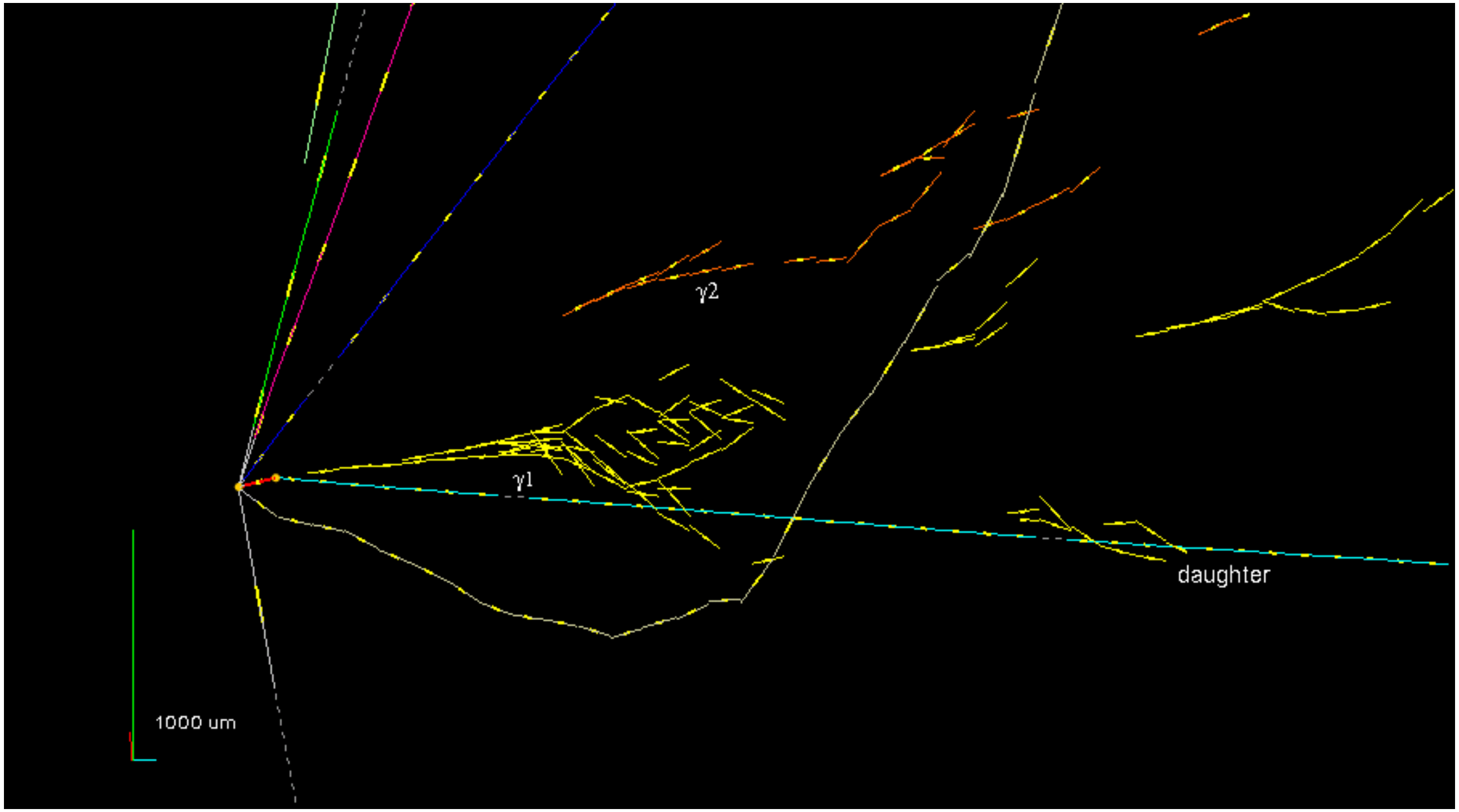
Results of the OPERA experiment

Giovanni De Lellis

University "Federico II" and INFN Napoli

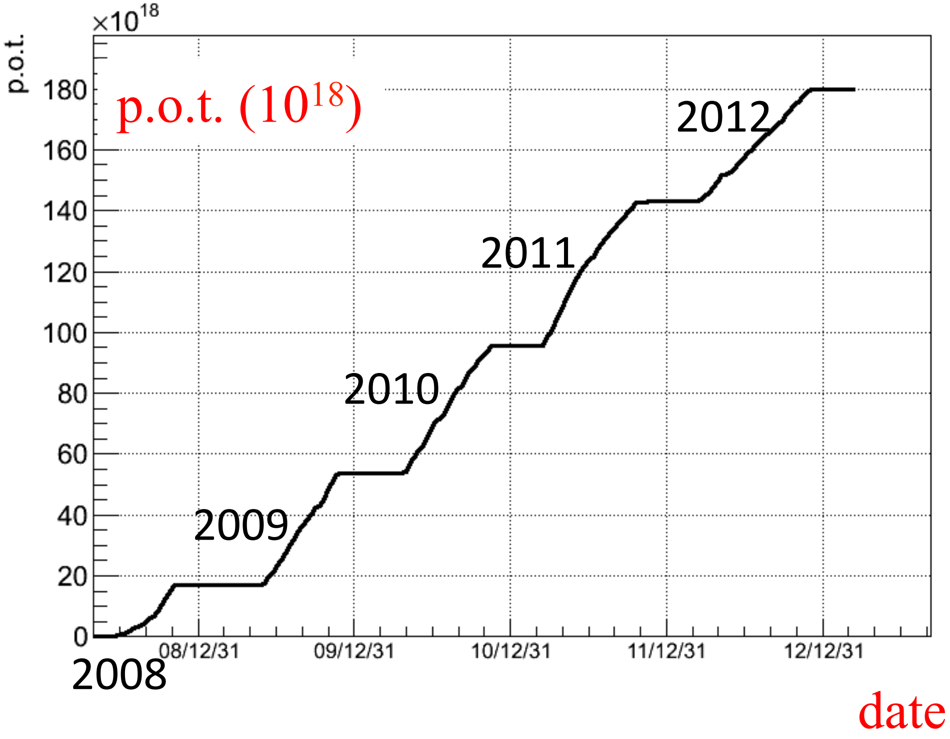
On behalf of the OPERA Collaboration

For the XLVII Meeting of the LNGSC Committee



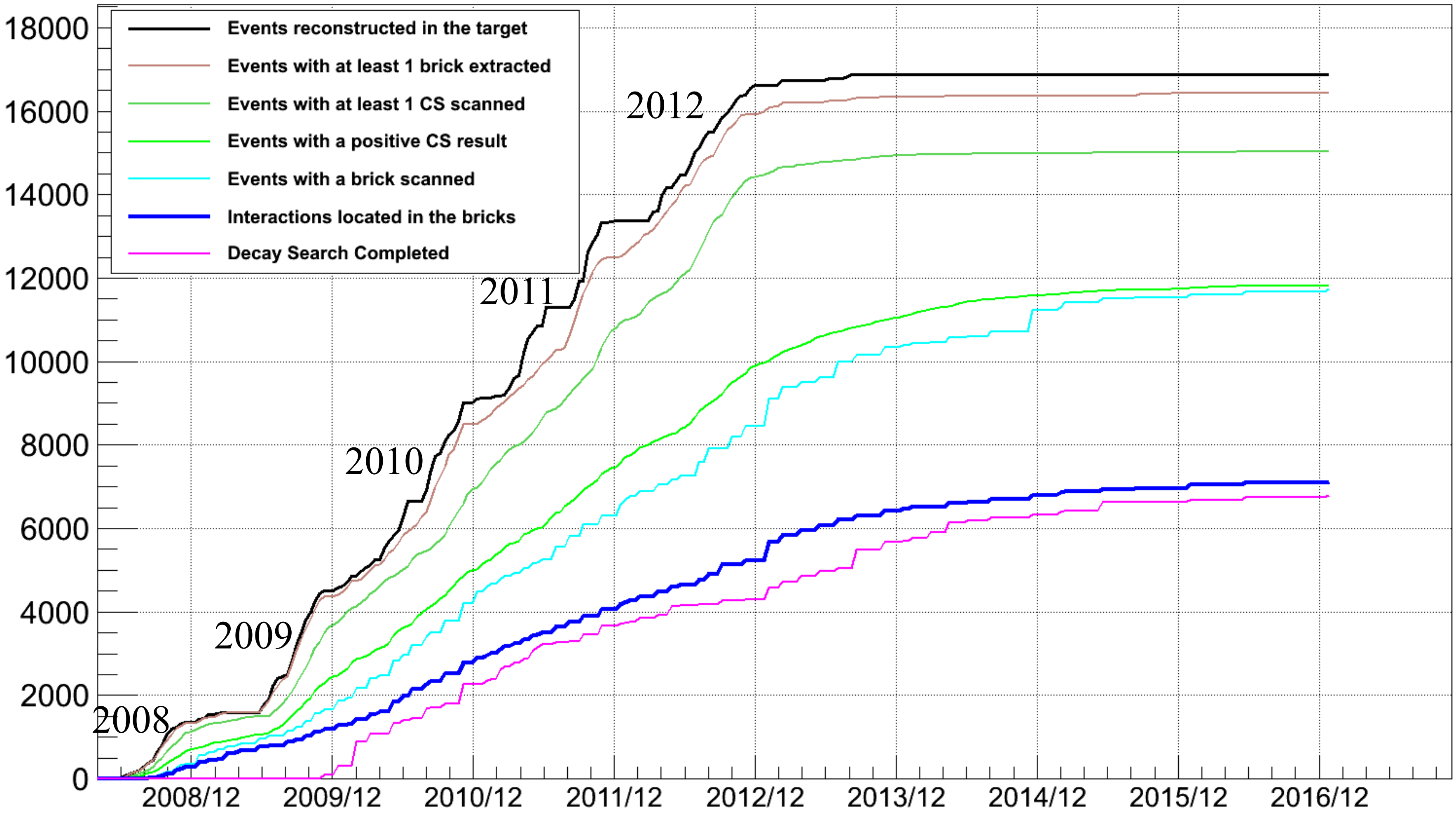
The CNGS beam along its five years of operation 2008 ÷ 2012

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**



DATA ANALYSIS COMPLETED

Run 2008 → 2012



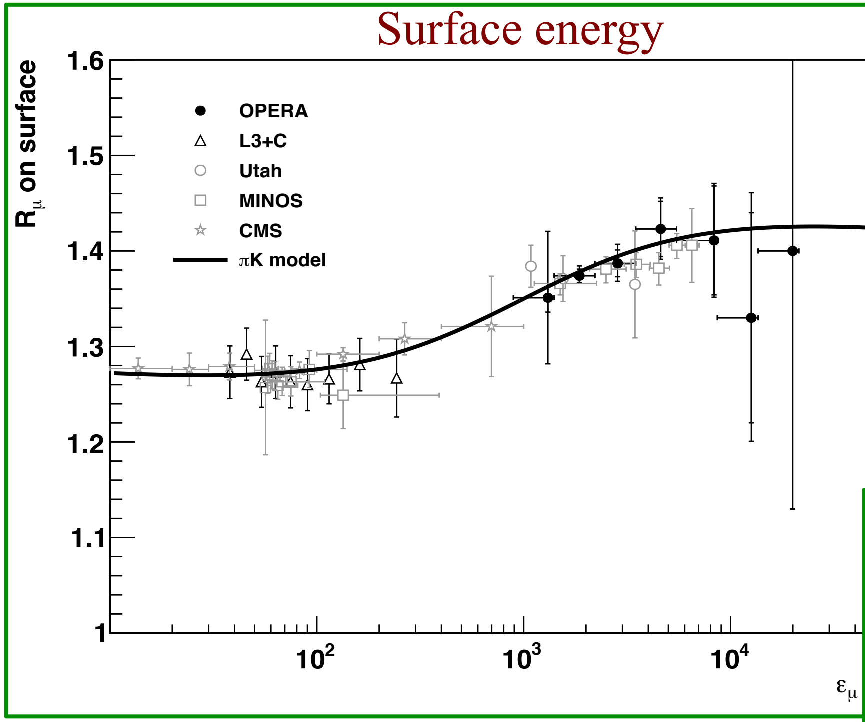
7132 located interactions

6785 decay search

NON-OSCILLATION PHYSICS

COSMIC-RAY PHYSICS

Surface energy

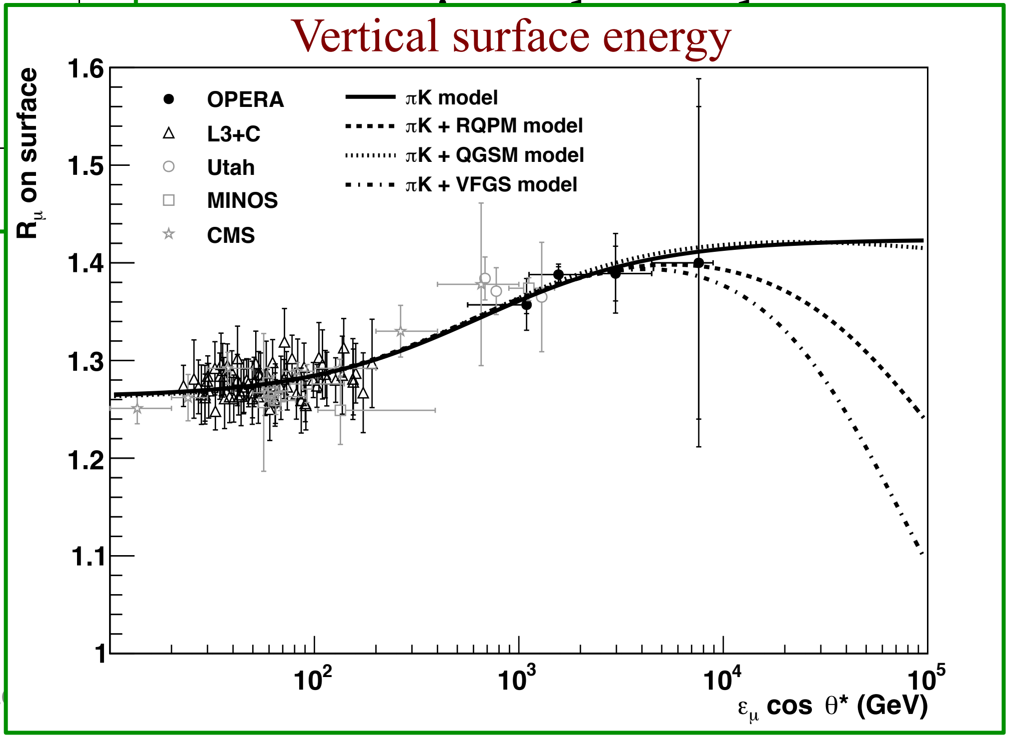


Measurement of TeV atmospheric muon charge ratio

Eur. Phys. J. C74 (2014) 2933

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

Vertical surface energy



Cosmic-muon rate and temperature dependence

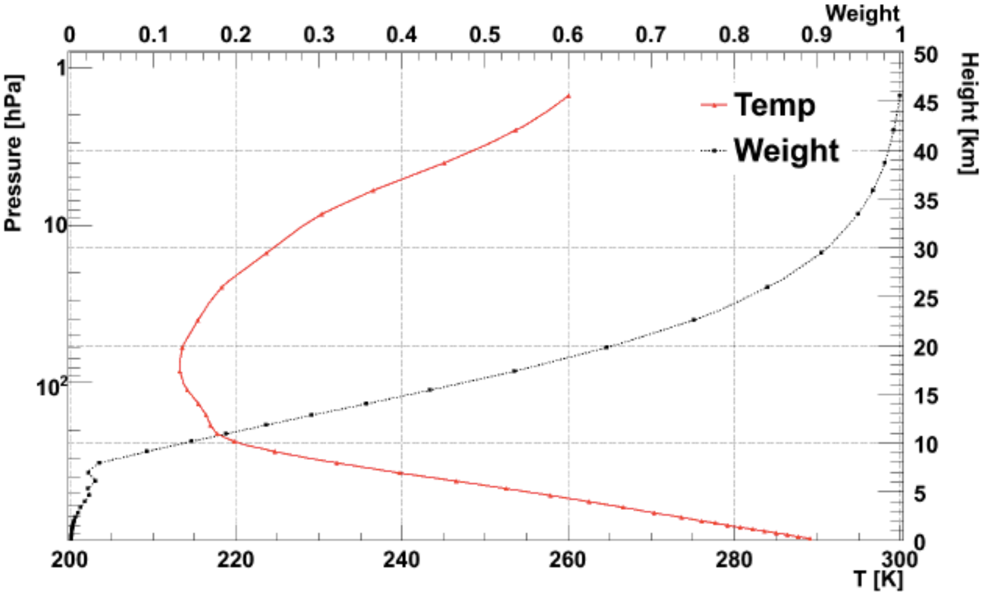
- Gran Sasso underground ~ 3800 m w.e. → Minimum muon energy ~ 1.8 TeV
- Atmospheric temperature increase → density decrease → increase the pion decay rate → muon rate increase

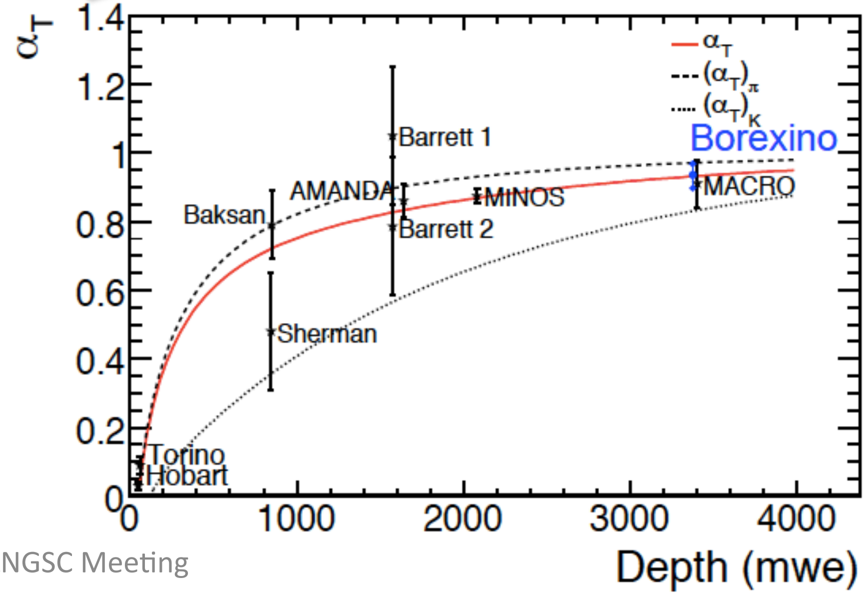
$$I_\mu(t) = I_\mu^0 + \Delta I_\mu = I_\mu^0 + \delta I_\mu \cos\left[\frac{2\pi}{T}(t - t_0)\right]$$

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

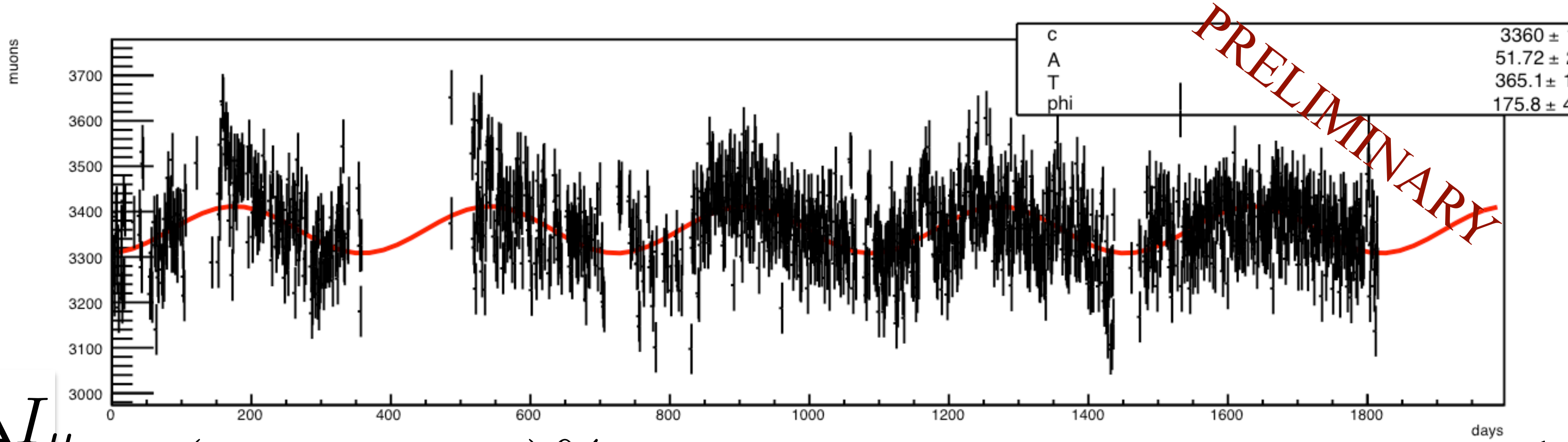
$$\frac{\Delta I_\mu}{I_\mu^0} = \alpha_T \frac{\Delta T_{\text{eff}}}{T_{\text{eff}}}$$

High W in high atmosphere → high energy muons



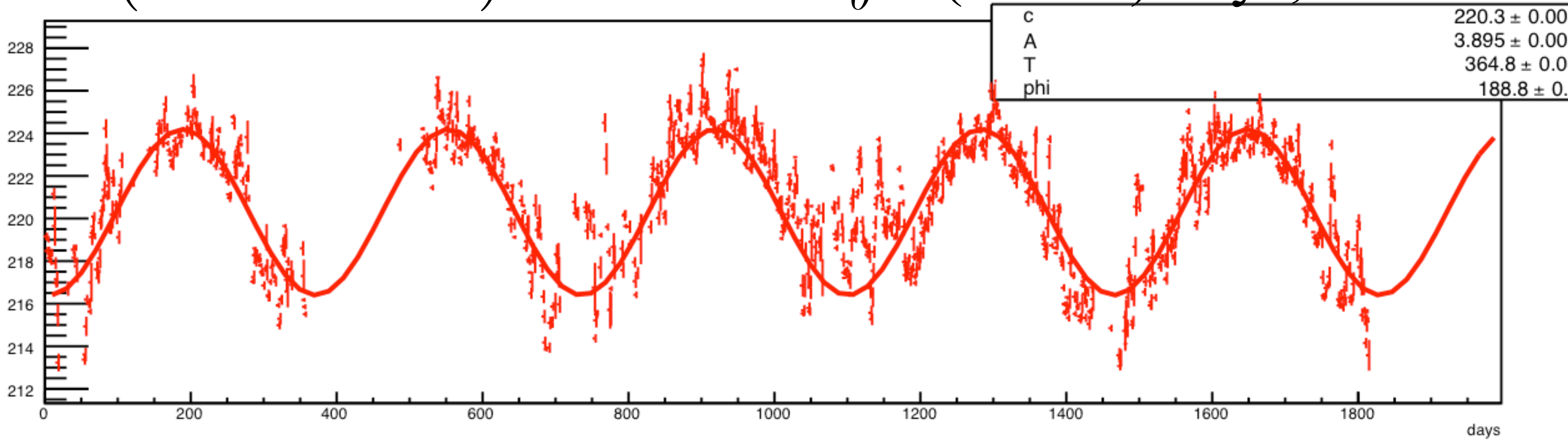


Annual modulation of cosmic-muon rate



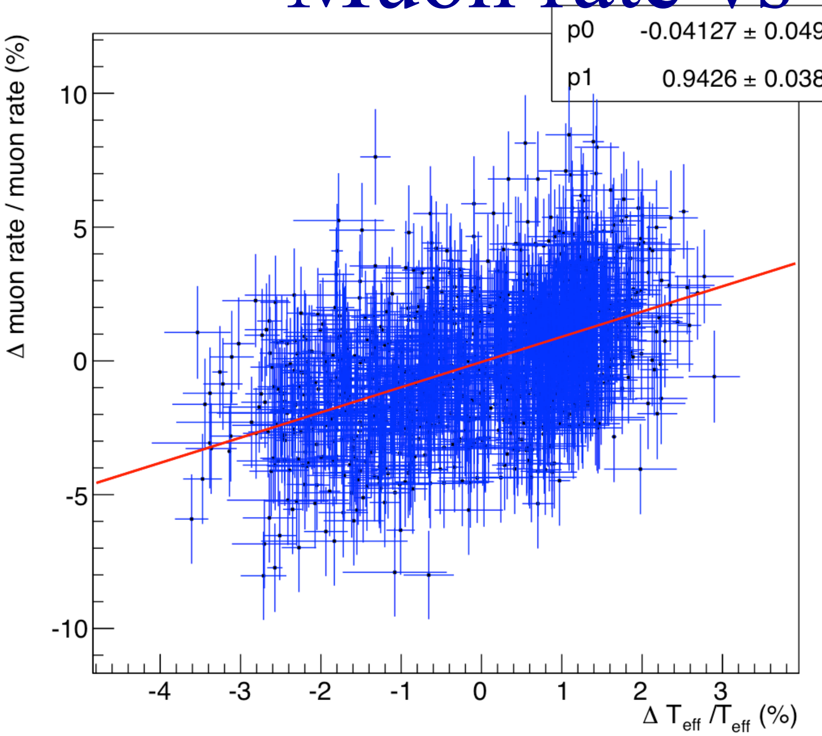
$$\frac{\Delta I_\mu}{I_\mu^0} = (1.54 \pm 0.07)\%$$

t_0 = (176±4) days, June 26th



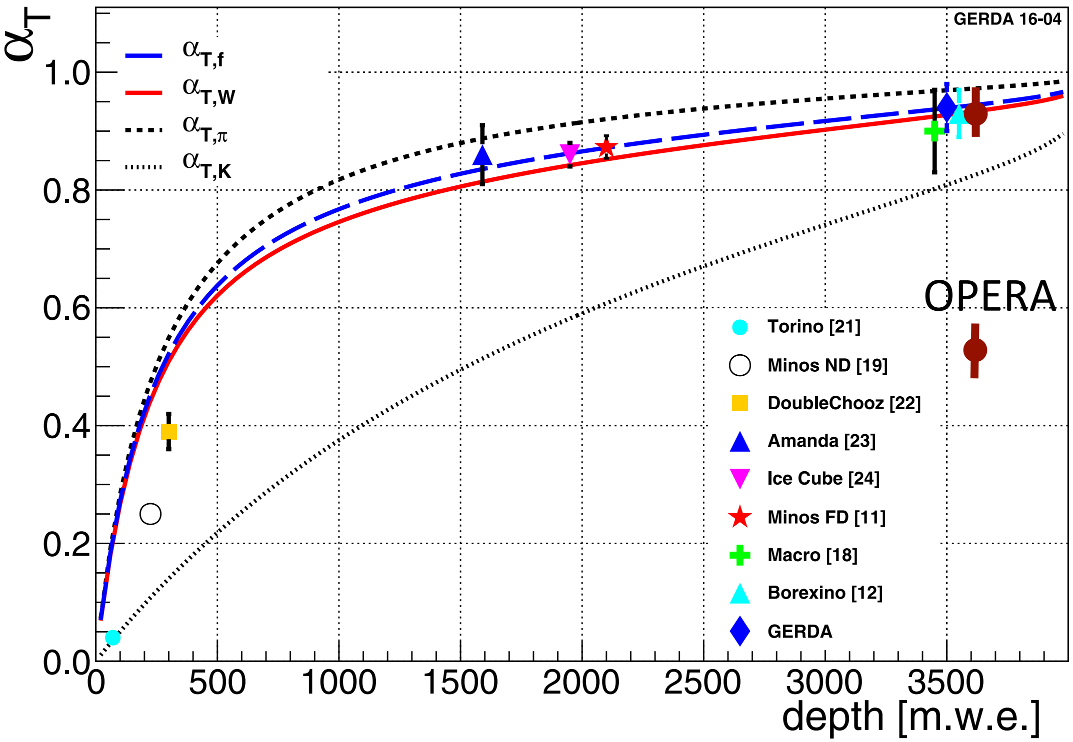
Temperature data by the European Center for Medium-range Weather Forecasts (ECMWF)

Muon rate vs temperature variations



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

$$\alpha_T = 0.94 \pm 0.04$$

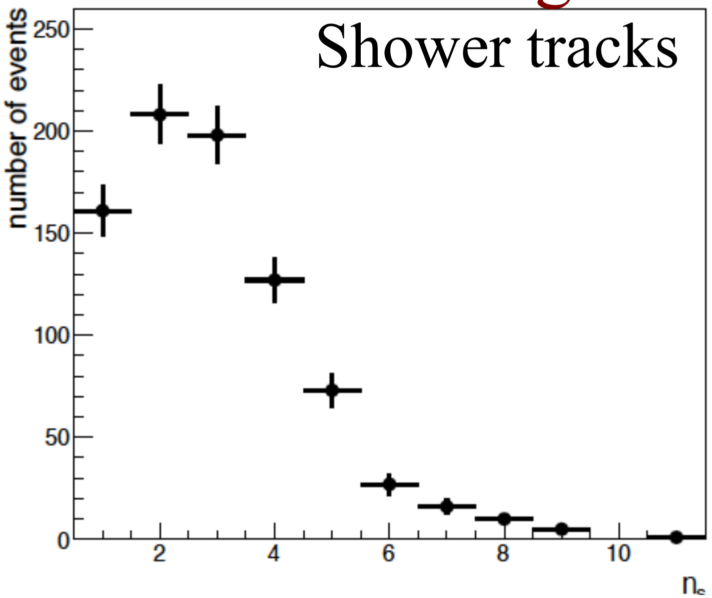


PRELIMINARY

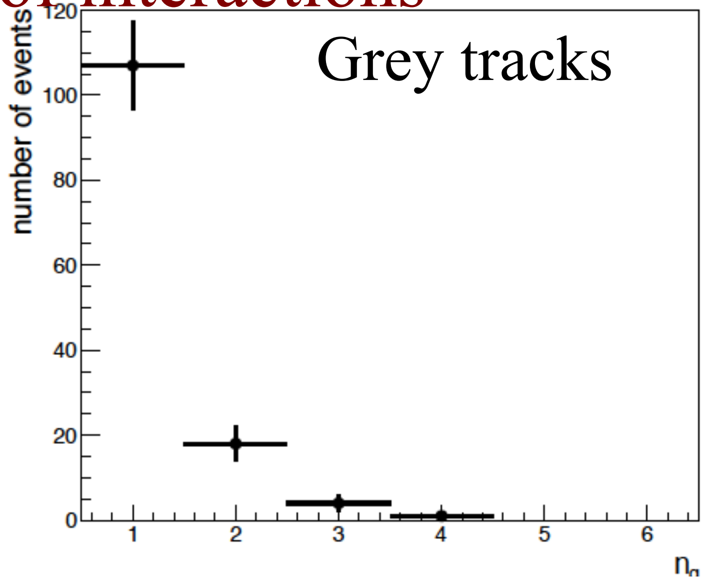
MULTIPLICITY STUDIES IN NEUTRINO–LEAD SCATTERING

Track multiplicity distributions

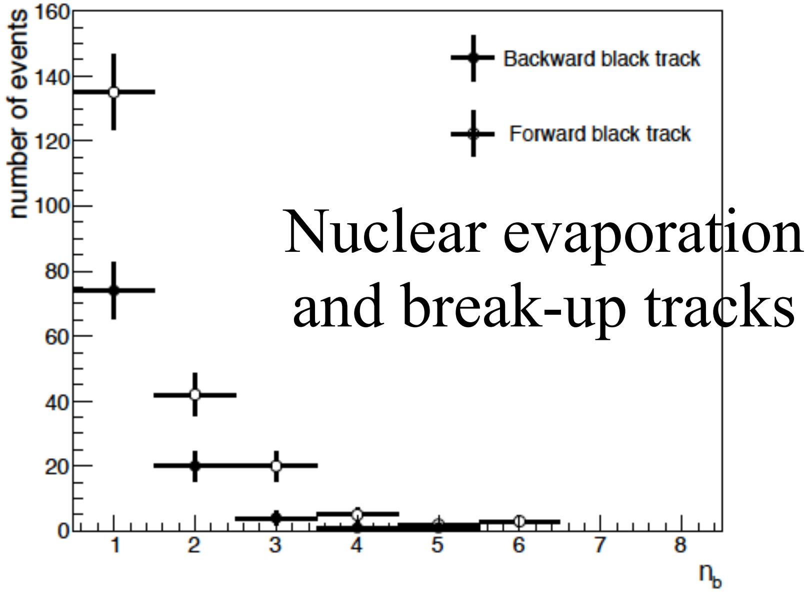
reflecting the dynamics of interactions



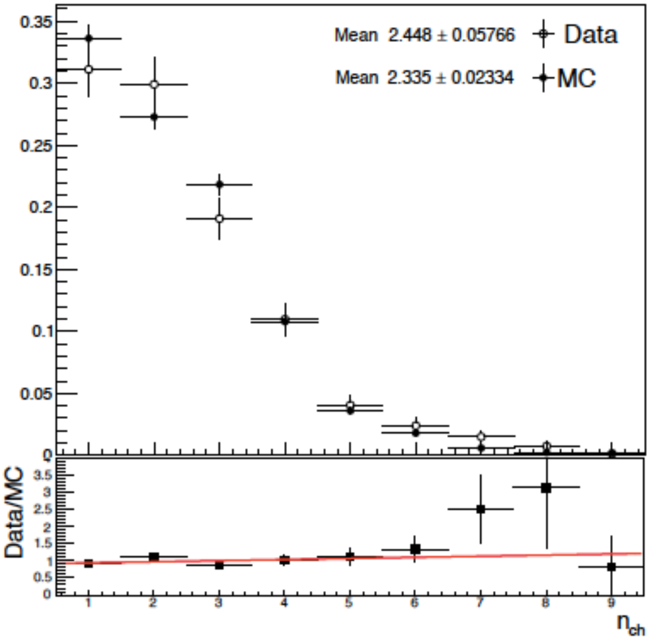
Shower tracks



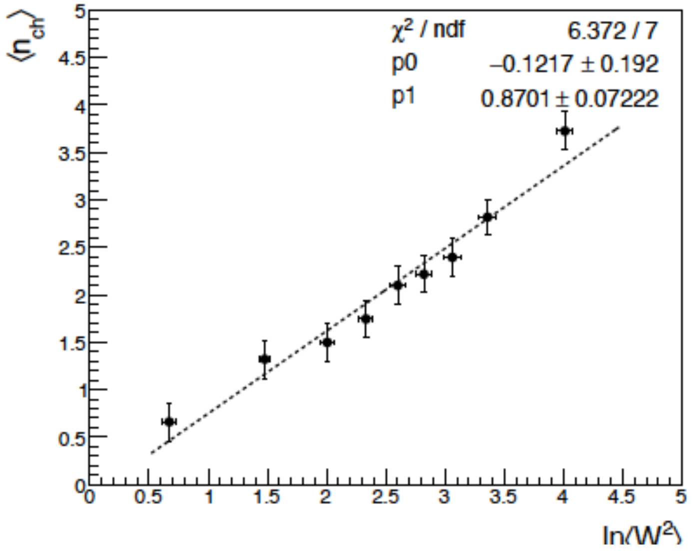
Grey tracks

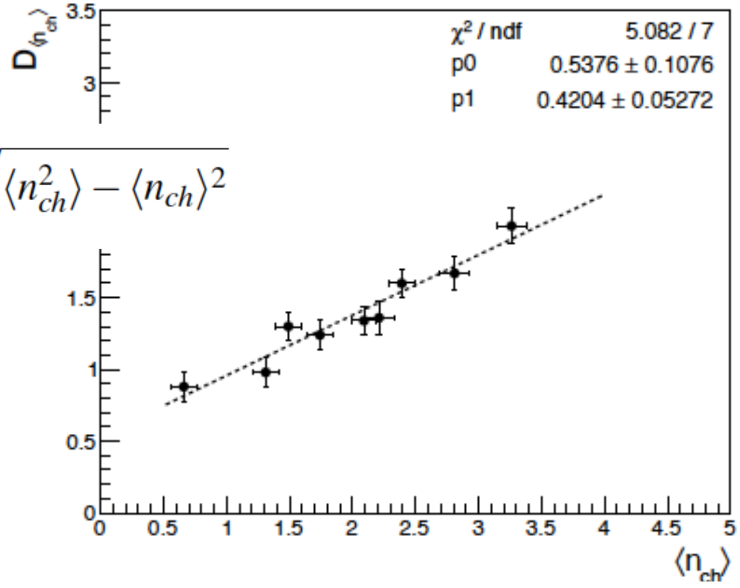


Nuclear evaporation and break-up tracks



Multiplicity features



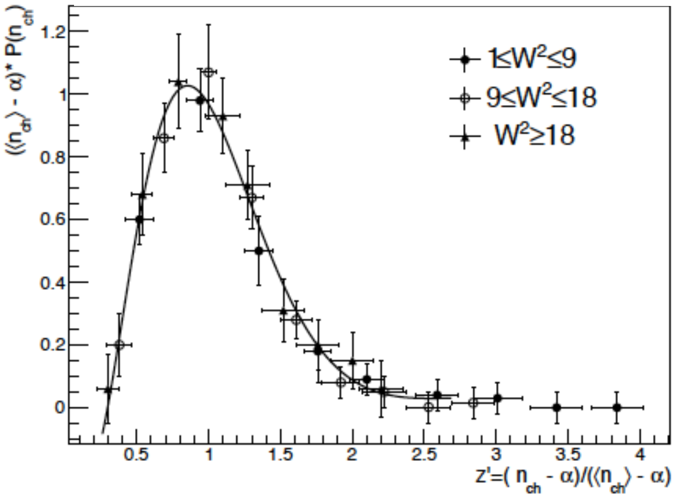


$$D_{ch} = \sqrt{\langle n_{ch}^2 \rangle - \langle n_{ch} \rangle^2}$$

Reaction	E_ν (GeV)	a	b	Ref.
ν_μ-emulsion	40	0.45± 0.24	0.94± 0.08	[5]
ν_μ-emulsion	50	1.92 ± 0.68	1.19± 0.23	[6]
ν_μ-emulsion	8.7	1.07 ± 0.05	1.32± 0.11	[7]
ν_μ-Lead	20	-0.12 ± 0.19	0.87± 0.07	OPERA

Reaction	A	B	Ref.
ν_μ-emulsion	1.18± 0.17	0.20± 0.05	[5]
ν_μ-p	0.36 ± 0.03	0.36± 0.03	[4]
ν_μ-Lead	0.53 ± 0.10	0.42± 0.05	OPERA

KNO Scaling

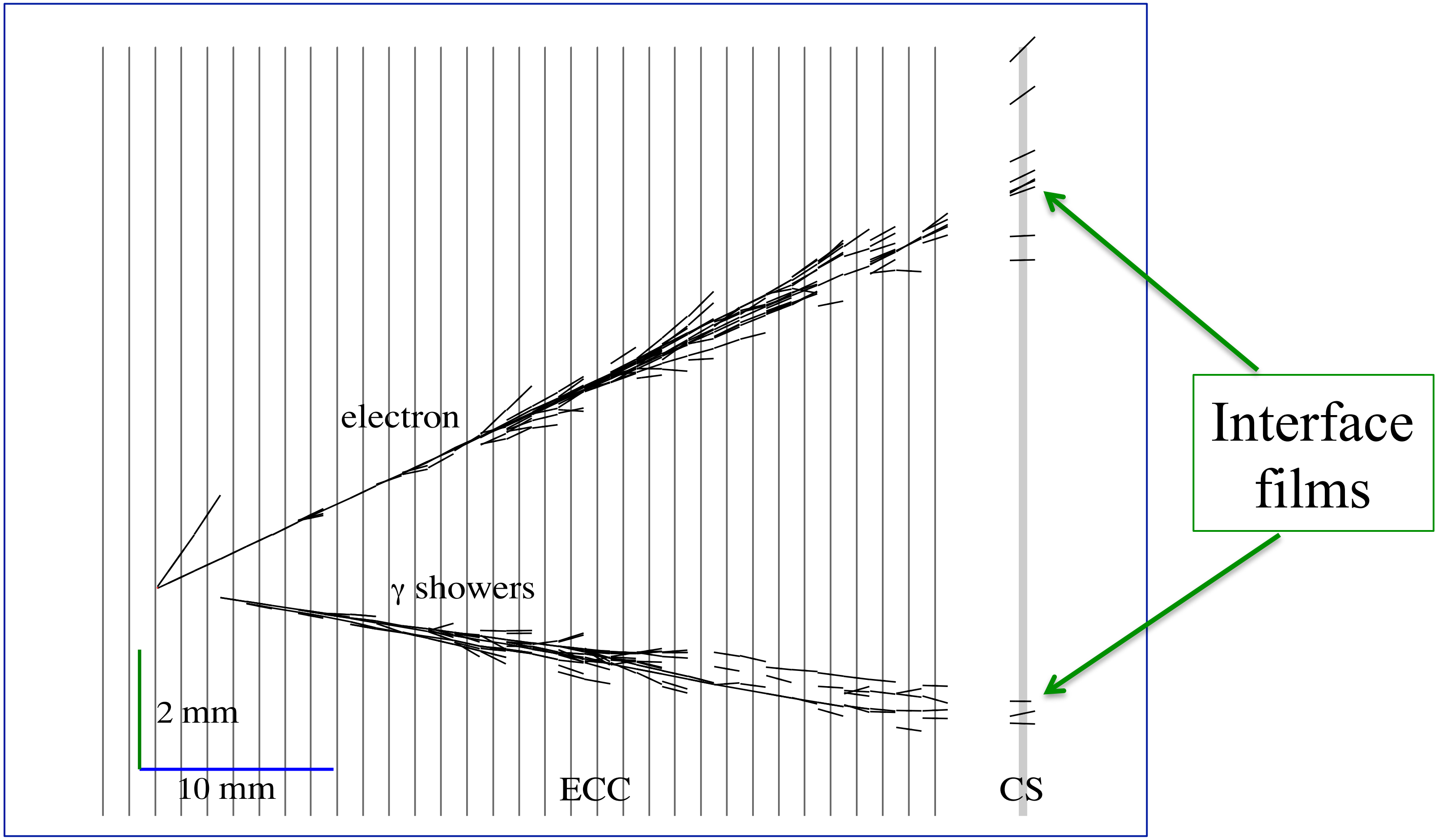


OSCILLATION PHYSICS

- $\nu_\mu \rightarrow \nu_e$ ANALYSIS
- $\nu_\mu \rightarrow \nu_\tau$ ANALYSIS

Electron neutrinos

one event with a π^0 as seen in the brick

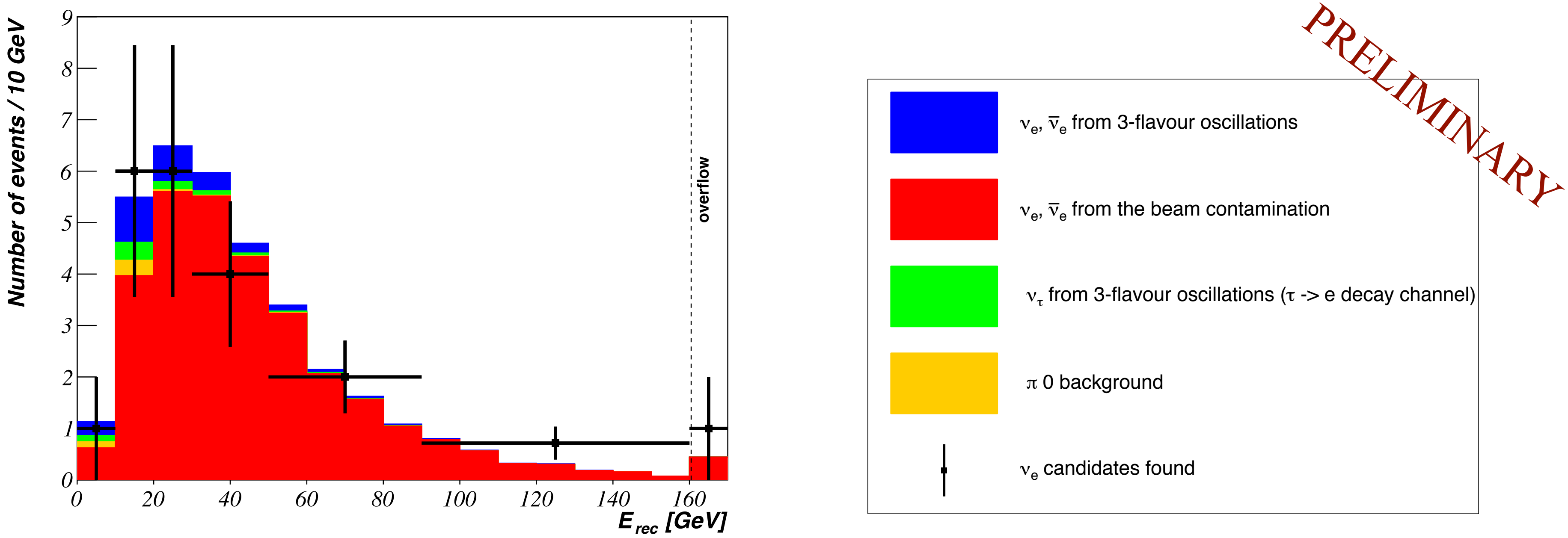


Interface films

35 candidates in the full data sample

Electron neutrino energy

Energy cut, GeV	10	20	30	40	50	No cut
ν_e, $\bar{\nu}_e$ from the beam contamination	0.6	4.6	10.2	15.7	20.0	30.8
π^0	0.1	0.4	0.5	0.5	0.5	0.5
ν_τ from 3-flavour oscillations ($\tau \to e$ channel)	0.1	0.5	0.6	0.7	0.8	0.9
Total expected BG	0.8	5.5	11.3	16.9	21.3	32.2
ν_e, $\bar{\nu}_e$ from 3-flavour oscillations	0.3	1.1	1.8	2.3	2.4	2.7
Expected spectrum in case of 3 flavour oscillations	1.1	6.6	13.1	19.2	23.7	34.9
Data	1	7	13	19	21	35



STERILE NEUTRINO SEARCH

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

~standard oscillation

Exotic oscillation

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

Interference term

$$\left\{\begin{aligned} &+ 0.5\, C \ \sin 2\theta_{\mu e} \ \cos \phi_{\mu e} \ \sin 2\Delta_{31} \ \sin 2\Delta_{41} \\ &- C \ \sin 2\theta_{\mu e} \ \sin \phi_{\mu e} \ \sin^2 \Delta_{31} \ \sin 2\Delta_{41} \\ &+ 2\, C \ \sin 2\theta_{\mu e} \ \cos \phi_{\mu e} \ \sin^2 \Delta_{31} \ \sin^2 \Delta_{41} \\ &+ C \ \sin 2\theta_{\mu e} \ \sin \phi_{\mu e} \ \sin 2\Delta_{31} \ \sin^2 \Delta_{41} \end{aligned}\right.$$

$$C = 2|U_{\mu 3} U_{e3}^*|$$

$$\Delta_{ij} = \frac{1.27 \Delta m_{ij}^2 L}{E}$$

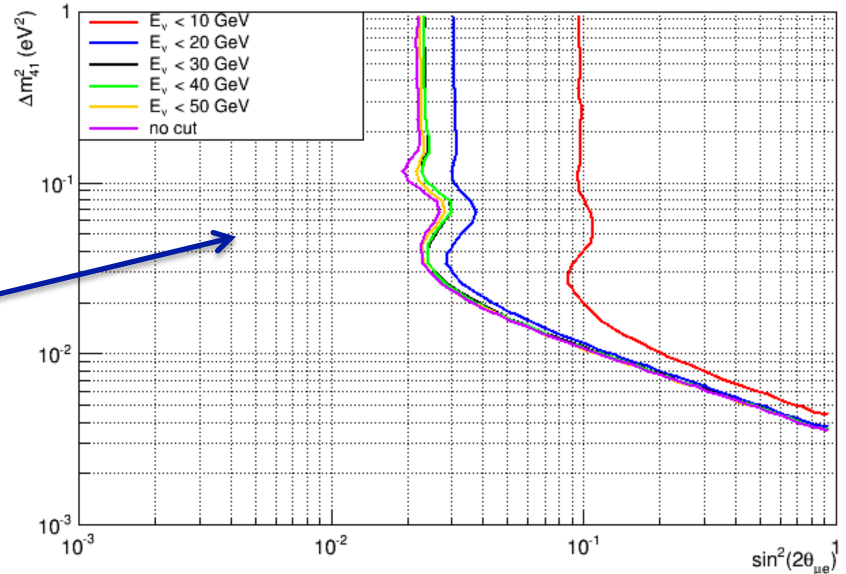
$$\phi_{\mu e} = Arg(U_{\mu 3} U_{e3}^* U_{\mu 4}^* U_{e4})$$

$$\sin^2 2\vartheta_{\mu e} = 4|U_{\mu 4}|^2 |U_{e4}|^2$$

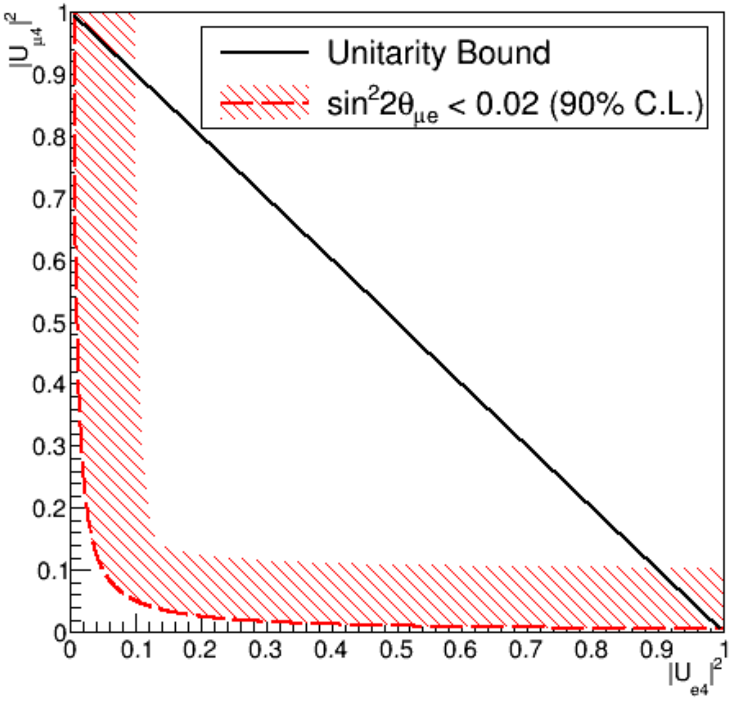
$$L = \prod_i Poisson(n_i; (1 + k_j) \cdot u_i) \times \prod_j Gauss(k_j; 0, \sigma_j) \times Gauss(\Delta m_{23}^2; \widehat{\Delta m_{23}^2}, \sigma_{\Delta m_{23}^2})$$

Energy distribution to constrain the parameter space: shape analysis

Sensitivity curves vs energy cut



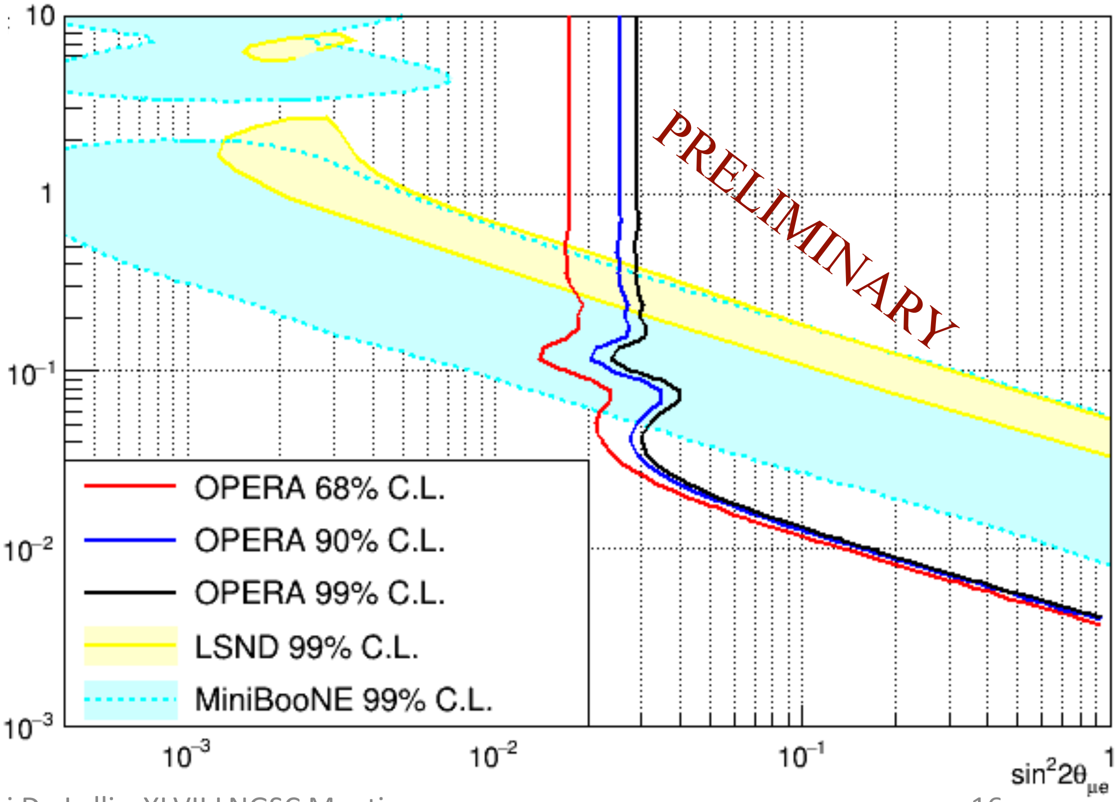
CONSTRAINING STERILE NEUTRINOS WITH A 3+1 MODEL



$$\sin^2 2\vartheta_{\mu e} = 4|U_{\mu 4}|^2|U_{e4}|^2$$

First sterile neutrino search in a long baseline with $\nu_\mu \rightarrow \nu_e$ and a 3+1 model

2 flavour approx. invalid at CNGS baselines



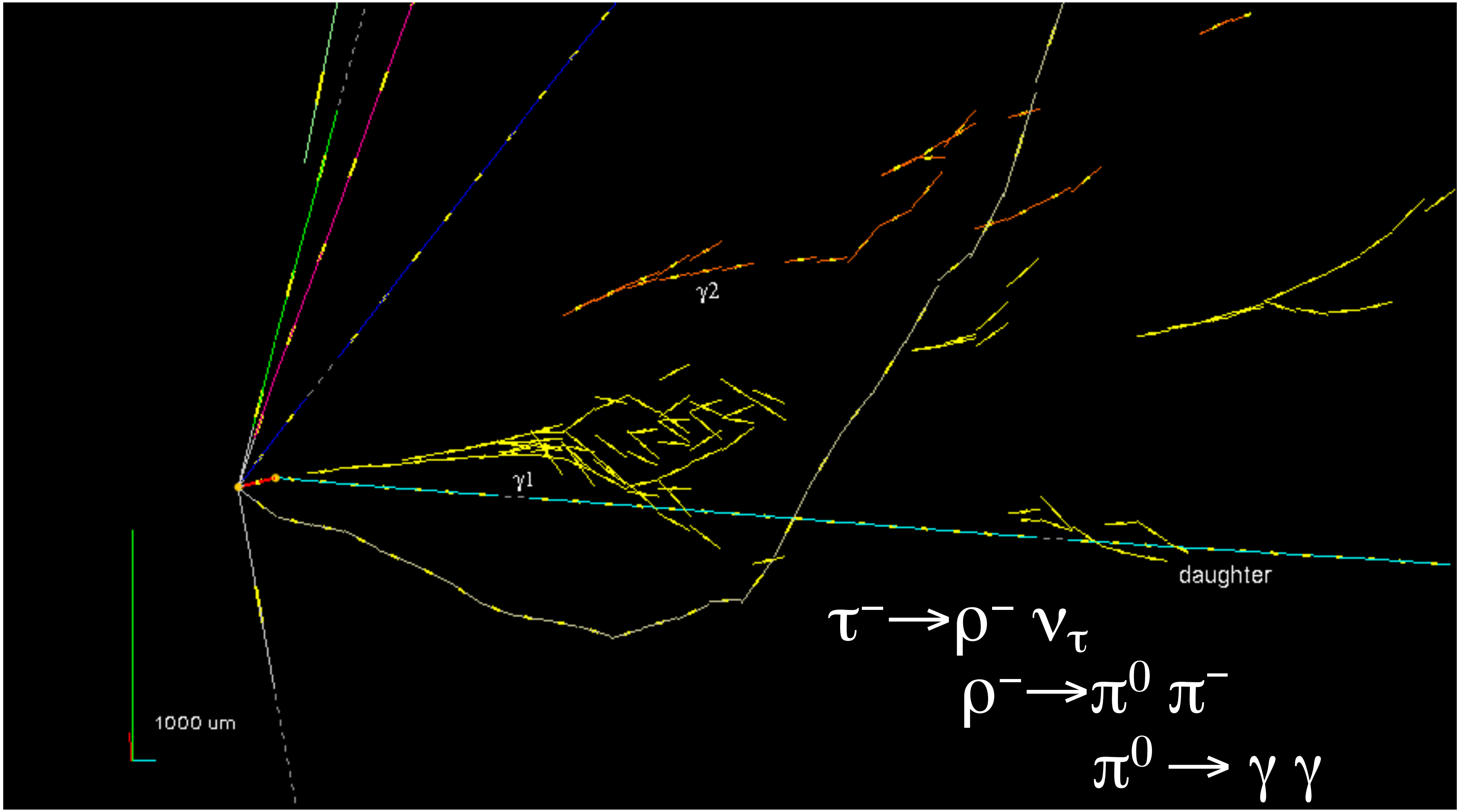
$\nu_\mu \rightarrow \nu_\tau$ ANALYSIS

$\nu_\mu \rightarrow \nu_\tau$ ANALYSIS STRATEGY

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

THE FIRST ν_τ CANDIDATE

in the brick



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

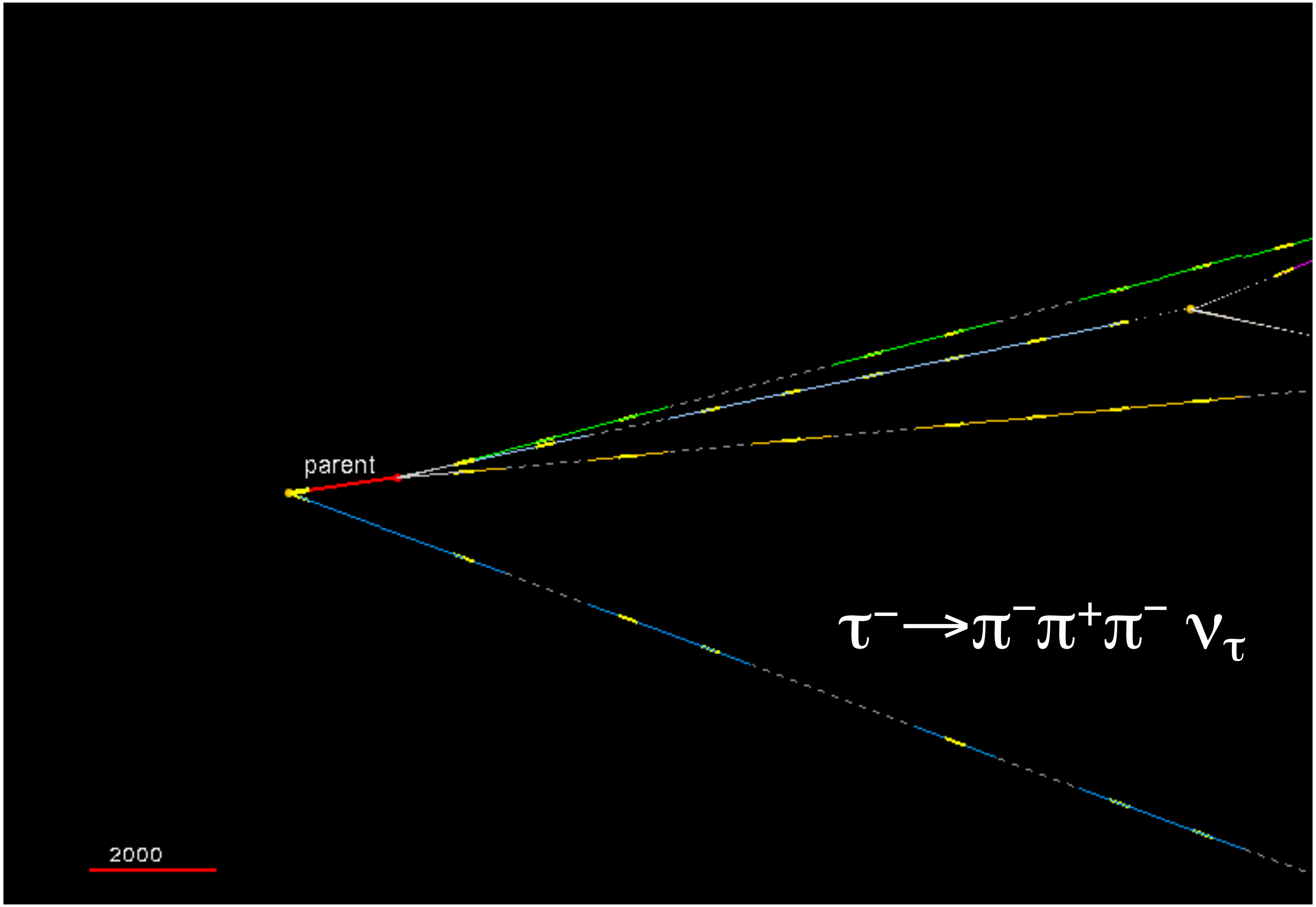
$\rho^- \rightarrow \pi^0 \, \pi^-$

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

Physics Letters B691 (2010) 138

THE SECOND ν_τ CANDIDATE

in the brick

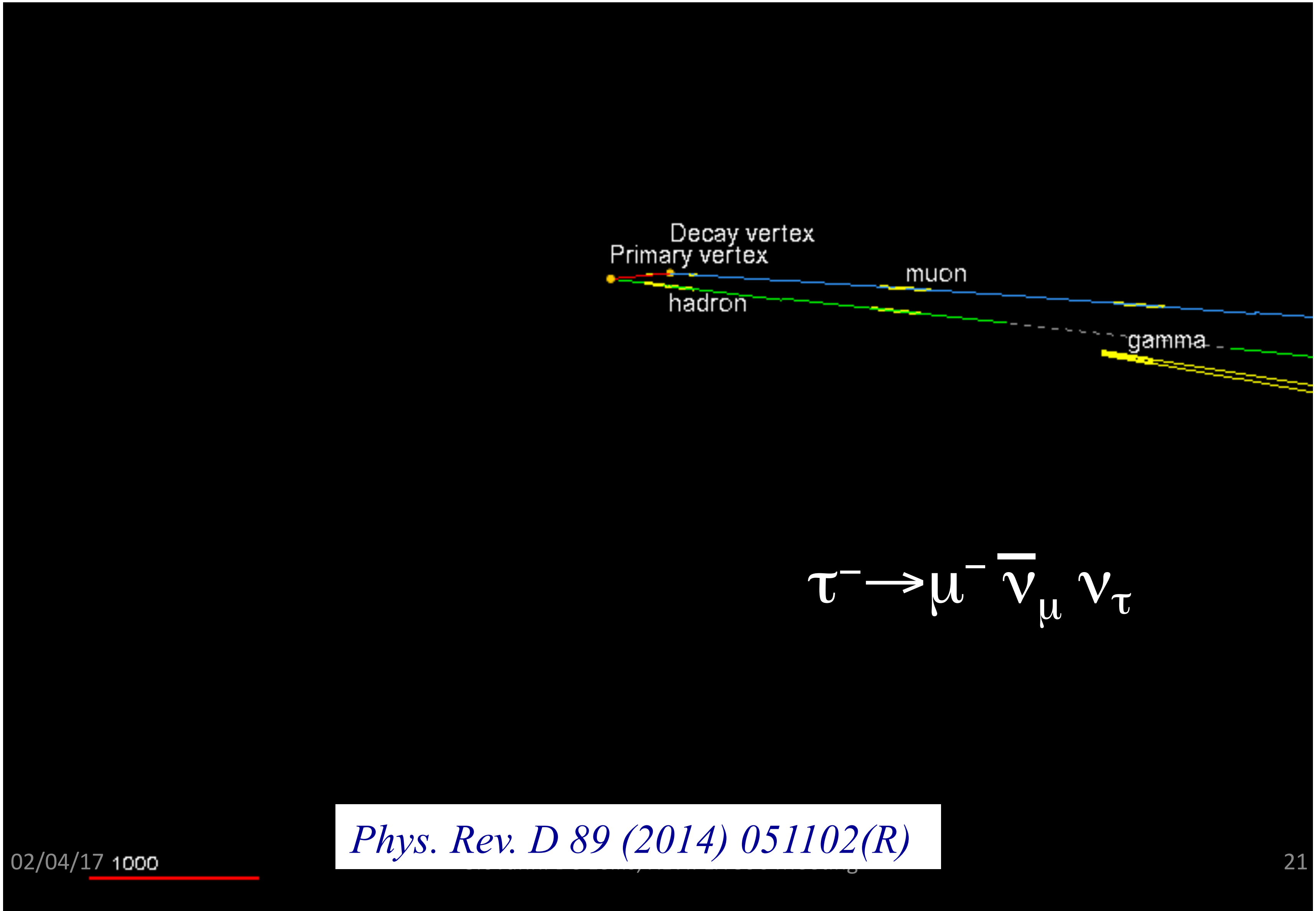


$\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$

Journal of High Energy Physics 11 (2013) 036

THE THIRD ν_τ CANDIDATE

in the brick

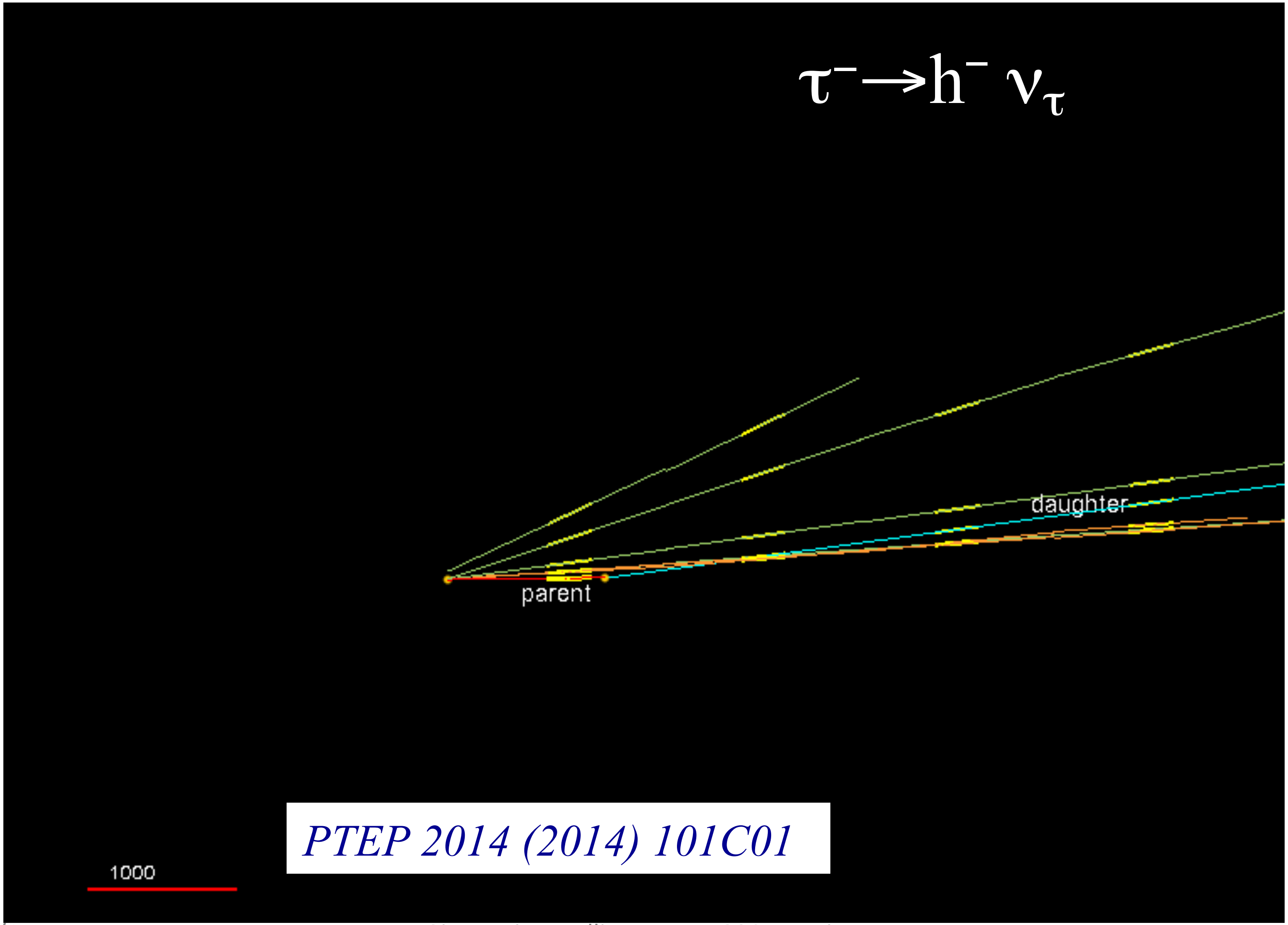


$$\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$$

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

THE FORTH ν_τ CANDIDATE

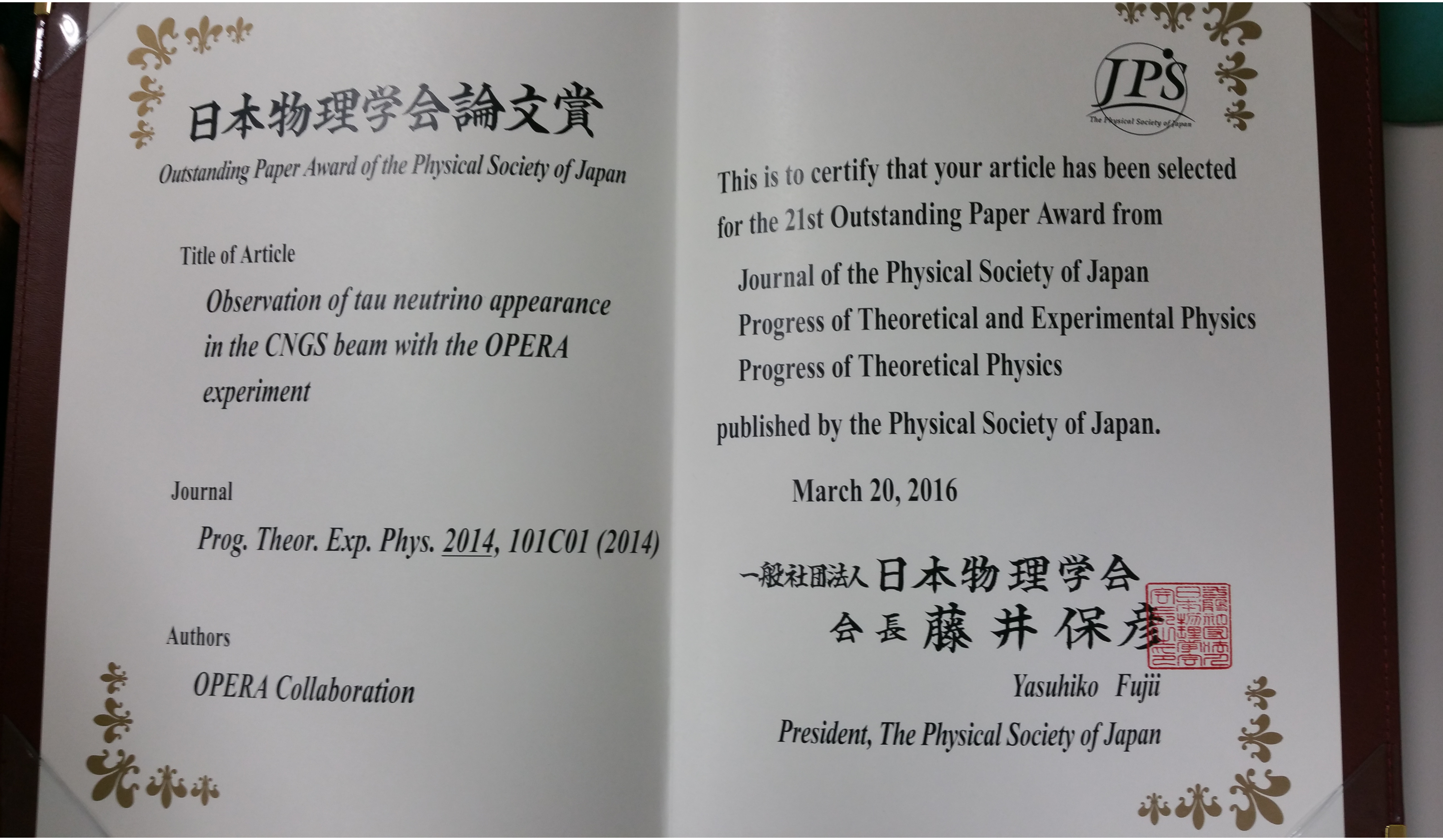
in the brick



$\tau^- \rightarrow h^- \nu_\tau$

PTEP 2014 (2014) 101C01

OUTSTANDING PAPER AWARD BY THE PHYSICAL SOCIETY OF JAPAN



日本物理学会論文賞

Outstanding Paper Award of the Physical Society of Japan

Title of Article

Observation of tau neutrino appearance in the CNGS beam with the OPERA experiment

Journal

Prog. Theor. Exp. Phys. 2014, 101C01 (2014)

Authors

OPERA Collaboration

This is to certify that your article has been selected for the 21st Outstanding Paper Award from

Journal of the Physical Society of Japan
Progress of Theoretical and Experimental Physics
Progress of Theoretical Physics

published by the Physical Society of Japan.

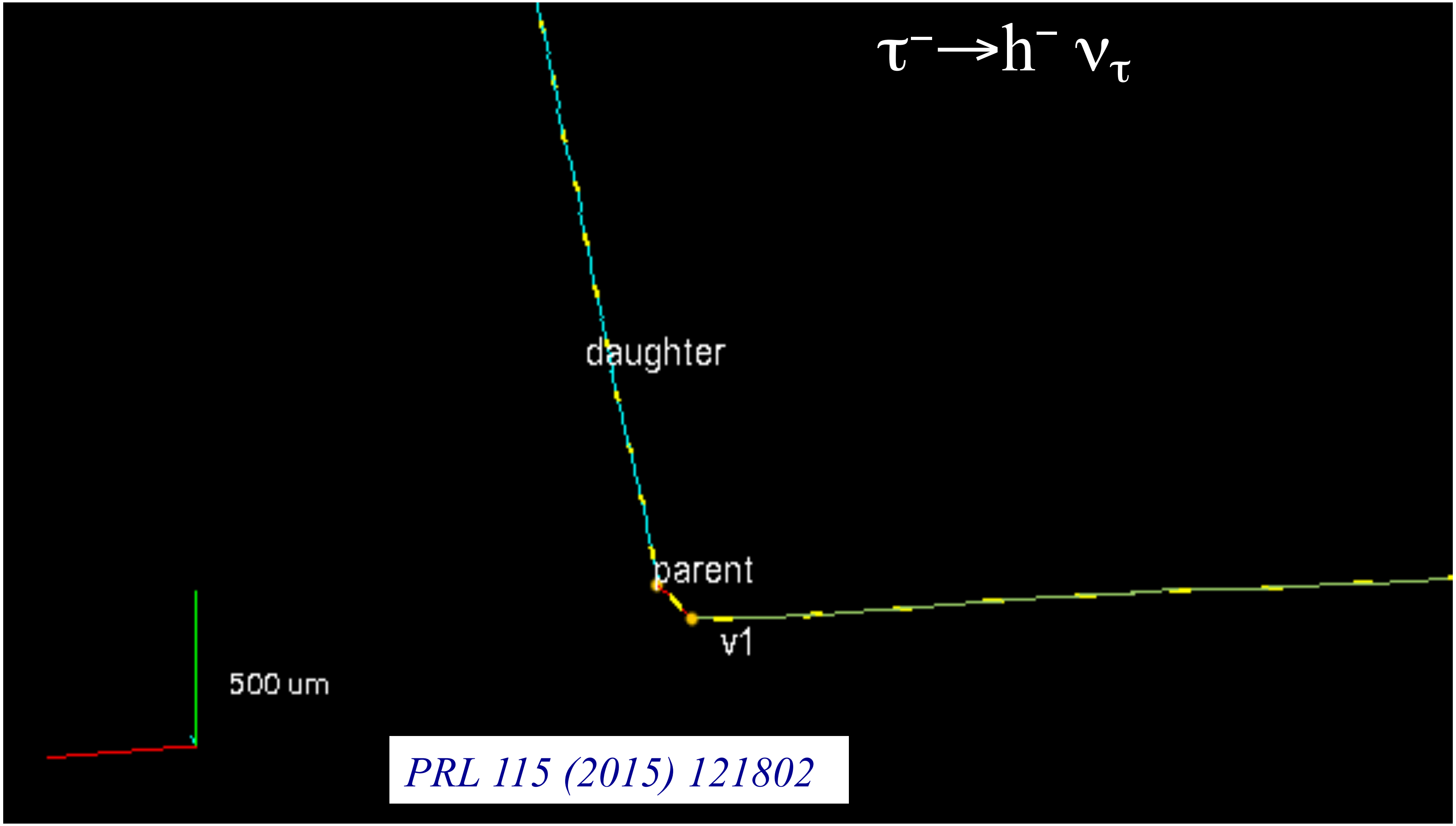
March 20, 2016

一般社団法人日本物理学会
会長 藤井保彦

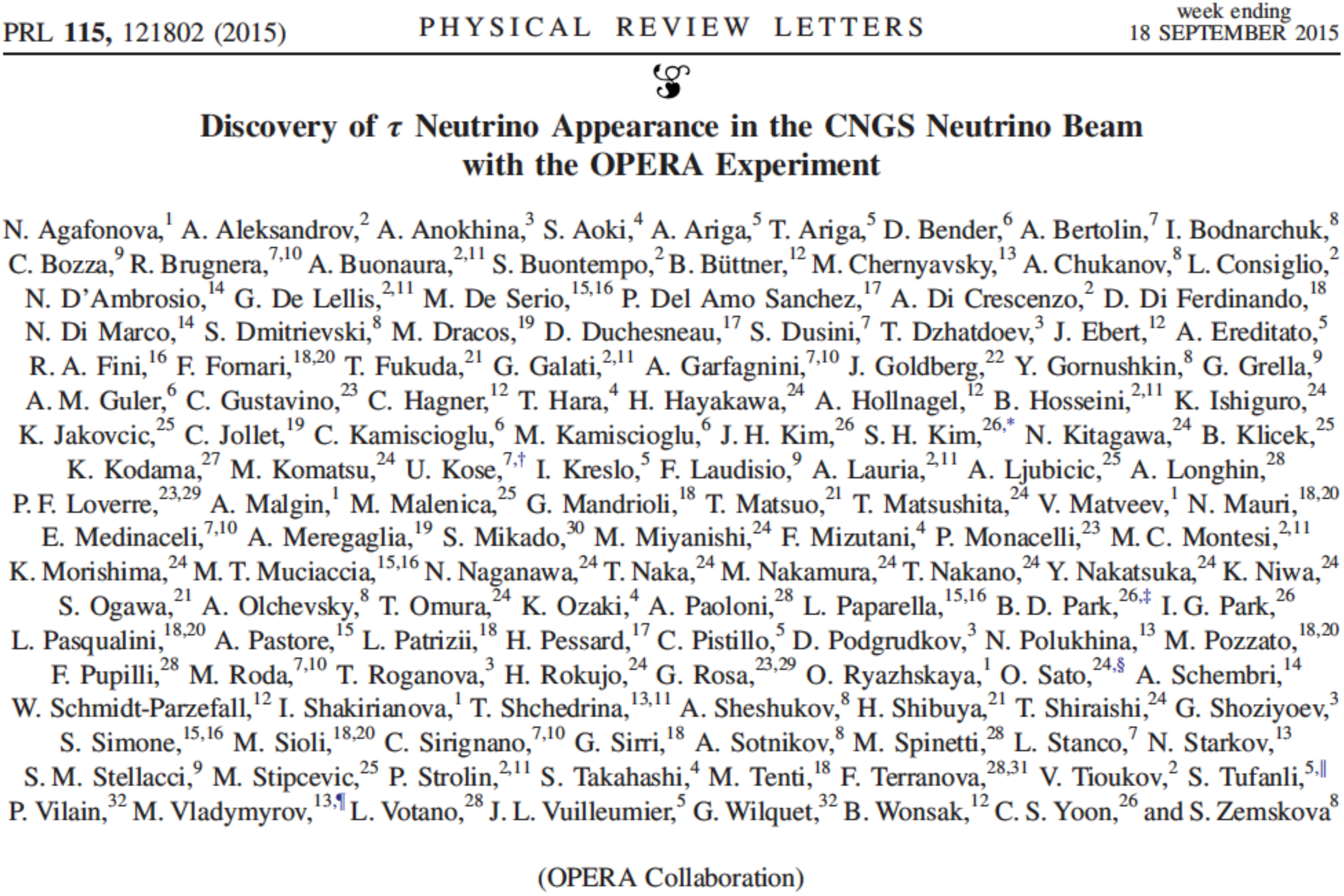
Yasuhiko Fujii
President, The Physical Society of Japan

THE FIFTH ν_τ CANDIDATE

in the brick



PRL 115 (2015) 121802



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

NEW EVENT ANALYSIS

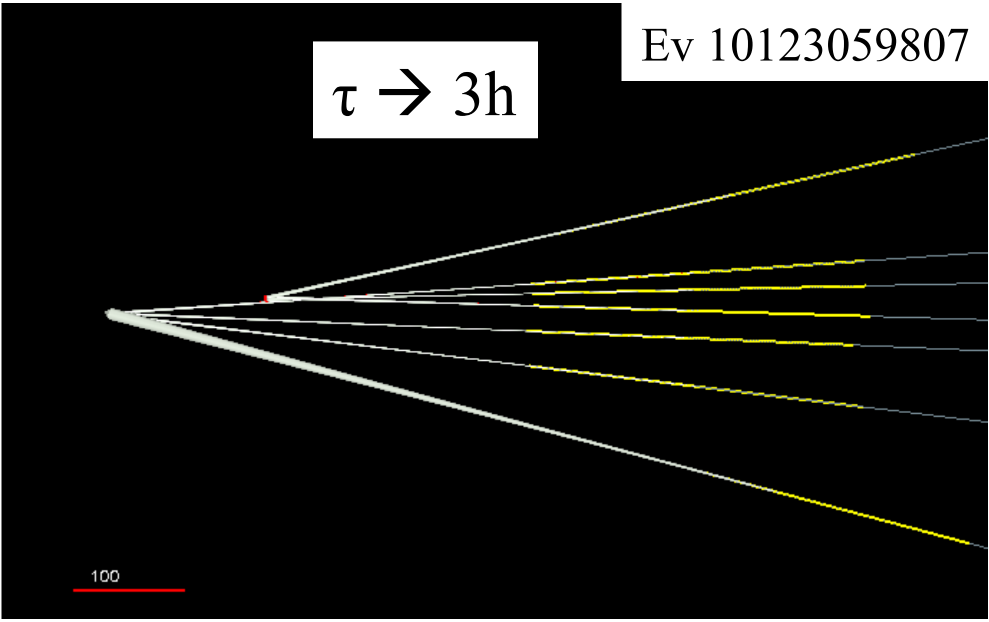
- Widen selection cuts to increase the statistics
- Candidate identification mostly topological with looser kinematical cuts
- Statistical gain to reduce uncertainties
- Use likelihood approach, simulation fully validated with data in all kinematical corners

NEW SELECTION

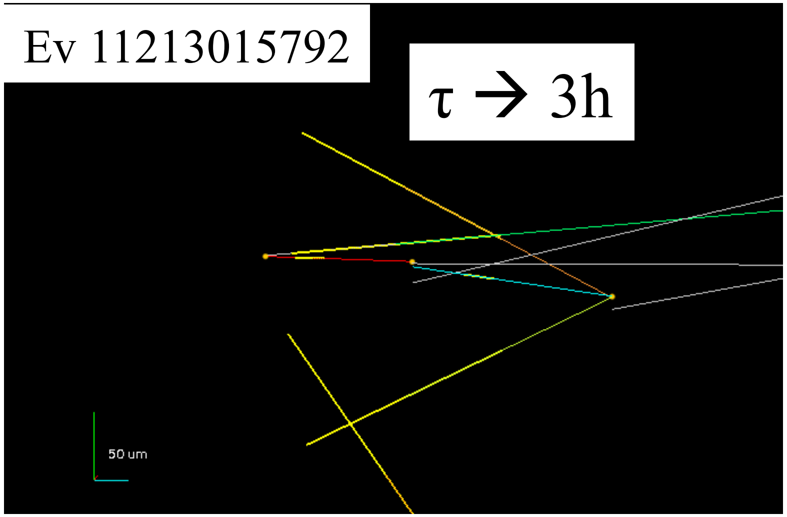
Variable	$\tau \to 1h$		$\tau \to 3h$		$\tau \to \mu$		$\tau \to e$	
	OLD	NEW	OLD	NEW	OLD	NEW	OLD	NEW
z_{dec} (μm)	$[44, 2600]$	<2600	<2600		$[44, 2600]$	<2600	<2600	
θ_{kink} (rad)	>0.02		<0.5	>0.02	>0.02		>0.02	
p_{2ry} (GeV/c)	>2	>1	>3	>1	$[1, 15]$		$[1, 15]$	>1
p_{2ry}^{T} (GeV/c)	$>0.6\,(0.3)$	>0.15	/		>0.25	>0.1	>0.1	
p_{miss}^{T} (GeV/c)	<1	/	<1	/	/		/	
ϕ_{lH} (rad)	$>\pi/2$	/	$>\pi/2$	/	/		/	
m, m_{min} (GeV/c^2)	/		$[0.5, 2]$	/	/		/	

Channel	**Expected Background**				**Expected Signal**	**Total Expected**
	Charm	Had. re-interaction	Large μ-scat.	Total		
$\tau \to 1h$	0.15	1.28	–	1.43	2.82	4.25
$\tau \to 3h$	0.44	0.09	–	0.52	1.75	2.27
$\tau \to \mu$	0.008	–	0.02	0.03	1.09	1.12
$\tau \to e$	0.035	–	–	0.03	0.80	0.83
Total	0.63	1.37	0.02	2.0 ± 0.5	6.5 ± 1.3	8.5 ± 1.8

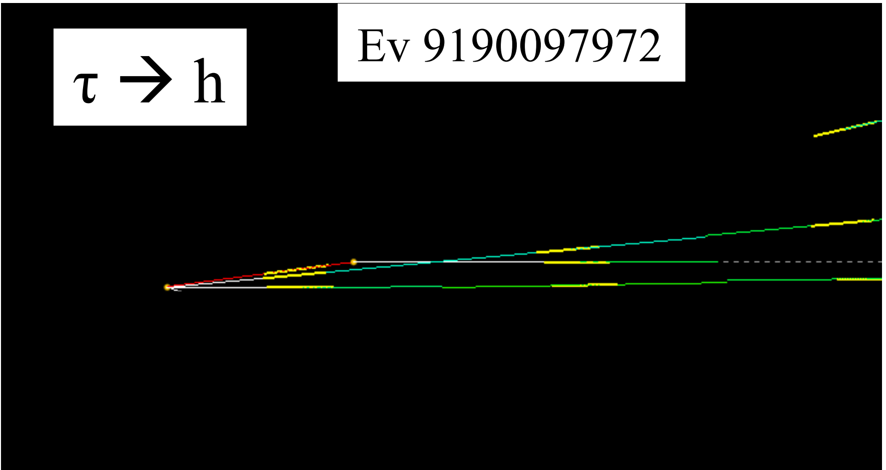
NEW TAU NEUTRINO CANDIDATES


Ev 10123059807

τ → 3h


Ev 11213015792

τ → 3h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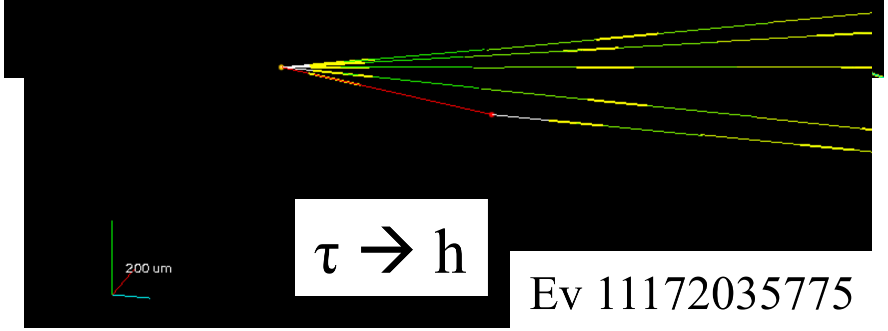
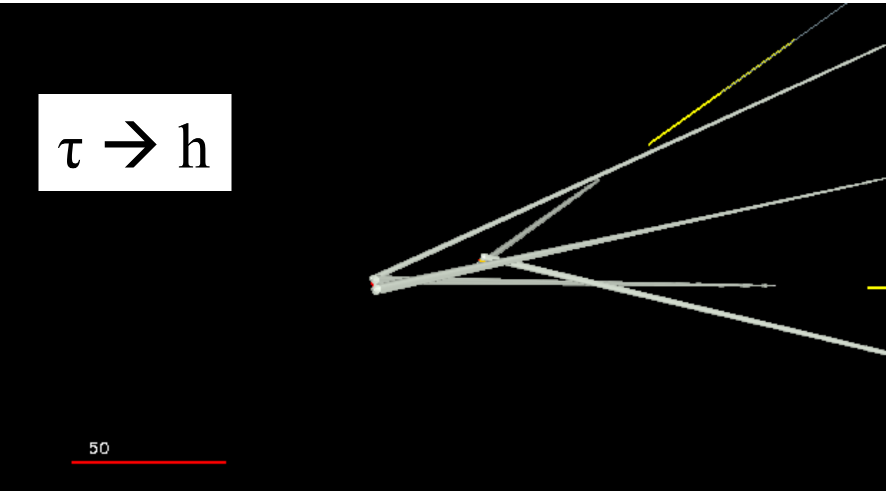
τ → h


τ → h

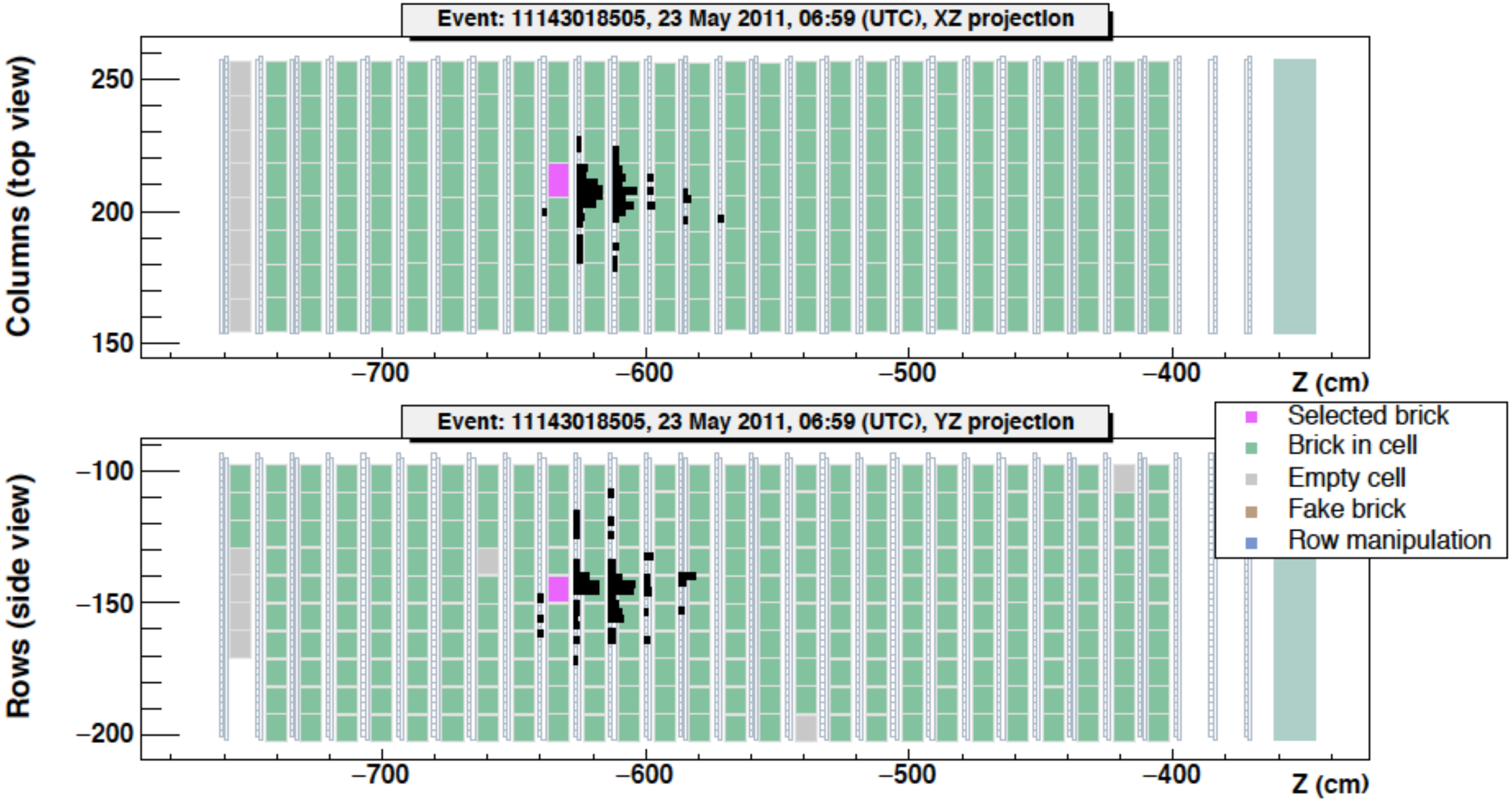
Ev 11172035775

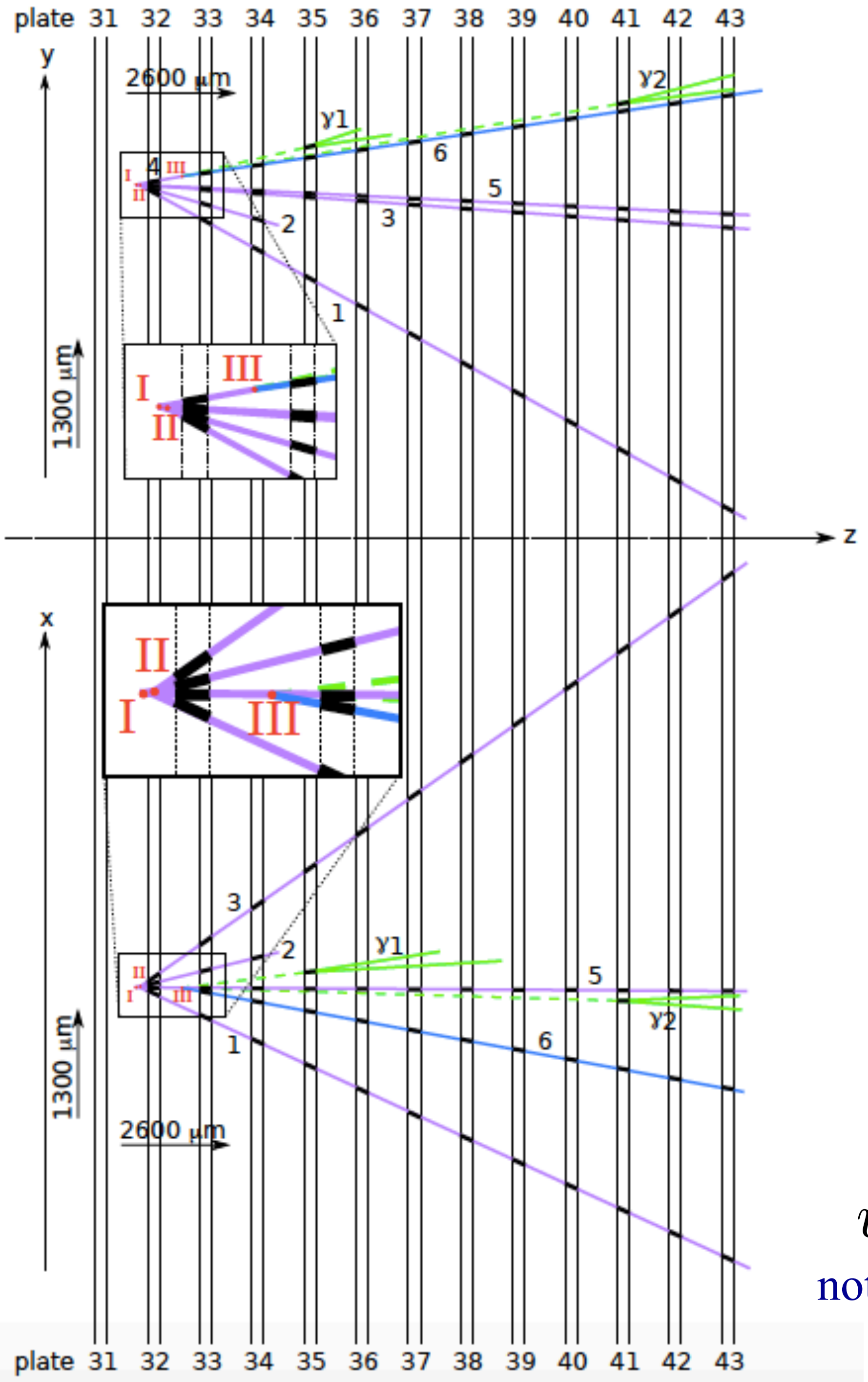
Ev 11143018505


τ → h

A CLOSER LOOK AT ONE OF THESE EVENTS

An event with Three vertices Without Any Muon in the final state



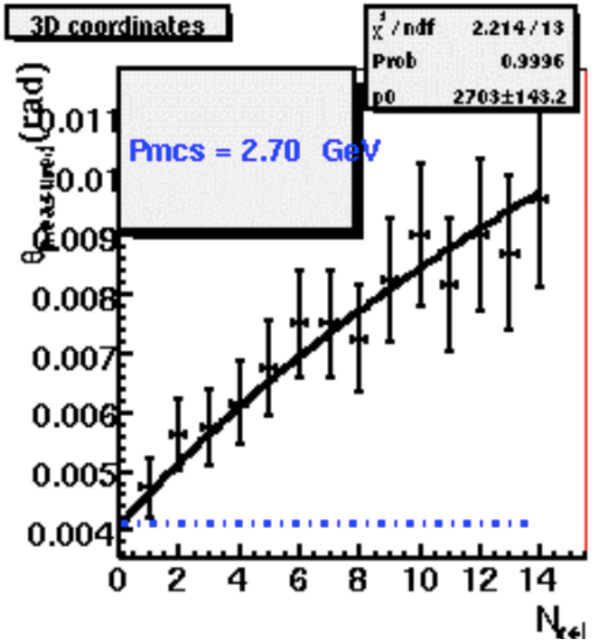


KINK TOPOLOGY

Flight Length = 1160 µm

With γ attached

IP = 8±8 µm

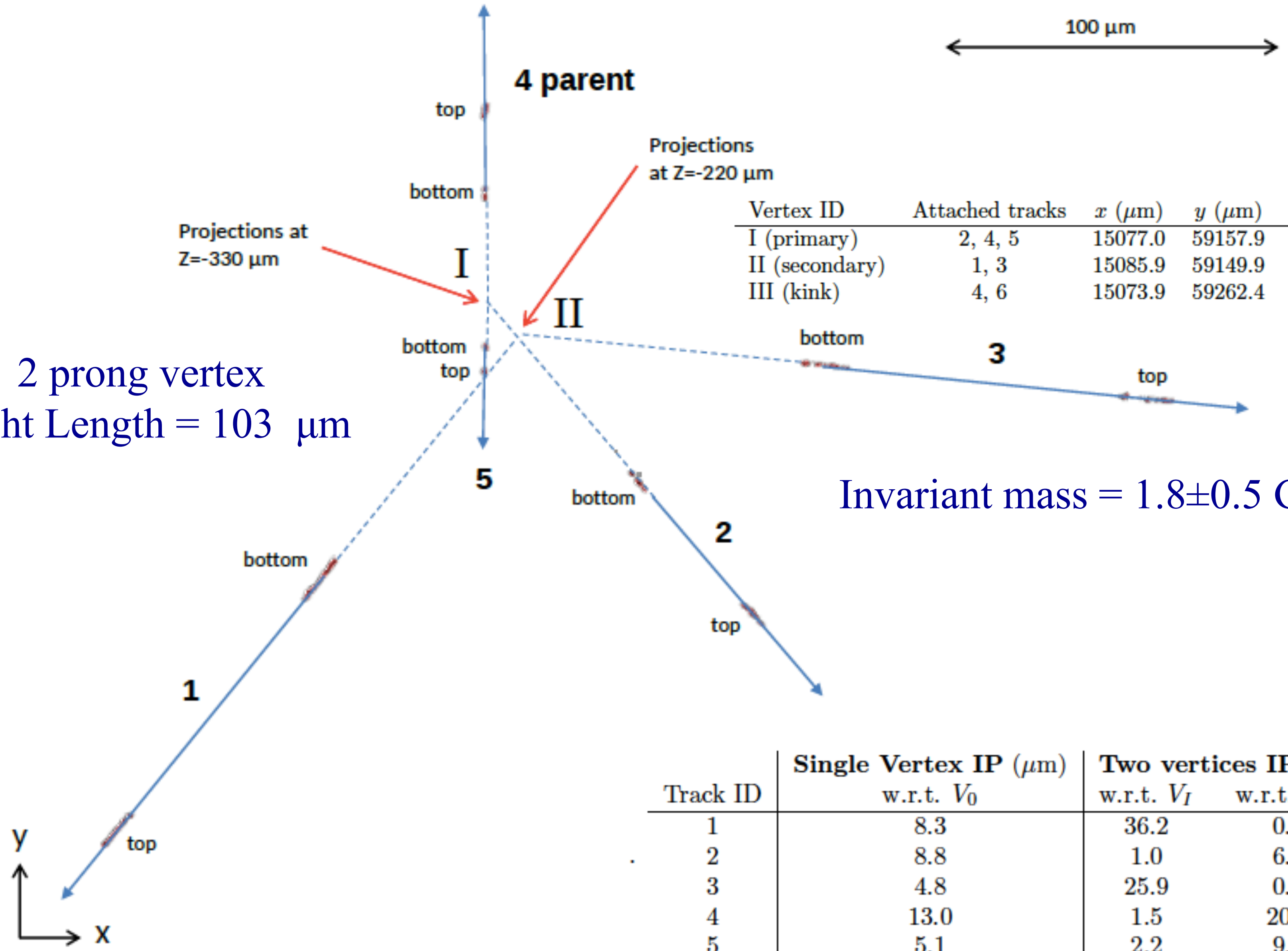


Track ID	p best fit (GeV/c)	68 % p range (GeV/c)
1	2.1	[1.6 ; 3.1]
3	4.3	[3.1 ; 7.1]
5	0.54	[0.45 ; 0.68]
6 (daughter)	2.7	[2.1 ; 3.7]

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

not passing the standard cuts to be a tau candidate

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



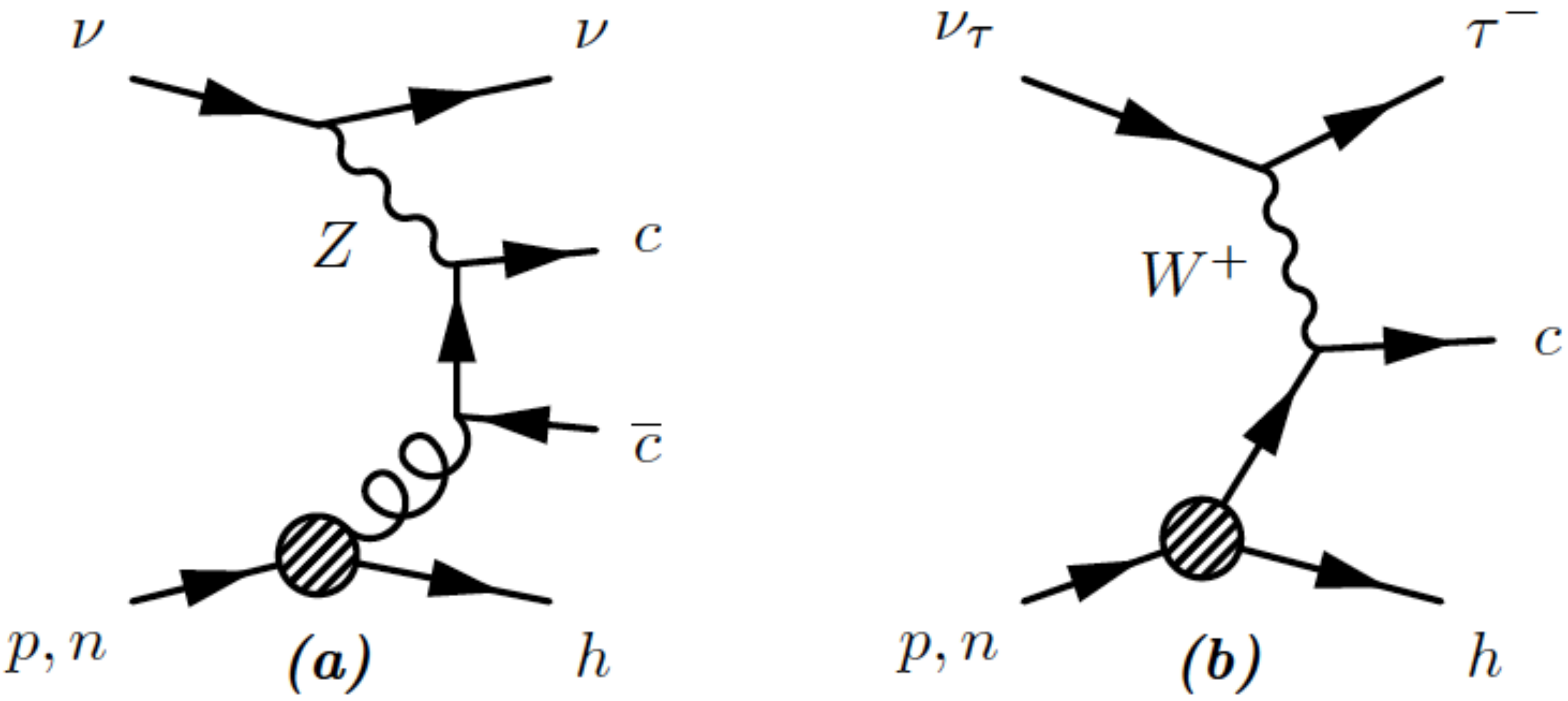
Vertex ID	Attached tracks	x (μm)	y (μm)	z (μm)
I (primary)	2, 4, 5	15077.0	59157.9	-33081.8
II (secondary)	1, 3	15085.9	59149.9	-32979.2
III (kink)	4, 6	15073.9	59262.4	-31926.4

2 prong vertex
Flight Length = 103 µm

Invariant mass = 1.8±0.5 GeV

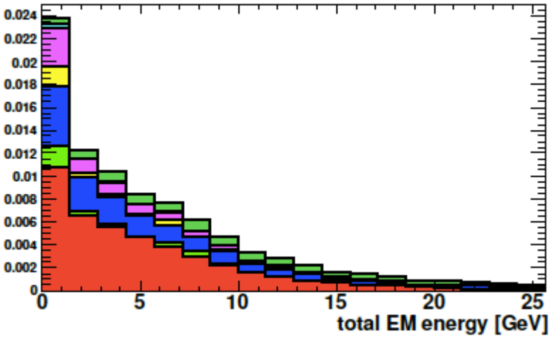
Track ID	**Single Vertex IP** (μm)	**Two vertices IP** (μm)	
	w.r.t. V_0	w.r.t. V_I	w.r.t. V_{II}
1	8.3	36.2	0.1
2	8.8	1.0	6.5
3	4.8	25.9	0.1
4	13.0	1.5	20.4
5	5.1	2.2	9.6

Leading Feynman diagrams

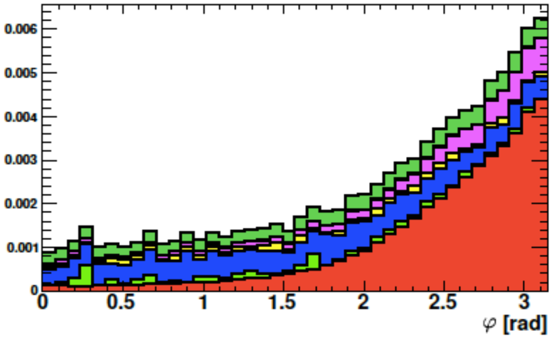


Expected yield and multivariate analysis

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

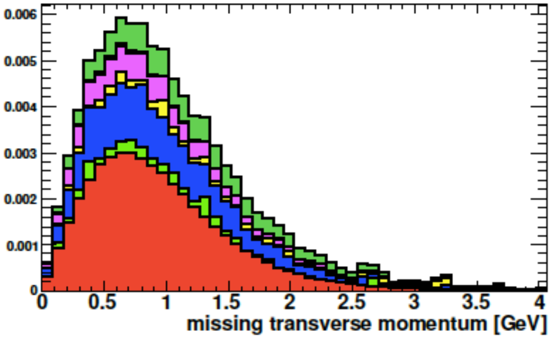


(a) Total EM energy

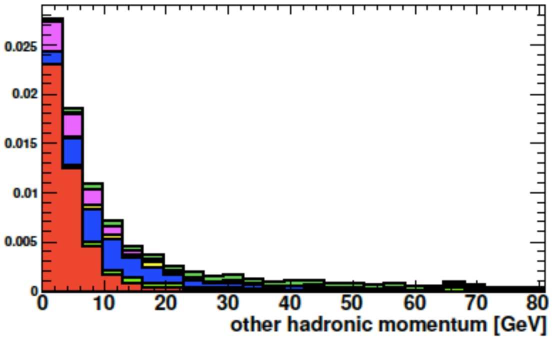


(b) φ

PRELIMINARY



(c) Missing transverse momentum

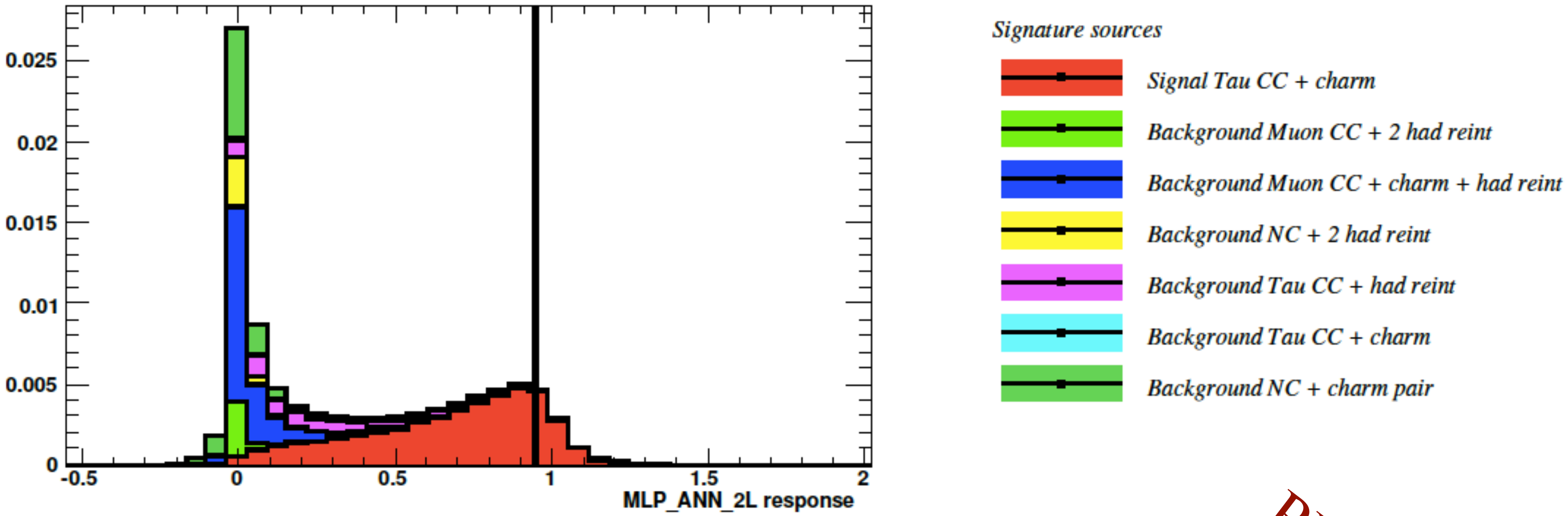


(d) Other hadronic momentum

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 output



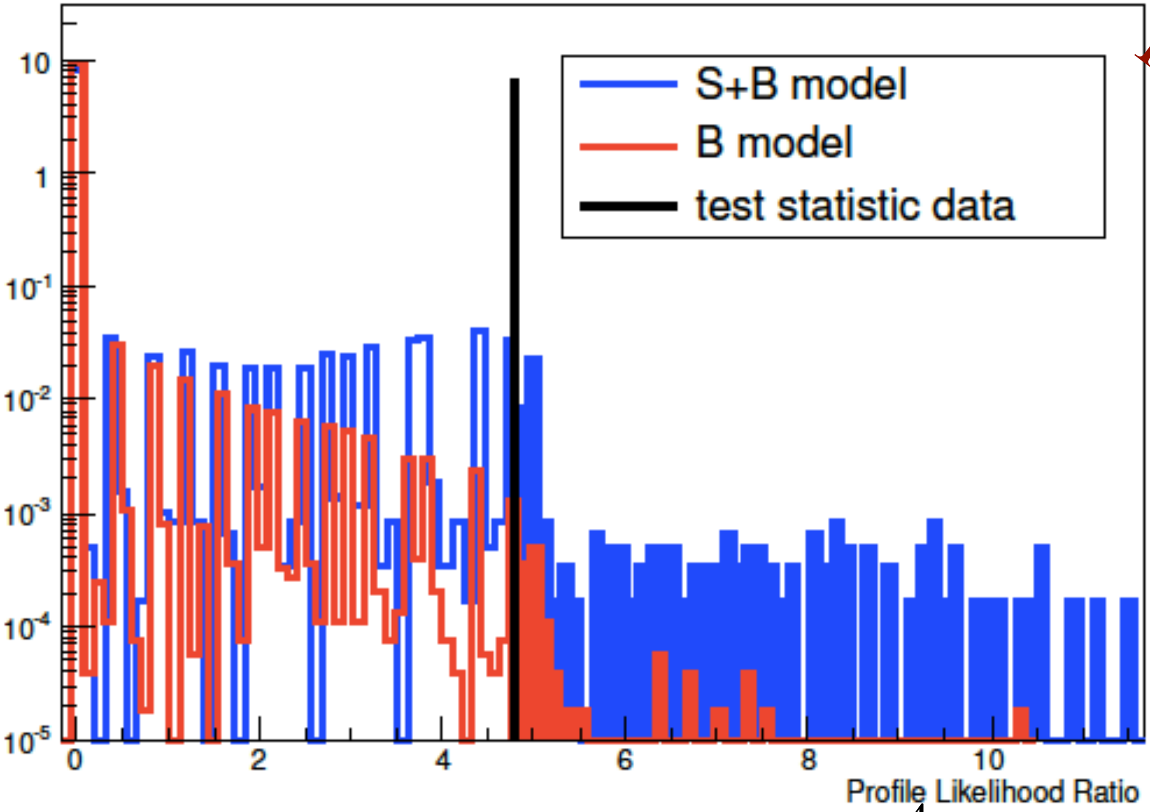
PRELIMINARY

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**

Observation of a tau neutrino interaction with a charmed hadron production

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

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



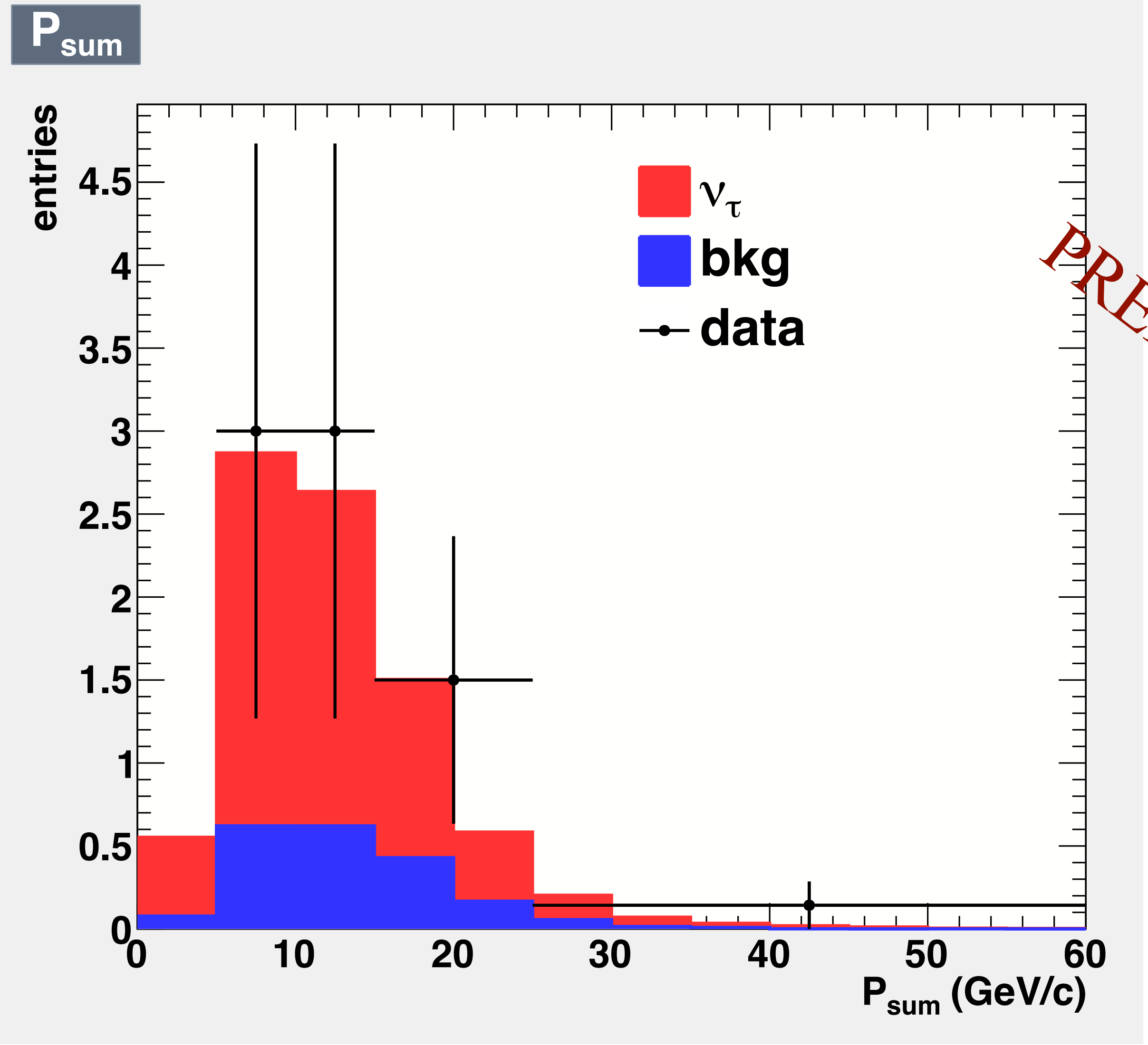
PRELIMINARY

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

ANALYSIS OF THE EXTENDED SAMPLE

VISIBLE ENERGY OF ALL CANDIDATES

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

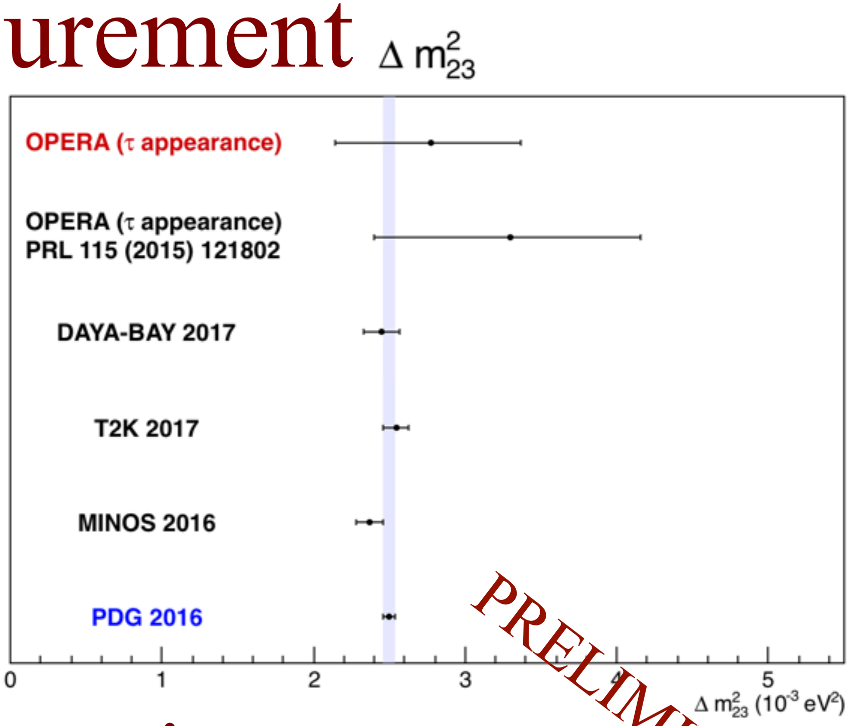


PRELIMINARY

Δm^2 measurement

$$N_{\nu_\tau} \propto P(\nu_\mu \to \nu_\tau)\sigma_{\nu_\tau}$$

Expected Signal	Expected Background	Observed ν_τ	Δm^2_{23} $(10^{-3}\ \mathrm{eV}^2)$
6.5	2.0	10	$2.8^{+0.6}_{-0.6}$ 68% C.L



ν_τ cross-section

$$\sigma_{\nu_\tau} = \sigma^0_{\nu_\tau} E K(E)$$

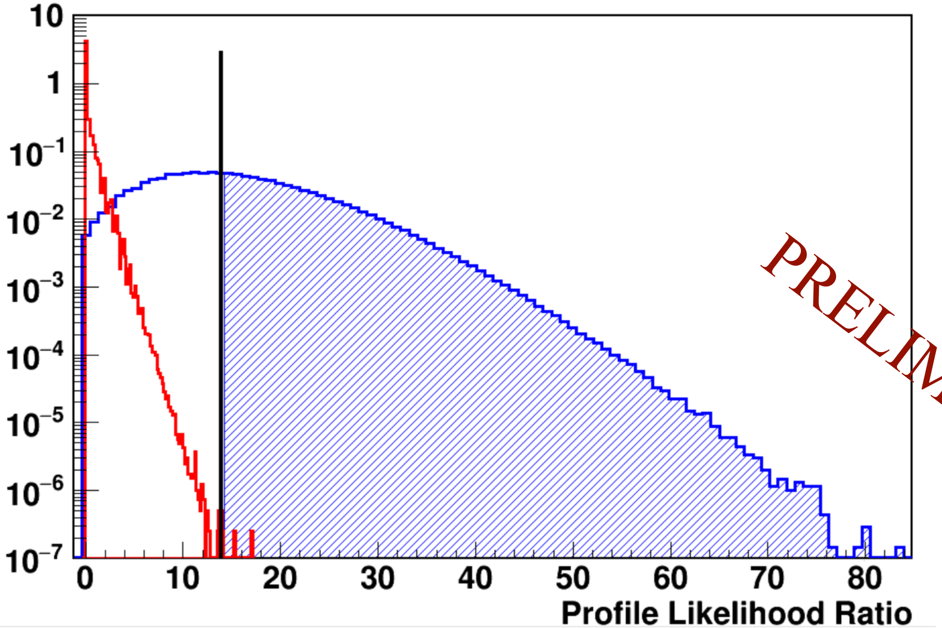
Δm^2_{23} $(10^{-3}\ \mathrm{eV}^2)$	Expected Signal	Expected Background	Observed ν_τ	$\sigma^0_{\nu_\tau}$ $(10^{-39}\mathrm{cm}^2\mathrm{GeV}^{-1})$
2.5	6.5	2.0	10	8^{+4}_{-3}

SM value $\sigma^0_{\nu_\tau} = 6.7 \times 10^{-39}\ \mathrm{cm}^2\ \mathrm{GeV}^{-1}$

Significance of the tau neutrino appearance

using 8 channels

Channel	**Expected Background**				**Expected Signal**	Observed
	Charm	Had. re-interaction	Large μ-scat.	Total		
$\tau \to 1h$	0.023	0.024	–	0.047	0.57	3
	0.13	1.26	–	1.39	2.25	3
$\tau \to 3h$	0.21	0.003	–	0.21	1.1	1
	0.23	0.08	–	0.31	0.66	2
$\tau \to \mu$	0.003	–	0.0002	0.003	0.55	1
	0.005	–	0.016	0.021	0.54	0
$\tau \to e$	0.035	–	–	0.03	0.75	0
	0.0004	–	–	0.0004	0.04	0
Total	0.63	1.37	0.02	2.0 ± 0.5	6.5 ± 1.3	10



PRELIMINARY

Test statistic:

Profile likelihood ratio one sided

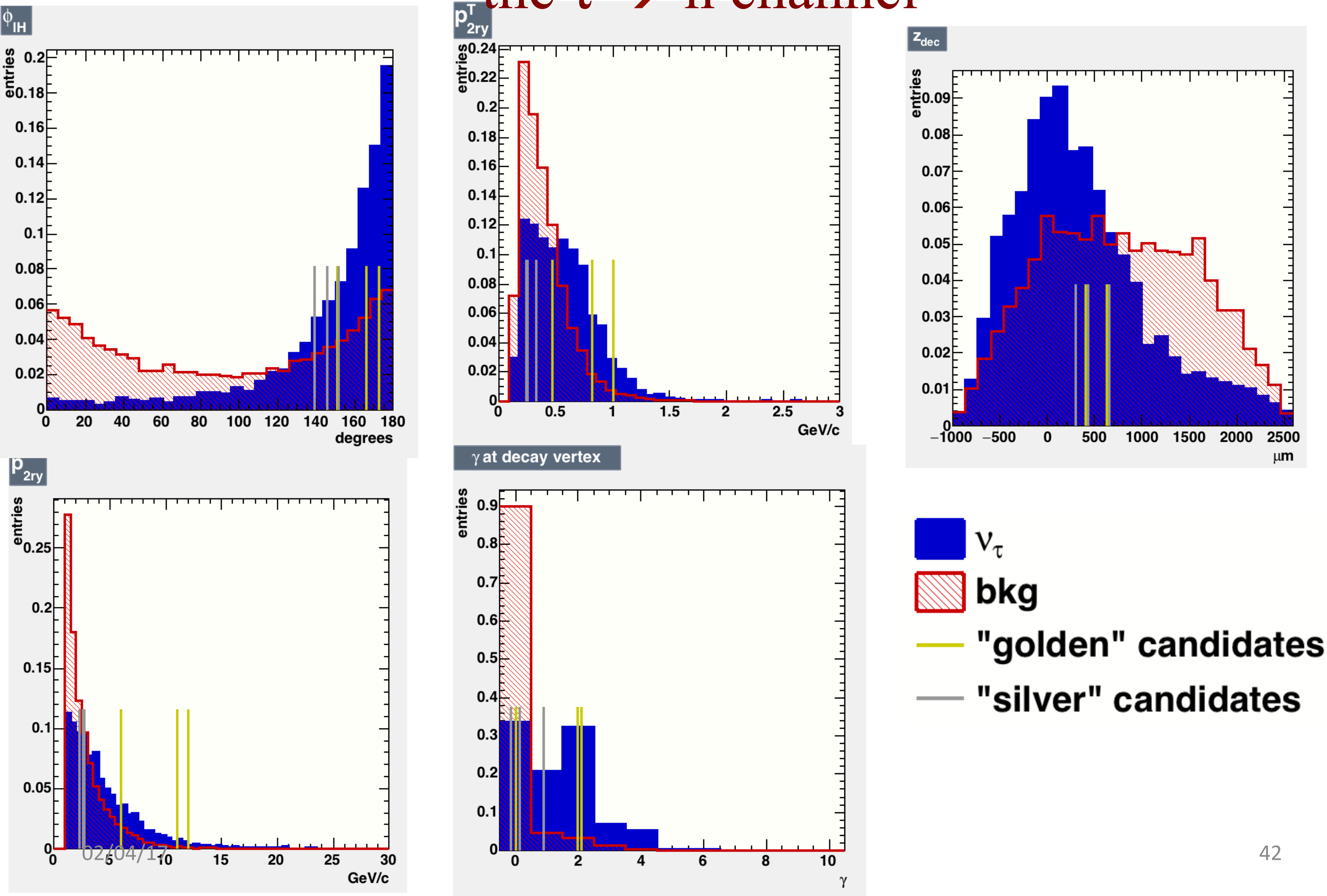
$$p_{\mathrm{value}} = 9.4 \times 10^{-8}$$

$5.2\,\sigma$ significance

90%CL interval on signal strength μ: [0.51, 2.6]

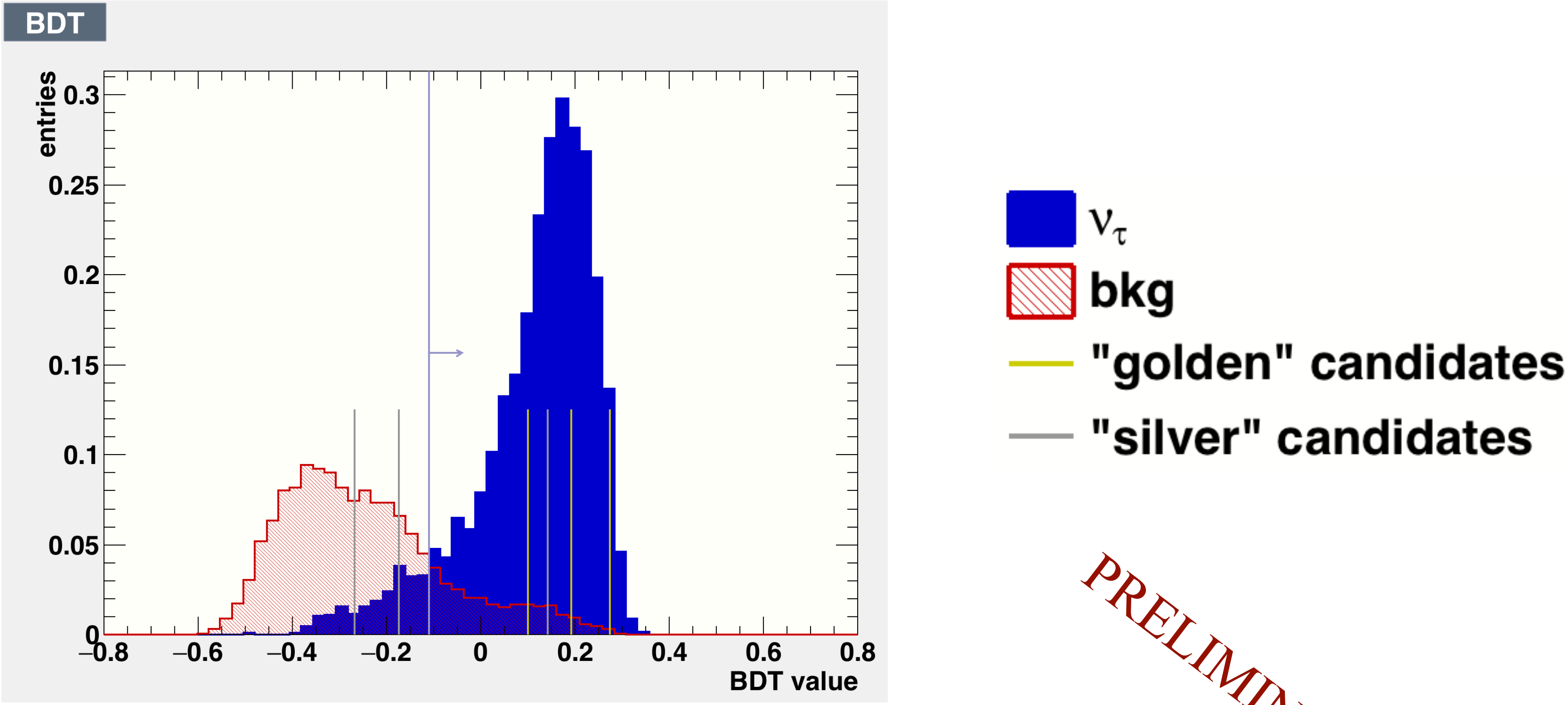
Input variables for BDT analysis

the $\tau \rightarrow$ h channel



BDT output

the $\tau \rightarrow h$ channel

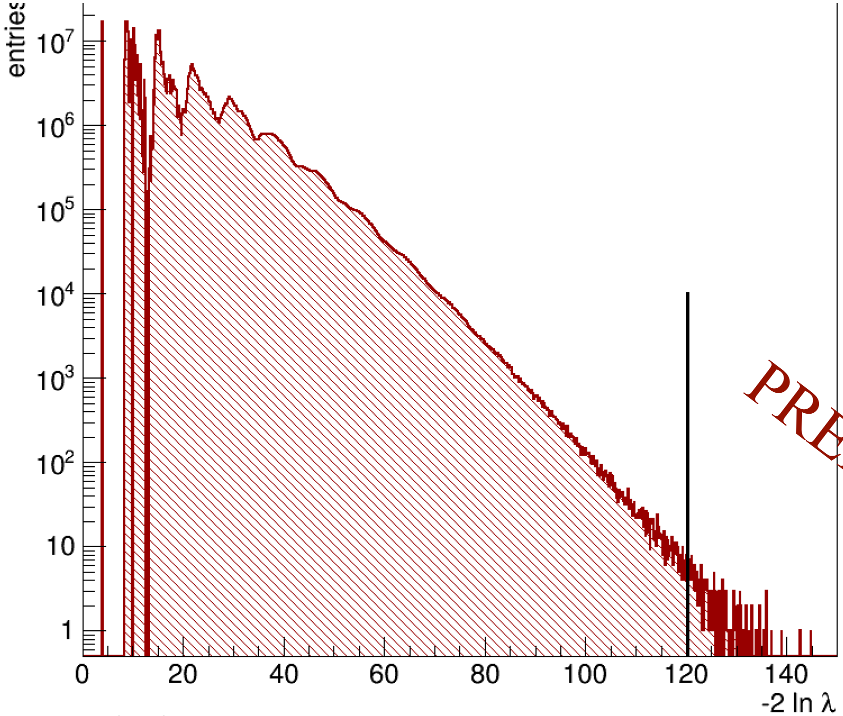


PRELIMINARY

Likelihood analysis with BDT discrimination

using 4 channels

Channel	**Expected Background**				**Expected Signal**	Observed
	Charm	Had. re-interaction	Large μ-scat.	Total		
$\tau \to 1h$	0.15	1.28	–	1.43	2.82	6
$\tau \to 3h$	0.44	0.09	–	0.52	1.75	3
$\tau \to \mu$	0.008	–	0.02	0.03	1.09	1
$\tau \to e$	0.035	–	–	0.03	0.80	0
Total	0.63	1.37	0.02	2.0 ± 0.5	6.5 ± 1.3	10



$$\mathcal{L} = \prod_{ch=1}^{4} \left(\frac{b_{ch}^{n_{ch}} e^{-b_{ch}}}{n_{ch}!} \cdot \prod_{i=1}^{n_{ch}} f(BDT_{ch_i}) \right)$$

PRELIMINARY

$$p_{value} = 2.95 \times 10^{-7}$$

$5.0\,\sigma$ significance

Publications being issued

- Cosmic-ray annual modulation
- Study of charged particle multiplicity in high-energy neutrino-lead interactions
- Search for sterile neutrinos in the muon to electron channel
- Observation of a tau neutrino candidate with charmed hadron production
- Extended $\nu_\mu \rightarrow \nu_\tau$ search and Δm^2 measurement in appearance mode

Forthcoming publications

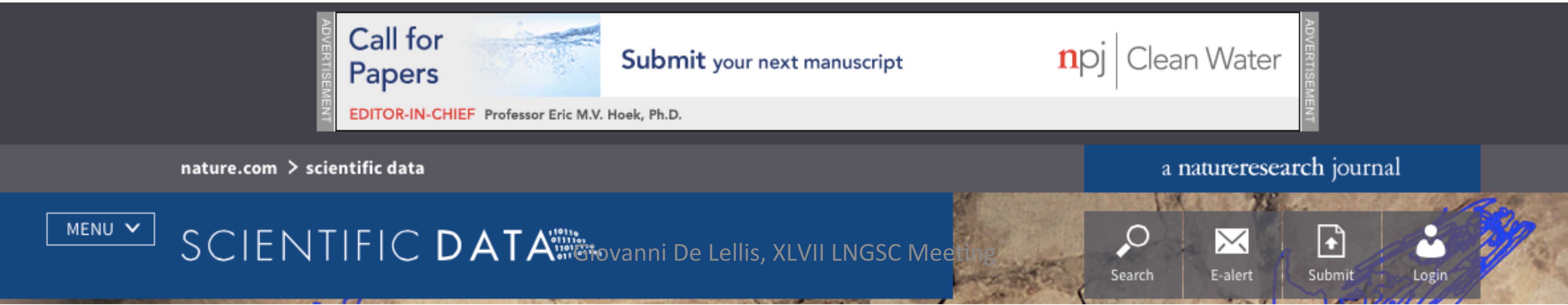
- Search for sterile neutrinos in the muon to tau channel with the full data sample
- Combination of electron and tau appearance with muon disappearance to constraint the oscillation parameters
- …

OPERA DATA PRESERVATION

- CERN willing to host OPERA data for its preservation
- OPERA data sample < 100 TB (~10 tapes) equivalent to one of the LEP experiments
- LEP support granted until 2030
- Agreement with data preservation office at CERN a year ago
- First data sets transferred
- Contacts with LNGS Computing Service for a similar action

OPERA OPEN DATA AT CERN

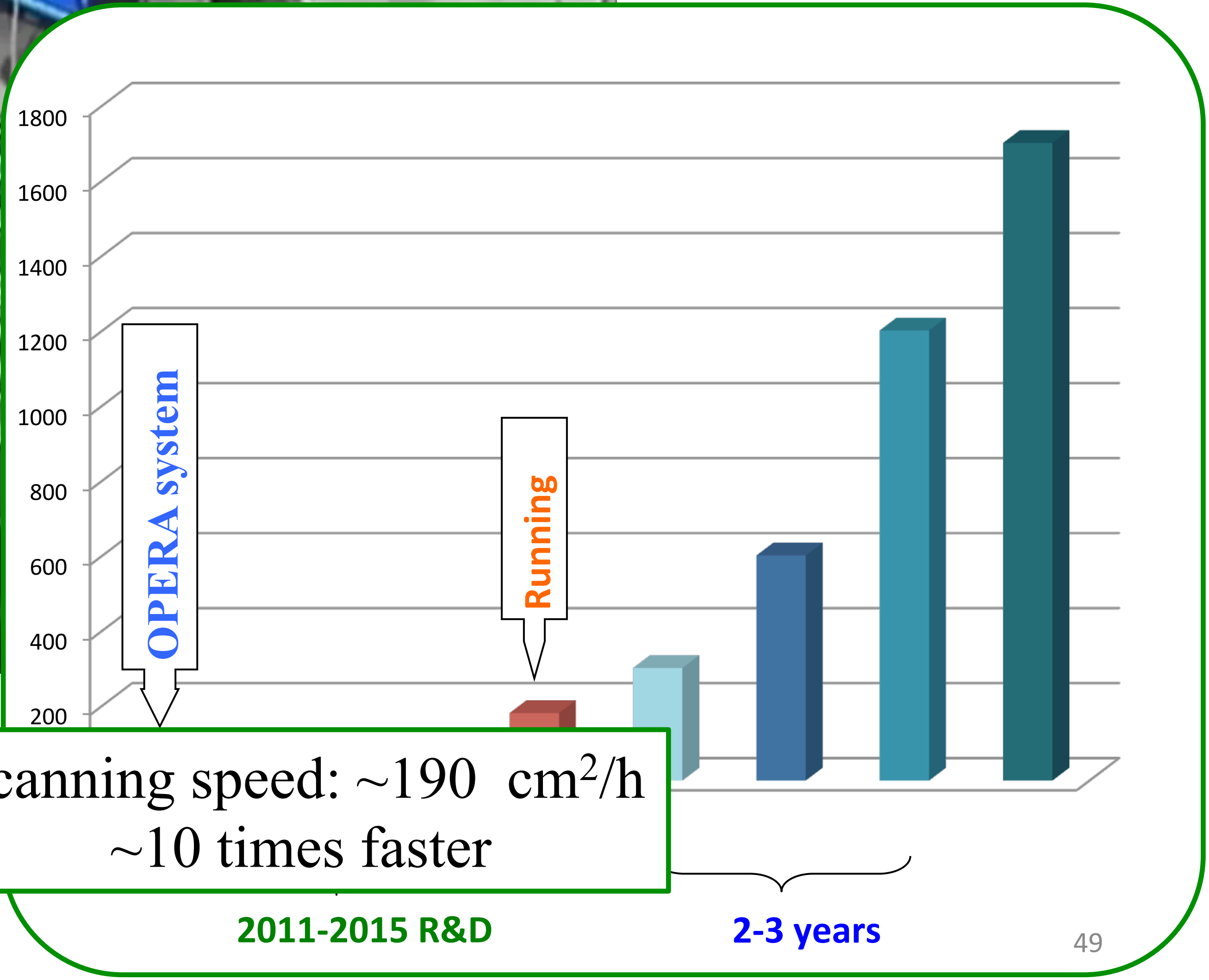
- CERN has a program of open data access mostly for educational purposes (CMS, LHCb, …)
- CERN willing to include OPERA data among the open data
- OPERA agreed to provide neutrino interactions reconstructed in the bricks: both data & event display (effective for educational purposes)



nature.com > scientific data

a natureresearch journal

TECHNOLOGICAL DEVELOPMENTS



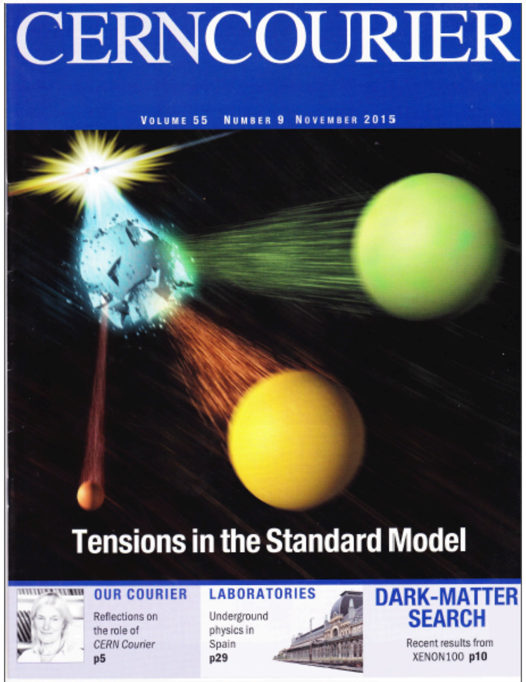
Scanning speed: ~190 cm^2/h
~10 times faster

JINST 8 (2013) P01023
JINST 10 (2015) P11006
JINST 11 (2016) P06002
…

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

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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 ▷

ACKNOWLEDGEMENTS

The OPERA Collaboration is very much indebted to:

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