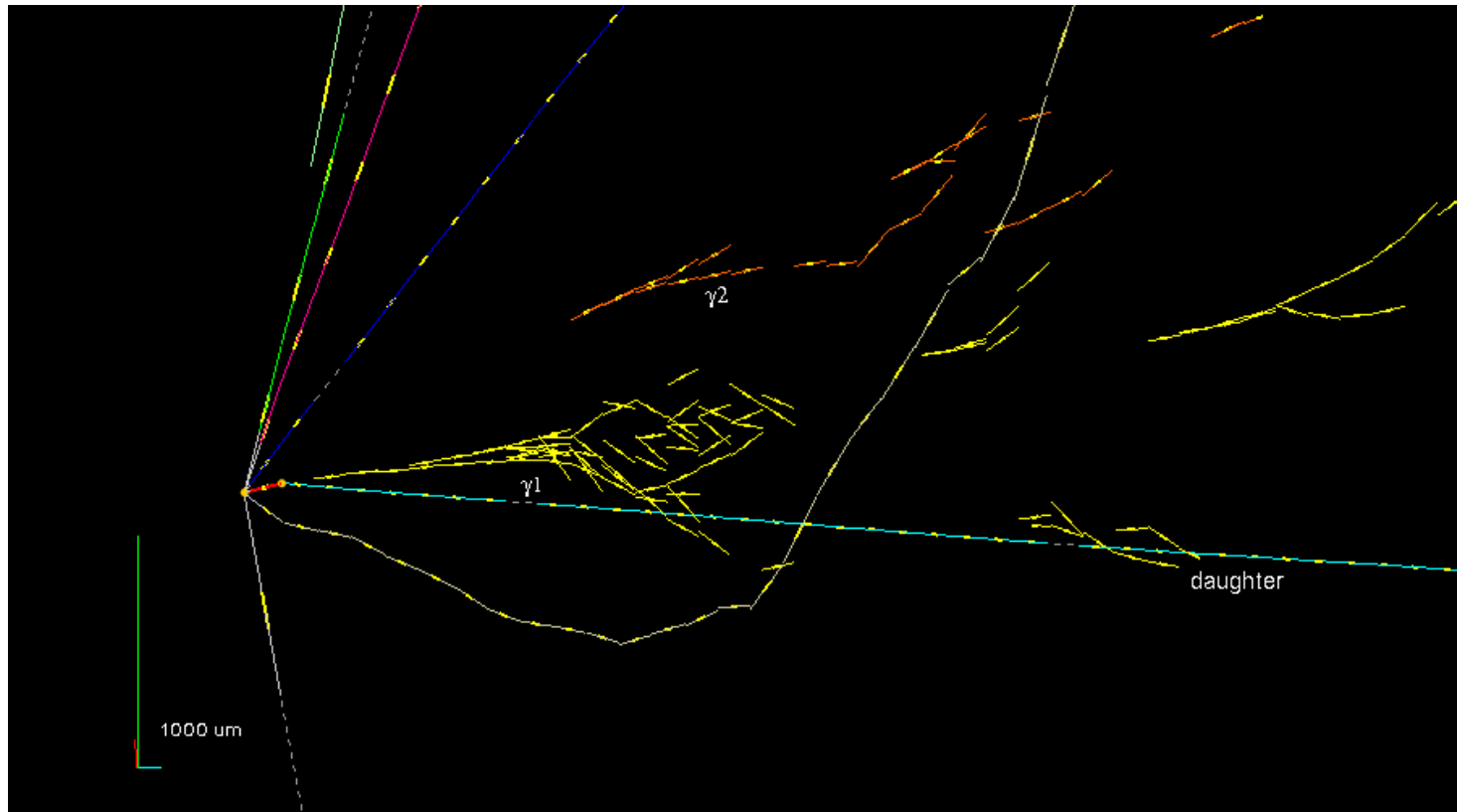# Results of the OPERA experiment

Giovanni De Lellis

University "Federico II" and INFN Napoli
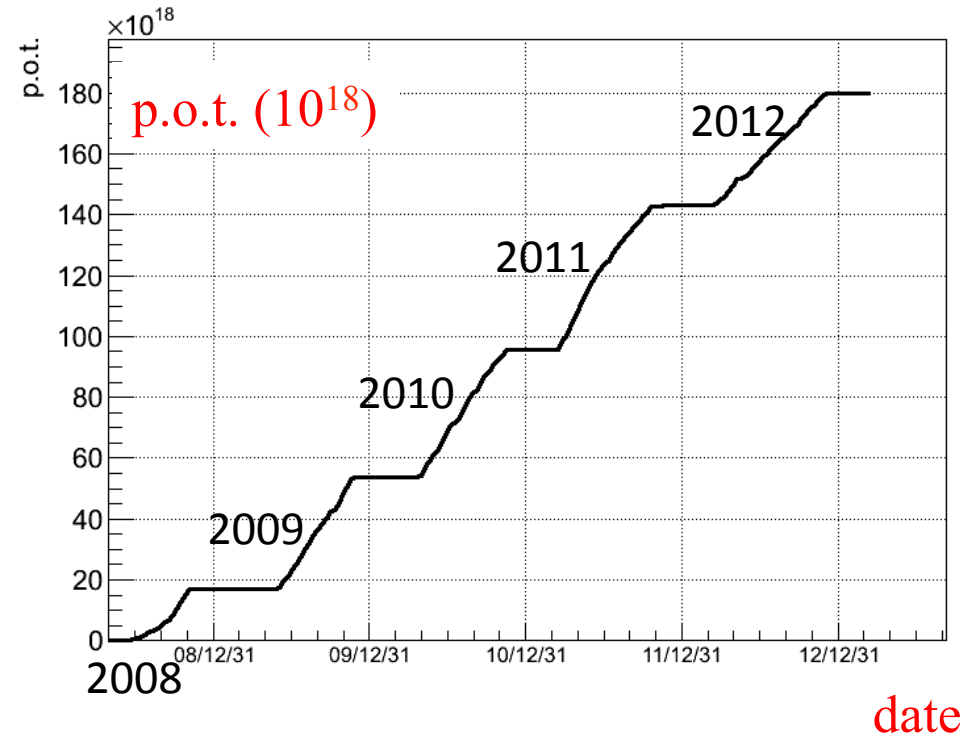
On behalf of the OPERA Collaboration

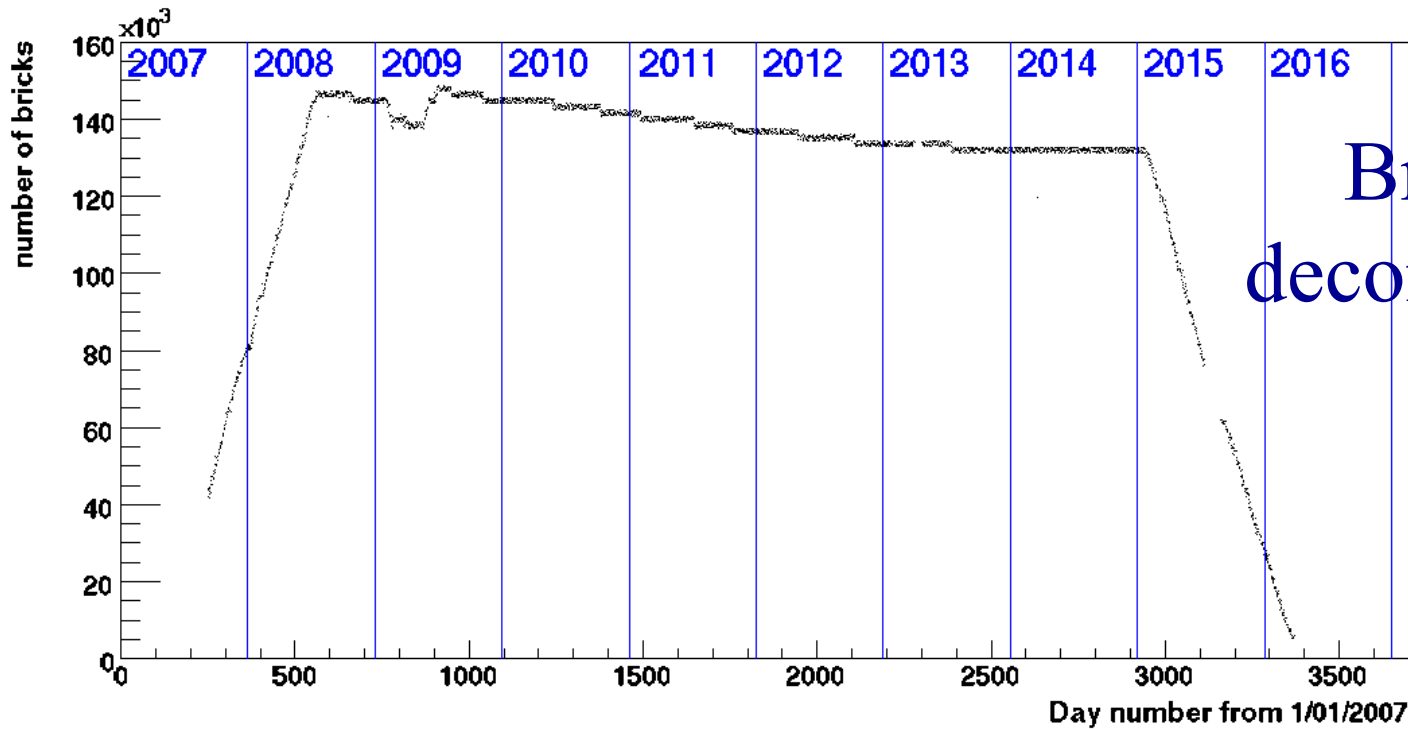*For the CXXII Meeting of the SPSC Committee*

The CNGS beam along its five years of operation 2008 ÷ 2012

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**

Last neutrino interaction recorded on December 3rd 2012

Brick target decommissioning

Brick development

12707 ECC developed

STATUS OF DATA ANALYSIS

7103 located interactions

6750 decay search
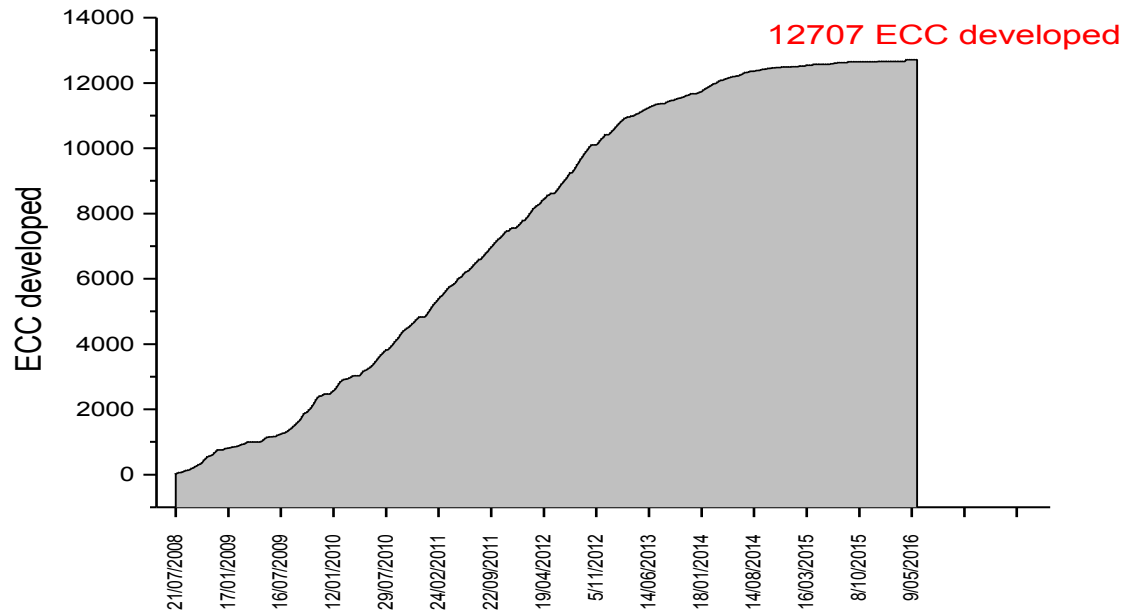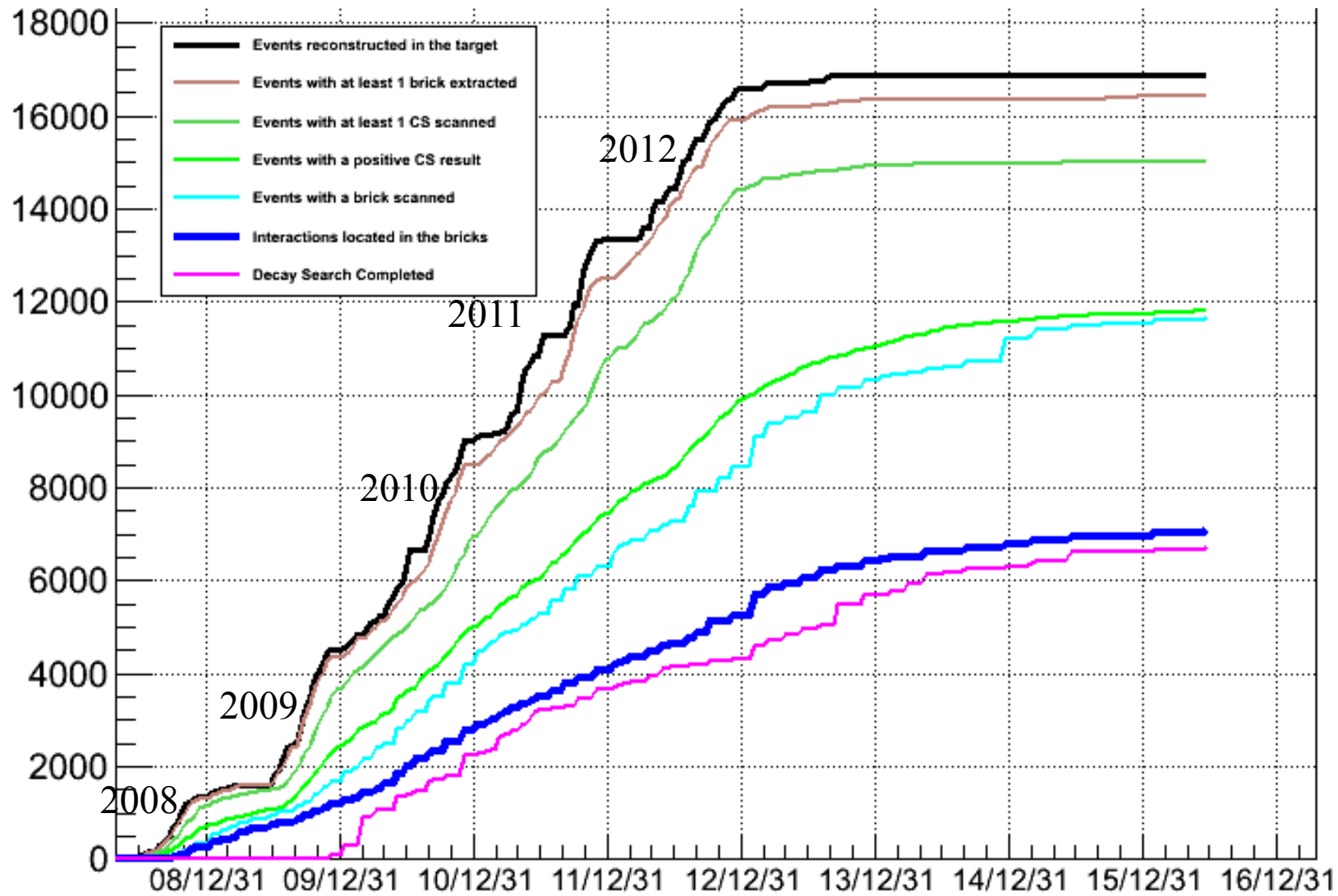
OSCILLATION PHYSICS

$\nu_\mu \rightarrow \nu_\tau$ 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
  - Pμ < 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
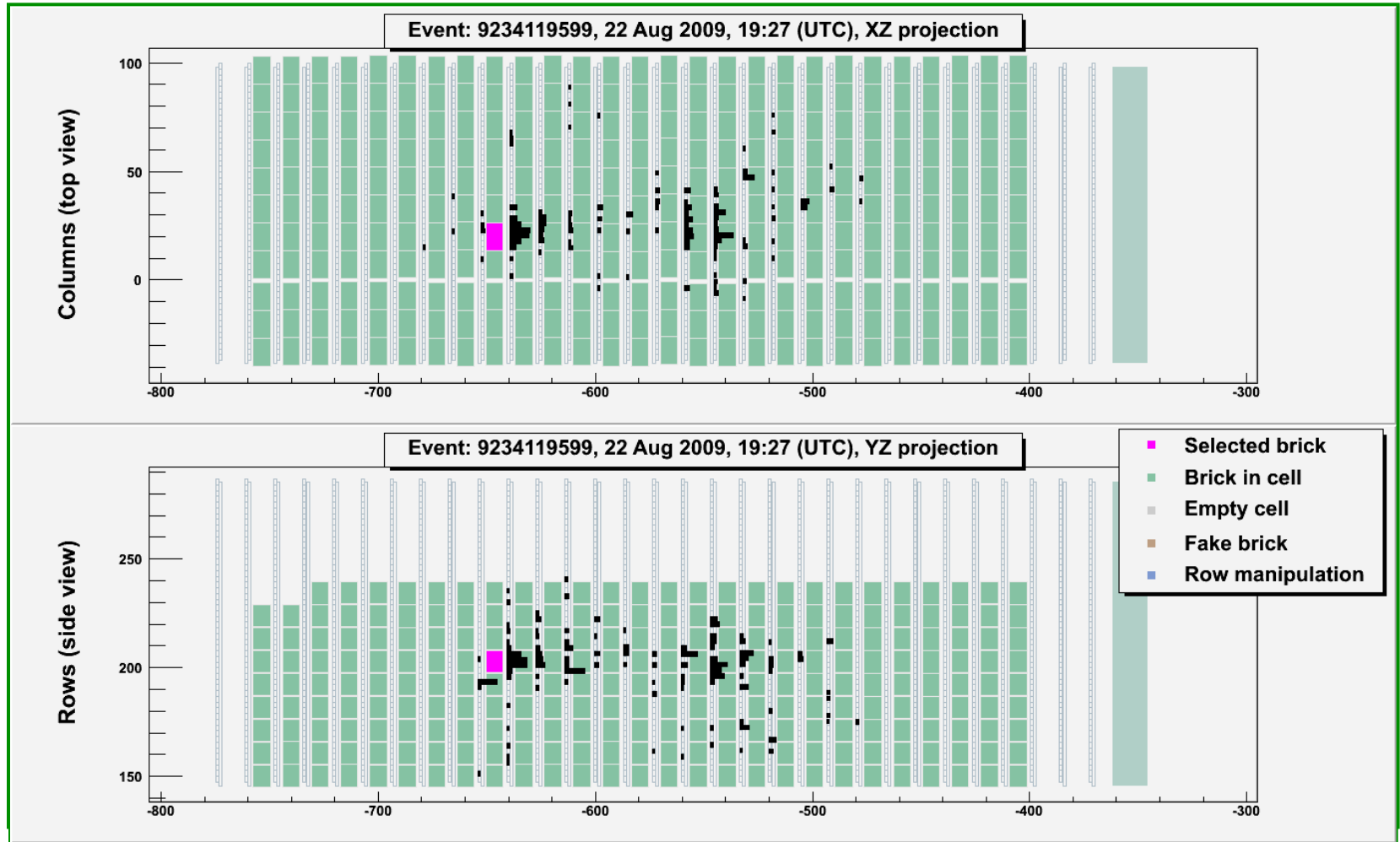
As seen by the electronic detectors …

THE FIRST ν_τ CANDIDATE
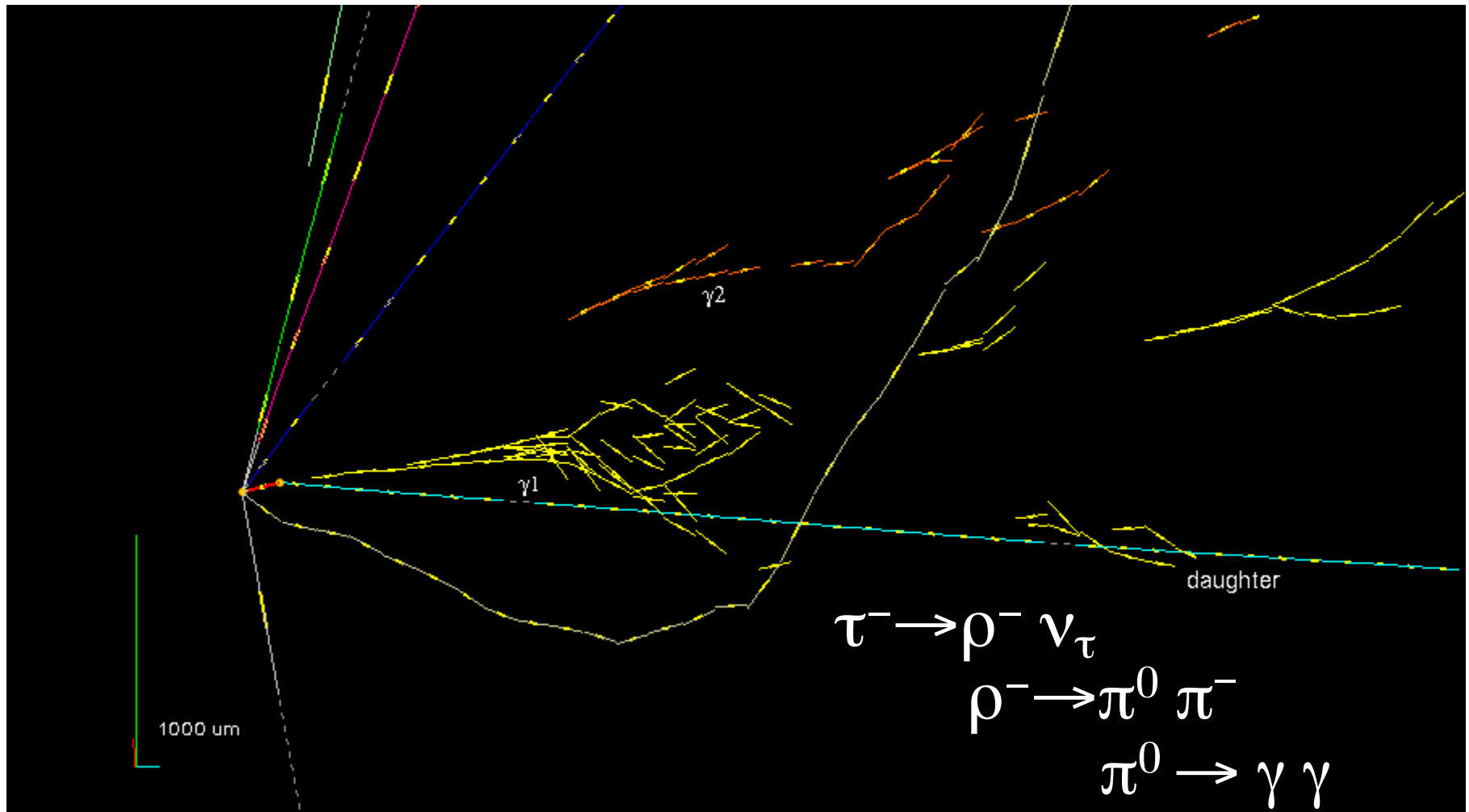
… and in the brick

$$\tau^- \rightarrow \rho^- \, \nu_\tau$$
$$\rho^- \rightarrow \pi^0 \, \pi^-$$
$$\pi^0 \rightarrow \gamma \, \gamma$$

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

THE THIRD ν_τ CANDIDATE

As seen by the electronic detectors …

2.8 GeV muon

Event: 12123032048, 2 May 2012, 10:12 (UTC), XZ projection

Event: 12123032048, 2 May 2012, 10:12 (UTC), YZ projection

Legend:
- ■ Selected brick
- ■ Brick in cell
- ■ Empty cell
- ■ Fake brick
- ■ Row manipulation
- ■ Second predicted brick
- ■ Third predicted brick

Phys. Rev. D 89 (2014) 051102(R)
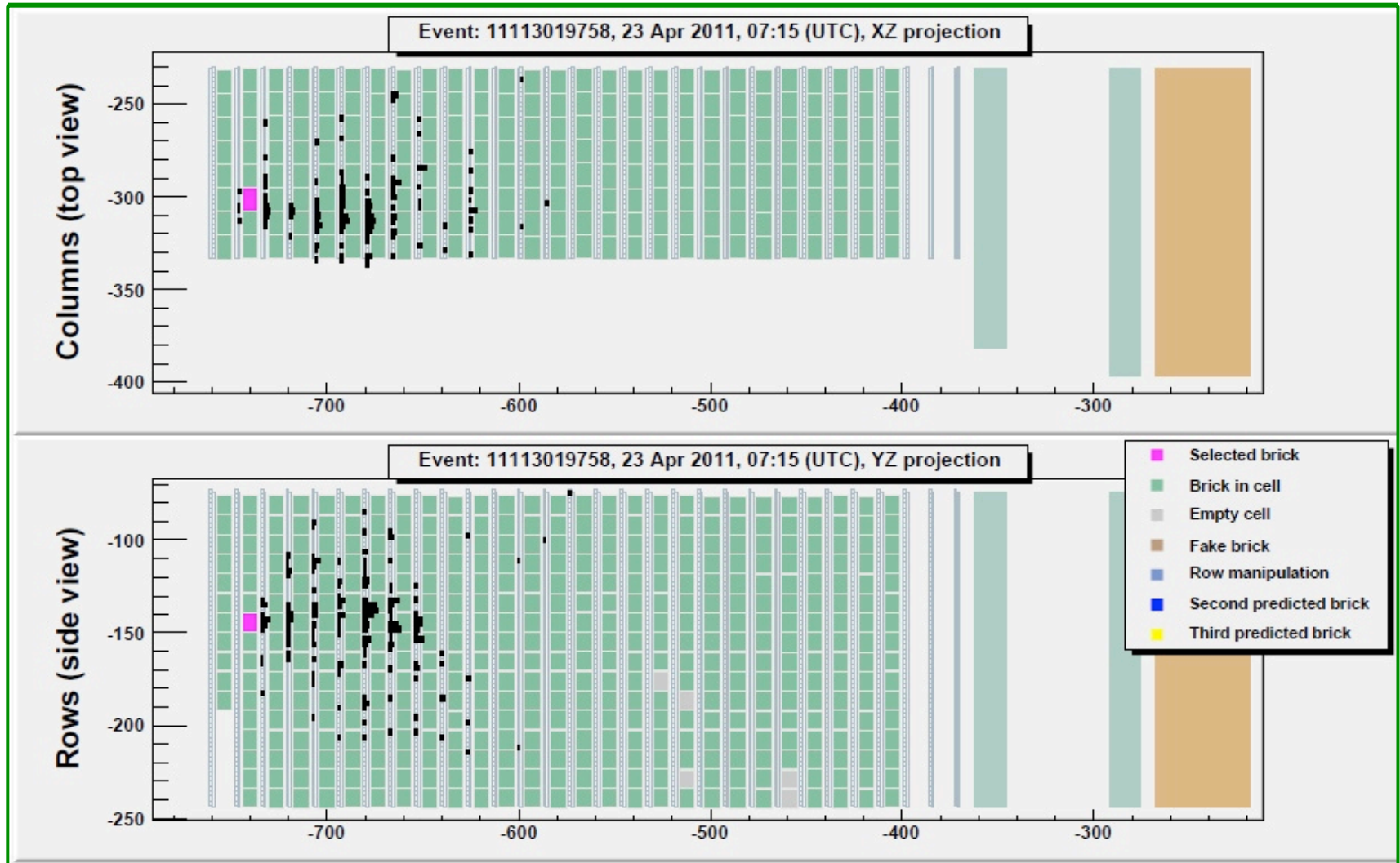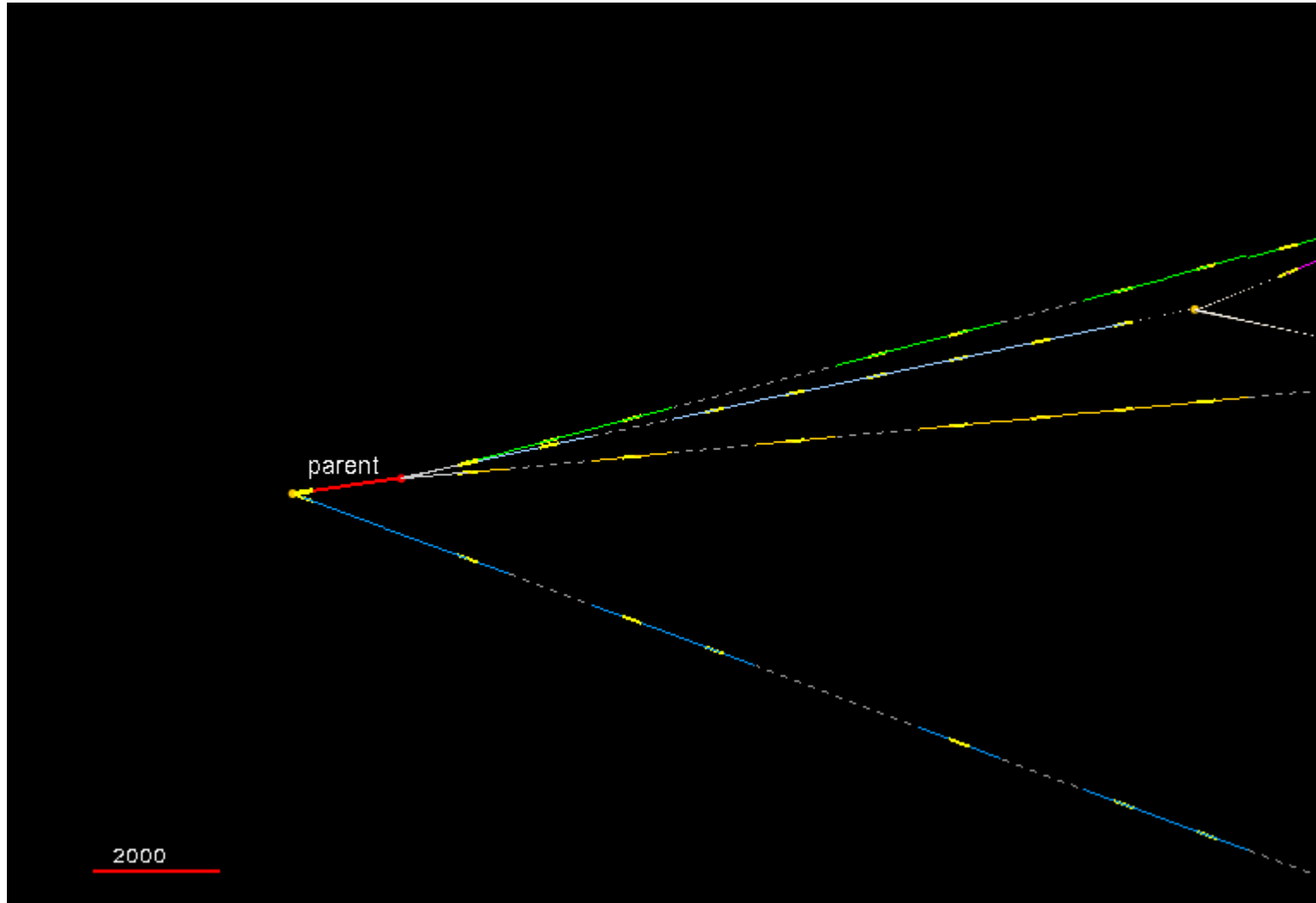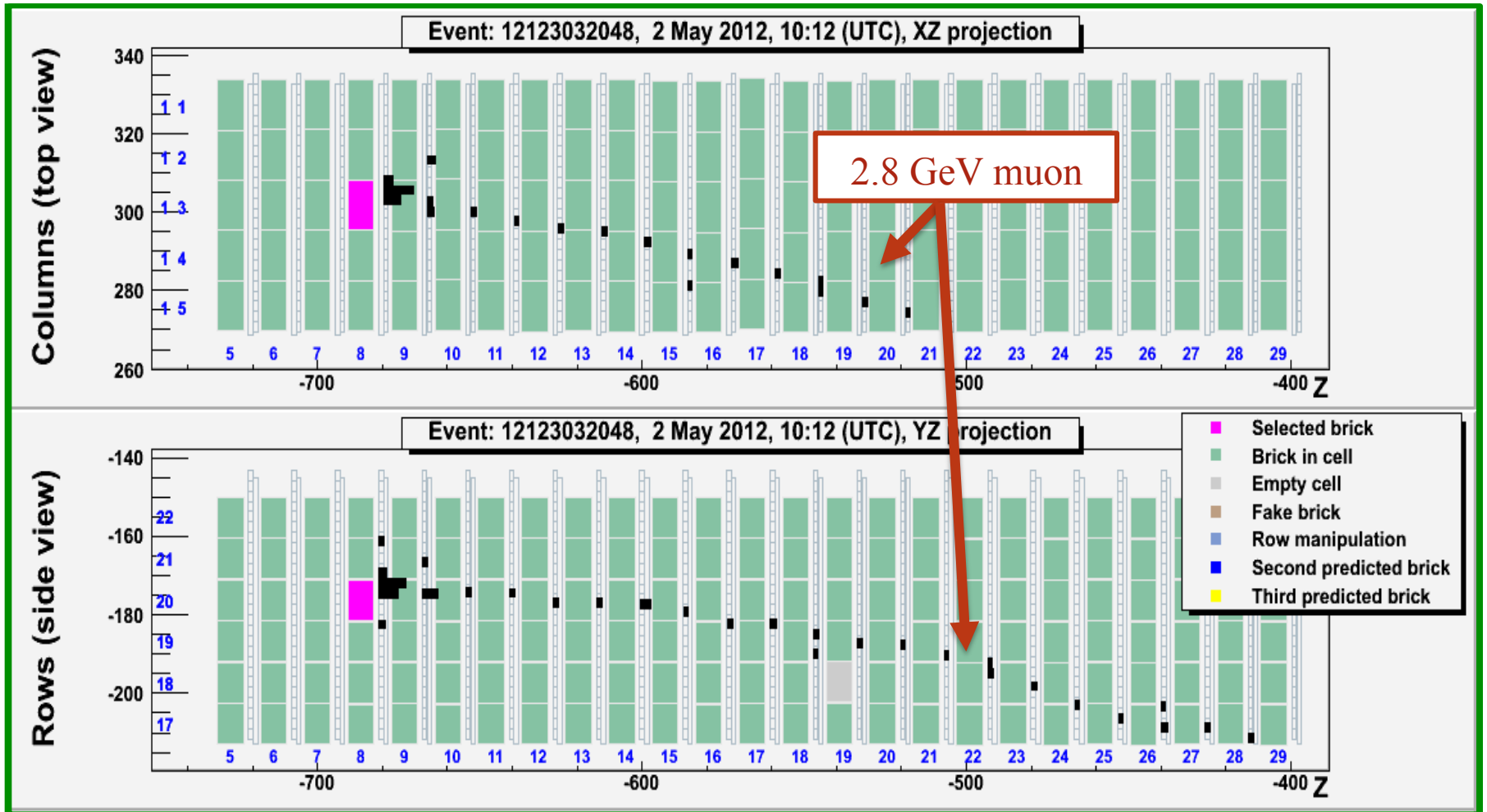
THE THIRD ν_τ CANDIDATE
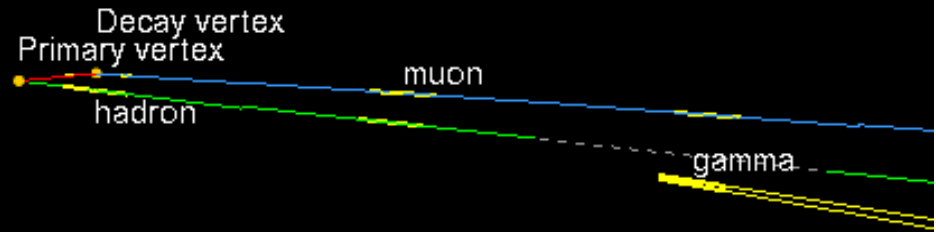
… and in the brick

THE FOURTH ν_τ CANDIDATE
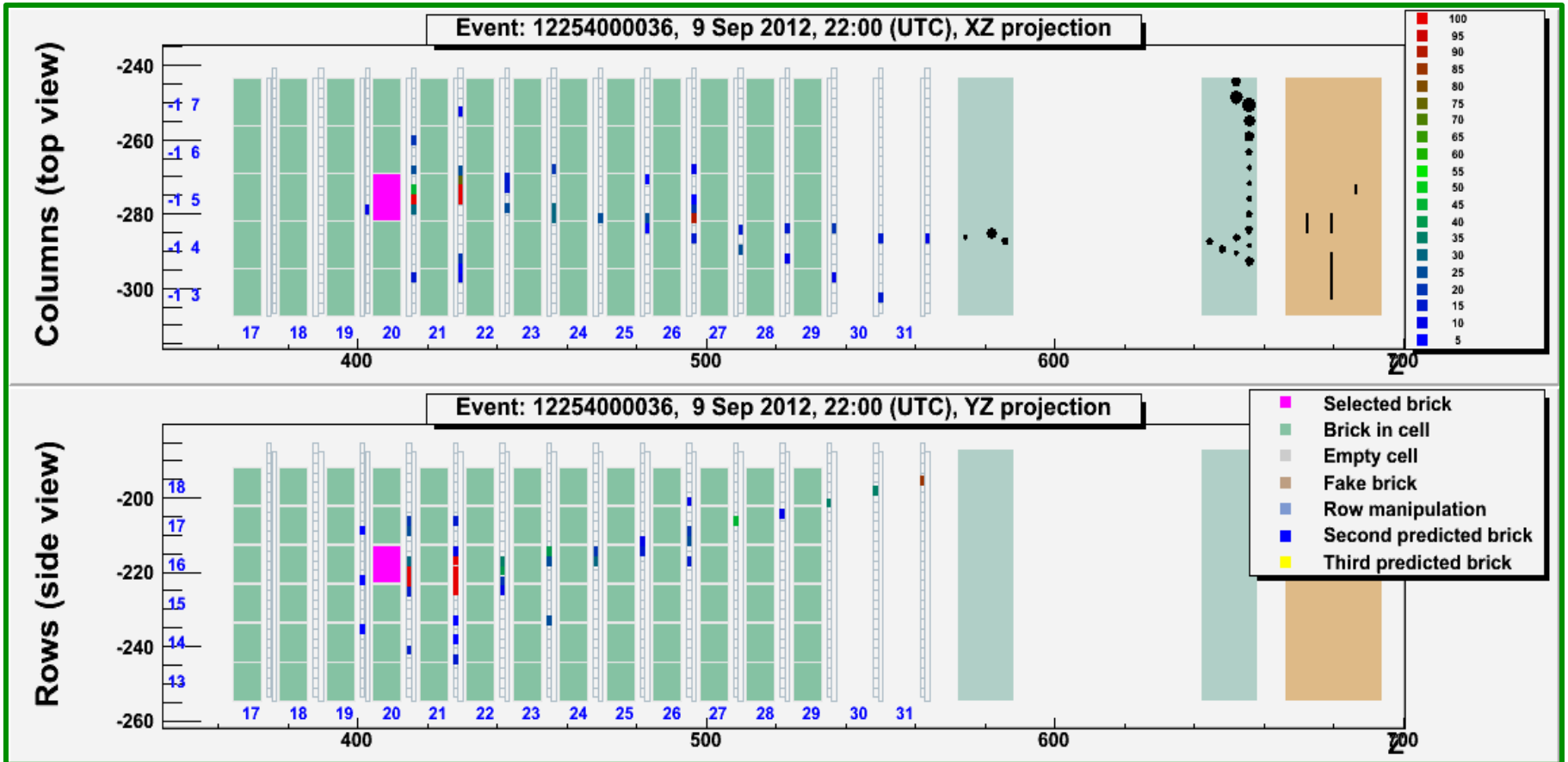
As seen by the electronic detectors …

THE FORTH ν_τ CANDIDATE

… and in the brick
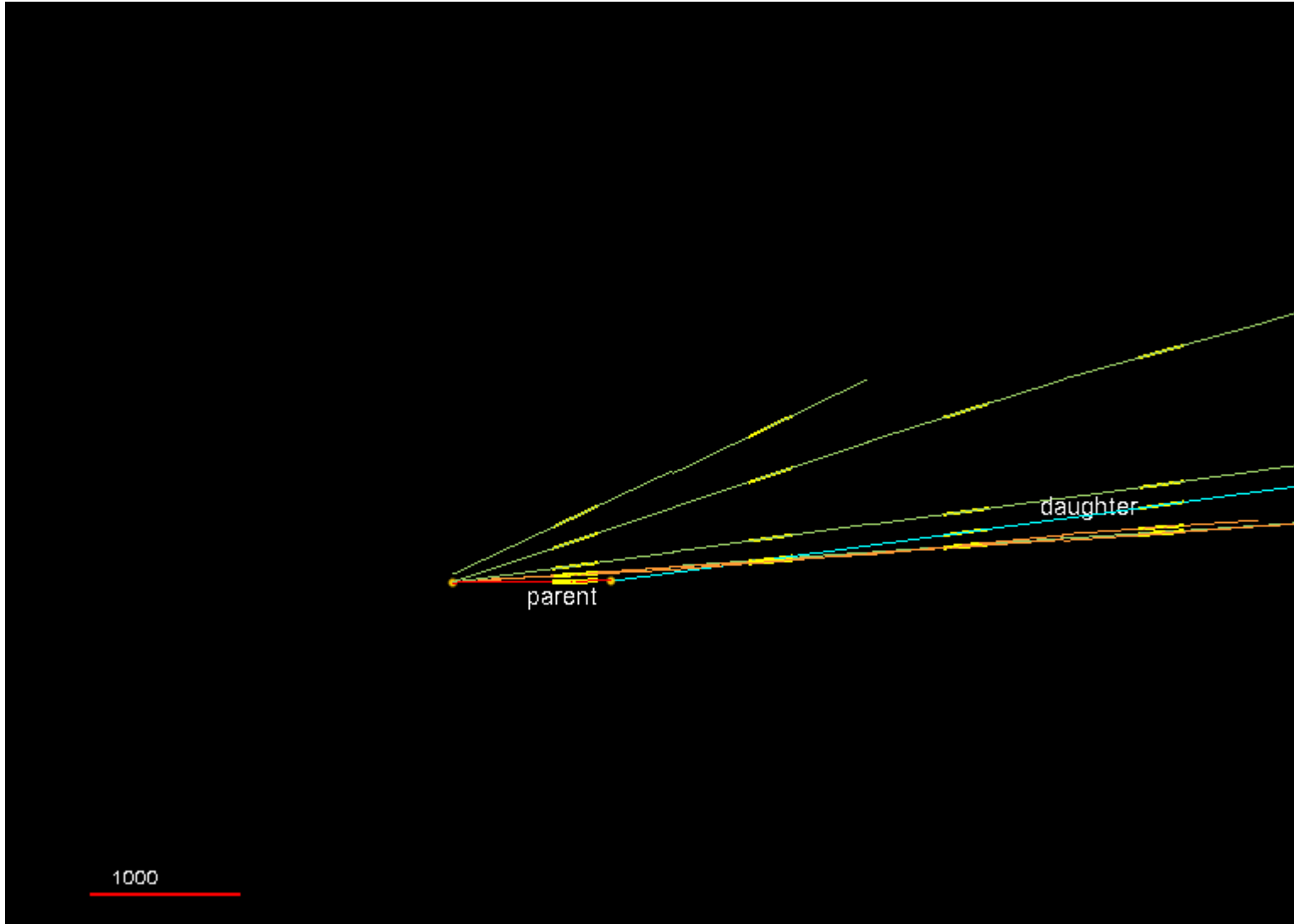
OUTSTANDING PAPER AWARD BY THE PHYSICAL SOCIETY OF JAPAN

THE FIFTH ν_τ CANDIDATE

As seen by the electronic detectors …

Event: 12227007334, 14 Aug 2012, 01:27 (UTC)
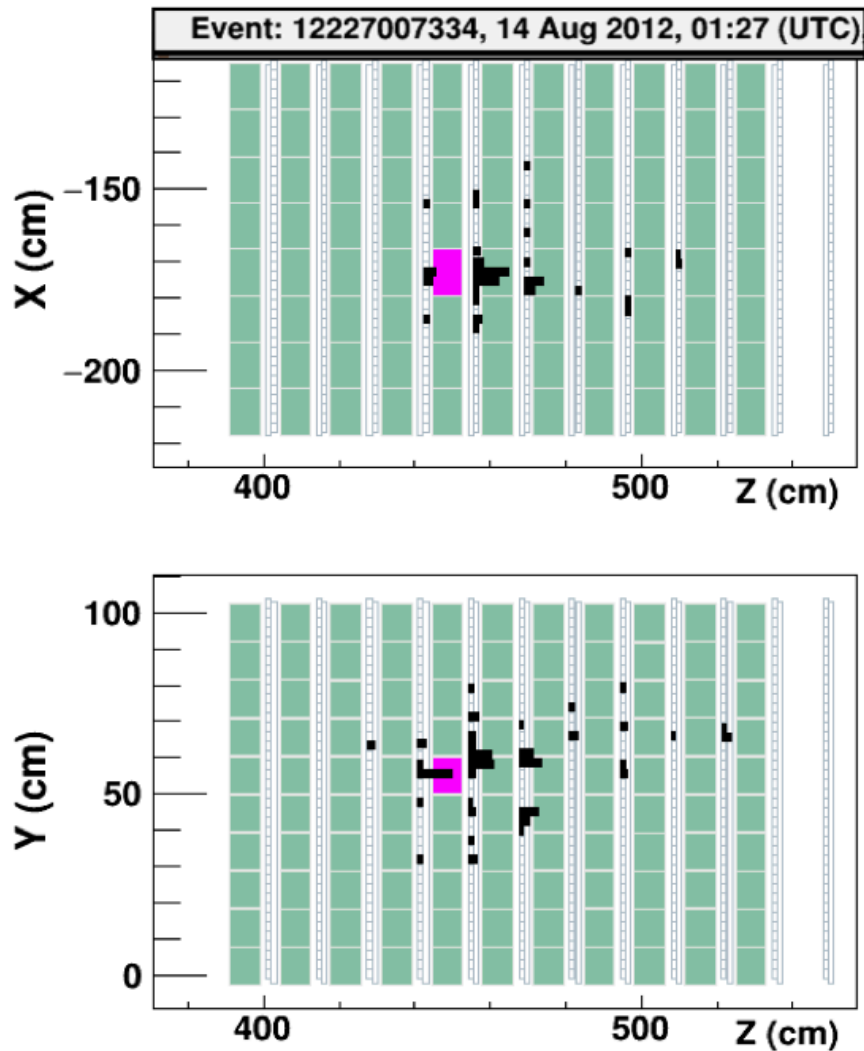
THE FIFTH ν_τ CANDIDATE

… and in the brick
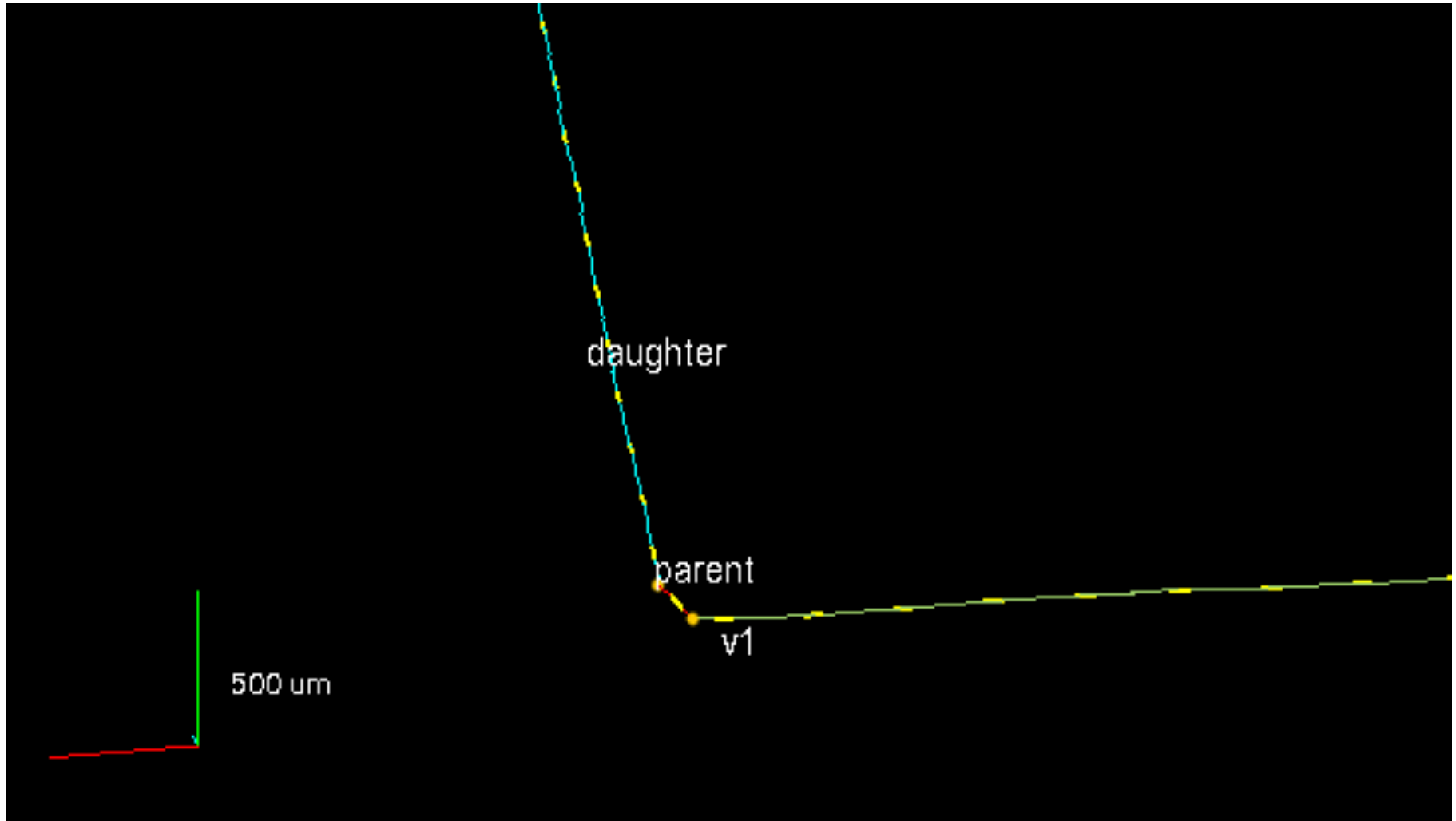
VISIBLE ENERGY OF ALL THE CANDIDATES

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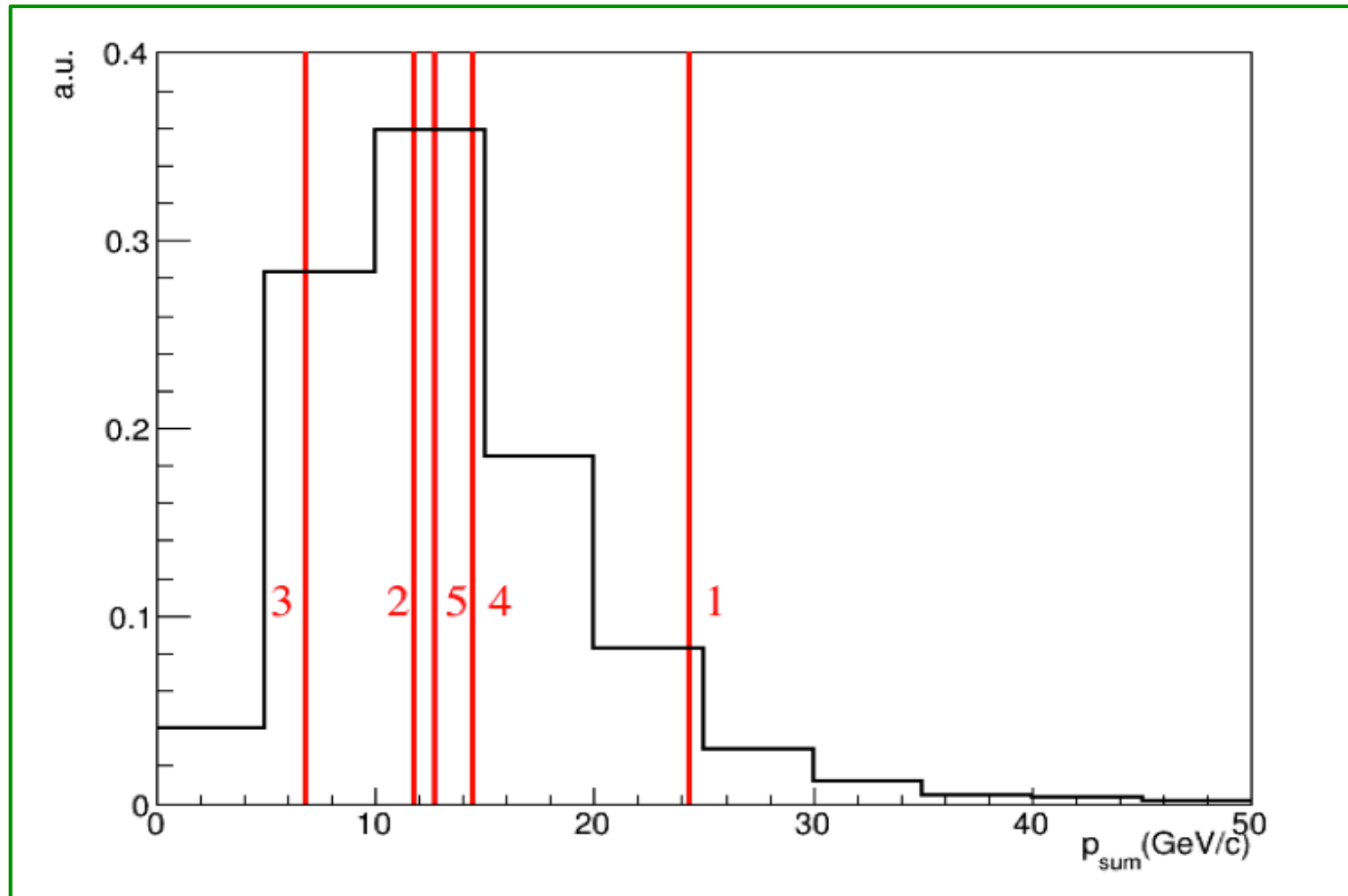
STATISTICAL CONSIDERATIONS

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

Two statistical methods:
- Fisher combination of single channel p-values
- Profile likelihood ratio

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

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

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

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

Discovery of τ Neutrino Appearance in the CNGS Neutrino Beam with the OPERA Experiment

N. Agafonova,[1] A. Aleksandrov,[2] A. Anokhina,[3] S. Aoki,[4] A. Ariga,[5] T. Ariga,[5] D. Bender,[6] A. Bertolin,[7] I. Bodnarchuk,[8] C. Bozza,[9] R. Brugnera,[7,10] A. Buonaura,[2,11] S. Buontempo,[2] B. Büttner,[12] M. Chernyavsky,[13] A. Chukanov,[8] L. Consiglio,[2] N. D'Ambrosio,[14] G. De Lellis,[2,11] M. De Serio,[15,16] P. Del Amo Sanchez,[17] A. Di Crescenzo,[2] D. Di Ferdinando,[18] N. Di Marco,[14] S. Dmitrievski,[8] M. Dracos,[19] D. Duchesneau,[17] S. Dusini,[7] T. Dzhatdoev,[3] J. Ebert,[12] A. Ereditato,[5] R. A. Fini,[16] F. Fornari,[18,20] T. Fukuda,[21] G. Galati,[2,11] A. Garfagnini,[7,10] J. Goldberg,[22] Y. Gornushkin,[8] G. Grella,[9] A. M. Guler,[6] C. Gustavino,[23] C. Hagner,[12] T. Hara,[4] H. Hayakawa,[24] A. Hollnagel,[12] B. Hosseini,[2,11] K. Ishiguro,[24] K. Jakovcic,[25] C. Jollet,[19] C. Kamiscioglu,[6] M. Kamiscioglu,[6] J. H. Kim,[26] S. H. Kim,[26,*] N. Kitagawa,[24] B. Klicek,[25] K. Kodama,[27] M. Komatsu,[24] U. Kose,[7,†] I. Kreslo,[5] F. Laudisio,[9] A. Lauria,[2,11] A. Ljubicic,[25] A. Longhin,[28] P. F. Loverre,[23,29] A. Malgin,[1] M. Malenica,[25] G. Mandrioli,[18] T. Matsuo,[21] T. Matsushita,[24] V. Matveev,[1] N. Mauri,[18,20] E. Medinaceli,[7,10] A. Meregaglia,[19] S. Mikado,[30] M. Miyanishi,[24] F. Mizutani,[4] P. Monacelli,[23] M. C. Montesi,[2,11] K. Morishima,[24] M. T. Muciaccia,[15,16] N. Naganawa,[24] T. Naka,[24] M. Nakamura,[24] T. Nakano,[24] Y. Nakatsuka,[24] K. Niwa,[24] S. Ogawa,[21] A. Olchevsky,[8] T. Omura,[24] K. Ozaki,[4] A. Paoloni,[28] L. Paparella,[15,16] B. D. Park,[26,‡] I. G. Park,[26] L. Pasqualini,[18,20] A. Pastore,[15] L. Patrizii,[18] H. Pessard,[17] C. Pistillo,[5] D. Podgrudkov,[3] N. Polukhina,[13] M. Pozzato,[18,20] F. Pupilli,[28] M. Roda,[7,10] T. Roganova,[3] H. Rokujo,[24] G. Rosa,[23,29] O. Ryazhskaya,[1] O. Sato,[24,§] A. Schembri,[14] W. Schmidt-Parzefall,[12] I. Shakirianova,[1] T. Shchedrina,[13,11] A. Sheshukov,[8] H. Shibuya,[21] T. Shiraishi,[24] G. Shoziyoev,[3] S. Simone,[15,16] M. Sioli,[18,20] C. Sirignano,[7,10] G. Sirri,[18] A. Sotnikov,[8] M. Spinetti,[28] L. Stanco,[7] N. Starkov,[13] S. M. Stellacci,[9] M. Stipcevic,[25] P. Strolin,[2,11] S. Takahashi,[4] M. Tenti,[18] F. Terranova,[28,31] V. Tioukov,[2] S. Tufanli,[5,‖] P. Vilain,[32] M. Vladymyrov,[13,¶] L. Votano,[28] J. L. Vuilleumier,[5] G. Wilquet,[32] B. Wonsak,[12] C. S. Yoon,[26] and S. Zemskova[8]

(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].

PRL 115 (2015) 121802

IN THE SAME DATA SAMPLE…

AN EVENT WITH THREE VERTICES
WITHOUT ANY MUON IN THE FINAL STATE

Event: 11143018505, 23 May 2011, 06:59 (UTC), XZ projection

Event: 11143018505, 23 May 2011, 06:59 (UTC), YZ projection

- Selected brick
- Brick in cell
- Empty cell
- Fake brick
- Row manipulation
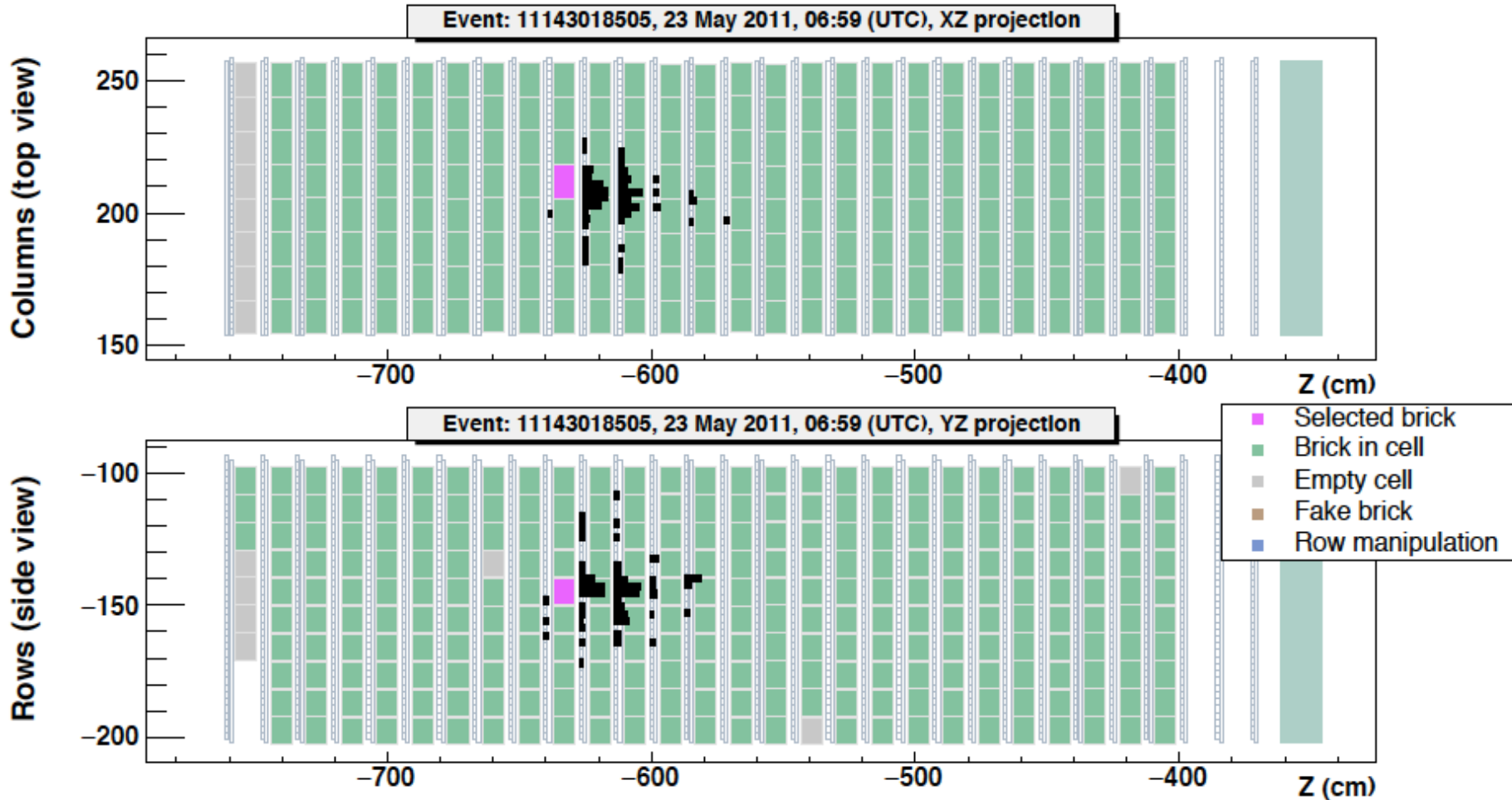
Interface emulsion films

Hint for
electromagnetic shower
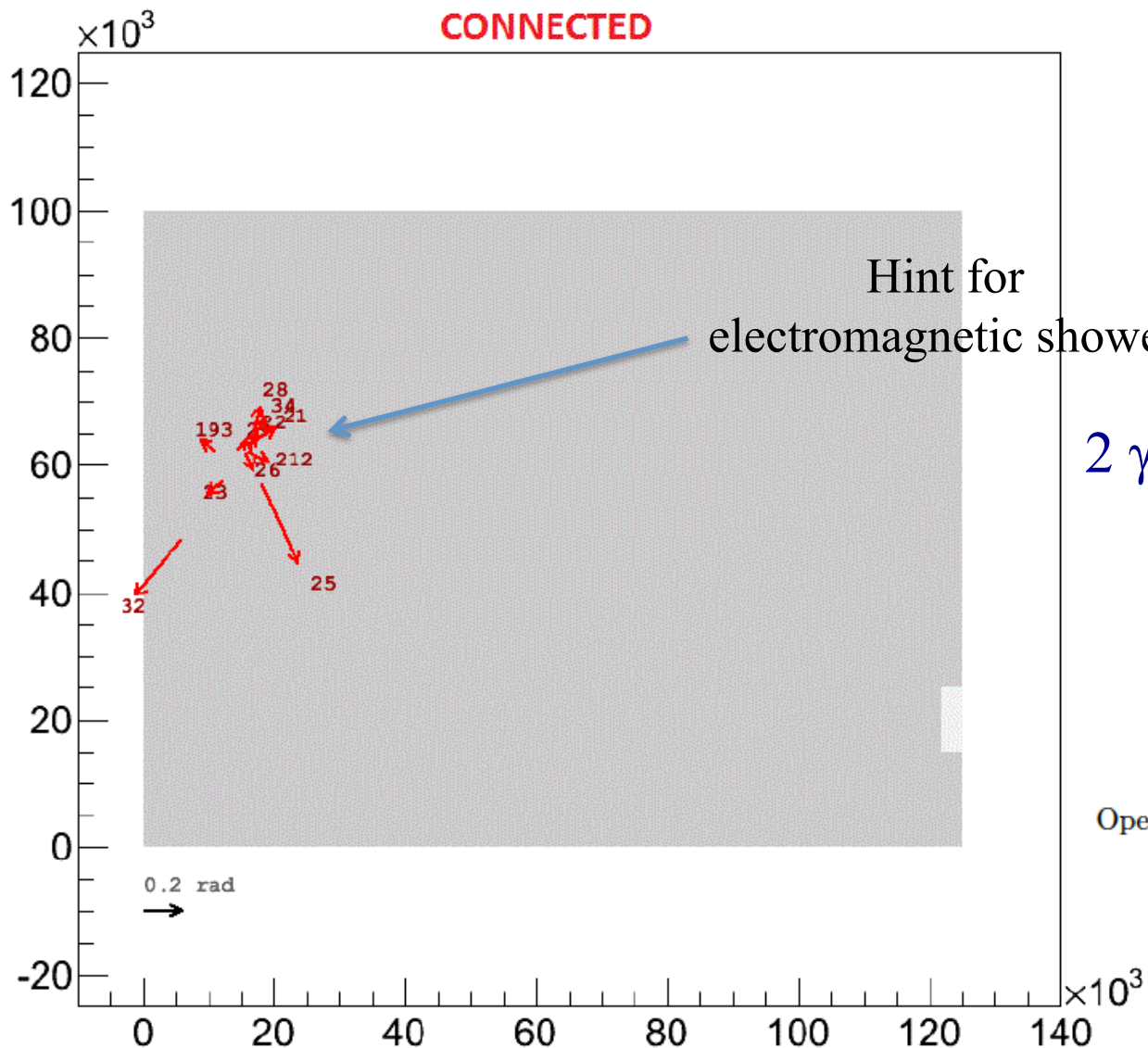
2 γ's detected in the brick

Shower ID	γ_1	γ_2
Starting plate	35	41
x (μm)	15271.0	14906.6
y (μm)	59647.0	60183.2
θ_x (rad)	0.050	-0.011
θ_y (rad)	0.122	0.085
IP_{III} (μm)	8 ± 8	40 ± 11
IP_{I} (μm)	30 ± 22	40 ± 23
Opening angle (rad)	0.027	0.029
Energy (GeV)	7.1 ± 1.7	5.3 ± 2.2

0.2 rad

KINK TOPOLOGY

Flight Length = 1160 µm
With γ attached
IP = 8±8 µm
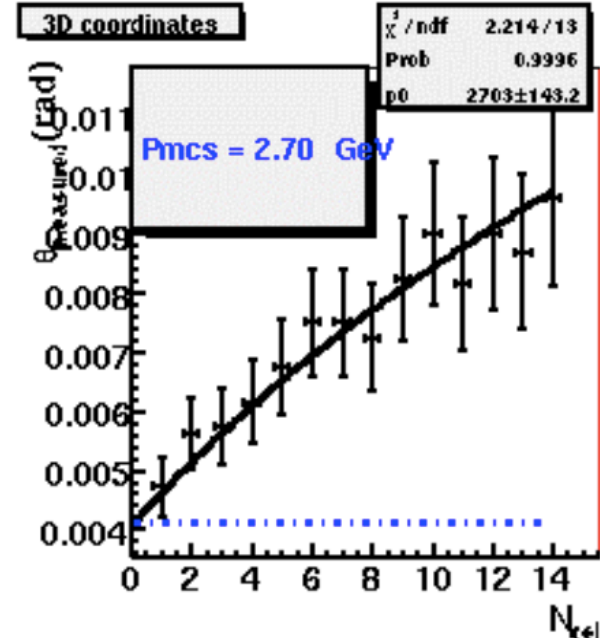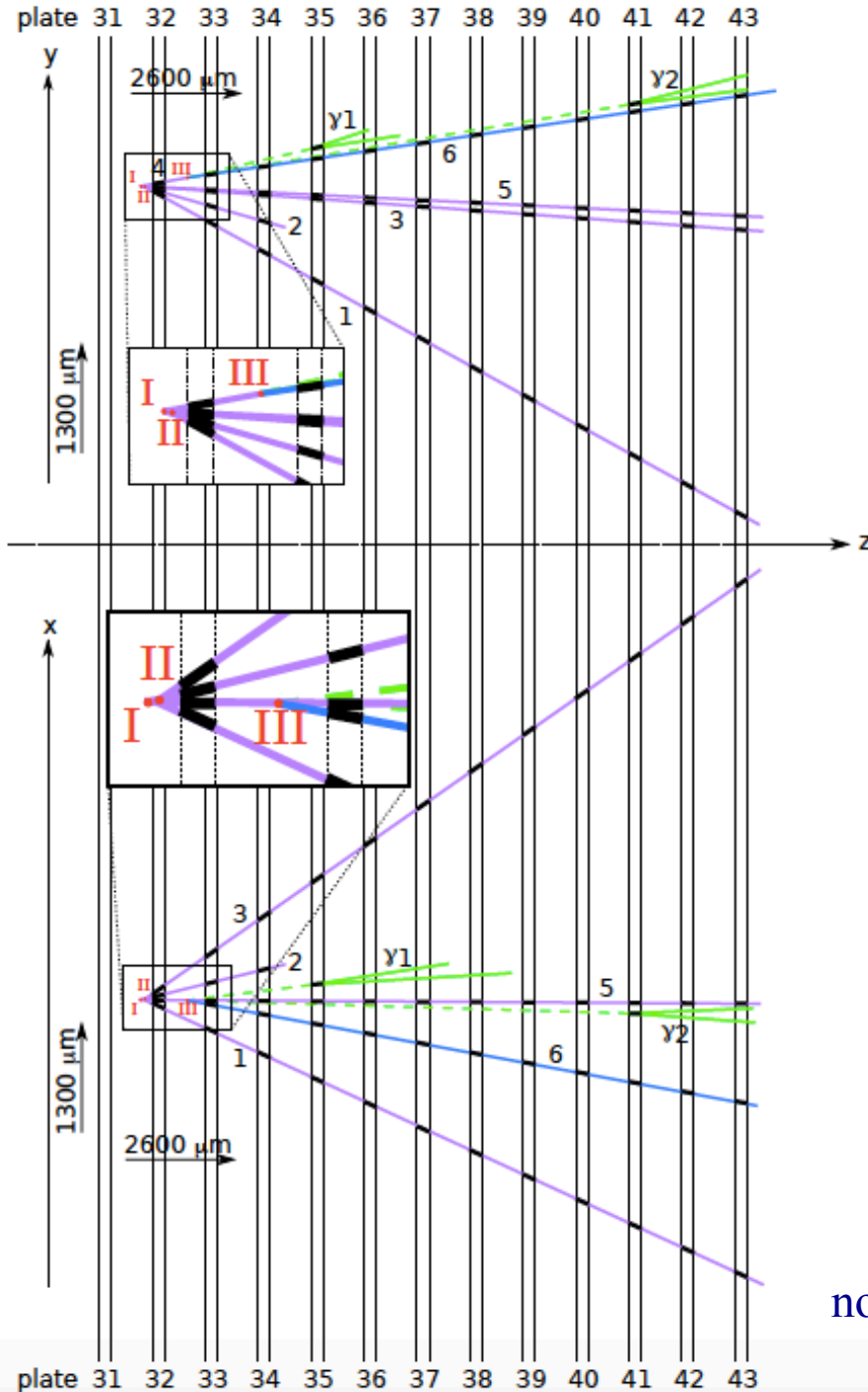
Track ID	p best fit (GeV/c)	68 % p range (GeV/c)
1	2.1	$[\,1.6\,;\,3.1\,]$
3	4.3	$[\,3.1\,;\,7.1\,]$
5	0.54	$[\,0.45\,;\,0.68\,]$
6 (daughter)	2.7	$[\,2.1\,;\,3.7\,]$

$$\vartheta_{\mathrm{kink}} = 90\,\mathrm{mrad} \rightarrow P_\perp = 240\,\mathrm{MeV}$$

not passing the standard cuts to be a tau candidate

Track segments showing a double vertex topology in the same lead plate

100 μm

4 parent

top

bottom

Projections at Z=-220 μm

Projections at Z=-330 μm

I

II

Vertex ID	Attached tracks	x (μm)	y (μm)	z (μm)
I (primary)	2, 4, 5	15077.0	59157.9	-33081.8
II (secondary)	1, 3	15085.9	59149.9	-32979.2
III (kink)	4, 6	15073.9	59262.4	-31926.4

bottom

bottom
top

bottom

3

top

2 prong vertex
Flight Length = 103 μm

5

bottom

2

Invariant mass = 1.9±0.5 GeV

top

1

bottom

top

y

x

Track ID	Single Vertex IP (μm) w.r.t. V_0	Two vertices IP (μm) w.r.t. V_I	w.r.t. V_{II}
1	8.3	36.2	0.1
2	8.8	1.0	6.5
3	4.8	25.9	0.1
4	13.0	1.5	20.4
5	5.1	2.2	9.6

Leading Feynman diagrams
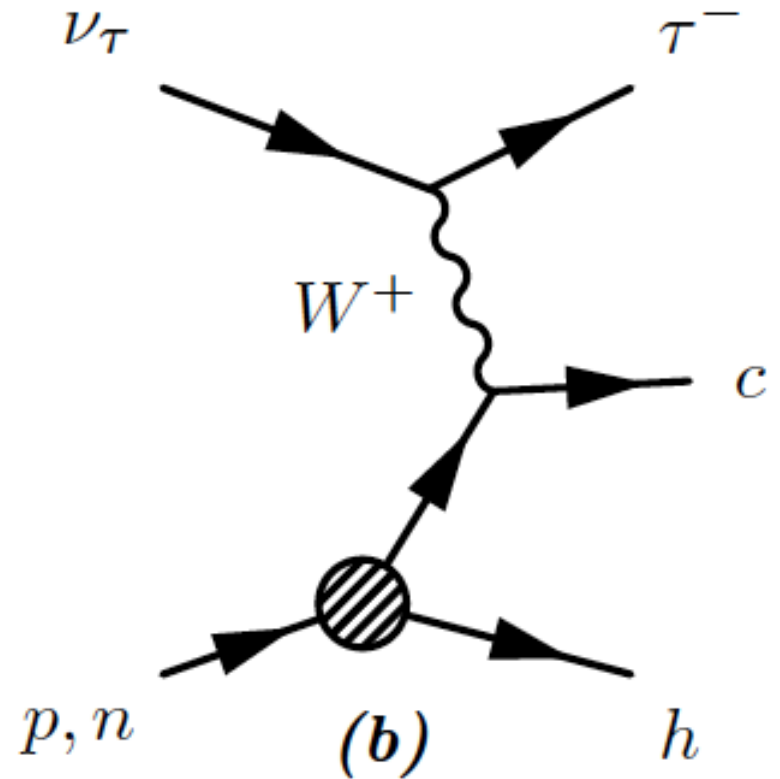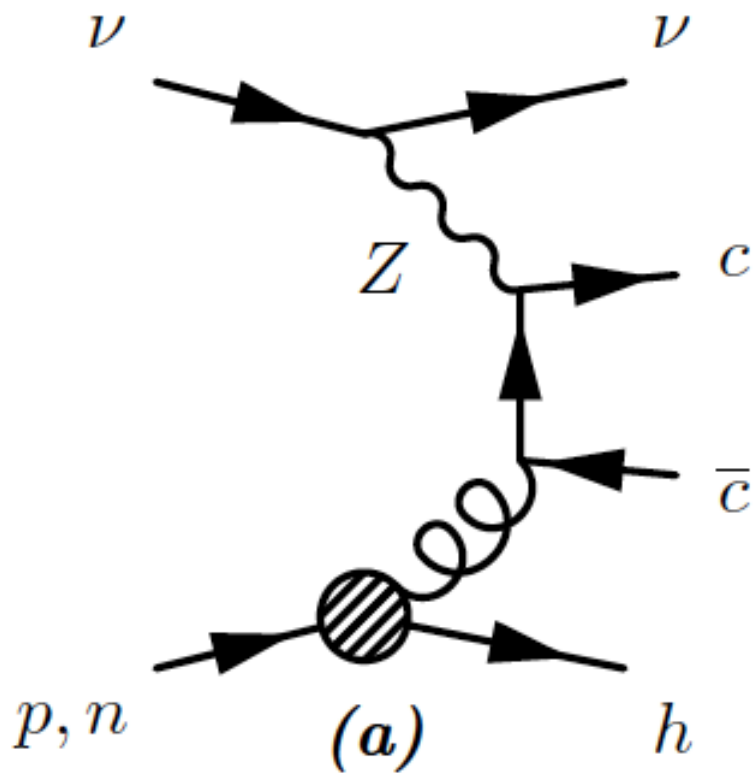
Expected yield after topological selection

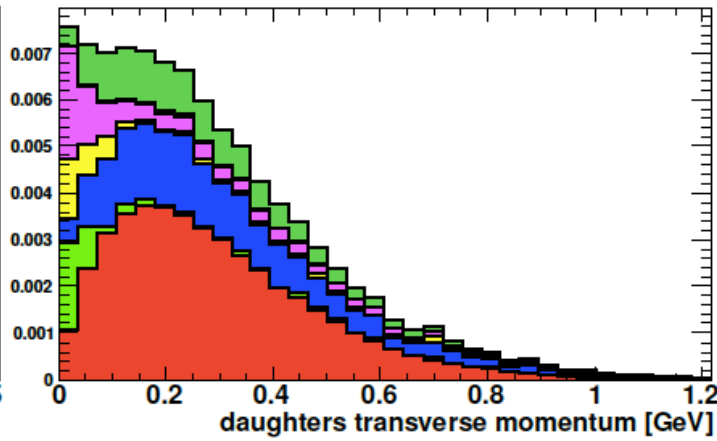| Sample	Muon misidentified	Expected events (10^{-3})
ν_τ CC + charm		45
ν_μ CC + charm + $h_{\rm int}$	yes	21
ν_μ NC + $c\bar{c}$		13
ν_τ CC + $h_{\rm int}$		9
ν_μ CC + $2h_{\rm int}$	yes	4
ν_μ NC + $2h_{\rm int}$		4
Total		100

Multivariate Analysis based on several kinematical features
- 1-prong vertex: Total momentum, transverse momentum, flight length
- 2-prong vertex: Total momentum, invariant mass, flight length
- Global features: Total e.m. energy, total hadronic energy, φ angle between 2 parents in the transverse plane, missing transverse momentum at 1ry
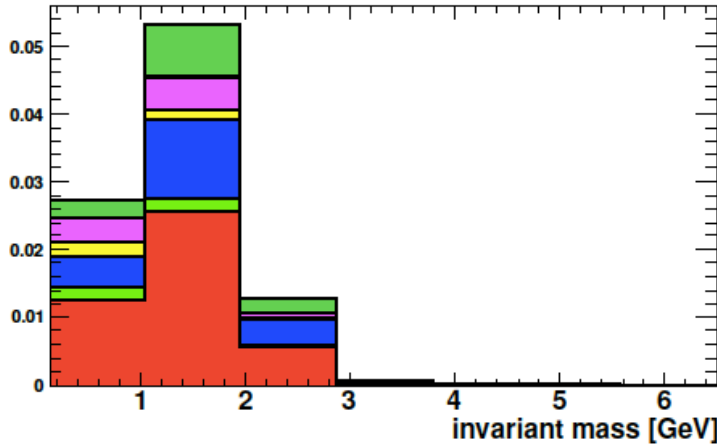
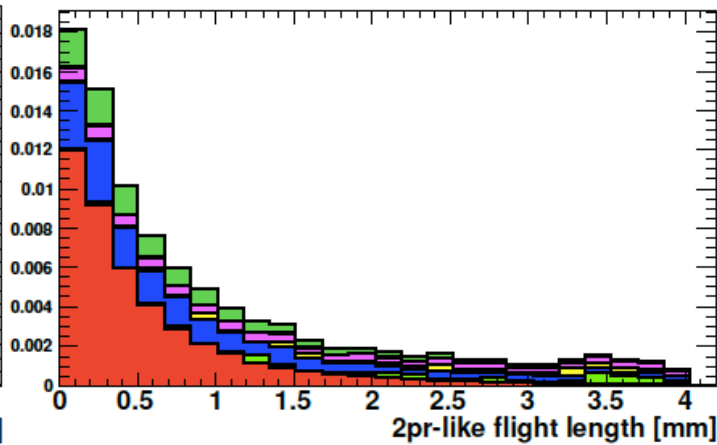# Multivariate analysis: 2-prong decay
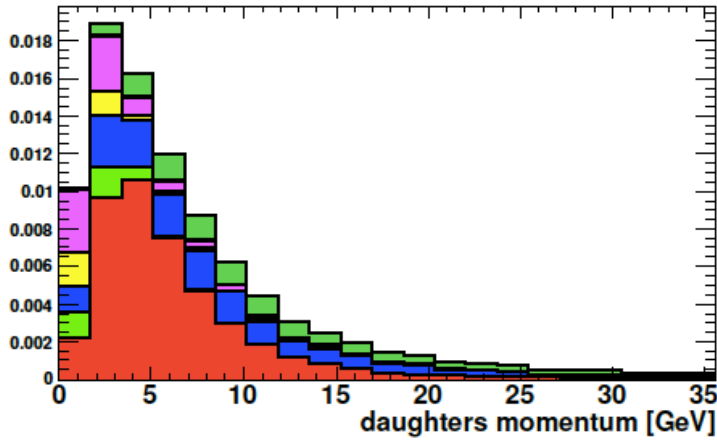
(a) Daughters momentum

(b) Daughters transverse momentum

(c) Invariant Mass

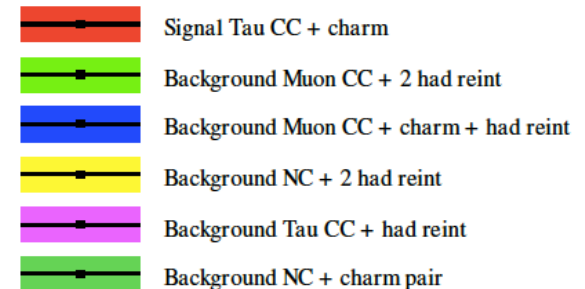(d) 2pr-like flight length

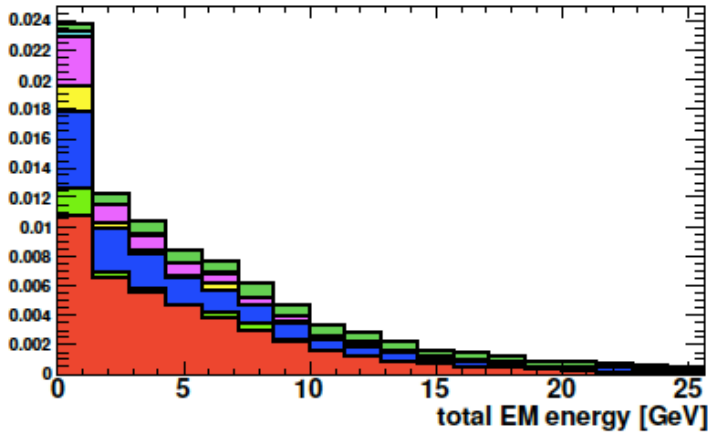PRELIMINARY

Signature sources

- Signal Tau CC + charm
- Background Muon CC + 2 had reint
- Background Muon CC + charm + had reint
- Background NC + 2 had reint
- Background Tau CC + had reint
- Background NC + charm pair
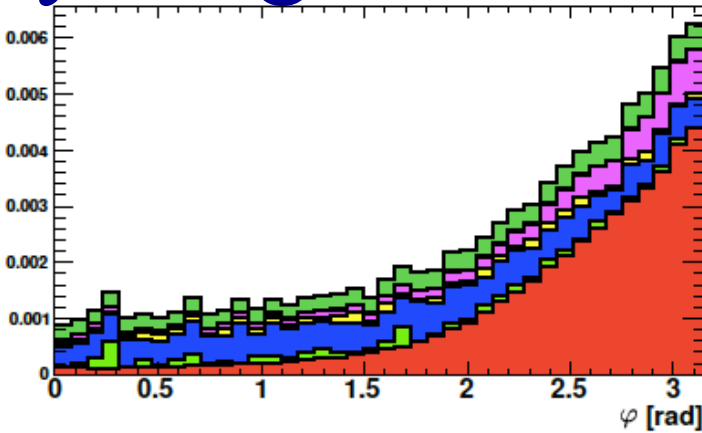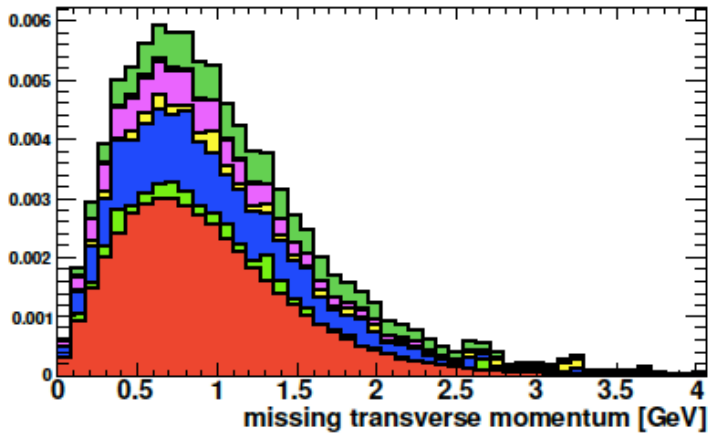
Multivariate analysis: global event features

(a) Total EM energy

(b) φ

(c) Missing transverse momentum
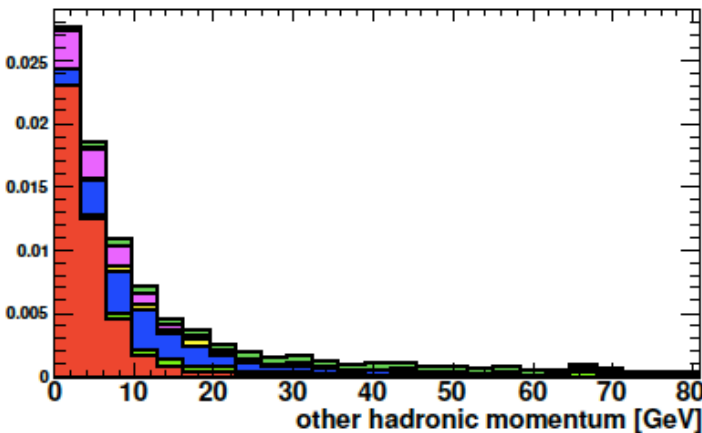
(d) Other hadronic momentum

PRELIMINARY

Signature sources

- Signal Tau CC + charm
- Background Muon CC + 2 had reint
- Background Muon CC + charm + had reint
- Background NC + 2 had reint
- Background Tau CC + had reint
- Background NC + charm pair

Neutral network result

Signature sources

- Signal Tau CC + charm
- Background Muon CC + 2 had reint
- Background Muon CC + charm + had reint
- Background NC + 2 had reint
- Background Tau CC + had reint
- Background Tau CC + charm
- Background NC + charm pair
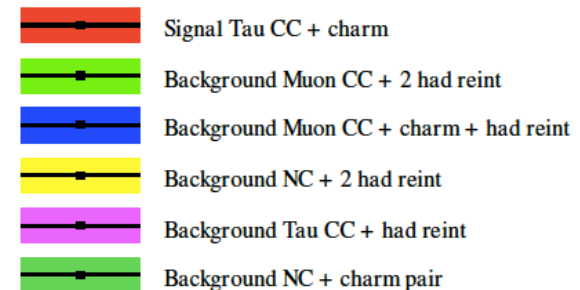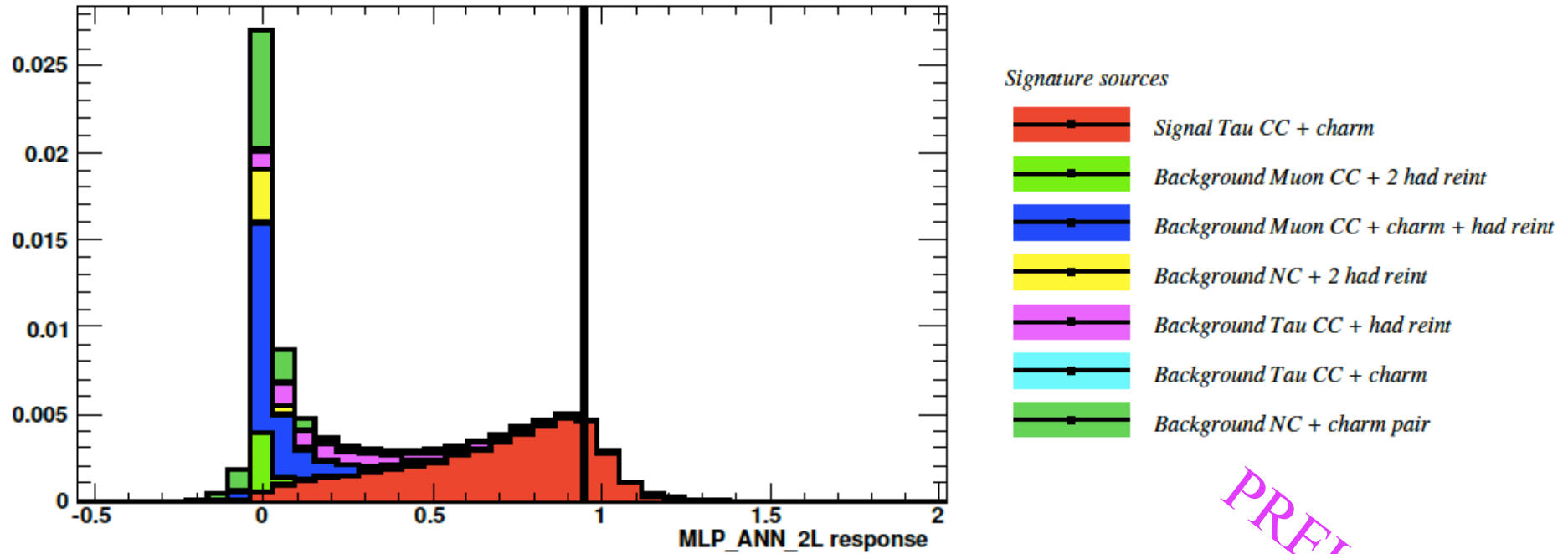
PRELIMINARY

variable	value
1pr-like daughter momentum	2.7 GeV/c
1pr-like daughter transverse momentum	0.242 GeV/c
Kink angle	90 mrad
1pr-like flight length	1.16 mm
2pr-like daughters momentum	6.17 GeV/c
2pr-like daughters transverse momentum	0.542 GeV/c
2pr-like invariant mass	1.86 GeV/c^2
2pr-like flight length	103 μm
Total EM energy	12.5 GeV
φ angle	2.41 rad
Missing transverse momentum	0.944 GeV/c
Other hadronic momentum	0.850 GeV/c
ANN output	**0.946**

Significance

$$\mathcal{L}(\mu|x) = \sum_{i \in B} n_i \cdot f_i(x) + \mu \sum_{j \in S} n_j \cdot f_j(x)$$

x PDF from ANN output
n_i = yield of i-th process
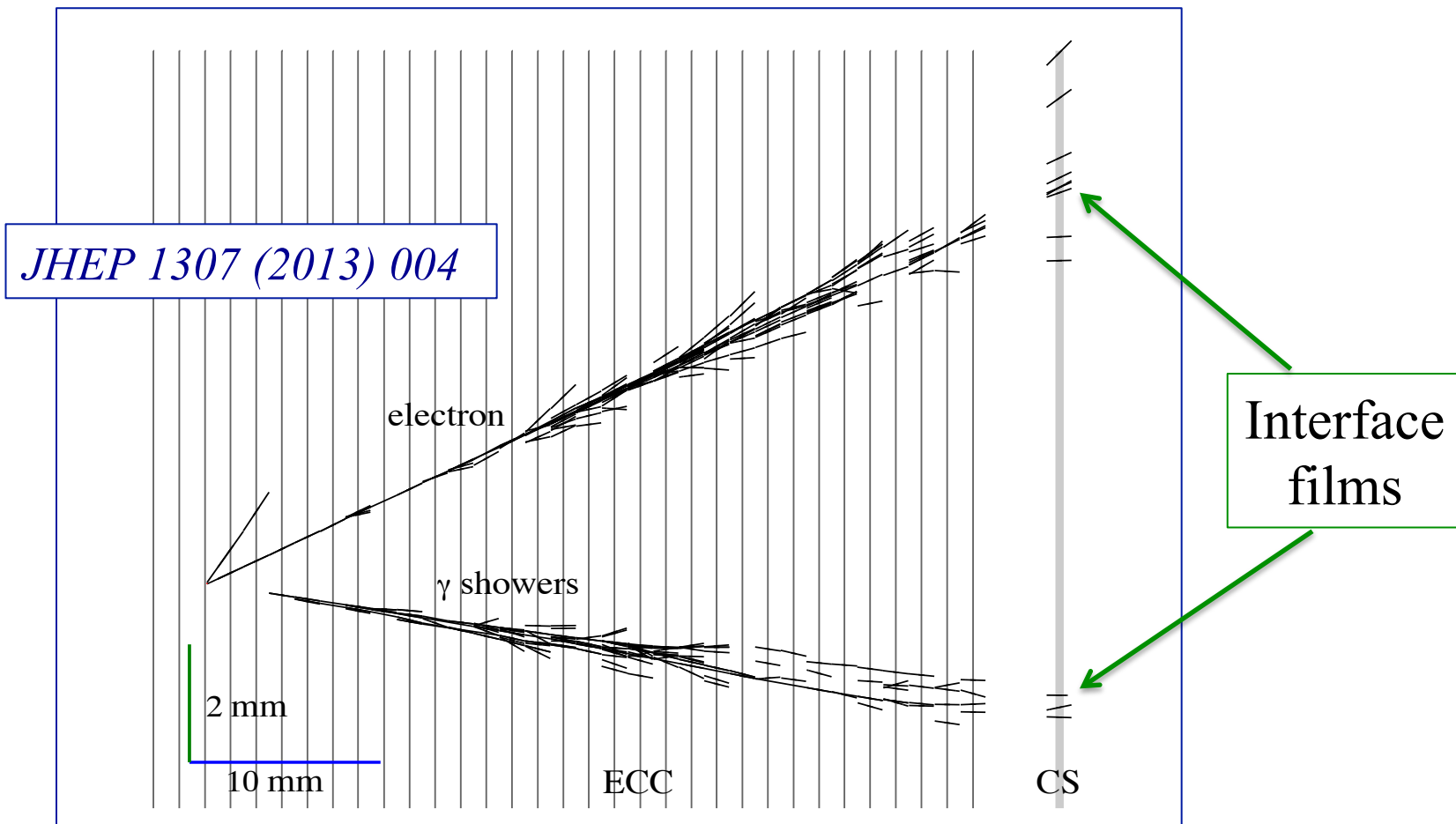Background only → $\mu = 0$

PRELIMINARY
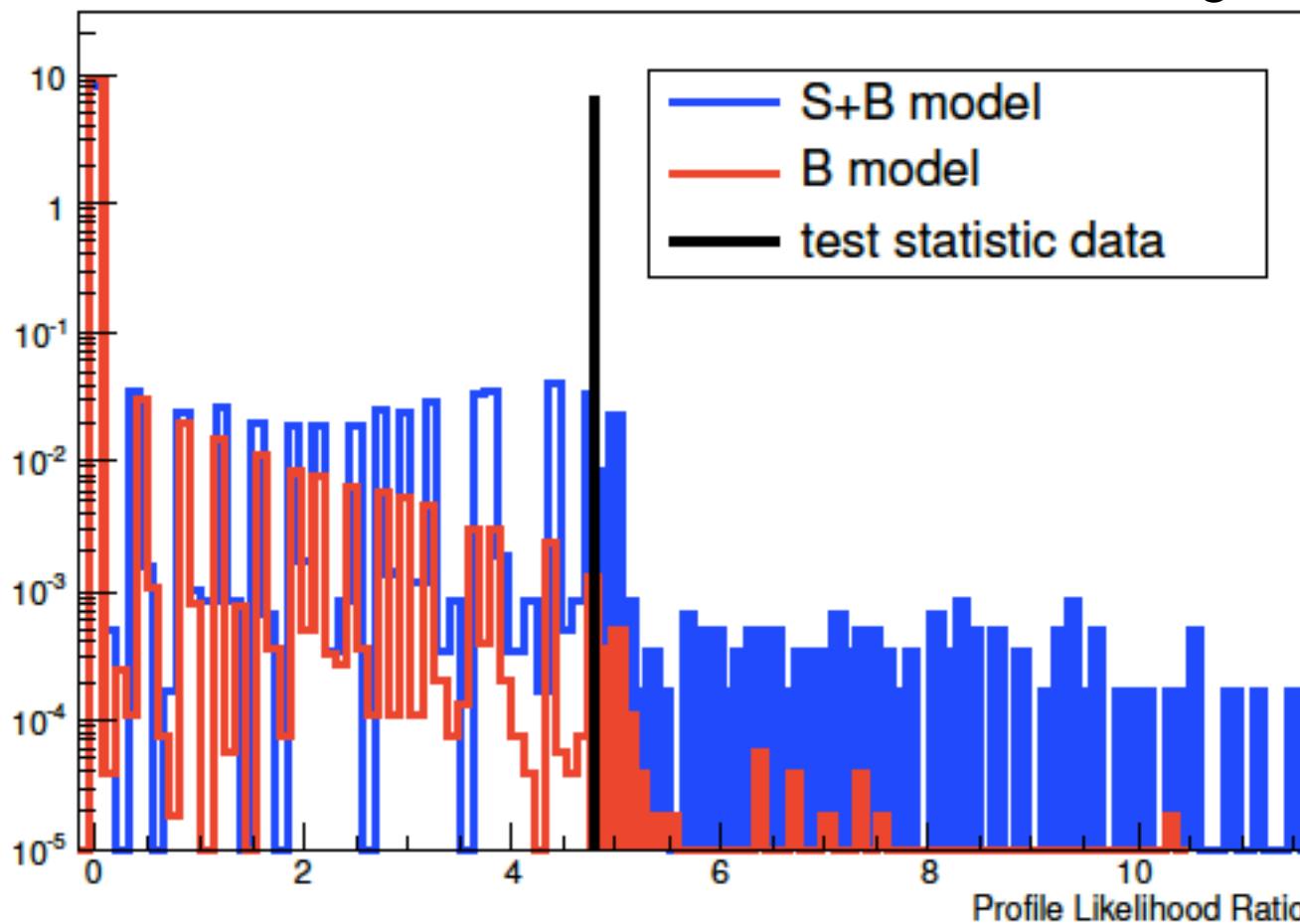
$$CL = (2.6 \pm 0.2) \times 10^{-4} \to 3.47\sigma$$

OTHER OSCILLATION ANALYSES

$\nu_\mu \rightarrow \nu_e$ ANALYSIS
one of the ν_e events with a π^0 as seen in the brick

JHEP 1307 (2013) 004

electron

γ showers

2 mm

10 mm

ECC

CS

Interface films

Analysis based on 2008-2009 run, 19 observed candidates (4 with E < 20 GeV)

SEARCH FOR NON-STANDARD OSCILLATIONS AT LARGE Δm^2 VALUES
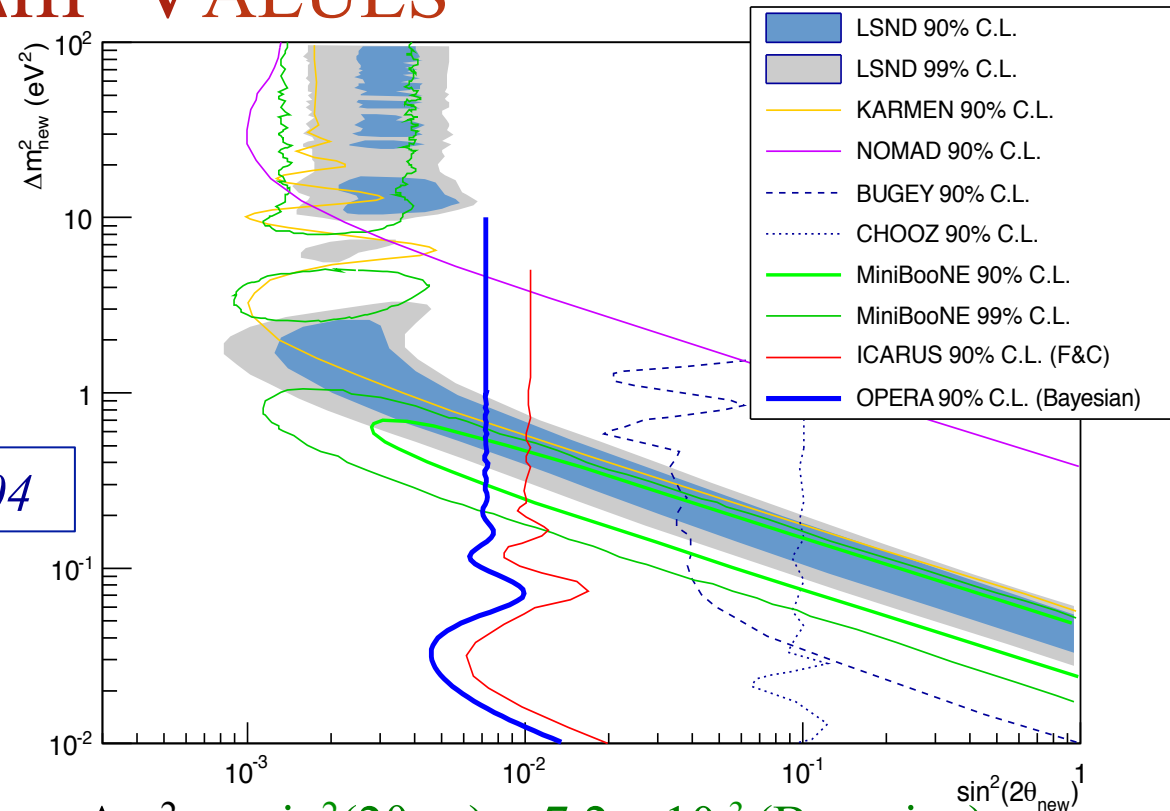
JHEP 1307 (2013) 004

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 ~twice candidates:

So far 53 observed candidates

Further selection → 34 events

7 with E < 20 GeV

2008-2012 preliminary distribution

Legend:
- oscillated, 3 flavour (1.2)
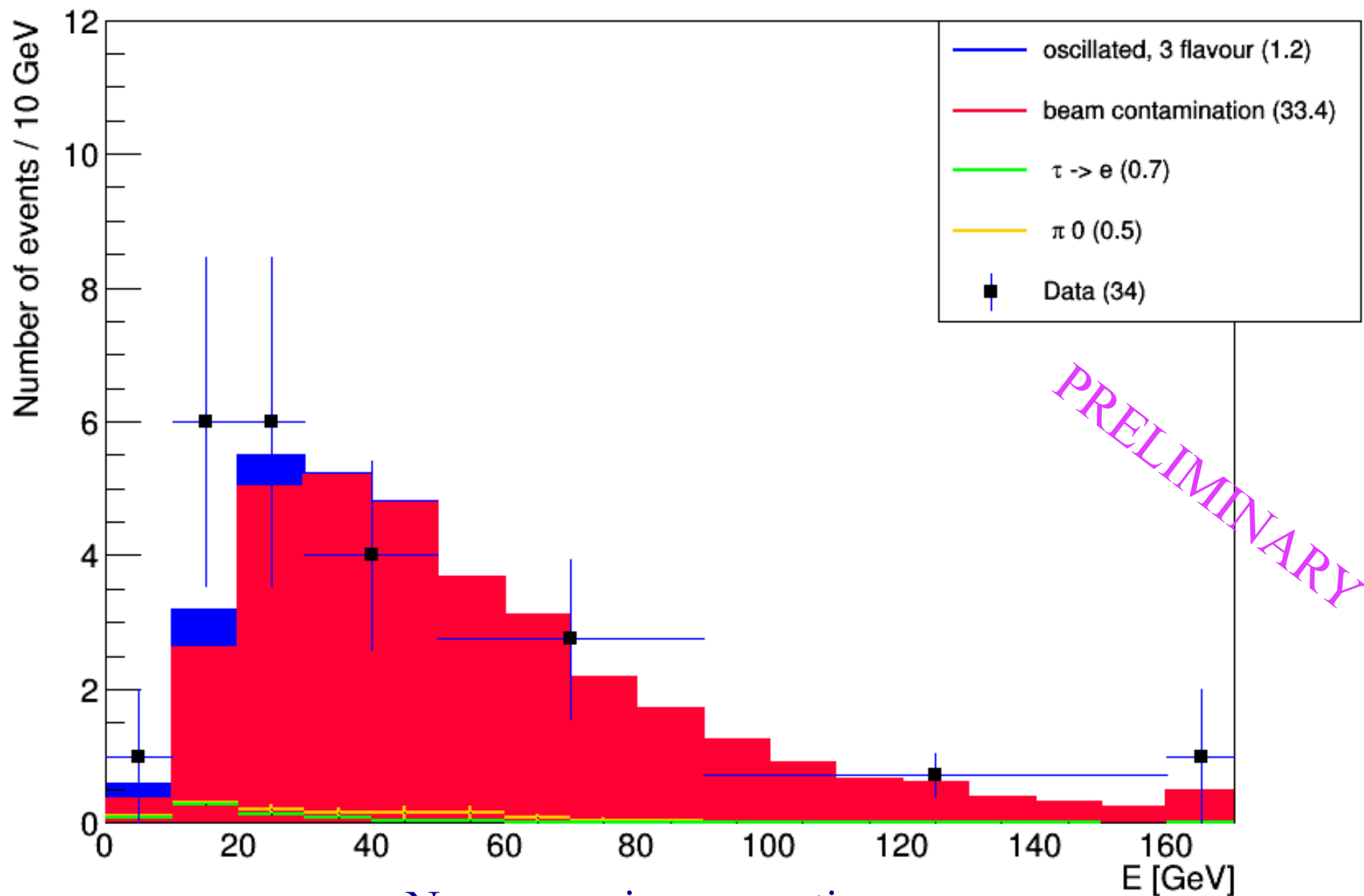- beam contamination (33.4)
- $\tau \rightarrow e$ (0.7)
- $\pi 0$ (0.5)
- Data (34)

Y-axis: Number of events / 10 GeV
X-axis: E [GeV]

PRELIMINARY

New paper in preparation

COSMIC-RAY ANALYSIS

Cosmic-muon rate and temperature dependence

- Gran Sasso underground ~ 3800 m w.e. → Minimum muon energy ~ 1.8 TeV
- Atmospheric temperature increase → density decrease → increase the pion decay rate → muon rate increase

$$I_\mu(t) = I_\mu^0 + \Delta I_\mu = I_\mu^0 + \delta I_\mu \cos\left[\frac{2\pi}{T}(t - t_0)\right]$$

$$T_{eff} = \frac{\int_0^\infty T(x)W(x)dx}{\int_0^\infty W(x)dx}$$

$$\frac{\Delta I_\mu}{I_\mu^0} = \alpha_T \frac{\Delta T_{\text{eff}}}{T_{\text{eff}}}$$

High W in high atmosphere → high energy muons
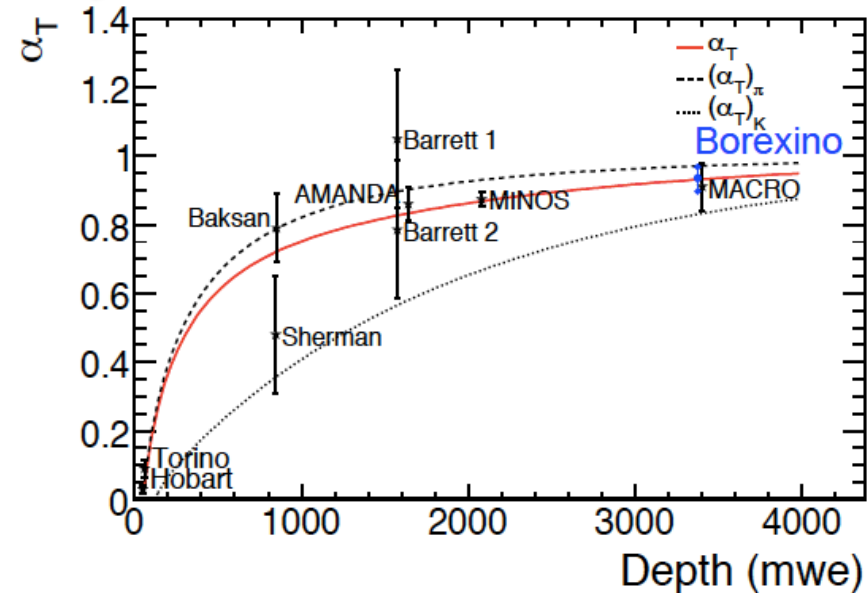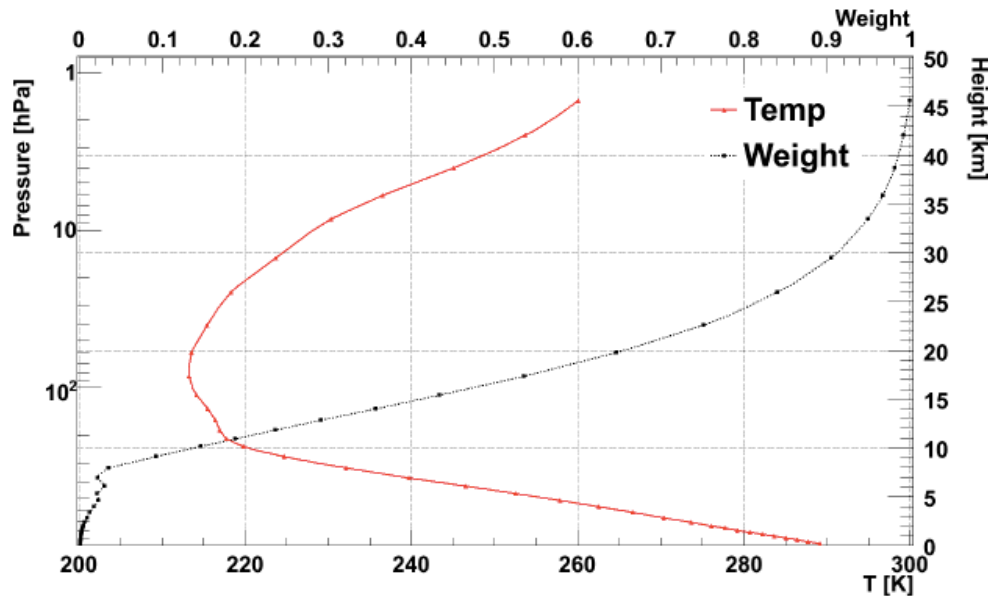
Annual modulation of cosmic-muon rate

χ^2 / ndf	1166 / 970
Prob	1.303e-05
c	1783 ± 1.354
A	23.49 ± 1.932
T	358.7 ± 4.714
phi	216.4 ± 15.66
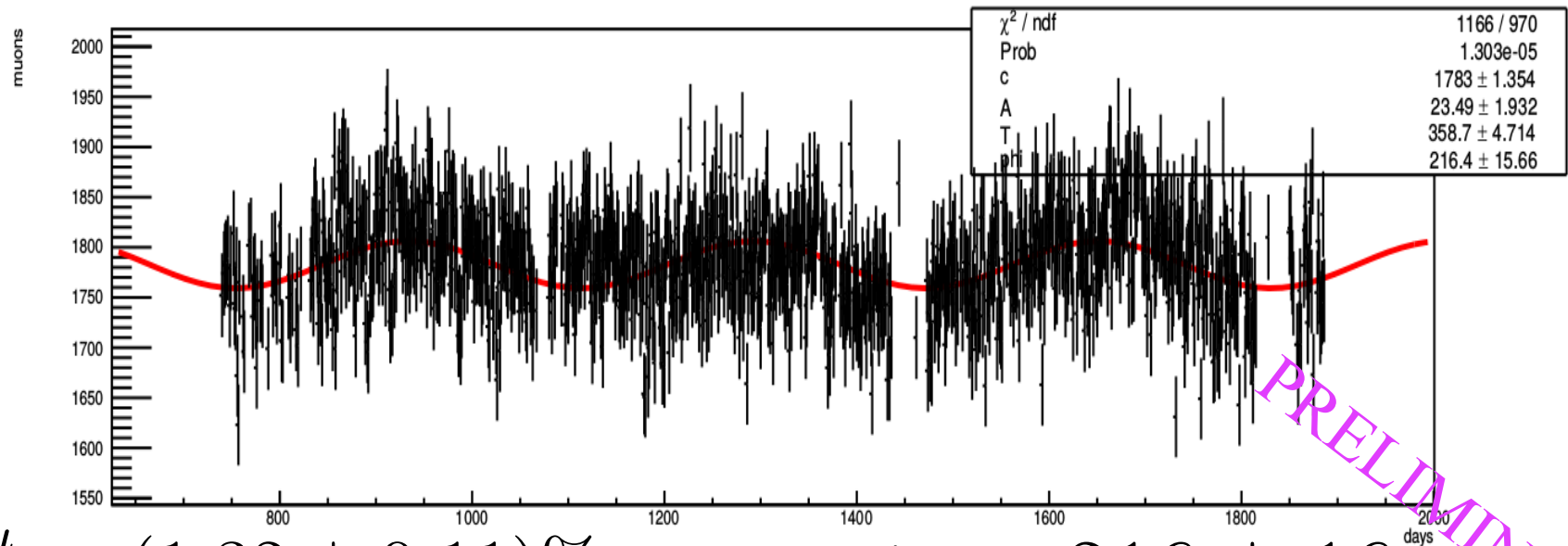
$$\frac{\Delta I_\mu}{I_\mu^0} = (1.32 \pm 0.11)\% \qquad t_0 = 216 \pm 16$$

PRELIMINARY

χ^2 / ndf	1.447e+05 / 970
Prob	0
c	220.4 ± 0.004543
A	3.868 ± 0.00626
T	358.9 ± 0.117
phi	206.7 ± 0.3783
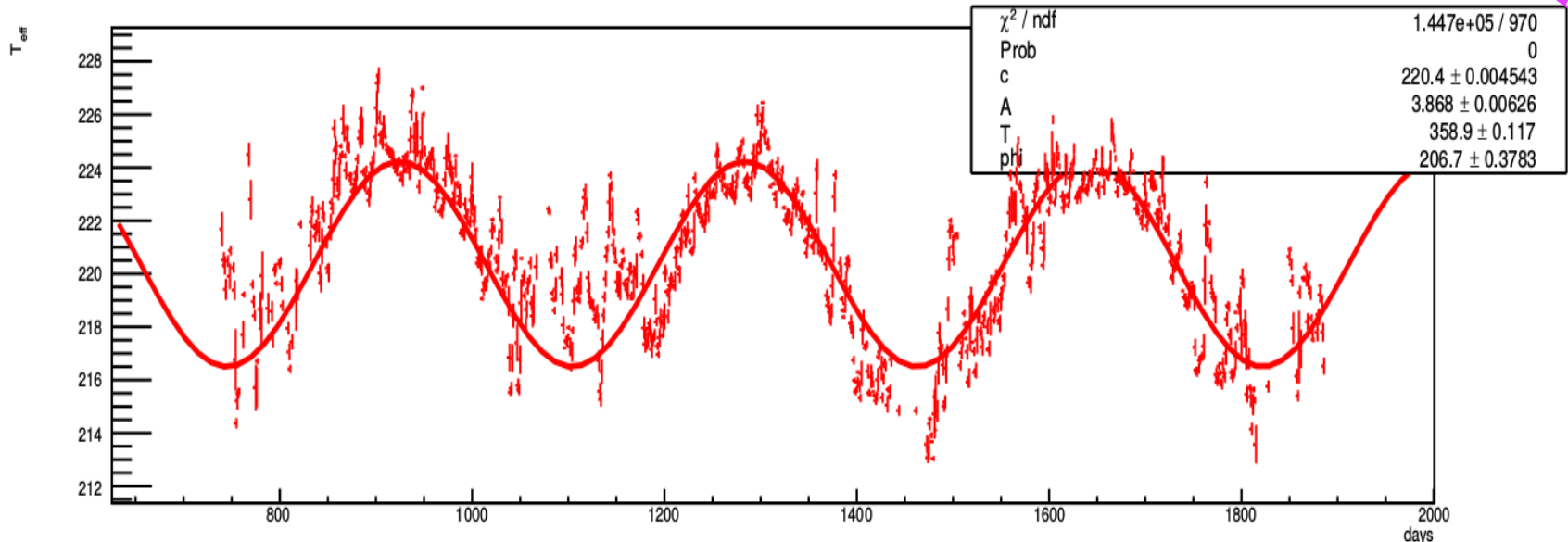
Temperature data by the European Center for Medium-range Weather Forecasts (ECMWF)

All data folded in one year

hRaY	
Entries	441
Mean	180.1
Std Dev	103.6
χ^2 / ndf	382.3 / 362
Prob	0.2221
c	1783 ± 1.4
A	23.43 ± 1.95
phi	195.1 ± 4.7

muon rate

days
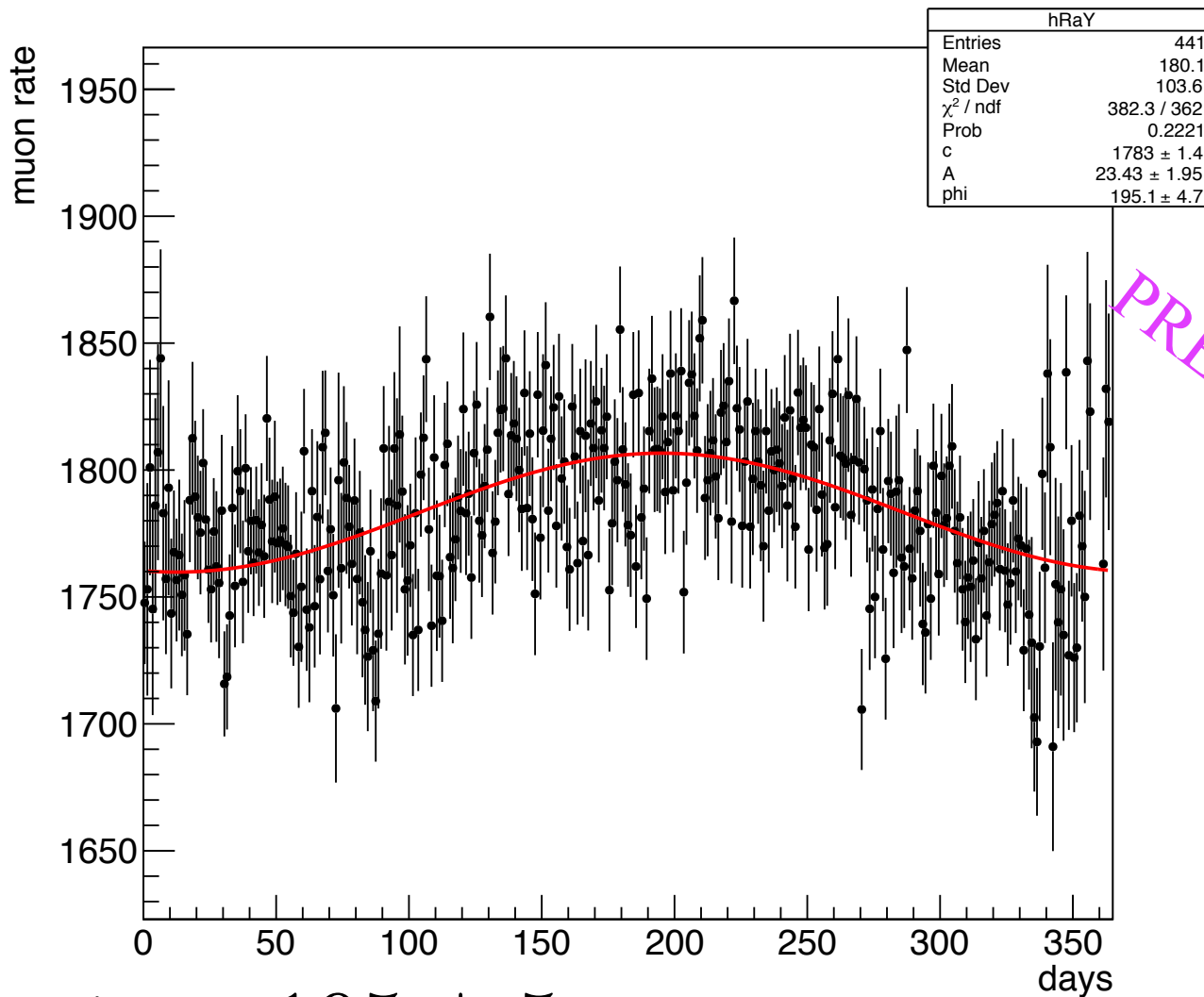
PRELIMINARY

$$t_0 = 195 \pm 5$$

Maximum on July 14th

Cross-correlation of rate and Temperature series

Narrow peak due to matching of short-scale (~ few day) rate-T correlations
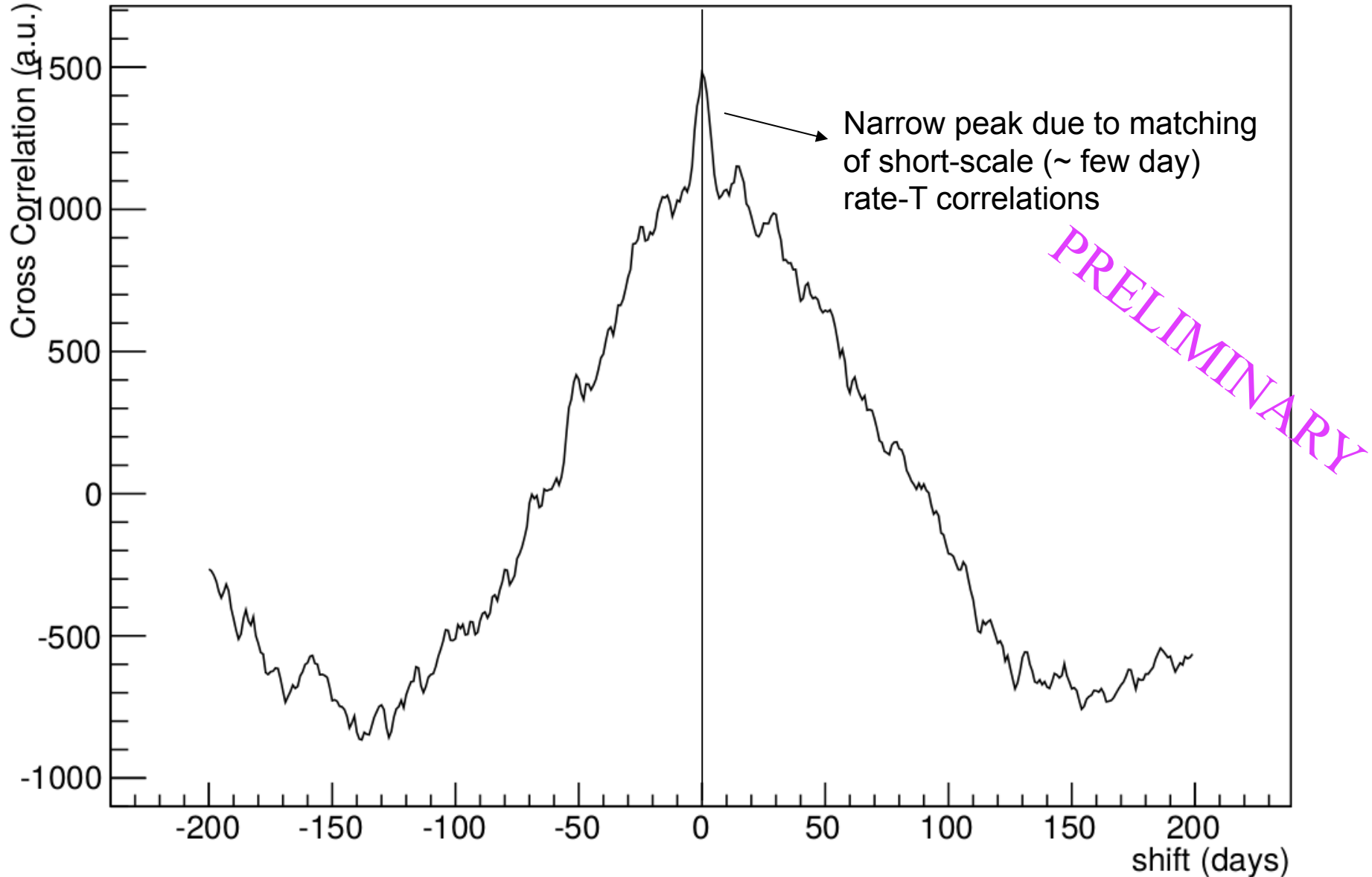
PRELIMINARY

Muon rate vs temperature variations

R = 0.42

χ^2 / ndf	1065 / 972
Prob	0.0201
p0	-0.05713 ± 0.07637
p1	0.9304 ± 0.05934
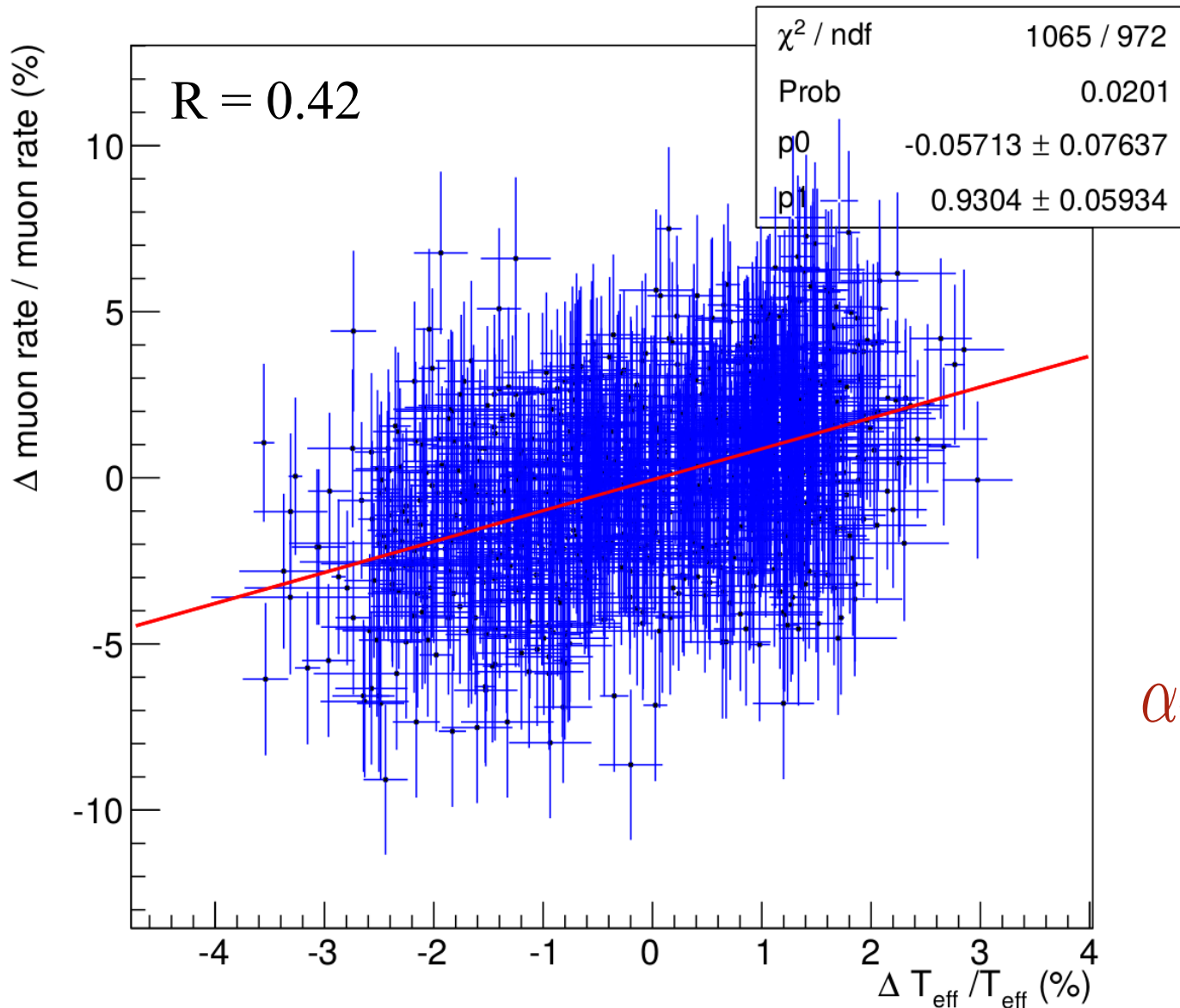
PRELIMINARY

$$\frac{\Delta I_\mu}{I_\mu^0} = \alpha_T \frac{\Delta T_{\text{eff}}}{T_{\text{eff}}}$$

$$\alpha_T = 0.93 \pm 0.06$$

ONGOING EVENT ANALYSIS

- Widen selection cuts to increase the statistics
- Mostly topological identification and looser kinematical cuts ($P_T >$ 100 MeV)
- Statistical gain beneficial to reduce the uncertainty (e.g. Δm^2 from tau appearance)
- Use likelihood approach, simulation fully validated with data in all kinematical corners
- Exploit unique feature of identifying all three flavours: use tau appearance, electron appearance and muon disappearance at the same time

OPERA DATA PRESERVATION AT CERN

- First meeting with Jamie Shiers at CERN in Dec 2015

- OPERA data < 100 TB (~10 tapes) equivalent to one of the LEP experiments

- Willing to host OPERA data at CERN

- LEP support until 2030 → support OPERA for 30 years

- Green light in January from new CERN management to the OPERA data preservation

- Launching the discussion with Jamie last February

- Getting started with a sub-sample of data

OPERA OPEN DATA AT CERN

- Discussion with S. Mele at CERN, willing to include OPERA data among the open data

- Notable examples at CERN: CMS and LHCb

- Provide OPERA neutrino interactions: vertex + all attached tracks

- ~7000 neutrino interactions fully studied up to the decay search: data & event display (electronic + emulsion) useful for educational purposes

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 m³ 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 1.8×10^{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 × 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 $\nu_\mu \rightarrow \nu_\tau$ 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 $\nu_\mu \rightarrow \nu_\tau$ 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 τ^- in one of the lead targets, where $\tau^- \rightarrow \rho^- \nu_\tau$. A second candidate, in the $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$ channel, was found in 2012, followed in 2013 by a candidate in the fully leptonic $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ decay. A fourth event was found in 2014 in the $\tau^- \rightarrow h^- \nu_\tau$ 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±0.05 events, the direct transition from muon to tau neutrinos has now been measured with the 5σ 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 ▷