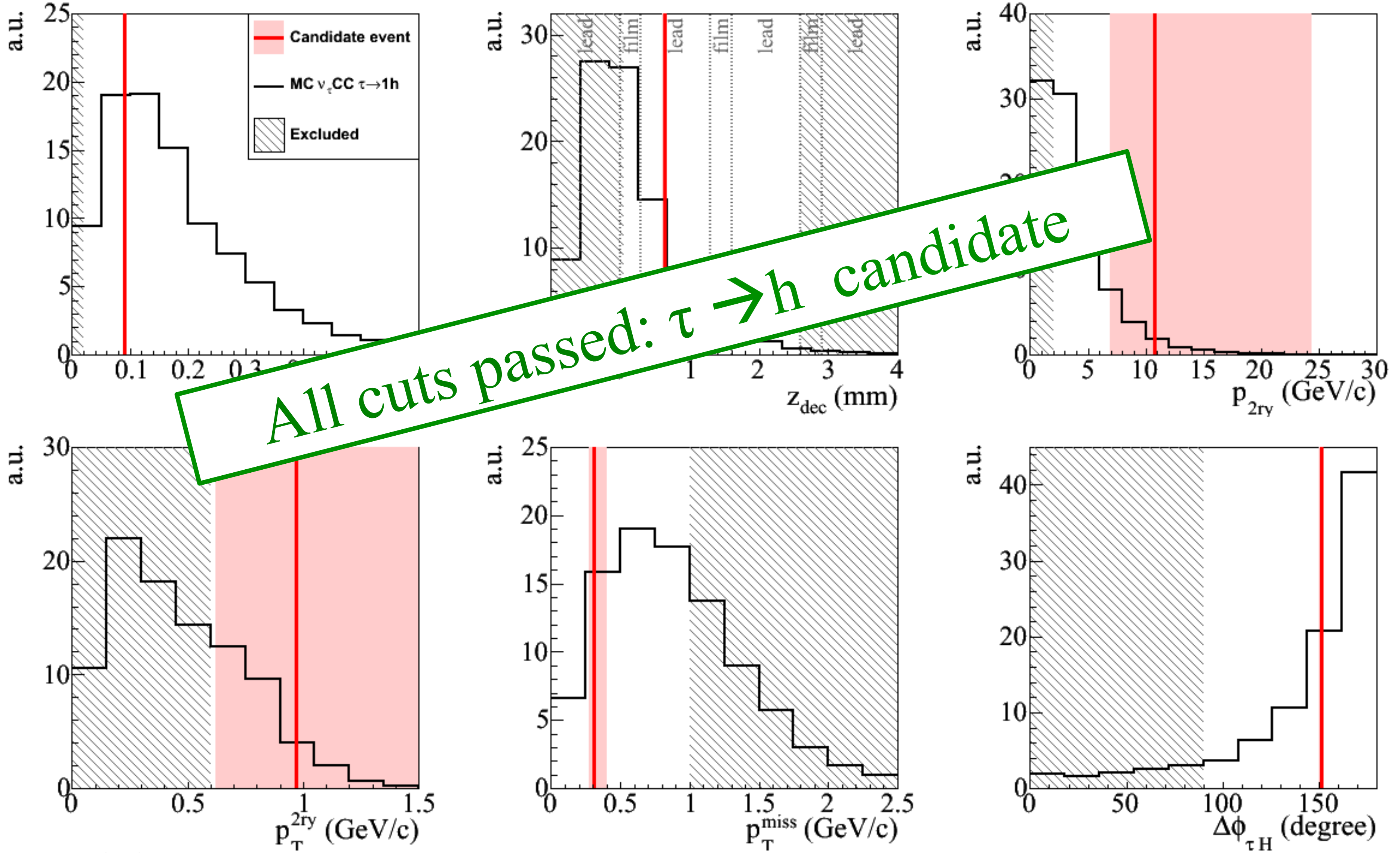
p = (1.0±0.2) GeV/c



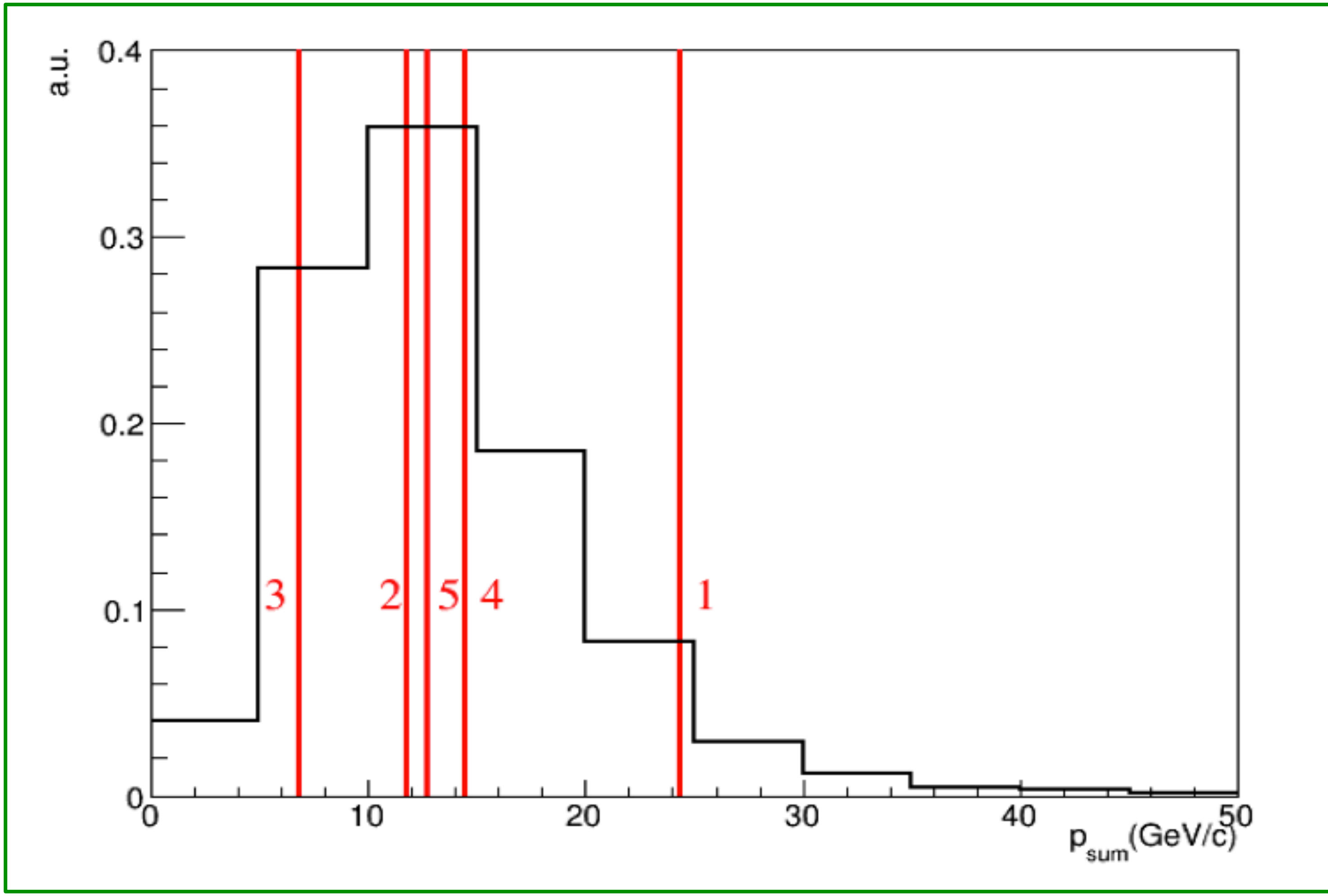
# The Fifth $\nu_\tau$ Candidate

Kinematical variables



# VISIBLE ENERGY OF ALL THE CANDIDATES

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

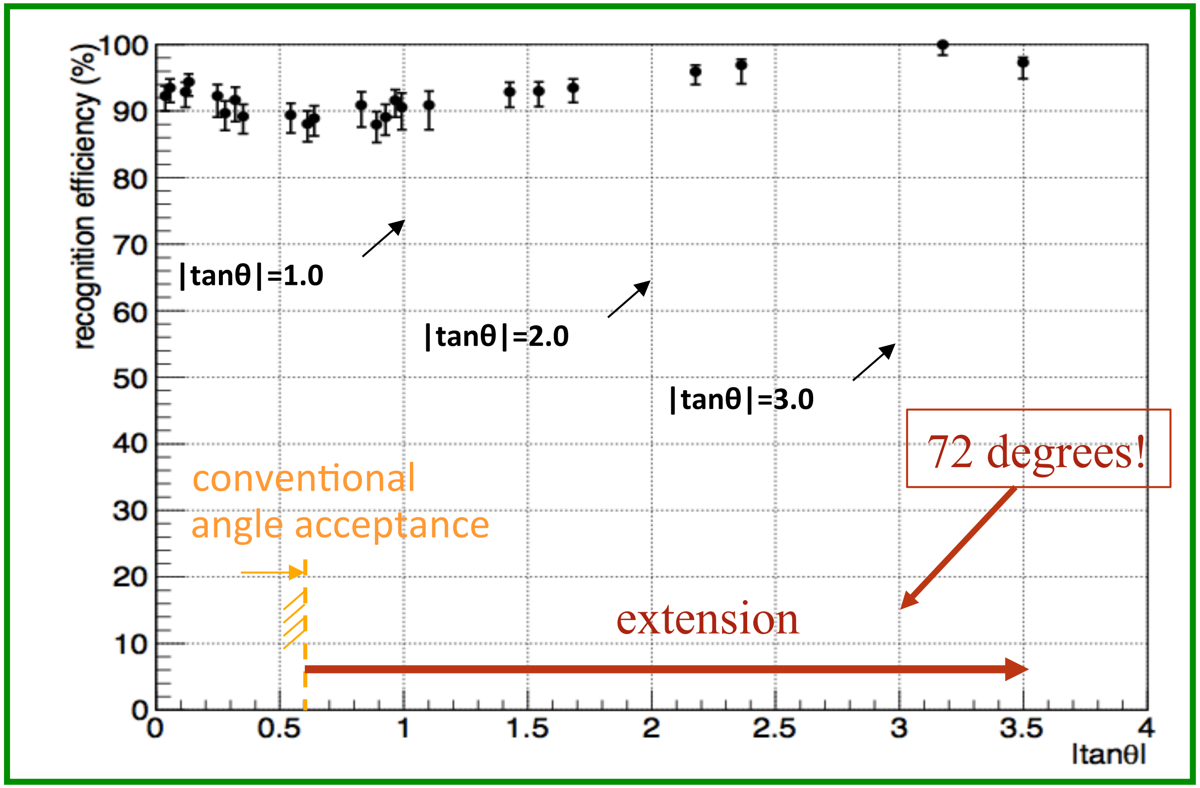


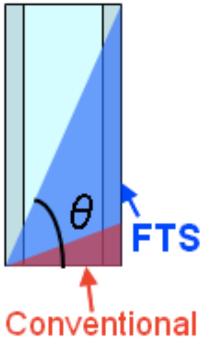
# Background studies

# 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



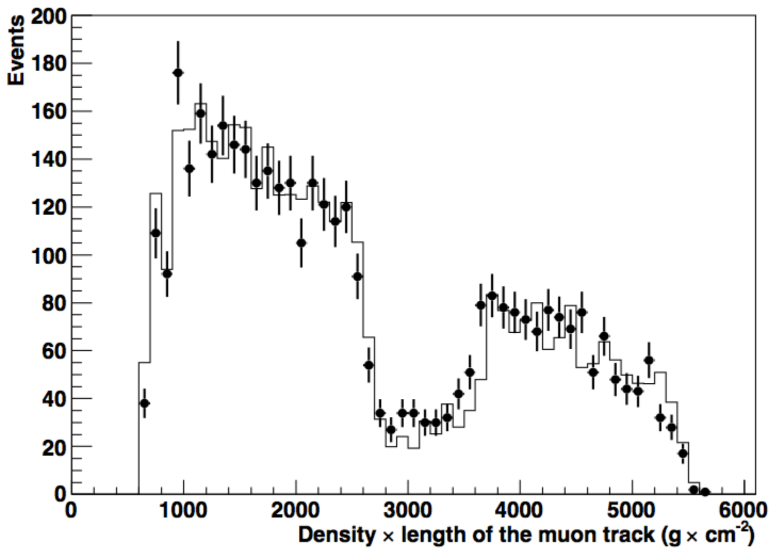

*JINST 9 (2014) P12017*
*JINST 10 (2015) no. 11 P11006*

# Charmed Particles Production

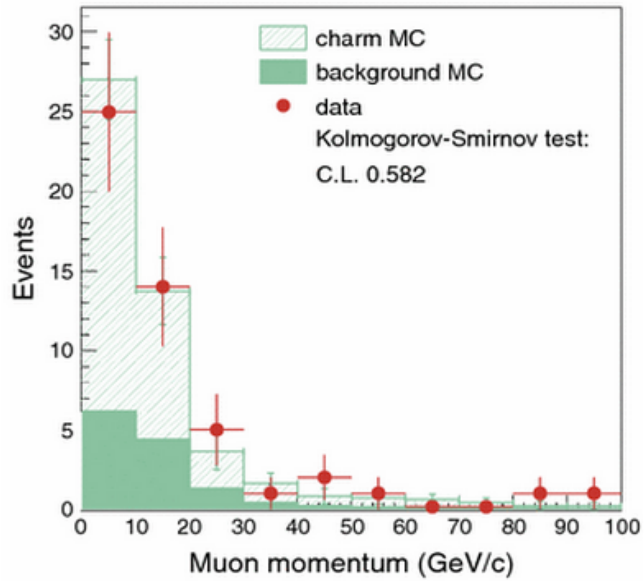
- Lifetimes and masses similar to the $\tau$
- Background when the primary muon is not identified

$\nu_\mu^{CC}$ 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*

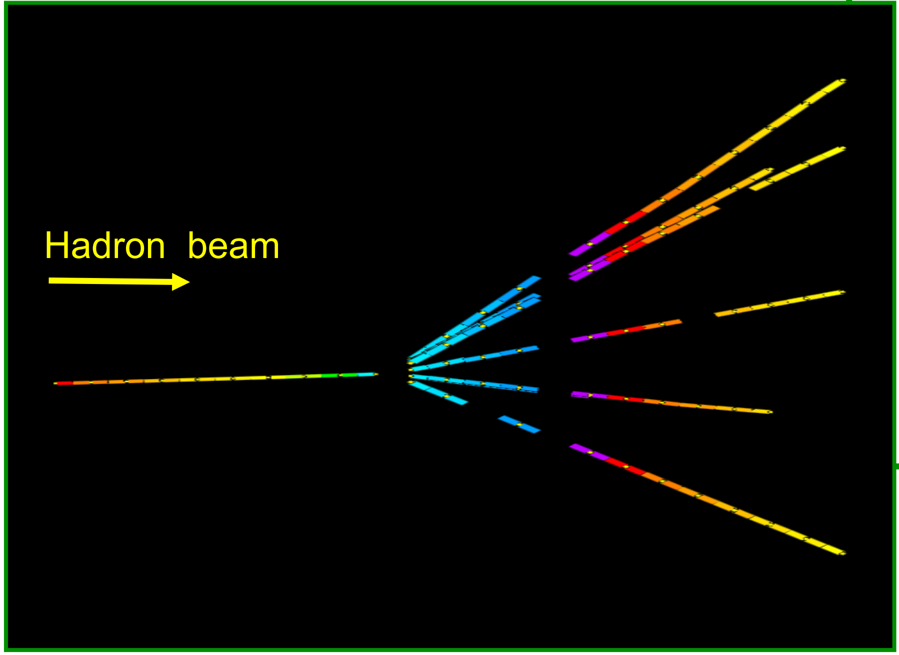
Good agreement in normalization and shape for the relevant kinematical variables in the charm detection and muon identification

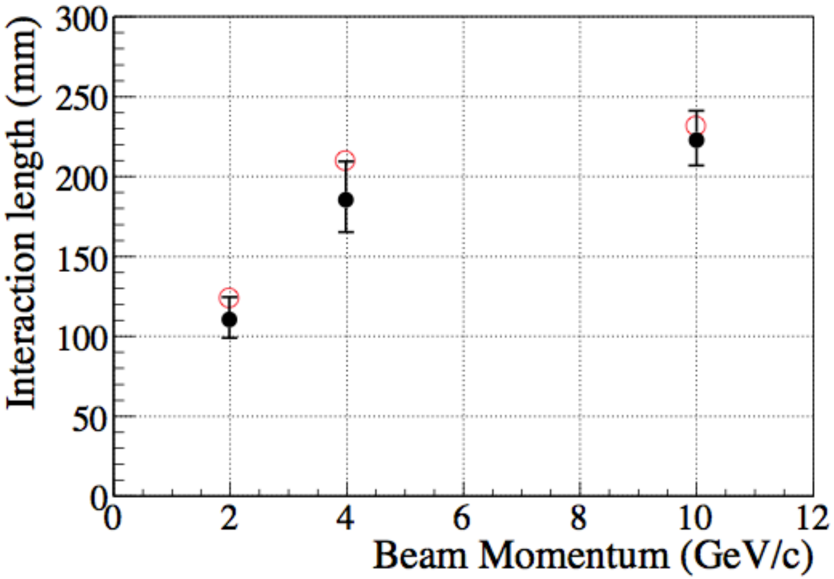
Constrain the background within 20%

# 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



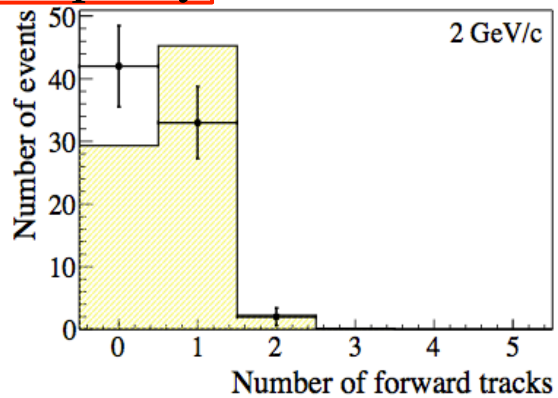

Black : $\pi^-$ beam data
Red : MC (FLUKA) simulation

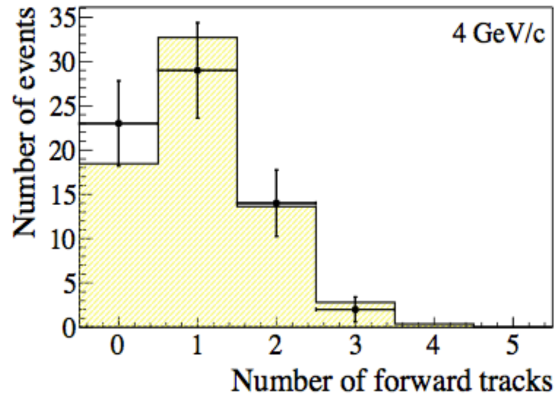
*PTEP 9 (2014) 093C01*

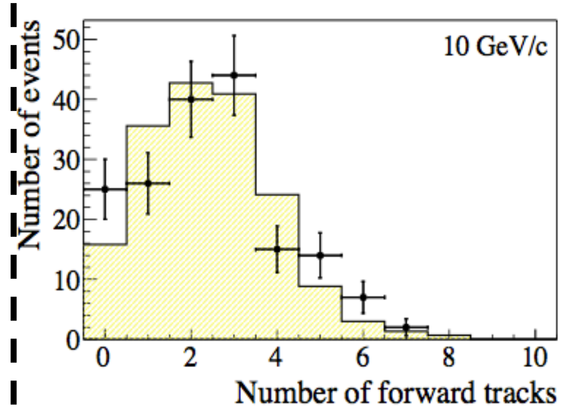
# SECONDARY TRACK EMISSION

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

## Multiplicity

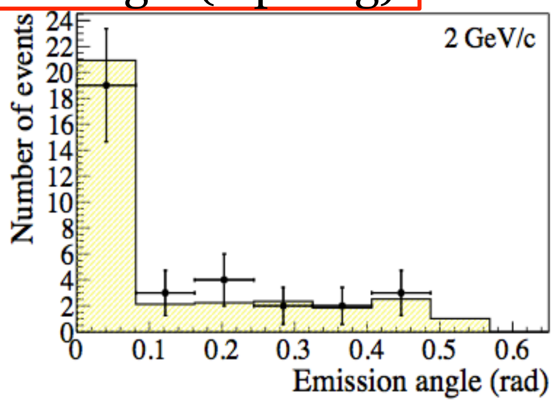


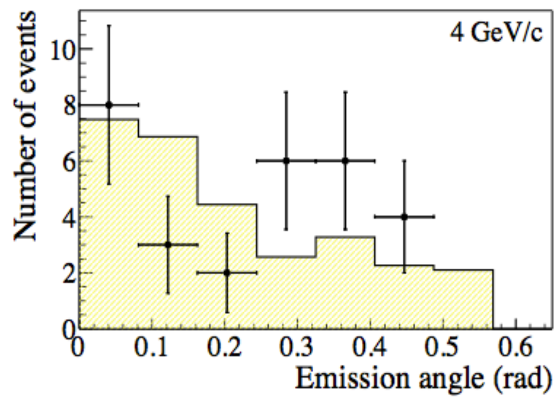



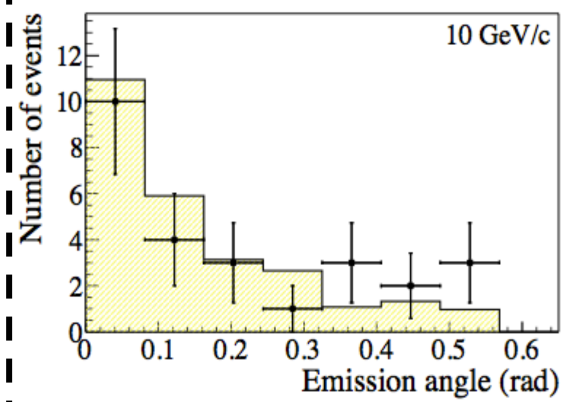




Error bars : Experimental data
Histogram : Simulated data

## Kink angle (1-prong)

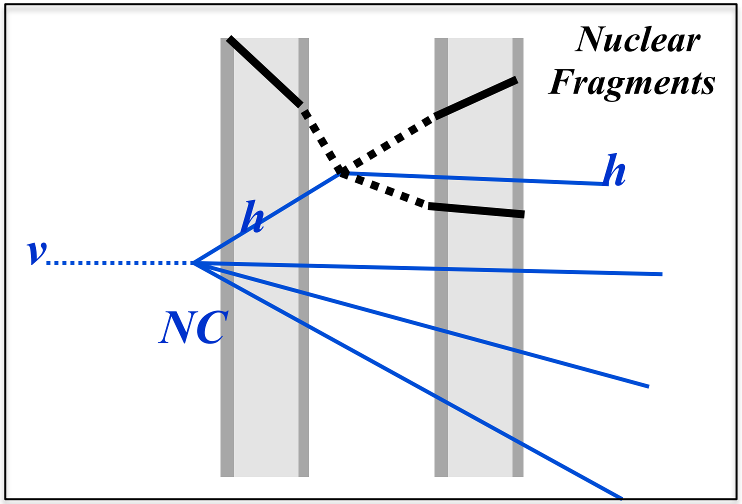


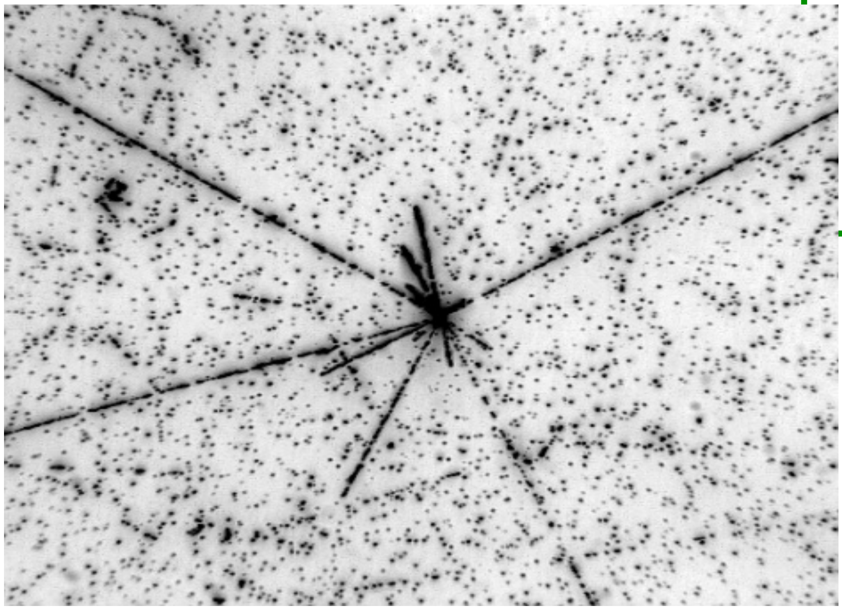




Good agreement within the statistical error: systematic error ~ 30%

# Nuclear Fragments Emission Probability

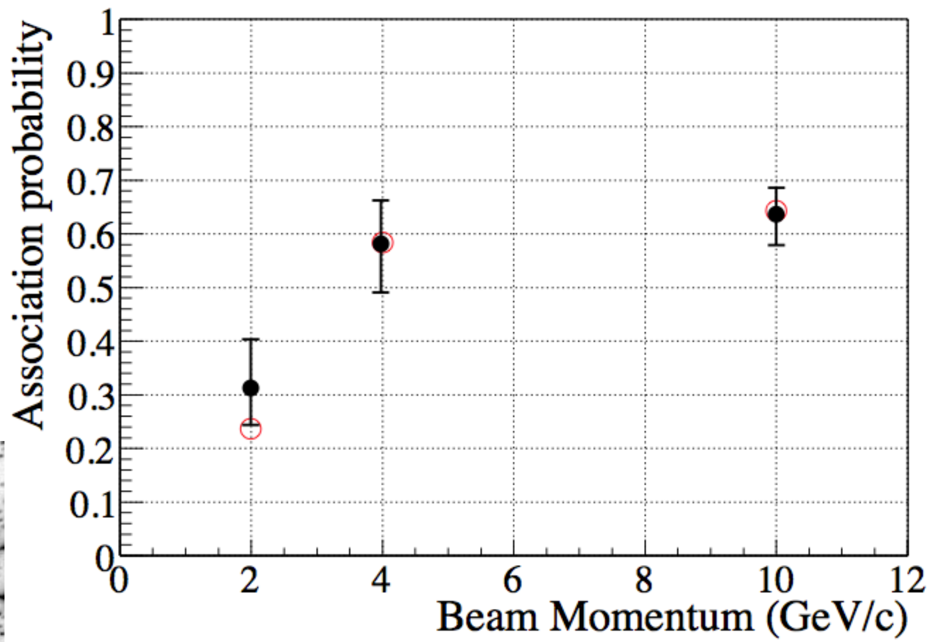



Highly ionizing fragments



150 µm

Additional background reduction




Black : experimental data

Red : simulated data (β= p/E = 0.7)

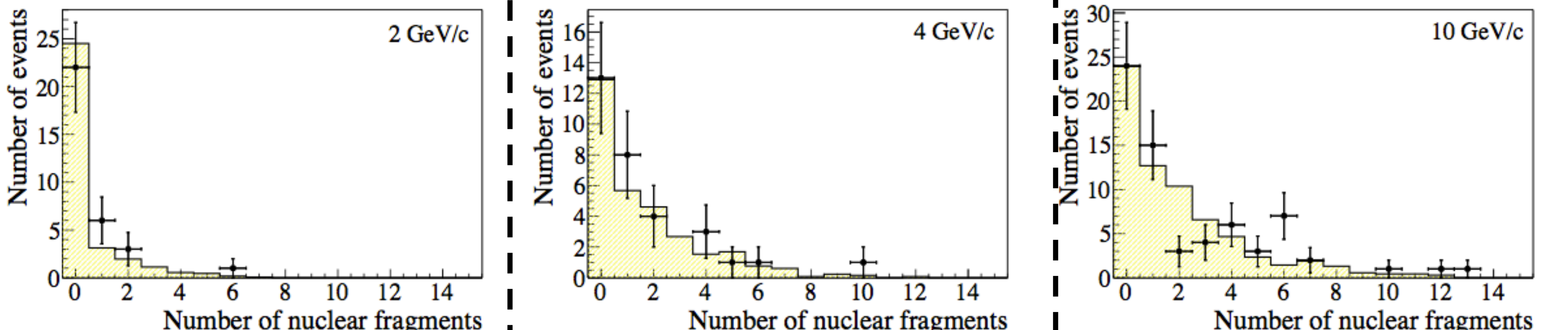
*PTEP 9 (2014) 093C01*

# NUCLEAR FRAGMENTS IN 1 AND 3 PRONG INTERACTIONS

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

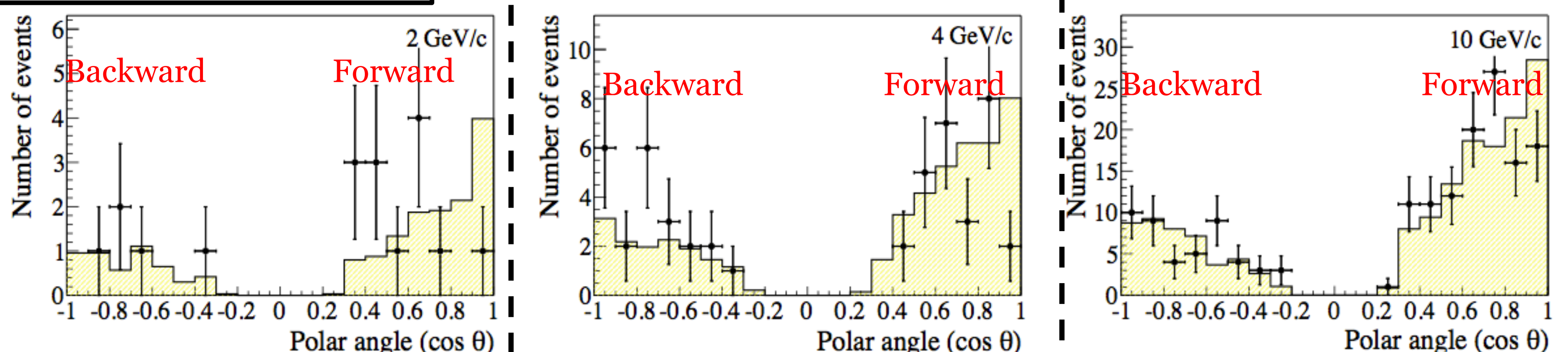
**Multiplicity**

MC: $\beta < 0.7$




Error bars : Experimental data
Histogram : Simulated data

**Emission angle(cos θ)**

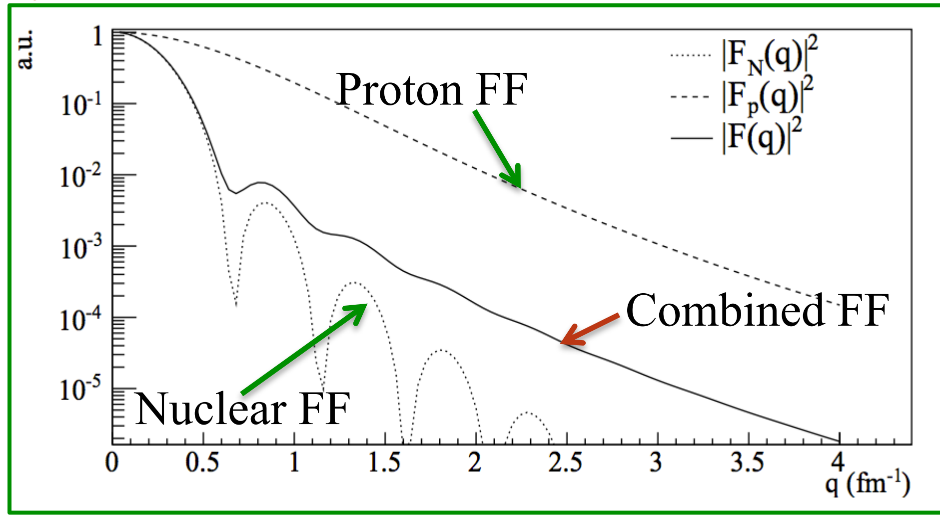



Agreement within the statistical error: systematic error is 10%

# LARGE ANGLE μ SCATTERING

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

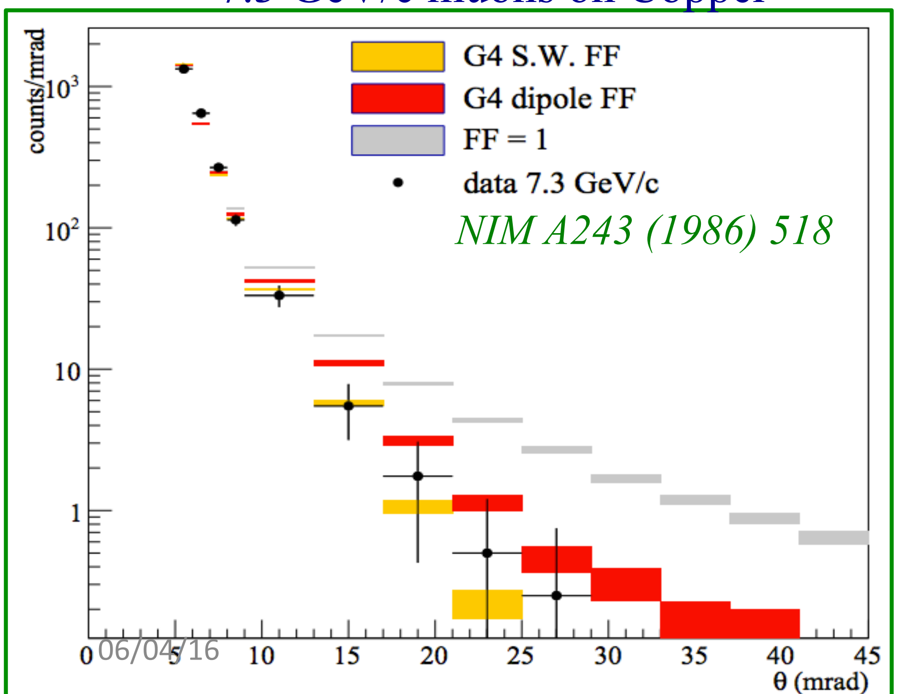
$$\rho_{SW}(r) = \rho_0 \left(1 + e^{\frac{r-b}{a}}\right)^{-1}$$



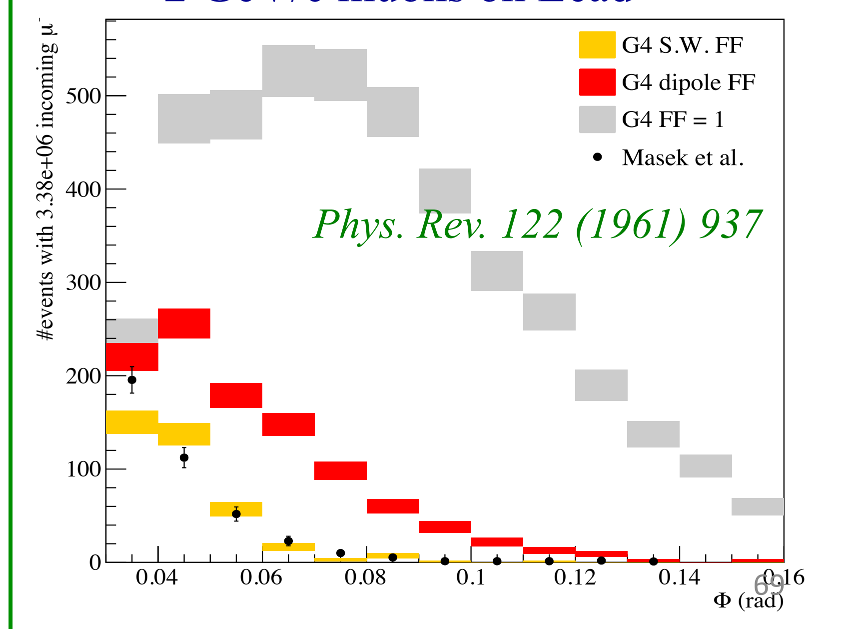

IEEE Transactions on Nuclear Science Vol. 62, No. 5, October 2015

MC predictions compared to available data

7.3 GeV/c muons on Copper

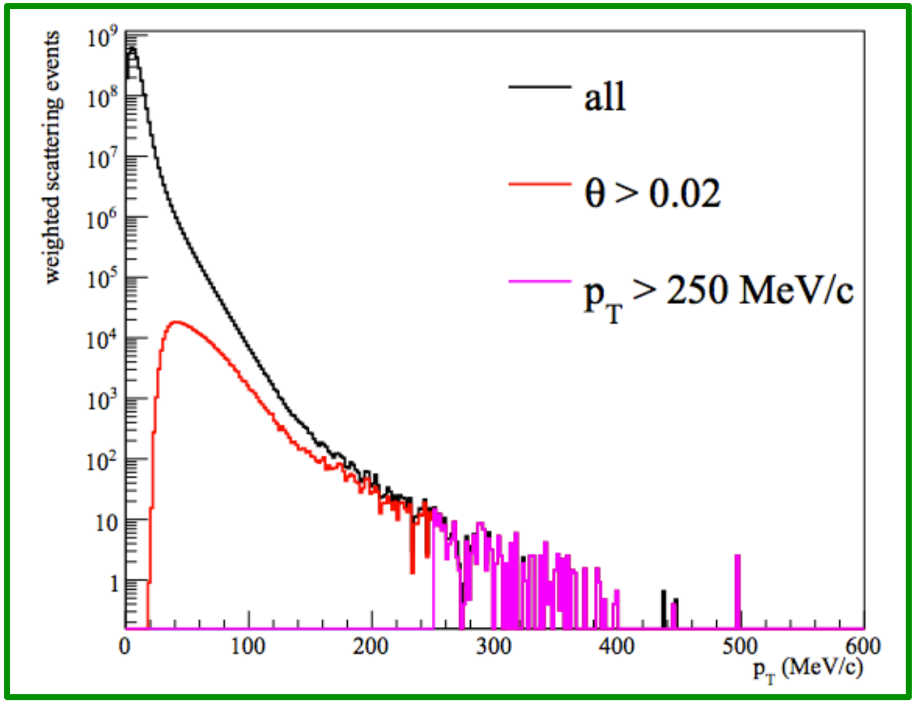



2 GeV/c muons on Lead

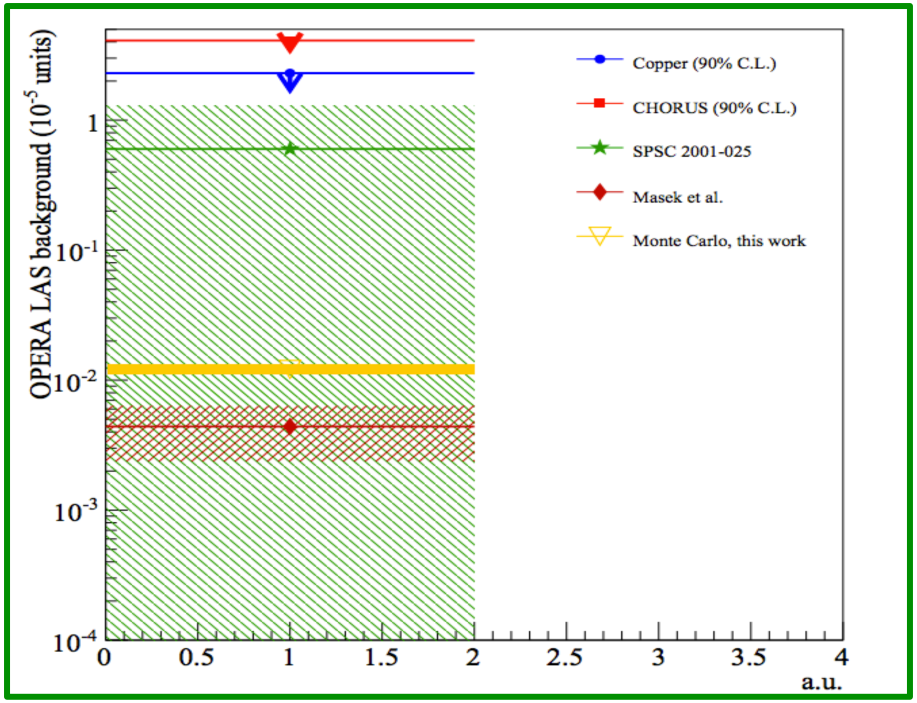


# LARGE ANGLE μ SCATTERING

CNGS $\nu_\mu$ 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

IEEE Transactions on Nuclear Science Vol. 62, No. 5, October 2015

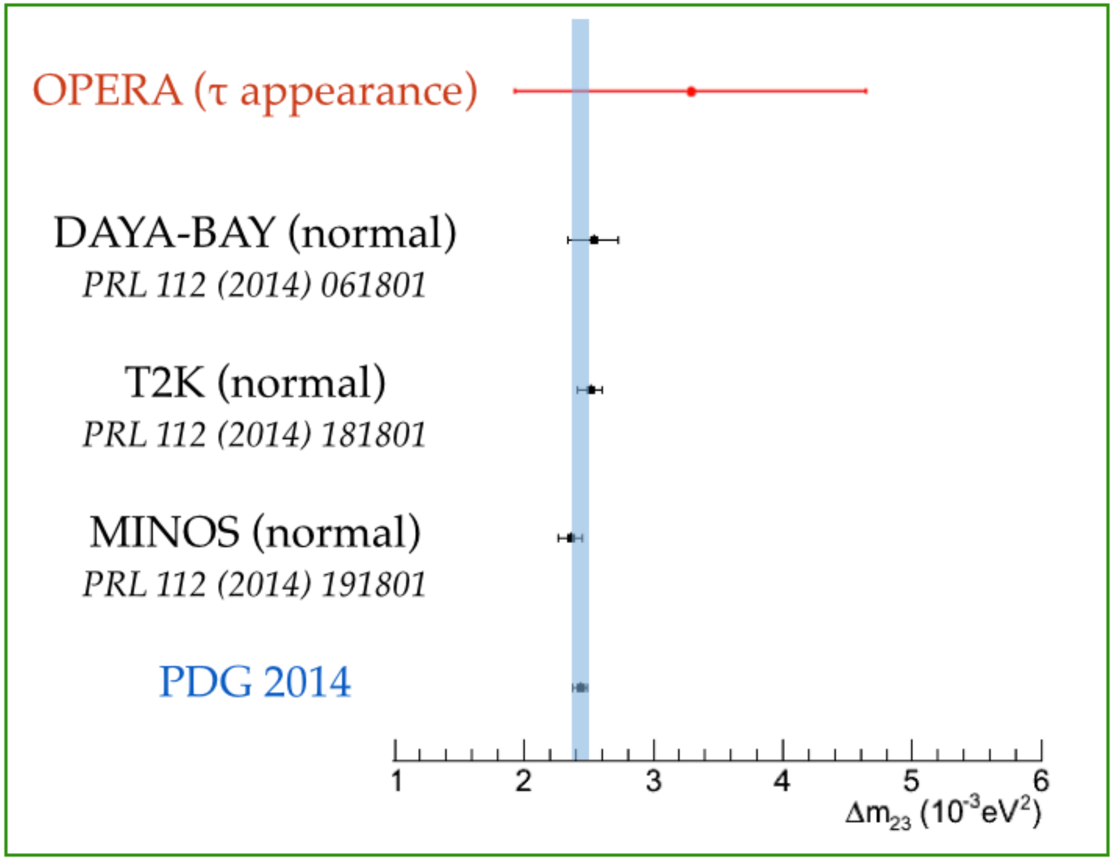
# FINAL RESULTS

# $\Delta m^2_{23}$ ESTIMATION

90% C.L. intervals on $\Delta m^2_{23}$ by Feldman & Cousins method

[2.0 – 4.7] x $10^{-3}$ $eV^2$

(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 |

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

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 { 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)

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# Discovery of $\tau$ Neutrino Appearance in the CNGS Neutrino Beam with the OPERA Experiment

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(OPERA Collaboration)


Scientific Background on the Nobel Prize in Physics 2015

# NEUTRINO OSCILLATIONS

compiled by the Class for Physics of the Royal Swedish Academy of Sciences

Super-Kamiokande's oscillation results were later confirmed by the detectors MACRO [55] and Soudan [56], the long-baseline accelerator experiments K2K [57], MINOS [58] and T2K [59] and more recently also by the large neutrino telescopes ANTARES [60] and IceCube [61]. Appearance of tau-neutrinos in a muon-neutrino beam has been demonstrated on an event-by-event basis by the OPERA experiment in Gran Sasso, with a neutrino beam from CERN [62].

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# More to Come from OPERA

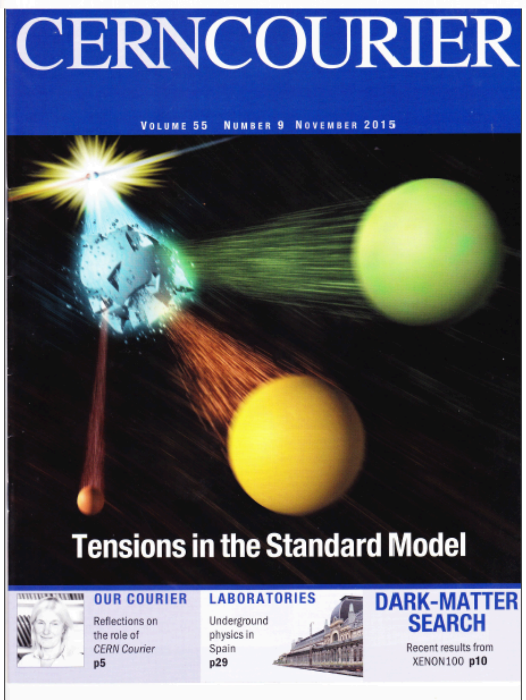
- Relaxing the cuts with a likelihood approach
- PMNS matrix with $\nu_\tau$ appearance combined with $\nu_e$ appearance and $\nu_\mu$ disappearance
- Improve the measurement of $\Delta m^2$ with $\nu_\tau$ appearance
- Sterile neutrino searches in $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ channels with the full data set
- First measurement of $\nu_\tau$ leptonic number
- …

Experiments' legacy

# What's next for OPERA's emulsion-detection technology?

While working on the analysis of their data, the collaboration is also looking into possible developments of their emulsion-detection technology, to be implemented in future experiments.

**Luciano Maiani**, Università La Sapienza and INFN Roma 1, and **Giovanni De Lellis**, Università Federico II and INFN Napoli.




Developed in the late 1990s, the OPERA detector design was based on a hybrid technology, using both real-time detectors and nuclear emulsions. The construction of the detector at the Gran Sasso underground laboratory in Italy started in 2003 and was completed in 2007 – a giant detector of around 4000 tonnes, with 2000 $m^3$ volume and nine million photographic films, arranged in around 150,000 target units, the so-called bricks. The emulsion films in the bricks act as tracking devices with micrometric accuracy, and are interleaved with lead plates acting as neutrino targets. The longitudinal size of a brick is around 10 radiation lengths, allowing for the detection of electron showers and the momentum measurement through the detection of multiple Coulomb scattering. The experiment took data for five years, from June 2008 until December 2012, integrating $1.8 \times 10^{20}$ protons on target.

The aim of the experiment was to perform the direct observation of the transition from muon to tau neutrinos in the neutrino beam from CERN. The distance from CERN to Gran Sasso and the SPS beam energy were just appropriate for tau-neutrino detection. In 1999, intense discussions took place between CERN management and Council delegations about the opportunity of building the CERN Neutrino to Gran Sasso (CNGS) beam facility and the way to fund it. The Italian National Institute for Nuclear Physics (INFN) was far-sighted in offering a sizable contribution. Many delegations supported the idea, and the CNGS beam was approved in December 1999. Commissioning was performed in 2006, when OPERA (at that time not fully equipped yet) detected the first muon-neutrino interactions.

With the CNGS programme, CERN was joining the global experimental effort to observe and study neutrino oscillations. The first experimental hints of neutrino oscillations were gathered from solar neutrinos in the 1970s. According to theory, neutrino oscillations originate from the fact that mass and weak-interaction eigenstates do not coincide and that neutrino masses are non-degenerate. Neutrino mixing and oscillations were introduced by Pontecorvo and by the Sakata group, assuming the existence of two sorts (flavours) of neutrinos. Neutrino oscillations with three flavours including CP and CPT violation were discussed by Cabibbo and by Bilenky and Pontecorvo, after the discovery of the tau lepton in 1975. The mixing of the three flavours of neutrinos can be described by the $3 \times 3$ Pontecorvo–Maki–Nakagawa–Sakata matrix with three angles – that have since been measured – and a CP-violating phase, which remains unknown at present. Two additional parameters (mass-squared differences) are needed to describe the oscillation probabilities.

Several experiments on solar, atmospheric, reactor and accelerator neutrinos have contributed to the understanding of neutrino oscillations. In the atmospheric sector, the strong deficit of muon neutrinos reported by the Super-Kamiokande experiment in 1998 was the first compelling observation of neutrino oscillations. Given that the deficit of muon neutrinos was not accompanied by an increase of electron neutrinos, the result was interpreted in terms of $\nu_\mu \to \nu_\tau$ oscillations, although in 1998 the tau neutrino had not yet been observed. The first direct evidence for tau neutrinos was announced by Fermilab's DONuT experiment in 2000, with four reported events. In 2008, the DONuT collaboration presented its final results, reporting nine observed events and an expected background of 1.5. The Super-Kamiokande result was later confirmed by the K2K and MINOS experiments with terrestrial beams. However, for an unambiguous confirmation of three-flavour neutrino oscillations, the appearance of tau neutrinos in $\nu_\mu \to \nu_\tau$ oscillations was required.

## OPERA comes into play

OPERA reported the observation of the first tau-neutrino candidate in 2010. The tau neutrino was detected by the production and decay of a $\tau^-$ in one of the lead targets, where $\tau^- \to \rho^- \nu_\tau$. A second candidate, in the $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$ channel, was found in 2012, followed in 2013 by a candidate in the fully leptonic $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$ decay. A fourth event was found in 2014 in the $\tau^- \to h^- \nu_\tau$ channel (where $h^-$ is a pion or a kaon), and a fifth one was reported a few months ago in the same channel. Given the extremely low expected background of $0.25 \pm 0.05$ events, the direct transition from muon to tau neutrinos has now been measured with the $5\sigma$ statistical precision conventionally required to firmly establish its observation, confirming the oscillation mechanism.

The extremely accurate detection technique provided by OPERA relies on the micrometric resolution of its nuclear emulsions, which are capable of resolving the neutrino-interaction point and the vertex-decay location of the tau lepton, a few hundred micrometres ▷