Results of the OPERA experiment

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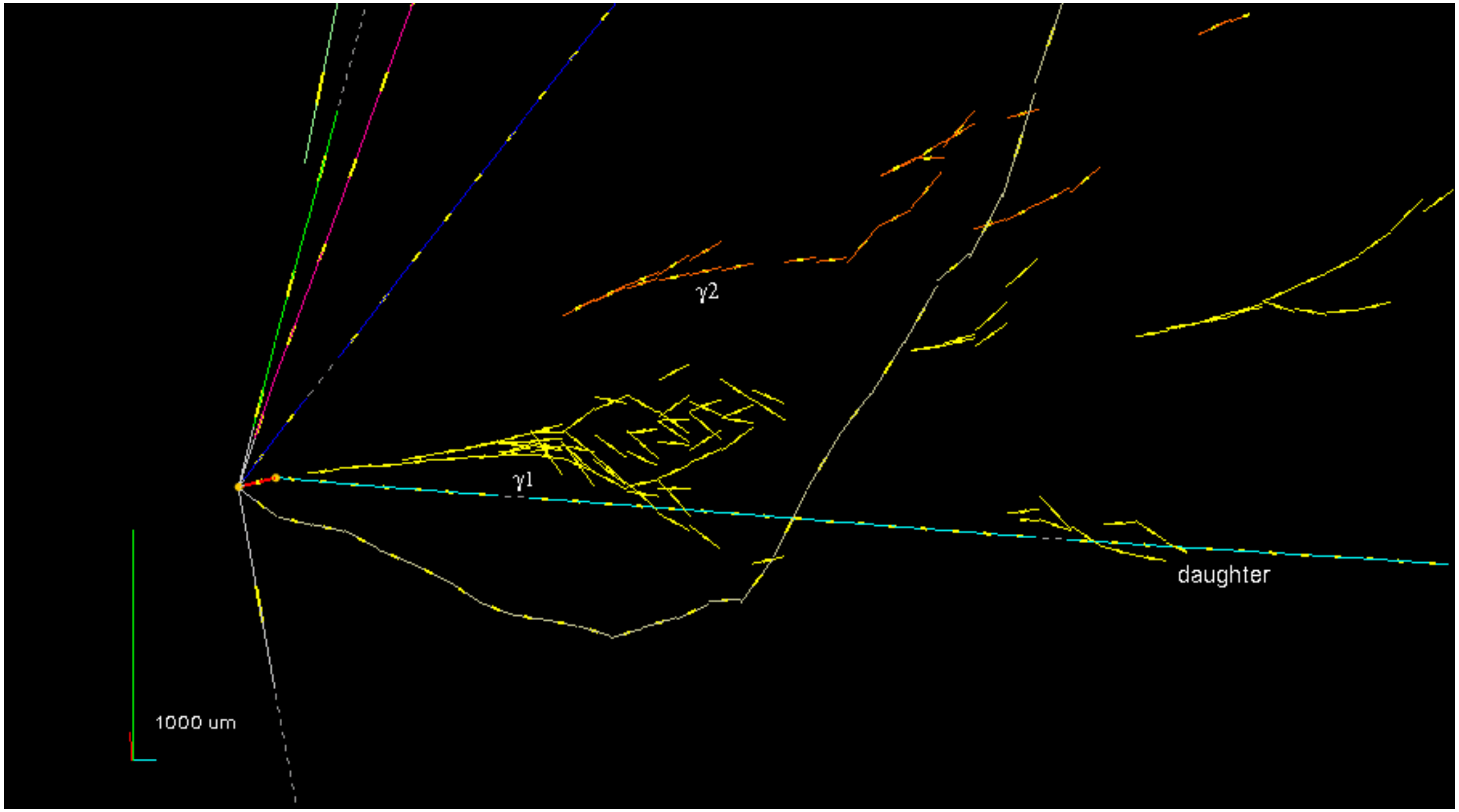
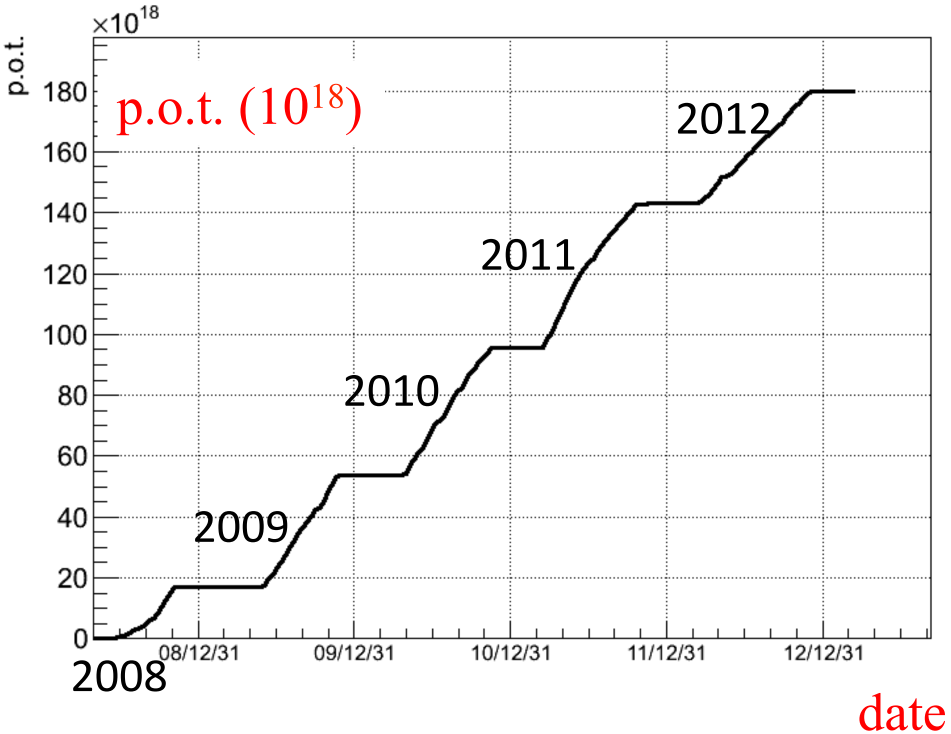
On behalf of the OPERA Collaboration



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**

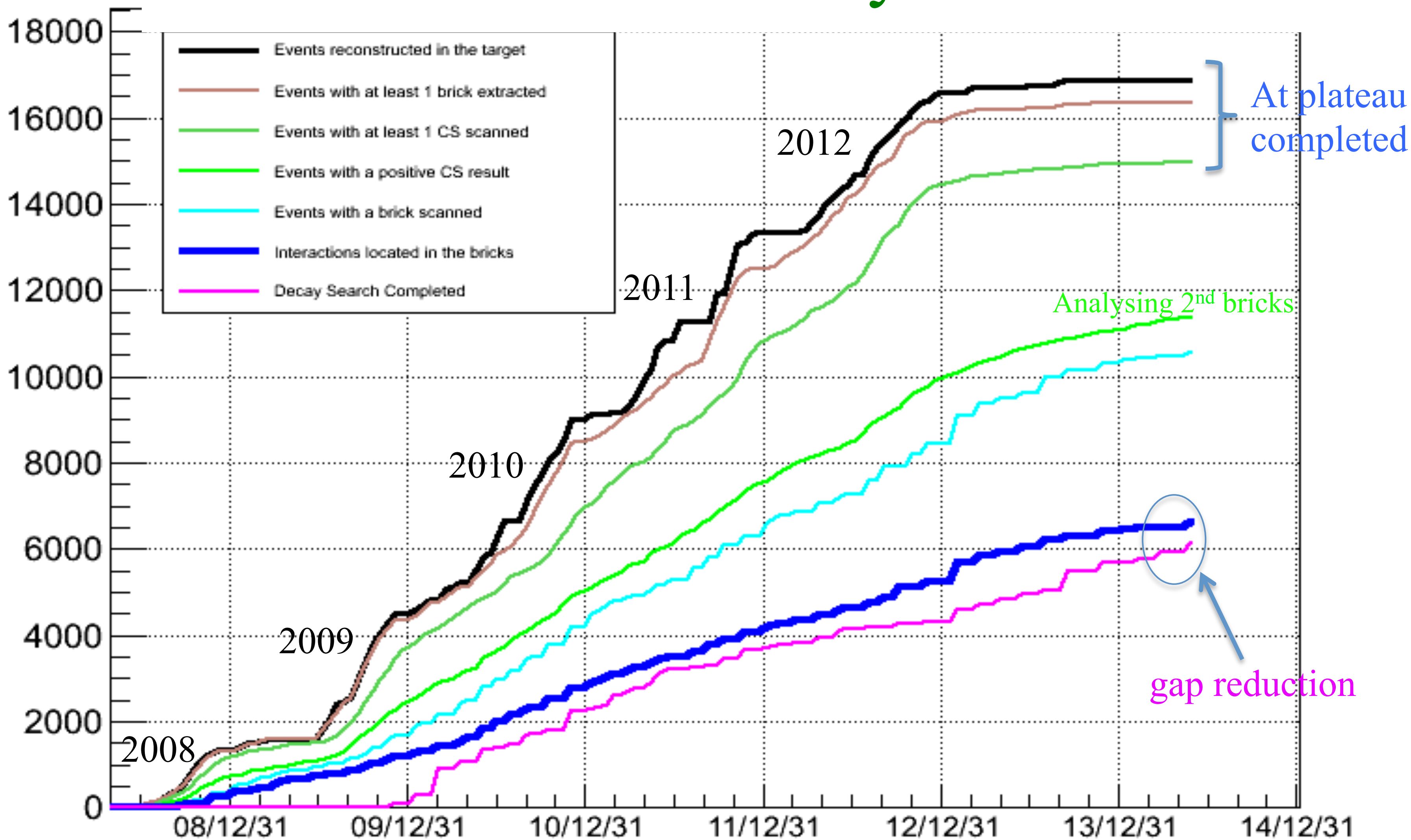


Record performances in 2011

Overall 20% less than the proposal value (22.5)

Last neutrino interaction recorded on December 3rd 2012

Present data analysis status



6604 located interactions

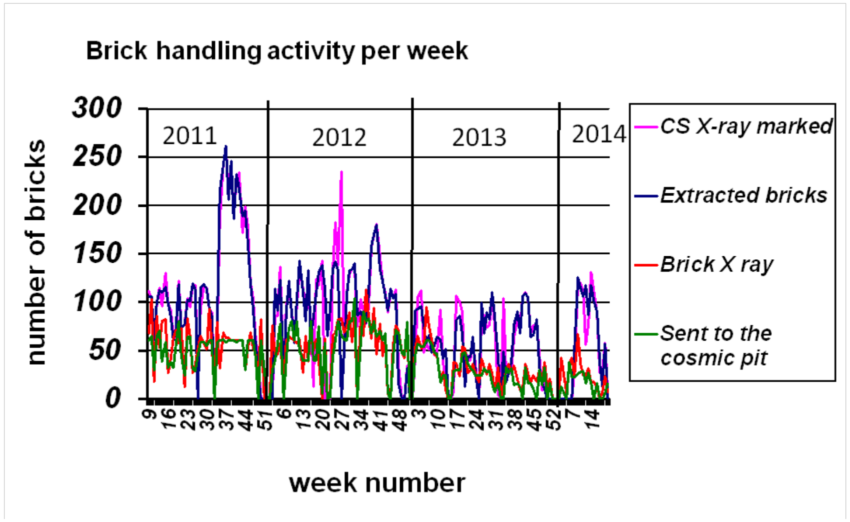
6148 decay search

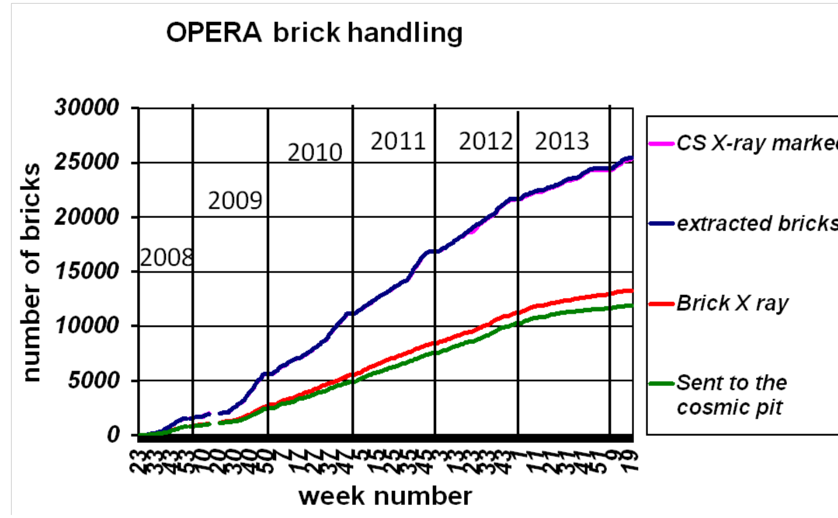
2008-2009 completed

2010 to 2012

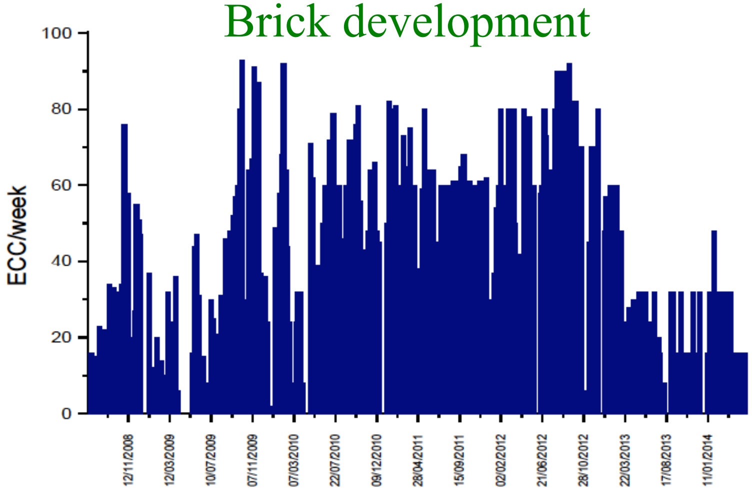
first brick completed

Facilities in operation



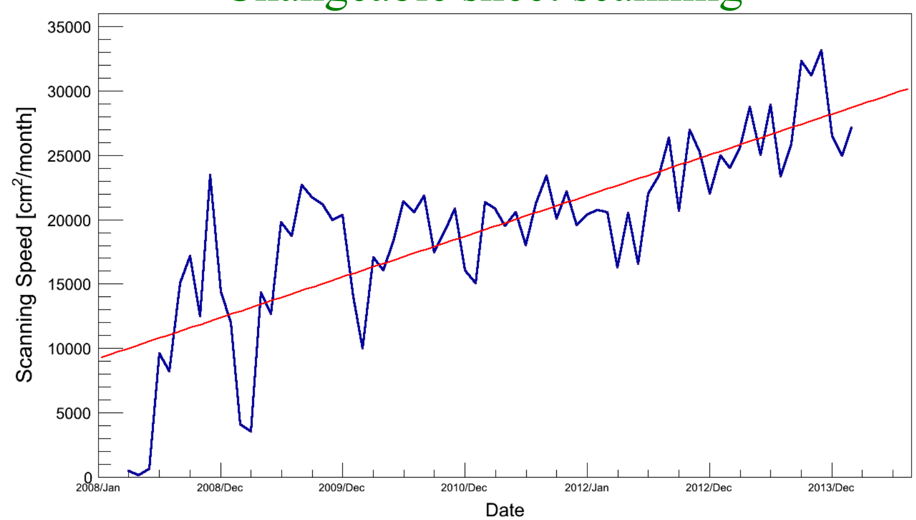


Brick development



To be operated also next year

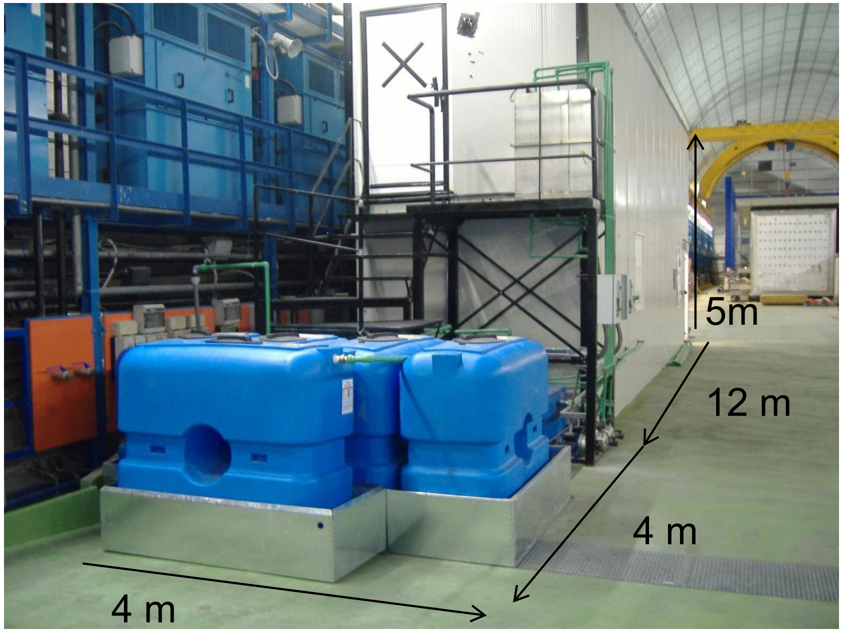
Changeable sheet scanning



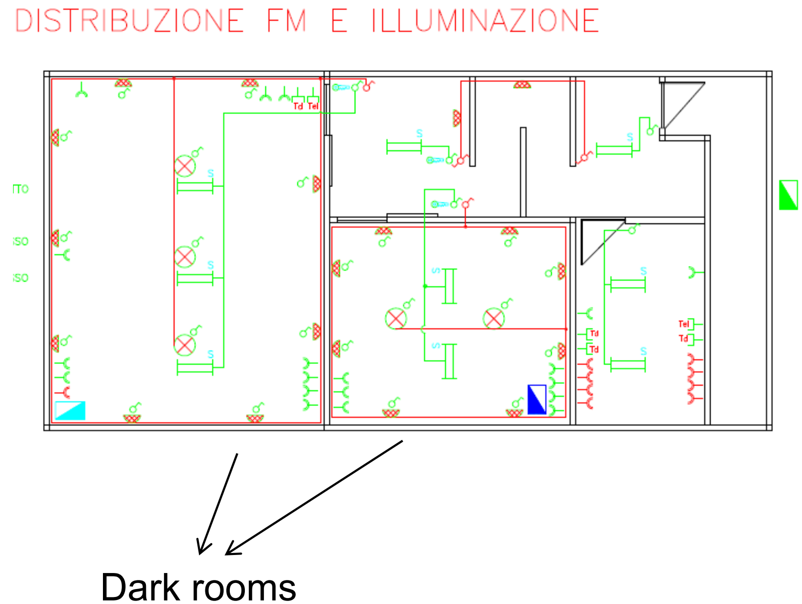
To be operated also next year

CS development facility underground:
moving to a new site in hall B (top of the shielded area)

Current location of the facility



Map of the new facility



New site in preparation
2 months stop required

Next steps

- MoU for decommissioning being signed by the Funding Agencies: to start early next year
- Analysis of 2nd bricks going on
- Extension of the analysis to 3rd and 4th bricks planned (already extracted)
- When a decay topology is identified → 10÷20 bricks around selected to reduce the background (discard muon hypothesis for primary tracks)
- For the candidates not identified by the end of 2014 → store surrounding bricks before or during the decommissioning
- A new site identified with LNGS for massive brick storage

Full revision of efficiencies and background
JHEP 11 (2013) 036

Expected number of ν_τ events

Current numbers based on

$$\Delta m^2_{23} = 2.32 \times 10^{-3}\ \mathrm{eV}^2$$

Location efficiency

Good agreement in normalization and shape for 1μ events

Good agreement in shape for 0μ events,

0μ data ~15% systematically lower than MC

Effect mainly due to bad quality films

In principle recoverable but lengthy → postponed

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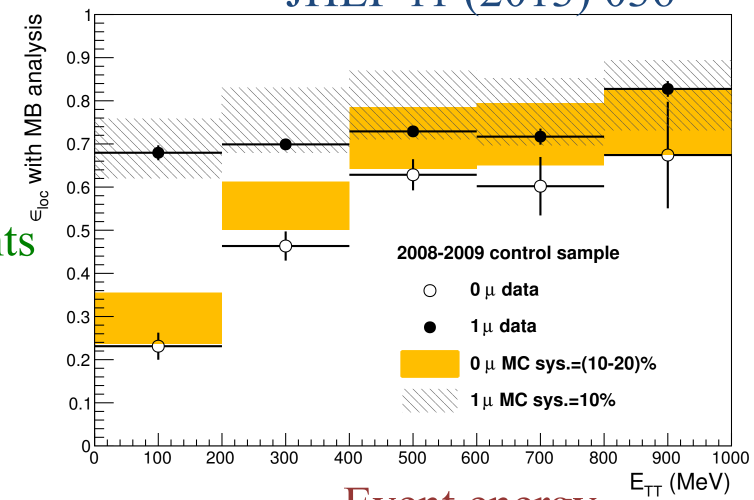


Event energy

Sample	Selection	Expected events
All runs	1st and 2nd bricks (MC)	3.2
All runs	1st and 2nd bricks (data)	2.8
Current sample	1st all runs, 2nd for 2008-09 (data)	2.1

Improvements still not accounted for:

Extension of the analysis to 3rd and 4th bricks in the probability map, ~ 20%

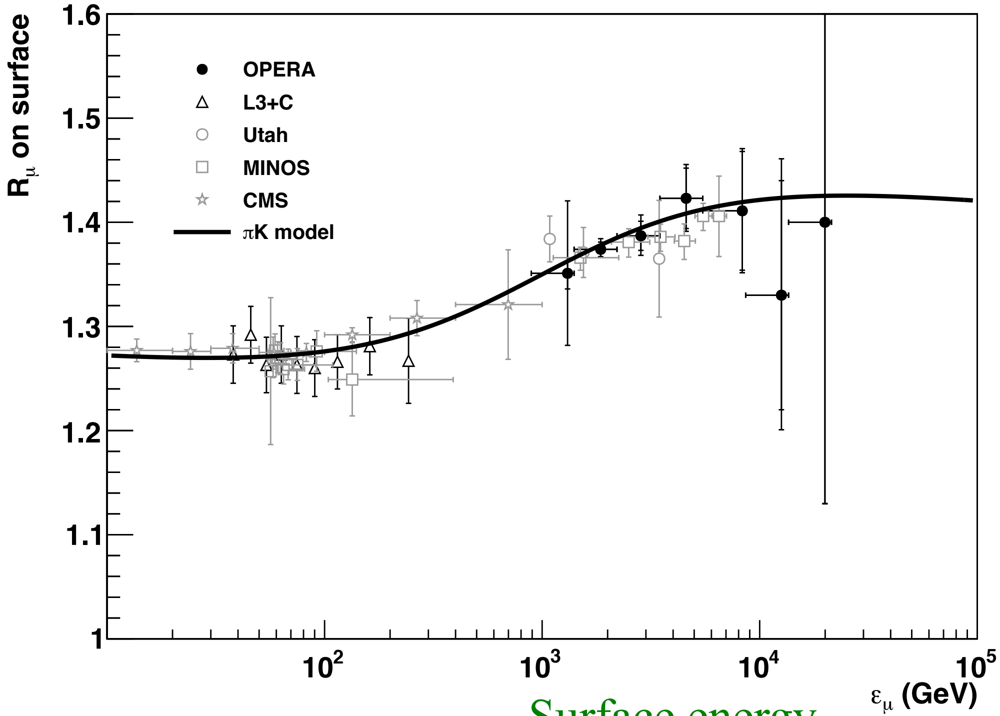
~ 5÷10% effect due to the migration of ν_τ events from one τ decay channel to another, increasing signal only

Cosmic-ray physics

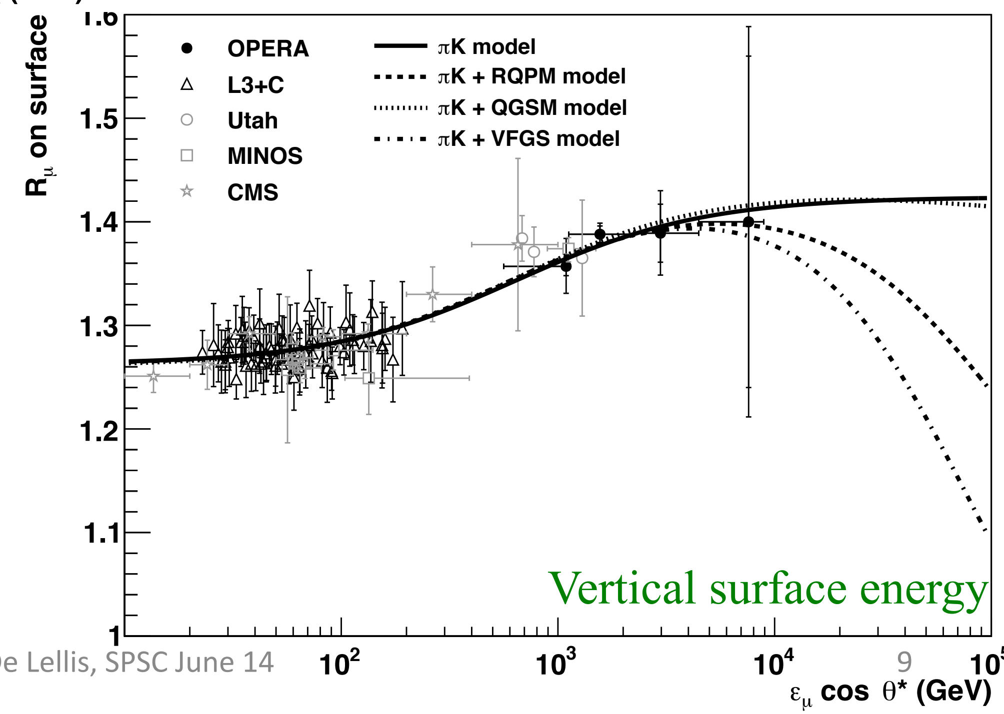
Measurement of TeV atmospheric muon charge ratio

arXiv:1403.0244
accepted by EPJC

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



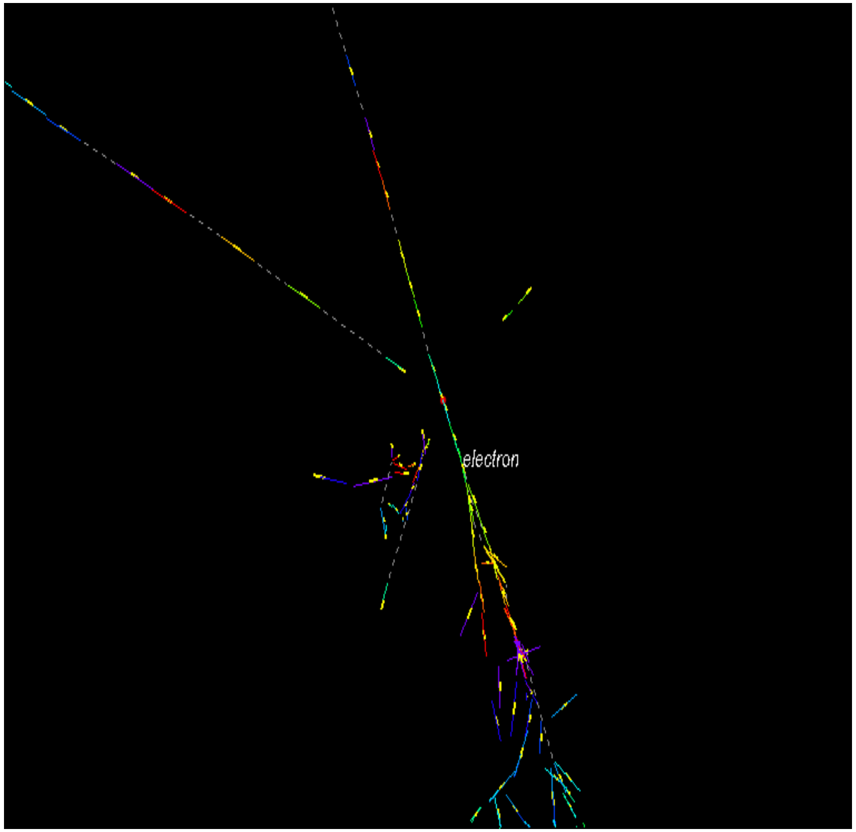
Surface energy



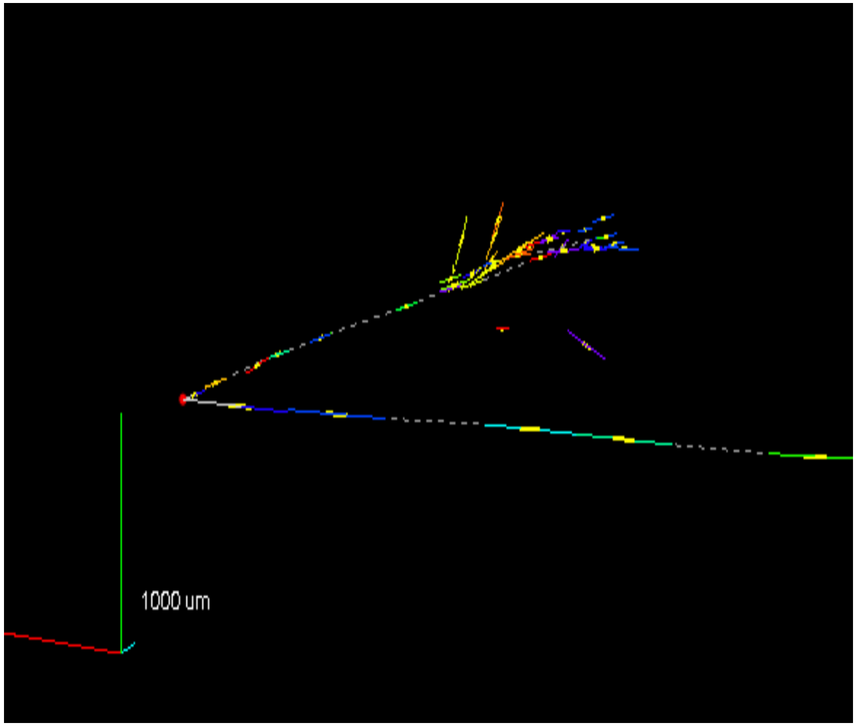
Vertical surface energy

Oscillation results

$\nu_\mu \rightarrow \nu_e$ analysis



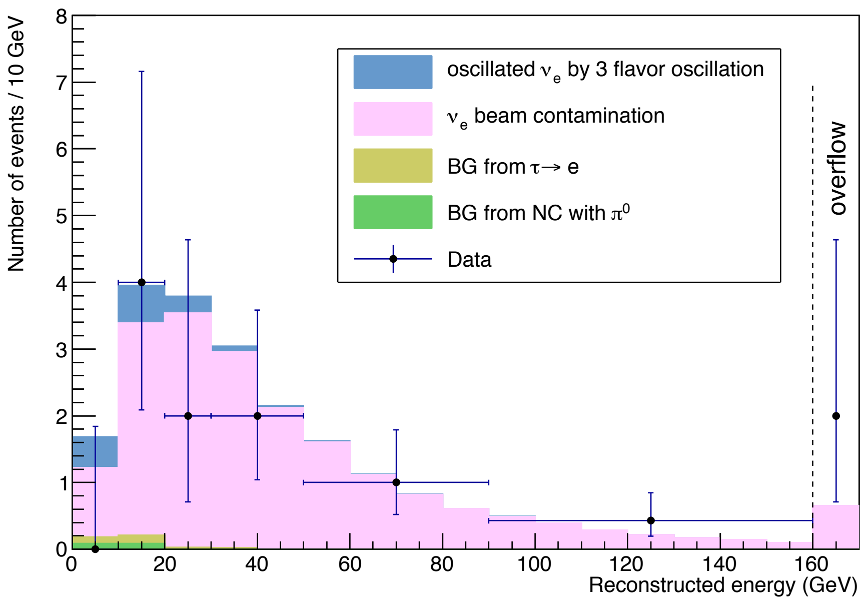
4.1 GeV electron

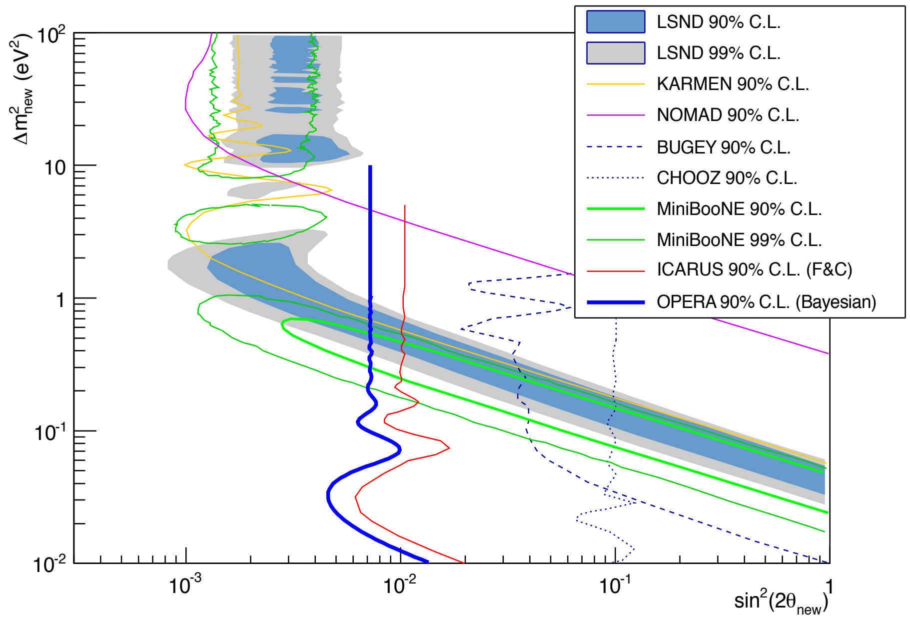


~ 40 events found in the analyzed sample

Non-standard oscillations (2008-2009 runs only)

JHEP 1307 (2013) 004





OPERA limit at large Δm^2, $\sin^2(2\theta_{new}) < 7.2 \times 10^{-3}$ (Bayesian)

New ICARUS limit at large Δm^2, $\sin^2(2\theta_{new}) < 6.8 \times 10^{-3}$ (F&C) EPJ C73 (2013) 2599

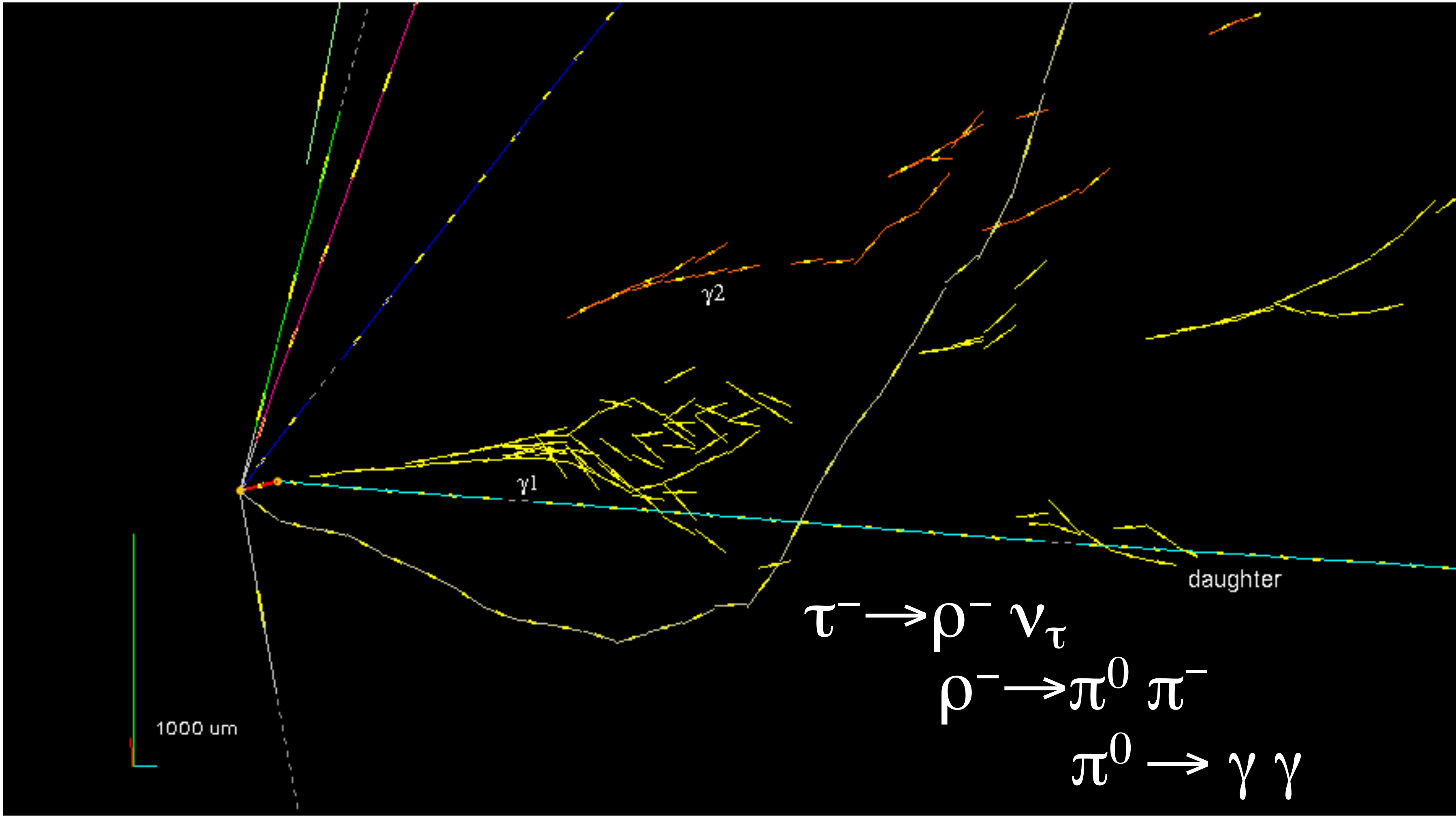
Energy cut		20 GeV	30 GeV	No cut
BG common to both analyses	BG (a) from π^0	0.2	0.2	0.2
	BG (b) from $\tau \to e$	0.2	0.3	0.3
	ν_e beam contamination	4.2	7.7	19.4
Total expected BG in 3-flavour oscillation analysis		4.6	8.2	19.8
BG to non-standard oscillation analysis only	ν_e via 3-flavour oscillation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

Caveat: experiments with different L/E values

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

- 2008-2009 runs without any kinematical selection
- Slower analysis speed (signal/noise not optimal)
- Good data/MC agreement demonstrated
- → Apply kinematical selection ($p < 15$ GeV μ momentum cut) for 2010, 2011 and 2012 runs
- Prioritize the analysis of the most probable brick for all the events: optimal ratio between efficiency and analysis time. Then analyse the second, and 3rd and 4th ones

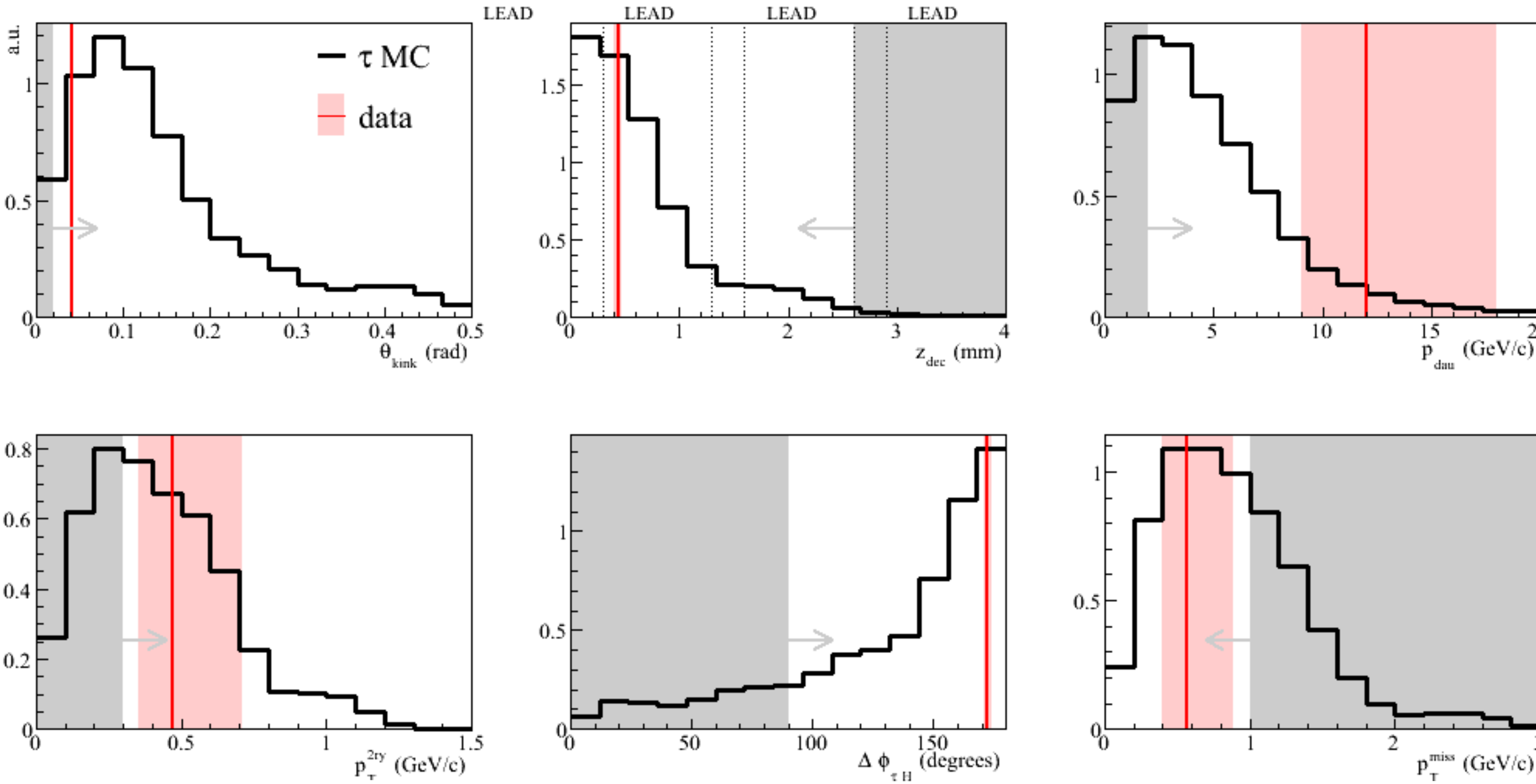
The first tau neutrino candidate event



Physics Letters B691 (2010) 138

Kinematical variables. All cuts passed: $\tau \rightarrow h$ candidate

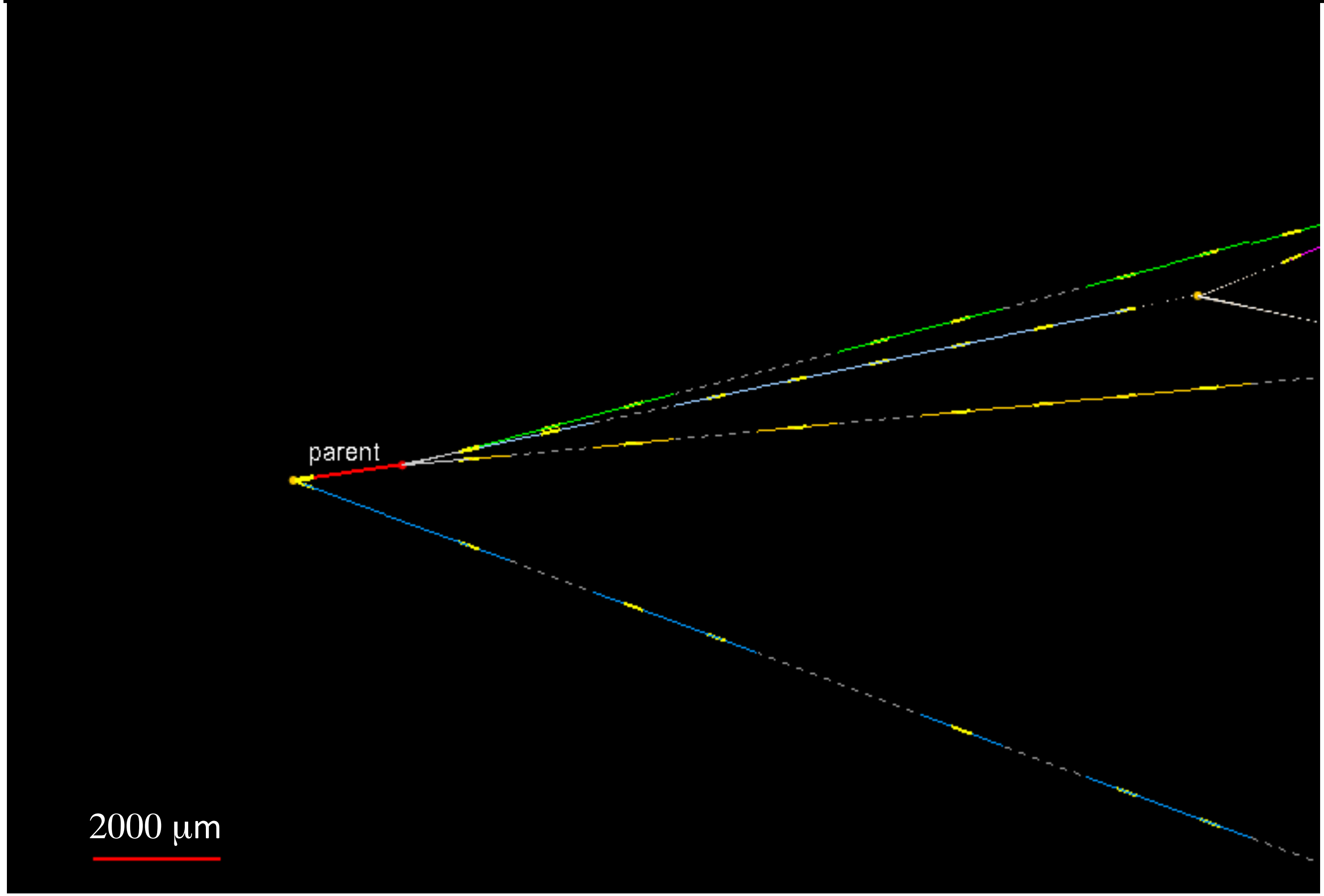
Physics Letters B691 (2010) 138



Kink angle (mrad)	**41 ± 2**
decay length (μm)	**1335 ± 35**
Φ (degrees)	**173±2**

P_{2ry}(GeV/c)	12^{+6}_{-3}
P_{tmiss} (MeV/c)	570^{+320}_{-170}
Pt_{2ry} (MeV/c)	470^{+240}_{-120}

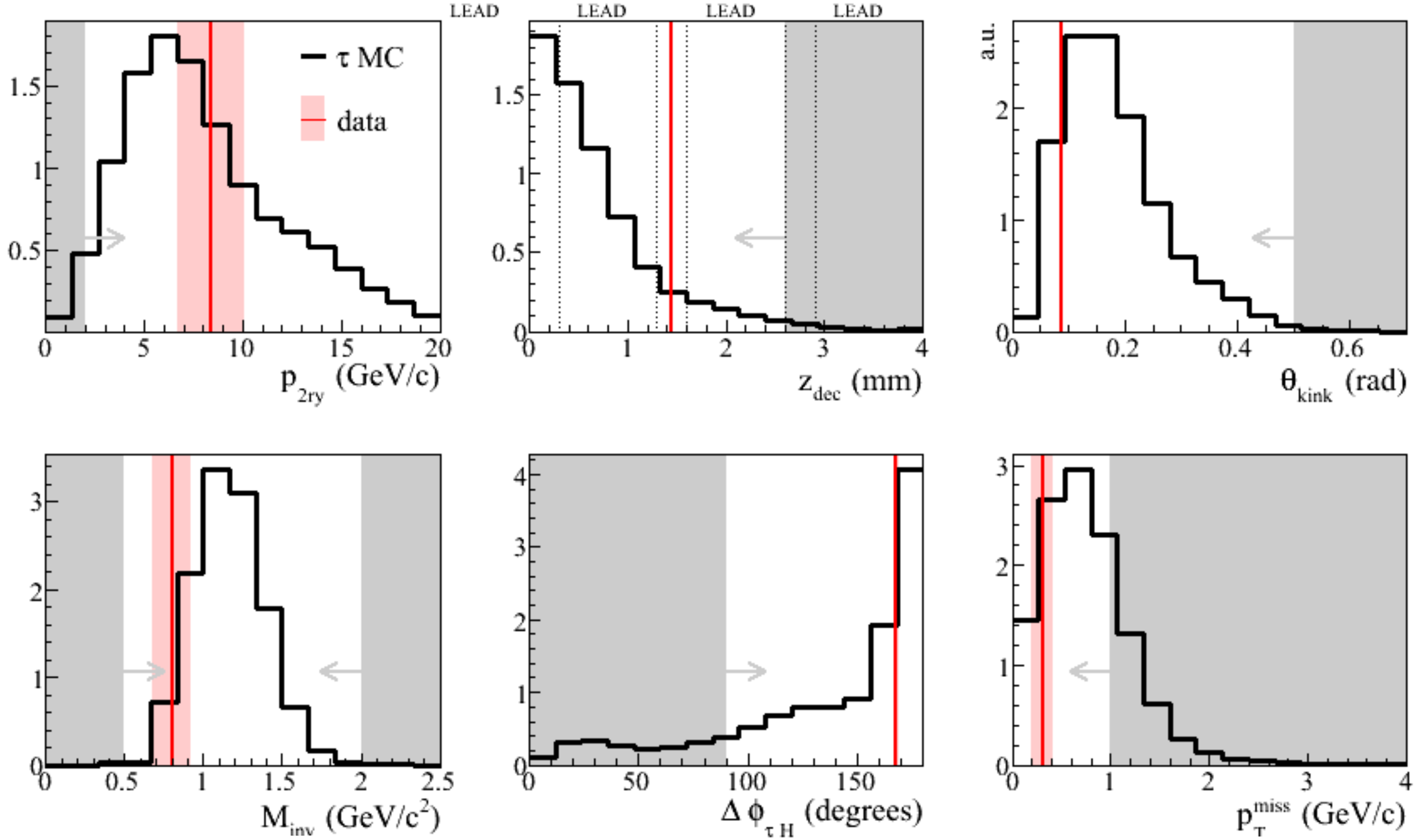
Second ν_τ Candidate Event



Journal of High Energy Physics 11 (2013) 036

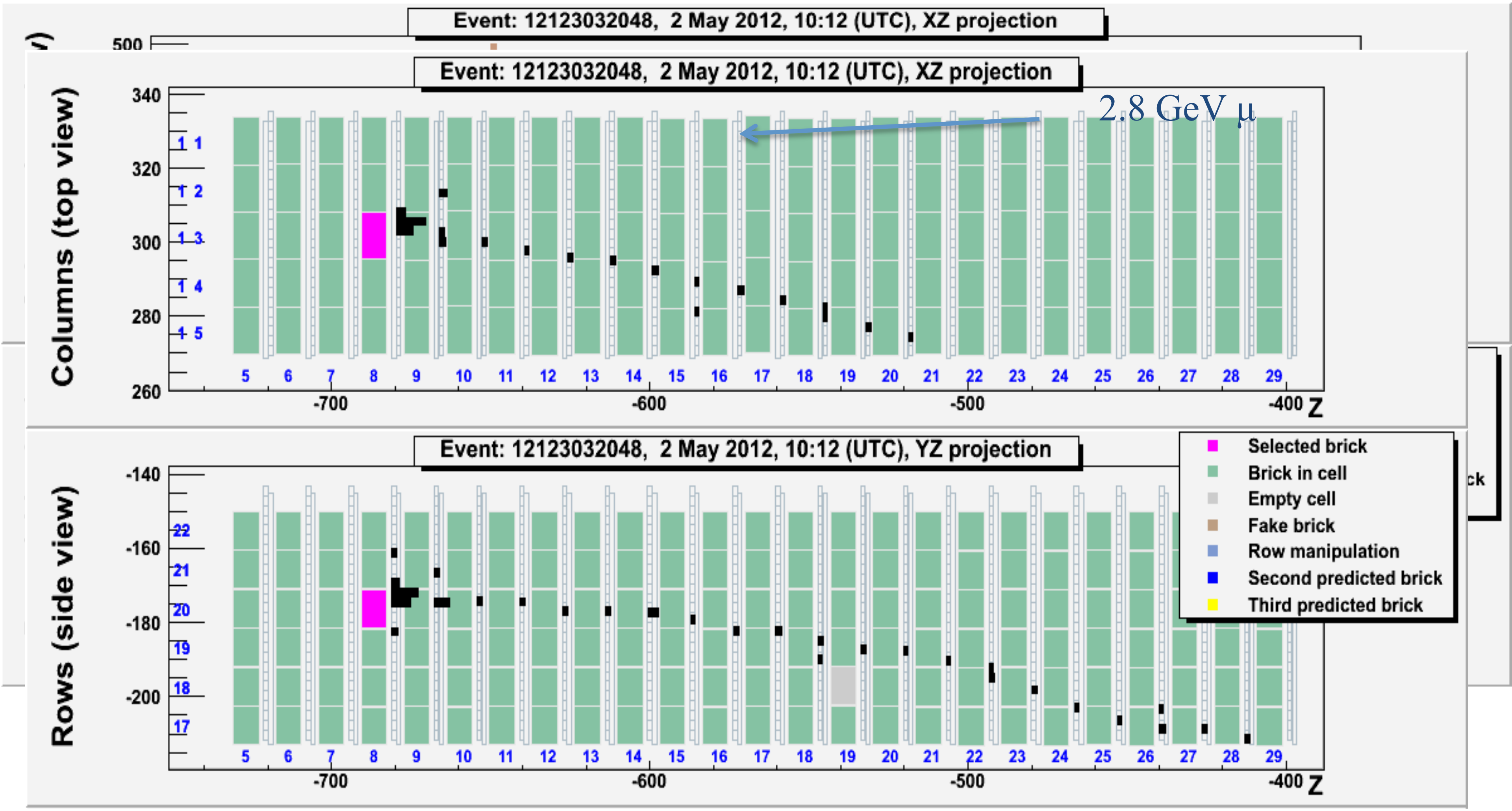
Kinematical variables. All cuts passed: τ →3h candidate

Journal of High Energy Physics 11 (2013) 036



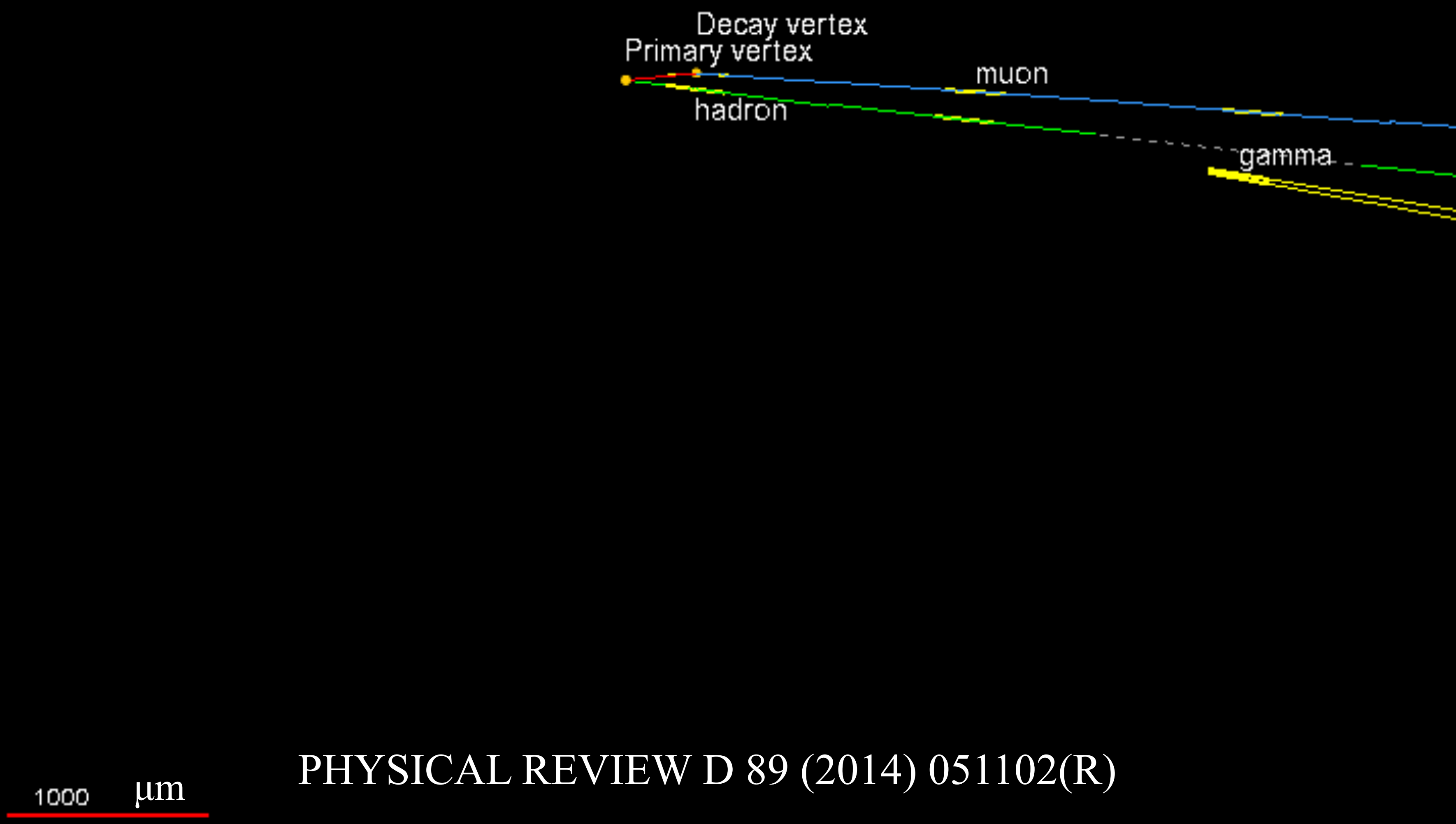
Average kink angle (mrad)	87.4 ± 1.5	P_{2ry}(GeV/c)	8.4±1.7
φ (degrees)	167.8±1.1	P_{tmiss} (MeV/c)	310±110
Decay length (μm)	1466±10	M (GeV/c^2)	0.80±0.12

Third tau neutrino event taken on May 2nd 2012



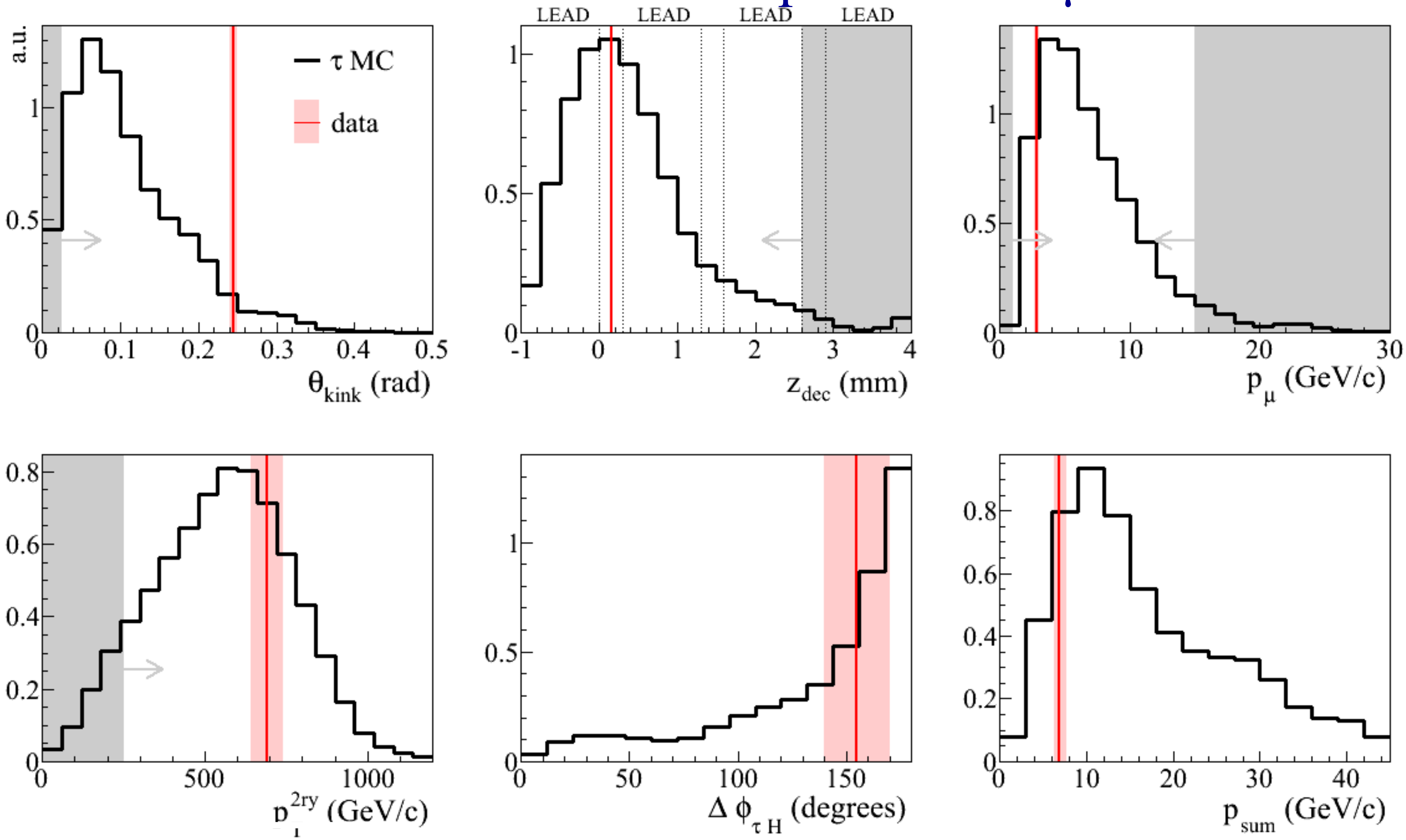
Third tau neutrino event

$\tau \rightarrow \mu$



PHYSICAL REVIEW D 89 (2014) 051102(R)

Kinematical variables. All cuts passed: $\tau \rightarrow \mu$ candidate



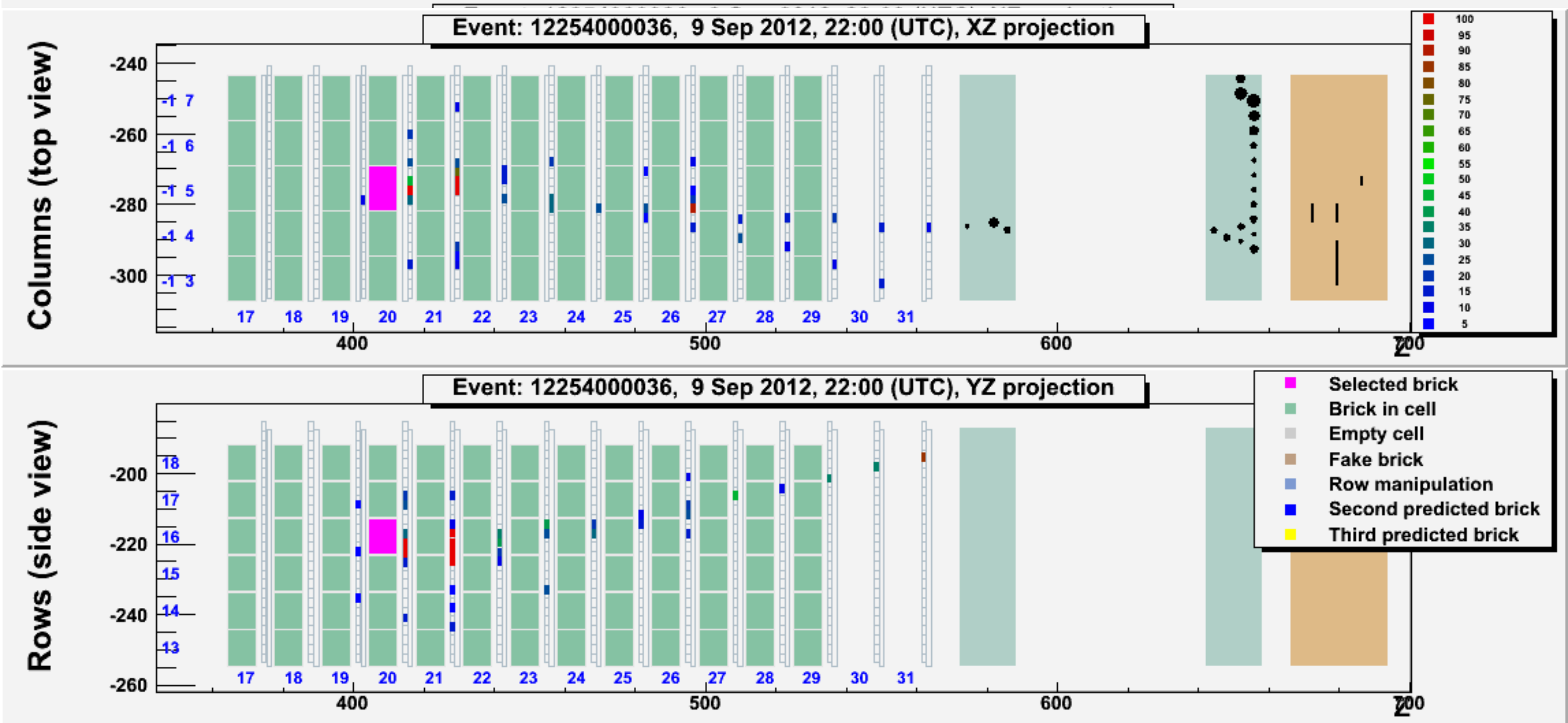
Kink angle (mrad) **245 ± 5**

decay length (μm) **376 ± 10**

PHYSICAL REVIEW D 89 (2014) 051102(R)

Pμ (GeV/c)	**2.8±0.2**
Pt (MeV/c)	**690±50**
ϕ (degrees)	**154.5 ± 1.5**

Fourth tau neutrino event taken in September 2012

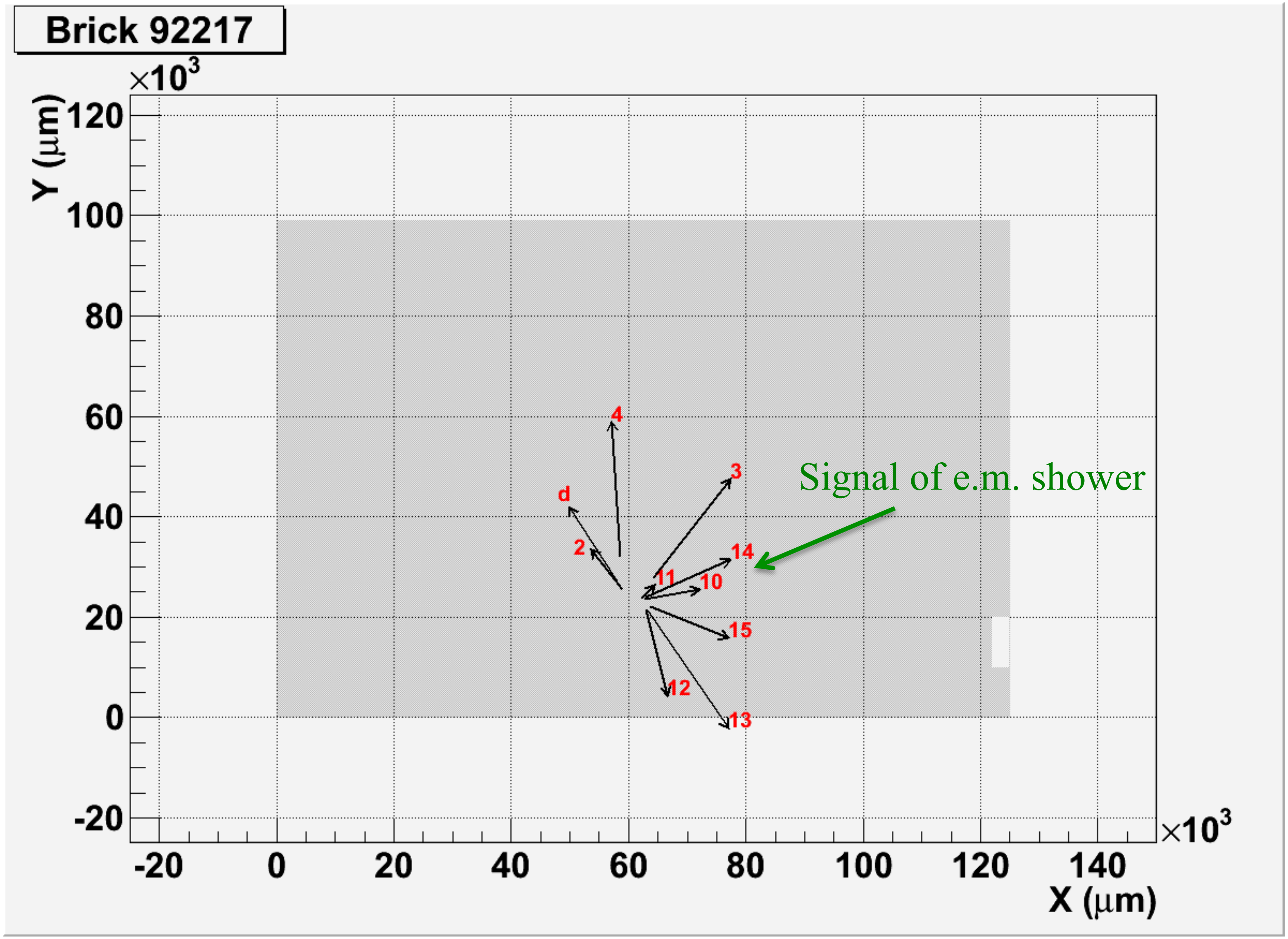


Brick finding information: Super module 2

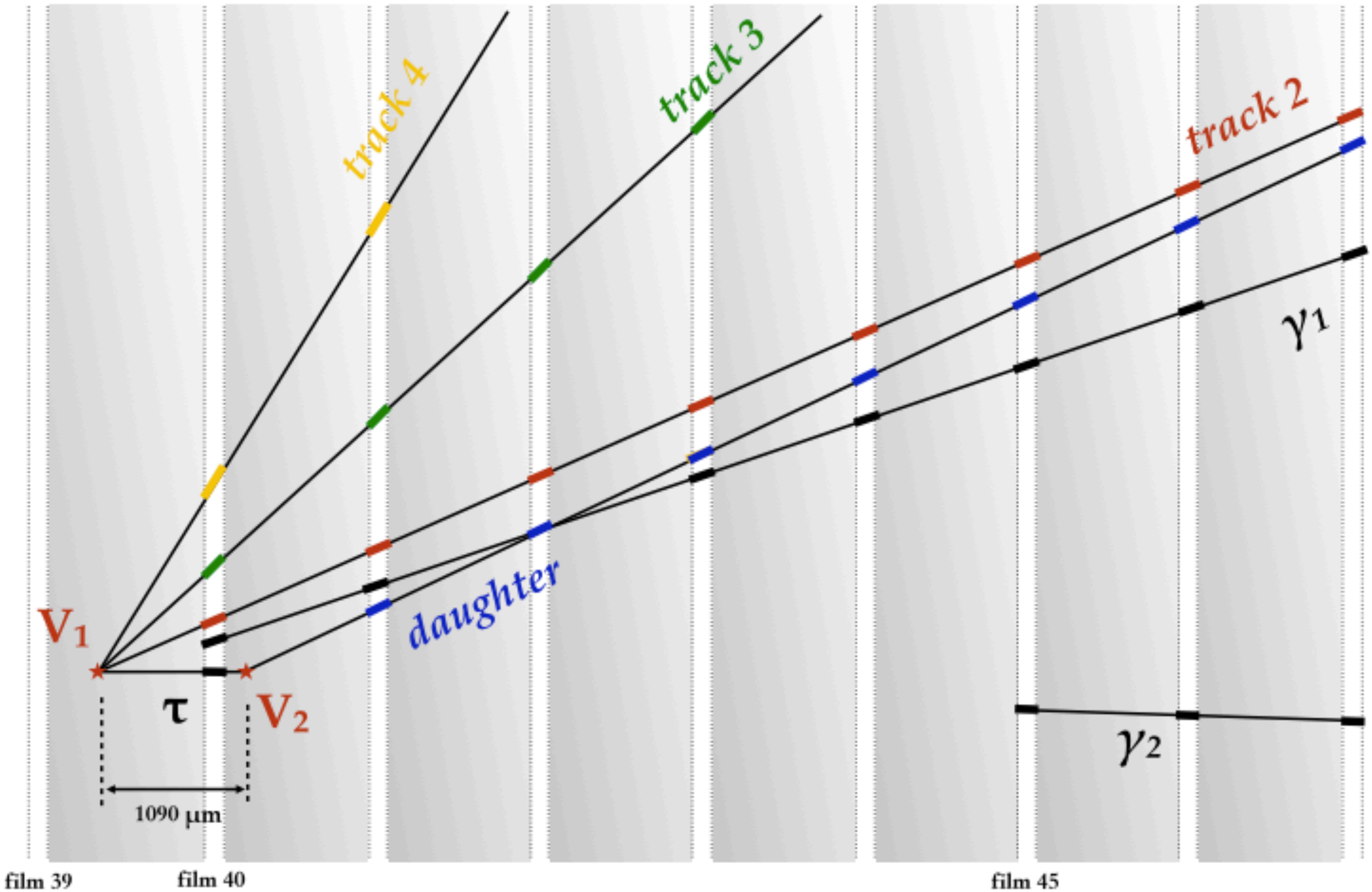
	BrickId	Wall	Side	Column	Row	Prob	CS x	CS y
brick 1:	1092217	20	-1	5	16	0.77	-1.0	-1.0
brick 2:	1089442	20	-1	5	15	0.12	-1.0	-1.0
brick 3:	1000527	21	-1	5	16	0.07	-1.0	-1.0

Muon track parameters:
Momentum: N/A
Tangent angle XZ: N/A
Tangent angle YZ: N/A

Analysis of interface emulsion films

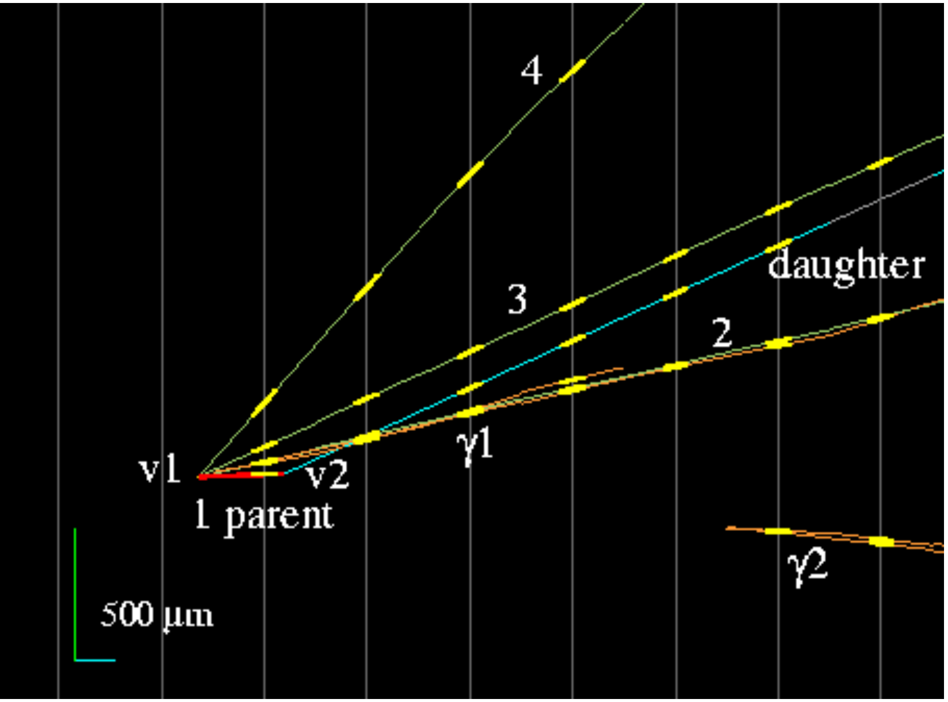


Schematic view of the event topology

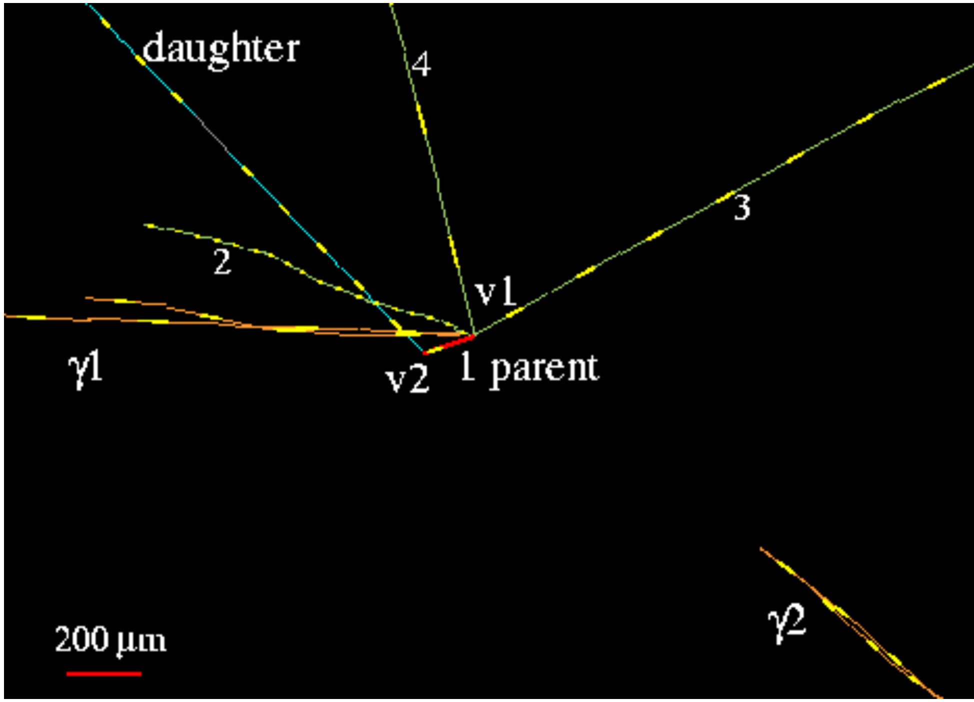


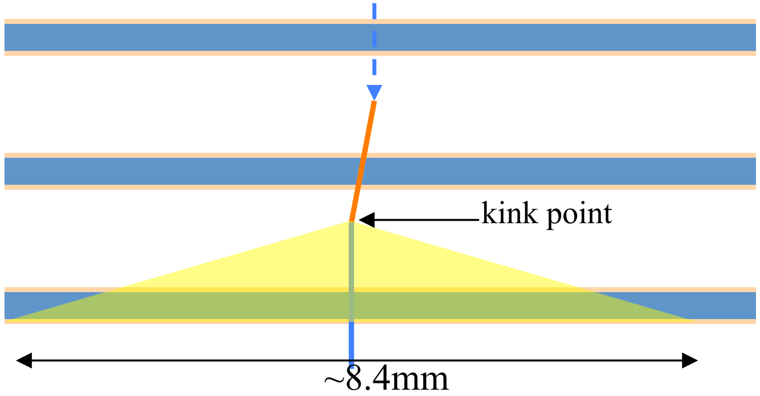
Event topology

Side view



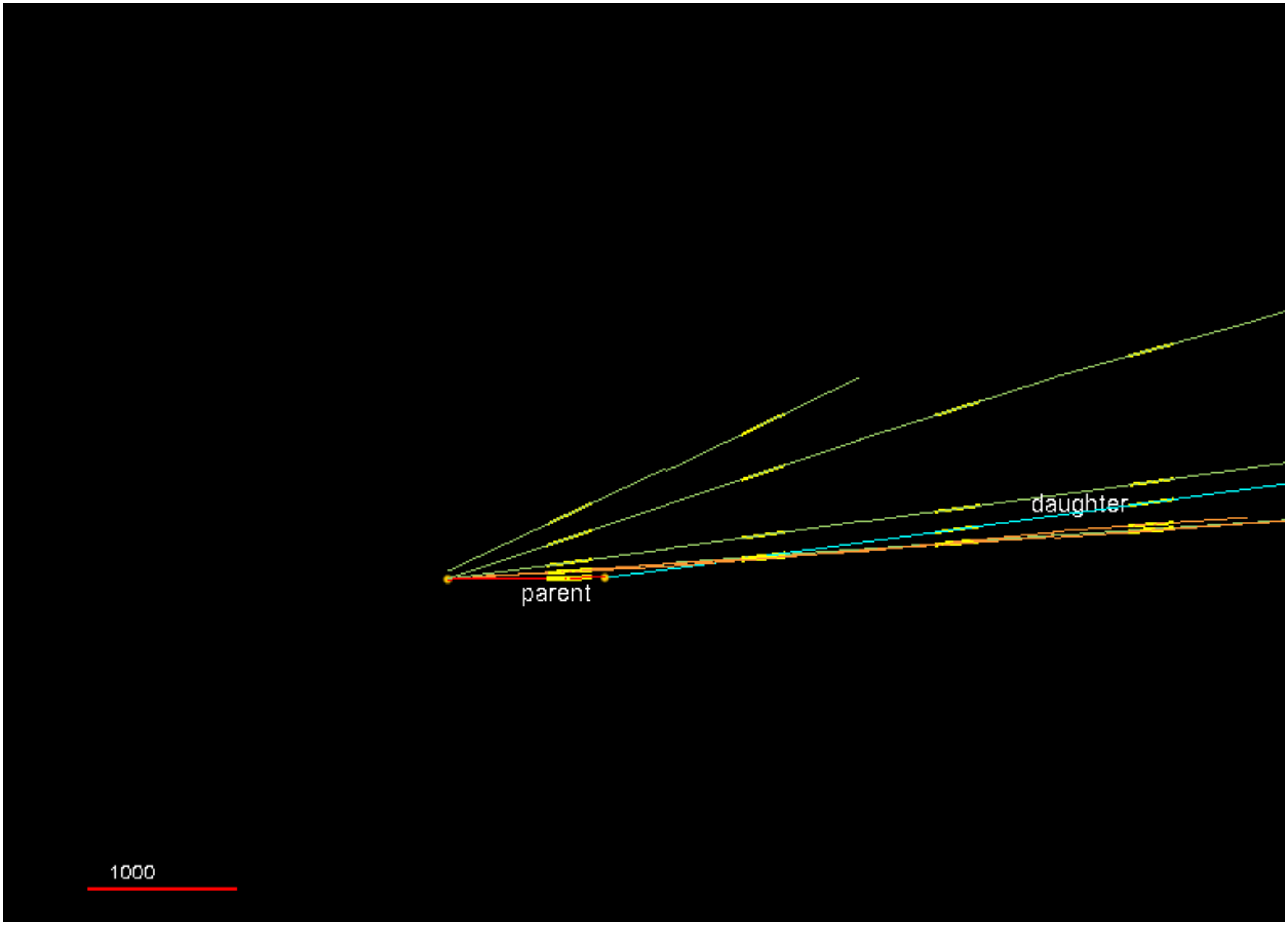
Beam view





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

Event topology



Track features

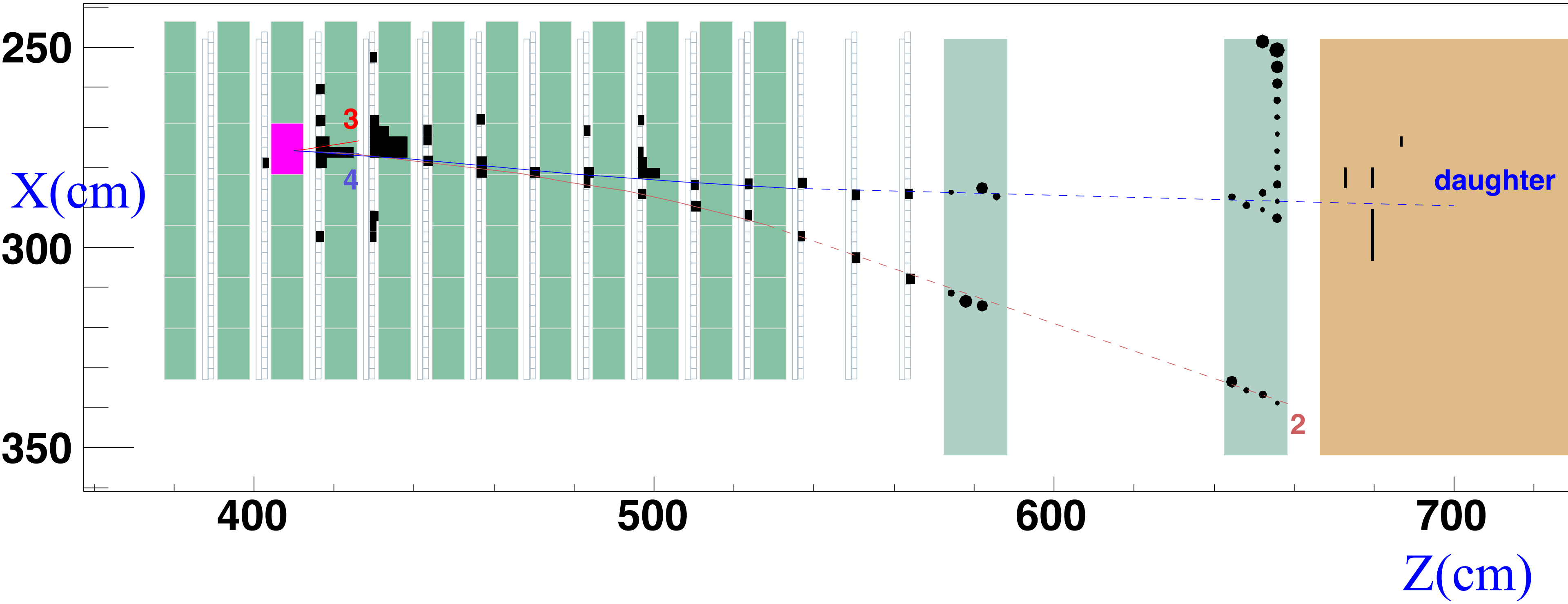
			First measurement	Second measurement	Average	
	Track ID	Particle ID	Slopes	Slopes	**Slopes**	**P (GeV/c)**
1ry	1 parent	τ	-0.143, 0.026	-0.145, 0.014	**-0.144, 0.020**	**-**
	2	Hadron (Range)	-0.044, 0.082	-0.047, 0.073	**-0.046, 0.078**	**1.9 [1.7, 2.2]**
	3	Hadron (interact)	0.122, 0.149	0.139, 0.143	**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]** pβ = 0.4 [0.3, 0.5]
	γ1	e-pair	-0.229, 0.068	-0.238, 0.055	**-0.234, 0.062**	**0.7 [0.6, 0.9]**
	γ2	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**
γ1	To 1ry	676	21.9	**2**	**8**	**OK**
γ2	To 1ry	7176	9.2	**33**	**43**	**OK**
	To 2ry	6124	9.2	**267**	**36**	**Excluded**

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

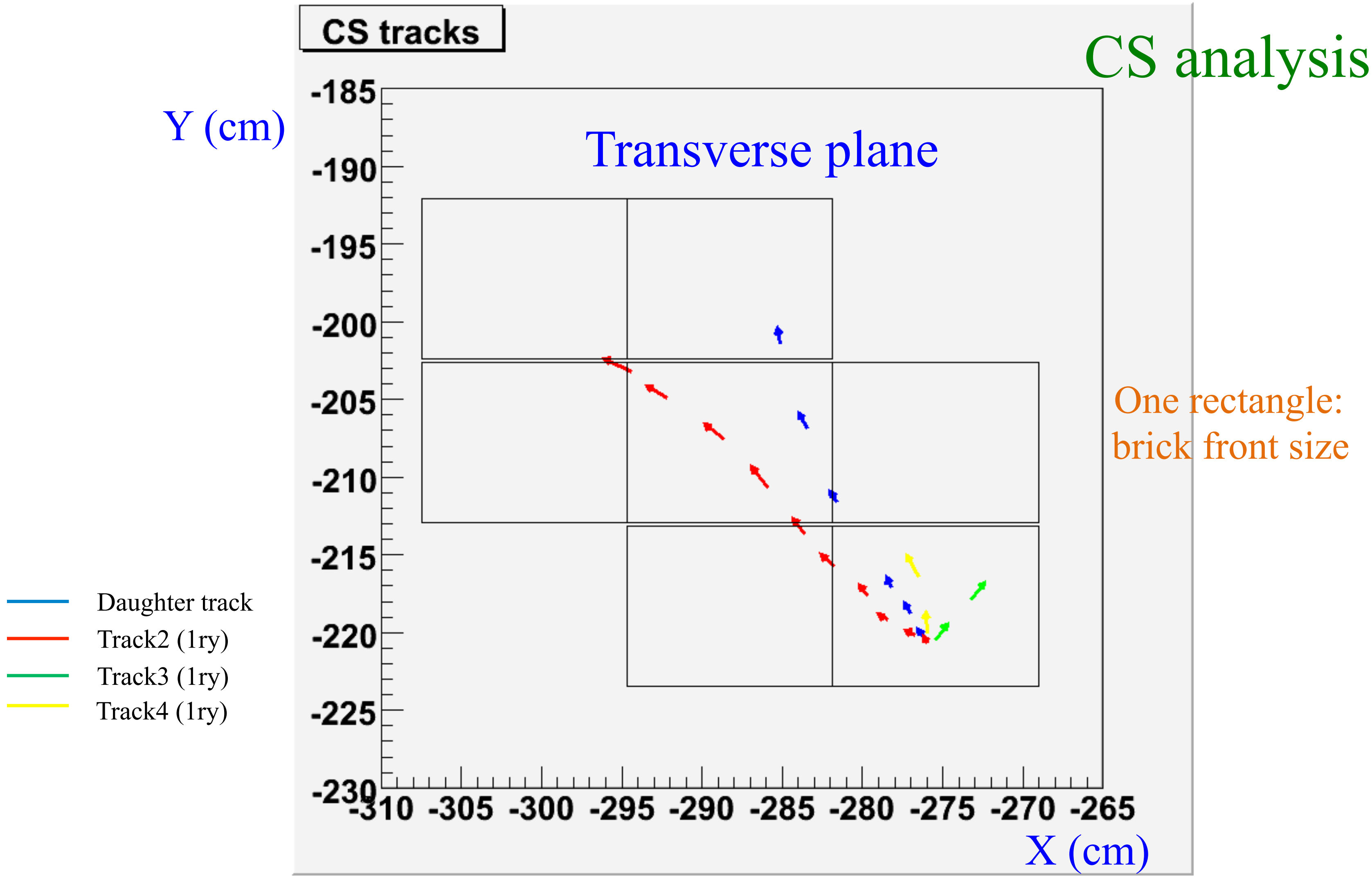
Not a single π^0

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

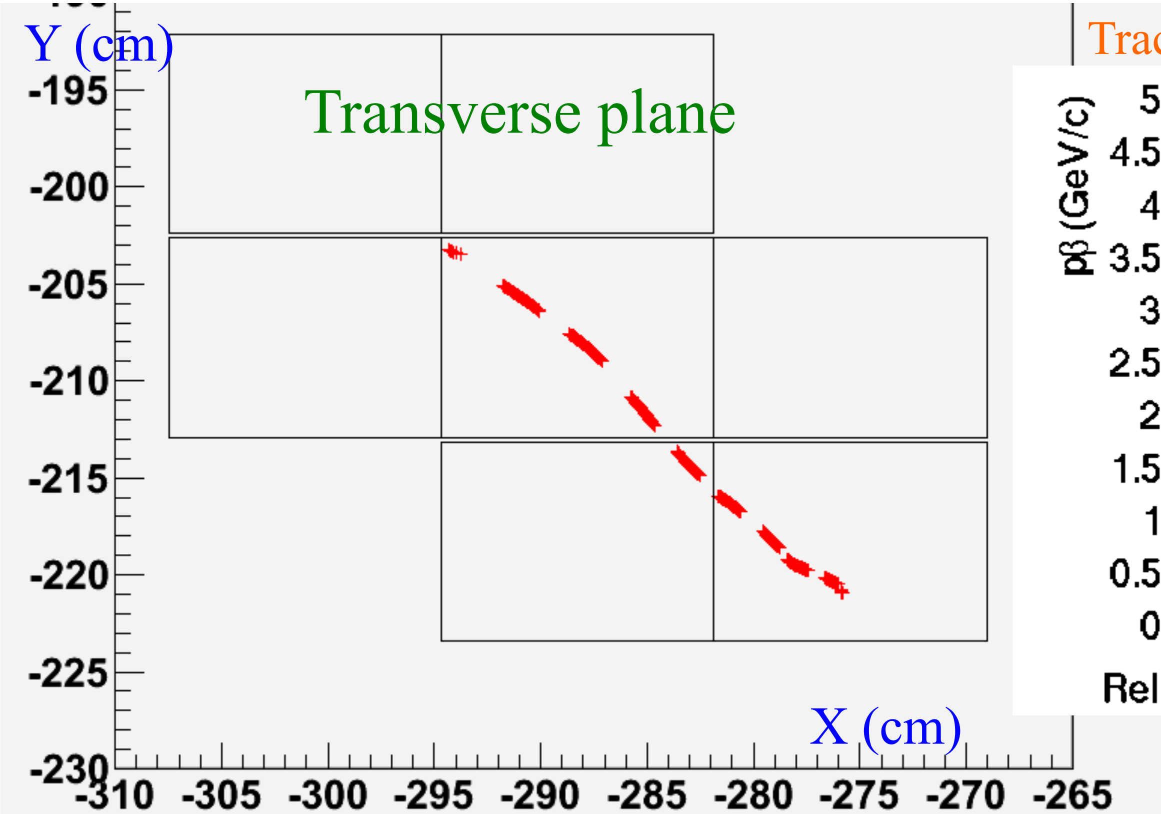


Follow-down all tracks in downstream bricks

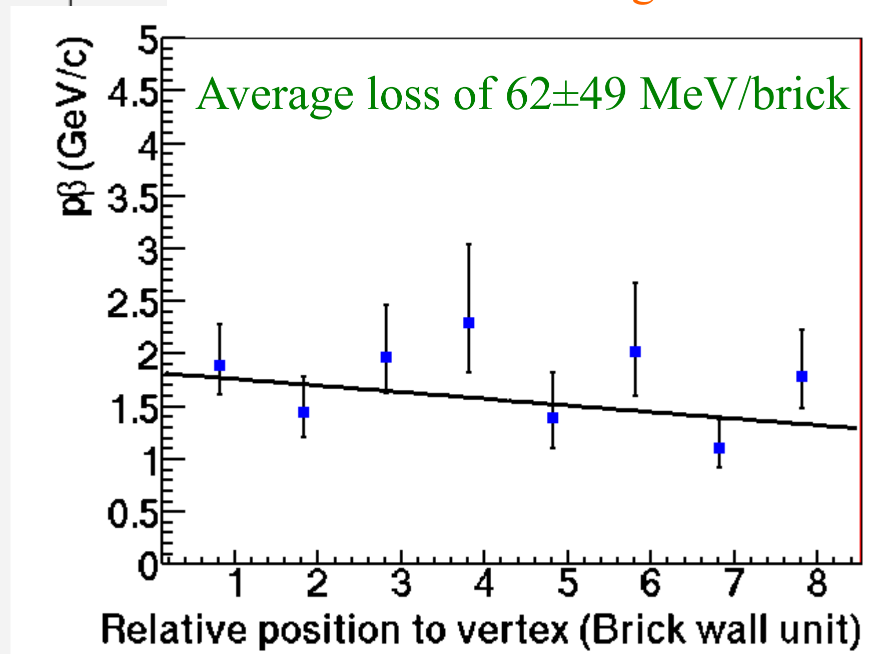
- 3 primary tracks to discard the charm hypothesis
- kink daughter to identify the τ decay channel

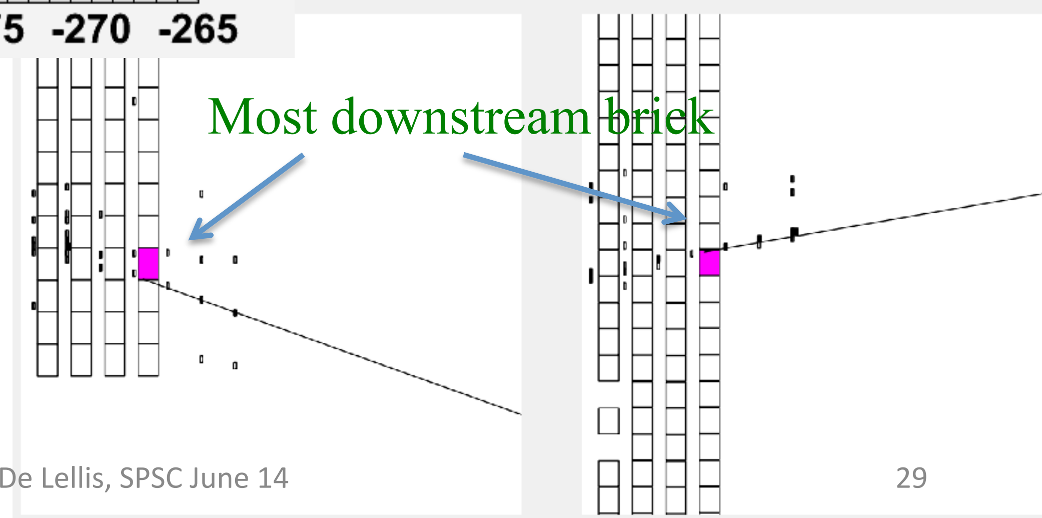


Track follow-down: primary track n. 2

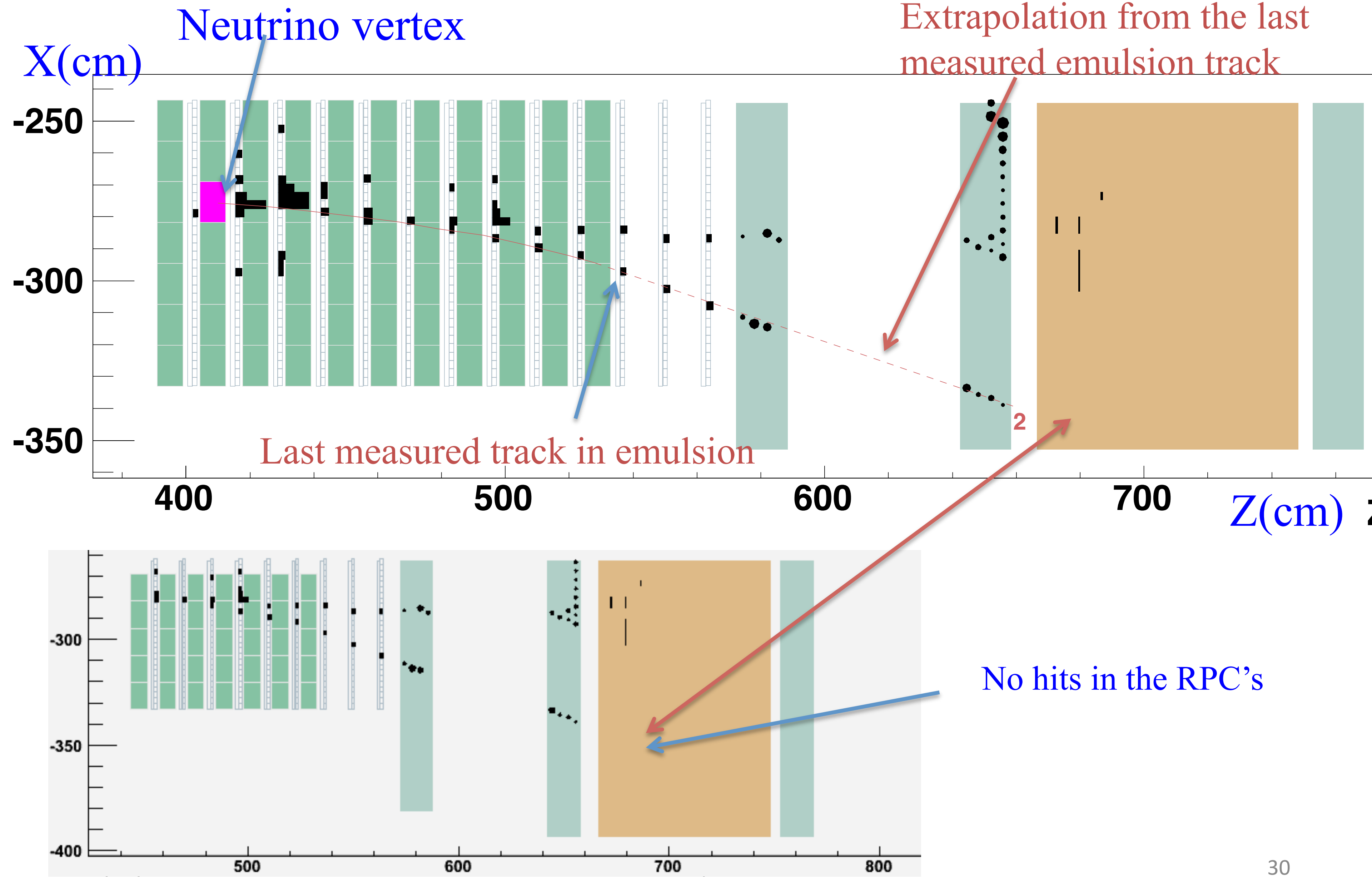


Track 2 followed-down along 10 bricks



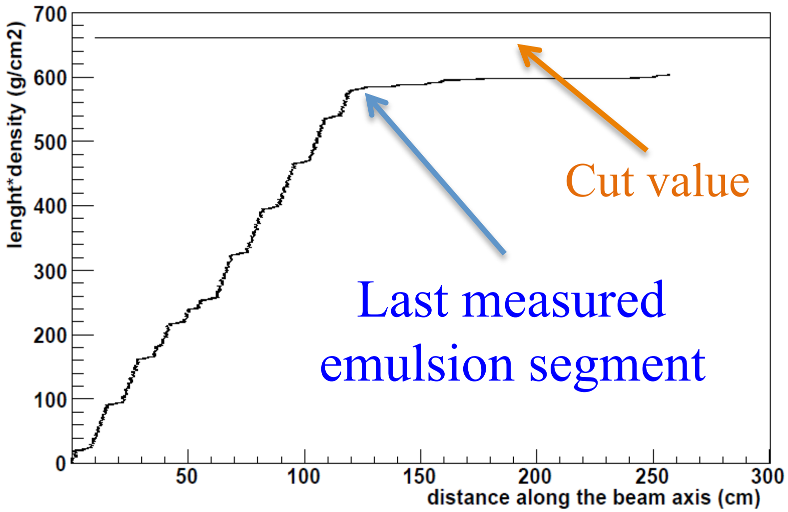


Track n. 2 follow-down

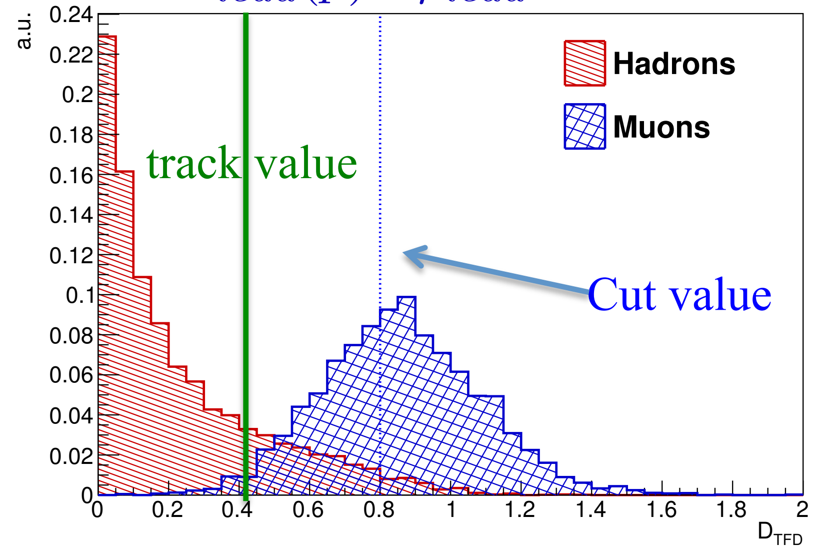


Measured length x density, Lρ

Lρ = 604 g/cm^2 (<660 g/cm^2)



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



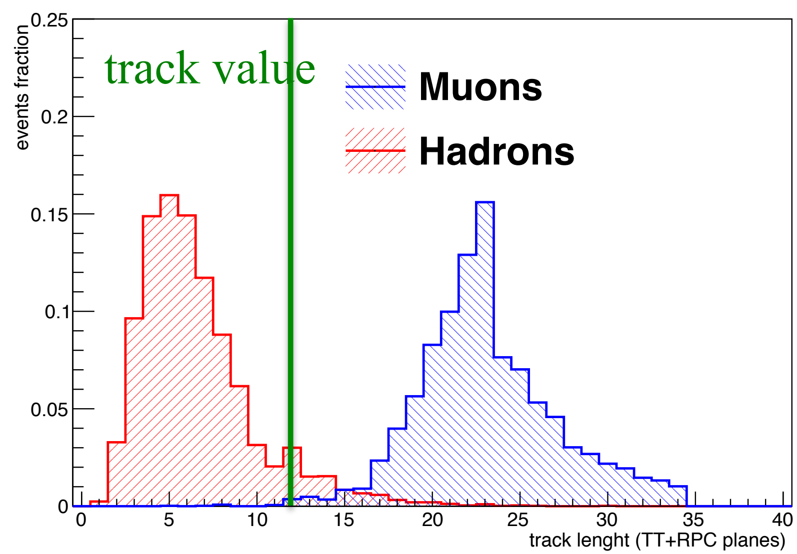
Muon hypothesis rejected

Additional check:
Generate π and μ tracks originating in the same position as the observed event with momenta

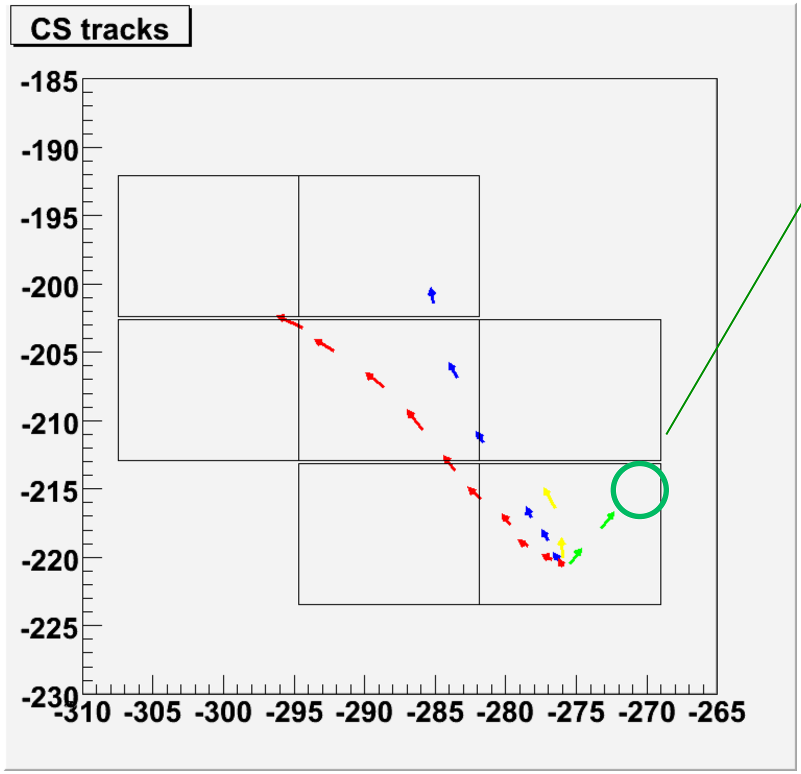
$$P = 1.9^{+0.3}_{-0.2}\ \mathrm{GeV}/c$$

- Prob. for a μ to cross ≤ 12 planes ~ 0.4%
- Prob. for a π to cross ≥ 12 planes ~ 9.2%

→ Confirm the rejection of the muon hypothesis

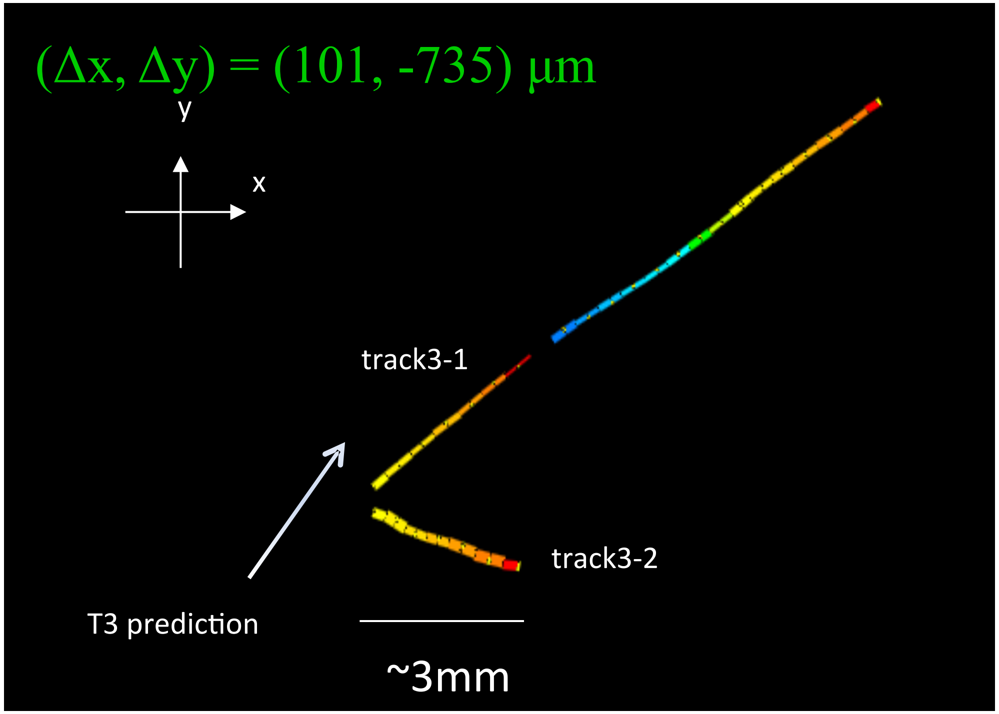


Track follow-down: primary track n. 3



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

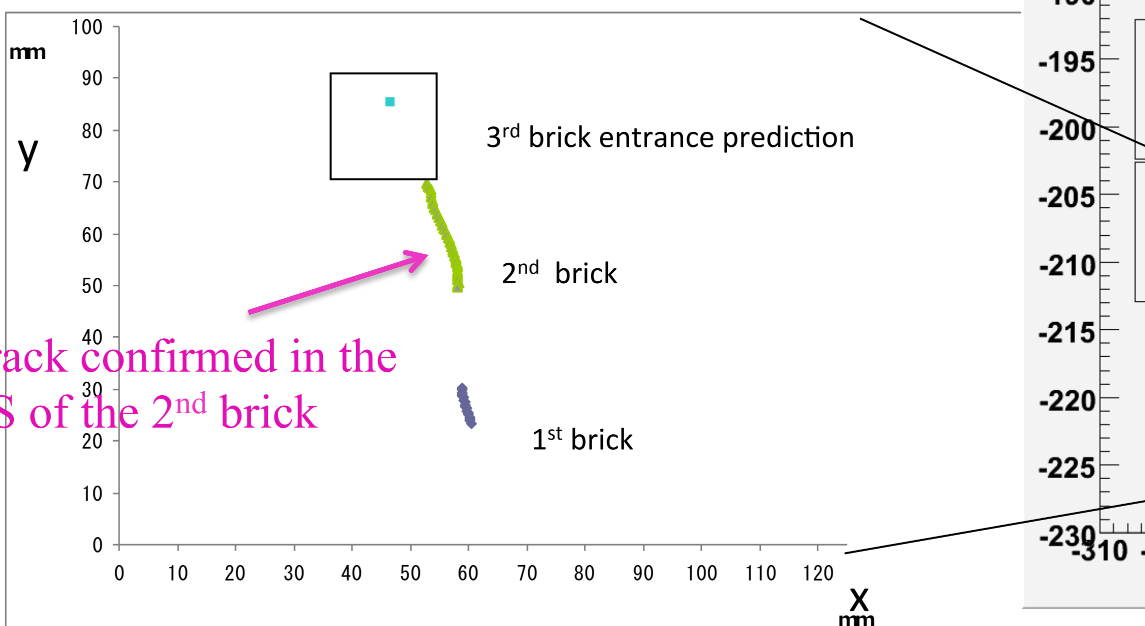
From the ionization, the proton hypothesis is made

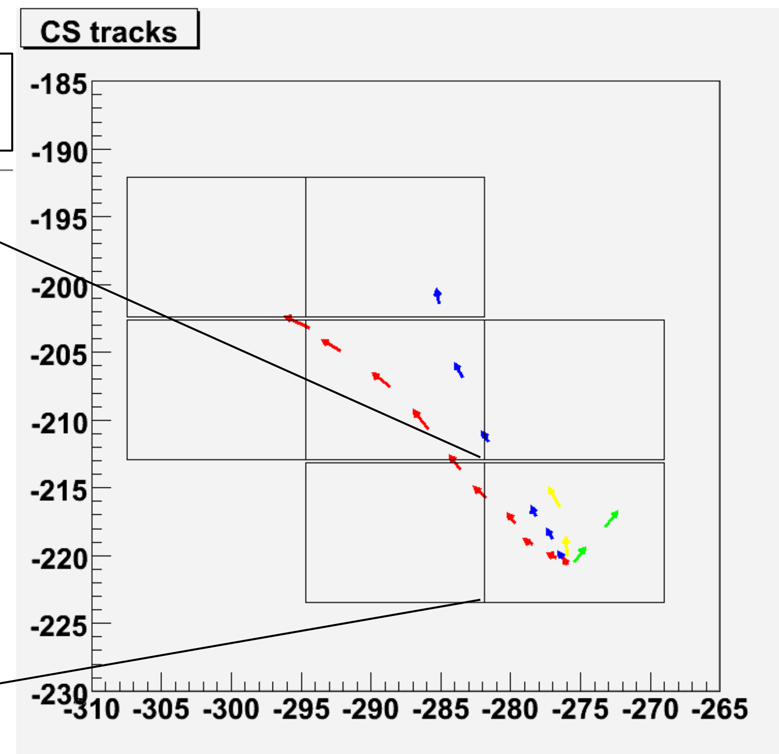
Pβ ~ 0.4, (P = 0.7 assuming proton mass)

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

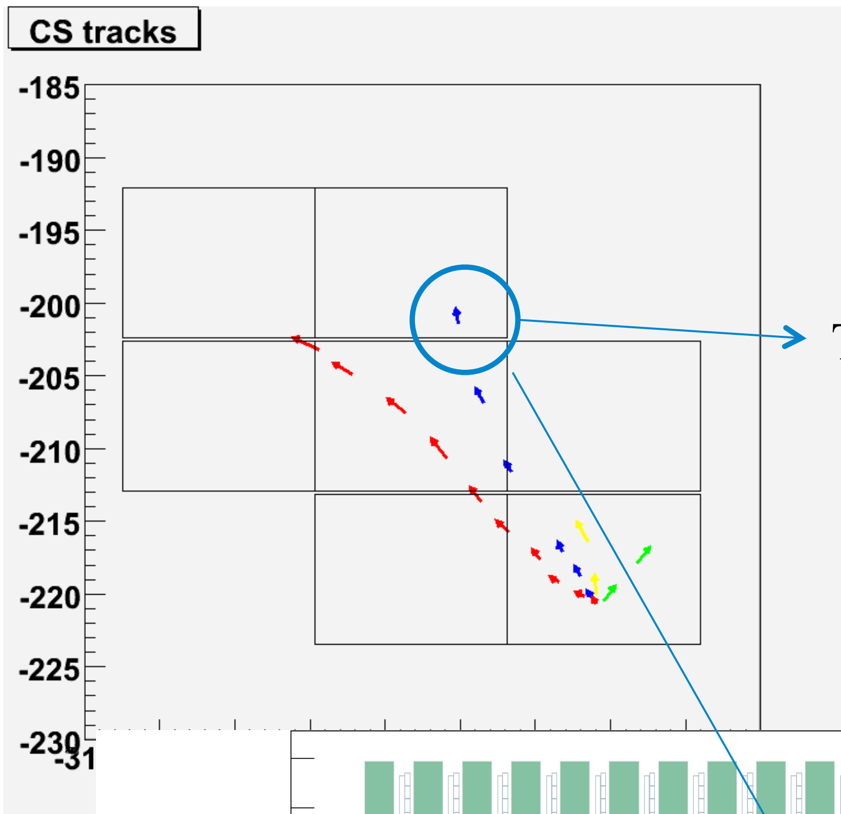
Expected Range/Mass from measured momentum ~ 70 [45-100] g cm^{-2} GeV^{-1}

Consistent with the **proton** hypothesis





Kink daughter track



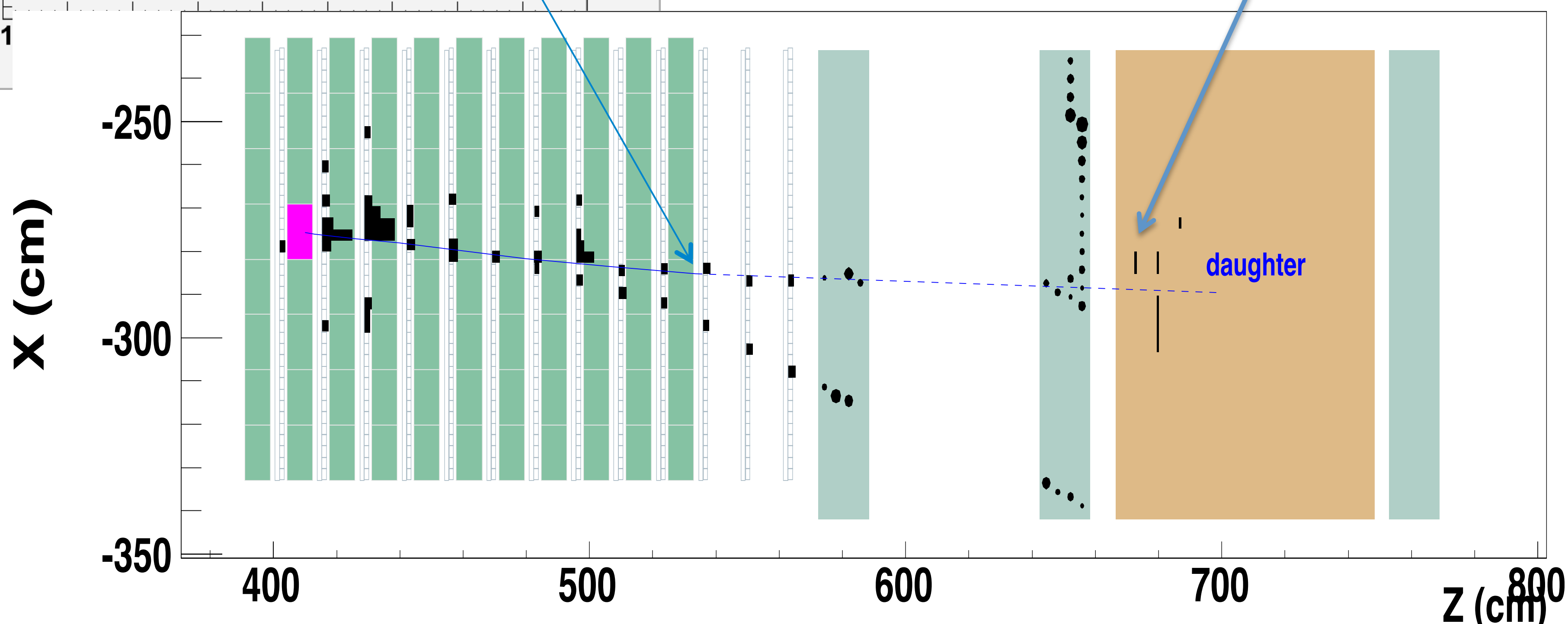
The track in the CS of the most downstream brick

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

Range/momentum → hadron

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

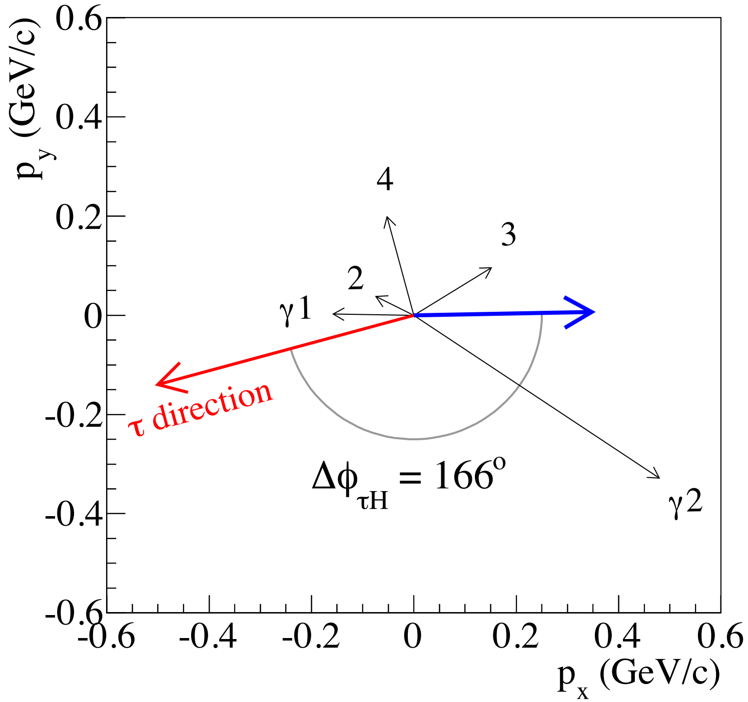
Sign of interaction



Kinematical variables

Variable	Selection	Measured value
θ_{kink} (mrad)	> 20	137 ± 4
z_{dec} (μm)	< 2600	406 ± 30
p_{2ry} (GeV/c)	> 2	$6.0^{+2.2}_{-1.2}$
p_T^{2ry} (GeV/c)	> 0.6 (0.3^*)	$0.82^{+0.30}_{-0.16}$
p_T^{miss} (GeV/c)	< 1	$0.55^{+0.30}_{-0.20}$
$\Delta\phi_{\tau H}$ (degrees)	> 90	166^{+2}_{-31}

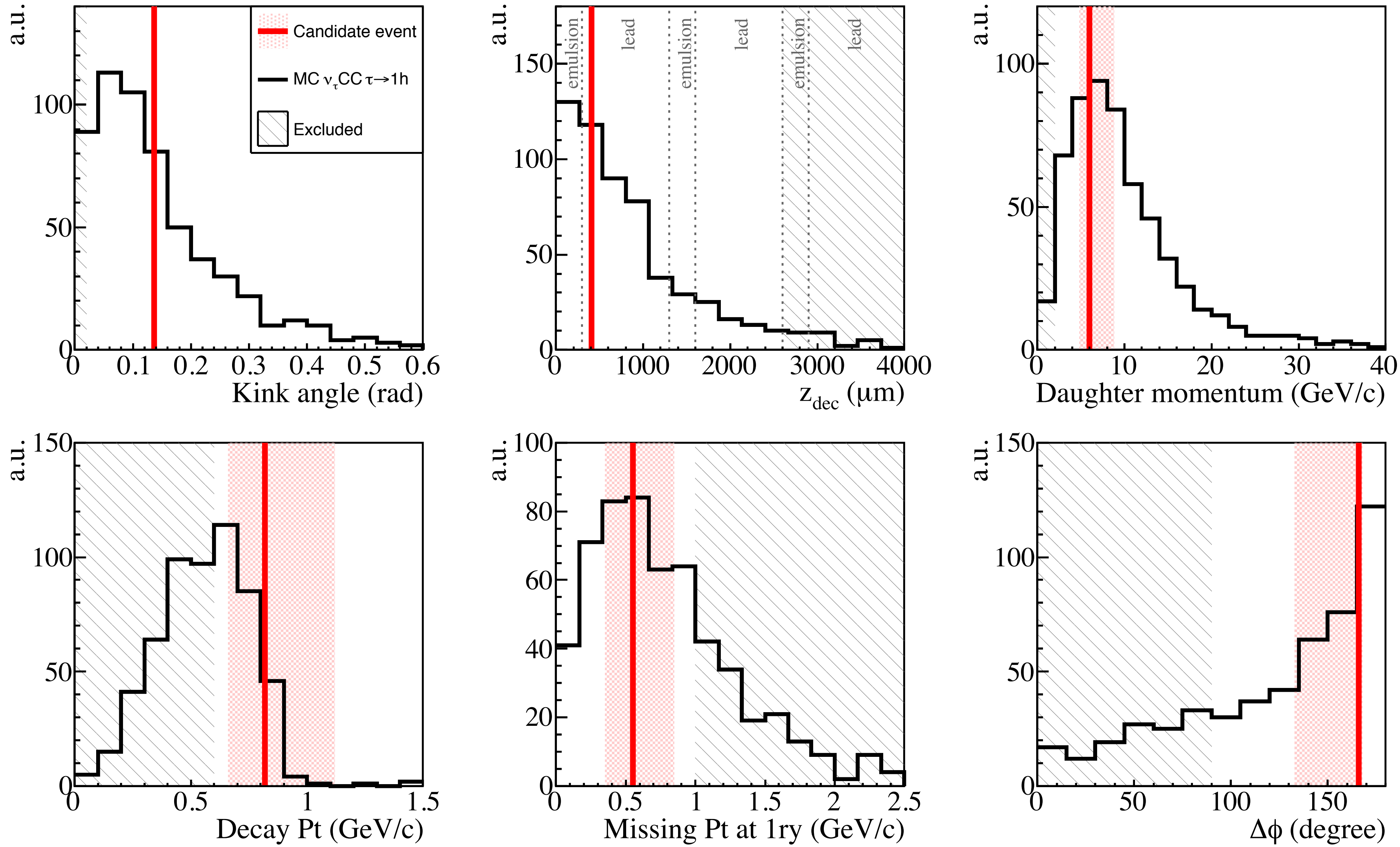
Transverse plane



It passes all the kinematical cuts

Paper being submitted

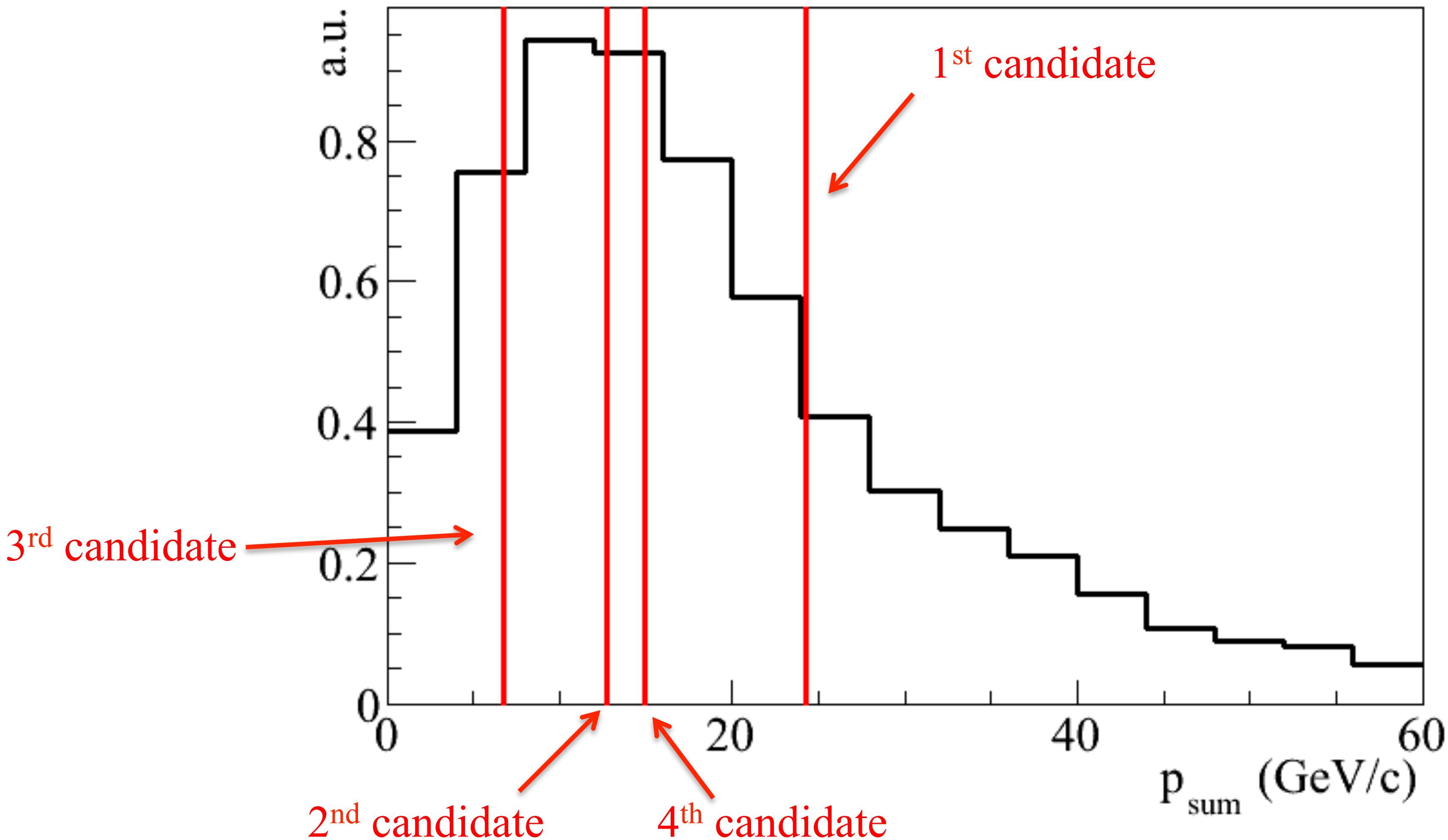
Kinematical variables: all cuts passed. τ → h channel



Paper being submitted

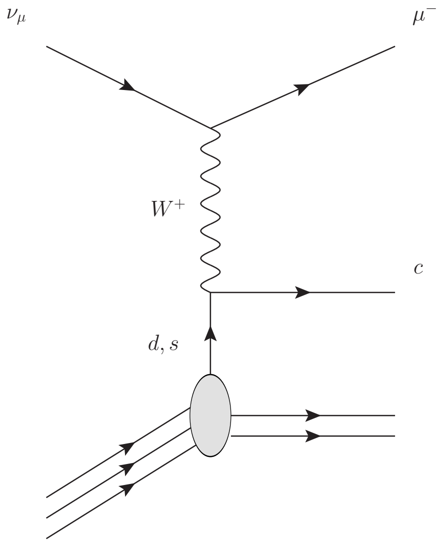
Visible energy of all the candidates

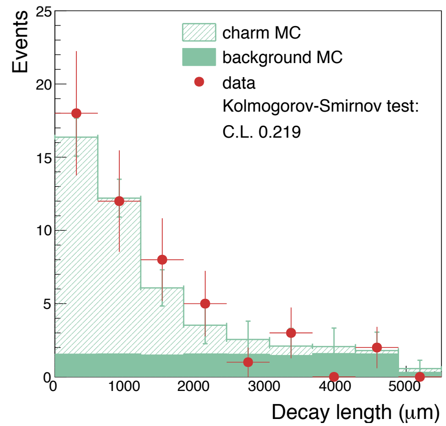
Sum of the momenta of charged particles and γ's measured in emulsion

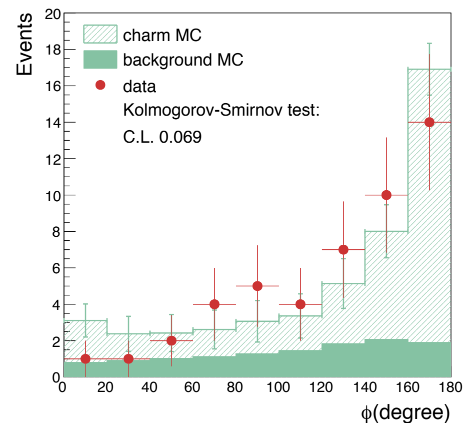


Control sample and background studies

Charm events as a control sample

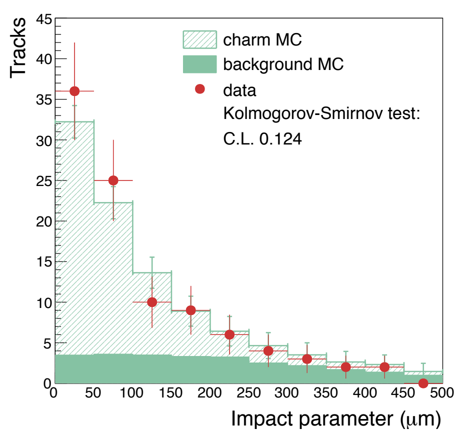


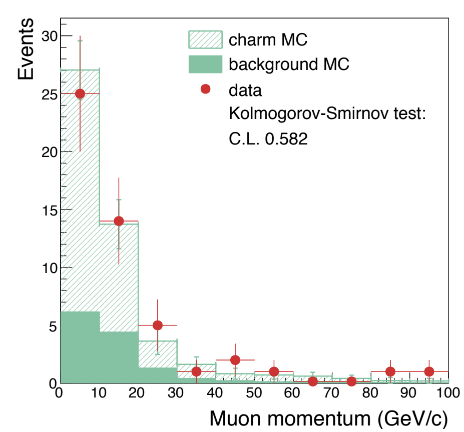




arXiv:1404.4357, being published on EPJC

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 ± 2	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



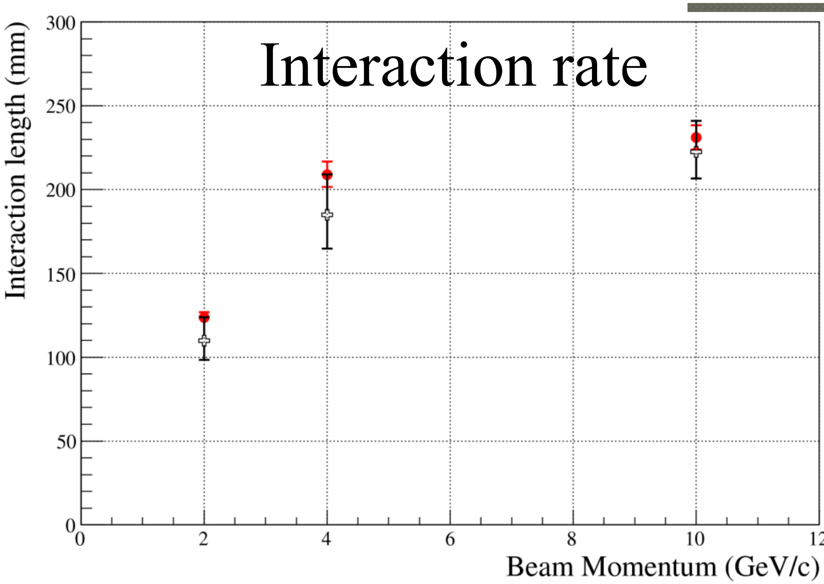


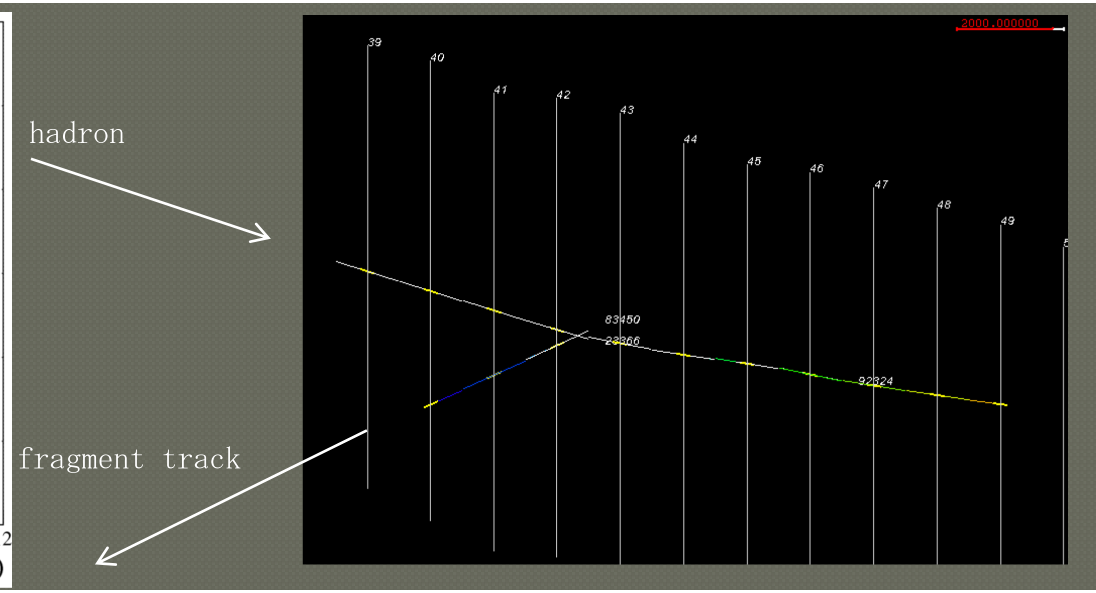
Good agreement both in normalization and in shape

Background studies: hadronic interactions

Comparison of large data sample (π^- 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



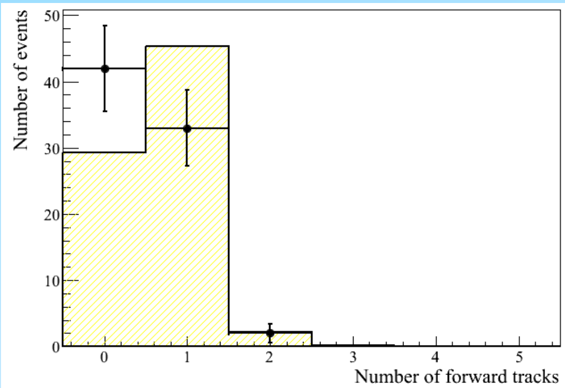


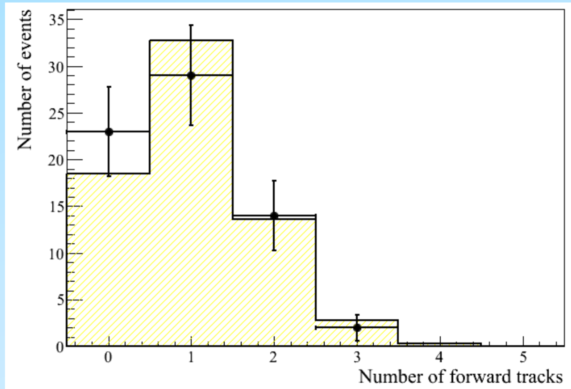
Black : π^- beam data
Red : MC (FLUKA) simulation

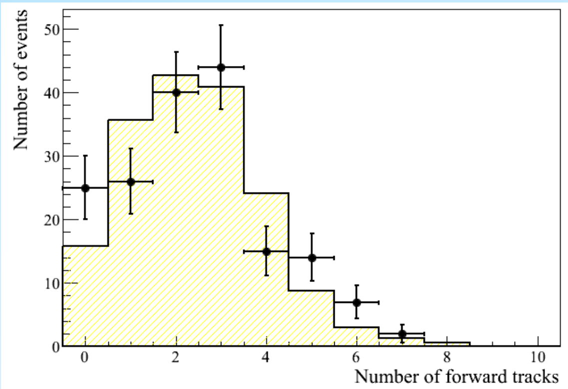
Secondary track emission

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

Multiplicity

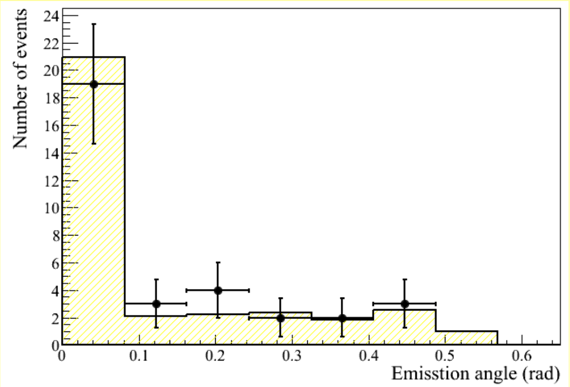


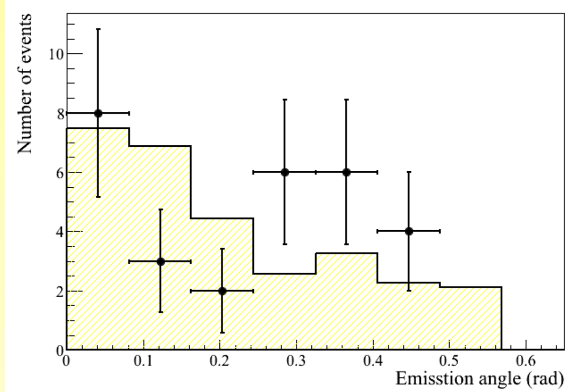


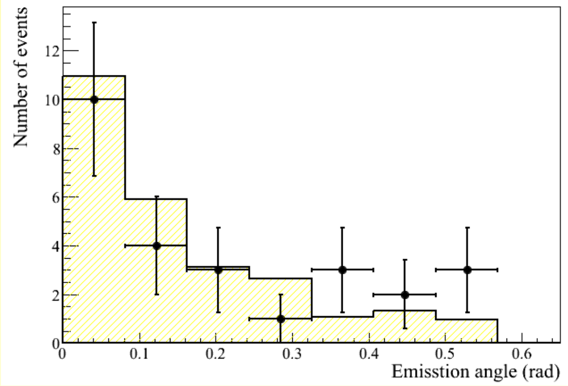


Error bars : Experimental data
Histogram : Simulated data

Kink angle (1-prong)

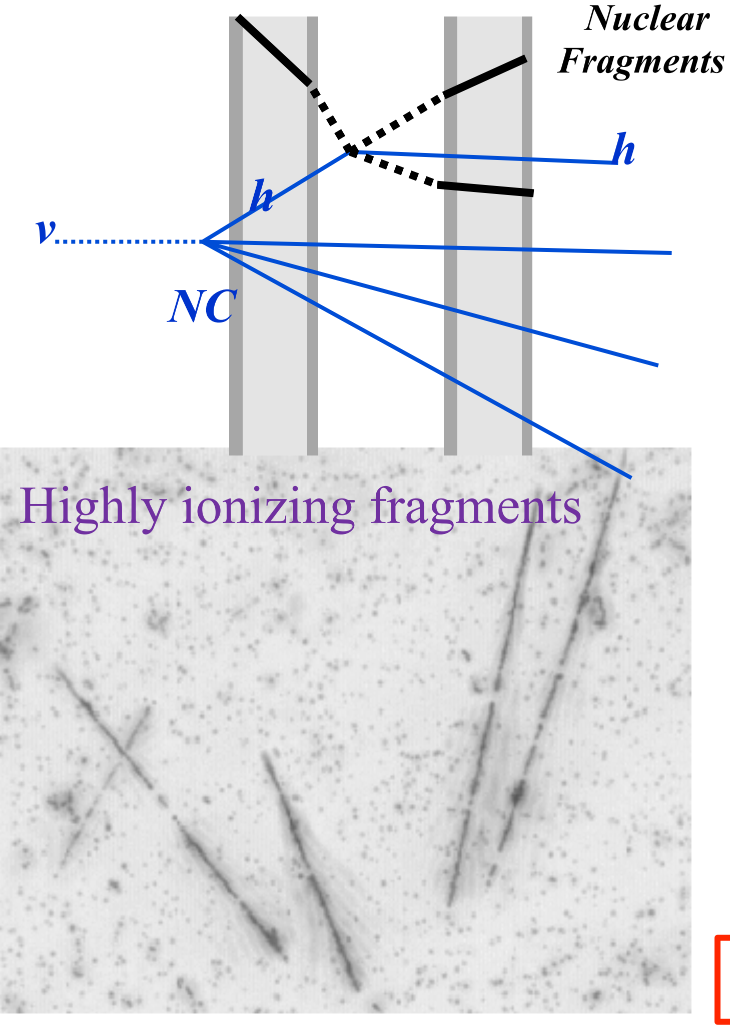


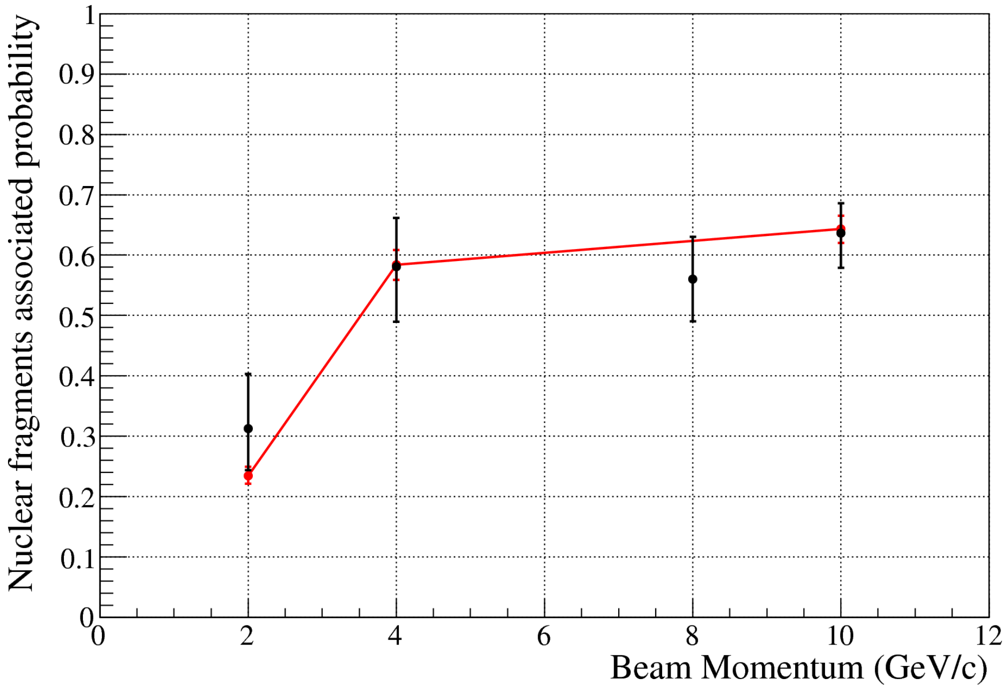




Good agreement within the statistical error: systematic error reduced to 30%

Nuclear fragments emission probability





Black : experimental data
Red : simulated data ($\beta = p/E = 0.7$)

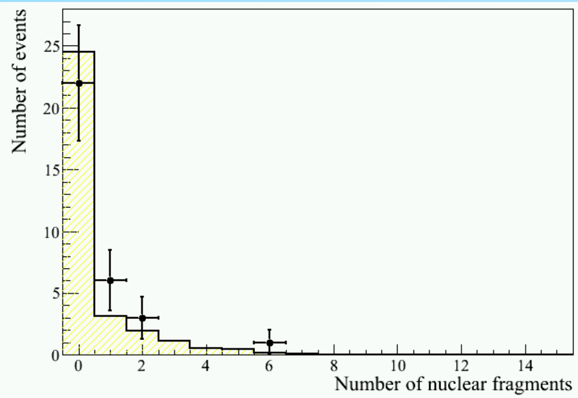
It provides additional background reduction.

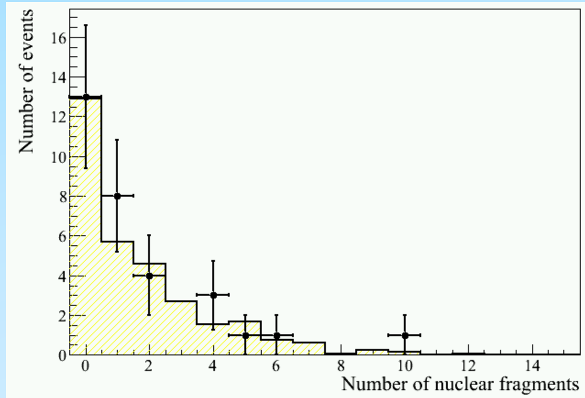
Nuclear fragments in 1 and 3 prong interactions

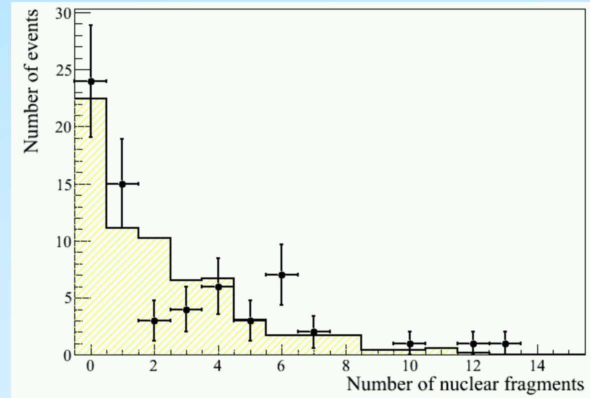
2GeV/c | 4GeV/c | 10GeV/c

Multiplicity

MC: $\beta < 0.7$

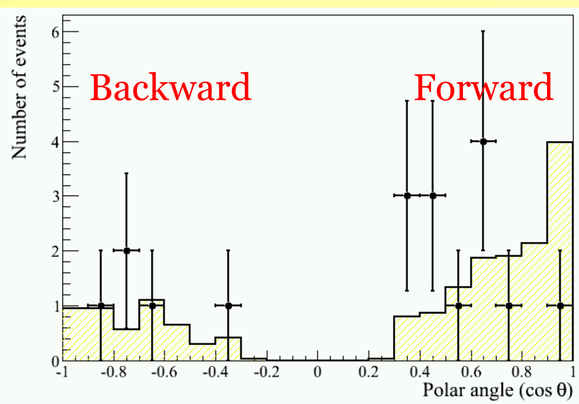


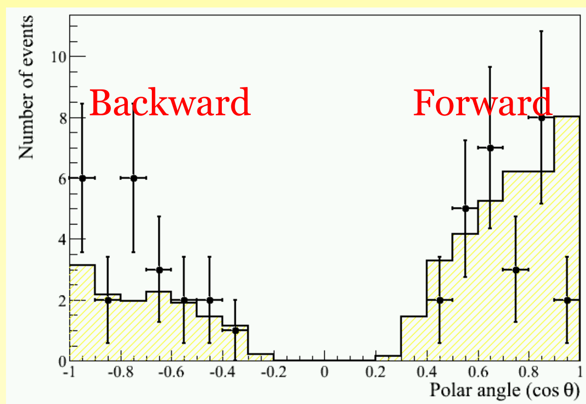


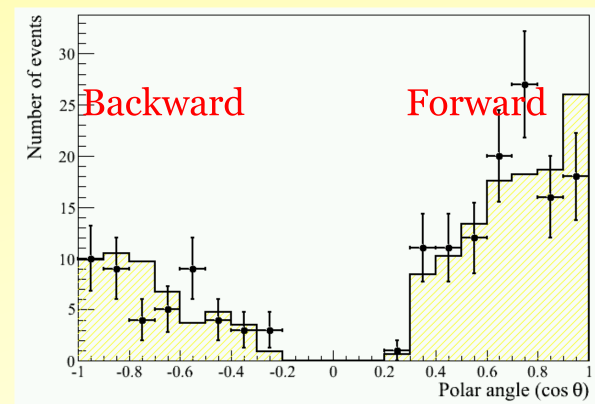


Error bars : experiment
Histogram : simulation

Emission angle(cos θ)

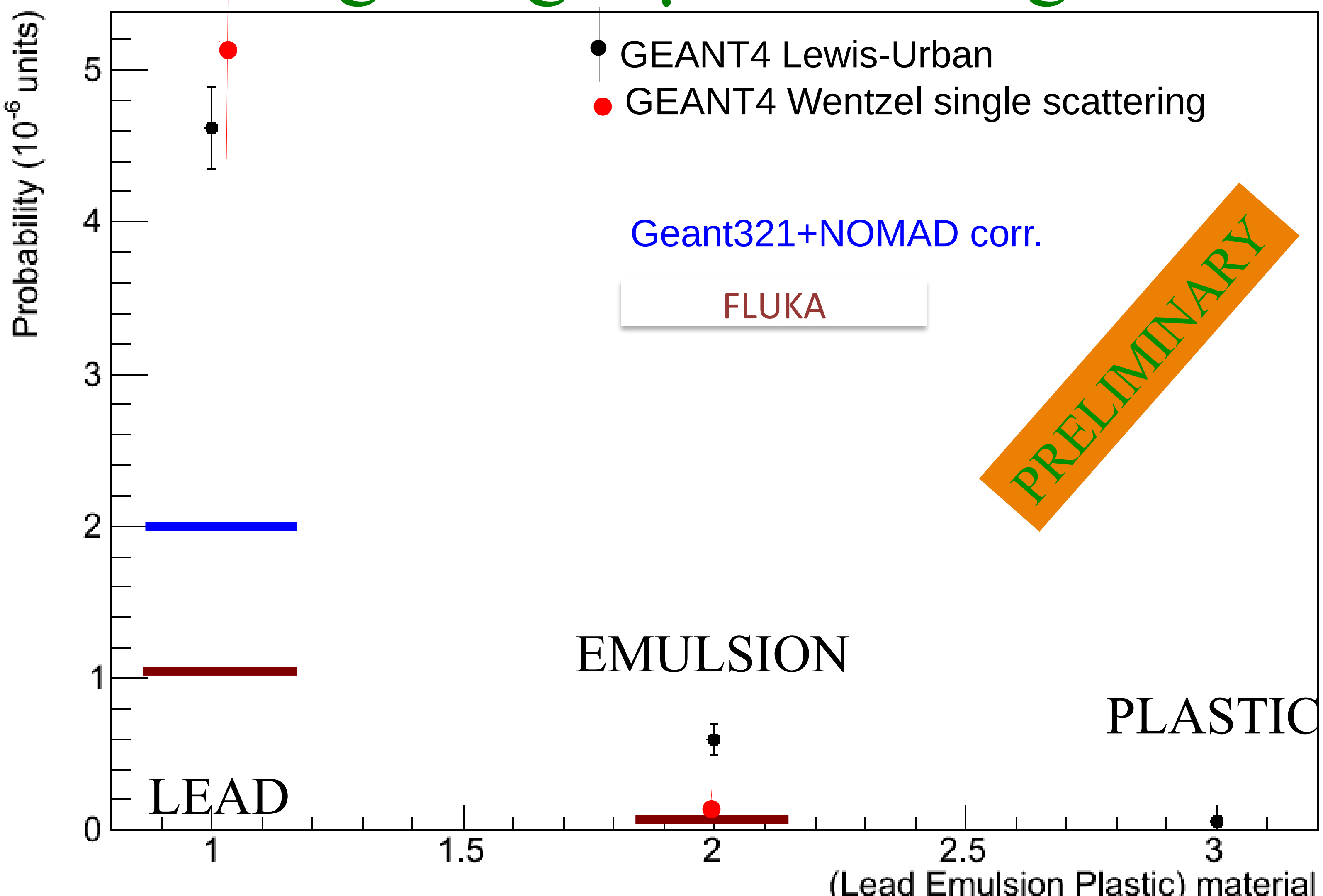






Agreement within the statistical error: systematic error is 10%.

Large angle μ scattering



Rate in lead (10^{-6}) and less in emulsion/base. 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 number by an experimental measurement with emulsion

Significance of the ν_τ appearance

Data sample:

2008/09 runs: 398 0μ + 1553 1μ events

2010/11/12 runs: 582 0μ + 2153 1μ events

The expected signal and background is normalized to the number of analysed events

$$n^{0\mu}(\nu_\tau^{CC}) = \frac{\langle \sigma(\nu_\tau^{CC}) \rangle}{\langle \sigma(\nu_\mu^{CC}) \rangle} \frac{\langle \epsilon^{0\mu}(\nu_\tau^{CC}) \rangle}{\langle \epsilon^{0\mu}(\nu_\tau^{CC}) \rangle + \alpha \langle \epsilon^{0\mu}(\nu_\tau^{NC}) \rangle} n^{0\mu} \qquad \alpha = \frac{NC}{CC}$$

Decay channel	Expected signal	Observed	Expected background			
			Total	Charm decays	Hadronic re-interactions	Large-angle muon scattering
$\tau \to 1h$	0.41 ± 0.08	2	0.033 ± 0.006	0.015 ± 0.003	0.018 ± 0.005	/
$\tau \to 3h$	0.57 ± 0.11	1	0.155 ± 0.030	0.152 ± 0.030	0.002 ± 0.001	/
$\tau \to \mu$	0.52 ± 0.10	1	0.018 ± 0.007	0.003 ± 0.001	/	0.014 ± 0.007
$\tau \to e$	0.62 ± 0.12	0	0.027 ± 0.005	0.027 ± 0.005	/	/
Total	2.11 ± 0.42	4	0.233 ± 0.041	0.198 ± 0.040	0.021 ± 0.006	0.014 ± 0.007

Two statistical methods:

- Fisher combination of single channel p-value
- Likelihood ratio

p-value = 1.03 x 10^{-5}

Non oscillation excluded at 4.2σ C.L. → observation of ν_τ appearance

First measurement of Δm^2_{32} with ν_τ appearance

$$N_{\nu_\tau} \propto \int \phi(E) \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) \epsilon(E)\sigma(E) dE$$

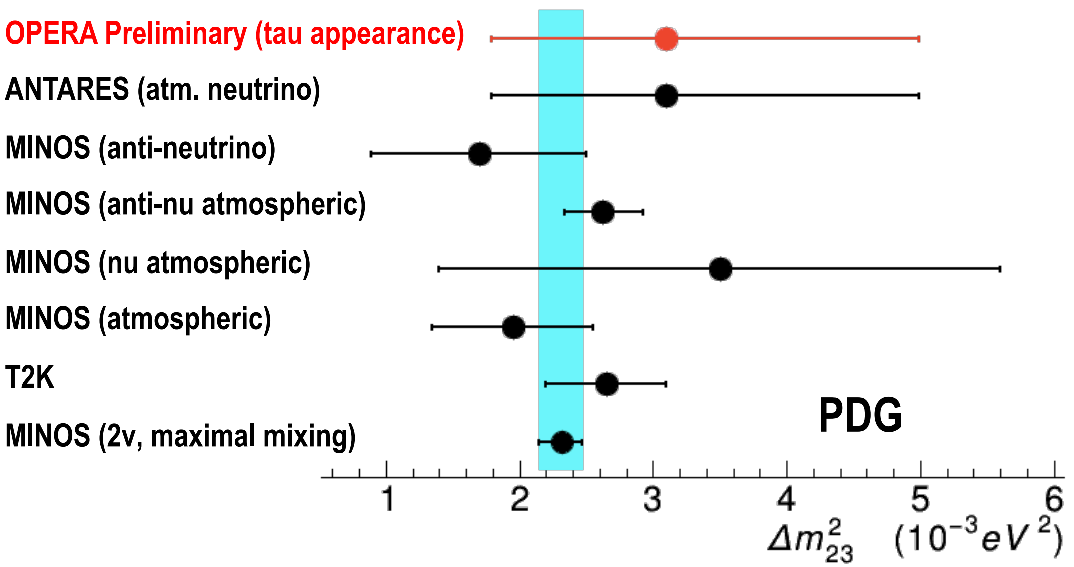
$$\propto (\Delta m^2_{32})^2 L^2 \int \phi(E)\epsilon(E)\frac{\sigma(E)}{E^2} dE$$

OPERA Off-peak
$L/\langle E\rangle \sim 43$ Km/GeV
$(L/\langle E\rangle)_{peak} \sim 500$ Km/GeV

dependent on Δm^2 → measure Δm^2 with counting experiment

90% CL intervals assuming $\sin^2(2\theta_{23}) = 1$

Feldman & Cousin:
$[1.8 – 5] \times 10^{-3}\ eV^2$
Bayesian:
$[1.9 – 5] \times 10^{-3}\ eV^2$



Sterile neutrinos

Tau appearance in presence of a sterile neutrino (3+1)

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{2E}$$

Solar driven oscillation neglected $\Delta_{21} \sim 0$

~ standard oscillation

pure exotic oscillation

$$P_{\nu_\mu \to \nu_\tau} = 4|U_{\mu 3}|^2 |U_{\tau 3}|^2 \sin^2 \frac{\Delta_{31}}{2} + 4|U_{\mu 4}|^2 |U_{\tau 4}|^2 \sin^2 \frac{\Delta_{41}}{2}$$

interference terms:

$$+2\Re[U^*_{\mu 4} U_{\tau 4} U_{\mu 3} U^*_{\tau 3}] \sin \Delta_{31} \sin \Delta_{41}$$

$$-4\Im[U^*_{\mu 4} U_{\tau 4} U_{\mu 3} U^*_{\tau 3}] \sin^2 \frac{\Delta_{31}}{2} \sin \Delta_{41}$$

$$+8\Re[U^*_{\mu 4} U_{\tau 4} U_{\mu 3} U^*_{\tau 3}] \sin^2 \frac{\Delta_{31}}{2} \sin^2 \frac{\Delta_{41}}{2}$$

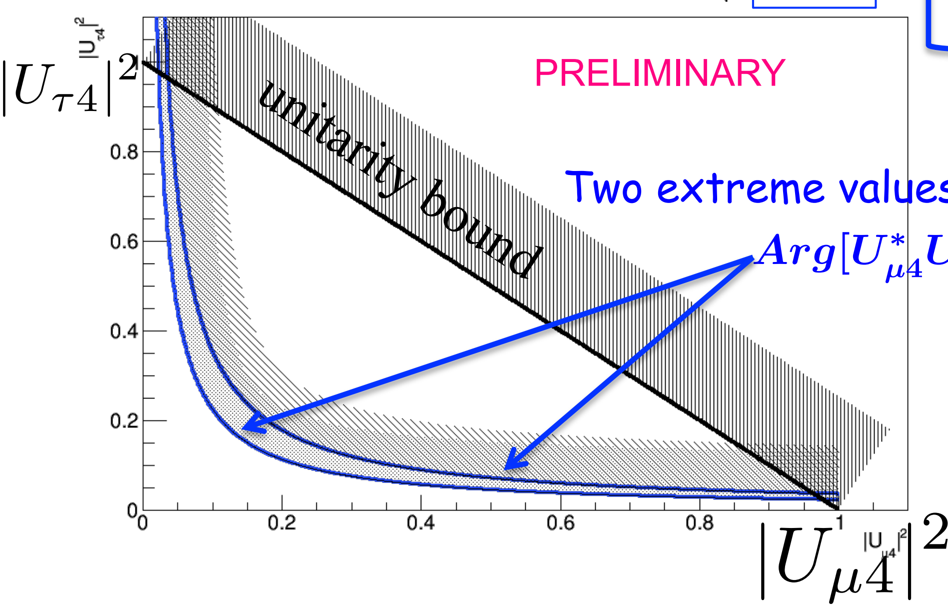
$$+4\Im[U^*_{\mu 4} U_{\tau 4} U_{\mu 3} U^*_{\tau 3}] \sin \Delta_{31} \sin^2 \frac{\Delta_{41}}{2}$$

Normal hierarchy

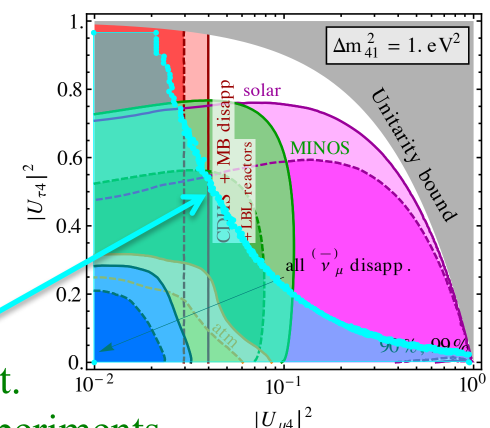
Profile likelihood using Tau rate only

$$\Delta m^2_{32} = 2.32 \times 10^{-3} eV^2$$

90% CL bounds on $U_{\tau 4}$ and $U_{\mu 4}$



Two extreme values ($\pi/2$, $3\pi/2$) of $Arg[U^*_{\mu 4} U_{\tau 4} U_{\mu 3} U^*_{\tau 3}]$



Kopp et al. JHEP 1305 (2013) 050

Complementary measurement w.r.t. disappearance experiments

Sterile neutrinos

Choosing a particular representation

$$U = R_{34}(\theta_{34})R_{24}(\theta_{24,\delta_2})R_{14}(\theta_{14})R_{23}(\theta_{23})R_{13}(\theta_{13},\delta_1)R_{12}(\theta_{12},\delta_3)$$

$\Delta_{21} \sim 0$ (solar oscillation)
$s_{14} \sim 0$ (reactor anomaly)
$\rightarrow \delta_1 = 0$

$$U = \begin{bmatrix} U_{e1} & U_{e2} & c_{14}s_{13}e^{-i\delta_1} & s_{14} \\ U_{\mu 1} & U_{\mu 2} & -s_{14}s_{13}e^{-i\delta_1}s_{24}e^{-i\delta_2} + c_{13}s_{23}c_{24} & c_{14}s_{24}e^{-i\delta_2} \\ U_{\tau 1} & U_{\tau 2} & -s_{14}c_{24}s_{34}s_{13}e^{-i\delta_1} - c_{13}s_{23}s_{34}s_{24}e^{i\delta_2} + c_{13}c_{23}c_{34} & c_{14}c_{24}s_{34} \\ U_{s1} & U_{s2} & -s_{14}c_{24}c_{34}s_{13}e^{-i\delta_1} - c_{13}s_{23}c_{34}s_{24}e^{i\delta_2} - c_{13}c_{23}s_{34} & c_{14}c_{24}c_{34} \end{bmatrix}$$

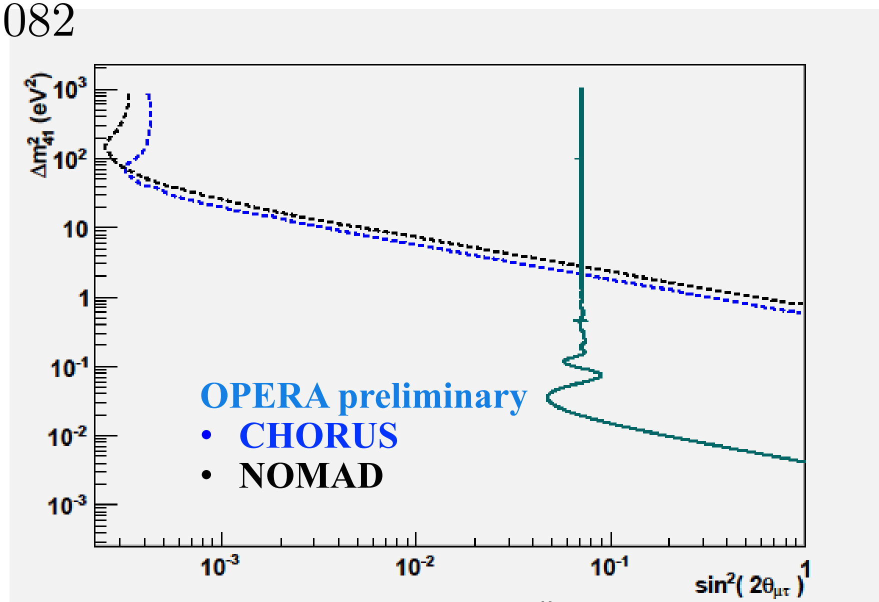
$$P = sin^2(2\theta_{\mu\tau})sin^2(1.27\Delta m^2_{41}L/E)$$

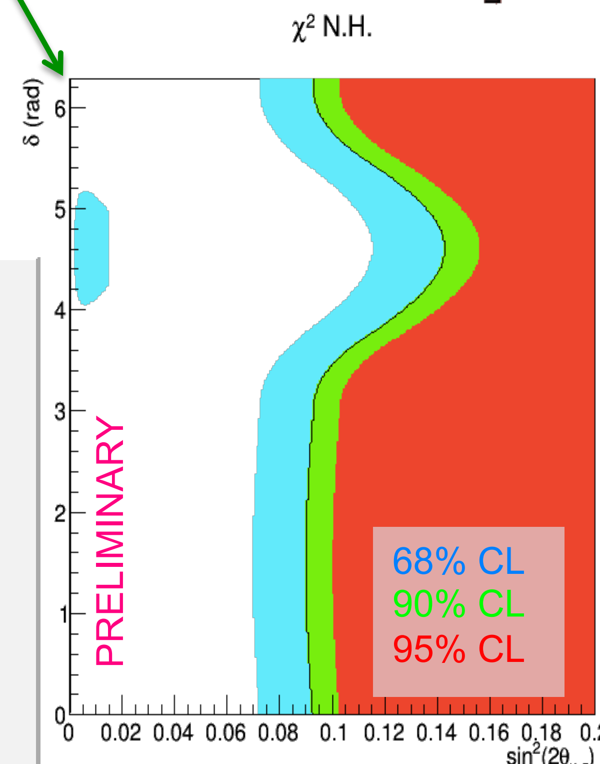
good approximation for $\delta_2 = 0$

4 observed events and a background of 2.3 ± 0.4 events

$\rightarrow$ upper limit of 6.6 events at 90% CL for extra ν_τ

$\rightarrow sin^2(2\theta_{\mu\tau}) < 0.082$





First observation of $\nu_\mu \rightarrow \nu_\tau$ in appearance mode

- *Four candidates reported in the analysed sample*
- *4.2σ significance*
- *First measurement of Δm^2 in appearance mode: [1.8 – 5.0] x 10^{-3} eV^2 (90% CL)*
- *Paper being submitted*
- *Constraints on sterile neutrinos: first limits on $|U_{\tau 4}|^2$ from direct measurement of $\nu_\mu \rightarrow \nu_\tau$ oscillations*

Outlook

- *ν_τ search being extended to the other bricks of the probability map*
- *Improvements in the statistical analysis*

Thank you for your attention