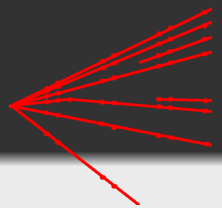


The OPERA Experiment

Observation of a First ν_τ Candidate Event in $\nu_\mu \rightarrow \nu_\tau$ Appearance Search

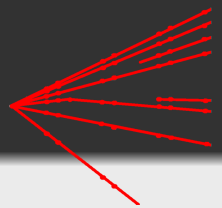
– Group Report –

Annika Hollnagel

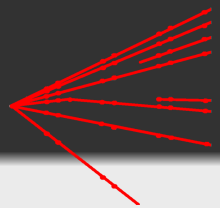
University of Hamburg
Institute for Experimental Physics

DPG Frühjahrstagung 2011, Karlsruhe

Bundesministerium für Bildung und Forschung



Overview



The OPERA Experiment

The OPERA Experiment

OPERA: Oscillation **P**roject with **E**mulsion T**r**acking **A**pperatus.

Goal: Appearance search

- Direct observation of $\nu_\mu \rightarrow \nu_\tau$ oscillations.

Concept:

- High-intensity long-baseline ν_μ-beam from CERN to LNGS.
- Detection of τ lepton production & decay.

Requirements:

- μm-**precision:** τ^- lepton decay after $\sim 600\,\mu\mathrm{m}$.
- **Large target mass:** Small ν interaction cross sections.

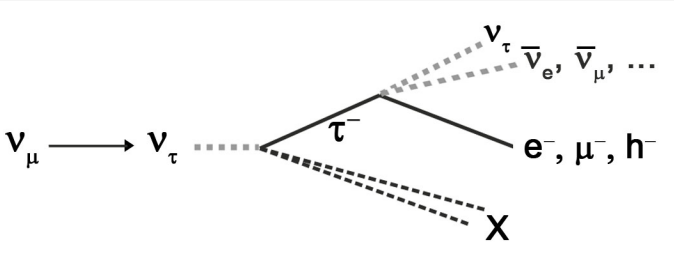
Realisation: Hybrid detector

- Electronic detector parts (ED).
- Emulsion cloud chamber photo emulsions (ECC).

τ Detection

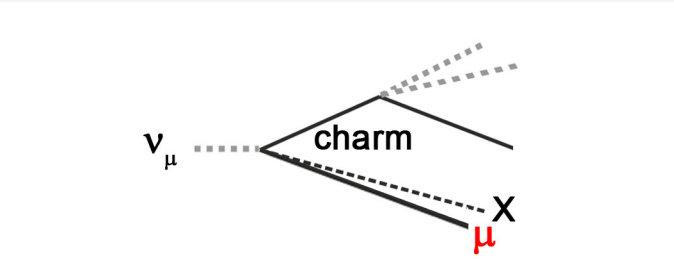
ν_τ signal:

- ν_τ CC interactions and τ^- lepton decay with 'kink' topology:



Background processes:

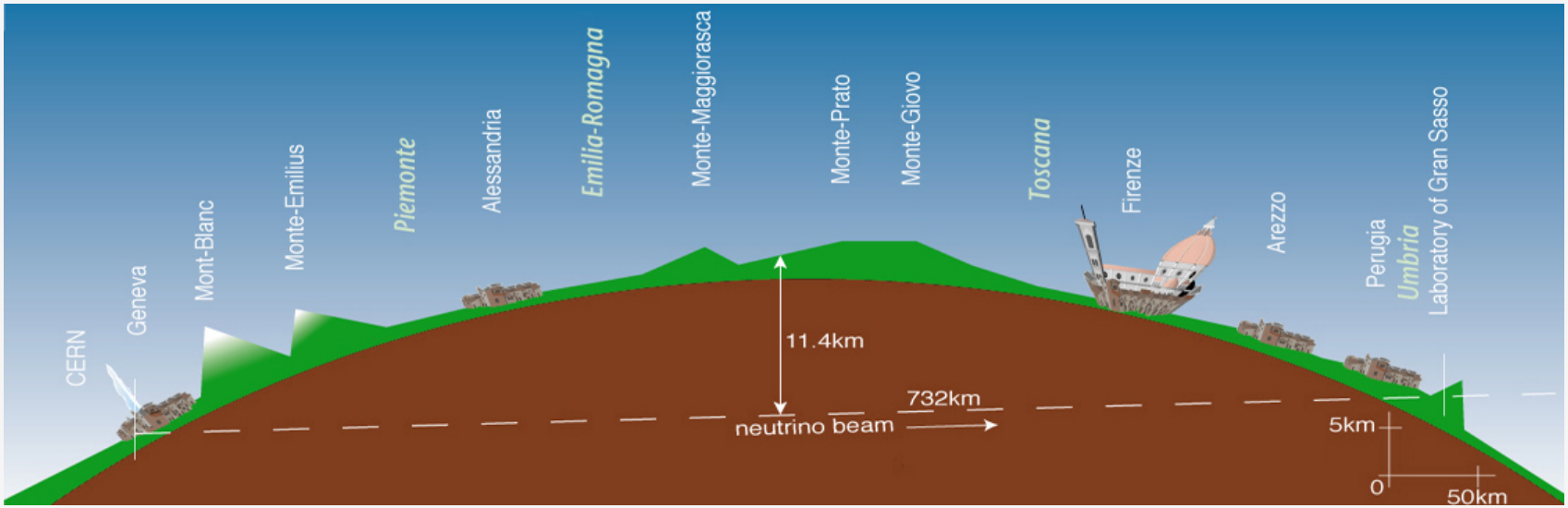
- ν_μ CC reactions with charm production & undetected 1ry μ:



- Hadronic re-interactions in lead.
- Large-angle μ scattering.

LNGS

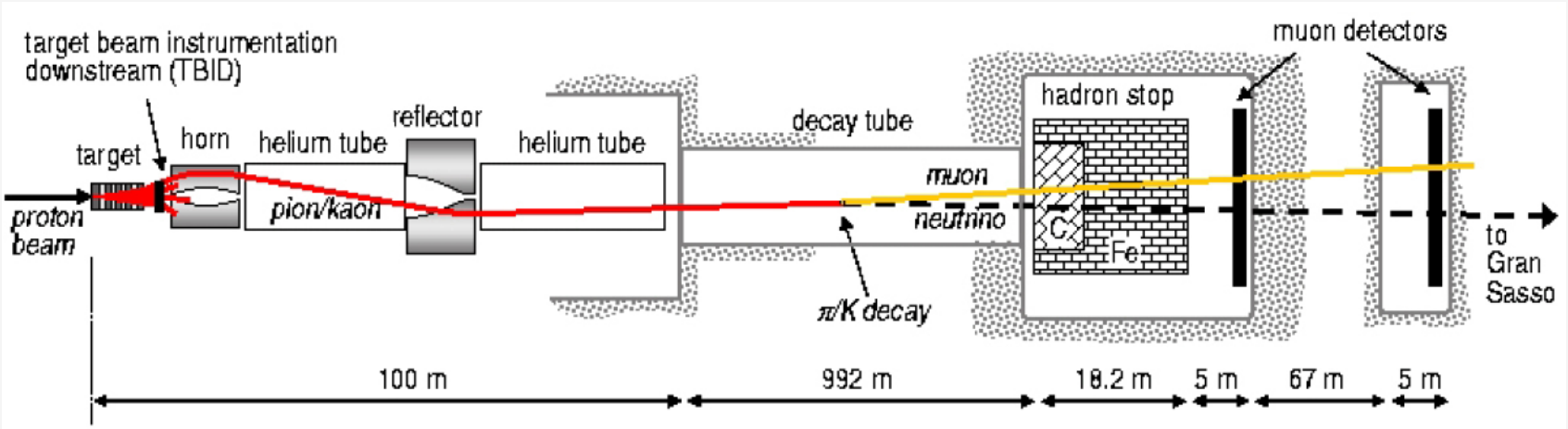
LNGS: Laboratori **N**azionali del **G**ran **S**asso.



- **Location:** Below Mt. Corno Grande of Gran Sasso, Italy.
- **Baseline:** 732 km away from the ν_μ source at CERN.
- **Vertical rock coverage:** 1 300 m (3 400 m *w.e.*).
- **Number of cosmic μ:** $\sim 1\,\mathrm{m}^{-2}\mathrm{h}^{-1}$.

The CNGS Beam

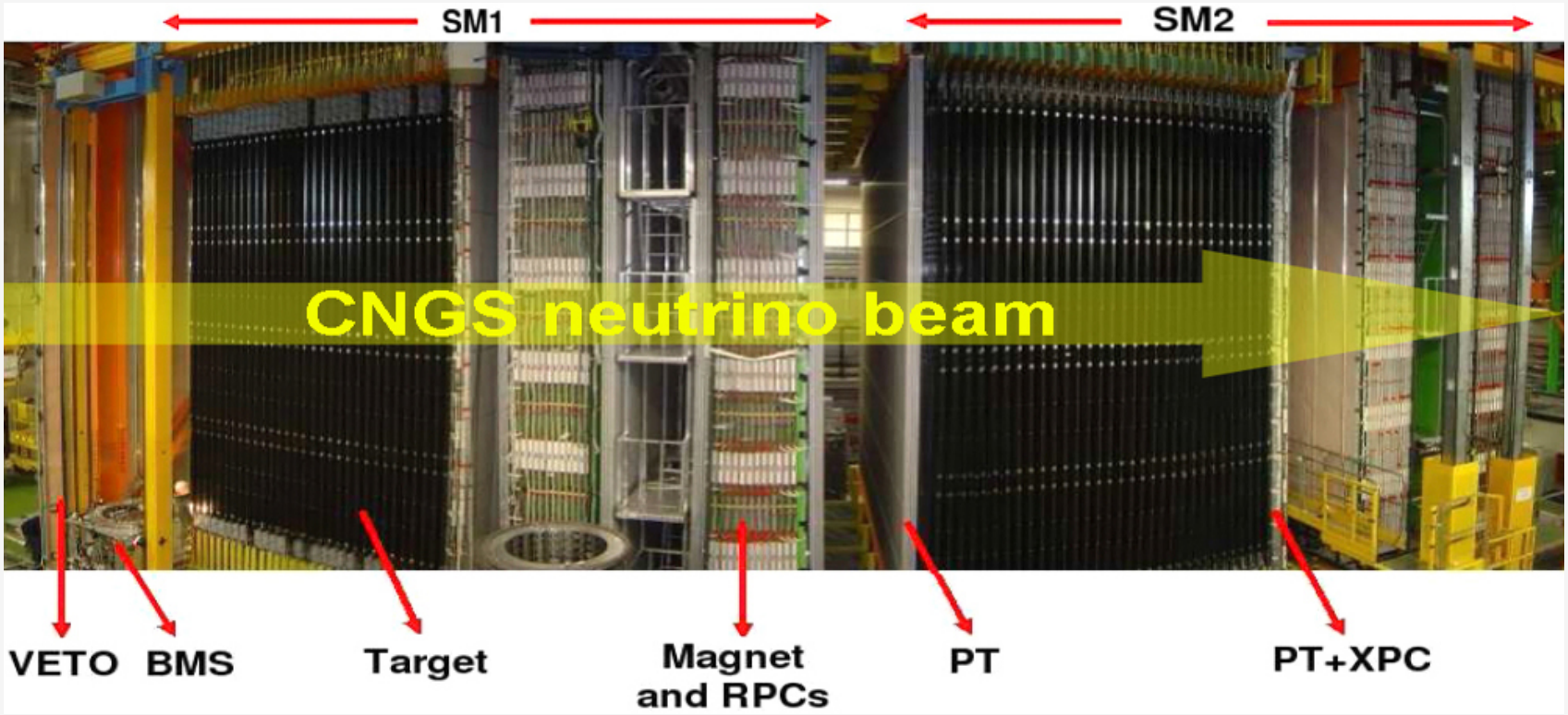
CNGS: CERN Neutrinos to Gran Sasso.



$\langle E_p \rangle$	400 GeV
p.o.t. 2008	1.78×10^{19}
p.o.t. 2009	3.52×10^{19}
p.o.t. 2010	4.04×10^{19}
p.o.t. 2011 expected	4.5×10^{19}
Nominal *p.o.t./year*	4.5×10^{19}
Total *p.o.t.* expected	22.5×10^{19}

$\langle E_\nu \rangle$	17.9 GeV
ν_e/ν_μ (CC)	0.89 %
$\overline{\nu}_\mu/\nu_\mu$ (CC)	2.4 %
$\overline{\nu}_e/\nu_\mu$ (CC)	0.06 %
ν_τ/ν_μ (CC)	$< 10^{-4}$ %

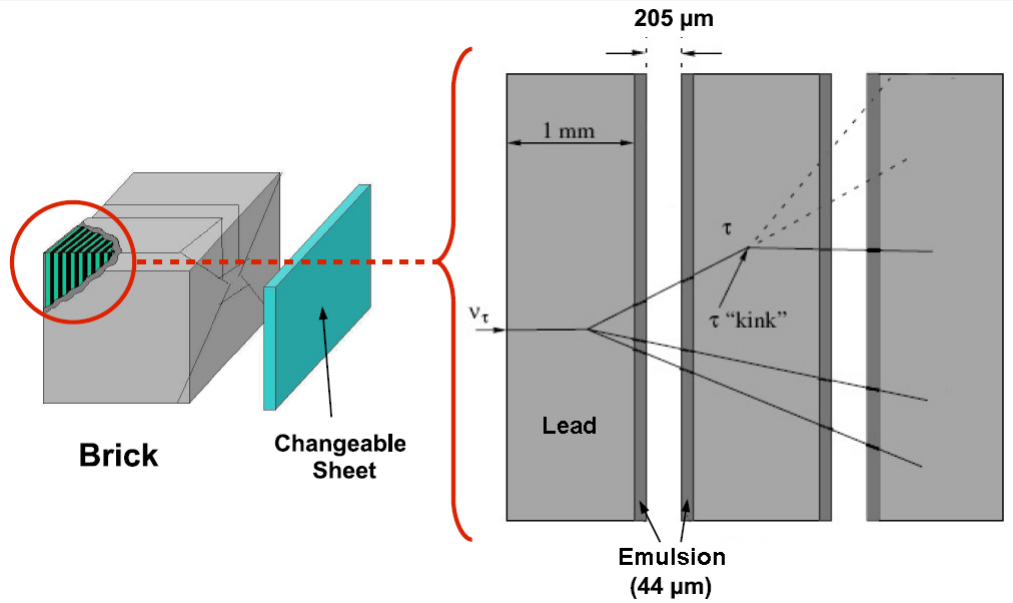
The OPERA Hybrid Detector

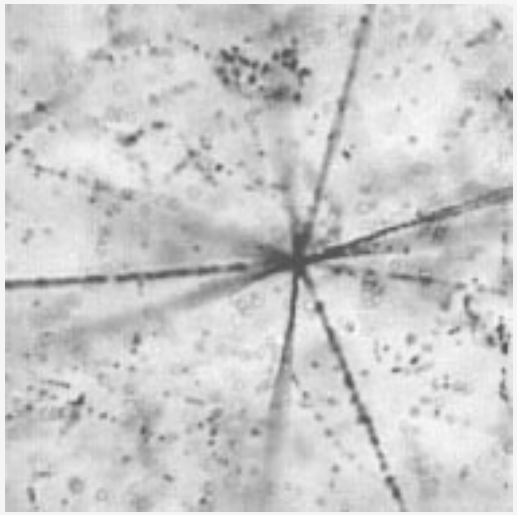


2 **identical Super Modules (SM), each consisting of:**

- **Target area**.
- **Magnetic spectrometer**.

Target Area

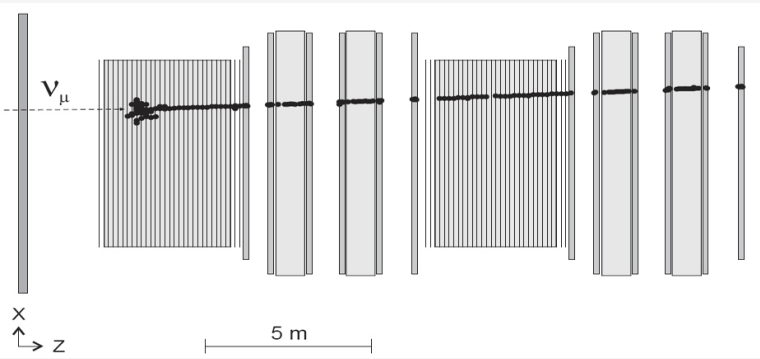


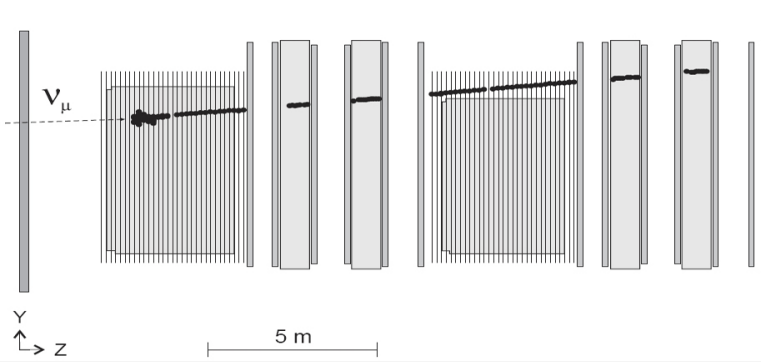


Emulsion Cloud Chamber (ECC) bricks:

- **Each brick:** 57×2 photo emulsions on plastic bases ($\sim 0.3\,\mathrm{mm}$), 56 lead plates ($1\,\mathrm{mm}$).
- **In total:** $\sim 150\,000$ bricks of $8.3\,\mathrm{kg}$ lead each ($\sim 1.28\,\mathrm{kt}$ target mass).

Event Reconstruction

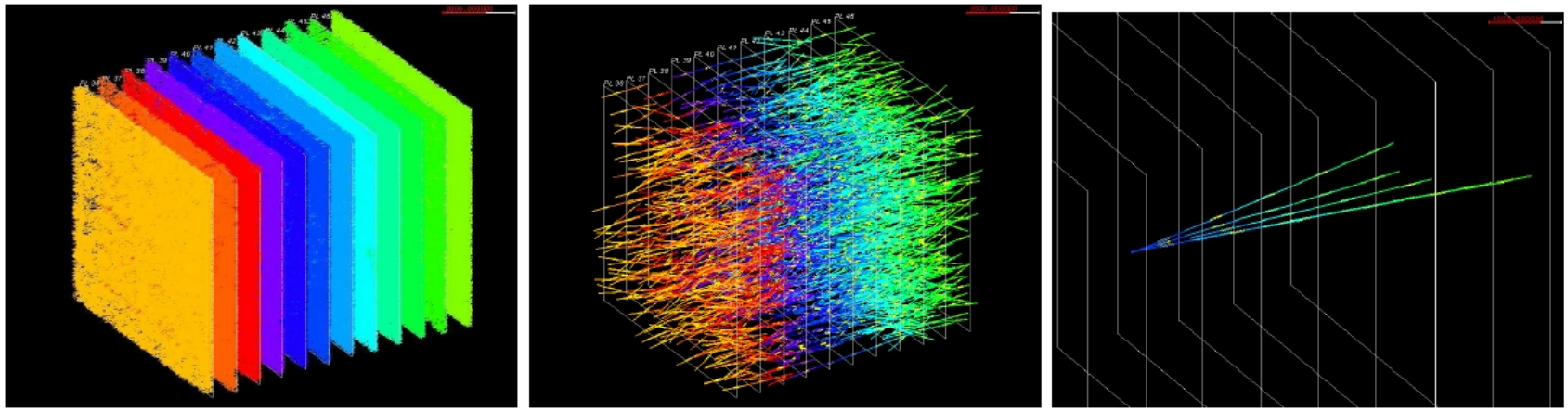




ED reconstruction:

- Provision of time resolution.
- ν interaction vertex localisation.
- CC/NC separation.
- μ identfication & momentum measurement.
- Hadronic shower energy reconstruction.

Event Reconstruction



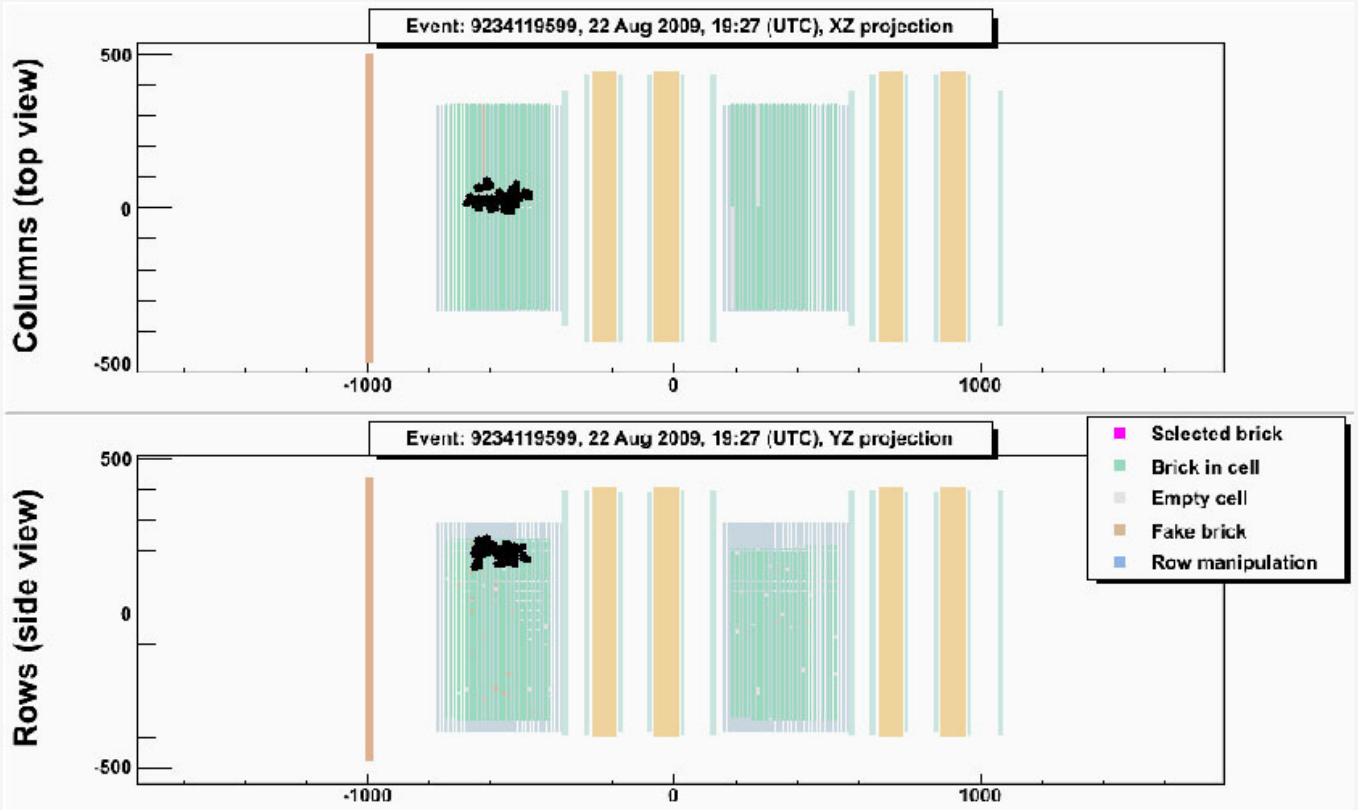
ECC event reconstruction:

- Reconstruction of $3D$ track segments.
- Rejection of passing-through and low-energy tracks.
- Vertex reconstruction.
- Decay search procedure.

The First ν_τ Candidate Event

The First ν_τ Candidate Event

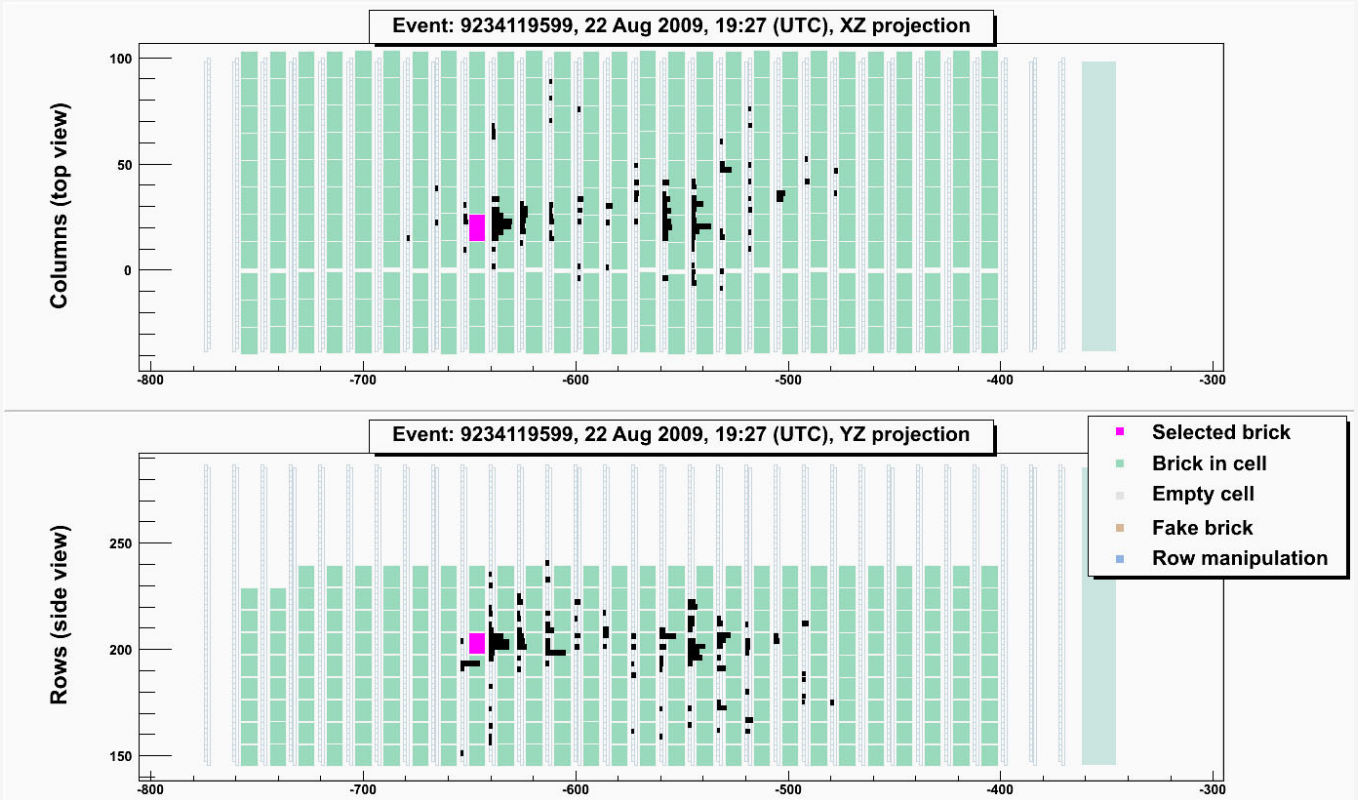
ED view:



- 22th of August 2009, 19:27h (UTC).
- Muonless event 9234119599.

The First ν_τ Candidate Event

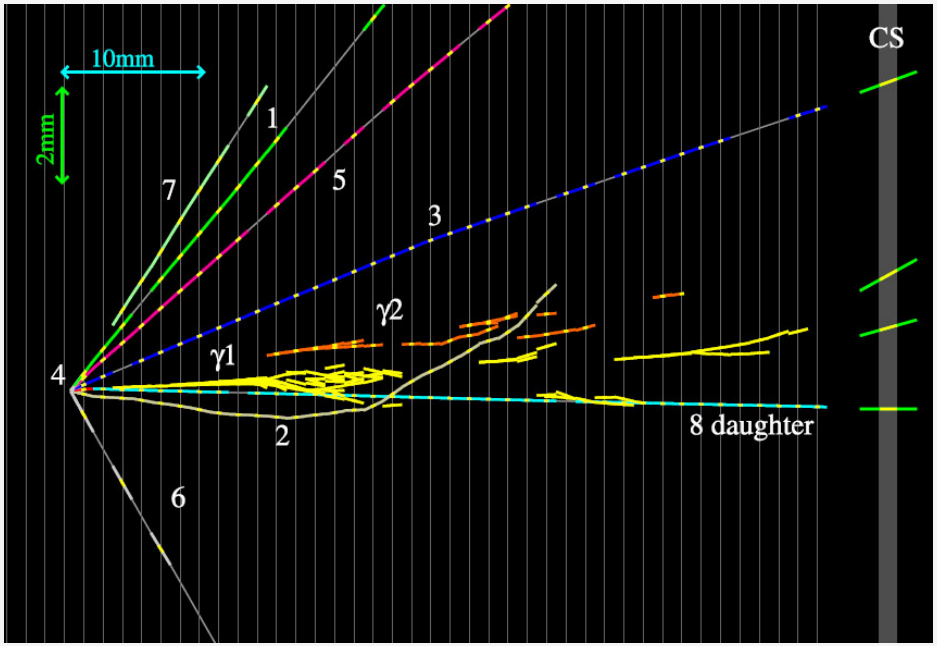
ED view:



- **Probability of undetected large-angle μ scattering:** $\sim 1\%$ by track follow-down (5% nominal value expected at the time of the experiment proposal, assumed for this analysis).

The First ν_τ Candidate Event

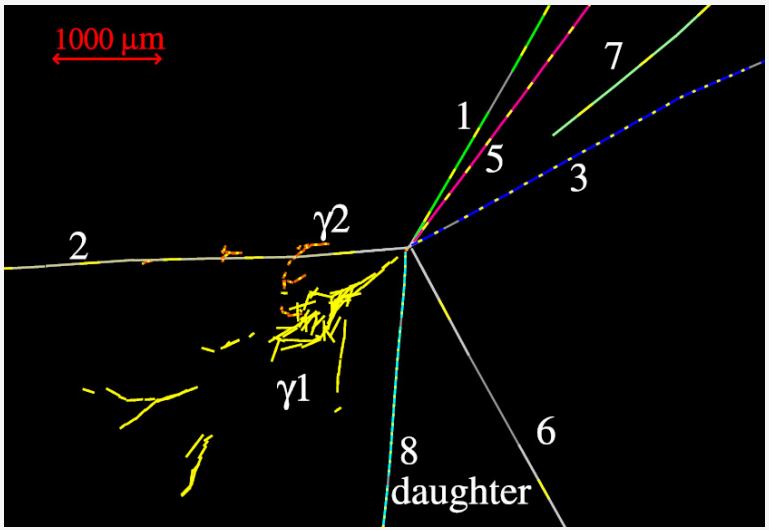
ECC reconstruction:

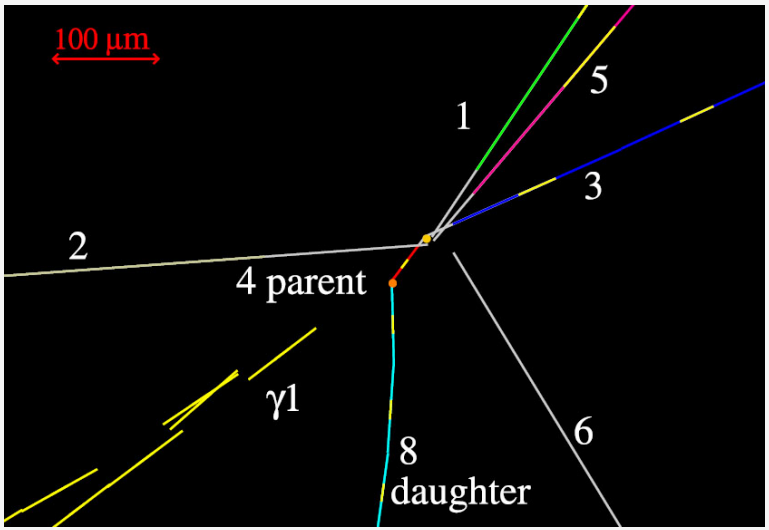


- **Primary ν interaction:** 7 tracks attached to 1ry vertex.
- **Tracks** 4, 8**:** Visible kink.
- **Track** 8**:** Attached to 2ry vertex, $IP = (55 \pm 4)\,\mu\mathrm{m}$ w.r.t. 1ry vertex.
- **Electromagnetic showers** $\gamma 1$, $\gamma 2$**:** Attached to 2ry vertex.

The First ν_τ Candidate Event

ECC reconstruction:

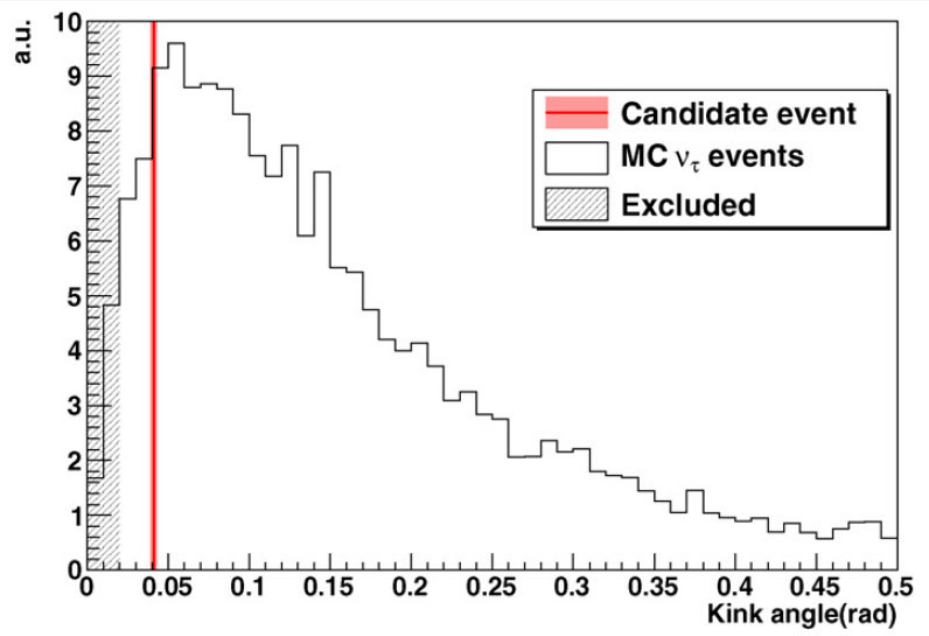




Track No	Particle type	p [GeV]
1	hadron	$0.78^{+0.13}_{-0.10}$
2	p	0.60 ± 0.05
3	hadron	$1.97^{+0.33}_{-0.25}$
5	hadron	$1.30^{+0.22}_{-0.16}$
6	pion	$0.36^{+0.18}_{-0.09}$
7	from prompt neutral	$0.49^{+0.29}_{-0.13}$

The First ν_τ Candidate Event

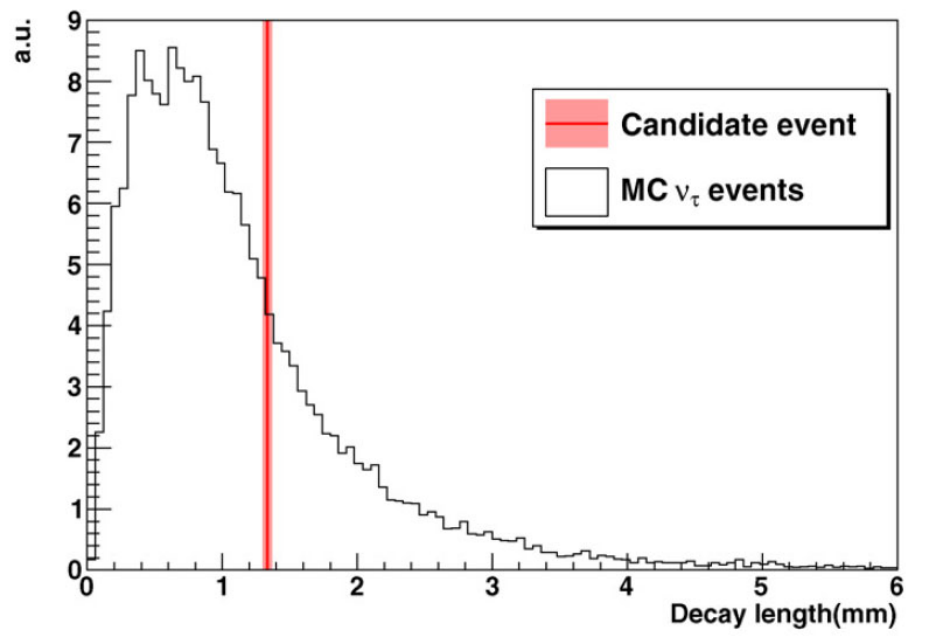
Kink angle:



- **Selection criteria:** $\theta_{kink} > 20\,\mathrm{mrad}$.
- ν_τ **candidate event:** $\theta_{kink} = (41 \pm 2)\,\mathrm{mrad}$.

The First ν_τ Candidate Event

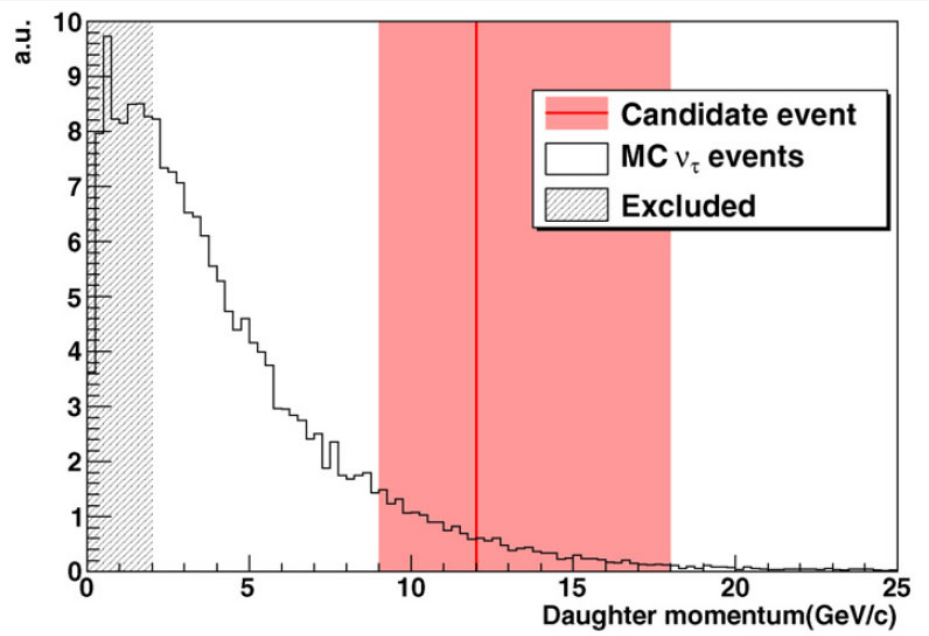
Decay length:



- **Selection criteria:** Decay vertex has to be within 2 lead plates downstream of 1ry vertex.
- ν_τ **candidate event:** $\mathrm{decaylength} = (1335 \pm 35)\,\mu\mathrm{m}$ $(\sim 15 c\tau)$.

The First ν_τ Candidate Event

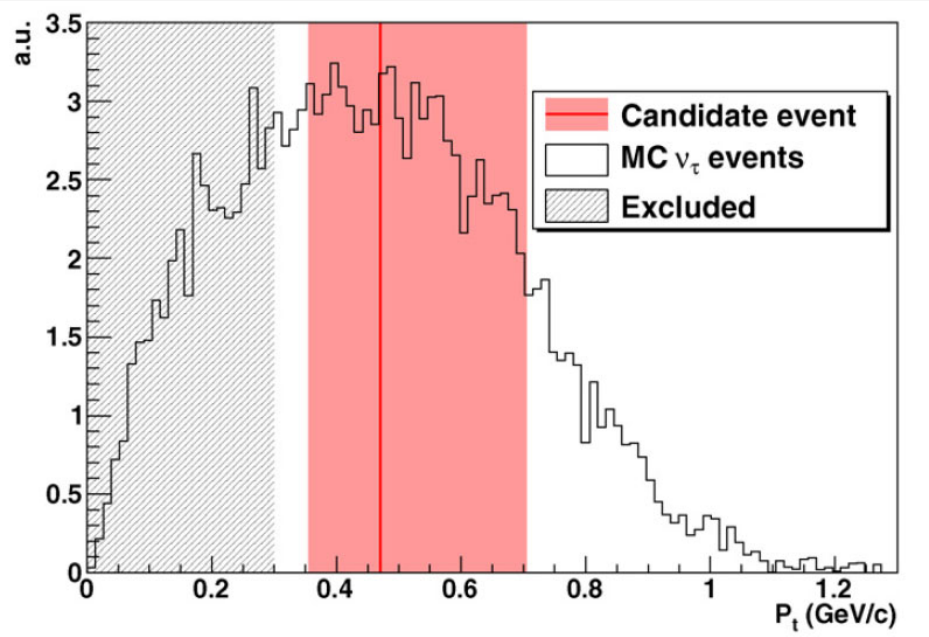
Daughter momentum:



- **Selection criteria:** $p_{daughter} > 2\,\mathrm{GeVc}^{-1}$.
- ν_τ **candidate event:** $p_{daughter} = (12^{+6}_{-3})\,\mathrm{GeVc}^{-1}$.

The First ν_τ Candidate Event

Daughter transverse momentum:



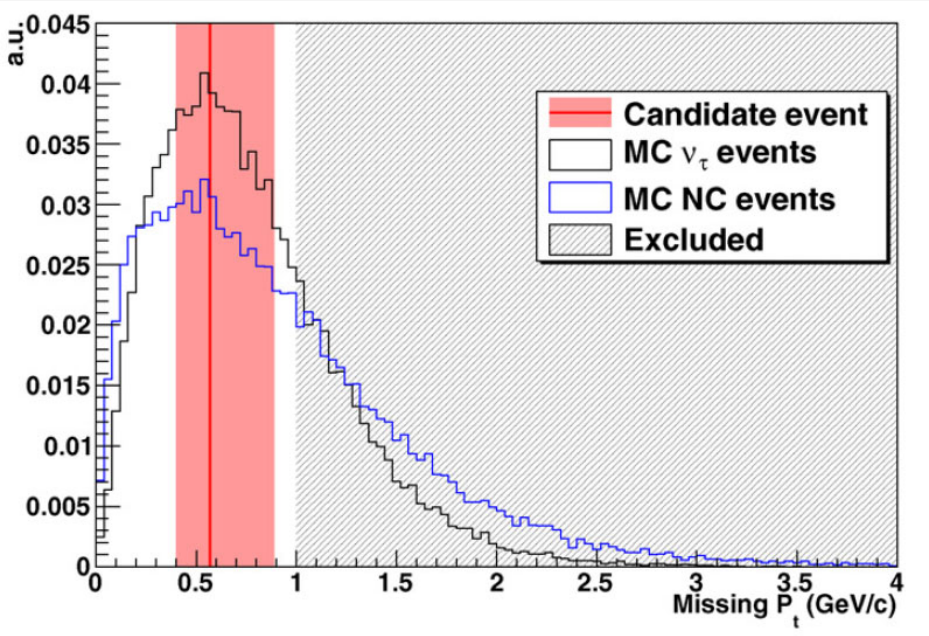
- **Selection criteria:** $p_{t,daughter} > 0.6\,\mathrm{GeVc}^{-1}$ if no γ attached,
  $p_{t,daughter} > 0.3\,\mathrm{GeVc}^{-1}$ if $\geq 1\gamma$ attached.

  ▷ Rejection of hadronic re-interactions.

- ν_τ **candidate event:** $p_{t,daughter} = (0.47^{+0.23}_{-0.12})\,\mathrm{GeVc}^{-1}$.

The First ν_τ Candidate Event

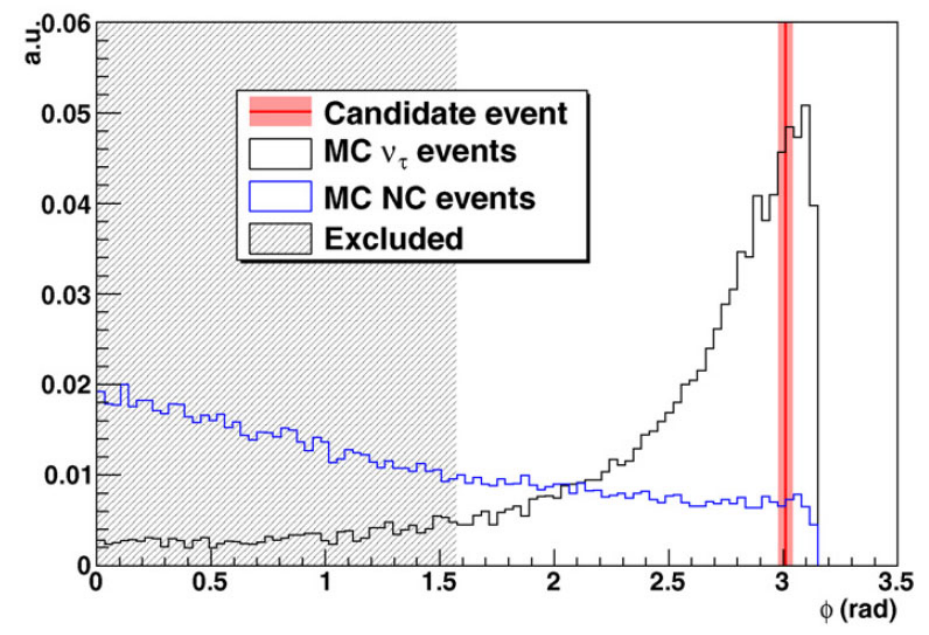
Missing transverse momentum:



- **Selection criteria:** $p_{t,miss} < 1\,\mathrm{GeVc}^{-1}$.
  - ▷ Rejection of NC interactions.
- ν_τ **candidate event:** $p_{t,miss} = (0.57^{+0.32}_{-0.17})\,\mathrm{GeVc}^{-1}$.

The First ν_τ Candidate Event

Angle between parent track and hadronic shower axis:



- **Selection criteria:** $\phi > \pi/2$.
- ν_τ **candidate event:** $\phi = (3.01 \pm 0.03)\,\mathrm{rad}$.

The First ν_τ Candidate Event

Kinematical cuts:

- All kinematical cuts for the 1-prong hadronic τ decay channel with ≥ 1 γ attached are passed.

Invariant mass of the decay products:

- **Invariant mass of the $\gamma\gamma$-system:** $(120 \pm 20 \pm 35)\,\mathrm{MeV}$.

  ▷ Consistent with π^0 mass $(135\,\mathrm{MeV})$.

- **Invariant mass of the $\pi^-\gamma\gamma$-system:** $(640^{+125+100}_{-80-90})\,\mathrm{MeV}$.

  ▷ Consistent with $\rho^-(770)$ mass $(775\,\mathrm{MeV})$.
  ($\rho^-(770)$ being created in 25% of τ^- decays: $\tau^- \to \rho^-(\pi^-\pi^0)\nu_\tau$.)

Significance of ν_τ Observation

Observation for 1088 decay-searched events:

- 1 event (1-prong hadronic τ decay channel).

Background expectation (1-prong hadronic τ decay channel):

- **Number of hadronic re-interaction events:** 0.011.
- **Number of charm events:** 0.007.

▷ 0.018 ± 0.007 (syst.) events.

▷ 1.8 % probability that the observed event is a background event.
▷ $2.36\,\sigma$ significance of ν_τ observation in OPERA.

Background expectation (all τ decay modes):

- **Number of background events:** 0.045 ± 0.020 (syst.).

▷ 4.5 % probability that the observed event is a background event.
▷ $2.01\,\sigma$ significance of ν_τ observation in OPERA.

Significance of ν_τ Observation

Observation for 1088 decay-searched events:

- 1 event (1-prong hadronic τ decay channel).

Assumptions:

- $\Delta m^2_{23} = 2.5 \times 10^{-3}\,\mathrm{eV}^2$.
- $sin^2 2\theta_{23} = 1$.

Signal expectation (1-prong hadronic τ decay channel):

- **Number of ν_τ CC events:** 0.16 ± 0.04 (syst.).

Signal expectation (all τ decay modes):

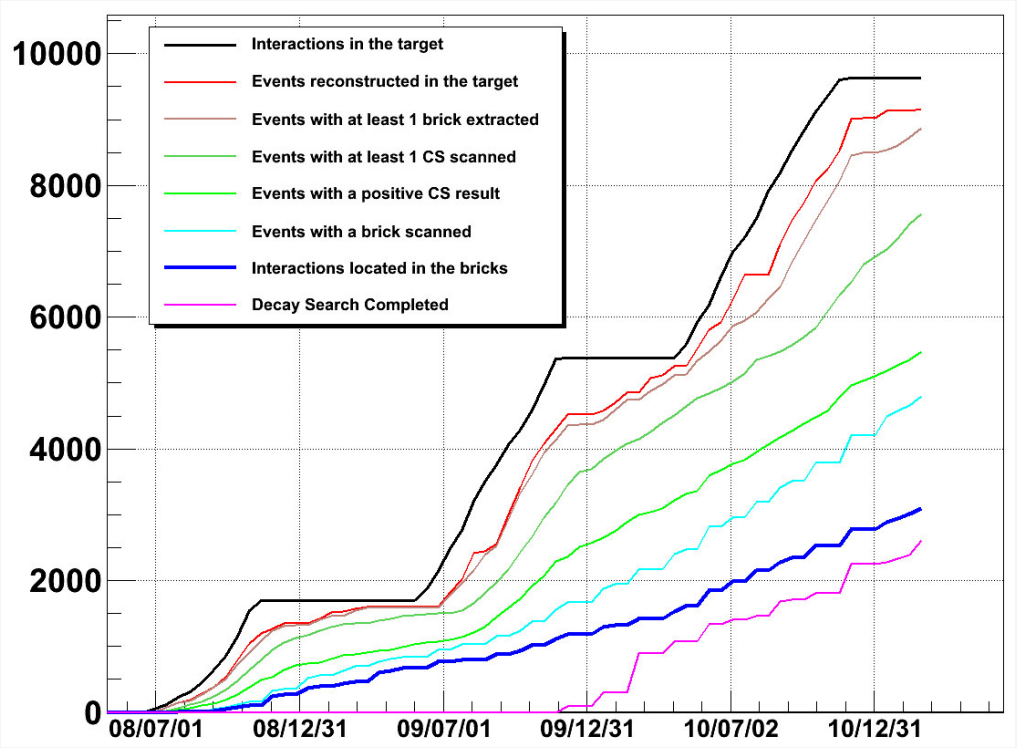
- **Number of ν_τ CC events:** 0.54 ± 0.13 (syst.).

Result (for $sin^2 2\theta_{23} = 1$):

- **Exclusion of:** $\Delta m^2_{23} > 7.5 \times 10^{-3}\,\mathrm{eV}^2$ at 90% CL.

Event Statistics

Analysis status:



- **Vertex located:** 3 108 events.
- **Decay search performed:** 2 614 events.

Conclusion & Outlook

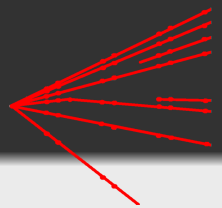
Conclusion & Outlook

Conclusion:

- Observation of a first ν_τ candidate event in $\nu_\mu \rightarrow \nu_\tau$ oscillations (22th of August 2009).
- Paper published in Physics Letters B:
  Observation of a first ν_τ candidate event in the OPERA experiment in the CNGS beam, Agafonova et al. / Physics Letters B 691 (2010) 138–145.

Outlook:

- New $\nu_\mu \rightarrow \nu_\tau$ paper with full statistics of 2008 & 2009 data soon to be published.
- Data taking foreseen for 2011 & 2012 (LHC closed for maintenance and upgrade in 2013).



Thank you for your attention!

The OPERA Collaboration

Belgium:
- IIHE-ULB Brussels

Croatia:
- IRB Zagreb

France:
- LAPP Annecy
- IPNL Lyon
- IPHC Strasbourg

Germany:
- Uni Hamburg

Israel:
- Technion Haifa

Italy:
- Bari
- Bologna
- LNF Frascati
- LNGS l'Aquila
- 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

Backup Slides

3-Flavour Oscillation Formalism

Neutrino mixing of mass and flavour eigenstates:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

U

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix:

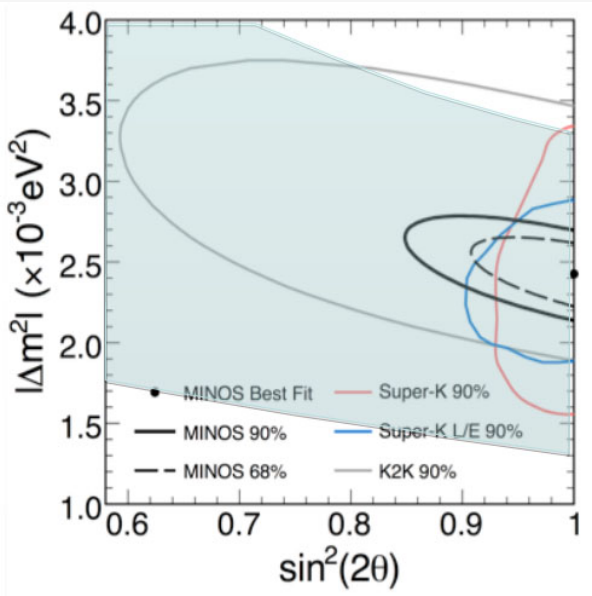
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\epsilon_1/2} & 0 & 0 \\ 0 & e^{i\epsilon_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric terms	Unknown terms	Solar terms	Majorana terms
SuperKamiokande MINOS, OPERA	**DoubleChooz, T2K**	**KamLAND**	

with $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$.

Oscillation Parameters

OPERA physics reach:



Black dot:

- $sin^2 2\theta_{23} = 1.$
- $\Delta m^2_{23} = 2.4 \times 10^{-3}\,\mathrm{eV}^2.$

Grey band:

- OPERA allowed region (90 % CL).
- $22.5 \times 10^{-19} p.o.t.$.

Oscillation parameters - present situation:

$\lvert\Delta m^2_{atm}\rvert = \lvert m^2_3 - m^2_2\rvert$	$\sim 2 \times 10^{-3}\,\mathrm{eV}^2$
$\Delta m^2_{sol} = m^2_2 - m^2_1$	$\sim 8 \times 10^{-5}\,\mathrm{eV}^2$
θ_{23}	$\sim 45\,^\circ$
θ_{12}	$\sim 33\,^\circ$
θ_{13}	$< 13\,^\circ$
δ	?

τ Detection

τ creation in ν_τ CC reactions:

$$\nu_\tau + N \rightarrow \tau^- + X$$

τ decay modes (1-prong):

- **Muonic:** $\tau^- \rightarrow \mu^- + \nu_\tau + \overline{\nu}_\mu$ (BR 17.4 %)
- **Electronic:** $\tau^- \rightarrow e^- + \nu_\tau + \overline{\nu}_e$ (BR 17.9 %)
- **Hadronic:** $\tau^- \rightarrow h^- + \nu_\tau + X^0$ (BR 49.2 %)

τ decay modes (3-prong):

- **Hadronic:** $\tau \rightarrow 2h^- + h^+ + \nu_\tau + X^0$ (BR 15.0 %)

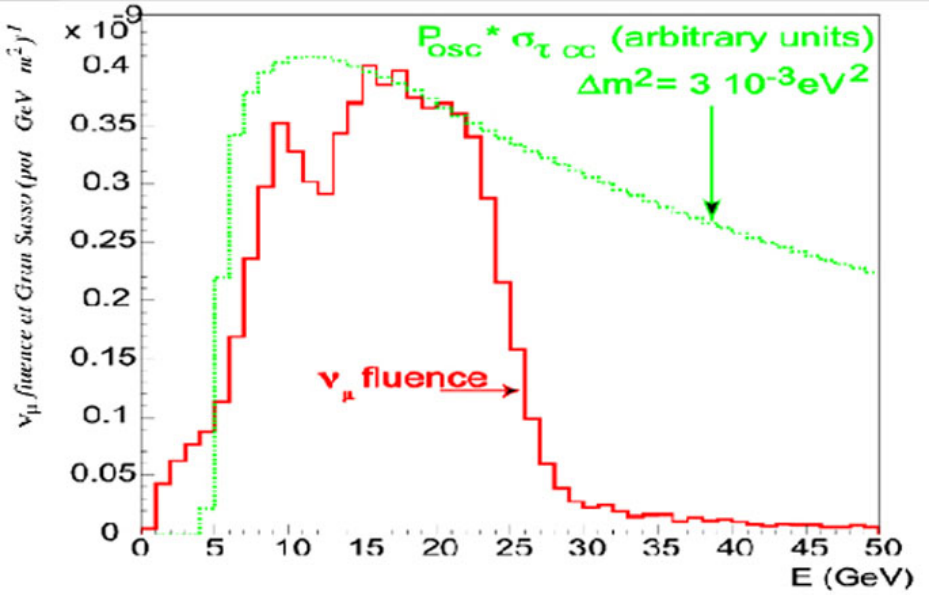
τ decay length:

- $\sim 600\,\mu\mathrm{m}$.

Beam Characteristics at LNGS

Oscillation probability:

$$P(\nu_\mu \to \nu_\tau) \sim \sin^2 2\theta_{23} \cos^4 \theta_{13} \sin^2(\Delta m^2_{23} \frac{L}{4E})$$

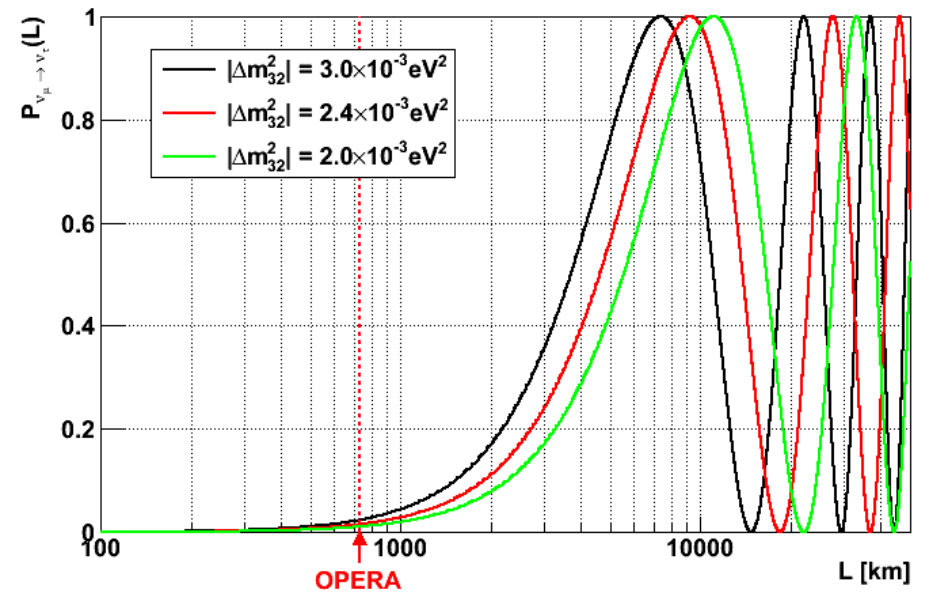


- ν_μ-**beam energy:** Optimsed for τ detection.

Beam Characteristics at LNGS

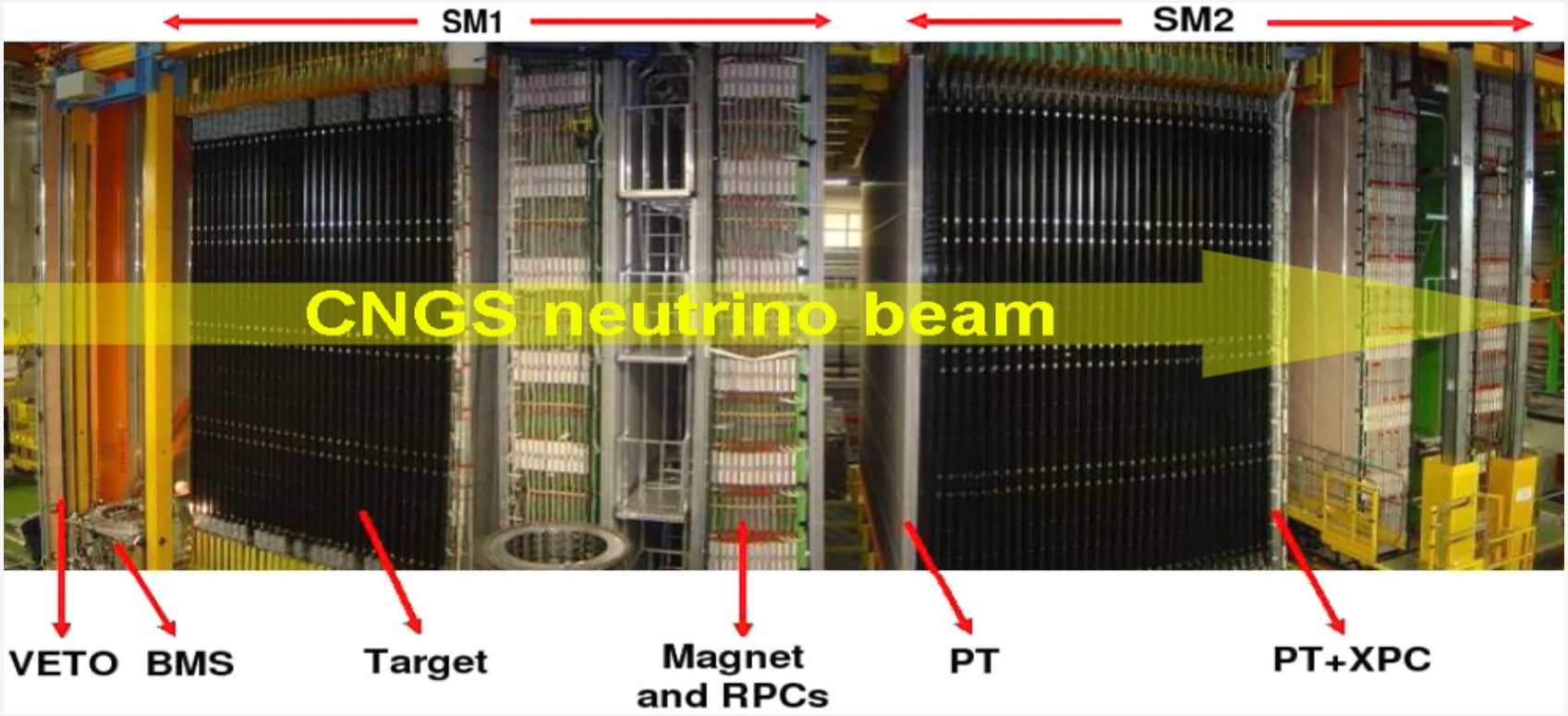
Oscillation probability:

$$P(\nu_\mu \to \nu_\tau) \sim \sin^2 2\theta_{23} \cos^4 \theta_{13} \sin^2(\Delta m^2_{23} \frac{L}{4E})$$



- **Location:** OPERA detector is at off-peak position.
- **Longer baseline:** Increase in ν_τ flux would be cancelled by greater ν_μ beam divergence.

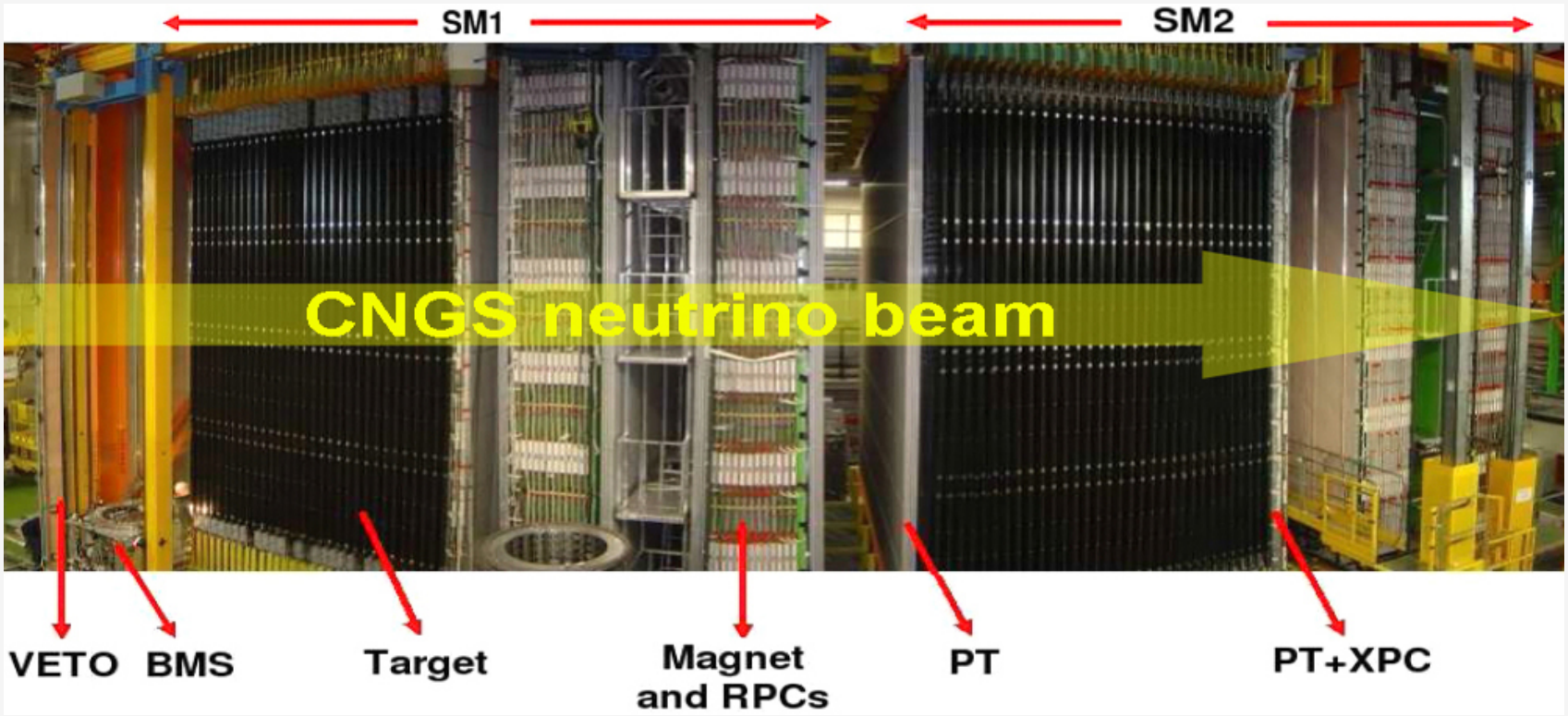
The OPERA Hybrid Detector



VETO system:

- 2 planes of glass resistive plate chambers in front of the detector.
- Rejection of upstream ν interactions.

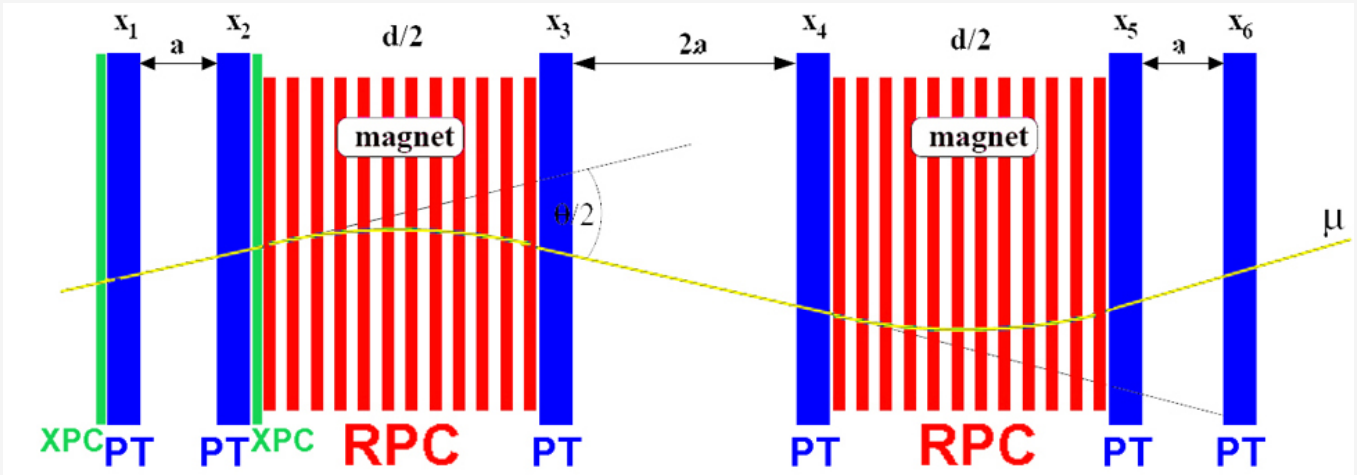
The OPERA Hybrid Detector



Brick Manipulator System (BMS):

- **Brick extraction:** Via 2 automatic robots (1 per semi-wall), parallel to CNGS data taking.
- **Extraction speed:** 25 ν interaction-bricks per 8 h-shift.

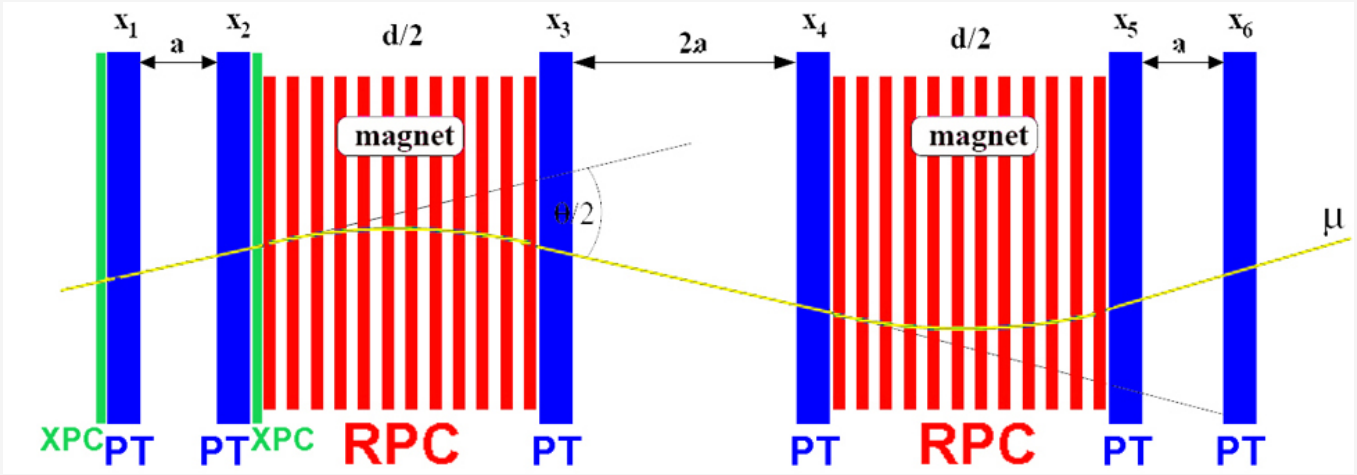
Magnetic Spectrometer



Magnetic spectrometer:

- **Each SM:** Downstream of the target area.
- **Dipole Magnets.**
- **Resistive Plate Chambers (RPC & XPC).**
- **High Precision Trackers (HPT).**

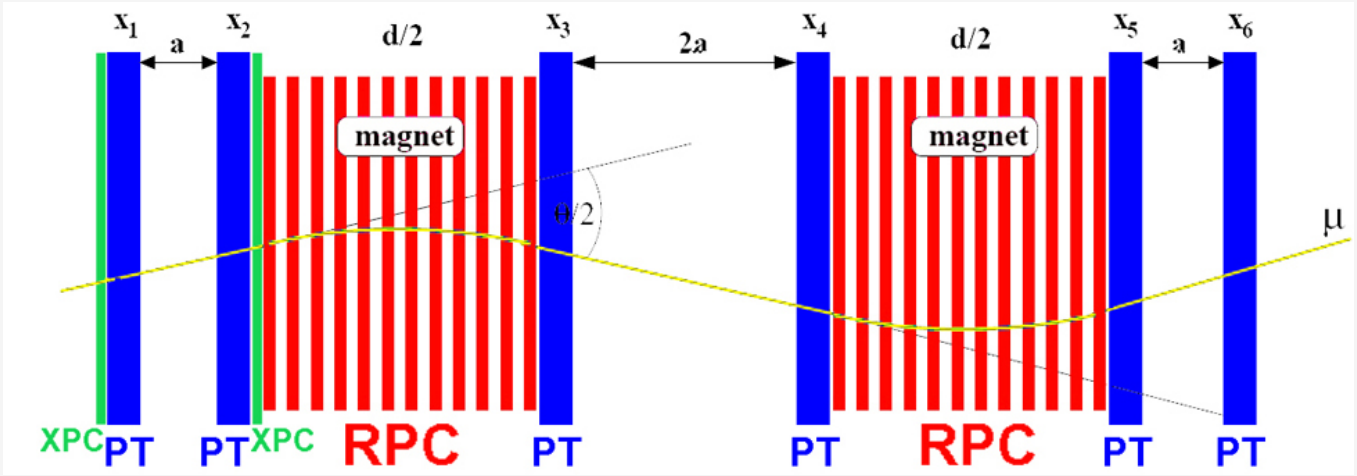
Magnetic Spectrometer



Dipole magnets:

- **Each SM:** Copper coils with 24 iron slabs.
- **Magnetic field:** $\sim 1.53\,\mathrm{T}$.
- Deflection of charged particles.

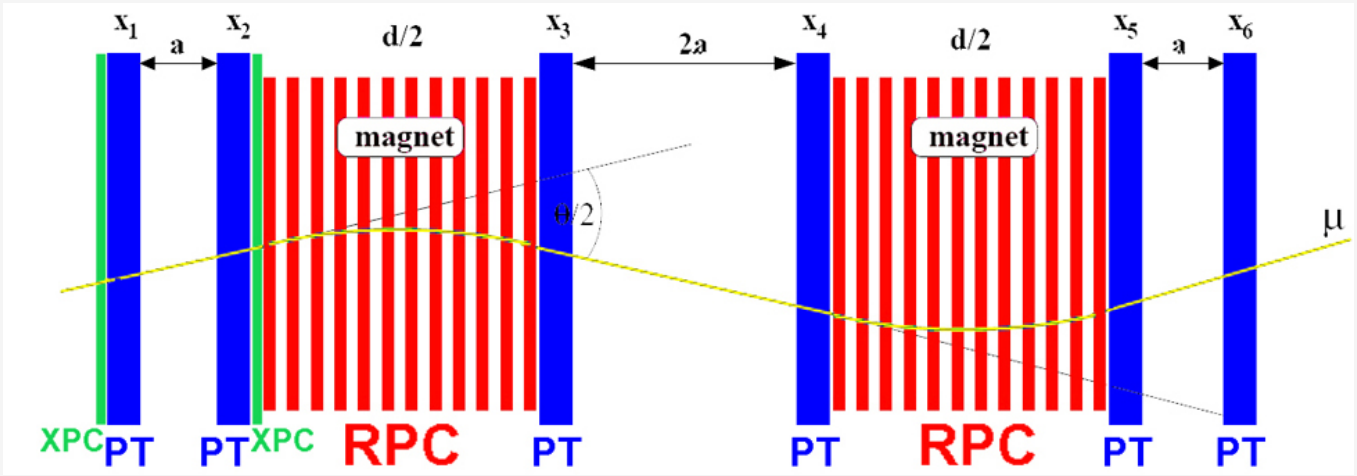
Magnetic Spectrometer



Resistive Plate Chambers (RPC & XPC):

- **Each SM:** 24 planes of RPC within the magnet, horizontally and vertically aligned (RPC), 2 extra planes upstream of the magnet, tilted by 42.6 ° (XPC).
- Bakelite resistive plate chambers.
- Hadronic energy reconstruction.
- μ **identification:** By range measurement.

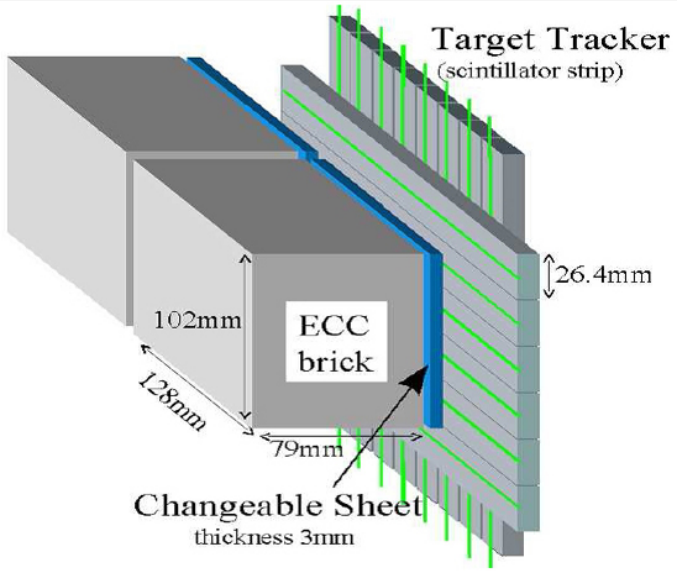
Magnetic Spectrometer



High Precision Trackers (HPT):

- **Each SM:** 6 walls of vertical drift tubes.
- **Spacial resolution:** $\sim 250\,\mu\mathrm{m}$.
- **Resolution:** $\sim 20\,\%$ for $p < 30\,\mathrm{GeV}$.
- Precise measurement of the angular deflection of charged particles.

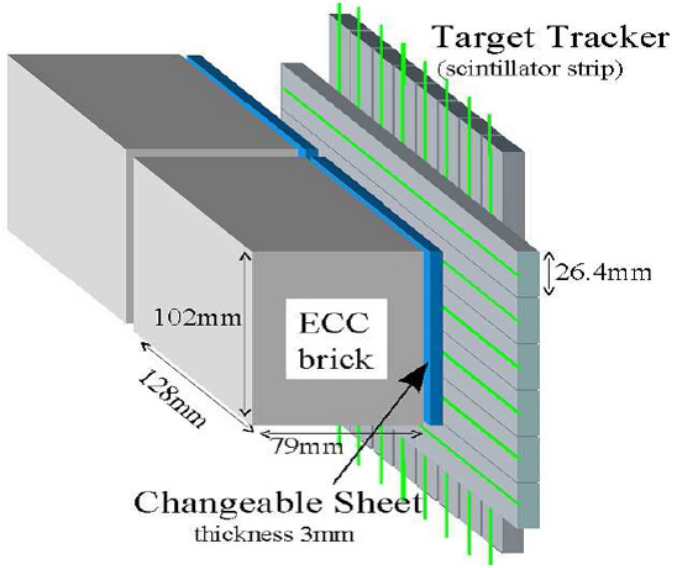
Target Area



Target area:

- **Target Trackers (TT).**
- **Emulsion Cloud Chamber (ECC) bricks.**

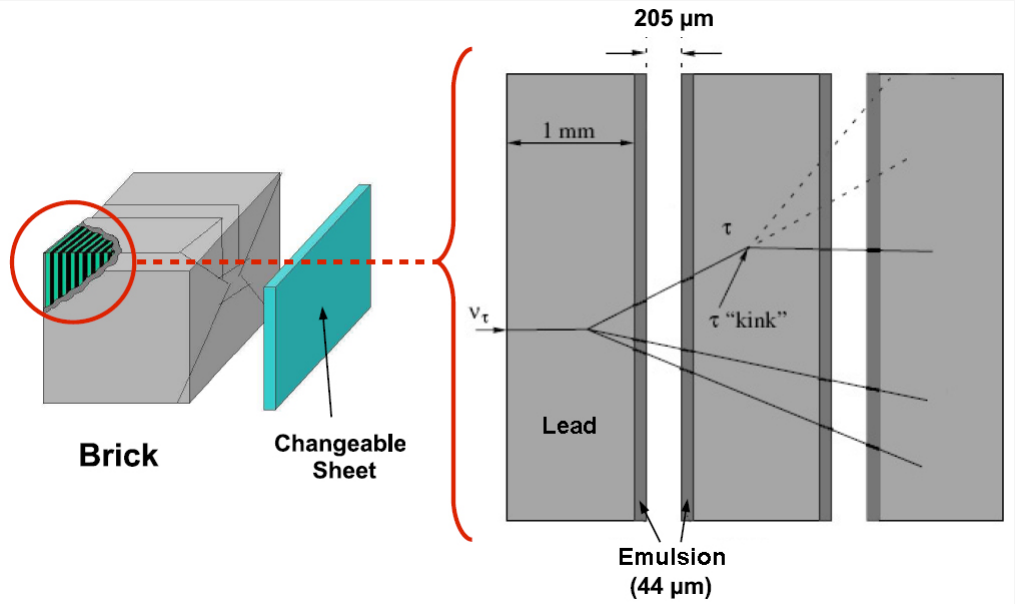
Target Area

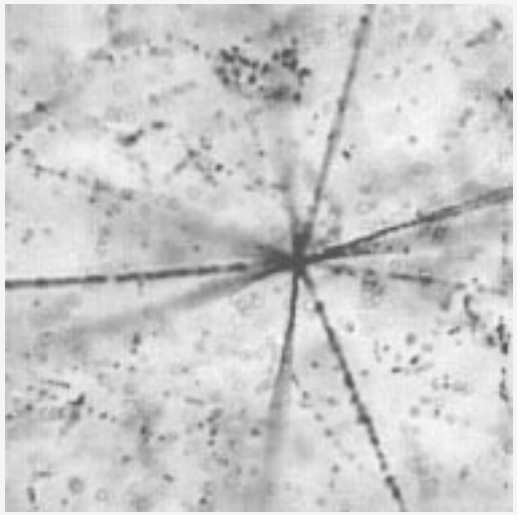


Target Trackers (TT):

- **Each SM:** 31 walls of plastic scintillator strips, horizontally and vertically aligned.
- **Position accuracy:** $\sim 8\,\mathrm{mm}$.
- **Angular accuracy:** $\sim 20\,\mathrm{mrad}$.
- **Brick finding efficiency:** $\sim 80\,\%$.

Target Area

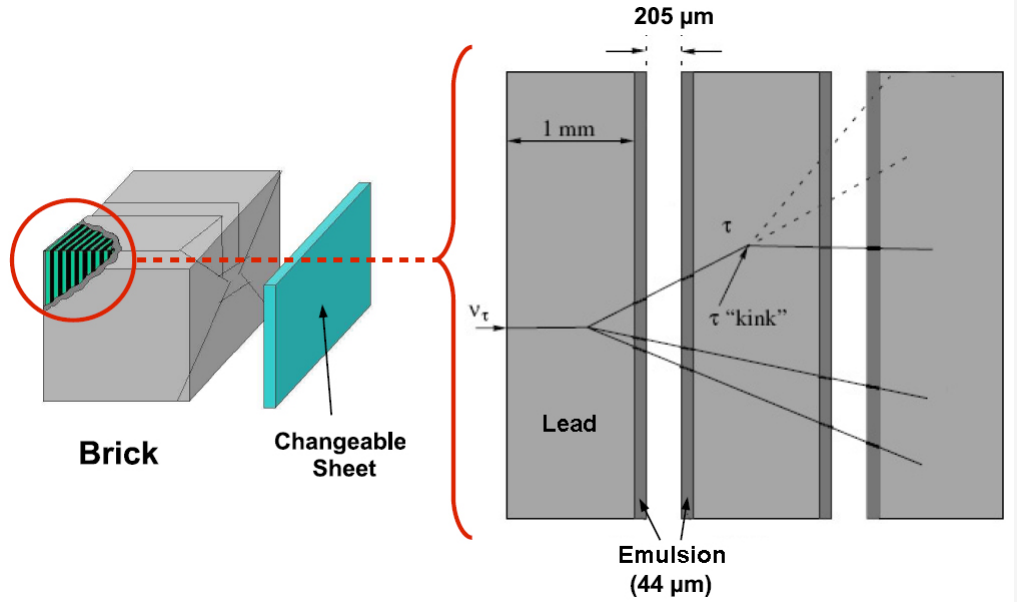


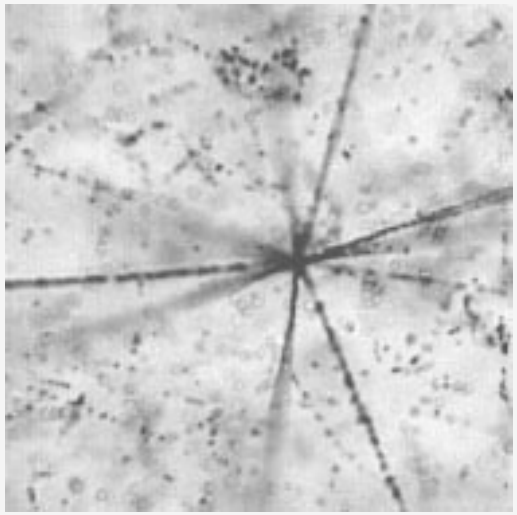


Changeable Sheets (CS):

- **Each brick:** 2 extra emulsion sheets on the downstream side.
- Second check whether the ν interaction occurred inside the brick.

Target Area



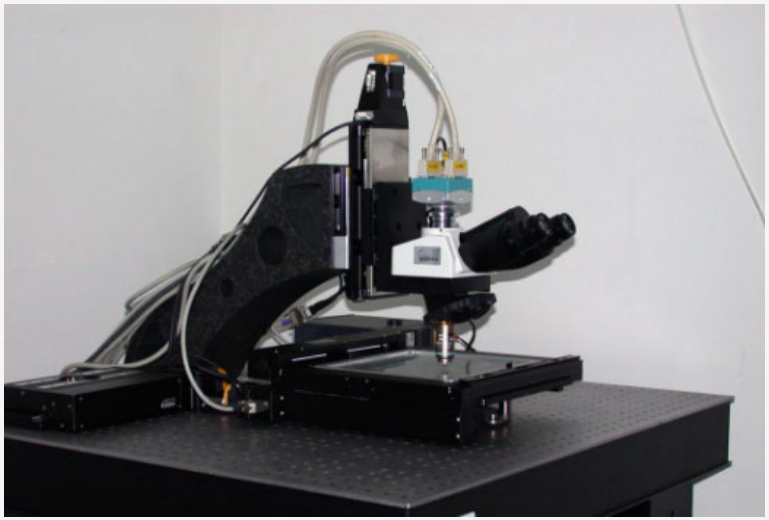


ECC photo emulsions:

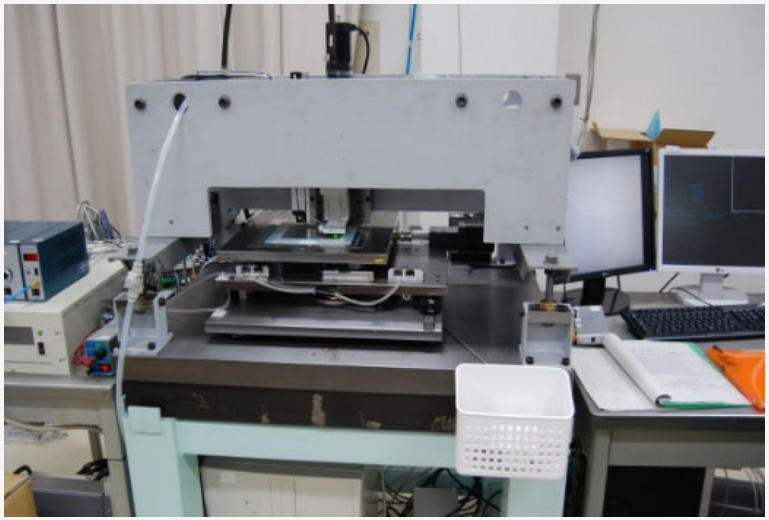
- **Basic detector elements:** AgBr crystals of $0.2\,\mu\mathrm{m}$ size.
- **Intrinsic resolution:** $50\,\mathrm{nm}$.
- Hadronic momentum measurement via Multiple Coulomb Scattering.
- π/μ separation at low energies via dE/dx measurements.
- e identification and energy measurements for e, γ.

Event Reconstruction

Europe:



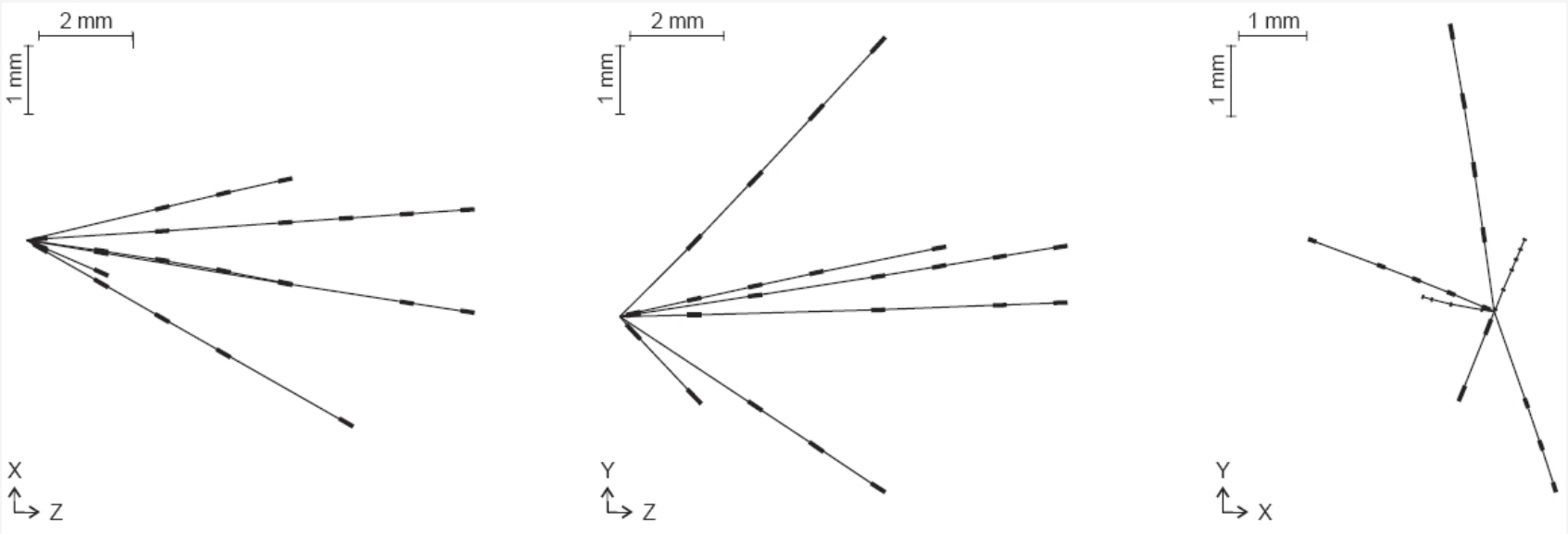
Japan:



ECC Scanning and alignment:

- **CS & ECC brick scanning:** Conducted by automatic microscopes at scanning labs in Europe & Japan.
- **CS & ECC brick alignment:** Via X-rays and cosmic ray-tracks.

Event Reconstruction

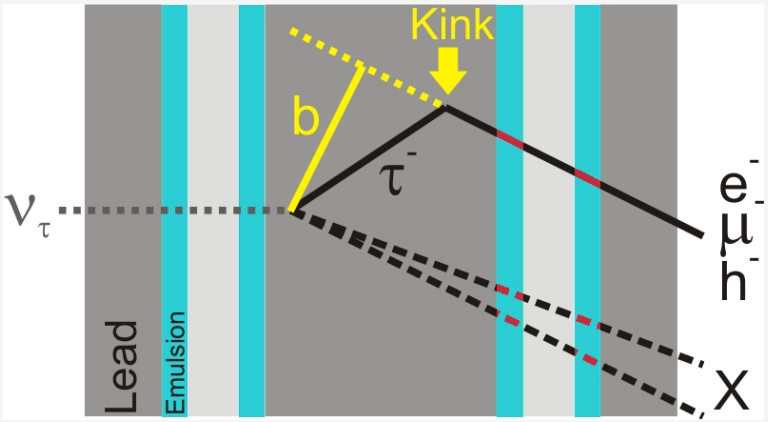


ECC vertex reconstruction:

- Scan-back of tracks found in CS.
- Volume-scan of $1\,\mathrm{cm}^2$ around supposed vertex.

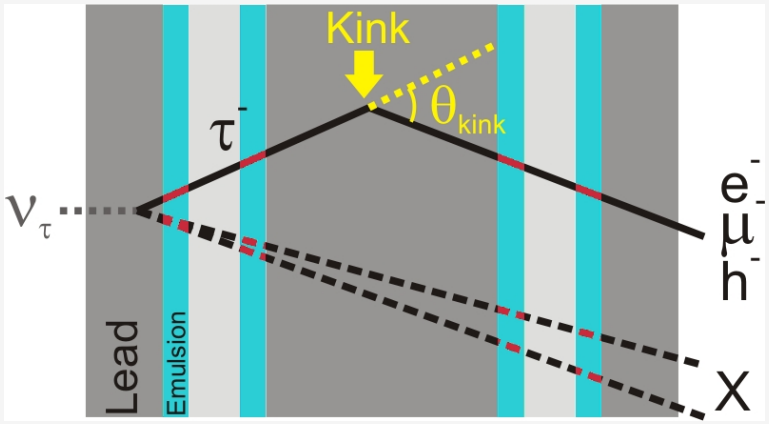
Event Reconstruction

Short decay:



- Impact parameter b.

Long decay:



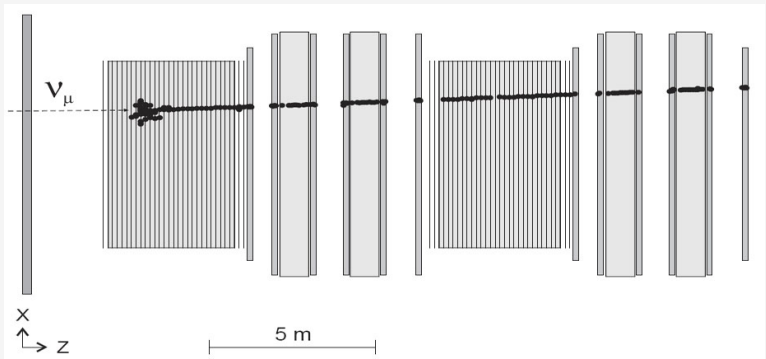
- Kink angle θ_{kink}.

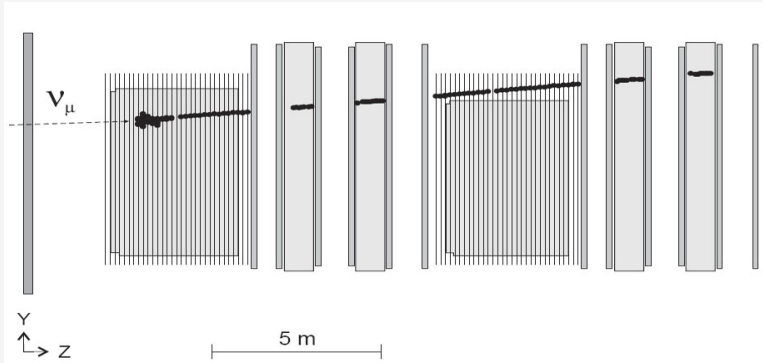
Decay search procedure:

- In-track decay search.
- Extra-track search.
- Measurement of θ_{kink} or b.

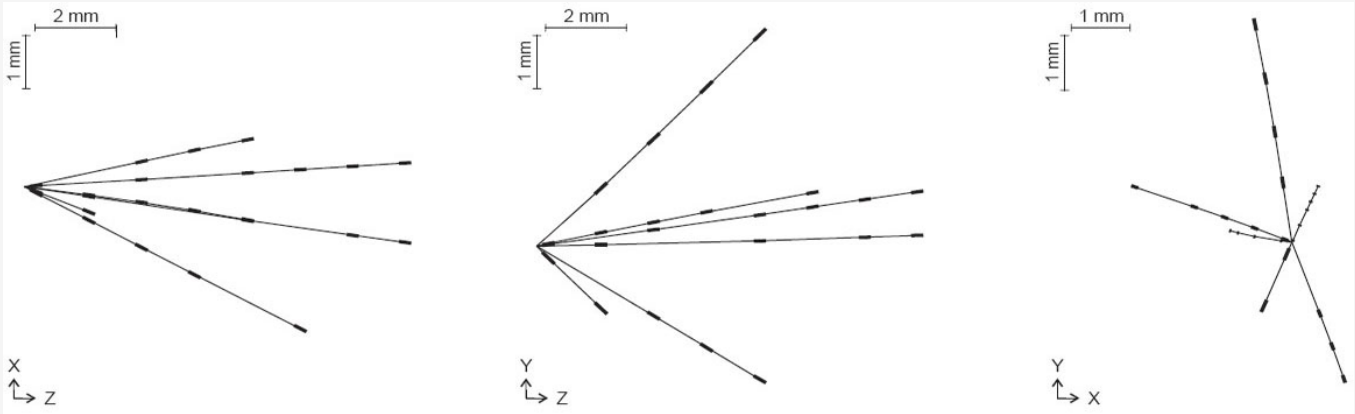
A Typical ν_μ Event (CC)

ED view:



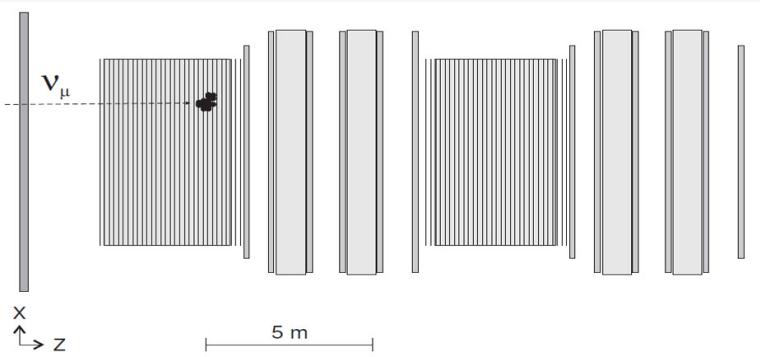


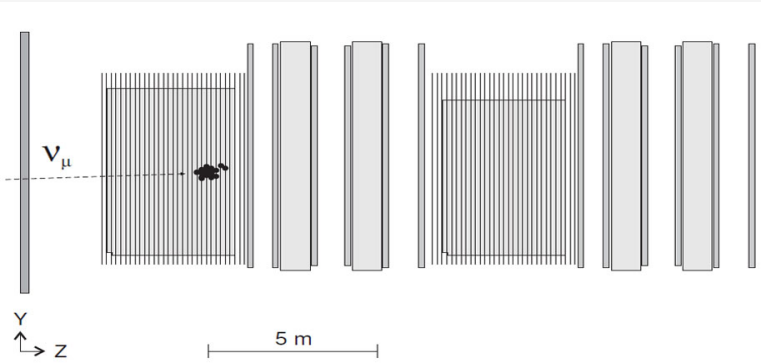
ECC reconstruction:



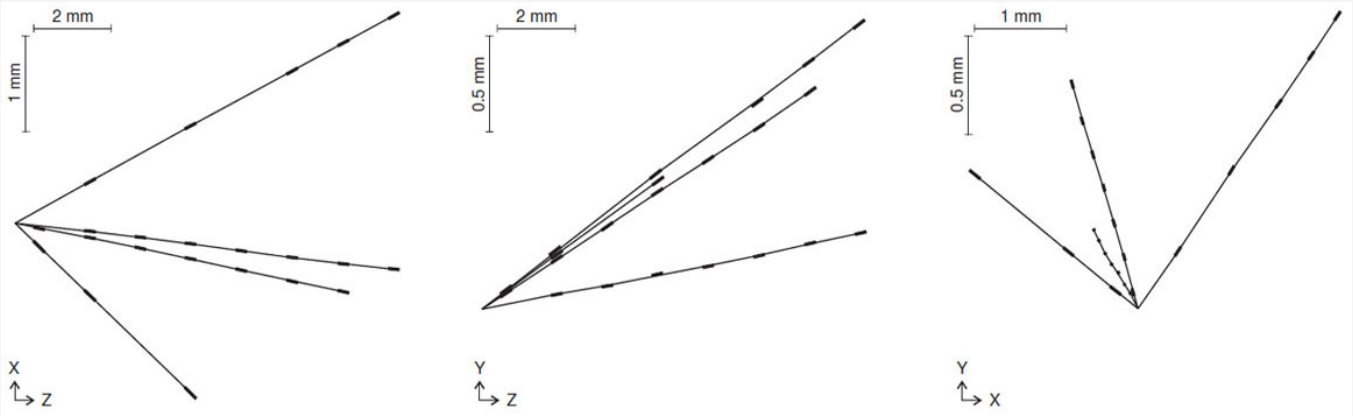
A Typical ν_μ Event (NC)

ED view:



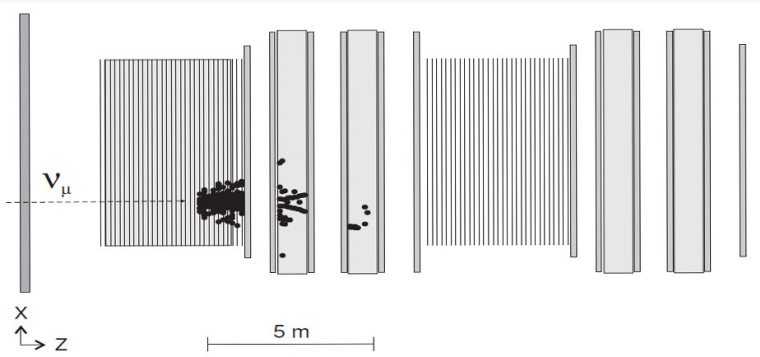


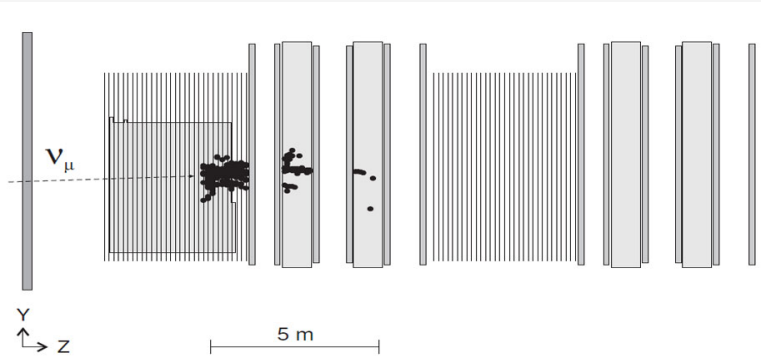
ECC reconstruction:



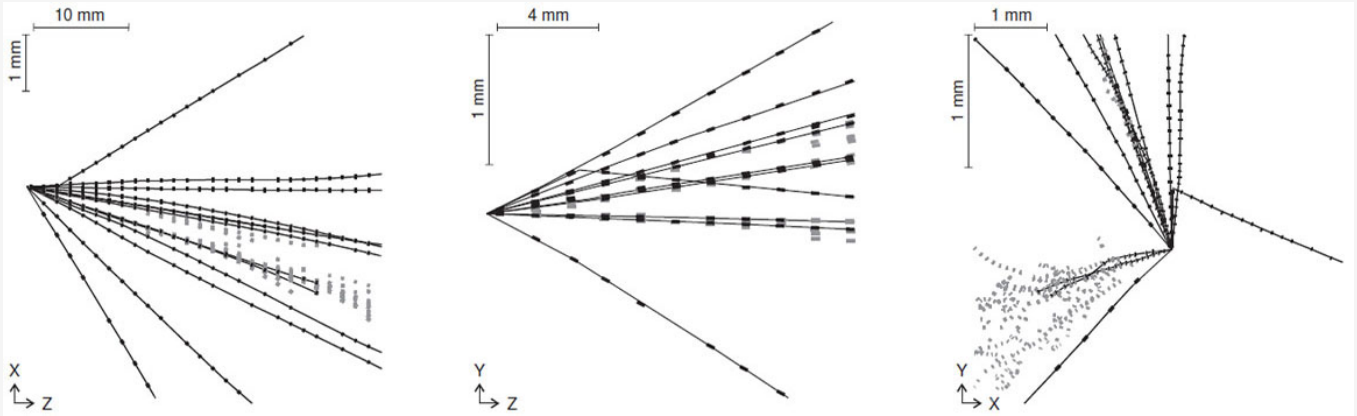
A ν_μ Charm Event

ED view:



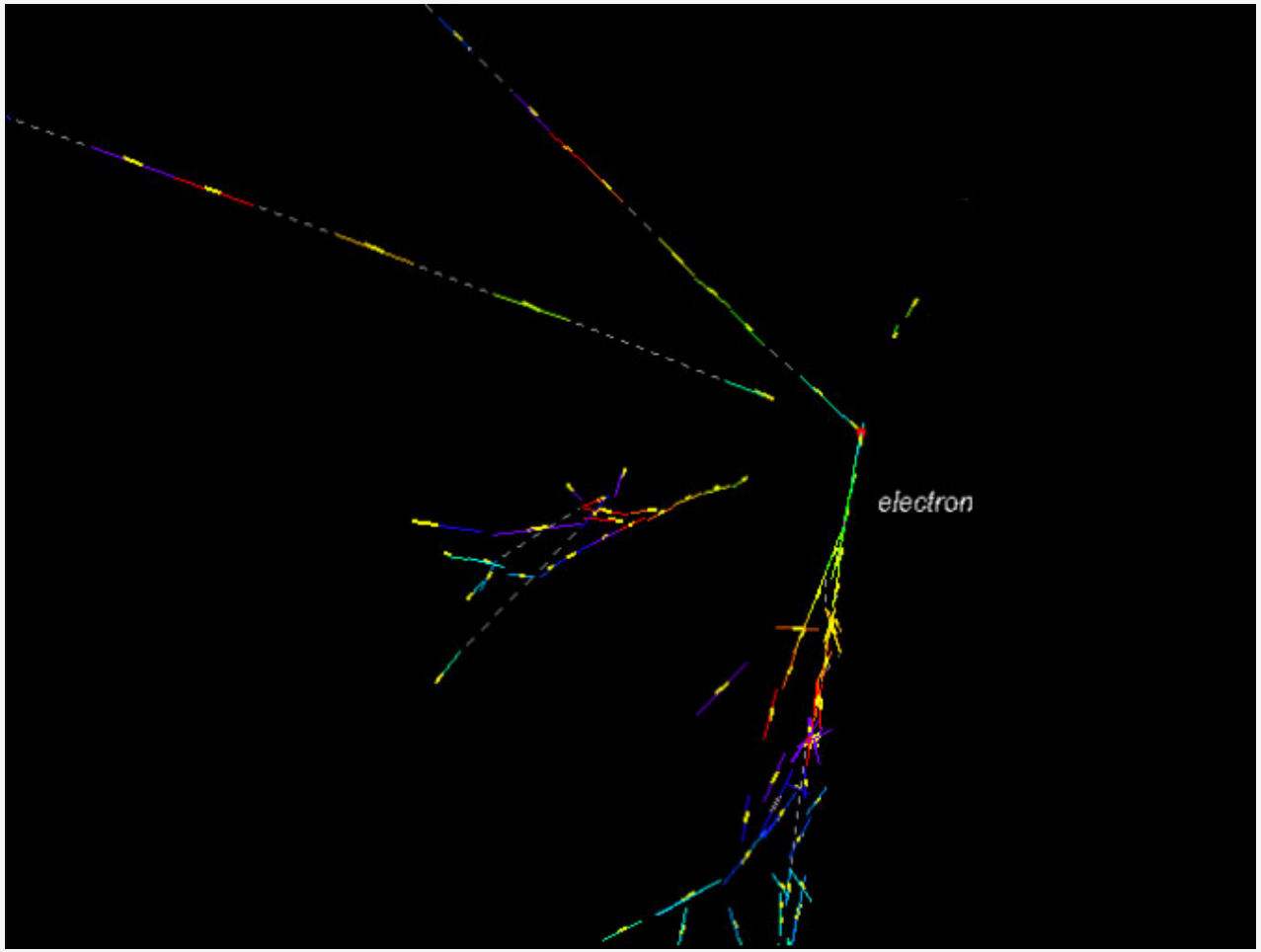


ECC reconstruction:



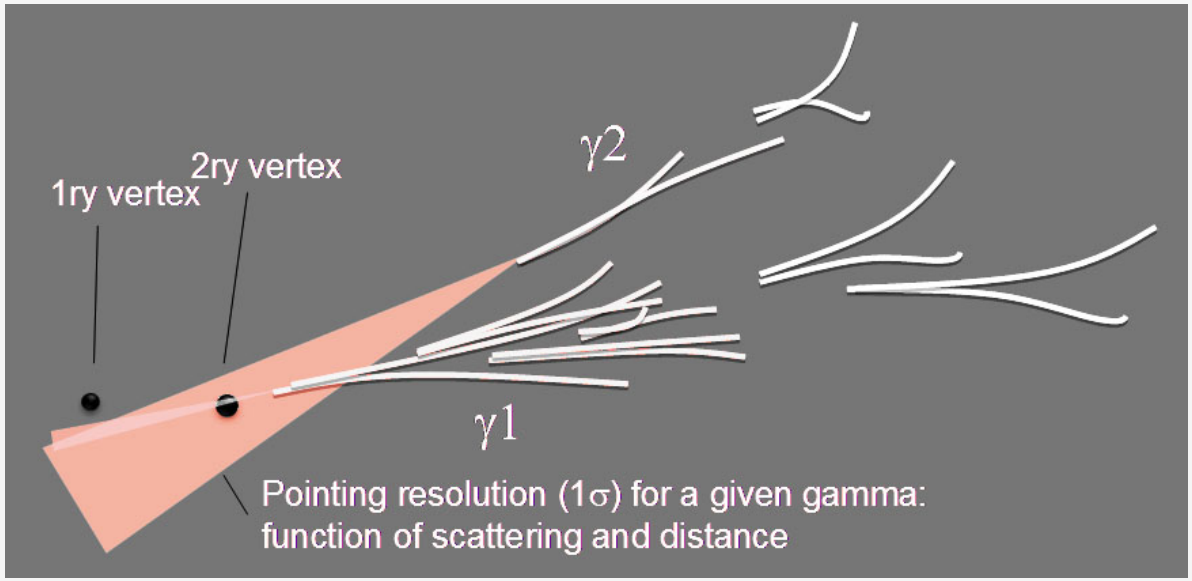
A ν_e Event

ECC reconstruction:



The First ν_τ Candidate Event

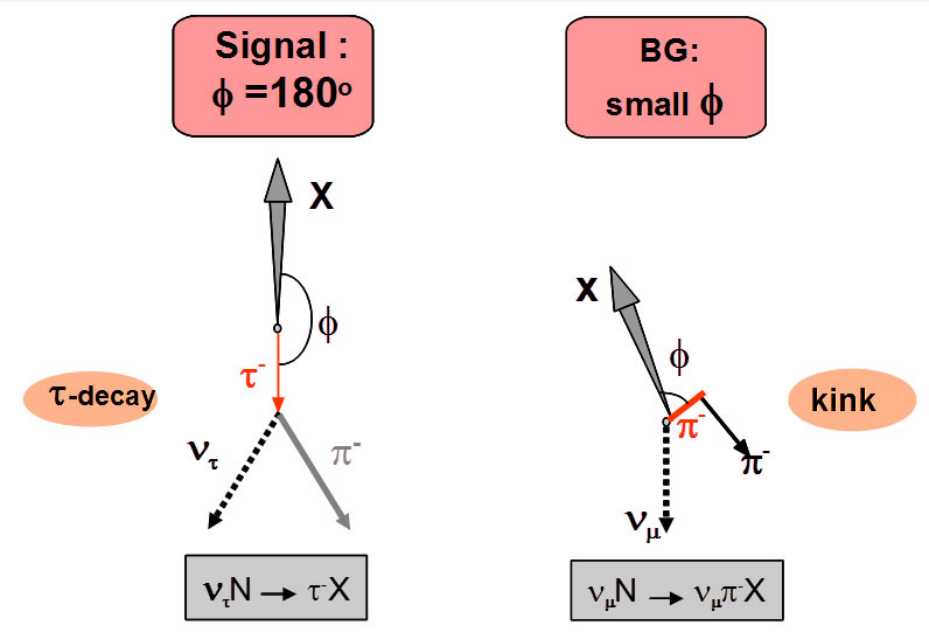
γ-attachment to the vertices:



	distance from 2ry vertex	*IP* w.r.t. 1ry vertex (resolution)	*IP* w.r.t. 2ry vertex (resolution)	Probability of attachment to 1ry vertex	Probability of attachment to 2ry vertex
$\gamma 1$	2.2 mm	45.0(11) μm	7.5(7) μm	$< 10^{-3}$	0.32
$\gamma 2$	12.6 mm	85.6(56) μm	22(50) μm	0.10	0.82

The First ν_τ Candidate Event

Angle between parent track and hadronic shower axis:



- **Selection criteria:** $\phi > \pi/2$.
- ν_τ **candidate event:** $\phi = (3.01 \pm 0.03)\,\mathrm{rad}$.

OPERA Expected Performance

Assumptions:

- $sin^2 2\theta_{23} = 1.$
- $\Delta m^2_{23} = 2.5 \times 10^{-3}\,\mathrm{eV}^2.$
- Total exposure of 22.5×10^{19} *p.o.t.*.

Expected performance:

- **Number of ν_μ CC + NC interactions:** $\sim 23600.$
- **Number of $\nu_e + \overline{\nu}_e$ CC interactions:** $\sim 160.$
- **Number of ν_τ CC interactions:** $\sim 115.$

τ decay channel	BR [%]	Number of signal events	Number of BG events
$\tau^- \to \mu^-$	17.7	2.9	0.17
$\tau^- \to e^-$	17.8	3.5	0.17
$\tau^- \to h^-$	49.5	3.1	0.24
$\tau^- \to 3h$	15.0	0.9	0.17
Total		10.4	0.75

Conclusion & Outlook

Other topics:

- $\nu_\mu \rightarrow \nu_\mu$ oscillation disappearance search.
- $\nu_\mu \rightarrow \nu_e$ oscillation appearance search.
- Atmospheric neutrino oscillation study.