Results from the OPERA experiment in the CNGS beam

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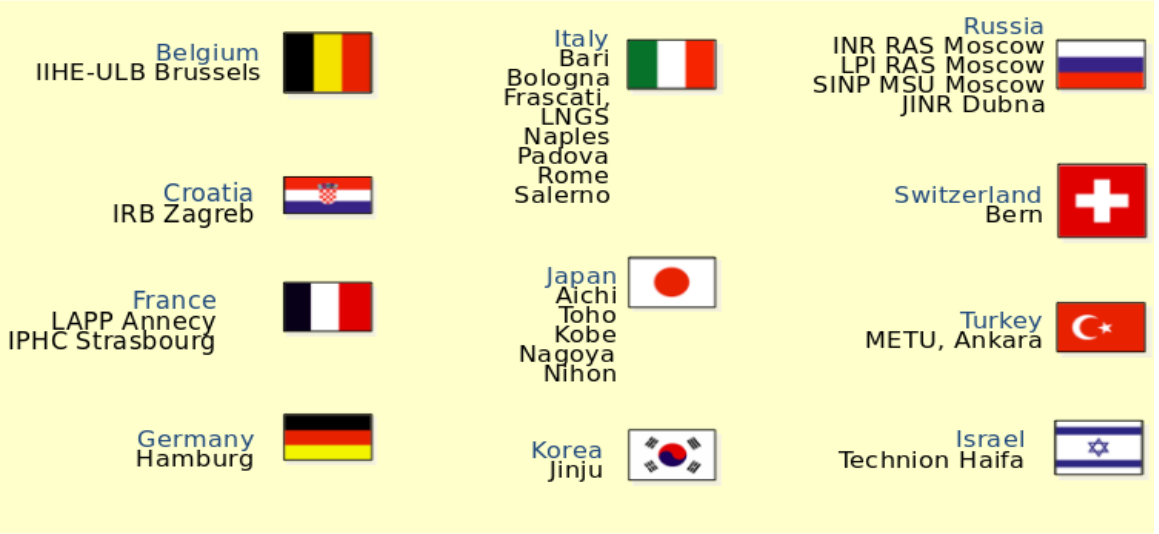
on behalf of the OPERA collaboration

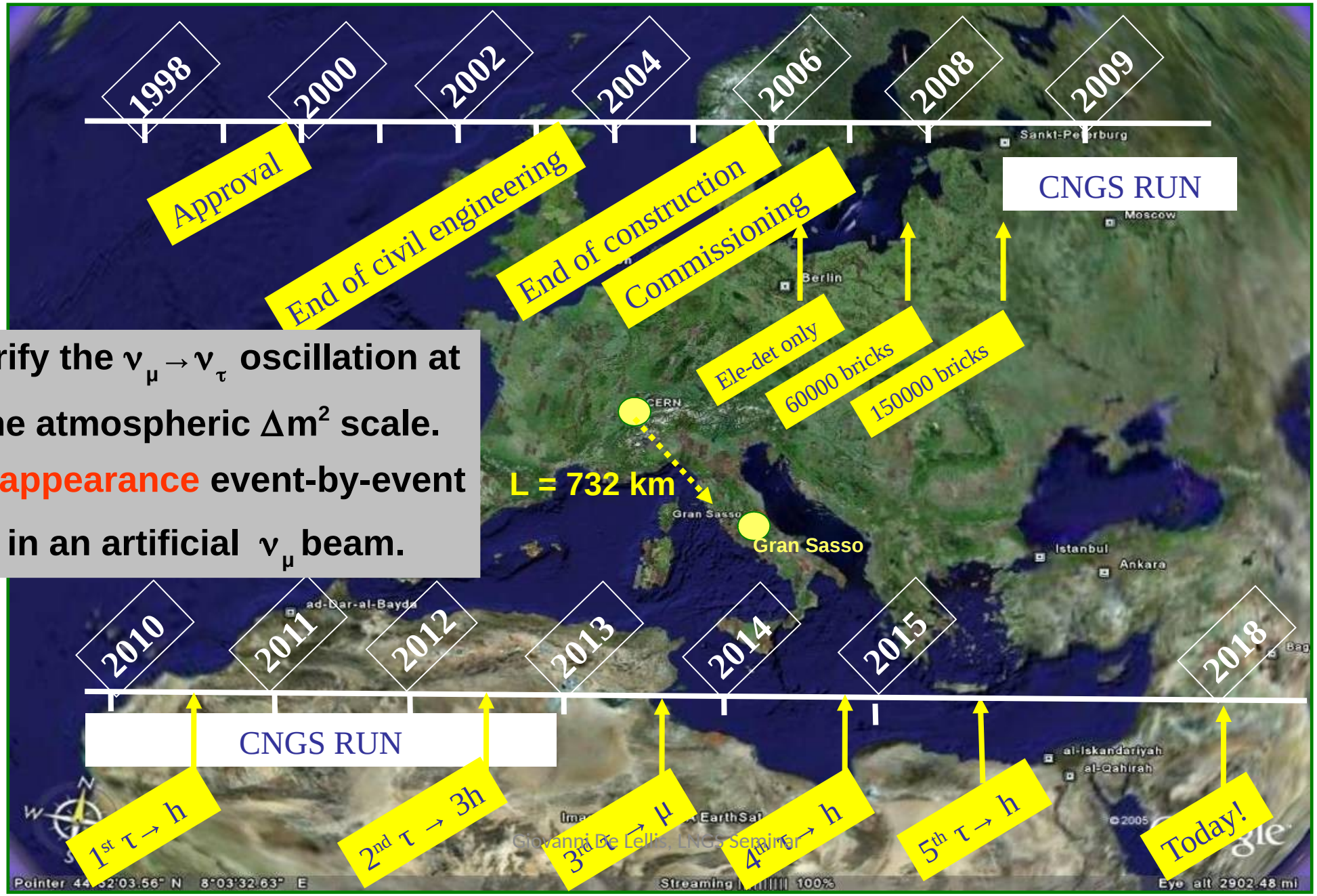
7th International Conference on New Frontiers in Physics (ICNFP 2018)

Creta, 4-12 July 2018

140 physicists, 11 countries, 26 institutions



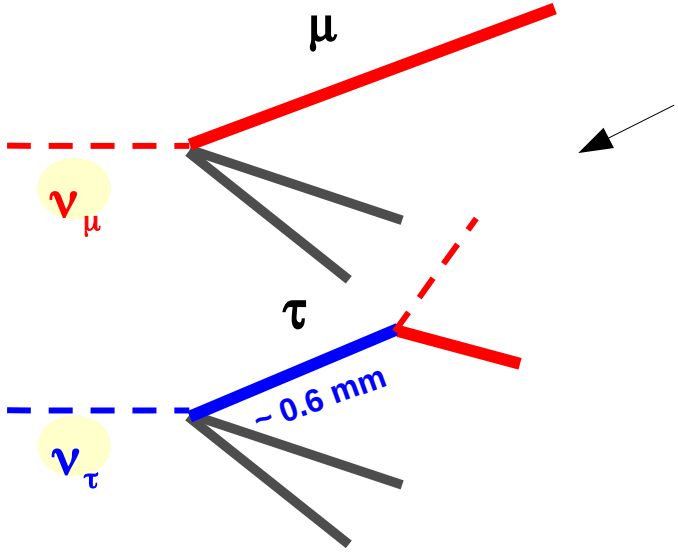
The OPERA experiment roadmap



Verify the $\nu_\mu \rightarrow \nu_\tau$ oscillation at the atmospheric Δm^2 scale.

ν_τ appearance event-by-event in an artificial ν_μ beam.

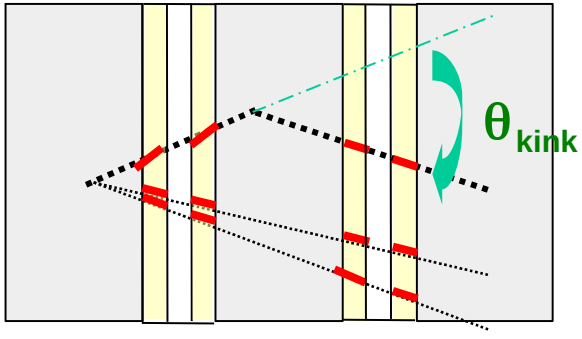
The ν_τ detection technique



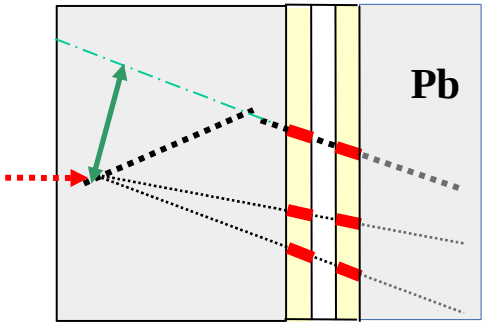
Detect a few ν_τ^{CC} from the bulk of ν_μ^{CC}

τ DECAY CHANNEL	BR (%)
$\tau \to \mu$	17.7
$\tau \to e$	17.8
$\tau \to h$	49.5
$\tau \to 3h$	15.0

"long" decays: kink



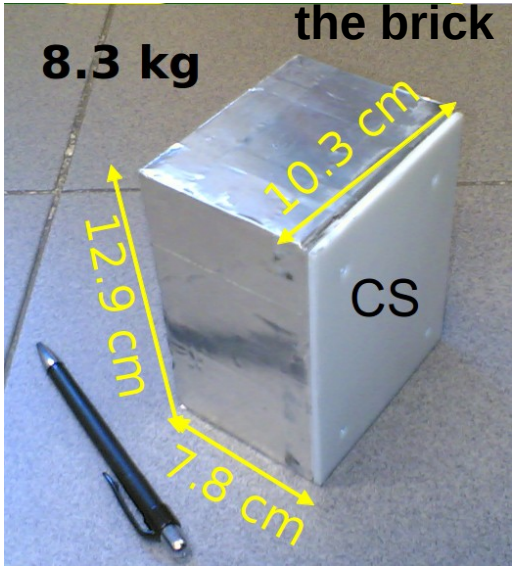
"short" decays: I.P.

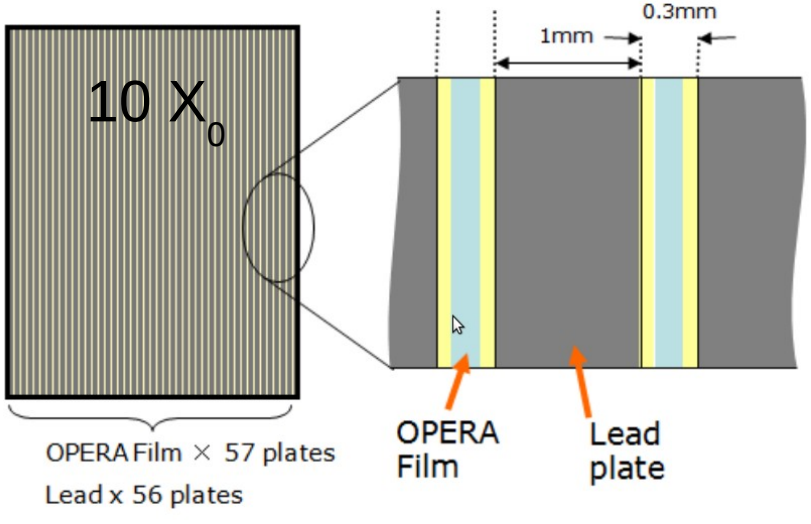


Modular detector of "Emulsion Cloud Chambers" (or bricks)

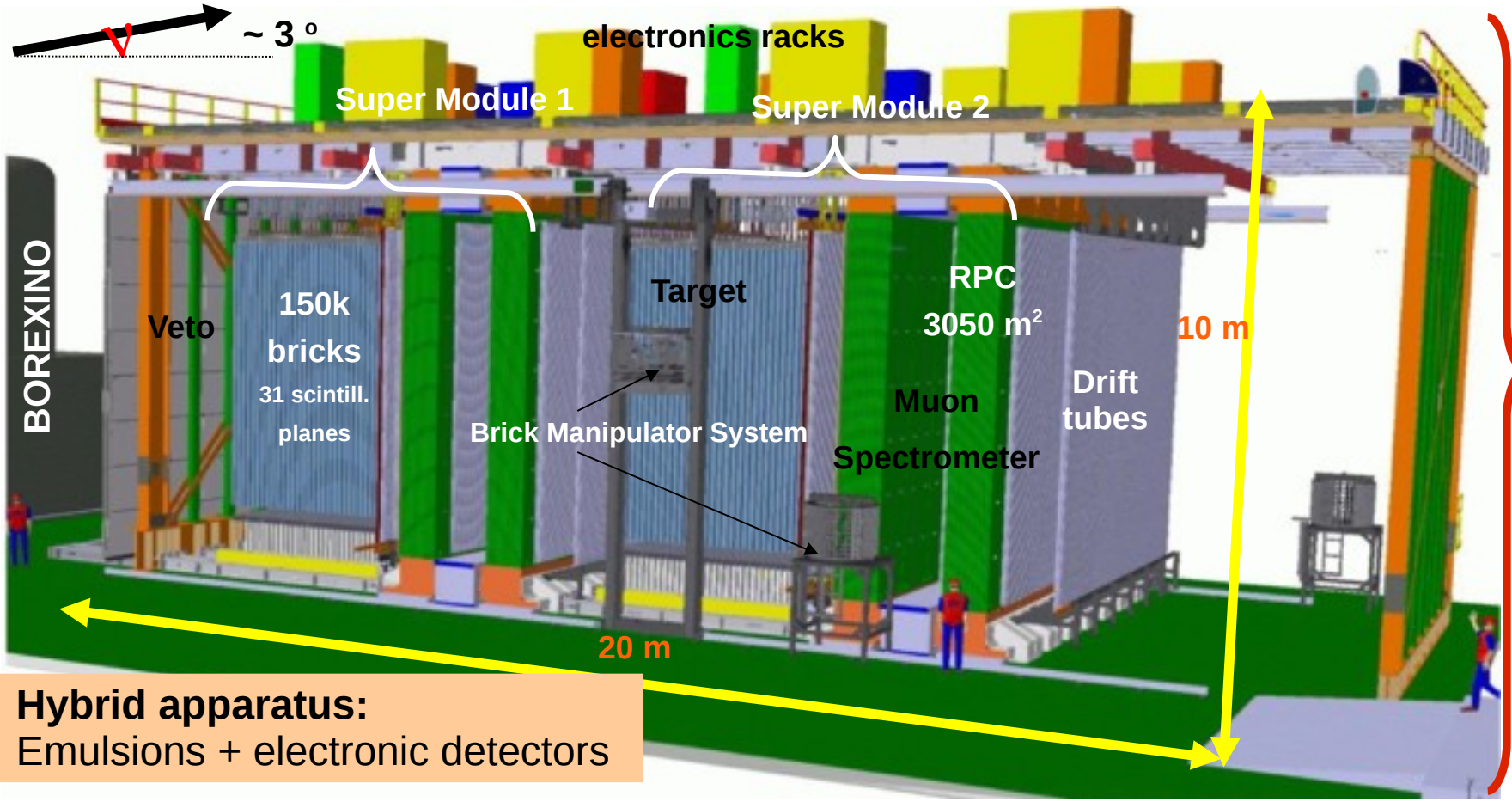
Reconciles the needs for:

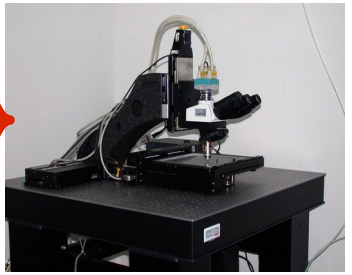
- **Large mass**
  - $N_\tau \propto (\Delta m^2)^2 M_{target}$
- **Extreme granularity**
  - **μm space resolution**

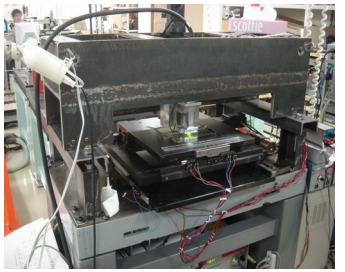




The OPERA experiment

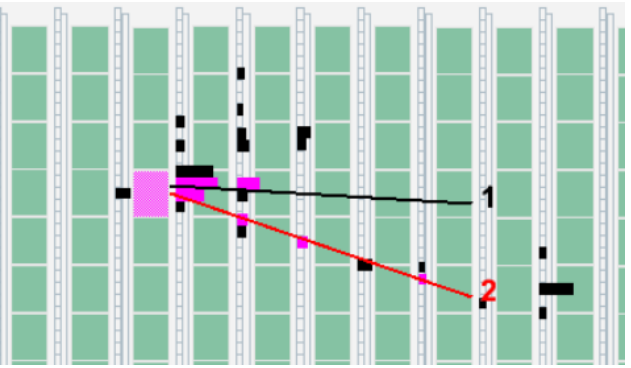






Hybrid apparatus:
Emulsions + electronic detectors

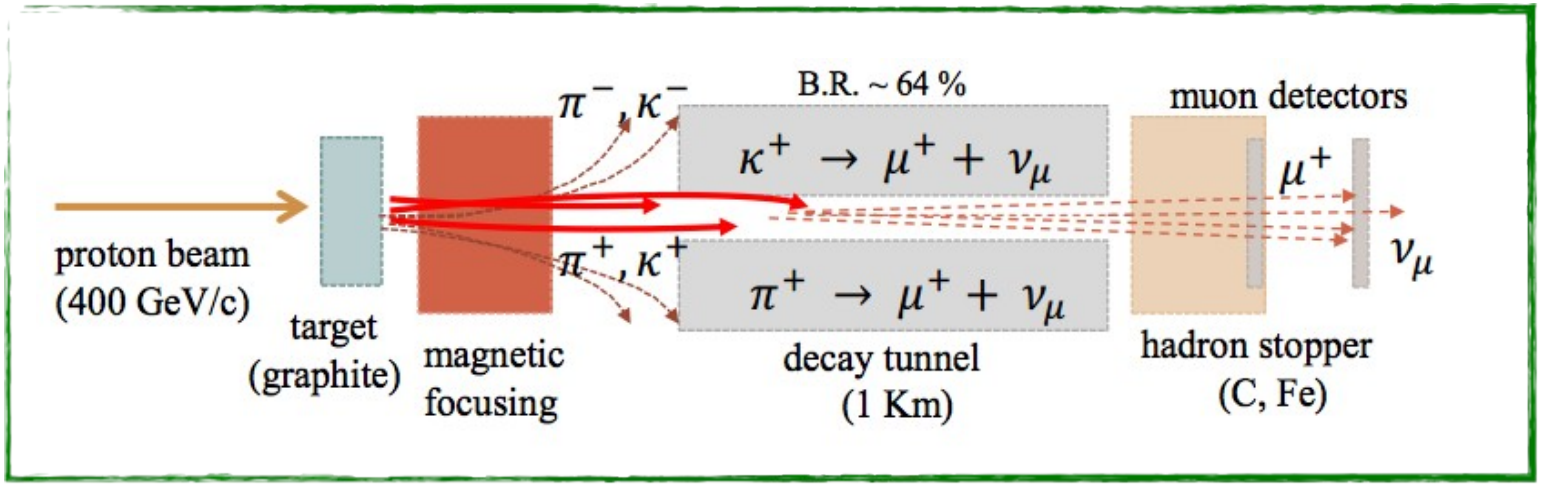
``Brick-finding''



+ several ancillary facilities "off-site":

- **Assembly/disassembly of bricks (LNGS)**
- **Brick Manipulator System (LNGS)**
- **Labelling and X ray marking (LNGS)**
- **Automatised development (LNGS)**
- **Scanning of CS doublets (LNGS+JP)**
- **Scanning bricks (Europe + JP)**

CERN Neutrinos to Gran Sasso



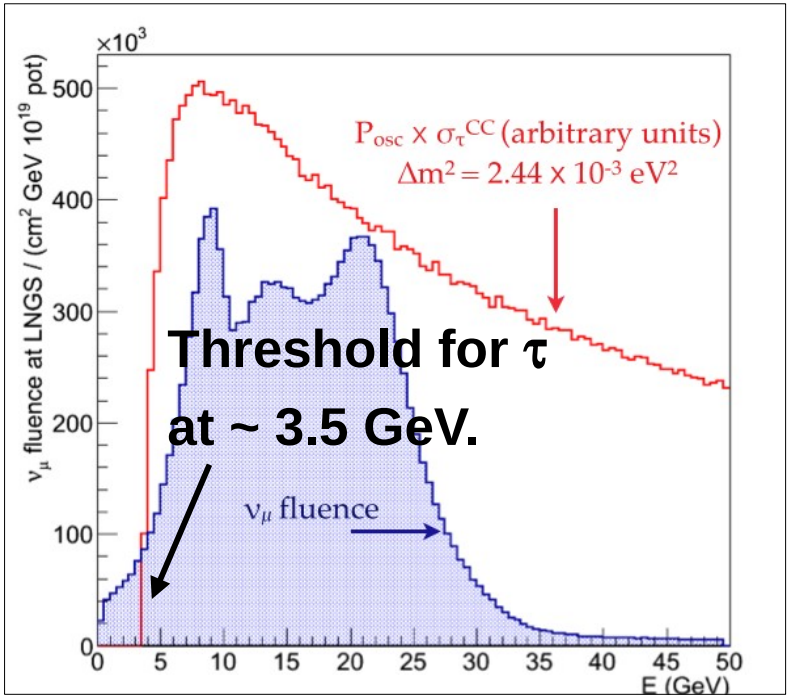
The oscillation peak for L= 732 km
at ~ 1.5 GeV (similar to NuMI) but the beam is designed to observe τ leptons:

$N(\tau) \sim Pr(\nu_\mu \rightarrow \nu_\tau) \times \sigma_{\nu(\tau)CC}(E) \times flux$

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



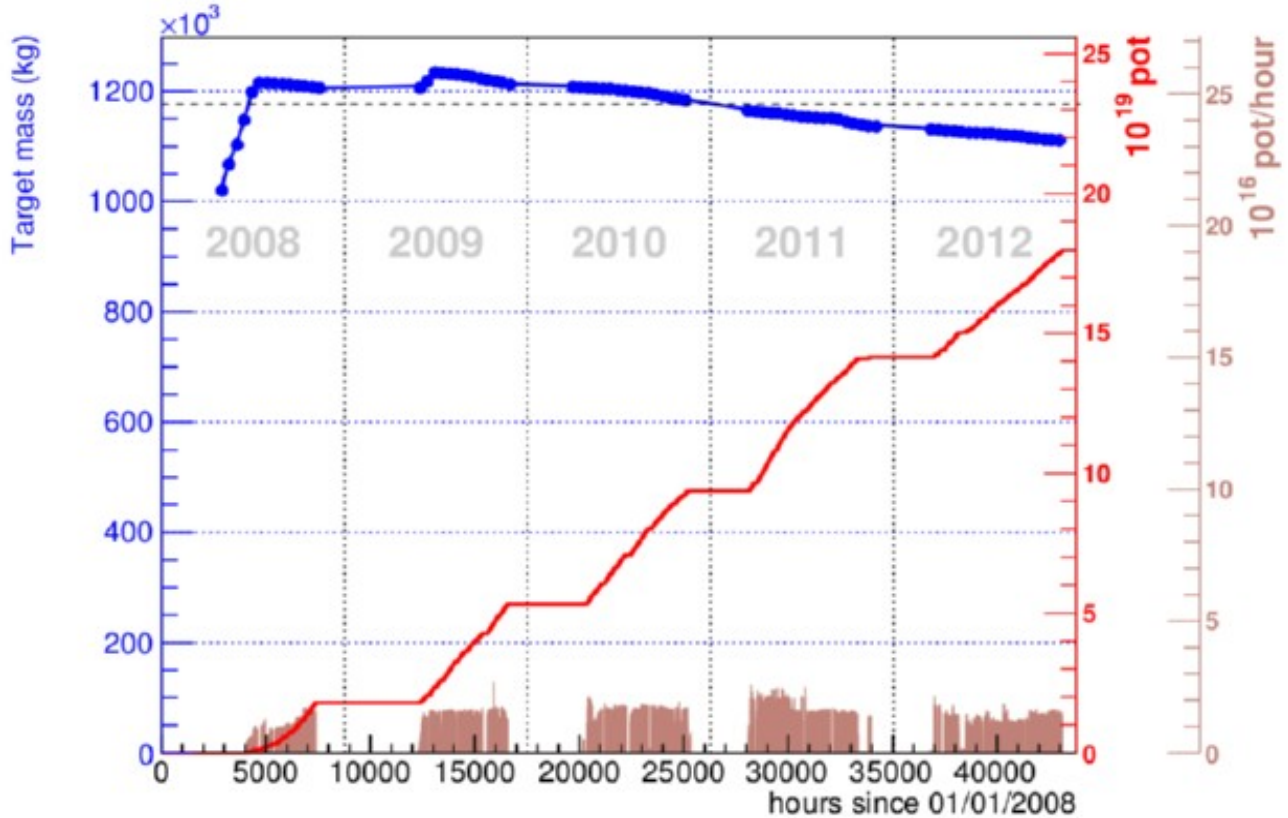
Collected data samples

The 5 year long CNGS run has ended in 2012.

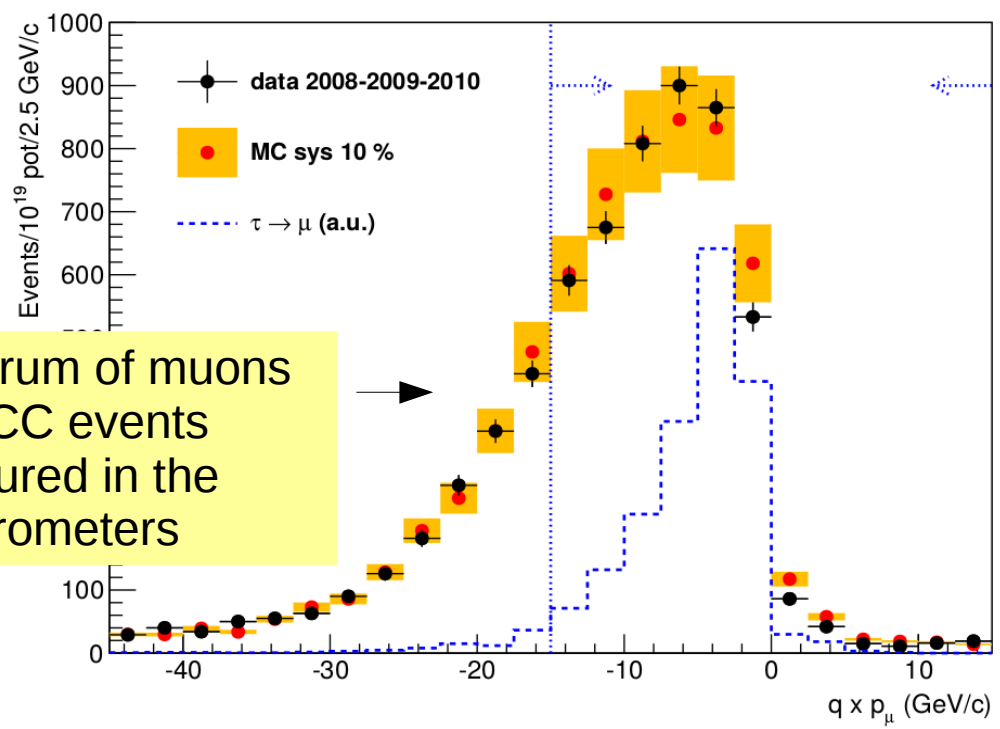
1.8 x 10^{20} p.o.t. collected
80% of the design (2.25 x 10^{20})

1.25 kton initial target mass (150 k bricks)

19505 neutrino interactions in the emulsion targets.



Year	Days	p.o.t. (10^{19})	ν interactions
2008	123	1.74	1698
2009	155	3.53	3693
2010	187	4.09	4248
2011	243	4.75	5131
2012	257	3.86	3923
tot	**965**	**17.97**	**19505**

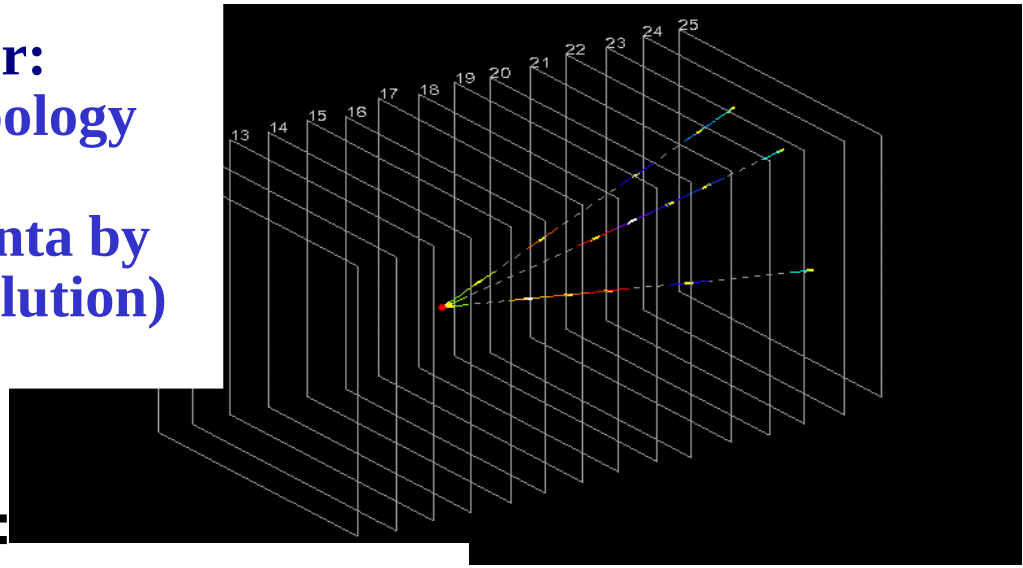


Spectrum of muons from CC events measured in the spectrometers

ν_τ candidate identification

The brick is a complete stand-alone detector:

- **Neutrino interaction vertex and decay topology reconstruction (Decay search)**
- **Measurement of charged particles' momenta by Multiple Coulomb Scattering (20-30% resolution)**
- **e/γ separation and energy measurement**



Kinematical cuts to increase S/B ratio:

variable	$\tau \to 1h$	$\tau \to 3h$	$\tau \to \mu$	$\tau \to e$
lepton-tag	No μ or e at the primary vertex			
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 and < 15	> 1 and < 15
θ_{kink} (mrad)	> 20	< 500	> 20	> 20
m, m_{min} (GeV/c^2)	/	> 0.5 and < 2	/	/

0.3 GeV/c in presence of γ in the decay vertex

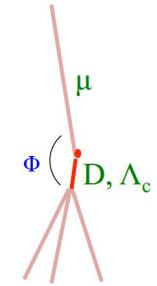
For candidate events, Track Follow Down (TFD) procedure:
All reconstructed event tracks followed from brick to brick,

- **to enhance μ-identification (99%)**
- **improve μ/h discrimination (range measurement and nuclear interaction detection)**

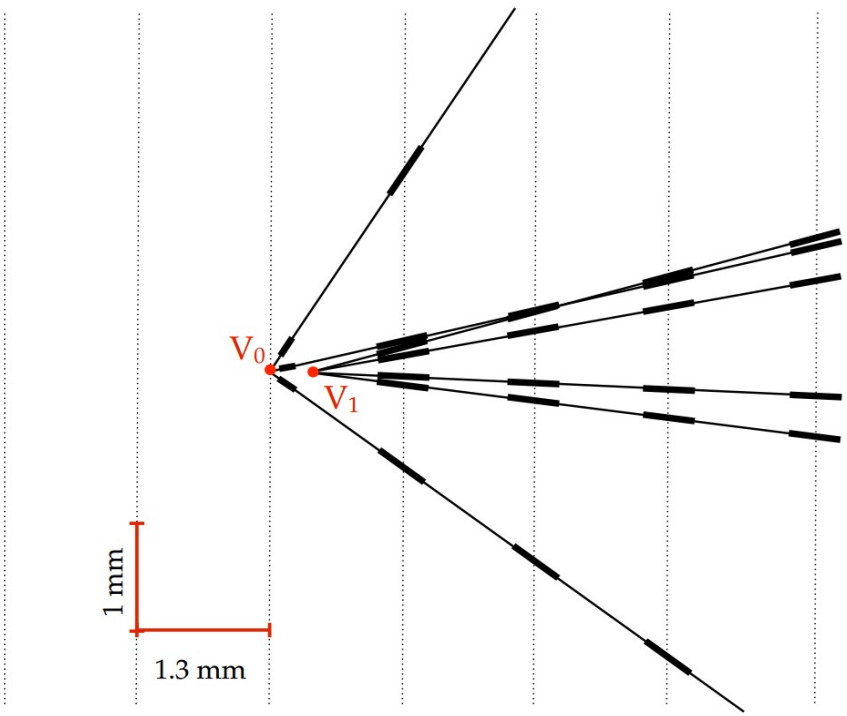
Validation with the CNGS charm events sample

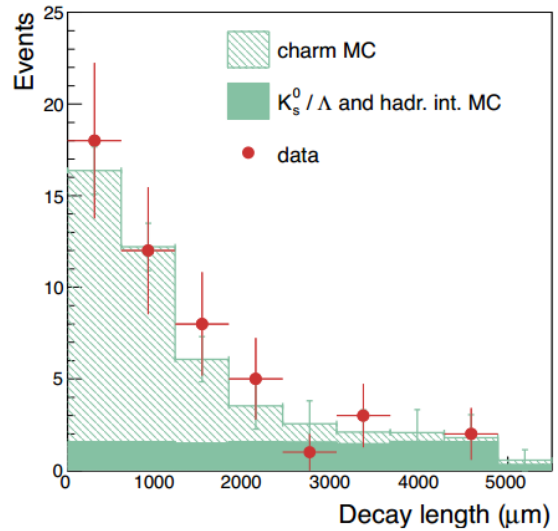
Charmed hadrons produced in ν_μ^{CC} events (μ at the primary vertex)

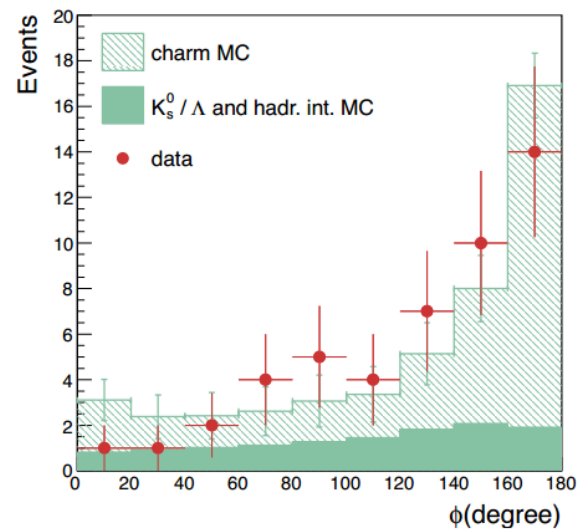
Charm and τ decays are topologically similar.
Test for: reconstruction efficiencies, description of kinematic variables, charm background.

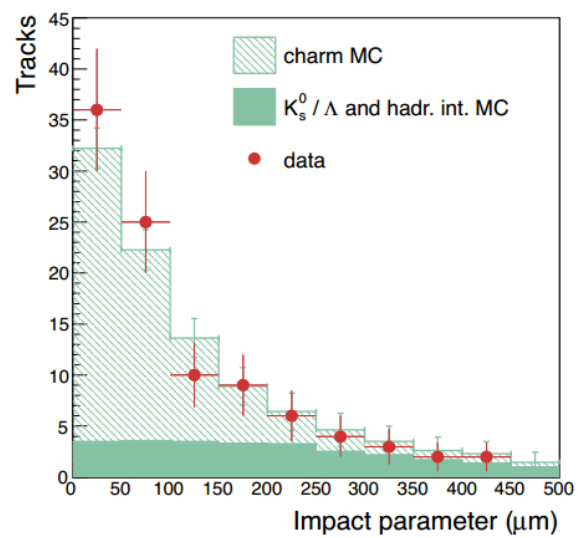


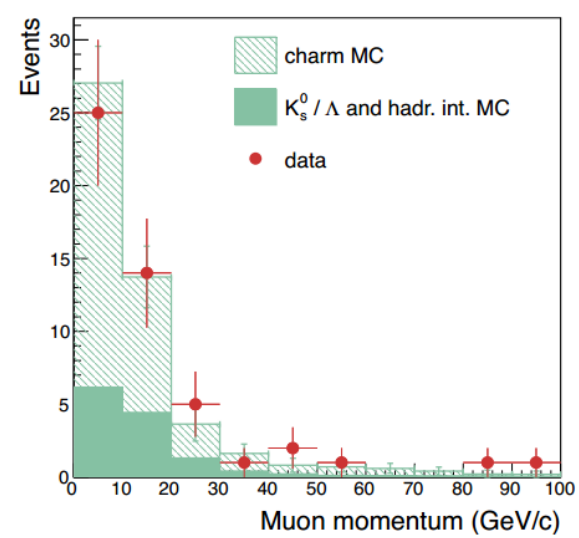
2008-2010 data sample:
54 ± 4 expected events
50 observed events











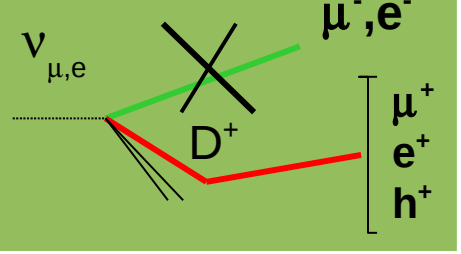
Eur.Phys.J. C74 (2014) 8, 2986

$\nu_\mu \rightarrow \nu_\tau$ background characterization

Monte Carlo simulation benchmarked on control samples.

In order of decreasing relevance

CC with charm production (all channels) IF the primary lepton is not identified and the daughter charge is not (or incorrectly) measured

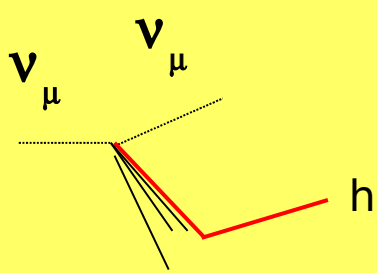


MC tuned on CHORUS data (cross section and fragmentation functions), validated with measured OPERA charm events.

Reduced by "track follow down" procedure and large angle scanning

Hadronic interactions

Background for $\tau \rightarrow$ h

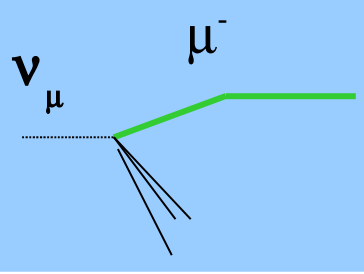


FLUKA + pion test beam data

Reduced by large angle scanning and nuclear fragment search

Large angle muon scattering

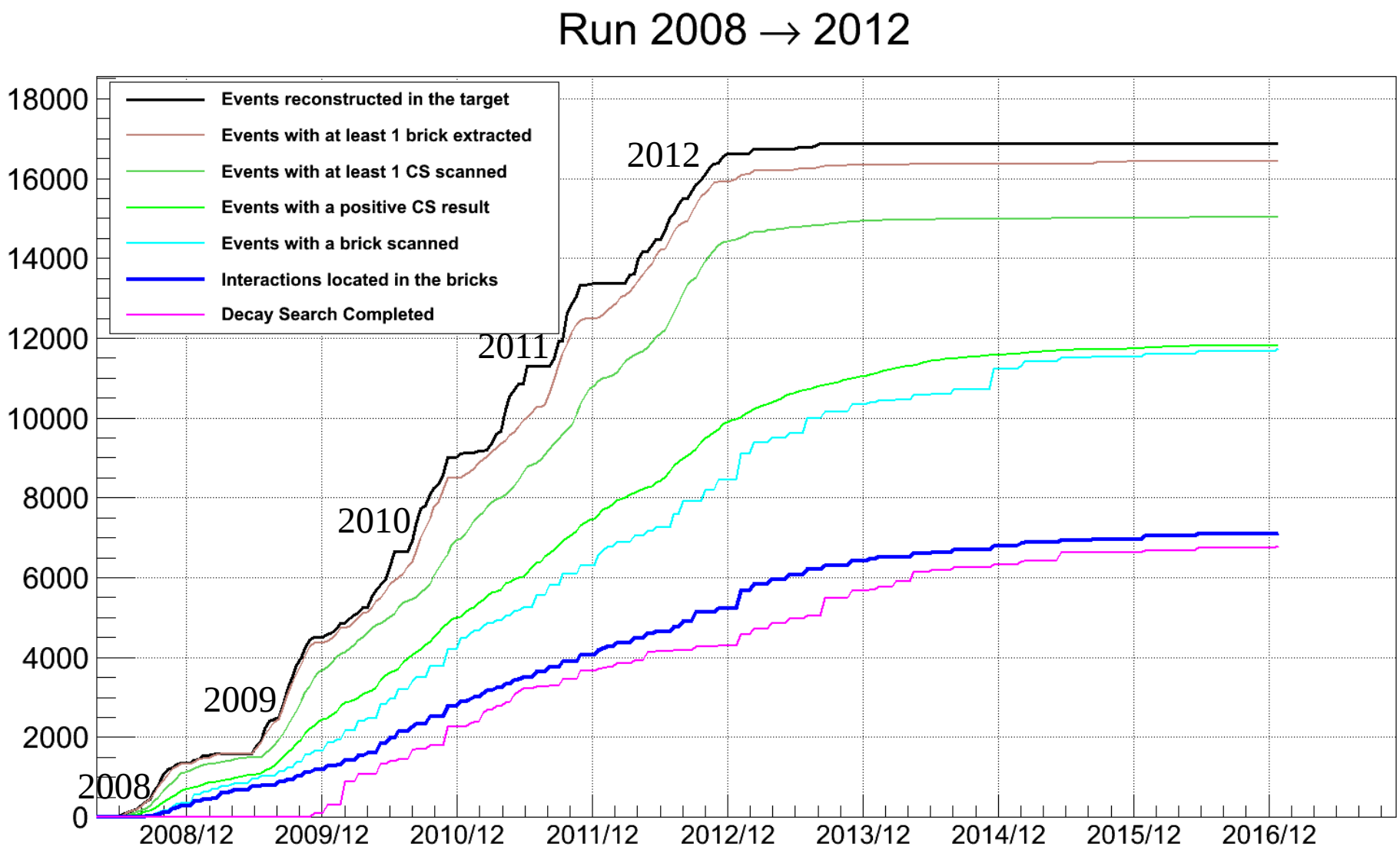
Background for $\tau \rightarrow \mu$



Measurements in the literature (Lead form factor), improved MC simulations

IEE TNS vol.62 N.5 October 2015, 2216

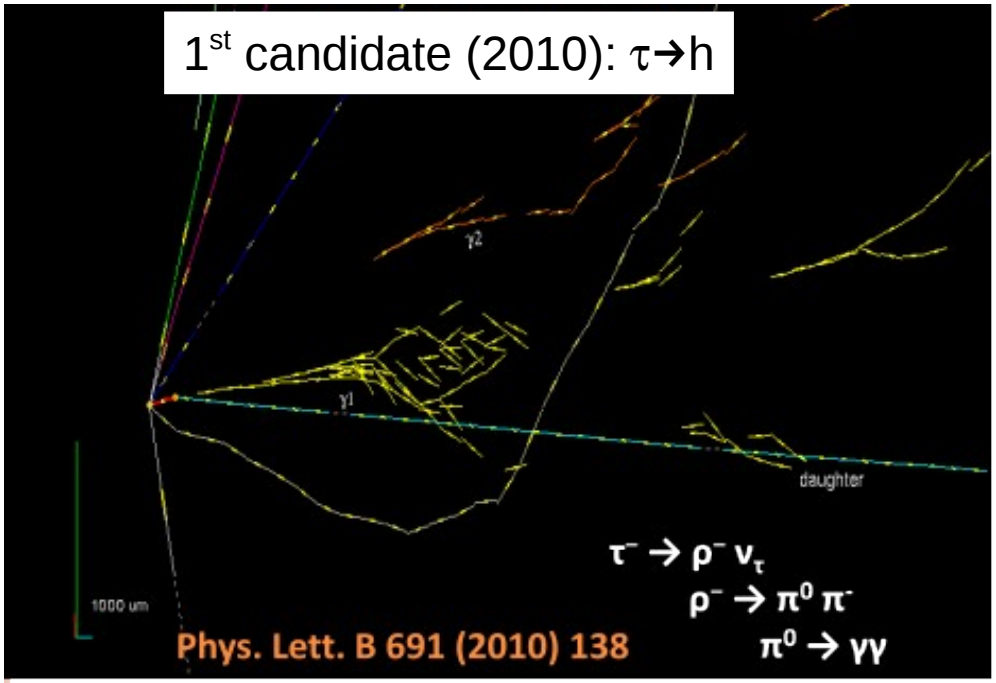
OPERA Data Analysis

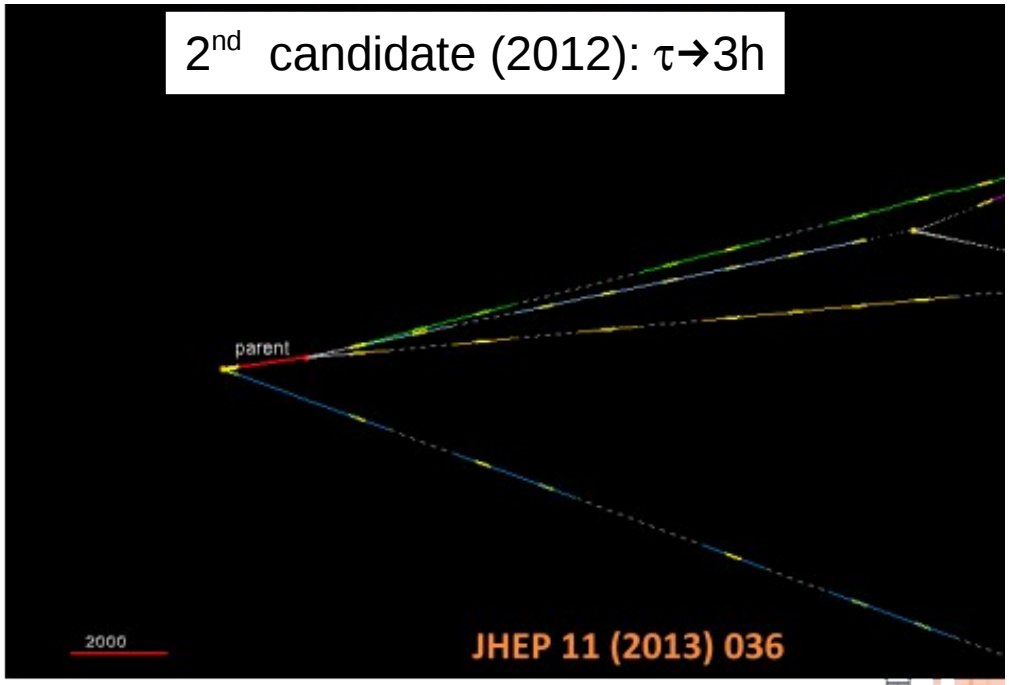


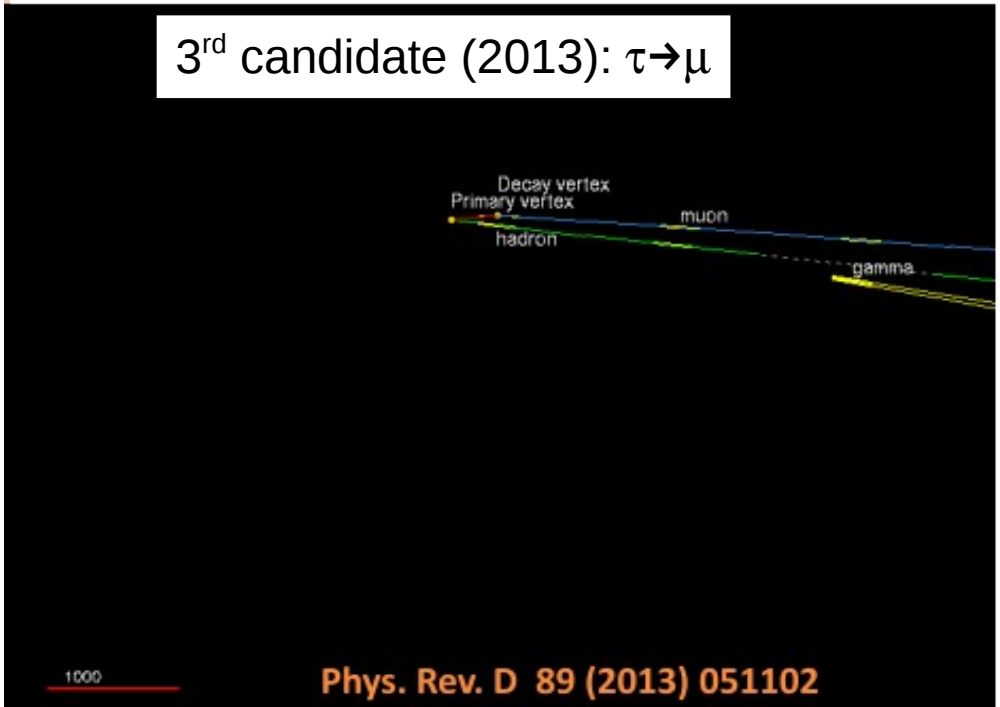
7132 located interactions

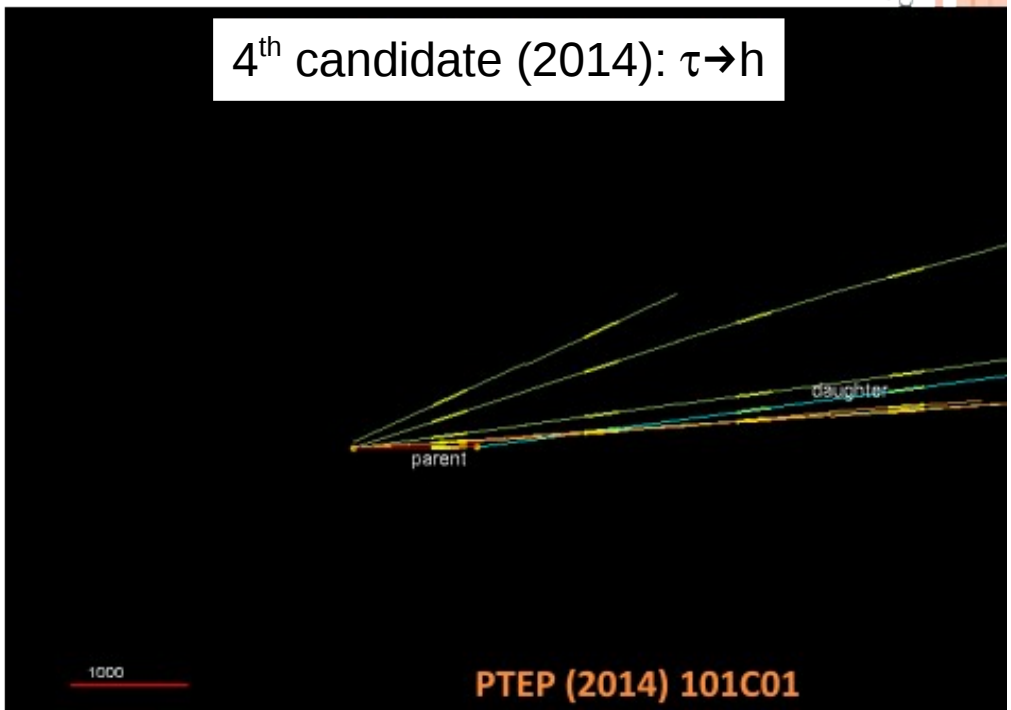
6785 decay search

ν_τ events observed in OPERA

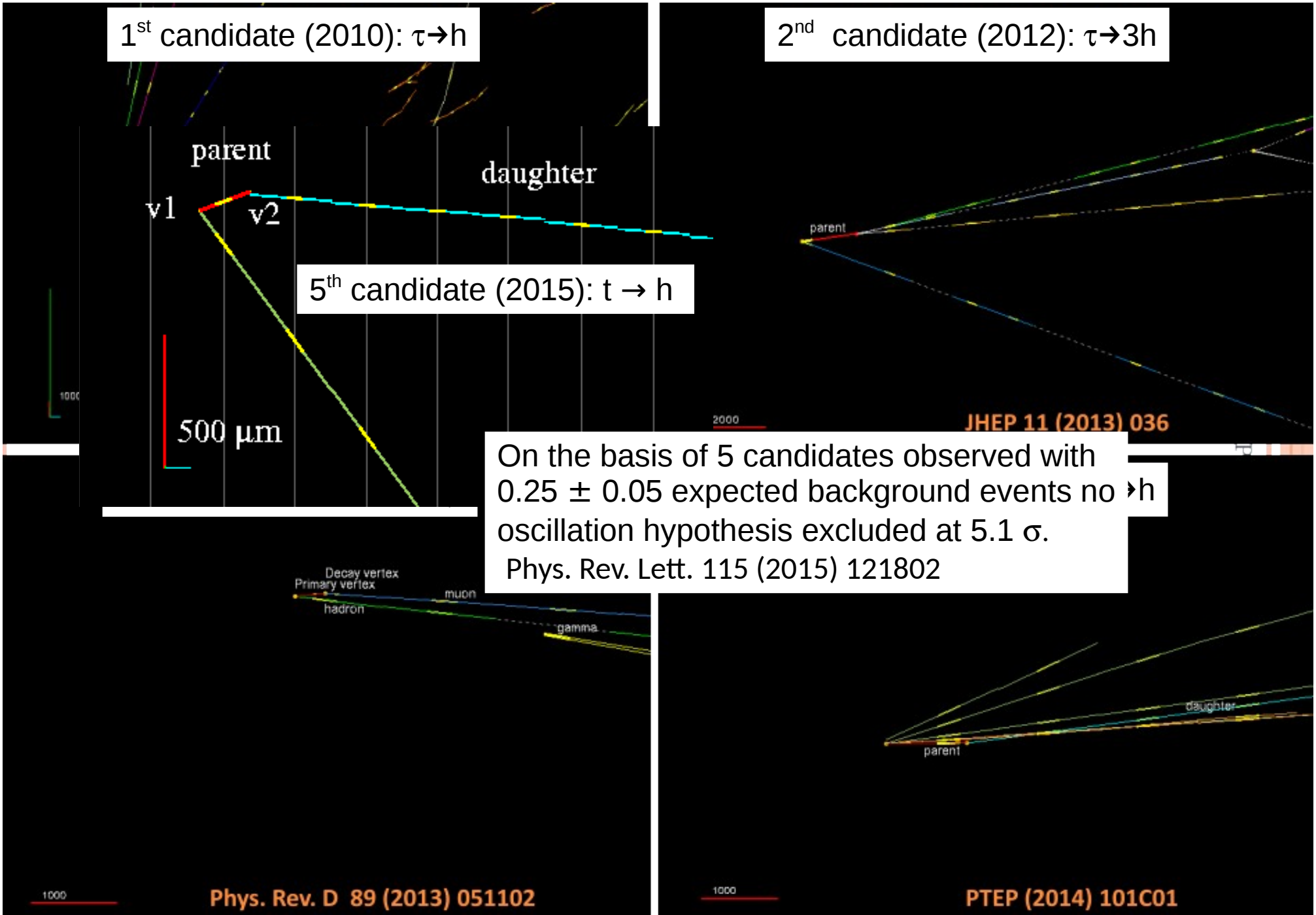








ν_τ events observed in OPERA



On the basis of 5 candidates observed with 0.25 ± 0.05 expected background events no oscillation hypothesis excluded at 5.1 σ.

Phys. Rev. Lett. 115 (2015) 121802

$\nu_\mu \rightarrow \nu_\tau$: preliminary results on sterile ν

3+1 model

standard

$$P(\nu_\mu \rightarrow \nu_\tau) = 4\left|U_{\mu 3}{}^2\right|\left|U_{\tau 3}{}^2\right|\sin^2\frac{\Delta_{31}}{2}$$

(normal hierarchy)

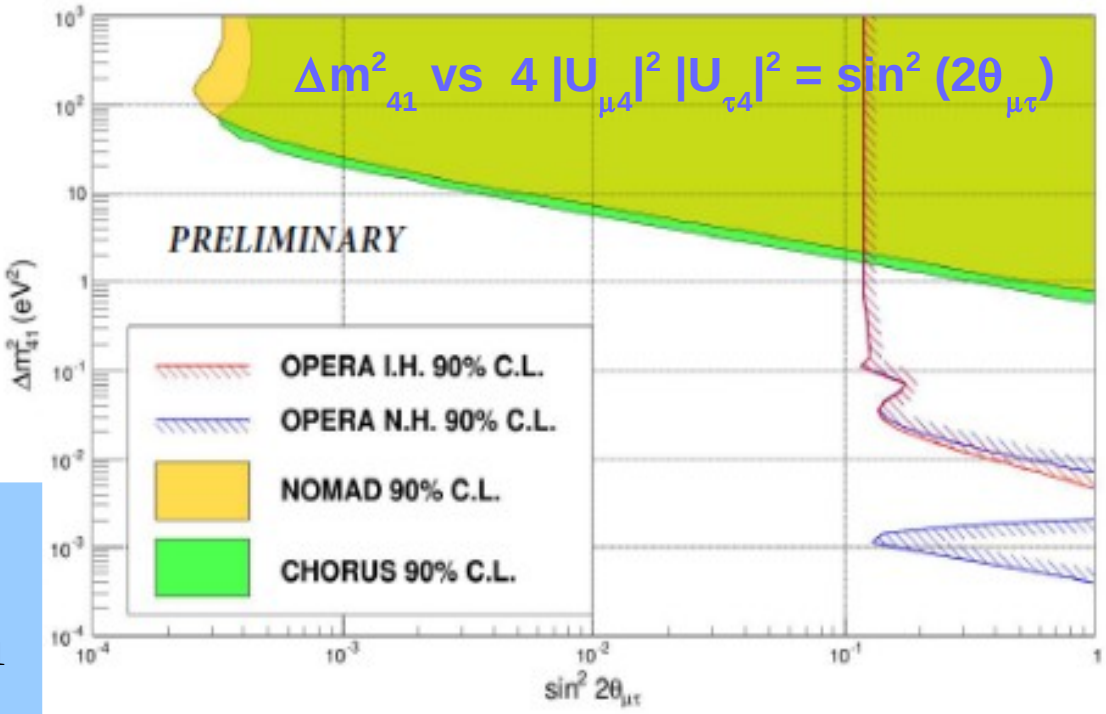
exotic

$$+4\left|U_{\mu 4}{}^2\right|\left|U_{\tau 4}{}^2\right|\sin^2\frac{\Delta_{41}}{2}$$

$$+2\Re\left[U^*_{\mu 4}U_{\tau 4}U_{\mu 3}U^*_{\tau 3}\right]\sin\Delta_{31}\sin\Delta_{41}$$
$$-4\Im\left[U^*_{\mu 4}U_{\tau 4}U_{\mu 3}U^*_{\tau 3}\right]\sin^2\frac{\Delta_{31}}{2}\sin\Delta_{41}$$
$$+8\Re\left[U^*_{\mu 4}U_{\tau 4}U_{\mu 3}U^*_{\tau 3}\right]\sin^2\frac{\Delta_{31}}{2}\sin\frac{\Delta_{41}}{2}$$
$$+4\Im\left[U^*_{\mu 4}U_{\tau 4}U_{\mu 3}U^*_{\tau 3}\right]\sin\Delta_{31}\sin\frac{\Delta_{41}}{2}$$

Interference term

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



- 90% CL exclusion limit on Δm^2_{41} lowered down to 10^{-2} eV^2 for $\sin^2(2\theta_{\mu\tau}) > 0.5$

- At large Δm^2_{41} : $\sin^2(2\theta_{\mu\tau}) < 0.119$ at 90% CL

Update of JHEP 1506 (2015) 069

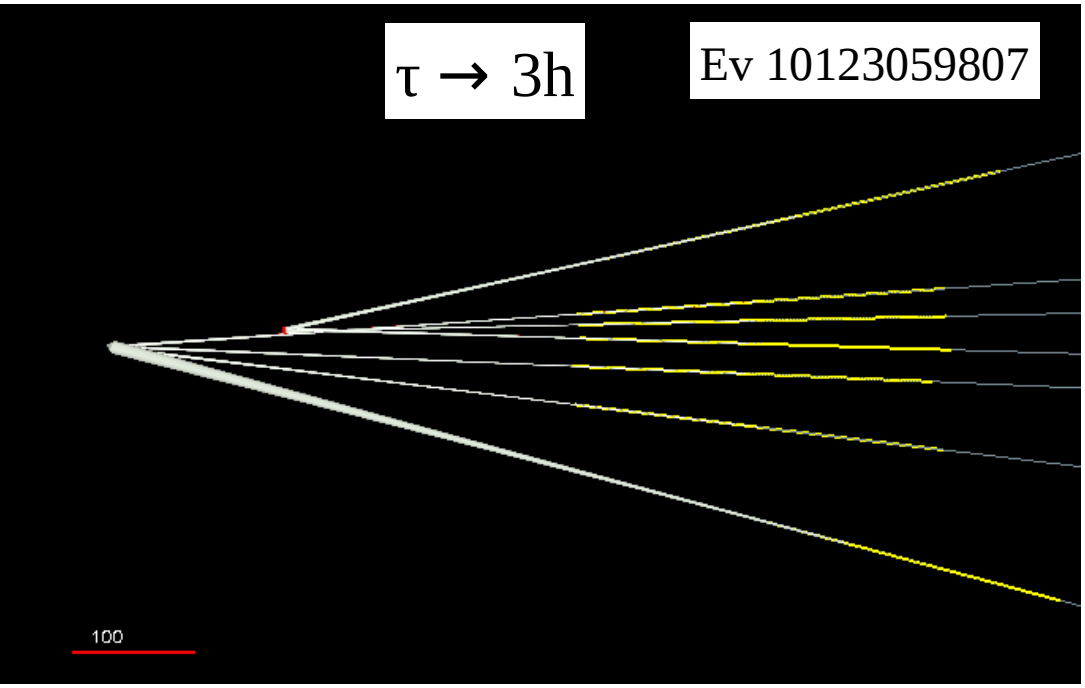
$\nu_\mu \rightarrow \nu_\tau$: Data sample re-analysis

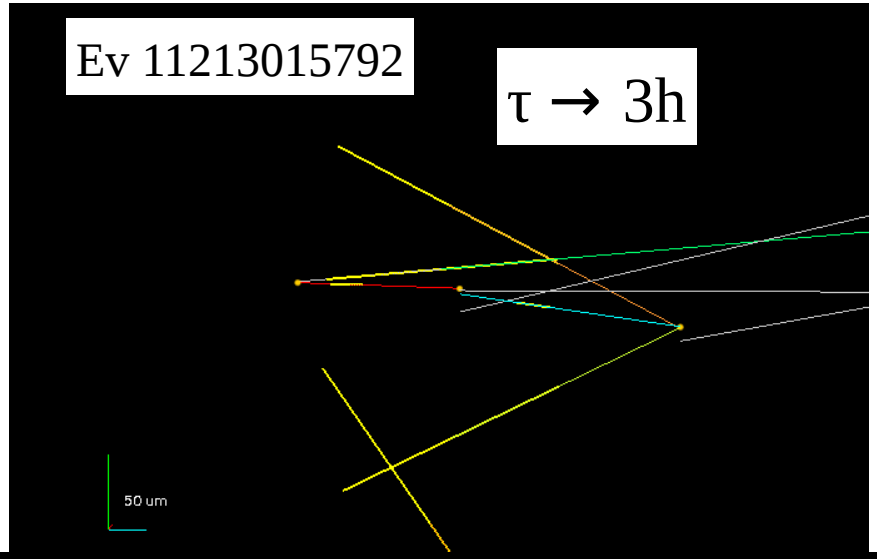
Phys. Rev. Lett. 120 (2018) 211801 : looser cuts and Multi-Variate classifier (BDT)

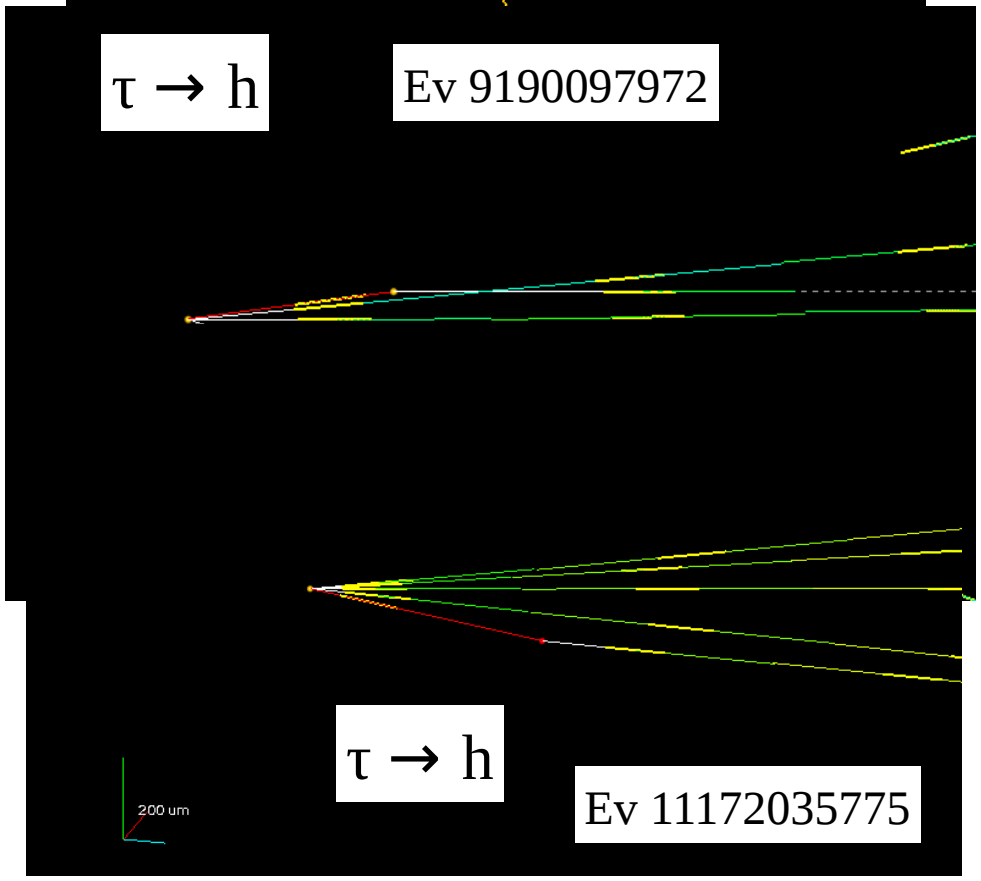
Variable	$\tau \rightarrow 1h$		$\tau \rightarrow 3h$		$\tau \rightarrow \mu$		$\tau \rightarrow e$	
	OLD	NEW	OLD	NEW	OLD	NEW	OLD	NEW
z_{dec} (μm)	$[44, 2600]$	<2600	<2600		$[44, 2600]$	<2600	<2600	
θ_{kink} (rad)	>0.02		<0.5	>0.02	>0.02		>0.02	
p_{2ry} (GeV/c)	>2	>1	>3	>1	$[1, 15]$		$[1, 15]$	>1
p^T_{2ry} (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)	/		$[0.5, 2]$	/	/		/	

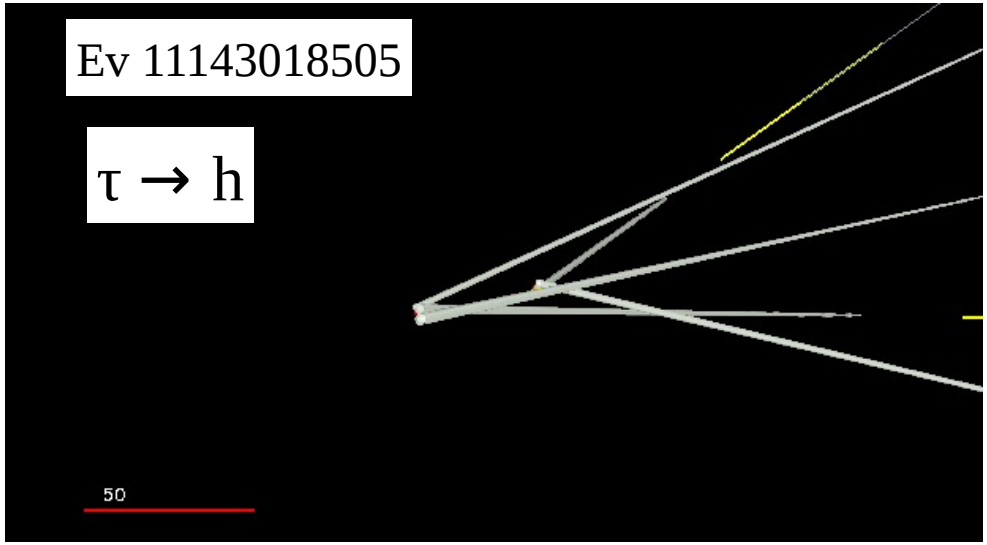
Channel	Expected Background				Expected Signal	Total Expected
	Charm	Had. re-interaction	Large μ-scat.	Total		
$\tau \rightarrow 1h$	0.15 ± 0.03	1.28 ± 0.38	–	1.43 ± 0.39	2.96 ± 0.59	4.39 ± 1.39
$\tau \rightarrow 3h$	0.44 ± 0.09	0.09 ± 0.03	–	0.52 ± 0.09	1.83 ± 0.37	2.35 ± 0.58
$\tau \rightarrow \mu$	0.008 ± 0.002	–	0.016 ± 0.008	0.024 ± 0.008	1.15 ± 0.23	1.18 ± 0.25
$\tau \rightarrow e$	0.035 ± 0.007	–	–	0.035 ± 0.007	0.84 ± 0.17	0.87 ± 0.18
Total	0.63 ± 0.10	1.37 ± 0.38	0.016 ± 0.008	2.0 ± 0.4	6.8 ± 1.4	8.8 ± 1.8

5 more ν_τ candidates.....

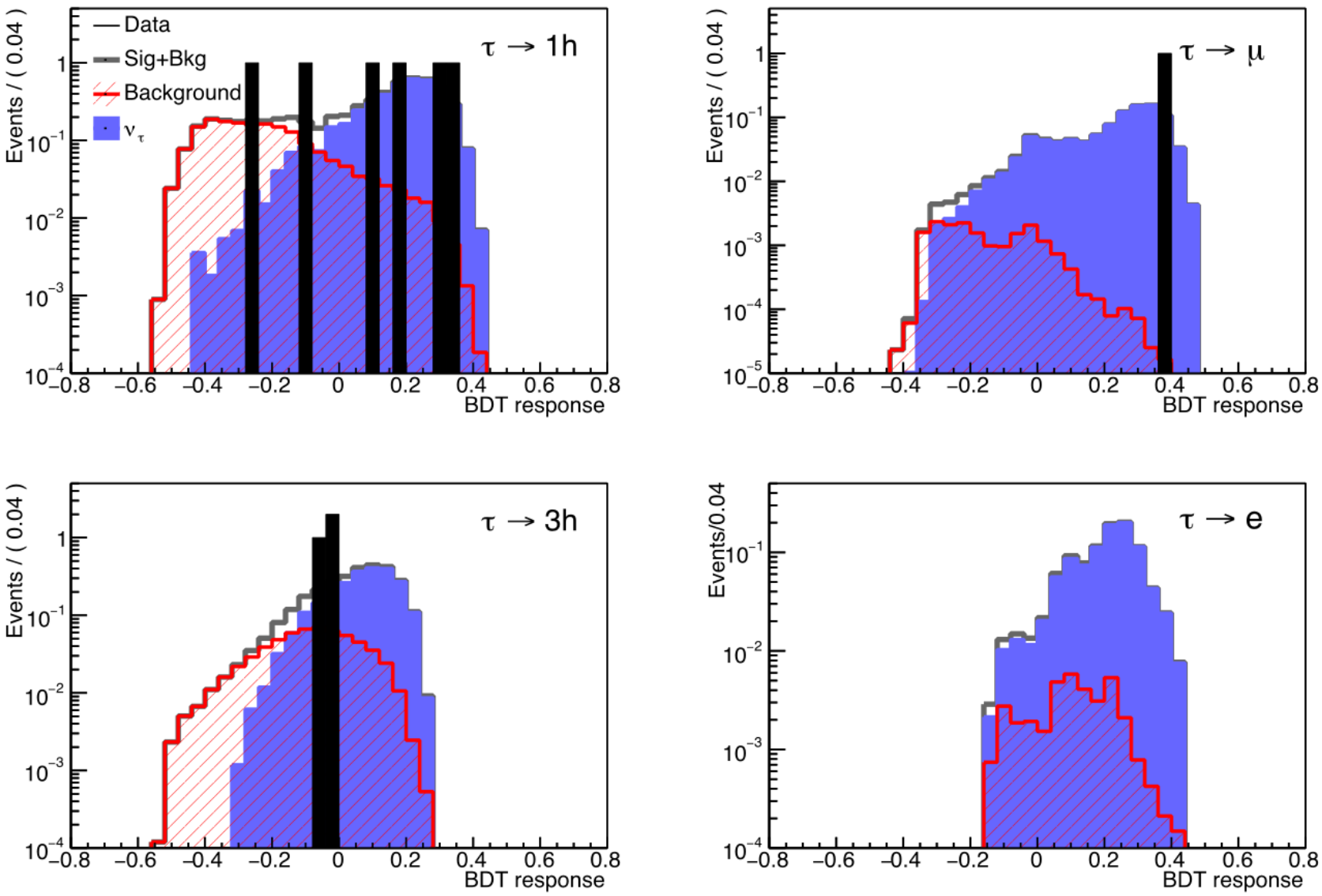






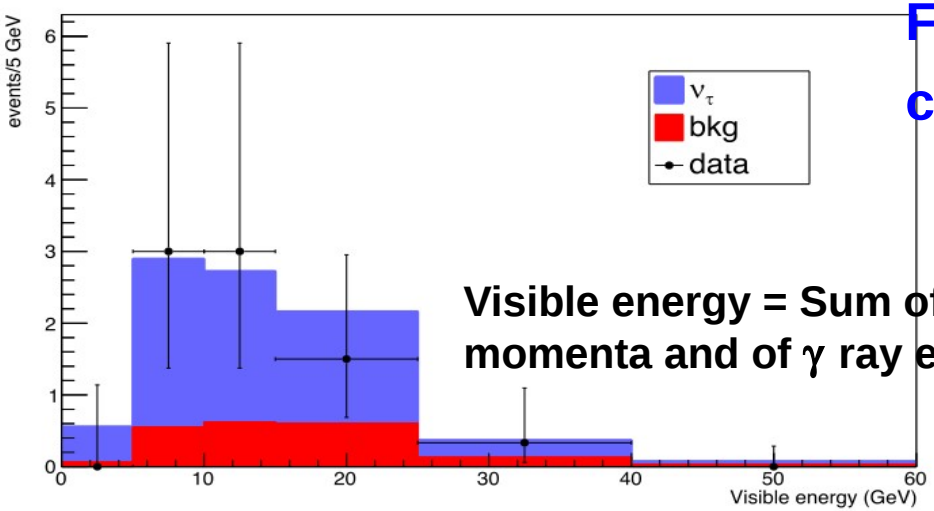


BDT response for all decay channels



Likelihood based analysis: No oscillation hypothesis excluded at 6.1 σ (P-value=4 10^{-10})

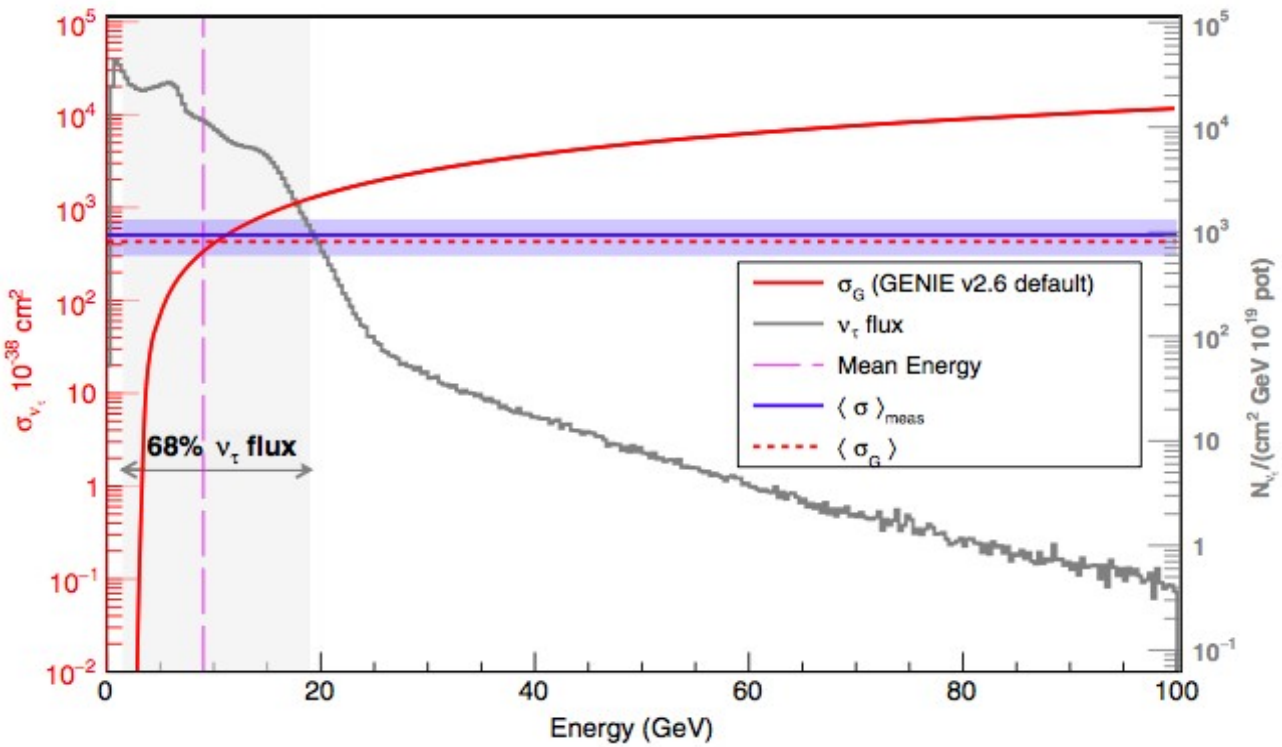
Cross section measurement



First ν_τ sample with negligible anti-neutrino contamination selected.....

$$N(\nu_\tau) \propto P(\nu_\mu \rightarrow \nu_\tau) \times \sigma(\nu_\tau CC)$$

Visible energy = Sum of charged particle momenta and of γ ray energy.



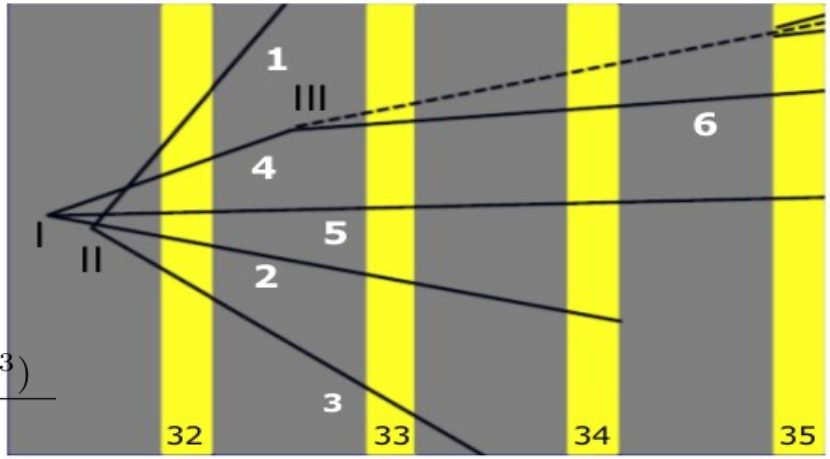
Measured average cross-section weighted over ν_τ flux:

$$\langle \sigma \rangle_{\rm meas} = (5.1^{+2.4}_{-2.0}) \times 10^{-36}\ {\rm cm}^2,$$

$$\langle \sigma \rangle_{meas} = (1.2^{+0.6}_{-0.5})\ \langle \sigma_G \rangle$$

Among the 5 new candidates: an event with 3 vertices

Vertex 2 can be a charmed particle decay.
Dedicated simulations and Artificial Neural Network (ANN) analysis have been performed.
Event classified as ν_τ interaction with charm production (first event ever observed).

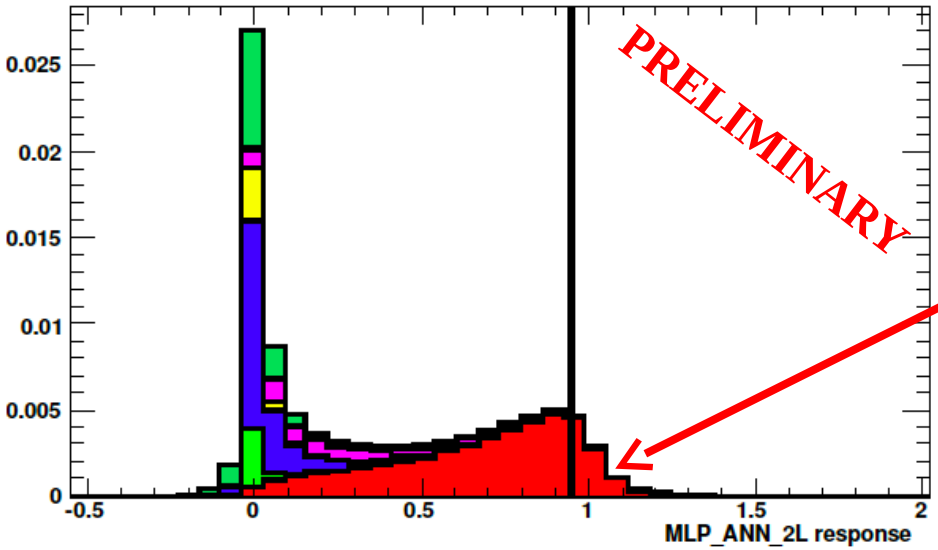


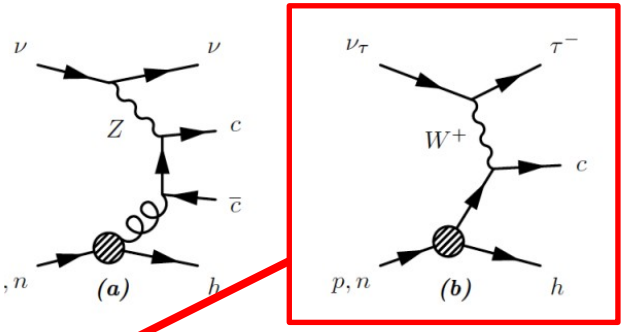
Sample	Muon misidentified	Expected events (10^{-3})
ν_τ CC + charm		45
ν_μ CC + charm + $h_{\rm int}$	yes	21
ν_μ NC + $c\bar{c}$		13
ν_τ CC + $h_{\rm int}$		9
ν_μ CC + $2h_{\rm int}$	yes	4
ν_μ NC + $2h_{\rm int}$		4
Total		100

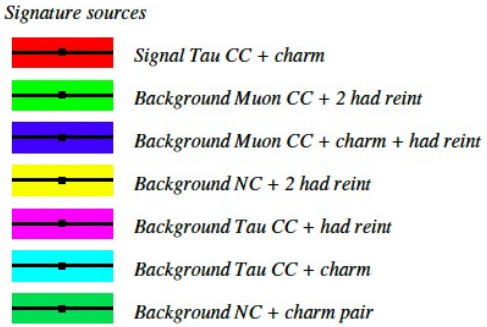
Bkg hypothesis rejected 3.4 σ CL.

Event presented @ ICNFP 2016 !

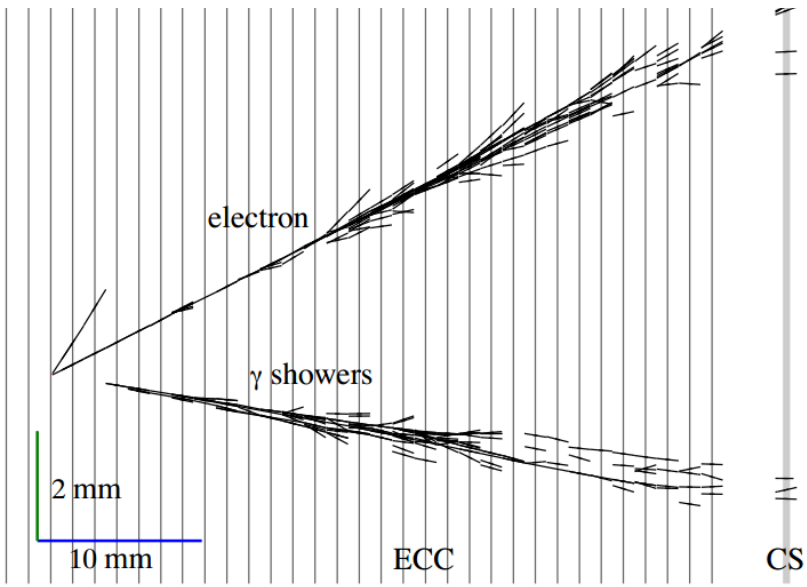
In total, less than 0.1 expected event.







$\nu_\mu \rightarrow \nu_e$ oscillation analysis

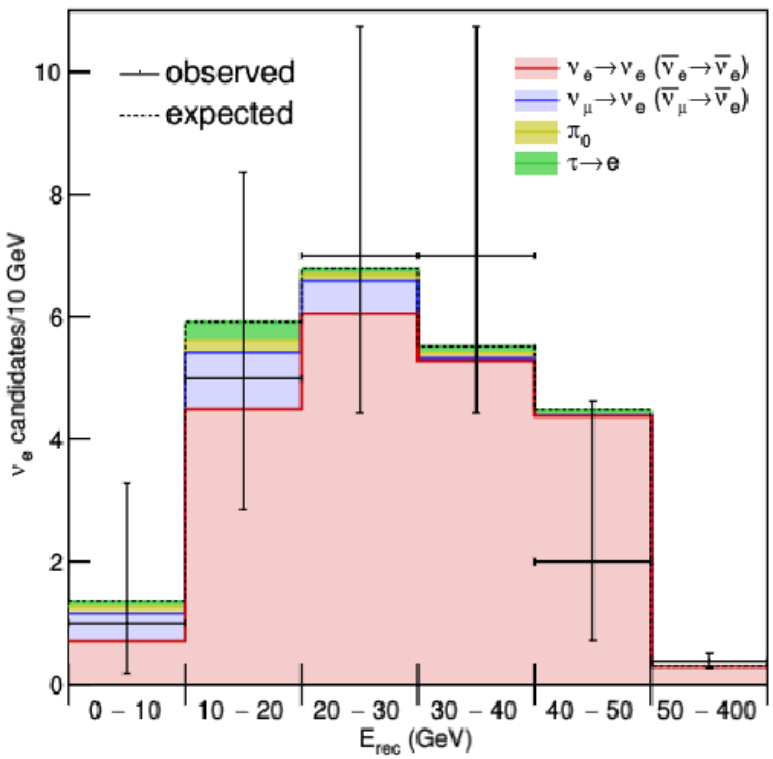


2008-2012 Full sample (17.97×10^{19} p.o.t.):
35 ν_e events observed.

Expected number of events:

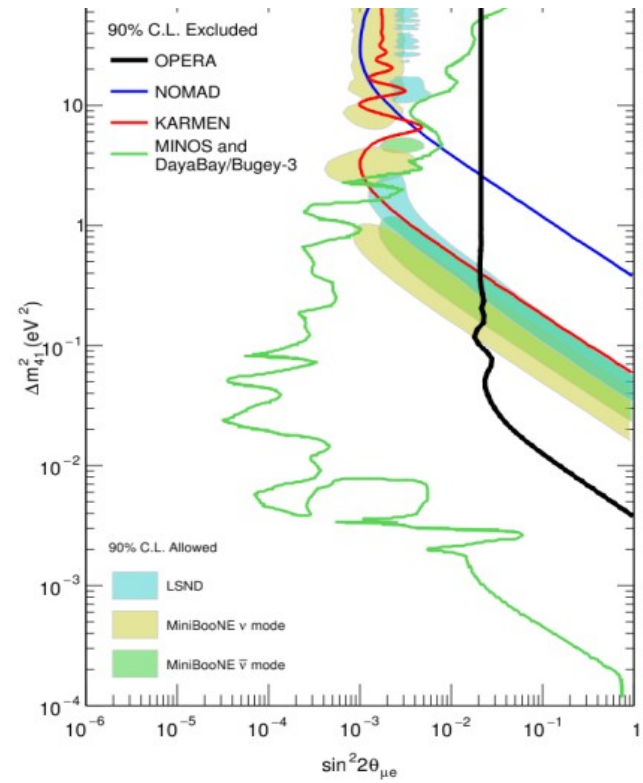
- **Total (with $\nu_\mu \rightarrow \nu_e$ oscillation): 34.3 ± 3.4**
- **ν_e beam contamination: 30.7 ± 3.1**
- **Other backgrounds ($\tau \rightarrow e$ and π^0 mis-id): 1.2 ± 0.5**

In the optimized neutrino energy range (0-40 GeV):
$\sin^2(2\theta_{13}) < 0.43$ @90% CL (3 ν framework)



3+1 framework analysis

ArXiv 1803.11400
JHEP Accepted.



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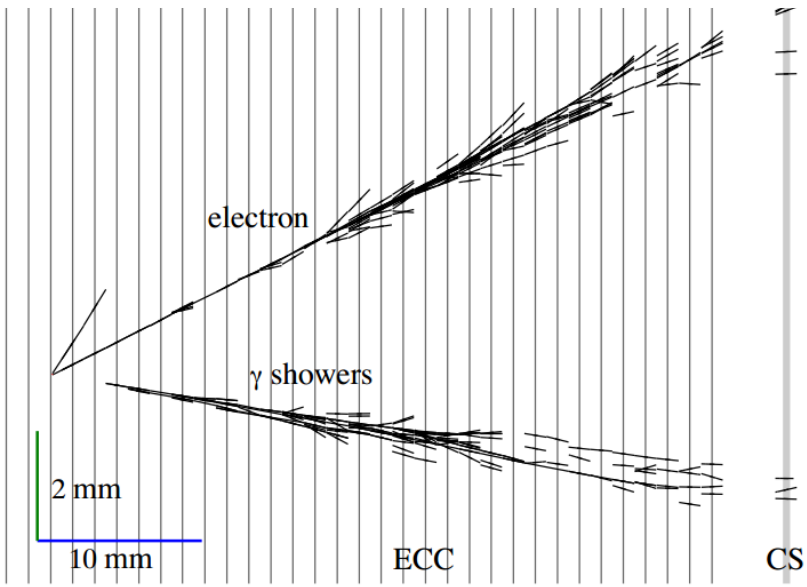

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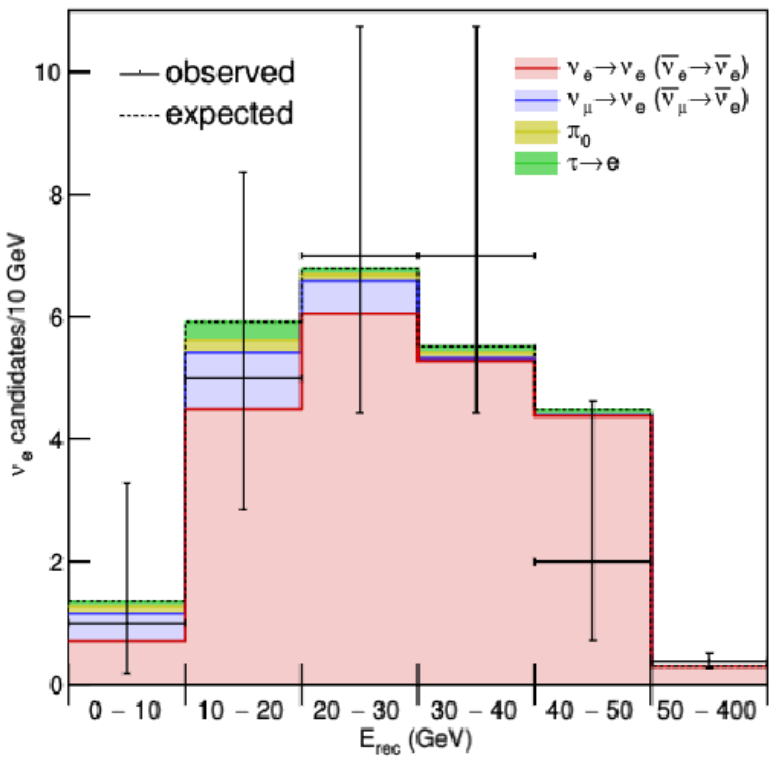
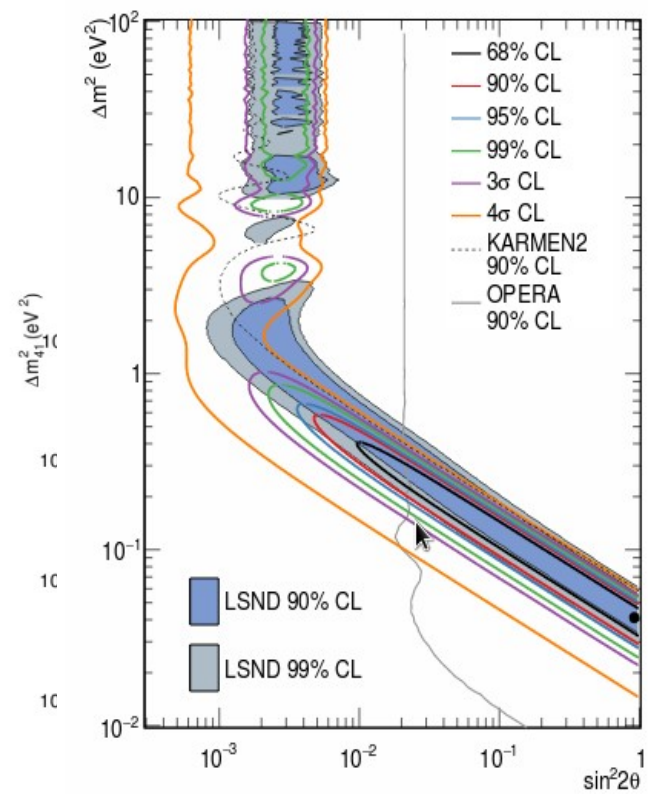
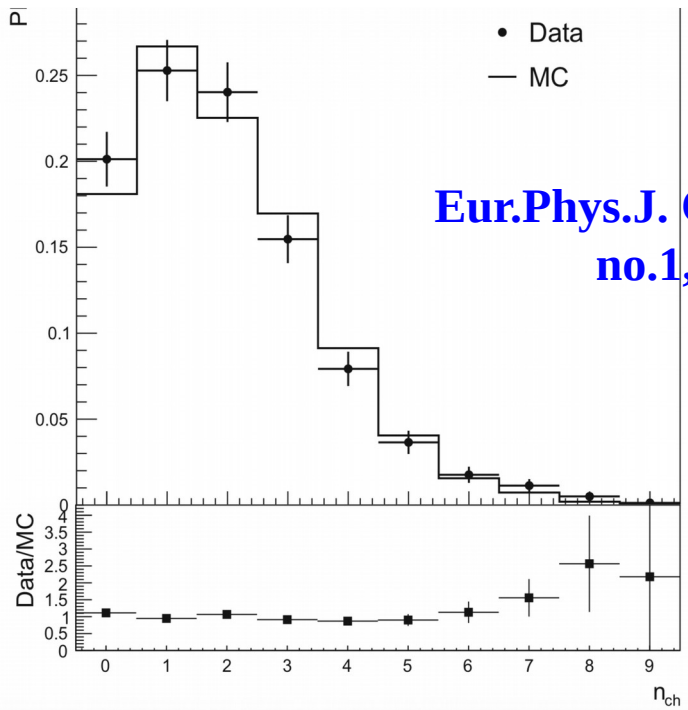


3+1 framework analysis

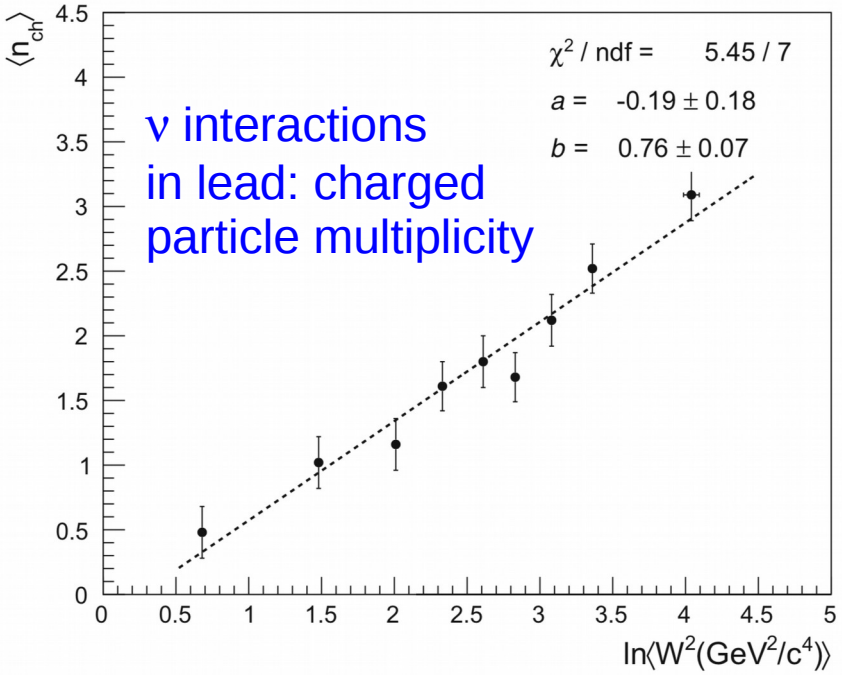
ArXiv 1803.11400
JHEP Accepted.
Cited in recent
MiniBoone paper.



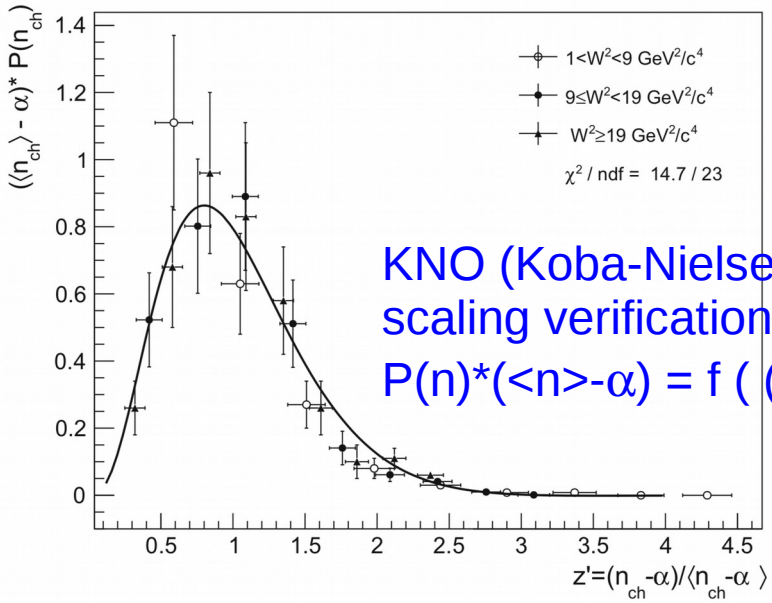
Multiplicity studies in neutrino interactions



Eur.Phys.J. C78 (2018) no.1, 62

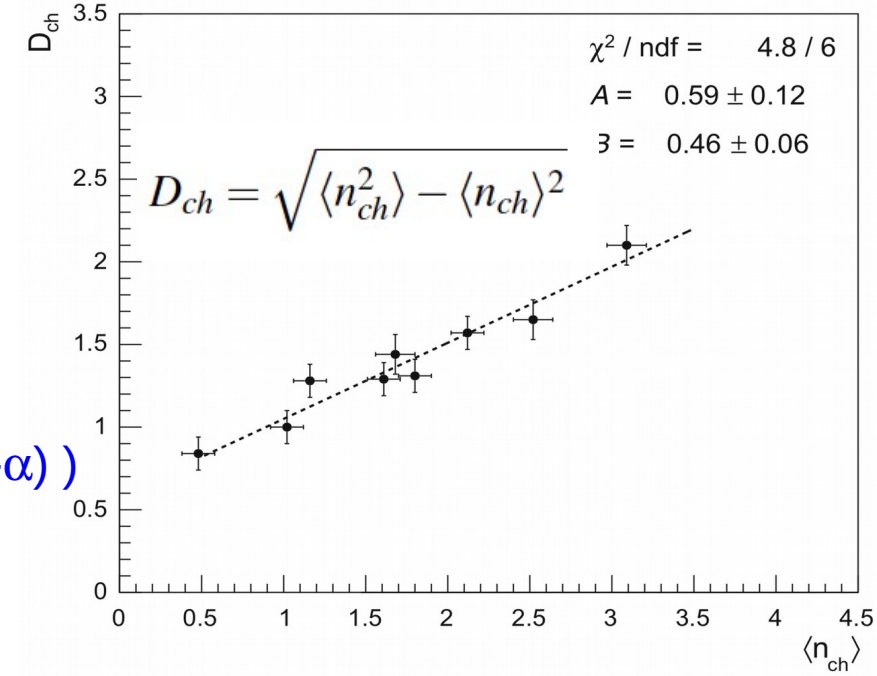


ν interactions in lead: charged particle multiplicity

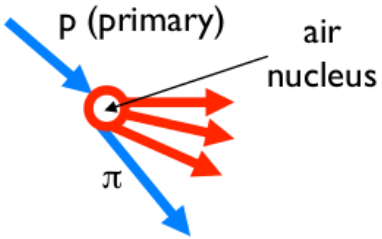


KNO (Koba-Nielsen-Olesen) scaling verification:

P(n)*(<n>-α) = f ((n-α)/(<n>-α))



Cosmic rays: $R = N_{\mu+}/N_{\mu-}$

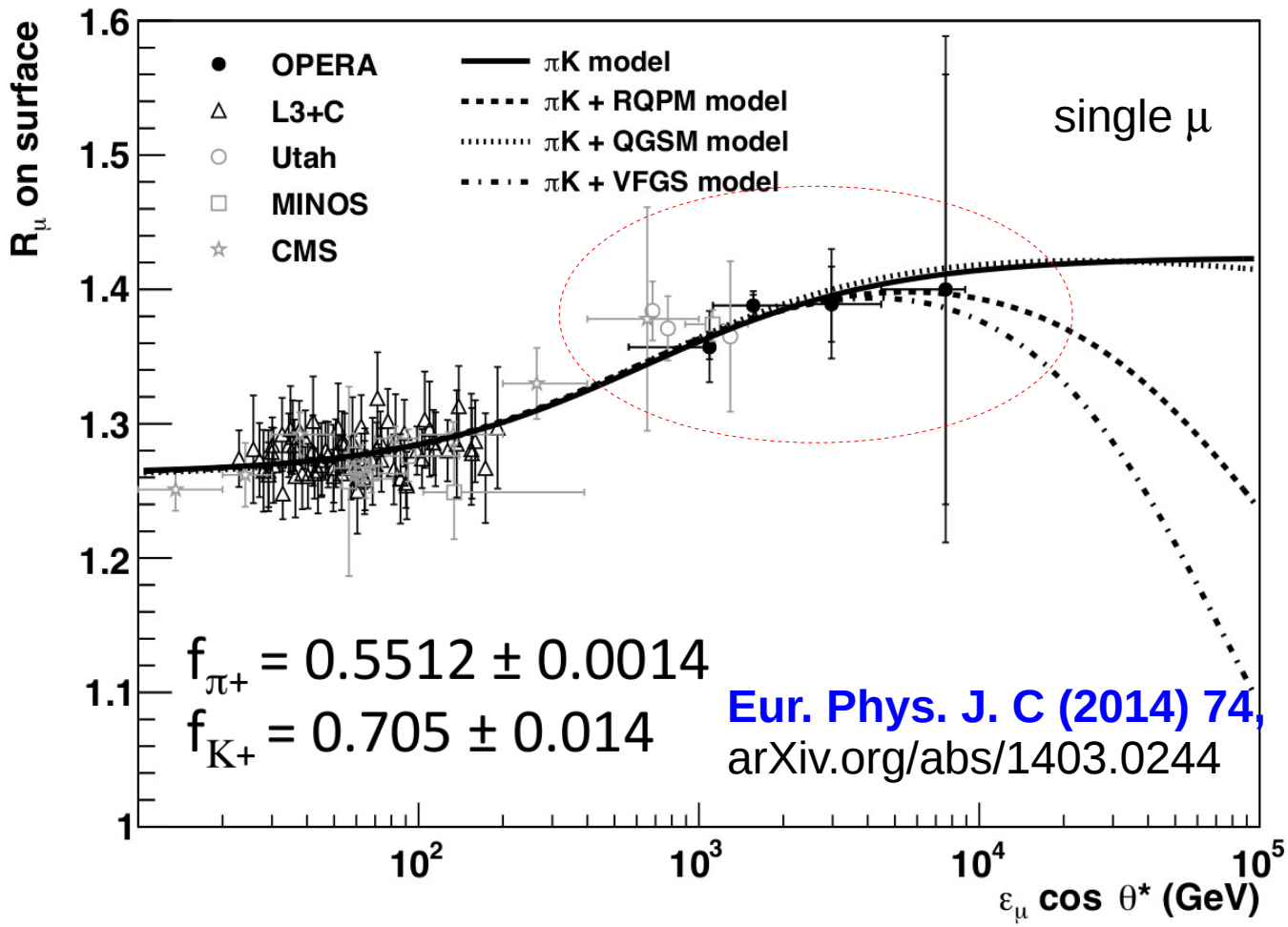


- Highest-E region reached!
- opposite magnet polarities runs → lower systematics
- Strong reduction of the charge ratio for multiple muon events

1 μ	1.377 ± 0.006
Multi-μ	1.098 ± 0.023

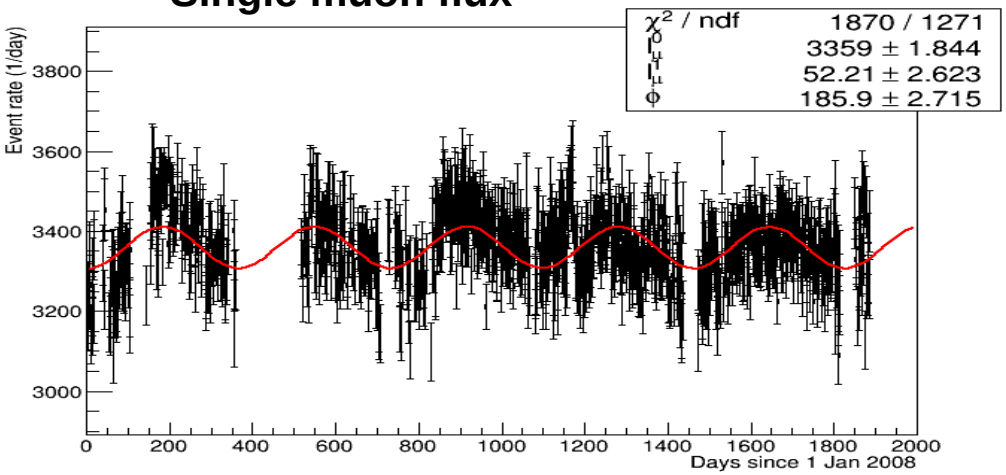
- Results compatible with a simple π-K model
- No significant contribution of the prompt component up to $E_\mu \cos\theta^* \sim 10$ TeV
- Validity of Feynman scaling in the fragmentation region up to $E_\mu \sim 20$ TeV ($E_N \sim 200$ TeV)

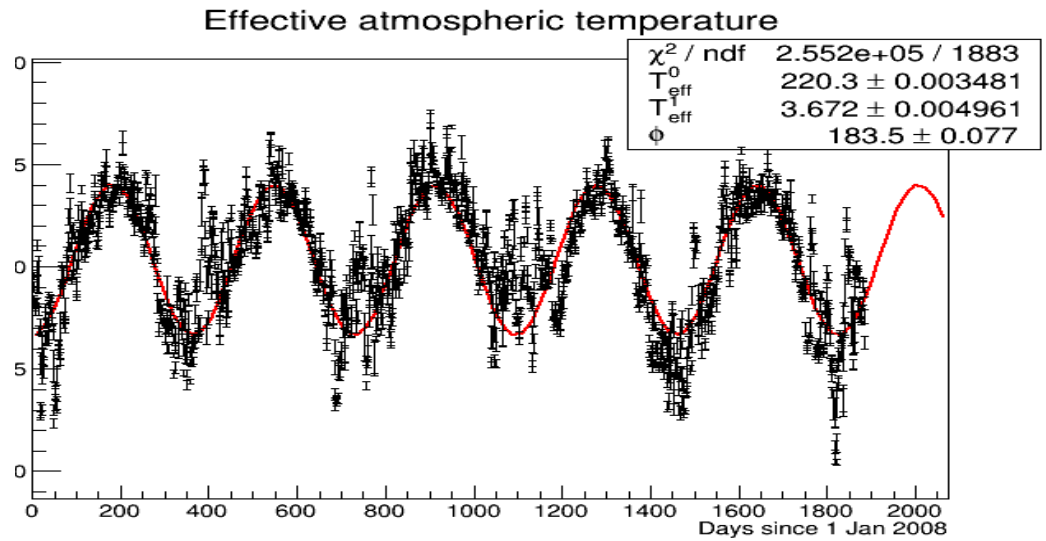
$$\phi_{\mu^\pm} \propto \frac{a_\pi f_{\pi^\pm}}{1 + b_\pi \mathcal{E}_\mu \cos\theta/\epsilon_\pi} + R_{K\pi} \frac{a_K f_{K^\pm}}{1 + b_K \mathcal{E}_\mu \cos\theta/\epsilon_K}$$



Cosmic ray annual modulation

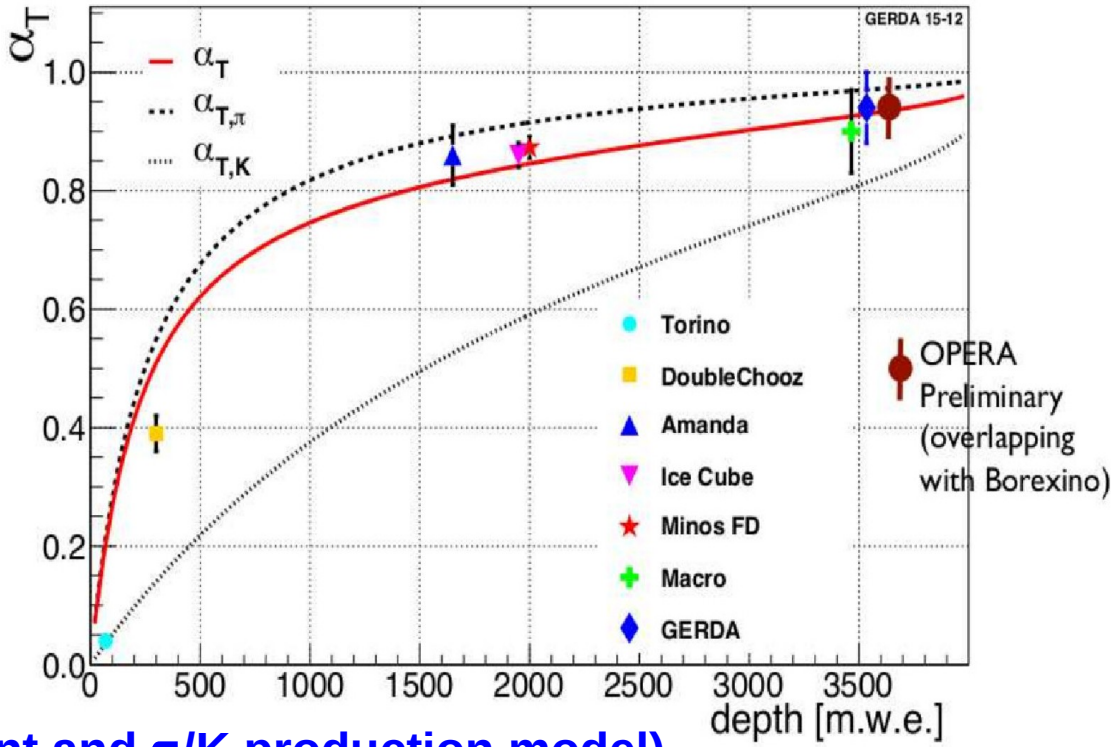
Single muon flux





Single muon flux I_μ and effective atmospheric temperature, T_{eff} (average temperature weighted by production probability of TeV muon reaching underground lab) fitted with $A(t) = A0 + A1 \cos(2\pi/T(t-\phi))$ (period T fixed at 365 days).

$$\Delta I_\mu / I^0_\mu = \alpha_T \, \Delta T_{eff} / T^0_{eff} .$$



α_T (OPERA) = 0.95 ± 0.04

(In agreement with other LNGS experiment and π/K production model).

Conclusions

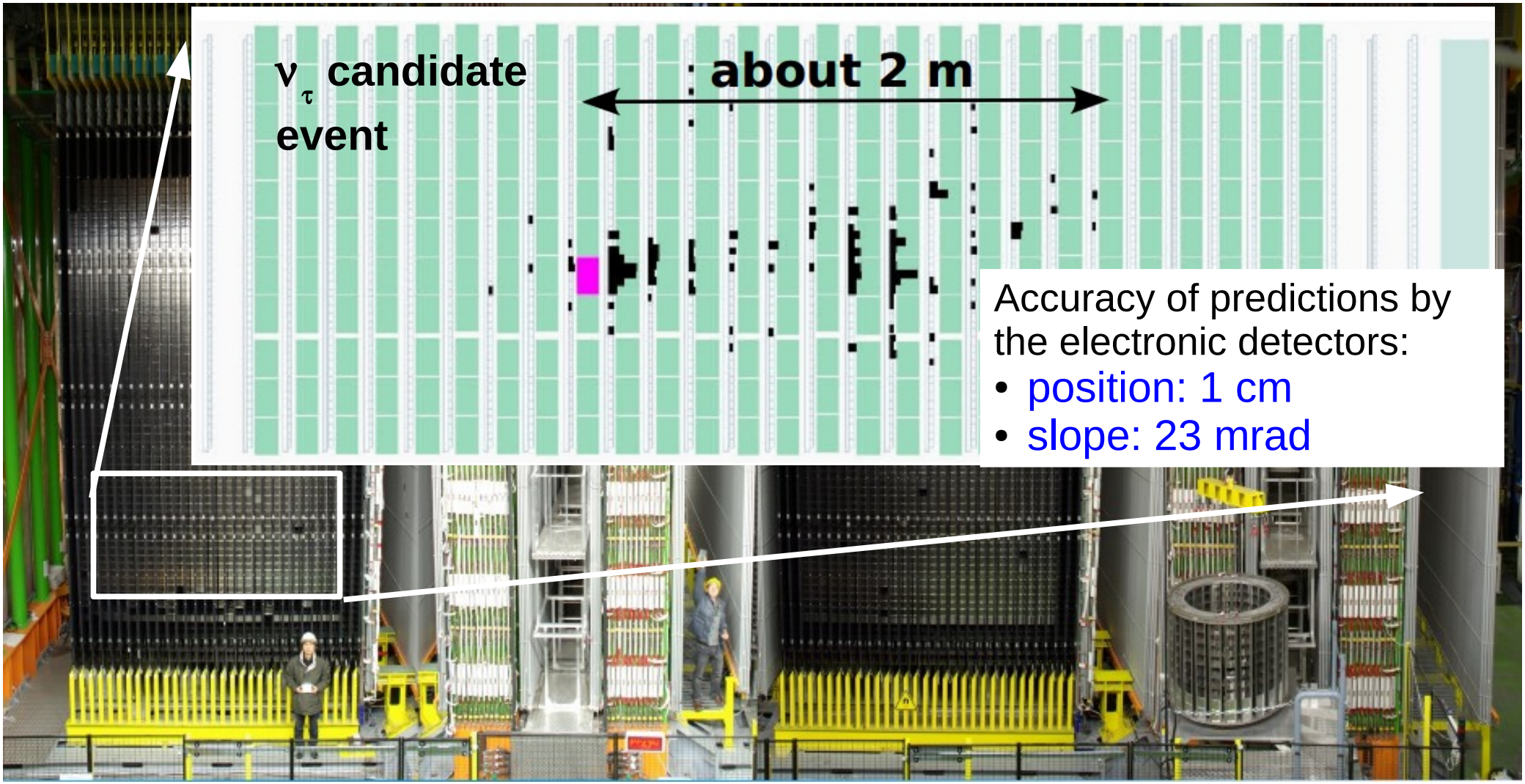
- 1.8×10^{20} pot by CNGS from 2008-12 (80% of design).
- 10 ν_τ candidates so far with 2.0 expected background events.
- No oscillation hypothesis excluded at **6.1 σ using a multi-variate analysis technique.**
- ν_τ CC cross section measurement in agreement with Genie.
- τ neutrino interaction with charm production observed.

- Study on $\nu_\mu \rightarrow \nu_e$ sub-dominant oscillation channel finished.
- Cosmic ray physics: atmospheric: cosmic ray modulation measured.
- More to come, stay tuned....

Spares

Brick finding

OPERA is a hybrid apparatus.
Electronic detectors predictions to locate bricks with neutrino interactions.

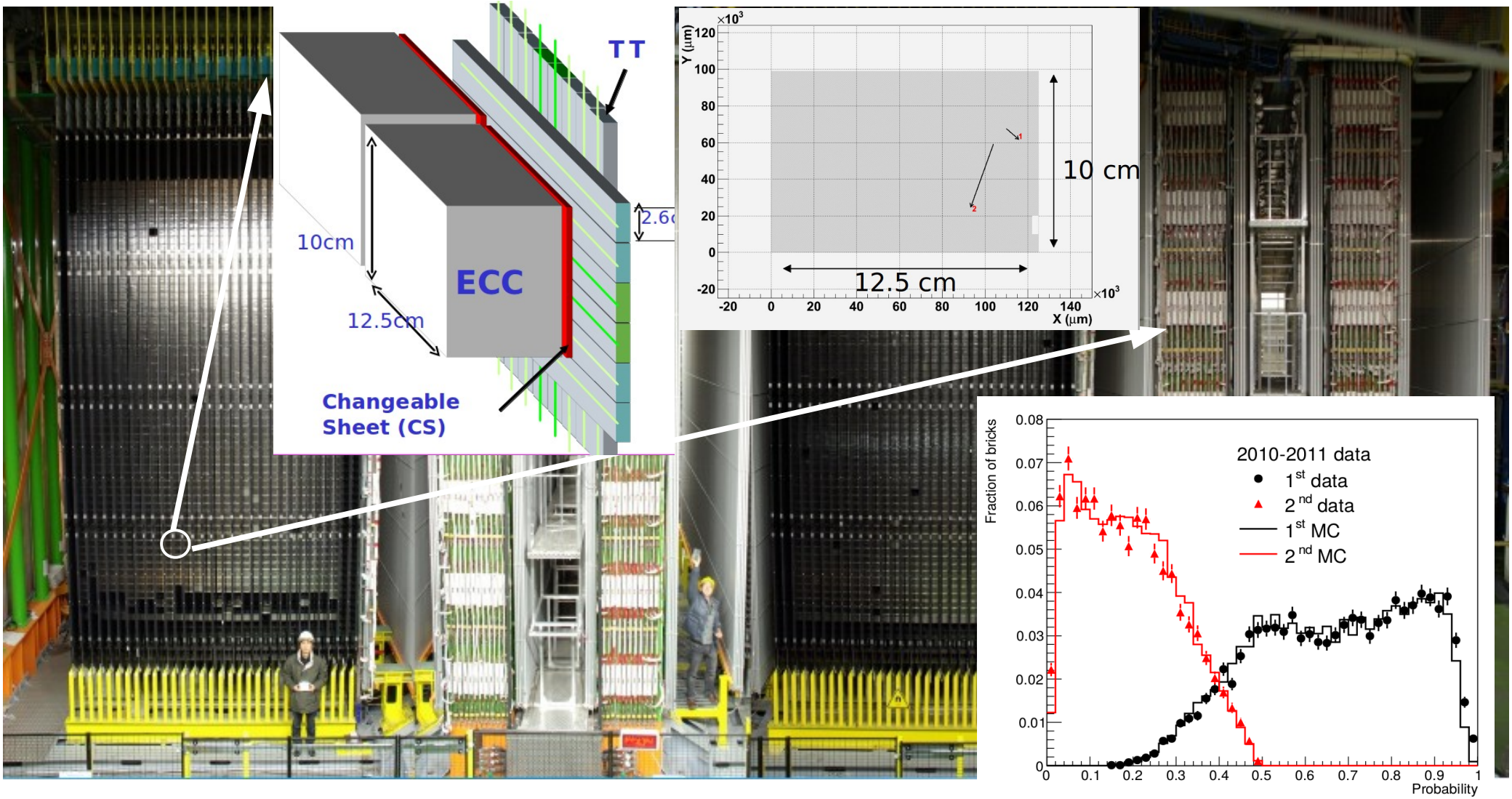


Accuracy of predictions by the electronic detectors:

- position: 1 cm
- slope: 23 mrad

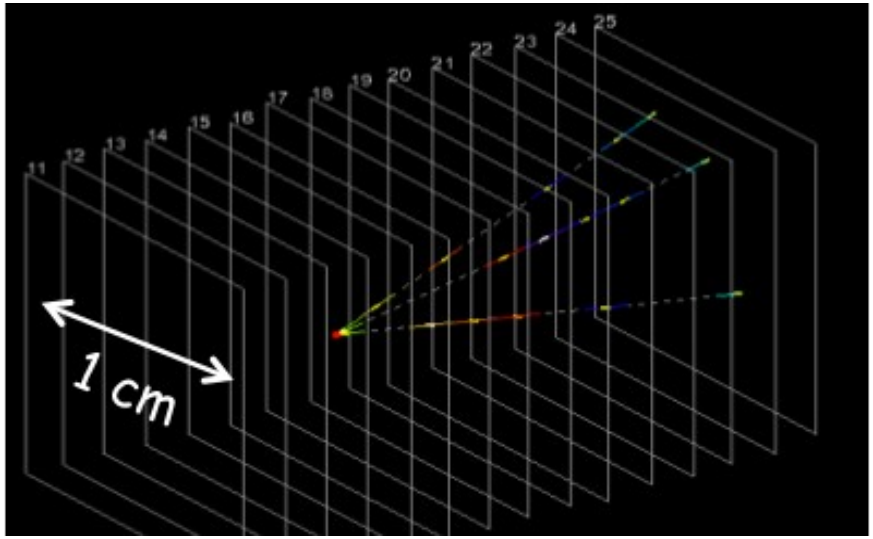
Brick finding

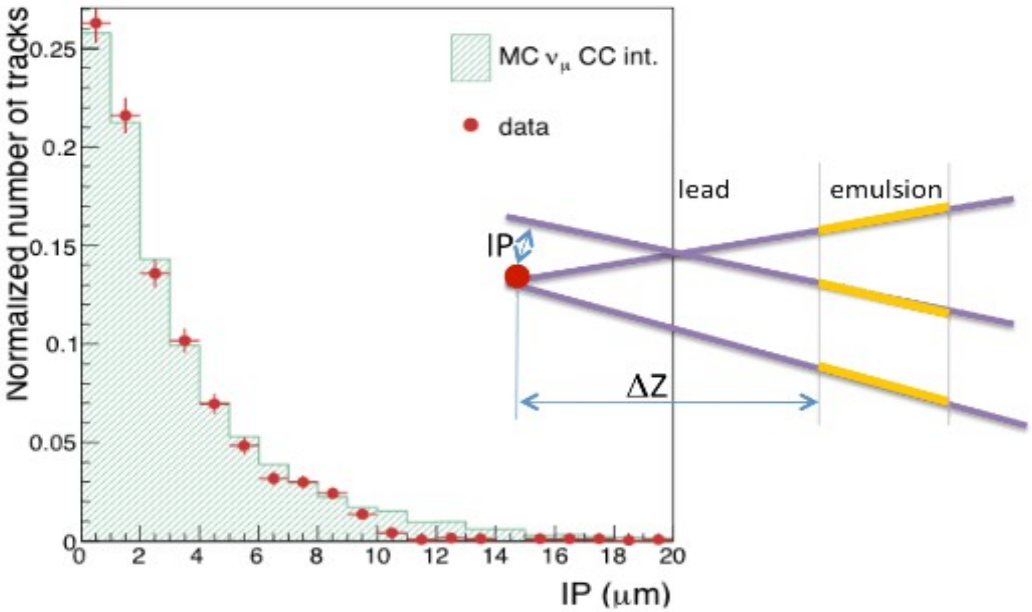
Changeable Sheets: the “bridge” from the cm scale of electronics detectors to μm scale of emulsions.
Electronic detector predictions to be confirmed by scanning of CS doublet.
Up to 4 bricks ranked in probability are considered for τ research.

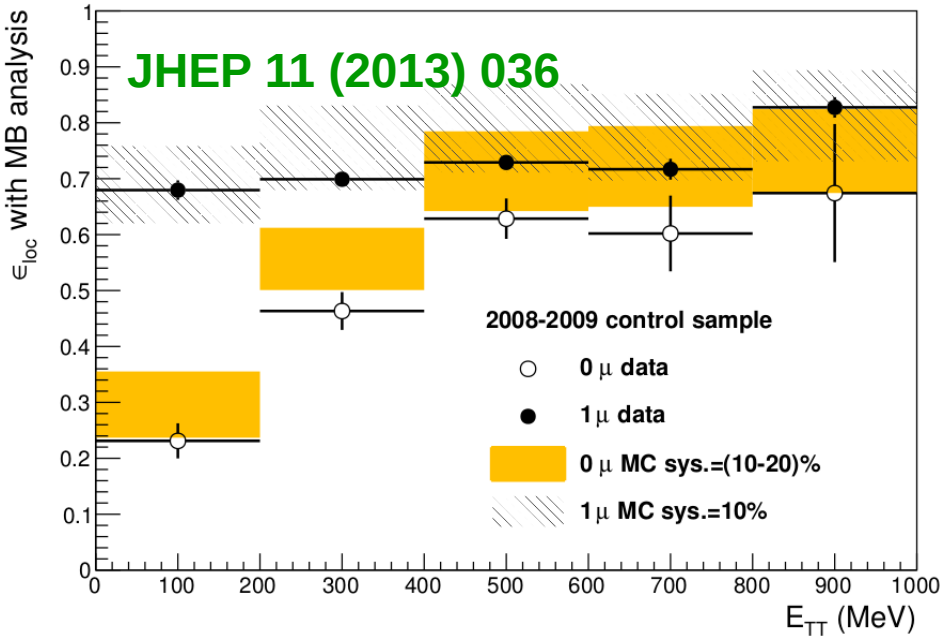


Vertex location and topology decay search in the brick

Tracks in the CS are followed upstream until a stopping point is found.
Vertex reconstruction by apposite algorithms.
Search of decay topologies (e.g. large impact parameters IP).



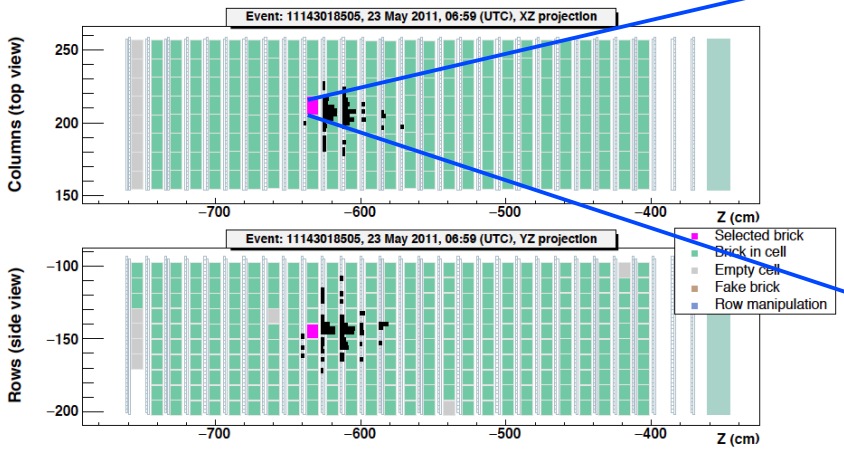


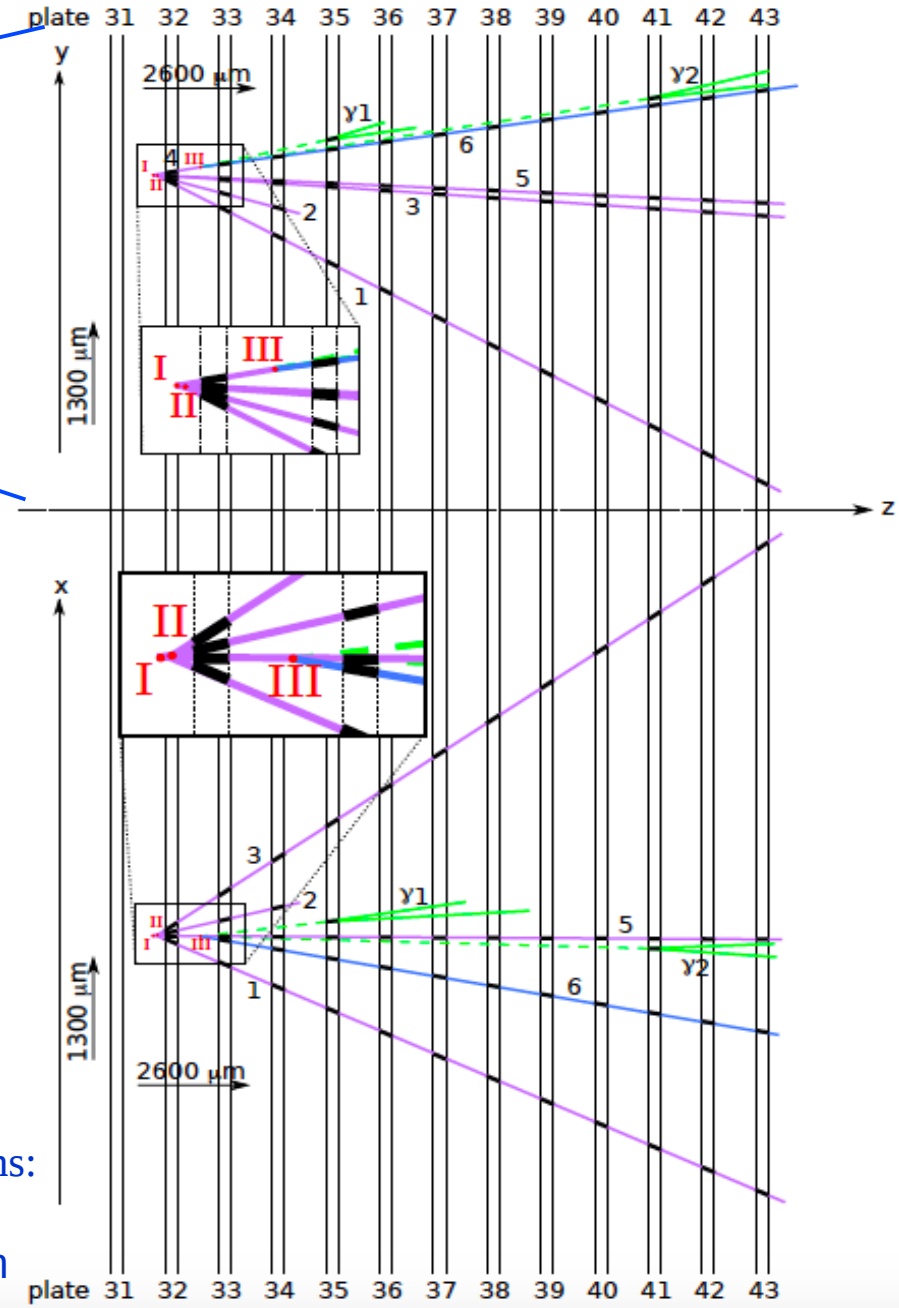


Full MC simulation of 0 μ and 1 μ samples.
Data/MonteCarlo in reasonable agreement.

A ν event with 3 vertices: description

Muonless event





A primary and two secondary vertices found in emulsi
Electromagnetic activity (γ's) at the kink point.

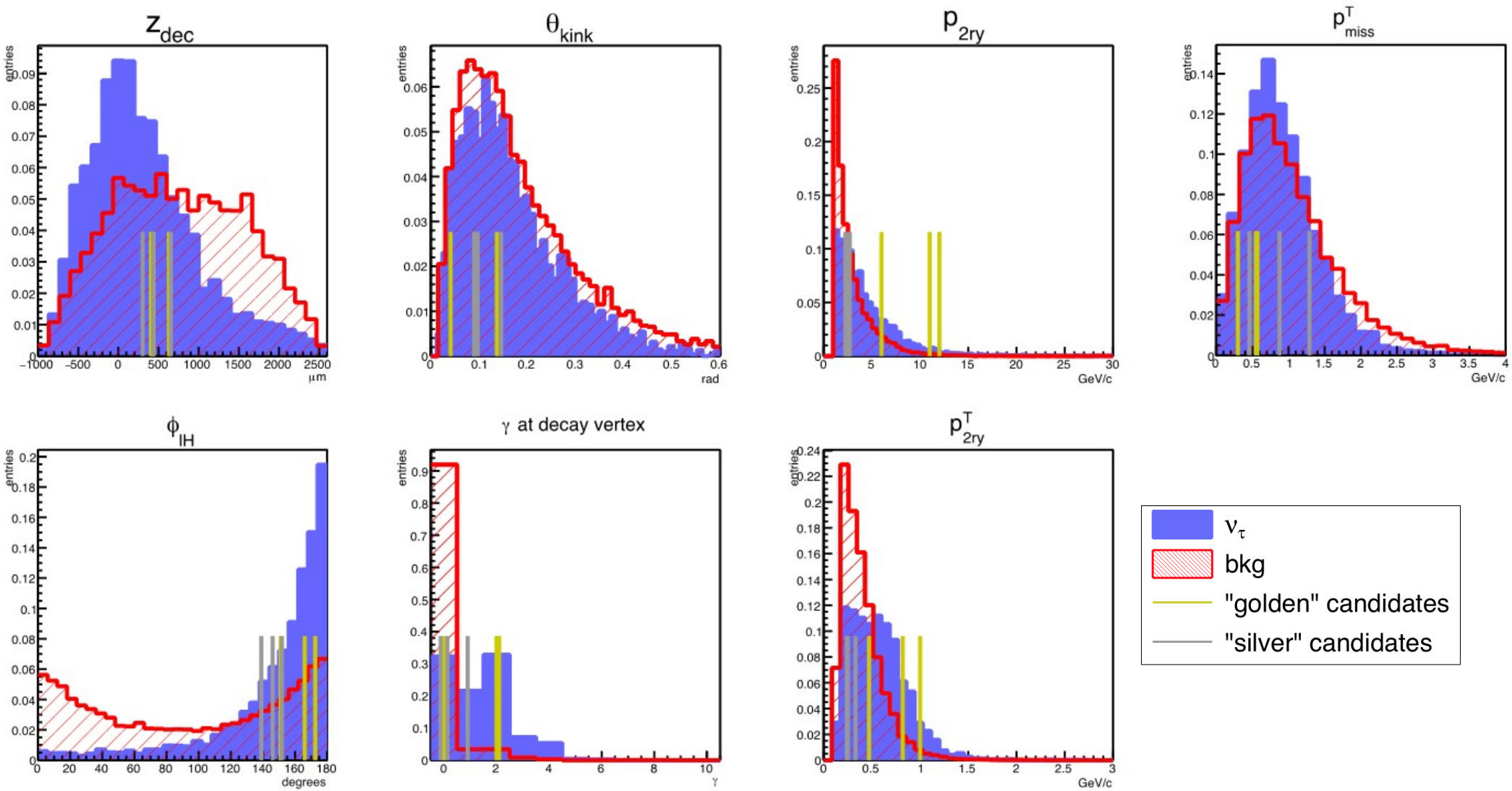
Vertex ID	Attached tracks	x (μm)	y (μm)	z (μm)
I (primary)	2, 4, 5	15077.0	59157.9	-33081.8
II (secondary)	1, 3	15085.9	59149.9	-32979.2
III (kink)	4, 6	15073.9	59262.4	-31926.4

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]

Flight lengths:
II: 103 μm
III: 1160 μm

Invariant masses at both secondary vertices larger than 1 GeV.

Input variables for the multi-variate analysis in the $\tau \rightarrow h$ decay channel



"golden", i.e. candidates passing the tight selection cuts
"silver", i.e. newly found candidates with looser cuts

Significance of ν_τ appearance

PHYSICAL REVIEW LETTERS **120,** 211801 (2018)

$$\mathcal{L}(\mu, \beta_c) = \prod_{c=1}^{4} \left(\mathrm{Pois}(n_c | \mu s_c + \beta_c) \prod_{i=1}^{n_c} f_c(x_{ci}) \right) \cdot \prod_{c=1}^{4} \mathrm{Gauss}(b_c | \beta_c, \sigma_{b_c})$$

- c: channels
- n_c: obs events in the cth channel
- μ: signal strength
- s_c: expected signal
- β_c: true bkg (floating param.)
- $f_c(x_{ci})$: BDT response
- b_c: expected bkg
- σ_{b_c}: uncertainty on exp bkg

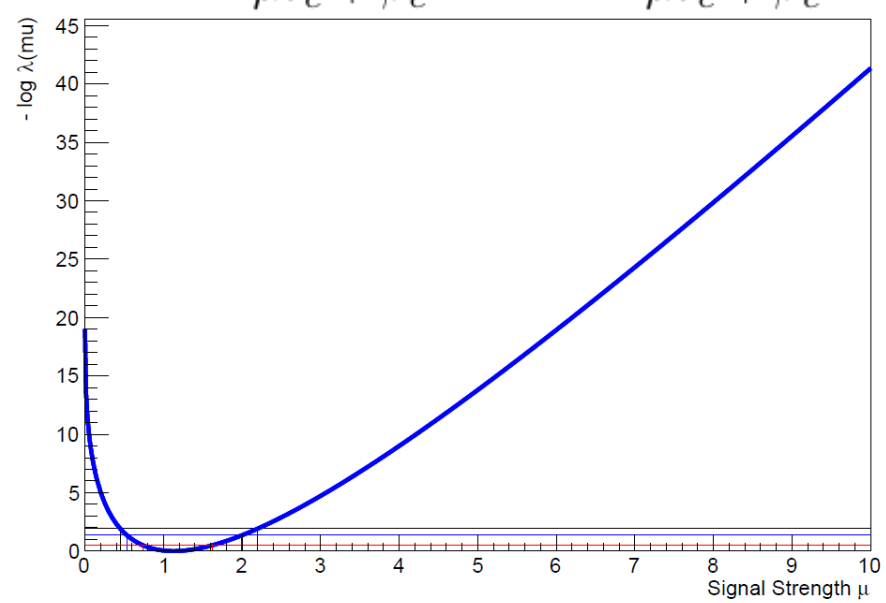
$$f_c(x_{ci}) = \frac{\mu s_c}{\mu s_c + \beta_c} \mathrm{PDF}_c^{\mathrm{sig}} + \frac{\beta_c}{\mu s_c + \beta_c} \mathrm{PDF}_c^{\mathrm{bkg}}$$

Test statistic: Likelihood ratio

Results: $\mu = 1.1^{+0.5}_{-0.4}$

$P_{value} = 4 \cdot 10^{-10}$

Significance = 6.1 σ



Δm^2_{23} measurement

PHYSICAL REVIEW LETTERS **120,** 211801 (2018)

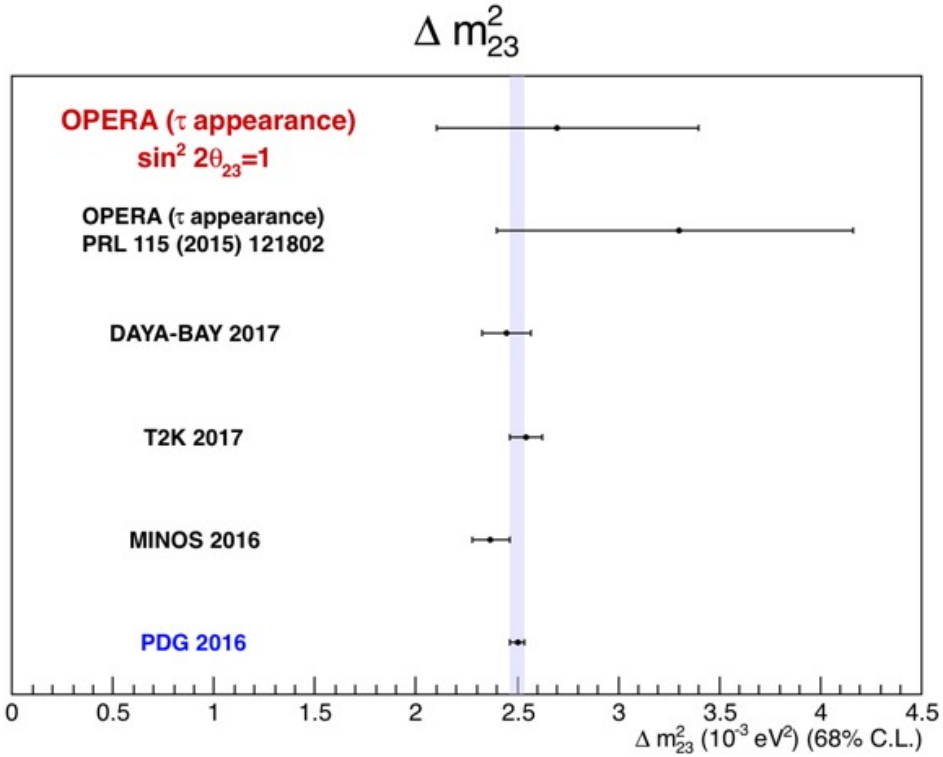
Experiment sensitive to the product $N_{\nu_\tau} \propto P(\nu_\mu \to \nu_\tau)\sigma_{\nu_\tau}$

Assumptions: maximal mixing, ν_τ CC interaction cross section as in Genie v2.6 default

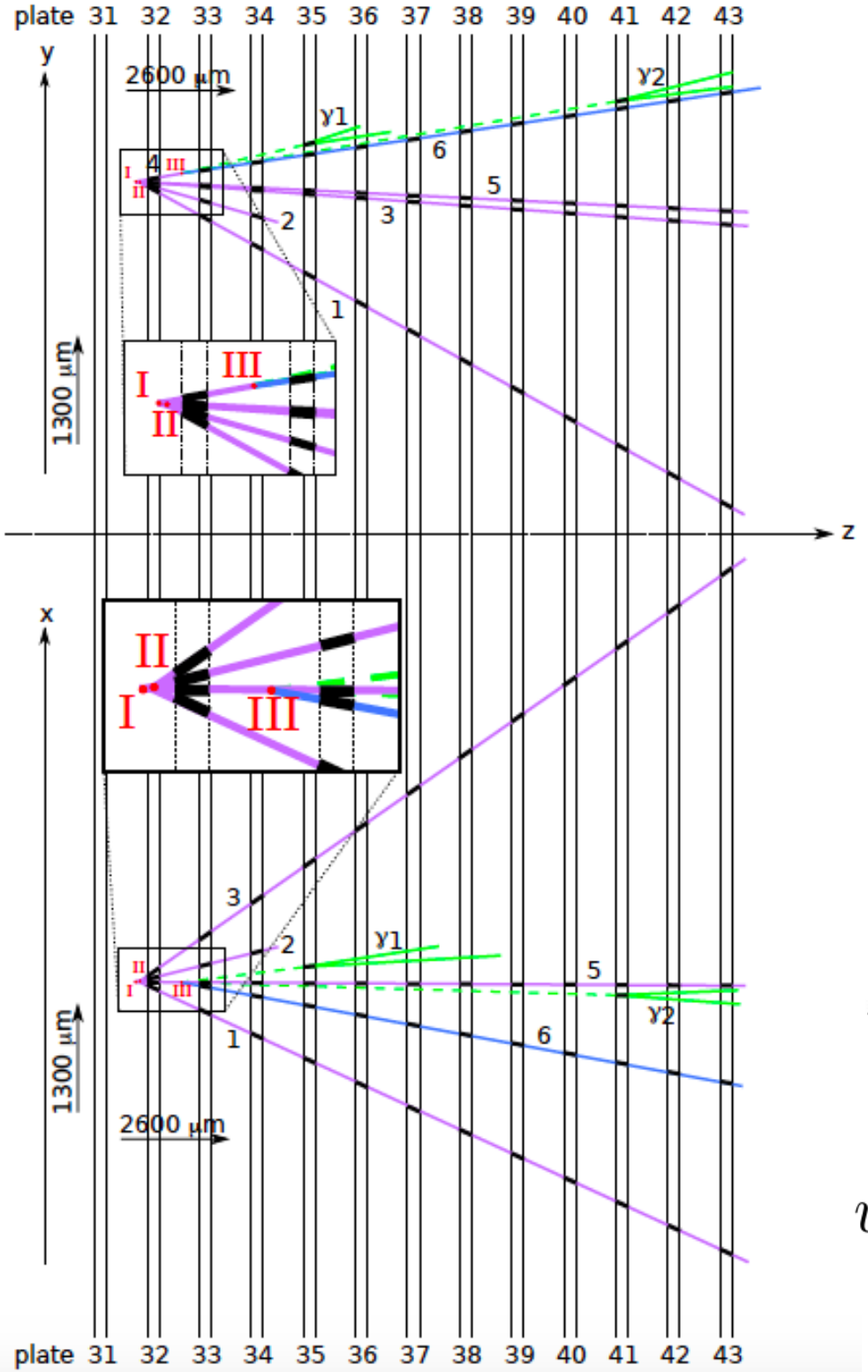
$$\langle \sigma_G \rangle = (4.29 \pm 0.04) \cdot 10^{-36} \mathrm{cm}^2$$

$$|\Delta m^2_{23\ \mathrm{meas}}| = 2.7^{+0.7}_{-0.6} \cdot 10^{-3} \mathrm{eV}^2$$

(68% C.L)



First measurement in appearance mode

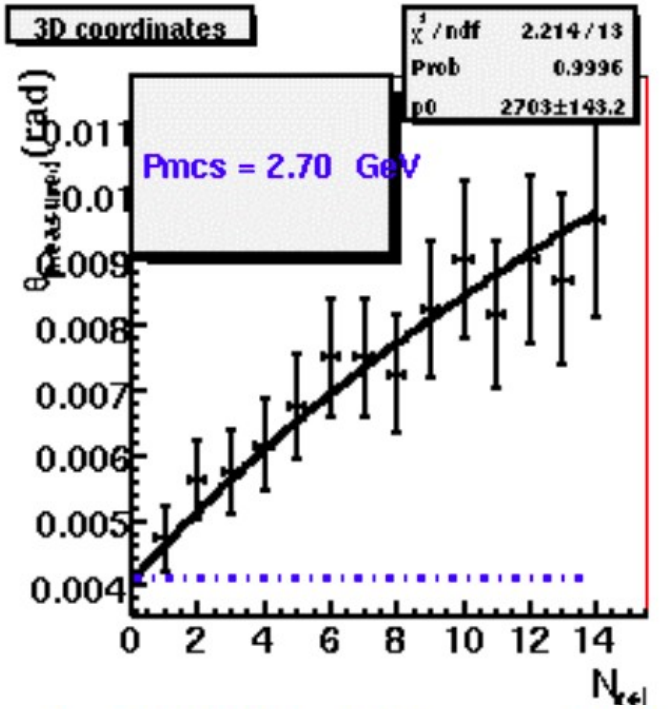


Kink topology

Flight Length = 1160 μm

With γ attached

IP = 8±8 μm



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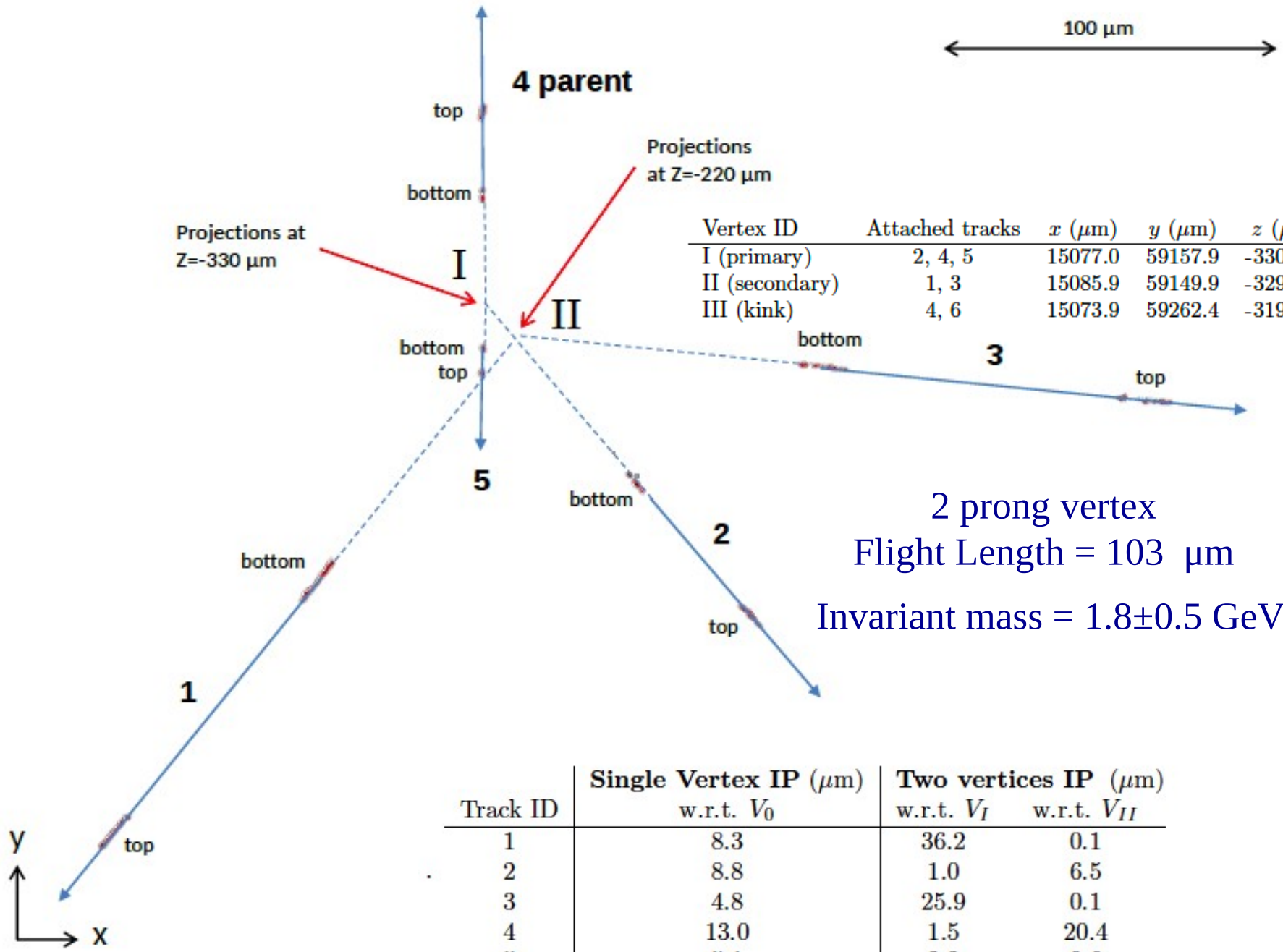
5	0.54	[0.45 ; 0.68]
6 (daughter)	2.7	[2.1 ; 3.7]

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

passing new selection cuts to be a tau candidate

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



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III (kink)	4, 6	15073.9	59262.4	-31926.4

2 prong vertex
Flight Length = 103 µm

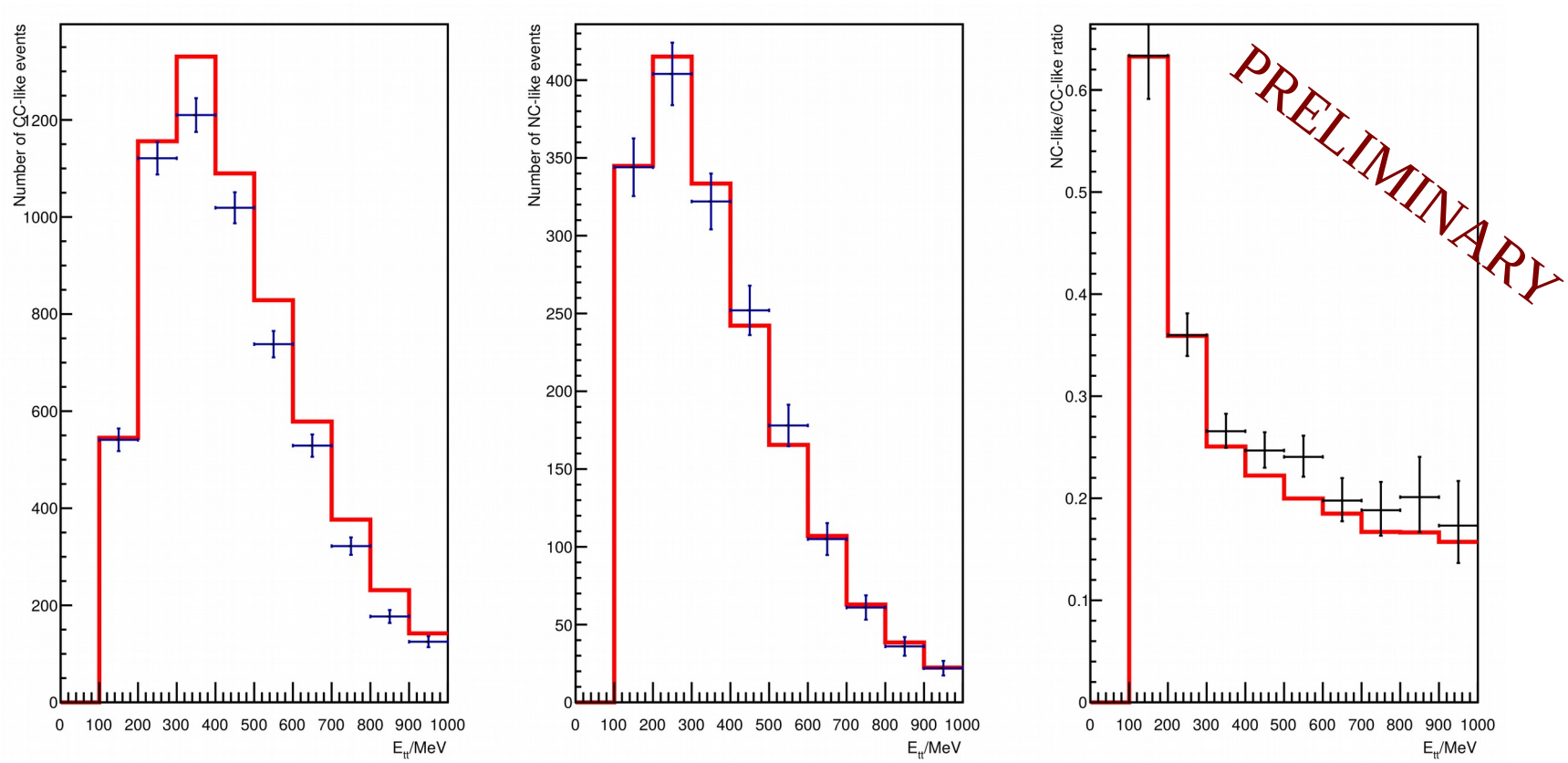
Invariant mass = 1.8±0.5 GeV

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

ν_μ disappearance

- Absence of a near detector to reduce systematics
- Oscillation analysis using only electronic detector data
- Analysis dominated by ν_μ disappearance, but appearance channels are non-negligible and are included in the analysis

NC-like / CC-like ratio used to mitigate the uncertainty from flux normalization



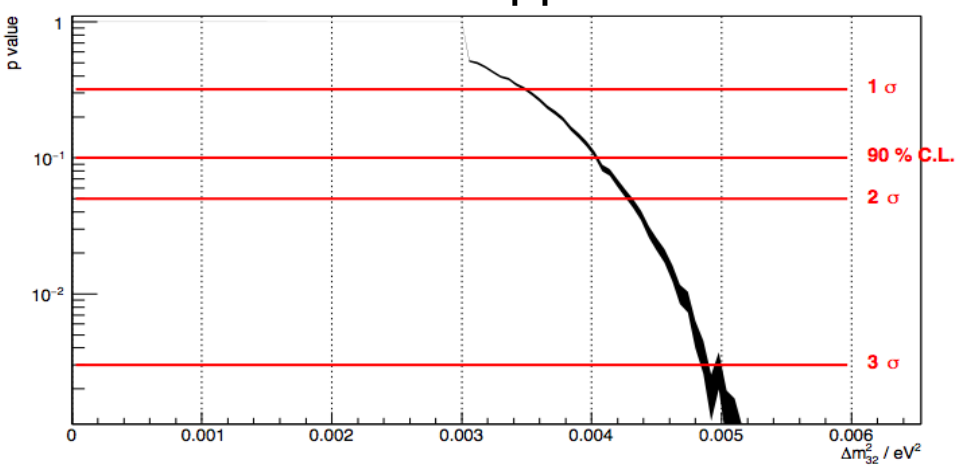
red – MC, expected number of events in case of no oscillations
crosses – data, vertical width is 68% CL

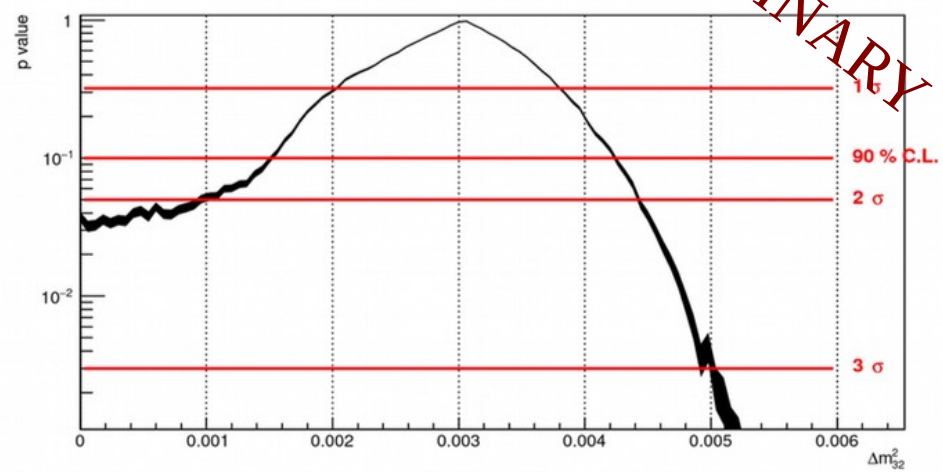
ν_μ disappearance

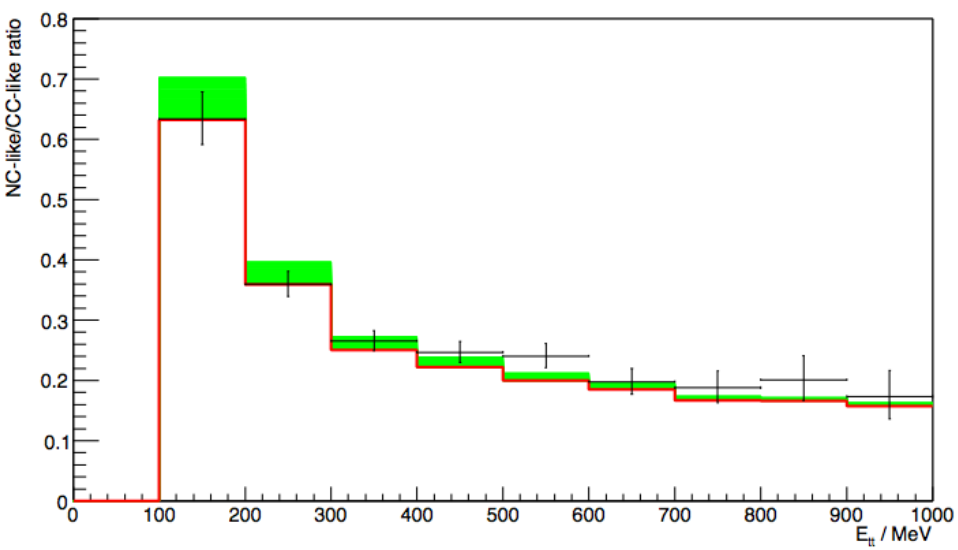
Dedicated statistical model

PRELIMINARY

Upper limit







red line – MC, no oscillations

green area – MC with oscillations using
$0 < \Delta m^2 < 4.1E\text{-}3\ eV^2$

crosses – data, vertical width is 68% CL

$$\left|\Delta m^2_{32}\right| < 4.1 \cdot 10^{-3}\ \mathrm{eV}^2\ @\ 90\%\ \mathrm{C.L.}$$

Open data at CERN

- OPERA is the first non-LHC experiment joining the educational and research program of the Open Data Portal service
- Two samples of muon and tau neutrino interactions are now available at CERN: data & event display (effective for education)

Education

The CMS (Compact Muon Solenoid) experiment is one of two large general-purpose detectors built on the Large Hadron Collider (LHC). Its goal is to investigate a wide range of physics such as the characteristics of the Higgs boson, extra dimensions or dark matter

Explore CMS ›

ALICE (A Large Ion Collider Experiment) is a heavy-ion detector designed to study the physics of strongly interacting matter at extreme energy densities, where a phase of matter called quark-gluon plasma forms. More than 1000 scientists are part of the collaboration

Explore ALICE ›

The ATLAS (A Toroidal LHC ApparatuS) experiment is a general-purpose detector exploring topics like the properties of the Higgs-like particle, extra dimensions of space, unification of fundamental forces and evidence for dark matter candidates in the Universe

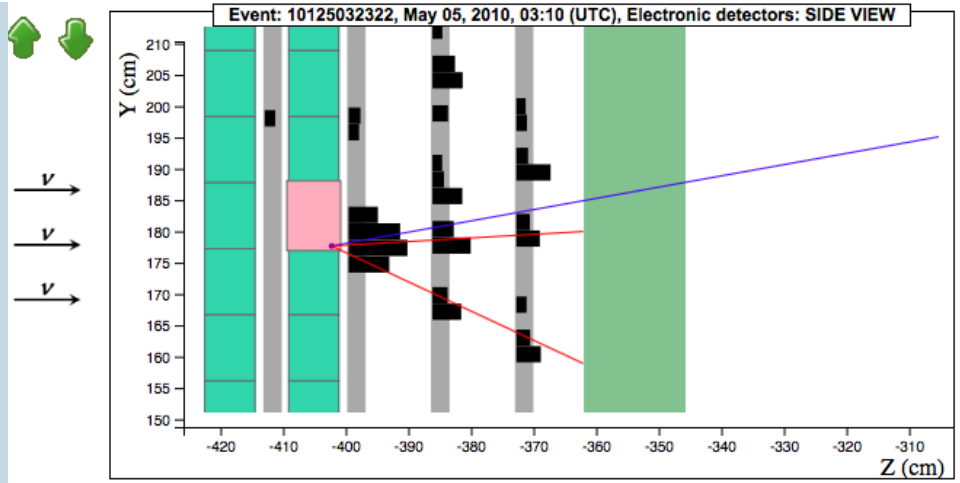
Explore ATLAS ›

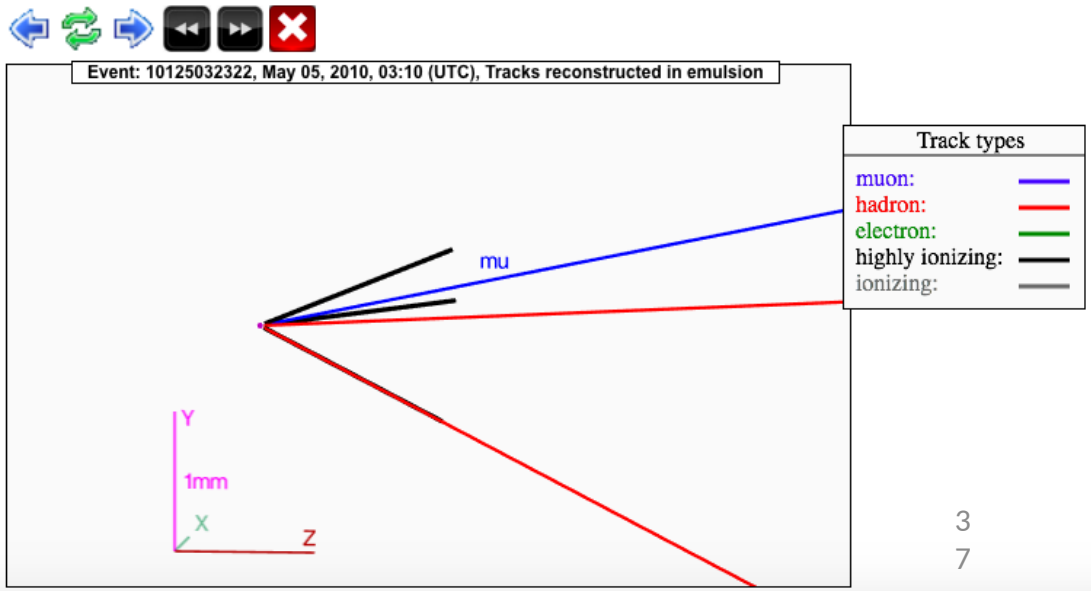
The LHCb (Large Hadron Collider beauty) experiment aims to record the decay of particles containing b and anti-b quarks, known as B mesons. The detector is designed to gather information about the identity, trajectory, momentum and energy of each

Explore LHCb ›

The Oscillation Project with Emulsion-tRacking Apparatus (OPERA) is a scientific experiment for detecting tau neutrinos from muon neutrino oscillations. The experiment is a collaboration between CERN in Geneva, Switzerland, and the Laboratori Nazionali d

Explore OPERA ›





Open data at CERN

http://opendata.cern.ch/visualise/events/opera

http://opendata.cern.ch/docs/opera-news-first-release-2018