The OPERA experiment : new results

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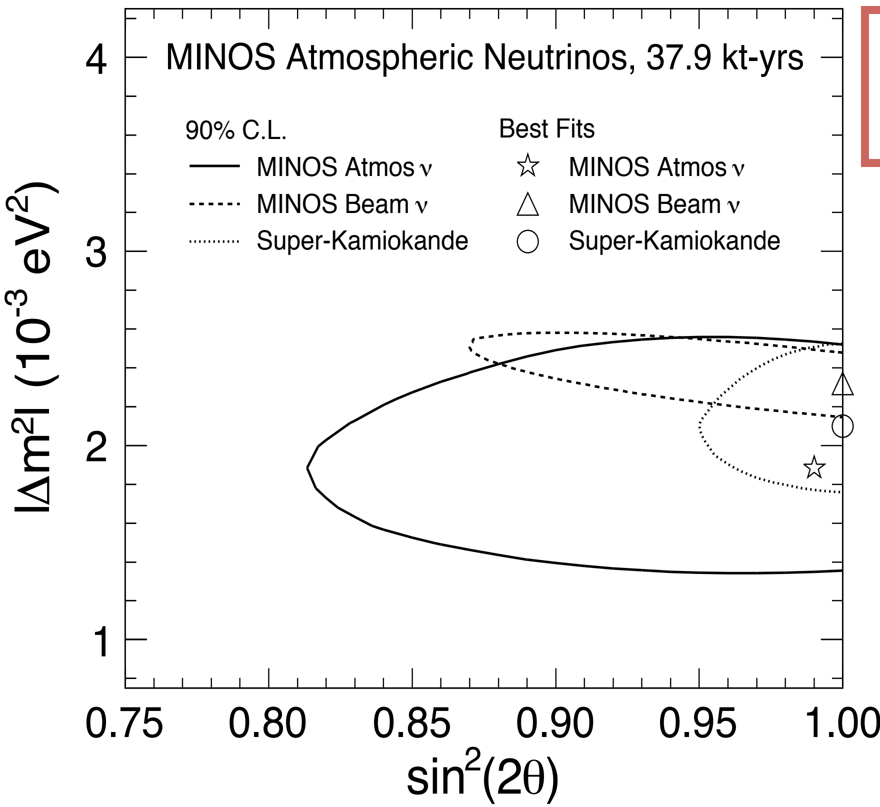
Vulcano Workshop 2014 – May 18-24 , Vulcano

Outline

- ✓ Introduction
- ✓ The *OPERA Detector*
- ✓ Data Analysis
- ✓ OPERA latest news …

Physics motivation

- Super-K (1998), MACRO and Soudan-2 : atmospheric neutrino anomaly interpretable as ν_μ->ν_τ oscillation
- K2K and MINOS (accelerator): confirmation of the Super –K ν_μ disappearance signal

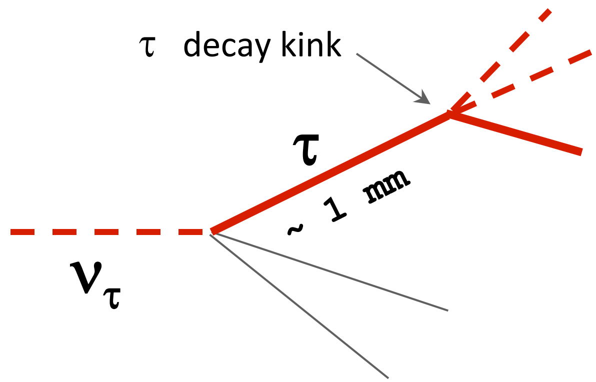


$$P(\nu_\mu \to \nu_\tau) \cong \sin^2(2\theta_{23})\cos^4(\theta_{13})\sin^2\left(\frac{1.27\Delta m^2_{32}L(\mathrm{Km})}{E(\mathrm{GeV})}\right)$$

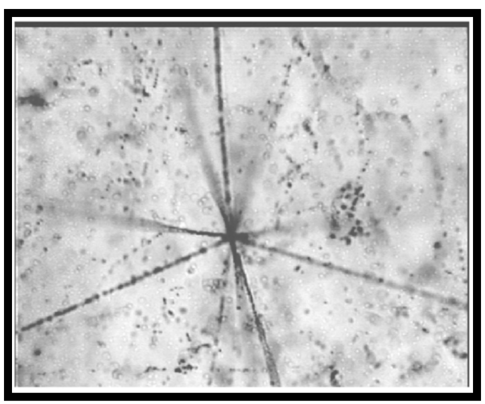
Opera was designed to confirm that the disappearance was because of an oscillation phenomena.

Challenge

Detection of ν_τ CC interaction by a full reconstruction of the primary interaction and observation of the t lepton decay topologies.



$\tau^- \rightarrow \mu^- \; \nu_\tau \, \nu_\mu$	17.4%
$\tau^- \rightarrow e^- \; \nu_\tau \, \nu_\varepsilon$	17.8%
$\tau^- \rightarrow h^- \; \nu_\tau \; n(\pi^o)$	49.5%
$\tau^- \rightarrow \pi^+ \pi^- \pi^- \; \nu_\tau \; n(\pi^o)$	14.5%



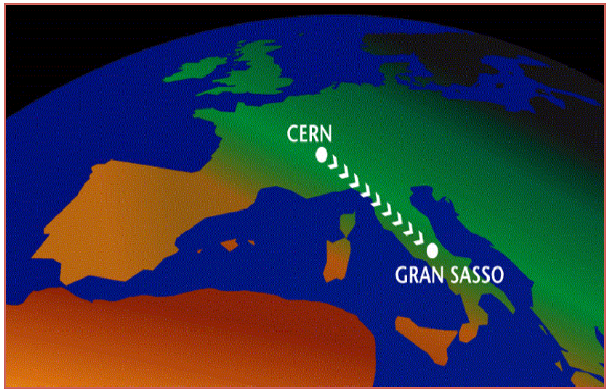
<u>Nuclear emulsions + Lead (ECC) "active target"</u>

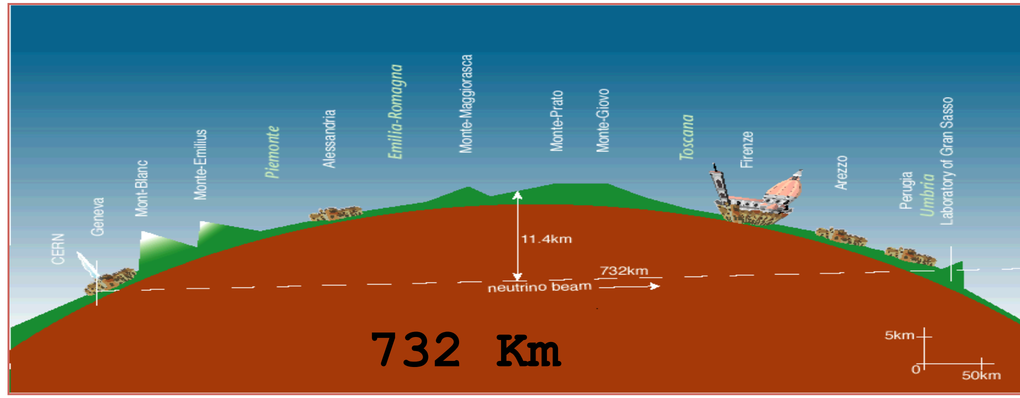
- 3D particle reconstruction
- Sub-micron spatial resolution

High background rejection

Oscillation Project with Emulsion tRacking Apparatus

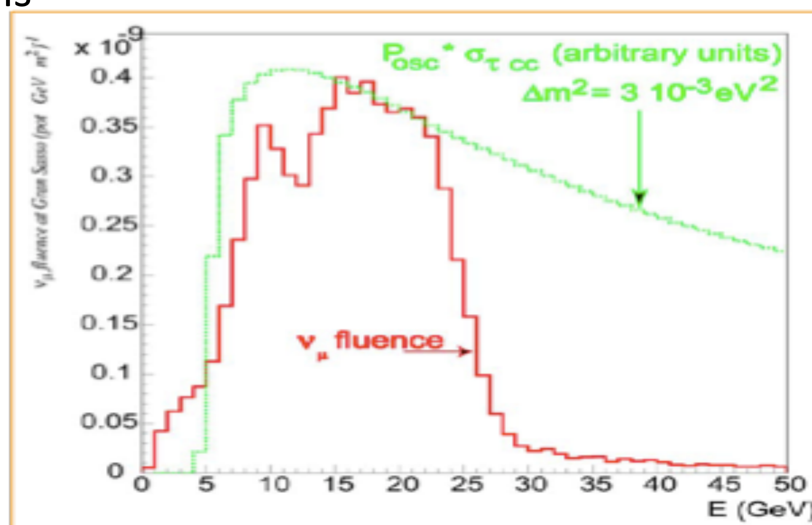
OPERA



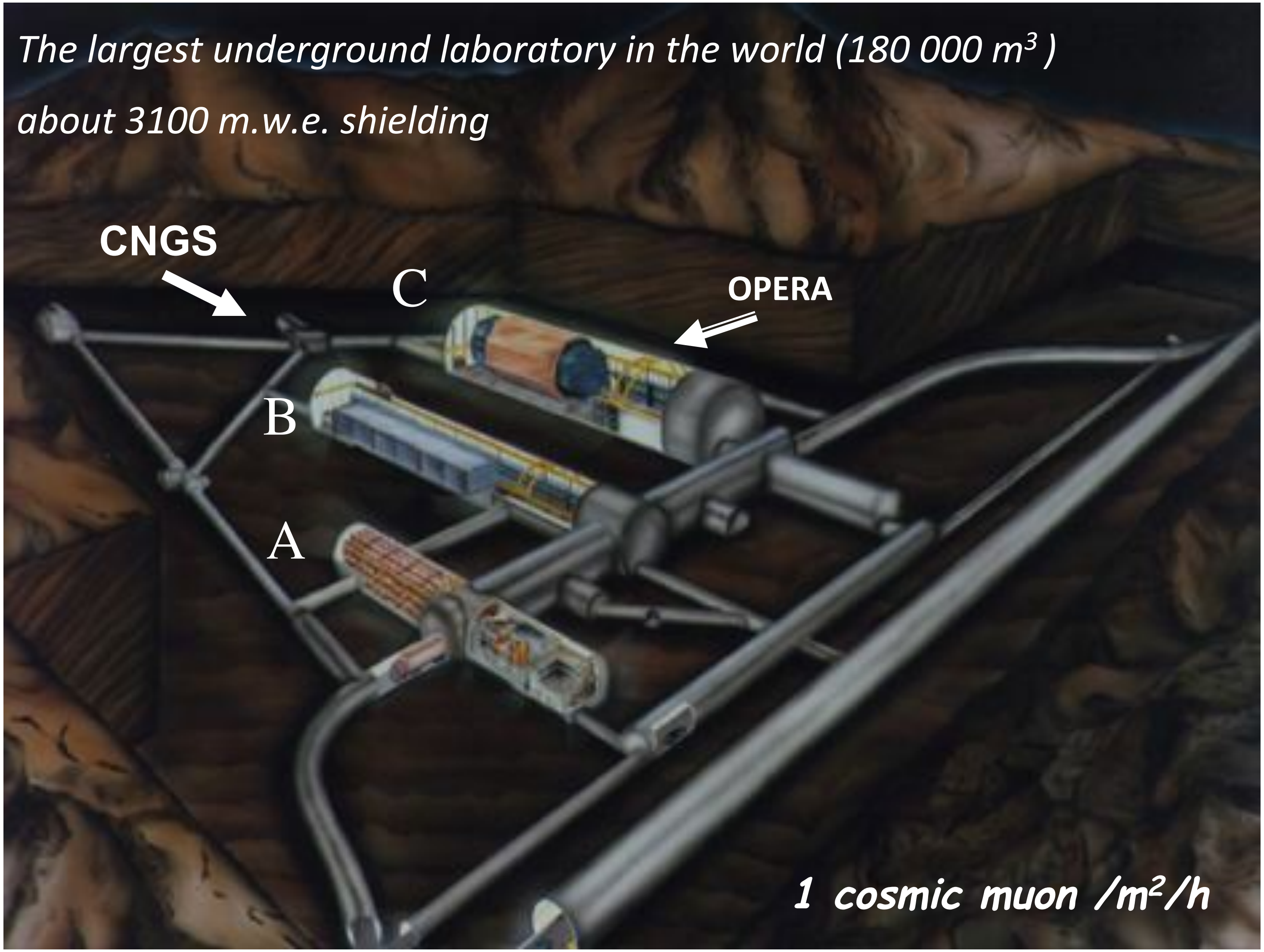


- Long baseline neutrino physics experiment
- ***CNGS*** quasi – pure wide band ν_μ beam, <L> = 732 km, <E> = 17 GeV optimized to maximize the number of ν_τ CC interactions

ν_μ(CC + NC)/year	~4700
ν_τ CC/year	~20
$(\nu_e + \bar{\nu}_e)/\ \nu_\mu$ CC	0.87%
$\bar{\nu}_\mu\ /\ \nu_\mu$ CC	2.1%
ν_τ prompt	negligible



LNGS – Gran Sasso National Lab



The OPERA Collaboration

140 physicists - 28 institutions - 11 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg

Germany
Hamburg

Israel
Technion Haifa

Italy
Bari
Bologna
LNF Frascati
LNGS
Naples
Padova
Rome
Salerno

Japan
Aichi
Toho
Kobe
Nagoya
Nihon

Korea
Jinju

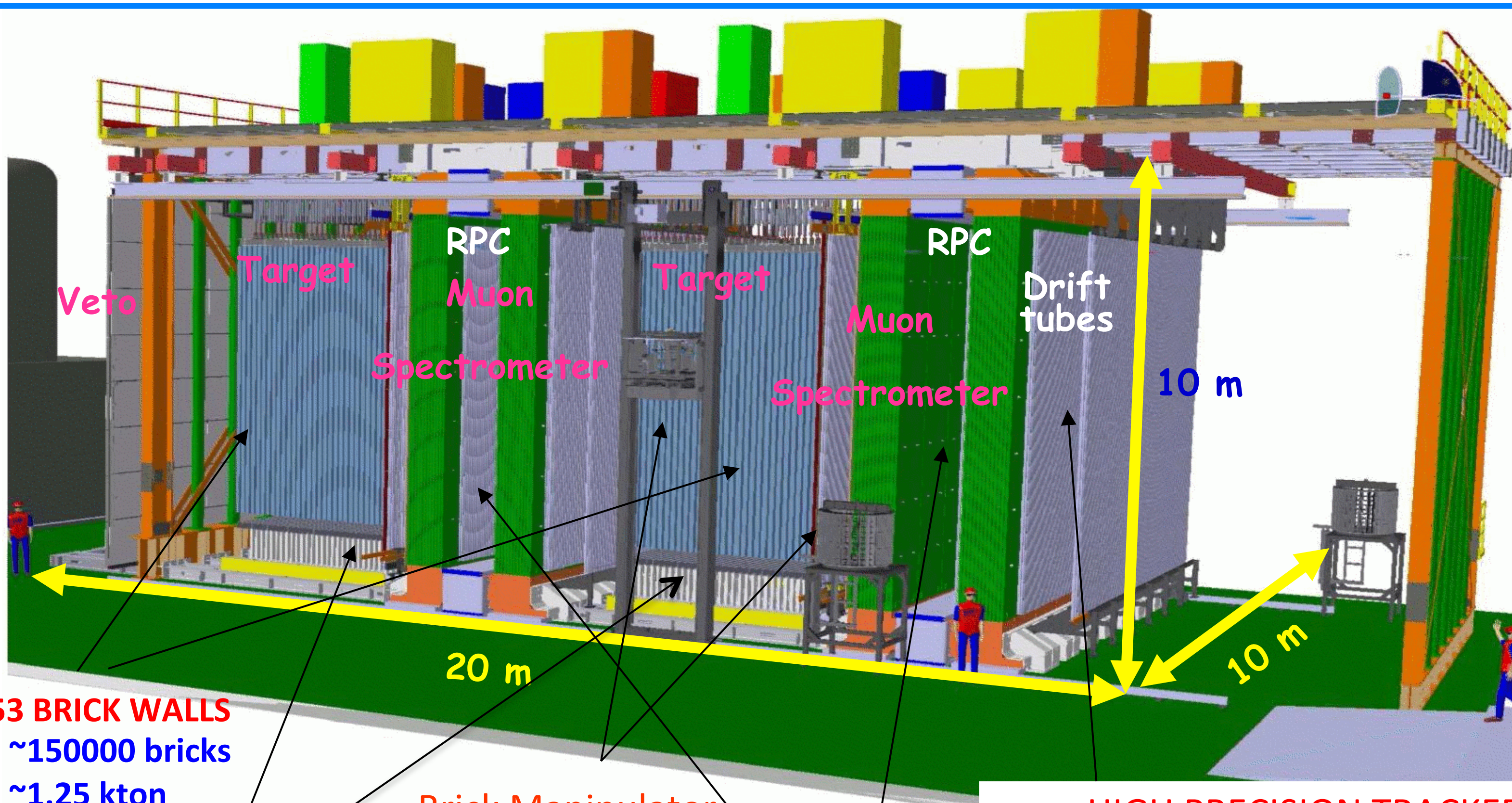
Russia
INR RAS Moscow
LPI RAS Moscow
SINP MSU Moscow
JINR Dubna

Switzerland
Bern

Turkey
METU Ankara

http://operaweb.lngs.infn.it

OPERA detector



53 BRICK WALLS
- **~150000 bricks**
- **~1.25 kton**

Brick Manipulator System

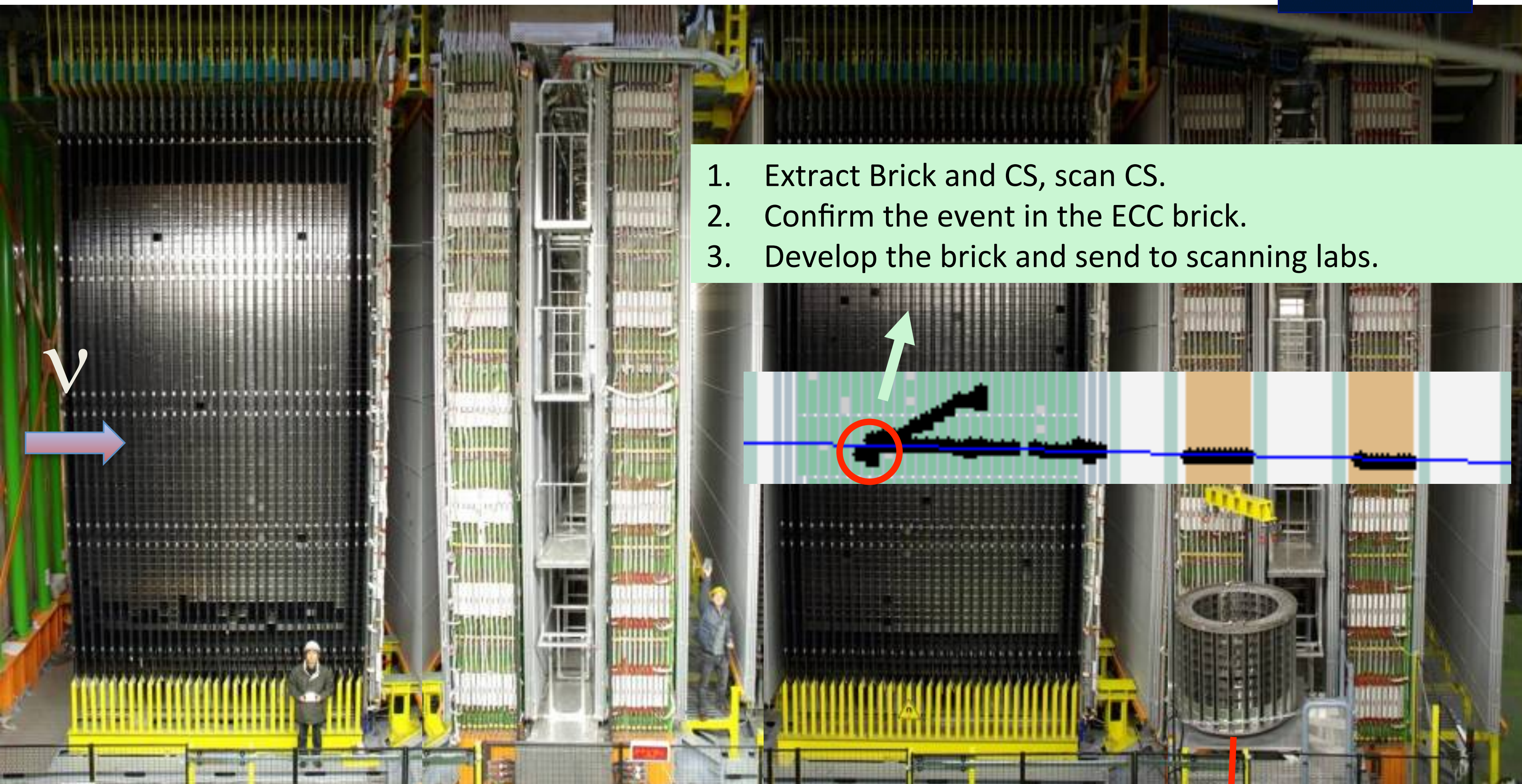
HIGH PRECISION TRACKERS
- spatial resolution < 0.5 mm

TARGET TRACKERS
- Trigger task
- Brick identification
- 2 x 31 scintillating strip walls read by PMT
- 0.8 cm resolution

INNER TRACKERS
- 990-ton dipole magnets (B = 1.55 T)
- RPC resolution ~1.3 cm

(Ref. JINST 4 (2009) P04018)

SM1 SM2



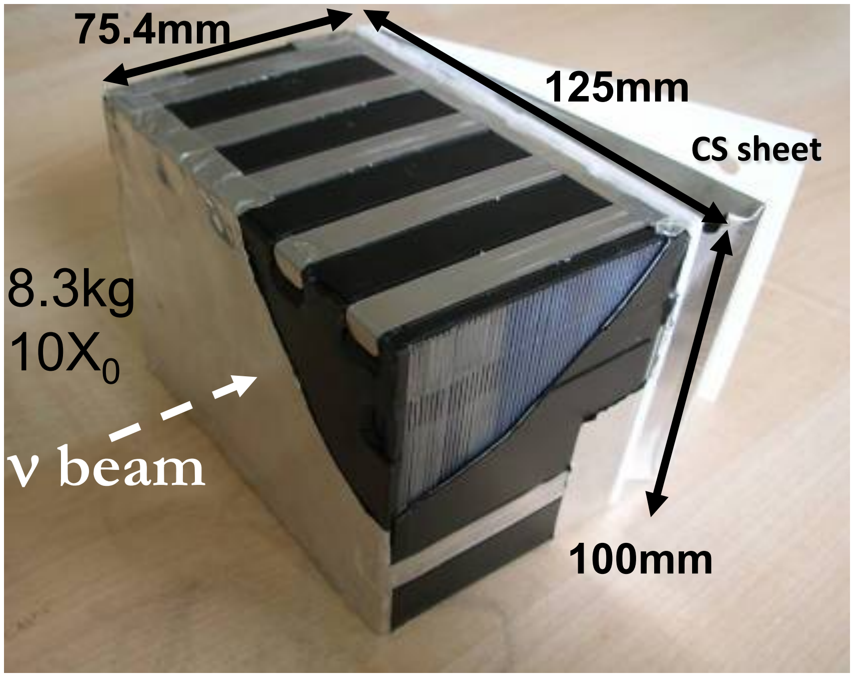
Target area

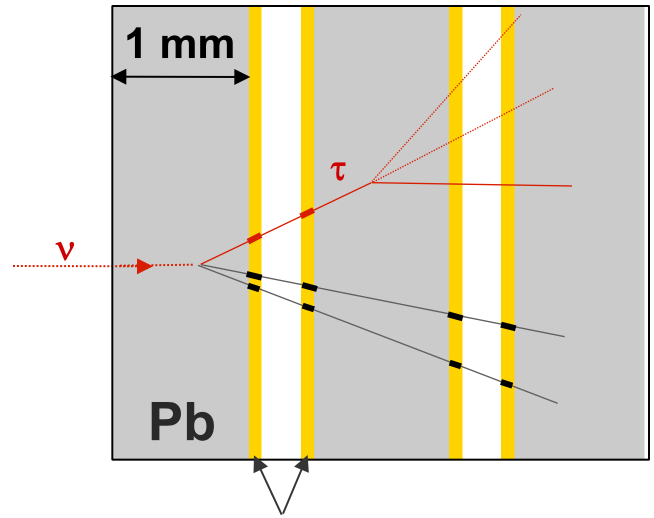
(ECC + CS + TT)

Muon spectrometer (Magnet+RPC+PT)

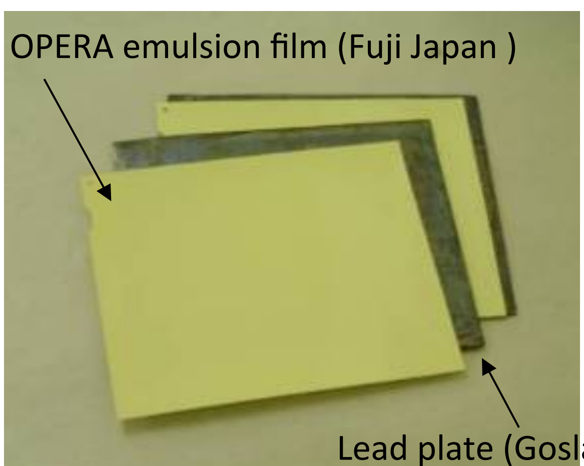
Brick Manipulator System

ECC target brick





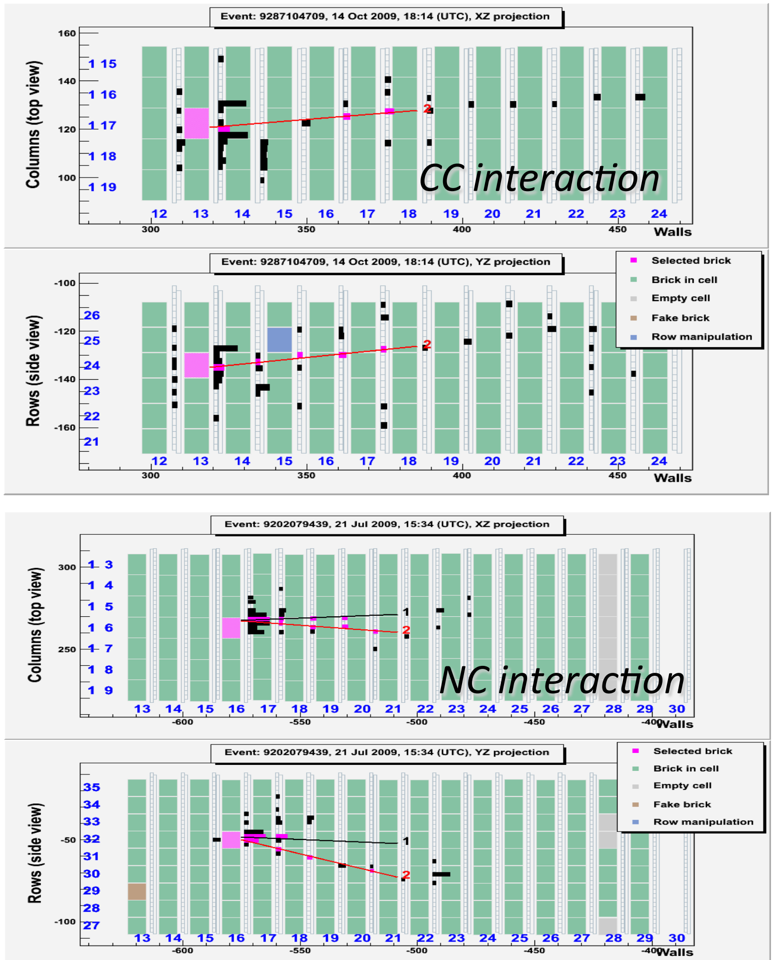
2 emulsion layers (42 μm thick)
poured on a 200 μm plastic base



57 emulsion films + 2 CS interface sheet *Ref: **NIM A556 (2006) 80-86***

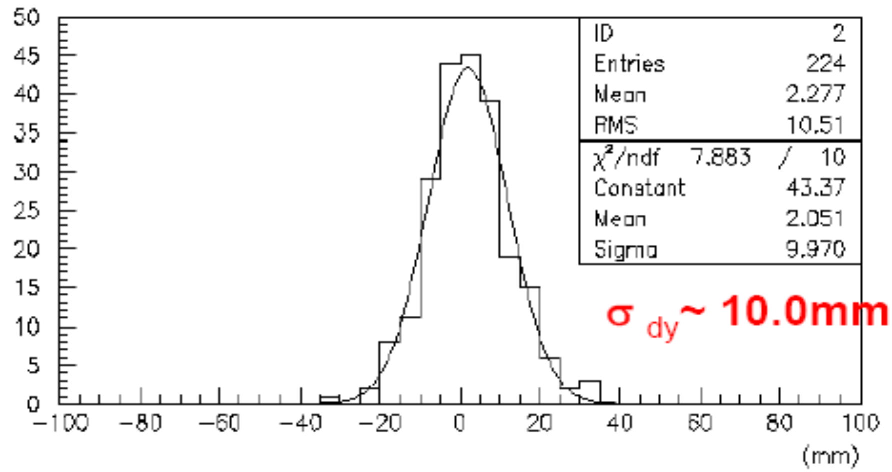
56 * 1 mm Pb (lead + 0.04 % Ca) plates *Ref: **JINST 3 P07002 (2008)***

CS interface sheet

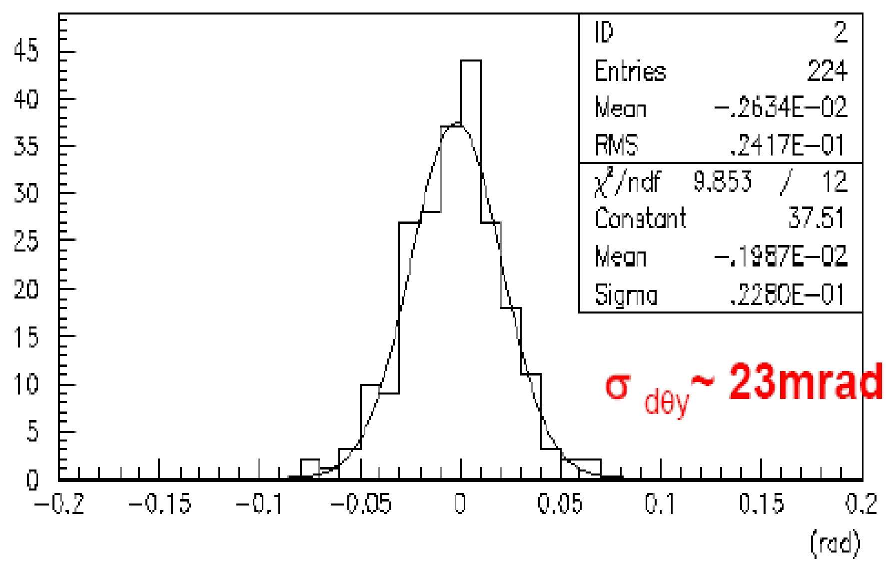


*Ref: **JINST 3 P07005 (2008)***

Interface emulsion films: high signal/noise ratio for event trigger and scanning time reduction



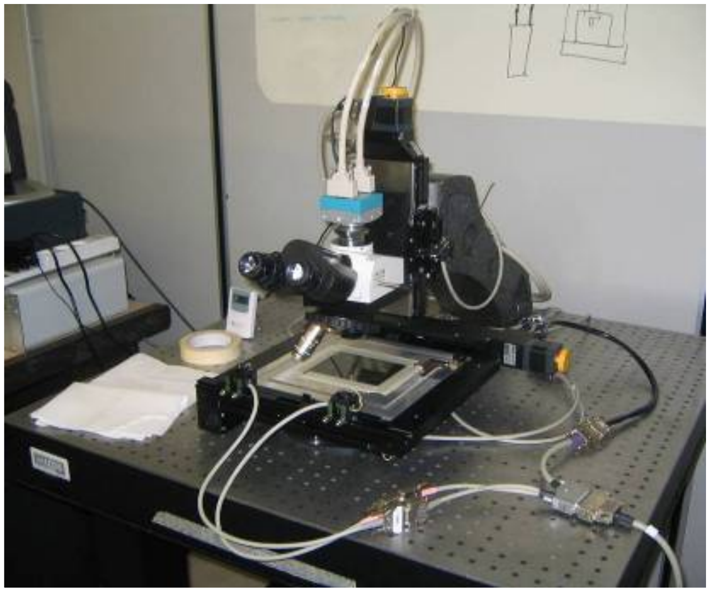
Position accuracy of the electronic predictions



Angular accuracy of the electronic predictions

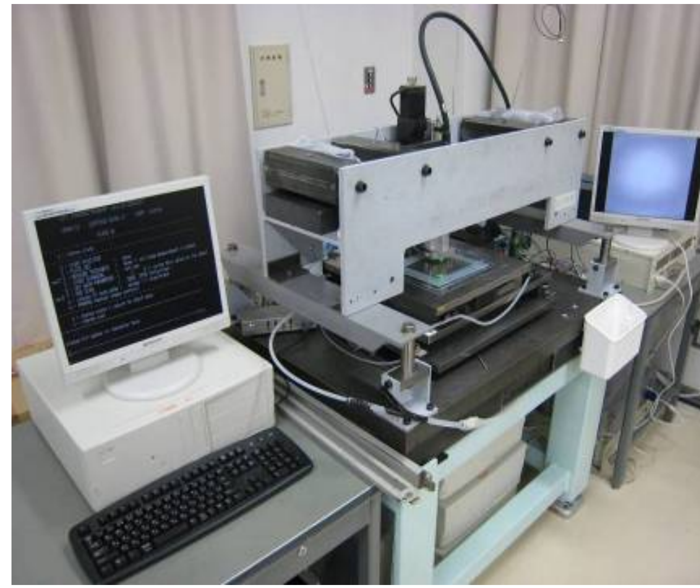
Emulsion films scanning

EU: ESS (European Scanning System)



- Scanning speed/system: 20cm^2/h
- Customized commercial optics and mechanics
- Asynchronous DAQ software

Japan: SUTS (Super Ultra Track Selector)



- Scanning speed/system: 75cm^2/h
- High speed CCD camera (3 kHz), Piezo-controlled objective lens
- FPGA Hard-coded algorithms

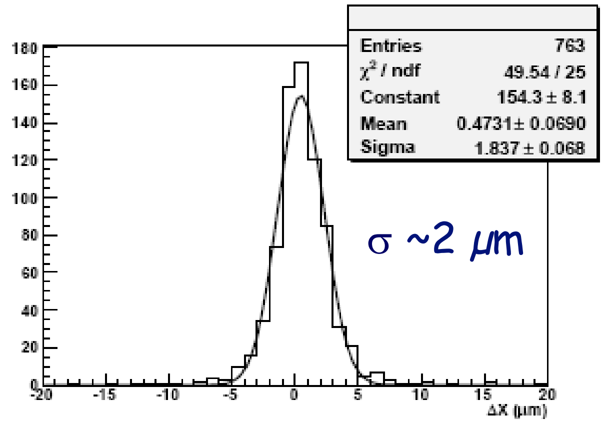
<u>Both systems demonstrate:</u>

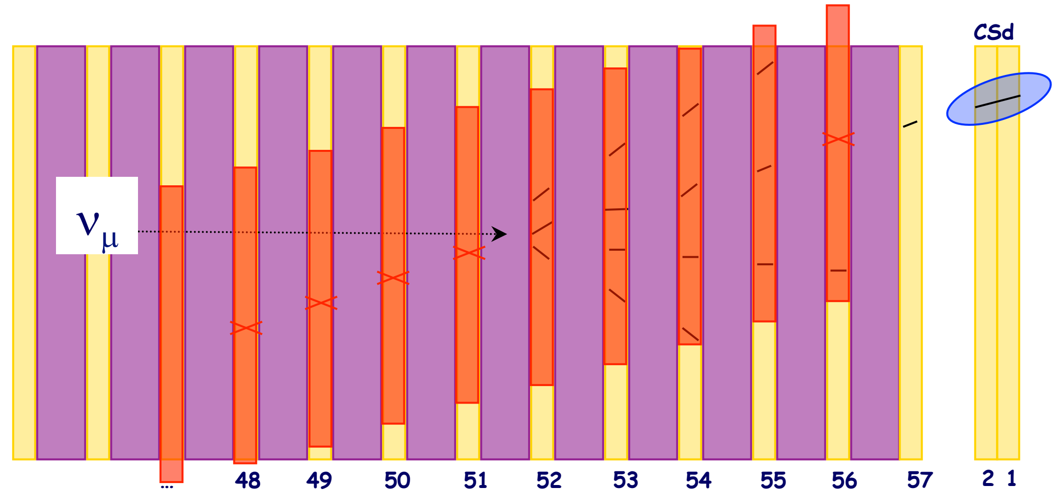
- ~ 0.3 μm spatial resolution
- ~ 2 mrad angular resolution
- ~ 95% base track detection efficiency

Vertex finding

Track follow-up film by film:

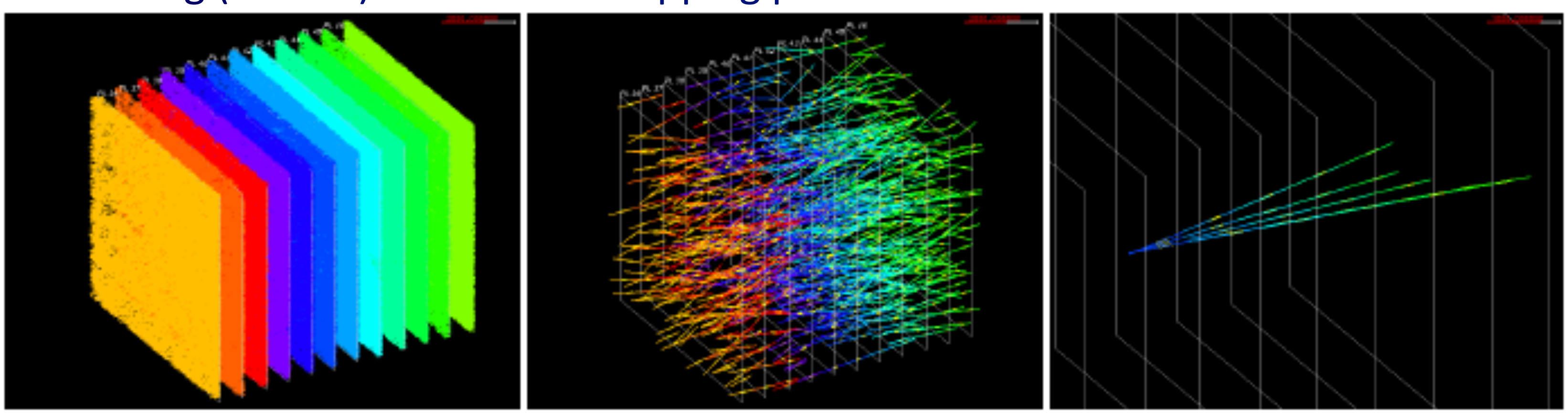
- alignment using cosmic ray tracks
- definition of the stopping point†



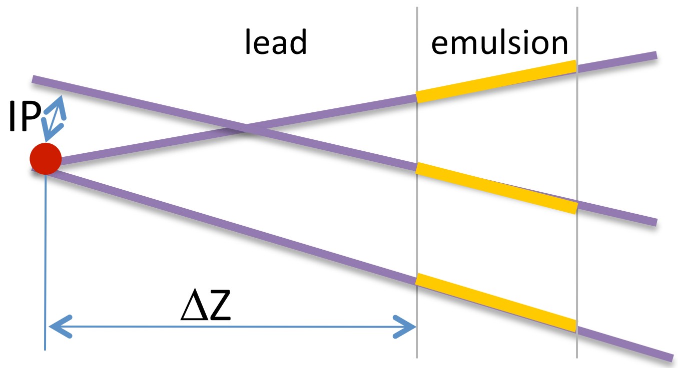


Ref. JINST 4 (2009) P06020

Volume scanning (~2 cm^3) around the stopping point



Decay search

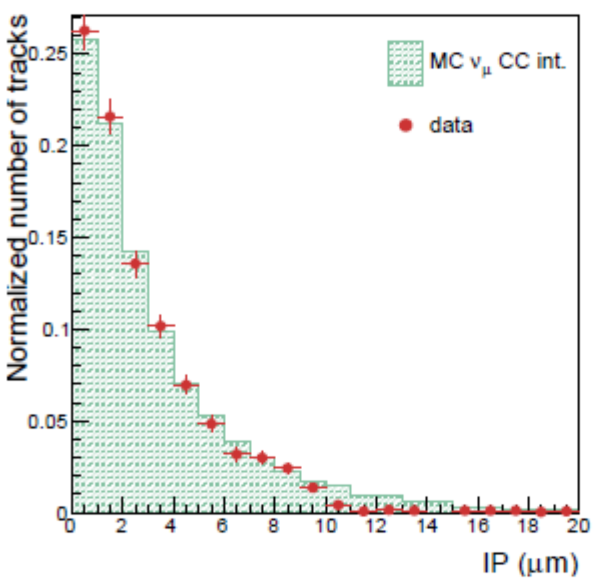


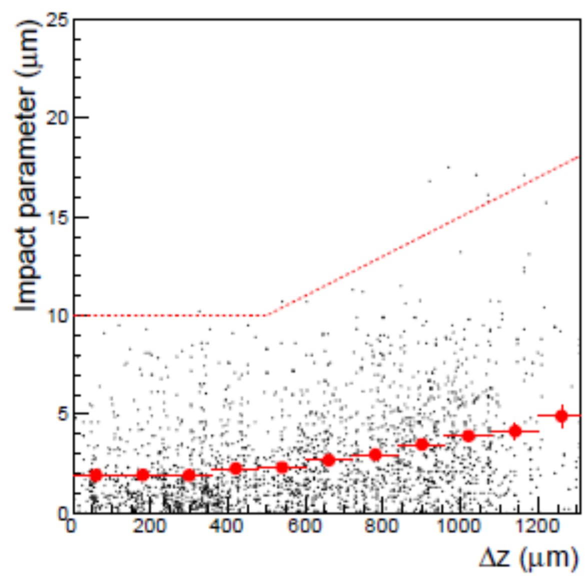
The IP evaluation is a crucial point in order to detect decay topologies

Each track is attached to the primary vertex only if

IP < 10 μm ΔZ < 500 μm

IP < 5 + 0.01 *ΔZ μm ΔZ > 500 μm



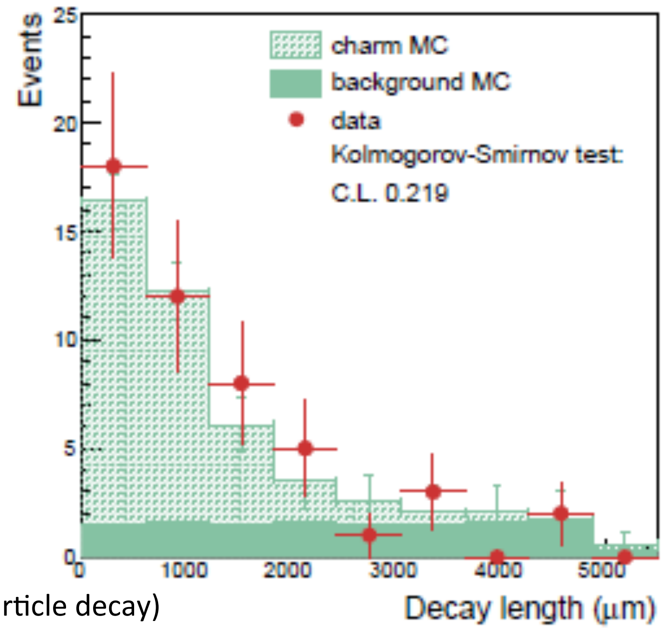


IP of the tracks attached to the neutrino vertices found

Charmed hadrons decay

The charmed hadrons decay has a simar topology to the tau lepton but the muon identified at the primary vertex, the charm sample was used as a «control sample».

	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**



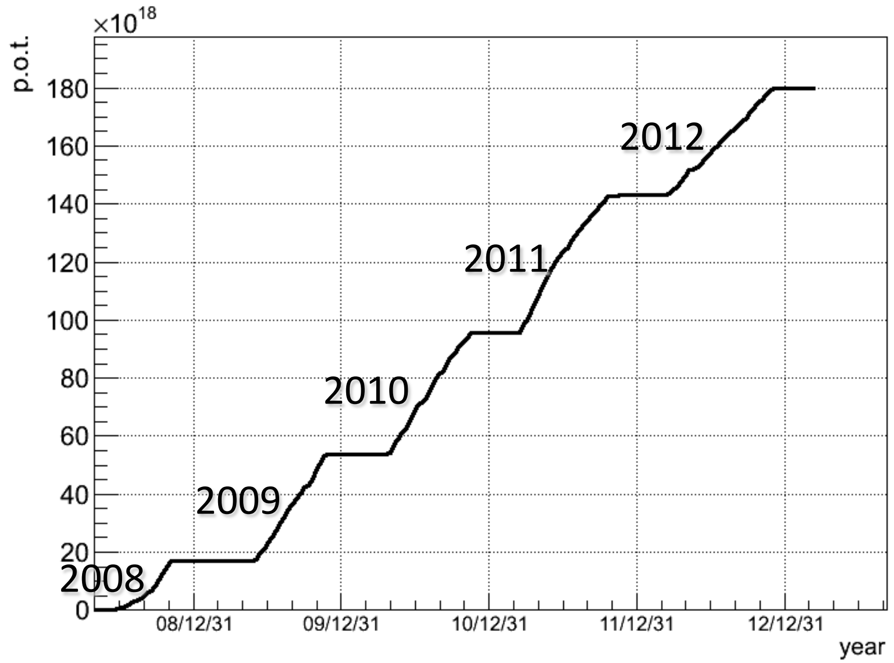
Background, mostly from hadronic interactions (contribution from strange particle decay)

arXiv:1404.4357 [hep-ex]

Data analysis

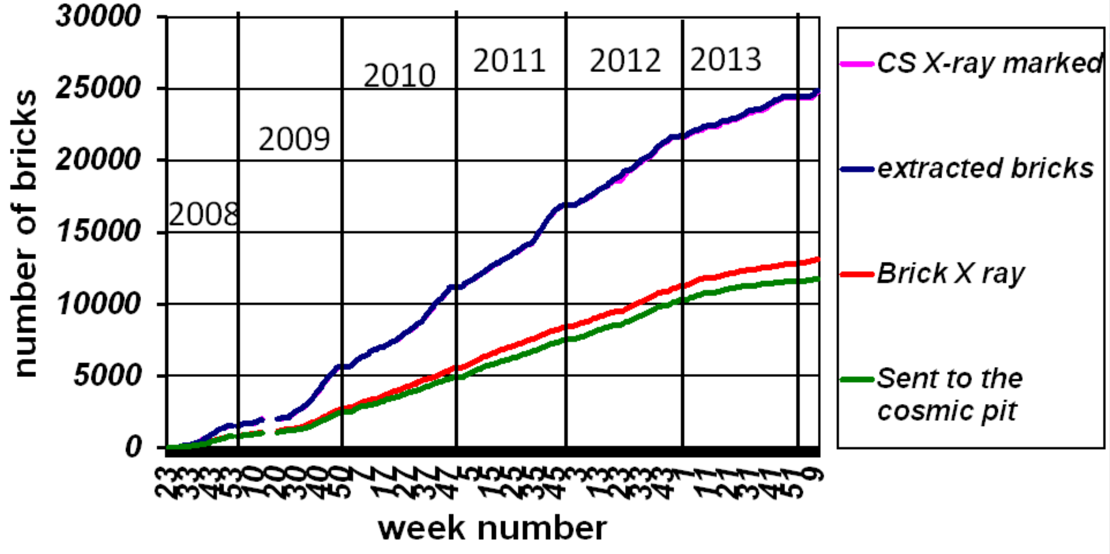
Final performances of the CNGS beam after five years (2008 ÷ 2012) of data taking

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**



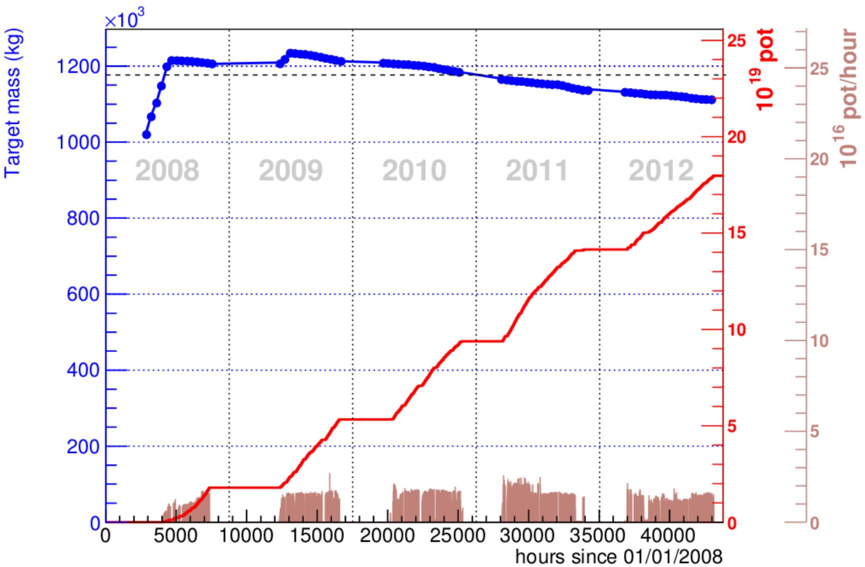
Record performances in 2011
Overall 20% less than the proposal value

OPERA brick handling

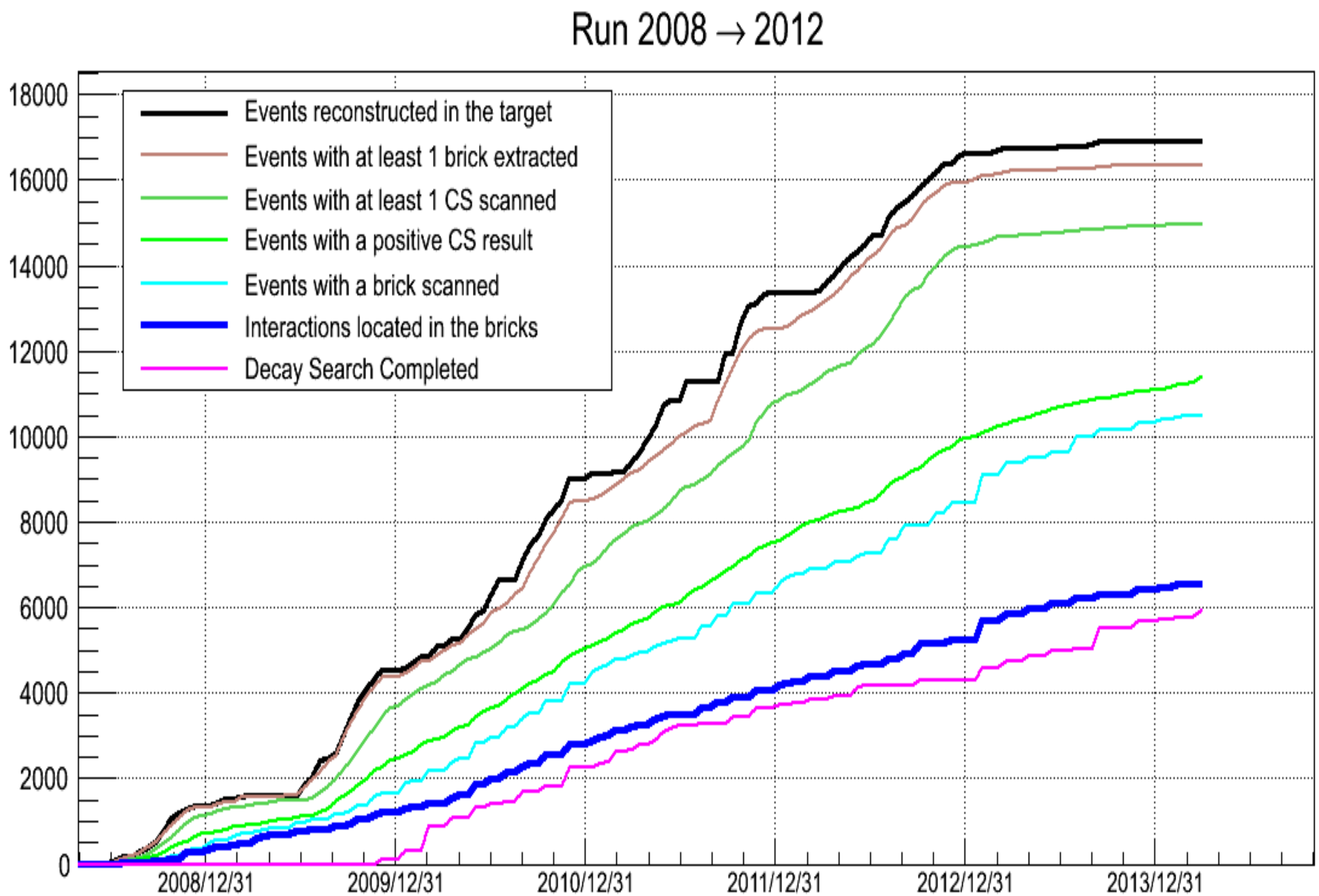


About 25000 bricks manipulated for event analysis, 12000 bricks developed

Average mass = 1.18 kton



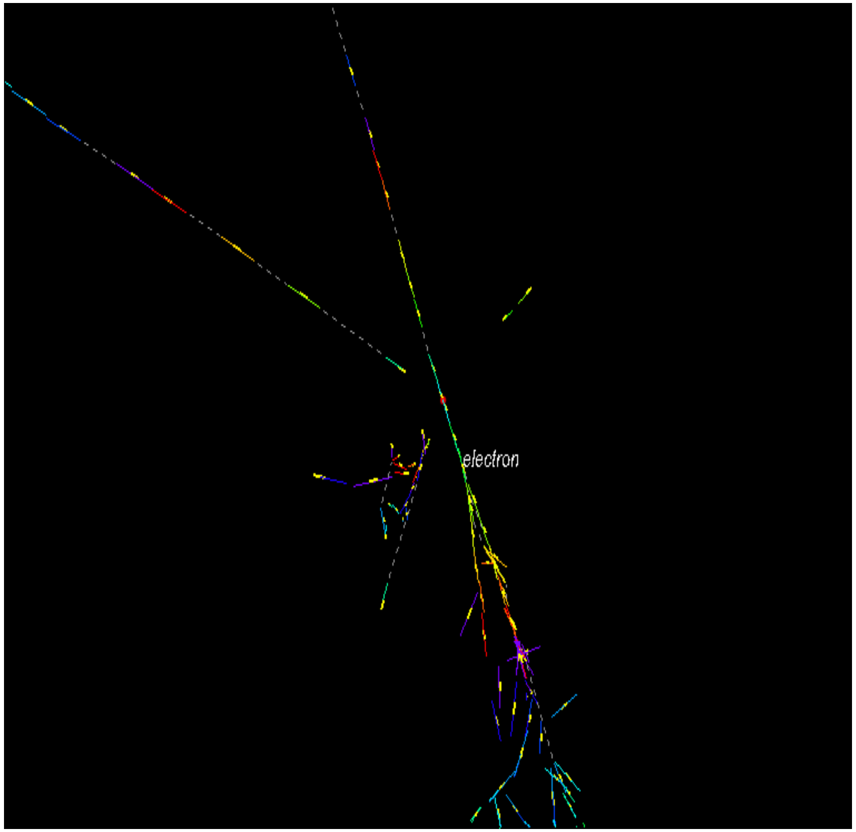
Data analysis



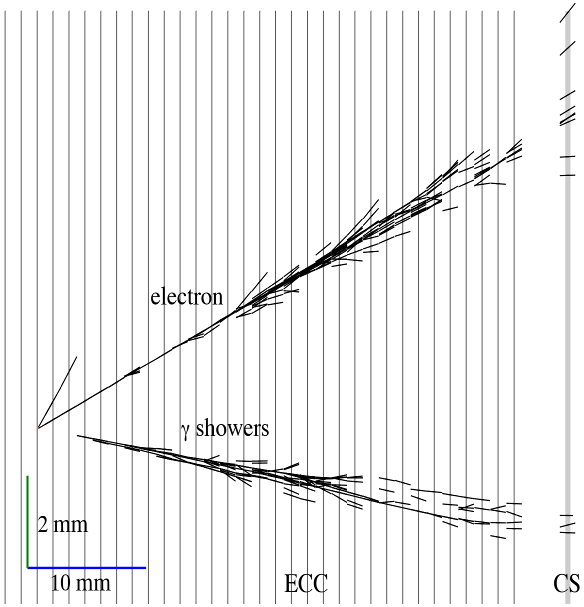
6520 located interactions

5917 decay search

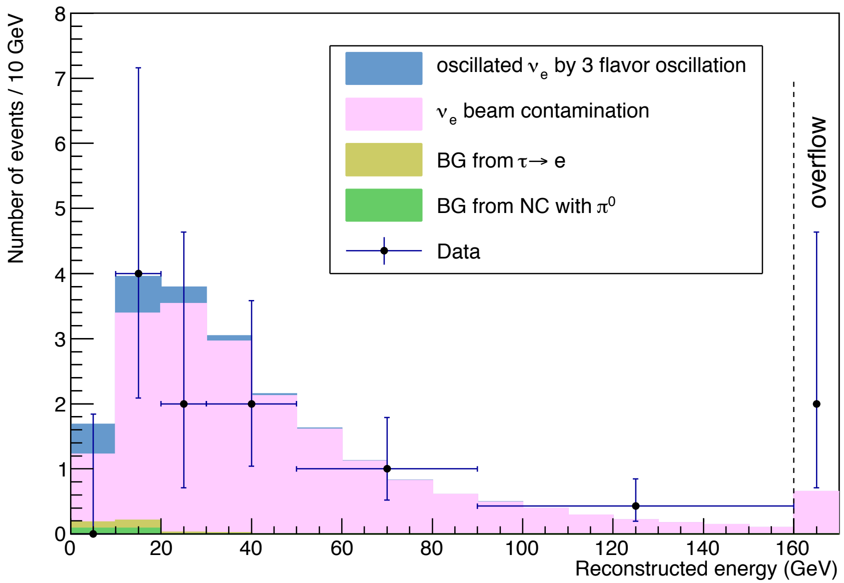
$\nu_\mu \rightarrow \nu_e$ analysis



4.1 GeV electron



≈ 40 events found in the analyzed sample



Energy distribution

Ref : ***JHEP 1307 (2013) 004***

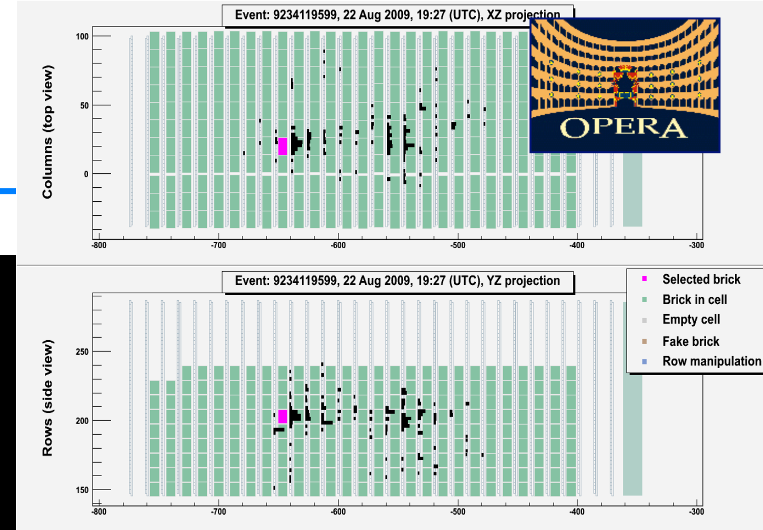
Energy cut		20 GeV	30 GeV	No cut
BG common to both analyses	BG (a) from π^0	0.2	0.2	0.2
	BG (b) from $\tau \to e$	0.2	0.3	0.3
	ν_e beam contamination	4.2	7.7	19.4
Total expected BG in 3-flavour oscillation analysis		4.6	8.2	19.8
BG to non-standard oscillation analysis only	ν_e via 3-flavour oscillation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

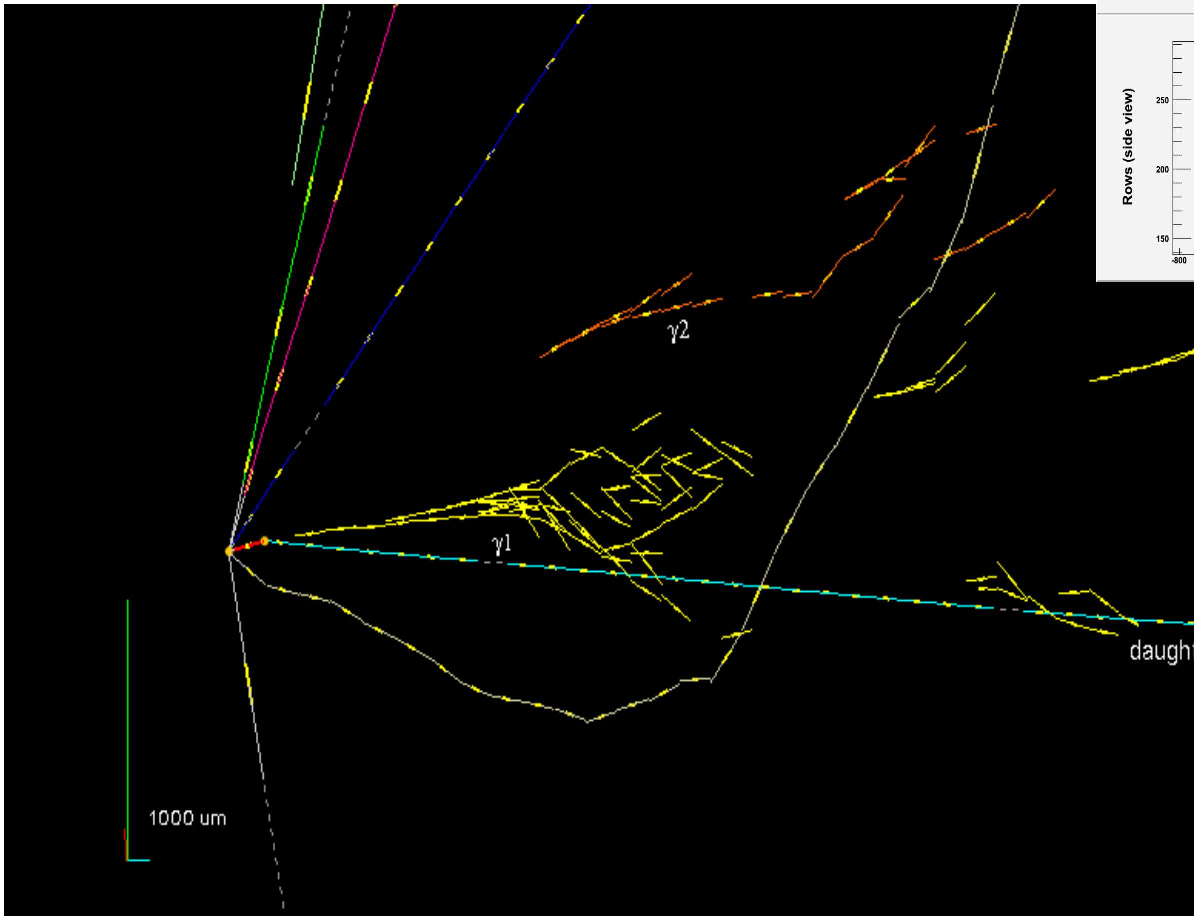
Observation compatible with background-only hypothesis: 19.8±2.8 (syst) events

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.

First ν_τ candidate



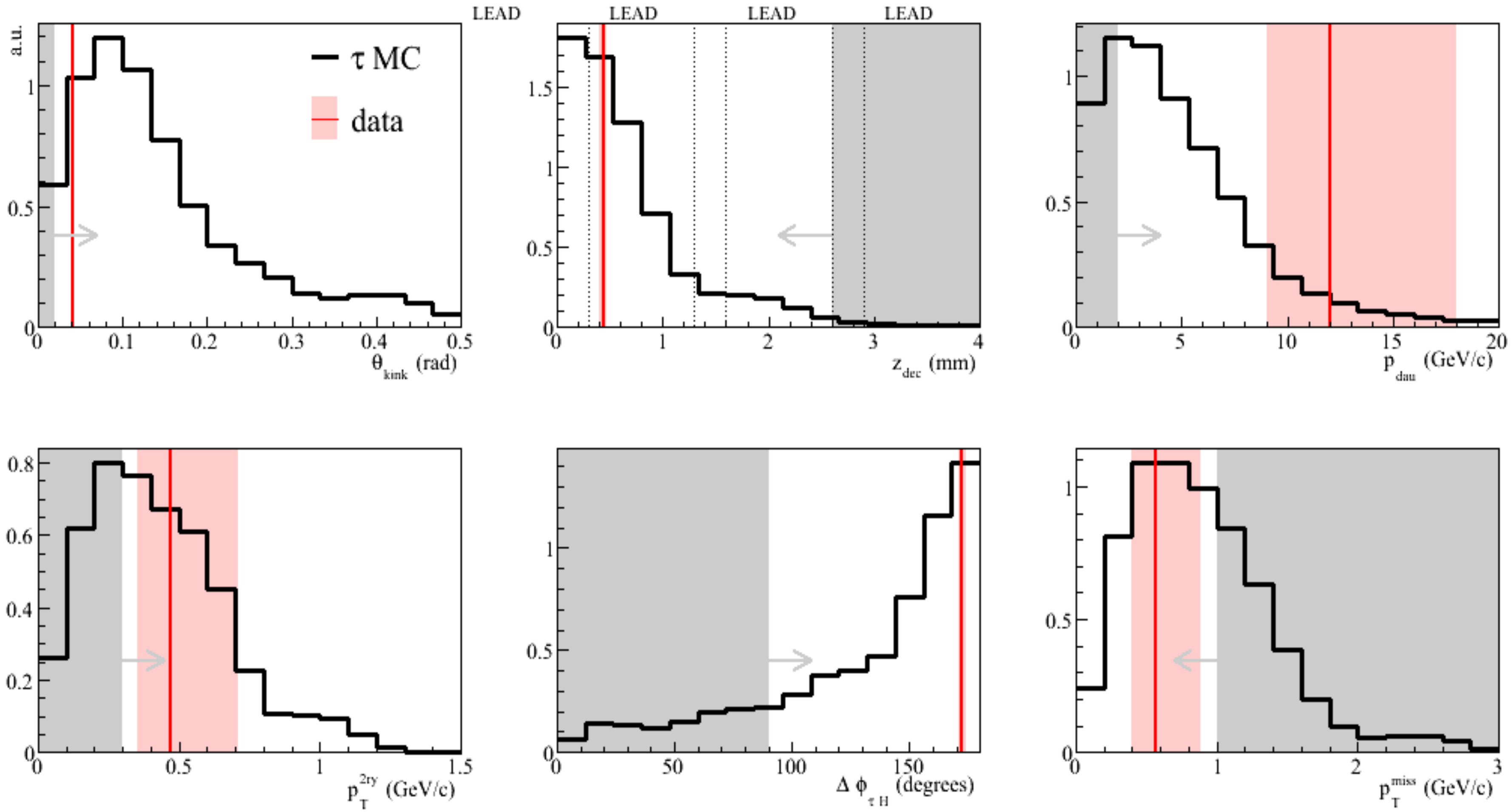


VARIABLE	AVERAGE
kink (mrad)	41 ± 2
decay length (μm)	1335 ± 35
P daughter (GeV/c)	12^{+6}_{-3}
Pt daughter (MeV/c)	470^{+230}_{-120}
missing Pt (MeV/c)	570^{+320}_{-170}
φ (deg)	173 ± 2

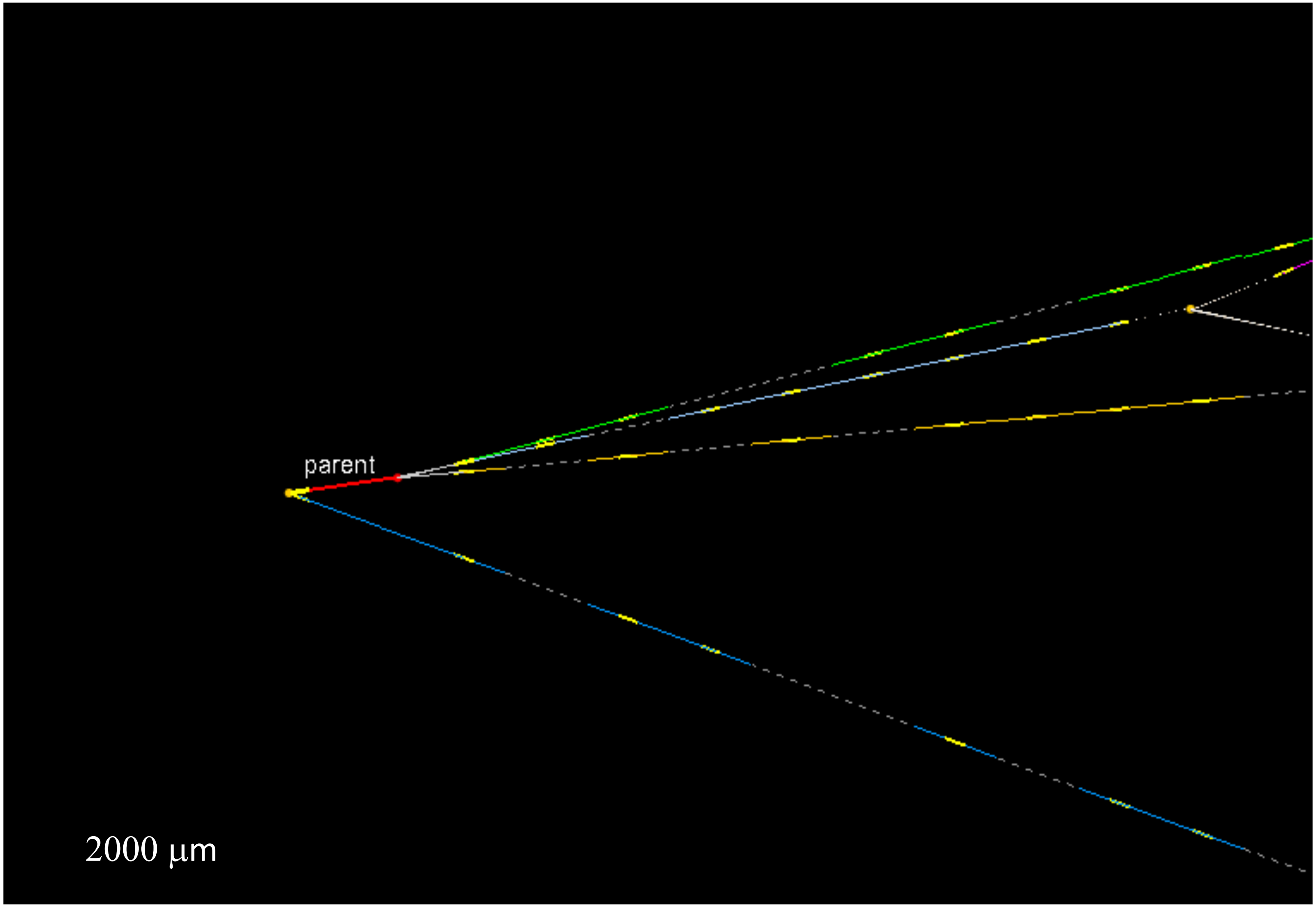
$\tau \rightarrow \rho\,(\pi^-\,\pi^0)\,\nu_\tau$

Ref :***Phys.Lett.B691:138-145 (2010)***

Kinematical cuts for a candidate event

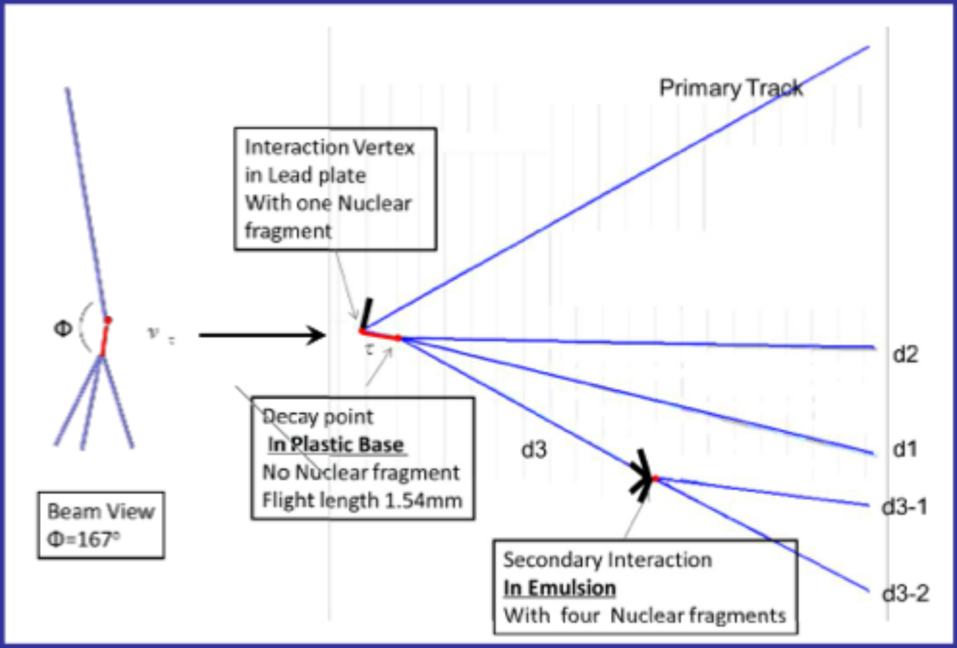


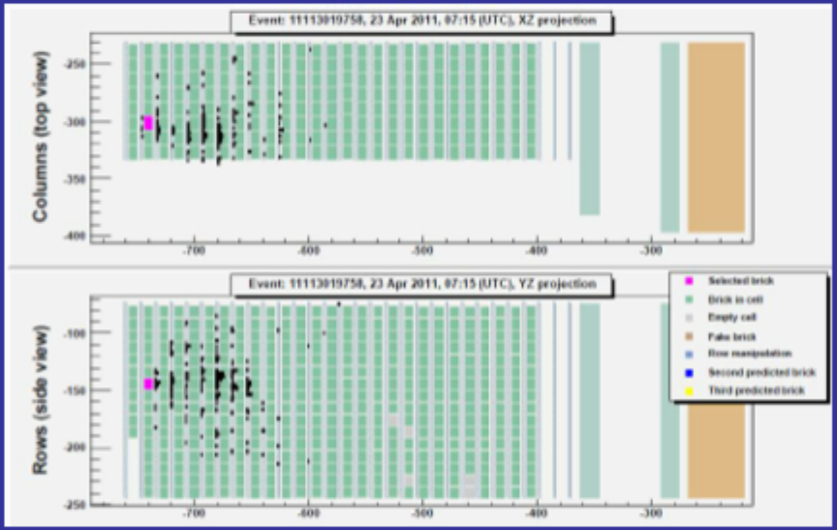
Second ν_τ candidate



$\nu_\mu \rightarrow \nu_\tau$ oscillation search

Ref: JHEP 11 (2013) 036





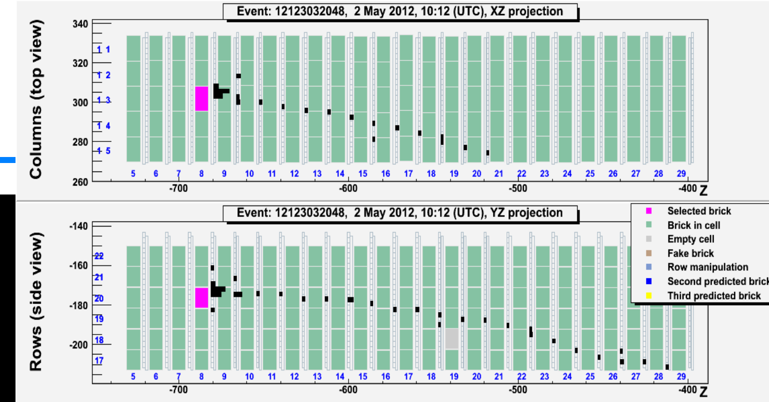
No muon detected at the primary vertex:

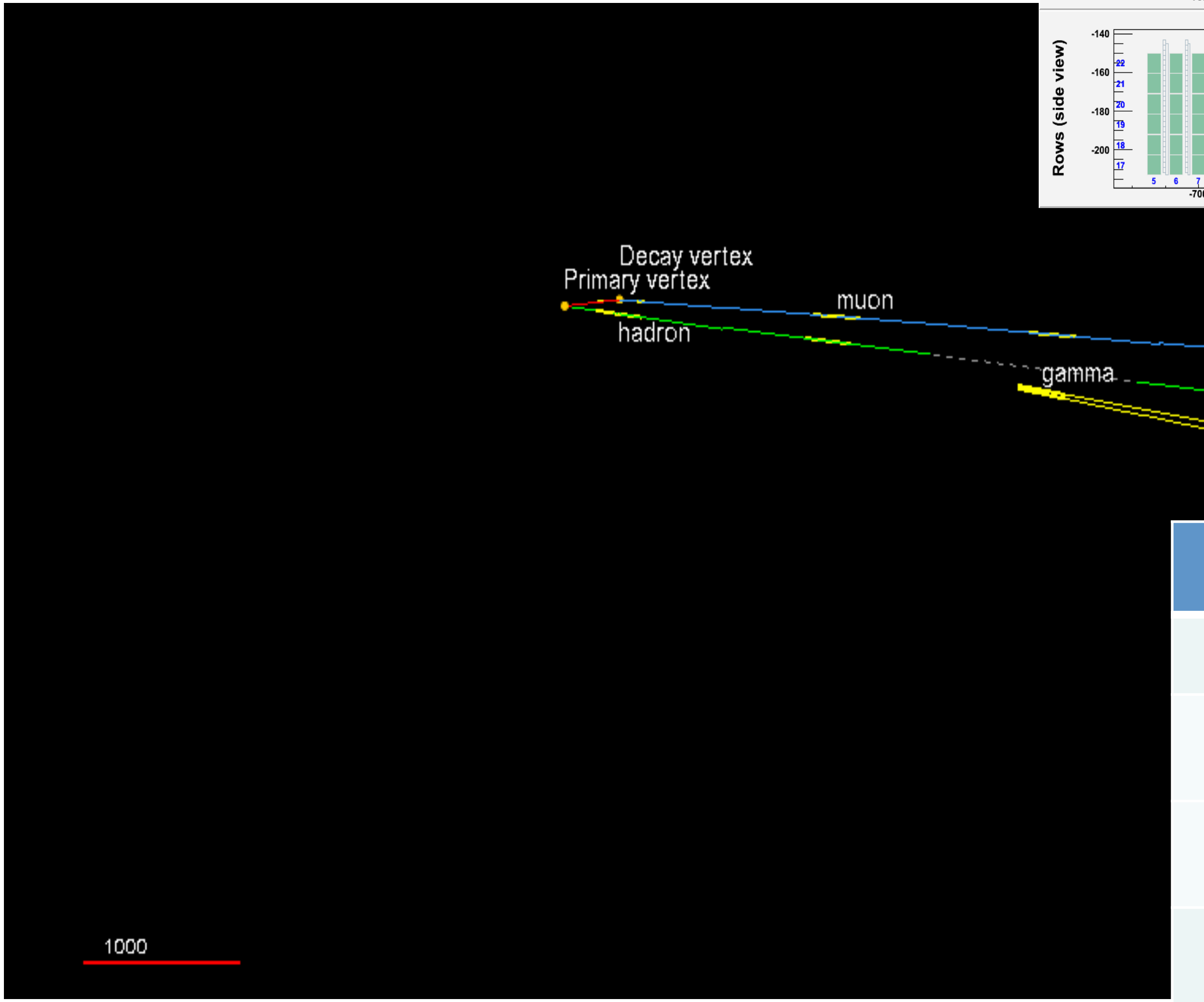
track other than τ lepton candidate not compatible with muon hypothesis based on momentum – range correlation

Event kinematics

	Cut	Value	Error
Phi (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/c²]	0.5 < < 2.0	0.96	± 0.13
Invariant mass [GeV/c²]	0.5 < < 2.0	0.80	± 0.12
Transverse Momentum at 1ry vtx [GeV/c]	< 1.0	0.31	± 0.11

Third ν_τ candidate





VARIABLE	AVERAGE
kink (mrad)	245 ± 5
decay length (μm)	376 ± 10
P daughter (GeV/c)	2.8 ± 0.2
Pt daughter (MeV/c)	690 ±50
φ (deg)	154.5 ± 1.5

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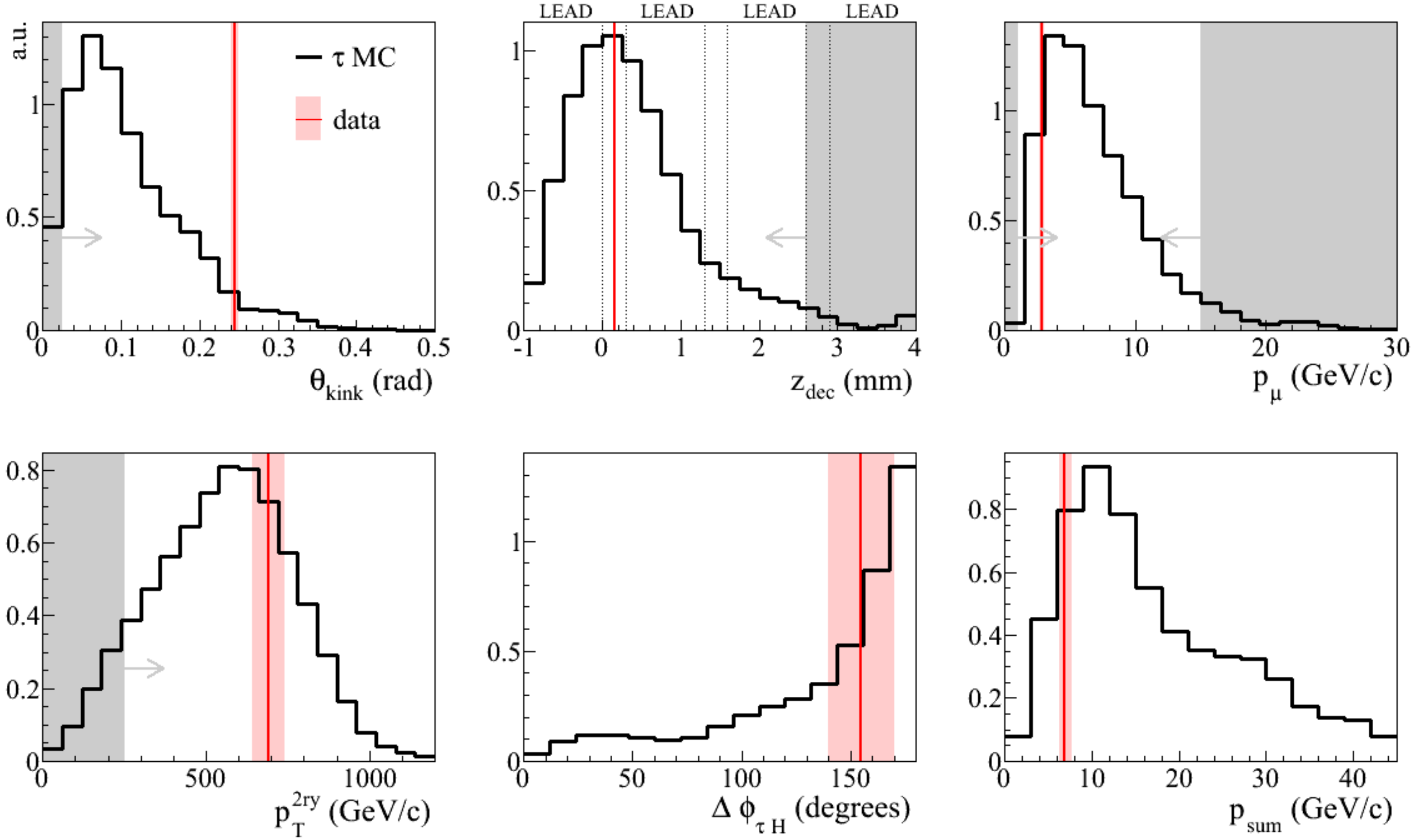
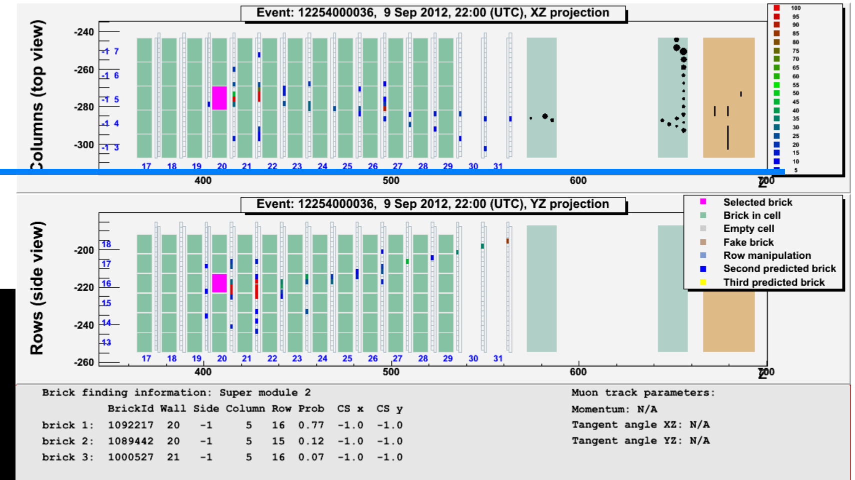
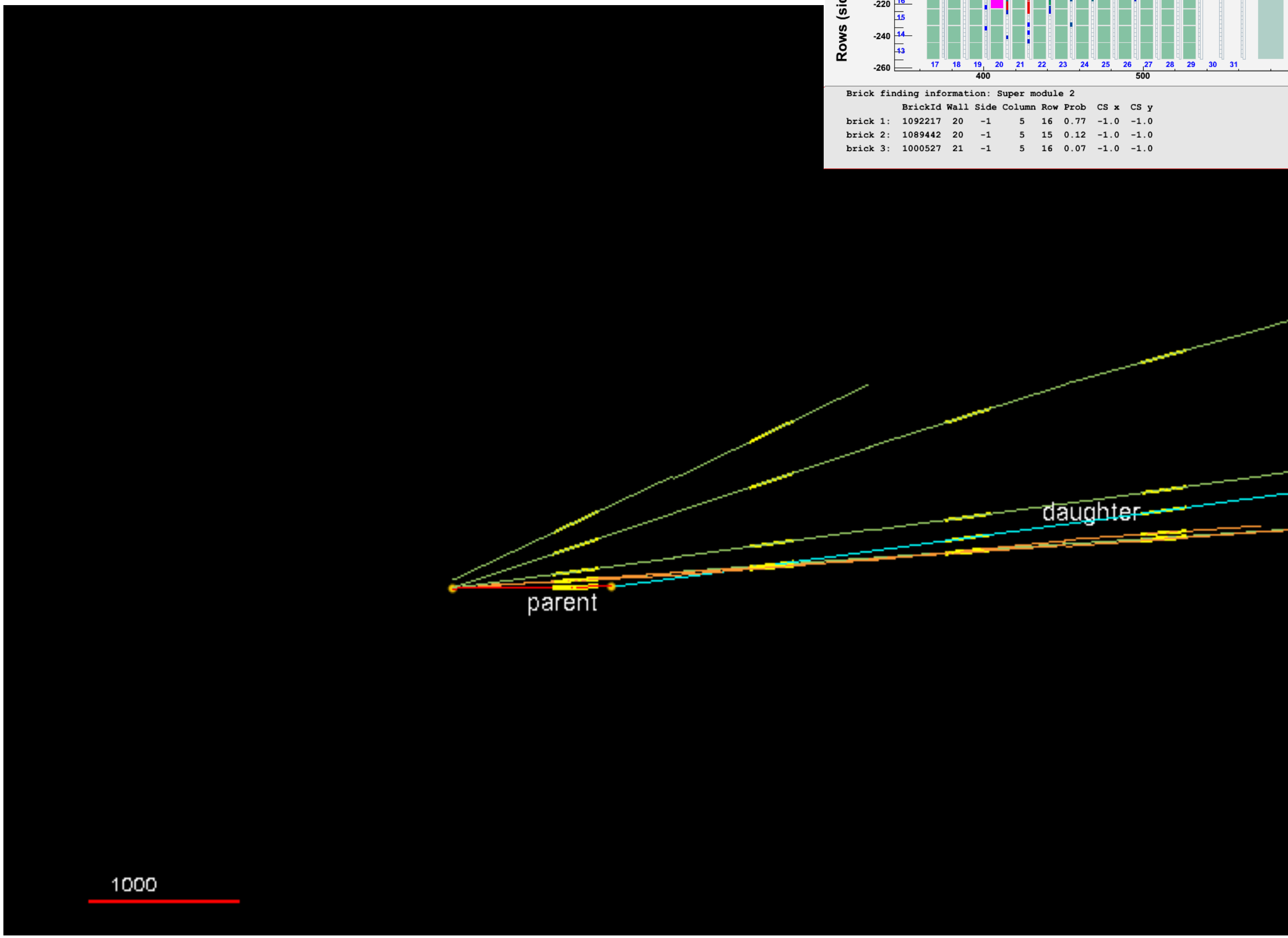
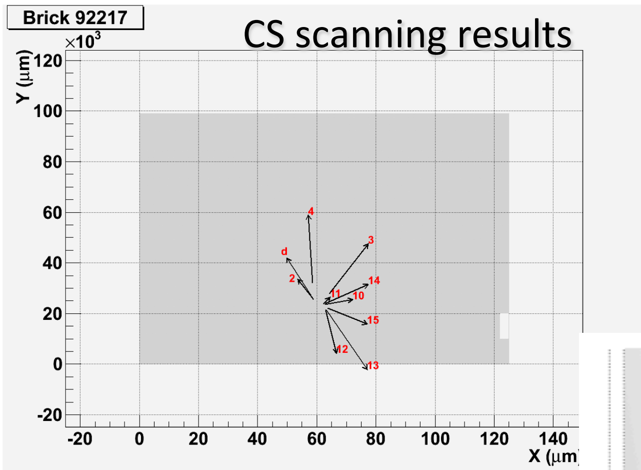

a.u.
τ MC
data
θ_{kink} (rad)
LEAD
LEAD
LEAD
LEAD
z_{dec} (mm)
p_{μ} (GeV/c)
p_T^{2ry} (GeV/c)
$\Delta\phi_{\tau H}$ (degrees)
p_{sum} (GeV/c)

NEW ν_τ candidate

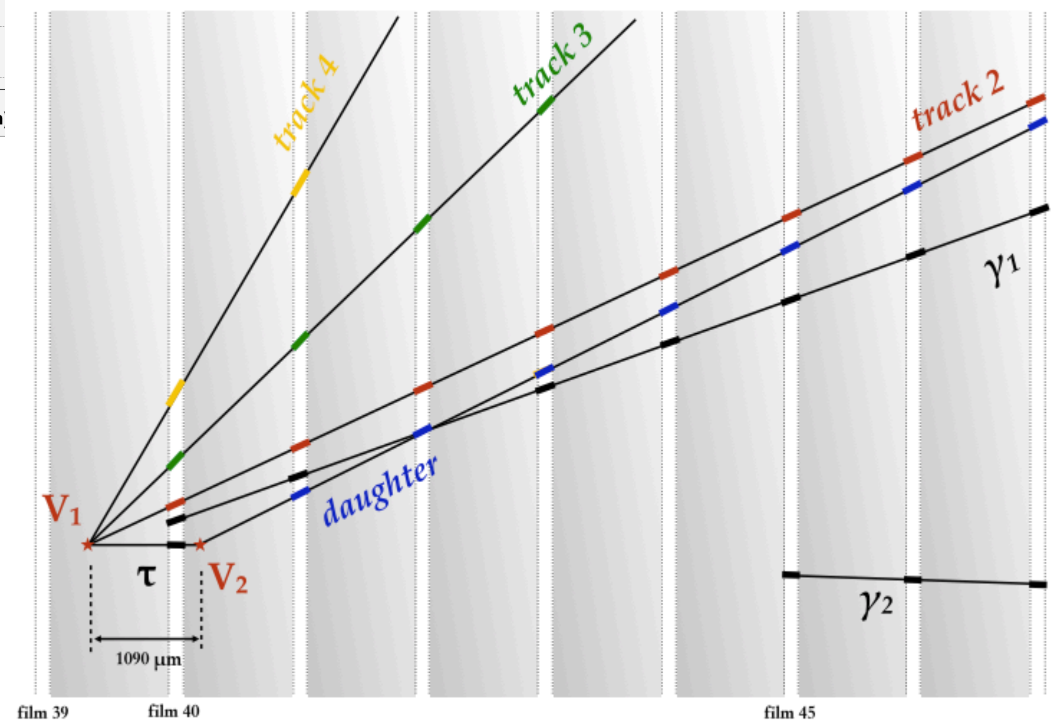




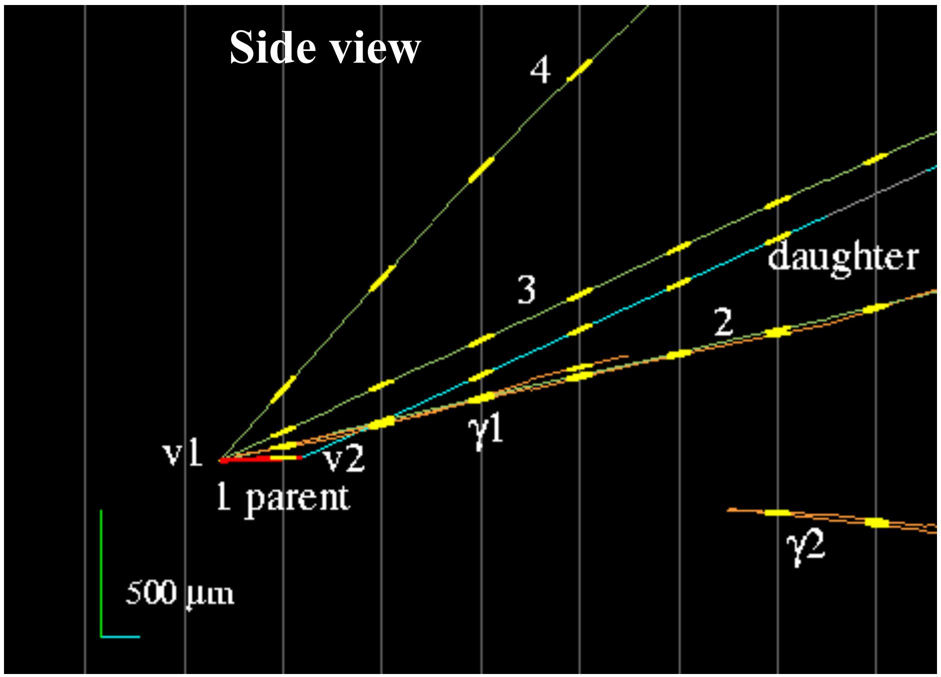
NEW ν_τ candidate

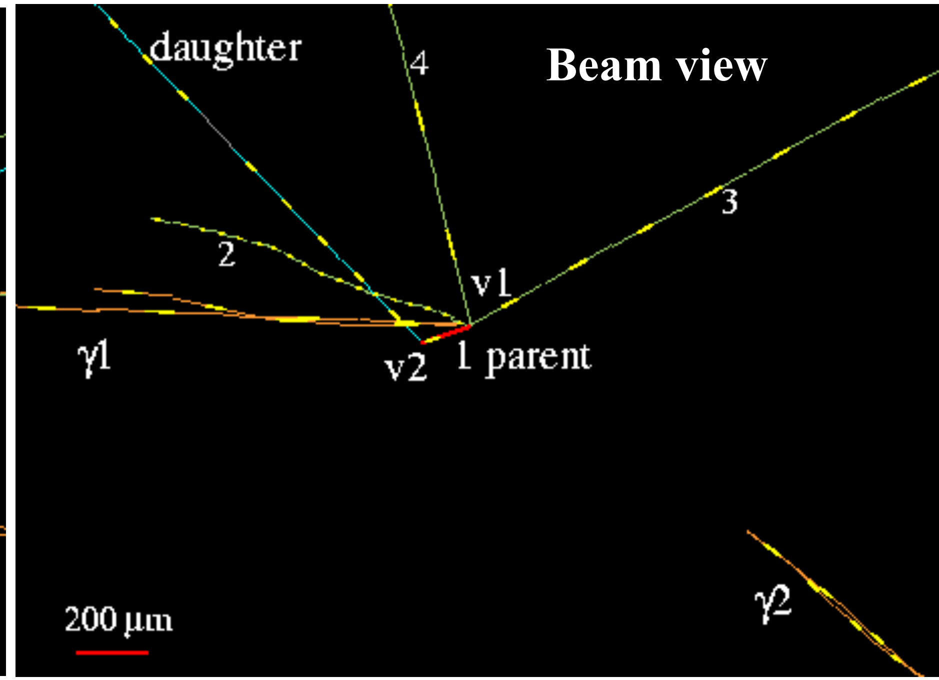


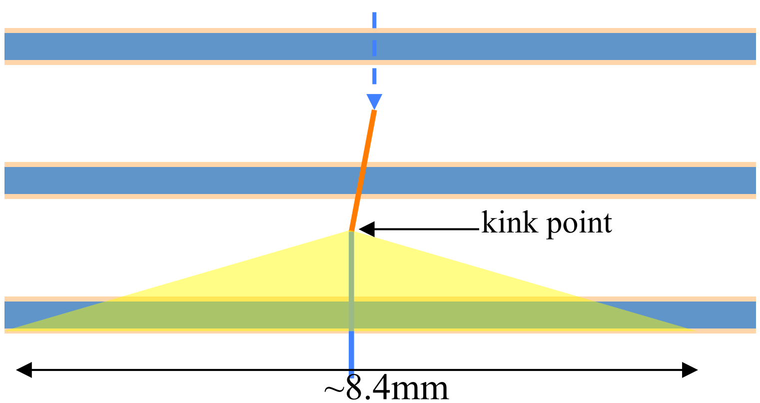
ECC scanning results



NEW ν_τ *candidate*



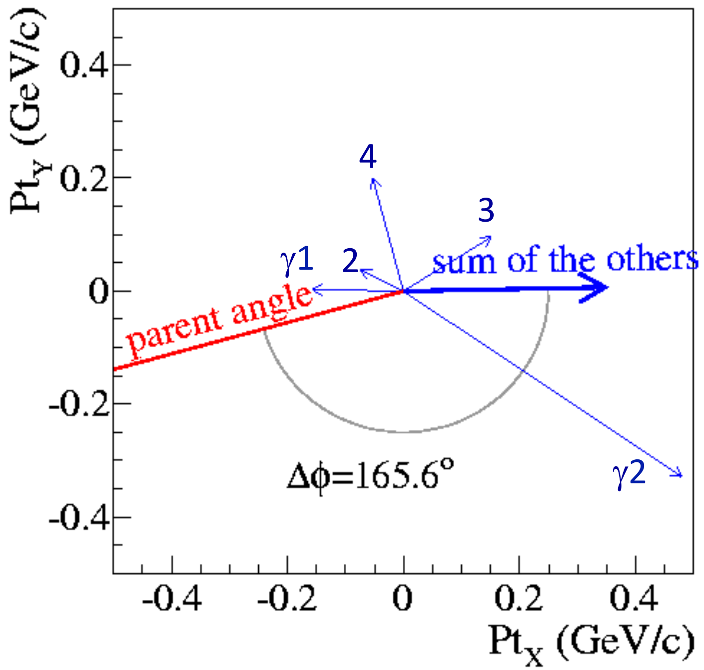




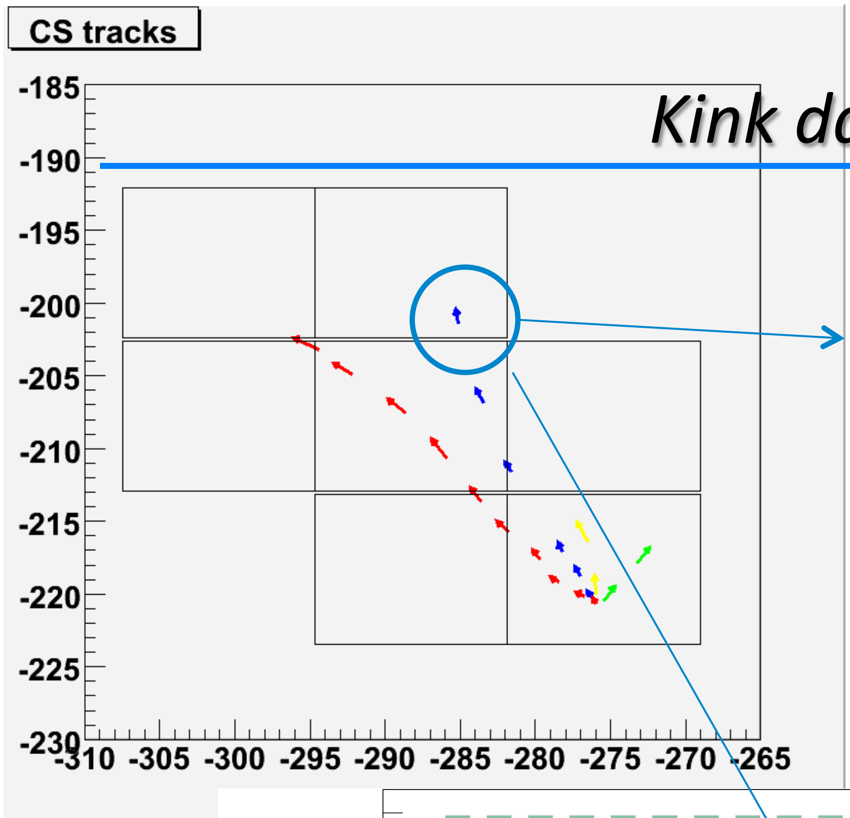
Search for nuclear fragments
in an extended angular range $|\tan\theta| \leq 3.5$
No track found

NEW ν_τ candidate

	Values	Selection
P daughter (GeV/c)	$6.0^{+2.2}_{-1.2}$	> 2
Kink P_t (GeV/c)	$0.82^{+0.30}_{-0.16}$	> 0.6
P_t at 1ry (GeV/c)	$0.55^{+0.30}_{-0.20}$	< 1.0
Phi (degrees)	166^{+2}_{-31}	> 90
Kink angle (mrad)	137 ± 4	> 20
Decay position (μm)	1090 ± 30	< 2600



Kink daughter track follow down

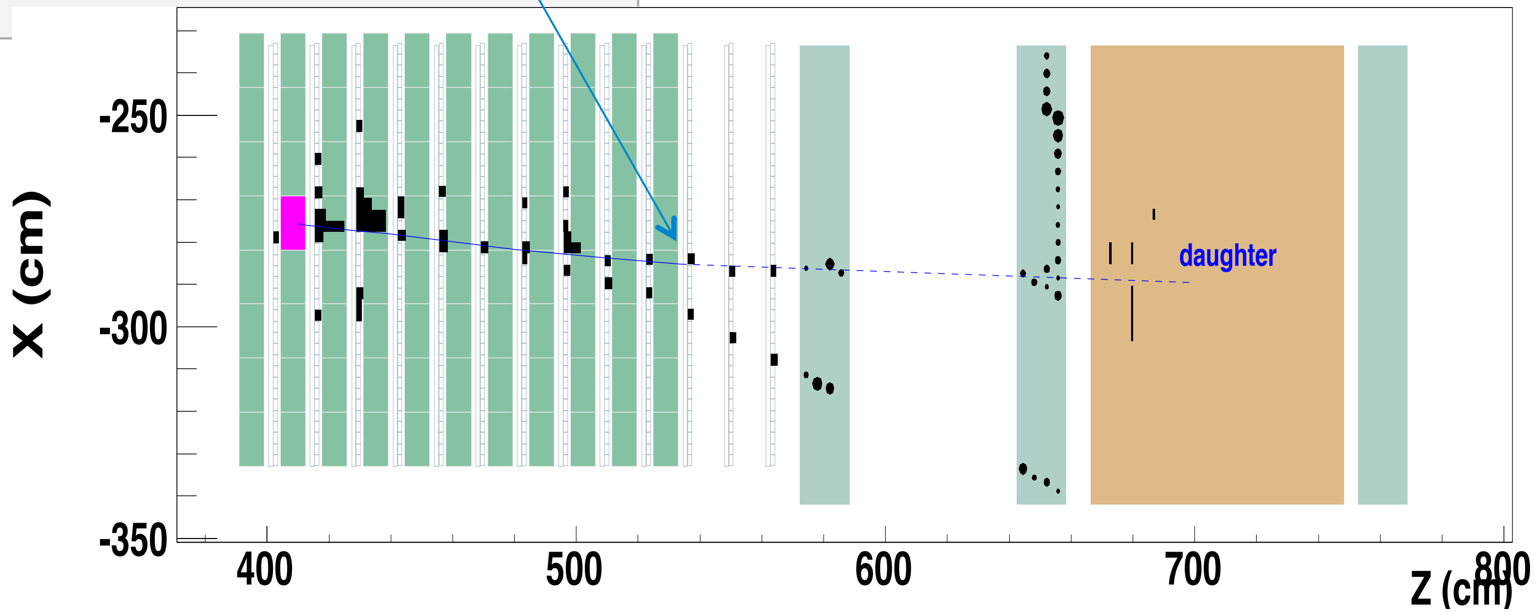


Found in the CS of the most downstream brick

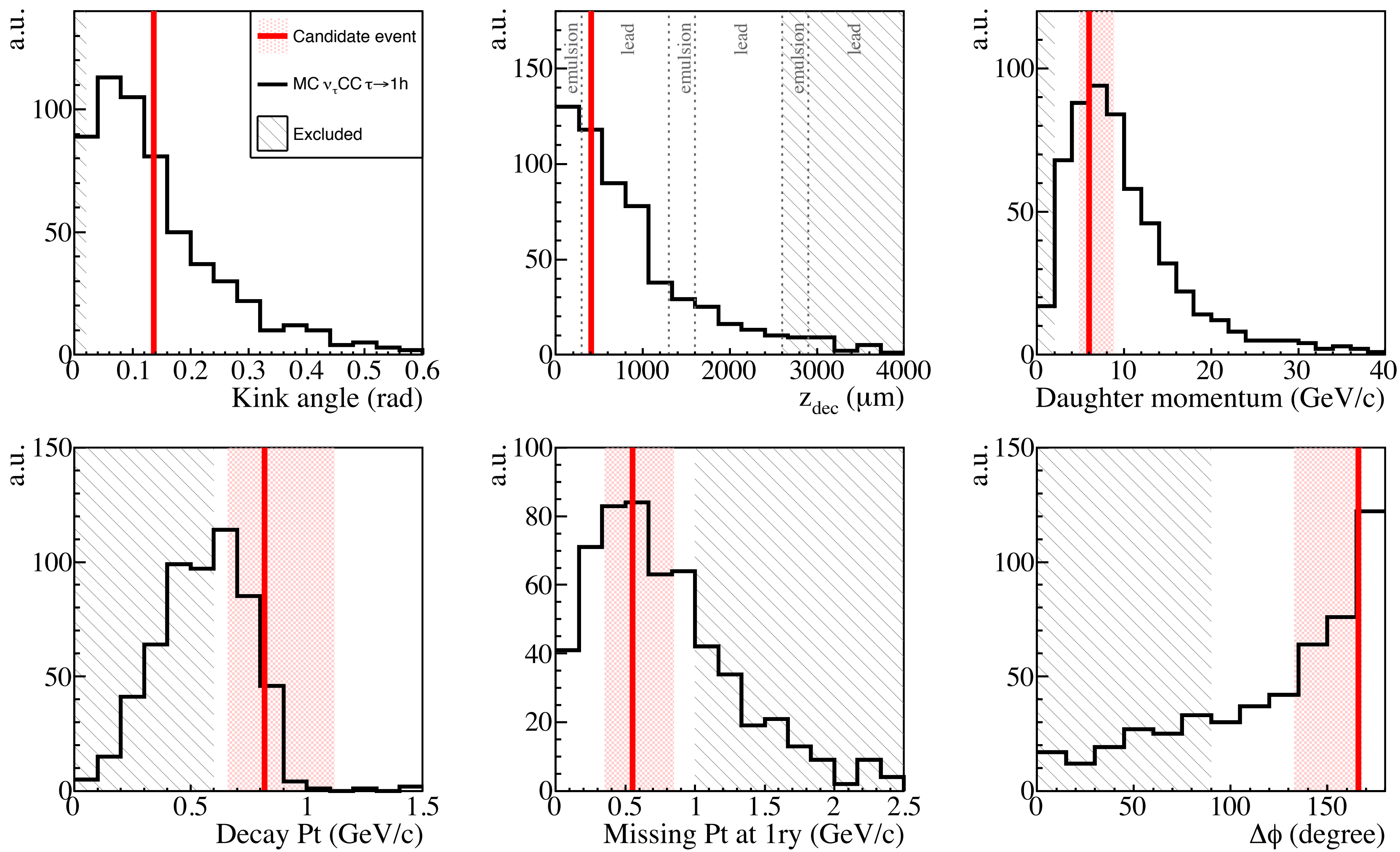
P = $6.0^{+2.0}_{-1.2}$ GeV/c

Range/momentum → hadron

$$D = \frac{L}{R_{lead}(p)} \frac{\rho_{average}}{\rho_{lead}} = 0.15$$



NEW ν_τ candidate



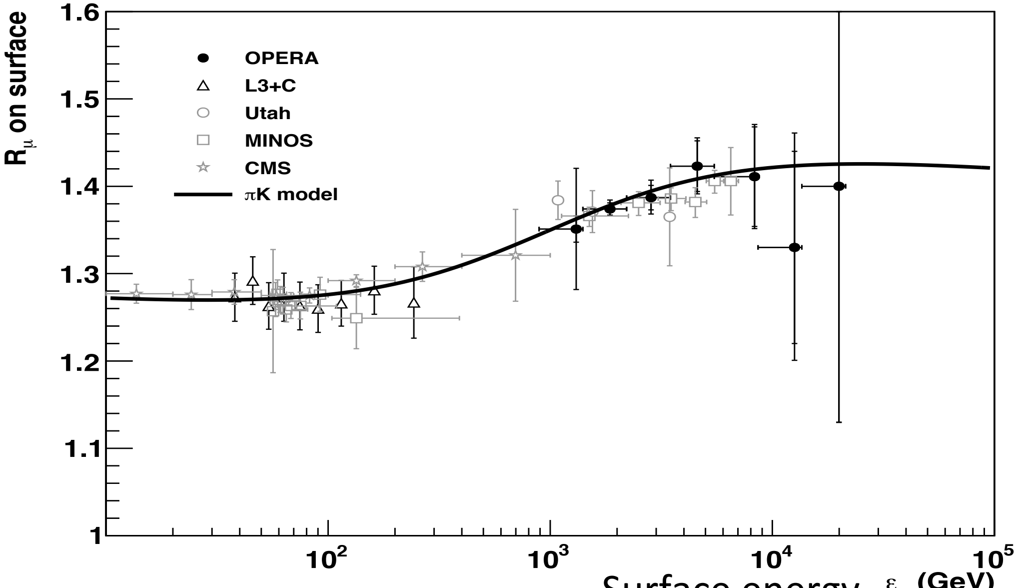
NEW ν_τ candidate

$\Delta m^2 = 2.32 \times 10^{-3}\ eV^2$	Expected	Observed	Background	Charm	μ scatt	had int
$\tau \to h$	0.38	2	0.03	0.014		0.019
$\tau \to 3h$	0.53	1	0.15	0.142		0.003
$\tau \to \mu$	0.58	1	0.02	0.004	0.016	
$\tau \to e$	0.58	0	0.02	0.025		
total	2.1	4	**0.22**	0.185	0.016	0.022

The p values of the single channels are combined into an estimator $p^\star = p_\mu\, p_e\, p_h\, p_{3h}$.
$p^\star \le p^\star$ (observed) gives the probability of the background-only hypothesis

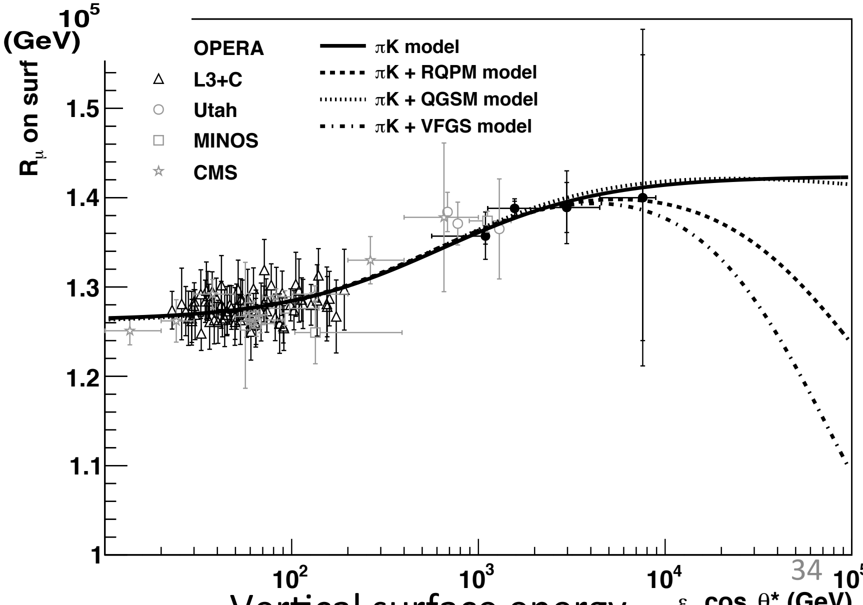
- ✓ *4 observed events with 0.22 background events expected*
- ✓ *Probability to be explained by background = 1.1×10^{-5}*
- ✓ *4.2 σ significance of non-null observation*

Measurement of TeV atmospheric muon charge ratio



Surface energy

arXiv:1403.0244
Submitted to EPJC



Vertical surface energy

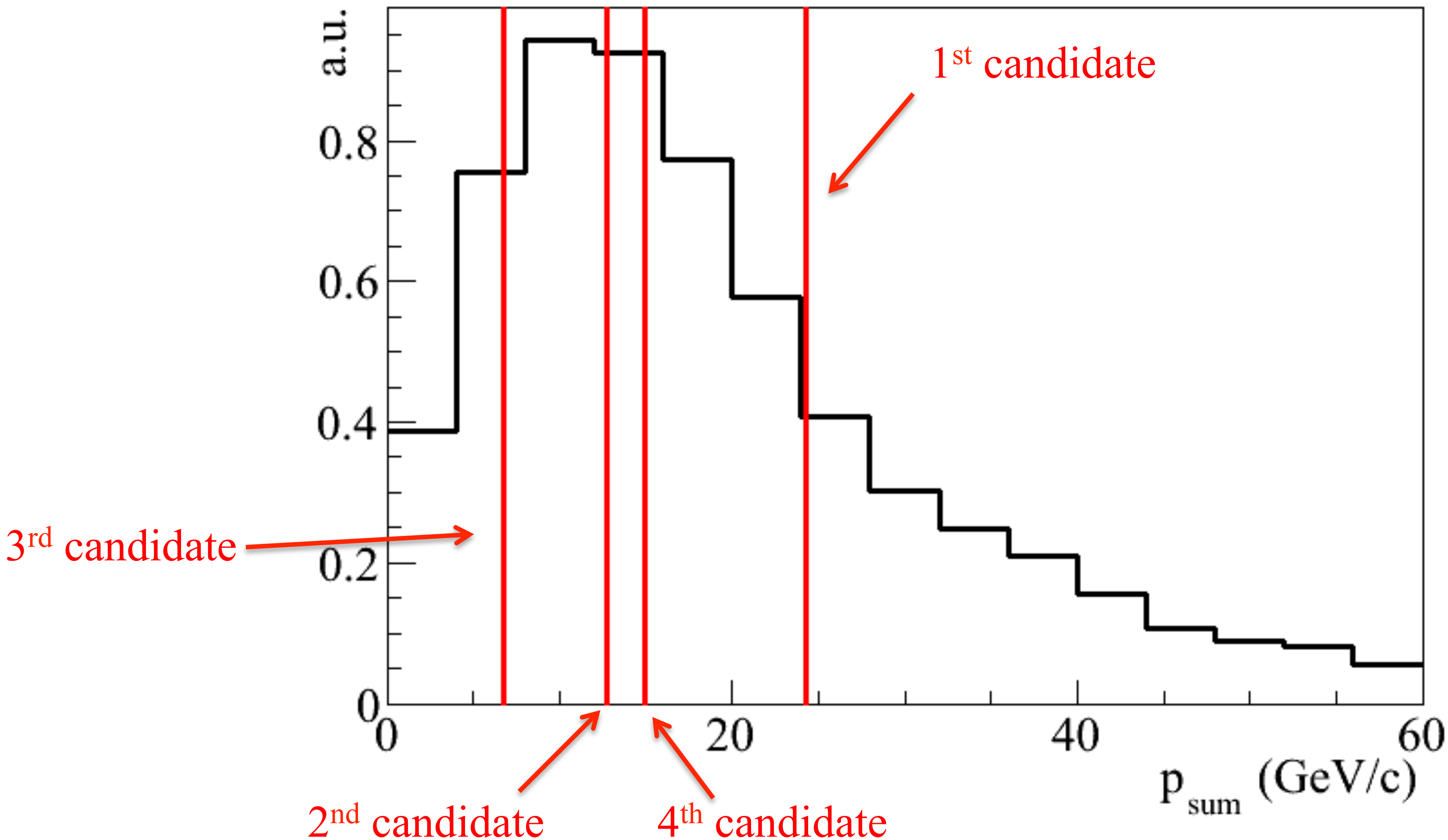
Conclusions

- *"OPERA RUN" is going on*
- *More than 6000 neutrino interactions fully reconstructed and studied in ECC.*
- *4 candidate events found*
- *4.2 σ significance of non-null observation*

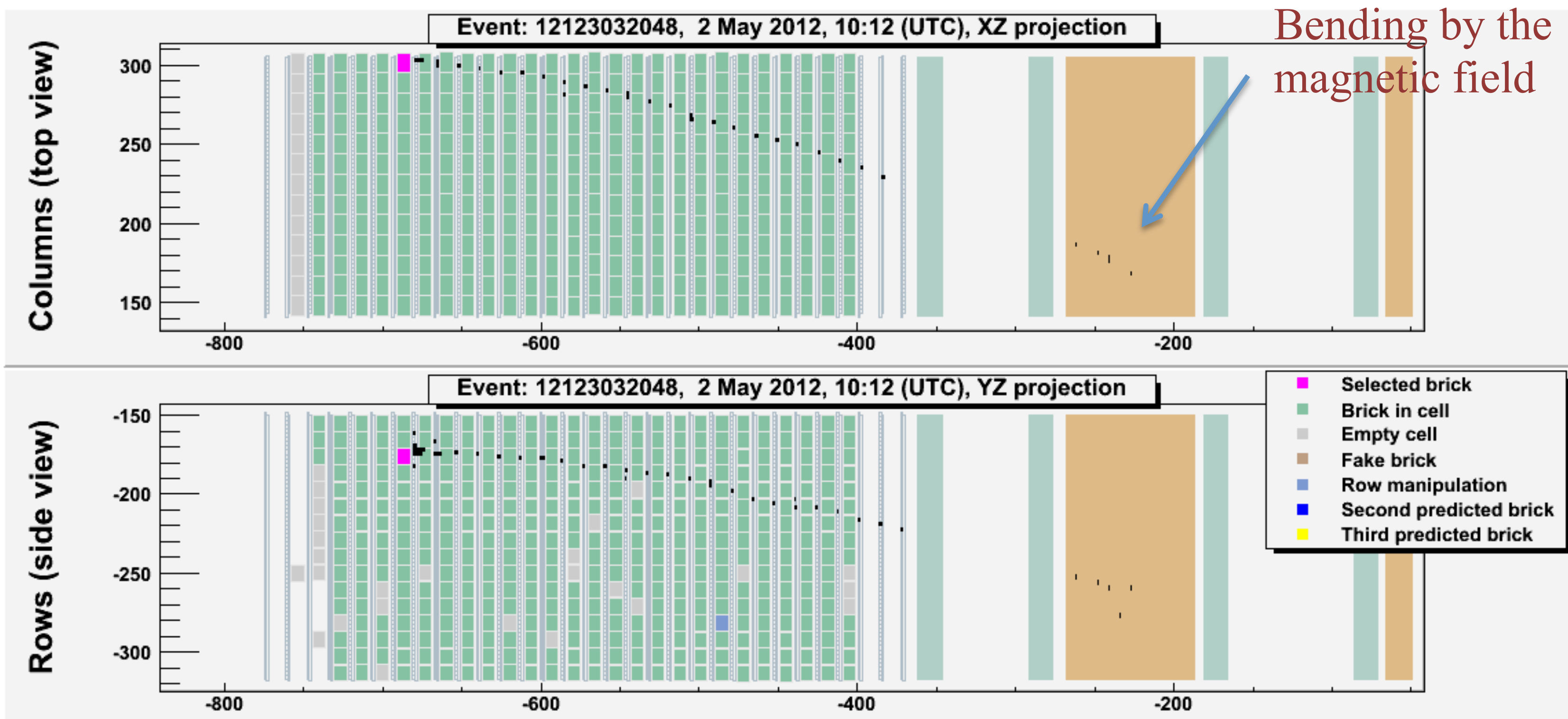
Spares

Visible energy of all the candidates

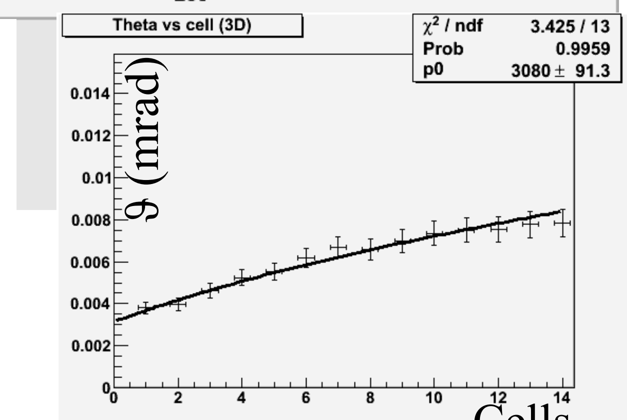
Sum of the momenta of charged particles and γ's measured in emulsion



Muon charge and momentum reconstruction



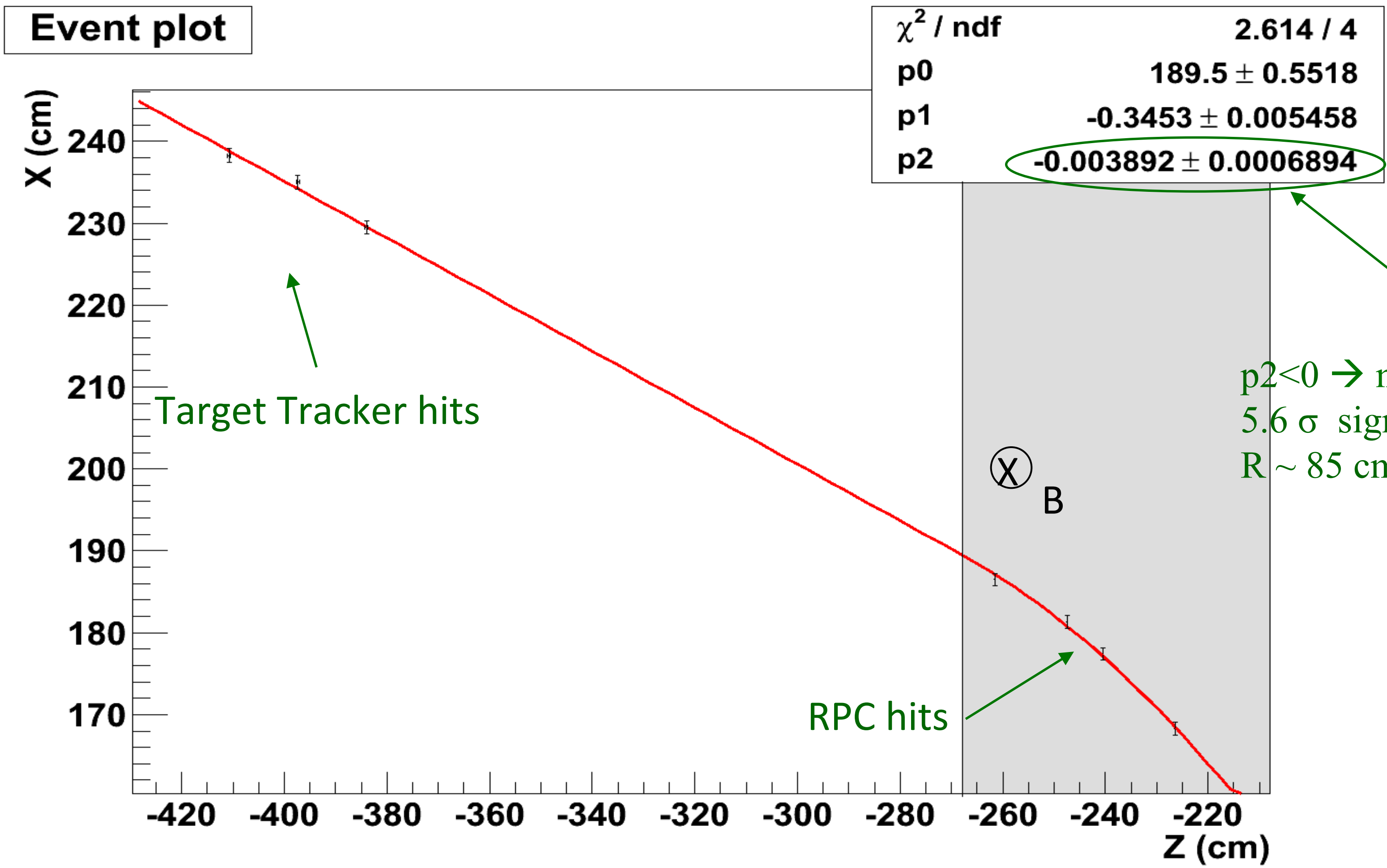
Muon momentum
by range in the electronic detector: 2.8±0.2 GeV/c
MCS in the brick consistent 3.1 [2.6,4.0] GeV/c



Muon charge and momentum reconstruction

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

Linear fit in the non-magnetized region



p2<0 → negative charge

5.6 σ significance

R ~ 85 cm

The negative muon charge rules out charm background!

Track features

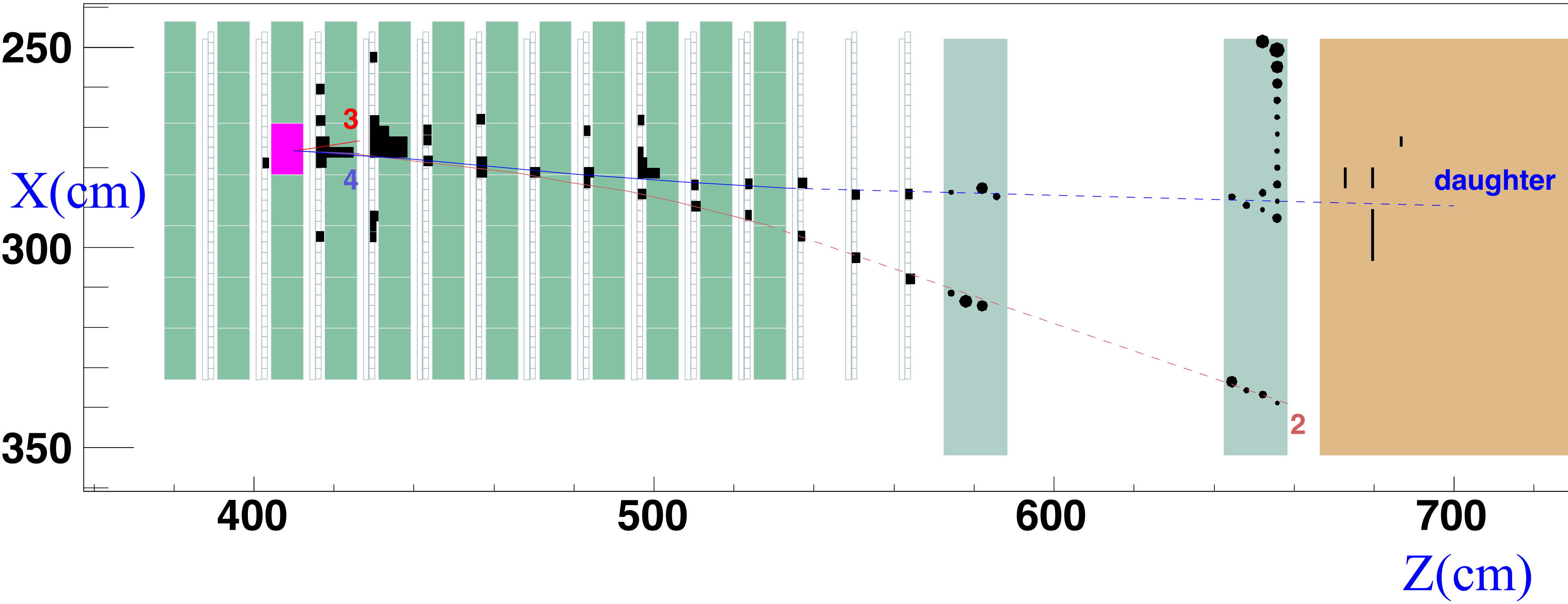
			First measurement	Second measurement	Average	
	Track ID	Particle ID	Slopes	Slopes	**Slopes**	**P (GeV/c)**
1ry	1 parent	τ	-0.143, 0.026	-0.145, 0.014	**-0.144, 0.020**	**-**
	2	Hadron (Range)	-0.044, 0.082	-0.047, 0.073	**-0.046, 0.078**	**1.9 [1.7, 2.2]**
	3	Hadron (interact)	0.122, 0.149	0.139, 0.143	**0.131, 0.146**	**1.1 [1.0, 1.2]**
	4	proton	-0.083, 0.348	-0.080, 0.355	**-0.082, 0.352**	**0.7 [0.6, 0.8]** $p\beta = 0.4$ [0.3, 0.5]
	$\gamma 1$	e-pair	-0.229, 0.068	-0.238, 0.055	**-0.234, 0.062**	**0.7 [0.6, 0.9]**
	$\gamma 2$	e-pair	0.111, -0.014	0.115,-0.034	**0.113,-0.024**	**4.0 [2.6, 8.7]**
2ry	daughter	Hadron (Range)	-0.084, 0.148	-0.091, 0.145	**-0.088, 0.147**	**6.0 [4.8, 8.2]**

		ΔZ (μm)	**$\delta\theta_{RM}$ (mrad)**	**IP (μm)**	**IP Resolution (μm)**	**Attachment**
$\gamma 1$	To 1ry	676	21.9	**2**	**8**	**OK**
$\gamma 2$	To 1ry	7176	9.2	**33**	**43**	**OK**
	To 2ry	6124	9.2	**267**	**36**	**Excluded**

$$M = 0.59^{+0.20}_{-0.15}\ \mathrm{GeV/c^2}$$

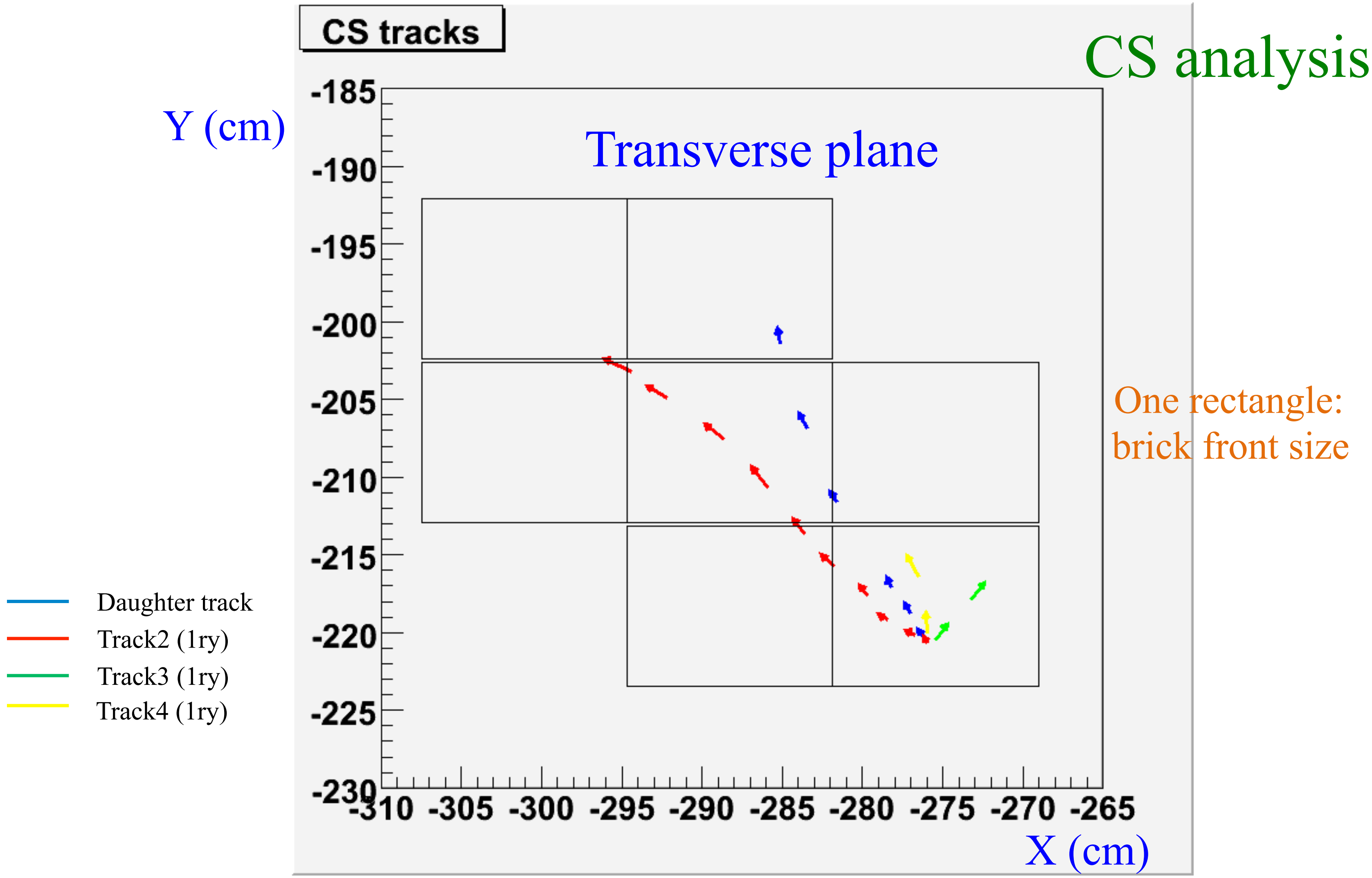
Not a single π^0

Track follow-down: a powerful tool to assess the muon-less nature of the event

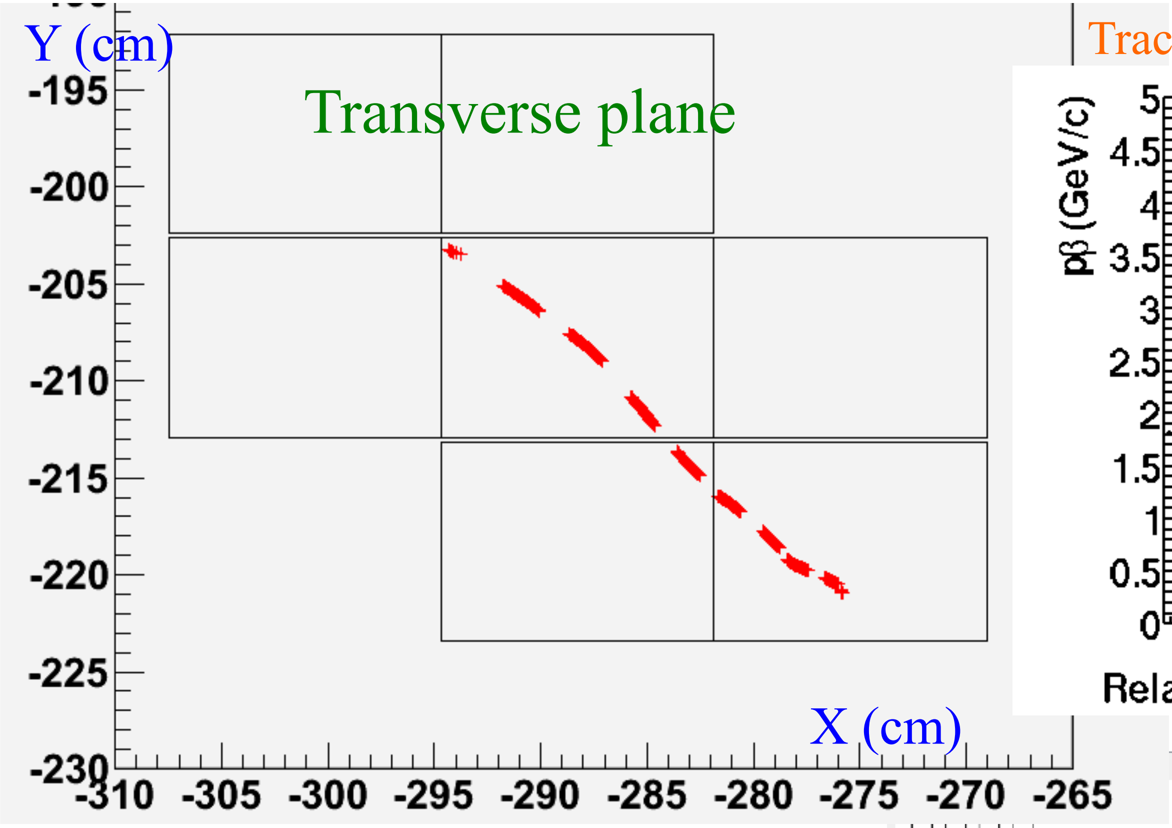


Follow-down all tracks in downstream bricks

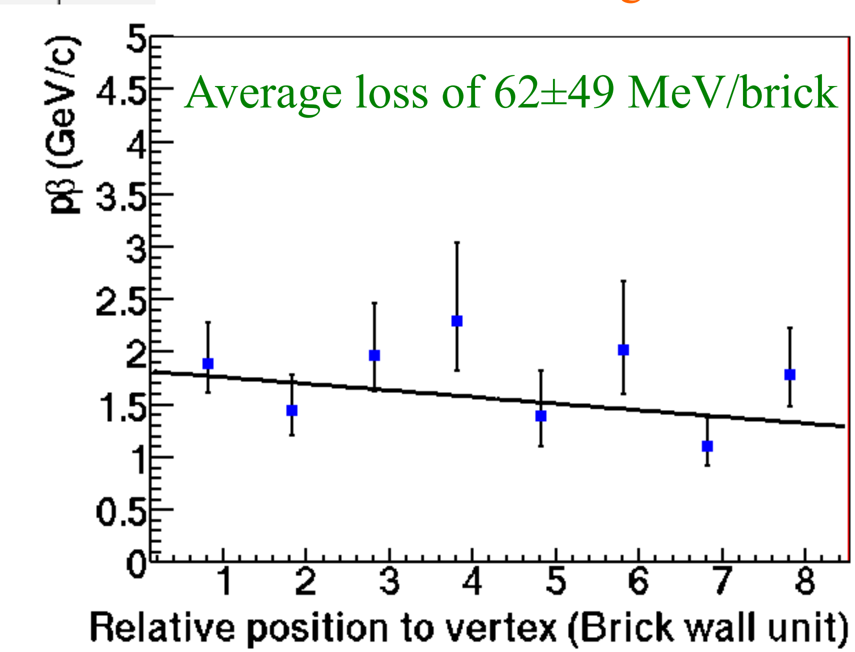
- 3 primary tracks to discard the charm hypothesis
- kink daughter to identify the τ decay channel

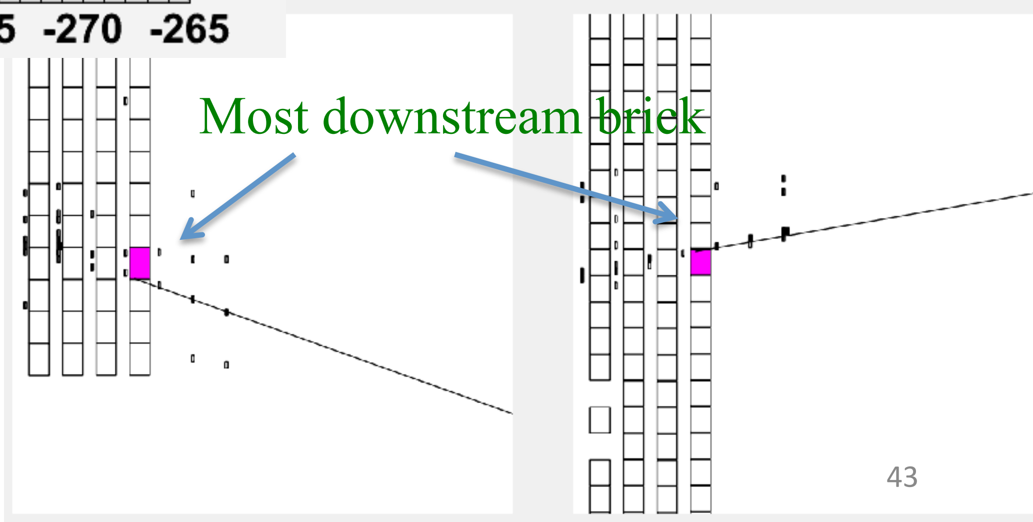


Track follow-down: primary track n. 2

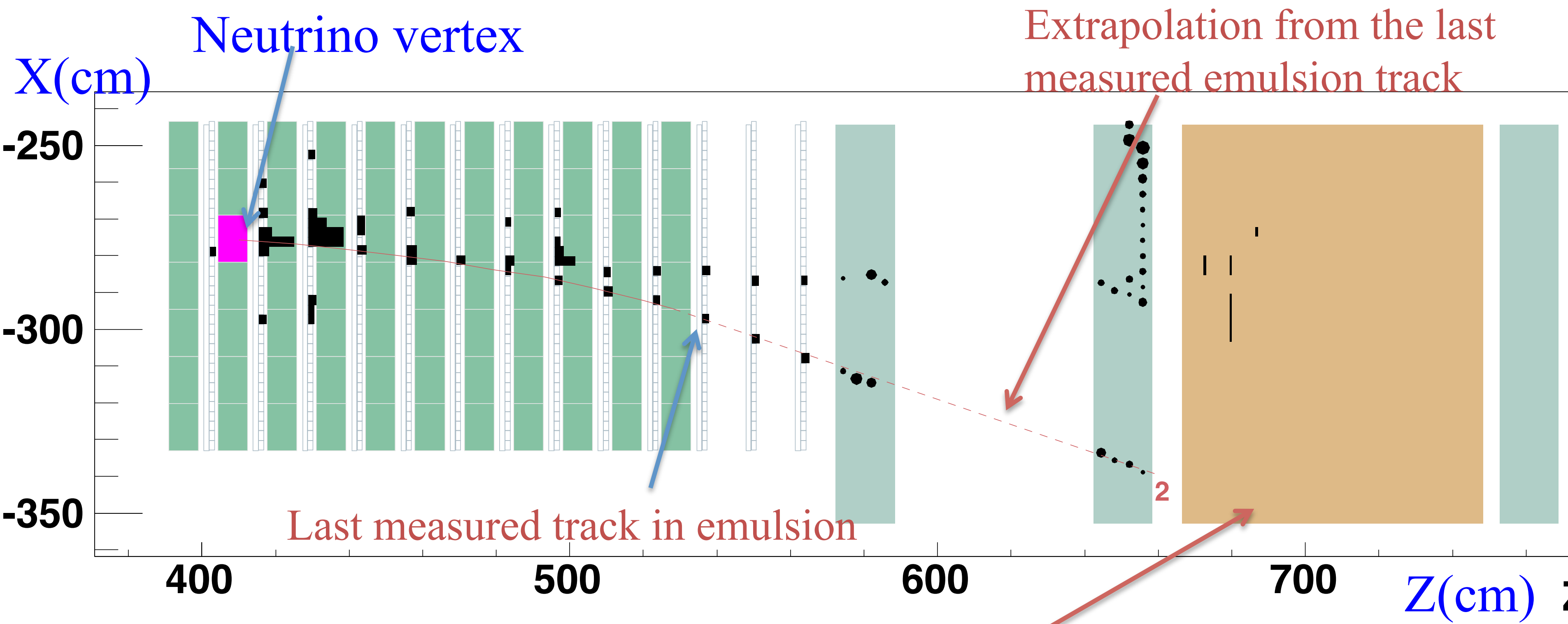


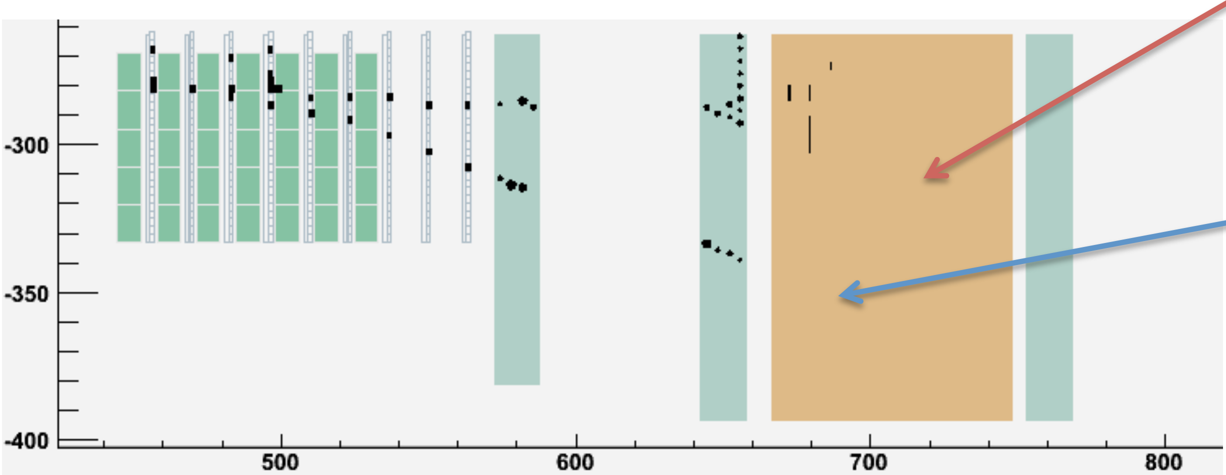
Track 2 followed-down along 10 bricks





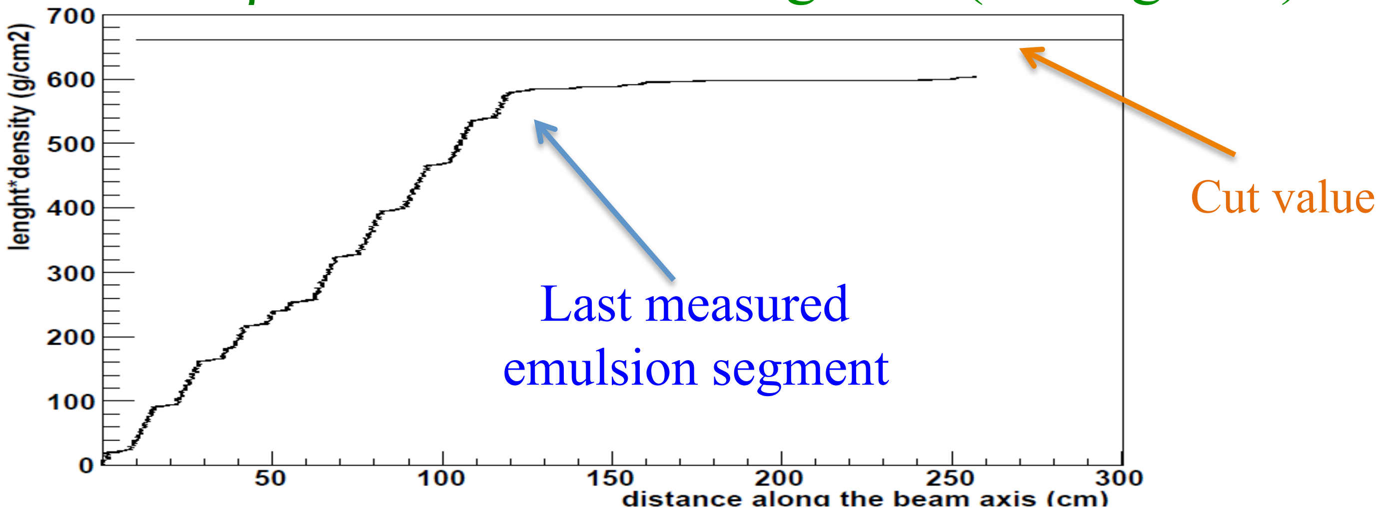
Track n. 2 follow-down



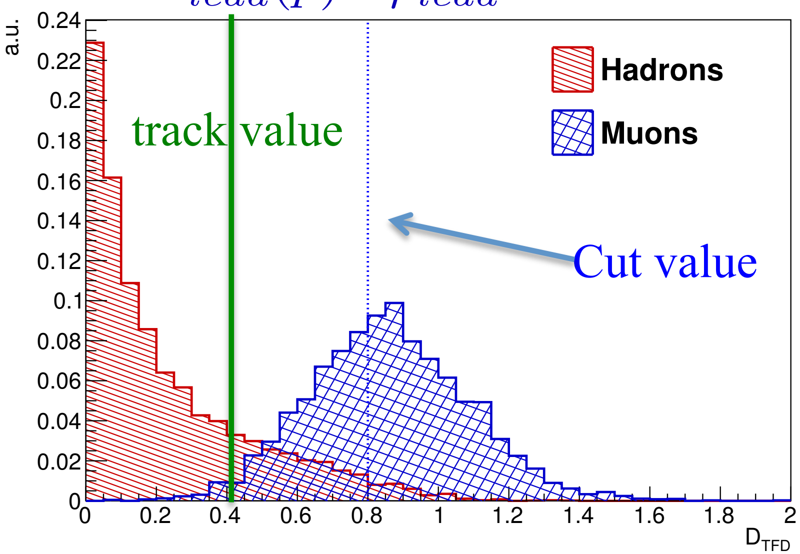


Measured length x density, Lρ

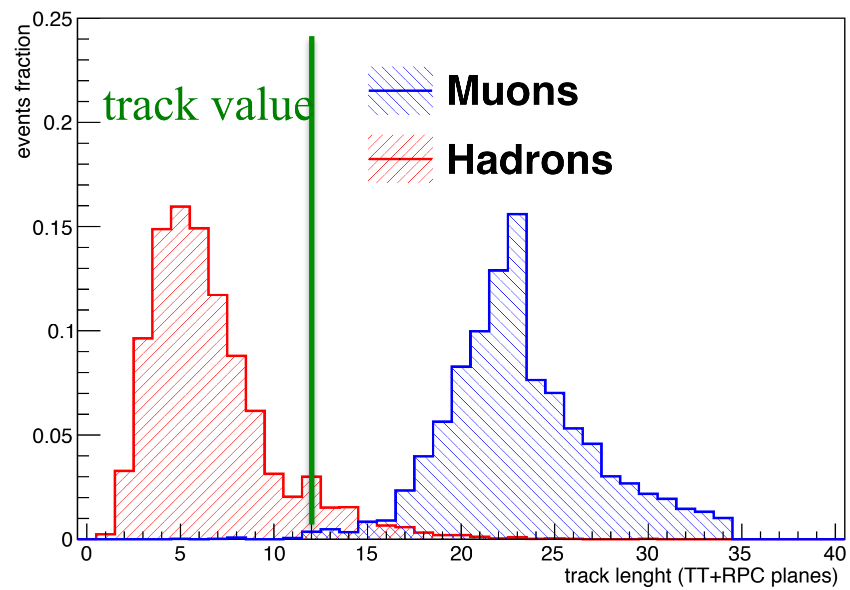
Lρ for the track = 604 g/cm^2 (<660 g/cm^2)



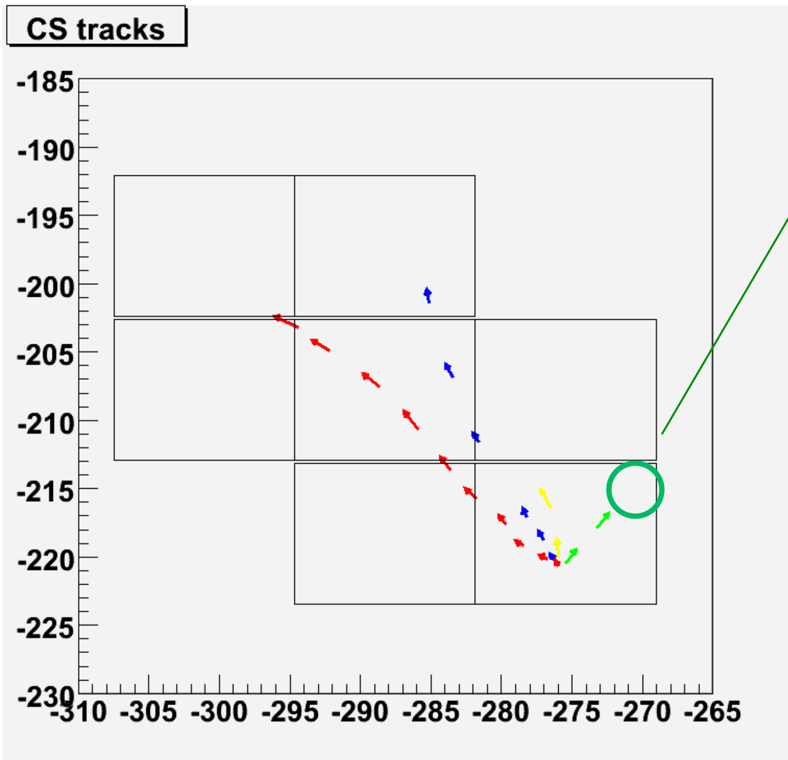
$$D = \frac{L}{R_{lead}(p)} \frac{\rho_{average}}{\rho_{lead}} = 0.40^{+0.04}_{-0.05}$$



- Prob. for a μ to cross ≤ 12 planes ~ 0.35%
- Prob. for a π to cross ≥ 12 planes ~ 10.2%

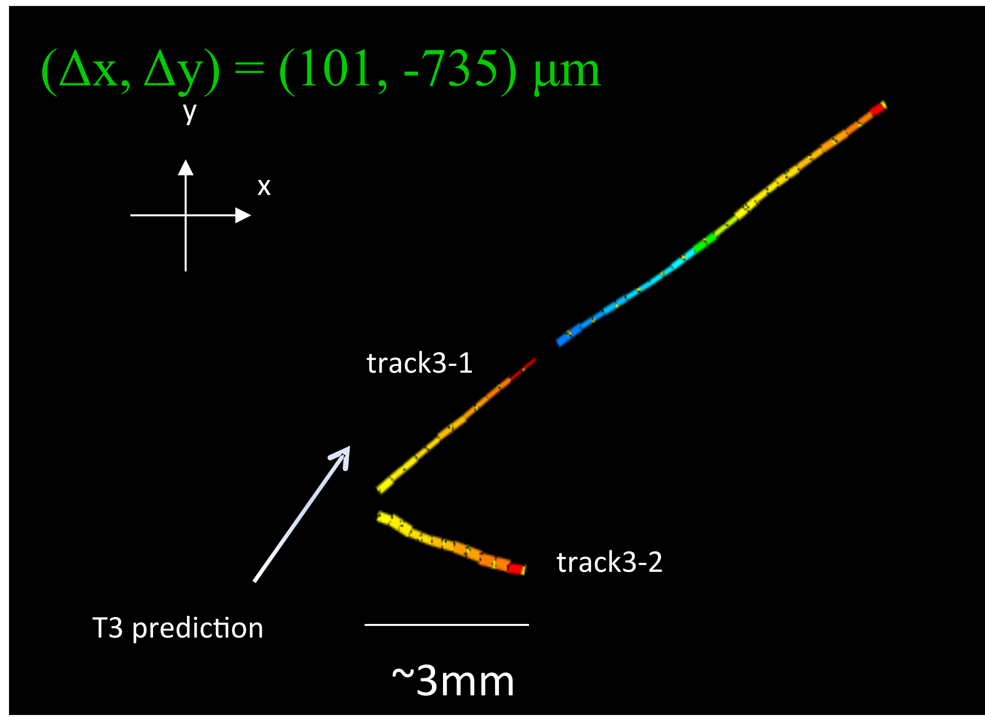


Track follow-down: primary track n. 3



Track 3 found down to the CS of the 2nd brick
P = 1.1 GeV/c at 2nd brick

A vertex found near its predicted position in the 3rd downstream brick



Interaction detected

Track follow-down: primary track n. 4

From the ionization, the proton hypothesis is made

$P\beta \sim 0.4$, ($P = 0.7$ assuming proton mass)

Track path of 77.8 mm lead, Range/Mass ~ 94 g cm^{-2} GeV^{-1}

Expected Range/Mass from measured momentum ~ 70 [45-100] g cm^{-2} GeV^{-1}

Consistent with the **proton** hypothesis