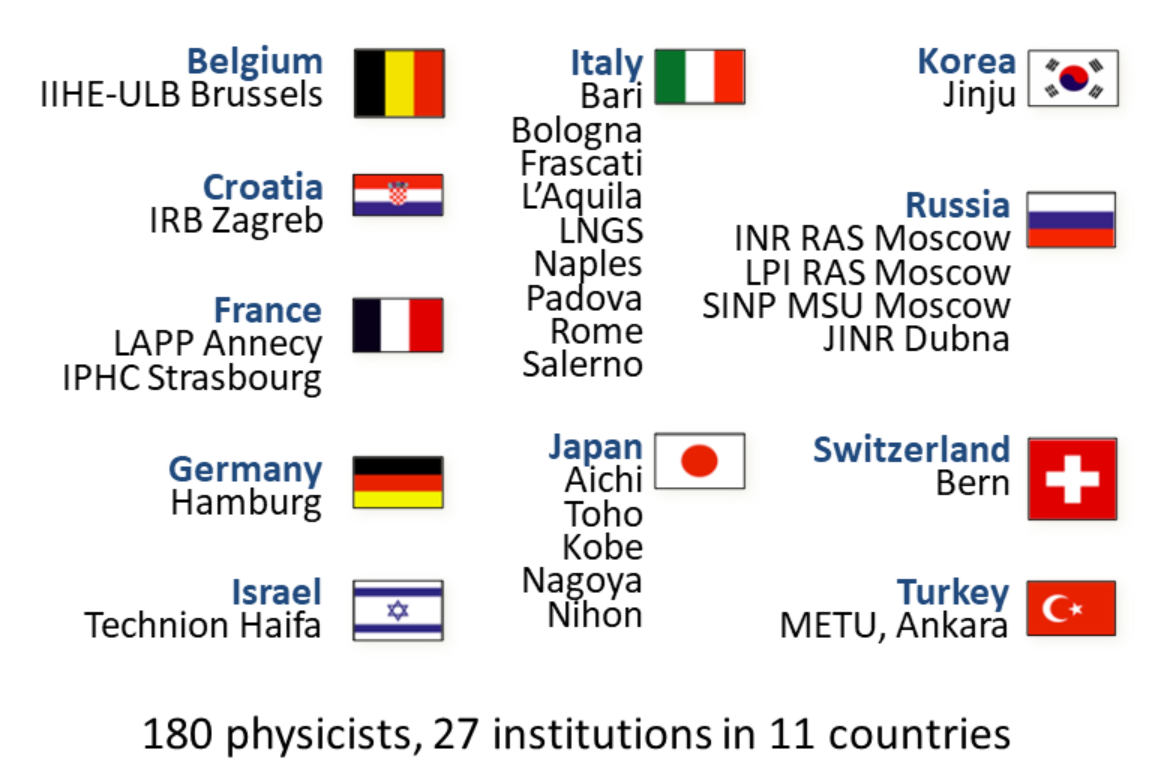
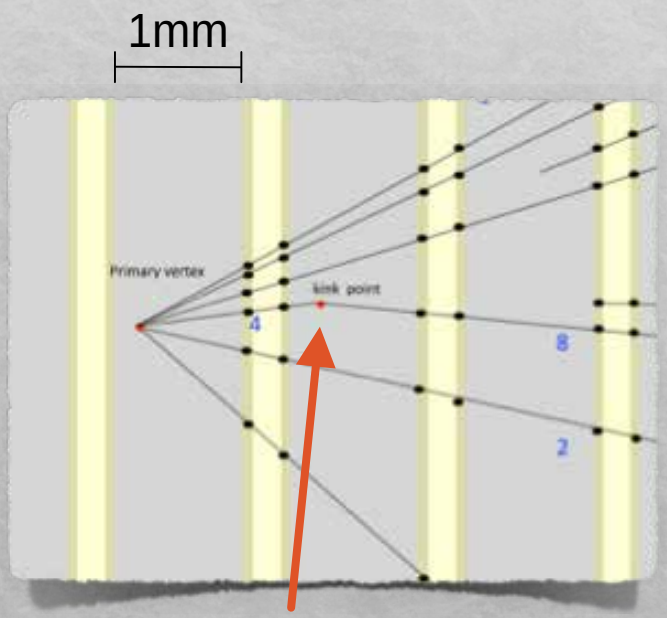
Final Results from the OPERA Experiment in the CNGS Neutrino Beam



Koichi Kodama for the OPERA collaboration,
Aichi University of Education
Windows on the Universe 2018 @ Quy Nhon, Vietnam 2018-08-07

Main Physics Goal



Detect τ decay from ν_τCC in emulsion @LNGS

Direct detection of $\nu_\mu \rightarrow \nu_\tau$ oscillations in appearance mode.

The CNGS beam

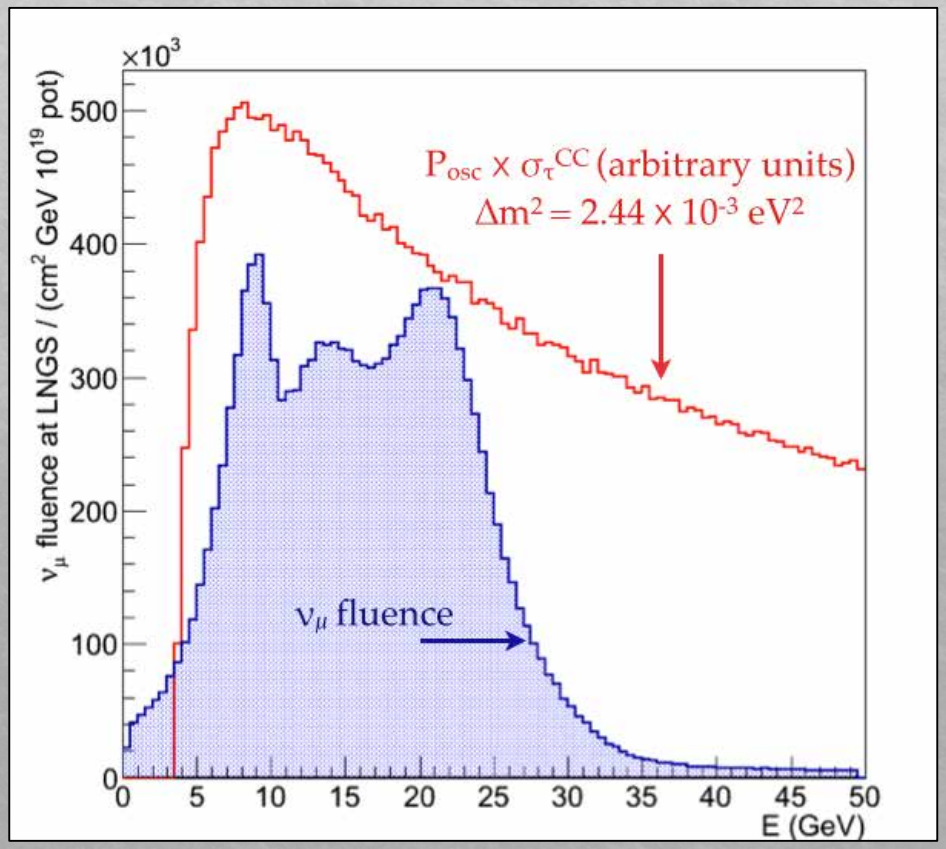
- Tutuned for ν_τ appearance at LNGS (L ~ 730 km)
  → Maximize the number of ν_τ CC interactions.
- <Eν> = 17GeV ← τ production threshold at ~3.5GeV

17.97×10^{19} POT

2008 ~ 2012

(80% of the design)

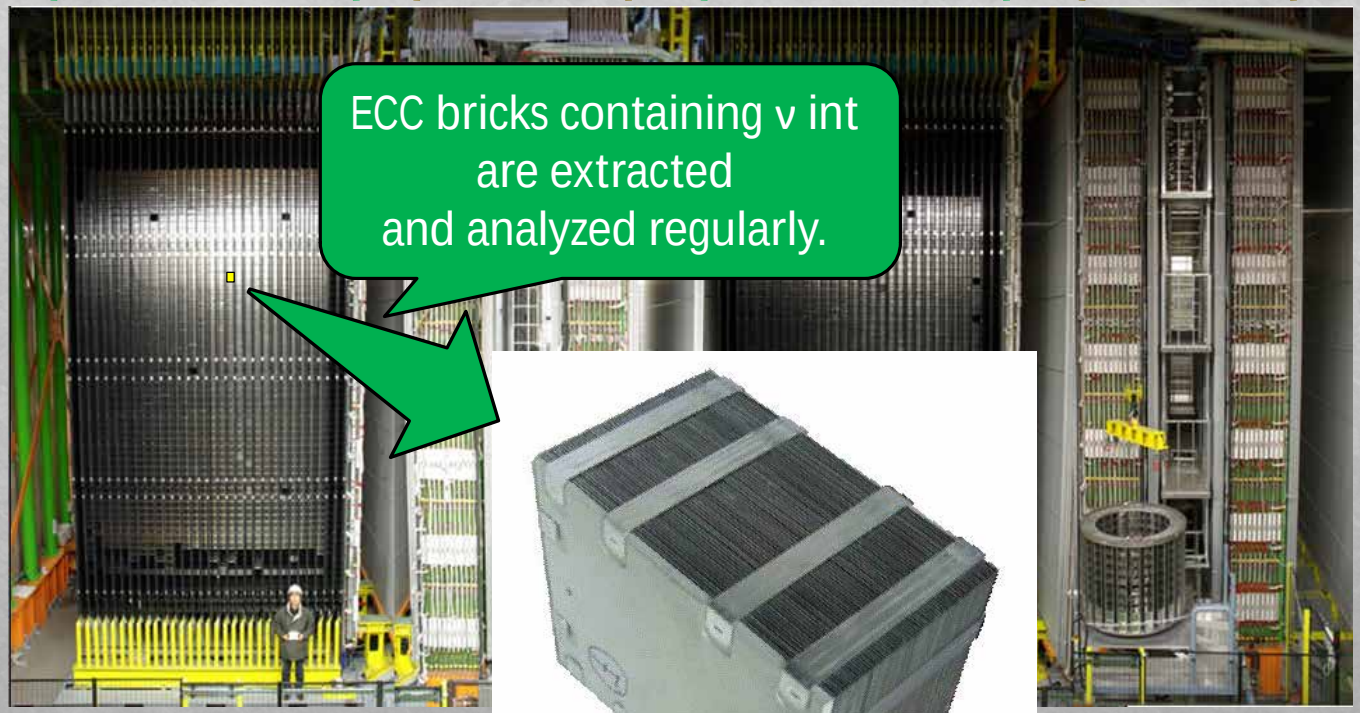
CC int in OPERA detector	
$(\nu_e + \bar{\nu}_e)/\nu_\mu$	0.9%
$\bar{\nu}_\mu/\nu_\mu$	2.1%
ν_τ prompt (from D_S)	negligible



The OPERA Detector in LNGS Underground

Target (ECC+TT)

Muon spectrometer

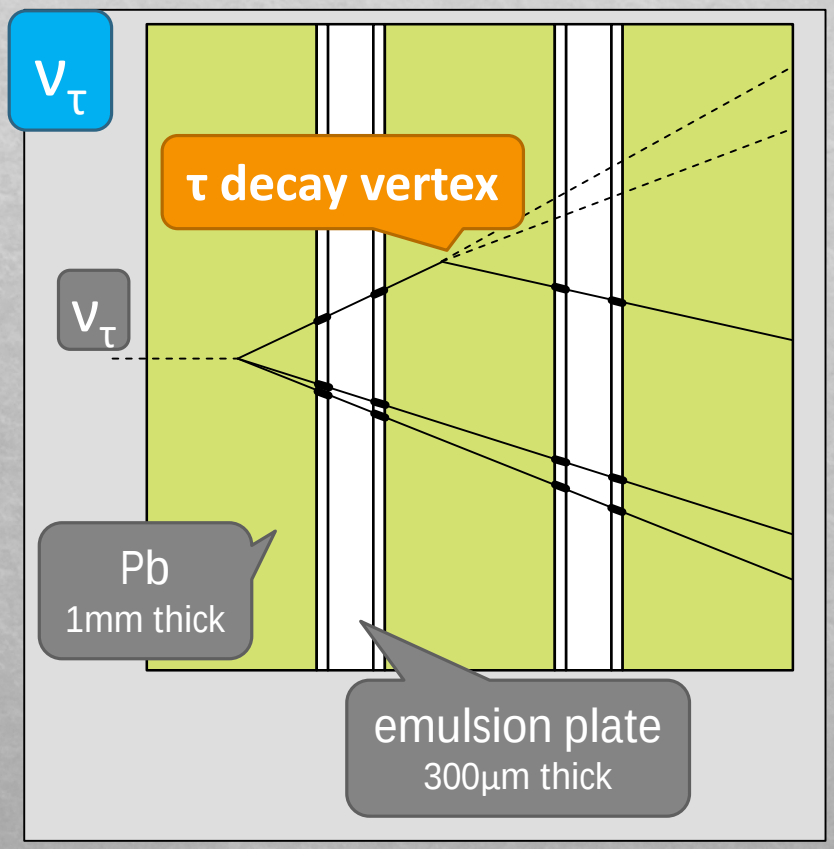


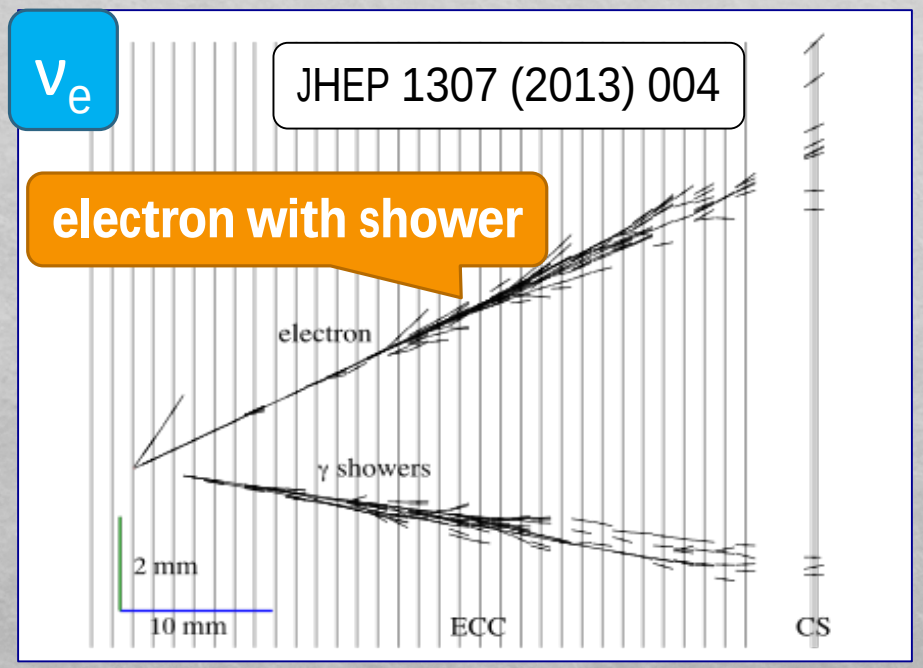
ECC brick → 8.3kg, $10X_0$

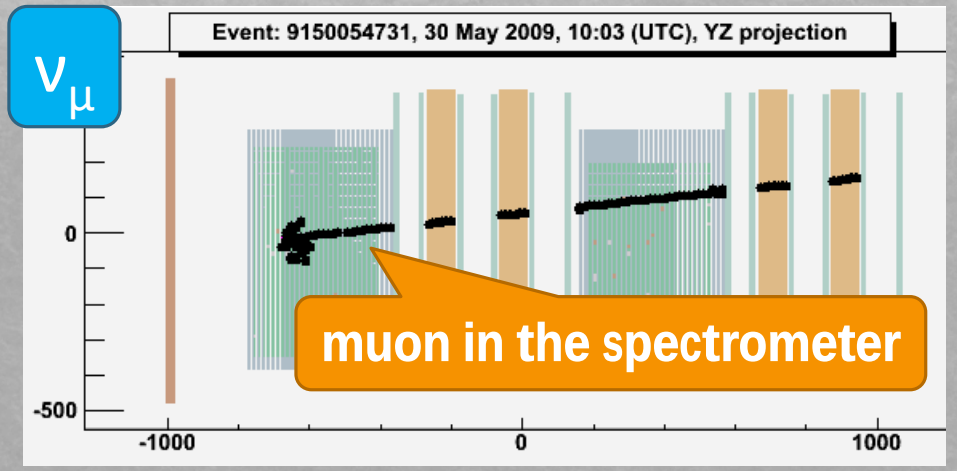
57 emulsion plates are interleaved with 56 Pb plates of 1mm thick

Target = 150k ECC bricks (initial mass ~1.25kt)

OPERA can Identify Three Netrino Flavours

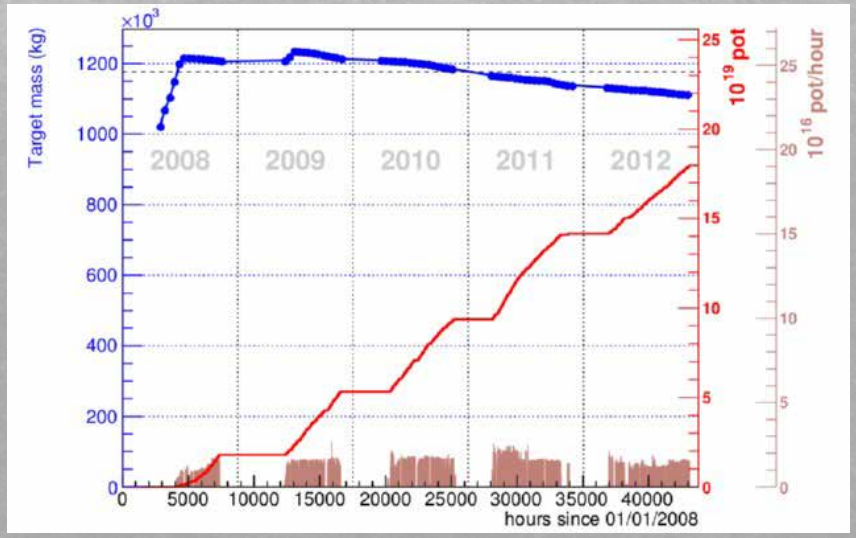




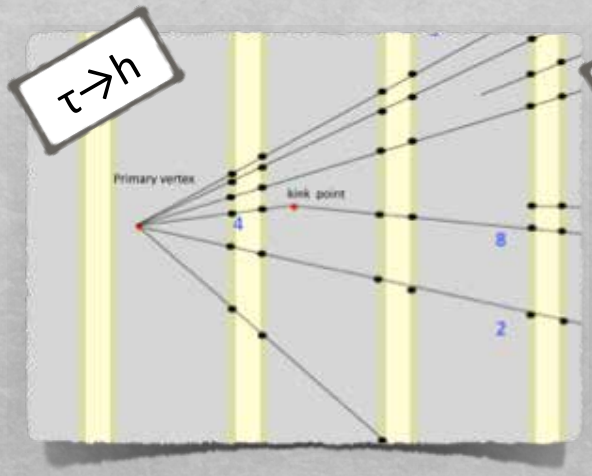


Summary of Event Statistics

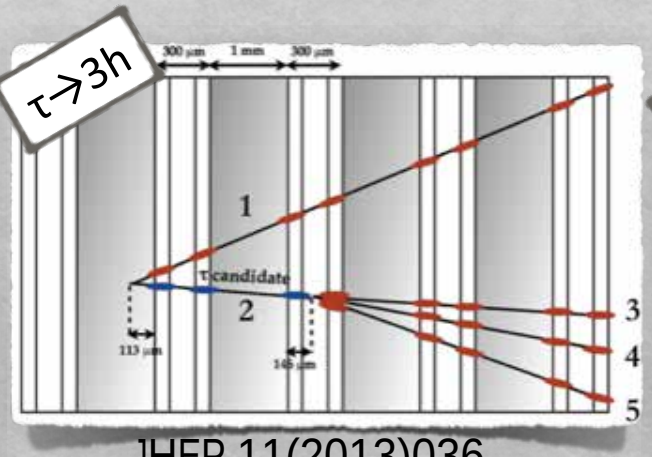
		2008	2009	2010	2011	2012	Total
POT (´ 10^{19})		1.74	3.53	4.09	4.75	3.86	17.97
n interactions		1698	3693	4248	5131	3923	19505
analyzed events	0m	150	255	278	291	223	1197
	1m	543	1024	1001	1031	807	4406
	Total	693	1279	1279	1322	1030	5603



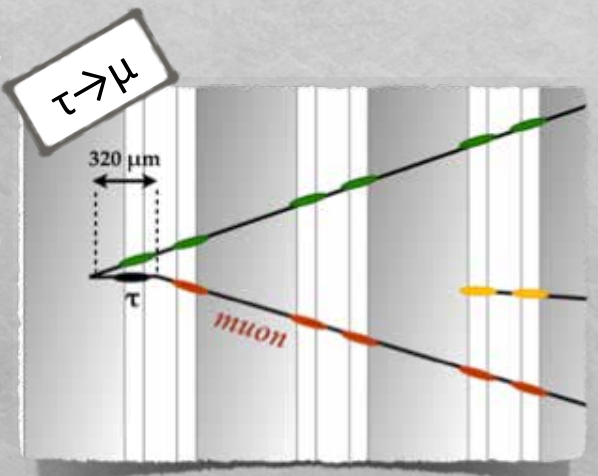
$5\nu_\tau$ Appearance Observation among 5400 Analyzed Interactions



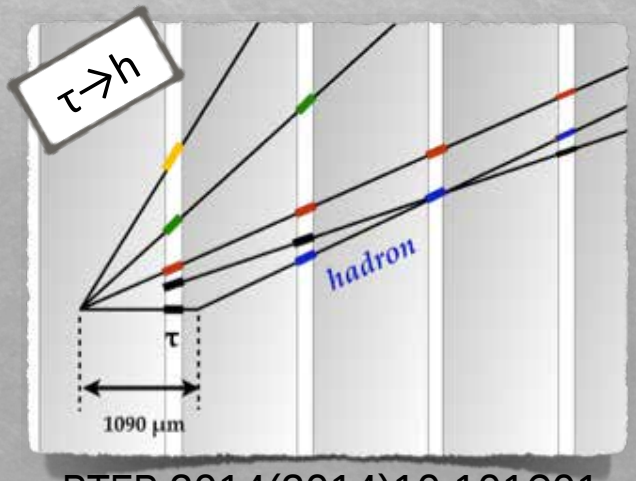
Phys. Lett. B691(2010)138



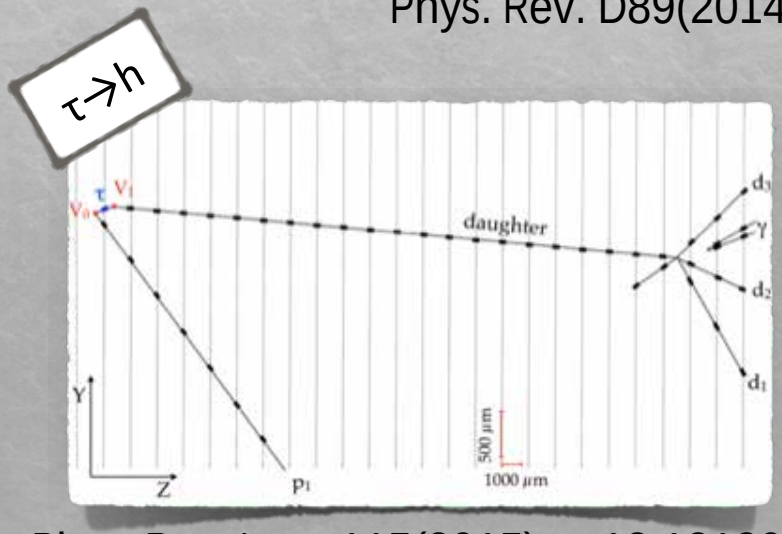
JHEP 11(2013)036



Phys. Rev. D89(2014)051102



PTEP 2014(2014)10,101C01



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

Discovery of ν_τ Appearance

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

Channel	Expected background				Expected signal	Observed
	Charm	Had. re-interac.	Large μ-scat.	Total		
$\tau \to 1h$	0.017 ± 0.003	0.022 ± 0.006	–	0.04 ± 0.01	0.52 ± 0.10	3
$\tau \to 3h$	0.17 ± 0.03	0.003 ± 0.001	–	0.17 ± 0.03	0.73 ± 0.14	1
$\tau \to \mu$	0.004 ± 0.001	–	0.0002 ± 0.0001	0.004 ± 0.001	0.61 ± 0.12	1
$\tau \to e$	0.03 ± 0.01	–	–	0.03 ± 0.01	0.78 ± 0.16	0
Total	0.22 ± 0.04	0.02 ± 0.01	0.0002 ± 0.0001	0.25 ± 0.05	2.64 ± 0.53	5

5 ν_τ events observation with background 0.25 events

$P_{value} = 1.1 \times 10^{-7} \rightarrow 5.1\sigma$ significance

New Analysis to reduce Statistical Uncertainties

Candidate Selection with Looser Kinematical Cuts

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

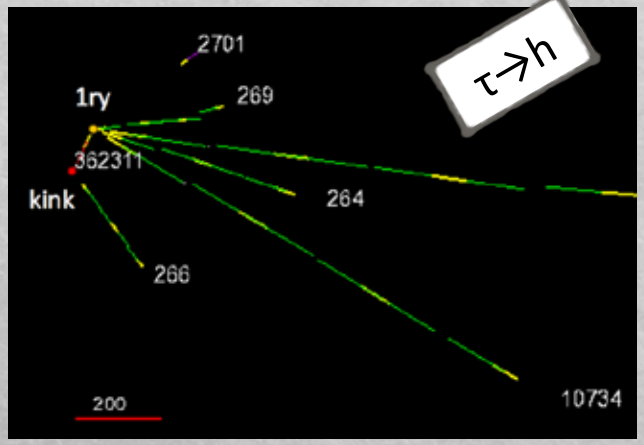
- Minimum selection to limit contribution from had. int. and large angle scattering bkg
- Negligible additional background from K/π decays
- S/B reduced from ~10 to ~3

	Expected background					
Channel	Charm	Hadron reinteraction	Large μ scattering	Total	ν_τ expected	Observed
$\tau \to 1h$	0.15 ± 0.03	1.28 ± 0.38		1.43 ± 0.39	2.96 ± 0.59	6
$\tau \to 3h$	0.44 ± 0.09	0.09 ± 0.03		0.52 ± 0.09	1.83 ± 0.37	3
$\tau \to \mu$	0.008 ± 0.002		0.016 ± 0.008	0.024 ± 0.008	1.15 ± 0.23	1
$\tau \to e$	0.035 ± 0.007			0.035 ± 0.007	0.84 ± 0.17	0
Total	0.63 ± 0.10	1.37 ± 0.38	0.016 ± 0.008	2.0 ± 0.4	6.8 ± 1.4	10

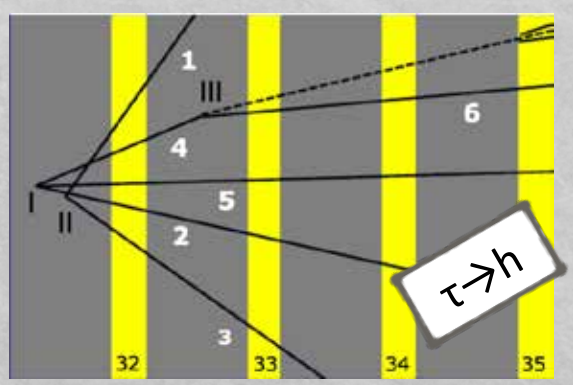
8.8 events expected → 10 events observed

PRL **120**,211801(2018)

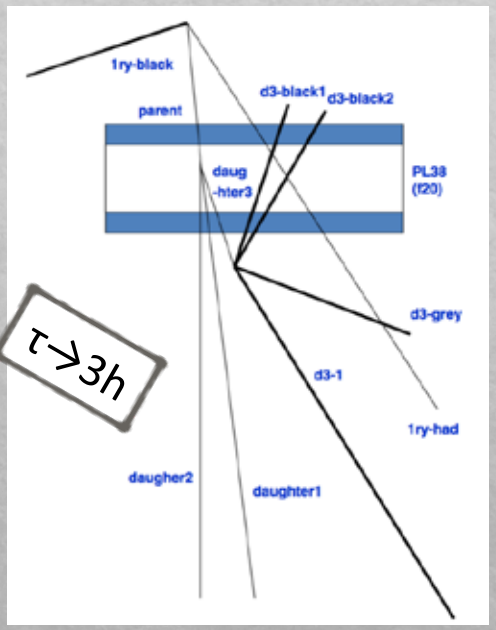
5 More ν_τ Candidates



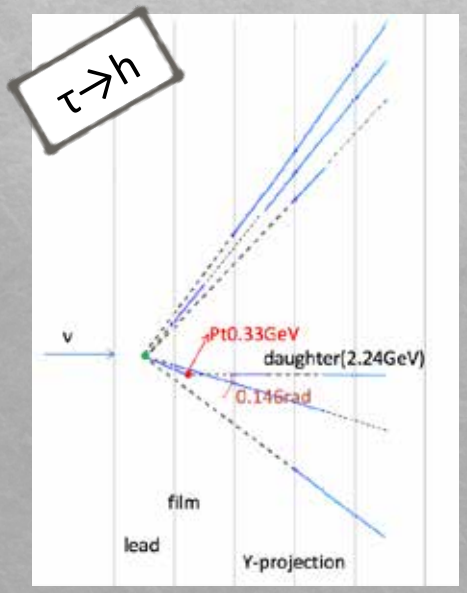
event 11172035775



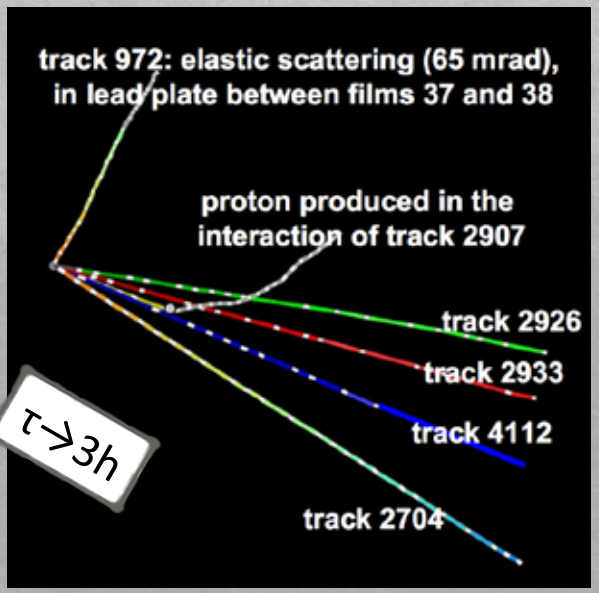
event 11143018505



event 11213015702



event 9190097972



event 10123059807

Multivariate Analysis based on Boosted Decision Tree

Kinematical variables used for the analysis.

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

TABLE IV. Kinematical variables and BDT response for all ν_τ candidates.

Brick ID	72 693	29 570	23 543	92 217	130 577	77 152	27 972	26 670	136 759	4838
Channel	$\tau \to 1h$	$\tau \to 3h$	$\tau \to \mu$	$\tau \to 1h$	$\tau \to 1h$	$\tau \to 1h$	$\tau \to 1h$	$\tau \to 1h$	$\tau \to 3h$	$\tau \to 3h$
z_{dec} (μm)	435	1446	151	406	630	430	652	303	−648	407
p^T_{miss} (GeV/c)	0.52	0.31		0.55	0.30	0.88	1.29	0.46	0.60	> 0.50
ϕ_{lH} (deg)	173	168		166	151	152	140	143	82	47
p^T_{2ry} (GeV/c)	0.47		0.69	0.82	1.00	0.24	0.25	0.33		
p_{2ry} (GeV/c)	12	8.4	2.8	6.0	11	2.7	2.6	2.2	6.7	> 6.3
θ_{kink} (mrad)	41	87	245	137	90	90	98	146	231	83
m (GeV/c^2)		0.80		1.2	> 0.94				1.2	> 0.94
γ at decay vtx	2	0	0	0	0	1	0	0	0	2
charge $_{2ry}$			−1							
BDT response	0.32	−0.05	0.37	0.12	0.35	0.18	−0.25	−0.10	−0.04	−0.03

The BDT response is a value between +1(signal-like) and -1(background-like)

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Final Results on ν_τ Appearance

signalstrangth

true bkg (floating param)

uncertainty on expected bkg

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

channels

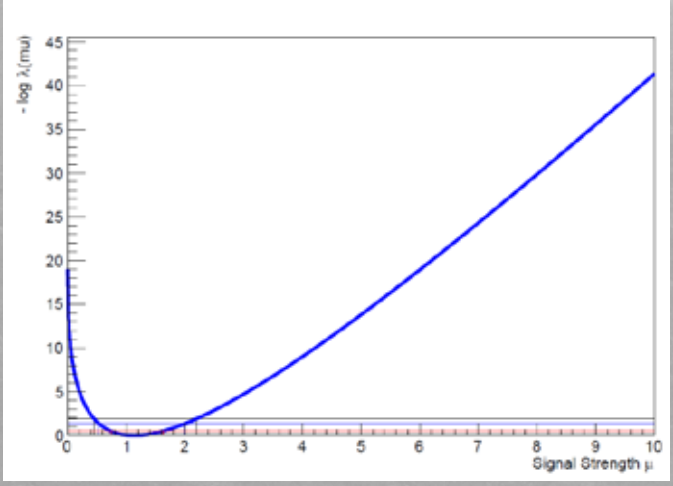
expected signal

expected bkg

observed events in the c[th] channel

BDT response

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



Test statistic : likelihood ratio

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

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

Significance = 6.1σ

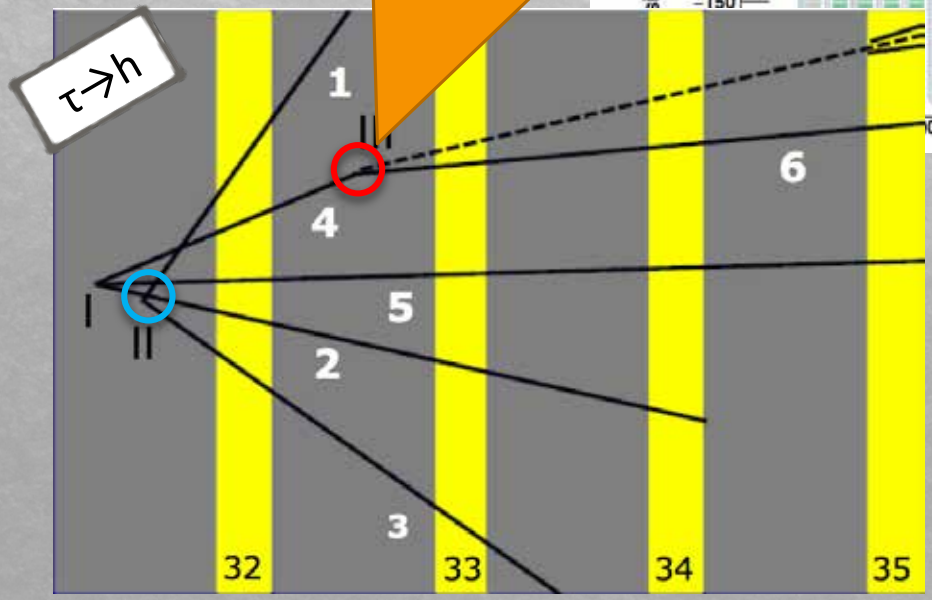
PRL **120**,211801(2018)

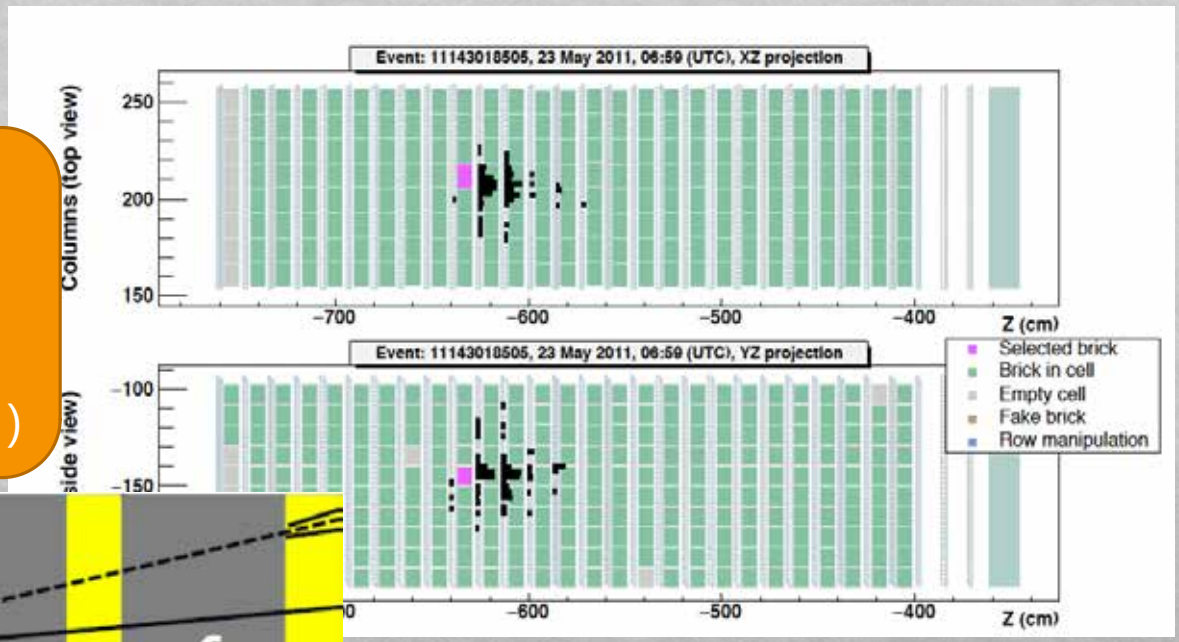
An Event with Three Vertices

without any muon in the final state

τ→h decay vertex

- $\theta_{kink} = 90\text{mrad}$
  $\rightarrow P_{\perp} = 240MeV$
- Flight length = 1160μm
- γ attached (IP = 8±8 μm)

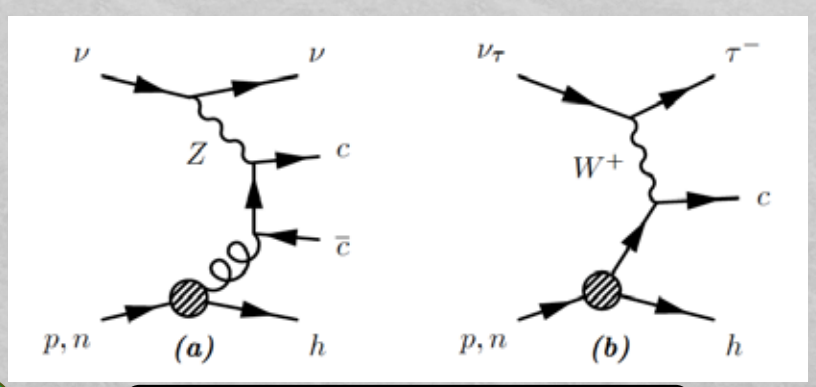




event 11143018505

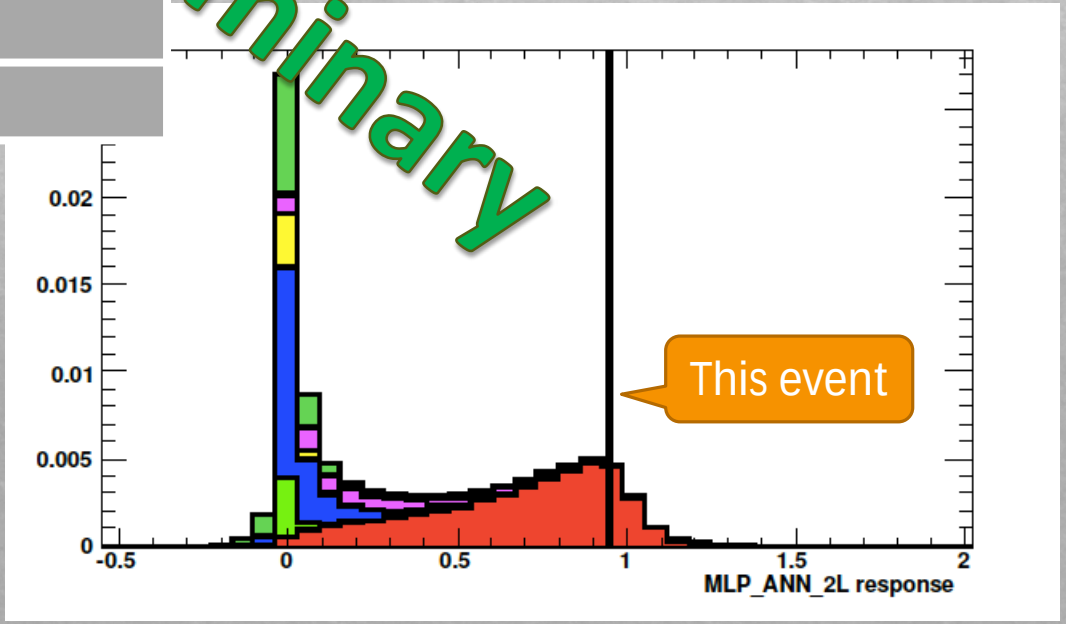
Expected Yield and Multivariate Analysis

sample	expected events(x10^{-3})
ν_τCC+charm	45
ν_μCC+charm+h_{int}	21
ν_μNC+$c\bar{c}$	13
ν_τCC+h_{int}	9
ν_μCC+2h_{int}	4
ν_μNC+2h_{int}	4
Total	100



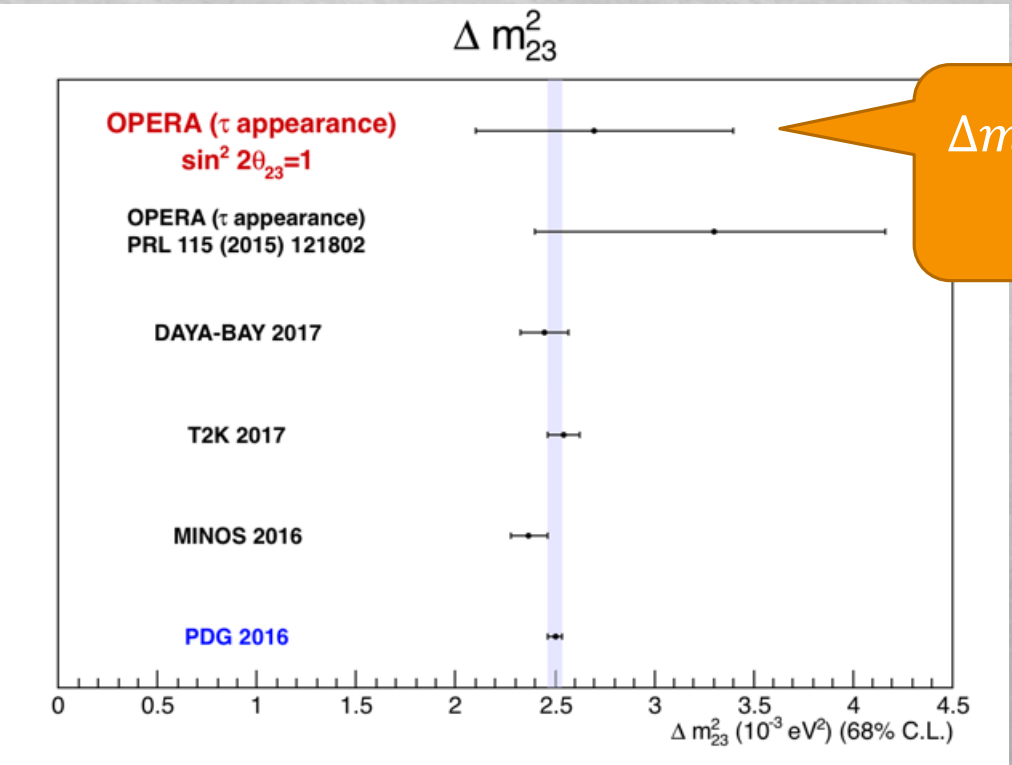
Leading Feynman Diagram

Preliminary



First Δm^2_{23} Measurement in Appearance Mode

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



$$\Delta m^2_{23} = (2.7^{+0.7}_{-0.6}) \times 10^{-3} eV^2$$

(68% C.L.)

PRL **120**,211801(2018)

Assumptions :

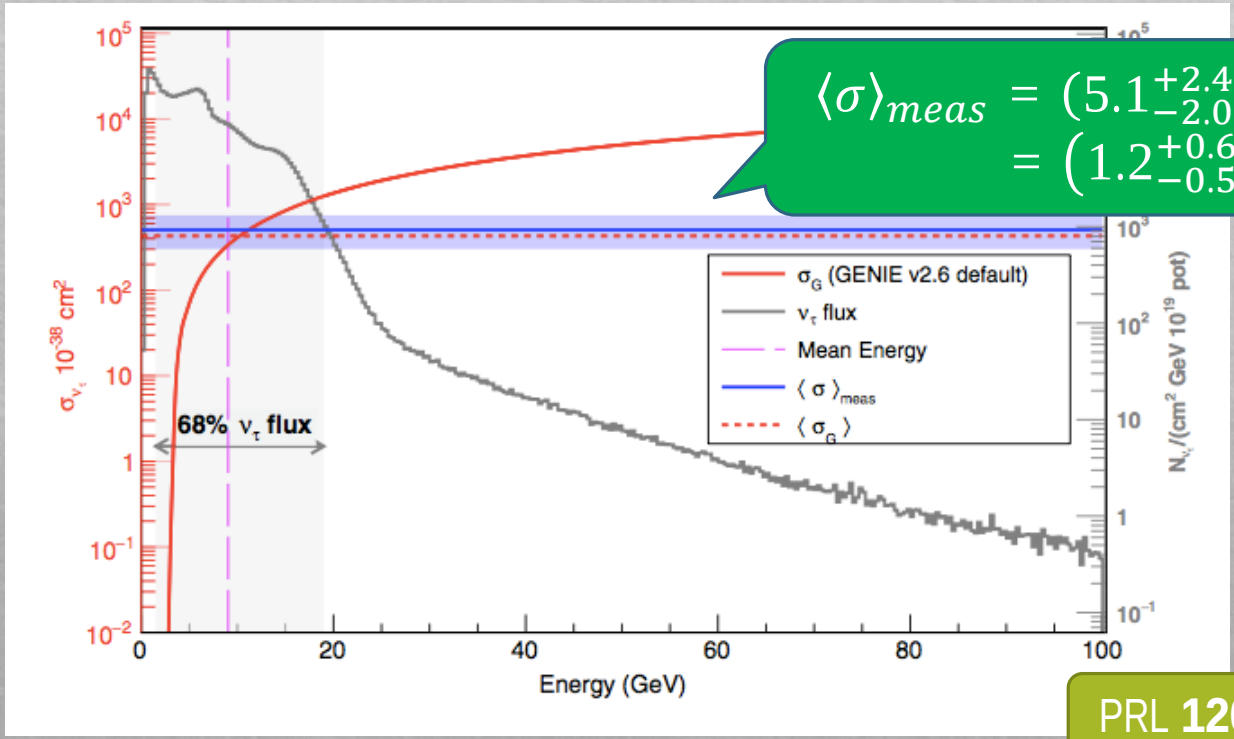
- maximal mixing $\rightarrow sin^2(2\theta_{23}) = 1$
- ν_τ cross section as in Genie v2.6 default $\rightarrow \langle \sigma_G \rangle = (4.29 \pm 0.04) \times 10^{-36} cm^2$

Tau Neutrino CC Cross Section

$$\langle\sigma\rangle_{meas} = \frac{\left(N^{obs} - N^{expB}\right)/(\varepsilon N_T)}{\int \Phi_{\nu_\mu}(E) P_{\nu_\mu \to \nu_\tau}(E) dE}$$

ε = 0.12 (overall efficiency)
N_T : Lead nuclei in the volume

assumptions : $\Delta m^2_{23} = (2.50 \pm 0.04) \times 10^{-3} eV^2$ (PDG), $sin^2 2\theta_{23} = 1$

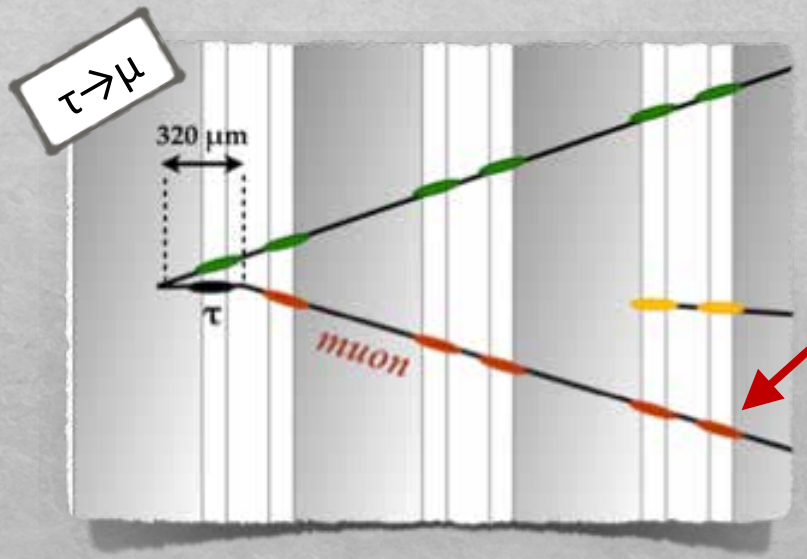


$$\langle\sigma\rangle_{meas} = (5.1^{+2.4}_{-2.0}) \times 10^{-36} cm^2 = \left(1.2^{+0.6}_{-0.5}\right)\langle\sigma_G\rangle$$

PRL **120**,211801(2018)

First measurement with negligible contamination from anti-ν_τ

ν_τ Lepton Number



Phys. Rev. D89(2014)051102

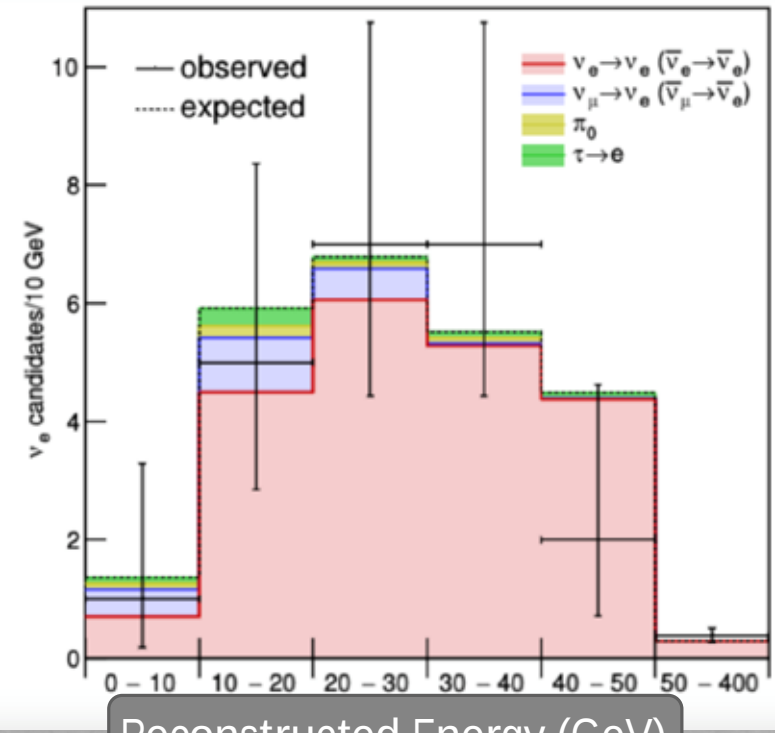
Muon chrge is negative with P_μ=2.8±0.2GeV/c

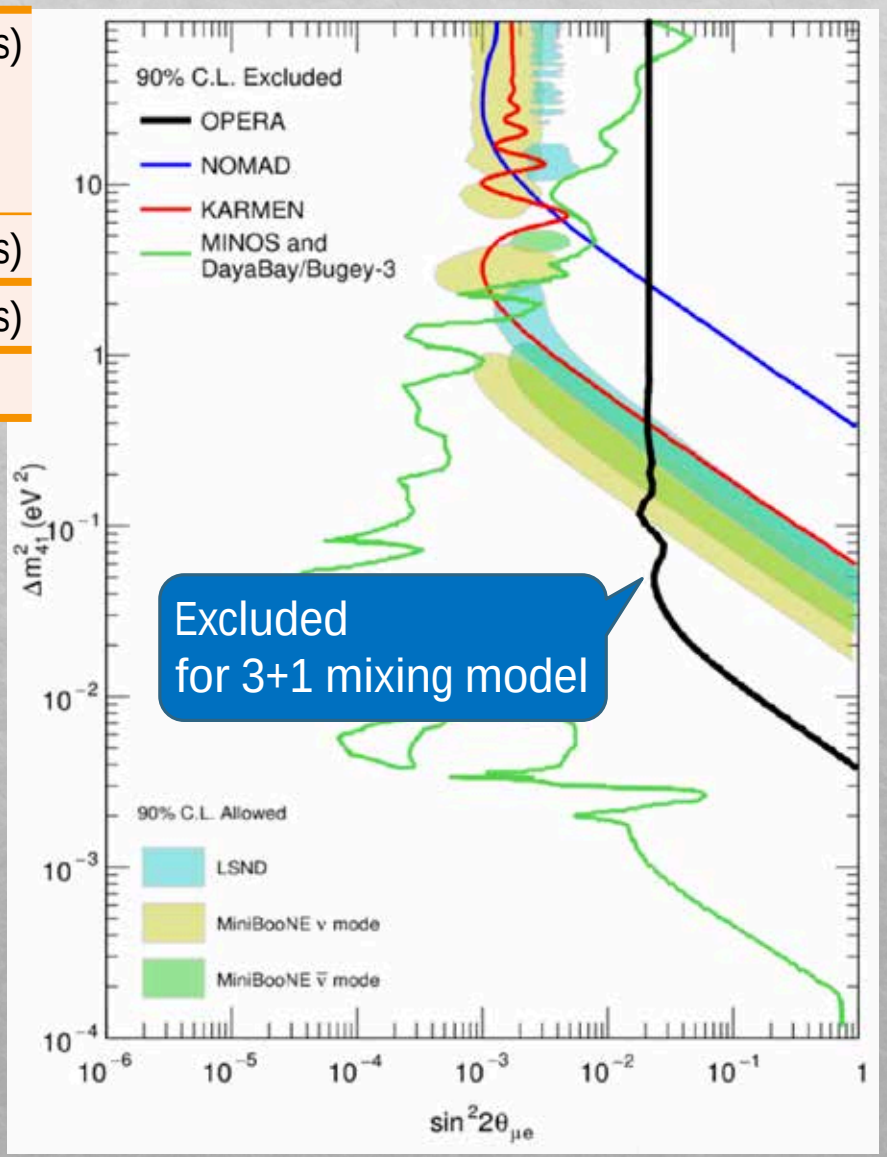
"$\overline{\nu_\tau}$ CC int due to $\overline{\nu_\mu}\rightarrow\overline{\nu_\tau}$ oscillations, with its μ's charge is mis-identified or not-measured" is also taken into account in BG. = 0.0024±0.0005

A significance of having observed $\tau^-\rightarrow\mu^-$ is 3.7σ. First direct evidence for the ν_τ lepton number

$\nu_\mu \rightarrow \nu_e$ Oscillation

$\nu_e, \bar{\nu_e}$ from beam contamination	30.7±0.9(stat) ±3.1(sys)
π^0	0.5±0.5(stat)
ν_τ from 3-flavor osc. ($\tau \rightarrow e$)	0.7±0.2(sys)
Total expected bg	31.9±1.0(stat) ±3.1(sys)
Expected in case of 3-flavor osc.	34.3±1.0(stat) ±3.4(sys)
Data	35





JHEP06(2018)151

Summary

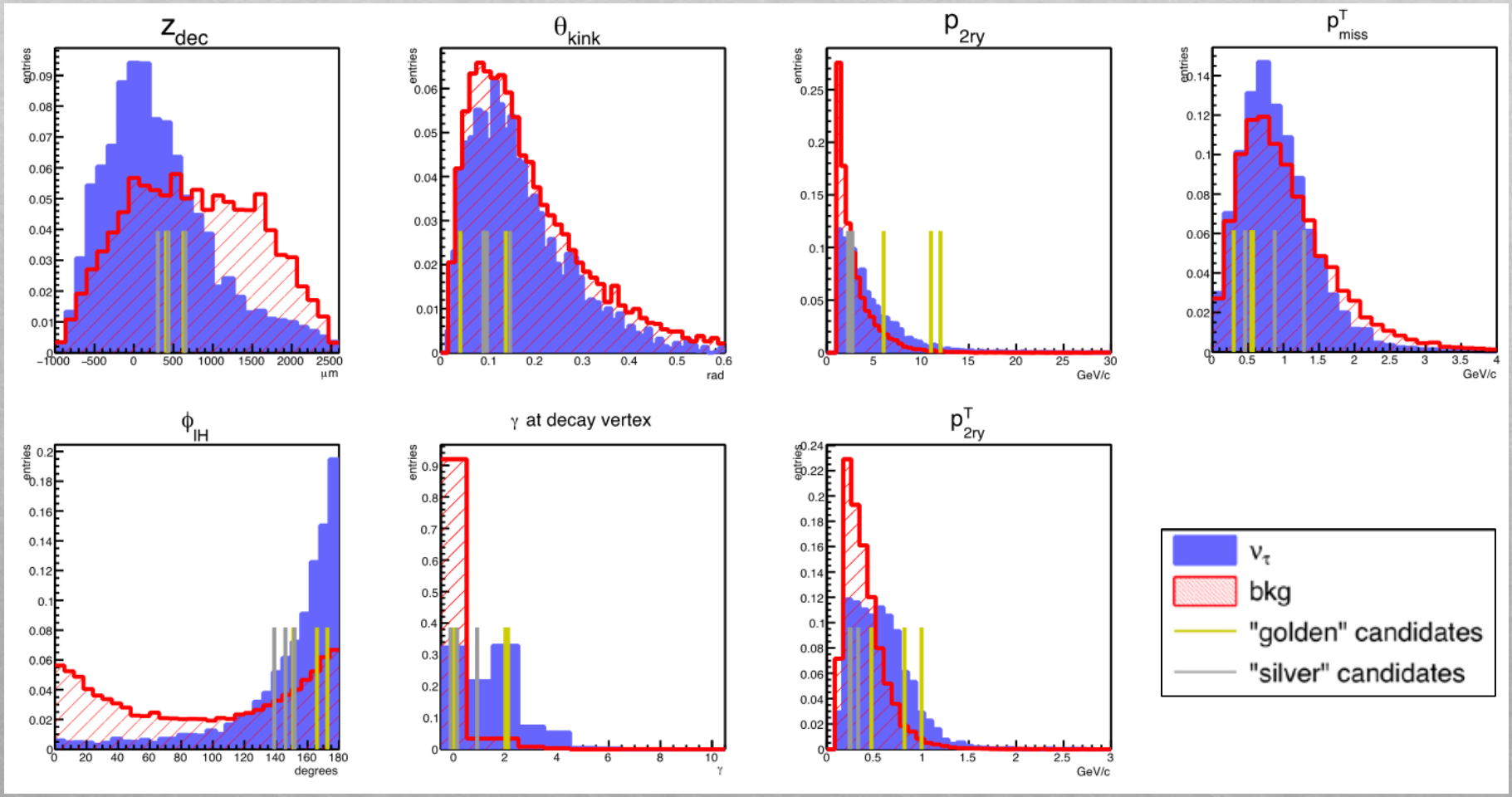
- OPERA aimed to detect the appearance of ν_τ by neutrino oscillation.
- The CNGS ν_μ beam exposed to 1.25kton Pb+emulsion targets, L=730km.
- 5 ν_τ events were reported by 2015 → 5.1σ significance.
- After the appearance observation, new selection to increase ν_τ statistics → improve Δm^2 and σ_τCC accuracy.
- 5 new candidates, thus total 10 ν_τ events are the final output from OPERA.
  - ν_τ appearance significance reached 6.1σ
  - $\Delta m^2 = \left(2.7^{+0.7}_{-0.6}\right) \times 10^{-3}\ eV^2$ ← The first from appearance experiment
  - $\sigma_\tau = \left(5.1^{+2.4}_{-2.0}\right) \times 10^{-38}\ cm^2$ ← with negligible contamination of $\overline{\nu_\tau}$
  - one event with $\tau \rightarrow \mu^-$ ← first ν_τ lepton number observation.
- $\nu_\mu \rightarrow \nu_e$ analysis have been performed and 35 ν_e were found.

Thank you for your attention!

Image taken using an **OPERA nuclear emulsion film**
with a pinhole hand made camera
courtesy by Donato Di Ferdinando

backup slides

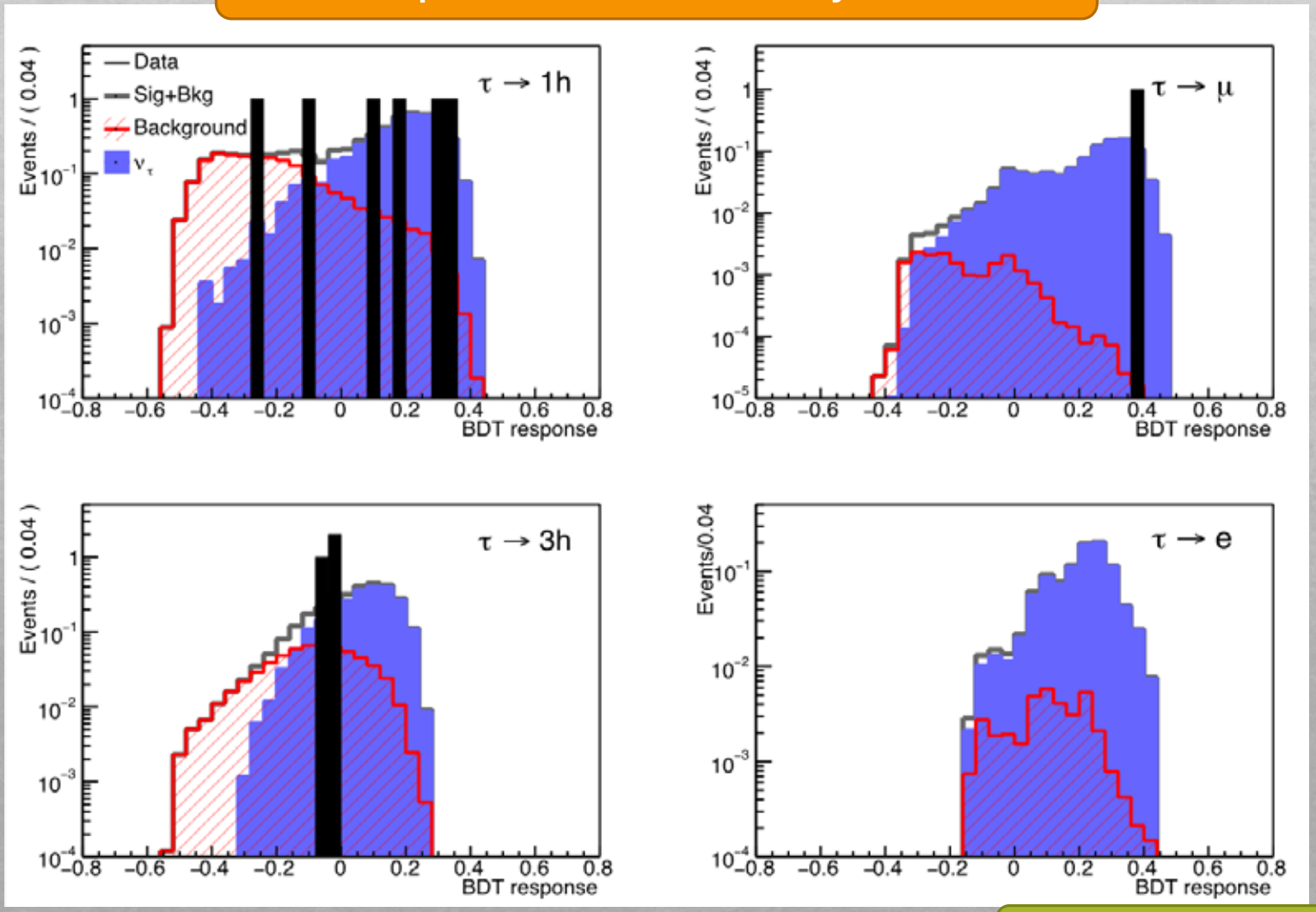
Input Variables for the Multivariate Analysis in the τ→h Decay Channel



"golden" → candidates passing the tight selection cuts
"silver"→ newly found candidates with looser cuts

Multivariate Analysis based on Boosted Decision Tree

BDT responses for all decay channels



PRL **120**,211801(2018)