Results of the OPERA experiment

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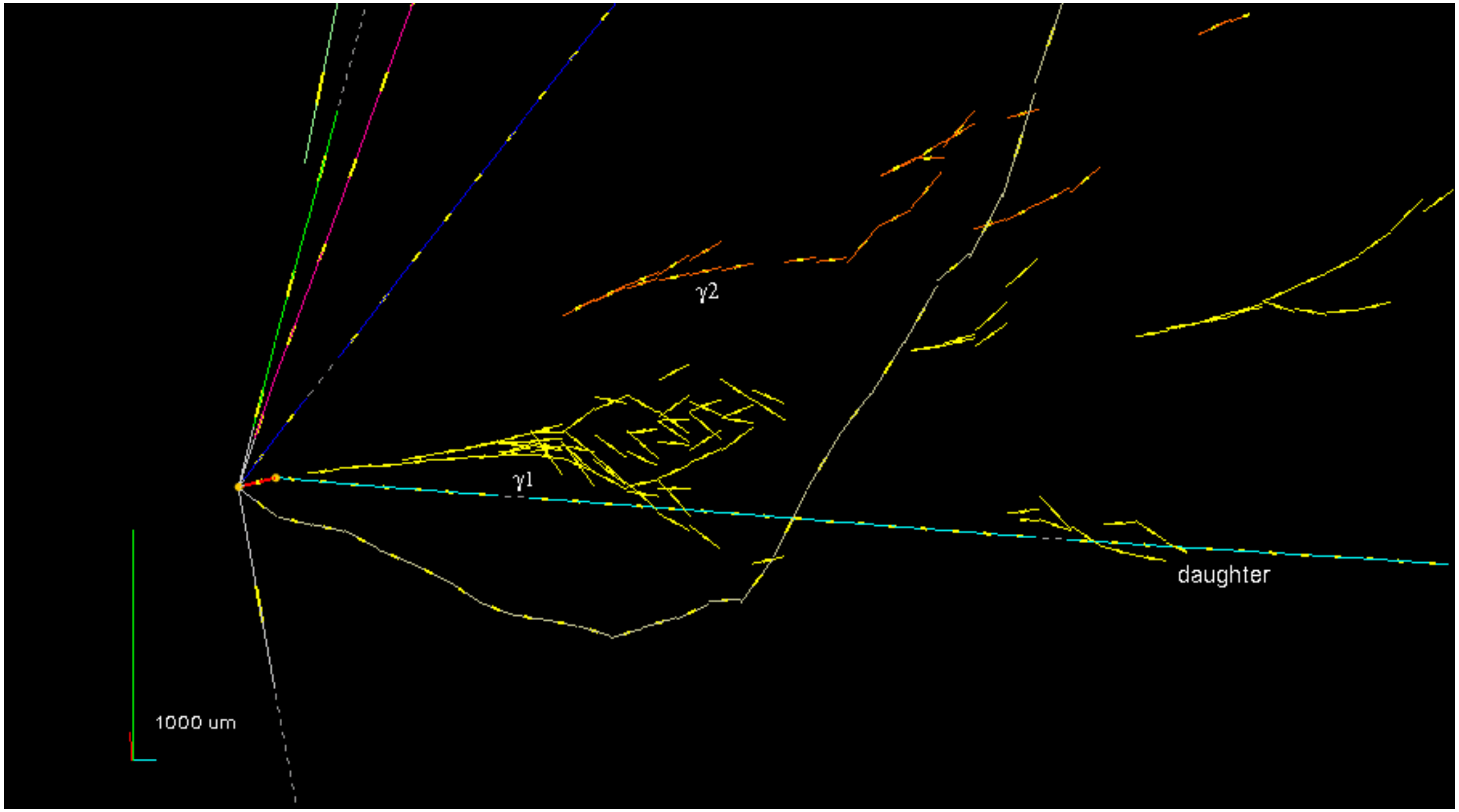
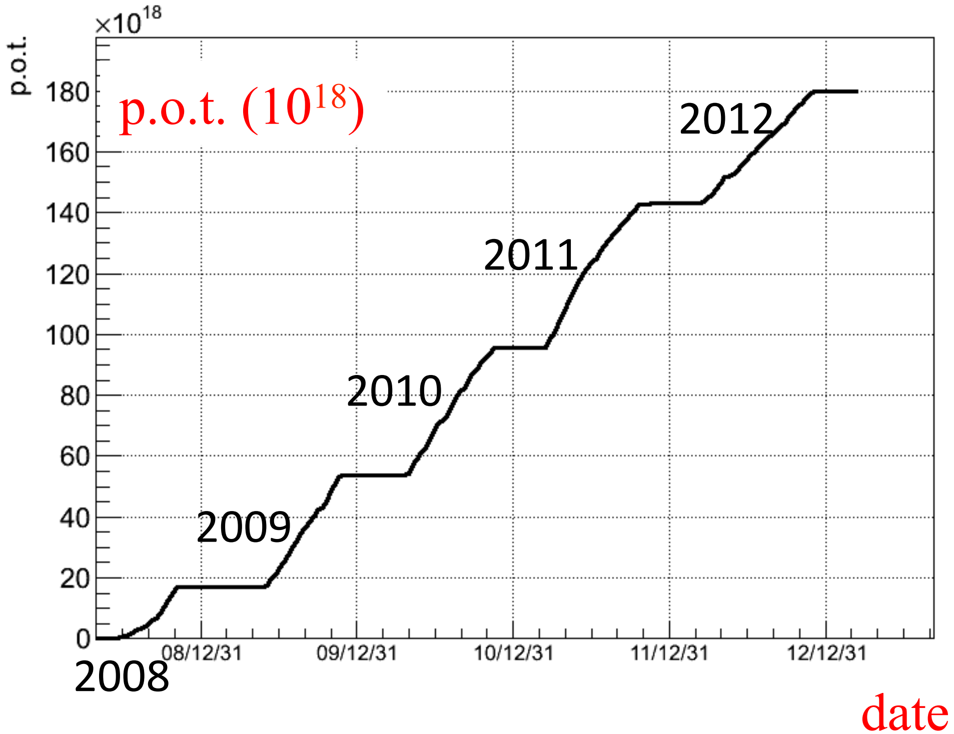
On behalf of the OPERA Collaboration



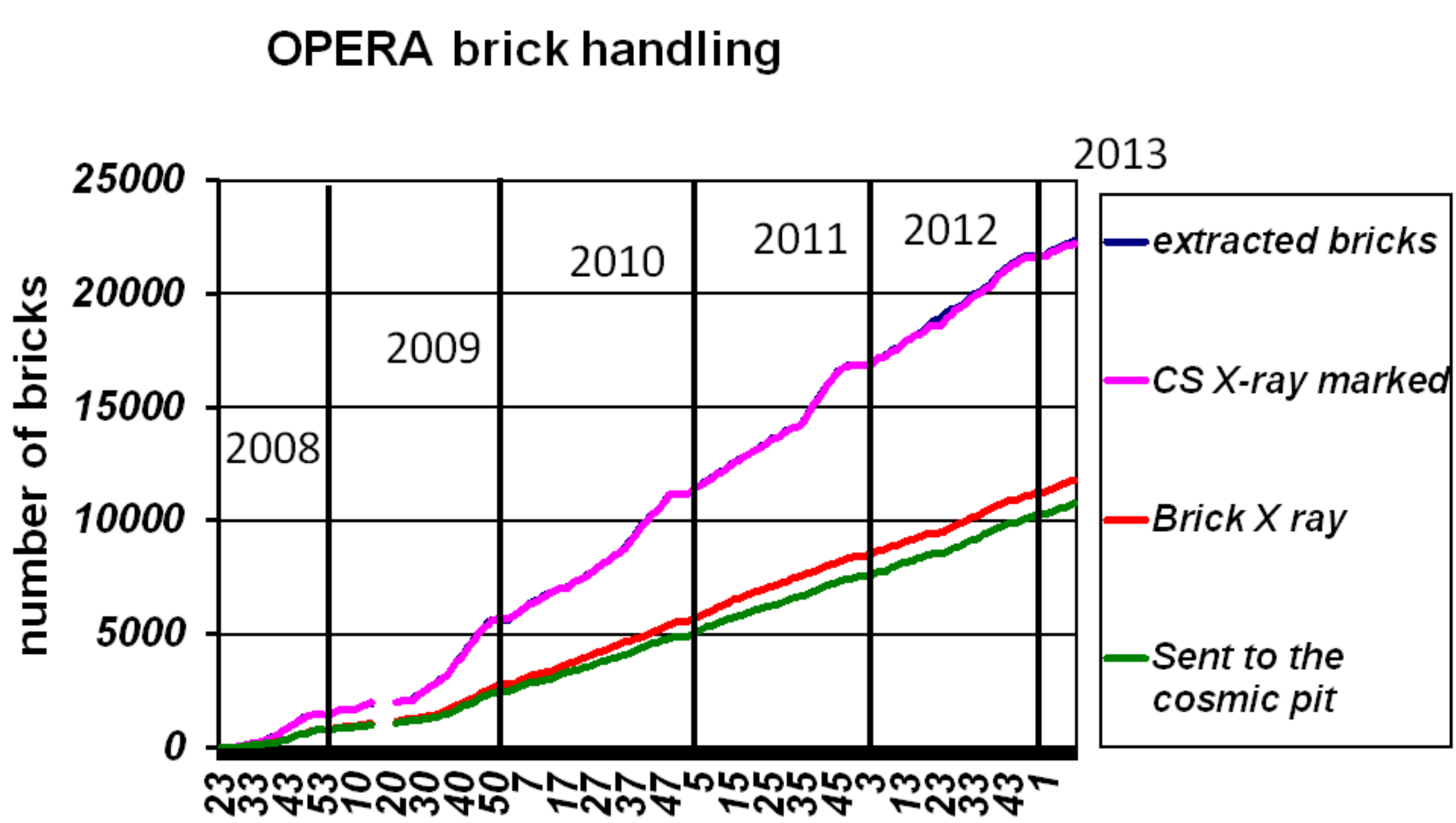
Final performances of the CNGS beam after five years (2008 ÷ 2012) of data taking

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

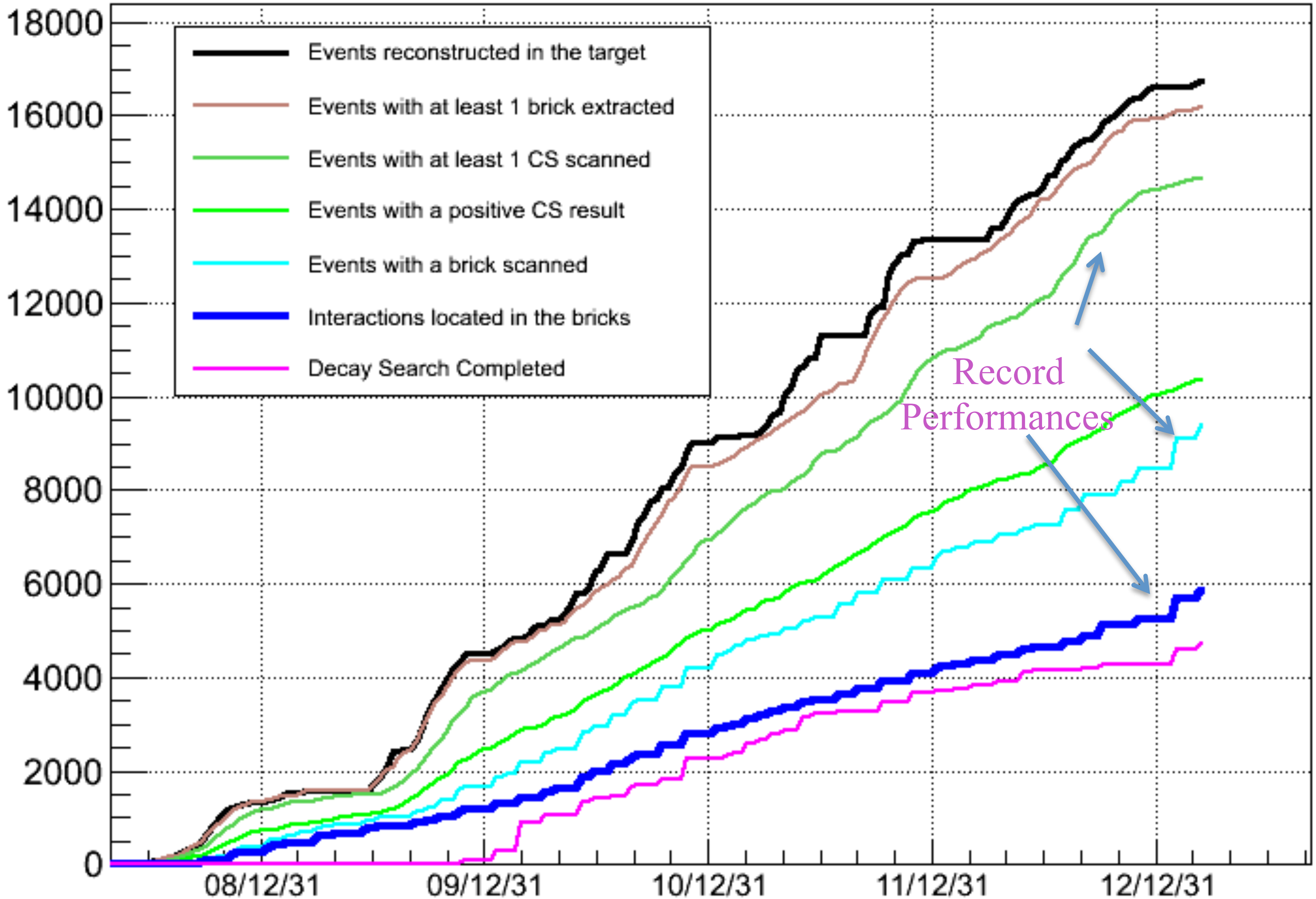
Overall 20% less than the proposal value (22.5)



22471 bricks extracted

Power failure of March 28th at LNGS damaged 4 routers and stopped our network services

Performance plot



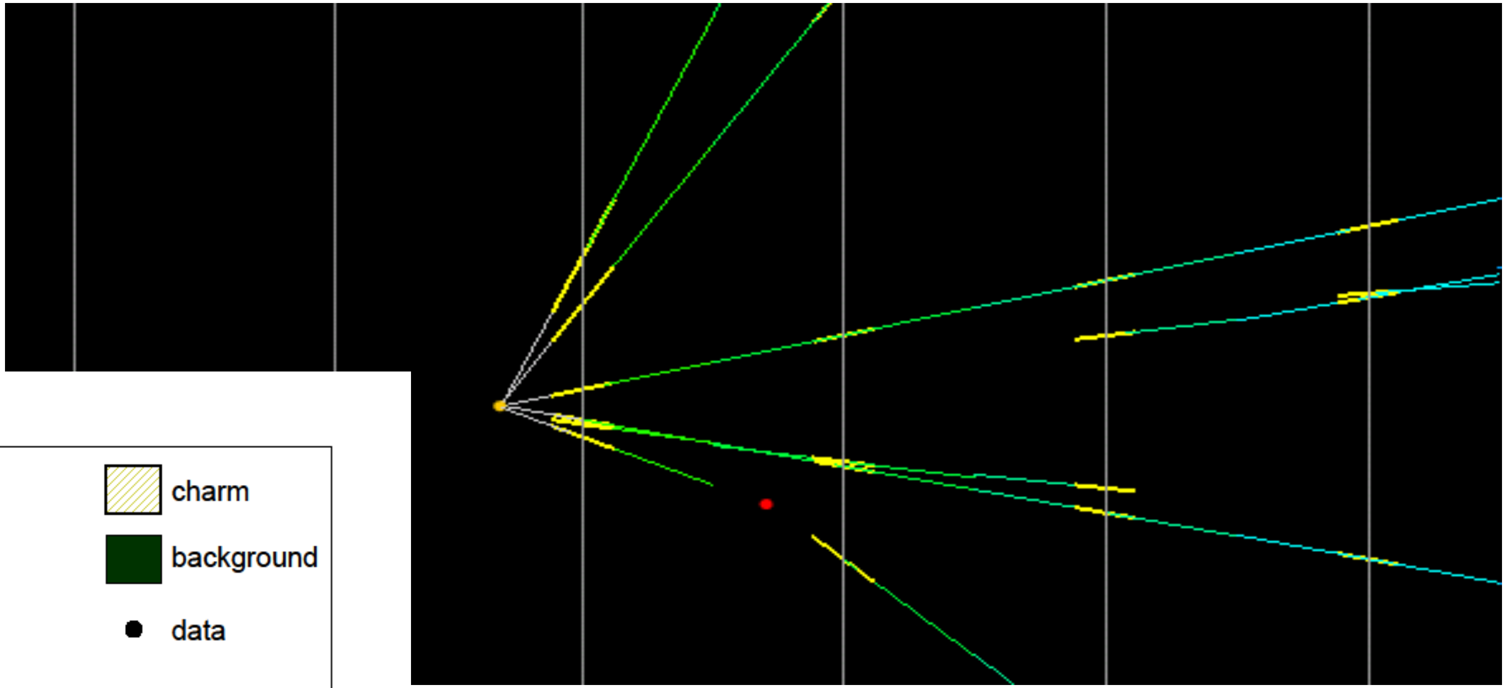
5844 located interactions

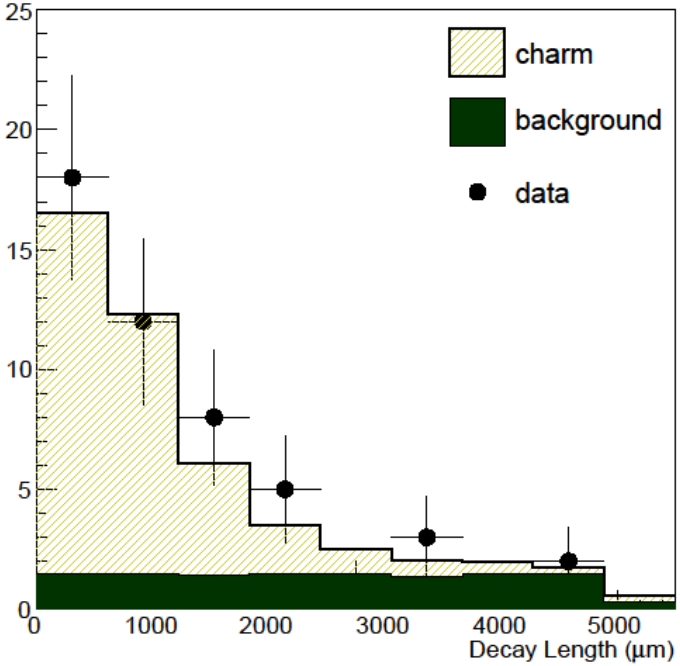
4725 decay search

Full revision of efficiencies and background

Charmed hadron production:
an application of the decay search
a control sample for τ

Charm sample:
same topology but muon at interaction vertex





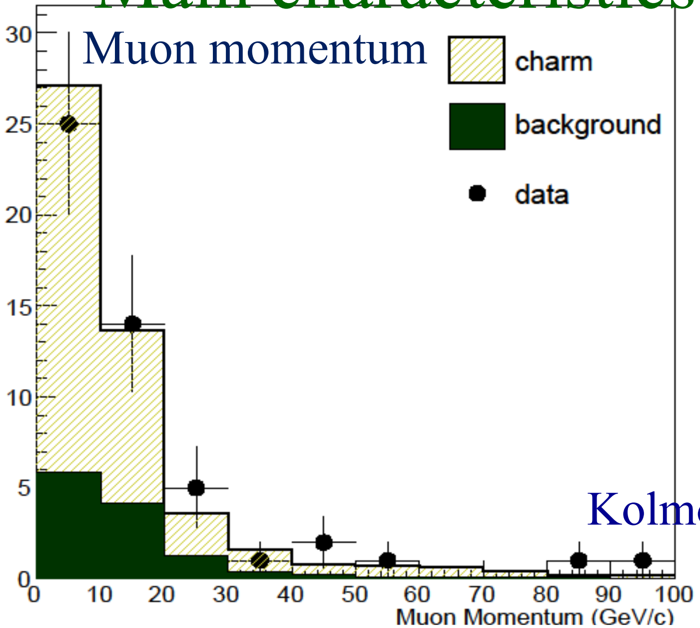
Charm yield from the analysis of 2008÷2010 data

	charm	background	expected	data
1 prong	20 ± 3	9 ± 3	29 ± 4	19
2 prong	15 ± 2	3.8 ± 1.1	19 ± 2	22
3 prong	5 ± 1	1.0 ± 0.3	6 ± 1	5
4 prong	0.8 ± 0.2	-	0.8 ± 0.2	4
All	**41±4**	**14±3**	**55±5**	**50**

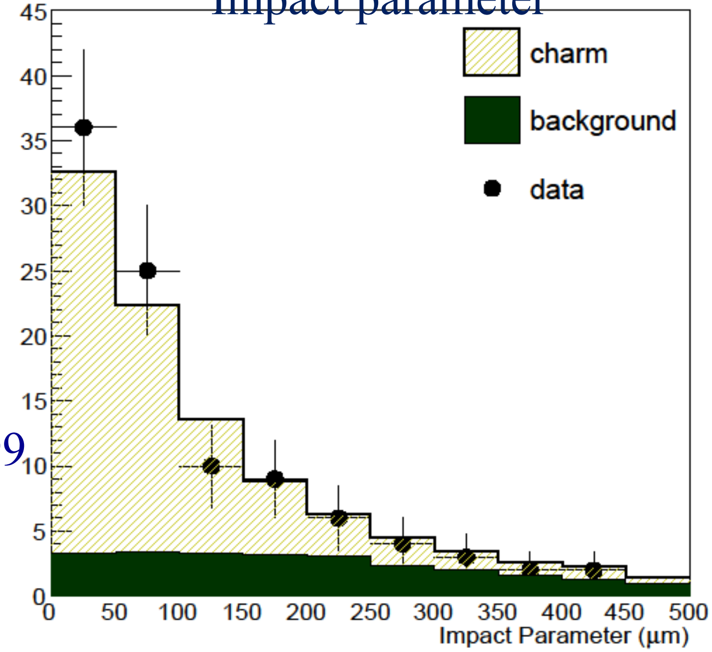
Background, mostly from hadronic interactions
(contribution from strange particle decay)

Main characteristics of the charm candidate events

Muon momentum

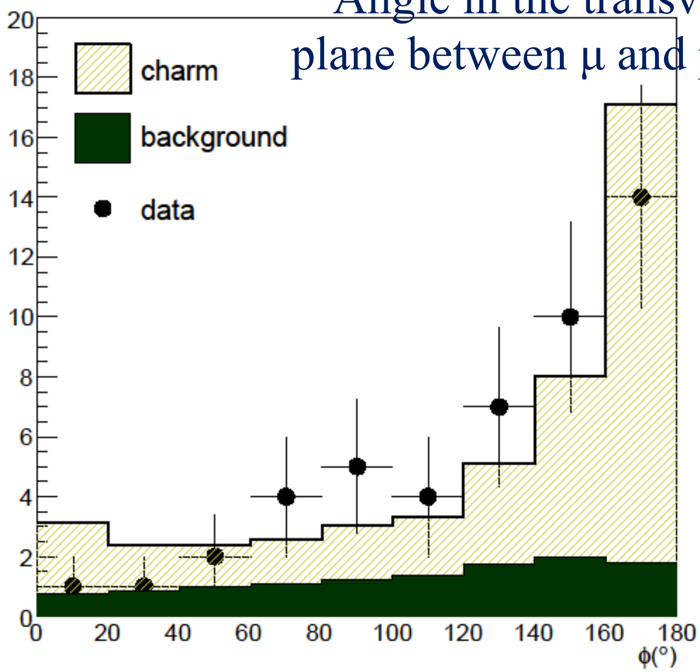


Impact parameter

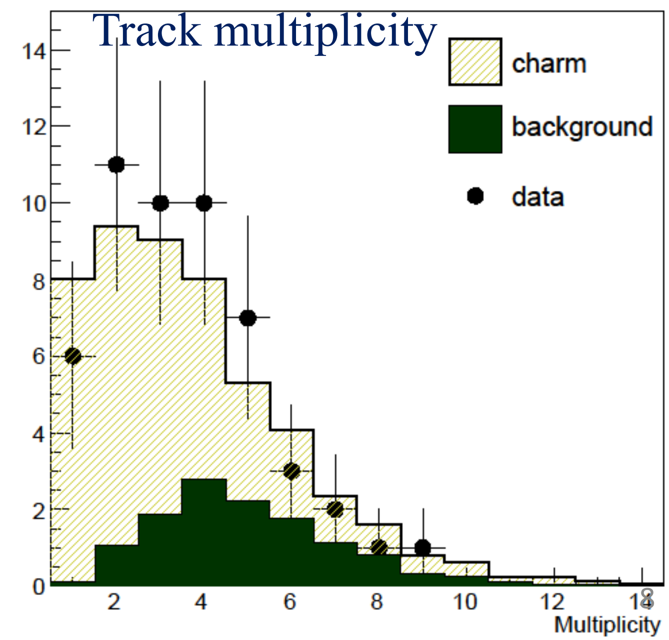


Kolmogorov test ≥ 0.99
all plots

Angle in the transverse plane between μ and parent



Track multiplicity



Physics results

$\nu_\mu \rightarrow \nu_e$ analysis with 2008 and 2009 run data

one of the ν_e events with a π^0 as seen in the brick

puted with a GEANT3 based MC simu
reconstructed with the same algorithms
ences in the scanning strategy used alo
account and enter in the evaluation of
sults of the simulation are shown in fig
relative to its efficiency is calculated to

7

Interface films

19 candidates found in a sample of 505 neutrino interactions without muon

Energy distribution of the 19 ν_e candidates

the expected background).

Given the underfluctuation of the data, t chosen for the exclusion plot shown in figure experiments, working at different L/E regime Δm^2_{new} values the OPERA 90% upper limit while the sensitivity corresponding to the pot

– 8

dependent detection efficiency, to obtain the number of ν_e CC eve oscillation.

– 7 –

Observation compatible with background-only hypothesis: 19.8±2.8 (syst) events

3 flavour analysis

Energy cut to increase the S/N

4 observed events
4.6 expected
$\Rightarrow \sin^2(2\theta_{13})<0.44$ at 90% C.L.

Search for non-standard oscillations at large Δm^2 values: exclusion plot in the $\sin^2(2\theta_{new})$ - Δm^2_{new} plane

arXiv:1303.3953

disappearance [20]), CHOOZ ($\overline{\nu}_e$ disappeara
[22]) and ICARUS ($\nu_\mu \rightarrow \nu_e$ [7], using F&C
regions corresponding to the positive indicatio
[5]) and MiniBooNE ($\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ [

Submitted to JHEP

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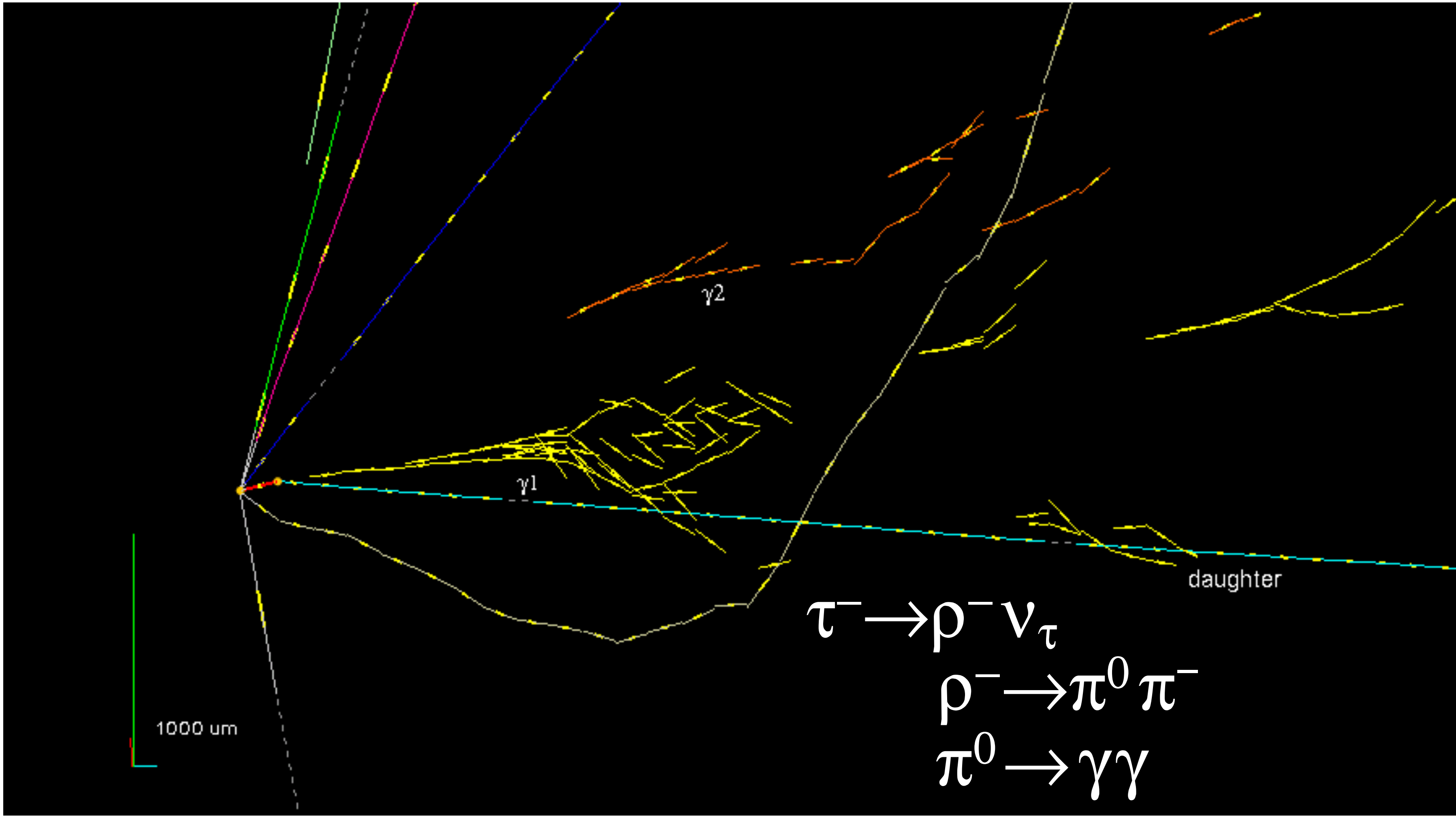
Caveat: experiments with different L/E values

$\nu_\mu \rightarrow \nu_\tau$ analysis

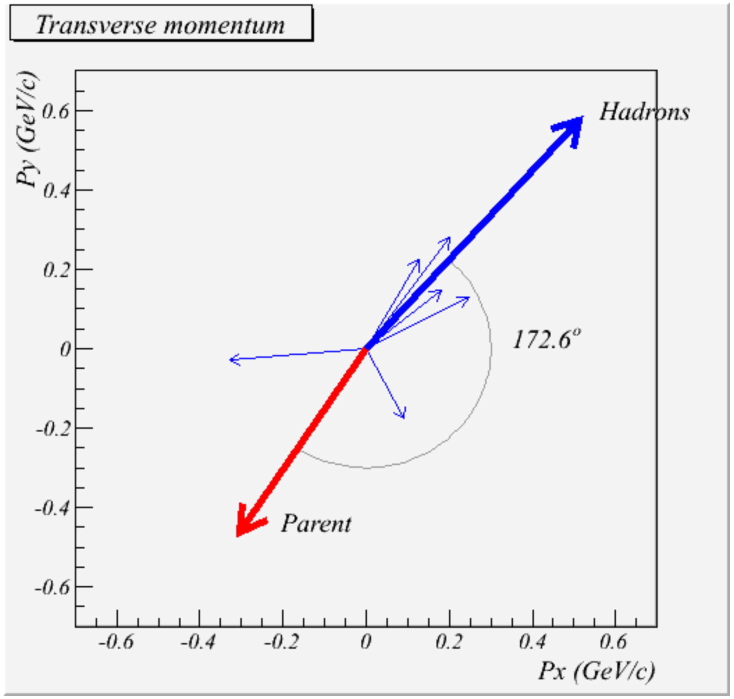
- 2008-2009 run analysis
- Conservative approach: get confidence on the detector performances before applying any kinematical cut
- No kinematical cut
- Slower analysis speed (signal/noise not optimal)
- Good data/MC agreement

Event reconstruction in the brick



Kinematical variables

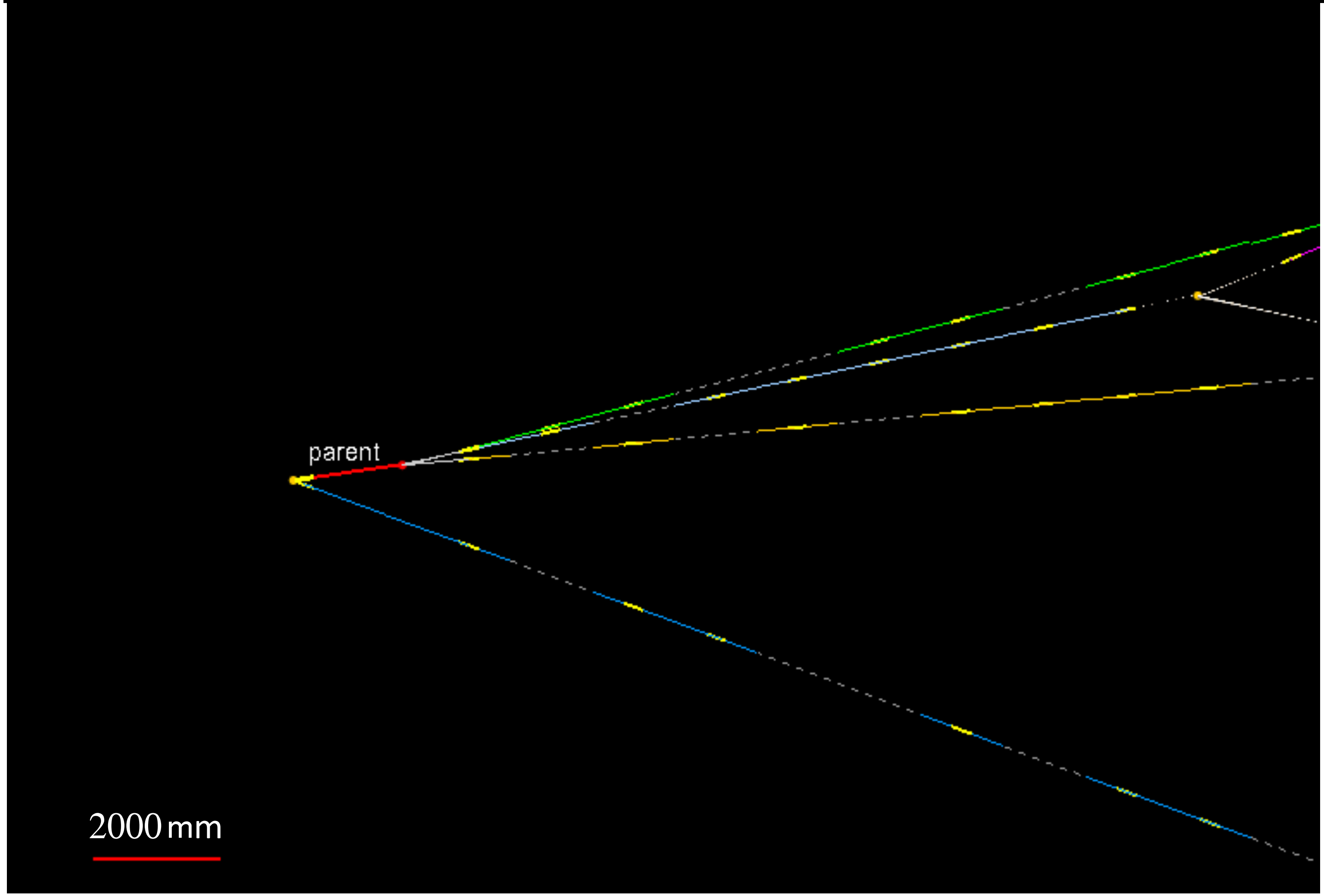
VARIABLE	AVERAGE
kink (mrad)	**41 ± 2**
decay length (mm)	**1335 ± 35**
P daughter (GeV/c)	**12^{+6}_{-3}**
Pt (MeV/c)	**470^{+240}_{-120}**
missing Pt (MeV/c)	**570^{+320}_{-170}**
ϕ (deg)	**173 ± 2**



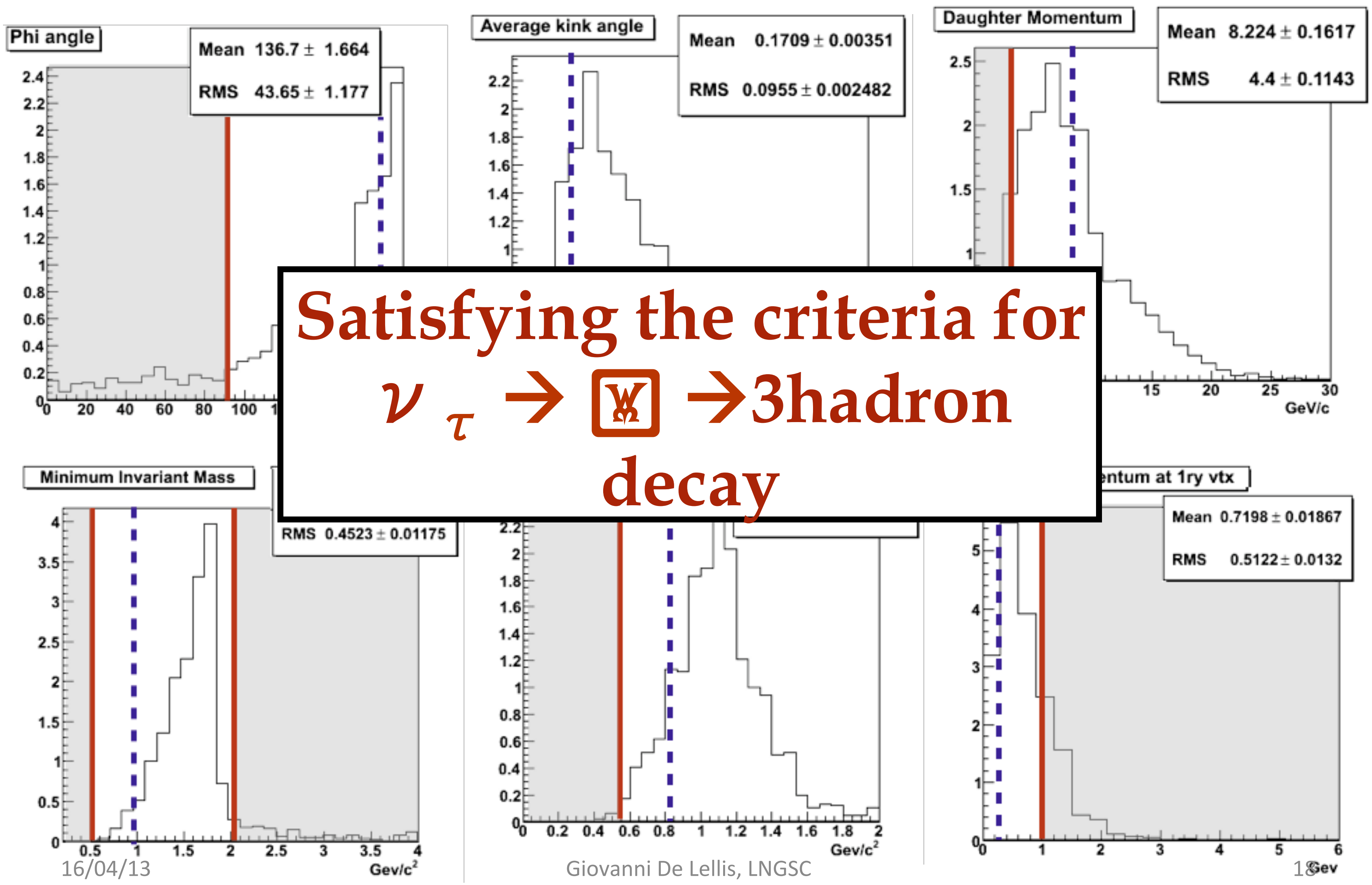
Strategy for the 2010÷2012 runs

- Apply kinematical selection
- 15 GeV μ momentum cut (upper bound)
- Anticipate the analysis of the most probable brick for all the events before moving to the second (and further ones): optimal ratio between efficiency and analysis time
- Anticipate the analysis of 0μ events (events without any μ in the final state)
- In view of 2012 Summer conferences: 1μ sample for 2010 run, for 2011 run stick to 0μ sample only, 2012 not yet analysed

Second ν_τ Candidate Event



Kinematics of the second candidate event

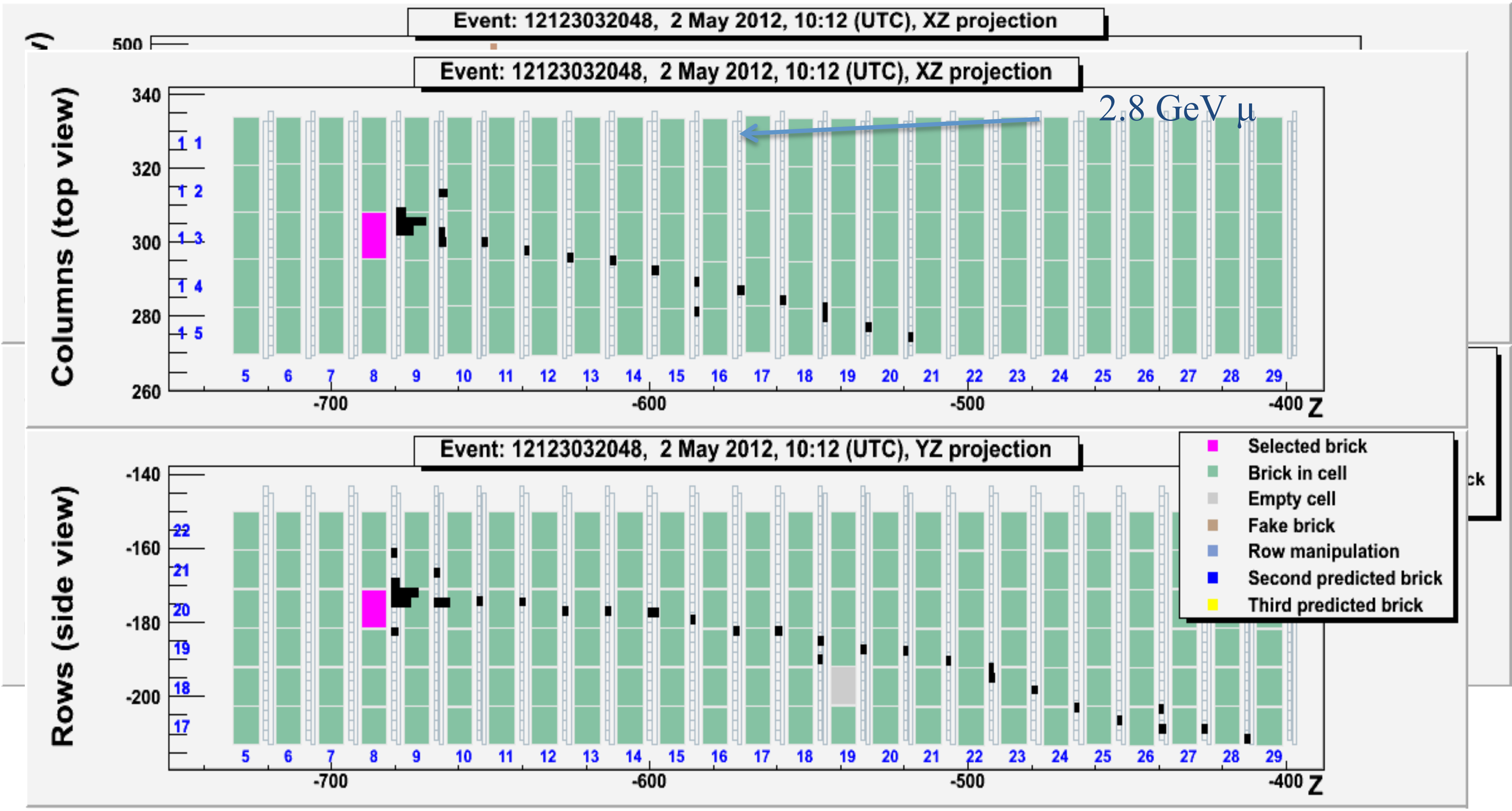


Satisfying the criteria for $\nu_\tau \to$ [illegible] $\to$ 3hadron decay

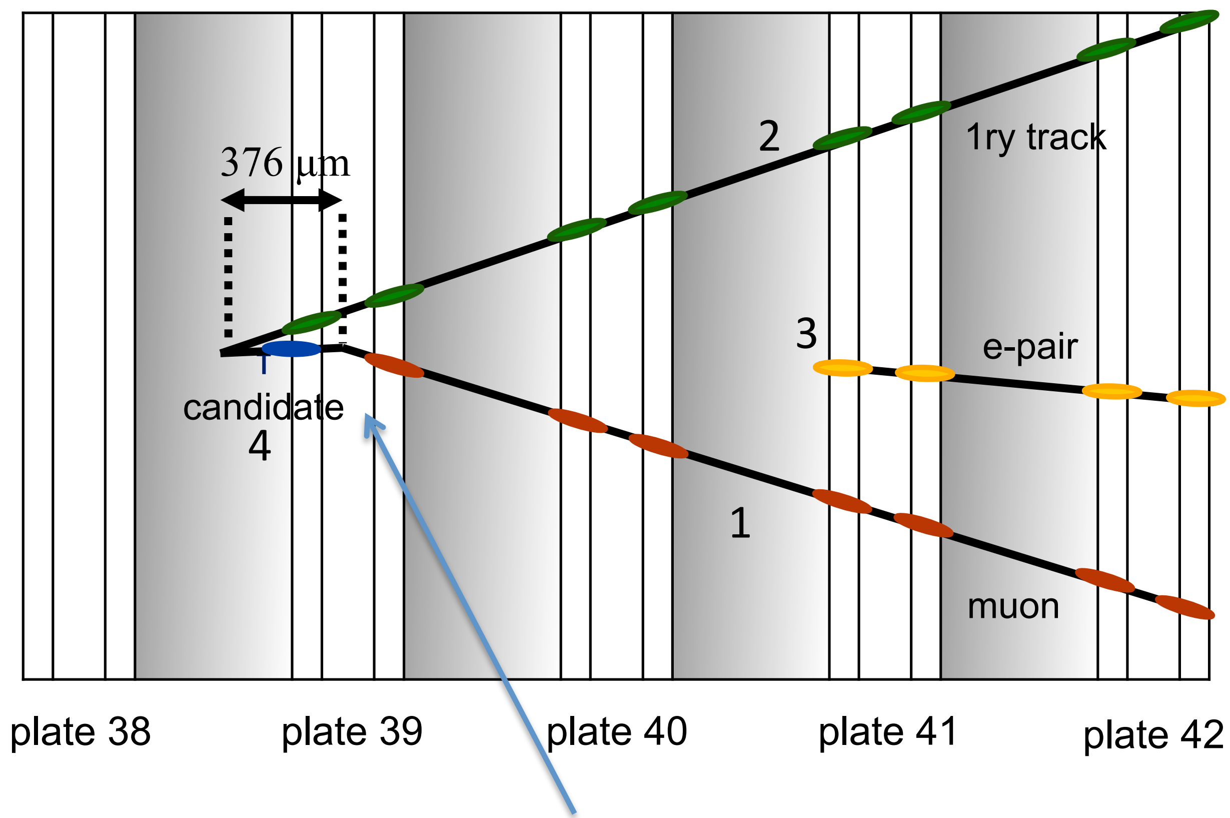
After 2012 Summer conferences

- *Extension of the analysed sample to events with one μ in the final state*

Third tau neutrino event taken on May 2nd 2012



$\tau \rightarrow \mu$ candidate
brick analysis and decay search



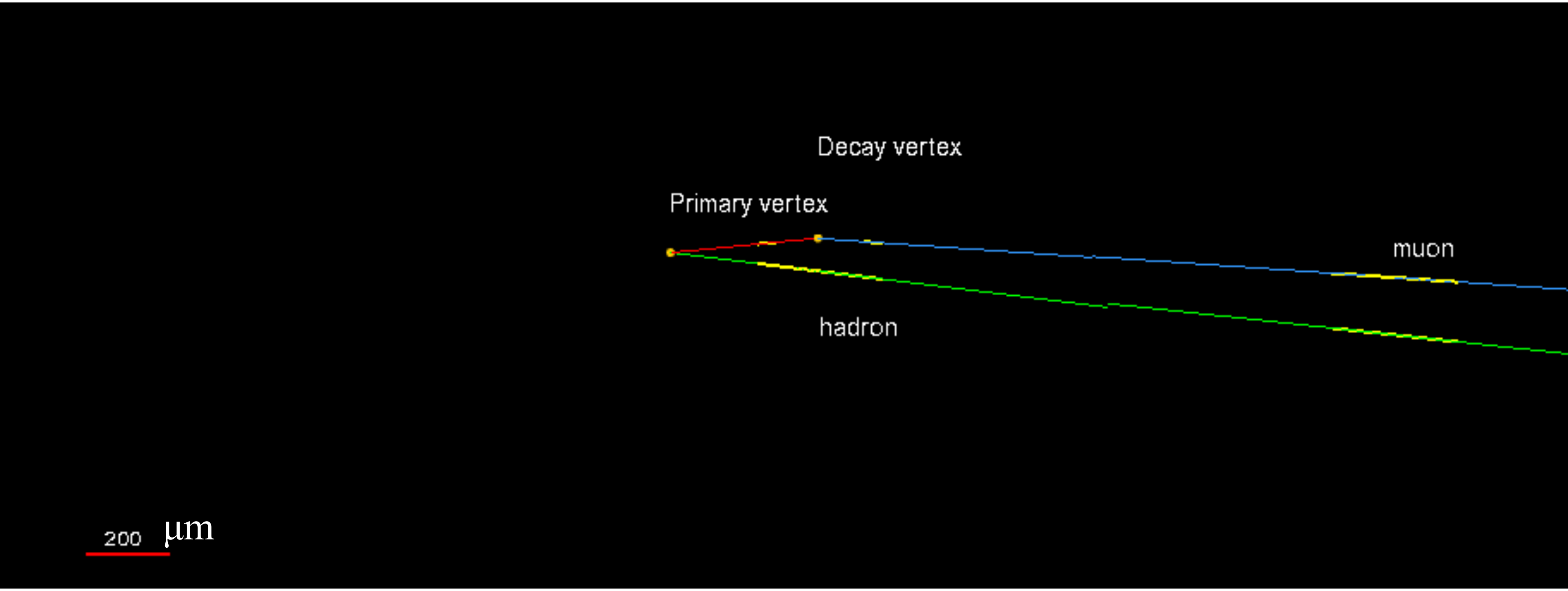
Decay in the plastic base

$\tau \rightarrow \mu$ candidate

μm

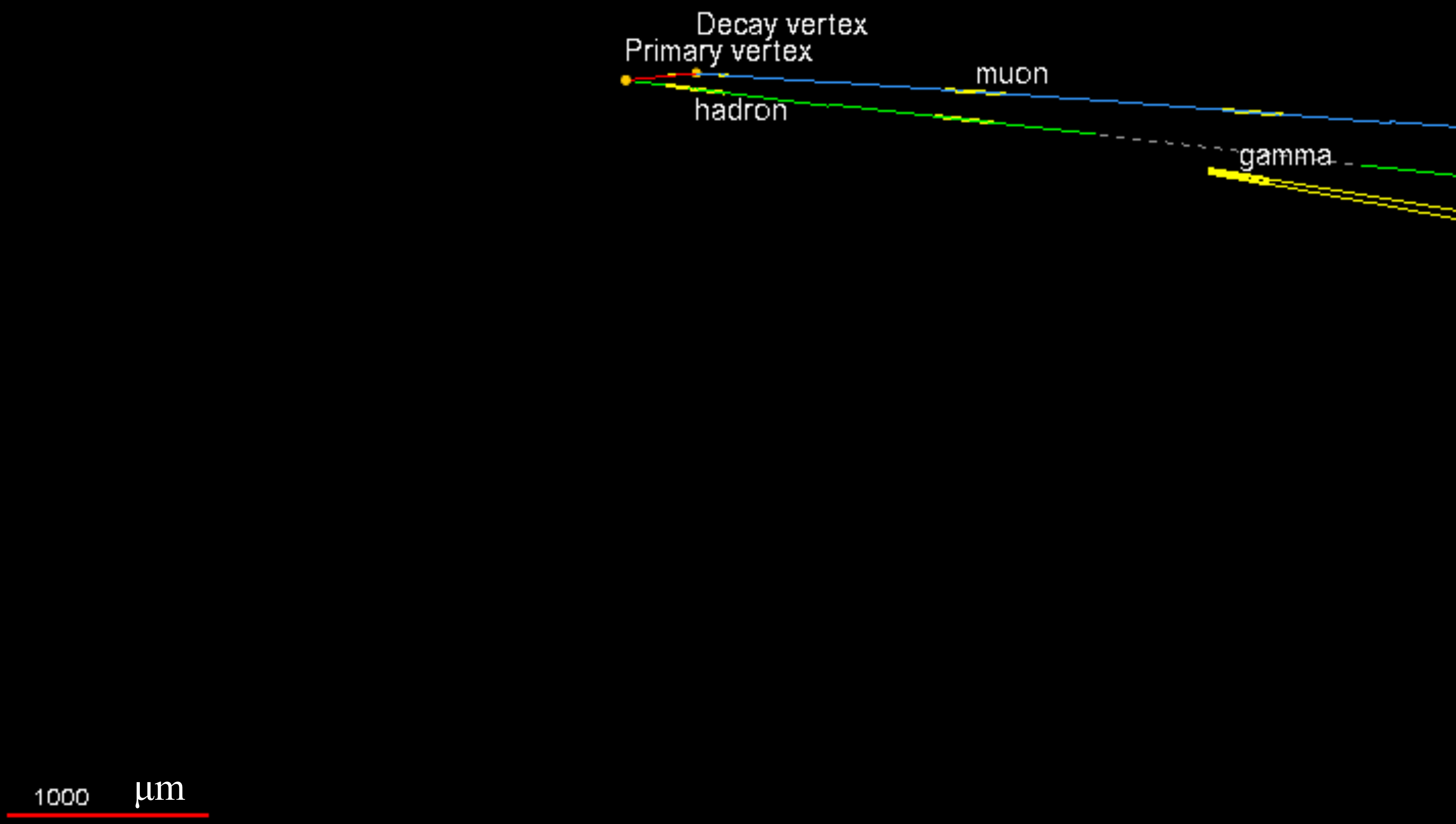
2

Third tau neutrino event
$\tau \rightarrow \mu$



Third tau neutrino event

$\tau \rightarrow \mu$



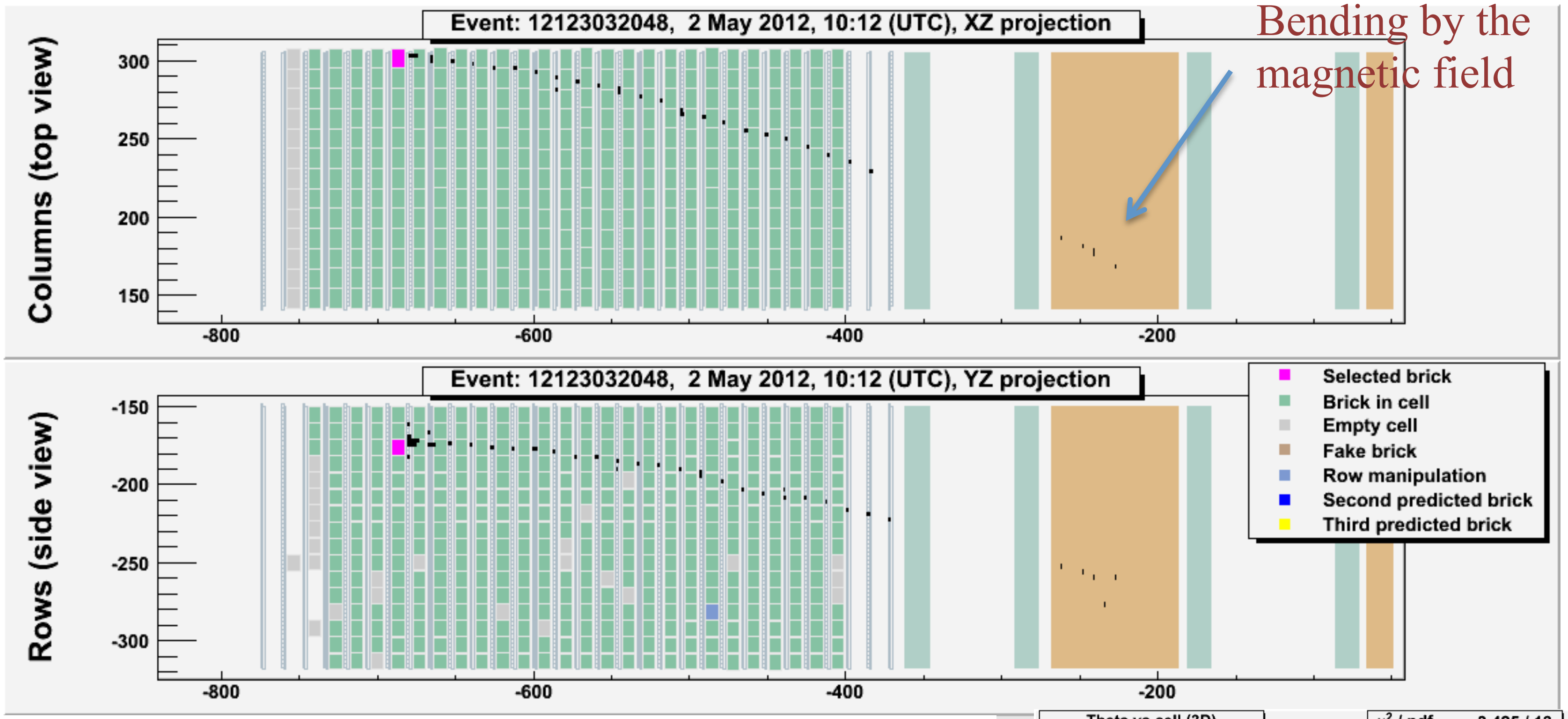
Event tracks' features

TRACK NUMBER	PID	MEASUREMENT 1			MEASUREMENT 2		
		Θ_X	Θ_Y	P (GeV/c)	Θ_X	Θ_Y	P (GeV/c)
1 DAUGHTER	MUON	-0.217	-0.069	3.1 [2.6,4.0]MCS	-0.223	-0.069	2.8±0.2 Range (TT+RPC)
2	HADRON Range	0.203	-0.125	0.85 [0.70,1.10]	0.205	-0.115	0.96 [0.76,1.22]
3	PHOTON	0.024	-0.155	2.64 [1.9,4.3]	0.029	-0.160	3.24 [2.52,4.55]
4 PARENT	TAU	-0.040	0.098		-0.035	0.096	

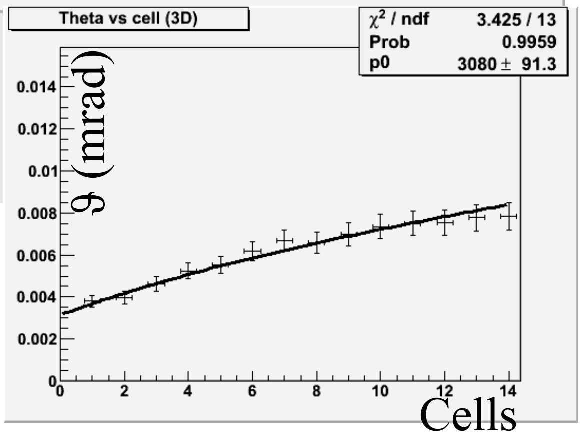
Gamma is clearly attached to the primary vertex

γ attachment

Muon charge and momentum reconstruction



Muon momentum
by range in the electronic detector: 2.8±0.2 GeV/c
MCS in the brick consistent 3.1 [2.6,4.0] GeV/c



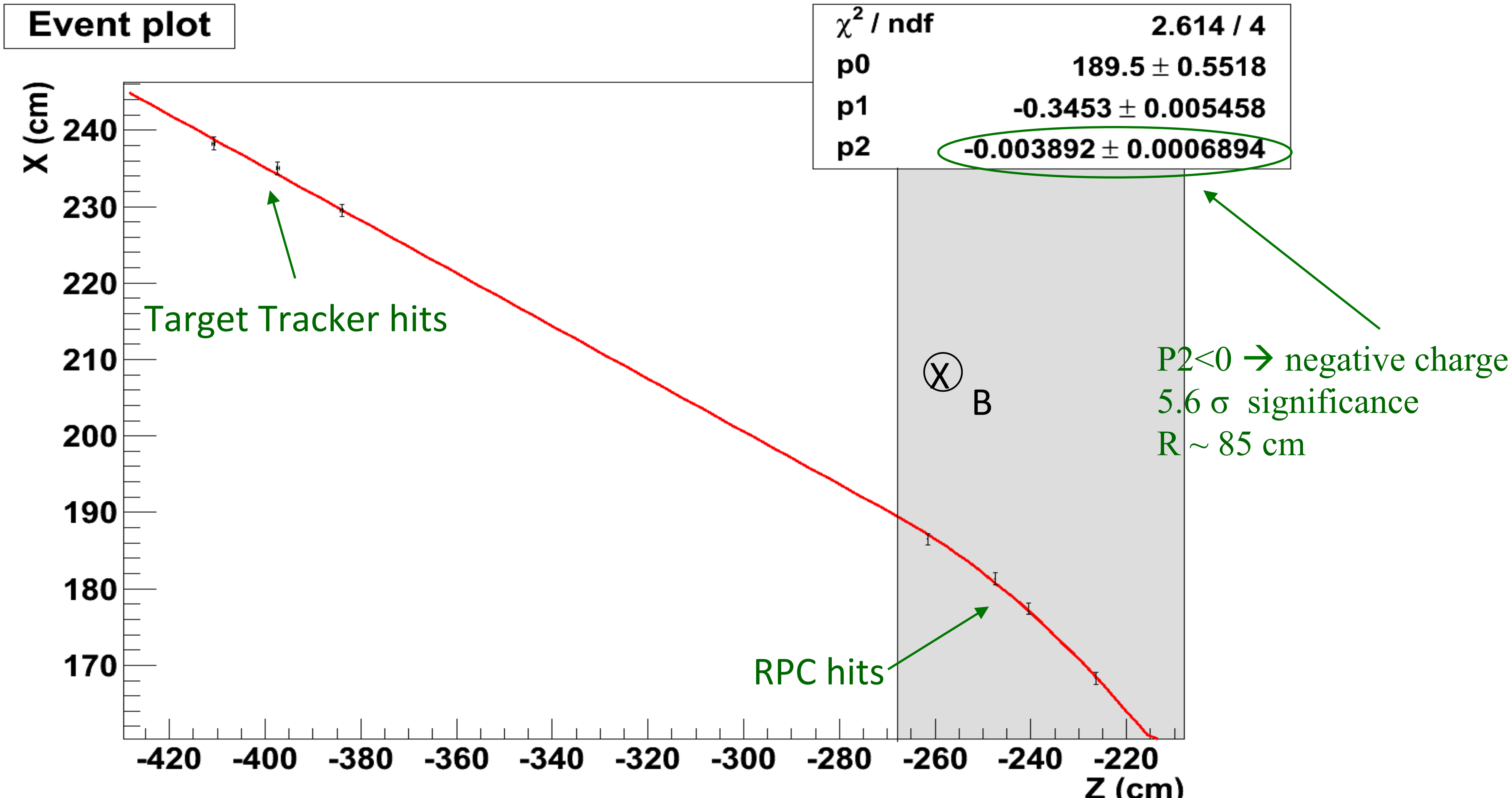
Charge determination of the muon

Charge measurement based on TT and RPC hits

Fit function:

$$X(z) = p0 + p1 \times (z-z0) + p2 \times (z-z0)^2 \quad \text{for } z>z0\text{, start of magnetized region}$$

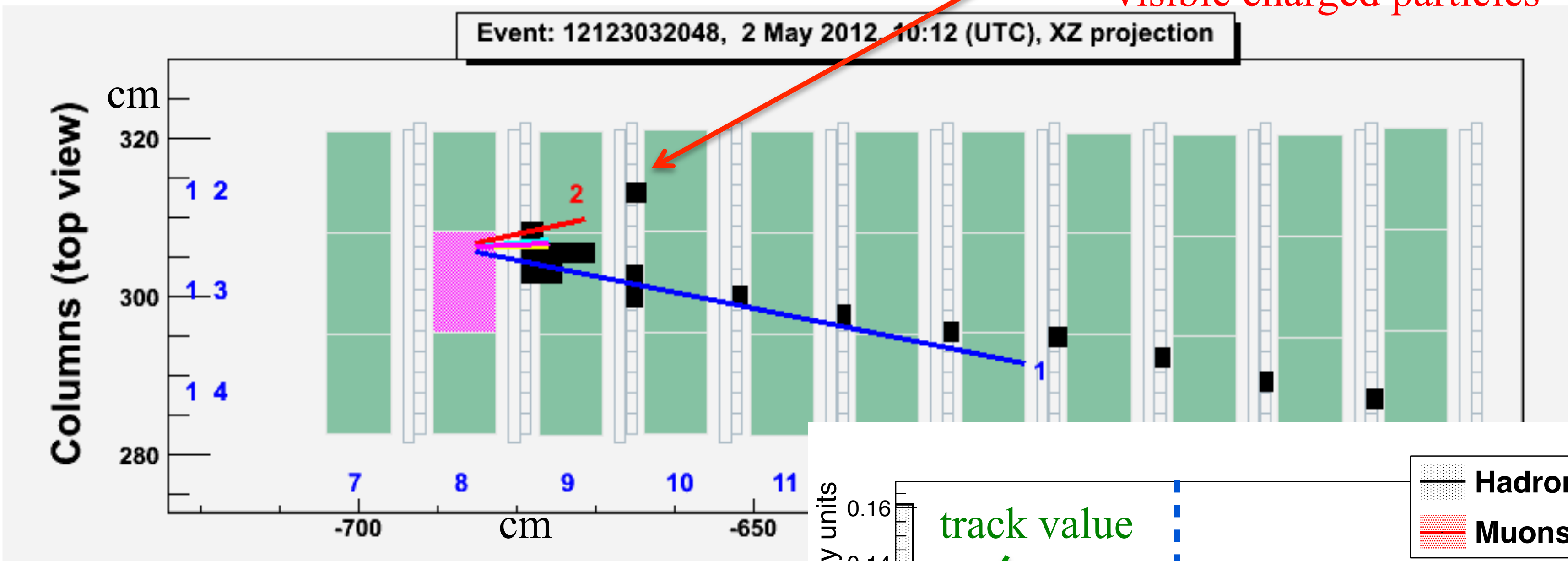
$$X(z) = p0 + p1 \times (z-z0) \quad \text{for } z<z0$$



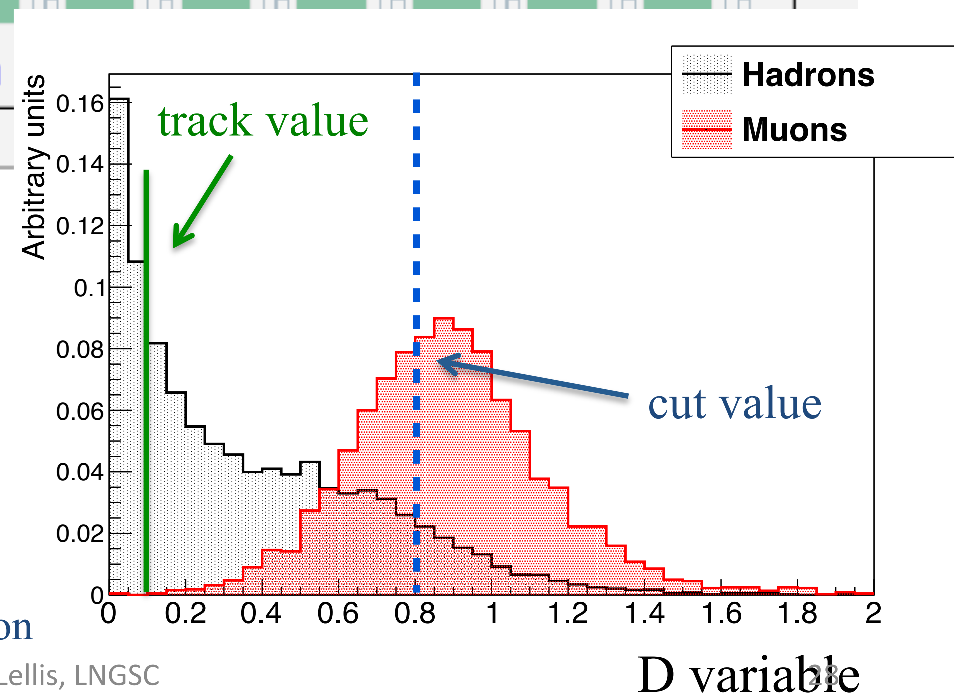
P-value = 0.063% (probability to reconstruct a m^+ stopping in the 7^{th} iron layer with p2 < -0.00389 cm^{-1})

Track follow down to assess the nature of track 2

Track 2 interacting in the downstream brick without visible charged particles



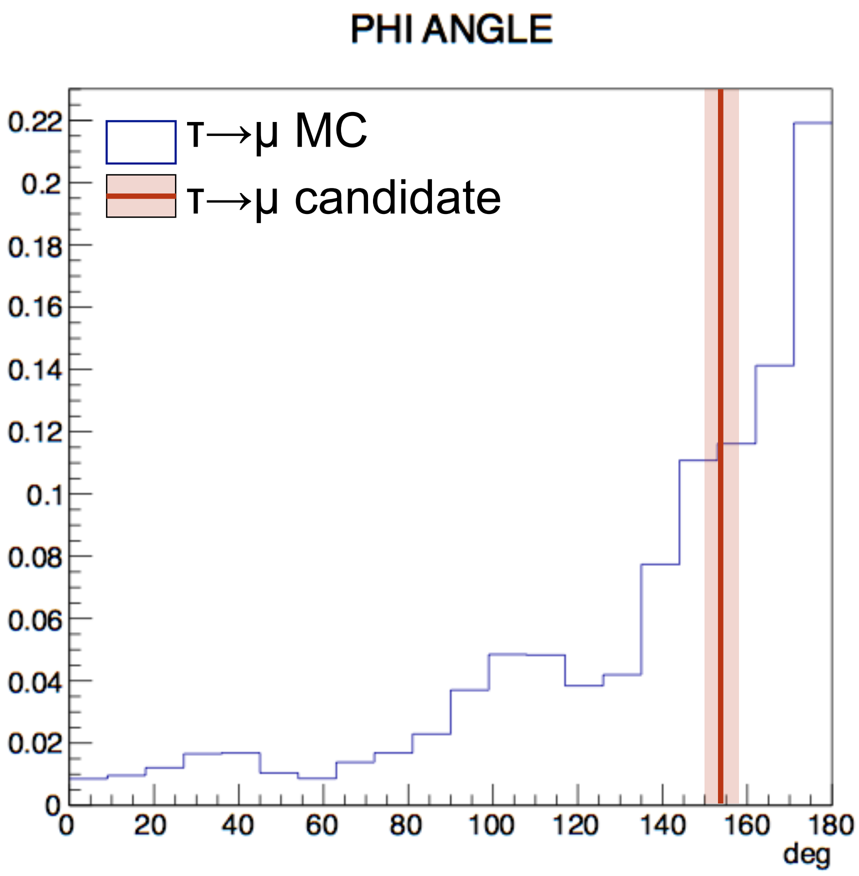
Momentum/range inconsistent with μ hypothesis
0.9 GeV/4 cm Lead



$$D = \frac{L}{R_{lead}(p)} \frac{\rho_{lead}}{\rho_{average}}$$

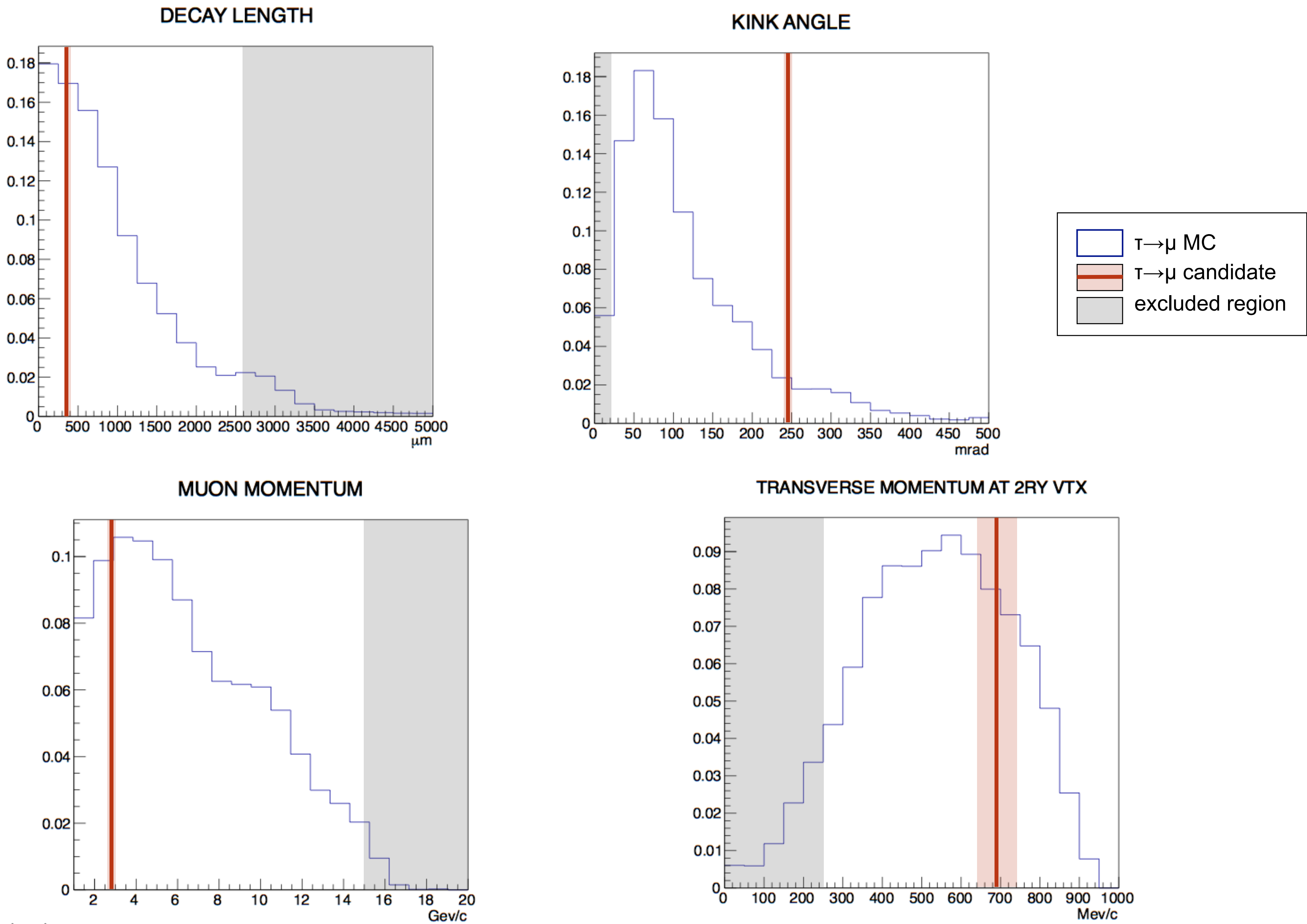
L = track length
R_{lead} = μ range
$\rho_{average}$ = average density
ρ_{lead} = lead density
p = momentum in emulsion

Kinematical variables



VARIABLE	AVERAGE
Kink angle (mrad)	**245 ± 5**
decay length (μm)	**376 ± 10**
Pμ (GeV/c)	**2.8±0.2**
Pt (MeV/c)	**690±50**
ϕ (degrees)	**154.5 ± 1.5**

Kinematical variables. All cuts passed: τ →μ candidate

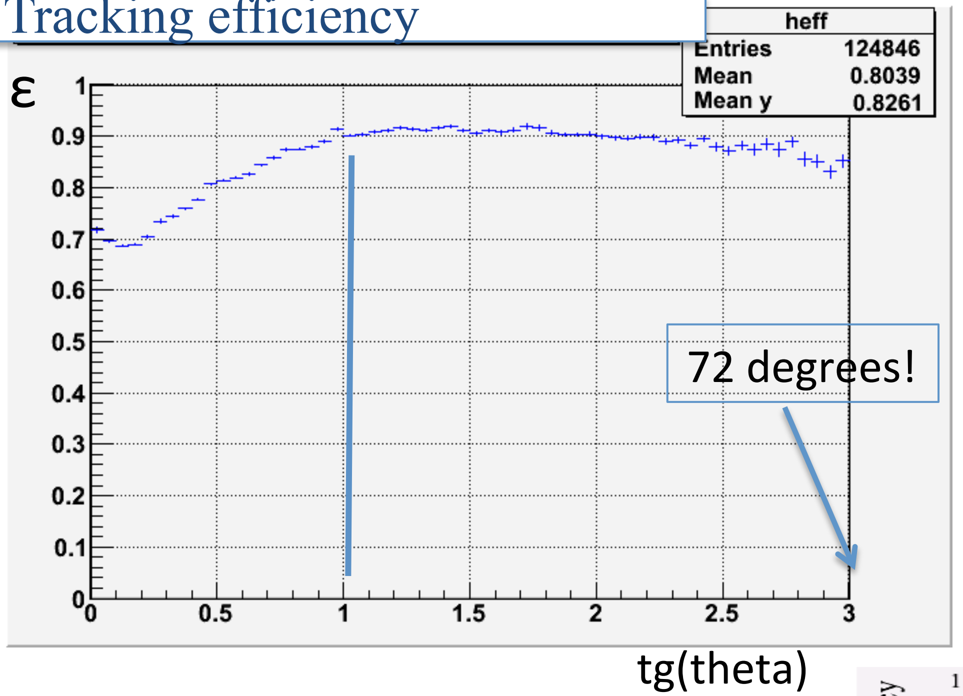


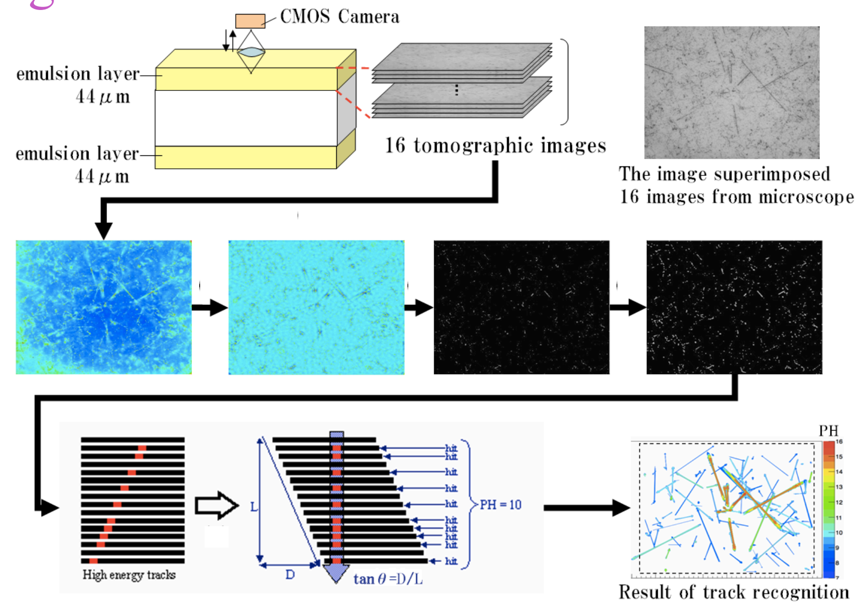
Improvements on the background rejection: large angle track detection

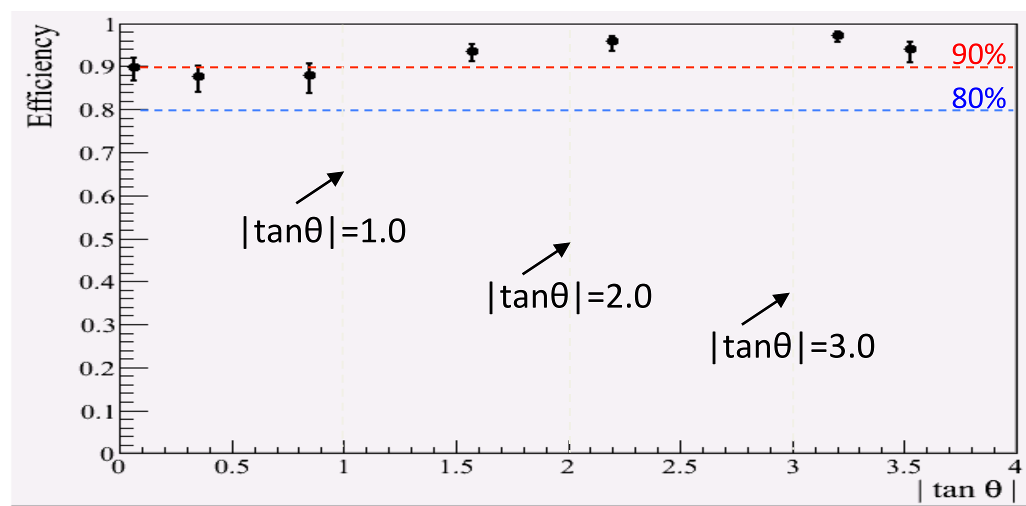
Undetected soft and large angle muons are the source of charm background

Detection of particles and nuclear fragments in hadronic interactions

Tracking efficiency





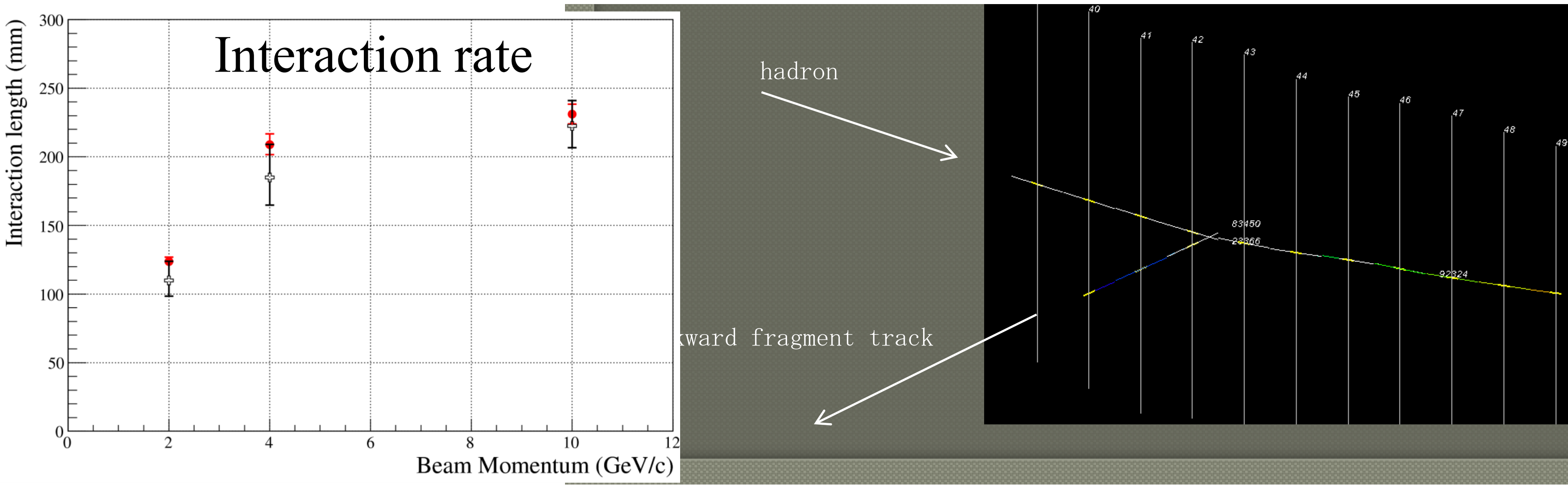


Two different approaches
get comparable results

Background studies: hadronic interactions

Comparison of large data sample (p⁻ beam test at CERN) with Fluka simulation: check the agreement and estimate the systematic error of simulation

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 : p^- beam data
Red : MC (FLUKA) simulation

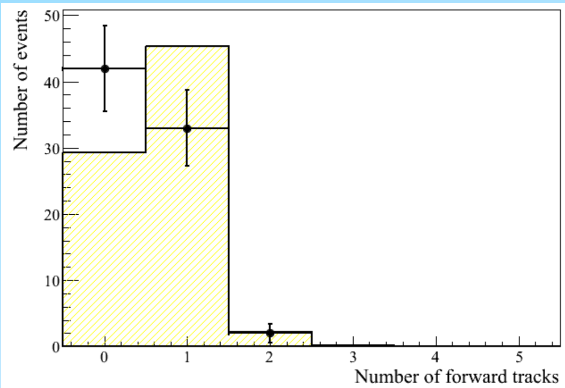
Secondary track emission

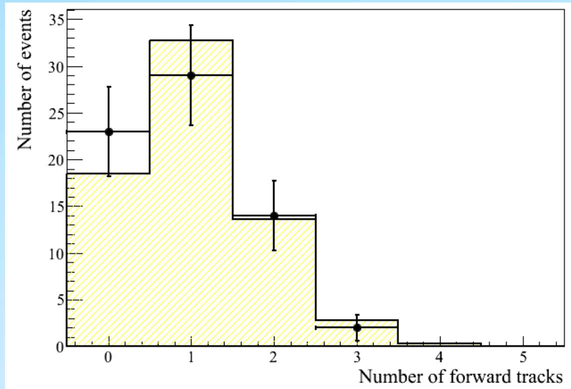
2GeV/c

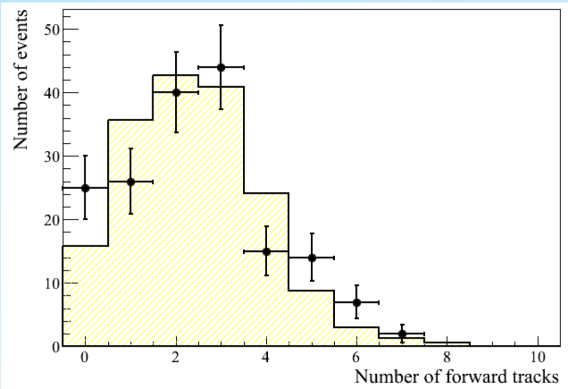
4GeV/c

10GeV/c

Multiplicity

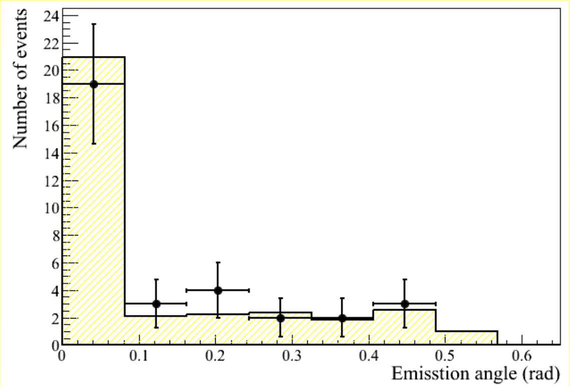


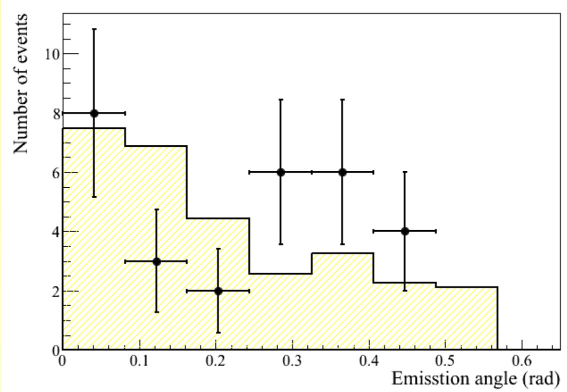


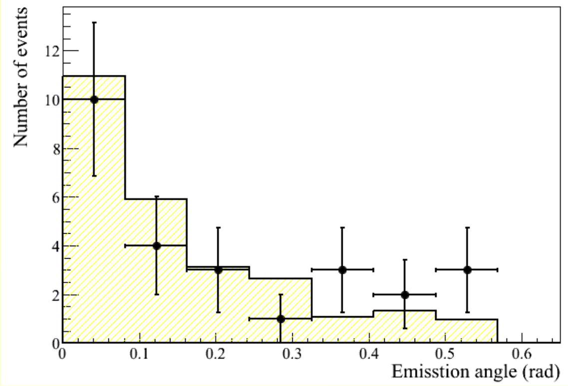


Error bars : Experimental data
Histogram : Simulated data

Kink angle (1-prong)

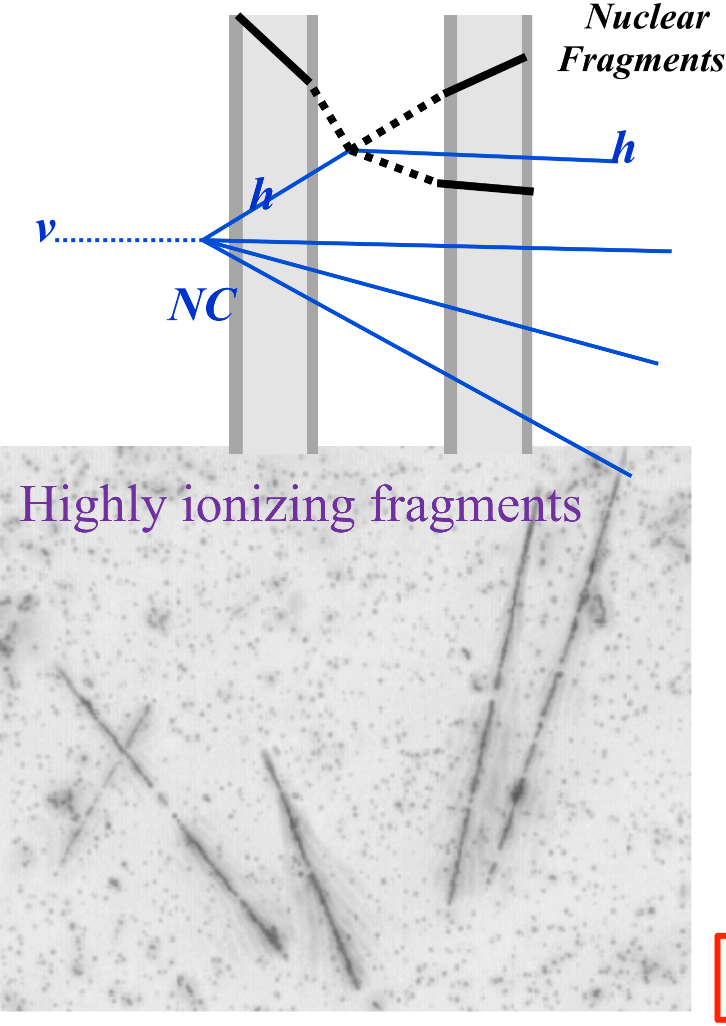


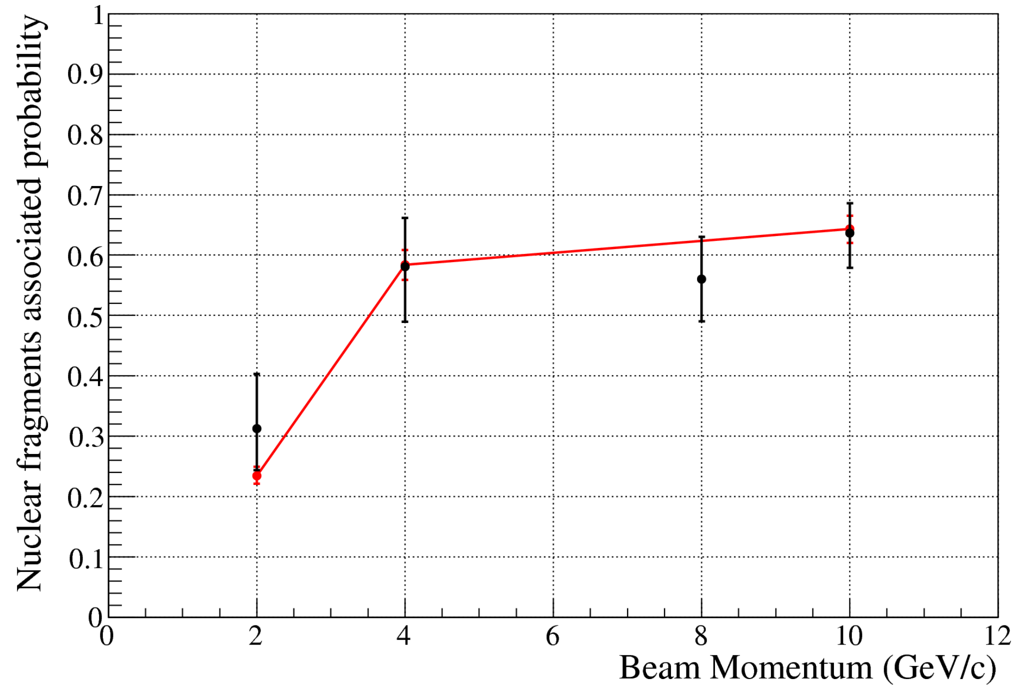




Good agreement within the statistical error: systematic error reduced to 30%

Nuclear fragments emission probability





Black : experimental data
Red : simulated data (b = p/E = 0.7)

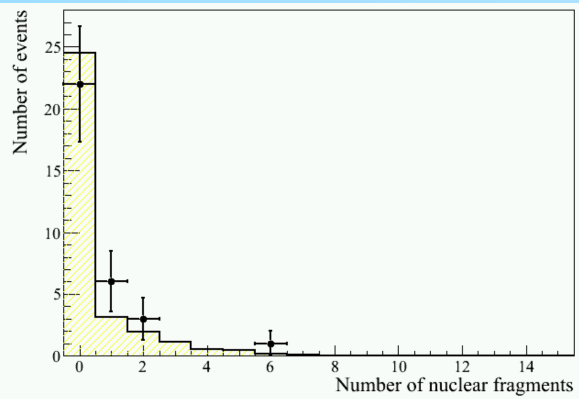
It provides additional background reduction.

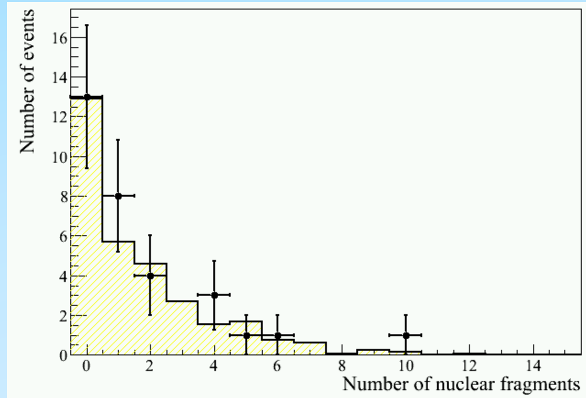
Nuclear fragments in 1 and 3 prong interactions

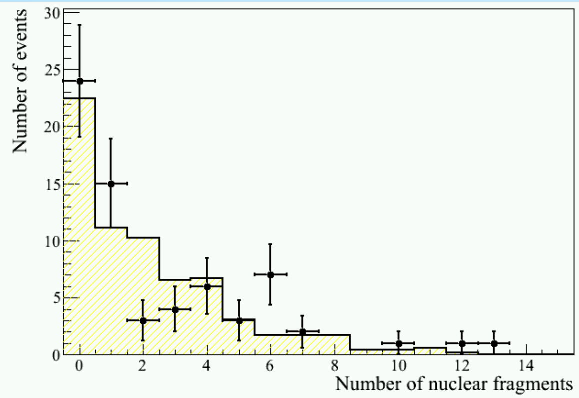
2GeV/c | 4GeV/c | 10GeV/c

Multiplicity

MC: b < 0.7

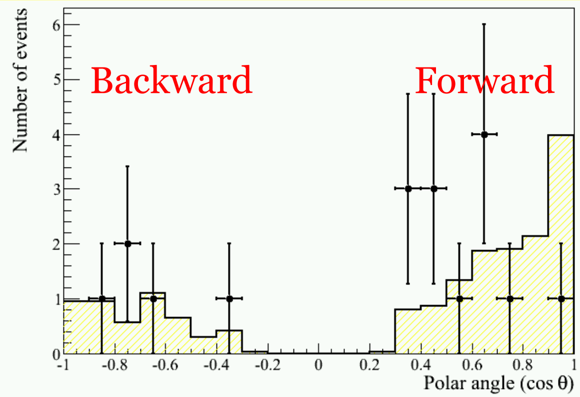


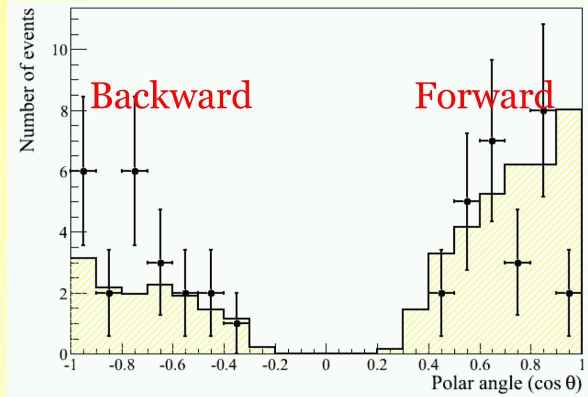


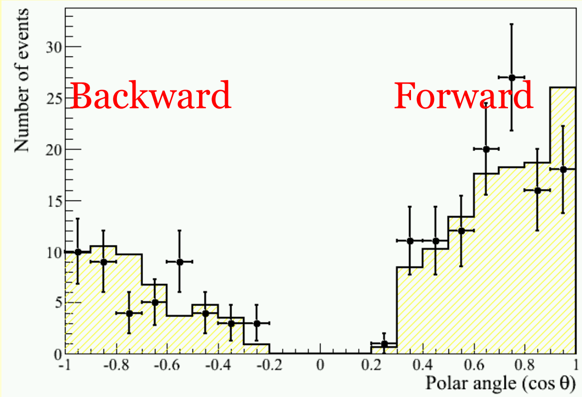


Error bars : experiment
Histogram : simulation

Emission angle(cos q)

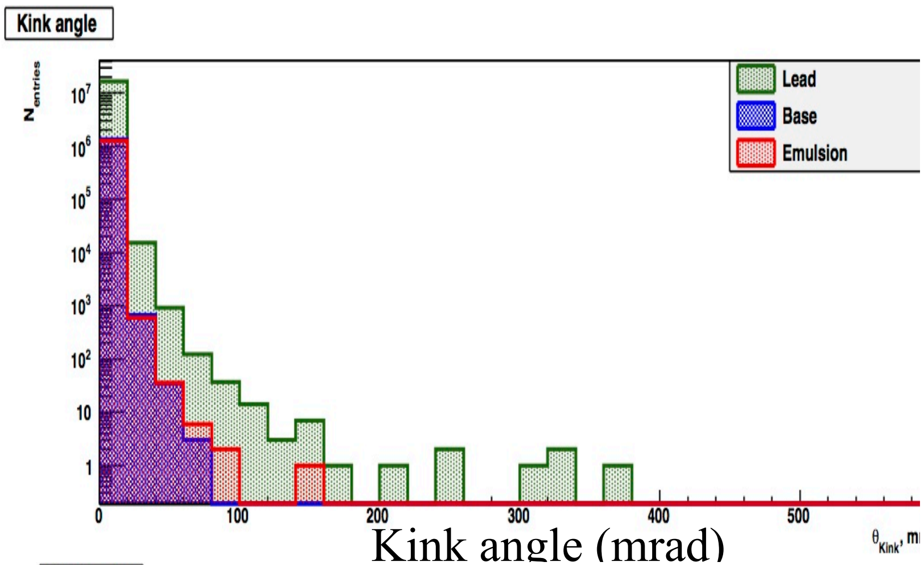


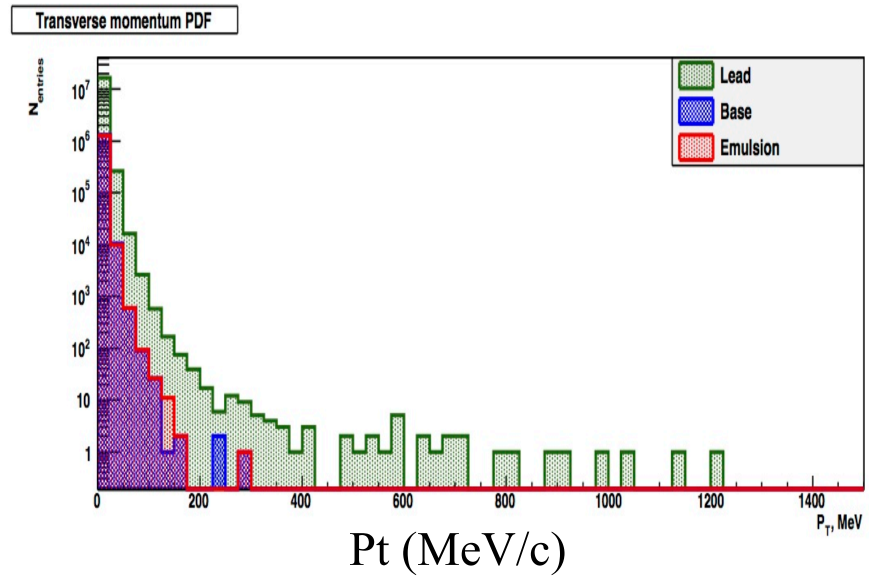


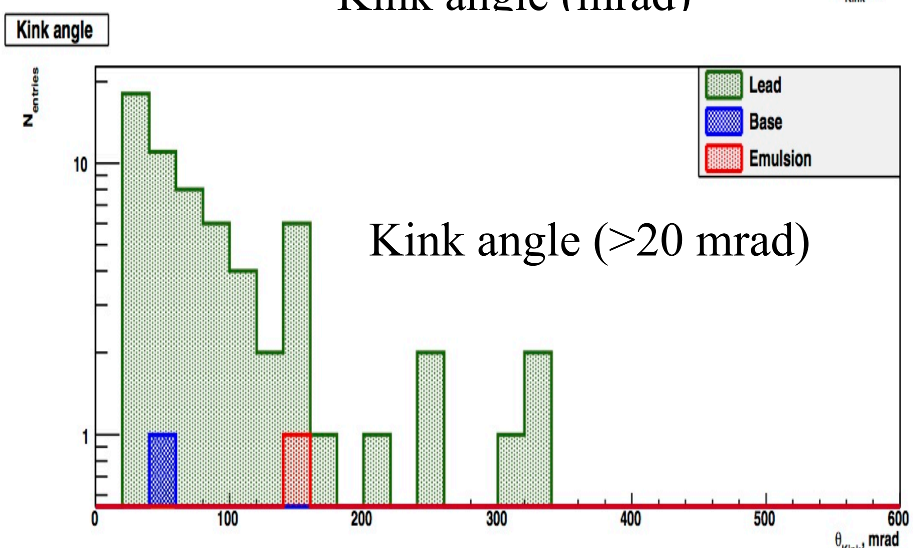


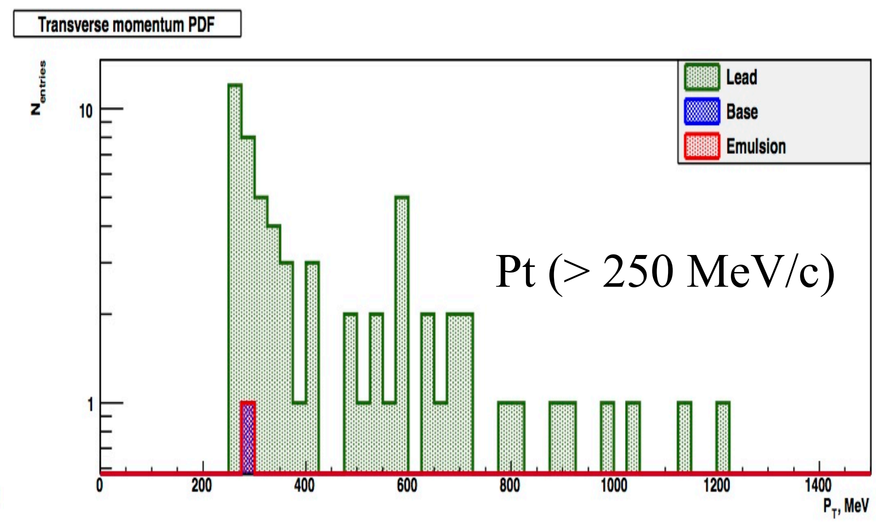
Agreement within the statistical error: systematic error is 10%.

Large angle muon scattering









Rate in lead (10^{-6}) and less in emulsion/base (10^{-8} to 10^{-7}). No measurements except an upper limit: S.A. Akimenko et al., NIM A423 (1986) 518 ($< 10^{-5}$ in lead). 10^{-5} rate used

Plan to revise this estimate by an experimental measurement with emulsion

Statistical considerations

Extended sample

	Signal	Background	Charm	μ scattering	had int
$\tau \rightarrow h$	0.66	0.045	0.029		0.016
$\tau \rightarrow 3h$	0.61	0.090	0.087		0.003
$\tau \rightarrow \mu$	0.56	0.026	0.0084	0.018	
$\tau \rightarrow e$	0.49	0.065	0.065		
total	2.32	**0.226**	0.19	0.018	0.019

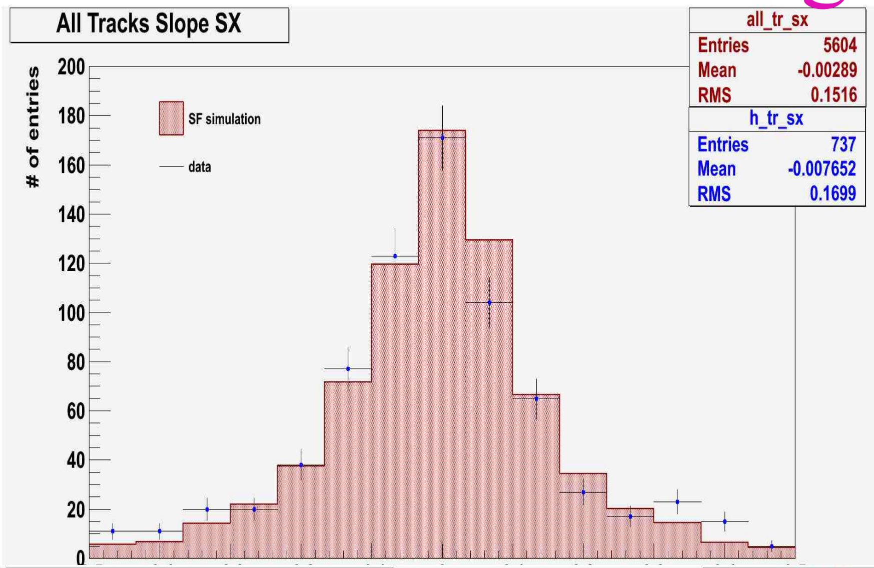
3 observed events in the $\tau \rightarrow h$ and $\tau \rightarrow 3h$ and $\tau \rightarrow \mu$ channels
Probability to be explained as a background = 7×10^{-4}
This corresponds to 3.2 σ significance of non-null observation

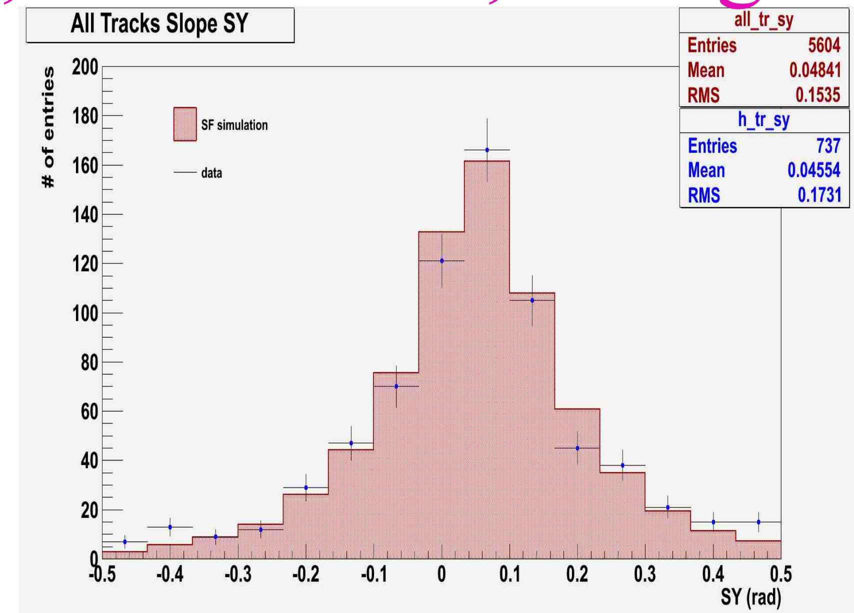
Likelihood analysis:
one of the discriminating variables

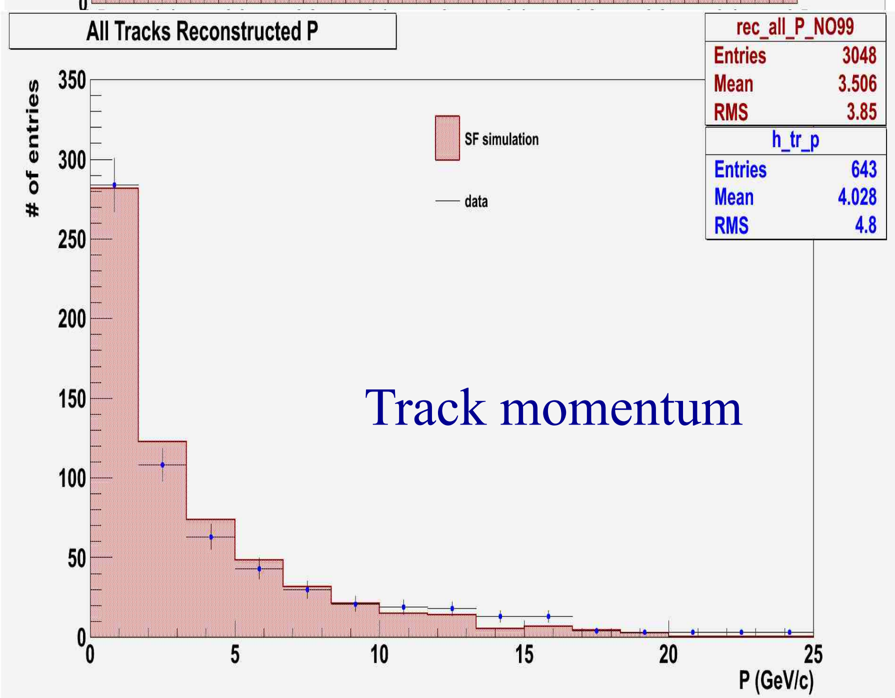
angle between the parent and the hadron jet in the transverse plan

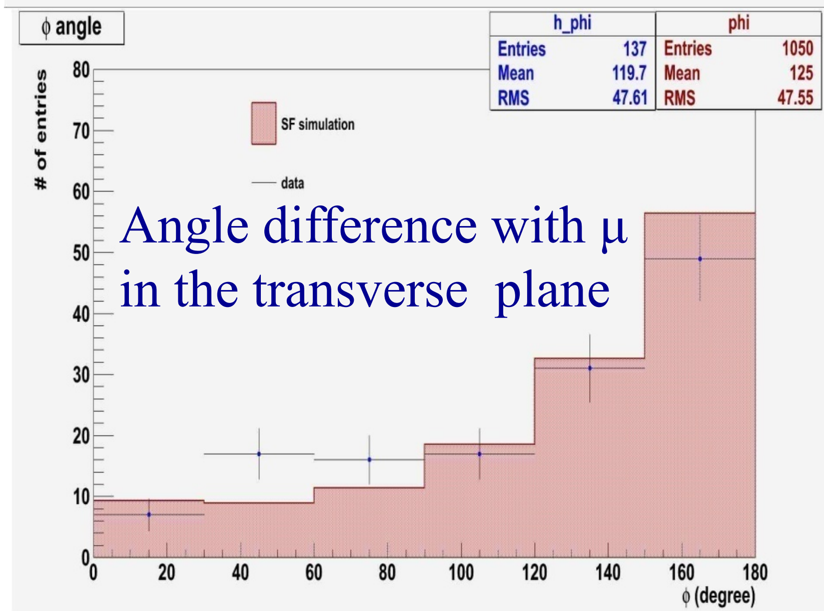
3h decay channels are reported in Figure 59. Th
selects 81% of the signal and 37% of the charm ba

Track emission angles, momentum, Φ angle









Statistical considerations

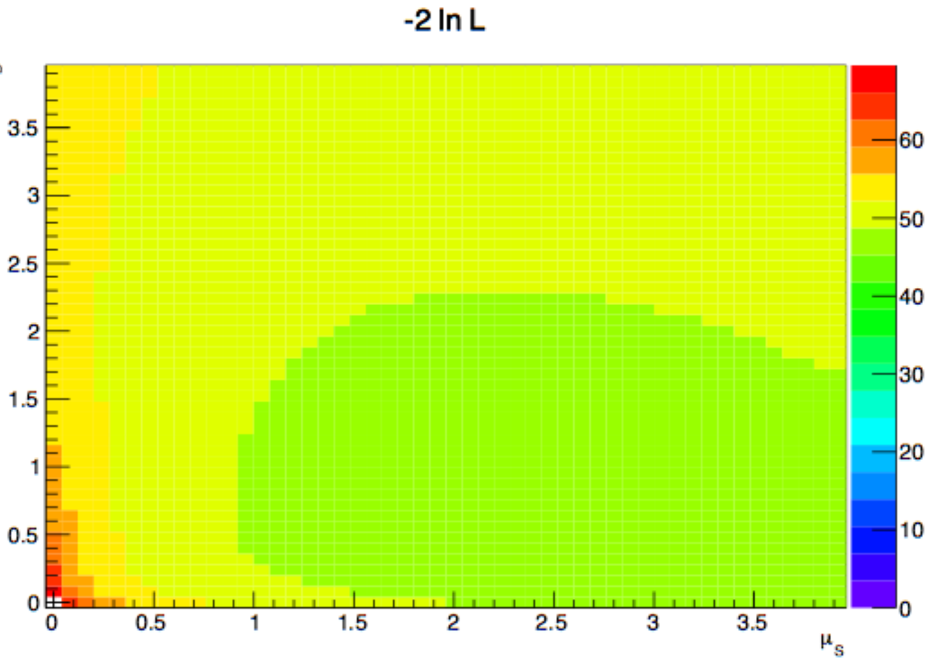
Combining different channels: Likelihood based method, see e.g.
G. Cowan et al., Eur. Phys. J. C71 (2011) 1554

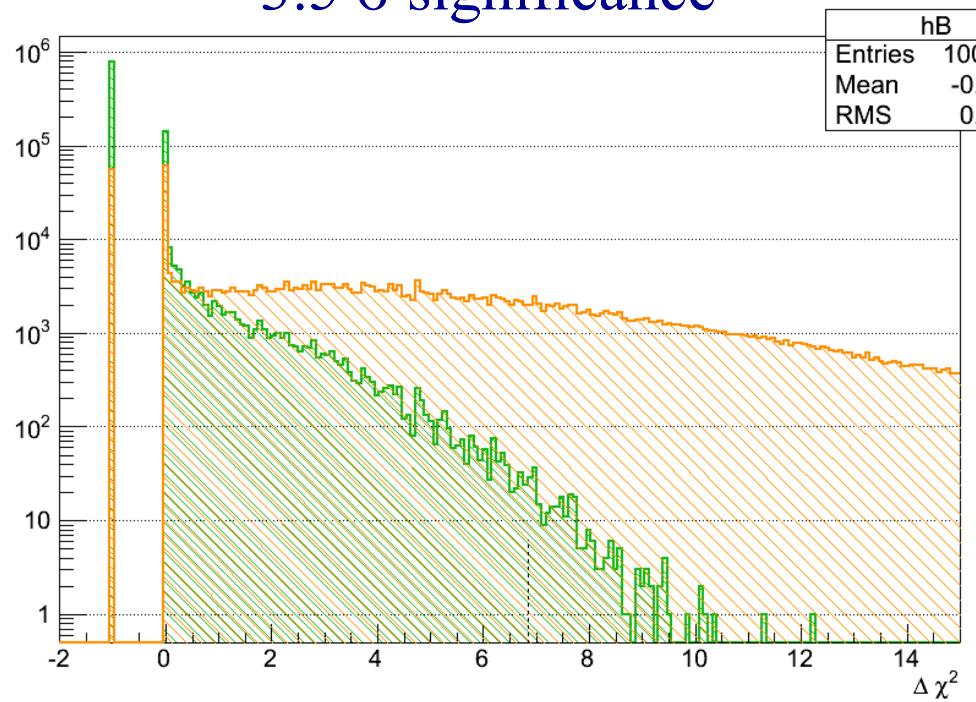
$$f^{S+B}(s,b,x) = \frac{s f_S(x) + b f_B(x)}{s+b}$$

$$\mathcal{L}(s,b) = \frac{(s+b)^n e^{-(s+b)}}{n!} \prod_{c=1}^{4} \prod_{i=0}^{n_c} \prod_{v=1}^{n_v} f_{v,c}^{S+B}(s,b,x_v)$$

$$LR = -2 \ln \frac{\mathcal{L}(0,b)}{\mathcal{L}(s,b)}$$

3.5 σ significance





Evidence for $\nu_\mu \rightarrow \nu_\tau$ in appearance mode

- *Three events reported in an extended sample*
- *Conservative background evaluation*
- *Significance of 3.2σ with simple counting method*
- *With a likelihood approach, 3.5σ level*
- *4σ observation within reach*