Results of the OPERA experiment

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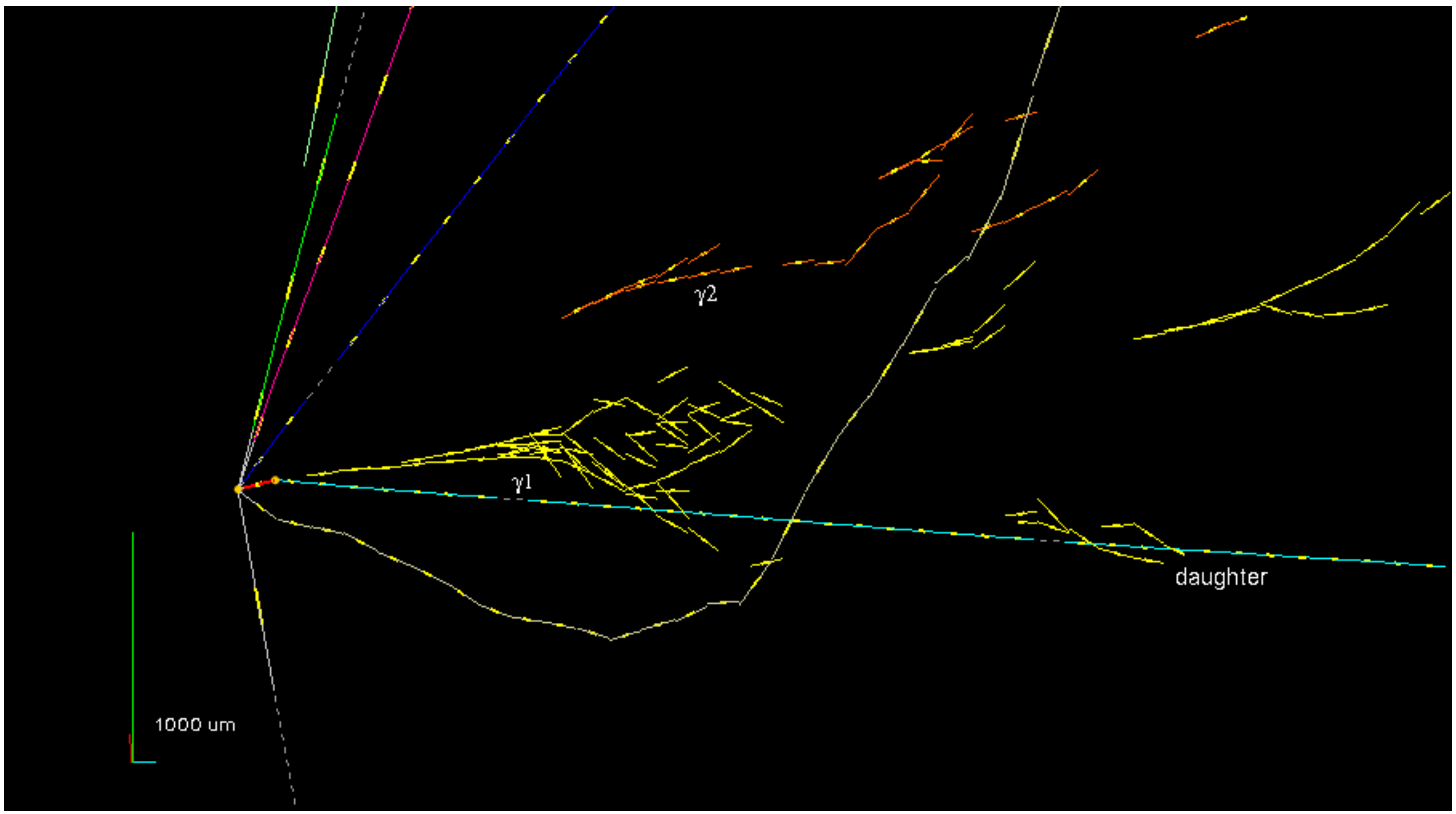
University "Federico II" and INFN Napoli



THE OPERA COLLABORATION

140 physicists, 28 institutions in 11 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

Italy
Bari
Bologna
Frascati
L'Aquila,
LNGS
Naples
Padova
Rome
Salerno

Japan
Aichi
Toho
Kobe
Nagoya
Utsunomiya

Korea
Jinju

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

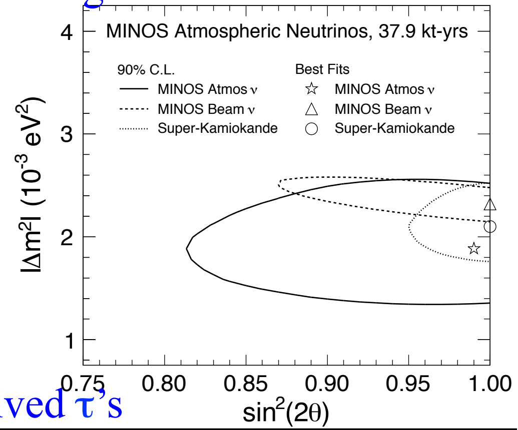
Switzerland
Bern

Turkey
METU, Ankara

http://operaweb.lngs.infn.it

OPERA: first direct detection of neutrino oscillations in appearance mode

following the Super-Kamiokande (Macro and Soudan-2) discovery of oscillations with atmospheric neutrinos and the confirmation with solar neutrinos and accelerator beams. An important, missing tile in the oscillation picture.

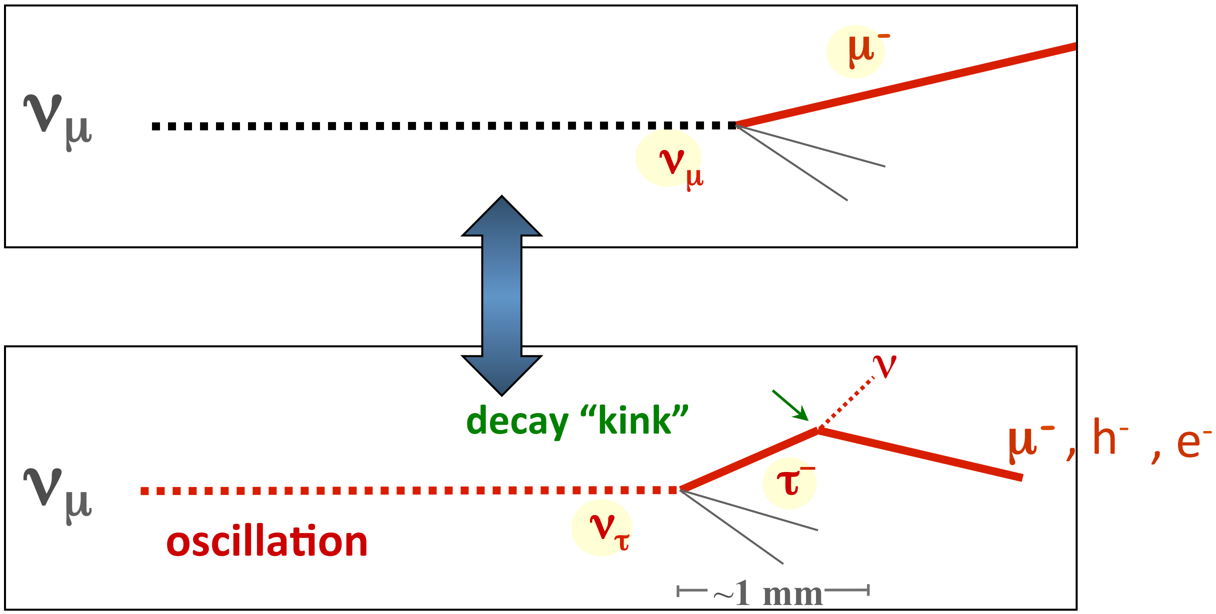


The PMNS 3-flavor oscillation formalism predicts:

$$P(\nu_\mu \rightarrow \nu_\tau) \sim \sin^2 2\theta_{23} \cos^4\theta_{13} \sin^2(\Delta m^2_{23} L/4E)$$

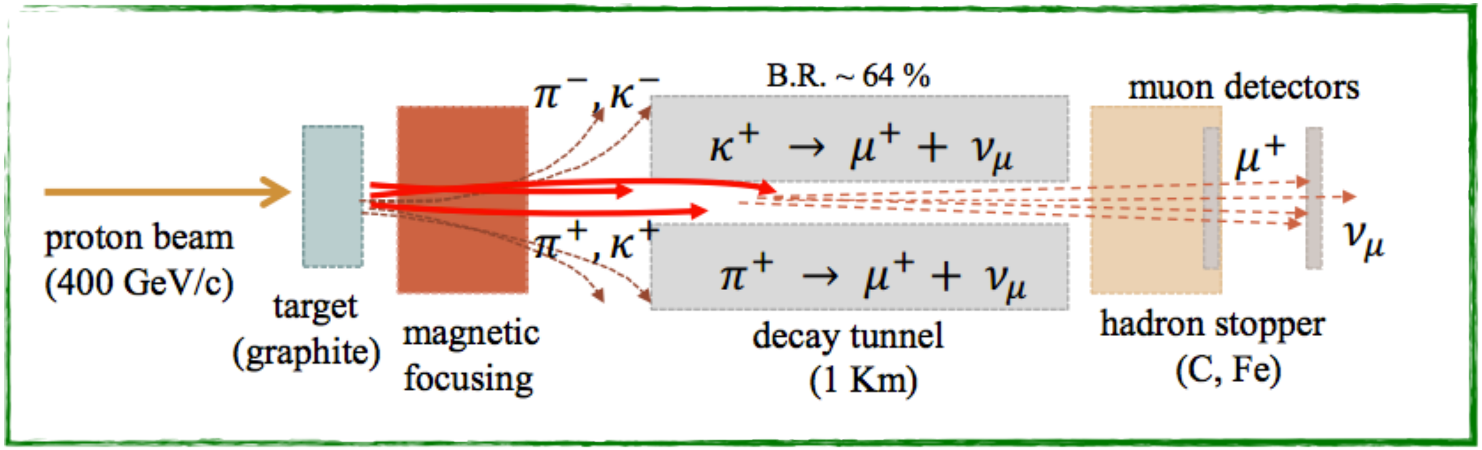
Requirements:

1) long baseline, 2) high neutrino energy, 3) high intensity beam, 4) detect short lived τ's



plus 3-prong decay modes

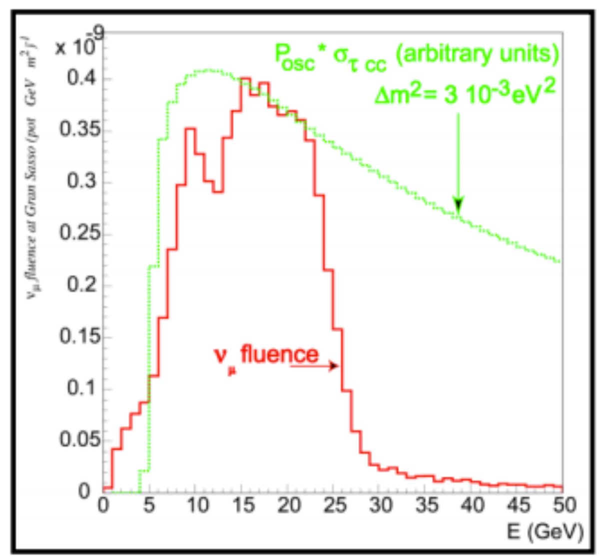
The CNGS Neutrino Beam



Beam parameters

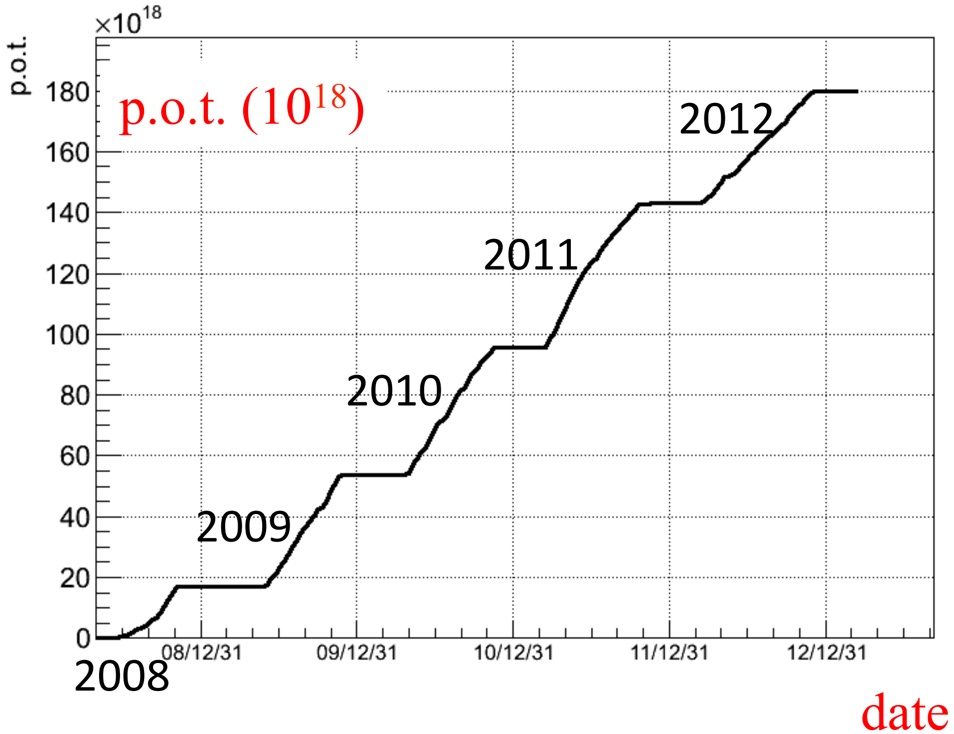
$<E\nu_\mu>$ (GeV)	17
$(\bar{\nu}_e+\nu_e)/\nu_\mu$	0.8% *
$\bar{\nu}_\mu/\nu_\mu$	2.0% *
ν_τ prompt	Negligible

* Interaction rate at LNGS



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

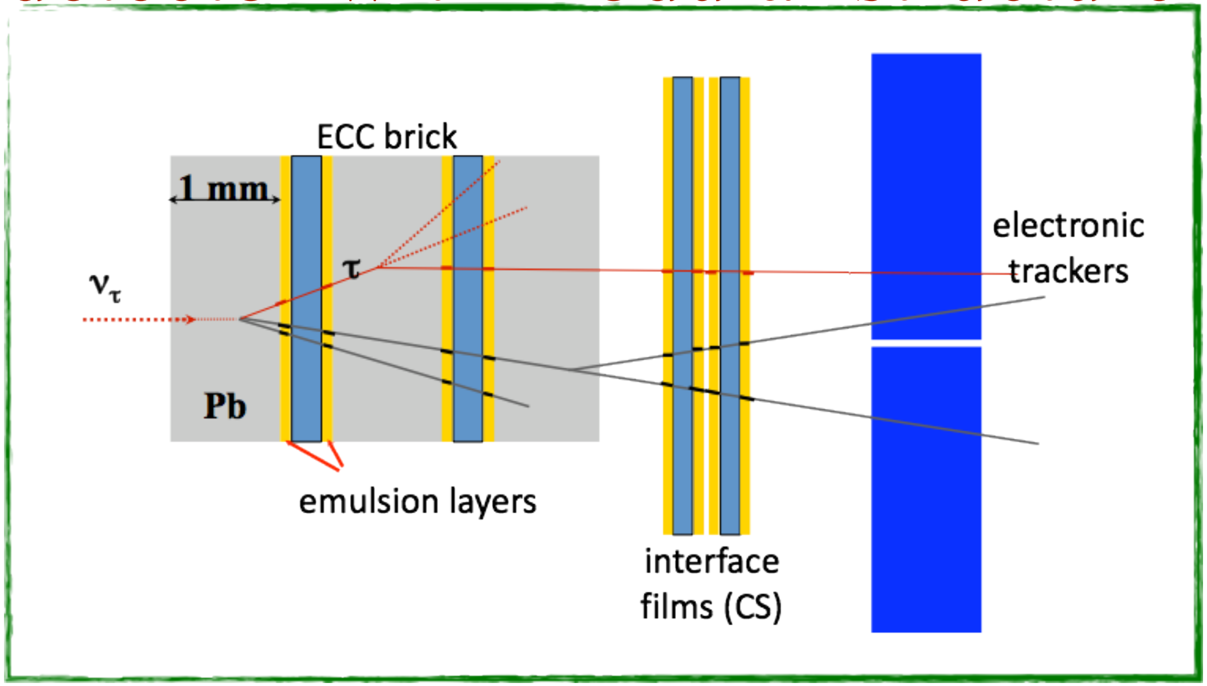
Year	Beam days	P.O.T. (10^{19})
2008	123	1.74
2009	155	3.53
2010	187	4.09
2011	243	4.75
2012	257	3.86
Total	**965**	**17.97**

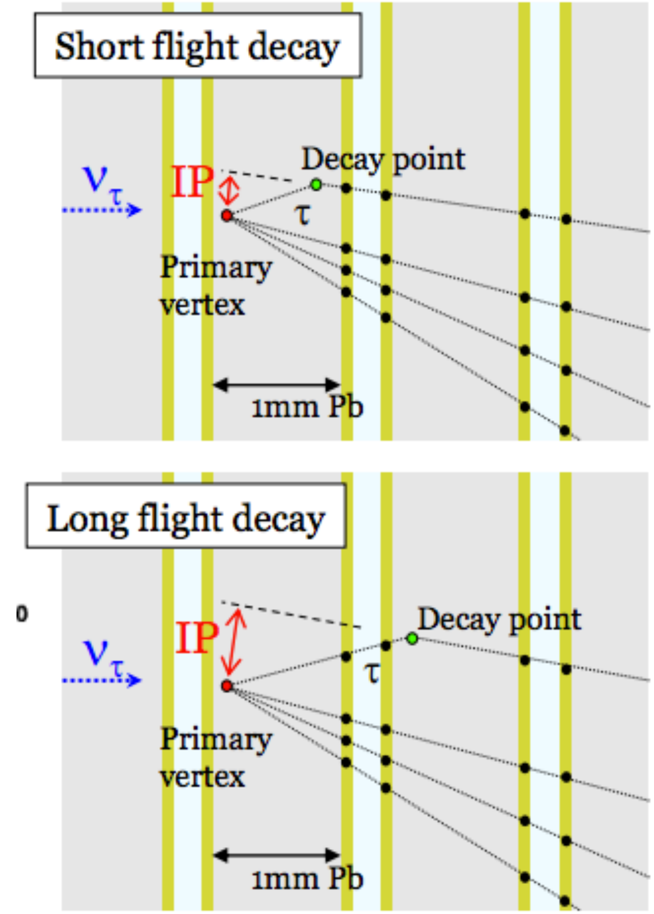


Record performances in 2011

Overall 20% less than the proposal value (22.5)

THE PRINCIPLE: hybrid detector with modular structure



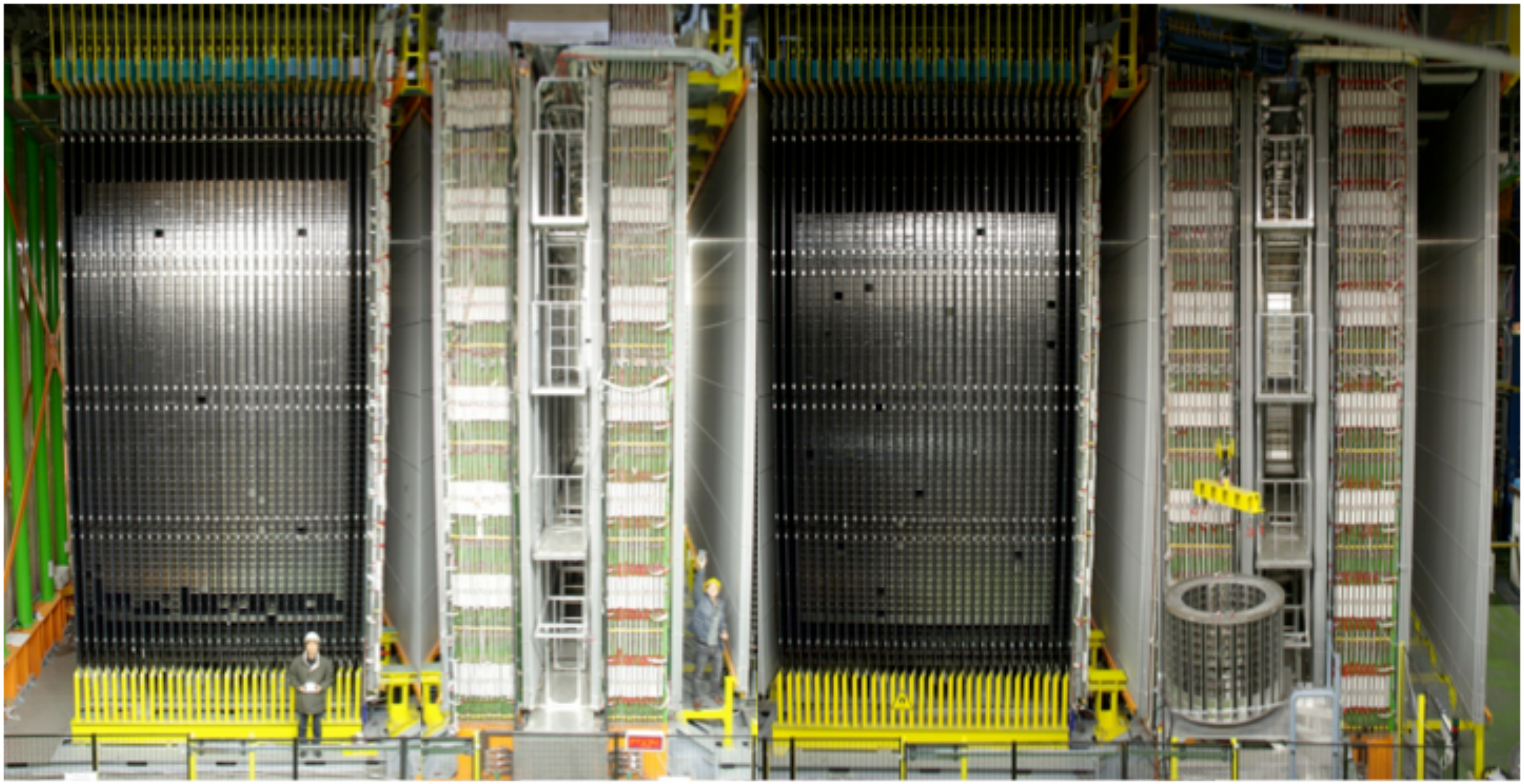


- Massive active target (1.25 kton) with micrometric space resolution
- Detect τ-lepton production and decay
- Underground location (10^6 reduction of cosmic ray flux)
- Electronic detectors to provide the "time stamp", preselect the interaction brick and reconstruct muon charge/momentum

τ DECAY CHANNEL	BR (%)
$\tau \rightarrow \mu$	17.7
$\tau \rightarrow e$	17.8
$\tau \rightarrow h$	49.5
$\tau \rightarrow 3h$	15.0

THE DETECTOR

SM-1 SM-2



Target
brick walls+ Target Tracker

Spectrometer
RPC+Drift Tubes

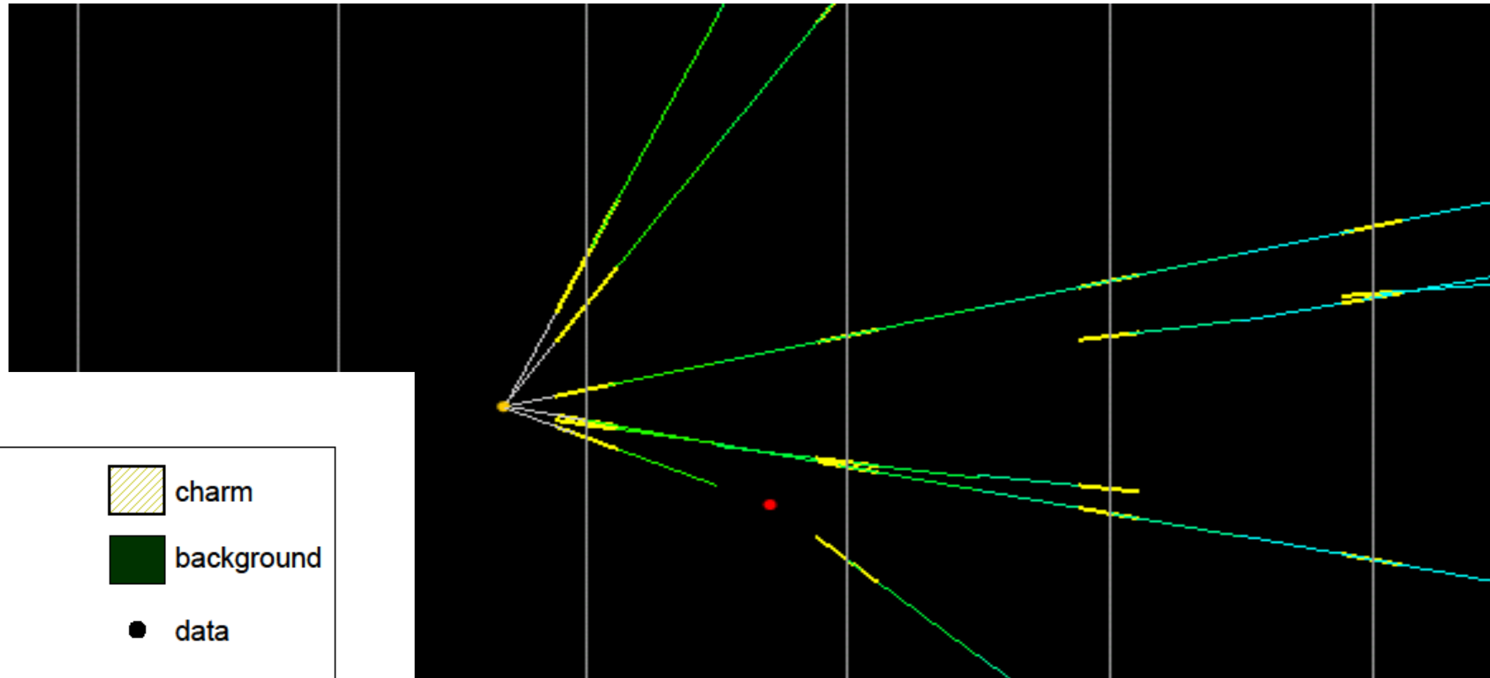
Target
brick walls+ Target Tracker

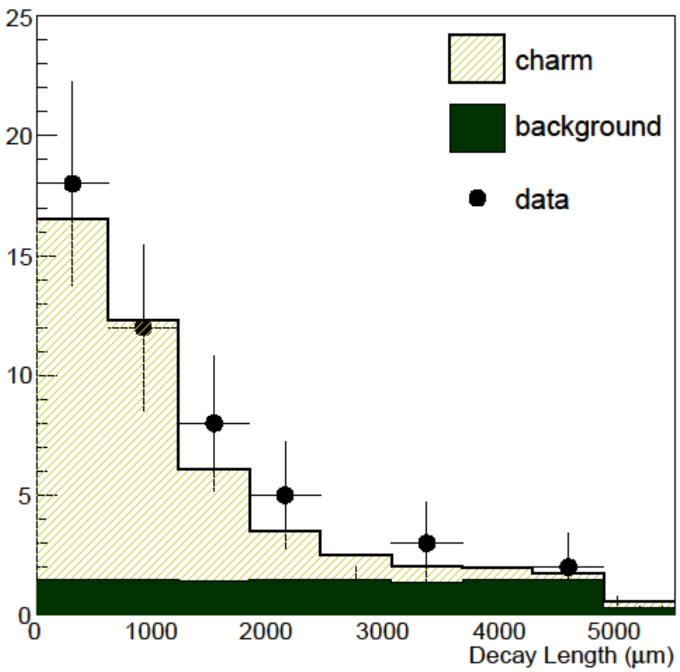
Spectrometer
RPC+Drift Tubes

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

Charm sample:

same topology but muon at interaction vertex





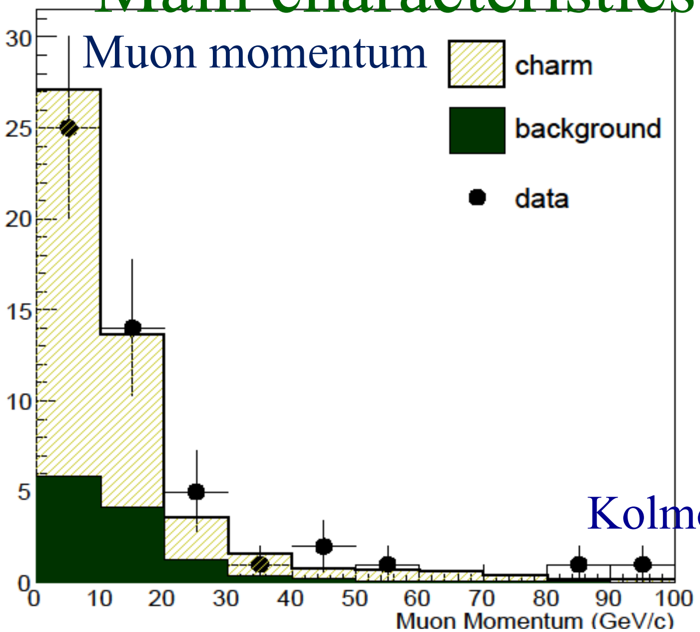
Charm yield from the analysis of 2008÷2010 data

	charm	background	expected	data
1 prong	20 ± 5	9 ± 3	29 ± 6	19
2 prong	15 ± 4	3.8 ± 1.1	19 ± 4	22
3 prong	5 ± 2	1.0 ± 0.3	6 ± 2	5
4 prong	0.8 ± 0.4	-	0.8 ± 0.4	4
All	**41±7**	**14±3**	**55±7**	**50**

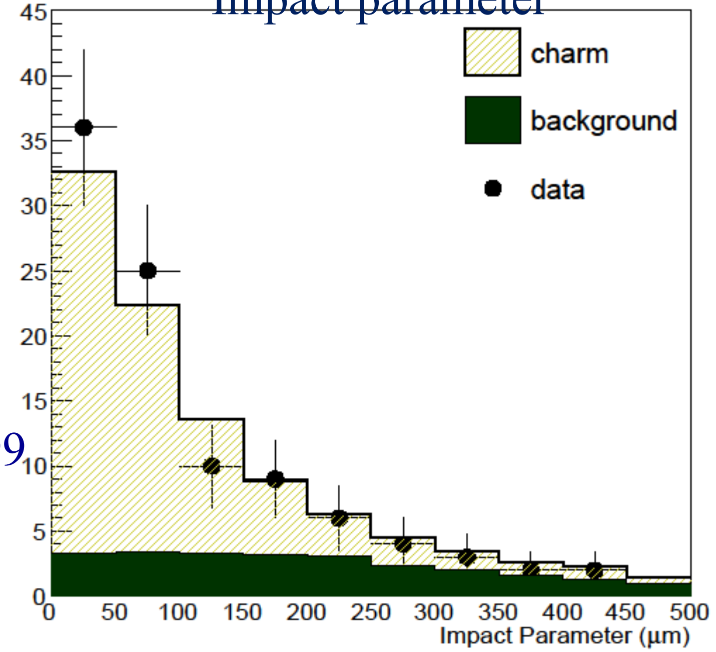
Background, mostly from hadronic interactions
(contribution from strange particle decay)

Main characteristics of the charm candidate events

Muon momentum

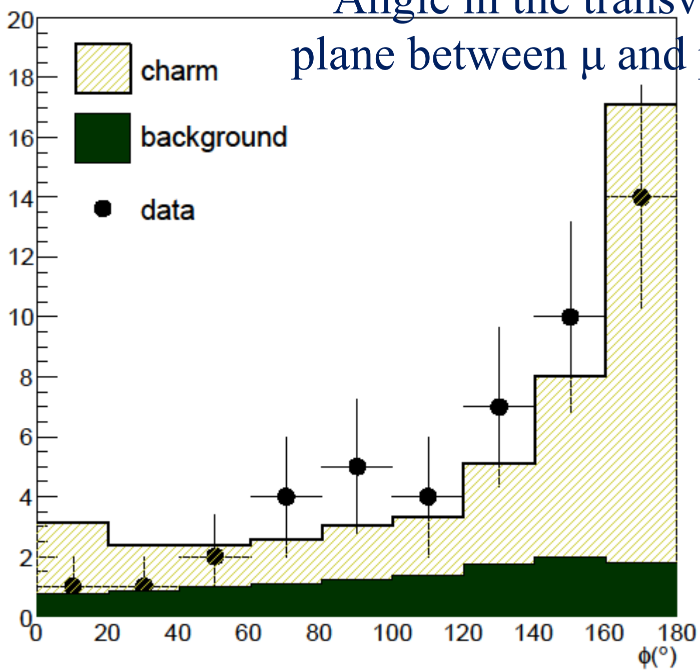


Impact parameter

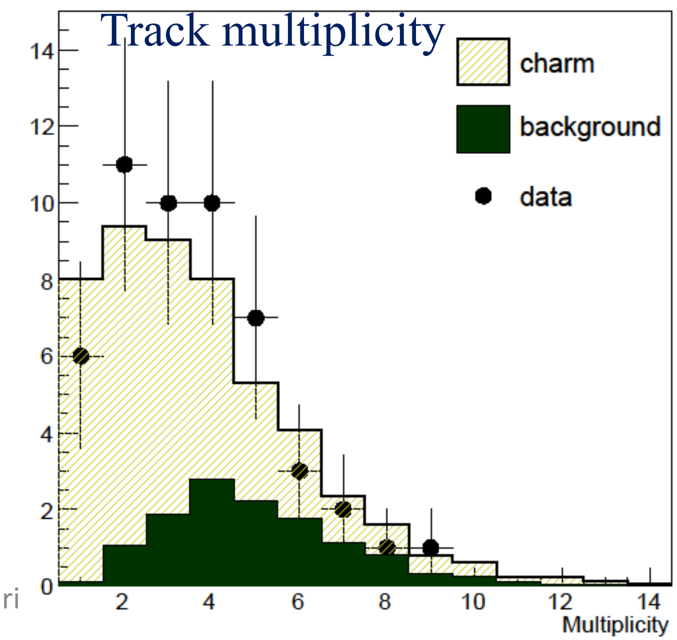


Kolmogorov test ≥ 0.99 all plots

Angle in the transverse plane between μ and parent

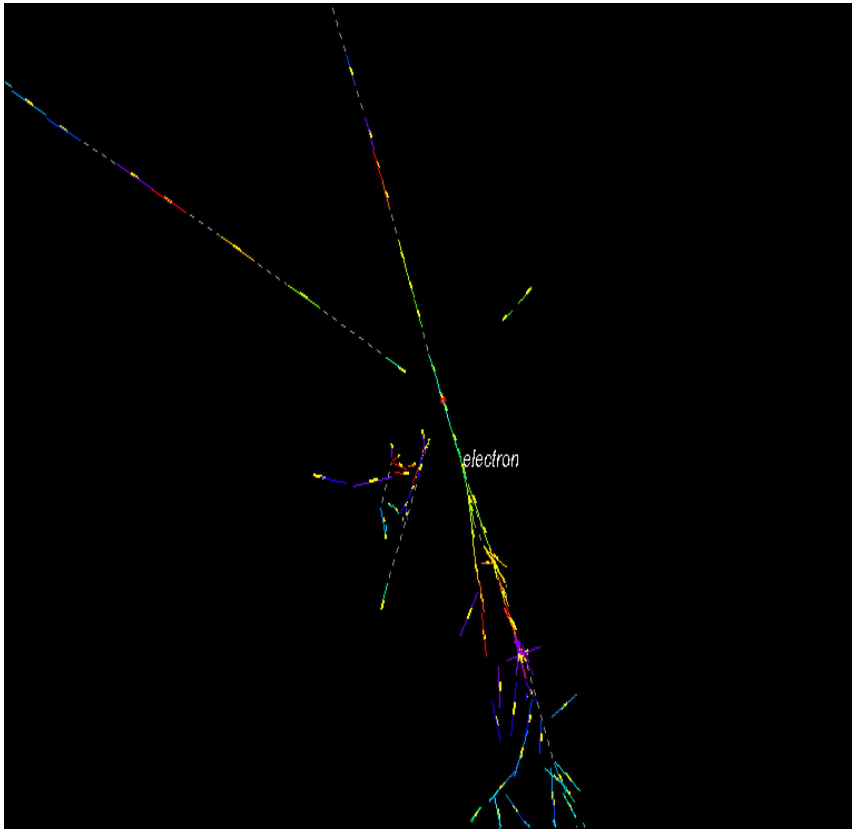


Track multiplicity

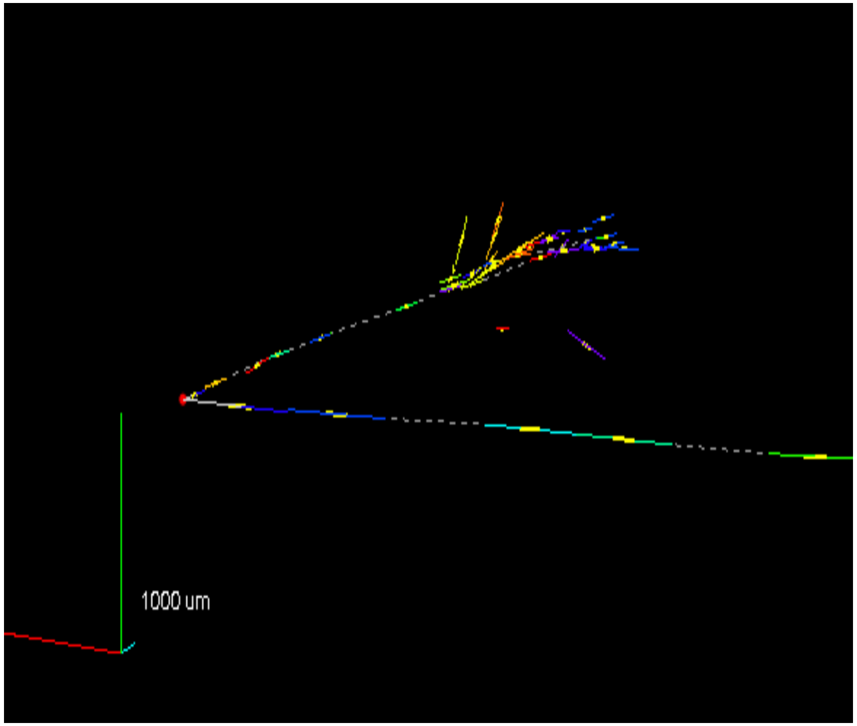


Physics results

$\nu_\mu \rightarrow \nu_e$ analysis

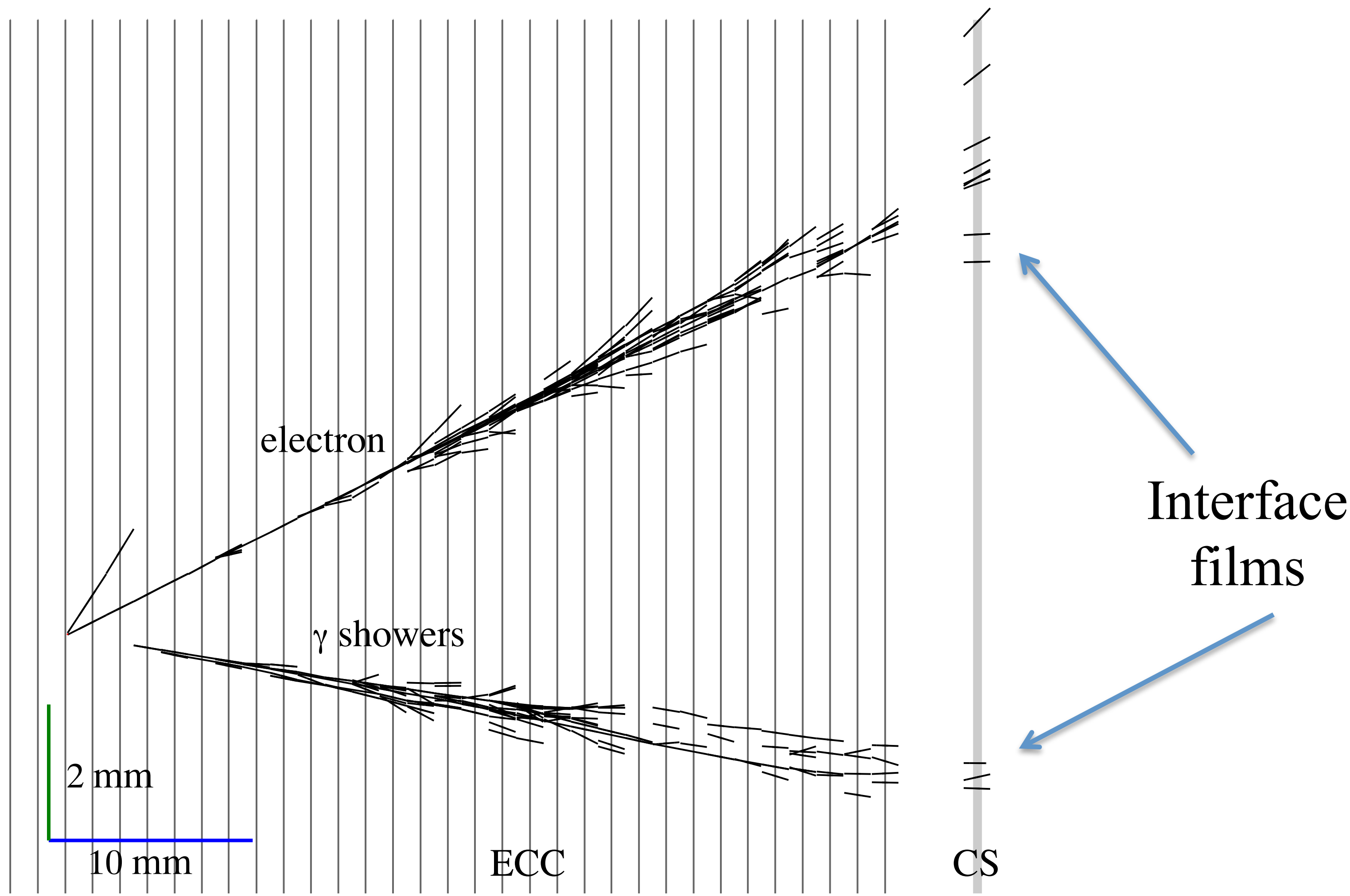


4.1 GeV electron



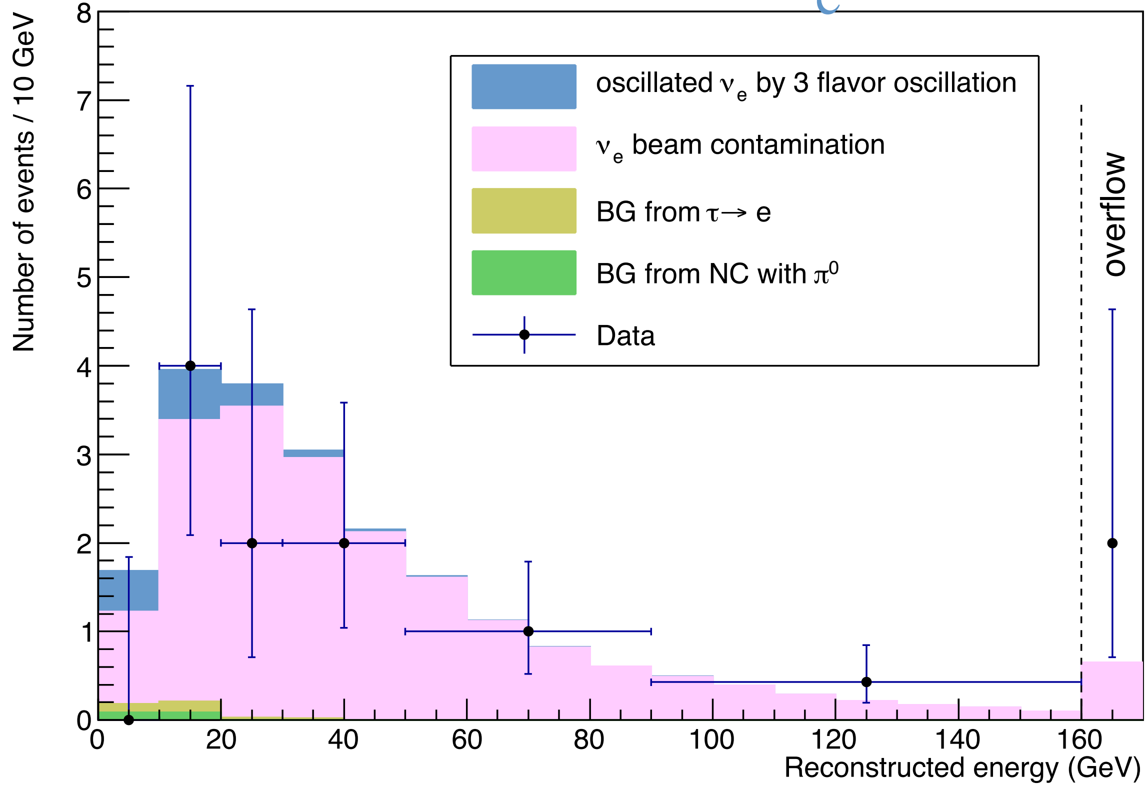
more than 30 events found in the analyzed sample

Electron neutrino search in 2008 and 2009 runs:
one of the ν_e events with a π^0 as seen in the brick



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

Energy distribution of the 19 ν_e candidates



Energy cut		20 GeV	30 GeV	No cut
BG common to both analyses	BG (a) from π^0	0.2	0.2	0.2
	BG (b) from $\tau \to e$	0.2	0.3	0.3
	ν_e beam contamination	4.2	7.7	19.4
Total expected BG in 3-flavour oscillation analysis		4.6	8.2	19.8
BG to non-standard oscillation analysis only	ν_e via 3-flavour oscillation	1.0	1.3	1.4
Total expected BG in non-standard oscillation analysis		5.6	9.4	21.3
Data		4	6	19

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

3 flavour analysis

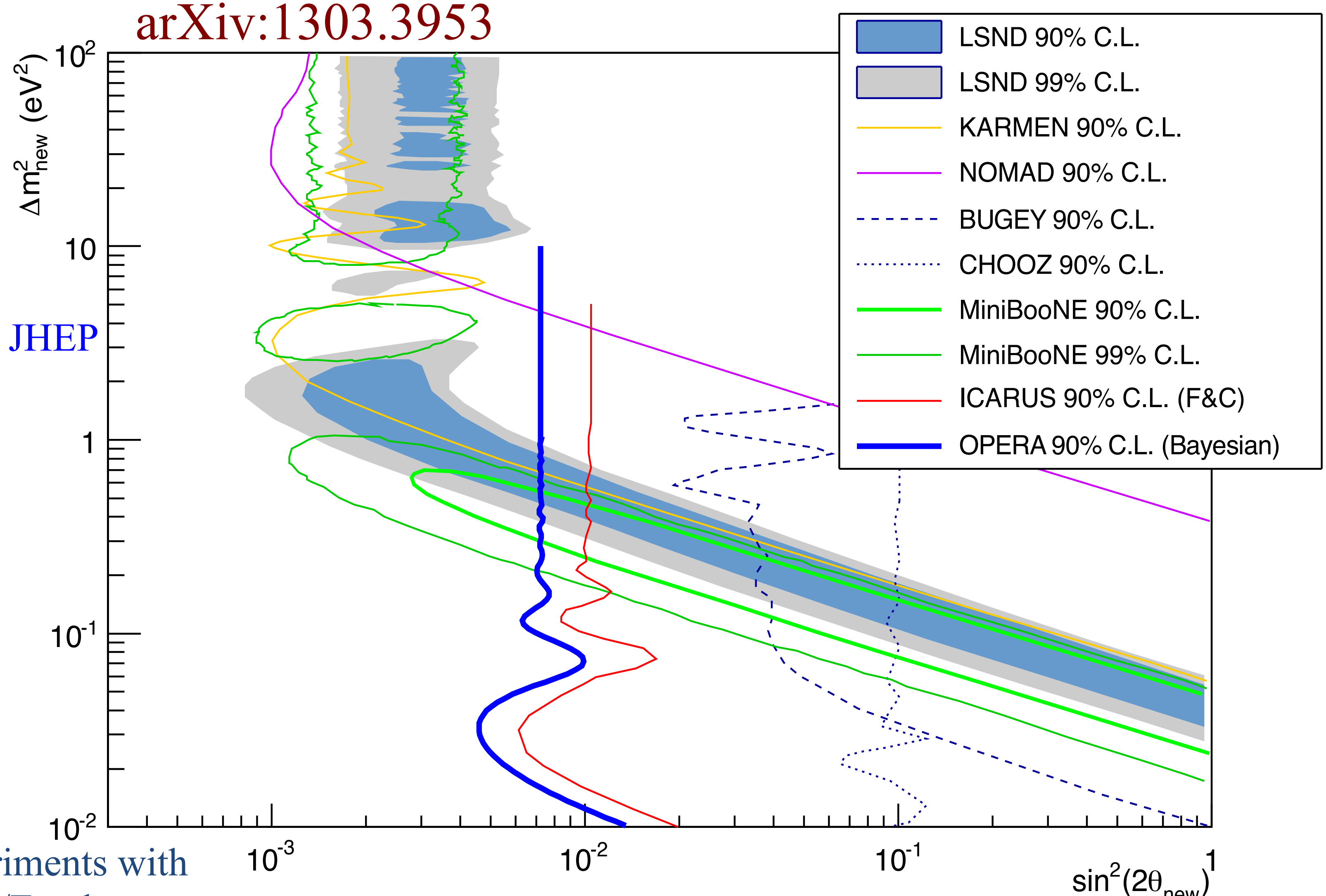
Energy cut to increase the S/N

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

Submitted to JHEP

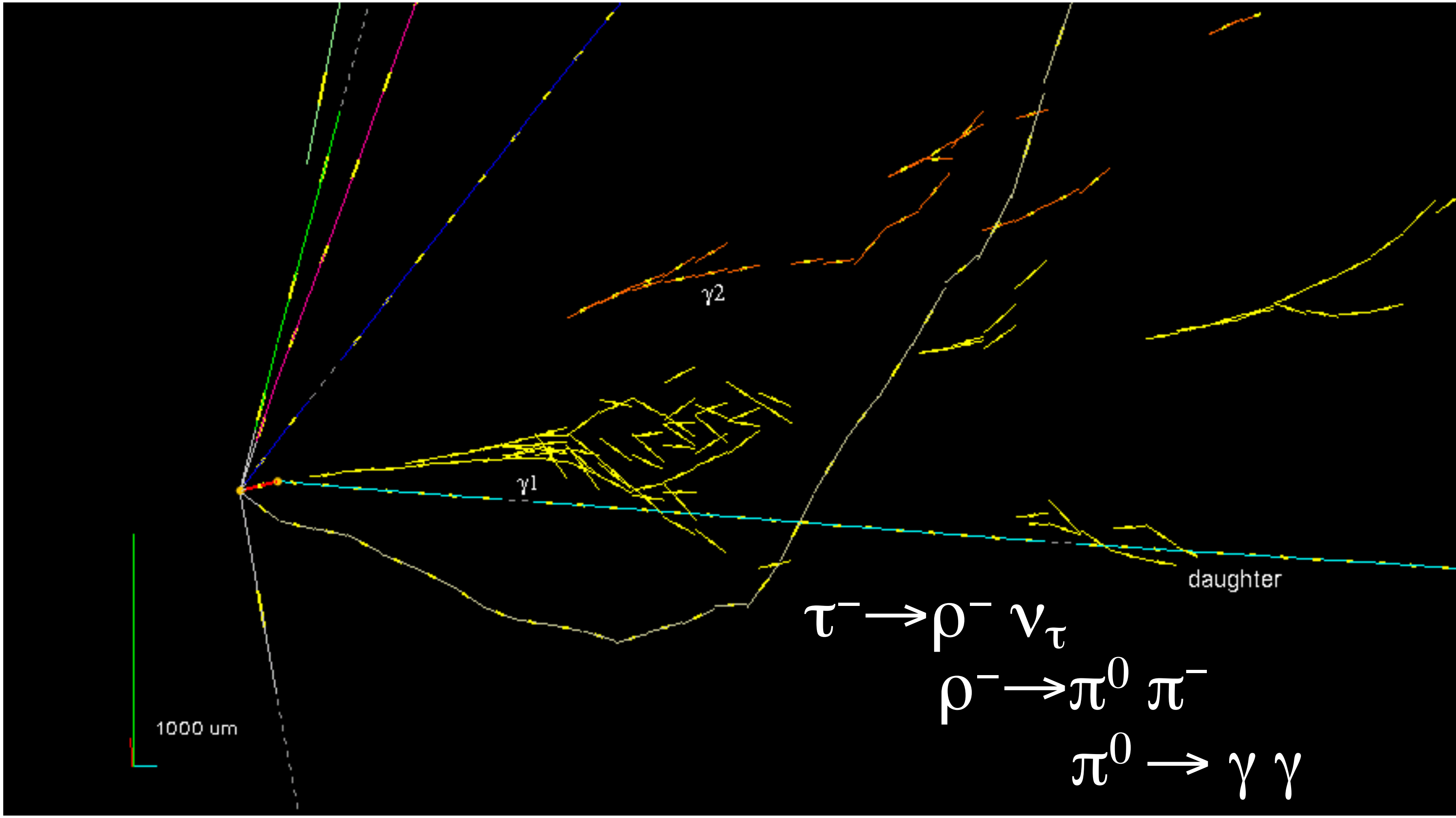


Caveat: experiments with different L/E values

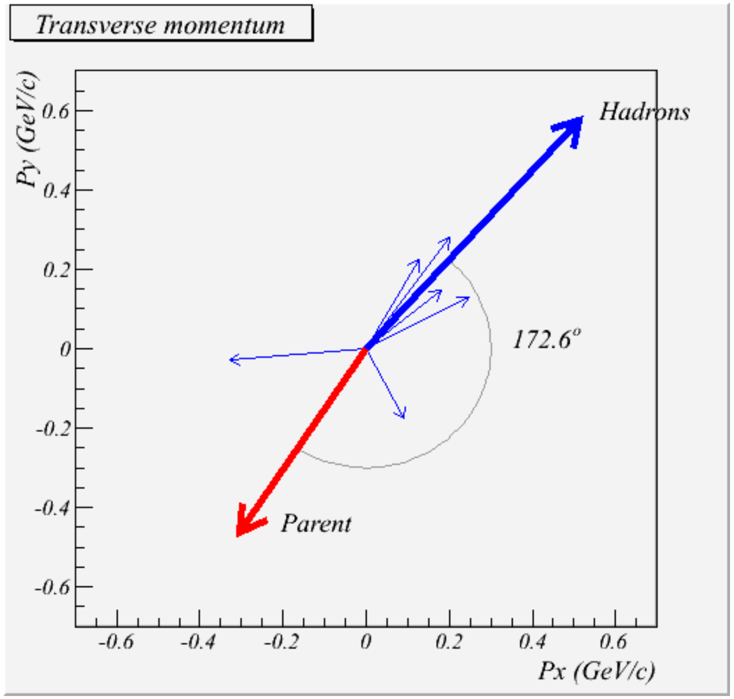
$\nu_\mu \rightarrow \nu_\tau$ analysis

- 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

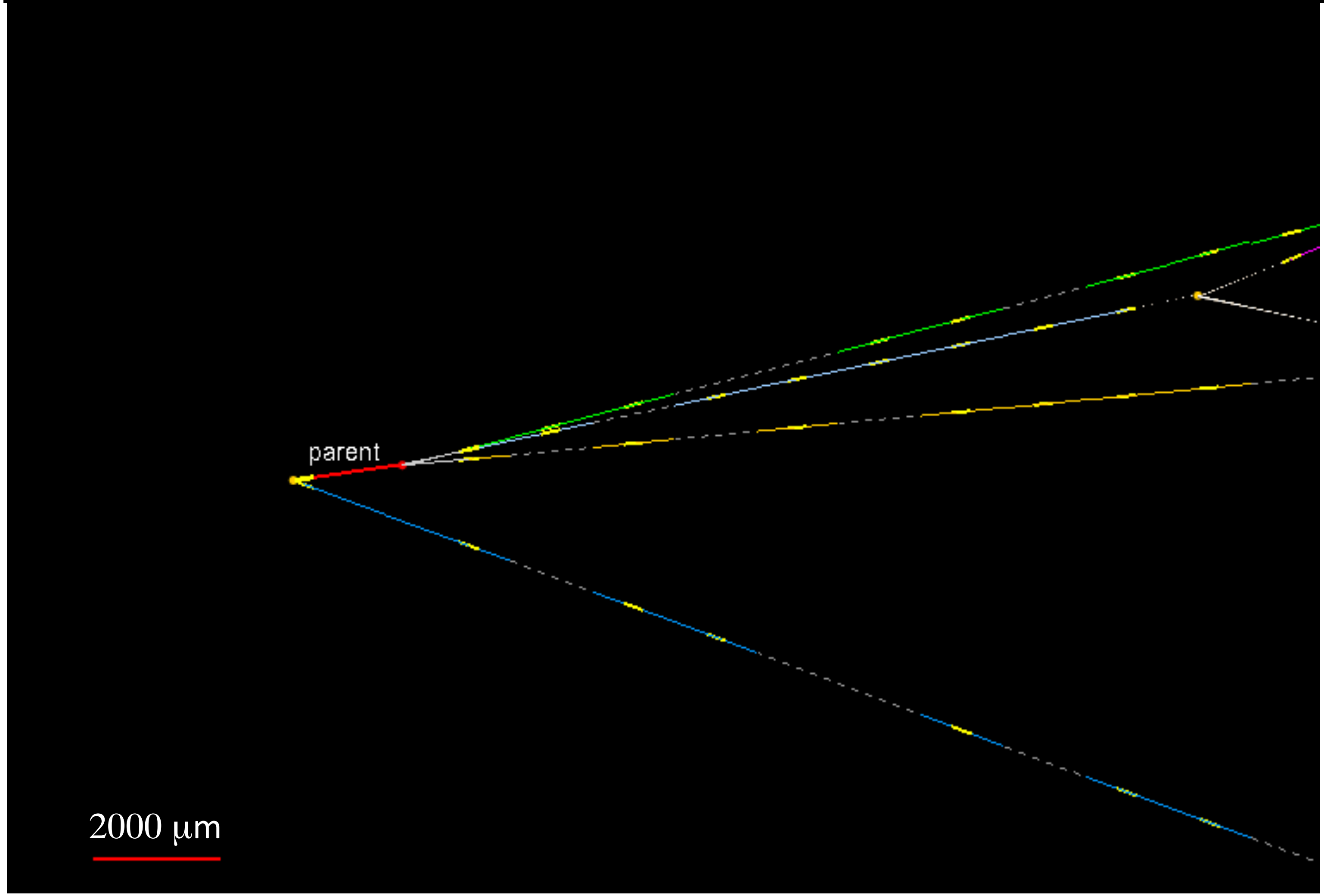


VARIABLE	AVERAGE
kink (mrad)	**41 ± 2**
decay length (μm)	**1335 ± 35**
P daughter (GeV/c)	**12^{+6}_{-3}**
Pt (MeV/c)	**470^{+240}_{-120}**
missing Pt (MeV/c)	**570^{+320}_{-170}**
ϕ (deg)	**173 ± 2**

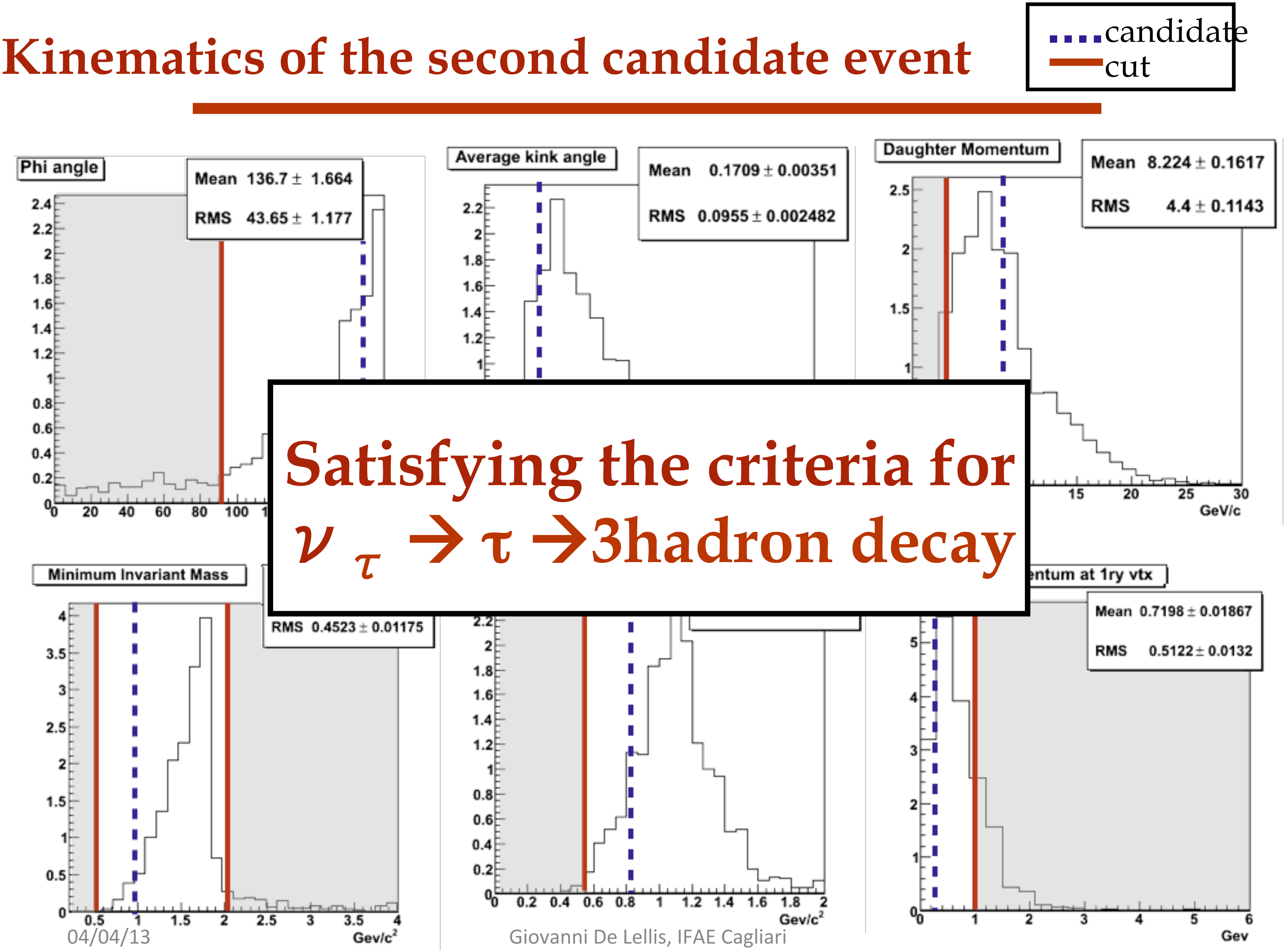
Strategy for the 2010÷2012 runs

- 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

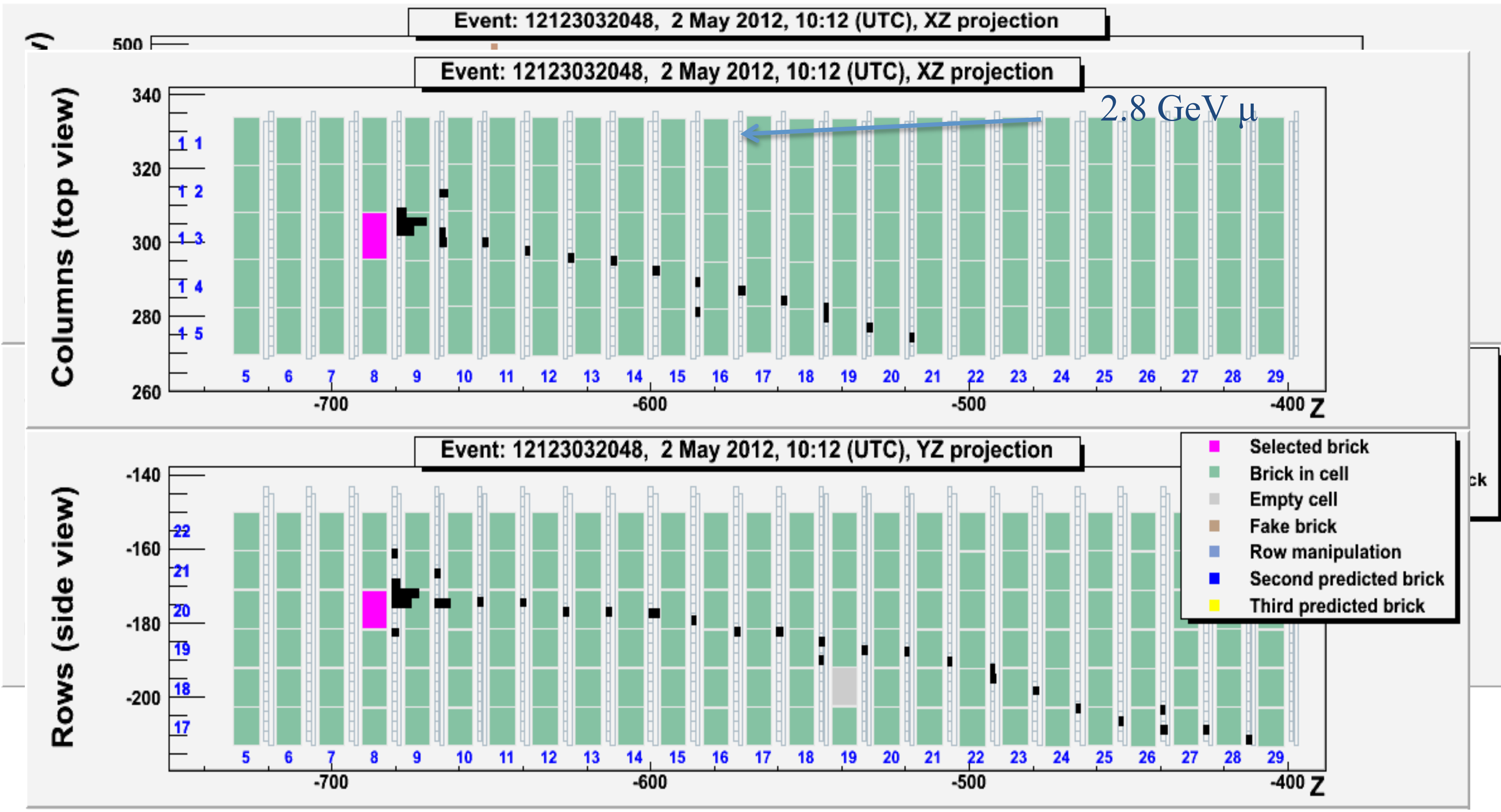


Satisfying the criteria for $\nu_\tau \rightarrow \tau \rightarrow$ 3hadron decay

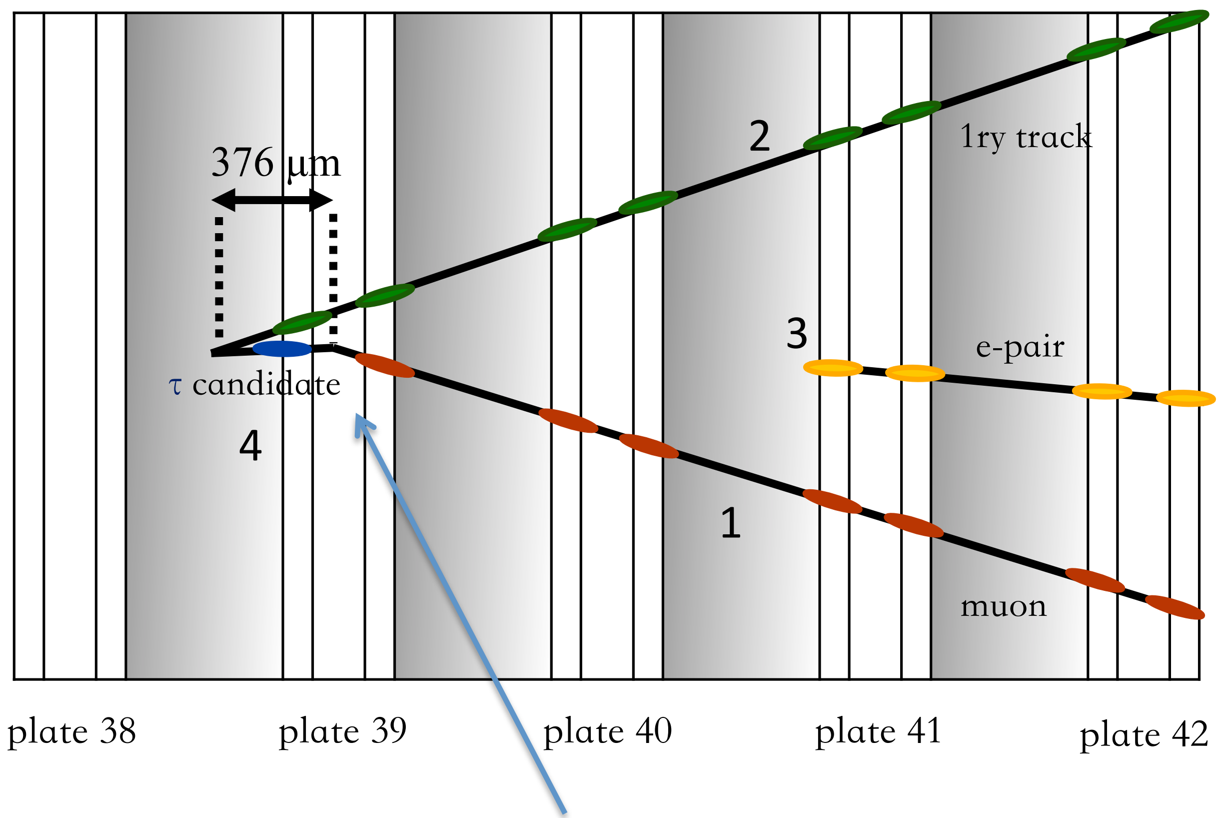
After 2012 Summer conferences

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

Third tau neutrino event taken on May 2nd 2012



τ⟶μ candidate brick analysis and decay search



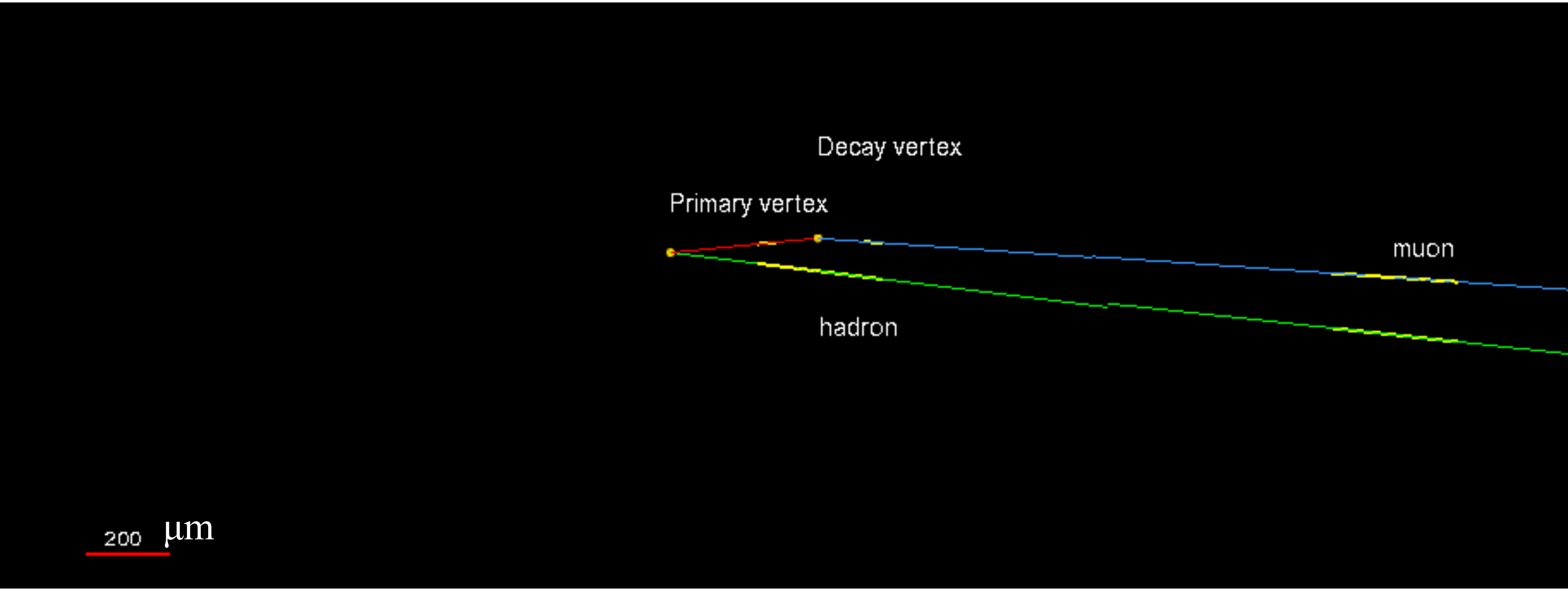
Decay in the plastic base

$\tau \rightarrow \mu$ candidate

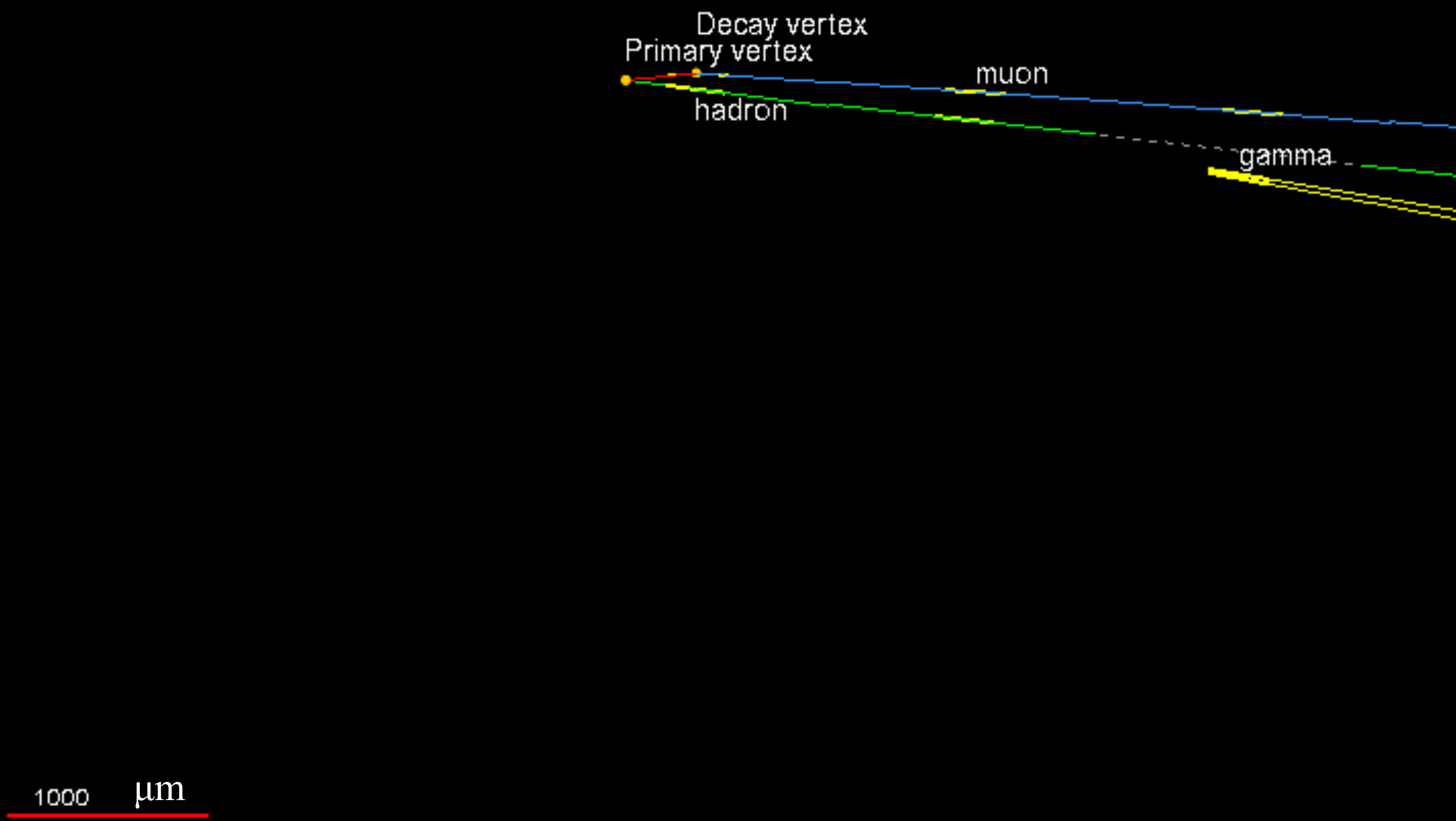
μm

2

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



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



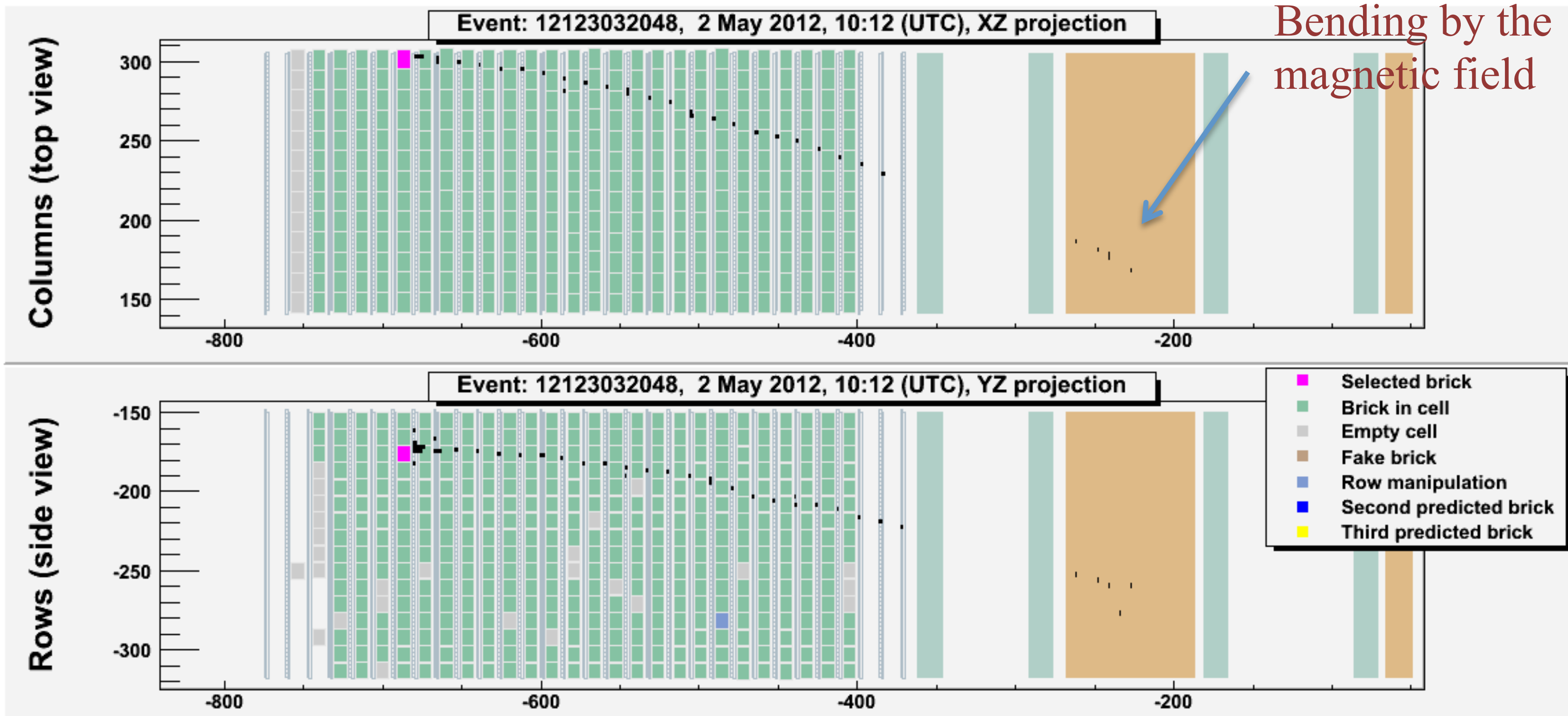
Event tracks' features

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	

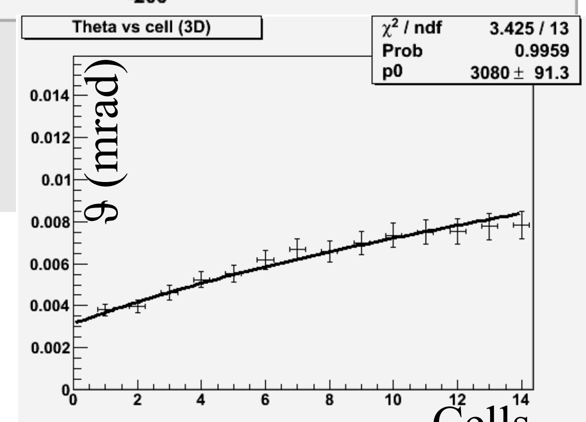
γ attachment

	$\delta\theta_{RMS}$ (mrad)	DZ (mm)	Measured IP (μm)	IP resolution (μm)	ATTACHMENT
1ry vertex	6	3.1	18.2	13.6	OK
2ry vertex	6	2.8	68.7	12.2	EXCLUDED

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



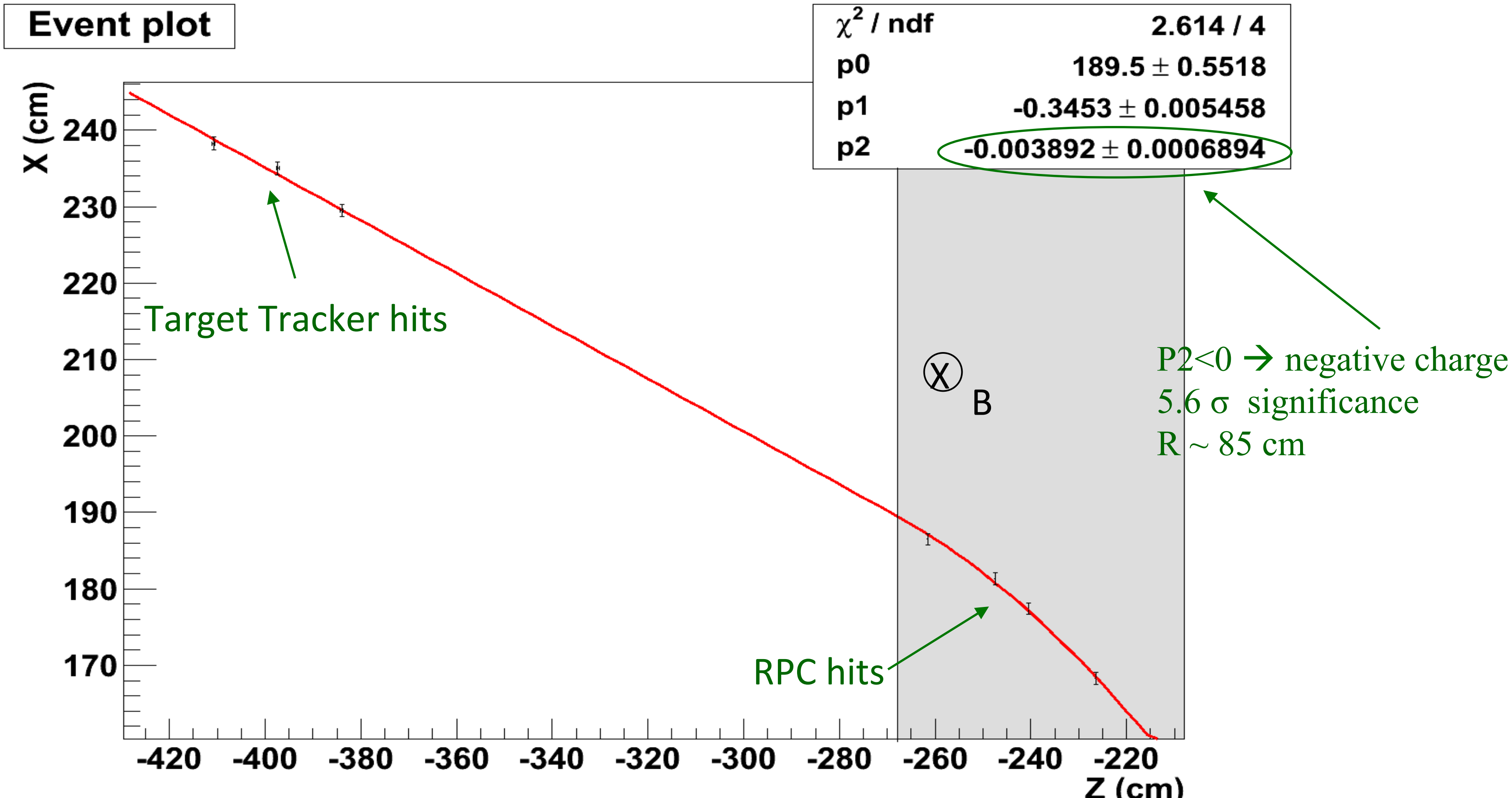
Charge determination of the muon

Charge measurement based on TT and RPC hits when no hits in drift tubes

Fit function:

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

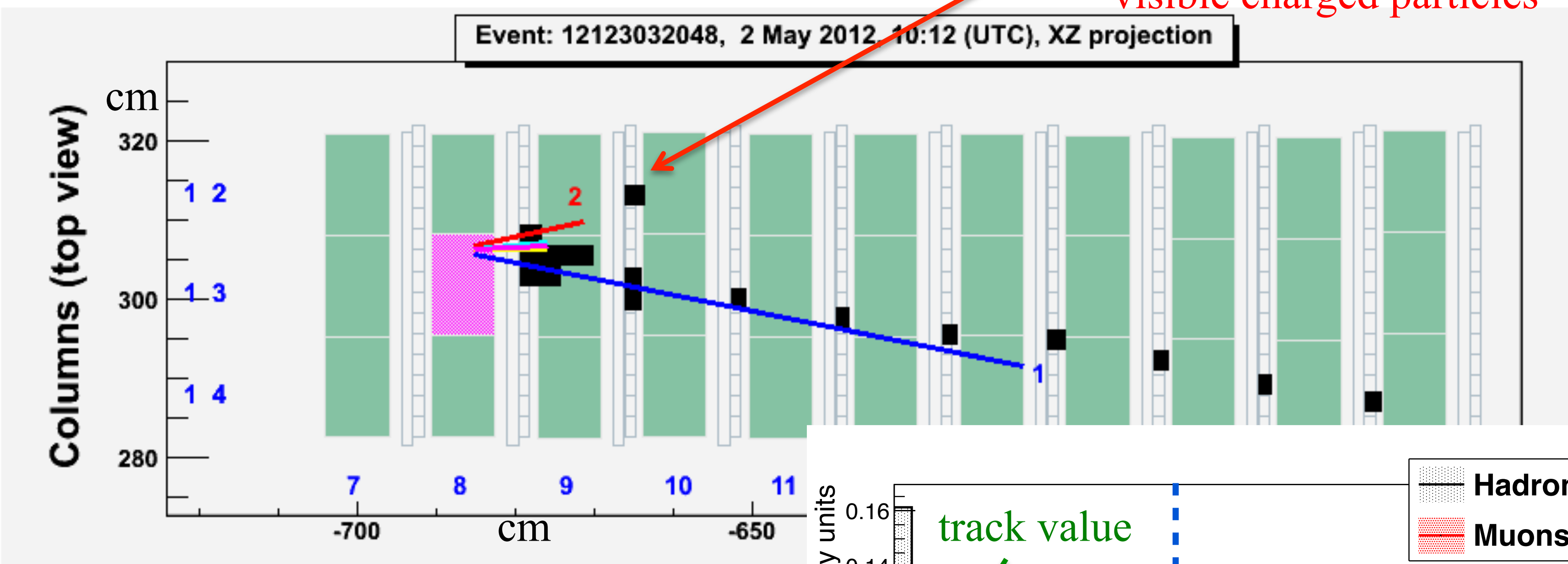
$X(z) = p0 + p1 \times (z-z0)$ for $z<z0$



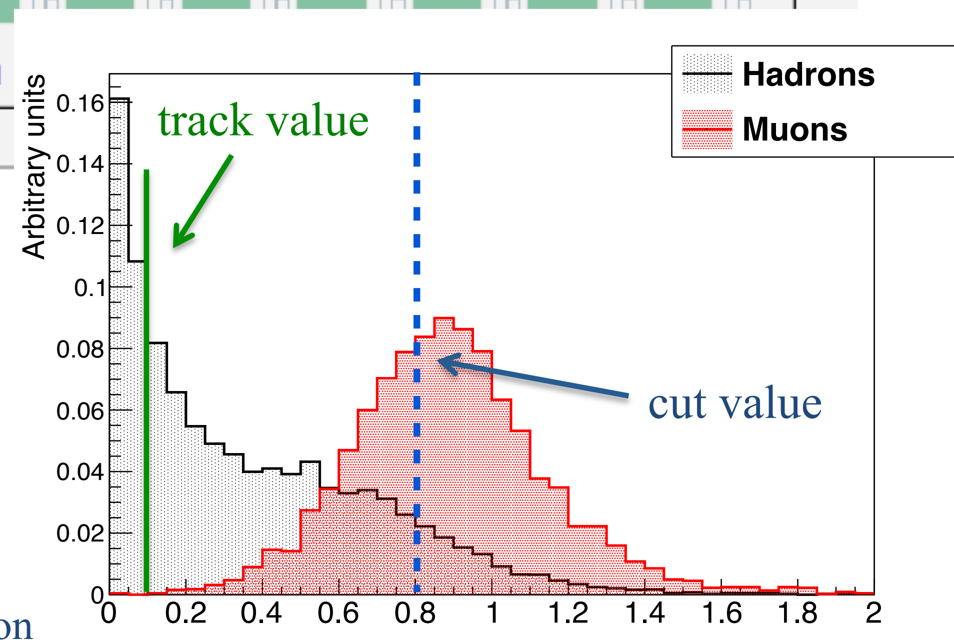
P-value = 0.063% (probability to reconstruct a μ^+ stopping in the 7^{th} iron layer with $p2 < -0.00389\ cm^{-1}$)

Track follow down to assess the nature of track 2

Track 2 interacting in the downstream brick without visible charged particles



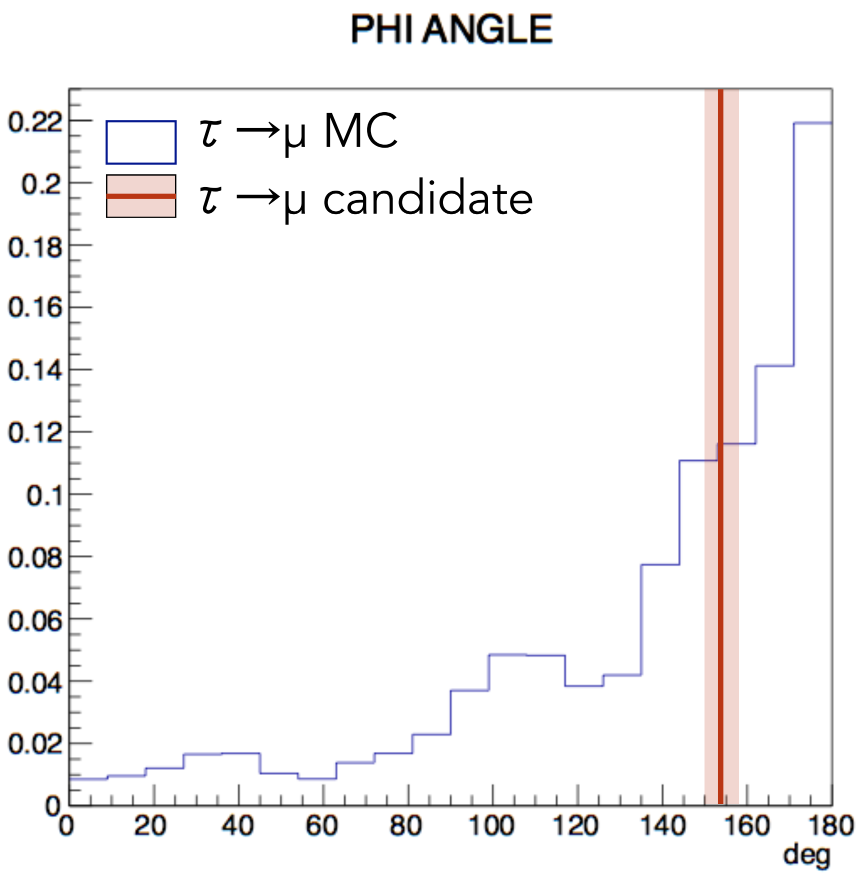
Momentum/range inconsistent with μ hypothesis
0.9 GeV/4 cm Lead



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

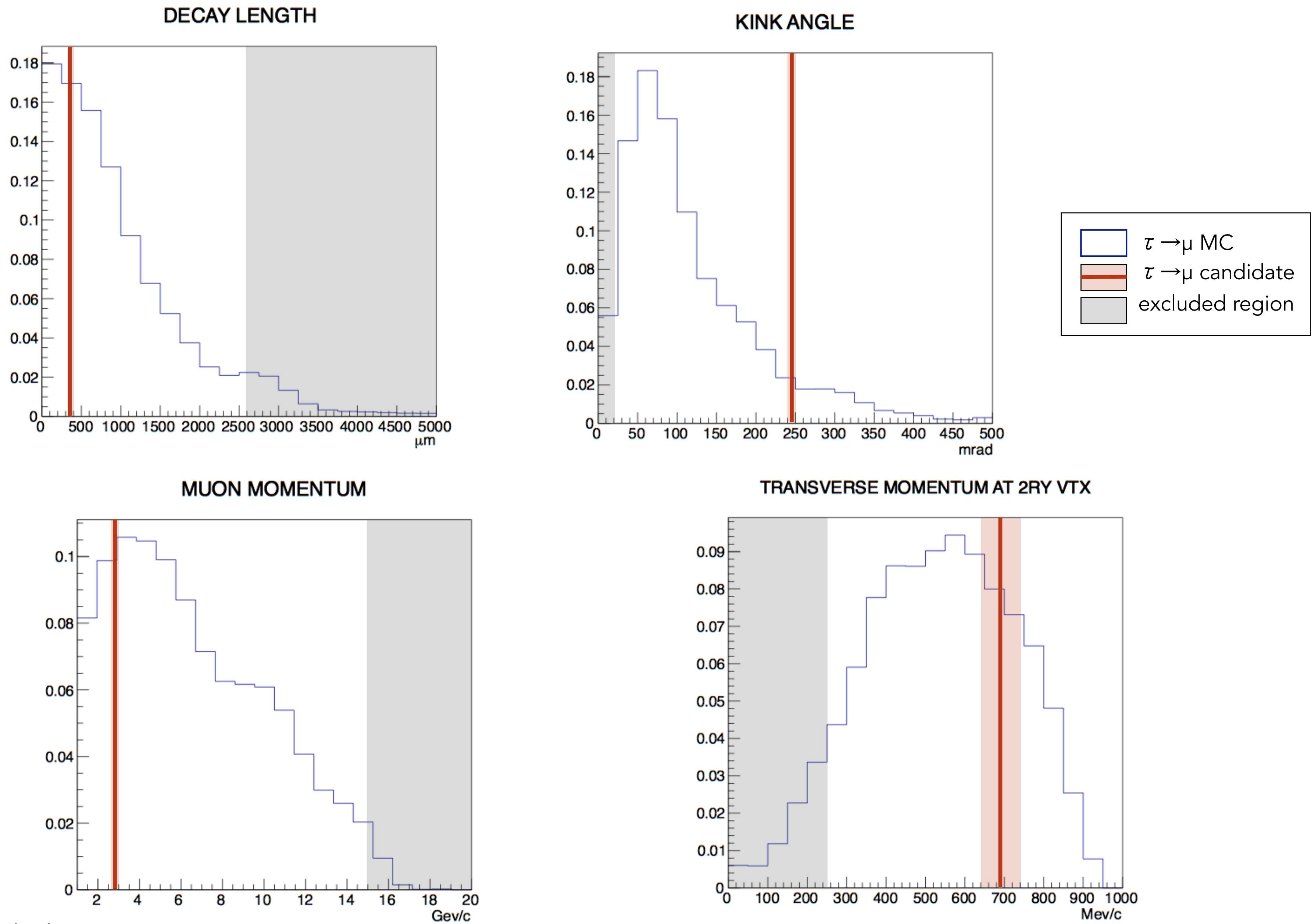
L = track length
R_{lead} = μ range
$\rho_{average}$ = average density
ρ_{lead} = lead density
p = momentum in emulsion

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: $\tau \rightarrow \mu$ candidate



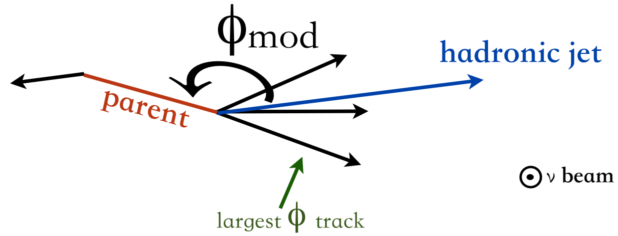
Statistical considerations

Extended sample

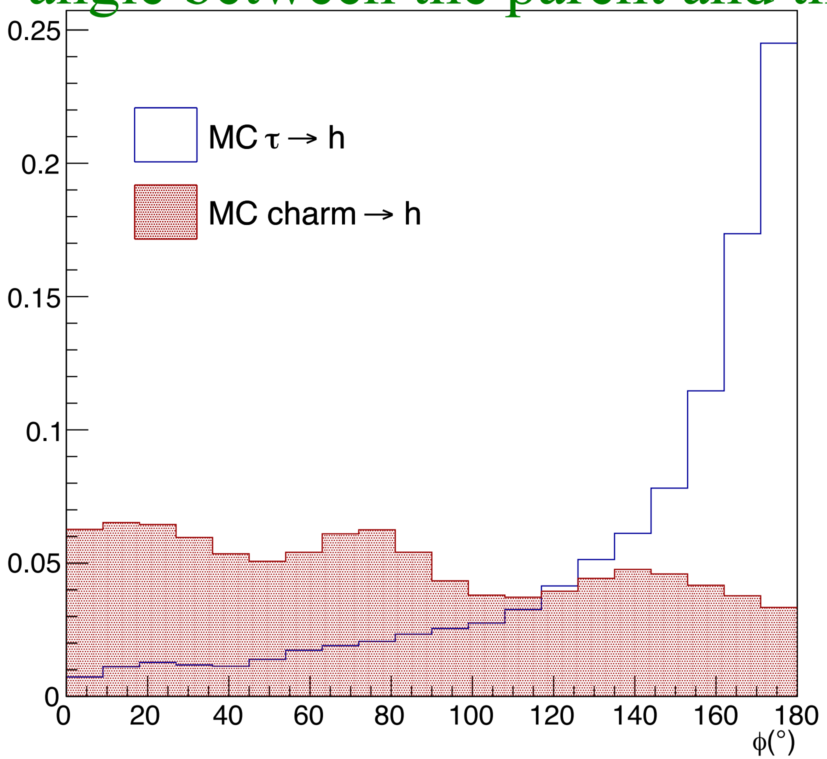
	Signal	Background	Charm	μ scattering	had int
$\tau \rightarrow$ h	0.66	0.045	0.029		0.016
$\tau \rightarrow$ 3h	0.61	0.090	0.087		0.003
$\tau \rightarrow \mu$	0.56	0.026	0.0084	0.018	
$\tau \rightarrow$ e	0.49	0.065	0.065		
total	2.32	**0.226**	0.19	0.018	0.019

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

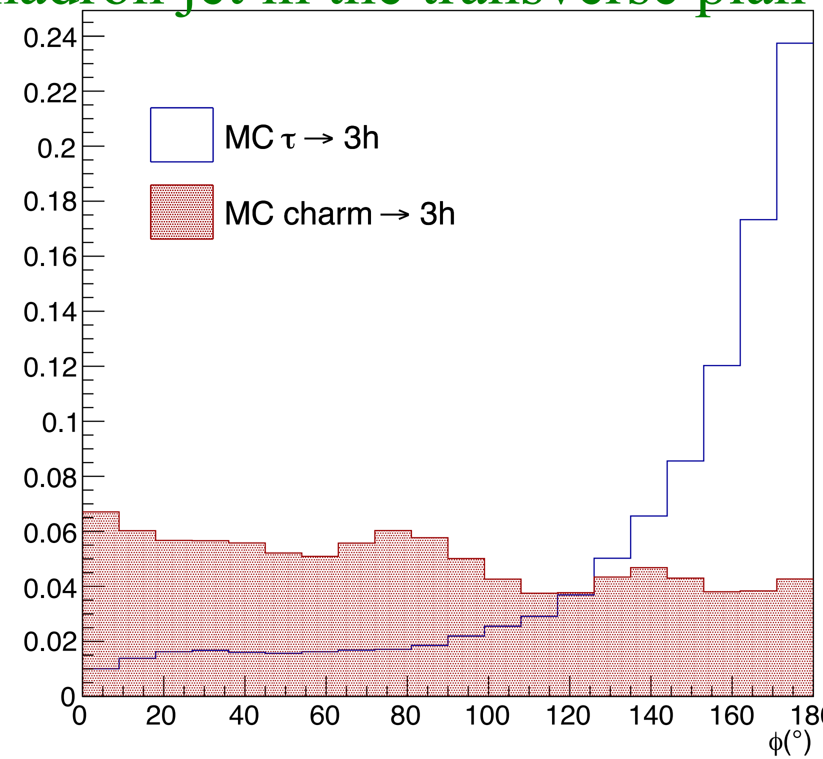
Likelihood analysis:
one of the discriminating variables



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



(a) $\tau \to h$



(b) $\tau \to 3h$

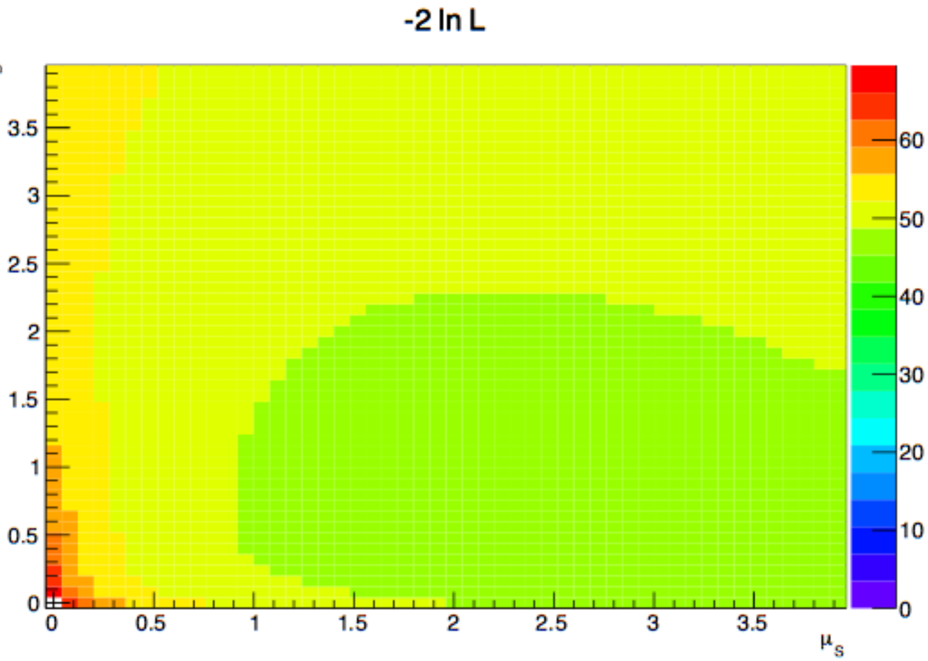
Statistical considerations

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

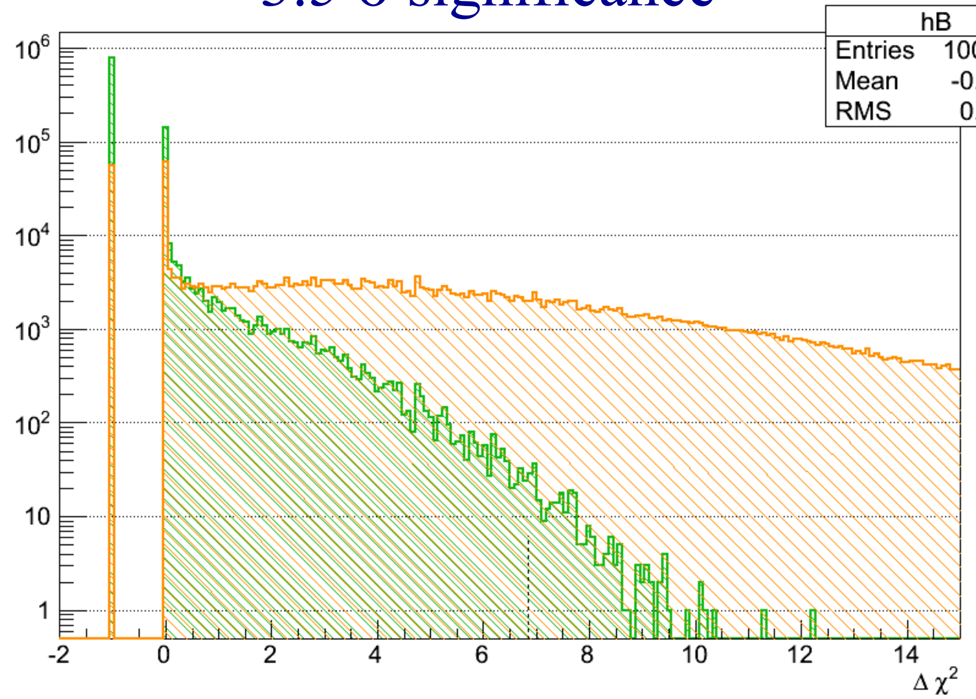
$$f^{S+B}(s,b,x) = \frac{s f_S(x) + b f_B(x)}{s+b}$$

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

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



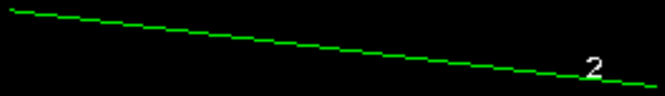
3.5 σ significance



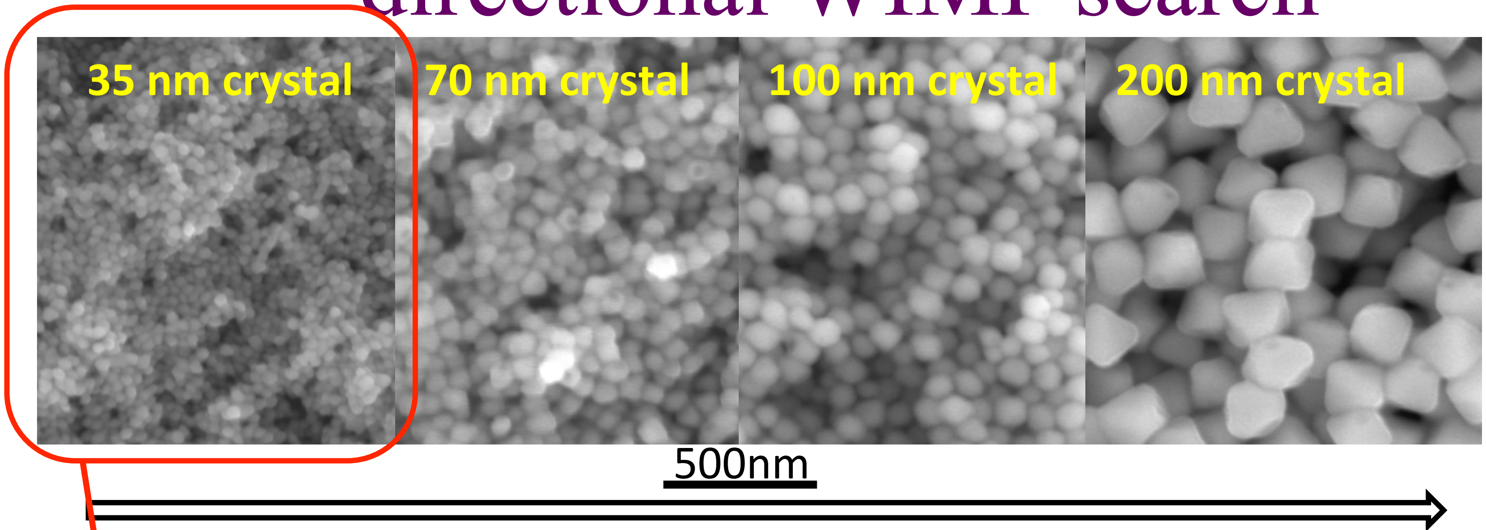
Evidence for $\nu_\mu \rightarrow \nu_\tau$ in appearance mode

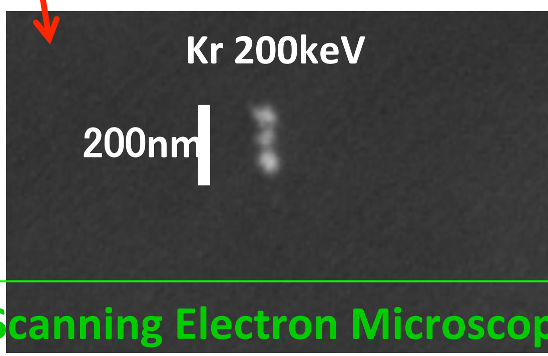
- *Three events reported in an extended sample*
- *Conservative background evaluation*
- *Significance of 3.2σ with simple counting method*
- *With a likelihood approach, 3.5σ level*
- *4σ observation within reach*

Thank you for your attention

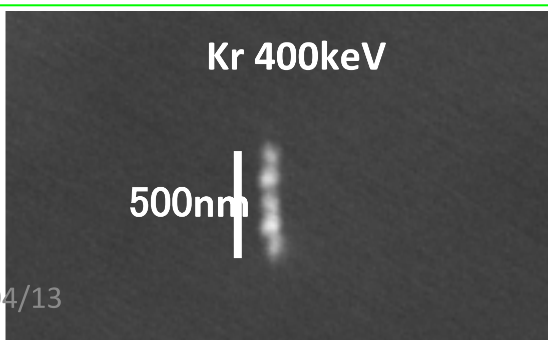


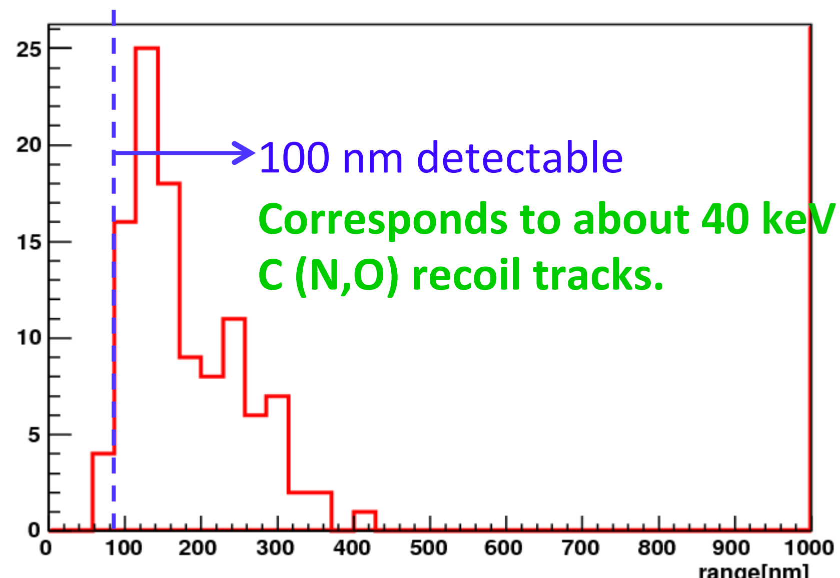
The future of nuclear emulsion technology: directional WIMP search





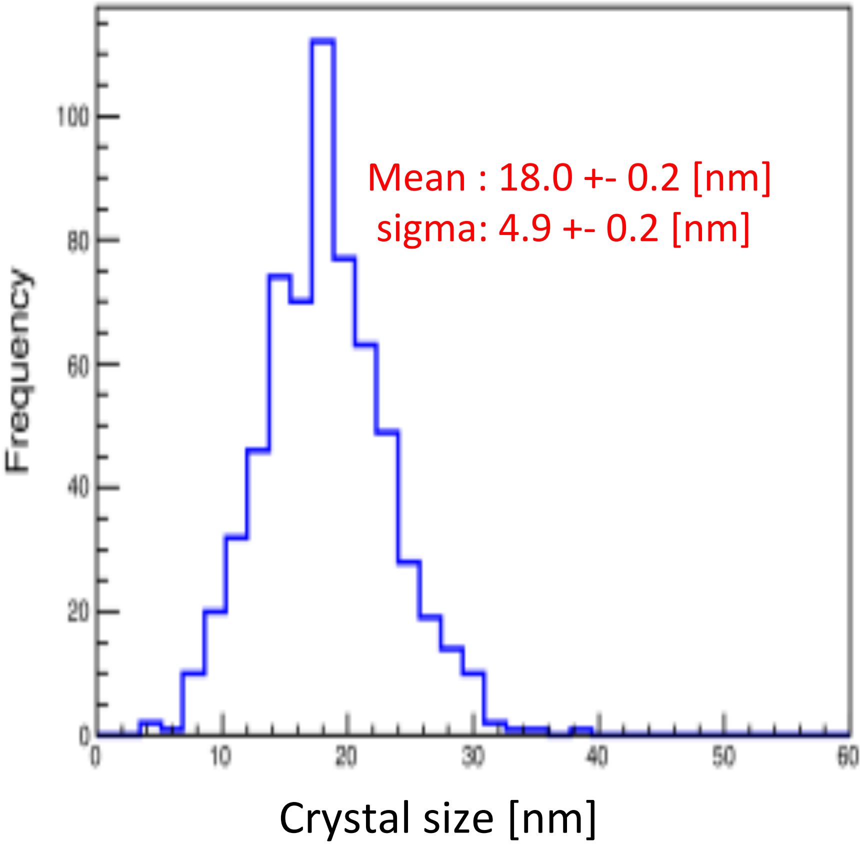
Scanning Electron Microscope





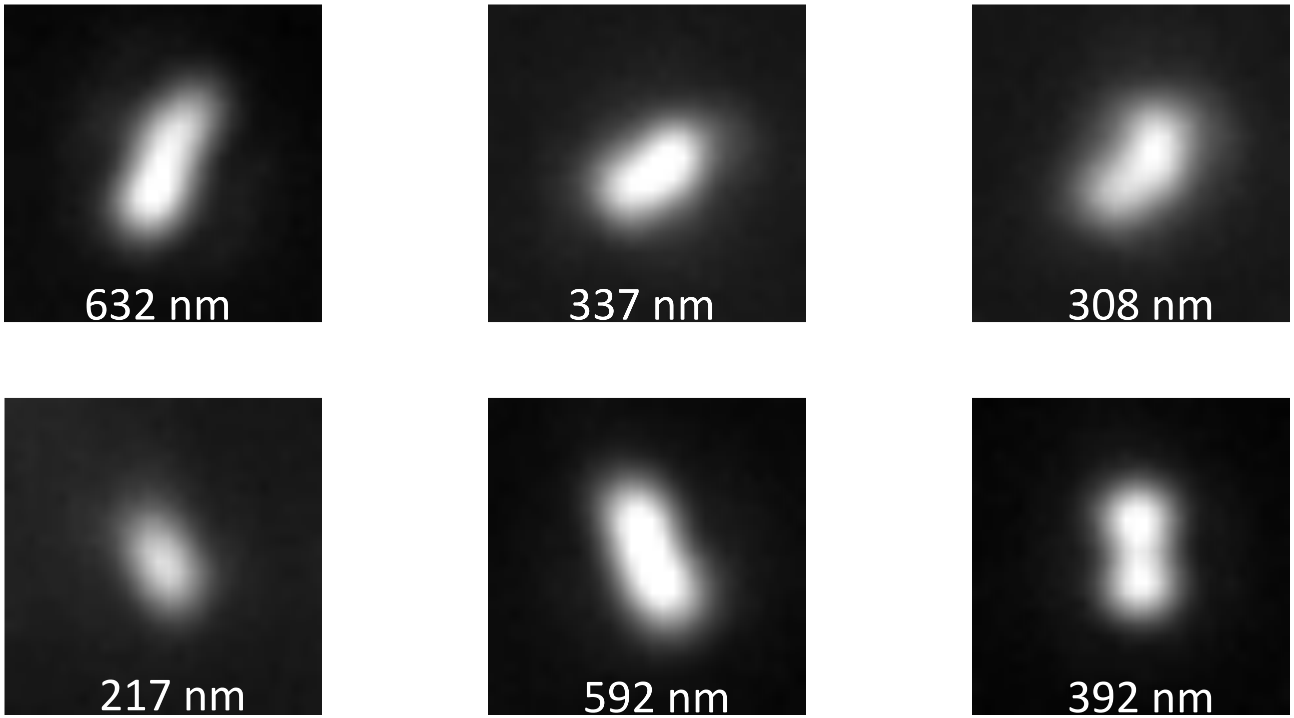
Range distribution [nm]

Reduced crystal size (200 nm in OPERA)



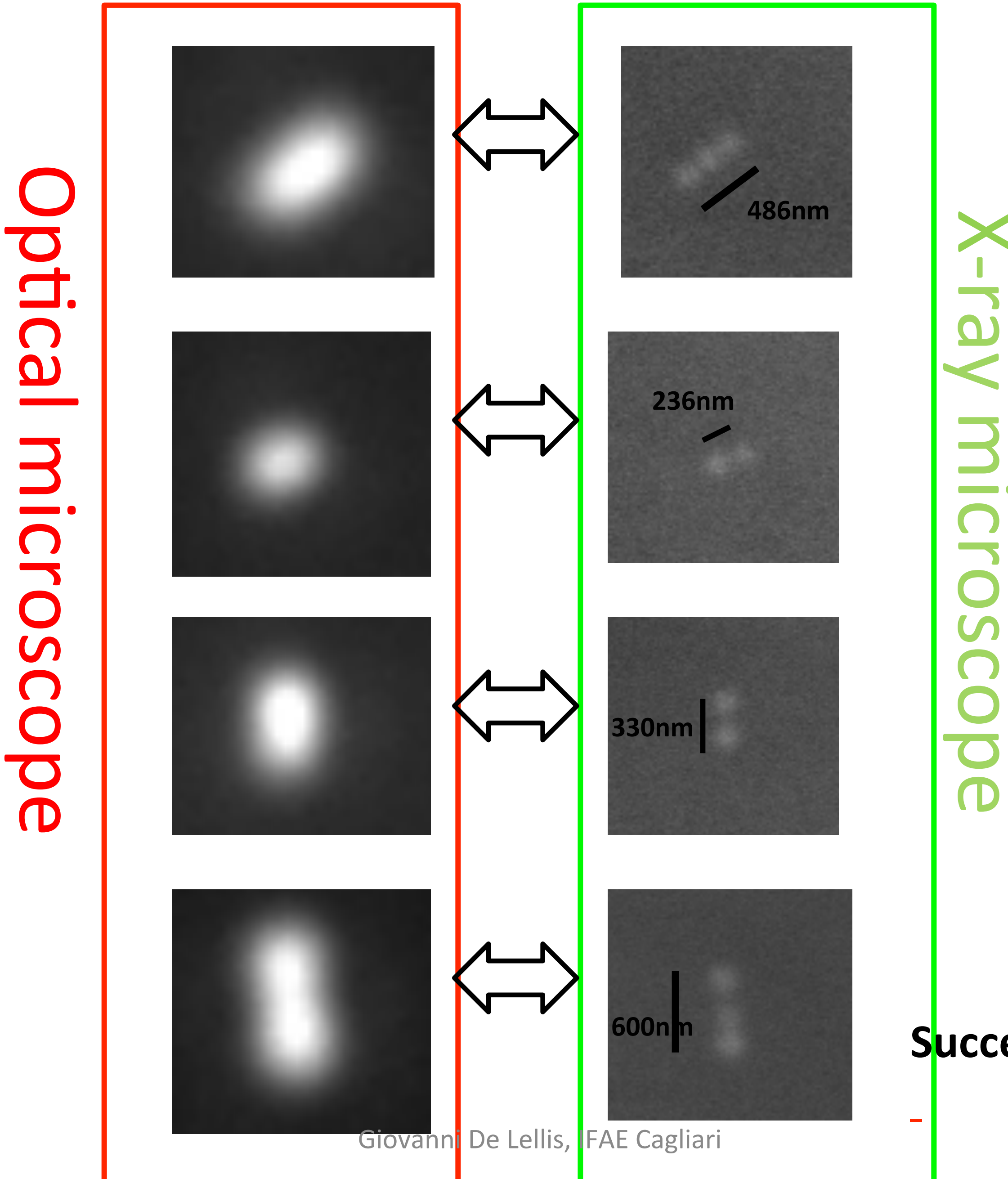
- reduce the energy threshold
- background rejection
  - ⇒ lower sensitivity for electrons
  - ⇒ improved S/N discrimination by increasing the number of grains

Heavy nuclei recoil tracks induced by 14 MeV neutron (D-T nuclear fission reaction)



Mostly Br recoil (170 - 600keV) (low sensitivity tuning)

Matching of recoiled tracks between Optical and X-ray microscope



Success rate of matching

<u>572/579=99%</u>