Belgium
ULB Brussels

Korea
Jinju

Russia
INR RAS Moscow
LPI RAS Moscow
SINP MSU Moscow
JINR Dubna

Switzerland
Bern

Italy
Bari
Bologna
LNF
LNGS
Naples
Padova
Rome
Salerno

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg

Japan
Aichi
Kobe
Nagoya
Toho
Nihon

Turkey
METU Ankara

Germany
Hamburg

Israel
Technion Haifa

Neutrino oscillations search with the OPERA experiment

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on behalf of the OPERA Collaboration

La Thuile 2017
March/6/2017

Goal of OPERA

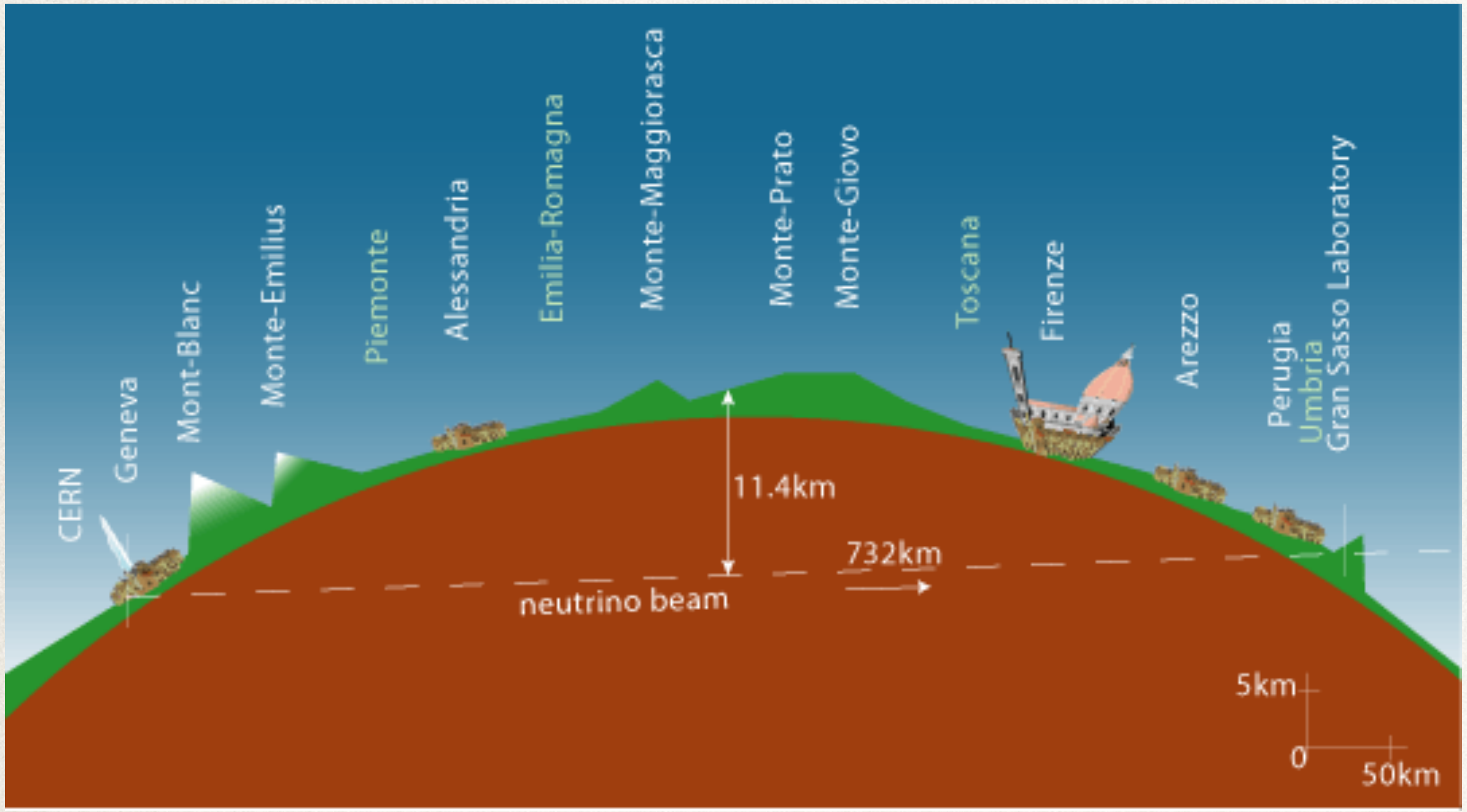
- **The OPERA experiment (Oscillation Project with Emulsion tRacking Apparatus) was designed to directly observe, for the first time in <u>APPEARANCE MODE</u>, the $\nu_\mu \rightarrow \nu_\tau$ oscillation in a pure ν_μ beam.**

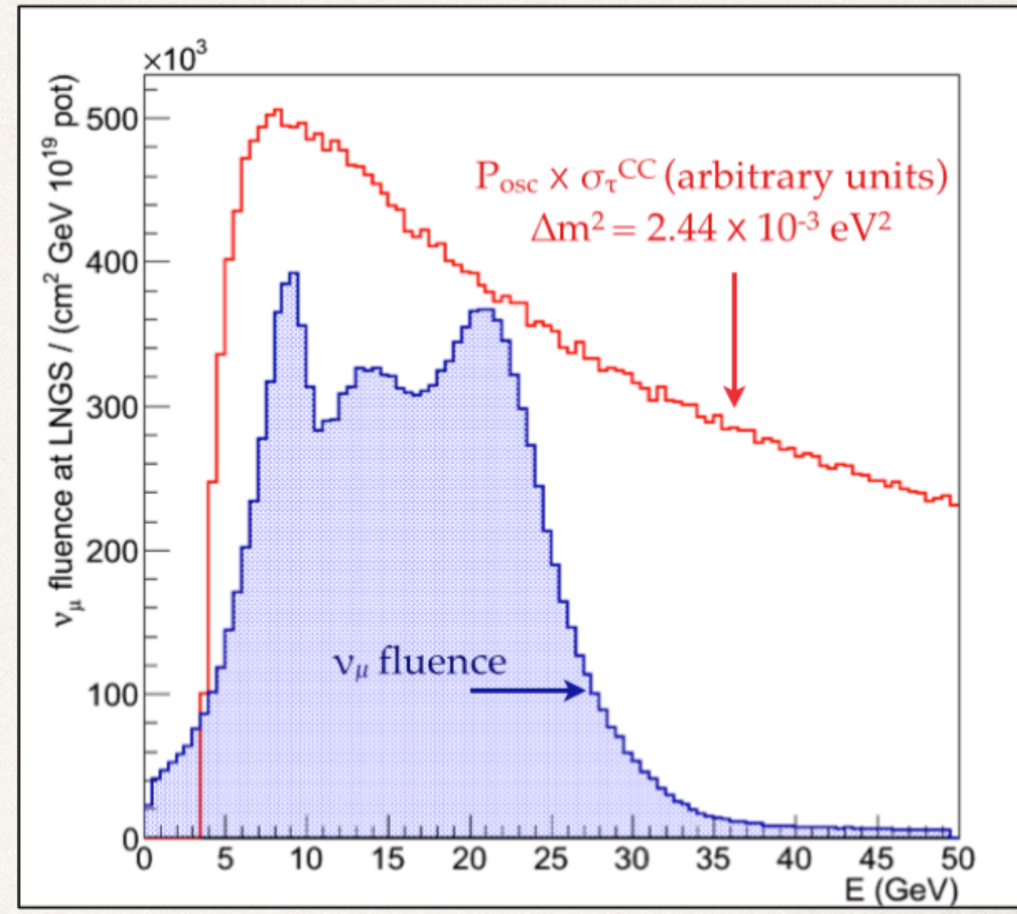
- The search for direct appearance was based on revealing the short-lived τ lepton produced in ν_τ charged-current interactions

Channel	BR
$\tau^- \rightarrow e^- \nu_\tau \overline{\nu_e}$	17.8%
$\tau^- \rightarrow \mu^- \nu_\tau \overline{\nu_\mu}$	17.7%
$\tau^- \rightarrow h^- \nu_\tau (n\pi^0)$	49.5%
$\tau^- \rightarrow 3h \nu_\tau (n\pi^0)$	15.0%

- Requirements:
  - High energy beam for τ production
  - Long baseline for oscillation at the atmospheric scale
  - High density and large target mass for statistics
  - Micrometric accuracy and resolution to identify τ decays and neutrino interaction kinematics

CERN Neutrinos to Gran Sasso





- Long baseline (730 km from CERN to LNGS)
- $<E_\nu>$ on target ~17 GeV
- L/E ~ 43 km/GeV

- $\overline{\nu}_\mu$ contamination = 2.1%
- ν_e and $\overline{\nu}_e$ contam. <1%
- ν_τ contamination negligible

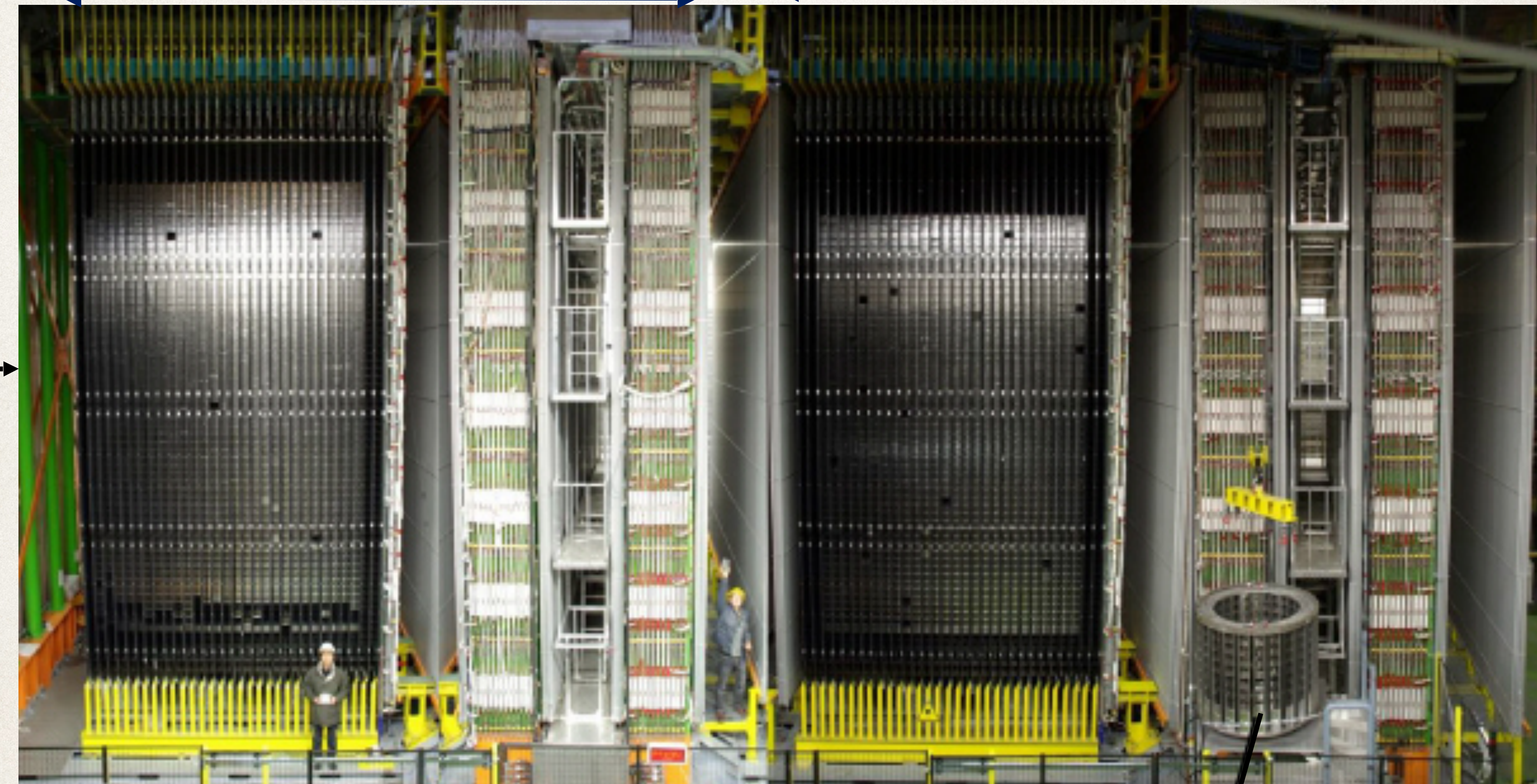
- Data taking from 2008 to 2012
- #p.o.t. = $1.8 \cdot 10^{20}$
- 5603 events used for the present analysis (almost full stat.)

The OPERA detector

SM1

SM2

ν



Target Area

Brick walls+Target Tracker

Scintillator strip planes

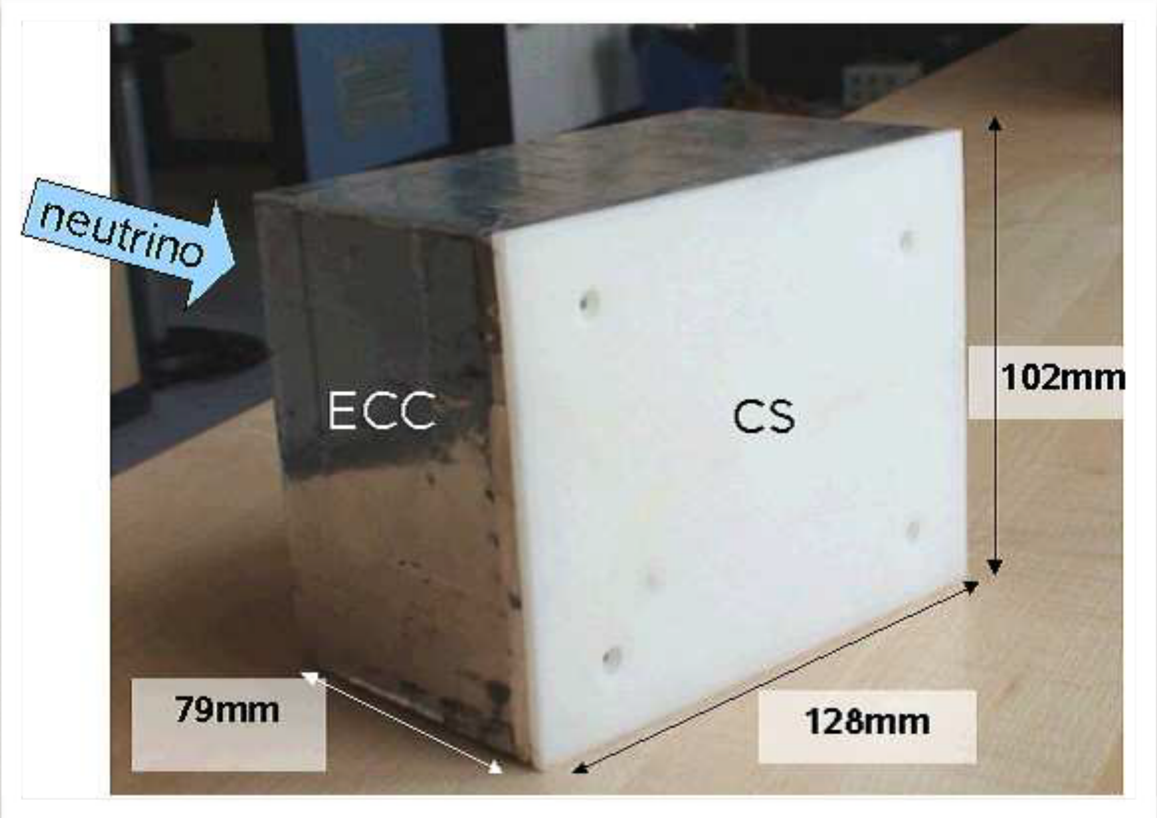
Spectrometer

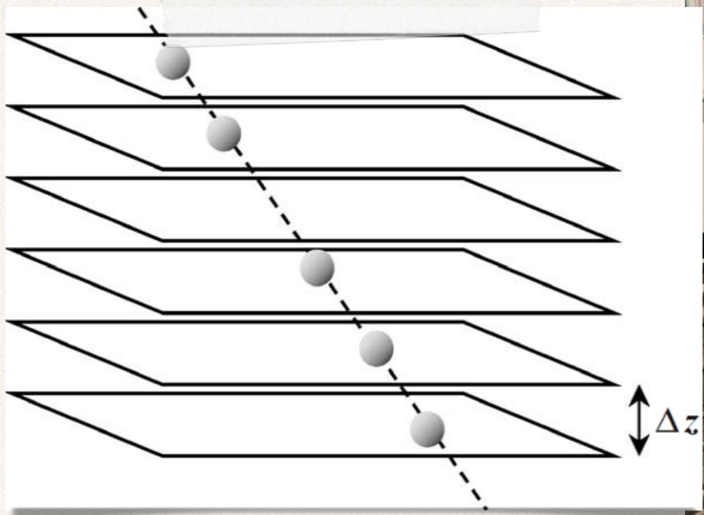
RPC+Drift Tubes

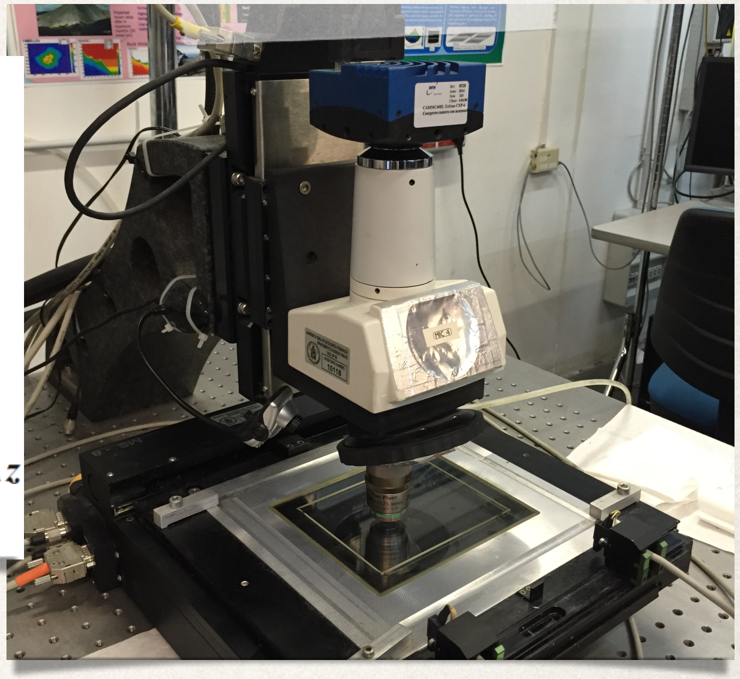
Brick Manipulating System

- Underground location (10^6 reduction of cosmic ray flux)

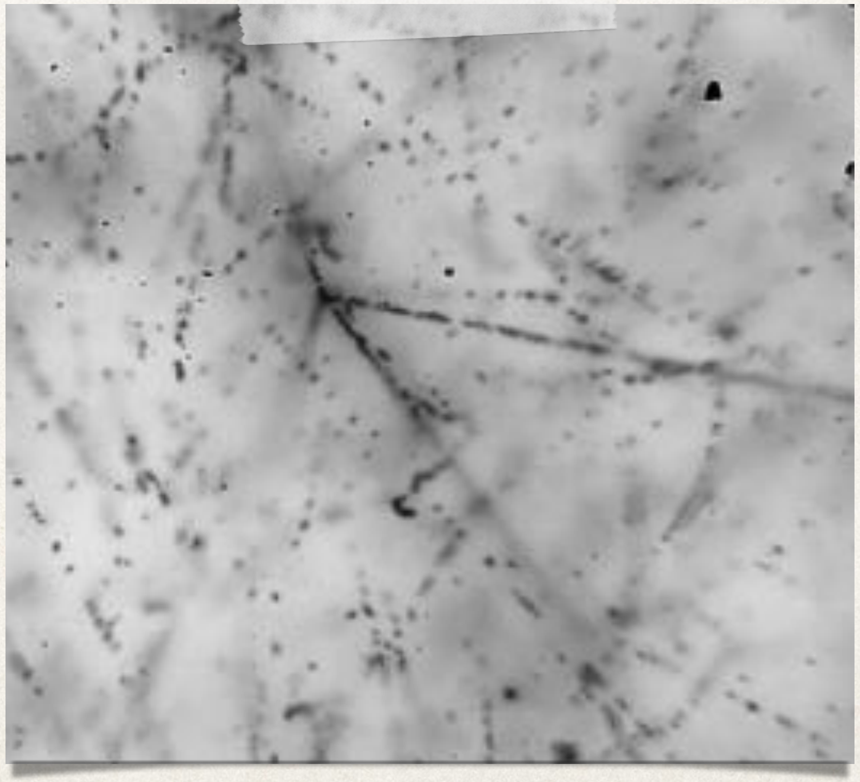
Emulsion Cloud Chamber

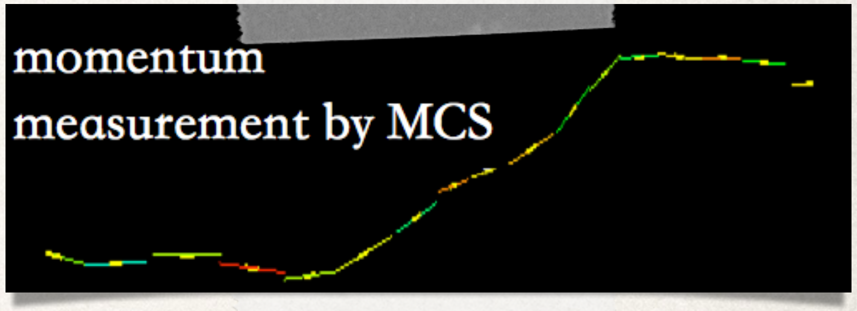


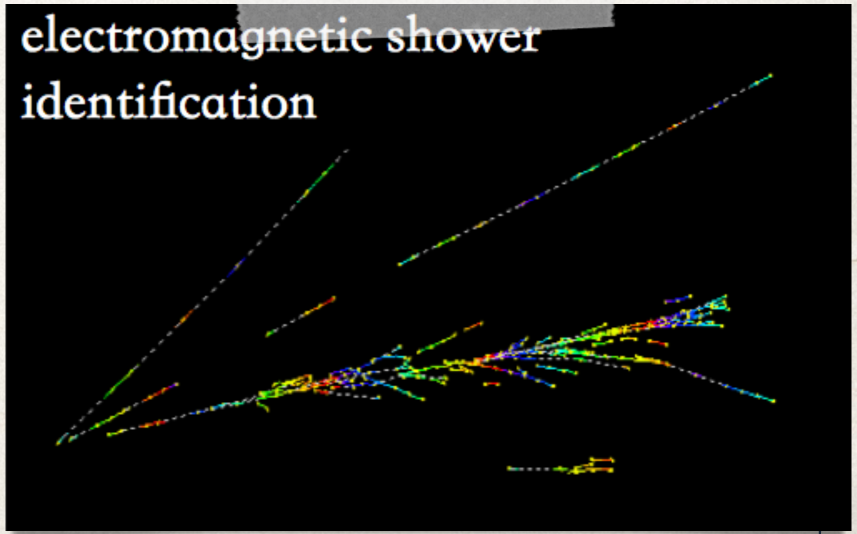




- 57 films of nuclear emulsion
- 56 lead plates (1mm thick)
- 2 Changeable Sheets
- 8.3 kg
- 10 X_0
- Fast fully automated optical microscopes
- 3D track reconstruction with micrometric resolution

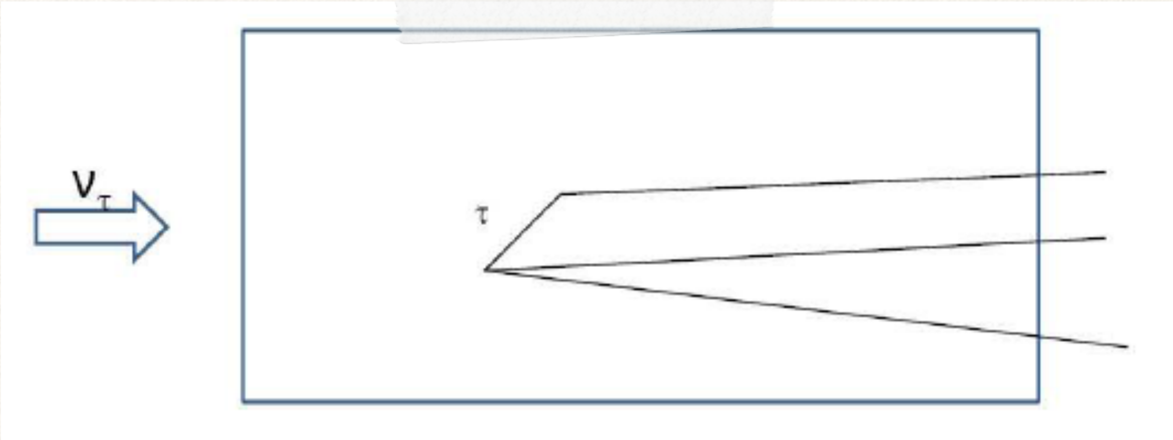






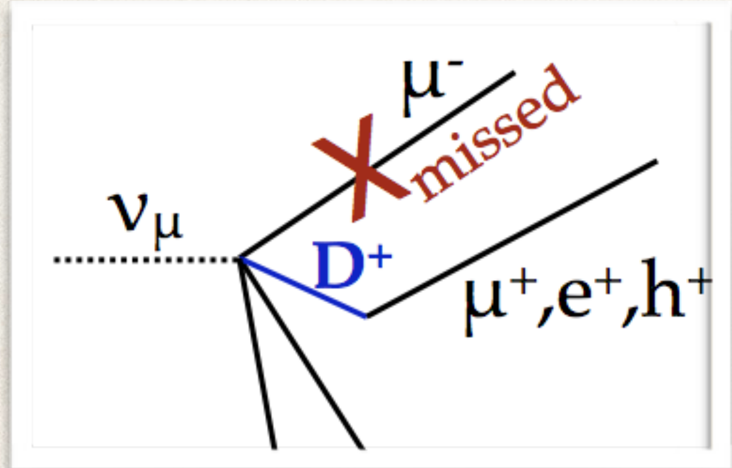
Main background sources

Signal topology:



Possible backgrounds:

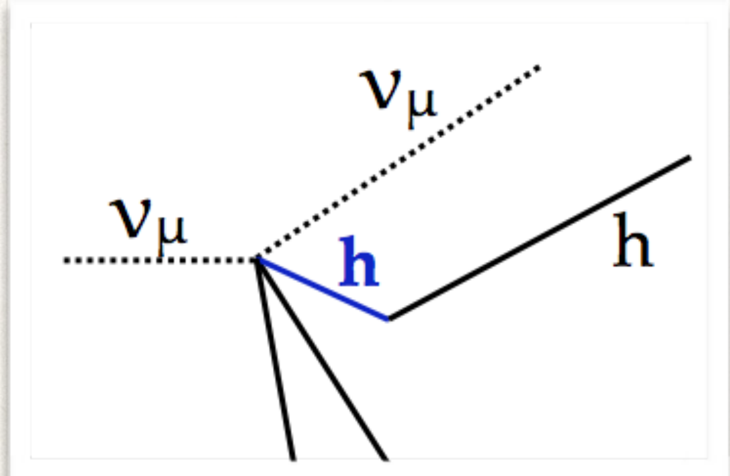
Charmed hadron decays where muon at 1ry vtx is not identified



Eur. Phys.J. C74 (2014) 2986

Reduced by Track Follow-down procedure

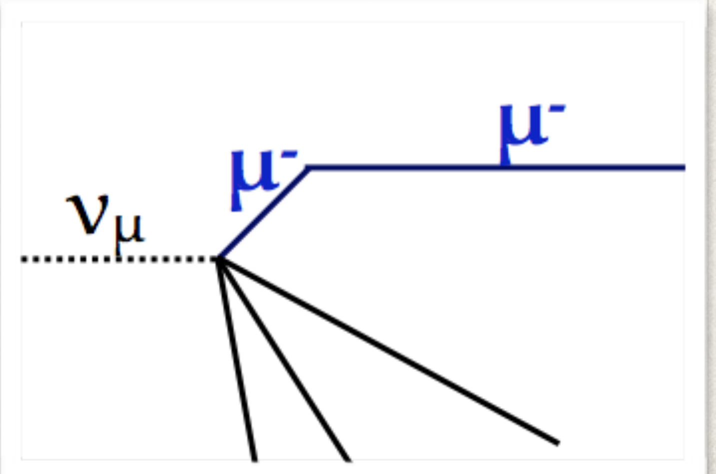
Hadronic re-interactions



PTEP9 (2014) 093C01

Reduced by large angle scanning and nuclear fragment search

Large angle muon scattering



IEEE Transactions on Nuclear Science Vol. 62, 5, 2015

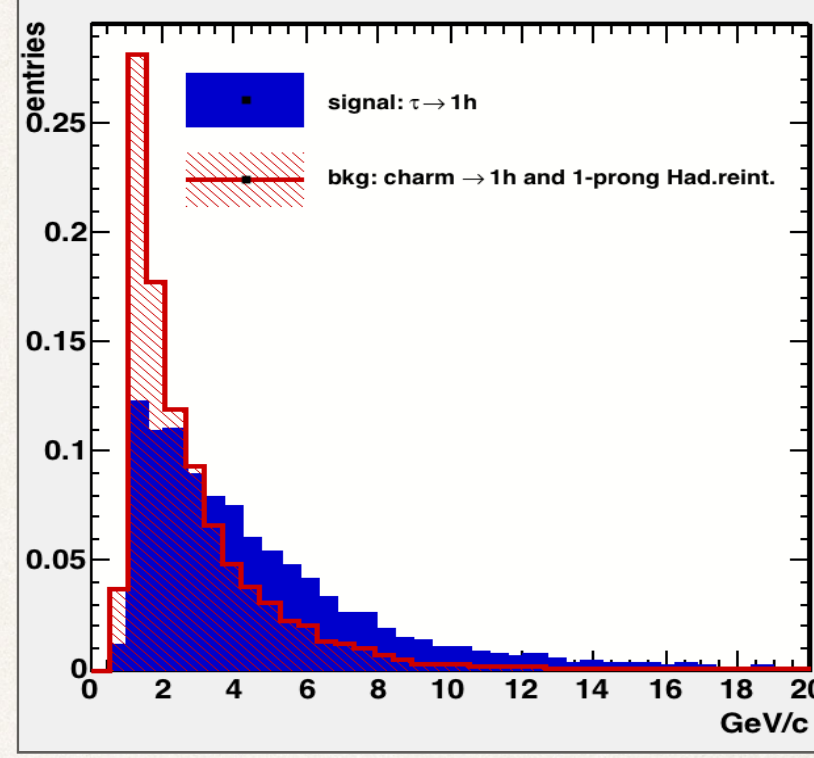
ν_τ Appearance kinematical selection

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

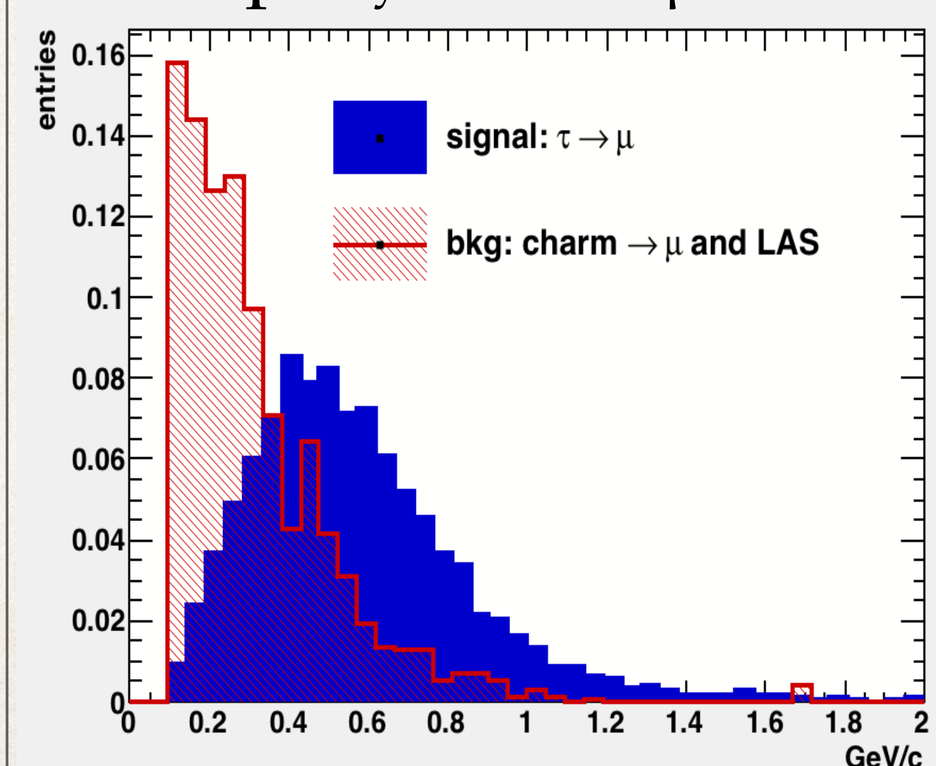
Cuts marked with $\star$ are not applied for Quasi-Elastic event

* p^T_{2ry} cut is 0.3 in the presence of γ particles associated to the decay vertex

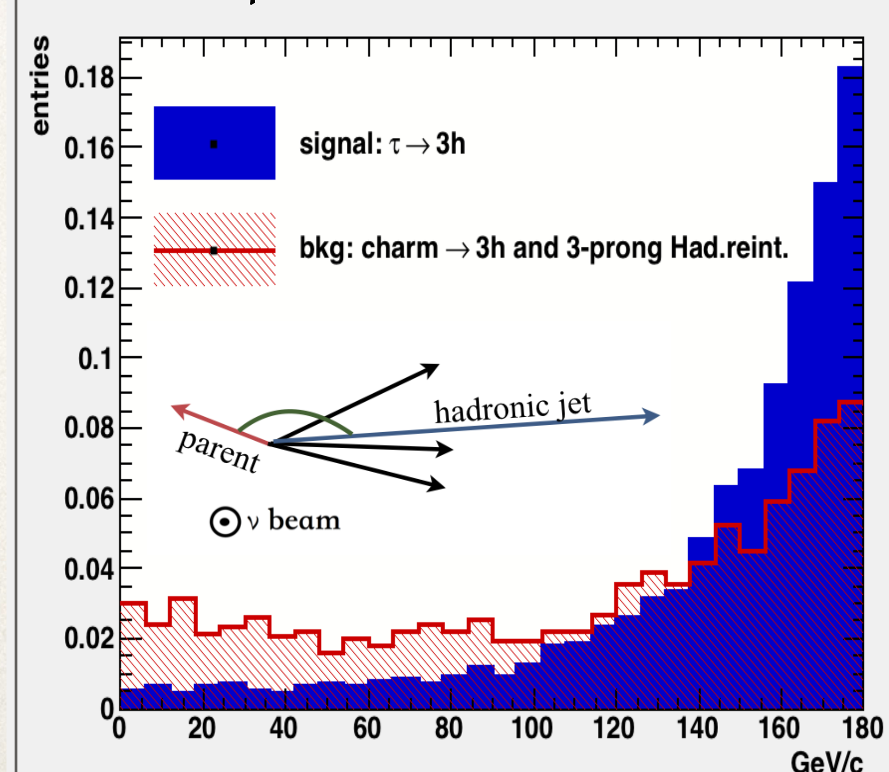
p_{2ry} for $\tau \to 1h$



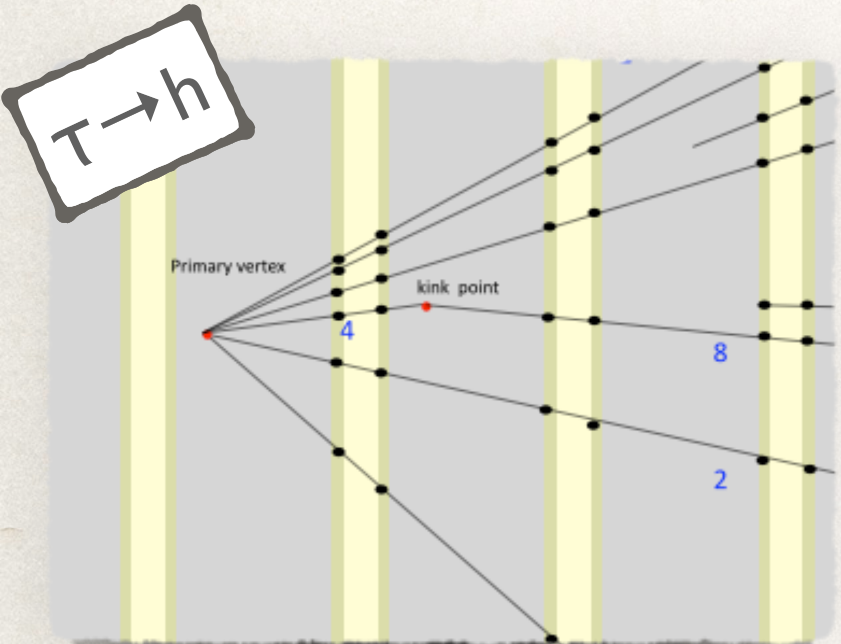
p^T_{2ry} for $\tau \to \mu$



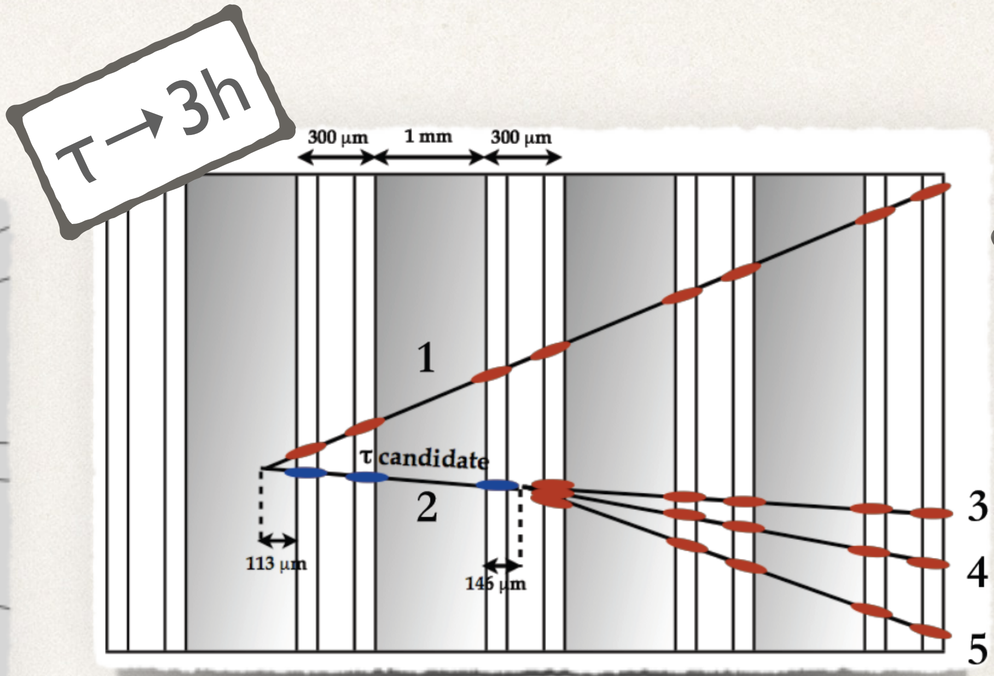
ϕ_{lH} for $\tau \to 3h$



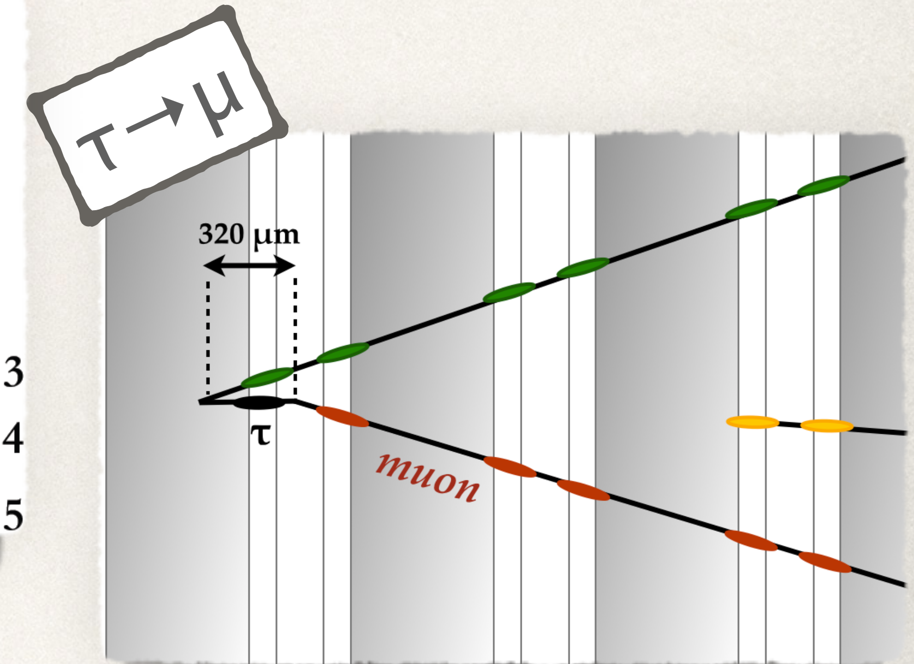
Five ν_τ Candidates observed



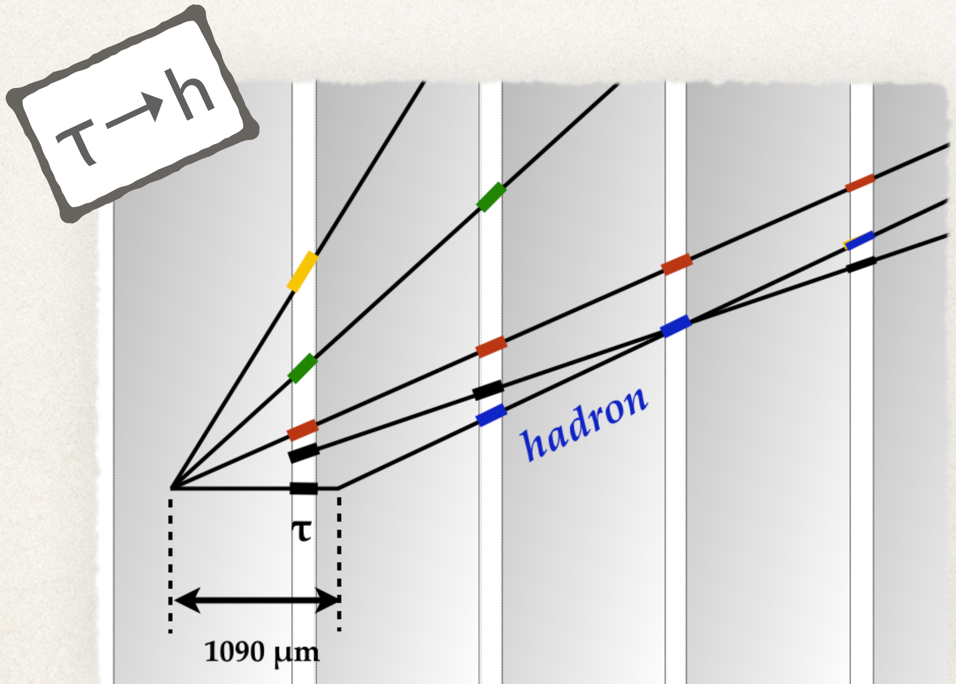
Phys. Lett. B 691 (2010) 138



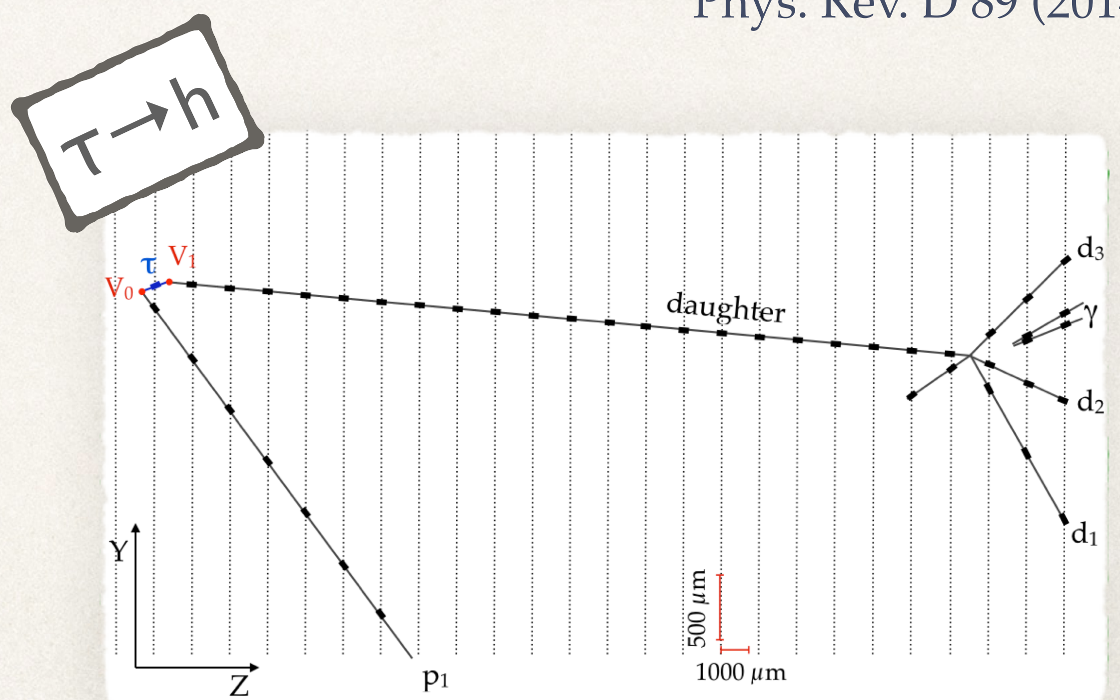
JHEP 11 (2013) 036



Phys. Rev. D 89 (2014) 051102



PTEP 2014 (2014) 10, 101C01



Phys.Rev.Lett. 115 (2015) no.12, 121802

Discovery of $\nu_\mu \rightarrow \nu_\tau$ appearance in the CNGS neutrino beam

DECAY CHANNEL	EXPECTED SIGNAL	TOTAL BACKGROUND	OBSERVED SIGNAL
$\tau \rightarrow h$	0.52±0.10	0.04±0.01	3
$\tau \rightarrow 3h$	0.73±0.14	0.17±0.03	1
$\tau \rightarrow \mu$	0.61±0.12	0.004±0.001	1
$\tau \rightarrow e$	0.78±0.16	0.03±0.01	0
TOTAL	**2.64±0.53**	**0.25±0.05**	**5**

Probability of background fluctuation = $1.1 \cdot 10^{-7}$

➙ absence of signal excluded with a significance of **5.1σ**

Ref: Discovery of tau neutrino appearance in the CNGS neutrino beam with the OPERA experiment PRL 115 (2015) 121802

Δm^2_{23} and ν_τ cross section estimation

New strategy defined in order to increase the number of ν_τ candidate $\Rightarrow$ estimate Δm^2_{23} (first measurement in appearance mode) and ν_τ cross section with less statistical uncertainty

New strategy:

- Minimum bias kinematical cuts
- Multivariate analysis: *Boosted Decision Tree*

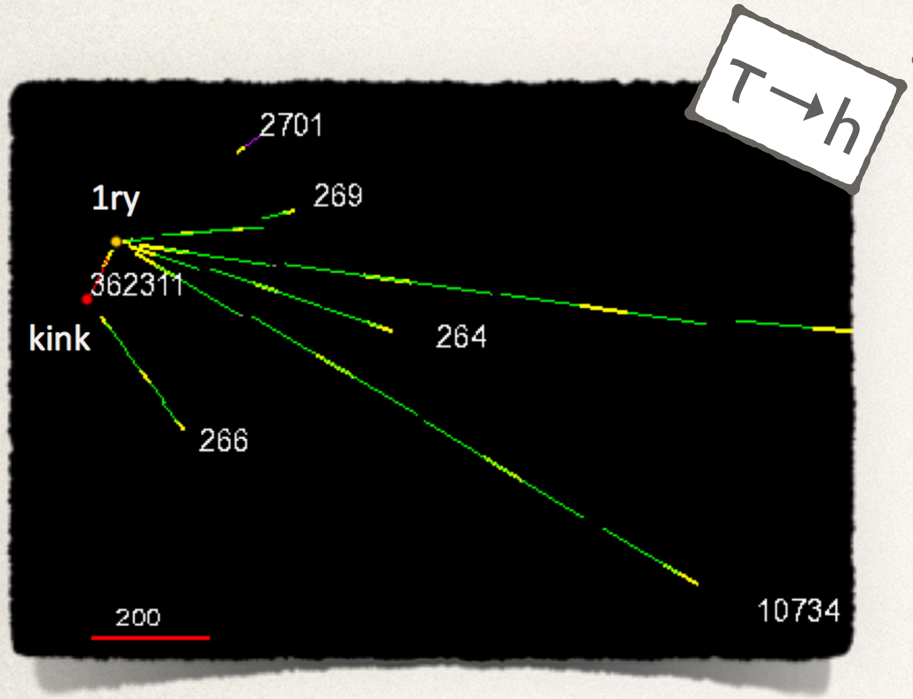
NEW Minimum bias selection:

Variable	$\tau \to 1h$	$\tau \to 3h$	$\tau \to \mu$	$\tau \to e$
z_{dec} (μm)	<2600	<2600	<2600	<2600
θ_{kink} (rad)	>0.02	>0.02	>0.02	>0.02
p_{2ry} (GeV/c)	>1	>1	>1	>1
p^T_{2ry} (GeV/c)	>0.15	/	>0.1	>0.1

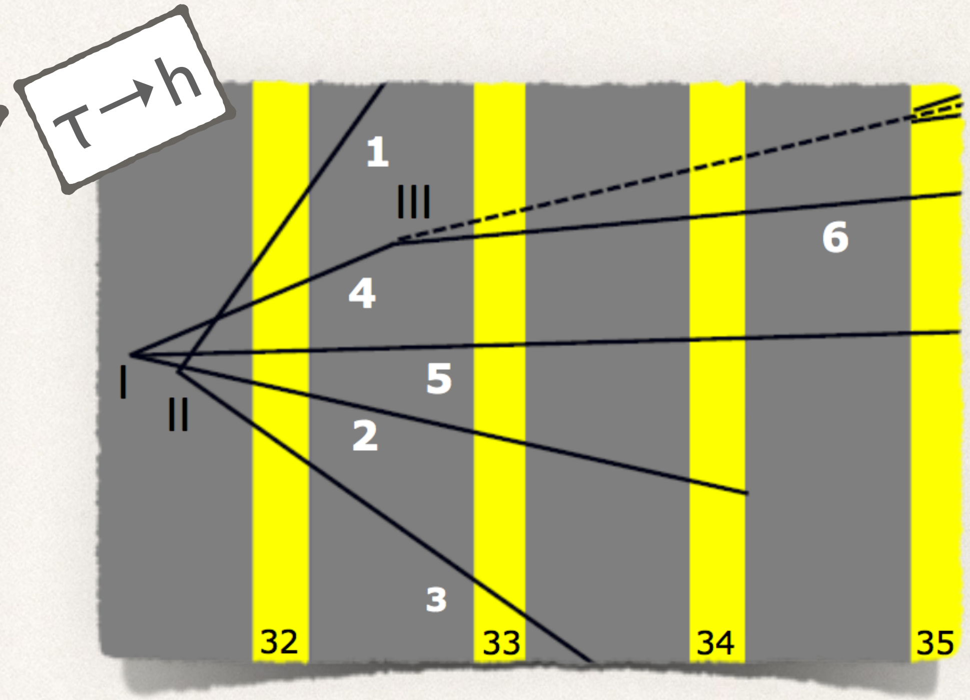
Preliminary

Channel	**Expected Background**				**Expected Signal**	Observed
	Charm	Had. re-interaction	Large μ-scat.	Total		
Total	0.52 ± 0.1	1.32 ± 0.4	0.017 ± 0.003	1.86 ± 0.5	5.88 ± 1.18	10

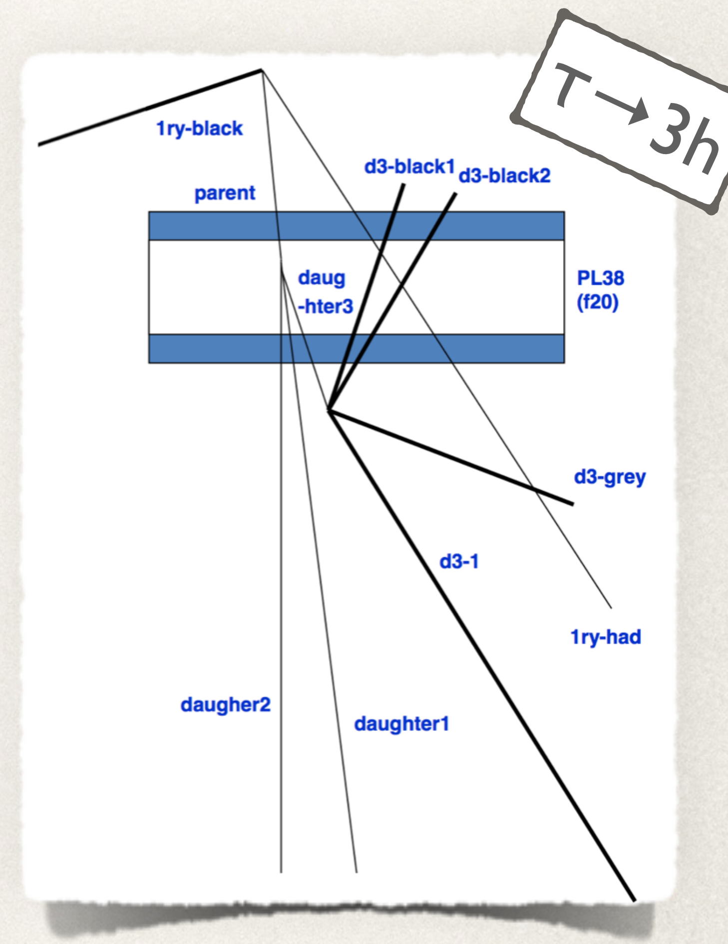
5 additional ν_τ candidates



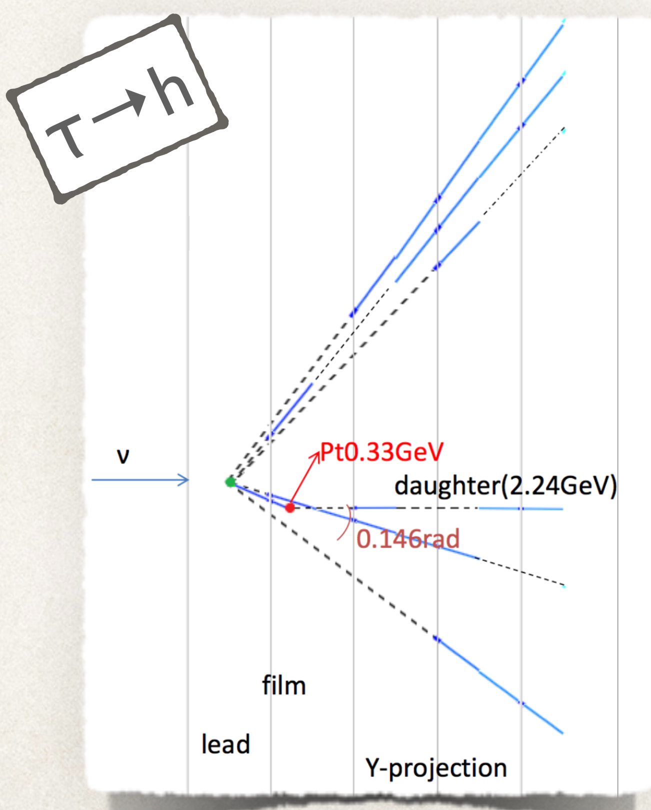
Event 11172035775



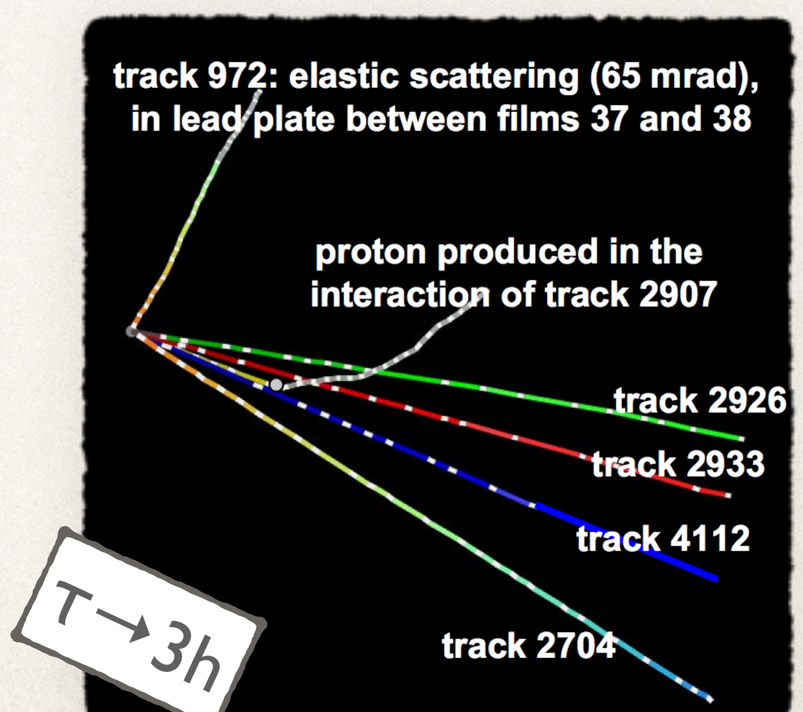
Event 11143018505



Event 11213015702



Event 9190097972

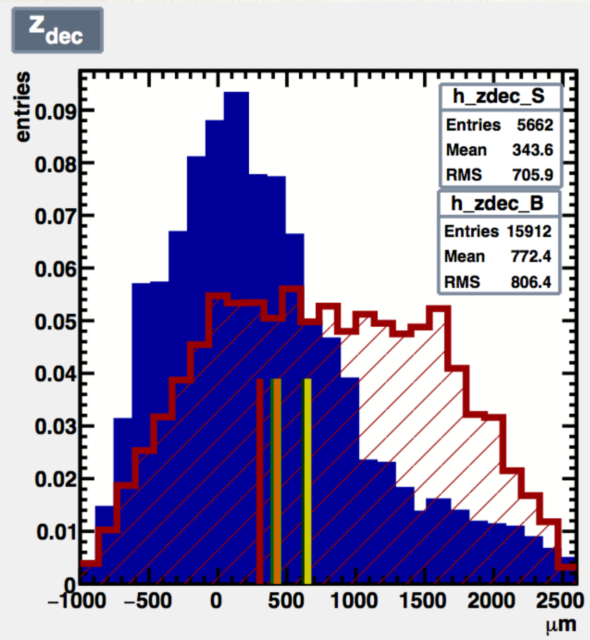


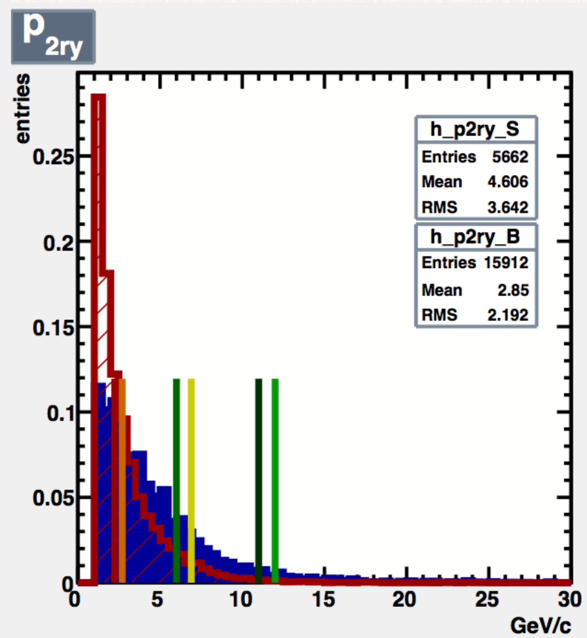
Event 10123059807

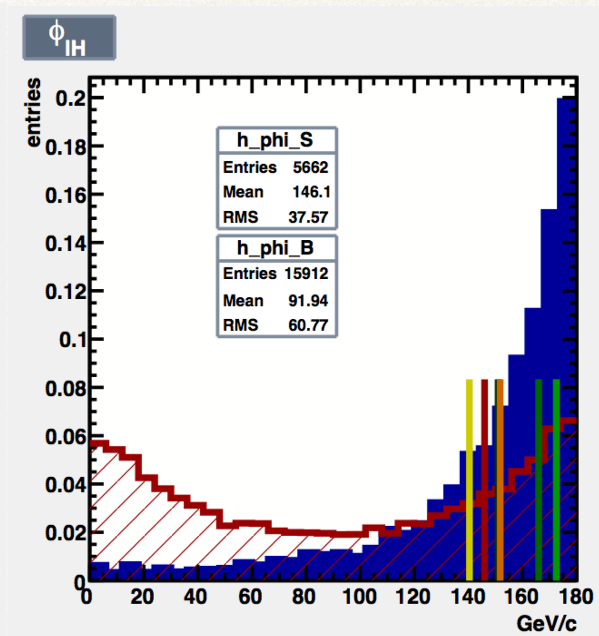
Examples of signal and background distributions for the most discriminating variables

$\tau \rightarrow 1h$: 6 ν_τ candidates

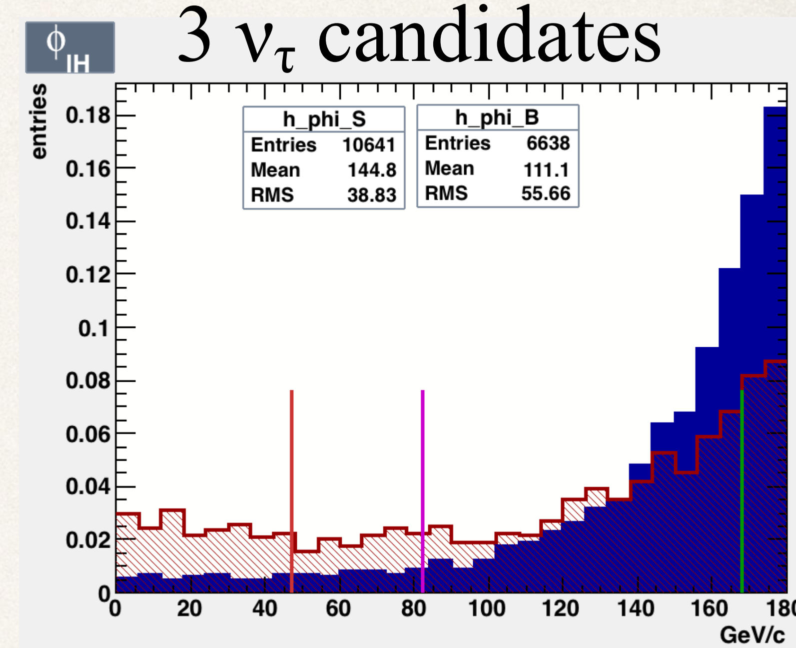
Signal: $\tau \rightarrow 1h$ (DIS + QE)
Background: charm$\rightarrow 1h$ (9%)
had reint (91%)





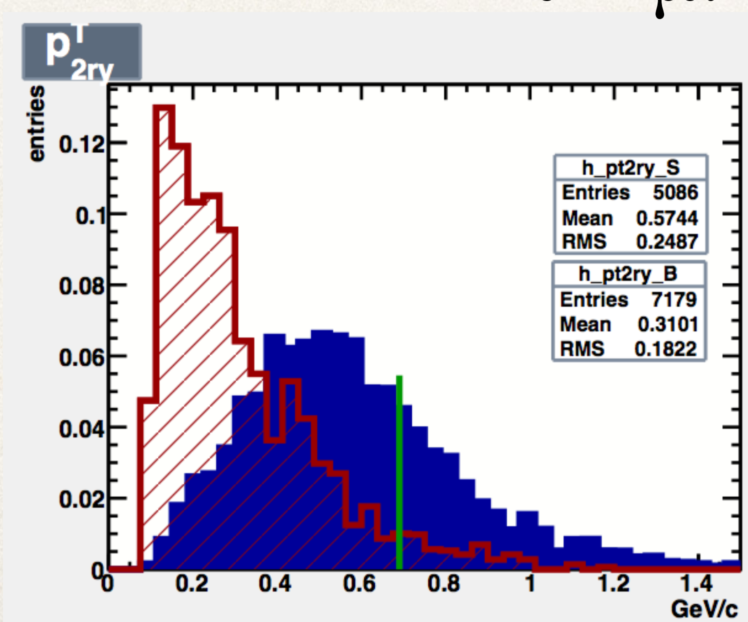


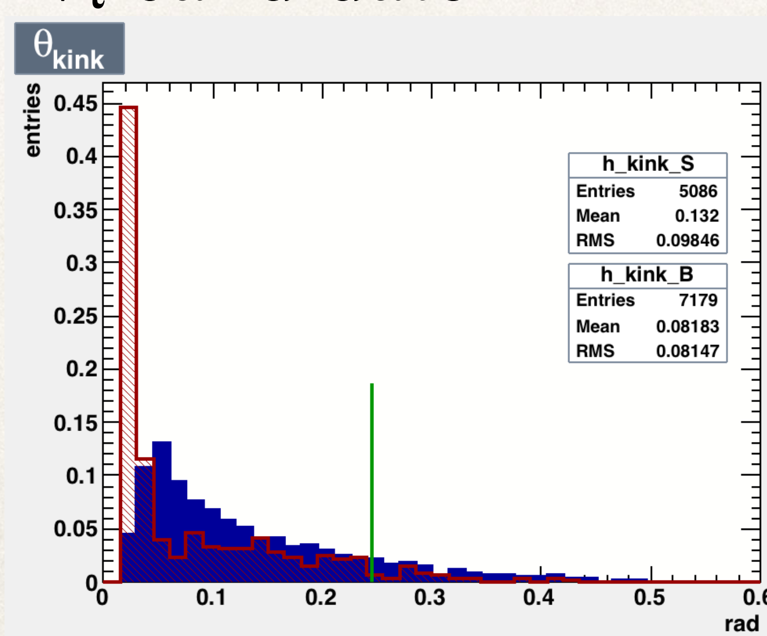
$\tau \rightarrow 3h$: 3 ν_τ candidates



Signal: $\tau \rightarrow 3h$ (DIS + QE)
Background: charm$\rightarrow 3h$ (81%)
had reint (19%)

$\tau \rightarrow \mu$: 1 ν_τ candidate



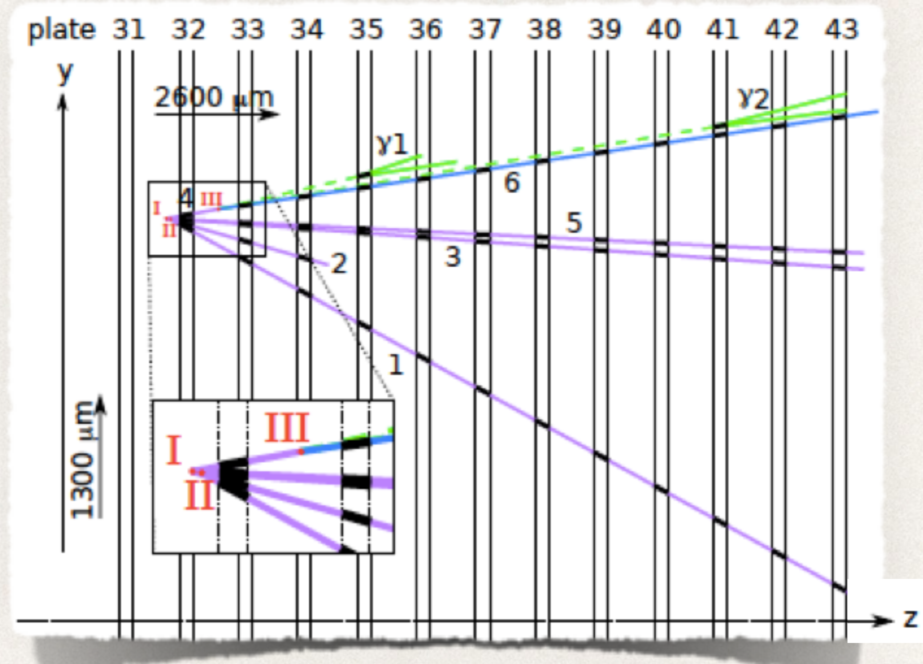


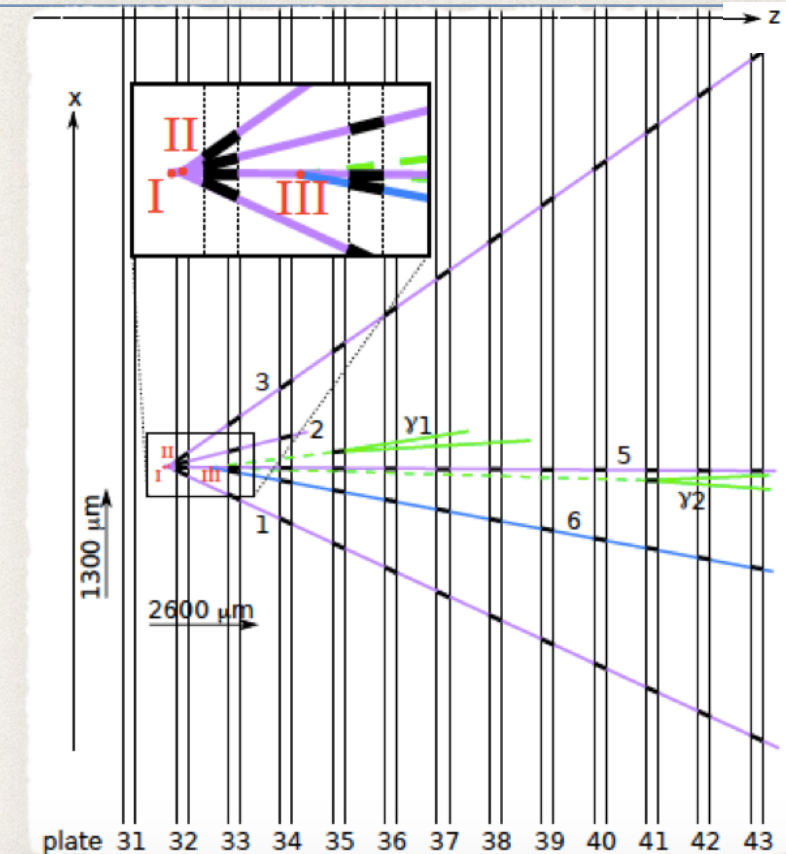
Signal: $\tau \rightarrow \mu$ (DIS + QE)
Background:
charm$\rightarrow \mu$ (53%)
Large angle scattering (47%)

An interesting event with peculiar topology

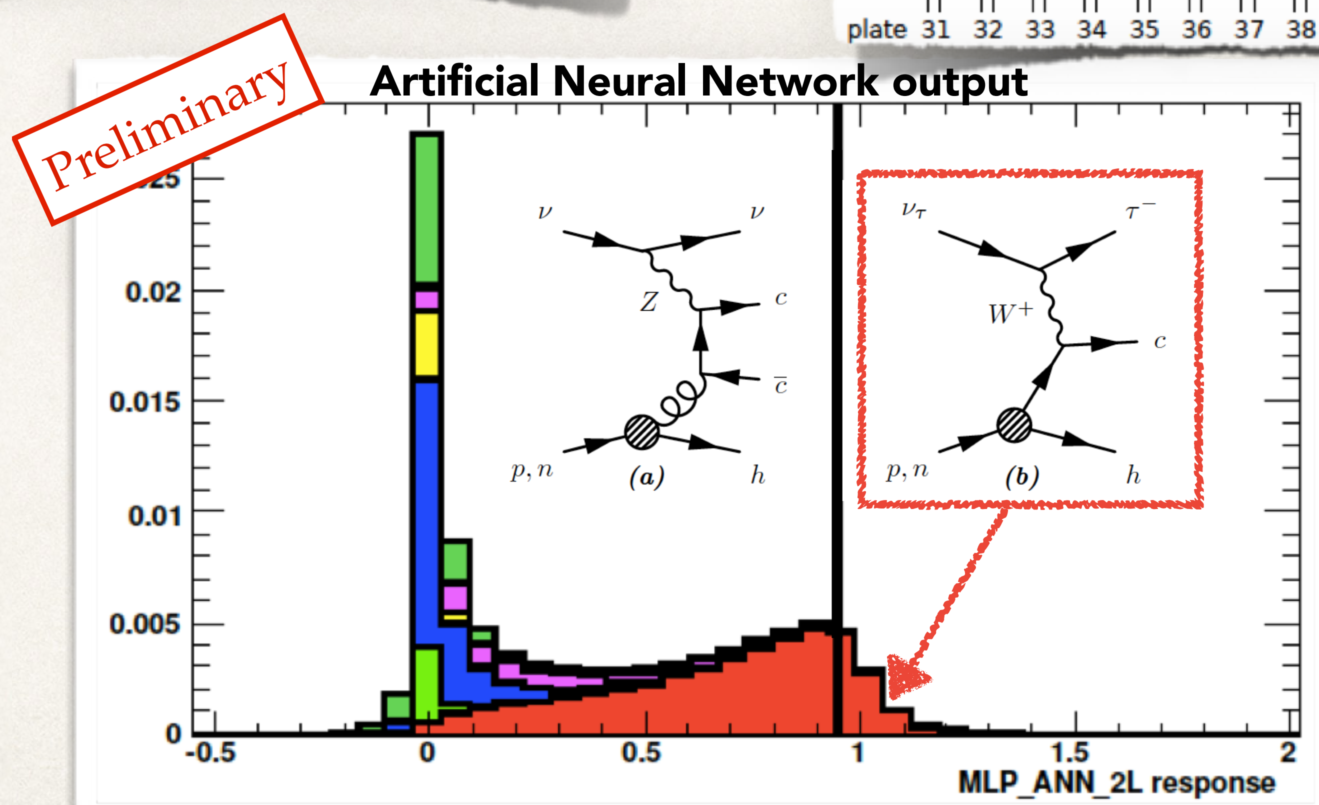
Muon-less event with 2 decay vertices

- *Ad hoc* simulations and multivariate analysis to distinguish between possible interpretations





Sample	μ mis-identified	Expected Events (10^{-3})
ν_τ CC + charm		45
ν_μ CC + charm + h_{int}	yes	21
ν_μ NC + cc_bar		13
ν_τ CC + h_{int}		9
ν_μ CC + 2h_{int}	yes	4
ν_μ NC + 2h_{int}		4
TOTAL		100



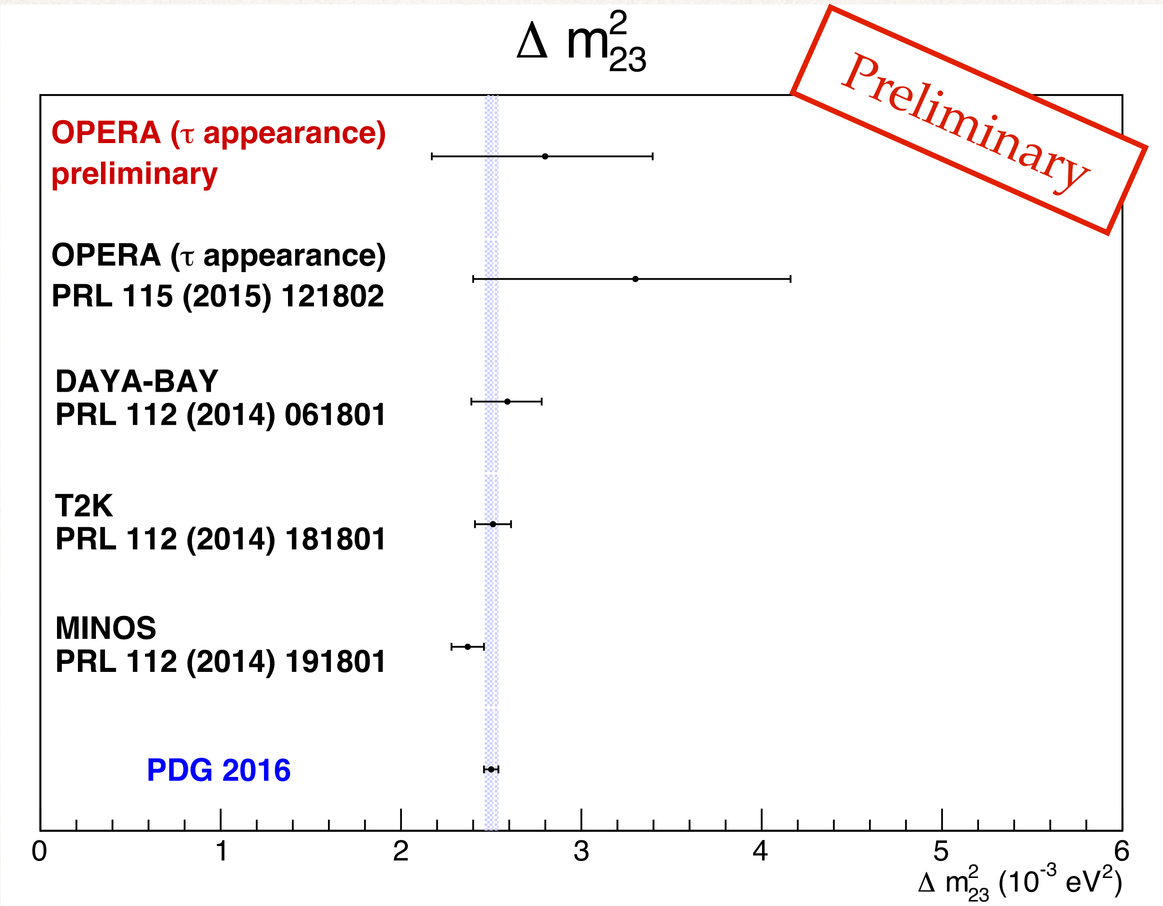
Probability of not being ν_τ CC + charm ~ 10^{-4}

→ **Significance = 3.5 σ**

Δm^2_{23} measurement *Appearance mode*

	Expected Signal	Expected Background	Observed ν_τ	Δm^2_{23} $(10^{-3}\ \mathrm{eV}^2)$ (68% C.L)	(90% C.L)
PRL 115 (2015) 121802 $\Delta m^2_{23} = 2.44 \cdot (10^{-3}\ \mathrm{eV}^2)$	2.56	0.25	5	$3.3^{+0.86}_{-0.90}$	[2.0; 5.0]
Preliminary $\Delta m^2_{23} = 2.5 \cdot (10^{-3}\ \mathrm{eV}^2)$	5.88	1.86	10	$2.95^{+0.62}_{-0.65}$	[1.98; 3.95]

(C.L. evaluated with Feldman-Cousins method)

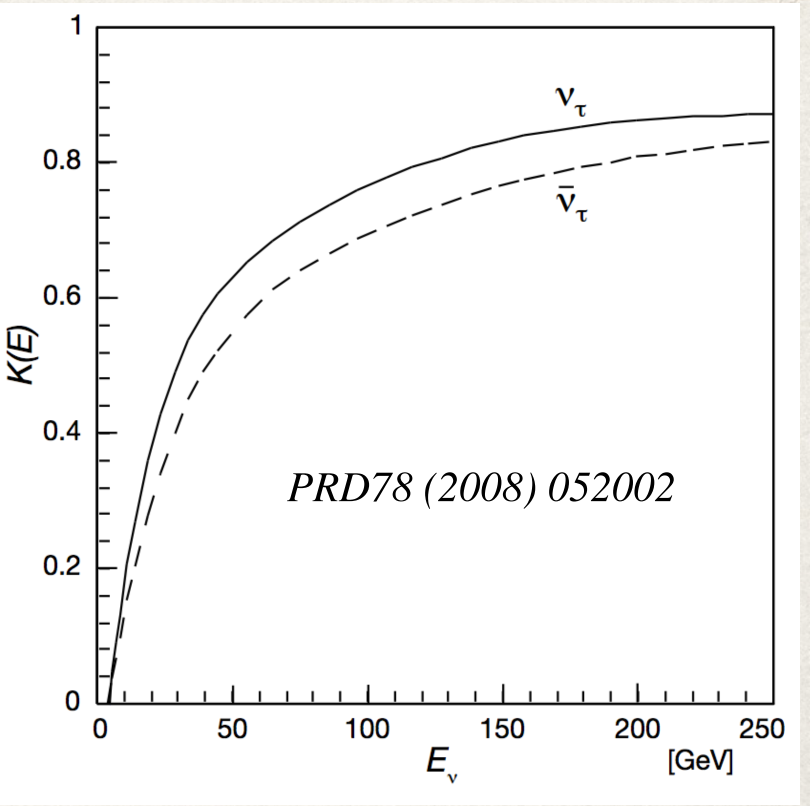


(68% C.L.)

Agreement with *PDG 2016* value within 1σ

Absolute ν_τ cross section

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



Until now, ν_τ cross section measured only by DONuT

DONuT could not distinguish ν_τ from anti-ν_τ

$$\sigma^{const}_{\nu_\tau+\bar{\nu}_\tau}(DONuT) = 0.72 \pm 0.24 \pm 0.36 \times 10^{-38} cm^2 GeV^{-1}$$

- OPERA: First measurement with ν_τ only

	Expected Signal	Expected Background	Observed ν_τ	$\sigma^{const}_{\nu_\tau}$ $(10^{-38}\mathrm{cm}^2\mathrm{GeV}^{-1})$ (68% C.L)	(90% C.L)
Preliminary $\Delta m^2_{23} = 2.5 \cdot (10^{-3}\ \mathrm{eV}^2)$	5.88	1.86	10	$0.96^{+0.43}_{-0.37}$	[0.42; 1.67]

Agreement with SM value $0.67 \cdot 10^{-38} cm^2 GeV^{-1}$ within 1σ

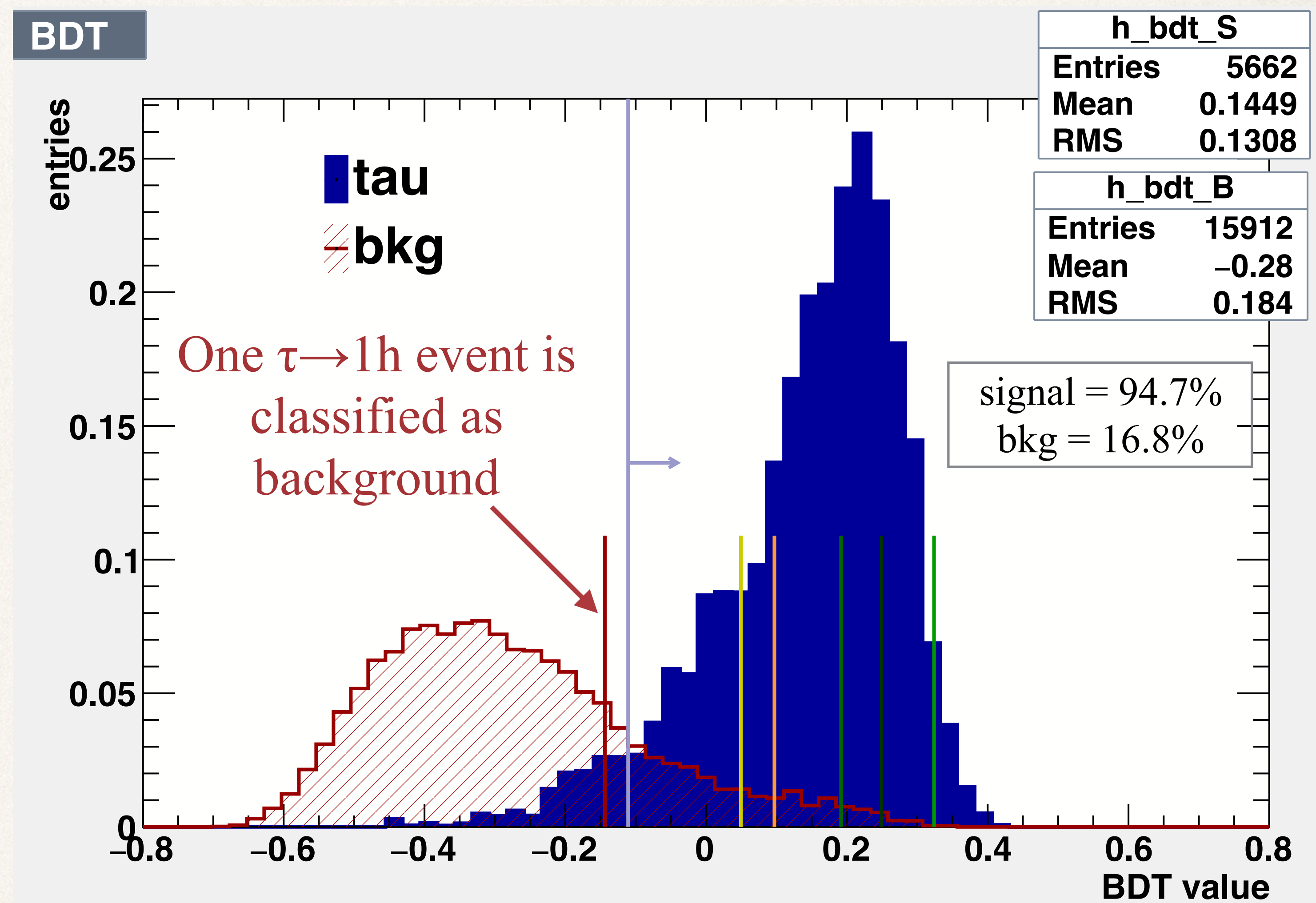
BDT analysis ($\tau \rightarrow 1h$)

Applying the minimum bias cut, the largest background is expected in $\tau \rightarrow 1h$ decay channel

In this decay channel, the *Boosted Decision Tree* method helps rejecting background.

The Boosted Decision Tree is a machine learning method used to classify observations.
It is based on a "forest" of trees of binary choices

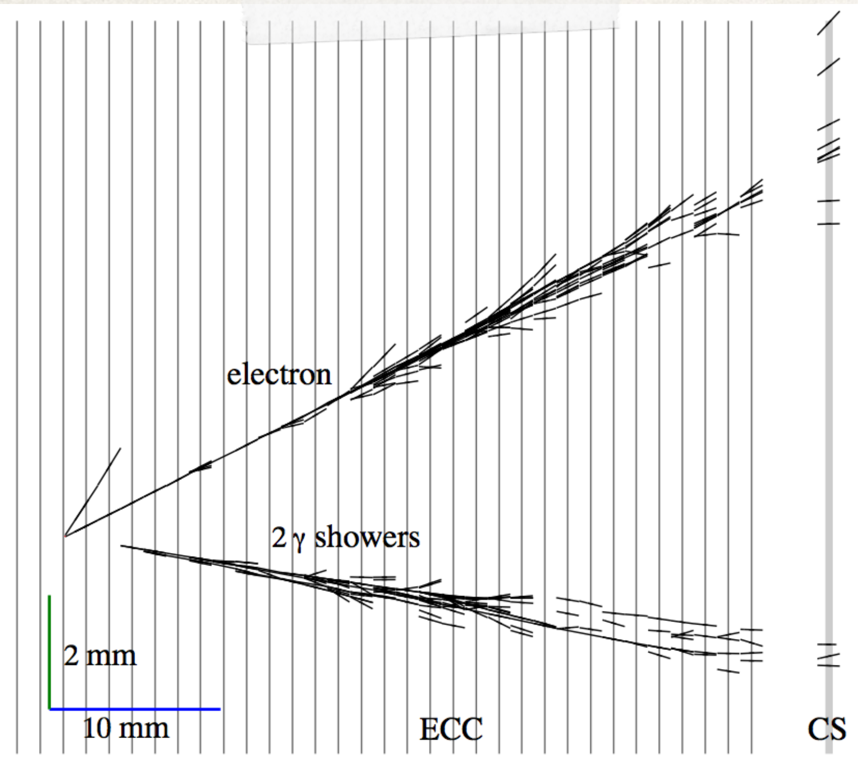
Maximising purity × efficiency, 83.2% of background is rejected.

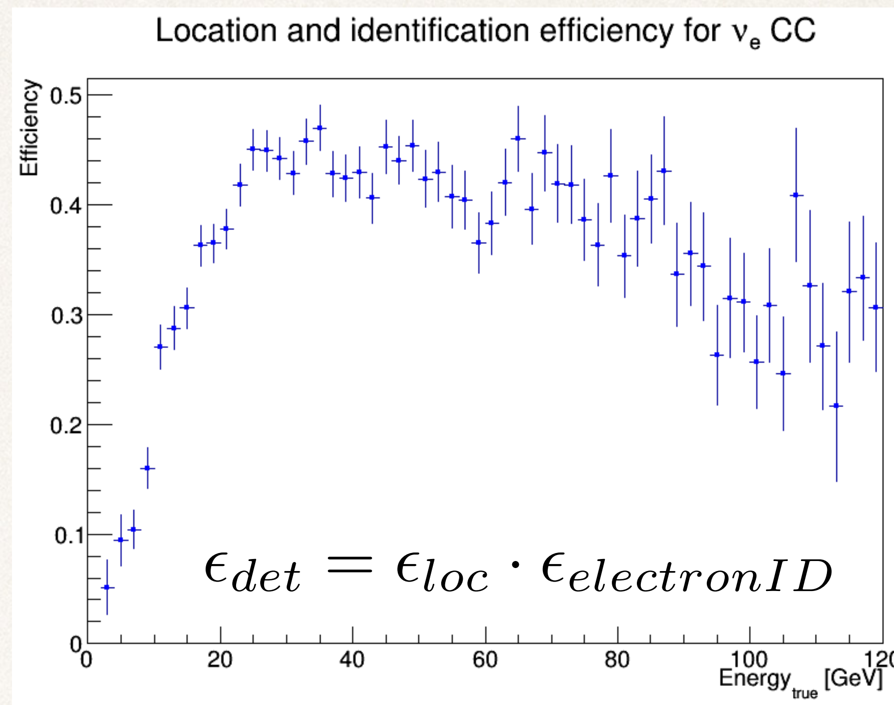


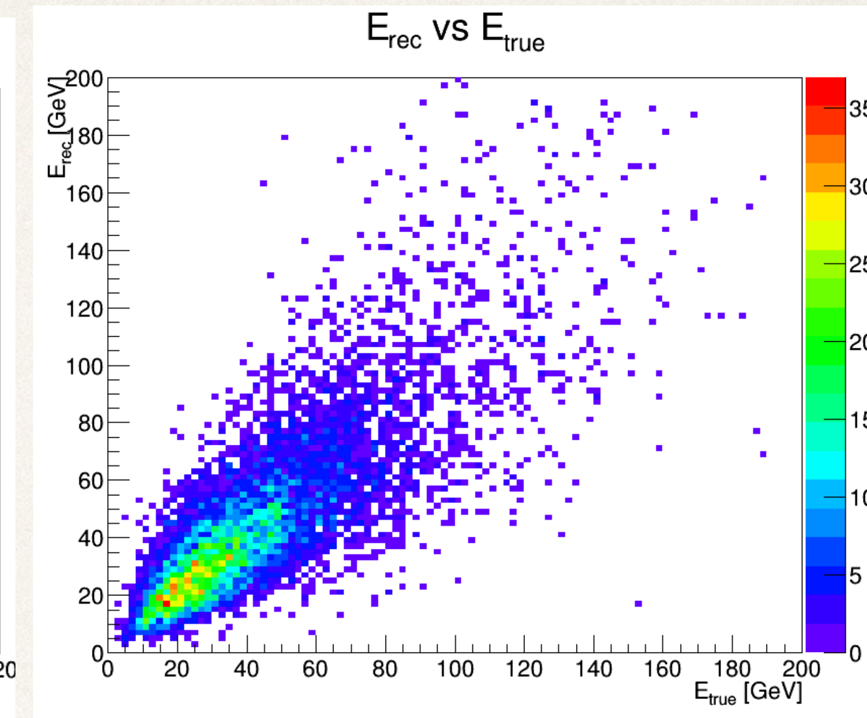
Input = events surviving the minimum bias selection
Signal & Bkg normalized to the number of expected events

1.36 expected event of bkg for $\tau \rightarrow 1h \Rightarrow$ 1 event classified as bkg:
good understanding of signal and background

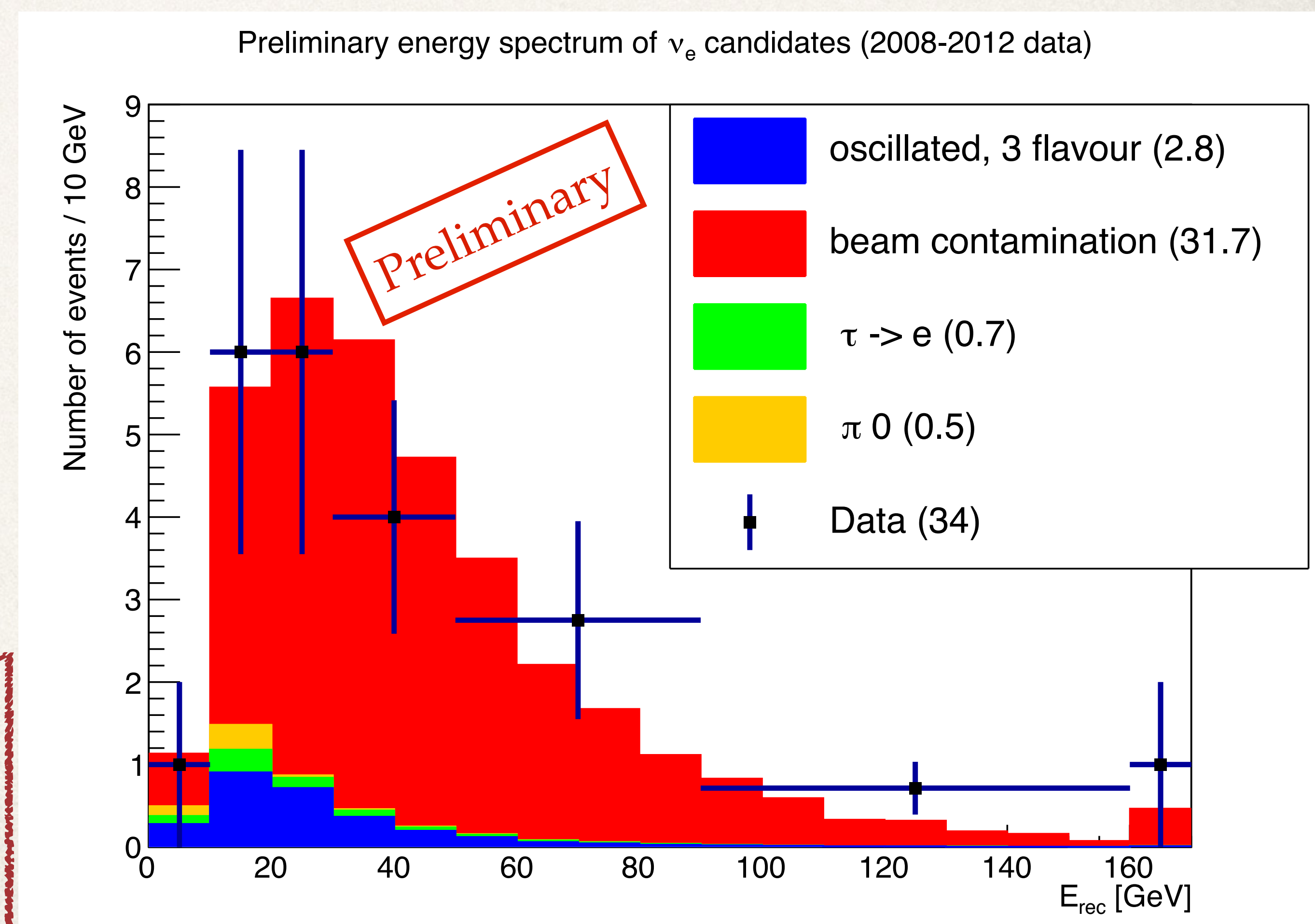
New result on $\nu_\mu \to \nu_e$ oscillations







- Expected ν_e events of bkg:
  - ν_e beam contamination: 33.2 ± 5
  - $\tau \to e$ + mis-id'd π_0: 1.2 ± 0.1
- From 3-flavor oscillation $\nu_\mu \to \nu_e$: 2.9 ± 0.4 ($\sin^2 2\theta_{13} = 0.098$)
- Observed: 34 ν_e events

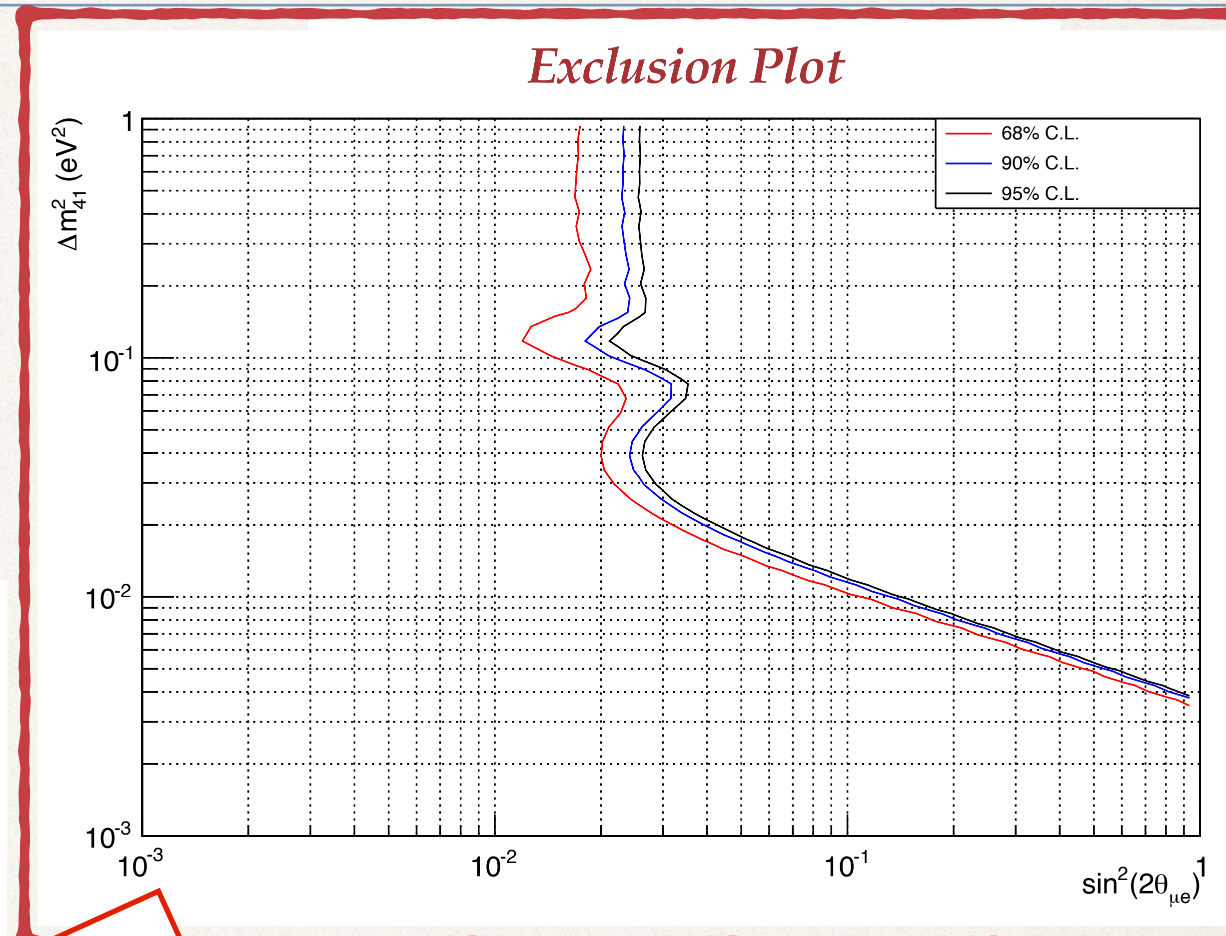


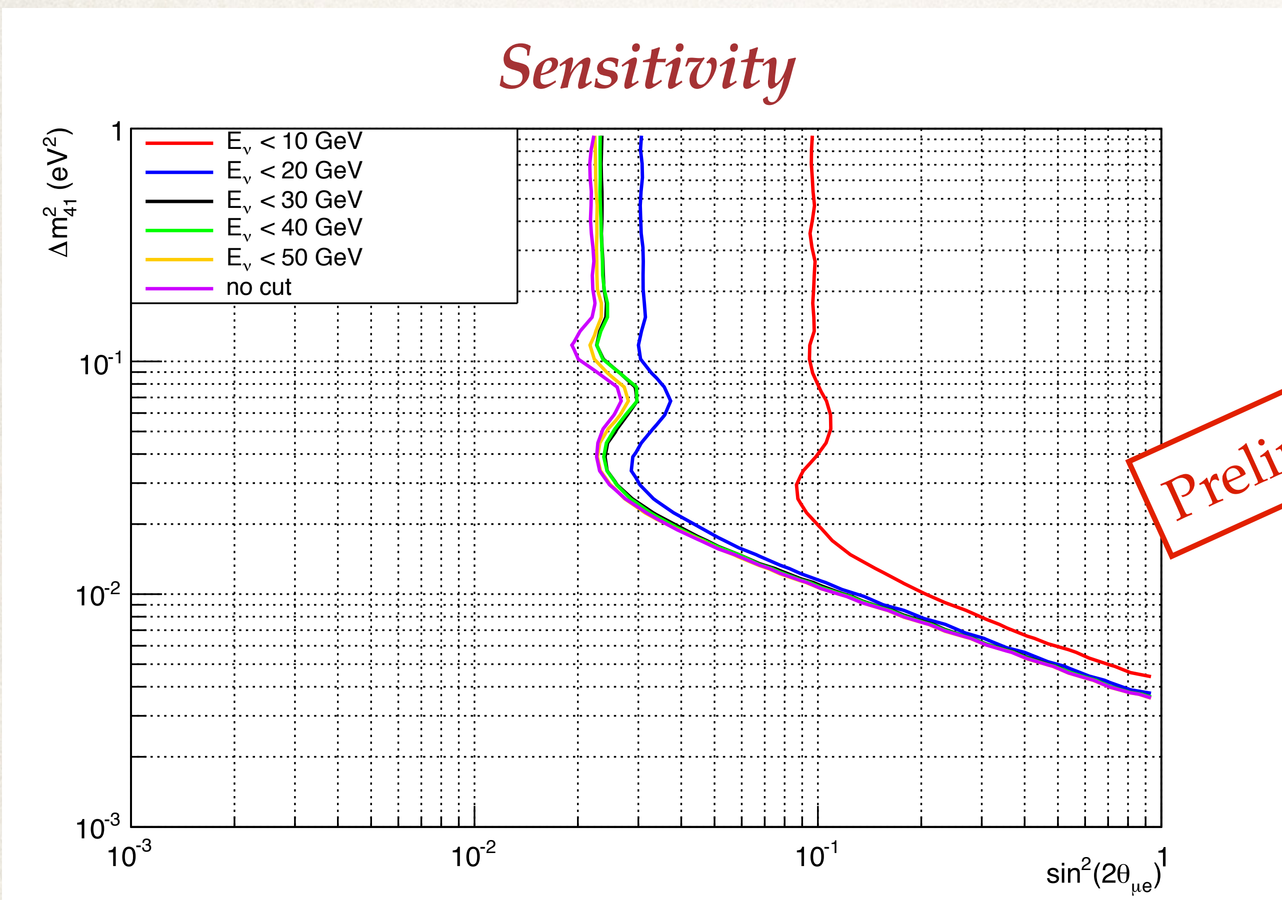
Observed events in agreement with expected background + standard oscillation

Sterile Neutrinos: $\nu_\mu \rightarrow \nu_e$ in 3+1 model

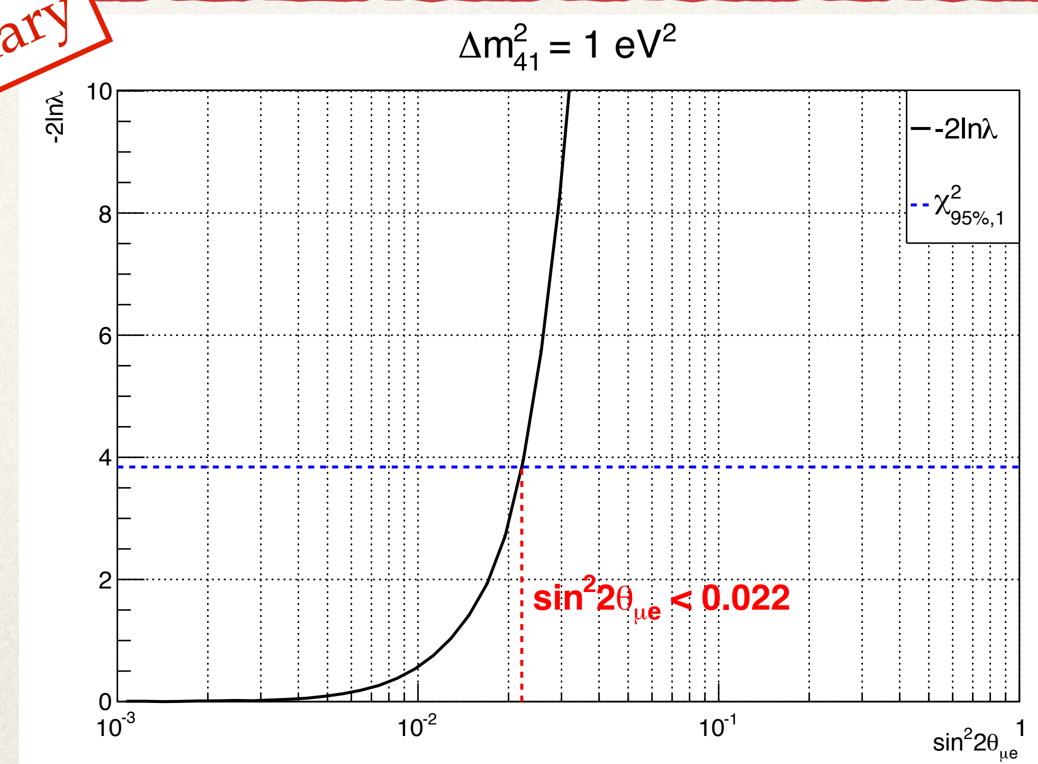
ν_e search results used to derive limits on the mixing parameters of a massive sterile neutrino in 3+1 neutrino model

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





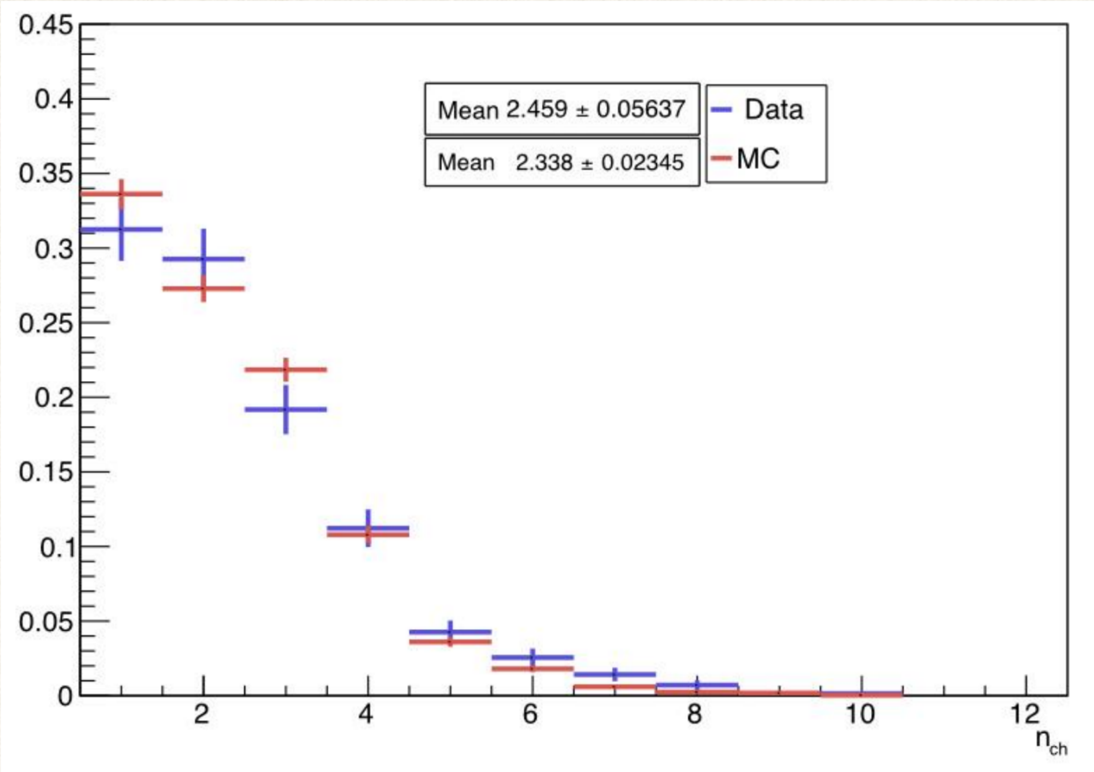
Preliminary

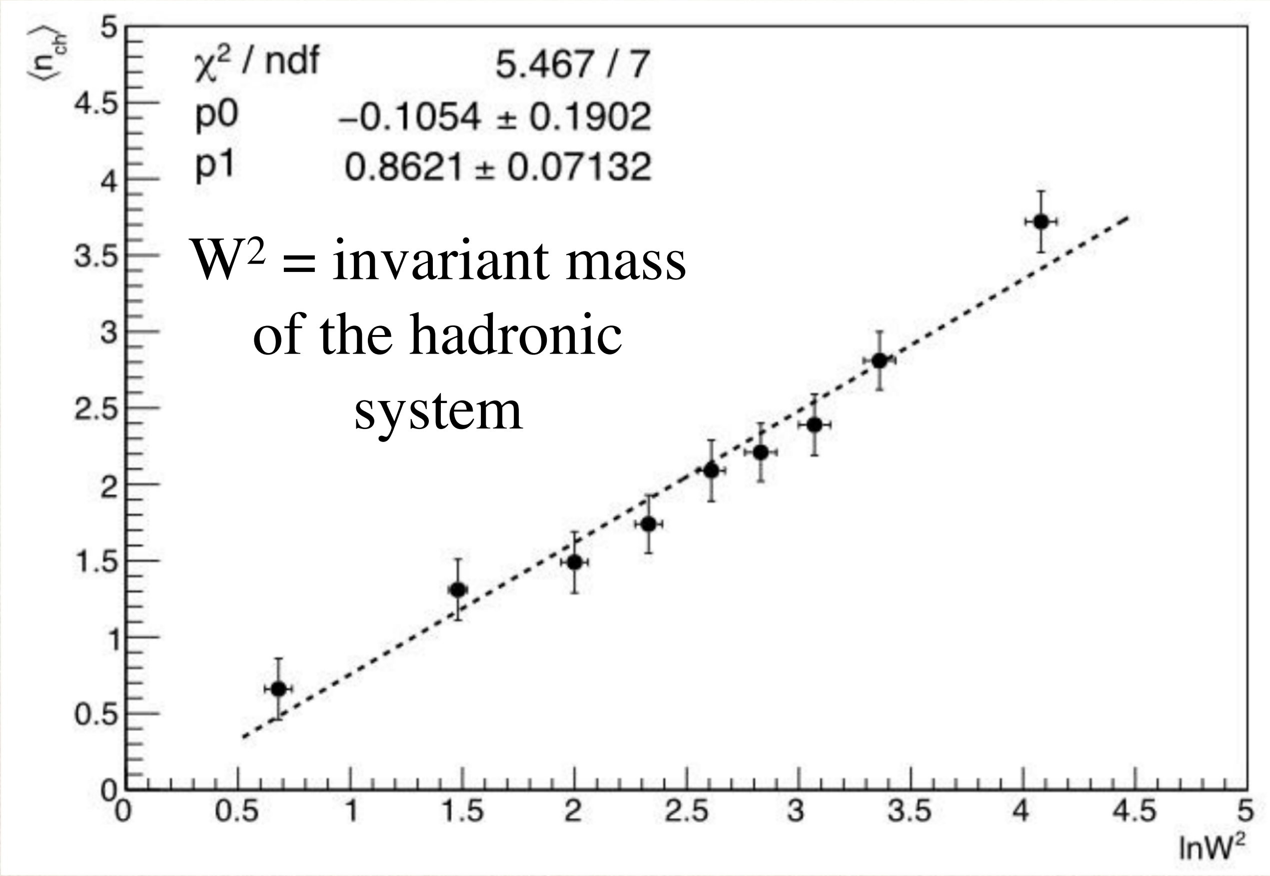


Study of Charged Particle Multiplicity Distributions

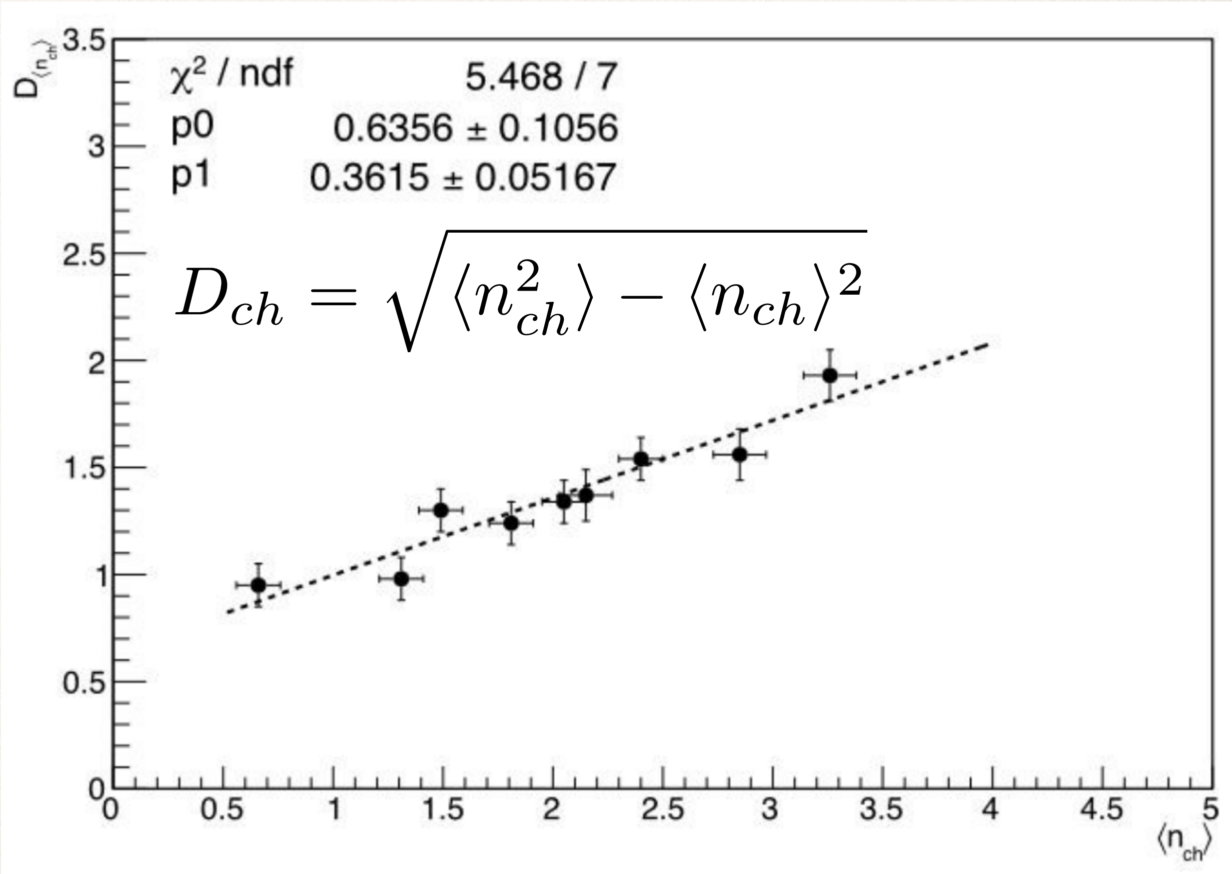
Multiplicity distribution of charged hadron particles in neutrino-lead interactions

Different phenomenological and theoretical models can be tested





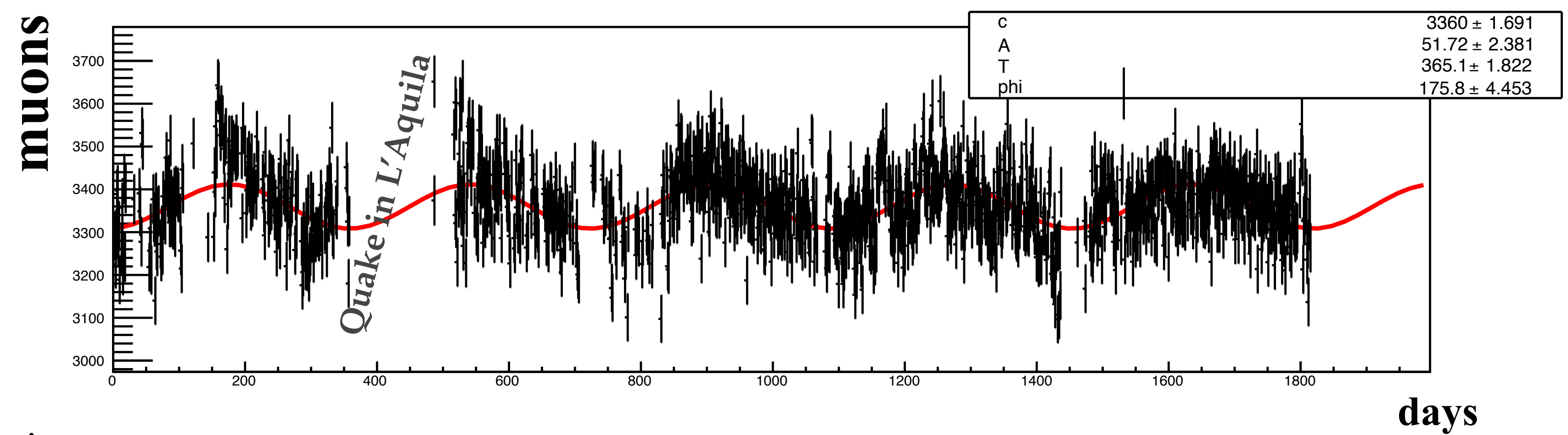
$$\langle n_{ch} \rangle = (-0.105 \pm 0.19) + (0.862 \pm 0.07) \ln W^2$$

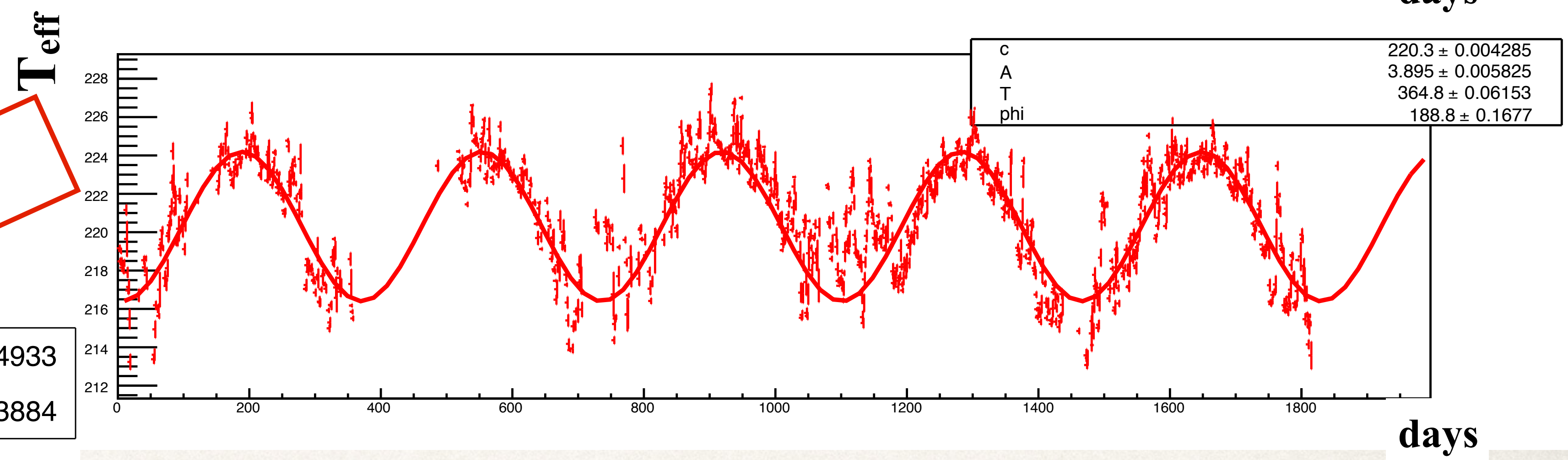


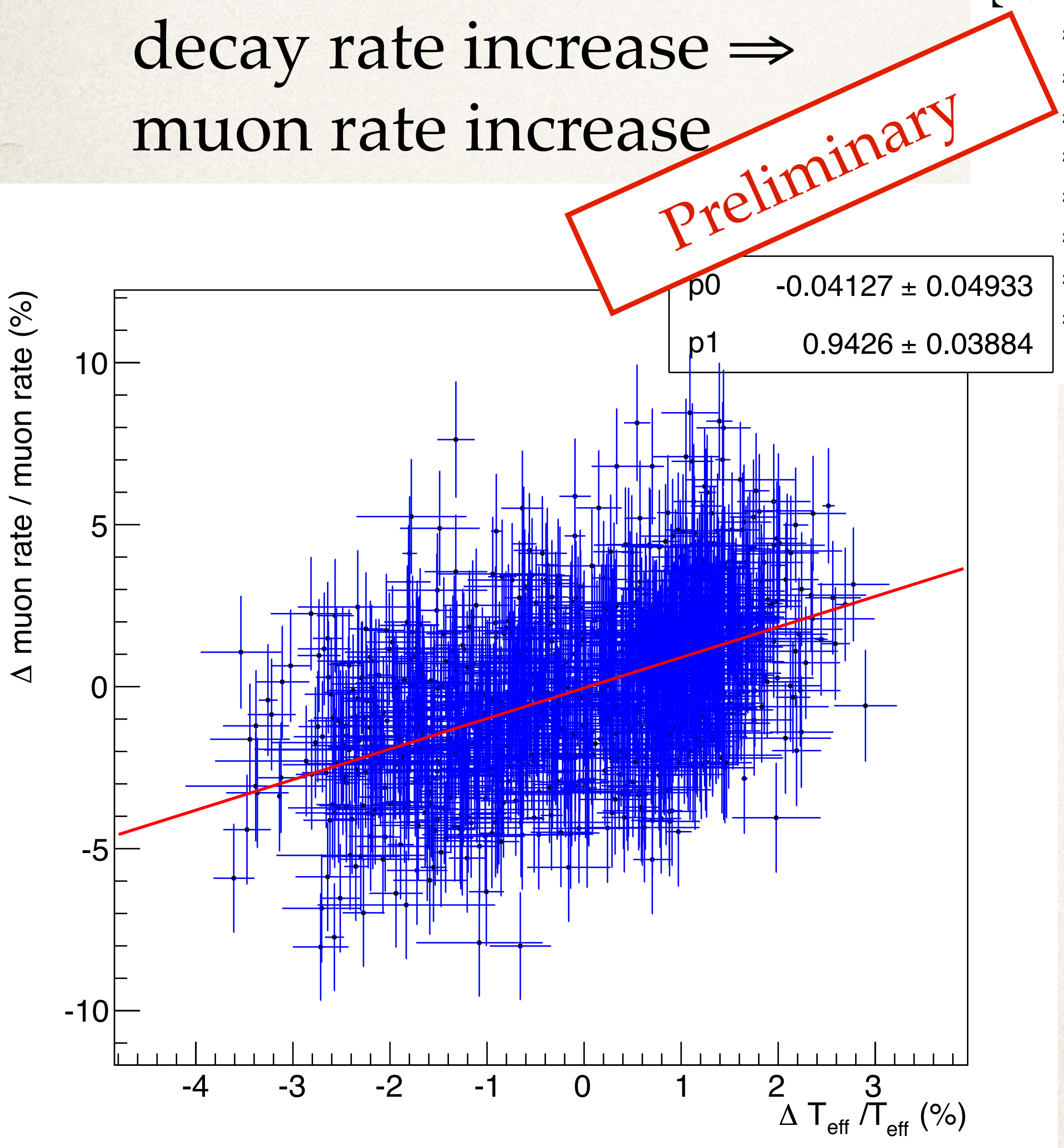
$$D_{\langle ch \rangle} = (0.63 \pm 0.10) + (0.36 \pm 0.05) \langle n_{ch} \rangle$$

Annual modulation of atmospheric muons

- Gran Sasso underground ~ 3800 m w.e. ⇒ Minimum muon energy ~ 1.8 TeV
- Atmospheric temperature increase ⇒ gas density decrease ⇒ the π and K decay rate increase ⇒ muon rate increase







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

$$T = 365 \pm 2$$

$$t_0 = 176 \pm 4$$

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

$$\alpha_T = 0.94 \pm 0.04$$

Conclusions

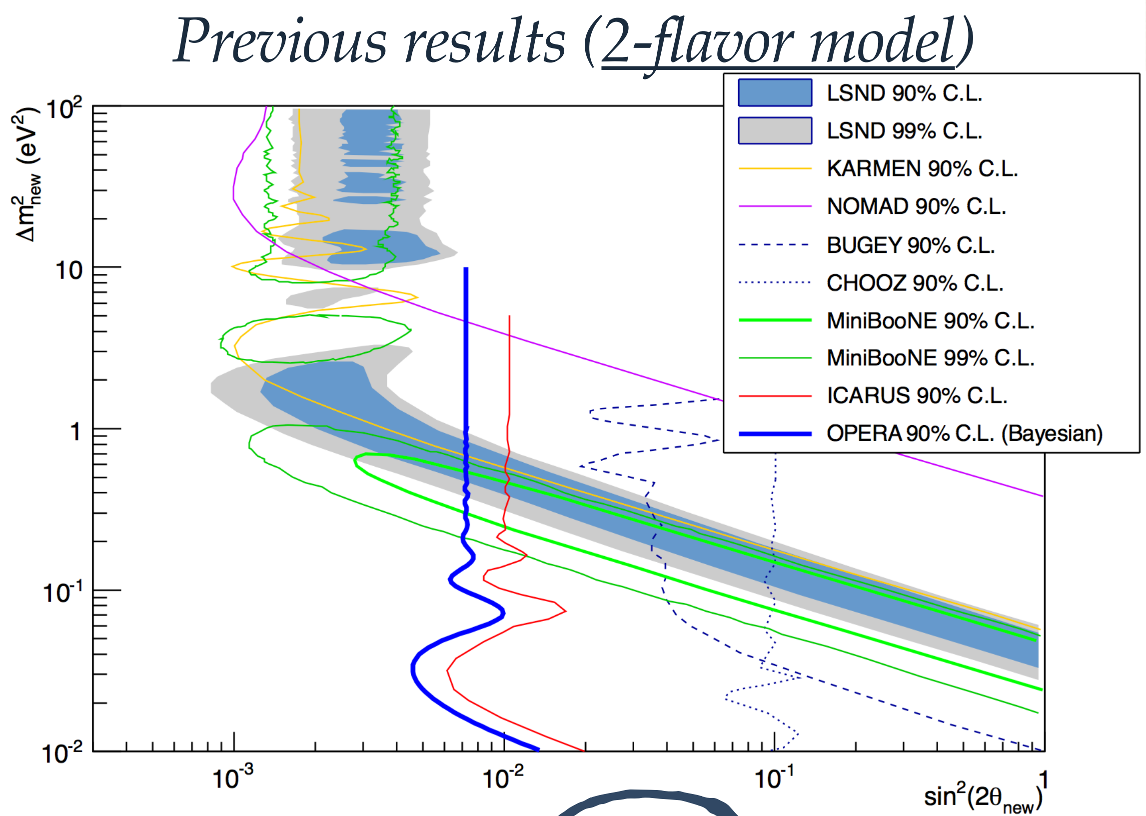
- **Discovery of $\nu_\mu \rightarrow \nu_\tau$ appearance** in the CNGS neutrino beam: 5.1σ
- Minimum bias analysis to increase the number of ν_τ candidates $\Rightarrow$ **measurement of Δm^2_{23} (first measurement in appearance mode) and absolute ν_τ cross section (first measurement)** with less statistical uncertainty. Preliminary results in agreement with PDG2016 at 1σ
- **$\nu_\mu \rightarrow \nu_e$ oscillation search**: number of events observed in agreement with expected background + standard oscillation
- Constraints on **sterile neutrinos** from $\nu_\mu \rightarrow \nu_e$ oscillation with the 3+1 flavor model
- Study of the **multiplicity distribution of charged hadron particles** in neutrino-lead interactions to aid in tuning neutrino-lead interaction models of the Monte Carlo event generators
- Non-oscillation Physics: OPERA data set is being used for studying **annual modulation of atmospheric muons**
- ***PERSPECTIVES***: Exploit unique feature of identifying all three flavors: use ν_τ appearance, ν_e appearance and ν_μ disappearance to constrain on the oscillation parameters with one single experiment

Thank you for your attention

Back-up slides

Sterile Neutrinos: $\nu_\mu \to \nu_e$ Exclusion Plots

Previous results (2-flavor model)



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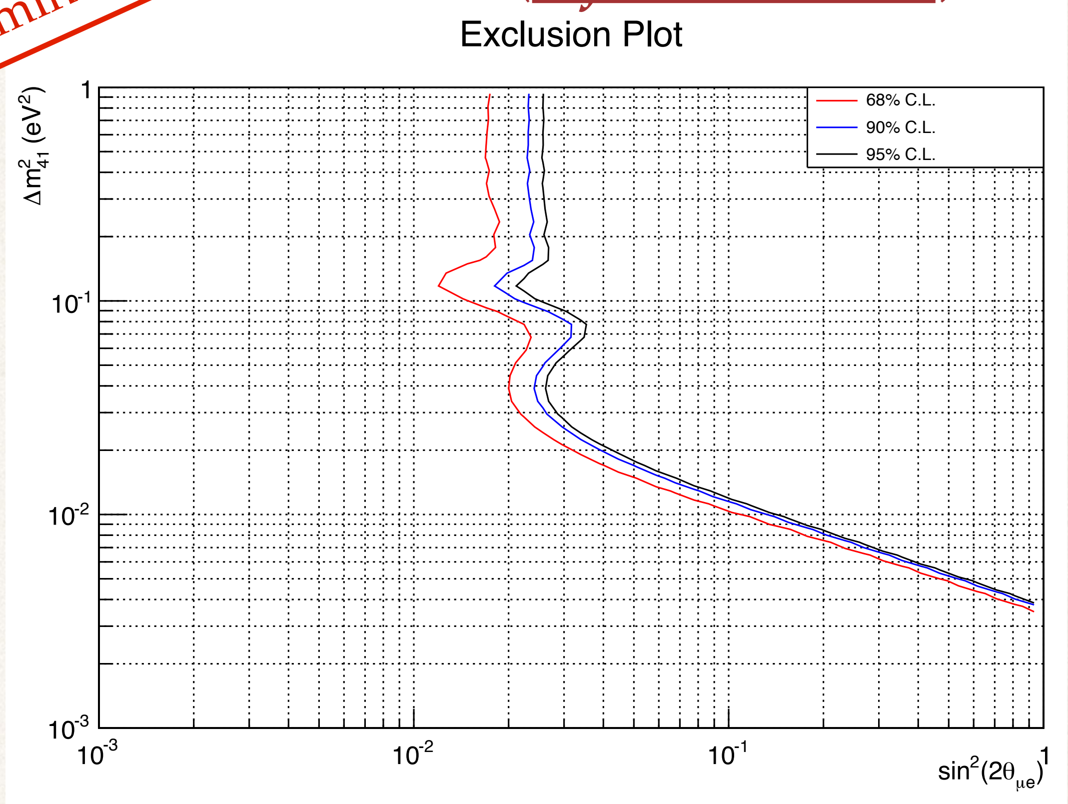
Limit on non-standard oscillations at large Δm^2:

$\sin^2(2\theta_{new})<7.2\cdot10^{-3}$ at 90% CL

Preliminary

New results (4-flavor model)



Limit on non-standard oscillations at large Δm^2:

$\sin^2(2\theta_{\mu e})<2.2\cdot10^{-2}$ at 95% CL

The 2-flavor description neglects sizable effects. The upper bounds on $\sin^2 2\theta_{\mu e}$ are relaxed by a factor of 3 with respect to those obtained in the 2-flavor description.

(PRD91 (2015) no.9, 091301)

$$\mathcal{P}_{\mu e} = \frac{1}{2}\sin^2 2\theta_{new}$$

$$\mathcal{P}_{\mu e}(sensitivity) < 5.2\times10^{-3}$$

$$\mathcal{P}_{\mu e}(upper\ limit) < 3.6\times10^{-3}$$

$$\mathcal{P}_{\mu e}(sensitivity) < 3.4\times10^{-3}$$

$$\mathcal{P}_{\mu e}(upper\ limit) < 3.1\times10^{-3}$$