Sensitivity of OPERA to θ_{13}

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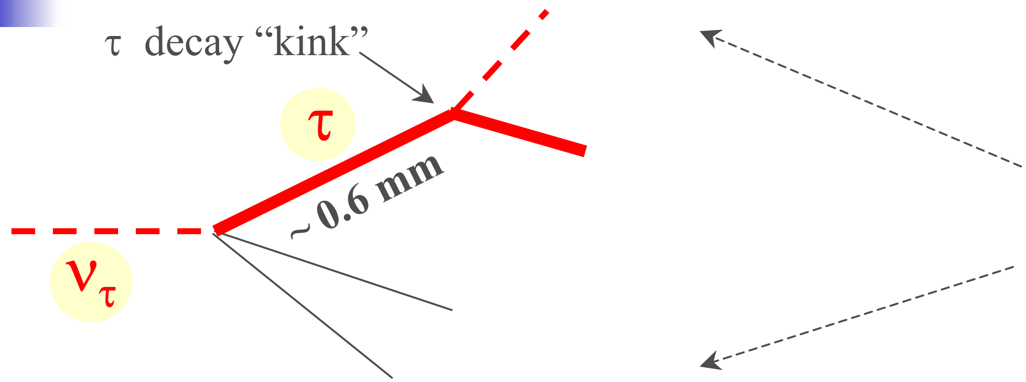
A note with more details is available as hep-ph/0210043

Motivations

- **Scientific motivation**
  - the search for θ_{13} is a very hot topic
- **Non-scientific motivations**
  - the common wisdom among neutrino physicist is that OPERA has no sensitivity to θ_{13}
  - in the paper V.D. Barger et al., Phys.Rev.D65(2002)053016 it is claimed that OPERA does not contribute to the θ_{13} sensitivity of next LBL experiments
  - different assumptions are made for different experiments running on the same beam

The θ_{13} search in OPERA is performed in parallel with the ν_τ appearance search

To identify τ leptons, “see” their decay topology

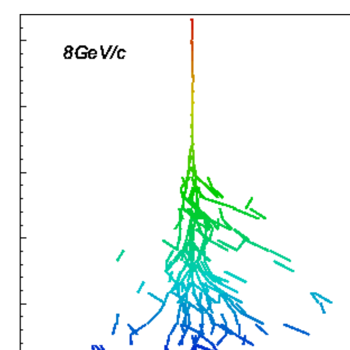


The challenge

ν oscillation → <u>massive</u> target <u>AND</u> **decay topology → <u>micron</u> resolution**

Lead – nuclear emulsion sandwich

"Emulsion Cloud Chamber", in brief "ECC"

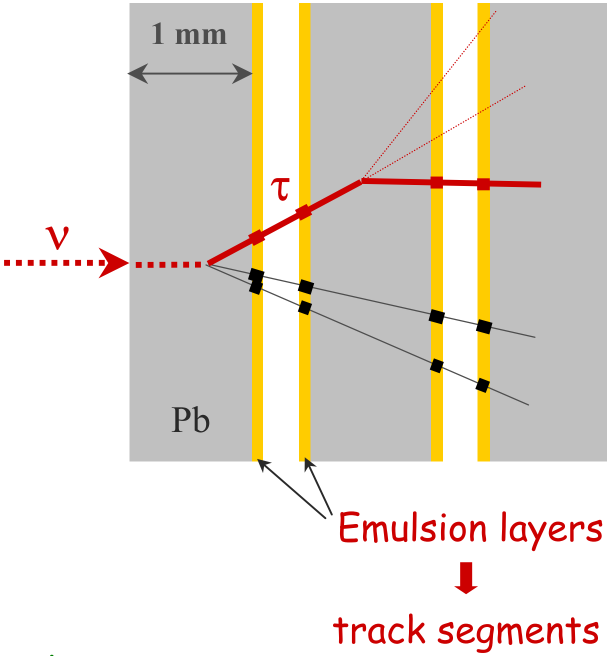


BUT the ECC also provides:

- electron and gamma detection plus energy measurement
- momentum measurement by multiple scattering

The Emulsion Cloud Chamber (ECC)

- Emulsions for tracking, passive material as target
  ↳ < μm space res. ↳ mass
  - Established technique
    - charmed "X-particle" first observed in cosmic rays (1971)
    - DONUT/FNAL beam-dump experiment: ν_τ observed (2000)

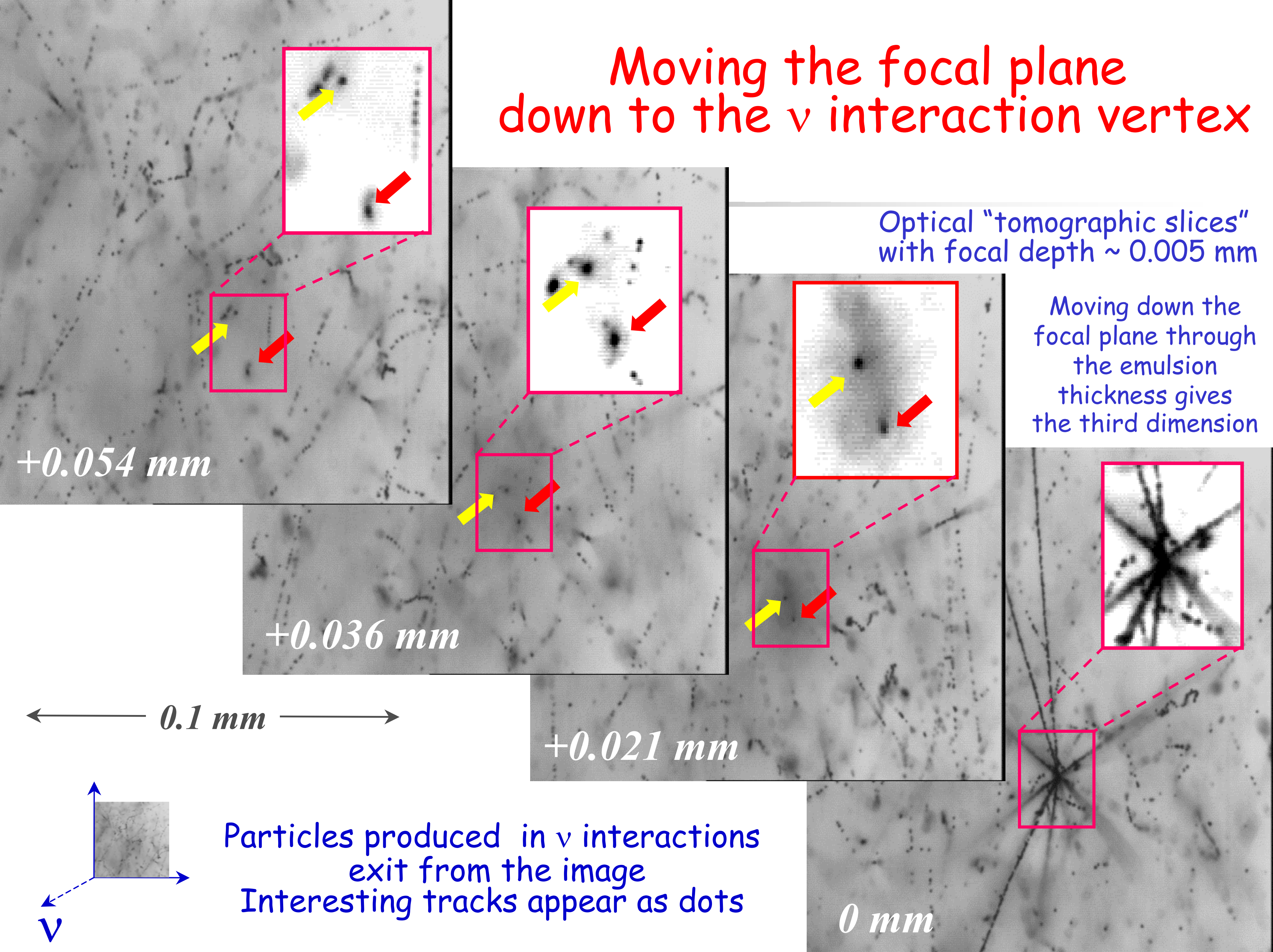


$\Delta m^2 = O\,(10^{-3}\ eV^2) \quad \rightarrow \quad M_{target} \sim\ 2\ kton$

modular structure ("bricks"): basic performance is preserved
large detector → sensitivity, complexity
required: "industrial" emulsions, fast automatic scanning

Experience with emulsions and/or ν_τ searches : E531, CHORUS, NOMAD and DONUT

Moving the focal plane down to the ν interaction vertex

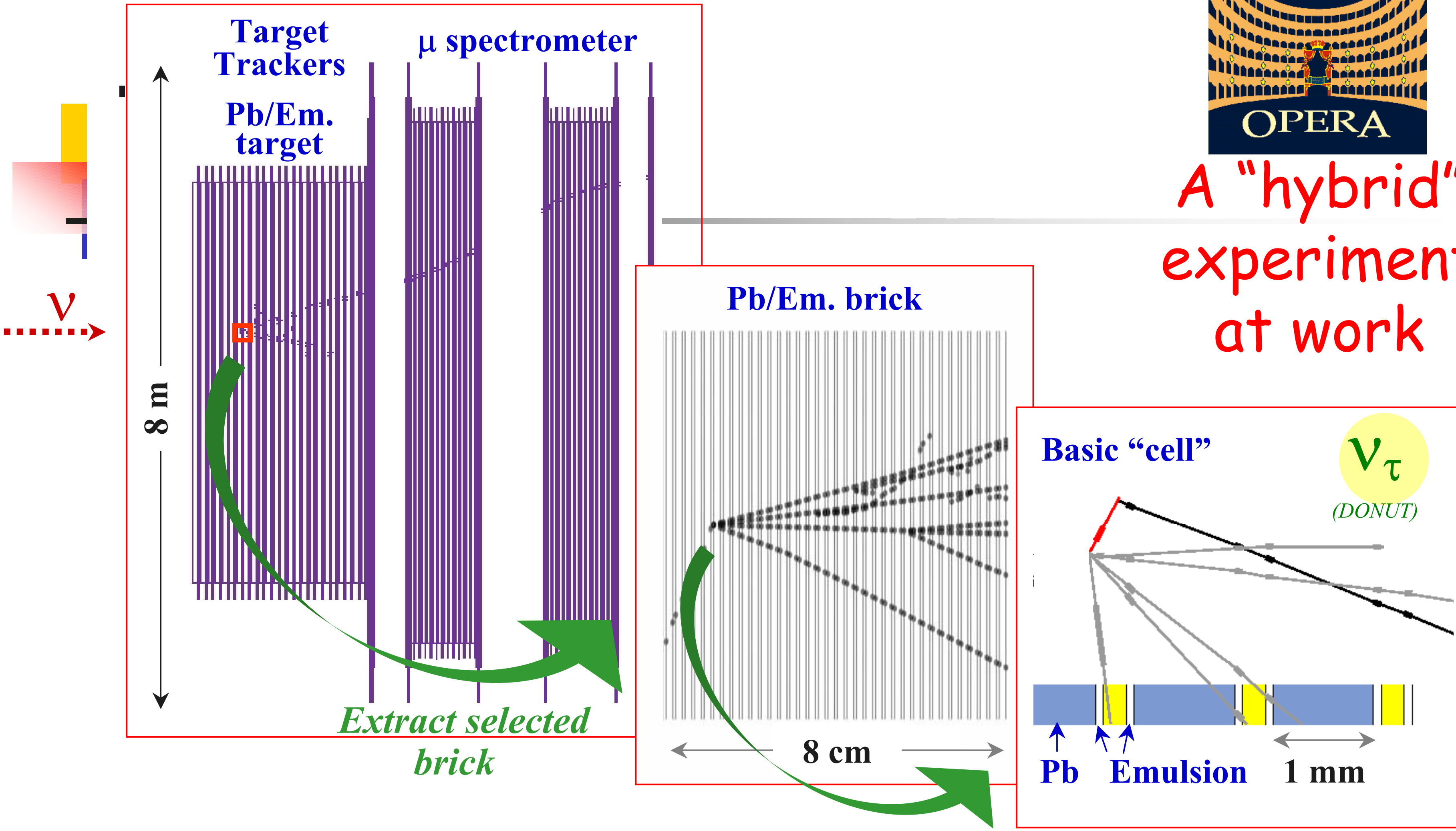


Optical "tomographic slices" with focal depth ~ 0.005 mm

Moving down the focal plane through the emulsion thickness gives the third dimension

Particles produced in ν interactions exit from the image
Interesting tracks appear as dots

A "hybrid" experiment at work



Electronic detectors

→ select ν interaction brick

→ μ ID, charge and p

Emulsion analysis

→ vertex search

→ decay search

→ e/γ ID, kinematics

The CNGS and the expected number of events in OPERA

Nominal ν beam (Nov. 2000)

Shared SPS operation

200 days/year

4.5×10^{19} pot / year

5 year run

1.65 kton average target mass

(accounting for mass reduction with time, due to brick removal for analysis)

Expected interactions

~ 30000 ν_μ NC+CC

~ 120 ν_τ CC

at $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2 and full mixing

Limiting factor for θ_{13} search:

ν_e + anti-ν_e beam contamination ~0.87%

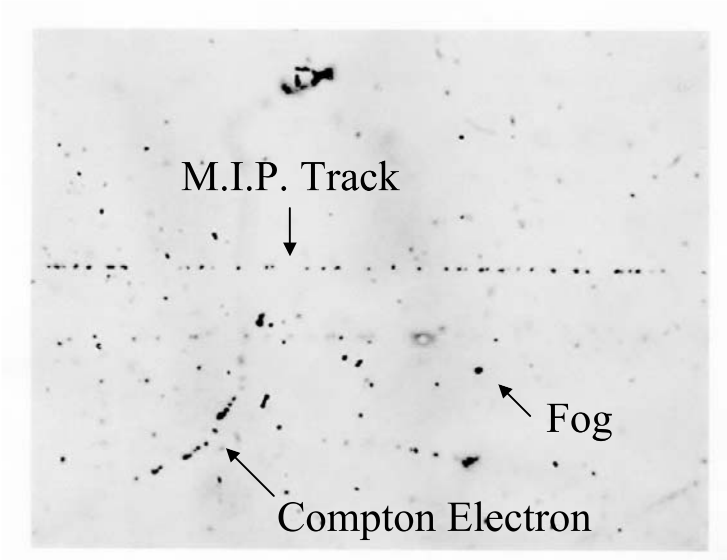
Beam systematics

- The main systematic uncertainty comes from K production
- We assume for consistency with other works a 5% error on the ν_e flux
- Given the small number of expected events in OPERA (see later) the sensitivity to θ_{13} is dominated by the statistical fluctuations of the background
  - A systematic error up to 10% does not change appreciably the experimental sensitivity
- With the OPERA detector it is possible to (thanks to the spectrometer)
  - Measure the μ^- energy spectrum (at high-energy ν_μ from K^+ decays dominate)
  - Measure the μ^+ energy spectrum (anti- ν_μ from K^- decays dominate)
    - Good samples (O(1Kevts)) to cross-check the beam simulation

An overview of possible measurements with emulsions

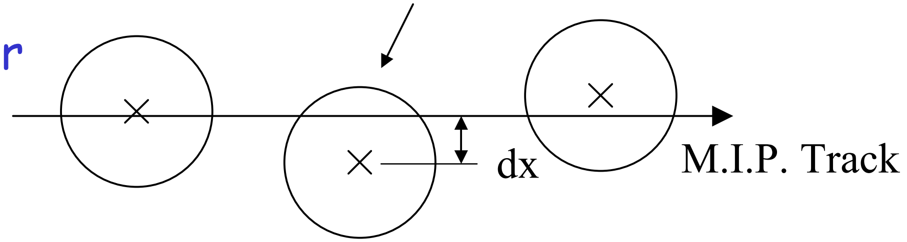
Intrinsic space resolution in tracking with emulsion

Cross sectional view of an emulsion layer



100 µm

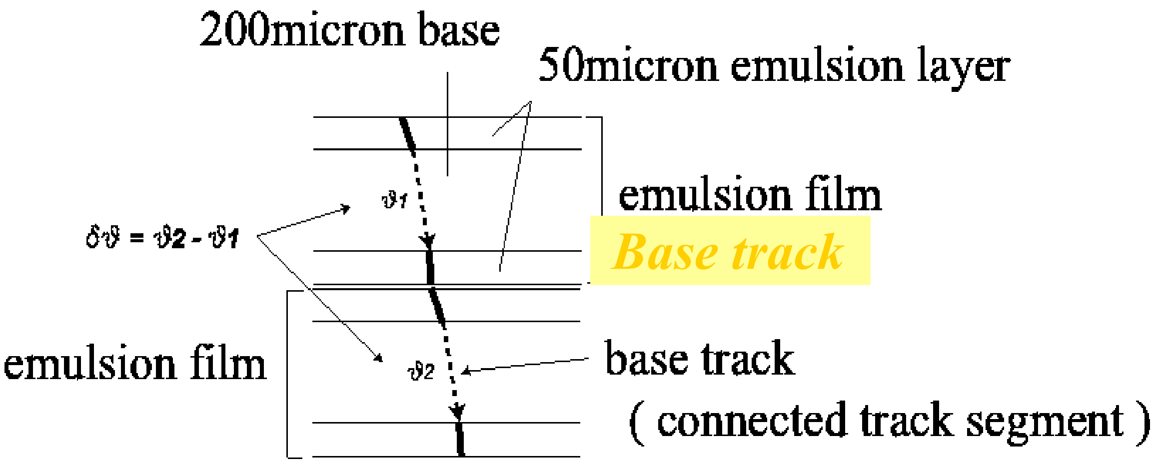
~ 30 grains / 100 µm
grain diameter ~ 0.6 µm

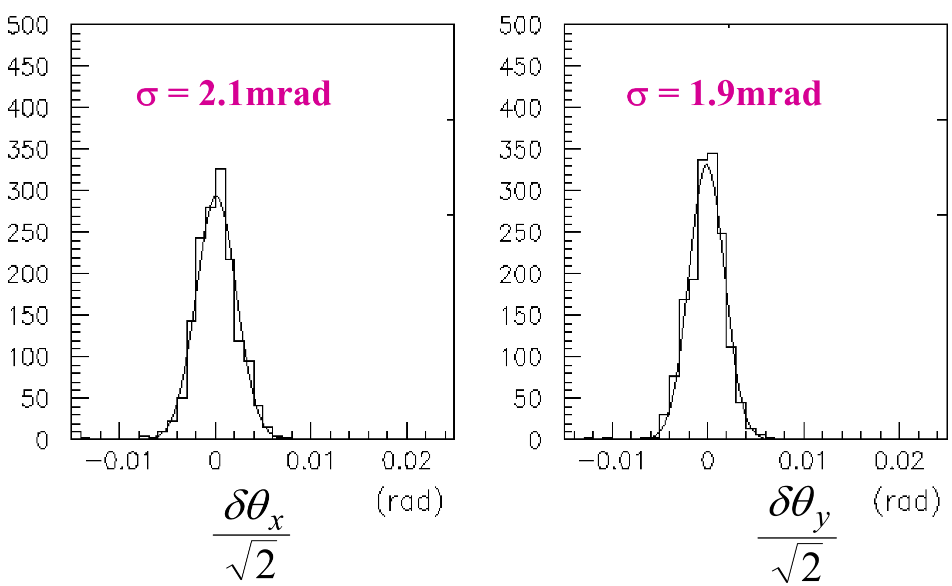


intrinsic tracking accuracy

$\sigma = 0.06\mu m$

Angular resolution with Track Selector readout





Base track resolution

(limited by digitisation error in image processing)

σ (angle) = 2.1 mrad

σ (position) = 0.21 μm

Precision measurements for small samples

↓

resolution close to the intrinsic resolution

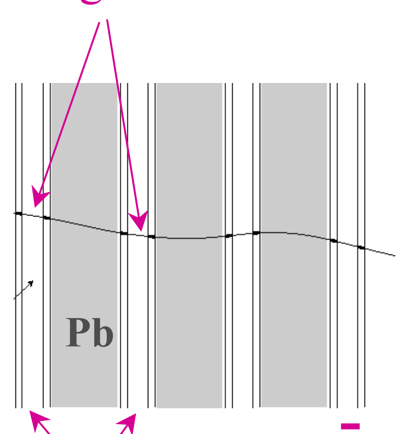
Momentum measurement from Multiple Coulomb Scattering

(allows additional b.g. rejection by kinematic criteria)

Angular method

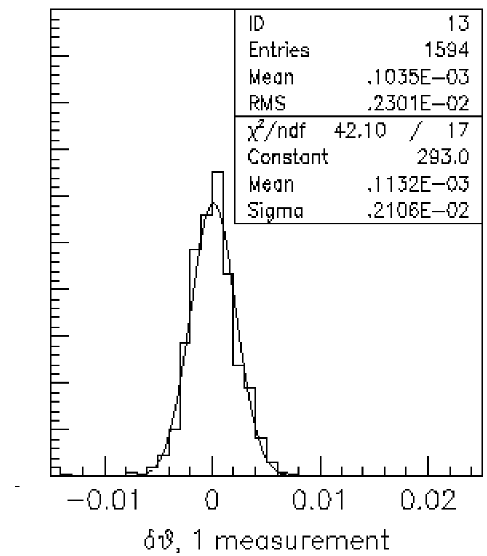
- Not relying on alignment of emulsion films
- Relying on parallelism of Pb plates and emulsion films

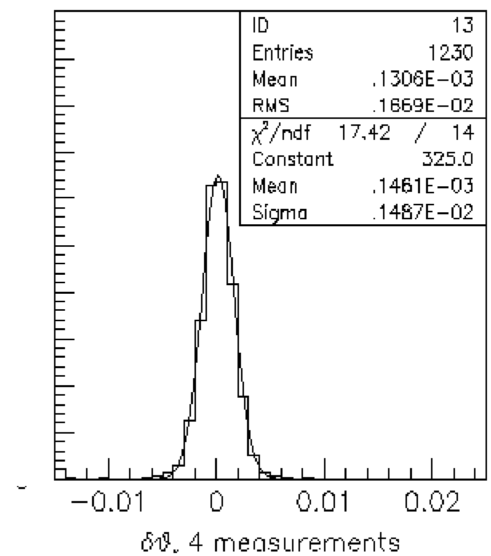
Angle difference



Film with emulsion layer on both sides of a plastic base

Plastic base thickness: lever arm for angle measurement



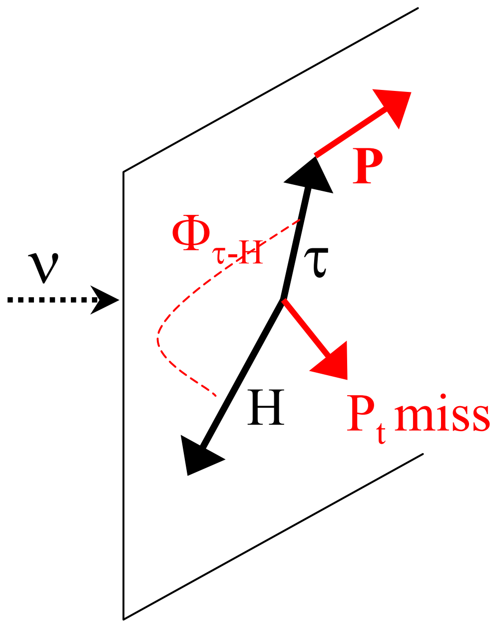


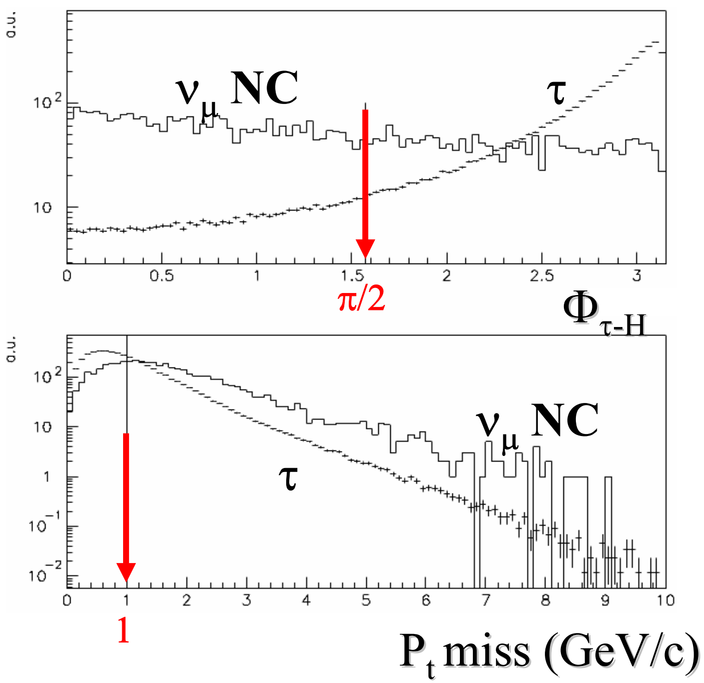
With intrinsic resolution 10.0 GeV/c

(max p measured with $\Delta p/p < 0.2$ after $5X_0$)

Global kinematics for $\tau \rightarrow h$

(for events with a τ decay candidate)

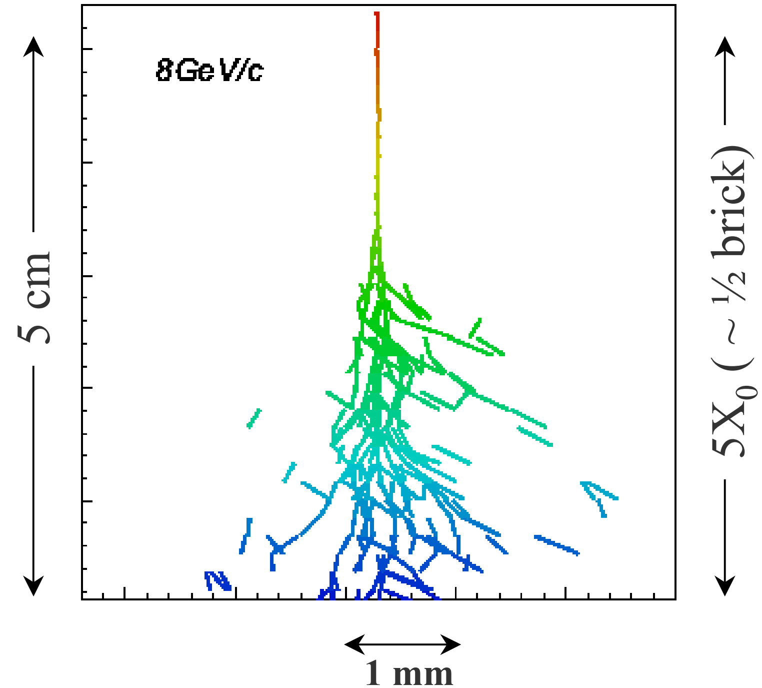




This is just an example: it works also (event better) for ν_eCC interactions

Electron identification and energy measurement (1)

- Electron identification close the Pb critical energy
- Performance estimated by reproducing the full chain:
  - Fuji-emulsions stored for about 2 months
  - Emulsion refreshing at the Nagoya University
  - Transportation of packed emulsions to CERN
  - Test exposure at the PS beam (mixture of e and π , Č upstream of the ECC)
  - Emulsion developed soon after the beam exposure
  - Scanning and analysis



Electron identification and energy measurement (2)

Identification

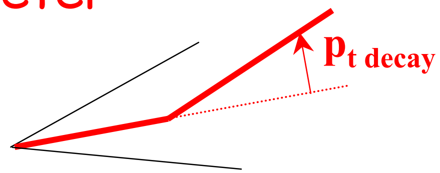
- Method based on shower identification and on MCS of the track
- e/π ratio is measured with Cerenkov and ECC (good agreement)
  - ECC 1.42±0.17 Cerenkov 1.46±0.11 at 2GeV
  - ECC 0.41±0.05 Cerenkov 0.32±0.03 at 4GeV
- ε_e = 88 (91) % at 2 (4) GeV (in agreement with MC)

Energy

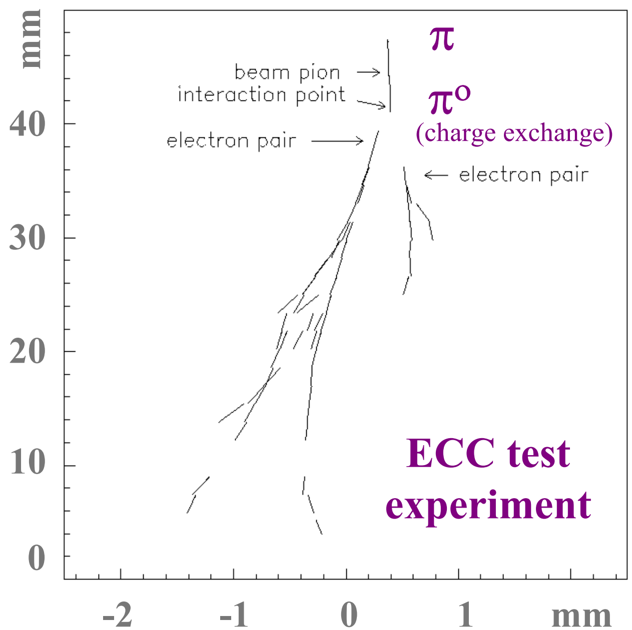
- Measured by counting the number of track segments into a cone along the electron track
- Multiple Coulomb Scattering before showering
- Resolution ~ 20%

γ/π^0 reconstruction

- γs assigned to primary or to decay vertex depending on Impact Parameter



- γs assigned to the decay vertex
  - improved $p_{t\ decay}$ resolution (charged+neutral)
  - looser cut and higher efficiency

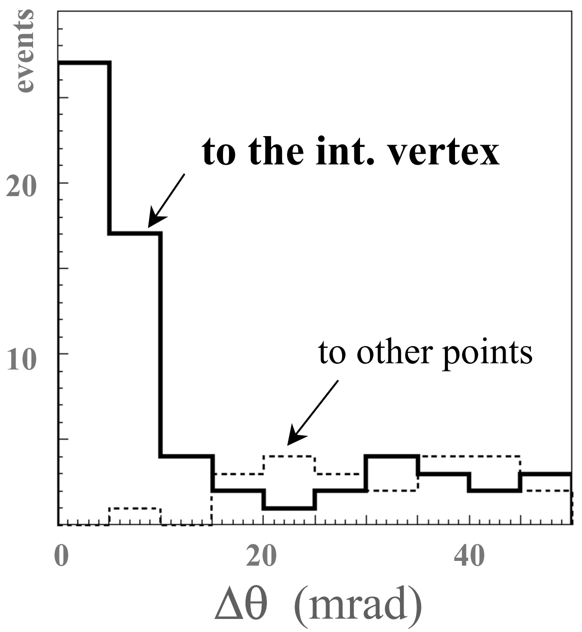


- γs assigned to the primary vertex
  - improved missing p_t resolution

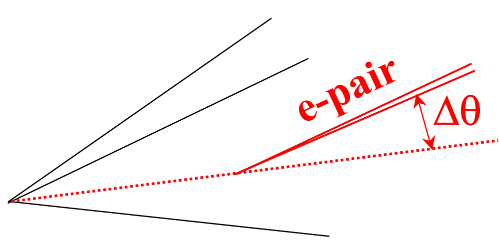
π^0 mass reconstruction also possible (Δm ~30%), but not used in the following analysis

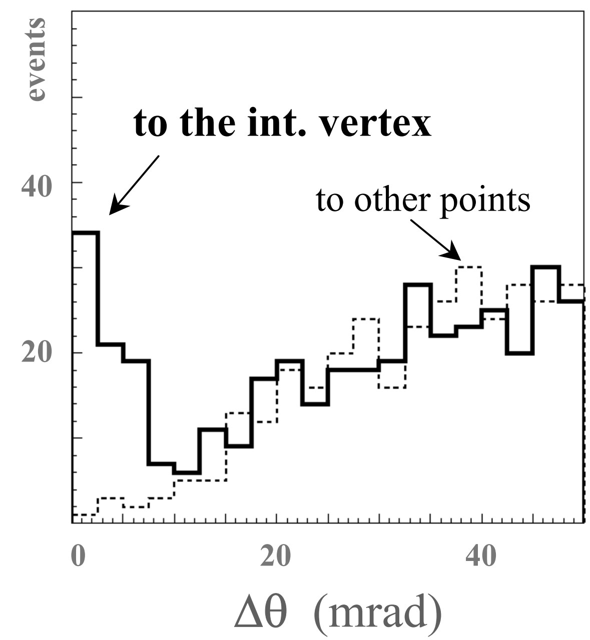
Pointing accuracy to the vertex of e-pairs from γ conversions

Studied in CHORUS and DONUT by NetScan
($\frac{1}{2}$ X_0 depth in ECC)



CHORUS

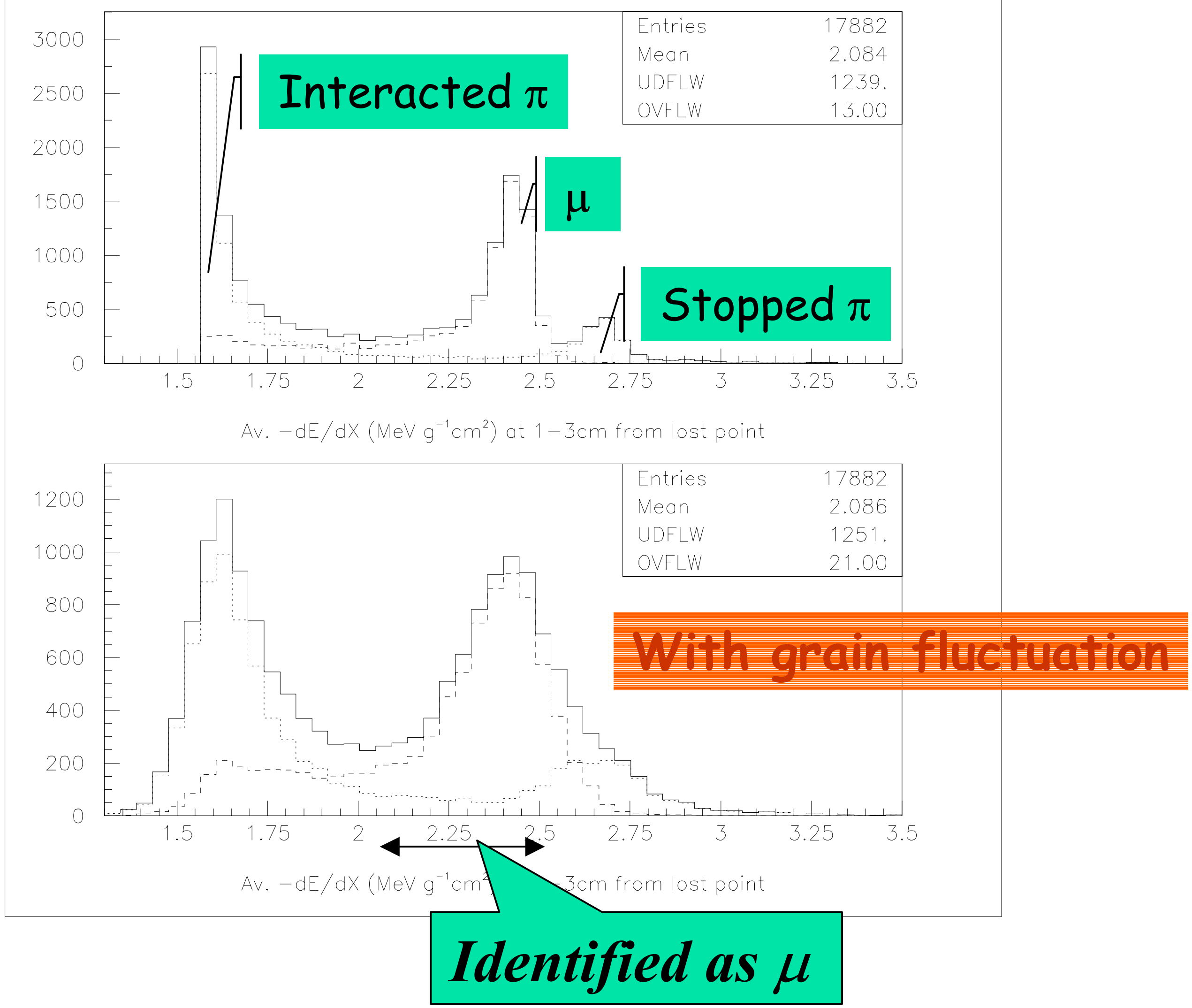




DONUT
(ECC Fe-emulsion)

Important for increasing the sensitivity to $\tau \rightarrow h\, n\pi^0$

Averaged dE/dX (under study)



Summary of the event reconstruction with OPERA

- High precision tracking ($\delta x < 1\mu m$ $\delta\theta < 1mrad$)
  - Kink decay topology
  - Electron and γ/π^0 identification
- Energy measurement
  - Multiple Coulomb Scattering
  - Track counting (calorimetric measurement)
- Ionization (dE/dx measurement)
  - π/μ separation
  - e/π^0 separation

⬇

Topological and kinematical analysis event by event

ν_μ->ν_e search with OPERA

Backgrounds

- π^0 identified as electrons produced in ν_μNC and ν_μCC with the μ not identified
- ν_e beam contamination
- $\tau \rightarrow e$ from $\nu_\mu \rightarrow \nu_\tau$ oscillations

In the following we assume a three family mixing scenario with $\theta_{23}=45°$

Background (1)

- Background from π^0 in both ν_μNC and ν_μCC events classified as NC
  - γ's (from π^0) converting to e^+e^- into the lead plate where the interaction occurred could be a large source of background.
  - The pairs can be identified
    - if the opening angle ($\Delta\theta$) is larger than 3mrad. This cut is fixed by the angular resolution achievable with emulsion films
    - if $\Delta\theta$ is smaller than 3mrad, we exploit the emulsion capability to count grains associated to a track. Having 30grains/100μm we require for a single electron that #grains/100μm $< 30 + 3 \times 30^{\frac{1}{2}}$. Conservately we use only the emulsion film downstream from the vertex lead plate
  - A cut E_e>1 GeV is also applied to reduce the soft γ component
  - A cut on the missing p_T (<1.5 GeV) is also applied to further reduce the NC component

Backgrounds (2)

- ν_eCC from the beam contamination
  - Very difficult to suppress. Identical to the signal we are looking for!
  - CC interactions of ν_e coming from oscillations are softer
    - E_{vis} has to be smaller than 20 GeV
- $\tau \rightarrow e$ from $\nu_\mu \rightarrow \nu_\tau$ oscillations
  - its amount depends on Δm^2_{23}. In the following we assume $\Delta m^2_{23}=2.5\times10^{-3}$ eV^2
  - in OPERA it is largely suppressed because only events with the decay kink not identified contribute to the background
  - it is slightly reduced by the missing p_T cut

$\nu_\mu \rightarrow \nu_e$: selection efficiencies

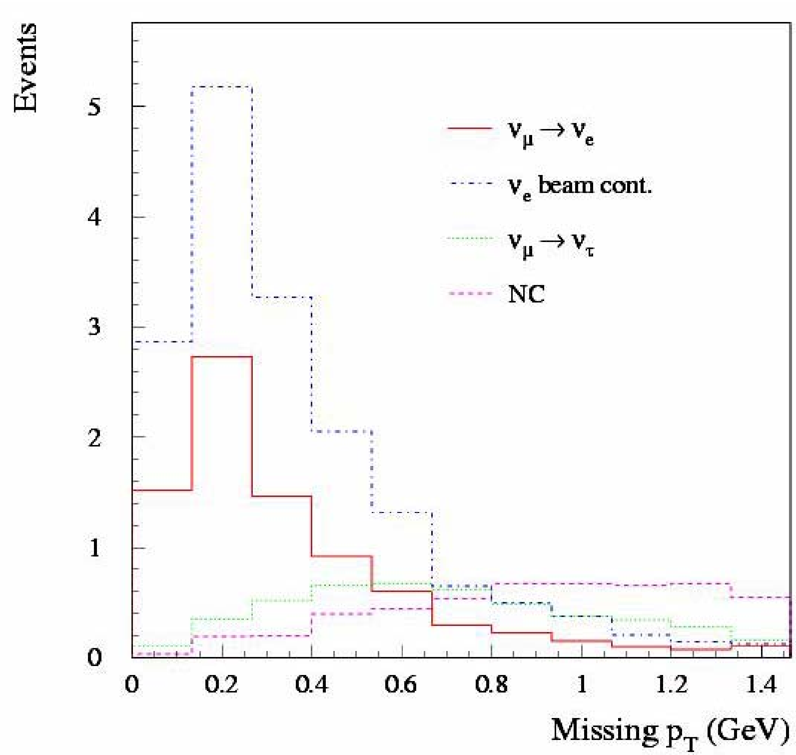
		signal	$\tau \rightarrow e$	$\nu_\mu CC$	$\nu_\mu NC$	$\nu_e CC$ beam
Location eff.	ξ	0.53	0.053	0.52	0.48	0.53
Total eff.	ε	0.31	0.032	0.34×10^{-4}	7.0×10^{-4}	0.082

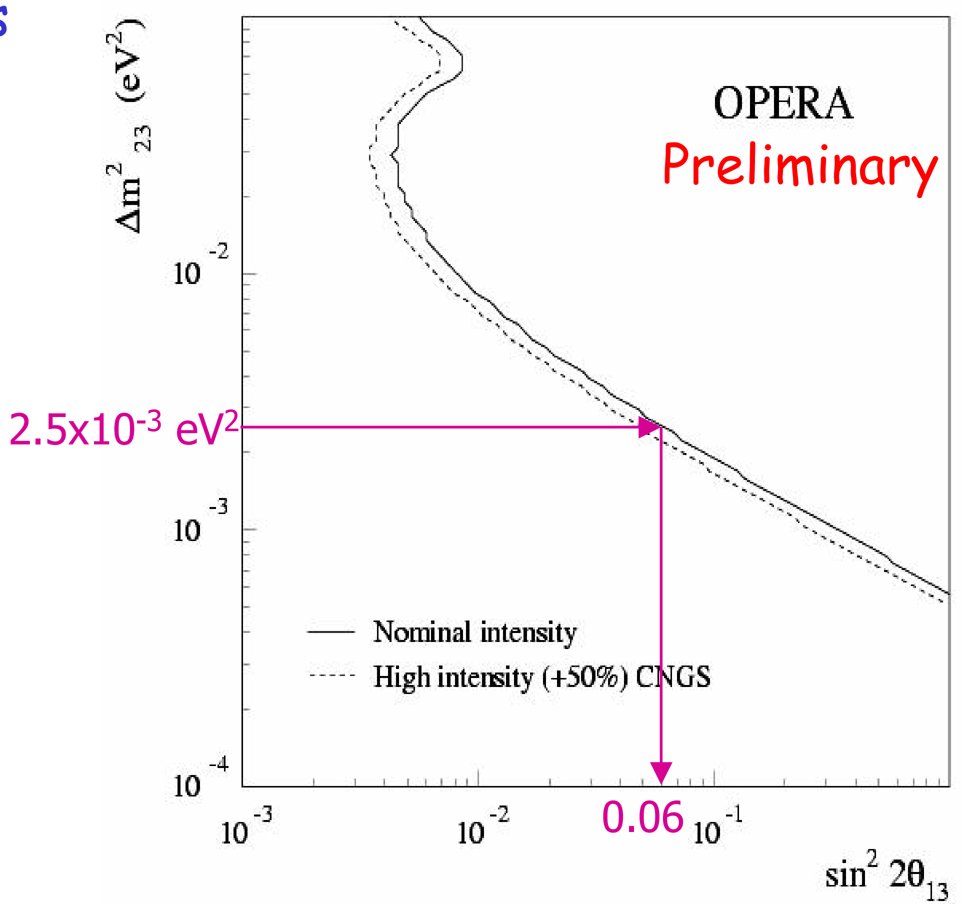
Expected signal and background assuming 5 years data taking with the nominal CNGS beam and $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1$

θ_{13}	signal	$\tau \rightarrow e$	$\nu_\mu CC$	$\nu_\mu NC$	$\nu_e CC$ beam
9°	9.3	4.5	1.0	5.2	18
8°	7.4	4.5	1.0	5.2	18
7°	5.8	4.6	1.0	5.2	18
5°	3.0	4.6	1.0	5.2	18
3°	1.2	4.7	1.0	5.2	18

OPERA sensitivity to θ_{13}

By fitting simultaneously the E_e, missing p_T and E_{vis} distributions we got the sensitivity at 90%



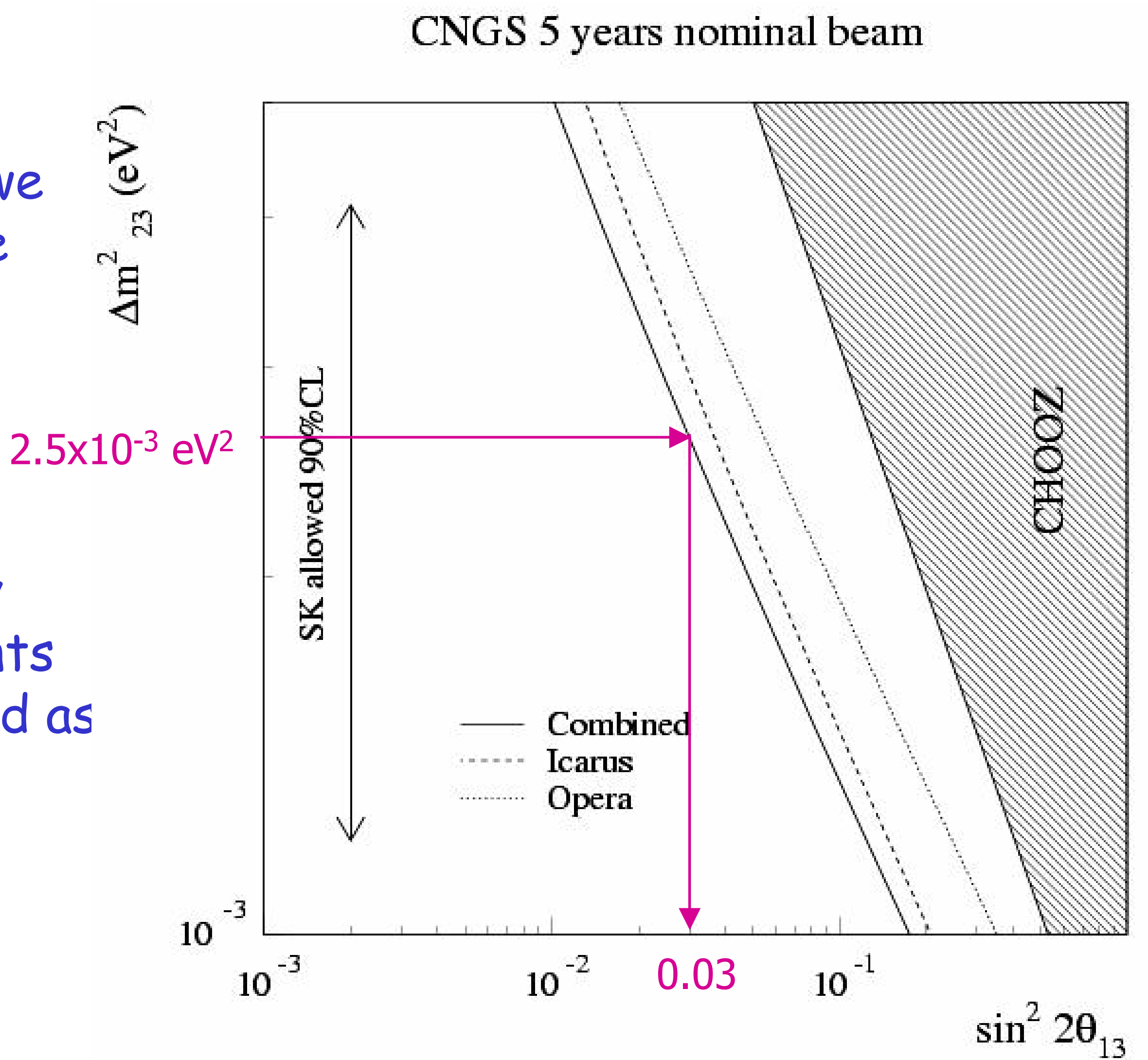


ν_μ->ν_e search combining ICARUS and OPERA

ICARUS and OPERA combined sensitivity

- By using the information reported in the proposal we managed to reproduce the ICARUS sensitivity curve at 90% C.L.
- Finally, we evaluated the CNGS sensitivity to θ_{13} by combining both experiments through a global χ^2 defined as

$$\chi^2 = \chi^2_{ICARUS} + \chi^2_{OPERA}$$



Comparing different scenarios

Limits at 90% C.L. on $\sin^2 2\theta_{13}$ and θ_{13}
($\Delta m^2_{23}=2.5\text{x}10^{-3}$ eV^2; $\sin^2 2\theta_{23}=1$)

Experiment	$\sin^2 2\theta_{13}$	θ_{13}
CHOOZ	<0.14	<11°
MINOS 2yr	<0.06	<7.1°
ICARUS 5yr	<0.04	<5.8°
OPERA 5yr	<0.06	<7.1°
ICARUS+OPERA 5yr ≡3yr CNGSx1.5	<0.03	<5.0°
ICARUS+OPERA 5yr CNGSx1.5	<0.025	<4.5°
ICARUS 5yr Low energy CNGS	<0.02	<4.1°
JHF 5yr	<0.006	<2.5°

Time is an important issue

Sensitivity to to θ_{13} as a function of the year

	2004	2005	2006	2007	2008	2009
CHOOZ	**<0.14**	**<0.14**	**<0.14**	**<0.14**	**<0.14**	**<0.14**
MINOS		→	<0.085	<0.06	<0.049	<0.042
CNGS*			→	<0.067	<0.047	<0.039
CNGSx1.5*			→	<0.056	<0.039	<0.033
Low energy CNGS				→	<0.040	<0.028
JHF					→	<0.013

* Designed for ν_τ appearance

Conclusion

- OPERA has sensitivity to θ_{13} comparable to the one of the other LBL experiments
  - $\sin^2 2\theta_{13} < 0.05\text{-}0.06$
- The sensitivity to θ_{13} combining ICARUS and OPERA is
  - $\sin^2 2\theta_{13} < 0.03$
- If the CNGS starts in 2006, by the time JHF will provide the first results (2009) the combined sensitivity of ICARUS and OPERA at $\Delta m^2_{23}=2.5\times10^{-3}\ \mathrm{eV}^2$, $\sin^2\theta_{23}=1$ will be a factor 4-5 better than the CHOOZ limit
- If we are lucky (θ_{13} just below the CHOOZ limit) the CNGS could provide the first measurement of θ_{13}!