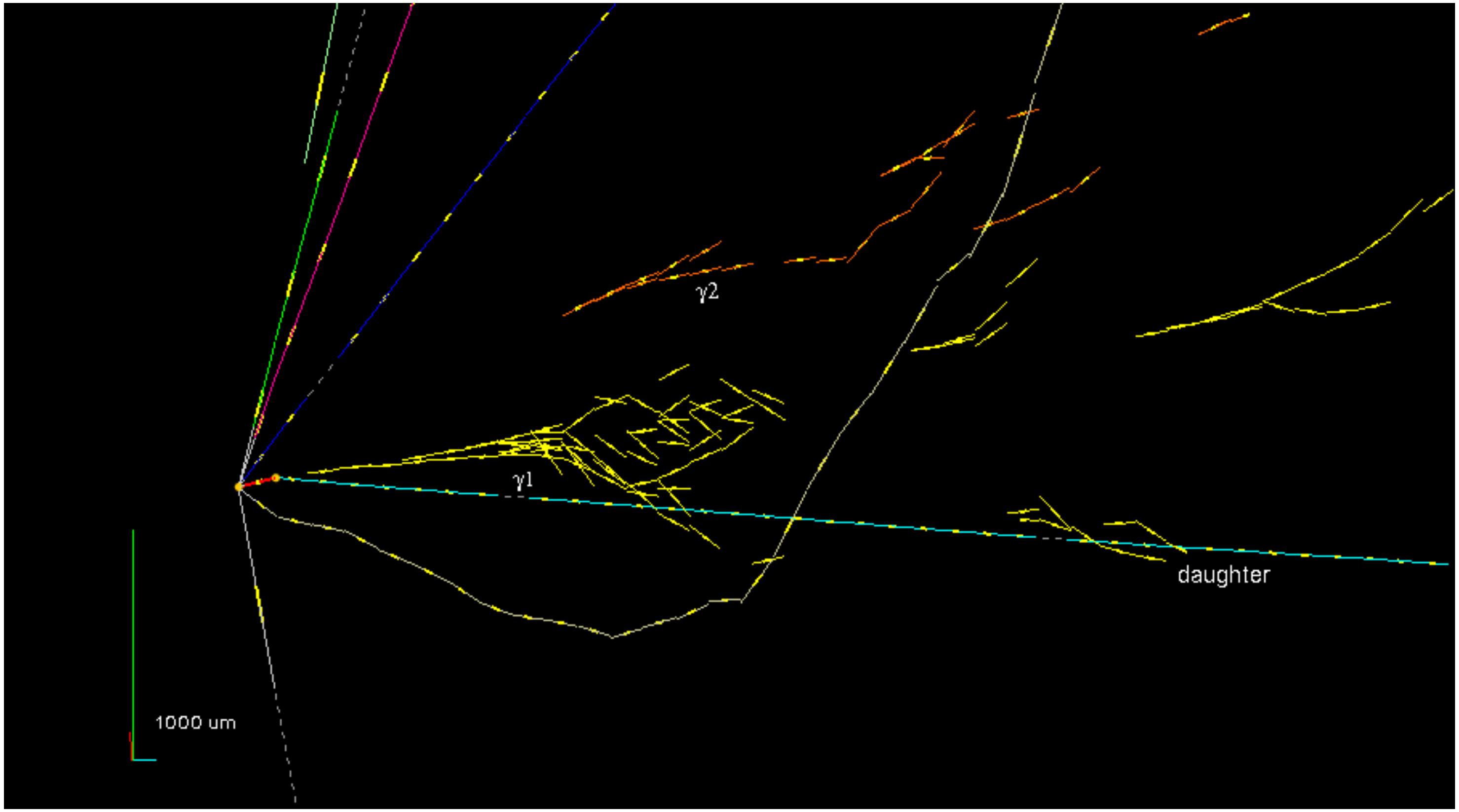
Evidence for $\nu_\mu \rightarrow \nu_\tau$ oscillations in the OPERA experiment

Giovanni De Lellis

University "Federico II" of Napoli and INFN Napoli

On behalf of the OPERA Collaboration



The OPERA Collaboration

150 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

Physics motivation in the neutrino physics landscape

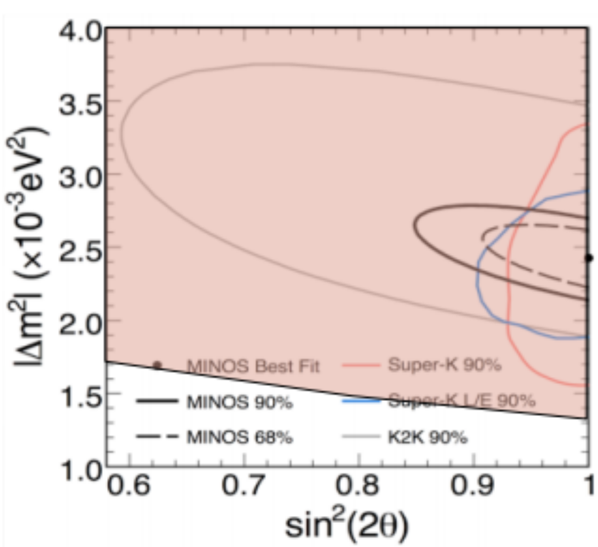
Super-K (1998): atmospheric neutrino anomaly interpretable as $\nu_\mu \rightarrow \nu_\tau$ oscillation

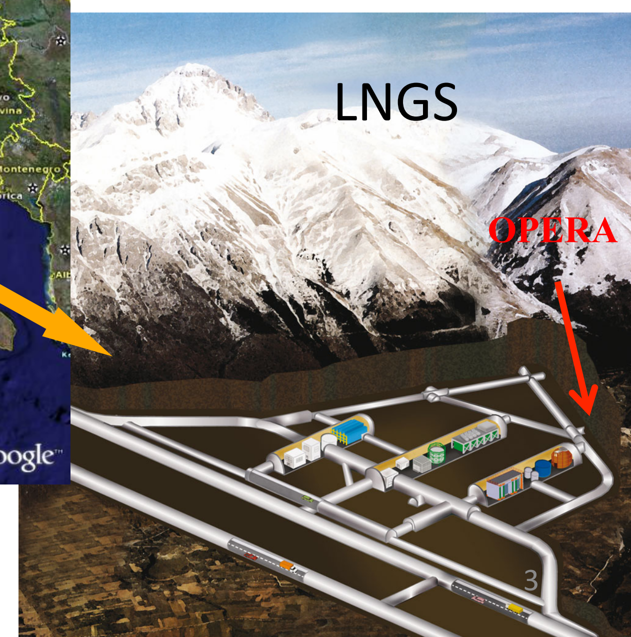
CHOOZ (reactor): $\nu_\mu \rightarrow \nu_e$ oscillation could not explain the anomaly

K2K and MINOS (accelerator) confirmed the ν_μ disappearance signal of Super-K

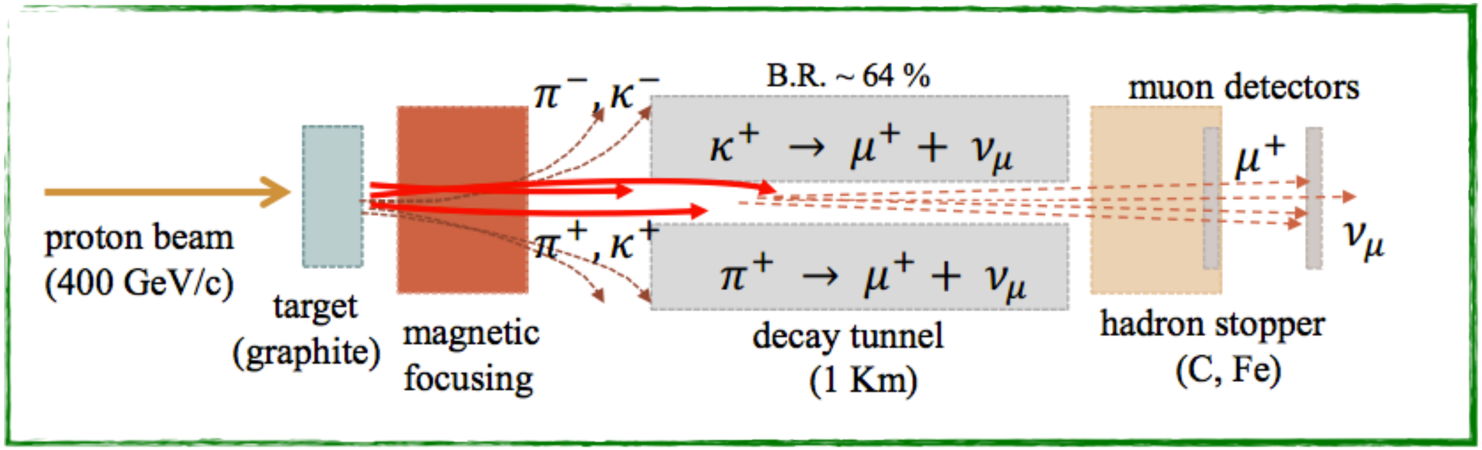
Missing tile: direct observation of ν_τ appearance in a pure ν_μ beam

Oscillation in appearance mode in the atmospheric sector





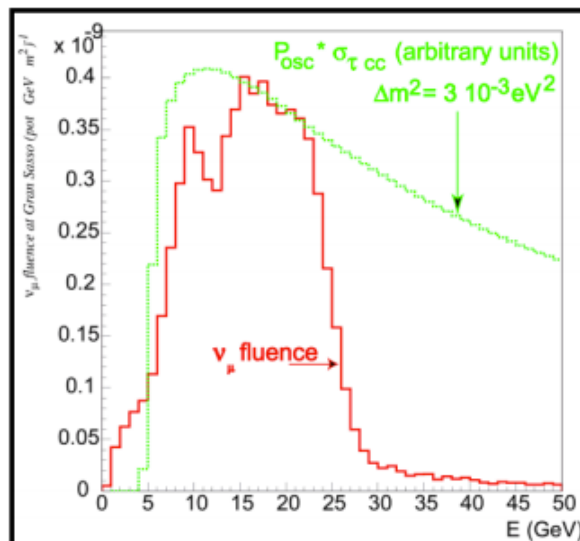
The CNGS Neutrino Beam



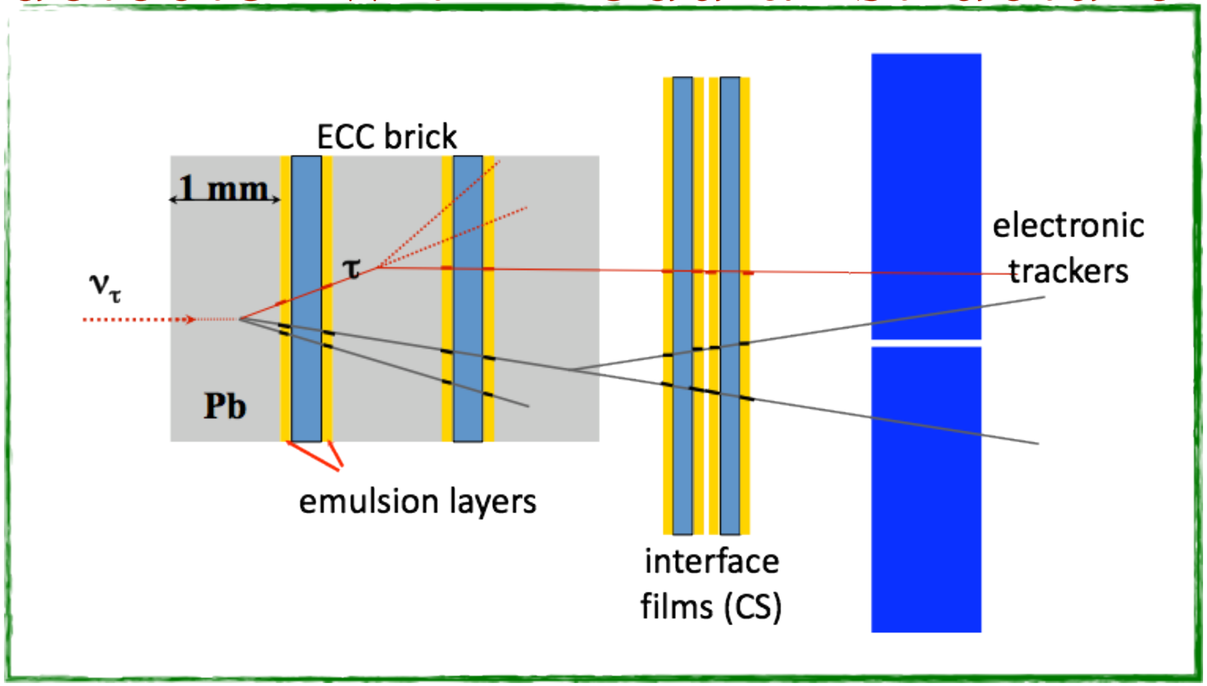
Beam parameters

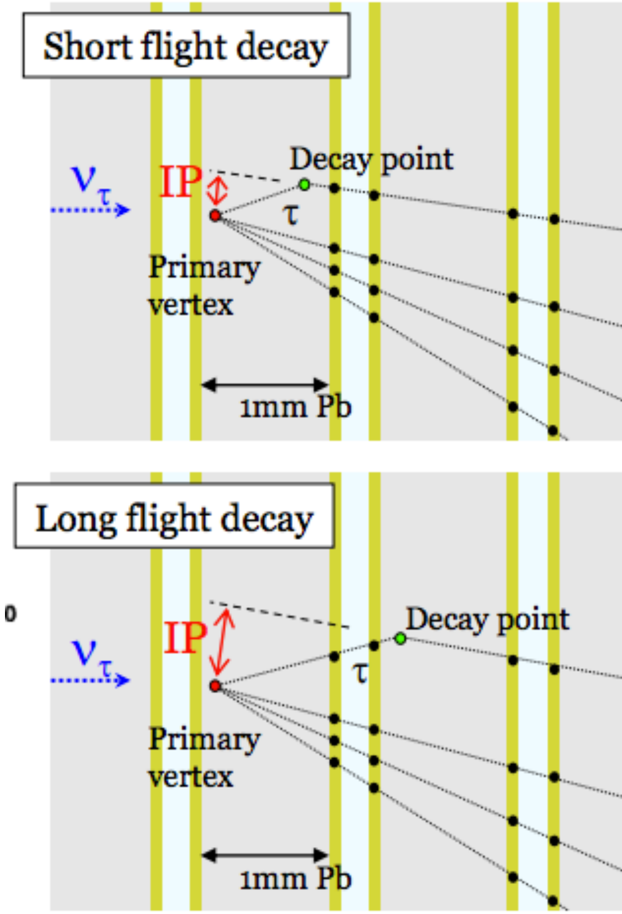
$<E\nu_\mu>$ (GeV)	17
$(\bar{\nu}_e+\nu_e)/\nu_\mu$	0.8% *
$\bar{\nu}_\mu/\nu_\mu$	2.0% *
ν_τ prompt	Negligible

* Interaction rate at LNGS



THE PRINCIPLE: hybrid detector with modular structure

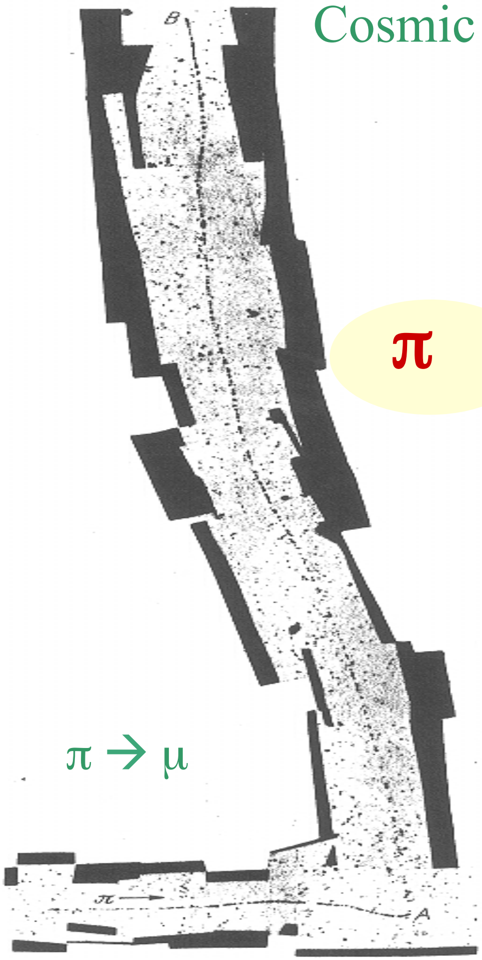




- Massive active target (1.25 kton) with micrometric space resolution
- Detect τ-lepton production and decay
- Underground location (10^6 reduction of cosmic ray flux)
- Electronic detectors to provide the "time stamp", preselect the interaction brick and reconstruct muon charge/momentum

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

Nuclear emulsions in particle physics
The discovery of the pion (1947)



Cosmic ray studies on an airplane at about 9 km and at Pic du Midi

600 μm thick emulsions with new gel to detect the passage of ionising particles (sensitive to m.i.p.) in collaboration with industry (Ilford)

By exposing these emulsions to cosmic rays,
Powell solved in 1947 the mistery of the Yukawa meson

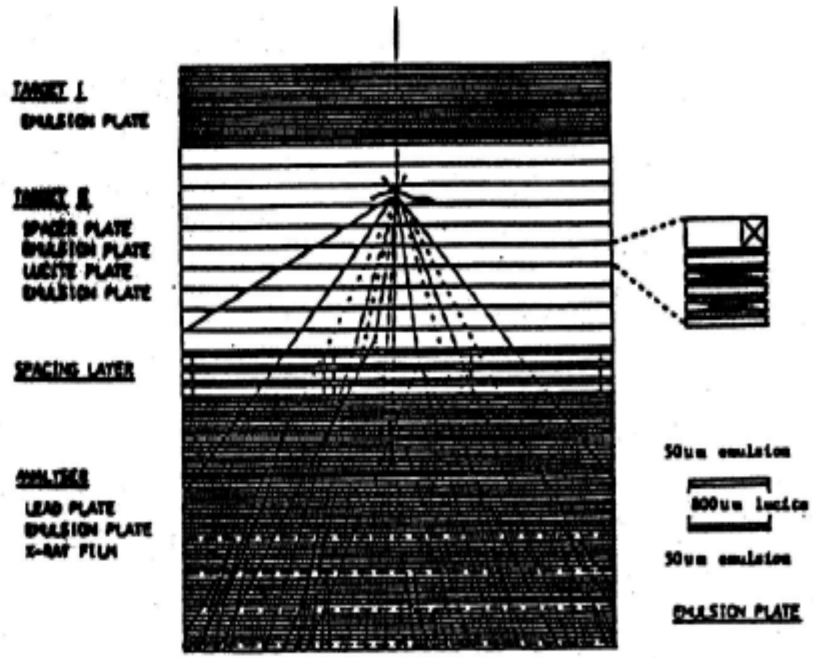
π

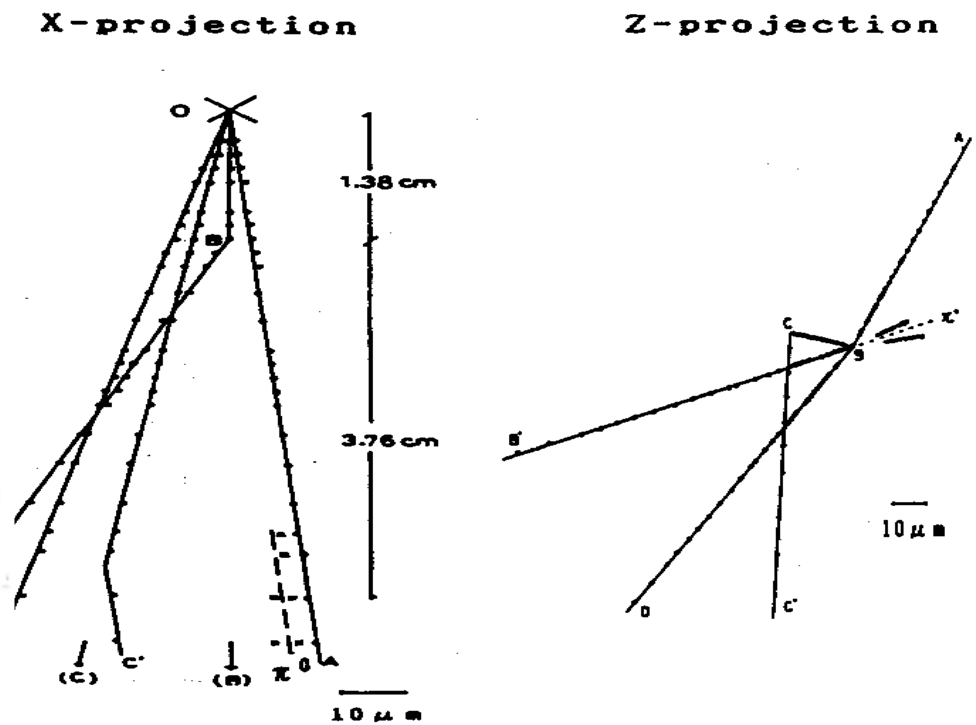
Lattes, Muirhead, Occhialini and Powell,
OBSERVATIONS ON THE TRACKS OF SLOW MESONS IN PHOTOGRAPHIC EMULSIONS, Nature 159 (1947) 694.

Powell got the Nobel Prize for Physics in1950.
The Committee underlined the simplicity of the used detector

"Charm" was born as *"X-particle"* (1971)

in a 500 h exposure of a ~ 50 kg Emulsion Cloud Chamber (ECC) on a Jet Cargo Airplane





(a) First evidence for the production and decay of short-lived particles (~ 10^{-13} s) in cosmic rays[49];
(b) the event was observed in an emulsion chamber.

Prog. Theor. Phys. Vol. 46 (1971), No. 5

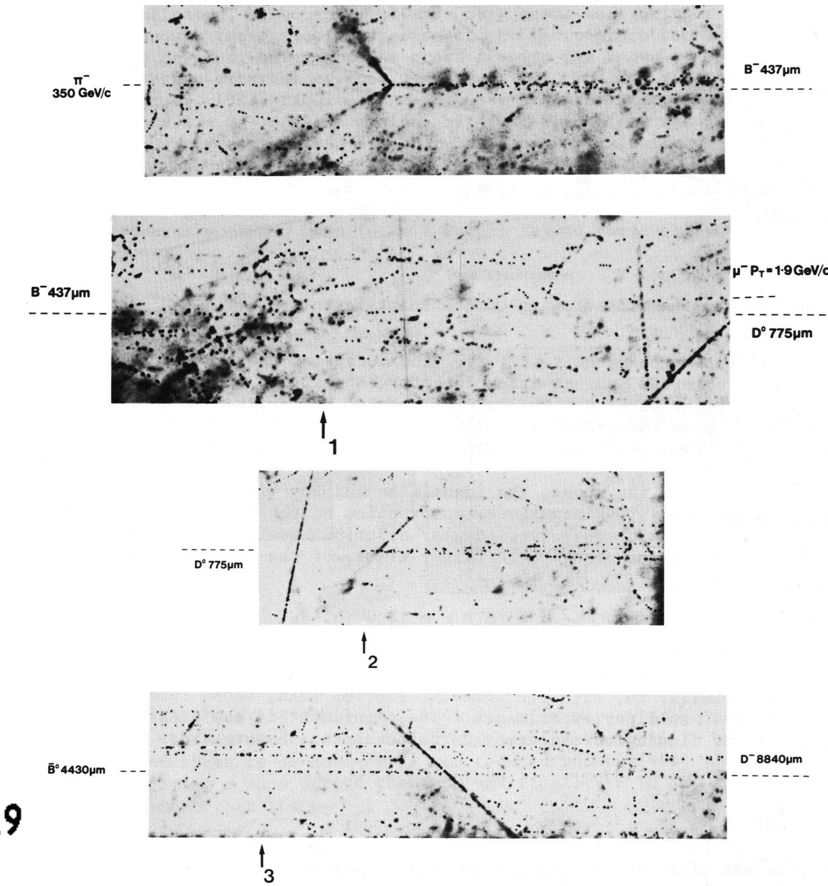
A Possible Decay in Flight of a New Type Particle

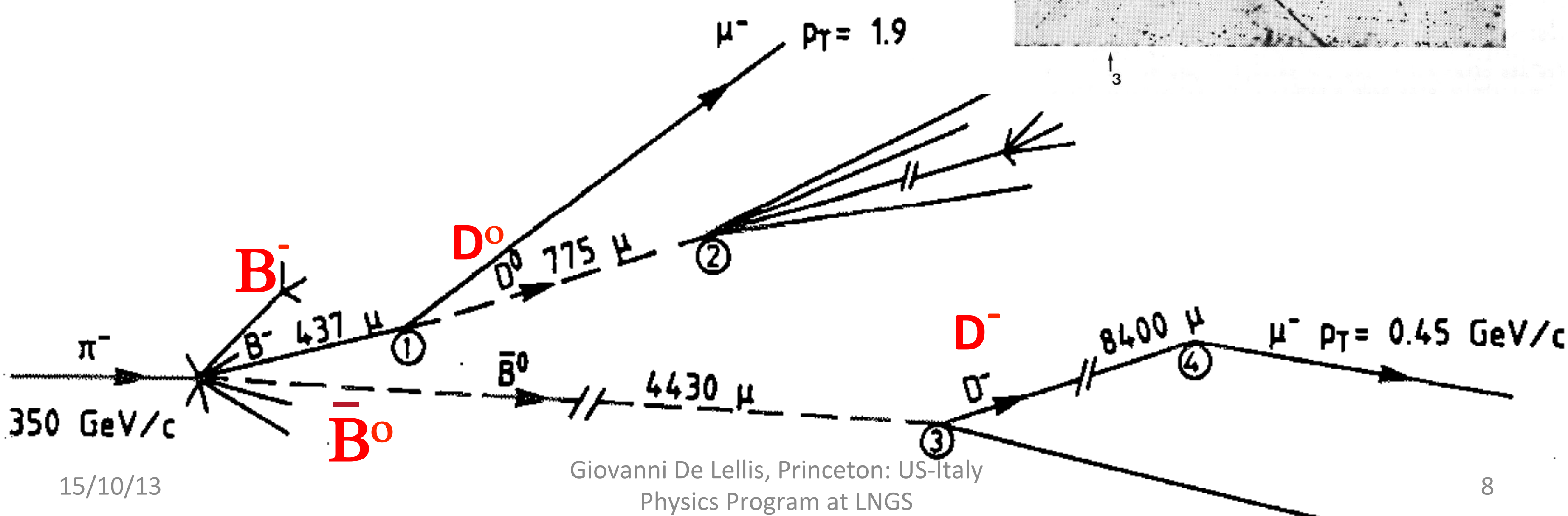
Kiyoshi NIU, Eiko MIKUMO and Yasuko MAEDA

our *X* particle could not be included either in strange particle or in resonance particle.

Direct observation production and decay of beauty particles

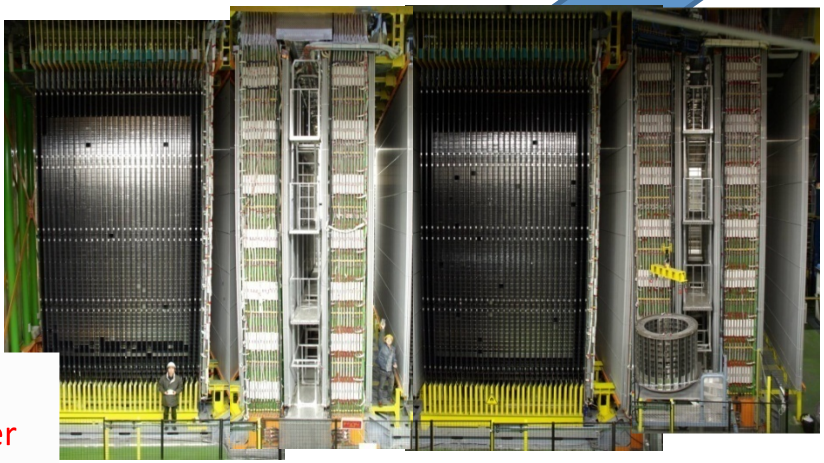
WA75 at CERN
Phys. Lett. 158B (1985) 186



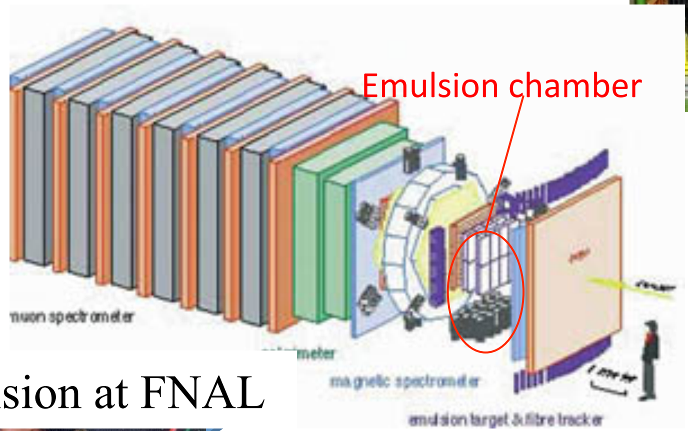


Nuclear Emulsion Experiments

Revival of the emulsion technique in 1990 due to the development of fully automated scanning systems



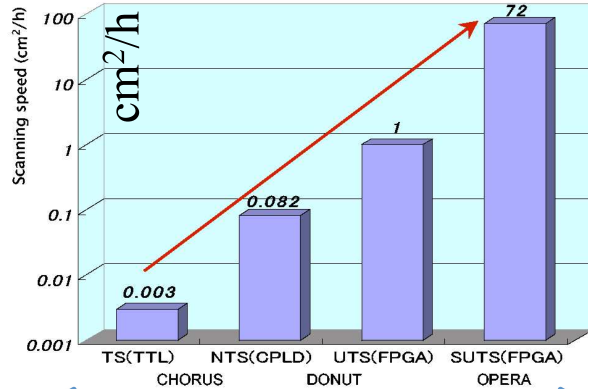
OPERA at LNGS: 30000kg emulsion



DONUT: 120kg emulsion at FNAL

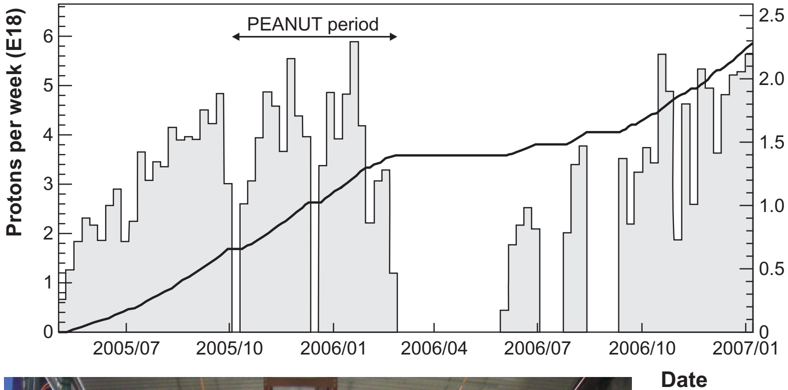
CHORUS at CERN:
780kg(140x140x3 cm³) emulsio

Evolution of the scanning speed



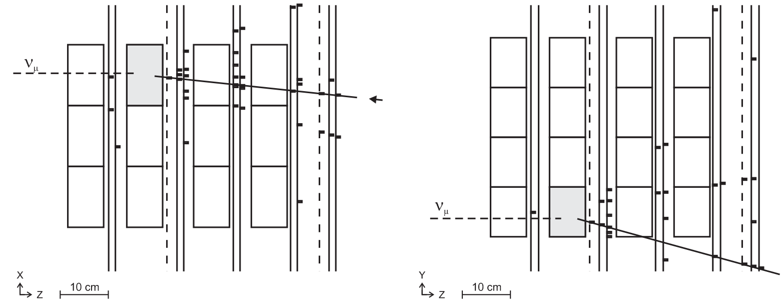
15 years

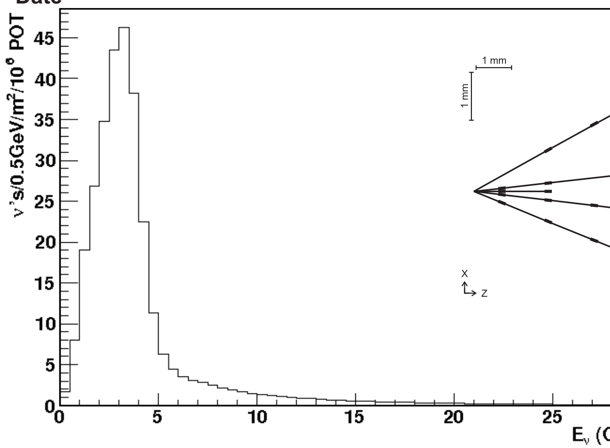
Early stages: prototype test at the NuMi beam at Fermilab

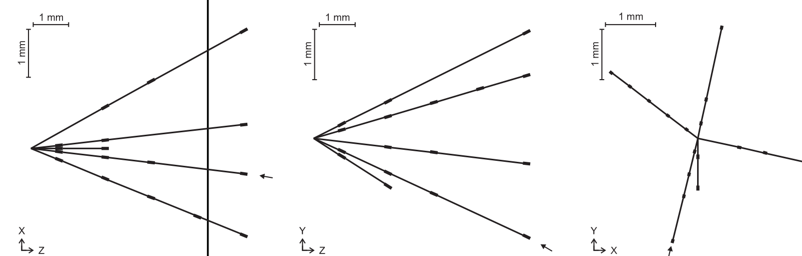


In Collaboration with Fermilab and Pittsburg University

T952
PEANUT
experiment





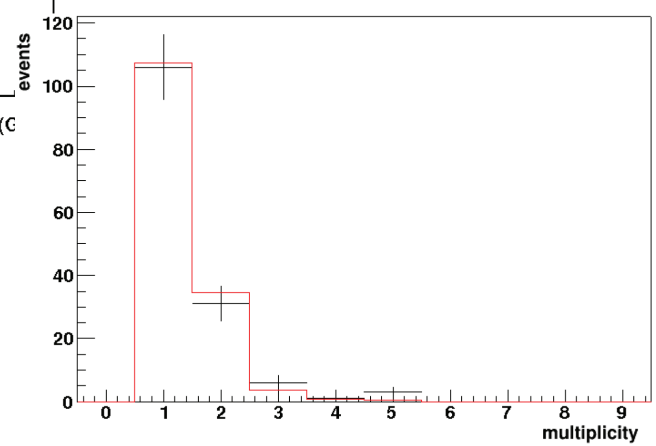


A sub-sample of 147 ν_μ CC interactions was analysed

$$a_{\rm dis} = 0.68^{+0.09}_{-0.11}\,({\rm stat}) \pm 0.02\,({\rm syst})$$

$$a_{\rm qe} = 0.20^{+0.06}_{-0.07}\,({\rm stat}) \pm 0.02\,({\rm syst})$$

$$a_{\rm res} = 0.12 \pm 0.04\,({\rm stat}) \pm 0.02\,({\rm syst}).$$



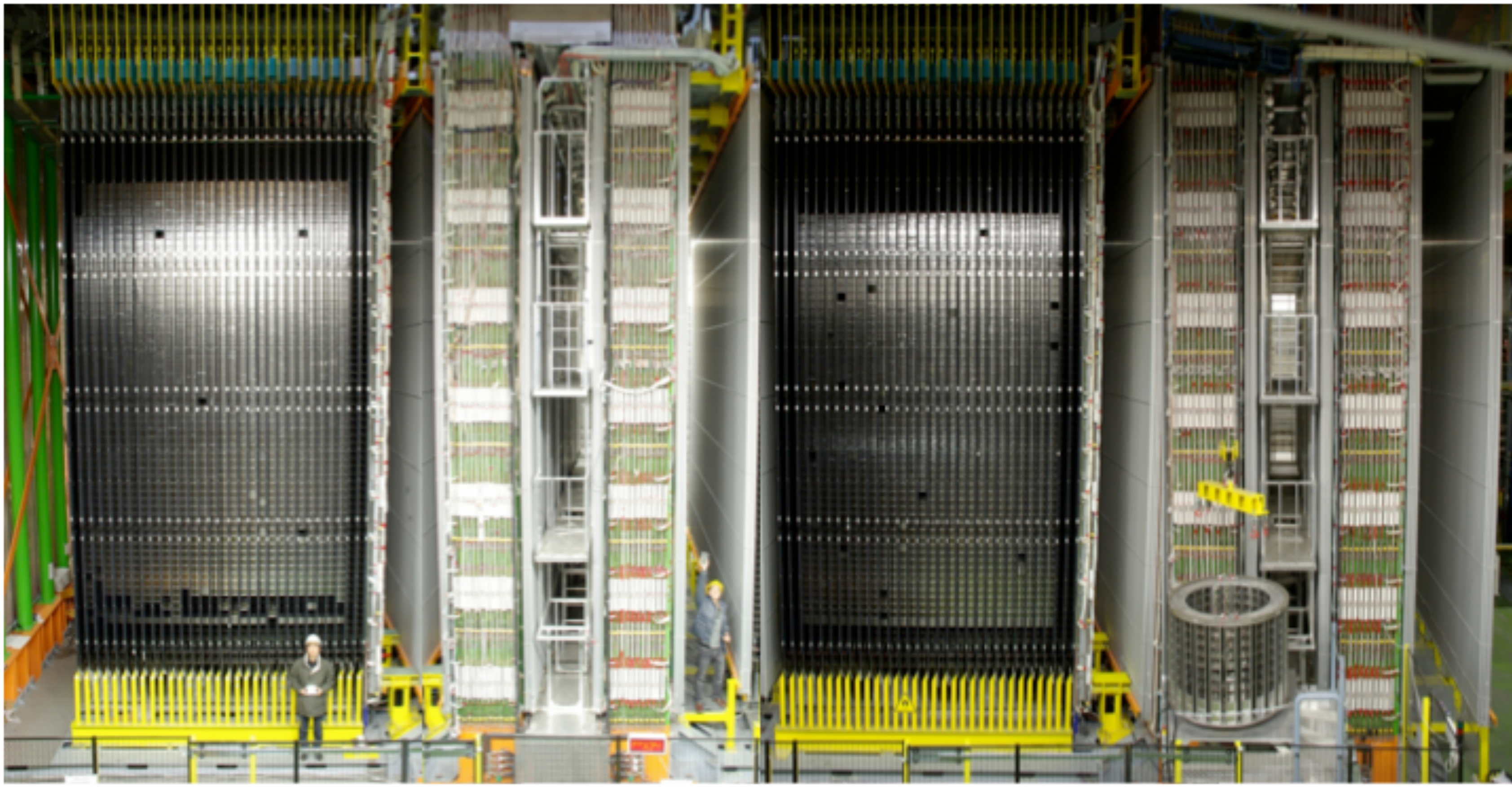
Emulsion Cloud Chamber and scintillating fibre tracker (1ton scale) in front of the MINOS near detector

New Journal of Physics 12 (2010) 113028

The Detector

SM-1

SM-2



Target

brick walls+ Target Tracker

Spectrometer

RPC+Drift Tubes

Target

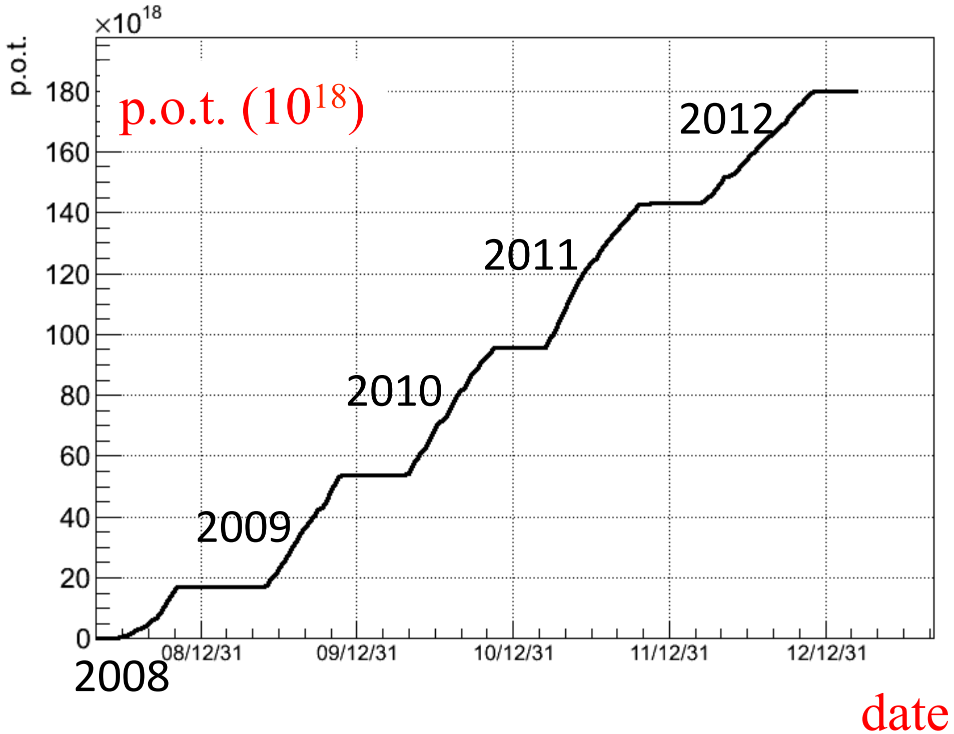
brick walls+ Target Tracker

Spectrometer

RPC+Drift Tubes

Final performances of the CNGS beam after five years 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**



20% less than the proposal value (22.5)

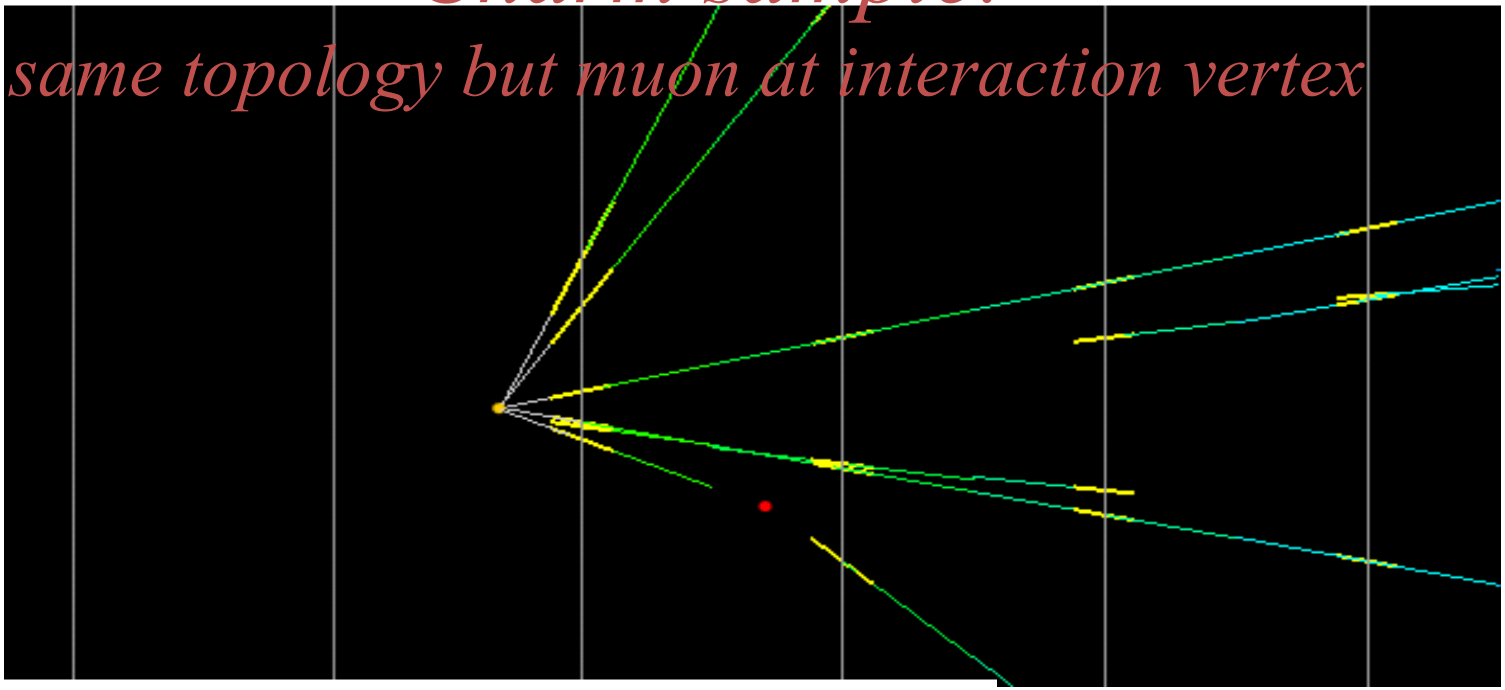
Charmed hadron production:

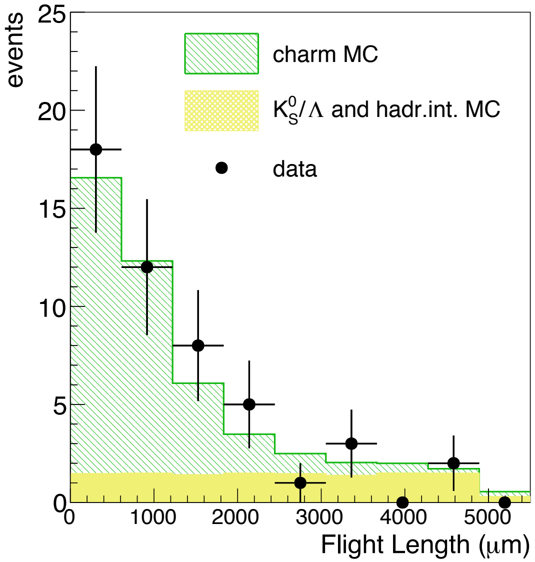
an application of the decay search

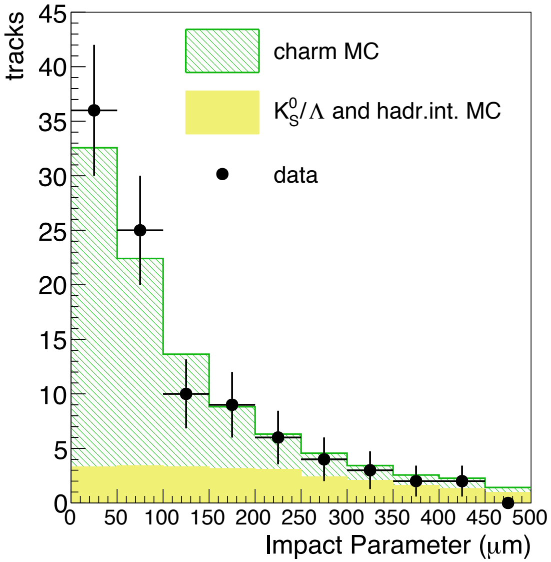
a control sample for τ

Charm sample:

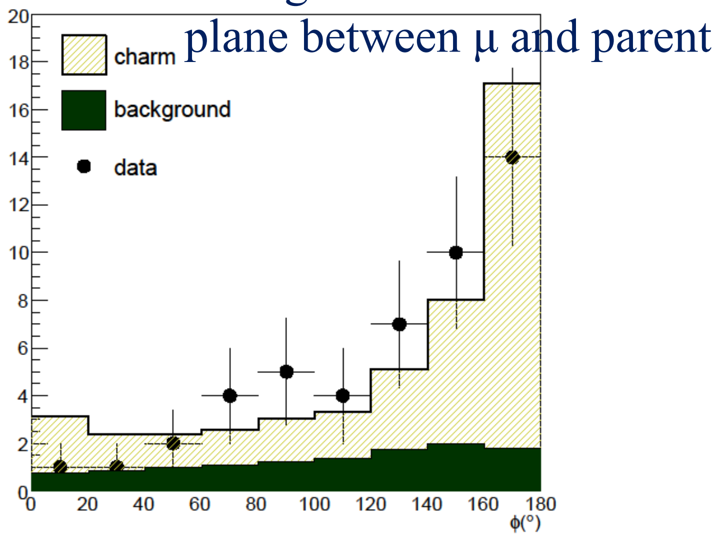
same topology but muon at interaction vertex







Angle in the transverse plane between μ and parent



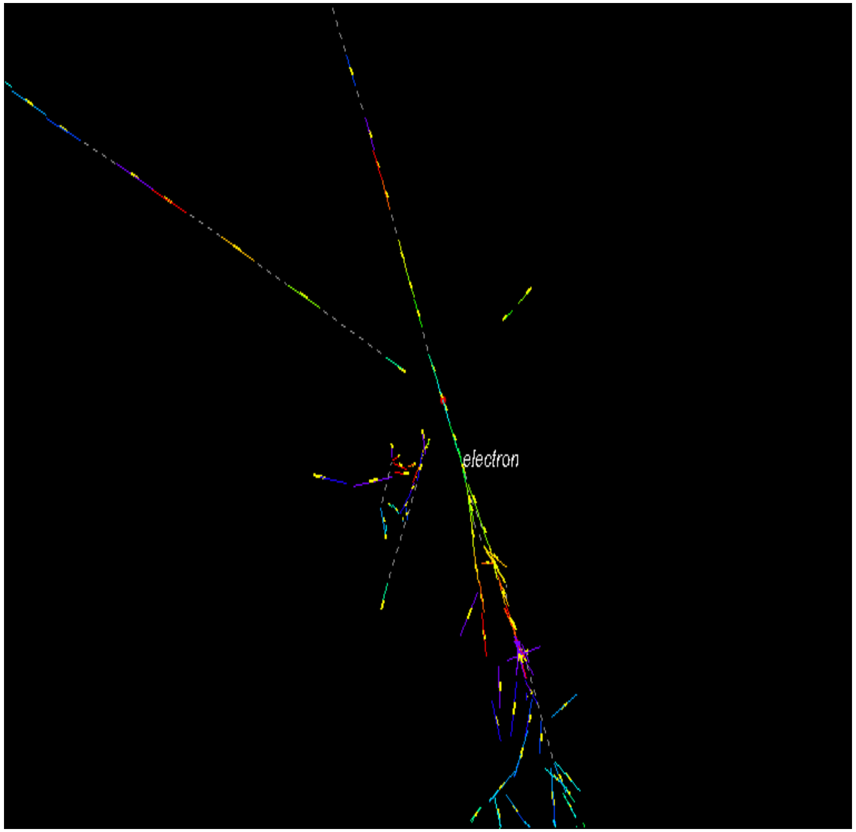
Charm yield from the analysis of 2008÷2010 data

	charm	Background	expected	data
1 prong	21 ± 2	9 ± 3	30 ± 4	19
2 prong	14 ± 1	4 ± 1	18 ± 2	22
3 prong	4 ± 1	1.0 ± 0.3	5 ± 1	5
4 prong	0.9 ± 0.2	-	0.9 ± 0.2	4
All	**40 ± 3**	**14 ± 3**	**54 ± 4**	**50**

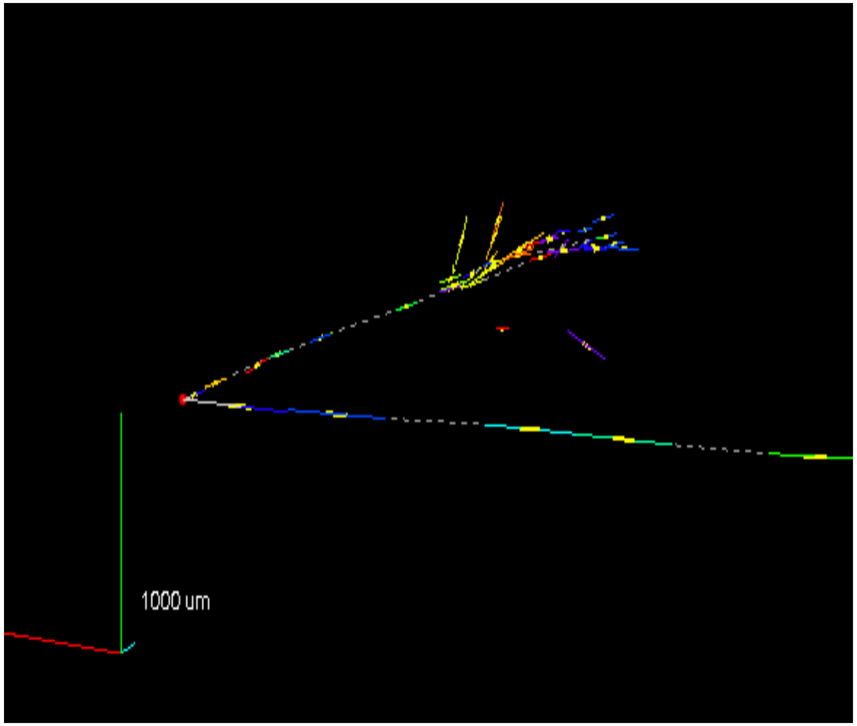
Background, mostly from hadronic interactions
(contribution from strange particle decay)

Oscillation results

$\nu_\mu \rightarrow \nu_e$ analysis



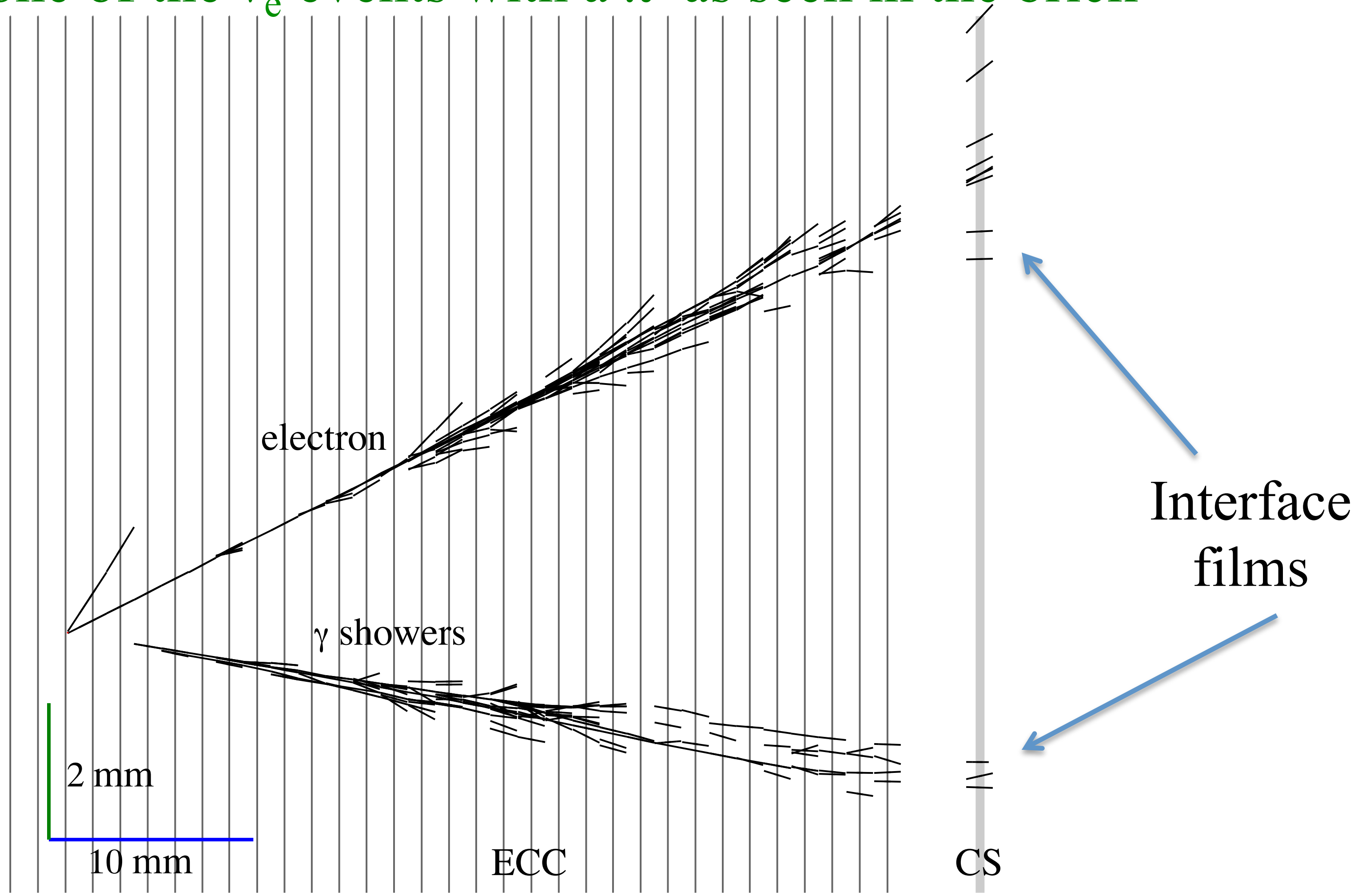
4.1 GeV electron



32 events found in the analyzed sample

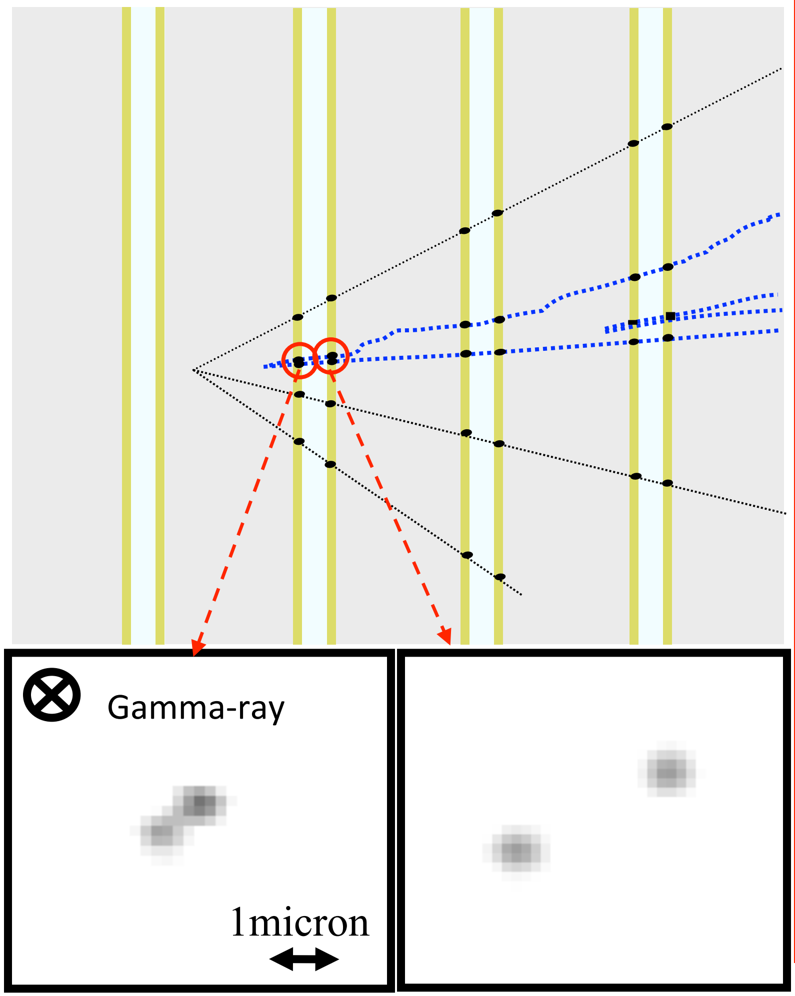
$\nu_\mu \rightarrow \nu_e$ analysis with 2008 and 2009 run data

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

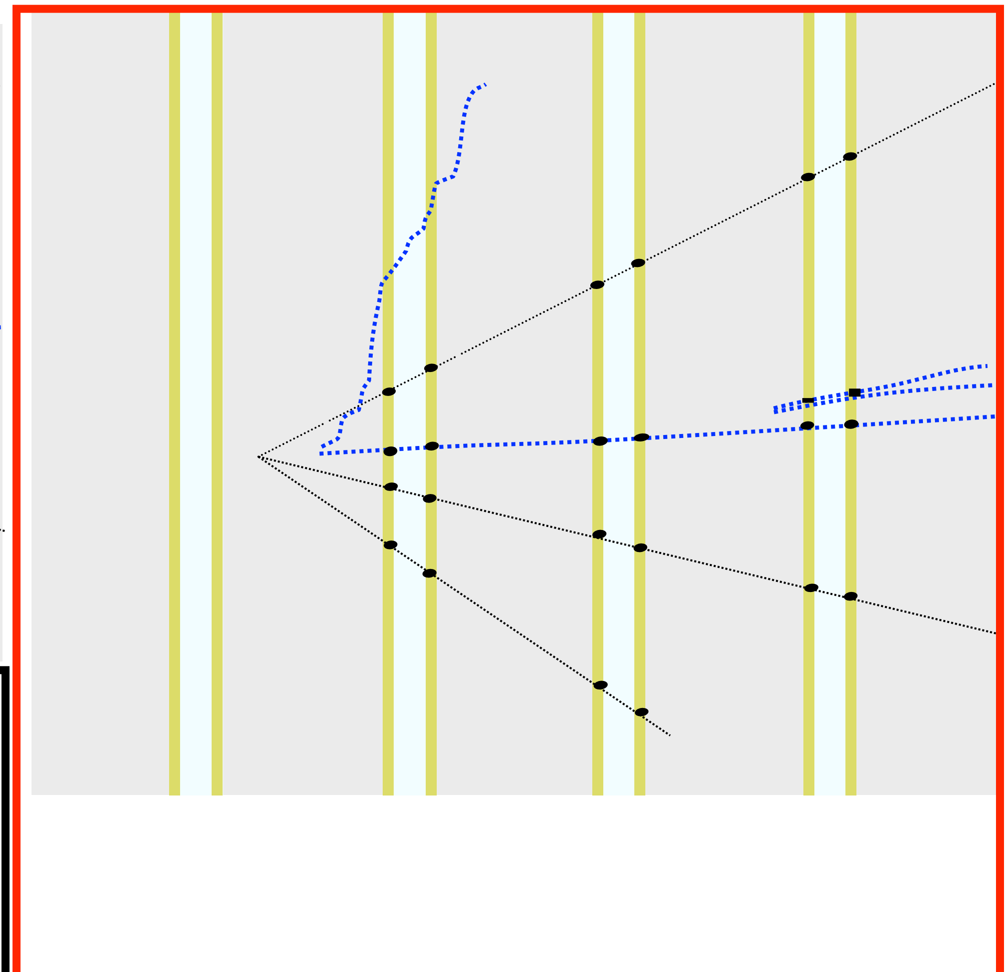


19 candidates found in a sample of 505 neutrino interactions without muon

Background from ν_μNC ($\pi^0 \rightarrow \gamma\gamma$)

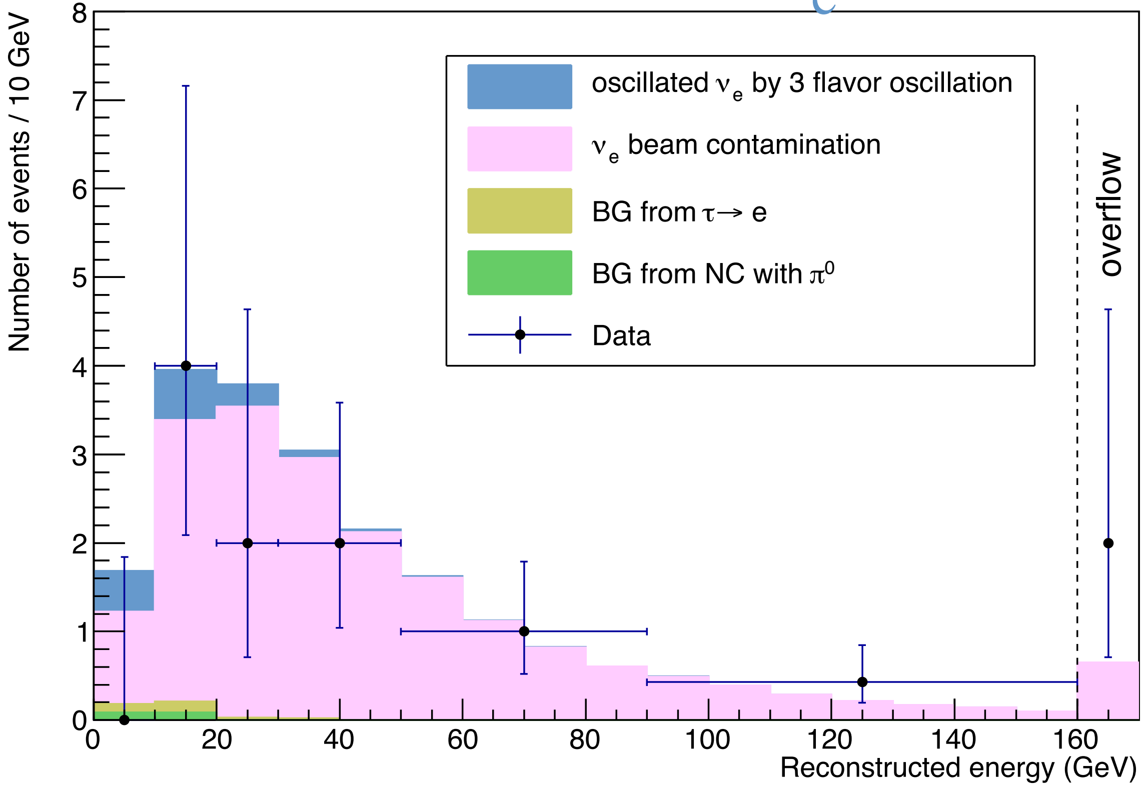


A close-up of an electron pair



BG: 0.17 events (less than 1%)

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

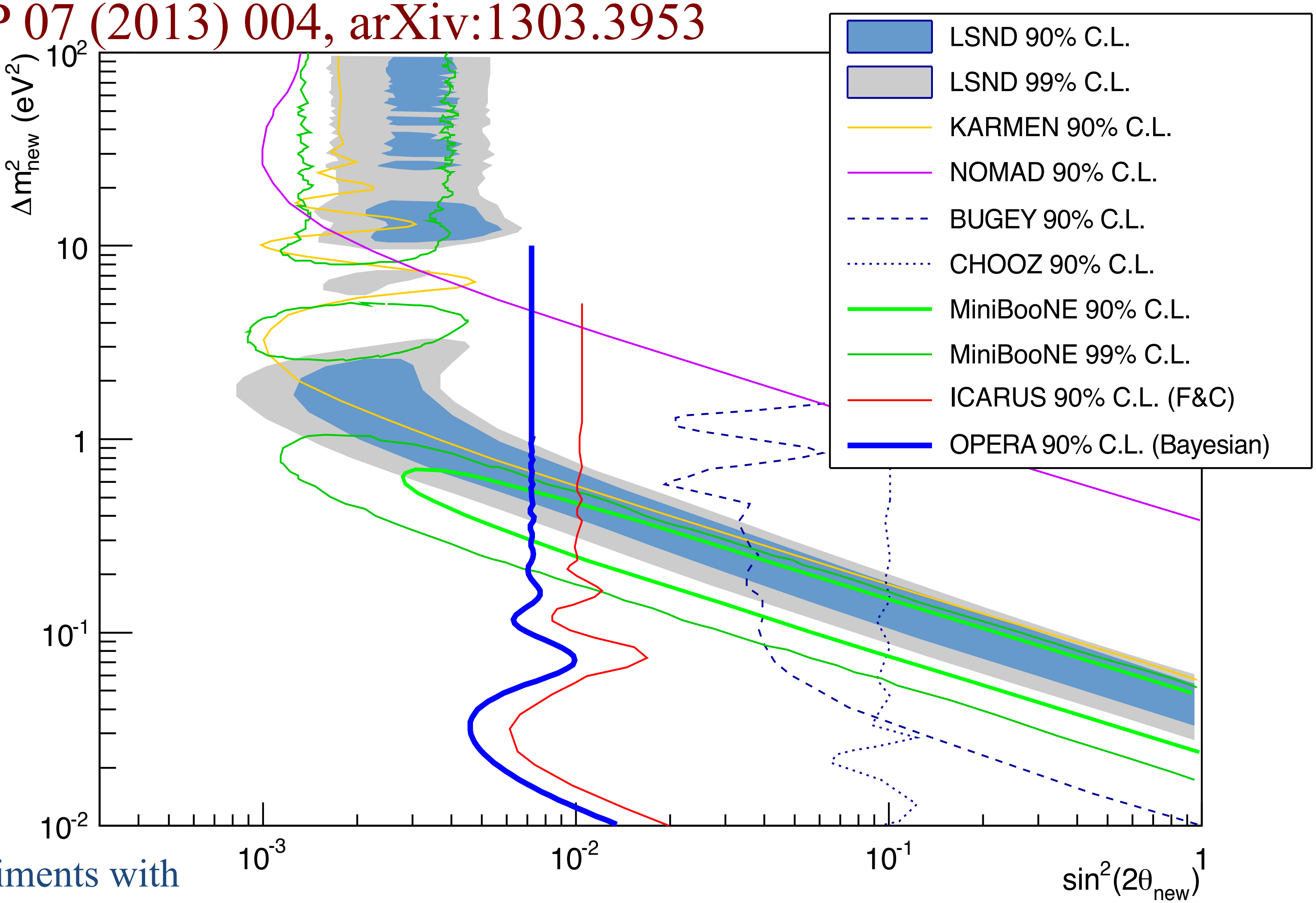
3 flavour analysis

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

JHEP 07 (2013) 004, arXiv:1303.3953



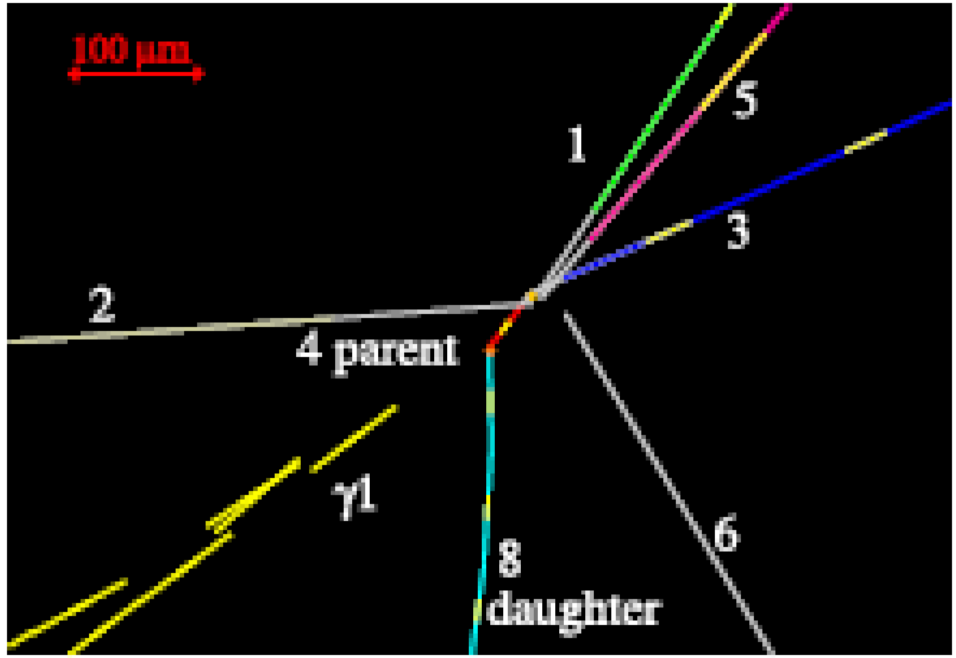
Caveat: experiments with different L/E values

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

- 2008-2009 run analysis
- 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 achieved

The first ν_τ “appearance” candidate (2010)

Candidate ν_τ interaction and τ decay from $\nu_\mu \rightarrow \nu_\tau$ oscillation



Physics Letters B 691 (2010) 138–145

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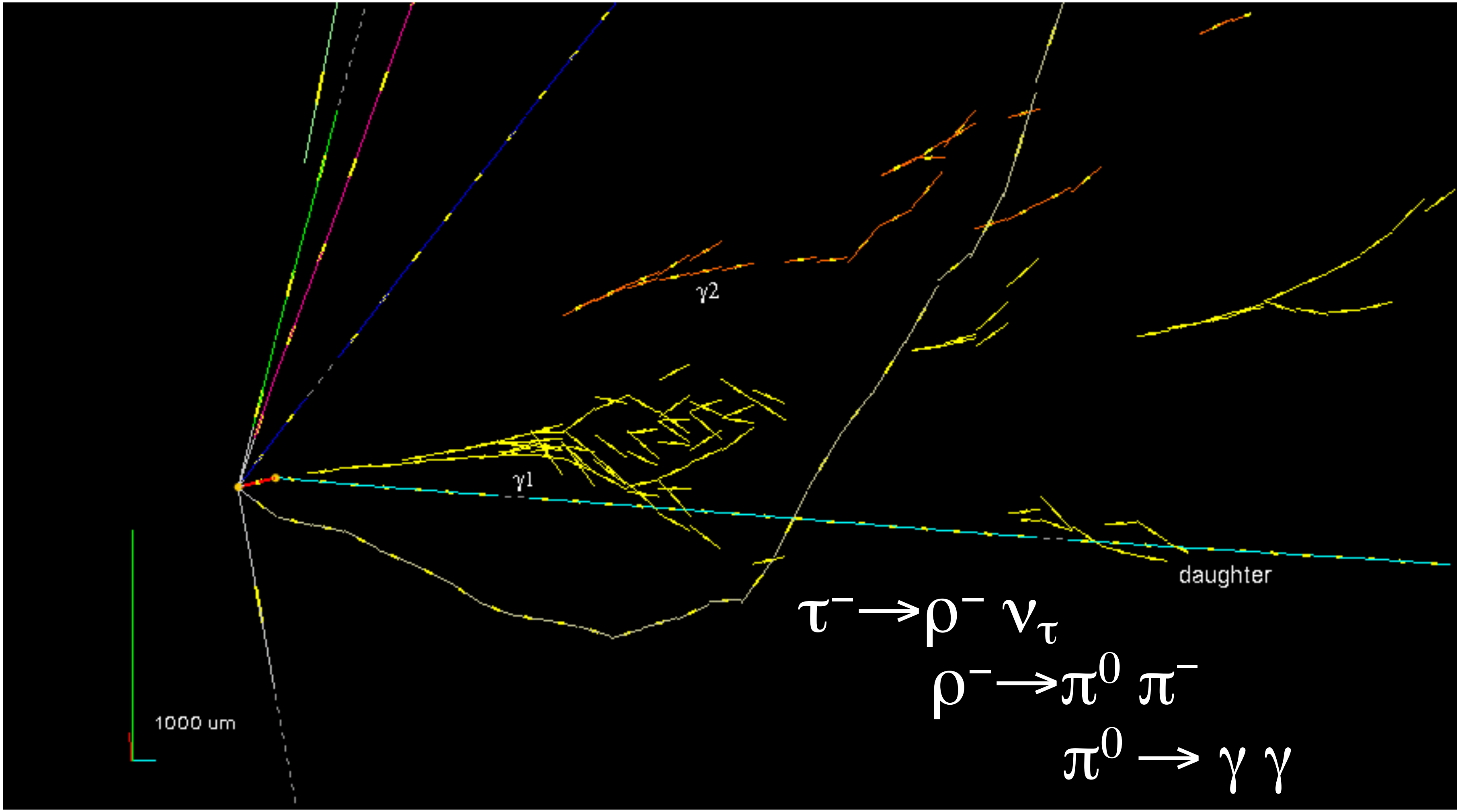
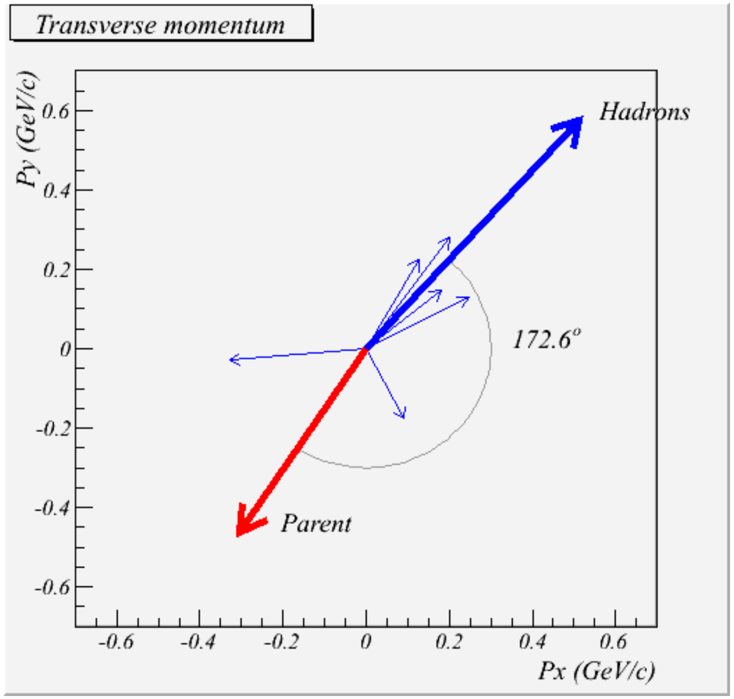
Observation of a first ν_τ candidate event in the OPERA experiment in the CNGS beam

Event reconstruction in the brick



$$\tau^- \rightarrow \rho^- \nu_\tau$$
$$\rho^- \rightarrow \pi^0 \pi^-$$
$$\pi^0 \rightarrow \gamma\,\gamma$$

Kinematical variables

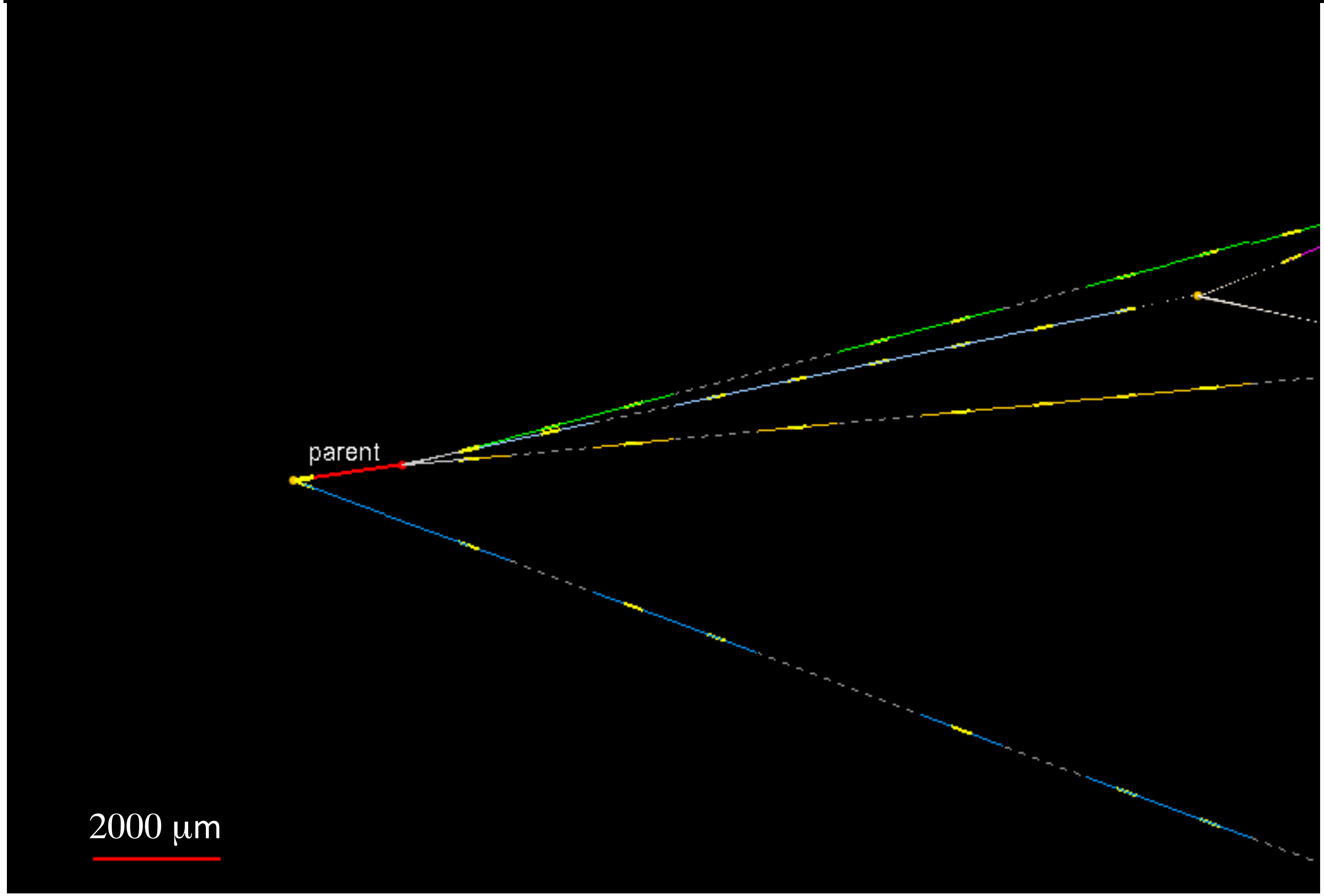


VARIABLE	AVERAGE
kink (mrad)	**41 ± 2**
decay length (μm)	**1335 ± 35**
P daughter (GeV/c)	**12^{+6}_{-3}**
Pt (MeV/c)	**470^{+240}_{-120}**
missing Pt (MeV/c)	**570^{+320}_{-170}**
ϕ (deg)	**173 ± 2**

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: optimal ratio between efficiency and analysis time
- Anticipate the analysis of 0μ events (events without any μ in the final state)

Second ν_τ Candidate Event



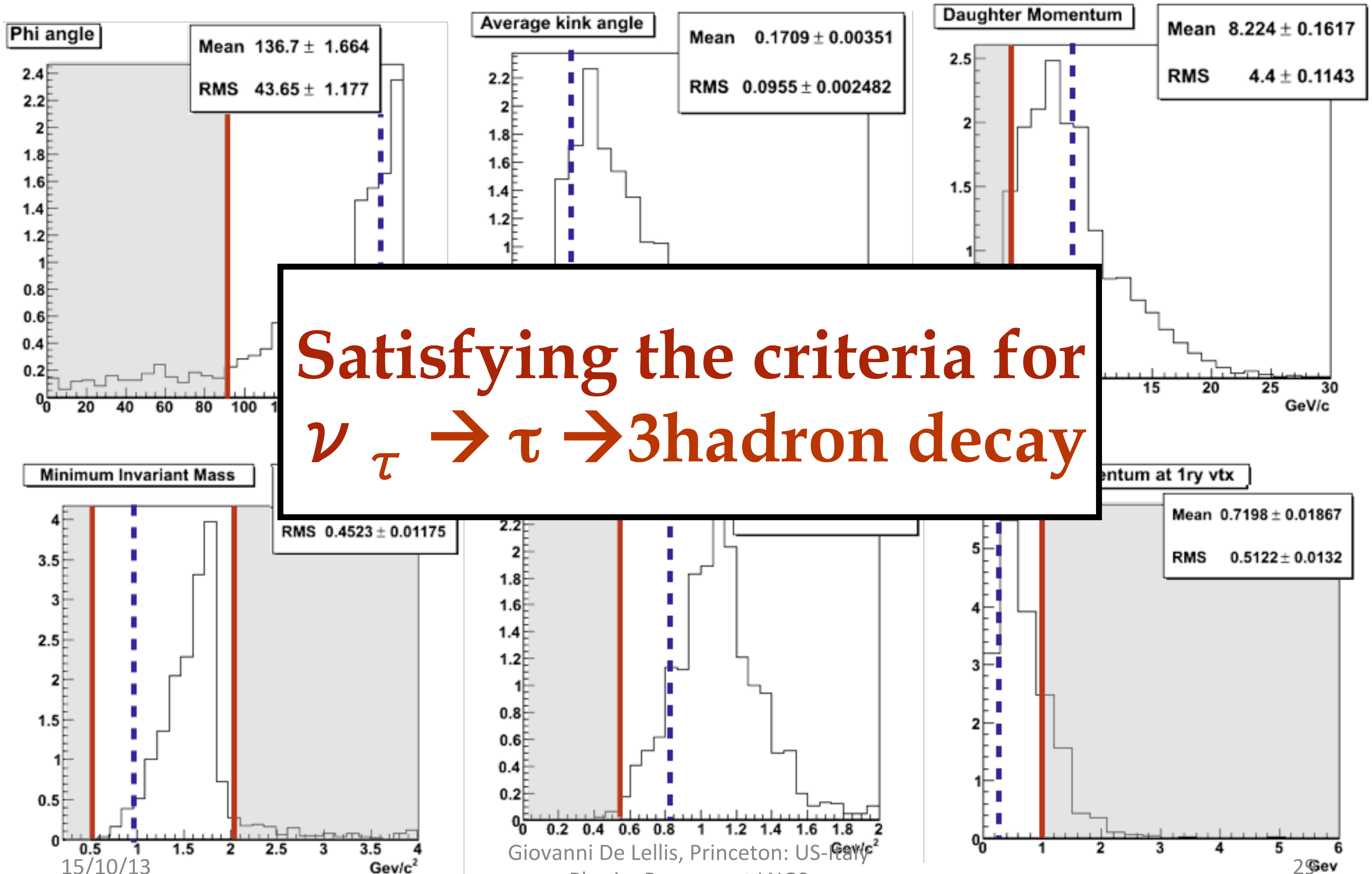
arXiv:1308.2553, to appear on JHEP

Kinematics of the second Candidate Event

	Cut	Value
φ (Tau - Hadron) [degree]	>90	167.8±1.1
average kink angle [mrad]	< 500	87.4±1.5
Total momentum at 2ry vtx [GeV/c]	> 3.0	8.4±1.7
Min Invariant mass [GeV/c^2]	0.5 < < 2.0	0.96±0.13
Invariant mass [GeV/c^2]	0.5 < < 2.0	0.80±0.12
Transverse Momentum at 1ry vtx [GeV/c]	< 1.0	0.31±0.11

Kinematics of the second candidate event

candidate
cut

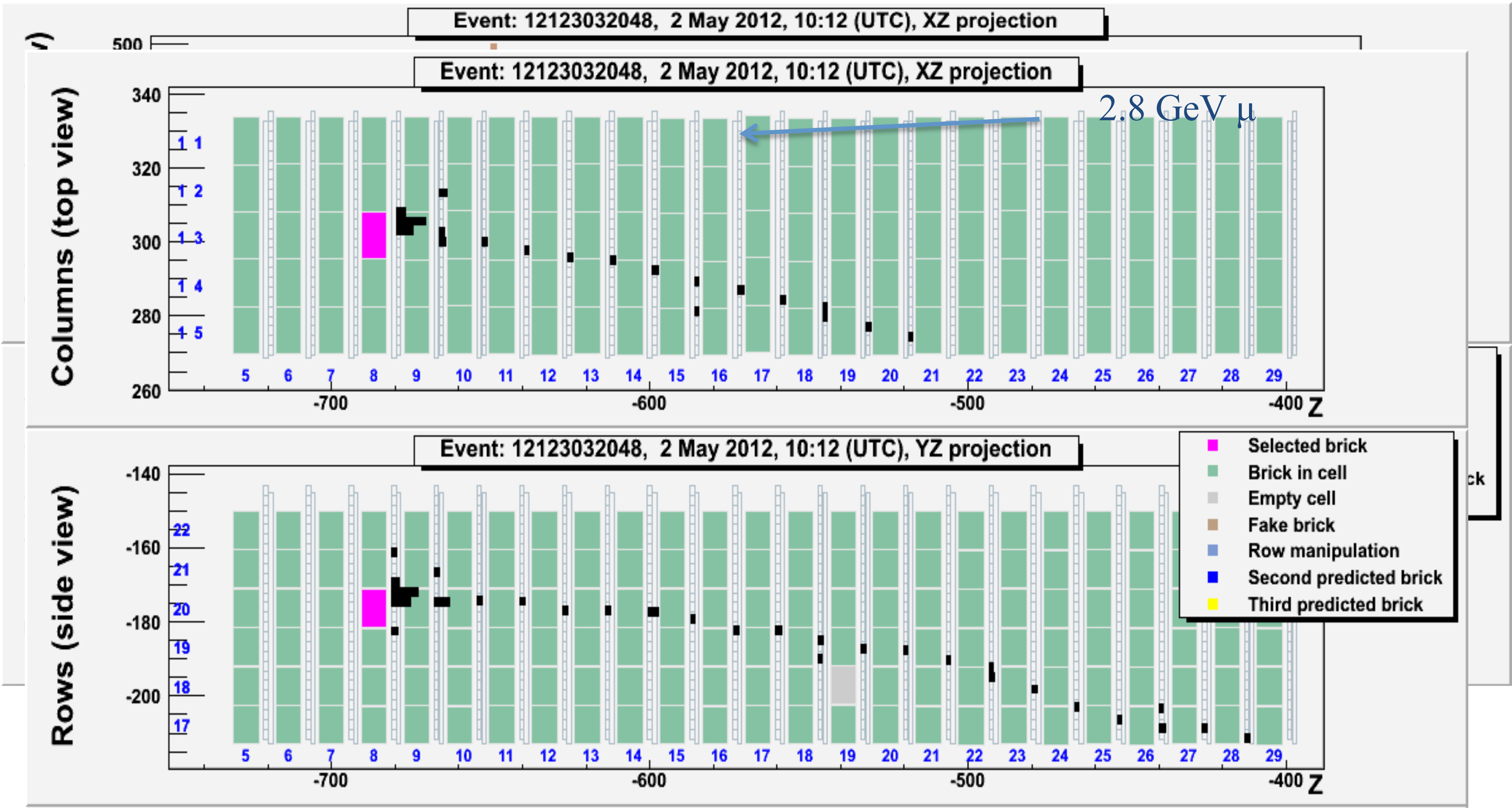


Satisfying the criteria for $\nu_\tau \to \tau \to$ 3hadron decay

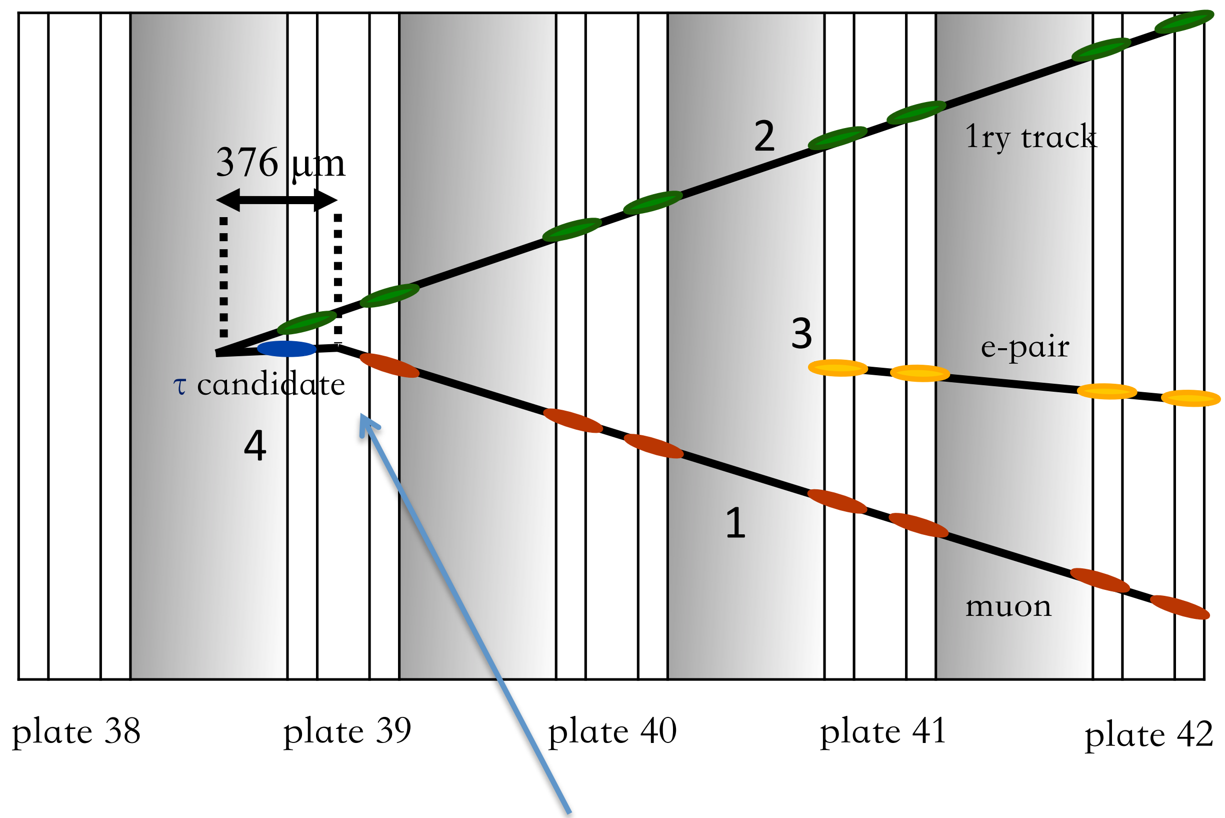
After 2012 Summer conferences

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

Third tau neutrino event taken on May 2nd 2012

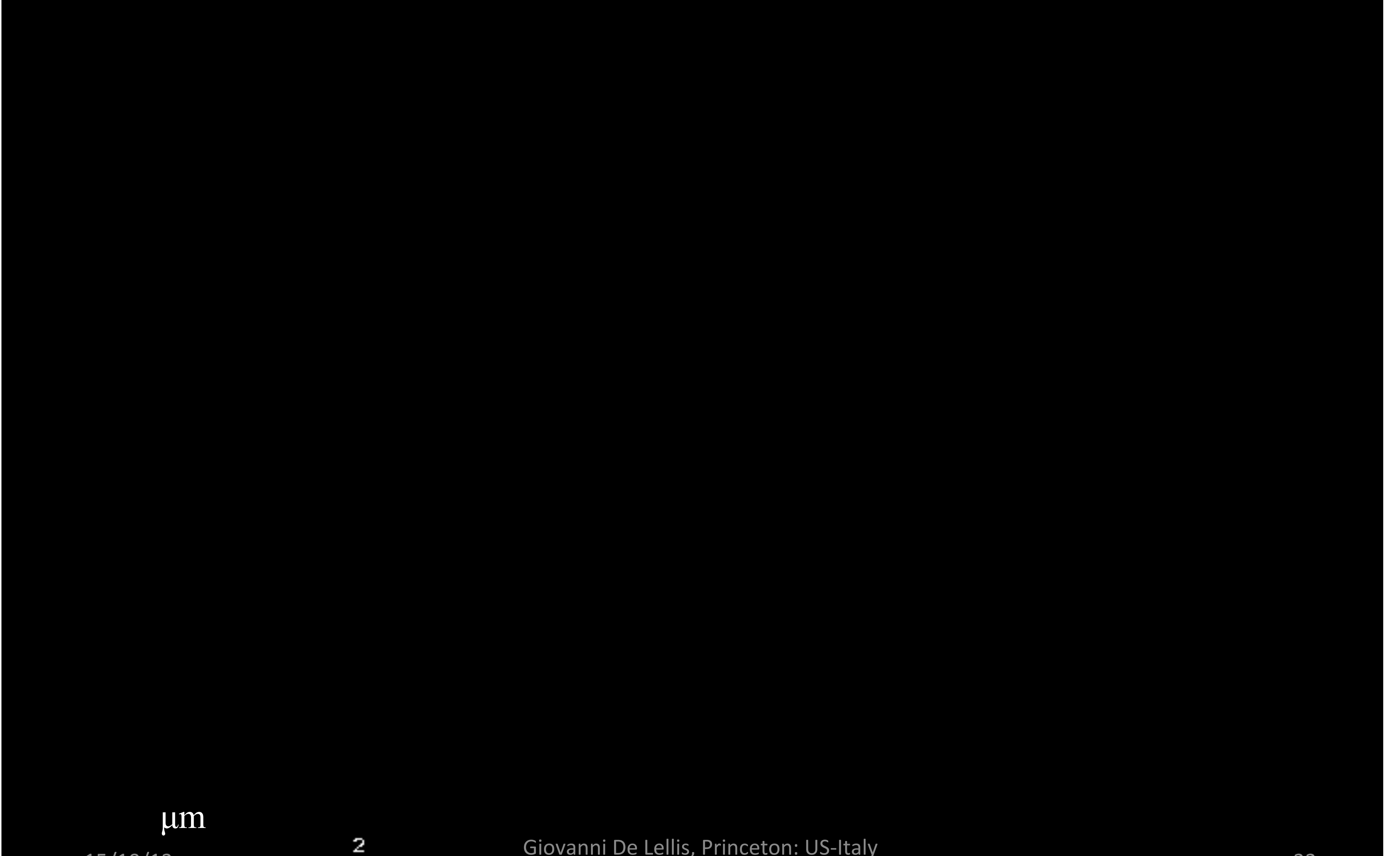


τ→μ candidate
brick analysis and decay search



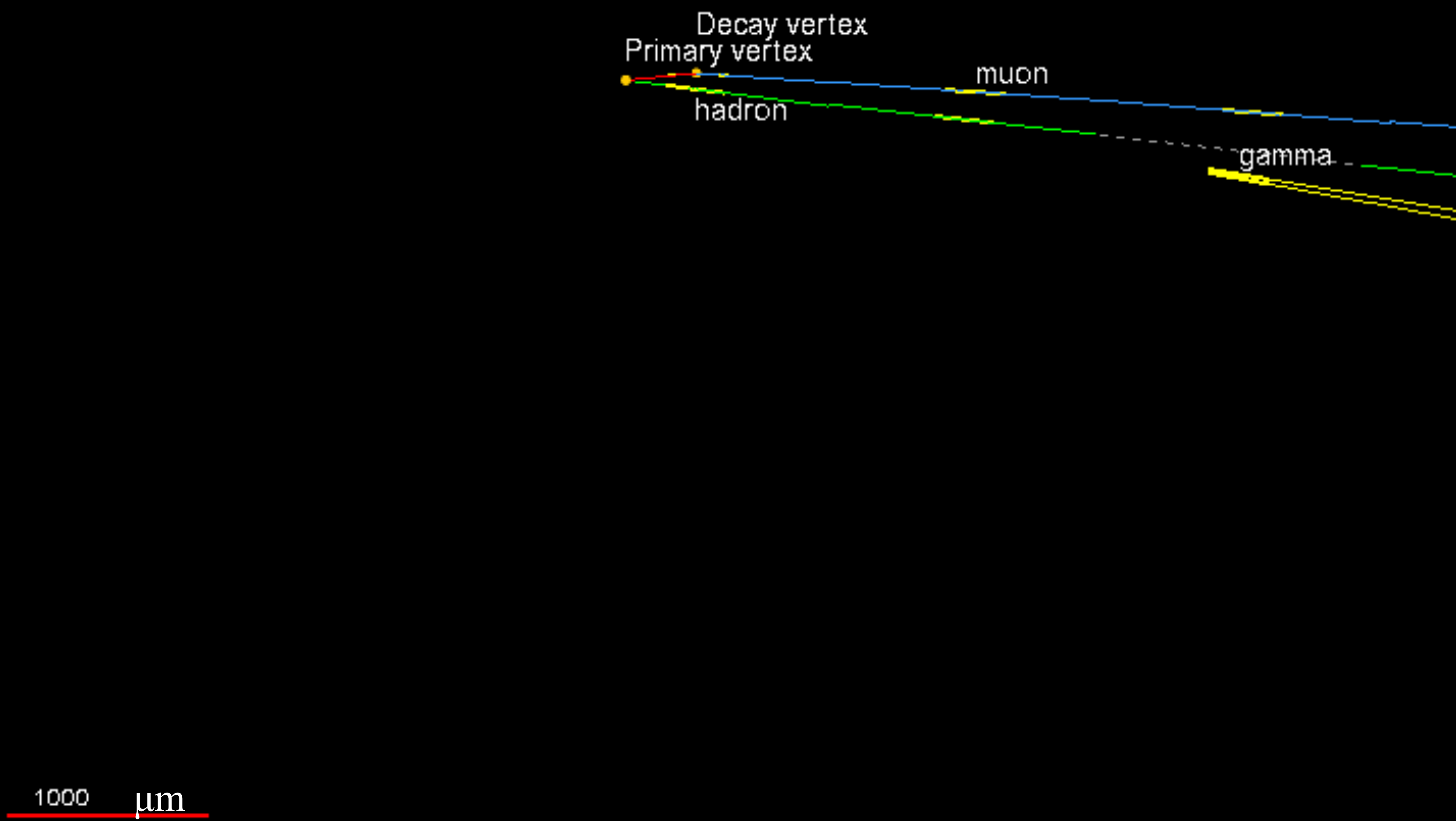
Decay in the plastic base

τ→μ candidate



Third tau neutrino event

$\tau \rightarrow \mu$



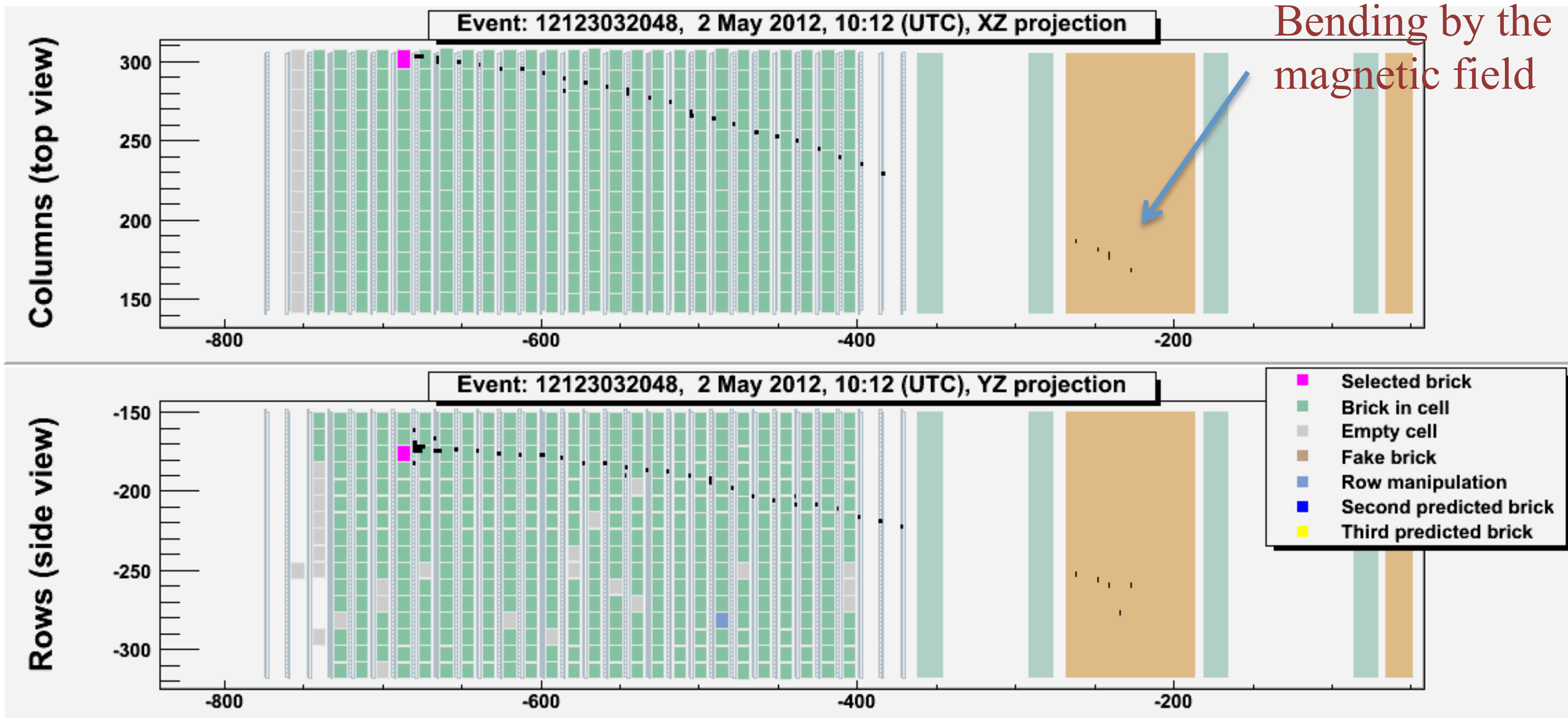
Event tracks' features

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	

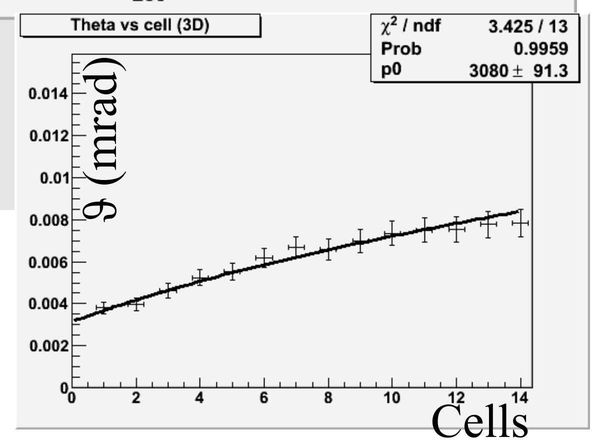
γ attachment

	$\delta\theta_{RMS}$ (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

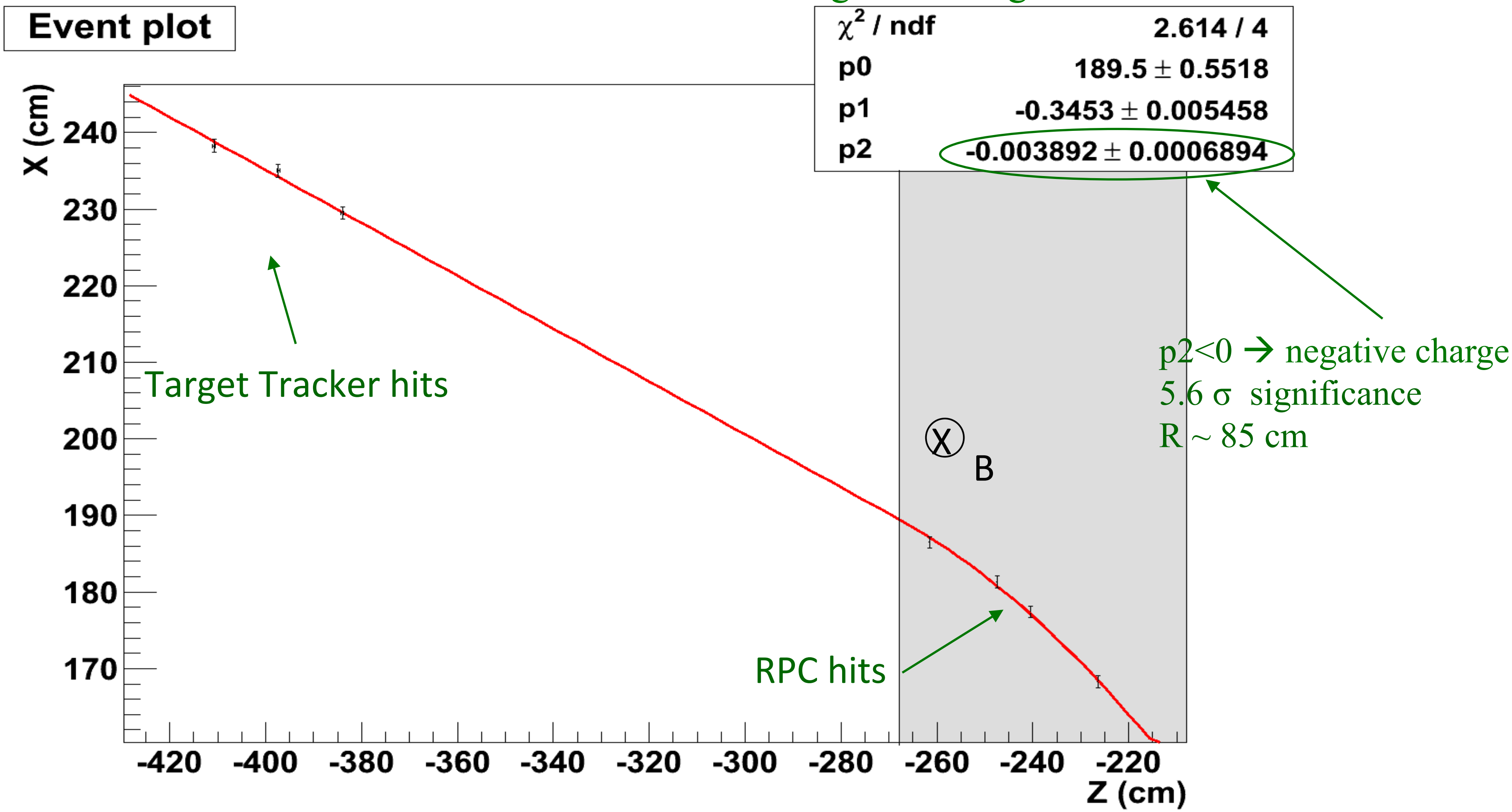


Charge determination of the muon

Charge measurement based on TT and RPC hits

Parabolic Fit with p2 as quadratic term coefficient in the magnetized region

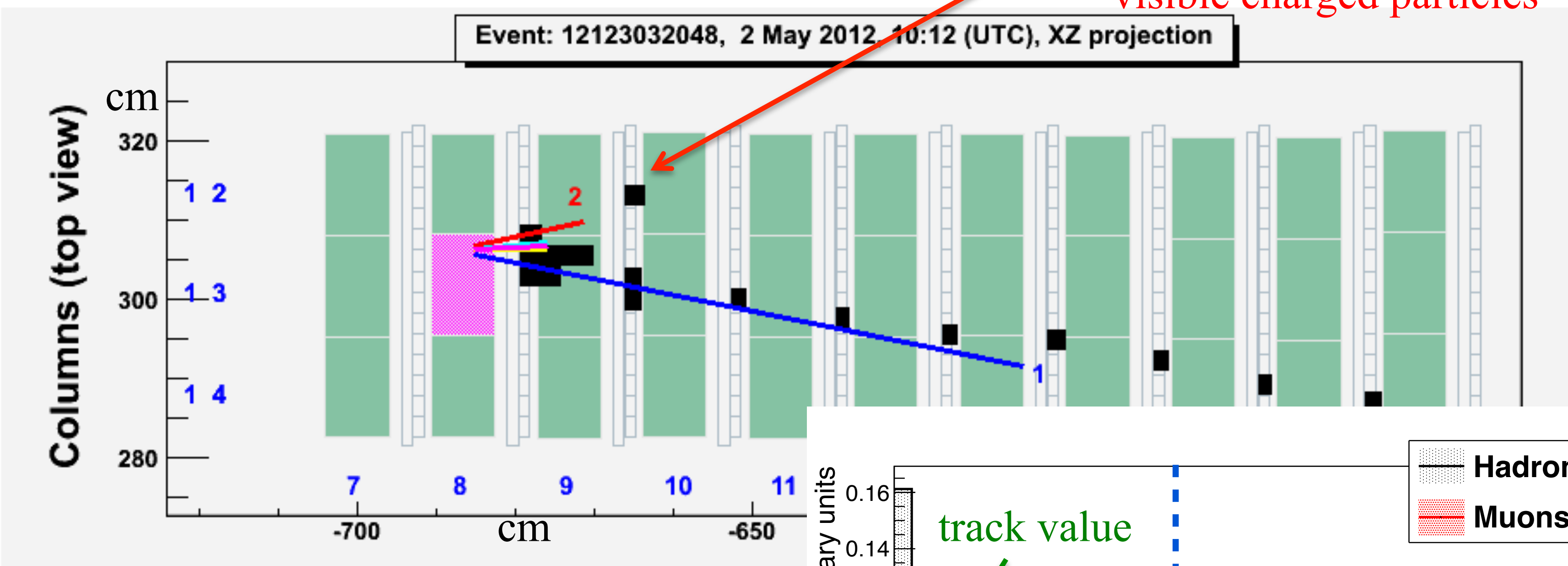
Linear fit in the non-magnetized region

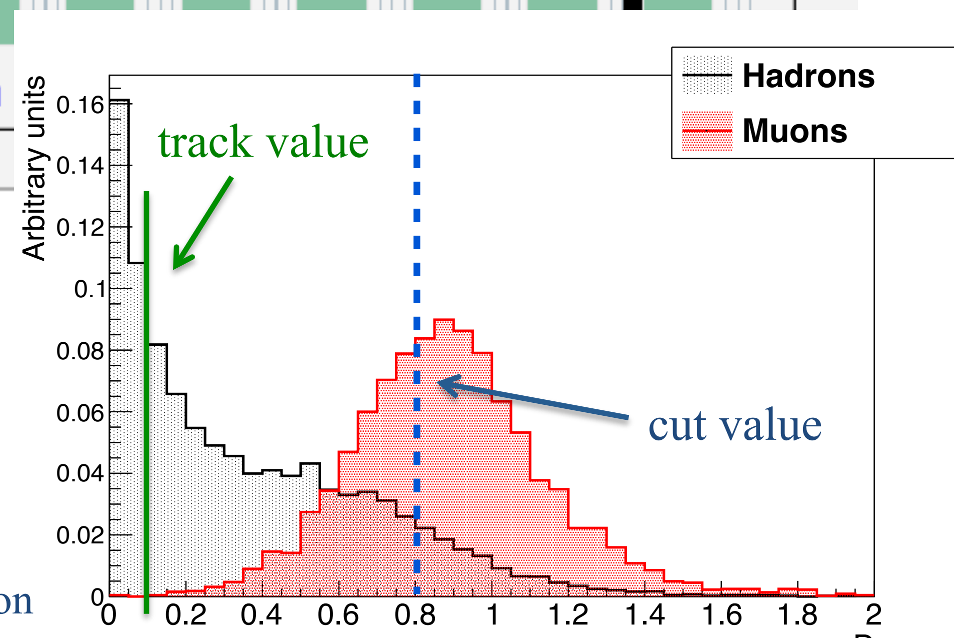


The negative muon charge rules out charm background!

Track follow down to assess the nature of track 2

Track 2 interacting in the downstream brick without visible charged particles





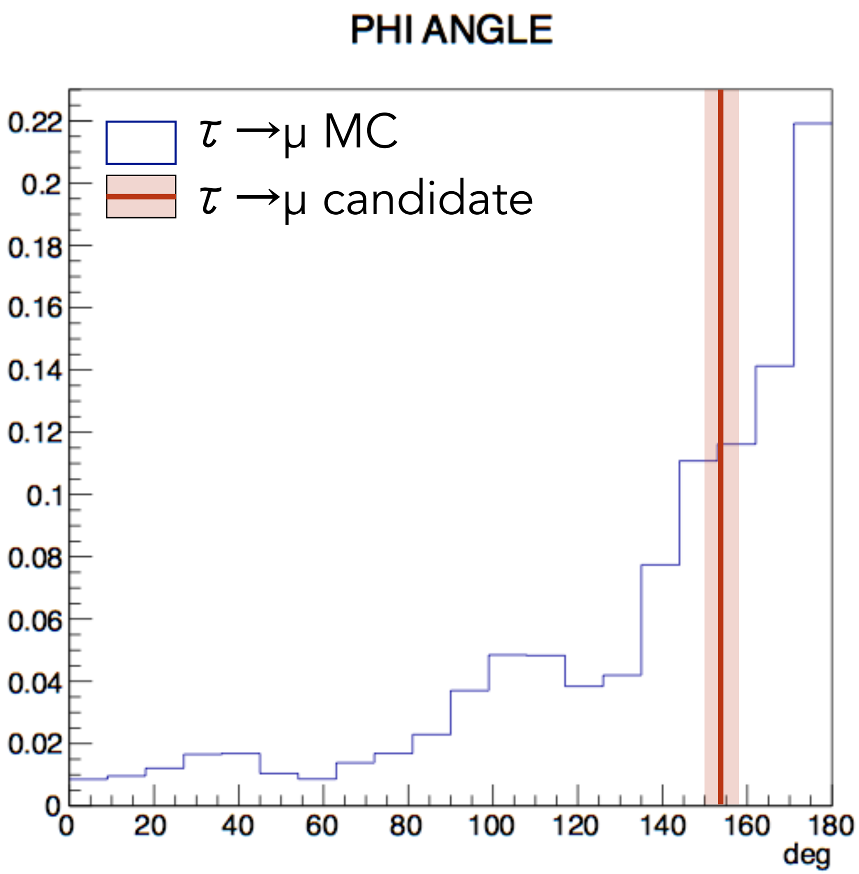
D variable

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

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

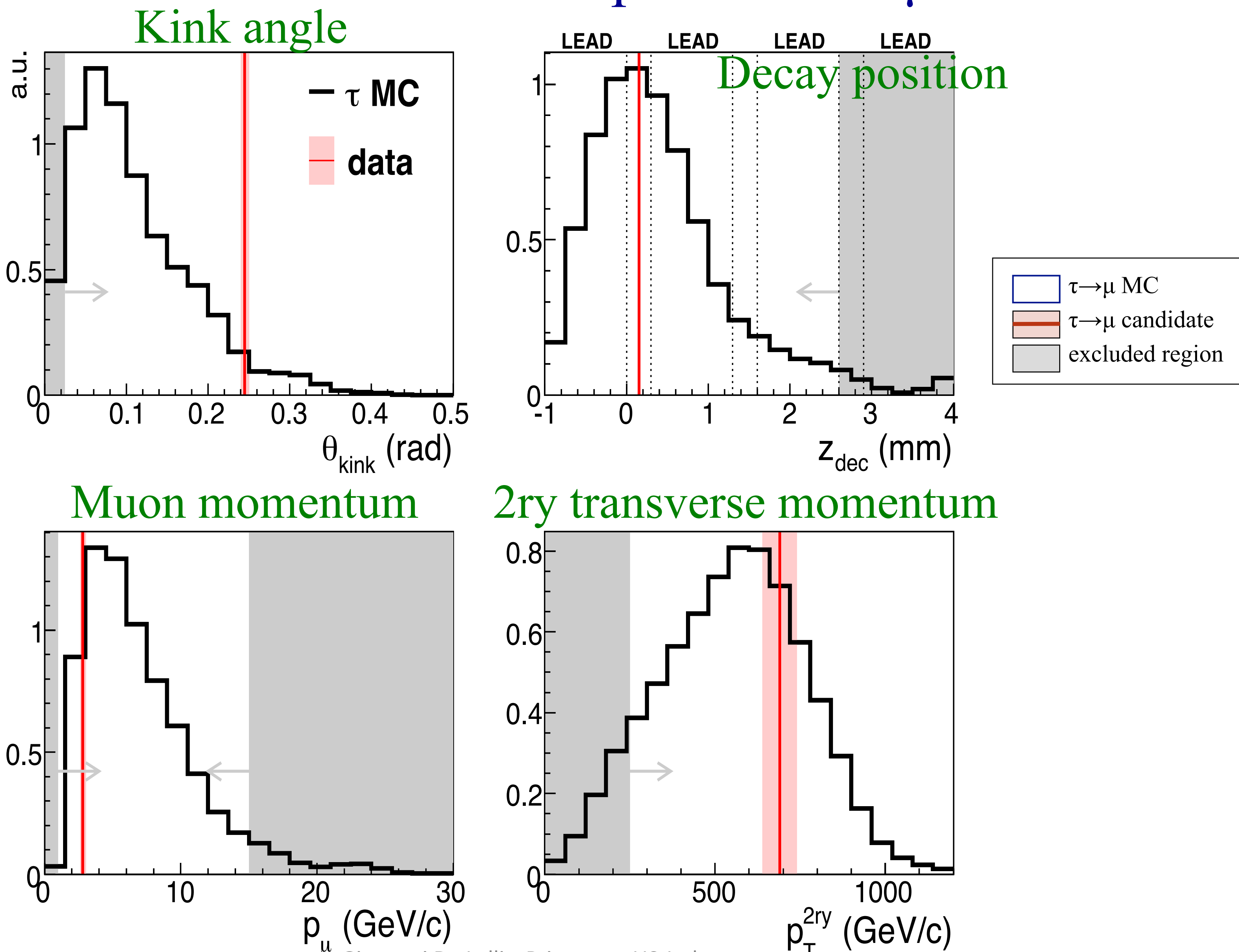
L = track length
R_{lead} = μ range
$\rho_{average}$ = average density
ρ_{lead} = lead density
p = momentum in emulsion

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



Statistical considerations

	Background	Charm	μ scattering	had int
$\tau \rightarrow h$	0.027±0.005	0.011		0.016
$\tau \rightarrow 3h$	0.12±02	0.11		0.0021
$\tau \rightarrow \mu$	0.02±0.01	0.0023	0.009	
$\tau \rightarrow e$	0.020±0.004	0.02		
total	**0.184±0.025**	0.15	0.018	0.019

3 events observed in the $\tau \rightarrow h$ and $\tau \rightarrow 3h$ and $\tau \rightarrow \mu$ channels with a total background of 0.184±0.025

p-values of each channel combined with an estimator $p^* = p_\mu p_e p_h p_{3h}$

Probability to be explained as a background, $p^* < p_{obs} = 2.9 \times 10^{-4}$

→ 3.4 σ significance of non-null observation

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

Thank you for your attention

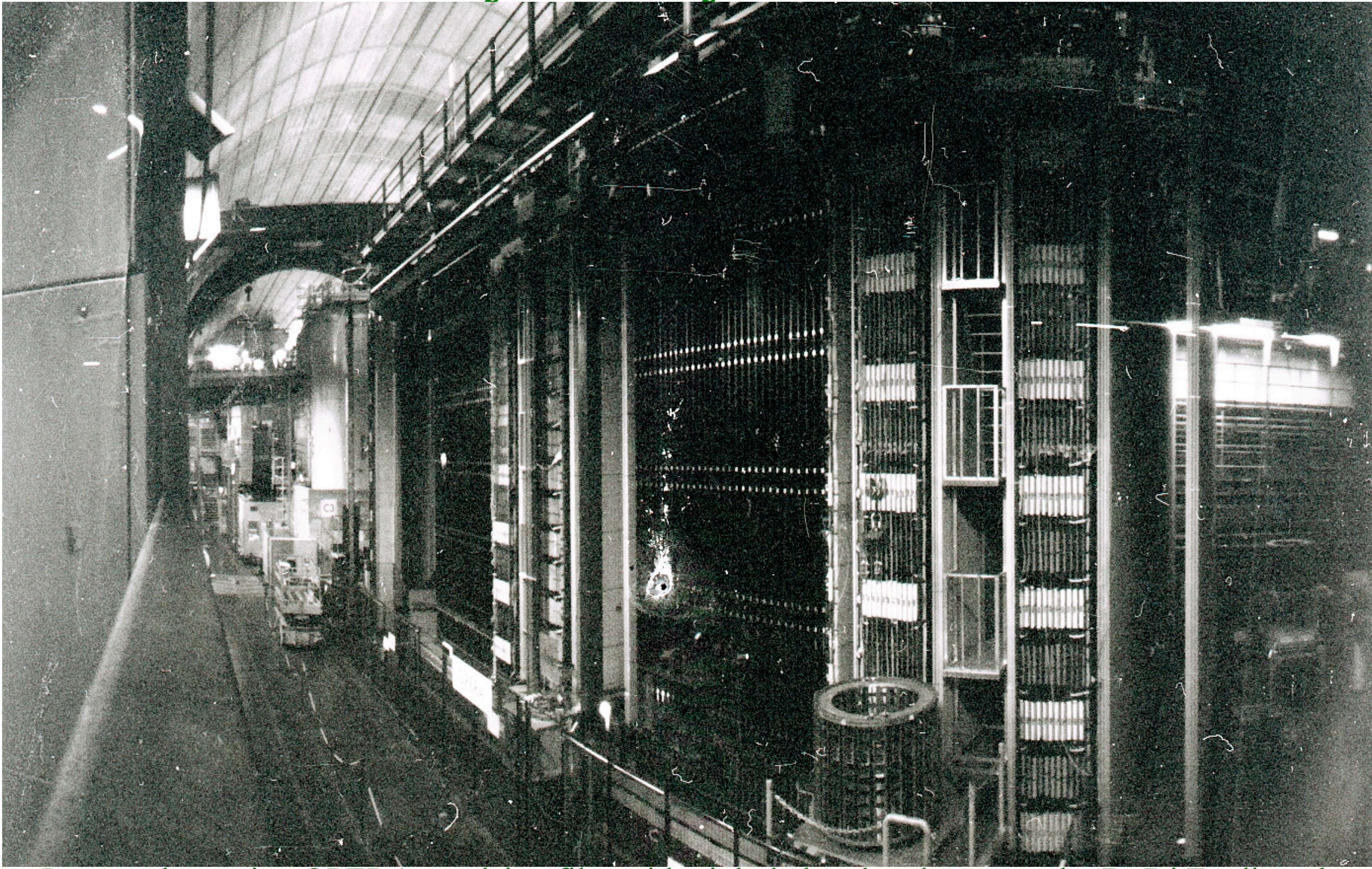


Image taken using OPERA emulsion film with pinhole handmade camera by D. Di Ferdinando