The OPERA emulsion detector for a long-baseline neutrino oscillation experiment

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Physics process: neutrino oscillation

ν_μ <–> ν_τ ⟶ τ^- + X

$\mu^- \ \nu_\tau \ \bar{\nu}_\mu$

$h^- \ \nu_\tau \ n\pi^0$

$e^- \ \nu_\tau \ \bar{\nu}_e$

$(\pi^+ \pi^- \pi^- \ \nu_\tau \ n\pi^0)$

$$P_{osc} = \sin^2 2\theta_{\mu\tau} \ \sin^2 \left(1.27 \times \Delta m^2(eV^2) \times L(km)/E(GeV)\right)$$

$$\Delta m^2_{min} = \sqrt{(P_{osc})} \times 1/1.27 \times E/L$$

ν_τ appearance esperiment ➡ direct τ–decay detection

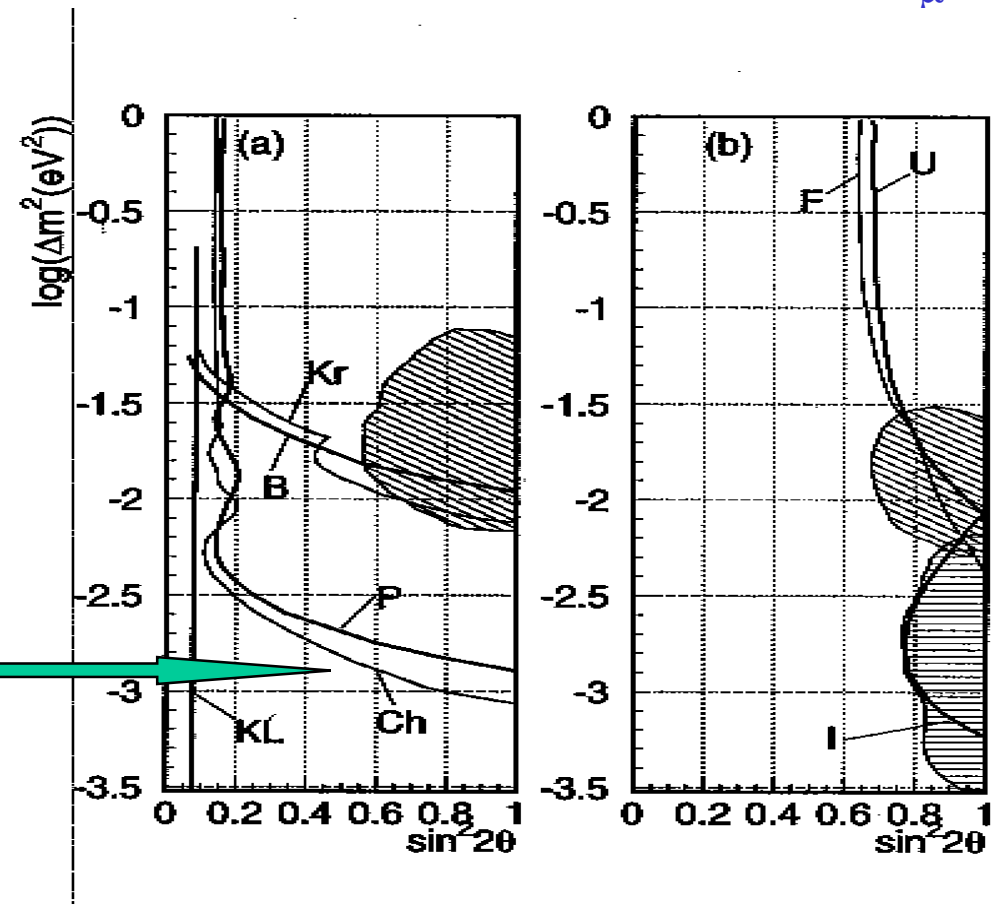
experimental technique ➡ “modern” nuclear emulsion

OPERA L.o.I: study the atmospheric neutrino anomaly, as indicated by Kamiokande

→ large mixing and $\Delta m^2 \sim 10^{-2}$ eV^2

New results from Super Kamiokande and CHOOZ: importance of ν_μ-ν_τ oscillation search

ν_μ-ν_e



ν_μ-ν_τ

CHOOZ

Kamiokande

SuperK.

After the SK result ....

Explore the possibility of a higher sensitivity search,

exploit → high intensity of the CERN **NGS** beam

increase of detector mass (modularity)

Perform the exercise with reference options:

→ optimization will be needed:

beam, detector design, mass

Assess the feasibility of the experiment: tests, simulations

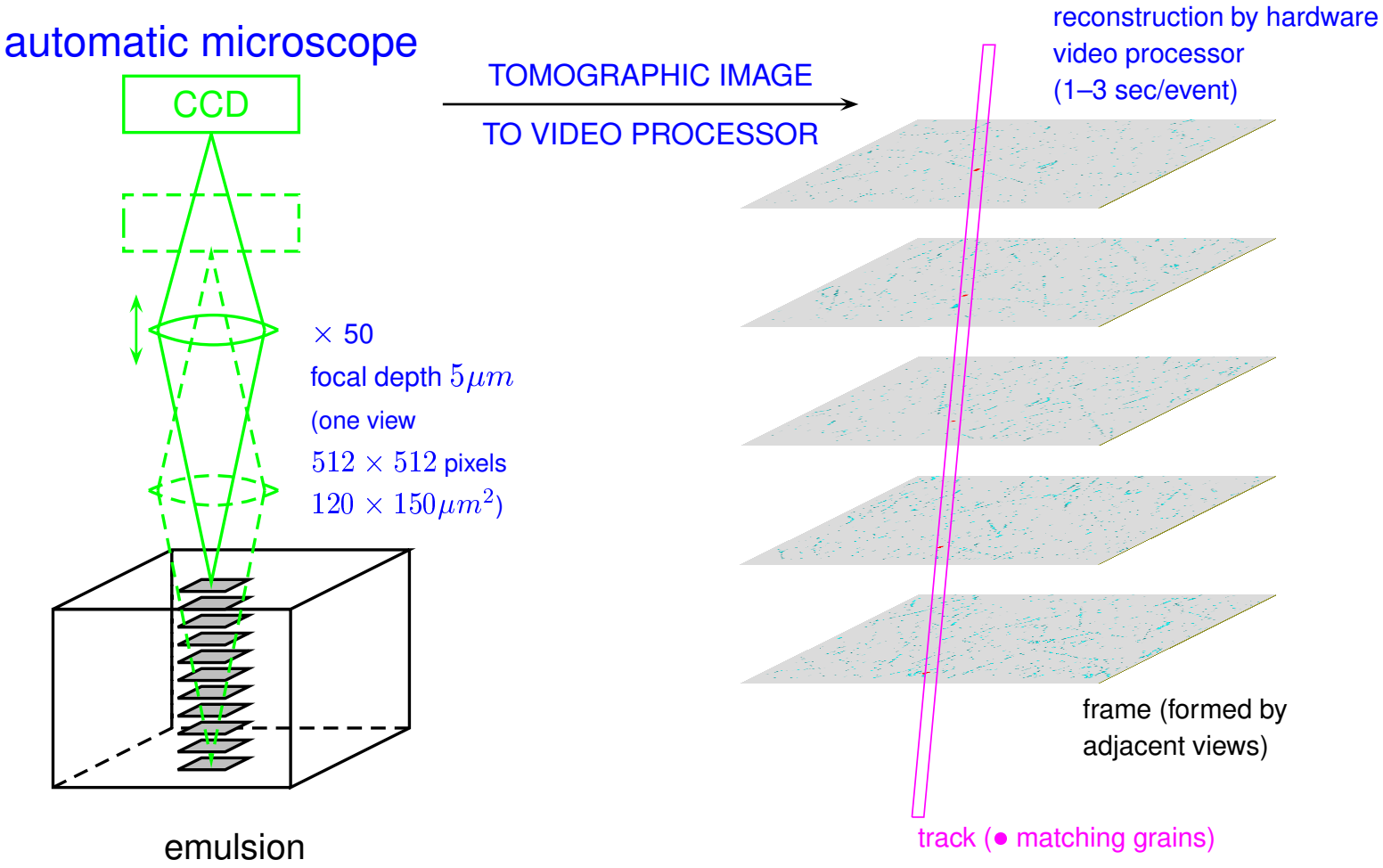
→ emulsion procurement and handling,

technical issues

Automatic emulsion scanning

- Pioneered by the Nagoya group: **Track Selector**
  → speed about x 100 w.r.t. semi-automatic systems
- **New Track Selector** routinely scanning in Japan and in Napoli (CHORUS analysis)
  → speed about x 10 w.r.t. Track Selector
- Other CHORUS laboratories actively scanning
- R&D going on at CERN, Nagoya, Napoli and Salerno: needed for a next generation experiment like OPERA
- Future prospects → **Ultra Track Selector** and **Multi Track Systems**

Automatic scanning: principle



Microscope event view

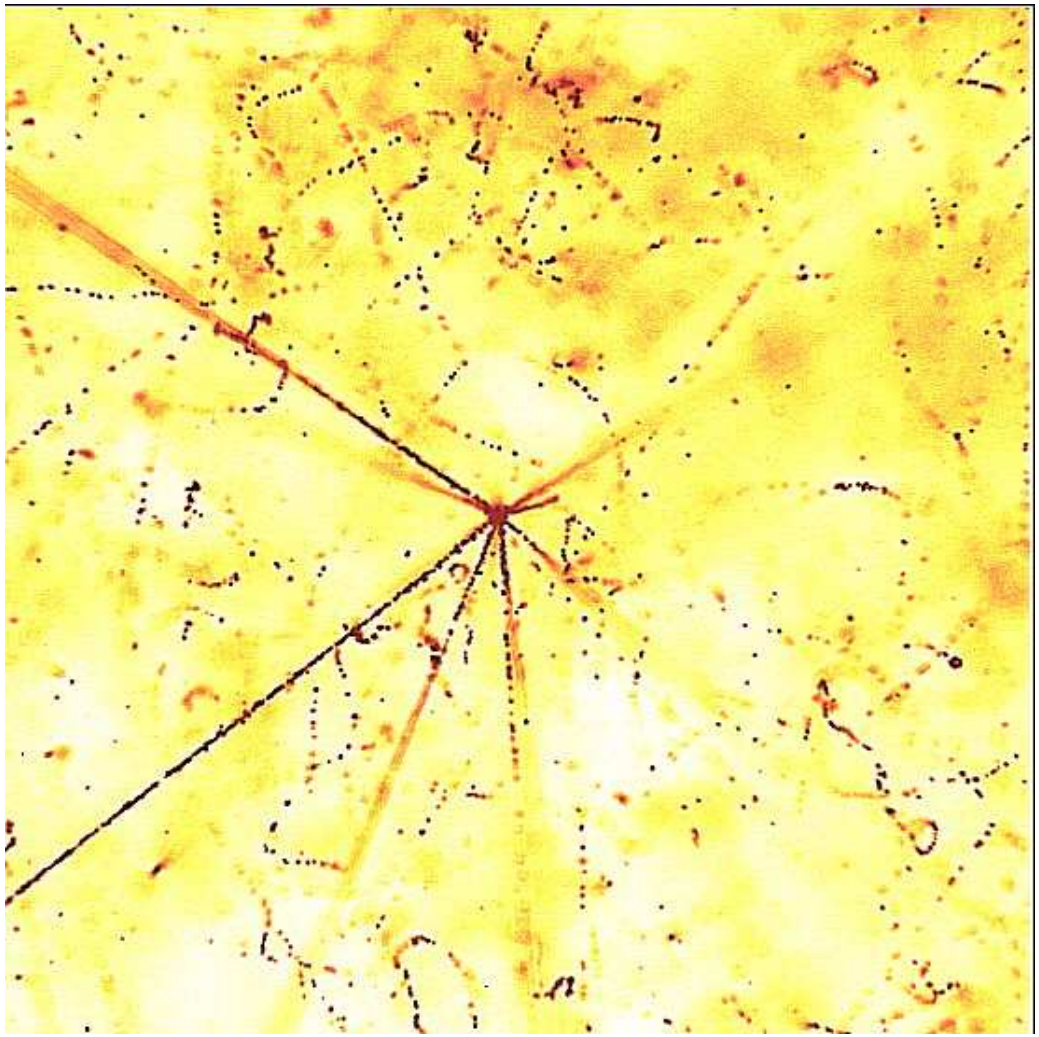
Emulsion
⊥
to beam

↓

Good tracks
appear as
dots

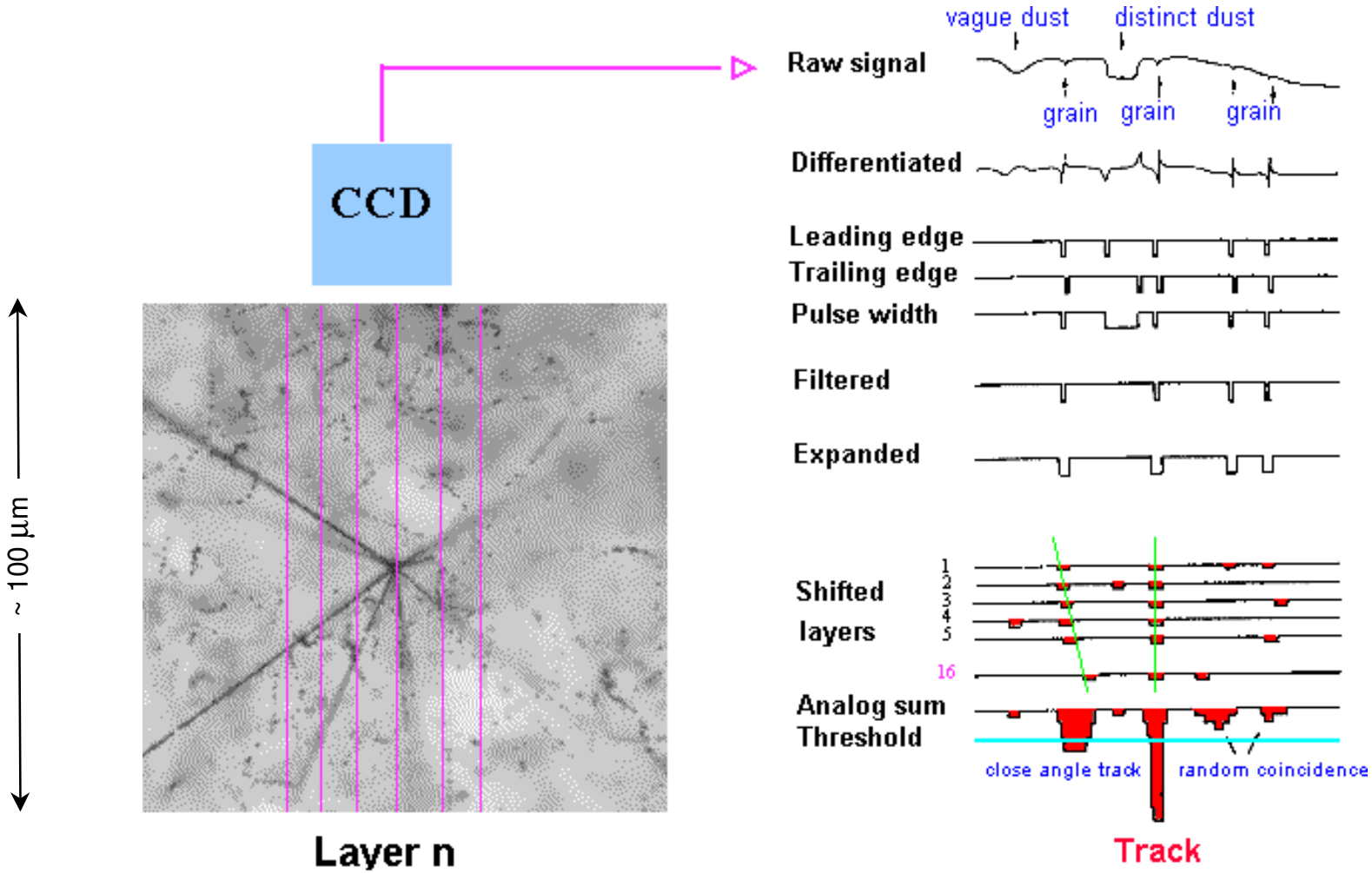
↓

Tracking
implies
connection of dots
in different
layers

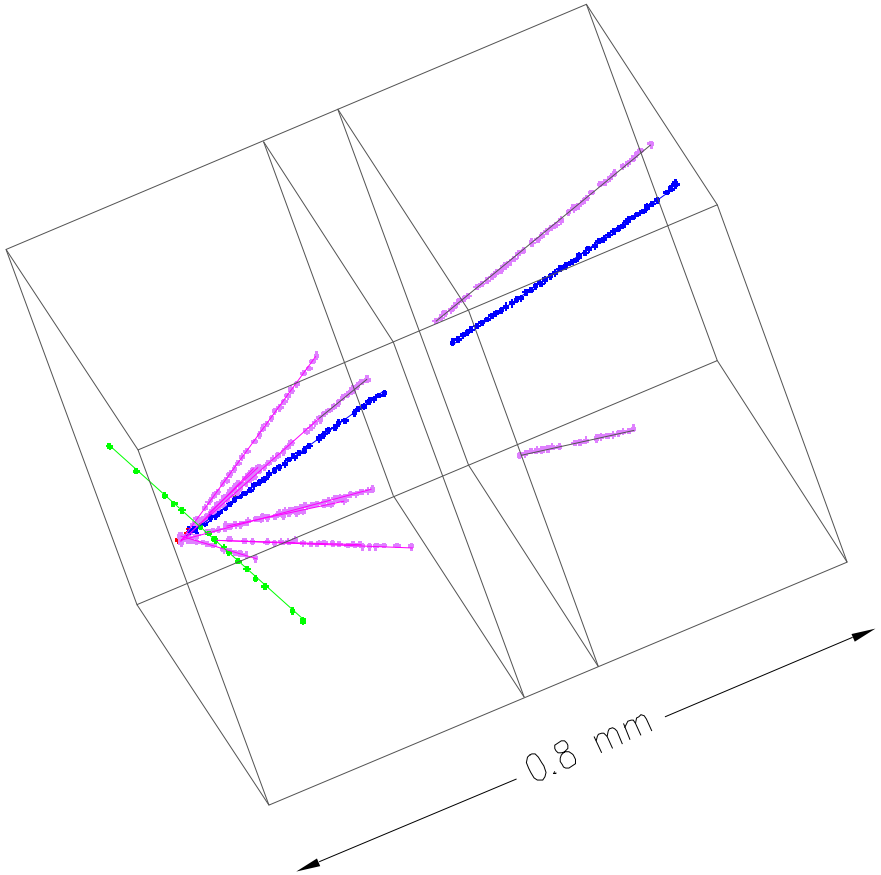


~100 μm

Track selector



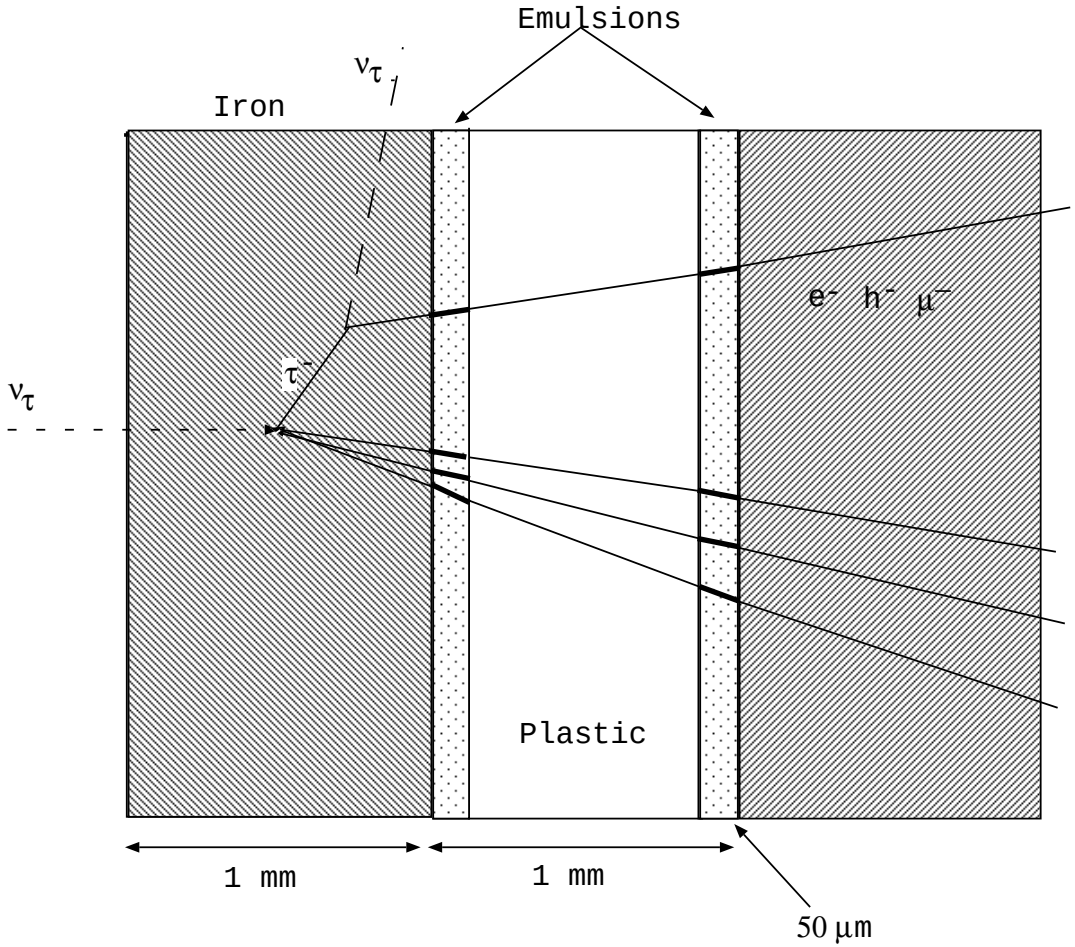
Digitized video-image of a CHORUS neutrino event



Aim, target mass and experimental technique

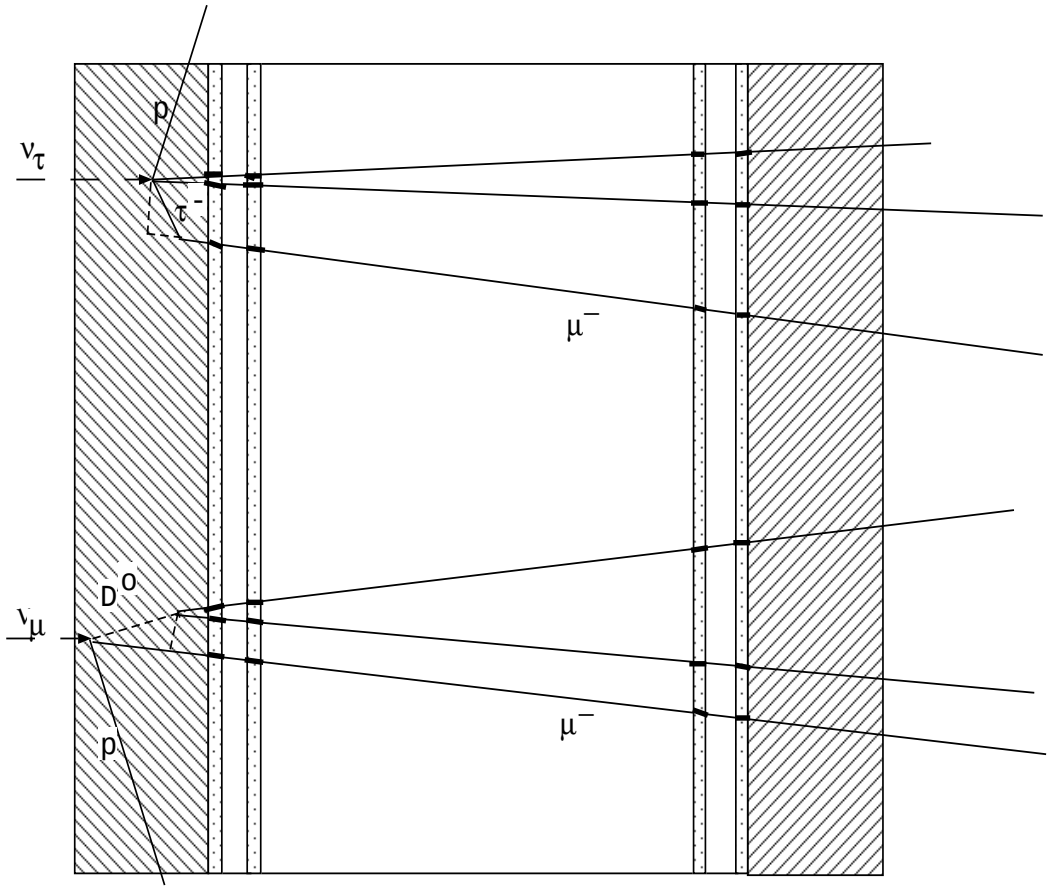
- Atmospheric neutrinos (SK) ➡ Δm^2 sensitivity 10^{-2} -10^{-3} eV^2
- NGS CERN-Gran Sasso beam ➡ M = *O* (1000) ton
- Impossible with pure emulsion target
  (CHORUS ~ 0.8 ton , TOSCA ~ 2.5 ton)
- Different approach required
  iron (lead)-emulsion sandwich:
  passive target material, emulsion for tracking
- Starting point : the **E**mulsion **C**loud **C**hamber (ECC)
  so far used both in accelerator and cosmic rays experiments

The Emulsion Cloud Chamber



- Recently used in neutrino experiments (i.e. E872/DONUT)
- ν interactions in metal plates
- Rough (~1 cm^2) event localization by electronic det.
- Emulsion tracking :
  - 50-100 μm em. layers on both sides of ~1 mm plastic base
  - 2 track segments in space
- τ decays identified by impact parameter
- Mult. Scattering measurement: $\Delta p/p$ < ~20% up to 30 GeV/c

Using impact parameter as in ECC



- Charm background to τ decays in the iron
  (shown for muonic decay)

- Similarly: background from hadron reinteractions in the metal plate

For a high sensitivity LBL experiment:

~ 100 (reint.) and ~30 (charm) for a 1000 ton ECC detector

Rethinking the ECC technique

- Charm decays and hadron reinteractions in the passive material : backgrounds using impact parameter
- The OPERA* detector concept**

  - select τ-decays in gaps between metal plates
  - small plate thickness (ε_τ) , 2 emulsion sheets
  - measure decay "kink" in space, by emulsion tracking

- Use decays in Pb for an independent analysis

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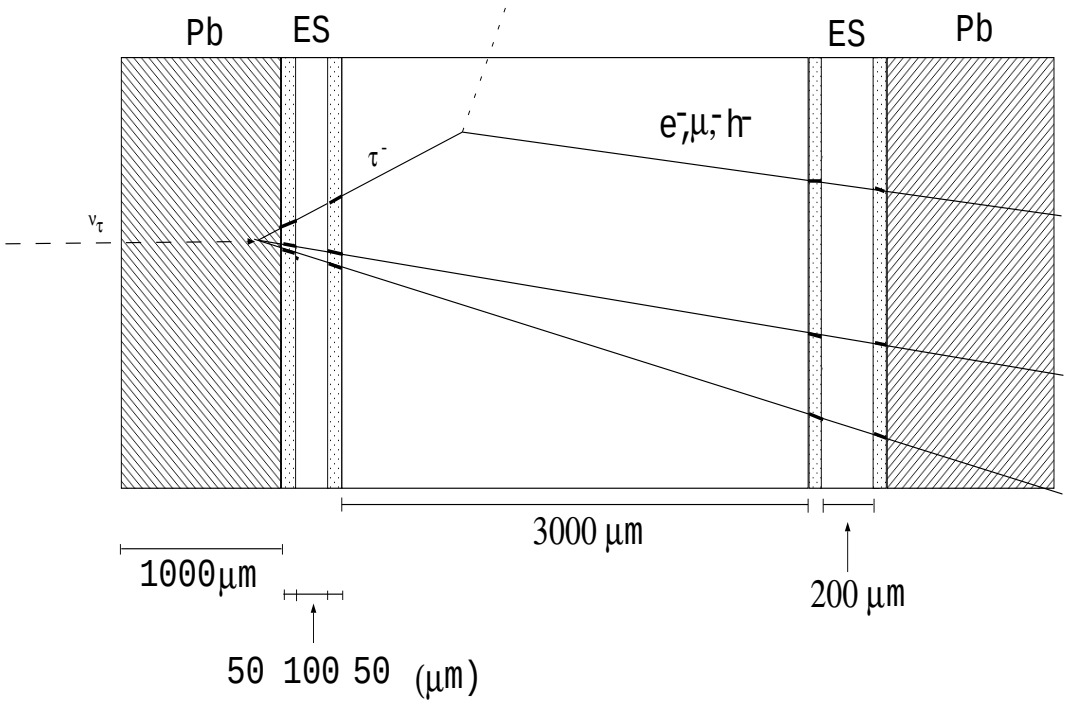
*) **O**scillation **P**roject with **E**mulsion t**R**acking **A**pparatus

**) A. Ereditato, K. Niwa, P. Strolin, INFN/AE 97/06

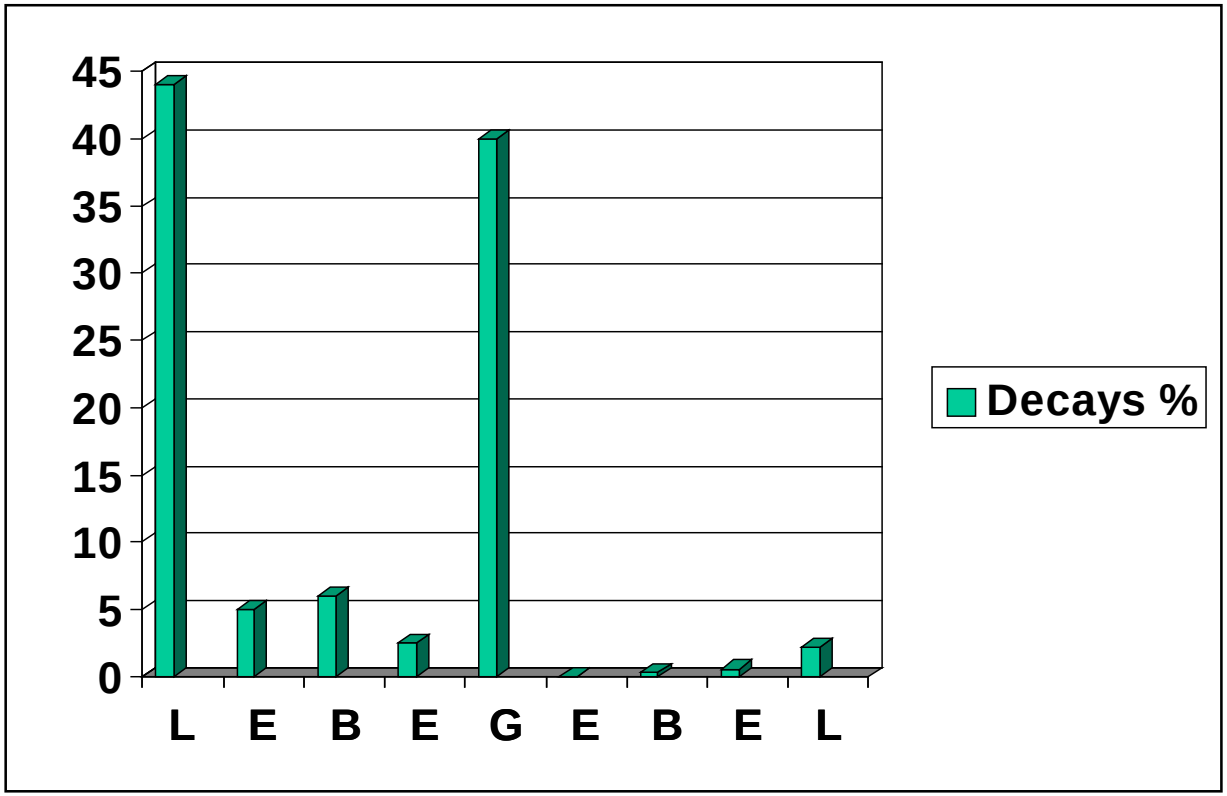
The OPERA concept



low density spacer

- thin lead plates :
  $1\ mm < \gamma c\tau \rightarrow \varepsilon_\tau \sim 0.5$
- two emulsion sheets (ES) for tracking, light spacer
- each ES :
  - 50 μm emulsion layers on both sides of 100 (200) μm plastic base
  - 2 high quality track segments in space (μm granularity)
- retain τ decays in the spacer
- decay topology (kink angle) detection in space

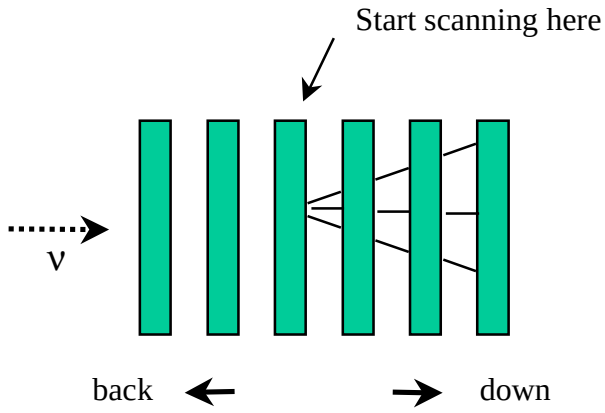
Fraction of τ's decaying in:
L (lead), **E** (emulsion layer), **B** (base), **G** (gap), **L** (long kinks)



For $\Delta m^2 = 2 \times 10^{-3}$ eV^2 and 1 mm lead, 3 mm gap

Event reconstruction

- Study all τ decay channels $\rightarrow e^-$, μ^-, h^-, (possibly into 3π)
- Track localization by electronic detectors
- Start scanning from ES upstream of event in electronic detector
- General scanning (in the most downstream ES and then scan back)
- Find vertex plate (Pb) and neutrino vertex
- Follow down tracks from vertex
- Kink search (in gaps between Pb)
- Kinematics of candidate events
  (few % of total)

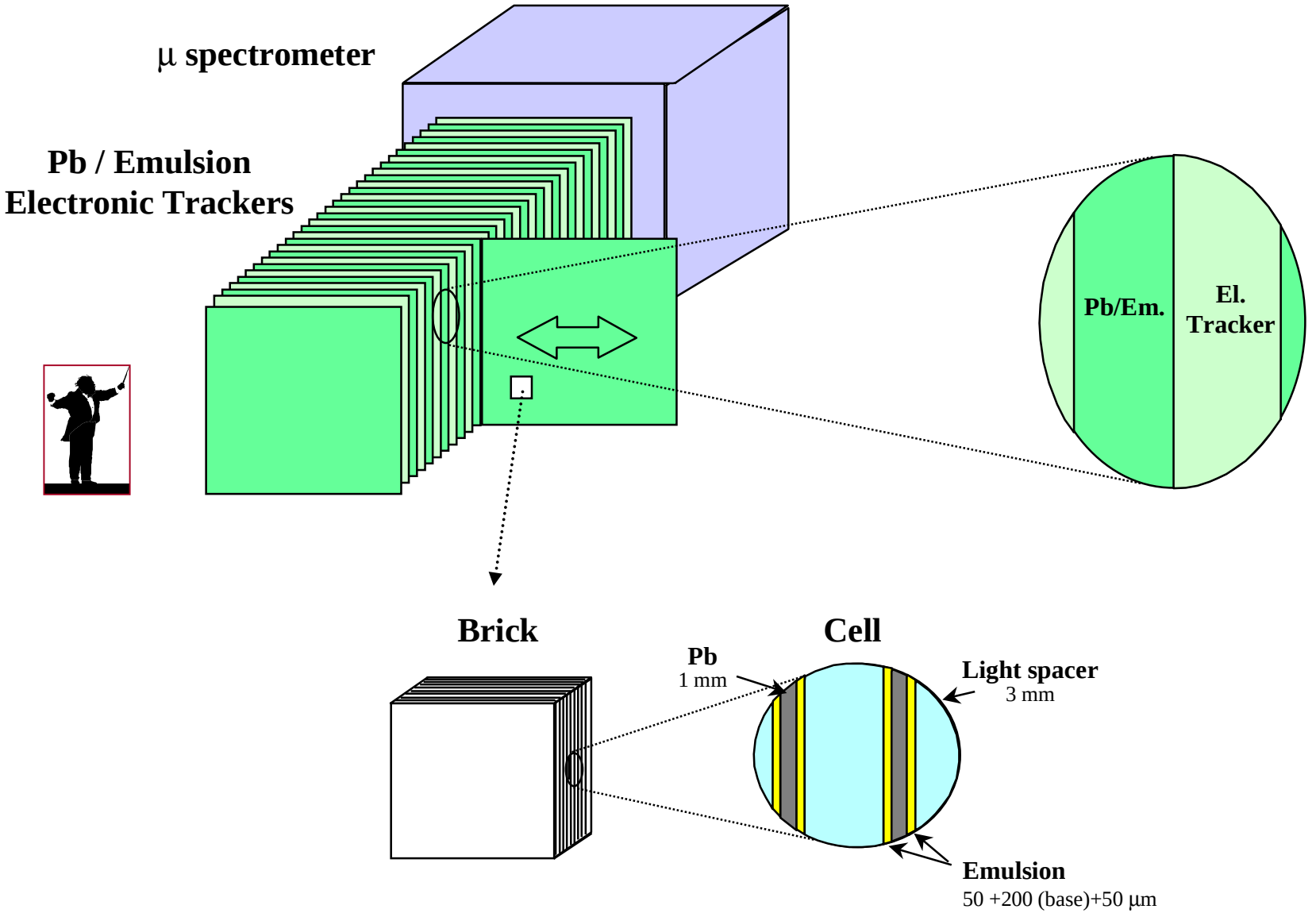


The detector

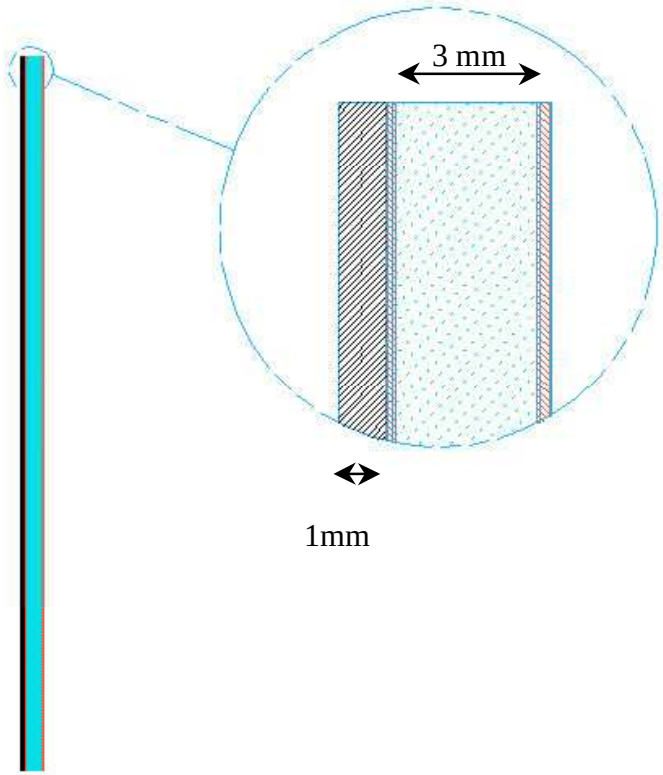
Preliminary design

- **Lead-emulsion target**
  - cell: 1 mm Pb, ES, 3 mm gap, ES
  - brick: stack of 30 elements (~ 13 cm thick, 15 x 15 cm^2 X-sect.)
  - module: 18 x 18 bricks (~ 2.8 x 2.8 m^2)
  - electronic detector planes following each module (~ 5 cm thick)
  - e.g. 300 modules: ~ 750 ton, subdivided into 10 identical supermodules
  - overall target dimensions ~ 3.5 x 3.5 x 40 m^3 (x 2)
  - detector mass is scalable (number of supermodules)
- **Muon detection**
  - tracking in the target (electronic detectors)
  - magnetised iron μ-spectrometer downstream: sign of charge (momentum)
- **Calorimetry**
  - in the target: Pb (each module ~ 5 X_0) + electronic det. (RPC, streamer tubes,..)
- **$\Delta p/p$** ~ 10-20 % at 1-30 GeV/c from multiple scattering in emulsion

An OPERA supermodule



Cell



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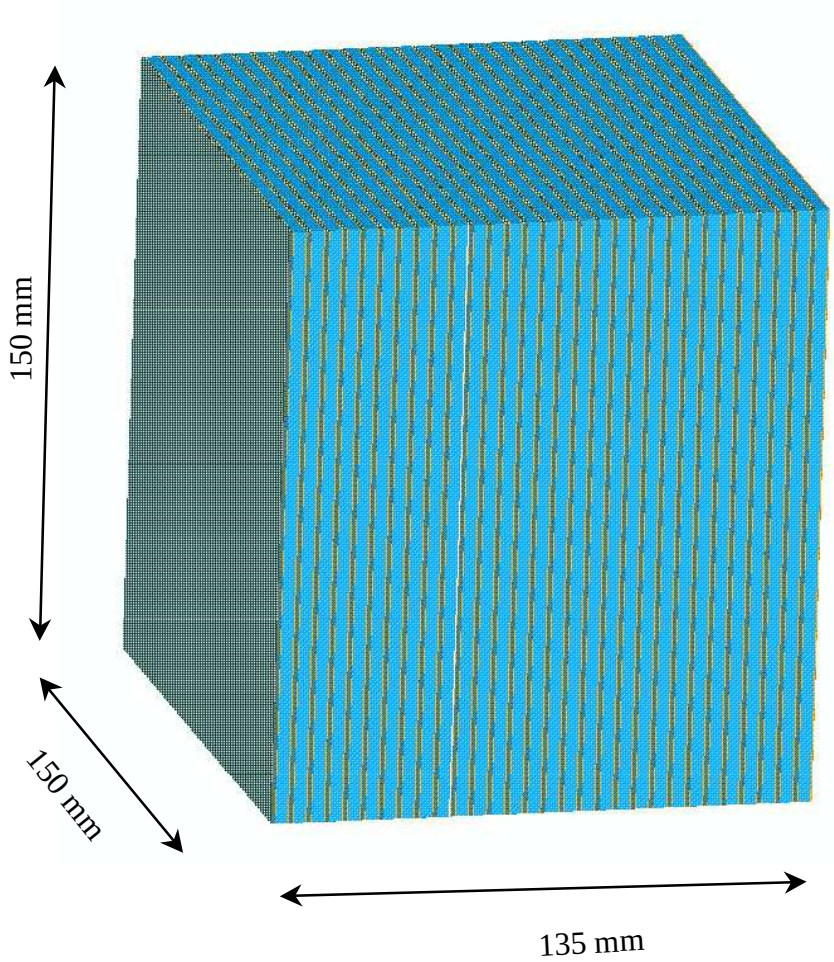
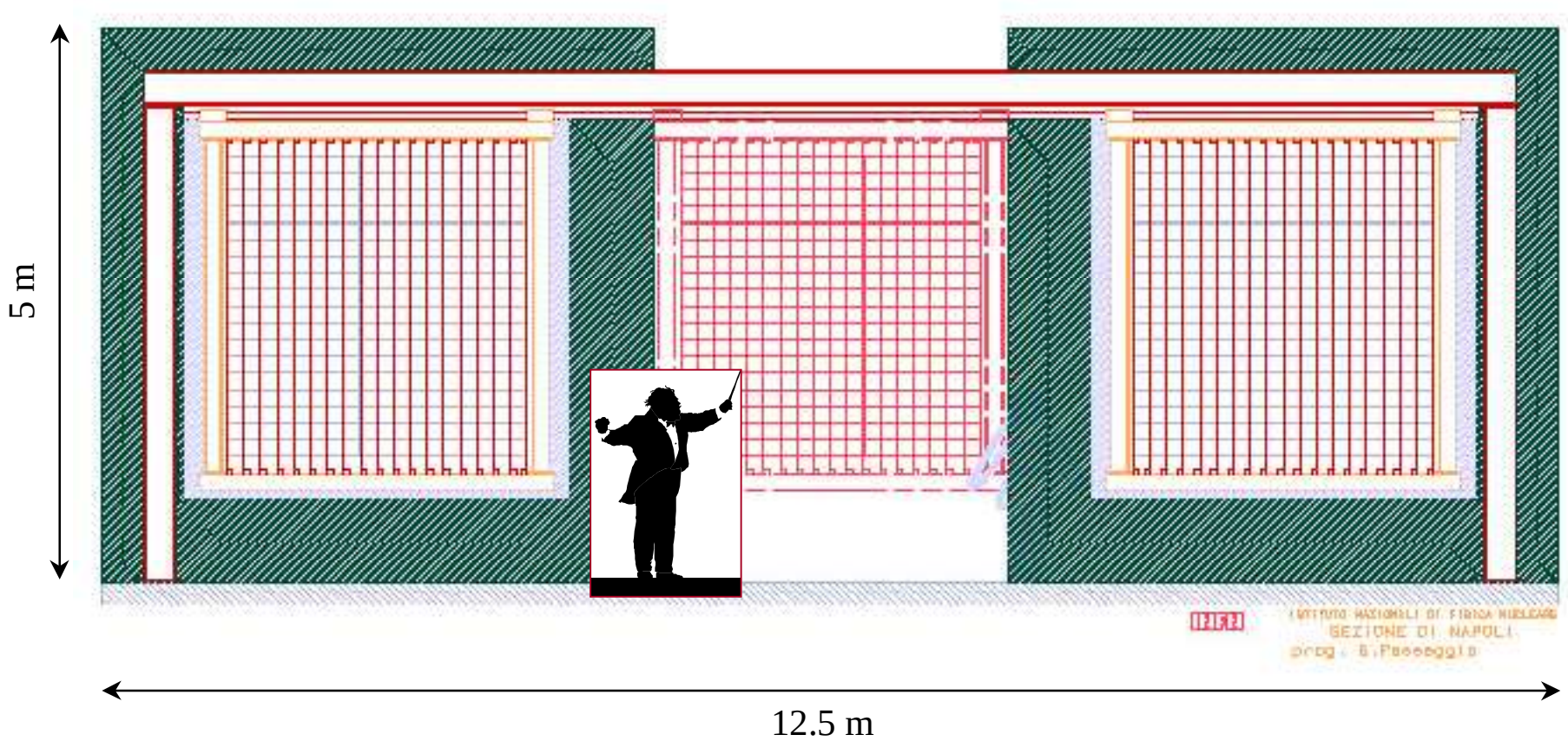
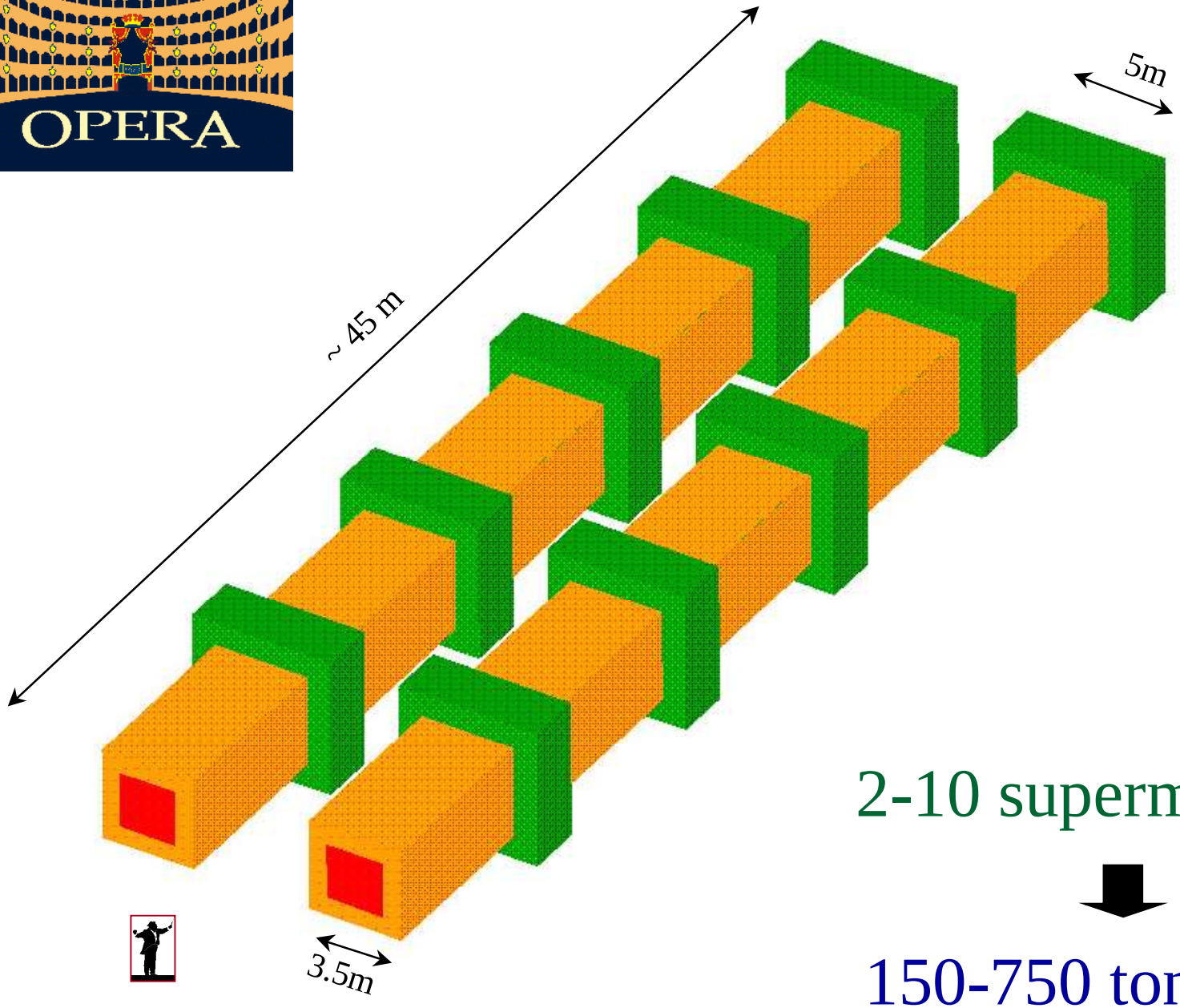
SEZIONE DI NAPOLI
prog. G.Passeggio

Brick



View along the beam





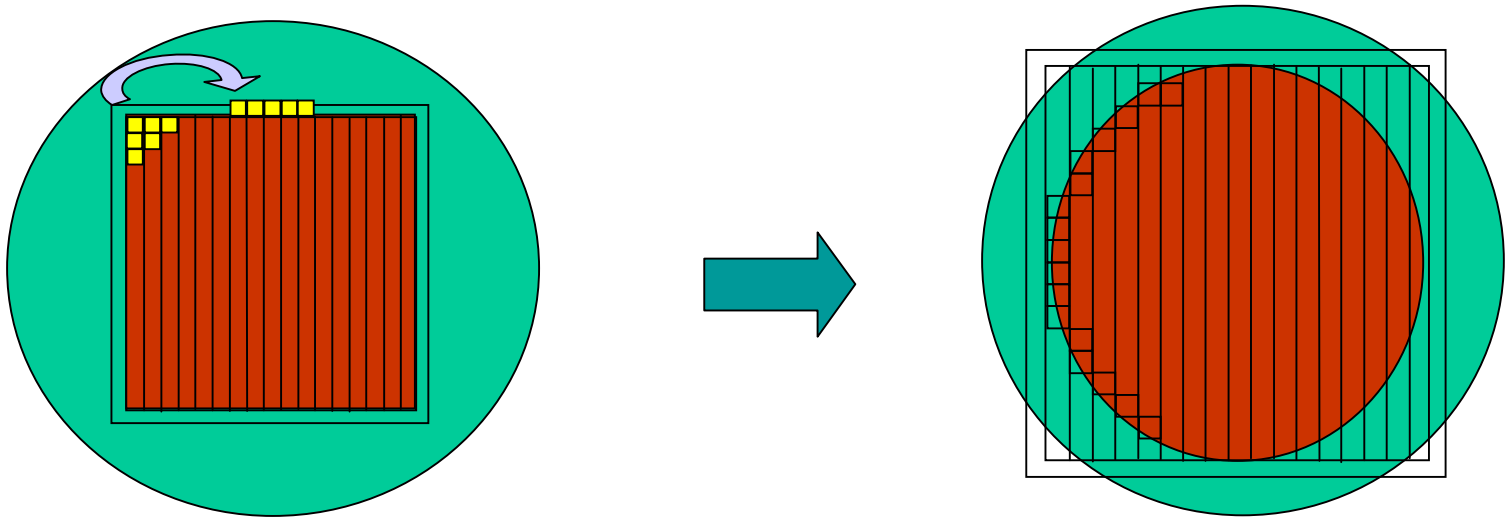
2-10 supermodules

150-750 ton target

A possible shape optimization

from present design....

... to quasi-circular geometry



Optimal use of the emulsion surface

..some numbers (750 t configuration)

18x18 =324 bricks/plane

30 planes/supermodule → 9720 bricks/supermodule

10 supermodules → 97200 bricks

30 cells/brick → ~ 3 x10^6 lead (spacer) plates

60 emulsion sheets/brick → ~ 6 x10^6 emulsion sheets (~13.5 km^2)

Industrial emulsion production needed
+ automatic brick assembly

Brick materials

Metal →
- inox
- lead alloy + nickel bath
- lead + inox glued
- …..

Spacer →
- polyurethane
- polyethylene
- expanded PVC
- paper honeycomb
- …..

} Low density (<50 kg/m^3)

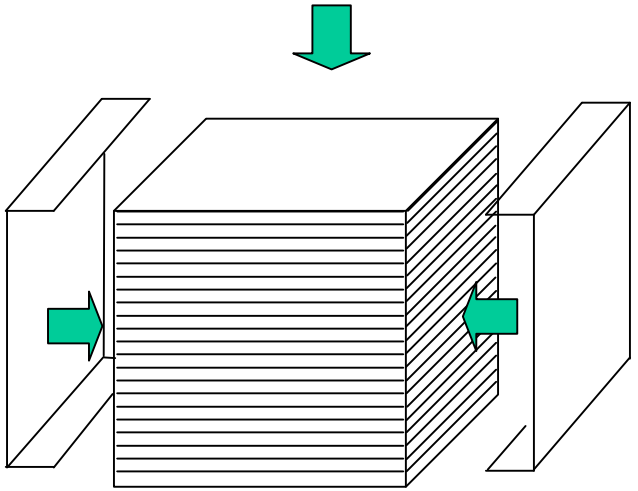
Emulsion

Brick materials

	Pro's	**&**	**contra**
Inox	easy to machine		light
nickel-plated lead	density		softness
Lead+inox plates	density+rigidity		-
….			
Polymers	density &price		viscosity
Paper honeycomb	very low total density		non uniform density & $
…..			

Tentative brick assembly

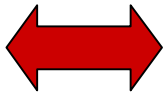
Pressure
compression ~ 0.3 mm
(spacer elasticity)



Schematic
not to scale

Inox C pieces
(<1 mm thickness)

Vacuum packing
maybe unnecessary



Gran Sasso Laboratory:
stable temperature and humidity

Brick assembly machine (1)

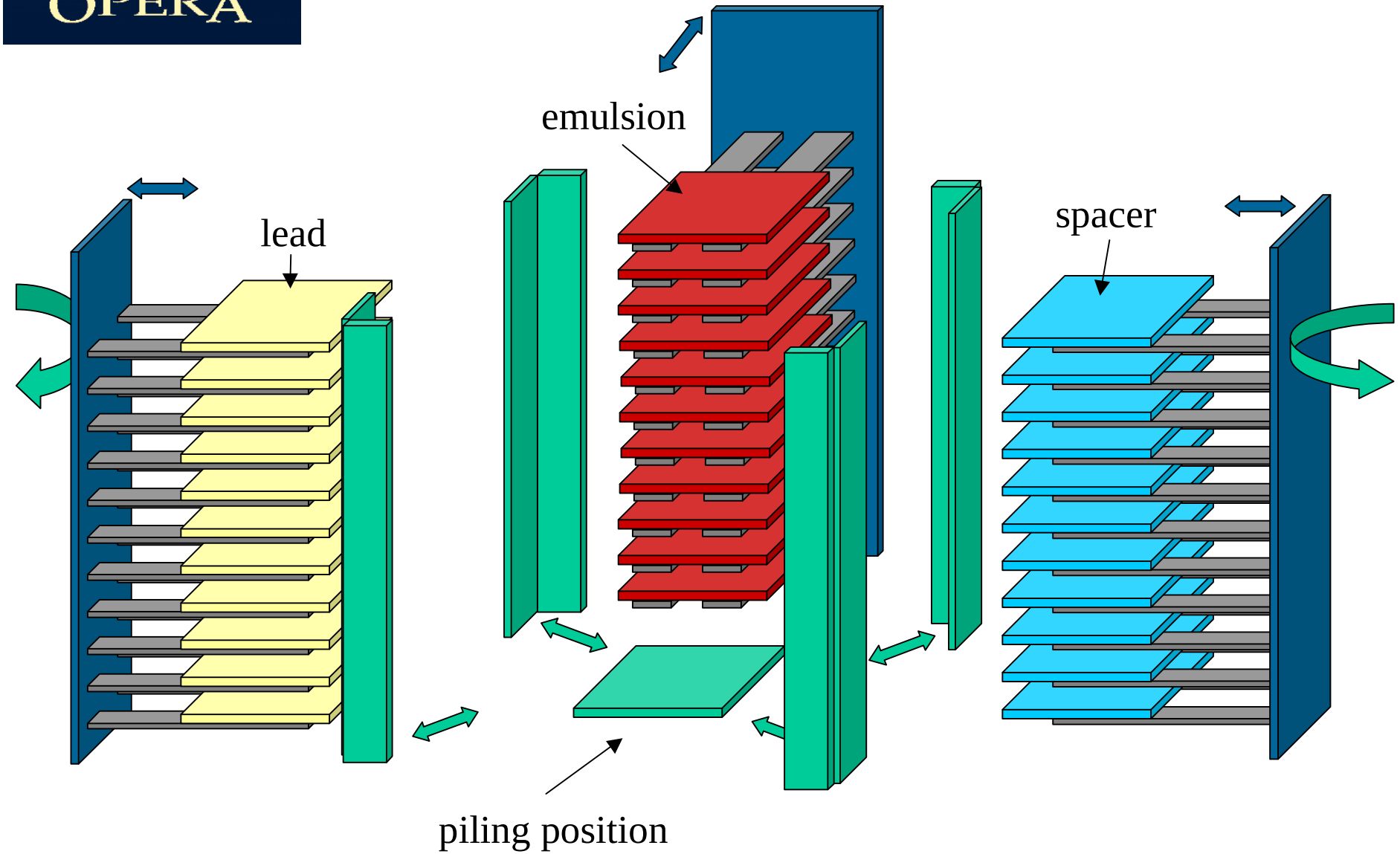
~ 10^5 bricks in 1 year (200 days)

~ 500 bricks/day (8 hours)

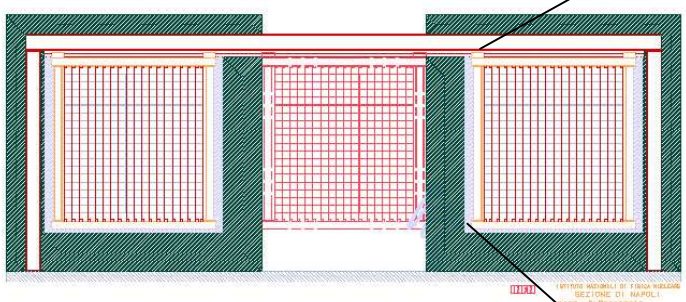
~ 60 bricks/hour

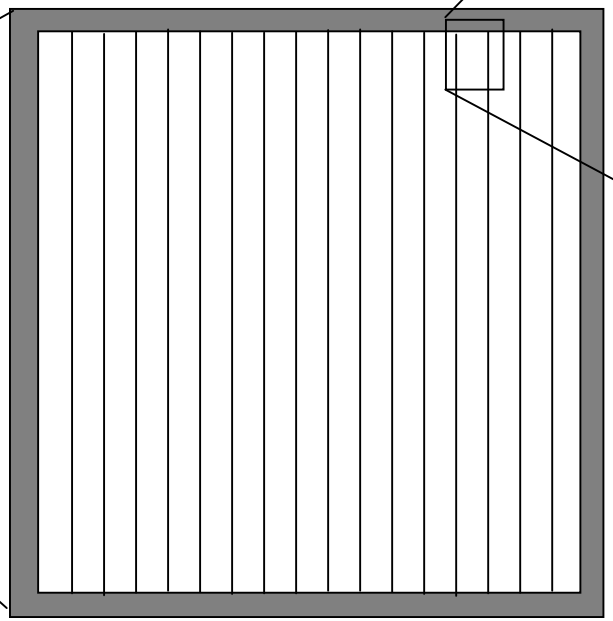
production lines = # minutes/brick

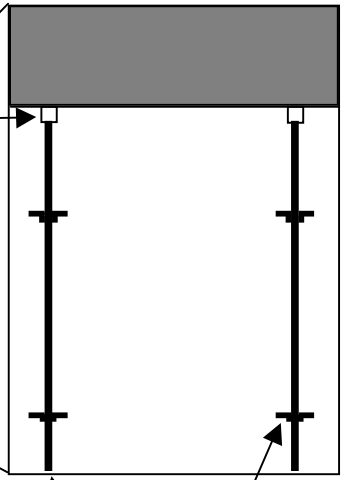
Brick assembly machine (2)



Plane frame







Tension
tuning device

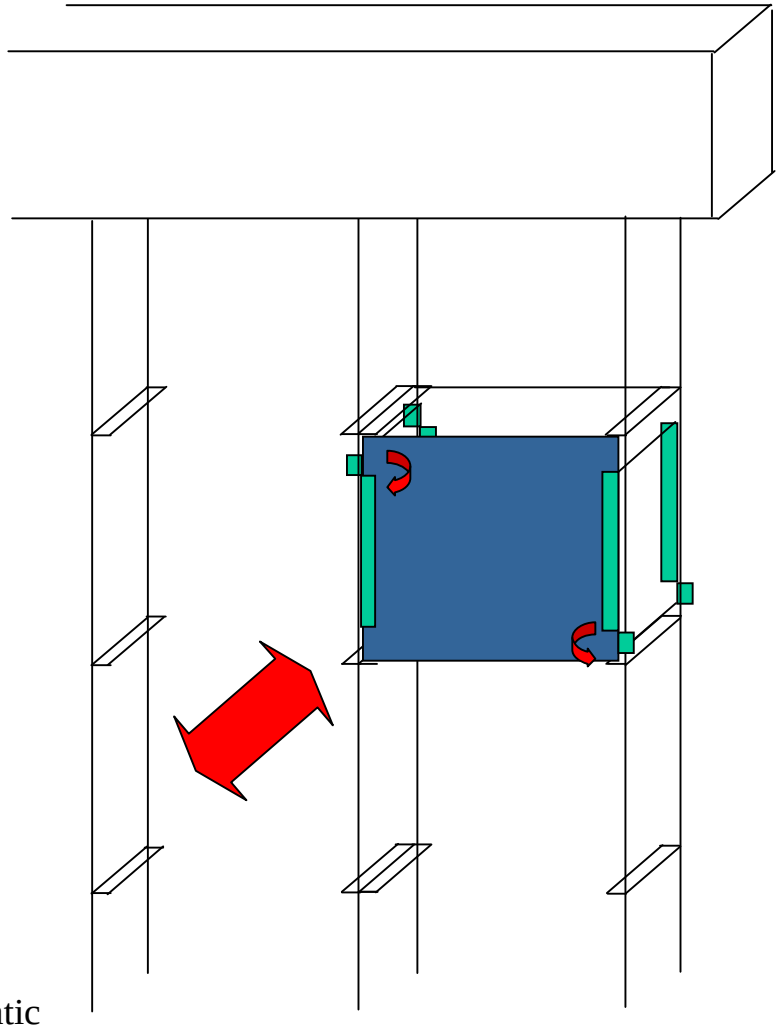
Iron sheet
(< 0.5 mm thickness)
soldered

Iron sheet
(< 1mm thickness)

~3m

Schematic
not to scale

Brick positioning



Schematic
not to scale

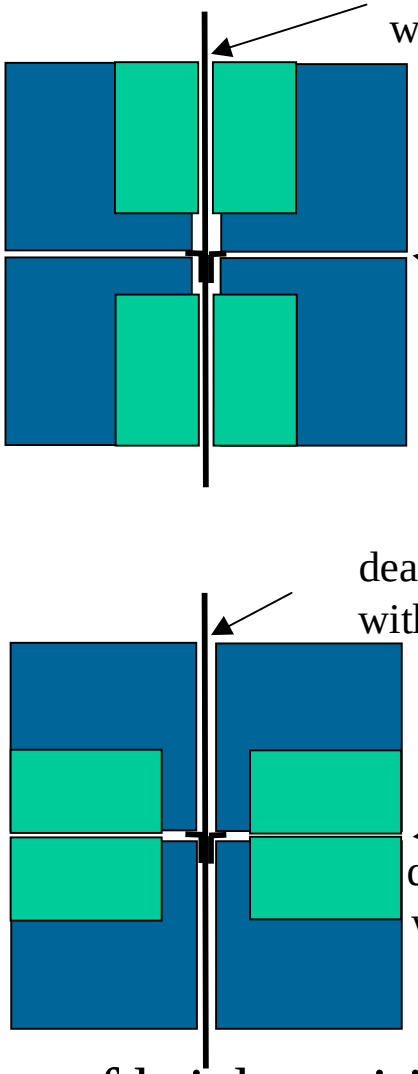
< 3.5 mm
dead space filled
with < 3mm iron

< 1 mm
dead space
with air

< 2.5 mm
dead space filled
with < 1mm iron

Alternative
solution

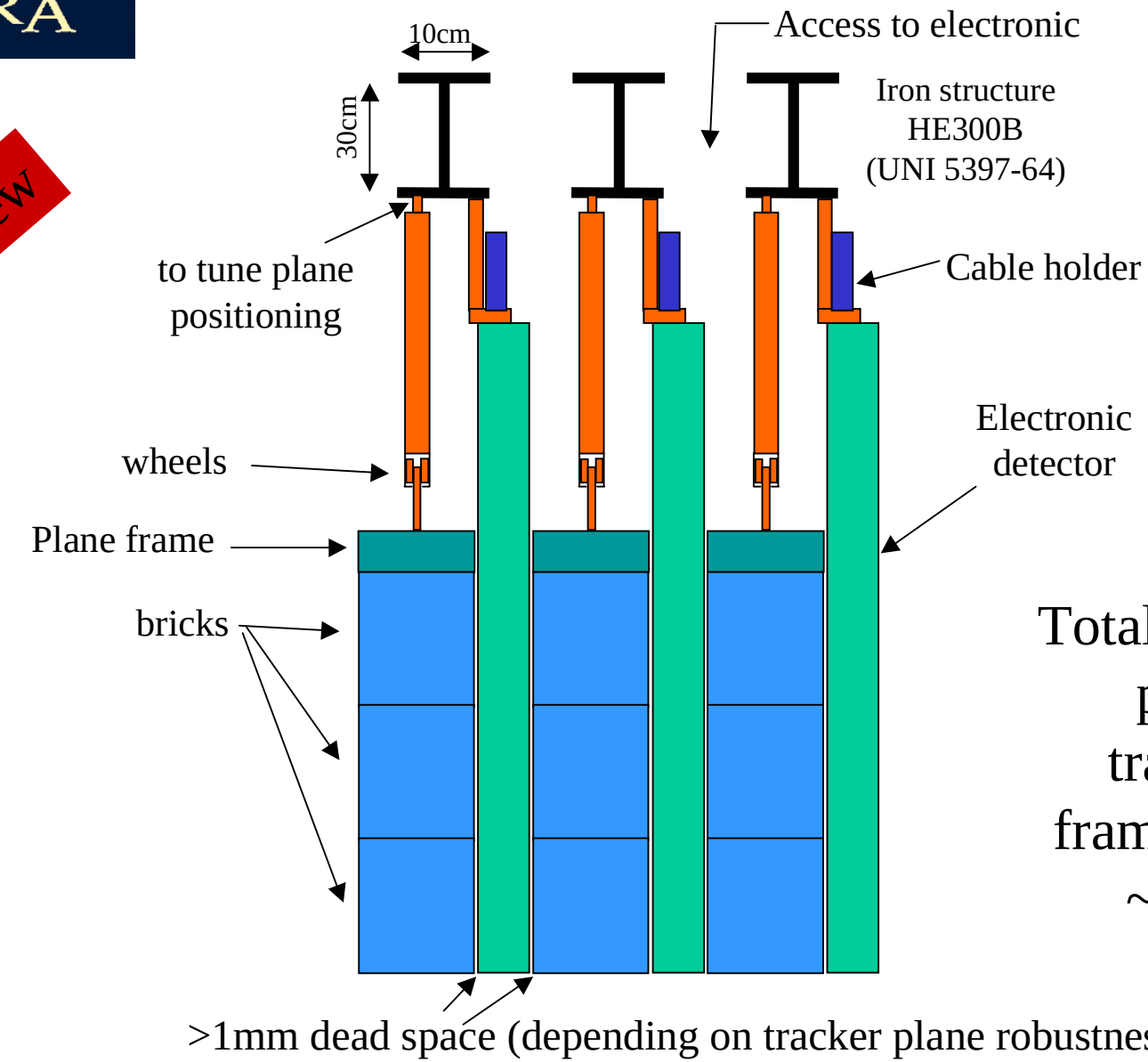
< 2.2 mm
dead space filled
with <2mm iron



Accuracy of brick positioning
to be defined

Plane positioning

Side view

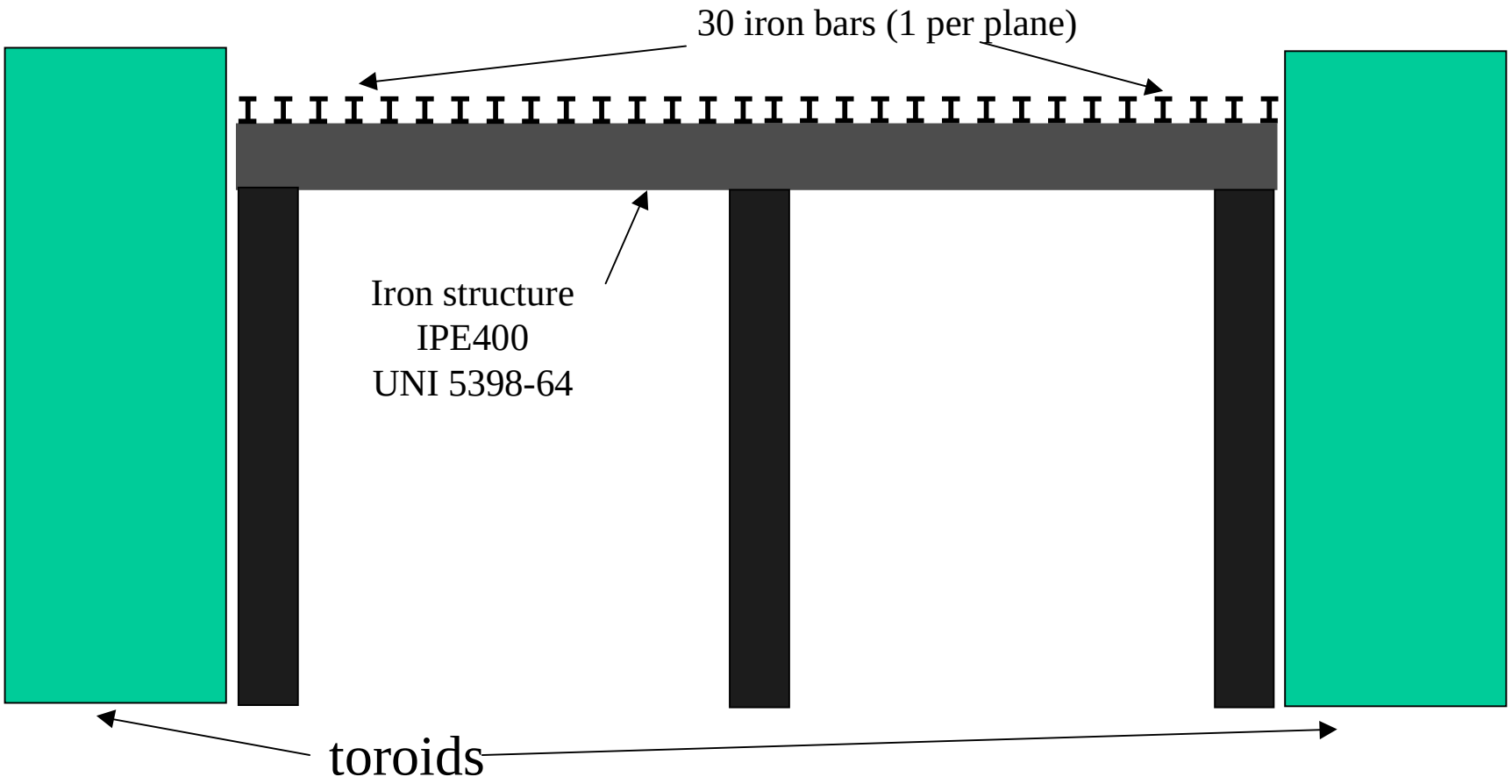


Schematic
not to scale

Total weight of:
plane +
trackers +
frame + cables
~ **3 tons**

2 Supermodule frame (side view)

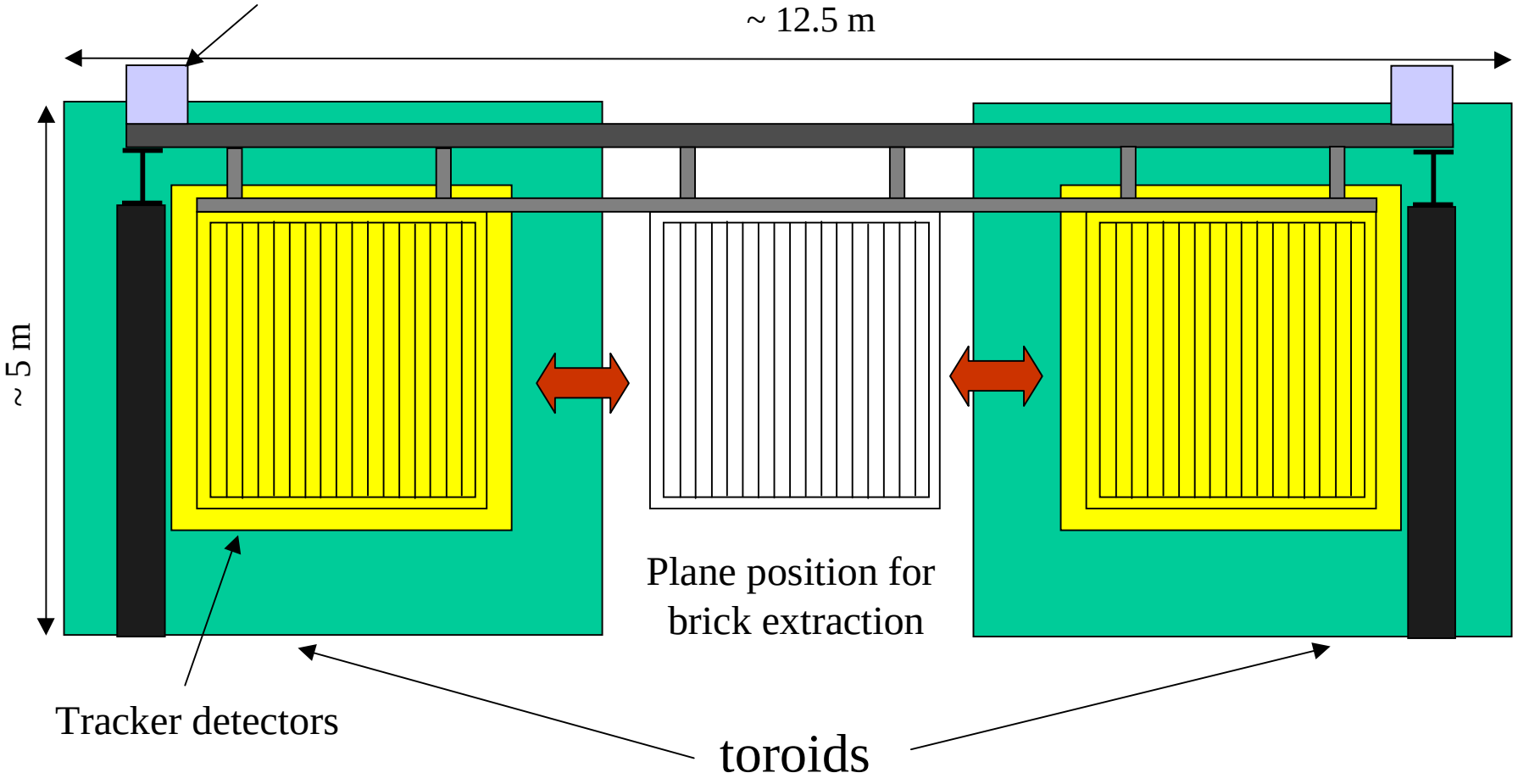
Schematic
not to scale



Total weight of 30+30 planes: 90 + 90 tons

2 Supermodule frame (front view)

Schematic
not to scale



Emulsion (1)

- No target ("bulk") emulsion, but still ~ 13 m^3 of emulsion layers (for 10 supermodules)
- Diluted emulsion: AgBr content 1/2-1/3 w.r.t.

  short baseline experiments: cost scales down

  (lower grain density allowed by automatic scanning and b.g. level)
- Industrial production: time schedule, lower cost
- Alternative: emulsion as for X-ray films
- R&D on emulsion: tests on prototype ES and bricks

  going on in Nagoya and Fuji company
- European and American companies will also be involved

Emulsion (2)

Electronic detectors (1)

- ***OPERA*** is a large detector: ~5000-7000 m^2 total surface needed
- Main task of electronic trackers: locate the event (shower center) moderate position resolution (few b.g. tracks): σ ~ 5-10 mm
- Need reconstruction behind each emulsion module
- Standard large-surface trackers can be used
- Additional tasks: event topology (CC/NC), calorimetry, timing measurement: granularity, low noise, analog r/o (?)
- Design/construction schedule: use well proven techniques

Electronic detectors (2)

Tracker technologies:

Limited streamer tubes (LST):

pros: streamer mode, many applications for tracking & calorimetry, well understood performance/cost, industrial production, 2-dim read-out, non flammable gas tested.

cons: timing meas., only rectangular shape, sensitive to γ.

Resistive plate chambers (RPC):

pros: no wires, robust construction, streamer/avalanche mode, non-flammable gas possible, 2-dim read-out, any shape, timing meas., not sensitive to γ, industrial production.

cons: limited size, space resolution, no experience with calorimetry, HV~10 kV.

Other possibilities: ***Monitored Drift Tubes, Honeycomb Chambers, Straw Tubes, Drift Chambers***

Muon spectrometers (1)

- Task: sign of the muon charge (background reduction)
- Possibly: momentum measurement (b.g. reduction, E_ν meas., beam monitoring)
- To study: kinematical domain, magnets size (match module size), required tracker precision, combine measurement in the target trackers, design/construction issues.

Kinematics ⟹ $\langle E_\mu \rangle = 10$ GeV, $\langle E_{CC} \rangle = 40$ GeV

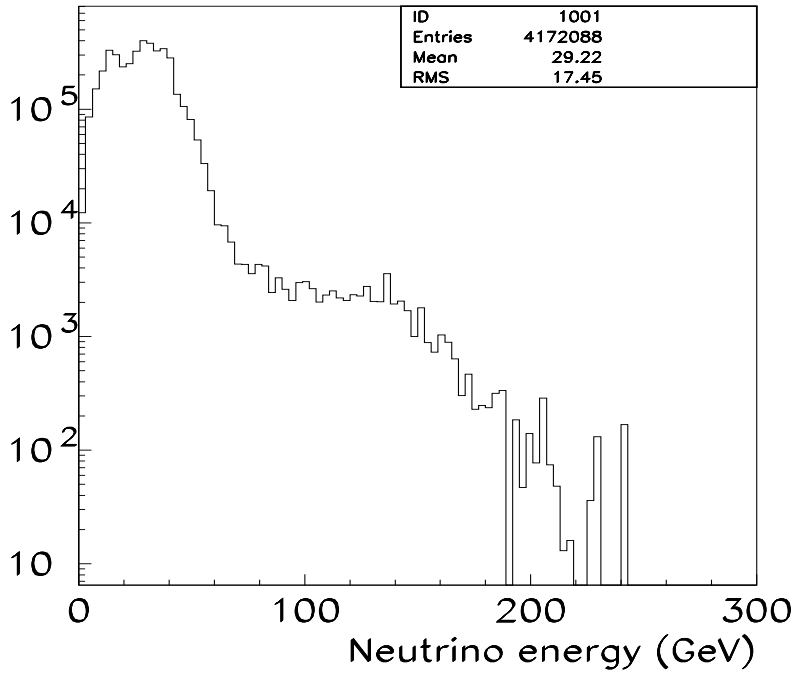
Constraints ⟹ μ energy loss: @10 GeV, 1.6 GeV/supermodule

if spectrometer length ⇓ field intensity and tracker precision ⇑

Muon spectrometers (2)

NGS beam: CERN SPS to Gran Sasso

ν_μ spectrum



$\langle E_\nu \rangle = 27$ GeV

L = 732 km

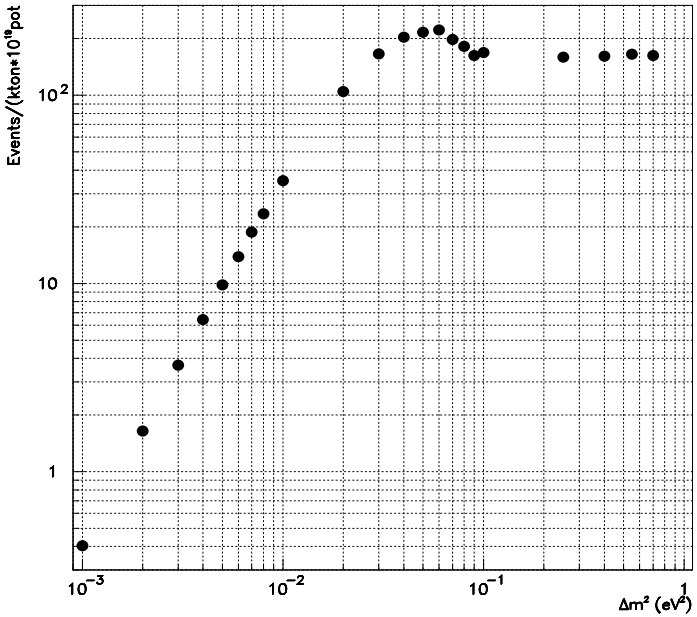
(spectrum of the NGS "reference" beam)

ν_τ interactions

- Scale reference option: 5 x 10^{19} pot/y (75% efficiency, 220 days run)

  → assume 2.0 x 10^{20} pot/4 years

- Data: ~ 660 CC+QE ν interactions/kton x 10^{19} pot (Gran Sasso)



→ ~ 10000 events in 4 years (750 ton detector)

~25 ν_τ interacting in OPERA ($\Delta m^2 = 2 \times 10^{-3}$ eV^2)

~150 " ($\Delta m^2 = 5 \times 10^{-3}$ eV^2)

~280 " ($\Delta m^2 = 7 \times 10^{-3}$ eV^2)

↓

possible improvements by design optimization

τ detection efficiency

- Decays outside Pb (1 mm) → $\varepsilon_{gap} \sim 0.52$
  (ε_{gap} depends on beam features)
- Kink finding efficiency ε_{kink} →
  0.85 $(\tau \rightarrow \mu)$
  0.84 $(\tau \rightarrow e)$
  0.88 $(\tau \rightarrow h)$

determined by the angular cuts:

(resolution) → $20 < \theta_{kink} < 500$ mrad ← (scanning & bg rejection)

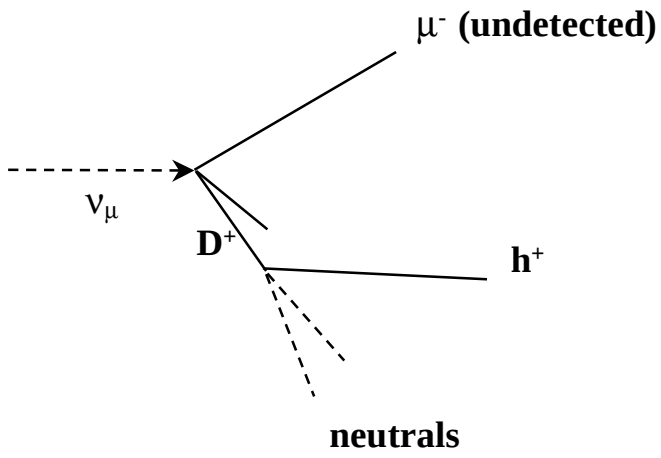
- BR $\tau \rightarrow \mu,\ e,\ h$ → 0.174 , 0.178 , 0.498
- Fiducial cuts & alignment → $\varepsilon_{geom} \sim 0.93$

Total efficiency for the 1-prong channels: **~ 0.35**
(3π channel under study)

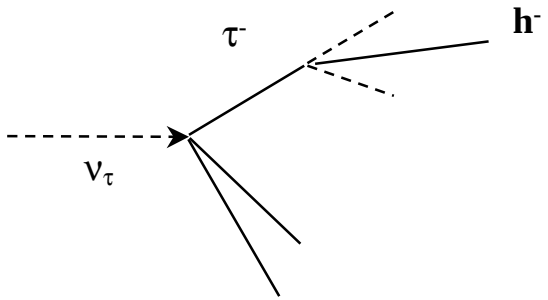
Background for $\tau^- \rightarrow \mu^-, e^-, h^-$

Charm induced background

background



signal



(sign of daughter only measured if muon)

Charm b.g. to $\tau^- \rightarrow h^-, \mu^-, e^-$

(before vertex kinematics of candidate events)

$N_{bg}(h^-)$	= 0.056	charm / CC
	x 0.37	D production probability
	x 0.26	BR (D $\rightarrow$ h + neutrals)
	x 0.47	D decay outside Pb
	x 0.86	ε_{kink}
	x 0.93	fiducial cuts & alignment
	x 0.05	μ^- CC not identified
	x 9000	CC events

~ 0.9 events (h^-)

BR (charged D $\rightarrow$ *l* + neutrals) ~ 0.075

μ charge measured by the downstream spectrometer (1-ε ~ 0.3)

~ 0.1 events (μ^-)

~ 0.3 events (e^-)

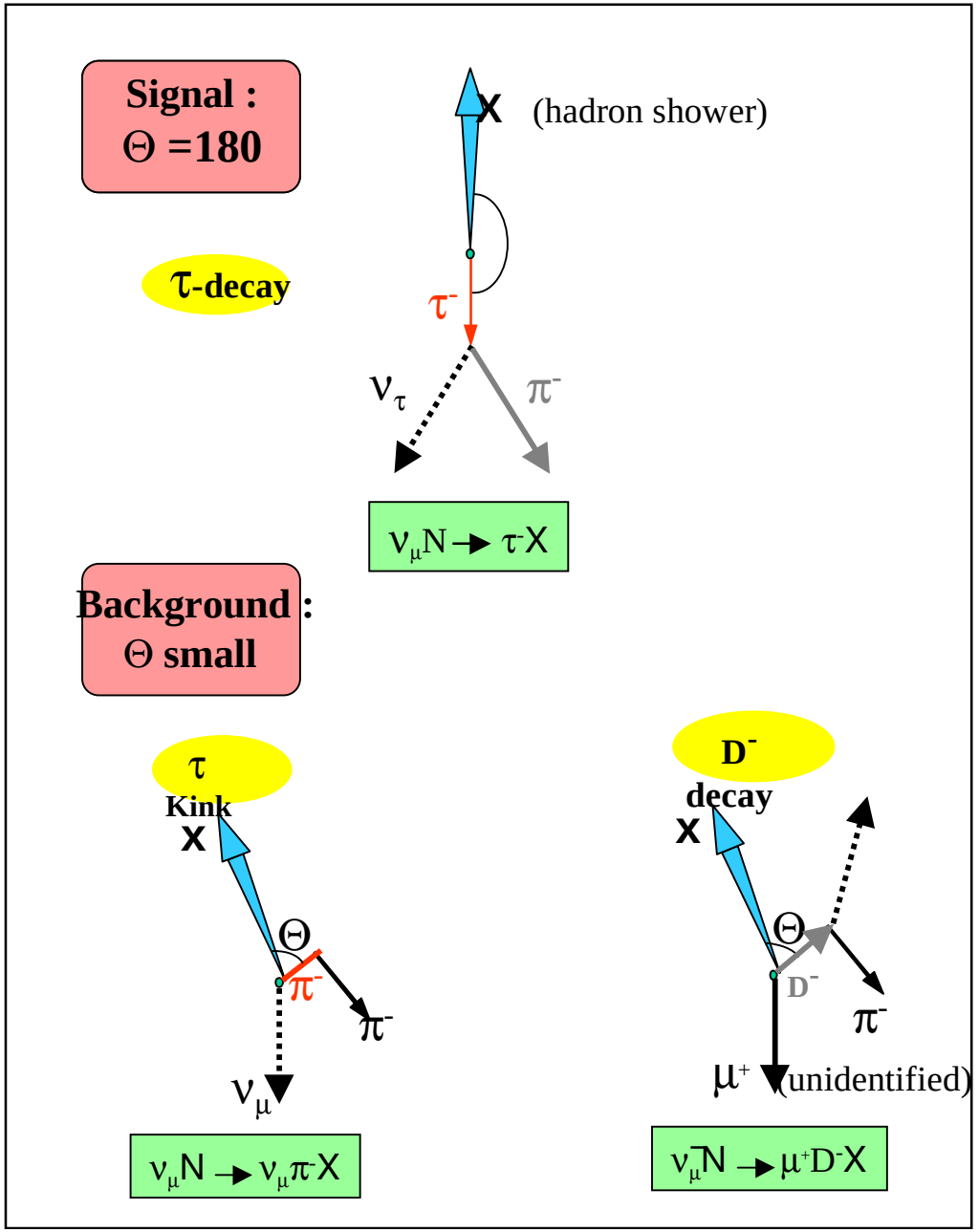
Total: 1.3 events from charm

Other backgrounds

- Prompt ν_τ in the beam: negligible (10^{-6} level)
- Hadron reinteractions : a few kinks in the spacer are rejected by the kink angle cut (20 mrad) and by the detection of heavy fragments
- π , K decays (CC and NC) : 0.4 events (further reduced by possible momentum cut)
- NC associated charm production : double decay topology: 0.3 events before the vertex kinematics

Charm b.g. rejection by vertex kinematics

- angles at vertex measured with high accuracy
- momentum measurement by multiple scattering
- electron ID by e.m. interactions
- search for photon conversion
- calorimetric information from electronic detectors



Charm b.g. rejection by vertex kinematics: cuts

(From the TOSCA L.o.I.)

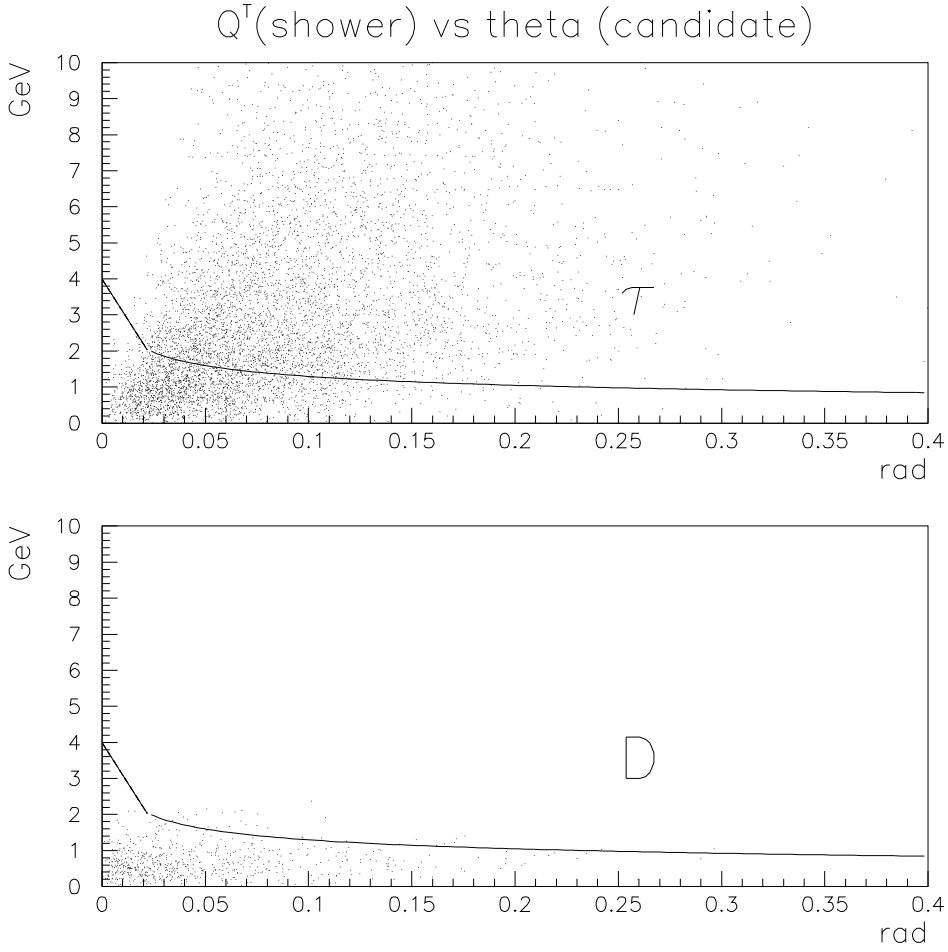
example

Q_T

(shower p_T w.r.t. kink parent)

vs.

angle between candidate and beam direction



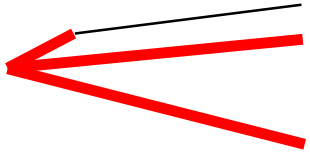
B.G. reduction by vertex kinematics

- Before kinematical analysis of candidate events

$N_{bg}(h^-)$ ~ 0.9 events $N_{bg}(\mu^-) + N_{bg}(e^-)$ ~ 0.4 events

N_{bg}(associated charm) ~ 0.3 events

- Vertex kinematics: aim → N_{bg} ~ N_{bg} / ~5 (to be studied)



N_{bg} (charm) < 1 event

Important : vertex kinematics require track **before** decay

possible only with emulsion granularity

Sensitivity and discovery potential

ν_μ CC σ_τ/σ_μ ε_τ x BR ε_{vert}

$\sin^2 2\theta_{\mu\tau}$ (large Δm^2) < 2 x 2.3 / (10000 x 0.53 x 0.35 x 0.95)

$< 2.5 \times 10^{-3}$

NO OBSERVED EVENTS

Δm^2 (full mixing) **$< 10^{-3}$ eV^2**

(90% CL)

If oscillation occurs @ :

$\Delta m^2 = 2 \times 10^{-3}$ eV^2 **~ 10 detected events**

$\Delta m^2 = 5 \times 10^{-3}$ eV^2 **~ 50 " "**

$\Delta m^2 = 7 \times 10^{-3}$ eV^2 **~ 100 " "**

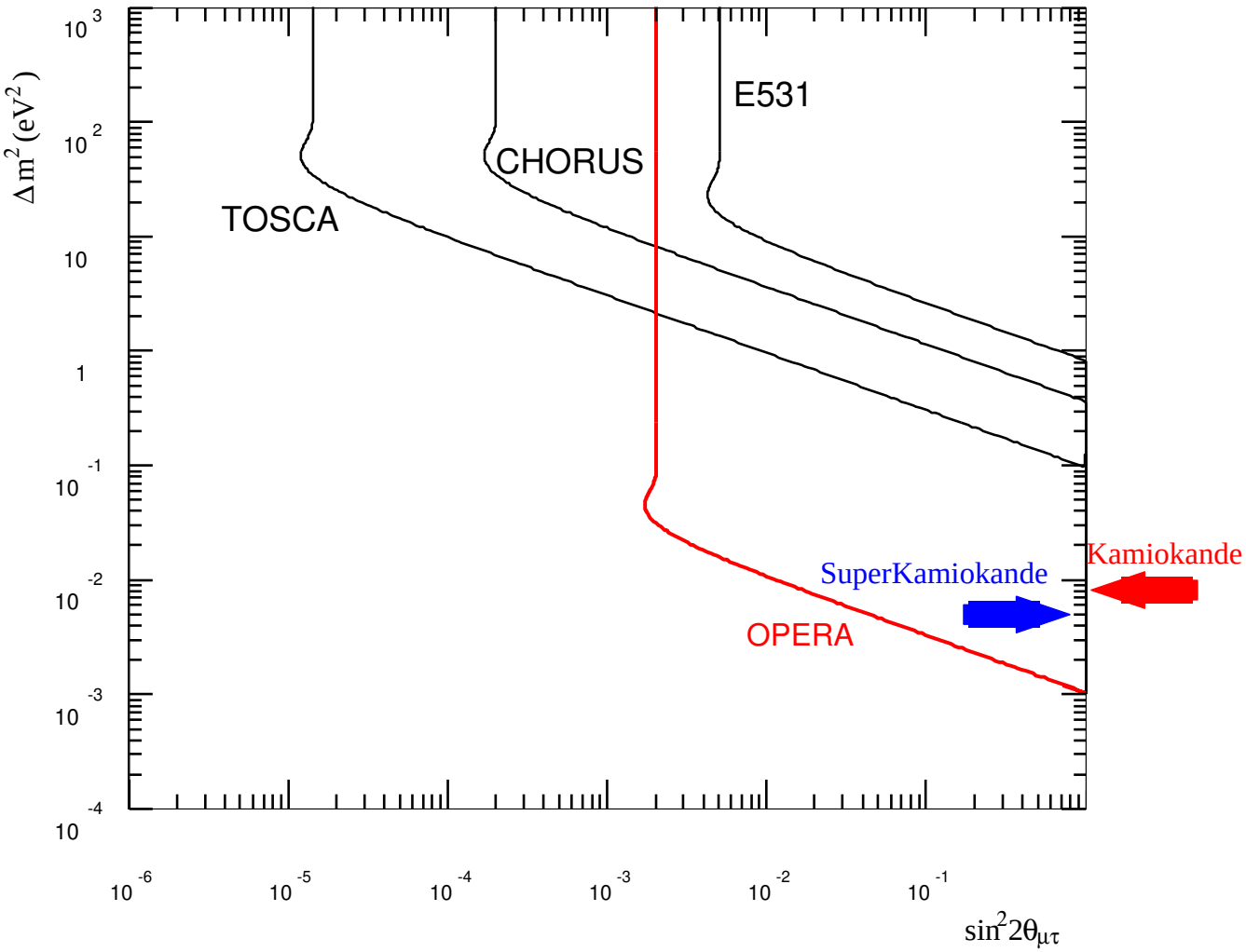
total b.g. < 1 event

Sensitivity vs detector mass

The mass (number of supermodules) may be scaled:

mass	supermodules	τ evts for 5×10^{-3} eV^2	7×10^{-3} eV^2
750t	**10**	**50**	**95**
600t	**8**	**40**	**75**
300t	**4**	**20**	**40**
150t	**2**	**10**	**20**

Exclusion plot



Emulsion scanning (1)

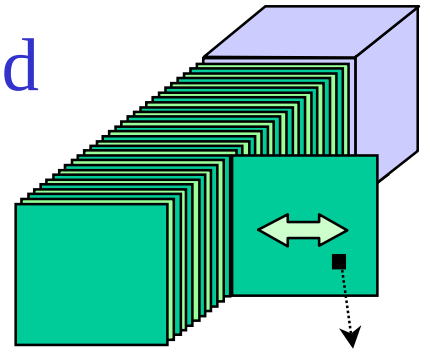
- ~ 15000 events ν_μ NC+CC to be scanned
  (achievable with fast automatic microscopes)
- rougher event localization w.r.t. short baseline exp.
  (allowed by low track density)
- fast general scanning (downstream ES): over few cm^2
- scan back of all found segments up to the vertex
- scanning more elaborate, special care for candidates
- exploit on-going progress and equipment for CHORUS

Emulsion scanning (2)

- ~ 15000 events/4 years

→ ~ 15000 /~100000 bricks to be removed

- aim: emulsion developed and "quasi on-line" scanning
- replace bricks (?)
- fading may "regenerate" the emulsion left in place



develop emulsion

↓

Prompt physics analysis

Emulsion experiment with a long-life

Feasibility studies, optimization and R&D (1)

- Emulsion ⇨ diluted emulsion: quality vs. cost
  procurement & handling
  ES manufacturing:
  dedicated pouring machine (industry?), X-ray films
  controlled fading
- Bricks ⇨ passive material: Pb vs. Fe, radioactivity
  spacers (plastic, paper honeycomb, ...):
  low density, rigid
  vacuum vs. mechanical packing (both ?)
  optimize dimensions: Montecarlo + prototype tests
- Electronic trackers ⇨ define requirements: space & time resolution
  optimize performance vs. cost
  industrial production
  tests on prototypes: track association to emulsion

Feasibility studies, optimization and R&D (2)

- Apparatus design ⇒ physics goal: optimize number of supermodules
  optmize bricks/module/supermodule dimensions
  temperature and humidity control
  detector mass and cost
  spectrometer design: performance requirements
- Tests ⇒ prototype bricks: mechanics & structure
  install bricks in the Gran Sasso Laboratory:
  ambient radioactivity, alignment by cosmics,
  hit density, optimize layer thickness
  beam tests:
  kink efficiency, angular resolution,
  vertex finding
- R&D ⇒ emulsion: collaboration with industry
  brick assembly machines
  dedicated scanning systems: fast general scanning
- Beam ⇒ optimize beam design: intensity, spectrum, <E>

A possible schedule for OPERA

- 1997 LoI: studies, conceptual design
- 1998 Tests, feasibility, design, proposal
- 1999 Approval, prototypes, tests
- 1999-2003 Construction
- 2003 Start neutrino data taking
- 2004 Early physics results

at Gran Sasso

- Possible design: **~750 ton , 2.0 x 10^{20} pot** (4 years)

  → **~13000** ν_μ CC+NC events

- Discovery potential: small bg, a few events are meaningful:

  @ $\Delta m^2 = 5 \times 10^{-3}$ **eV**^{2} → **~ 50** τ events (<1 b.g.)

- Negative search: $\Delta m^2 < 10^{-3}$ **eV**^{2} ; $\sin^2 2\theta_{\mu\tau} < 2.5 \times 10^{-3}$

  → covers ν_{atm} (Super Kamiokande)

- Modular structure: scalable detector mass (~150-750 t)

↓

High sensitivity ν_μ-ν_τ ***search***

↓

explore the atmospheric neutrino signal

Prospects for improvements

Aim: increase sensitivity at low Δm^2

possible handles:

optimize beam design:
- lower ν energy ? (E/L ratio);
- higher beam intensity.

increase detection efficiency:
- add $\tau \rightarrow 3\pi$ decay channel;
- (partial) use of events with decay in the lead.

Conclusions

- Appealing technique to detect ν_μ-ν_τ oscillation with a Long Baseline Experiment at the Gran Sasso

- Further studies, tests and R&D needed to fully assess the feasibility of the experiment

- Explore the parameter region with low Δm^2 (indicated by SK) **to determine the source of the atmospheric neutrino signal**