Final results from OPERA

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on behalf of the OPERA Collaboration

NOW 2018 – Neutrino Oscillation Workshop, Rosa Marina (Ostuni, Italy), Sept. 9-16, 2018

26 institutions

~150 physicists

IRB Zagreb

METU Ankara

Technion Haifa

Bari
Bologna
LNF Frascati
LNGS
Napoli
Padova
Roma
Salerno

Aichi
Toho
Kobe
Nagoya
NIhon

LAPP Annecy
IPHC Strasbourg

INR Moscow
LPI Moscow
SINP MSU Moscow
JINR Dubna

LHEP Bern

IHE Brussels

Hamburg

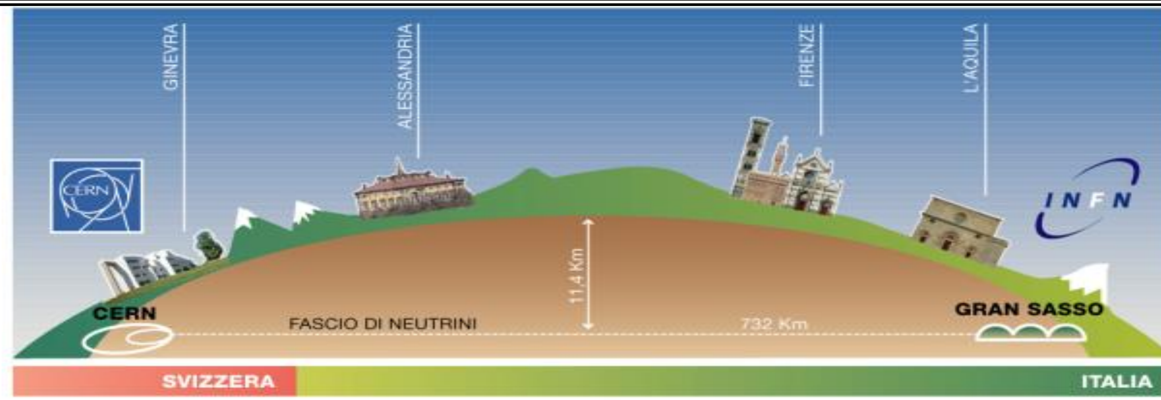
Jinjiu

- ✓ ν_τ appearance (std & looser selection)
- ✓ ν_e search update
- ✓ ν_μ disappearance
- ✓ sterile neutrinos
- ✓ non-oscillation physics

Oscillations Project with Emulsion TRacking Apparatus

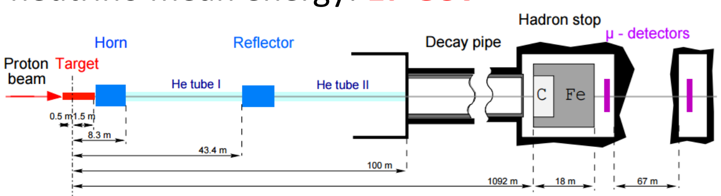
[CERN-SPSC-2000-028, 2000]

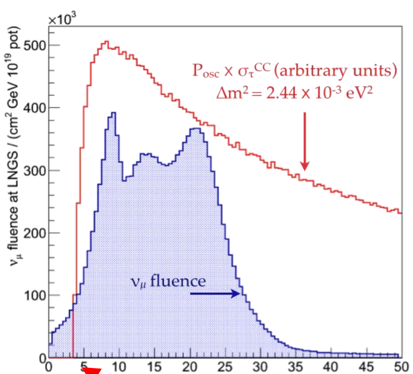
- **Long baseline** experiment: 735 km
- Aim: **verify the $\nu_\mu \to \nu_\tau$** oscillations at atmospheric Δm^2 scale
- How: ν_τ **appearance** on **event-by-event** basis in a ν_μ beam



Conventional muon neutrino beam

neutrino mean energy: **17 GeV**

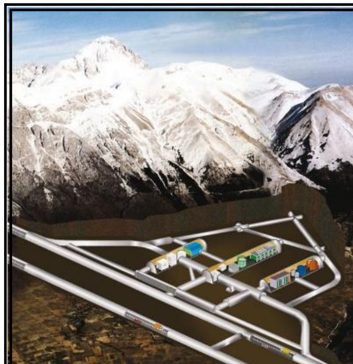




- Optimized for ν_τ appearance at LNGS
- Maximize the number of ν_τ CC interactions

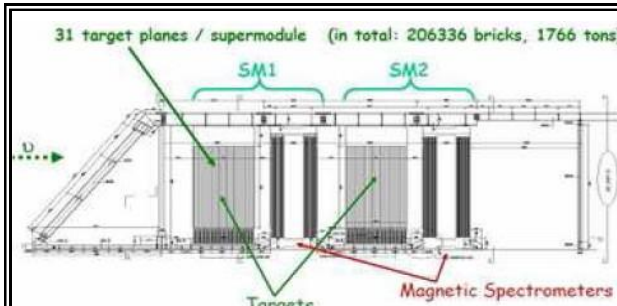
$(\nu_e + \bar{\nu}_e)/\nu_\mu$	0.9 %
$\bar{\nu}_\mu/\nu_\mu$	2.1%
ν_τ prompt	negligible

threshold: 3.5 GeV [m_τ = 1.7 GeV]



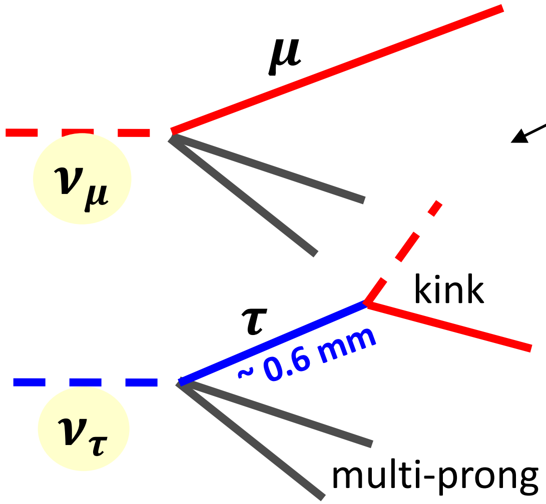
Low background environment

Laboratori Nazionali del Gran Sasso (Italy)
- 1400 m rock overburden
- atm. μ reduction ~ 10^6 [$1\mu/(m^2 \cdot h)$]
- low radioactivity rock



Detector:
hybrid apparatus
- Massive (1.25 kt) and
- fine-grained (100μm)

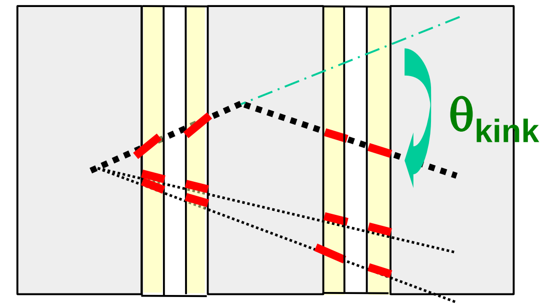
The ν_τ detection challenge



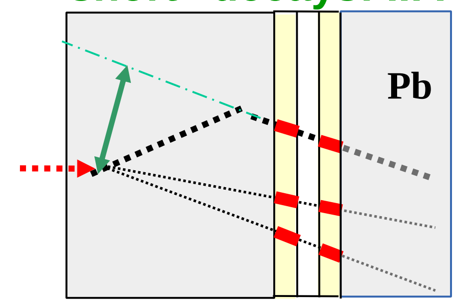
Detect a few ν_τ^{CC} from the bulk of ν_μ^{CC}

$\tau^- \to \mu^- \nu_\tau \nu_\mu$	17 %
$\tau^- \to e^- \nu_\tau \nu_e$	18 %
$\tau^- \to h^- \nu_\tau\, n(\pi^0)$	50 %
$\tau^- \to \pi^-\pi^+\pi^- \nu_\tau\, n(\pi^0)$	14 %

"long" decays: kink



"short" decays: I.P.



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

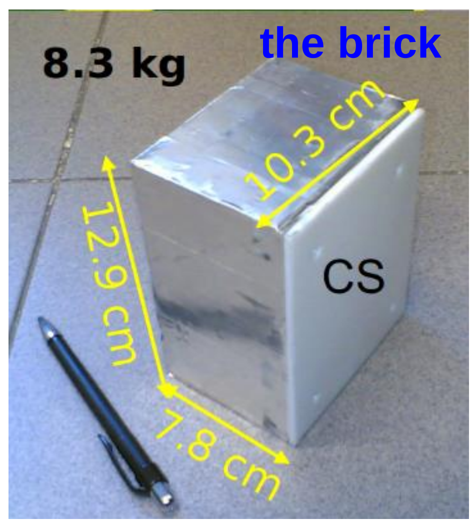
Match the needs for:

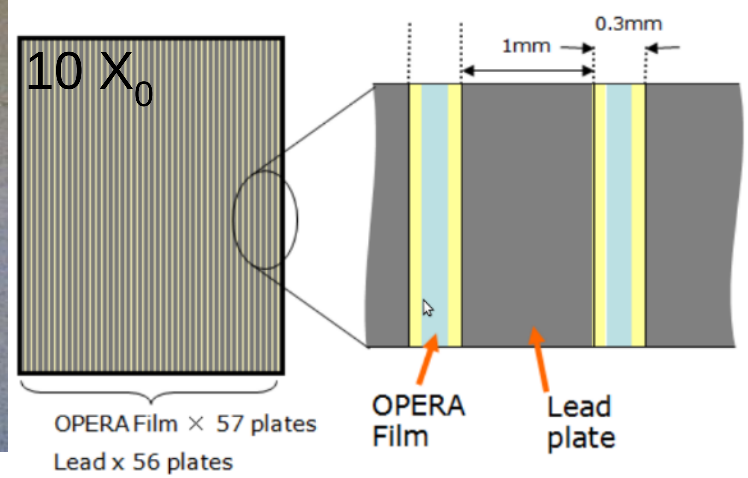
Large mass

$N_\tau \propto (\Delta m^2)^2 M_{target}$

Extreme granularity

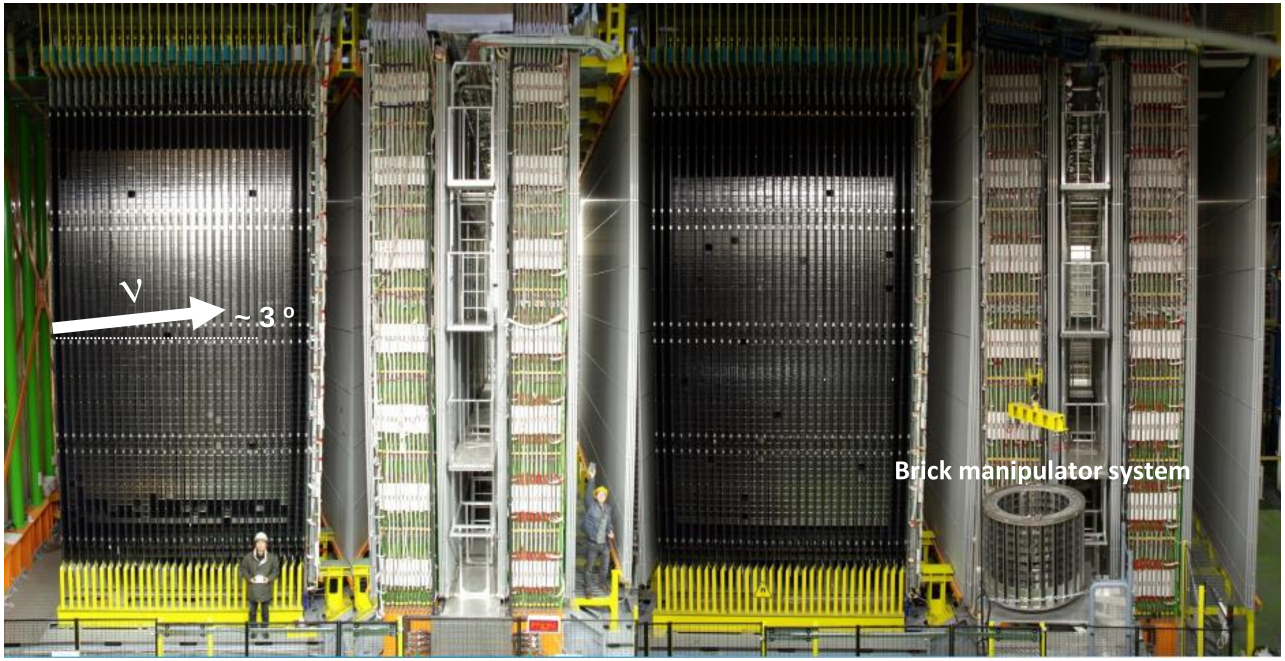
$\sim\mu$m space resolution





The OPERA detector

← Super Module 1 → ← Super Module 2 →



Target section (6.7 x 6.7 m^2):

- **Target**
  ~ 625 ton
  ~ 75000 bricks in 27 walls
- **Target Tracker**
  31 XY doublets of 256 scintillator strips planes

Tracking of the target region
Brick selection
Calorimetry

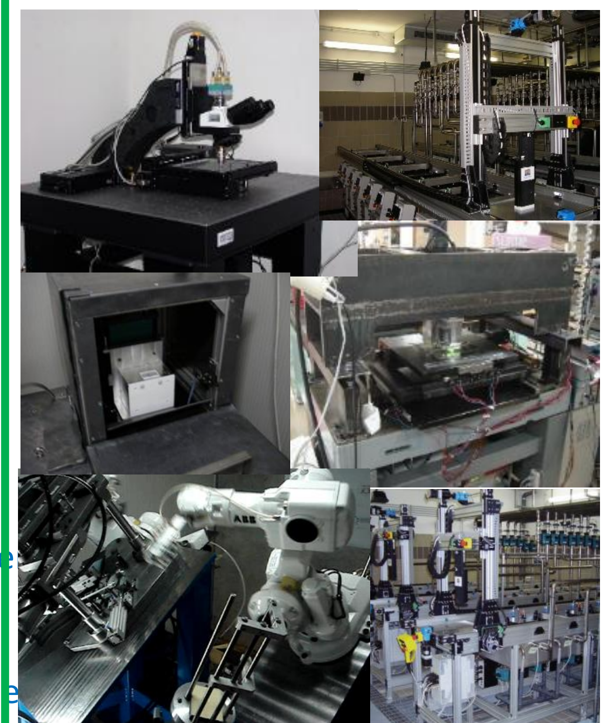
Muon spectrometer (8 x 10 m^2)

- 1.53 T magnet
- 22 XY RPC planes +
  2 RPC planes rotated by 42.6°
- 6 stations of 4-fold drift tubes laye

μ Identification +
charge and momentum measureme

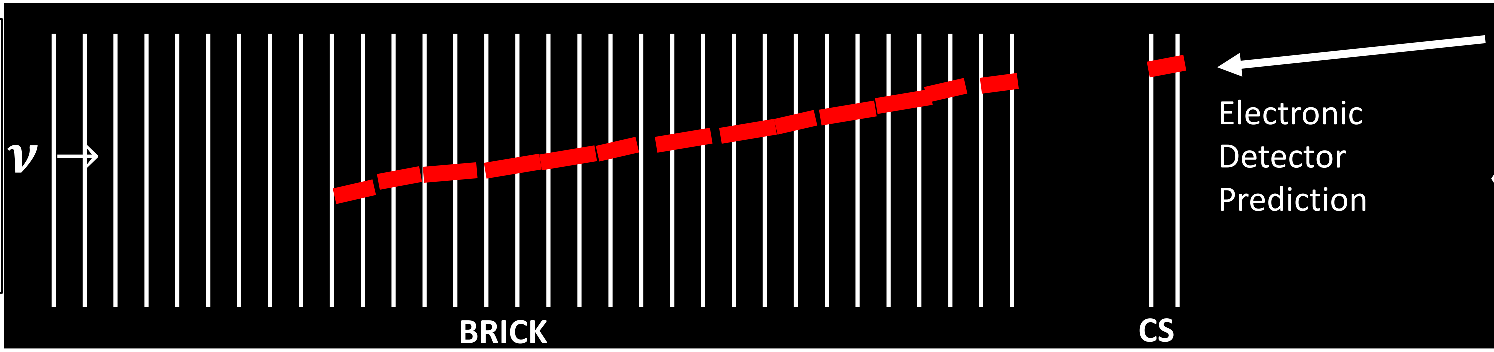
+ several ancillary facilities "off-site":

- **Assembly of bricks (LNGS)**
- **Brick Manipulator System (LNGS)**
- **Labelling and X ray marking (LNGS)**
- **Automatized development (LNGS)**
- **Scanning of CS doublets (LNGS+JP)**
- **Scanning bricks (European Labs + JP)**



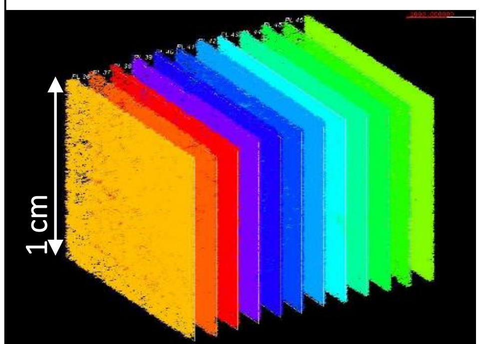
Vertex hunting in the brick

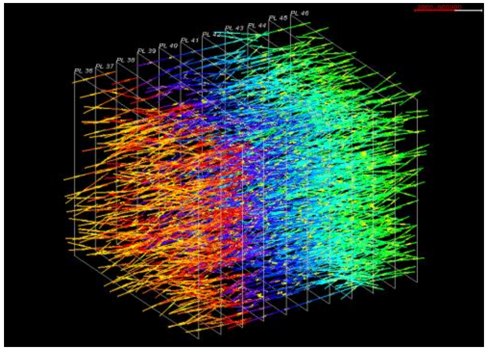
vtx location

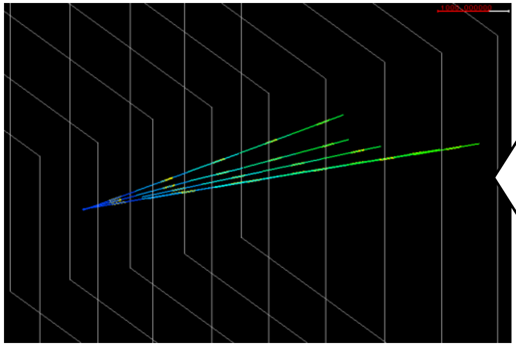


Small area scan guided by prediction

vtx reconstruction







Wide area scan

0) tracks tagged in the CS films followed upstream to **stopping point**

1) 1 cm³ **volume centered in the stopping point** scanned and tracks reconstructed

2) cosmic ray tracks (from a dedicated exposure) used for the fine **alignment** of films

3) passing through tracks discarded, the **vertexing algorithm** reconstructs the vertex

4) Short-lived particle decays identified (**decay search**)

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

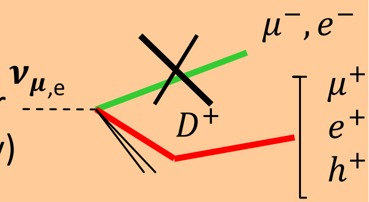
[JHEP 1311 (2013) 036]

Monte Carlo simulation benchmarked on control samples

In order of decreasing relevance

CC with charm production (all channels)

If primary lepton is not identified and the daughter charge is not (or incorrectly) measured



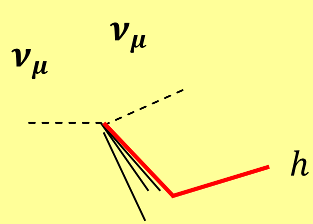
MC tuned on CHORUS data (cross section and fragmentation functions), validated with measured OPERA charm events.

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

[Eur.Phys.J. C74 (2014) 2986]

Hadronic interactions

Background for $\tau \rightarrow h$



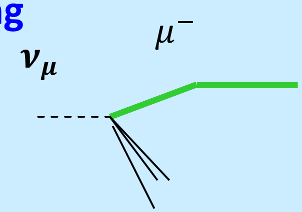
FLUKA + pion test beam data

Reduced by large angle scanning and nuclear fragment search

[PTEP9 (2014) 093C01]

Large angle muon scattering

Background for $\tau \rightarrow \mu$



Measurements in the literature (Lead form factor)

Improved MC simulations

[IEEE Trans.Nucl.Sci. 62 (2015) no.5, 2216-2225]

ν_τ appearance discovery (2015)

[Phys. Rev. Lett. 115, 121802 (2015)]

The 5 years long CNGS run

- **1.8×10^{20} p.o.t.** collected (**80%** of the design)
- **19505** ν interactions in the emulsion targets.
- **5 ν_τ candidate events** fulfill kinematical selection **[S/B ratio ~10]**

Observed Data: **4 hadronic + 1 muonic candidates**

Channel	Expected background	Expected signal	Observed
$\tau \to 1h$	0.04 ± 0.01	0.52 ± 0.10	3
$\tau \to 3h$	0.17 ± 0.03	0.73 ± 0.14	1
$\tau \to \mu$	0.004 ± 0.001	0.61 ± 0.12	1
$\tau \to e$	0.03 ± 0.01	0.78 ± 0.16	0
Total	0.25 ± 0.05	2.64 ± 0.53	5

Signal Background Modelization

- *Multichannel (uncorrelated)* ***counting model*** *based on Poisson Statistics*
- *Gaussian for Background Uncertainties*

$$\mathcal{L} = \prod \text{Pois}(n_i, \mu s_i + b_i)\ \text{Gaus}(b_{0i}, b_i, \sigma_{bi})$$

μ → **strength of the signal** (parameter of interest)
with $\mu = 0$: **background-only** hypothesis
and $\mu = 1$: **nominal signal+background**

test statistics:
i) Profile Likelihood Ratio;
ii) Fisher's rule ($\mu = 0$) .

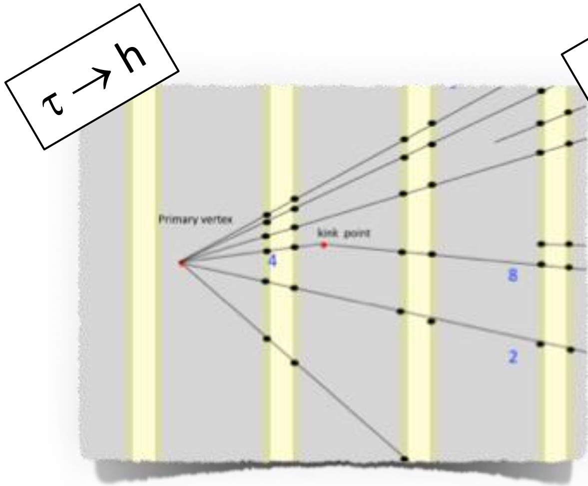
Background-only hypothesis:

- p-value = 1.1×10^{-7}
- **excluded at 5.1σ significance**

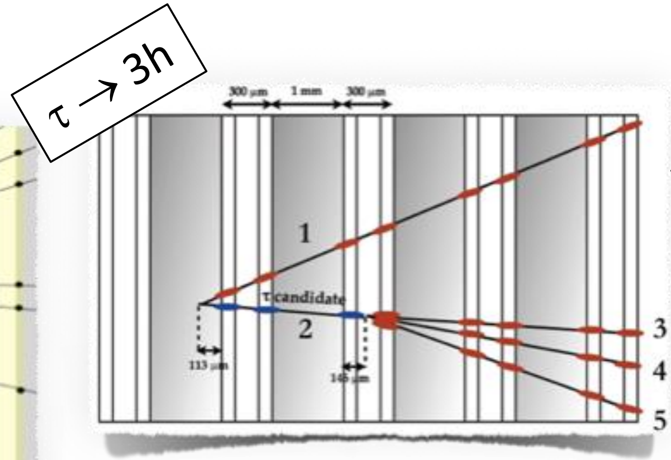
Compatibility with 3ν oscillation:
$\hat{\mu} = 1.8^{+1.8}_{-1.1}$ at 90% C.L

Probability of less likely data:
17% based on total number
6.4% if channels considered

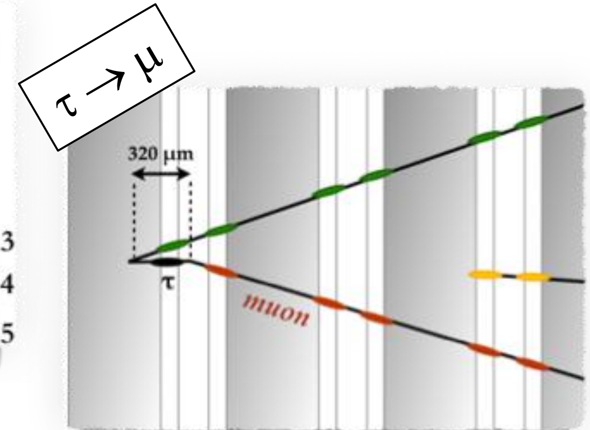
The five ν_τ candidates (2015)



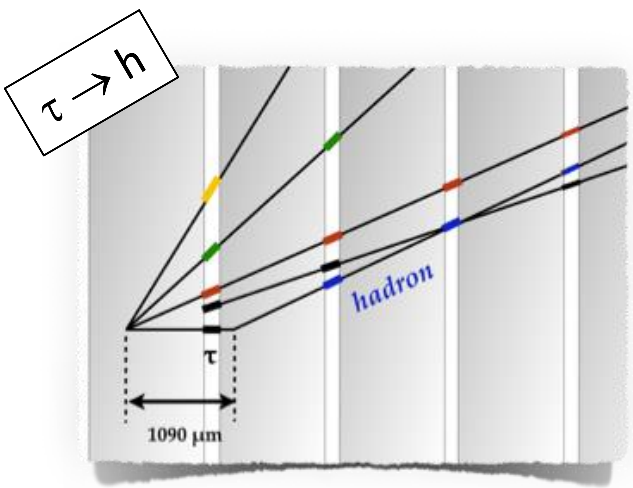
Phys. Lett. B 691 (2010) 138



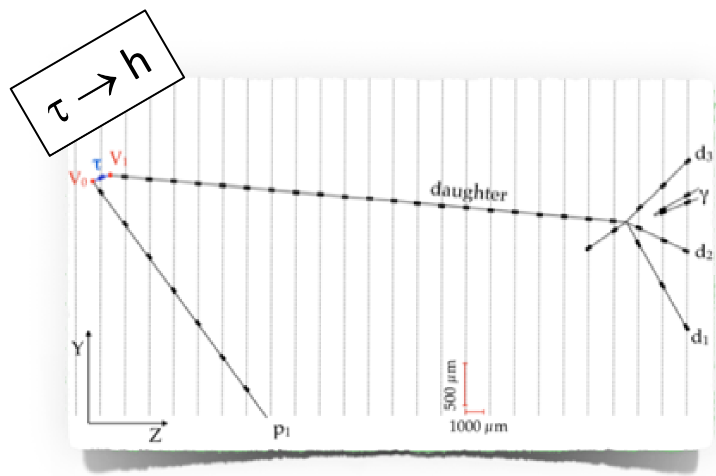
JHEP 11 (2013) 036



Phys. Rev. D 89 (2014) 051102



PTEP 2014 (2014) 10, 101C01



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

ν_τ appearance: loose event selection (2018)

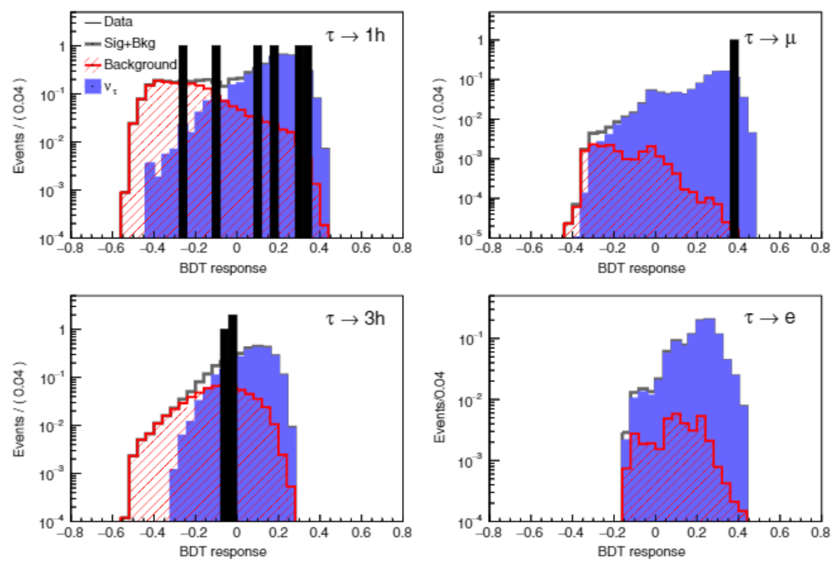
[Phys.Rev.Lett. 120 (2018) no.21, 211801]

- Loose kinematical cuts:
  - **Minimal requirements** to identify the topologies showing 2 vertices
  - **Negligible additional background** from K/π decays

Variable	$\tau \to 1h$	$\tau \to 3h$	$\tau \to \mu$	$\tau \to e$
z_{dec} (mm)	<2.6	<2.6	<2.6	<2.6
θ_{kink} (rad)	>0.02	>0.02	>0.02	>0.02
p_{2ry} (GeV/c)	>1	>1	[1, 15]	>1
p_{2ry}^T (GeV/c)	>0.15		>0.1	>0.1
Charge$_{2ry}$			Negative or unknown	

	Expected background	ν_τ expected	Observed
Total	2.0 ± 0.4	6.8 ± 1.4	10

- **Increment of ν_τ sample: *x2***
- **Reduction of S/B** from ***~10*** *to* ***~3***



- **Multivariate approach** (based on BDT)
  - exploit kinematical, topological information and their correlations

    → **higher discrimination power**

⇒ Improvement in $|\Delta m^2_{23}|$ or alternatively $\langle\sigma\rangle$ estimation

Statistical Analysis and Results (2018)

[Phys.Rev.Lett. 120 (2018) no.21, 211801]

- Likelihood:

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

- where

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

- Test statistic: **profile likelihood ratio**
- Using **asymptotic approximation** [Eur.Phys.J.C71:1554,2011], null hypothesis excluded with **6.1σ** significance
- Best-fit signal strength:

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

$$\mu \propto |\Delta m^2_{32}|^2 \cdot \langle\sigma\rangle$$

$$|\Delta m^2_{32}| = (2.7^{+0.7}_{-0.6}) \times 10^{-3}\ eV^2$$

assuming maximal mixing

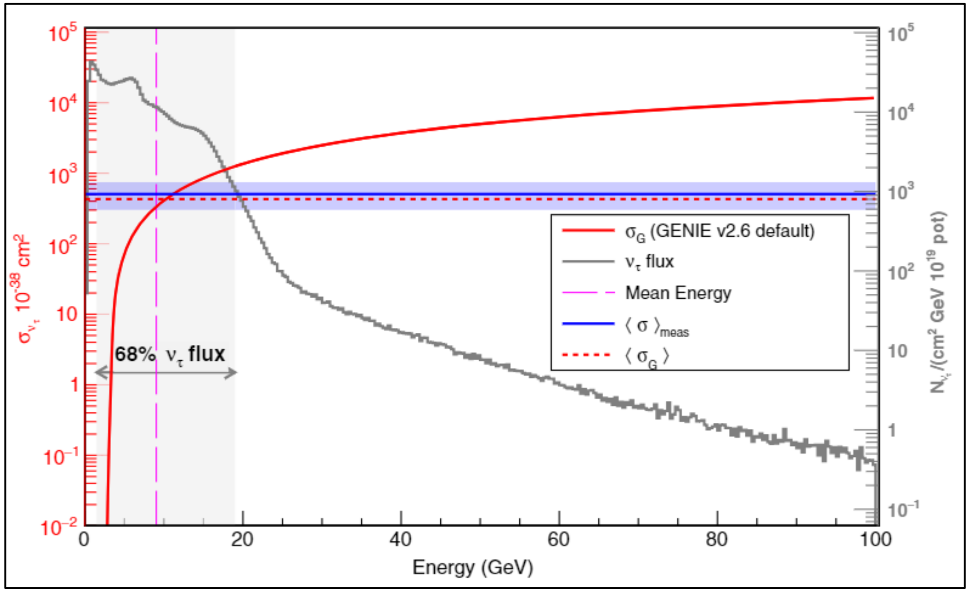
first measure in appearance mode

effective tau neutrino cross section

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

assuming maximal mixing and $|\Delta m^2_{32}| = 2.5 \times 10^{-3}\ eV^2$

$$\langle\sigma_{Genie}\rangle = 4.29 \pm 0.04 \times 10^{-36}\ cm^2$$

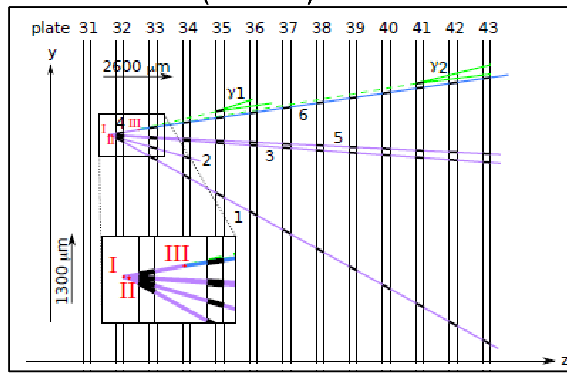


Peculiar event

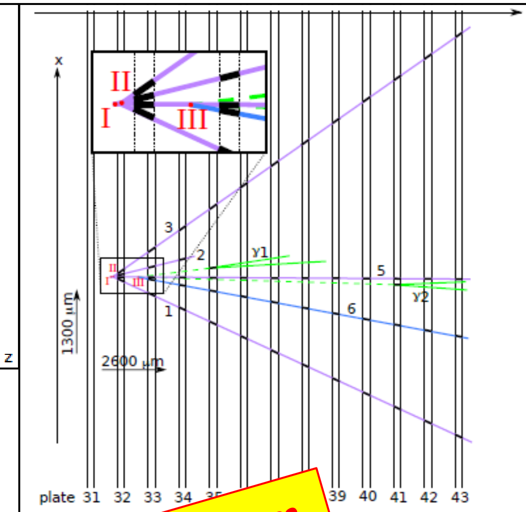
Preliminary

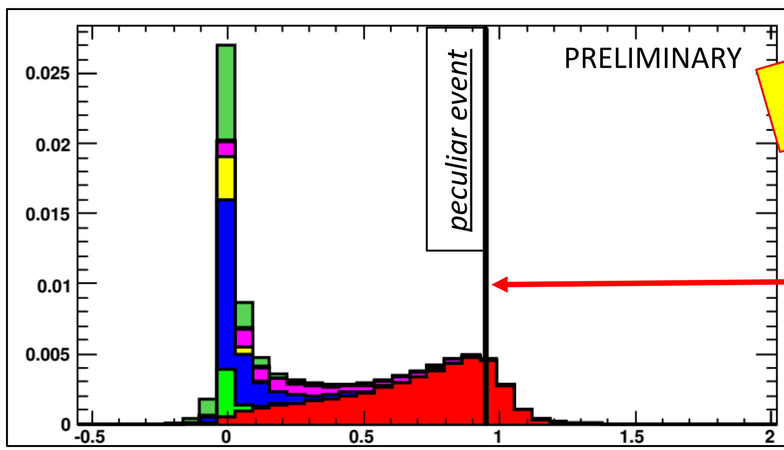
- Muon-less neutrino event
- Most probable topology:
  ν interaction vertex + 2 decay vertices
- **Rare topology** not considered in the experiment proposal
  (0.1 events expected in full data sample)
- **Dedicated simulations + ANN** (2 Layers MLP) to disentangle possible interpretations:
  - $\boldsymbol{\nu_\tau CC + c}$
  - $\boldsymbol{\nu_\mu CC + c + had.\ int.}$
  - $\boldsymbol{\nu_\mu NC + c\bar{c}}$
  - $\boldsymbol{\nu_\tau CC + had.\ int.}$
  - $\boldsymbol{\nu_\mu CC + 2\ had.\ int.}$
  - $\boldsymbol{\nu_\mu NC + 2\ had.\ int.}$

yz view
(vertical)



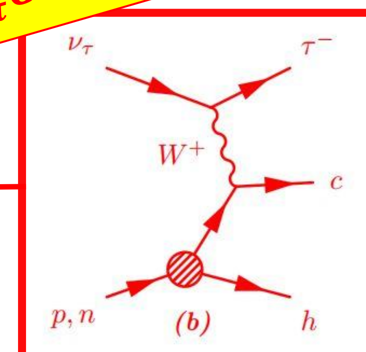
yz view
(horizontal)





ANN output

$\nu_\tau CC + charm$



The hypothesis the event not being ν_τ CC + charm is excluded:

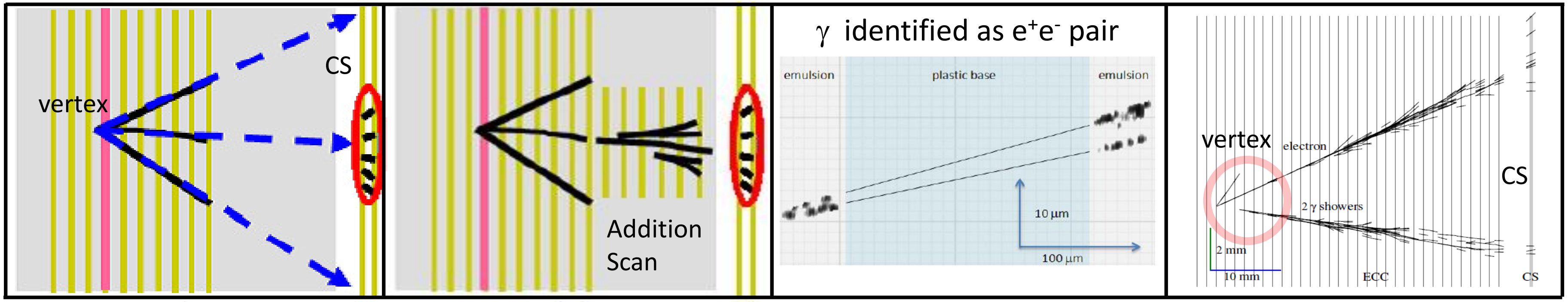
p-value ~ 10^{-4} → Significance = 3.4 σ

Preliminary

ν_e search

[JHEP 1806 (2018) 151]
[JHEP 1307 (2013) 004]

- OPERA detector granularity allows e.m. shower id → **ν_e search**.
- A **dedicated procedure**, balancing time need vs efficiency.

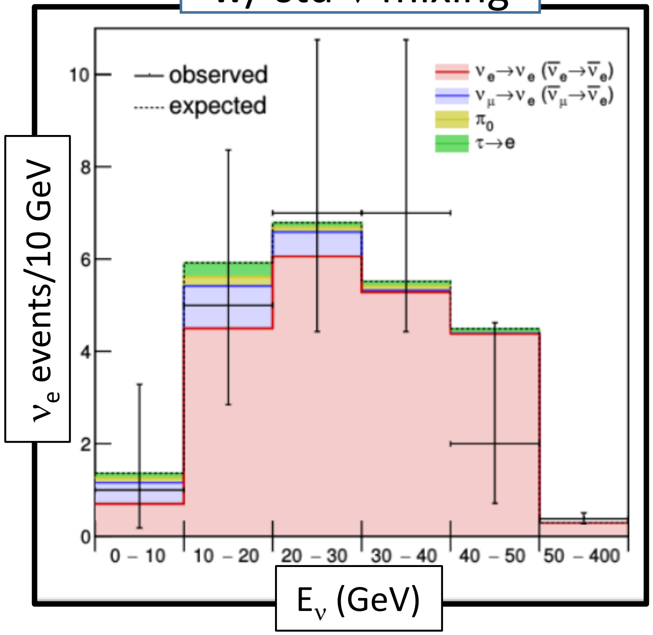


- Project vtx tracks
- Find cluster of similar slope CS tracks

⇨ Reconstruct e.m. shower ⇨ Exclude γ ⇨ Identify ν_e event

Component	Expectations w/o ν mixing	Expectations w/ std ν mixing
$\nu_e \to \nu_e \ (\overline{\nu}_e \to \overline{\nu}_e)$	*30.7*	*31.1*
τ (unidentified) → e	0.7	0.7
$\pi^0 \to \gamma$ (misidentified)	0.5	0.5
$\nu_\mu \to \nu_e \ (\overline{\nu}_\mu \to \overline{\nu}_e)$	*0.0*	*2.0*
Total	*31.9*	*34.3*
observed	***35***	

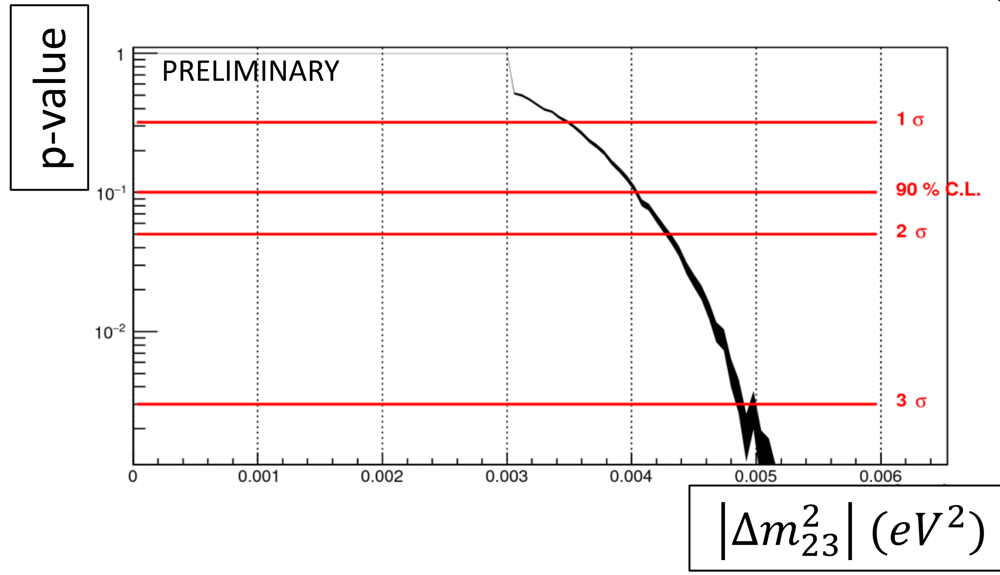
w/ std ν mixing



ν_μ disappearance

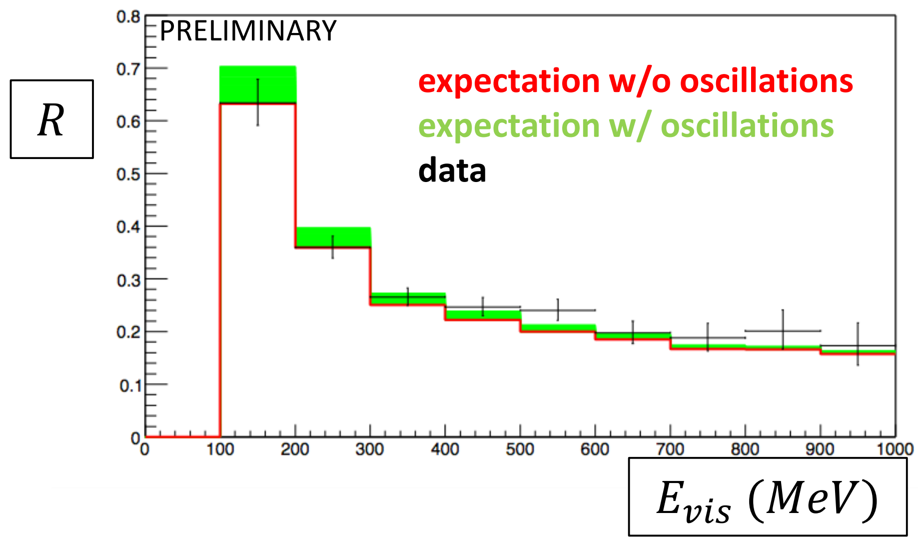
PRELIMINARY

ν_μ disappearance sensitivity **limited** by flux uncertainties
$\rightarrow$ no NEAR detector



Ratio (R) of NC-like over CC-like **mitigates limitation** due to flux uncertainties

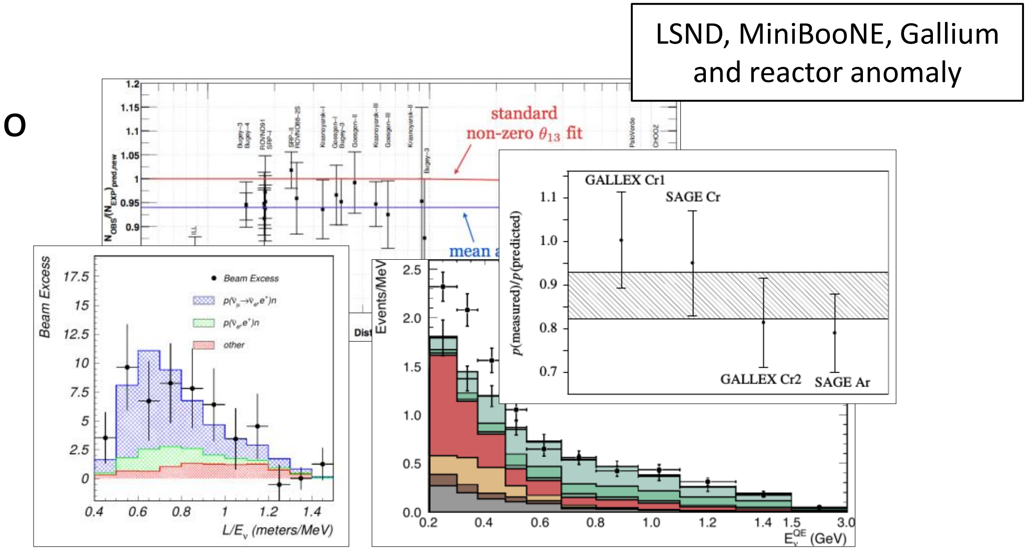
Electronic detector data:
smaller uncertainties w.r.t. emulsion data



Test compatibility with expectation for given values of $|\Delta m^2_{23}|$ (**assuming maximal mixing**)

$$|\boldsymbol{\Delta m^2_{23}}| < \mathbf{4.1 \times 10^{-3}}\ \boldsymbol{eV^2}\ @\ \mathbf{90\%}\ \boldsymbol{C.L.}$$

Some experimental results may hint to an additional massive (~1 eV^2) **sterile** neutrino



Mixing described by 4 x 4 matrix

$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

- **ν_e appearance**
- ν_μ disappearance
- **ν_τ appearance**
- NC disappearance

OPERA can test the sterile neutrino hypothesis looking for deviations from predictions in the electron neutrino appearance or tau neutrino appearance channels.

Predictions of the **3+1 model** evaluated with **GLOBES**

- **Δm^2_{21}** fixed to *PDG* value
- Gaussian constraint on **Δm^2_{31}** (*PDG* mean and sigma)
- **Matter effects**: constant Earth crust density (PREM onion shell model) [Phys. Earth Planet. Interiors 25 (1981) 297]
- **Δm^2_{41} > 0** favored by $\sum m_\nu$ result from cosmological surveys [A&A 594, A13 (2016)]
- **Profiled likelihood ratio** λ (nuisance parameter profiled out)
- Representation: $U = R_{34}R_{24}\hat{R}_{23}R_{14}\hat{R}_{13}\hat{R}_{12}$

… with ν_τ

[OPERA note 175]

[JHEP 1506 (2015) 069]

$\nu_\mu \rightarrow \nu_\tau$ oscillation probability in presence of a sterile neutrino:

~ standard oscillation

pure exotic oscillation

$$
\begin{aligned}
P(Energy) = {} & C^2 \sin^2 \frac{\Delta_{31}}{2} + \sin^2 2\theta_{\mu\tau} \sin^2 \frac{\Delta_{41}}{2} \\
& + \frac{1}{2} C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin \Delta_{31} \sin \Delta_{41} \\
& - C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin^2 \frac{\Delta_{31}}{2} \sin \Delta_{41} \\
& + 2\, C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin^2 \frac{\Delta_{31}}{2} \sin^2 \frac{\Delta_{41}}{2} \\
& + C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin \Delta_{31} \sin^2 \frac{\Delta_{41}}{2}
\end{aligned}
$$

+ Δm^2_{21} terms …

Effective mixing parameter (leading mixing term at SBL)

interference terms

CP-violating terms

Mass Hierarchy dependence

Effective parameters

$$C = 2|U_{\mu 3}||U_{\tau 3}|$$

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

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

… with ν_τ

PRELIMINARY

- **Counting** analysis

$$L = Pois(n;\mu) \times Gaus(\widehat{\Delta m^2_{23}}; \Delta m^2_{23}, \widehat{\sigma_{\Delta m}})$$

μ: expectation (GLoBES)
n: observation (data)

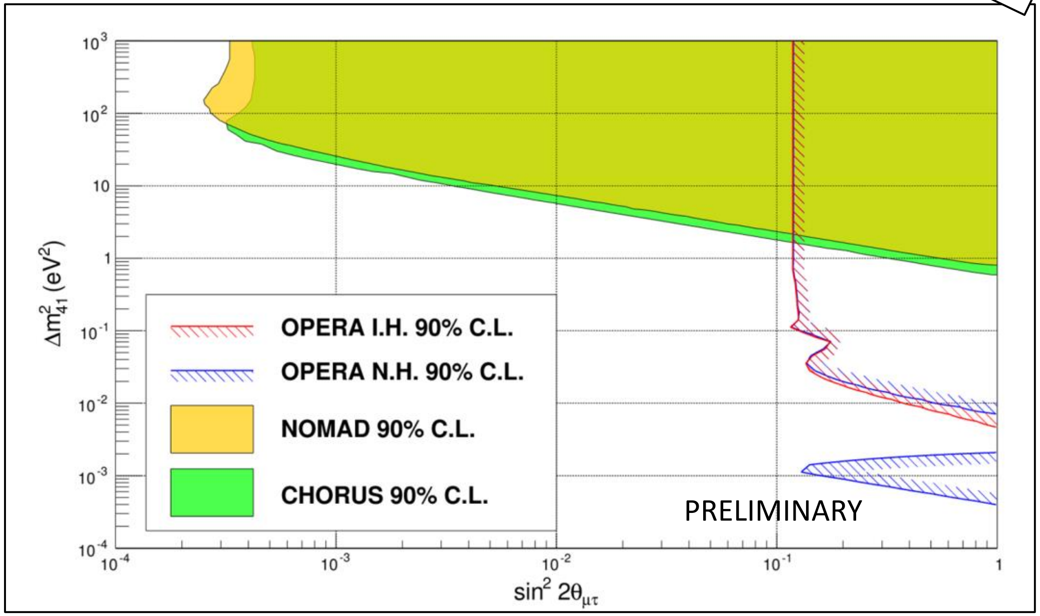
$\widehat{\Delta m^2_{23}}, \widehat{\sigma_{\Delta m}}$ PDG values

- Both **normal** and **inverted** neutrino mass hierarchies considered

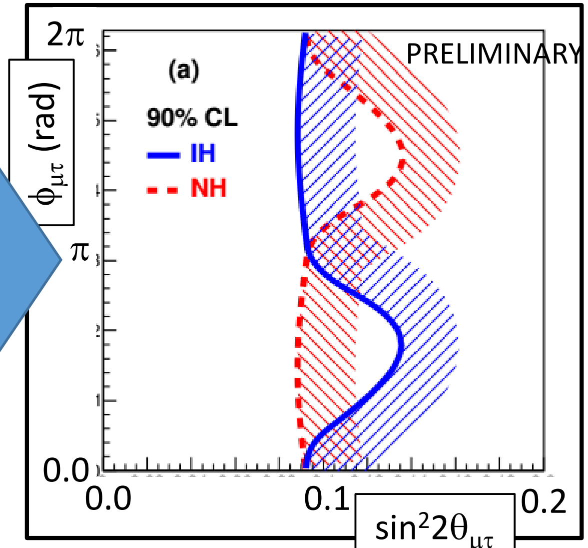
- Exclusion region on **Δm^2_{41} vs $\sin^2 2\theta_{\mu\tau}$** plane

- **Energy selection** (E_ν < 30 GeV) maximizes sensitivity

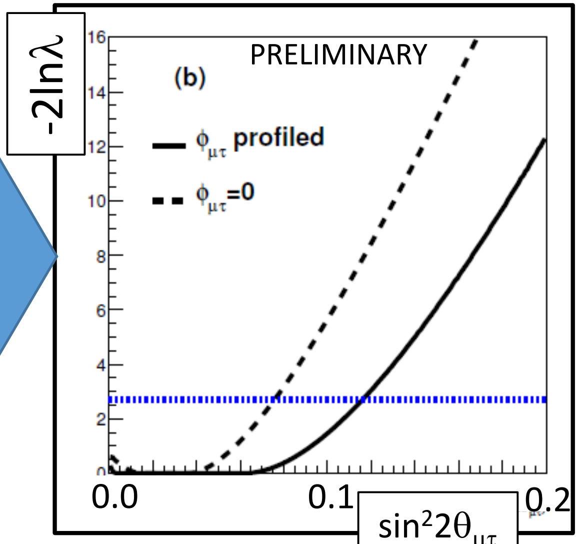
Update of [JHEP 1506 (2015) 069]



At high Δm^2_{41}



Profiling out $\phi_{\mu\tau}$
$\sin^2 2\theta_{\mu\tau}$ < 0.119
90% C.L



… with ν_e

[JHEP 1806 (2018) 151]

- **ν_e energy distribution**
  to evaluate exclusion region on:

Δm^2_{41} vs $\sin^2 2\theta_{\mu e}$

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

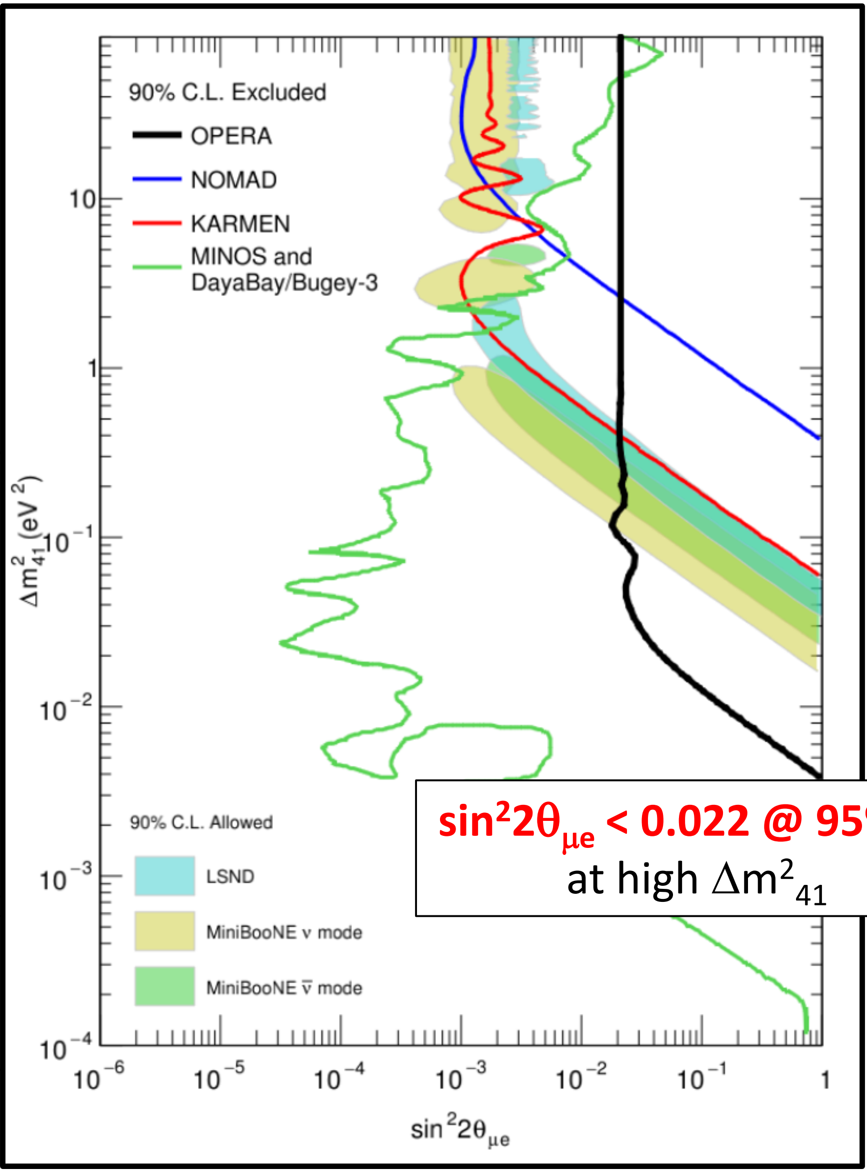
Systematics errors σ_i due to:
- Beam and efficiencies uncertainties
- 20% E_ν < 10 GeV & 10% E_ν > 10 GeV
- Bin-to-bin uncorrelated **(conservative approach)**

Likelihood

$$L = \left(\prod_i Pois(n_i;\mu_i(1+k_i)) \times Gaus(0;k_i,\sigma_i)\right) \times Gaus(\widehat{\Delta m^2_{23}};\Delta m^2_{23},\widehat{\sigma_{\Delta m}})$$

Constraints on Δm^2_{23}

$\widehat{\Delta m^2_{23}}, \widehat{\sigma_{\Delta m}}$ from PDG



$\sin^2 2\theta_{\mu e}$ < 0.022 @ 95%CL
at high Δm^2_{41}

Combining ν_τ and ν_e

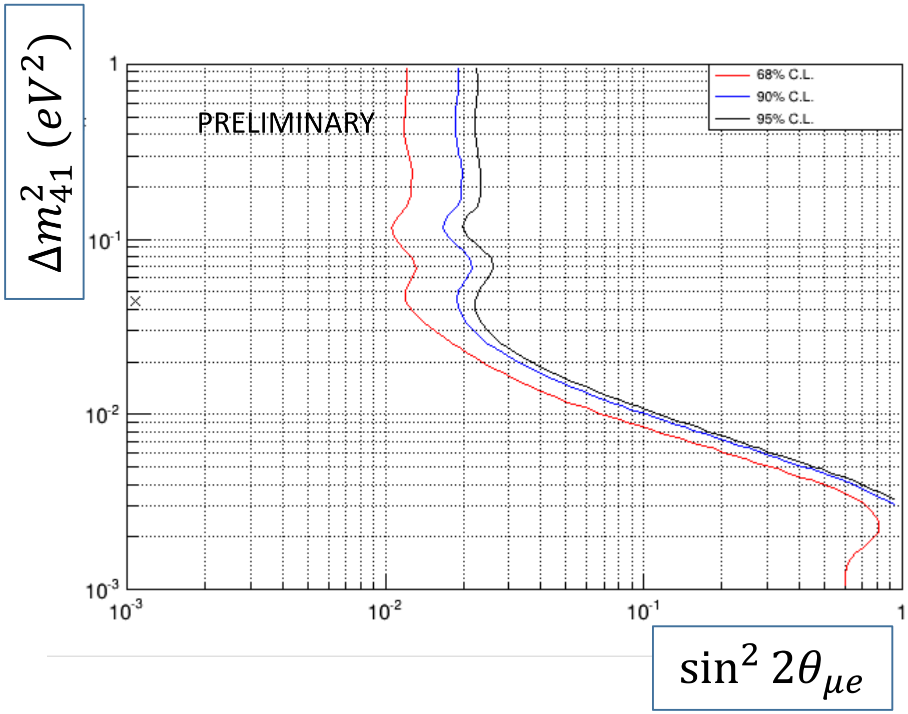
Exploiting **simultaneously** results of

- ν_τ search: 10 candidates
- ν_e search: 35 candidates

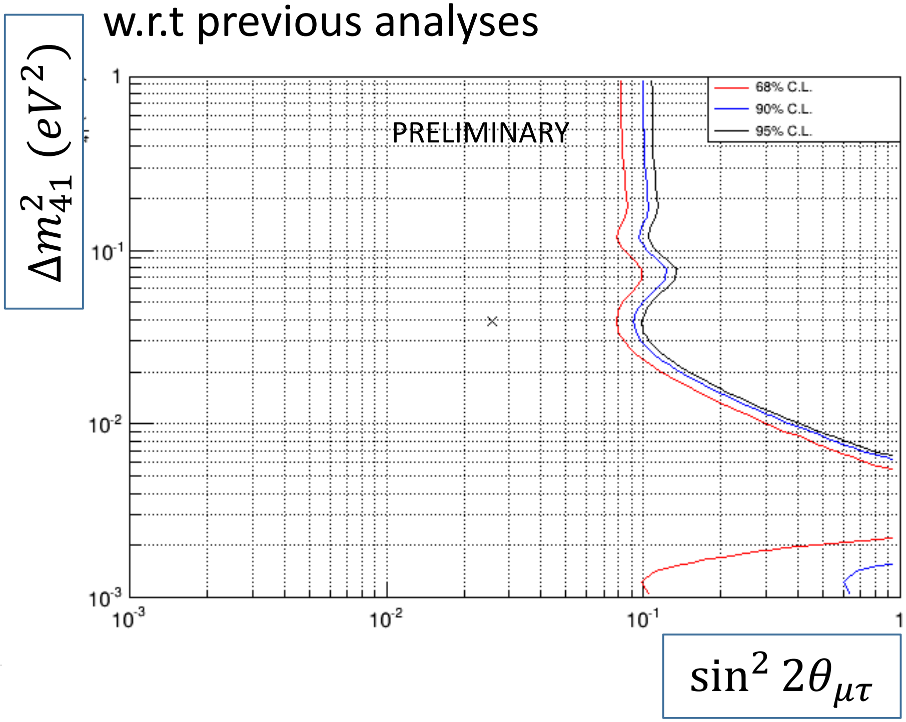
....

... to extract limits on the parameters of the 3 + 1 neutrino model

(Small) **exclusion power enhancement** w.r.t previous analyses



$\sin^2 2\theta_{\mu e} < 0.019$ [90% C.L.] @ $\Delta m^2_{41} \sim 1\ eV^2$



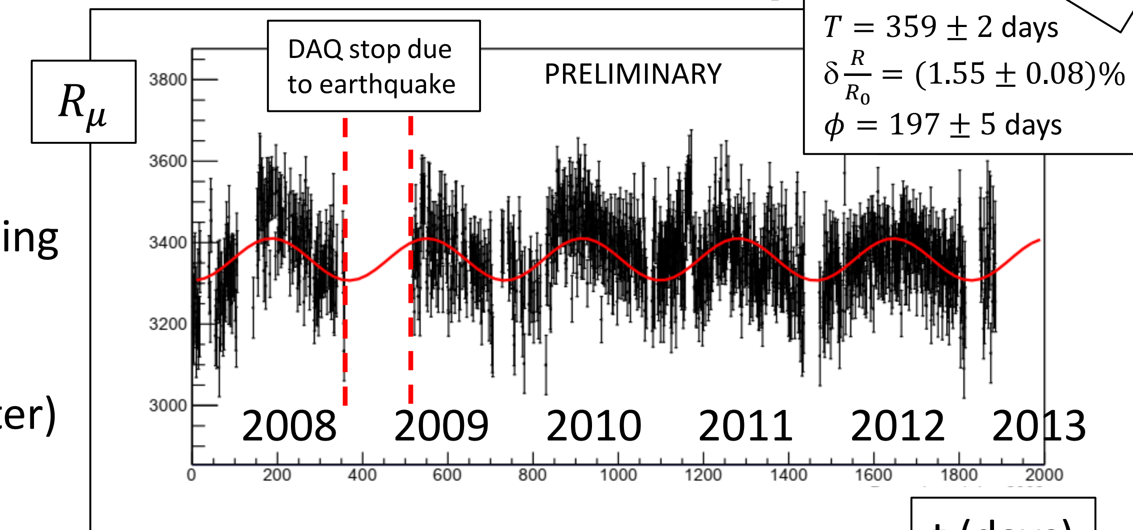
$\sin^2 2\theta_{\mu\tau} < 0.099$ [90% C.L.] @ $\Delta m^2_{41} \sim 1\ eV^2$

Annual μ rate modulation

PRELIMINARY

Fit with: $R_\mu = R_0 + \delta R \cos\frac{2\pi}{T}(t - \phi)$

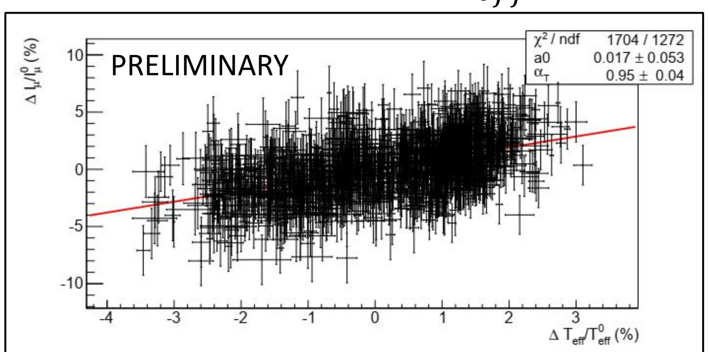
ΔT in the upper atmosphere
- ⇒ variation in atm. density
- ⇒ variation in π interaction length
- ⇒ variation in the fraction of mesons decaying before interacting



Annual modulation of μ rate (R_μ)
(More muons in summer than in winter)

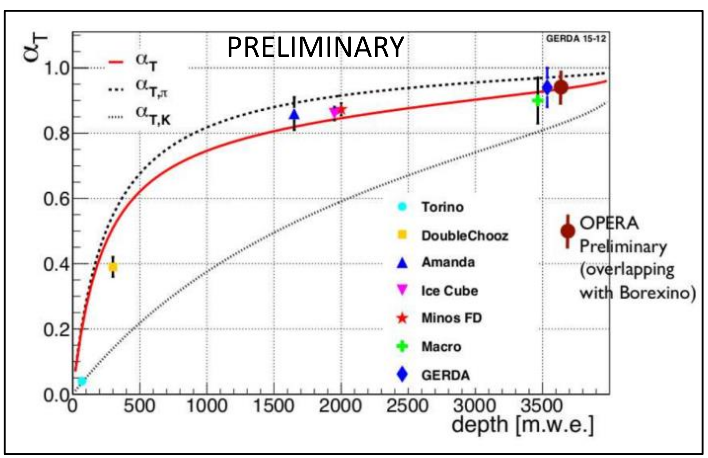
If T is set to 365 days → ϕ = 5th July

Correlation of R_μ and the effective temperature (T_{eff})



$$\alpha_T = \frac{\Delta R_\mu}{\Delta T_{eff}} = 0.95 \pm 0.04$$

α_T VS depth



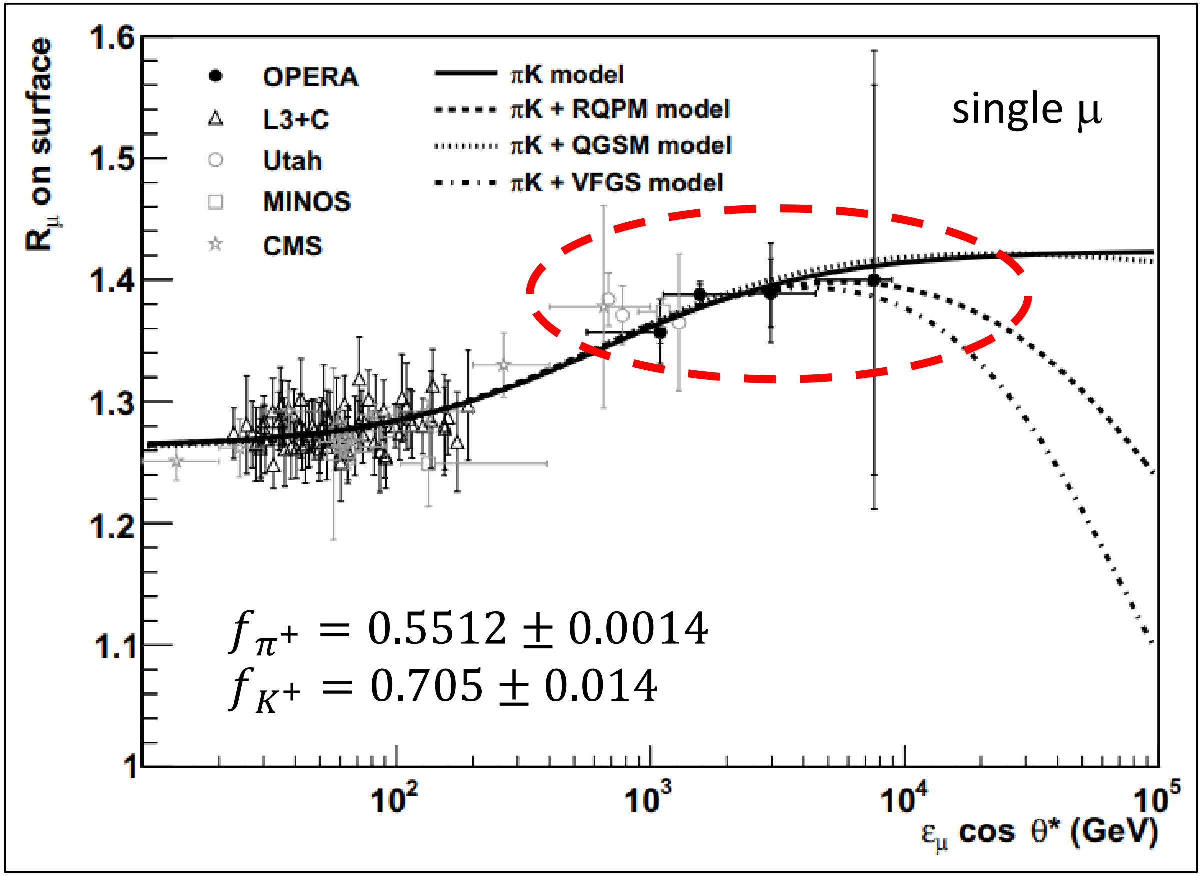
Atmospheric muon charge ratio

[Eur. Phys. J. C (2014) 74]

- **Highest-E region** reached
- **Opposite magnet polarities** runs $\rightarrow$ lower **systematics**

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

- Strong reduction of the charge ratio for multiple muon events
  - single-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)

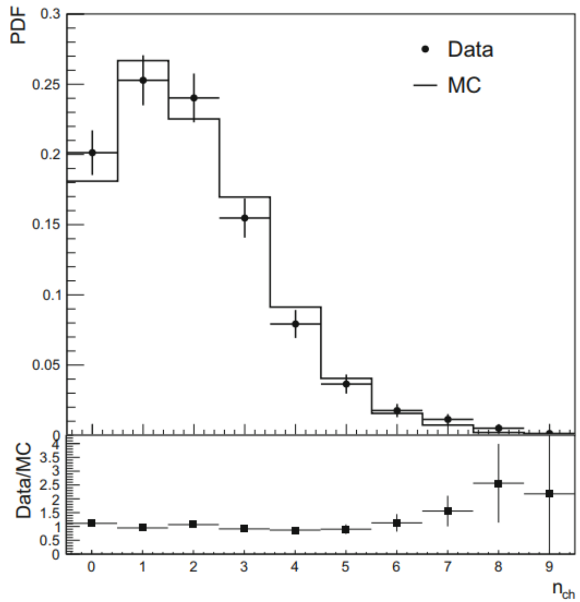


Neutrino interactions multiplicity

unbiased sample of $\nu_\mu CC$ interactions

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

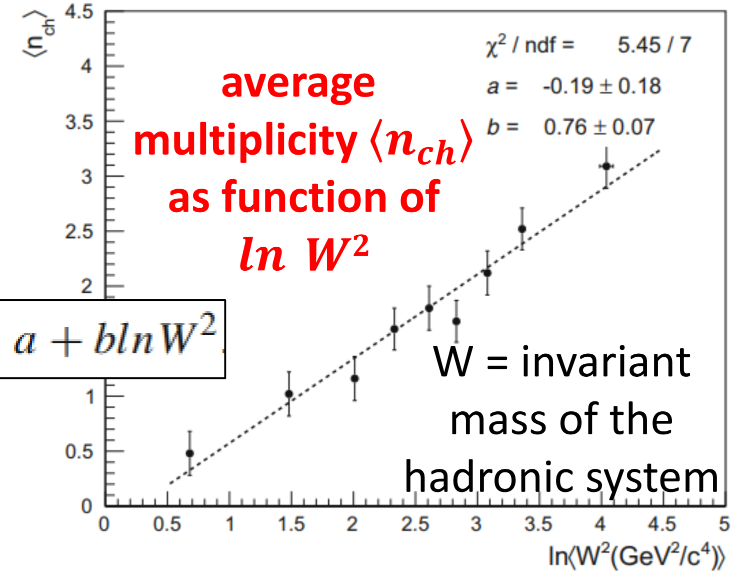
charged hadron multiplicity distribution



average multiplicity $\langle n_{ch}\rangle$ as function of $ln\ W^2$

$$\langle n_{ch}\rangle = a + b\ln W^2$$

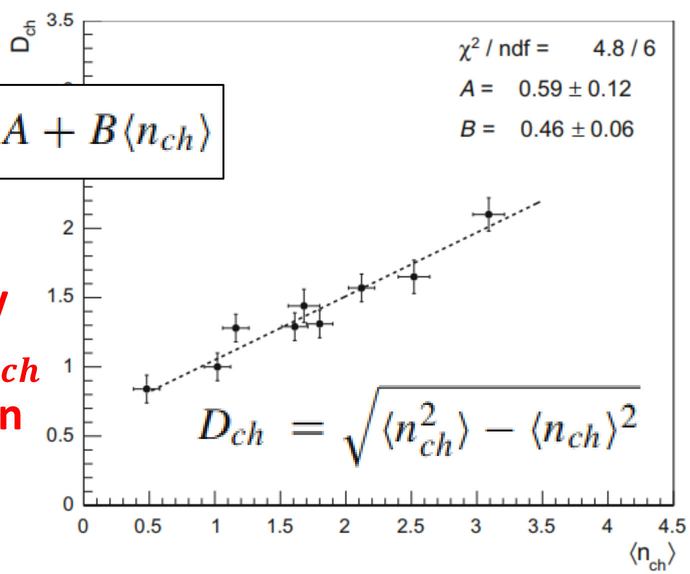
W = invariant mass of the hadronic system



average multiplicity dispersion D_{ch} as a function of $\langle n_{ch}\rangle$

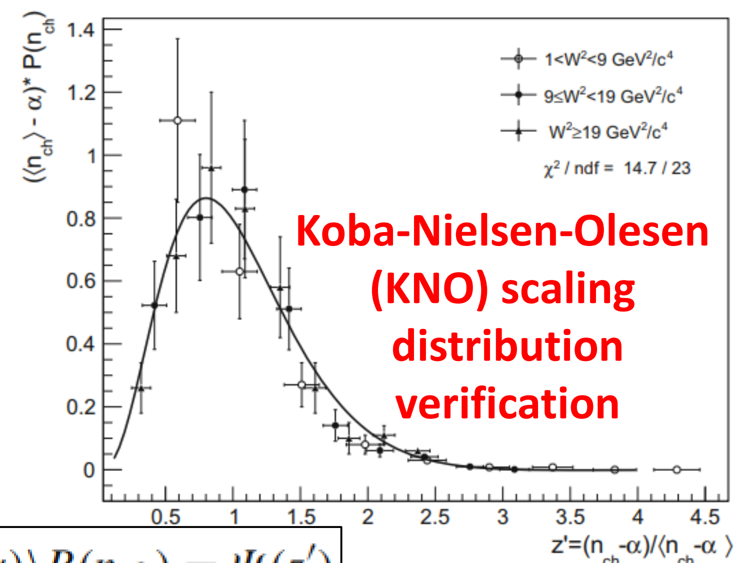
$$D_{ch} = A + B\langle n_{ch}\rangle$$

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



Koba-Nielsen-Olesen (KNO) scaling distribution verification

$$\langle(n_{ch} - \alpha)\rangle P(n_{ch}) = \Psi(z')$$



Summary

- **Discovery of $\nu_\mu \rightarrow \nu_\tau$ appearance** in the CNGS neutrino beam: 5.1σ

- Loose selection analysis **increase discovery significance** 6.1σ
  - Measurement of Δm^2_{23} (first measurement in appearance mode)
  - Measurement of effective ν_τ cross-section

- Muon-less **double decay event** has been reported.
  Favored interpretation ν_τ CC interaction with charm production

- **Final results from $\nu_\mu \rightarrow \nu_e$ oscillation search**

- Search for **ν_μ disappearance**
  - Upper limit on Δm^2_{23}

- Constraints on **sterile neutrinos**
  from $\nu_\mu \rightarrow \nu_e$, $\nu_\mu \rightarrow \nu_\tau$ and their combination
  in the 3+1 flavor model

- **Non-oscillation Physics:**
  - atmospheric muons charge ratio
  - annual modulation of atmospheric muons rate
  - Neutrino interactions charged multiplicity study

OPERA taking a "selfie"... Thank you!

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