NUFACT BLACKSBURG, VIRGINIA

http://operaweb.lngs.infn.it

FINAL results from the experiment in the CNGS neutrino beam

OPERA

M. Tenti

On behalf of the OPERA Collaboration

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France
LAPP Annecy
IPHC Strasbourg

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Israel
Technion Haifa

Korea
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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

180 physicists, 11 countries, 27 institutions

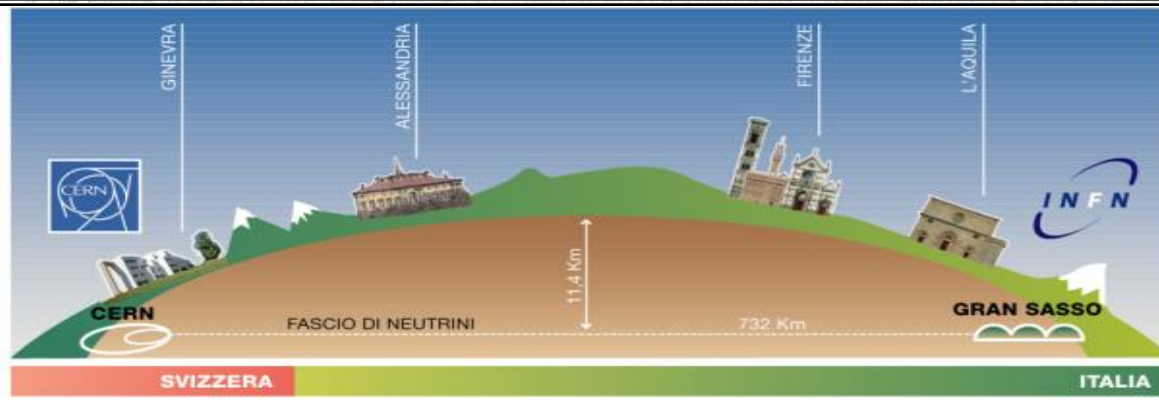
- ✓ **ν_τ appearance (std & looser selection)**
- ✓ **ν_e search update**
- ✓ **ν_μ disappearance**
- ✓ **sterile neutrinos**
- ✓ **non-oscillation physics**

AUGUST 12-18, 2018

[CERN-SPSC-2000-028, 2000]

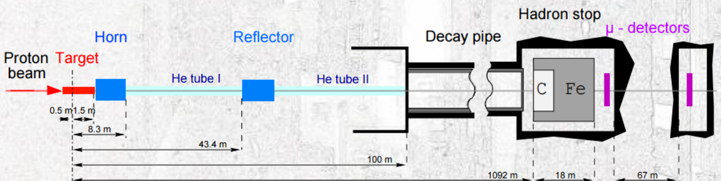
The Oscillations Project with Emulsion TRacking Apparatus

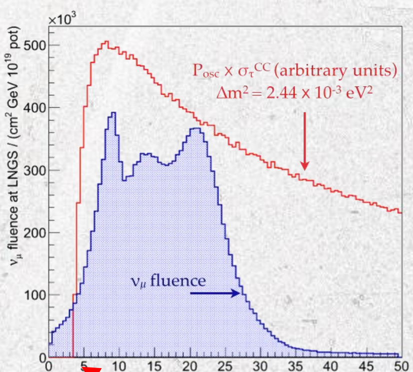
- **Long baseline** experiment: 735 km
- Aim: **verify the $\nu_\mu \rightarrow \nu_\tau$** oscillations at atmospheric Δm^2 scale
- How: observe ν_τ appearance on **event-by-event** basis in a conventional ν_μ beam



Conventional muon neutrino beam

neutrino mean energy: **17 GeV**

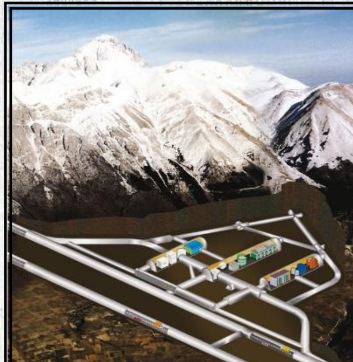




threshold: 3.5 GeV [m_τ = 1.7 GeV]

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

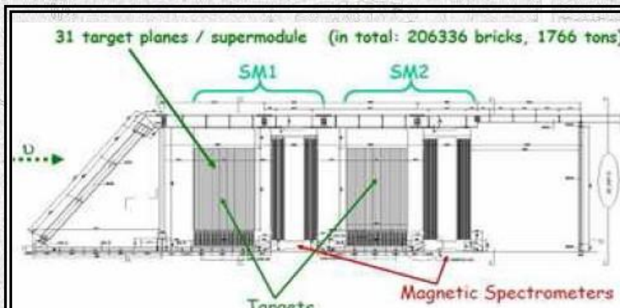
$(\nu_e + \bar{\nu}_e)/\nu_\mu$	0.9 %
$\bar{\nu}_\mu/\nu_\mu$	2.1%
ν_τ prompt	negligible



Low background environment

Laboratori Nazionali del Gran Sasso (Italy)

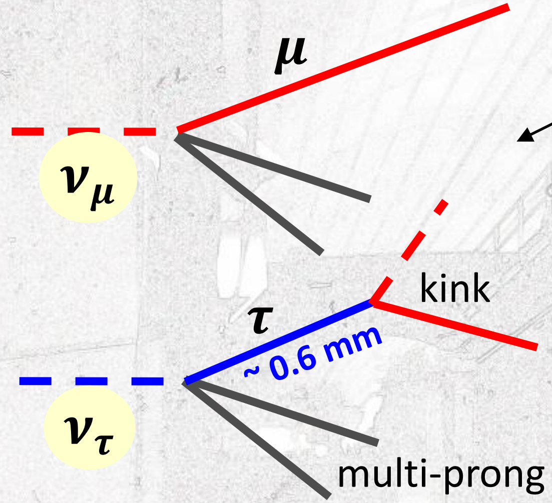
- 1400 m rock overburden
- atm. μ reduction ~ 10^6 [1μ/(m²·h)]
- low radioactivity rock



Detector:

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

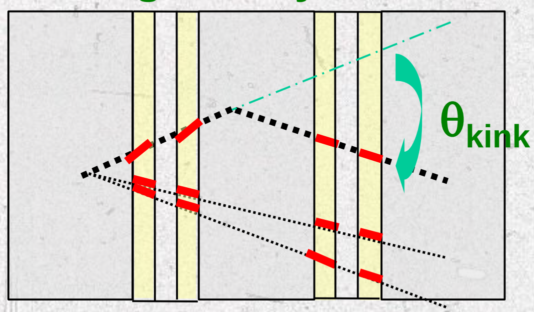
The ν_τ detection technique



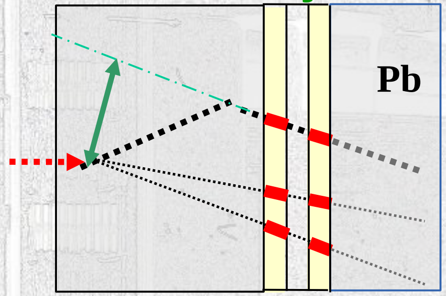
Detect a few ν_τ^{CC} amid the bulk of ν_μ^{CC}

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



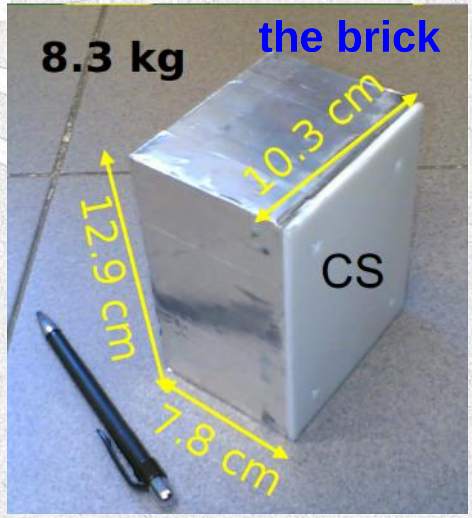
Modular detector of **bricks**
[56 Lead-Emulsion Cloud Chambers (ECC) sandwiched]

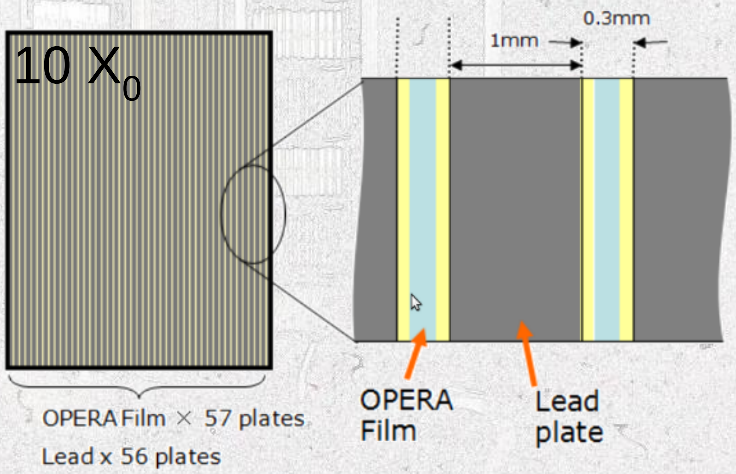
Large mass

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

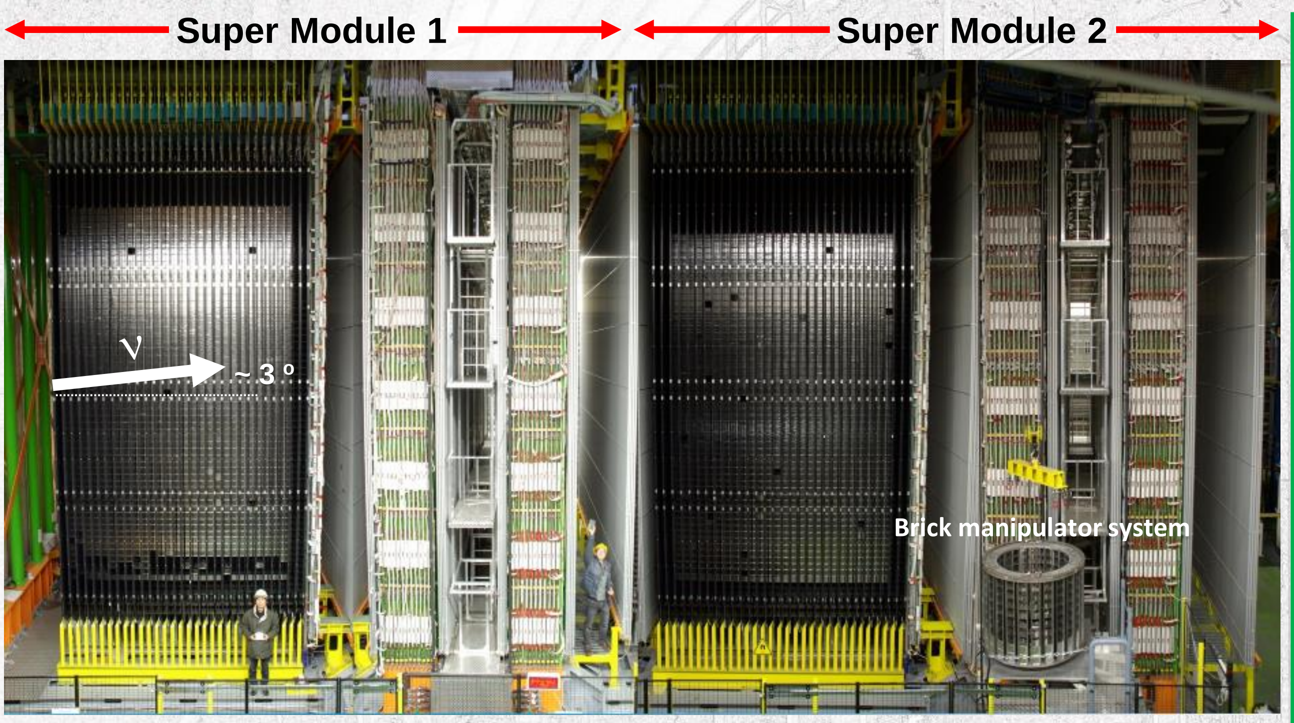
Extreme granularity

$\sim\mu$m space resolution





The OPERA detector



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

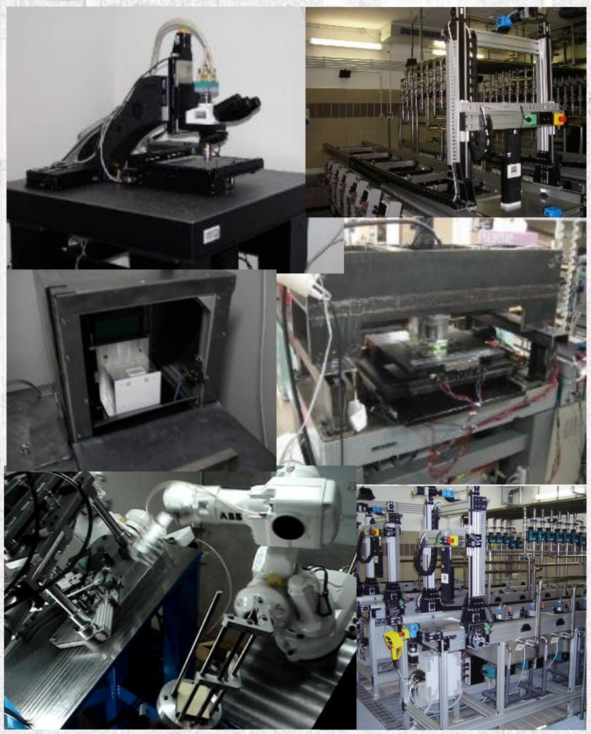
Muon spectrometer (8 x 10 m^2)

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

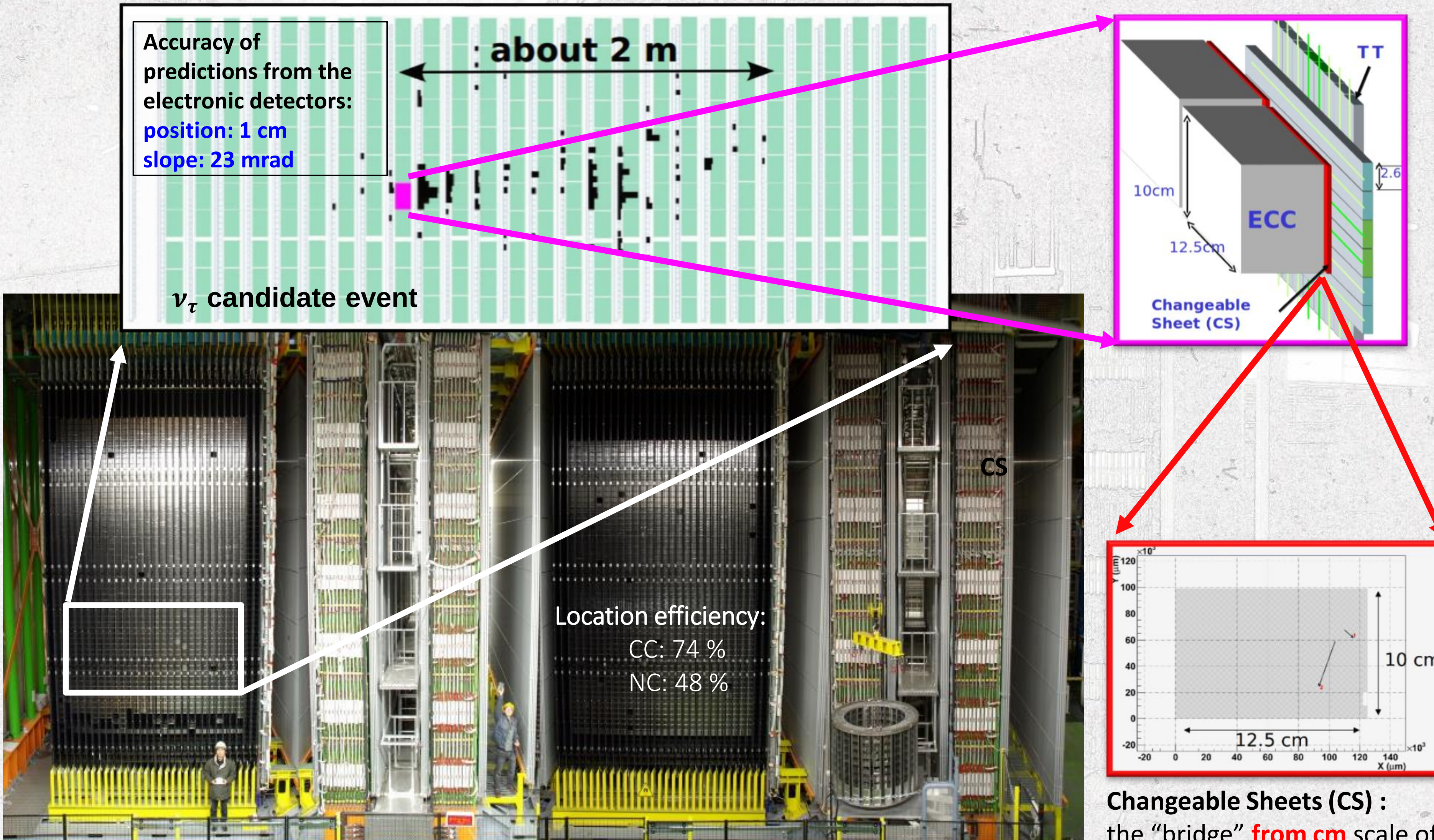
μ Identification +
charge and momentum measurements

+ 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

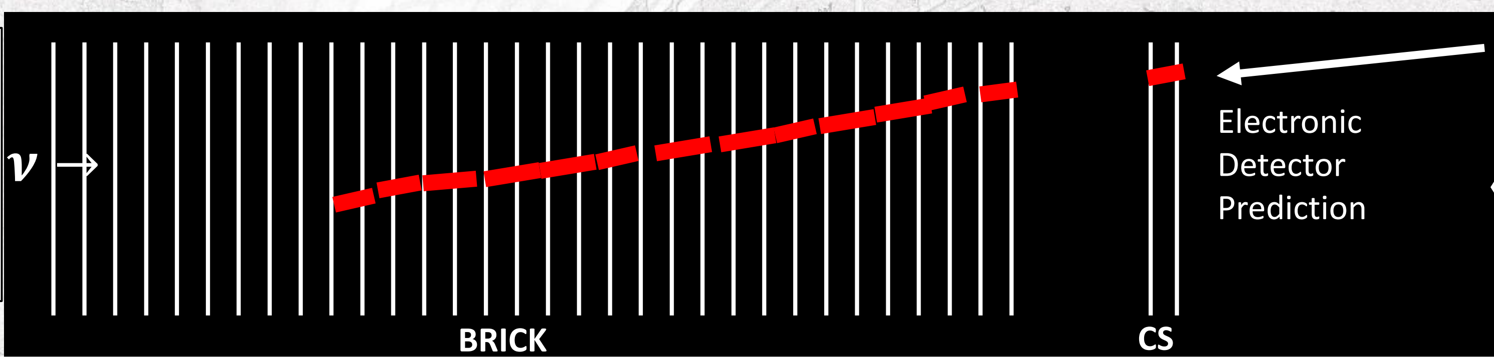


Super Module 1 — Super Module 2

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

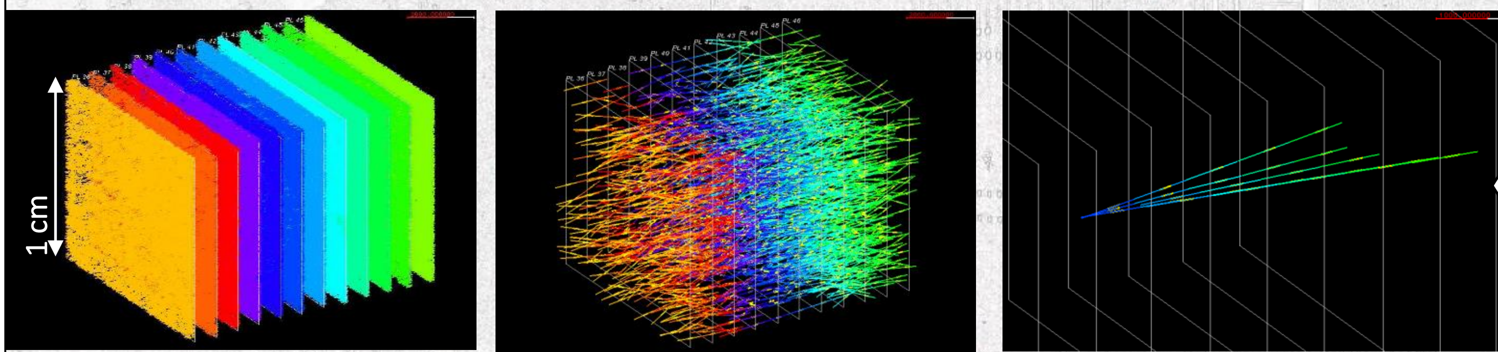
Vertex hunting in the brick

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 cm^3 **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

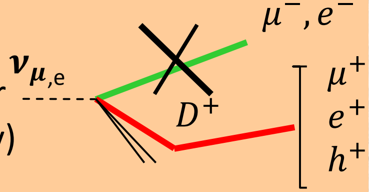
[JHEP 1311 (2013) 036]

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



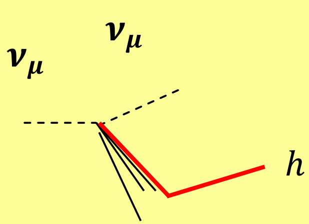
MC tuned on CHORUS data (cross section and fragmentation functions), validated with measured OPERA charm events.

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

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

Hadronic interactions

Background for $\tau \rightarrow h$



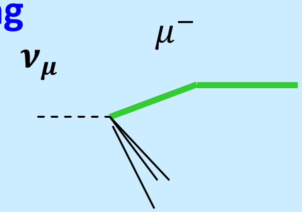
FLUKA + pion test beam data

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 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*

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

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

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

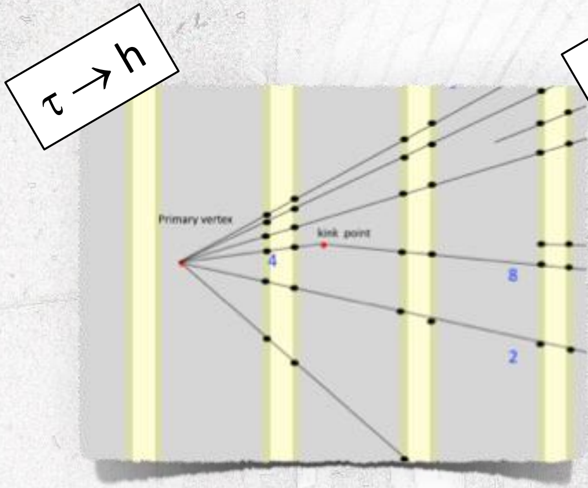
Background-only hypothesis:

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

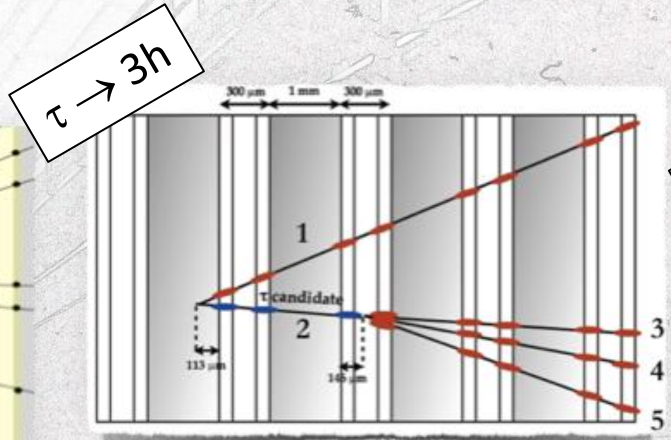
Compatibility with 3ν oscillation:
$\hat{\mu} = 1.8^{+1.8}_{-1.1}$ at 90% C.L

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

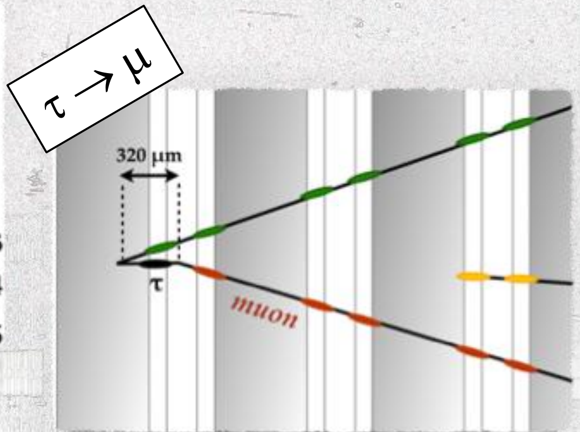
The five ν_τ candidates observed



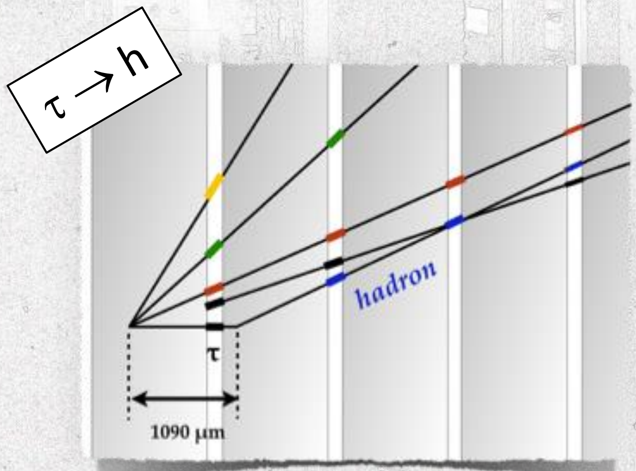
Phys. Lett. B 691 (2010) 138



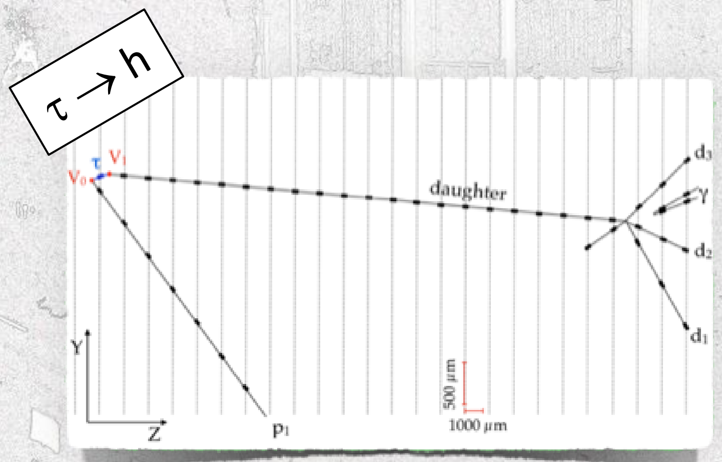
JHEP 11 (2013) 036



Phys. Rev. D 89 (2014) 051102



PTEP 2014 (2014) 10, 101C01



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

Loosing ν_τ event selection

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

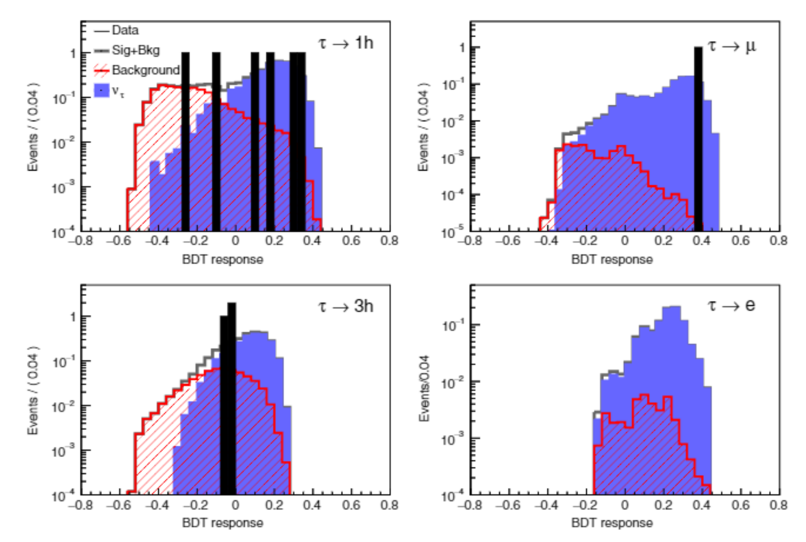
- Loose kinematical cuts:
  - **Minimal requirements** to identify the topologies showing 2 vertices
  - **Negligible additional background** from K/π decays

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^T_{2ry} (GeV/c)	>0.15		>0.1	>0.1
Charge$_{2ry}$			Negative or unknown	

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

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

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



- **Multivariate approach** (based on BDT)
  - Use kinematical, topological variables and their correlations
    → **higher discrimination power**

Statistical Analysis and Results

[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:

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

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

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

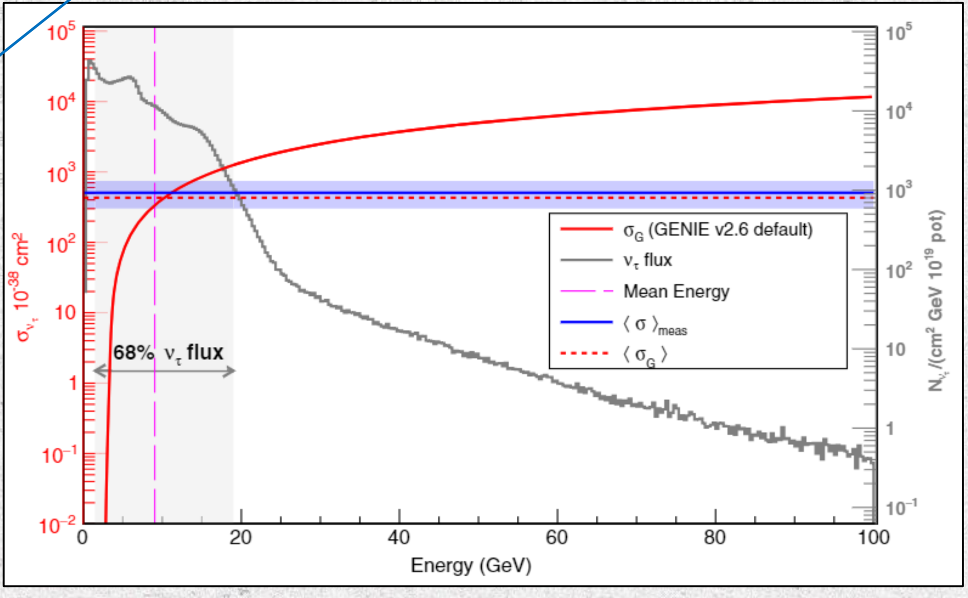
assuming maximal mixing and $|\Delta m^2_{32}| = 2.5\times 10^{-3}\ eV^2$

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

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

assuming maximal mixing

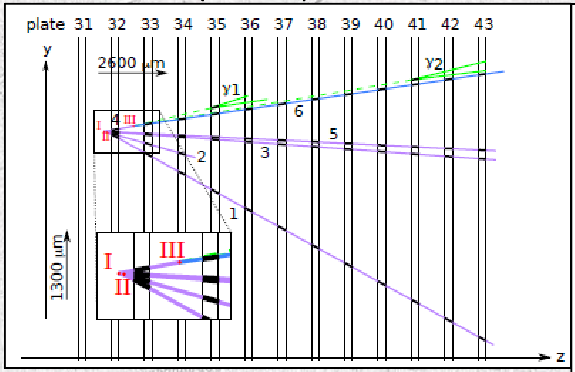
first measure in appearance mode



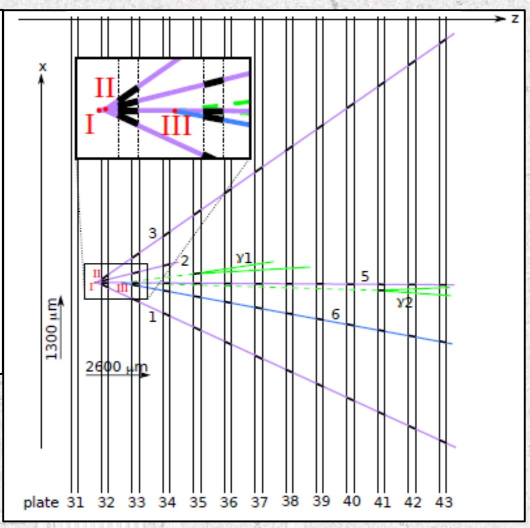
Peculiar event

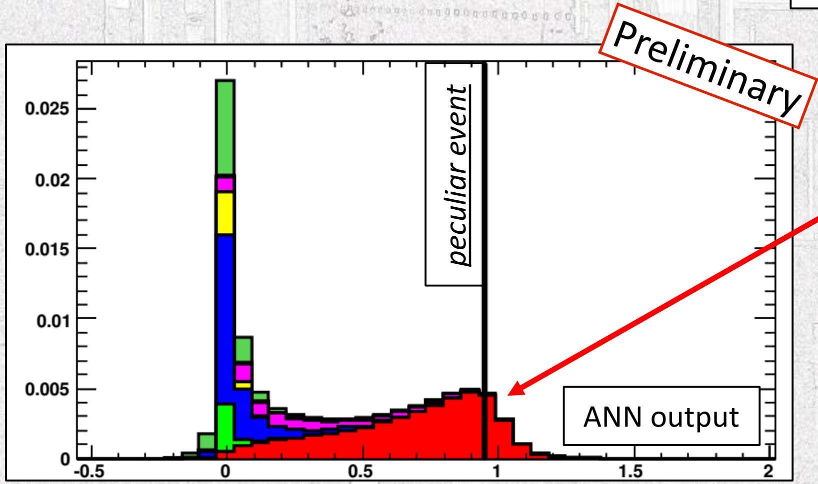
- Muon-less neutrino event
- Most probable topology:
  ν interaction vertex + 2 decay vertices
- **Rare topology** not considered in the experiment proposal
  (0.1 events expected in full data sample)
- Ad **hoc simulations + ANN** (2 Layers MLP) to distinguish between possible interpretations:
  - $\nu_\tau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

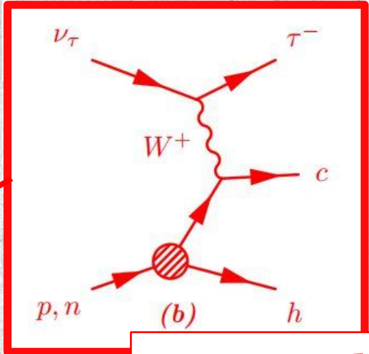
yz view
(vertical)



yz view
(horizontal)







$\nu_\tau CC + charm$

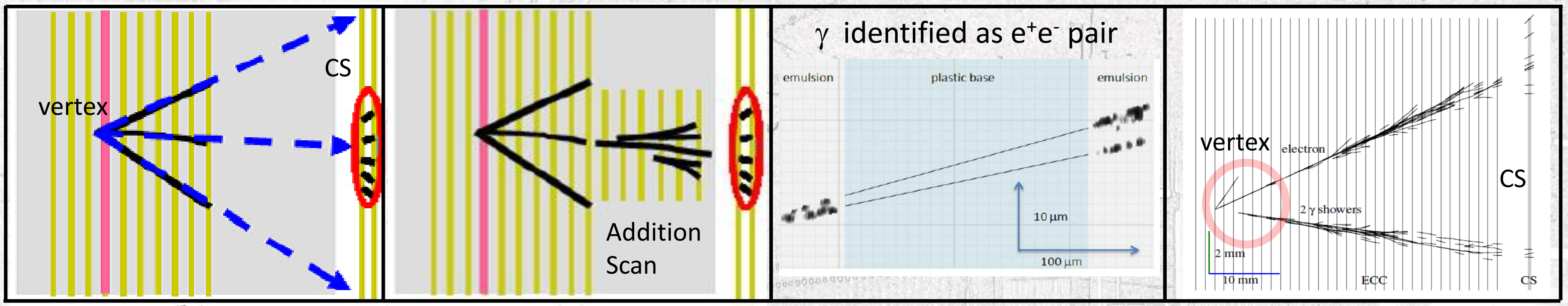
Preliminary

Assuming the event not being ν_τ CC + charm: p-value ~ 10^{-4} → Significance = 3.4 σ

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.

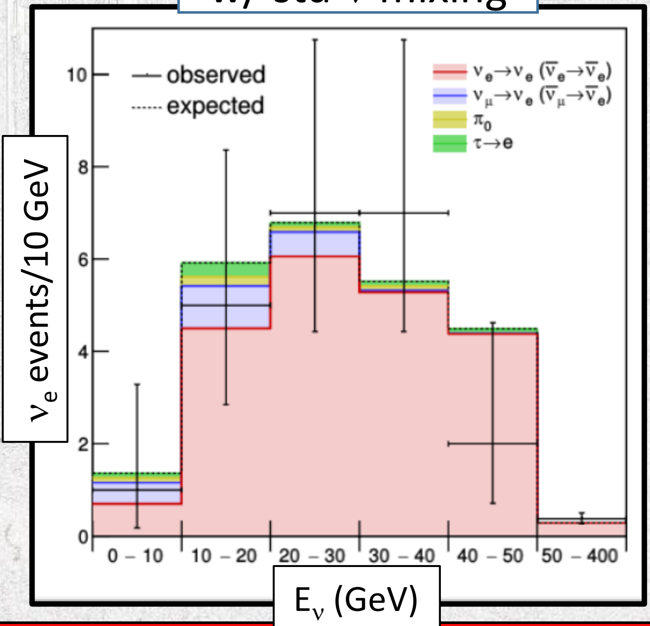


- Project vtx tracks
- Find cluster of similar slope CS tracks

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

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

w/ std ν mixing



ν_μ disappearance

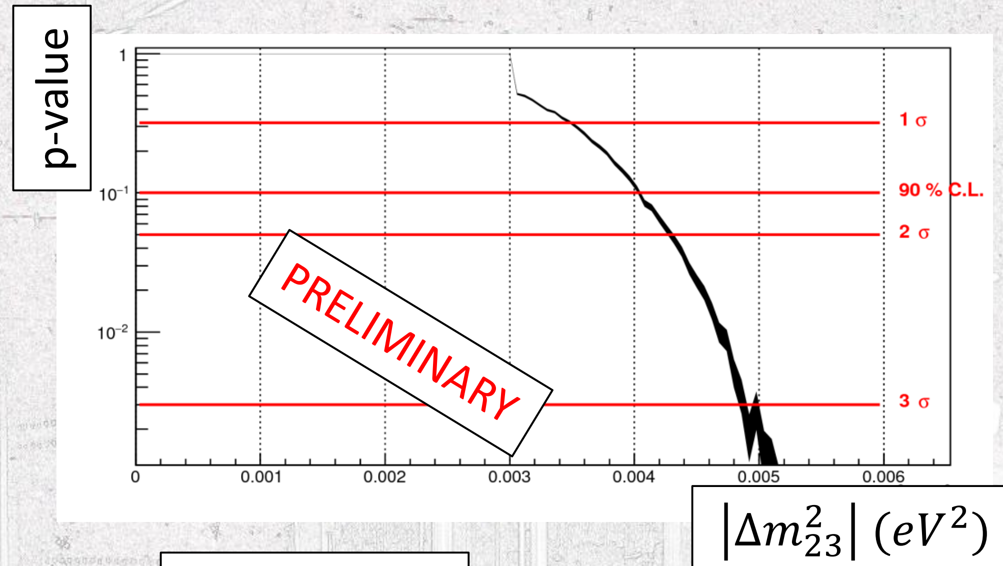
ν_μ disappearance sensitivity **limited** by flux uncertainties
$\rightarrow$ no NEAR detector

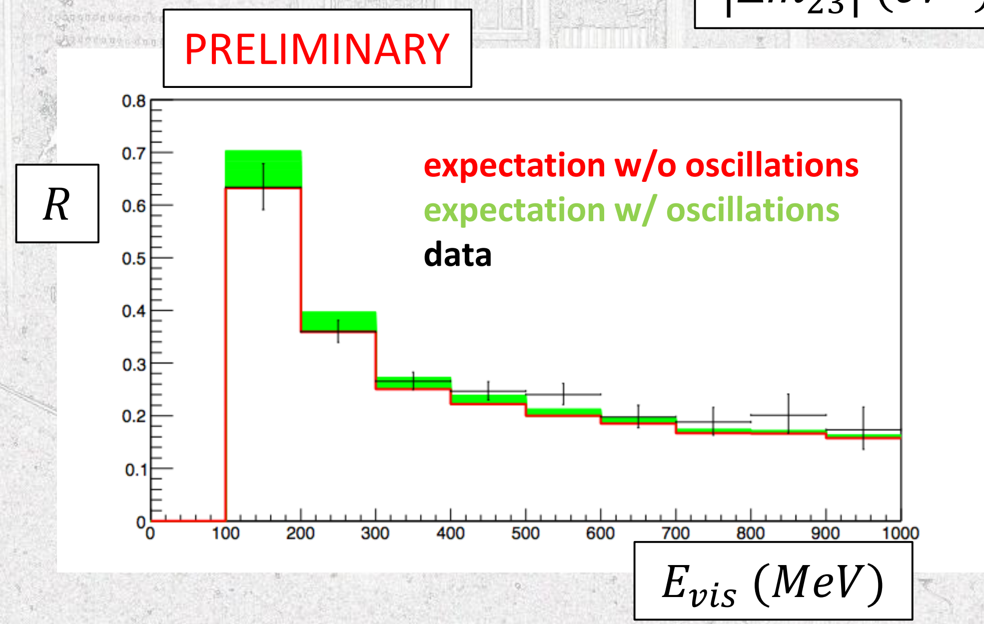
Ratio (R) of NC-like over CC-like **mitigates limitation** due to flux uncertainties

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)

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

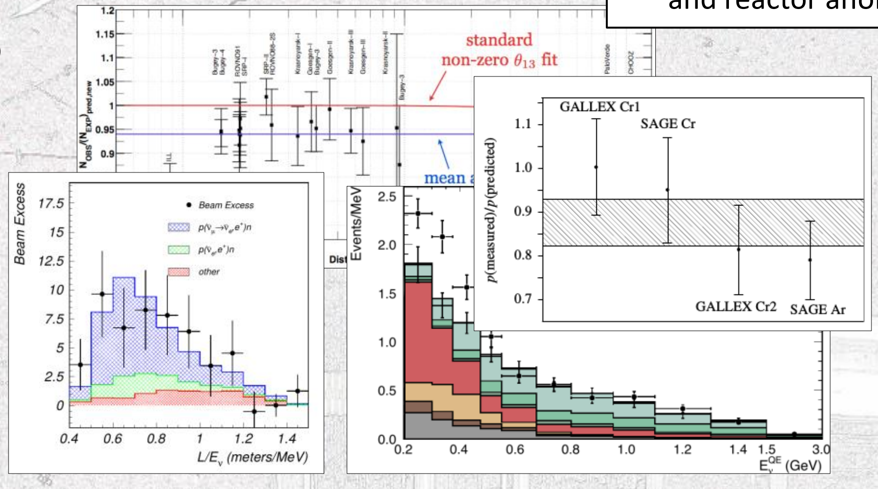




Sterile neutrino search

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

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

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

OPERA can test the sterile neutrino hypothesis looking for deviations from predictions 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]
- $\Delta m^2_{41} > 0$ 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}:

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

~ standard oscillation

pure exotic oscillation

Effective mixing parameter (leading mixing term at SBL)

interference terms

CP-violating terms

Mass Hierarchy dependence

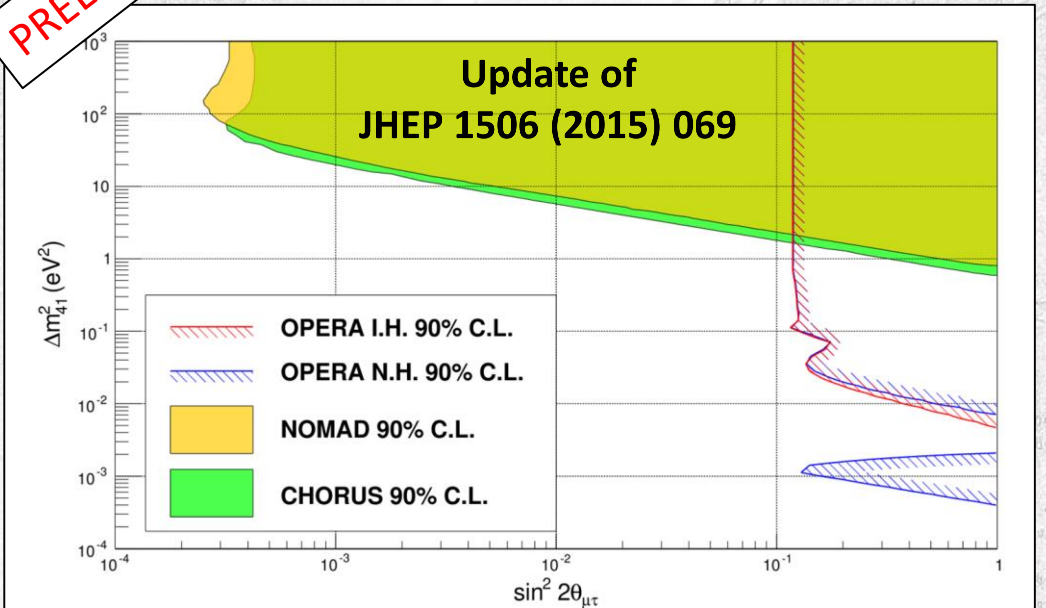
Effective parameters

$$C = 2|U_{\mu 3}||U_{\tau 3}|$$
$$\phi_{\mu\tau} = Arg(U_{\mu 3}U^*_{\tau 3}U^*_{\mu 4}U_{\tau 4})$$
$$\sin^2 2\theta_{\mu\tau} = 2|U_{\mu 4}||U_{\tau 4}|$$

... with ν_τ

[OPERA note 175]
[JHEP 1506 (2015) 069]

PRELIMINARY



- **Counting** analysis

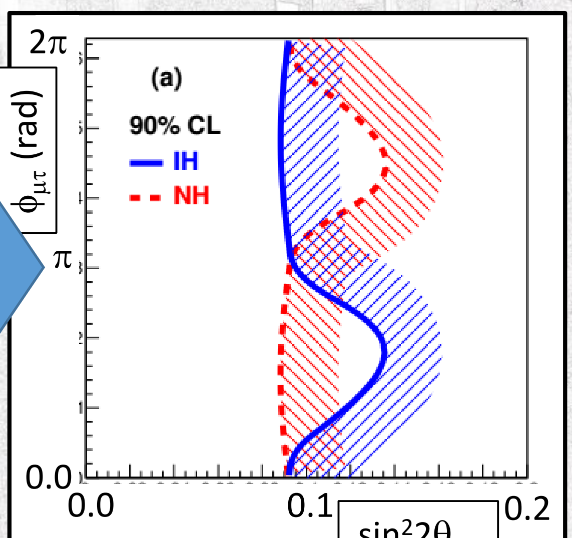
$$L = \boldsymbol{Pois(n;\mu)} \times \boldsymbol{Gaus(\Delta m^2_{23}; \widehat{\Delta m^2_{23}}, \widehat{\sigma_{\Delta m}})}$$

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

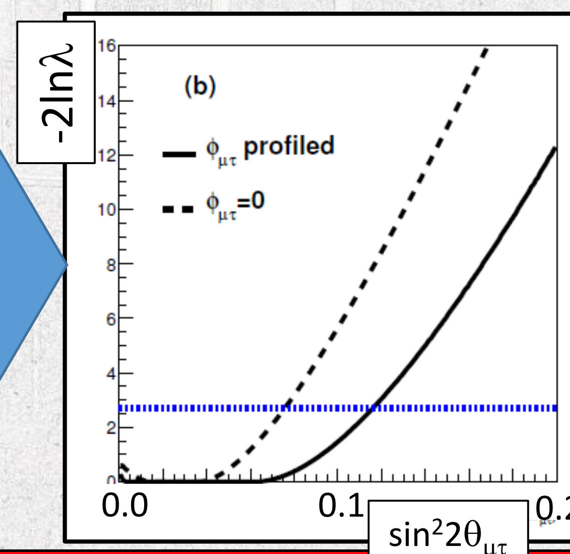
$\widehat{\Delta m^2_{23}}, \widehat{\sigma_{\Delta m}}$ PDG values

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



… with ν_e

[JHEP 1806 (2018) 151]

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

Δm^2_{41} vs $\sin^2 2\theta_{\mu e}$

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

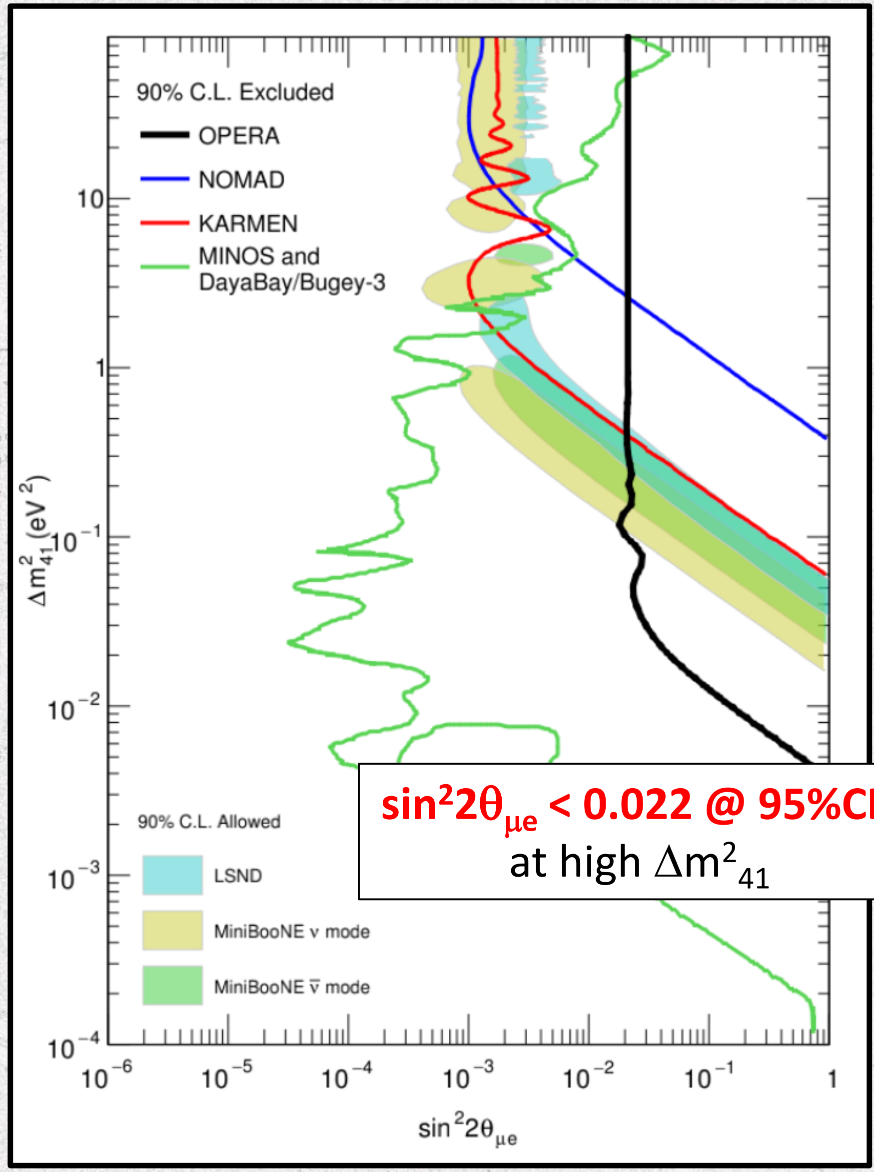
Systematics errors σ_i due to:
- Beam and efficiencies uncertainties
- 20% E_ν < 10 GeV & 10% E_ν > 10 GeV
- Bin-to-bin uncorrelated **(conservative approach)**

Likelihood

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

Prior on Δm^2_{23}

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



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

Combining ν_τ and ν_e

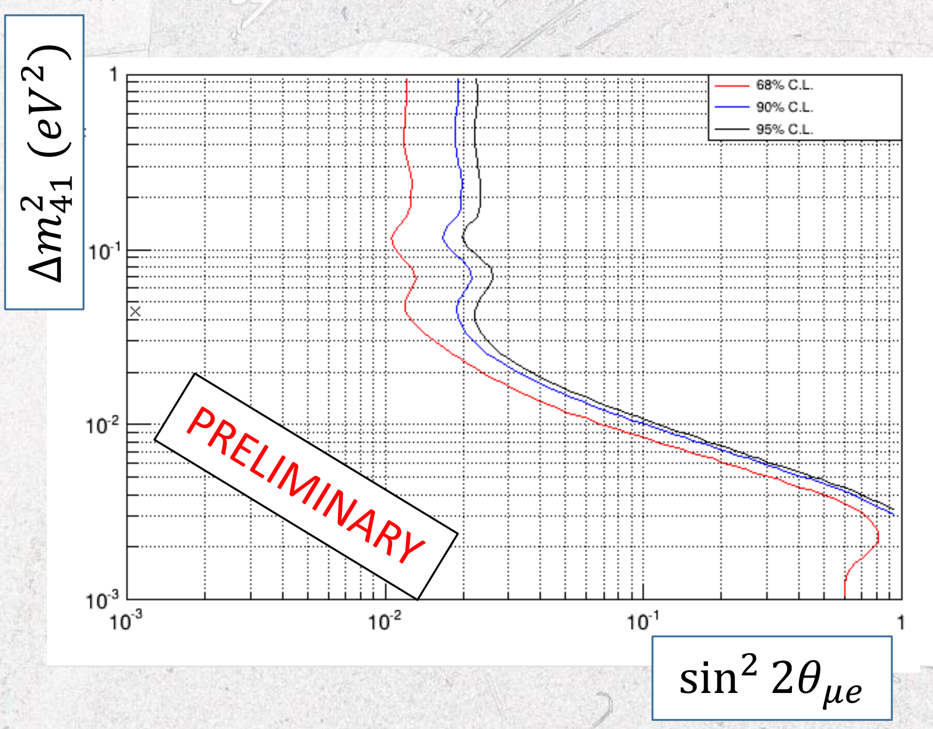
Exploiting **simultaneously** results of

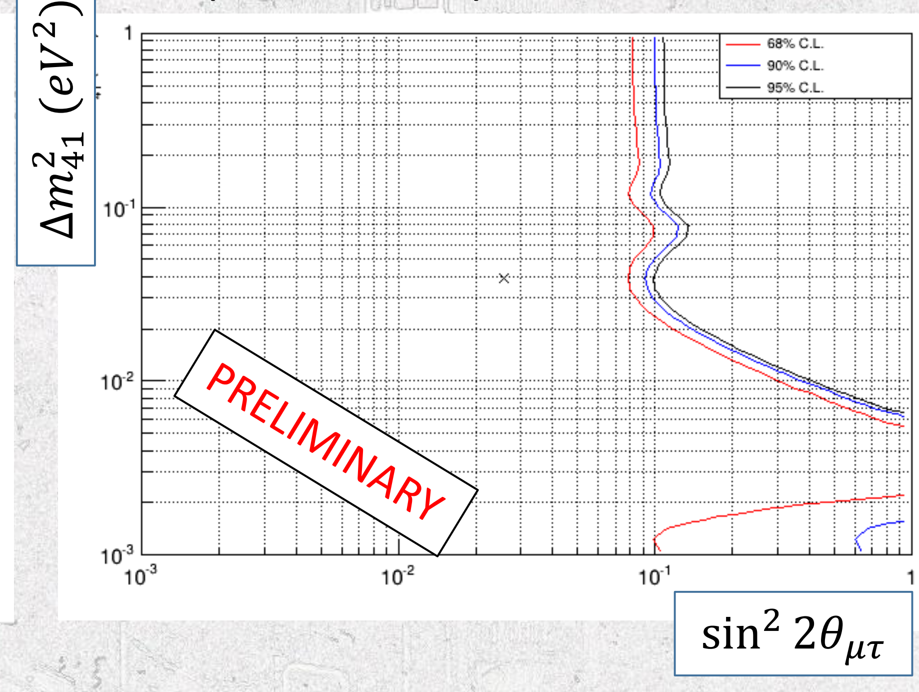
- ν_τ search: 10 candidates
- ν_e search: 35 candidates

….

… 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

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)

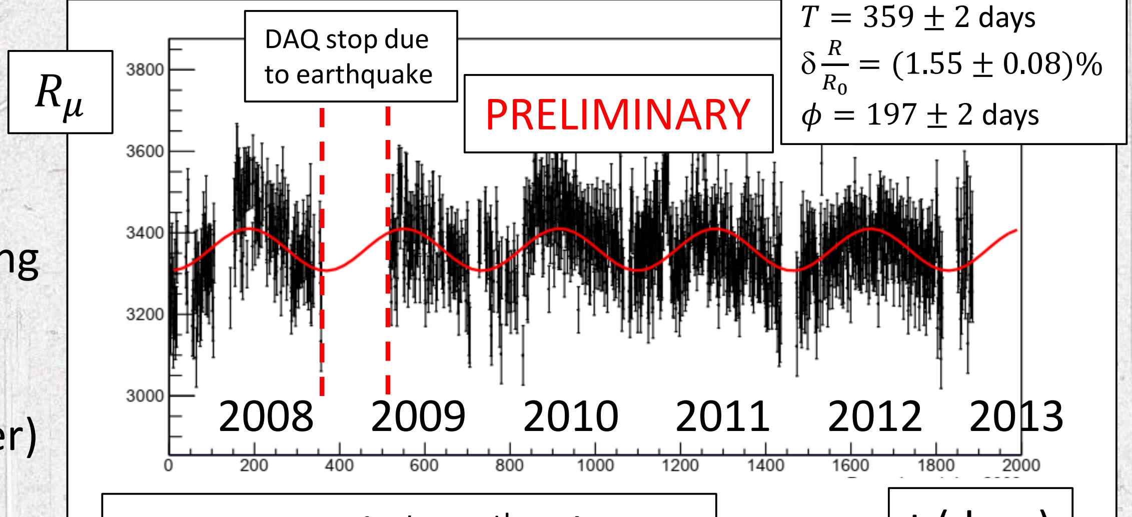
(More muons in summer than in winter)

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

$T = 359 \pm 2$ days

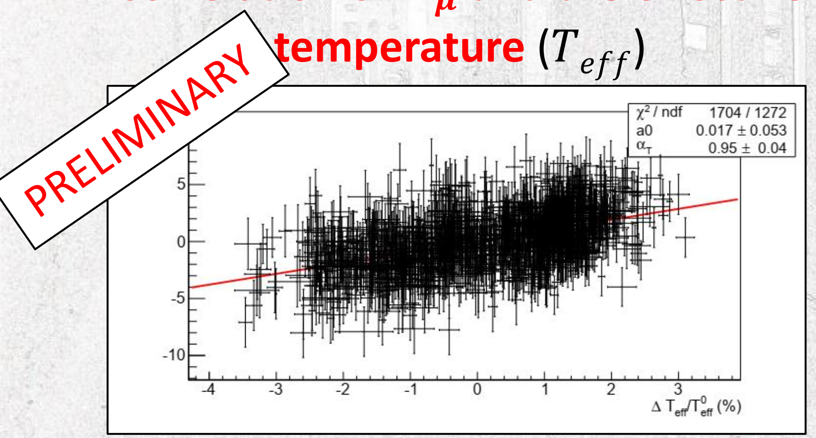
$\delta\frac{R}{R_0} = (1.55 \pm 0.08)\%$

$\phi = 197 \pm 2$ days



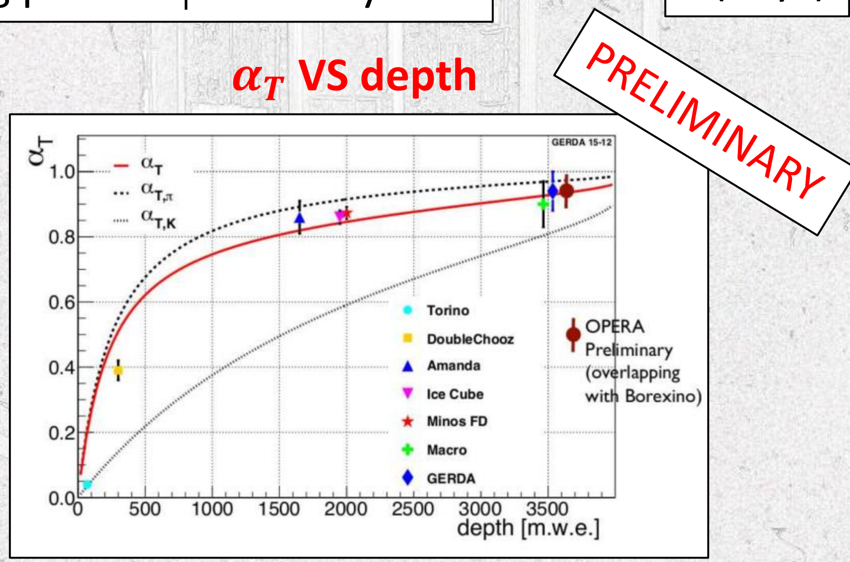
Fixing period: ϕ = 5th July

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



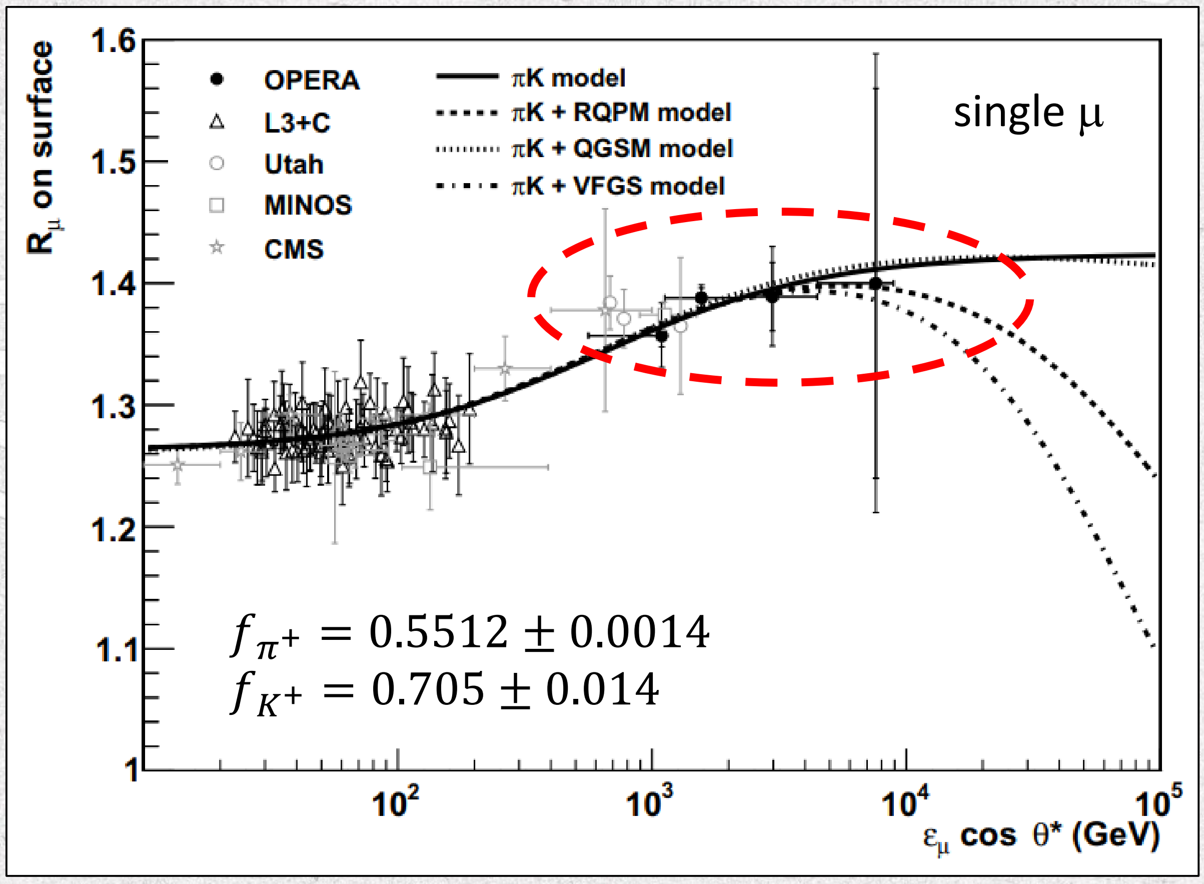
Atmospheric muon charge ratio

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

- **Highest-E region** reached
- **Opposite magnet polarities** runs → 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)

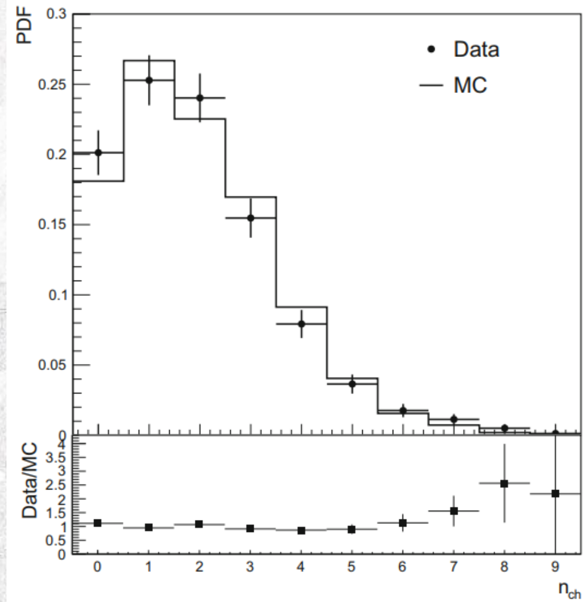


$f_{\pi^+} = 0.5512 \pm 0.0014$
$f_{K^+} = 0.705 \pm 0.014$

Neutrino interactions multiplicity

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

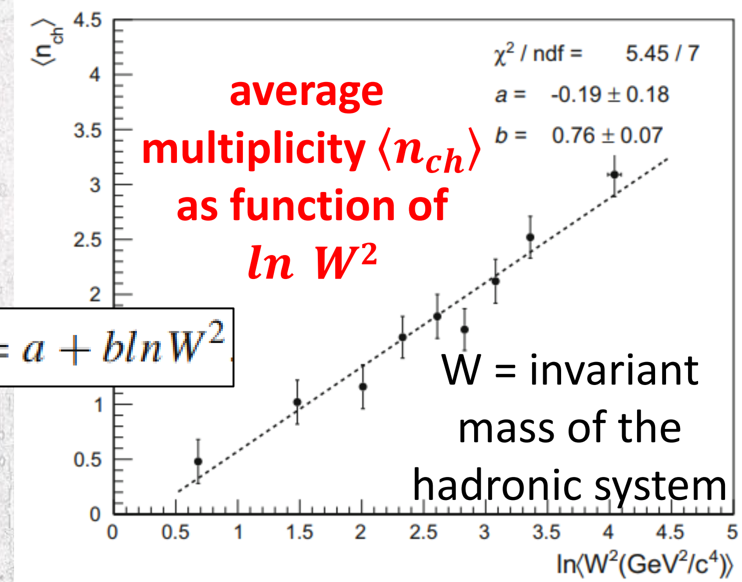
charged hadron multiplicity distribution



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

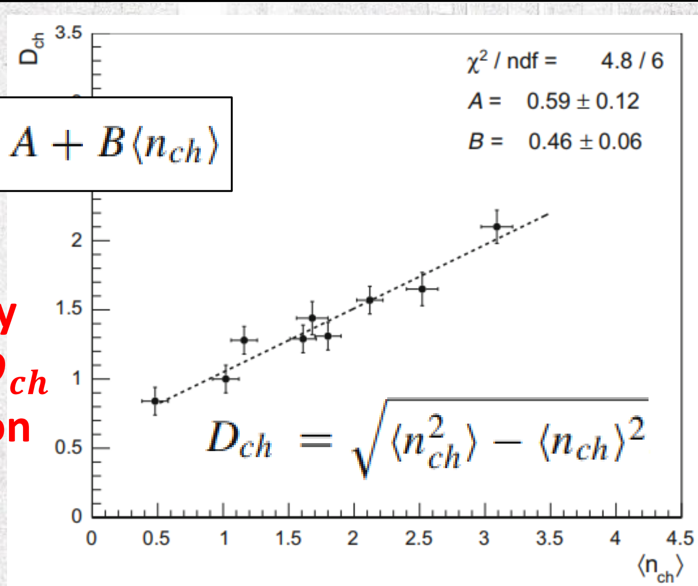
$$\langle n_{ch} \rangle = a + b \ln W^2$$

W = invariant mass of the hadronic system



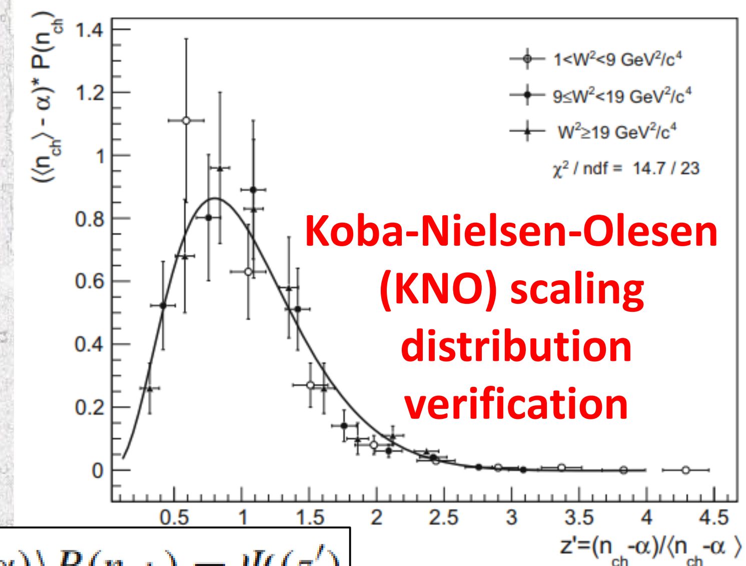
$$D_{ch} = A + B \langle n_{ch} \rangle$$

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



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

Koba-Nielsen-Olesen (KNO) scaling distribution verification



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

Conclusions

- **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

Thank you for your attention!

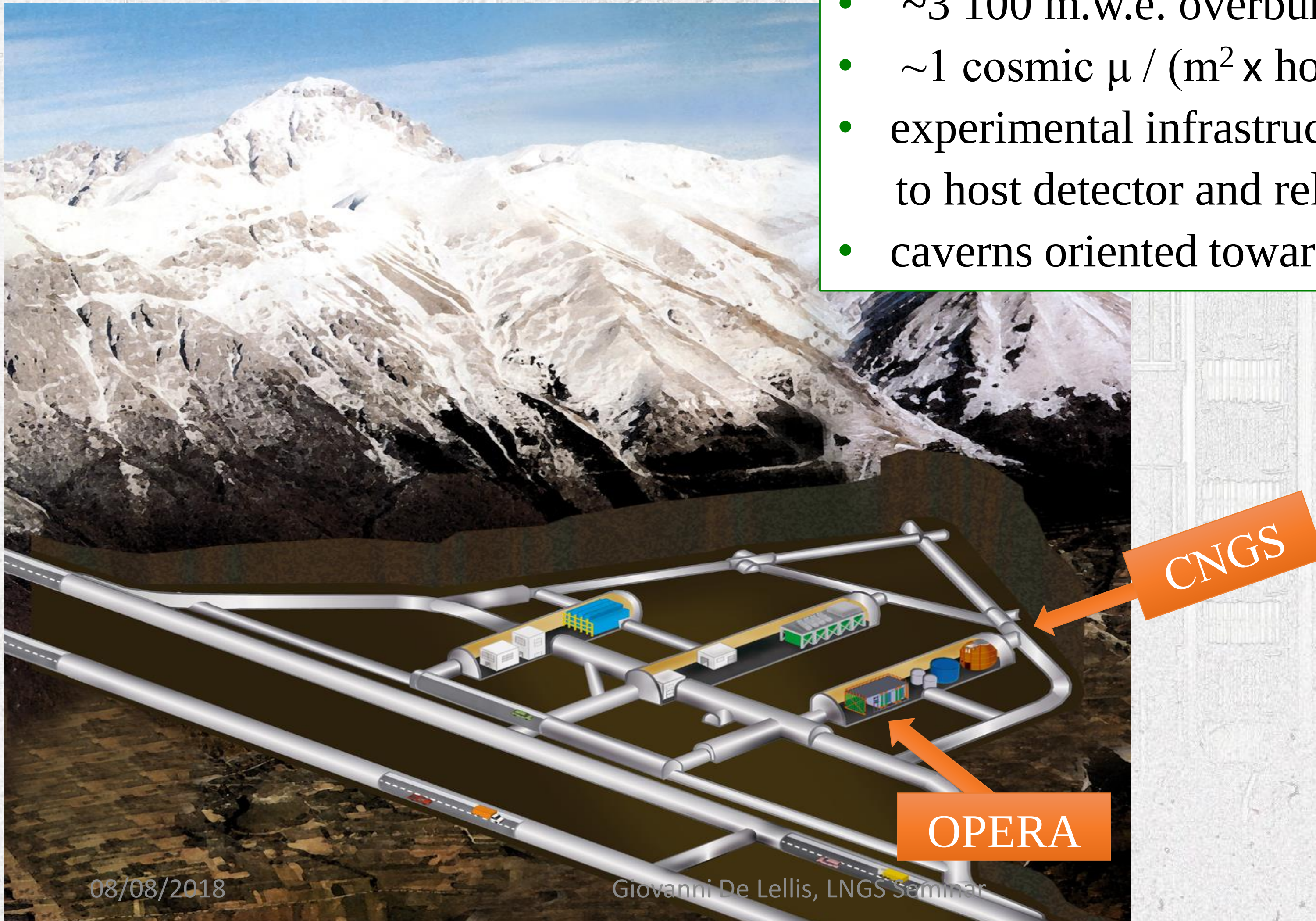
Image taken using **OPERA nuclear emulsion film** with a pinhole hand made camera
courtesy by Donato Di Ferdinando

Spares

LNGS OF INFN

The world largest underground physics laboratory

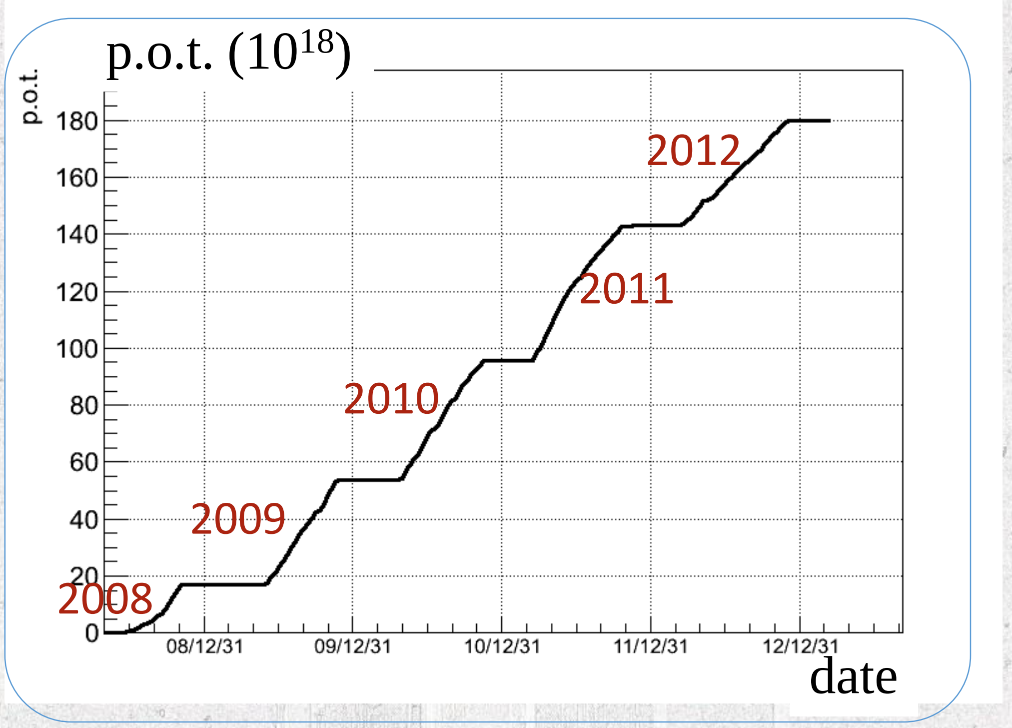
- ~180 000 m^3 caverns' volume
- ~3 100 m.w.e. overburden
- ~1 cosmic μ / (m^2 x hour)
- experimental infrastructure suitable to host detector and related facilities
- caverns oriented towards CERN



CNGS Performances

Along five years (2008 ÷ 2012) of data taking

Year	Beam days	p.o.t. (10^{19})
2008	123	1.74
2009	155	3.53
2010	187	4.09
2011	243	4.75
2012	257	3.86
Total	**965**	**17.97**



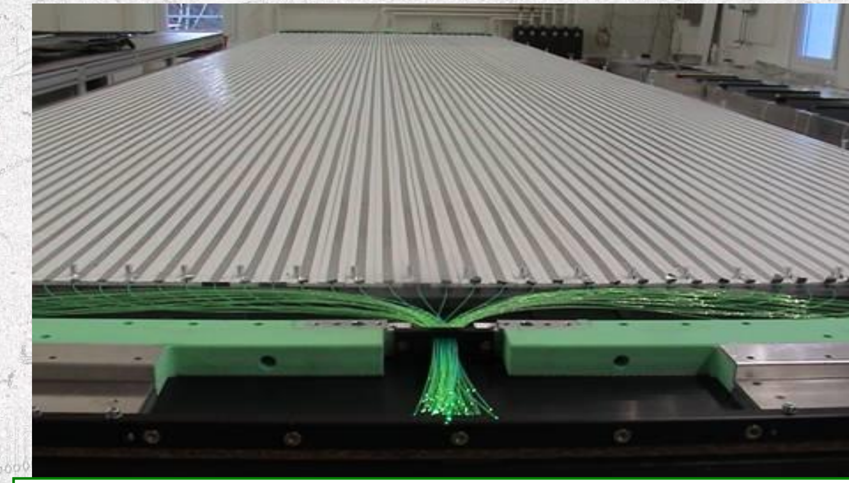
Record performances in 2011

Overall 20% less than the proposal value (22.5)

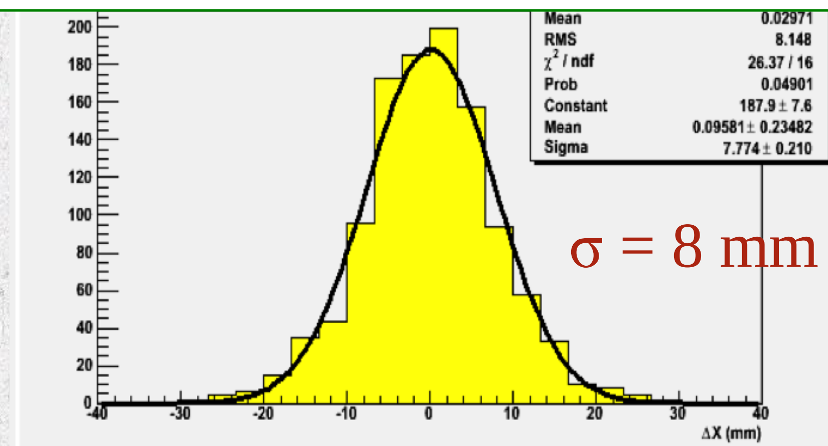
SCINTILLATOR STRIPS TARGET TRACKER AND BRICK TRAYS

NIM A577 (2007) 523

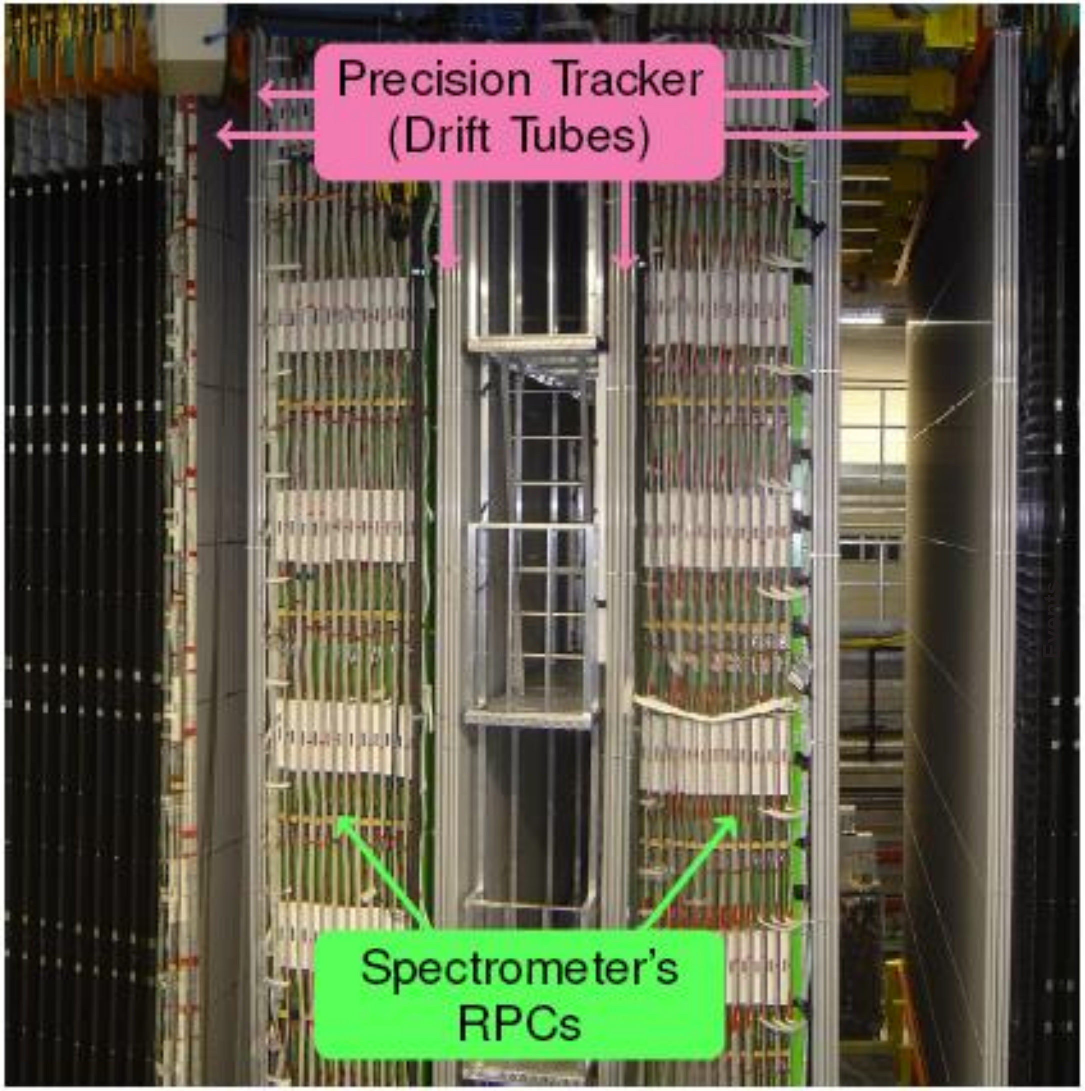
mechanical structure:
brick trays, only 0.5% of target mass



- > 5 p.e. for a m.i.p.
- ~ 99% detection efficiency ⇒ trigger
- position accuracy: ~ 8 mm
- angular accuracy: ~ 15 mrad

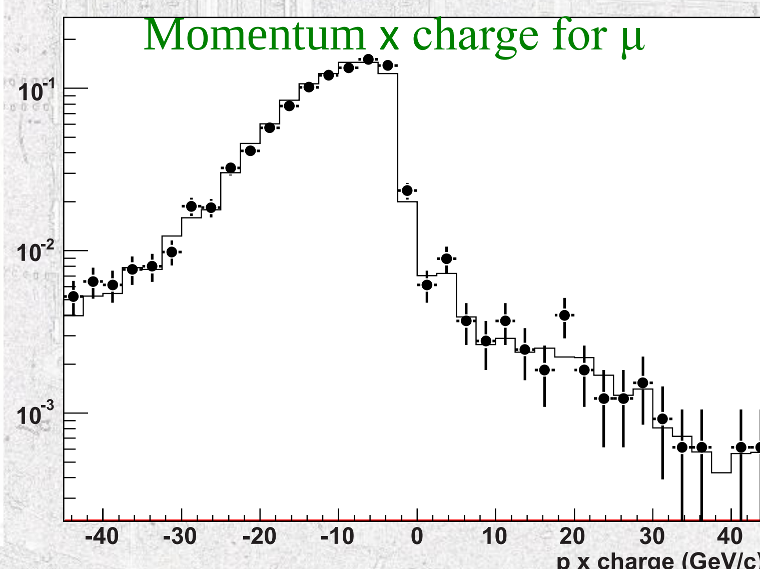


The Magnetic Spectrometer



NIM A602 (2009) 631-634

- **1.55 T** magnetic field bending particles in the horizontal plane
- 24 slabs of magnetized iron interleaved with RPC planes
- 6 drift tube stations for precision measurement of the angular deflection
- momentum resolution:
  20% below 30 GeV



New Journal of Physics 13 (2011) 053051

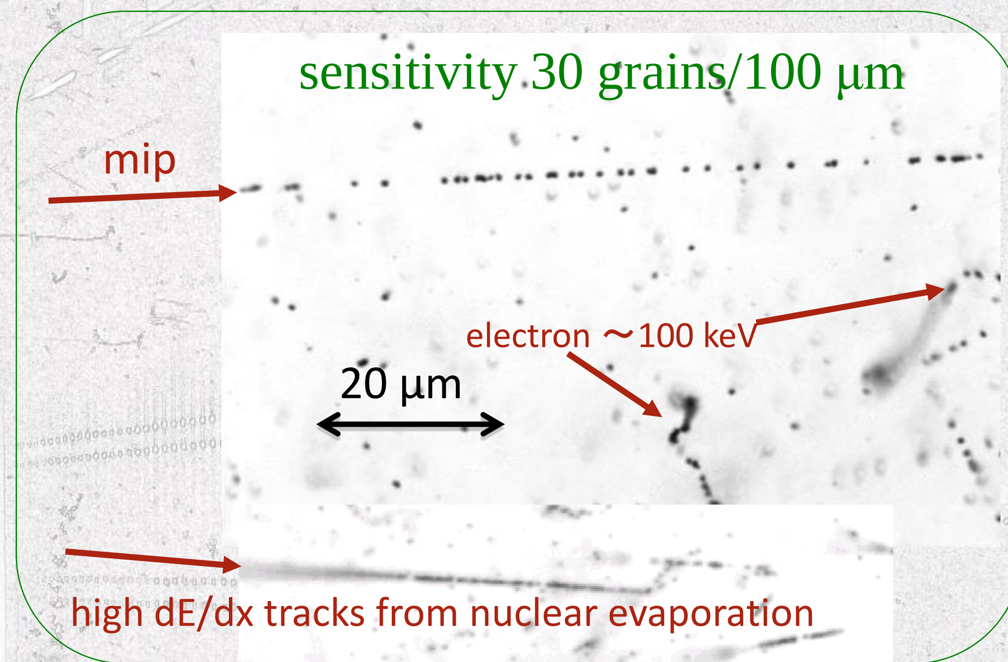
THE ECC TARGET BRICKS

The heart of the experiment

<u>Emulsion Cloud Chamber</u>

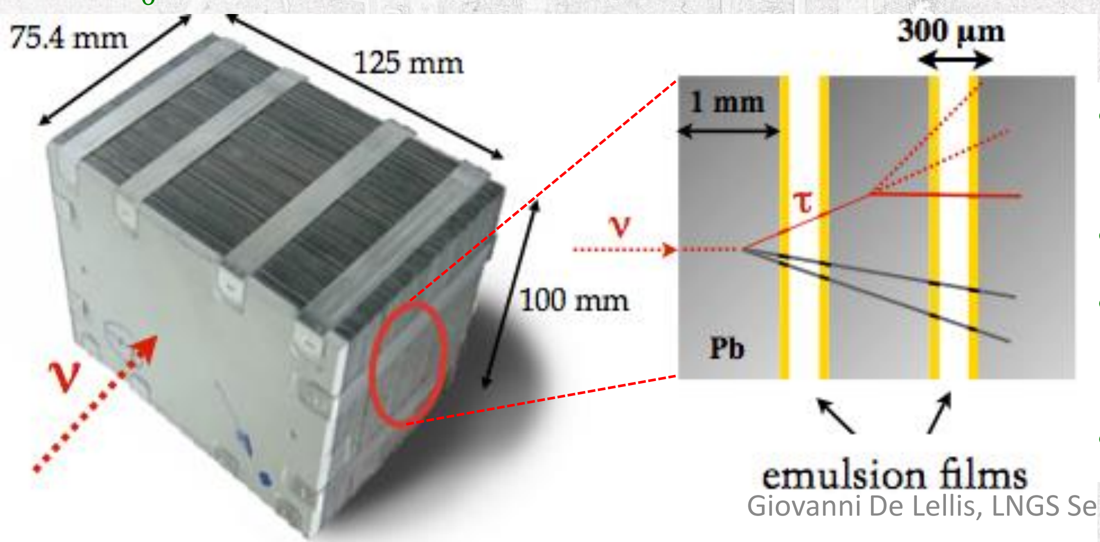
ECC

- passive material → lead
  (massive target)
- tracking device → nuclear emulsions
  (high resolution)



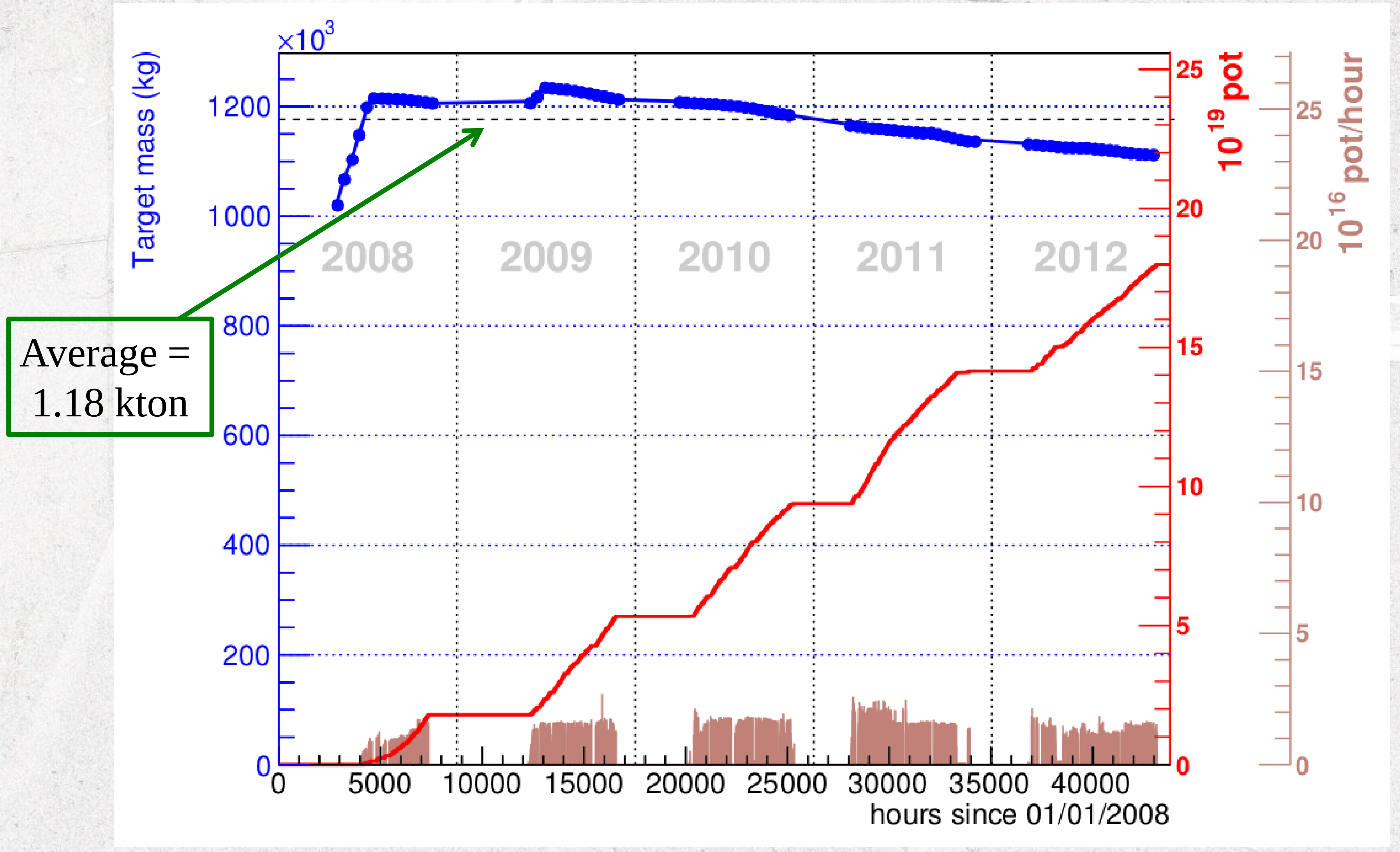
NIM A556 (2006) 80-86

10 X_0



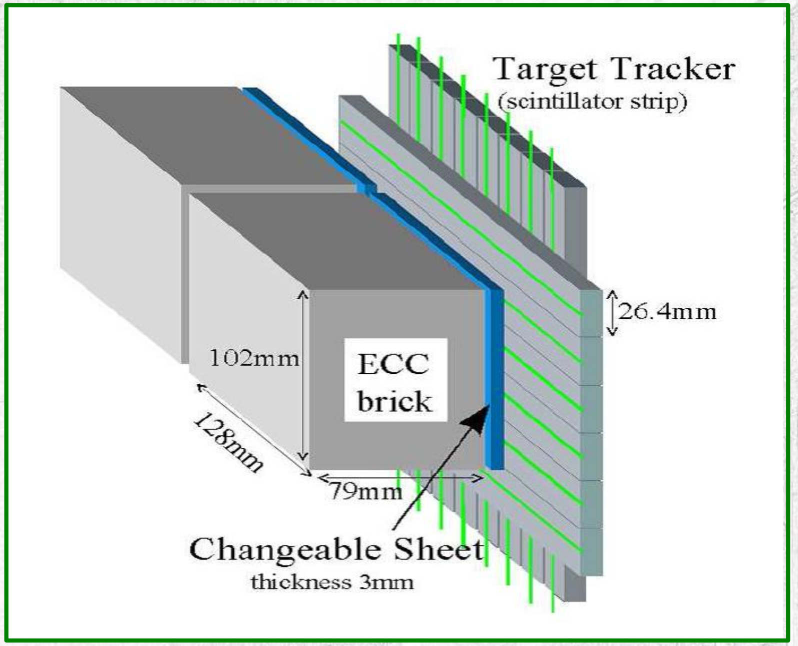
- The OPERA target consists of 150’000 ECC bricks
- Total lead surface: 105’000 m^2
- Total film surface: 110’000 m^2
  (~ 9 million films)
- Total target mass ~ 1.2 kton

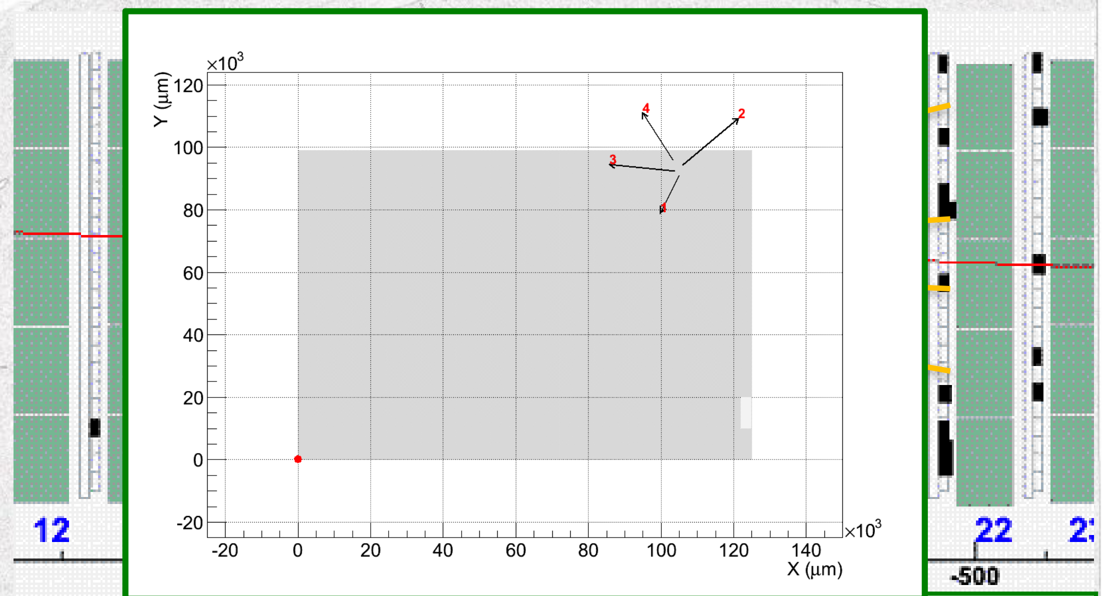
Target Mass Evolution During Runs

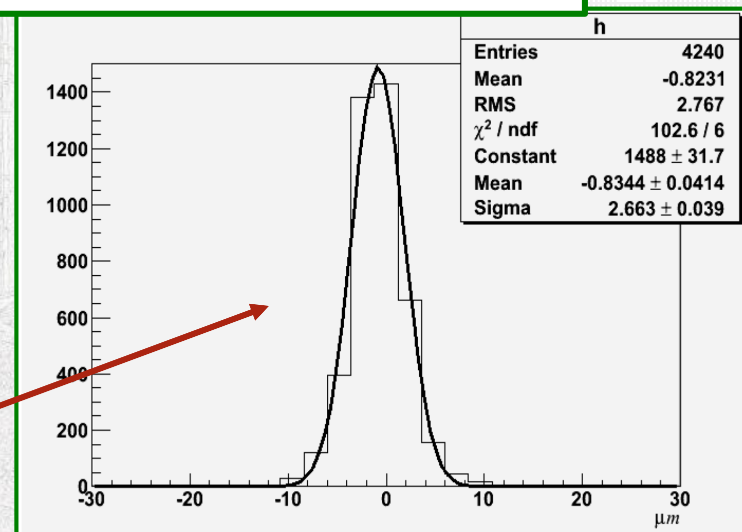


Interface Films

for the brick validation







Two interface (changeable, CS) films packed in a detachable box, glued downstream of each brick

Alignment of CS films by Compton electrons: 2.5 μm

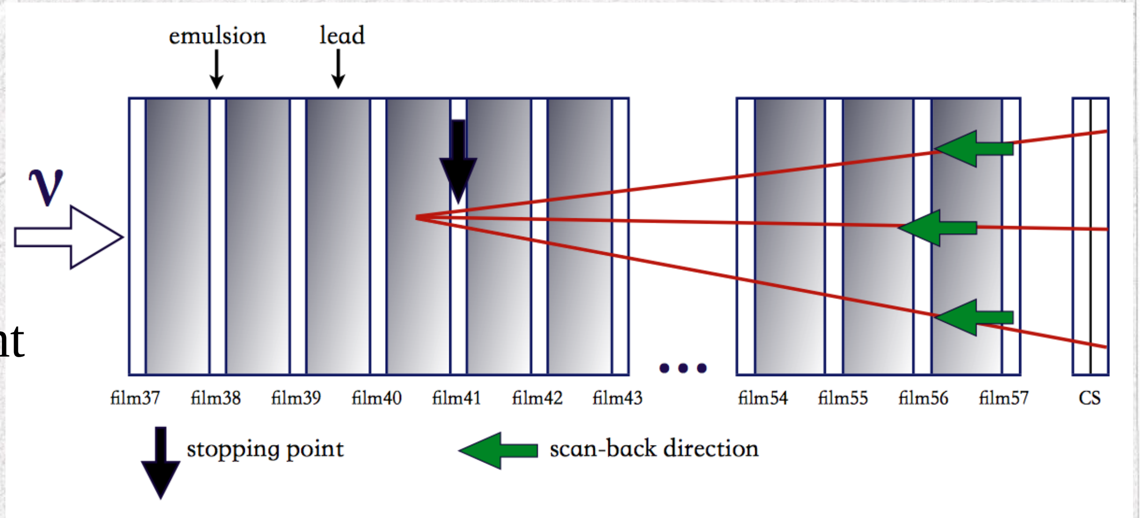
JINST 3 (2008) P07005

About ~ 4’000’000 cm^2 of CS surface analysed

TRACK FOLLOW-UP AND VERTEX FINDING

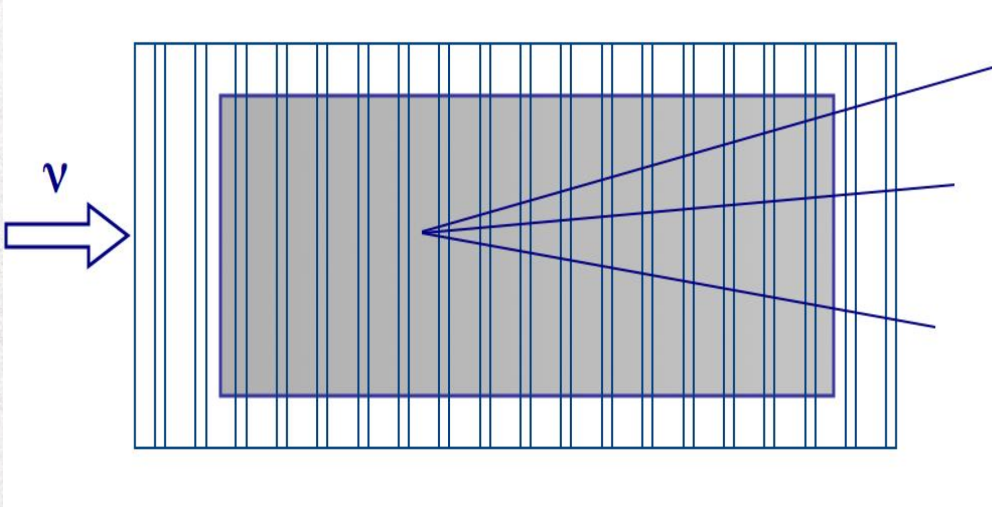
Track follow-up film by film:

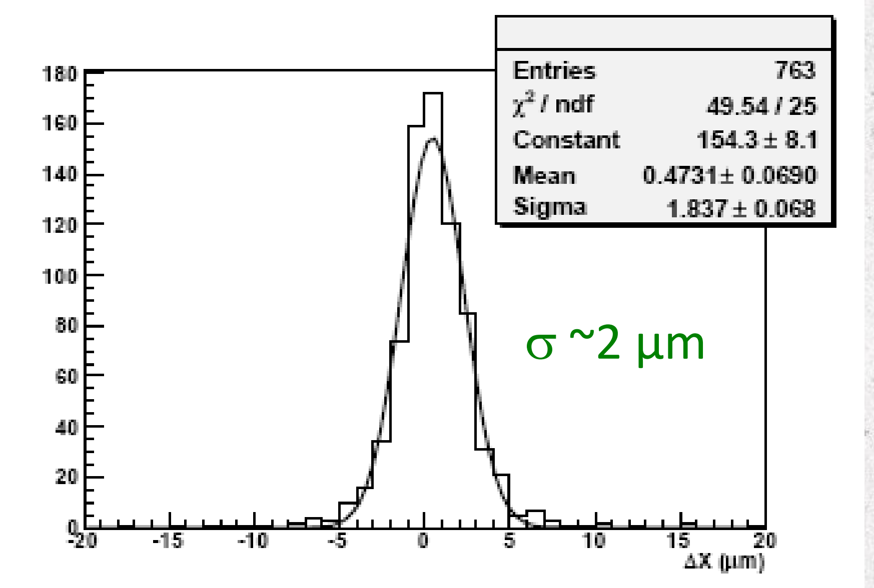
- Brick exposure at the surface laboratory to cosmic-rays for alignment
- Definition of the stopping point



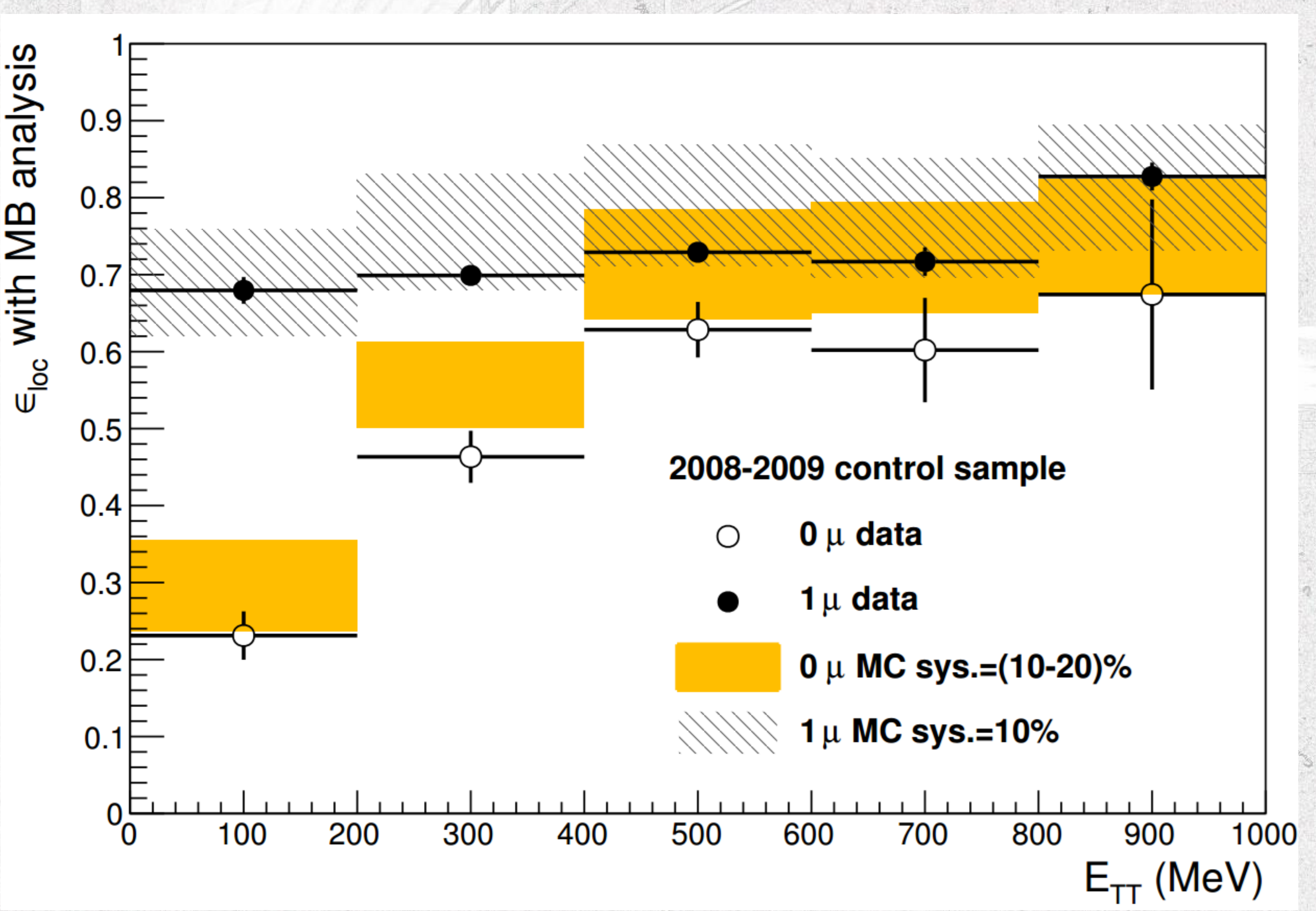
Volume scan:

- ~2 cm^3 around the stopping point



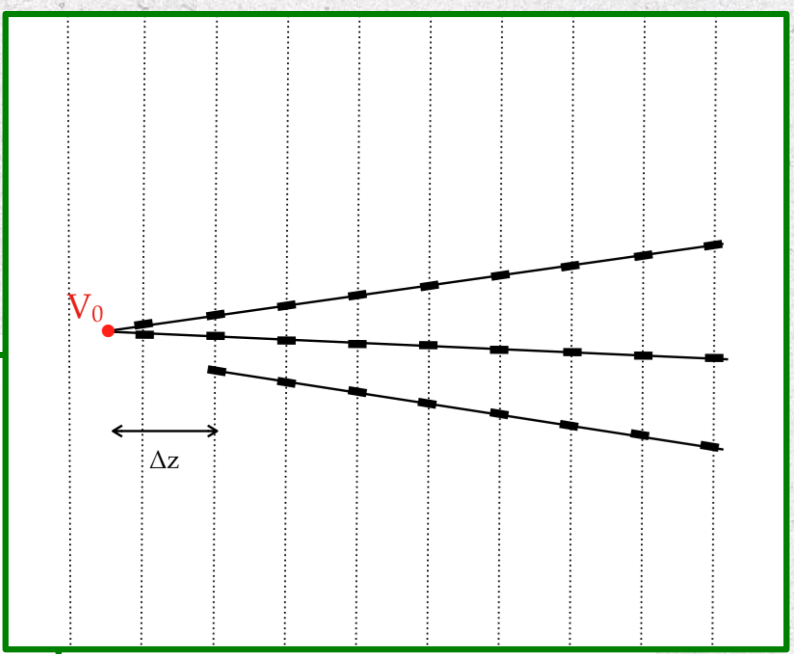


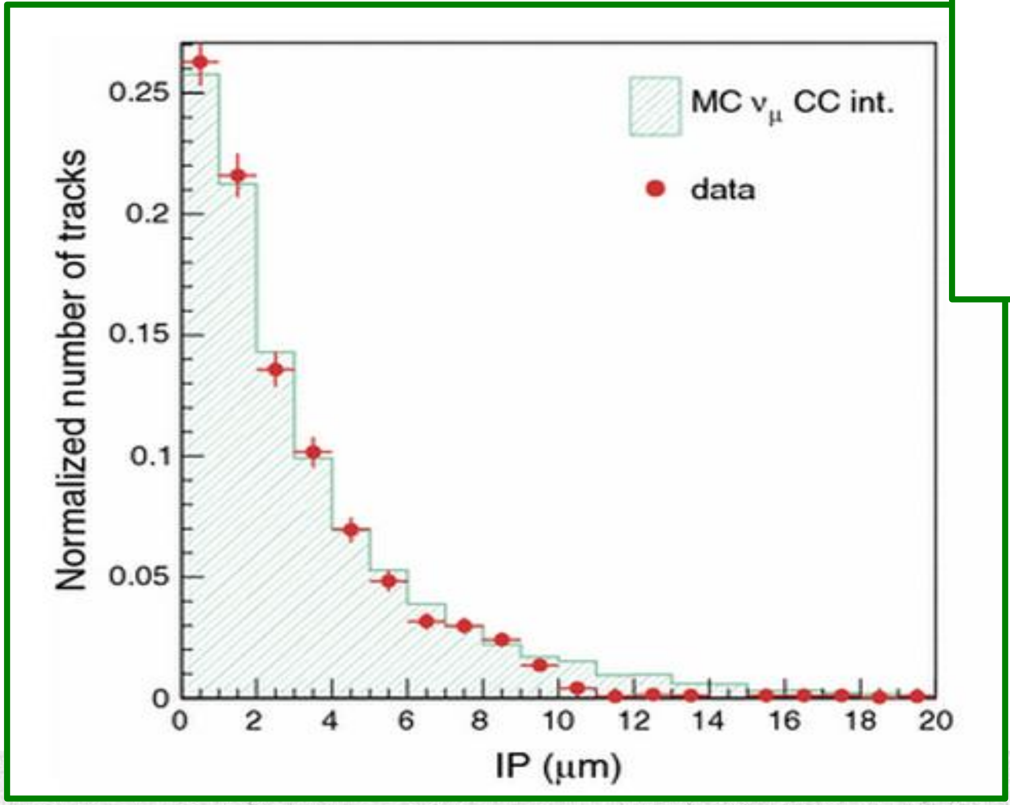
Vertex location efficiency



DECAY SEARCH

- **Primary vertex definition**
  - inspection of segments on the vertex plate
  - impact parameter <10 (5+0.01 Δz) μm,
    if Δz<(≥)500 μm





Decay Search

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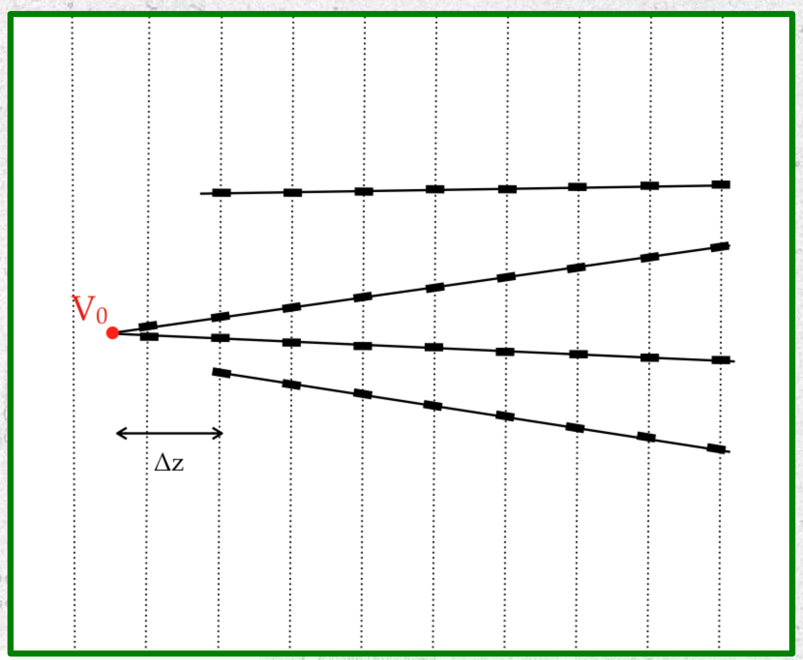
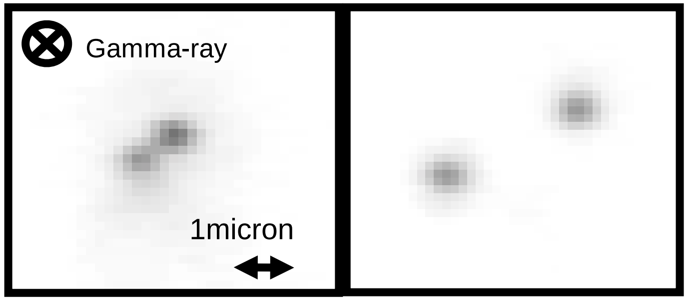


- **Extra-track search**

  - selection of tracks reconstructed in the volume but not attached to primary vertex
  - identification of e^+e^- pairs by visual inspection



A close-up of an electron pair

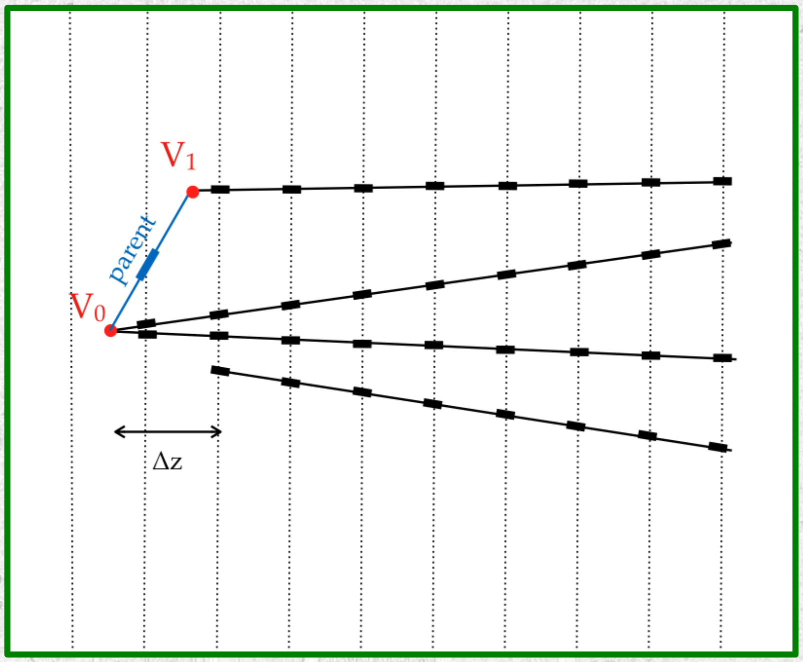
DECAY SEARCH

- **Primary vertex definition**

  - inspection of segments on the vertex plate

  - impact parameter <10 (5+0.01 Δz) μm,

    if Δz<(≥)500 μm



- **Extra-track search**

  - selection of tracks reconstructed in the volume but not attached to primary vertex

  - identification of e^+e^- pairs by visual inspection

- **In-track search**

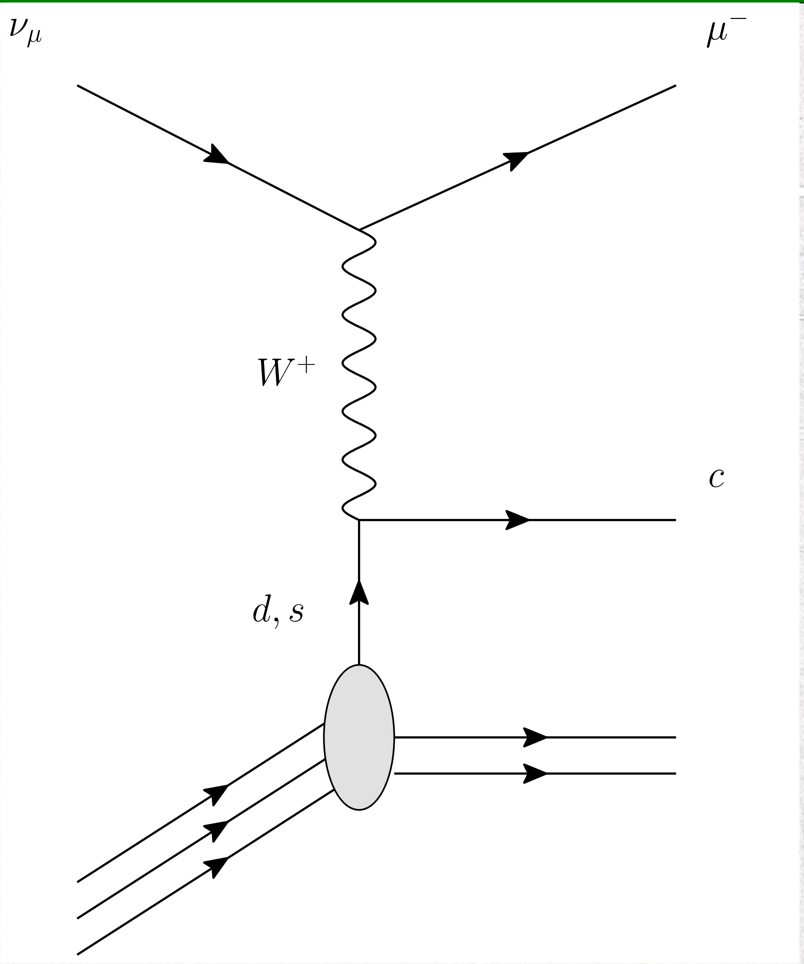
  - search for small kinks along the tracks attached to the primary vertex

- **Parent search**

  - search for a track connecting the selected extra-track and the primary vertex

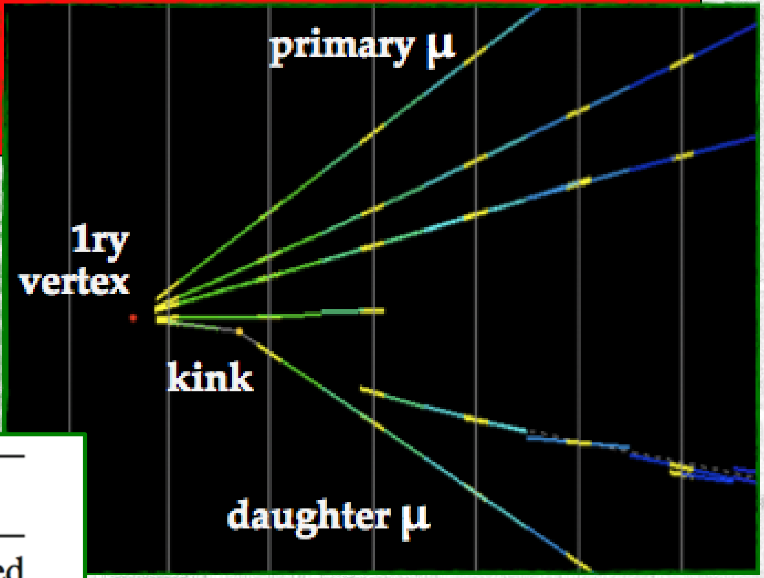
Charmed Hadron Production

control sample for the τ search
to check the efficiency → signal expectation



Charmed Hadron Production

- Charm and τ decays have the same topology
- Similar lifetime and masses
- Charmed hadrons from ν_μ CC interactions
- Muon at the primary vertex
- Used as "control sample"



Decay topology	Events			
	Expected charm	Expected background	Expected total	Observed
1-prong	21 ± 2	9 ± 3	30 ± 4	19
2-prong	14 ± 1	4 ± 1	18 ± 1	22
3-prong	4 ± 1	1.0 ± 0.3	5 ± 1	5
4-prong	0.9 ± 0.2	–	0.9 ± 0.2	4
Total	40 ± 3	14 ± 3	54 ± 4	50

Eur. Phys. J. C74 (2014) 2986

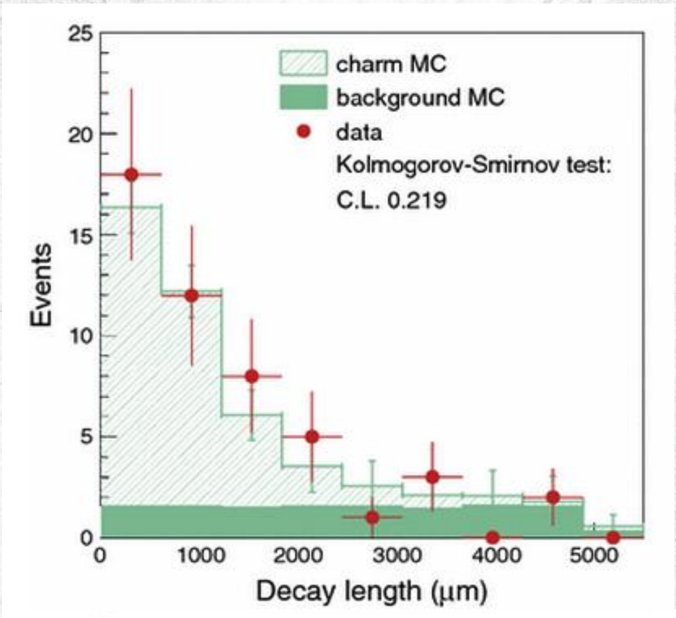
Background from hadronic interactions (87%) and strange particle decays (13%)

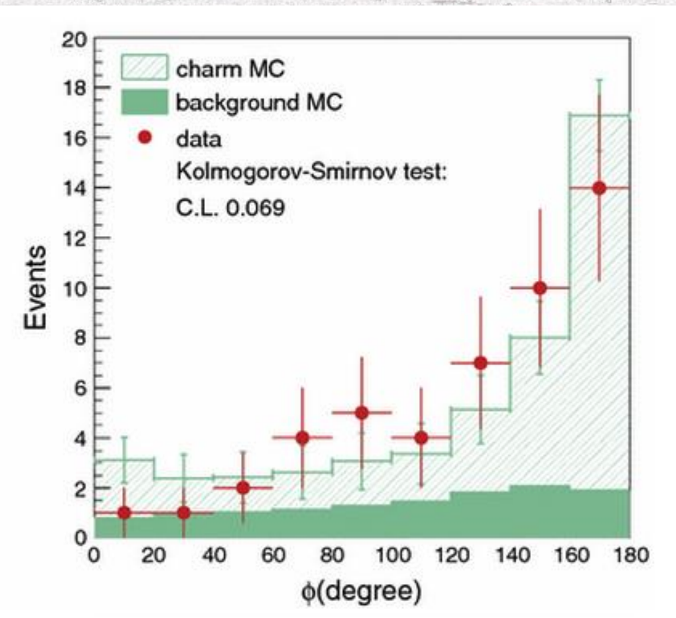
Good agreement between data and expectations ~10%

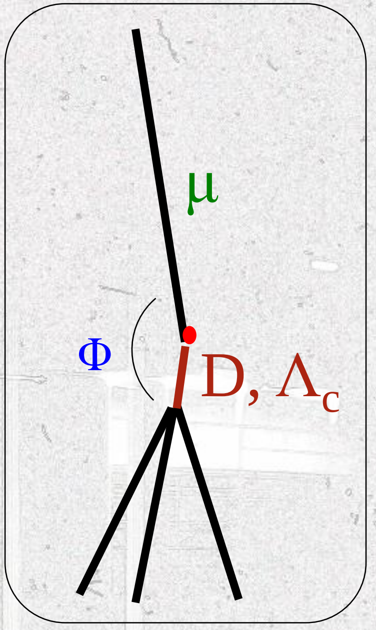
KINEMATICAL VARIABLES

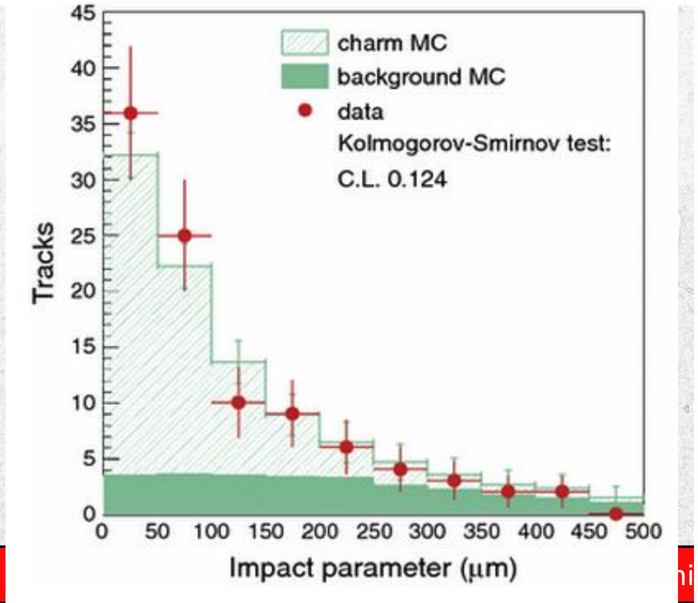
Fair agreement between data and Monte Carlo

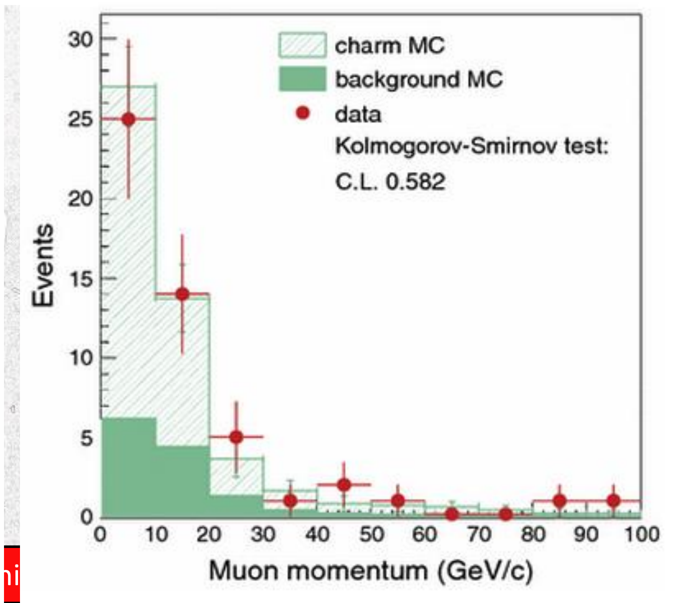
Eur. Phys. J. C74 (2014) 2986



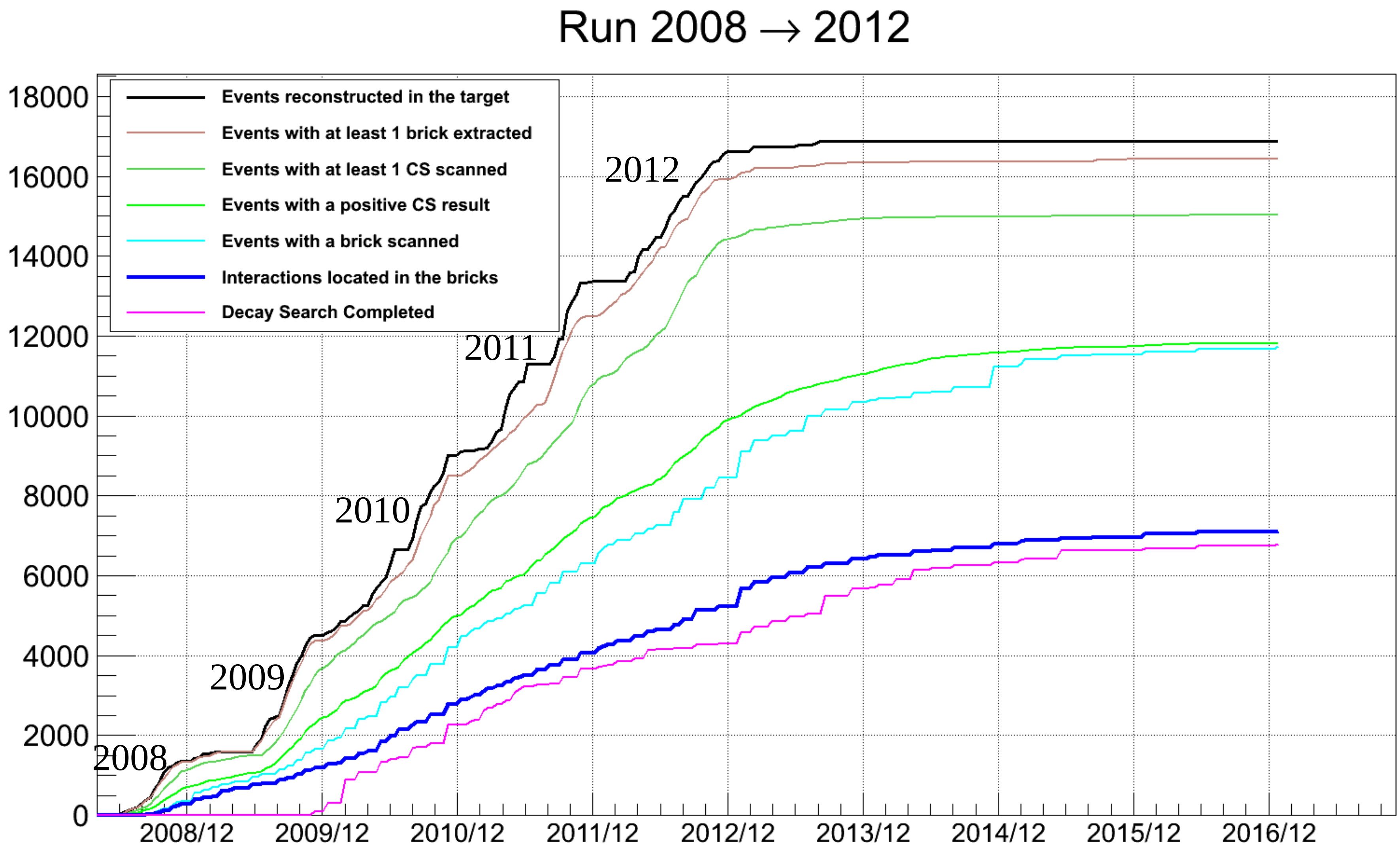








DATA ANALYSIS COMPLETED

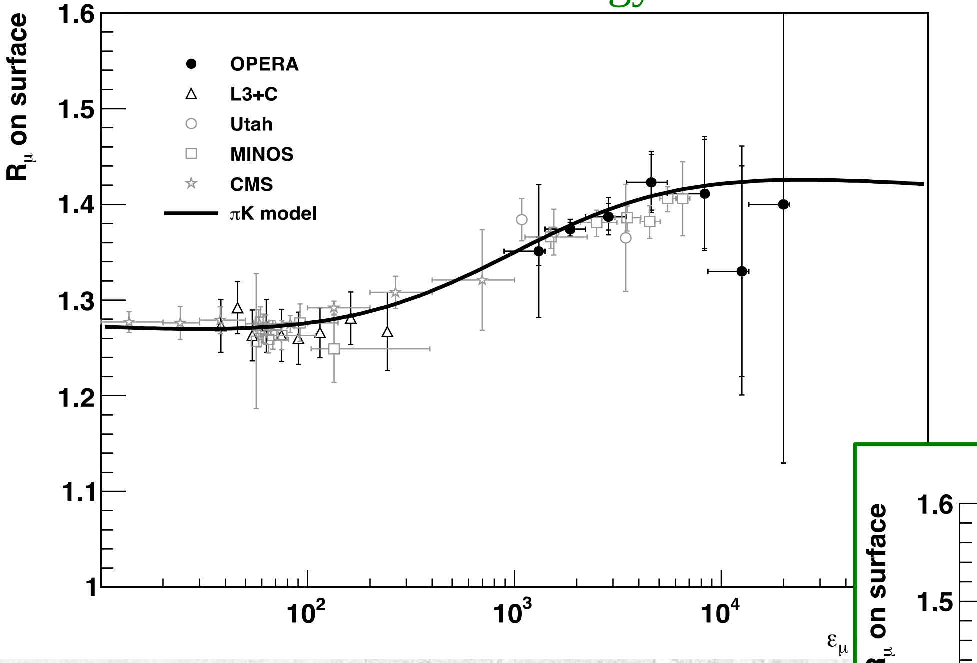


7132 located interactions

6785 decay search

COSMIC-RAY PHYSICS

Surface energy

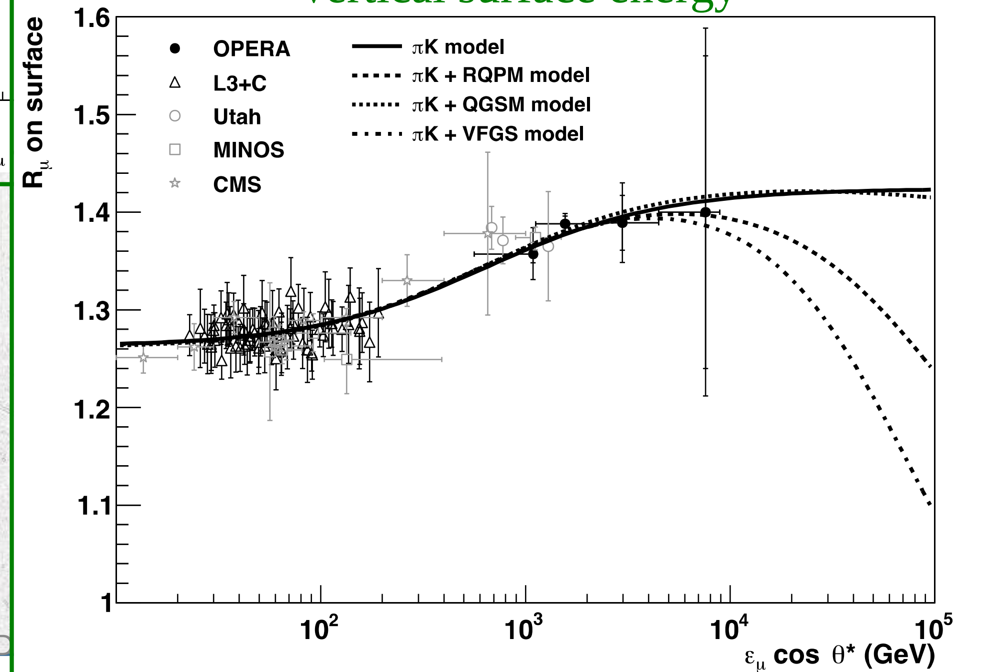


Measurement of TeV atmospheric muon charge ratio

Eur. Phys. J. C74 (2014) 2933

$$R_\mu \equiv N_{\mu^+}/N_{\mu^-}$$

Vertical surface energy



COSMIC-MUON RATE AND TEMPERATURE DEPENDENCE

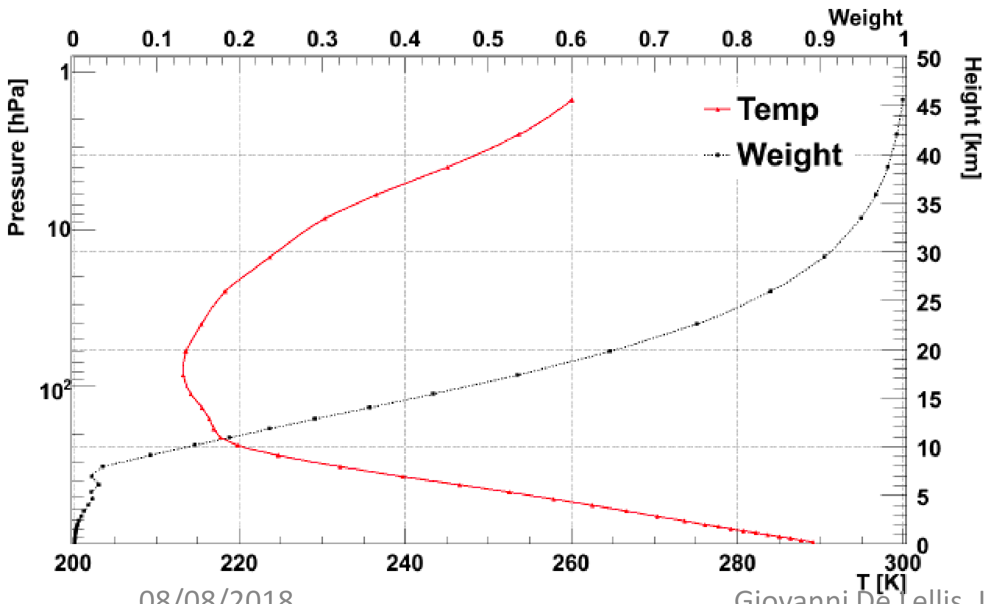
- Gran Sasso underground~3800 m w.e.→Minimum muon energy~1.4TeV
- Atmospheric temperature increase → density decrease → increase the pion decay rate → muon rate increase

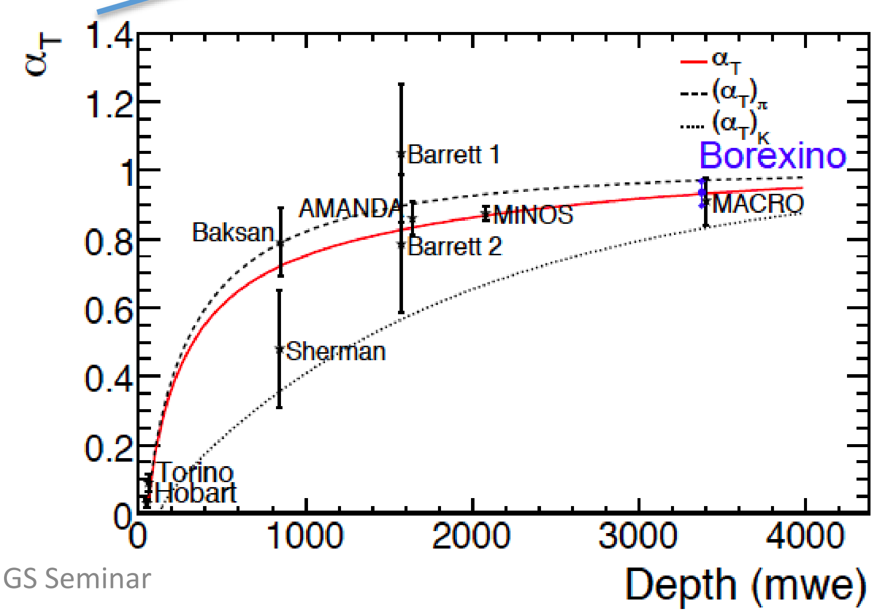
$$I_\mu(t) = I_\mu^0 + \Delta I_\mu = I_\mu^0 + \delta I_\mu \cos\left[\frac{2\pi}{T}(t - t_0)\right]$$

$$T_{eff} = \frac{\int_0^\infty T(x)W(x)dx}{\int_0^\infty W(x)dx}$$

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

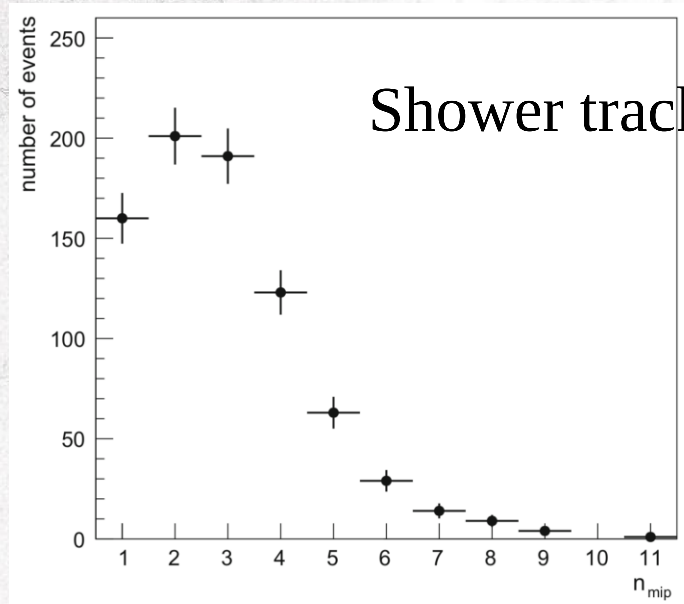
High W in high atmosphere → high energy muons



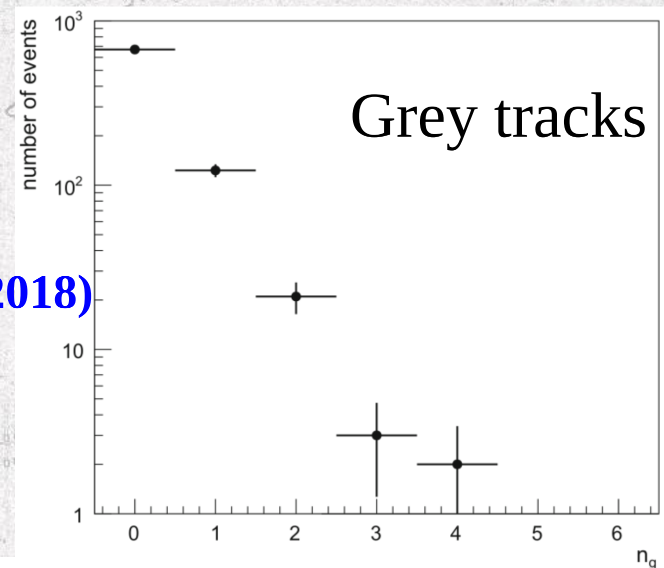


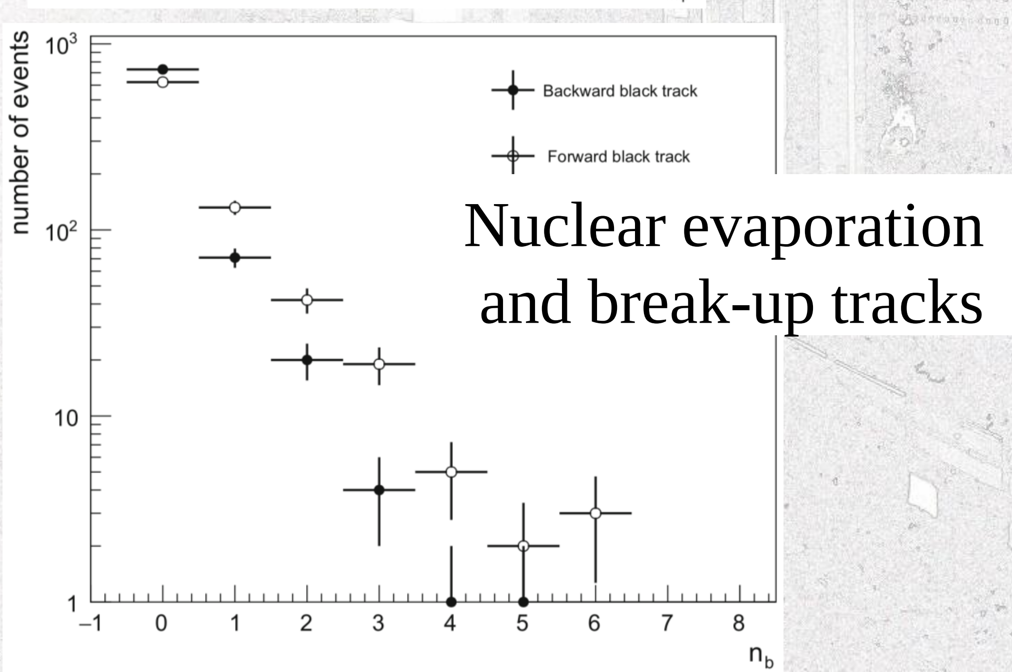
TRACK MULTIPLICITY DISTRIBUTIONS

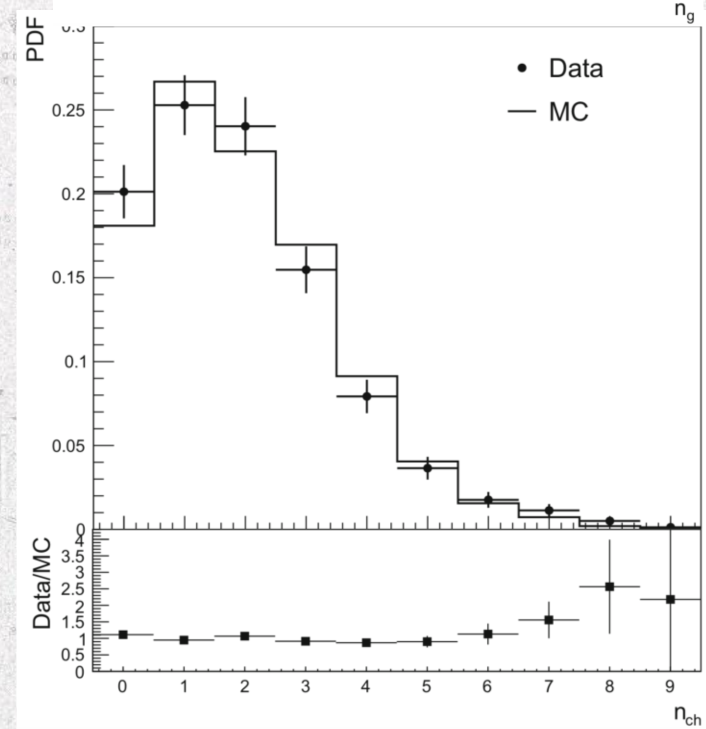
REFLECTING THE DYNAMICS OF INTERACTIONS



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

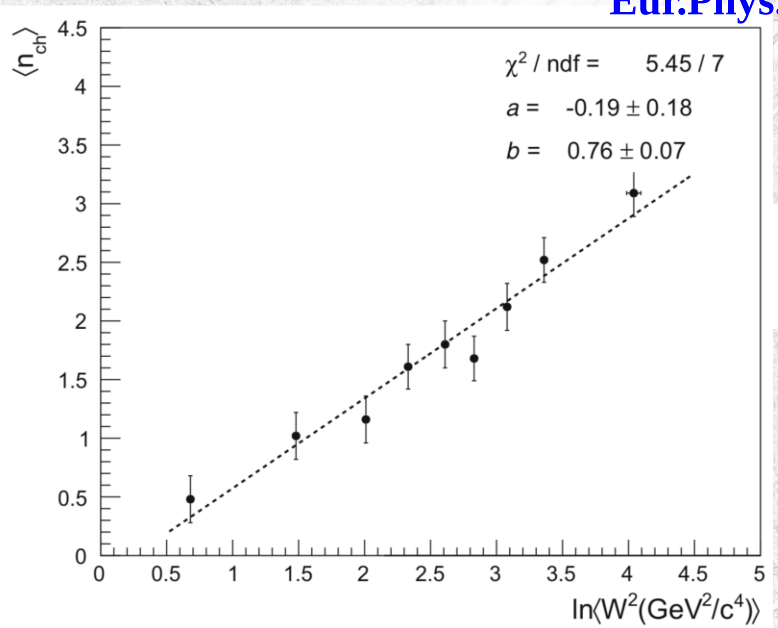




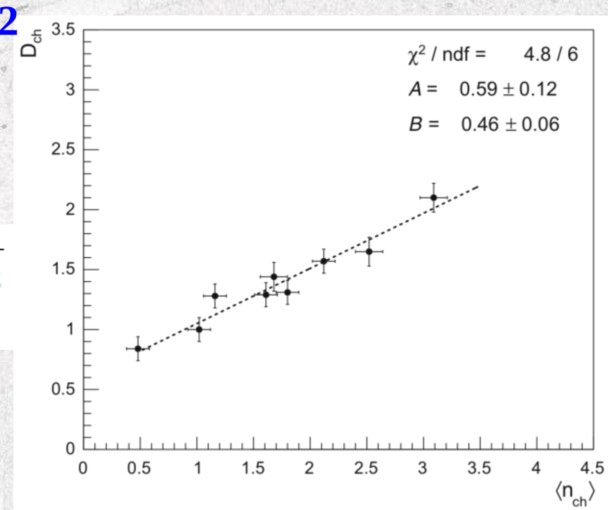


MULTIPLICITY FEATURES

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



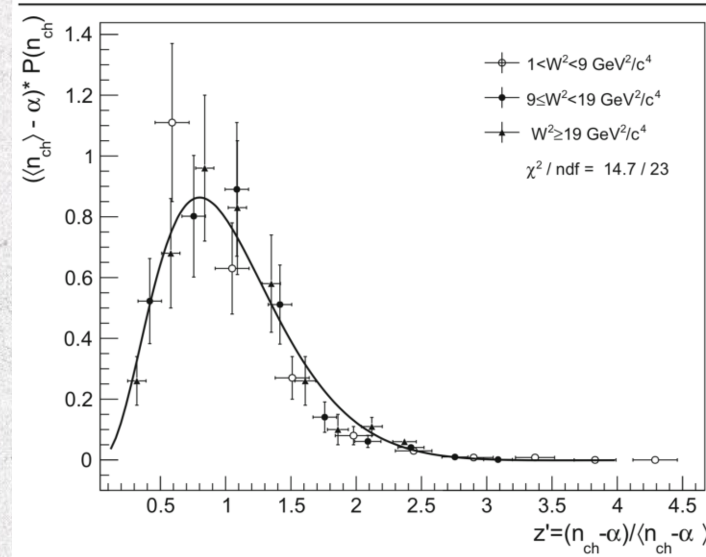
$$D_{ch} = \sqrt{\langle n_{ch}^2 \rangle - \langle n_{ch} \rangle^2}$$



Reaction	$\langle E_\nu \rangle$(GeV)	a	b
ν_μ-emulsion	38	0.45 ± 0.24	0.94 ± 0.08
ν_μ-emulsion	50	1.92 ± 0.68	1.19 ± 0.23
ν_μ-emulsion	8.7	1.07 ± 0.05	1.32 ± 0.11
ν_μ-lead	20	-0.19 ± 0.18	0.76 ± 0.07

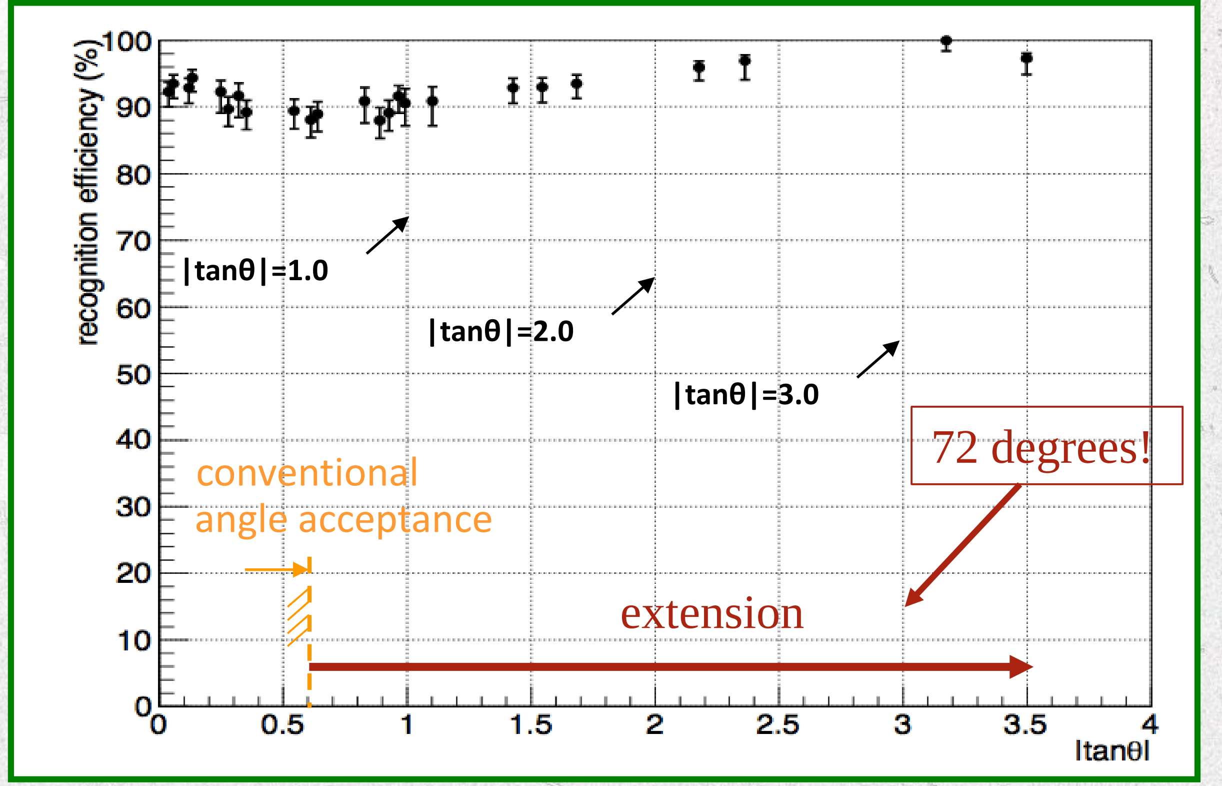
Reaction	$\langle E_\nu \rangle$(GeV)	a	b
ν_μ-emulsion	38	0.45 ± 0.24	0.94 ± 0.08
ν_μ-emulsion	50	1.92 ± 0.68	1.19 ± 0.23
ν_μ-emulsion	8.7	1.07 ± 0.05	1.32 ± 0.11
ν_μ-lead	20	-0.19 ± 0.18	0.76 ± 0.07

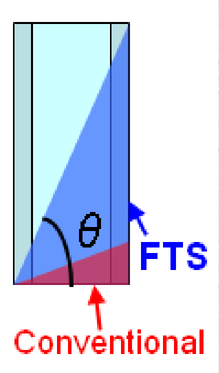
KNO Scaling



IMPROVEMENTS 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





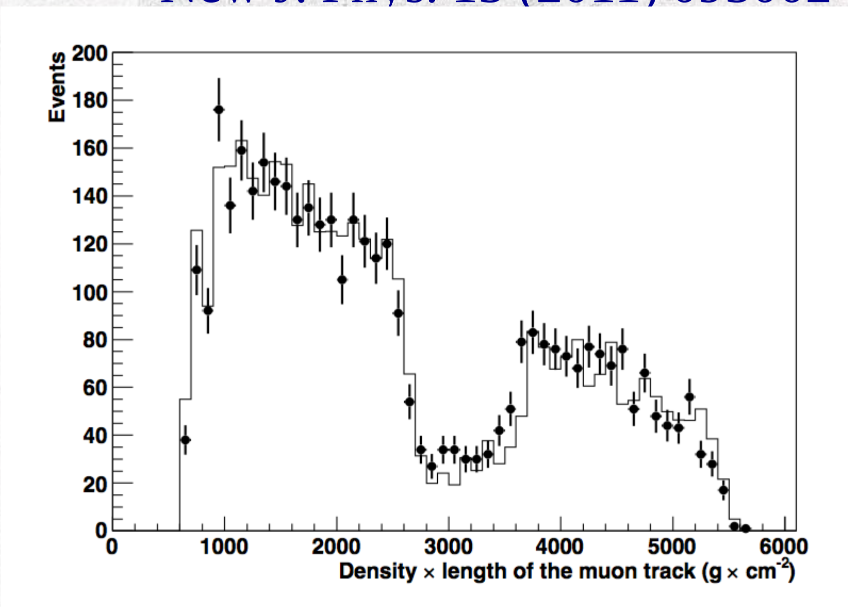
JINST 9 (2014) P12017
JINST 10 (2015) P11006

CHARMED PARTICLES PRODUCTION

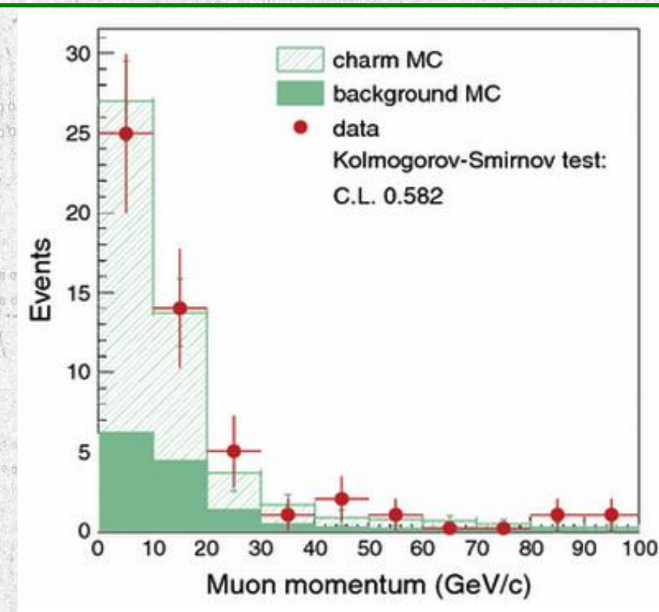
- Lifetimes and masses similar to the τ
- Background when the primary muon is not identified

ν_μ^{CC} interactions with charm quark production derived from CHORUS measurements
New J. Phys. 13 (2011) 093002

$$\frac{\sigma(\nu_\mu N \to \mu^- C X)}{\sigma(\nu_\mu N \to \mu^- X)} = (4.38 \pm 0.26)\%$$



New J. Phys. 13 (2011) 053051



Eur. Phys. J. C74 (2014) 2986

Good agreement in normalization and shape for the relevant kinematical variables in the charm detection and muon identification
Constrain the background within 20%

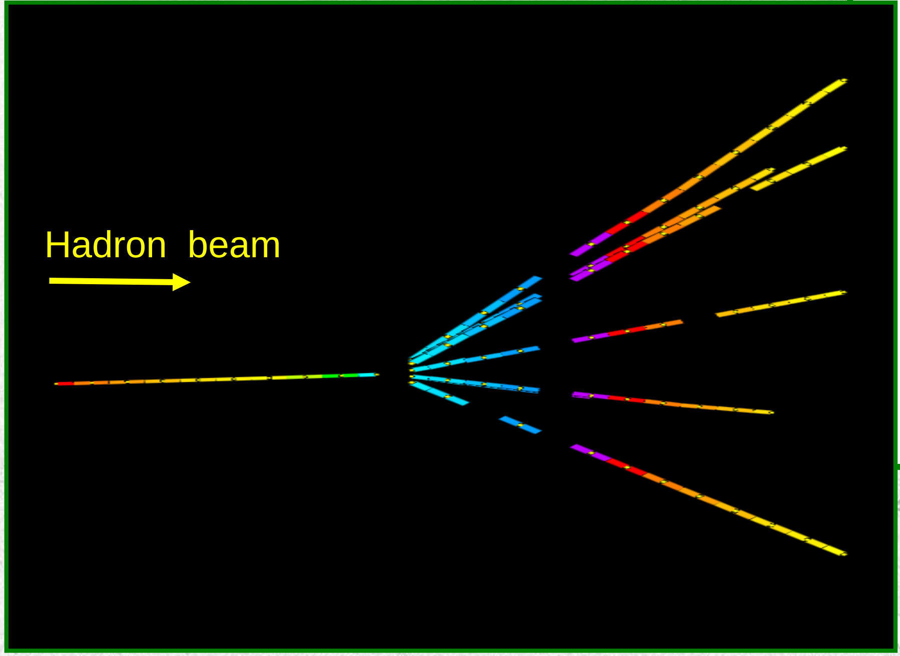
BACKGROUND STUDIES: HADRONIC INTERACTIONS

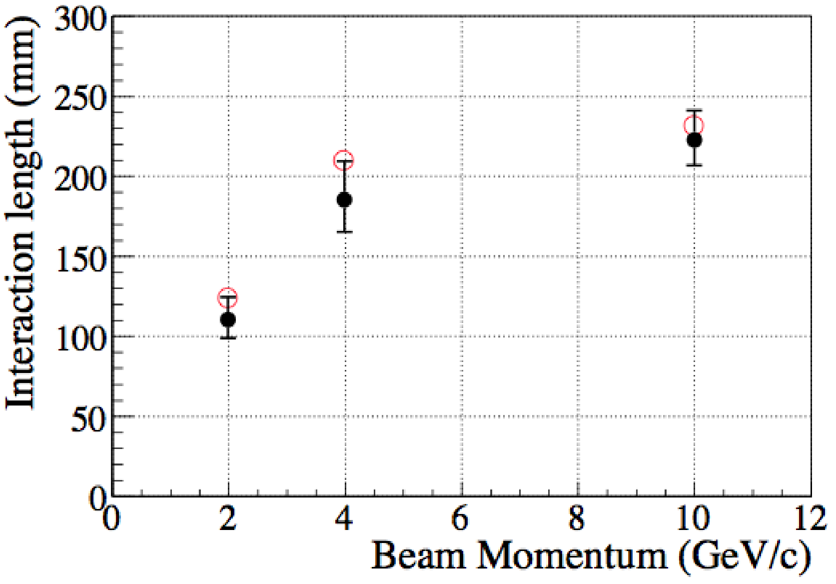
Comparison of large data sample (π^- beam test at CERN) with Fluka simulation

→ 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





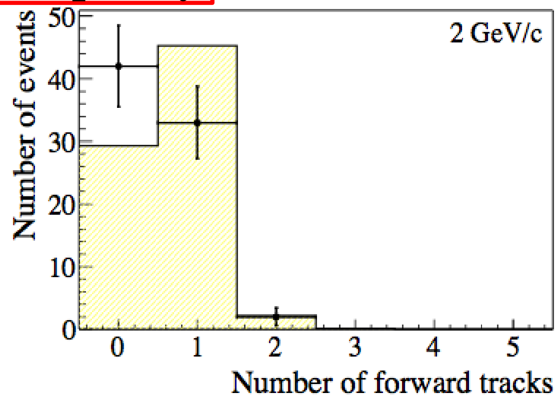
Black : π^- beam data
Red : MC (FLUKA) simulation

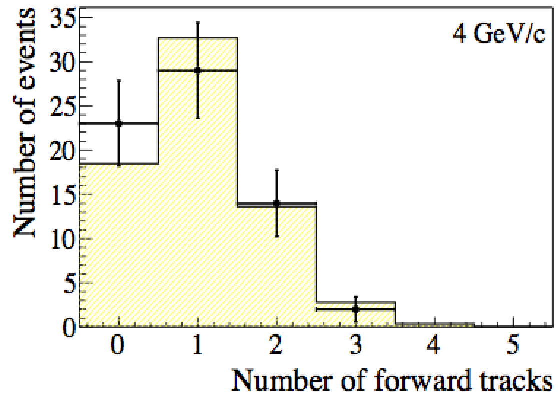
PTEP 9 (2014) 093C01

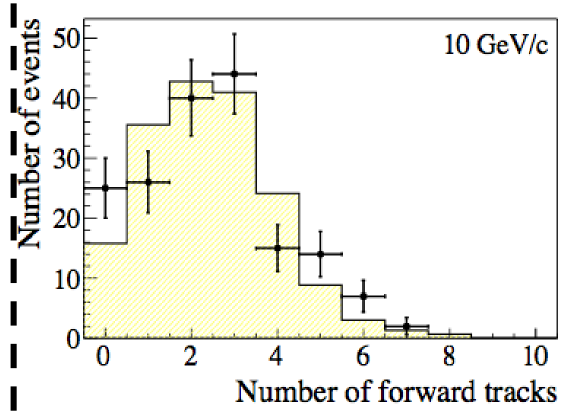
SECONDARY TRACK EMISSION

2GeV/c | 4GeV/c | 10GeV/c

Multiplicity

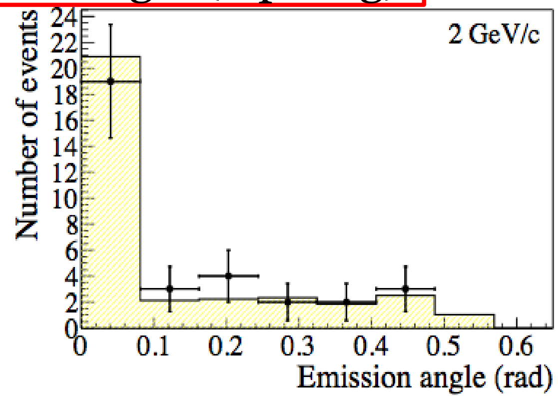


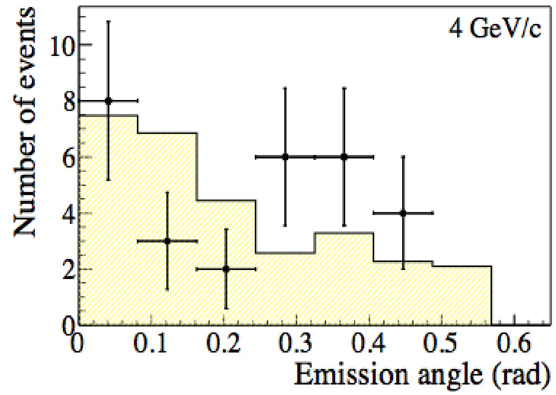


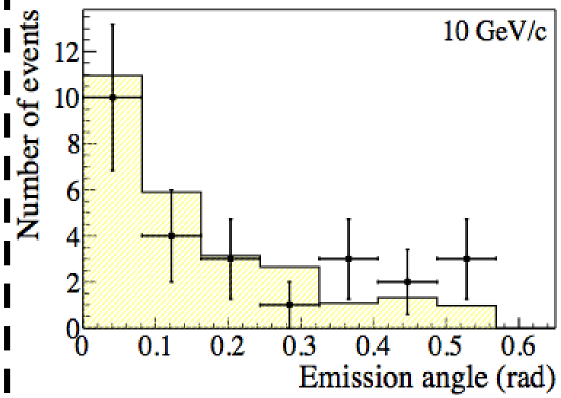


Error bars : Experimental data
Histogram : Simulated data

Kink angle (1-prong)

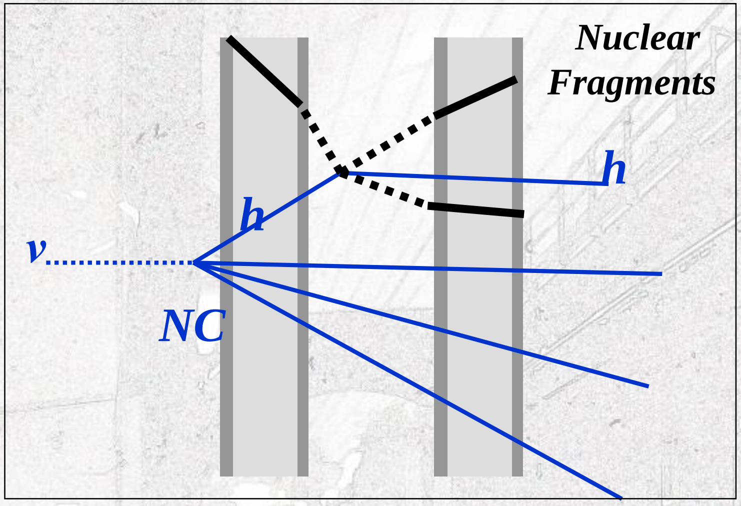




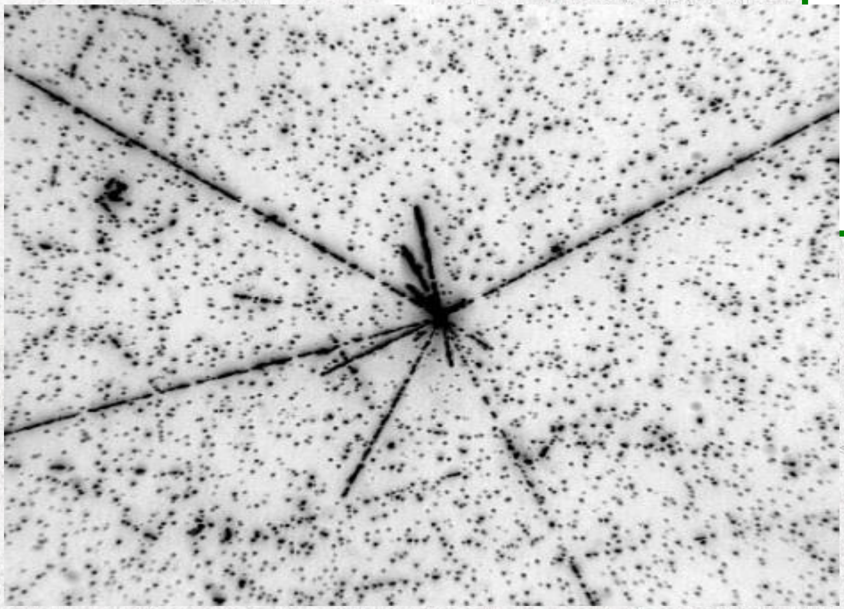


Good agreement within the statistical error: systematic error ~ 30%

NUCLEAR FRAGMENTS EMISSION PROBABILITY

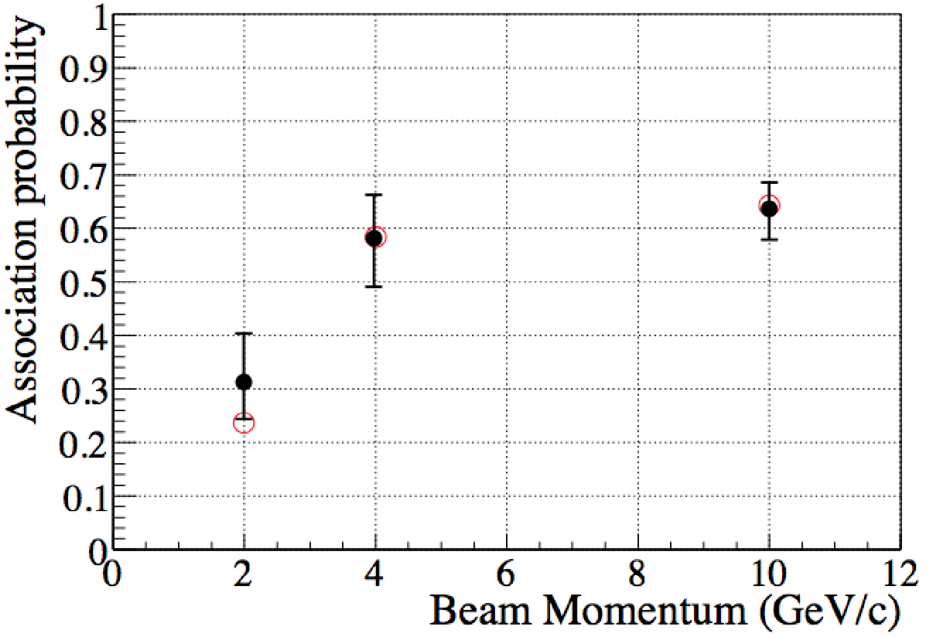


Highly ionizing fragments



150 µm

Additional background reduction



Black : experimental data

Red : simulated data (β= p/E = 0.7)

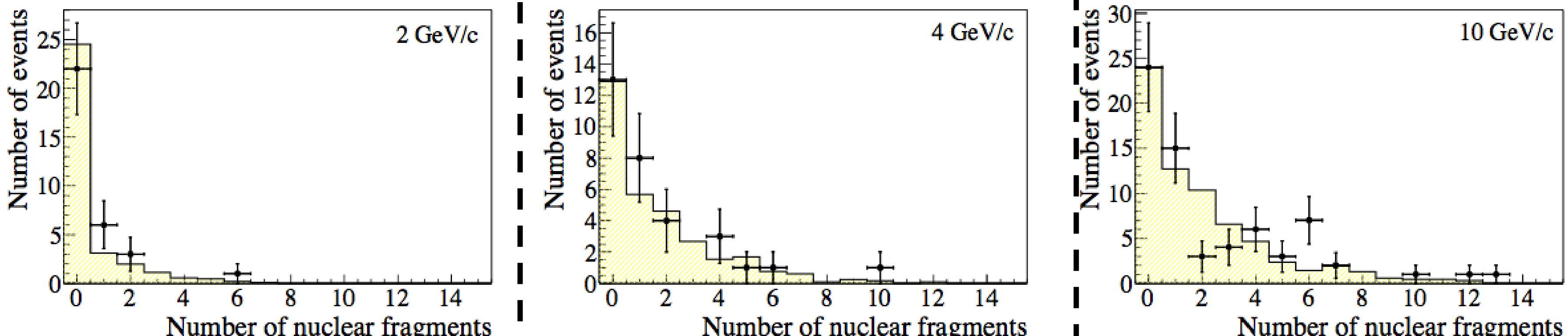
PTEP 9 (2014) 093C01

Nuclear Fragments In 1 And 3 Prong Interactions

2GeV/c | 4GeV/c | 10GeV/c

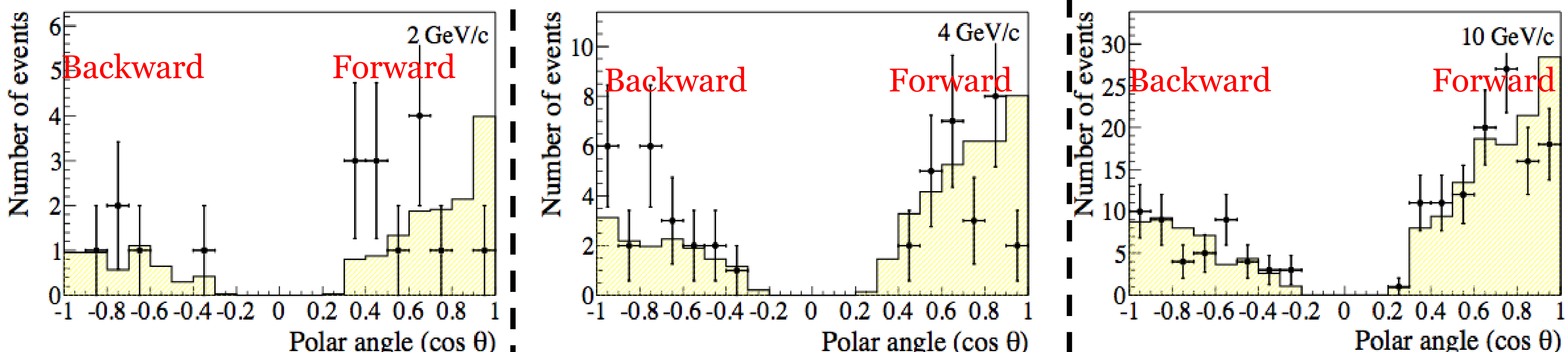
Multiplicity

MC: β < 0.7



Error bars : Experimental data
Histogram : Simulated data

Emission angle(cos θ)



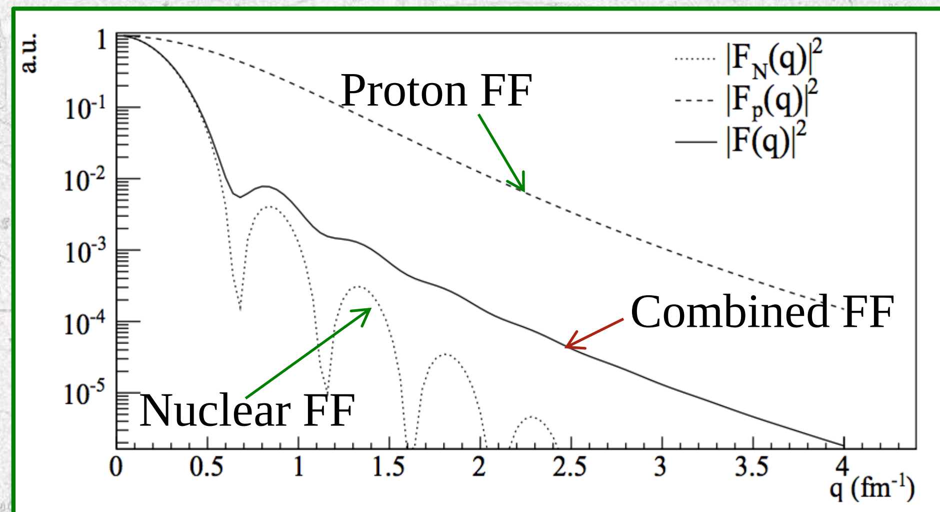
Agreement within the statistical error: systematic error is 10%

LARGE ANGLE μ SCATTERING

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

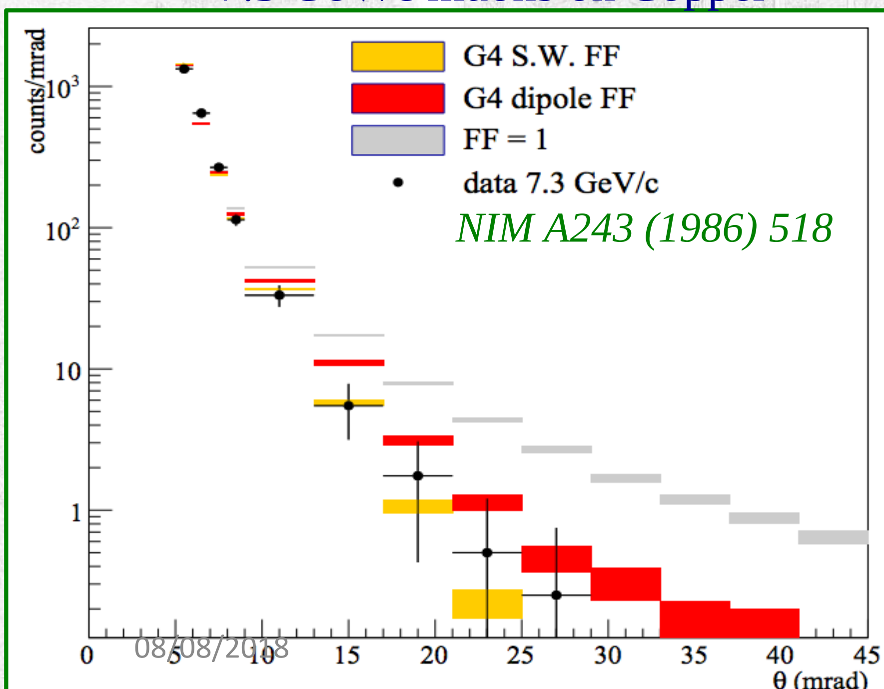
$$\rho_{SW}(r) = \rho_0 \left(1 + e^{\frac{r-b}{a}}\right)^{-1}$$

IEEE Transactions on Nuclear Science Vol. 62, No. 5, October 2015

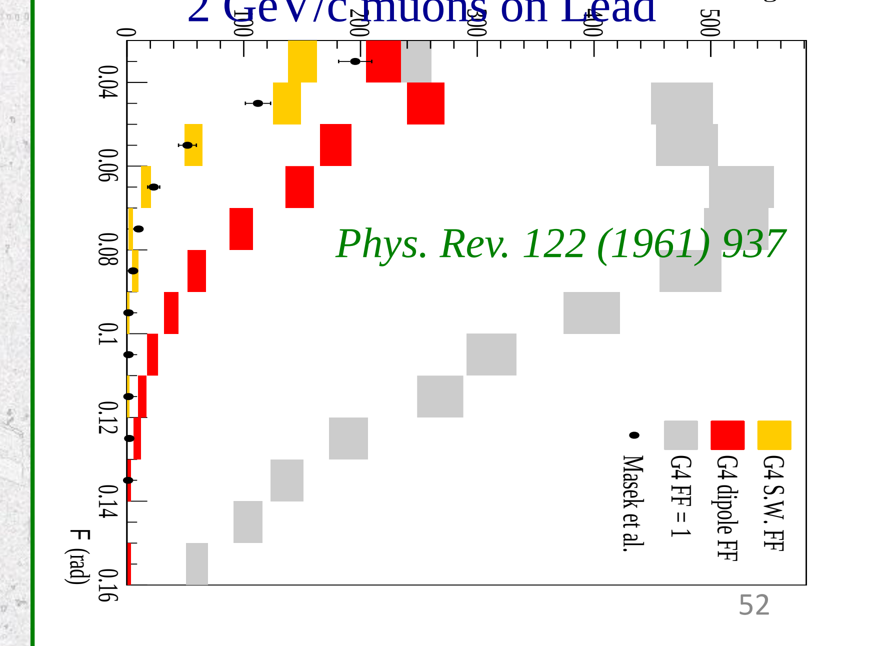


MC predictions compared to available data

7.3 GeV/c muons on Copper

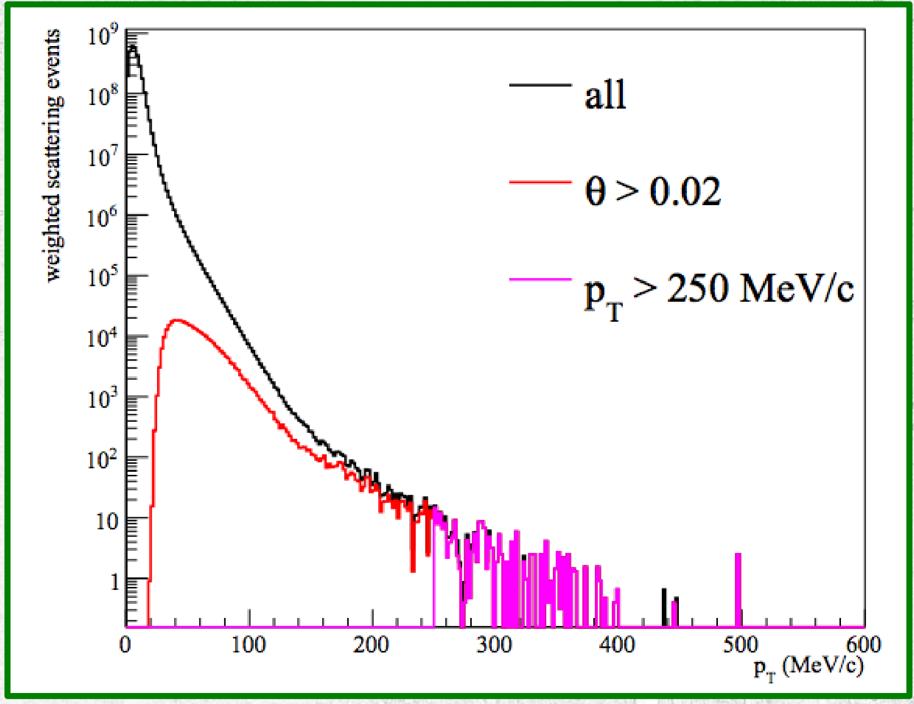


2 GeV/c muons on Lead

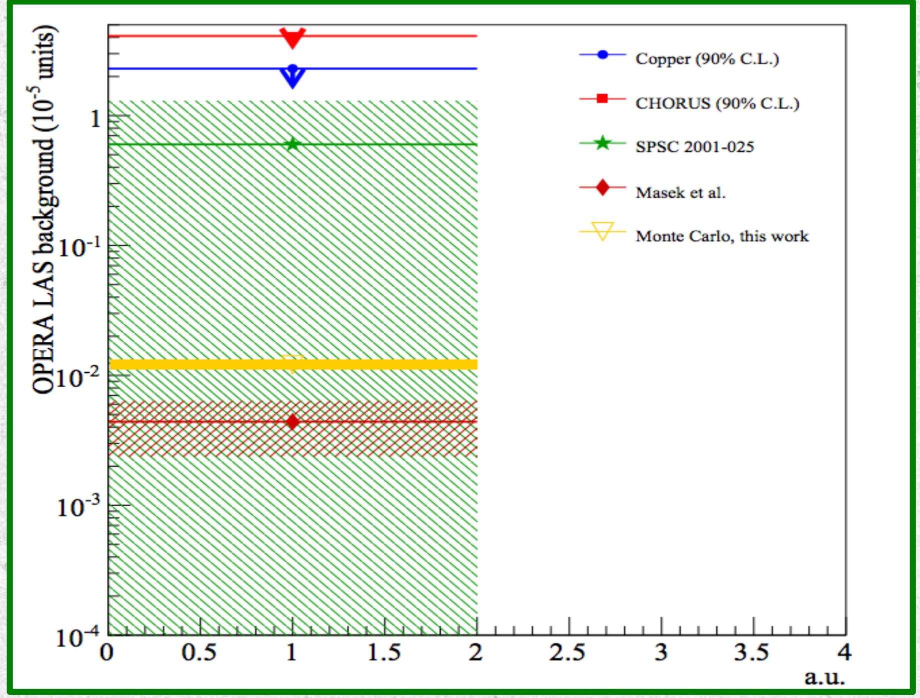


LARGE ANGLE μ SCATTERING

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



Main background in the τ →μ 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 Vol. 62, No. 5, October 2015

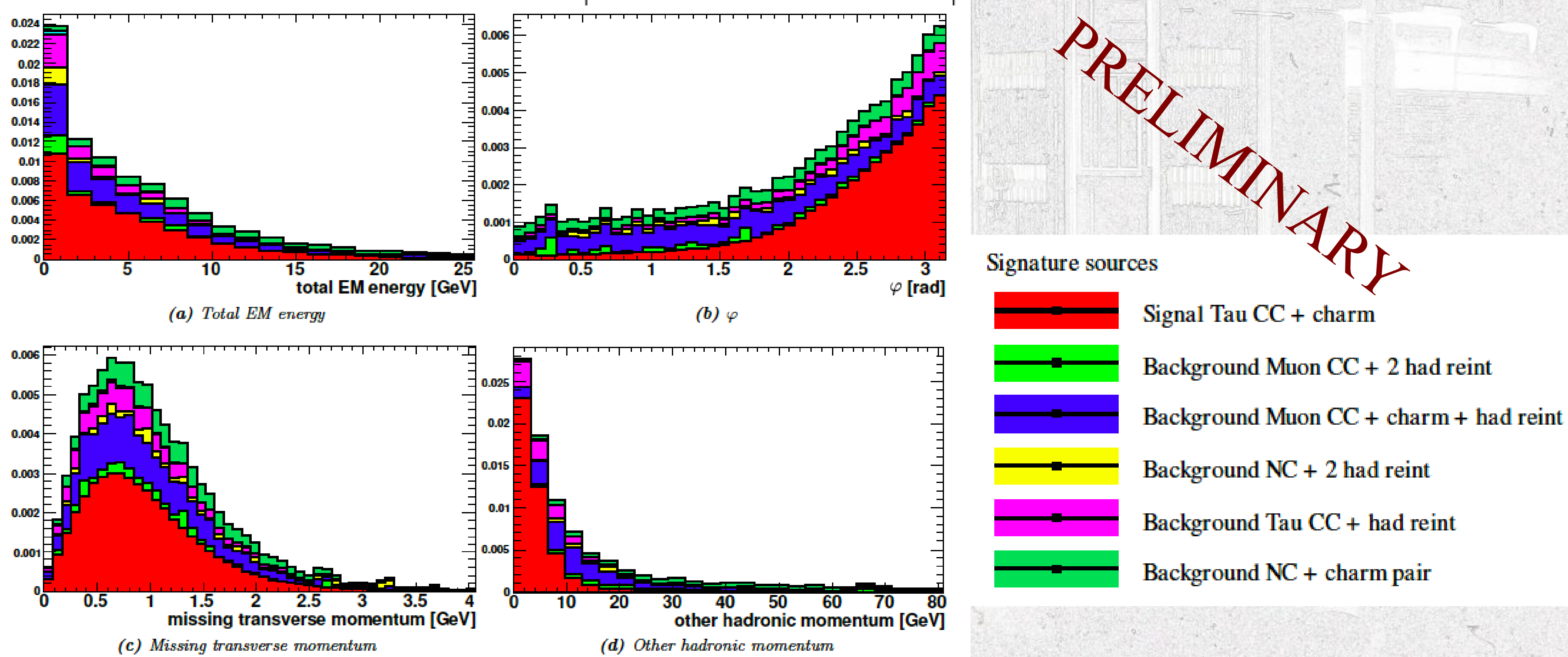
New Selection

Variable	$\tau \to 1h$ OLD	$\tau \to 1h$ NEW	$\tau \to 3h$ OLD	$\tau \to 3h$ NEW	$\tau \to \mu$ OLD	$\tau \to \mu$ NEW	$\tau \to e$ OLD	$\tau \to e$ 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: Charm	Had. re-interaction	Large μ-scat.	Total	Expected Signal	Total Expected
$\tau \to 1h$	0.15 ± 0.03	1.28 ± 0.38	–	1.43 ± 0.39	2.96 ± 0.59	4.39 ± 1.39
$\tau \to 3h$	0.44 ± 0.09	0.09 ± 0.03	–	0.52 ± 0.09	1.83 ± 0.37	2.35 ± 0.58
$\tau \to \mu$	0.008 ± 0.002	–	0.016 ± 0.008	0.024 ± 0.008	1.15 ± 0.23	1.18 ± 0.25
$\tau \to e$	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

EXPECTED YIELD AND MULTIVARIATE ANALYSIS

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



(a) Total EM energy

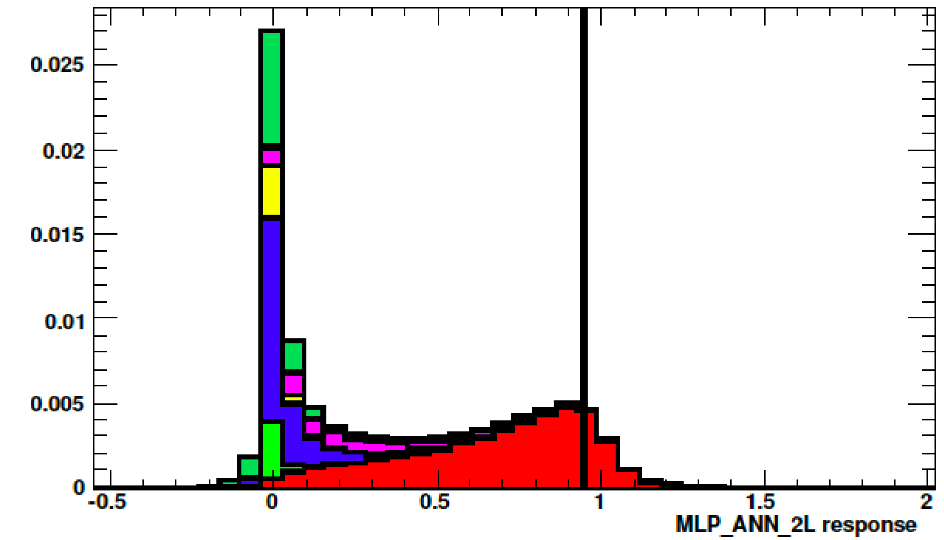
(b) φ

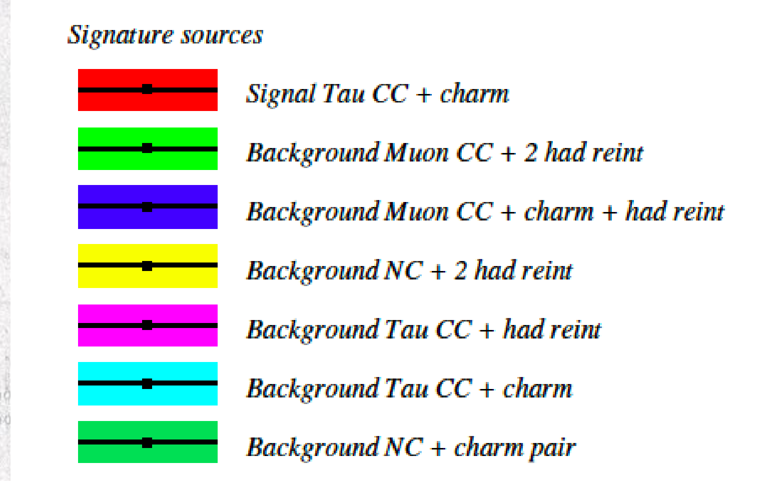
(c) Missing transverse momentum

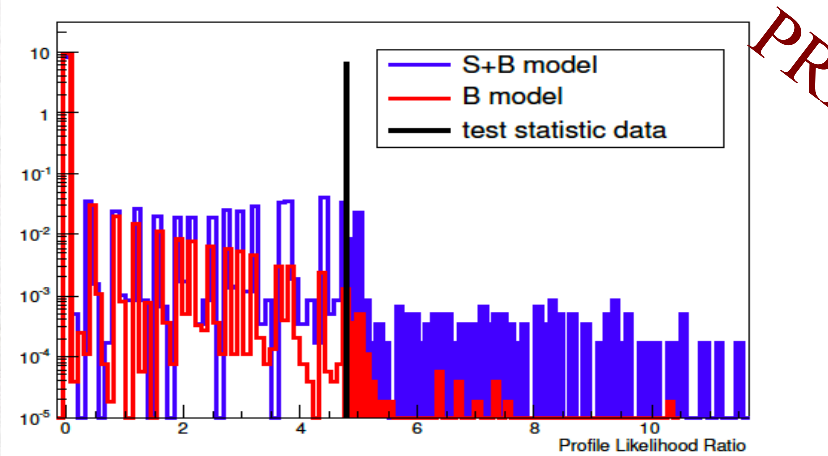
(d) Other hadronic momentum

OBSERVATION OF A ν_τ INTERACTION WITH A CHARMED HADRON PRODUCTION

Neural network output







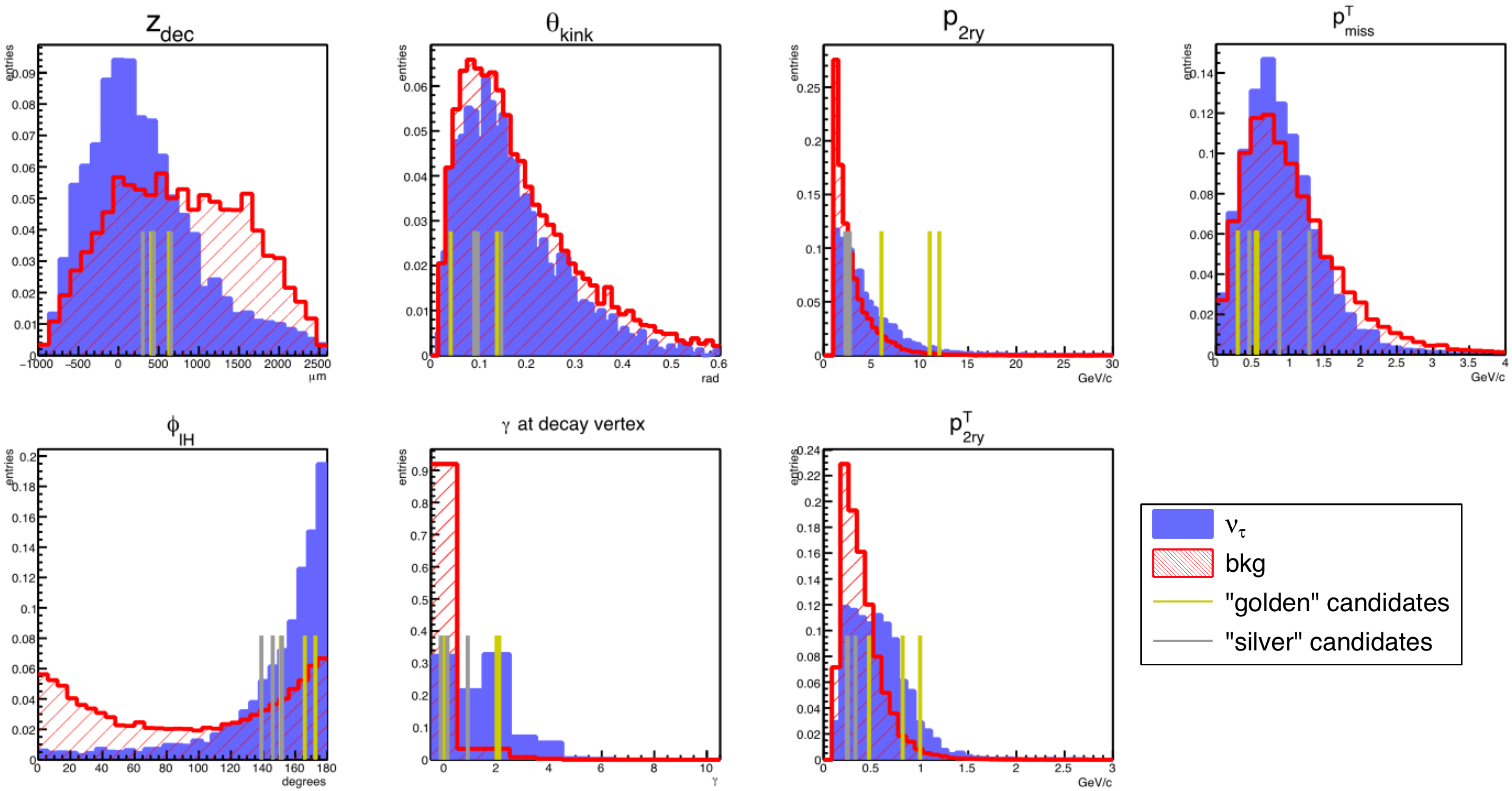
PRELIMINARY

$$\mathcal{L}(\mu|x) = \sum_{i\in B} n_i \cdot f_i(x) + \mu \sum_{j\in S} n_i \cdot f_i(x)$$

x PDF from ANN output
n_i = yield of i-th process
Background only → $\mu = 0$

$$\mathrm{CL} = 2.6 \times 10^{-4} \rightarrow 3.4\ \sigma$$

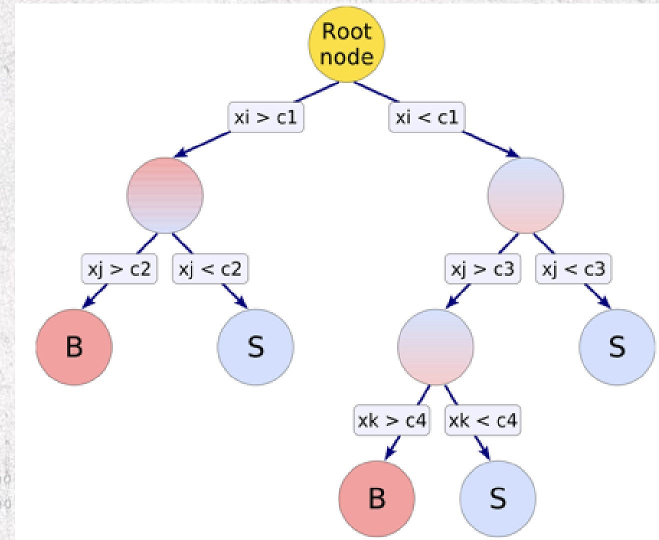
INPUT VARIABLES FOR THE MULTIVARIATE ANALYSIS IN THE $\tau \to h$ DECAY CHANNEL



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

The Boosted Decision Tree (BDT)

- Multivariate machine learning method to classify observations
- It is based on a "forest" of trees of binary choices
- The BDT response is a value between 1 (signal-like events) and -1 (background-like events)



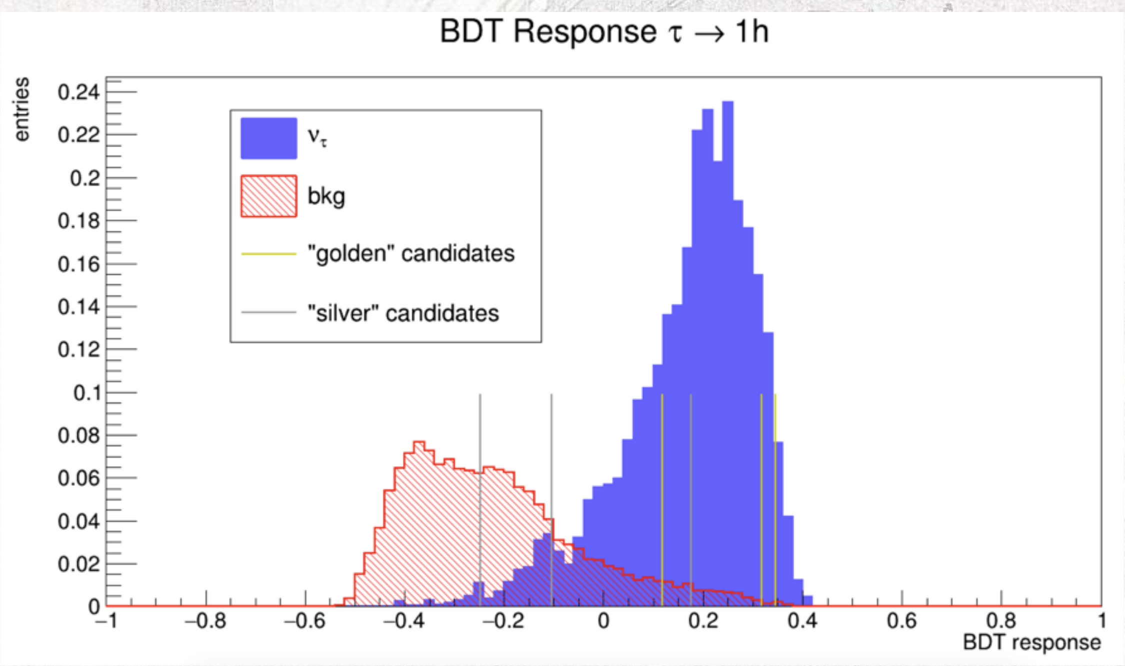
TMVA: Toolkit for Multivariate Data Analysis. PoS, ACAT:040 2007

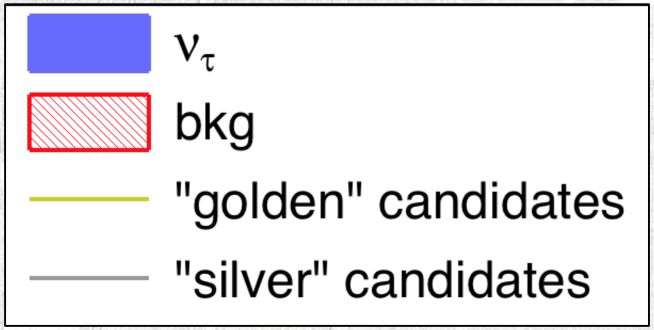
PHYSICAL REVIEW LETTERS **120**, 211801 (2018)

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

BDT Response 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

$\Delta m_{23}{}^2$ MEASUREMENT

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

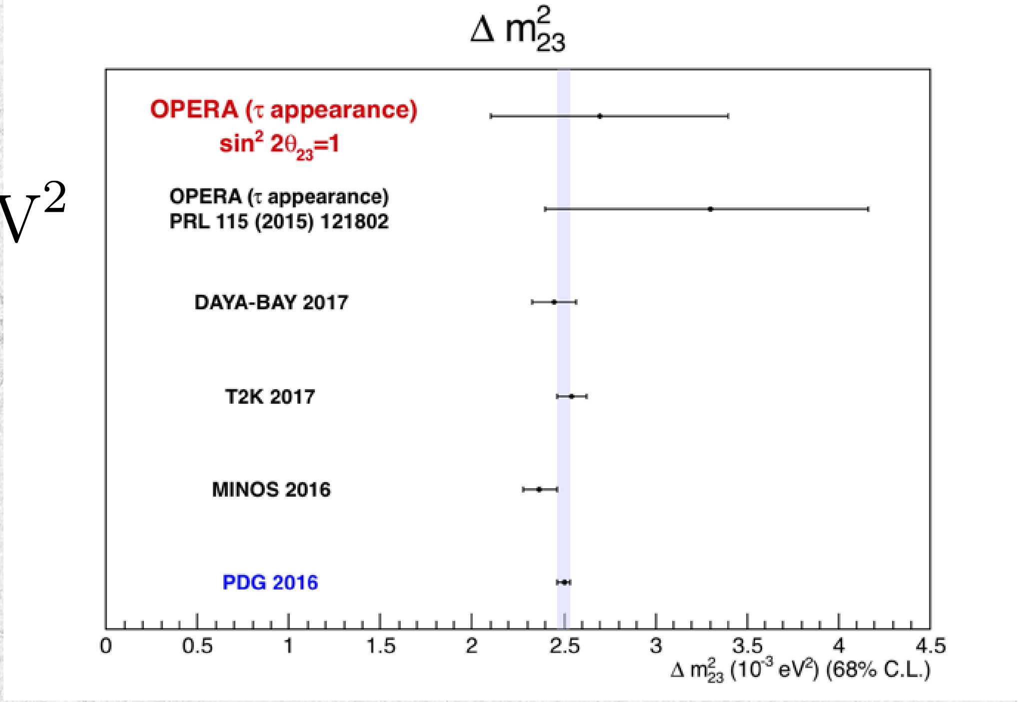
Experiment sensitive to the product $N_{\nu_\tau} \propto P(\nu_\mu \to \nu_\tau)\sigma_{\nu_\tau}$

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

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

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

(68% C.L)



First measurement in appearance mode

ν_τ CC Cross-Section

$$\langle\sigma\rangle_{meas} = \frac{(N^{obs} - N^{expB})/(\epsilon N_T)}{\int \Phi_{\nu_\mu}(E)\mathcal{P}_{\nu_\mu\to\nu_\tau}(E)dE}$$

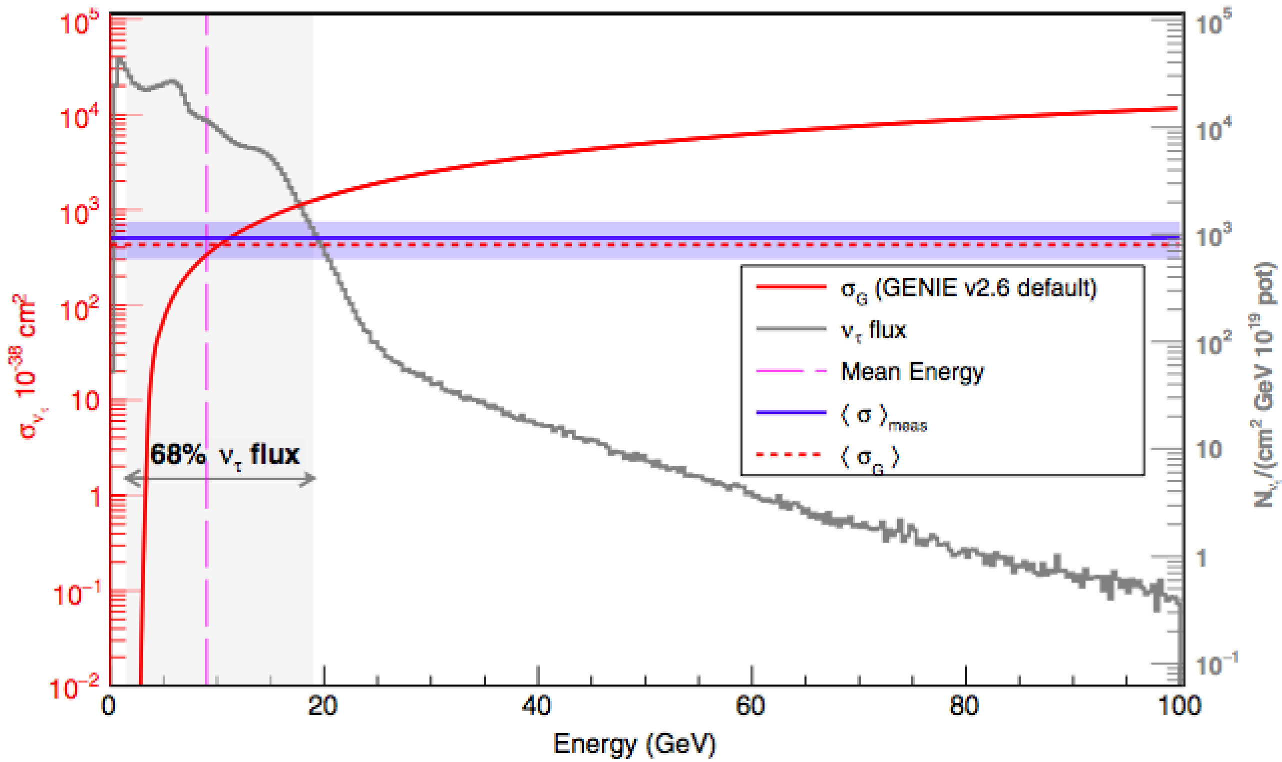
ϵ overall efficiency

N_T lead nuclei in the fiducial volume

$$\Delta m^2_{23\ \mathrm{PDG}} = (2.50 \pm 0.04)\cdot 10^{-3}\mathrm{eV}^2$$

First measurement with negligible contamination from anti-ν_τ

PHYSICAL REVIEW LETTERS 120, 211801 (2018)



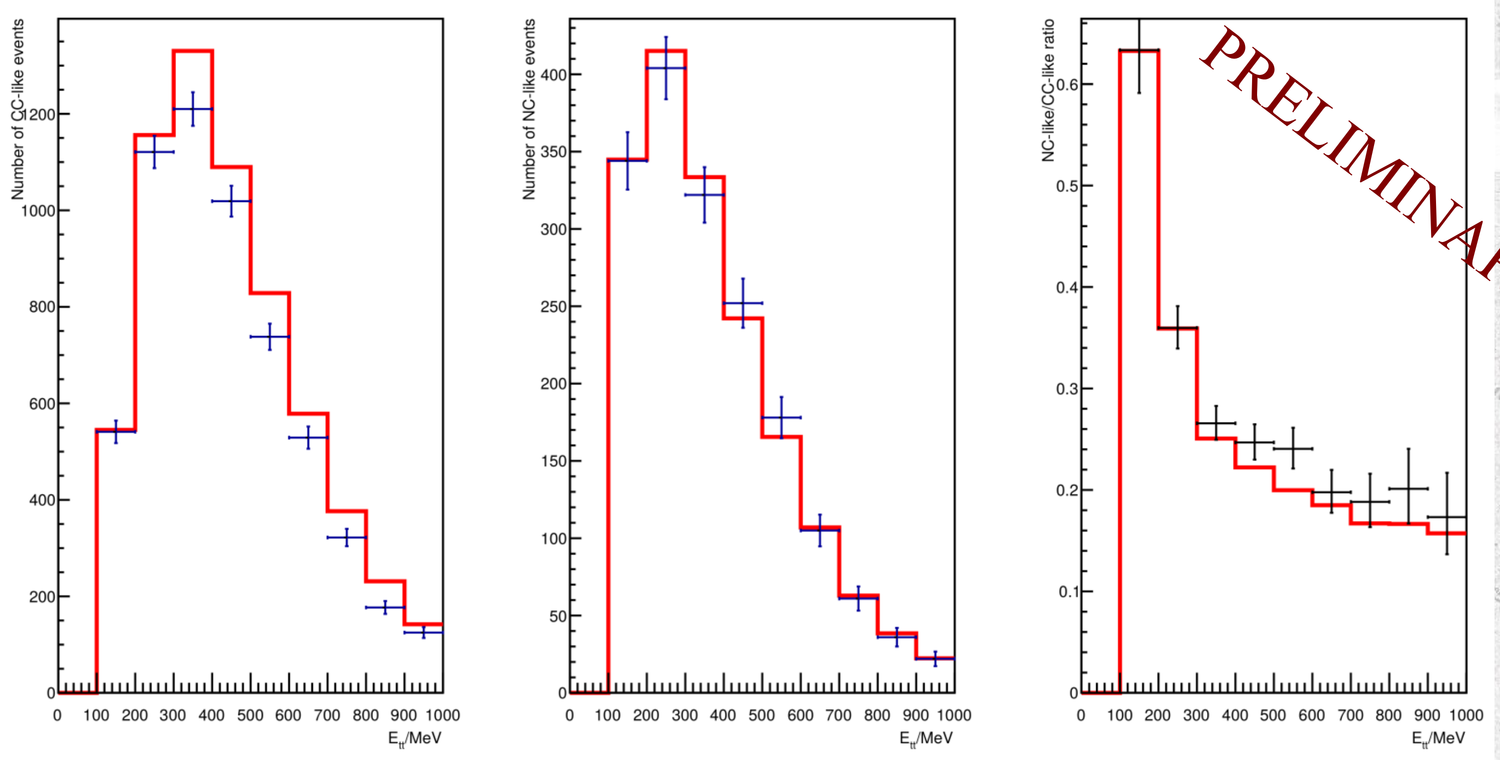
$$\langle\sigma\rangle_{\mathrm{meas}} = (5.1^{+2.4}_{-2.0}) \times 10^{-36}\ \mathrm{cm}^2$$

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

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

arXiv:1805.12028 [hep-ex]

MiniBooNE

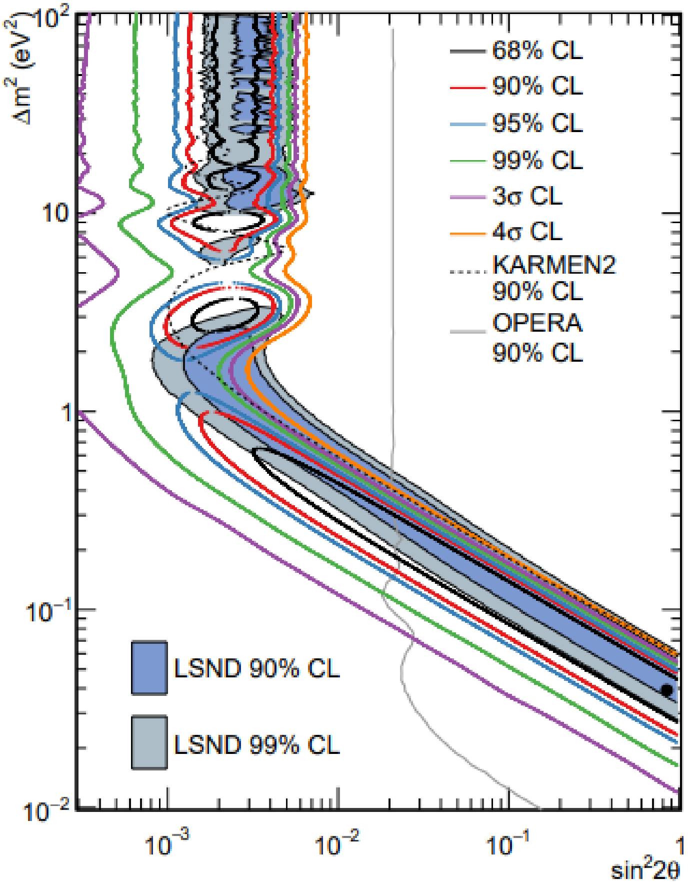


FIG. 4: MiniBooNE allowed regions in neutrino mode (12.84×10^{20} POT) for events with $200 < E_\nu^{QE} < 1250$ MeV within a two-neutrino oscillation model. The shaded areas show the 90% and 99% C.L. LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ allowed regions. The black circle shows the MiniBooNE best fit point. Also shown are 90% C.L. limits from the KARMEN [34] and OPERA [35] experiments.

$$(\Delta m^2, \sin^2 2\theta) = (0.037 \text{ eV}^2, 0.958)$$

is excluded by OPERA @ 90% C.L.

OPERA fit

- For $\sin^2 2\theta_{\mu e} \sim 0.9$ and $\Delta m^2_{41} \sim 0.04\ \text{eV}^2$, the best fit parameter values are:
  - $\theta_{12} = 0.0$
  - $\theta_{13} = 0.35$
  - $\theta_{23} = 1.57$
  - $\theta_{14} = -0.78$
  - $\theta_{24} = -1.31$
  - $\theta_{34} = 0.0$
  - $\delta_1 = 1.0$
  - $\delta_2 = -0.45$
  - $\delta_3 = 1.49$
  - $\Delta m^2_{31} = 2.54 \times 10^{-3}\ \text{eV}^2$
- with systematics
  - below 10 GeV: $k_1 = -0.984$ ($\sigma_1 = 0.2$)
  - above 10 GeV: $k_2 = -0.981$ ($\sigma_2 = 0.1$)

It means > 98% reduction of number of the expected events (μ_i) with respect to the nominal ones (μ_i^0).

$$\mu_i = \mu_i^0(1 + k_j) \quad \text{where} \quad \begin{cases} j = 1, & \text{if } i = 1 \\ j = 2, & \text{otherwise} \end{cases}.$$

and a significant contribution to -2 ln L

$$-2\ln L = -2\sum_i^N (n_i \ln \mu_i - N\mu_i) + \sum_{j=1}^{2} \frac{k_j^2}{\sigma_j^2} + \frac{\left(\Delta m^2_{31} - \widehat{\Delta m^2_{31}}\right)^2}{\sigma^2_{\Delta m^2_{31}}}.$$

OPERA
[$\sin^2 2\theta_{\mu e} \sim 0.9$; $\Delta m^2_{41} \sim 0.04\ eV^2$]