



RESULTS FROM THE OPERA EXPERIMENT

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Napoli, Italy
on behalf of OPERA Collaboration

5th International Conference on New Frontiers in Physics
6th-14th July, 2016



THE OPERA COLLABORATION

140 physicists, 26 institutions in 11 countries

Belgium
IIHE-ULB Brussels



Croatia
IRB Zagreb



France
LAPP Annecy
IPHC Strasbourg



Germany
Hamburg



Israel
Technion Haifa



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



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



Switzerland
Bern



Japan
Aichi
Toho
Kobe
Nagoya
Nihon



Turkey
METU Ankara



Korea
Jinju



<http://operaweb.web.cern.ch/operaweb/index.shtml>



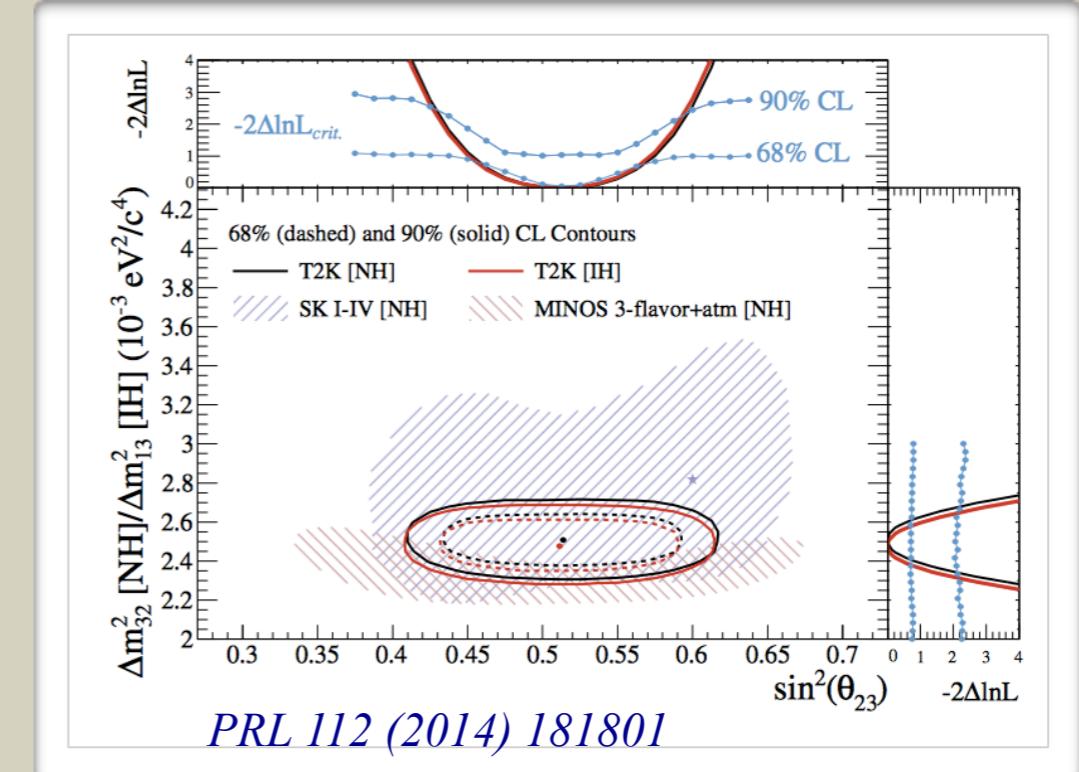
OUTLINE

- The OPERA experiment
 - Physics goal
 - Detection principle
 - The OPERA detector
- Detector performances
- Physics results
- Conclusions



THE OPERA EXPERIMENT

Oscillation Project with Emulsion-tRacking Apparatus



- Long baseline neutrino oscillation experiment in the CNGS (CERN Neutrino to Gran Sasso) ν_μ beam
- Direct detection of $\nu_\mu \rightarrow \nu_\tau$ oscillations in **APPEARANCE** mode
- Full coverage of the parameter space for atmospheric neutrino sector
- Search for subdominant $\nu_\mu \rightarrow \nu_e$ oscillations

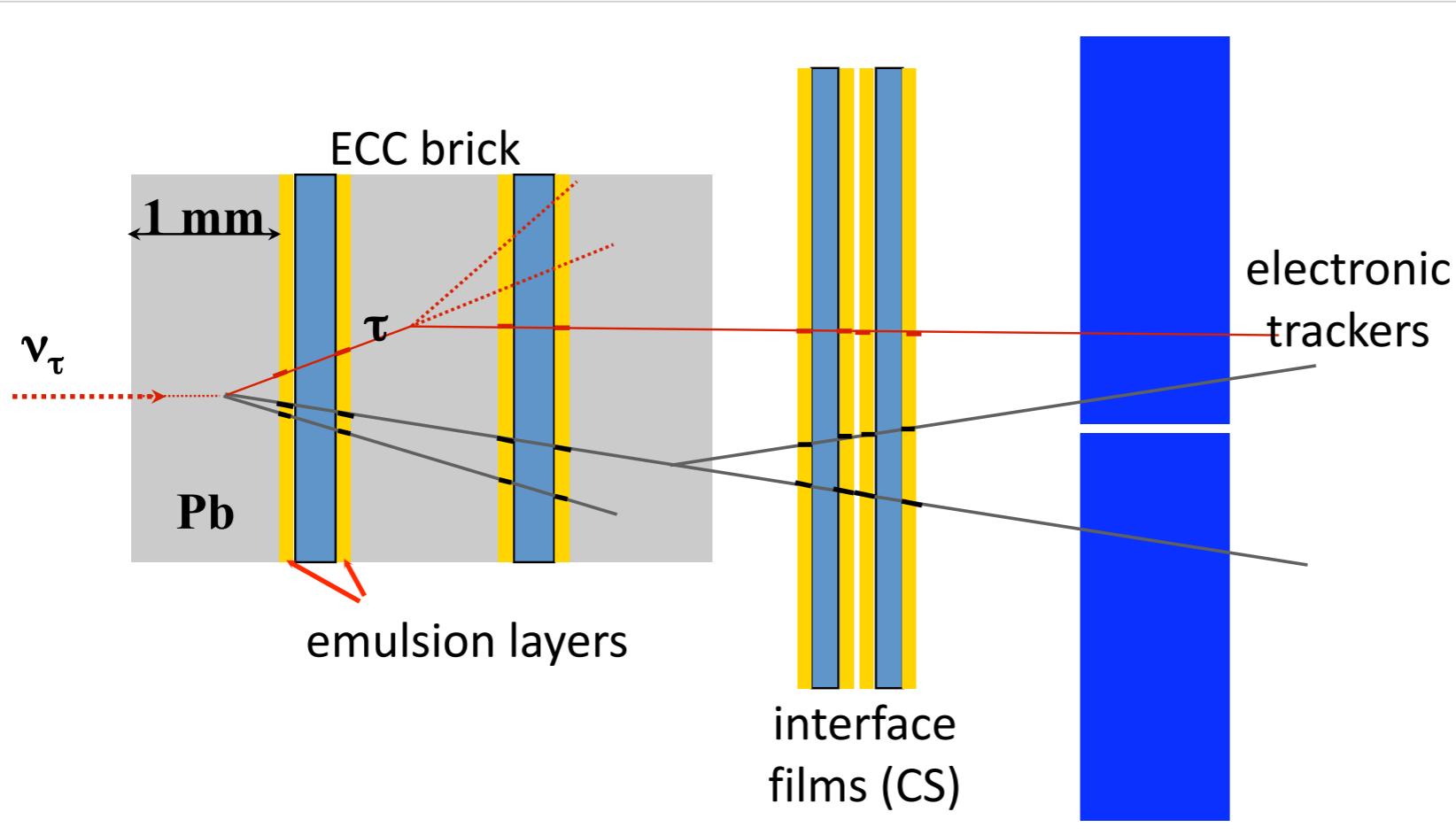
BEAM PARAMETERS

$\langle E\nu_\mu \rangle$ (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

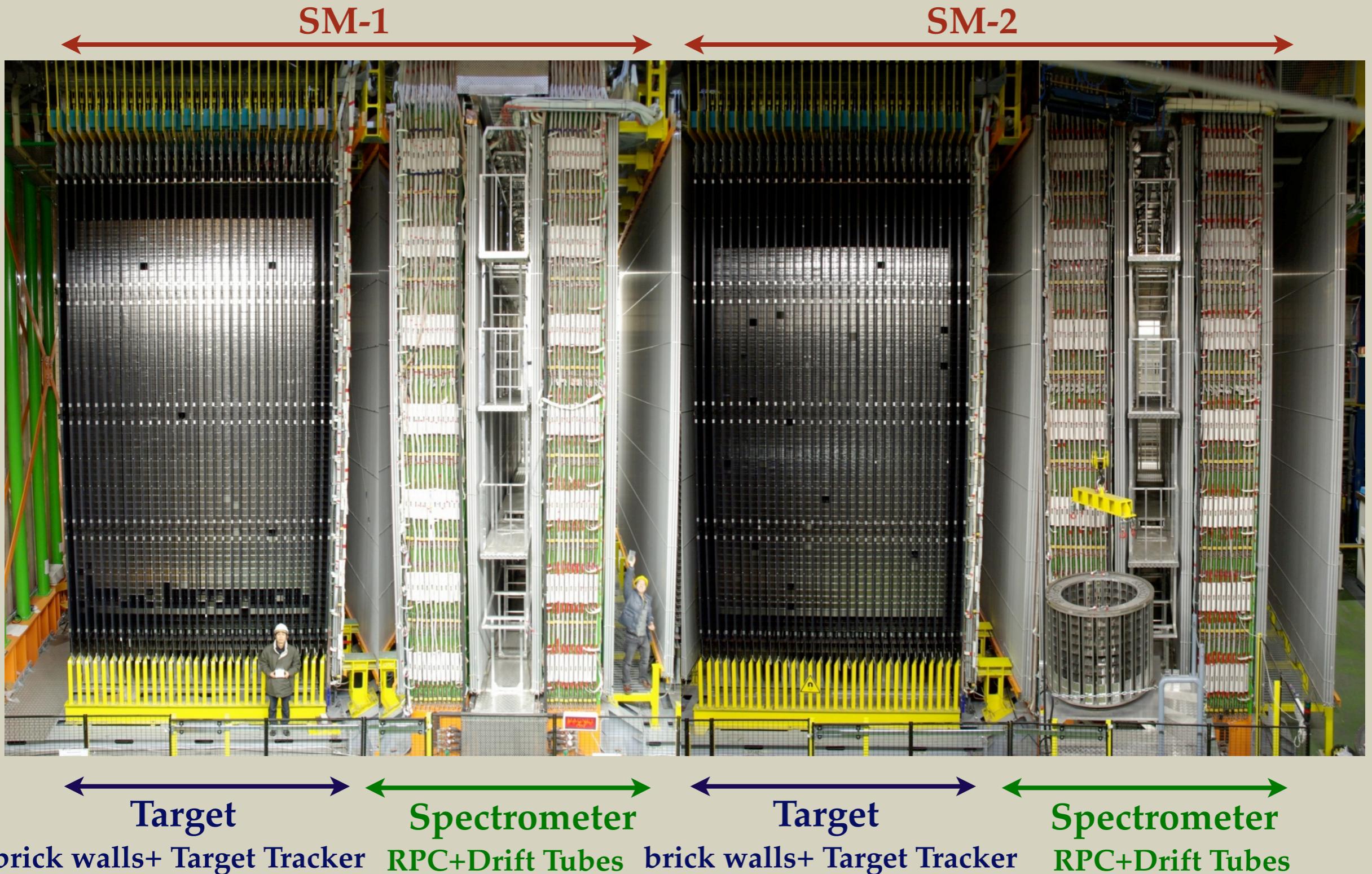


τ DECAY CHANNEL	BR (%)
$\tau \rightarrow \mu$	17.7
$\tau \rightarrow e$	17.8
$\tau \rightarrow h$	49.5
$\tau \rightarrow 3h$	15.0

- Massive active target with micrometric space resolution
- Detect τ -lepton production and decay
- Underground location (10^6 reduction of cosmic ray flux)
- Usage of electronic detectors to provide “time resolution” to the emulsions and preselect the interaction region



THE DETECTOR





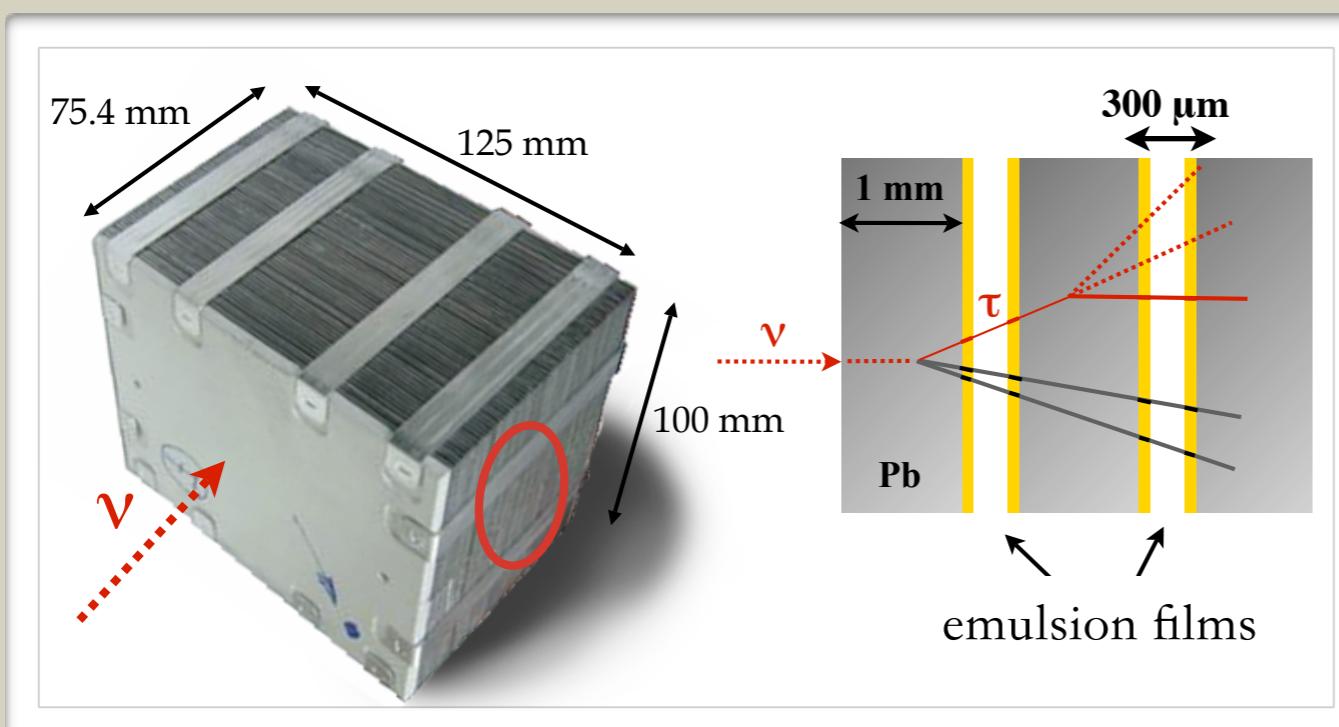
THE TARGET

MADE OF ~150000 BRICKS

Emulsion Cloud Chamber

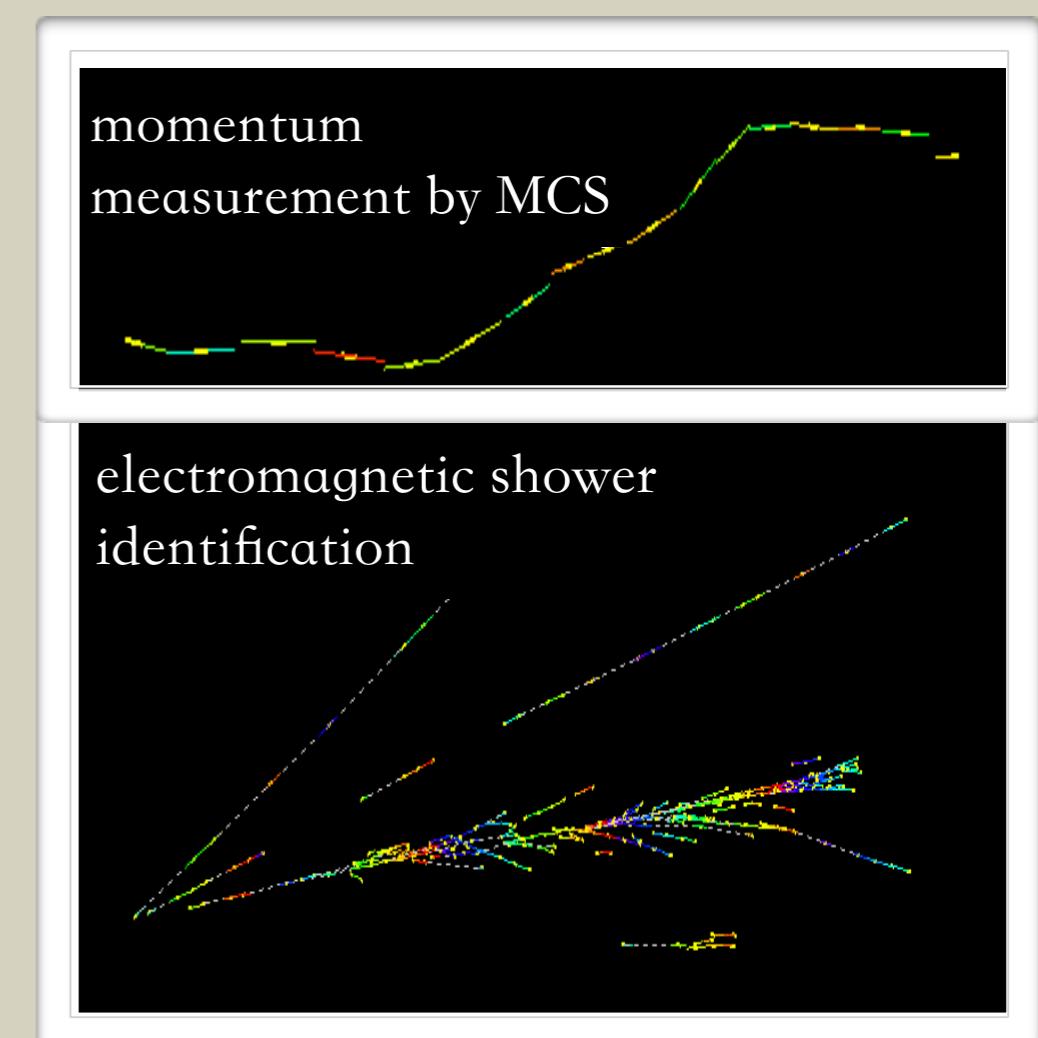
ECC

- passive material → lead (massive target)
- tracking device → nuclear emulsion (high resolution)



Brick

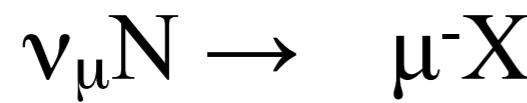
- 57 emulsion films
- 56 lead plates
- 1 Changeable Sheet doublet
- 10 X_0
- 8.3 kg



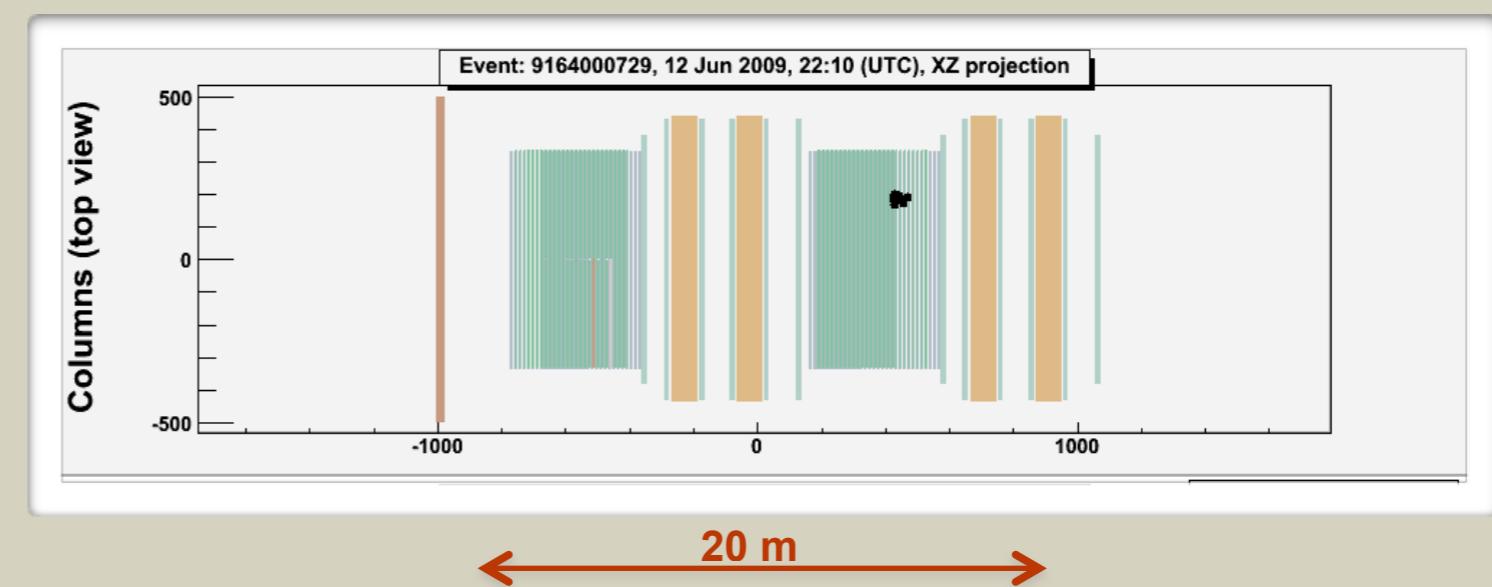
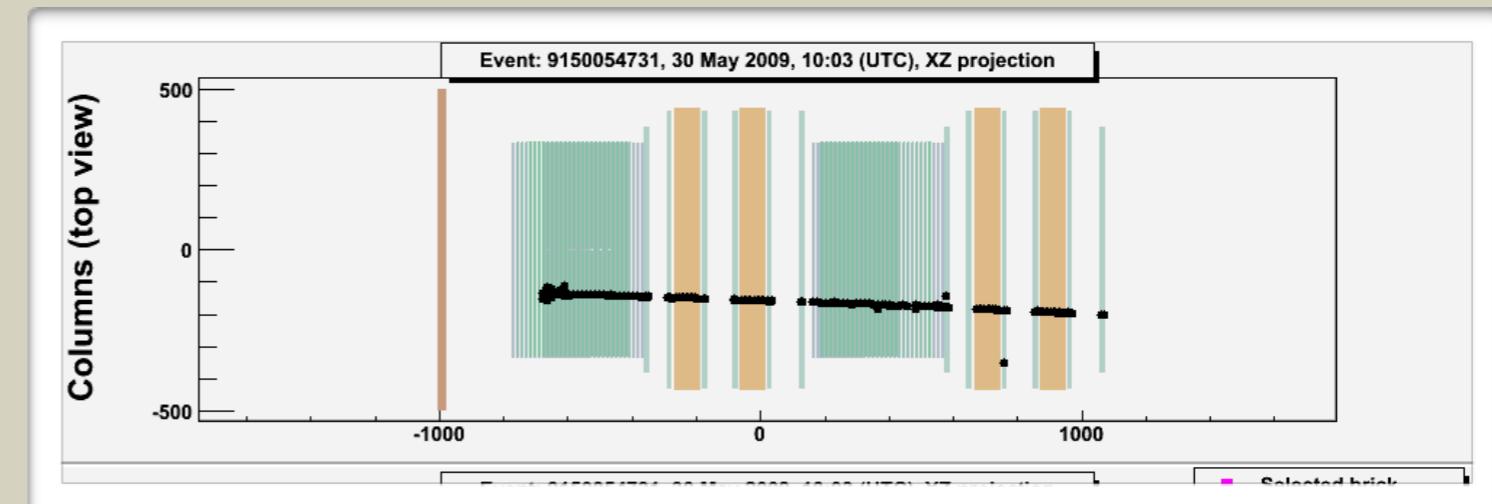
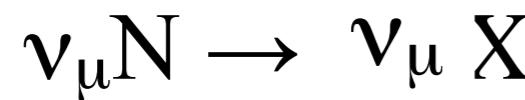


NEUTRINO INTERACTIONS IN THE TARGET

“1 μ ” Event



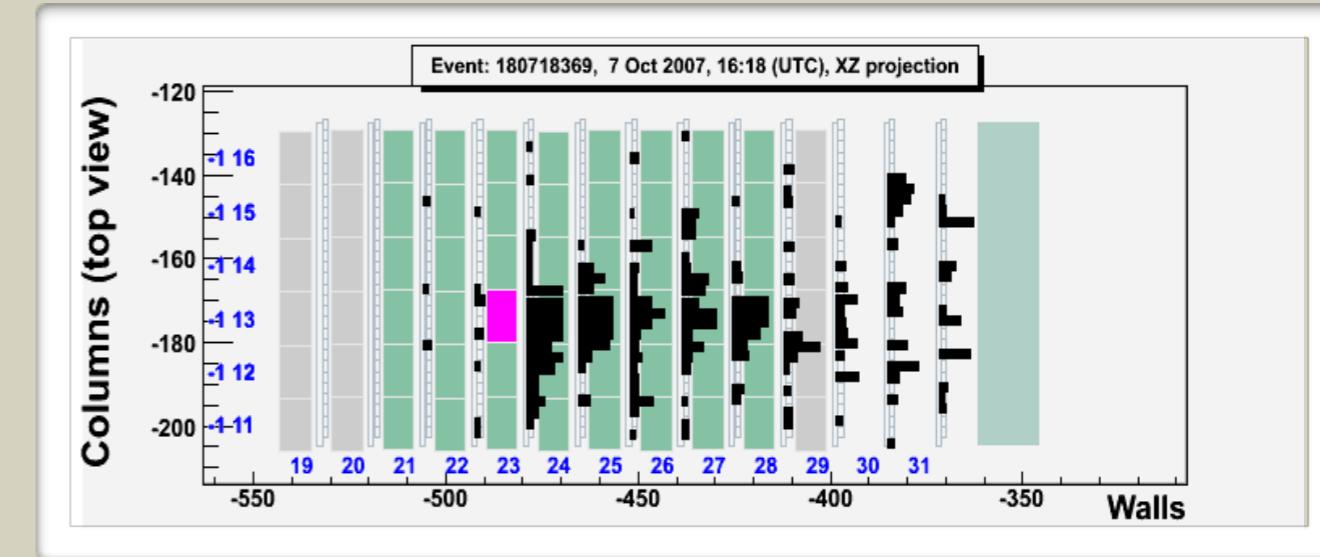
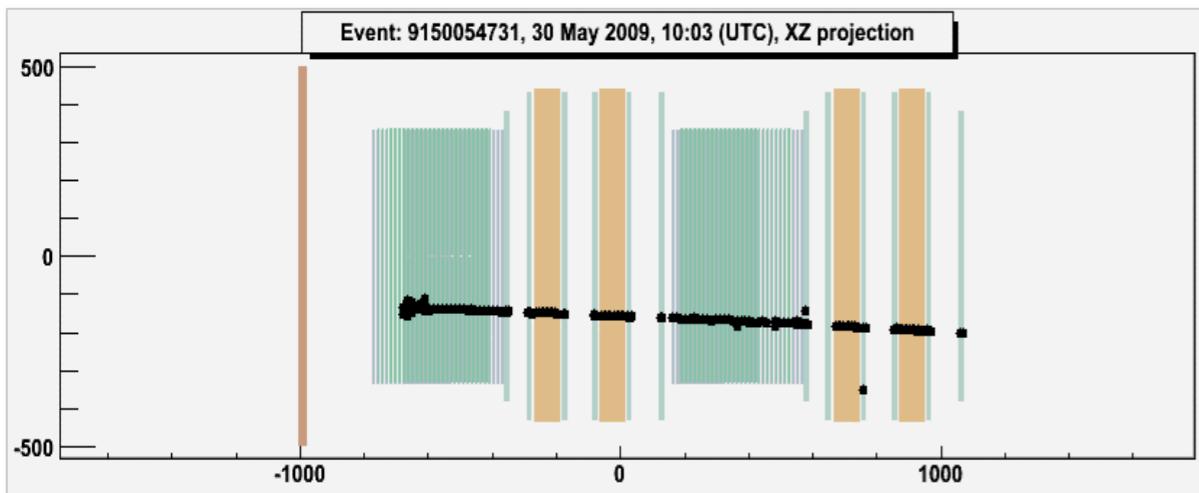
“0 μ ” Event



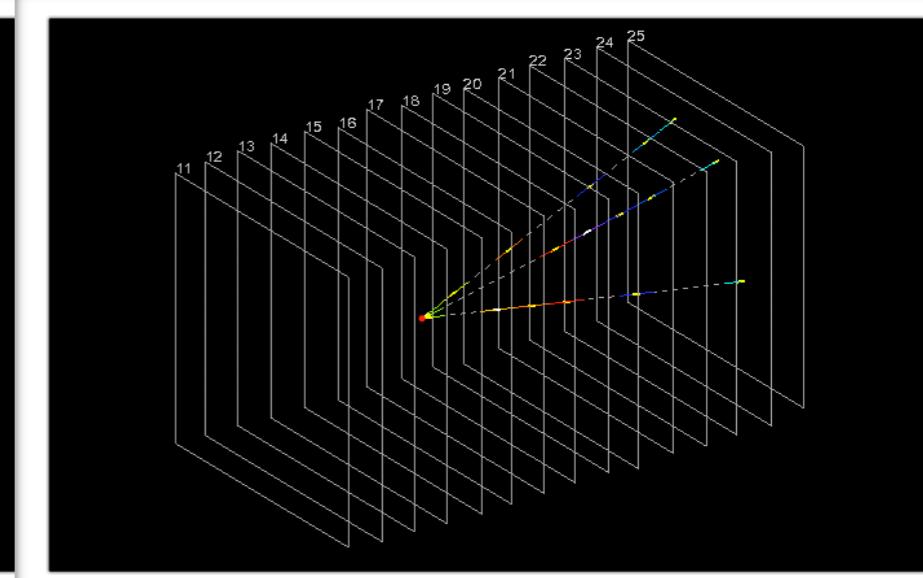
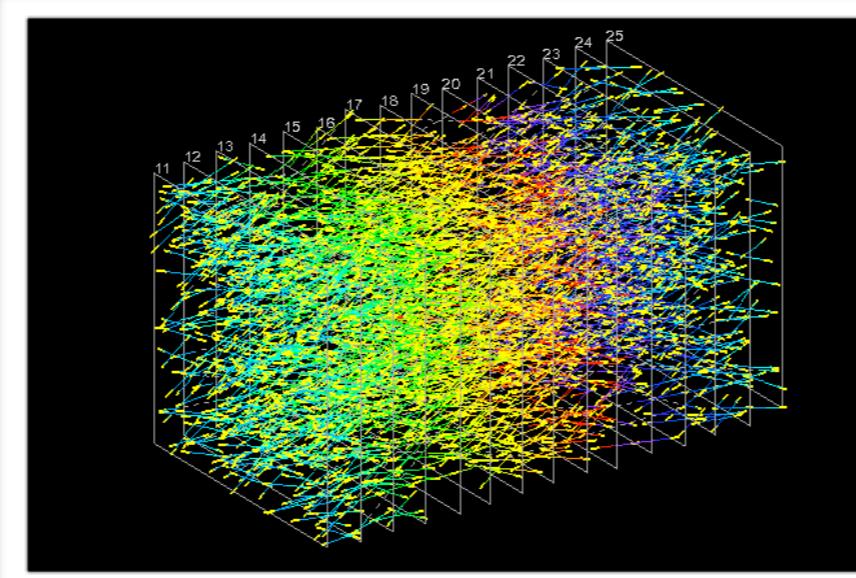
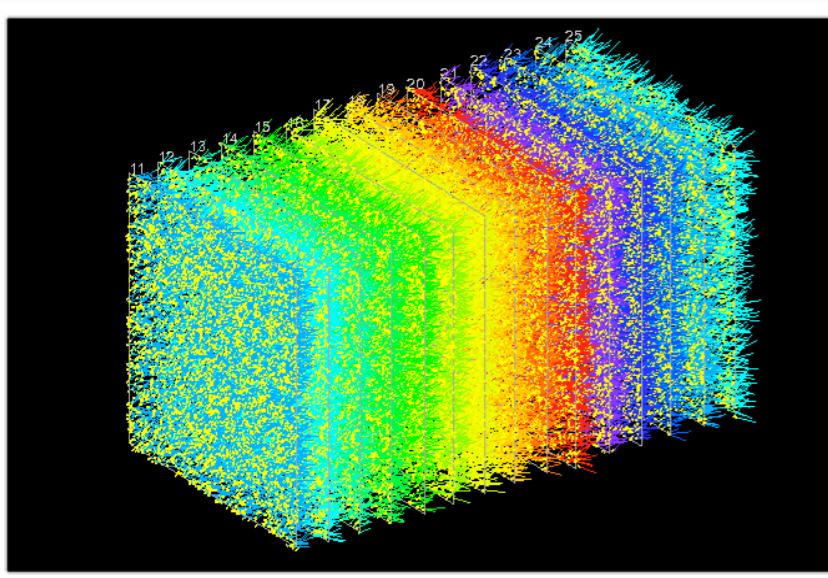


EVENT ANALYSIS

ELECTRONIC DETECTOR RECONSTRUCTION



VERTEX LOCATION IN THE BRICK



1. Scan 15 emulsion films
around stopping plate

2. Reject passing
through tracks

3. Search tracks
making vertex

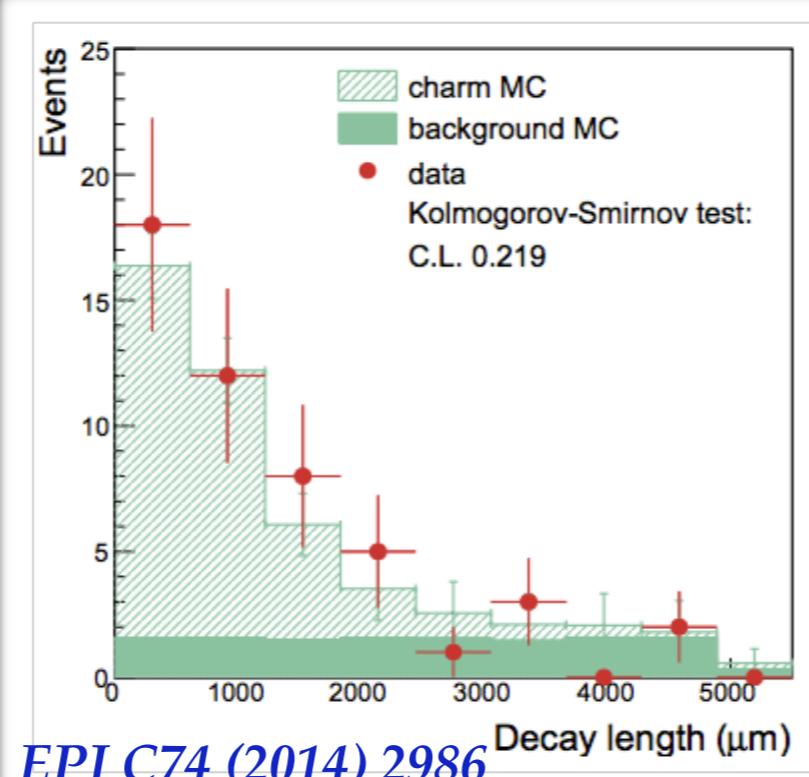
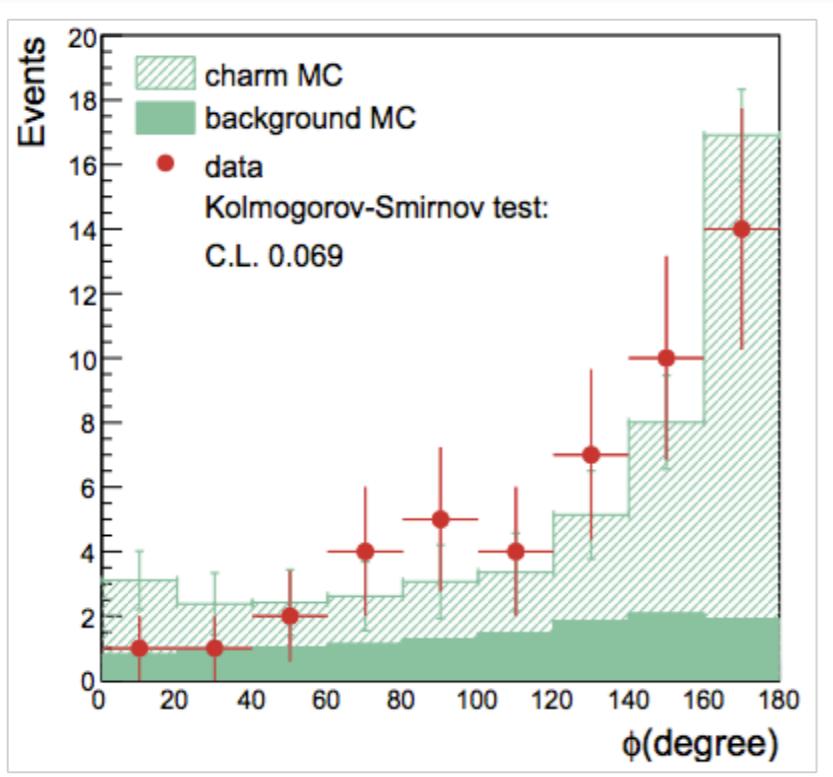
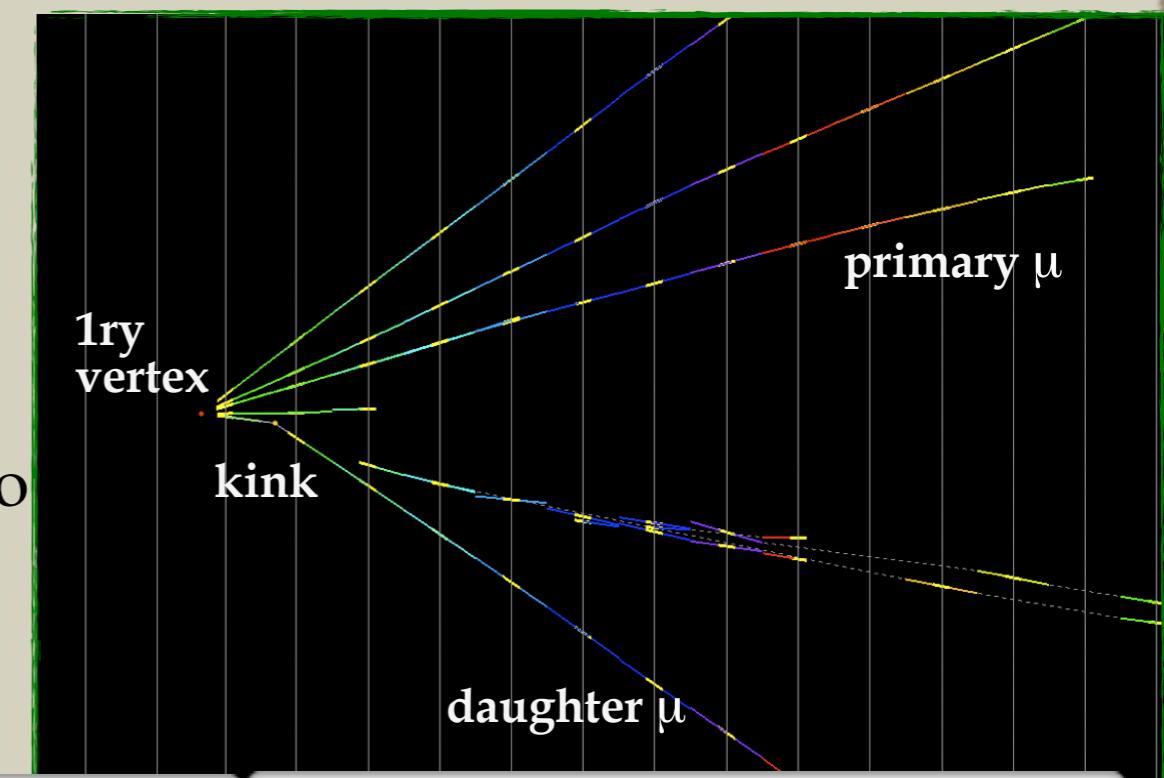


CHARM DATA SAMPLE

PROOF OF τ DETECTION EFFICIENCY

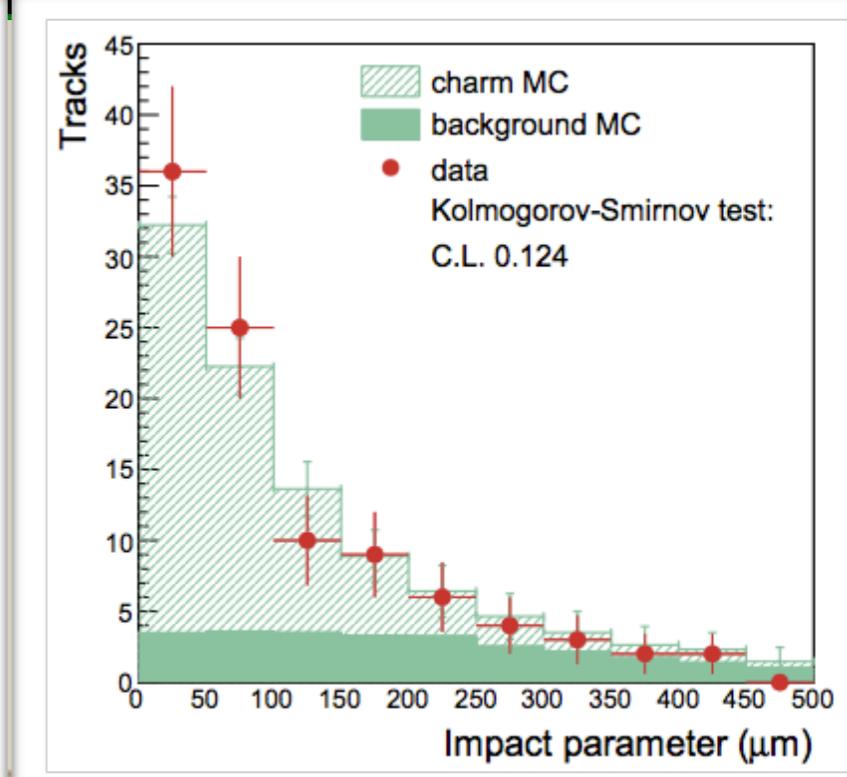
- Charm decay has the same topology as the τ
- Charmed hadrons from ν_μ CC interactions
- Muon at the primary vertex
- Used as “control sample”
- Good agreement between data and Monte Carlo

Observed: 50
Expected: 54 ± 4



EPJ C74 (2014) 2986

A. Di Crescenzo, ICNFP 2016





COLLECTED DATA

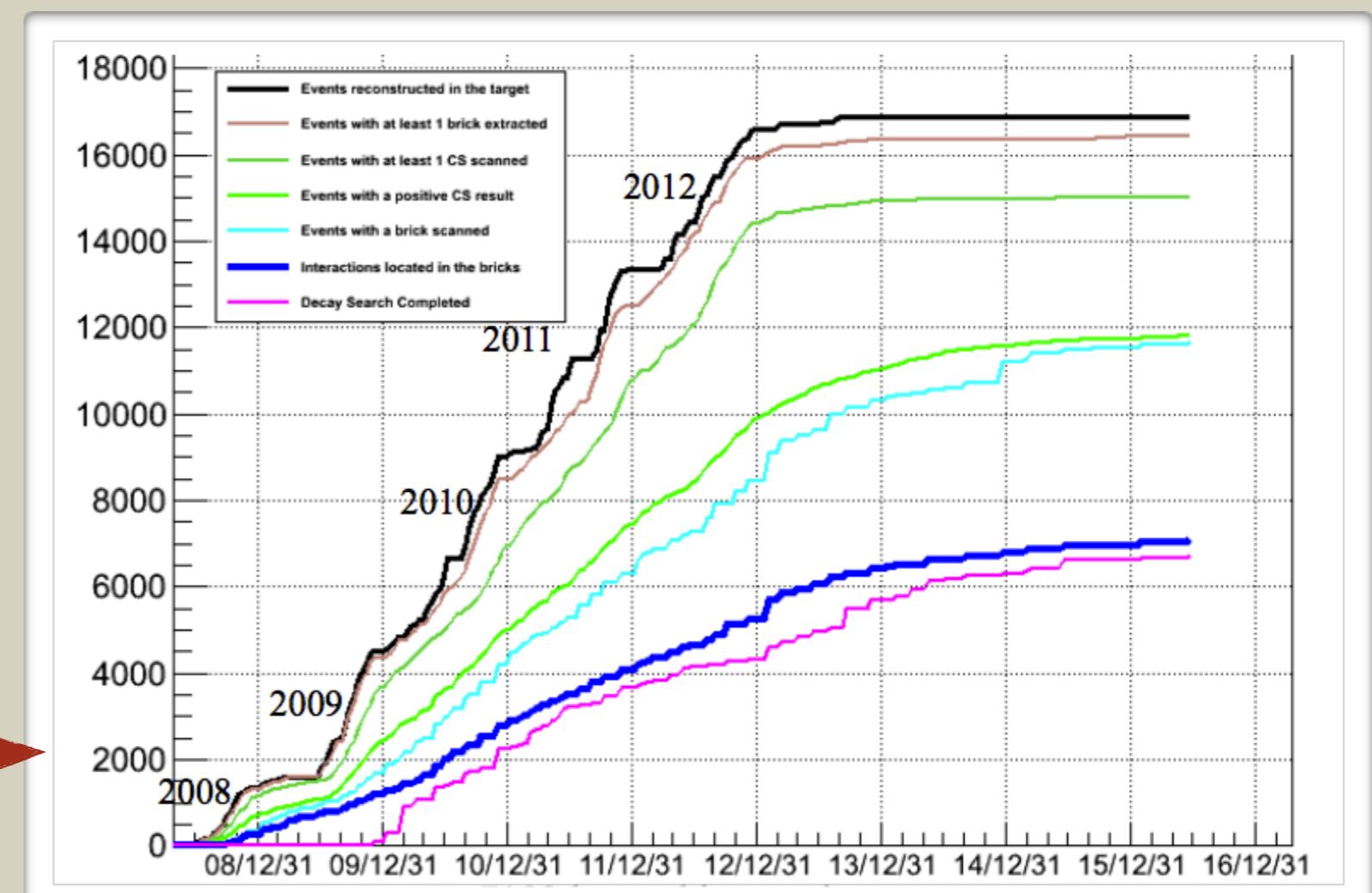
YEAR	P.O.T. (10^{19})	Number of ν interactions
2008	1.74	1931
2009	3.53	4005
2010	4.09	4515
2011	4.75	5131
2012	3.86	3923
Total	17.97	19505

80% of the nominal value

7103 located interactions
6750 decay search

DATA SAMPLE

- 2008-2009: 1st and 2nd probable brick
- 2010-2012: 1st probable brick
- Extension of the analysis up to 4th probable brick in progress

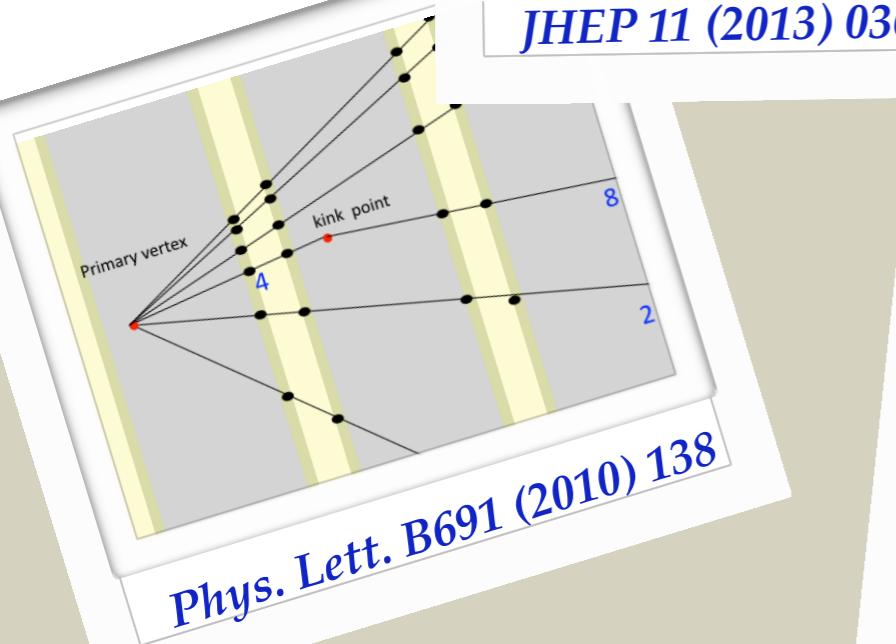




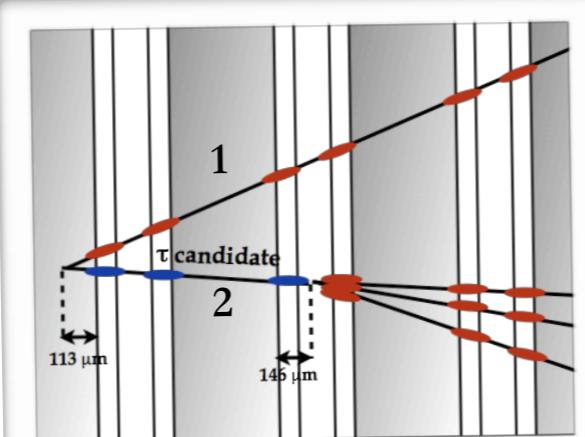
$\nu_\mu \rightarrow \nu_\tau$ OSCILLATION SEARCH

5 ν_τ candidate events observed in the analysed sample

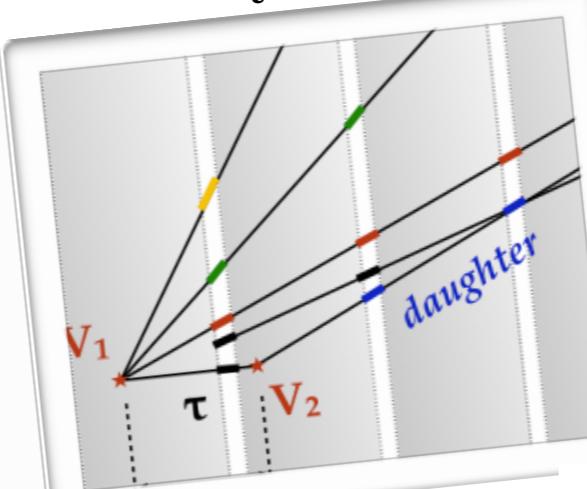
1st candidate:
 $\tau \rightarrow h$



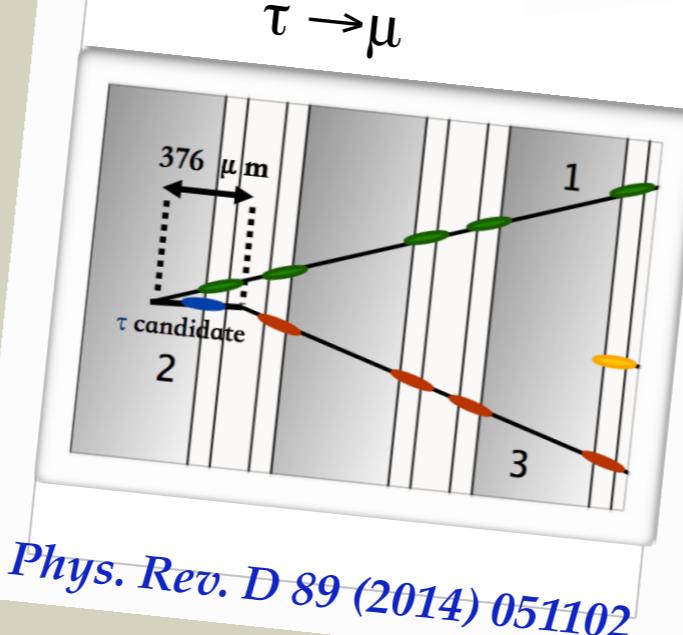
2nd candidate:
 $\tau \rightarrow 3h$



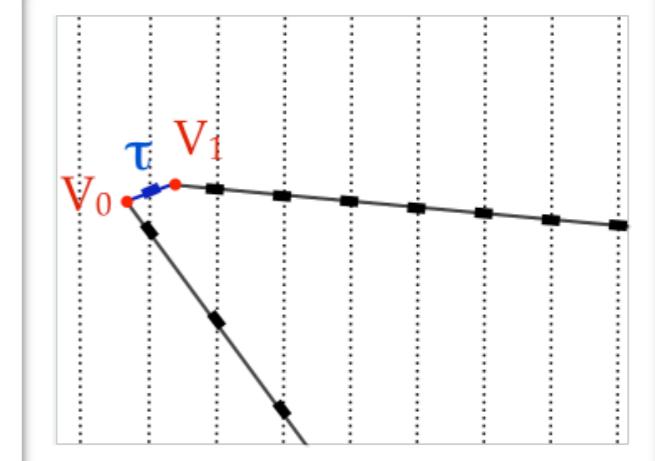
4th candidate:
 $\tau \rightarrow h$



3rd candidate:
 $\tau \rightarrow \mu$



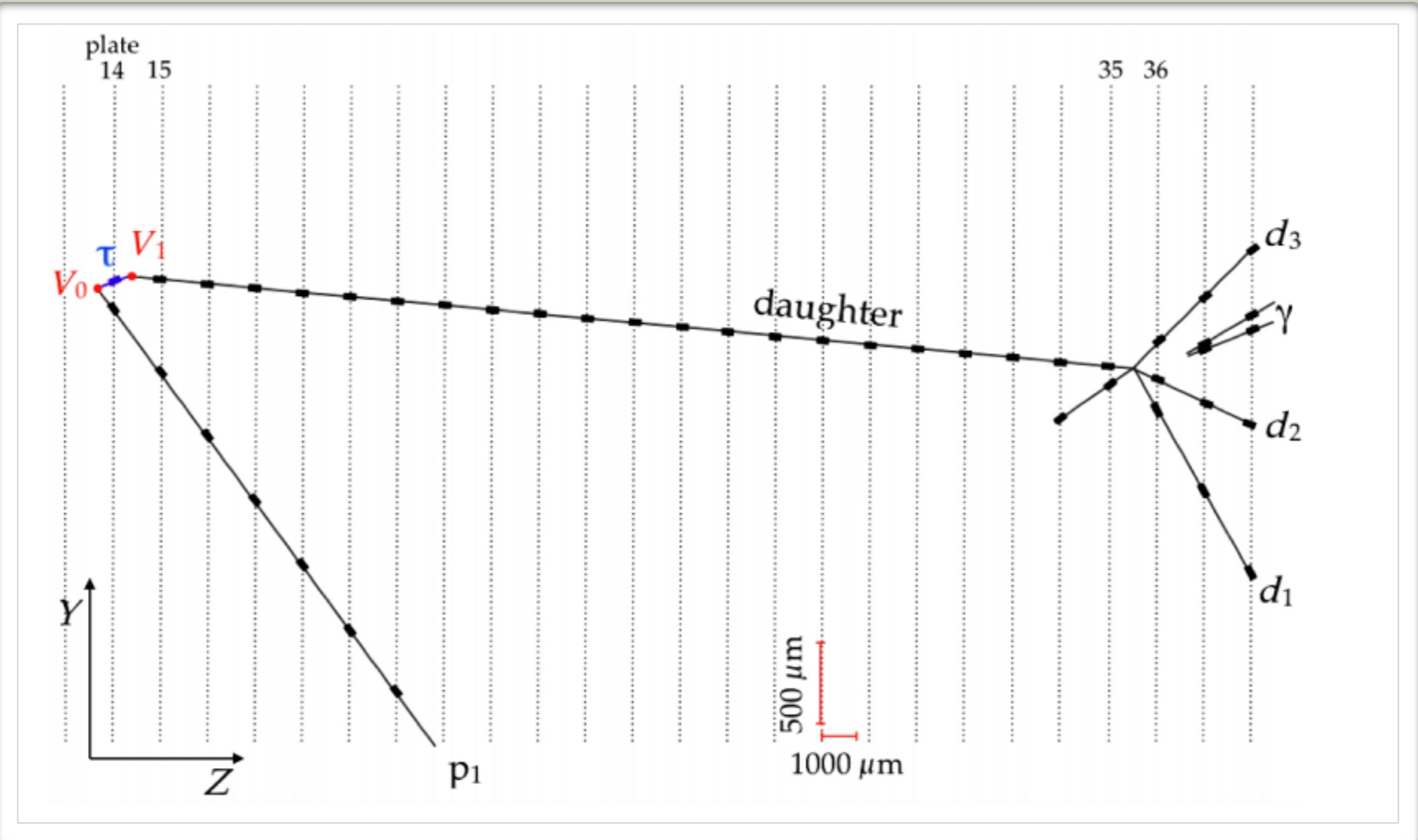
5th candidate:
 $\tau \rightarrow h$





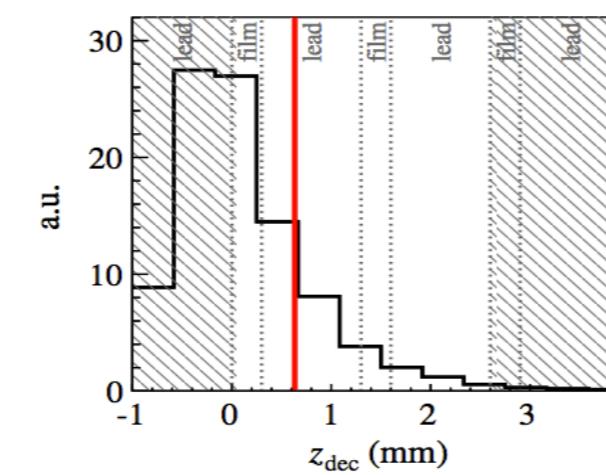
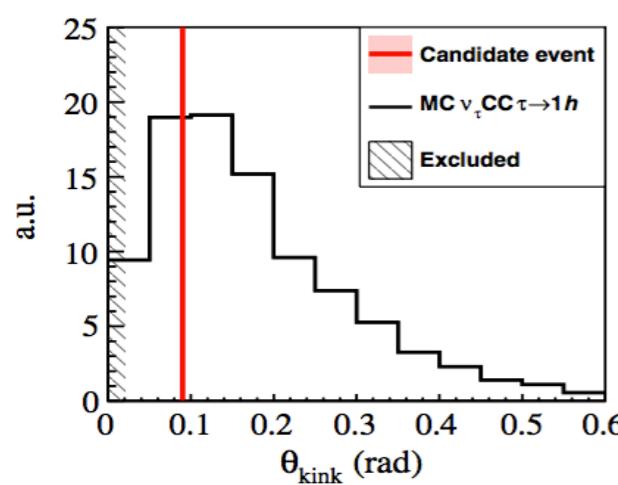
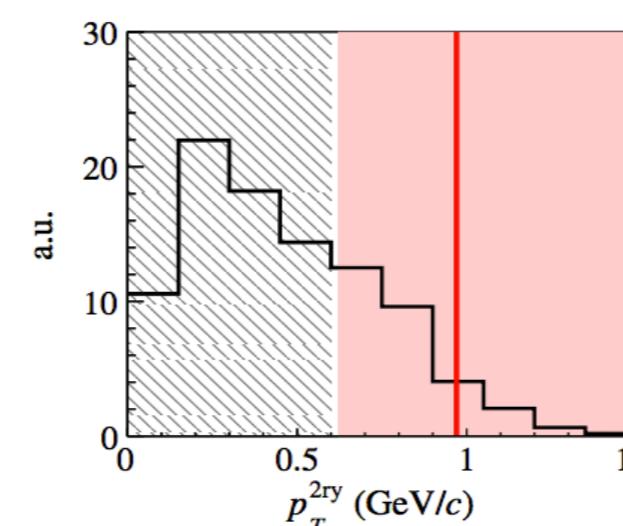
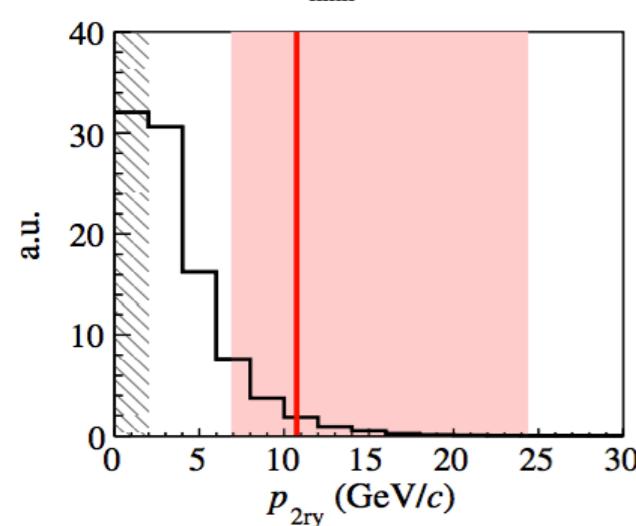
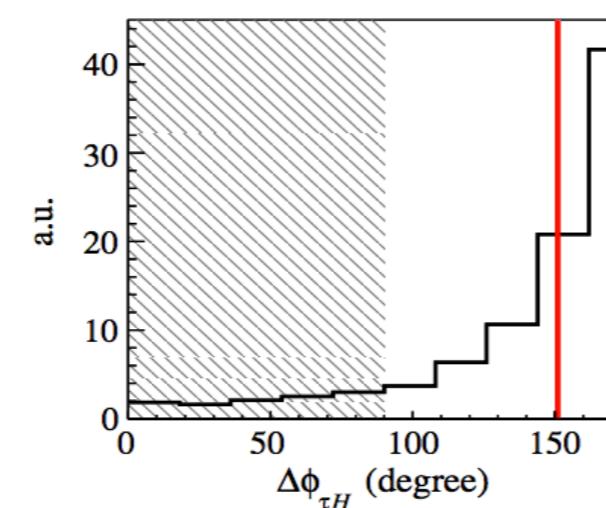
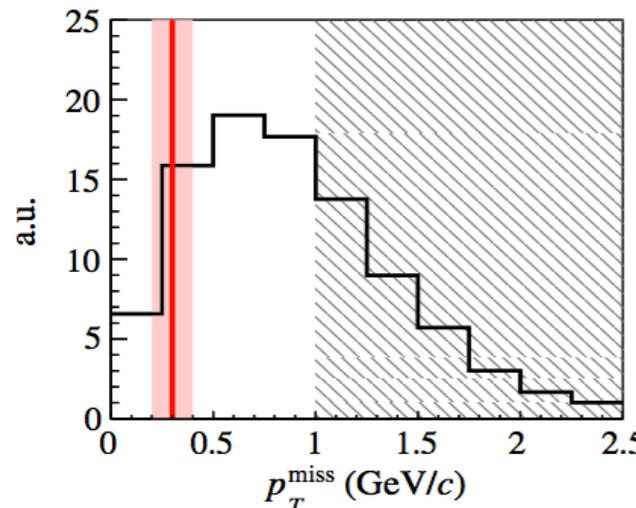
THE 5TH ν_τ CANDIDATE EVENT

RECONSTRUCTION IN THE BRICK





THE 5TH ν_τ CANDIDATE EVENT

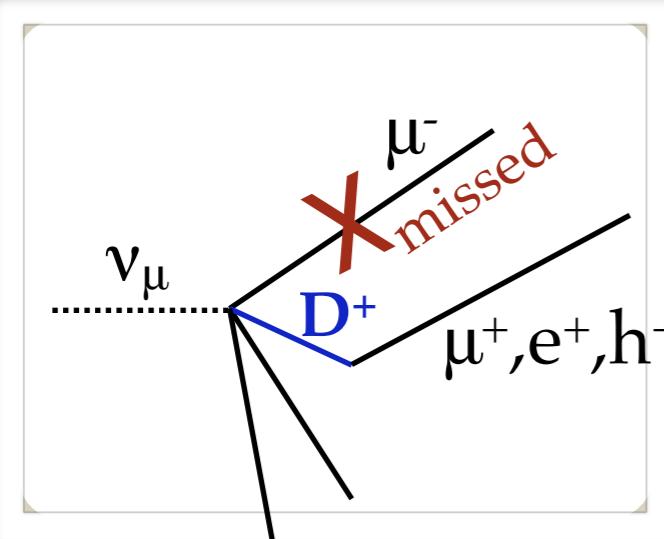


SELECTION CRITERIA	MEASURED
kink > 20 mrad	90 ± 2 mrad
decay length < 2600 μm	634 ± 30 μm
P daughter > 2 GeV/c	11^{+14}_{-4} GeV/c
P _t > 600 MeV/c	1000^{+1200}_{-400} MeV/c
missing P _t < 1 GeV/c	300 ± 100 GeV/c
$\varphi > 90^\circ$	151 ± 1 °

The event passes all the required kinematical cuts

BACKGROUND SOURCES

Charmed hadron decay
with missed muon at
primary vertex

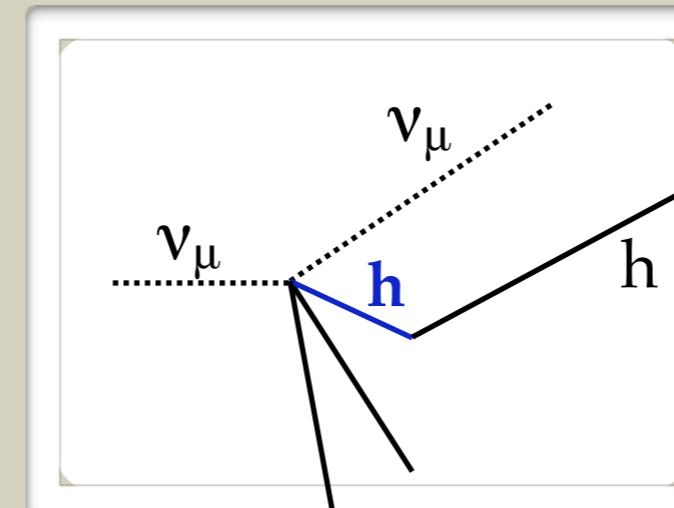


Eur. Phys.J. C74 (2014) 2986

MC tuned on CHORUS
data

Reduced by Track Follow-
down procedure

Hadronic interaction

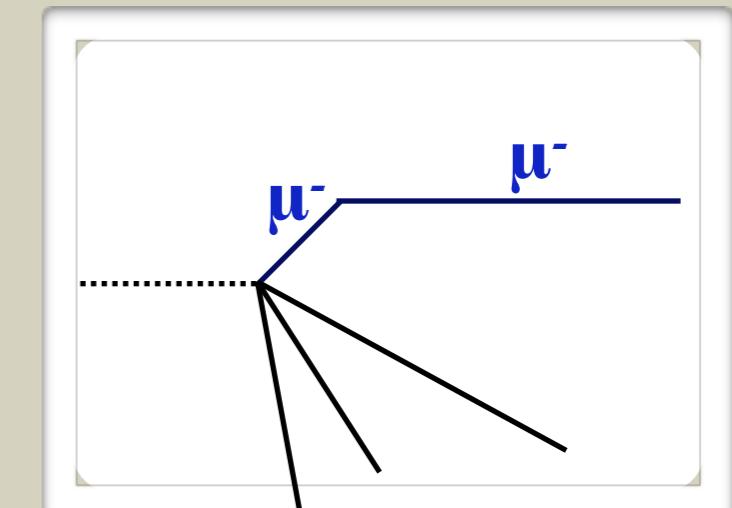


PTEP9 (2014) 093C01

FLUKA + test beam data

Reduced by large angle
scanning and nuclear
fragment search

Large angle muon
scattering



*IEEE Transactions on
Nuclear Science
Vol. 62, 5, 2015*

MC tuned on old
measurements on lead
form factor

$\nu_\mu \rightarrow \nu_\tau$ RESULTS

Exposure	17.97×10^{19} p.o.t.
Interactions in the target volume	19505
Located interactions	6932

Physics Review Letters
115 (2015) 121802

$$\Delta m^2 = 2.44 \cdot 10^{-3} \text{ eV}^2$$

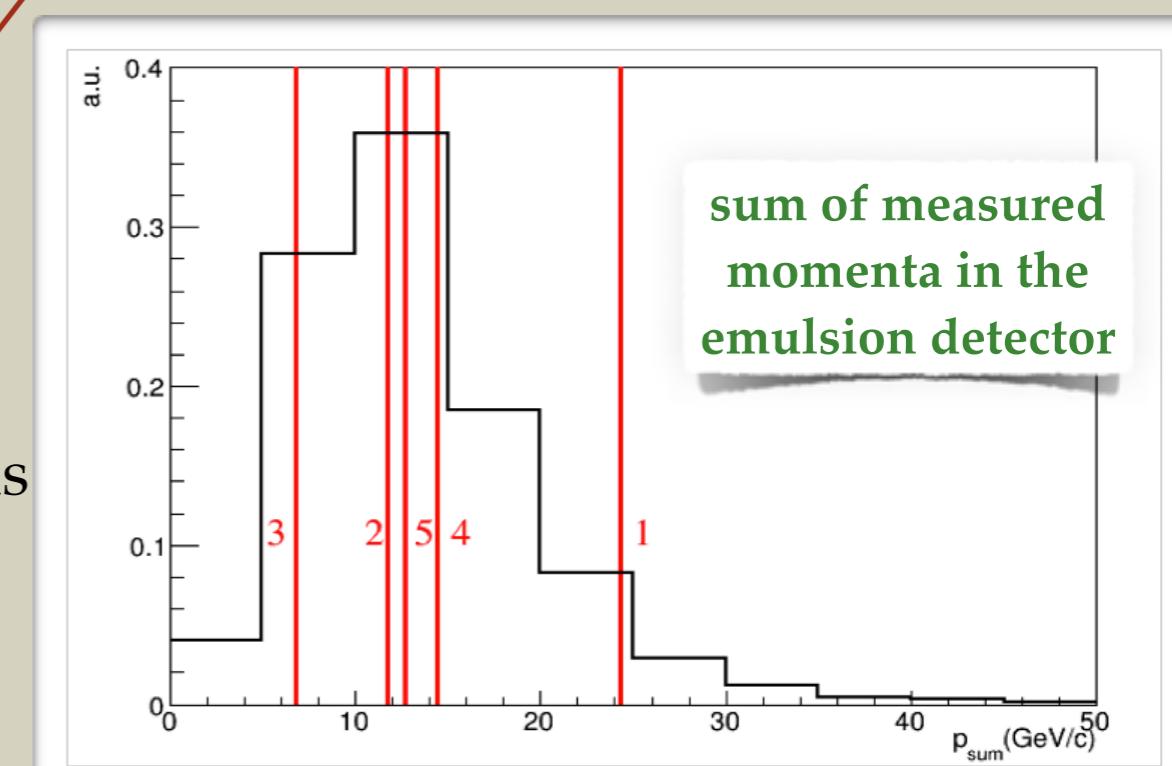
Decay Channel	Signal Expectation	Total Background	Observed
$\tau \rightarrow h$	0.52 ± 0.10	0.04 ± 0.01	3
$\tau \rightarrow 3h$	0.73 ± 0.14	0.17 ± 0.03	1
$\tau \rightarrow \mu$	0.61 ± 0.12	0.004 ± 0.001	1
$\tau \rightarrow e$	0.78 ± 0.16	0.03 ± 0.01	0
Total	2.64 ± 0.53	0.25 ± 0.05	5

- 5 observed events with 0.25 background events
- **5.1 σ** exclusion of the background-only hypothesis

Two statistical methods:

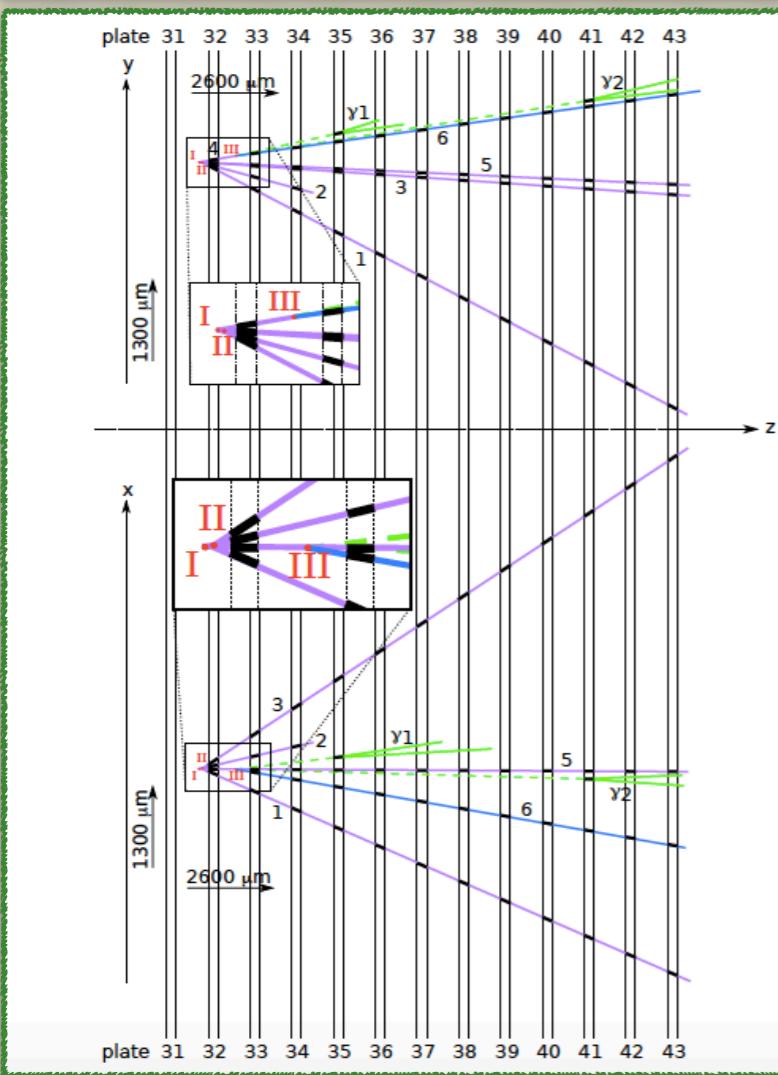
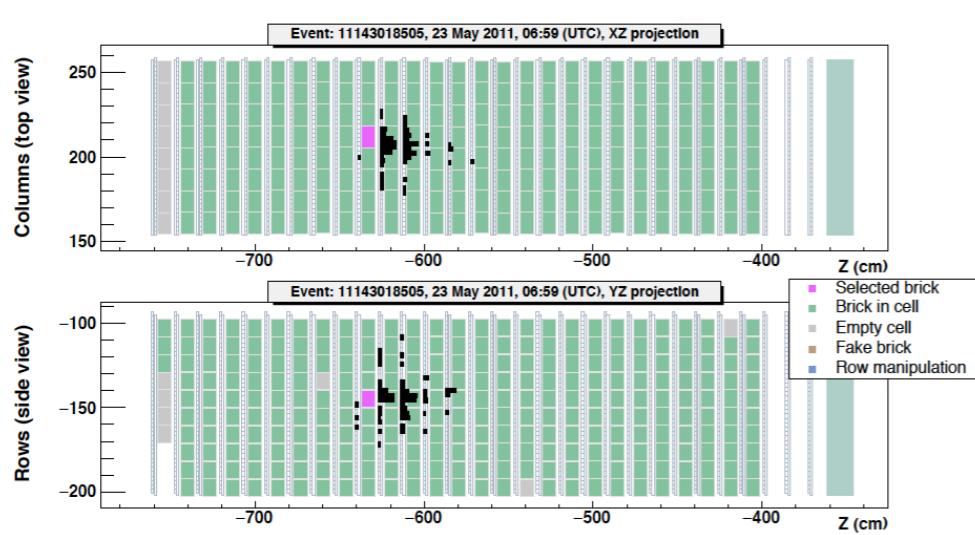
- Fisher combination of single channel p-values
- Profile likelihood ratio

Compatible with expectations in standard 3-flavours neutrino model





ν INTERACTION WITH 3 VERTICES



- Muonless event
- A primary and two secondary vertices found in emulsion
- Electromagnetic activity (γ 's) at the kink point

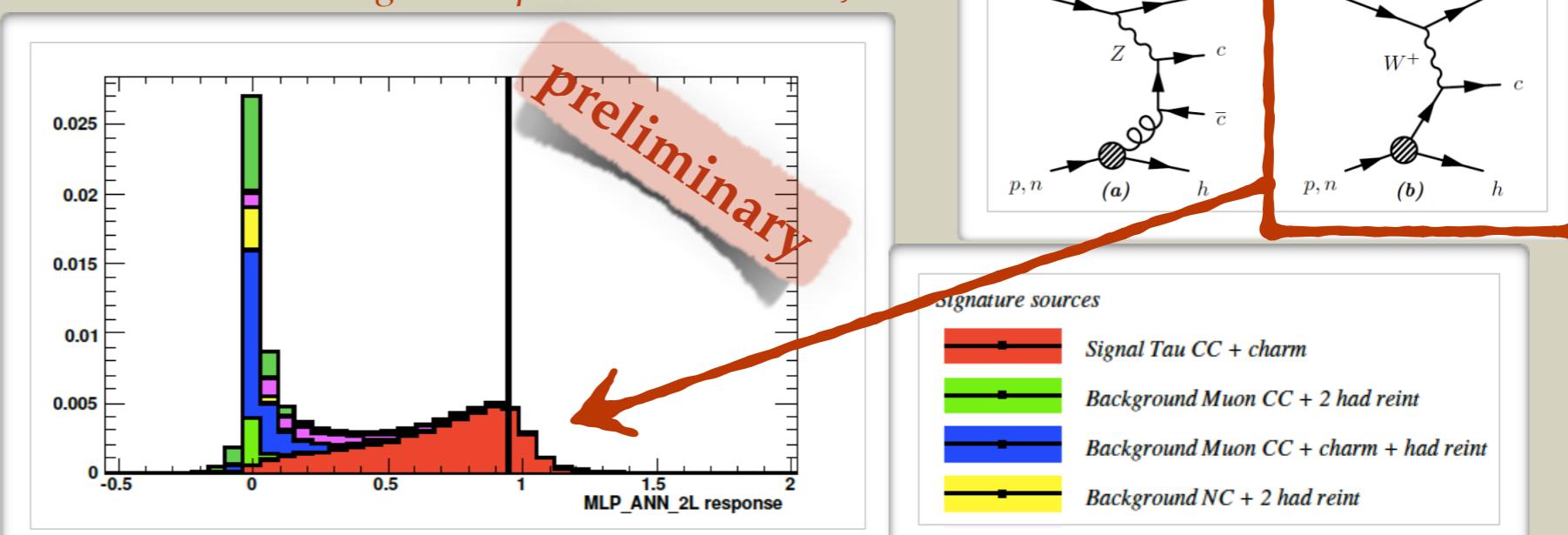
Vertex ID	Attached tracks	x (μm)	y (μm)	z (μm)
I (primary)	2, 4, 5	15077.0	59157.9	-33081.8
II (secondary)	1, 3	15085.9	59149.9	-32979.2
III (kink)	4, 6	15073.9	59262.4	-31926.4

Track ID	p best fit (GeV/c)	68 % p range (GeV/c)
1	2.1	[1.6 ; 3.1]
3	4.3	[3.1 ; 7.1]
5	0.54	[0.45 ; 0.68]
6 (daughter)	2.7	[2.1 ; 3.7]

Flight lengths:
II: 103 μm
III: 1160 μm

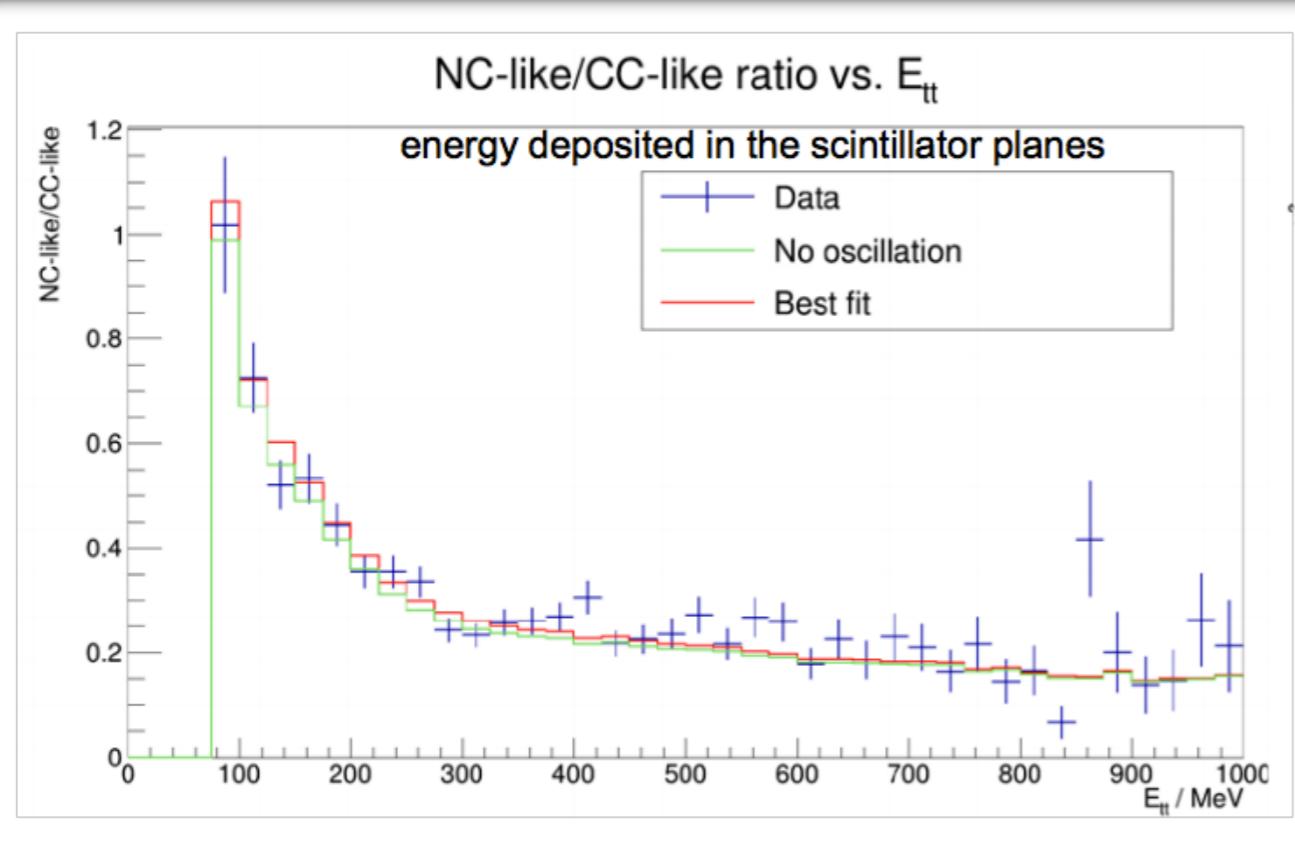
- Invariant masses at both secondary vertices are larger than 1 GeV
- Event not classified as ν_τ interaction candidate by standard analysis
- Ad hoc simulations and multivariate analysis performed to distinguish between possible interpretations

More detail in C. Sirignano's presentation on 9th Jul

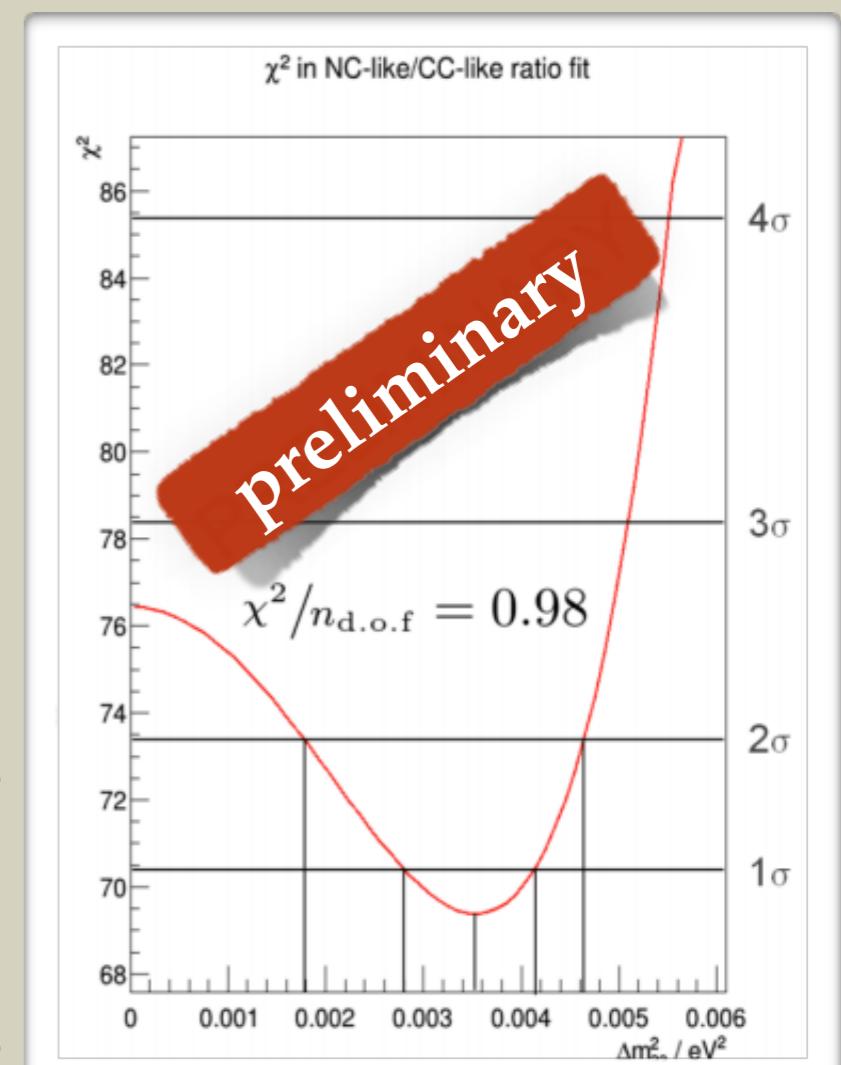




ν_μ DISAPPEARANCE



- Full data sample (2008-2012)
- Use of electronic detector data only and separation between CC and NC like events
- To reduce systematic effects coming from the beam uncertainty (no near detector), NC like over CC like ratio is used



- A fit using NC-like/CC-like ratio in which all mixing parameters are fixed to the PDG values BUT Δm^2_{23}
- Reweighting MC according to oscillation probability and minimizing χ^2 between MC and data
- Systematics under study

Preliminary measurement of Δm^2_{23}
Consistent with the world average and the internal OPERA
appearance results



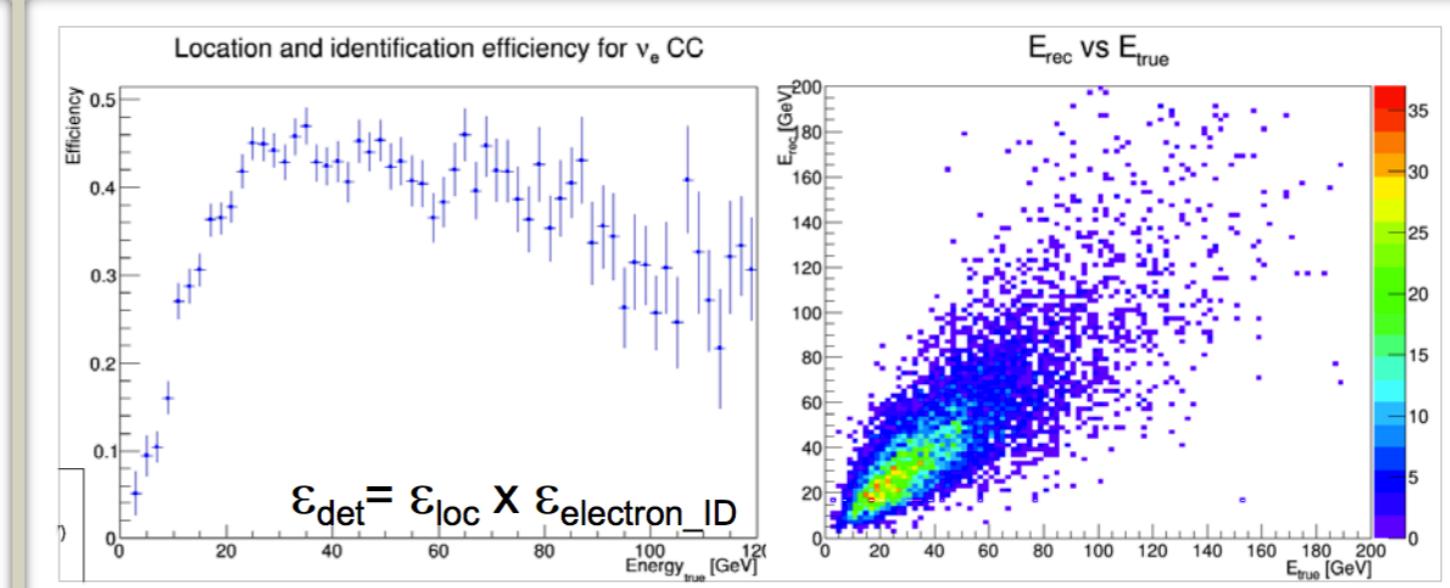
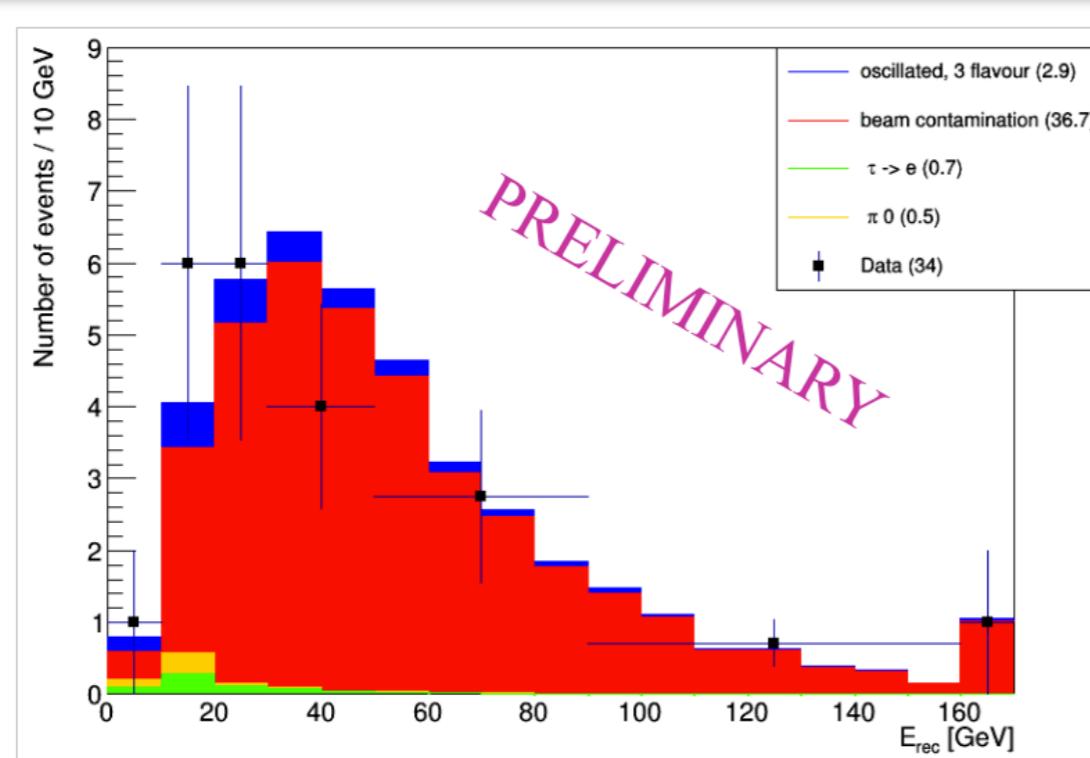
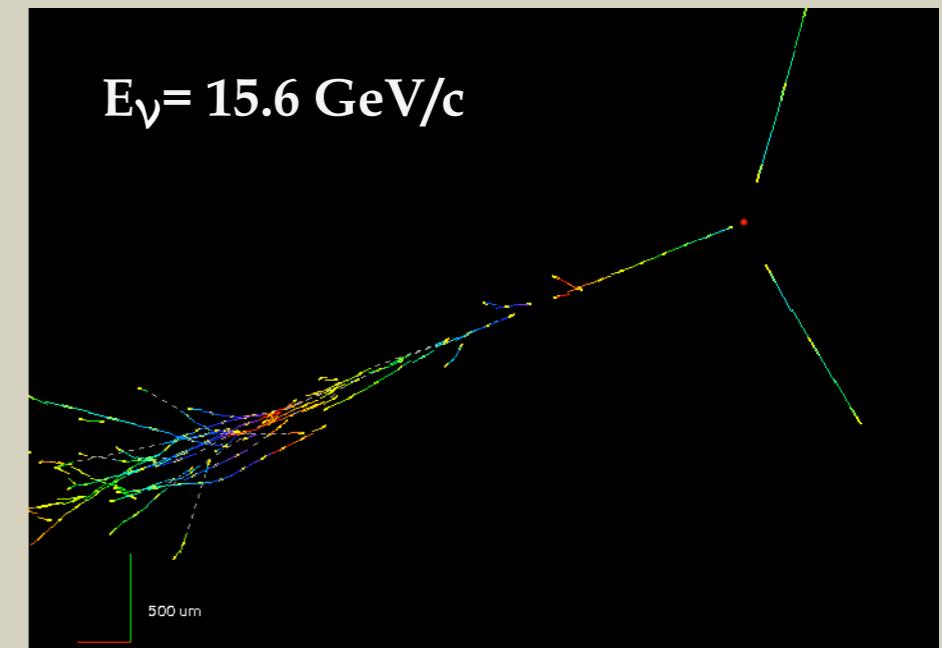
ν_e APPEARANCE SEARCH

2008-2012 data sample (17.97×10^{19} p.o.t.)

Observed ν_e events: 34

Expected ν_e events

from ν_e beam contamination	37 ± 5
from bkg $\tau \rightarrow e + \text{mis-id } \pi^0$	1.2 ± 0.1
from 3-flavour oscillation	2.9 ± 0.4 $\sin^2(2\theta_{13}) = 0.098$



Work in progress to extract exclusion limits on sterile search



ν_τ APPEARANCE IN 3+1 MODEL

$\nu_\mu \rightarrow \nu_\tau$ oscillation probability in presence of a **sterile neutrino**
neglecting solar driven oscillation $\Delta m^2_{21} \sim 0$

Effective mixing

$$C = 2 | U_{\mu 3} U_{\tau 3}^* |$$

$$\phi_{\mu\tau} = \text{Arg}(U_{\mu 3} U_{\tau 3}^* U_{\mu 4}^* U_{\tau 4})$$

$$\sin^2 2\theta_{\mu\tau} = 4 | U_{\mu 4} |^2 | U_{\tau 4} |^2$$

$$\Delta_{ij} = \frac{1.27 \Delta m_{ij}^2 L}{E}$$

~standard oscillation

exotic oscillation

$$\begin{aligned}
 P_{\nu_\mu \rightarrow \nu_\tau} = & C^2 \sin^2 \Delta_{31} + \sin^2 2\theta_{\mu\tau} \sin^2 \Delta_{41} \\
 & + 0.5C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin 2\Delta_{31} \sin 2\Delta_{41} \\
 & - C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin^2 \Delta_{31} \sin 2\Delta_{41} \\
 & + 2C \sin 2\theta_{\mu\tau} \cos \phi_{\mu\tau} \sin^2 \Delta_{31} \sin^2 \Delta_{41} \\
 & + C \sin 2\theta_{\mu\tau} \sin \phi_{\mu\tau} \sin 2\Delta_{31} \sin^2 \Delta_{41}
 \end{aligned}$$

CP-violating terms

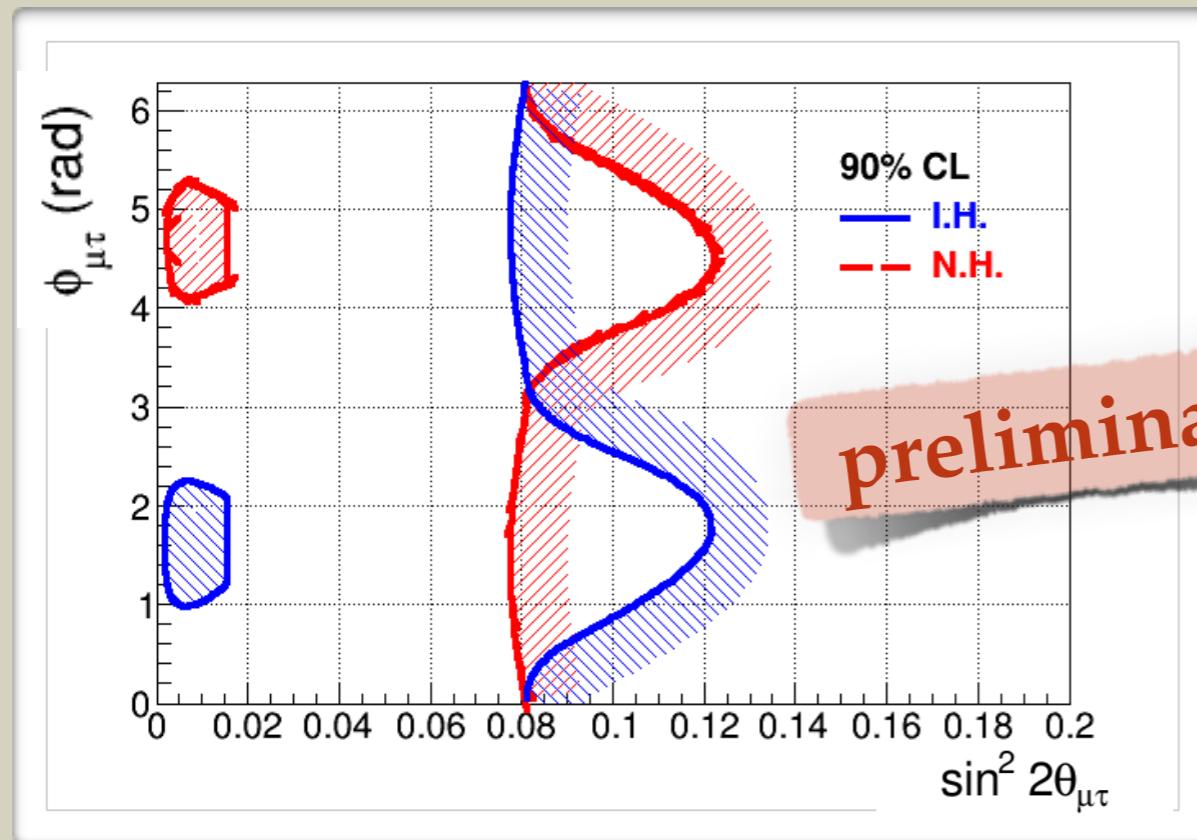
interference term

Mass hierarchy dependence

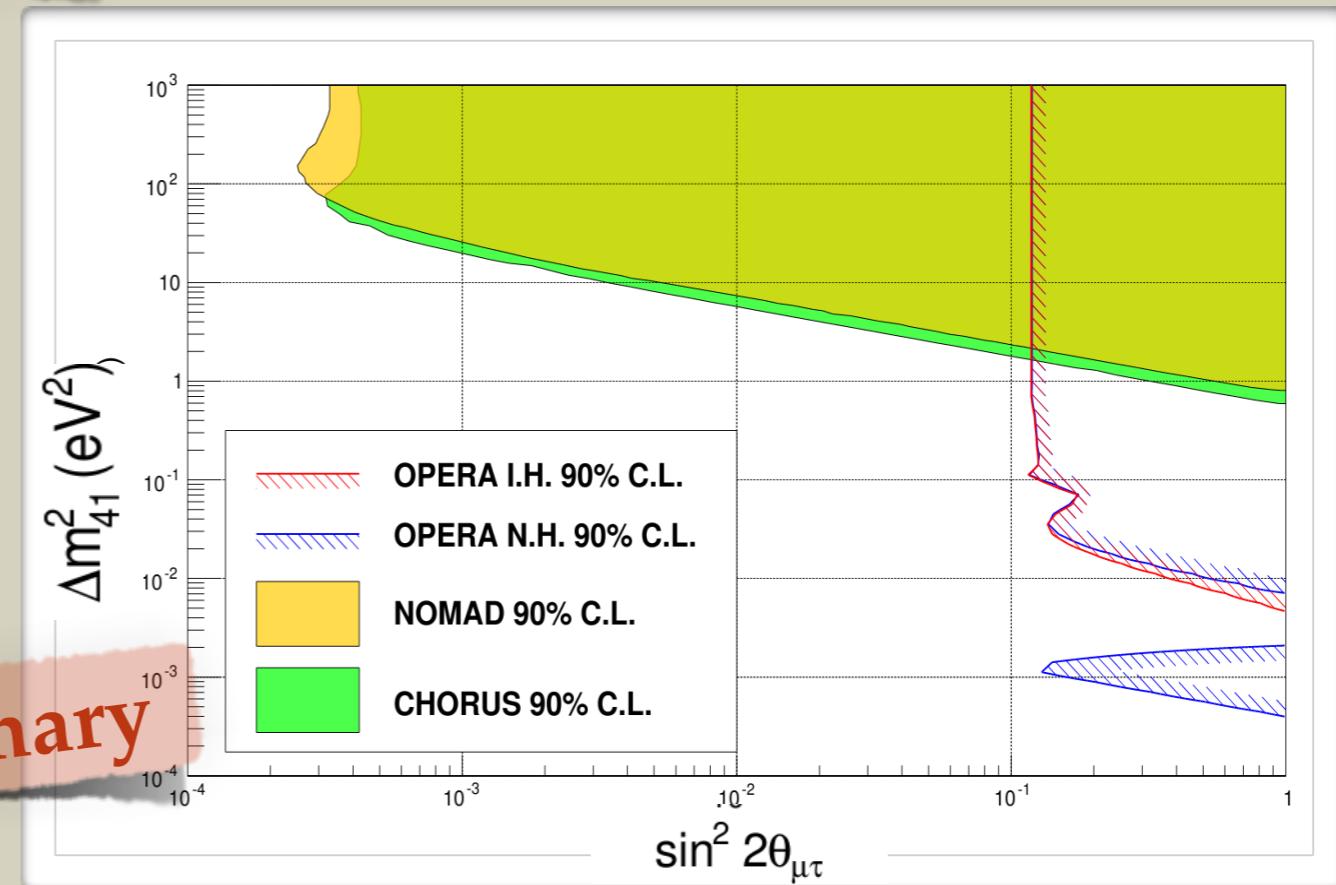


RESULTS WITH $5\nu_\tau$ CANDIDATES

Results based on $4\nu_\tau$ candidates in JHEP, 6 (2015) 69



$\sin^2 2\theta_{\mu\tau} < 0.119$ at 90% C.L.
when integrating over ϕ
(almost identical results for NH and IH)





CONCLUSIONS

- First observation of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode
- **5 ν_τ candidate** events found with 0.23 background
- No oscillation hypothesis excluded at **5.1 σ**
- ν_μ disappearance analysis => preliminary Δm^2_{32} consistent with world average
- $\nu_\mu \rightarrow \nu_e$ oscillation search => number of events observed in agreement with expected background + standard oscillation
- Sterile neutrino oscillation constraints from ν_e and ν_τ studies

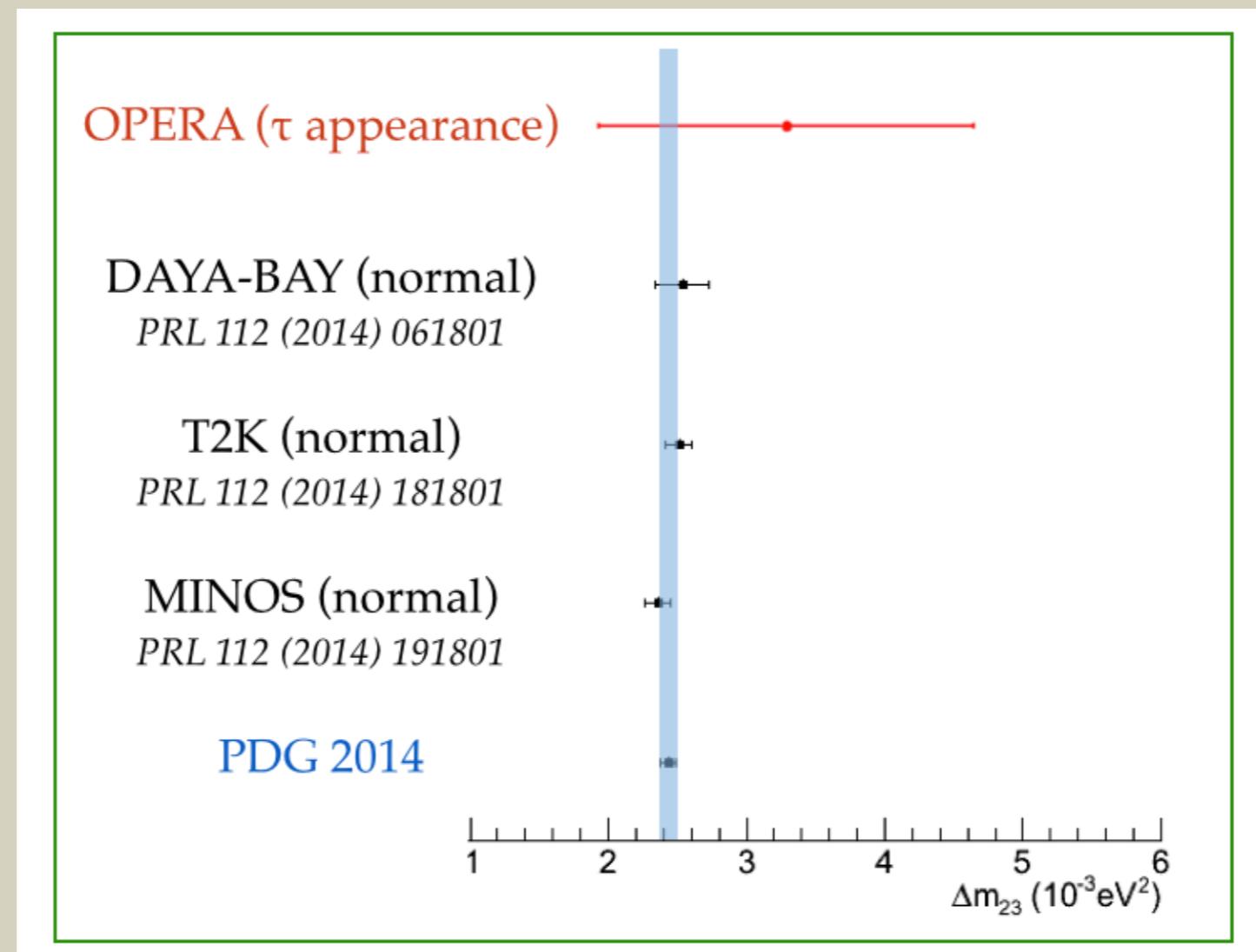
PERSPECTIVES

- re-analysis of the data with looser selection and multivariate analysis: more signal and background but significant statistical gain
- Exploiting the unique feature of being able to identify all three neutrino flavours:
 ν_τ appearance + ν_e appearance + ν_μ disappearance data
=> Constraints on the oscillation parameters with one single experiment



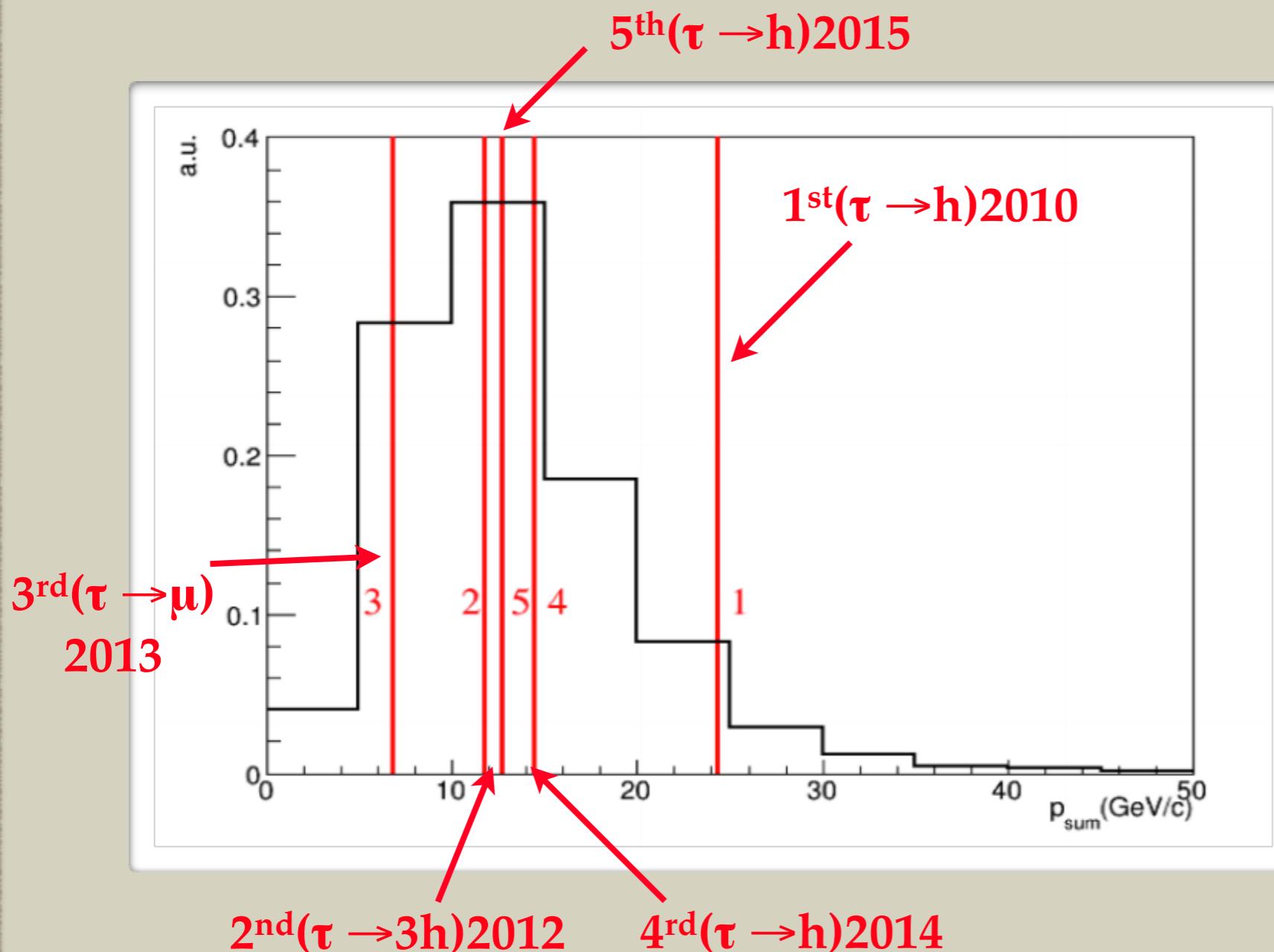
Δm^2_{23} ESTIMATION

90% C.L. intervals on Δm^2_{23} by Feldman & Cousins method
 $[2.0 - 4.7] \times 10^{-3} \text{ eV}^2$
(assuming full mixing)



SUMMARY OF FOUR EVENTS

Visible energy of all ν_τ events
 Scalar sum of momentum and γ energies

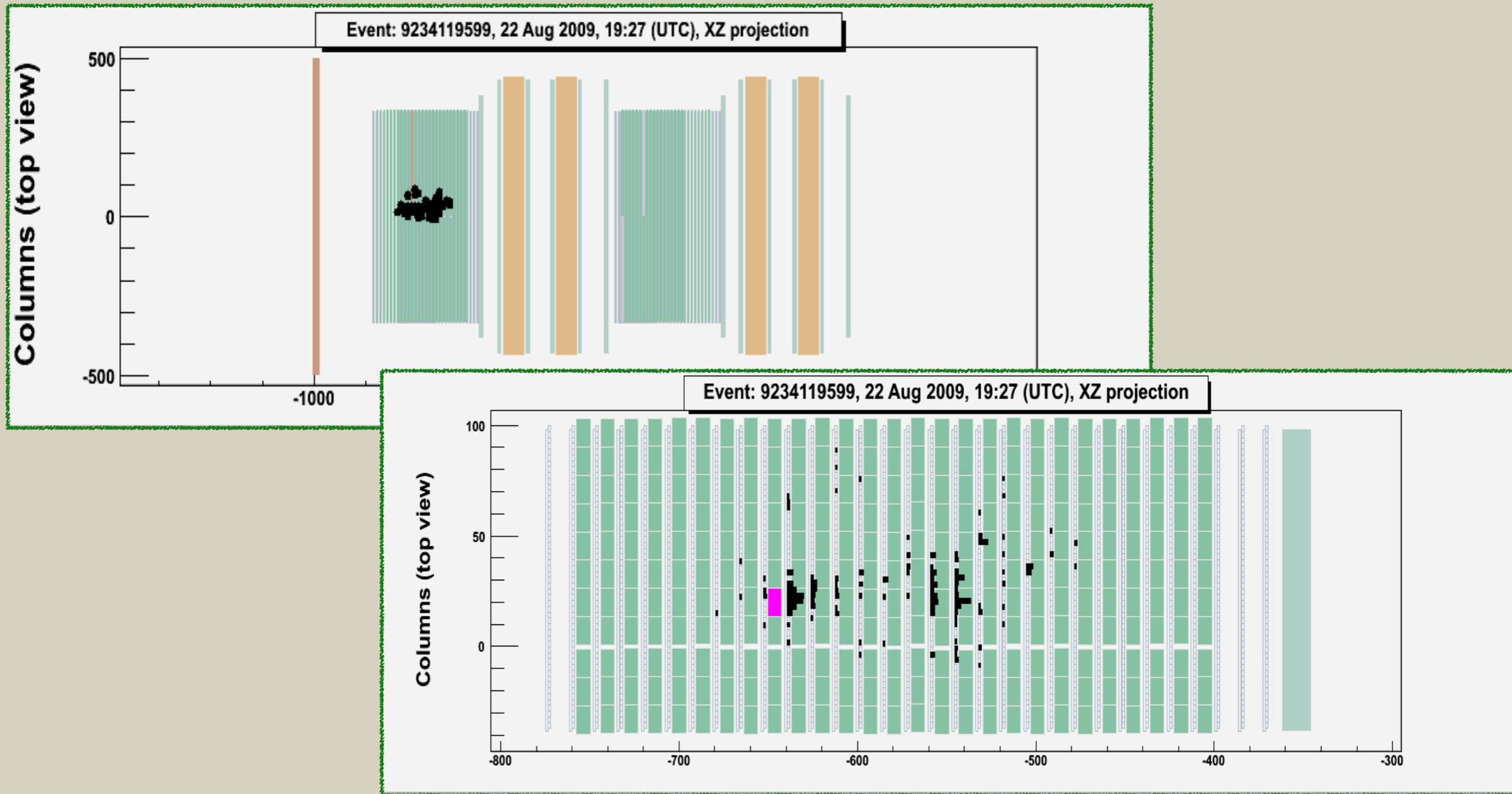


	MODE	P_{sum} (GeV/c)
1 st	$\tau \rightarrow h$	$24.3^{+6.1}_{-3.2}$
2 nd	$\tau \rightarrow 3h$	$12.7^{+2.3}_{-1.7}$
3 rd	$\tau \rightarrow \mu$	$6.8^{+0.9}_{-0.6}$
4 th	$\tau \rightarrow h$	$14.4^{+3.9}_{-2.7}$
5 th	$\tau \rightarrow h$	11^{+14}_{-4}



THE FIRST ν_τ CANDIDATE

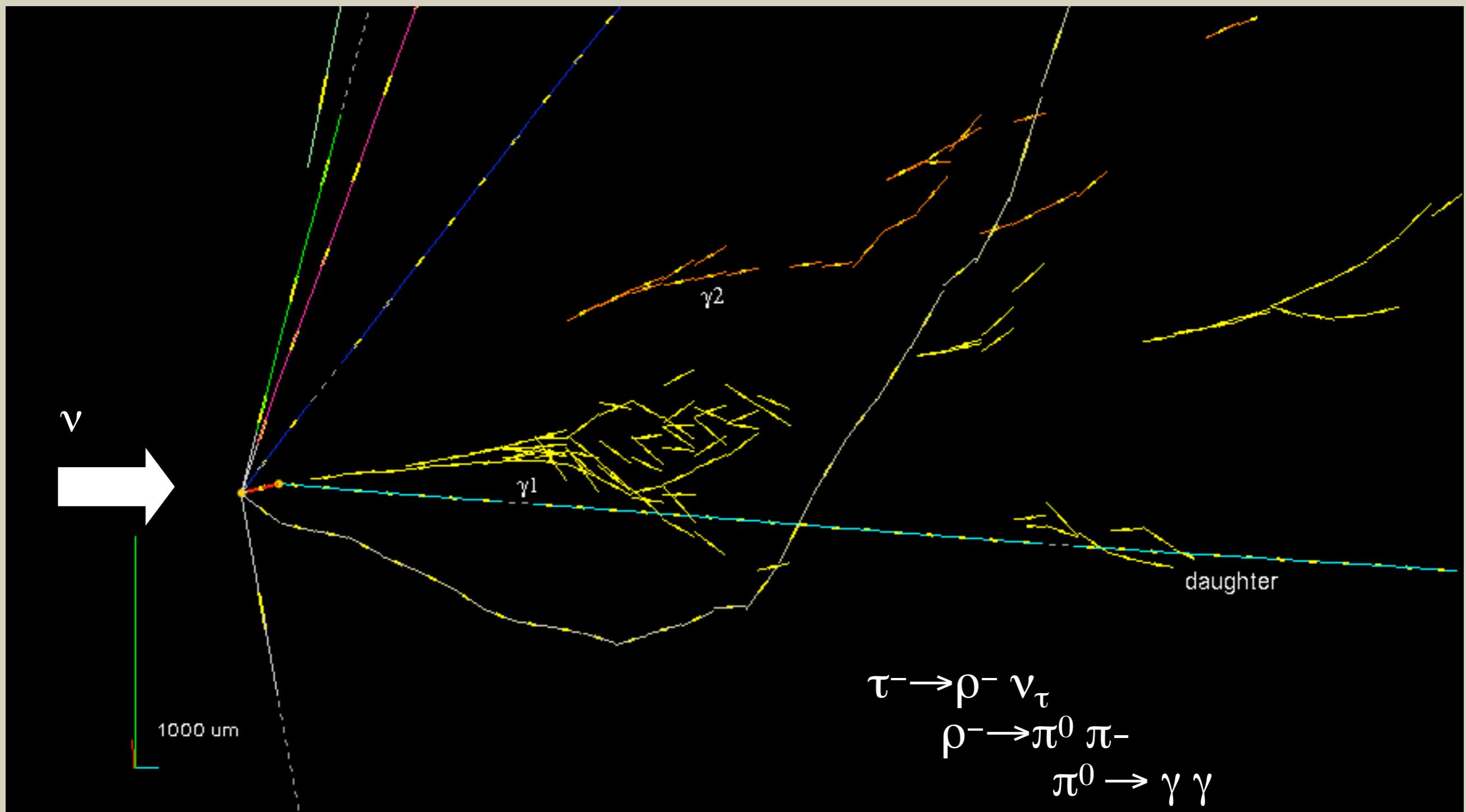
As Seen By ELECTRONIC DETECTORS ...





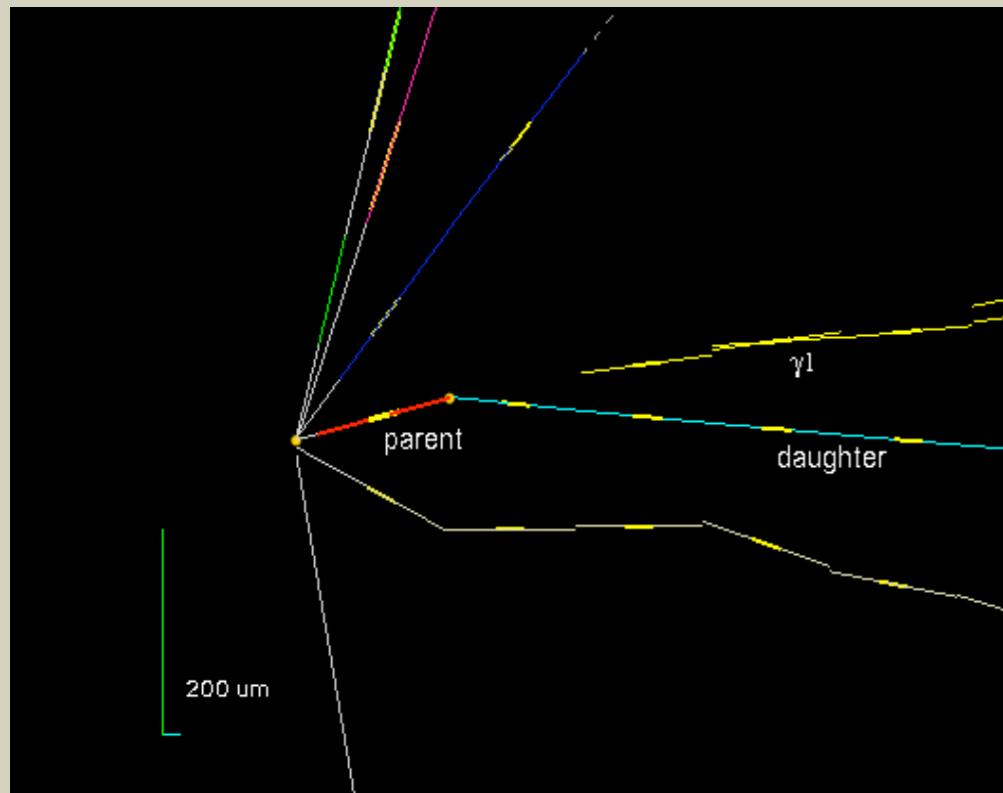
THE FIRST ν_τ CANDIDATE

... AND IN THE BRICK





THE FIRST ν_τ CANDIDATE



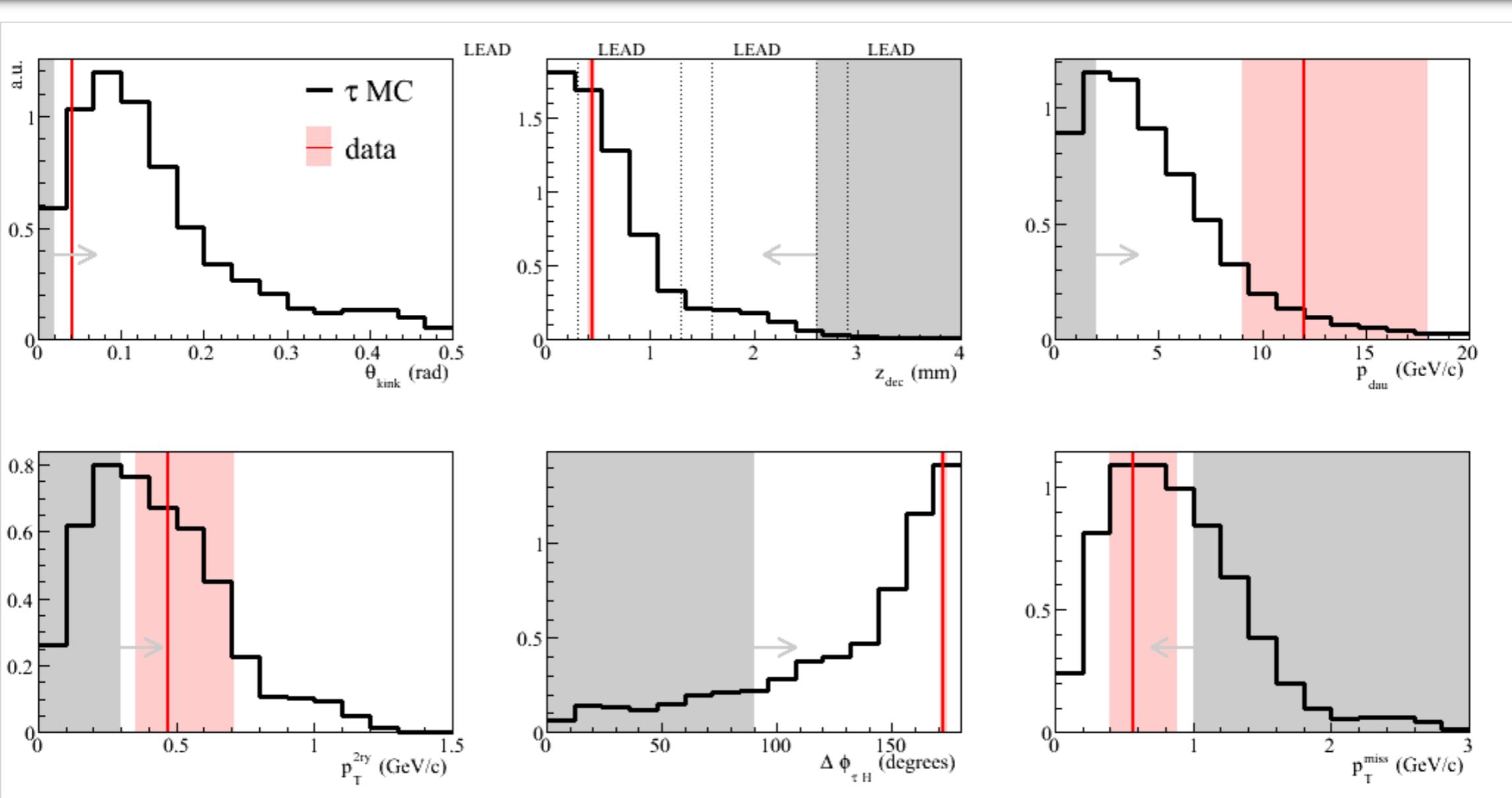
SELECTION CRITERIA	MEASURED
$kink > 20 \text{ mrad}$	$41 \pm 2 \text{ mrad}$
decay length $< 2600 \mu\text{m}$	$1335 \pm 35 \mu\text{m}$
$P_{\text{daughter}} > 2 \text{ GeV/c}$	$12^{+6}_{-3} \text{ GeV/c}$
$P_t > 300 \text{ MeV/c}$	$470^{+230}_{-120} \text{ MeV/c}$
missing $P_t < 1 \text{ GeV/c}$	$0.57^{+0.32}_{-0.17} \text{ GeV/c}$
$\varphi > 90^\circ$	$173 \pm 2^\circ$

The event passes all the kinematical cuts required



THE FIRST ν_τ CANDIDATE

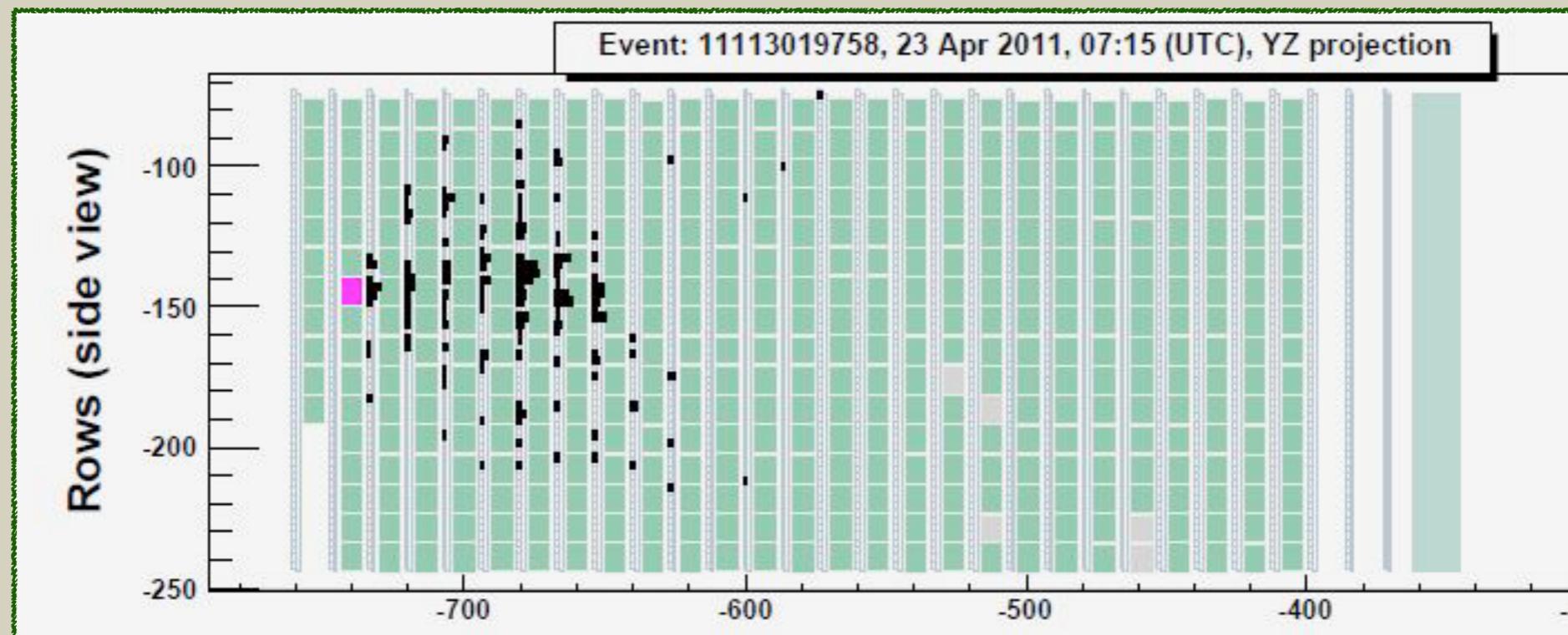
Kinematical selection for $\tau \rightarrow h$ decay channel





THE SECOND ν_τ CANDIDATE

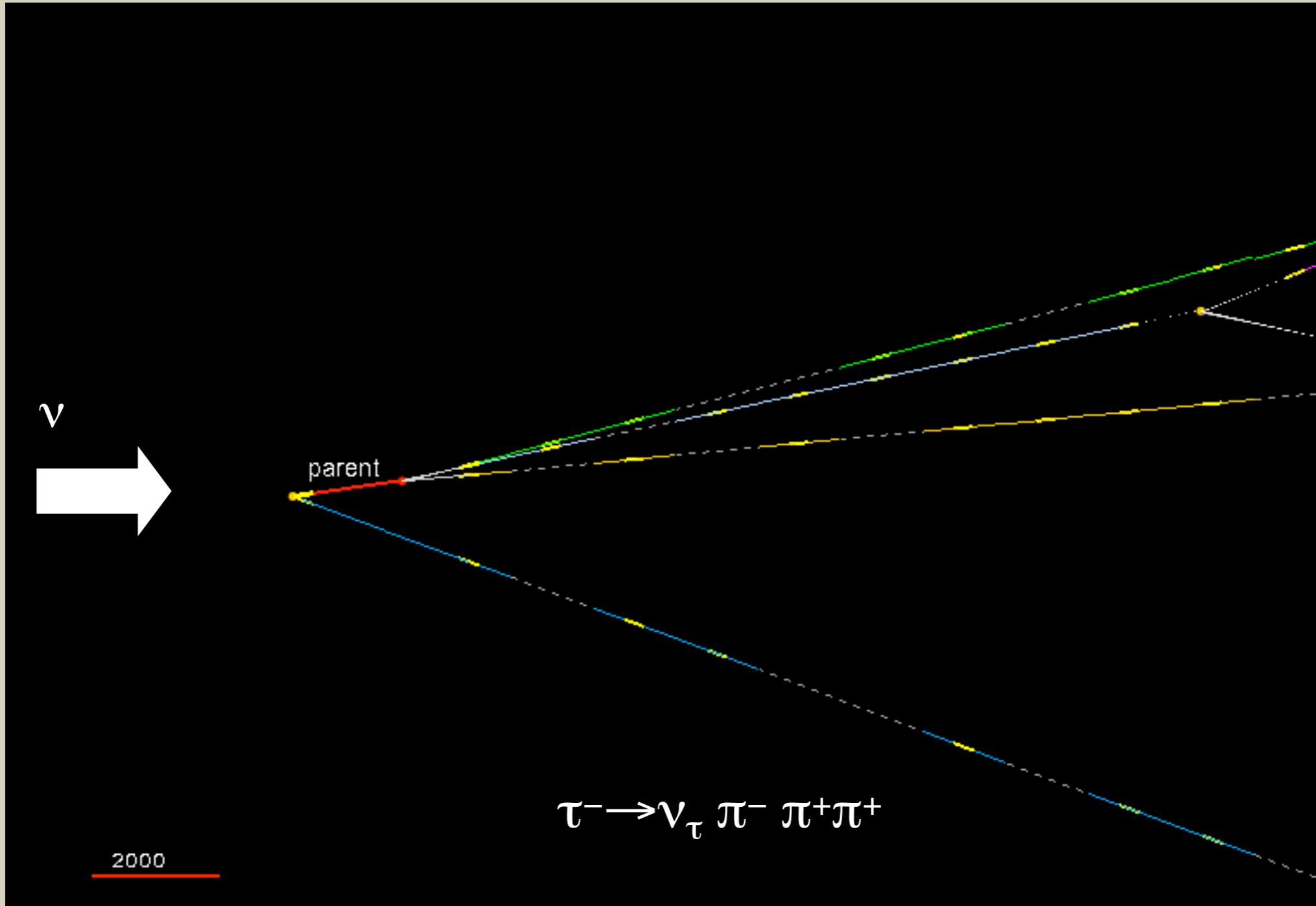
AS SEEN BY ELECTRONIC DETECTORS ...





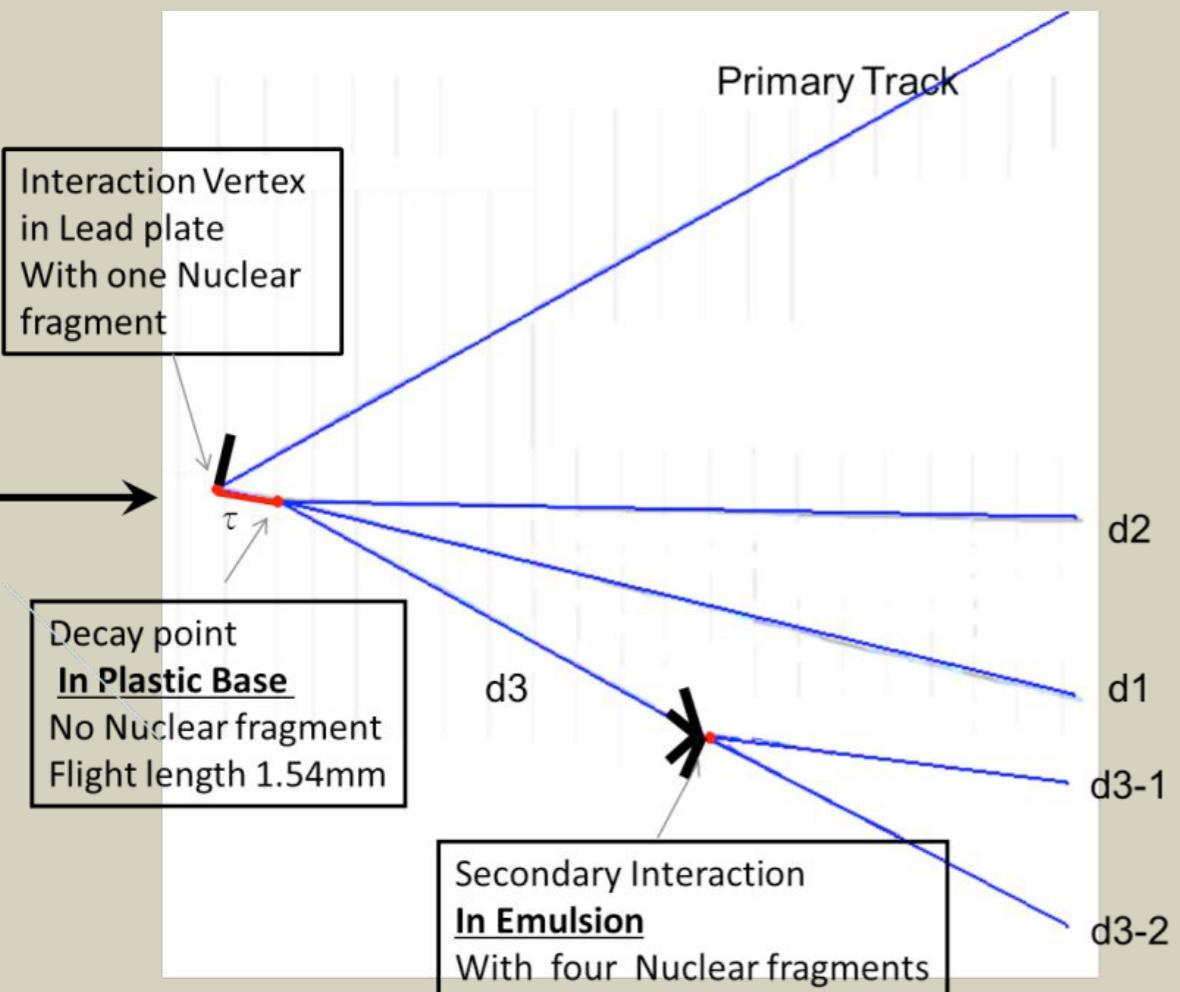
THE SECOND ν_τ CANDIDATE

... AND IN THE BRICK





THE SECOND ν_τ CANDIDATE



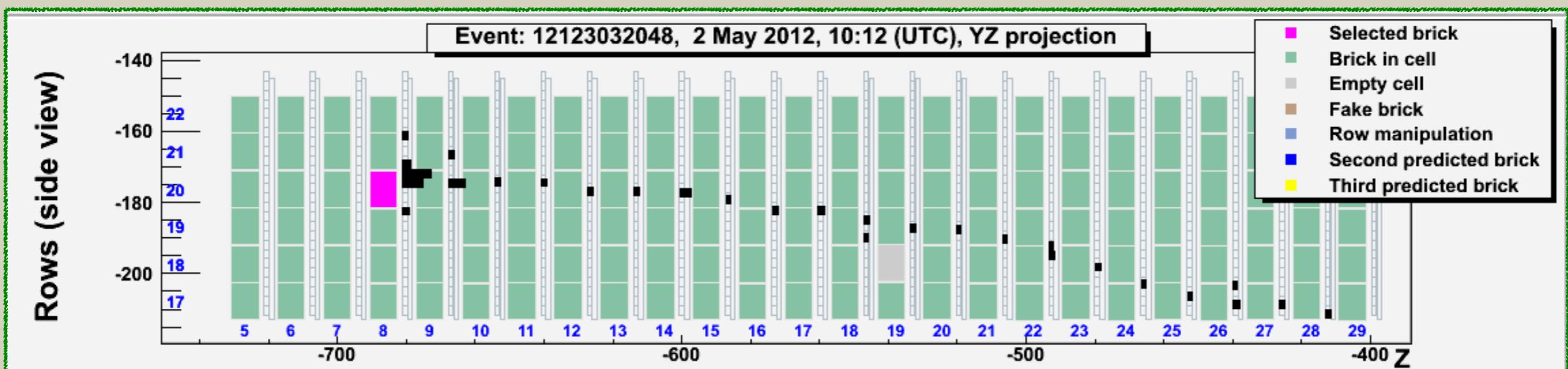
SELECTION CRITERIA	MEASURED
$kink < 500 \text{ mrad}$	$87.4 \pm 1.5 \text{ mrad}$
$0.5 \text{ GeV}/c^2 < \text{Inv Mass} < 2 \text{ GeV}/c^2$	$0.80 \pm 0.12 \text{ GeV}/c^2$
$0.5 \text{ GeV}/c^2 < \text{Min Inv Mass} < 2 \text{ GeV}/c^2$	$0.96 \pm 0.13 \text{ GeV}/c^2$
$P_{\text{daughters}} > 3 \text{ GeV}/c$	$8.4 \pm 1.7 \text{ GeV}/c$
$\text{missing } P_t < 1 \text{ GeV}/c$	$0.31 \pm 0.11 \text{ GeV}/c$
$\varphi > 90^\circ$	$167.8 \pm 1.1^\circ$

The event passes all the kinematical cuts required



THE THIRD ν_τ CANDIDATE

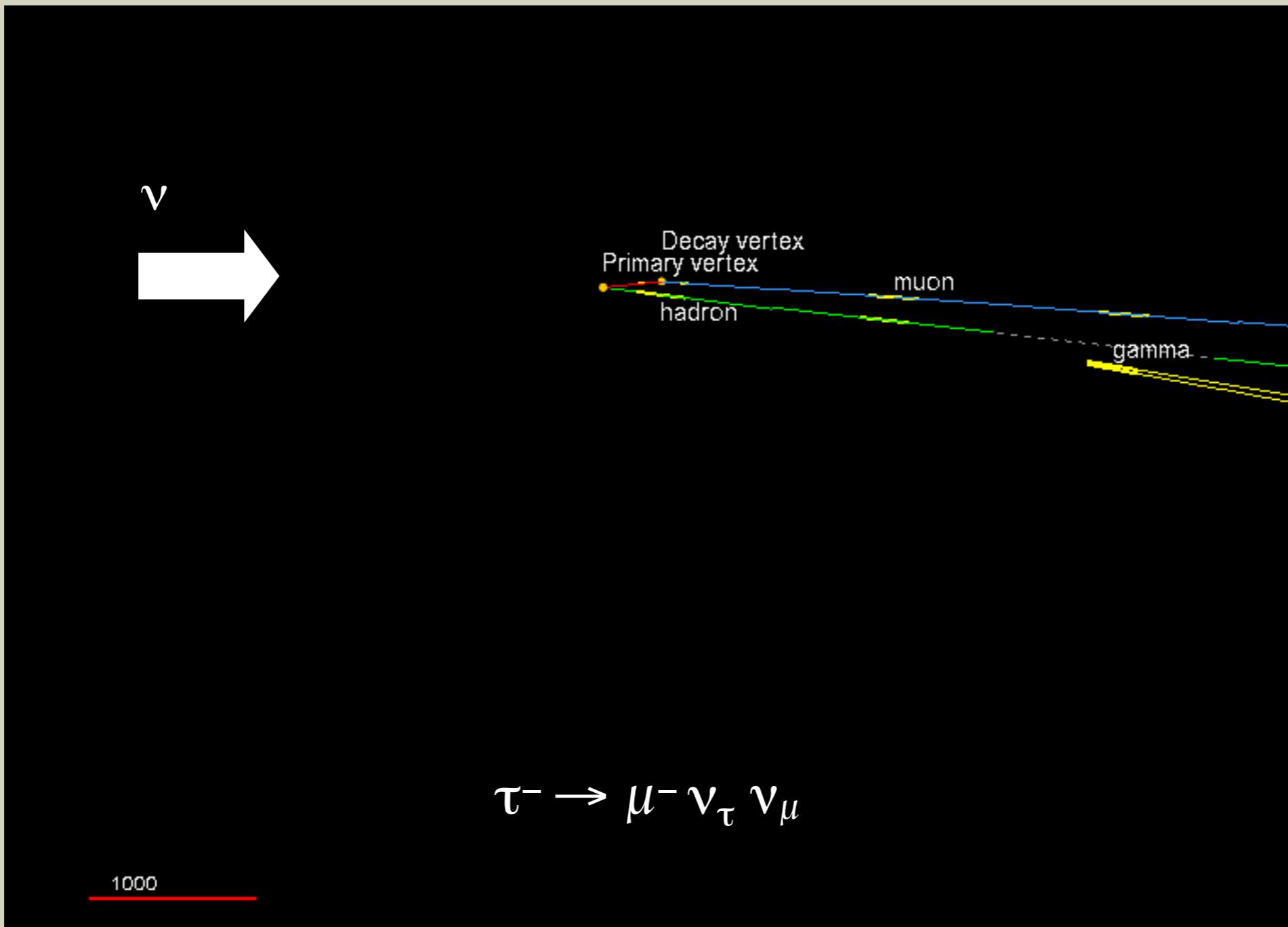
AS SEEN BY ELECTRONIC DETECTORS ...





THE THIRD ν_τ CANDIDATE

... AND IN THE BRICK





THE THIRD ν_τ CANDIDATE

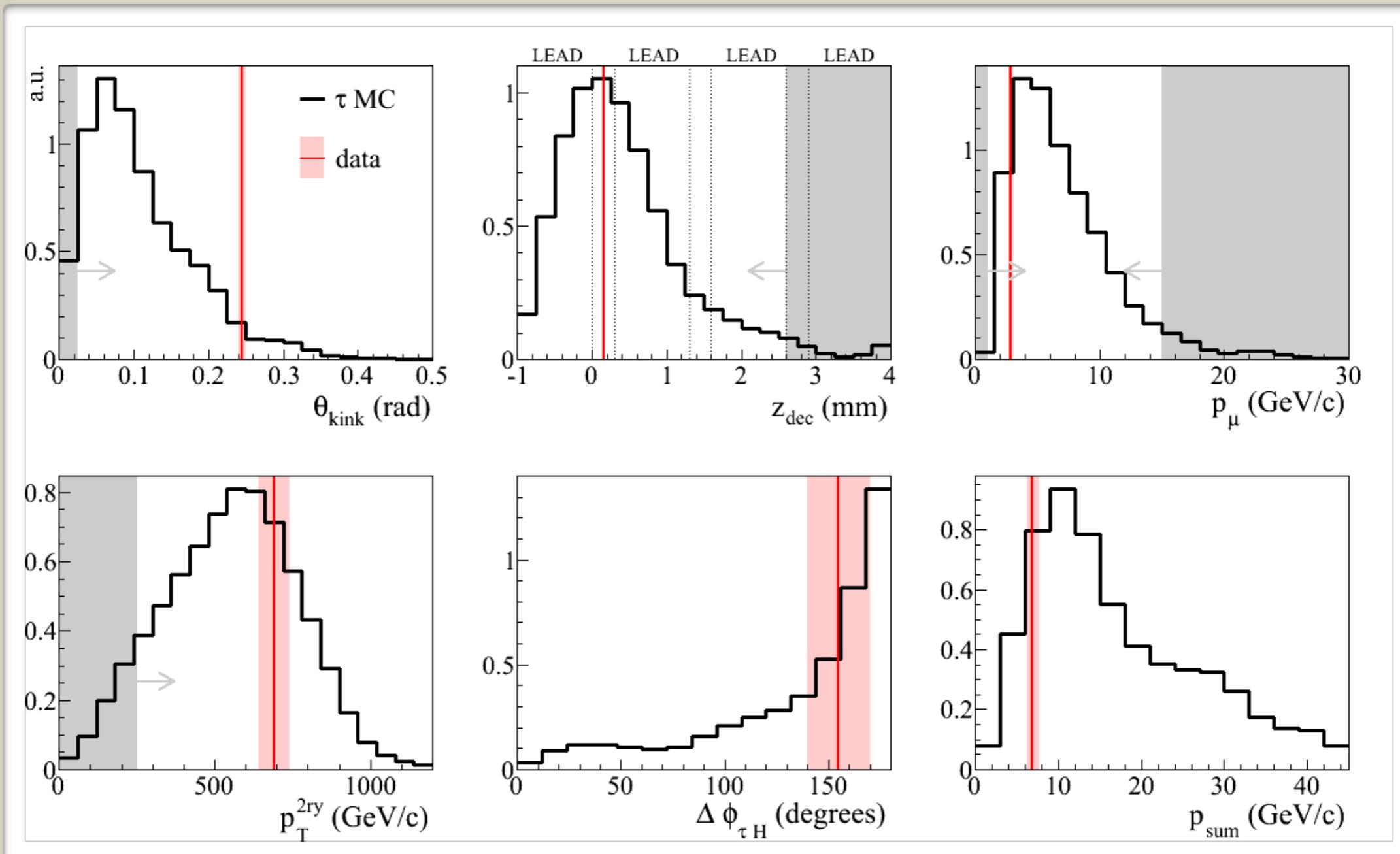
SELECTION CRITERIA	MEASURED
$kink > 20 \text{ mrad}$	$245 \pm 5 \text{ mrad}$
decay length $< 2600 \mu\text{m}$	$376 \pm 10 \mu\text{m}$
$P_{\text{muon}} > 1 \text{ GeV}/c$	$2.8 \pm 0.2 \text{ GeV}/c$
$P_t > 250 \text{ MeV}/c$	$690 \pm 50 \text{ MeV}/c$

The event passes all the kinematical cuts required



THE THIRD ν_τ CANDIDATE

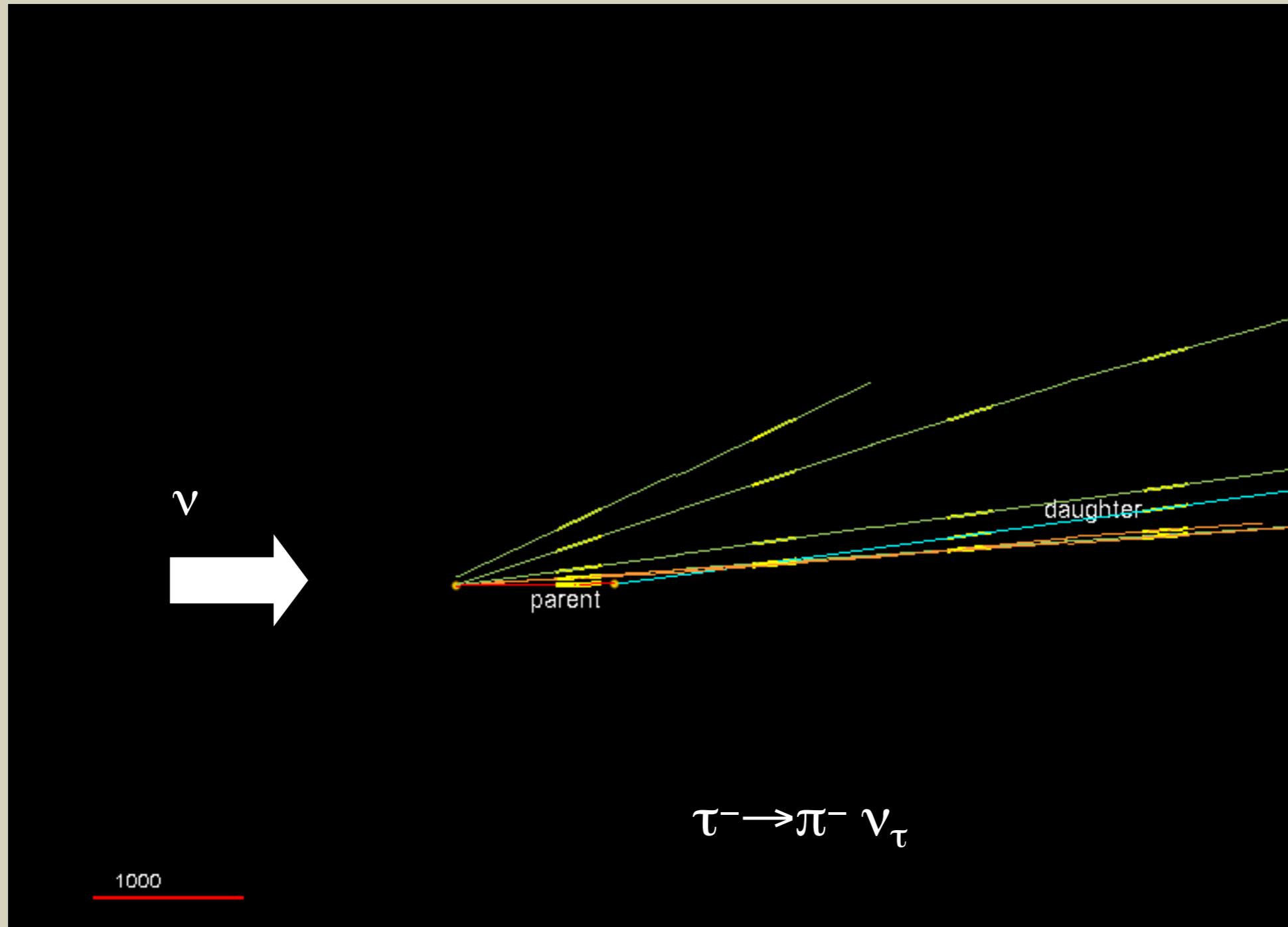
Kinematical selection for $\tau \rightarrow \mu$ decay channel





THE 4TH ν_τ CANDIDATE EVENT

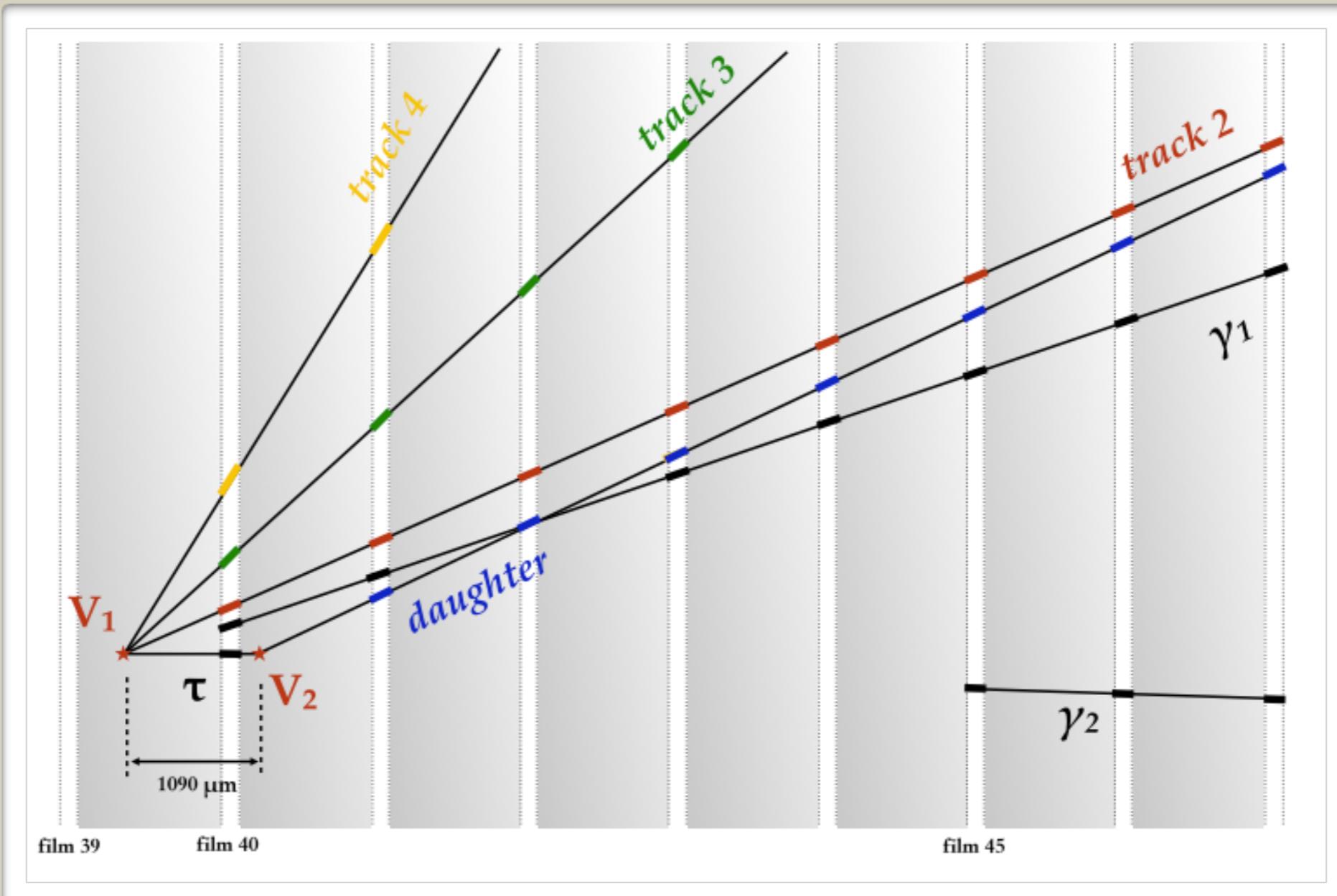
... AND IN THE BRICK





THE 4TH ν_τ CANDIDATE EVENT

RECONSTRUCTION IN THE BRICK

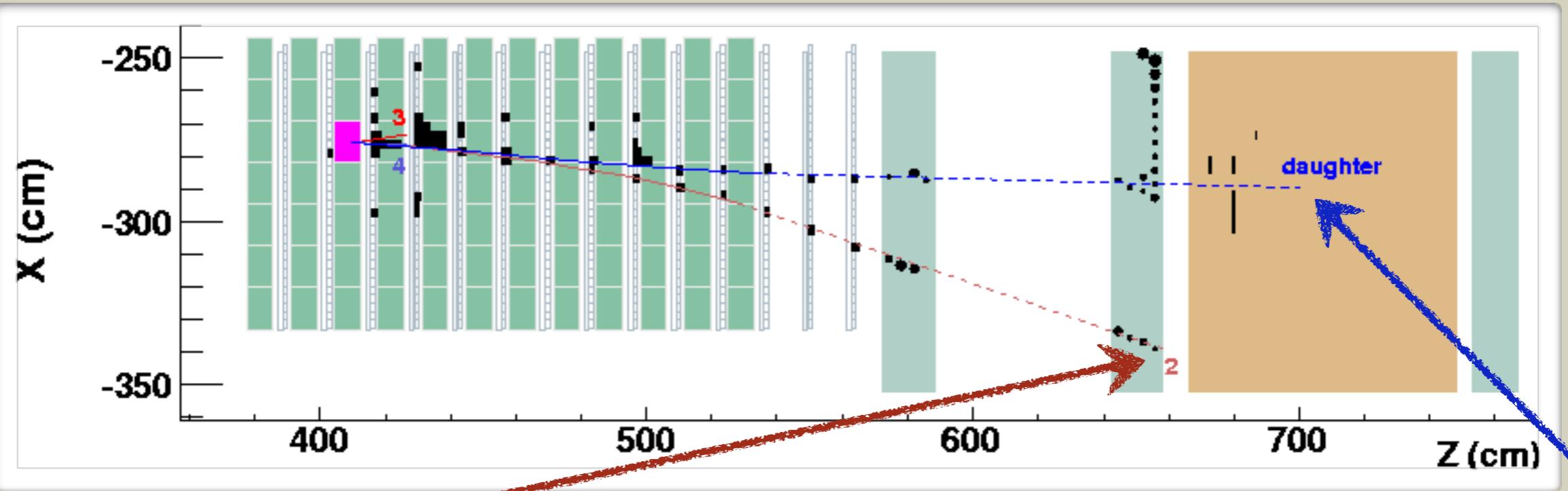


$$\tau^- \rightarrow \pi^- \nu_\tau$$



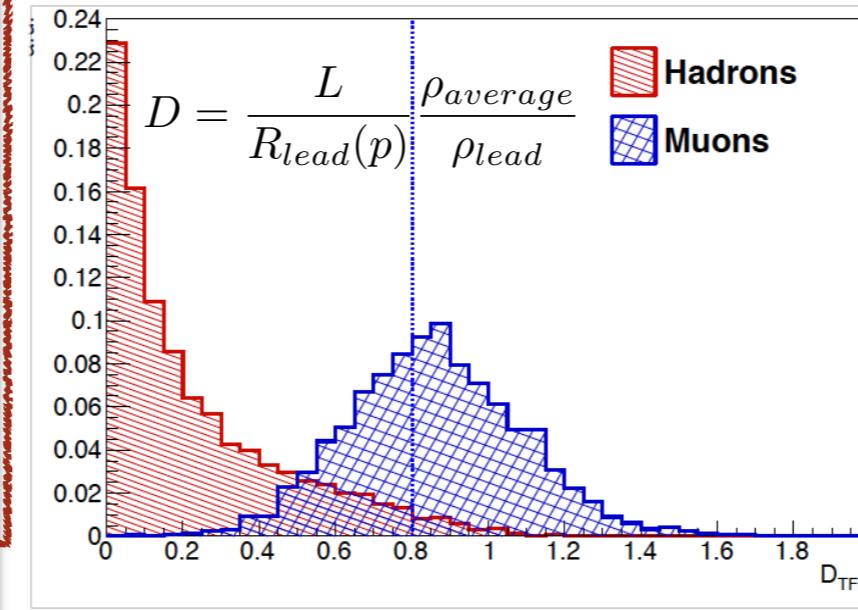
PARTICLE IDENTIFICATION

TRACK FOLLOW-DOWN



Track 2 from neutrino interaction vertex
- $p = 1.9 \text{ GeV}/c$
- stopping in the first iron slab of the magnet
- muon hypothesis rejected
 $D = 0.40^{+0.04}_{-0.05}$

Charm background hypothesis rejected



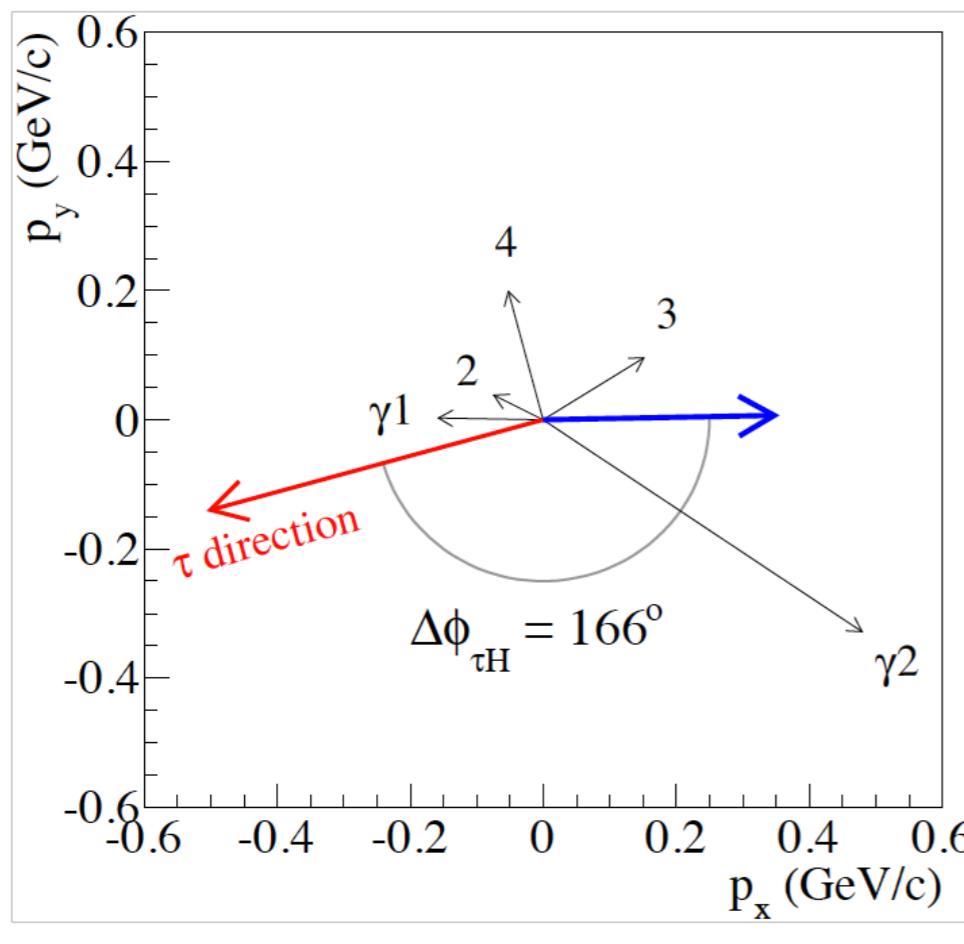
Daughter track from τ decay
- $p = 6.0 \text{ GeV}/c$
- stopping in the first arm of the spectrometer
- classified as **hadron**

$$D = 0.18 \pm 0.04$$

Hadronic decay channel



THE 4TH ν_τ CANDIDATE EVENT



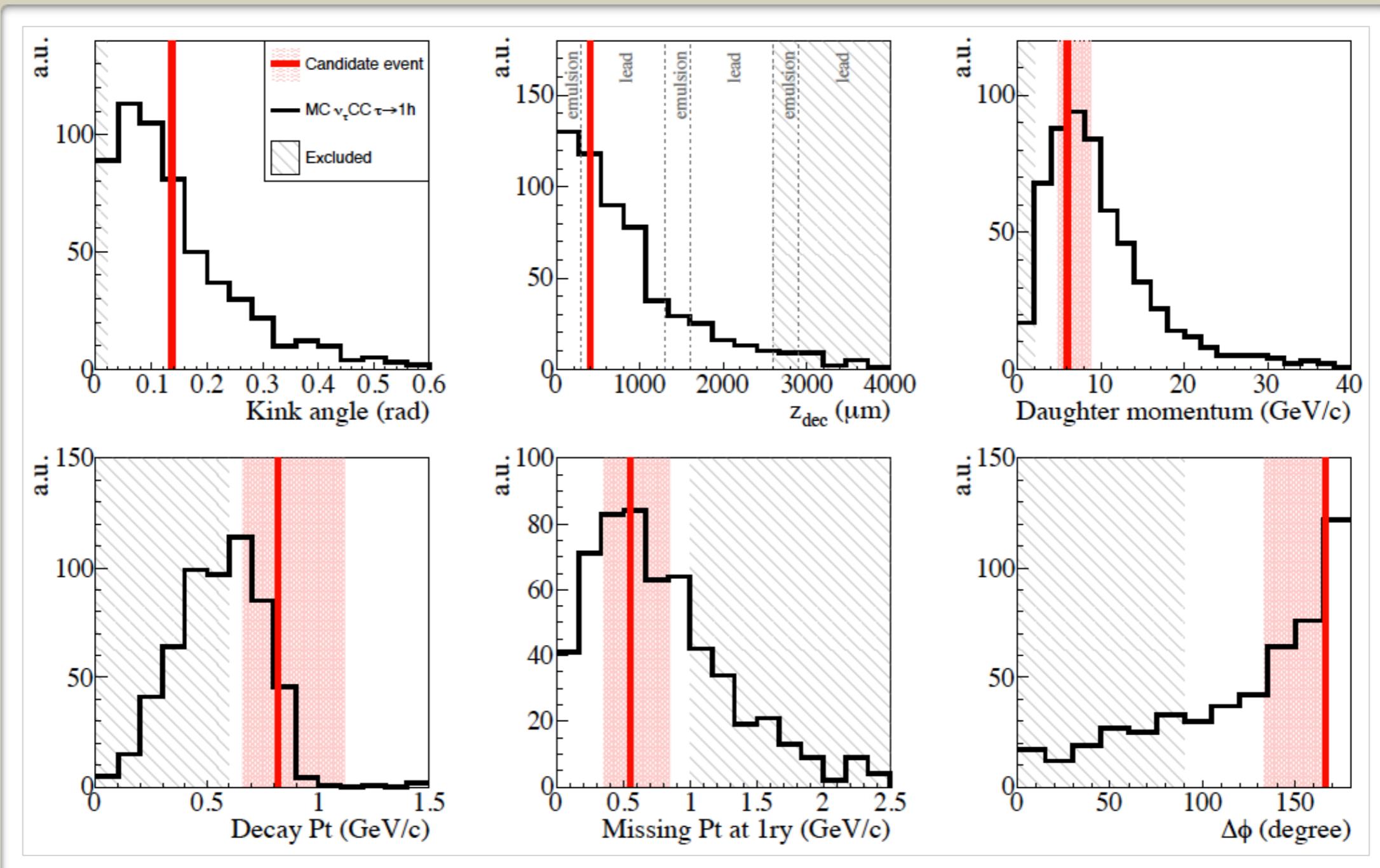
SELECTION CRITERIA	MEASURED
kink > 20 mrad	137 ± 4 mrad
decay length < 2600 μ m	1090 ± 30 μ m
$P_{\text{daughter}} > 2$ GeV/c	$6.0^{+2.2}_{-1.2}$ GeV/c
$P_t > 600$ MeV/c	820^{+300}_{-160} MeV/c
missing $P_t < 1$ GeV/c	$0.55^{+0.30}_{-0.20}$ GeV/c
$\varphi > 90^\circ$	166^{+2}_{-31} $^\circ$

The event passes all the required kinematical cuts



THE 4TH ν_τ CANDIDATE EVENT

Kinematical selection for $\tau \rightarrow h$ decay channel

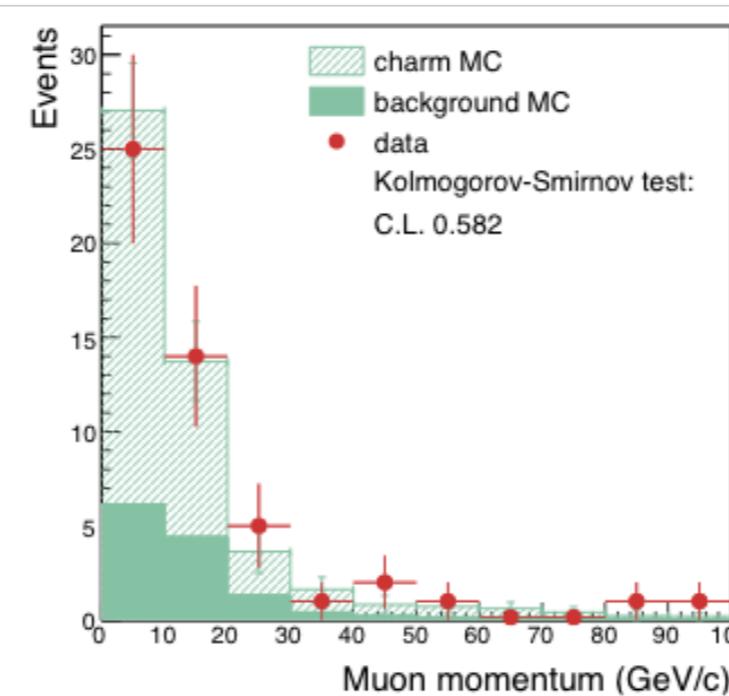
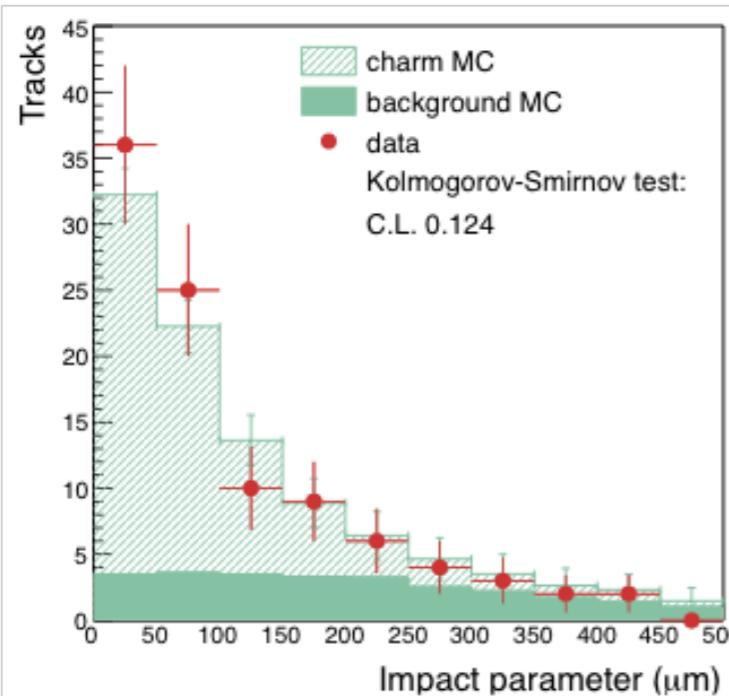
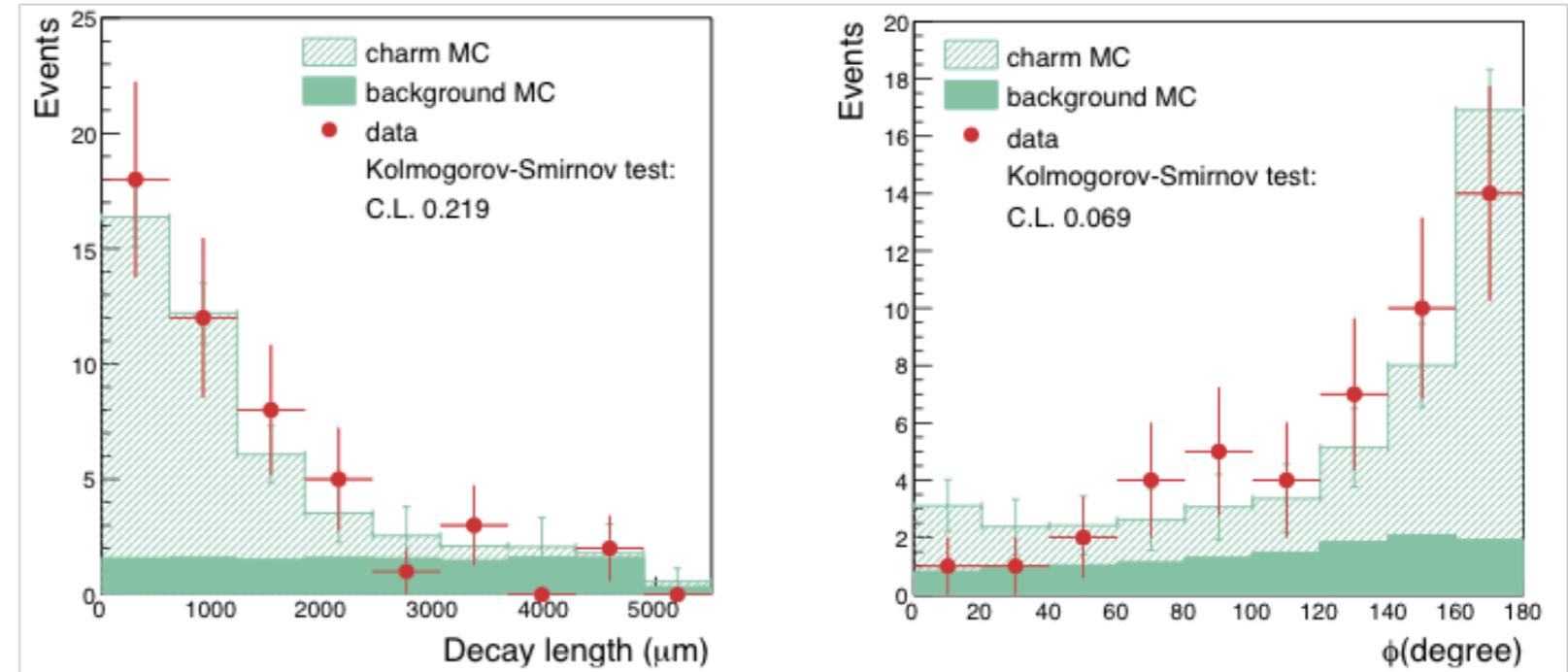




CHARM DATA SAMPLE

DATA/MC COMPARISON

Observed: 50
Expected: 54 ± 4



Good agreement between data and Monte Carlo