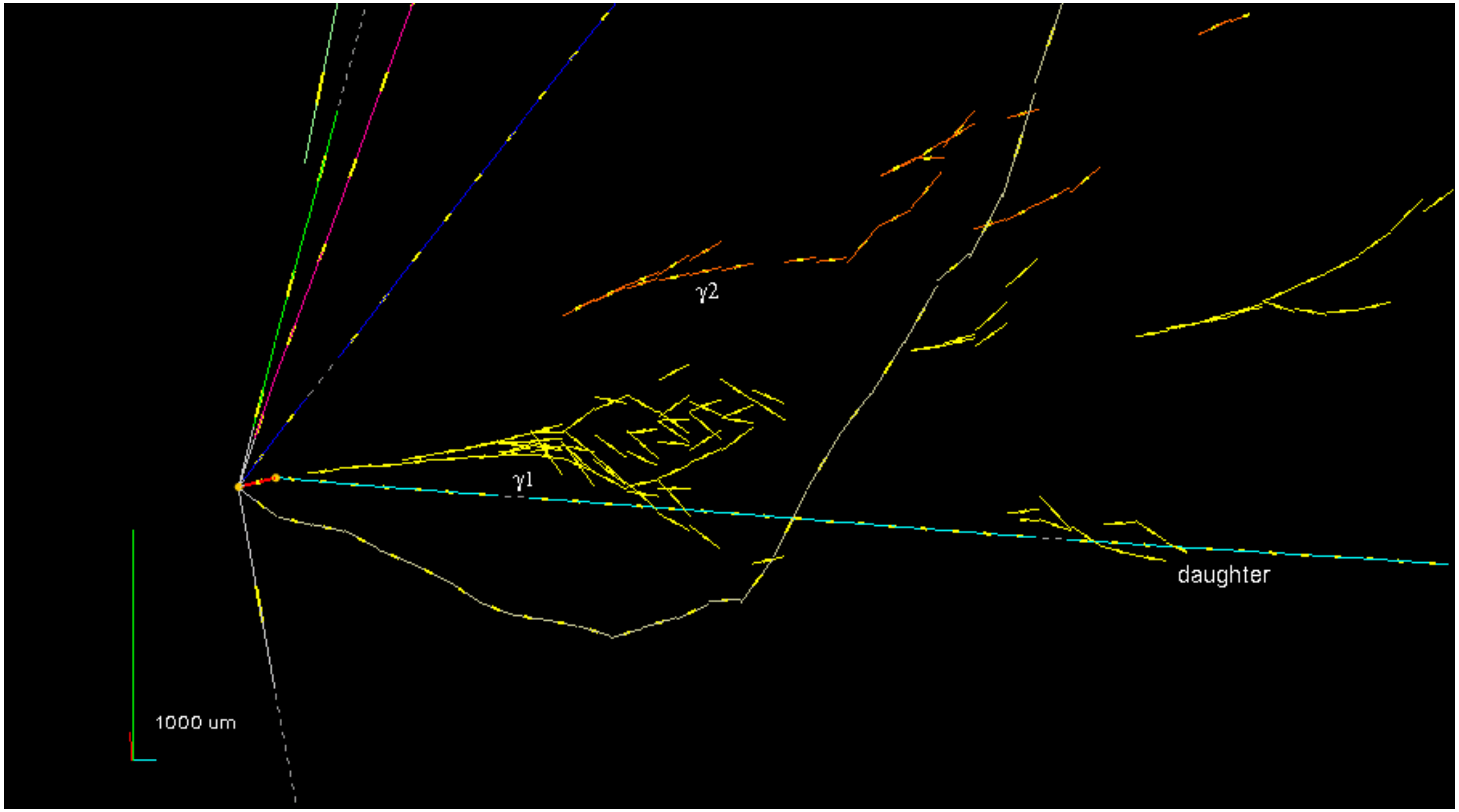
Results of the OPERA experiment

Giovanni De Lellis

University "Federico II" and INFN Napoli

On behalf of the OPERA Collaboration

For the CXXVI SPSC Meeting



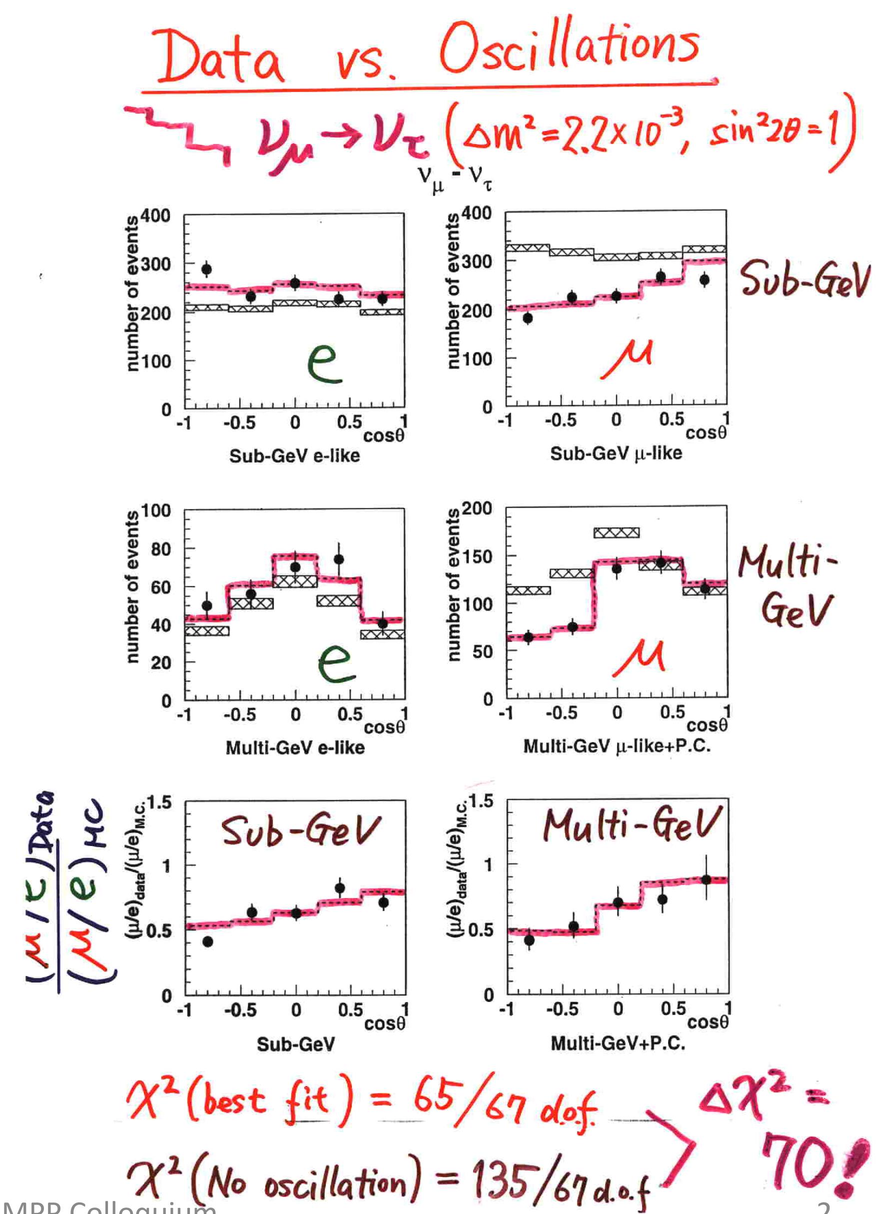
Back to 1998: Neutrino98, Takayama, Japan

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

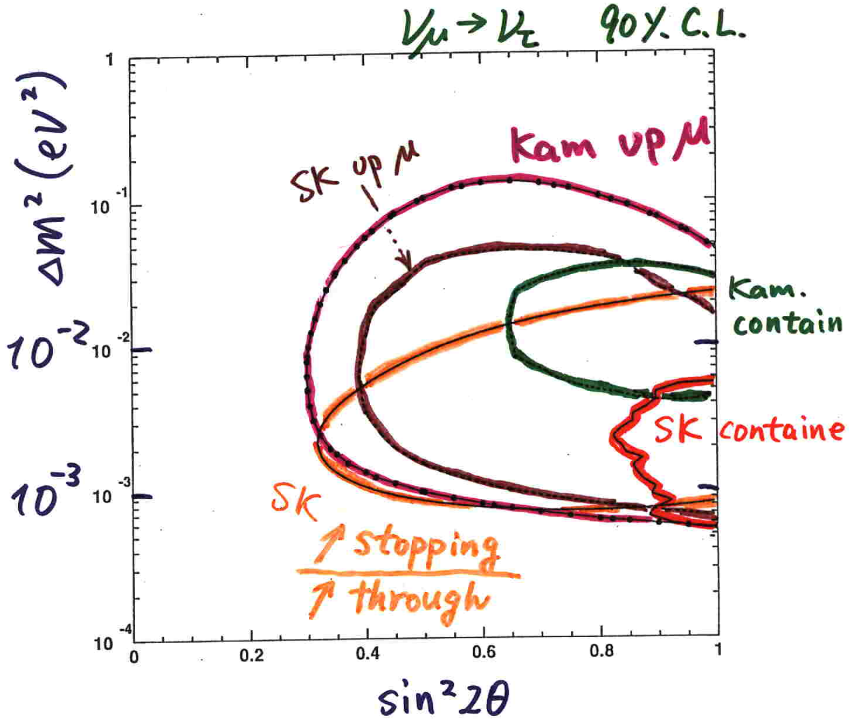


T. Kajita
Nobel Laureate 2015

By T. Kajita

Summary

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

PRD 95 (2017) 096014

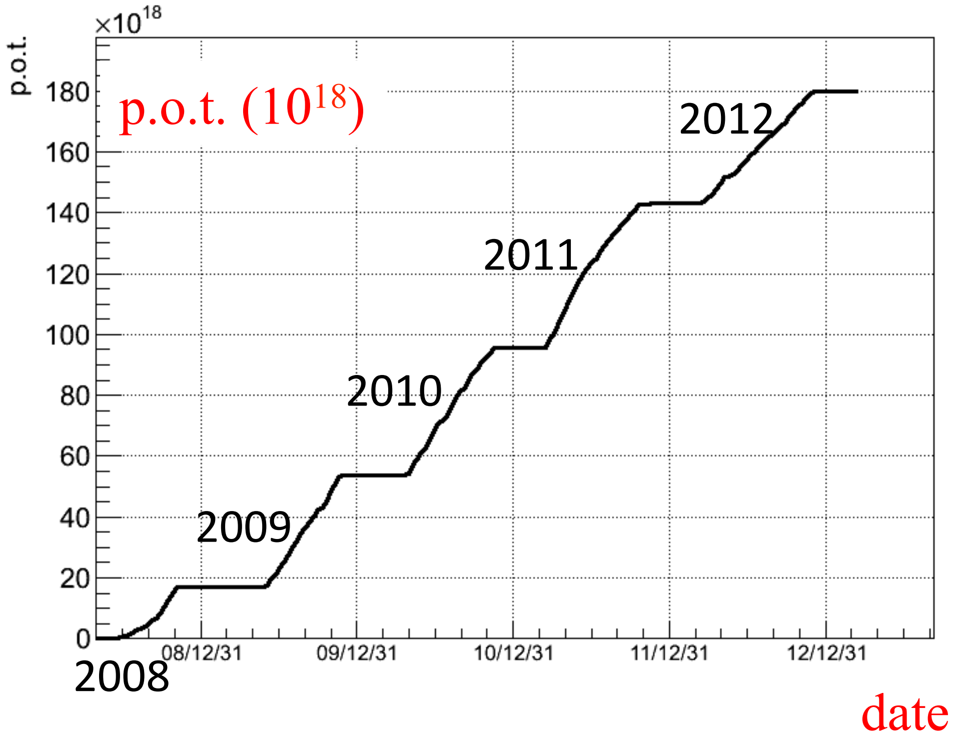
Parameter	Ordering	Best fit
$\delta m^2/10^{-5}$ eV^2	NO, IO, any	7.37
$\sin^2\theta_{12}/10^{-1}$	NO, IO, any	2.97
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.525
	IO	2.505
	Any	2.525
$\sin^2\theta_{13}/10^{-2}$	NO	2.15
	IO	2.16
	Any	2.15
$\sin^2\theta_{23}/10^{-1}$	NO	4.25
	IO	5.89
	Any	4.25
δ/π	NO	1.38
	IO	1.31
	Any	1.38

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

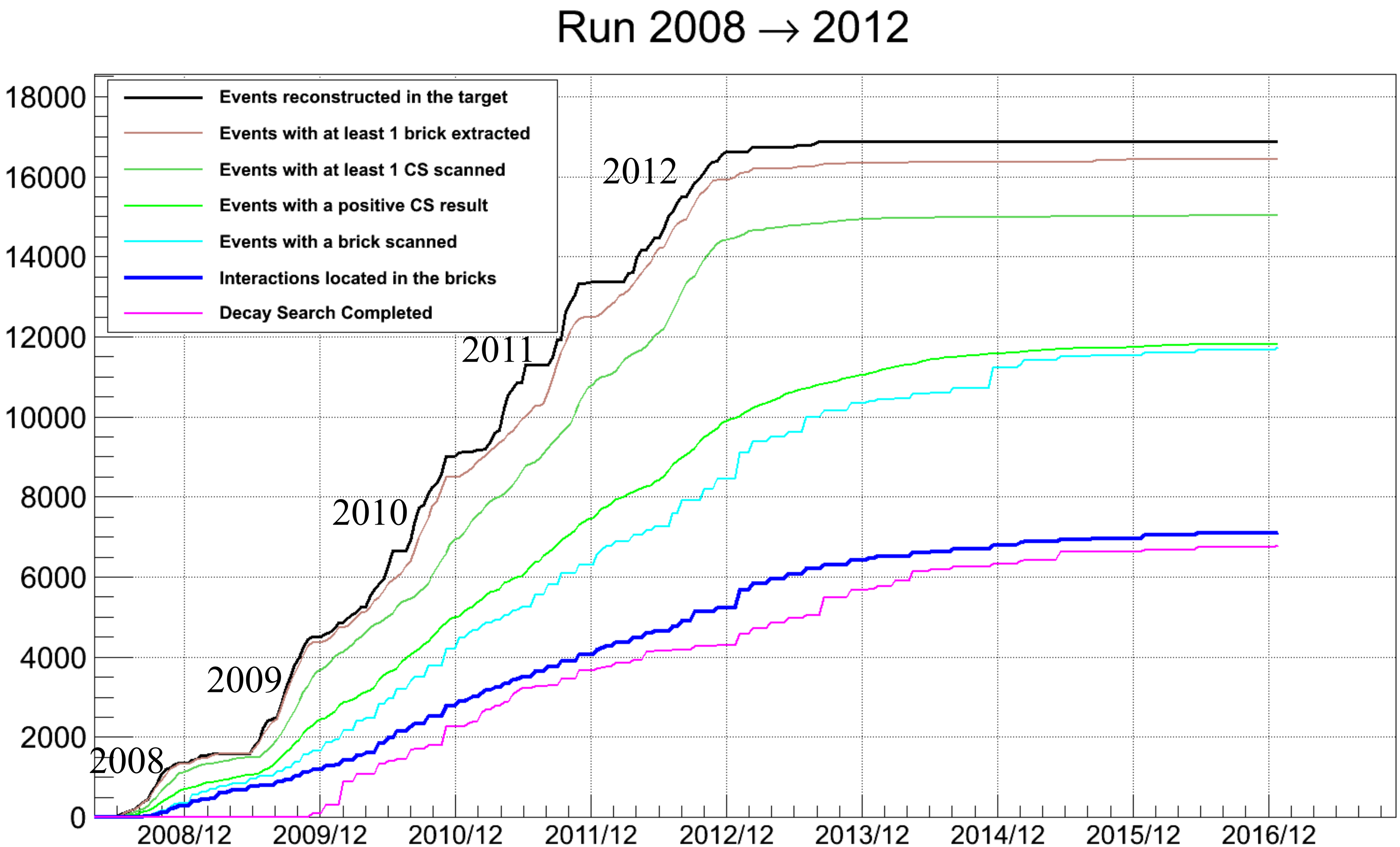
- ν_τ not yet seen in 1998!
- First indication of ν_τ in 2001 at Fermilab (DONUT)

The 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



7132 located interactions

6785 decay search

Non-Oscillation physics

Cosmic-muon rate and temperature dependence

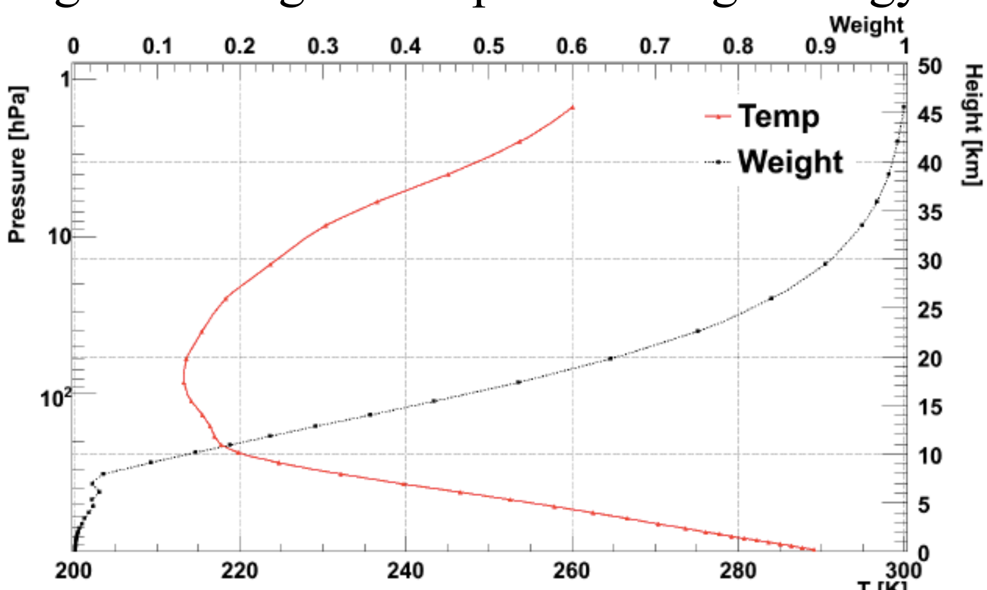
- Gran Sasso underground ~ 3800 m w.e. → Minimum muon energy ~ 1.8 TeV
- Atmospheric temperature increase → density decrease → increase the pion decay rate → muon rate increase

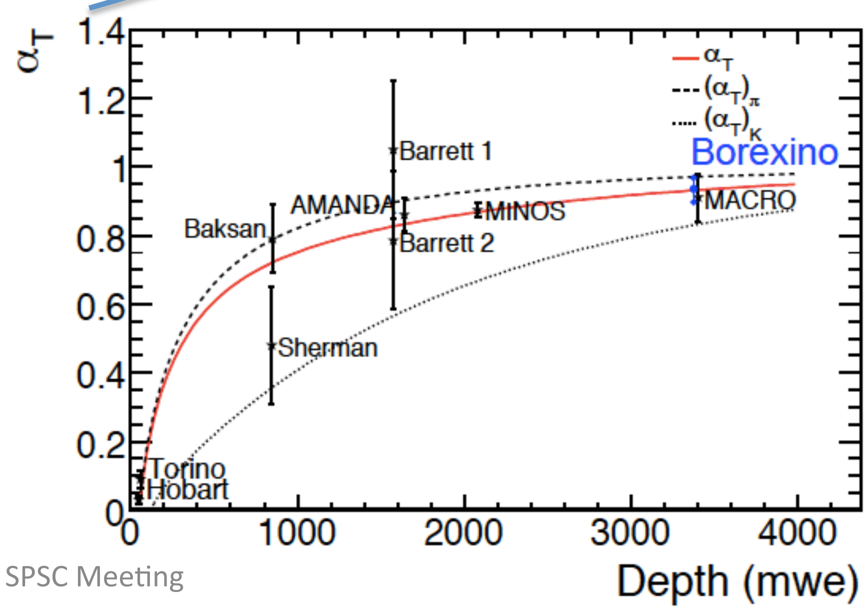
$$I_\mu(t) = I_\mu^0 + \Delta I_\mu = I_\mu^0 + \delta I_\mu \cos\left[\frac{2\pi}{T}(t - t_0)\right]$$

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

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

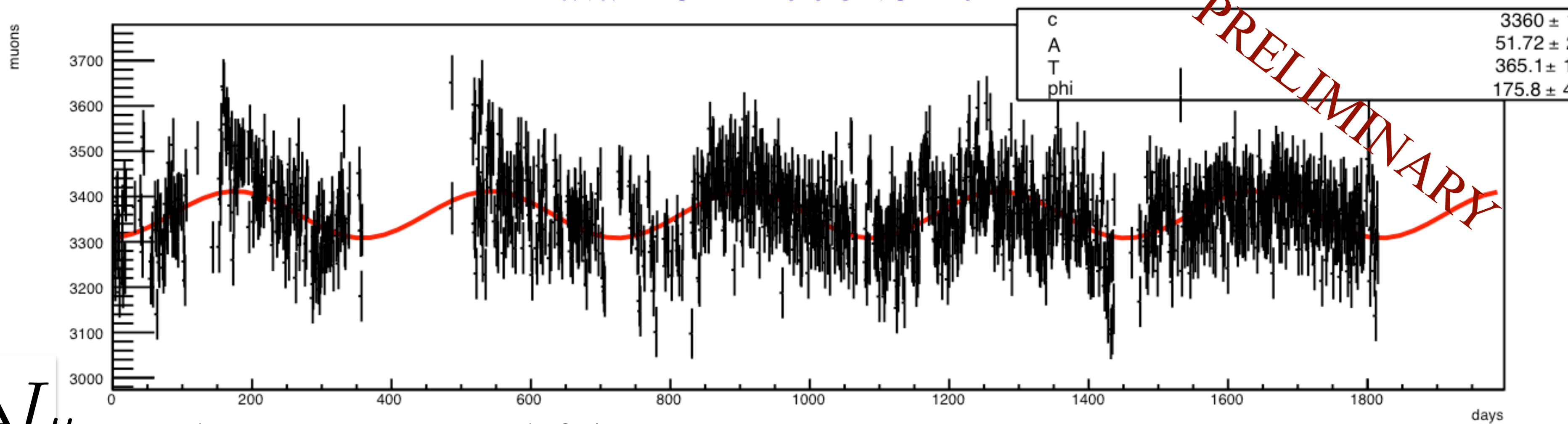
High W in high atmosphere → high energy muons





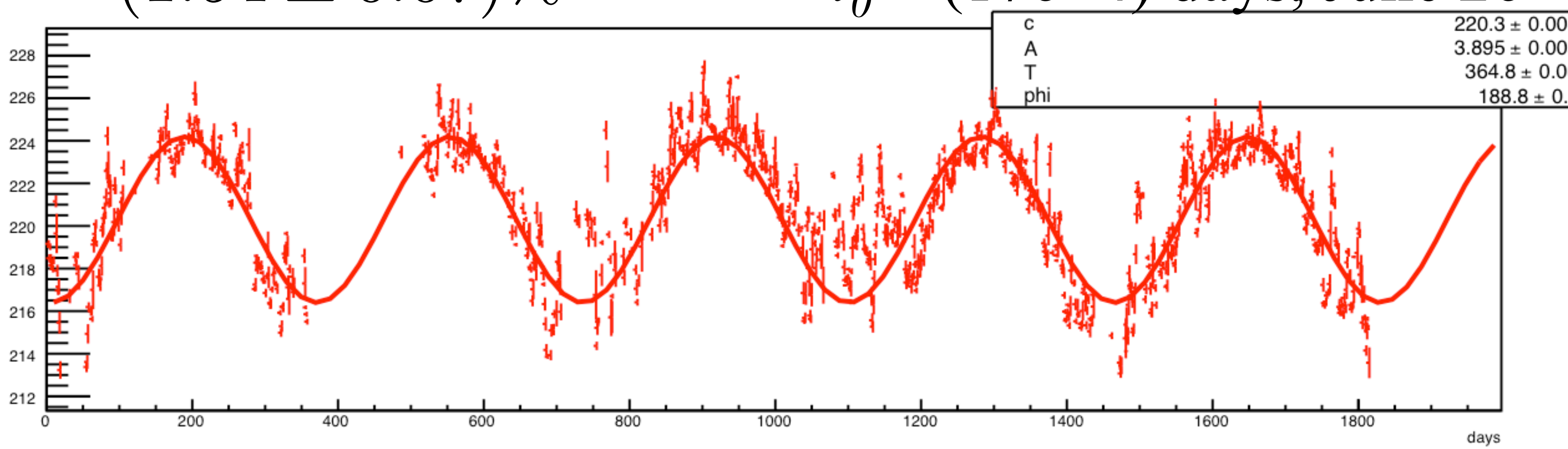
Annual modulation of cosmic-muon rate

Data from 2008 to 2012



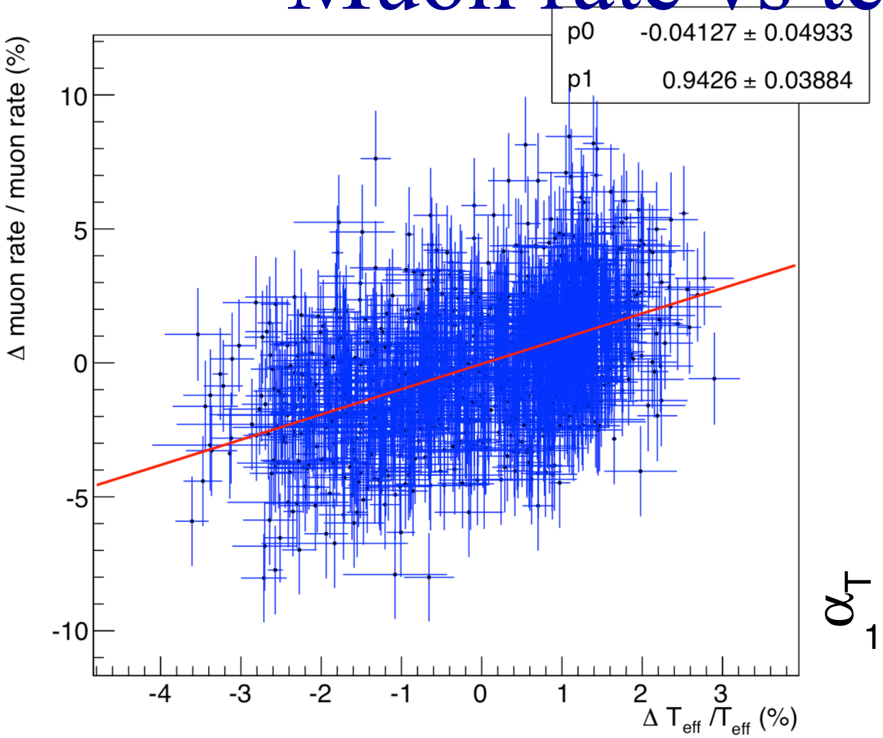
$$\frac{\Delta I_\mu}{I_\mu^0} = (1.54 \pm 0.07)\%$$

$t_0 = (176 \pm 4)$ days, June 26th



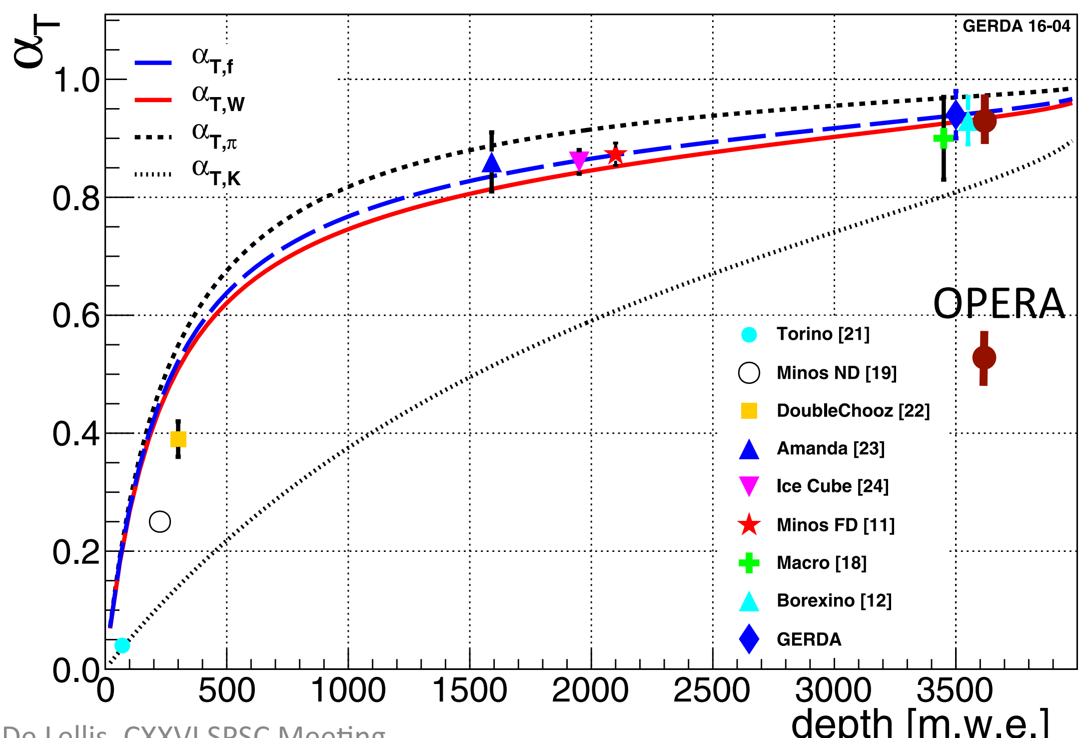
Temperature data by the European Center for Medium-range Weather Forecasts (ECMWF)

Muon rate vs temperature variations



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

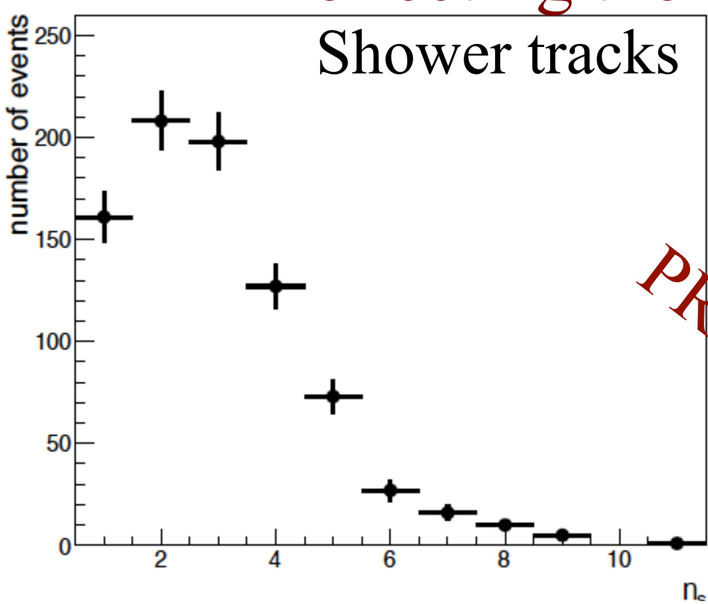
$$\alpha_T = 0.94 \pm 0.04$$

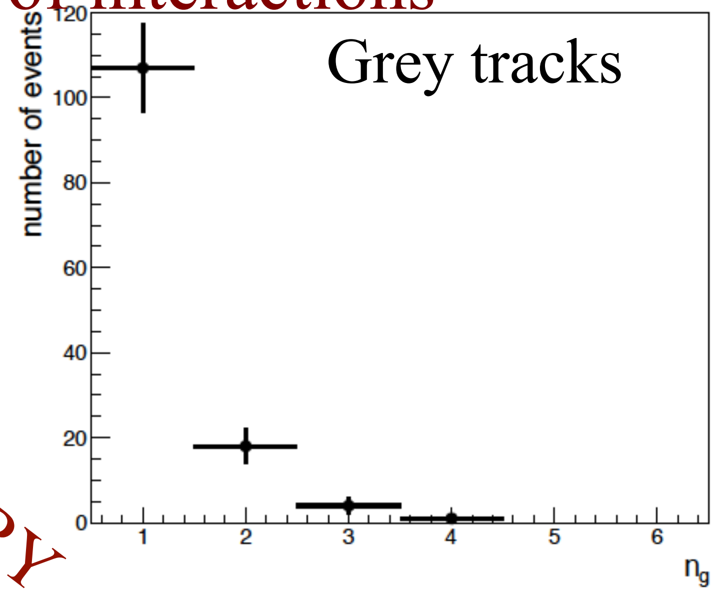


PRELIMINARY

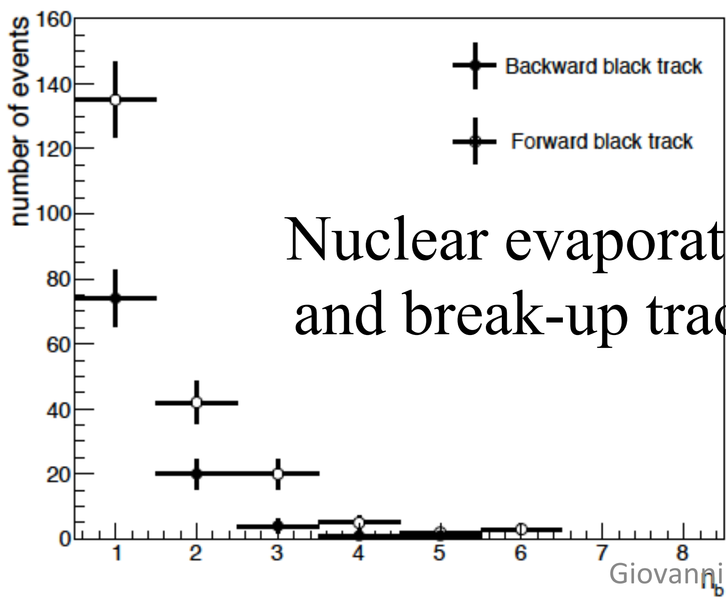
MULTIPLICITY STUDIES IN NEUTRINO–LEAD SCATTERING

Track multiplicity distributions
reflecting the dynamics of interactions

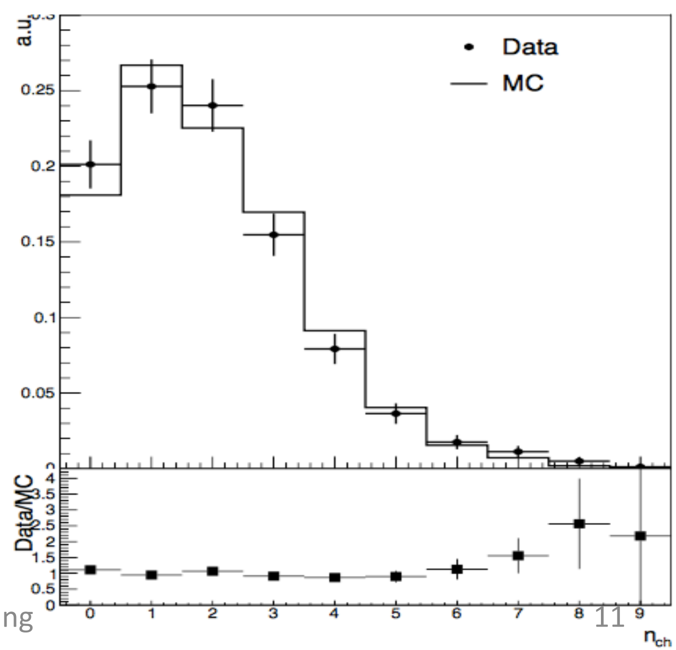




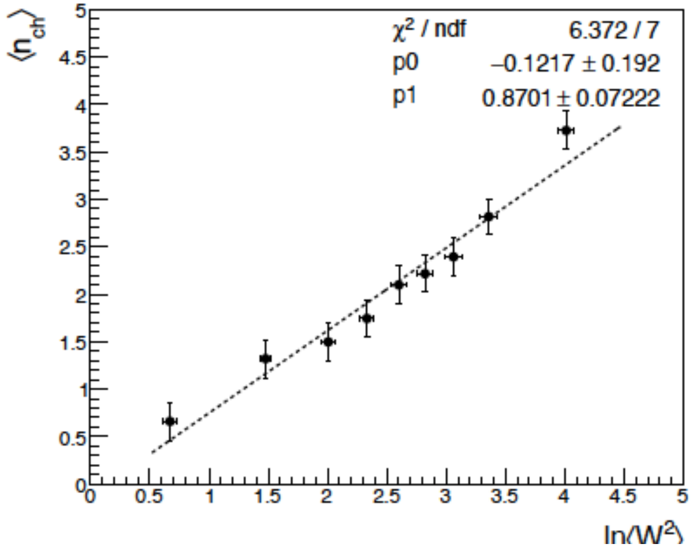
PRELIMINARY



Nuclear evaporation and break-up tracks

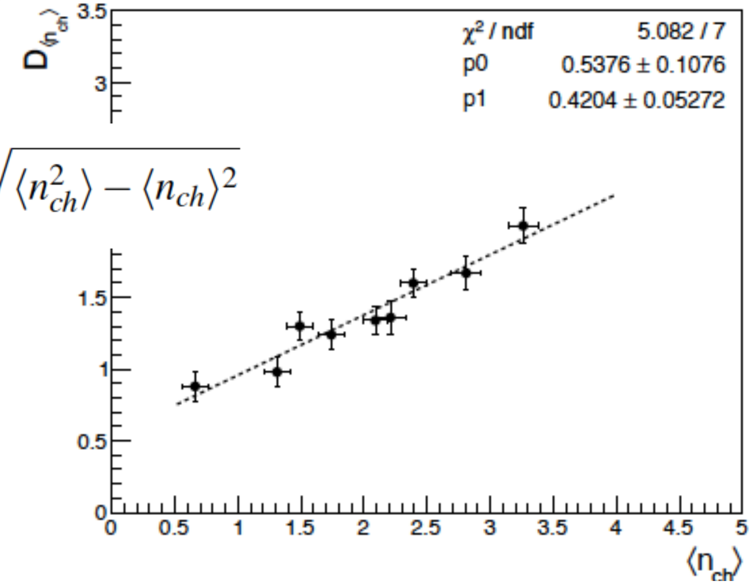


Multiplicity features



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

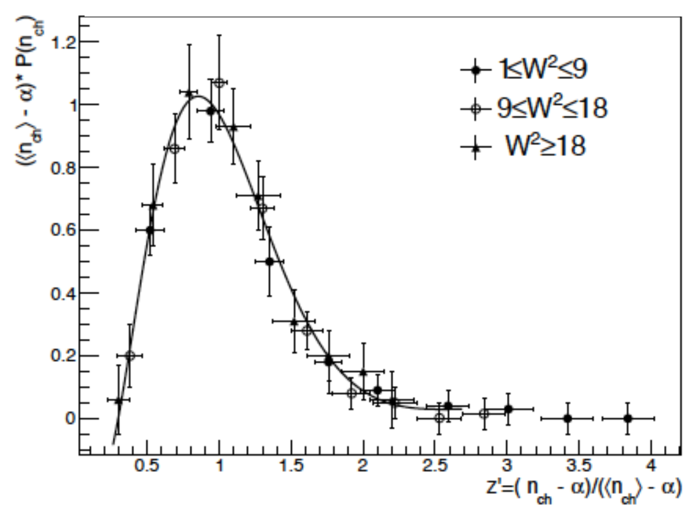
$$D_{ch} = \sqrt{\langle n_{ch}^2 \rangle - \langle n_{ch} \rangle^2}$$



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

PRELIMINARY

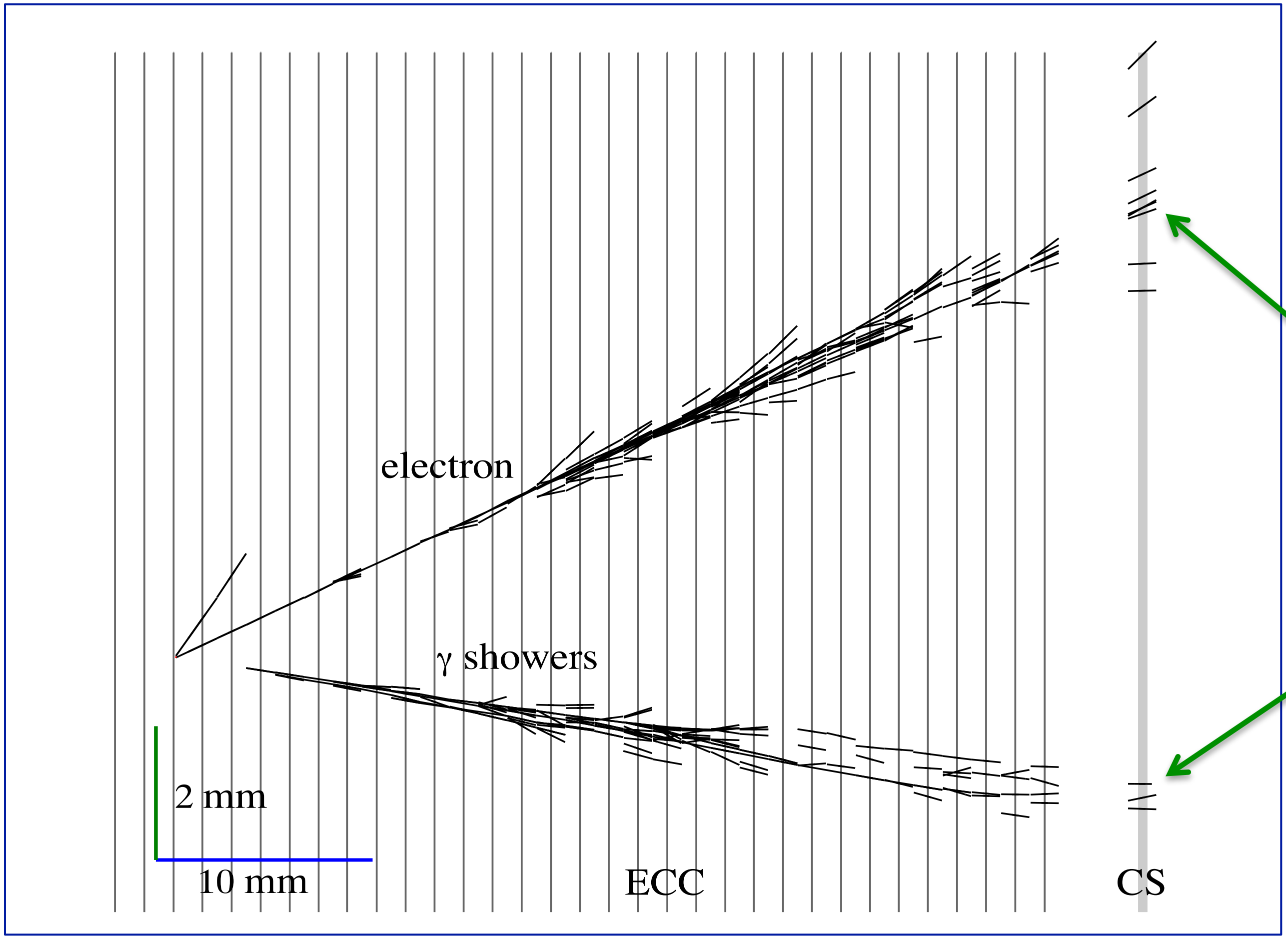


OSCILLATION PHYSICS

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

Electron neutrinos

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

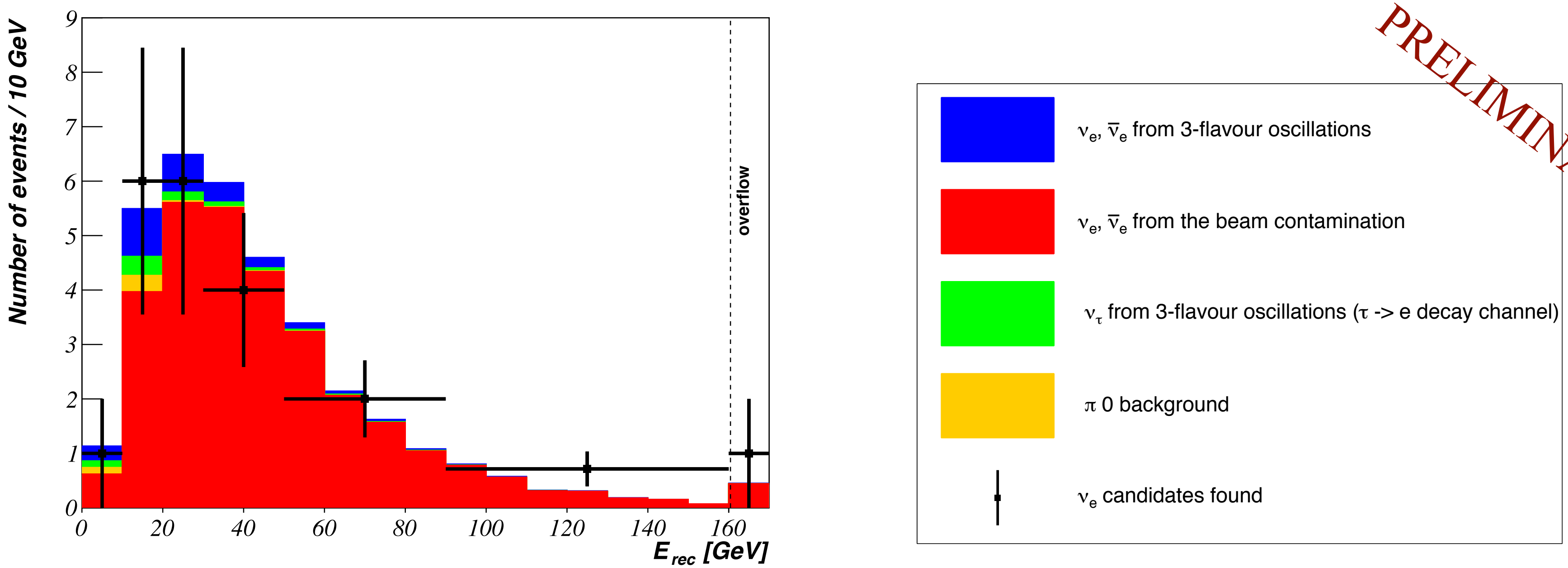


Interface films

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 ($\tau \rightarrow e$ 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



PRELIMINARY

STERILE NEUTRINO SEARCH

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

~standard oscillation — Exotic oscillation

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

Interference term:

$$+ 0.5\, C \sin 2\theta_{\mu e} \cos\phi_{\mu e} \sin 2\Delta_{31} \sin 2\Delta_{41}$$
$$- C \sin 2\theta_{\mu e} \sin\phi_{\mu e} \sin^2\Delta_{31} \sin 2\Delta_{41}$$
$$+ 2\, C \sin 2\theta_{\mu e} \cos\phi_{\mu e} \sin^2\Delta_{31} \sin^2\Delta_{41}$$
$$+ C \sin 2\theta_{\mu e} \sin\phi_{\mu e} \sin 2\Delta_{31} \sin^2\Delta_{41}$$

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

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

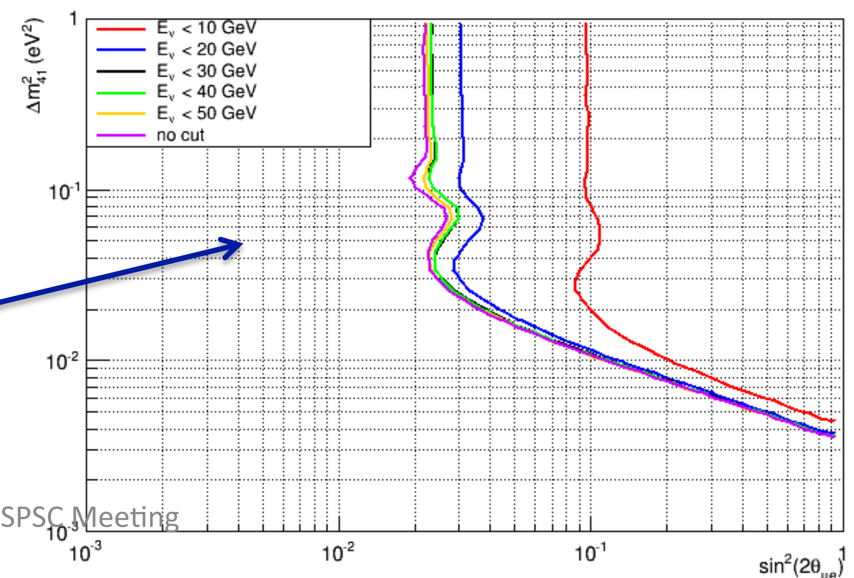
$$\phi_{\mu e} = Arg(U_{\mu 3} U^*_{e3} U^*_{\mu 4} U_{e4})$$

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

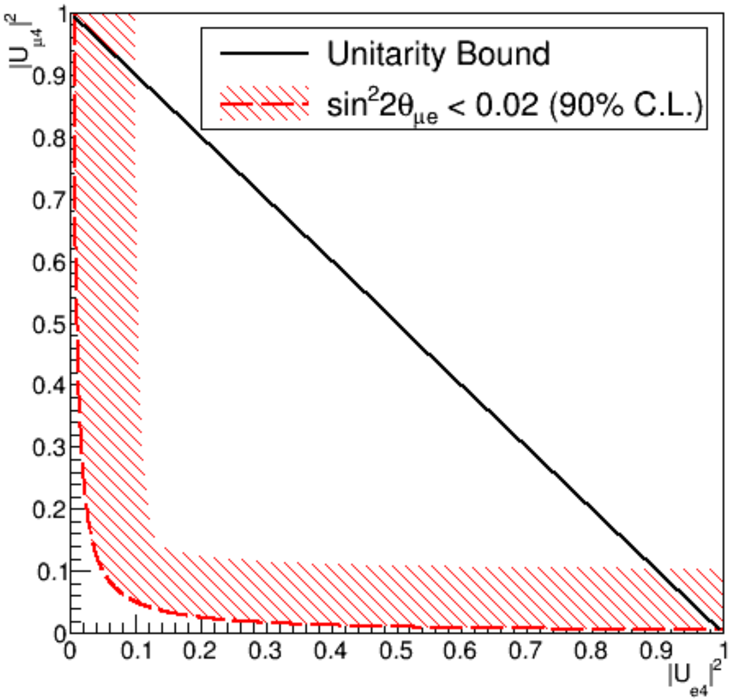
$$L = \prod_i Poisson(n_i; (1+k_j)\cdot u_i) \times \prod_j Gauss(k_j; 0, \sigma_j) \times Gauss(\Delta m^2_{23}; \widehat{\Delta m^2_{23}}, \sigma_{\Delta m^2_{23}})$$

Energy distribution to constrain the parameter space: shape analysis

Sensitivity curves vs energy cut



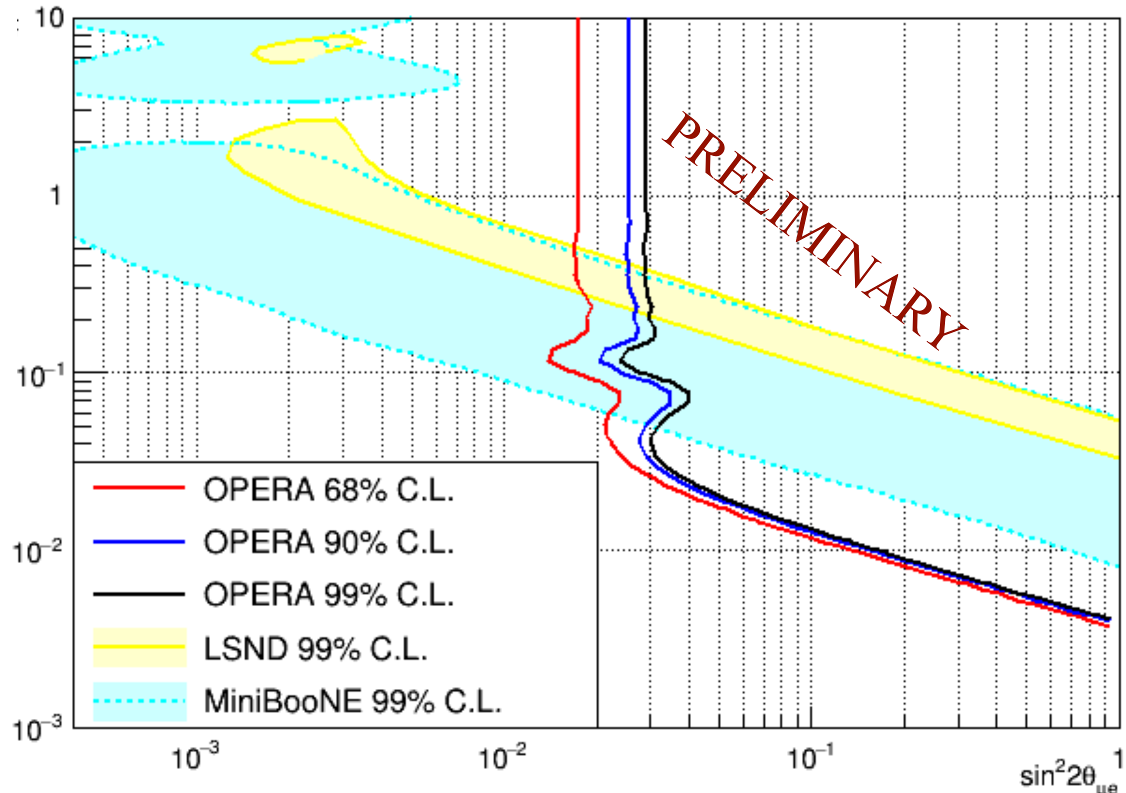
Constraining Sterile Neutrinos with a 3+1 Model



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

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



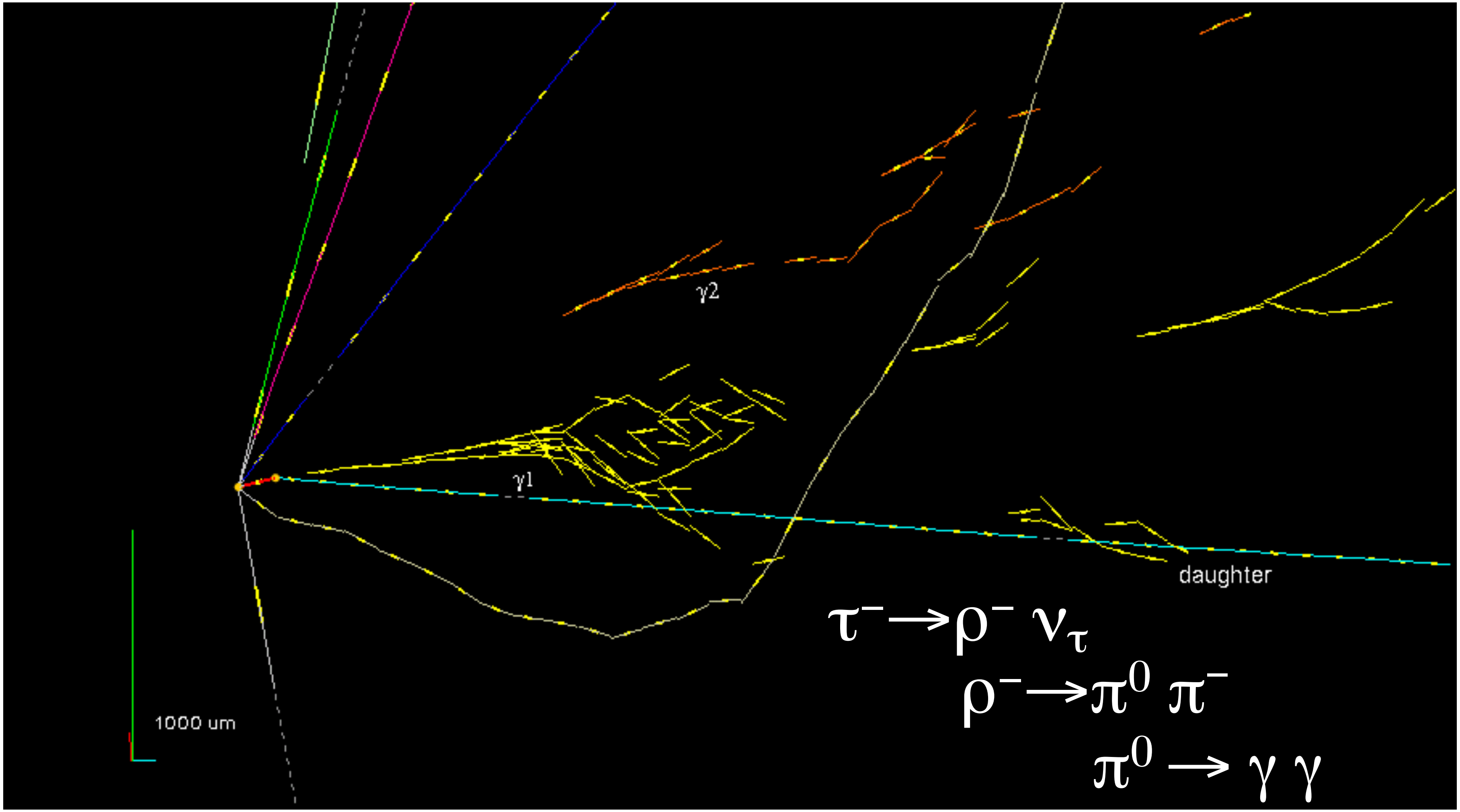
$\nu_\mu \to \nu_\tau$ ANALYSIS

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

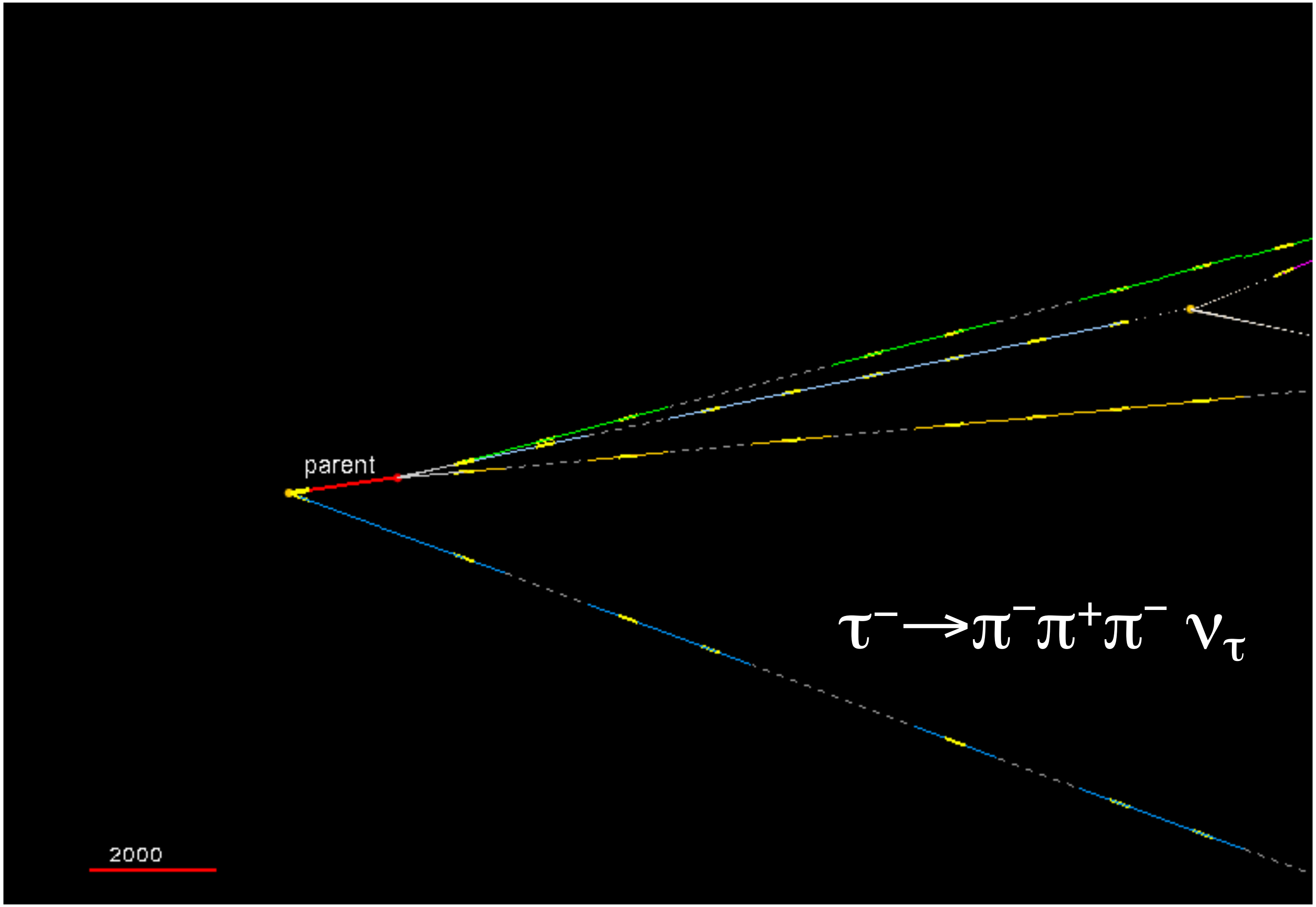
in the brick



Physics Letters B691 (2010) 138

THE SECOND ν_τ CANDIDATE

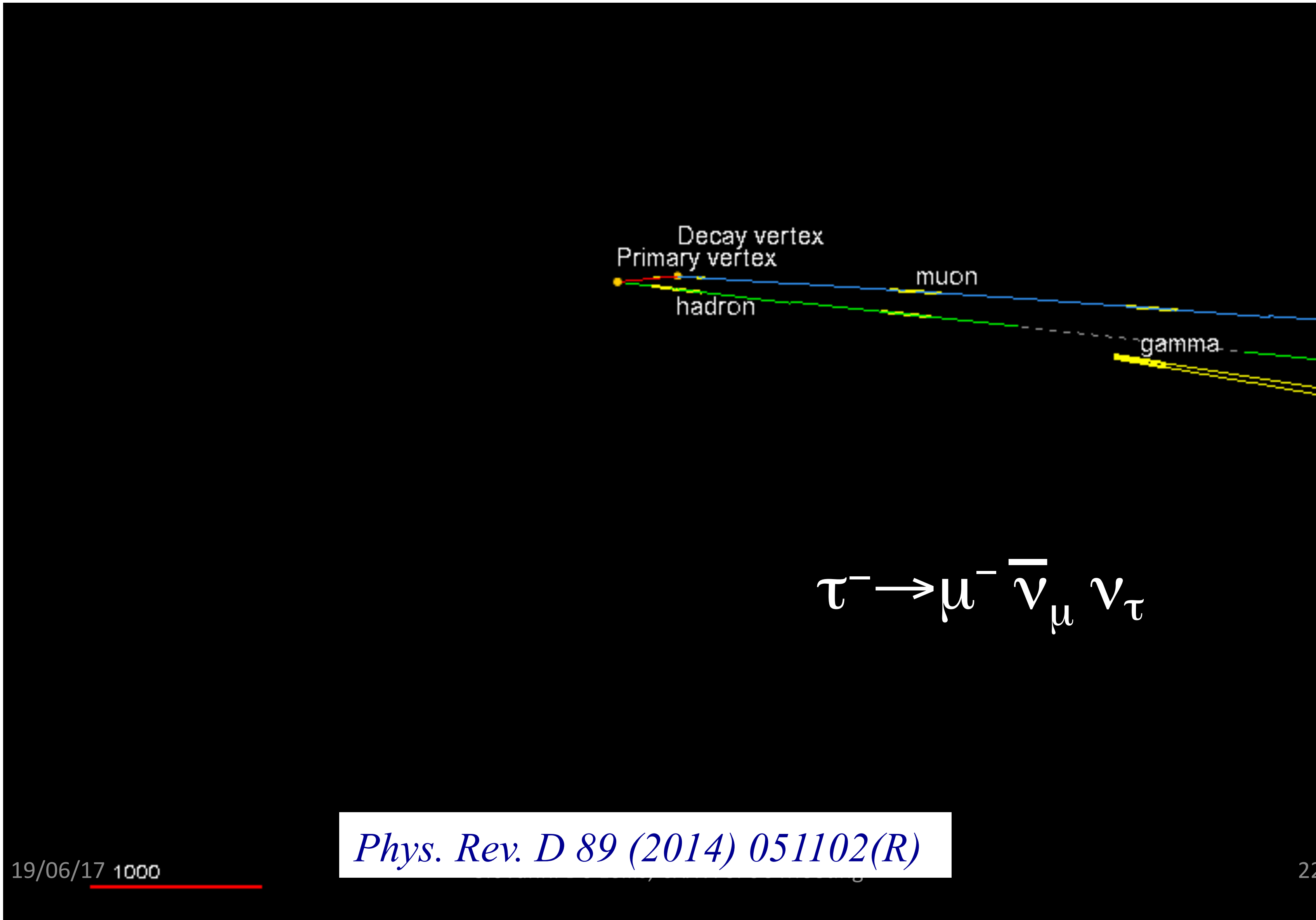
in the brick



Journal of High Energy Physics 11 (2013) 036

THE THIRD ν_τ CANDIDATE

in the brick

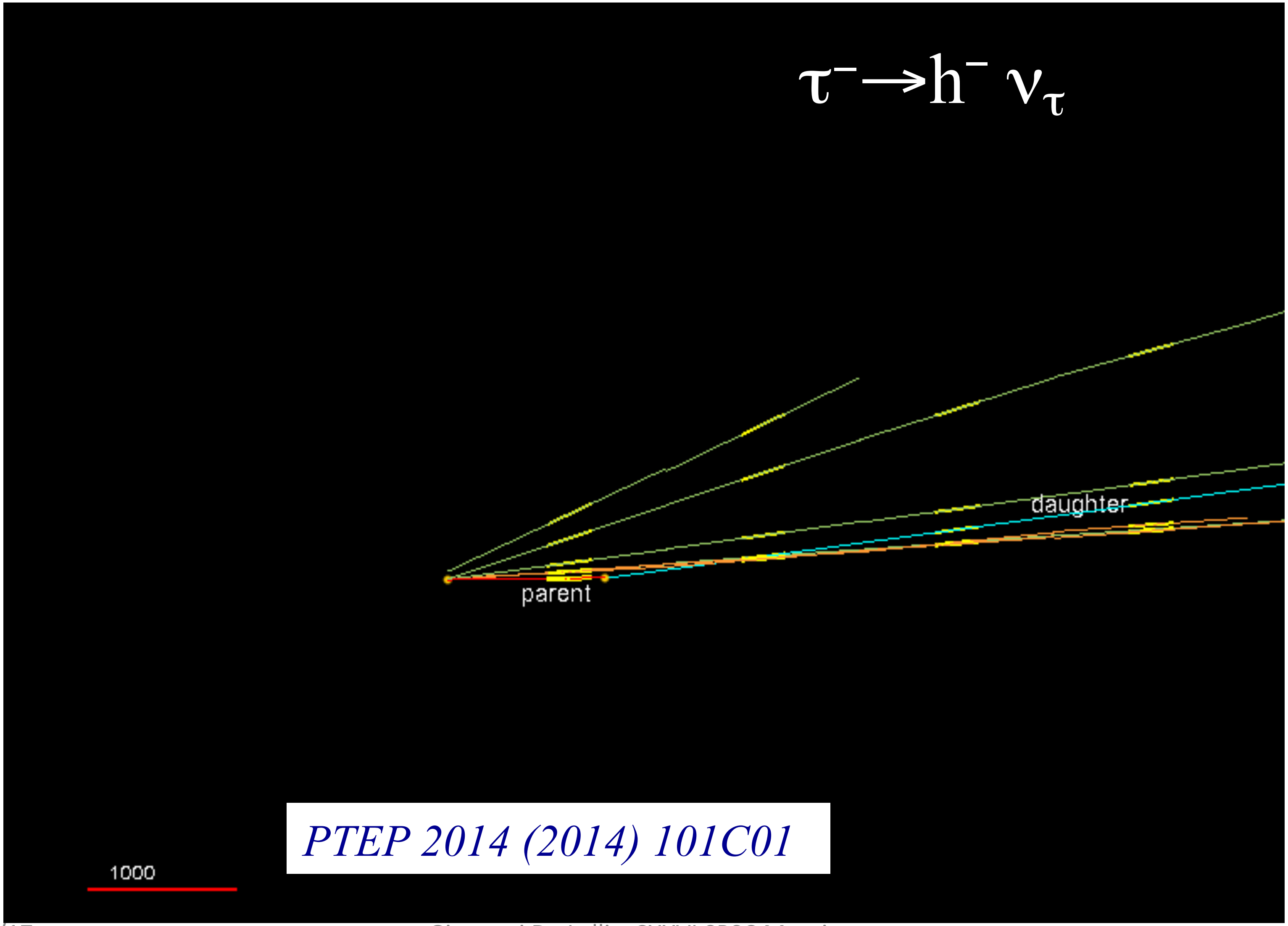


$$\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$$

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

THE FORTH ν_τ CANDIDATE

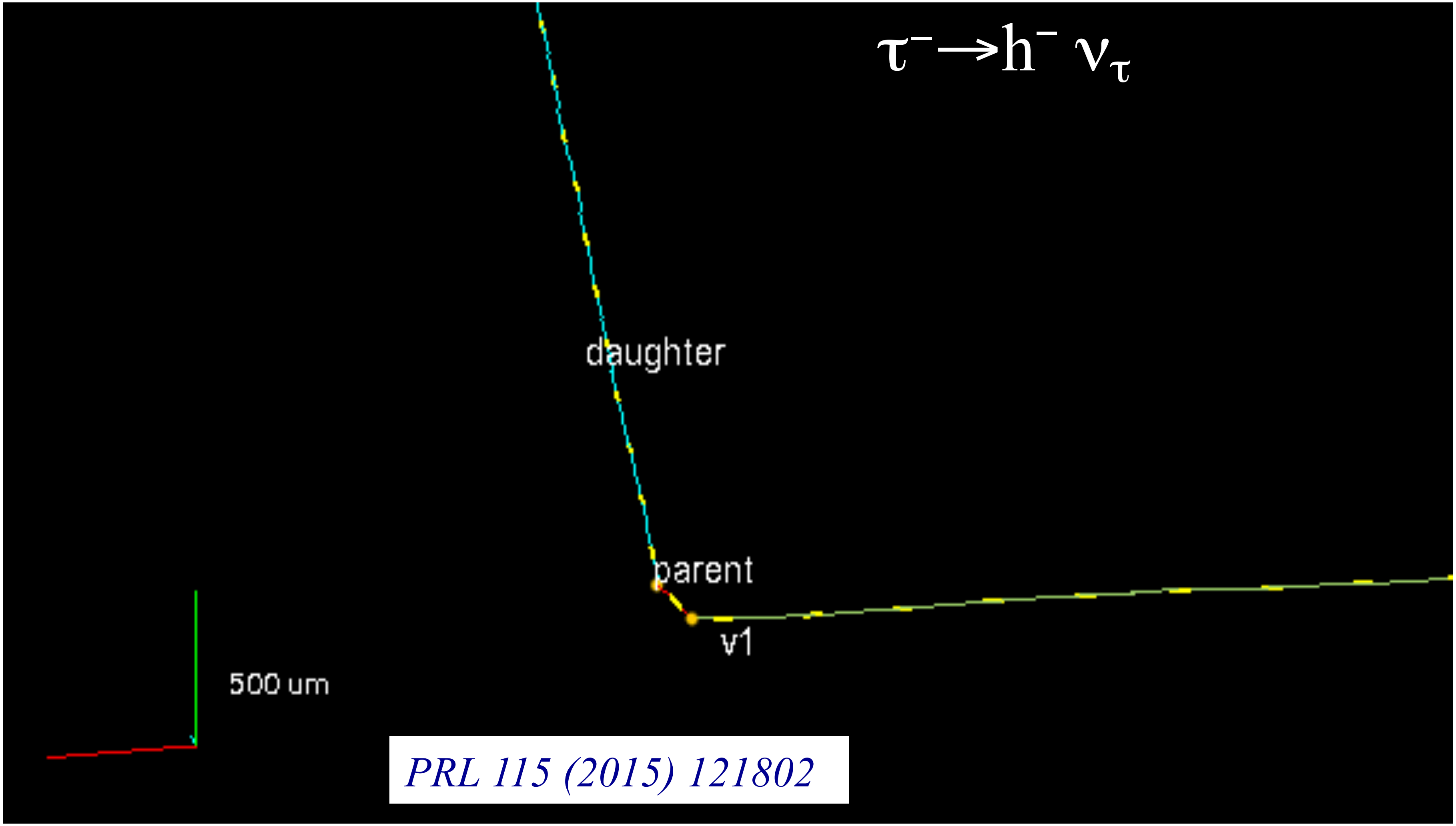
in the brick



PTEP 2014 (2014) 101C01

The Fifth ν_τ Candidate

in the brick



PRL 115 (2015) 121802

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].

Tau neutrino discovery paper: PRL 115 (2015) 121802

New Event Analysis

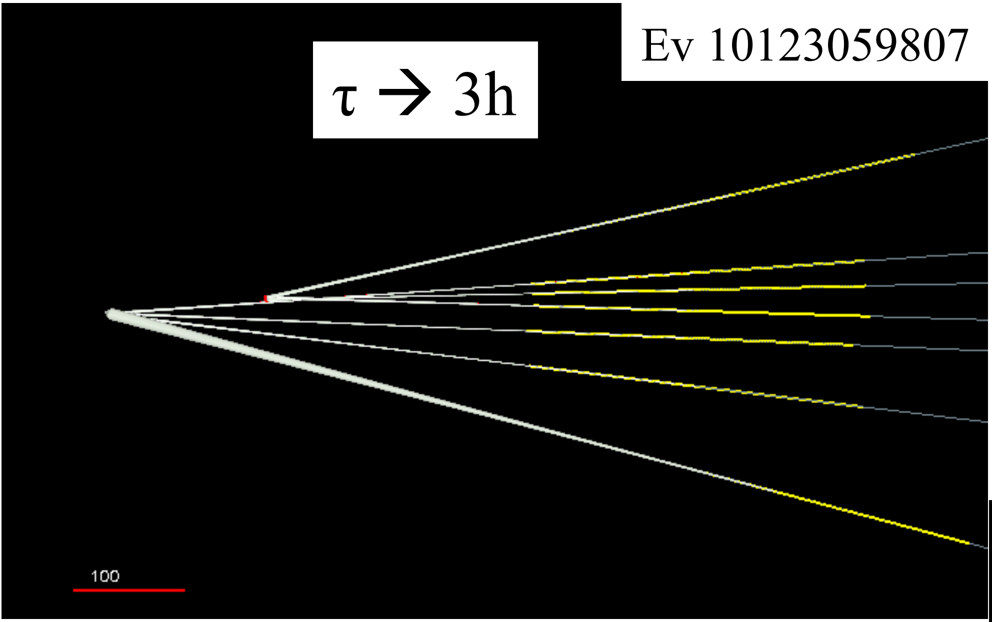
- Widen selection cuts to increase the statistics
- Candidate identification mostly topological with looser kinematical cuts
- Statistical gain to reduce uncertainties
- Simulation fully validated with data in all kinematical corners → use likelihood approach

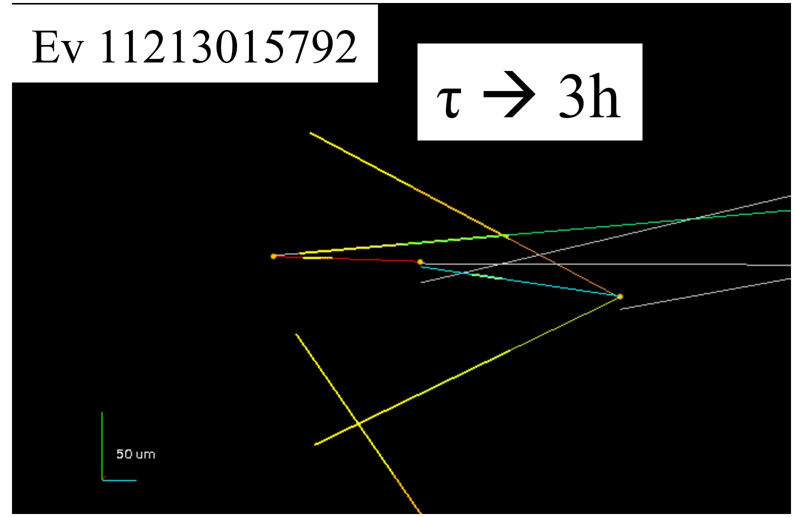
New Selection

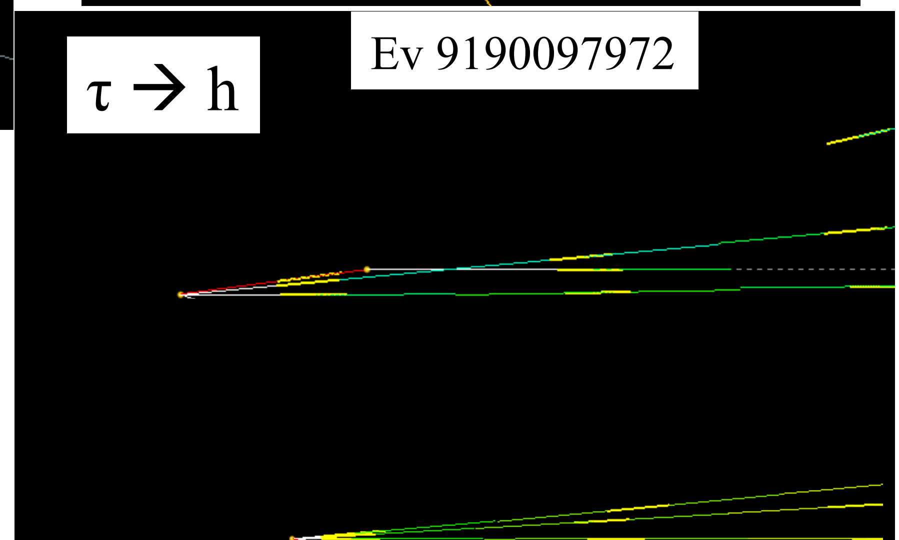
Variable	$\tau \to 1h$		$\tau \to 3h$		$\tau \to \mu$		$\tau \to e$	
	OLD	NEW	OLD	NEW	OLD	NEW	OLD	NEW
z_{dec} (μm)	$[44, 2600]$	<2600	<2600		$[44, 2600]$	<2600	<2600	
θ_{kink} (rad)	>0.02		<0.5	>0.02	>0.02		>0.02	
p_{2ry} (GeV/c)	>2	>1	>3	>1	$[1, 15]$		$[1, 15]$	>1
p^T_{2ry} (GeV/c)	$>0.6\,(0.3)$	>0.15	/		>0.25	>0.1	>0.1	
p^T_{miss} (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
	Charm	Had. re-interaction	Large μ-scat.	Total		Expected
$\tau \to 1h$	0.15	1.28	–	1.43	2.96	4.39
$\tau \to 3h$	0.44	0.09	–	0.52	1.83	2.35
$\tau \to \mu$	0.008	–	0.02	0.03	1.15	1.18
$\tau \to e$	0.035	–	–	0.03	0.84	0.87
Total	0.63	1.37	0.02	2.0 ± 0.5	6.8 ± 1.4	8.8 ± 1.9

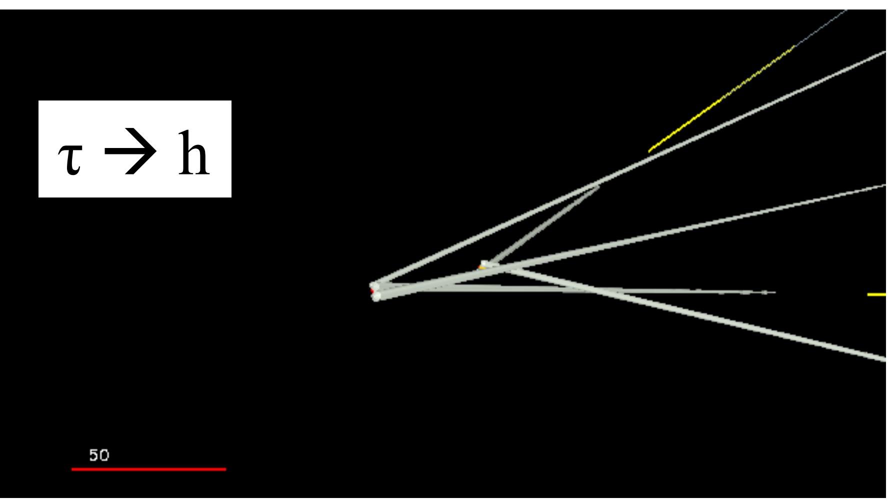
New Tau Neutrino Candidates

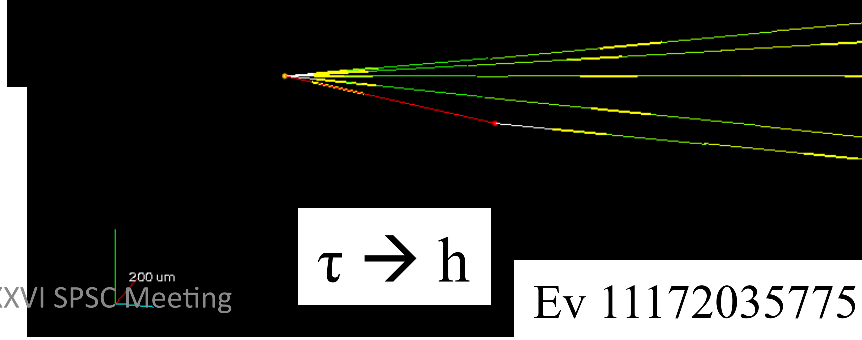






Ev 11143018505

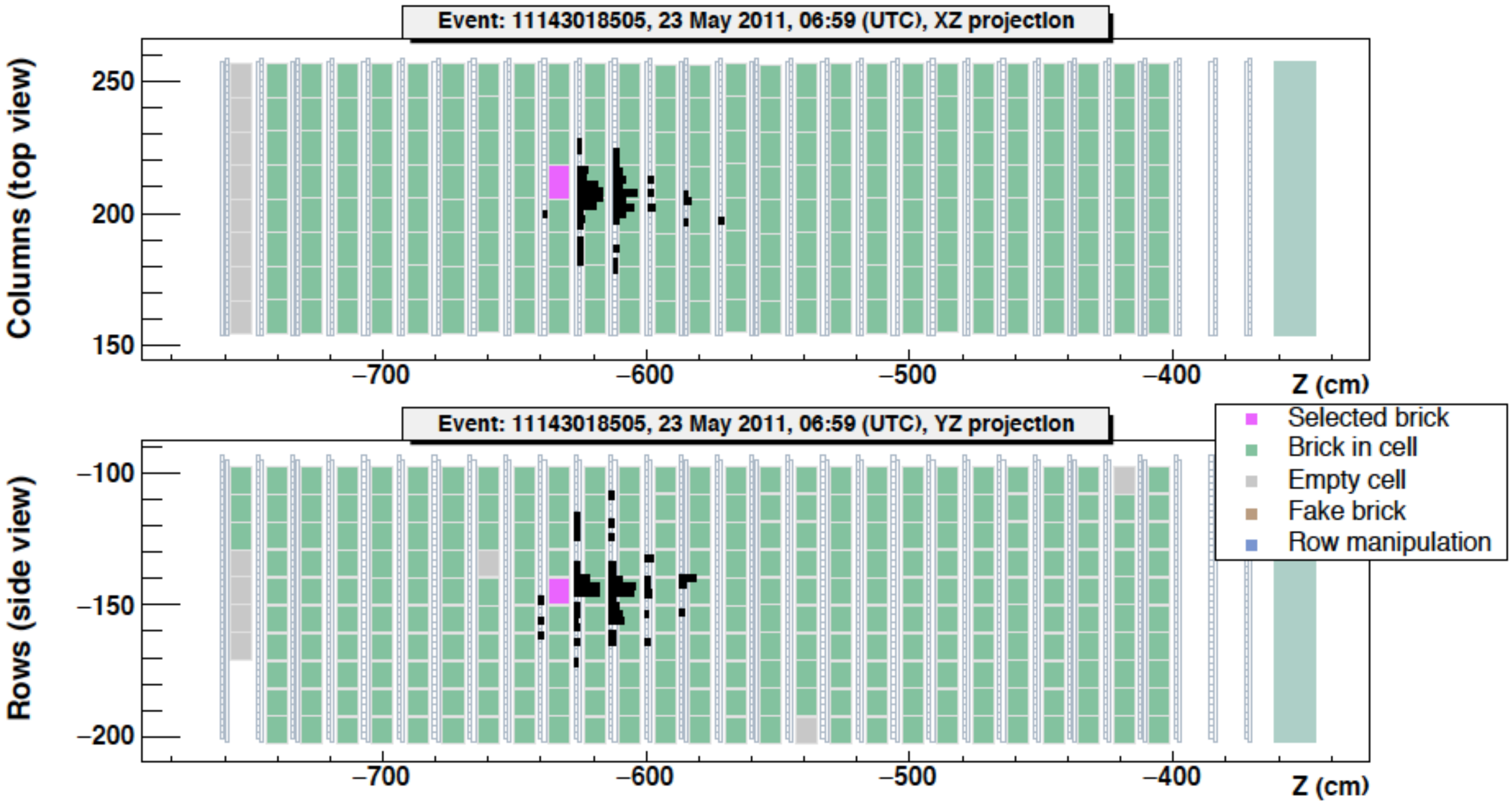


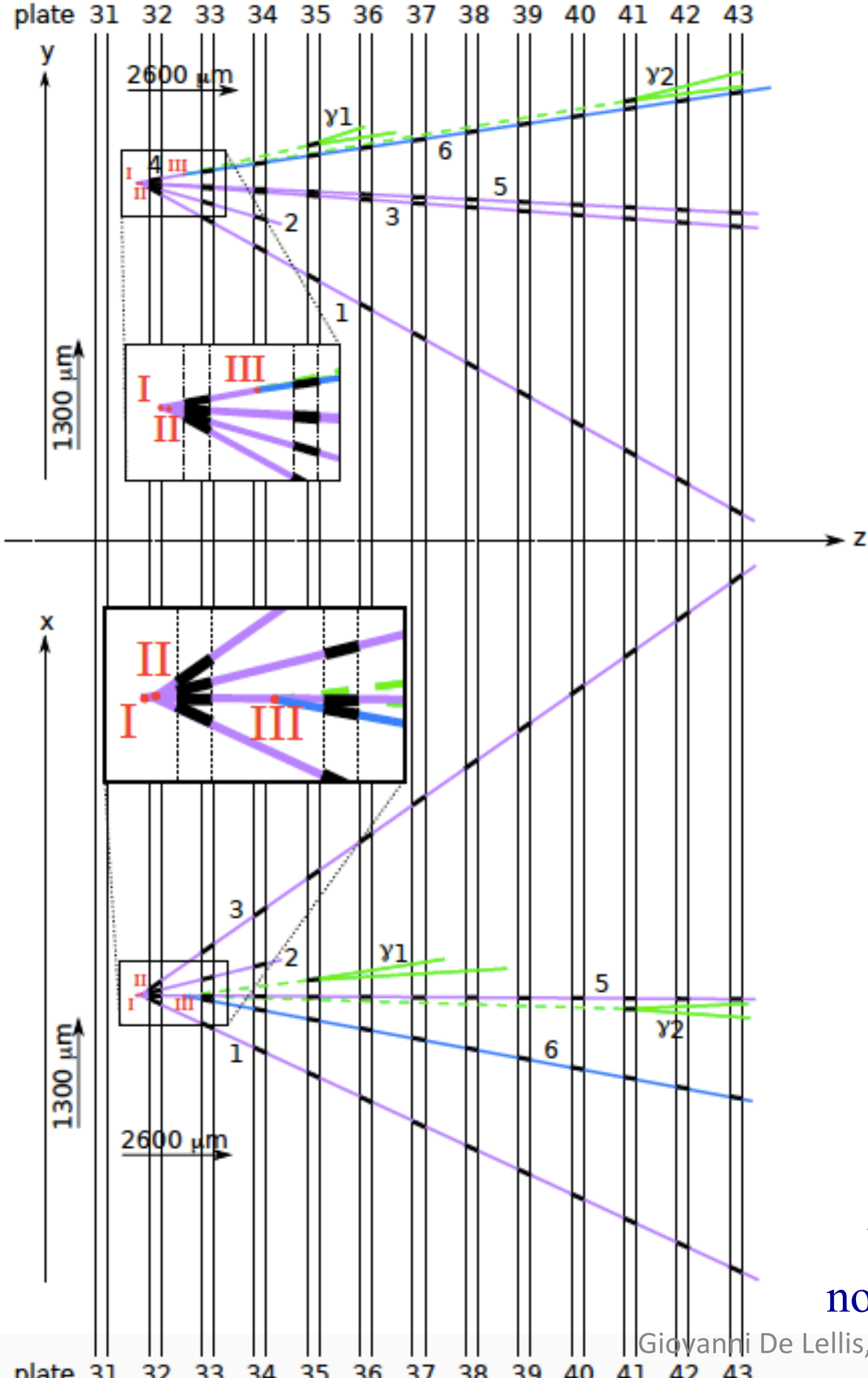


Ev 11172035775

A Closer Look at One of these Events

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



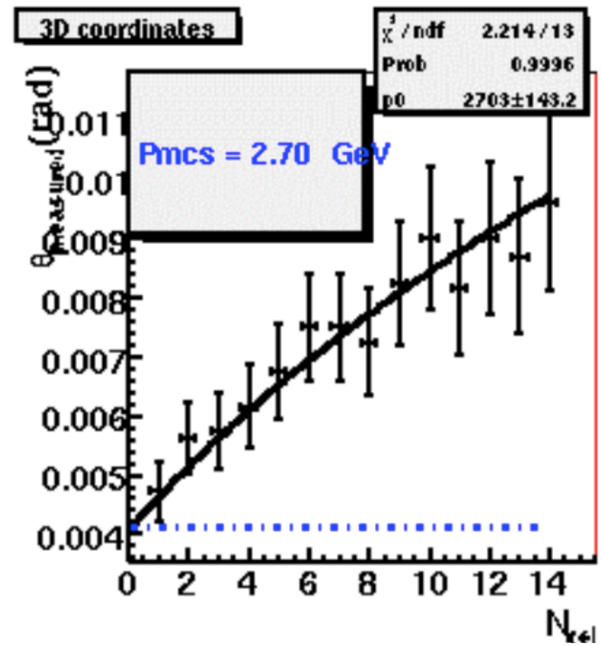


KINK TOPOLOGY

Flight Length = 1160 μm

With γ attached

IP = 8±8 μm

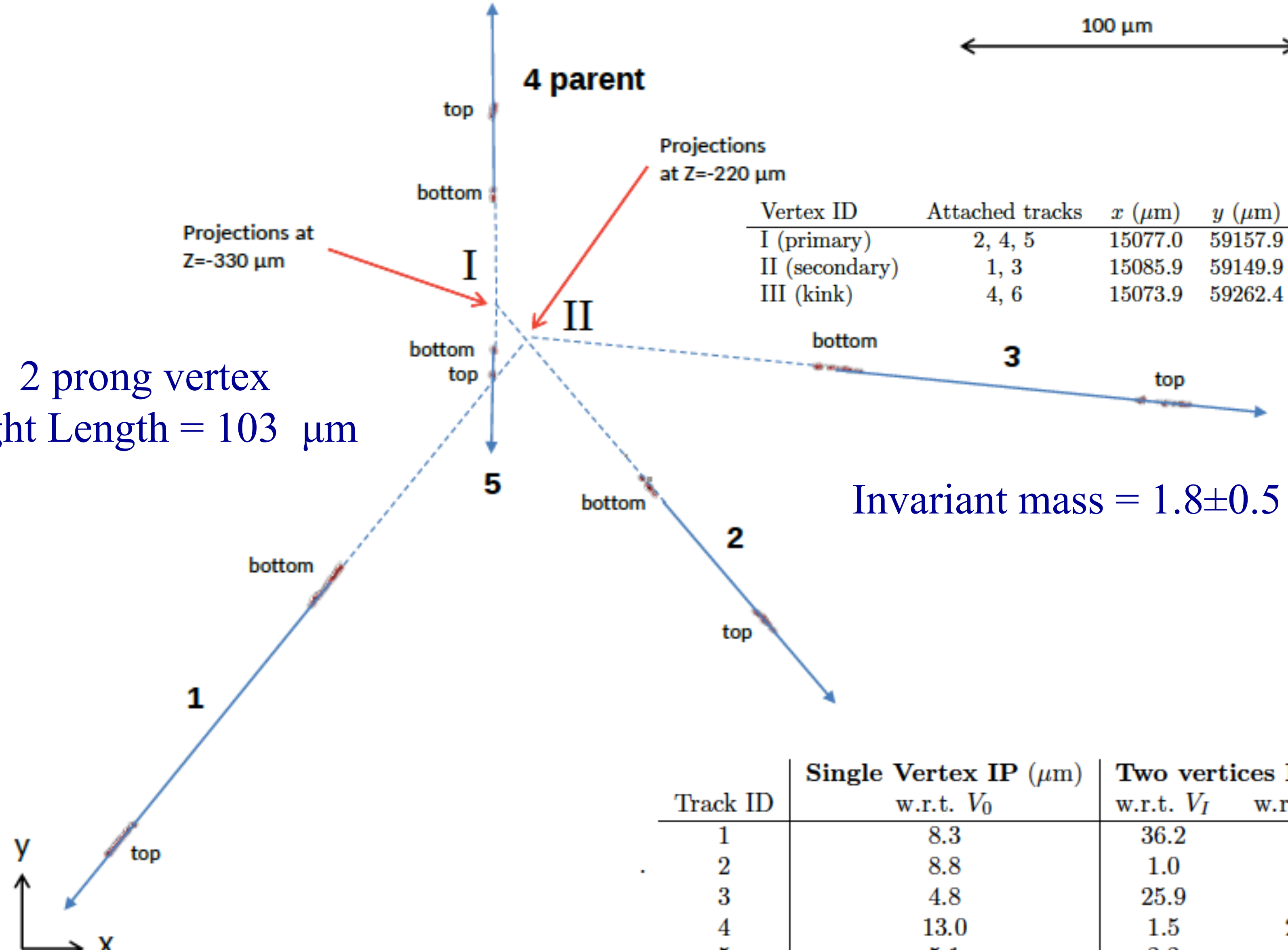


Track ID	p best fit (GeV/c)	68 % p range (GeV/c)
1	2.1	[1.6 ; 3.1]
3	4.3	[3.1 ; 7.1]
5	0.54	[0.45 ; 0.68]
6 (daughter)	2.7	[2.1 ; 3.7]

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

not passing the standard cuts to be a tau candidate

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



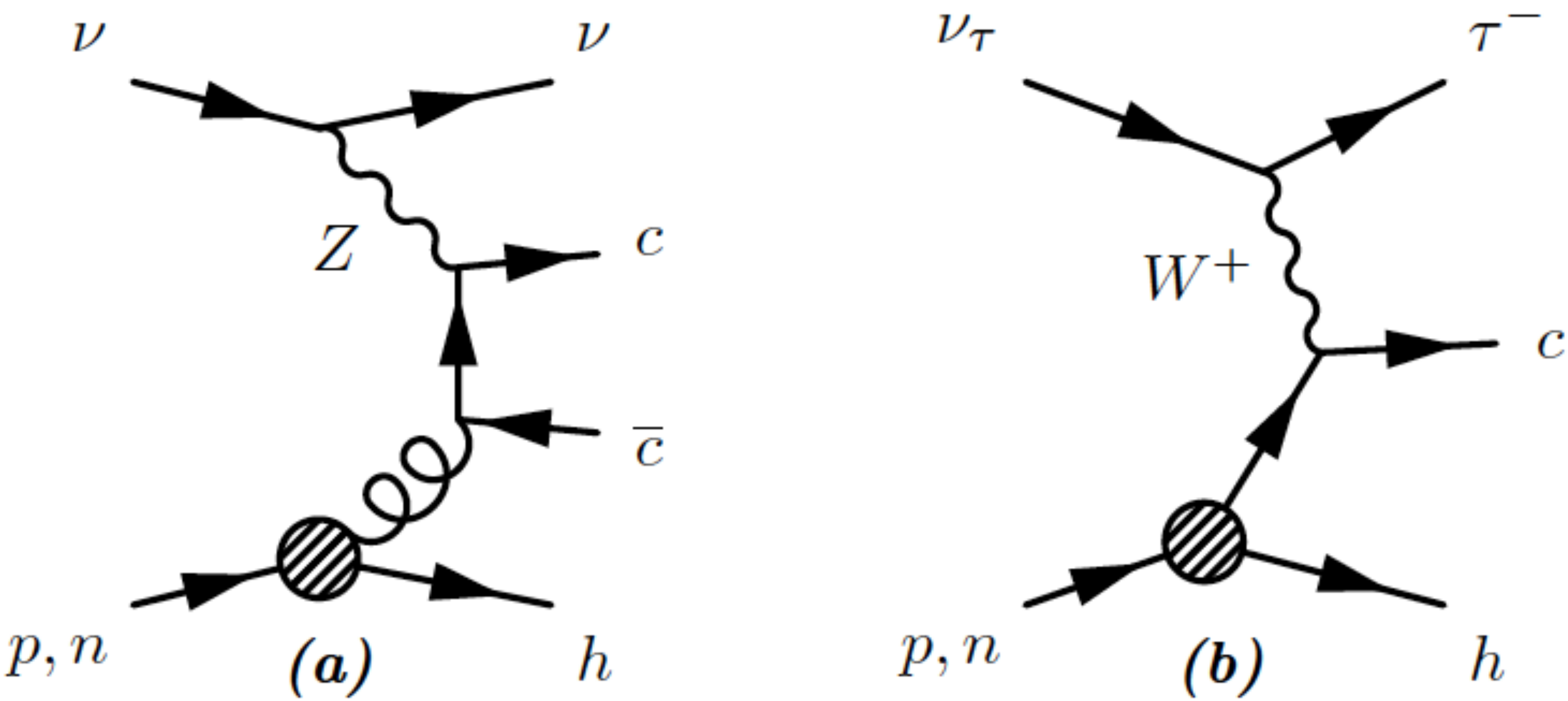
Vertex ID	Attached tracks	x (μm)	y (μm)	z (μm)
I (primary)	2, 4, 5	15077.0	59157.9	-33081.8
II (secondary)	1, 3	15085.9	59149.9	-32979.2
III (kink)	4, 6	15073.9	59262.4	-31926.4

2 prong vertex
Flight Length = 103 µm

Invariant mass = 1.8±0.5 GeV

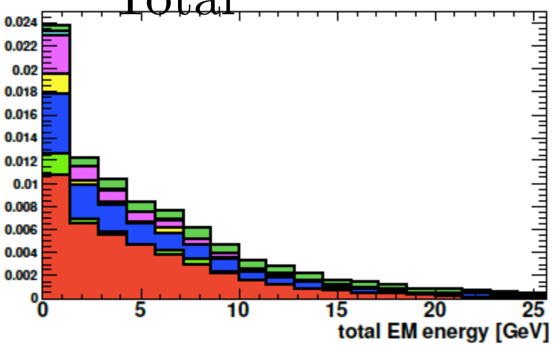
Track ID	**Single Vertex IP** (μm)	**Two vertices IP** (μm)	
	w.r.t. V_0	w.r.t. V_I	w.r.t. V_{II}
1	8.3	36.2	0.1
2	8.8	1.0	6.5
3	4.8	25.9	0.1
4	13.0	1.5	20.4
5	5.1	2.2	9.6

Leading Feynman diagrams

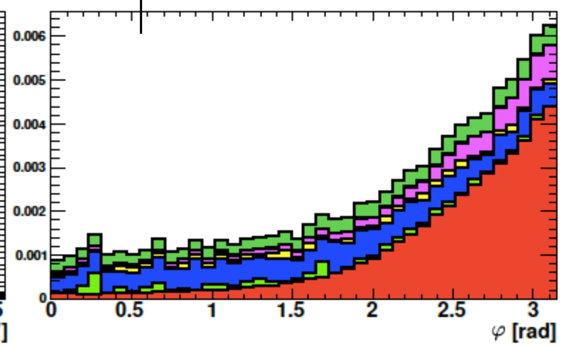


Expected yield and multivariate analysis

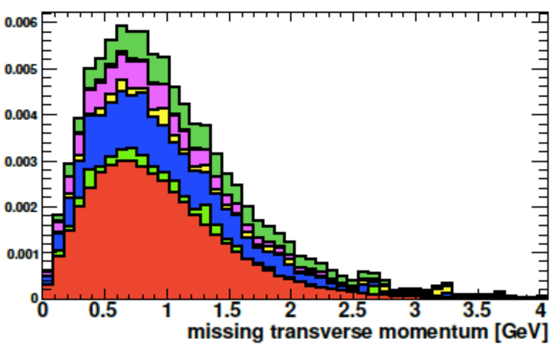
Sample	Muon misidentified	Expected events (10^{-3})
ν_τ CC + charm		45
ν_μ CC + charm + h_{int}	yes	21
ν_μ NC + $c\bar{c}$		13
ν_τ CC + h_{int}		9
ν_μ CC + $2h_{\text{int}}$	yes	4
ν_μ NC + $2h_{\text{int}}$		4
Total		100



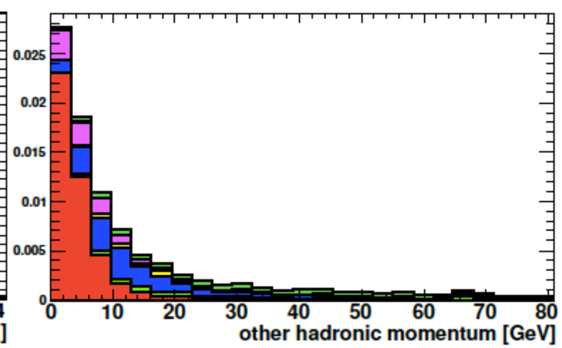
(a) Total EM energy



(b) φ

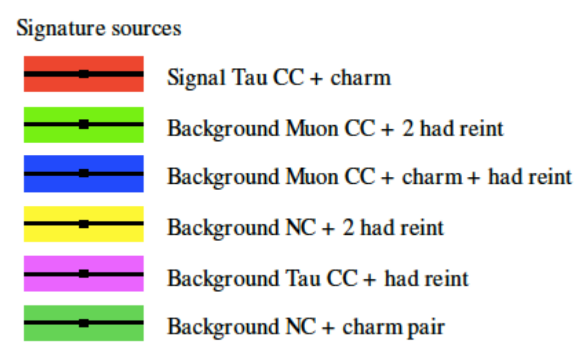


(c) Missing transverse momentum

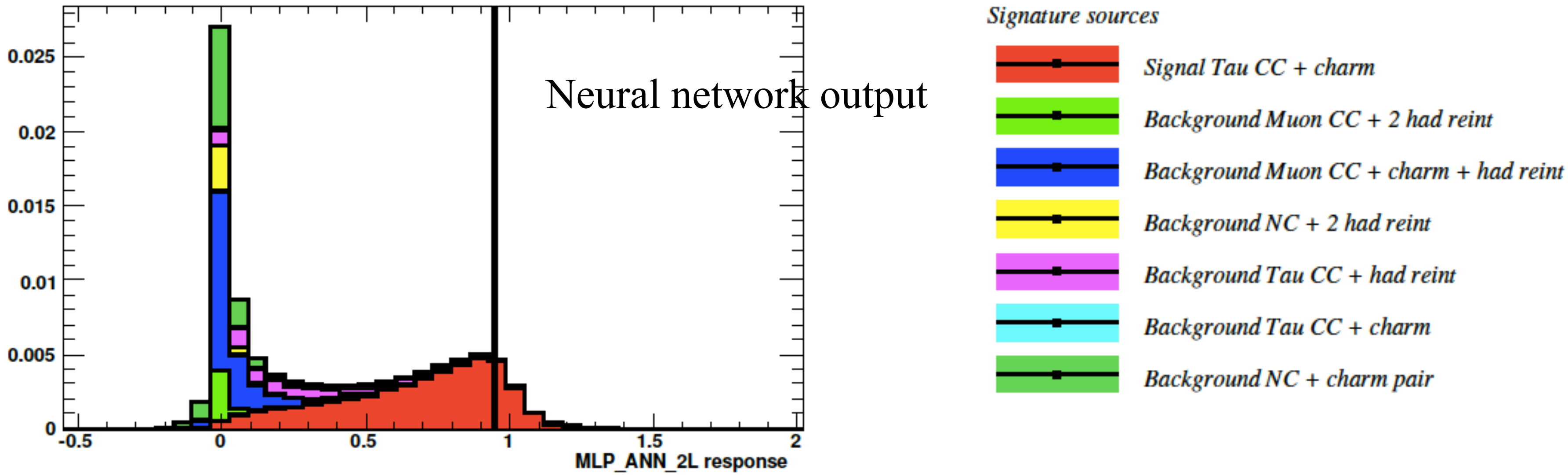


(d) Other hadronic momentum

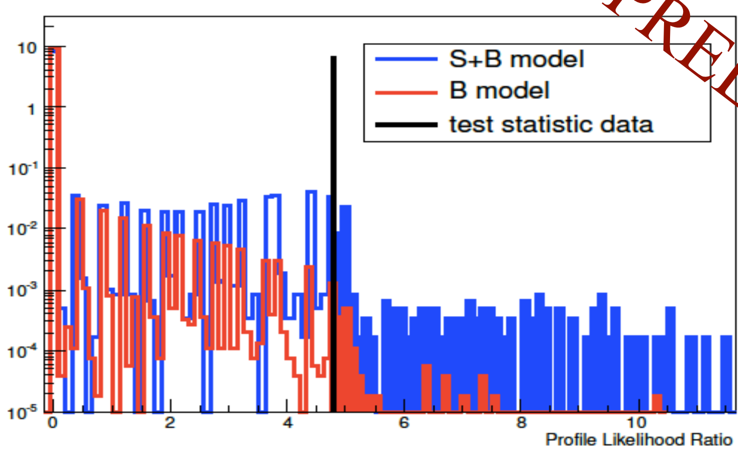
PRELIMINARY



Observation of a tau neutrino interaction with a charmed hadron production



PRELIMINARY



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

x PDF from ANN output

n_i = yield of i-th process

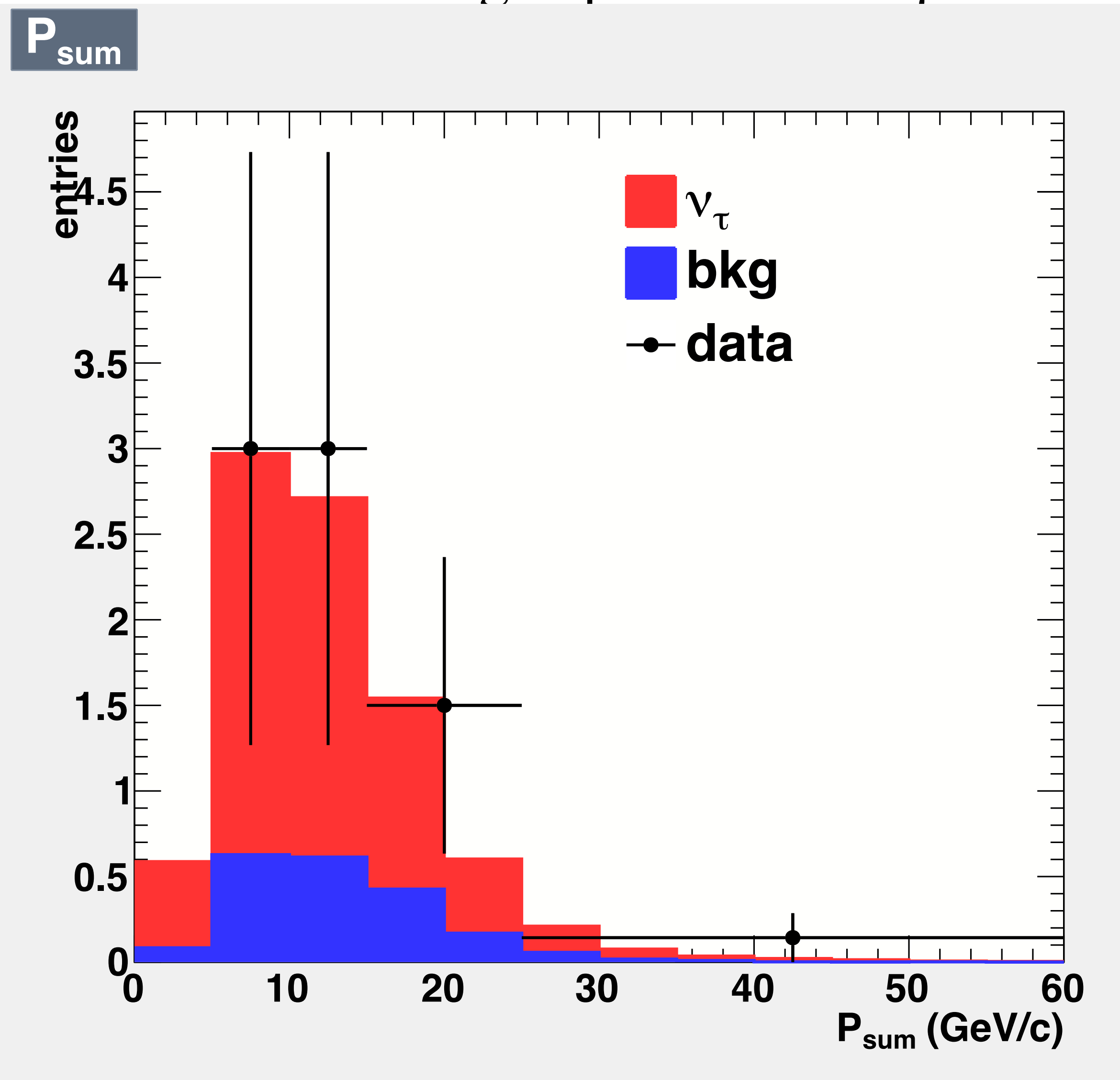
Background only → $\mu = 0$

$$\mathrm{CL} = 2.6 \times 10^{-4} \rightarrow 3.4\ \sigma$$

Analysis of the Extended Sample

VISIBLE ENERGY OF ALL CANDIDATES

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

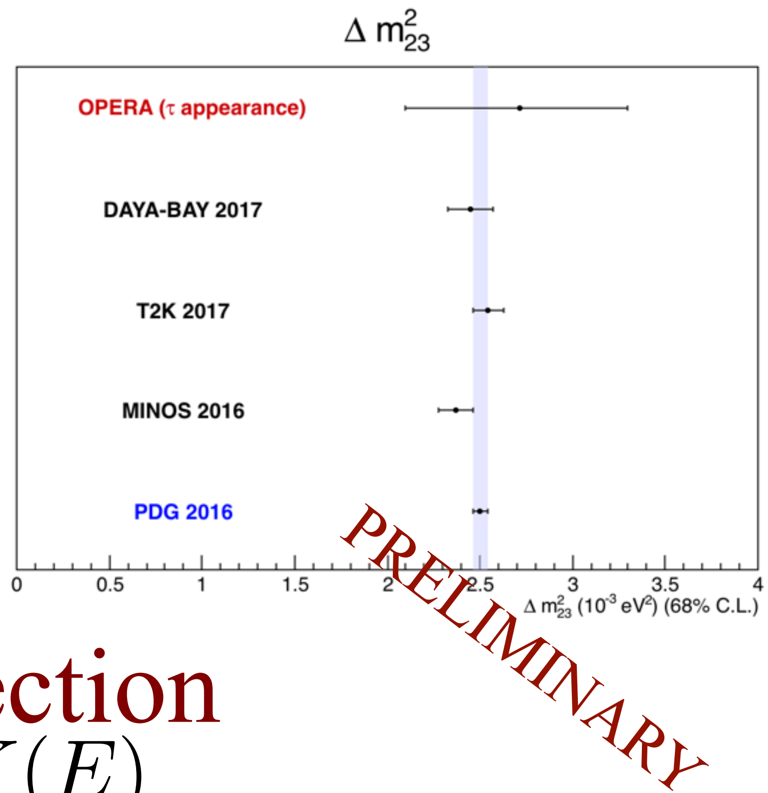


PRELIMINARY

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} $(10^{-3}\ \mathrm{eV}^2)$
6.8	2.0	10	2.7 ± 0.6 68% C.L



ν_τ cross-section

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

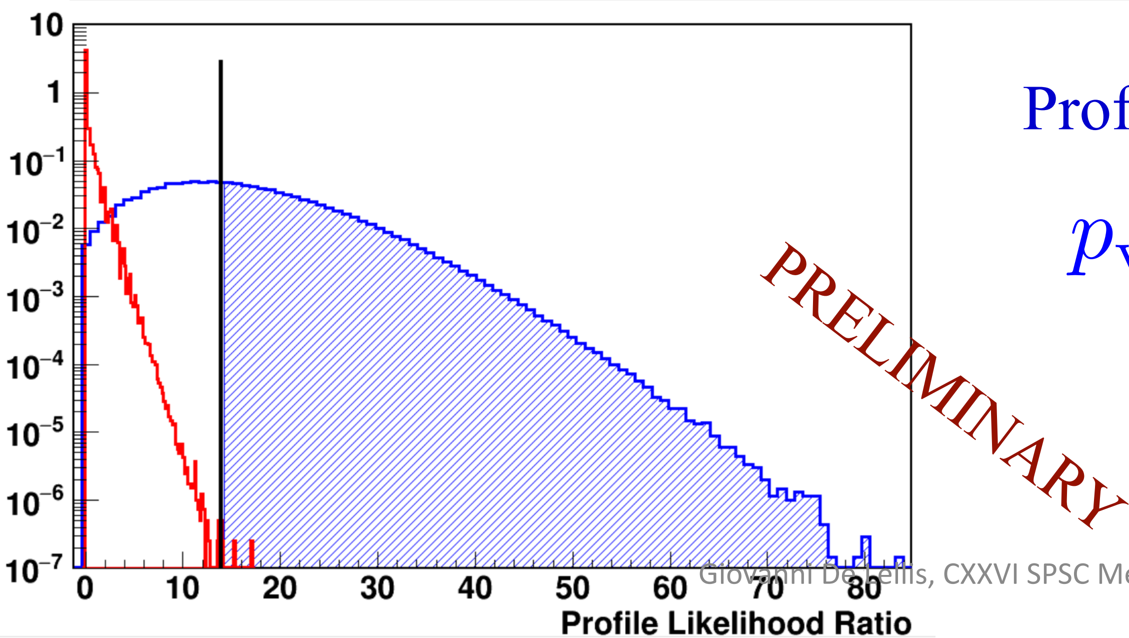
Δm^2_{23} $(10^{-3}\ \mathrm{eV}^2)$	Expected Signal	Expected Background	Observed ν_τ	$\sigma^0_{\nu_\tau}$ $(10^{-39}\mathrm{cm}^2\mathrm{GeV}^{-1})$
2.5	6.8	2.0	10	8^{+4}_{-3}

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	0.60	3
	0.13	1.26	–	1.39	2.36	3
$\tau \to 3h$	0.21	0.003	–	0.21	1.14	1
	0.23	0.08	–	0.31	0.69	2
$\tau \to \mu$	0.003	–	0.0002	0.003	0.57	1
	0.005	–	0.016	0.021	0.57	0
$\tau \to e$	0.035	–	–	0.03	0.79	0
	0.0004	–	–	0.0004	0.04	0
Total	0.63	1.37	0.02	2.0 ± 0.5	6.8 ± 1.4	10



Test statistic:

Profile likelihood ratio one sided

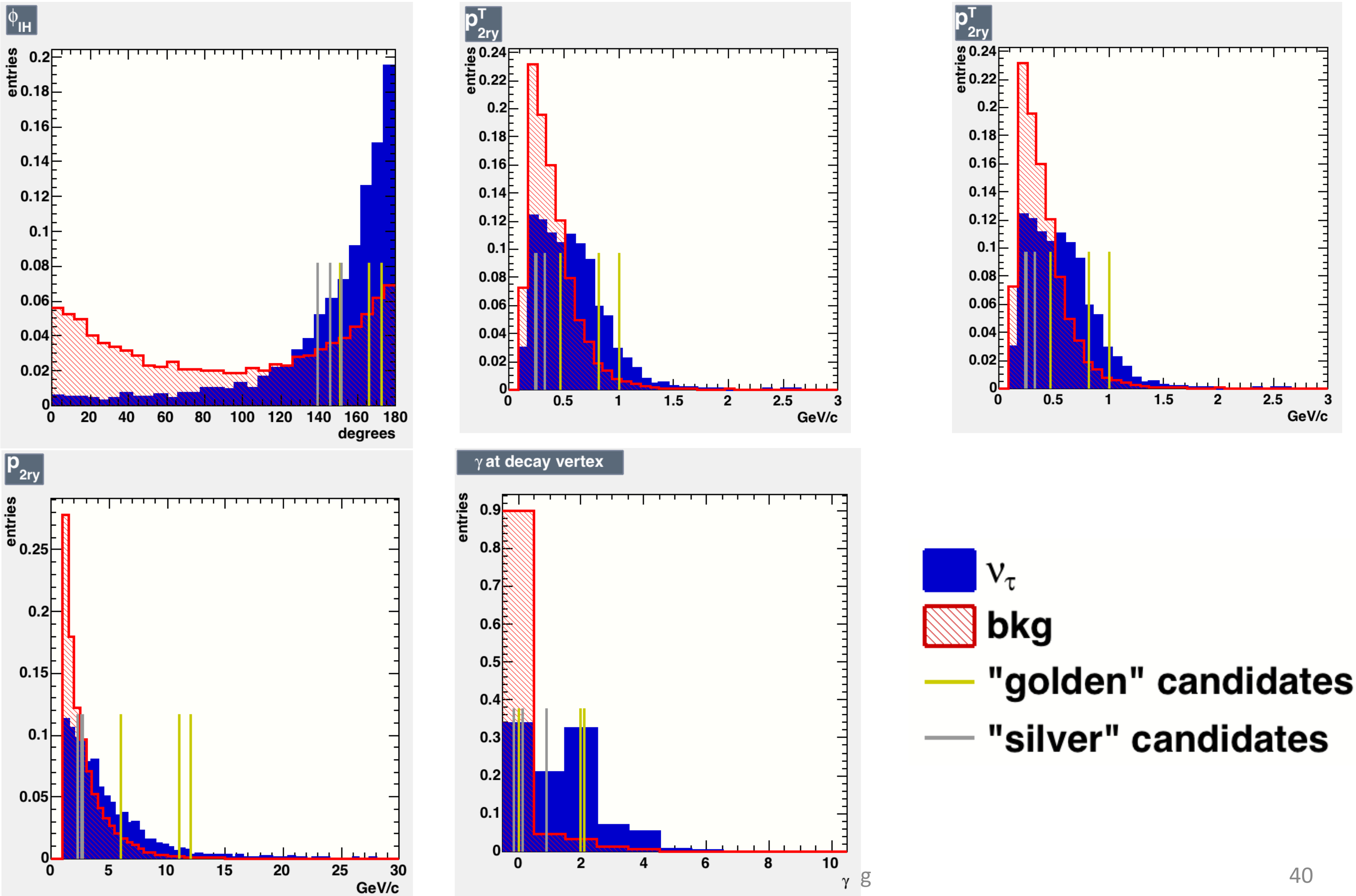
$$p_{\text{value}} = 9.4 \times 10^{-8}$$

$5.2\,\sigma$ significance

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

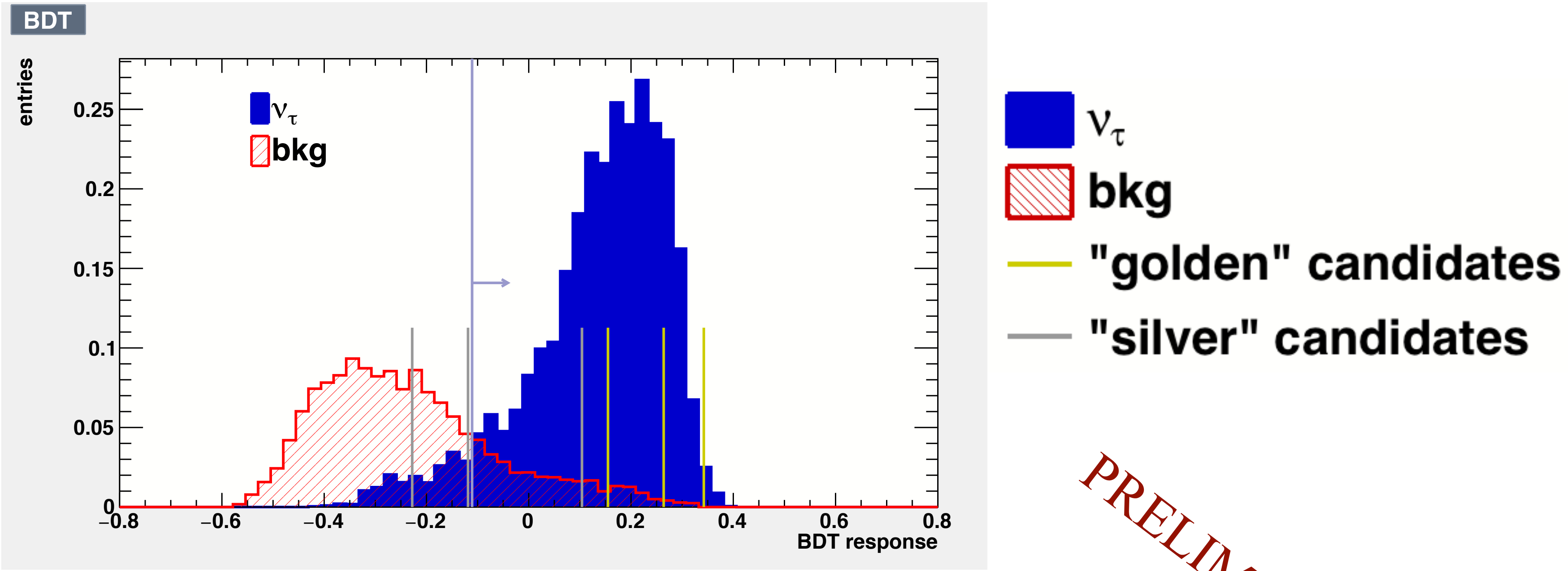
Input variables for BDT analysis

the $\tau \rightarrow h$ channel



BDT output

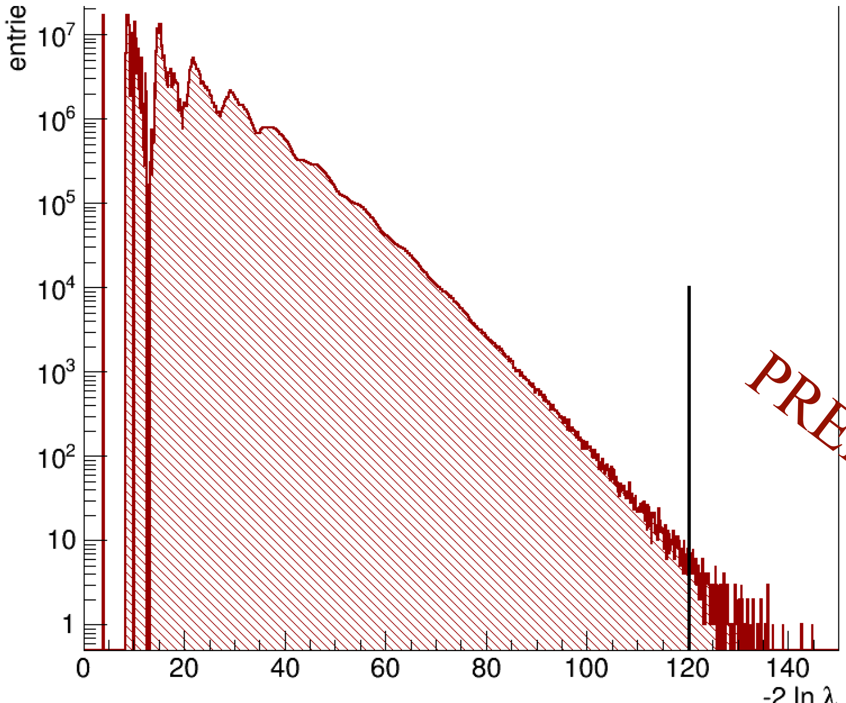
the $\tau \rightarrow h$ channel



PRELIMINARY

Likelihood analysis with BDT discrimination
using 4 channels

Channel	Expected Background				Exp. Signal	Observed
	Charm	Had. re-interaction	Large μ-scat.	Total		
$\tau \to 1h$	0.15	1.28	–	1.43	2.96	6
$\tau \to 3h$	0.44	0.09	–	0.52	1.83	3
$\tau \to \mu$	0.008	–	0.02	0.03	1.15	1
$\tau \to e$	0.035	–	–	0.03	0.84	0
Total	0.63	1.37	0.02	2.0 ± 0.5	6.8 ± 1.3	10



PRELIMINARY

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

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

$5.0\,\sigma$ significance

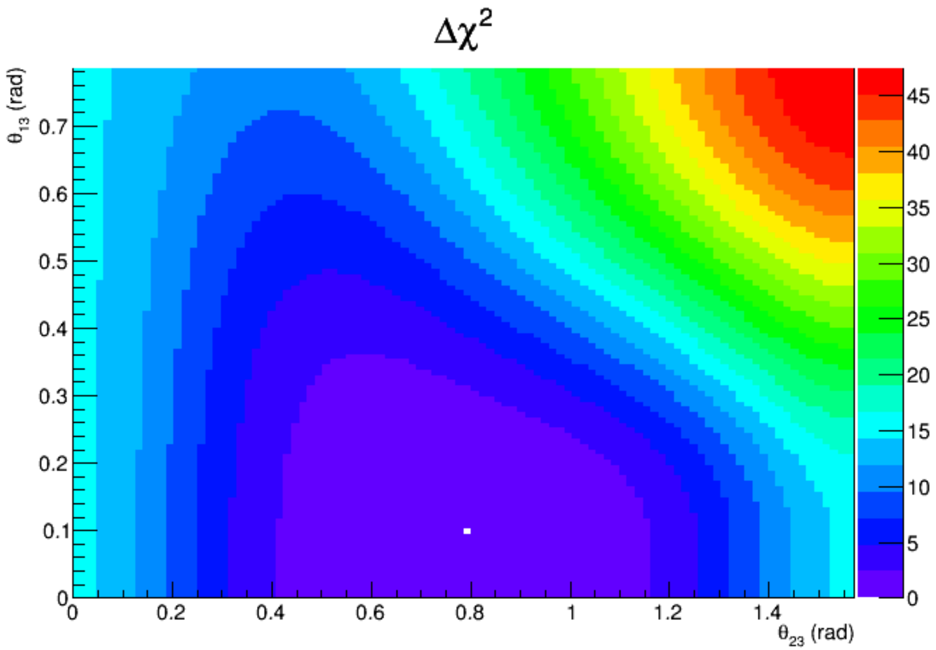
Publications being issued

- 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

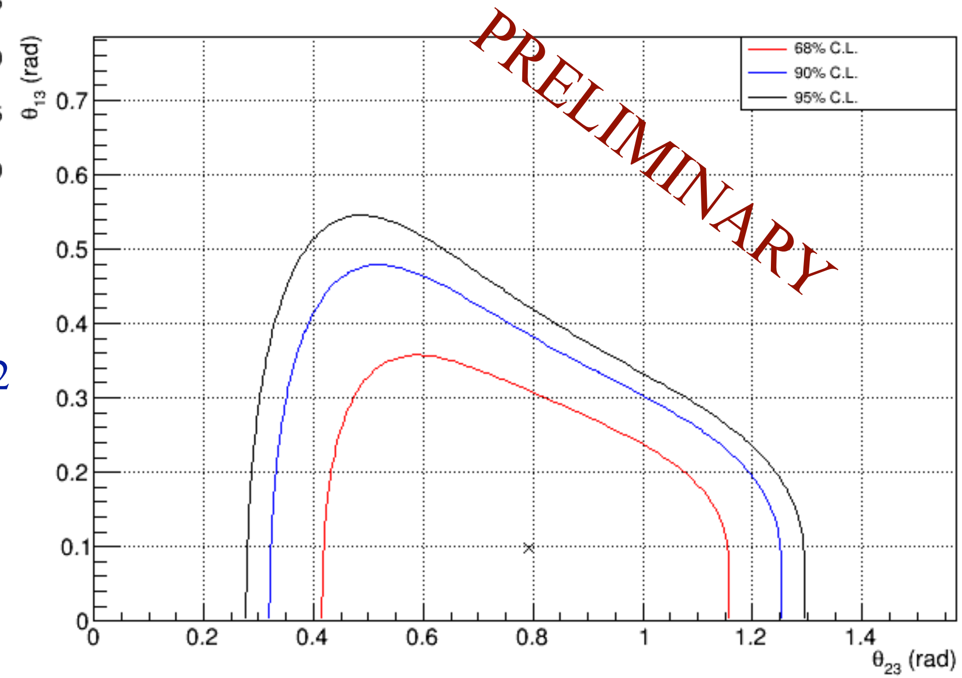
Forthcoming publications

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

Combining $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ searches



10 ν_τ candidates
35 ν_e candidates



$\Delta m^2_{31} = (2.54 \pm 0.05) \times 10^{-3}$ eV^2

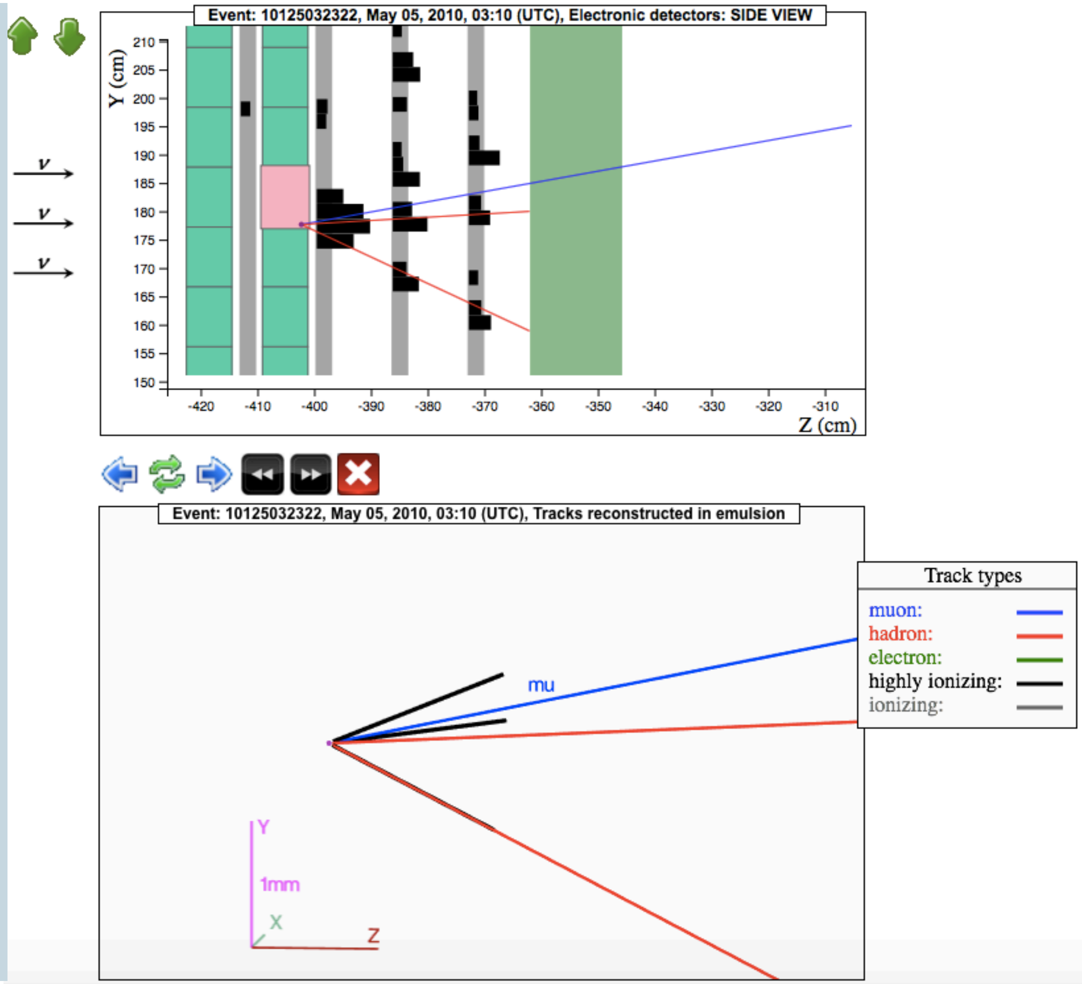
$\Delta m^2_{21} = 7.37 \times 10^{-5}$ eV^2

Standard 3 flavour scheme

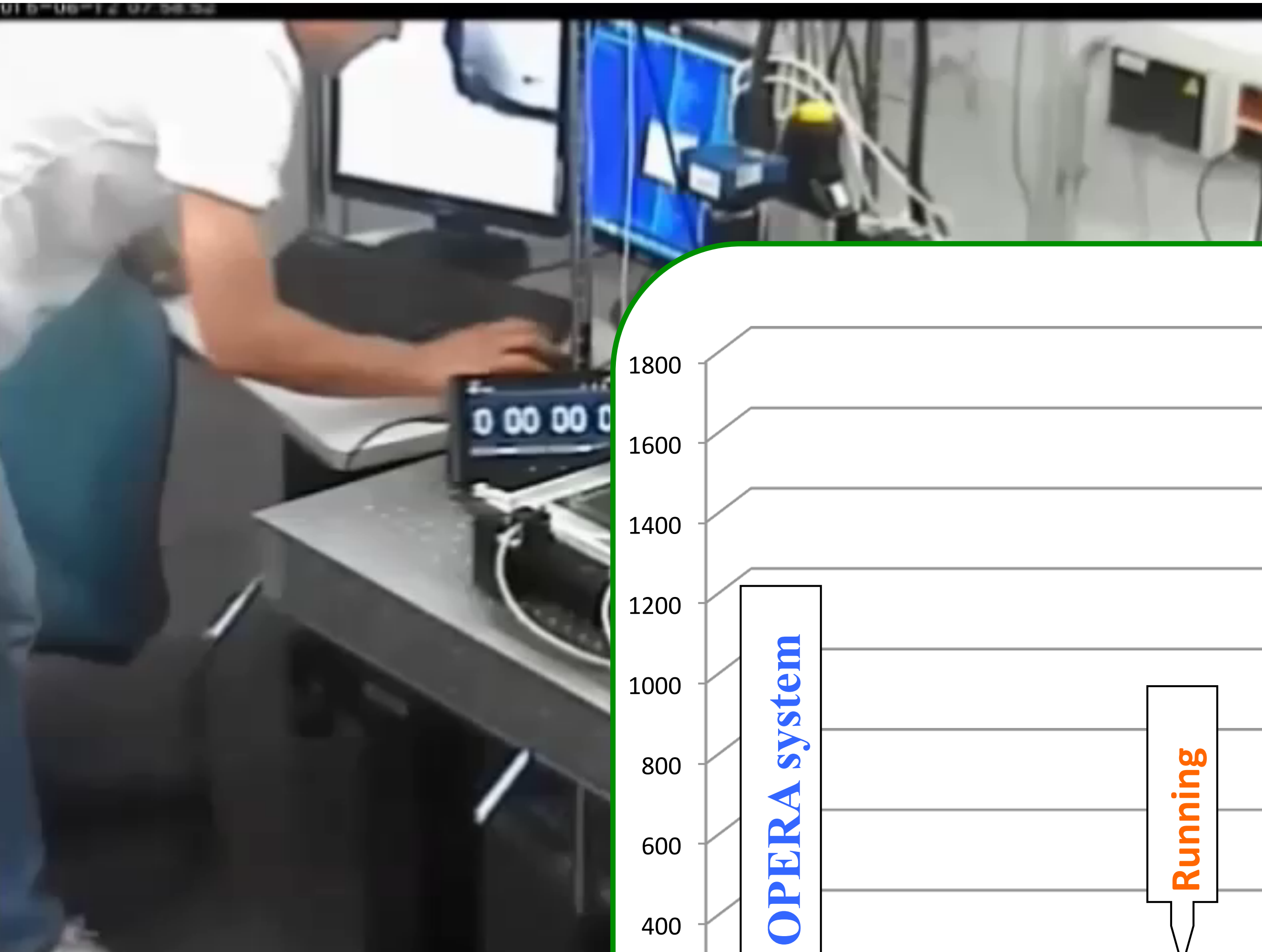
Best fit: $(\theta_{23}, \theta_{13}) = (0.79, 0.10)$ [rad]

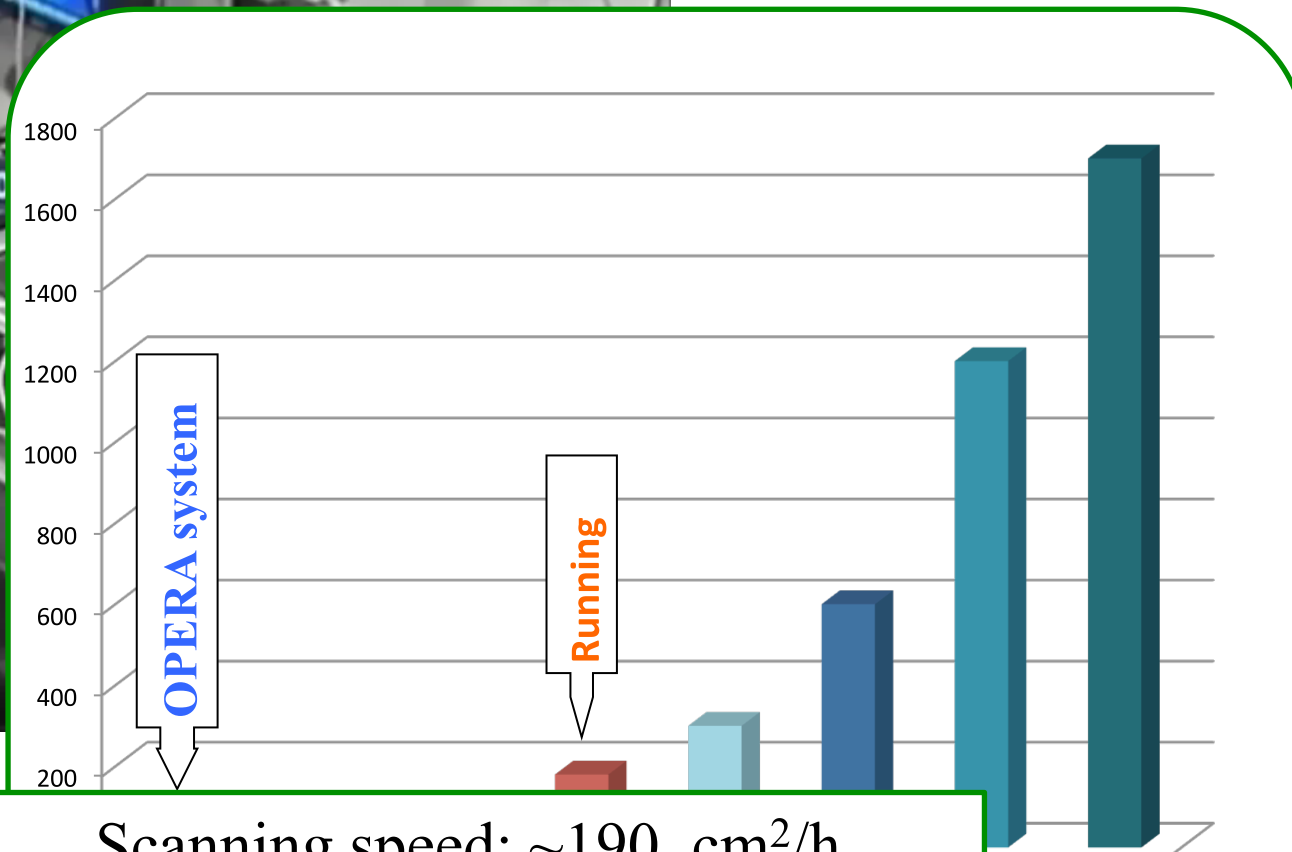
OPERA Open Data at CERN

- OPERA is the first non-LHC experiment joining the educational and research program of the Open Data Access group
- A sample of neutrino interactions reconstructed in the bricks now available at CERN: data & event display (effective for education)



TECHNOLOGICAL DEVELOPMENTS





Scanning speed: ~190 cm^2/h
~10 times faster
with a much wider angular acceptance

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

THANKS FOR YOUR ATTENTION

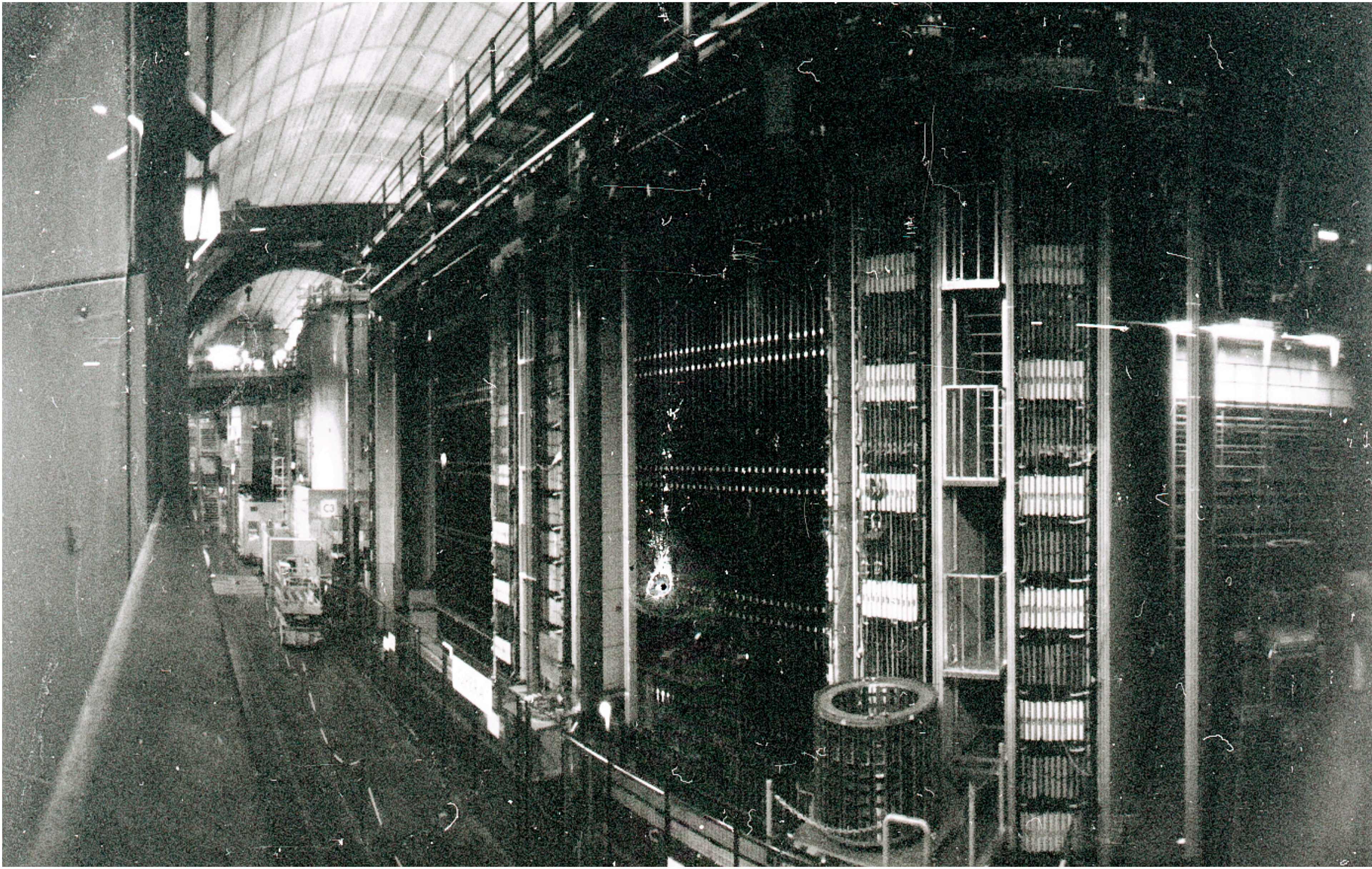


Image taken using OPERA emulsion film with pinhole handmade camera (Di Ferdinando)