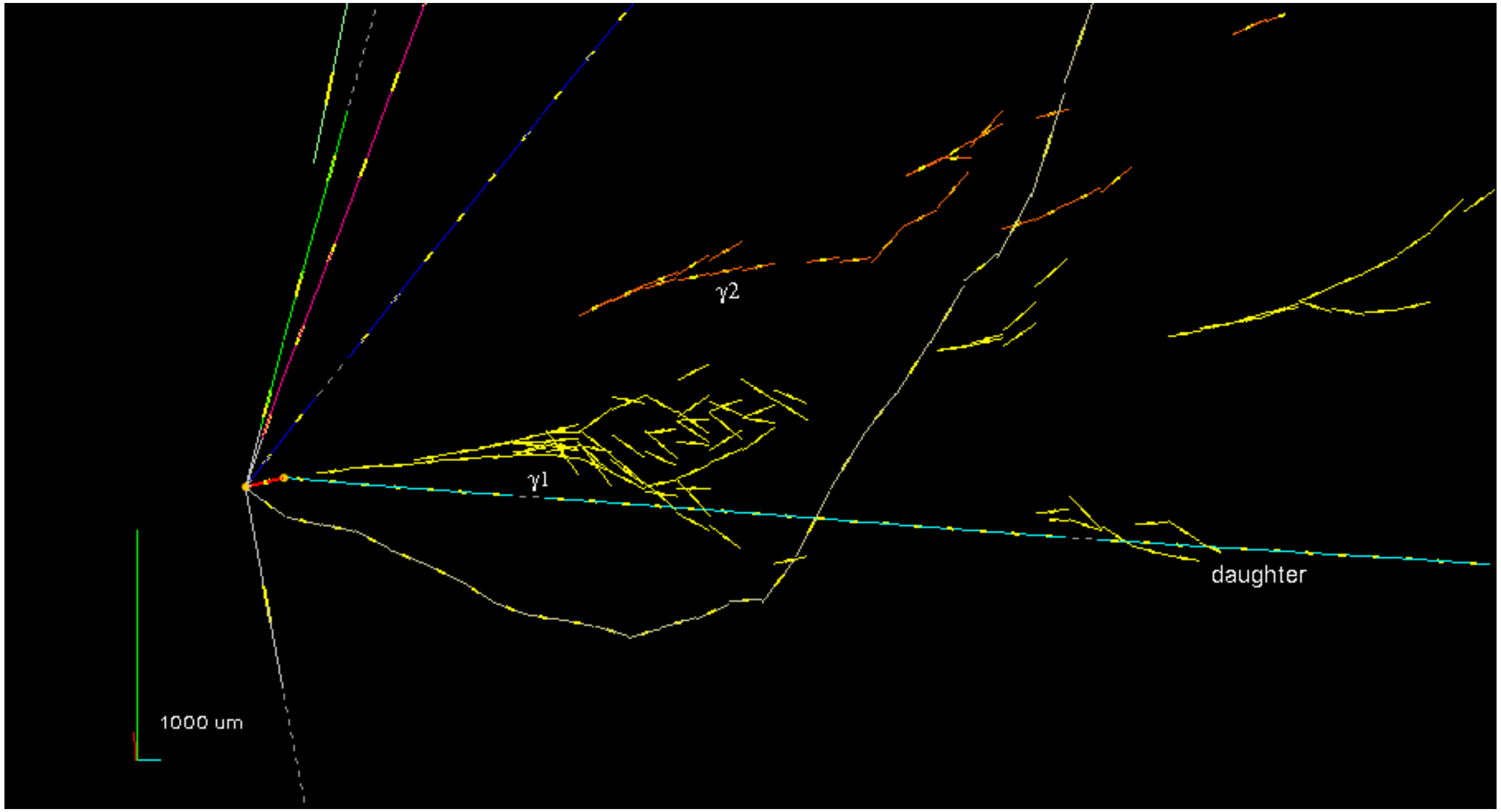
NEUTRINO PHYSICS WITH THE OPERA EXPERIMENT

Giovanni De Lellis

University "Federico II" and INFN Napoli

On behalf of the OPERA Collaboration



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, …

$\Delta m^2_{32} = (2.50 \pm 0.04)\ 10^{-3}\ eV^2$

$\theta_{32} = (45.8 \pm 3.2)°$

$\theta_{13} = (8.88 \pm 0.39)°$

PDG 2016

$\Delta m^2_{21} = (7.37 \pm 0.16)\ 10^{-5}\ eV^2$

$\theta_{12} = (33.4 \pm 0.85)°$

Back to 1998: Neutrino98, Takayama, Japan

ν98, @Takayam
June 1998

Atmospheric neutrino results
from Super-Kamiokande & Kamiokand

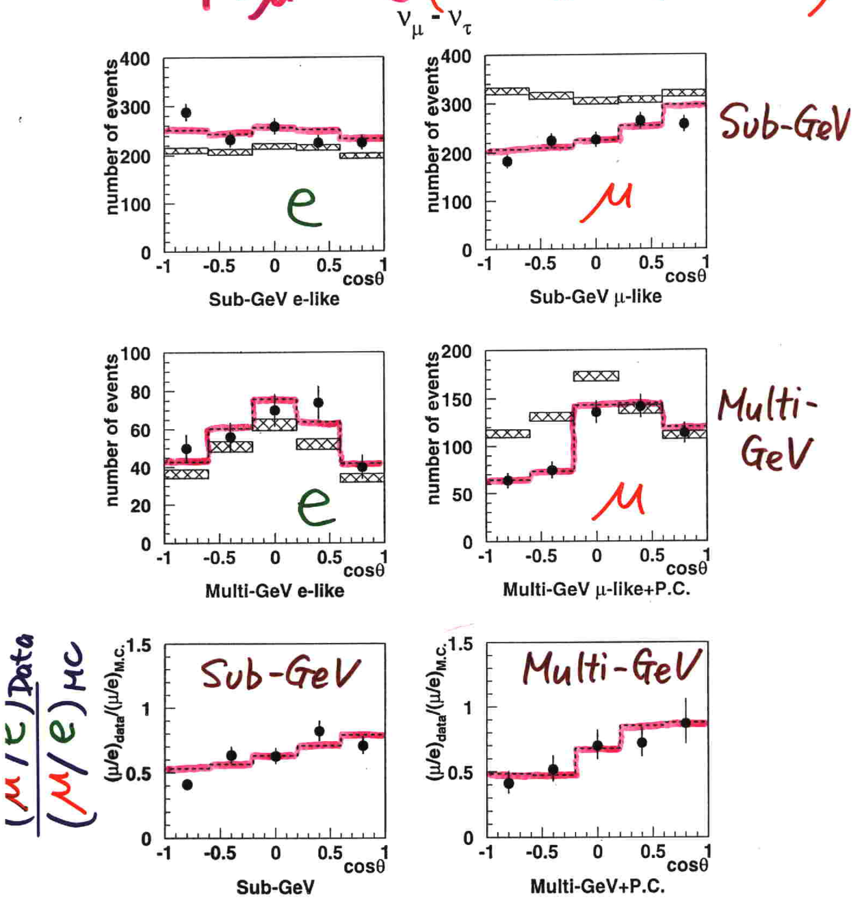
— Evidence for ν_μ oscillations —

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

T. Kajita
Nobel Laureate 2015

Data vs. Oscillations

$\nu_\mu \to \nu_\tau$ $(\Delta m^2 = 2.2\times10^{-3},\ \sin^2 2\theta = 1)$



χ^2 (best fit) = 65/67 d.o.f.

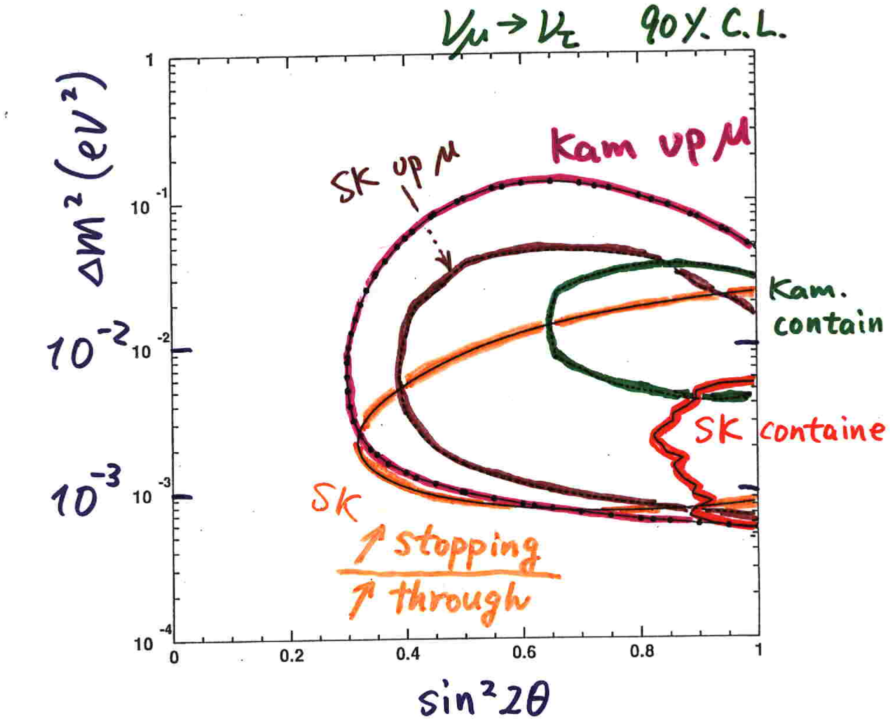
χ^2 (No oscillation) = 135/67 d.o.f

$\Delta\chi^2$ = 70!

Summary

By T. Kajita

Evidence for ν_μ oscillations

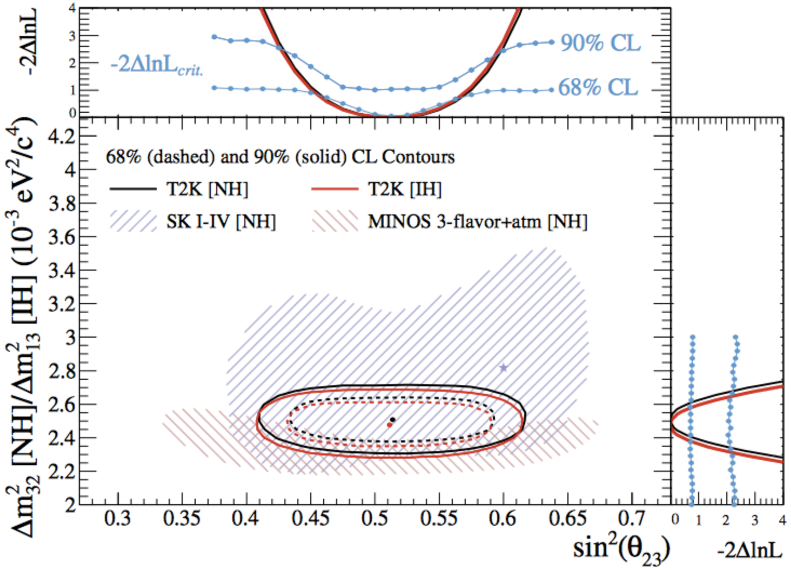


- $\begin{cases} \sin^2 2\theta > 0.8 \\ \Delta m^2 \sim 10^{-3} \sim 10^{-2} \end{cases}$

(• $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$?)

Current status

PRL 112 (2014) 181801



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

- ν_τ not yet seen in 1998!
- First indication of ν_τ 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

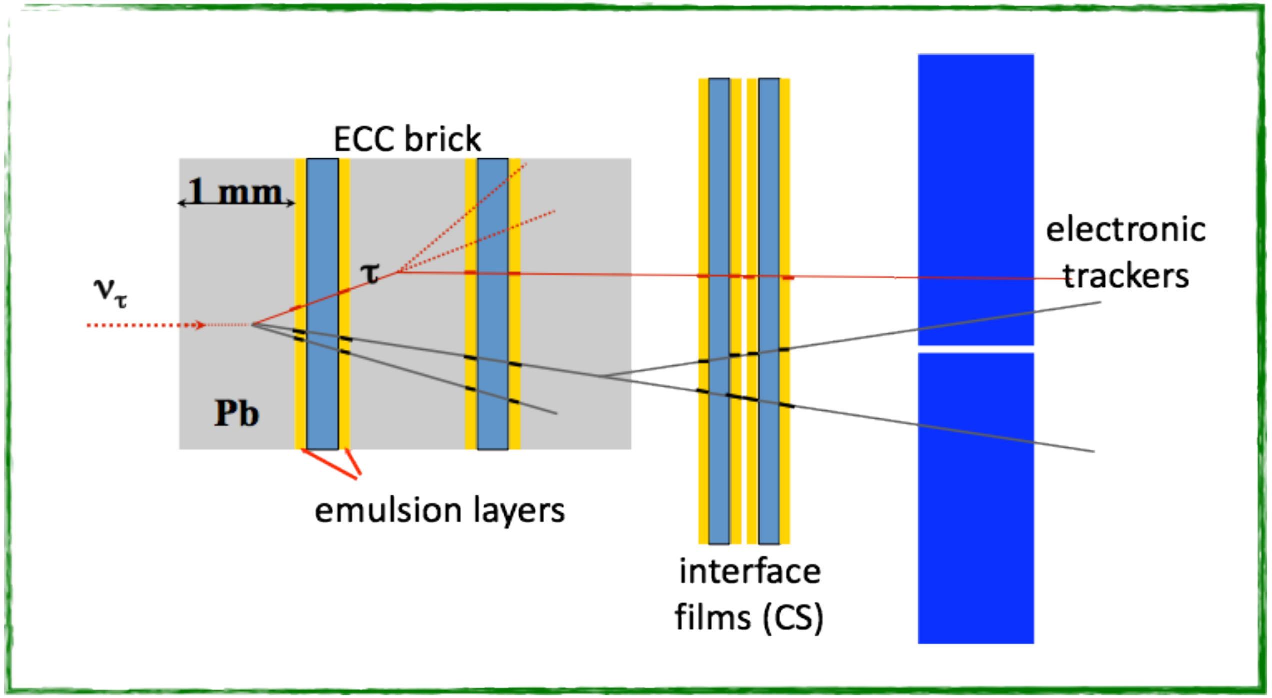
CNGS (CERN to Gran Sasso) beam approved at CERN in December 1999

The PMNS 3-flavor oscillation formalism predicts:

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

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 (%)
τ →μ	17.7
τ →e	17.8
τ →h	49.5
τ →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, 28 institutions in 11 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

Italy
Bari
Bologna
Frascati,
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

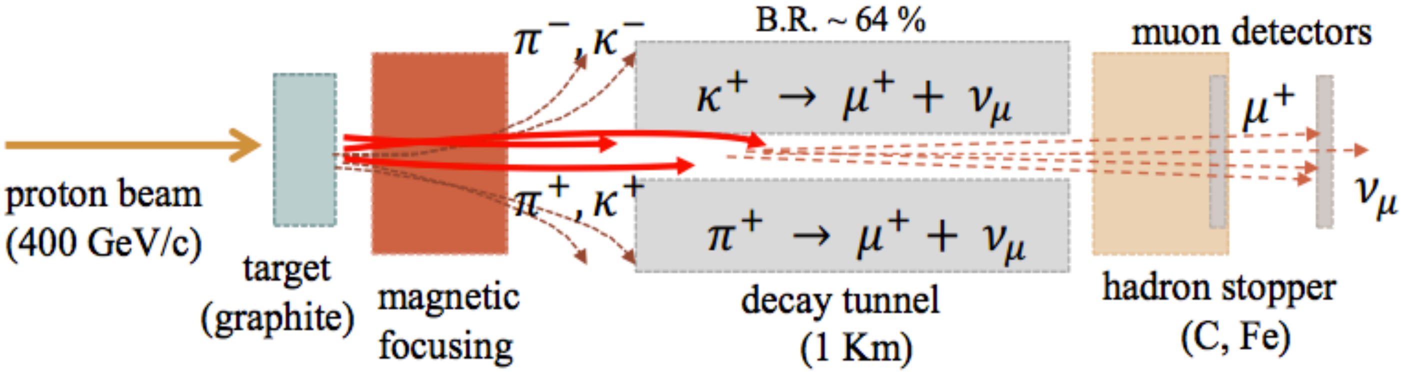
http://operaweb.lngs.infn.it

JULY 2008

CNGS BEAM AND LNGS SITE

CNGS BEAM

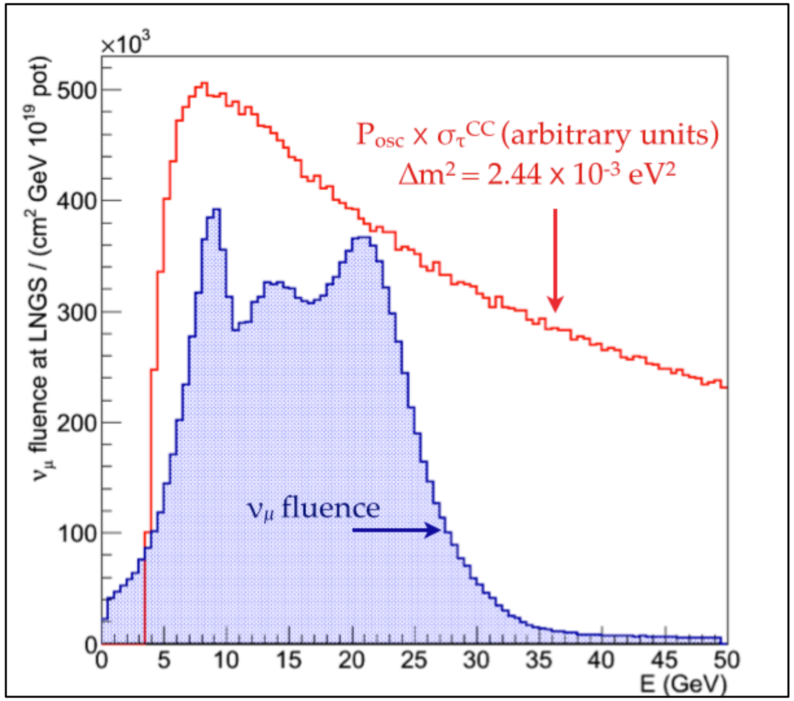
Tuned for ν_τ-appearance at LNGS



CNGS ν beam

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

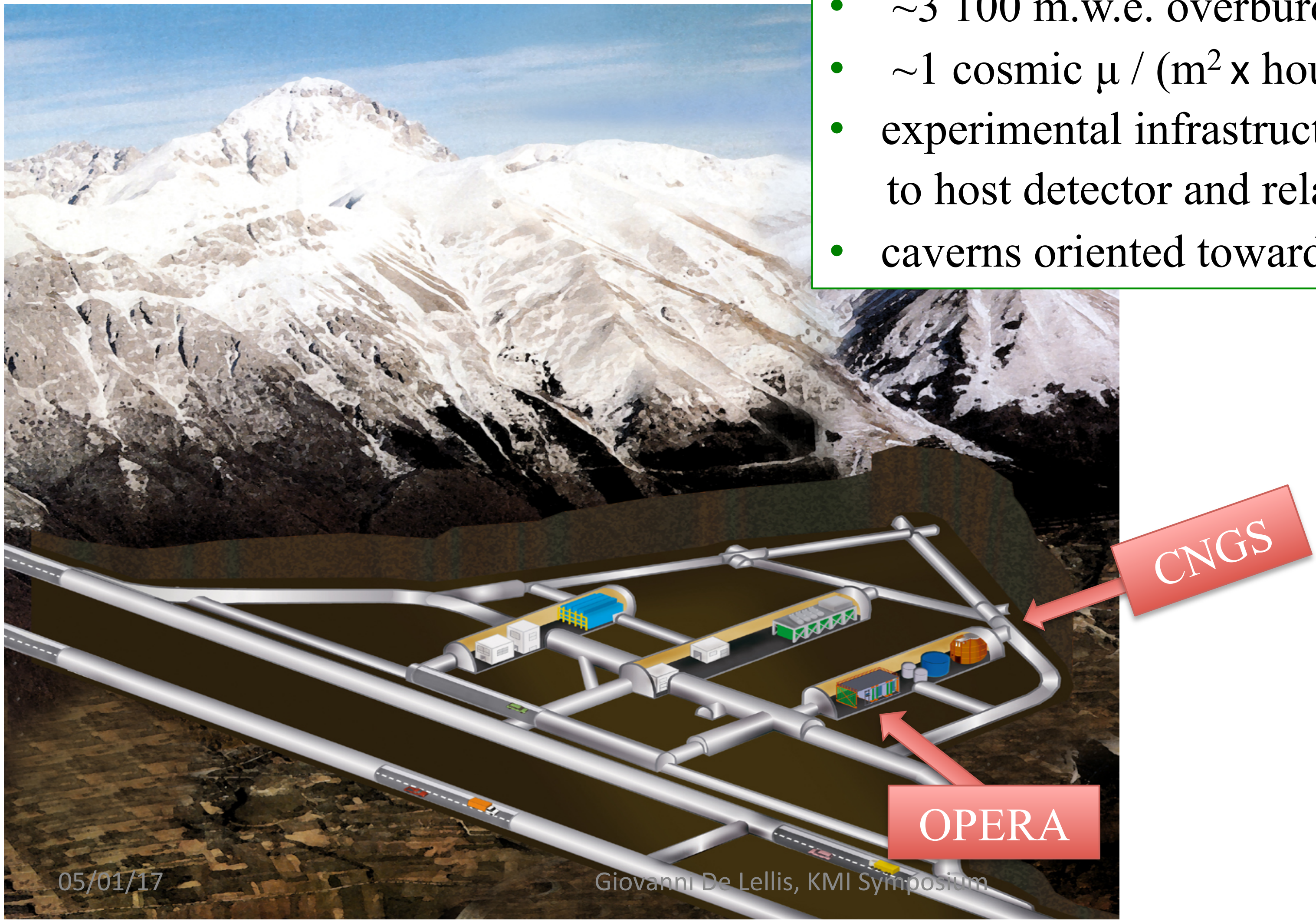
* Interaction rate at LNGS



LNGS OF INFN

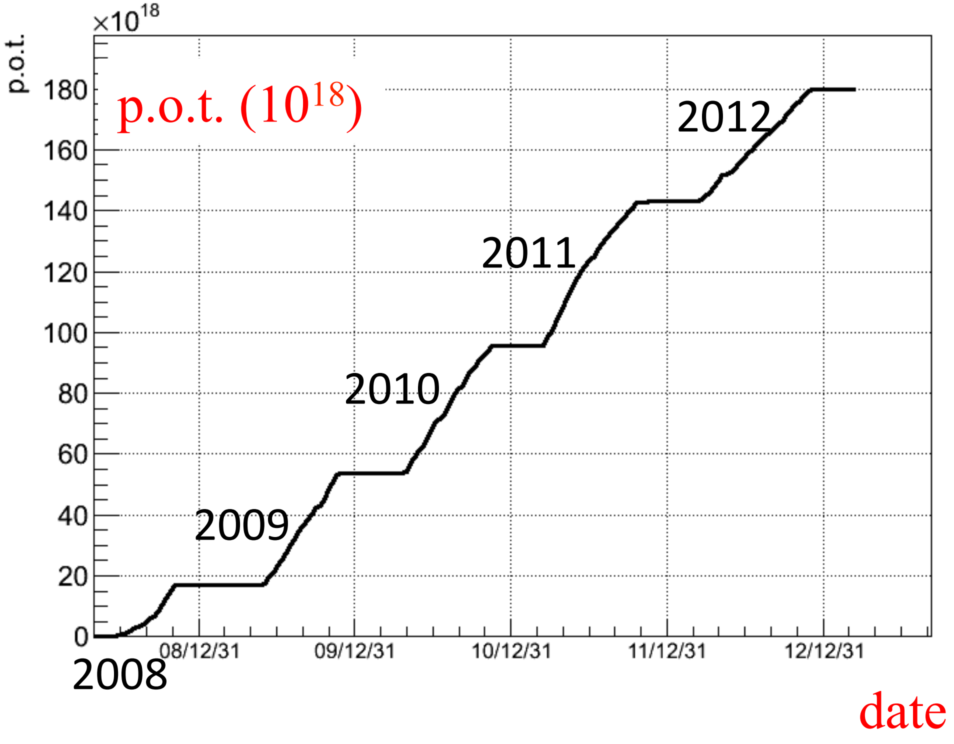
The world largest underground physics laboratory

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



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

PHYSICS RESULTS

COSMIC-RAY ANALYSIS

Cosmic-muon rate and temperature dependence

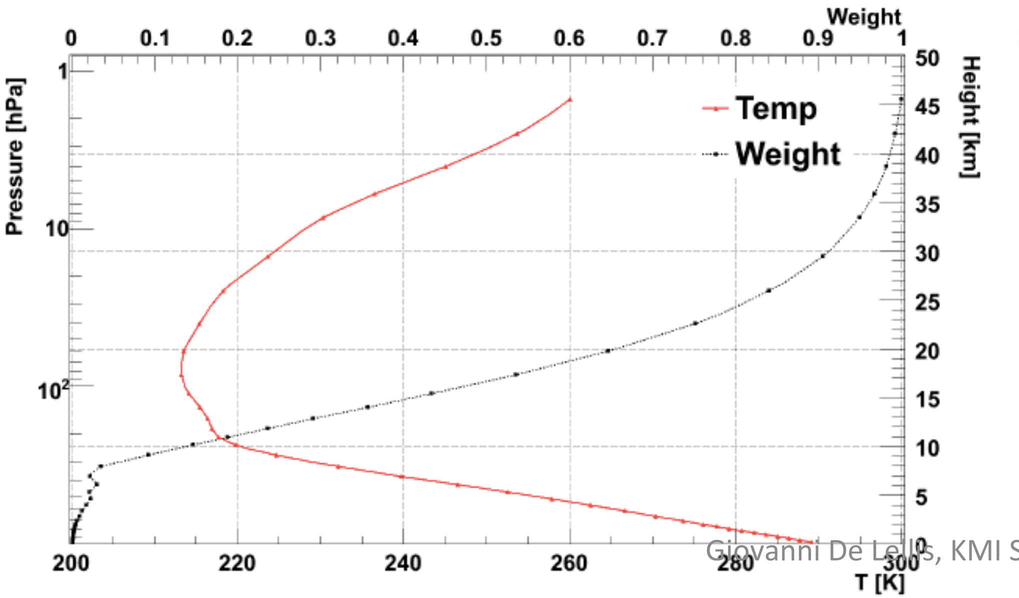
- Gran Sasso underground ~ 3800 m w.e. → Minimum muon energy ~ 1.8 TeV
- Atmospheric temperature increase → density decrease → increase the pion decay rate → muon rate increase

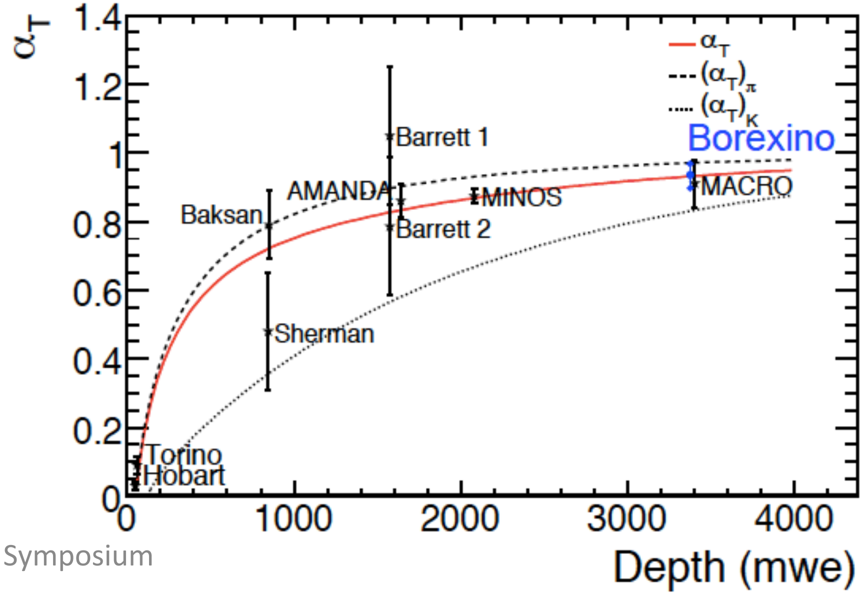
$$I_\mu(t) = I_\mu^0 + \Delta I_\mu = I_\mu^0 + \delta I_\mu \cos\left[\frac{2\pi}{T}(t - t_0)\right]$$

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

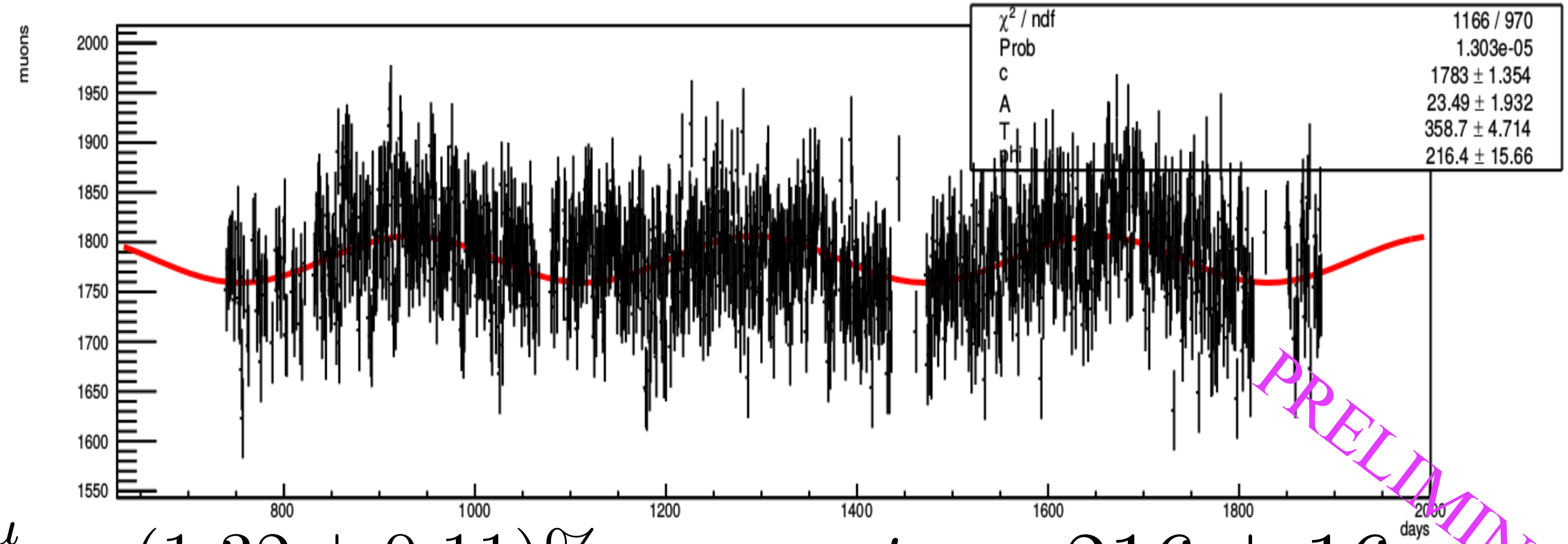
$$\frac{\Delta I_\mu}{I_\mu^0} = \alpha_T \frac{\Delta T_{\rm eff}}{T_{\rm eff}}$$

High W in high atmosphere → high energy muons





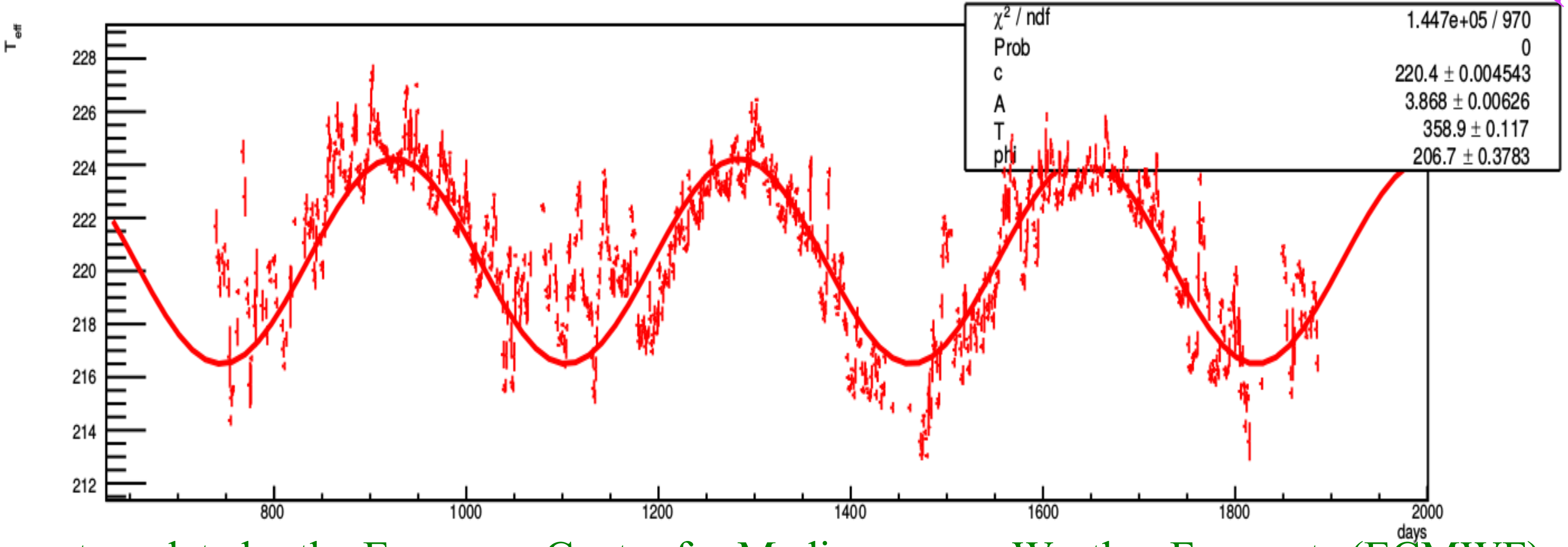
Annual modulation of cosmic-muon rate



$$\frac{\Delta I_\mu}{I_\mu^0} = (1.32 \pm 0.11)\%$$

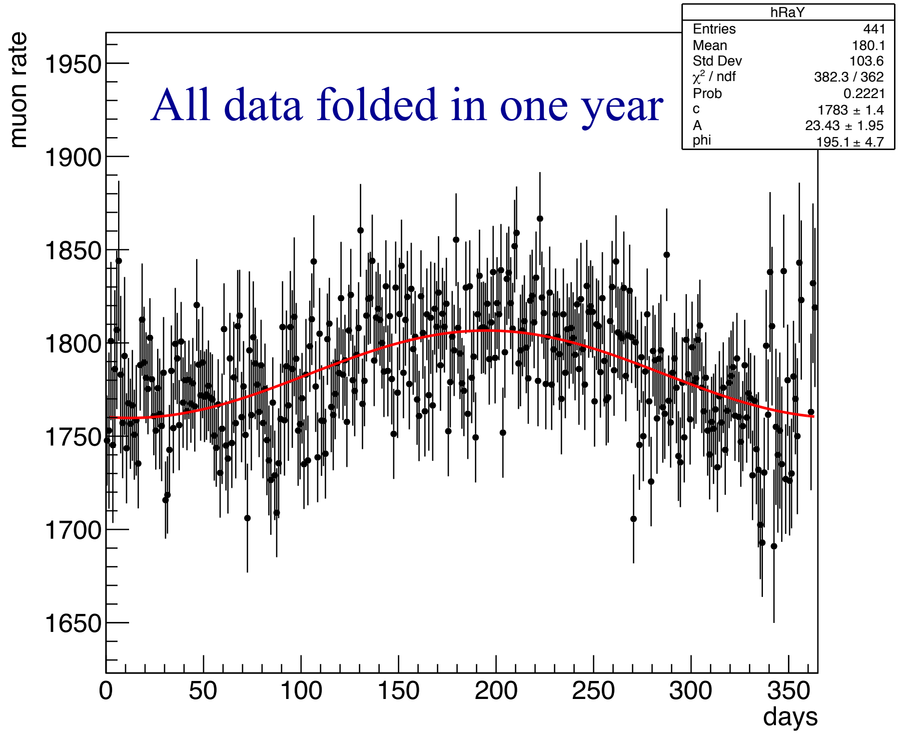
$$t_0 = 216 \pm 16$$

PRELIMINARY



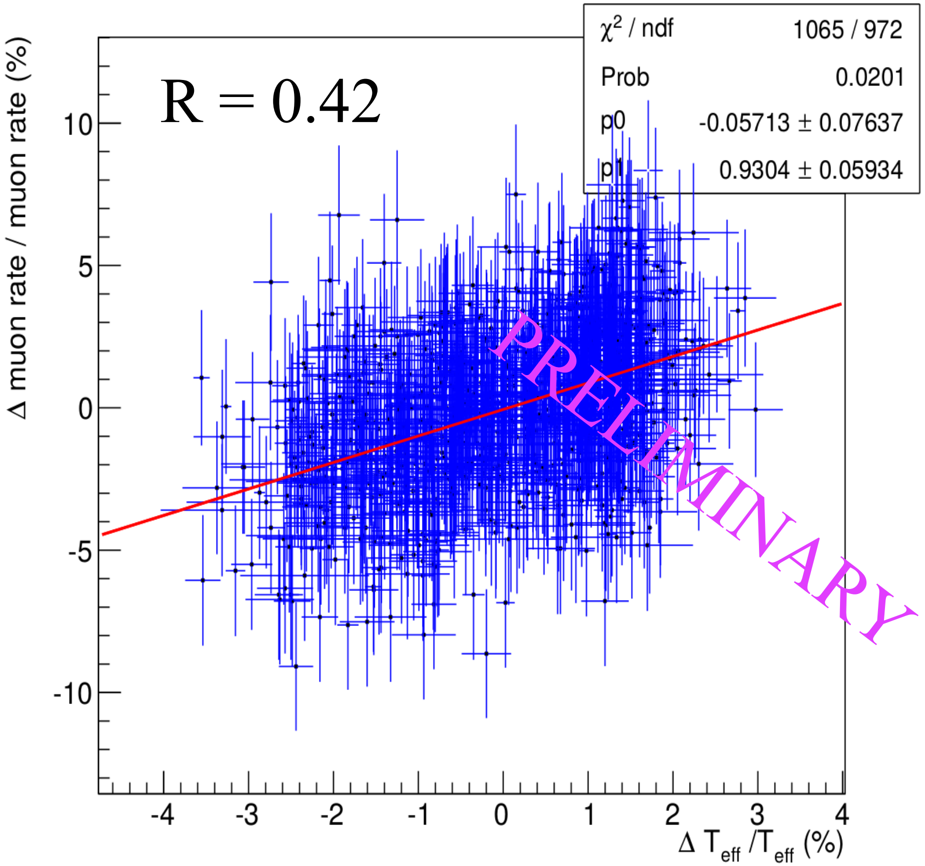
Temperature data by the European Center for Medium-range Weather Forecasts (ECMWF)

Muon rate vs temperature variations



$$t_0 = 195 \pm 5$$

Maximum on July 14th



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

$$\alpha_T = 0.93 \pm 0.06$$

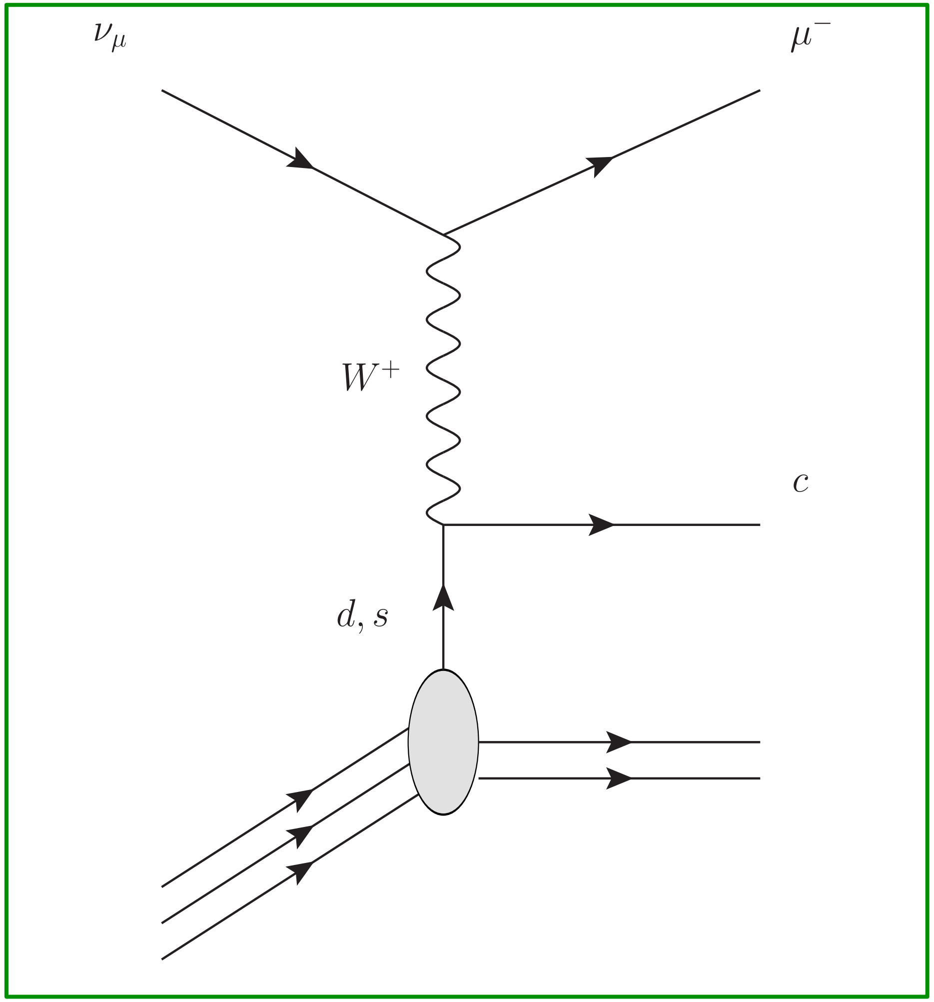
OSCILLATION PHYSICS

$\nu_\mu \rightarrow \nu_\tau$ 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
  - $P\mu < 15$ 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

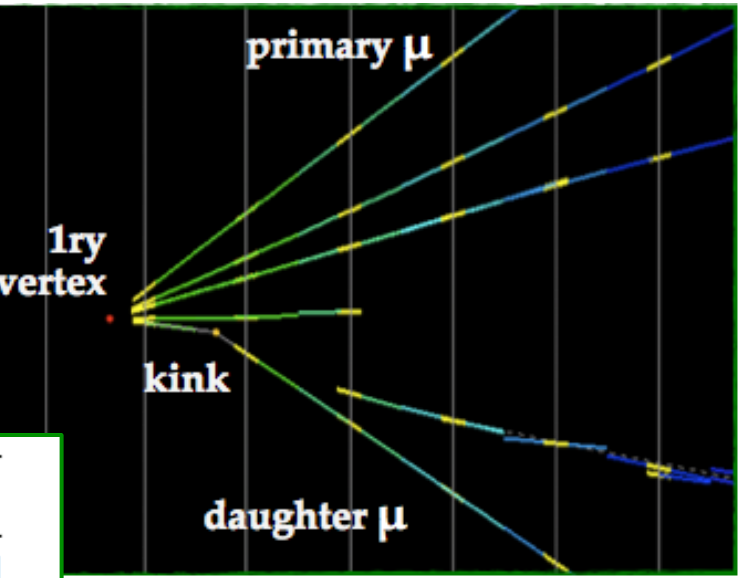
CHARMED HADRON PRODUCTION

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

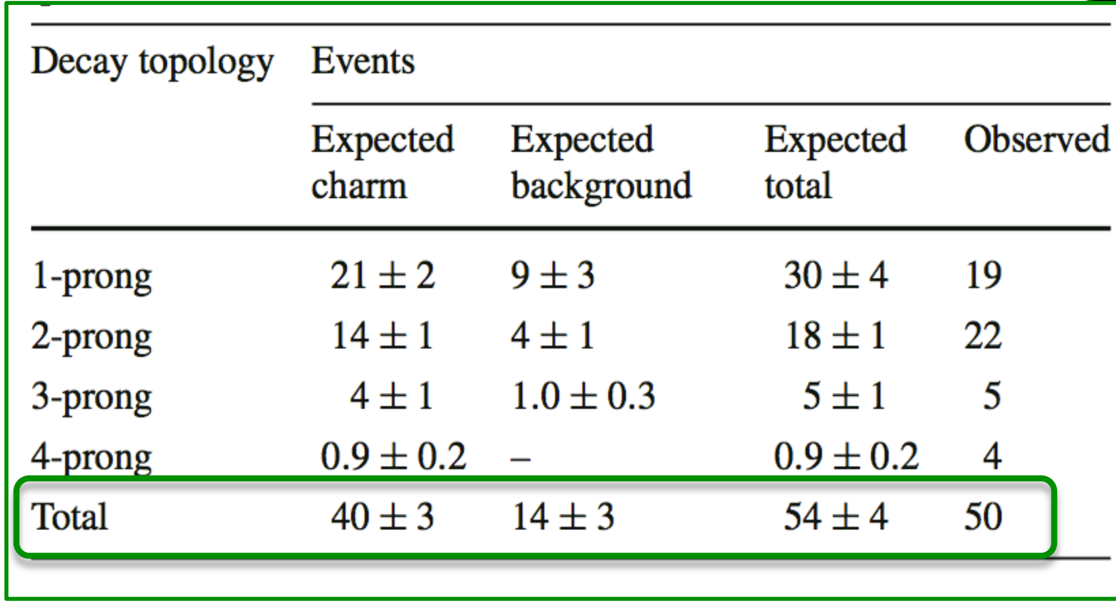


CHARMED HADRON PRODUCTION

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



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



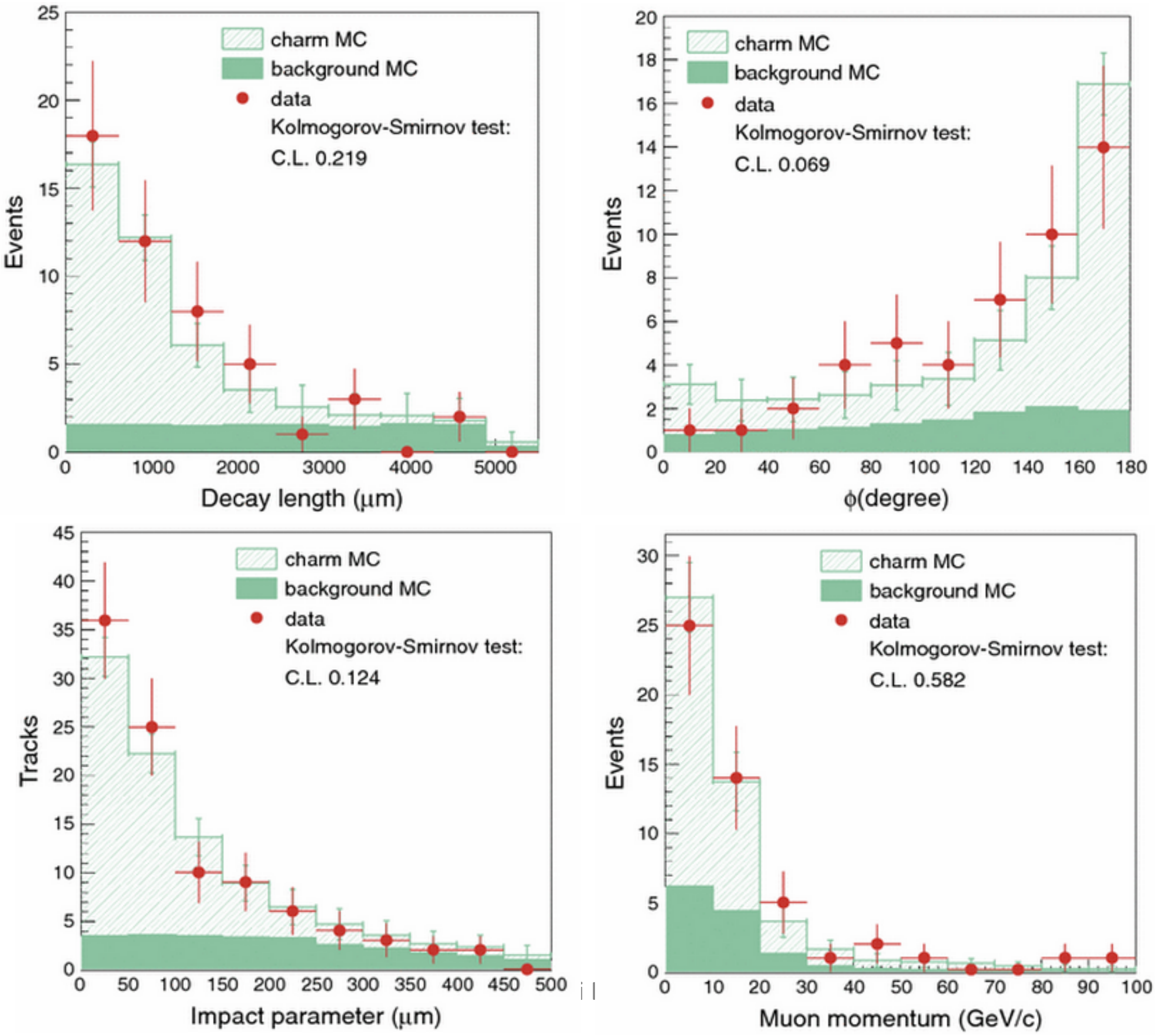
Decay topology	Events			
	Expected charm	Expected background	Expected total	Observed
1-prong	21 ± 2	9 ± 3	30 ± 4	19
2-prong	14 ± 1	4 ± 1	18 ± 1	22
3-prong	4 ± 1	1.0 ± 0.3	5 ± 1	5
4-prong	0.9 ± 0.2	–	0.9 ± 0.2	4
Total	40 ± 3	14 ± 3	54 ± 4	50

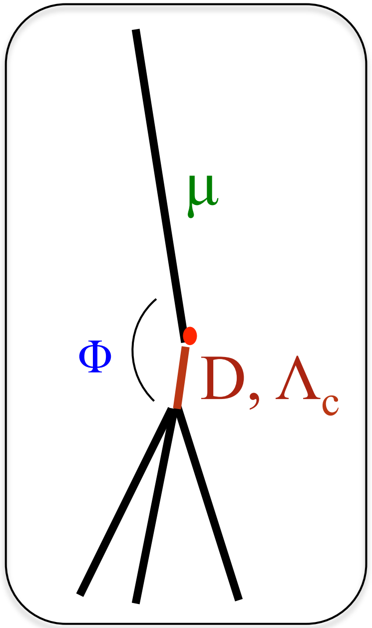
Eur. Phys. J. C74 (2014) 2986

Good agreement between data and expectations ~10%

KINEMATICAL VARIABLES

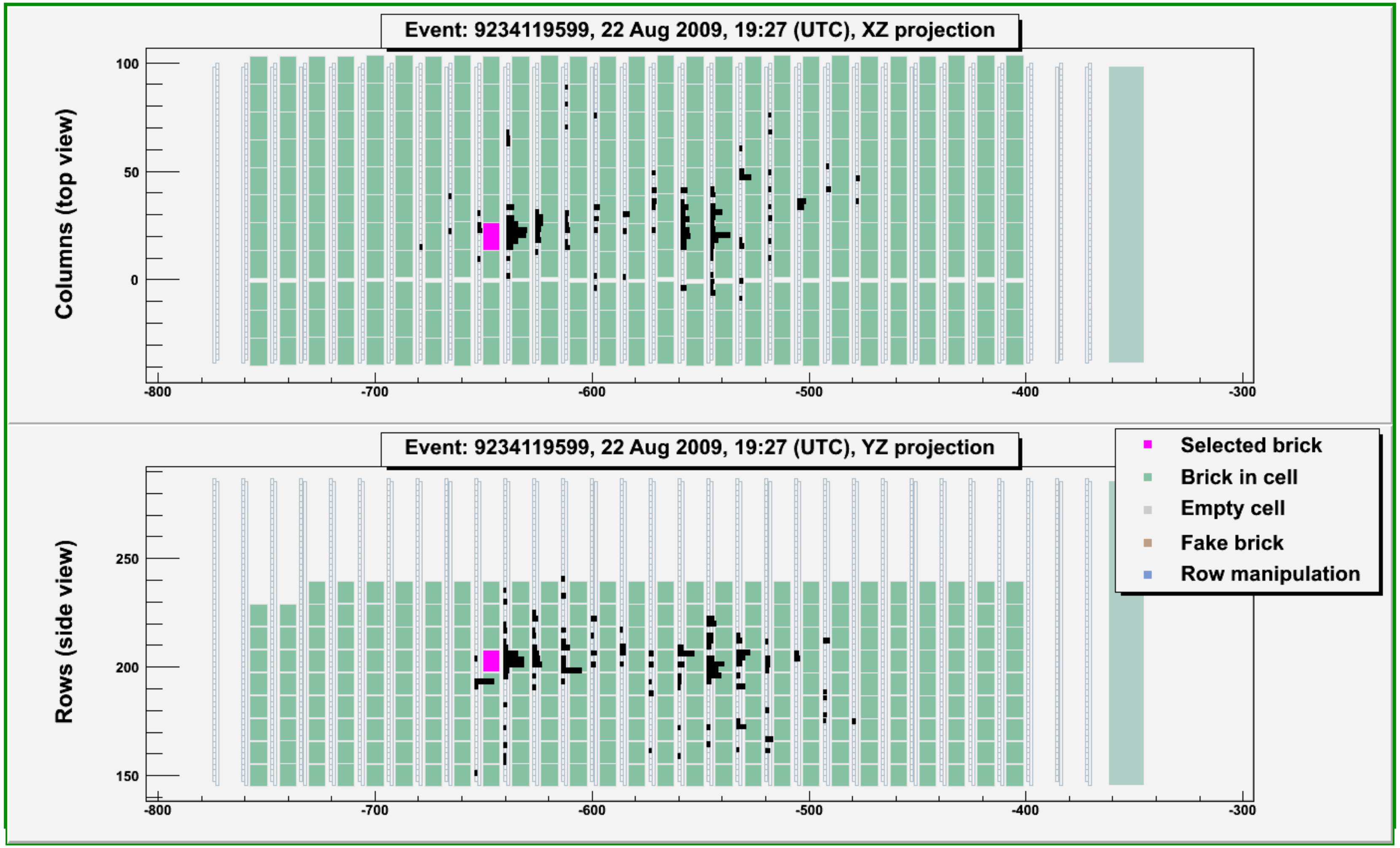
Fair agreement between data and Monte Carlo *Eur. Phys. J. C74 (2014) 2986*





THE FIRST ν_τ CANDIDATE

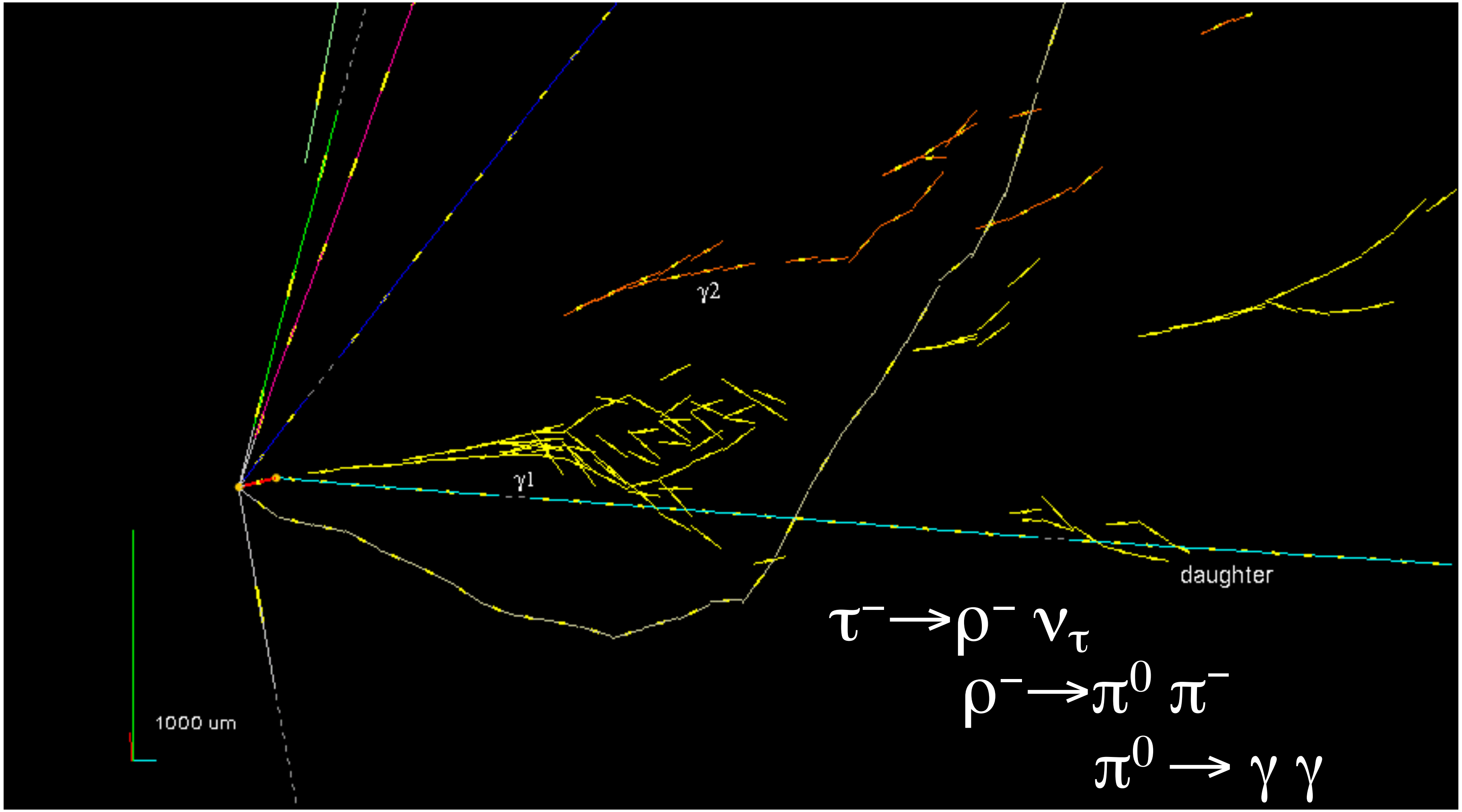
As seen by the electronic detectors …



Physics Letters B691 (2010) 138

THE FIRST ν_τ CANDIDATE

… and in the brick

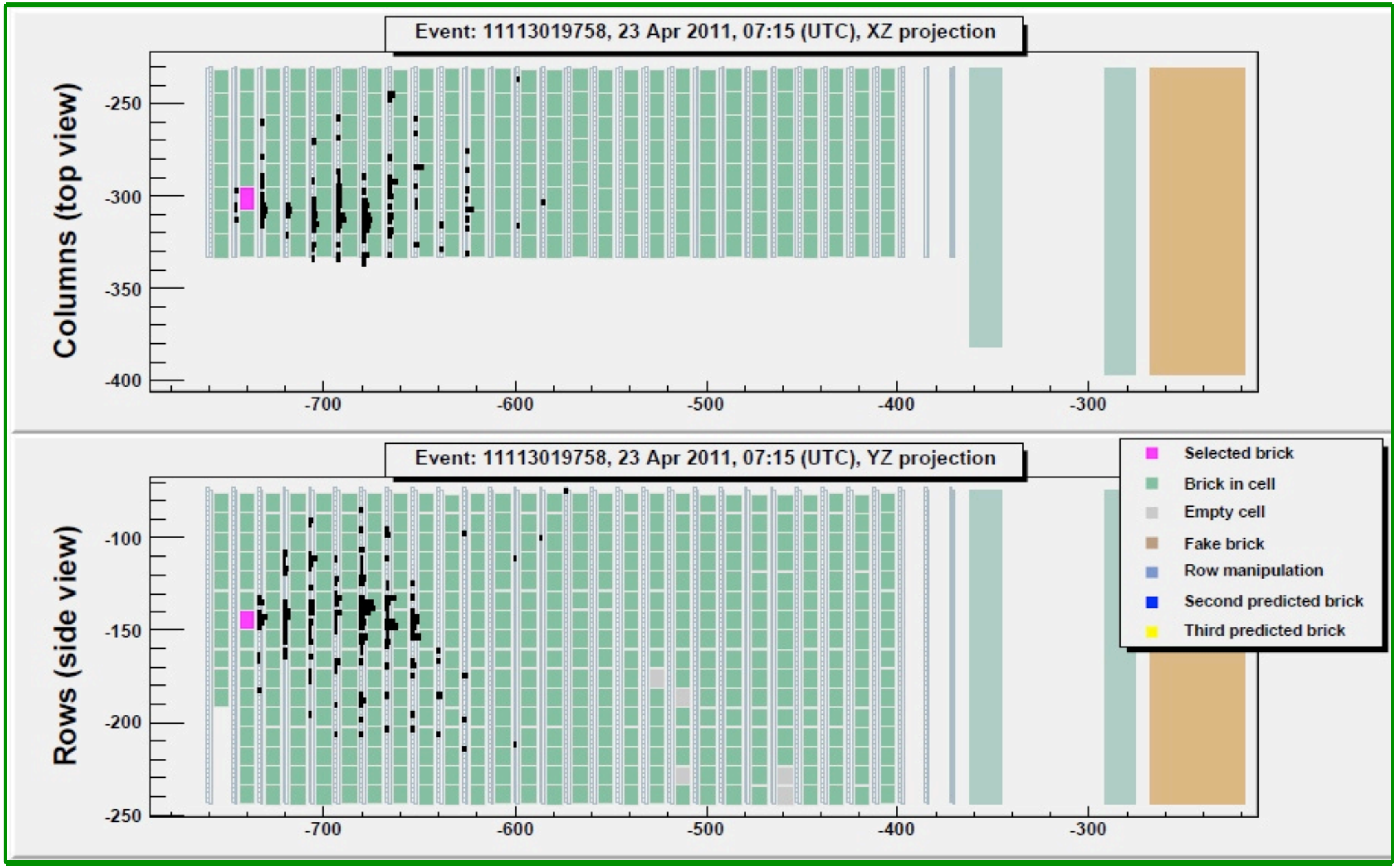


$$\tau^- \rightarrow \rho^- \nu_\tau$$
$$\rho^- \rightarrow \pi^0 \pi^-$$
$$\pi^0 \rightarrow \gamma\gamma$$

Physics Letters B691 (2010) 138

THE SECOND ν_τ CANDIDATE

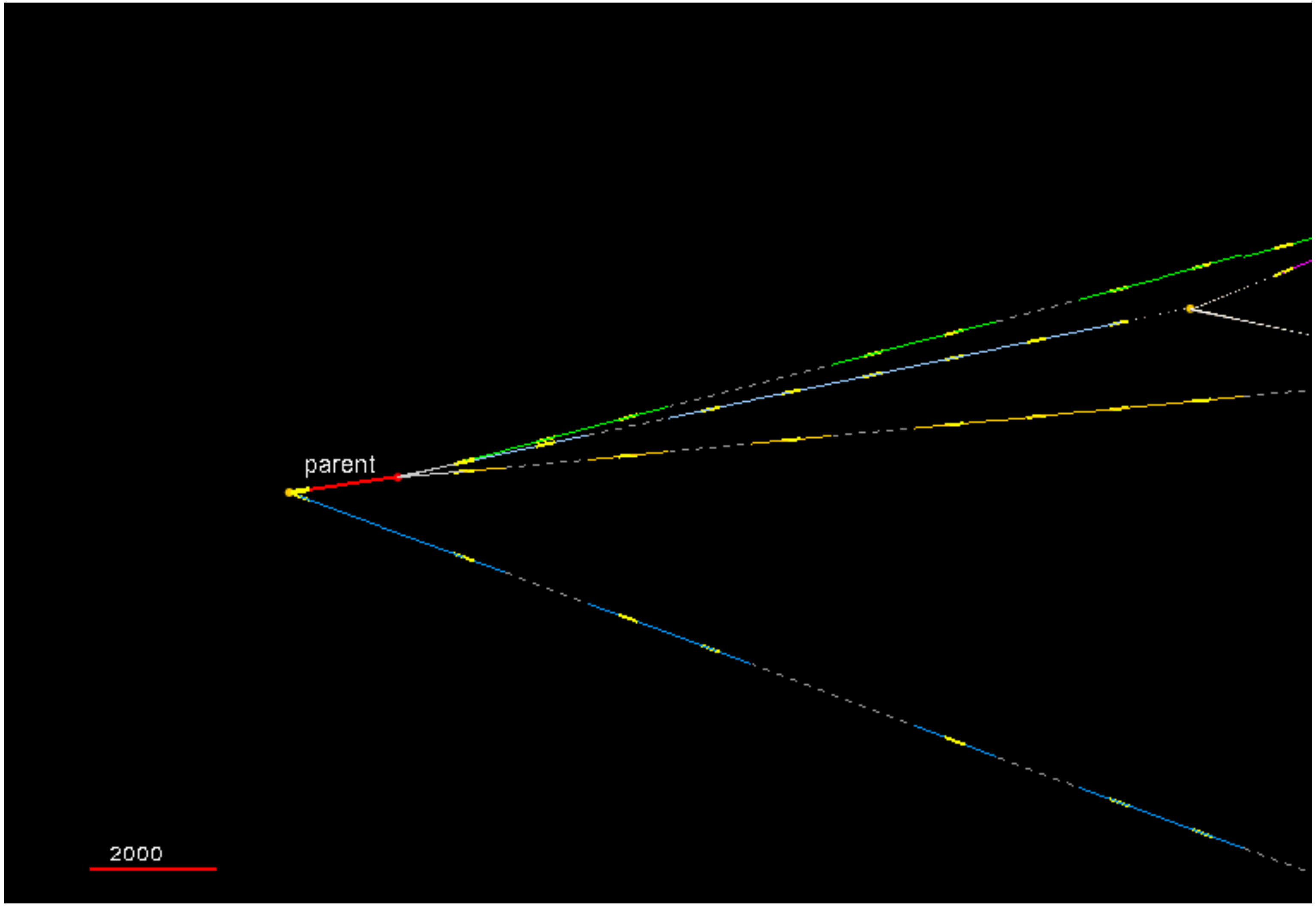
As seen by the electronic detectors …



Journal of High Energy Physics 11 (2013) 036

THE SECOND ν_τ CANDIDATE

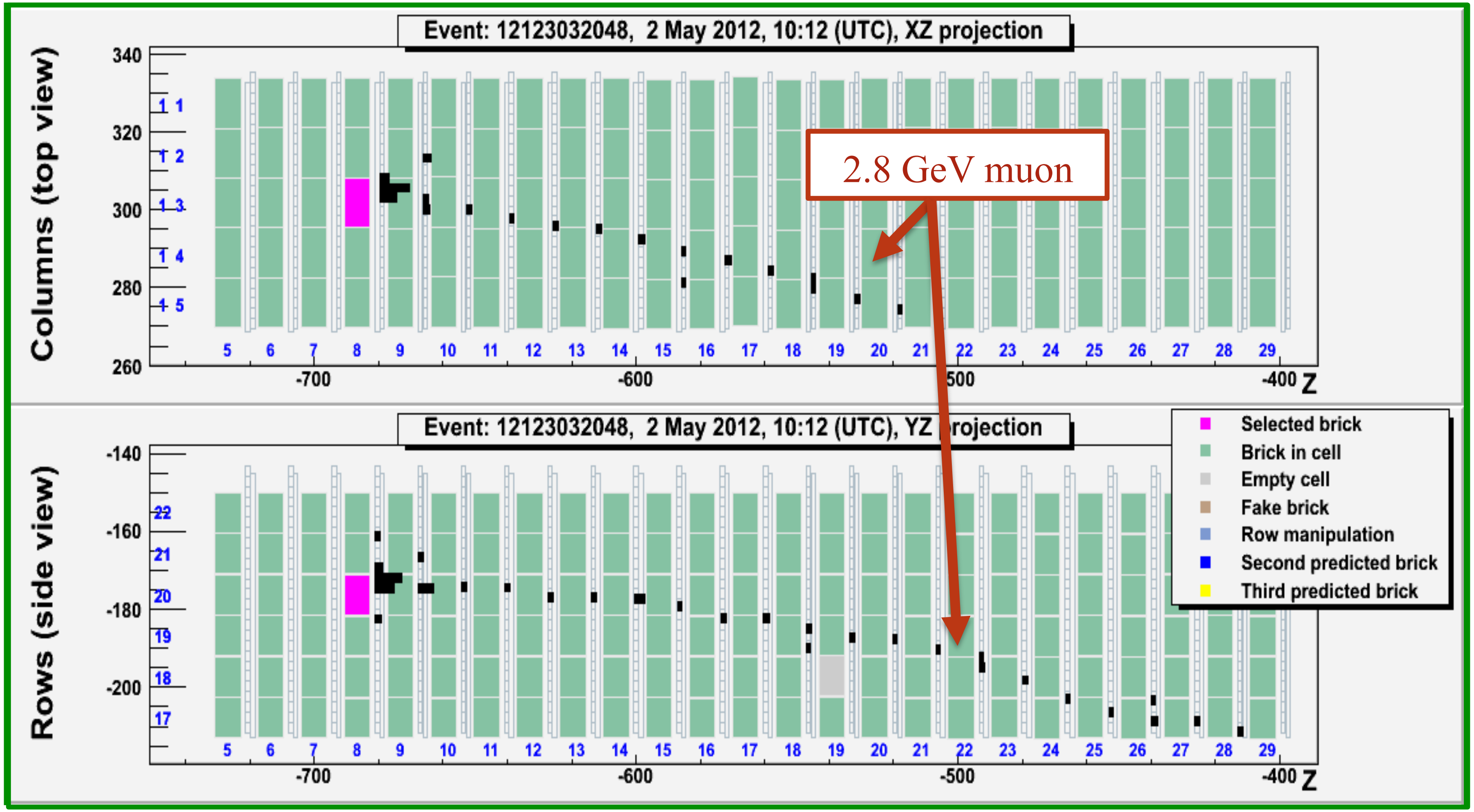
… and in the brick



Journal of High Energy Physics 11 (2013) 036

THE THIRD ν_τ CANDIDATE

As seen by the electronic detectors …

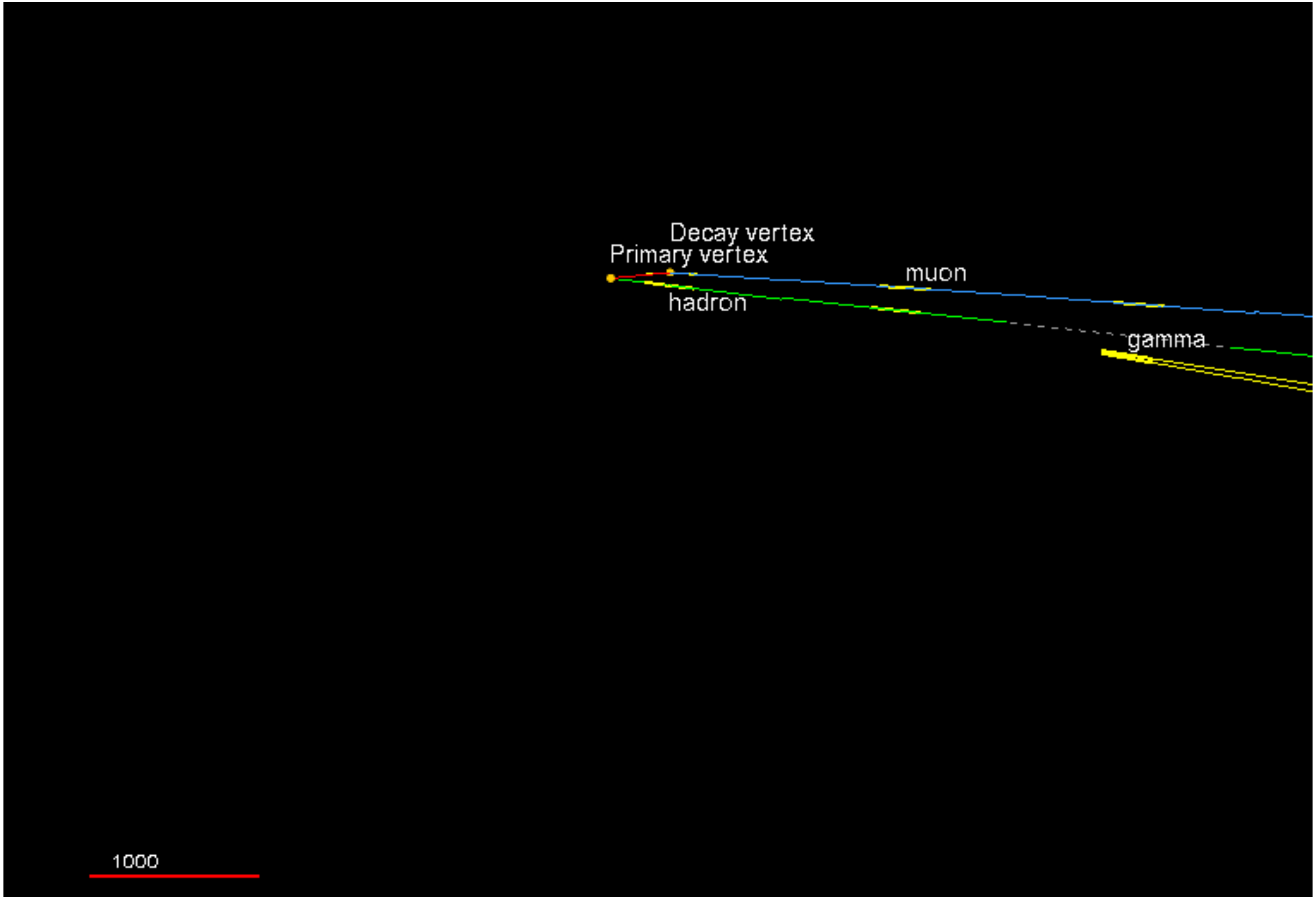


2.8 GeV muon

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

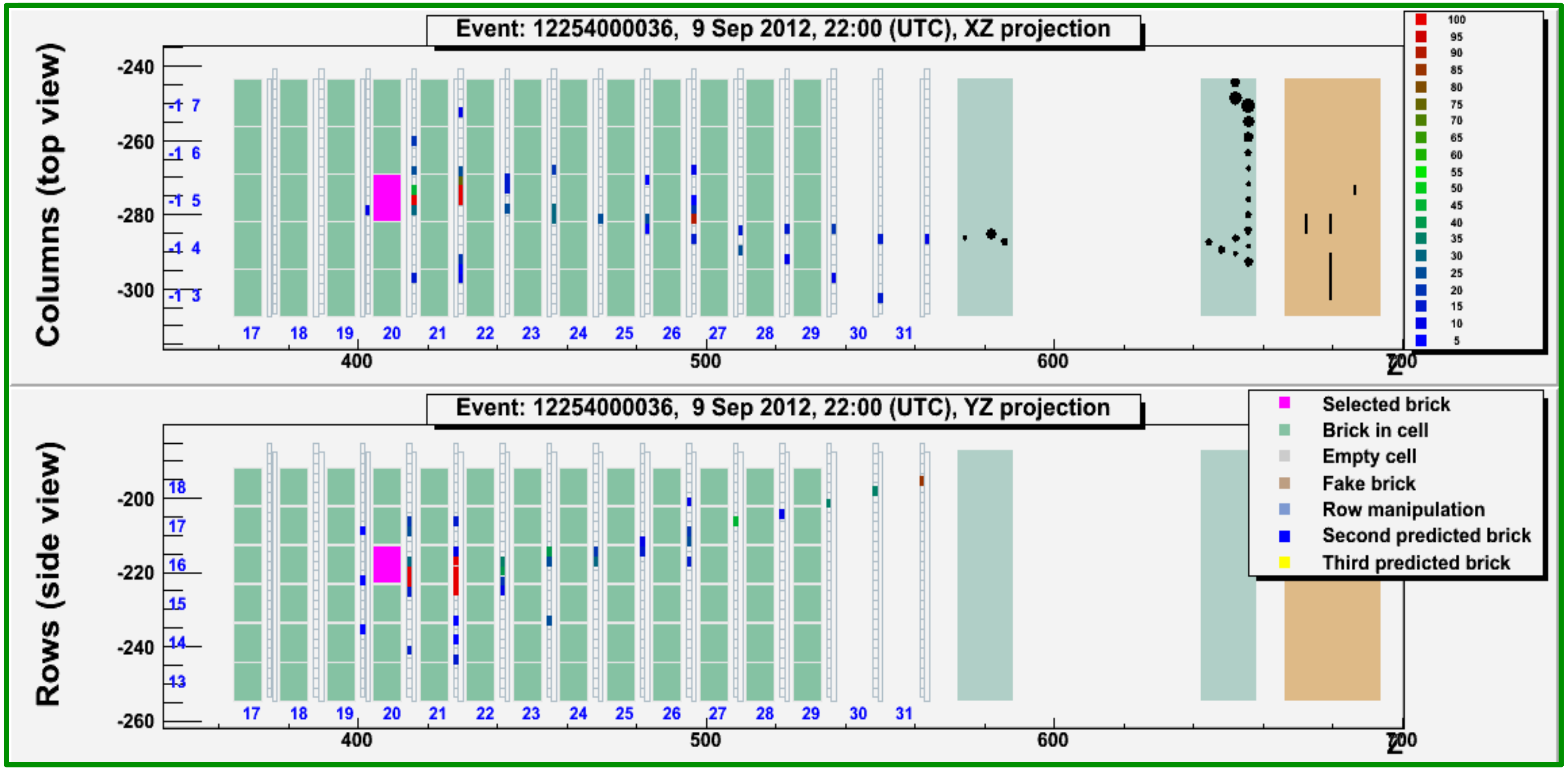
THE THIRD ν_τ CANDIDATE

… and in the brick



THE FOURTH ν_τ CANDIDATE

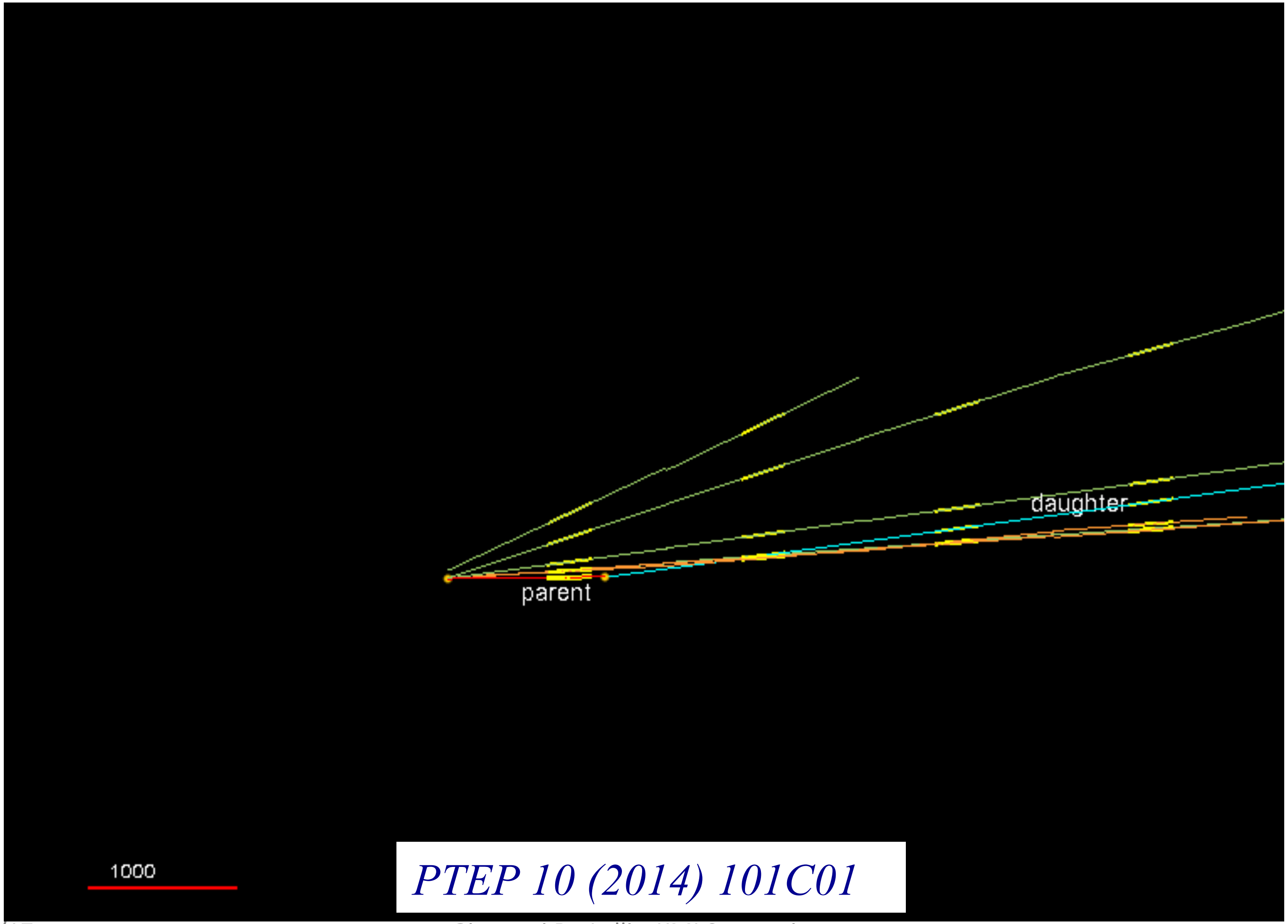
As seen by the electronic detectors …



PTEP 10 (2014) 101C01

THE FORTH ν_τ CANDIDATE

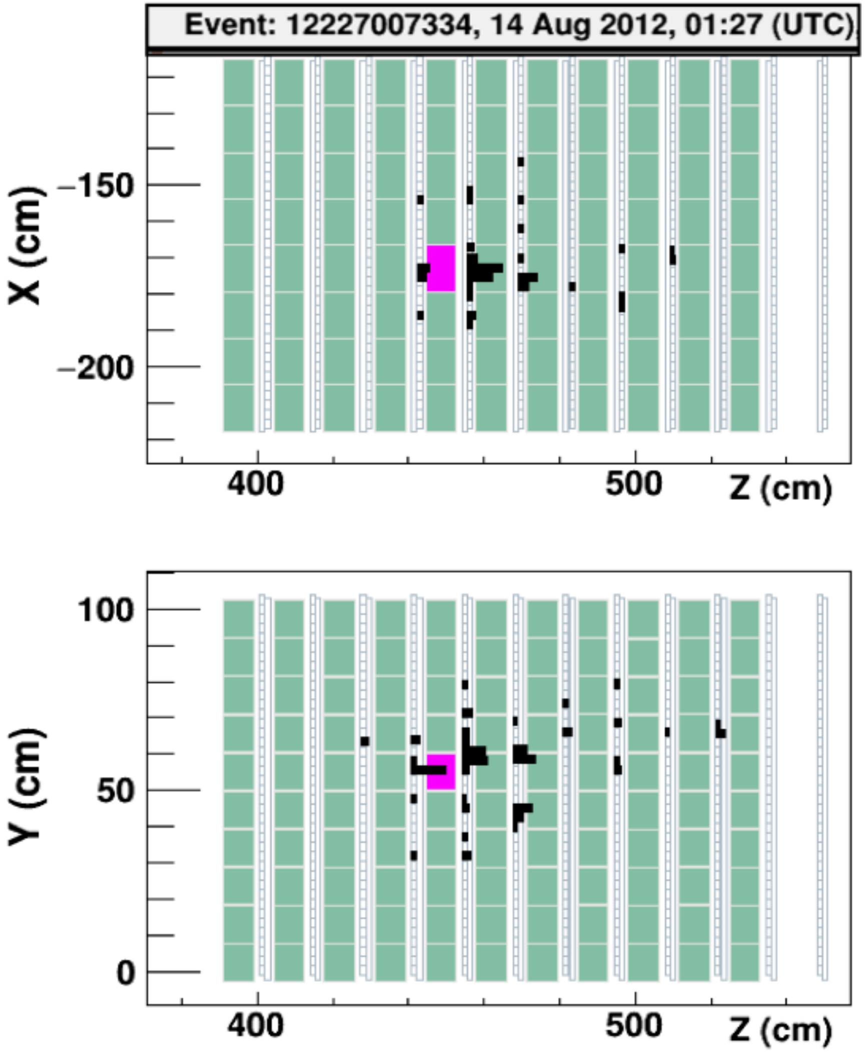
… and in the brick



PTEP 10 (2014) 101C01

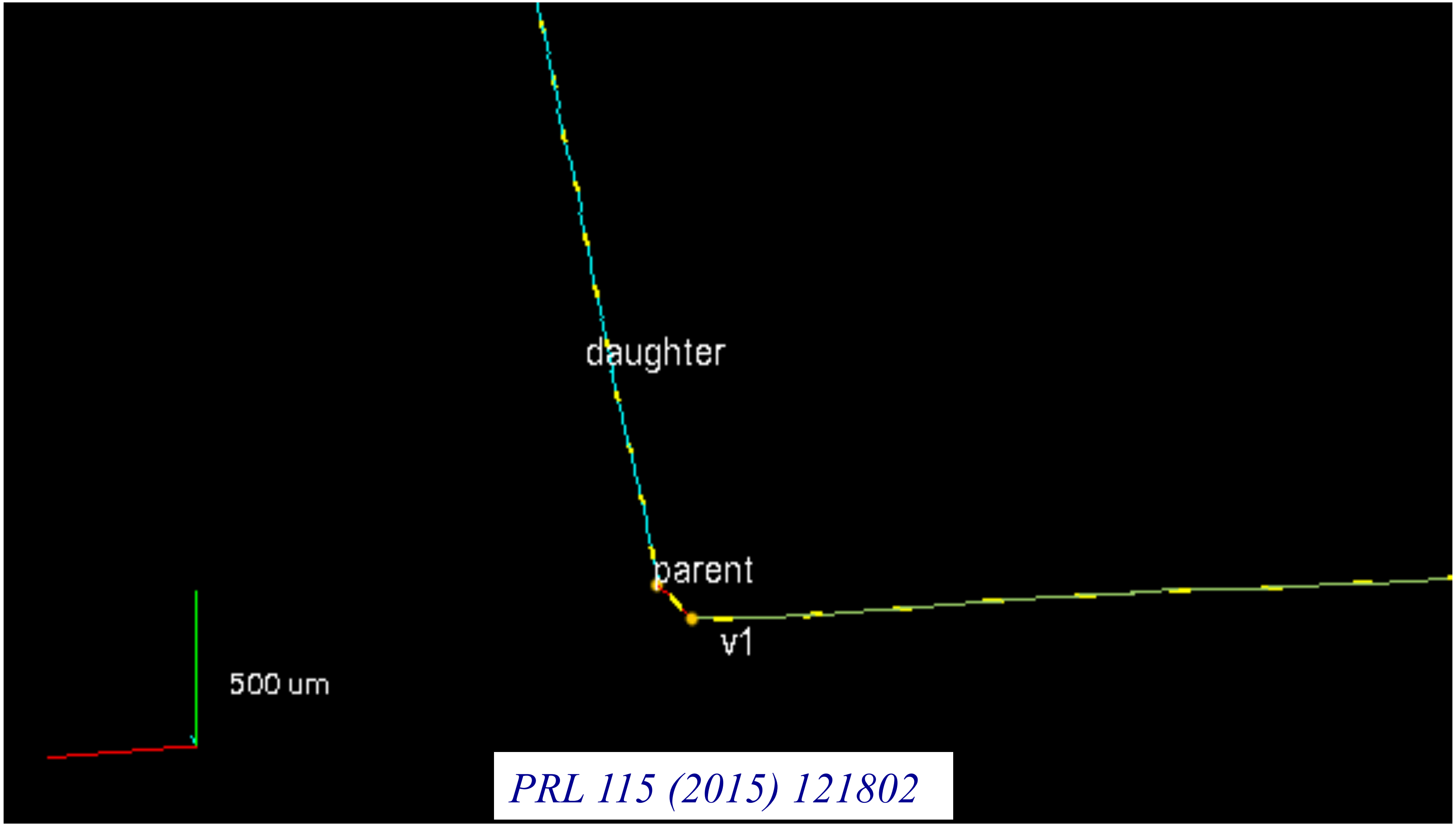
THE FIFTH ν_τ CANDIDATE

As seen by the electronic detectors …



THE FIFTH ν_τ CANDIDATE

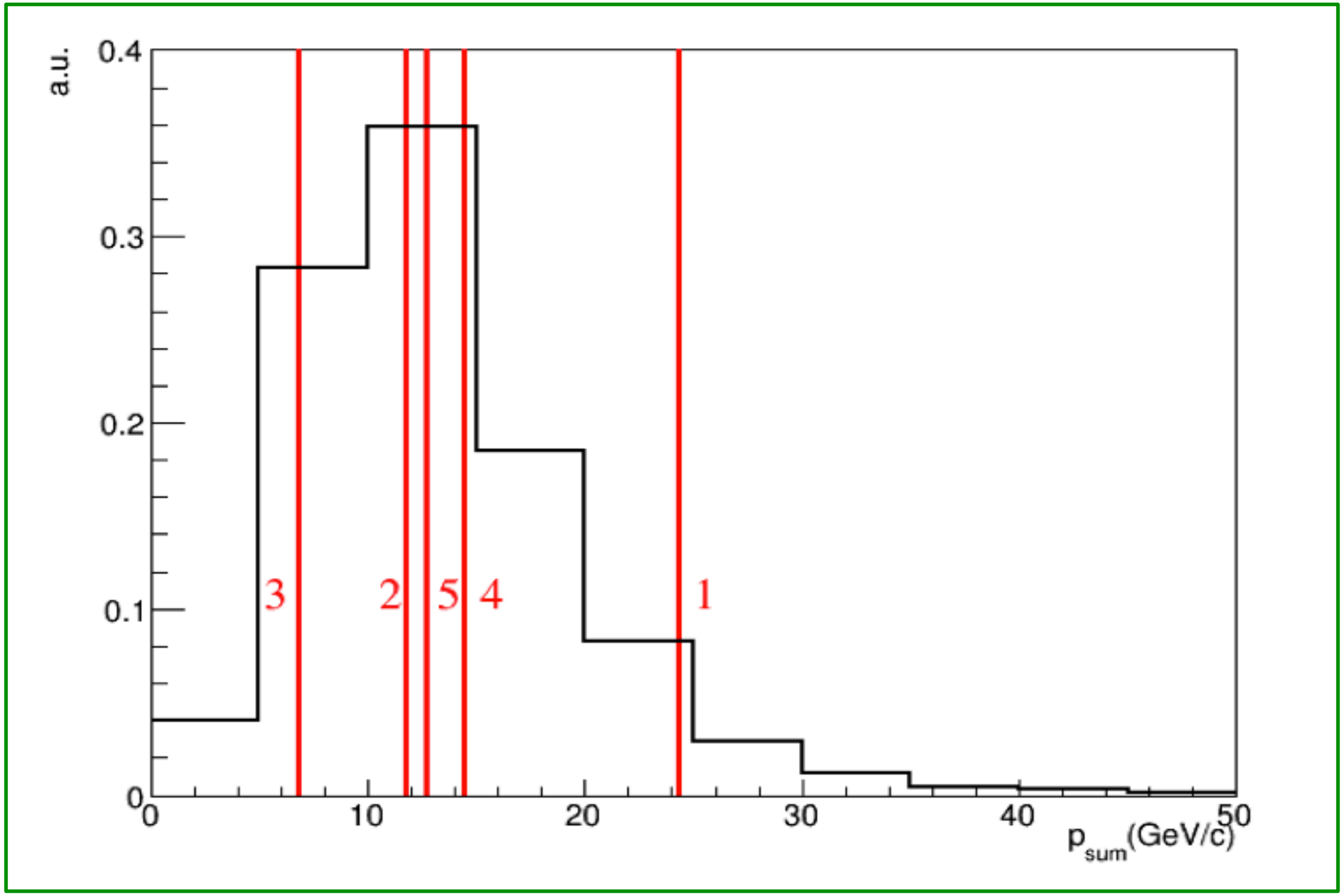
… and in the brick



PRL 115 (2015) 121802

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

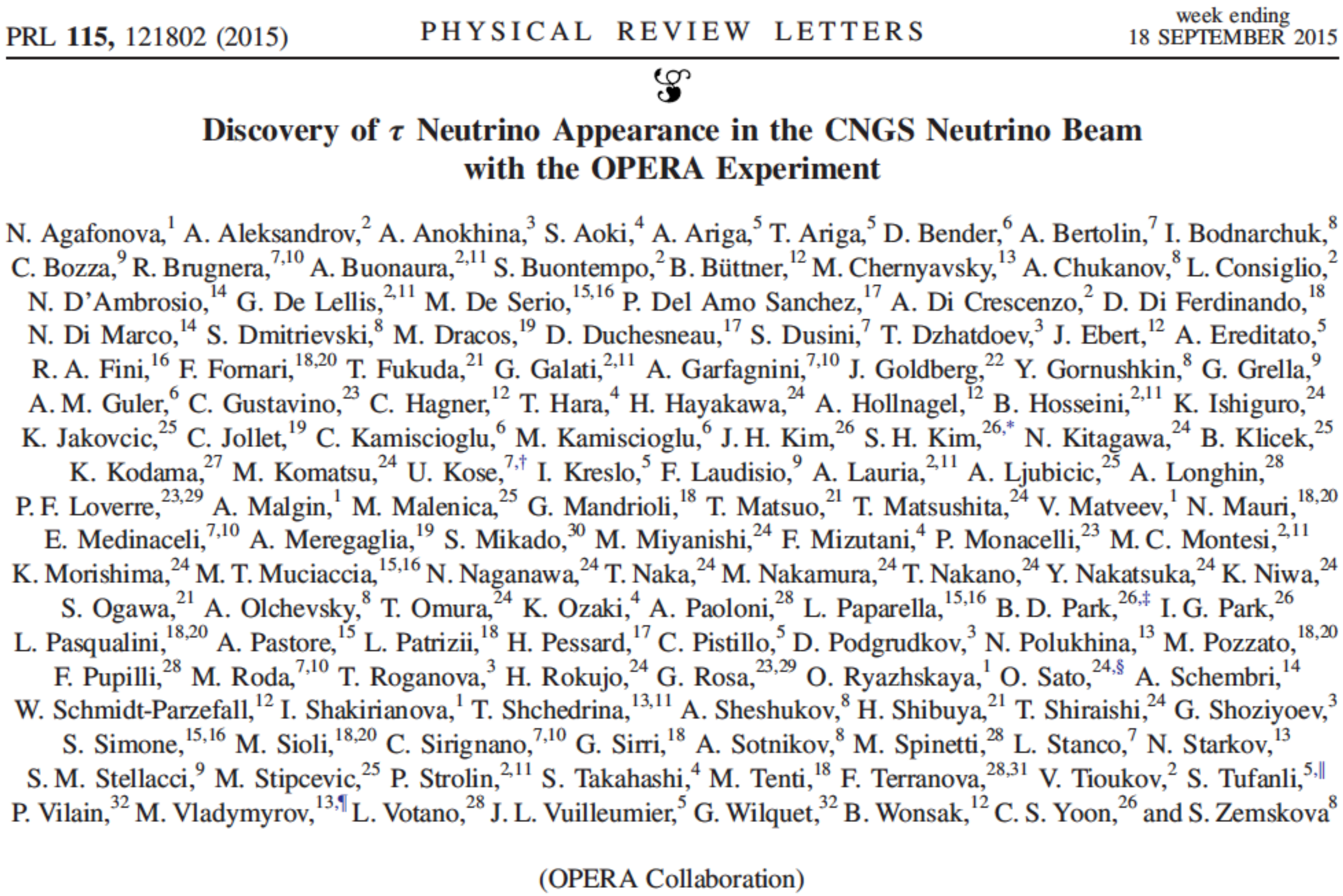
$$\text{Probability to be explained by background} \begin{cases} \text{Fisher} = 1.10 \times 10^{-7} \\ \text{Profile likelihood} = 1.07 \times 10^{-7} \end{cases}$$

This corresponds to 5.1 σ significance of non-null observation

$$P(n \geq 5 \mid \mu = 2.9) = 16.6\ \%$$

$$P^{\dagger} = 6.4\%$$

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



PRL **115,** 121802 (2015) PHYSICAL REVIEW LETTERS week ending 18 SEPTEMBER 2015

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

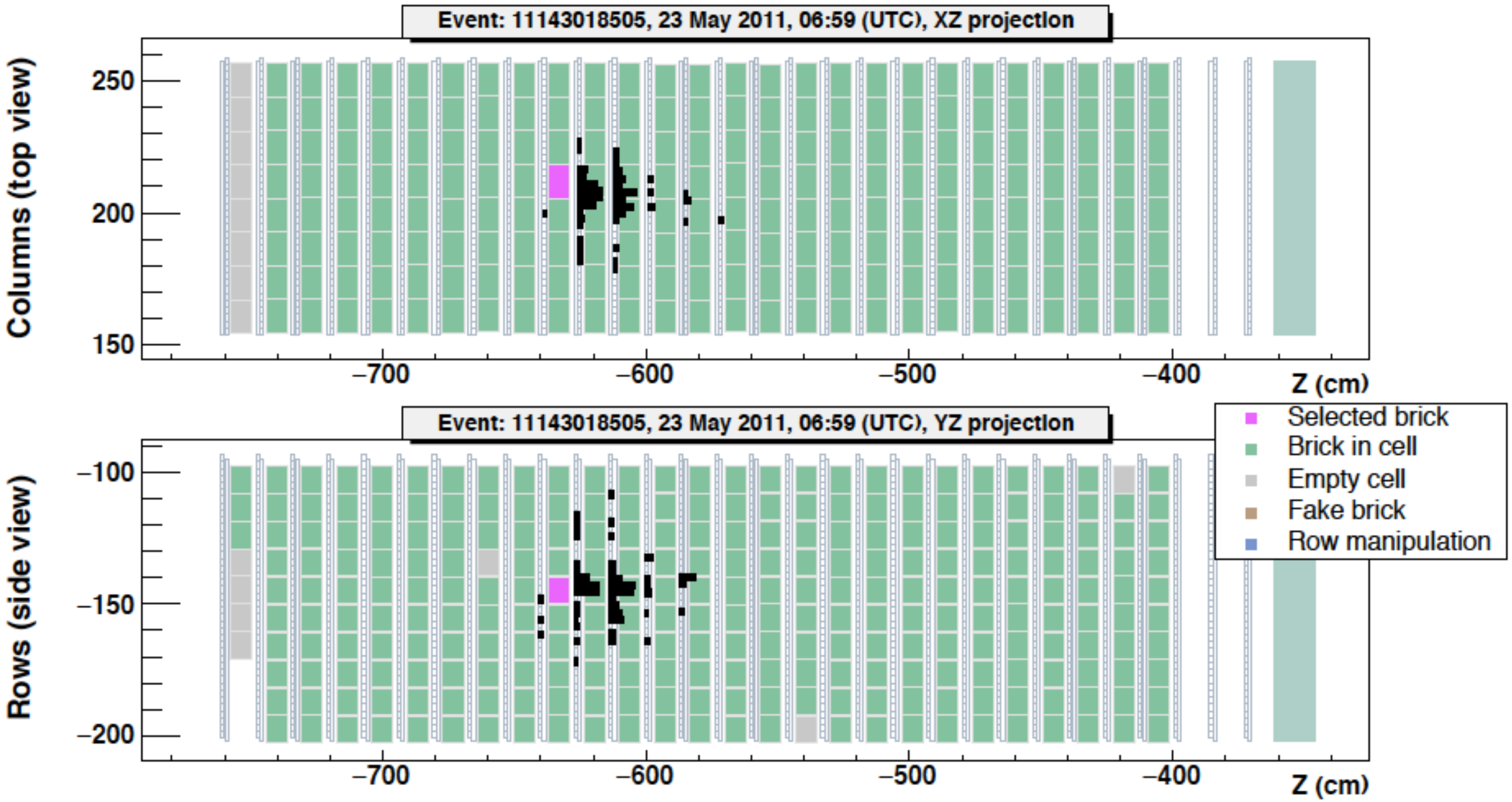
compiled by the Class for Physics of the Royal Swedish Academy of Sciences

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].

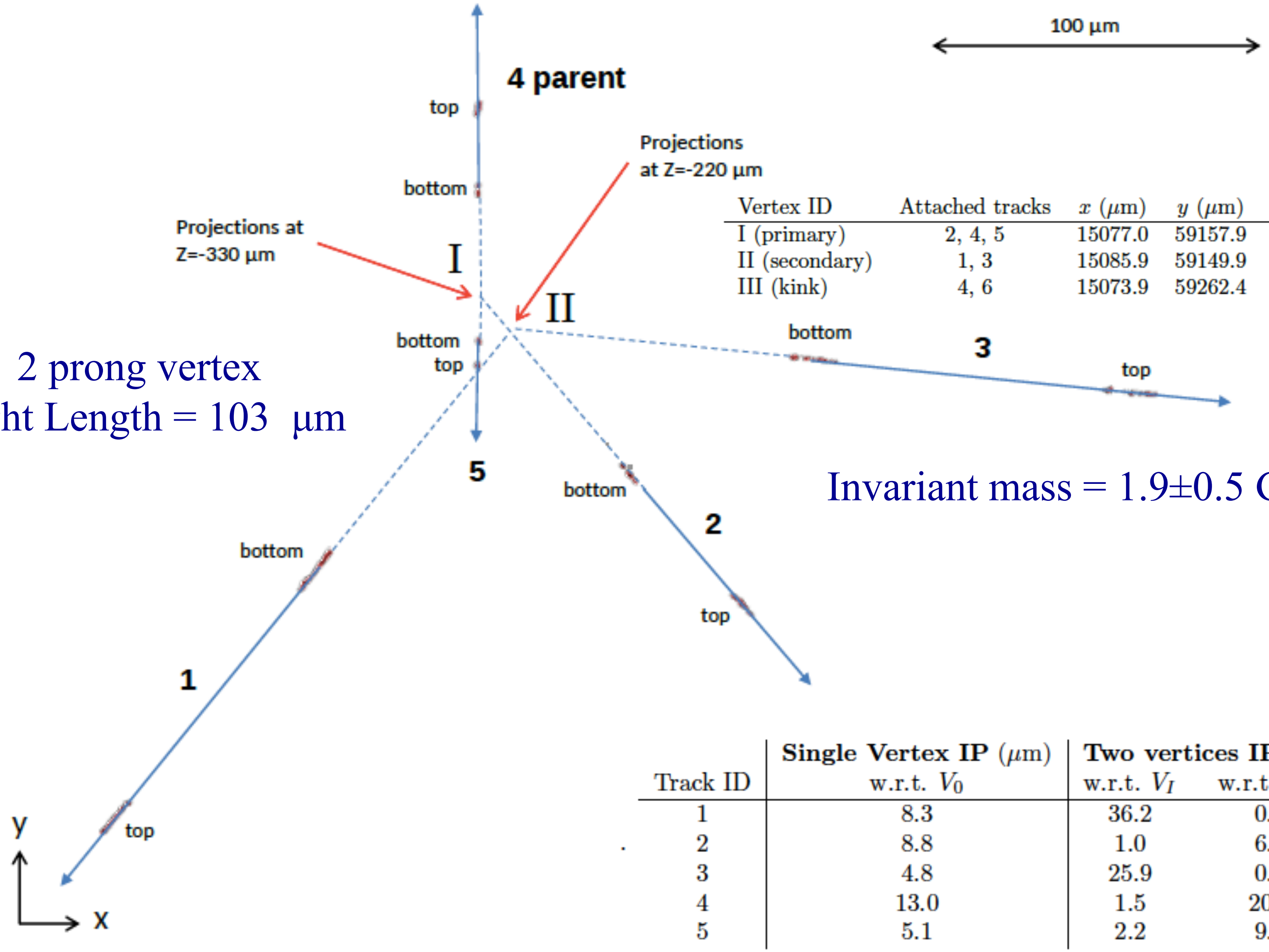
PRL 115 (2015) 121802

IN THE SAME DATA SAMPLE…

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



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



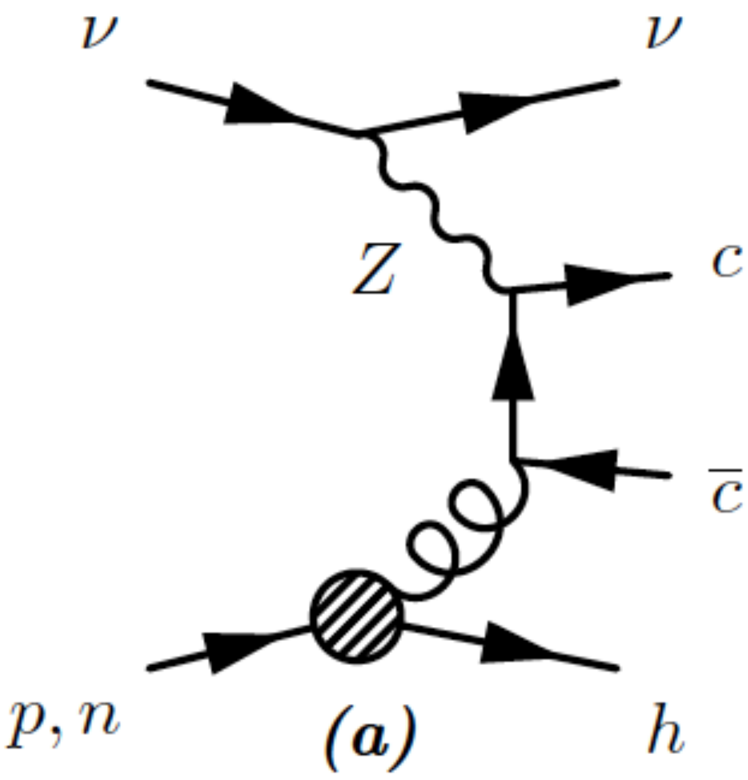
Vertex ID	Attached tracks	x (μm)	y (μm)	z (μm)
I (primary)	2, 4, 5	15077.0	59157.9	-33081.8
II (secondary)	1, 3	15085.9	59149.9	-32979.2
III (kink)	4, 6	15073.9	59262.4	-31926.4

2 prong vertex
Flight Length = 103 µm

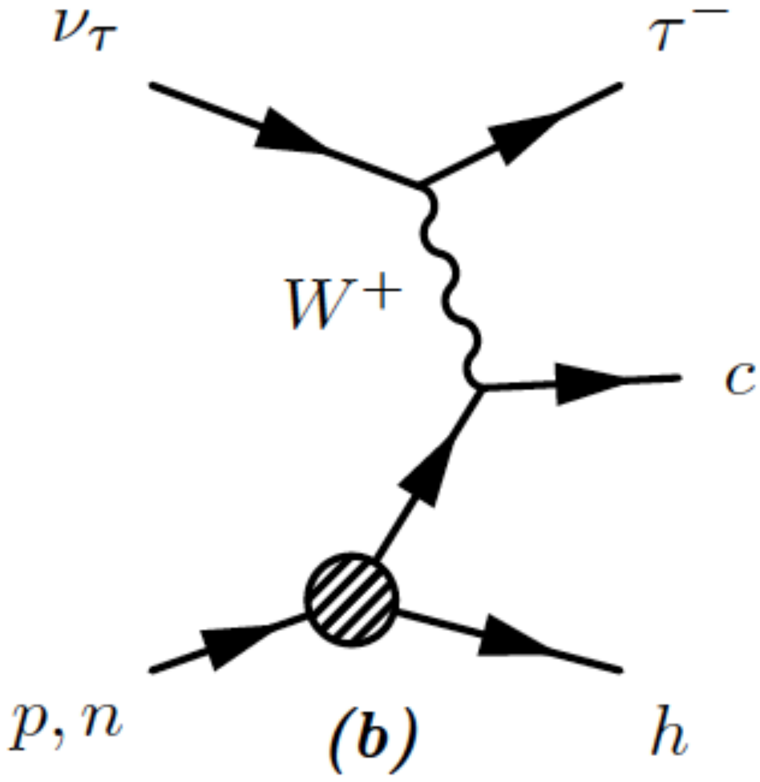
Invariant mass = 1.9±0.5 GeV

	Single Vertex IP (μm)	**Two vertices IP** (μm)	
Track ID	w.r.t. V_0	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



(a)



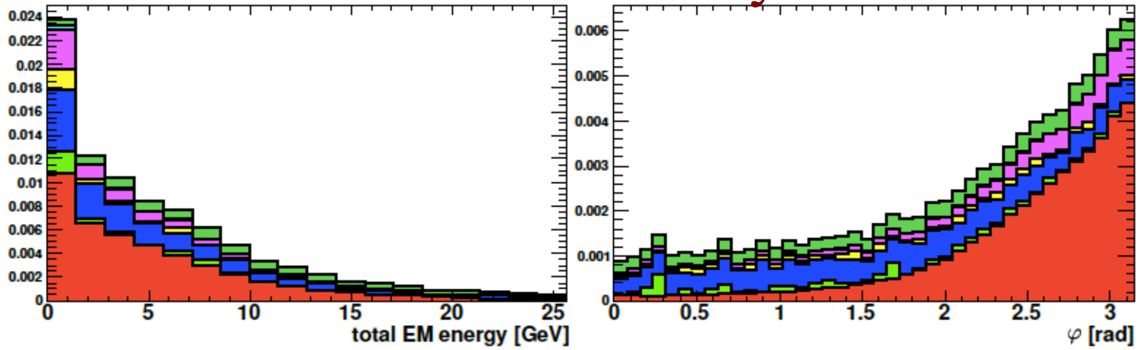
(b)

Expected yield after topological selection

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

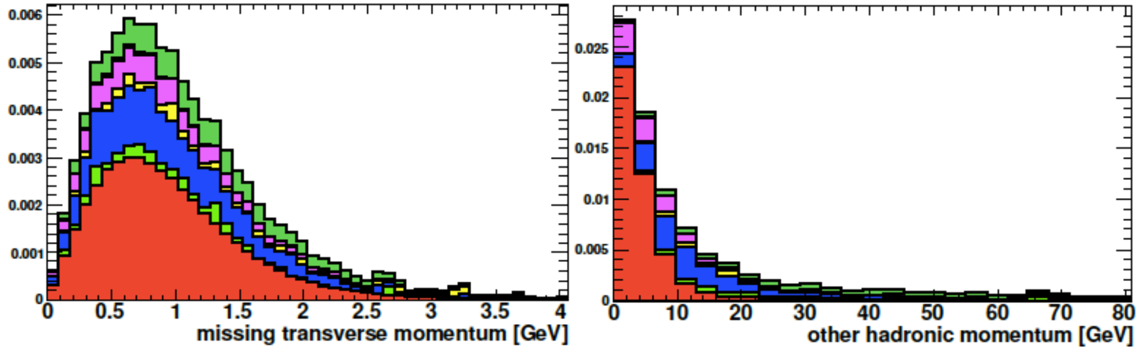
PRELIMINARY

Multivariate Analysis



(a) Total EM energy

(b) φ



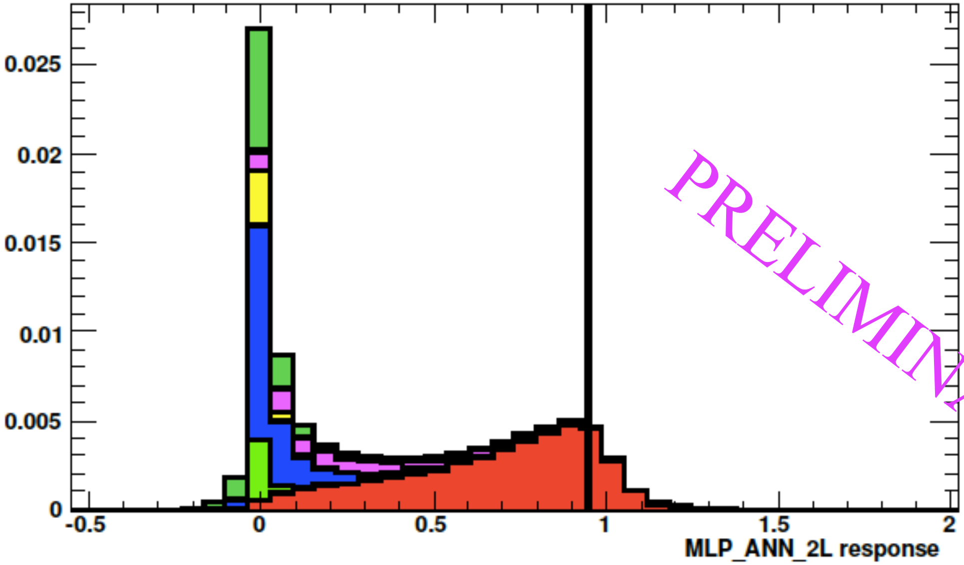
(c) Missing transverse momentum

(d) Other hadronic momentum

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 and significance



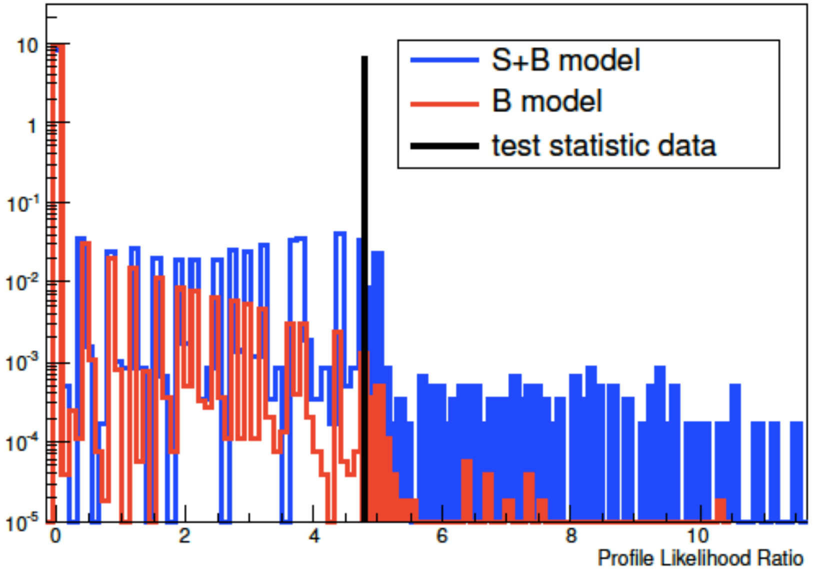
variable	value
1pr-like daughter momentum	2.7 GeV/c
1pr-like daughter transverse momentum	0.242 GeV/c
Kink angle	90 mrad
1pr-like flight length	1.16 mm
2pr-like daughters momentum	6.17 GeV/c
2pr-like daughters transverse momentum	0.542 GeV/c
2pr-like invariant mass	1.86 GeV/c^2
2pr-like flight length	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**

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

x PDF from ANN output

n_i = yield of i-th process

Background only → $\mu = 0$



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

OTHER OSCILLATION ANALYSES

STERILE NEUTRINOS

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

~standard oscillation

exotic oscillation

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

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

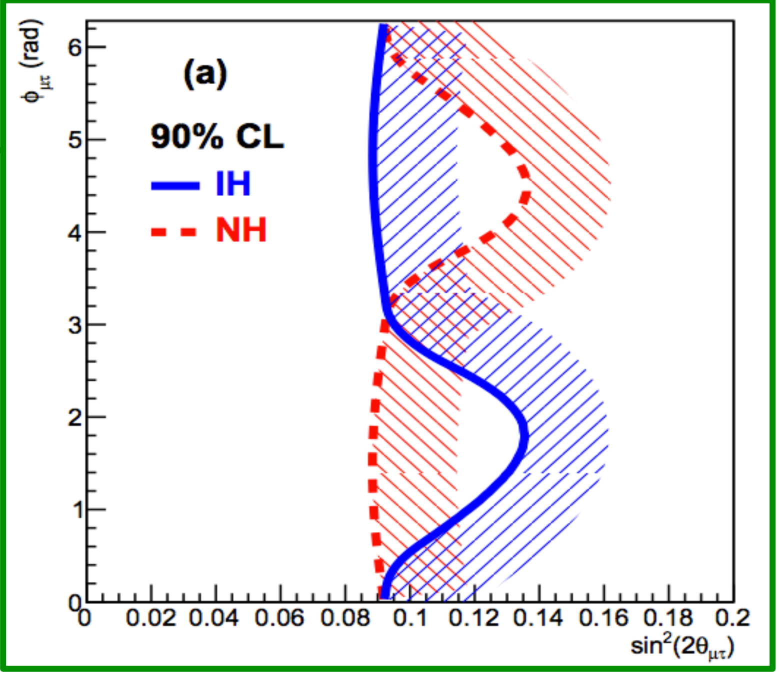
$$\tilde{L}(\phi_{\mu\tau}, sin^2 2\theta_{\mu\tau})$$

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

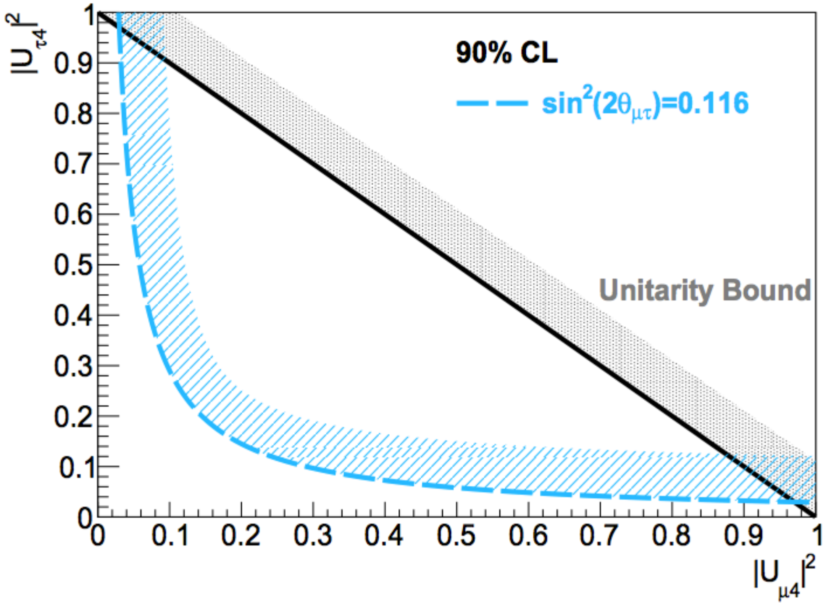
$$C = 2\,|\,U_{\mu3}U^*_{\tau3}\,|,$$

$$\phi_{\mu\tau} = Arg(U_{\mu3}U^*_{\tau3}U^*_{\mu4}U_{\tau4})$$

JHEP 1506 (2015) 069



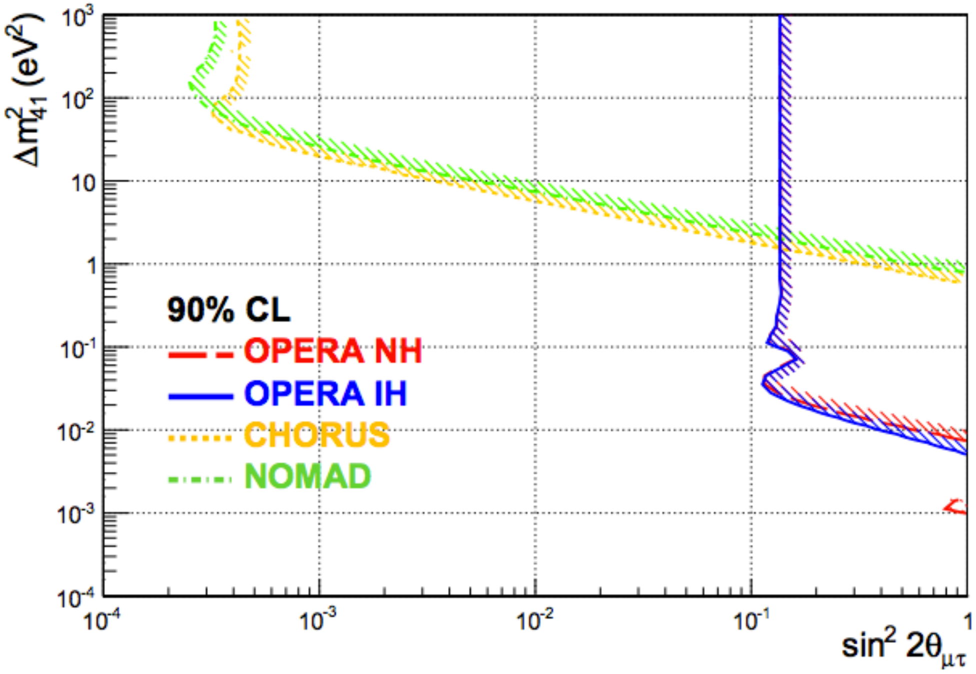
STERILE NEUTRINOS



Effective mixing:

$$\sin^2 2\theta_{\mu\tau} = 4\,|U_{\mu4}|^2 |U_{\tau4}|^2$$

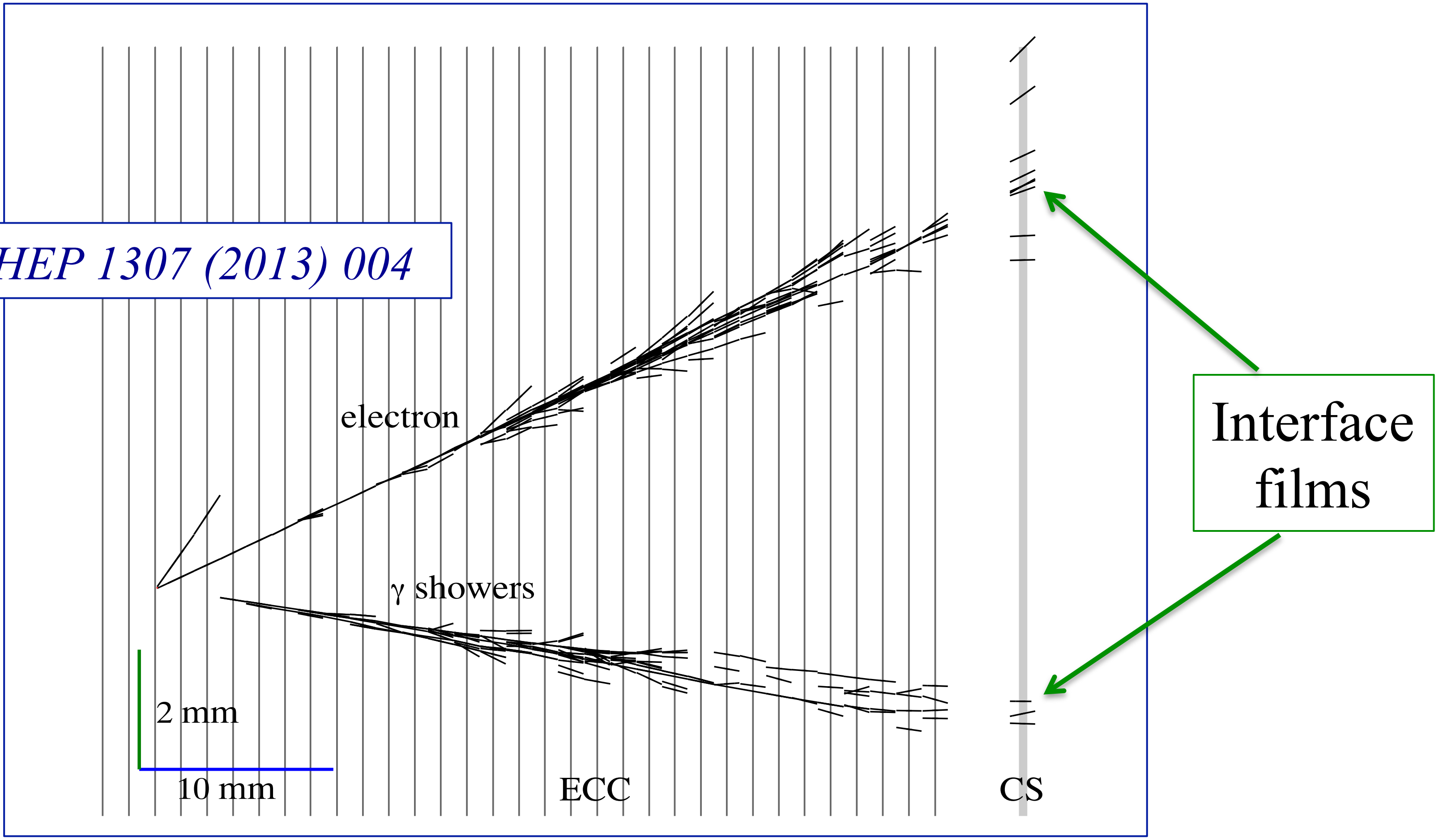
JHEP 1506 (2015) 069



$\nu_\mu \rightarrow \nu_e$ ANALYSIS

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

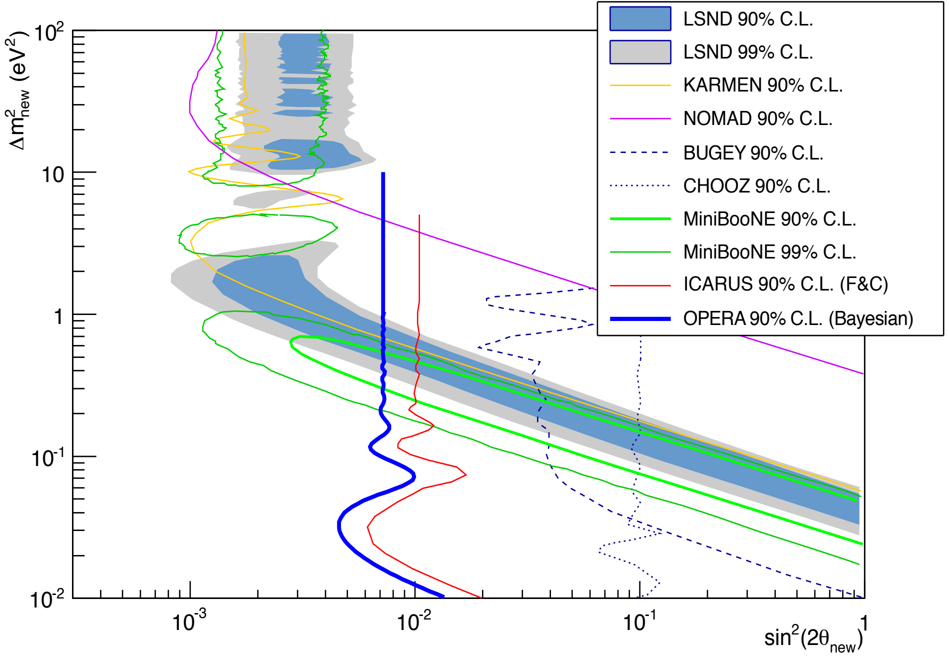
JHEP 1307 (2013) 004

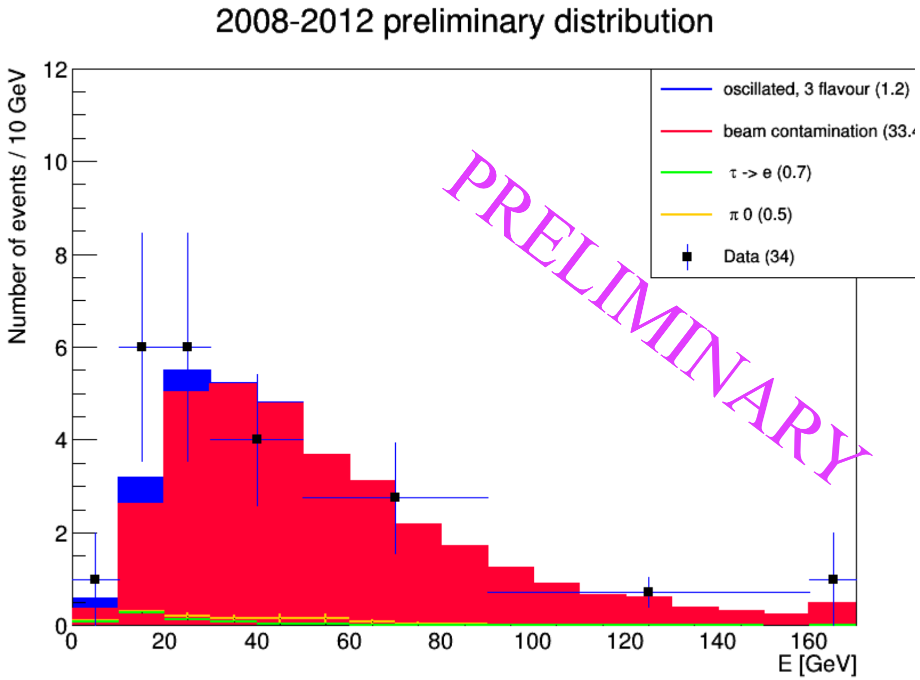


Analysis based on 2008-2009 run, 19 observed candidates (4 with E < 20 GeV)

SEARCH FOR STERILE NEUTRINOS IN $\nu_\mu \rightarrow \nu_e$

JHEP 1307 (2013) 004





Current sample extended with ~twice candidates: 34 events

New paper in preparation

ONGOING EVENT ANALYSIS

- Widen selection cuts to increase the statistics
- Topological identification and looser kinematical cuts
- Statistical gain → reduce uncertainty (e.g. Δm^2 from tau appearance)

- Use likelihood approach

- Exploit unique feature of identifying all three flavours: use tau appearance, electron appearance and muon disappearance at the same time

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.

CERNCOURIER

VOLUME 55 NUMBER 9 NOVEMBER 2015

Tensions in the Standard Model

OUR COURIER
Reflections on the role of CERN Courier
p5

LABORATORIES
Underground physics in Spain
p29

DARK-MATTER SEARCH
Recent results from XENON100 p10

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 1.8×10^{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 ▷