The OPERA nuclear emulsion detector: performances, analysis and results

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Outline

- OPERA goal and neutrino beam
- Detector structure and analysis chain
- Background sources
- Results for $\nu_\mu \rightarrow \nu_\tau$ oscillation analysis

OPERA collaboration

Belgium
ULB Brussels

Croatia
IRB Zagreb

France
LAPP Annecy
IPNL Lyon
IPHC Strasbourg

Germany
Hamburg

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

Japan
Aichi edu.
Kobe
Nagoya
Toho
Utsunomiya

Korea
Jinju

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

Switzerland
Bern
ETH Zurich

Turkey
METU Ankara

（11 countries, 30 Institutes, ~160 researchers）

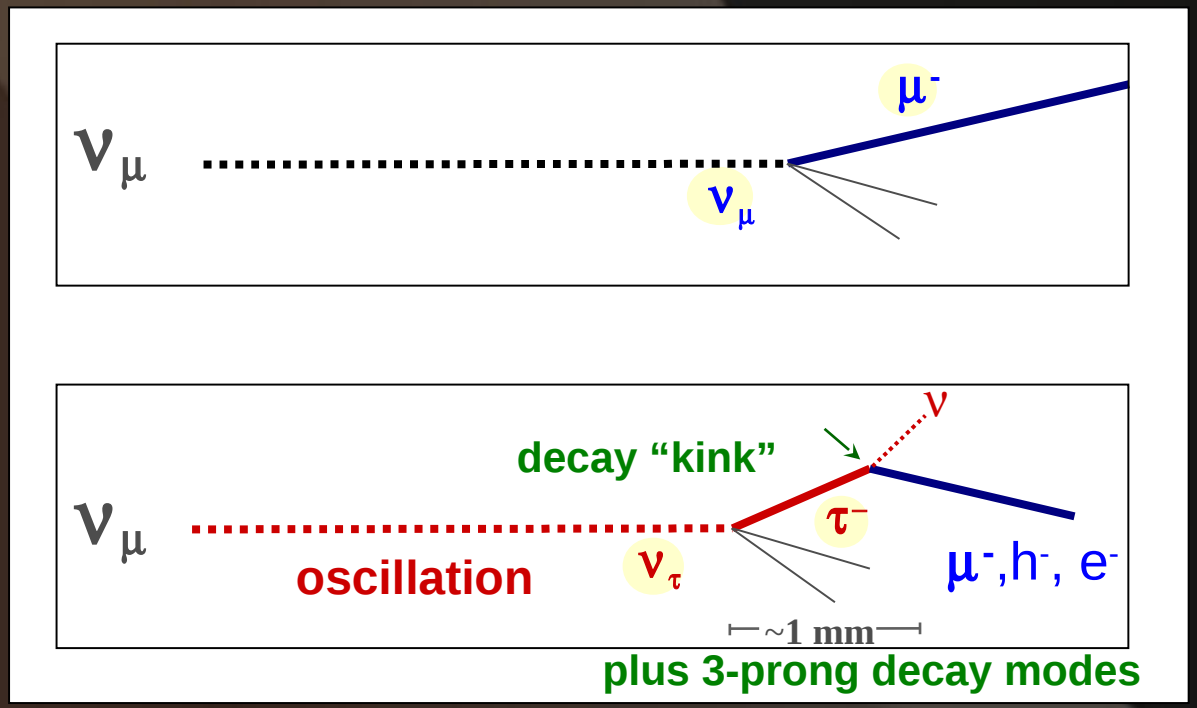
Oscillation Project with Emulsion tRacking Apparatus

- Goal: first detection of neutrino oscillation in appearance mode — ν_τ appearance in ν_μ beam.
- Signal: observation of tau lepton decay in event-by-event analysis.

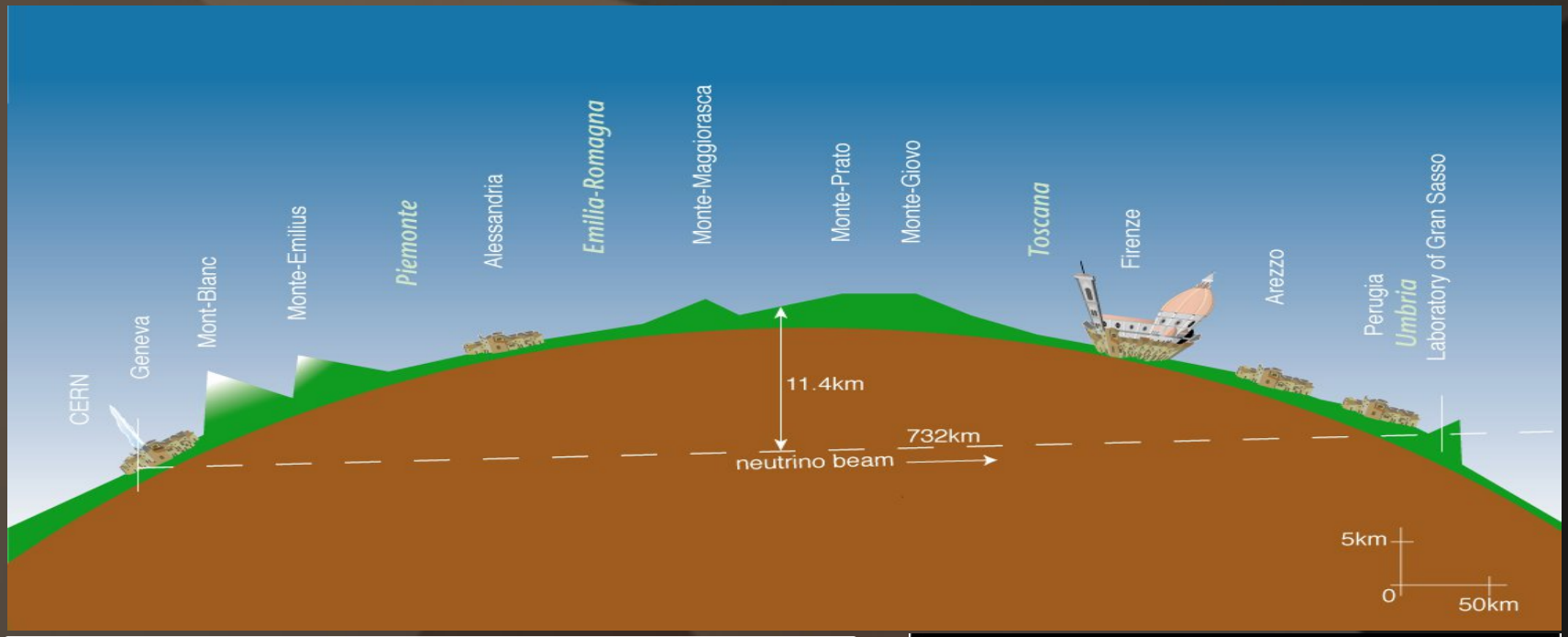
Requirements:

Neutrino beam: high intensity, long baseline.

Detector: large mass, fine structure, micron resolution.



Cern Neutrino to Gran Sasso



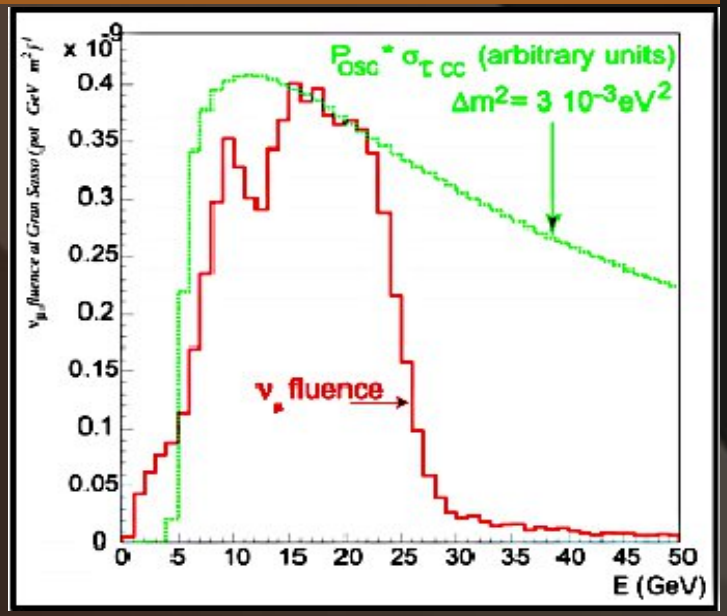
$L_{CNGS} = 732$ km

$\langle E\nu_\mu \rangle = 17$ GeV

$(\bar{\nu}_e + \nu_e)/\nu_\mu = 0.9\%$ int

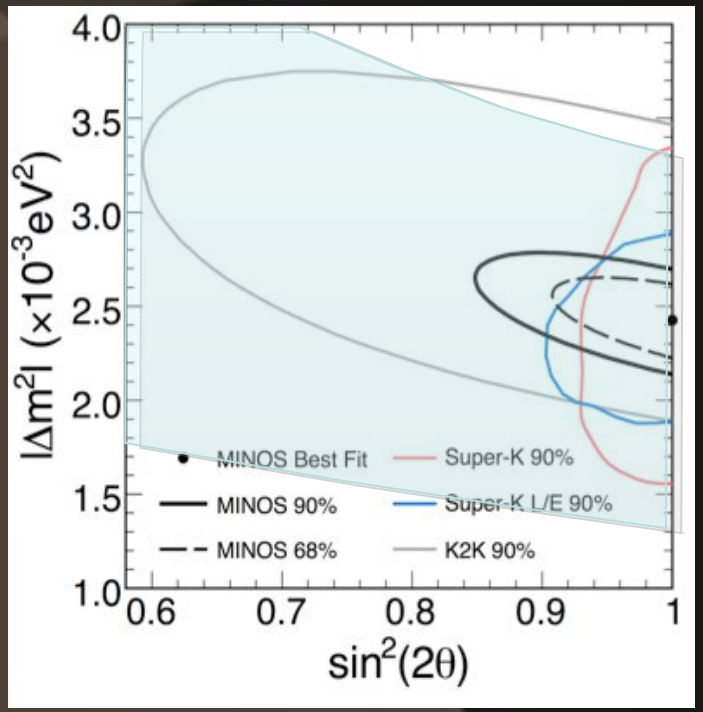
$\bar{\nu}_\mu/\nu_\mu = 2.0\%$ int

ν_τ prompt = negligible



CNGS beam performance

Year	**POT x 10^{19}**	Interactions
2008	1.74	1698
2009	3.53	3557
2010	4.09	3912
2011	4.75	4210
2012	3.86	3680
Total	17.97 (80%)	17057



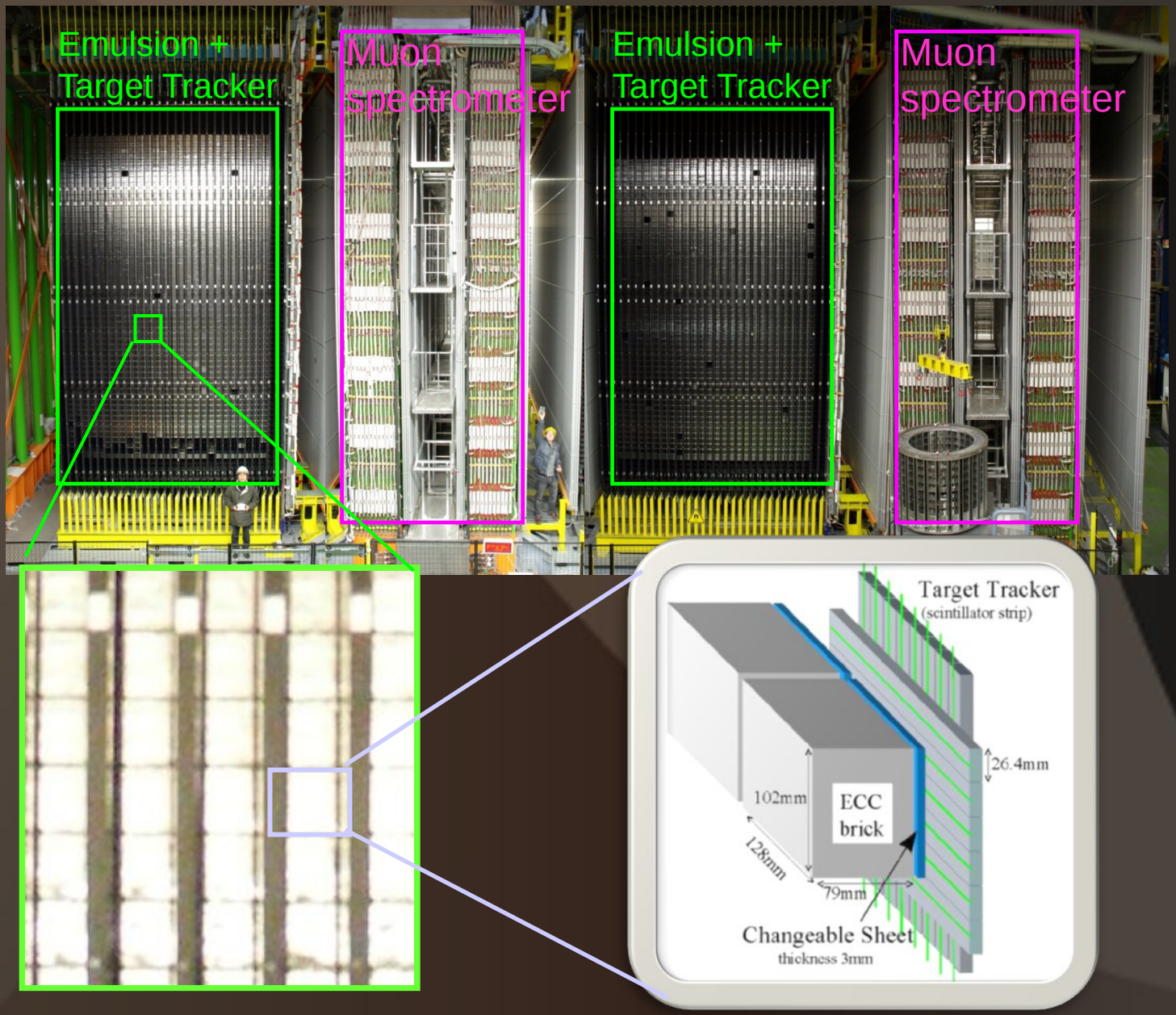
For 22.5x10^{19} POT Expected Events: 7.6 Signal, 0.7 Background

Ref: New Journal of Physics 14(2012)033017

OPERA detector structure

- Emulsion Cloud Chamber — active target: 1.25 kton of lead, interleaved with nuclear emulsion.
- Electronic Target Trackers — event timing, cosmic veto, preselection of interaction region.
  Scintillator strips.
- Magnetic spectrometer: muon momentum and charge measurement.
  Magnetized iron, interleaved with RPC planes + drift tubes.

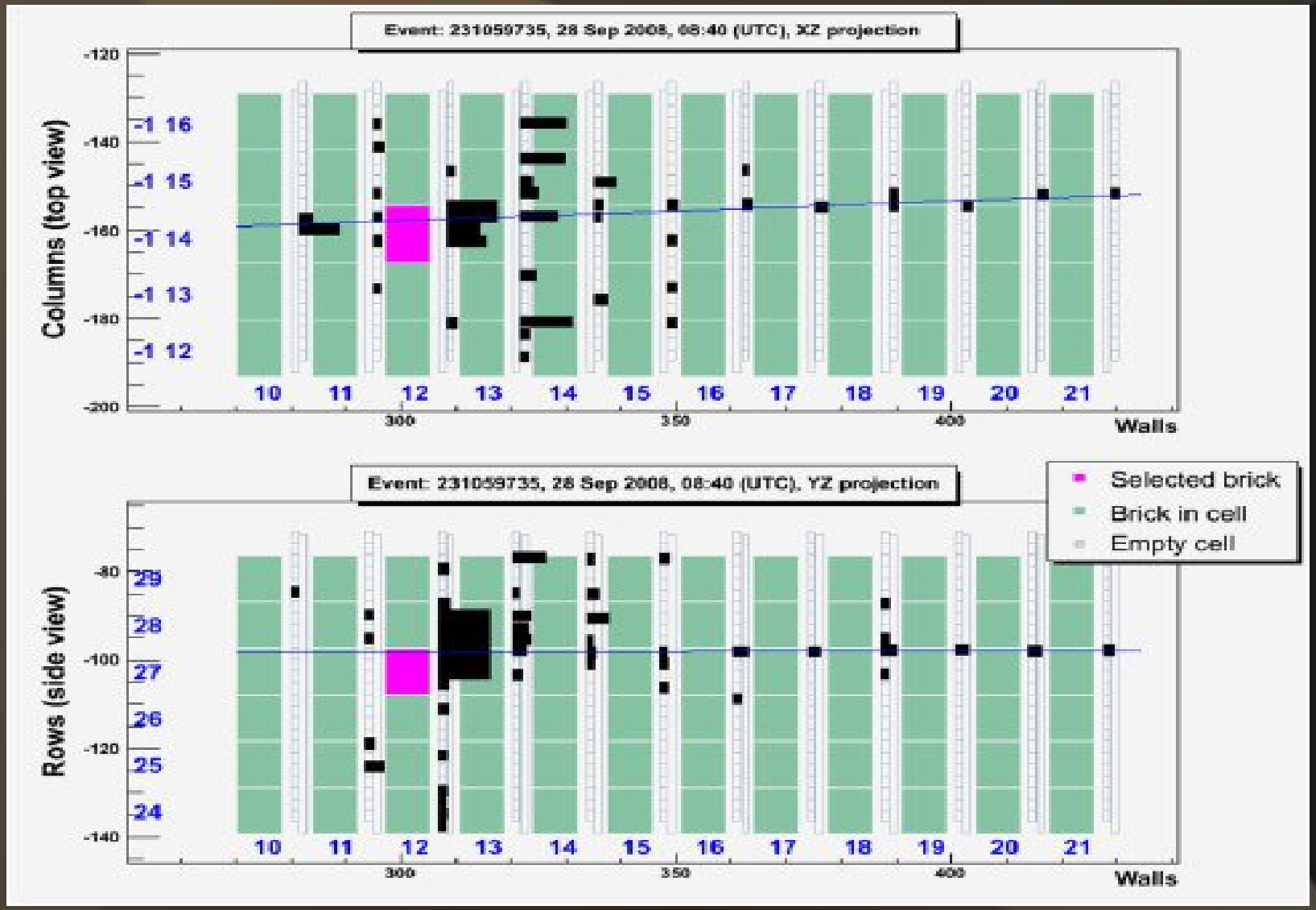
OPERA detector structure



Event preselection chain: electronic detectors

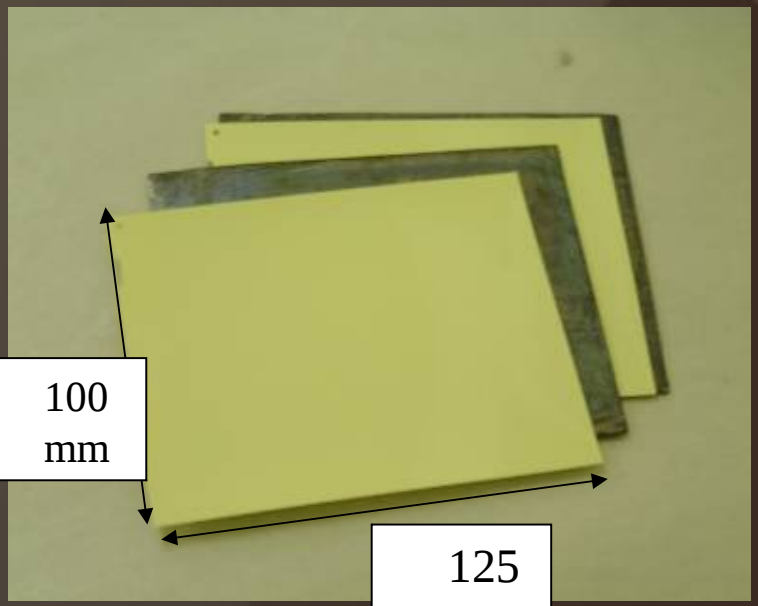
- Interaction is seen as hits in electronic detectors.
- Tracks in TT are reconstructed. Their energies are evaluated (if possible).
- If muon is present, its charge and energy are evaluated from spectrometer.
- Based on presence of muon, event is classified to be ν_μ CC or NC candidate.
- Special algorithm (Neural network) is applied to determine the interaction brick.
  Output — 3 most probable bricks.

Brick finding by TT

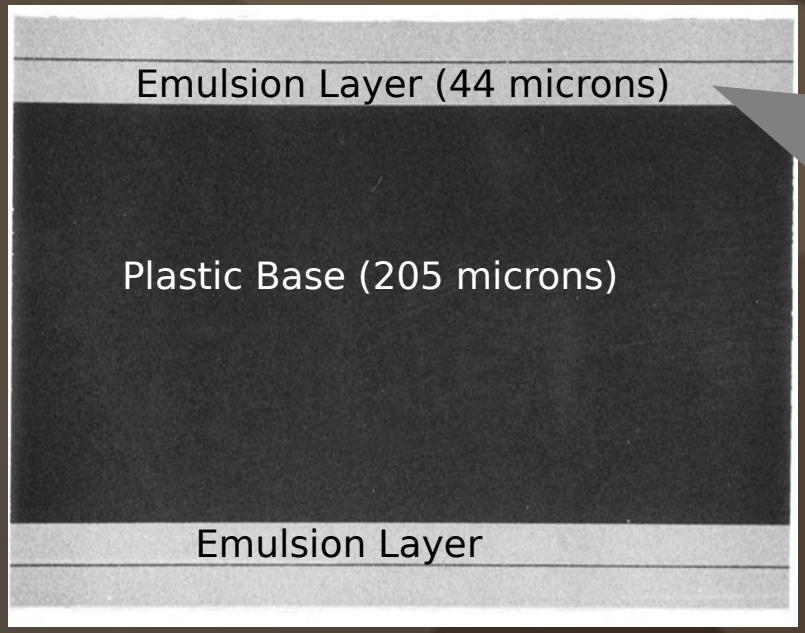


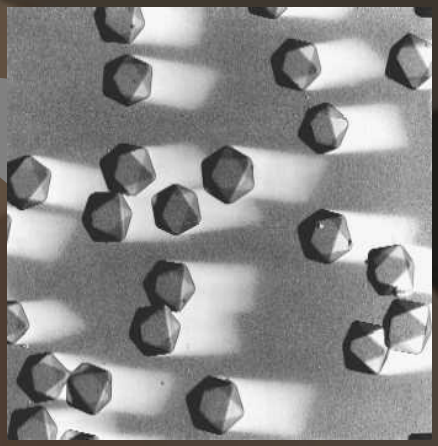
OPERA emulsion detector module: ECC brick

- 56 Pb plates + 57 emulsion plates
- Mass = 8 kg.
- L = 10 X_0
- 10cm X 12.5 cm



OPERA nuclear emulsion





Basic detector:

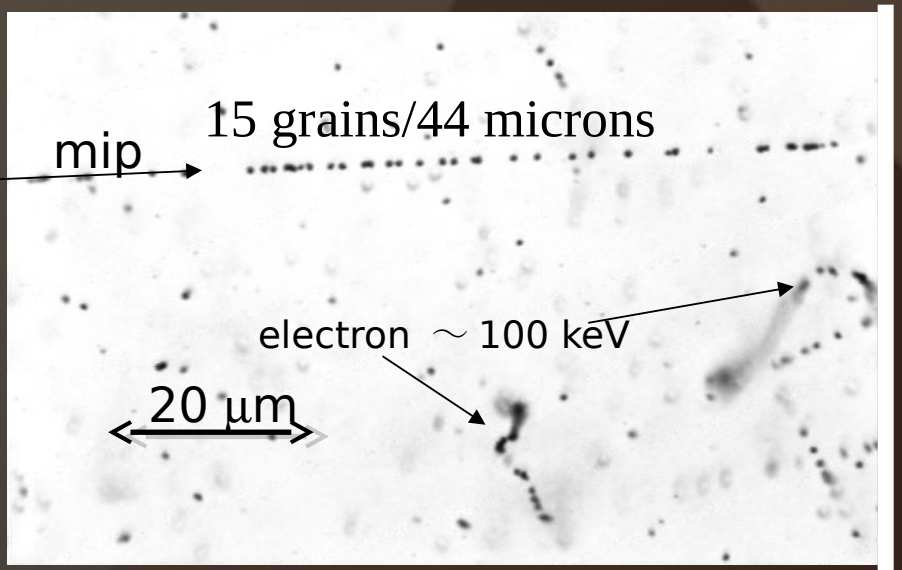
Ag-Br crystal,

size = 0.2 micron

detection eff.= 0.16/crystal

10^{13} "detectors" per film

Development: ionized crystals become Ag grains

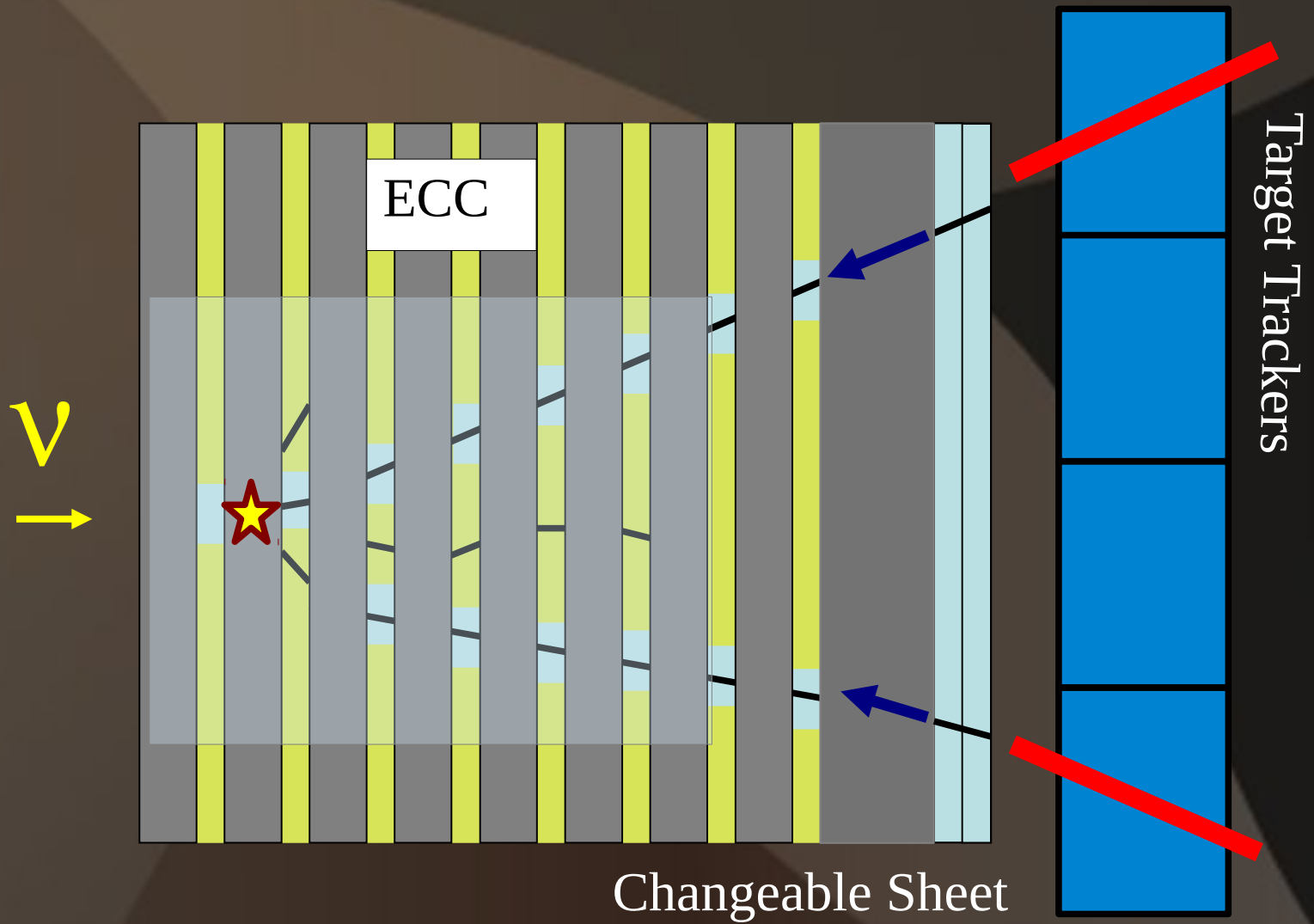


Density of grains along depends on dE/dx. Highly ionizing particles (i.e. heavy nuclear fragments) can be seen as black tracks.

Event location in ECC

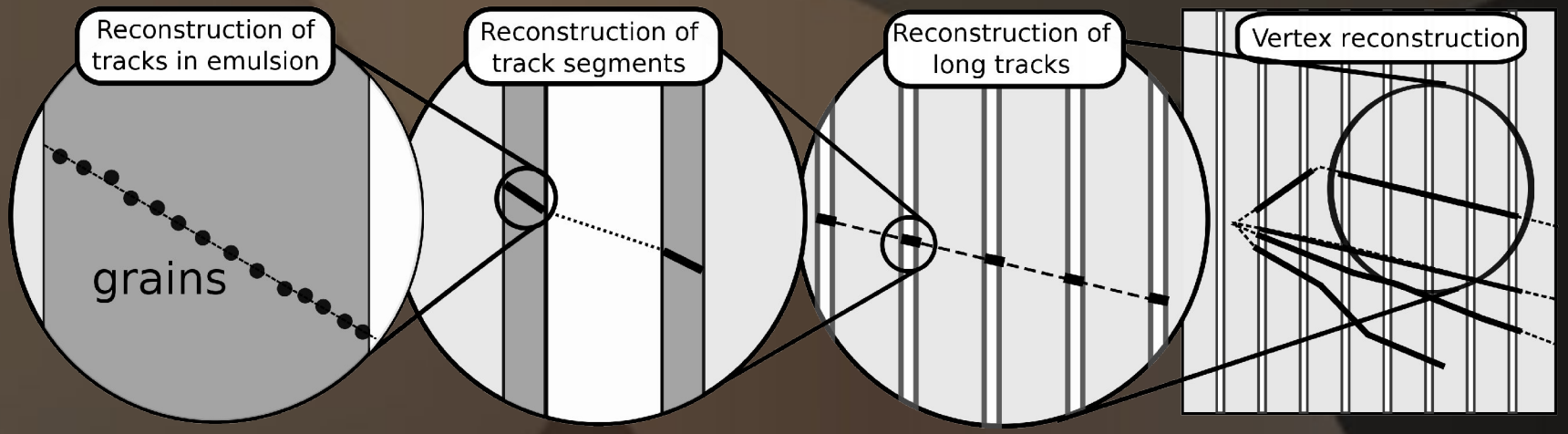
- After the most probable interaction brick was selected, it is extracted from detector.
- Interface films (Changeable Sheet) are scanned in attempt to find tracks in emulsion, corresponding to predictions from TT.
- *a)* muon track found in CS, or
  b) tracks in CS make a converging pattern → Analyze the brick
- Tracks, found in CS are followed upstream in ECC brick, until stopping point (vertex?) is found.
- Large area scan around stopping point is performed. (1 cm2, 5 plates upstream, 10 plates downstream).
- Tracks and primary vertex are reconstructed → Event located
- Decay Search procedure is applied on event.

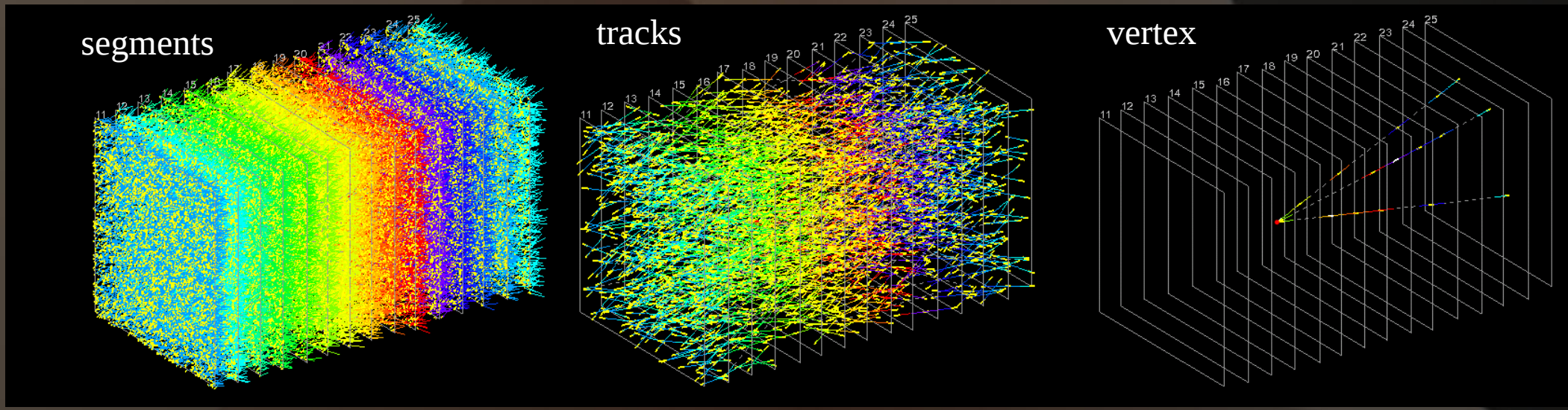
Event location in ECC



Alignment between two CS: X-ray marks and Compton electron tracks
Alignment between CS and ECC: X-ray marks
Alignment between plates of ECC: X-ray marks and cosmic rays.

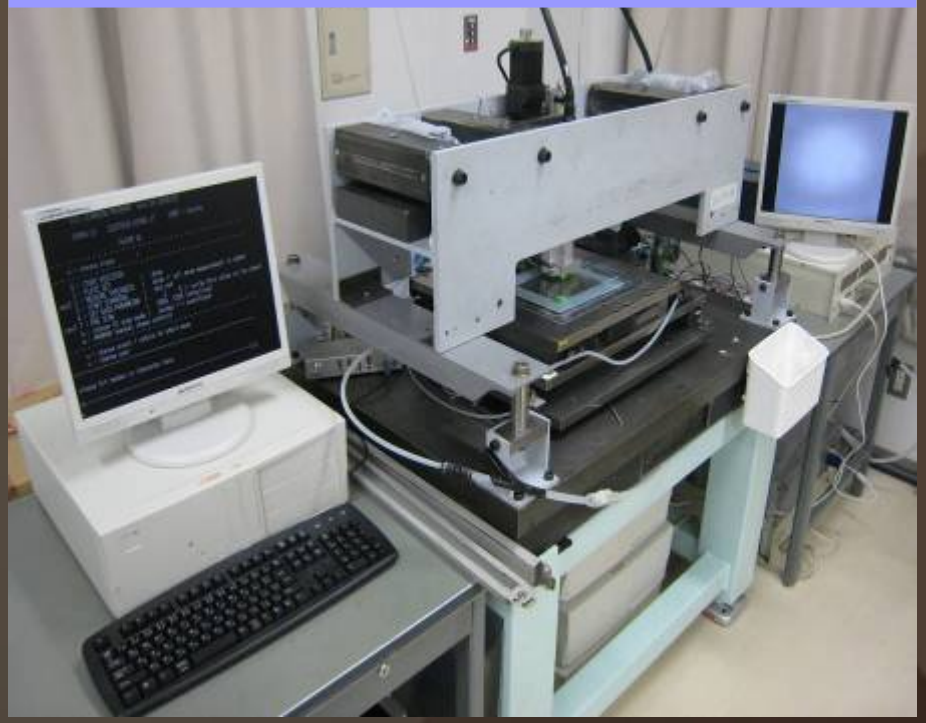
Emulsion data processing





Automatic scanning microscopes

Japanese Scanning System (S-UTS)



Scanning speed/system: 75cm²/h

*High speed CCD camera (3 kHz)
*Piezo-controlled objective lens
*FPGA Hard-coded algorithms

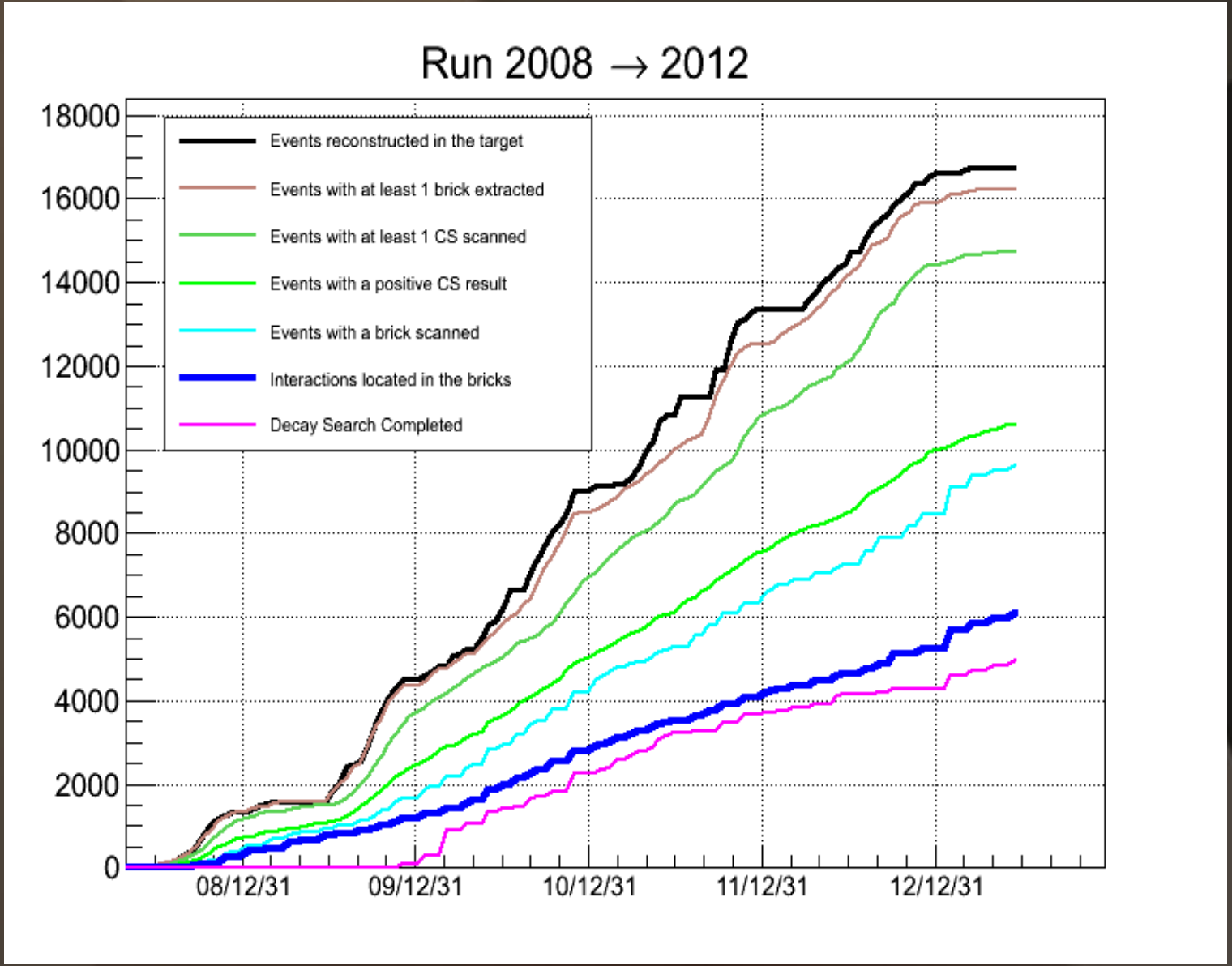
European Scanning System (ESS)

Scanning speed/system: 20cm²/h

*Customized commercial Optics and mechanics
*Asynchronous DAQ software

New systems are being developed with improved speed, efficiency and angular acceptance

Event analysis status



CS scanned
14737

CS found
10585

ECC scanned
9629

Located
6067

DS
4949

Background sources

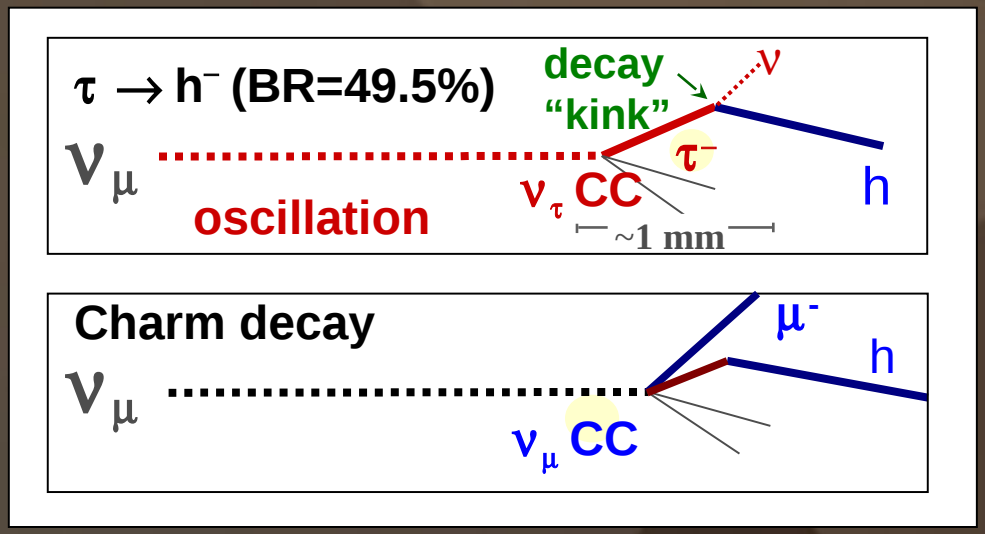
Tau decay branching ratios:

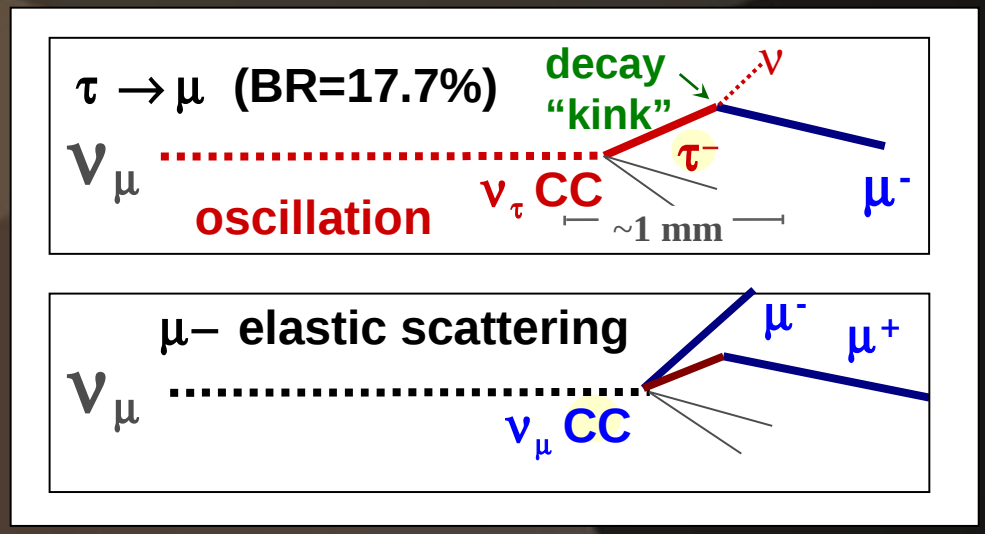
Decay channel	$\tau \to \mu$	$\tau \to h$	$\tau \to 3h$	$\tau \to e$
BR (%)	17.7	49.5	15.0	17.8

- Hadrons from ν_μ NC reinteracting in detector: BG for $\tau \to h$, $\tau \to 3h$
- Muons from ν_μ CC scattering in detector: BG for $\tau \to \mu$
- Charmed hadrons, produced in ν_μ DIS on nucleus, have similar mass, life time and decay modes as τ:
  BG for all channels.

  Background level is estimated with MC simulation, but for each background source we need a cross-check.

Background studies: charmed mesons





- Bad background — contributes to all tau decay channels.
- Rejection if primary muon was observed.
- Rejection if daughter muon charge reconstructed as positive.
- Since charmed meson is produced inside hadronic jet,
  its direction (ϕ angle) in transverse plane will not be very different from average direction of other hadrons → rejection ϕ>90 deg..

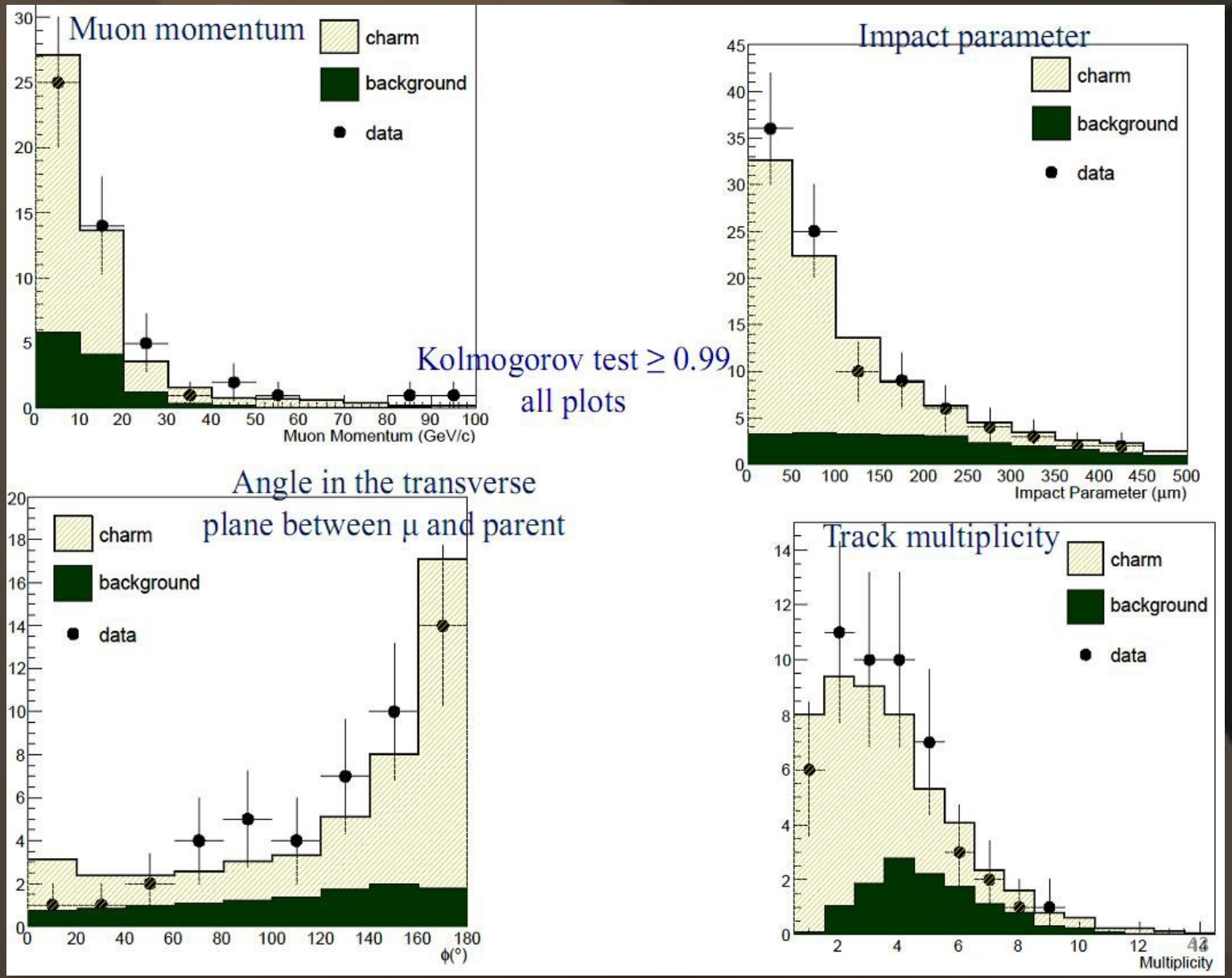
Background studies: charm sample data vs. MC

Using rejected (i.e. identified as charm decay) sample, we can check our Decay Search procedure.

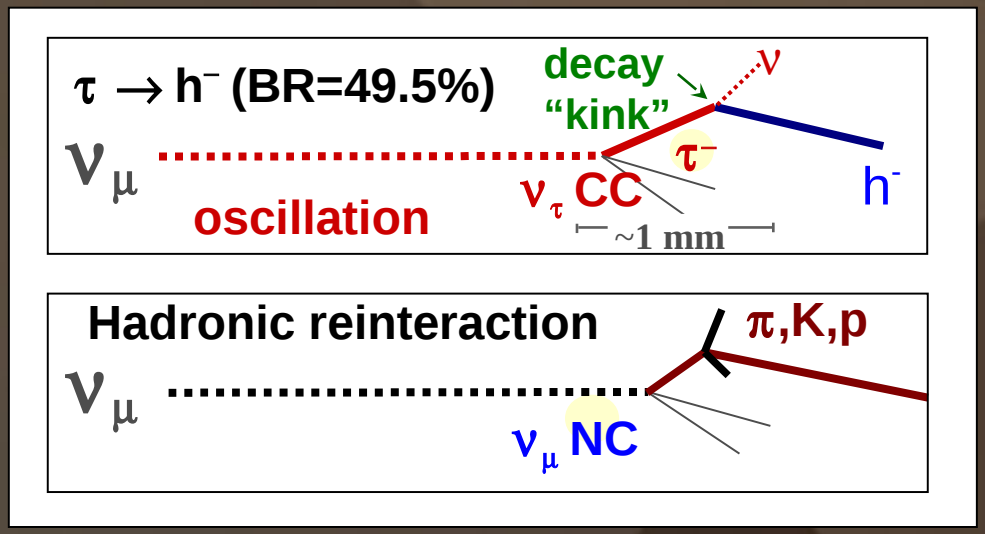
	charm	**background**	**expected**	**data**
1 prong	20 ± 3	9 ± 3	29 ± 4	19
2 prong	15 ± 2	3.8 ± 1.1	19 ± 2	22
3 prong	5 ± 1	1.0 ± 0.3	6 ± 1	5
4 prong	0.8 ± 0.2		0.8 ± 0.2	4
Total	**41 ± 4**	**14 ± 3**	**55 ± 5**	**50**

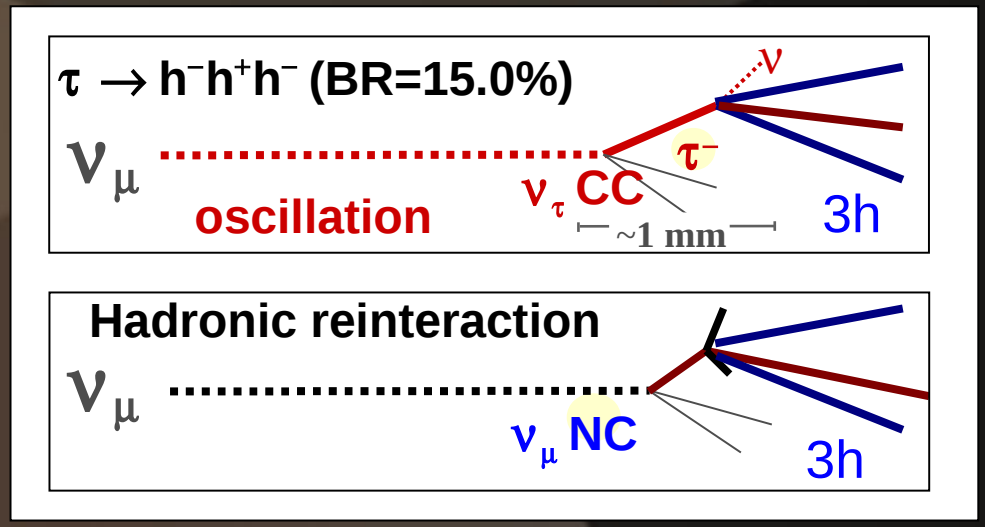
Background mostly comes from hadronic interactions.

Background studies: charm sample data vs. MC



Background studies: hadronic interasctions





- Rejection by topology (1 or 3 prongs, 1 prong Kink>20 mrad)
- Rejection by kinematics for 1-prong (P_d> 2 GeV/c, P_T>600 MeV/c or P_T>300 MeV/c if EM shower found)
- Rejection if backscattering track or heavy nuclear fragment is observed in «decay» vertex.

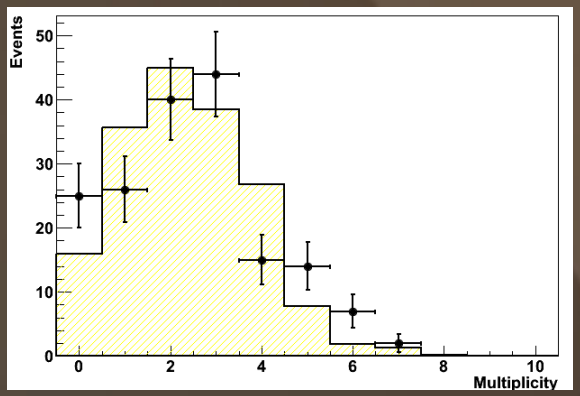
Hadronic interactions: MC validation

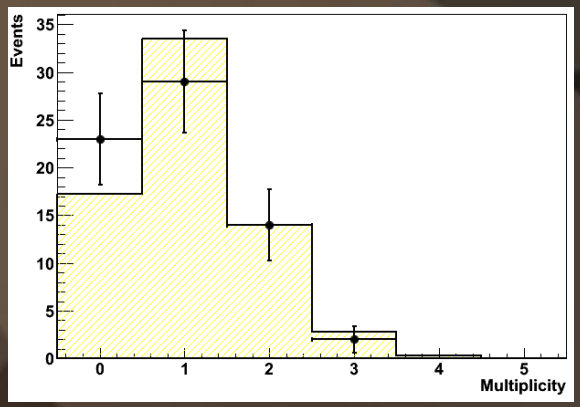
- Probability for hadronic reinteraction to pass there rejection criteria was estimated using FLUKA MC.
- To validate hadronic interactions model in MC, a dedicated experiment was carried out: ECC brick was exposed to charged pion beams of different energies.
- Volume scan and reconstruction were performed to obtain pion interaction vertices. Large statistics was analyzed.
- Comparison of parameters, which are crutial for background rejection: event topology, heavy fragments emission.
- Evaluate systematic error.

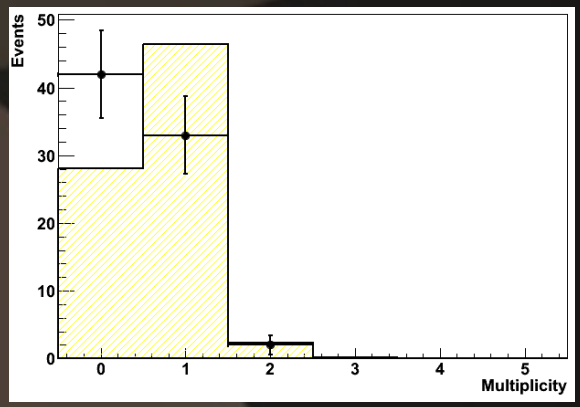
Hadronic interactions: beamtest comparison

10 GeV/c **4 GeV/c** **2 GeV/c**

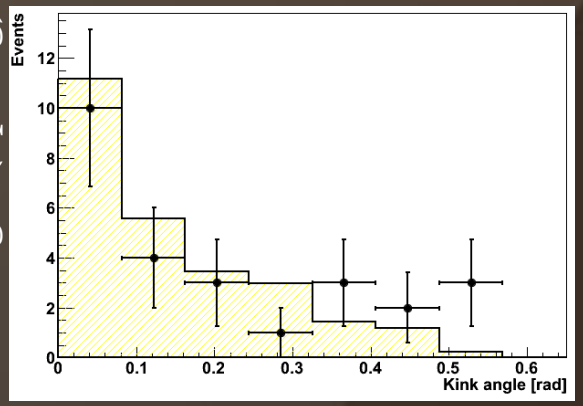
Multiplicity

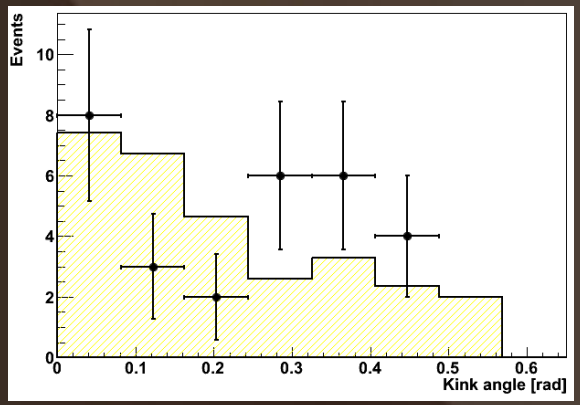


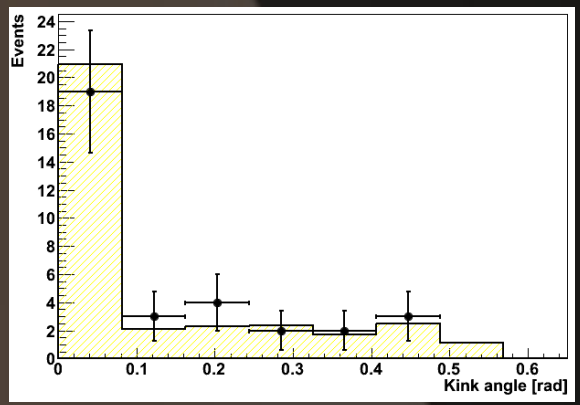




Kink angle (1prong)





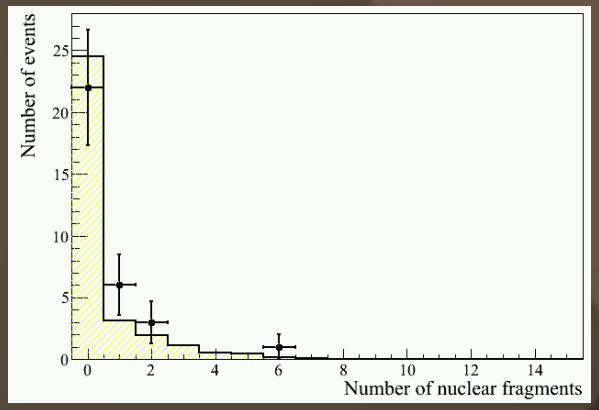


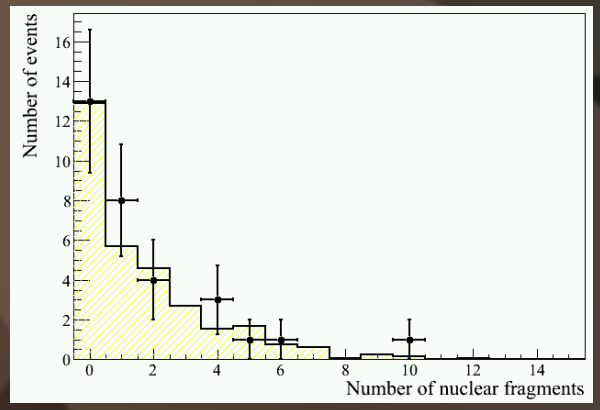
Comparison of topological variables.
Agreement both in interaction rate and in shape within 30% systematic error.

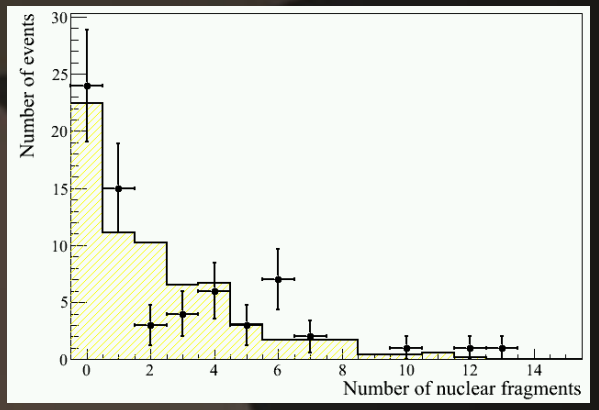
Hadronic interactions: beamtest comparison

10 GeV/c **4 GeV/c** **2 GeV/c**

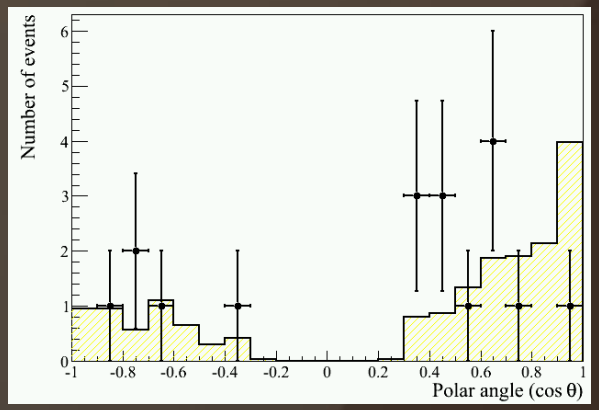
Multiplicity

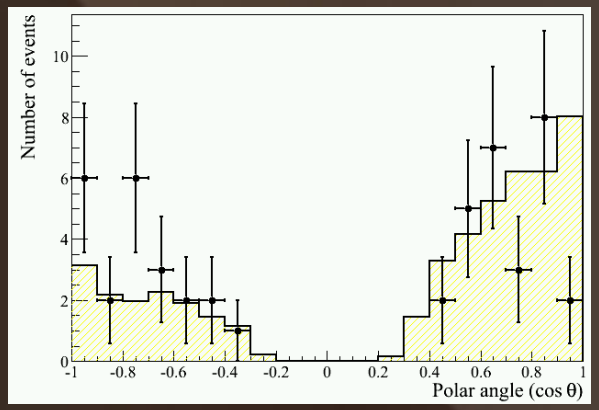


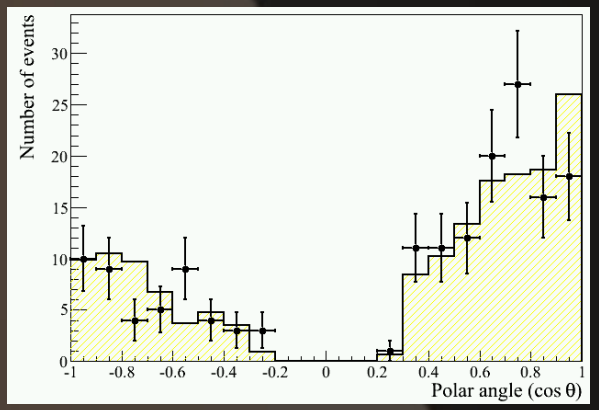




Emission angle

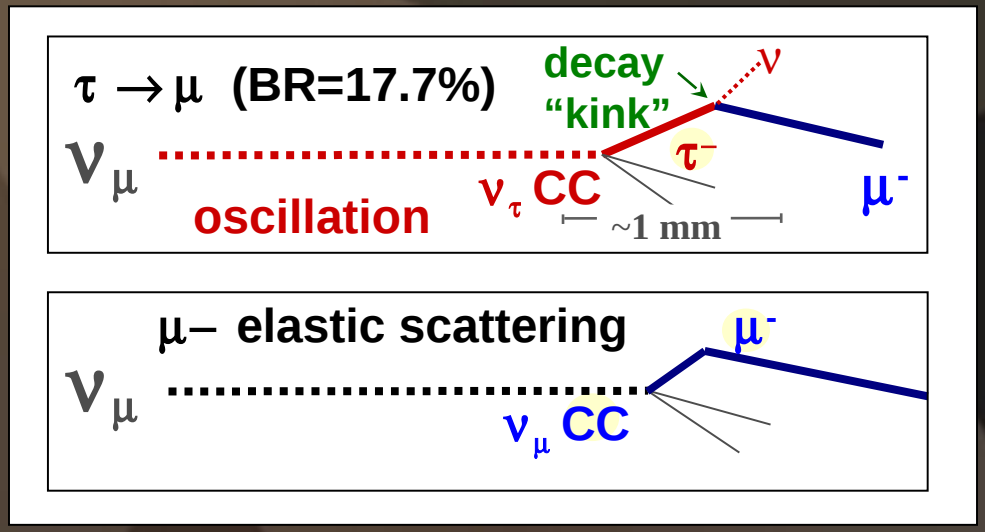






Comparison of heavy fragments emission.
Agreement both in interaction rate and in shape within 10% systematic error

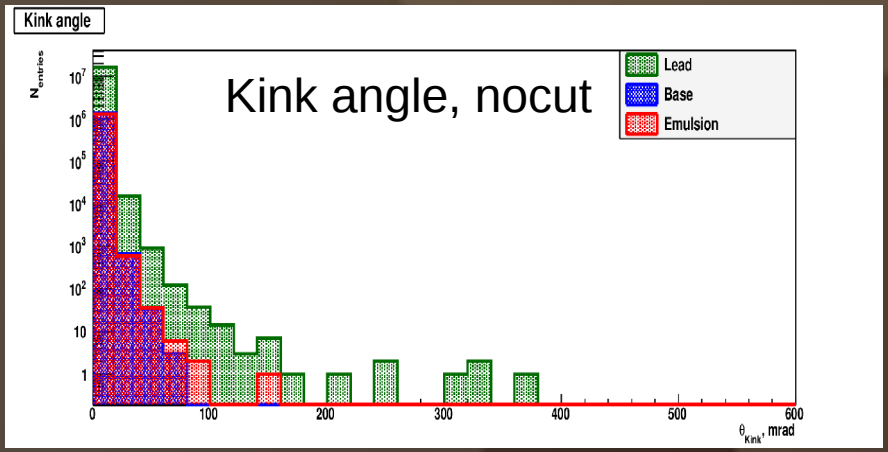
Large angle muon scattering

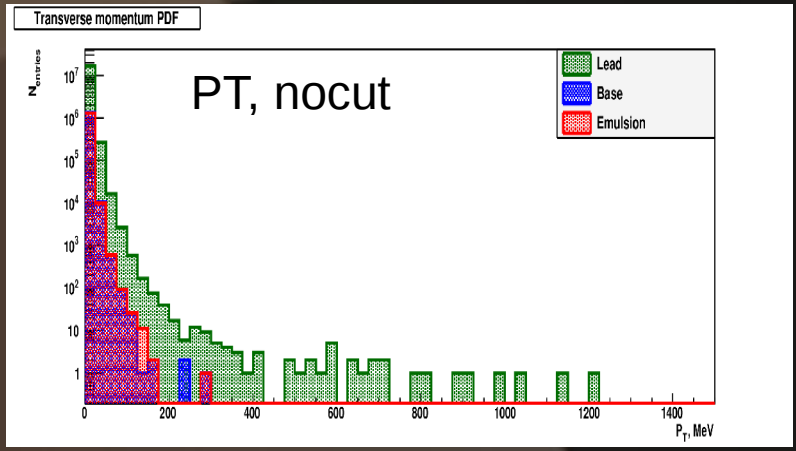


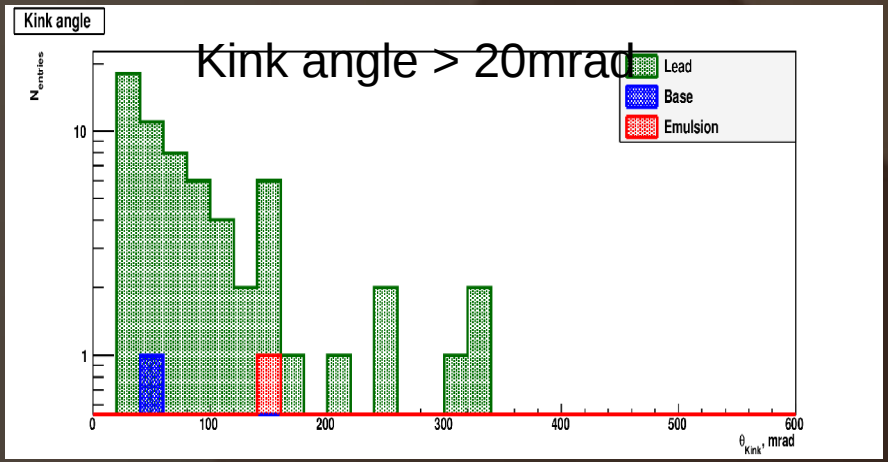
- Evaluate probability for a muon of given energy to produce a kink.
- No meaurements available except for upper limit of 10^{-5} : S.A. Akimenko et al., NIM A423 (1986)
- Muon scattering study was performed with both with FLUKA and Geant 4 MC.
- Result is strongly dependent on nuclear Form Factors and scattering parameters in MC.

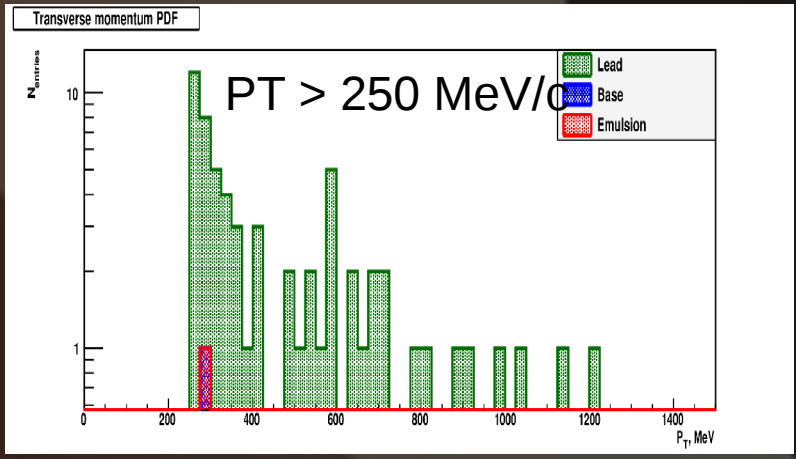
Large angle muon scattering

- 4x10 ^{8} muons with 1<E<15 GeV simulated.
- Kink probability for each layer was plotted









- Study is not finished, reliable MC simulation needed. Using conservative limit from measurements.

$\nu_\mu \rightarrow \nu_\tau$ analysis results: expected and observed events

- These are expectations for full mixing and $\Delta m^2_{12} = 2.3 \times 10^{-5}$ eV^2
- Selection efficiency estimated with MC and normalized to currently processed data sample.

Decay mode	Signal	Background	Charm	μ scattering	Hadr int
τ → h	0.66	0.045	0.029		0.016
τ → 3h	0.61	0.090	0.087		0.003
τ → m	0.56	0.026	0.0084	0.018	
τ → e	0.49	0.065	0.065		
Total	**2.32**	**0.226**	**0.19**	**0.018**	**0.019**

- Observed in data: 3 events = 1 τ →h + 1 τ →3h + 1 τ →μ
- This corresponds to 3.2σ significance vs background hypothesis.

Conclusions

- OPERA experiment performs event-by-event analysis of neutrino interactions.
- CNGS run is finished, data is being analyzed.
- Background evaluation for different τ decay channels was done using MC.
- Several experimental cross-checks with MC show good agreement.
- So far 3 tau neutrino interactions were selected, $\nu_\mu \rightarrow \nu_\tau$ oscillations confirmed with significance $>3\sigma$.