The OPERA Experiment and Recent Results

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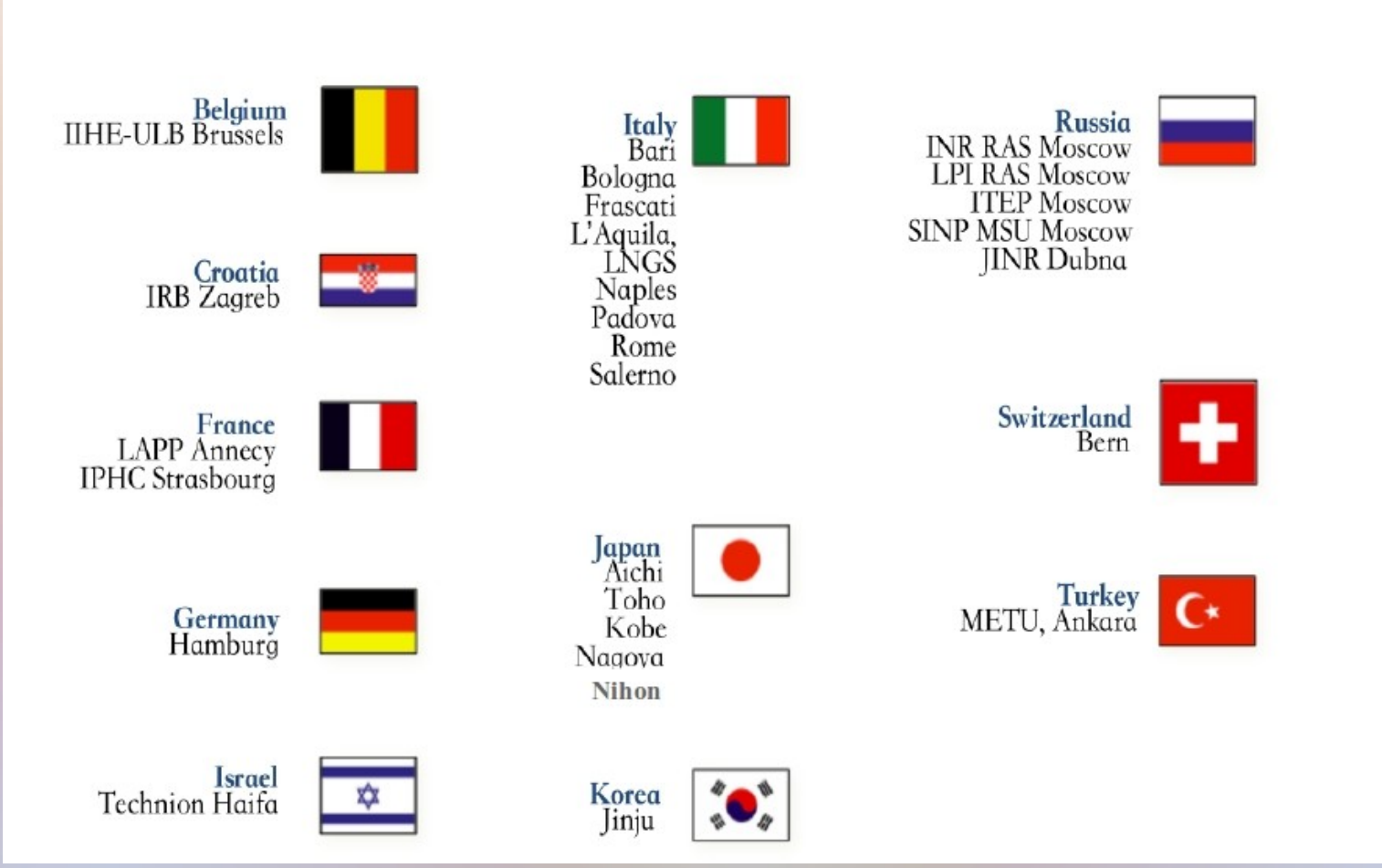
on behalf of the OPERA Collaboration

International Conference on New Frontiers in Physics
28 August - 5 September 2013
Kolymbari, Crete, Greece

The OPERA Collaboration

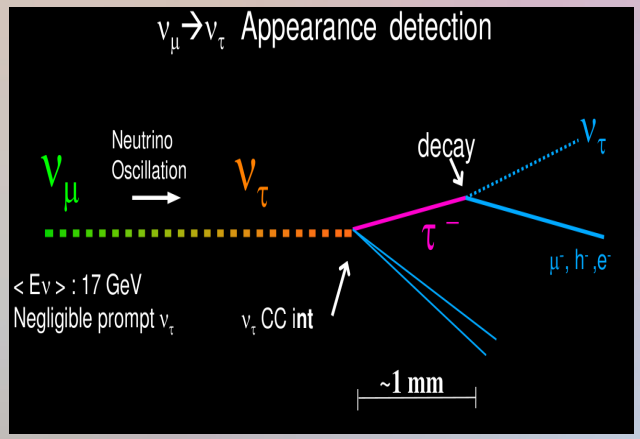
140 physicists, 28 institutions from 11 countries



http://operaweb.lngs.infn.it/

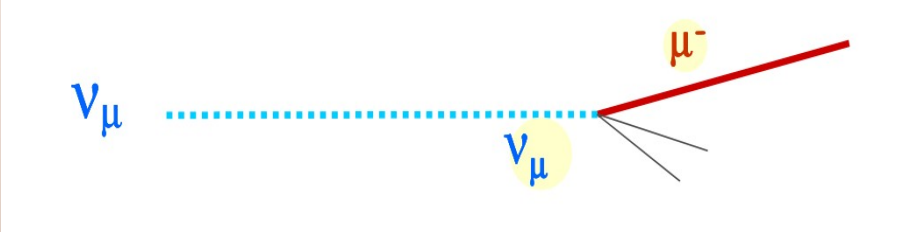
The OPERA Experiment
(Oscillation Project with Emulsion tRacking Apparatus)

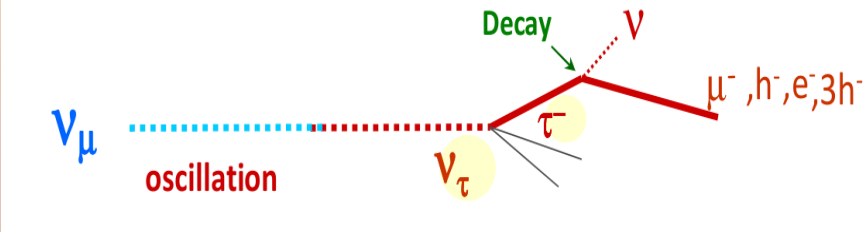
- Long baseline neutrino oscillation experiment in CNGS(CERN Neutrinos to Gran Sasso) ν_μ beam.
- Physical goals:
  - Aiming at to first direct detection of neutrino oscillation in appearance mode in $\nu_\mu \rightarrow \nu_\tau$ oscillation.
  - Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillation.
- Method : Direct observation of ν_τ events in nuclear emulsion detectors



ν_τ Detection Principle

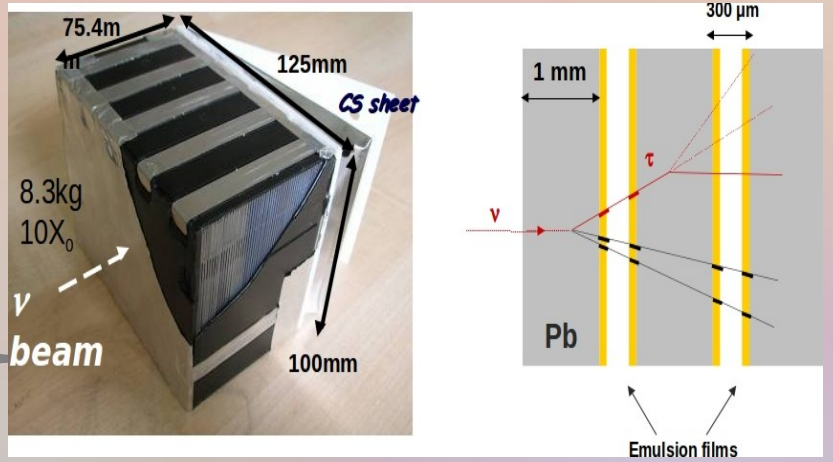
- Event by event separation of ν_τ CC interactions from dominant ν_μ interactions by direct observation of tau lepton.





Requirements

- Conventional ν_μ beam optimized for ν_τ appearance
- Large target mass to compensate for small neutrino interaction cross section
- Micro metric resolution to observe tau decay kink
  → nuclear emulsions
- High muon identification efficiency to reduce charm background
  → electronic detectors

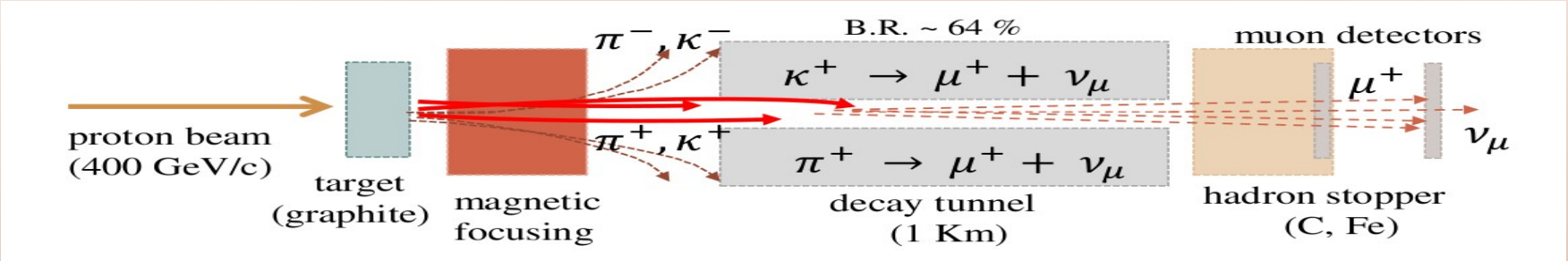


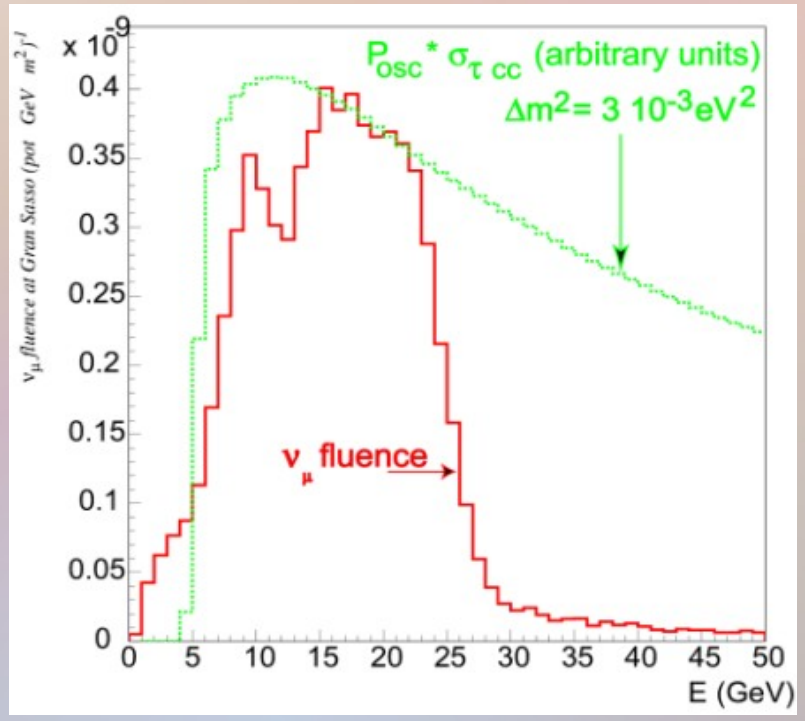
ECC (Emulsion Cloud Chamber)

- 57 layers of nuclear emulsion interleaved with 56 layers of 1 mm thick lead.
- "stand alone" detector with a sub-micron resolution.

Neutrino Beam - CNGS

Neutrinos are produced by the 400 GeV/c CERN-SPS proton beam and sent to the Gran Sasso.

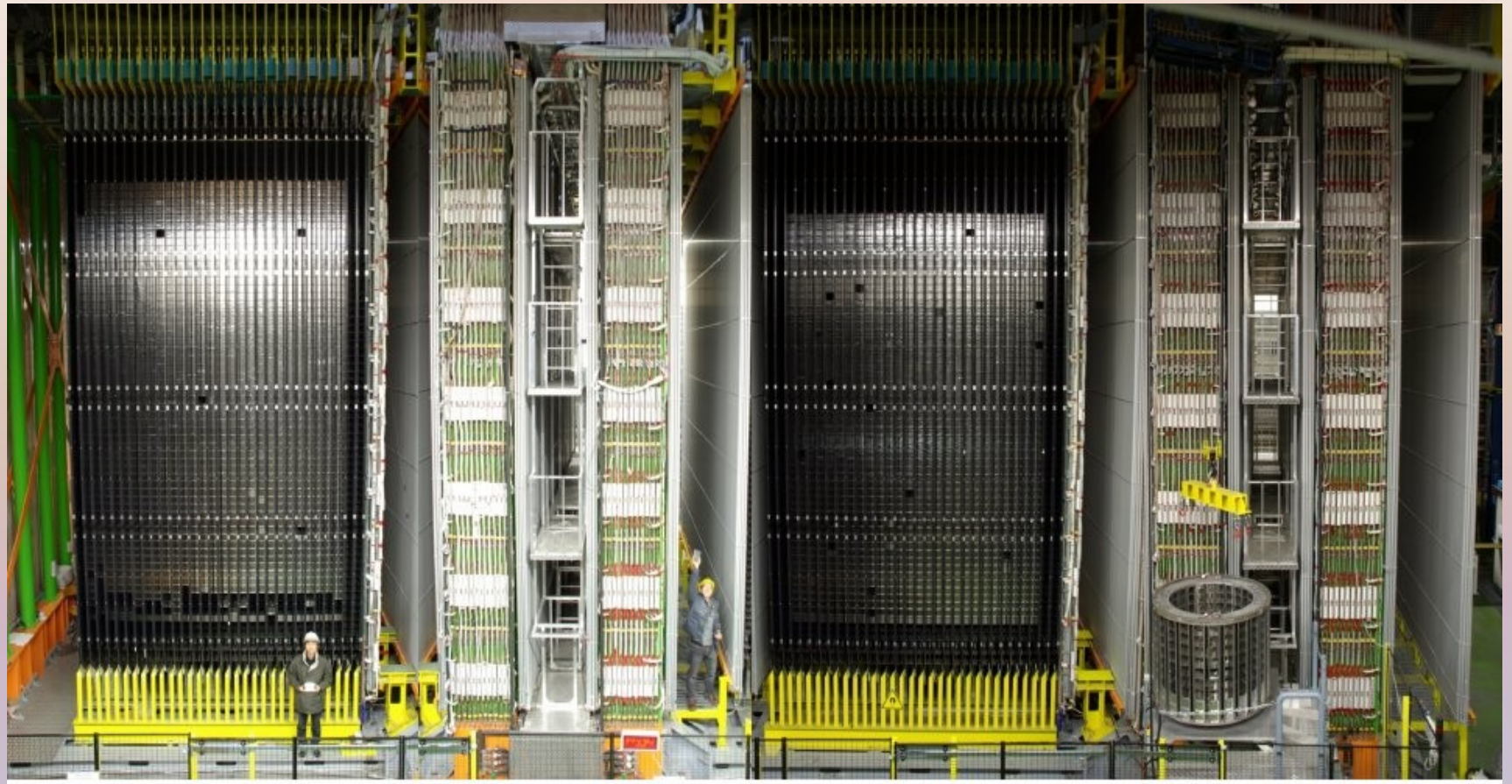




Beam parameters	
$<E_{\nu_\mu}>$	17 GeV
ν_e/ν_μ	0.8 %
$\overline{\nu_\mu}/\nu_\mu$	2.0 %
$\overline{\nu_e}/\nu_\mu$	0.05 %
ν_τ	negligible

The OPERA Detector

JINST 4, P0418 (2009)



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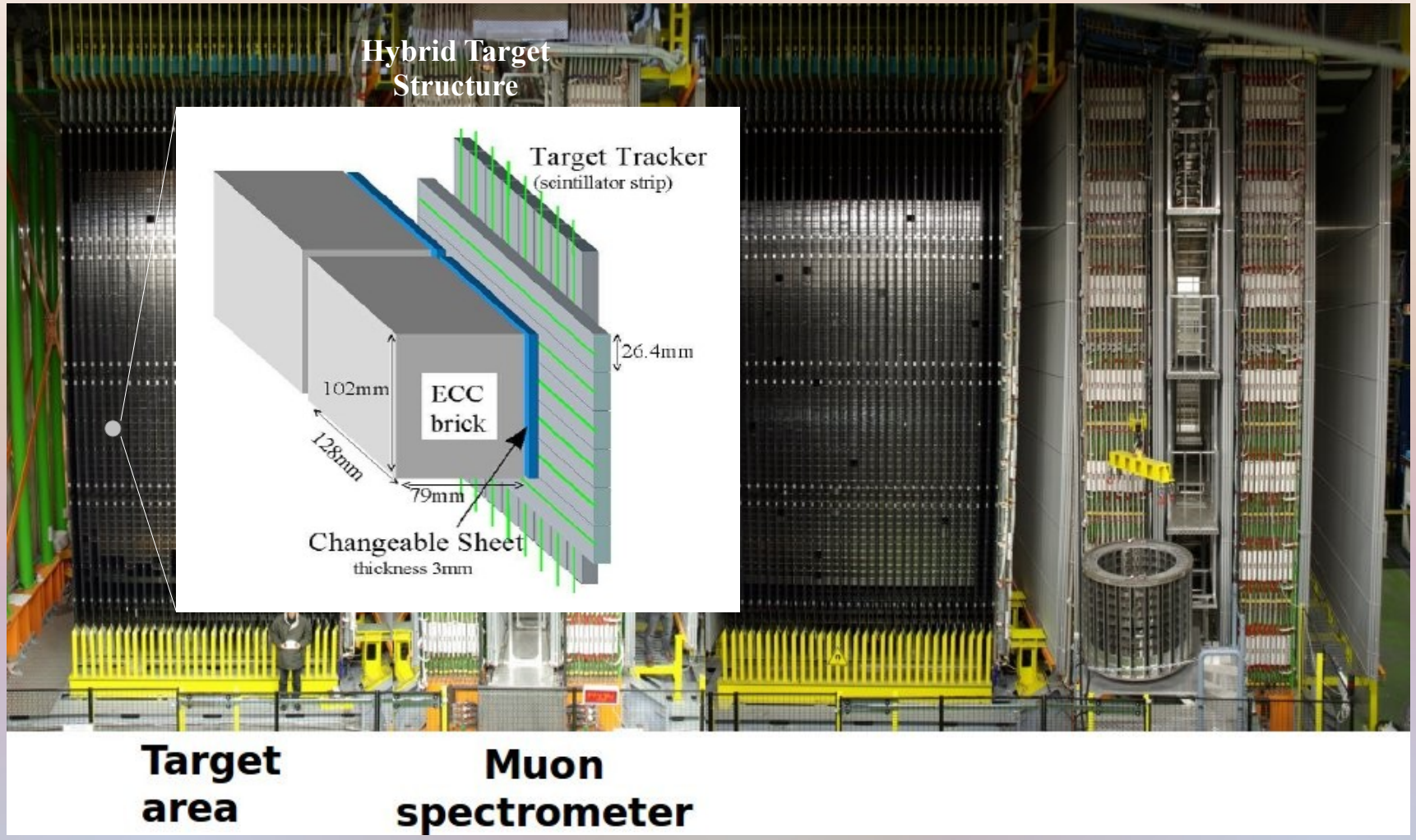

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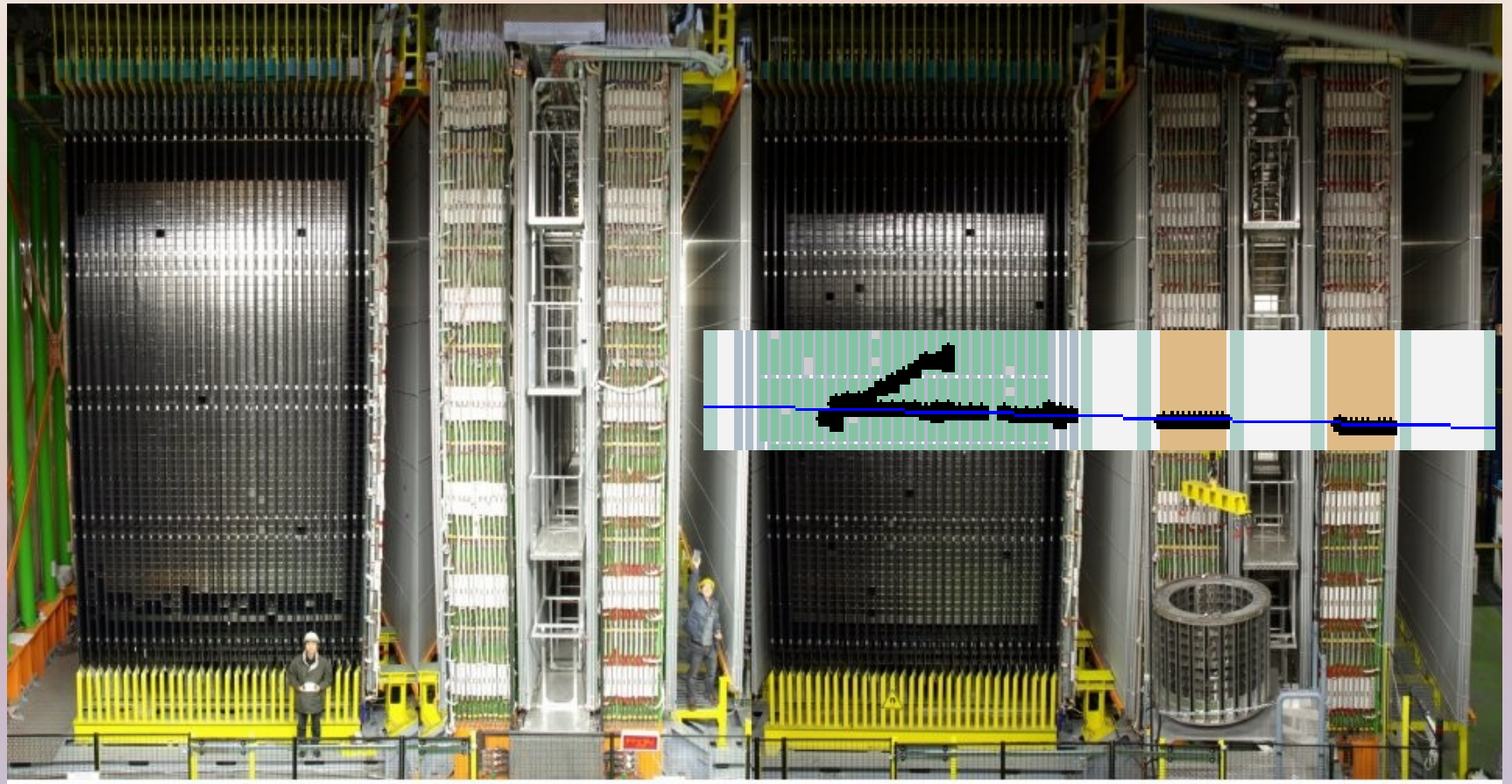

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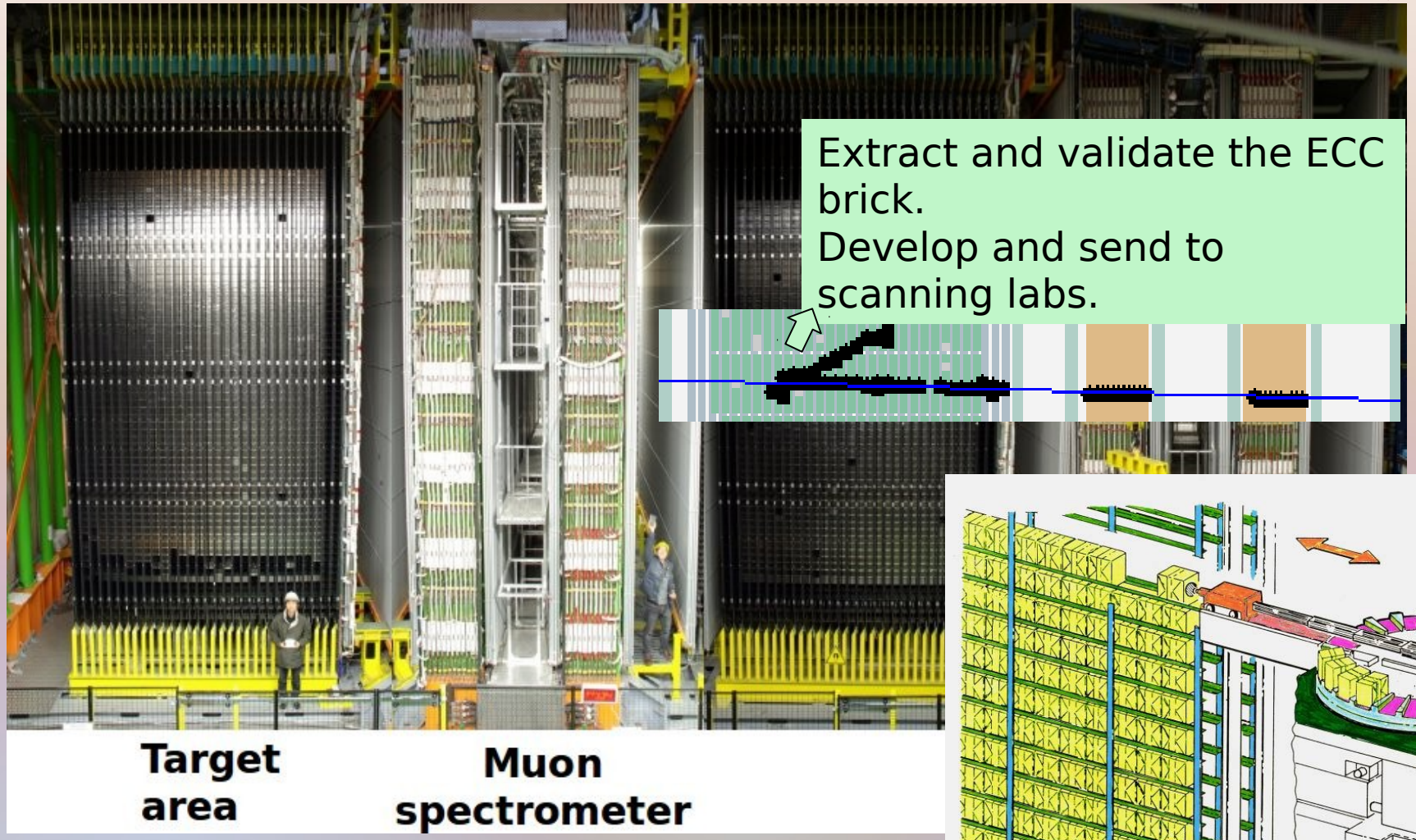


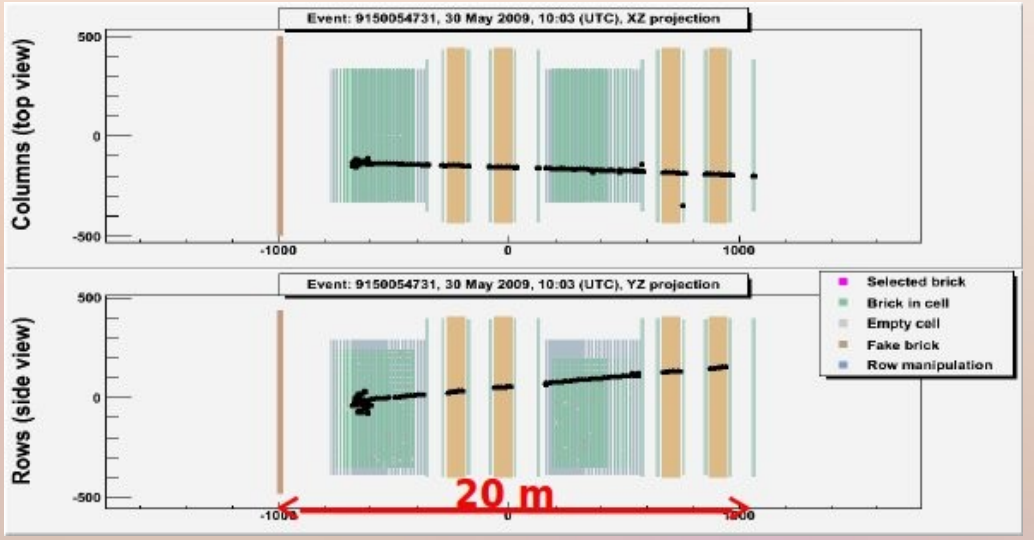
Neutrino Interactions In the Target

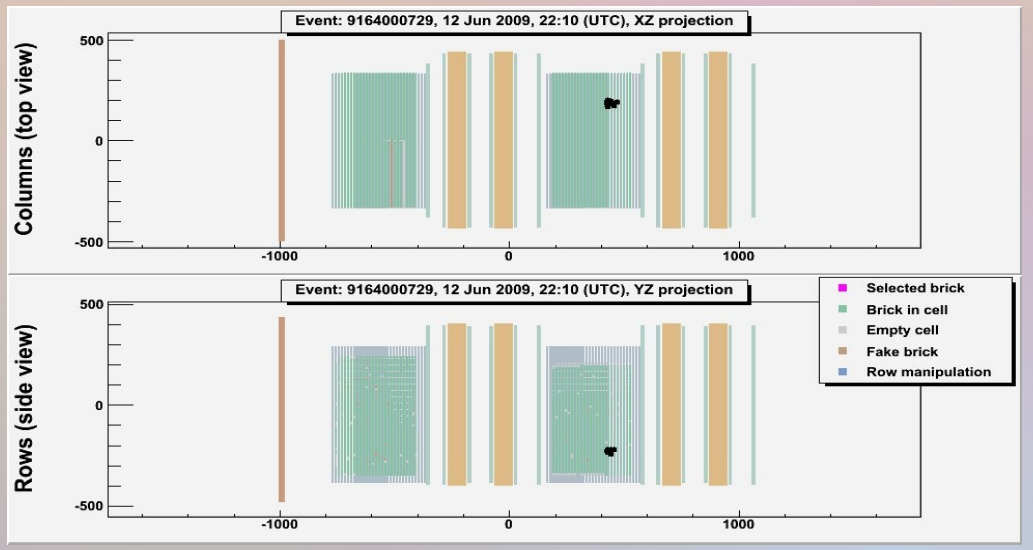
With μ:

* ν_μ CC
* ν_τ CC, $\tau \rightarrow \mu$ (17.4 %)

Without μ:

* ν NC
* ν_τ CC, $\tau \rightarrow$ e (17.8 %)
* ν_τ CC, $\tau \rightarrow$ h,3h (64.8 %)
* ν_e CC



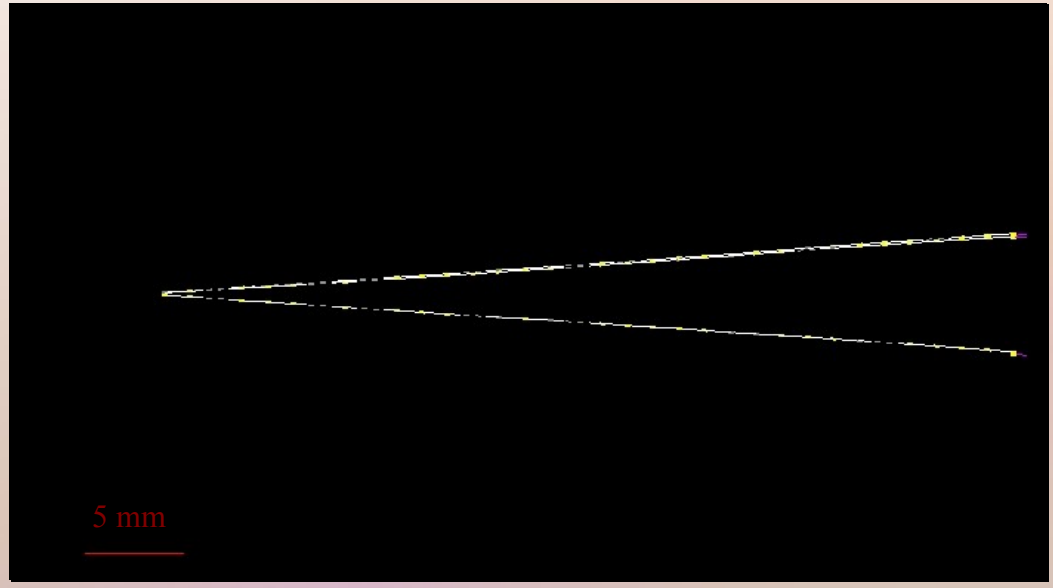


Neutrino Interaction Location in ECC

Step 1:

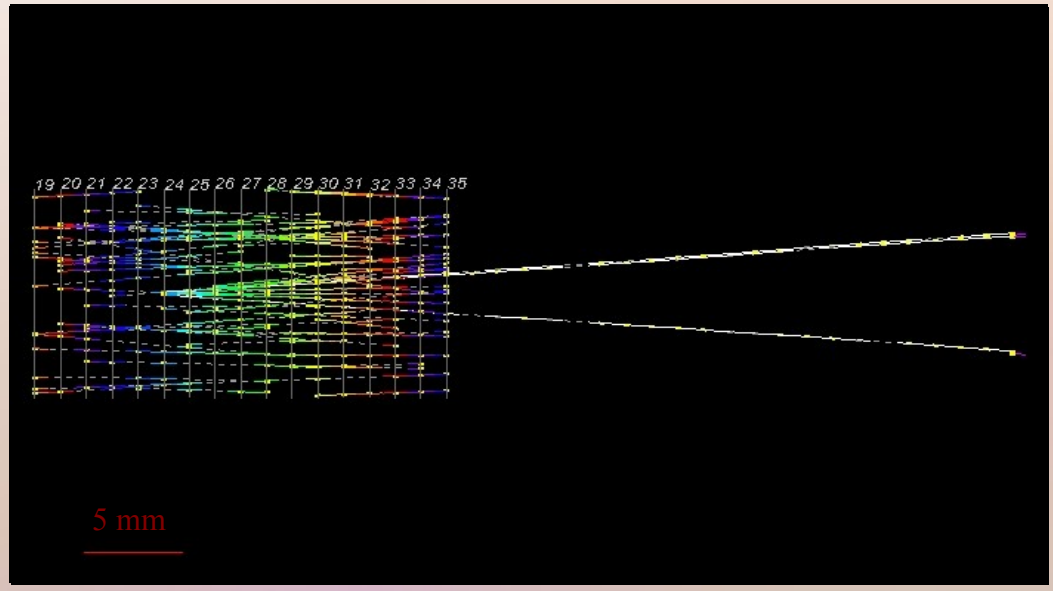
Changeable Sheet (CS) Scanning

Neutrino Interaction Location in ECC



Step 1:
Changeable Sheet (CS) Scanning
Step2:
CS - ECC connection, Scanback

Neutrino Interaction Location in ECC



Step 1:
Changeable Sheet (CS) Scanning
Step2:
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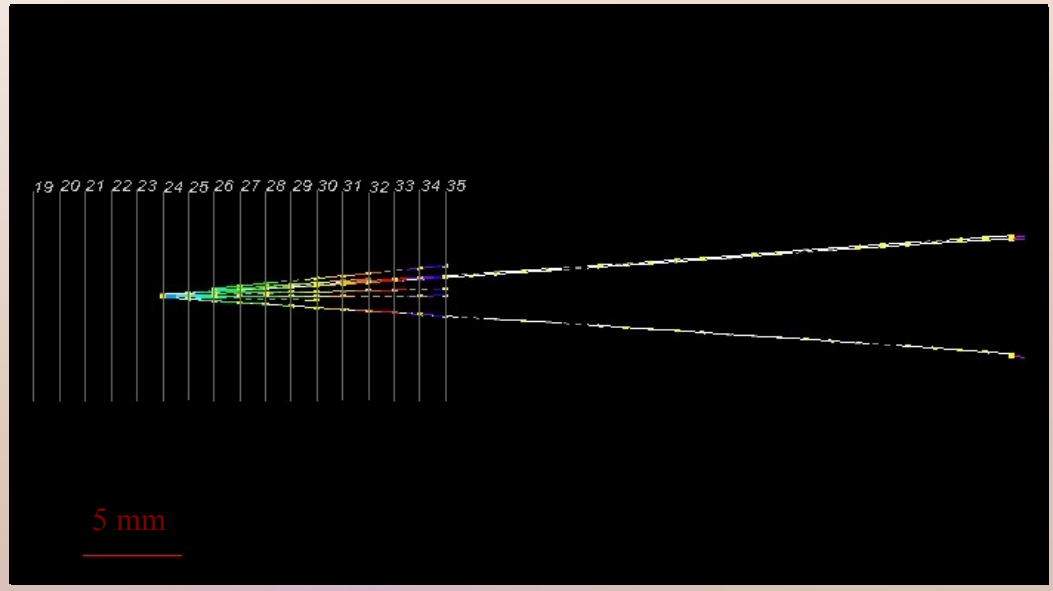
Step3:
Volume data taking

Neutrino Interaction Location in ECC



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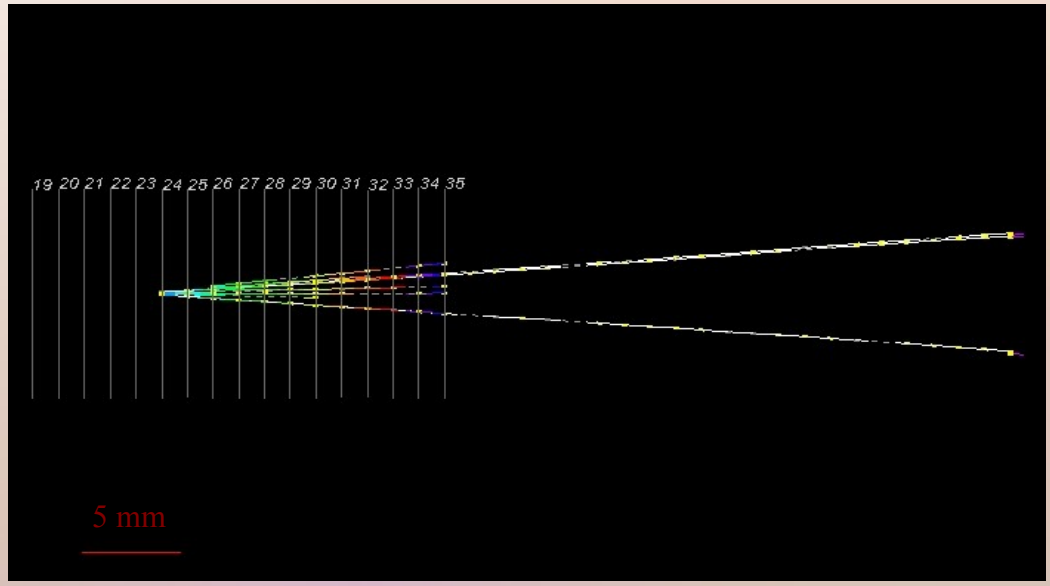
Step3:
Volume data taking

Step4:
Validation of neutrino interaction vertex

Neutrino Interaction Location in ECC

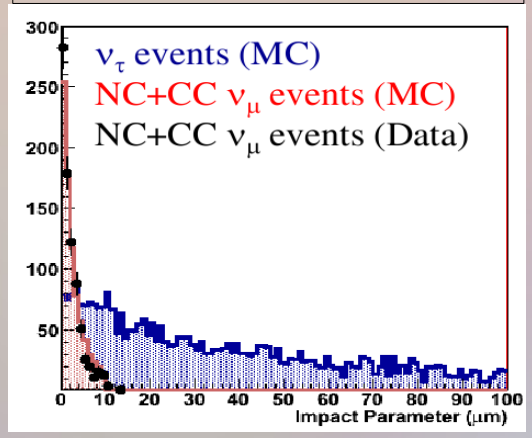


Step 1:
Changeable Sheet (CS) Scanning
Step2:
CS - ECC connection, Scanback
Step3:
Volume data taking
Step4:
Validation of neutrino interaction vertex
Step5:
Decay search for short lived particles

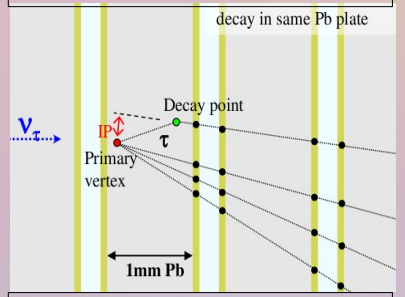
DECAY SEARCH

Tau decay topologies		
Kink	$\tau^- \rightarrow e^-$	**17.8 %**
	$\tau^- \rightarrow \mu^-$	**17.4 %**
	$\tau^- \rightarrow h^-$	**49.5 %**
Trident	$\tau^- \rightarrow h^- h^- h^+$	**15.2 %**

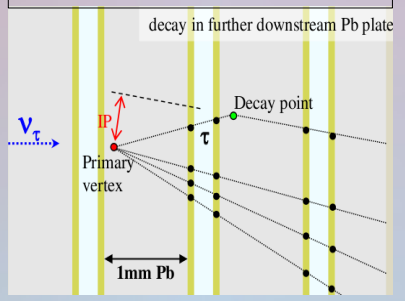
Impact Parameter Distribution



Short Decay of Tau

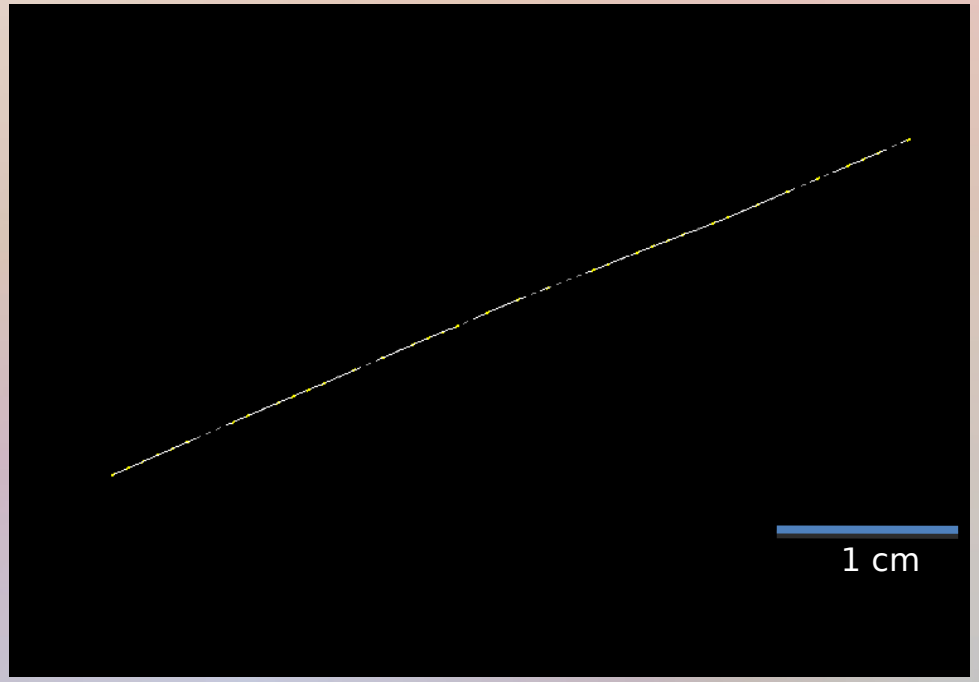


Long Decay of Tau



Momentum Reconstruction

- Scan forth (SF) is the last step of the OPERA analysis chain.
- SF provides "reconstructed momentum" .
- Crucial for kinematical parameter calculations.
- Uses Multiple Coulomb Scattering to calculate the momentum.(New J. Phys. 14 (2012) 013026)



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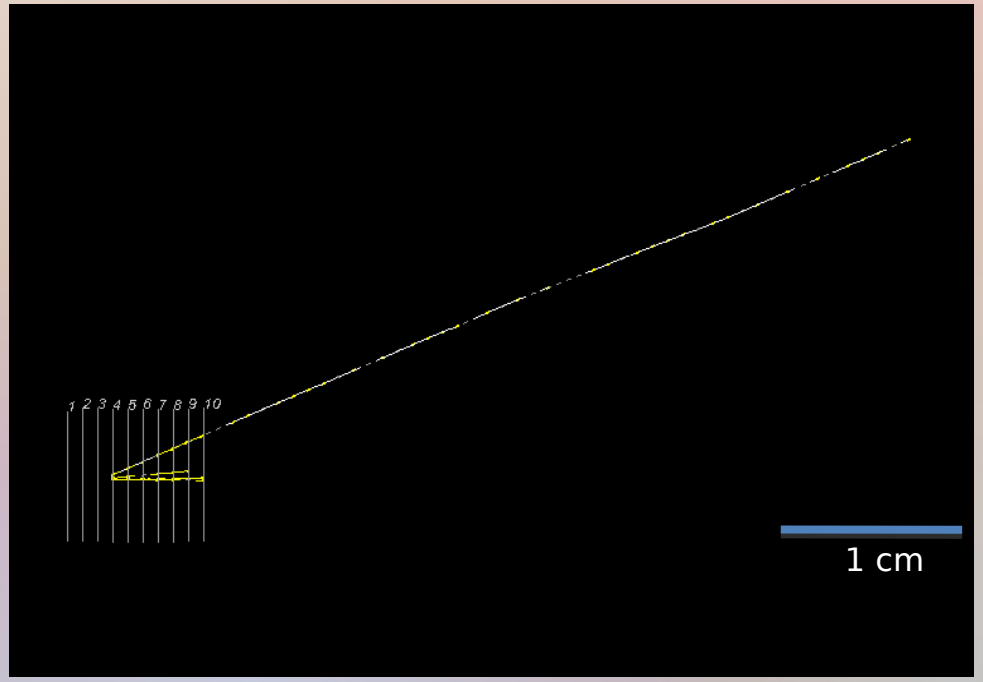

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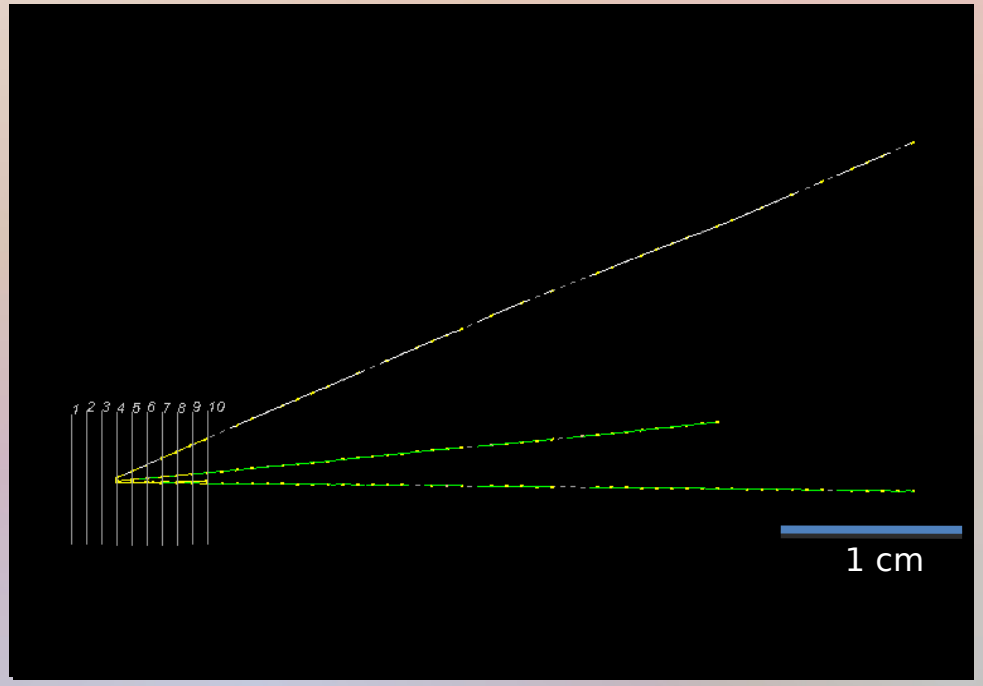

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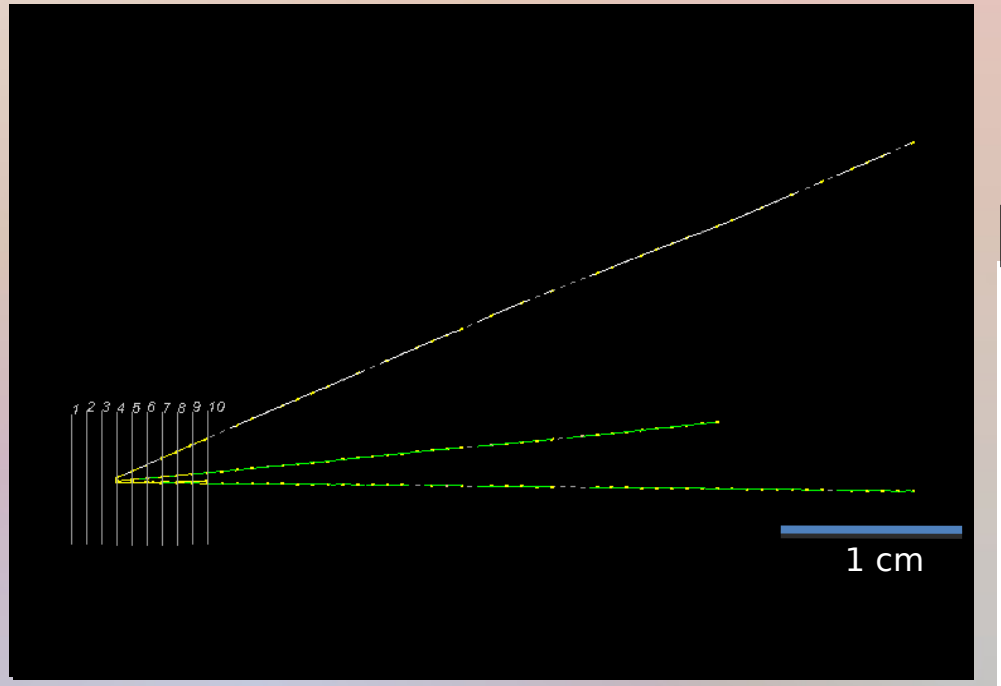
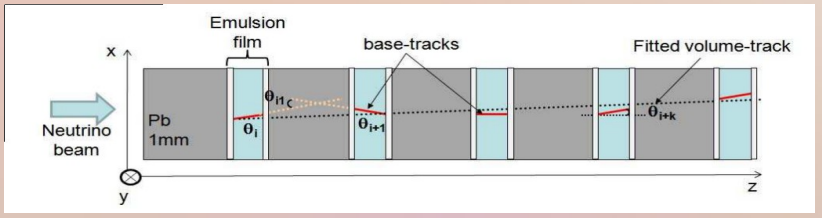
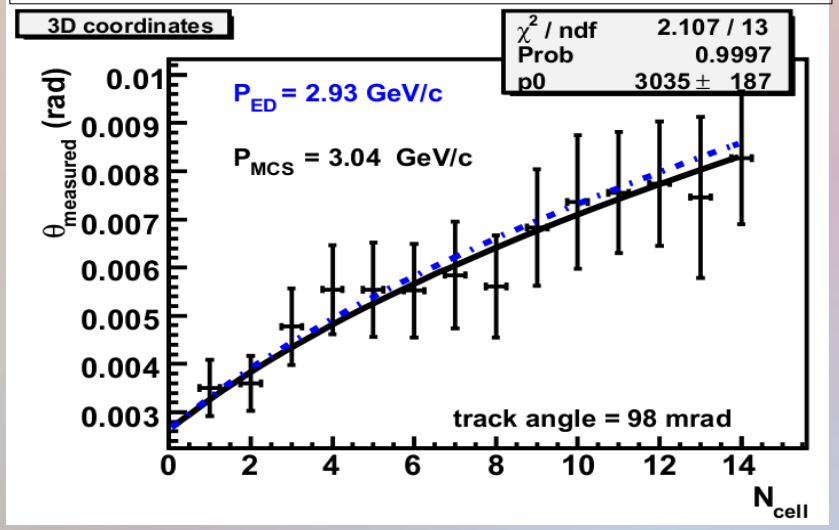




Scale and measured momentum

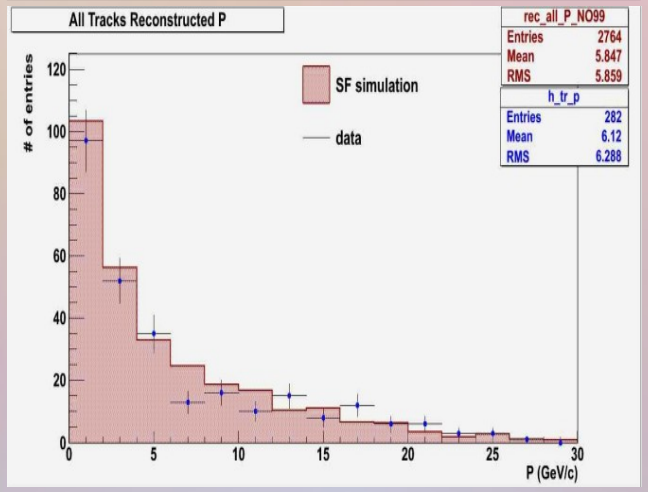


Event Kinematics

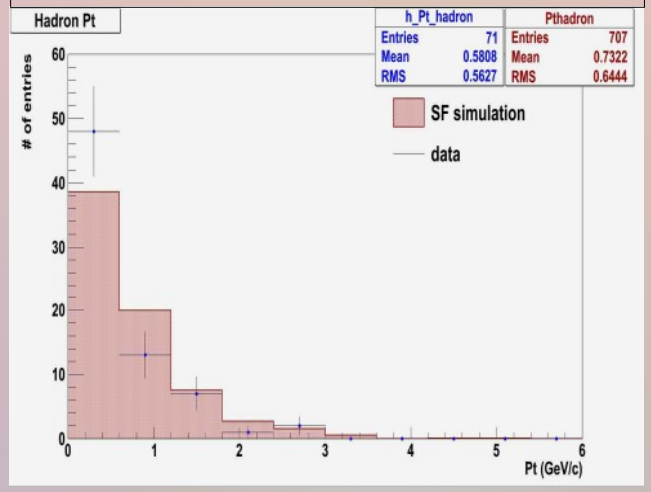
Preliminary

- Minimum bias sample has been created from OPERA CC events. Scan Forth applied to the selected events
  - Random sampling from 2008,2009,2010 data
- Scan forth simulation has been implemented in the OPERA simulation tool.
- Preliminary data / MC comparison performed

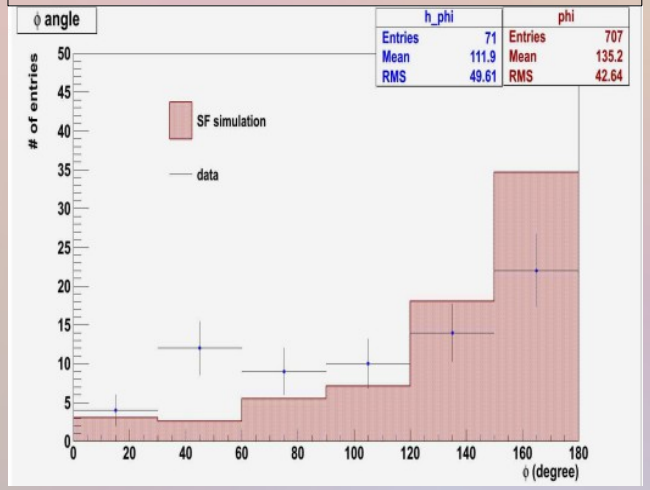
Reconstructed P for tracks

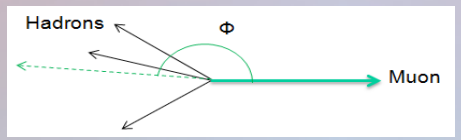


$P_{transverse}$ of hadrons



Φ angle

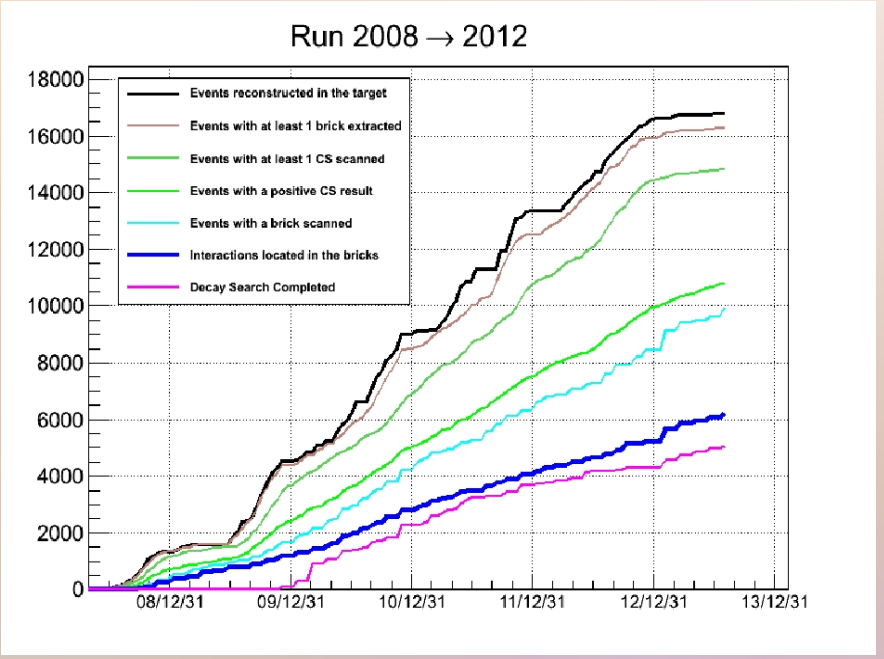




Phi angle = Slope between muon and hadron sector in the beam transverse plane.

Status of the Experiment

Year	Proton on Target (Effective POT 10^{19})	Number of neutrino interactions	Integrated POT/proposal value
2008	1.74	1698	7.7%
2009	3.53	3557	23.4%
2010	4.09	3912	41.6%
2011	4.75	4210	62.7%
2012	3.86	3680	79.9%
Total **17.97x10^{19}** effective POT → **80% of the nominal value (22.5x10^{19})**			

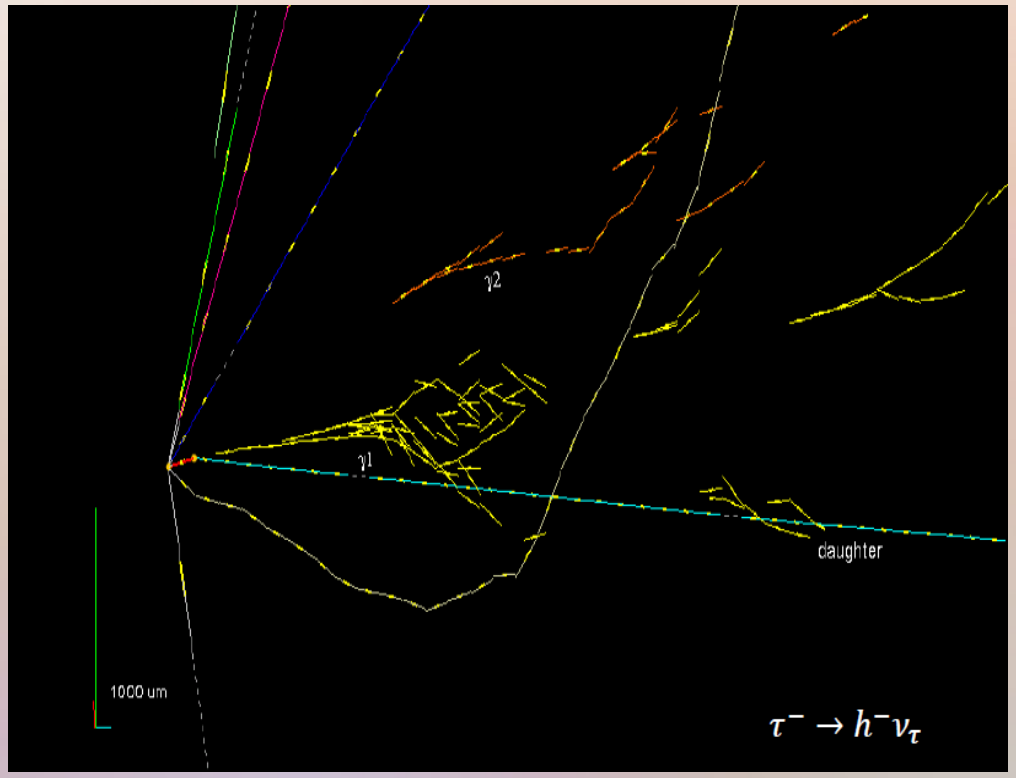


Located neutrino interactions	6211
Fully analyzed events	5036
ν_τ candidate events	**3**

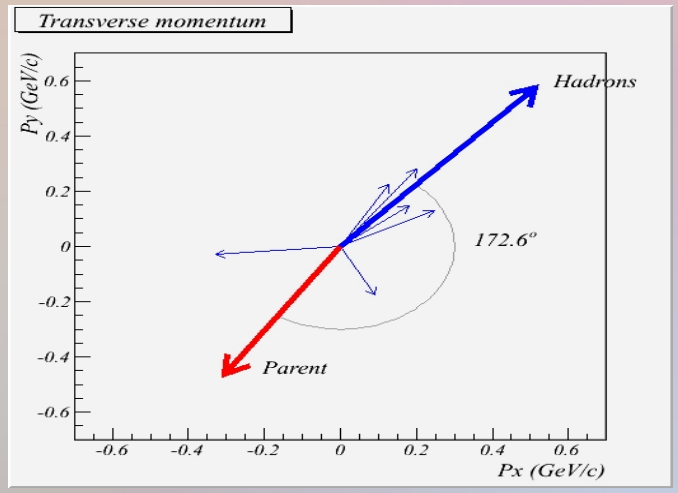
Analysis is Ongoing

The first ν_τ candidate event

Phys. Lett. B 691(2010)138



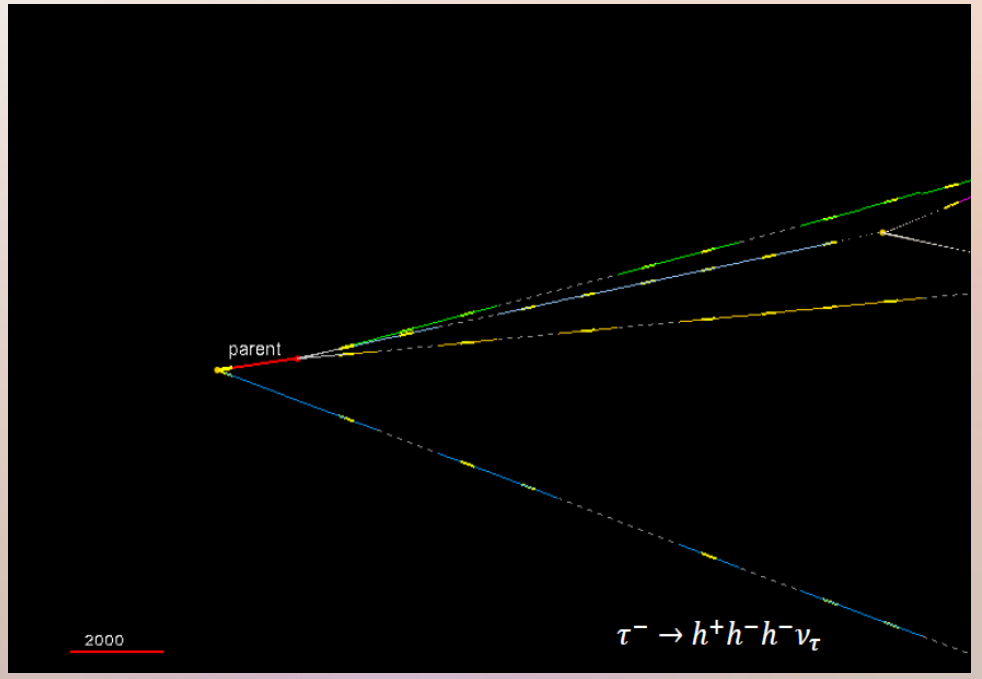
Event Kinematics		
VARIABLE	AVERAGE	Selection criteria
kink [mrad]	41 ± 2	>20
decay length [μm]	1335 ± 35	within 2 lead plates
P daughter [GeV/c]	12^{+6}_{-3}	>2
Pt [MeV/c]	470^{+230}_{-120}	>300 (γ attached)
missing Pt [MeV/c]	570^{+320}_{-170}	<1000
ϕ [deg]	173 ± 2	>90

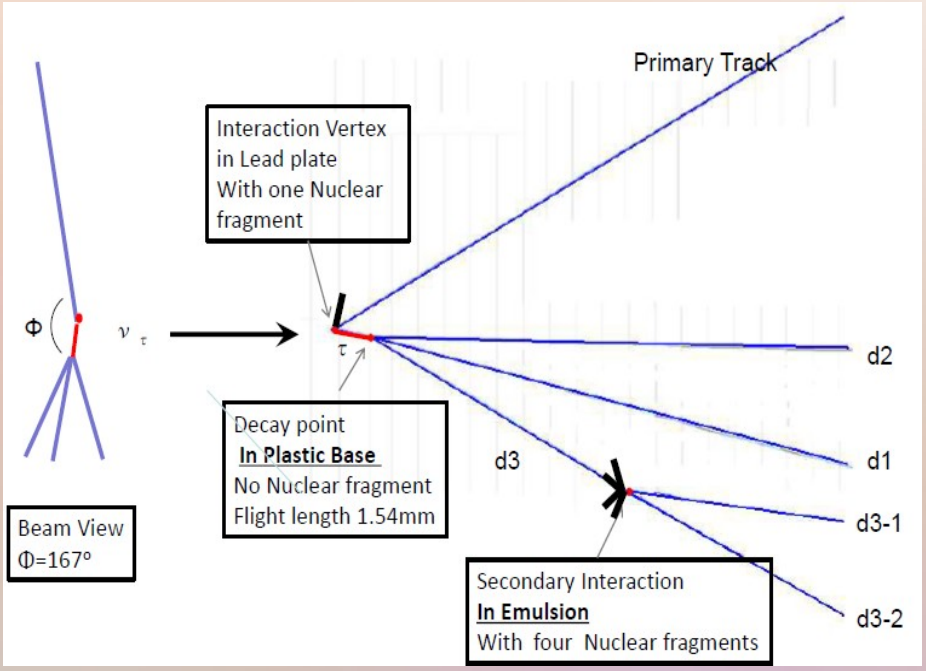


First direct detection of $\nu_\mu \rightarrow \nu_\tau$ oscillation in appearance mode.

The second ν_τ candidate

arXiv:1308.2553





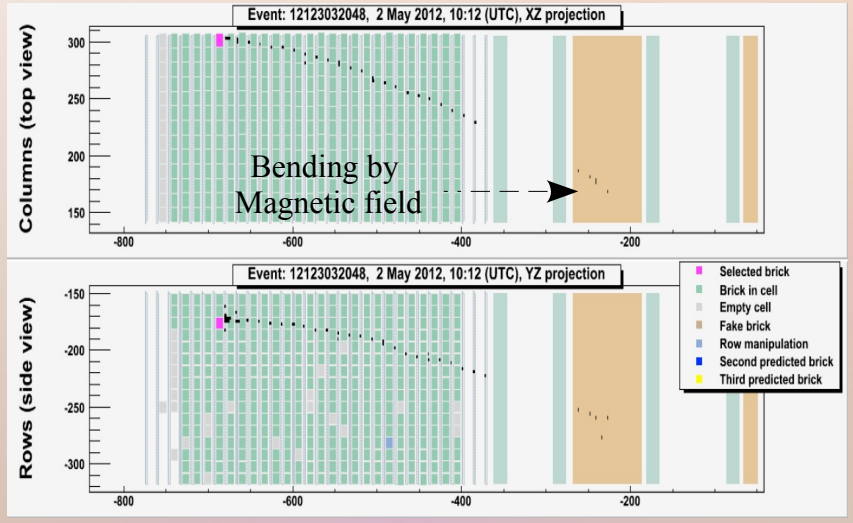
Event Kinematics

VARIABLE	AVERAGE	Selection criteria
kink [mrad]	87.4 ± 1.5	< 500
P at 2ry vtx [GeV/c]	8.4 ± 1.7	> 3.0
Pt at 1ry vtx [GeV/c]	0.31 ± 0.11	< 1.0
Min Invariant mass [GeV/c^2]	0.96 ± 0.13	0.5 < m < 2.0
Invariant mass [GeV/c^2]	0.8 ± 0.12	0.5 < m < 2.0
$\phi\,(\tau - hadron)$[deg]	167.8 ± 1.1	>90

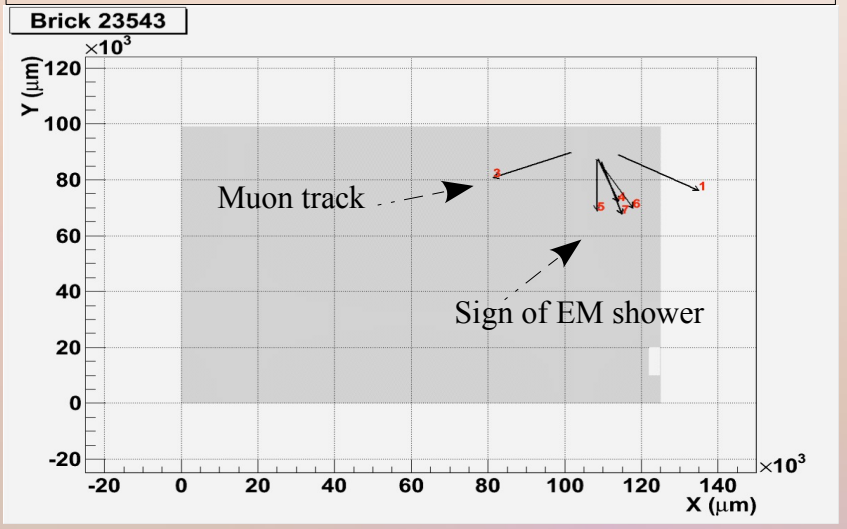
- No muon detected in the primary vertex. Other primary track has 2.8 GeV/c momentum and stops after 2 brick walls. Incompatible with muon hypothesis (26-44 brick walls).
- All tracks other than tau were identified as hadrons.

The third ν_τ candidate

Event in Electronic Detectors



Event in Interface Films (CS)

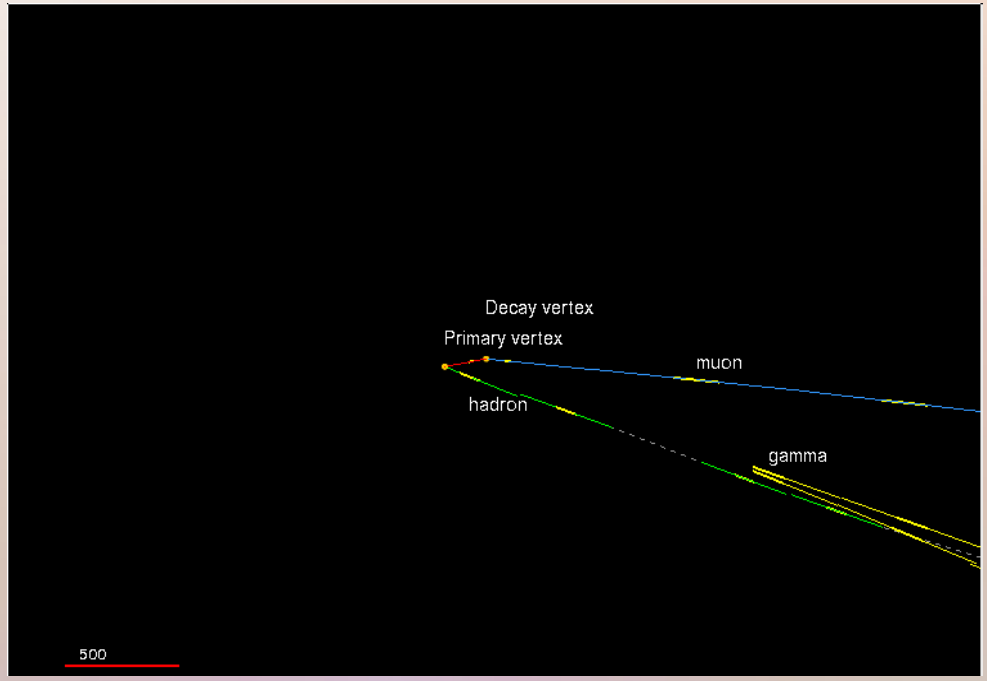


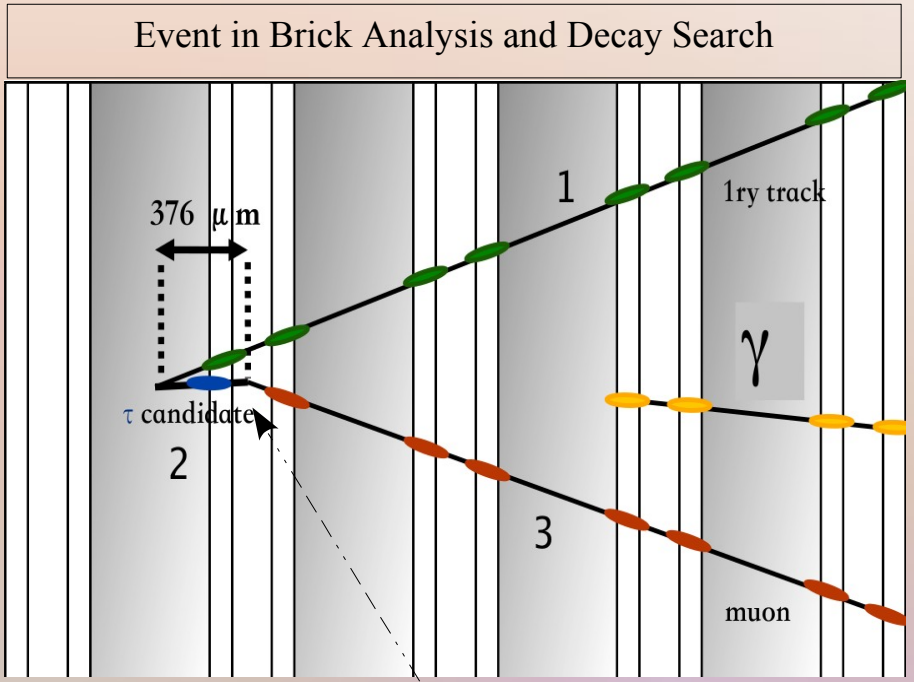
The first τ → μ candidate in the OPERA.

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

- Charge measurement based on TT and RPC. Negative charge with 5.6σ significance.

The third ν_τ candidate

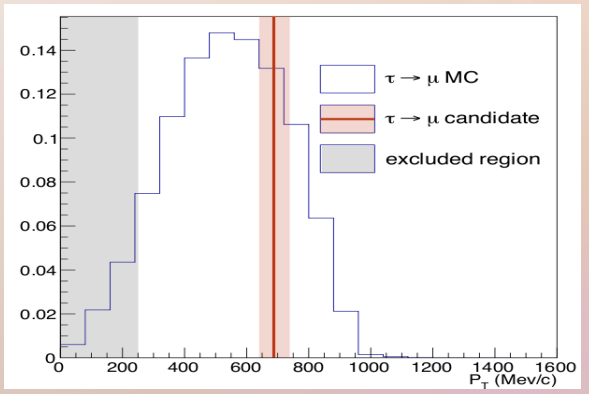




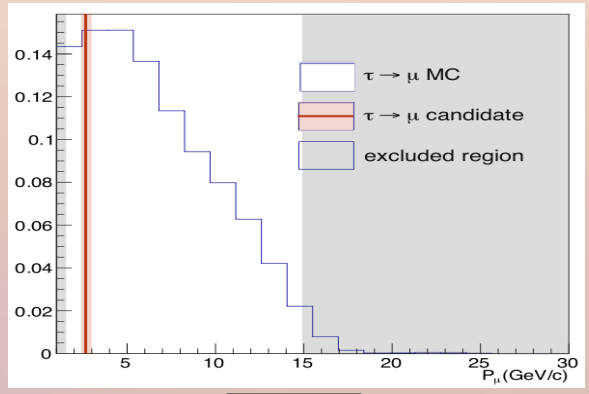
Charged track	Momentum (GeV/c)
Track 1	0.9 ± 0.2
Track 3	2.8 ± 0.2
Shower	Energy (GeV)
γ	2.9 ± 0.3

The third ν_τ candidate

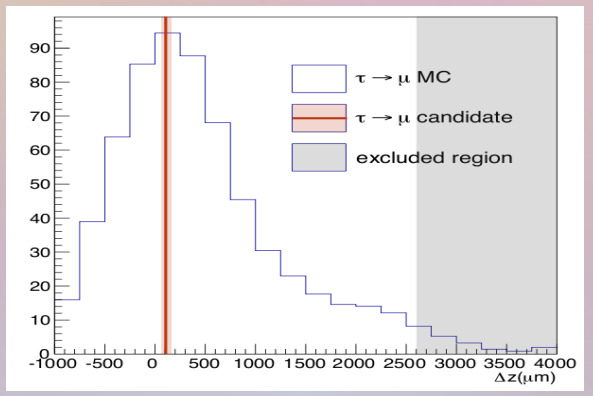
Event Kinamatics



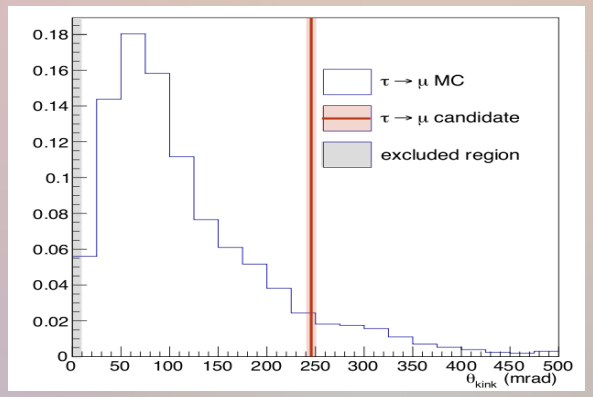
P_t



$P_{daughter}$



Δ_z



θ_{kink}

Variable	Selection ($\tau \to \mu$)	Measurement
θ_{kink}(mrad)	> 20	245 ± 5
Δz (μm)	< 2600	151 ± 10
P_μ (GeV/c)	$[1 - 15]$	2.8 ± 0.2
p_T (MeV/c)	> 250	690 ± 50

The event passed all the required kinematical cuts !!

Statistical Significance

Signal and background expectations for the analyzed sample

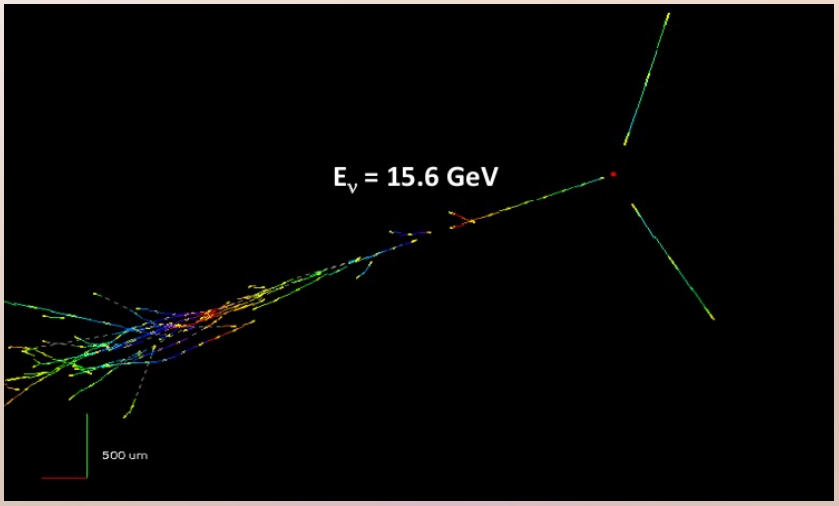
	Signal	Background	Charm	μ scattering	had int
τ→ h	0.66	0.045	0.029		0.016
τ → 3h	0.61	0.090	0.087		0.003
τ → μ	0.56	0.026	0.0084	0.018	
τ → e	0.49	0.065	0.065		
total	2.32	**0.226**	0.19	0.018	0.019

- 3 observed events in τ → h, τ → 3h, τ → μ channels.
- P value = 1.125×10^{-4}
- 3.2σ significance of non-null observation

$\nu_\mu \rightarrow \nu_e$ Analysis

Published at

JHEP 07(2013)004



* 19 events observed, compatible with background-only hypothesis expectation of 20±2.8(sys)

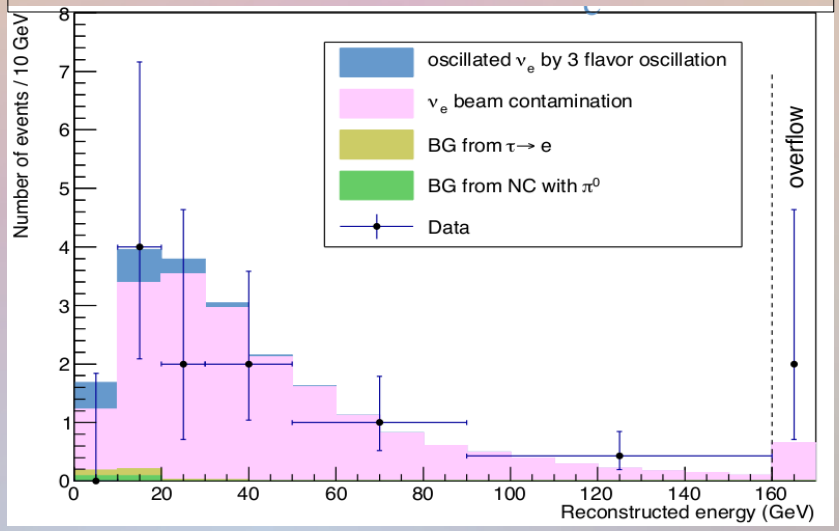
* Applying E<20 GeV to increase S/N ratio we observe 4 events with 5.7 events expectation. Gives an upper limit

$\sin^2(2\theta_{13}) < 0.44$ at 90% CL

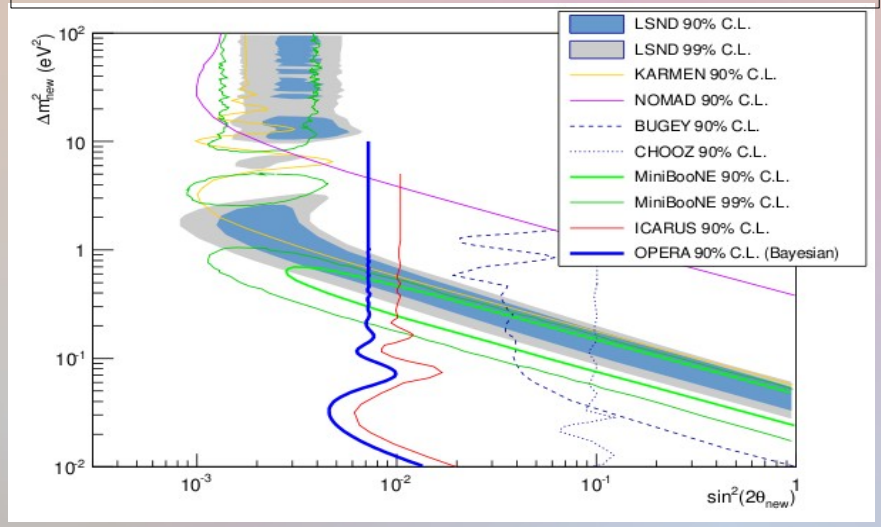
* Search at large Δm^2_{new} : We observed 6 events below 30 GeV with 9.4±1.3 expected events. This yields an upper limit of

7.2×10^{-3} at 90% CL on $\sin^2(2\theta_{new})$

Energy distribution for 19 ν_e candidates



Exclusion plot in the plane $\sin^2(2\theta_{new})$ – Δm^2_{new}



Conclusions

- OPERA successfully collected data from 2008 to 2012. Analysis is still going on.
- A total number of 17.97 x 10^{19} p.o.t integrated.
- $\nu_\mu \rightarrow \nu_\tau$ oscillation results:
  - **Evidence for $\nu_\mu \rightarrow \nu_\tau$ oscillation in the appearance mode.**
    - 3 events reported in the analyzed sample
    - 3.2σ significance with simple counting method
    - More sophisticated statistical analysis is under study
- $\nu_\mu \rightarrow \nu_e$ oscillation results:
  - Upper limit $\sin^2(2\theta_{13}) < 0.44$ at 90% CL
  - Upper limit of 7.2 x 10^{-3} at 90% CL on $\sin^2(2\theta_{new})$