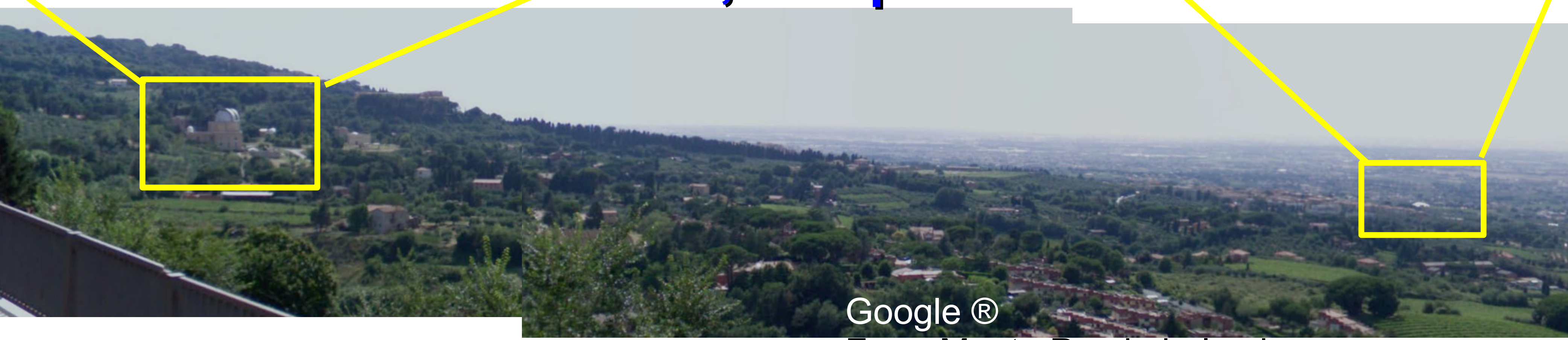
↔

synergy meeting
LNF, 16 April 2014



From Monte Porzio belvedere

Neutrinos

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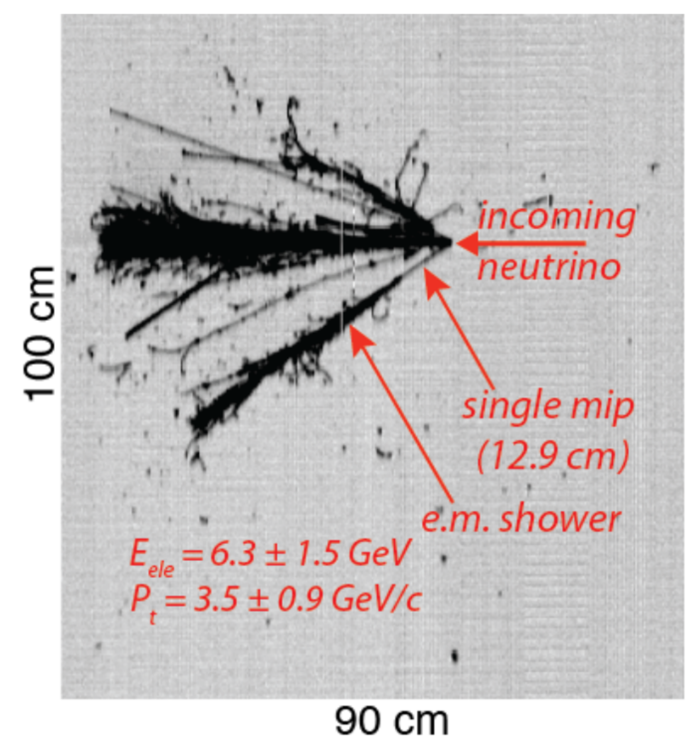
Laboratori Nazionali di Frascati

INFN Istituto Nazionale di Fisica Nucleare

Contents

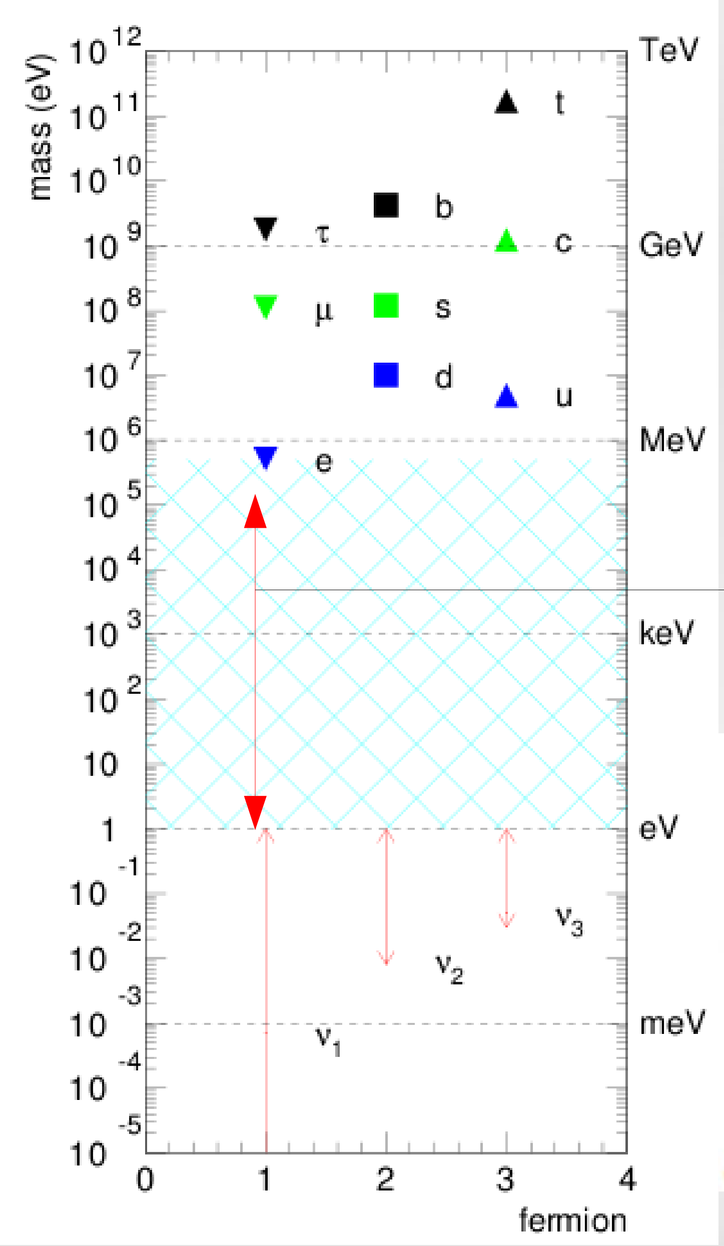
I will try to highlight neutrino physics activities within INFN with a special focus on those with LNF direct involvement



- Physics goals (INFN perspective)
- Experimental techniques and tools

An (incomplete!) description of our activities to stimulate ideas potential collaborations among our communities.

Neutrino masses



``Tiny" masses!
> 6 order of magnitude lighter than the electron! Why ?

Points to physics at the GUT scale through the simple see-saw mechanism

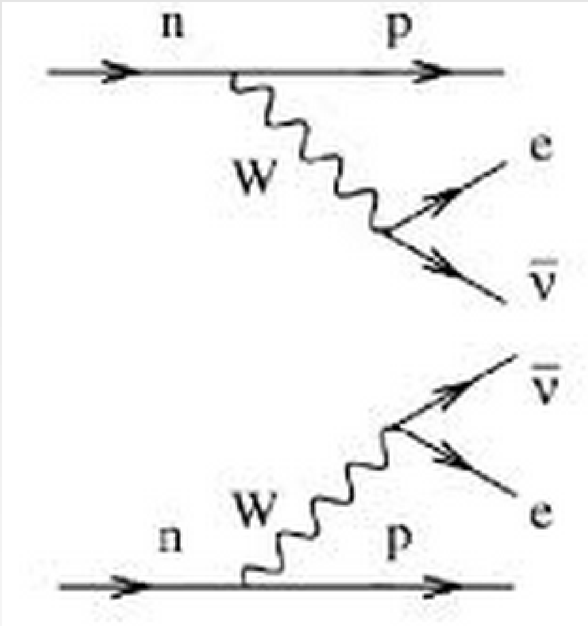
$$\text{meV} \sim (10^2\ \text{GeV})^2 / 10^{16}\ \text{GeV}$$

Neutrinos might be special fermions (of Majorana type). Mass contribution not only from Higgs couplings.

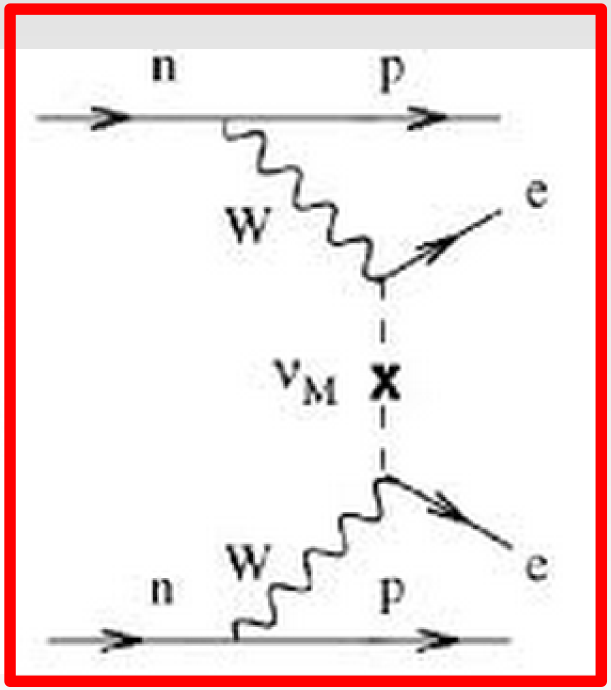
Nature of neutrinos

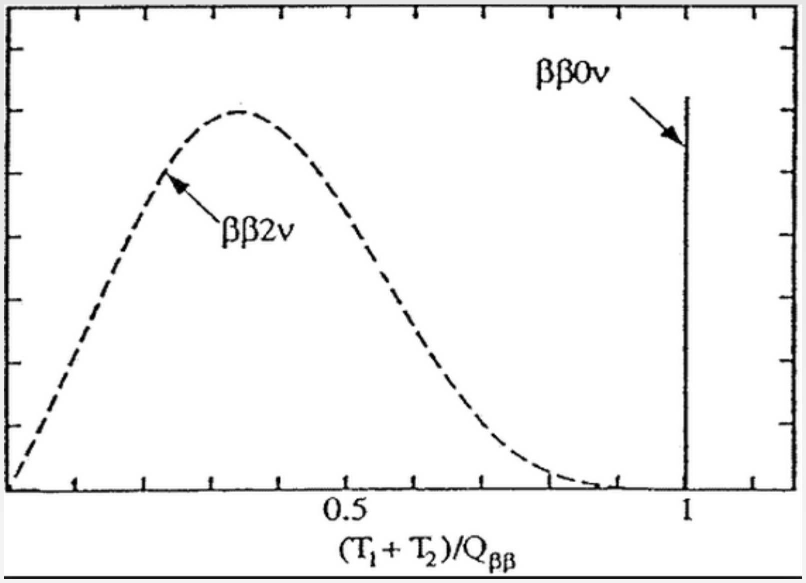
Are neutrinos described as Dirac or Majorana fermions ?
does the double beta decay without neutrinos (ββ0ν) exist ?

ββ2ν (measured)



ββ0ν ?





More realistically measurable with inverted hierarchy

ν mixing and oscillations

Mass eigenstates (ν_1,ν_2,ν_3) ↔ weak eigenstates (ν_e,ν_μ,ν_τ) $|\nu_\alpha(t)\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i(t)\rangle$

U: “Pontecorvo-Maki-Nakagawa-Sakata” matrix ~ CKM for quarks

Δm^2_{31} | $s_{ij} \equiv \sin(\theta_{ij})$, $c_{ij} \equiv \cos(\theta_{ij})$ | Δm^2_{21}

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

SuperK, K2K, MINOS, OPERA, ICARUS, T2K
atmospheric+LBL

Chooz, Daya Bay, RENO
T2K, MINOS, NOvA
Chooz

SuperK, SNO, KamLAND
solar+KamLAND

3 mixing angles θ_{12} θ_{13} θ_{23}

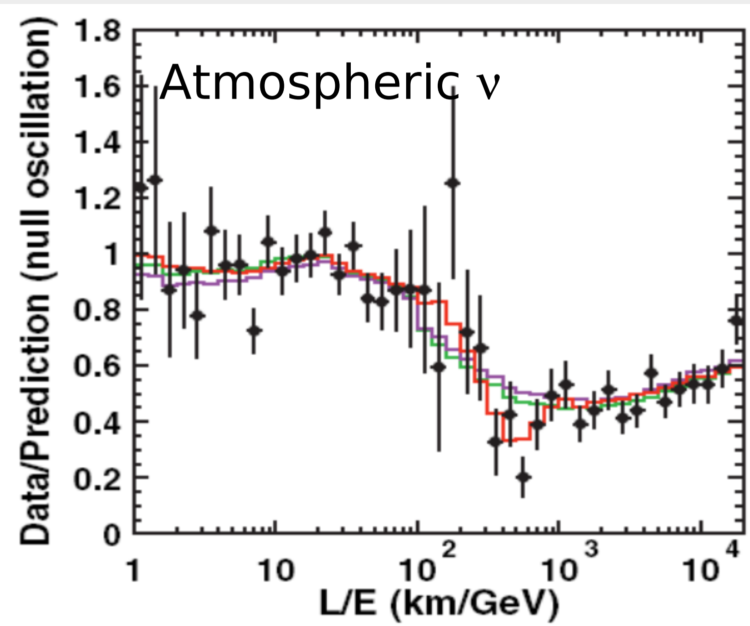
1 CP phase: δ

2 mass-squared differences $\Delta m^2_{ij} = m_i^2 - m_j^2$

measured with ν–oscillations:
flavor transitions during propagation

$$P_{\alpha\to\beta} = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2\ L}{E_\nu}\right)$$

In the 2-flavour approximation
(L [Km], E_ν [GeV])



Neutrino mixing matrix

Why is lepton mixing so “weird” ?

quarks

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

~(roughly) diagonal

neutrinos

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

Anarchy ?

The most recent step forward is the θ_{13} measurement (2012). Could have been the ”mission impossible” … and now it is the best known angle.

$\sin^2 2\theta_{13}$

- < 0.15 – before 2012 – CHOOZ limit (90% CL)
- 0.11 (0.14) – best fit of T2K in 2011 (2.5 σ)
- 0.092 ± 0.017 – Daya Bay, 2012 (5.2 σ)

Paves the way to future CP violation measurements →

Neutrino physics: LCPV

CP violation ~
δ ≠ 0 and δ ≠ π

Is CP violated in ν oscillations ?

$$\mathcal{A}_{CP} = \frac{\mathcal{P}_{\nu_\mu \to \nu_e} - \mathcal{P}_{\bar{\nu}_\mu \to \bar{\nu}_e}}{\mathcal{P}_{\nu_\mu \to \nu_e} + \mathcal{P}_{\bar{\nu}_\mu \to \bar{\nu}_e}} \simeq \frac{\Delta m^2_{12} L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} . \sin \delta_{CP} - \frac{V_C L}{E_\nu} \frac{\cos\left(\frac{\Delta m^2_{23} L}{4E_\nu}\right)}{\sin\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right)}$$

Room for much larger CP violating effects than in the quark sector

$J_{CKM} = 3.05 \times 10^{-5}$

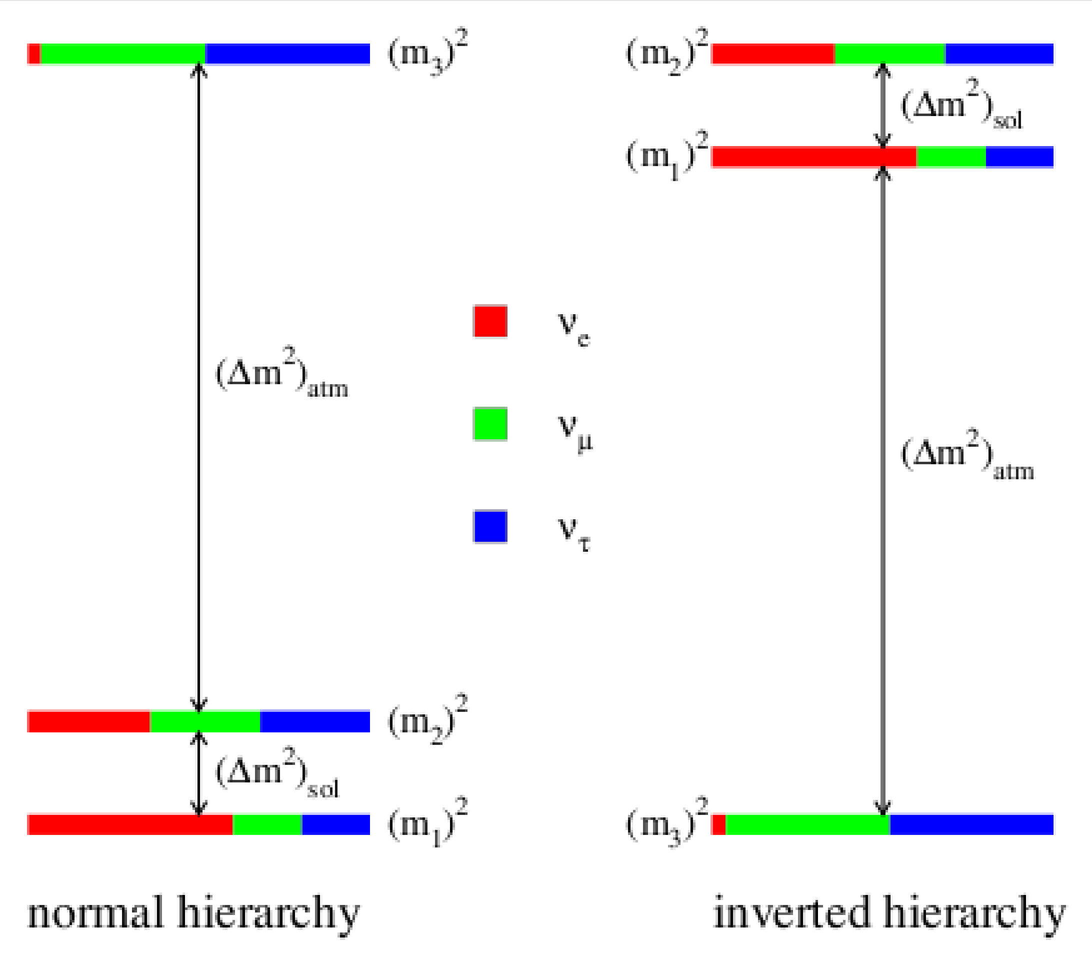
$J_{PMNS} = O(1) \times \sin \delta_{CP}$

J = Jarlskog invariant: proportional to the area of the unitary triangle

CPV with "light" neutrinos would (indirectly) favor
→ leptogenesis an explanation of matter-antimatter asymmetry (BAU)

This is the measurement on which the effort of the community in the next decades is focusing

Neutrinos: more questions



Is ν_3 mostly ν_μ or ν_τ ? (i.e is θ_{23} exactly $\pi/4$?). If Y why ?

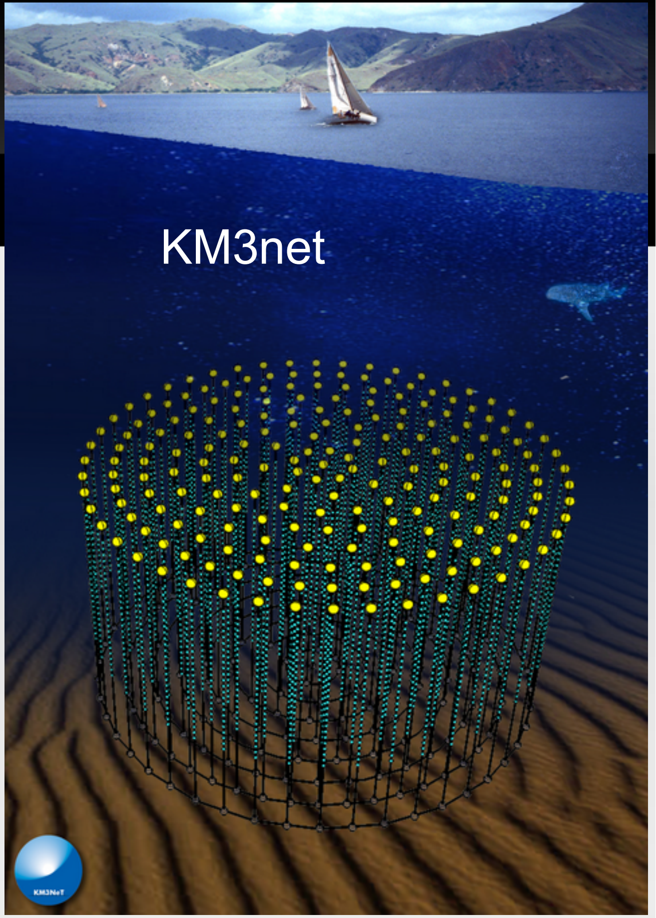
Which is the mass ordering ? (normal/inverted hierarchy)

The "standard" 3 flavors theory is (nearly) crystal-clear. But ...
... is it just enough ?

Are there light "sterile" states ? surprises ?

Refer to the talk by A. Paoloni (tomorrow)

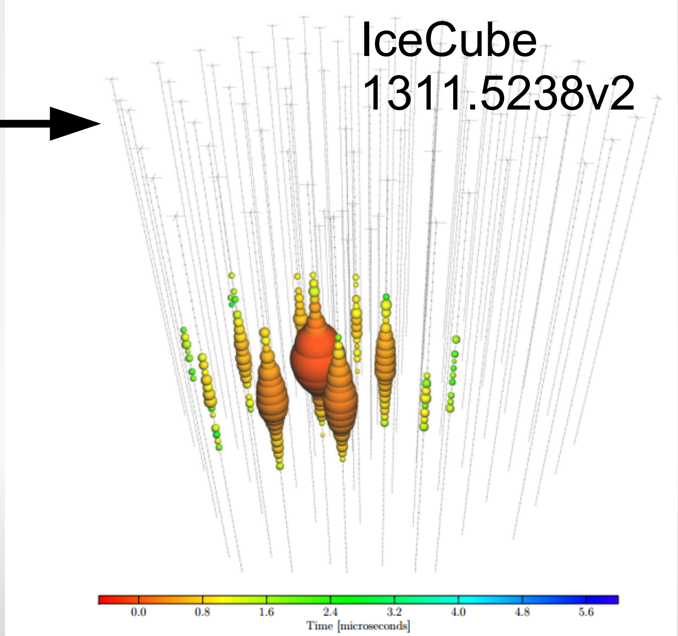
Looking at the sky: information from/about νs

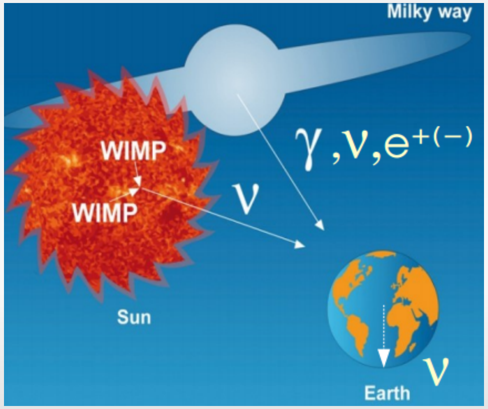


FROM

Neutrino-astronomy ? (``multi-messenger")

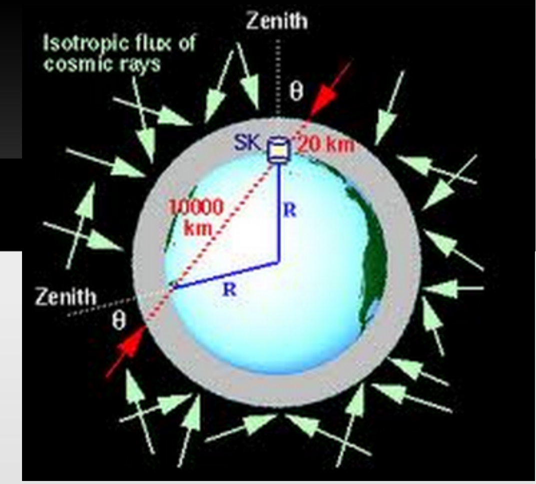
- Low cross-section → **transparent universe** event at the highest energies
- no e.m. interaction → no deflection in galactic B fields → **point to sources**!
- "No-lose-theorem": if the acceleration mechanism is "**hadronic**", besides γ (from π^0) **neutrinos also expected** (i.e. from charged π decays)
- First evidence from IceCube! (see later) →





Direct Dark-matter searches from annihilations into ν

Looking at the sky: information from/about neutrinos



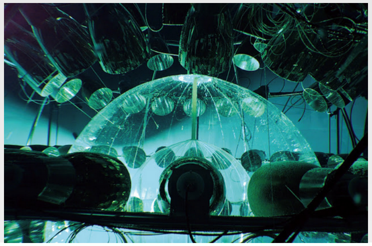
ABOUT

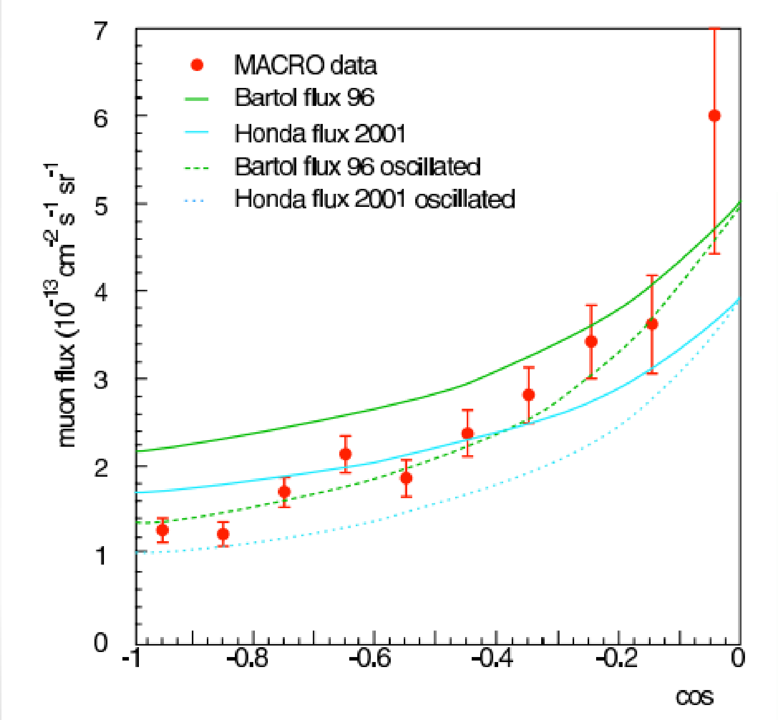
Solar + atmospheric neutrinos

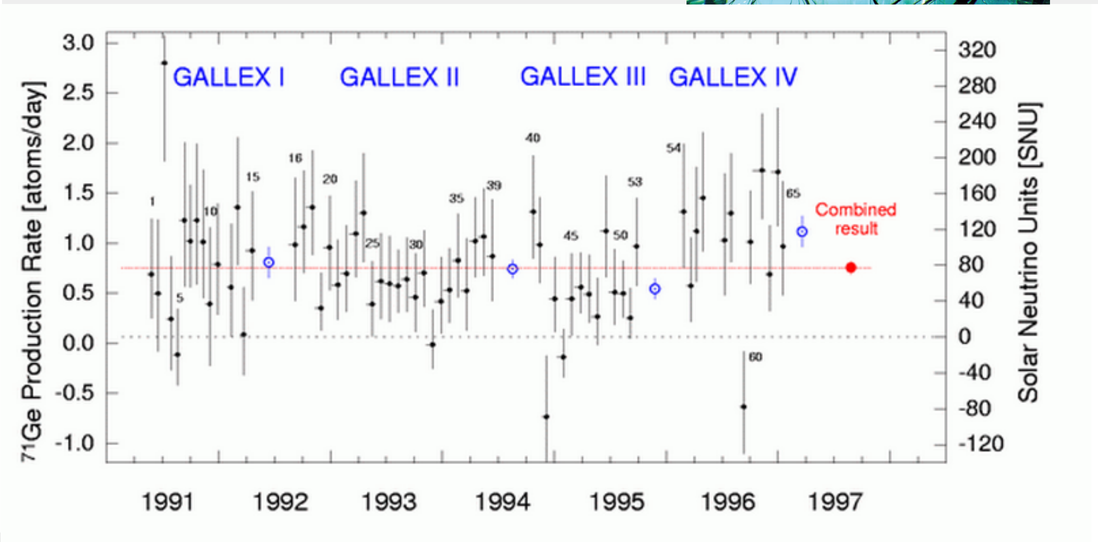
This is a piece of the history of physics: discovery of neutrino oscillations, we learned that neutrinos are massive and not degenerate!

Key contributions of INFN with (MACRO, Gallex-GNO, Borexino) at Gran Sasso

LNF



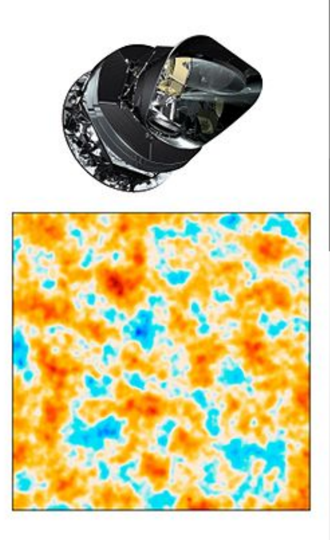


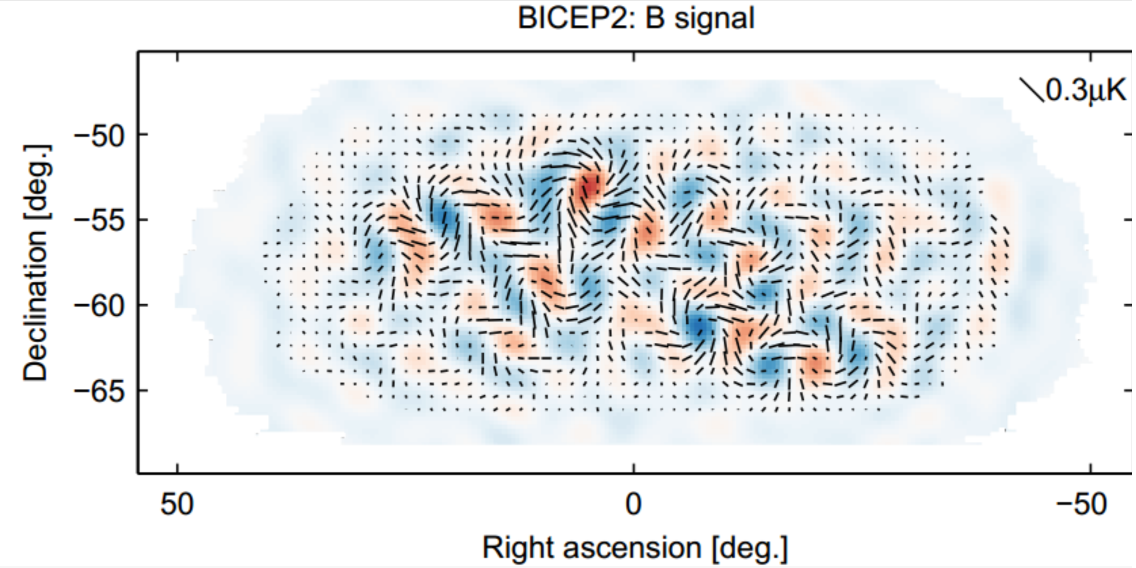


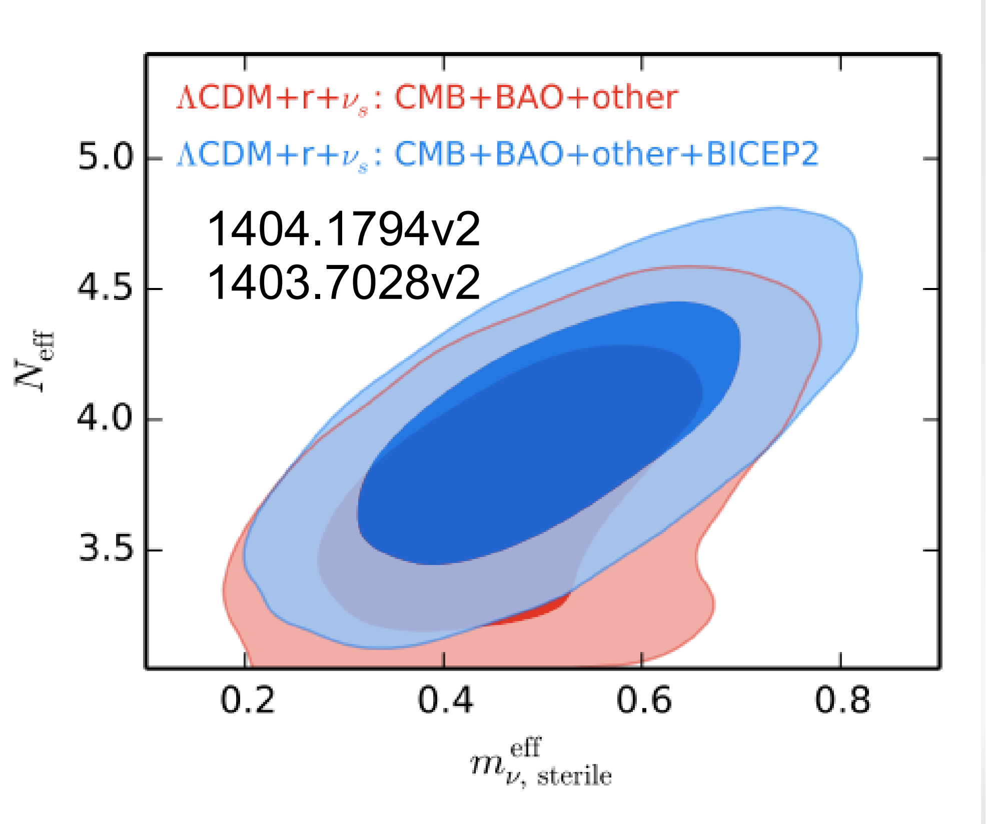
Looking at the sky: information from/about neutrinos

ABOUT

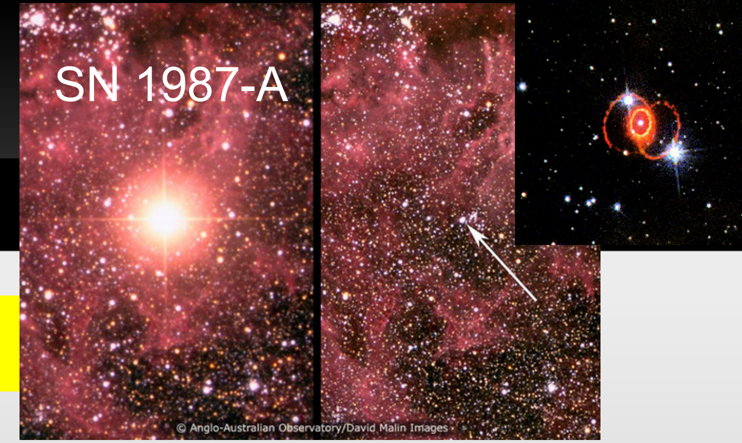
Observational cosmology (CMB, LSS, …) is providing more and more stringent measurements on the <u>sum of the masses of neutrinos</u> and the possible existence of extra-states not coupling to Z and W bosons (<u>``sterile” neutrinos</u>)



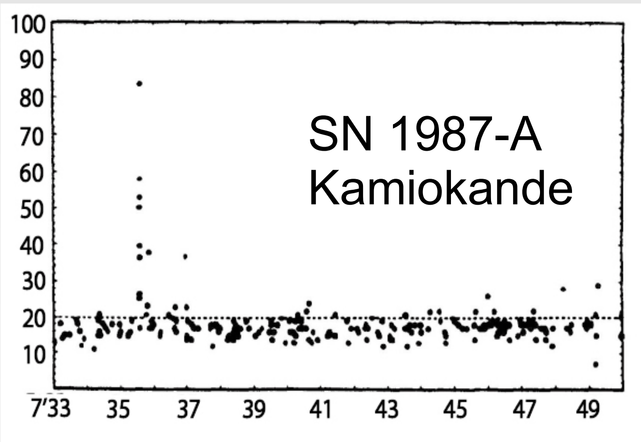




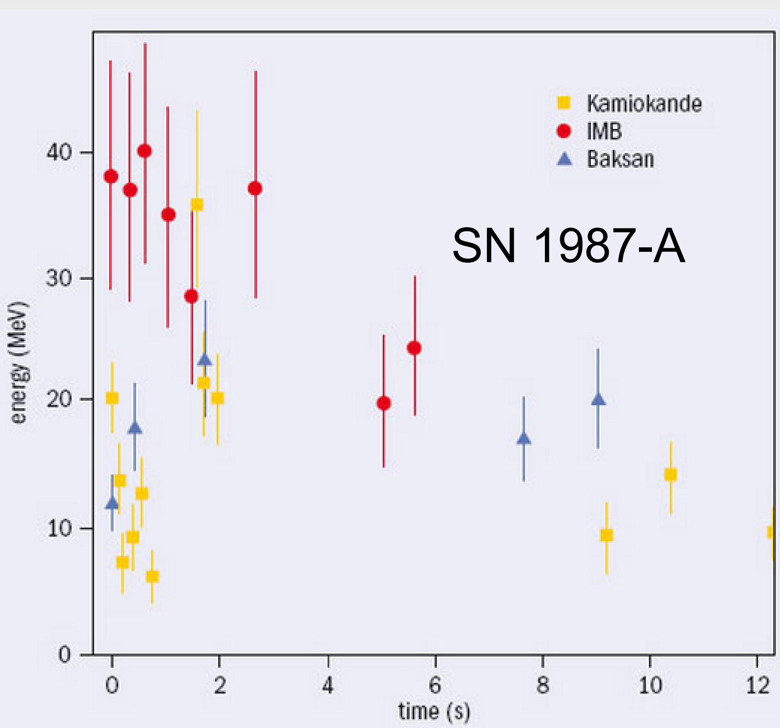
Looking at the sky: information from/about νs

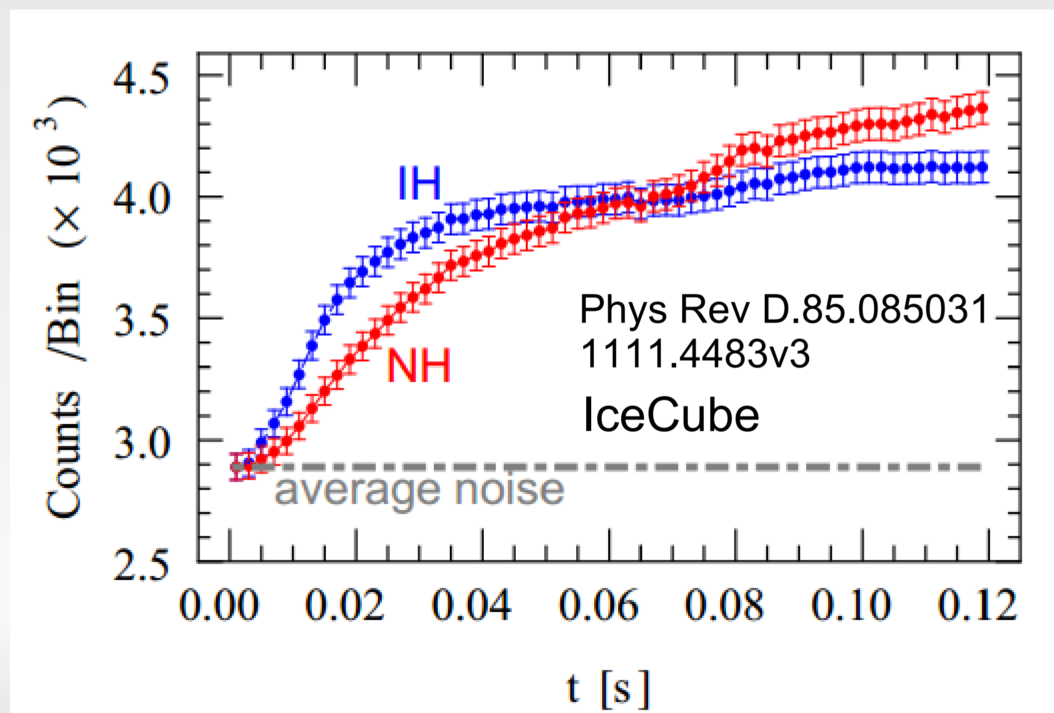


ABOUT SuperNova core collapse neutrinos



With new large detectors (IceCube, SuperKamiokande, LVD) and high statistics one could get insight on Supernova physics and the mass hierarchy





Neutrino activities within INFN

Blue = LNF involvment

artificial / natural

Sources	Physics	Experiments
Artificial beams from p accelerators	ν mixing, oscillations, sterile states ?	OPERA, ICARUS, T2K, NESSiE
Nuclear reactors	ν mixing, oscillations, mass hierarchy	JUNO
β decay	Absolute ν masses	MARE, HOLMES
Special isotopes (ν-less double β decay)	Particle physics (Dirac or Majorana nature ?)	CUORE, GERDA
Atmospheric ν	ν mixing, oscillations	MACRO
Solar ν	ν mixing, oscillations	GALLEX-GNO, Borexino
Dark matter annihilation ?	Dark matter searches	KM3net, IceCube
Supernova neutrinos	Astrophysics, mass hierarchy	LVD, IceCube, KM3net
Astrophysical sources ?	ν astronomy!	KM3net, IceCube
/	ν masses sum, sterile states	ICARUS-NESSiE

Detection techniques

The wide range of energies and the experimental goals produces a broad zoology:

- TeO_2 bolometers (CUORE)
- Germanium crystals (GERDA)
- Low-radioactivity cryogenic environments (CUORE, GERDA)
- Transition Edge Sensors (MARE, HOLMES)
- Liquid scintillators (pseudo-cumene, BOREXINO, JUNO)
- Liquid Argon time-projection-chambers (ICARUS)
- Photo-multipliers in liquids (KM3net, BOREXINO)
- Nuclear emulsions (OPERA)
- Resistive plate chamber detectors
- Plastic scintillator trackers (OPERA, T2K)
- Gaseous time-projection chambers with MicroMegas readout (T2K)

A wide effort: detectors, mechanics, cryogenics, electronics DAQ, software development

Neutrinos from SuperNovae: LVD

Large Volume Detector

Detection of neutrino bursts from gravitational collapses inside our Galaxy or in Magellanic Clouds.

Liquid scintillator tanks (1 kt).

Active since 1992.

SNEWS (SuperNova Early Warning System)

$$\bar{\nu}_{\mathrm{e}}\mathrm{p} \rightarrow \mathrm{e}^{+}\mathrm{n}$$

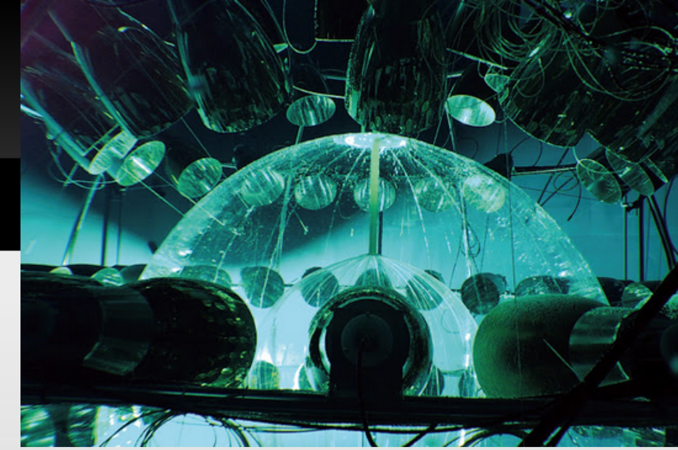
$$\mathrm{np} \rightarrow \mathrm{d}\gamma$$

$$E_{\mathrm{vis}} \simeq E_{\bar{\nu}_{\mathrm{e}}} - 1.8\ \mathrm{MeV} + 2\ \mathrm{m_e c^2}$$

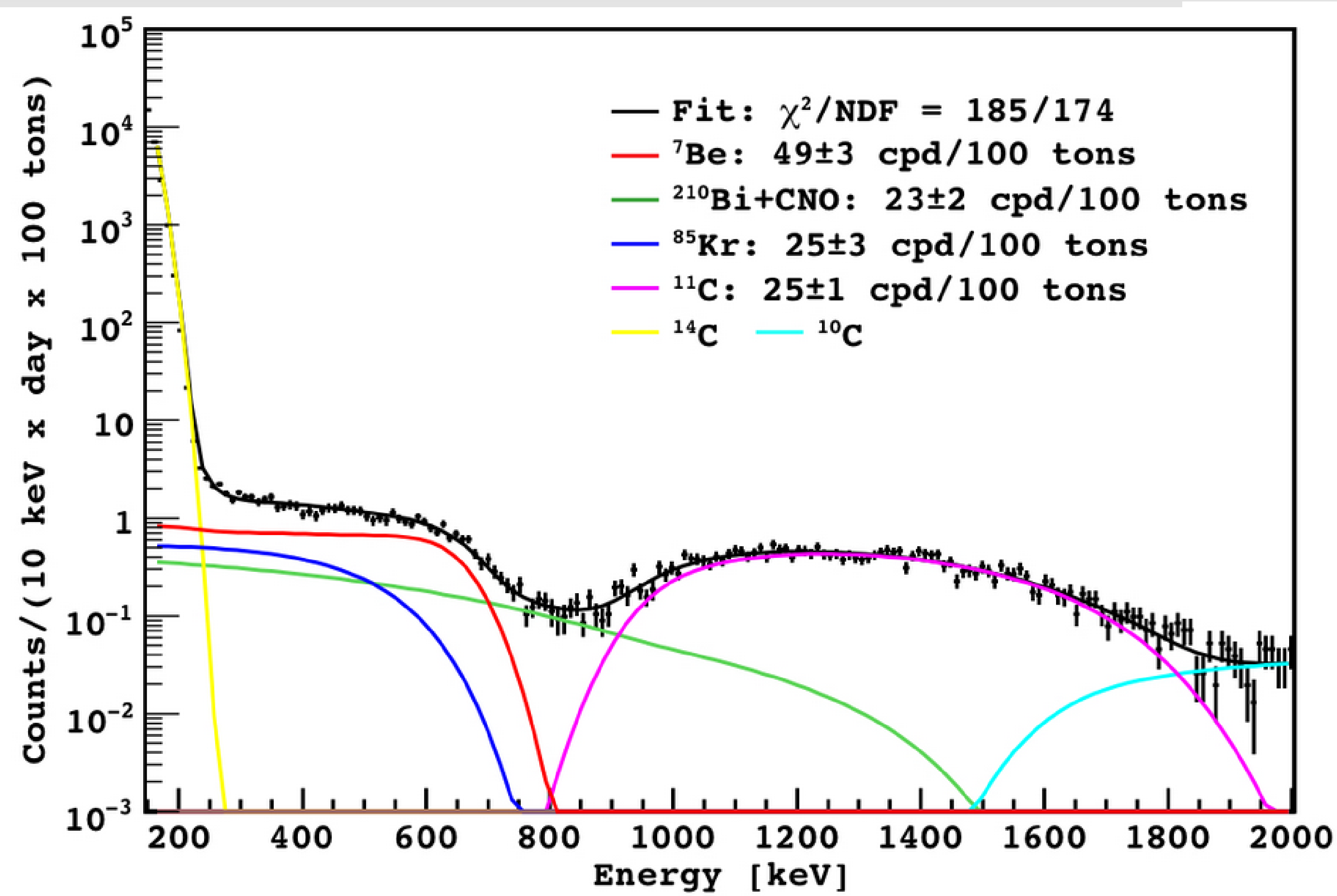
$$E_{\gamma} = 2.2\ \mathrm{MeV} \quad \simeq 185\ \mu\mathrm{s}$$

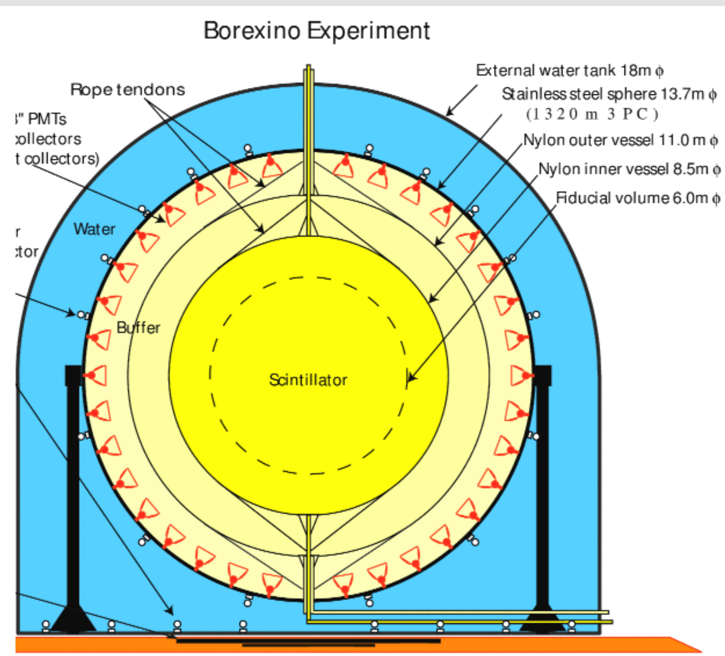
LNF involvement in the past

Solar neutrinos: Borexino



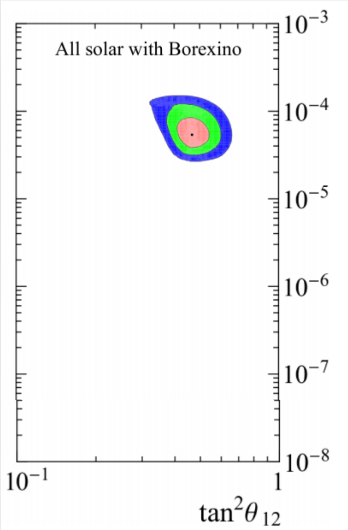
Liquid scintillator (pseudo-cumene, 300 t) detector at Gran Sasso. Exceptional radiopurity levels reached
Measures the 0.862 MeV ^{7}Be line of solar neutrinos
In real-time using interactions on electrons

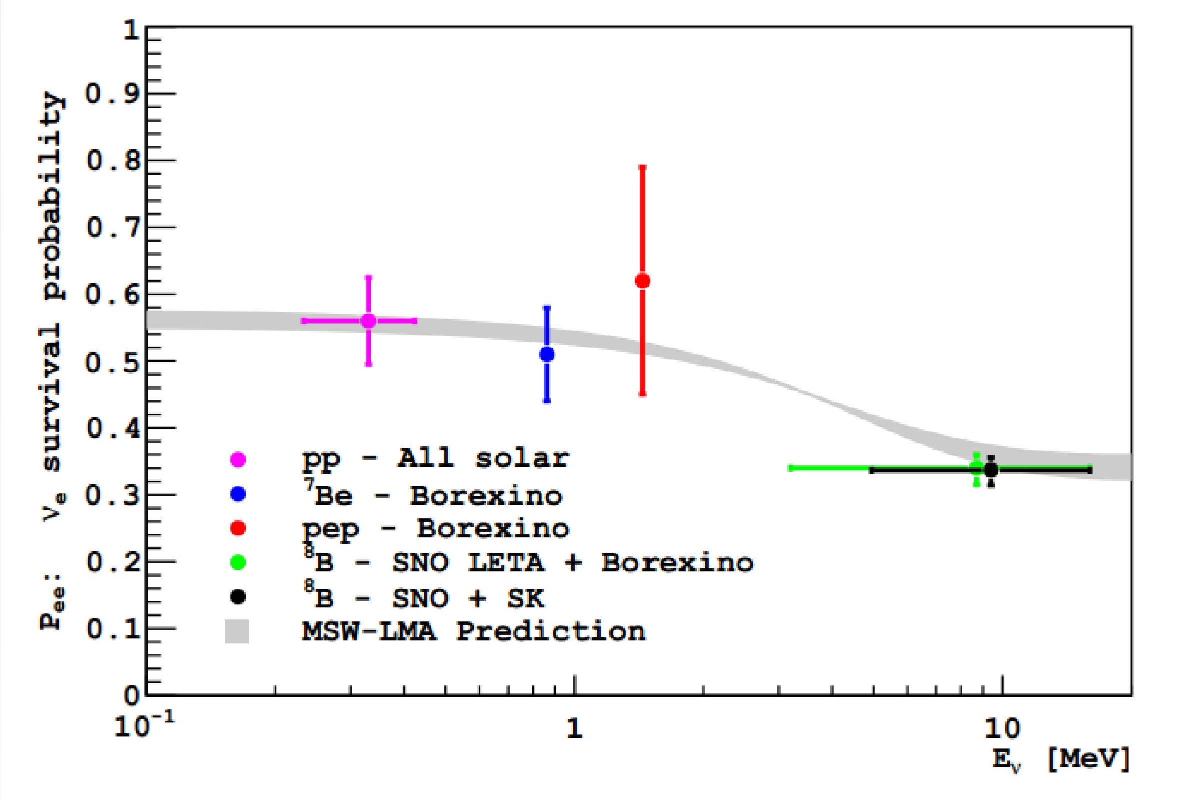


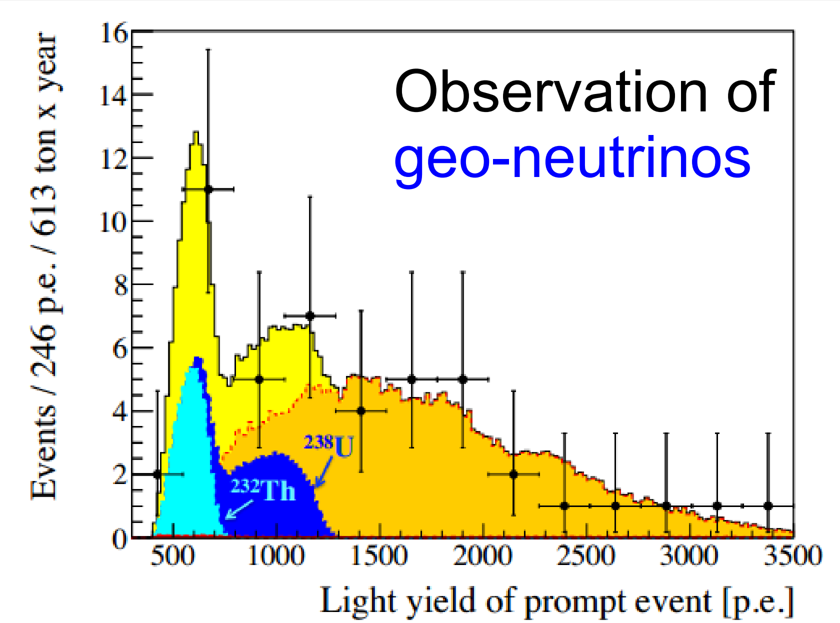


Solar neutrinos: Borexino

Confirms and deeply tests MSW-LMA as a solution for the solar neutrino oscillations



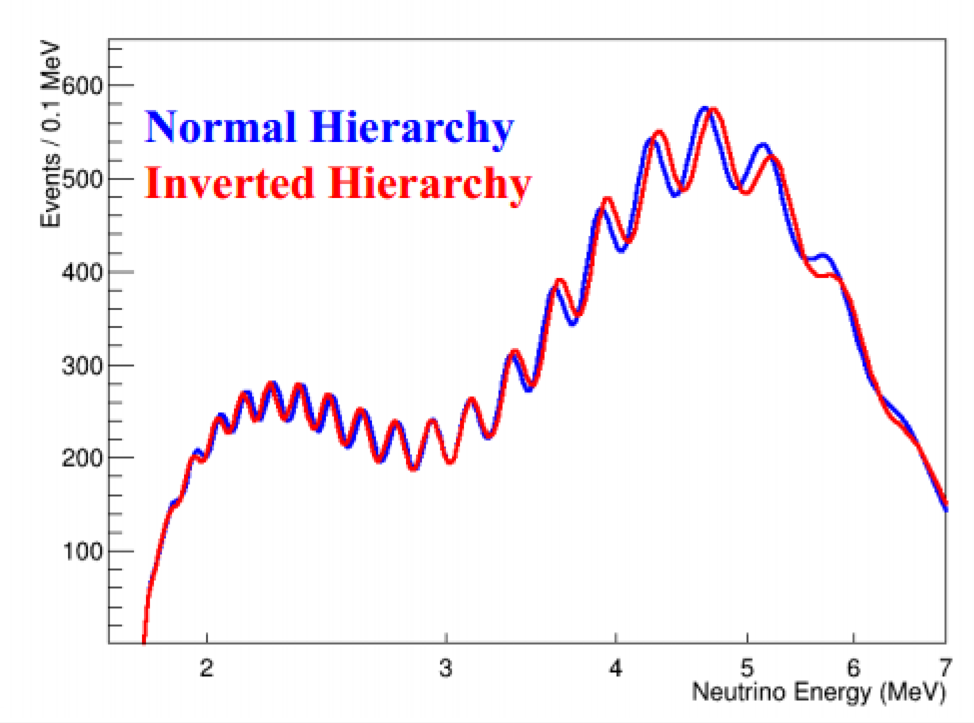




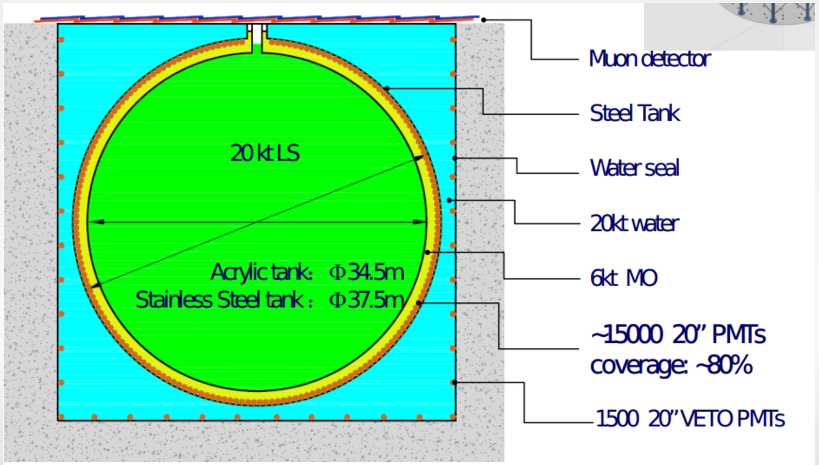
Observation of geo-neutrinos

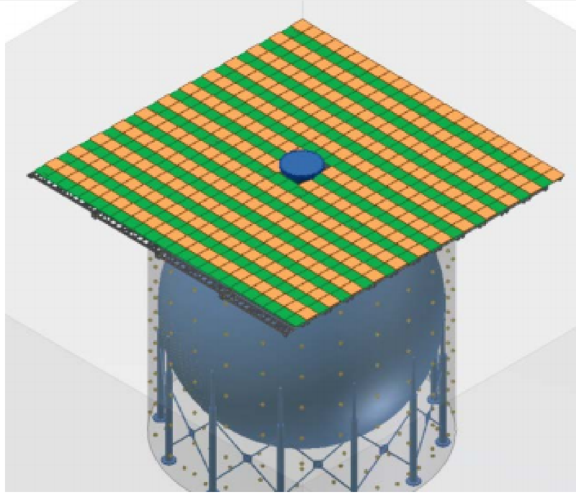
Inputs for the standard solar model: metallicity issue

JUNO (Jangmen neutrino observatory)



Liquid Scintillator detector (20 kt)
53 km from two powerful power-plants
→ Mass hierarchy at 3-4 σ in 6 y
→ Precision meas. of the mixing matrix
→ SuperNova neutrinos
Construction will start in next years





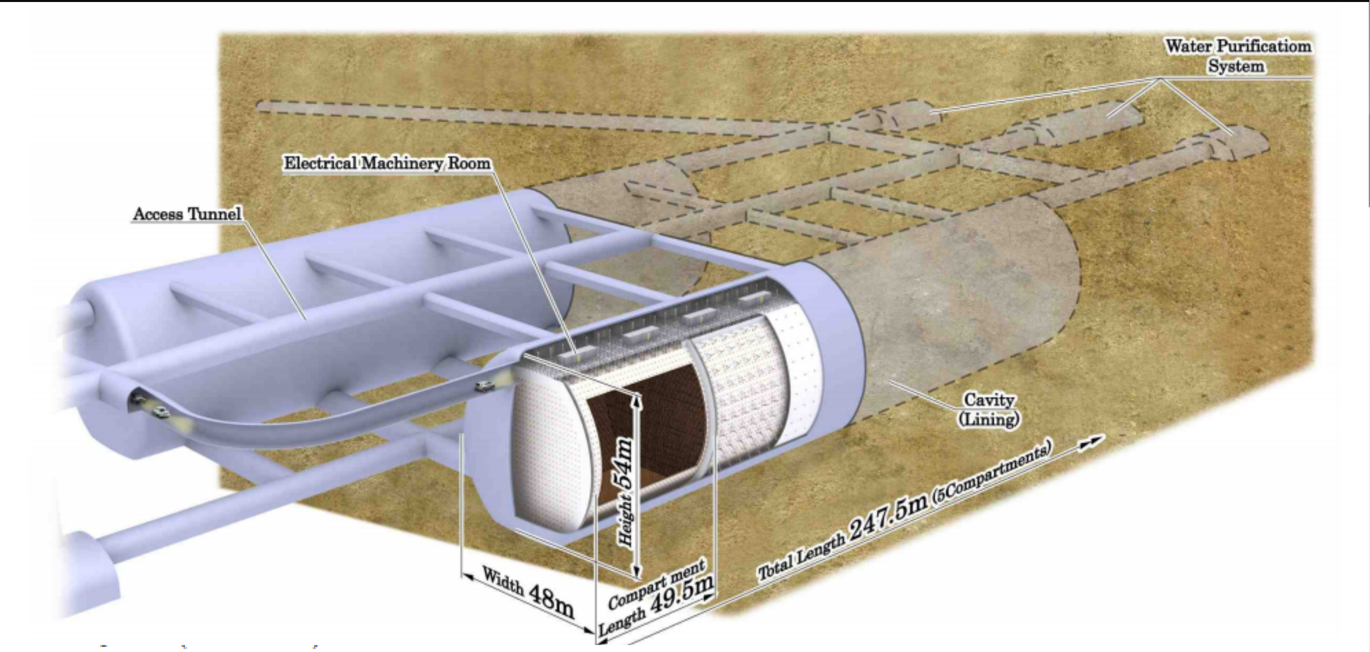
	Borexino	Daya Bay II
LS mass	~0.3 kt	20 kt
Energy Resolution	5%/√E	3%/√E
Light yield	500 p.e./MeV	~1300-1400 p.e./MeV

Hyper-Kamiokande

Water-Cherenkov detector 560 kt foreseen in Japan

Main goal: leptonic CP violation ($\nu_\mu \rightarrow \nu_e$ over L=295 km)

Astrophysics reach:



Solar neutrinos		
– ^{8}B ν from Sun	200 ν's / day	7.0 MeV threshold (total energy) w/ osc.
– ^{8}B ν day/night accuracy	$< 1\%$	5 years, only stat. w/ SK-I BG $\times 20$
Astrophysical objects		
– Supernova burst ν	170,000~260,000 ν's	@ Galactic center (10 kpc)
	30~50 ν's	@ M31 (Andromeda galaxy)
– Supernova relic ν	830 ν's / 10 years	
– WIMP annihilation at Sun		5 years observation
	$\sigma_{SD} = 10^{-39}\text{cm}^2$	@ $M_{\text{WIMP}} = 10$ GeV, $\chi\chi \rightarrow b\bar{b}$ dominant
	$\sigma_{SD} = 10^{-40}\text{cm}^2$	@ $M_{\text{WIMP}} = 100$ GeV, $\chi\chi \rightarrow W^+W^-$ dominant

Neutrino astronomy: IceCube

Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

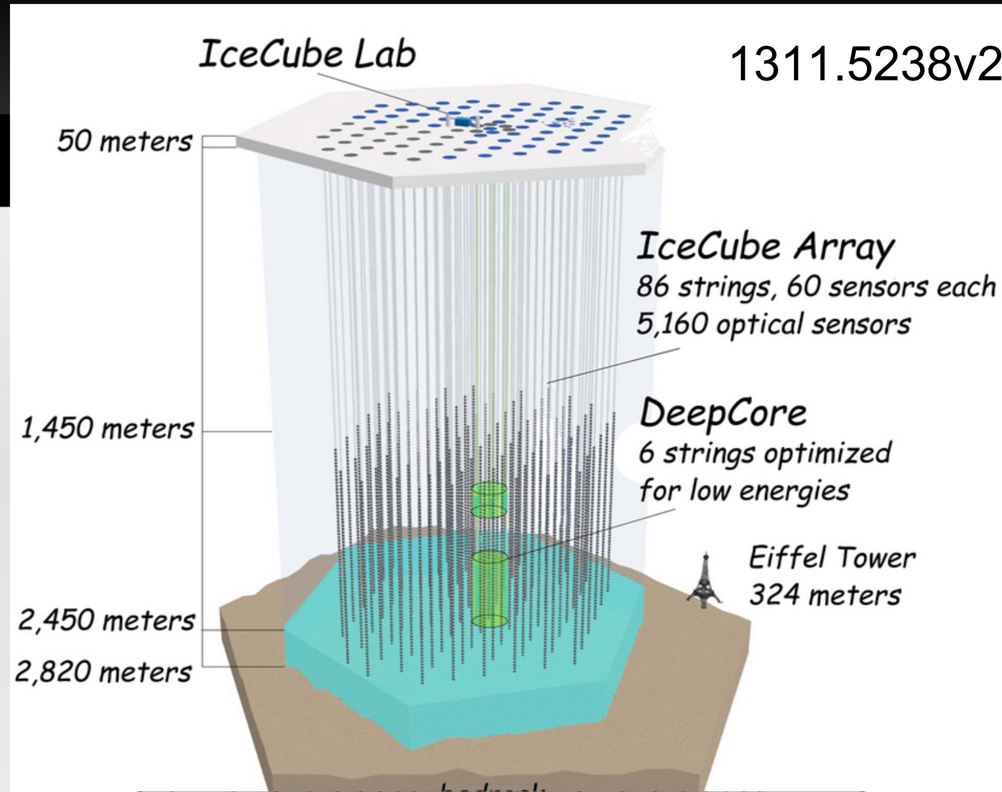
1311.5238v2

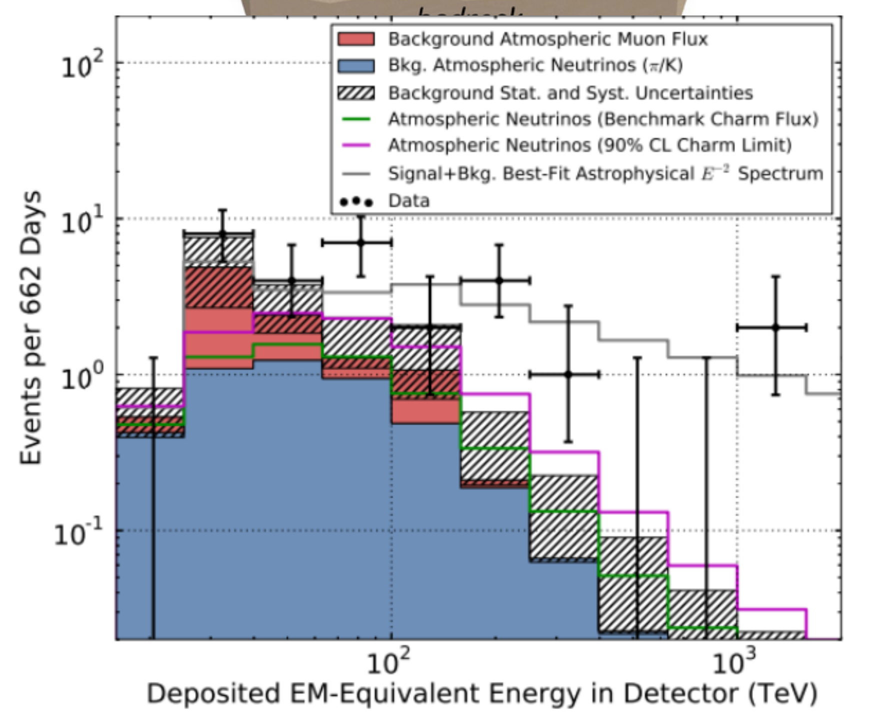
Observed 28 events (2010-2012). 4 down-going. Background: $10.5^{+5.0}_{-3.6}$.

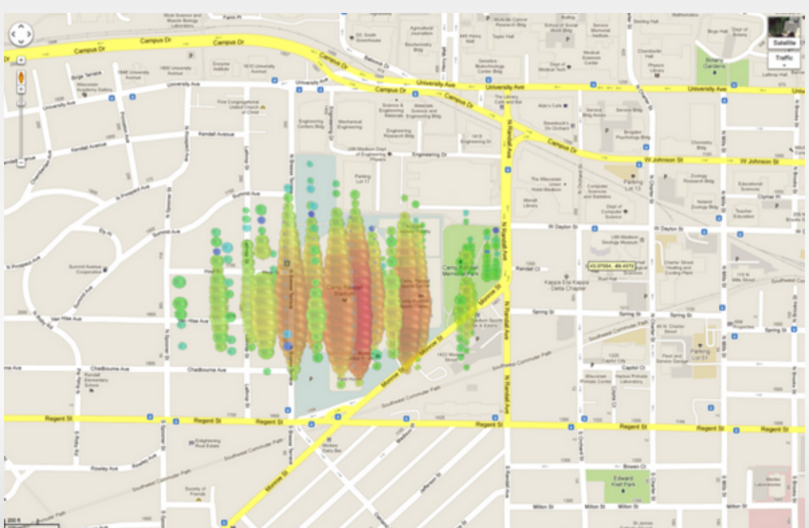
Explanation with atmospheric ν only excluded at ~ 4 σ. Consistent with generic models (E^{-2}) of extraterrestrial ν.

Energies up to PeV (2 events).

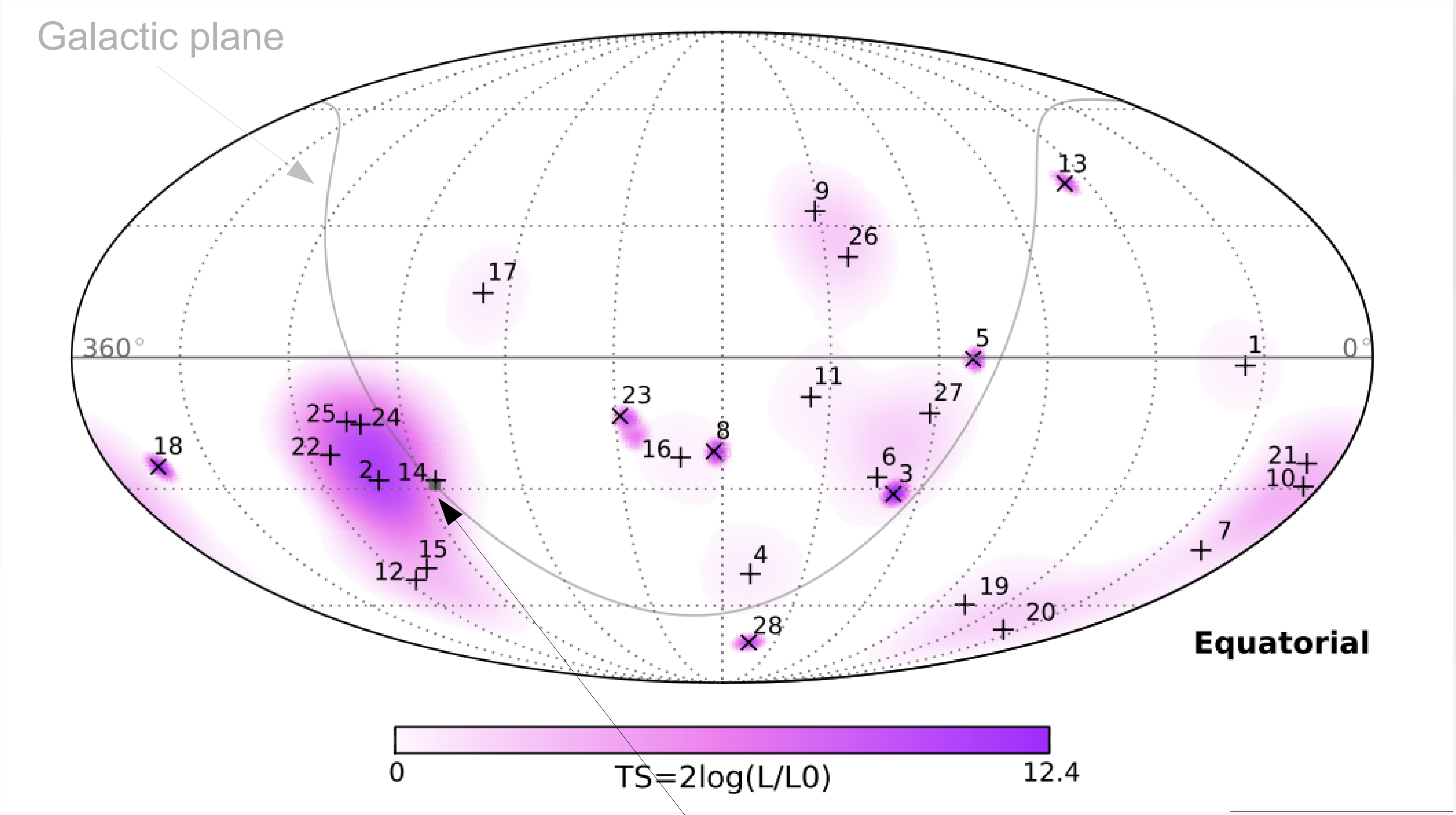
7 track +14 shower-like: consistent w. equal mixture of ν_μ , ν_e and ν_τ.





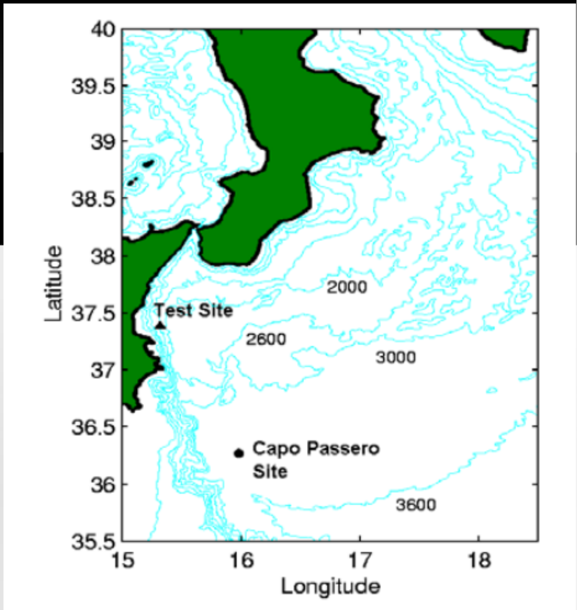


Neutrino astronomy: IceCube



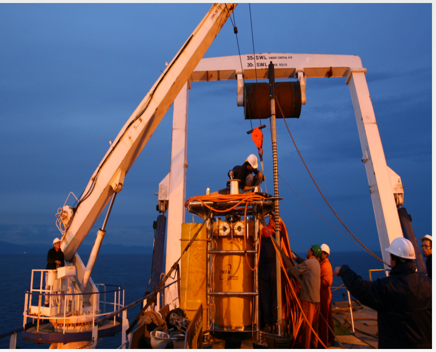
5 shower-like events pointing to the galactic center (including the 2nd highest E) but wit low significance (8%).

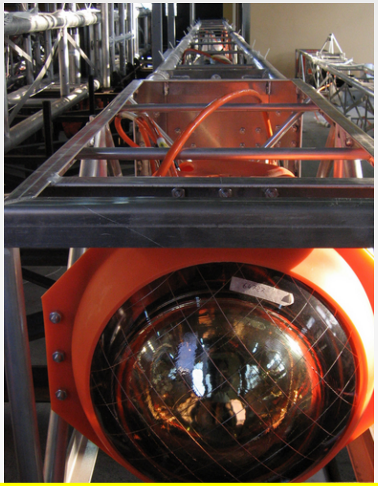
ν astronomy from the N hemisphere: NEMO / KM3net

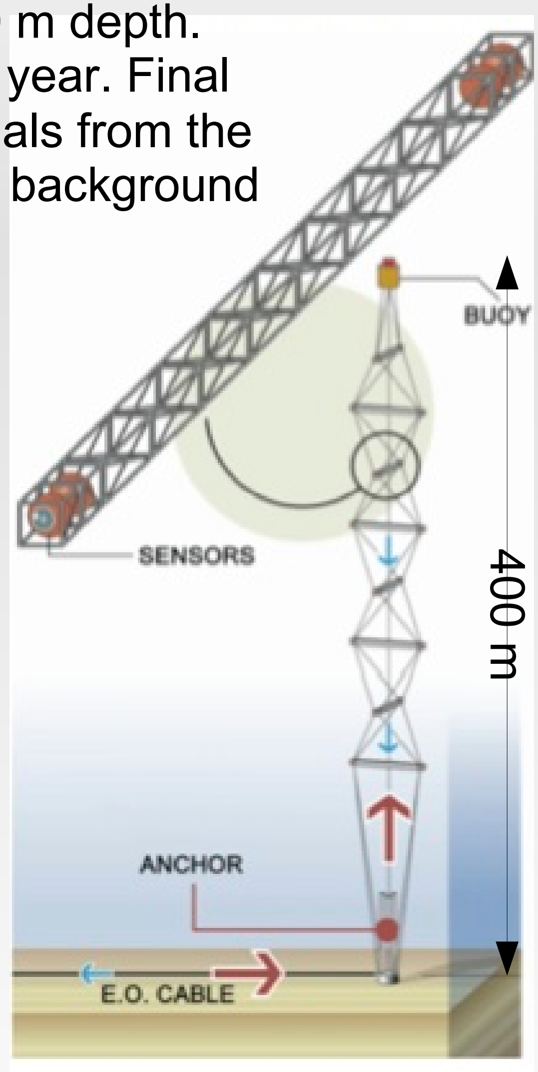


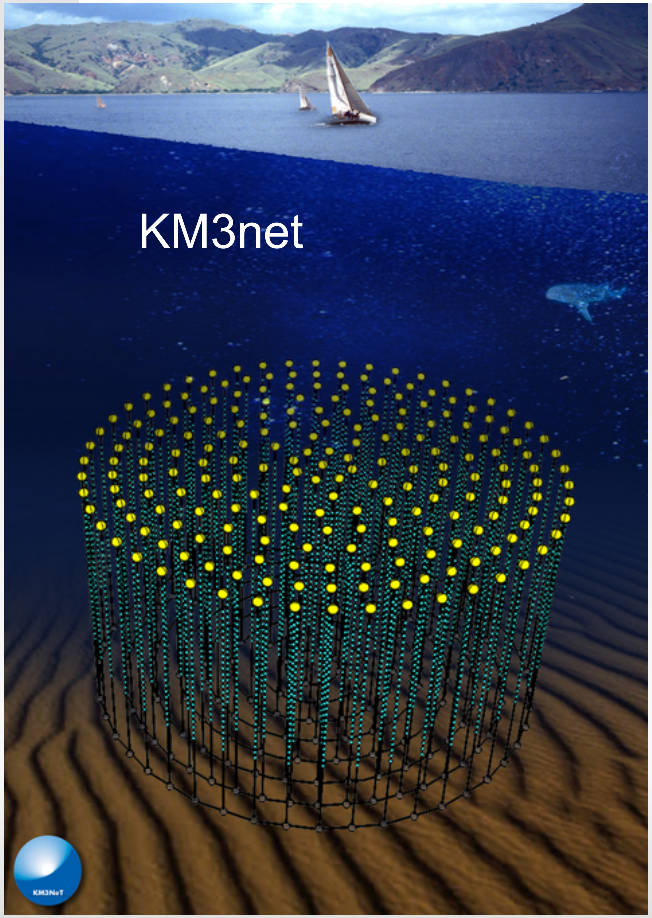
Capo Passero site 80 km, offshore, 3500 m depth. Installation of ”towers” ongoing since ~1 year. Final goal is to instrument 1 km^3 of water. Signals from the galactic center up-going: no atmospheric background

NEMO Shore Station – an old warehouse at the port adapted to accommodate the INFN laboratory



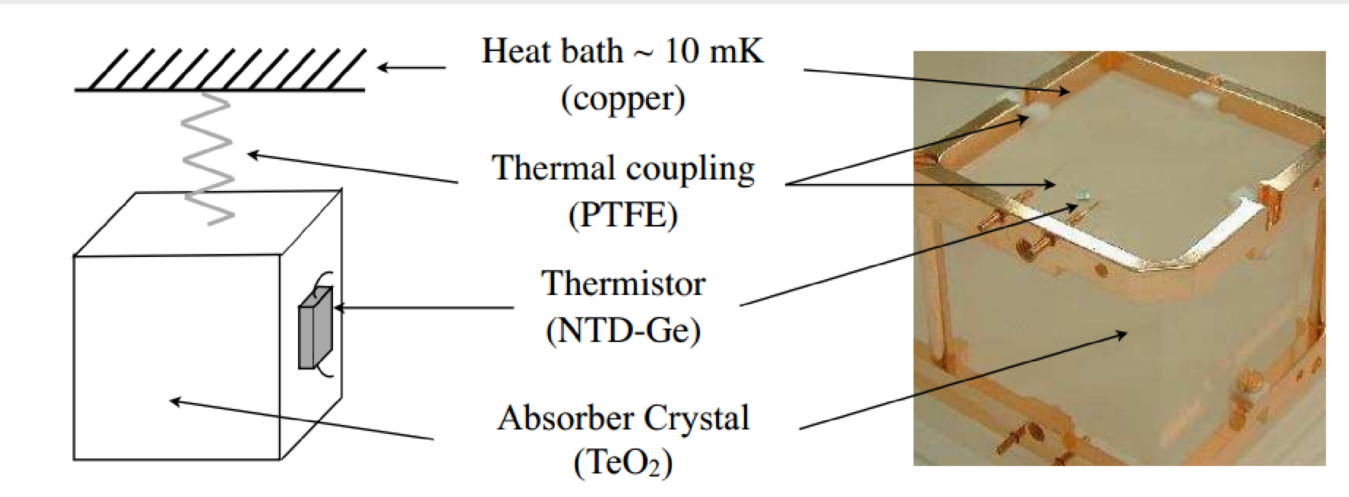






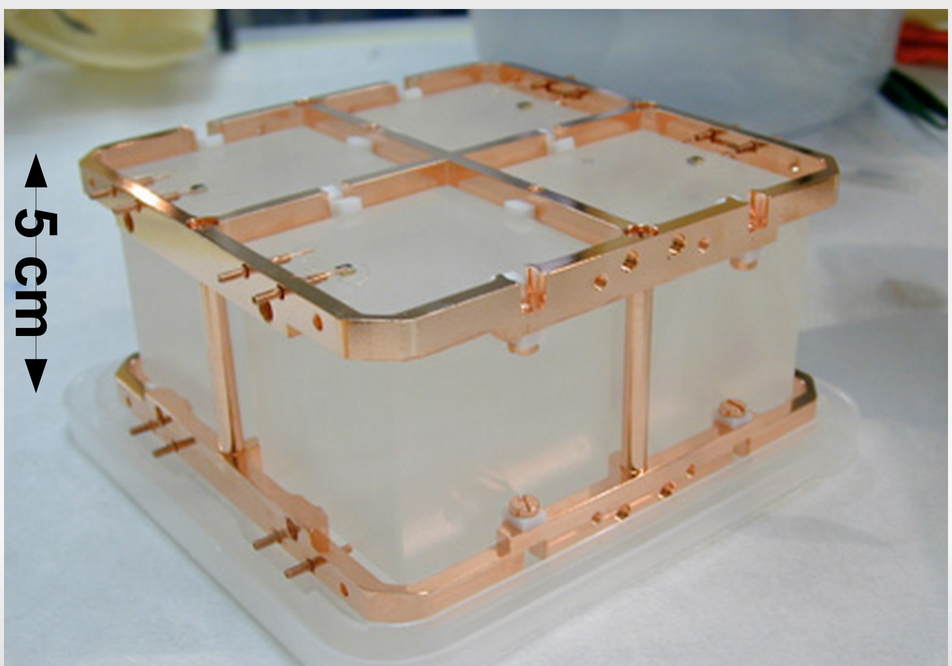
LNF involvement in control system/electronics.
Assembly of future towers will be hosted in the lab.

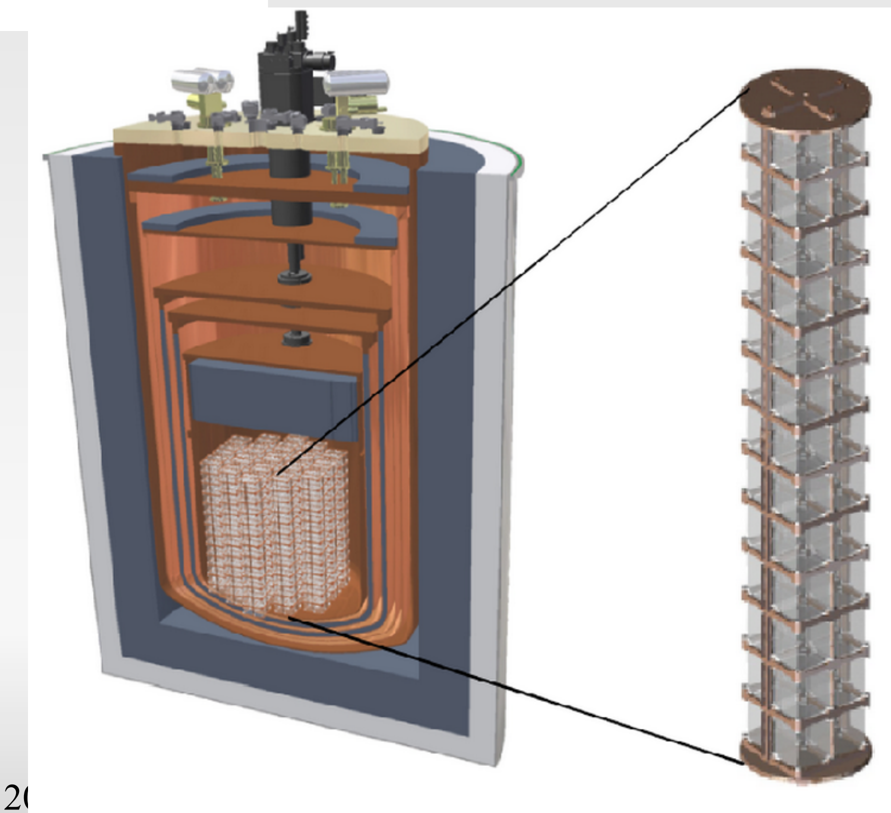
The CUORE experiment on ^{130}Te $0\nu\beta\beta$



Ionisation of charged particles @1mK: heat capacity gets small enough to give measurable variations of T (→ variations of resistance). $\Delta T/\Delta E$ ~15 μK/MeV

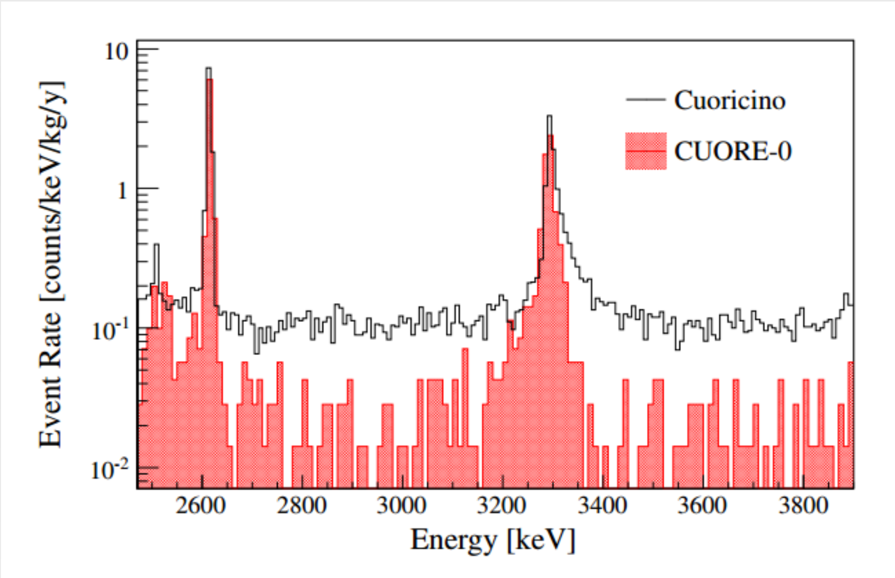
988 TeO_2 bolometers, 19 towers.
Under construction (Gran Sasso)





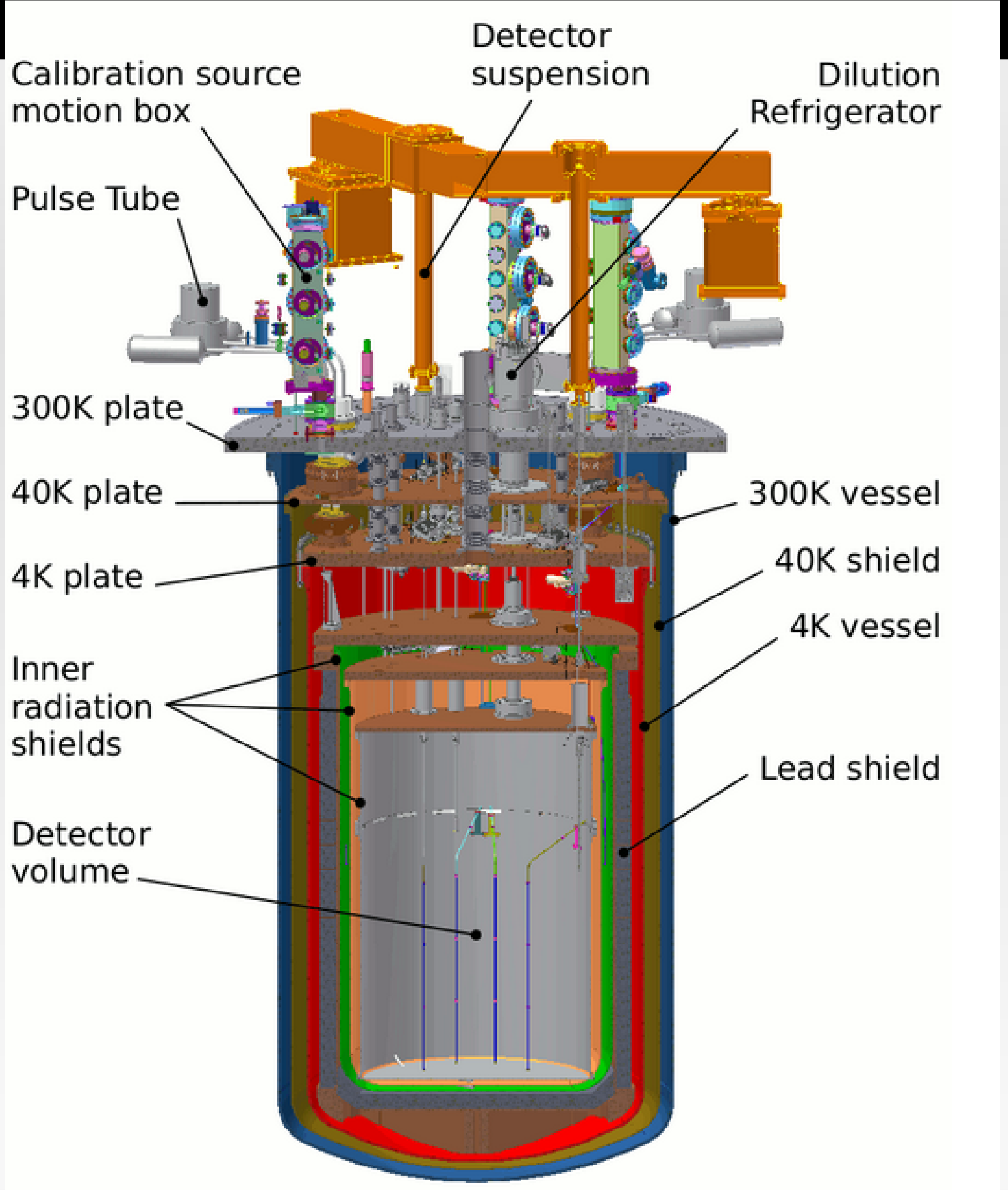
The CUORE experiment on ^{130}Te $0\nu\beta\beta$

Searching for a peak @ 2528 keV



Capable of excluding half-lifetimes $> 10^{24}$ years

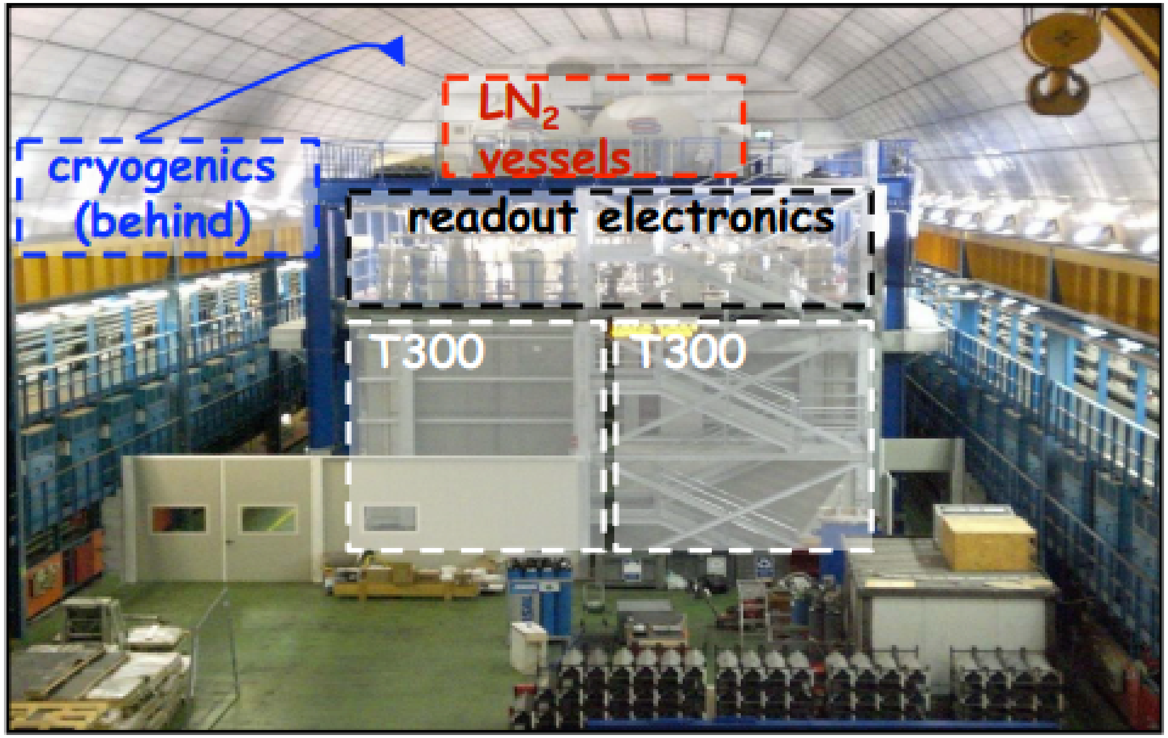
If the hierarchy is inverted and the neutrino is a Majorana particle a potential signals start to be almost "guaranteed"

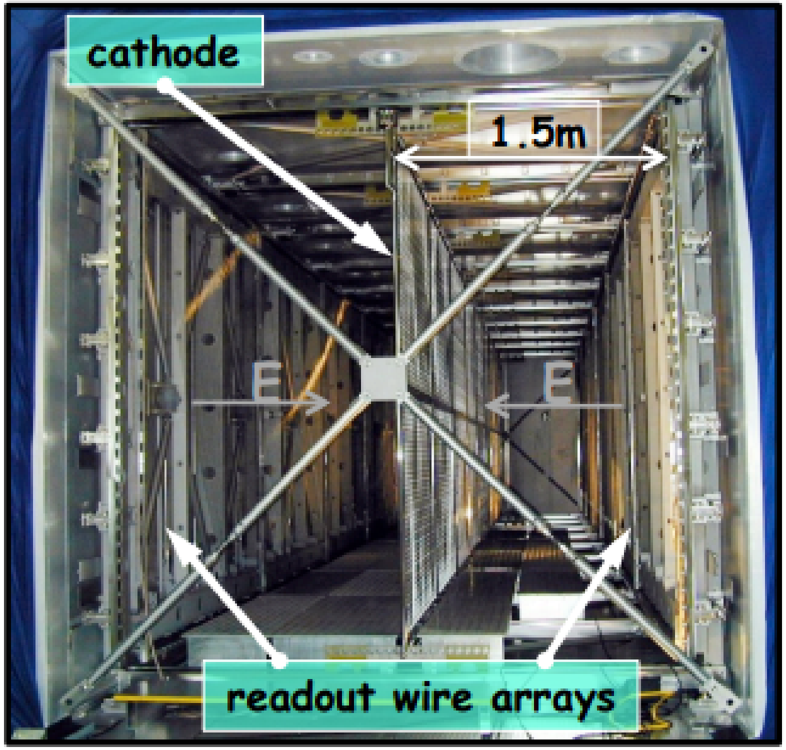


LNF involved in mechanics, cryogenics, technical coordination

The ICARUS T600 detector

LNF involvment

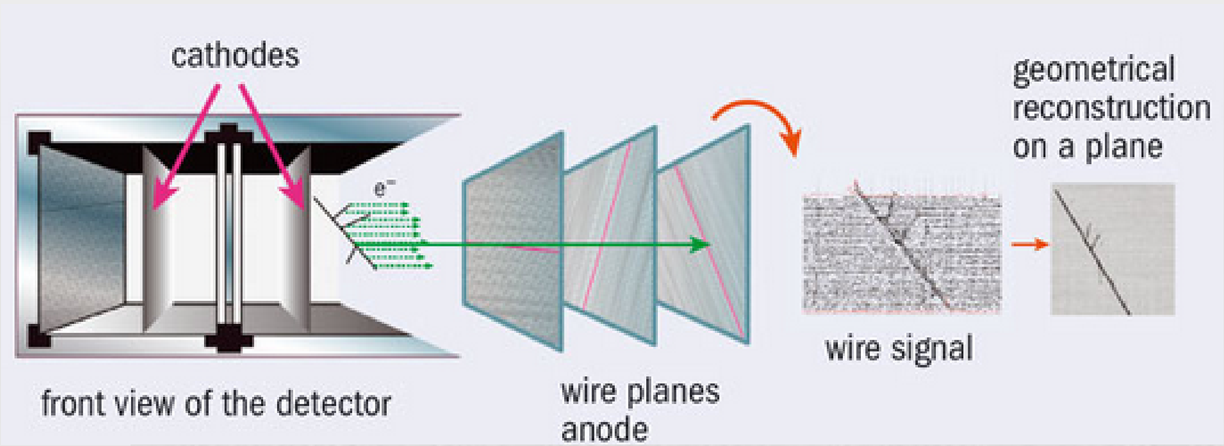




- Two identical modules
  - 3.6 x 3.9 x 19.6 ≈ 275 m^3 each
  - Liquid Ar active mass: ≈ 476 t
  - Drift length = 1.5 m (1 ms)
  - HV = -75 kV E = 0.5 kV/cm
  - v-drift = 1.55 mm/μs

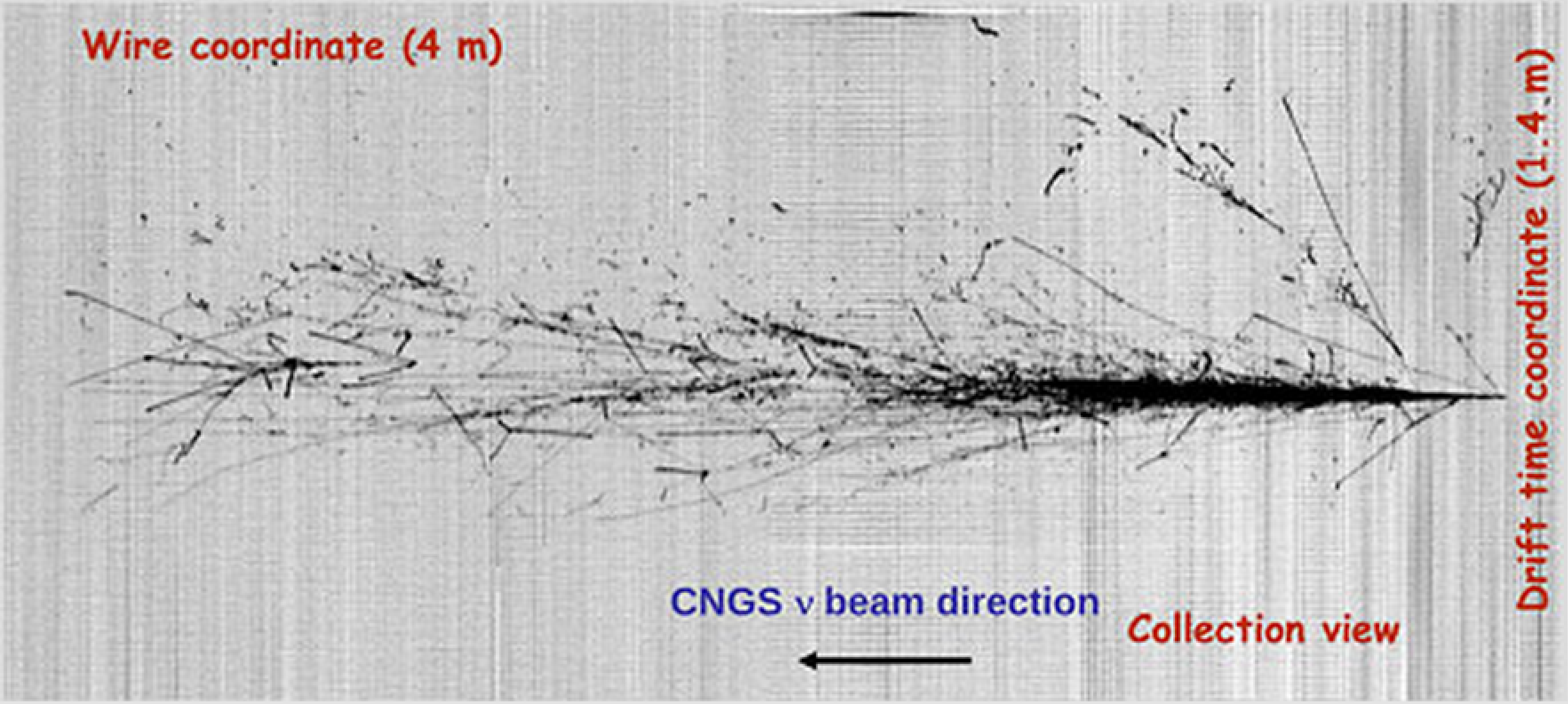
- 4 wire chambers (TPC):
  - 2 chambers per module
  - 3 readout wire planes/chamber, @ 0,±60°
  - ~54000 wires, 3mm pitch,3mm plane spacing
- 20+54 PMTs , 8" Ø, for scintillation light:
  - VUV light (128nm) with wave shifter (TPB)

The ICARUS T600 LAr TPC

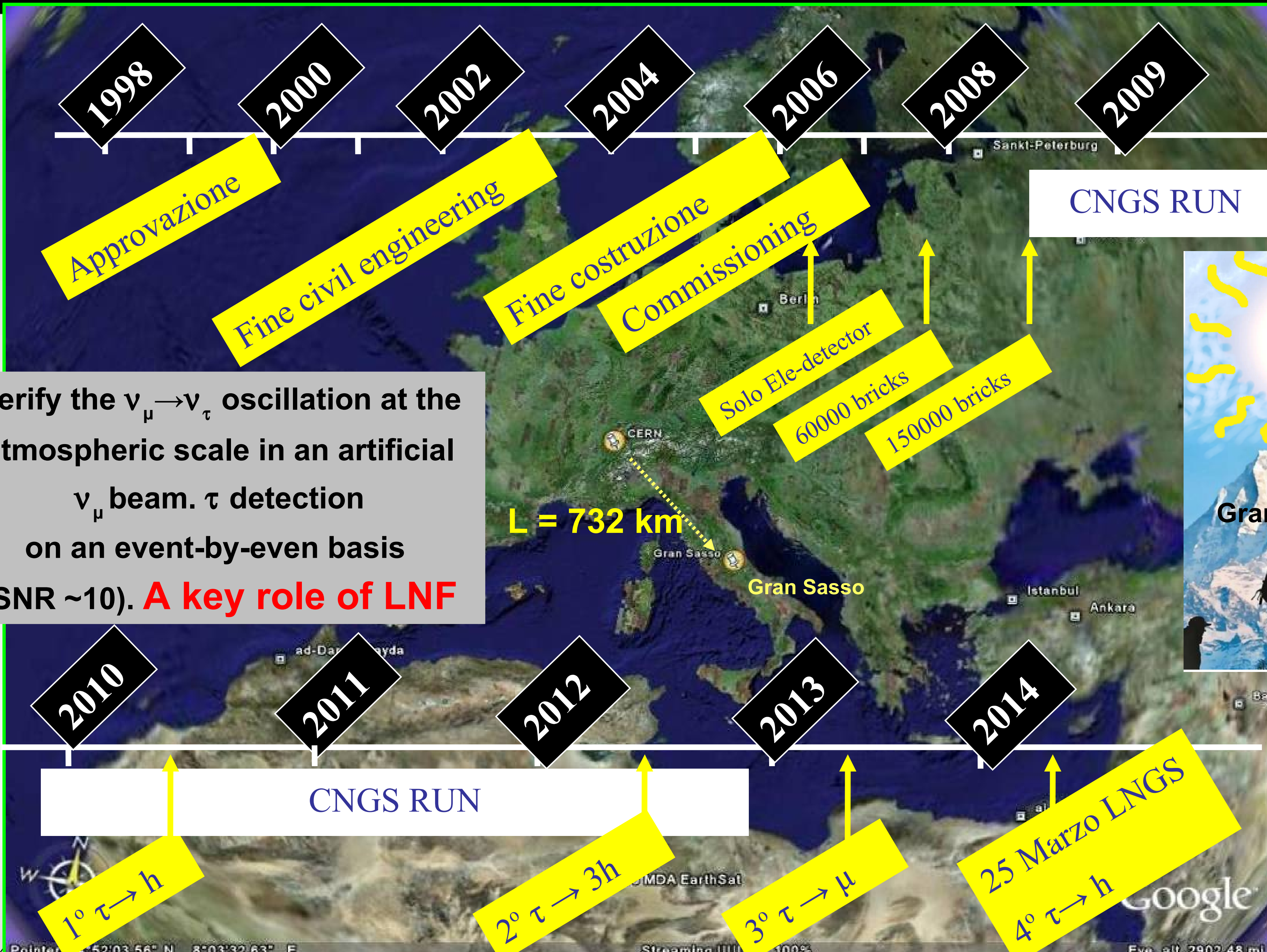


A key technology for future long-baseline experiments on leptonic CP violation.

US-based LBNE project

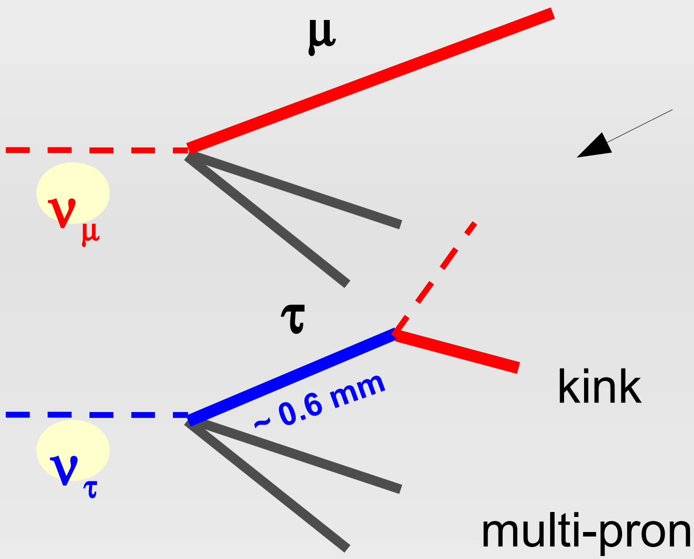


Direct evidence of $\nu_\mu \rightarrow \nu_\tau$: OPERA



Verify the $\nu_\mu \rightarrow \nu_\tau$ oscillation at the atmospheric scale in an artificial ν_μ beam. τ detection on an event-by-even basis (SNR ~10). **A key role of LNF**

The challenge of ν_τ detection



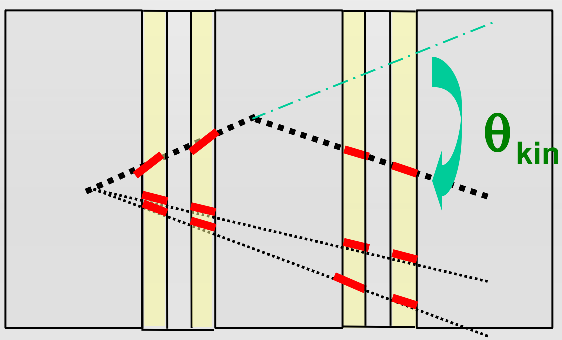
A handful of ν_τ CC in the ν_μ CC bulk

kink

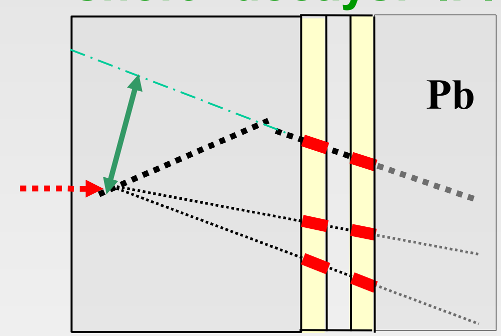
$\tau^- \rightarrow \mu^- \nu_\tau \nu_\mu$	17 %
$\tau^- \rightarrow e^- \nu_\tau \nu_e$	18 %
$\tau^- \rightarrow h^- \nu_\tau n(\pi^0)$	50 %
$\tau^- \rightarrow \pi^+ \pi^- \pi^- \nu_\tau n(\pi^0)$	14 %

multi-prong

"long" decays: kink



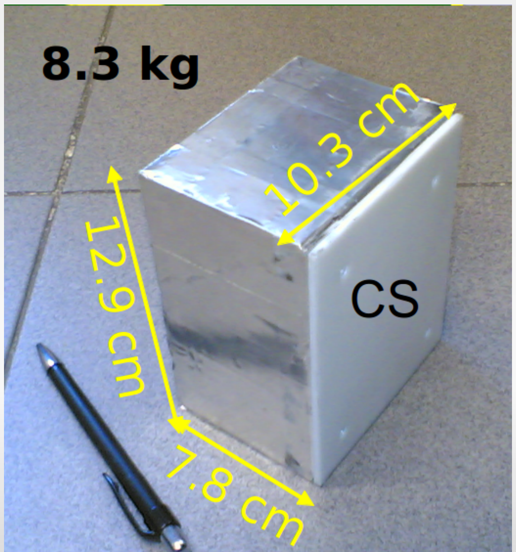
"short" decays: I.P.

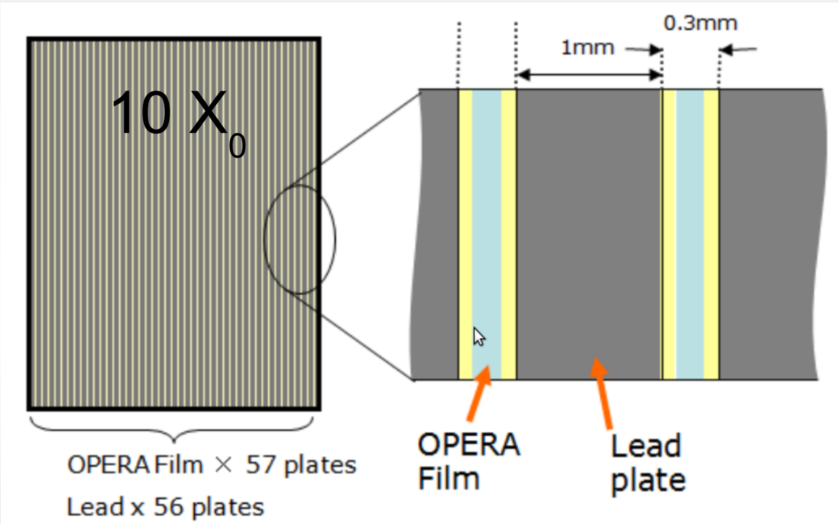


Molular stack of "Emulsion Cloud Chambers"

Reconcile the necessity of

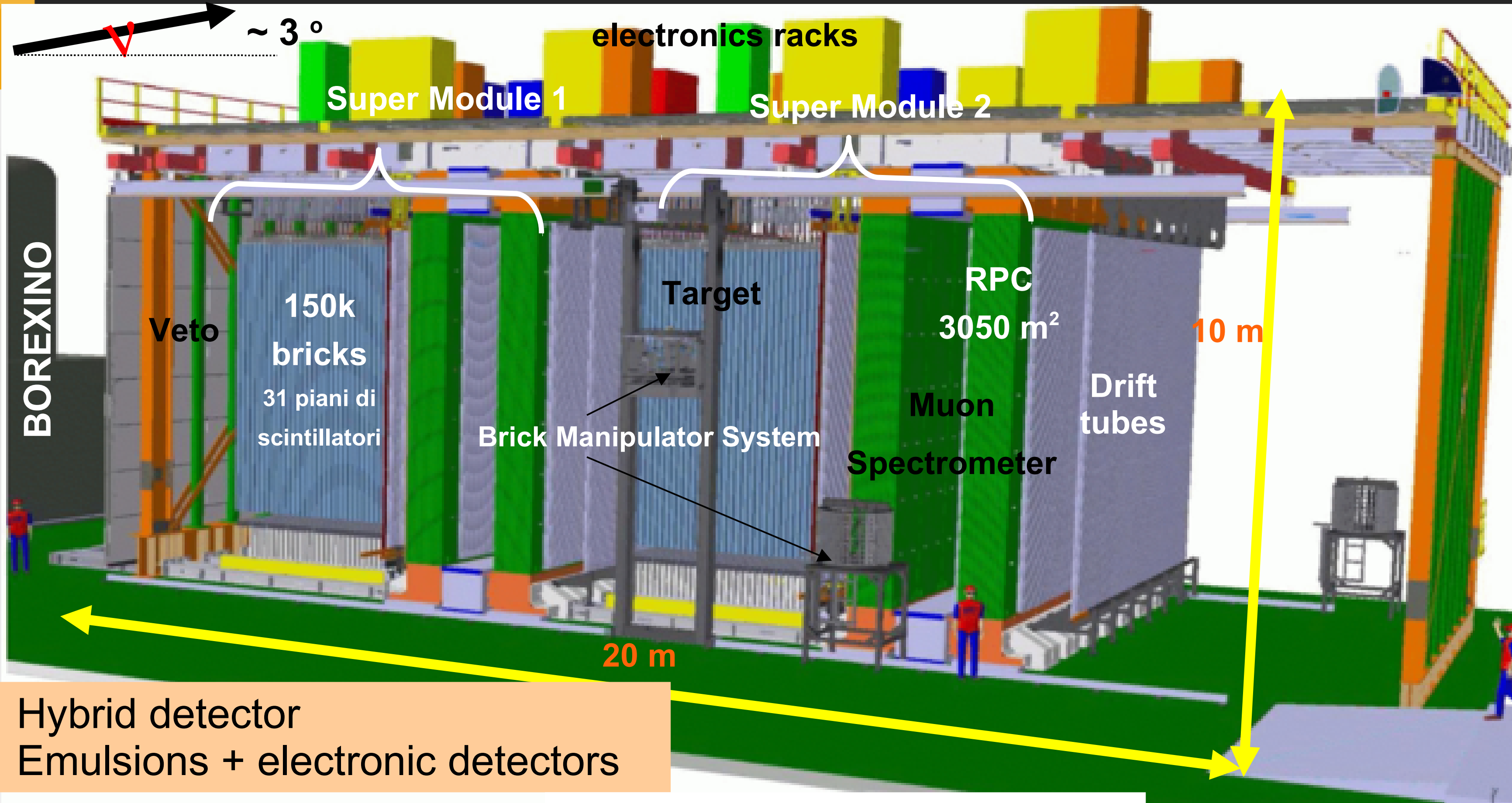
- **O(kt) mass**
  - $N_\tau \propto (\Delta m^2)^2 M_{target}$
- **High granularity**
  - $\sim \mu m$



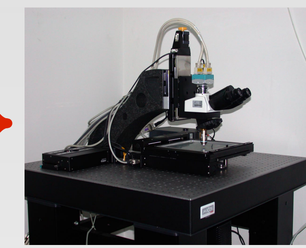


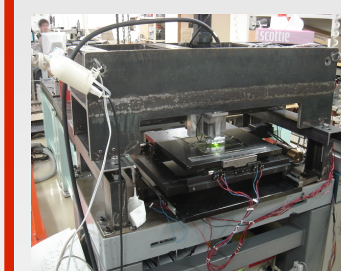
The OPERA detector

A gigantic high-granularity “vertex detector”

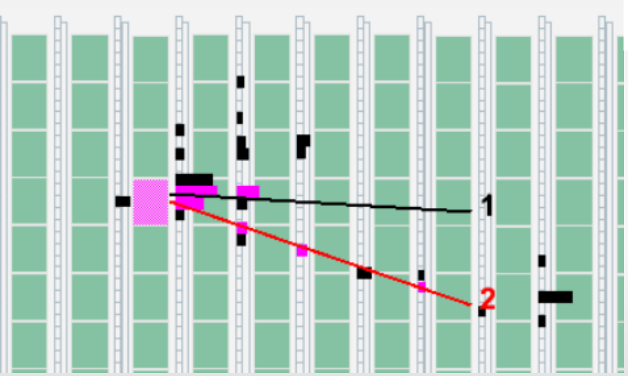


Hybrid detector
Emulsions + electronic detectors

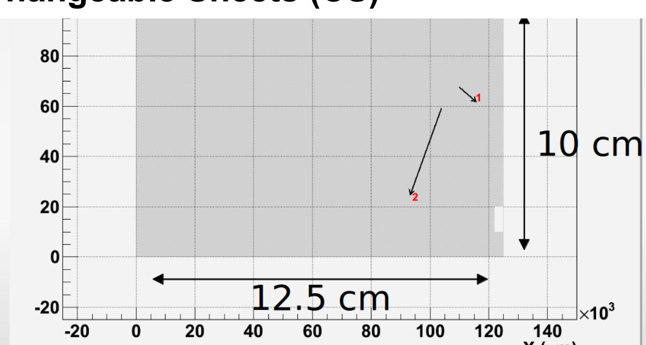




``Brick-finding"



Conferma e innesco dello scanning nel brick grazie ai doppietti di emulsioni Changeable Sheets (CS)



+ svariate installazioni ancillari “off-site”:

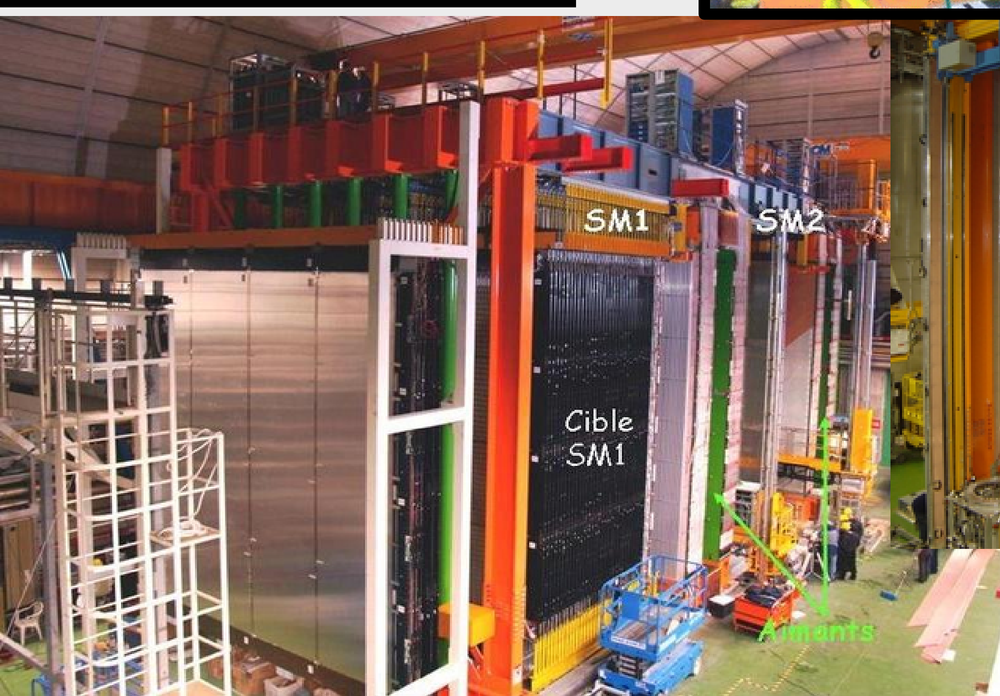
- “refreshing” emulsioni (JP e LNGS)
- Assemblaggio/smontaggio brick (LNGS)
- Labelling e marcatura con X ray (LNGS)
- Sviluppo automatico (LNGS)
- Scanning CS (LNGS)
- Scanning bricks (Europa + JP)

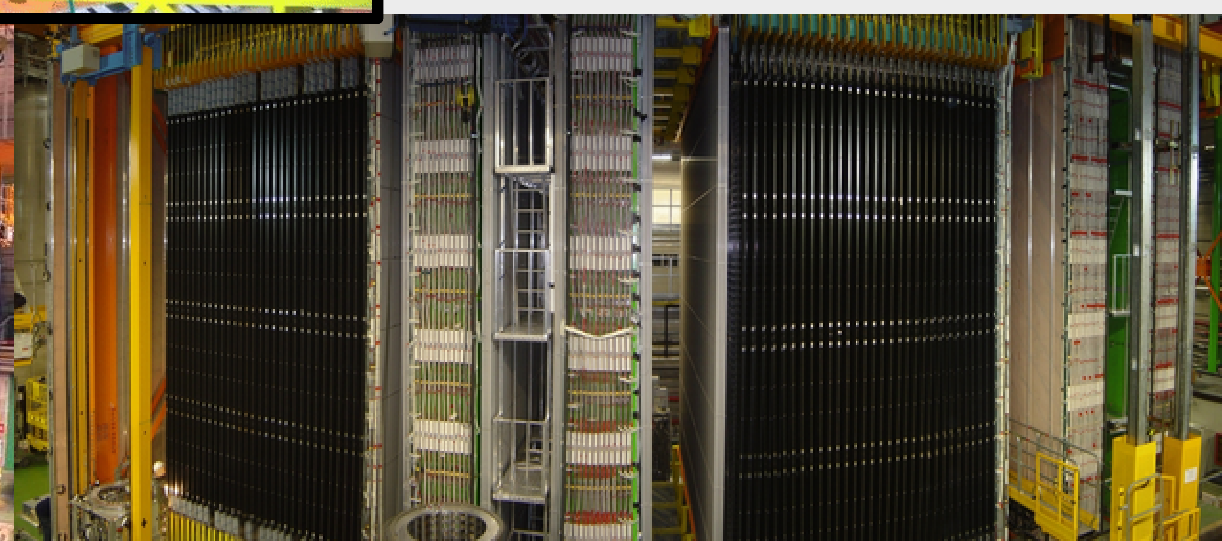
September 2003

... 2004

Heavy LNF involvement

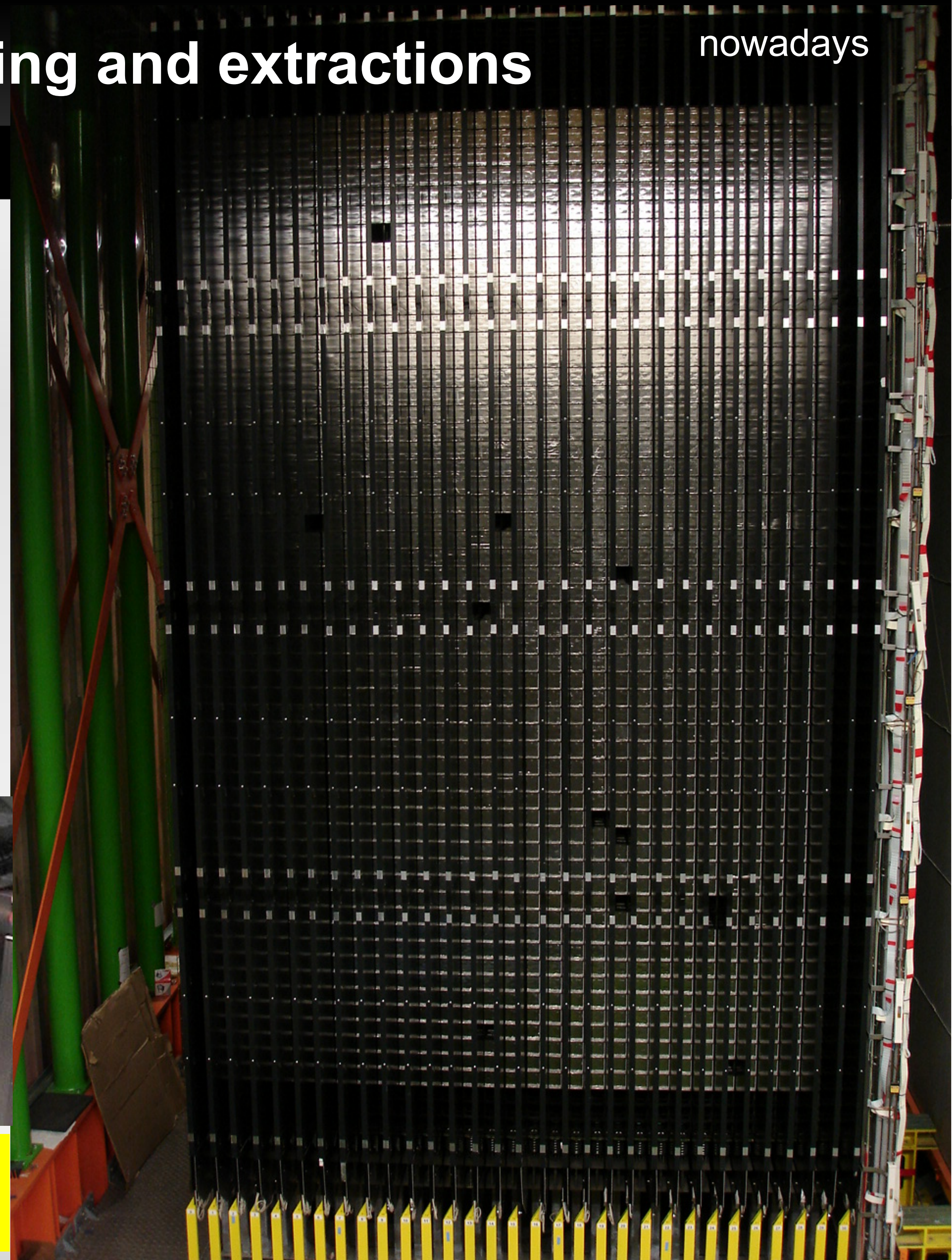
... 2005





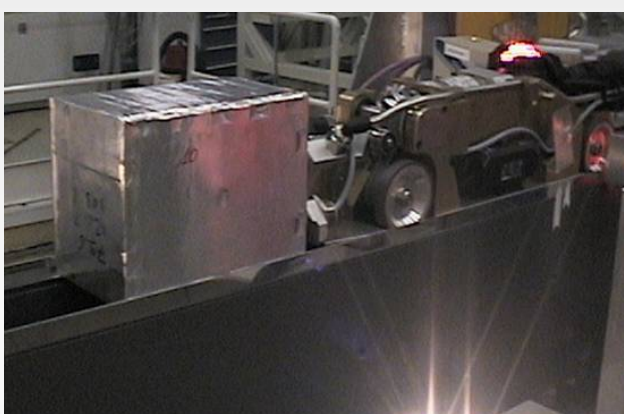
Brick filling and extractions

LAPP Annecy



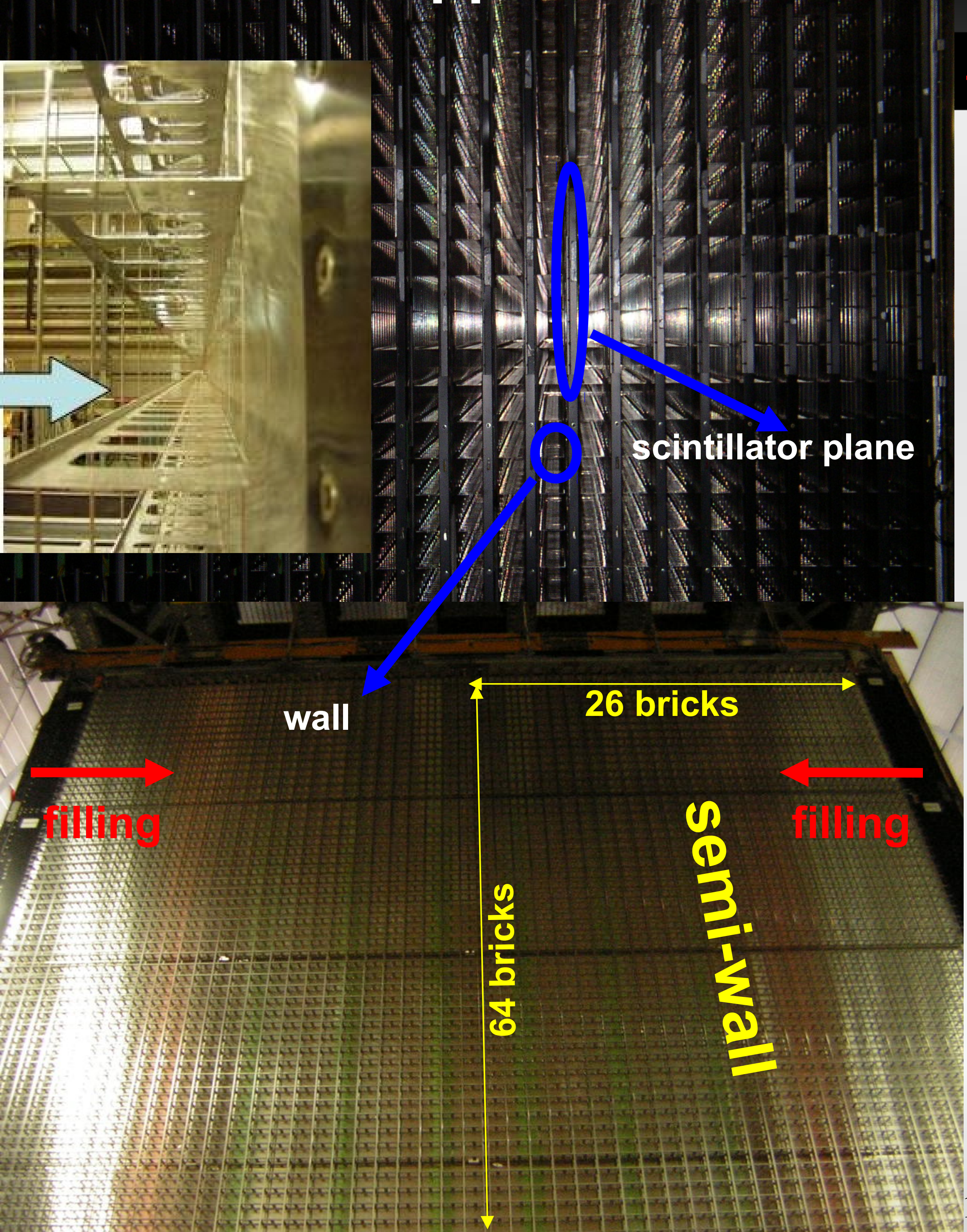
Accomplished smoothly in parallel to brick production in ~ 1.5 y

Routine extractions in 2008 run:



Up to 25 bricks per shift (8h). OK!

The bricks support structure



LNF responsibility

Tight mechanical tolerances for brick positioning accuracy and low mass to minimize interactions in passive target

Holds **3328 bricks ~ 28 ton**

Ultra-light: **0.4% of bricks mass**

Stainless steel vertical ribbons (0.8 x10 x 6780 mm)

Laser-welded U-shaped trays (0.7mm)

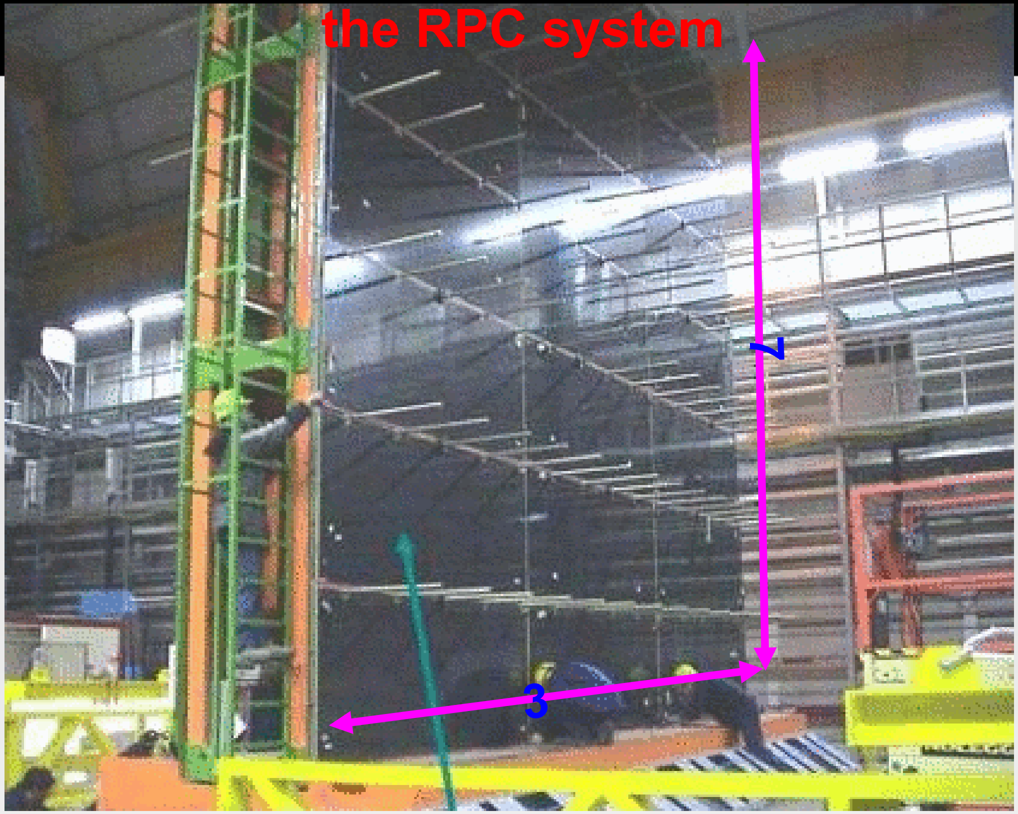
Spring tensioning system

Achieved precisions:

- construction *(w. mech. gauges)* (105.3 ± 0.1 / 82.6 ± 0.25 / 7330 ± 0.6) mm
- positioning *(measured during installation w. high. res photogrammetry)*
  - vertical < 0.3 mm
  - transverse & longitudinal < 0.5 mm
  - planarity < 1 mm

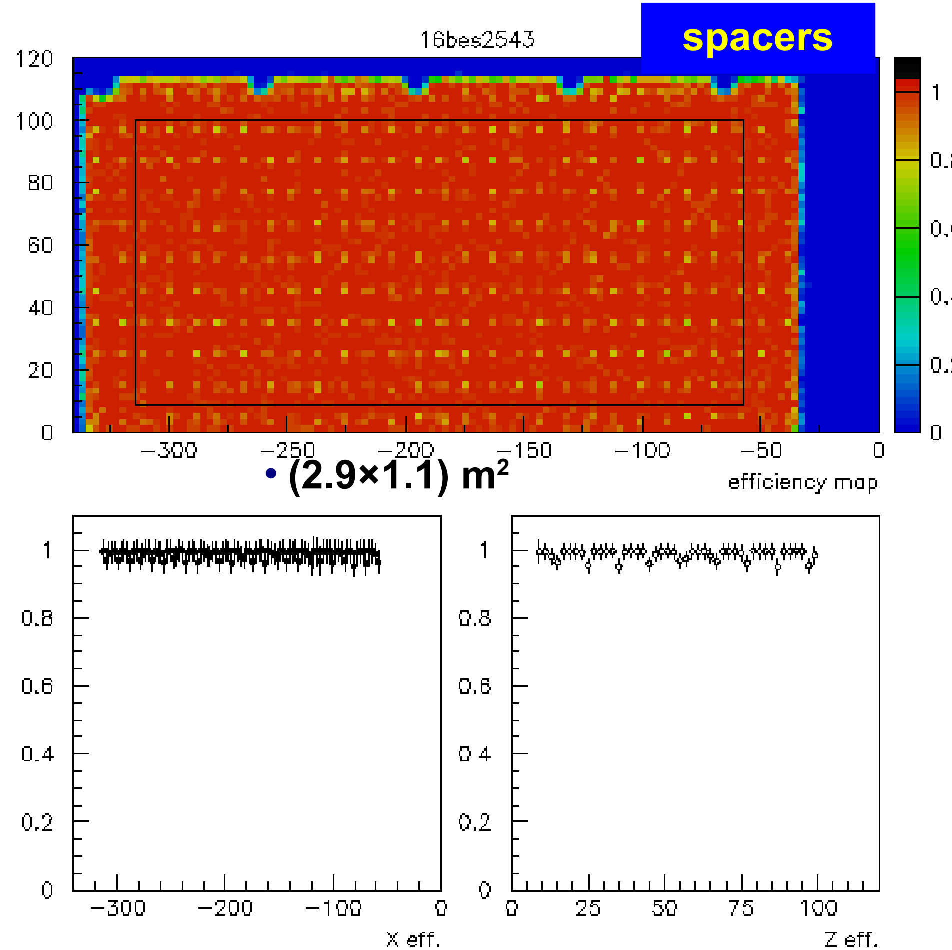
The inner trackers (RPC)

LNF expertise, quality tests, spectrometer installation underground



Bakelite Resistive Plate Chambers with 2 mm gaps and Linseed oil coating

cosmic ray efficiency map for 1 chamber (at surface!)



- (2.9×1.1) m^2

- 462 (Bakelite RPC) + 42 (XPC) x 2 ~ 1000
- tot. surface: 3326 m^2
- digital channels: ~ 27000
- strip pitches: 2.6, 3.5 cm (Vert, Hor)
- Front-End Boards: 468
- Controller Boards: 52
- Gas: 76%Ar+20%TFE+4%Iso+0.6%SF_6
- 8 kV/2mm

Muon spectrometer close-up

Iron spectrometer designed and build by LNF

38 mm diam. **8 m** long tubes.
(never so long before!)

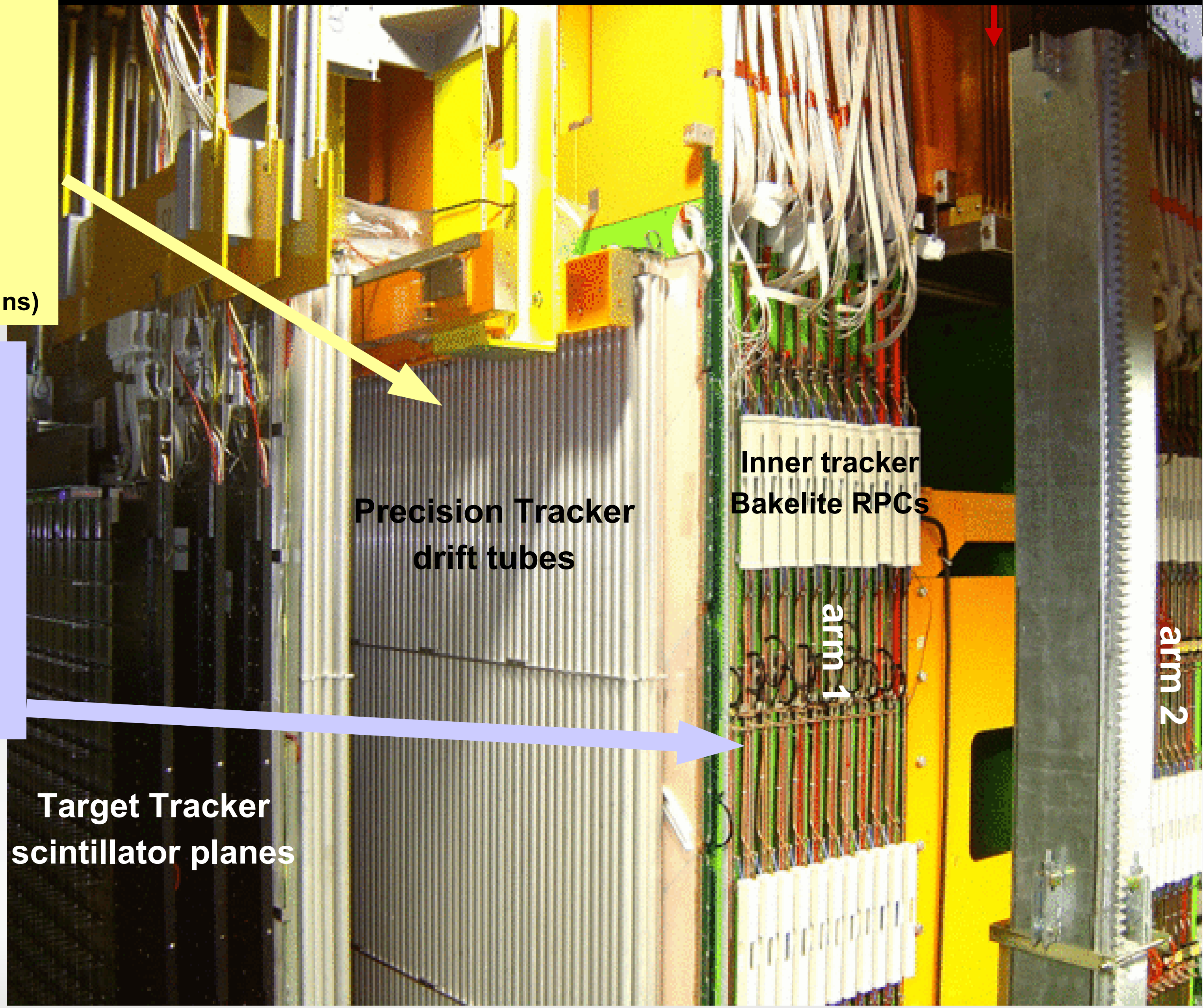
10.000 drift tubes
4 layers modules (staggered)

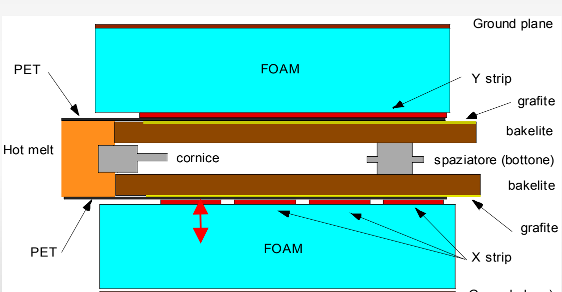
Ar/CO_2: 80/20% @ 1005±5 mbar
(80 m^3 exchange 1m^3/h)

0.85 mm thick. **45 μm** wire.

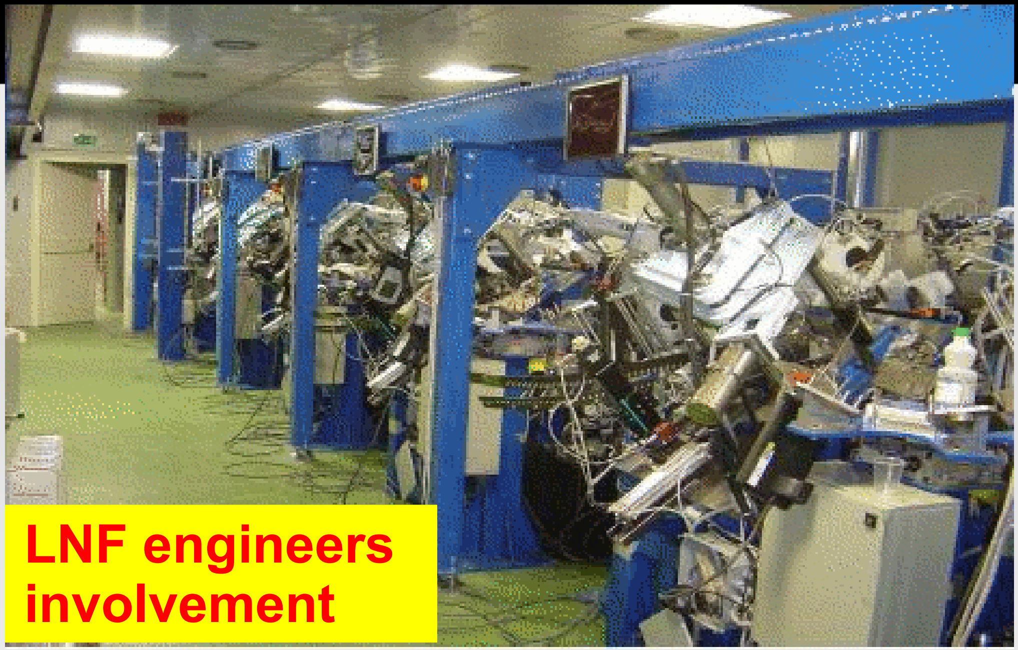
RPC-triggered, 3.2 μs TDCs (LSB 1.5 ns)

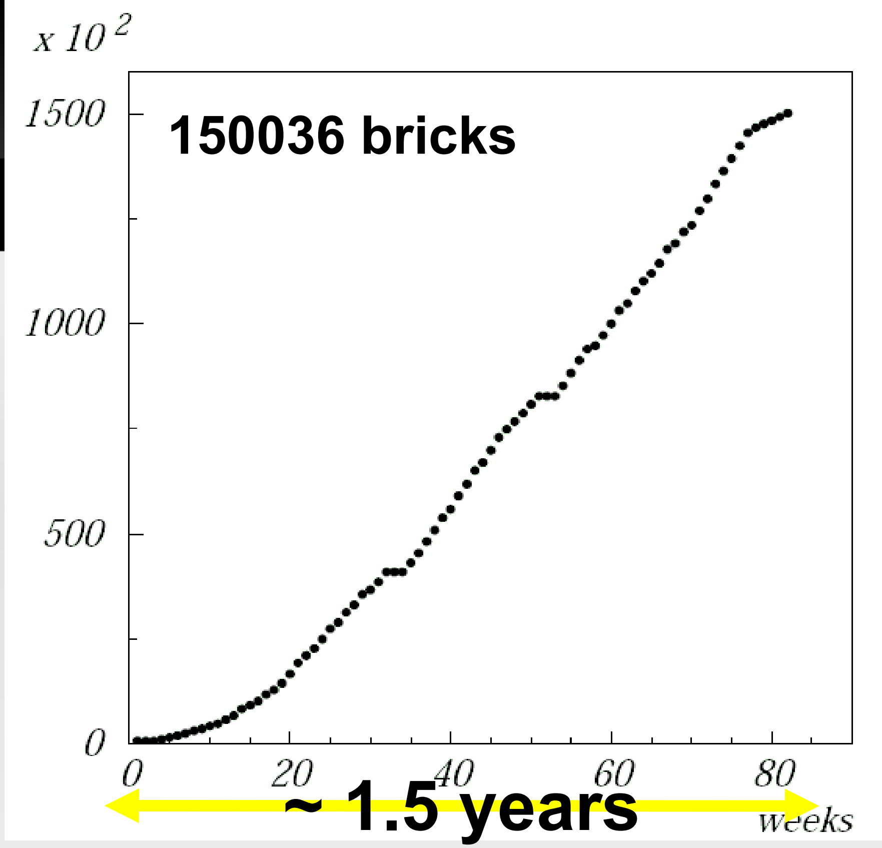
- Bakelite RPC (streamer mode)
- 462 RPC + 42 (XPC) x 2 ~ 1000
- 3326 m^2 (2.9 x 1.1 m^2 each)
- digital channels: ~ 27000
- Strips pitch: 2.6, 3.5 cm (Vert, Hor)
- Front-End Boards: 468
- Controller Boards: 52
- 76%Ar+20%TFE+4%Iso+0.6%SF_6
- 8 kV / 2mm

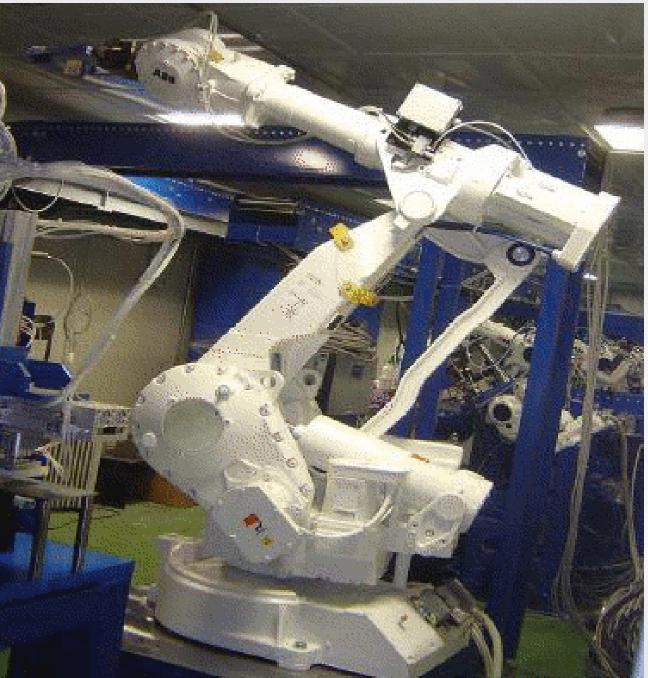




The brick assembly machine





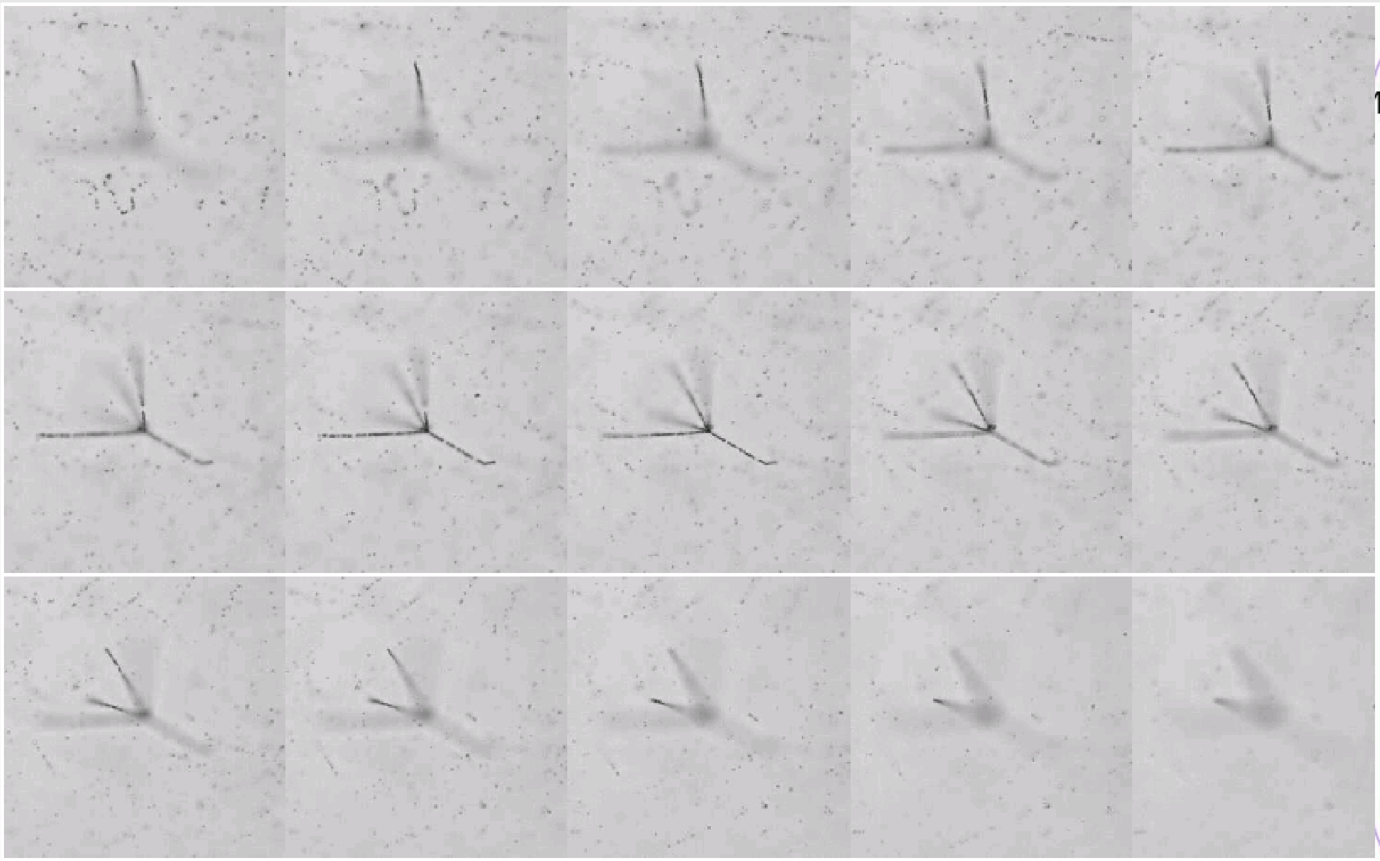

Anthropomorphic robot for brick wrapping

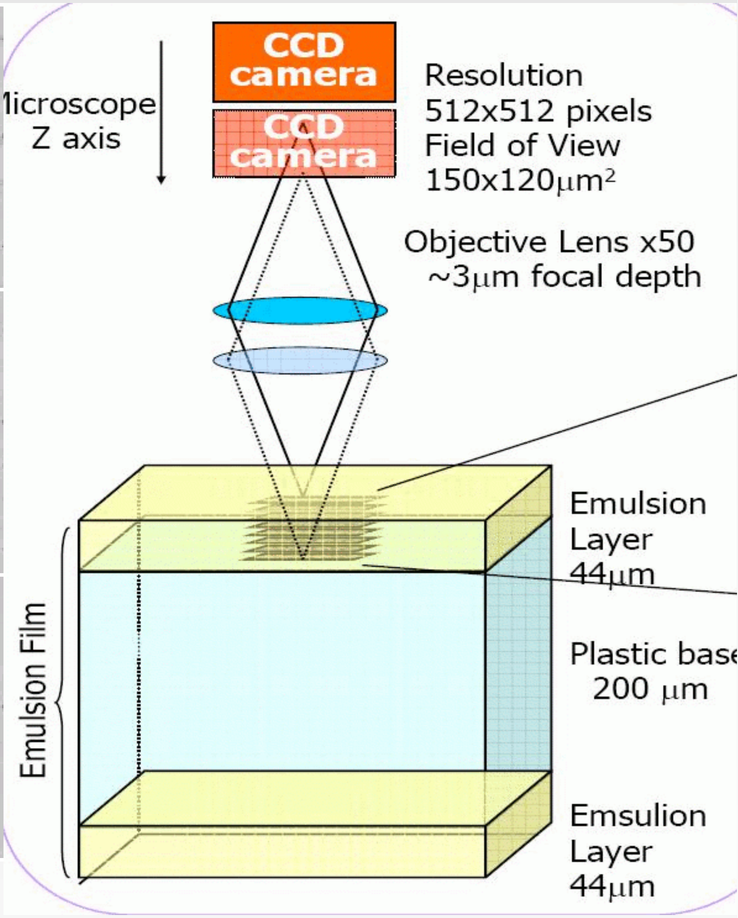
Automatic stacking and packaging
5 robotized parallel piling stations
Operations underground in dark room

150k bricks → 9 M emulsion and lead plates
On average ~650 bricks/day   2 (8h long) shifts/day * 5 days/week (7 operators+1 site manager)

Nuclear emulsion scanning: principle

Emulsion cuts at different ”z”

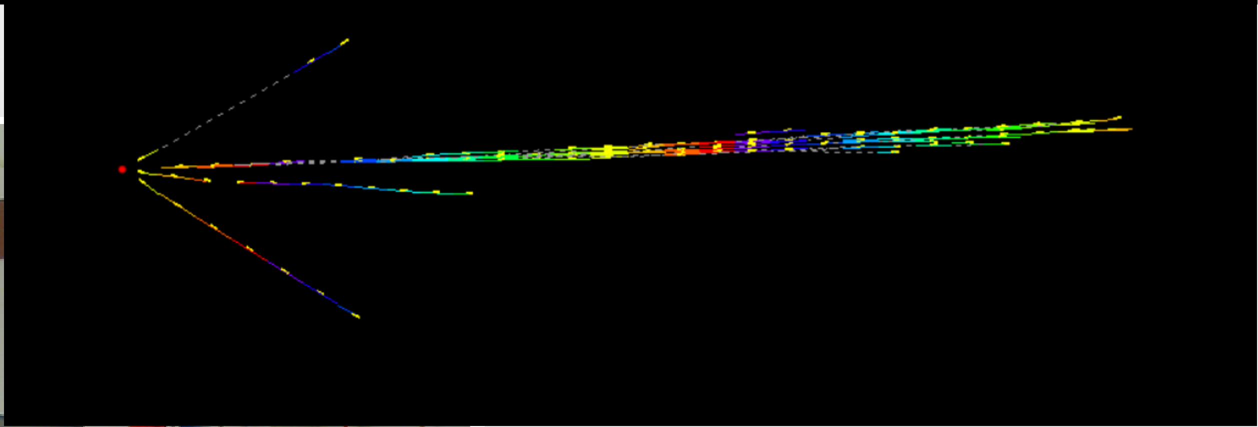


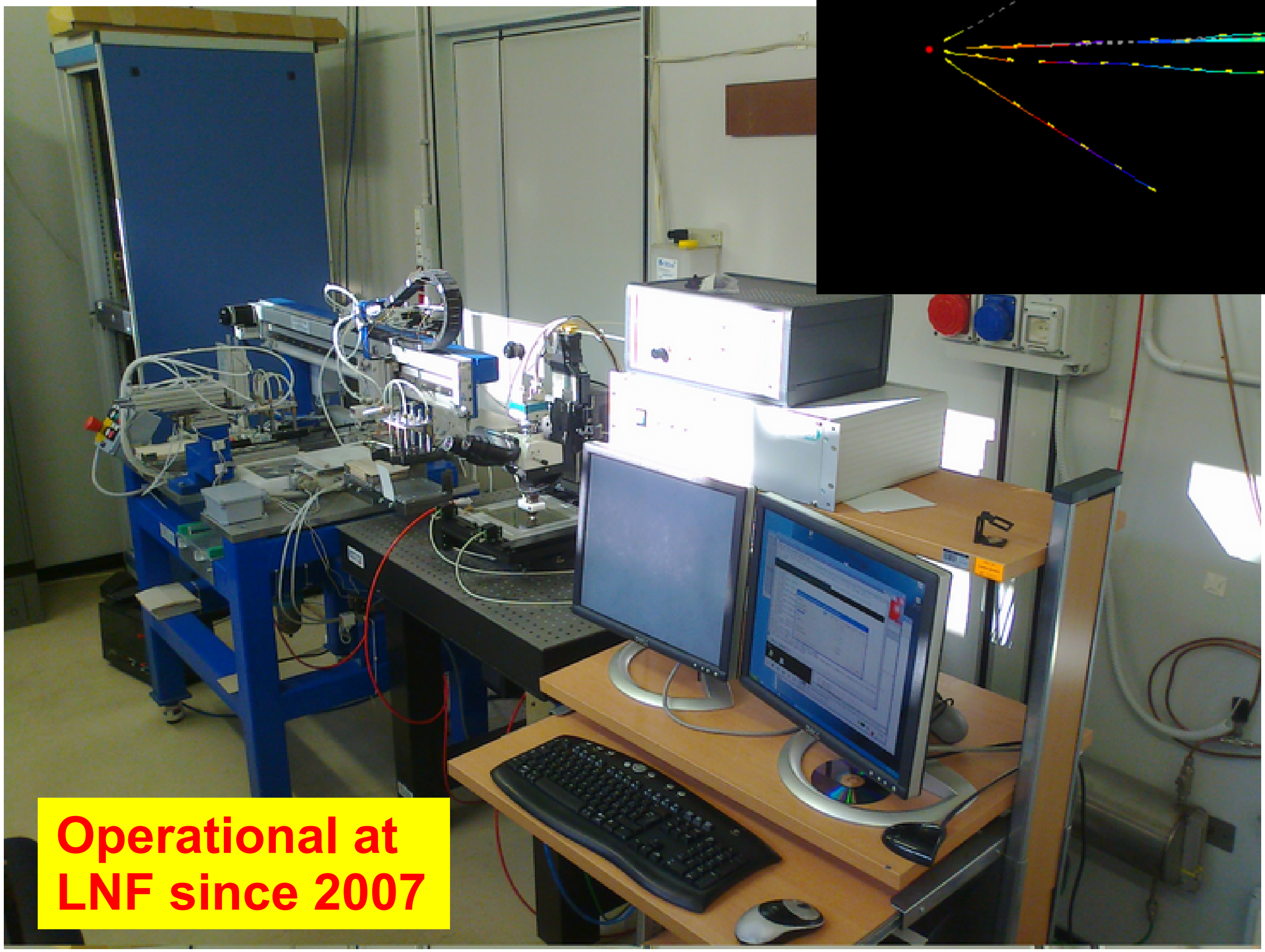


From the cascade alpha decays of heavy elements in natural deacy chains (i.e. U and Th) present in emulsions. The shown zone is only a small fraction of the microscope view (~ 300x400 μm)

The OPERA scanning laboratory at LNF

An CNGS interaction measured at LNF





Operational at LNF since 2007

Network of laboratories (Nagoya, Bari, Bern, Bologna, LNGS Padova, Roma1, Salerno) Analyse the OPERA emulsion data. Neutrino interactions are localized in the brick and the decay topology is studied at a micrometric scale to search for the occurrence of oscillated tau neutrinos interactions.

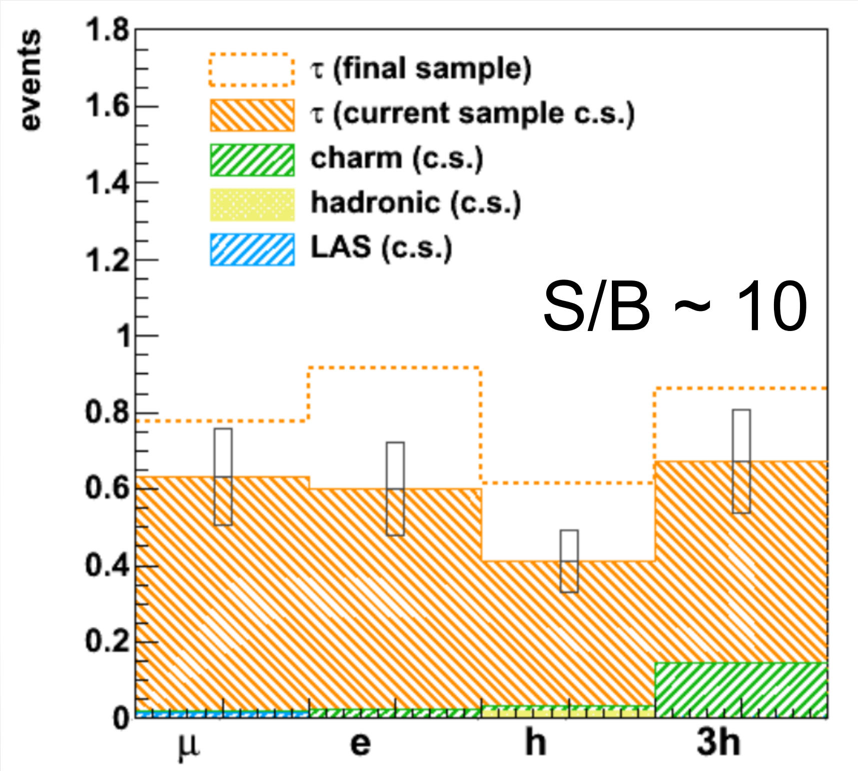
https://www.lnf.infn.it/esperimenti/opera/scanning.html
https://www.lnf.infn.it/esperimenti/opera/scanning/figs/animation_54105.gif

Results on the analysed sample

	Expected Signal	Observed Signal	Background	Charm	μ scattering	had int
τ → h	0.38	2	0.03	0.014		0.019
τ → 3h	0.53	1	0.15	0.142		0.003
τ → μ	0.58	1	0.02	0.004	0.016	
τ → e	0.58	0	0.02	0.025		
total	2.1		**0.22**	0.185	0.016	0.022

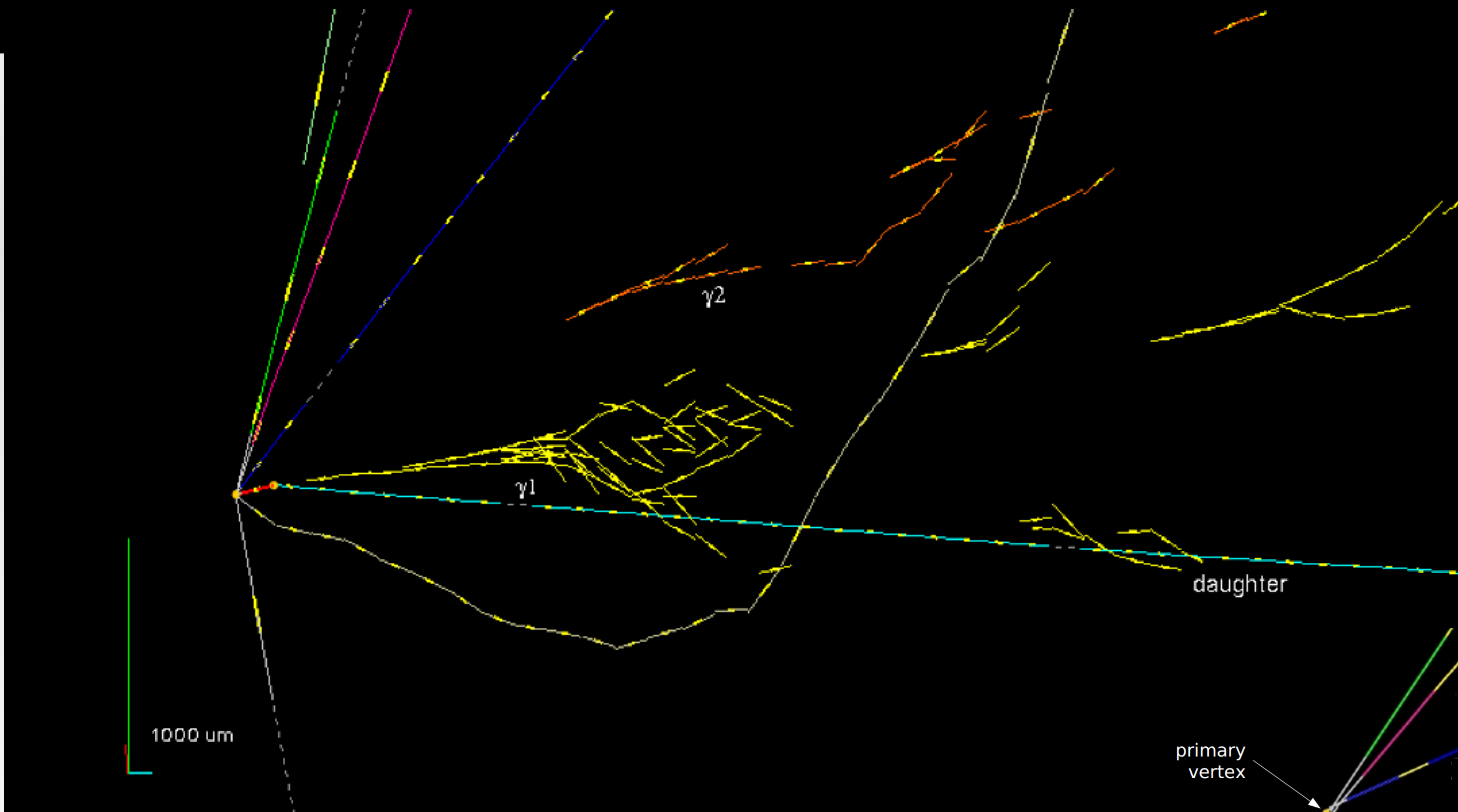
Attesi: S =2.1 ev. B = 0.22 ev.
4 candidati osservati
(3 adronici + 1 muonico)

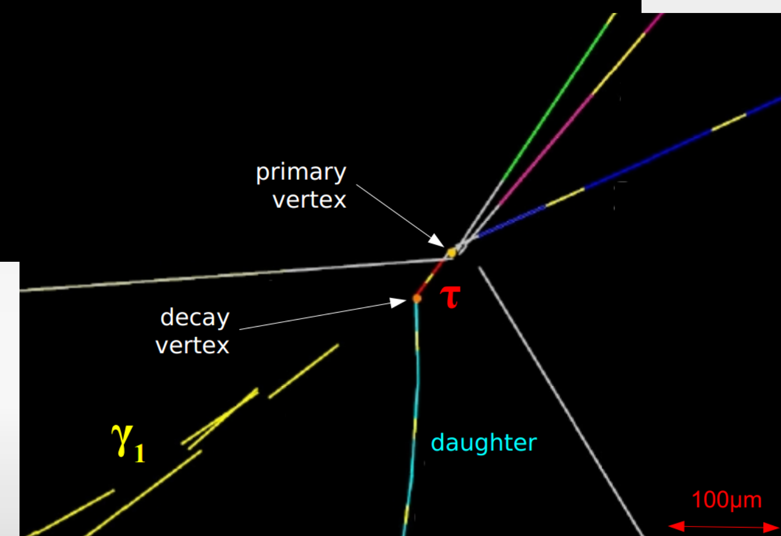
Esclusione ipotesi nulla: 4.2 σ
(semplice conteggio, ”channel-aware”)



Il 1° candidato ($\tau \to 1h$)

Phys. Lett. B691 (2010) 138





$\tau^- \to \rho^- + \nu_\tau$ (B.R. ~25%)

$\rho^- \to \pi^0 + \pi^-$

$\pi^0 \to \gamma\gamma$

640^{+125}_{-80} (stat.)$^{+100}_{-90}$ (sys.) MeV/c^2

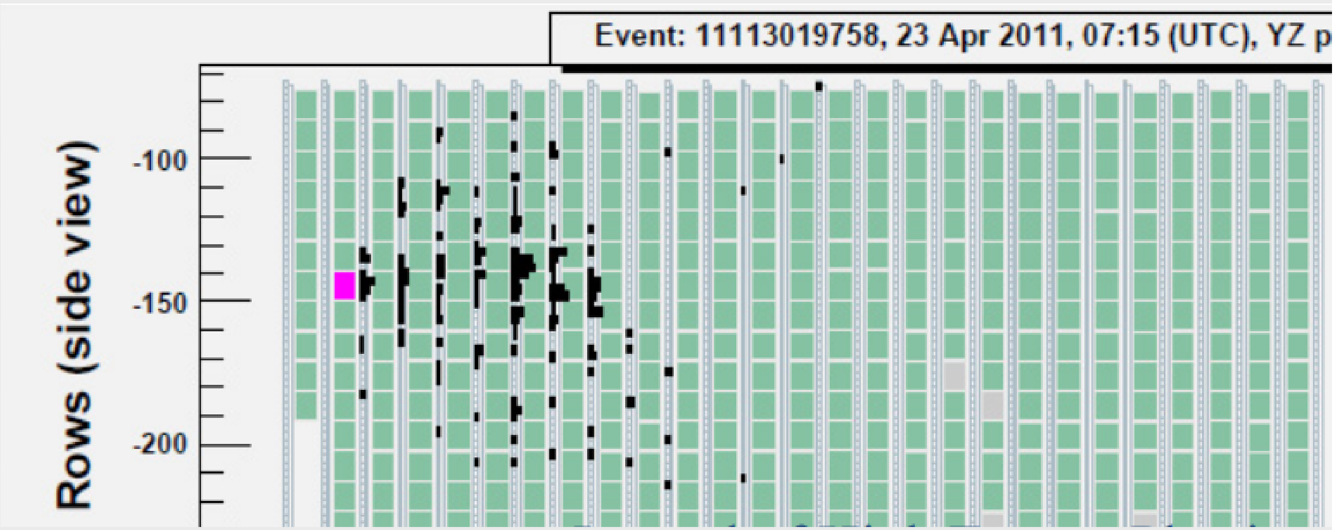
120 ± 20(stat.) $\pm$ 35(sys.) MeV/c^2

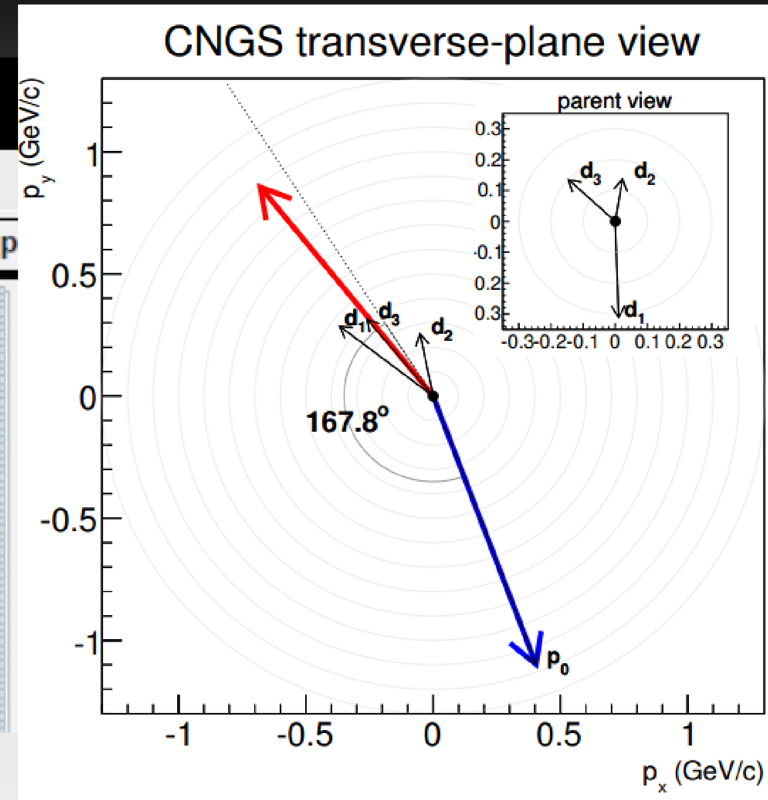
Summary

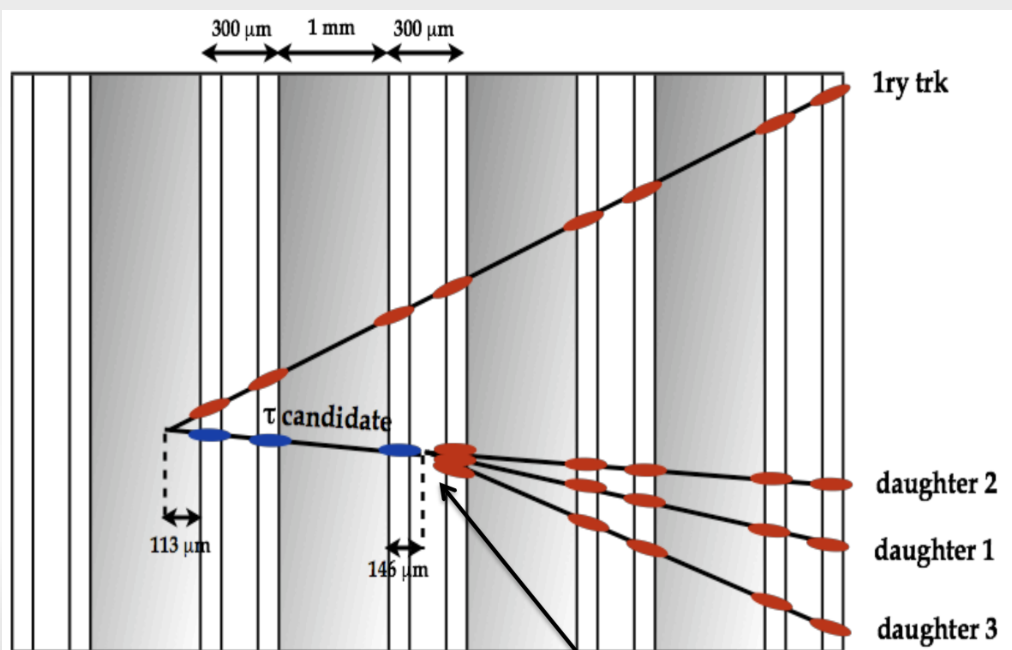
- Neutrinos are of central interest for Fundamental Physics
- A lot of what we have learnt about them (especially at the beginning) came by looking "outside" (the atmosphere, the Sun). Then tests with artificial sources came (accelerator beams, reactors)
- Today, observational cosmology is giving further important information (sum of masses, extra states) → a recurring interplay!
- First indications of the possibility to use neutrinos for astronomy (multi-messenger).
- Broad range of detection techniques developed in the last decades within INFN and LNF : (MACRO, LVD), ICARUS, OPERA, NESSiE, (T2K), KM3net.

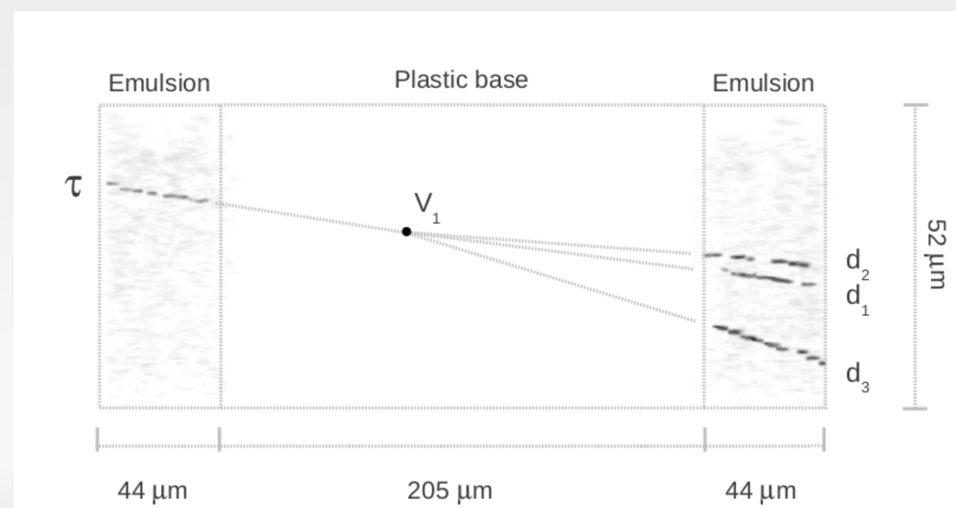
Il 2° candidato ($\tau \rightarrow 3h$)

JHEP 11 (2013) 036







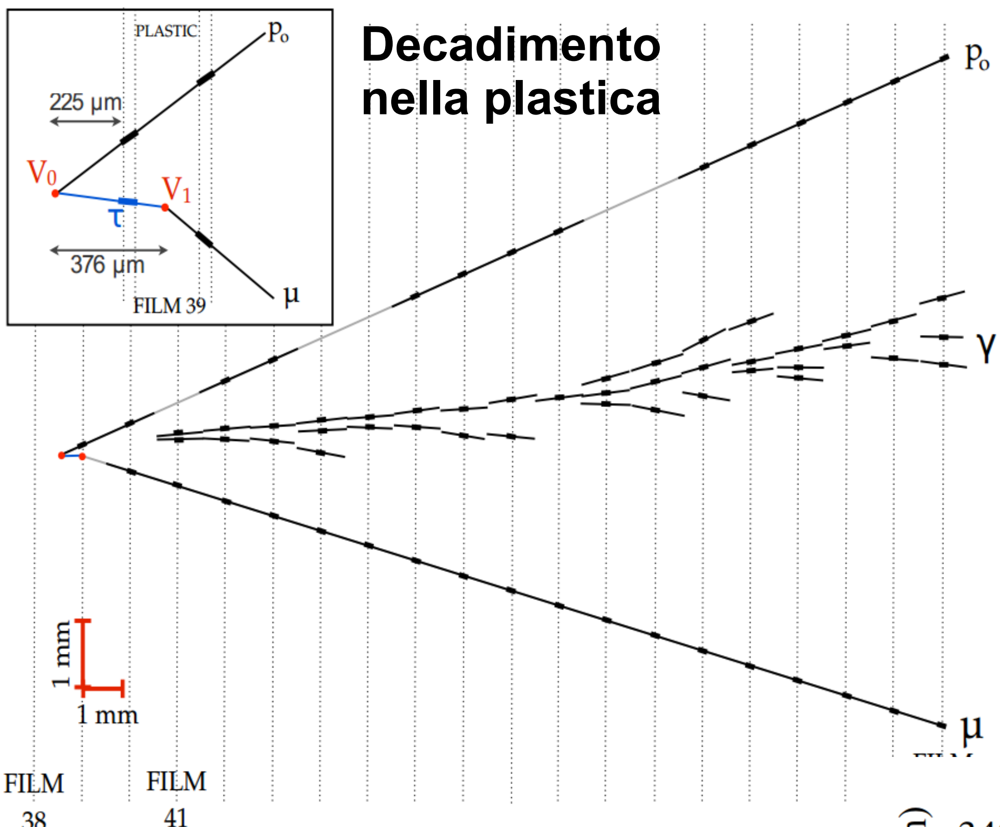


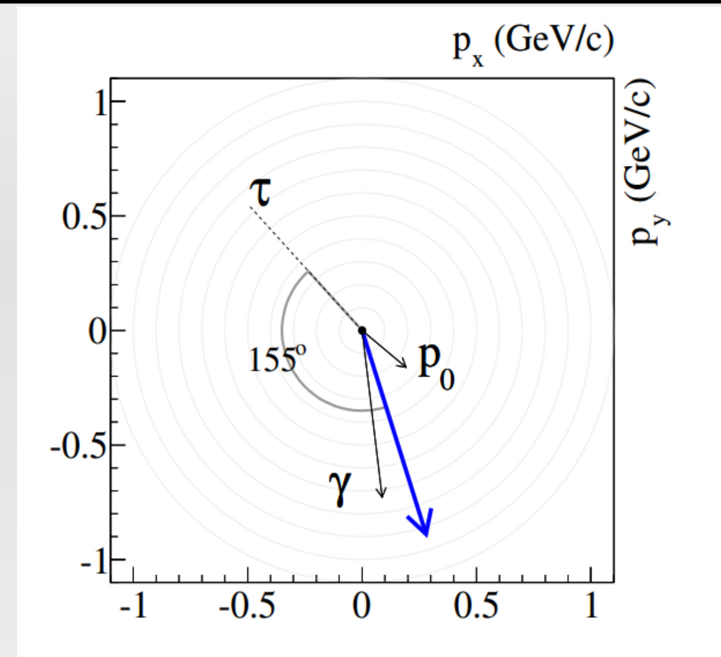
Decadimento nella plastica

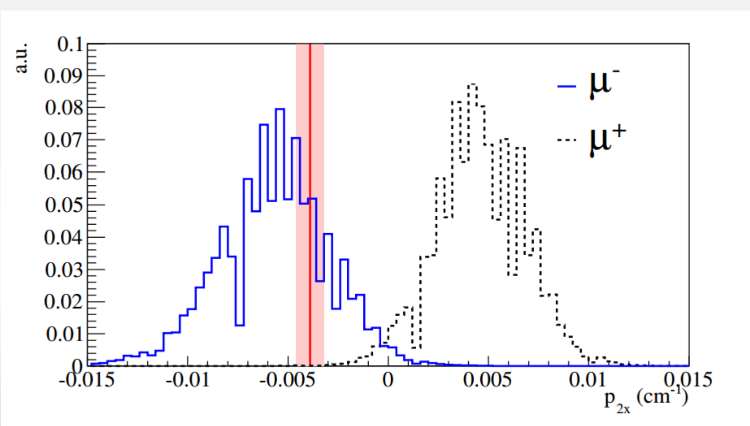
Il 3° candidato ($\tau \rightarrow \mu$)

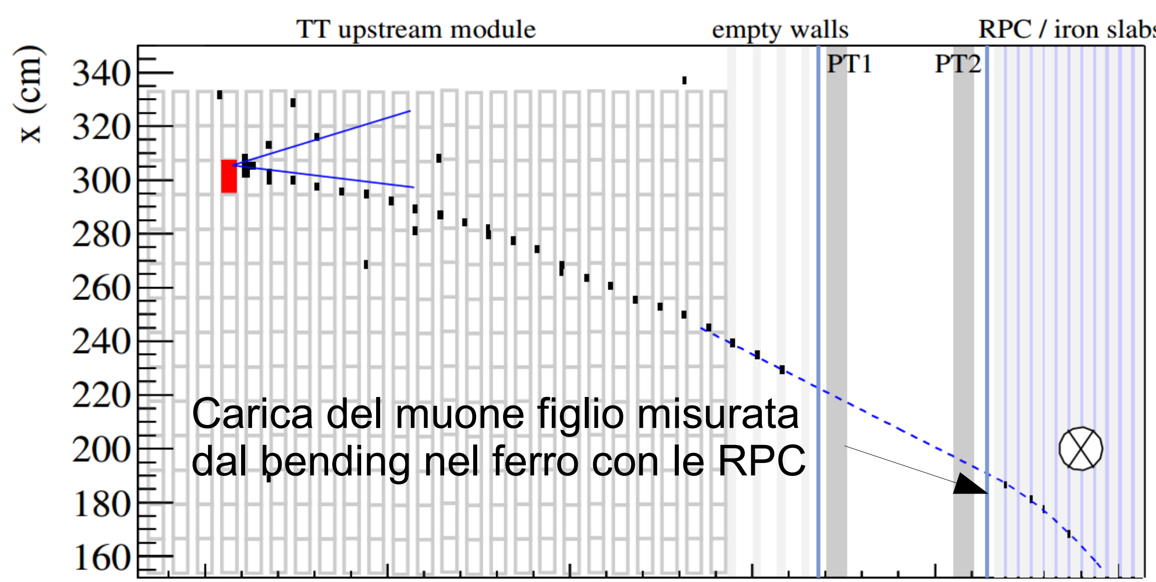
Phys. Rev. D 89 (2014) 051102(R)

Decadimento nella plastica

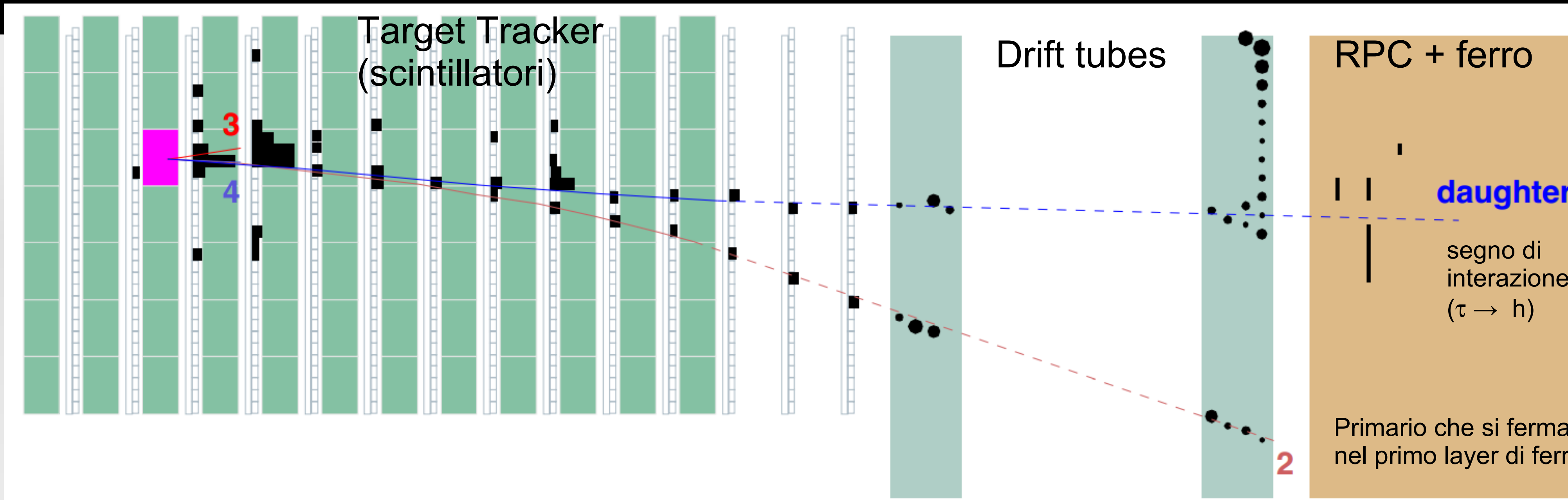


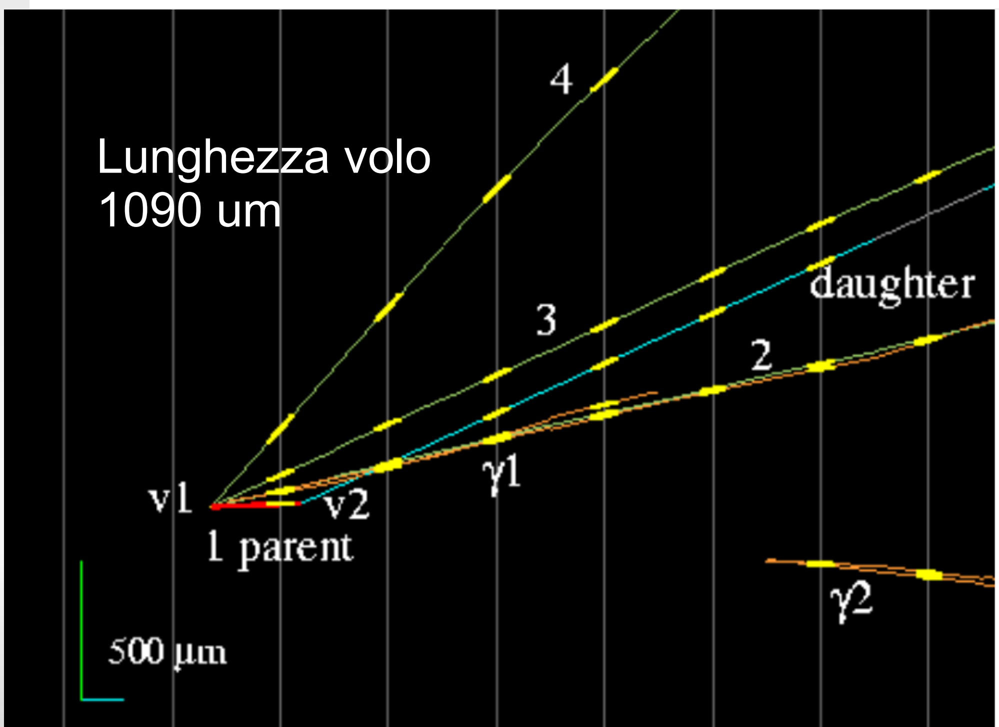


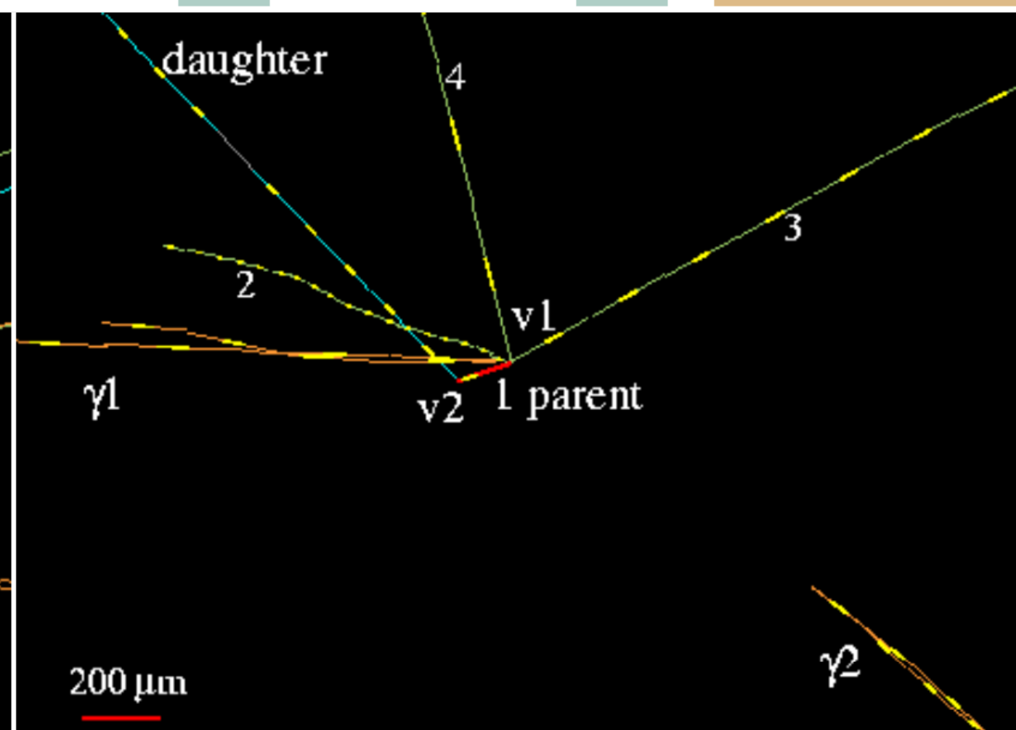




Il 4° candidato ($\tau \rightarrow 1h$, 25 Marzo 2014)







T2K

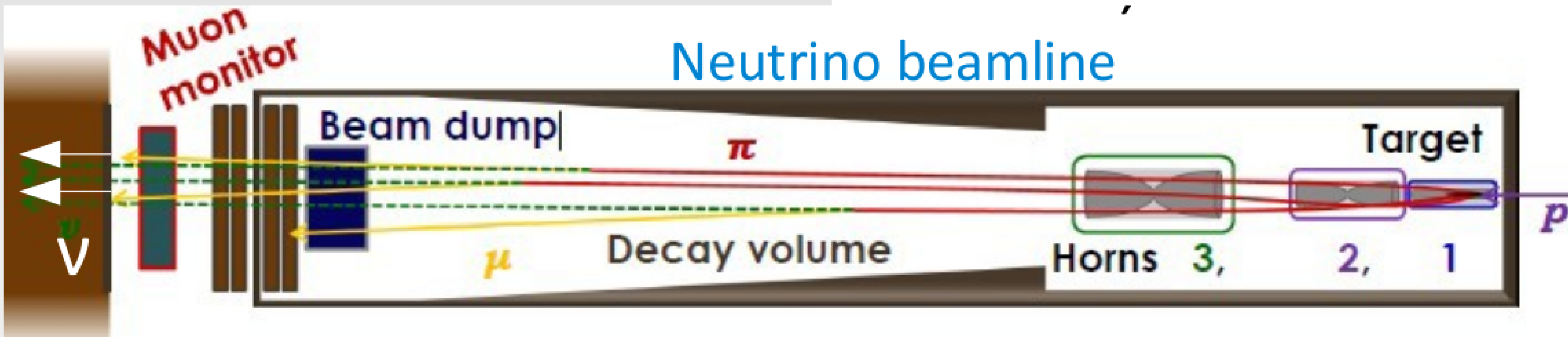
Ricerca di oscillazioni in un fascio di ν_μ

Apparizione di ν_e – sensibile a θ_{13} e δ_{CP}

Scomparsa di ν_μ – sensibile a θ_{23} e Δm^2_{23}

Inoltre: sezioni d'urto, ν sterili, effetti inattesi ?

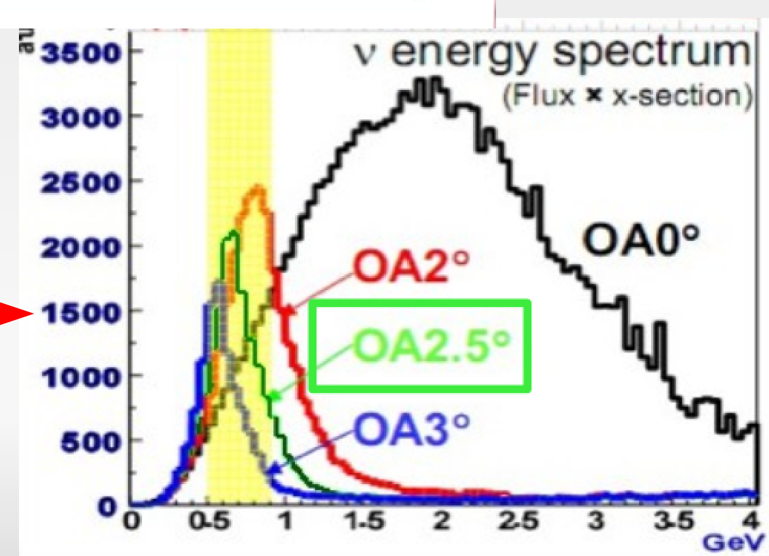
~ 500 membri, 59 istituti, 11 paesi



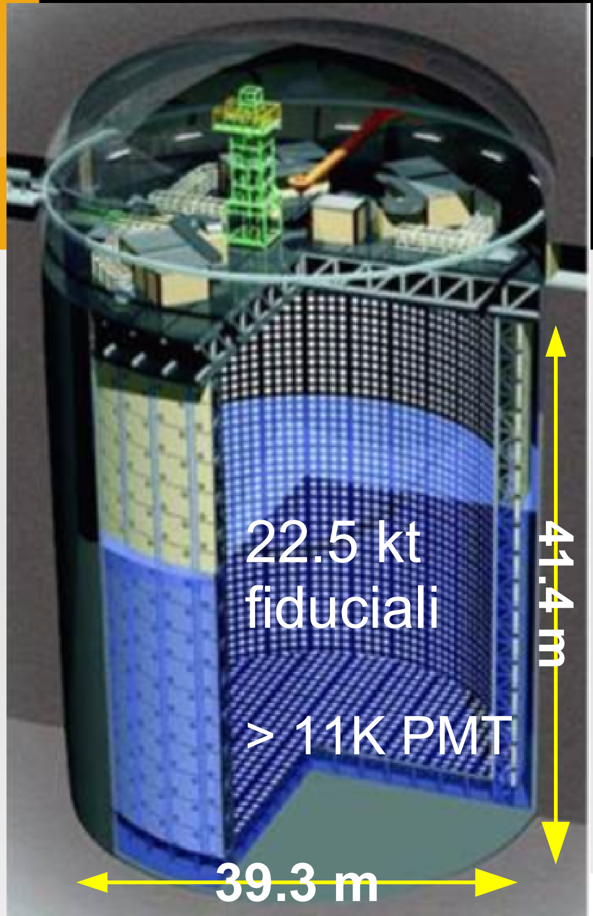
← **30 GeV**

Primo **fascio "off-axis"**

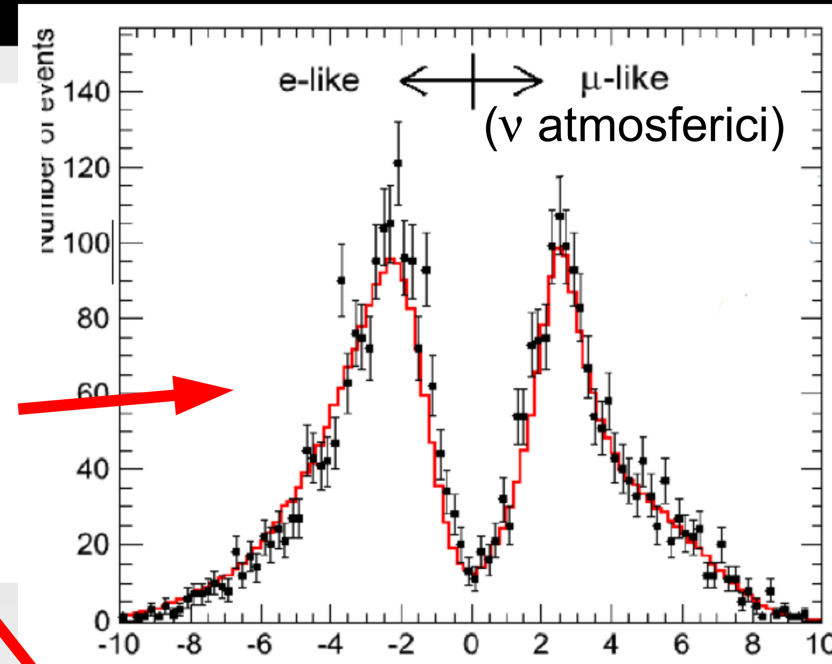
- 2.5° → picco a ~ 0.6 GeV
- Campione arricchito in interazioni quasi-elastiche (buona misura di E_ν)
- Ridotto fondo da ν_e intrinseci
- Ridotto fondo da NC π^0 (~ poco D.I.S.)
- Doppio rivelatore **a 280 m e 295 km**

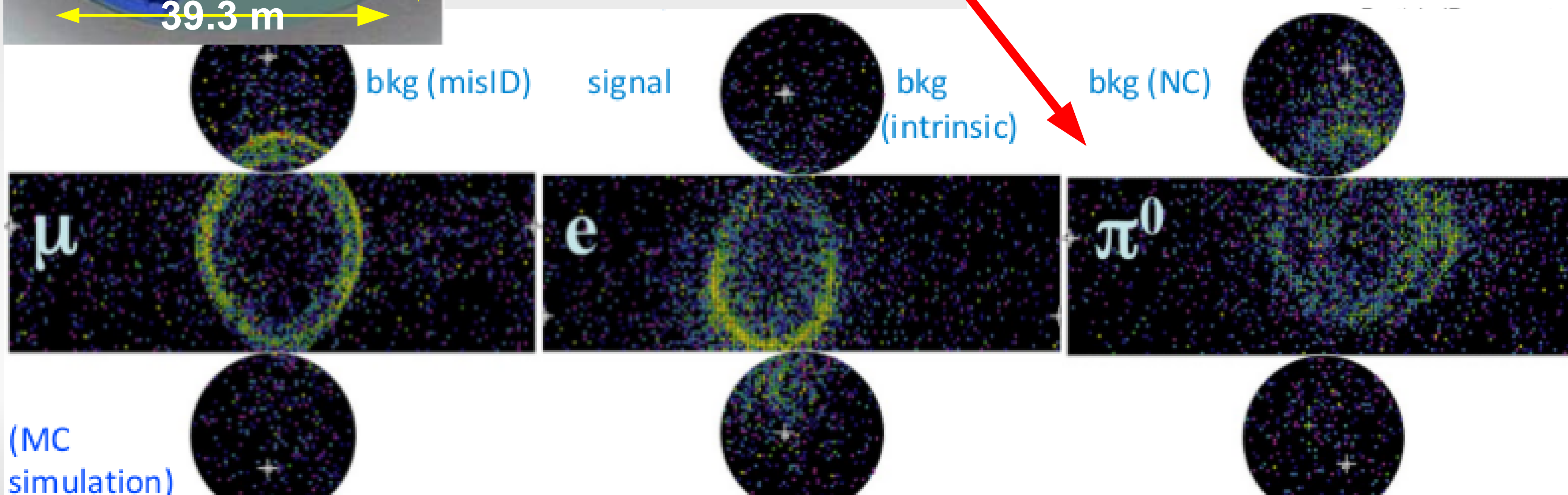


Il rivelatore a 295 km: Super-Kamiokande



- Water Cherenkov
  - ΔE/E ~10% per le interazioni quasi-elastiche (QE)
- Ottima separazione μ/e
- Rivelazione dei π^0
  - 2 anelli "*e*-like"





Apparizione dei ν_e

Phys. Rev. Lett. 112, 061802

Eventi attesi nel volume fiduciale:

Segnale $\nu_\mu \rightarrow \nu_e$: (20.4 ± 1.8)

(per $\sin^2 2\theta_{13} = 0.1$, $\sin^2 2\theta_{23} = 1.0$, $\delta_{CP}=0$, N.I.)

Fondo: (4.64 ± 0.53)

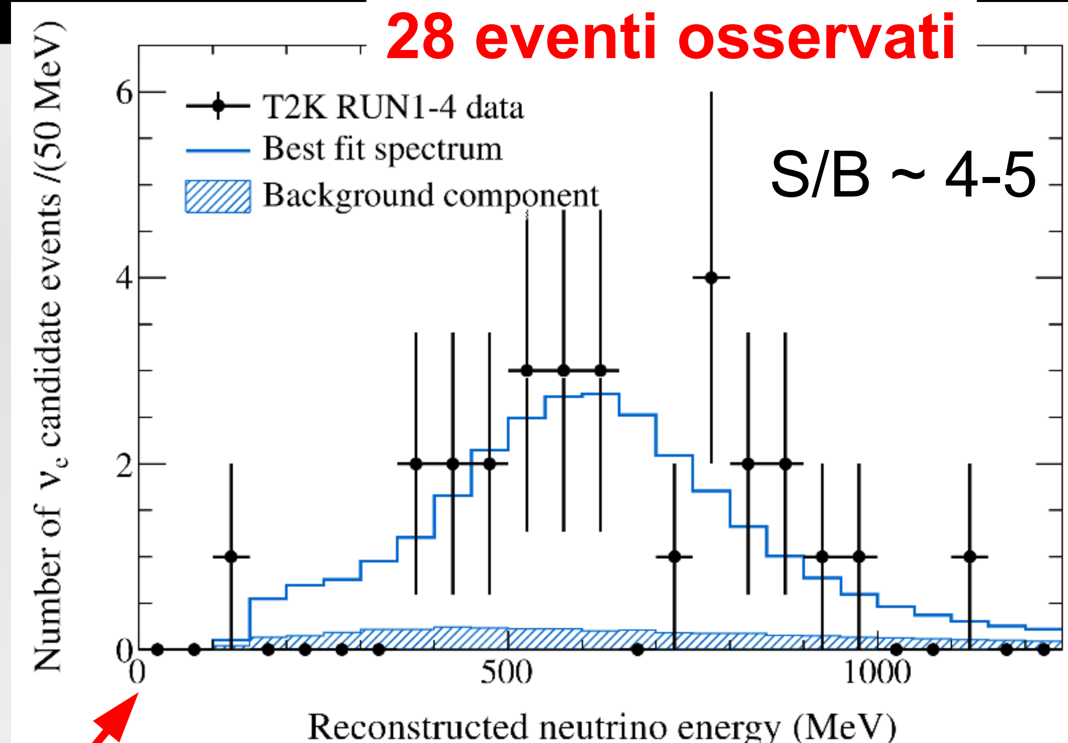
- **3.2 – contaminazione di ν_e nel fascio**
- **0.9 – da ν_μ NC con π^0 (rimosso il 70% del fondo non rigettato dall'analisi precedente)**
- 0.4 – ν_e (dal termine "solare")
- 0.3 – da anti-ν

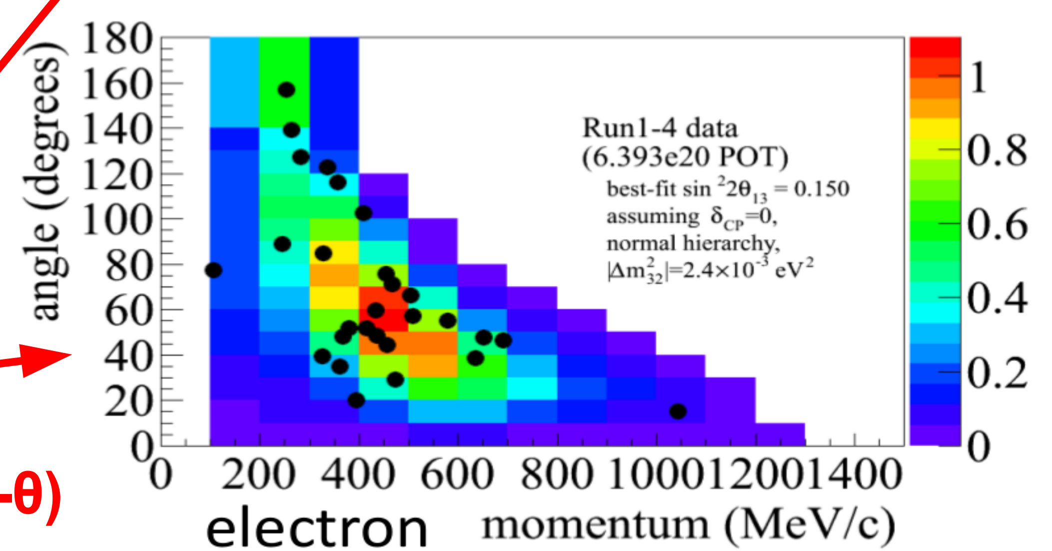
Esclusione attesa di $\{\theta_{13}= 0\}$: 5.5 σ

Due analisi indipendenti:

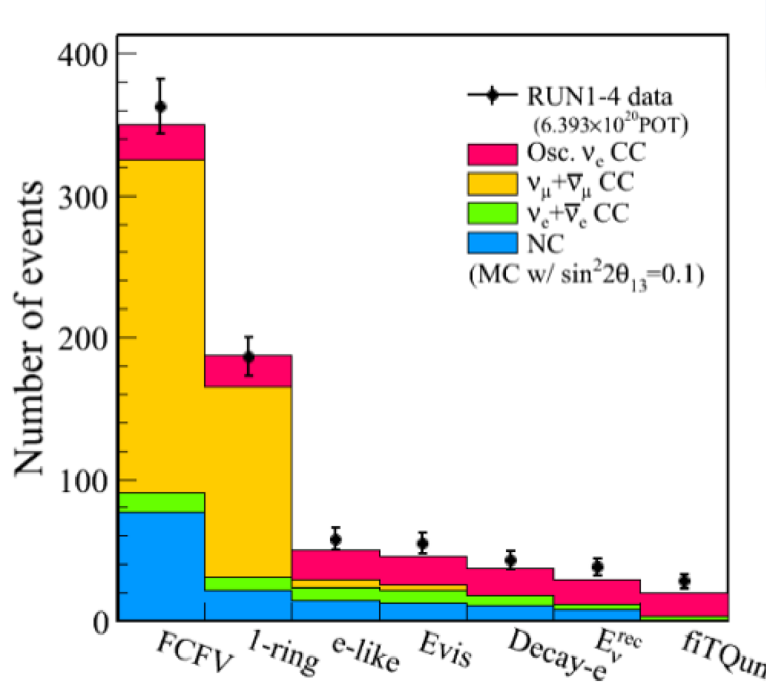
1) spettro dell'E ricostruita del ν_e

2) distribuzione in θ e p dell'e





Significanza di $7.5\ \sigma$ per $\theta_{13} \neq 0$ (p-θ)



Phys. Rev. Lett. 112, 061802

Apparizione dei ν_e: θ_{13} e δ_{CP}

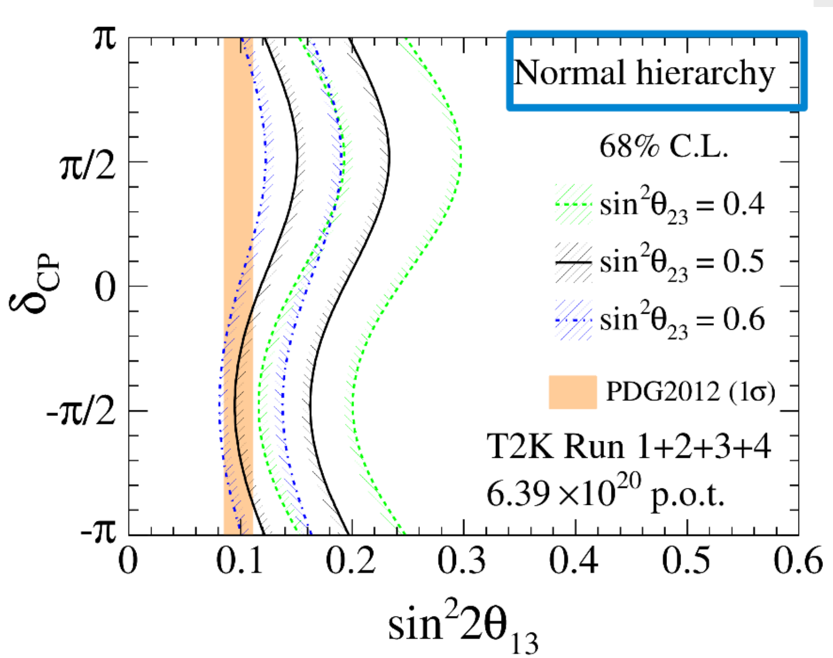
$$P_{\mu\to e} \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

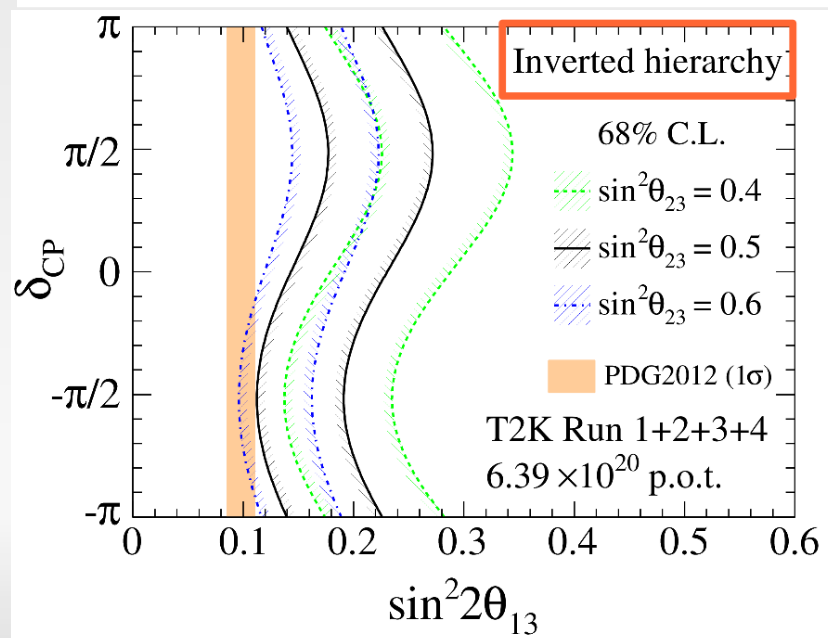
Dipendenza da θ_{23} asimmetrica rispetto $\pi/4$, sensitivita\` all' ottante

I reattori misurano un valore centrale minore: θ_{23} nel 2° ottante e $\delta_{CP} \sim -\pi/2$ leggermente favoriti

Gerarchia normale best fit: **0.150**
@ 90% CL: **$0.097 < \sin^2 2\theta_{13} < 0.218$**

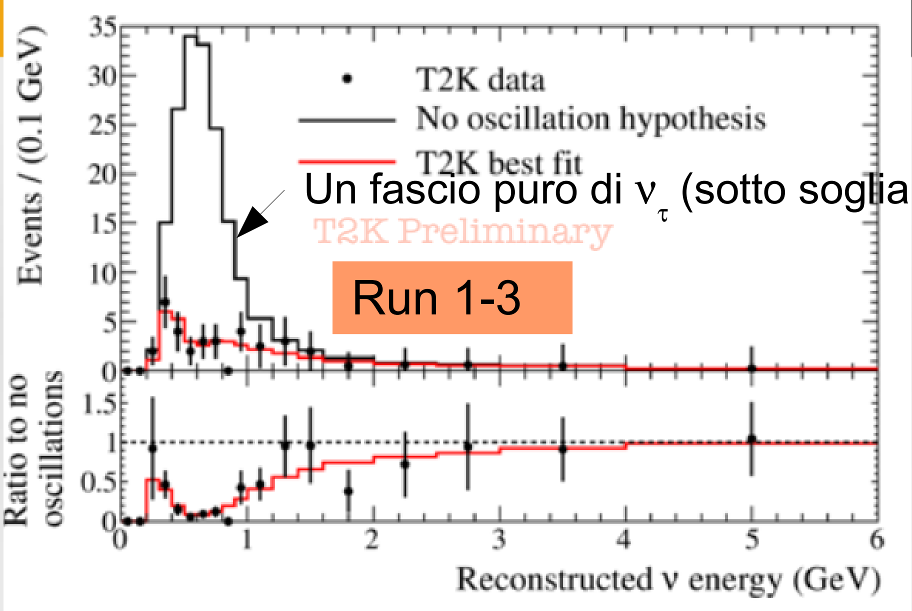
Gerarchia inversa, best fit **0.182**
@ 90% CL: **$0.118 < \sin^2 2\theta_{13} < 0.261$**

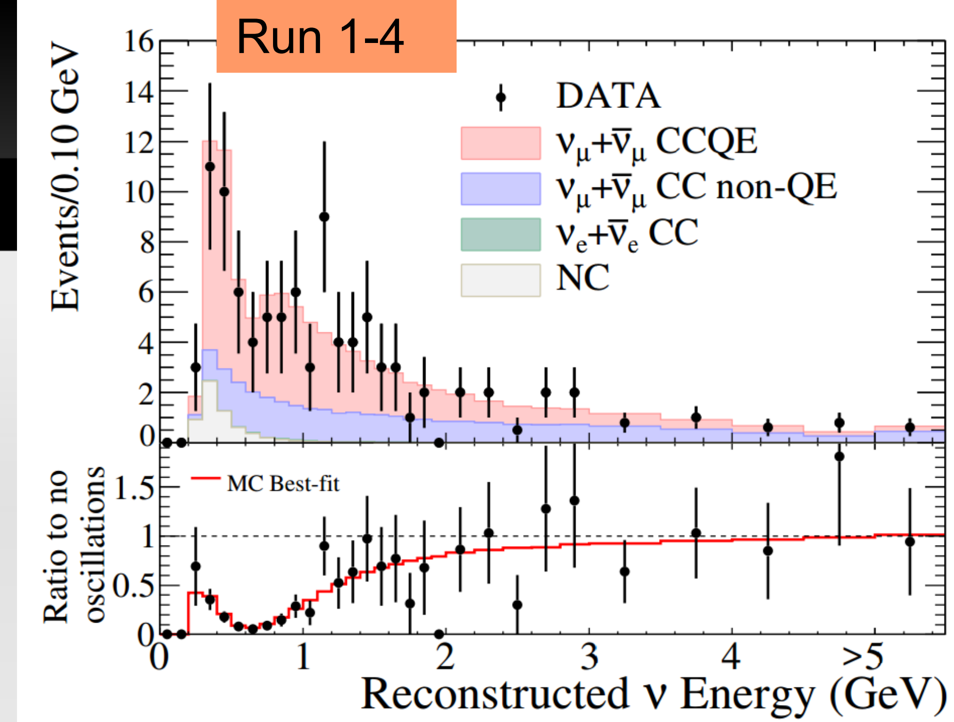




Scomparsa dei ν_μ

hep-ex/1403.1532





$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\frac{\Delta m^2_{32} L}{4E}$$

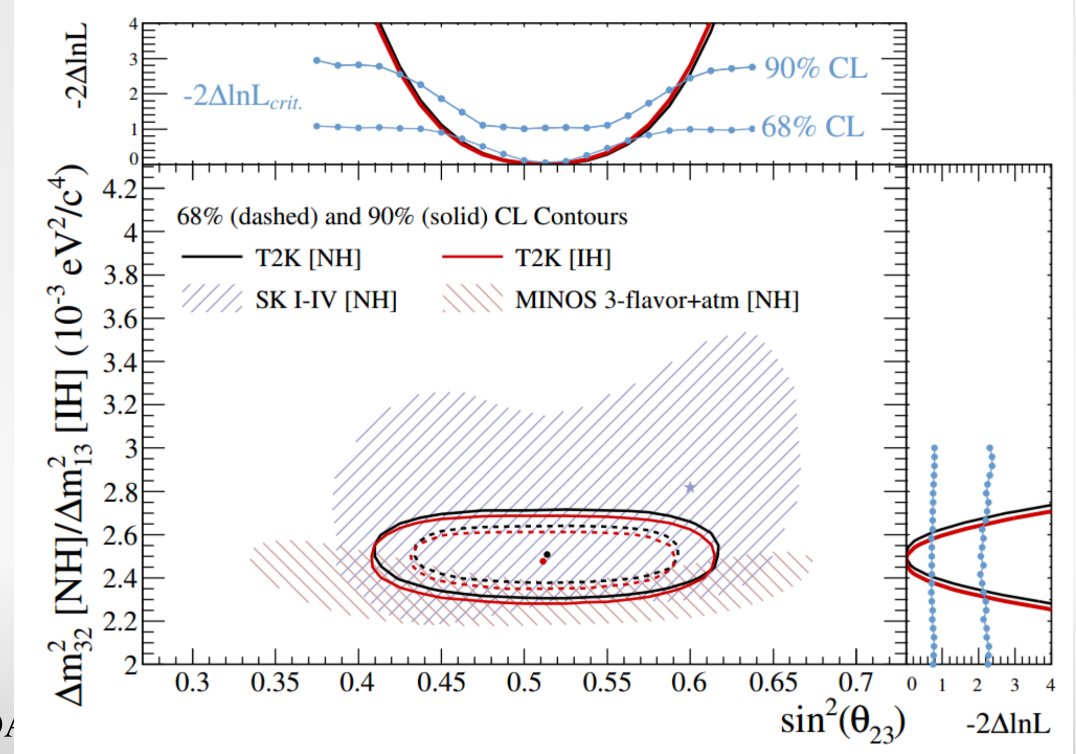
- Il primo fascio disegnato con una precisa determinazione del Δm^2 (soppressione massimale esattamente al picco!). **Attesi in assenza di osc. 446 ± 22.5 (sys.). Osservati 110.**
- Analisi a 3ν (dipendenza da θ_{23} non $\pi/4$ simmetrica nel termine subleading modulato da θ_{13})
- **Migliore misura mondiale di θ_{23}** (~11%)
- Δm^2 ci si sta avvicinando alle precisione di MINOS

Gerarchia normale — Inversa

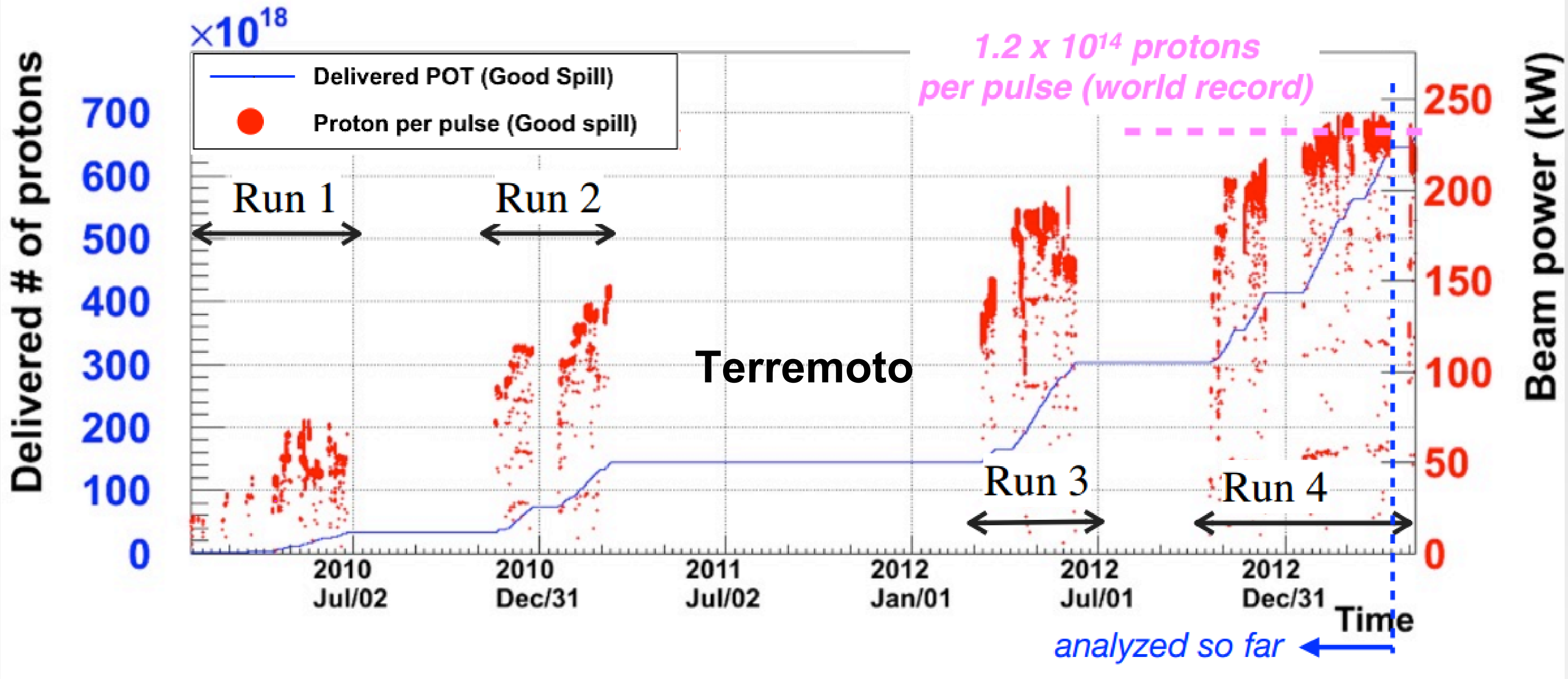
$$\sin^2(\theta_{23}) = 0.514^{+0.055}_{-0.056}\ (0.511 \pm 0.055)$$

$$\Delta m^2_{13} = 2.48 \pm 0.10 \times 10^{-3}\ \mathrm{eV}^2/c^4 \quad \text{inversa}$$

$$\Delta m^2_{32} = 2.51 \pm 0.10 \times 10^{-3}\ \mathrm{eV}^2/c^4 \quad \text{normale}$$



T2K: prospettive



J-PARC stabilmente a 220 kW per la maggior parte dell'ultimo run
$6.63 \cdot 10^{20}$ POT accumulati (8% del valore di disegno finale)

Prospettive: Run di anti-ν per migliorare la sensitivita` alla fase di CP entro l'estate. Analisi combinata di ν_μ e ν_e

Eur. Phys. J. C73 (2013) 2345
arXiv:1307.4699

Data sample and event rates

$\nu_\mu \to \nu_e$ con ICARUS

4 eventi osservati
(E < 30 GeV)

First result based on the analysis of 1091 ν events (3.3×10^{19} pot, 2010-2011 data, half the total statistic) published in Eur. Phys. J. C73 (2013).

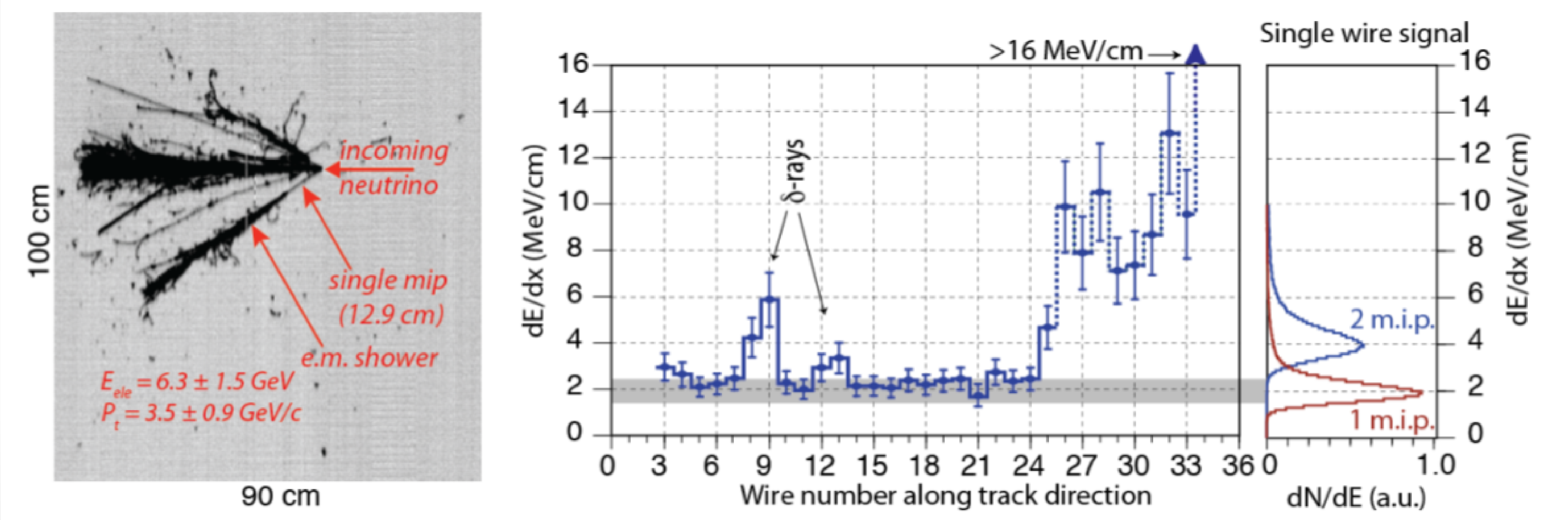
Analysis presented here refers to 1995 ν events (6.0×10^{19} pot)

Expected number of ν_e events:

- 5.7 ± 0.8, due to the intrinsic ν_e beam contamination,
- 2.3 ± 0.5, due to θ_{13} oscillations, $\sin^2(\theta_{13}) = 0.0242 \pm 0.0026$,
- 1.3 ± 0.1, from $\nu_\mu \to \nu_\tau$ oscillations with subsequent electron production, (3ν mixing).

Total: 9.3 ± 0.9 expected events.
Expected events, weighting for efficiency: 6.4 ± 0.9 events.

Esempio:



Slide: 14

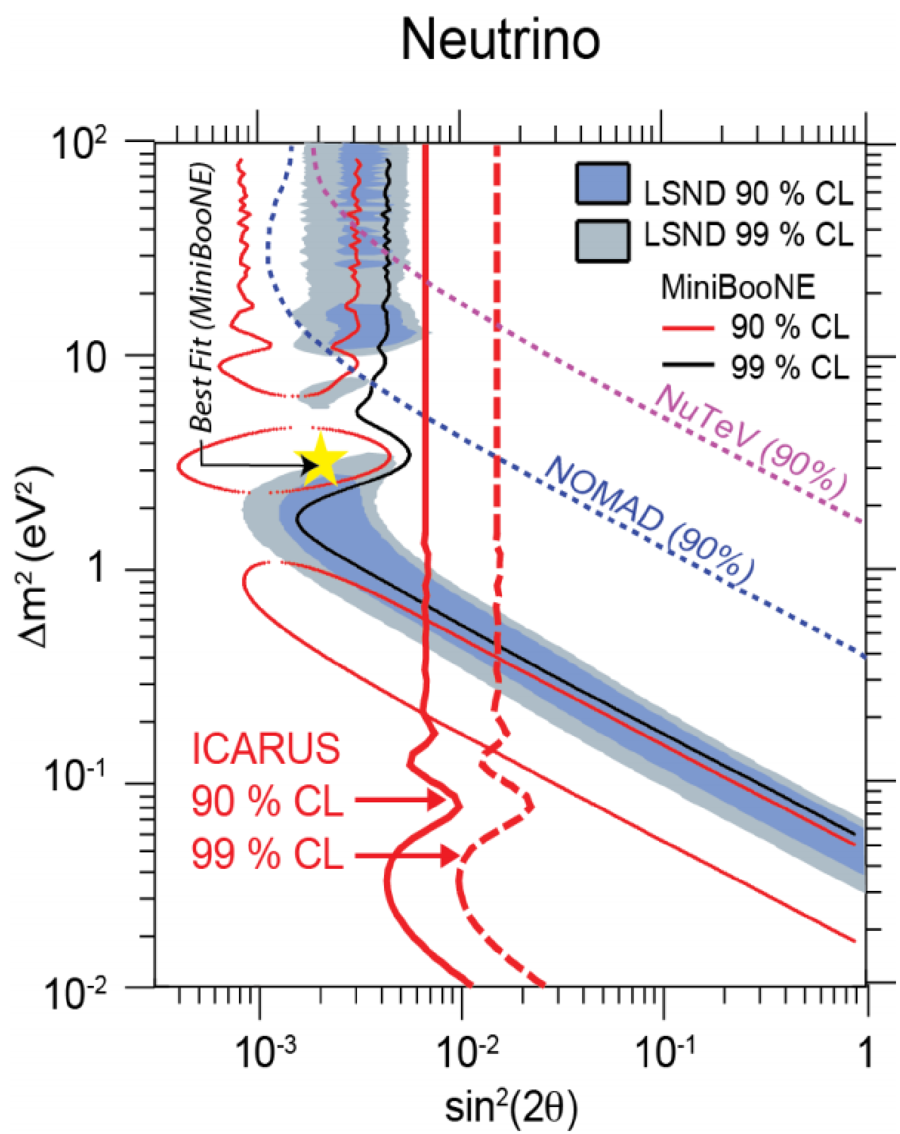
$\nu_\mu \rightarrow \nu_e$ esotica con ICARUS

ICARUS results on the LSND-anomaly search (double statistics)

Within the present observation, our results is consistent with the absence of the LSND anomaly.

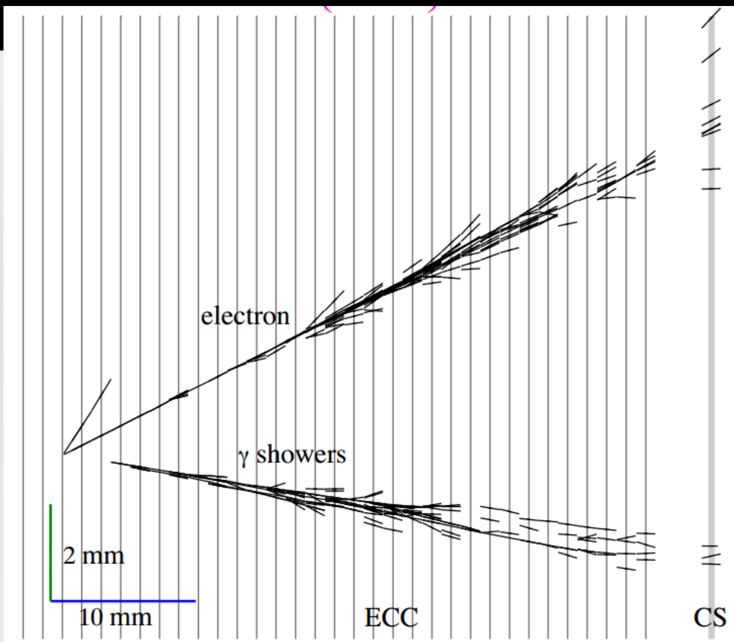
Weighting for efficiency, our limits on the number of events due to LSND anomaly are:
3.68 (90% CL) and
8.34 (99% CL).

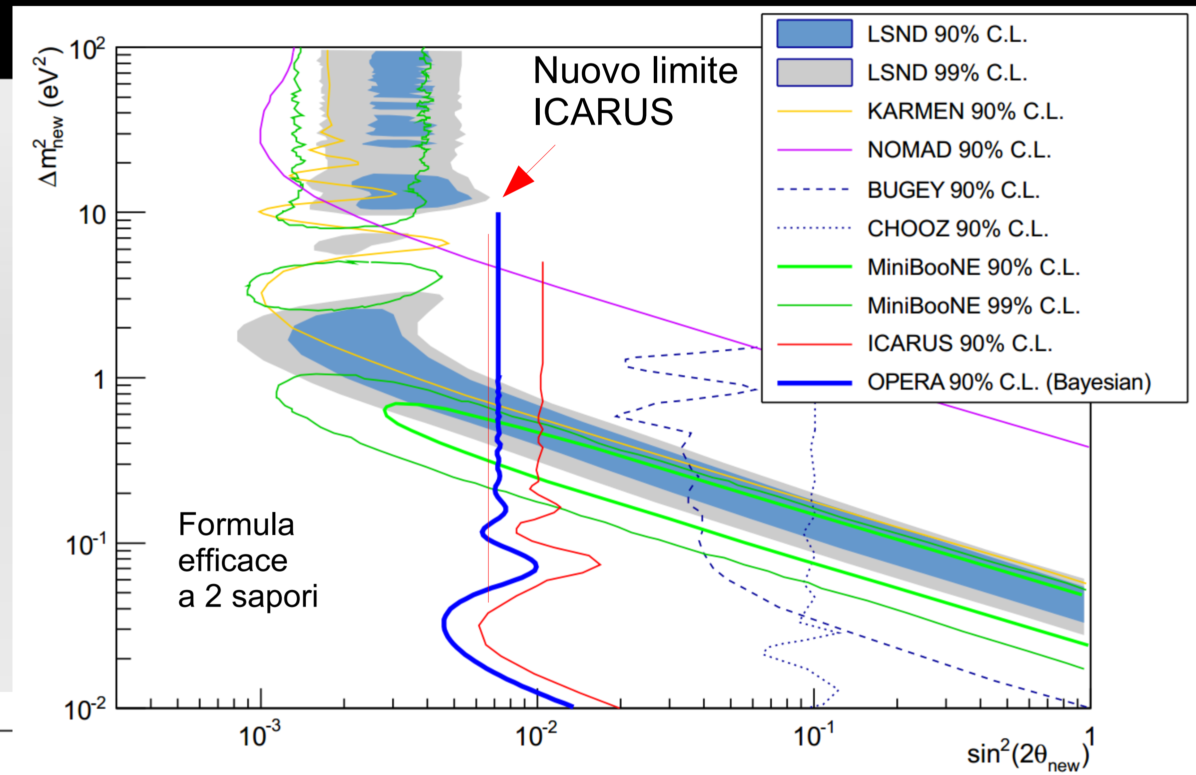
which give the limits on oscillation probabilities:
$P(\nu_\mu \rightarrow \nu_e) \leq 3.4 \times 10^{-3}$ (90% CL);
$P(\nu_\mu \rightarrow \nu_e) \leq 7.6 \times 10^{-3}$ (99% CL).

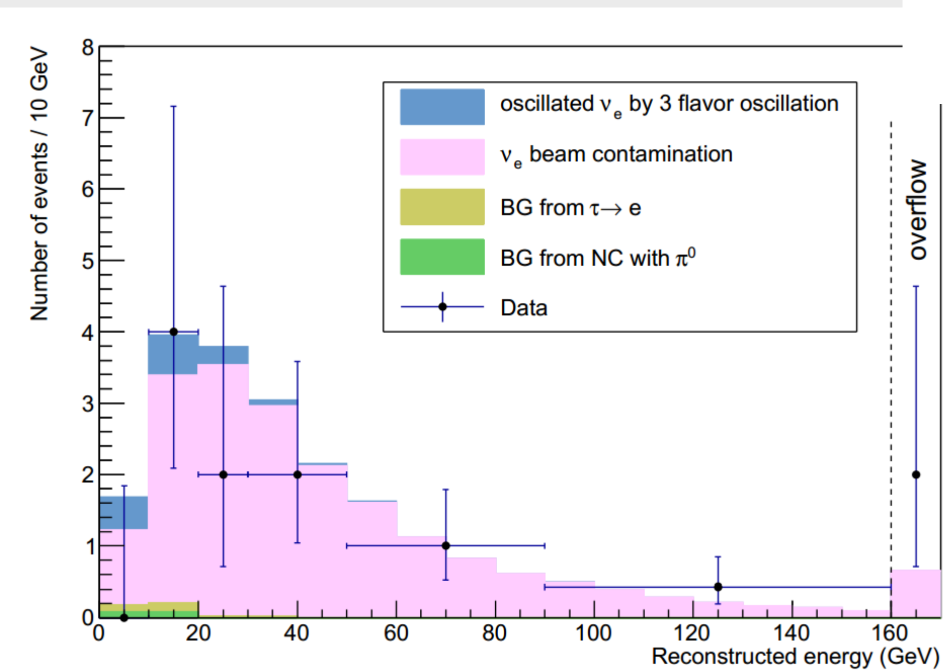


$\nu_\mu \rightarrow \nu_e$ con OPERA

JHEP 1307 (2013) 004, arXiv:1303.3953







505 interazioni senza muoni identificati (~ meta` della statistica finale)

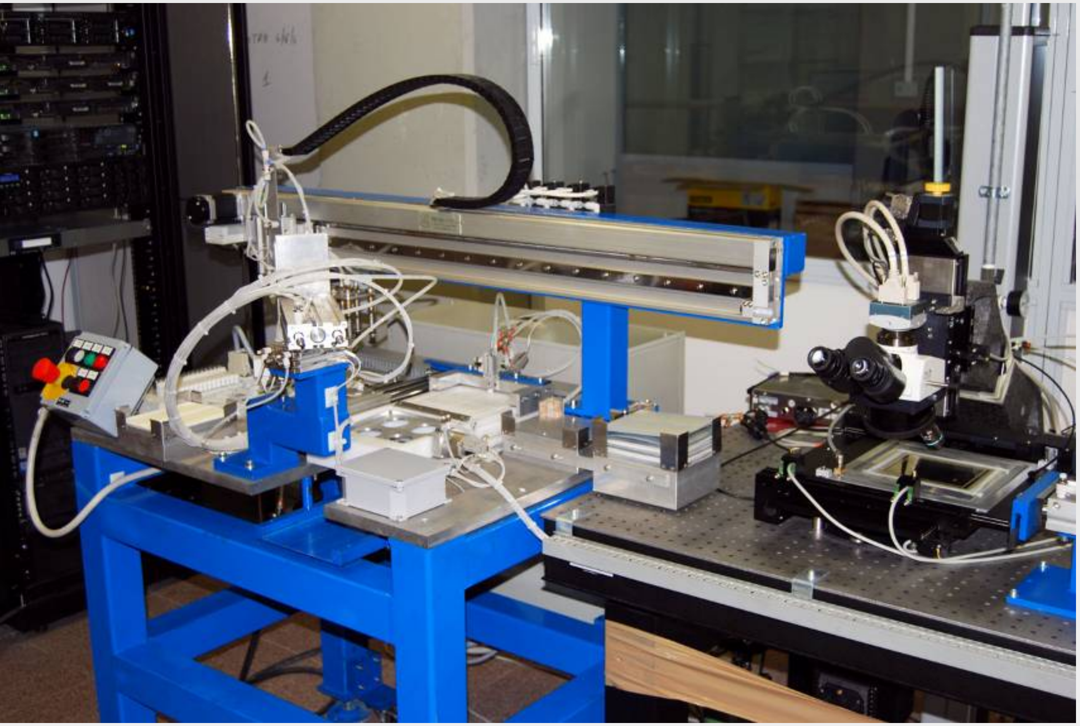
		E < 20 GeV
Candidati ν_e	19	4
Fondo atteso	19.8 ± 2.8 (sys.)	4.6

$\sin^2 2\theta_{NEW} < 7.2 \times 10^{-3}$ (90% CL)

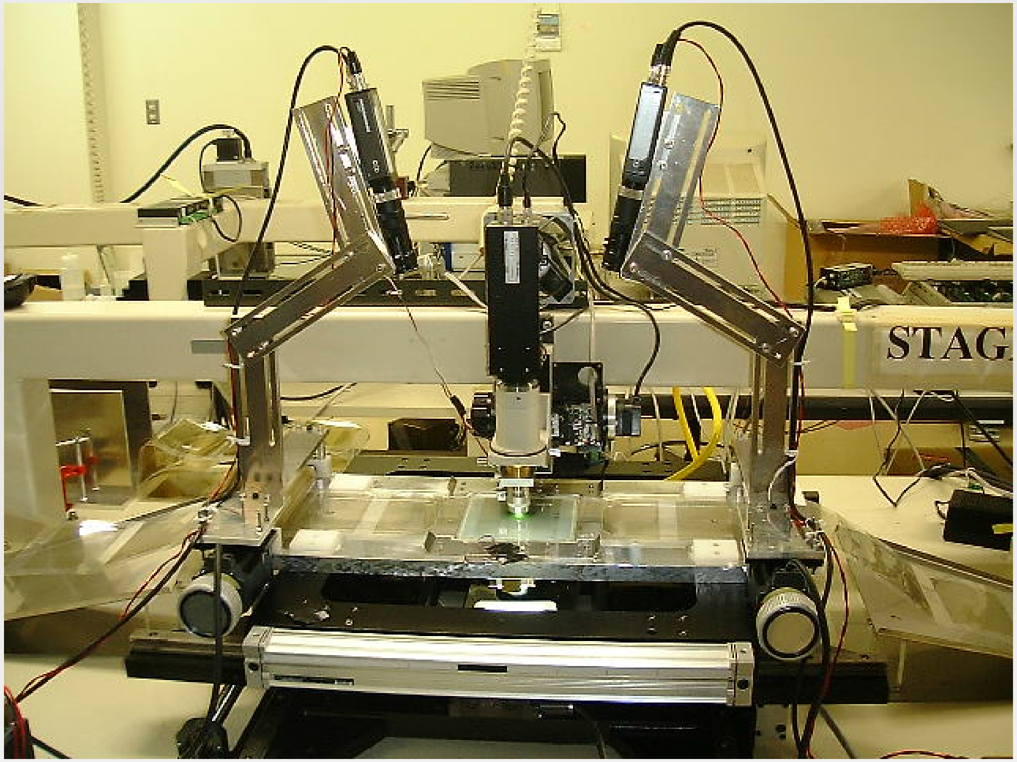
$\sin^2 2\theta_{13} < 0.44$ (90% CL)

Auxiliary systems to automate the scan-back procedure

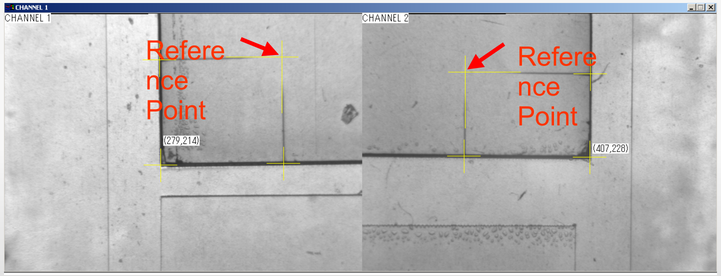
Europe: mechanical plate changer

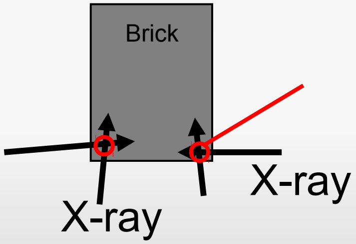


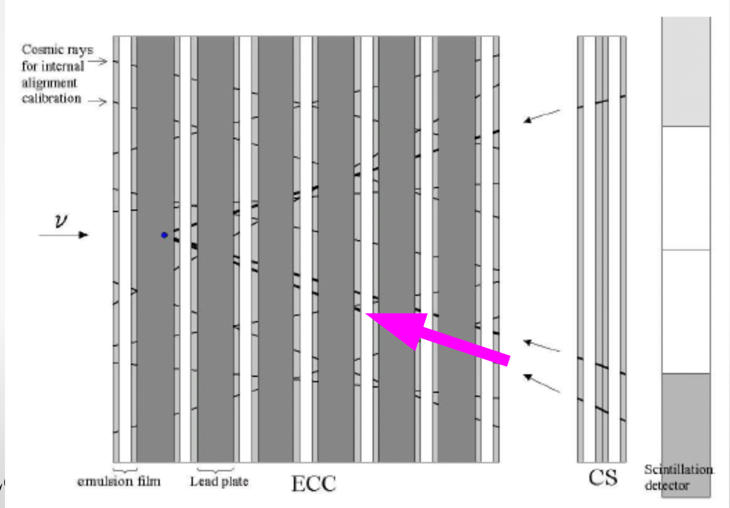
Japan- emulsion glued to a rolling strip



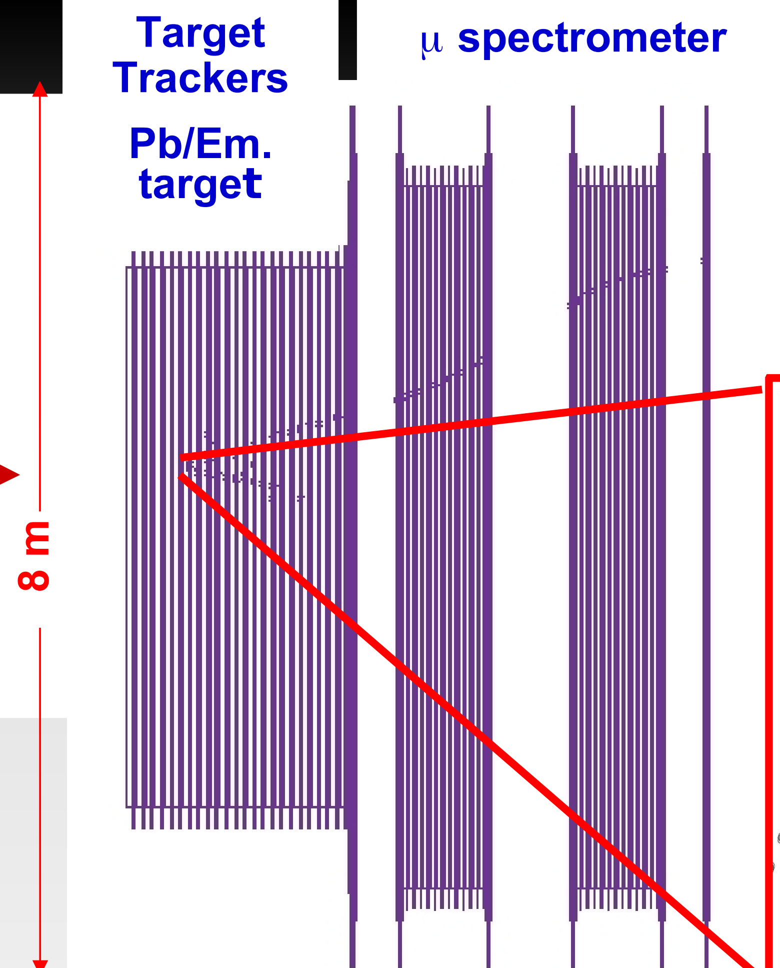
Allows to run the scan-back procedure without human intervention (i.e. overnight)





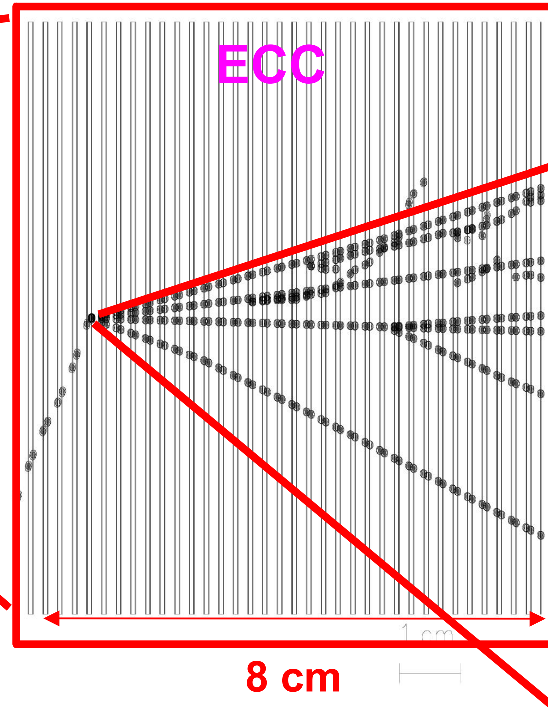


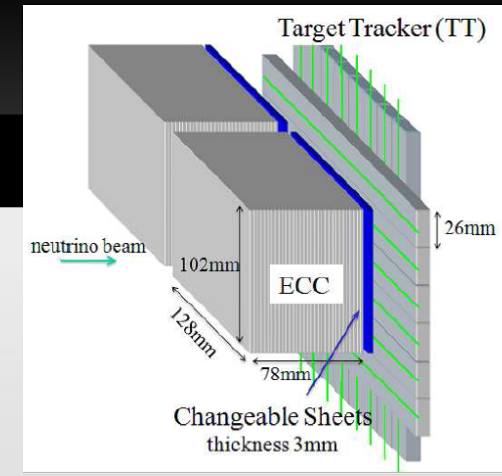
The OPERA way

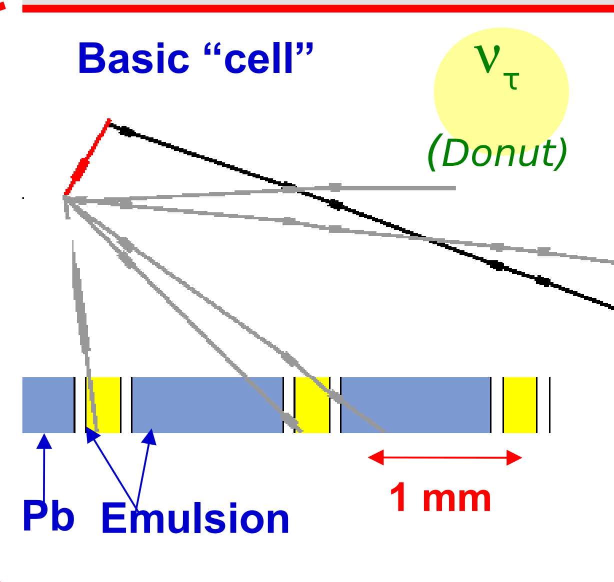


Extract bricks according to electronic det. prediction

Pb/Em. brick







A “hybrid” detector

Electronic detectors

detect ν interaction, brick finding

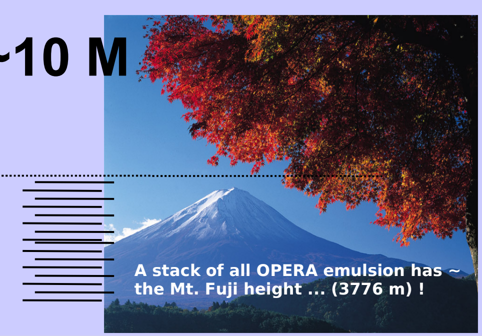
μ-ID, Q and p : bckg suppression

based on the only **proven technology** (DONUT) to identify ν_τ on an event-by-event basis (**nucl.emuls.&lead driven by real time detectors**). A **major engineering achievement:** brought such technology to an **immense size (1.25 kton)**

Emulsion detectors:

modular structure of 150000 ECCs
mass industrial production with high standards
FAST-AUTOMATIC scanning
vertex search, decay search, e/μ ID, event kinematics

~10 M

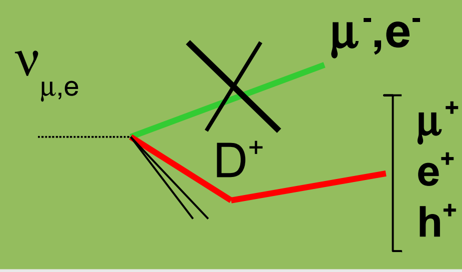


Caratterizzazione dei fondi

Simulazione Monte Carlo coadiuvata da campioni di controllo.

Per importanza decrescente

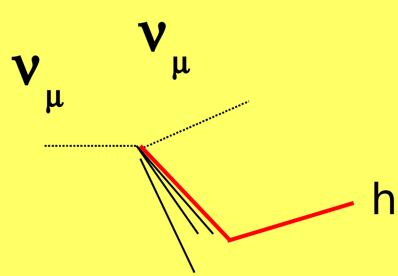
CC con produzione di charm (tutti i canali)
SE leptone primario non identificato e carica del figlio non misurata



Misure di CHORUS, campione di eventi di charm al CNGS

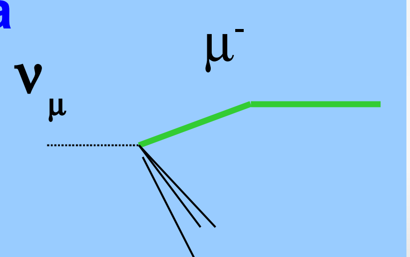
Interazioni adroniche

Fondo per $\tau \rightarrow h$



FLUKA + dati da test beam di brick esposti a pioni

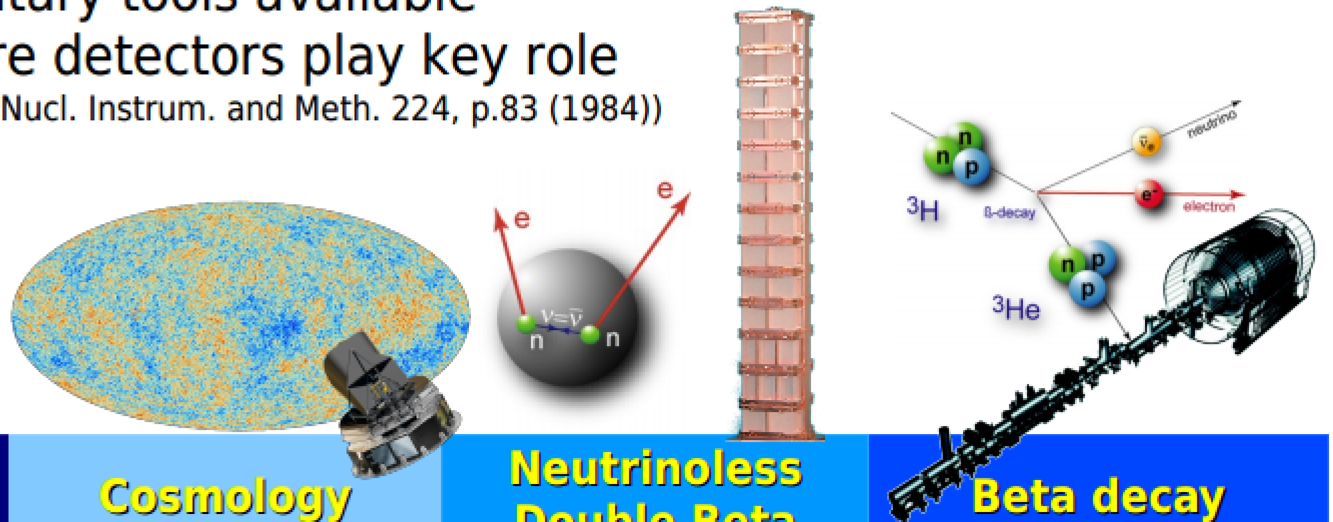
Diffusione Coulombiana ad alto angolo dei μ nel Pb
Fondo al $\tau \rightarrow \mu$



Misure in letteratura sul fattore di forma del Pb, simulazioni e test-beam dedicati (in corso)

Experimental tools / 1

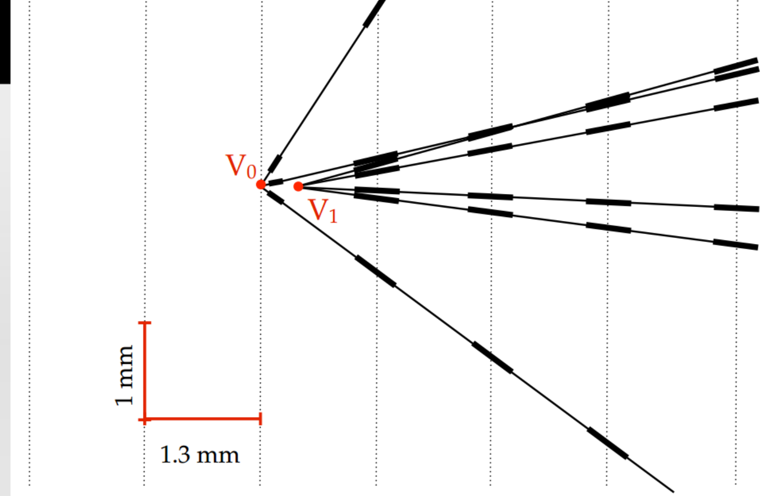
three complementary tools available
→ low temperature detectors play key role
(E. Fiorini and T. Niinikoski, Nucl. Instrum. and Meth. 224, p.83 (1984))

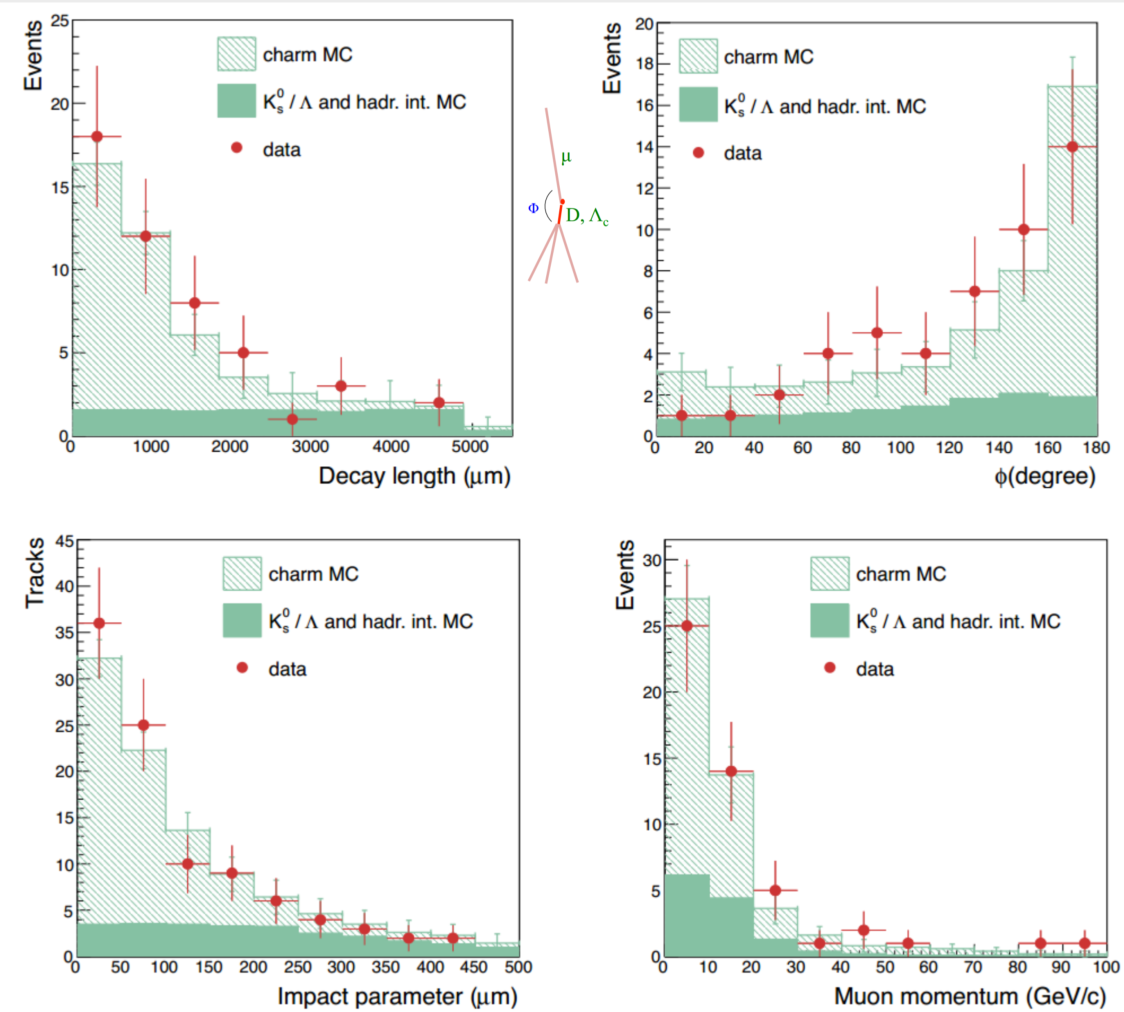


tool	Cosmology CMB+LSS+...	Neutrinoless Double Beta decay	Beta decay end-point
observable	$m_\Sigma=\Sigma_k m_{\nu_k}$	$m_{\beta\beta}=\lvert\Sigma_k m_{\nu_k} U_{ek}^2\rvert$	$m_\beta=(\Sigma_k m_{\nu_k}^2 \lvert U_{ek}\rvert^2)^{1/2}$
present sensitivity	≈0.1 eV	≈0.1 eV	2 eV
future sensitivity	**0.01 eV**	**0.01 eV**	**0.2 eV**
model dependency	yes ☹	yes ☹	no ☺
systematics	large ☹	yes 😐	large ☹

OPERA: validazione Monte Carlo su campioni di controllo

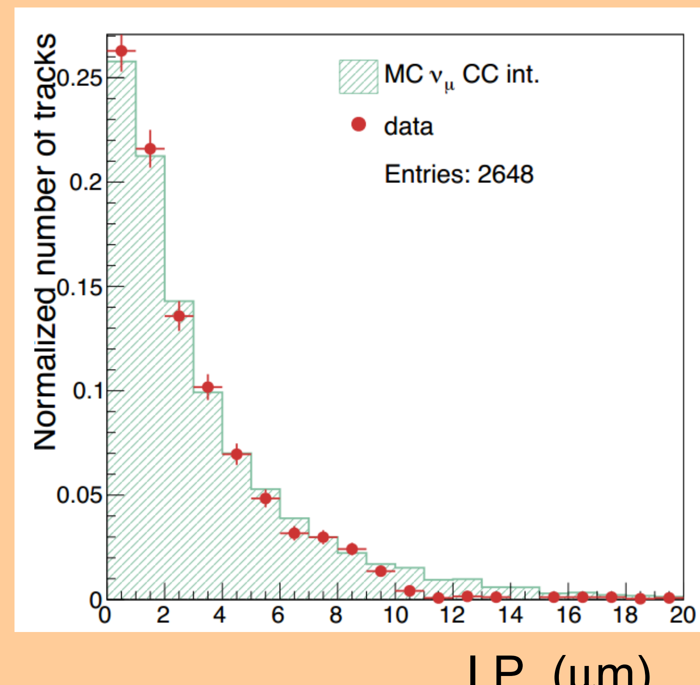
Charm: topologicamente simile ai decadimenti dei τ





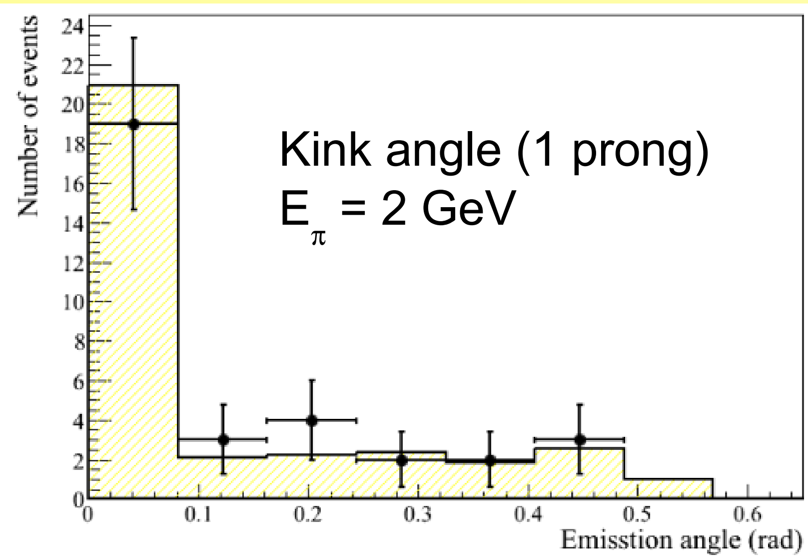
Controllo efficienze, descrizione delle variabili cinematiche, fondo da charm.

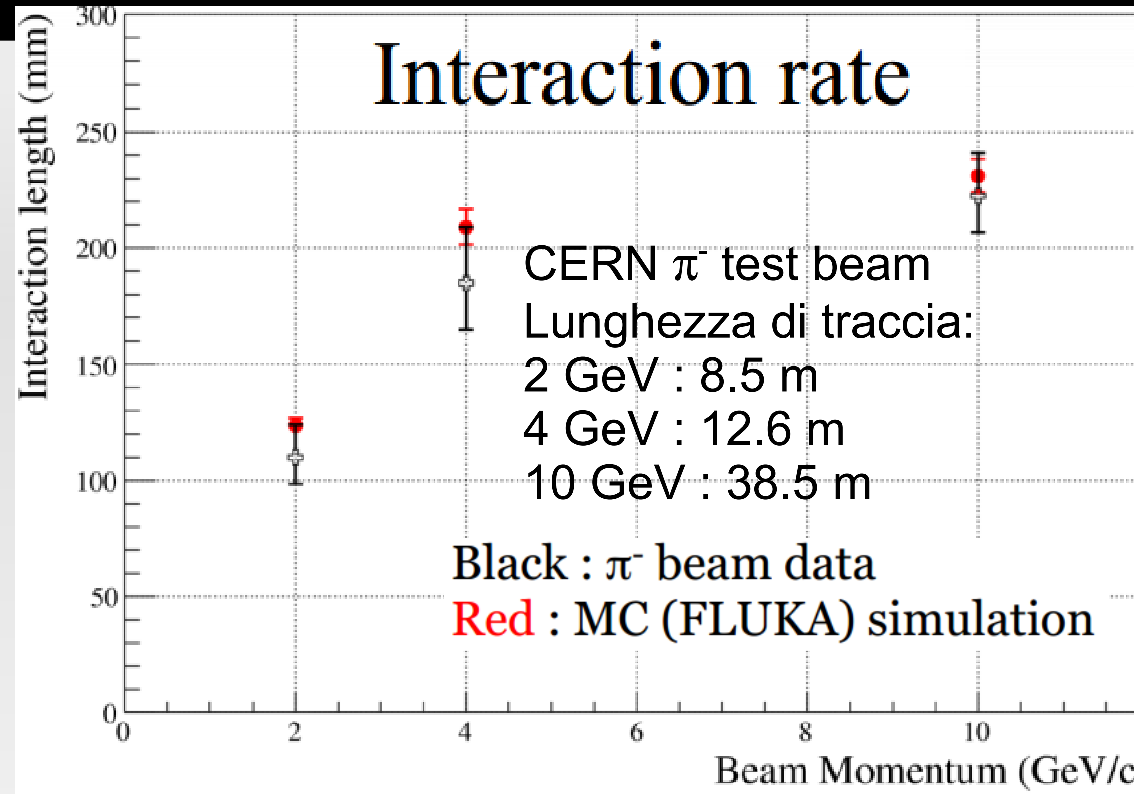
Data-MC per il parametro d'impatto delle tracce in eventi ν_μCC

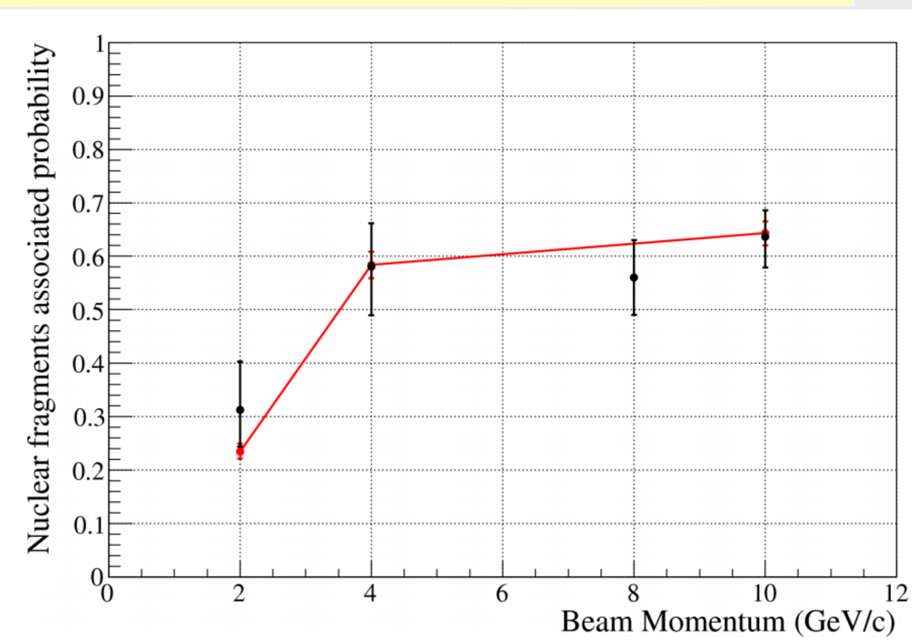


54 ± 4 attesi ↔ 50 osservati

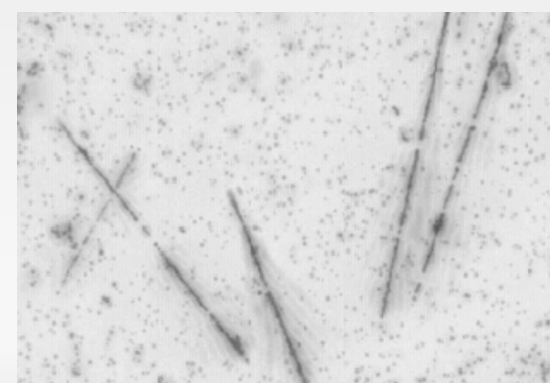
OPERA: validazione fondo adronico





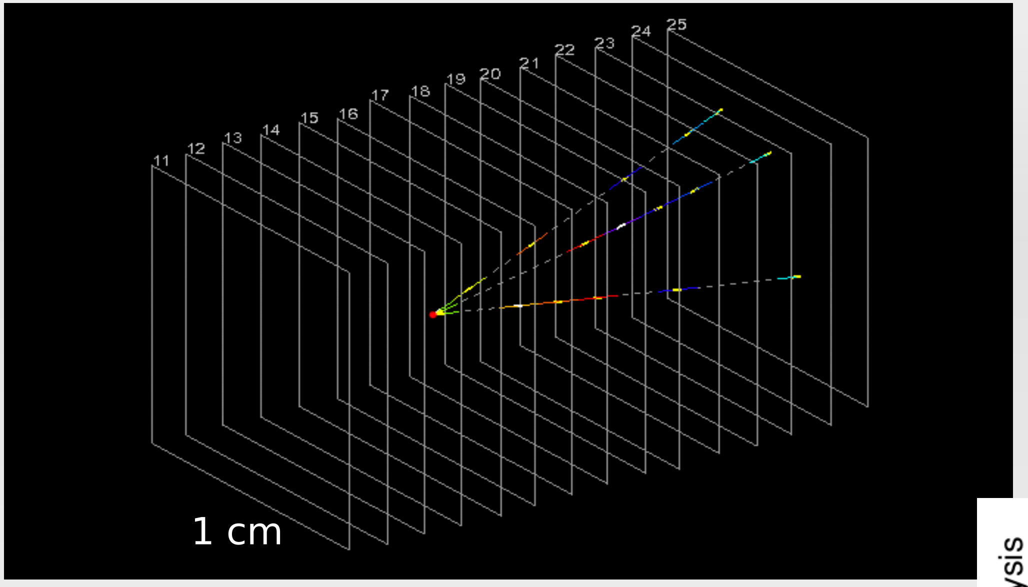


Probabilita` di emissione di frammenti nucleari (smoking gun per distinguere un'interazione da un decadimento!)



Efficienza di localizzazione

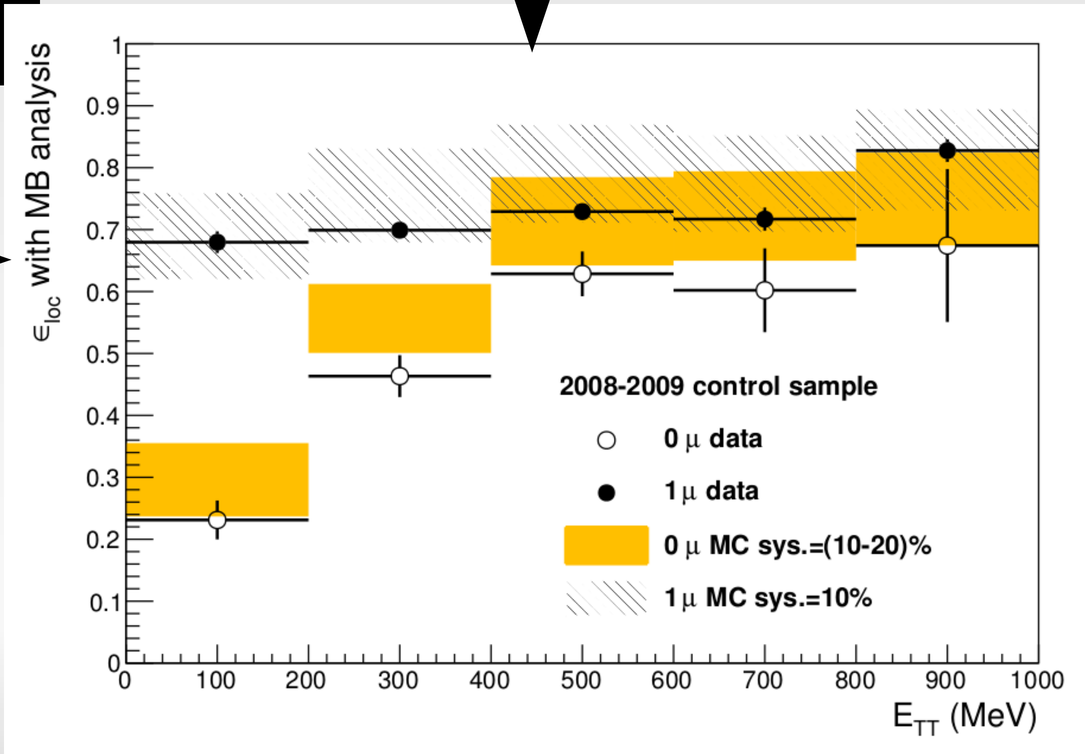
JHEP 11 (2013) 036



Confronto dati-Monte Carlo per l'efficienza di localizzazione in funzione dell'energia nel target tracker per il campioni 0μ e 1μ.

Rivelatore ibrido: simulazione complessa! Ragionevole accordo.

Le predizioni per segnale e fondi sono normalizzati ai campioni 0μ e 1μ osservati nei dati e non sulle efficienze della simulazione.



Il fascio CNGS per l'“appearance”

$< E_\nu >$	***17 GeV***
$L / < E_\nu >$	***43 km/GeV***

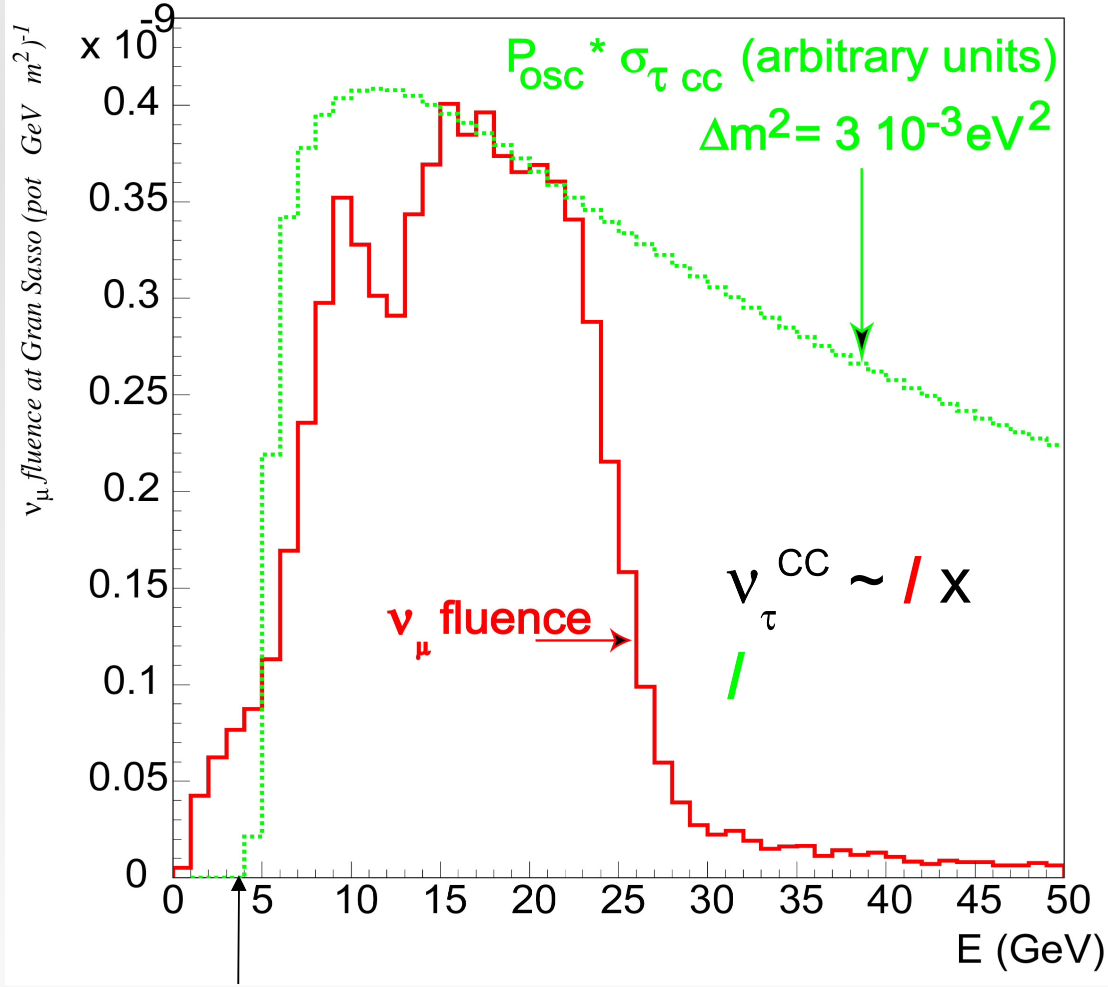
Il picco di oscillazione per L= 732 km cade a ~ 1.5 GeV (vedi NuMI) ma il goal e' la produzione di τ
→ sbilanciamento a energie piu' alte

$$N(\tau) \sim Pr(\nu_\mu \rightarrow \nu_\tau) \times \sigma_{\nu(\tau)CC}(E) \times flux$$

$(\nu_e+\bar{\nu}_e) / \nu_\mu$	**0.9 %**
$\bar{\nu}_\mu / \nu_\mu$	**2.1 %**
ν_τ prompt (da D_s)	**trascurabili**

(simulazione FLUKA)

DESIGN: $4.5 \cdot 10^{19}$ pot/year, 200 days/y per 5 y



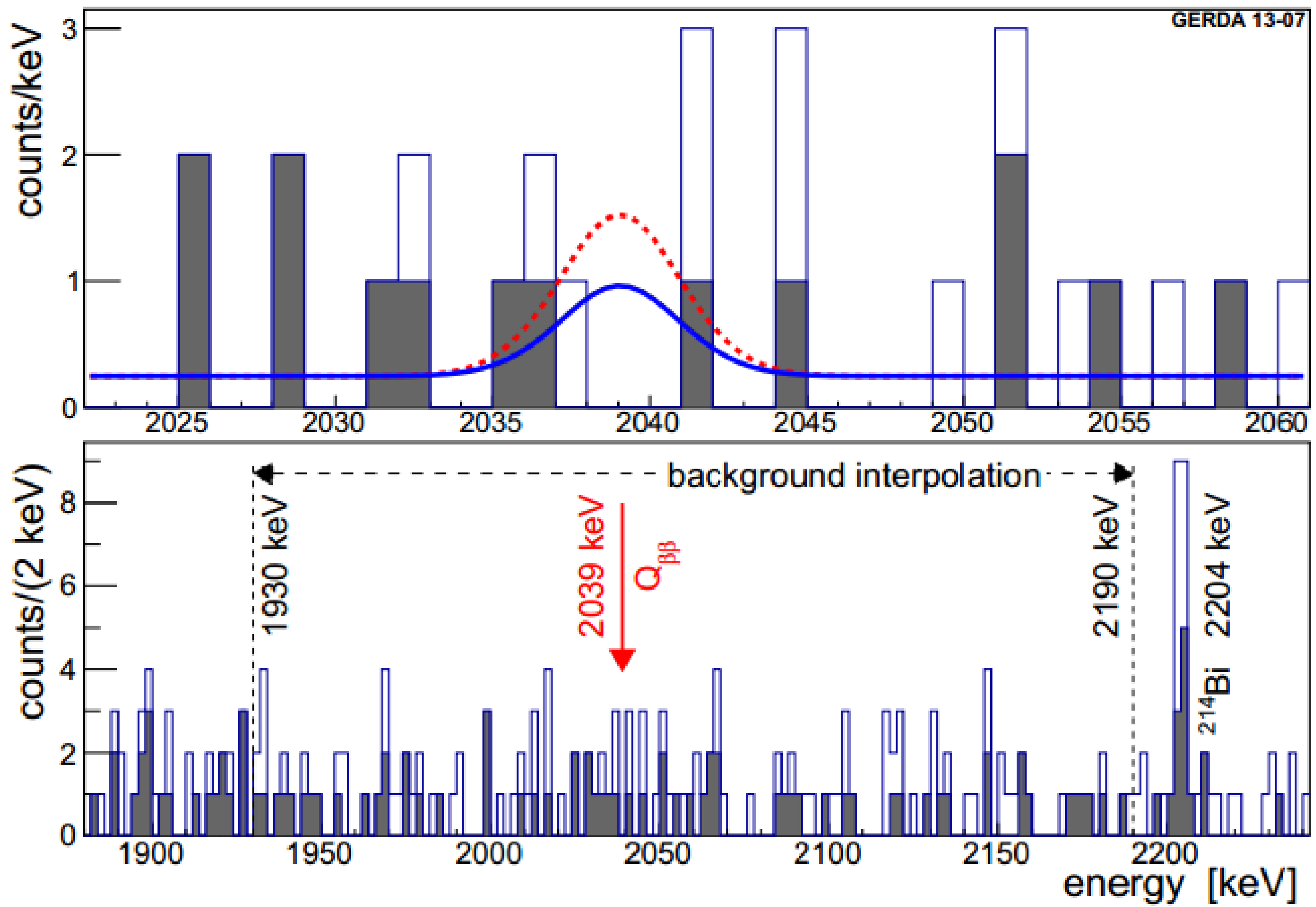
Soglia produzione τ a ~ 3.5 GeV.
Salita lenta.

The GERDA experiment on ^{76}Ge $0\nu\beta\beta$

Running at LNGS

Charge deposition in high purity Germanium crystals enriched in the 76Ge isotope

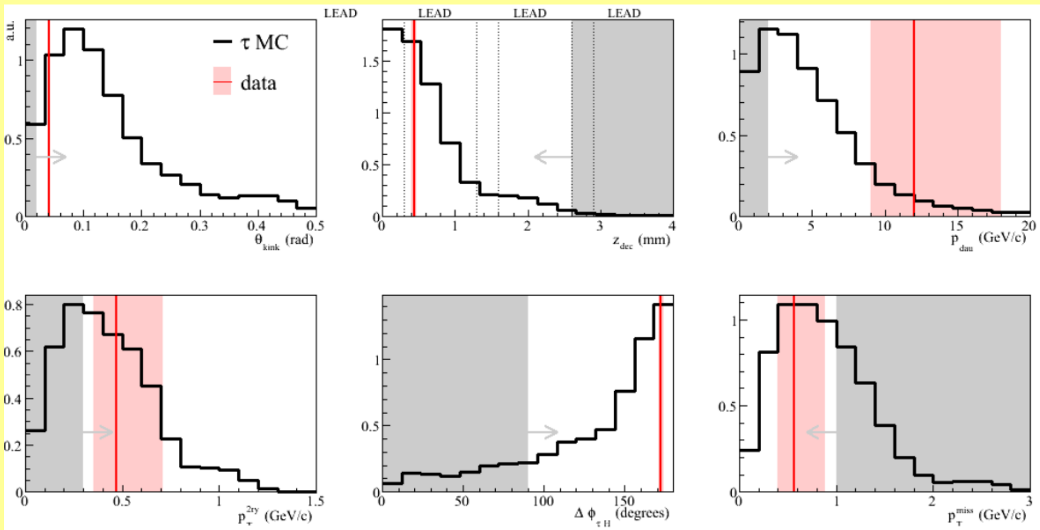
The GERDA experiment on ^{76}Ge $0\nu\beta\beta$



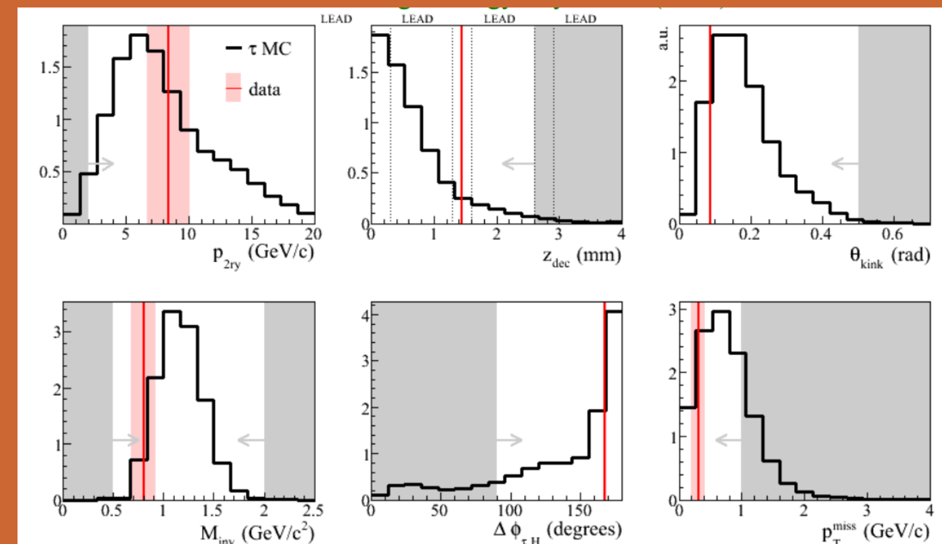
$$T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}\ \text{yr} \quad (90\,\%\ \ \text{C.L.})$$

Variabili cinematiche per i quattro candidati

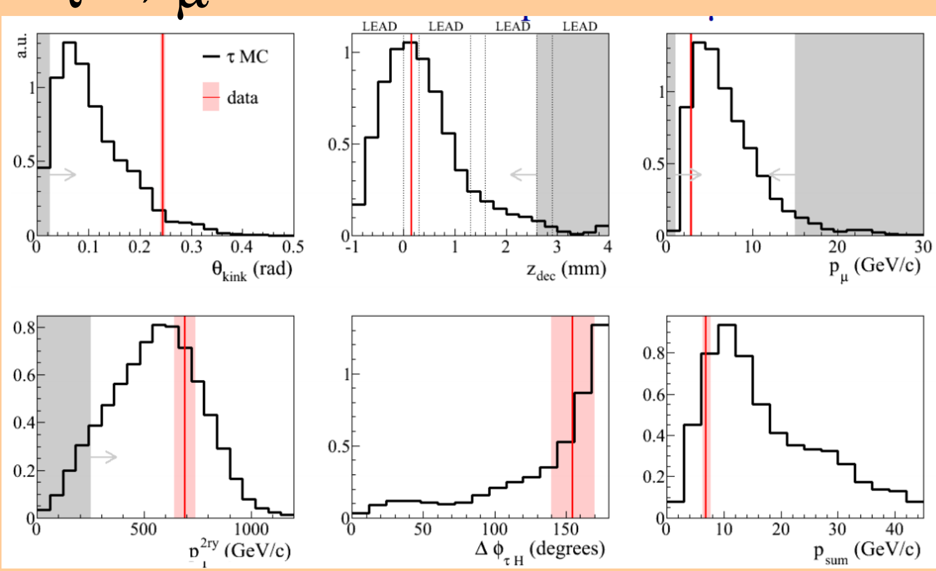
$\tau \rightarrow 1h$



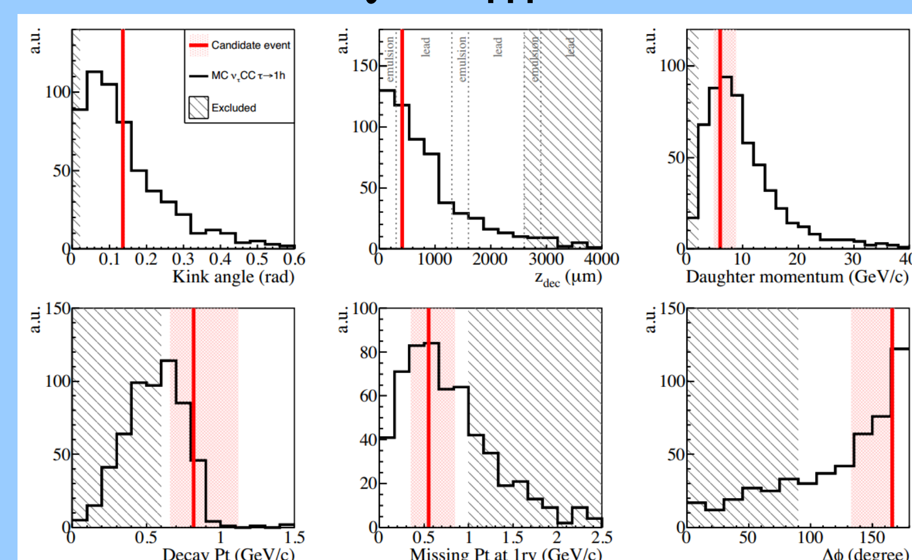
$\tau \rightarrow 3h$



$\tau \rightarrow \mu$

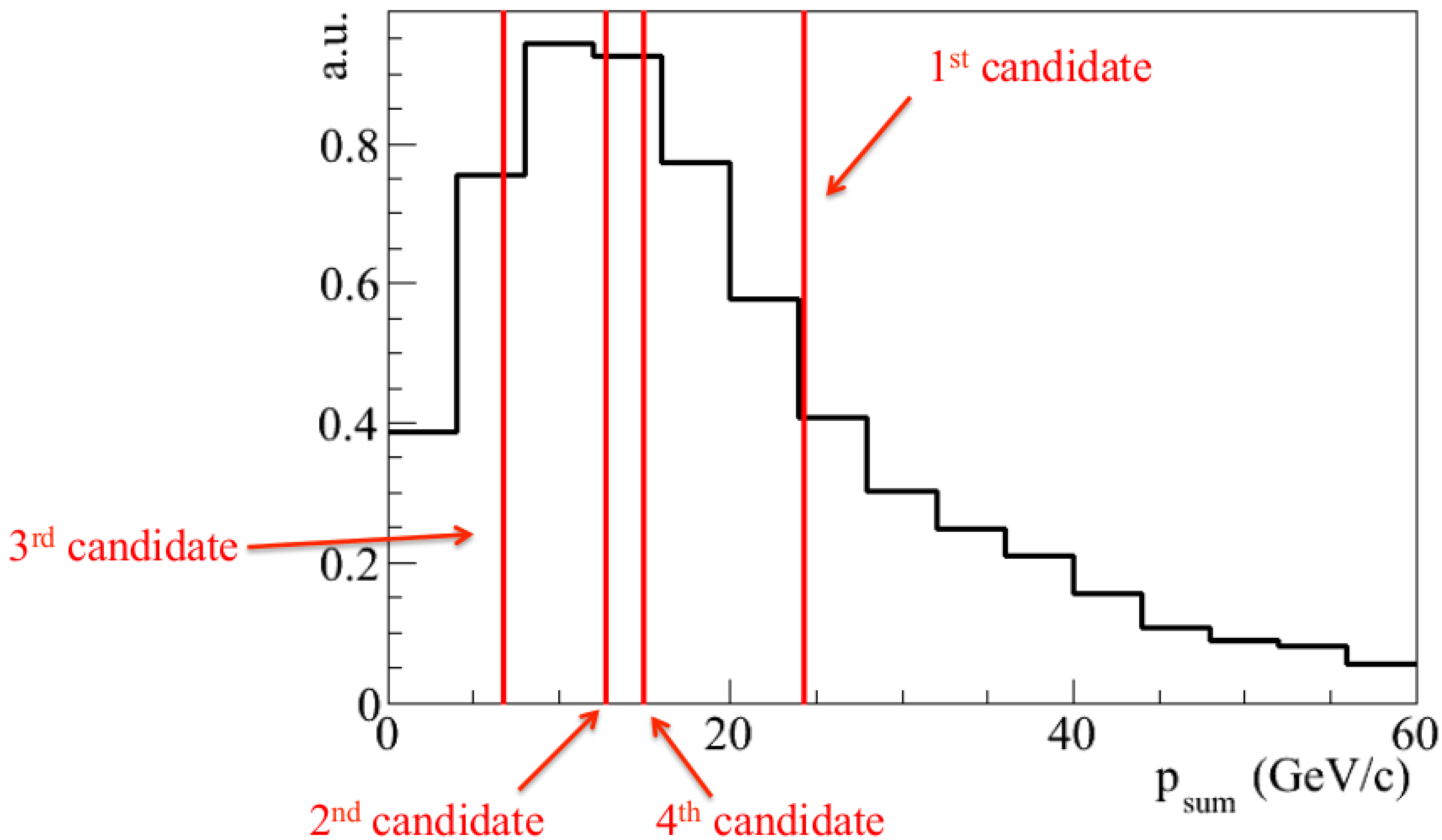


$\tau \rightarrow 1h$



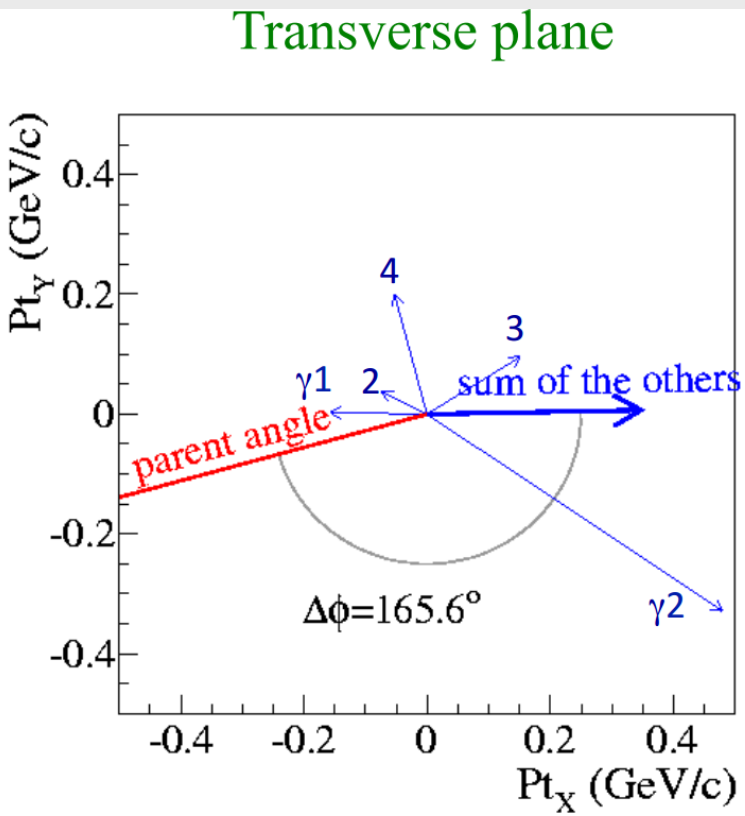
Visible energy of all the candidates

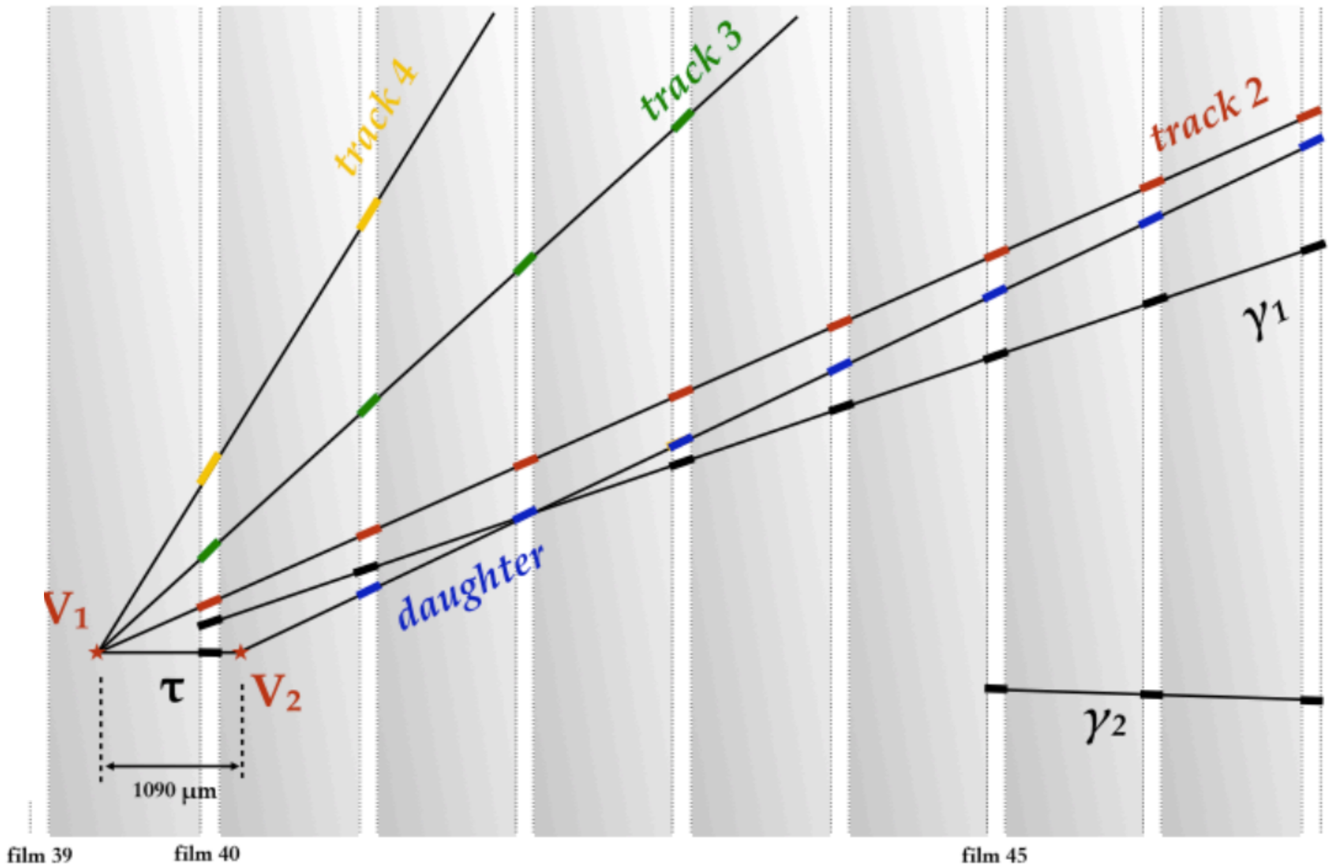
Sum of the momenta of charged particles and γ's measured in emulsion



25/03/14 Giovanni De Lellis, LNGS Seminar 78

Vista schematica a bilanciamento in pT



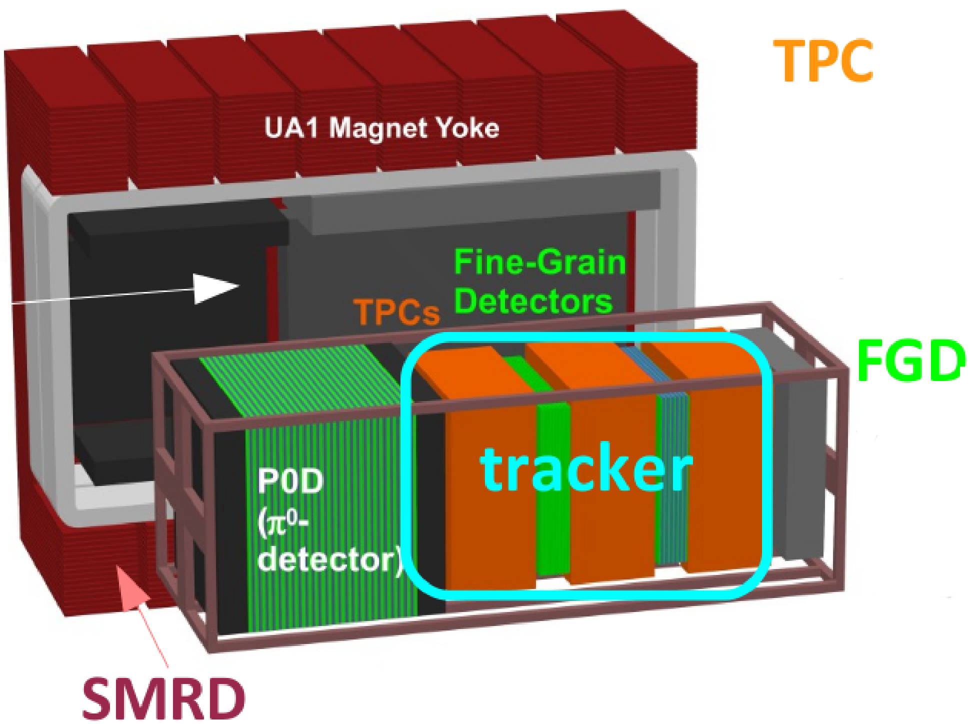


Il rivelatore vicino (280 m)

ND280 (off-axis)

Misura flusso ν_μ e ν_e e sezioni d'urto

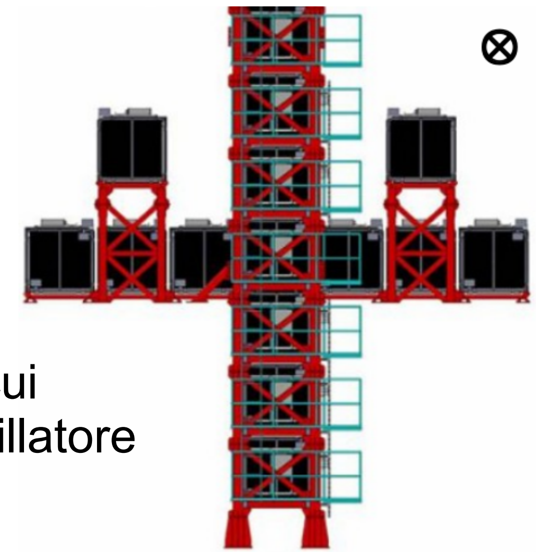
Magnete B = 0.2 T
TPC: misura impulso e particle-ID con il dE/dx
FGD: Fine grained detectors (2 x 0.8 t): rivelazione del protone
SMRD: misura del range dei muoni



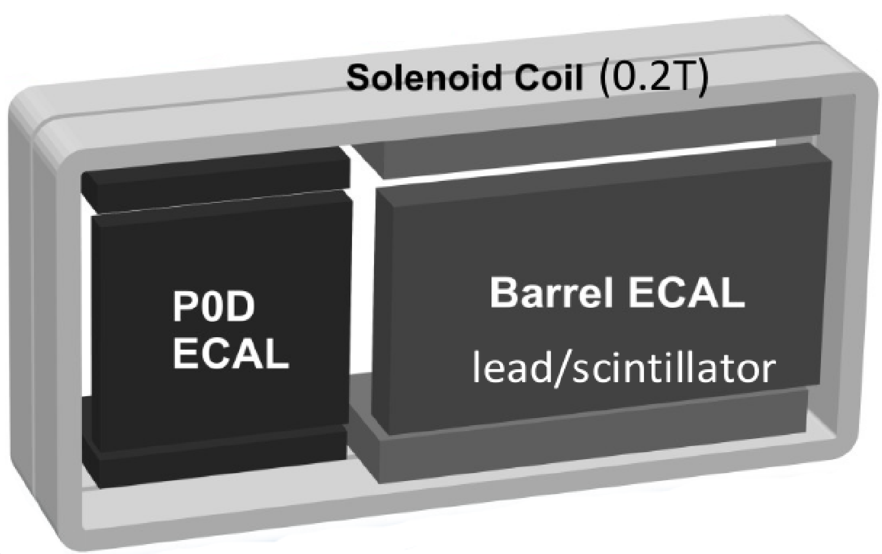
P0D: pi-zero detector (Pb/ottone-H_2O-scintillatore)
ECAL: calorimetro elettromagnetico

INGRID (on-axis)

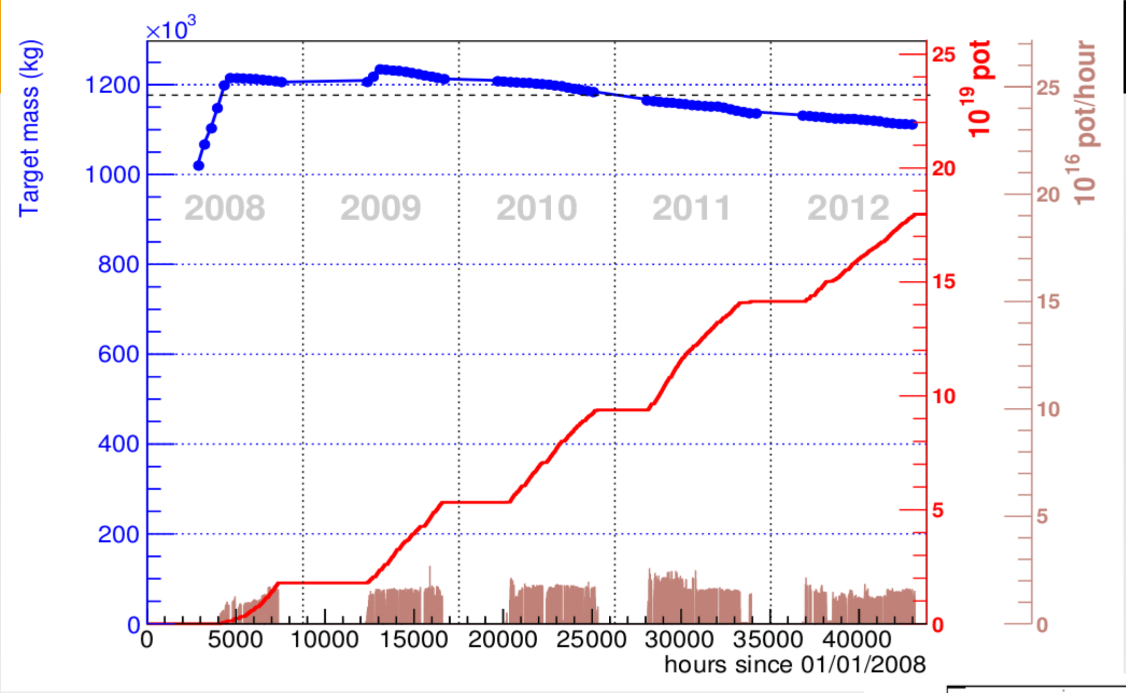
rate delle interazioni CC → profilo del fascio Calorimetri traccianti Fe/scintillatore



16 moduli di cui
1 di solo scintillatore



Campioni e avanzamento dell'analisi delle emulsioni



Year	Beam days	P.O.T. (10^{19})
2008	123	1.74
2009	155	3.53
2010	187	4.09
2011	243	4.75
2012	257	3.86
Total	**965**	**17.97**

POT ~ 80% del design (2.25 x 10^{20})

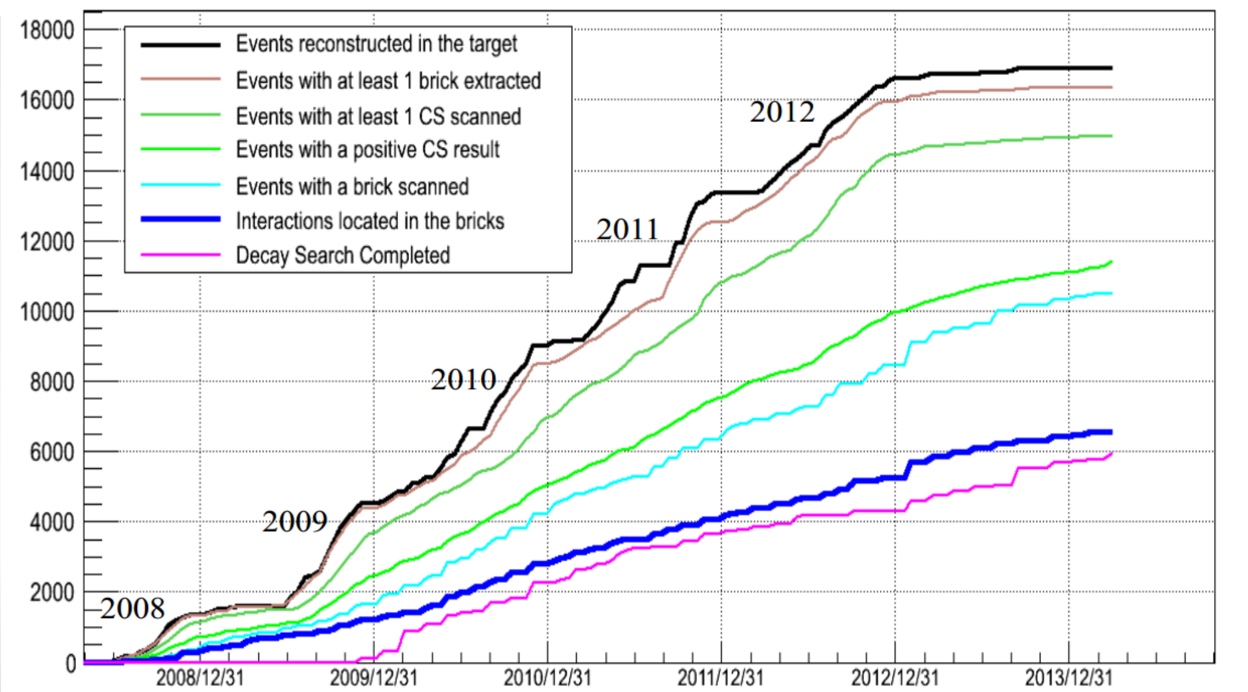
Analisi delle emulsioni:

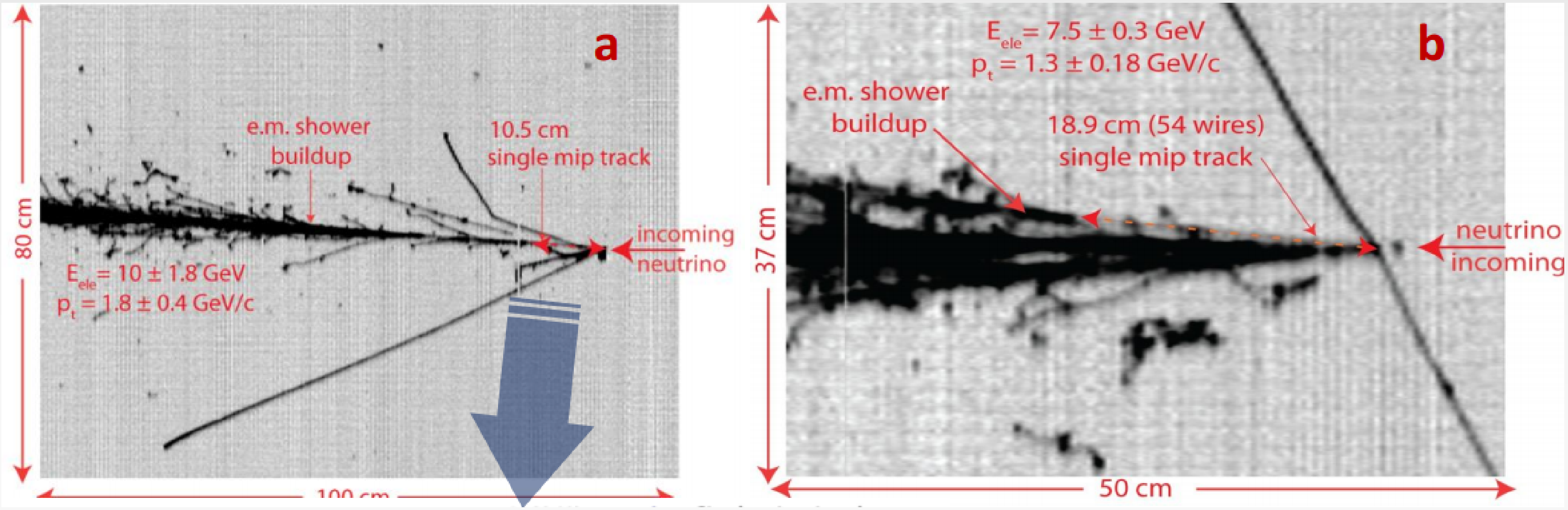
Bricks ordinati per probabilita` di contenere il vertice di interazione.

2008-2009 analisi dei primi e dei secondi brick

2010-2012 analisi dei ``primi brick'' quasi interamente completata

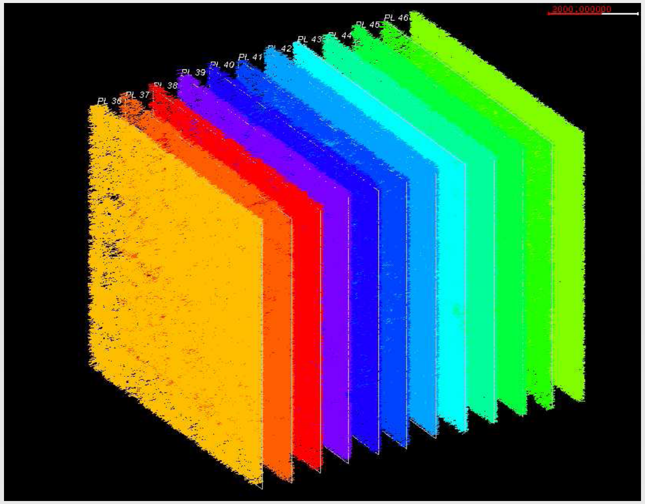
~ 6000 bricks completati

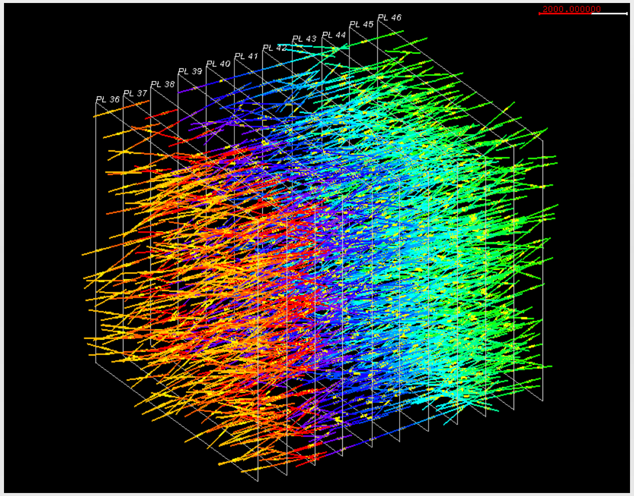


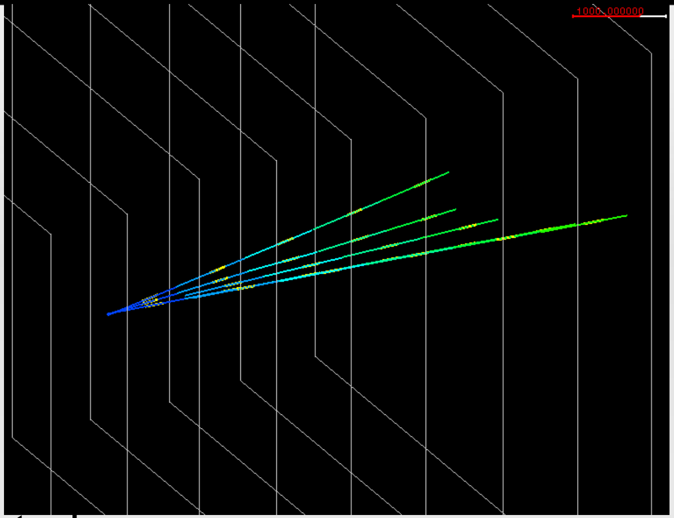


a
e.m. shower
buildup
10.5 cm
single mip track
incoming
neutrino
80 cm
E_{ele} = 10 ± 1.8 GeV
p_t = 1.8 ± 0.4 GeV/c
b
E_{ele} = 7.5 ± 0.3 GeV
p_t = 1.3 ± 0.18 GeV/c
e.m. shower
buildup
18.9 cm (54 wires)
single mip track
neutrino
incoming
37 cm
50 cm

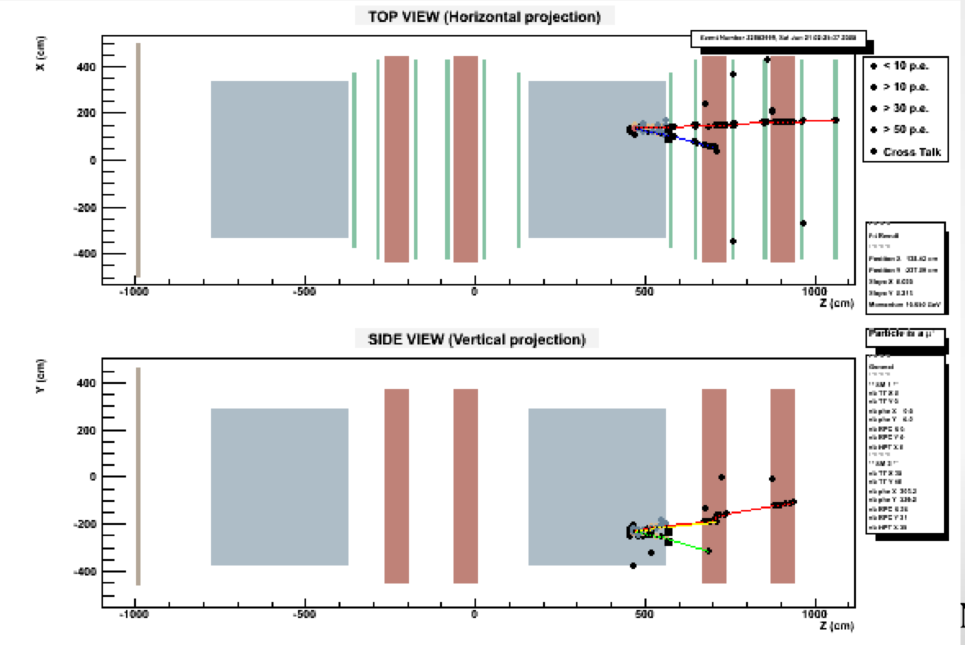
Steps of volume scanning







1) all base-tracks in the 11 films of the volume are reconstructed
2) they participate to the alignment process from which tracks are reconstructed
3) passing-through tracks are discarded and the vertexing algorithm reconstructs the vertex.

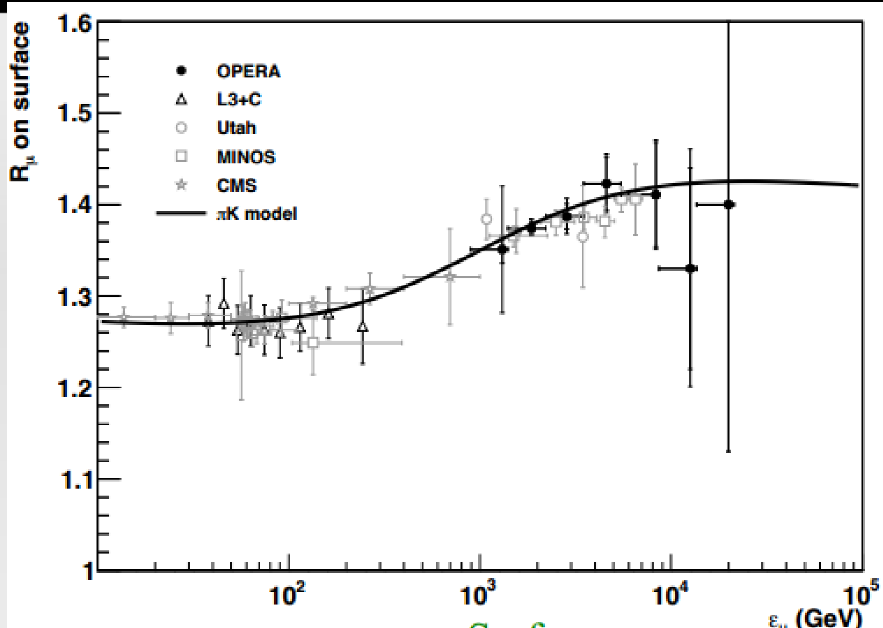


Cosmic-ray physics

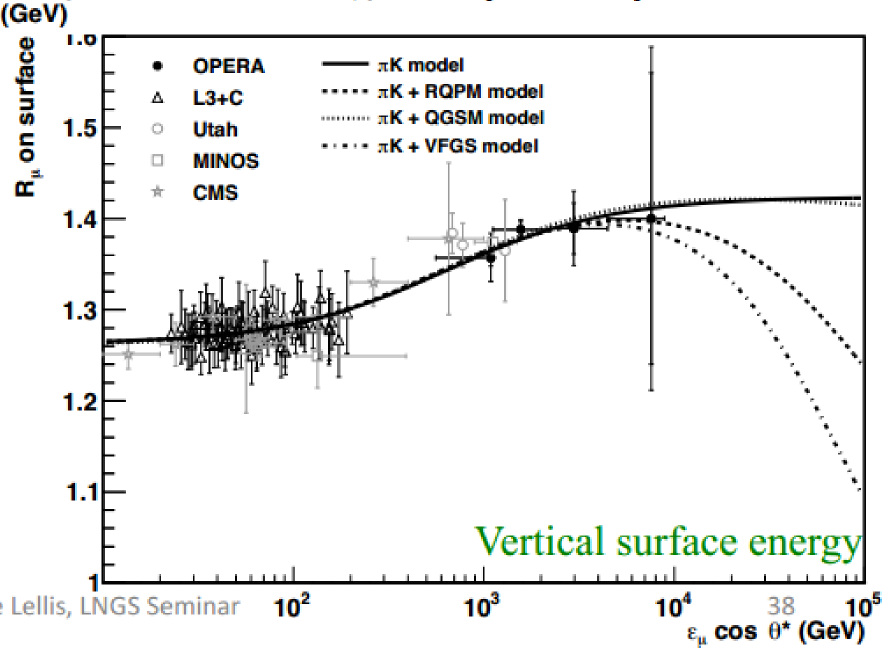
Measurement of TeV atmospheric muon charge ratio

arXiv:1403.0244

$$R_\mu \equiv N_{\mu^+}/N_{\mu^-}$$



Surface energy

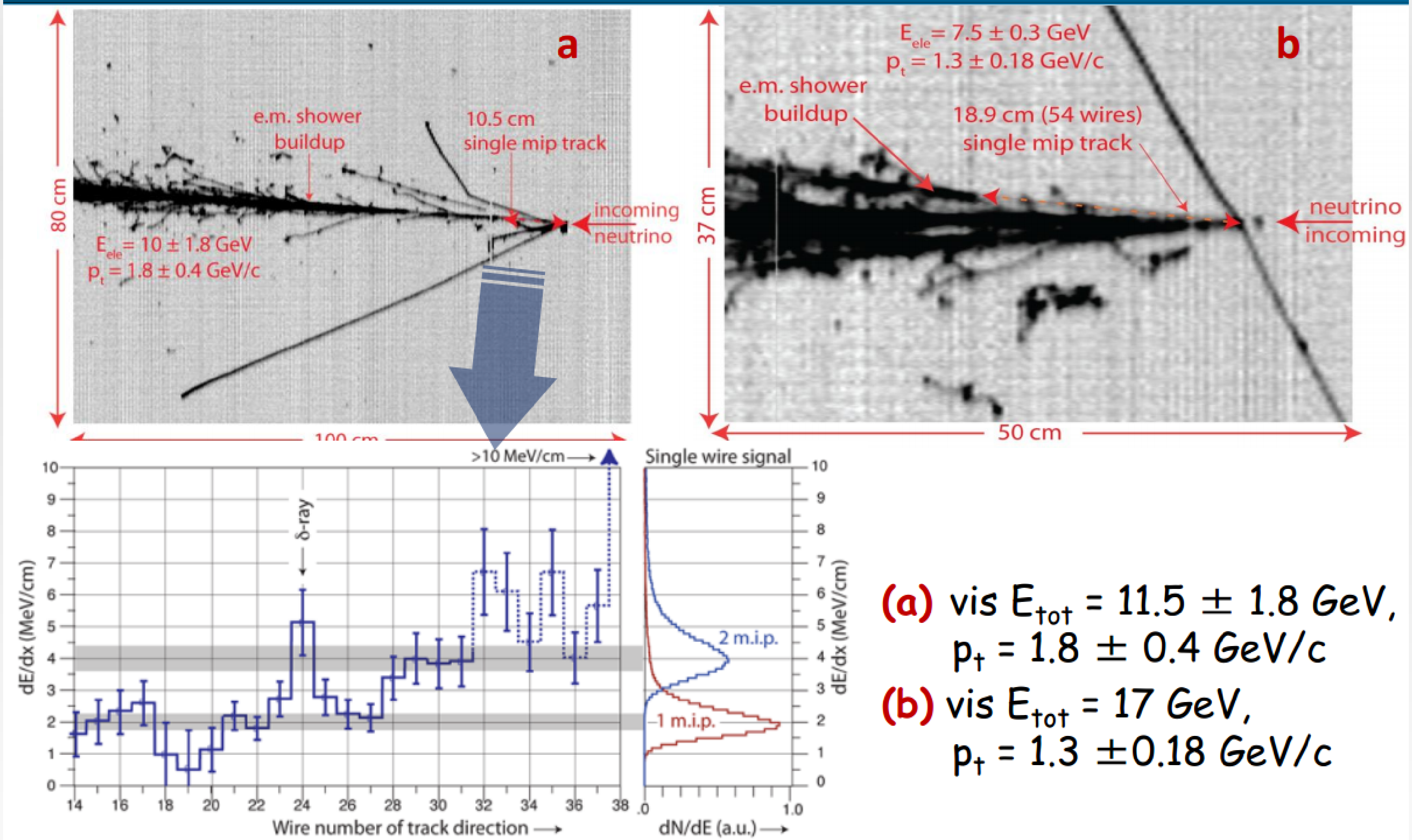


25/03/14 Giovanni De Lellis, LNGS Seminar 38

$\nu_\mu \rightarrow \nu_e$ al CNGS con ICARUS

Eur. Phys. J. C73 (2013) 2345
arXiv:1307.4699

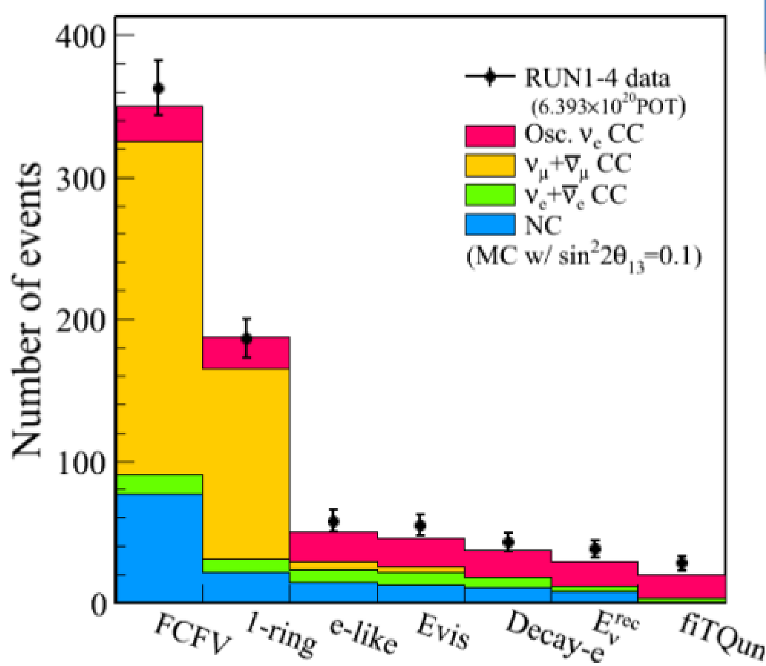
Example: 2 (out of 4) ν_e CC events observed in 1995 events



(a) vis E_{tot} = 11.5 ± 1.8 GeV, p_t = 1.8 ± 0.4 GeV/c
(b) vis E_{tot} = 17 GeV, p_t = 1.3 ±0.18 GeV/c

In all events: single electron shower in the transverse plane clearly opposite to hadronic component

Natal WIN September 2013 Slide: 15



Apparizione dei ν_e: $\sin^2 2\theta_{13}$, δ_{CP}

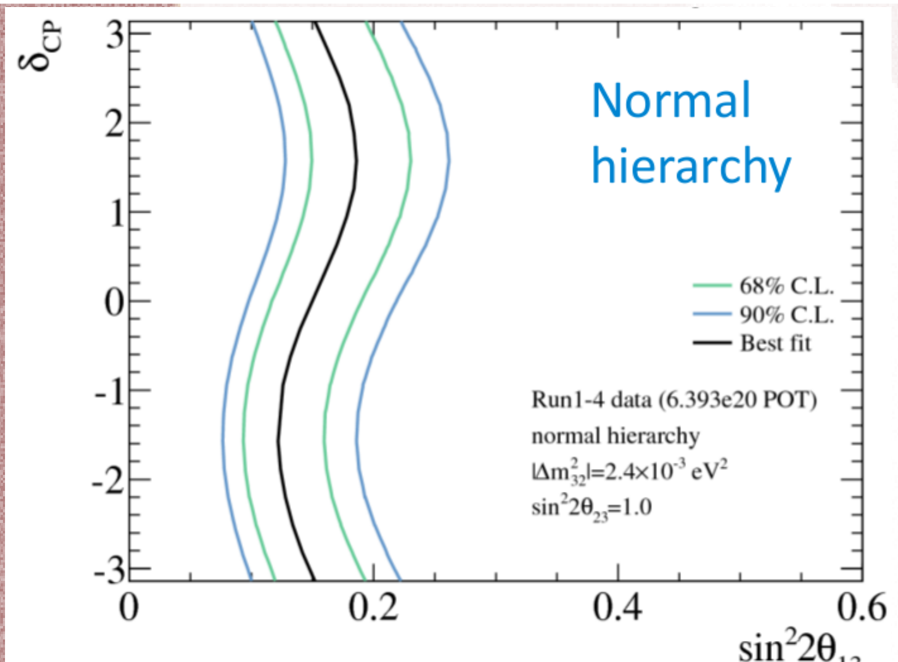
28 eventi osservati (20.4 ± 1.8 attesi)

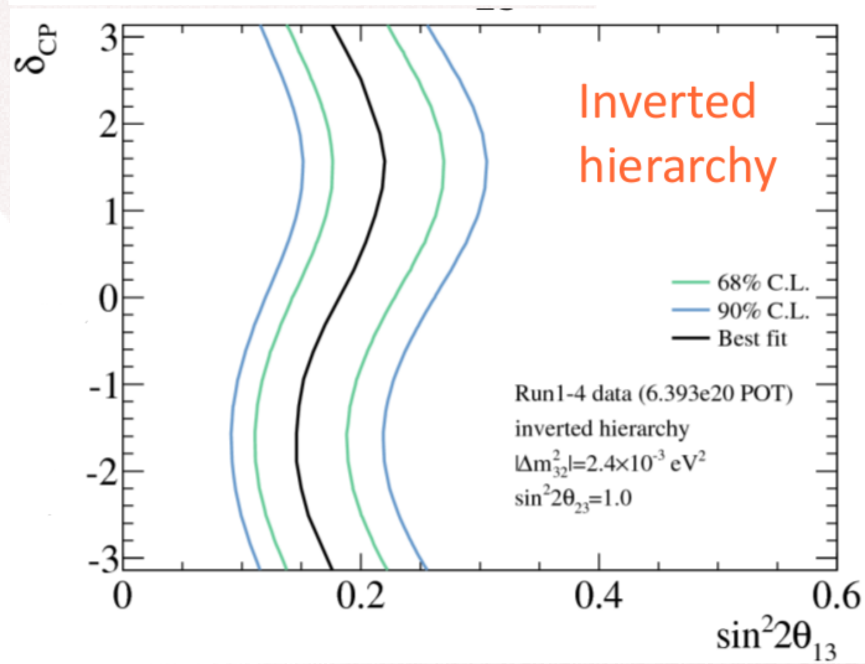
Significanza di 7.5 σ per $\theta_{13} \neq 0$ (p-θ)

Prima osservazione (> 5σ) di appearance

Gerarchia normale best fit: **0.150**
@ 90% CL: **$0.097 < \sin^2 2\theta_{13} < 0.218$**

Gerarchia inversa, best fit **0.182**
@ 90% CL: **$0.118 < \sin^2 2\theta_{13} < 0.261$**

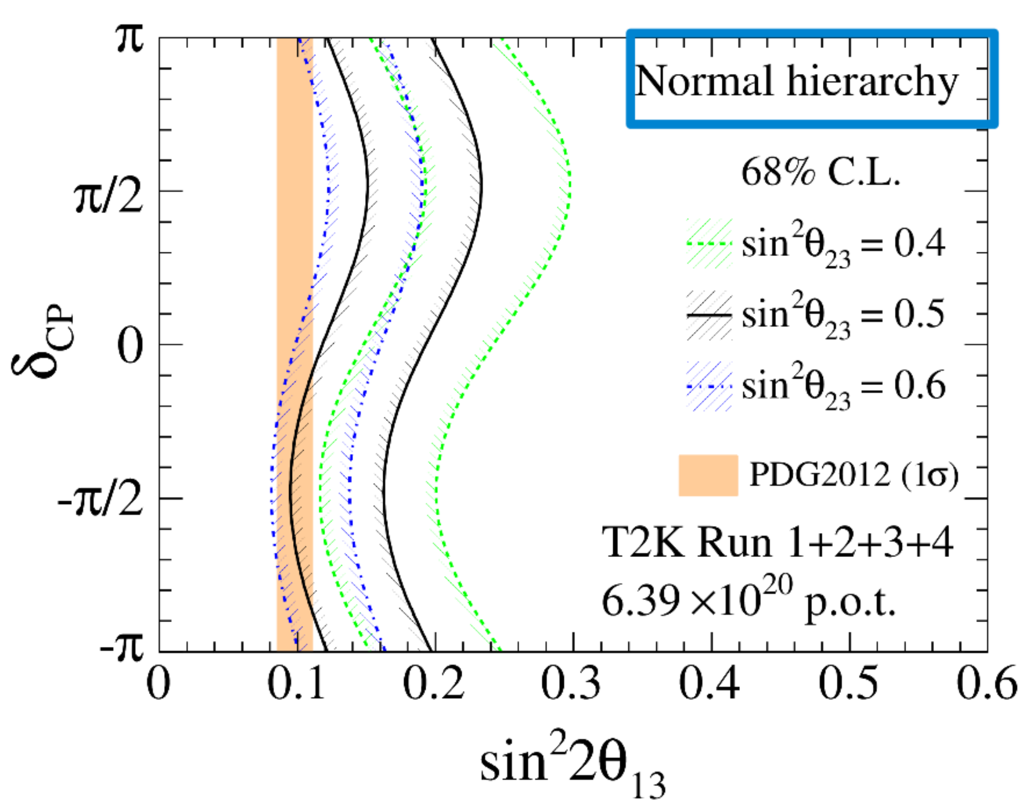


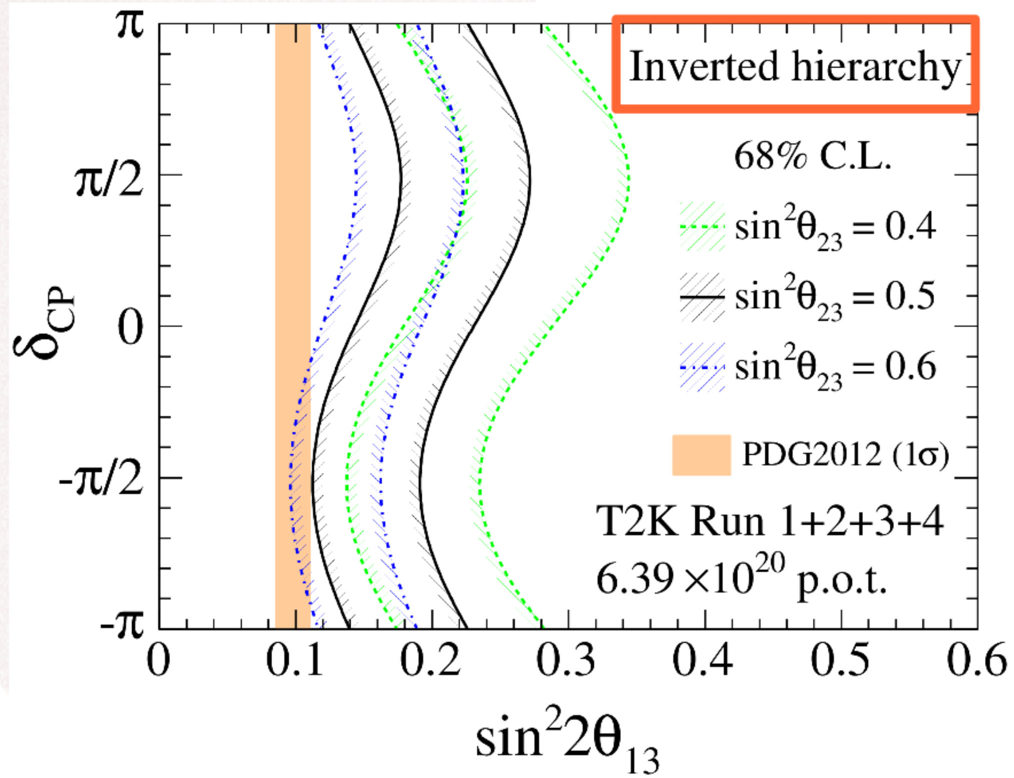


Apparizione di ν_e e θ_{23}

$$P_{\mu\to e} \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

Dipendenza da θ_{23} asimmetrica rispetto a $\pi/4$





Variazioni nella zona permessa quando θ_{23} e' variato entro l'incertezza.

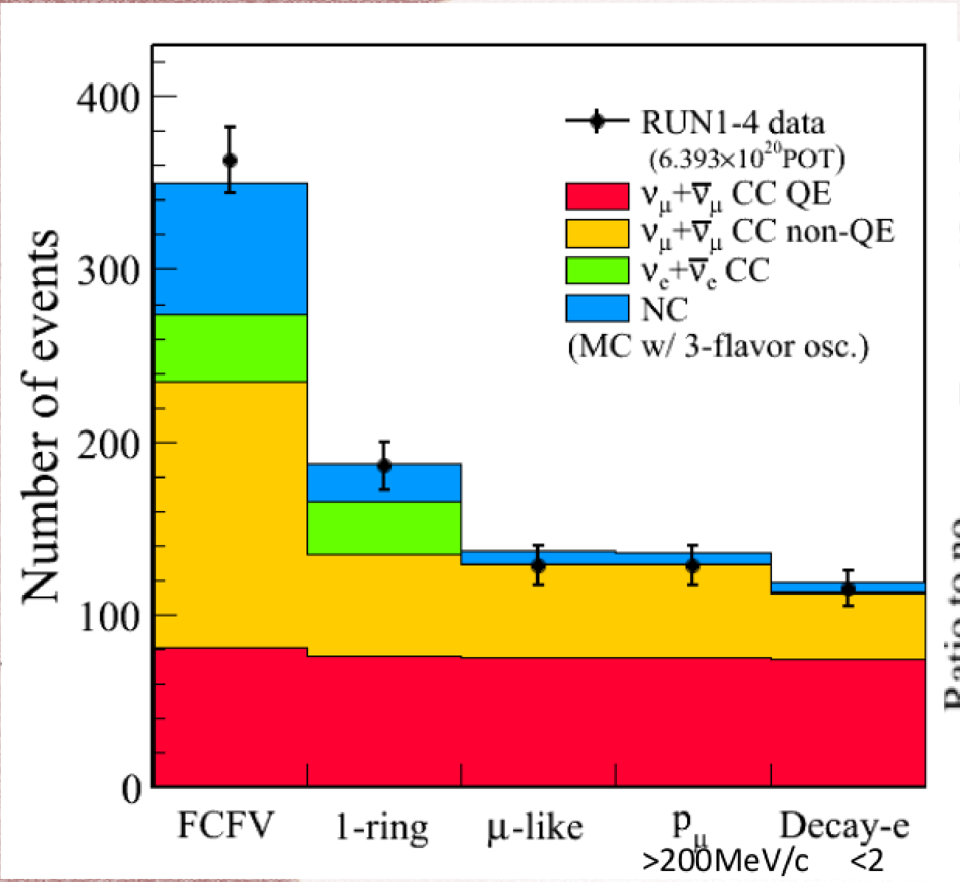
I **reattori** misurano un valore centrale minore: θ_{23} nel 2° ottante e $\delta_{CP} \sim -\pi/2$ leggermente favoriti → Una fenomenologia molto ricca !

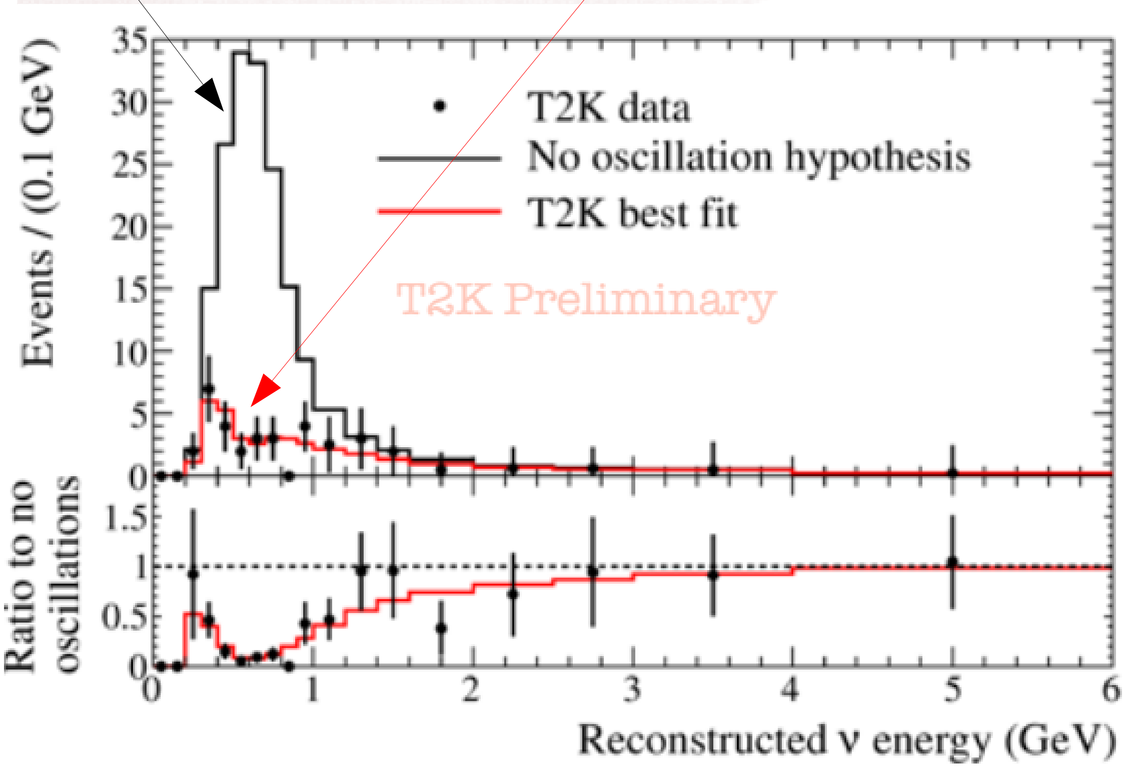
Scomparsa dei ν_μ

Con 3.01 ·10^{20} POT

205 eventi attesi, 58 osservati !

Selezione dei dati

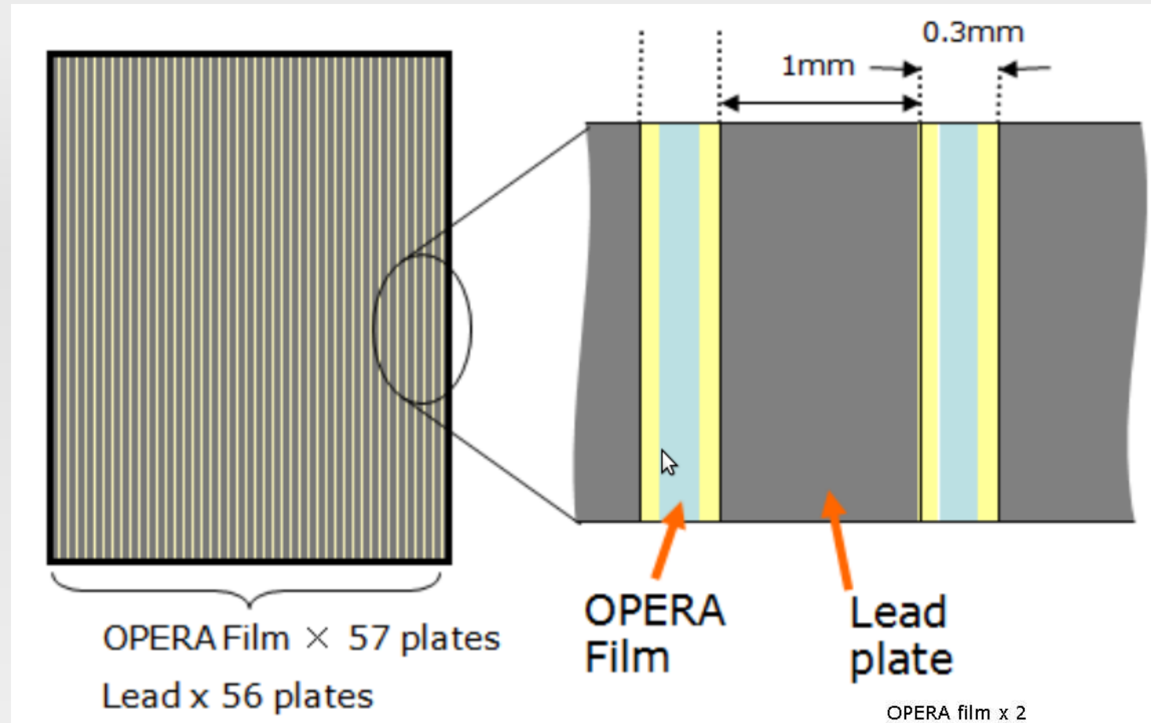


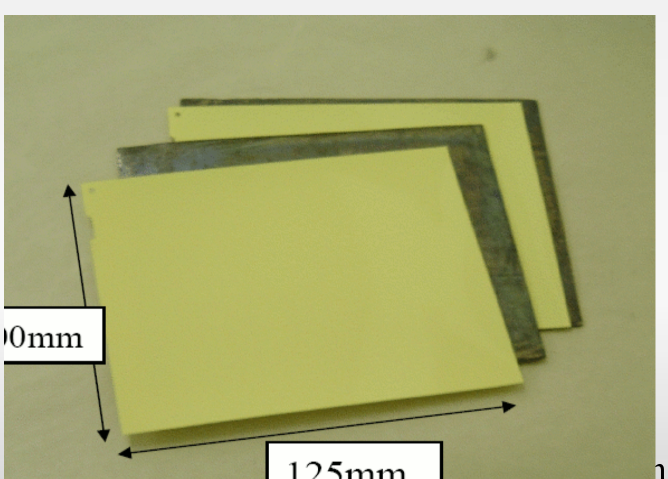


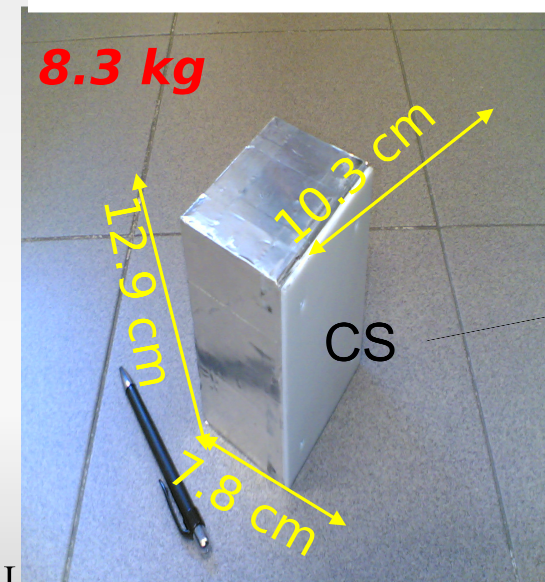
Il primo fascio disegnato con una precisa determinazione del Δm^2 (soppressione massimale esattamente al picco!)

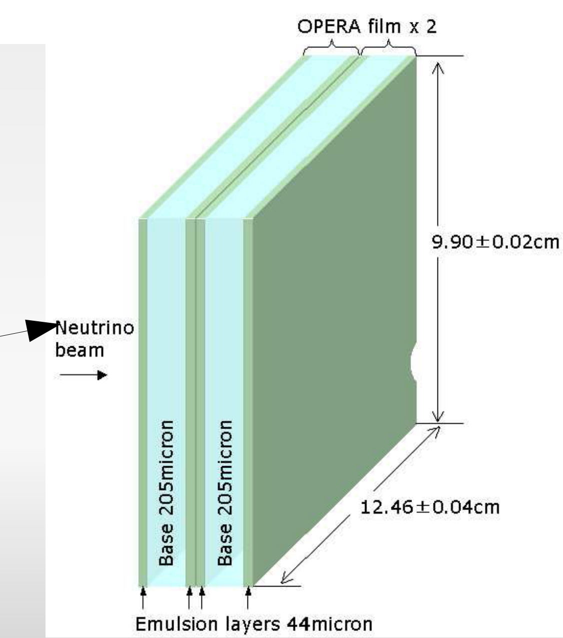
The ECC (emulsion cloud chamber)

• Brick
56 lead plates (1 mm) + 56 emulsions (300 μm)
• Changeable Sheet (CS):
low -background removable emulsion doublet attached downstream of brick
- validates the occurrence of event in the selected brick before unpacking and developing
- "Bridge" between electronic detectors and brick.(thanks to low track density: 10^{-4} tracks/cm^2 in the doublet due to special treatment)

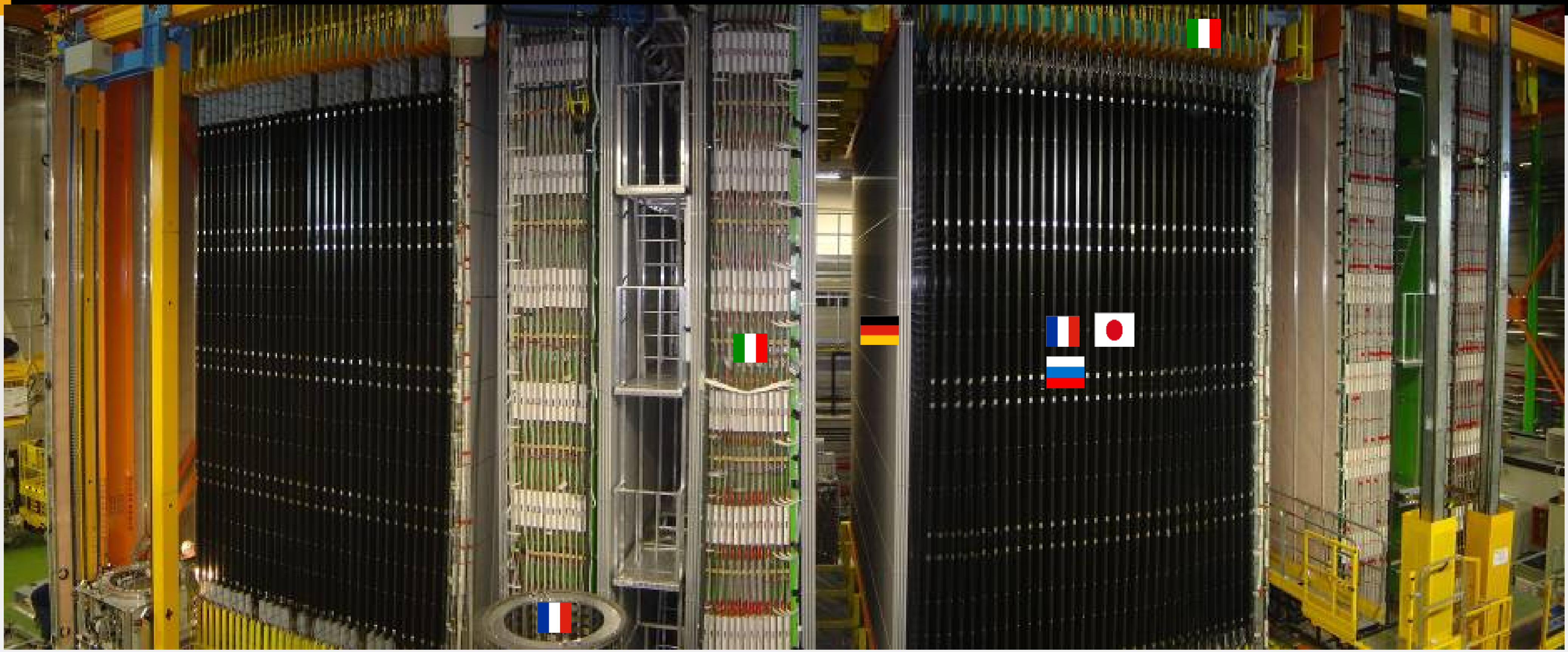








The OPERA detector fish-eye



Electronic detectors fully instrumented and tested since 2007

French contributions:

- Target Tracker (IrES Strasbourg)
- Brick manipulator system (LAPP Annecy),
- DAQ (IPNL Lyon + scanning)

The BMS (brick manipulator system)

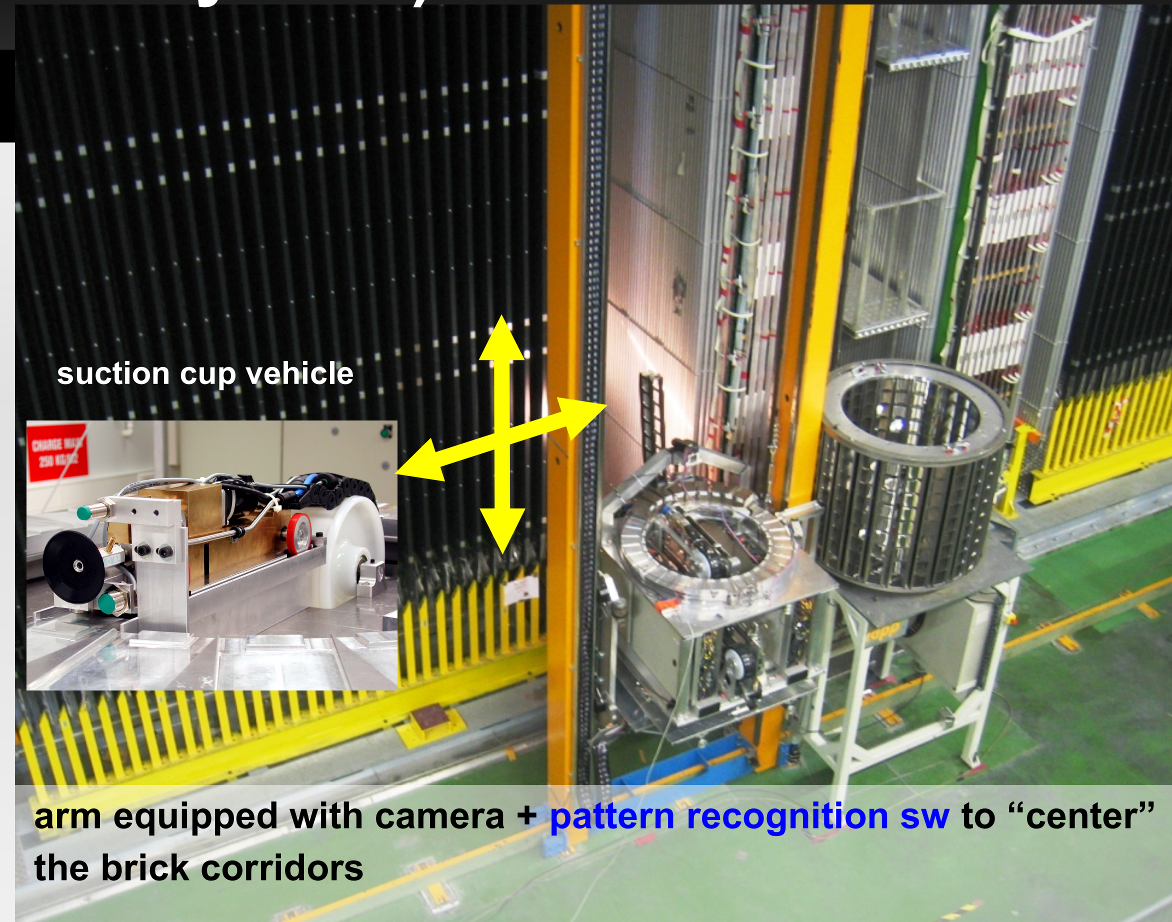
- Automated detector filling
- Routine extractions of bricks containing ν interactions
- "holes-filling" to keep the detector compact (no refilling of extracted bricks foreseen ~ -10%/5y)

Replicated on both detector sides

0.1 mm accuracy in positioning over ~ 8 m
platform weight: 1.3 tons

Continuous brick mapping (extraction/reinsertion) managed by a relational DB

For efficient tracing and retrieval of heterogeneous data: brick and film handling, DAQ, scanning data in various labs, etc.. are also managed by DB



loaded "drum": 256 bricks filled automatically by the BAM

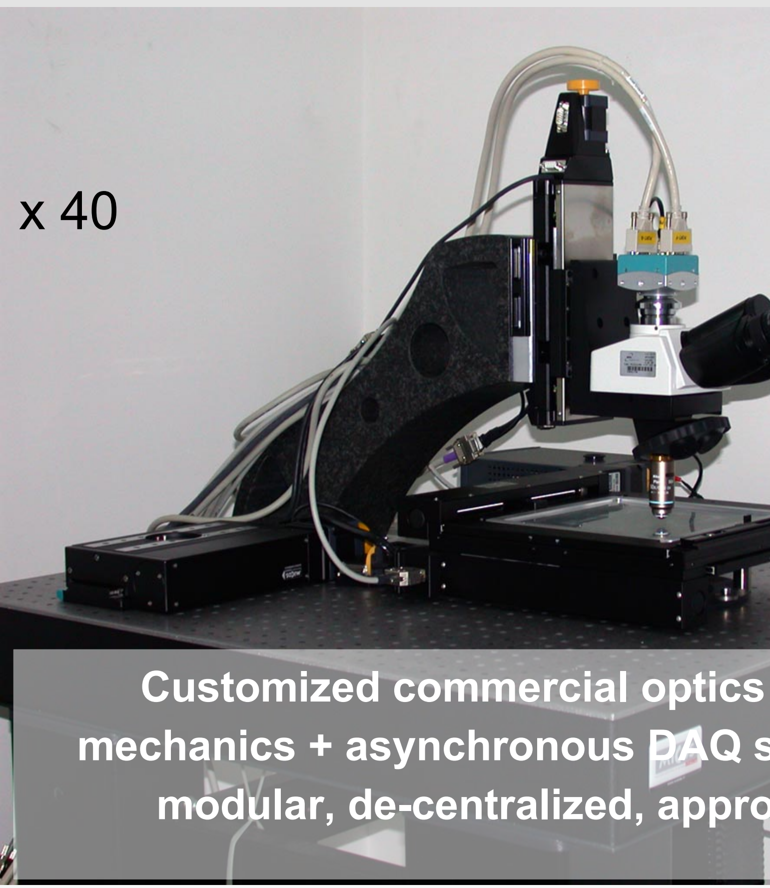
Emulsion scanning: 'offline' ... data taking !

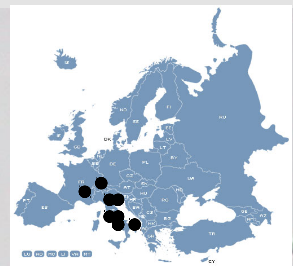
~ 24 bricks will be daily extracted and analysed using high-speed automatic systems
~ 40 microscopes distributed in Europe and Japan

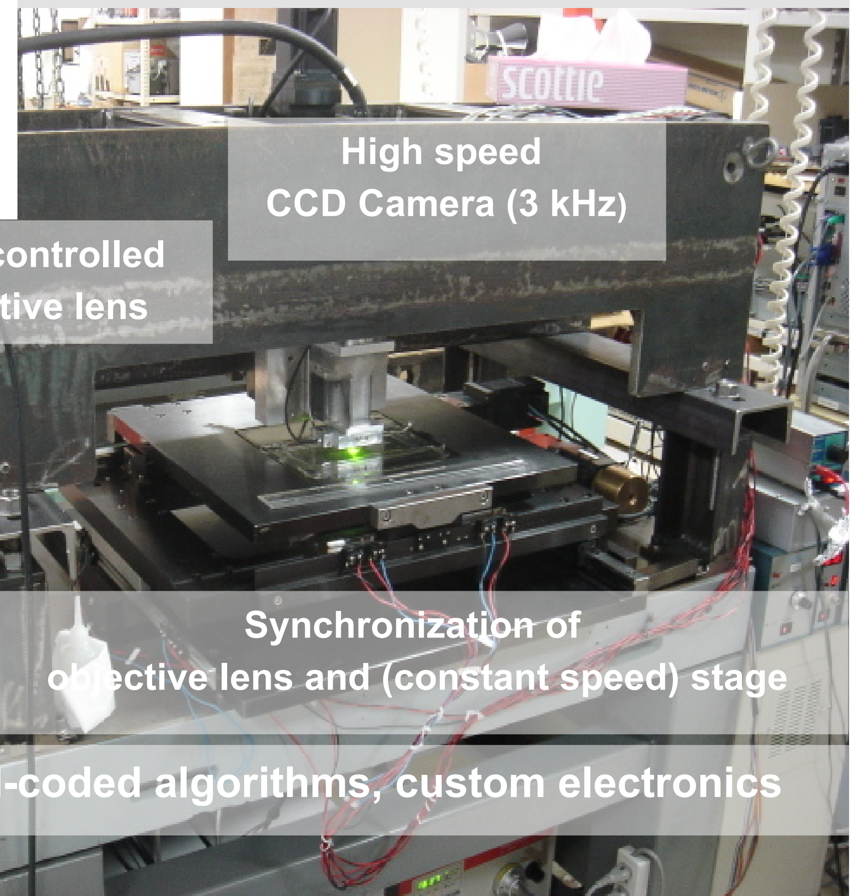
2 “schools”. Many useful cross checks are possible !
Common Data Base for data sharing/publication

European Scanning System

S-UTS (Japan)







scanning speed ~ 20 cm^2 / h proposal goal

Up to ~ 72 cm^2 / h

Development lab

Commercial up-to-date technologies
Chemical solutions are prepared by an industrial-type plant
fully automated up to 3000 films/day (~53 bricks)

6 parallel motorized chains connected to a series of tanks that contain the chemical solutions

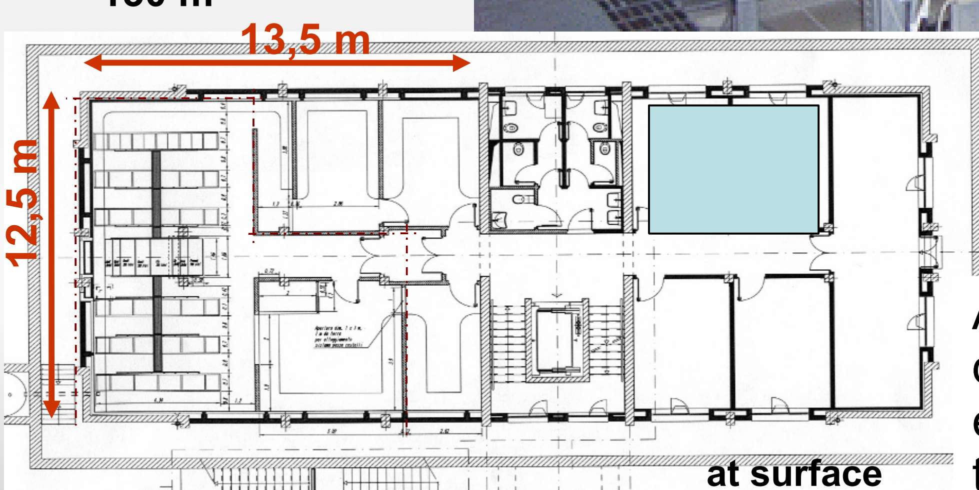
movable arms under PLCcontrol displace and insert the plate holders in/out of each tank at scheduled times

development/stopping/fixing/thickening/washing

each phase is from 5' →~20'
>= 1 brick per chain simultaneously

automatic exhaustion of chemical waste and insertion of fresh ones

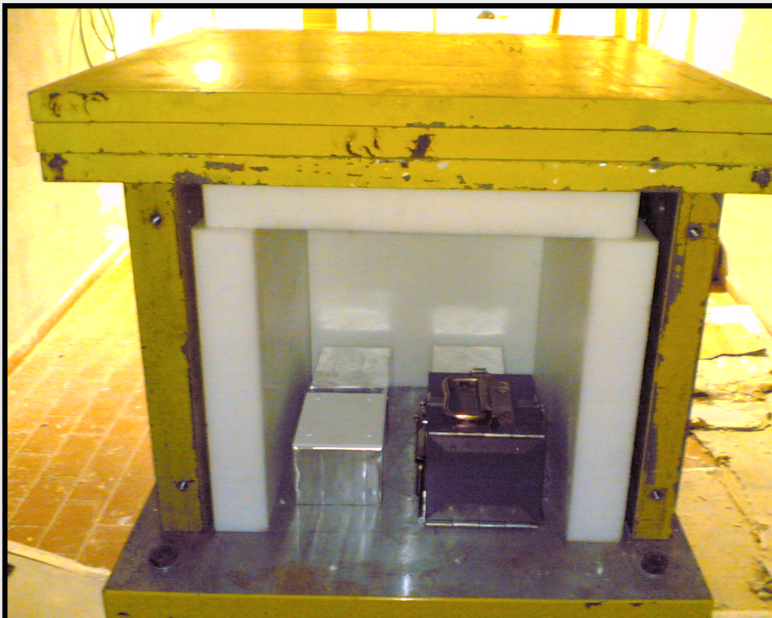
~ 130 m²

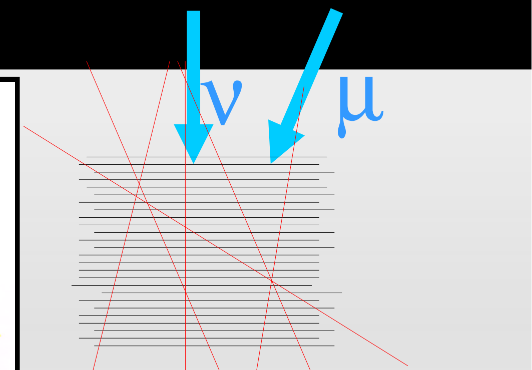


A smaller independent development facility exists underground for the changeable sheets

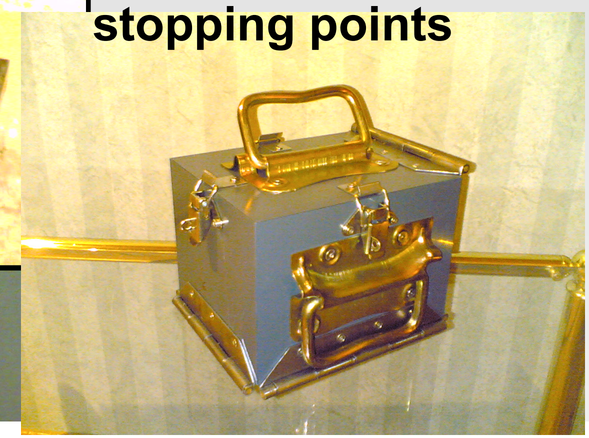
Cosmic ray exposure

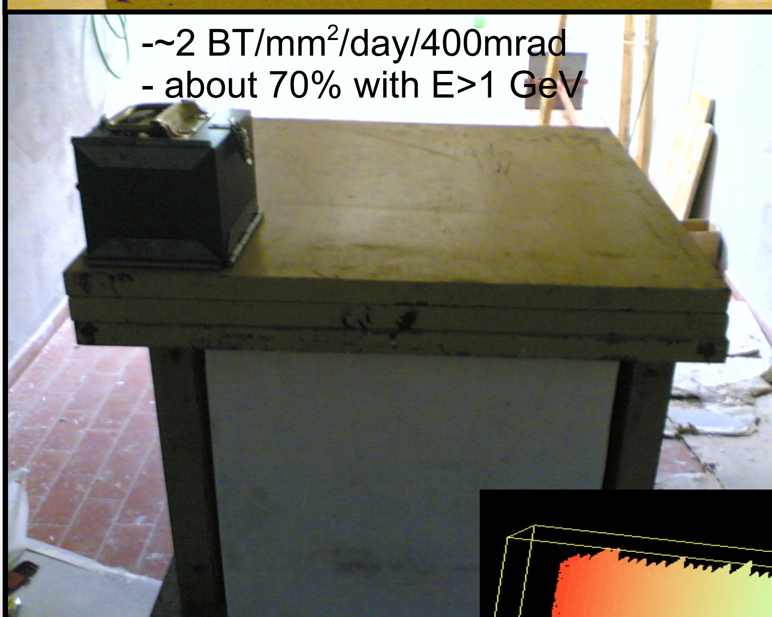
high energy cosmic rays used for local alignment ("pins") of different emulsions in the brick. Exposure at surface done after brick extraction in a properly designed pit (to suppress the low E component).



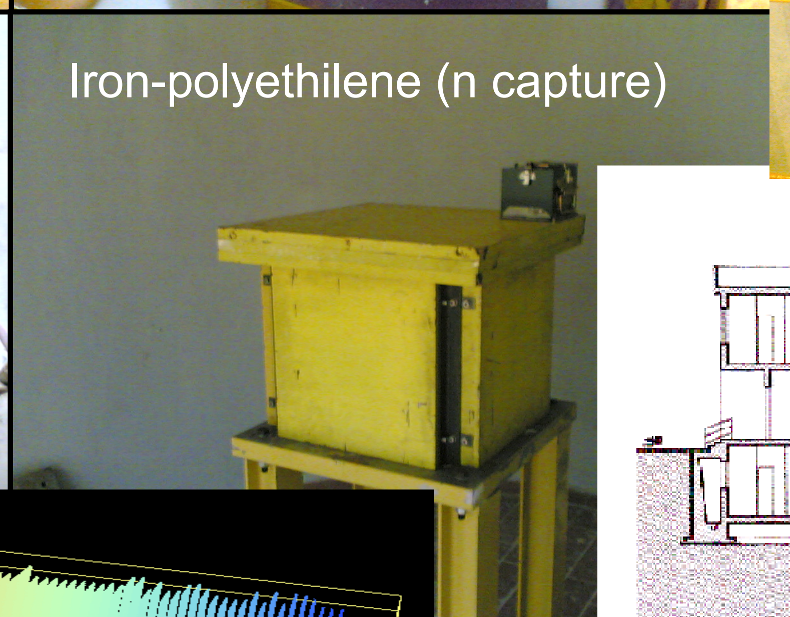


To prevent fake stopping points

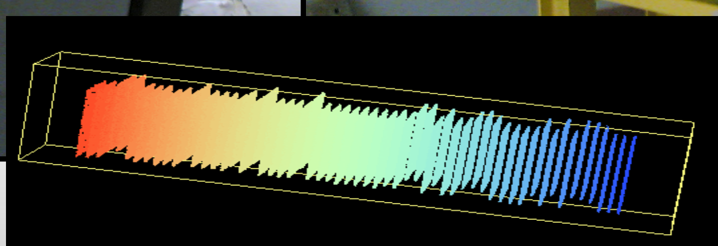


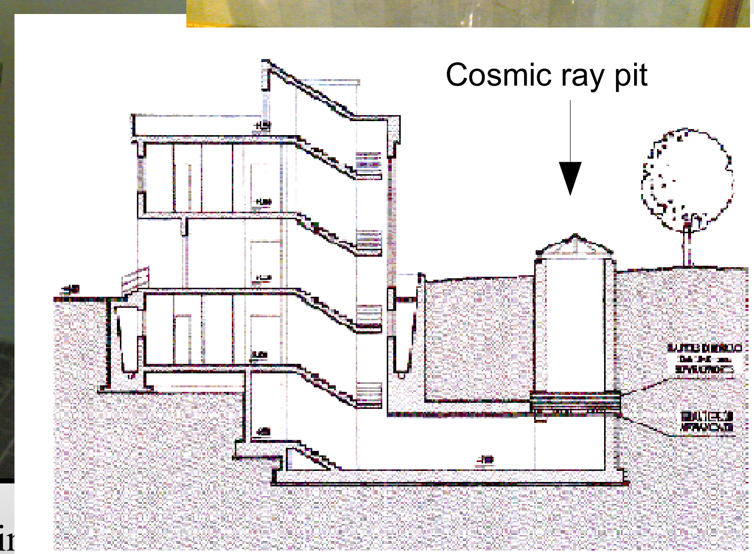


-~2 BT/mm^2/day/400mrad
- about 70% with E>1 GeV



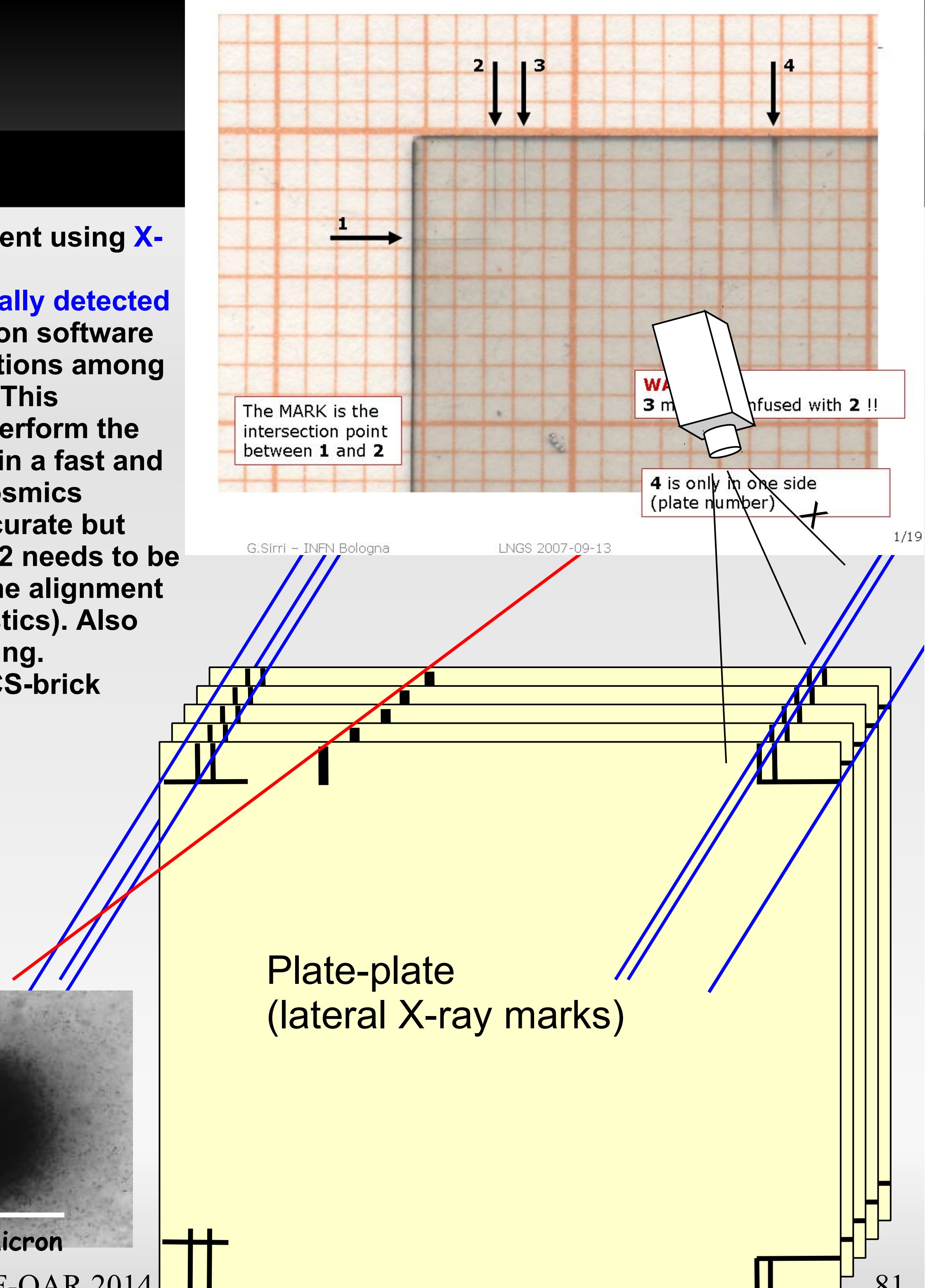
Iron-polyethilene (n capture)



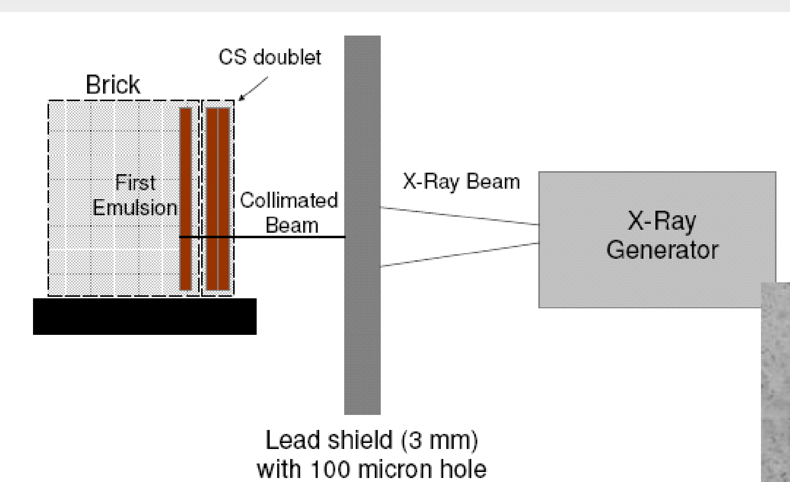


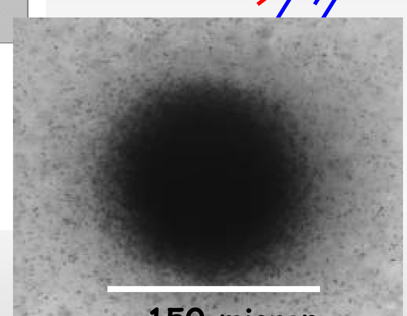
X-ray marking

- Faster global alignment using **X-ray marks**
- **Marks are automatically detected by a** pattern recognition software and affine transformations among plates are calculated. This procedure allows to perform the scan back procedure in a fast and effective way while cosmics alignment is more accurate but slow (a zone of ~1 cm2 needs to be scanned to perform the alignment with reasonable statistics). Also provide plate numbering.
- same technique for CS-brick alignment



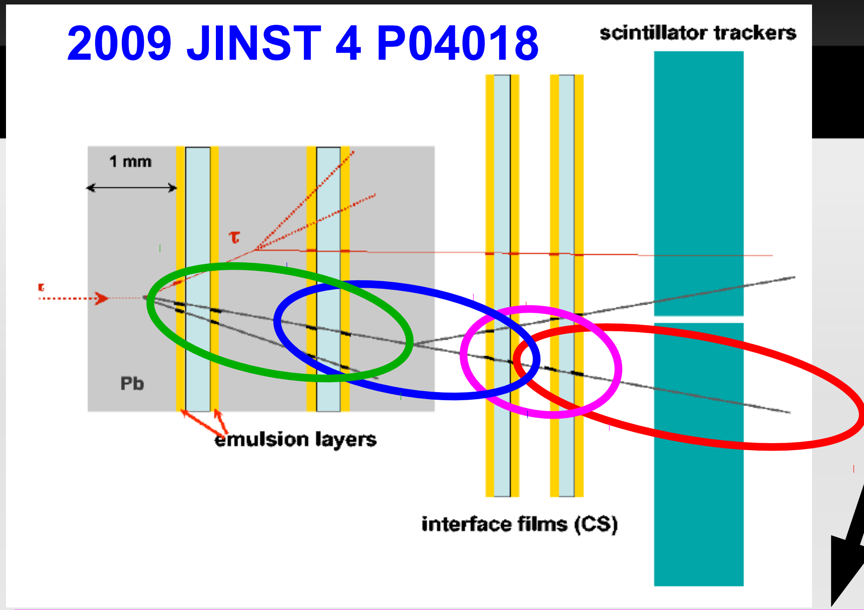
CS-brick (frontal Xray marks)





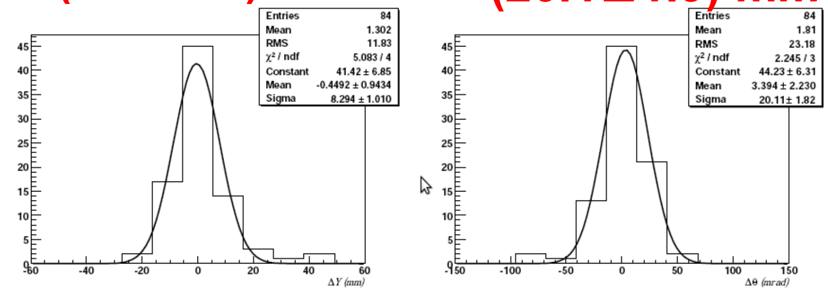
5 circular spots on CS films and most downstreamfilm of the brick.
precise alignment btw CS1-2 and brick

From electronic detectors to vertices in emulsions

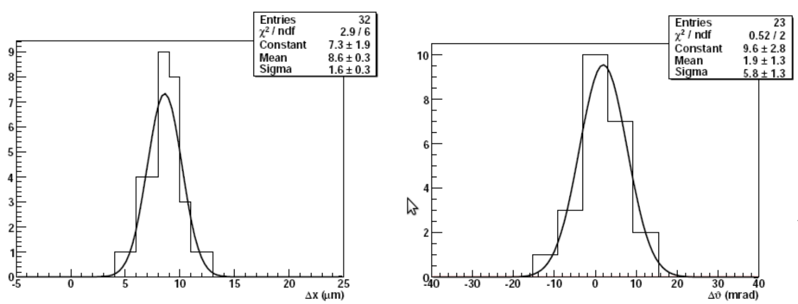


Electronic detectors - Changeable sheet

(8.3±1.0) mm (20.1±1.9) mm



CS1-2 (1.6±0.3) μm (6.8±1.3) mrad



CS brick

74 μm 8.2 mrad

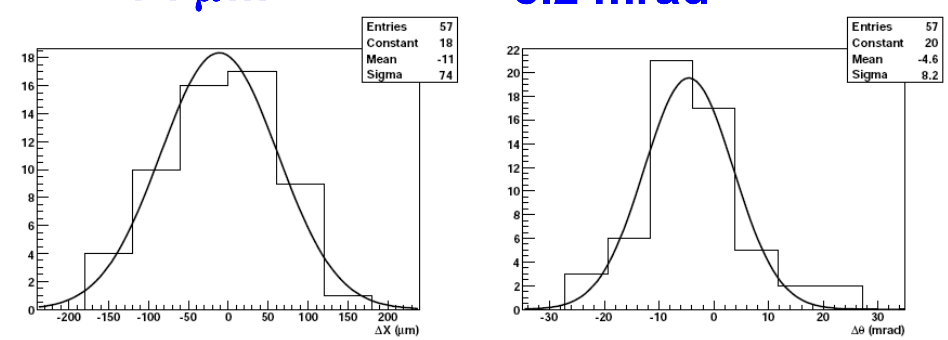
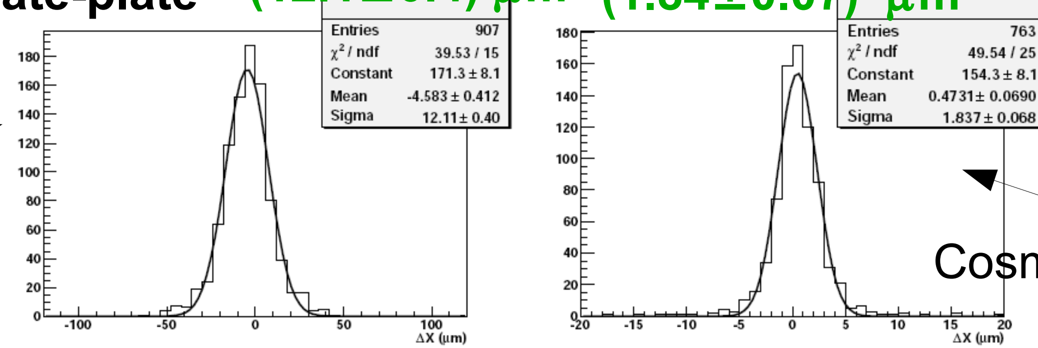


plate-plate (12.1±0.4) μm (1.84±0.07) μm



Lateral X-ray marks

Cosmic ray alignment

leap of a factor 10000 in precision !

Beam monitors

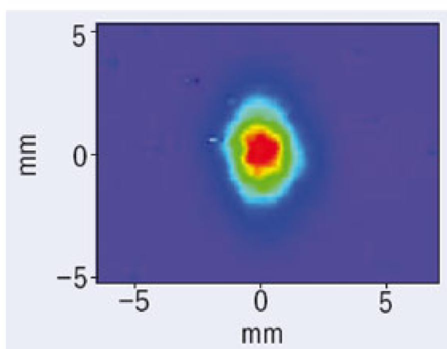
22+1 BPM (Beam Position Monitors)
button electrode monitors from LEP. tol ± 0.6 mm

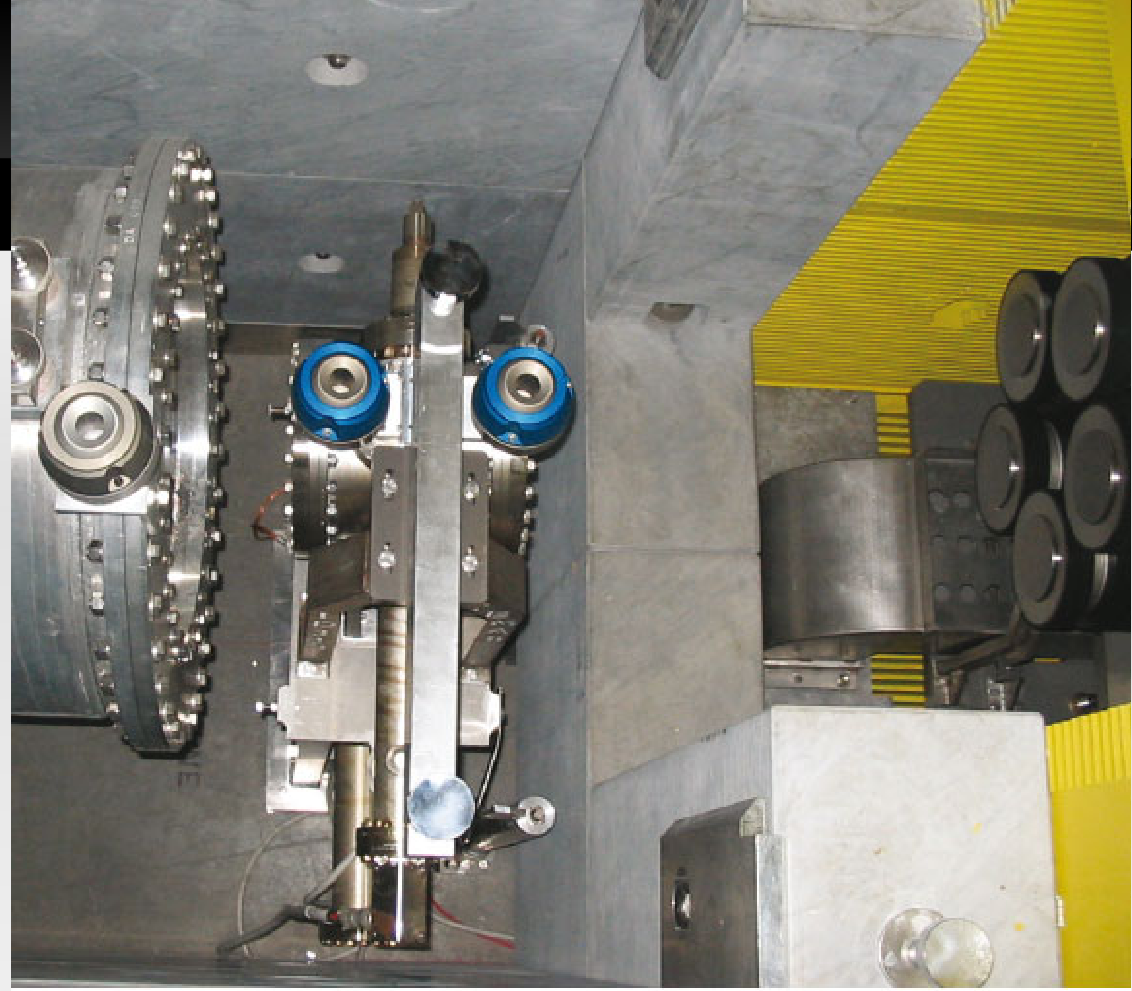
last BPM: tol ± 0.035 mm
strip-line coupler pick-up mechanically connected with target

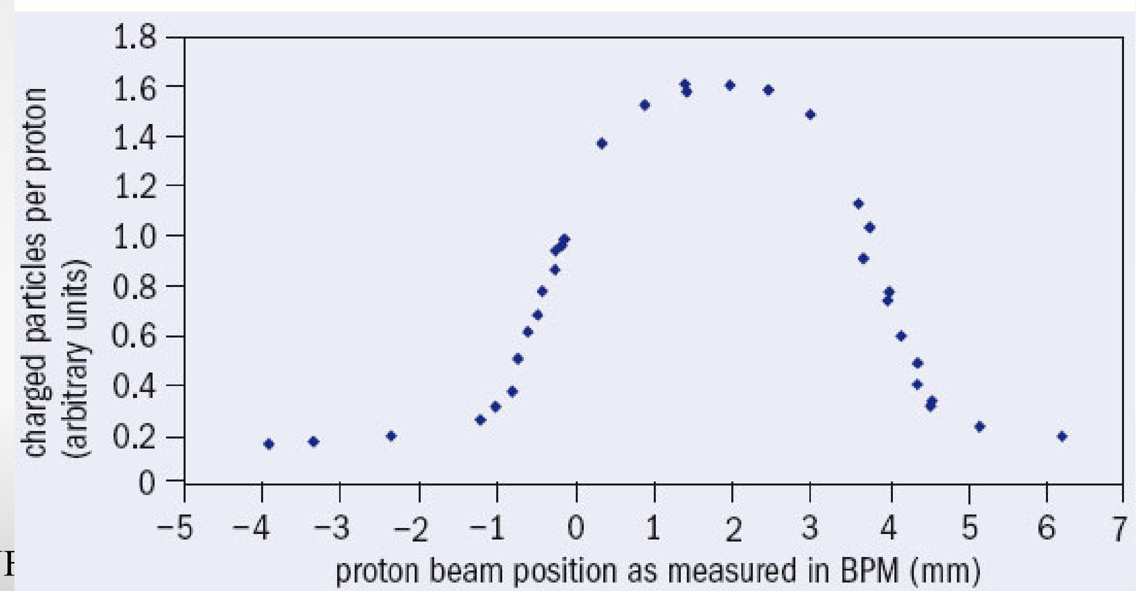
8 BPM (beam profile monitor)
OTR (optical transition radiation monitors)
75 μm C(high.int) 12 μm Ti (low int.)

2 BCT (beam current transformer):
beam intens. at start and end.

18 BML (beam loss monitor)
N_2 filled ioniz. chambers



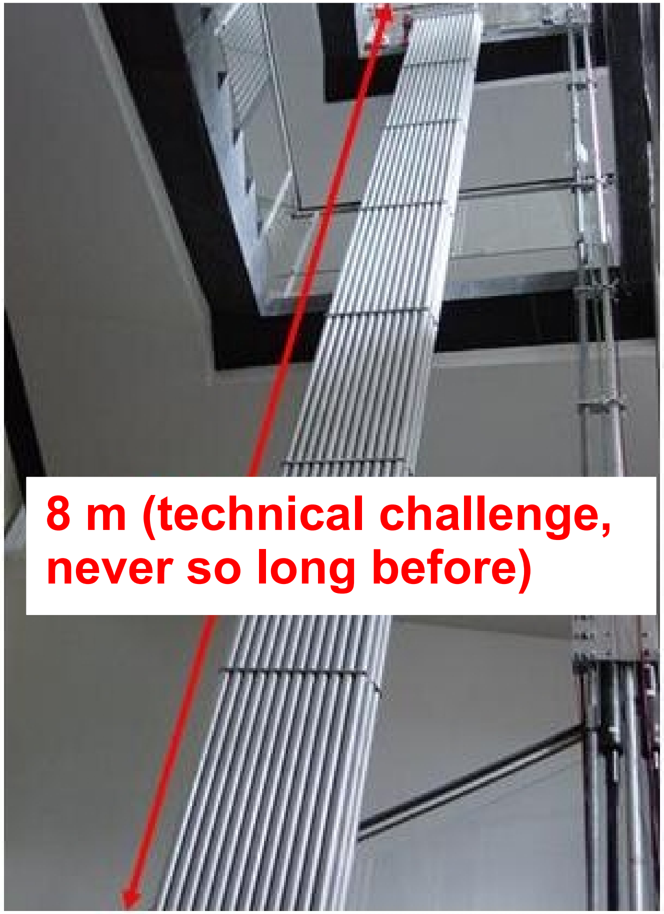


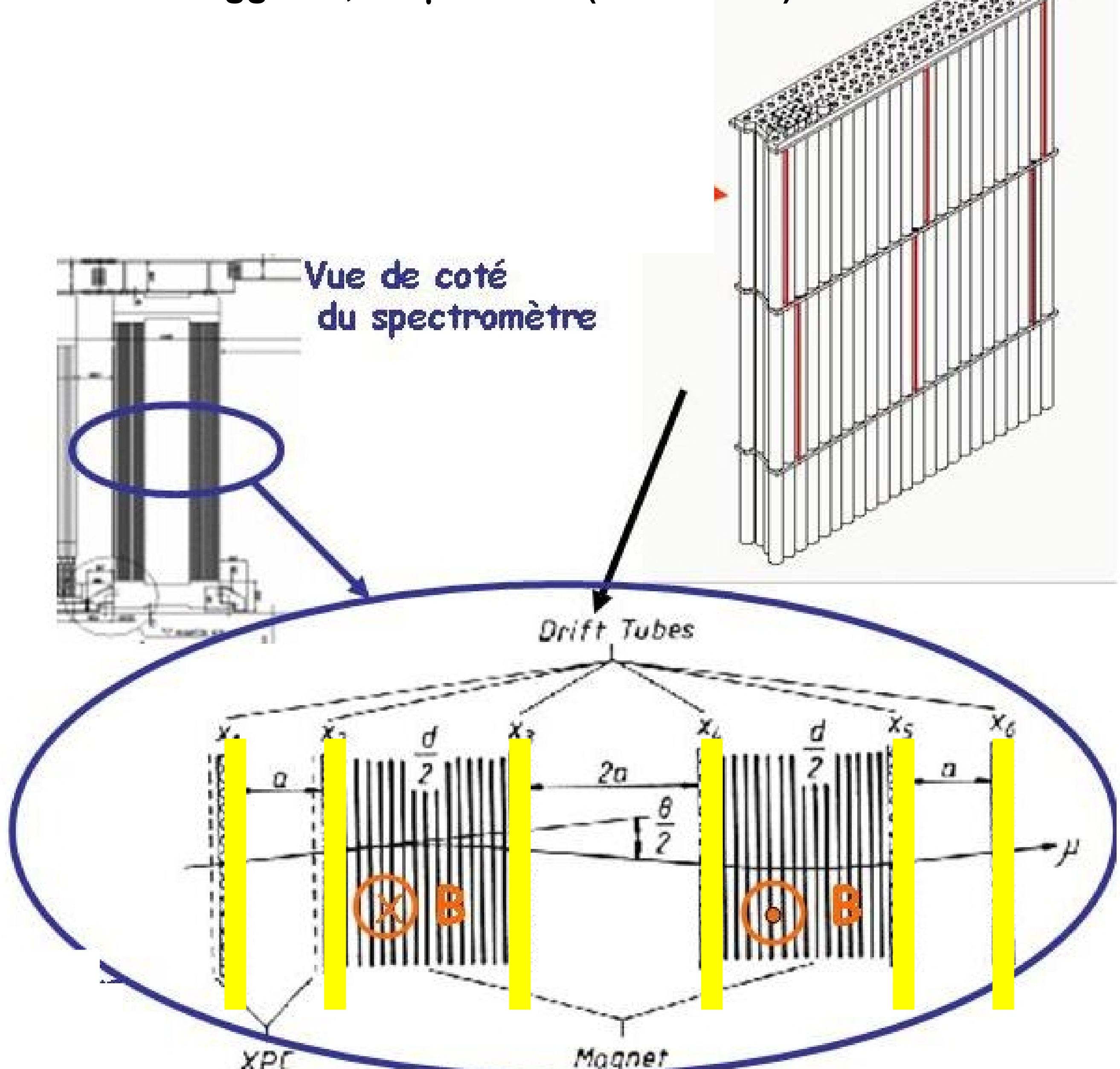


The precision trackers

38 mm diam. 8 m long tubes. 0.85 mm thick. 45 μm wire.
4 layers modules (staggered)
10.000 drift tubes
Ar/CO_2: 80/20% @ 1005±5 mbar (80 m^3 exchange 1m^3/h)
RPC-triggered, 3.2 μs TDCs (LSB 1.5 ns)

prototype in Hamburg

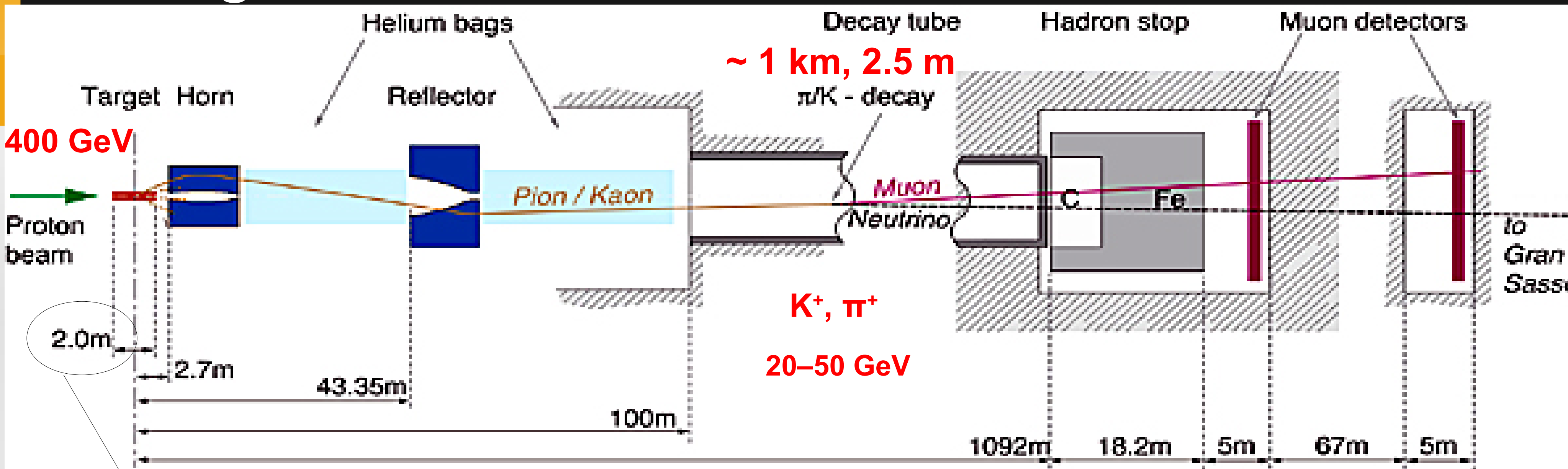


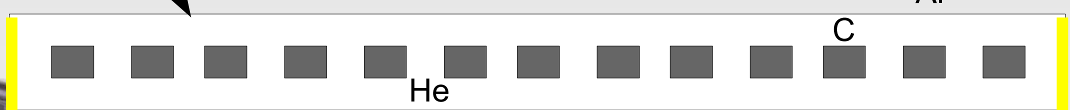


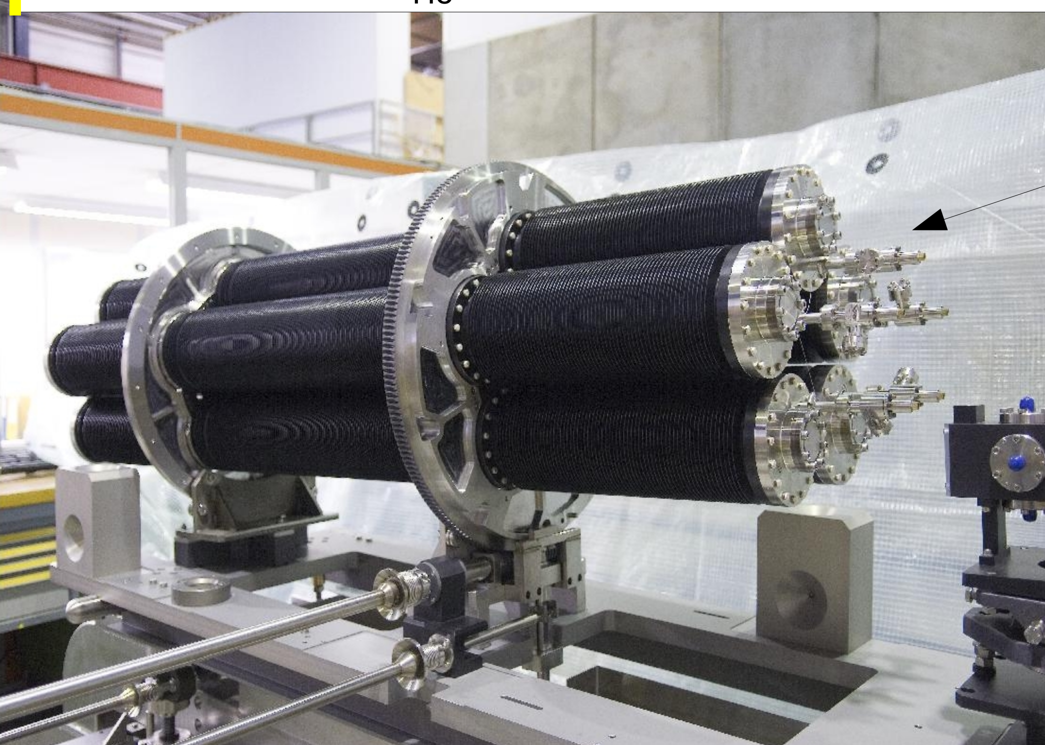
spatial resolution < 300 μm

single tube hit eff > 98%
+ correct r ~> 90%

The target downstream beamline







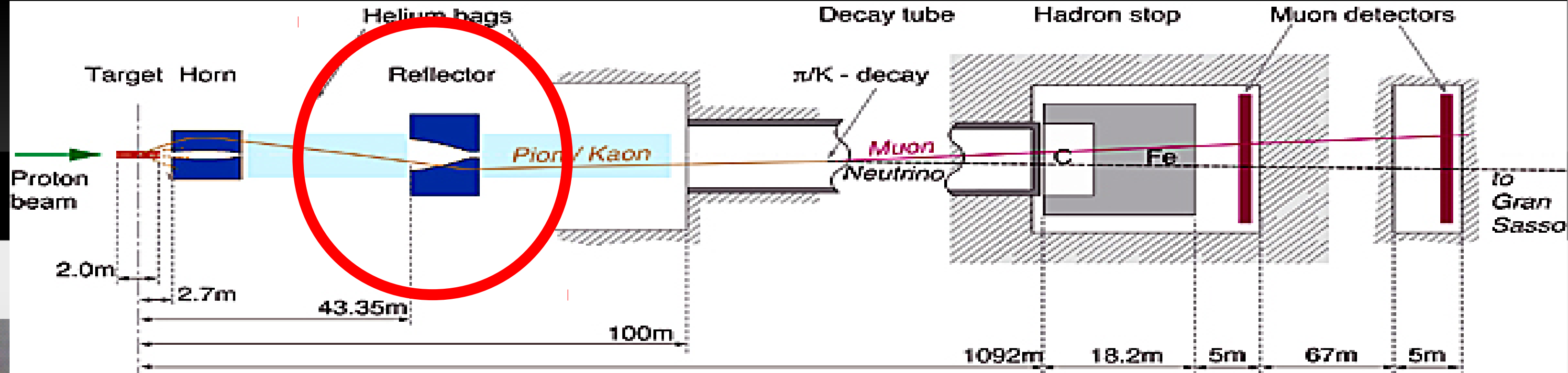
13 10cm-long graphite rods separated by 9 cm gaps. r=4 mm (5mm the first).

”Revolver” design. 1 target + 4 in situ spares

designed to withstand beam induced stress up to 3.5 10^{13} p/extraction with 400 GeV (up to **750kW** average power)

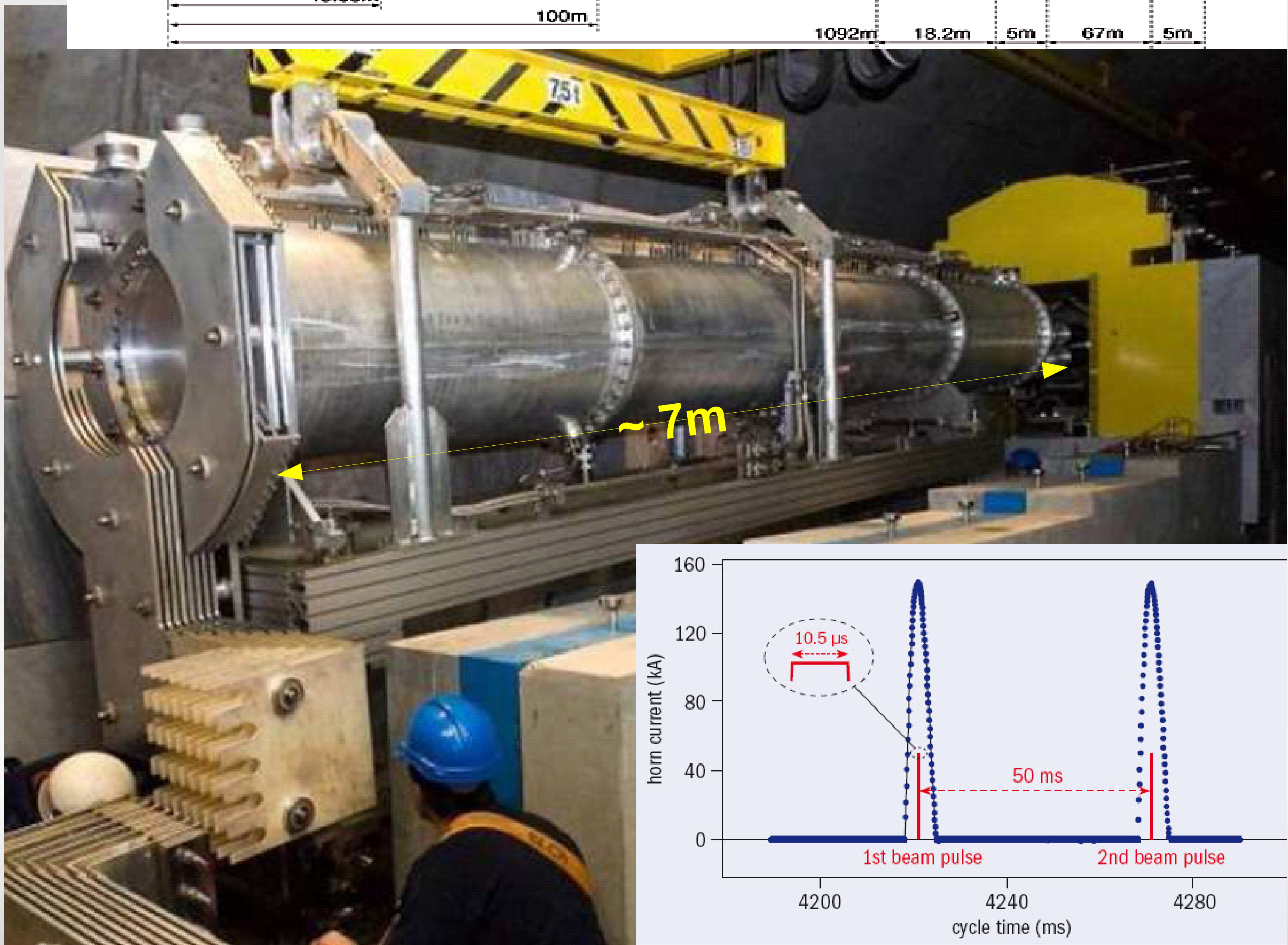
σ = 0.5 mm (tunable in 0.25-1 mm)
beam position stability onto the target averaged over several days ~ **50 μ m** (r.m.s.)

Horn

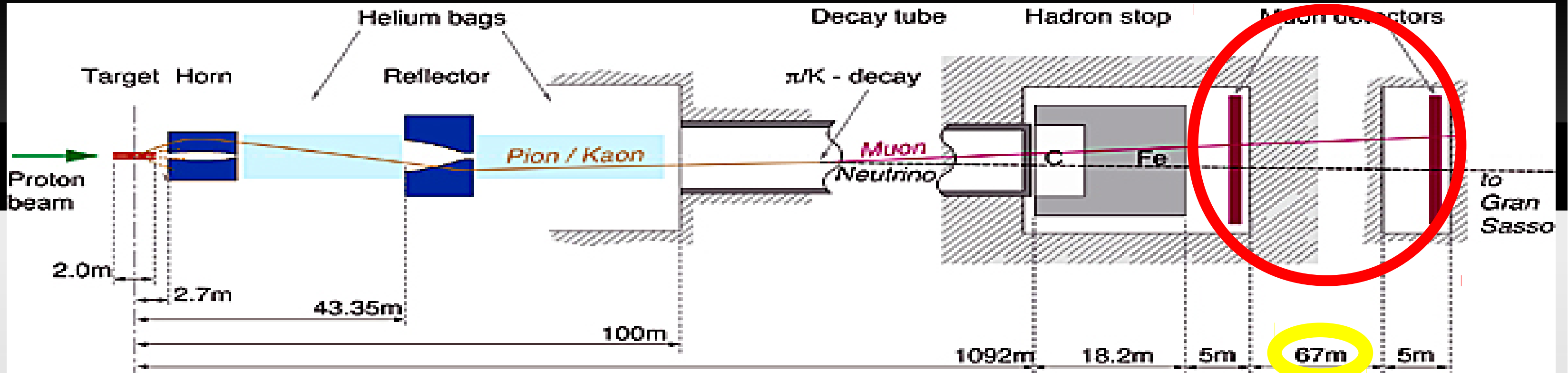


I=150 kA for a few ms (180 kA for the reflector)

water cooled



μ monitors



2 stations. 67 m rock in between

Station1: 4.0 x 10^5 μ / cm^2 / 10^{13} p

Station2: 2.5 x 10^7 μ / cm^2 / 10^{13} p

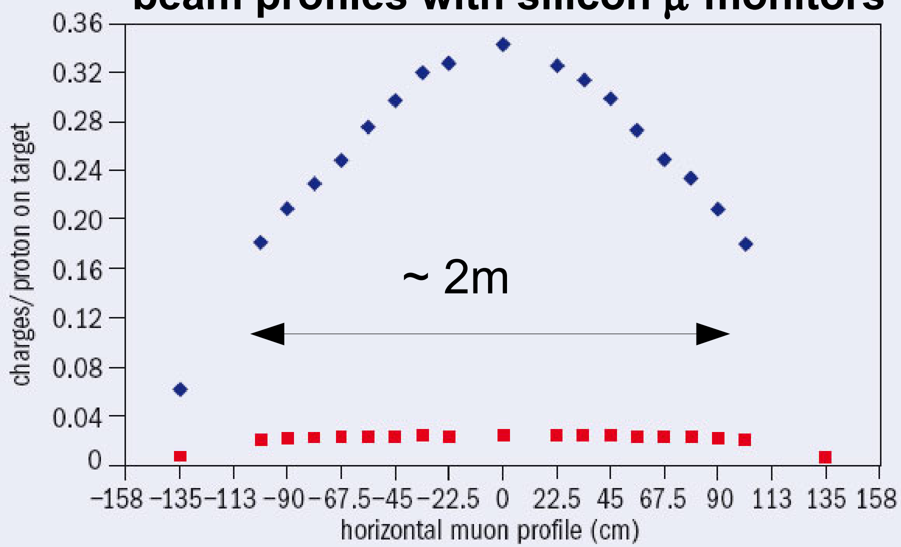
from Aug. 06 run

10^8 μ/cm^2/10 μs: high rate!

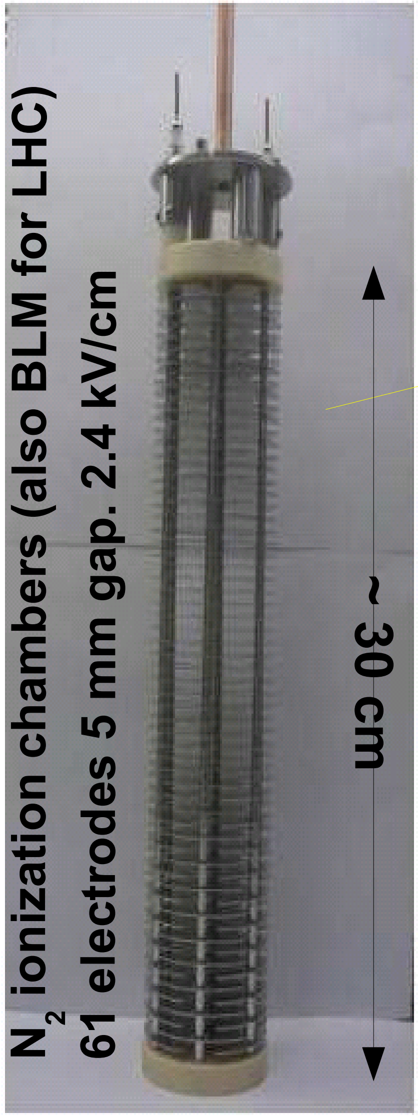
Stat. 1: E_μ > 20GeV. Target-horn alignm.

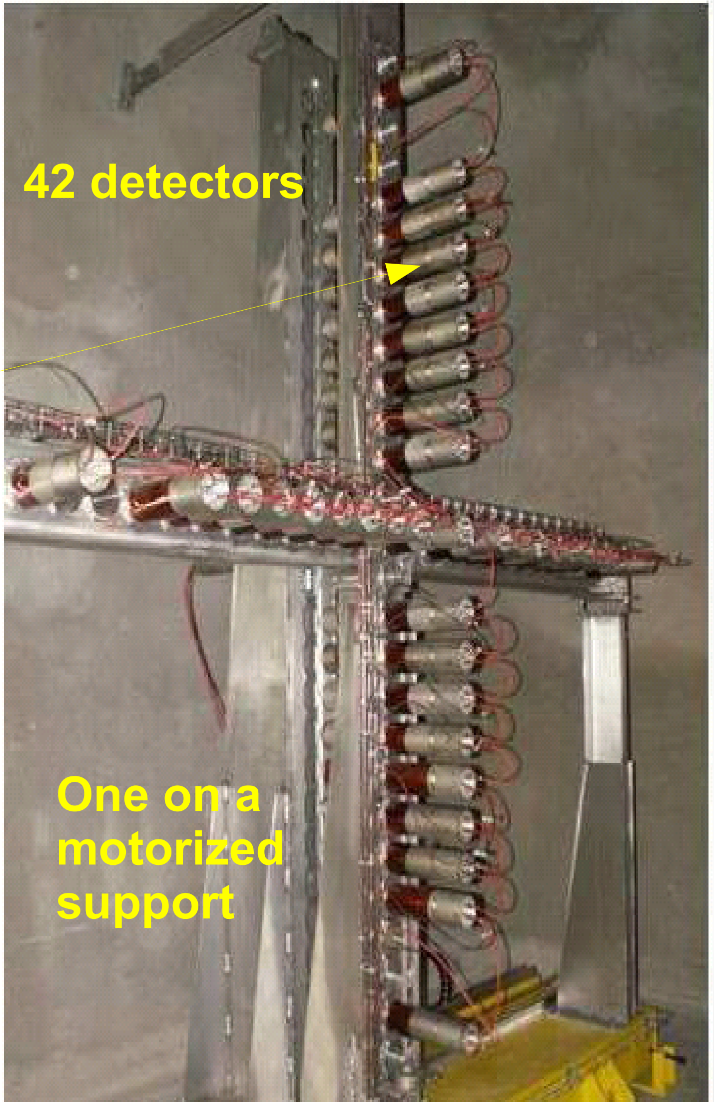
Stat. 2: E_μ > 50GeV. beam-target alignm.

beam profiles with silicon μ monitors



Horn ON/OFF

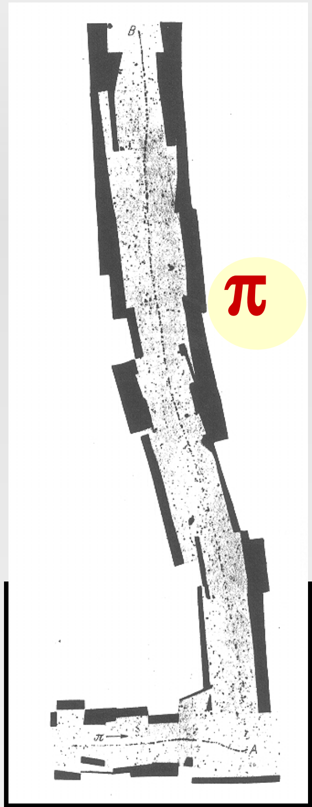




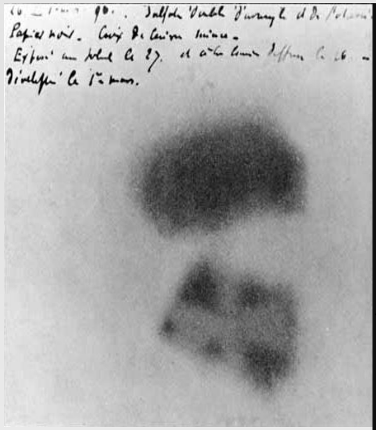
Nuclear emulsions: a “curriculum” of discoveries

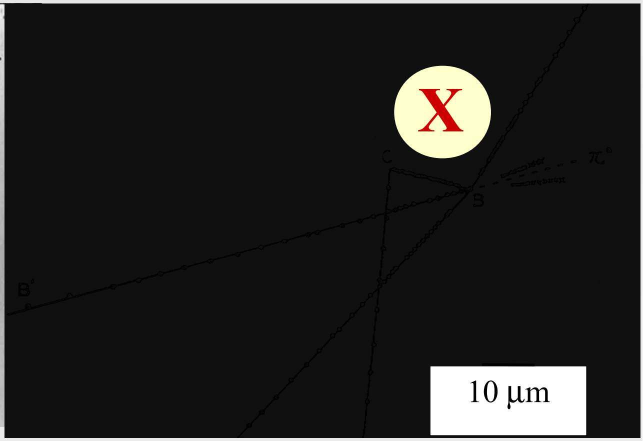
Unique tool to “see” the decay short-lived particles

1896 : radioactivity Bequerel U salts
1947 : pion
discovered in cosmic rays
1971 : charmed mesons
Pb + emulsion sandwich
formerly seen as ‘*X-particle*’ in cosmic rays
1985 : beauty mesons
WA75 hybrid experiment
first observation
2000 : tau ν
DONUT “beam-dump” exp.



•Established technique





<u>nowadays</u>
Large scale automatic scanning
+ massive targets

τ decay search in ν_τ^{CC}

~ “zero background” exp. small statistics is acceptable

Further experience of E531, CHORUS

CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN

LHC or CNGS ?!

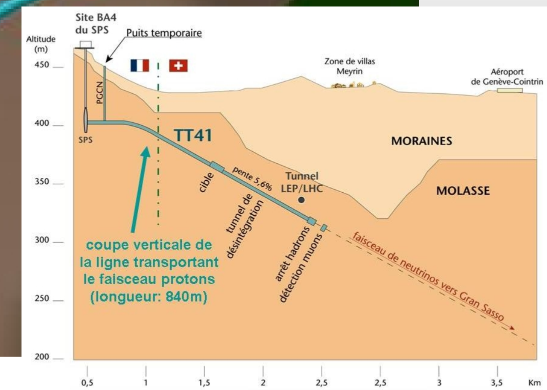
620 m arc + 120 m focusing section

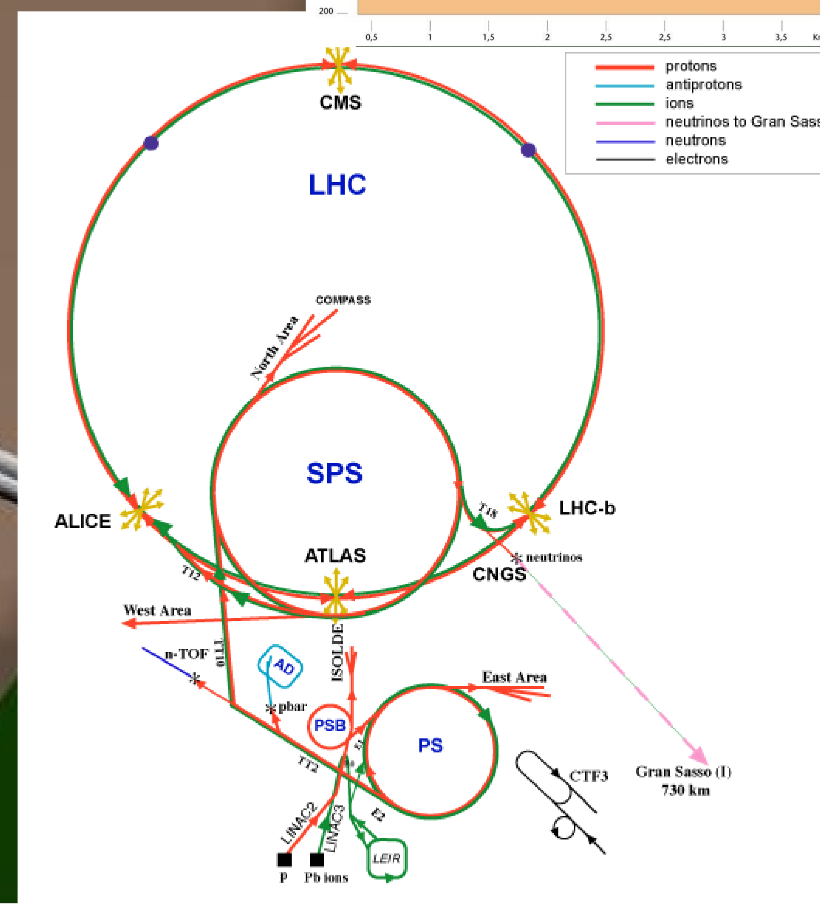
E: 350-450 GeV

73 dipoles: 1.7 T @ 400 GeV
20 quadrupoles: 40 T/m
12 corrector magnet: max. defl. 80 µrad.

5.6 % slope ~ 3 degrees

32 horizontal dipoles tilted by 12.8 deg.





22+1 BPM (Beam Position Monitors)
button electrode monitors from LEP. tol ± 0.6 mm

last BPM: tol ± 0.035 mm
strip-line coupler pick-up mechanically connected with target

8 BPM (beam profile monitor)
OTR (optical transition radiation monitors)
75 µm C(high.int) 12 µm Ti (low int.)

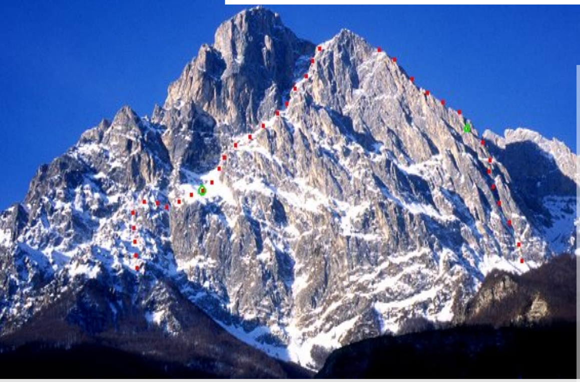
2 BCT (beam current transformer):
beam intens. at start and end.

18 BML (beam loss monitor)
N_2 filled ioniz. chambers

Finally at LNGS !

Laboratori Nazionali del Gran Sasso (the largest underground lab)

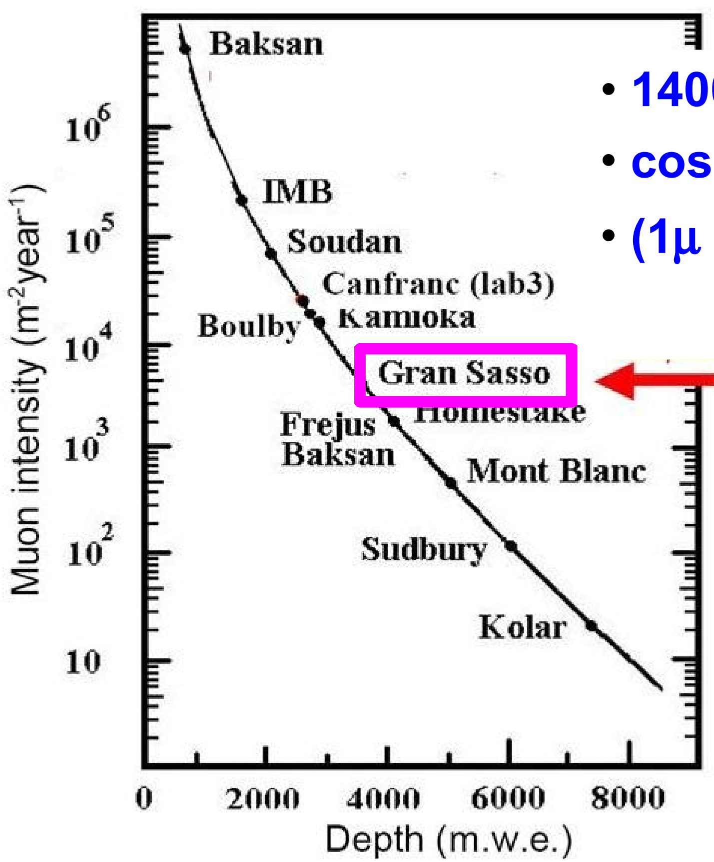
2912 m



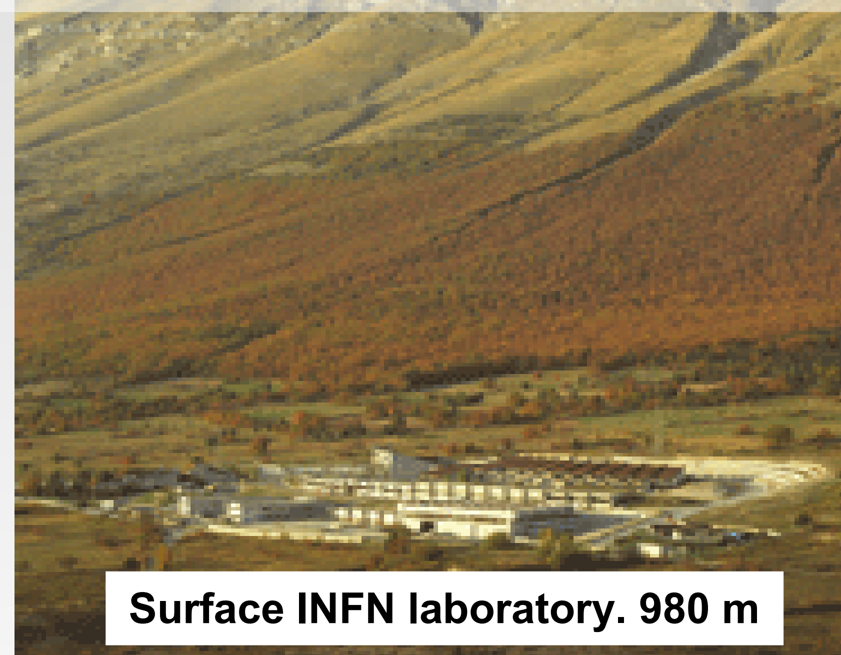
- ν phys. ($\beta\beta 0\nu$ solar-ν, atm.-ν, LB ν-osc.)

HM$\beta\beta$, MACRO, GNO, BOREXINO, OPERA, ICARUS, CUORICINO, COBRA, CUORE, GERDA

- DM - CRESST, DAMA, LIBRA, HDMS, GENIUS-TF, XENON, WARP
- Particle & nuclear astrophysics - EASTOP, LVD, LUNA, VIP
- Gravitational waves - LISA / Geophys., seismology - ERMES, UNDERSEIS, TELLUS, GIGS. Biology - ZOO, CRYO-STEM



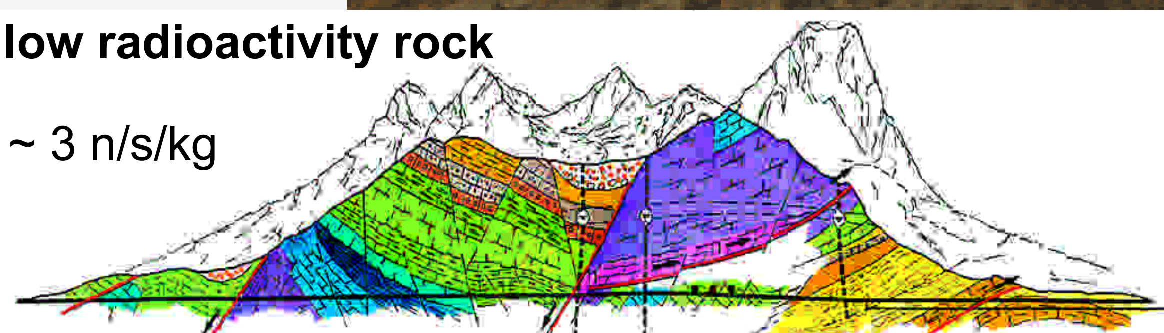
- 1400 m rock overburden
- cosmic μ reduction ~ 10^6
- (1μ /m^2/h)



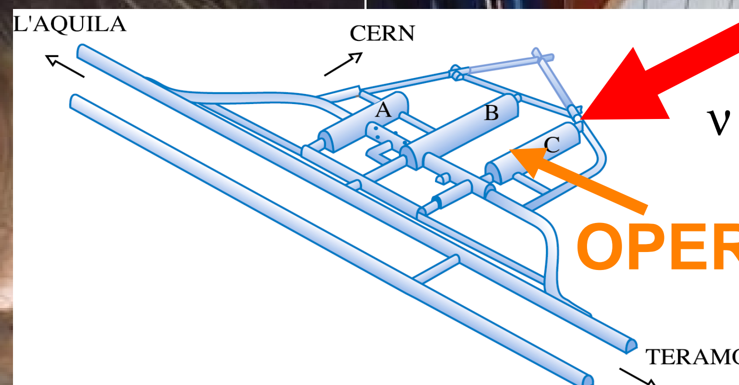
Surface INFN laboratory. 980 m

low radioactivity rock

~ 3 n/s/kg

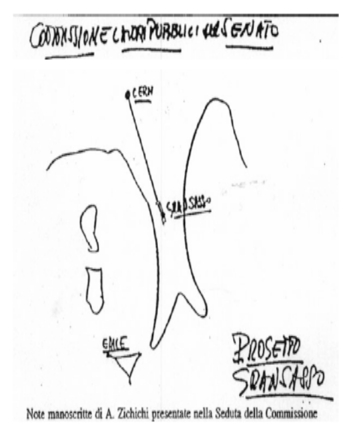


1982 Construction



- ~ 750 scientists from 25 countries

1979



Note manoscritte di A. Zichichi presentate nella Seduta della Commissione

To summarize, the scientific aims of the "Cran Sasso" laboratory are the study of:

1) nuclear stability;
2) neutrino astrophysics;
3) new cosmic phenomenology;
4) neutrino oscillations;
5) biologically active matter;
6) ground stability.

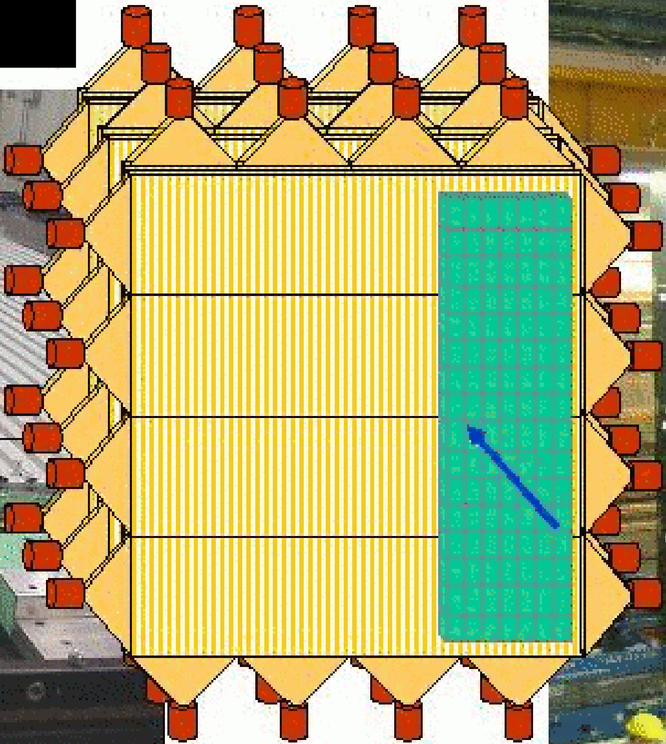
NOT only $\tau_p \neq \infty$

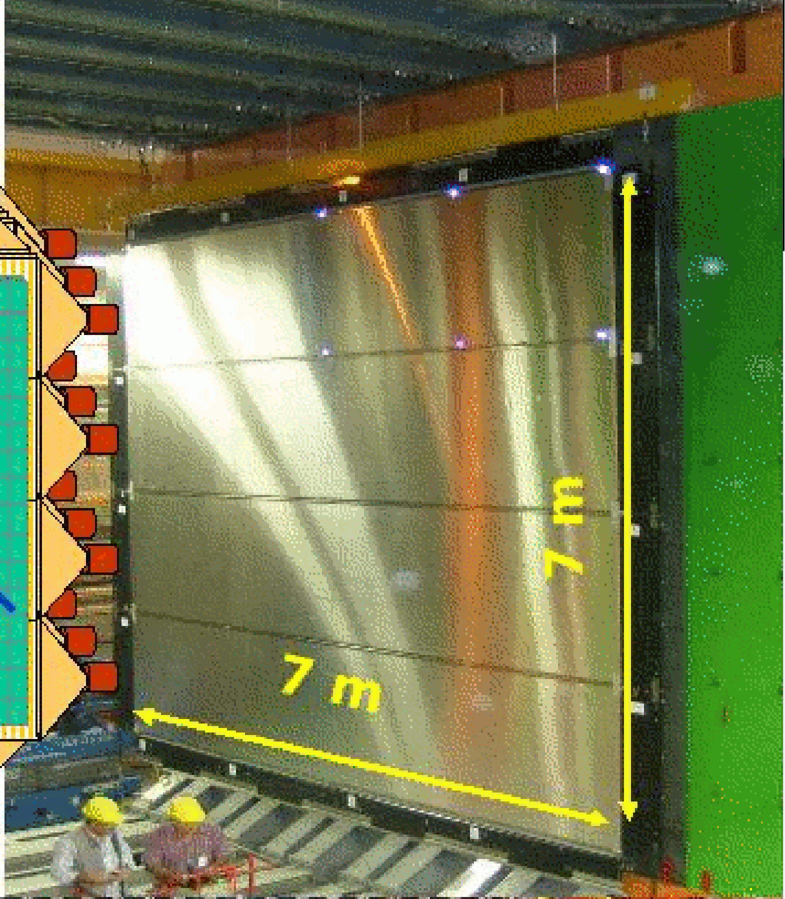
- 3 big experimental halls
- ~ 100 X 20 X 20 m
- ~ 18 000 m² underground
- easy access (motorway)
- aligned to CERN to ~1° level !

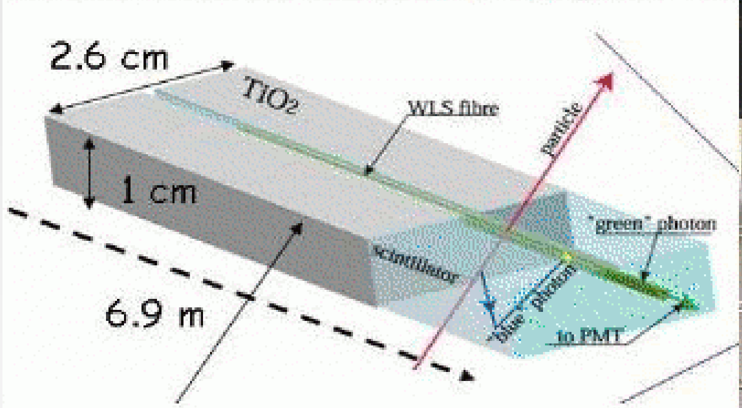
Target tracker

tasks

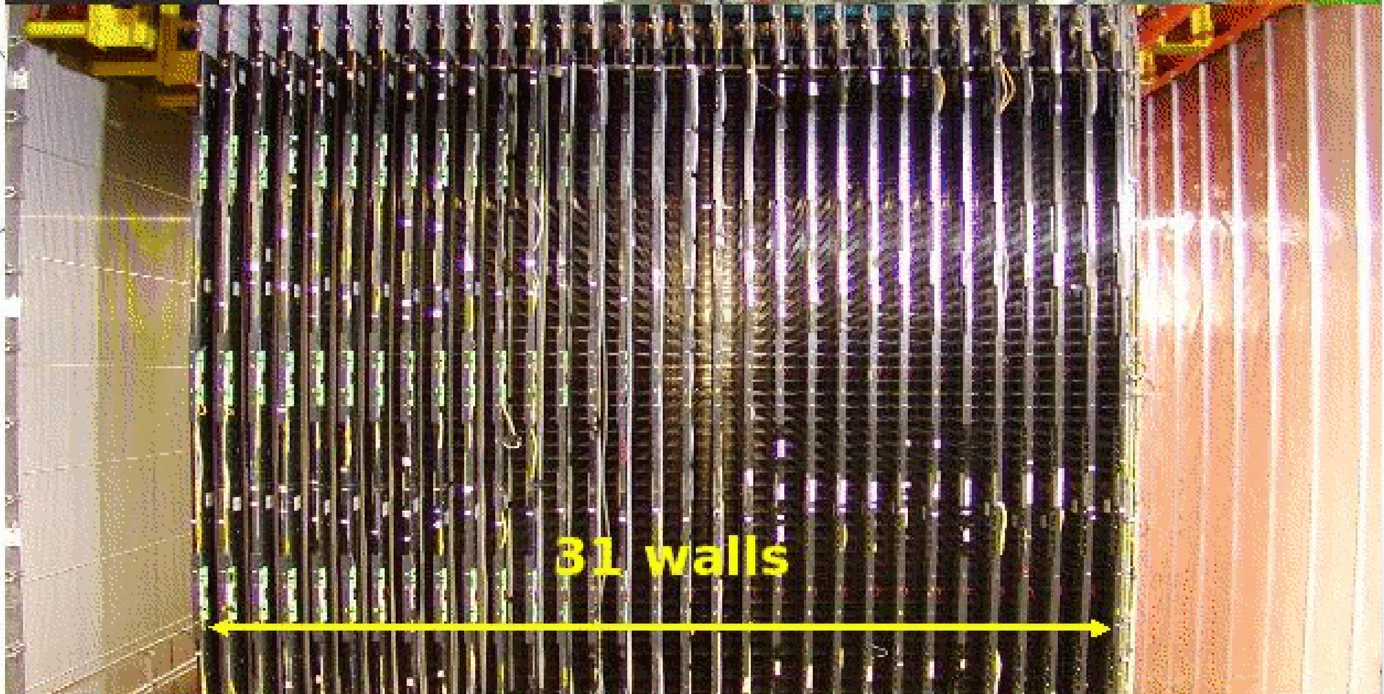
- Brick finding
- Initiate muon tagging
- provide calorimetric info







- Plastic scintillator strips
- 670 x 2.6 x 1 cm
- R/O by WLS fibres
- 2 ends R/O
- Hamamatsu PMT's (64 ch.)
- 6 p.e. minimum
- Probability 0 p.e. = 0.2 %



Lead production

- Pb + 0.07% Ca with packaging in air
  - ✓ good mechanical properties
    - 10 μ m planarity and 100 μ m at edge
  - ✓ low radioactivity
- produced in Germany (JL Goslar GmbH)
- sent by trucks (~ 100 shipments)

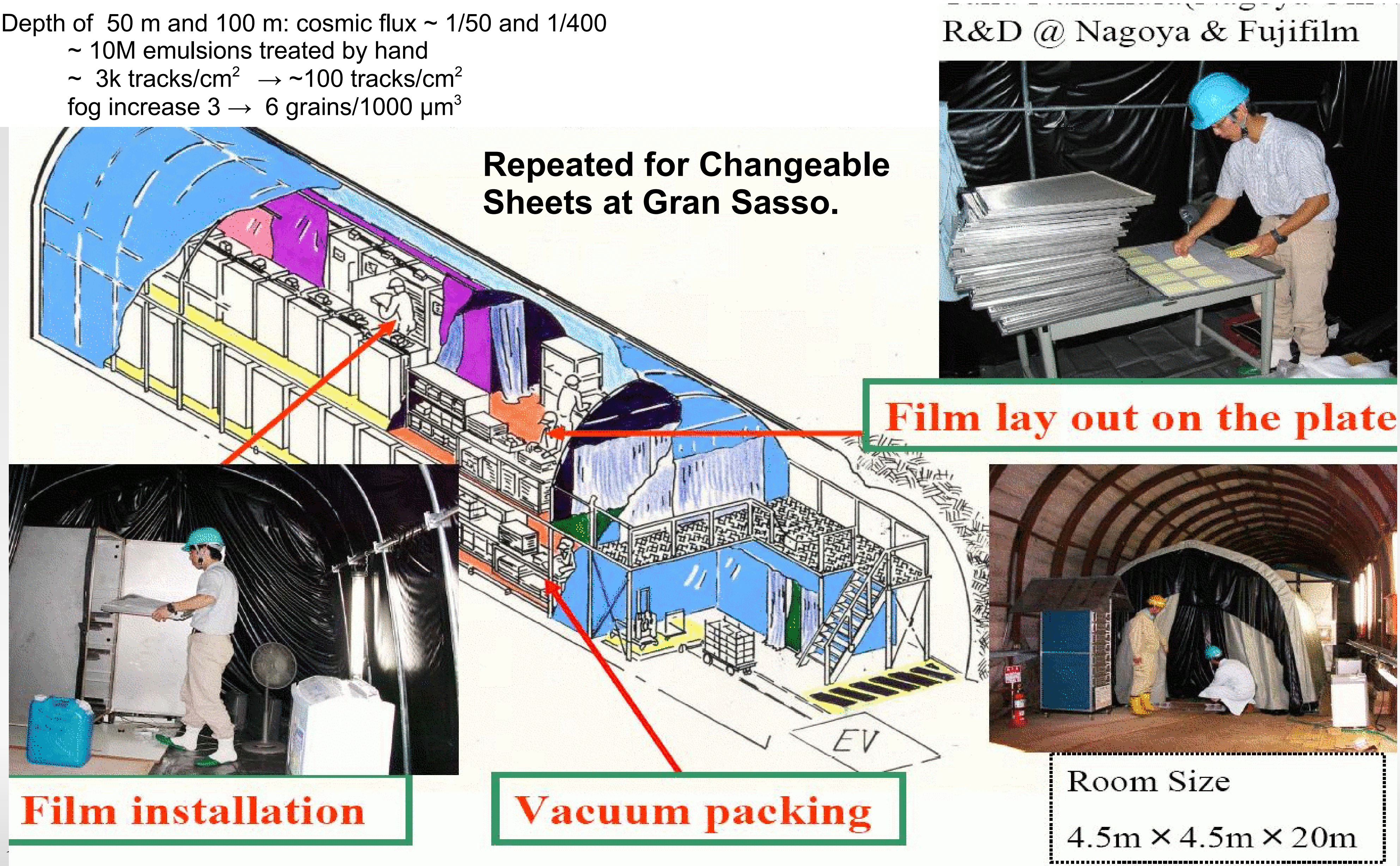
The refreshing at Tono mine (a huge work!)

Production ~ 1 month ~ 3k tracks/cm^2 (cosmic) >> max density = 100 tracks/cm^2 for brick analysis =>
REFRESHING (stimulated fading of latent image, "erasing" of previous history)

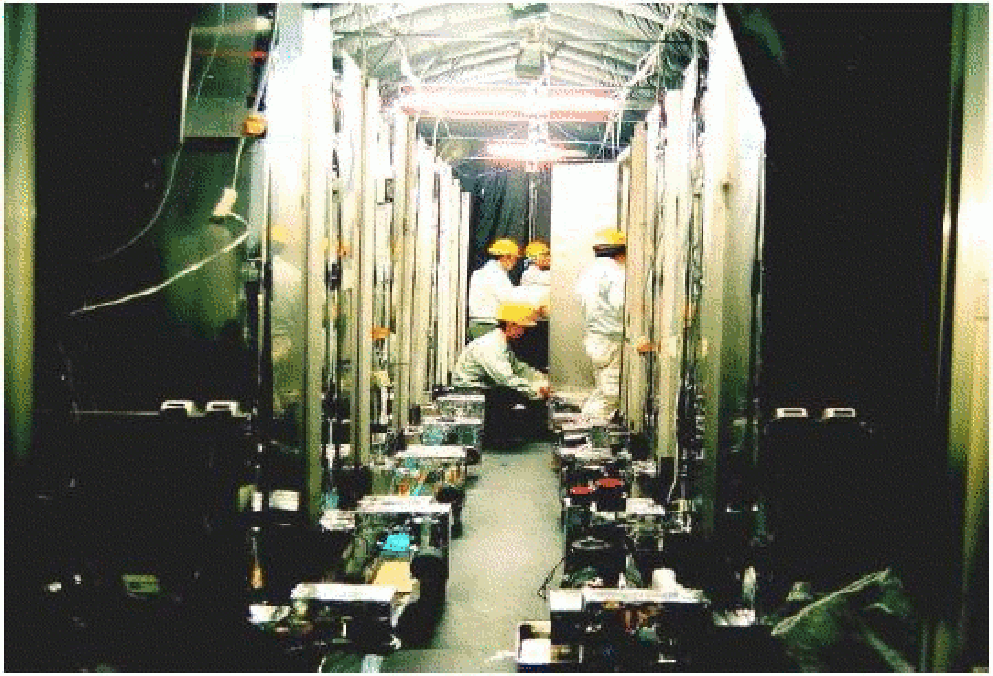
3days @ 98% RH and 27°C: grain density of tracks: 36 → <10 grains/100µm with unvaried sensitivity (34 grains/100µm)

Depth of 50 m and 100 m: cosmic flux ~ 1/50 and 1/400
- ~ 10M emulsions treated by hand
- ~ 3k tracks/cm^2 → ~100 tracks/cm^2
- fog increase 3 → 6 grains/1000 µm^3

Repeated for Changeable Sheets at Gran Sasso.



Emulsion delivery (2005)



• Shipment to Gran Sasso by sea in ~ 1 month (kept at 15 C and vertical: less cosmics, especially electrons w.r.t. Aircraft): ~ 1000 /cm^2

• Special underground storage at Gran Sasso (Hall B). 5 cm Fe shielding @ 15-18 C (1 μ/m^2/h)

• Memory of emulsion order during transportation (from Japan to Europe) is kept and taken into account during brick assembly. Segments which are aligned assuming a spacing equal to the emulsion thickness (cosmics recorded during transportation) are discarded at analysis level : ”virtual erasing” concept. Very powerful technique:

• 43±4 (Tono)→113±20 tracks/cm^2 with virtual erasing and 1000±50 /cm^2 without !

The BMS eyes

Pictures of a tray taken by the BMS vision system before (left) and after (right) insertion of bricks. The shadow of the tray visible on the brick surface is used to compute the distance of the brick with respect to the tray border.

The muon spectrometer

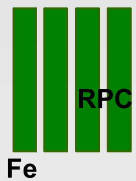
(one per supermodule)

Charm background rejection

- Muon identification (Spectrometer+TT) > 95%
- $\Delta p / p < 20\%$ for $p<30$ GeV
- Charge misidentification < 0.3%

- **Inner trackers** iron yoke gaps instrumented with **RPCs**
  horizontal and vertical strips with digital readout $\sigma \sim$ cm
  - Tracking and p from range for stopping mu
- **Precision trackers** 6 vertical **drift tubes** stations. $\sigma \sim 0.3$ mm
  - Precise charge mis-ID / p measurement

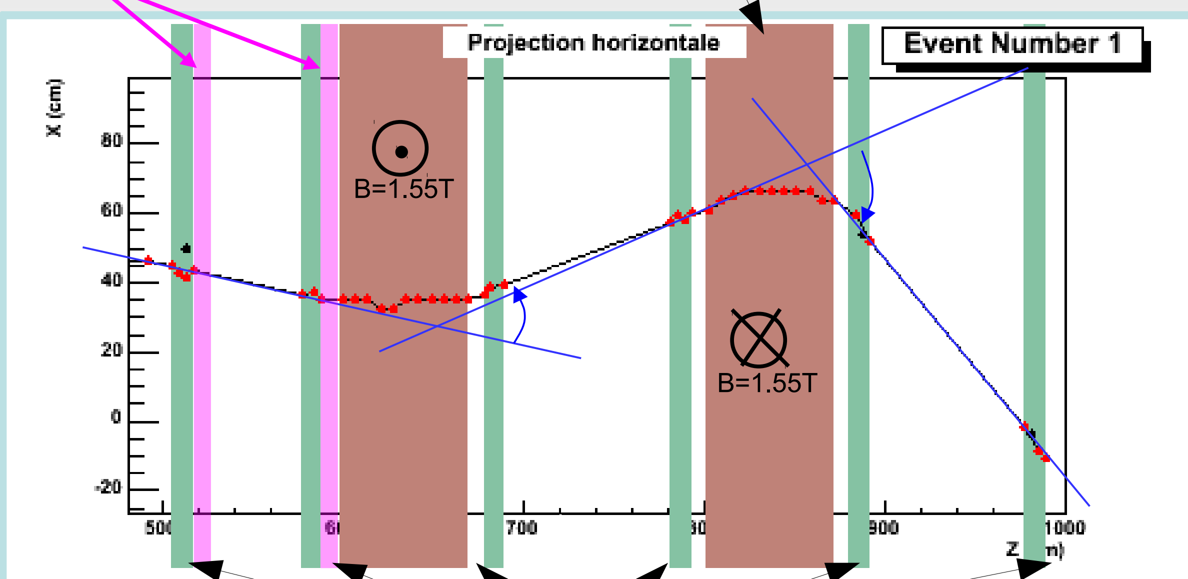
- Bipolar magnet (B=1.55 T)



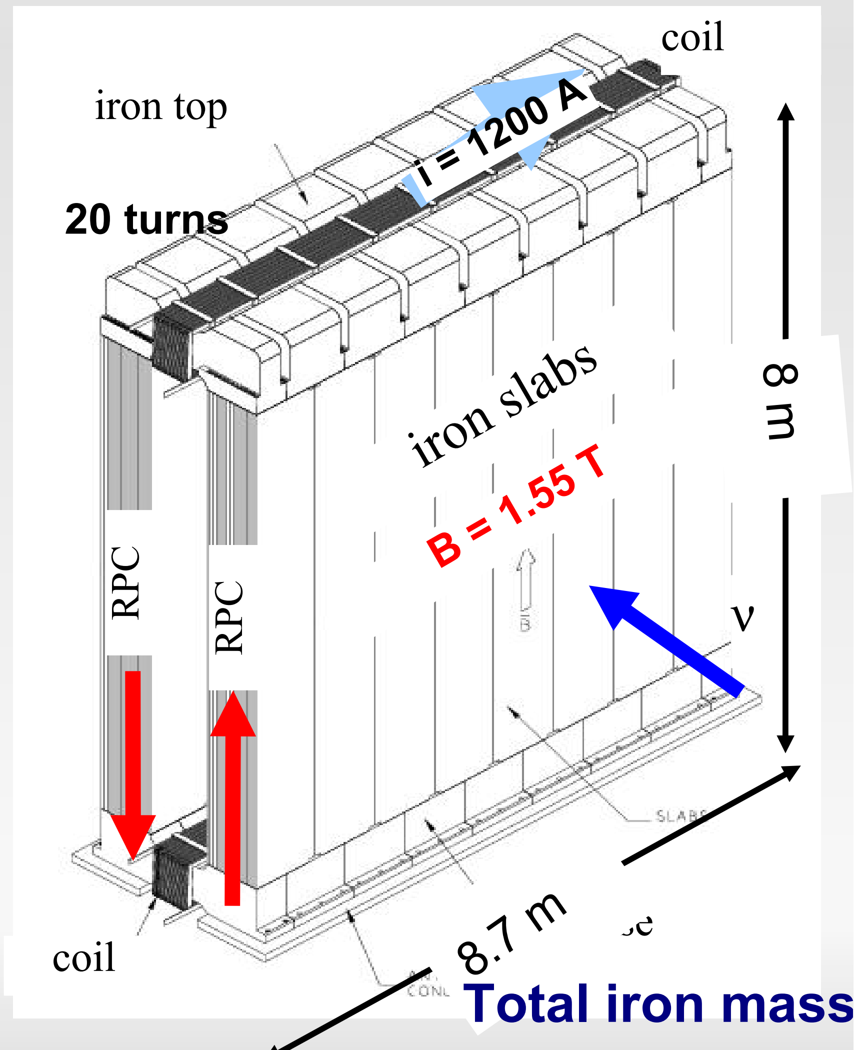
- 24 iron slabs, 5 cm thick + 2 cm gap

RPC with inclined strips
(to solve PR ambiguities)

top view



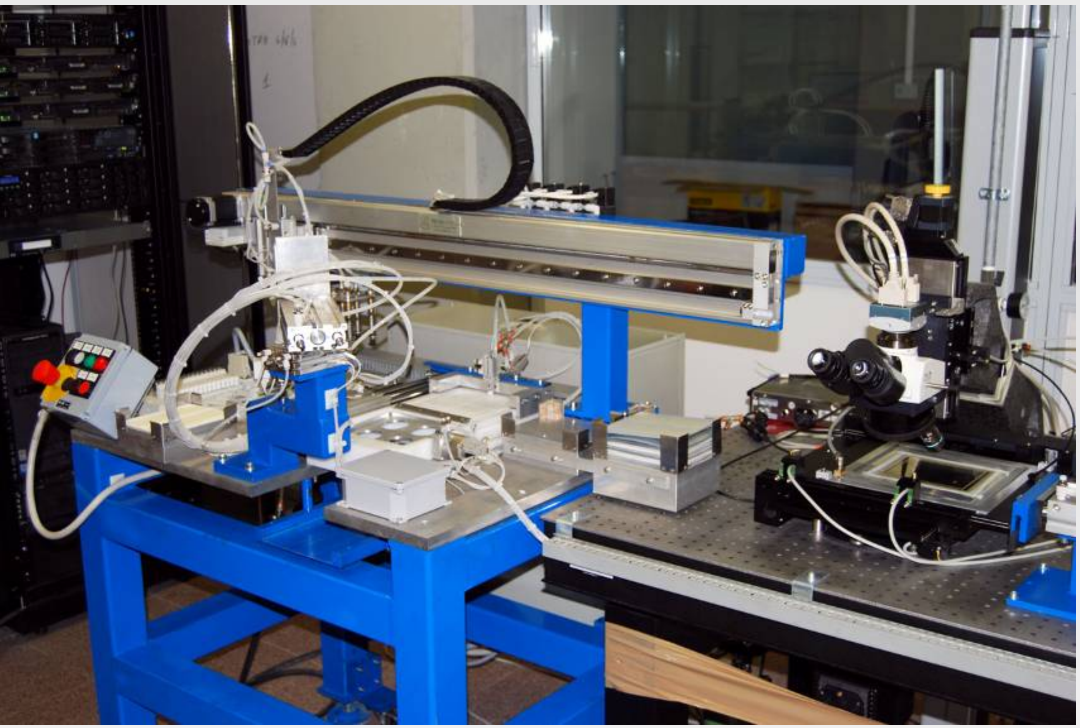
Drift tubes



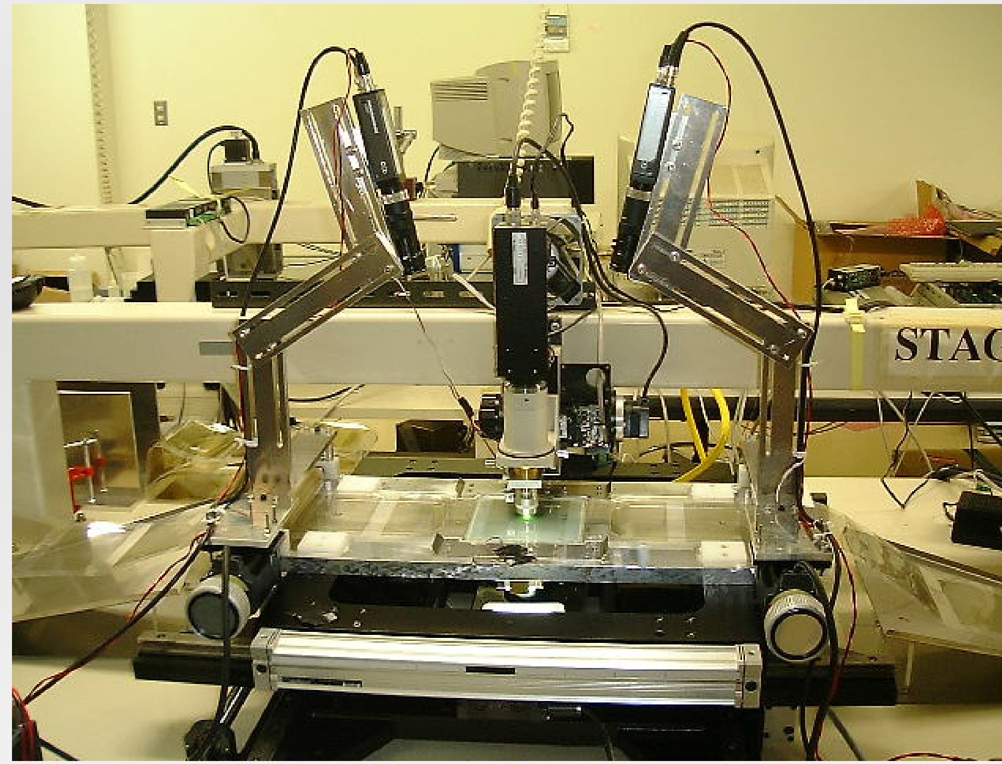
Total iron mass 1.3 Kton

Auxiliary systems to automate the scan-back procedure

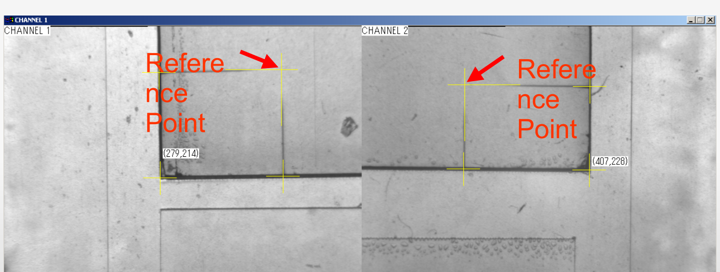
Europe: mechanical plate changer

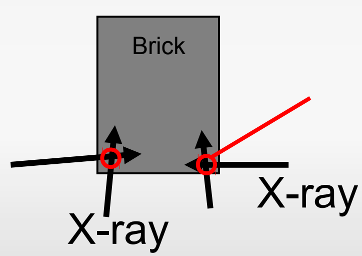


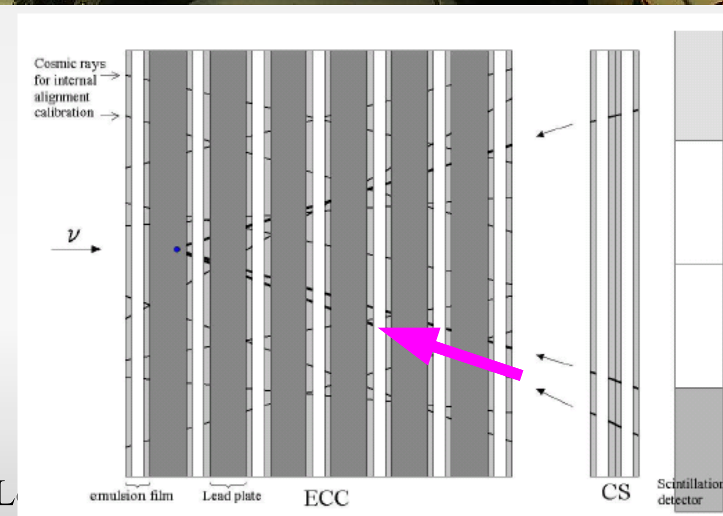
Japan- emulsion glued to a rolling strip



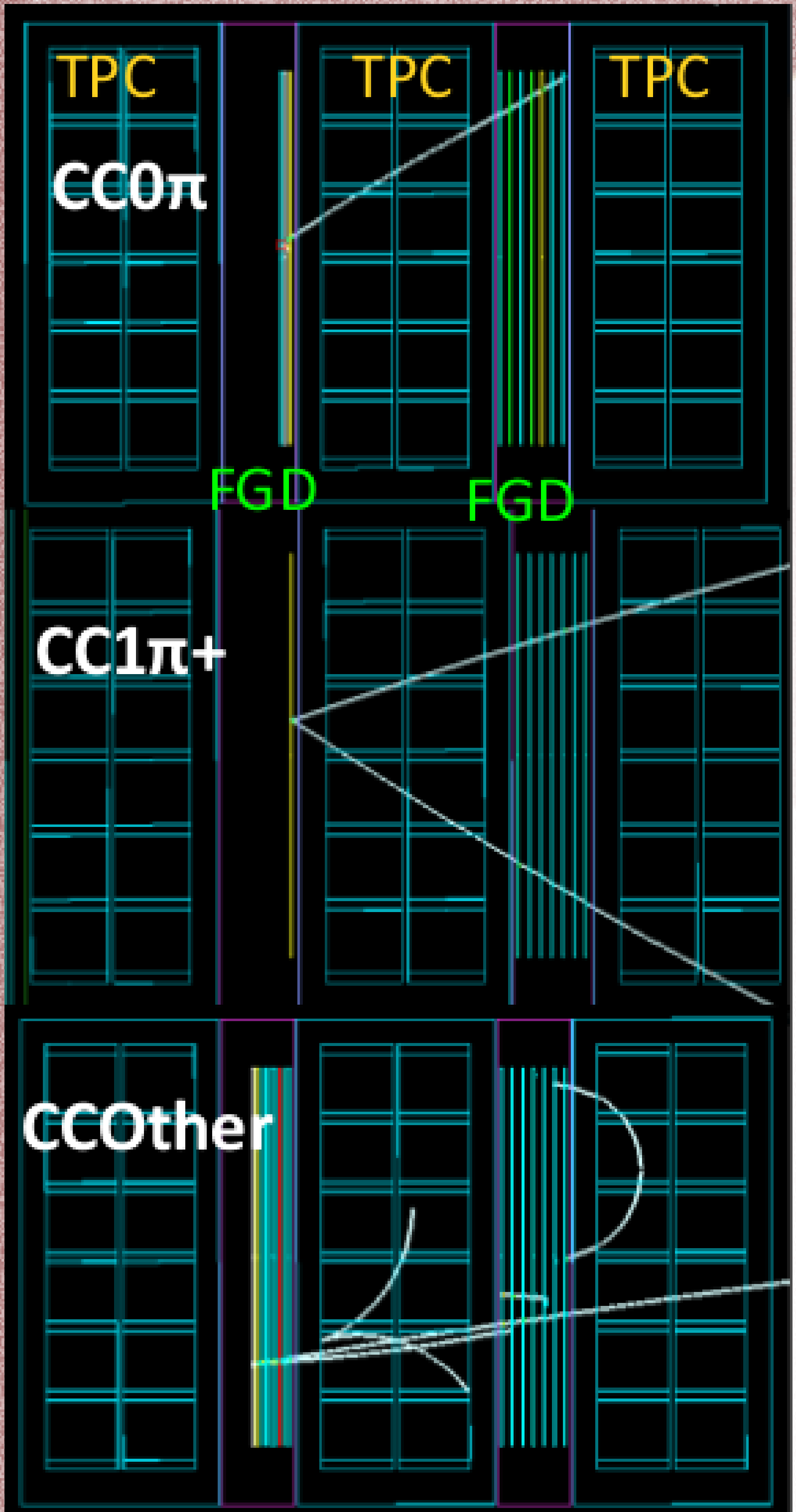
Allows to run the scan-back procedure without human intervention (i.e. overnight)





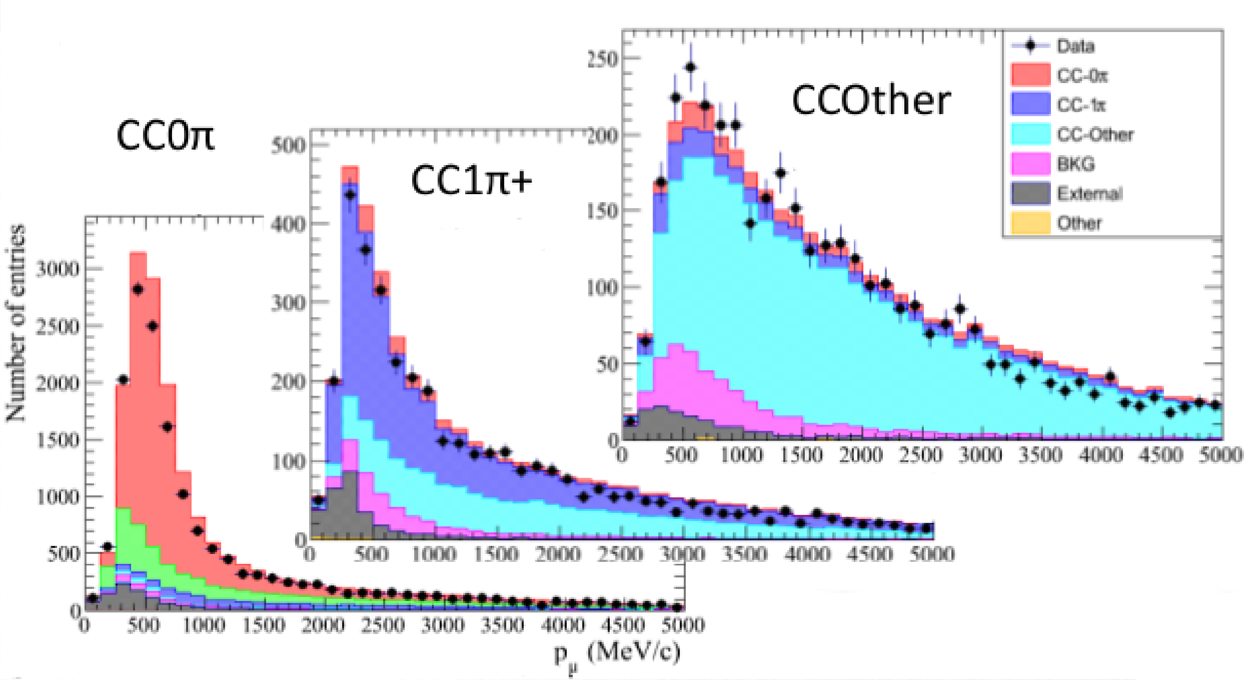


Analisi al rivelatore vicino off-axis



Fit dello spettro dei ν_μ per vincolare il flusso e la sezione d'urto (i ν_μ vincolano anche i ν_e)

3 sotto-campioni con π nello stato finale: "CC 0π", "CC 1π" e "CC other"

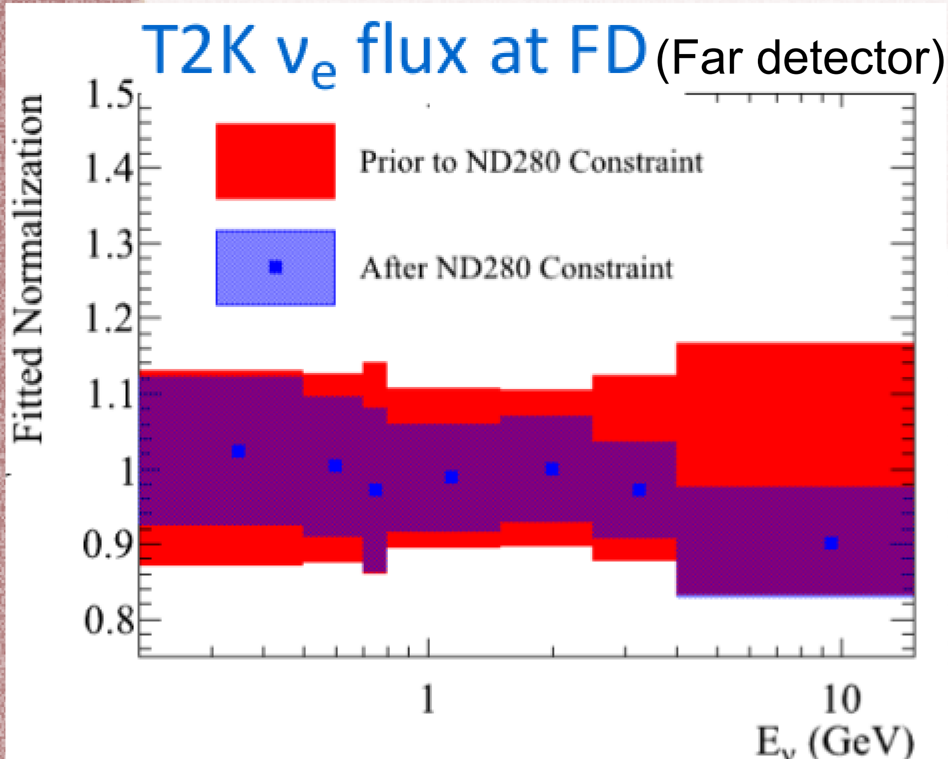


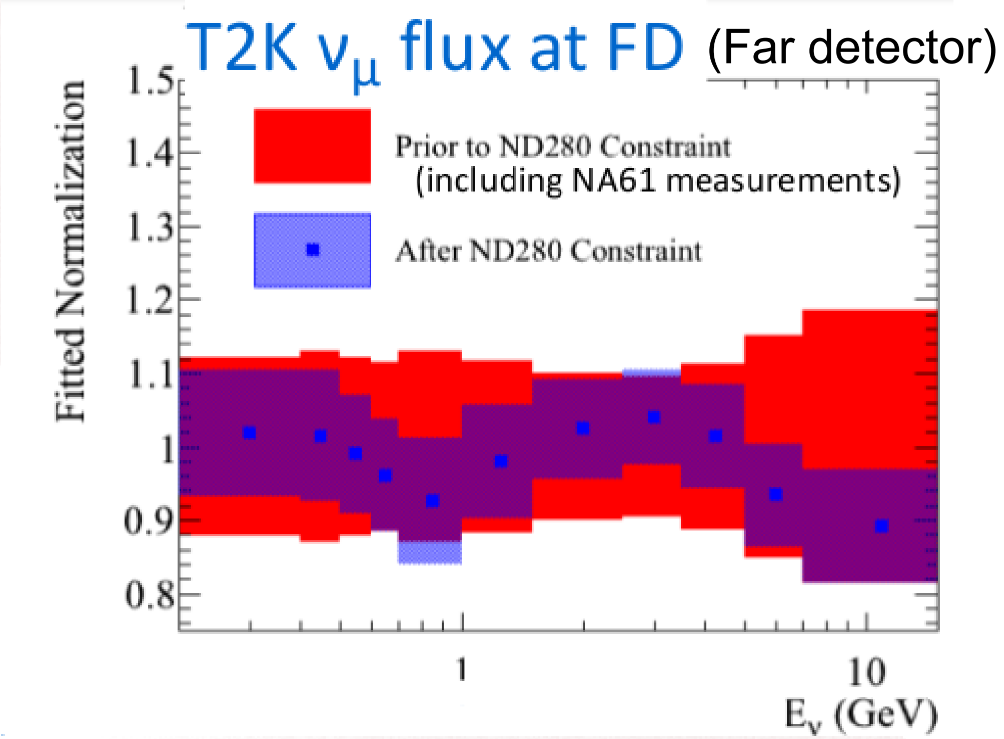
“Impatto” del rivelatore vicino

Adro-produzione da misure dirette al CERN su una replica esatta del bersaglio (esperimento NA61)

Riduzione del sistematico sugli eventi al far da incertezze sul fascio e sulle sezioni d'urto

Parametro	Prima	Con la misura di ND280
M_A^{QE} (GeV)	1.21 ± 0.45	1.223 ± 0.072
M_A^{RES} (GeV)	1.41 ± 0.22	0.963 ± 0.063
Norm. CC-QE	1.00 ± 0.11	0.961 ± 0.076
Norm. CC-1π	1.15 ± 0.32	1.22 ± 0.16
Norm. NC-1π^0	0.96 ± 0.33	1.10 ± 0.25

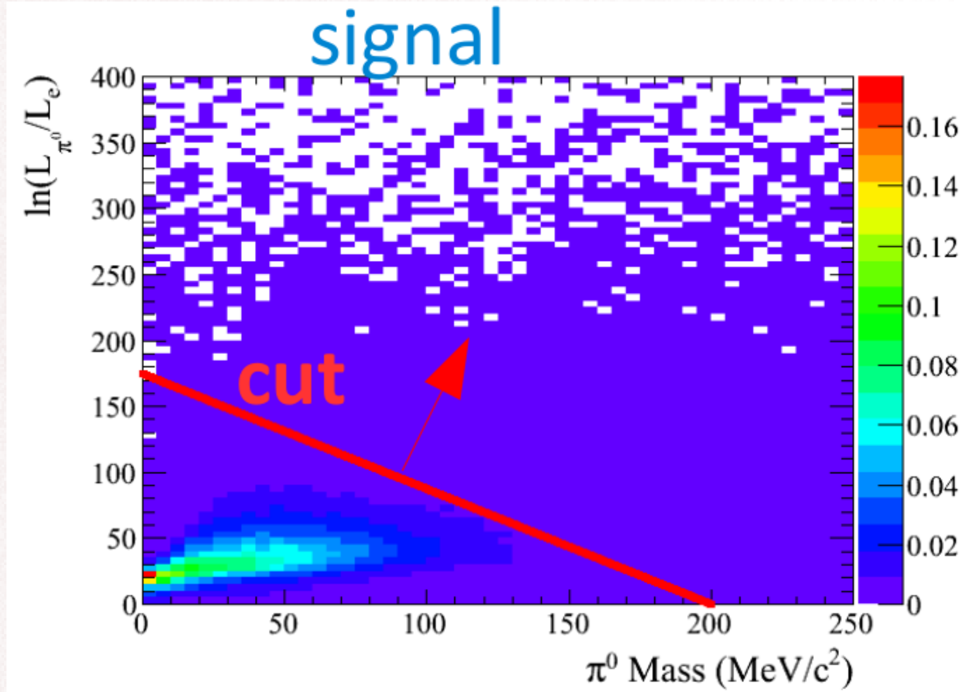


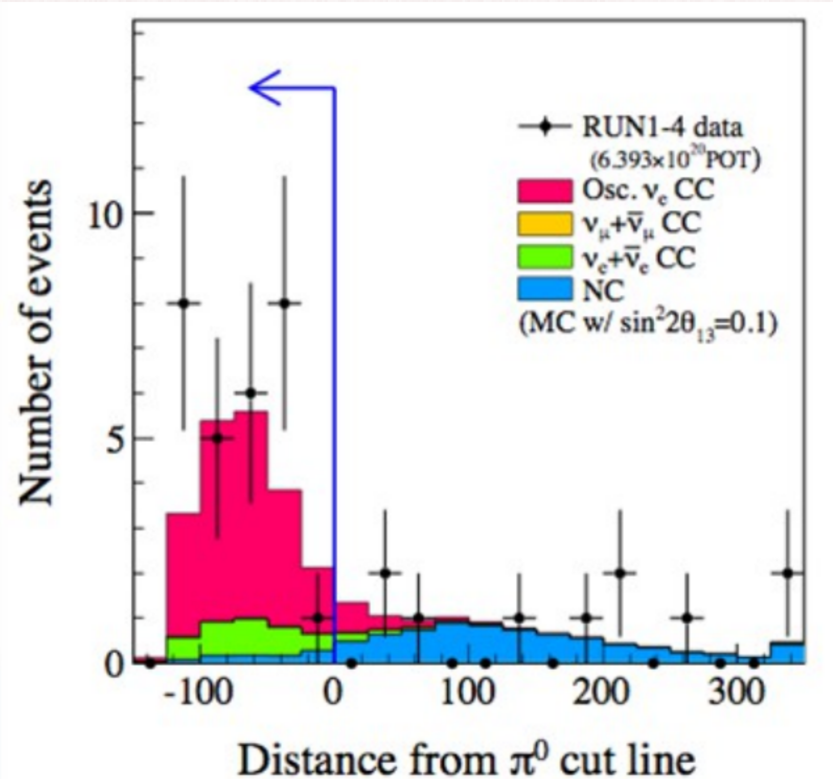


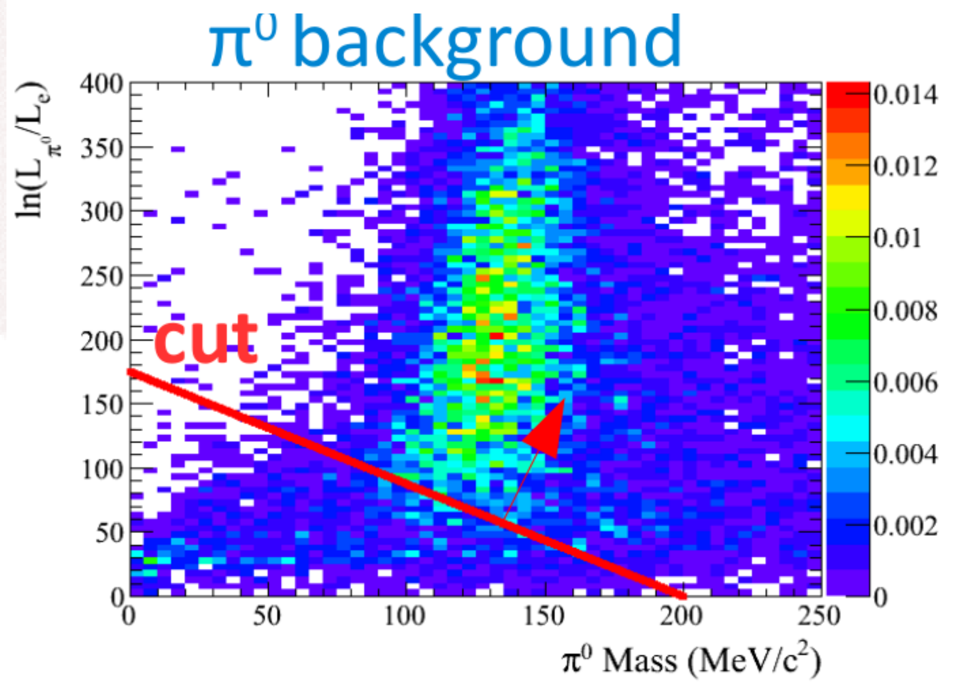
Miglioramento nella reiezione dei π^0 in Super-K

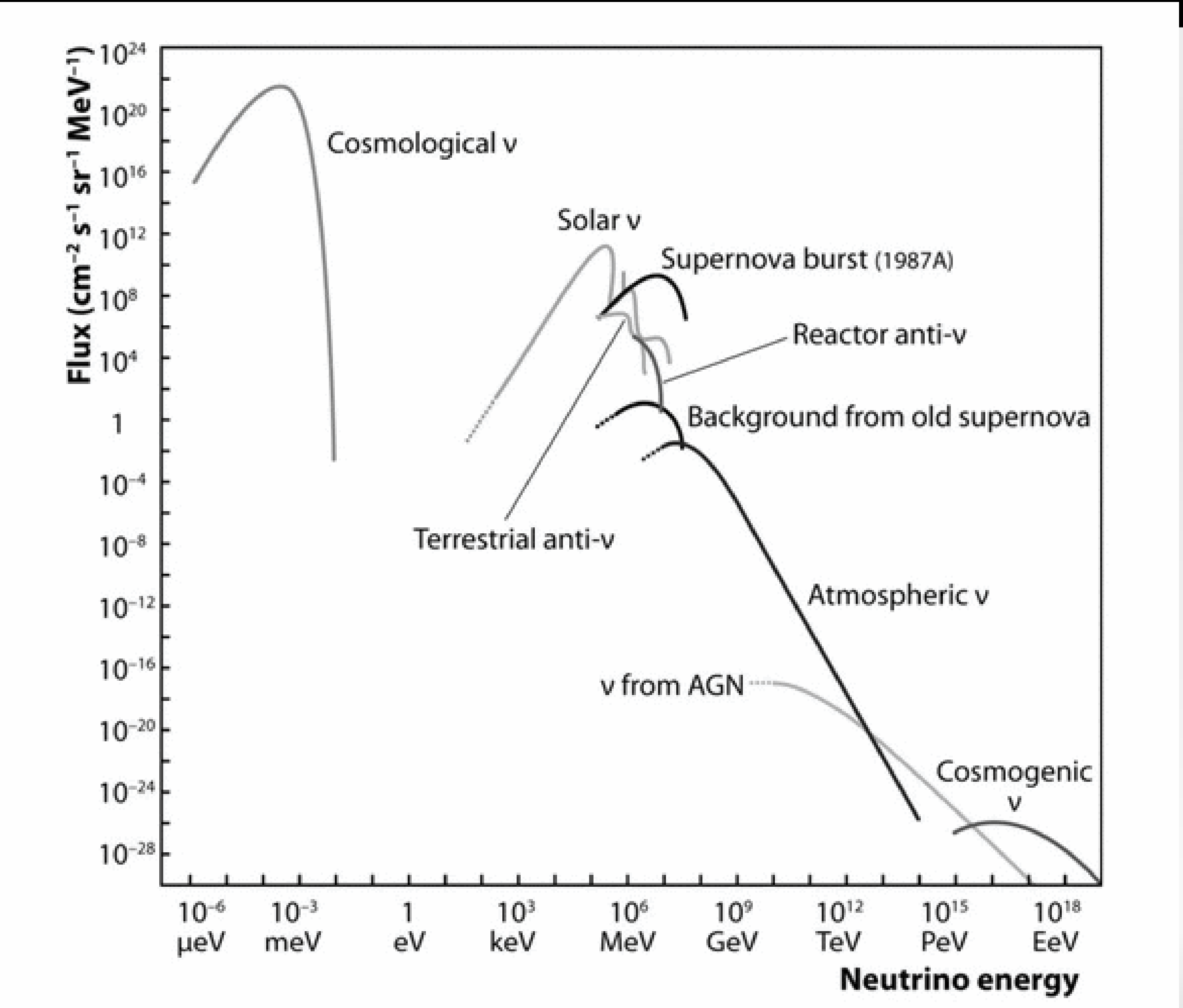
- PDF di carica e tempo per ogni PMT e ogni topologia di evento (e, μ, π^0)
- confronto tra le likelihood di best-fit (e/μ, 1/2/3 rings etc.) → si seleziona la migliore ipotesi
- migliore particle-ID e risoluzione in momento
- usato per rigettare i π^0 (fondo dominante dei ν_e)
- il taglio in 2D rimuove il 70% dei π^0 che sopravvivevano usando l'algoritmo precedente

→ **riduzione totale del fondo del 27%!**





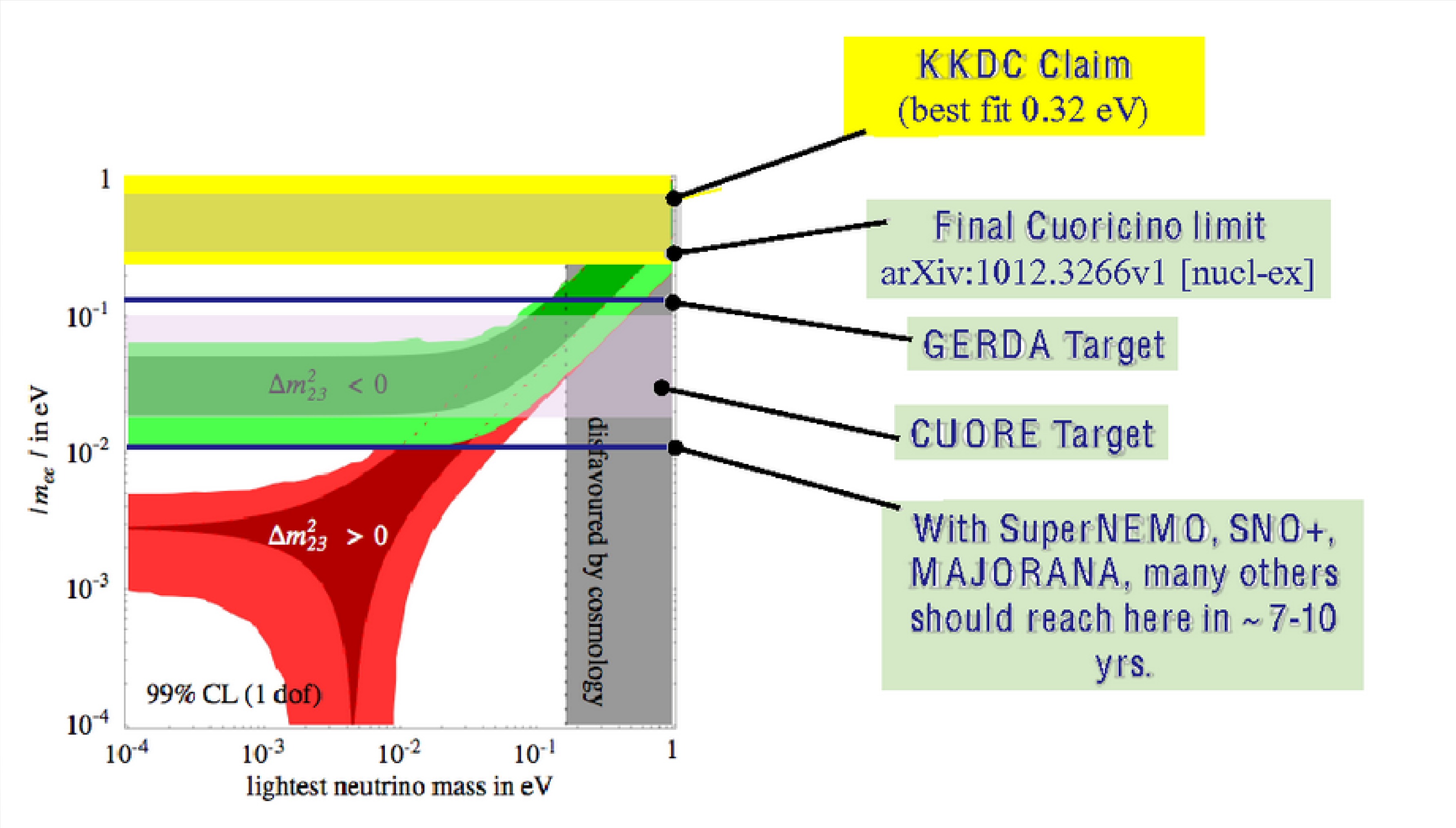




Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10^24
10^20
10^16
10^12
10^8
10^4
1
10^-4
10^-8
10^-12
10^-16
10^-20
10^-24
10^-28
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernova
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
10^-6 μeV
10^-3 meV
1 eV
10^3 keV
10^6 MeV
10^9 GeV
10^12 TeV
10^15 PeV
10^18 EeV
Neutrino energy

Towards the inverted hierarchy

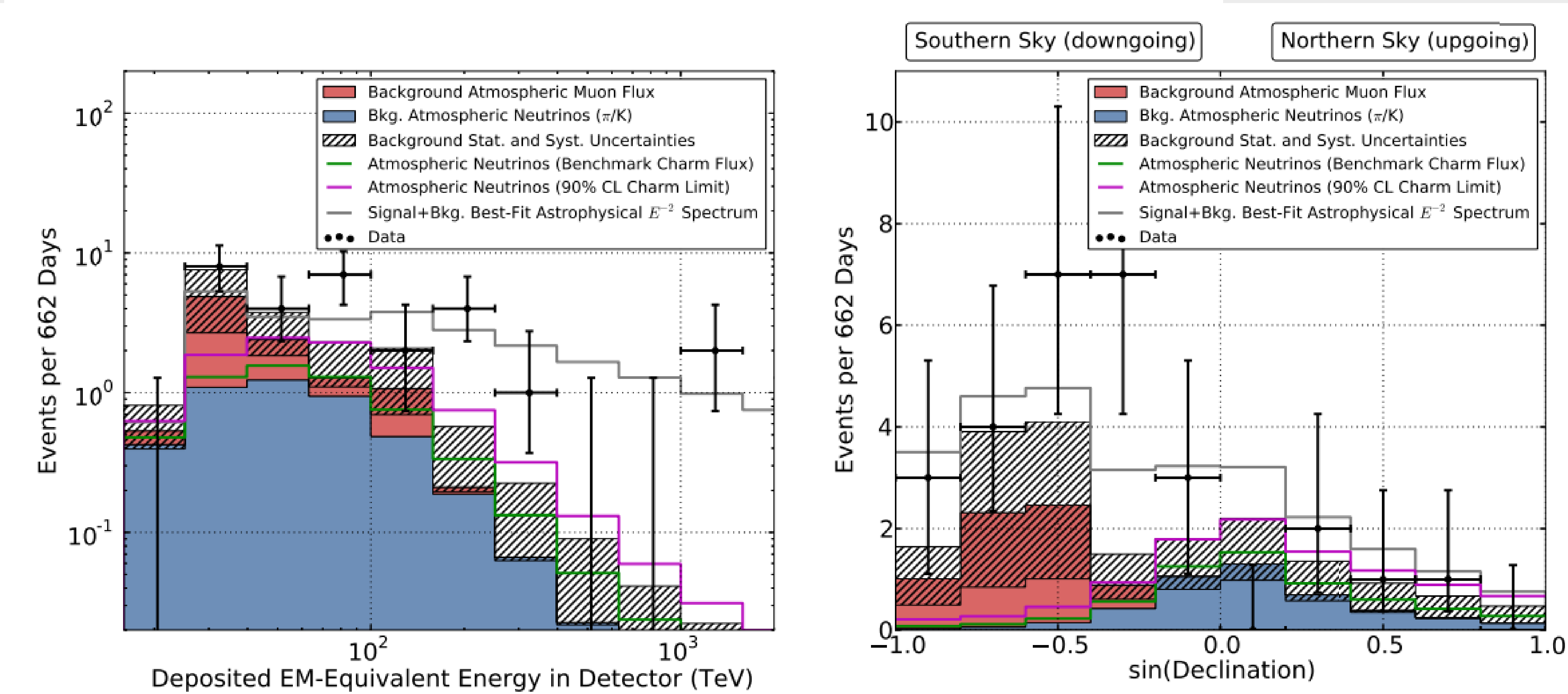
If the hierarchy is inverted and the neutrino is a Majorana particle signals should be seen in the next generation of experiments



IceCube results

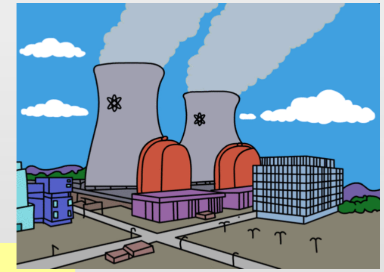
1311.5238v2

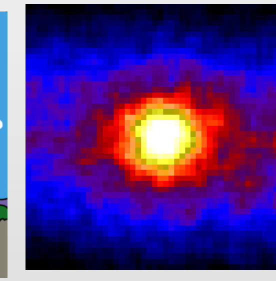
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector



28 events (2010-2012). 4 down-going. Background: $10.5^{+5.0}_{-3.6}$. Explanation with atmospheric ν only excluded at ~ 4 σ. Consistent with generic models (E^{-2}) of extraterrestrial neutrinos. Energies up to PeV (2 events). 7 track +14 shower-like: consistent w. equal mixture of ν_μ , ν_e and ν_τ.

La ``lunga strada” verso l'appearance





– **Scomparsa** dei ν_μ effetto “leading”: deficit atmosferici (1998)
  - scoperta oscillazioni Super-KAMIOKANDE, MACRO

– Al contrario se guardiamo all'**appearance:**

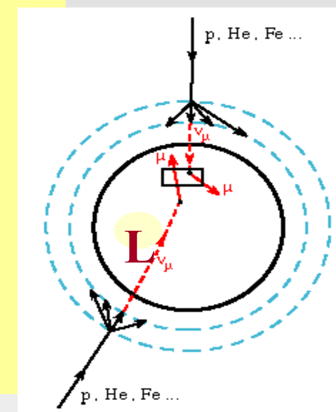
Alla **scala solare**: Sorgenti: reattori e ν solari

$\nu_e \rightarrow \nu_\mu$ stato finale con μ sotto soglia! (SNO conta i NC)

Alla **scala atmosferica** Sorgenti: ν atmosferici, fasci artificiali

$\nu_\mu \rightarrow \nu_e$ stato finale "RARO"! soppressione da θ_{13} ?

$\nu_\mu \rightarrow \nu_\tau$ stato finale “DIFFICILE” ! (per massa e $c\tau$)



Com'e' “andata a finire” ?

$\nu_\mu \rightarrow \nu_\tau$ Rivelazione (evento-per-evento): una sfida sperimentale e ingegneristica di primo livello.

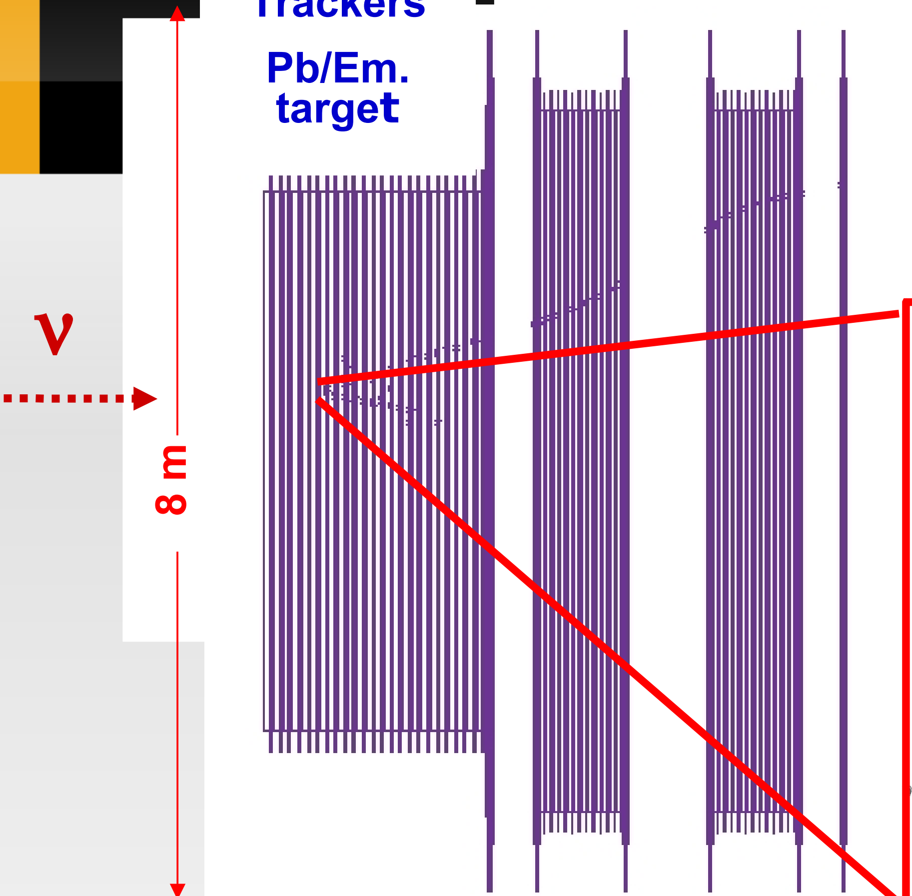
Fascio O(10) piu' energetico (17 GeV) di ogni altro LBL (m(τ))

Rivelatori “fine-grained O(100) piu' massicci dei predecessori SBL (i.e. CHORUS)

$\nu_\mu \rightarrow \nu_e$

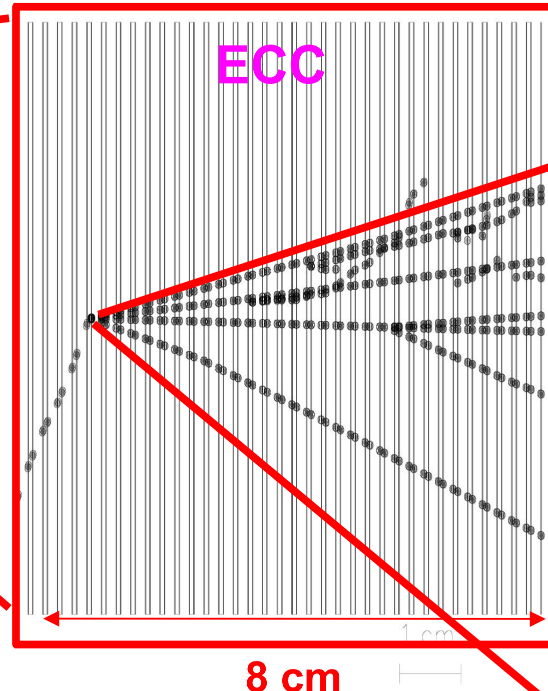
- Nuovo fascio (0.6 GeV) → grande Water-Cherenkov pre-esistente (SK).
- Nuovo rivelatore vicino per caratterizzare i fondi e la normalizzazione.
- Scomparsa anti-ν_e ai reattori (2012,Daya-Bay, RENO, DCHOOZ) θ_{13} si e' rivelato “grande” !

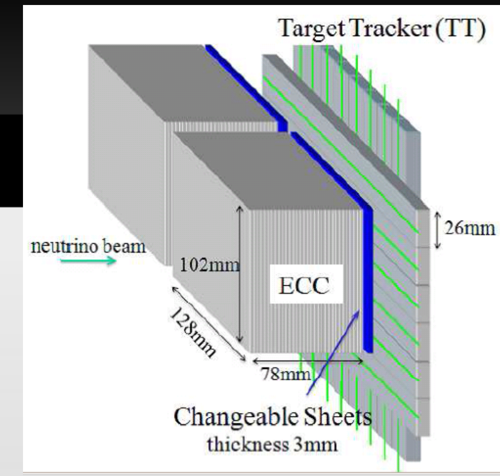
The OPERA way

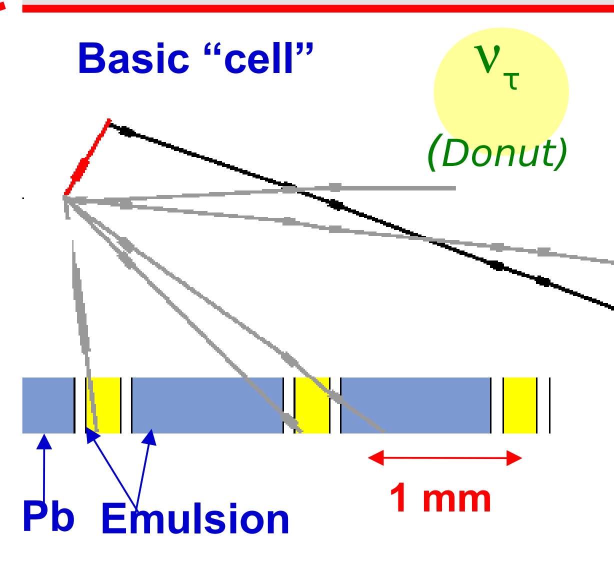


Extract bricks according to electronic det. prediction

Pb/Em. brick







A "hybrid" detector

Electronic detectors

detect ν interaction, brick finding

μ-ID, Q and p : bckg suppression

based on the only **proven technology** (DONUT) to identify ν_τ on an event-by-event basis (**nucl.emuls.&lead driven by real time detectors**). A **major engineering achievement:** brought such technology to an **immense size (1.25 kton)**

Emulsion detectors:

modular structure of 150000 ECCs
mass industrial production with high standards
FAST-AUTOMATIC scanning
vertex search, decay search, e/μ ID, event kinematics

~10 M