Universität Hamburg
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Latest Results from the OPERA Experiment (and new Charge Reconstruction)

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on behalf of the

OPERA Collaboration

University of Hamburg
Institute for Experimental Physics

Astroparticle Physics 2014, Amsterdam

bmb+f - Förderschwerpunkt
OPERA
Großgeräte der physikalischen Grundlagenforschung

Overview

- The OPERA Experiment
- Oscillation Search: $\nu_\mu \rightarrow \nu_\tau$
- Oscillation Search: $\nu_\mu \rightarrow \nu_e$
- Charge Reconstruction with AMM
- Conclusion and Outlook

The OPERA Experiment

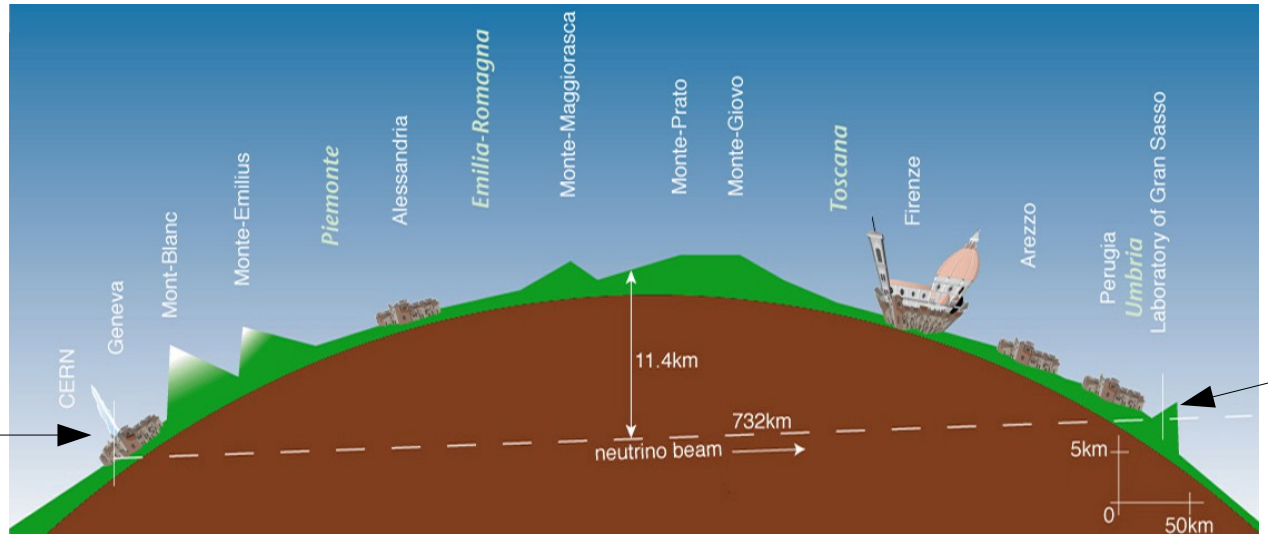
OPERA: **O**scillation **P**roject with **E**mulsion T**r**acking **A**pparatus

$$P(\nu_\mu \rightarrow \nu_\tau) \approx \sin^2(2\theta_{23}) \sin^2(\Delta m^2_{23} \frac{L}{4E})$$

Appearance measurement:

- First direct observation of $\nu_\mu \rightarrow \nu_\tau$ oscillation
  - Observation of ν_τ interactions and decay of τ leptons

The OPERA Experiment

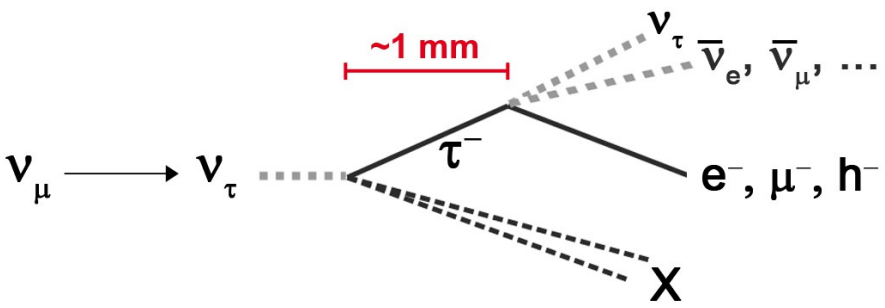


Realisation:

- High-energy long-baseline pure ν_μ beam
  - $<E_\nu>$ = 17 GeV
  - ~ 730 km distance from CERN to LNGS
- Large target mass with μm precision:
  - Emulsion Cloud Chambers (ECC): lead plates and nuclear emulsion films
  - Spectrometer for background reduction

ν_τ Detection

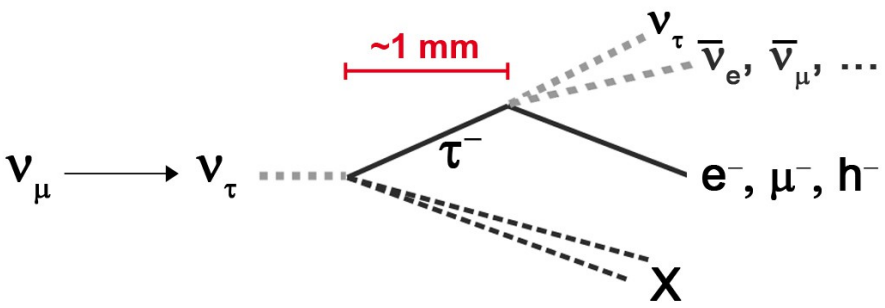
ν_τ signal:



- τ^- creation in ν_τ CC interaction
- Decay of the τ^- lepton after ~ 600 μm
  - Topology: 'kink' characteristic of the tau decay (missing energy)

ν_τ Detection

ν_τ signal:



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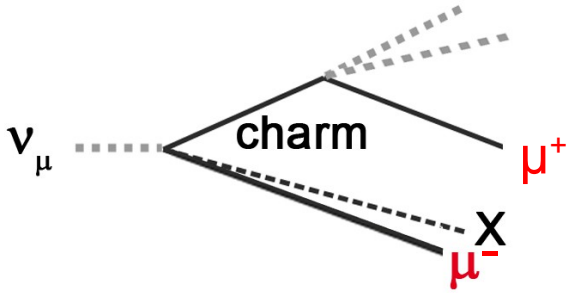
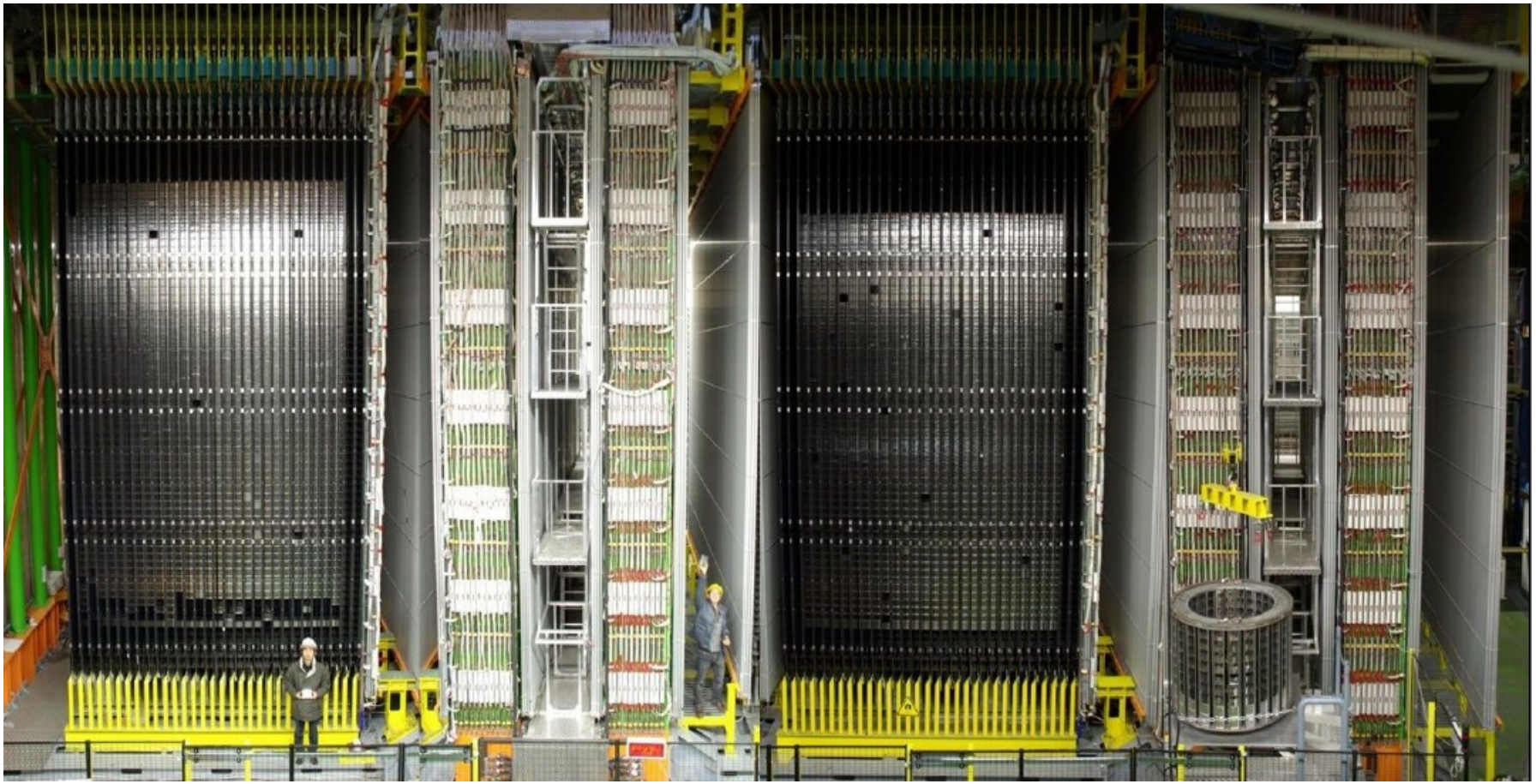
Background processes:



- ν_μ CC interactions with charm production & undetected muon(s)
- Hadronic re-interactions of secondary hadrons in lead
- Large-angle μ scattering

The OPERA Hybrid Detector



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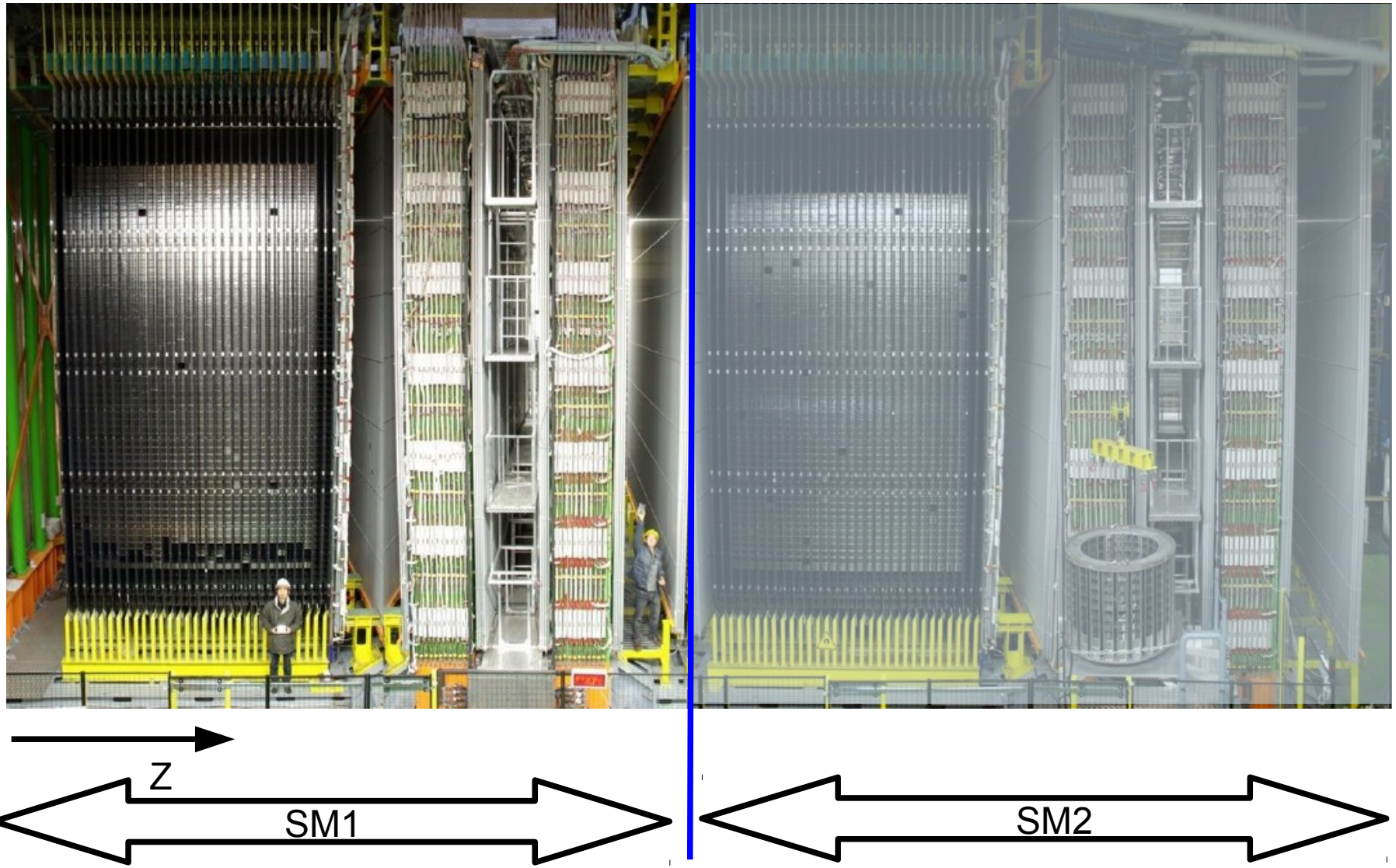

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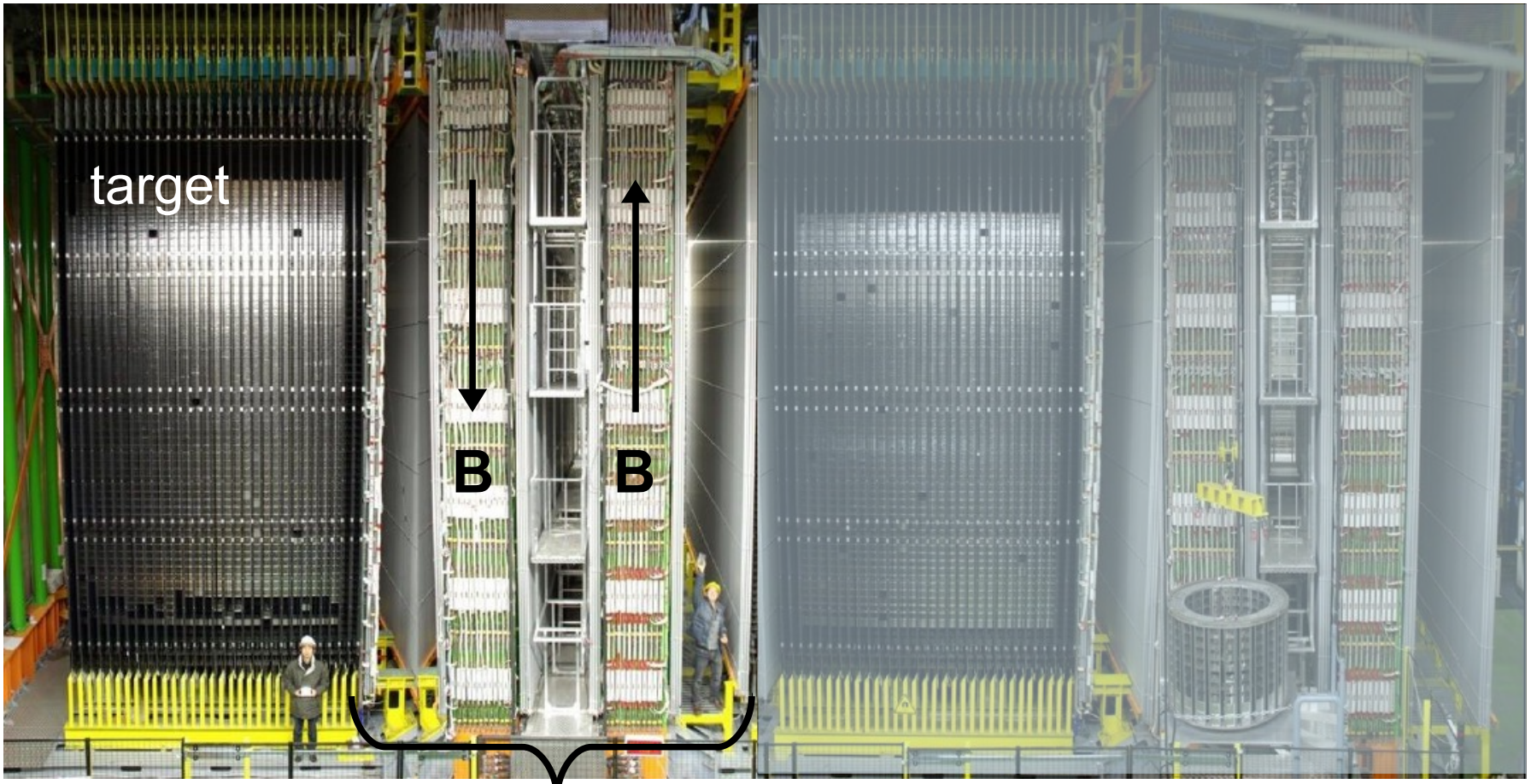

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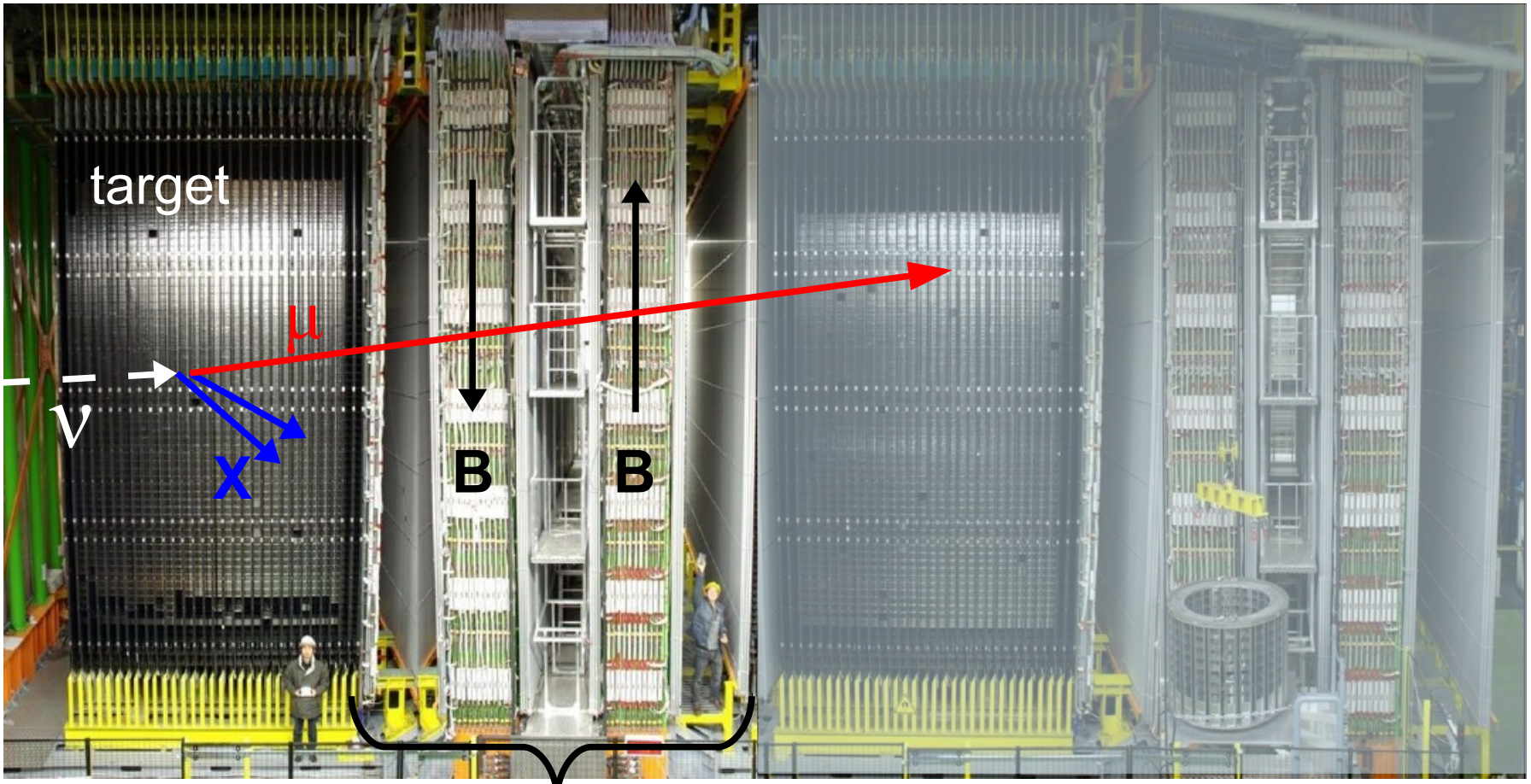
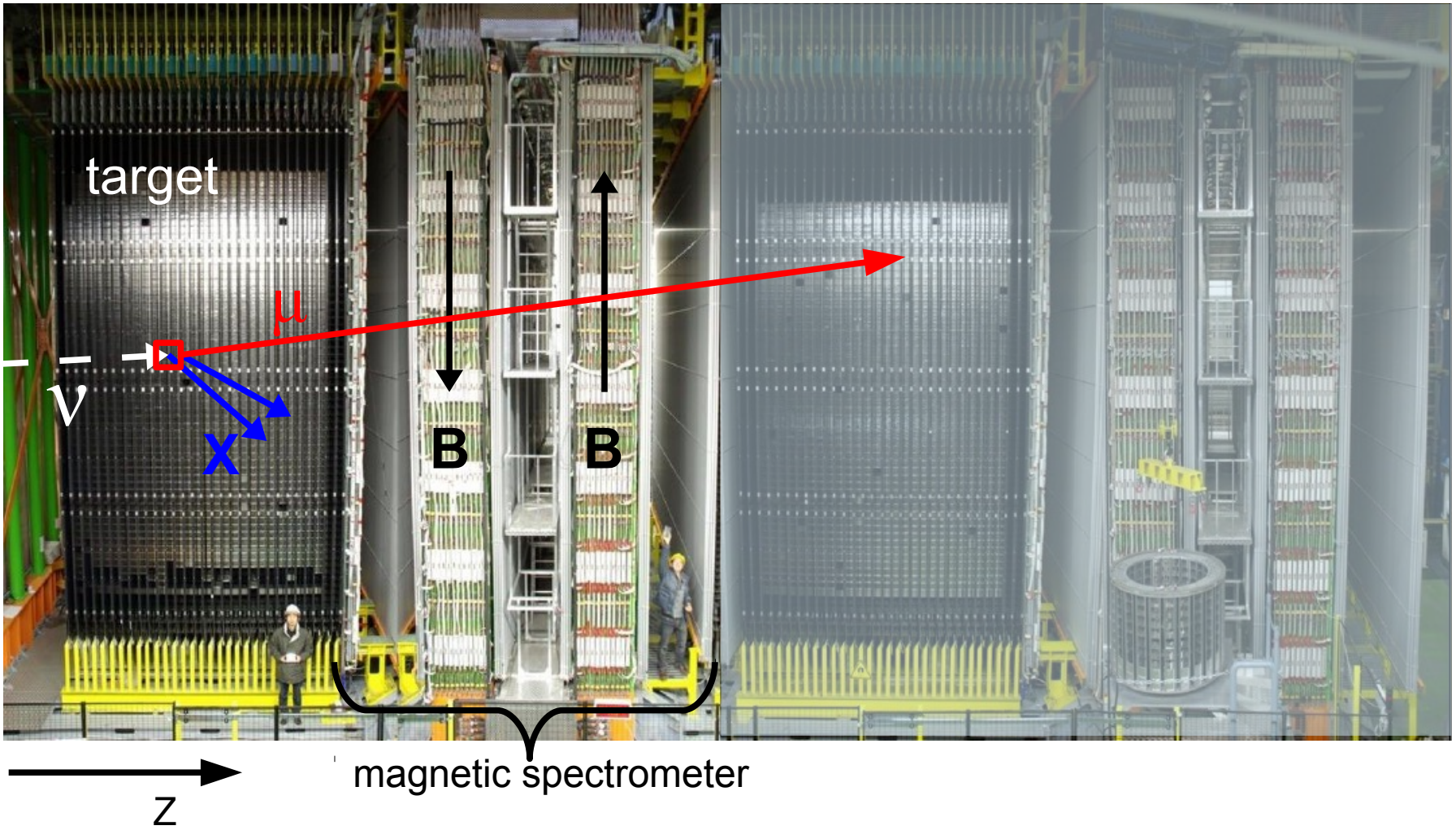
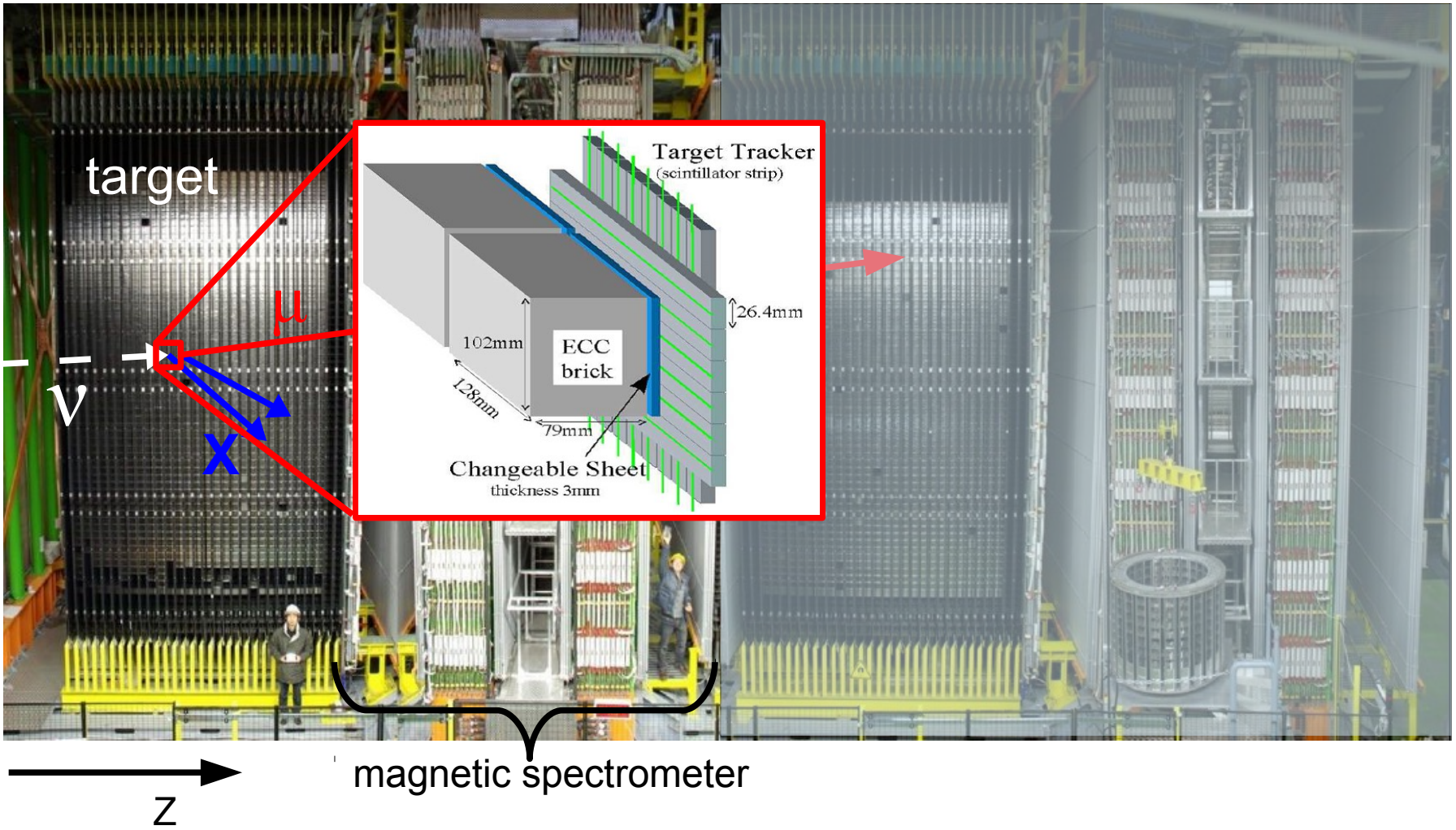


The OPERA Hybrid Detector



The OPERA Hybrid Detector



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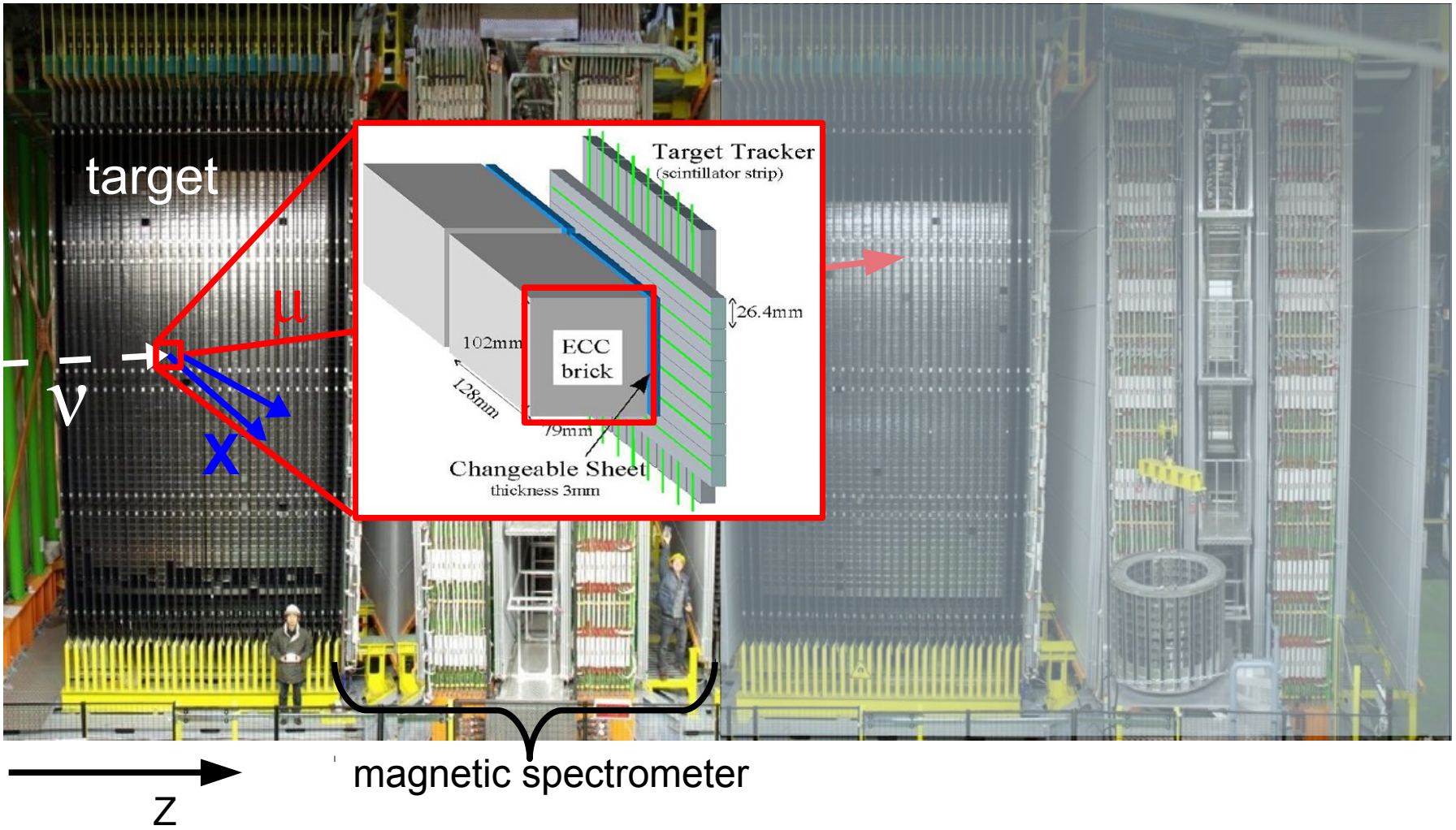

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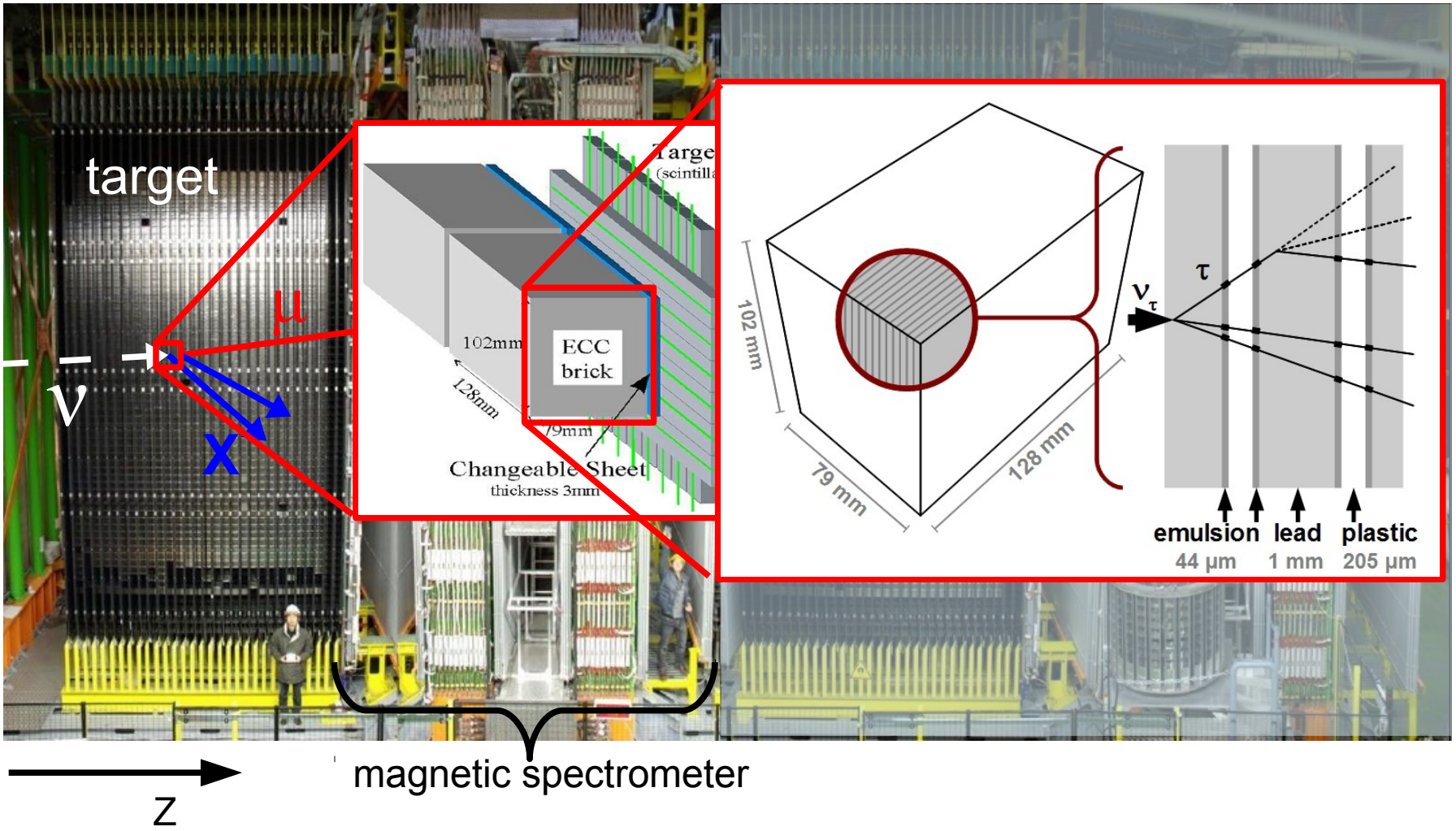
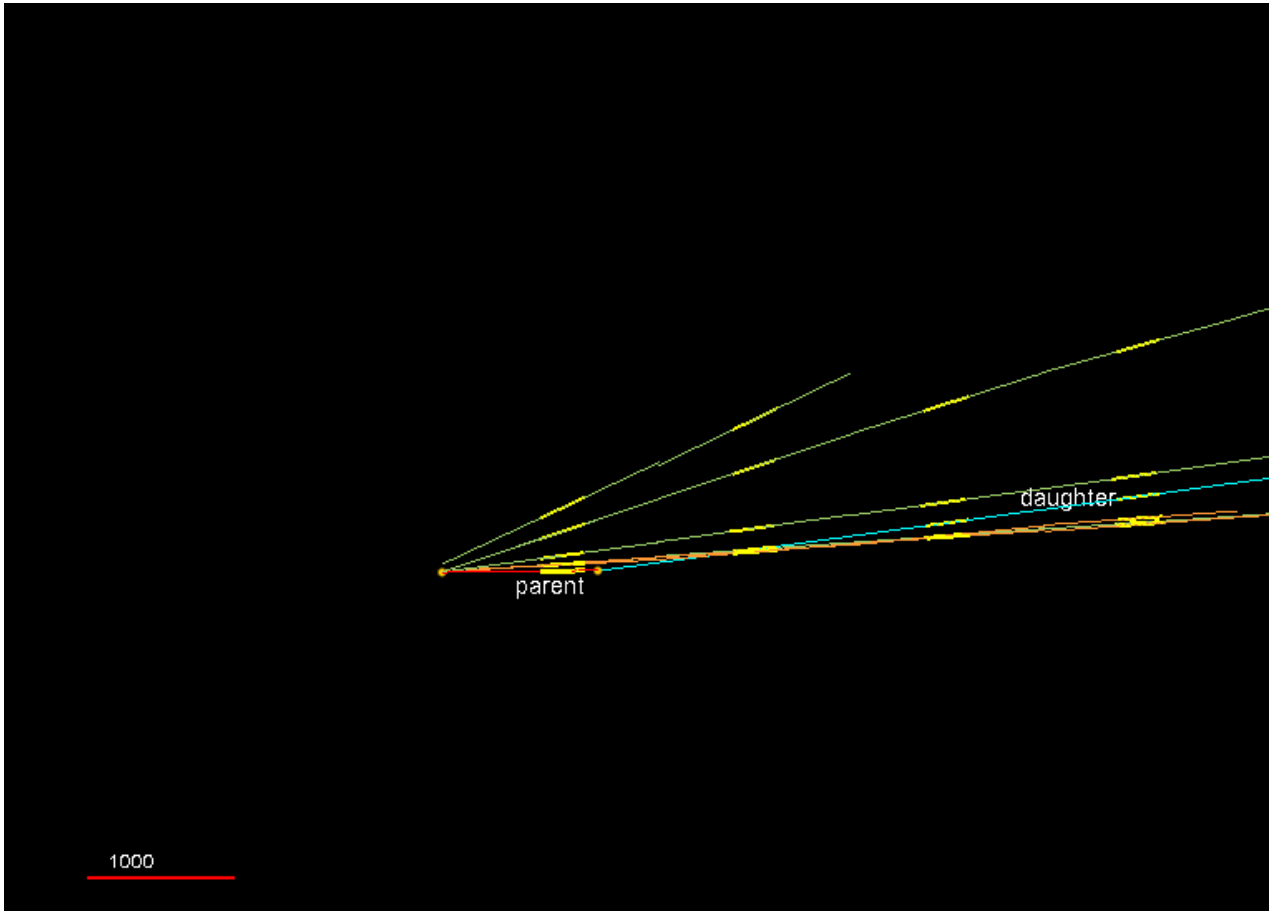


$\nu_\mu \rightarrow \nu_\tau$ Oscillation Search (main goal)

The 4th ν_τ Candidate Event

ECC reconstruction

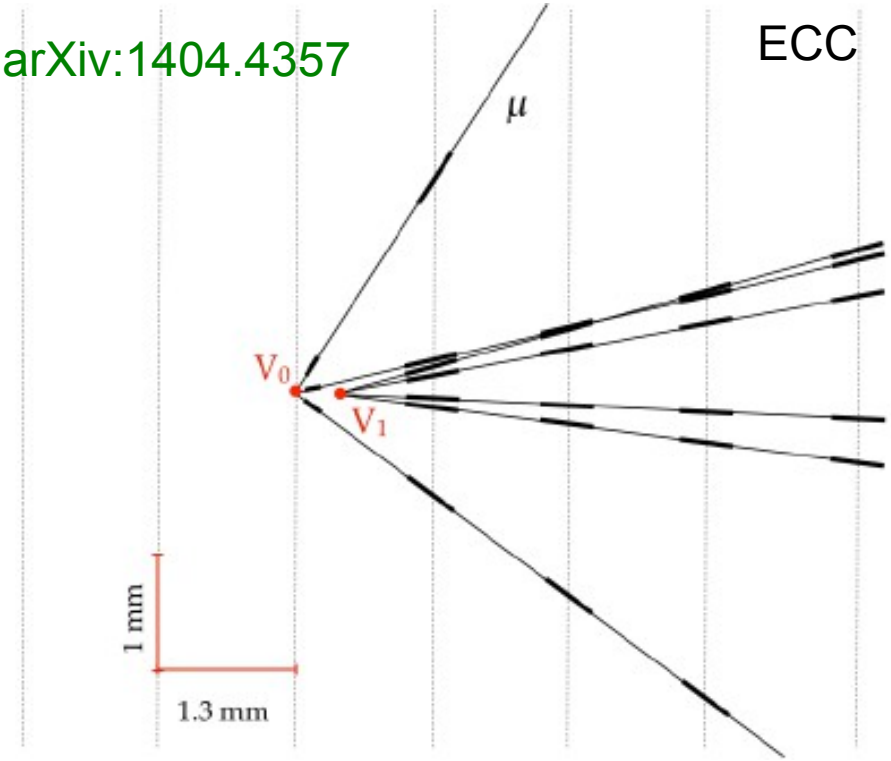


- Primary vertex: 4 tracks
- Red track: tau decay secondary candidate after 1.09 mm
- Decay channel: $\tau \rightarrow 1h$

Charm Control Sample

2008 – 2010 OPERA data set

arXiv:1404.4357



54 ± 4 charm events expected
50 observed in control sample

Reconstructed ν_μ CC interaction
with a charmed hadron in the final state

$\nu_\mu \rightarrow \nu_\tau$ Analysis Overview

17.97 * 10^{19} p.o.t total (~80% of the proposal) and 19505 ν target interactions

Data sample:

OPERA recent results at Neutrino 2014

4688 events (2008 – 2009: two most probable bricks, 2010 – 2012: first most probable brick)

- 4 signal events observed vs. 0.232 expected background events
- p-value for background fluctuation 1.03 * 10^{-5}
- No oscillation hypothesis excluded at 4.2 σ

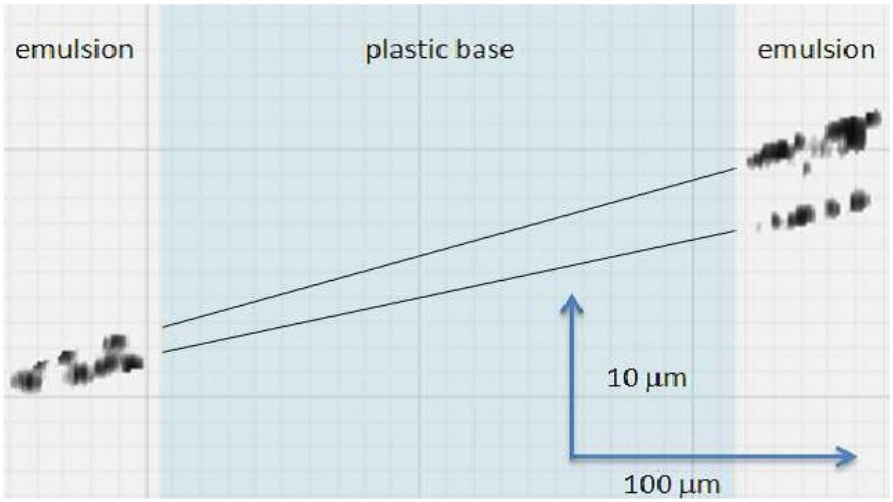
τ decay channel	Expected signal $\Delta m_{23}^2 = 2.32$ meV^2	Background analyzed sample	Observed events
$\tau^- \rightarrow \mu^-$	0.52 ± 0.1	0.018 ± 0.007	1
$\tau^- \rightarrow e^-$	0.61 ± 0.12	0.027 ± 0.005	0
$\tau^- \rightarrow h^-$	0.4 ± 0.08	0.033 ± 0.006	2
$\tau^- \rightarrow 3h$	0.57 ± 0.11	0.155 ± 0.03	1
Overall	2.1 ± 0.42	0.232 ± 0.041	4

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

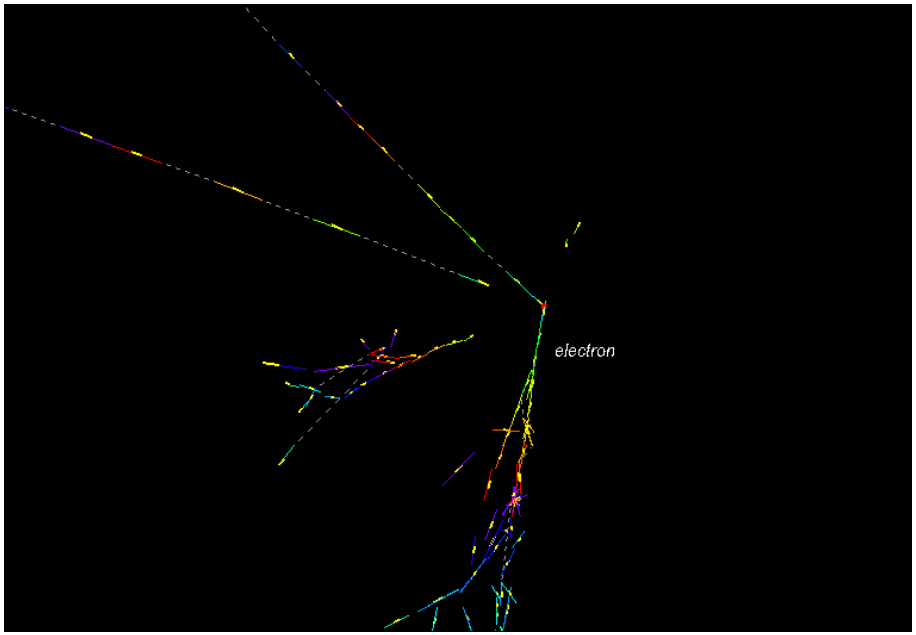
ν_e Appearance

ν_e searched in 505 (~ 30% full statistic) Neutrino Interactions without a Muon in the final state

JHEP 1307 (2013) 004



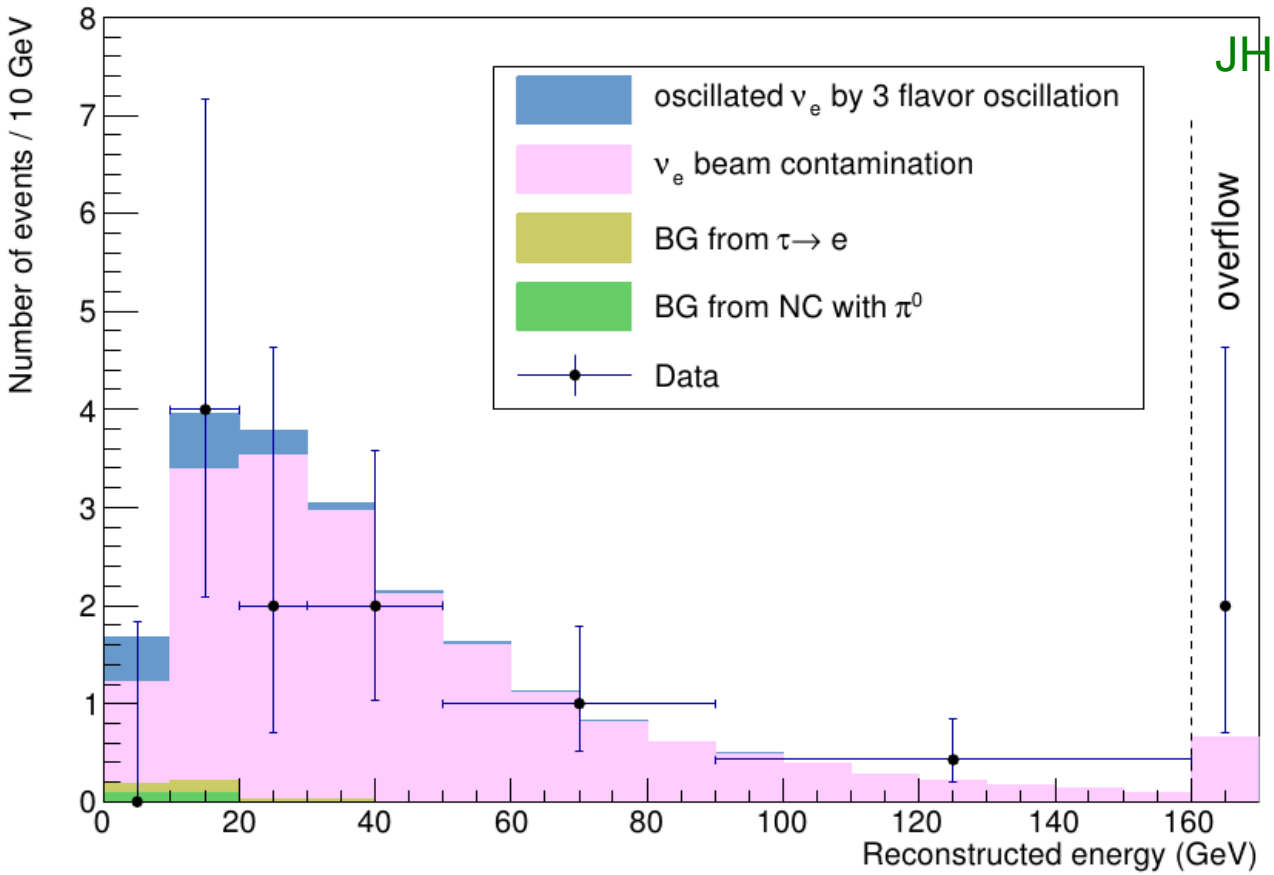
1µm resolution in the ECC Films
separation of e^+ e^- pairs and single e^-



ν_e interaction in ECC

ν_e Appearance

Distribution of reconstructed Energy of the ν_e Events



JHEP 1307 (2013) 004

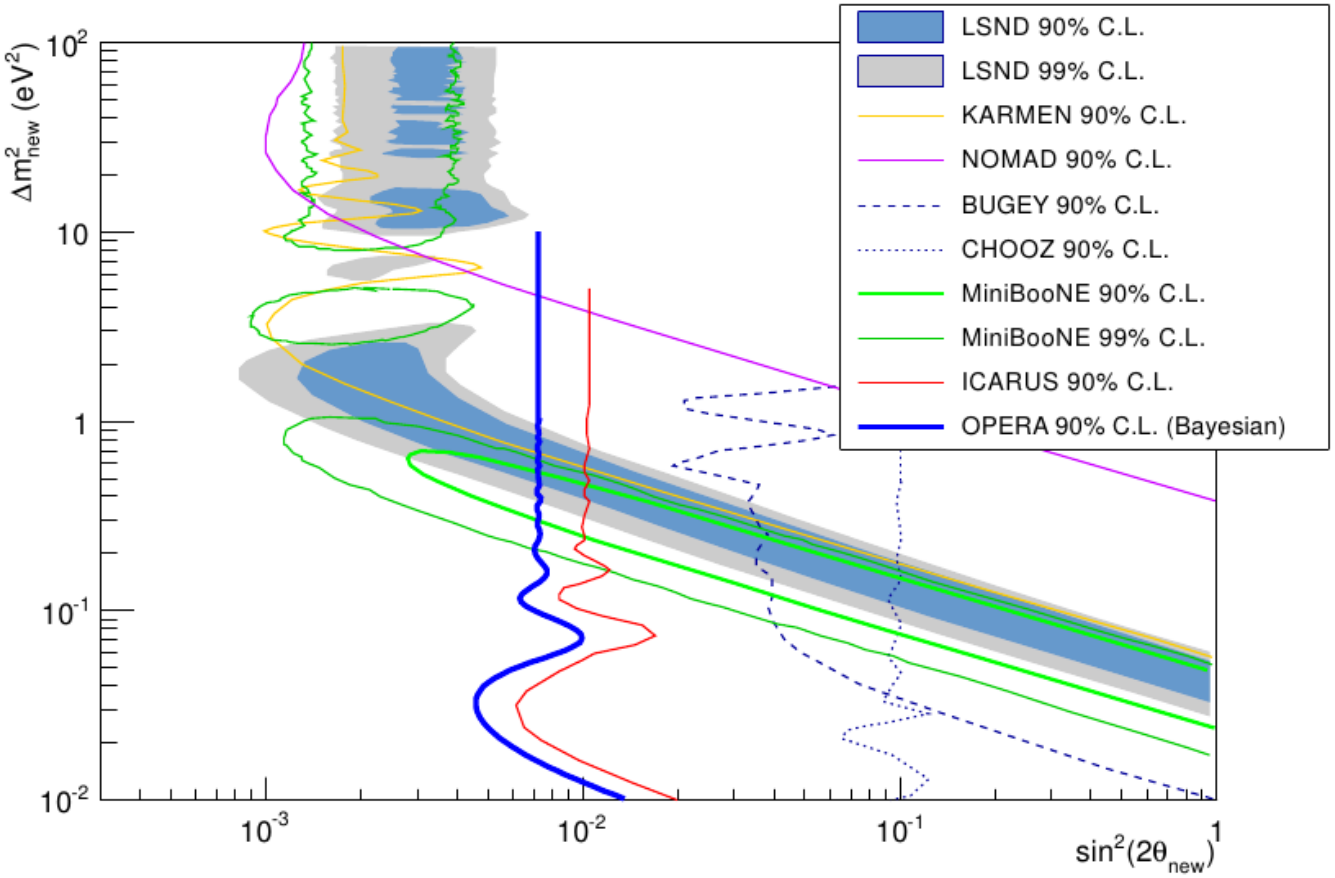
Compatible with no oscillation hypothesis

Expected Background for 3-flavour Analysis: 19.8
Observed Events : 19

ν_e Appearance

Exclusion limits for a fourth sterile neutrino

JHEP 1307 (2013) 004

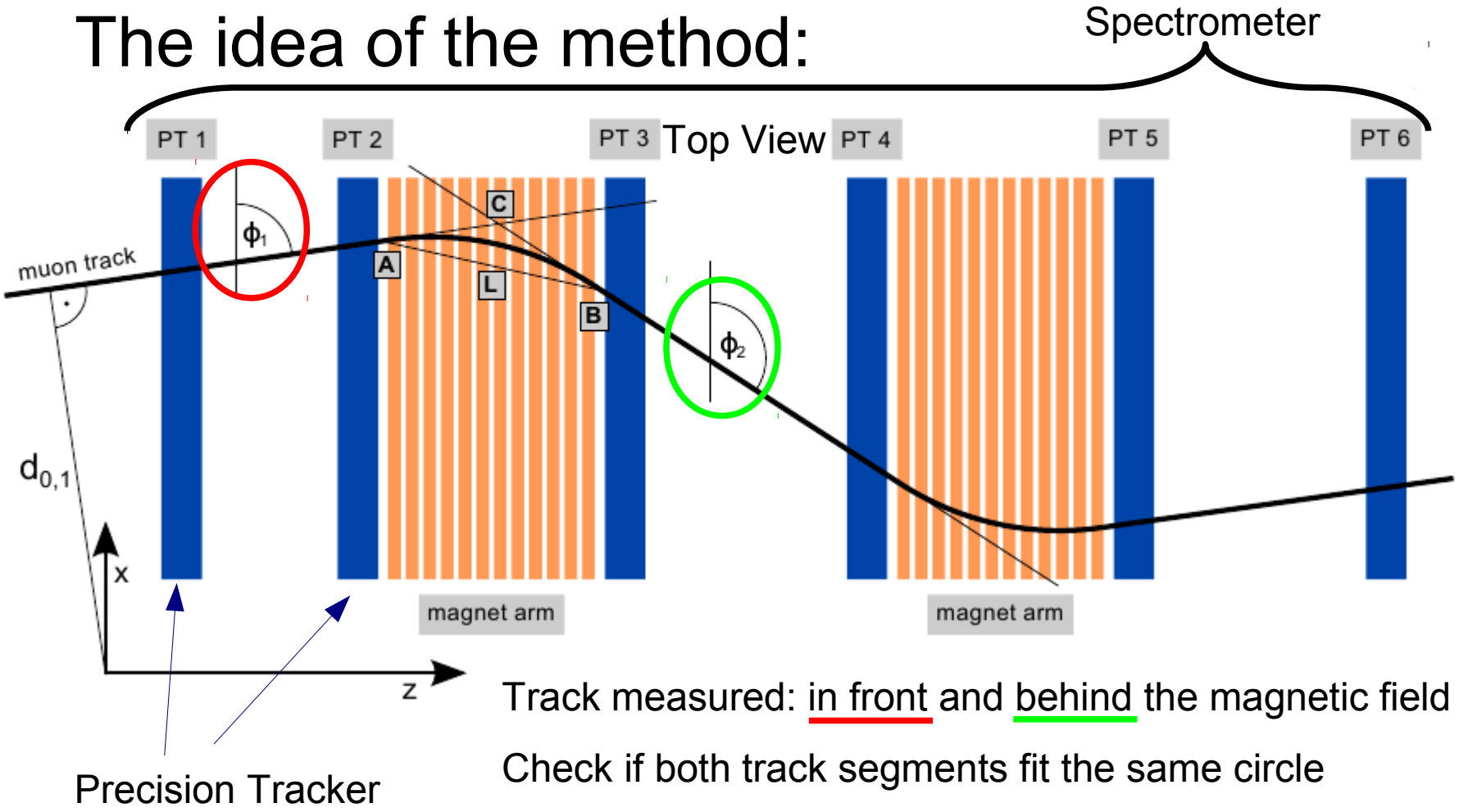


$\sin^2(2\theta_{new}) < 7.2 \times 10^{-3}$ (90% CL) at large values of Δm^2

Charge Reconstruction with the new Angular Matching Method

Angular Matching Method (AMM)

The idea of the method:



Track measured: in front and behind the magnetic field

Check if both track segments fit the same circle

Construct a weight to indicate the accuracy of fit (from 0 to 1)

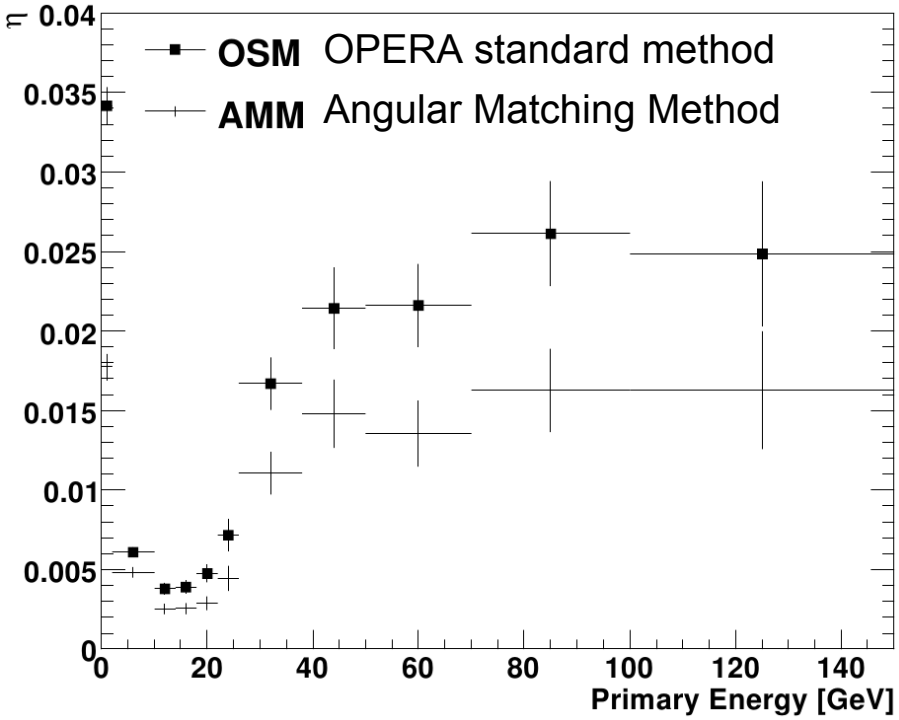
Impurity with AMM

arXiv:1404.5933

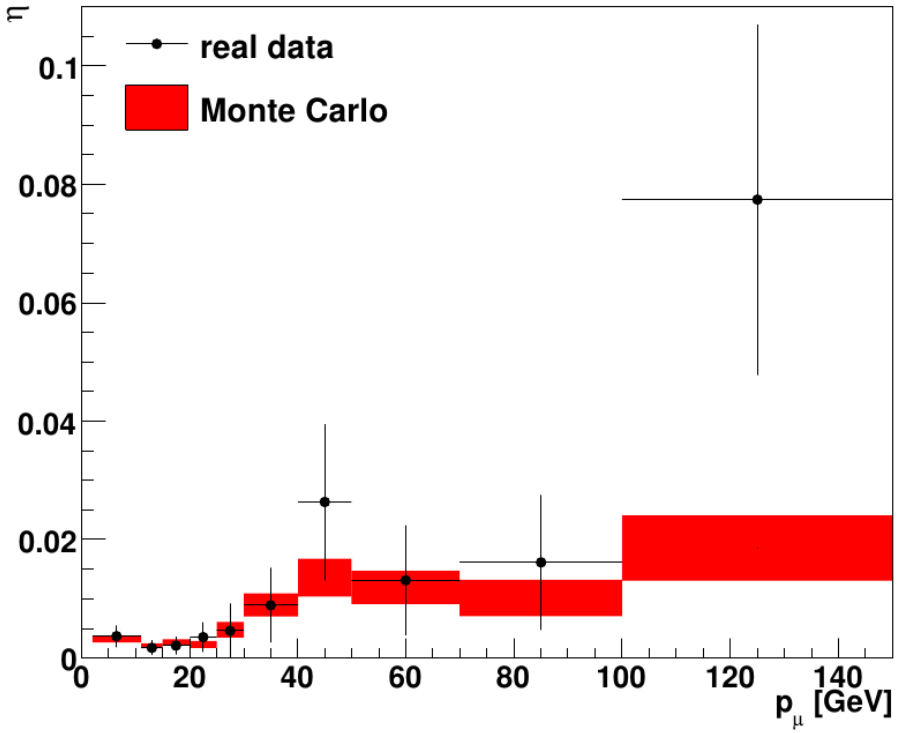
Impurity: $\eta = n_w / n_c$ n_w : number of wrong charge sign determination

n_c : number of events with charge sign determination

Realistic beam Monte Carlo (MC II)



Impurity for one super module



Conclusion and Outlook

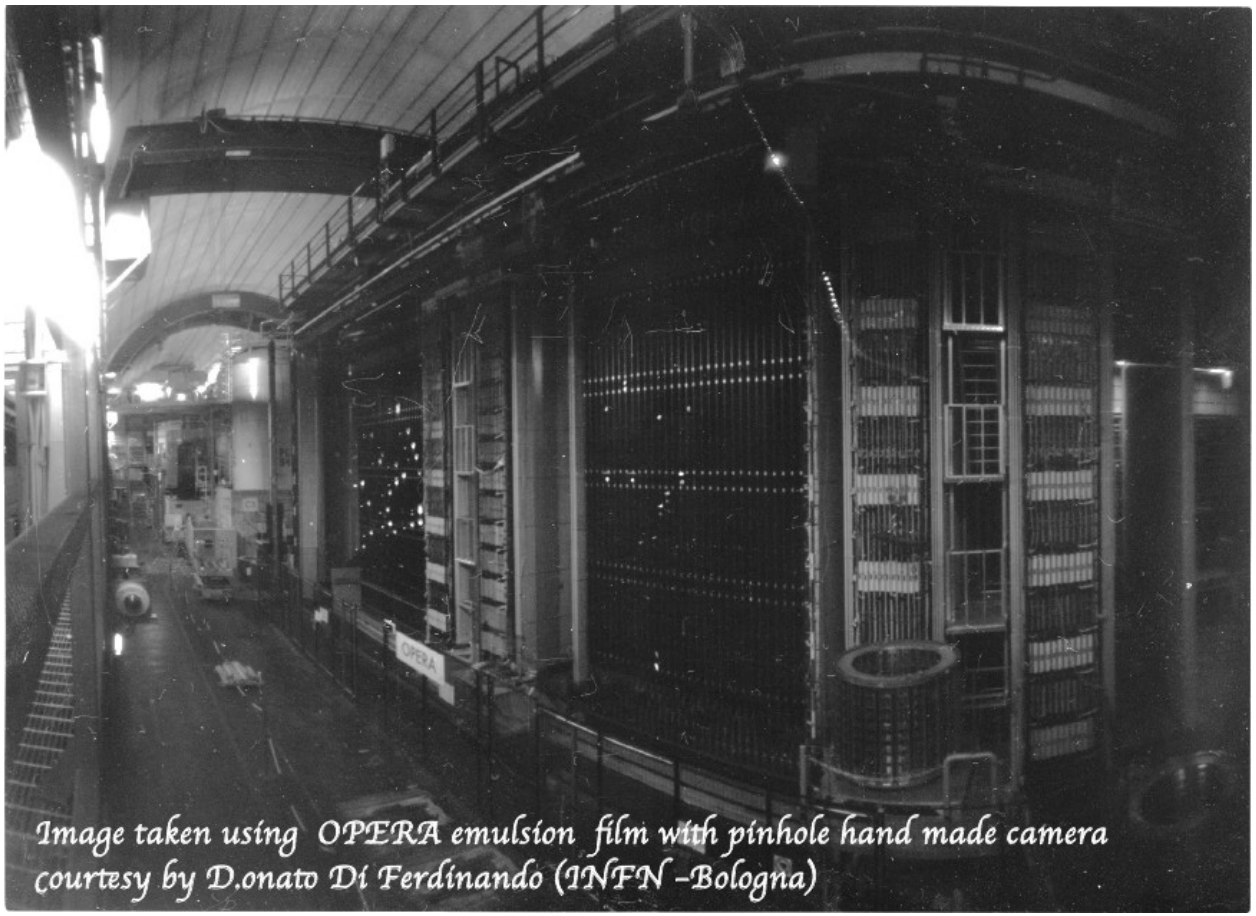
Conclusion

- CNGS beam concluded: 2008 – 2012
  - 17.97 * 10^{19} p.o.t. (80% of the proposed)
  - 19505 ν beam target interactions
- τ appearance:
  - Confirmed ν_τ candidate events: 4
  - Non oscillation excluded at 4.2 σ (conservative approximation)
- e appearance:
  - Measured events compatible with no oscillation hypothesis
  - Limit for sterile neutrino $\sin^2(2\theta_{new}) < 7.2 \times 10^{-3}$ (90% CL) at high Δm^2

Outlook

- τ appearance:
  - Completing scanning and analysis
  - Improve background studies
  - Likelihood fit
- e appearance:
  - Analysis with full data sample
- Angular Matching Method (AMM):
  - Capability to reduce charm background

Thank you for your attention!



OPERA Publications

• N. Agafonova et al. [OPERA Collaboration], Evidence for $\nu_\mu \rightarrow \nu_\tau$ appearance in the CNGS neutrino bean with the OPERA experiment,
Phys. Rev. D 89, 051102(R) (2014)

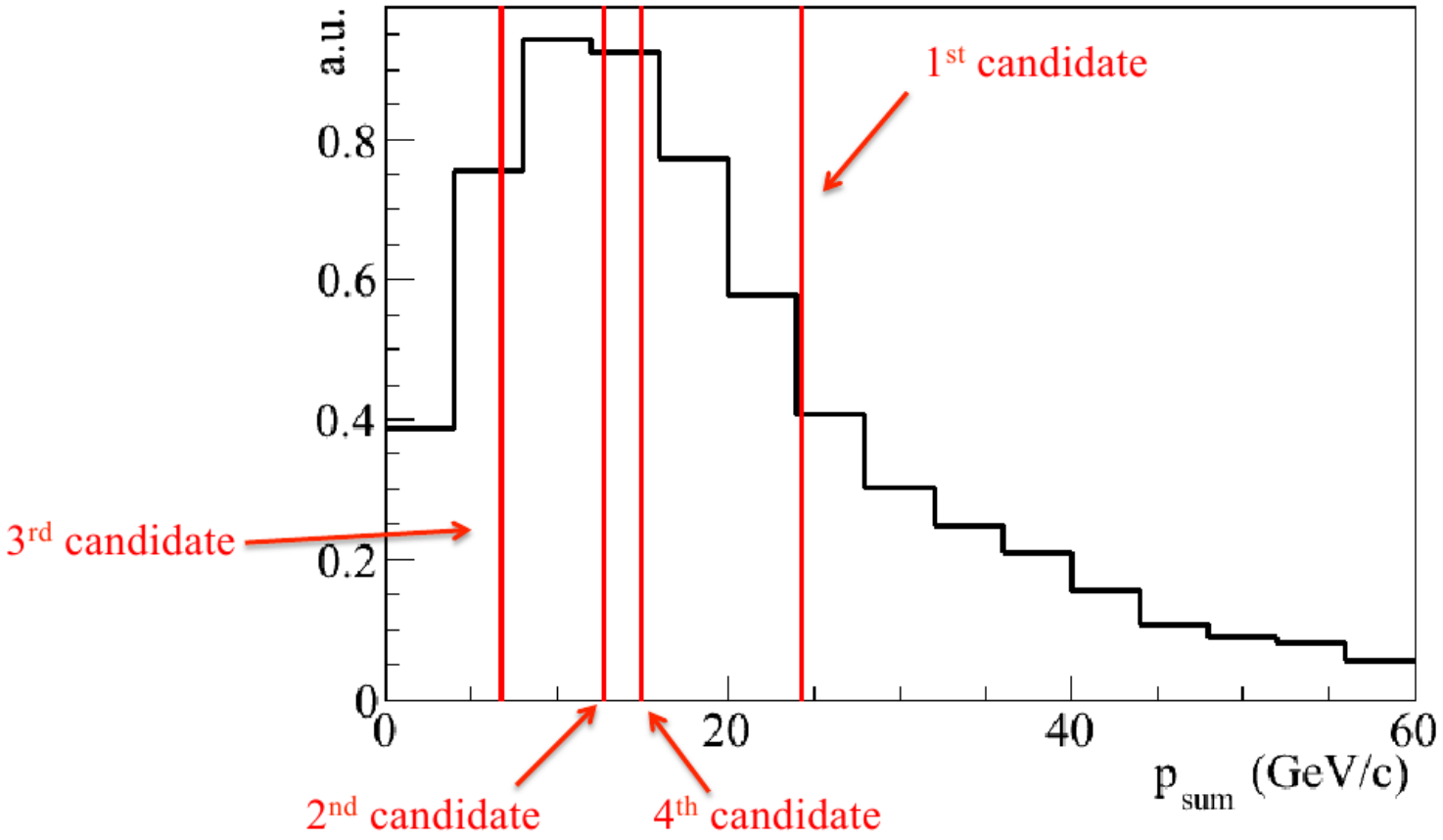
• N. Agafonova et al. [OPERA Collaboration], Search for $\nu_\mu \rightarrow \nu_e$ oscillations with the OPERA experiment in the CNGS beam,
JHEP 1307 (2013) 004

• N. Agafonova et al. [OPERA Collaboration], The Angular Matching Method for the Muon Charge Sign Measurement in the OPERA Experiment,
arXiv:1404.5933 (2014)

Backup

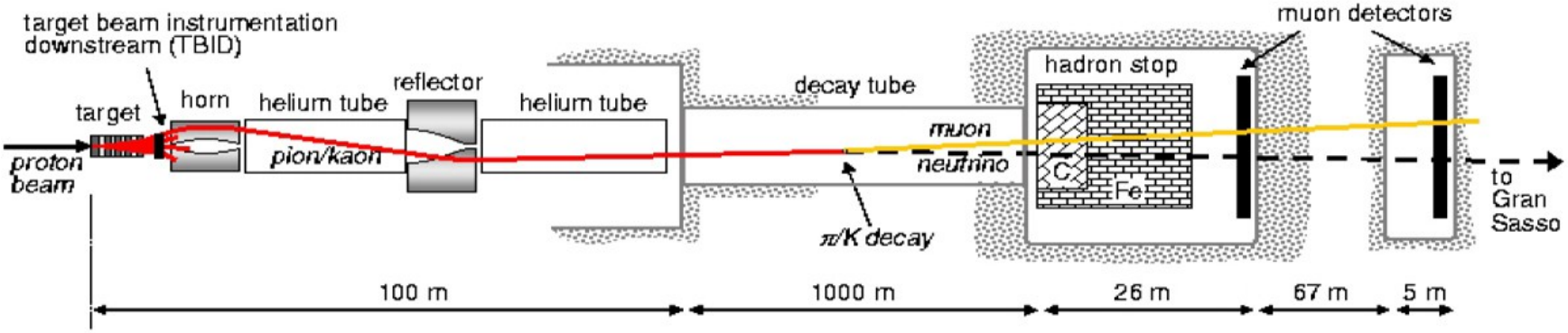
Visible Energy of all Tau Candidates

Sum of the momenta of charged particles and γ's measured in emulsion



The CNGS ν_μ Beam

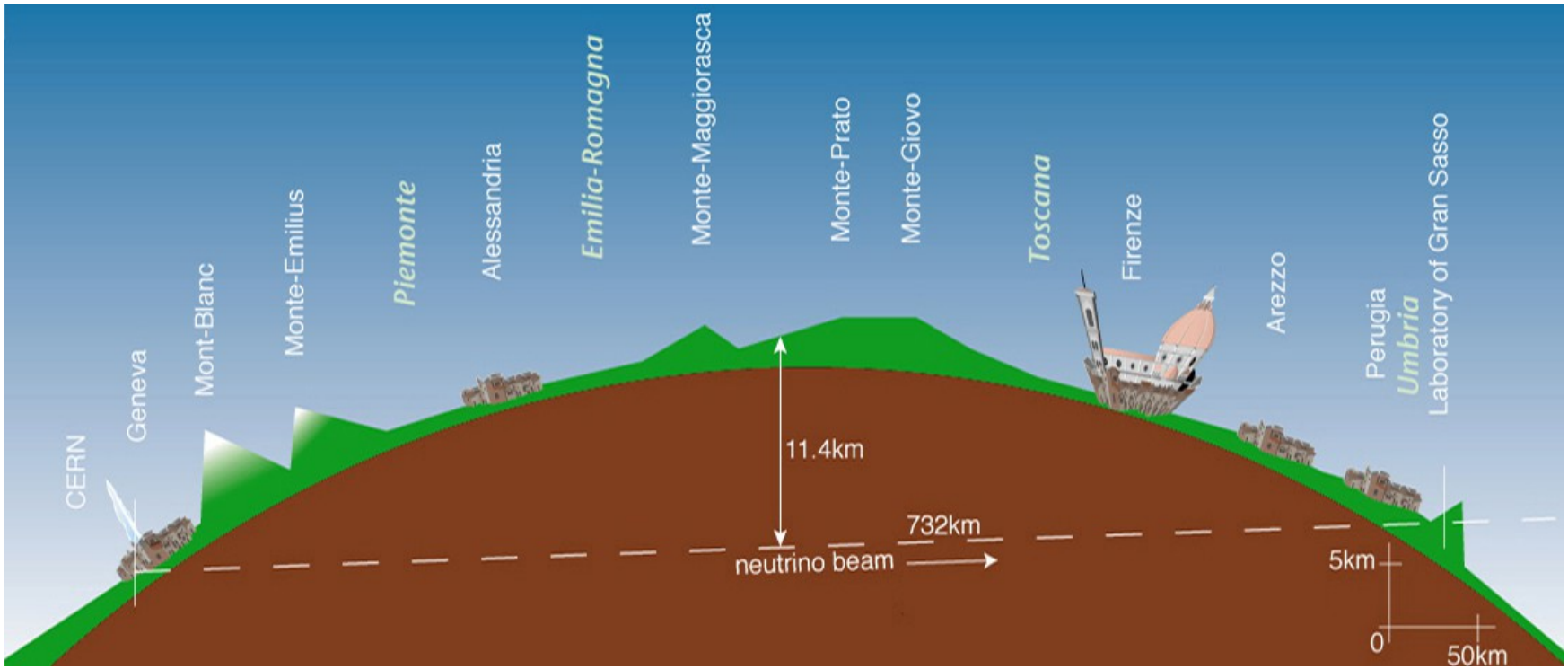
CNGS: **C**ERN **N**eutrinos to **G**ran **S**asso



$\langle E_p \rangle$		400 GeV
$\langle E_\nu \rangle$		17 GeV
$\overline{\nu}_\mu / \nu_\mu$	CC	2.1 %
ν_e / ν_μ	CC	0.89 %
$\overline{\nu}_e / \nu_\mu$	CC	0.06 %
ν_τ / ν_μ	CC	$< 10^{-4}$ %

The CNGS ν_μ Beam

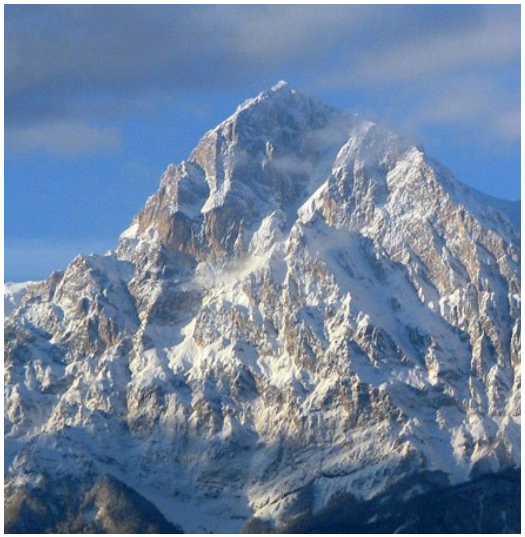
CNGS: **C**ERN **N**eutrinos to **G**ran **S**asso



- Baseline: ~ 730 km distance form CERN to LNGS

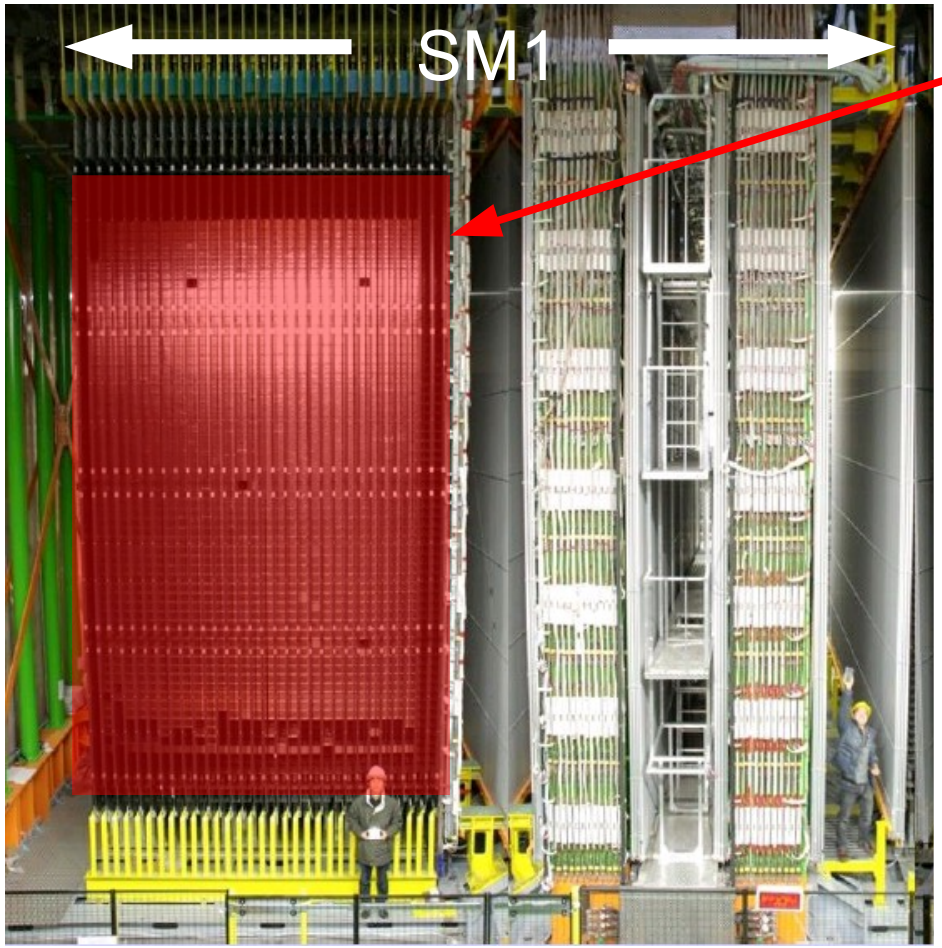
LNGS

LNGS: **L**aboratori **N**azionali del **G**ran **S**asso



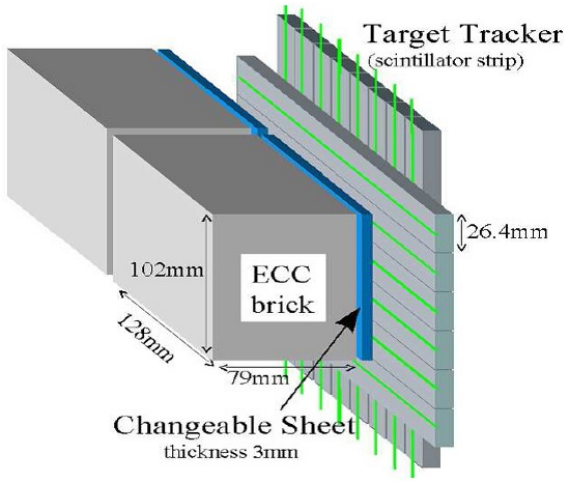
- Location: Below mountain Corno Grande of Gran Sasso, Italy
- Vertical rock coverage: 1400 m (3800 m.w.e.)
- Cosmic μ rate: ~ 1 $m^{-2}\,h^{-1}$

The Target Area

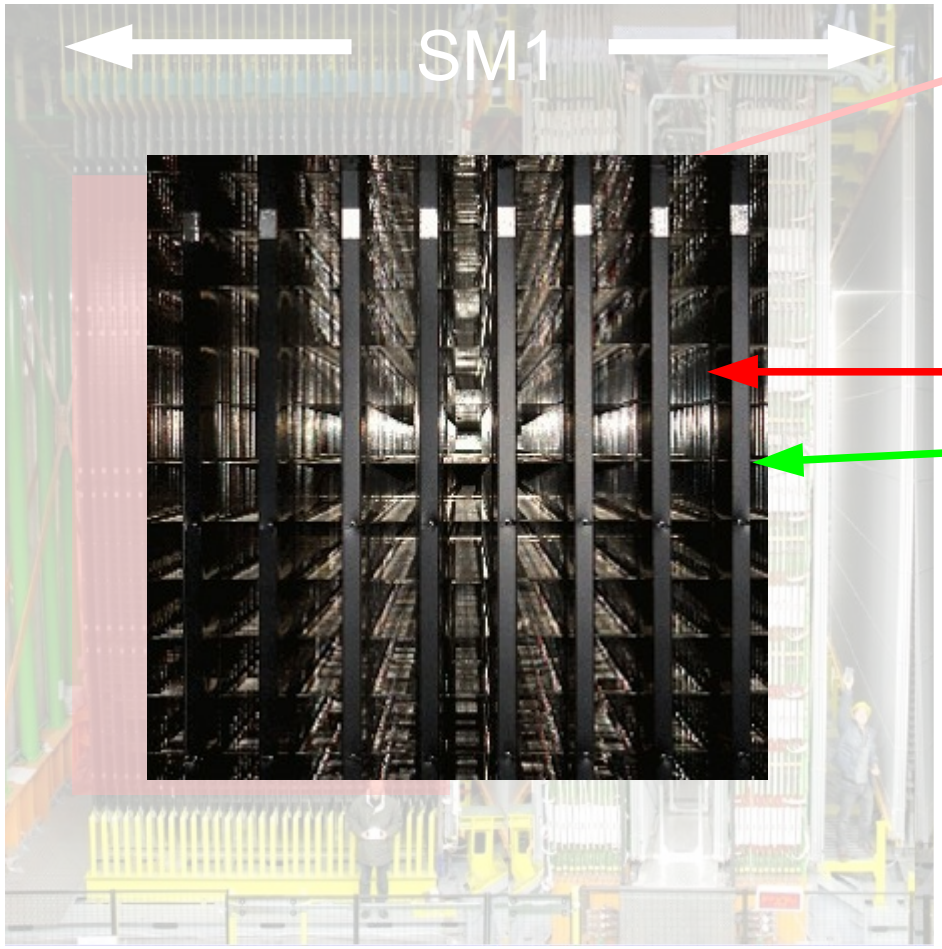


Target Area consist of:

- Emulsion Cloud Chambers (ECC) called bricks
- 31 walls of holder infrastructure for ECC bricks and Target Tracker (TT)

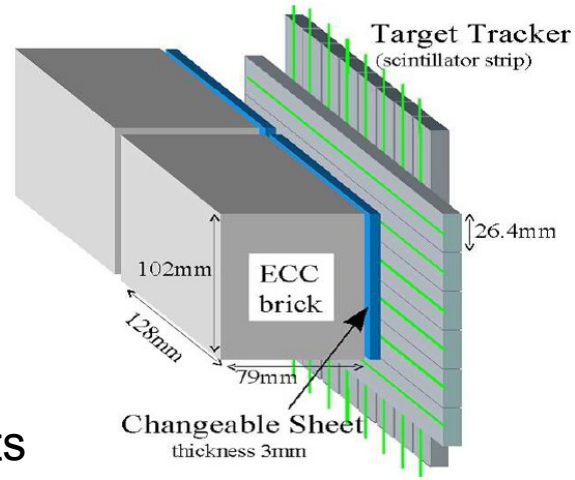


The Target Area



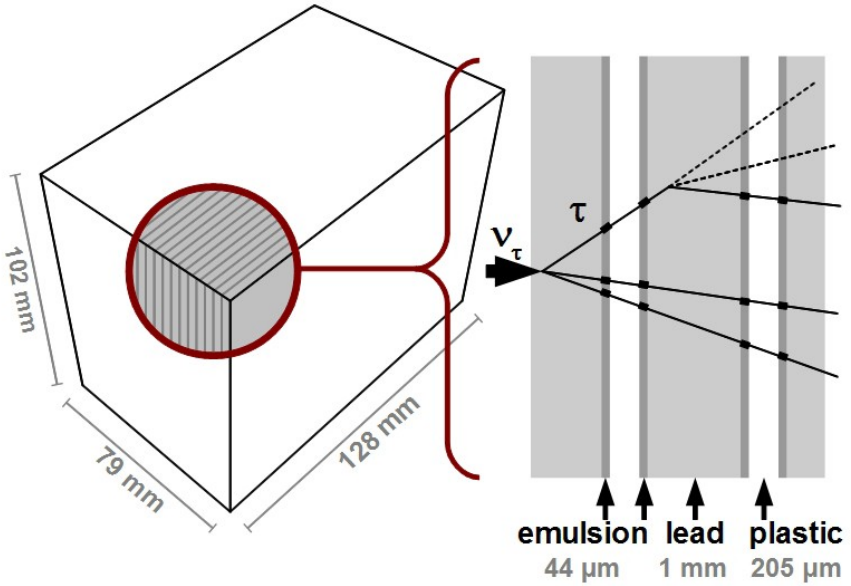
Target Area consist of:

- Emulsion Cloud Chambers (ECC) called bricks
- 31 walls of holder infrastructure for ECC bricks and Target Tracker (TT) plastic scintillator strips (horizontal & vertical)



Changeable Sheets (CS): 2 extra emulsion sheets

Emulsion Cloud Chamber



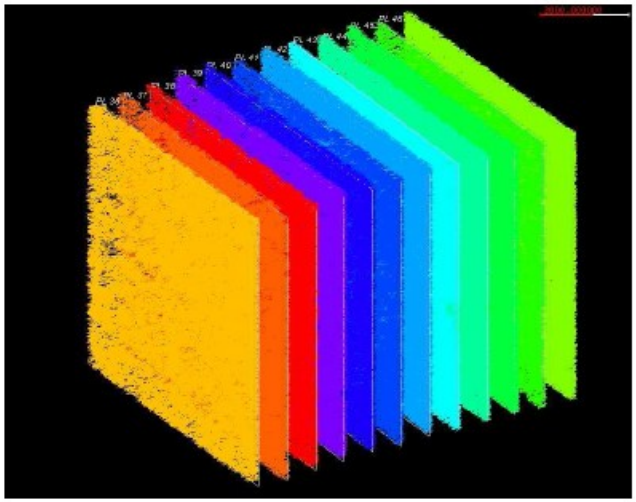
Emulsion Cloud Chamber (ECC) bricks:

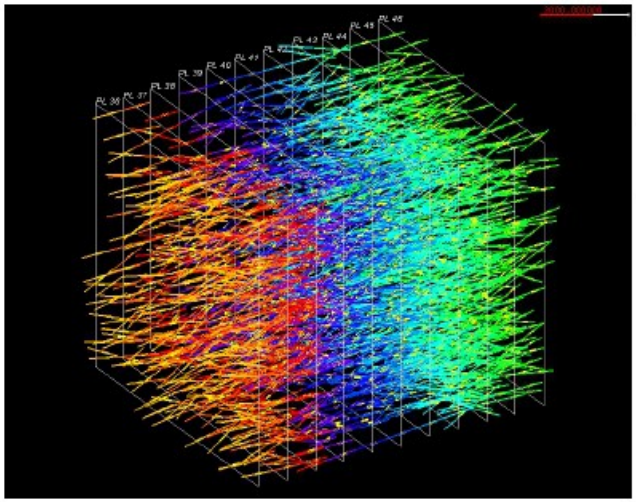
- **Per brick:** 57 x 2 nuclear emulsions in plastic base, 56 lead plates (altogether corresponding to ~ 10 X_0)
- **Total:** ~ 150 000 bricks of 8.3 kg each (~ 1.25 kt total target mass)
- **Spatial / angular resulution:** ~ 1 µm / ~ 2 mrad

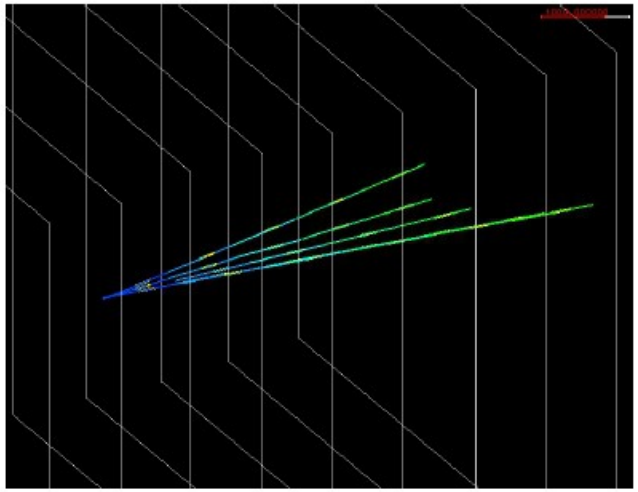
Event Reconstruction

Event Reconstruction performed in 2 steps:

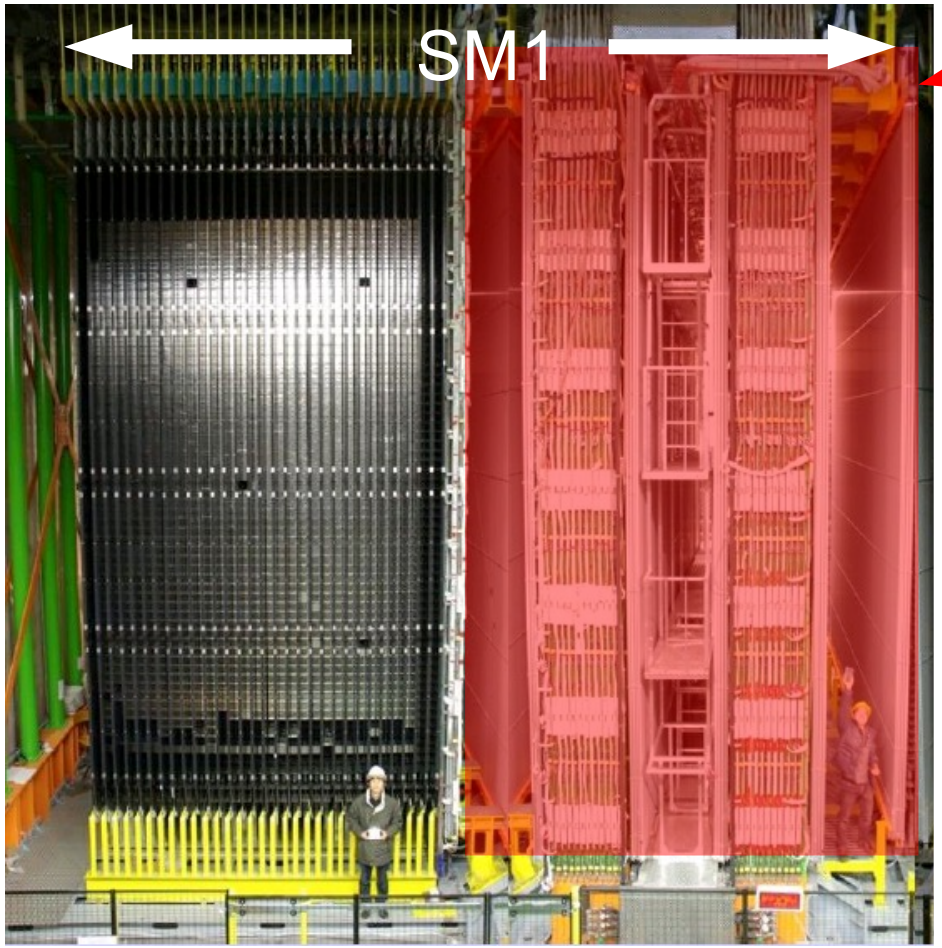
- Brick search with ED
- Emulsion (ECC):
  - Emulsions scanned by automatic microscopes
  - Track & ν interaction vertex reconstruction
  - Kinematical analysis







Magnetic Spectrometer



Magnetic Spectrometer:

- Downstream of each target area

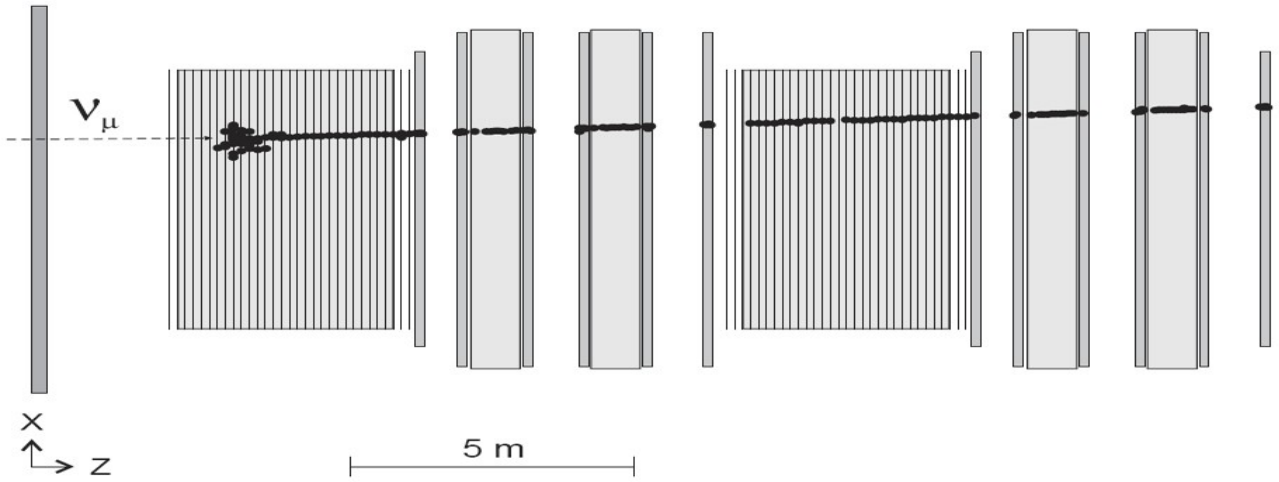
Consist of:

- Dipol magnets with 1.53 T
- Resistive Plate Chamber (RPC & XPC) detectors
- Precision Tracker (PT) drift tubes

Event Reconstruction

Event Reconstruction performed in 2 steps:

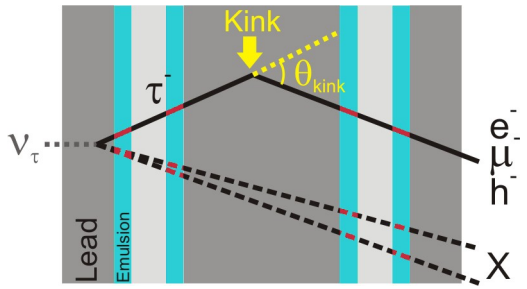
- Electronic detector:
  - ν interaction vertex localisation (with Target Tracker)
  - μ identification (CC/NC separation) & momentum measurement
  - Hadronic shower energy estimation
  - ➢ Triggers ECC event reconstruction



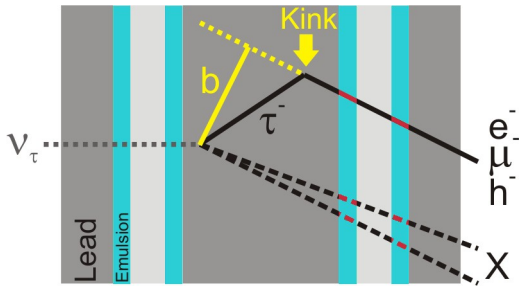
Event Reconstruction

τ decay search procedure:

- In-track kink search
- Search for extra tracks
- Measurement of the kink angle θ_{kink} or the impact parameter b



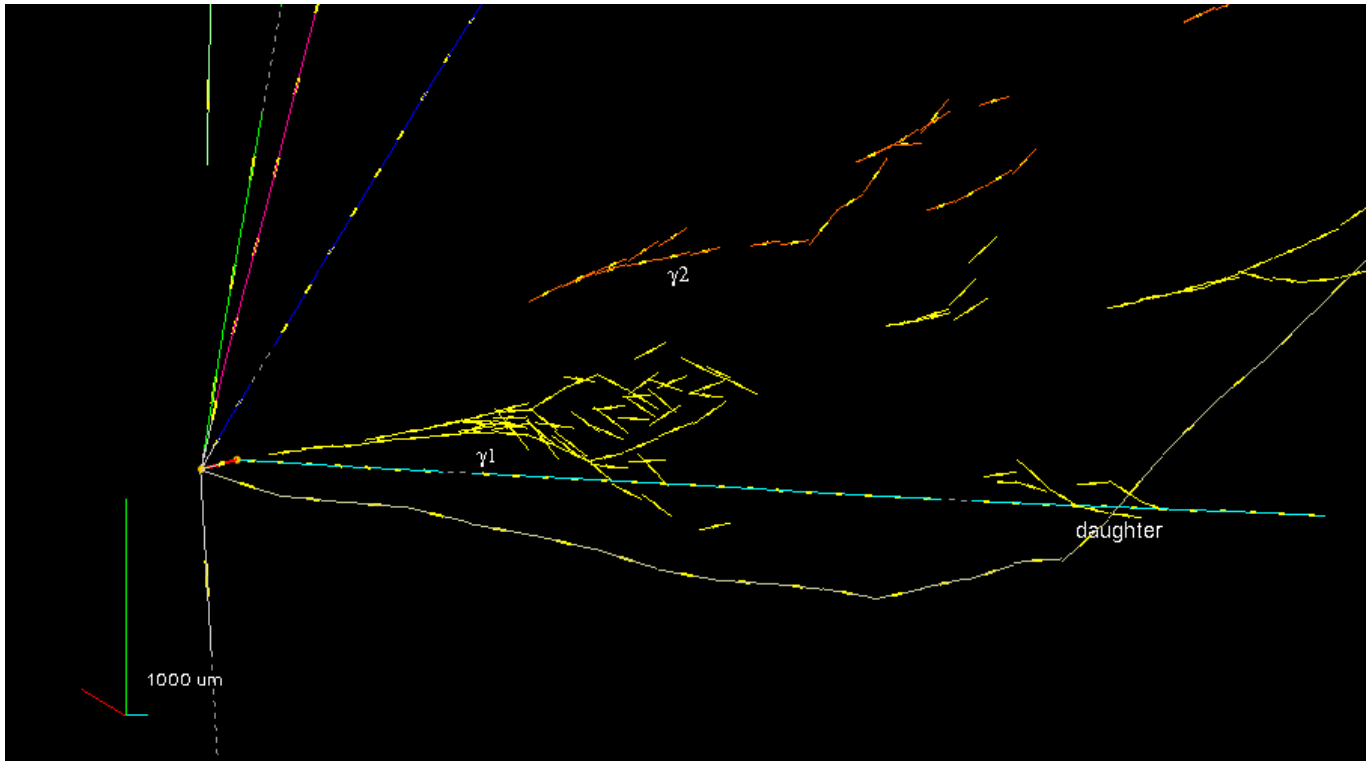
long decay



short decay

The 1st ν_τ Candidate Event

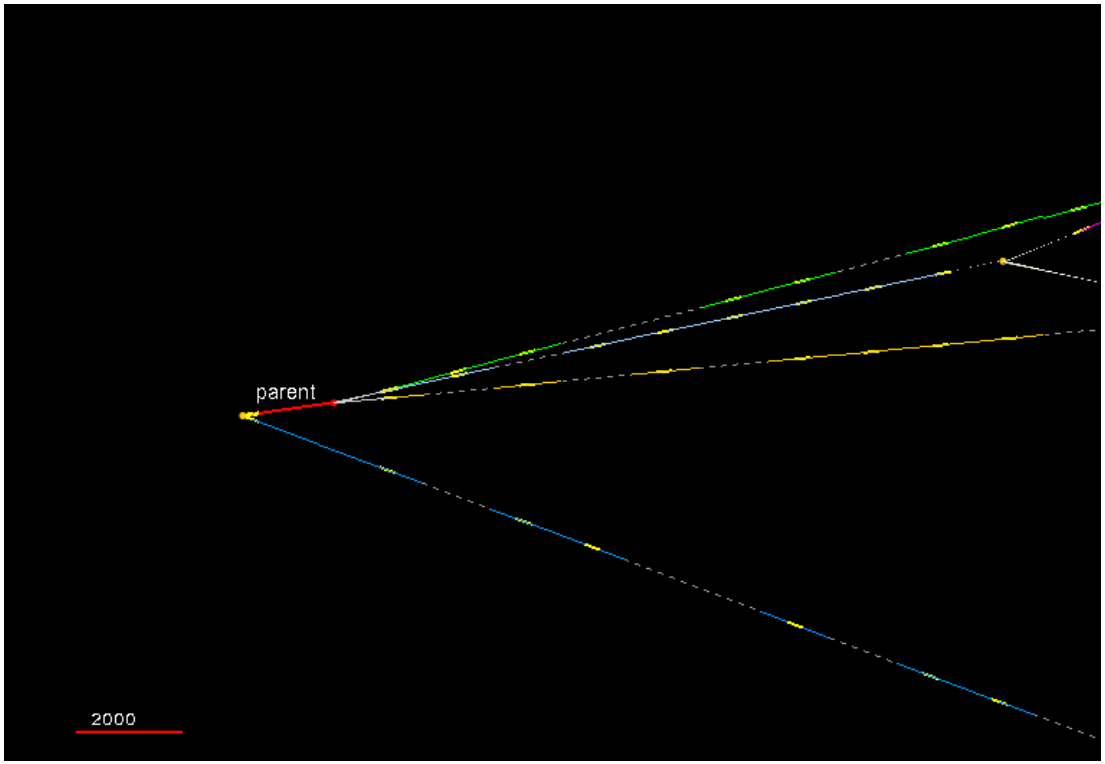
ECC reconstruction:



- Primary vertex: 7 tracks
- Red / cyan track(s): kink after 1.35 mm
- Decay channel: $\tau \rightarrow h\ (\tau^- \rightarrow \rho^-\ (\pi^-\pi^0)\nu_\tau)$

The 2nd ν_τ Candidate Event

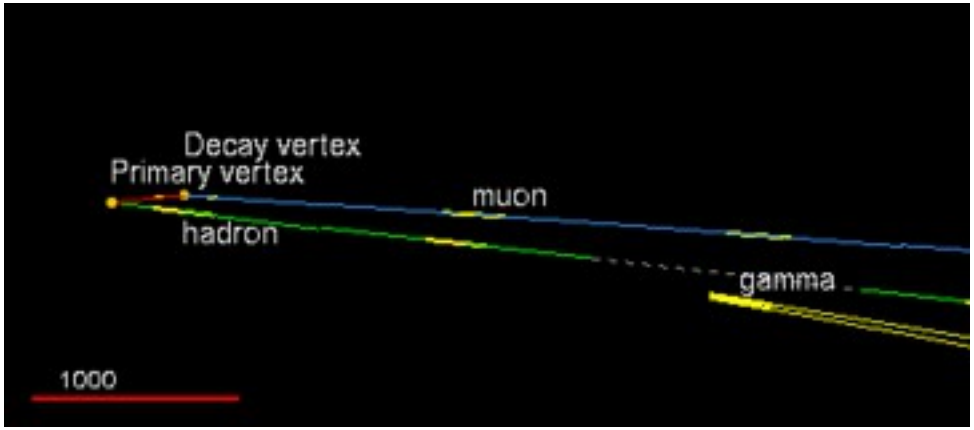
ECC reconstruction:



- Primary vertex: 2 tracks
- Red track: 3-prong decay after 1.54 mm
- Decay channel: $\tau \rightarrow 3h$

The 3th ν_τ Candidate Event

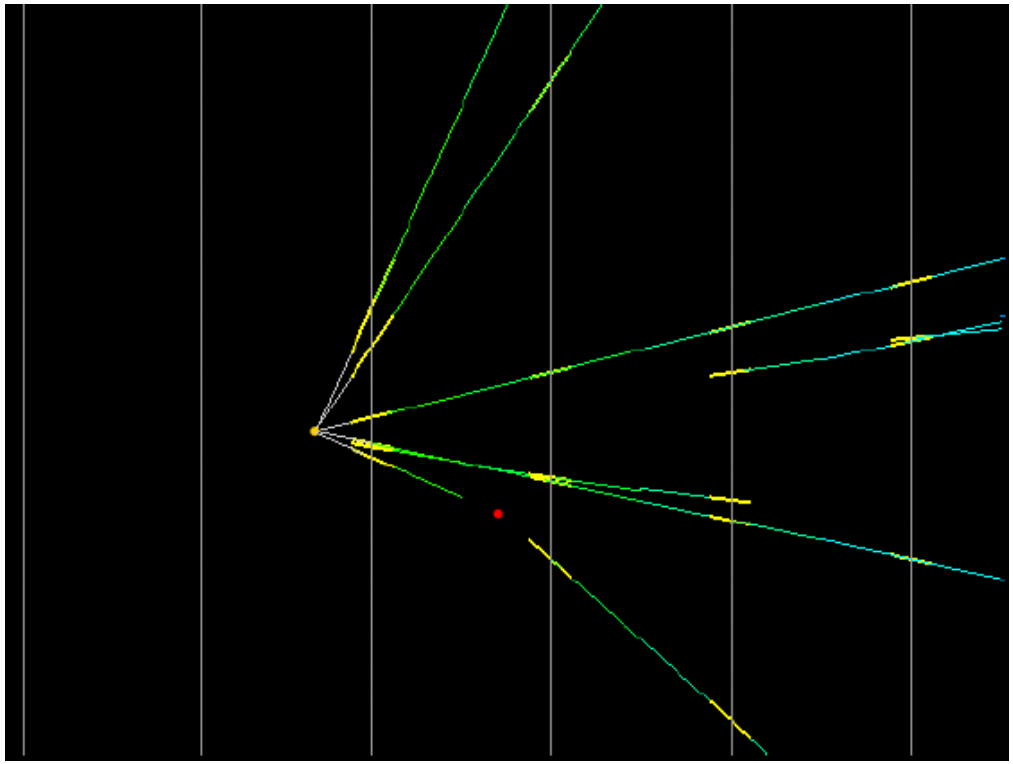
ECC reconstruction:



- Primary vertex: 2 tracks
- Red track: after 0.376 mm
- Decay channel: $\tau \rightarrow \mu$

Charm Bachground

ECC reconstruction: Hadron production with charm



- Topology similar to τ-decay (modes and lifetime)
- But with μ at primary vertex
- Good control sample

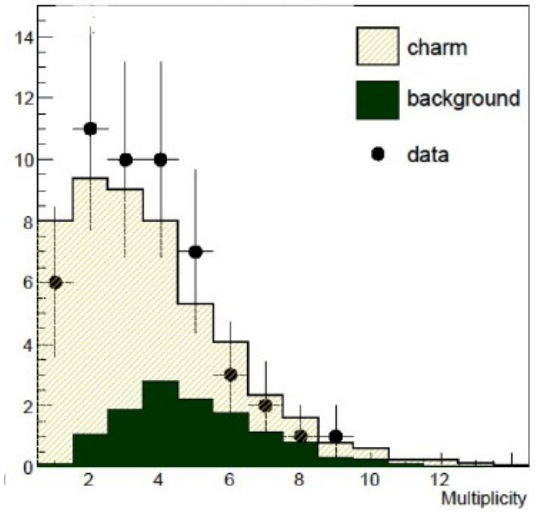
Charm Bachground

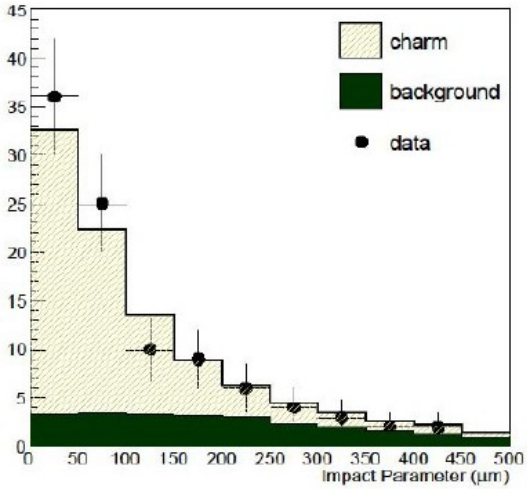
OPERA recent results at Neutrino 2014

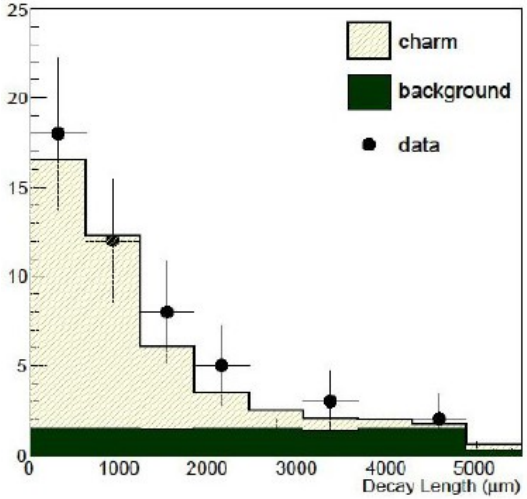
	charm	back-ground	expected	data
1 prong	21 ± 2	9 ± 3	30 ± 4	19
2 prong	14 ± 1	4 ± 1	18 ± 2	22
3 prong	4 ± 1	1.0 ± 0.3	5 ± 1	5
4 prong	0.9 ± 0.2	-	0.9 ± 0.2	4
All	**40±3**	**14±3**	**54±4**	**50**

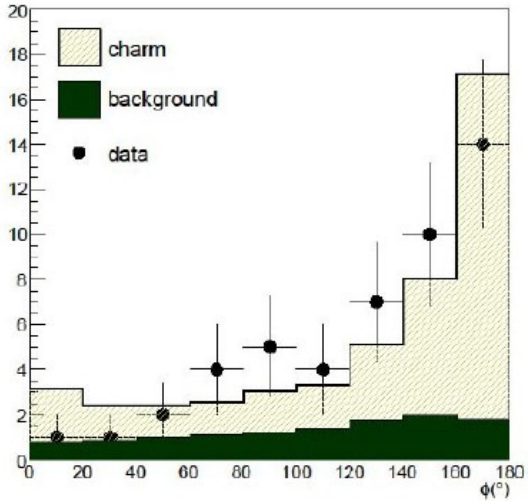
Charm Bachground

2008 – 2010 data analysis:



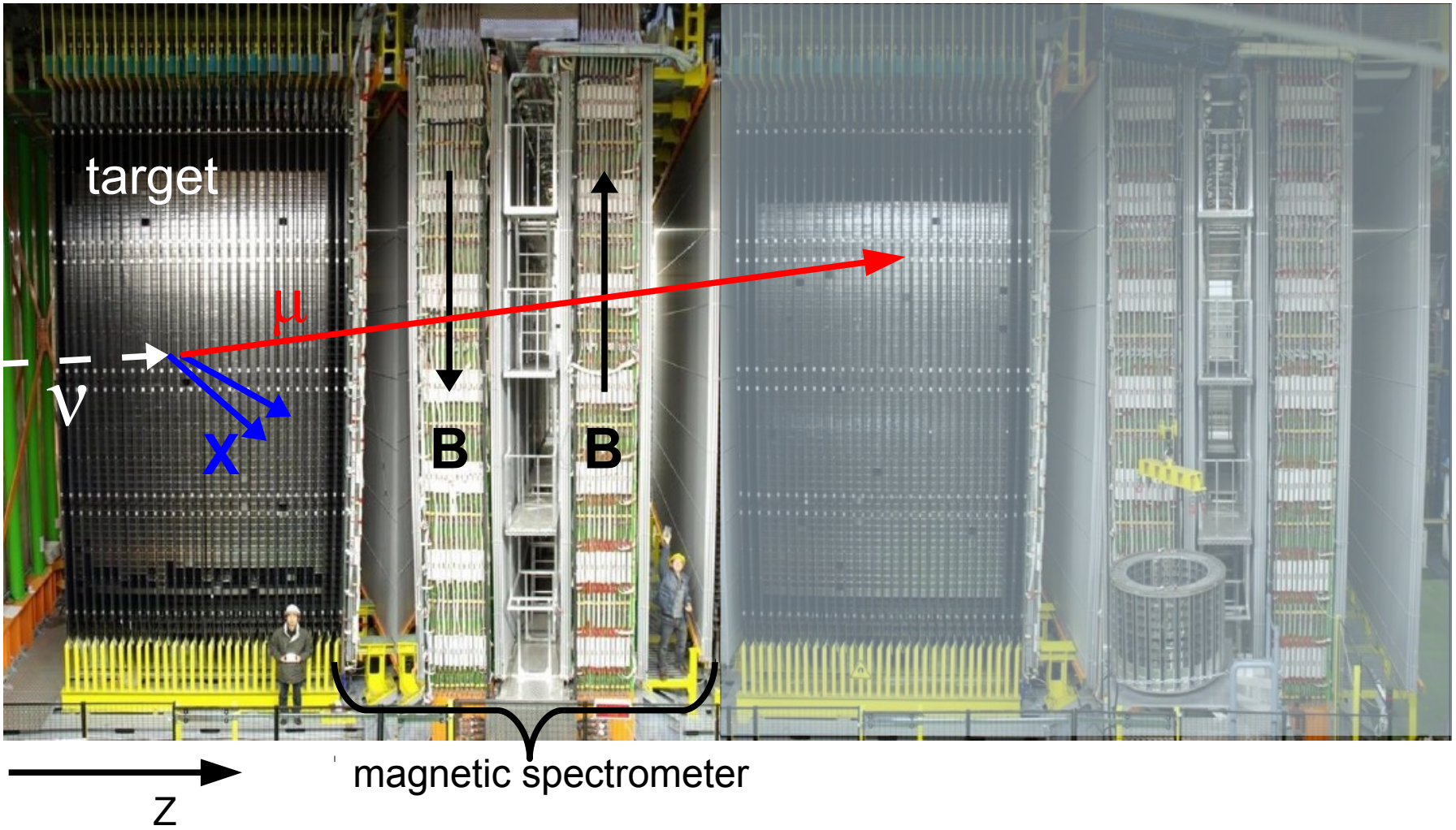




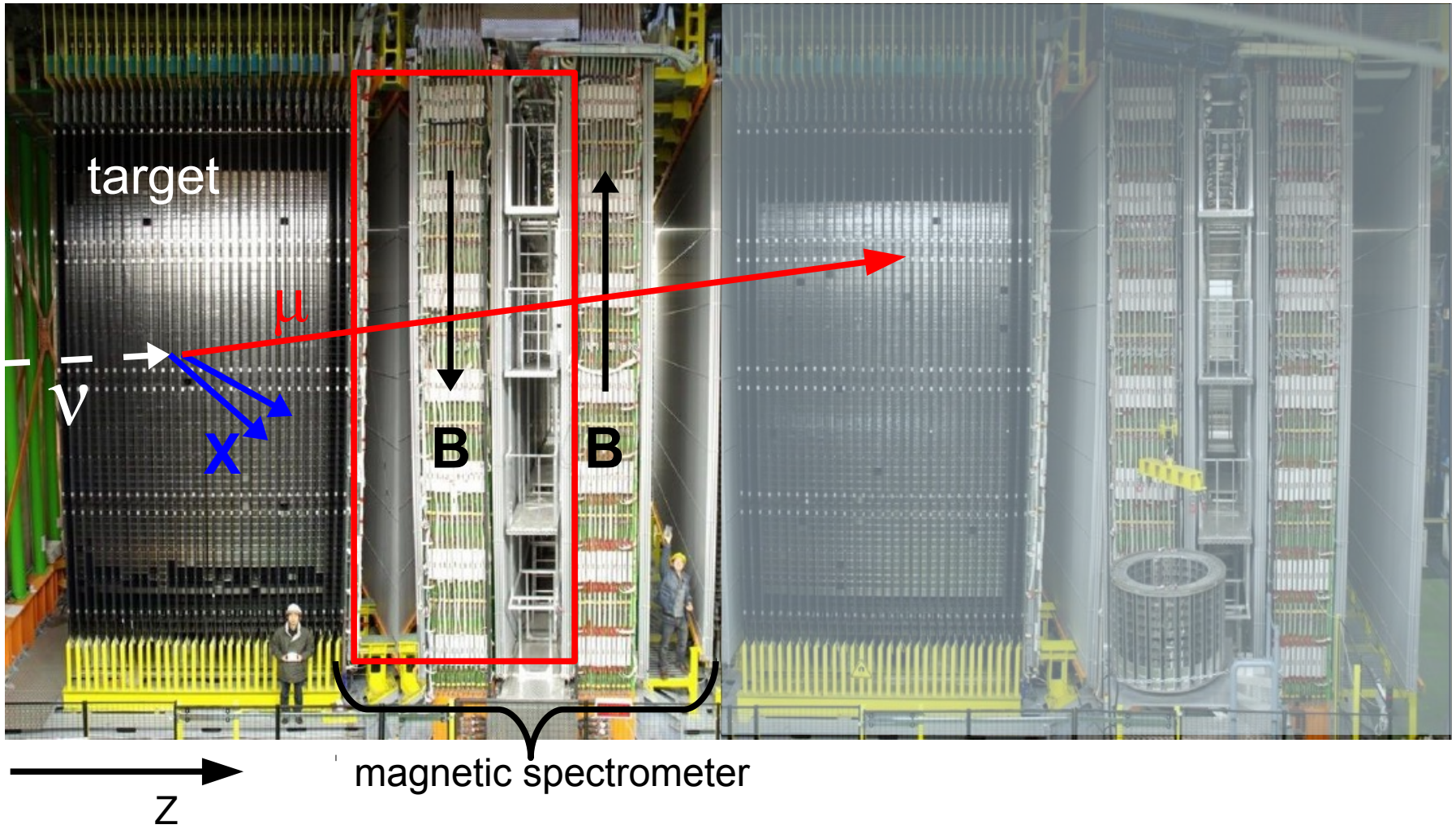


Charge Reconstruction with AMM

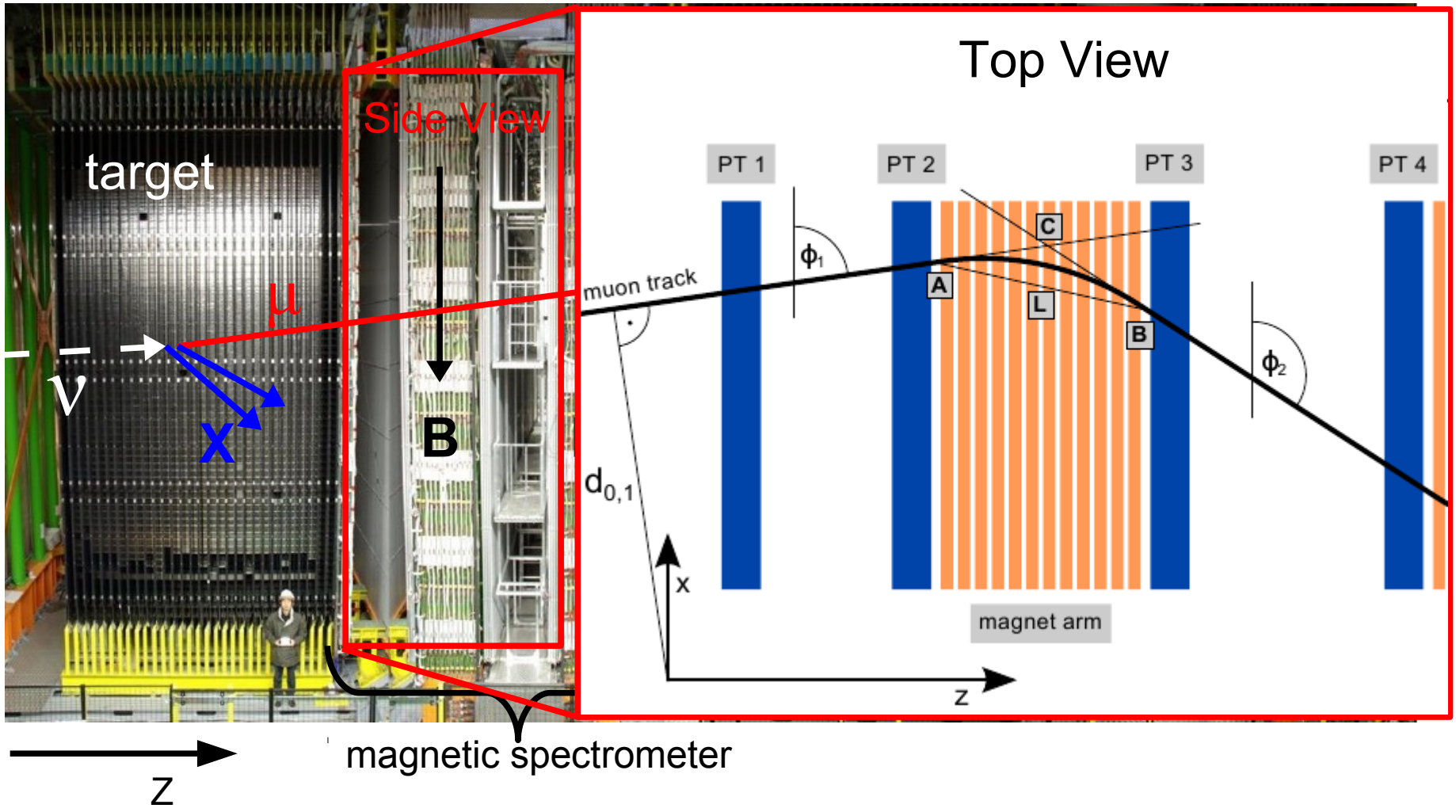
The OPERA Hybrid Detector



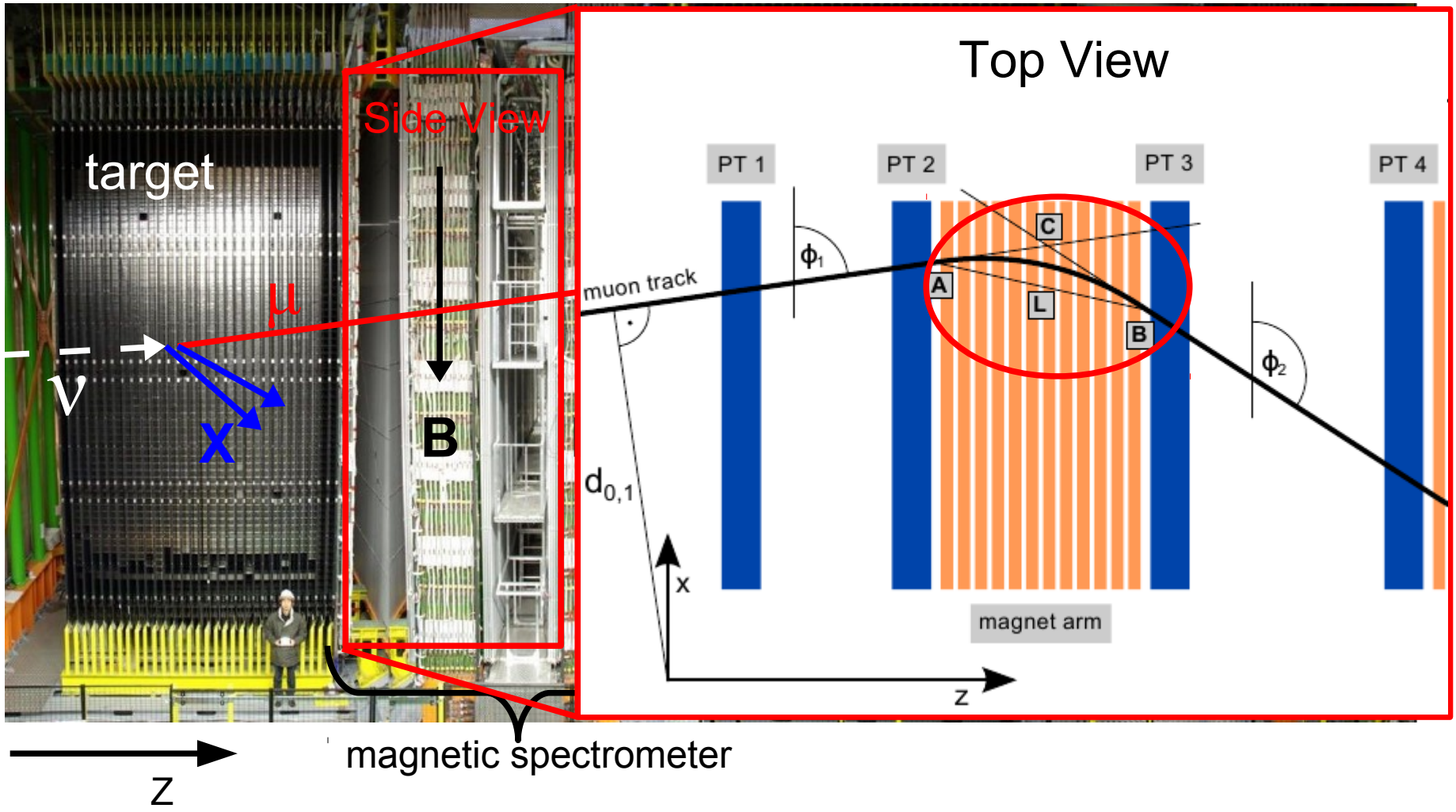
The OPERA Hybrid Detector



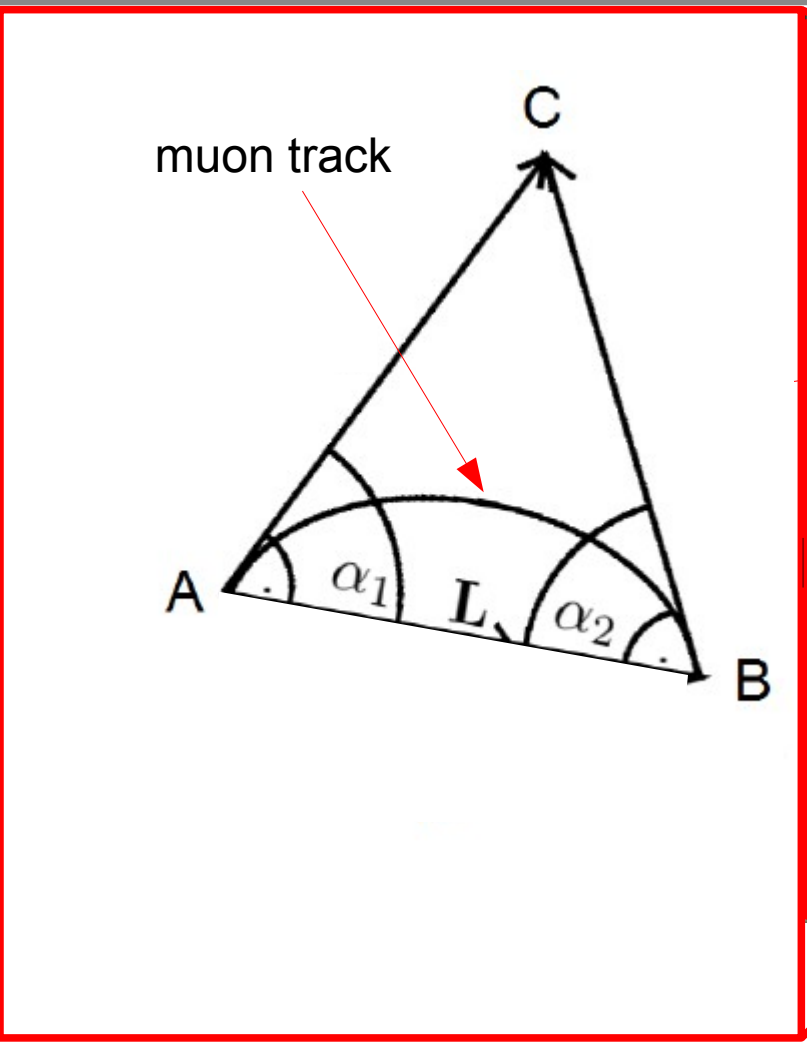
The OPERA Hybrid Detector

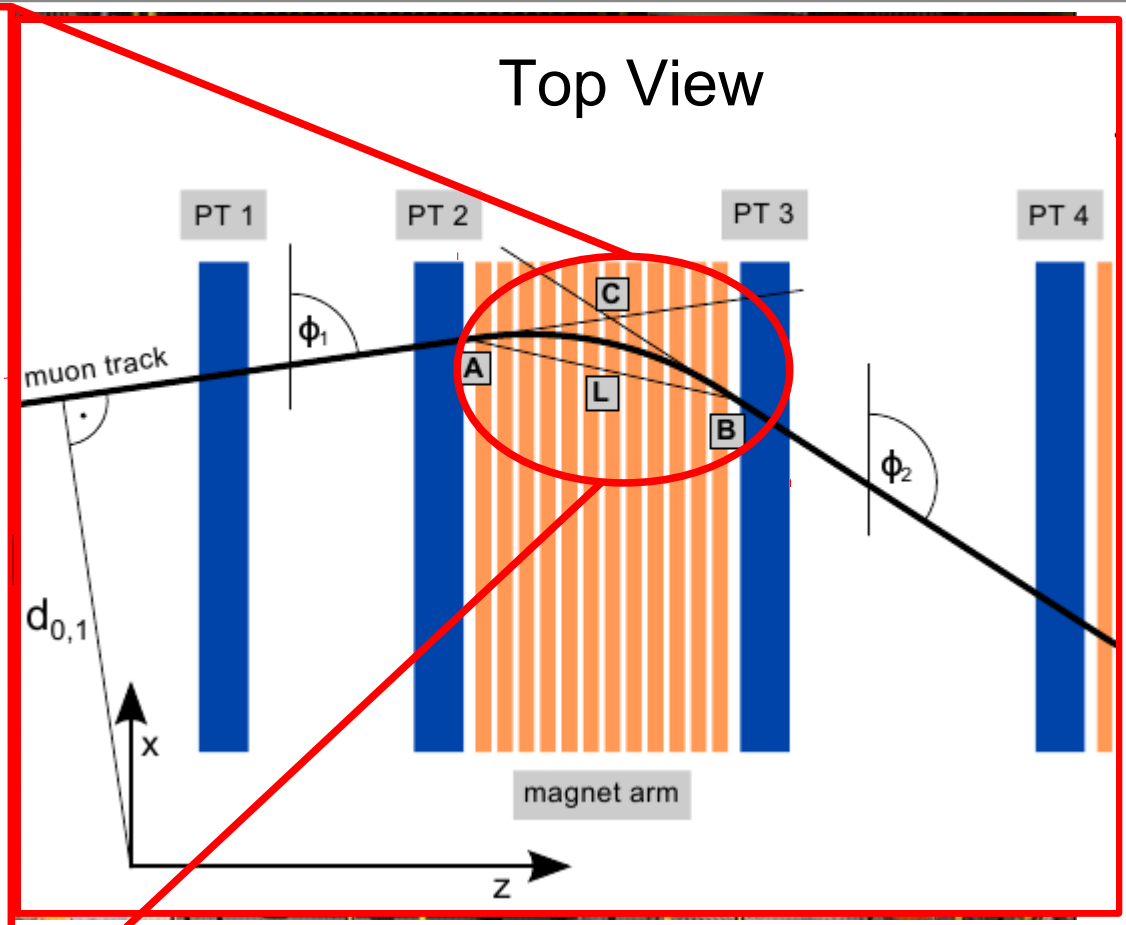


The OPERA Hybrid Detector

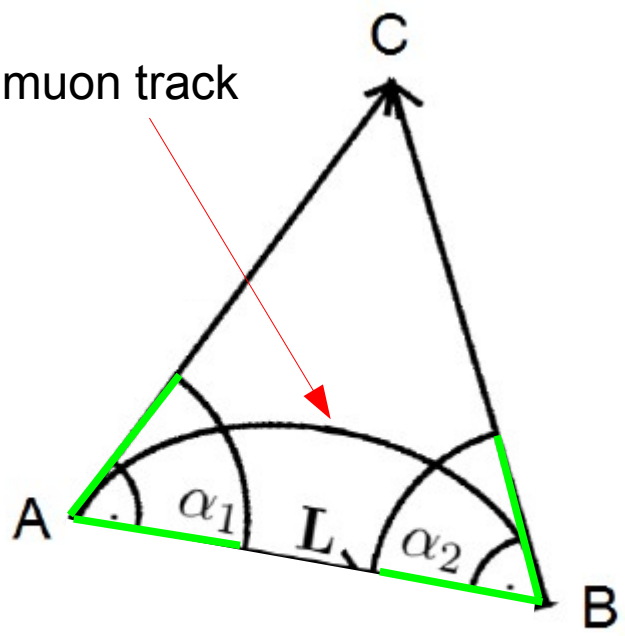


The OPERA Hybrid Detector



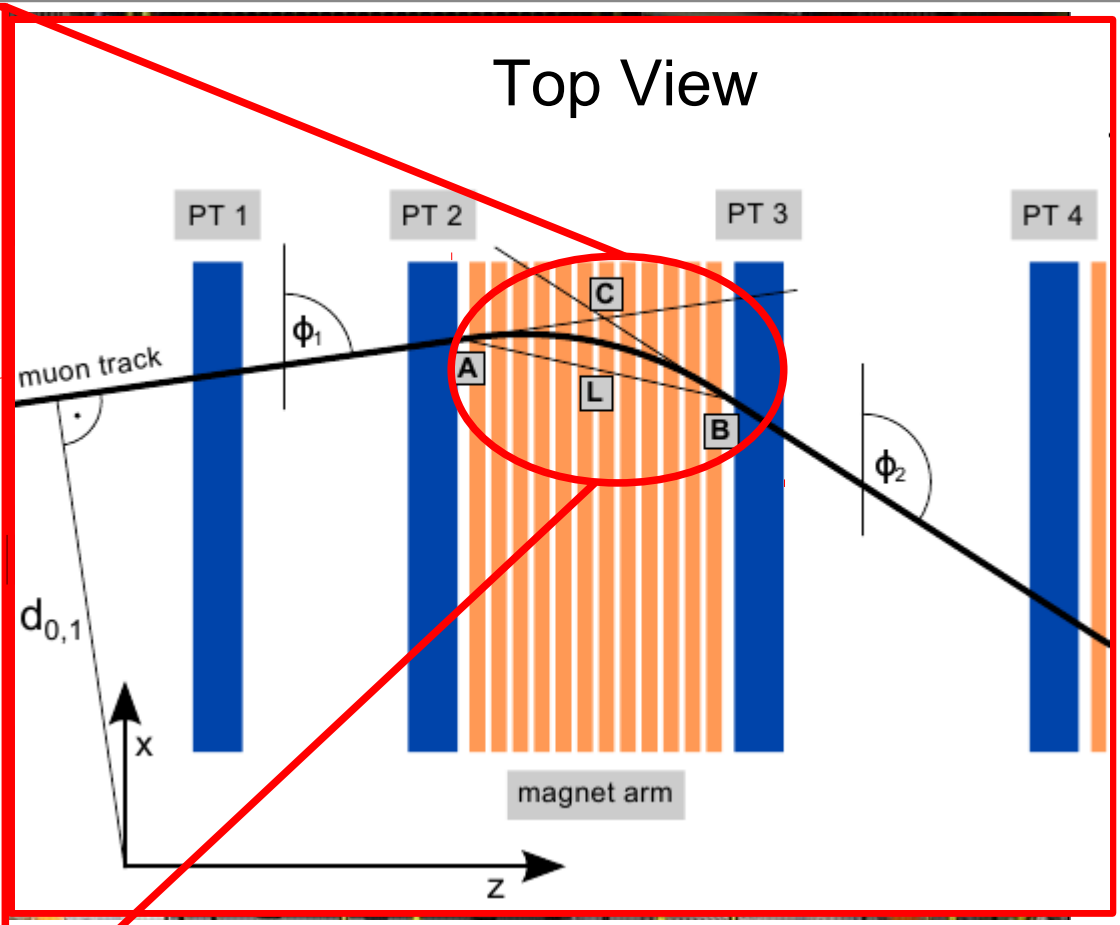


The OPERA Hybrid Detector



for a perfect circle
(neglecting energy loss):

$$\alpha_1 = \alpha_2$$



Angular Matching Method (AMM)

1. Calculate the asymmetry:

$$\Delta(\alpha)_{rel} = 2\frac{\alpha_1 - \alpha_2}{\alpha_1 + \alpha_2}$$

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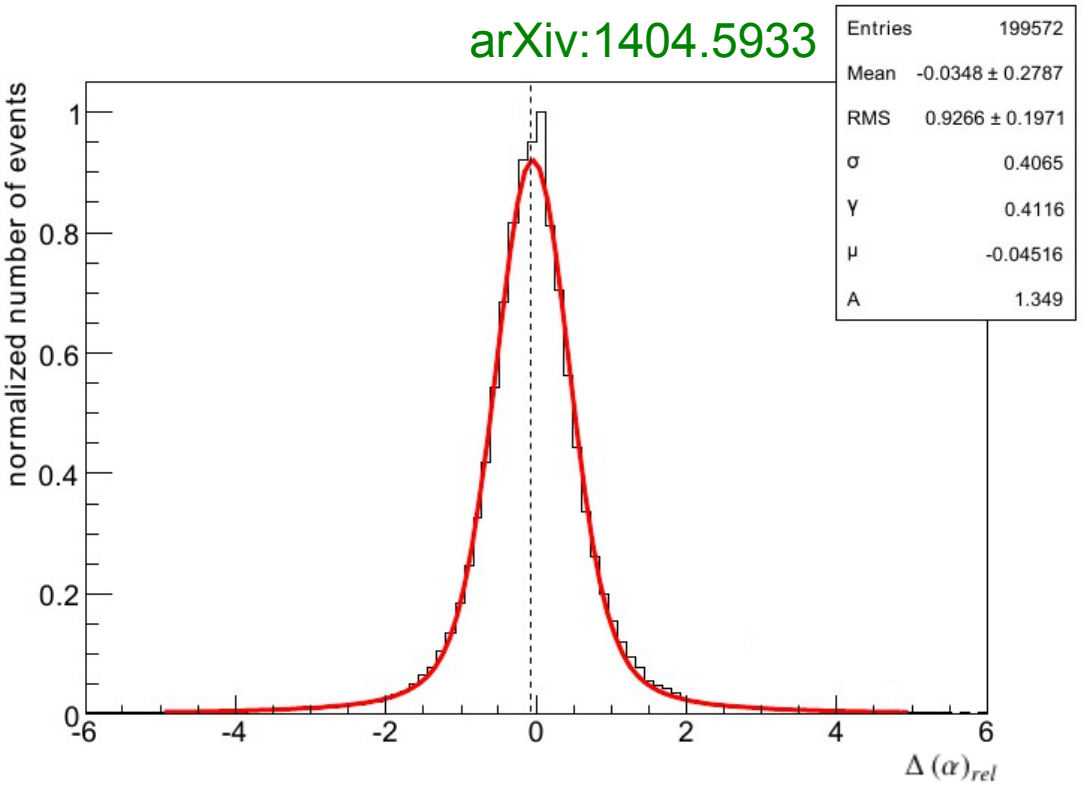
$$\Delta(\alpha)_{rel} = 2\frac{\alpha_1 - \alpha_2}{\alpha_1 + \alpha_2}$$

2. Plot the distribution:

arXiv:1404.5933

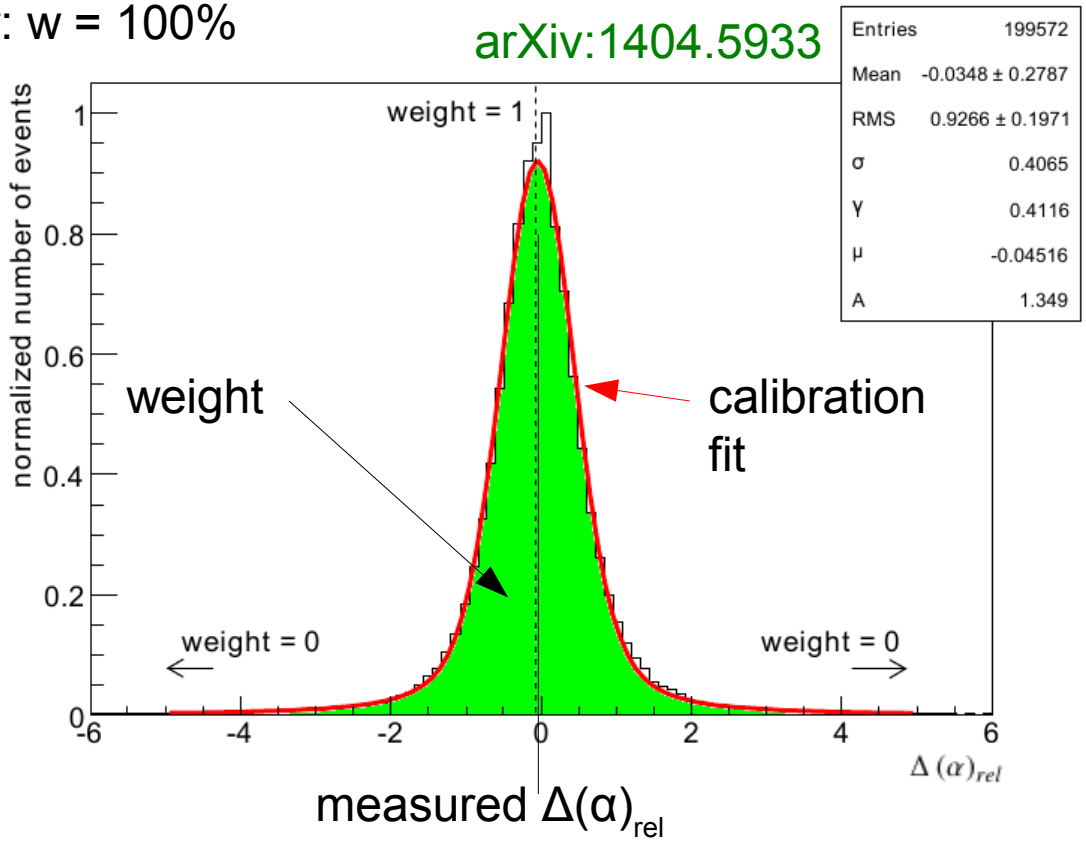


Angular Matching Method (AMM)

3. Definition of weight:

- Area under the distribution from the edges to the measured absolute value
- Maximum weight at peak center: w = 100%
- At the edges: w ≈ 0%
- Weight: green area

$$\Delta(\alpha)_{rel} = 2\frac{\alpha_1 - \alpha_2}{\alpha_1 + \alpha_2}$$



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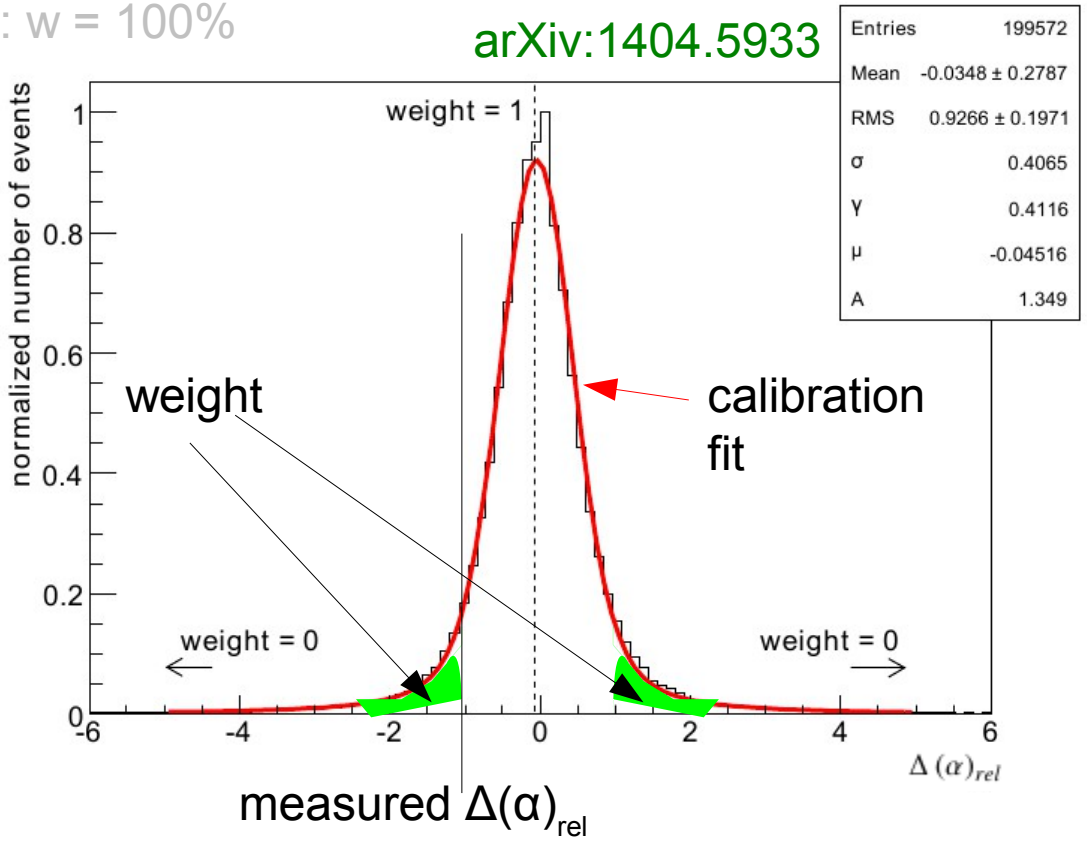
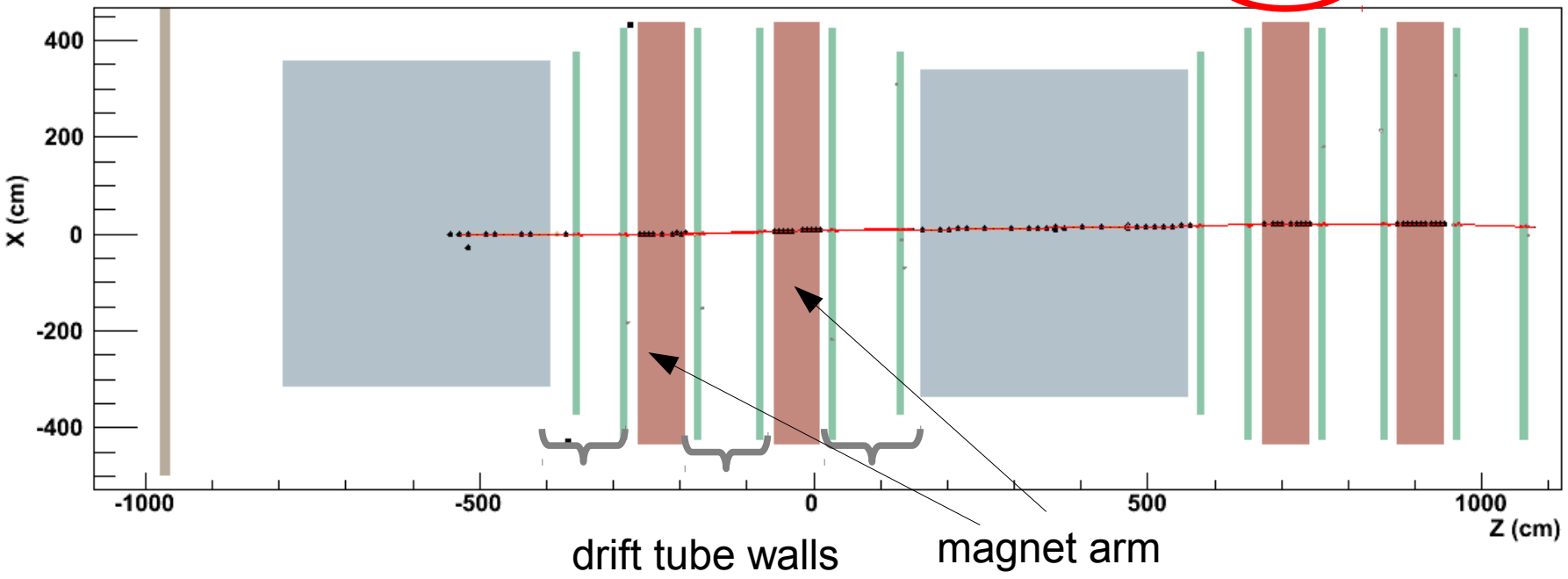


Angular Matching Method (AMM)

Wrong charge sign measurements mostly have a low weight

Monte Carlo event: Muon was simulated

measured charge sign	-1	-1	+1	-1
weight:	-0.83	-0.82	+0.04	-0.56

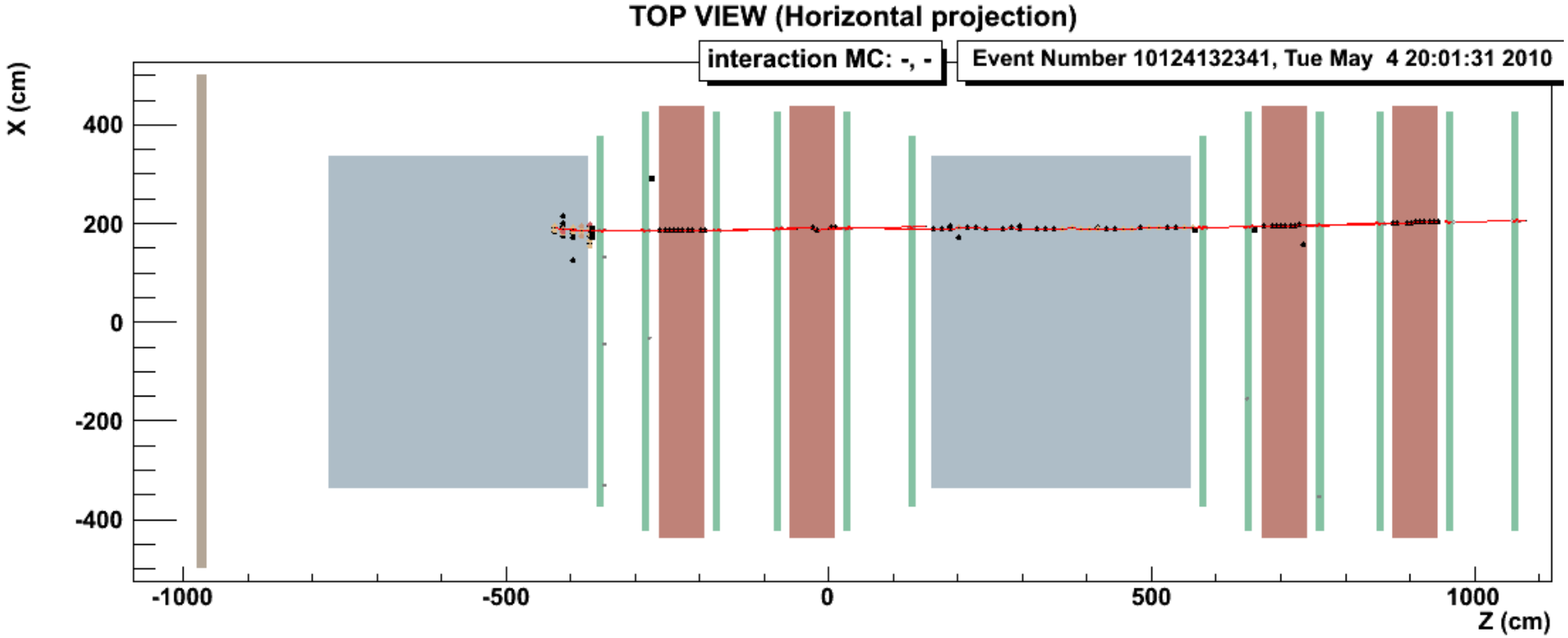


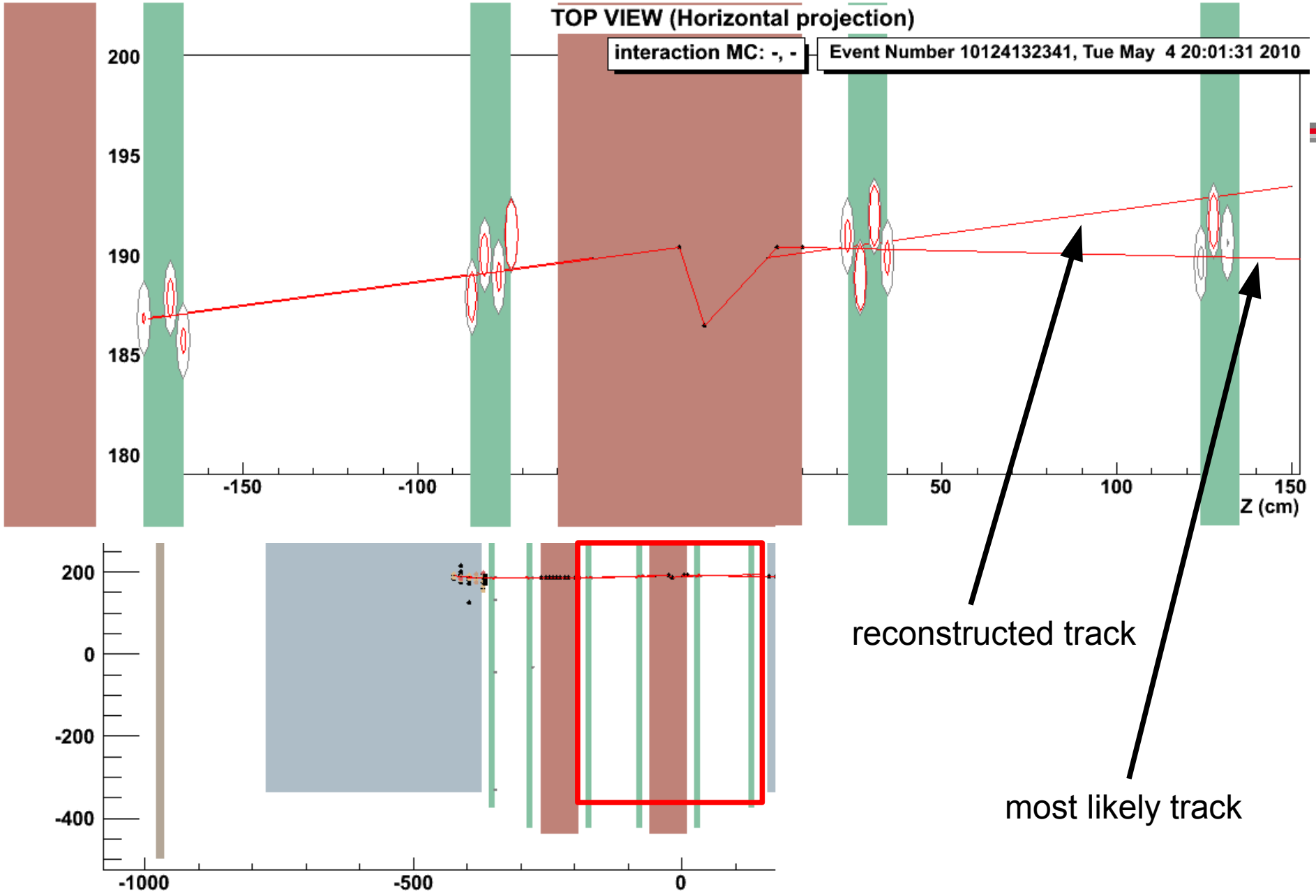
Angular Matching Method (AMM)

Low weight indicates something strange

Real data event

measured charge sign:	-1	+1			-1	-1
weight:	-0.656	+0.0008			-0.867	-0.031



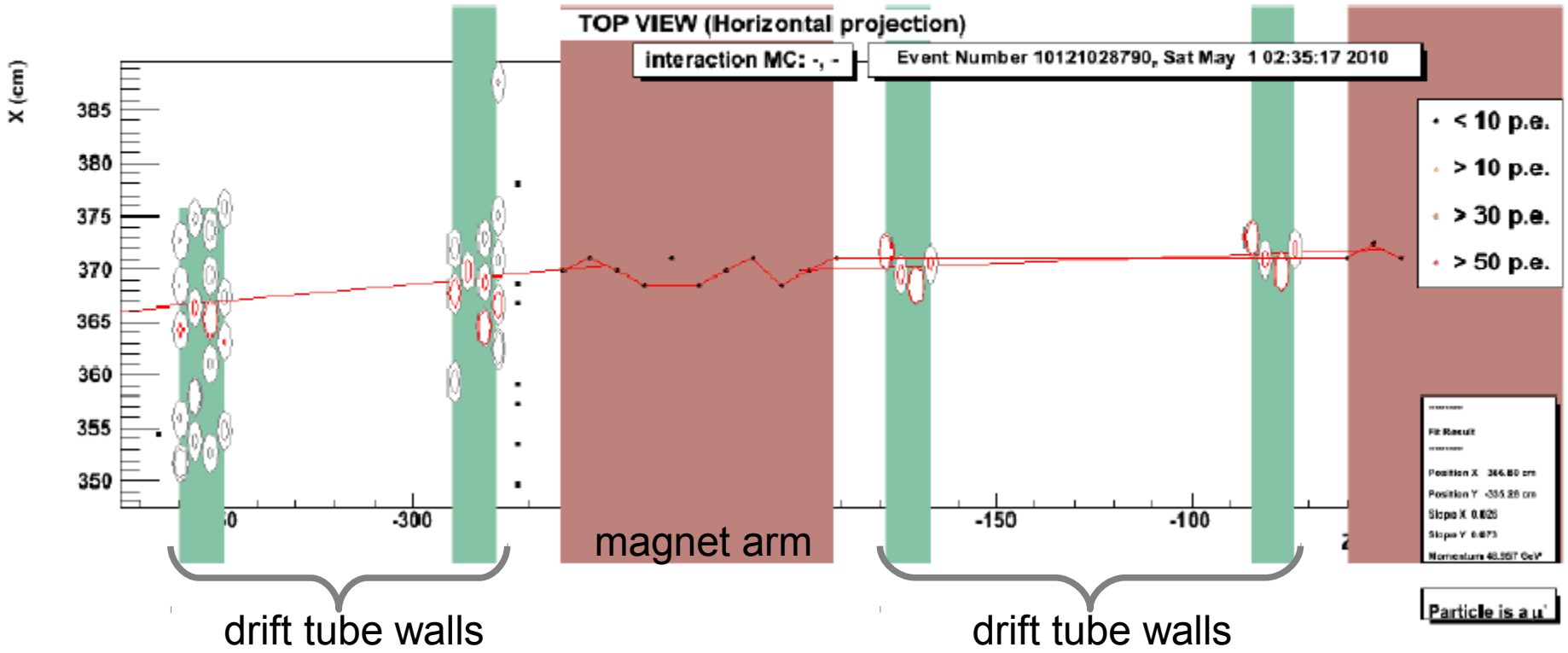

TOP VIEW (Horizontal projection)
interaction MC: -, -
Event Number 10124132341, Tue May 4 20:01:31 2010
200
195
190
185
180
-150
-100
50
100
150
Z (cm)
200
0
-200
-400
-1000
-500
0
reconstructed track
most likely track

Find strange events with AMM

Low weight indicates something strange happens

real date: showered particle

weight +0,007



Impurity with AMM

Impurity for real data

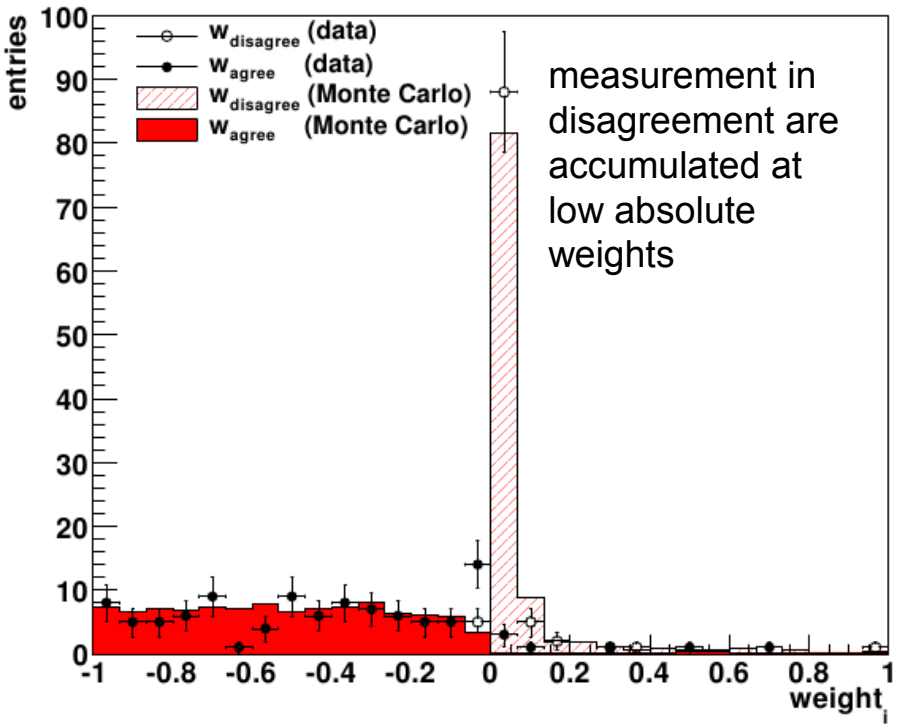
charge sign not equal in both super modules

$$\frac{n^{+-}}{n} = 2\eta\,(1-\eta)$$

number of all events

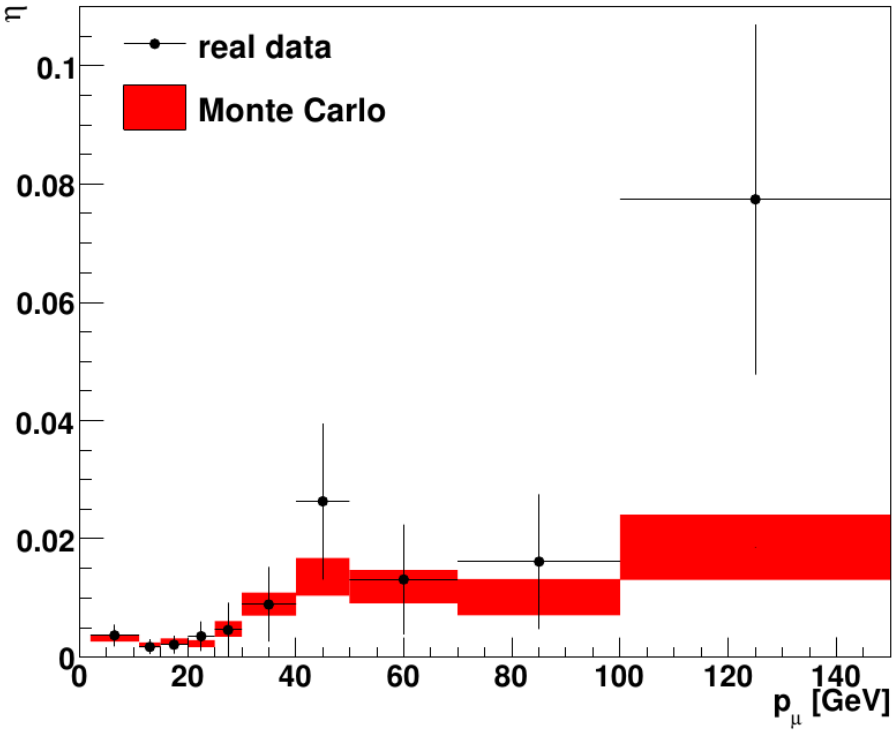
arXiv:1404.5933

Four charge measurements
Three in agreement, one in disagreement



measurement in disagreement are accumulated at low absolute weights

Impurity for one super module



Paper about the AMM on arXiv

The Angular Matching Method for the Muon Charge Sign Measurement in the OPERA Experiment

N. Agafonova[a], A. Aleksandrov[b], A. Anokhina[c], A. Ariga[d], T. Ariga[d], D. Bender[e], A. Bertolin[f], C. Bozza[g], R. Brugnera[h,f], A. Buonaura[b,i], S. Buontempo[b], B. Büttner[j], M. Chernyavsky[k], A. Chukanov[l], L. Consiglio[b], N. D'Ambrosio[m], G. De Lellis[b,i], M. De Serio[n,o], P. Del Amo Sanchez[p], A. Di Crescenzo[b], D. Di Ferdinando[q], N. Di Marco[m], S. Dmitrievski[l], M. Dracos[r], D. Duchesneau[p], S. Dusini[f], T. Dzhatdoev[c], J. Ebert[j], A. Ereditato[d], R. A. Fini[n], T. Fukuda[s], G. Galati[n], A. Garfagnini[h,f], G. Giacomelli[t,q], C. Göllnitz[j], J. Goldberg[u], D. Goloubkov[v], Y. Gornushkin[l], G. Grella[g], M. Guler[e], C. Gustavino[w], C. Hagner[j], T. Hara[x], A. Hollnagel[j], B. Hosseini[b,i], H. Ishida[s], K. Ishiguro[y], K. Jakovcic[z], C. Jollet[r], C. Kamiscioglu[e,aa], M. Kamiscioglu[e], J. Kawada[d], J. H. Kim[ab], S. H. Kim[ab,1], N. Kitagawa[y], B. Klicek[z], K. Kodama[ac], M. Komatsu[y], U. Kose[f], I. Kreslo[d], A. Lauria[b,i], J. Lenkeit[j], A. Ljubicic[z], A. Longhin[ad], P. Loverre[ae,w], A. Malgin[a], M. Malenica[z], G. Mandrioli[q], T. Matsuo[s], V. Matveev[a], N. Mauri[t,q], E. Medinaceli[h,f], A. Meregaglia[r], M. Meyer[j,*], S. Mikado[s], P. Monacelli[af], M. C. Montesi[b,i], K. Morishima[y], M. T. Muciaccia[n,o], N. Naganawa[y], T. Naka[y], M. Nakamura[y], T. Nakano[y], Y. Nakatsuka[y], K. Niwa[y], S. Ogawa[s], N. Okateva[k], A. Olshevsky[l], T. Omura[y], K. Ozaki[x], A. Paoloni[ad], B. D. Park[ab,2], I. G. Park[ab], L. Pasqualini[t,q], A. Pastore[n], L. Patrizii[q], H. Pessard[p], C. Pistillo[d], D. Podgrudkov[c], N. Polukhina[k], M. Pozzato[t,q], F. Pupilli[m], M. Roda[h,f], H. Rokujo[y], T. Roganova[c], G. Rosa[ae,w], I. Rostovtseva[v], O. Ryazhskaya[a], O. Sato[y], Y. Sato[ag], A. Schembri[m], I. Shakiryanova[a], T. Shchedrina[b], A. Sheshukov[b], H. Shibuya[s], T. Shiraishi[y], G. Shoziyoev[c], S. Simone[n,o], M. Sioli[t,q], C. Sirignano[h,f], G. Sirri[q], M. Spinetti[ad], L. Stanco[f], N. Starkov[k], S. M. Stellacci[g], M. Stipcevic[z], P. Strolin[b,i], S. Takahashi[x], M. Tenti[t,q], F. Terranova[ad,ah], V. Tioukov[b], S. Tufanli[d], P. Vilain[ai], M. Vladimirov[k], L. Votano[ad], J. L. Vuilleumier[d], G. Wilquet[ai], B. Wonsak[j,*], C. S. Yoon[ab], Y. Zaitsev[v], S. Zemskova[l], A. Zghiche[p]

arXiv:1404.5933v1 [physics.ins-det] 23 Apr 2014