LATEST RESULTS OF THE OPERA EXPERIMENT

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on behalf of OPERA Collaboration

Les Rencontres de Physique de la Vallee d'Aoste
La Thuile
25th February - 2nd March, 2013

THE OPERA COLLABORATION

180 physicists, 32 institutions in 12 countries

Belgium
IIHE-ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPHC Strasbourg
IPNL Lyon

Germany
Hamburg
Münster

Israel
Technion Haifa

Italy
Bari
Bologna
LNF 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
ETH Zurich

Tunisia
CNSTN Tunis

Turkey
METU Ankara

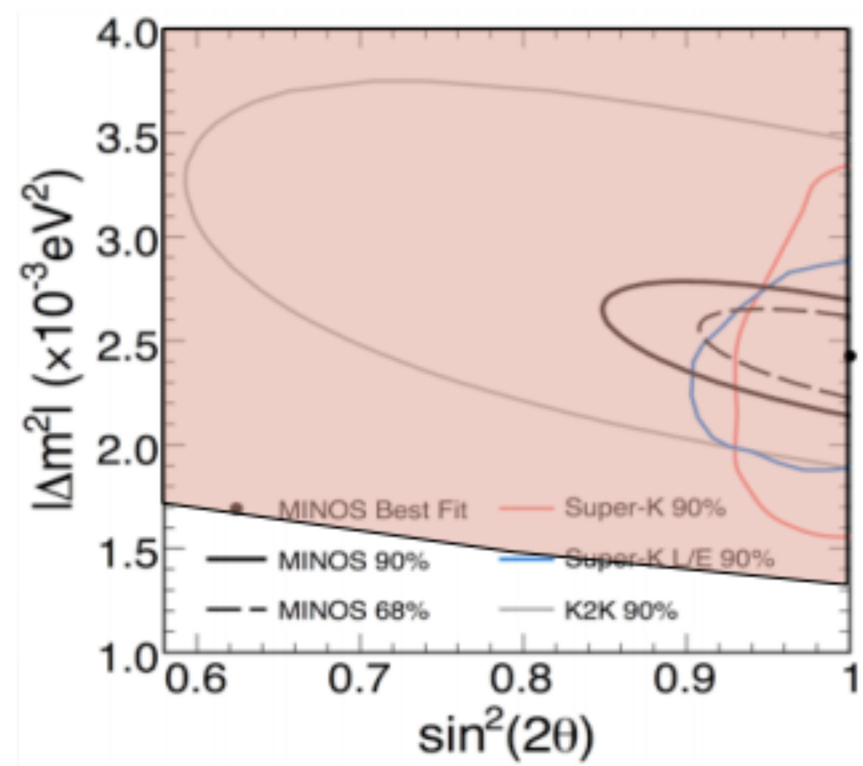
http://operaweb.web.cern.ch/operaweb/index.shtml

OUTLINE

- Introduction
- The OPERA experiment
  - Physics goal
  - Detection principle
  - The CNGS neutrino beam
  - The OPERA detector
- Detector performances
- Physics results
- Conclusions

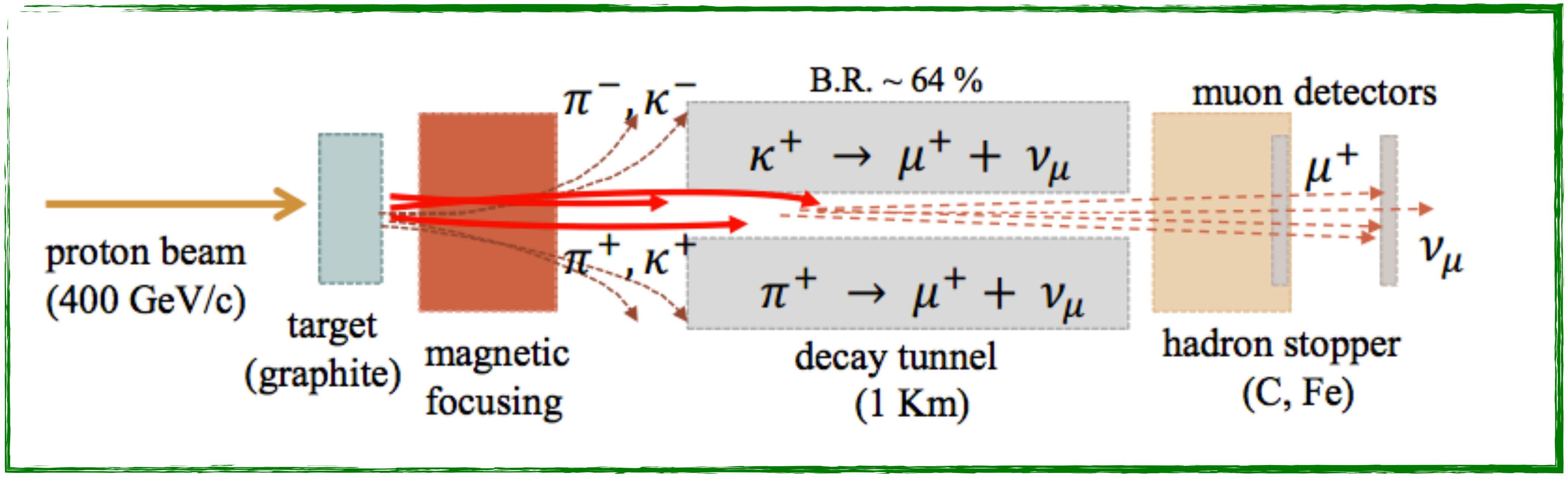
The OPERA Experiment

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

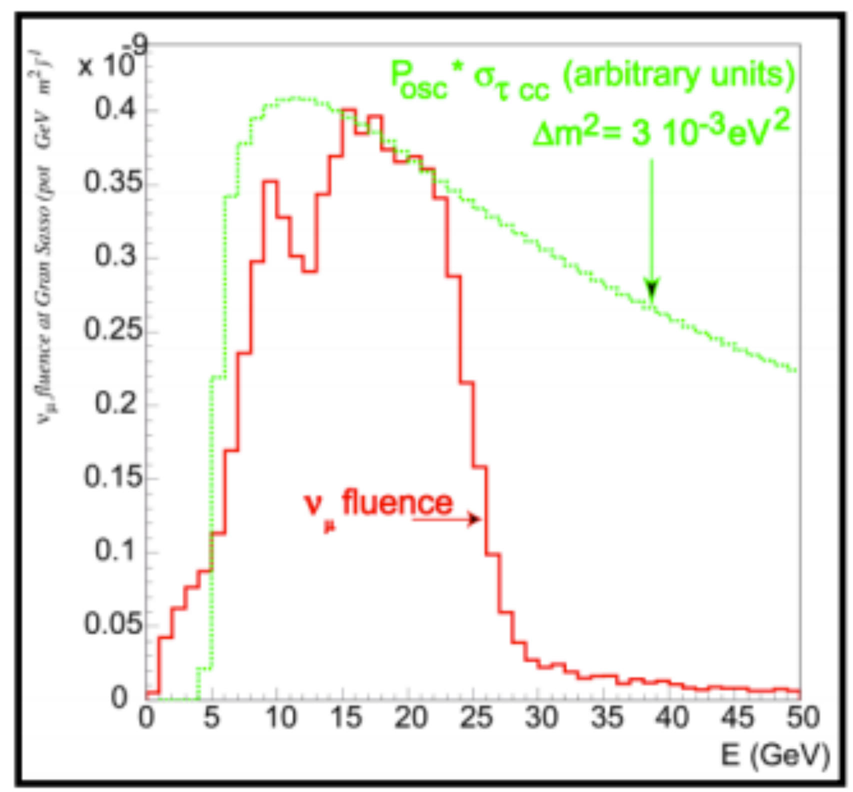
THE CNGS NEUTRINO BEAM



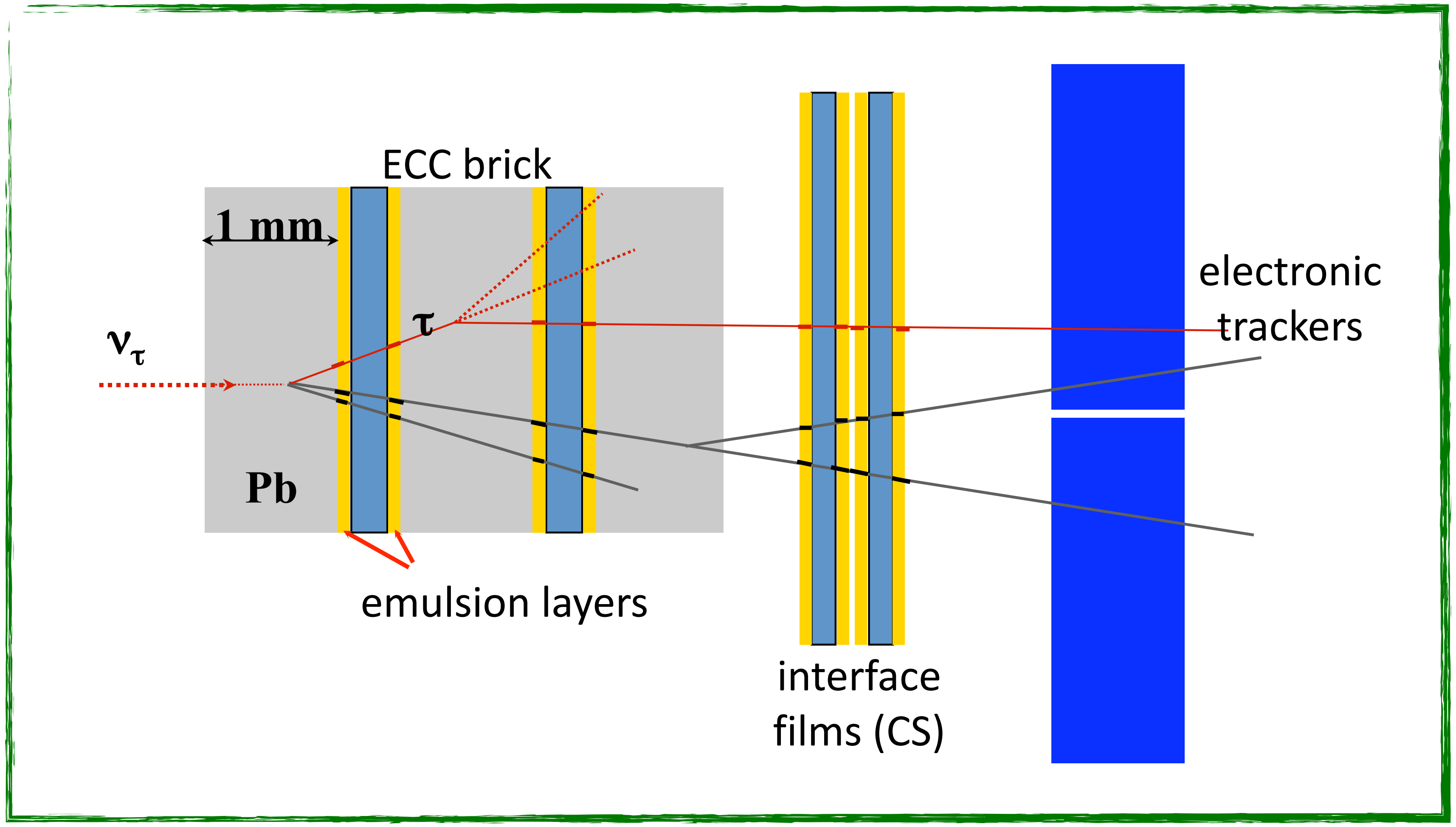
Beam parameters

$<E\nu_\mu>$ (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



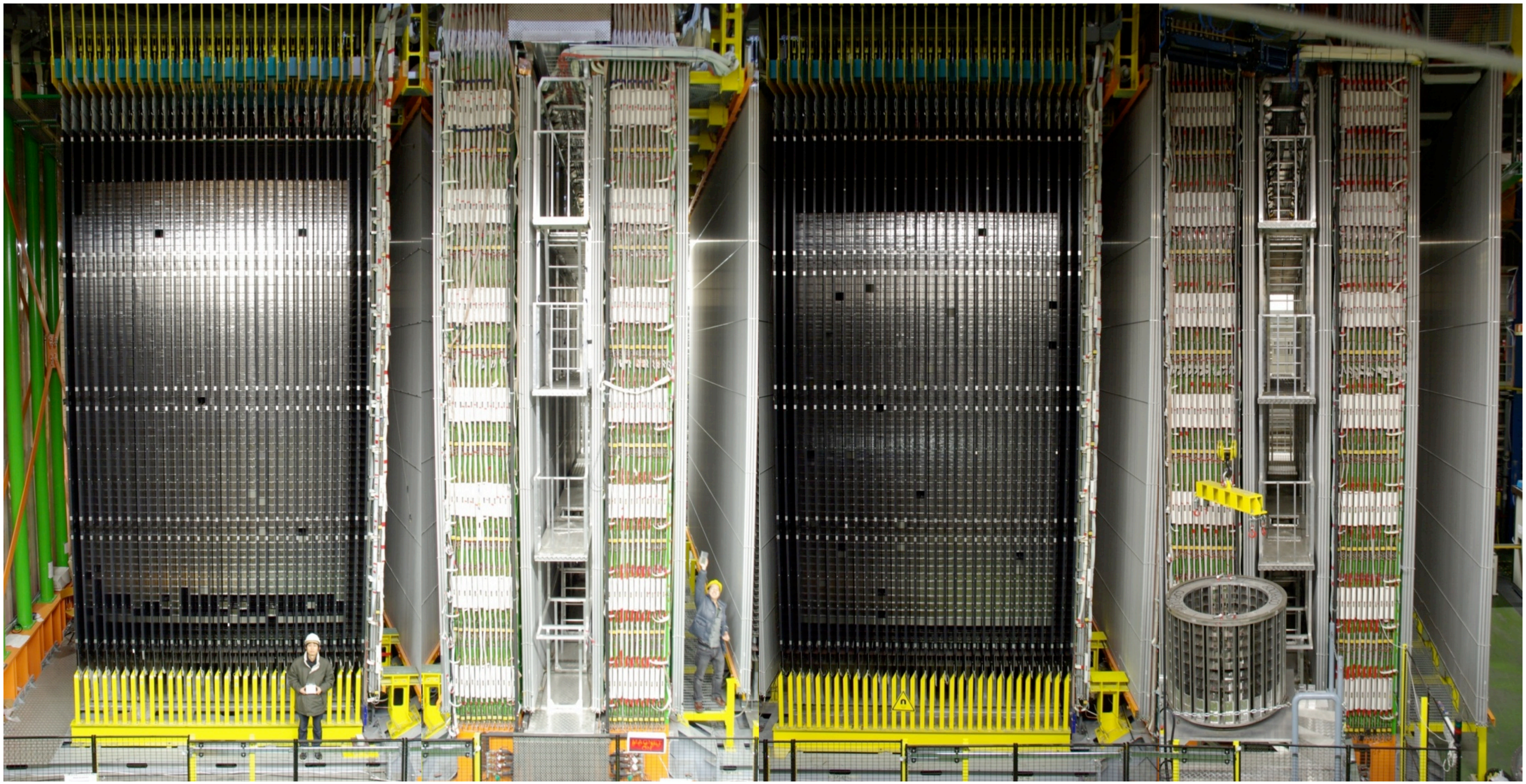
The Principle



- 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

SM-1 SM-2



Target — brick walls+ Target Tracker | **Spectrometer** — RPC+Drift Tubes | **Target** — brick walls+ Target Tracker | **Spectrometer** — RPC+Drift Tubes

The Target

made of ~150000 bricks

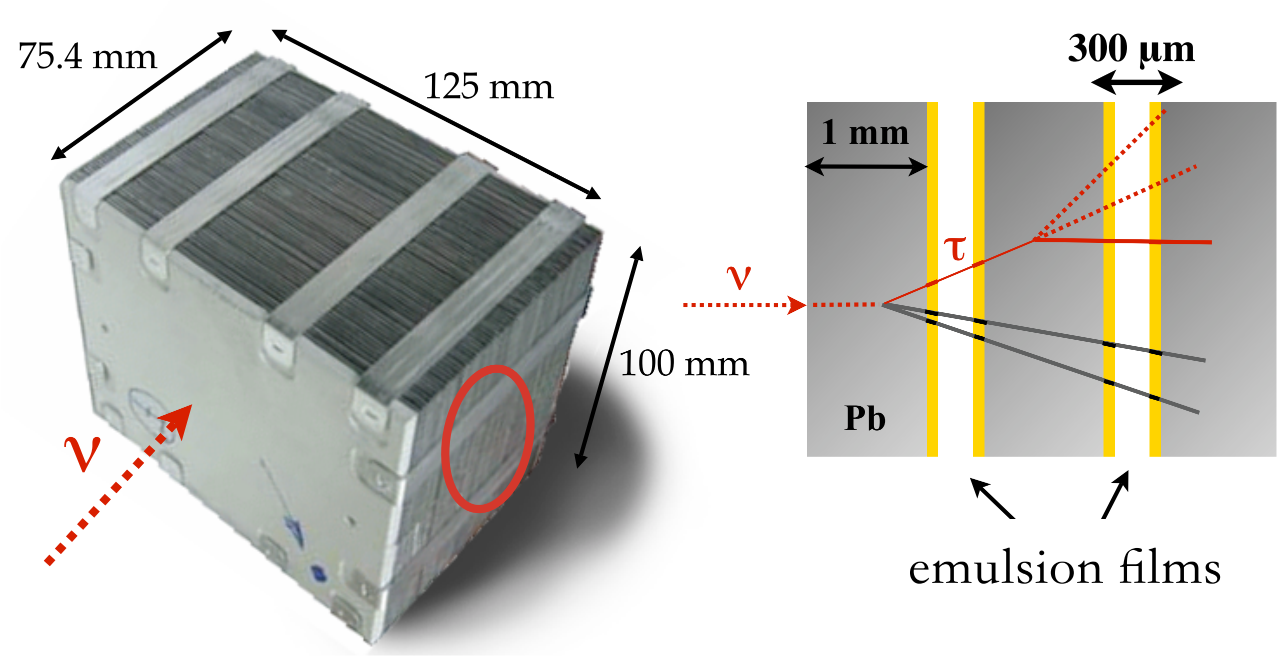
Emulsion Cloud Chamber

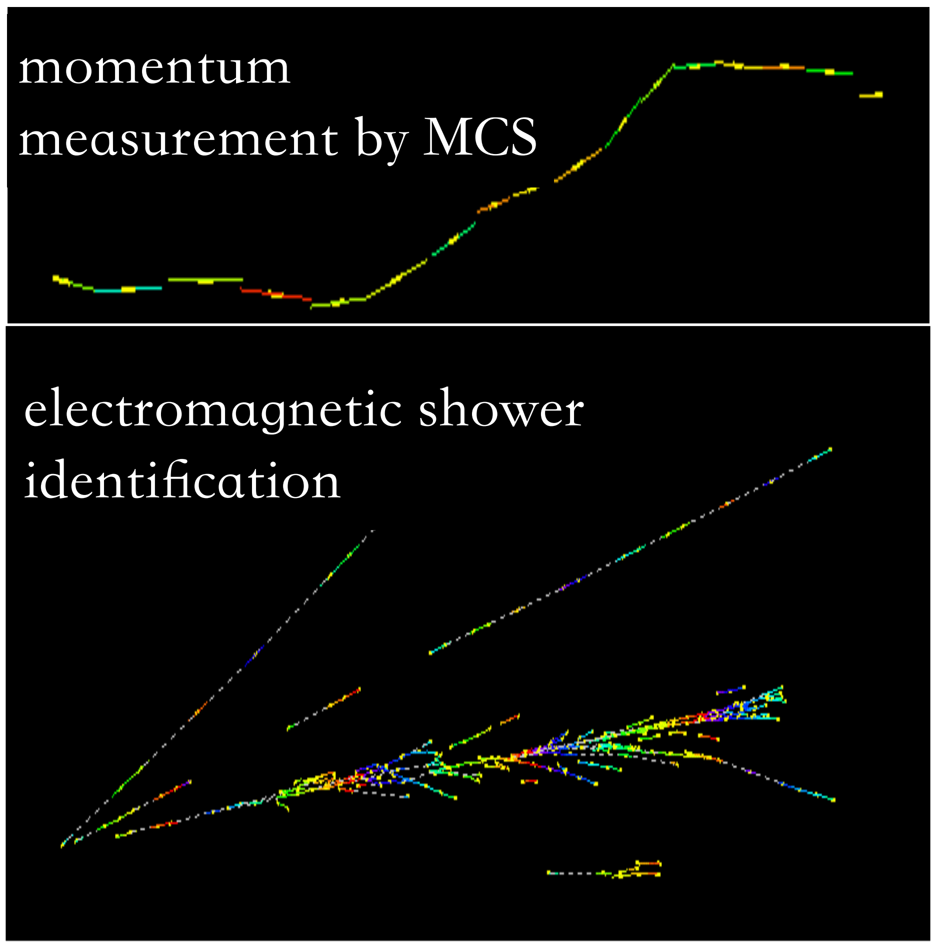
ECC

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

Brick

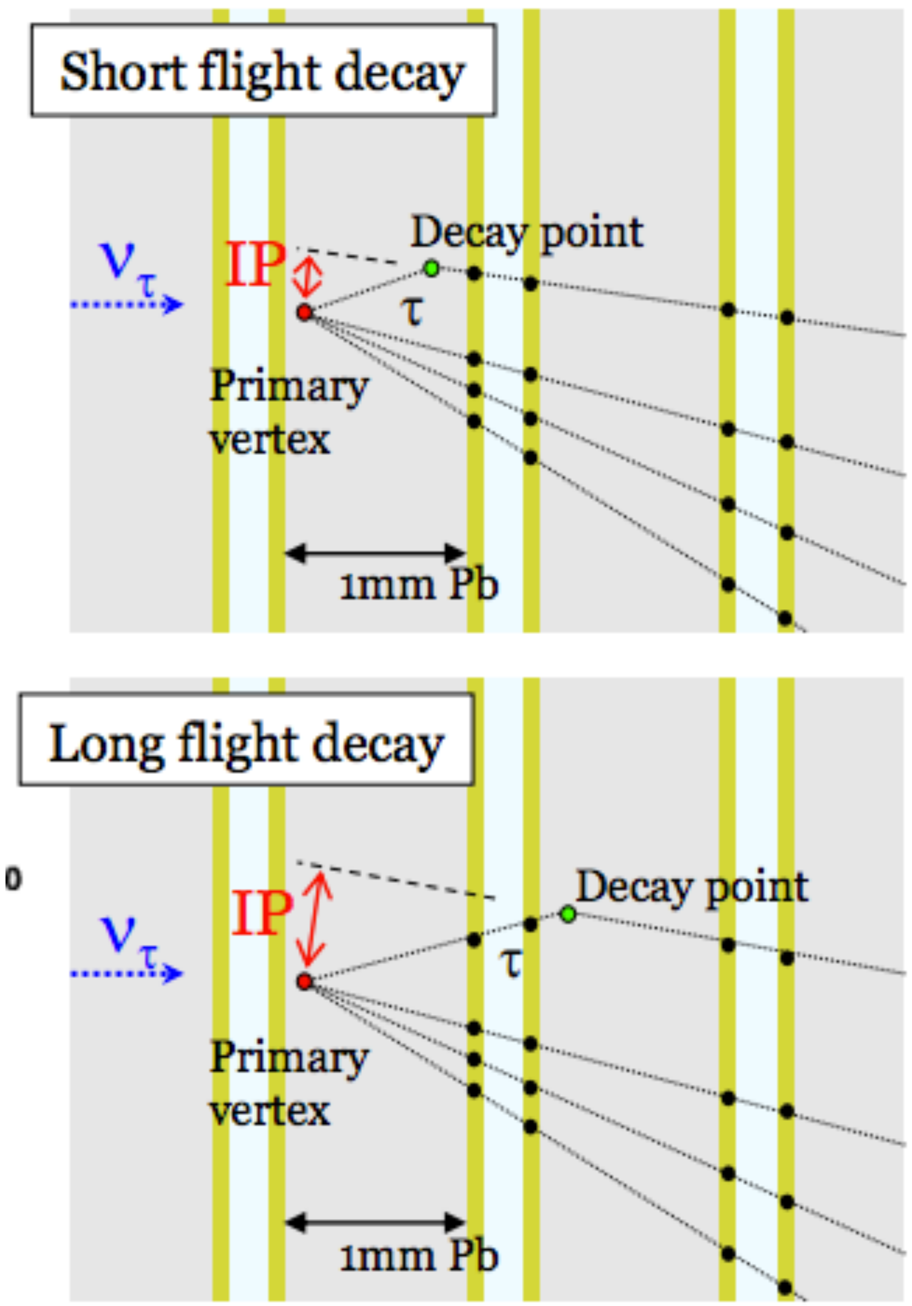
- 57 emulsion films
- 56 lead plates
- 1 Changeable Sheet doublet
- 10 X_0
- 8.3 kg





ECC FEATURES

- Each brick is a "stand alone" detector with a sub-micrometric resolution

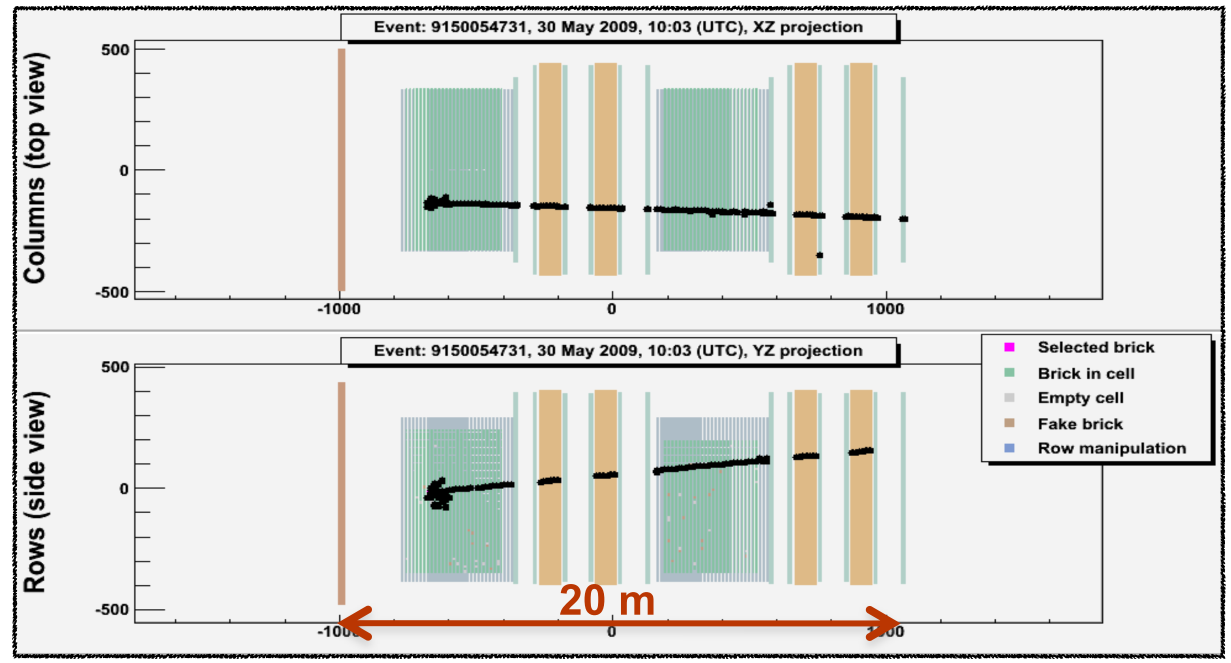


τ DECAY CHANNEL	BR (%)
$\tau \rightarrow \mu$	17.7
$\tau \rightarrow \mathbf{e}$	17.8
$\tau \rightarrow \mathbf{h}$	49.5
$\tau \rightarrow \mathbf{3h}$	15.0

Neutrino Interactions In The Target

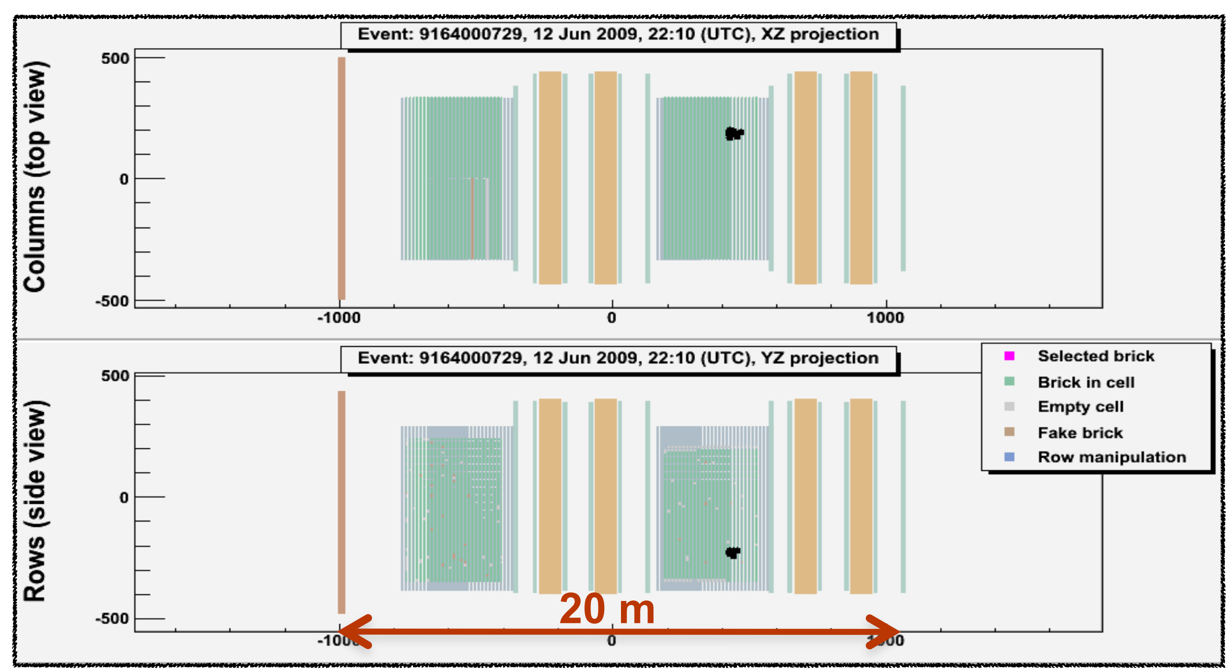
Charged Current Event

$$\nu_\mu N \rightarrow \mu^- X$$



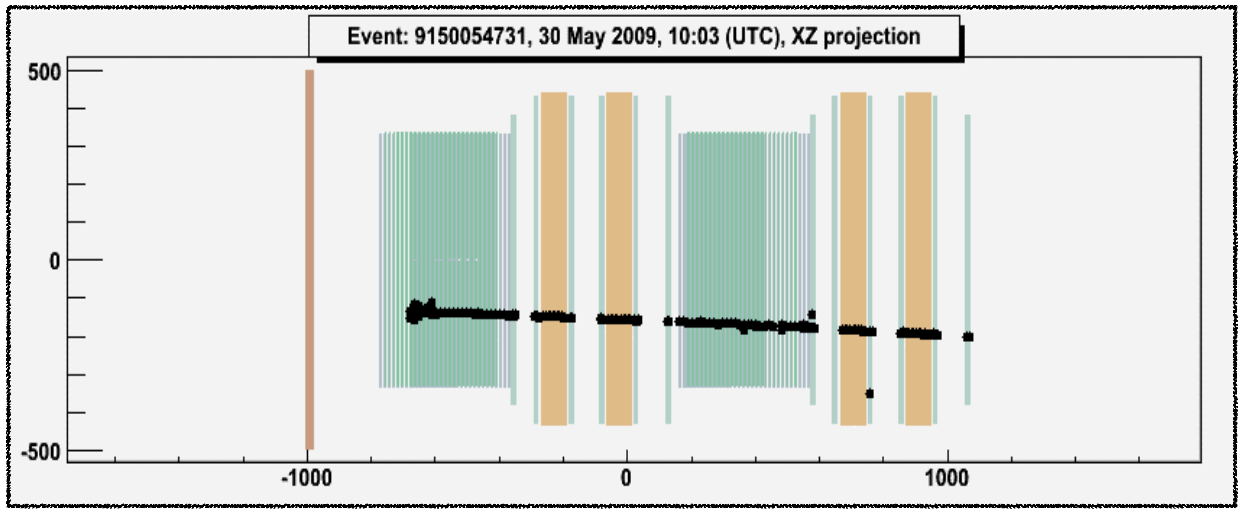
Neutral Current Event

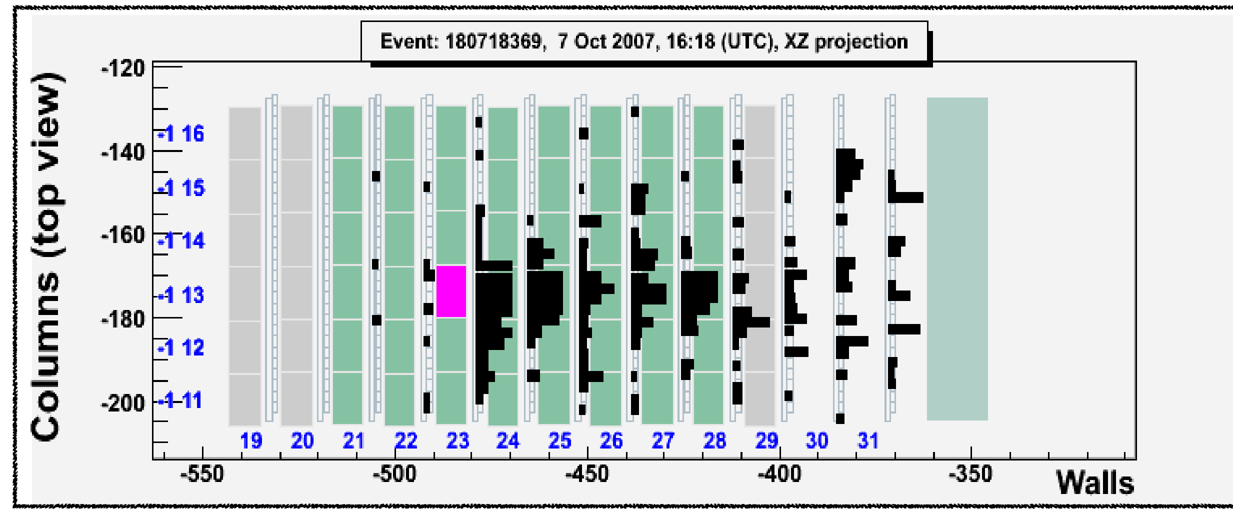
$$\nu_\mu N \rightarrow \nu_\mu X$$



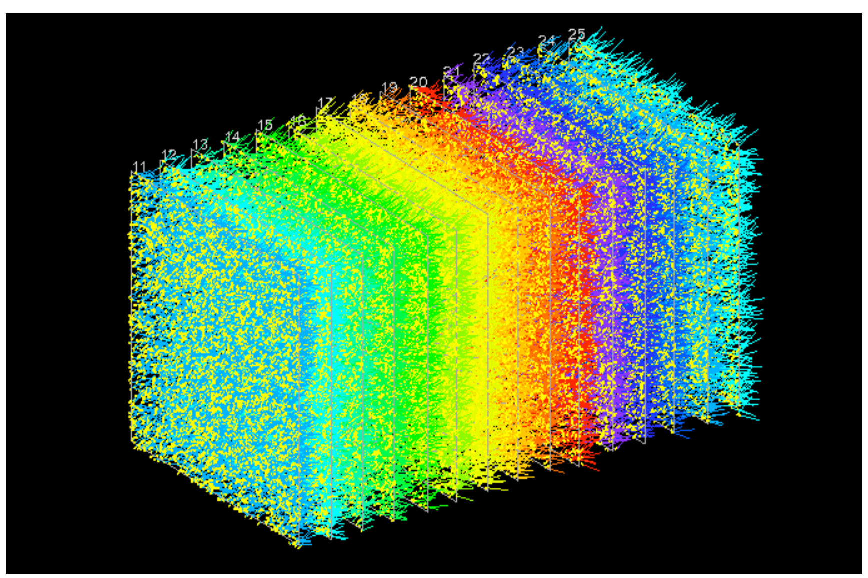
Event Analysis

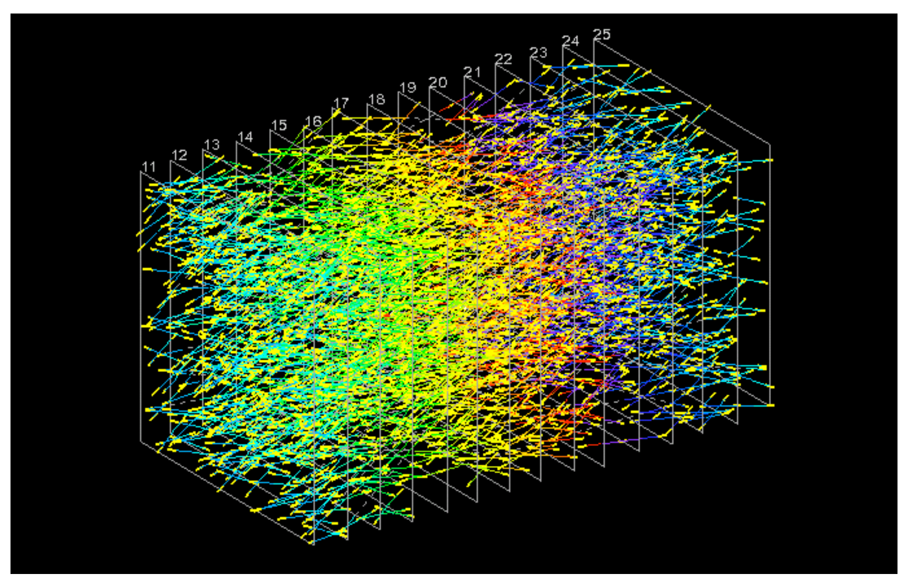
Electronic detector reconstruction

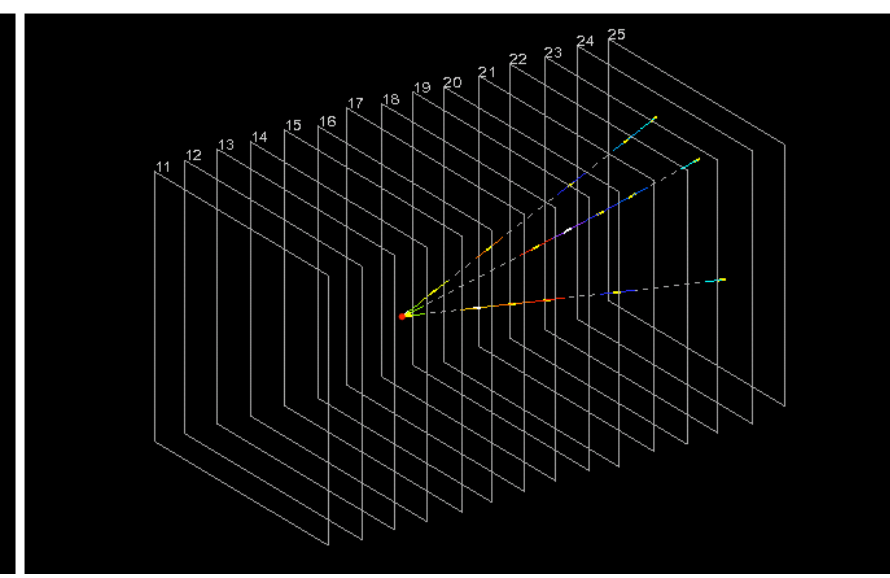




Vertex location in the brick







1. Scan 15 emulsion films around stopping plate

2. Reject passing through tracks

3. Search tracks making vertex

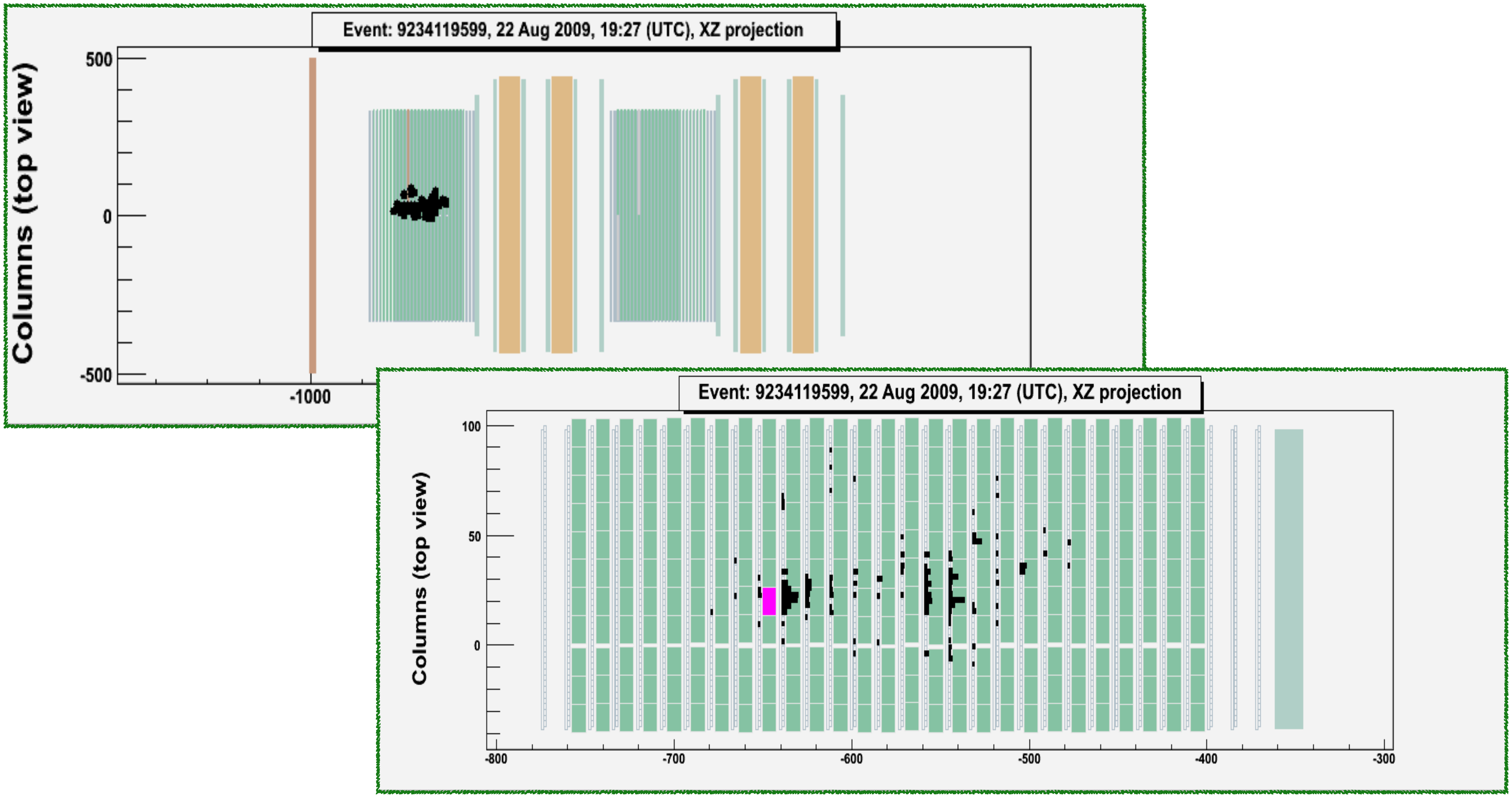
Data Taking Status

YEAR	P.O.T. (10^{19})	Number of neutrino interactions
2008	1.74	1698
2009	3.53	3557
2010	4.09	3912
2011	4.75	4210
2012	3.86	3680
Total	17.97 x 10^{19} effective p.o.t → 80% of the nominal value	

YEAR	Analysis status	Number of decay searched events
2008-2009	Completed	2783
2010-2011-2012	On going	1722
Total		4505

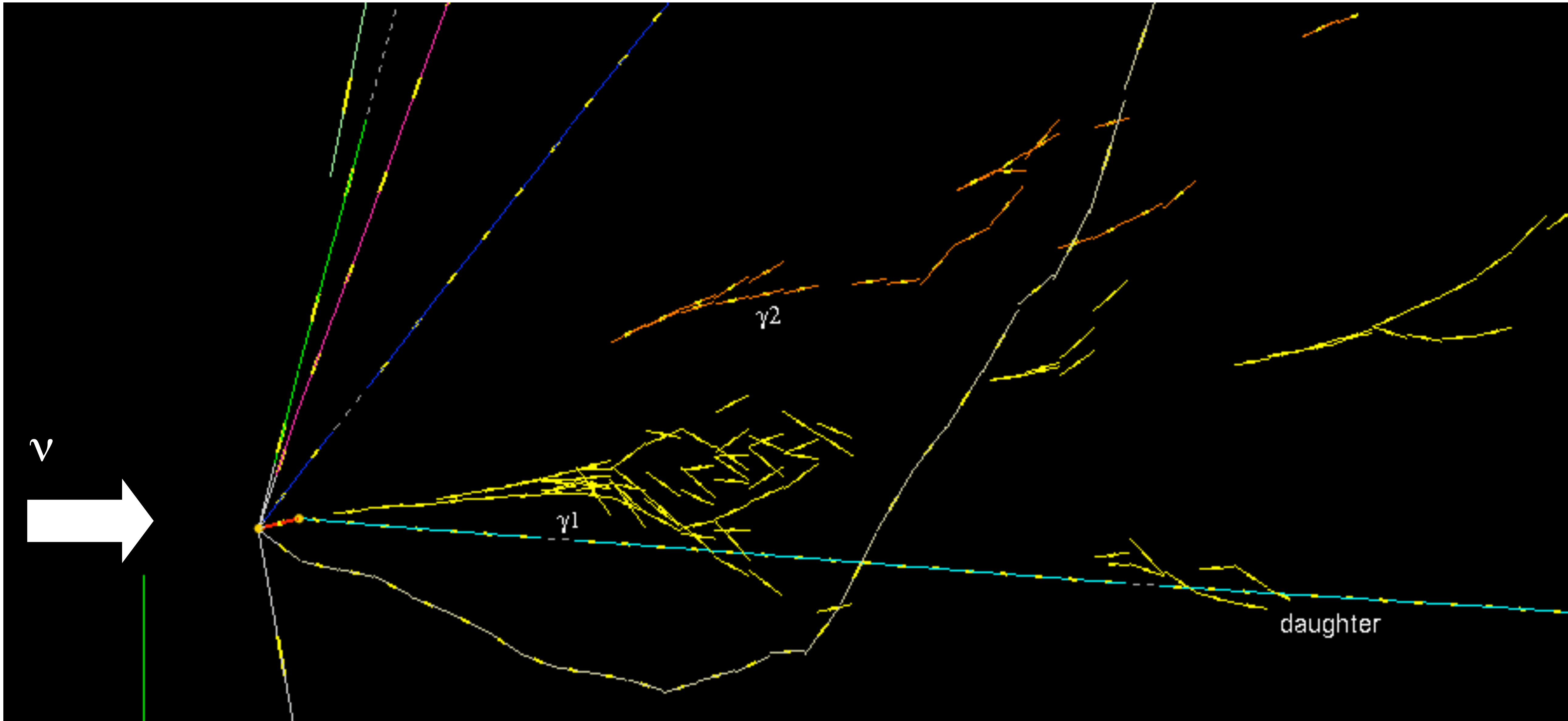
The First ν_τ Candidate

As Seen By Electronic Detectors ...



THE FIRST ν_τ CANDIDATE

... AND IN THE BRICK

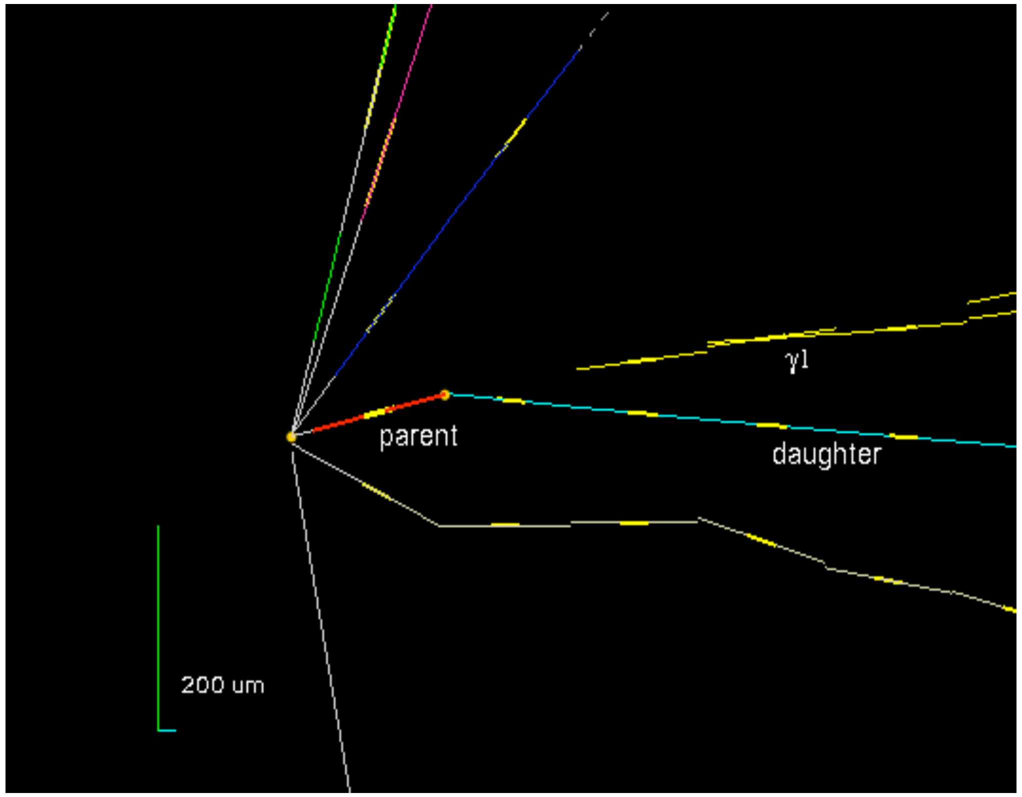


$\tau^- \rightarrow \rho^- \nu_\tau$

$\rho^- \rightarrow \pi^0 \pi^-$

$\pi^0 \rightarrow \gamma \gamma$

THE FIRST ν_τ CANDIDATE

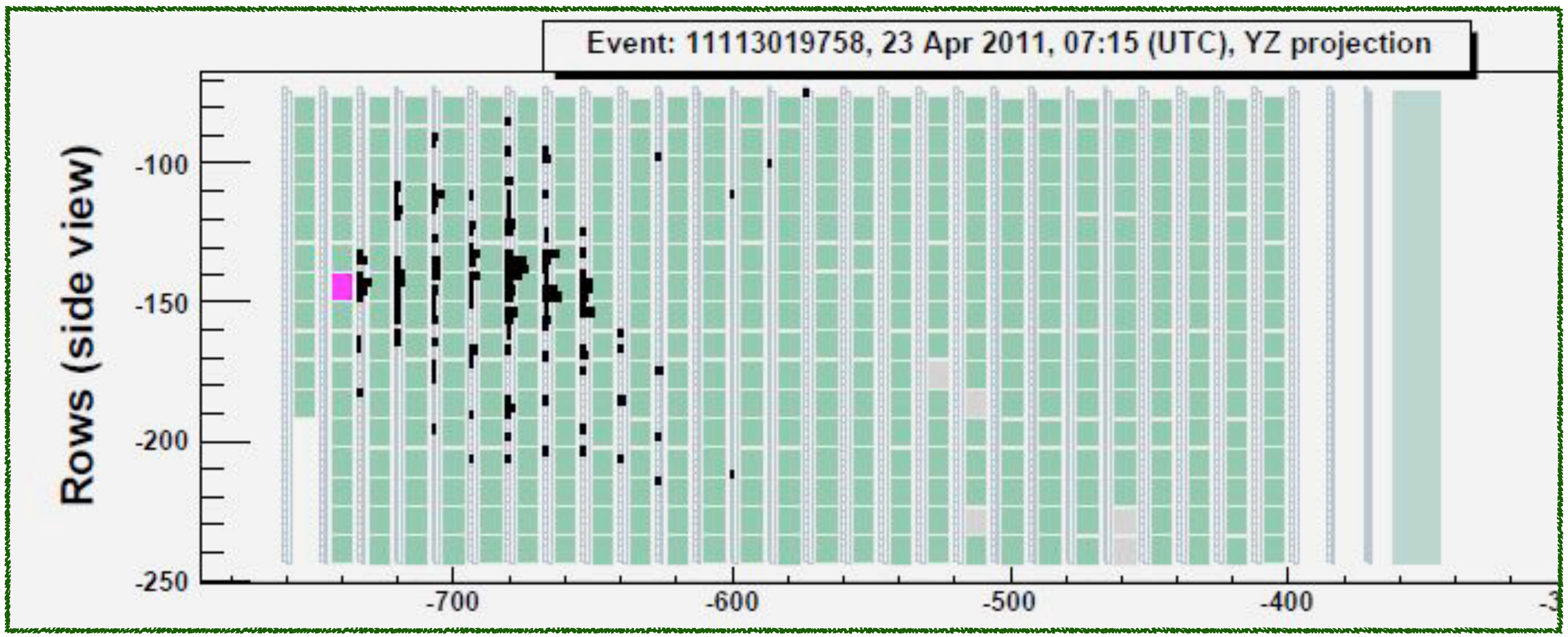


SELECTION CRITERIA	MEASURED
kink > 20 mrad	41 ± 2 mrad
decay length < 2600 μm	1335 ± 35 μm
P daughter > 2 GeV/c	12^{+6}_{-3} GeV/c
P_t > 300 MeV/c	470^{+230}_{-120} MeV/c
missing P_t < 1 GeV/c	$0.57^{+0.32}_{-0.17}$ GeV/c
φ > 90°	173 ± 2 °

The event passes all the kinematical cuts required

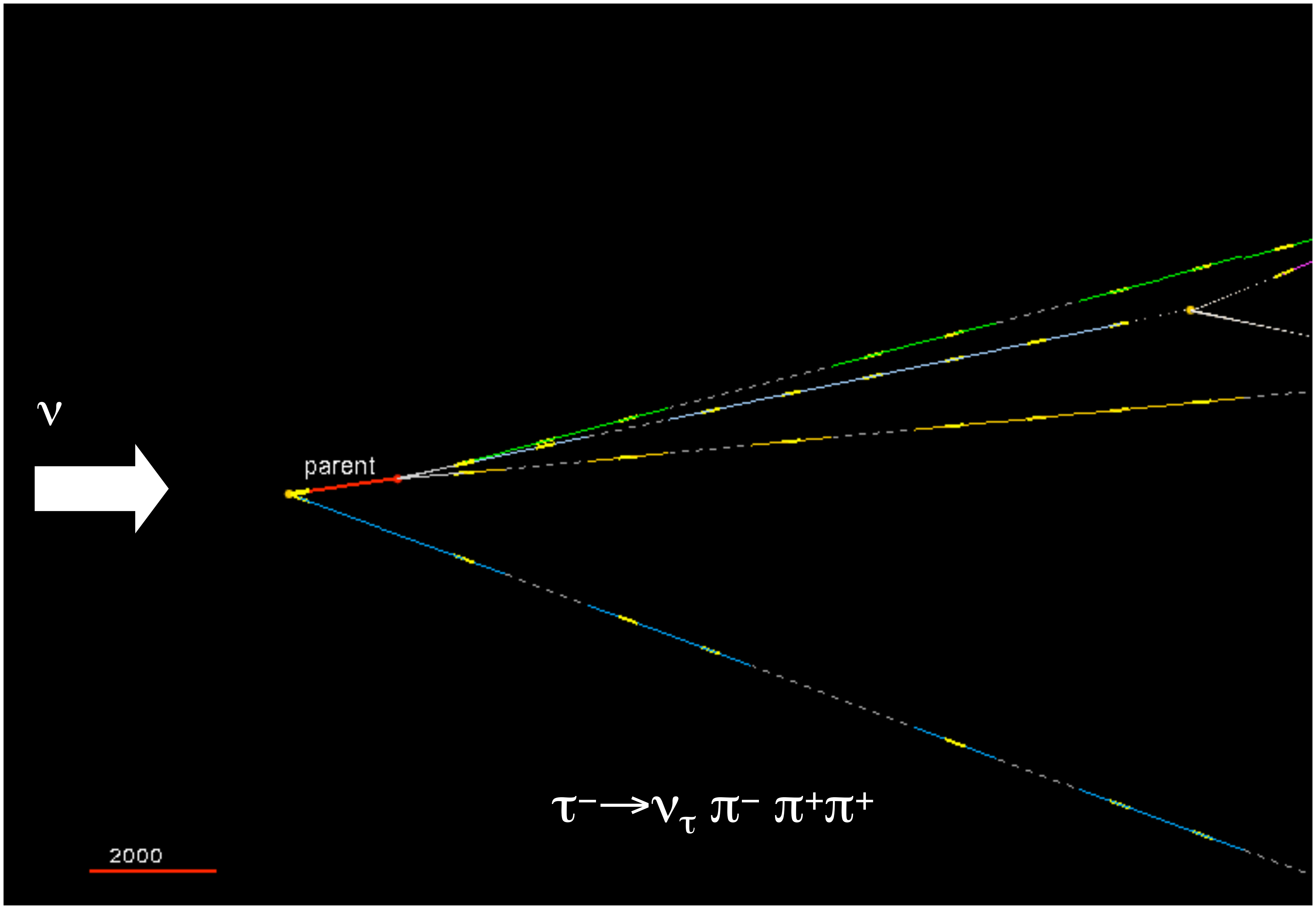
THE SECOND ν_τ CANDIDATE

AS SEEN BY ELECTRONIC DETECTORS ...

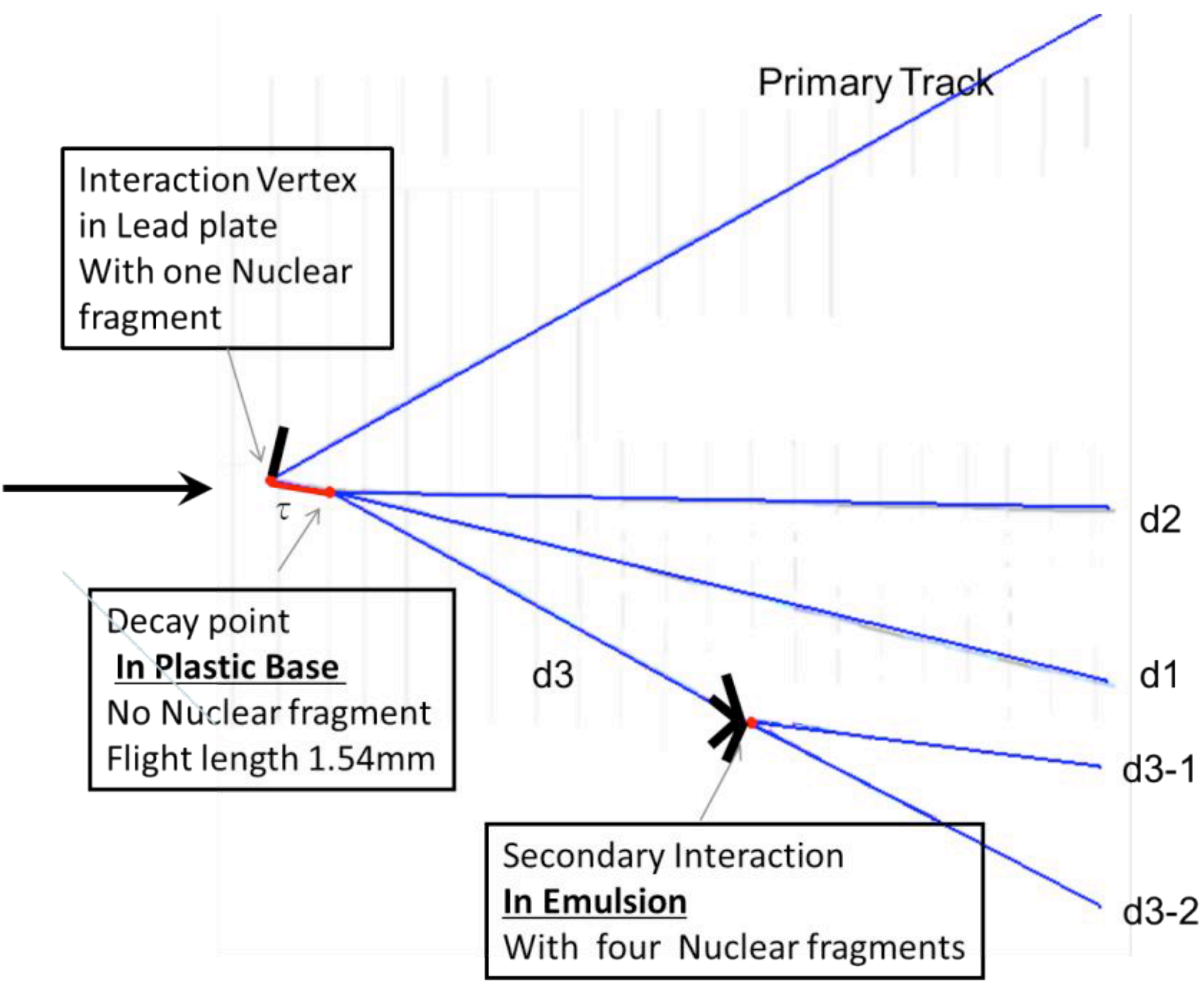


THE SECOND ν_τ CANDIDATE

... AND IN THE BRICK



THE SECOND ν_τ CANDIDATE



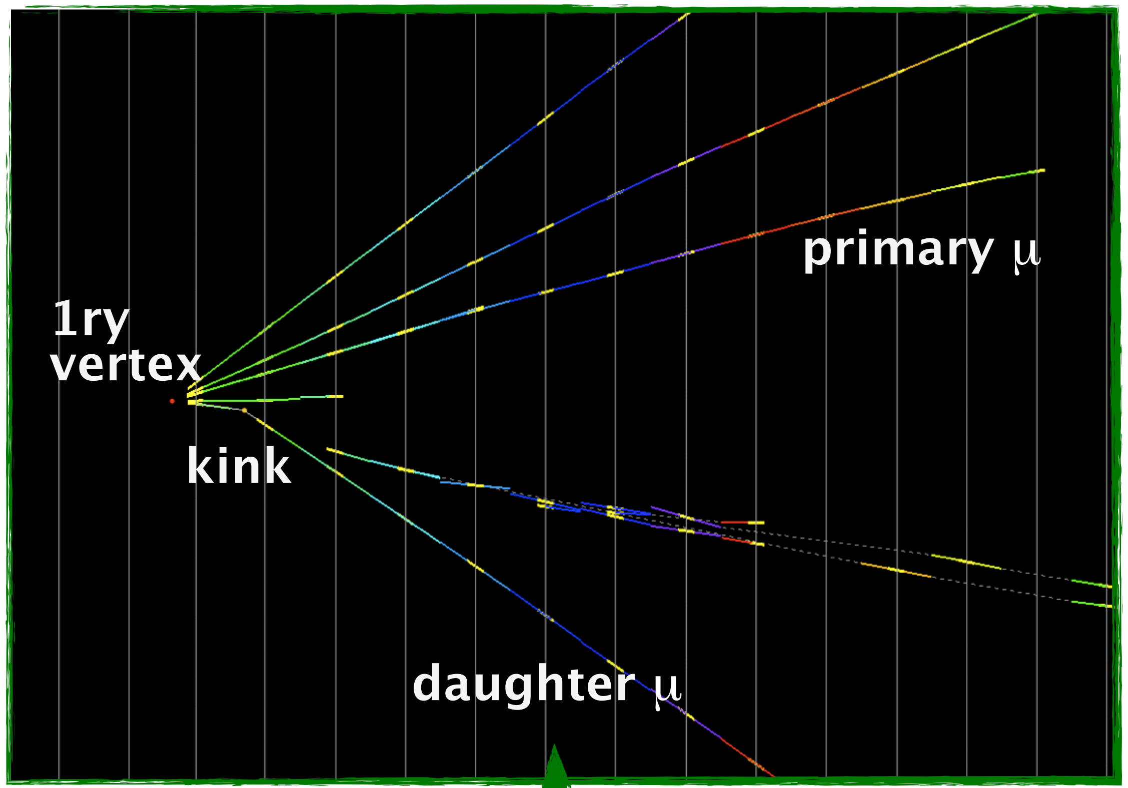
SELECTION CRITERIA	MEASURED
kink < 500 mrad	87.4 ± 1.5 mrad
0.5 GeV/c^2<Inv Mass < 2 GeV/c^2	0.80 ± 0.12 GeV/c^2
0.5 GeV/c^2<Min Inv Mass < 2 GeV/c^2	0.96 ± 0.13 GeV/c^2
P daughters > 3 GeV/c	8.4 ± 1.7 GeV/c
missing P_t < 1 GeV/c	0.31 ± 0.11 GeV/c
$\varphi > 90^\circ$	167.8 ± 1.1 °

The event passes all the kinematical cuts required

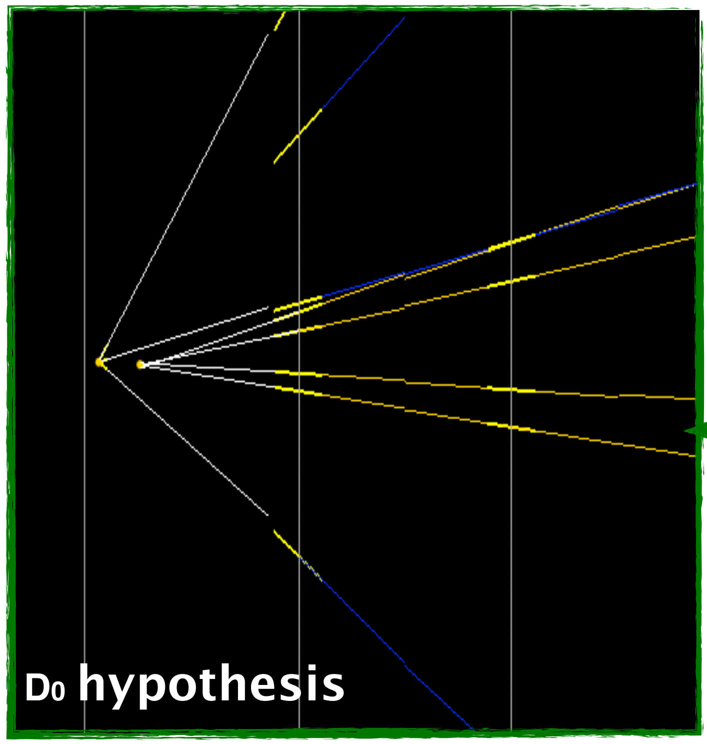
Charm Data Sample

Proof of the τ efficiency

Observed: 49
Expected: 51.0 ± 7.5



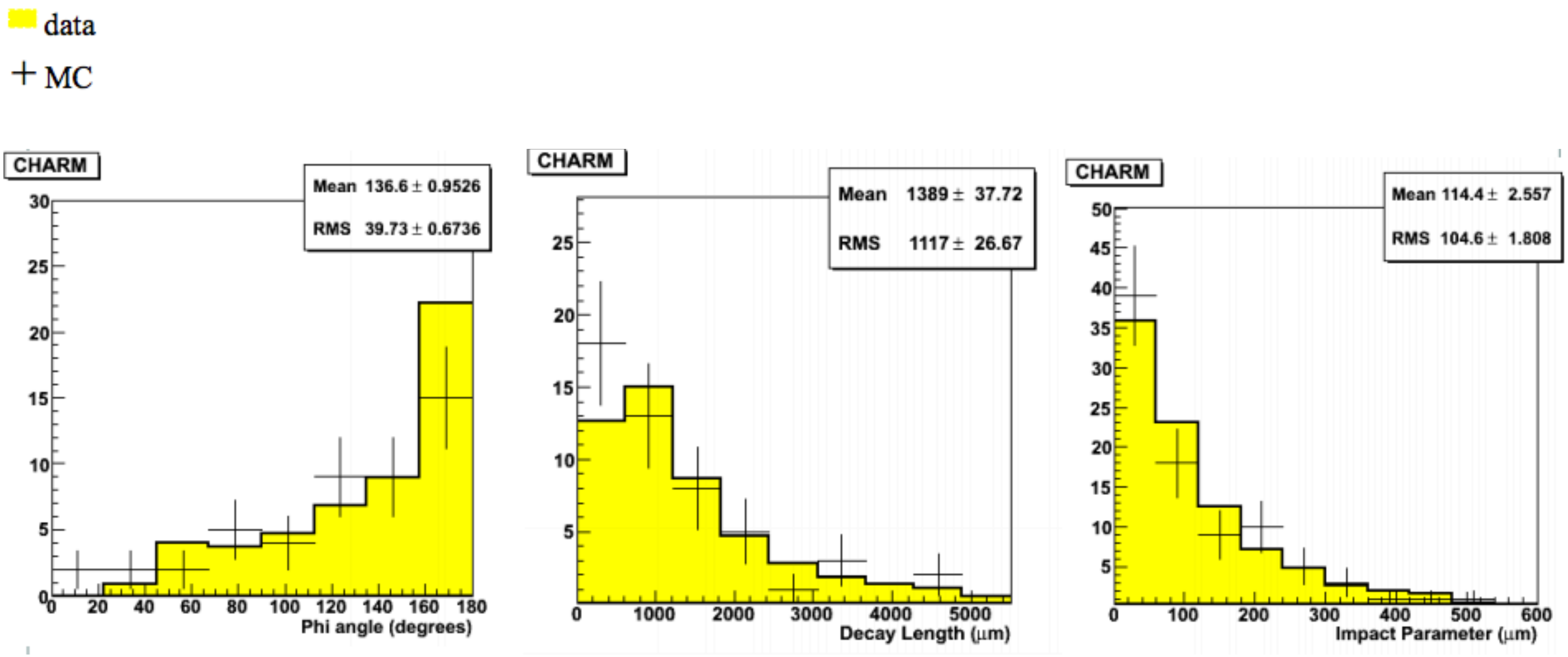
flight length: 1330 μm
kink angle: 209 mrad
IP of the daughter: 262 μm
daughter μ: 2.2 GeV/c
decay Pt: 0.46 GeV/c



flight length: 313 μm
φ angle: 173.2 °
invariant mass: 1.7 GeV

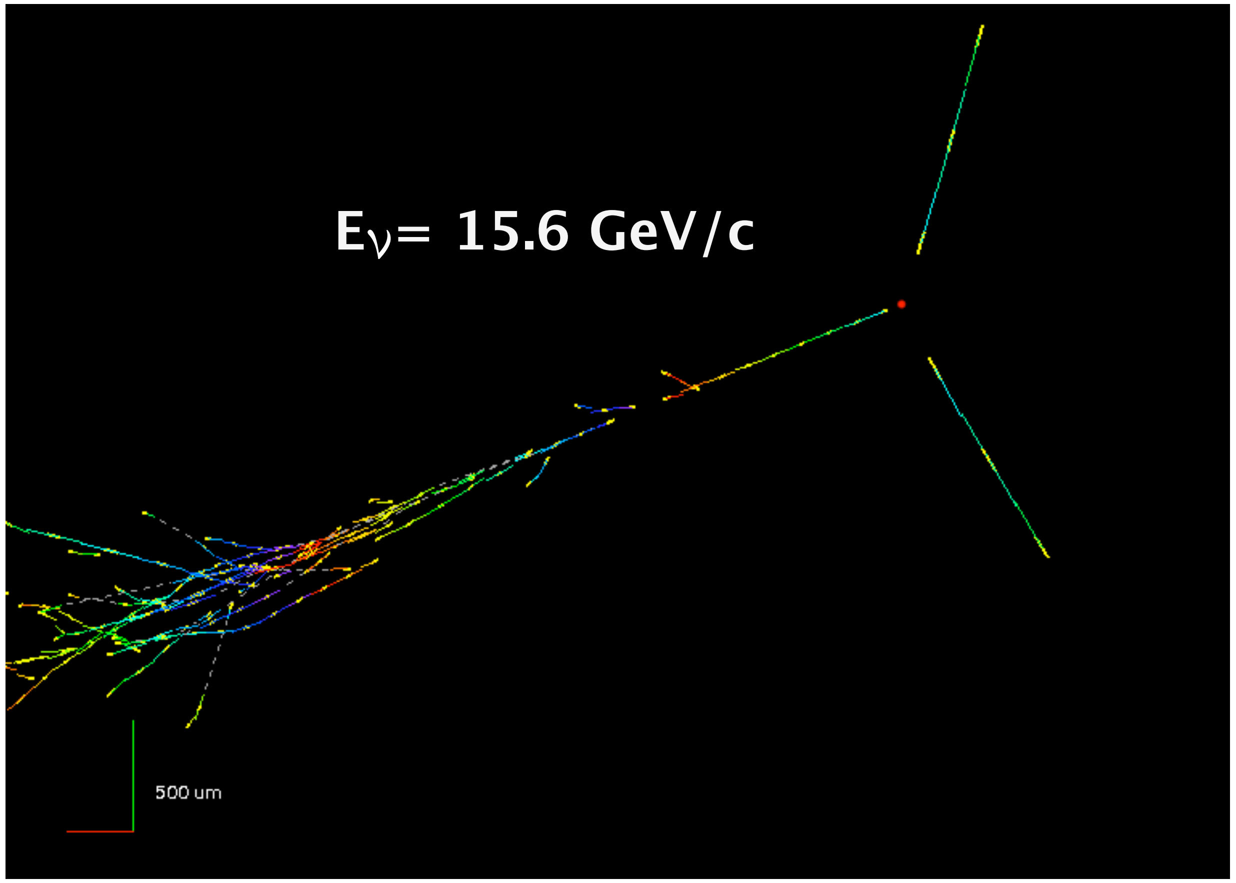
CHARM DATA SAMPLE

DATA/MC comparison



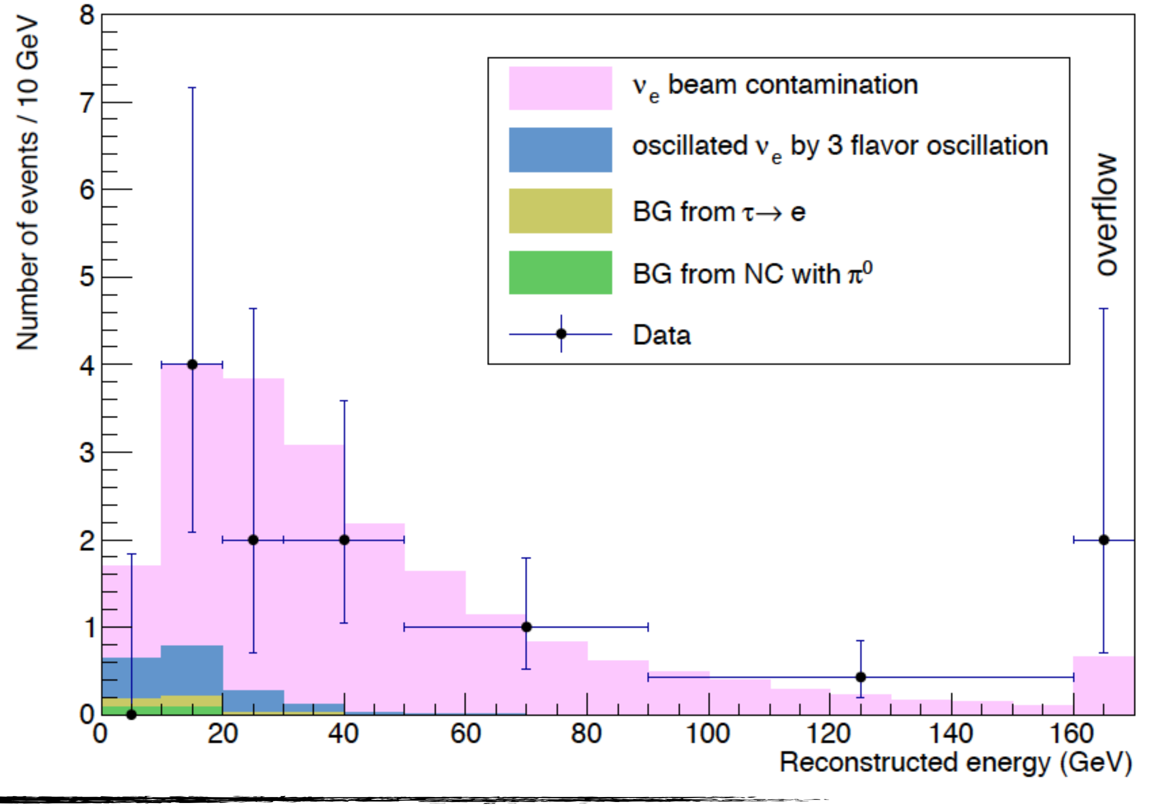
$\nu_\mu \rightarrow \nu_e$ Oscillation Search

Preliminary results



Systematic search for electron neutrinos applied to 505 located events without muon in the final state (runs 2008 - 2009)

Observed ν_e events: 19
compatible with background-only hypothesis expectation of 20±2.8 (syst)



Applying cut on reconstructed energy in order to increase signal to background ratio

Observed events: 4
with an expectation of 4.6
⇒ limit on oscillation parameters:
$\sin^2(2\theta_{13})<0.44$ at 90% C.L.

$\nu_\mu \rightarrow \nu_e$ Oscillation Search

Preliminary results

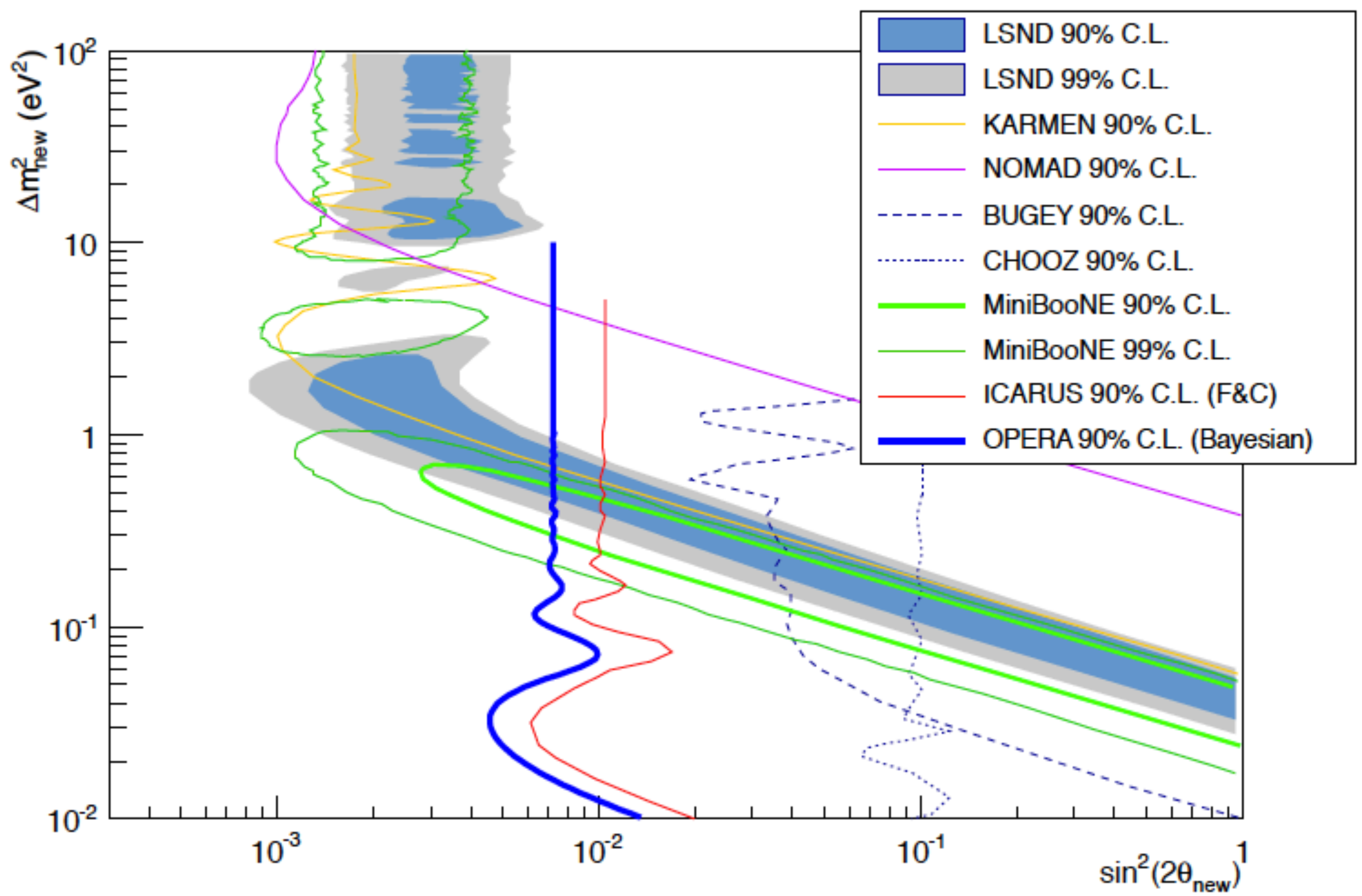
Search at large Δm^2

Standard approach of translating the $\nu_\mu \rightarrow \nu_e$ oscillation probability as

$$P = \sin^2(2\theta_{new}) \cdot \sin^2(1.27 \Delta m^2_{new} L(\text{km})/E(\text{GeV}))$$

Cut on E_ν < 30 GeV

Observed events: 6
with an expectation of 9.4±1.3
⇒ limit on oscillation parameters:
$\sin^2(2\theta_{new}) < 7.2 \times 10^{-3}$ at 90% C.L.



CONCLUSIONS

- OPERA is successfully collecting data from 2008 to 2012
- A total number of 17.97 x 10^{19} p.o.t. has been integrated
- $\nu_\mu \rightarrow \nu_\tau$ **oscillation search:**
  - 2 ν_τ candidates events found
  (2.1 expected, with 0.2 background)
  - estimation of detection efficiency and background in progress
- $\nu_\mu \rightarrow \nu_e$ **oscillation search:**
  - 19 ν_e events found in the 2008-2009 run, 4 with E_ν<20 GeV
  (expectation: 20±2.8 events, 4.6 with E_ν<20 GeV)
  - at large Δm^2 region, 6 events observed
  (expectation: 9.4±1.3 events)
  $\Rightarrow$upper limit of 7.2×10^{-3} at 90% C.L. on $\sin^2(2\theta_{new})$

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

Back-up slides

$\nu_\mu \rightarrow \nu_\tau$ Oscillation Search

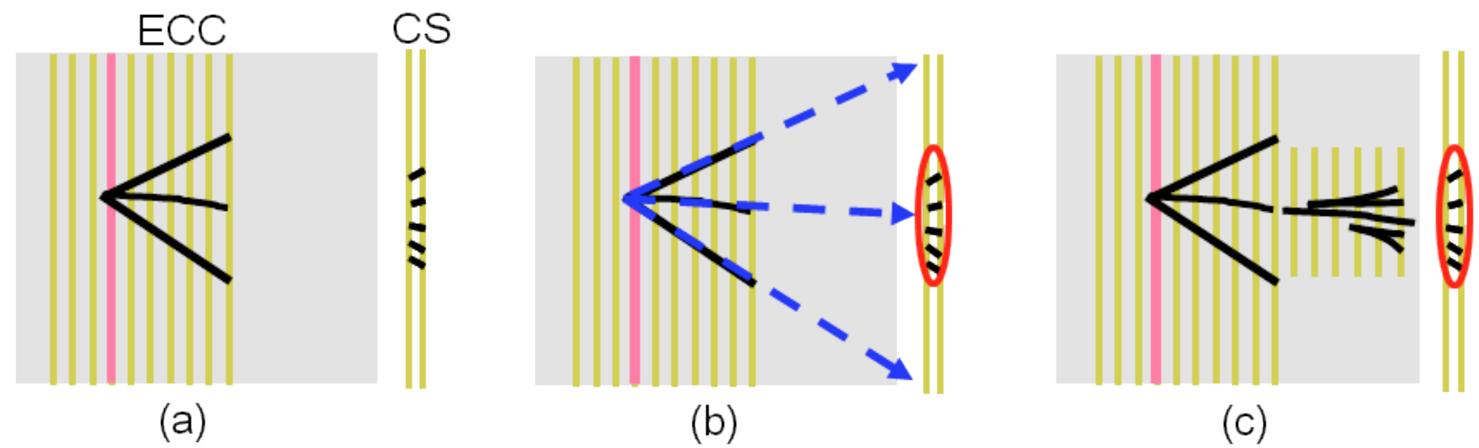
	SIGNAL	BKG	CHARM	MUON SCATTERING	HADRONS
$\tau \rightarrow \mu$	0.49	0.02	0.01	0.02	0.00
$\tau \rightarrow e$	0.68	0.05	0.05	0.00	0.00
$\tau \rightarrow h$	0.56	0.06	0.03	0.00	0.03
$\tau \rightarrow 3h$	0.18	0.05	0.05	0.00	0.00
TOTAL	1.91	0.18	0.14	0.02	0.03

$\nu_\mu \rightarrow \nu_e$ Oscillation Search

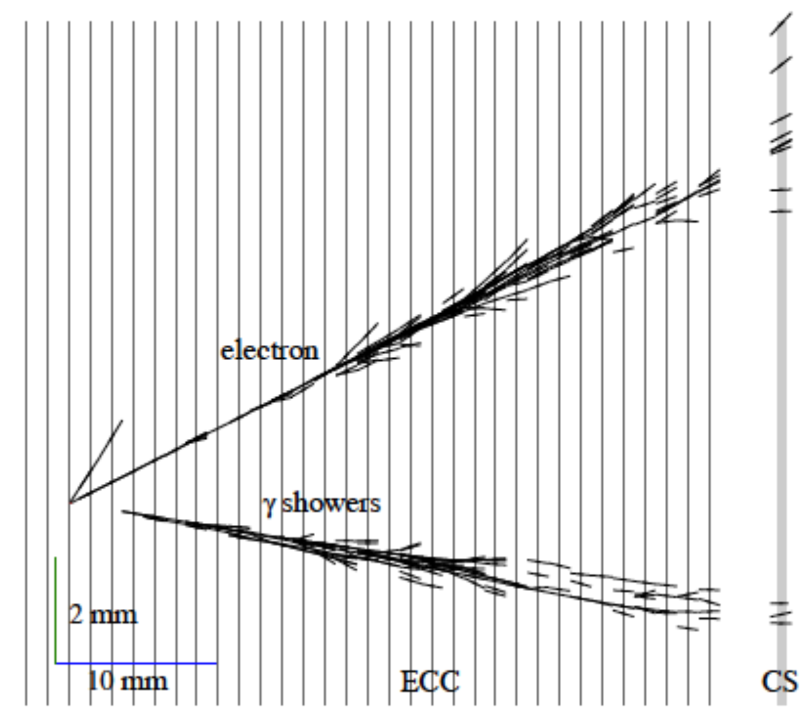
Systematic search for electron neutrinos applied to 505 located events without muon in the final state (runs 2008 - 2009)

For each located event:

- extrapolate primary tracks to CS
- search for cluster of shower on CS
- if shower hints found on CS, open an additional volume



If a shower is found, the corresponding primary track becomes an electron candidate. The candidate is carefully inspected in the first two emulsion films.
- Check if the track is is due to a single particle or to an e^+e^- pair -> reject electromagnetic showers initiated by early conversion of a gamma from a pi^0 decay. Emulsion guarantee the capability of measuring tracks with a micrometric resolution.
- Check the IP of the track w.r.t. primary vertex -> reject nu_tau CC interactions with electron decay



The energy of the nu_e is estimated from the calorimetric measurement in the TT.

OPERA

$\nu_\mu \rightarrow \nu_e$ Oscillation Search

E = 15.6 GeV/c

A signal for this oscillation should appear as a significant excess of electron events with respect to the expected background, mainly due to nu_e from the beam contamination

The expected number of nu_e events due to the three flavour oscillation scenario is estimated to 1.44 events in the whole energy range.

Figure: reconstructed energy distribution of the 19 nu_e candidates, compared with the expected reconstructed energy spectra from the the nu_e beam contamination, the oscillated nu_e from the three flavour oscillation and the background

To increase the signal/bk ratio a cut E<20 has been applied on the reconstructed energy of the event. Within this cut 1.0 events from oscillations 4.6 events are expected, while 4 are observed. The number of observed events is compatible with the non-oscillated hypothesis and an upper limit <0.44 is derived at 90 C.L.

$\nu_\mu \rightarrow \nu_e$ Oscillation Search

Search at large Δm^2

We have used OPERA data to set an upper limit on non-standard nu_mu -> nu_e oscillations.

We used the conventional approach of translating the nu_mu -> nu_e oscillation probability in terms of the formula

The nu_mu flux at the detector has been weighted by oscillation probability, by CC cross-section and by detection efficiency

A cut on nu_energy is applied: 6 events observed and 9.4 expected

The 90% CL limit on $\sin^2(2\theta_{new})$ is computed by comparing the expectation from oscillation plus background, with the observed events.

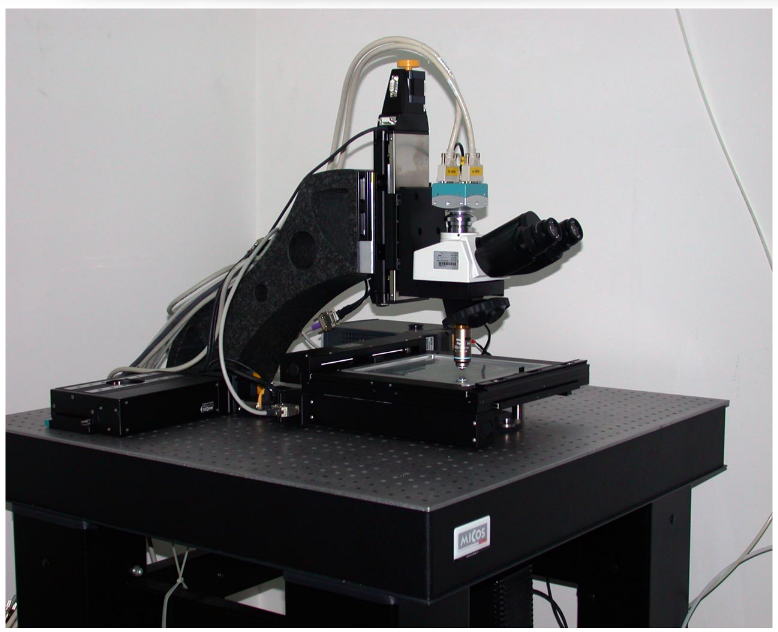
Given the uderfluctuation of data, we provide the exclusion curve with Bayesian interval. The resulting exclusion plot is shown with the results of other experiments working at different L/E regimes. For large Δm^2 values the OPERA 90%C.L upper limit on $\sin^2(2\theta_{new})$ reaches the value of $7.2\text{x}10^{-3}$

OPERA Film Data Taking

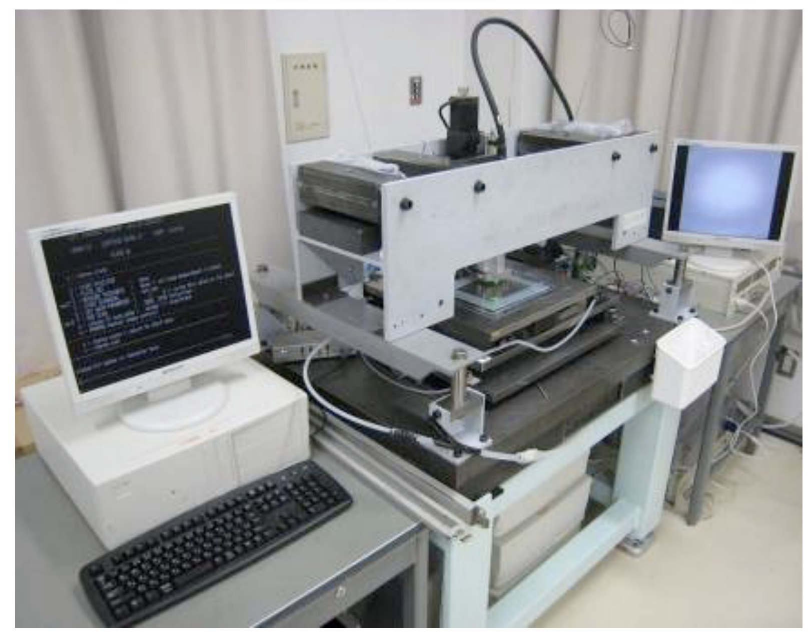
~20 bricks daily extracted from the target
analyzed using high-speed automated systems (~20 cm^2/h)

European Scanning System **S-UTS (Japan)**

Common Data Base for data sharing/publication



- Customized commercial optics and mechanics
- Asynchronous DAQ software modular, decentralized, approach

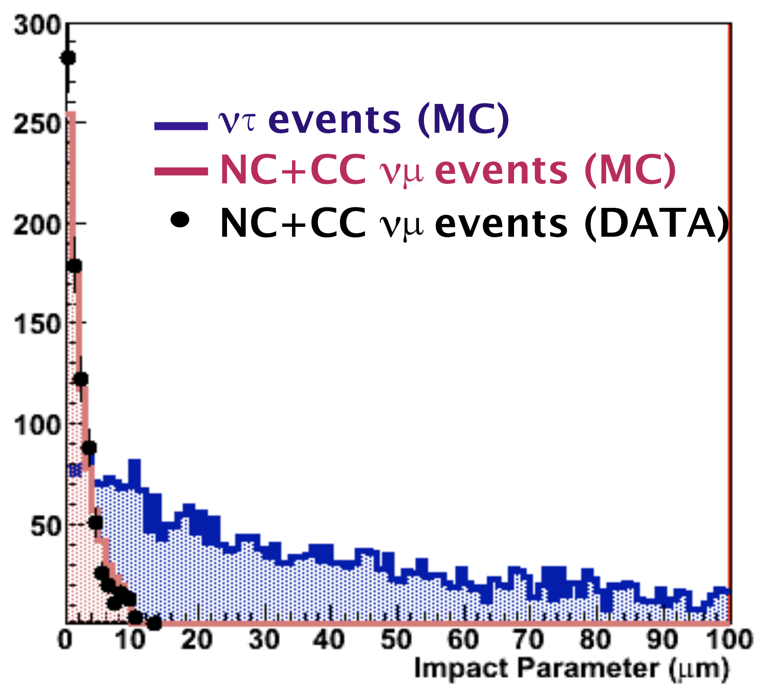


- Synchronization of objective lens and (constant speed) stage
- Hard-coded algorithms, custom electronics

~90% tracking efficiency
spatial resolution <1μm & angular resolution < 2 mrad

ECC FEATURES

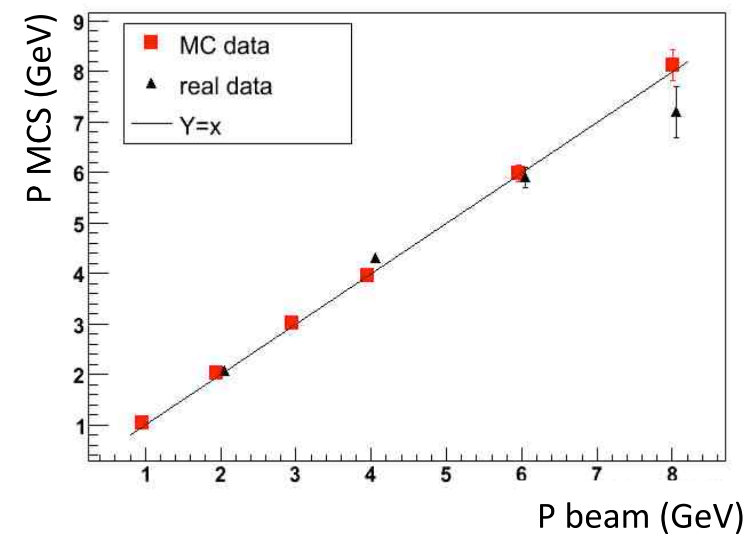
Impact parameter measurement



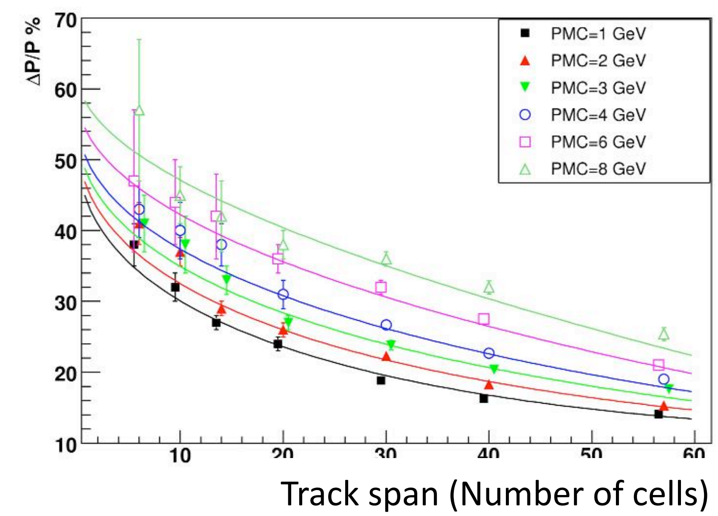
The detection of decay topologies is triggered by the observation of a track with large IP wrt the primary vertex, in addition to kink detection

Momentum measurement by MCS

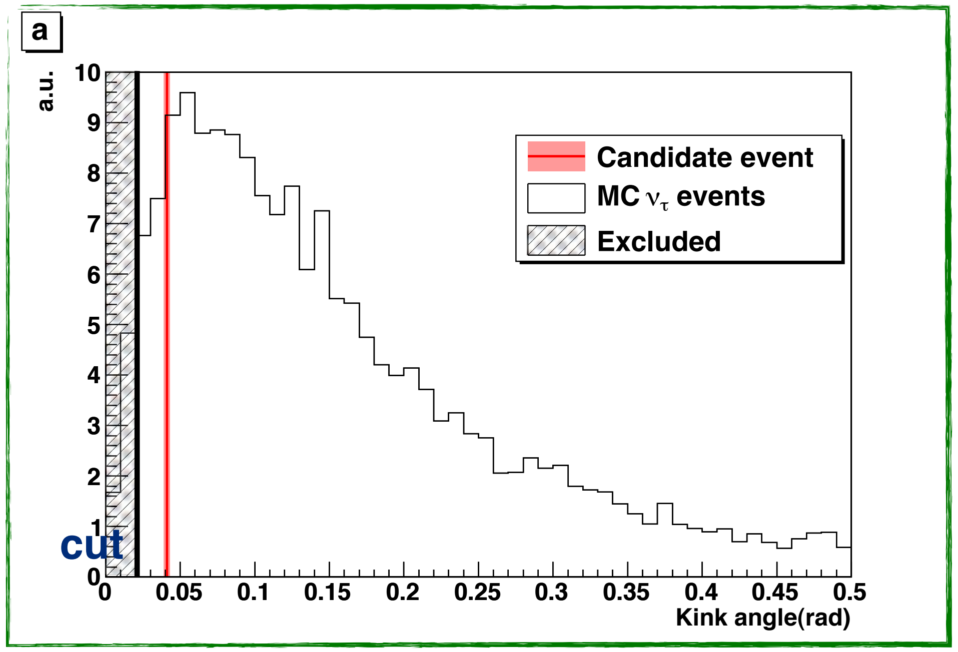
Linearity of momentum center



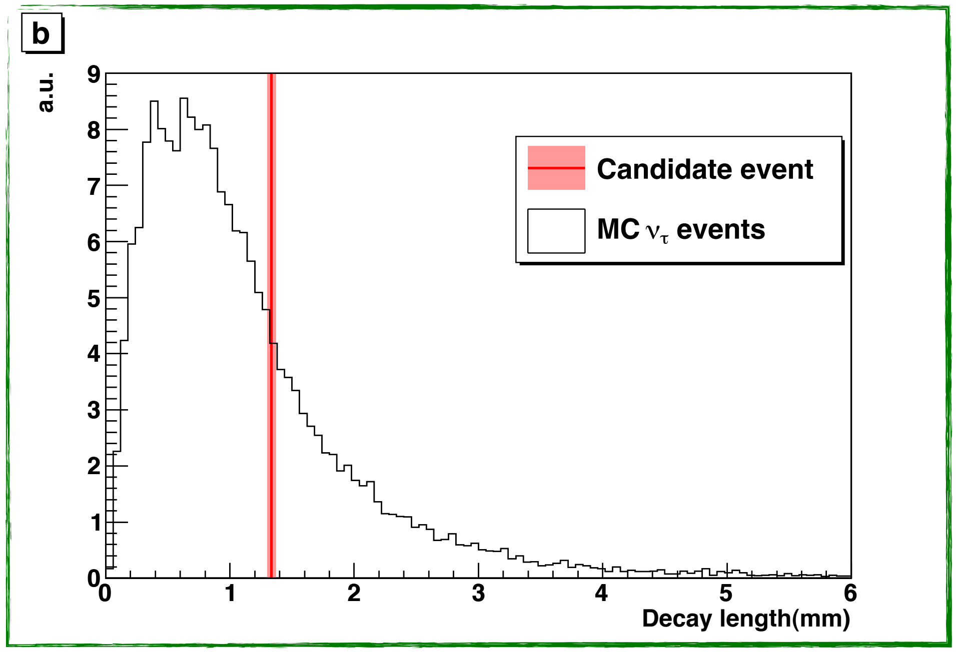
Resolution

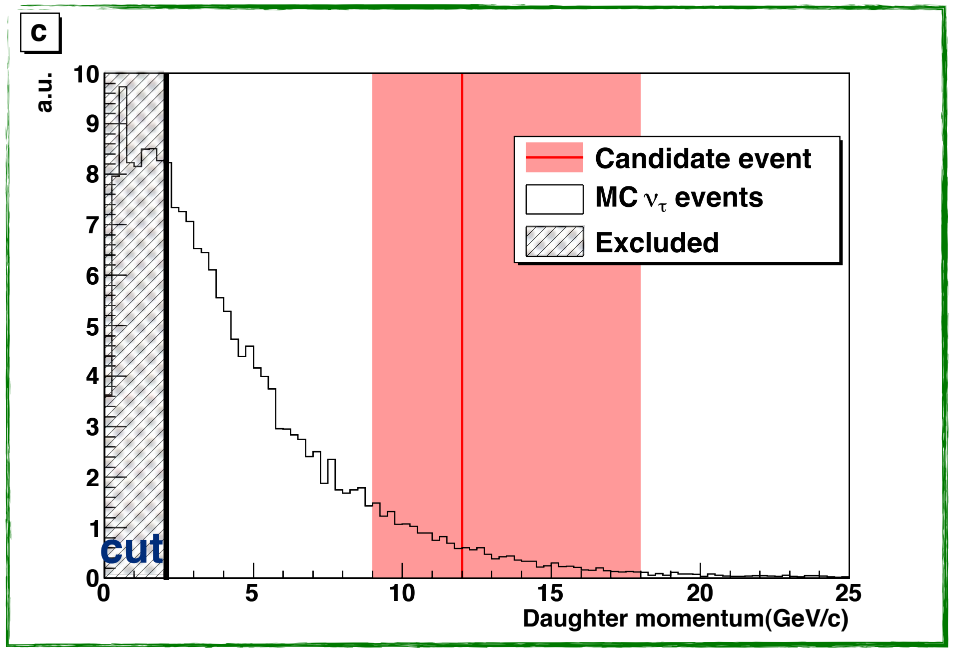


THE FIRST ν_τ CANDIDATE



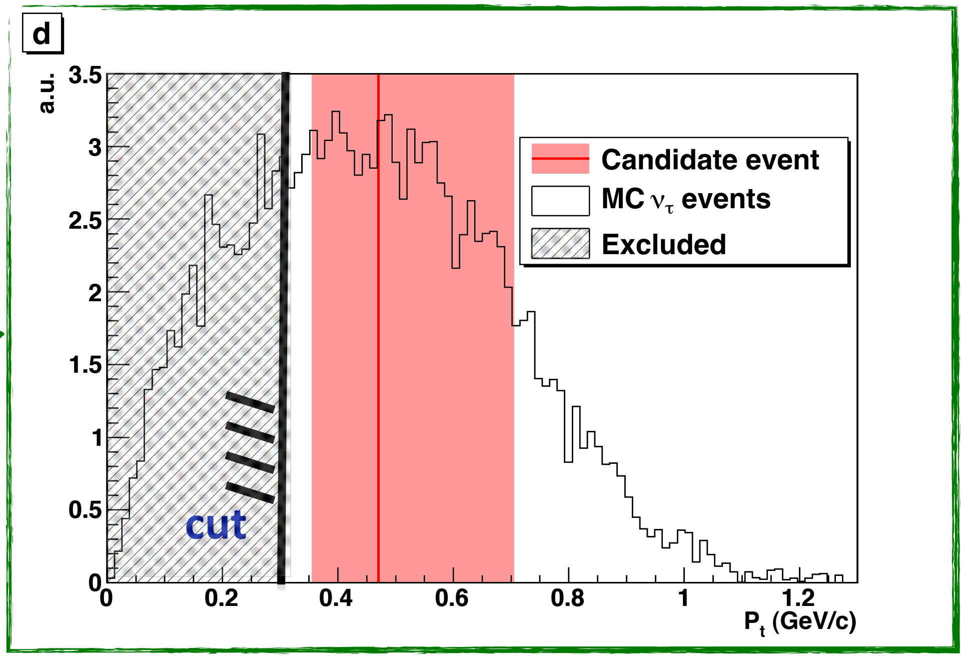
red bands: values for the "interesting" event with bands



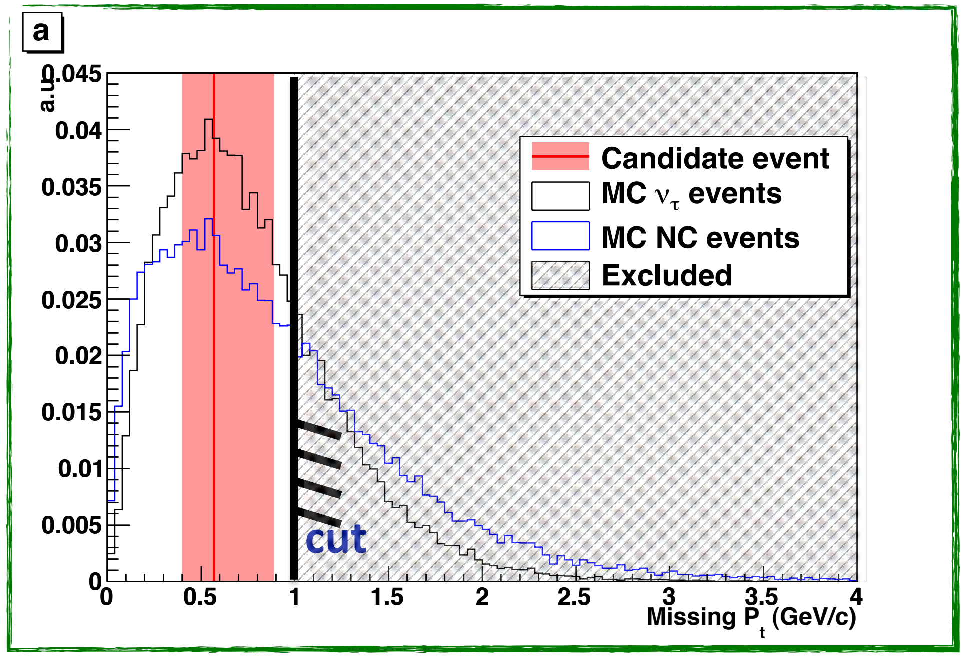


The First ν_τ Candidate

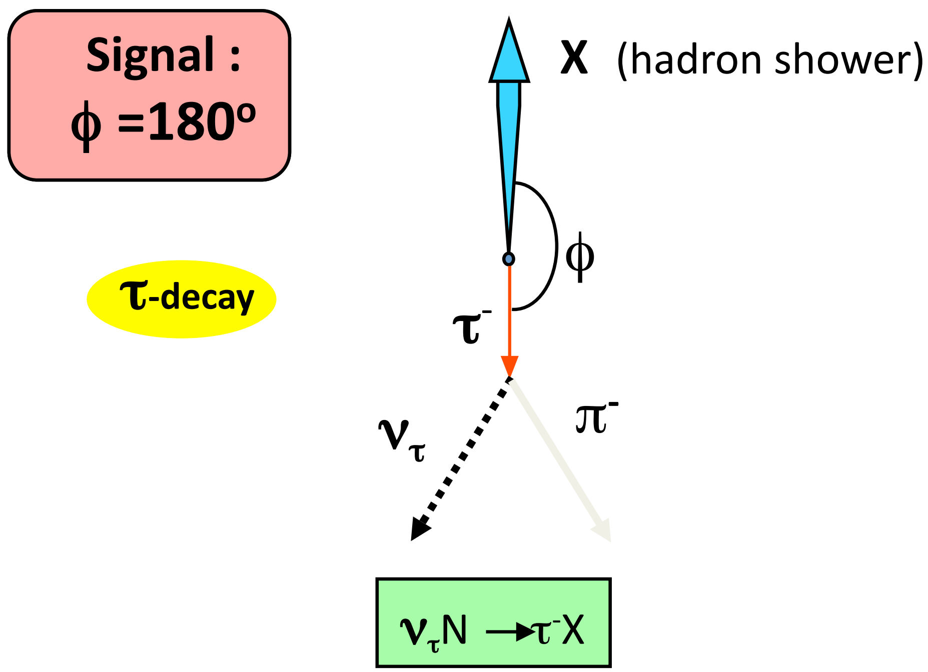
Reject hadron interactions with small P_t at secondary vertex

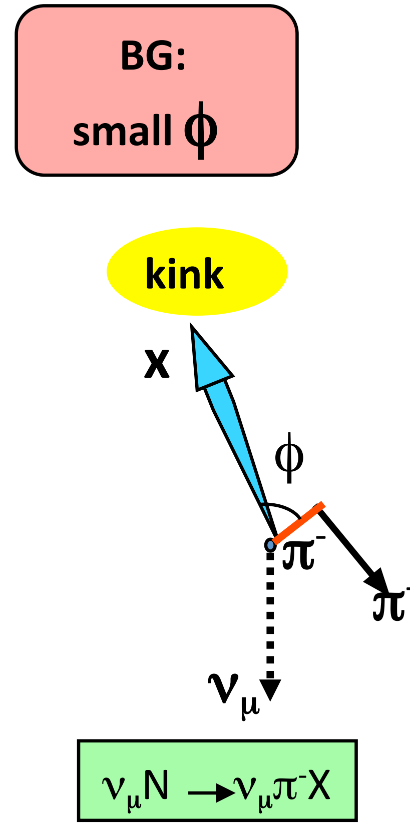


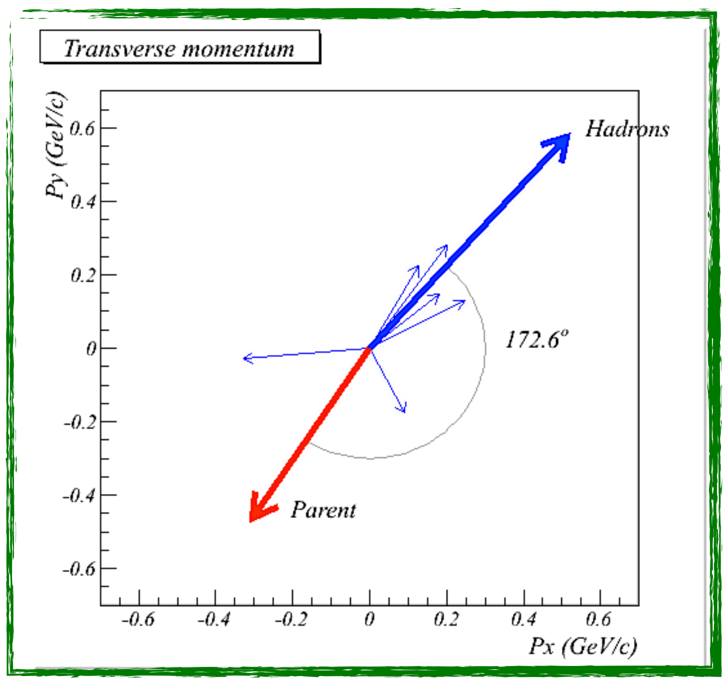
Reject NC events with large missing P_t at primary vertex

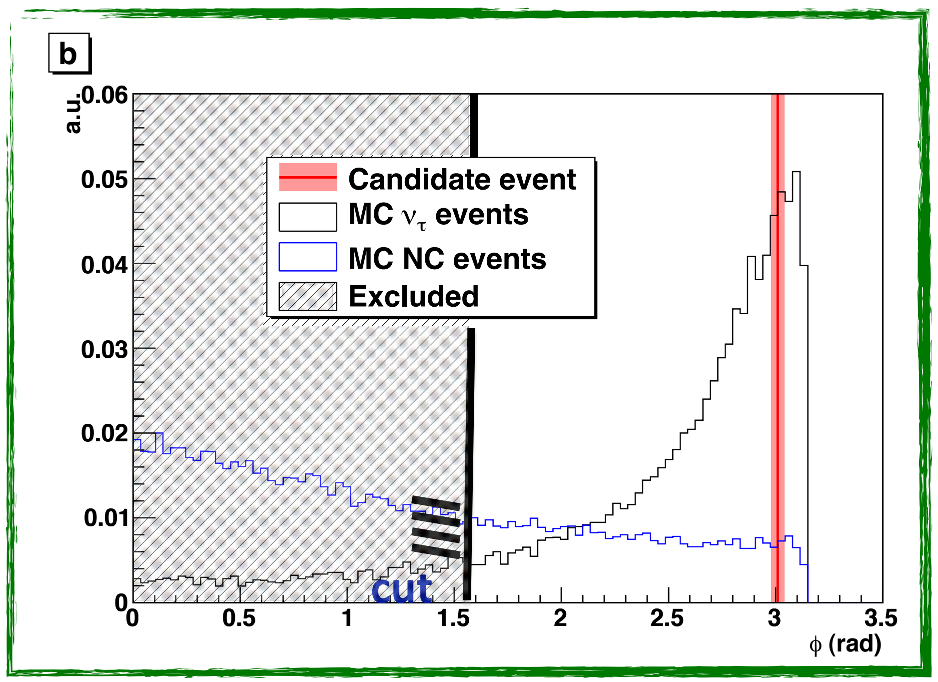


THE FIRST ν_τ CANDIDATE

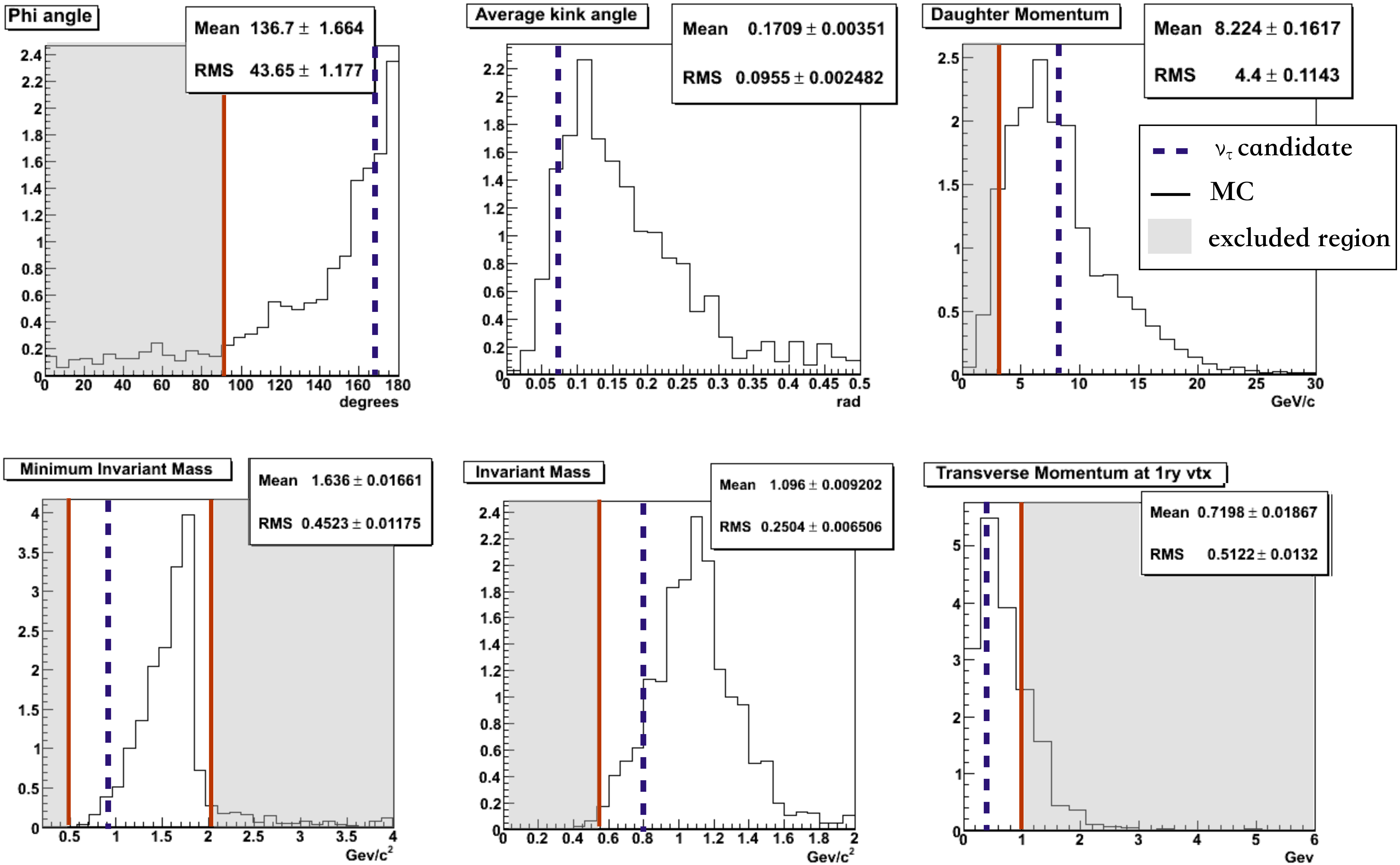








The Second ν_τ Candidate



Background sources

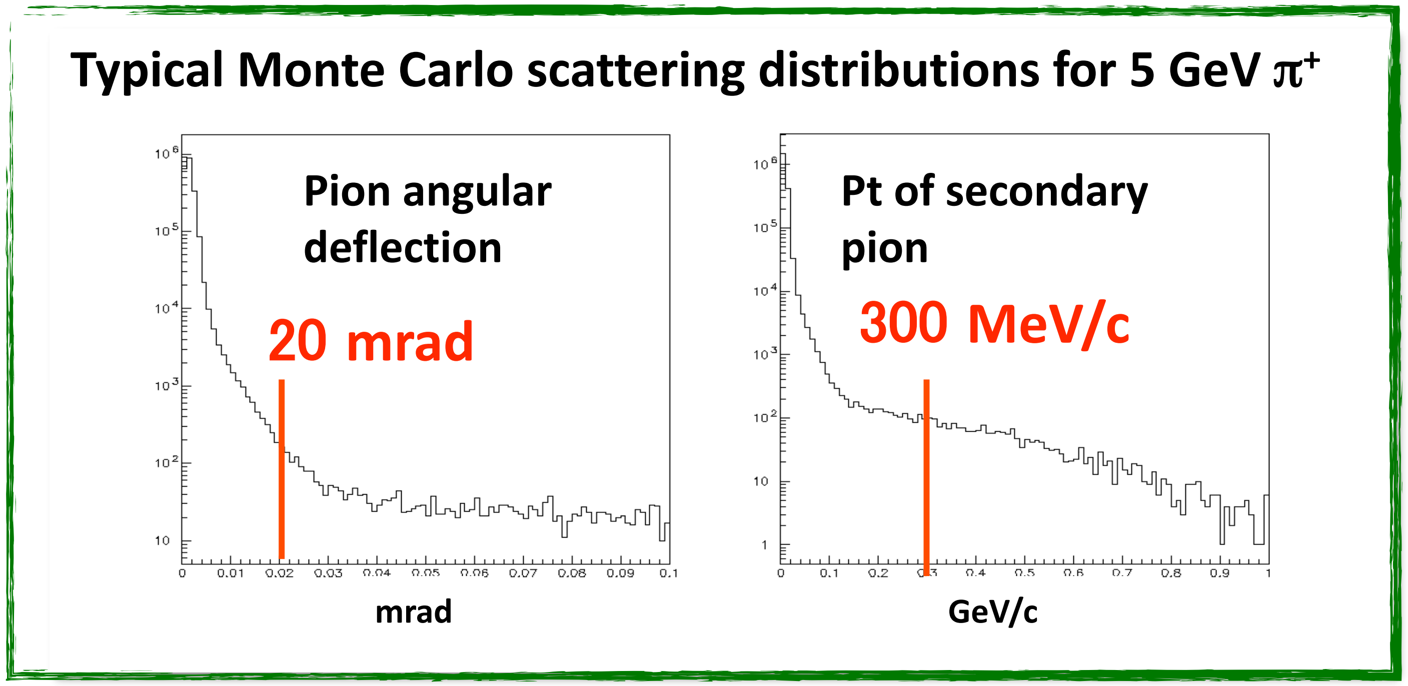
- Prompt ν_τ ~10^{-7}/CC
- Decay of charmed particles produced in ν_e interactions ~10^{-6} /CC
- Double charm production ~10^{-6} /CC

Main backgrounds:

- Decay of charmed particles produced in ν_μ interactions ~10^{-5} /CC
- Hadronic reinteractions ~10^{-5} /CC

Simulation of the hadronic BG

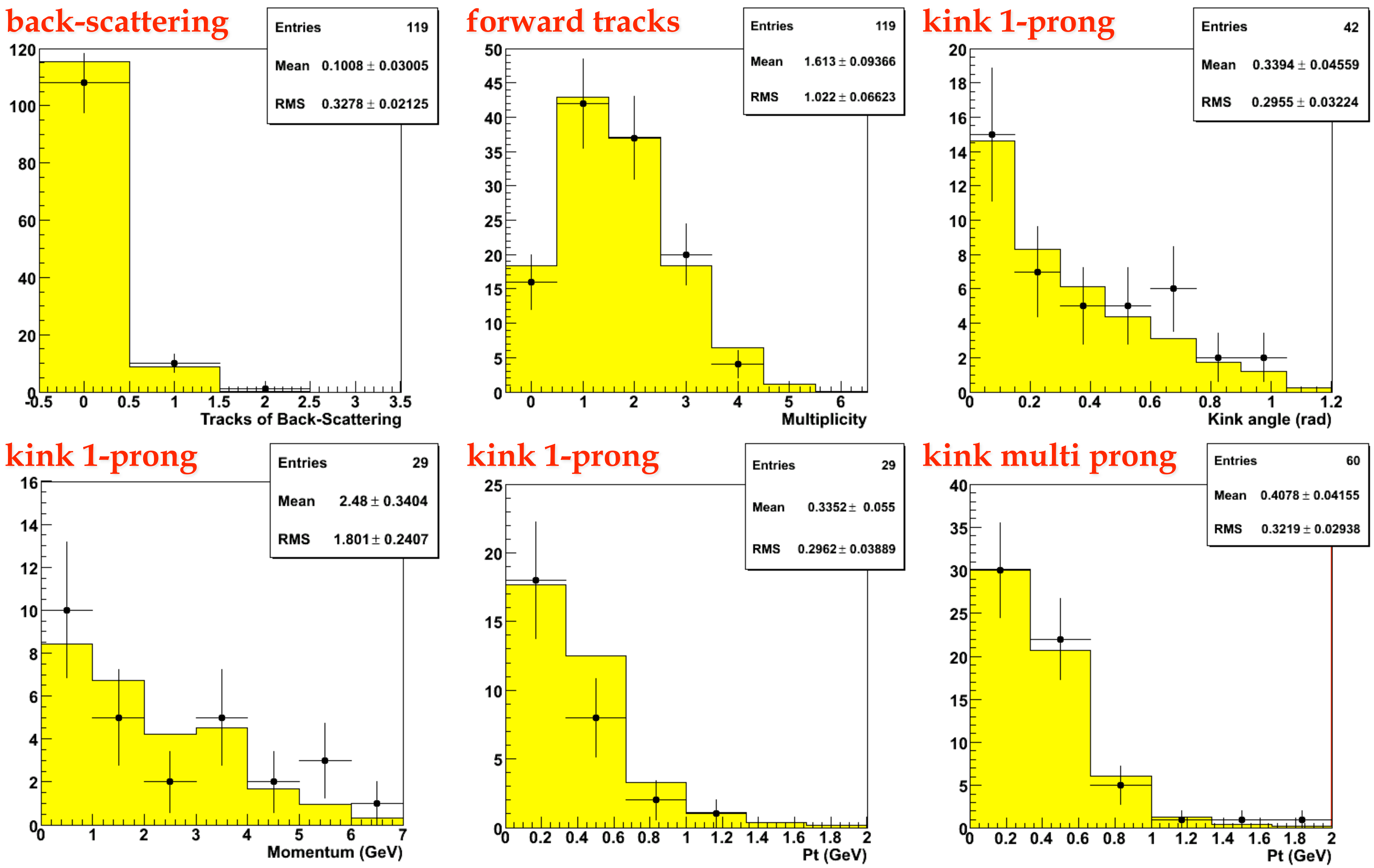
- 160 million events (0.5 – 15 GeV/c) of $\pi^+\pi^-k^+k^-p$ impinging 1 mm of lead, equivalent to 160 km of hadronic track length produced with FLUKA



- Kink probability integrated over the ν_μ NC hadronic spectrum after 2 mm of Pb and taking in to account the cuts on the event global kinematics:

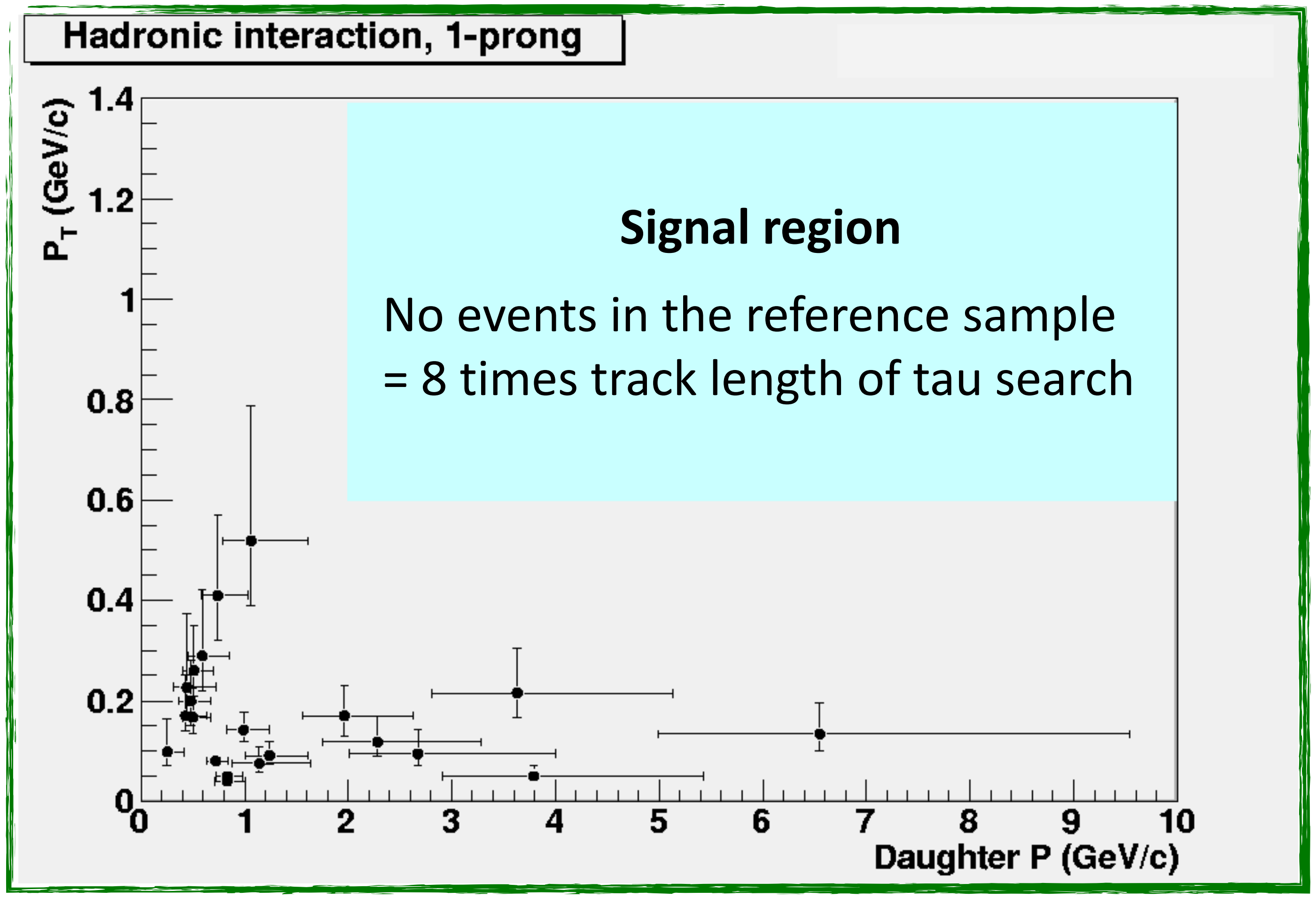
$(3.8 \pm 0.2) \times 10^{-5}$ kinks/NC

MC validation by beam test π events



- ECC brick exposed to 4 GeV/c pion: 18 times track length (20m) of τ search
- DATA/MC comparison: good agreement in normalization and shape

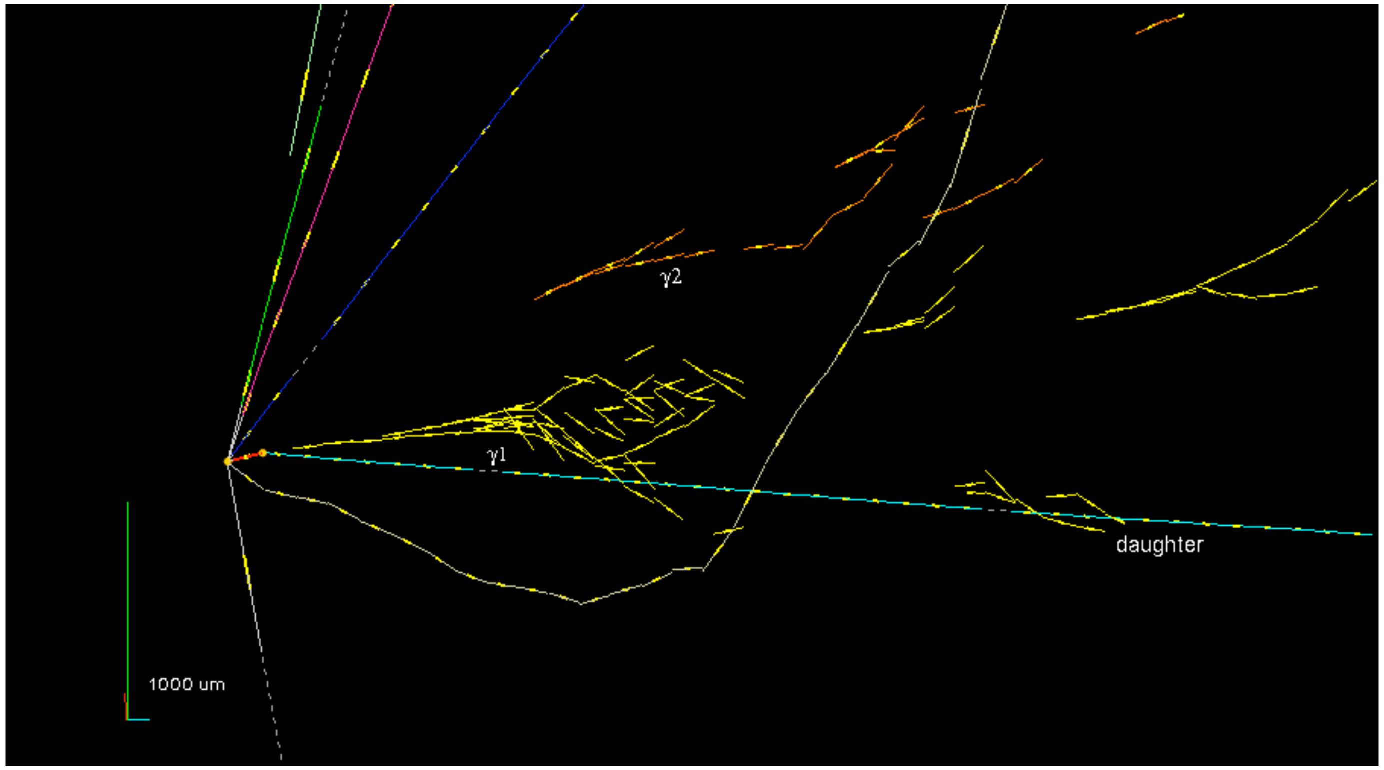
Hadronic BG study with data



- Search for "decay-like" interactions track far away from the primary vertex
- No background-like interaction has been found in the signal region
- The probability to have a background kink over 2 mm of lead is less than **1.54 x 10^{-3}** at 90% CL

Event interpretation

- This event passes all cuts, with the presence of at least 1 γ pointing to the secondary vertex
- This event is a ν_τ candidate with the $\tau \rightarrow$1-prong decay mode
- The invariant mass of the two detected γ is consistent with the mass π^0 value
- The invariant mass of the $\pi^-\gamma\gamma$ system is compatible with taht of ρ (770). The ρ appears in about 25% of the τ decays:

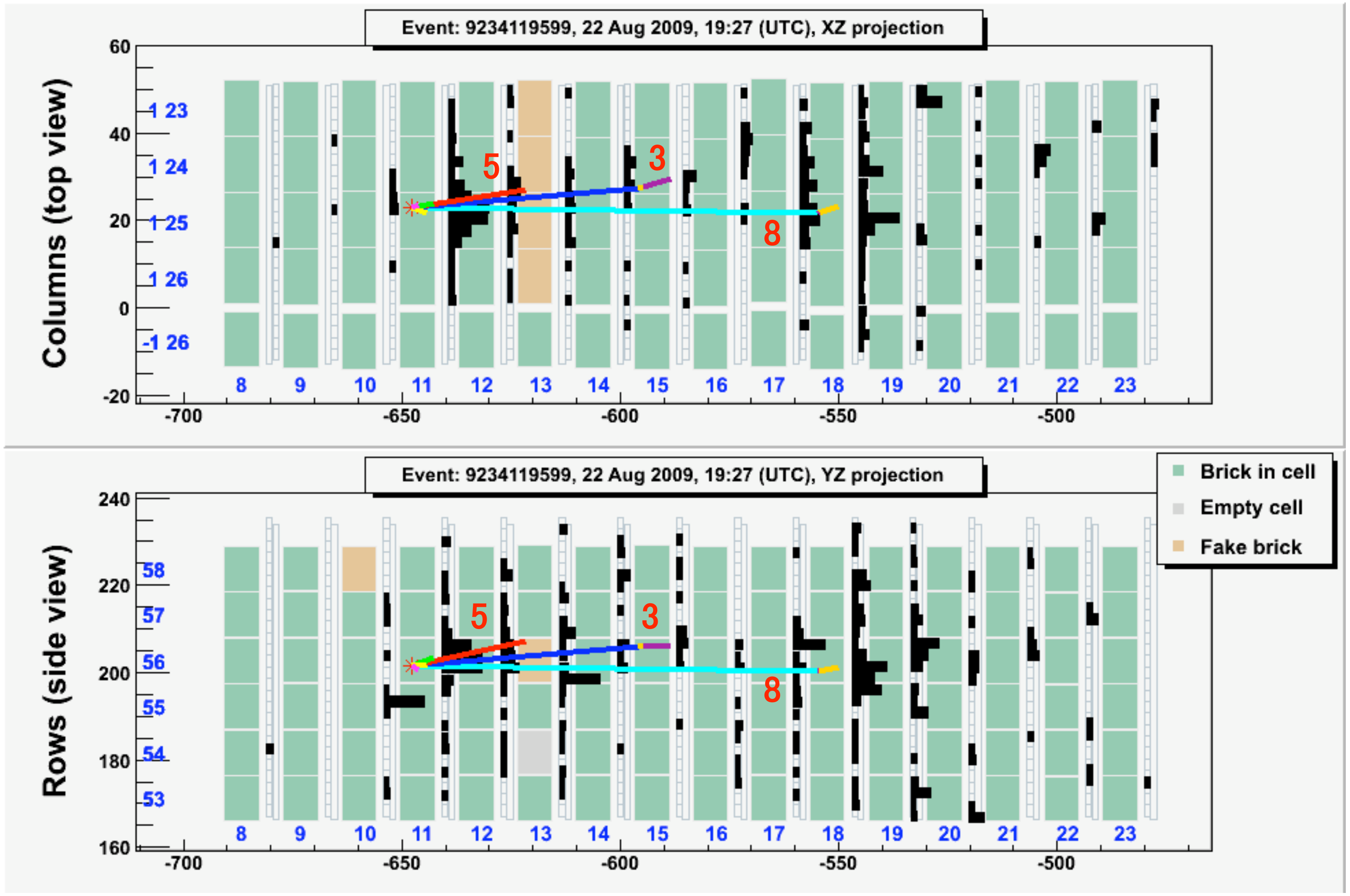


$$\tau \rightarrow \rho\ (\pi^-\ \pi^0)\ \nu_\tau$$

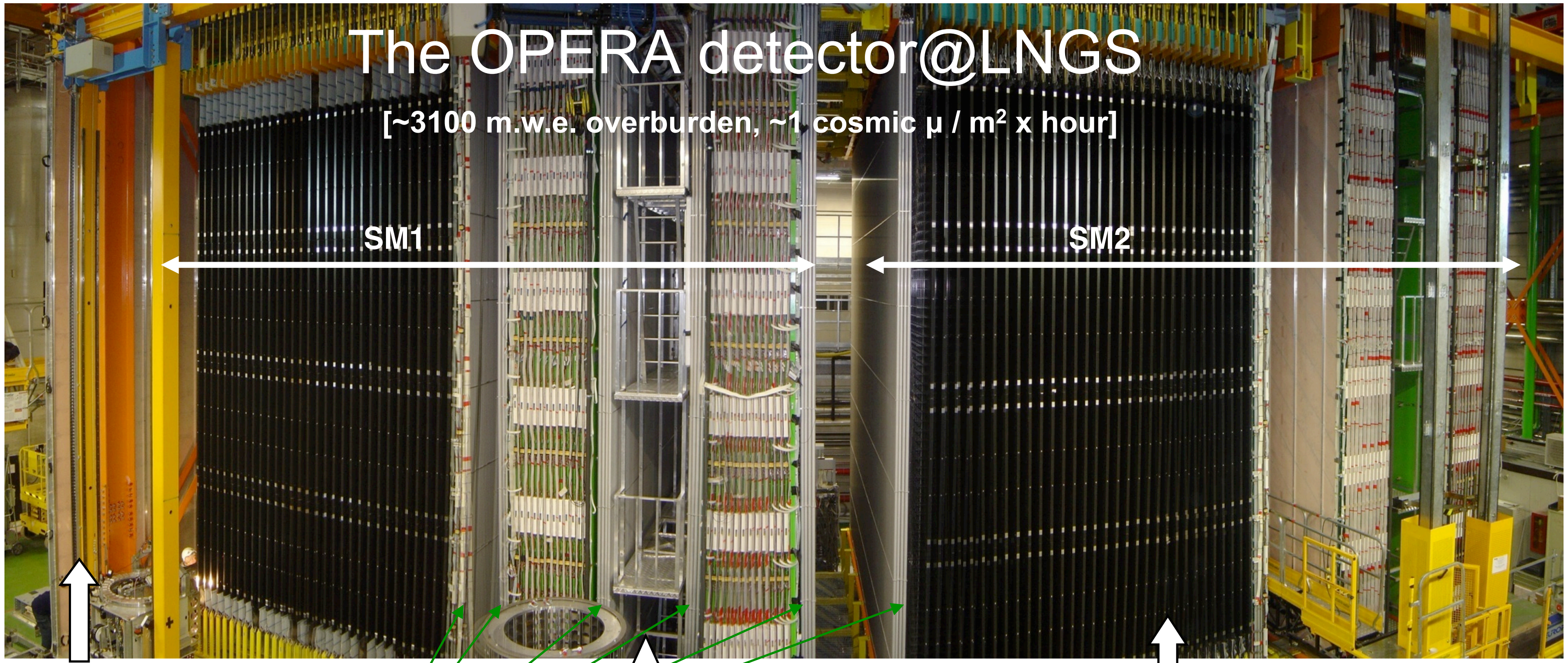
π^0 mass	ρ mass
120 ± 20 ± 35 MeV	$640^{+125}_{-80}{}^{+100}_{-90}$ MeV

The first $\nu\tau$ candidate

Vertex tracks followed down (through several bricks) to assess the
muon-less nature of the event.
Residual probability of ν_μCC event (due to a possibly undetected large angle muon) ~ 1%
“Nominal” value of 5% assumed



The detector



Veto (RPC)

High precision tracker
- 6 4-fold layers of drift tubes

Dipole magnet
- 1.53 *T*
- 22 XY planes of RPC

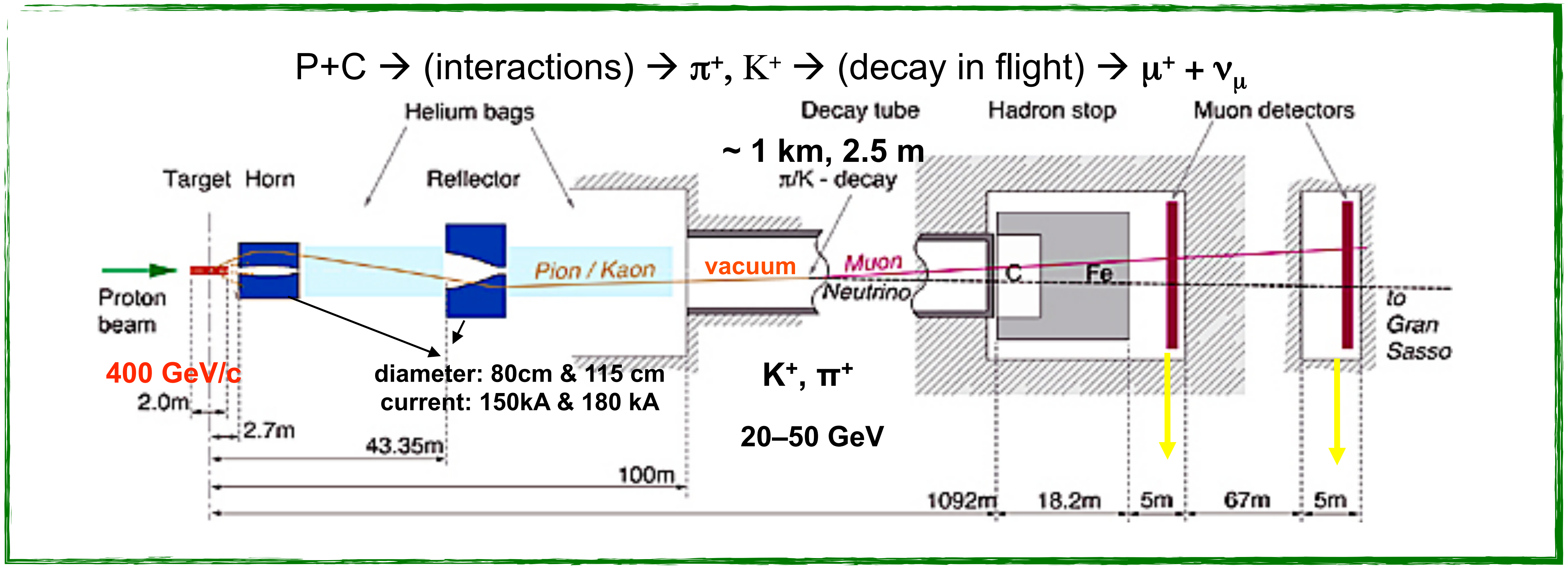
muon spectrometer (8×10 m^2)

Target + Target Tracker (6.7*m*)^2

- target/SM: ~75000 *bricks* *(Pb – nuclear emulsions)* Mass/SM 0.625 kt
- Target tracker : 31 doublets XY (256 plastic scintillator strip + WLS fibres+ multi-anodes PMT) for trigger, brick selection and calorimetry

[Ref. JINST 4 (2009) P04018]

The CNGS Neutrino Beam



- 400 GeV/c proton from the CERN SPS on graphite target, producing pions and kaons
- Helium tubes are placed in the free space of the target in order to reduce the interaction probability for secondary hadrons
- Pions and kaons are directed towards the decay tunnel to produce ν_μ beam
- Muon detectors are used for online monitoring and tuning of the beam

EMULSION SCANNING

Parallel ECC analysis in ~10 labs
Number of labs is increasing

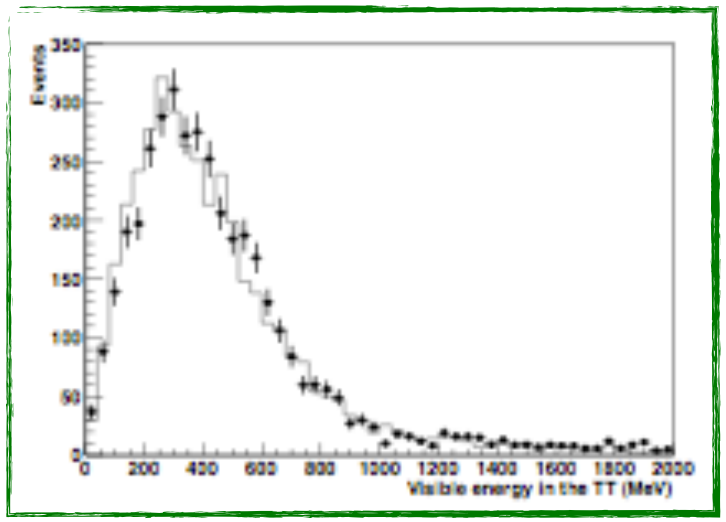
NAPOLI SCANNING LAB

ECC Brick Scan & Analysis Load

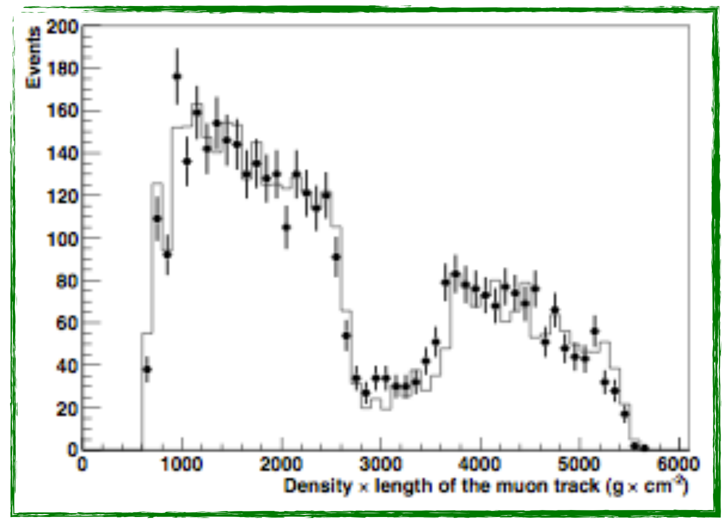
JAPAN : EU = 50 : 50

Electronic Detectors

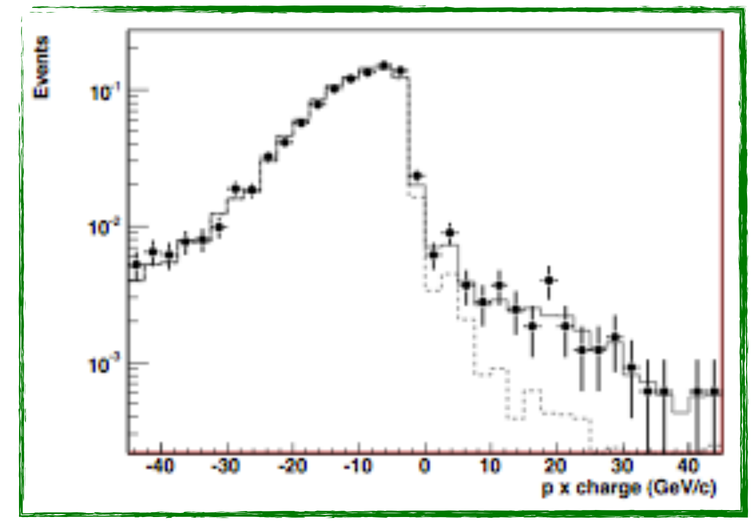
Hadronic energy deposite in TT



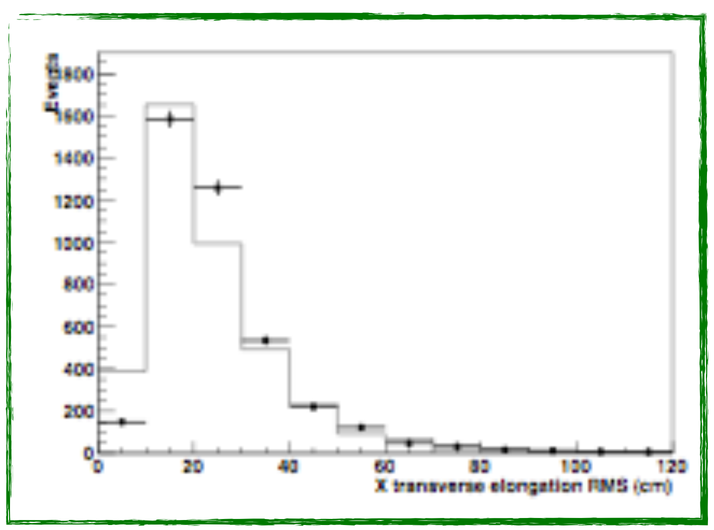
Density x length of the muon track



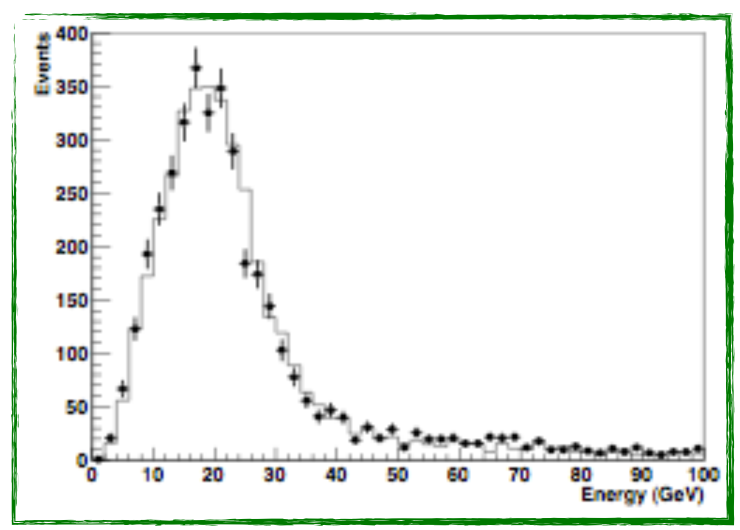
Momentum x charge of the muon



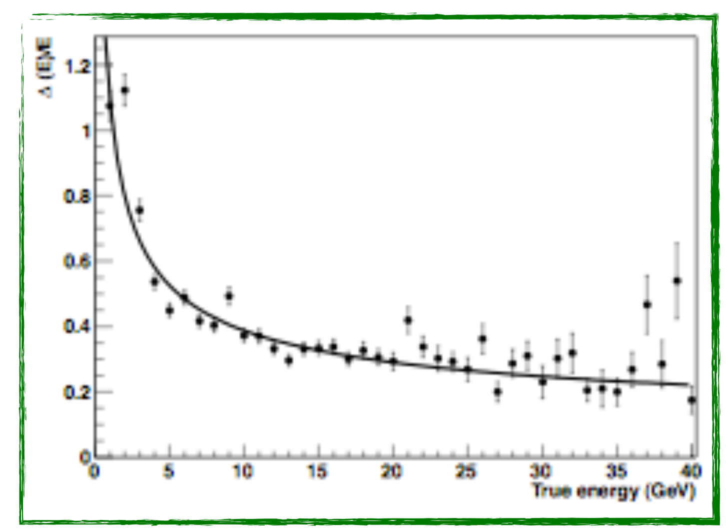
Transverse profile of hadronic showers



Total reconstructed energy in events with at least one identified muon



Energy resolution



NEUTRINO OSCILLATIONS

$$(\nu_e,\, \nu_\mu,\, \nu_\tau)^T = U\,(\nu_1,\, \nu_2,\, \nu_3)^T$$

eigenstates of flavor

eigenstates of mass

Unitary matrix: 3 Eulero rotation angles + 1 CP phase

PMNS (Pontecorvo-Maki-Nakagawa-Sakata) Matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij},\; s_{ij} = \sin\theta_{ij}$

Measured by atmospheric and accelerator ν experiments

Mainly constrained by reactor experiments

Measured by ν solar experiments

NEUTRINO OSCILLATIONS

$$(\nu_e,\, \nu_\mu,\, \nu_\tau)^T = U\,(\nu_1,\, \nu_2,\, \nu_3)^T$$

eigenstates of flavor **eigenstates of mass**

Unitary matrix: 3 Eulero rotation angles + 1 CP phase

In the simplified scheme of oscillations between two neutrino flavors, they are described by two quantities:

- the mixing parameter $\sin^2 2\theta$
- the mass squared difference Δm^2 between the two mass eigenstates

$$P_{\nu_\mu \to \nu_\tau} = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2(eV^2)L(Km)}{E(GeV)}\right)$$

NEUTRINO OSCILLATIONS

In the last decades several experiments provided evidence for neutrino oscillations (disappearance mode)

- **CHOOZ** (1997): The main oscillation channel responsible for atmospheric neutrino disappearance is not $\nu_\mu \rightarrow \nu_e$;
- **SK** (1998): The main oscillation channel responsible for atmospheric neutrino anomaly is not $\nu_\mu \rightarrow \nu_e$ and can be interpreted as $\nu_\mu \rightarrow \nu_\tau$ oscillation.
- (2004-2009) **K2K,MINOS**: precision measurements of ν_μ disappearance