XVII International Workshop on Neutrino Telescopes, 13 - 17 March 2017, Venice, Italy

More Results From The Experiment

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on behalf of the
OPERA Collaboration

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Belgium
ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

Korea
Jinju

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

Switzerland
Bern

Turkey
METU Ankara

Italy
Bari
Bologna
LNF
LNGS
Naples
Padova
Rome
Salerno

Japan
Aichi
Kobe
Nagoya
Toho
Nihon

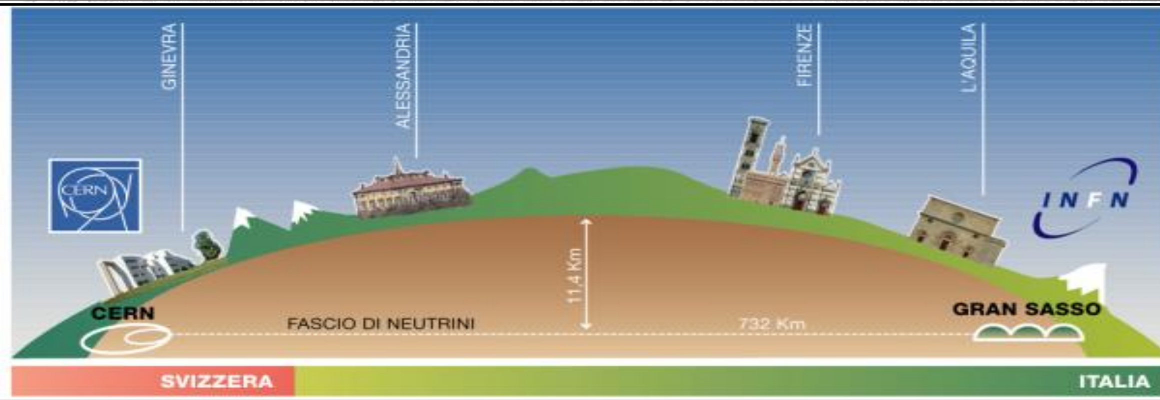
140 physicists, 11 countries, 28 institutions

- ✓ **Looser selection analysis**
- ✓ **Δm^2_{32} measurement update**
- ✓ **ν_e search update**
- ✓ **sterile neutrinos**
- ✓ **μ annual modulation**

[CERN-SPSC-2000-028, 2000]

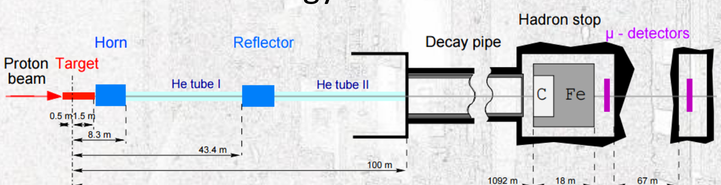
The Oscillations Project with Emulsion TRacking Apparatus

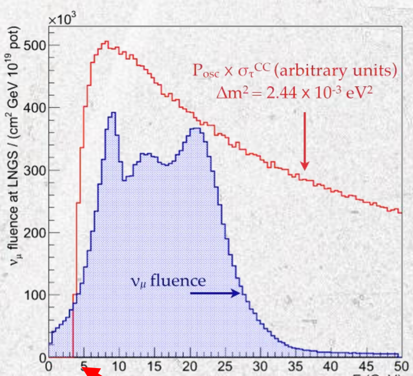
- **Long baseline** experiment: 735 km
- Aim: **verify the $\nu_\mu \rightarrow \nu_\tau$** oscillations at atmospheric Δm^2 scale
- How: observe ν_τ appearance on **event-by-event** basis in a conventional ν_μ beam



Conventional muon neutrino beam

neutrino mean energy: **17 GeV**

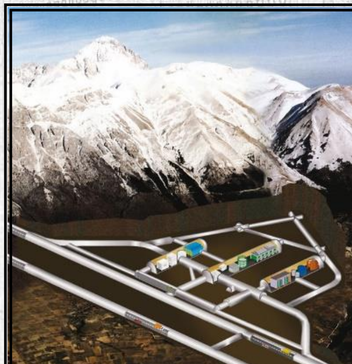




threshold: 3.5 GeV [m_τ = 1.7 GeV]

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

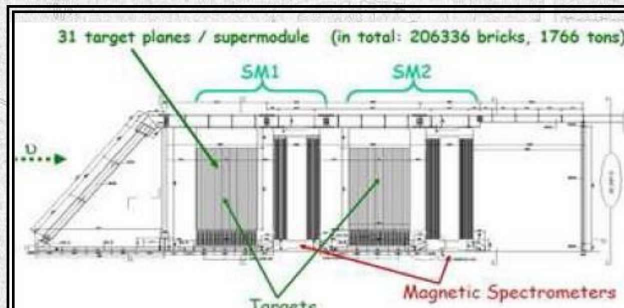
$(\nu_e + \bar{\nu}_e)/\nu_\mu$	0.9 %
$\bar{\nu}_\mu/\nu_\mu$	2.1%
ν_τ prompt	negligible



Low background environment

Laboratori Nazionali del Gran Sasso (Italy)

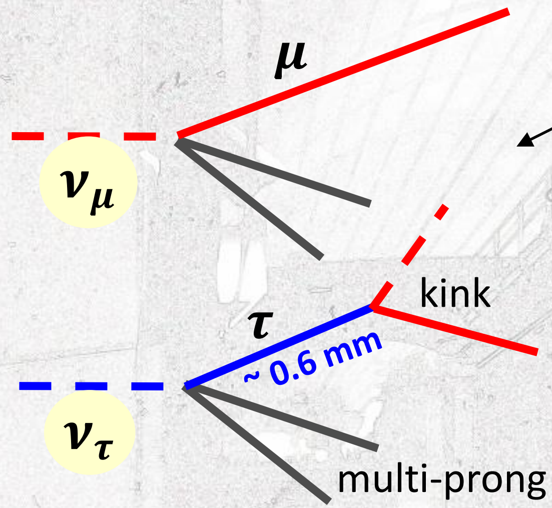
- 1400 m rock overburden
- atm. μ reduction ~ 10^6 [1μ/(m²·h)]
- low radioactivity rock



Detector:

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

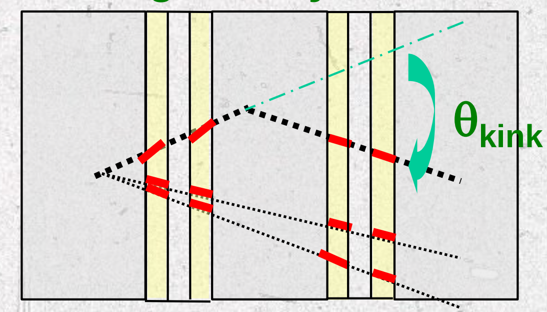
The ν_τ detection technique



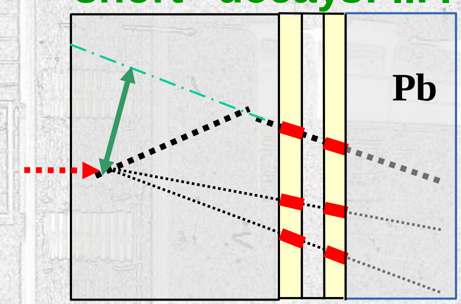
Detect a few ν_τ^{CC} amid the bulk of ν_μ^{CC}

$\tau^- \to \mu^- \nu_\tau \nu_\mu$	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.



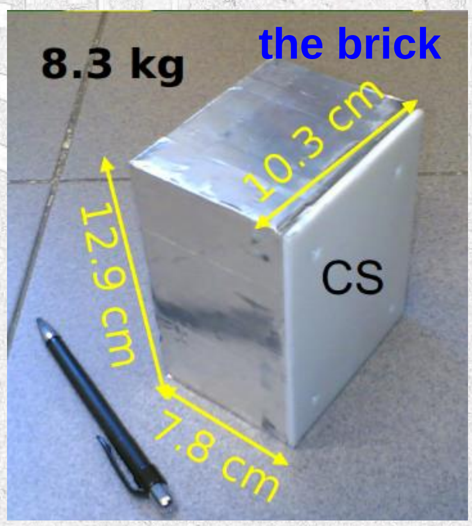
Modular detector of bricks
[56 Lead-Emulsion Cloud Chambers (ECC) sandwiched]

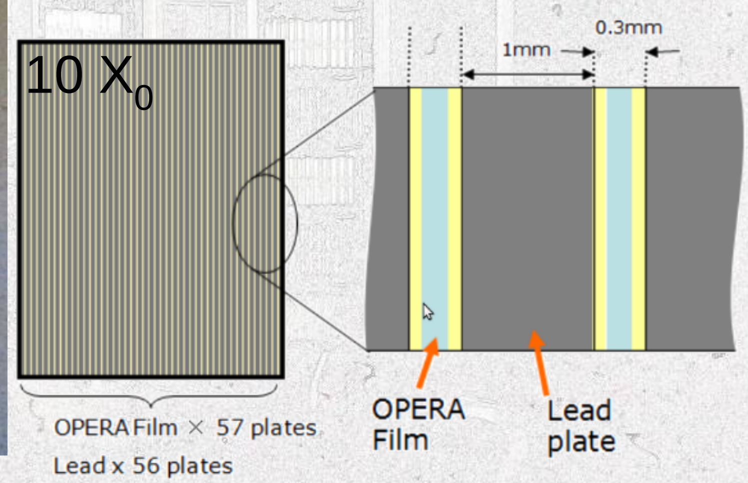
Large mass

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

Extreme granularity

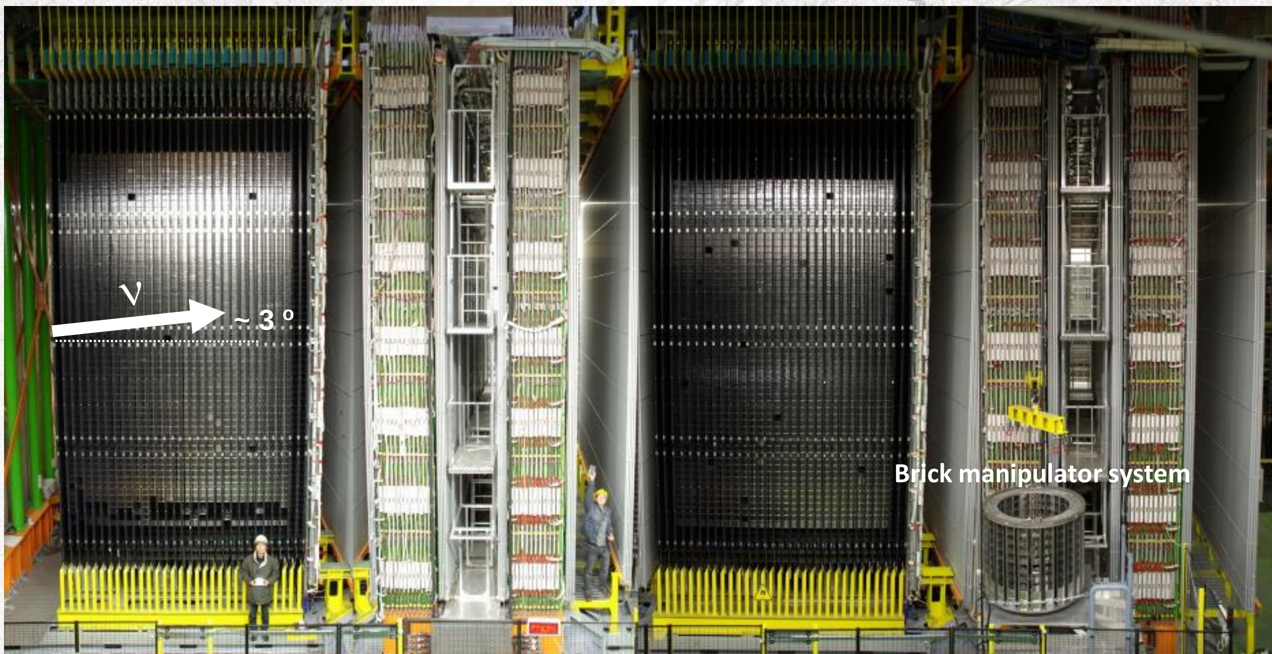
$\sim\mu$m space resolution





The OPERA detector

Super Module 1 Super Module 2



Target section (6.7 x 6.7 m^2):

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

Tracking of the target region
Brick selection
Calorimetry

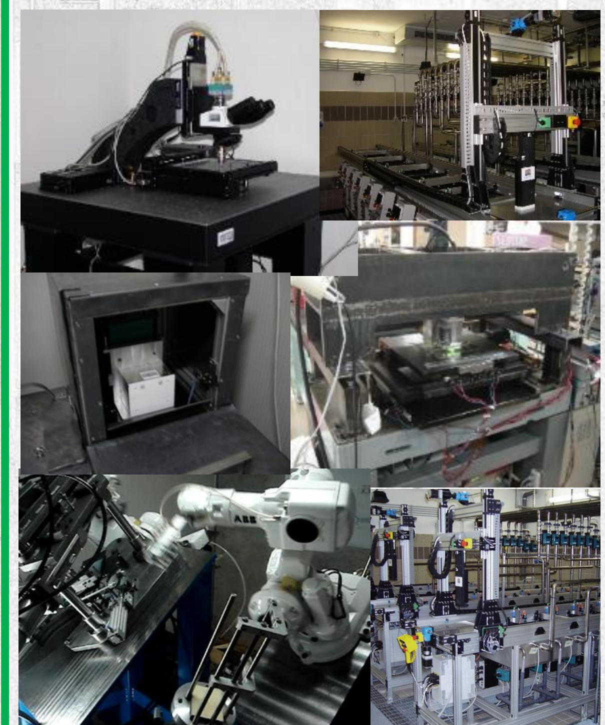
Muon spectrometer (8 x 10 m^2)

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

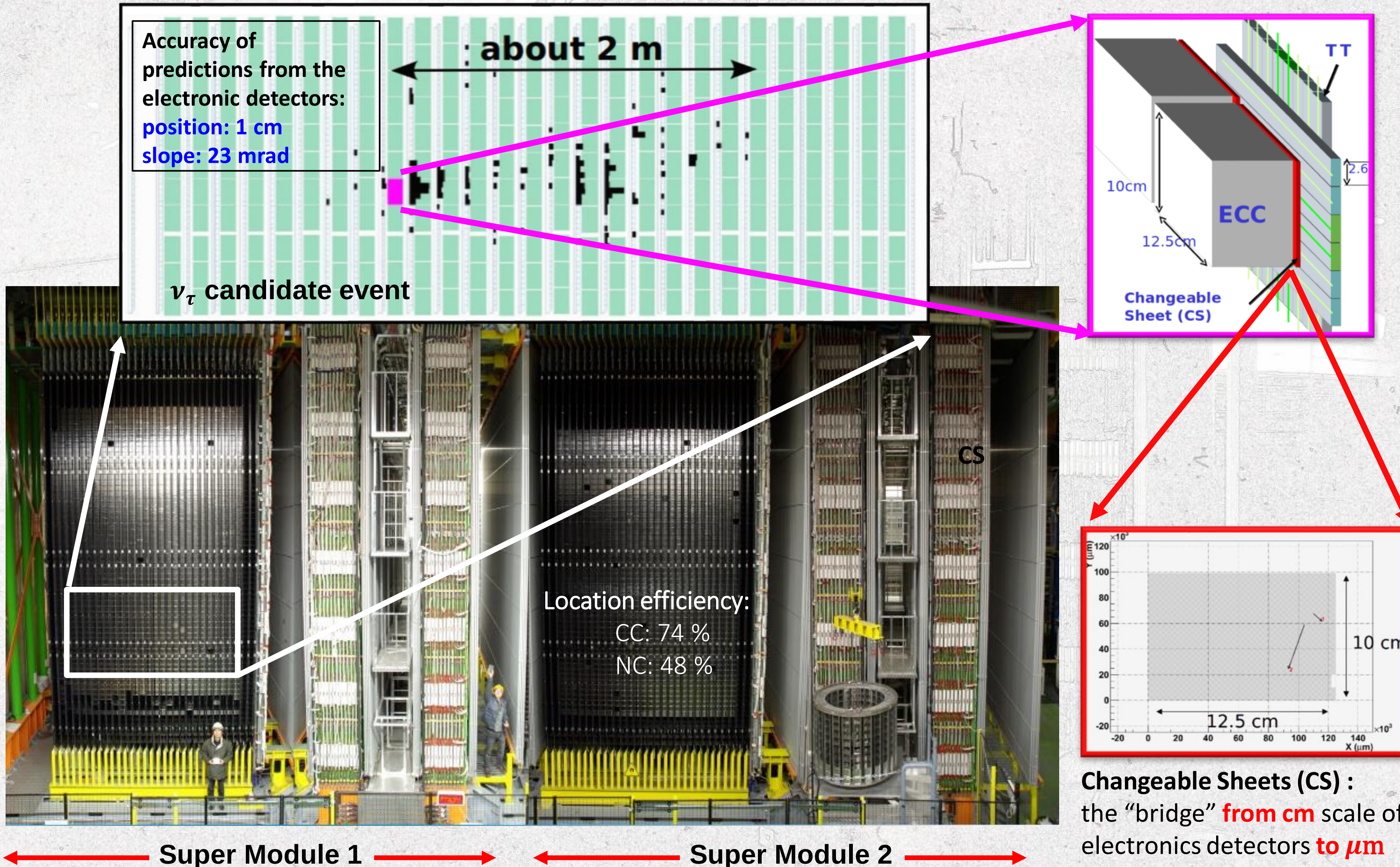
μ Identification +
charge and momentum measurements

+ 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)**



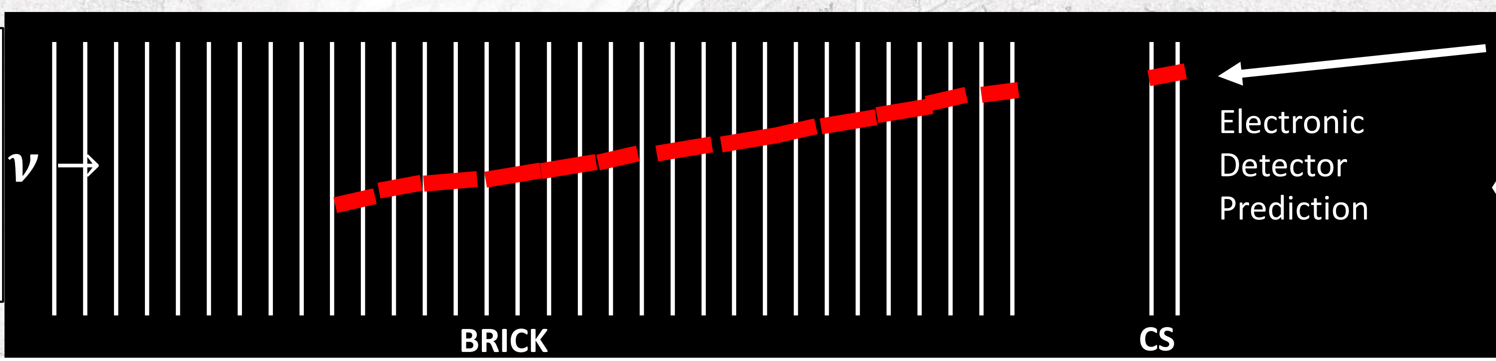
Event reconstruction



Changeable Sheets (CS) : the "bridge" **from cm** scale of electronics detectors **to μm** scale of emulsions.

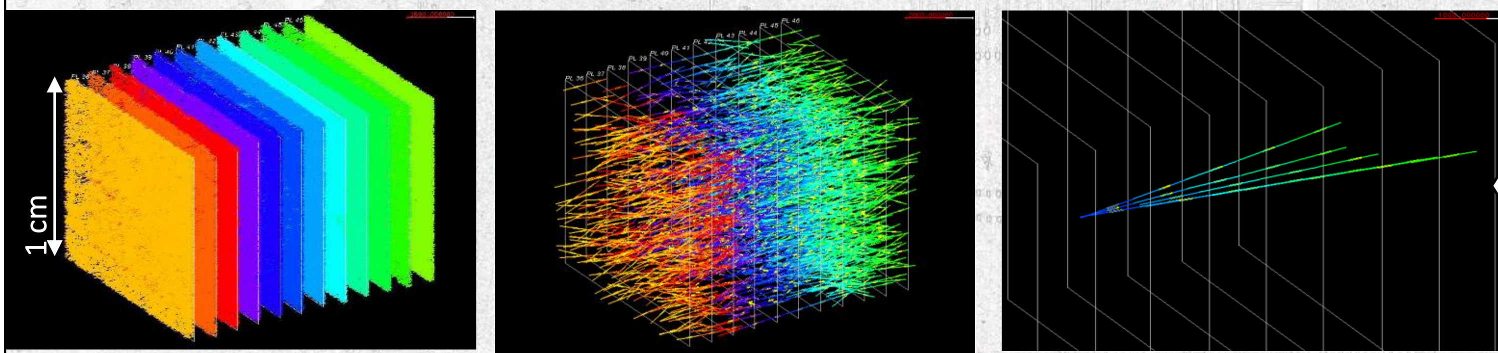
Vertex hunting in the brick

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

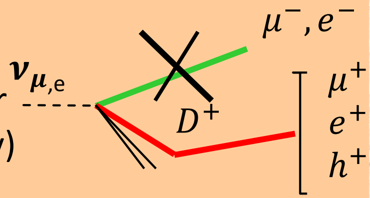
[JHEP 1311 (2013) 036]

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



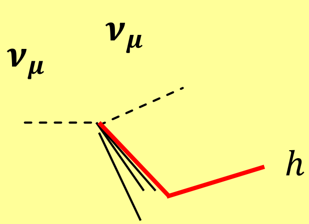
MC tuned on CHORUS data (cross section and fragmentation functions), validated with measured OPERA charm events.

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

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

Hadronic interactions

Background for $\tau \rightarrow h$



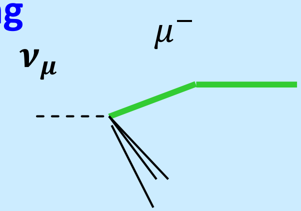
FLUKA + pion test beam data

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), simulations

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

ν_τ appearance discovered

[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 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*

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

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 ($\mu = 0$) .

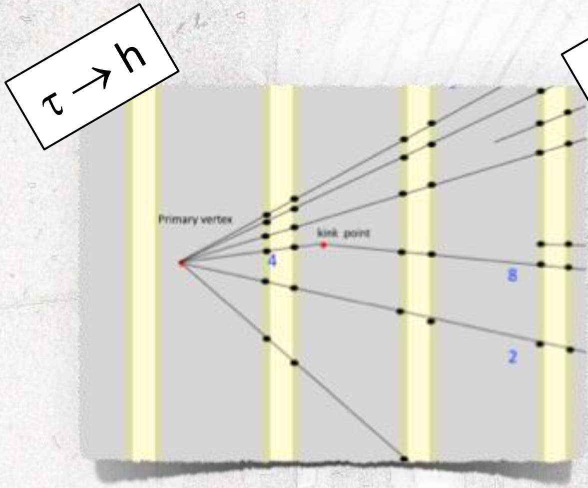
Background-only hypothesis:

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

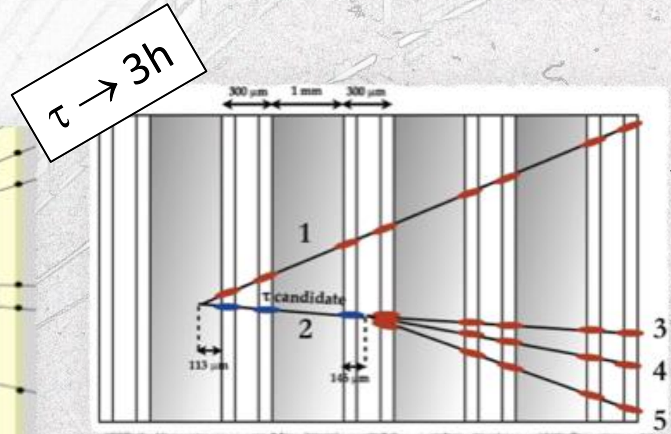
Compatibility with 3ν oscillation:
$\hat{\mu} = 1.8^{+1.8}_{-1.1}$ at 90% C.L

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

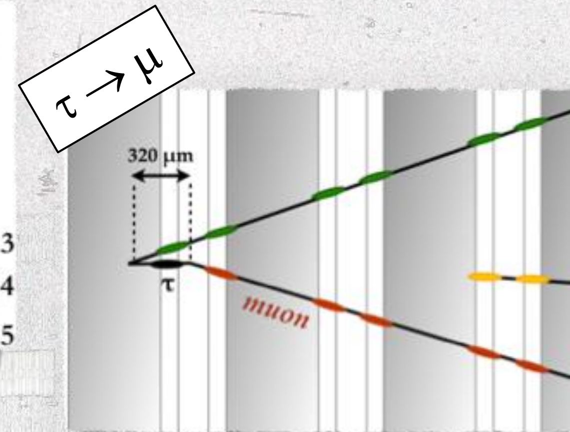
The five ν_τ candidates observed



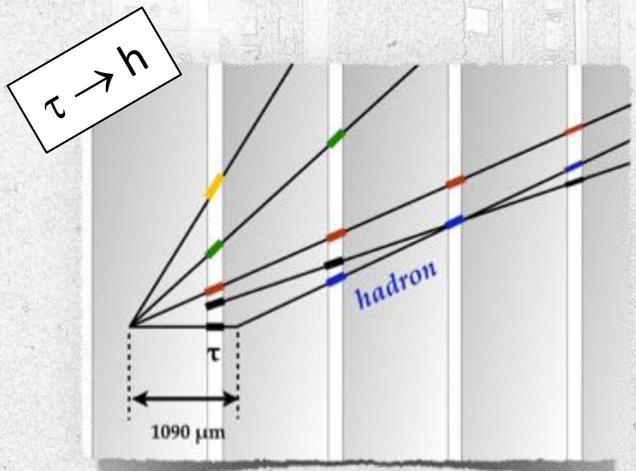
Phys. Lett. B 691 (2010) 138



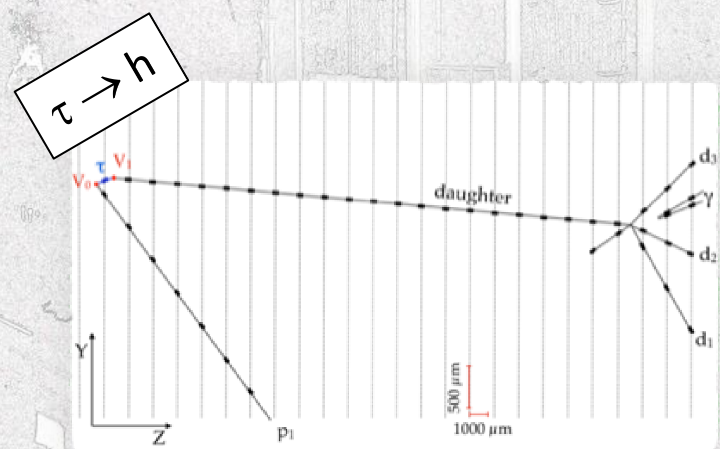
JHEP 11 (2013) 036



Phys. Rev. D 89 (2014) 051102



PTEP 2014 (2014) 10, 101C01



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

Loosing ν_τ event selection

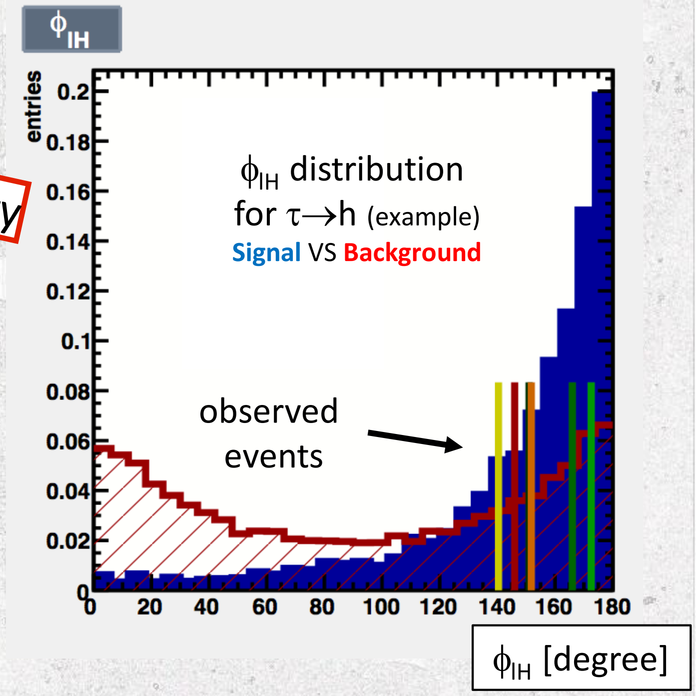
- Loose kinematical cuts:
  - **Minimum selection** to limit contribution from had. int. and large angle scattering bkg
  - **Negligible additional background** from K/π decays

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

- Boost Decision Tree
  - Use kinematical, topological variables and their **correlations**
  - Selection optimized, FOM: **efficiency x purity**

Preliminary

Expected Background	Expected Signal	Observed
1.86 ± 0.5	5.88 ± 1.18	10



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

⇒ Improvement in Δm^2_{23} measurement
(first measurement in appearance mode)

Measurement of Δm^2_{23}

$$N_{\nu_\tau} \propto \int \phi(E) \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) \epsilon(E)\sigma(E) dE$$
$$\propto (\Delta m^2_{32})^2 L^2 \int \phi(E)\epsilon(E)\frac{\sigma(E)}{E^2} dE$$

$\left({}^{L}/_{\langle E\rangle}\right)_{opera} \sim 43$ km/GeV

$\left({}^{L}/_{\langle E\rangle}\right)_{PEAK} \sim 500$ km/GeV

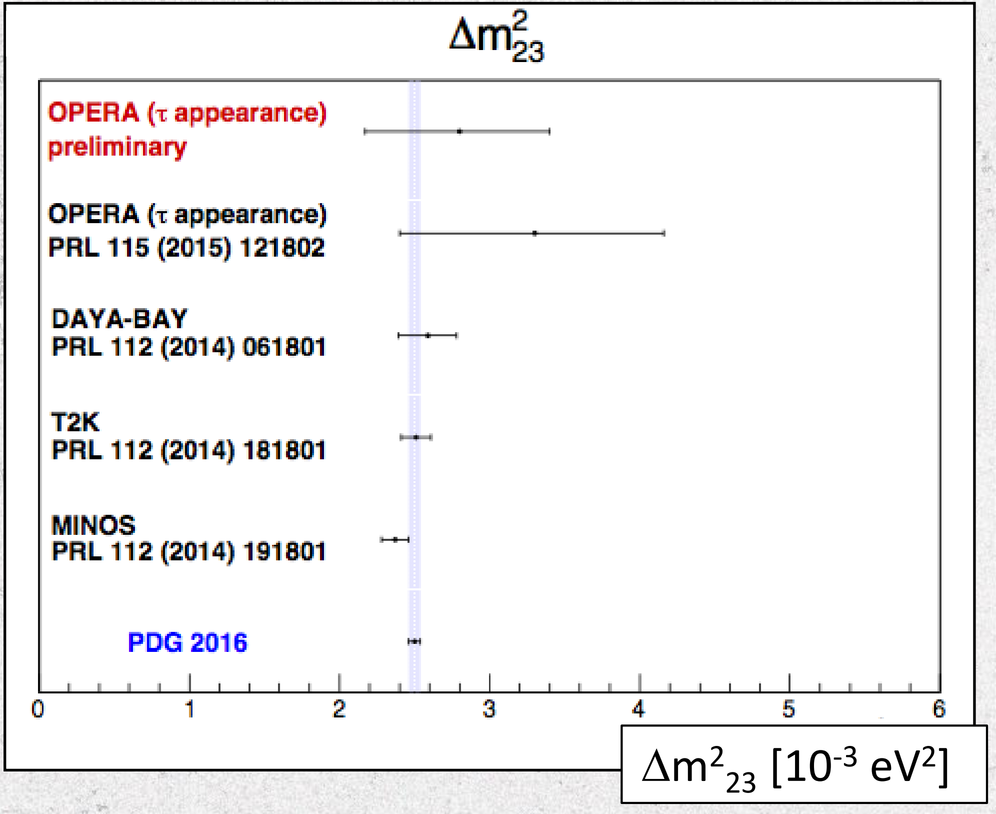
"Steep" $\mathbf{\Delta m^2_{23}}$ dependence

→ counting based measurement

90% C.L. interval
by Feldman & Cousins method

$$\mathbf{\Delta m^2_{23} = [1.98 - 3.95]\ 10^{-3}\ \ eV^2}$$

(assuming full mixing)



Peculiar event

- Muon-less neutrino event

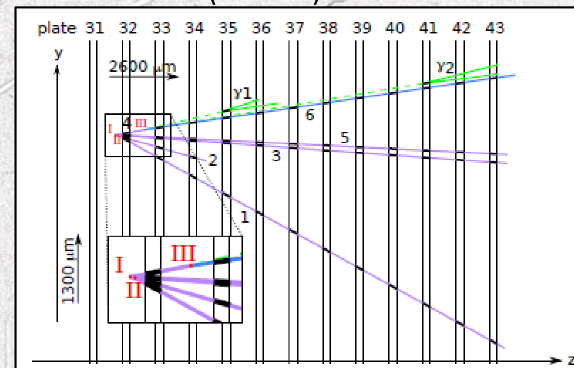
- Most probable topology:
  ν interaction vertex + 2 decay vertices

- **Rare topology** not considered in the experiment proposal
  (0.1 events expected in full data sample)

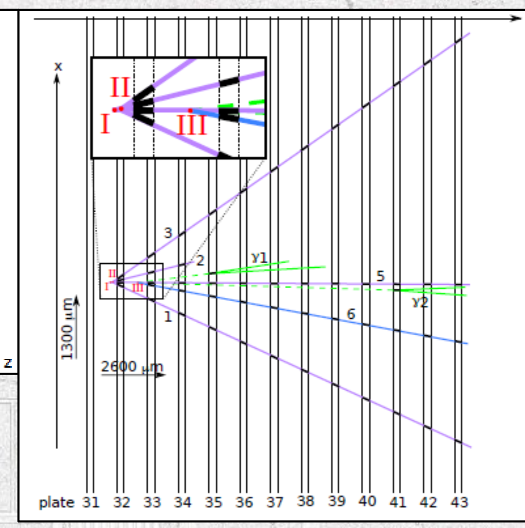
- Ad **hoc simulations + ANN** (2 Layers MLP) to distinguish between possible interpretations:

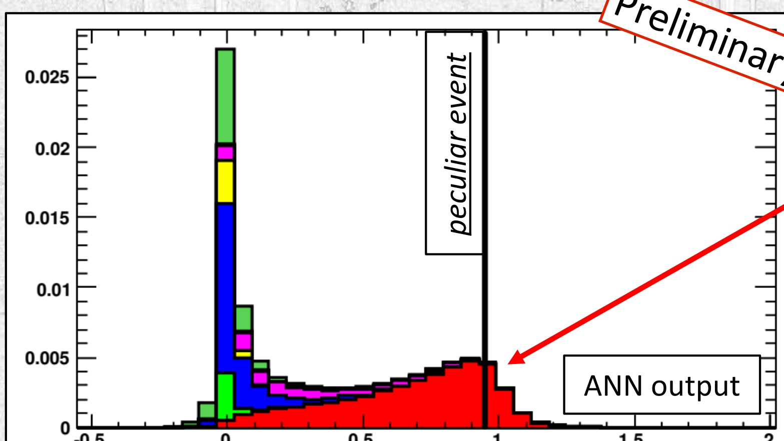
  - $\nu_\tau CC + c$
  - $\nu_\mu CC + c + had.\ int.$
  - $\nu_\mu NC + c\bar{c}$
  - $\nu_\tau CC + had.\ int.$
  - $\nu_\mu CC + 2\ had.\ int.$
  - $\nu_\mu NC + 2\ had.\ int.$

yz view
(vertical)

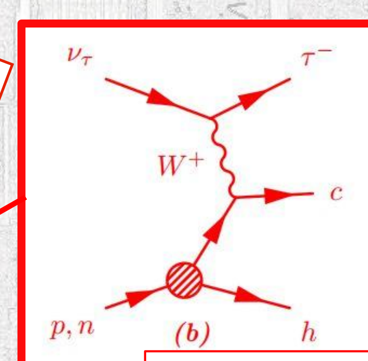


yz view
(horizontal)





Preliminary



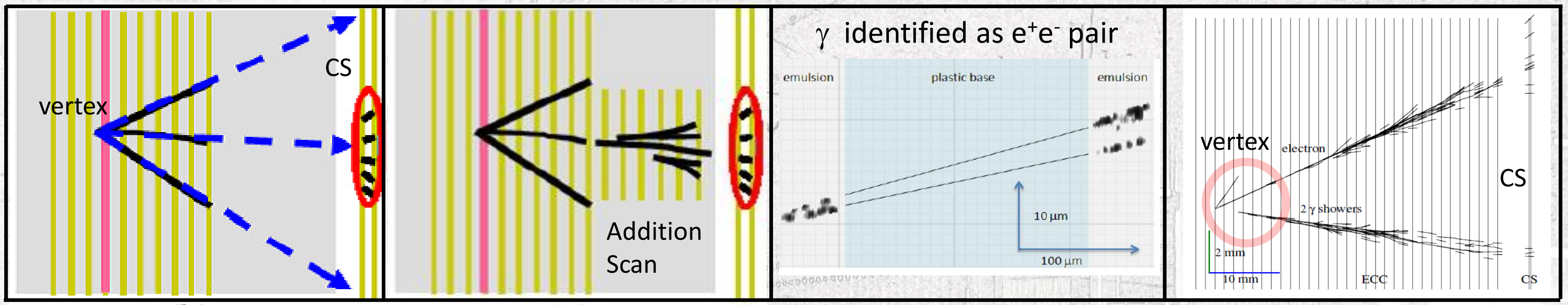
$\nu_\tau CC + charm$

Preliminary

Assuming the event not being ν_τ CC + charm: p-value ~ 10^{-4} → Significance = 3.5 σ

ν_e analysis

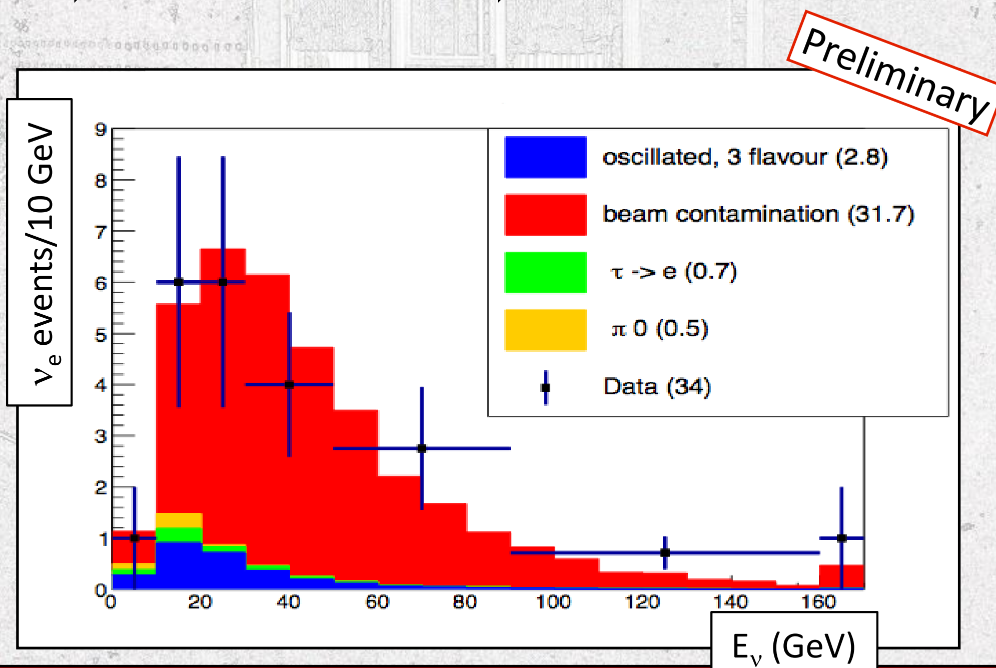
- OPERA detector granularity allows e.m. shower id $\rightarrow$ **ν_e search**.
- A **dedicated procedure**, balancing time need vs efficiency.



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

$\Rightarrow$ Reconstruct e.m. shower $\Rightarrow$ Exclude γ $\Rightarrow$ Identify ν_e event

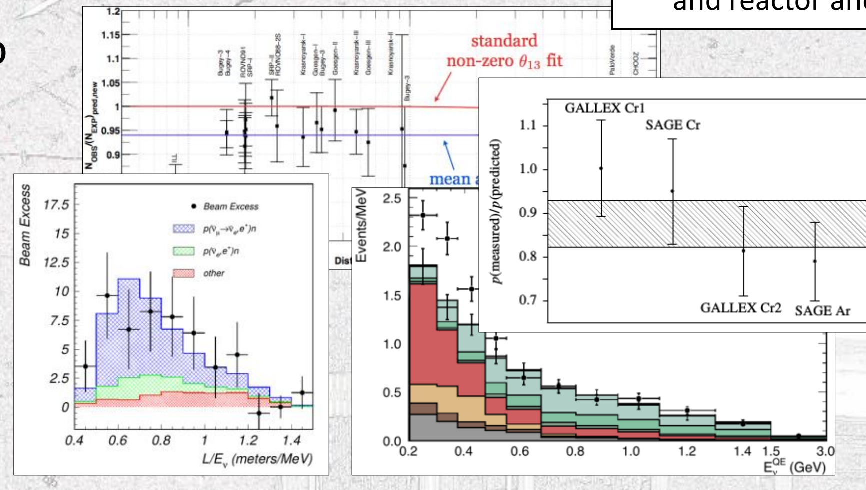
Contribution	# events for 19.97 x 10^{19} pot
ν_e beam	*31.7*
τ (unidentified) $\rightarrow$ e	0.7
$\pi^0 \rightarrow \gamma$ (misidentified)	0.5
$\nu_\mu \rightarrow \nu_e$ oscillations	*2.8*
Total	*35.7 (32.9 w/o osc.)*
observed	*34*



Sterile neutrino search

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

LSND, MiniBooNE, Gallium and reactor anomaly



Mixing described by 4 x 4 matrix

$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$

ν_e appearance
ν_μ disappearance
ν_τ appearance
NC disappearance

OPERA can test the sterile neutrino hypothesis looking for deviations from predictions of the standard flavors oscillations probability.

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

- **Δm^2_{21}** fixed to *PDG* value
- Gaussian prior 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 neglecting Δm^2_{21}:

~ standard oscillation

pure exotic oscillation

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

Effective mixing parameter (leading mixing term at SBL)

interference terms

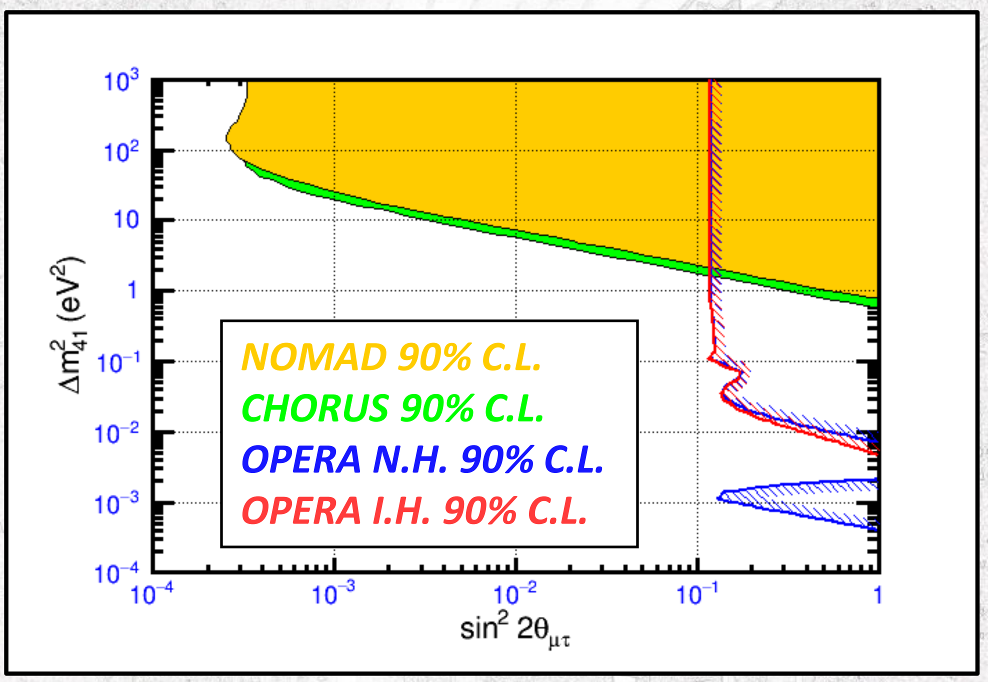
CP-violating terms

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



- **Counting** analysis

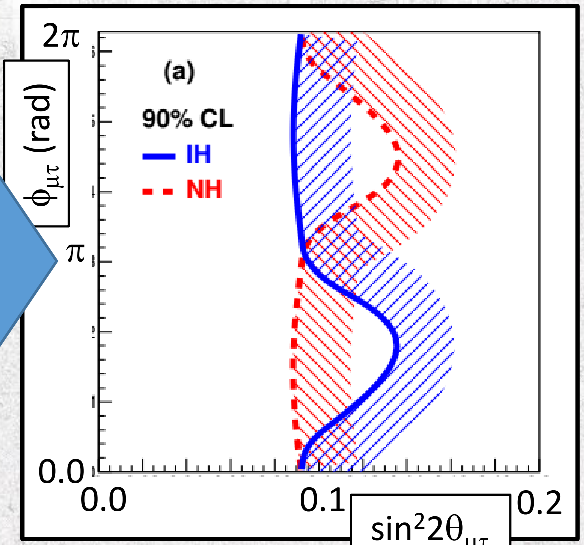
$$L = \boldsymbol{Pois(n;\mu)} \times \boldsymbol{Gaus(\Delta m^2_{23}; \widehat{\Delta m^2_{23}}, \widehat{\sigma_{\Delta m}})}$$

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

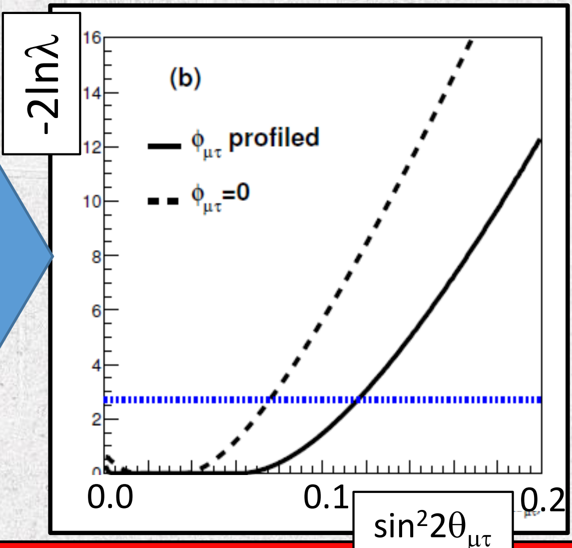
$\widehat{\Delta m^2_{23}}, \widehat{\sigma_{\Delta m}}$ PDG values

- 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

At high Δm^2_{41}



Profiling out $\phi_{\mu\tau}$
$\sin^2 2\theta_{\mu\tau} < 0.116$
90% C.L



… with ν_e

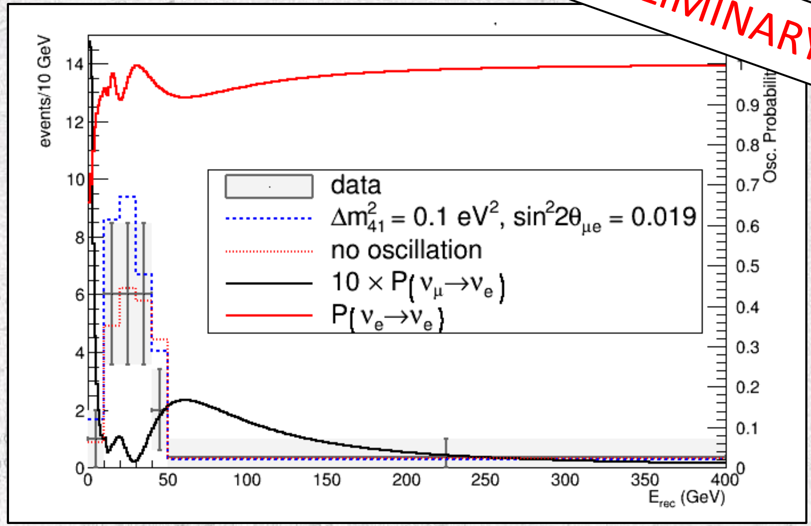
PRELIMINARY

- **ν_e energy distribution** used to obtain exclusion region on:

  Δm^2_{41} vs $\sin^2 2\theta_{\mu e}$

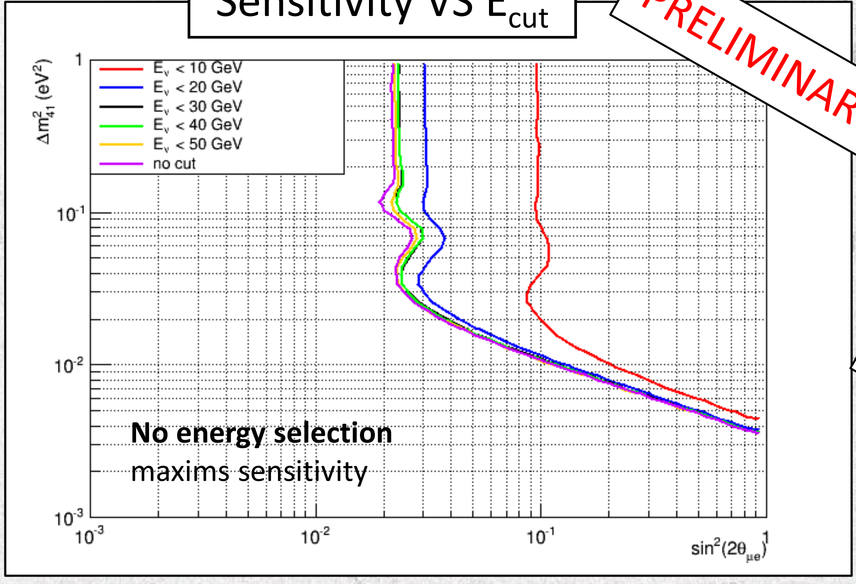
  with $\sin^2 2\theta_{\mu e} = 4|U_{\mu 4}|^2|U_{e4}|^2$

- **ν_e beam dependence on oscillation parameters** (no constant background)



Sensitivity VS E_{cut}

PRELIMINARY



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)**

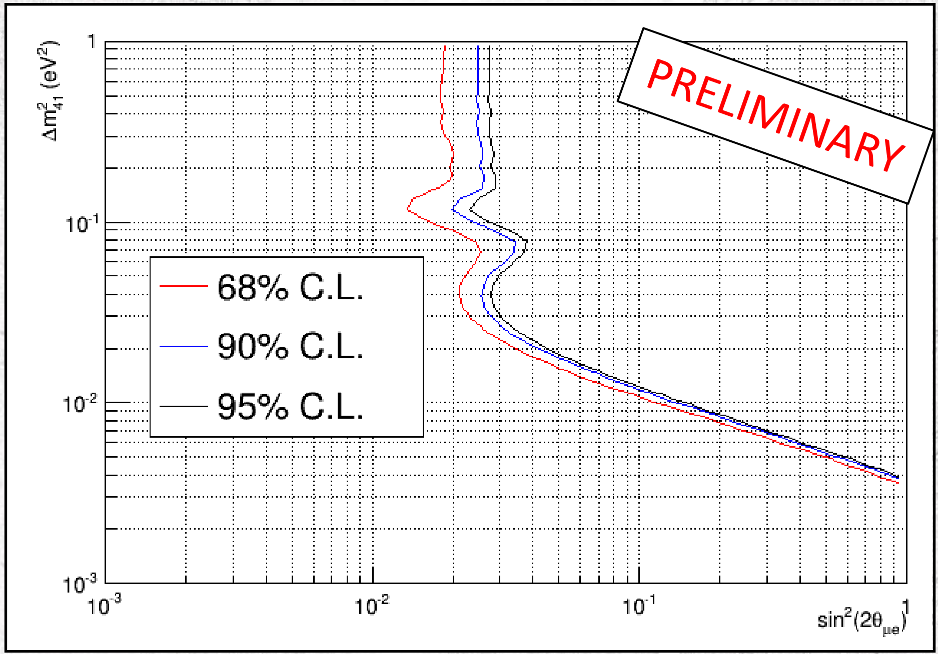
Likelihood

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

Prior on Δm^2_{23}

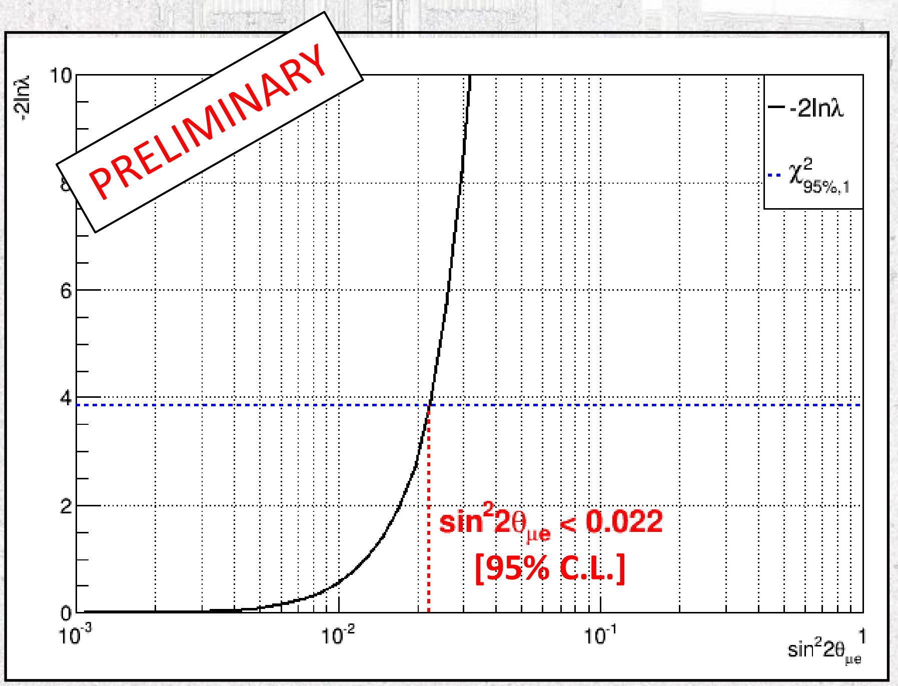
$\widehat{\Delta m^2_{23}}, \widehat{\sigma_{\Delta m}}$ from PDG

... with ν_e



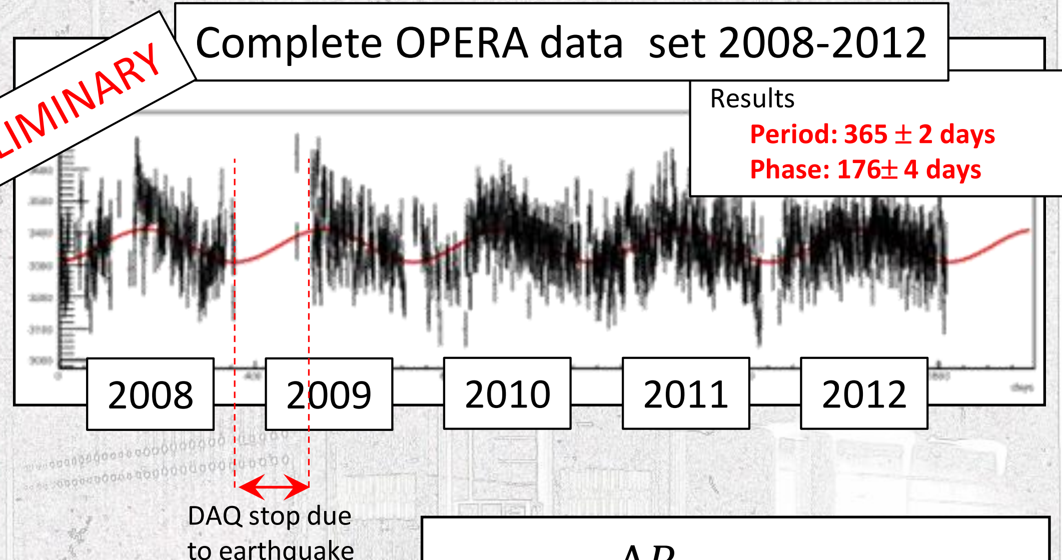
Exclusion plot on
Δm^2_{41} vs $\sin^2 2\theta_{\mu e}$

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



Annual μ rate modulation

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



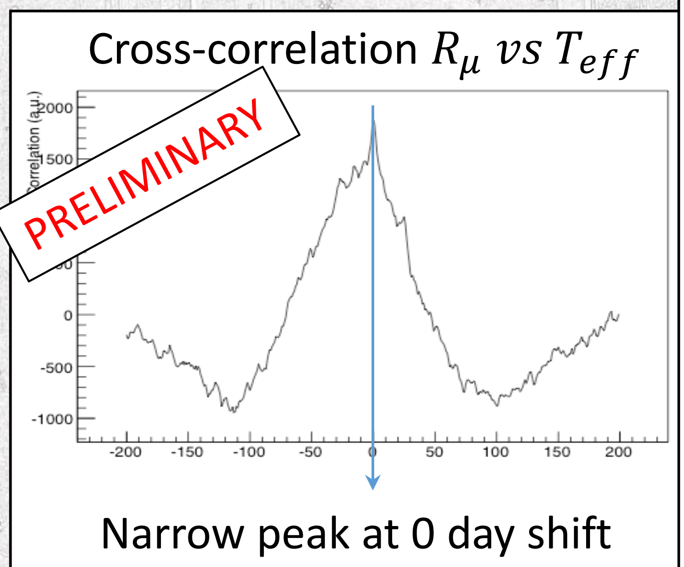
Annual modulation of μ rate (R_μ)
(More muons in summer than in winter)

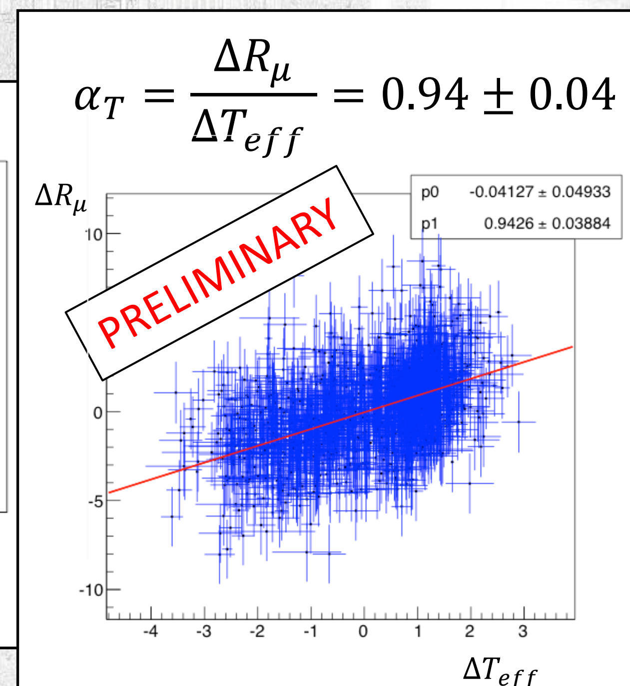
Comparison with DAMA
and other experiments

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

Measurement of

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





Conclusions

- **Discovery of $\nu_\mu \rightarrow \nu_\tau$ appearance** in the CNGS neutrino beam: 5.1σ
- Loose selection analysis to increase the number of ν_τ candidates ⇒ improve OPERA **measurement of Δm^2_{23} (first measurement in appearance mode)**
- Muon-less **double decay event** has been reported.
  Favored interpretation ν_τ CC interaction with charm production
- **$\nu_\mu \rightarrow \nu_e$ oscillation search**
- Constraints on **sterile neutrinos**
  from $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ with the 3+1 flavor model
- Non-oscillation Physics: **annual modulation of atmospheric muons**
- ***PERSPECTIVES***: Exploit OPERA unique feature of identifying all three flavors:
    - ν_τ appearance
    - ν_e appearance
    - ν_μ disappearance

  to constrain oscillations parameters with one single experiment

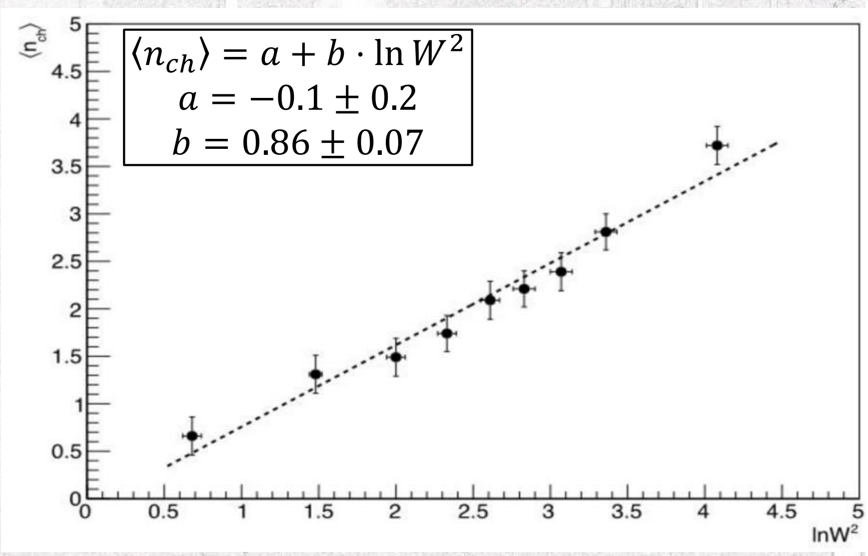
Thank you for your attention!

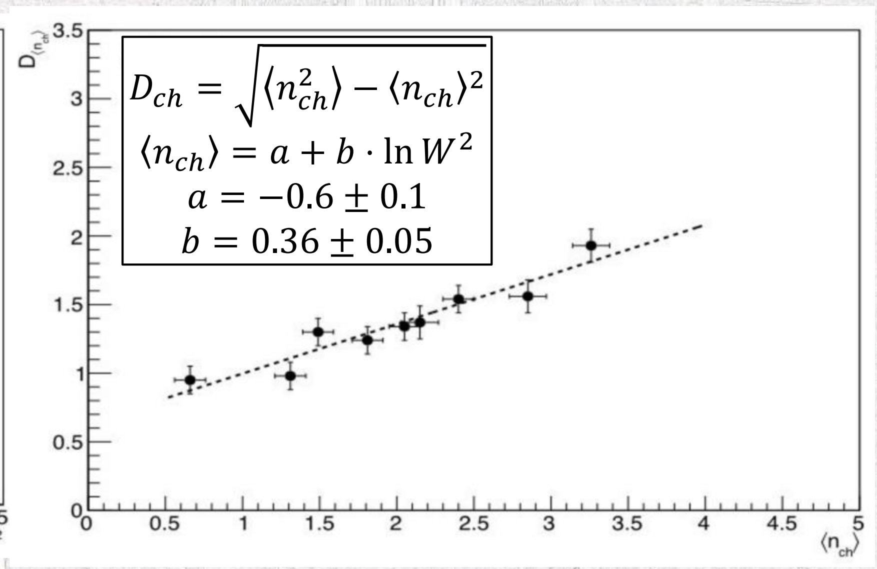
Image taken using **OPERA nuclear emulsion film**
with a pinhole hand made camera
courtesy by Donato Di Ferdinando

Study of Charged Particle Multiplicity Distribution

Measure average $\langle n_{ch} \rangle$ and dispersion D_{ch} multiplicities for charged particles in order to

- Test phenomenological and theoretical models
- Provide data to tune MC event generators.
- Test KNO Scaling





Measurement of Δm^2_{23}

Accepted by PRL, arXiv:1507.01417

$$N_{\nu_\tau} \propto \int \phi(E)\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)\epsilon(E)\sigma(E)dE$$
$$\propto (\Delta m^2_{32})^2 L^2 \int \phi(E)\epsilon(E)\frac{\sigma(E)}{E^2}dE$$

$\left({}^{L}/_{\langle E\rangle}\right)_{opera}$ ~43 km/GeV

$\left({}^{L}/_{\langle E\rangle}\right)_{PEAK}$ ~500 km/GeV

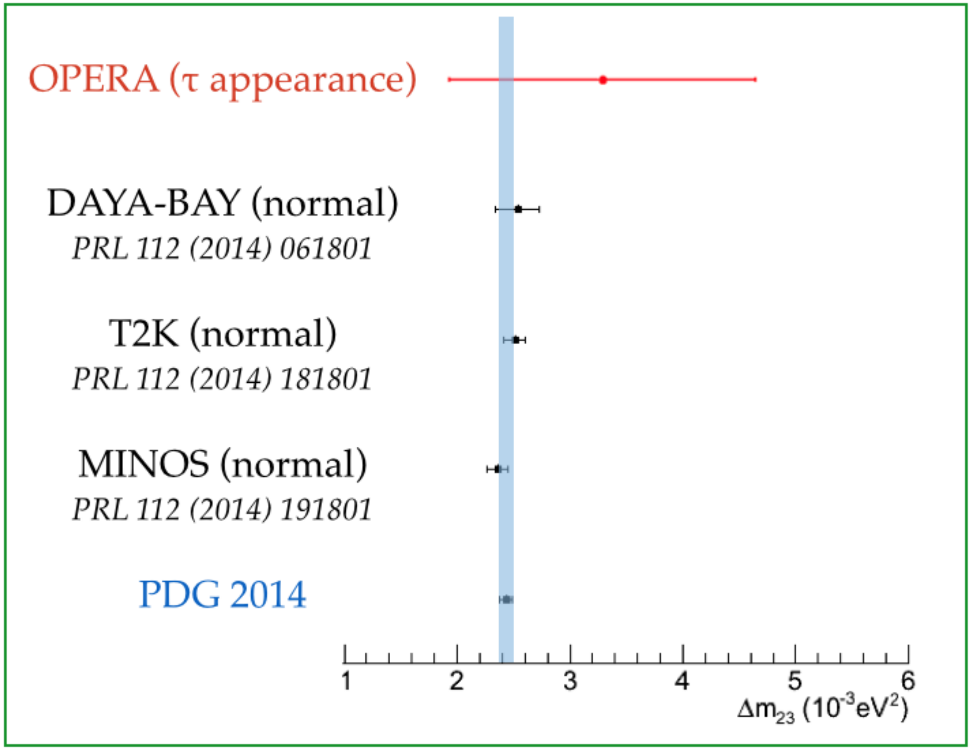
"Steep" $\mathbf{\Delta m^2_{23}}$ dependence

→ counting based measurement

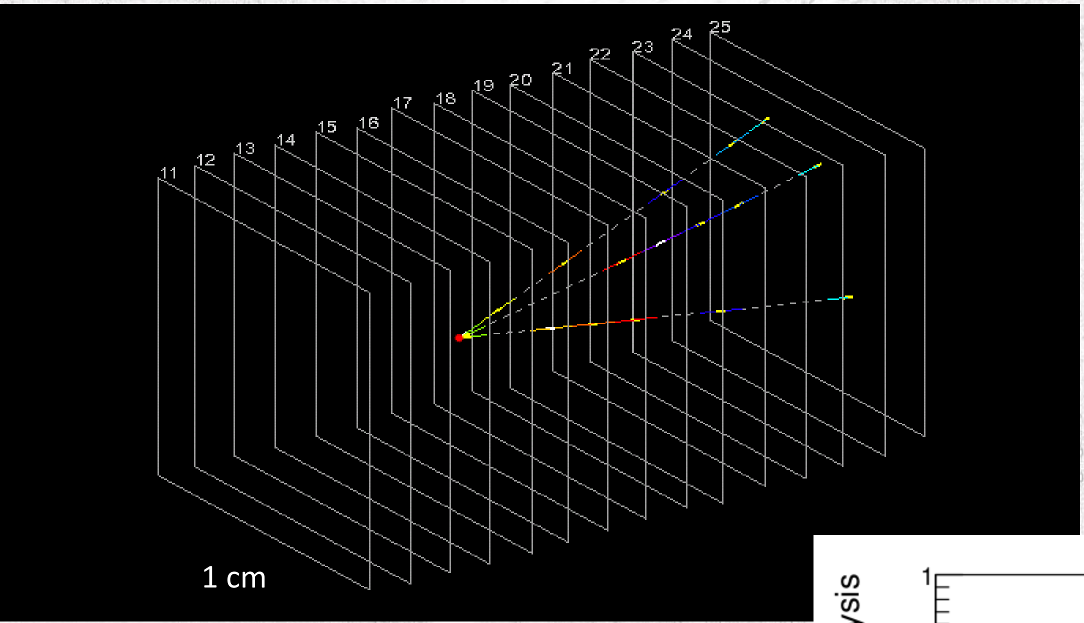
90% C.L. intervals
by Feldman & Cousins method

$$\mathbf{\Delta m^2_{23} = [2.0 - 4.7]\ 10^{-3}\ \ eV^2}$$

(assuming full mixing)



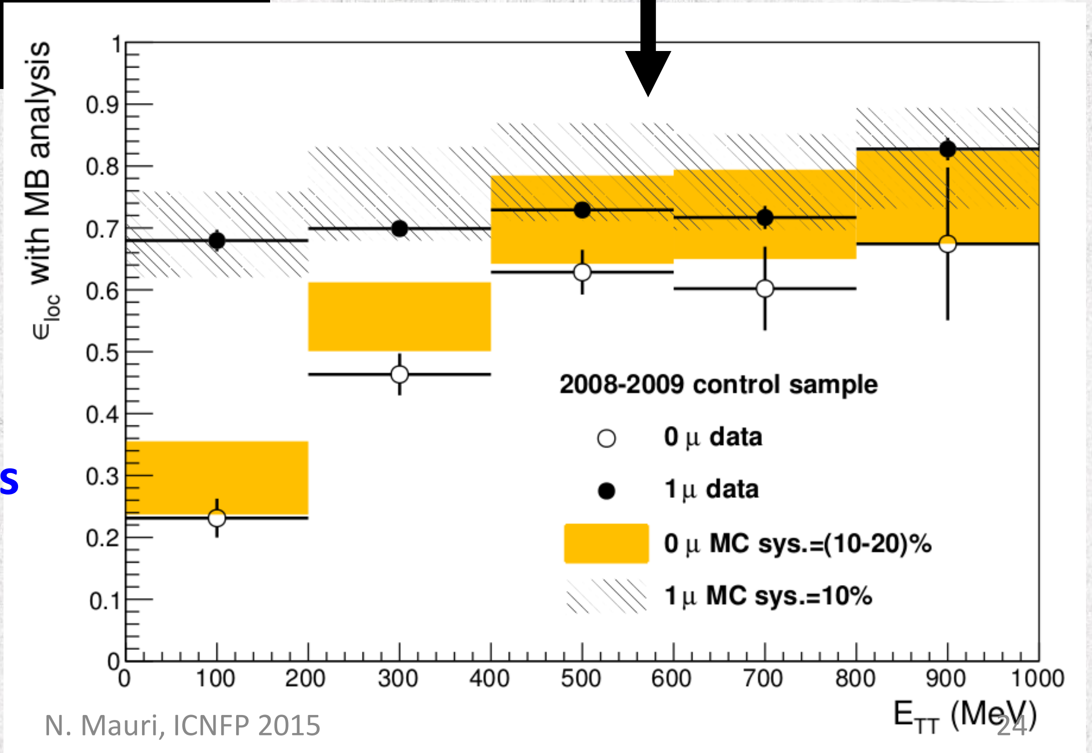
Location efficiency



[JHEP 11 (2013) 036]

0μ–like and **1μ-like** samples

Data-Monte Carlo comparison of the **location efficiency** as a function of the visible energy in the target scintillators



Hybrid detector:
a complex simulation!
Reasonable agreement.

The **prediction for the τ signal** and **backgrounds** is based on **efficiencies** derived from the observed **0μ–like** and **1μ-like** samples

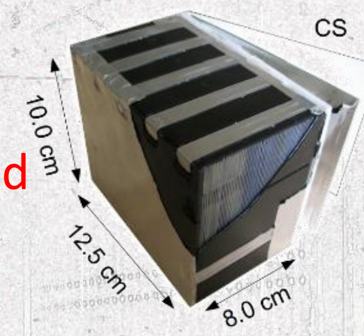
Analysis of the emulsion films

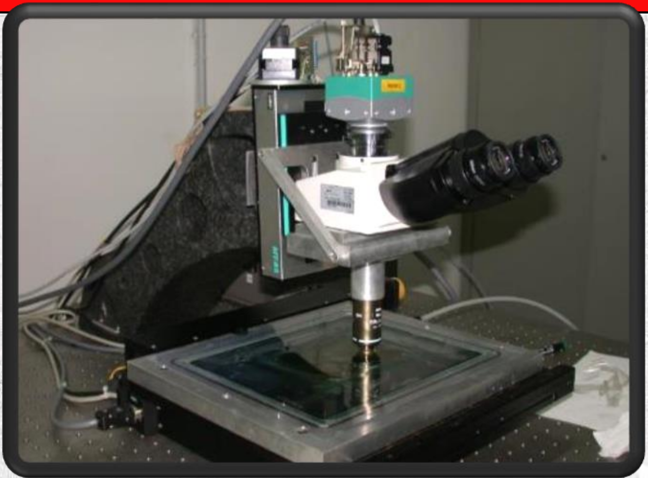
Bricks are **ordered** according to their probability of containing the interaction vertex.

Analysis status:

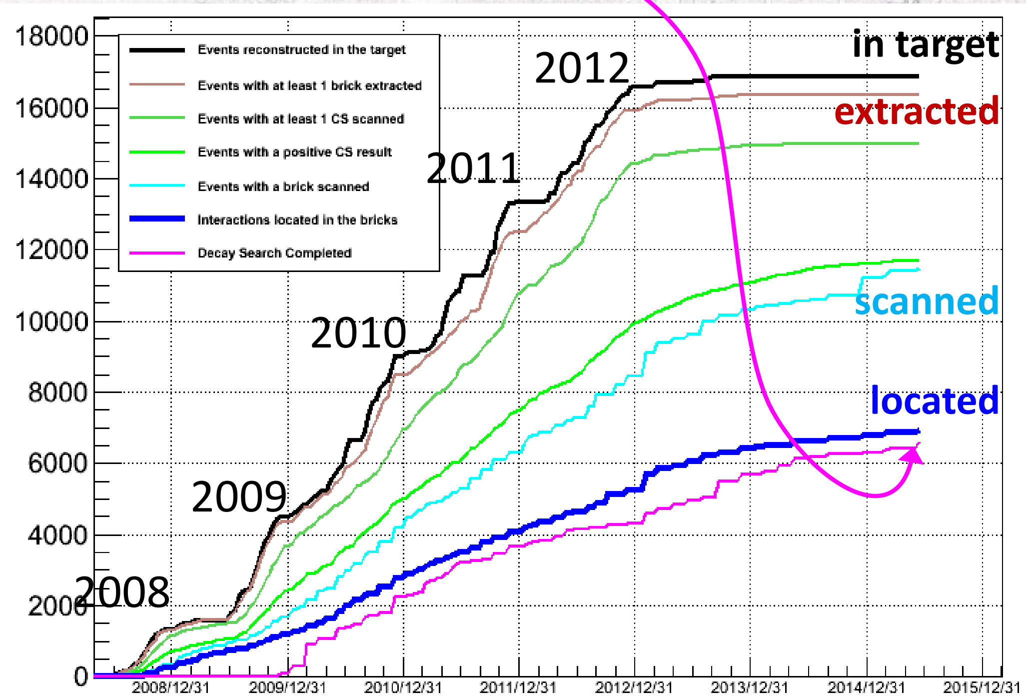
2008-09 completed up to 4th brick

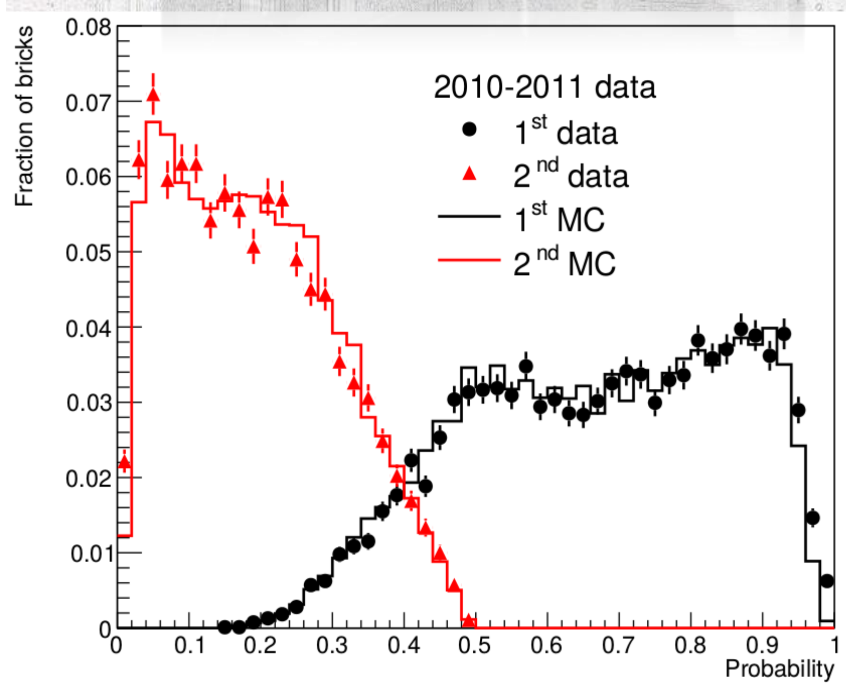
2010-12 1st and 2nd bricks completed





> 6600 fully analysed bricks





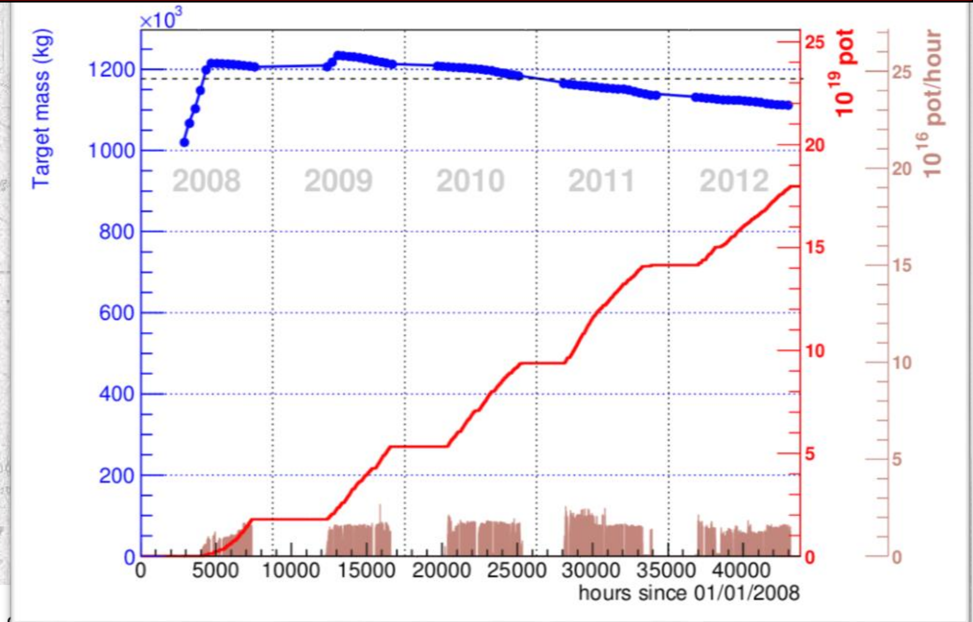
Data sample

The 5years long CNGS run ended in 2012.

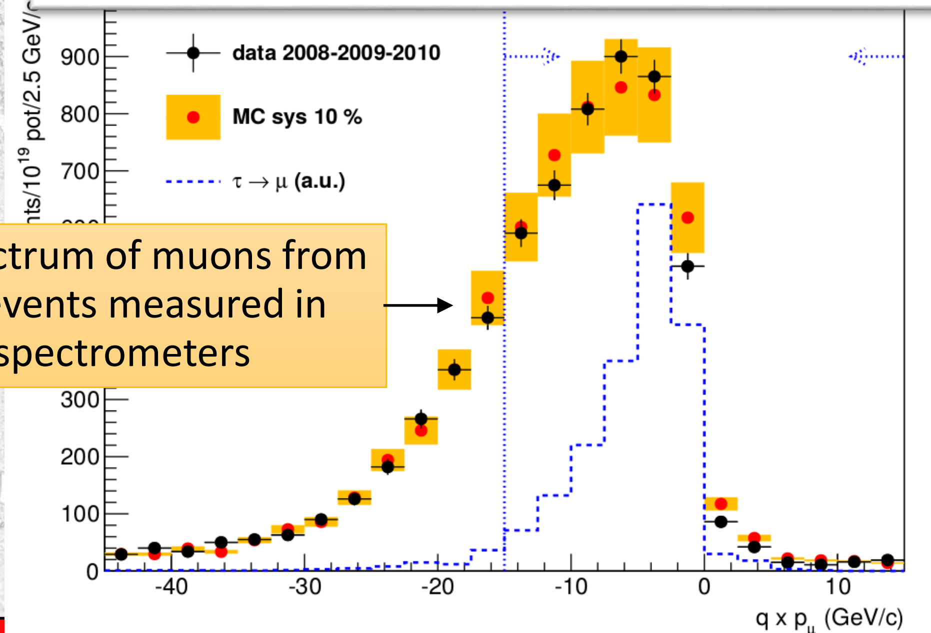
$1.8 \cdot 10^{20}$ p.o.t. collected
(80% of the design)

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

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	/	/

variable	
lepton-tag	
z_{dec} (μm)	• the *flight length* with respect to the primary vertex;
p_T^{miss} (GeV/c)	• the *missing transverse momentum at primary* with respect to the beam direction;
ϕ_{lH} (rad)	• the *transverse angle* with respect to the beam direction between the tracks which end up in 1pr-like and 2pr-lik vertices, so called φ;
p_T^{2ry} (GeV/c)	• the *transverse daughters momentum* with respect to the parent direction;
p^{2ry} (GeV/c)	• the *daughters momentum*, which is the module of total momentum of the daughters;
θ_{kink} (mrad)	• the *kink* angle between parent and daughter;
m, m_{min} (GeV/c^2)	• the *invariant mass* of the daughters, for which the daughters masses are assumed to be equal to the pion mass;

- the *daughter momentum* coming from the vertex; p_{2ry}
- the *daughter transverse momentum* with respect to the parent direction; p_{2ry}^T
- the *kink* angle between parent and daughter; θ_{kink}
- the *flight length* with respect to the primary vertex; z_{dec}

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_{2ry}^T (GeV/c)	>0.15	/	>0.1	>0.1

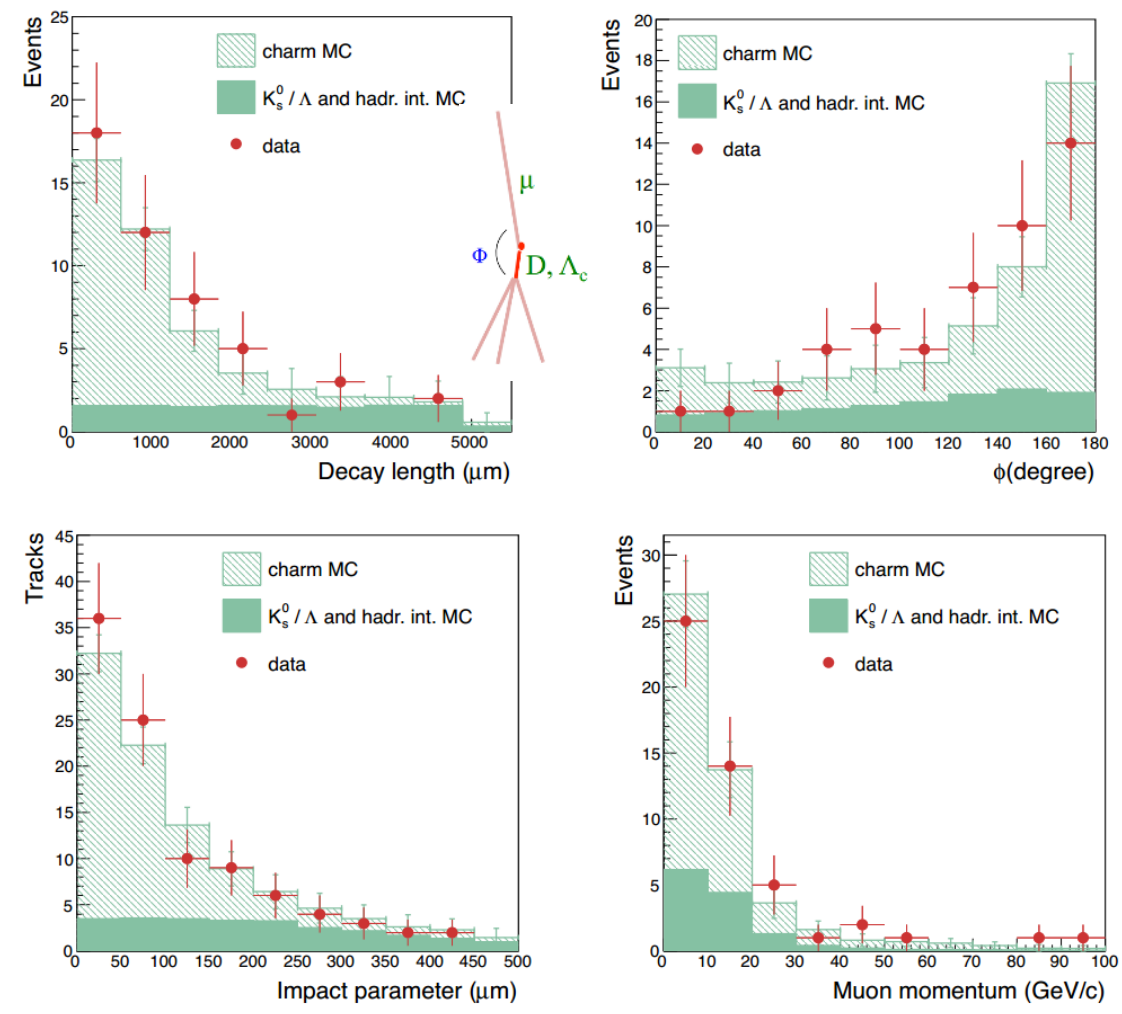
BACK UP
- BACKGROUND

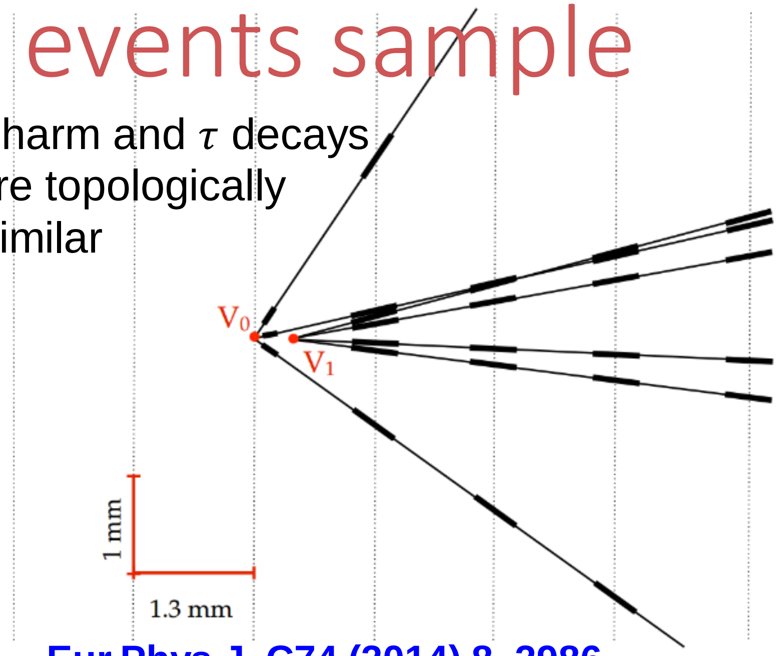
Validation with the charm events sample

Test for: reconstruction efficiencies, description of kinematical variables, charm background.

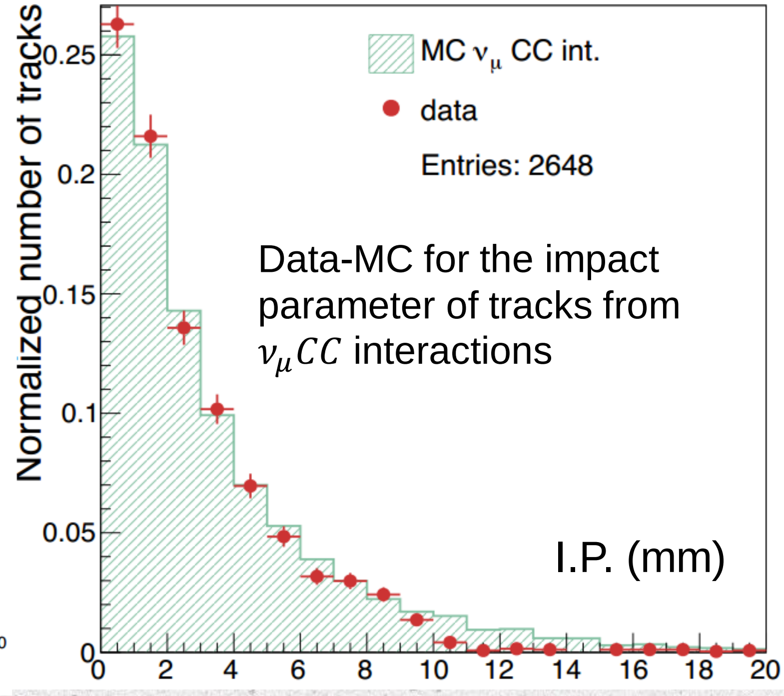
54 ± 4 expected ⟷ 50 observed

Charm and τ decays are topologically Similar





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

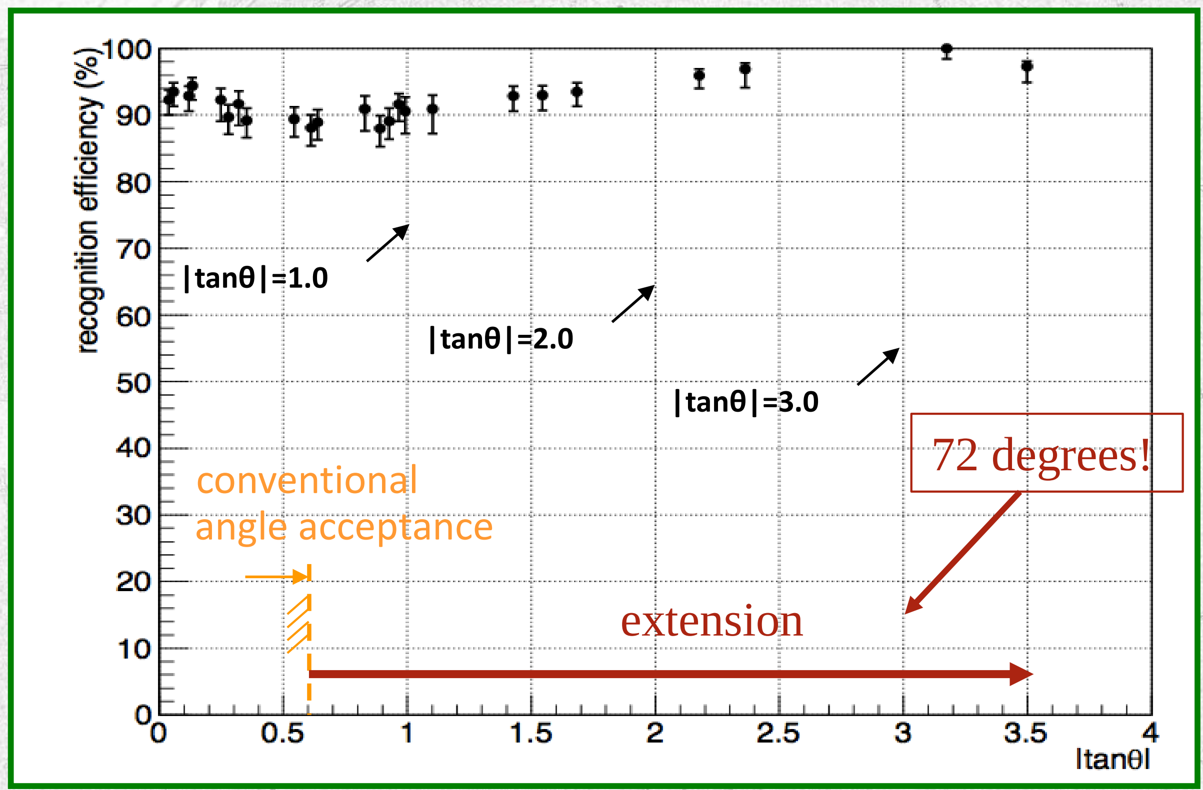


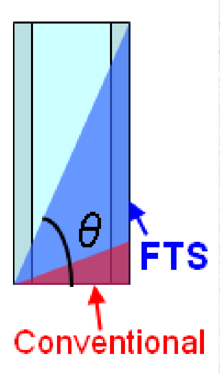
Data-MC for the impact parameter of tracks from $\nu_\mu CC$ interactions

Improvement on the background rejection

Large angle track detection

Undetected soft and large angle muons are the source of charm background
Detection of particles and nuclear fragments in hadronic interactions

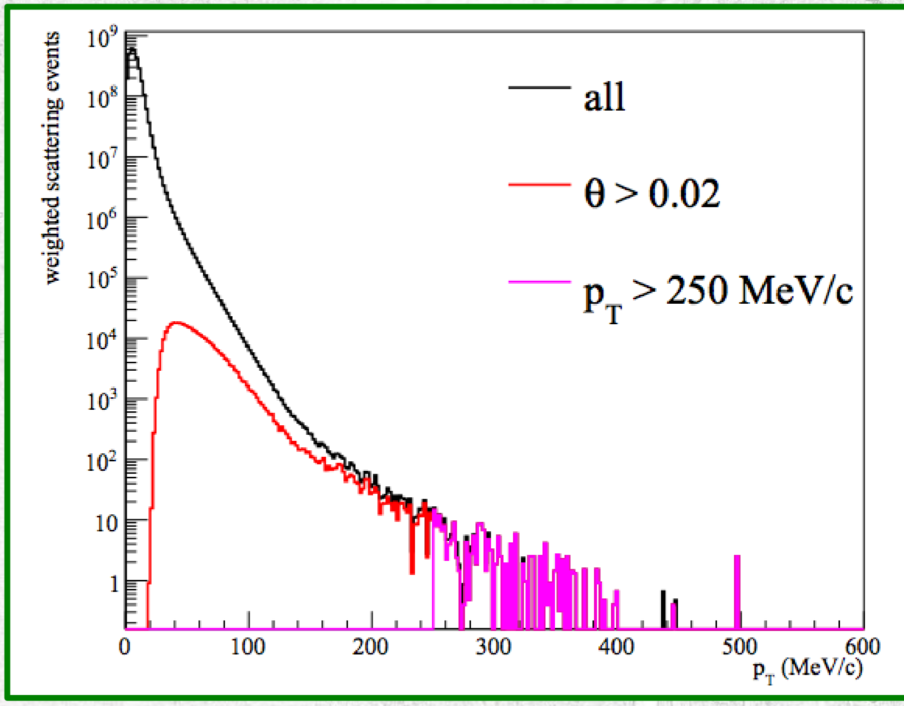




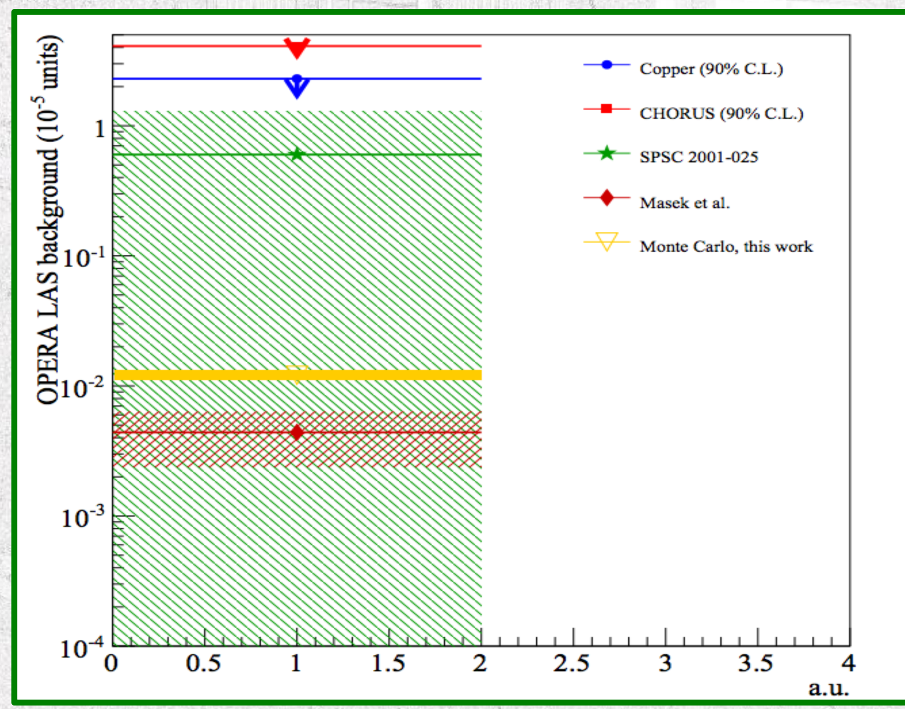
JINST 9 (2014) P12017

Large angle μ scattering

CNGS ν_μ CC muons on Lead $1 < p_\mu < 15$ GeV/c



Main background in the $\tau \rightarrow \mu$ decay channel when using upper limits in the past



LAS background estimation

$$(1.2 \pm 0.1) \times 10^{-7} / \nu_\mu^{CC}$$

well below the values considered so far

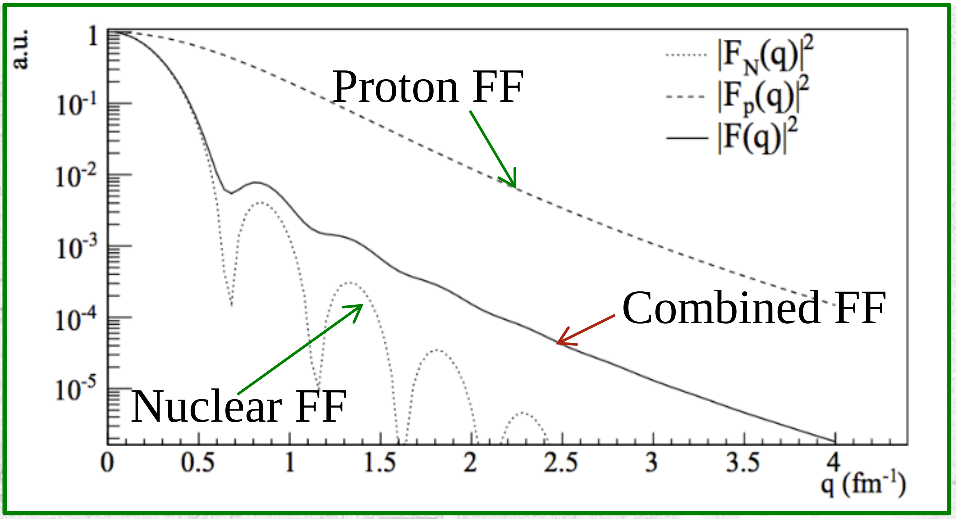
IEEE Transactions on Nuclear Science

Large angle μ scattering

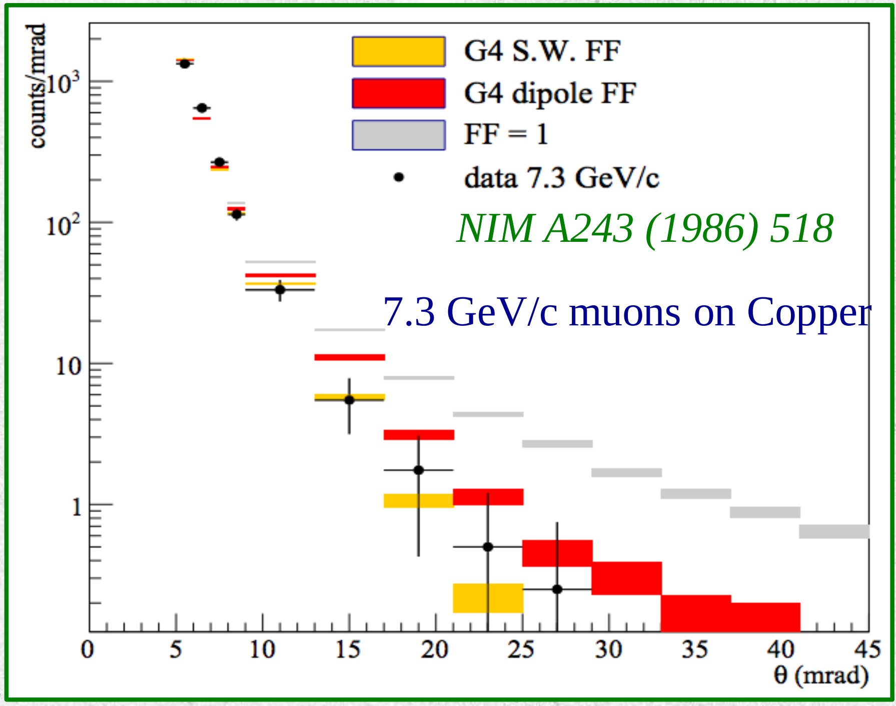
New estimate based on GEANT4
- Simulation modified by introducing form factors (FF) for Lead
  (Saxon-Woods parameterization)

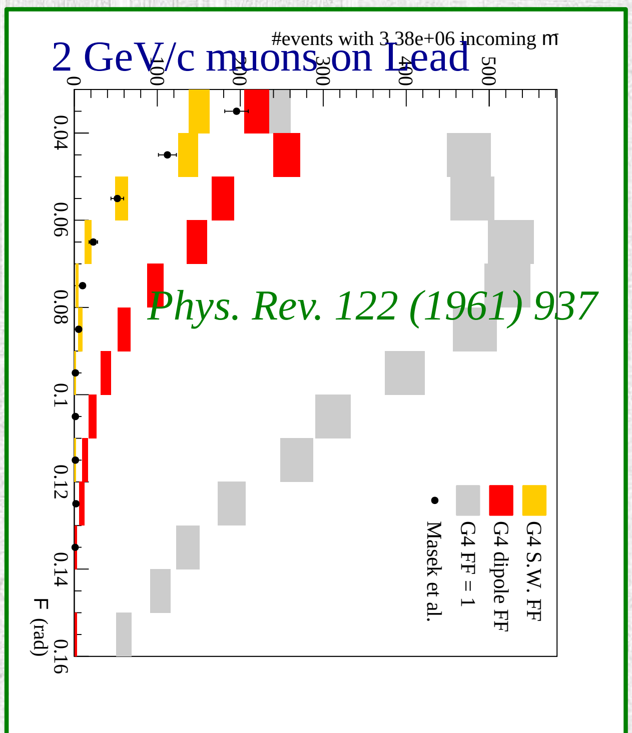
$$\rho_{SW}(r) = \rho_0 \left(1 + e^{\frac{r-b}{a}}\right)^{-1}$$

IEEE Transactions on Nuclear Science



MC predictions compared to available data





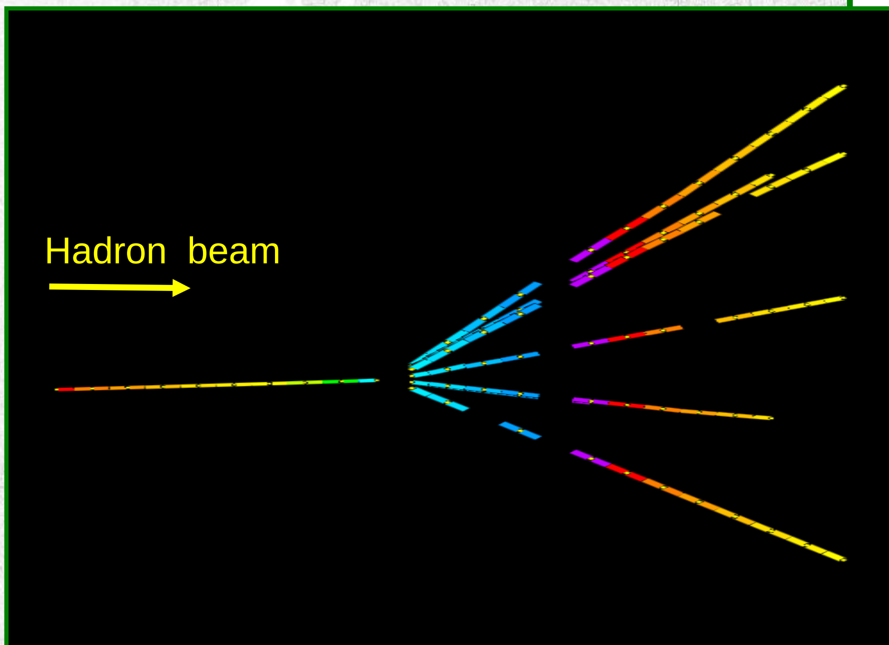
Background studies: hadronic interactions

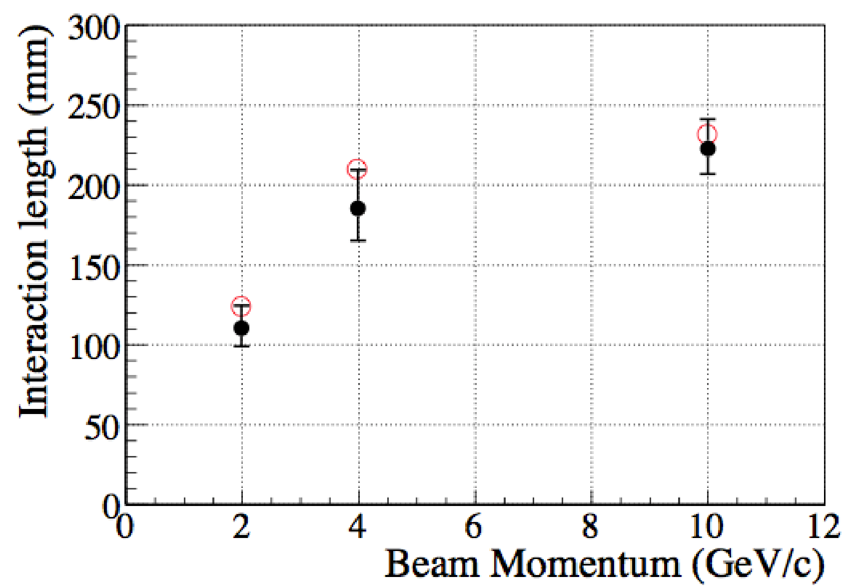
Comparison of large data sample (π^- beam test at CERN) with Fluka simulation

→ check the agreement and estimate the systematic uncertainty

Track length analysed in the brick:

- 2 GeV/c : 8.5 m
- 4 GeV/c : 12.6 m
- 10 GeV/c : 38.5 m



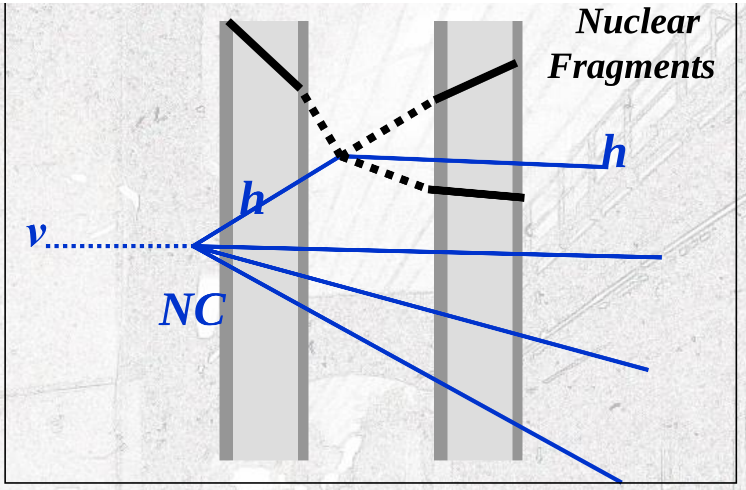


Black : π^- beam data

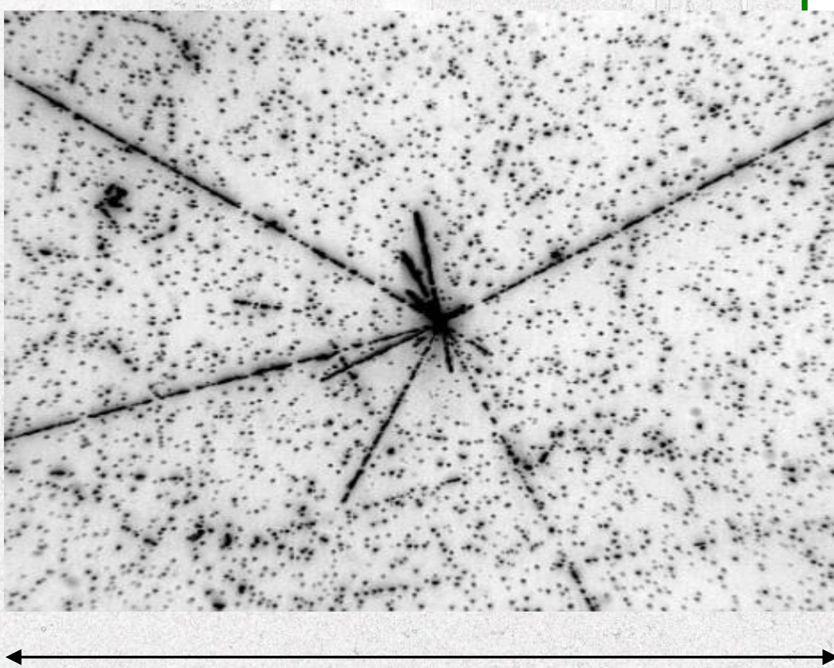
Red : MC (FLUKA) simulation

PTEP 9 (2014) 093C01

Nuclear fragments emission probability

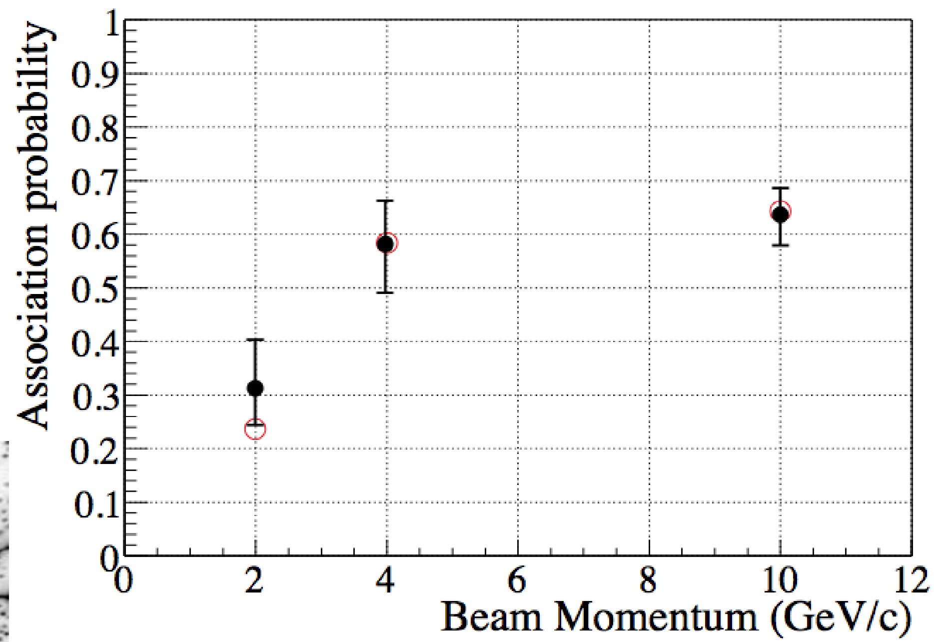


Highly ionizing fragments



150 µm

Additional background reduction



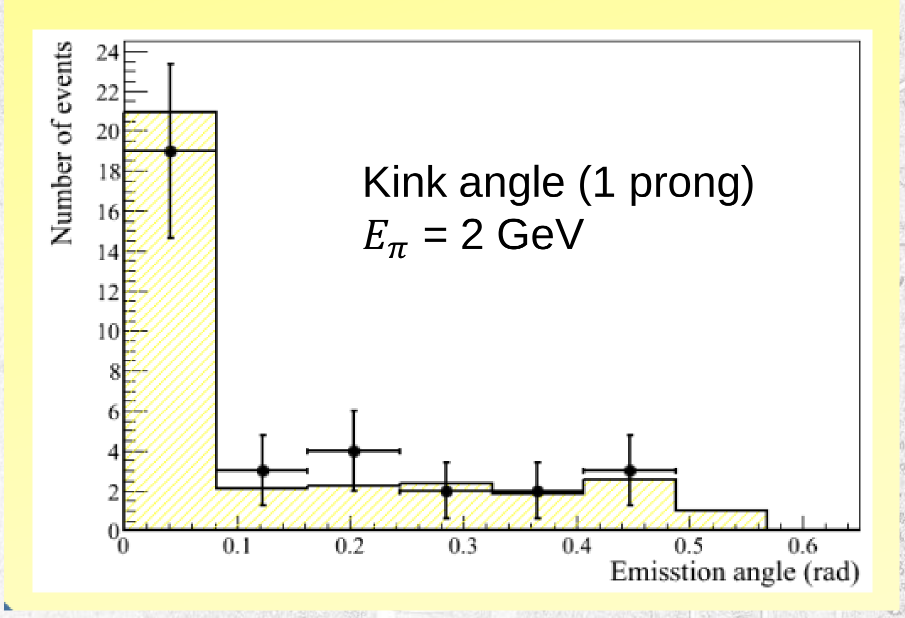
Black : experimental data

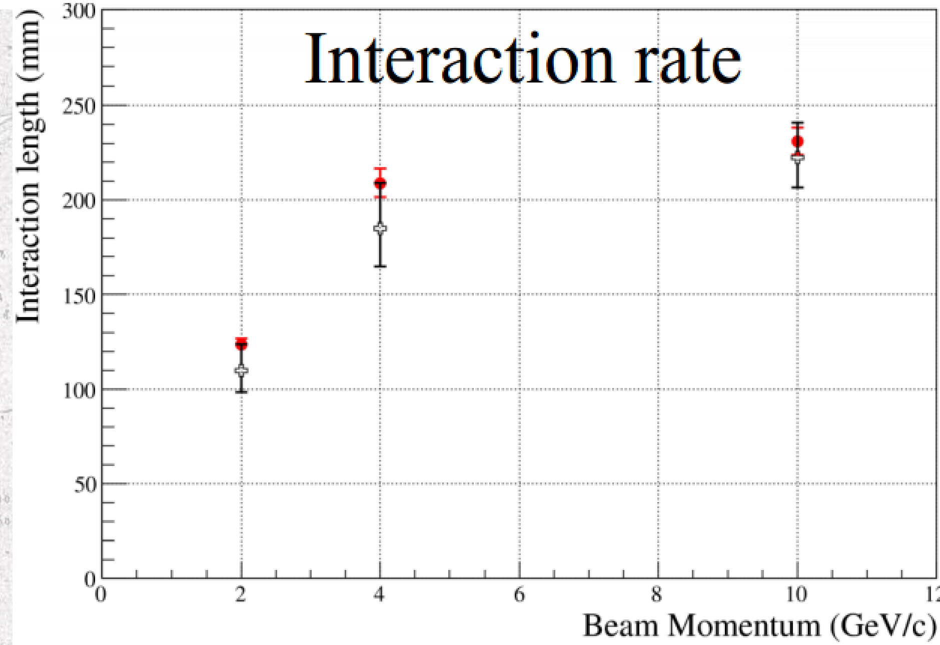
Red : simulated data (β= p/E = 0.7)

PTEP 9 (2014) 093C01

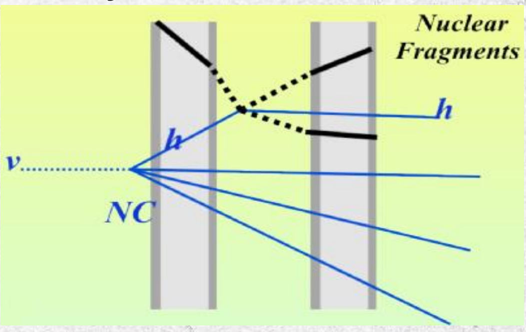
Hadronic background: π test beam

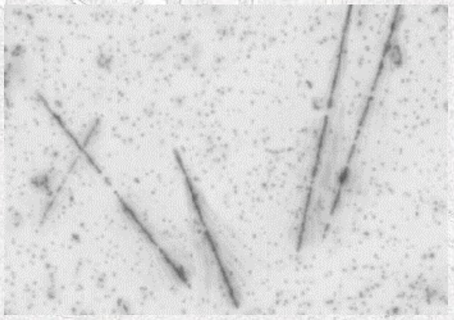
CERN π test beam

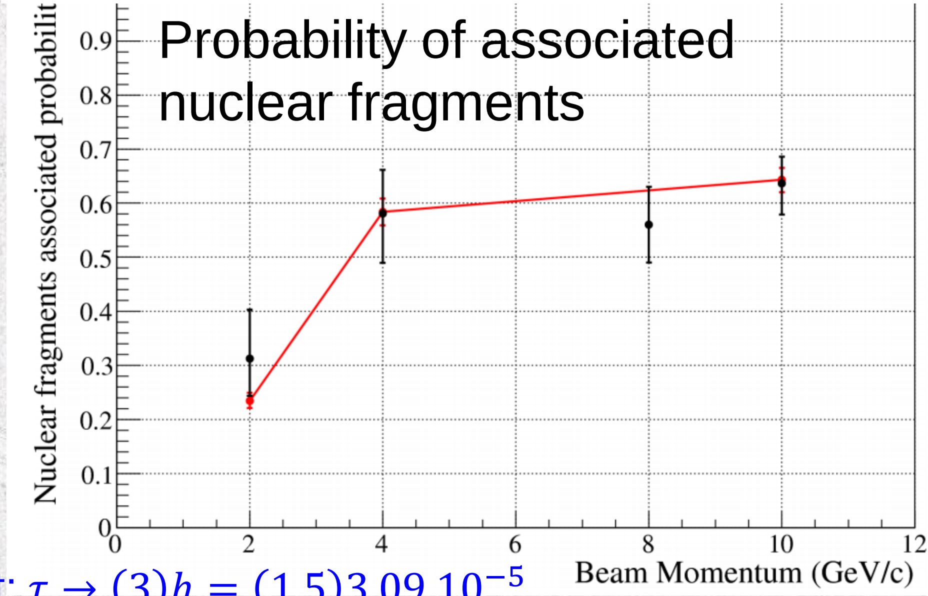




Nuclear fragments: a smoking gun for the occurrence of an π interaction instead of a decay.



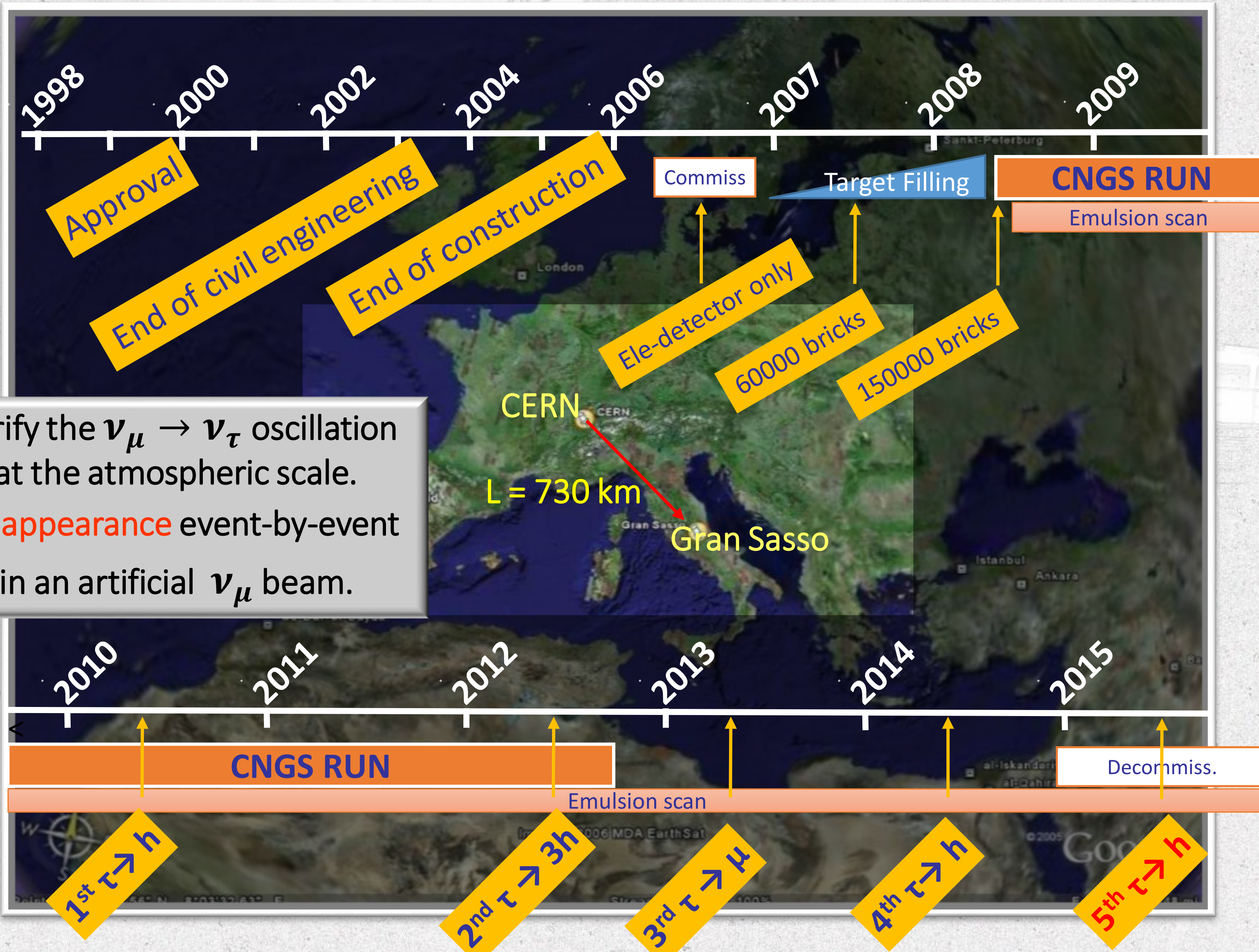


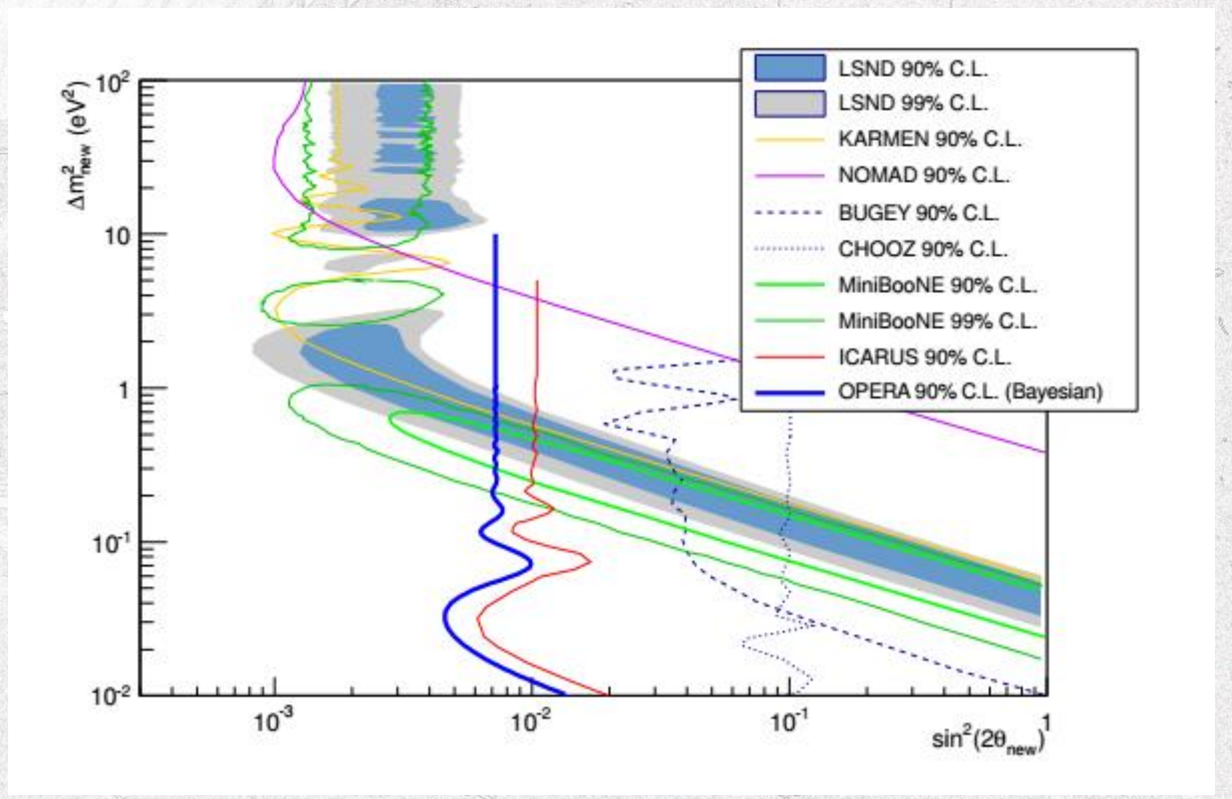


Hadronic background rate per located event: $\tau \to (3)h = (1.5)3.09\ 10^{-5}$

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

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




LSND 90% C.L.
LSND 99% C.L.
KARMEN 90% C.L.
NOMAD 90% C.L.
BUGEY 90% C.L.
CHOOZ 90% C.L.
MiniBooNE 90% C.L.
MiniBooNE 99% C.L.
ICARUS 90% C.L.
OPERA 90% C.L. (Bayesian)
Δm^2_{new} (eV^2)
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2(2\theta_{new})$