Next generation long baseline neutrinos experiments: what are the options for Europe ?

André Rubbia (ETH-Zürich)

DAPNIA/SPP seminar
June 18th, 2007

Neutrino oscillations

- Neutrino flavour oscillation is well established both at the solar and atmospheric scale.
- The effects can be mostly naturally explained when neutrino mass and flavor eigenstates are different, expressed with a matrix equation:

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

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- The matrix can be written in terms of 3 mixing angles and 1 complex phase as:

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

  where c_{ij} stands for $\cos(\theta_{ij})$ and s_{ij} stands for $\sin(\theta_{ij})$.

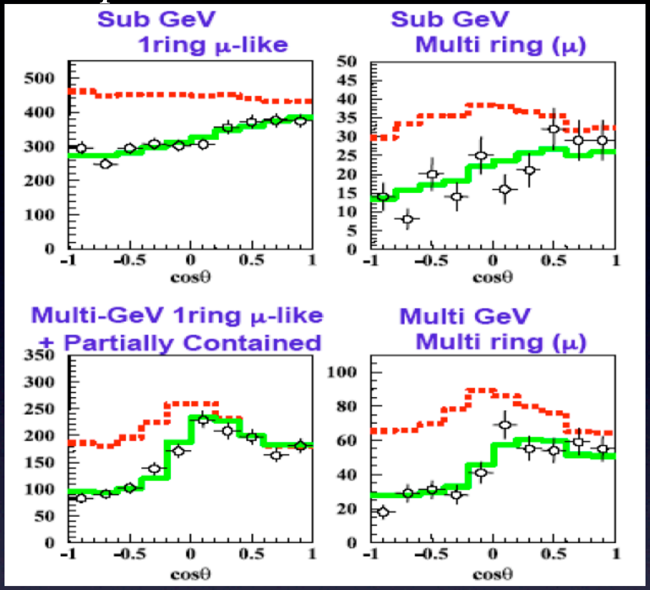
- The probability of oscillation from a flavour to a different one
  - ✦can be expressed as a function of the 3 mixing angles (θ_{12}, θ_{13}, θ_{23}), the complex phase (δ) and 2 neutrino mass differences (Δm^2_{21}, Δm^2_{32})
  - ✦depends on the ratio L/E where L is the distance between the source and the detector (baseline) and E the energy of the neutrino.

"Atmospheric" Δm^2 data

Disappearance:

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\Delta m^2_{32} \frac{L}{4E}\right)$$

Superkamiokande



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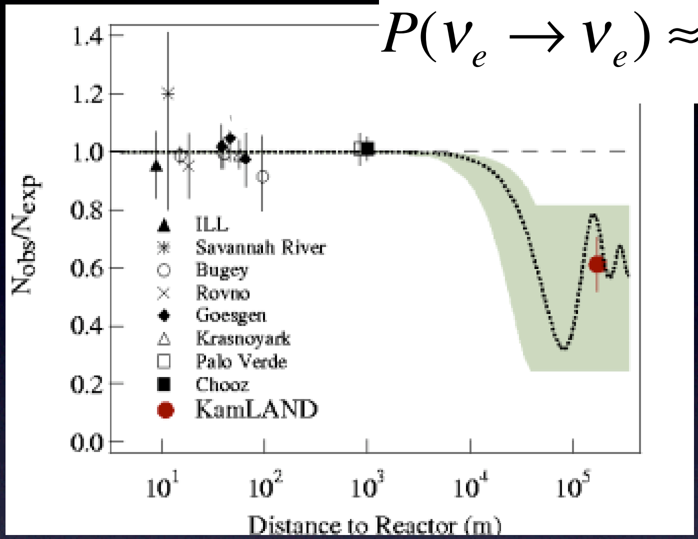

$$\Delta m^2_{32} \approx 2.5 \times 10^{-3} eV^2,$$
$$\theta_{23} \approx 45^o,$$
$$\theta_{13} <\approx 11^o$$

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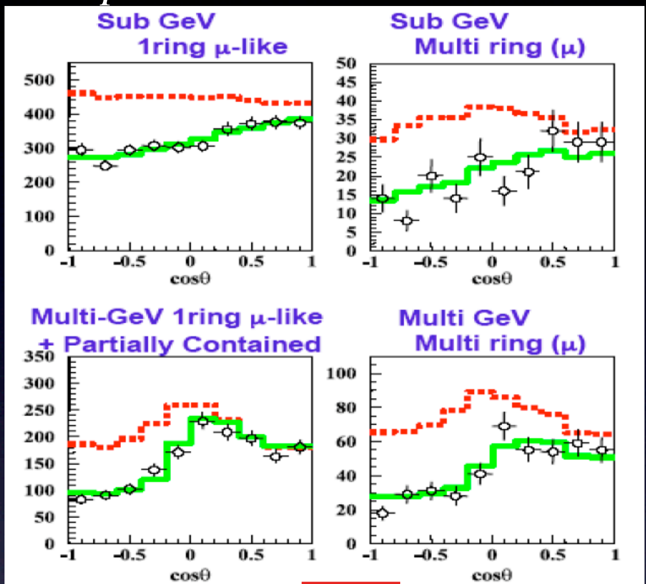

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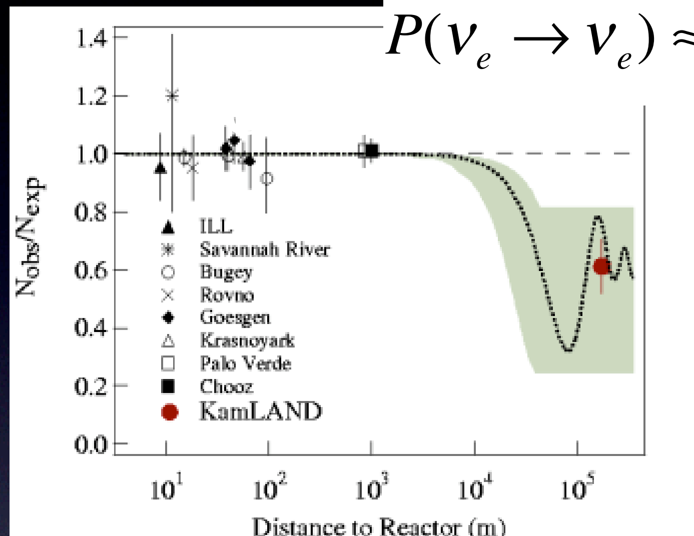

$$\Delta m^2_{32} \approx 2.5 \times 10^{-3} eV^2,$$
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Appearance:

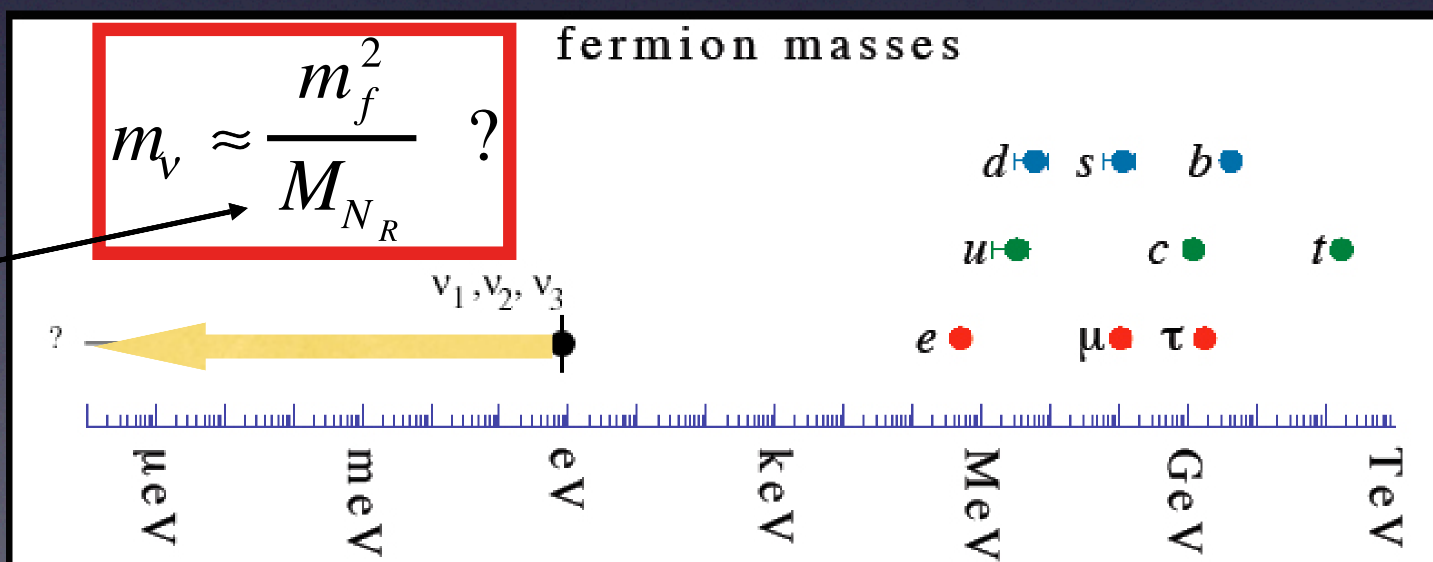
$$P(\nu_\mu \overset{?}{\to} \nu_\tau) = \cos^4\theta_{13} \sin^2 2\theta_{23} \sin^2\left(\Delta m^2_{32} \frac{L}{4E}\right)$$ OPERA

$$P(\nu_\mu \overset{?}{\to} \nu_e) = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\Delta m^2_{32} \frac{L}{4E}\right)$$ T2K, NOVA, ...?

Neutrino masses: viewpoint from fundamental theory

Neutrino masses: viewpoint from fundamental theory

- ★ Non-vanishing neutrino masses are a clear indication of new physics beyond the Standard Model (so far the only one)
  - Dirac mass: Even if Higgs boson is discovered at LHC, Higgs mechanism cannot explain neutrino masses unless we postulate the existence of right-handed neutrinos
  - Majorana mass: completely beyond the SM, since implies lepton number violating terms in the basic theory.
  - Mixed: See-saw mechanism, explains why neutrinos are so light, but implies existence of super heavy neutrinos: new physics beyond SM
- ★ Discovery of CP-violation in the leptonic sector would be relevant to lepto-genesis and could help understand the matter-antimatter asymmetry in the Universe.



Super heavy neutrino ?

Relevant questions

Relevant questions

- The goal of long baseline neutrino oscillation experiments is to precisely measure the mixing matrix and mass differences (squared) and answer to important questions such as:
  - ✓Is θ_{23} mixing maximal? (present limit: $\sin^2(2\theta_{23})>0.92$ at 90% C.L)
  - ✓Is θ_{13} different from zero? (present limit: $\sin^2(2\theta_{13})<0.1$ at 90% C.L)
  - ✓Is there CP violation in the leptonic sector? (i.e. is $\delta\neq 0$?)
  - ✓Is there normal or inverted hierarchy? (i.e. which is the sign of Δm^2_{32}?).
- The first question could be answered with a precise measurement of ν_μ disappearance, that would provide a better knowledge on the parameters θ_{23} and Δm^2_{32} ($\approx \Delta m^2_{31}$):

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2\left(\Delta m^2_{32}\frac{L}{4E}\right)$$

- The other questions could be answered studying $\nu_e \leftrightarrow \nu_\mu$ transitions (e.g. $\nu_\mu \to \nu_e$ oscillation) with the frequency of the atmospheric neutrinos. This has not been observed so far.

Three flavors phenomenology

- The 3-flavour neutrino $\nu_\mu \rightarrow \nu_e$ oscillation probability including matter effects can be expressed as:

$$P(\nu_\mu \rightarrow \nu_e) = \Sigma_{i=1,4} P_i$$

$$P_1 = \sin^2\theta_{23}\sin^2(2\theta_{13})\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\frac{B_\pm L}{2}$$ Atmospheric term

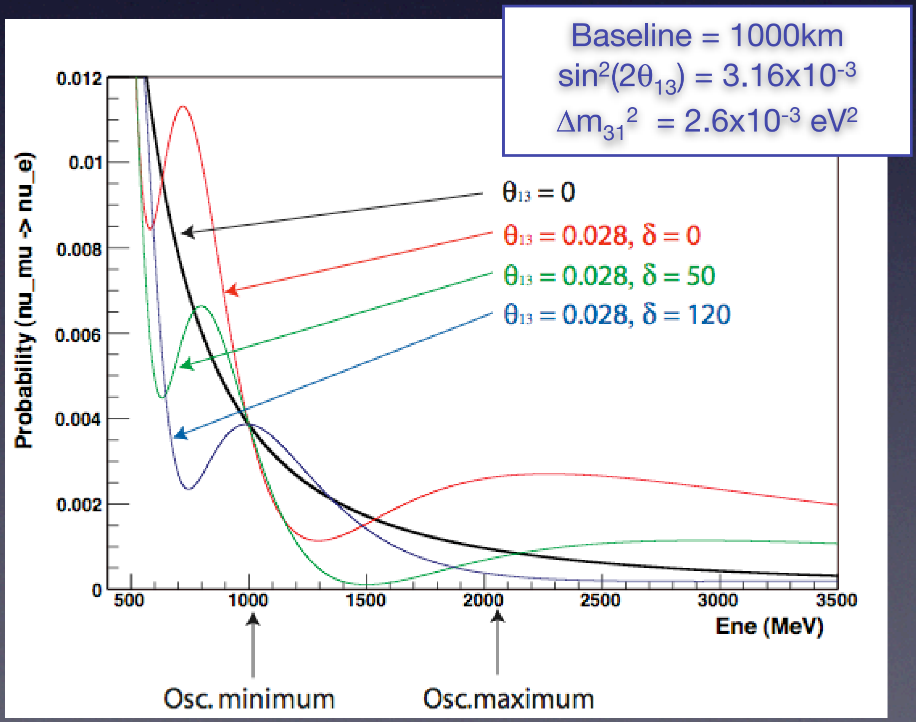
$$P_2 = \cos^2\theta_{23}\sin^2(2\theta_{12})\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\frac{AL}{2}$$ Solar term

$$P_3 = J\cos\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\cos\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

$$P_4 = \mp J\sin\delta\left(\frac{\Delta_{12}}{A}\right)\left(\frac{\Delta_{13}}{B_\pm}\right)\sin\frac{\Delta_{13}L}{2}\sin\frac{AL}{2}\sin\frac{B_\pm L}{2}$$

Interference terms

$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu}$$
$$A = \sqrt{2}G_F n_e$$
$$B_\pm = |A \pm \Delta_{13}|$$
$$J = \cos\theta_{13}\sin(2\theta_{12})\sin(2\theta_{13})\sin(2\theta_{23})$$



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Interference terms (P_3, P_4)

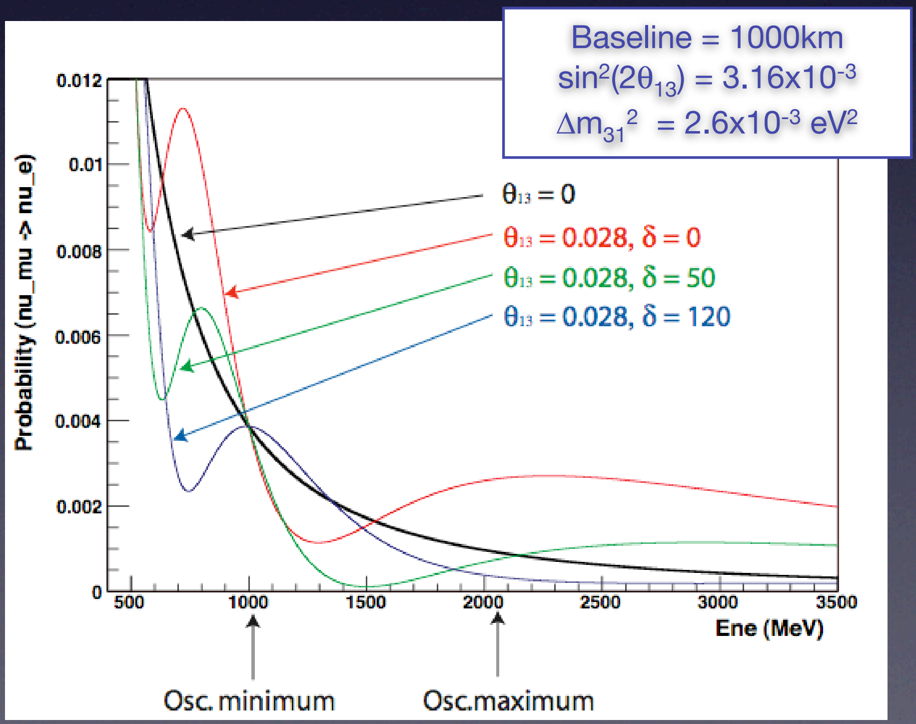
$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu}$$

$$A = \sqrt{2}G_F n_e$$

$$B_\pm = |A \pm \Delta_{13}|$$

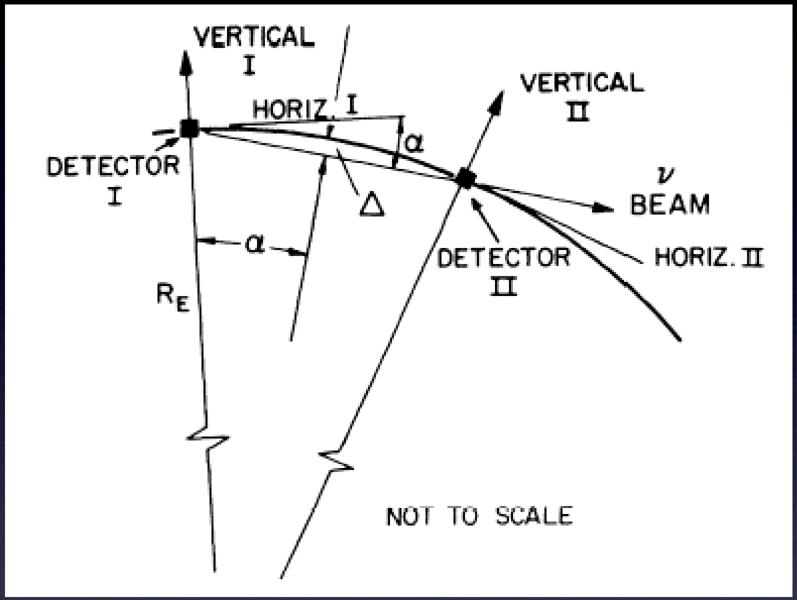
$$J = \cos\theta_{13}\sin(2\theta_{12})\sin(2\theta_{13})\sin(2\theta_{23})$$

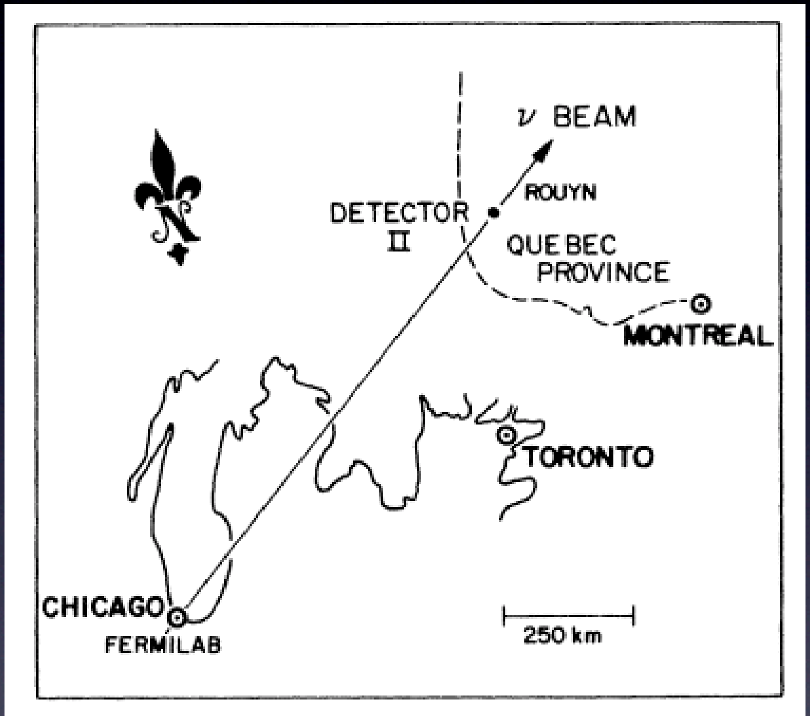
- θ_{13} must be proved to be non-zero. Otherwise $P_1=P_2=P_3=P_4=0$
- P_3 & P_4 depend strongly on the value of δ.
- The sign of Δm^2_{31} also affects the oscillation probability through the Earth:
  - $\Delta m^2_{31}>0$: (anti)neutrino oscillation (suppressed) enhanced
  - $\Delta m^2_{31}<0$: (anti)neutrino oscillation (enhanced) suppressed



The first concrete idea

A.K. Mann, H. Primakoff, "Neutrino oscillations and the number of neutrino types", Phys.Rev. D 15 (1977) 655





L= 1000 km, α=78 mrad, Δ=19 km

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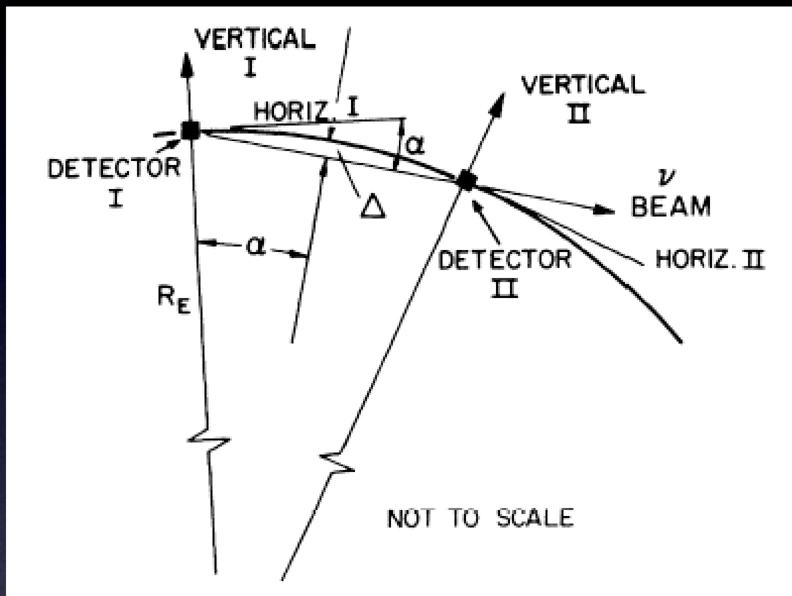

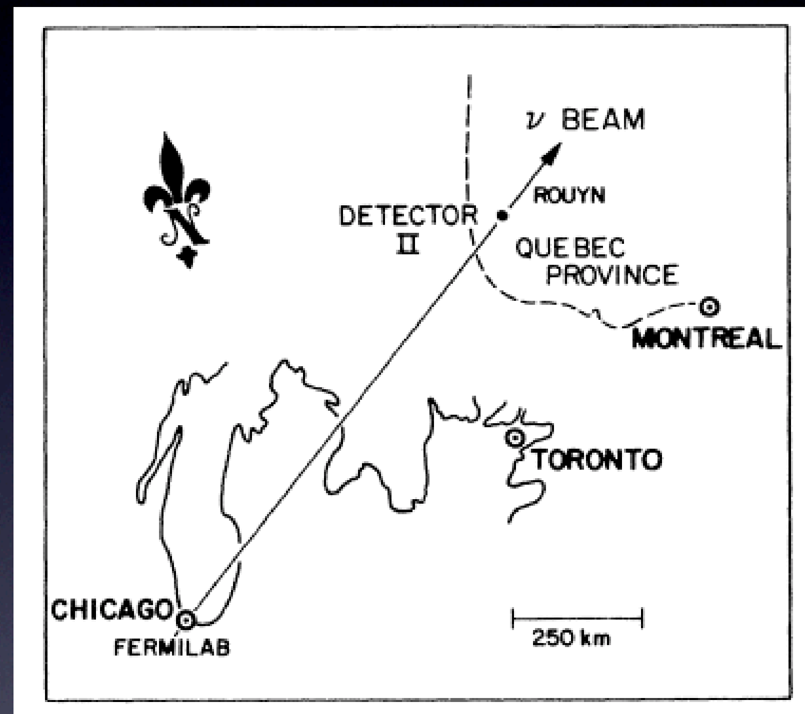

L= 1000 km, α=78 mrad,
Δ=19 km

"None of our speculations on the lower limit of the oscillation length at $p\nu \leq 20$ GeV appears to be significantly larger than the distance between the accelerator and the distant detector (1000 km)"
"It is perhaps worth mentioning again that any actual neutrino-oscillation phenomenon might conceivably provide another means of observing CP violation"

Super-K Results

50 kton water Cherenkov detector, located 1000 m underground
2 analyses on atmospheric neutrinos

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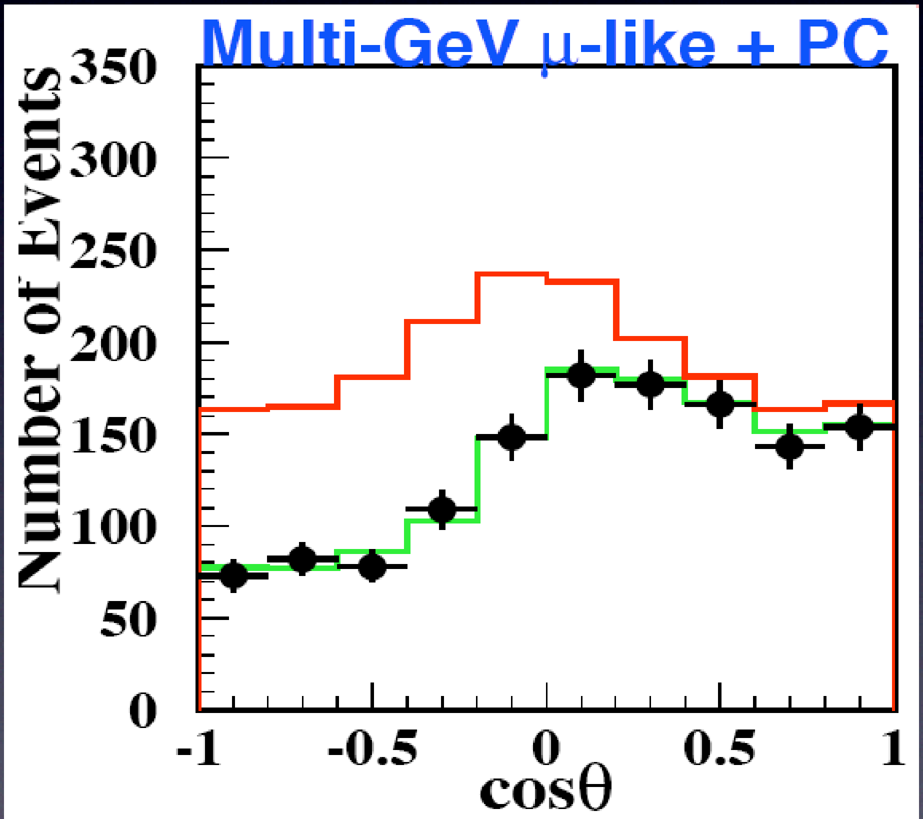

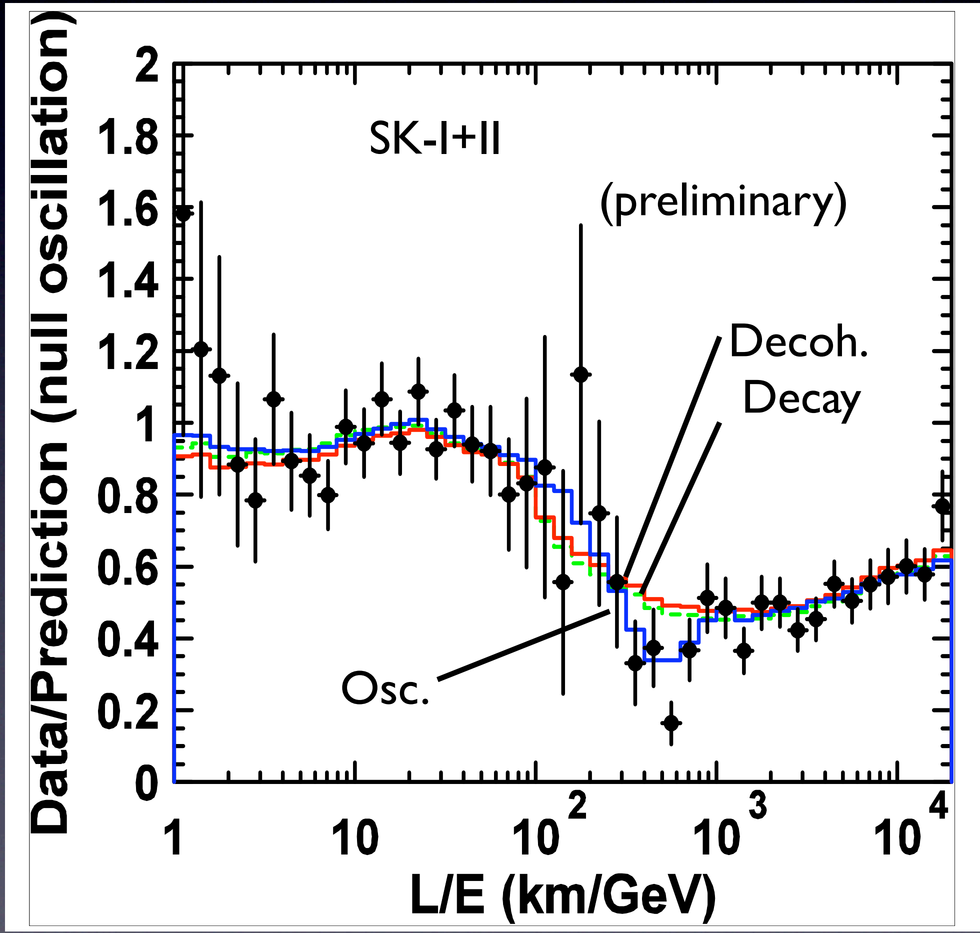

Upgoing: L ~ 10000km
Downgoing: L ~10km

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K2K Experiment

(Phys. Rev. D74 (2006) 072003)

- ν_μ beam from KEK with L=250 km
- 'Near' detector + 'Far' Super-K detector
- Accumulated 0.9×10^{20} 12 GeV protons over ~5 years

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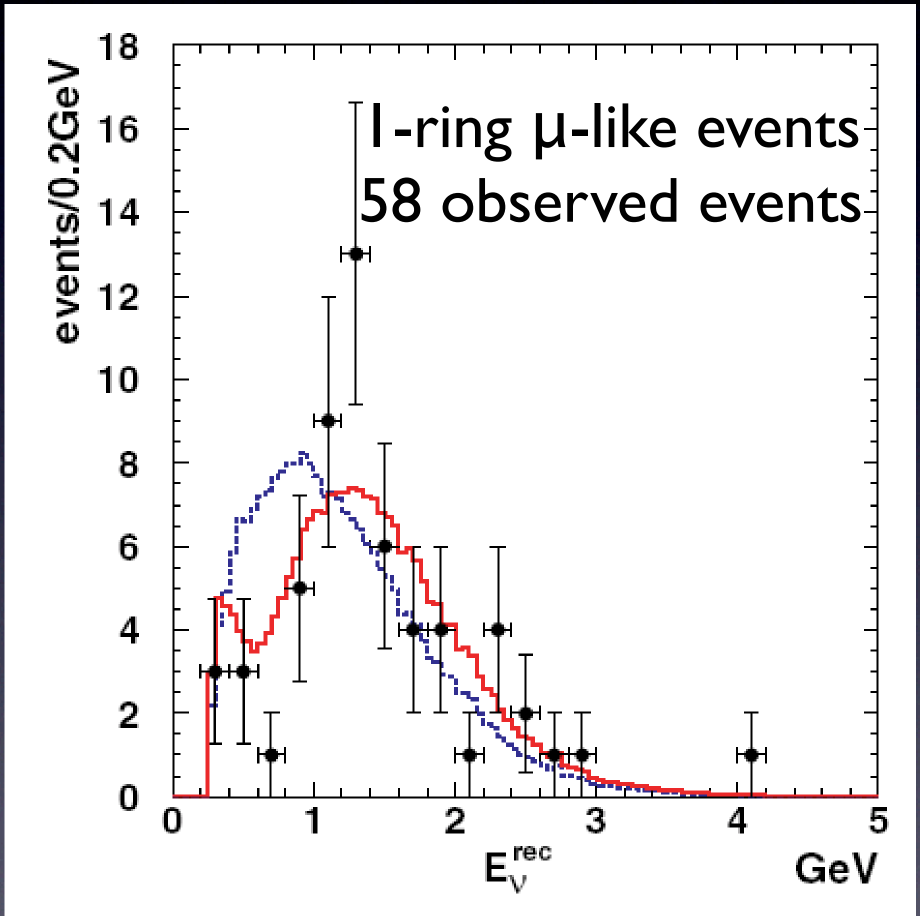
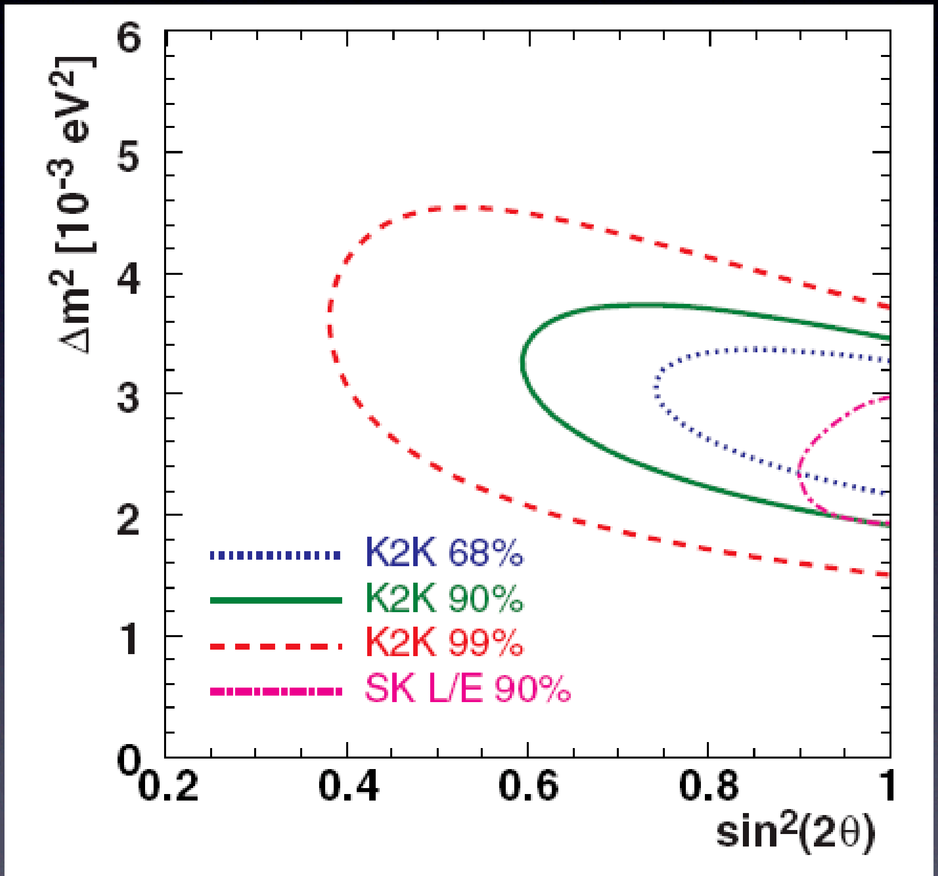


112 FC events observed
158±9 FC expected (no osc)



Best fit parameters:
Maximum mixing
$\Delta m^2 = 2.8 \times 10^{-3}$ eV^2

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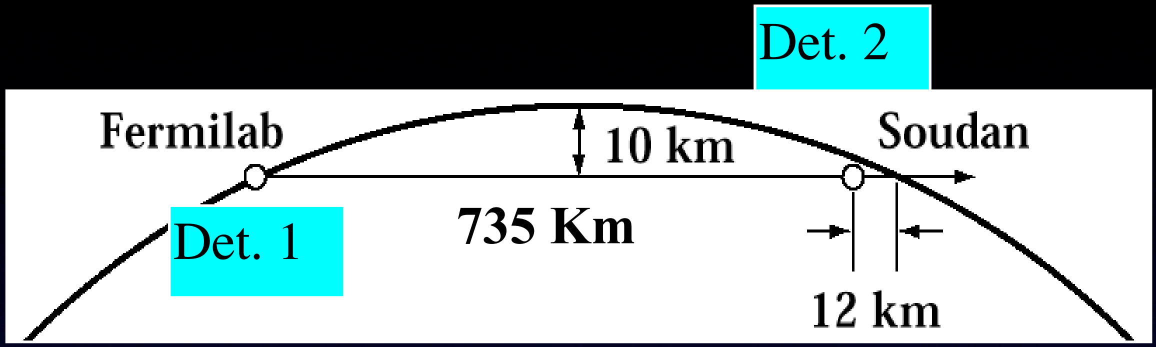
NUMI: ν's at FNAL/MI



First proposals in 1989 !

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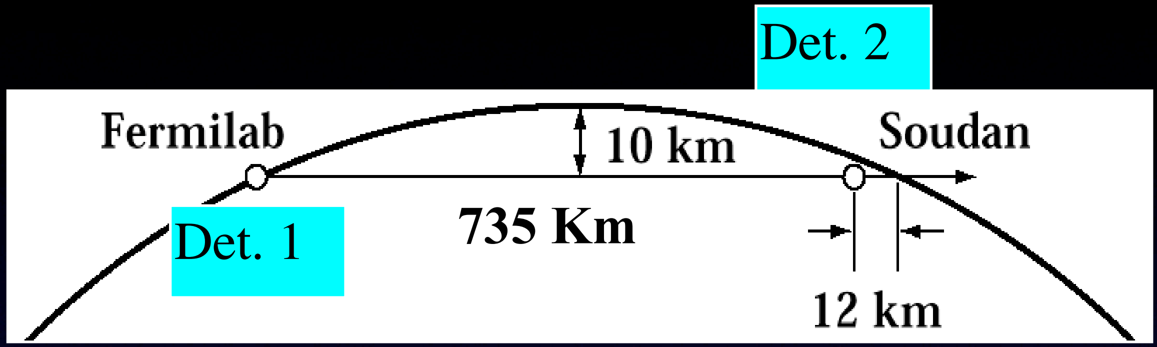

First proposals in 1989 !

- A neutrino beam from Fermilab to northern Minnesota
  - over 735 km to Soudan mine (MINOS far detector)
  - a large near hall at ~ 1 km from the target (MINOS near detector, MINERνA, PEANUT (exposure of OPERA bricks))
- A high power neutrino beam
  - 120 GeV protons from Main Injector
  - facility designed for up to 0.4 MW (4×10^{13} ppp every 1.9 s)

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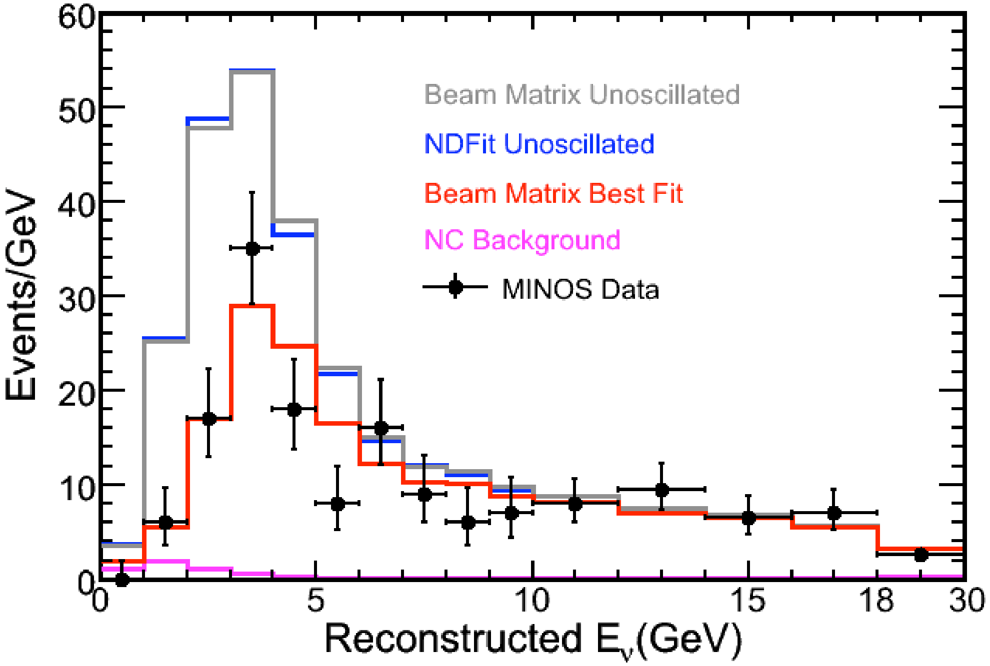
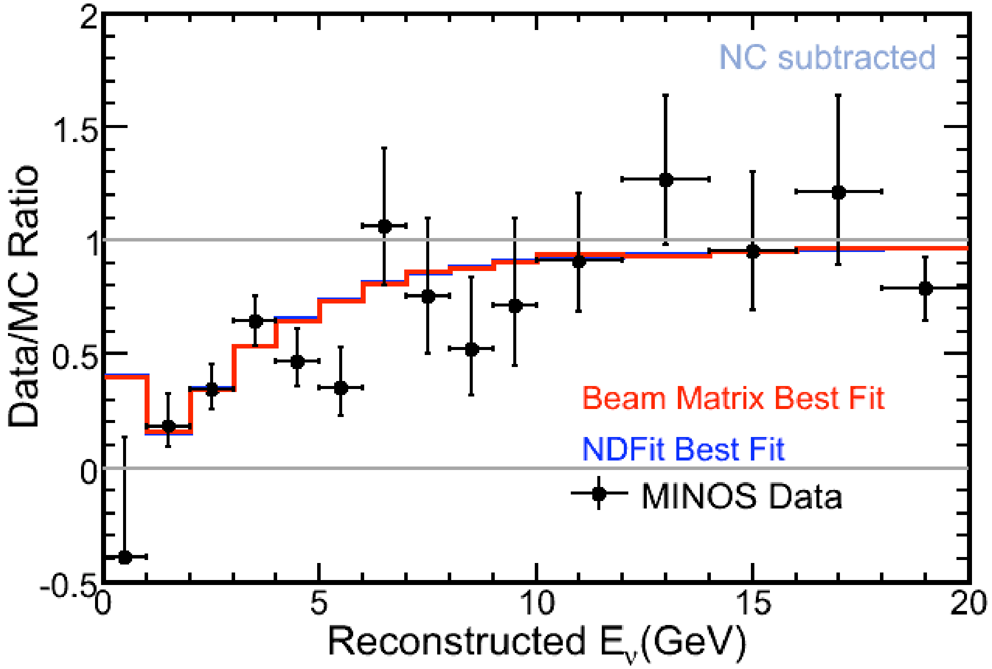
MINOS best-fit spectrum

(Phys. Rev. Lett. 97 (2006) 191801)





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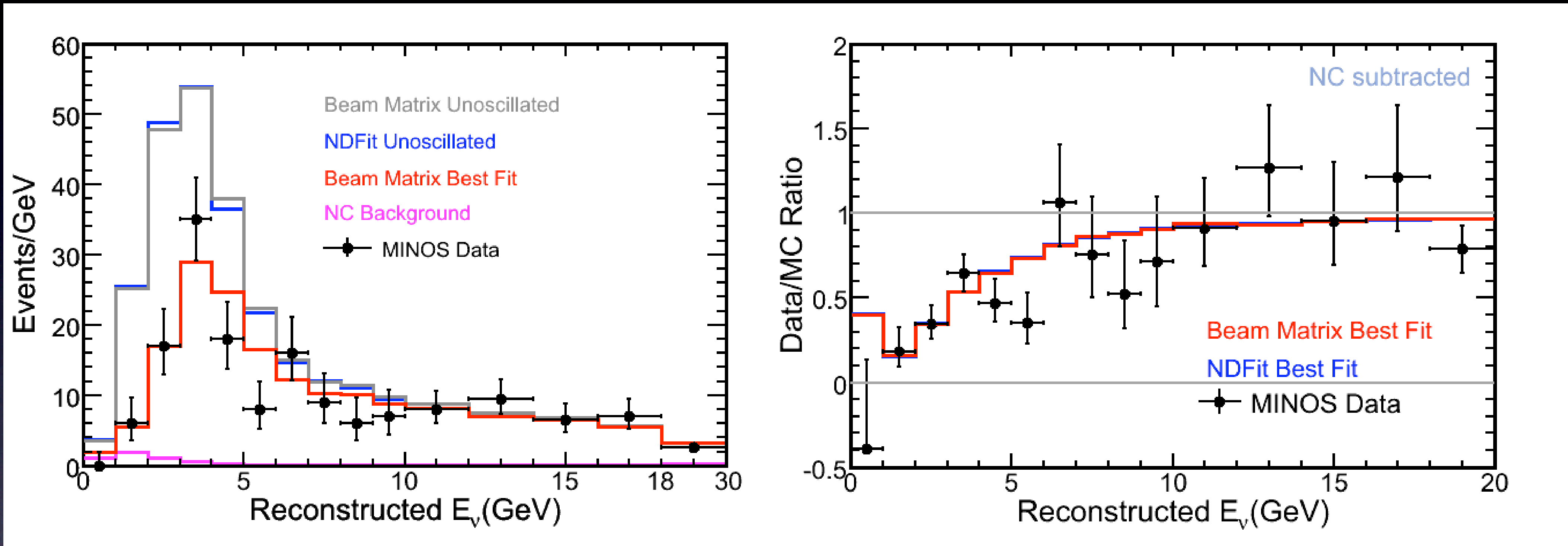


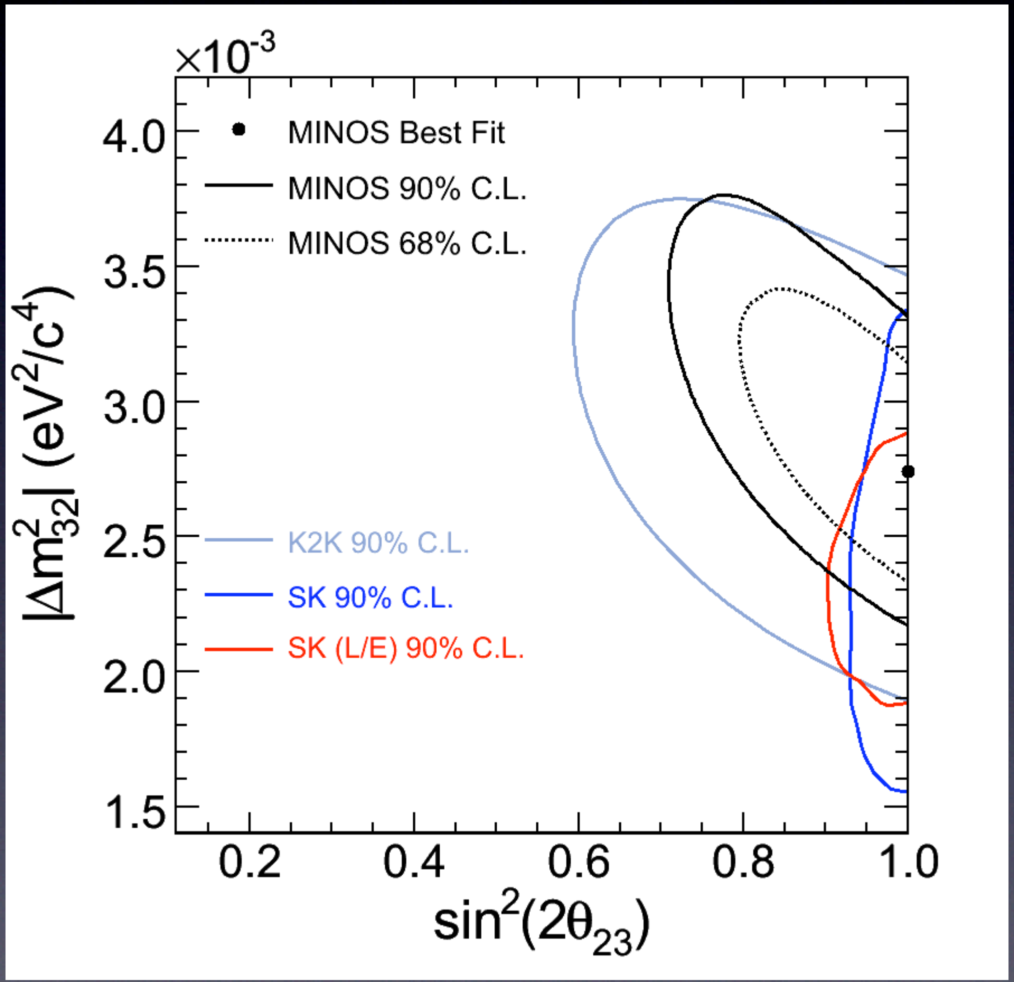
$$|\Delta m^2_{32}| = 2.74^{+0.44}_{-0.26}(stat + syst) \times 10^{-3} eV^2$$

$$sin^2(2\theta_{23}) = 1.00_{-0.13}(stat + syst)$$

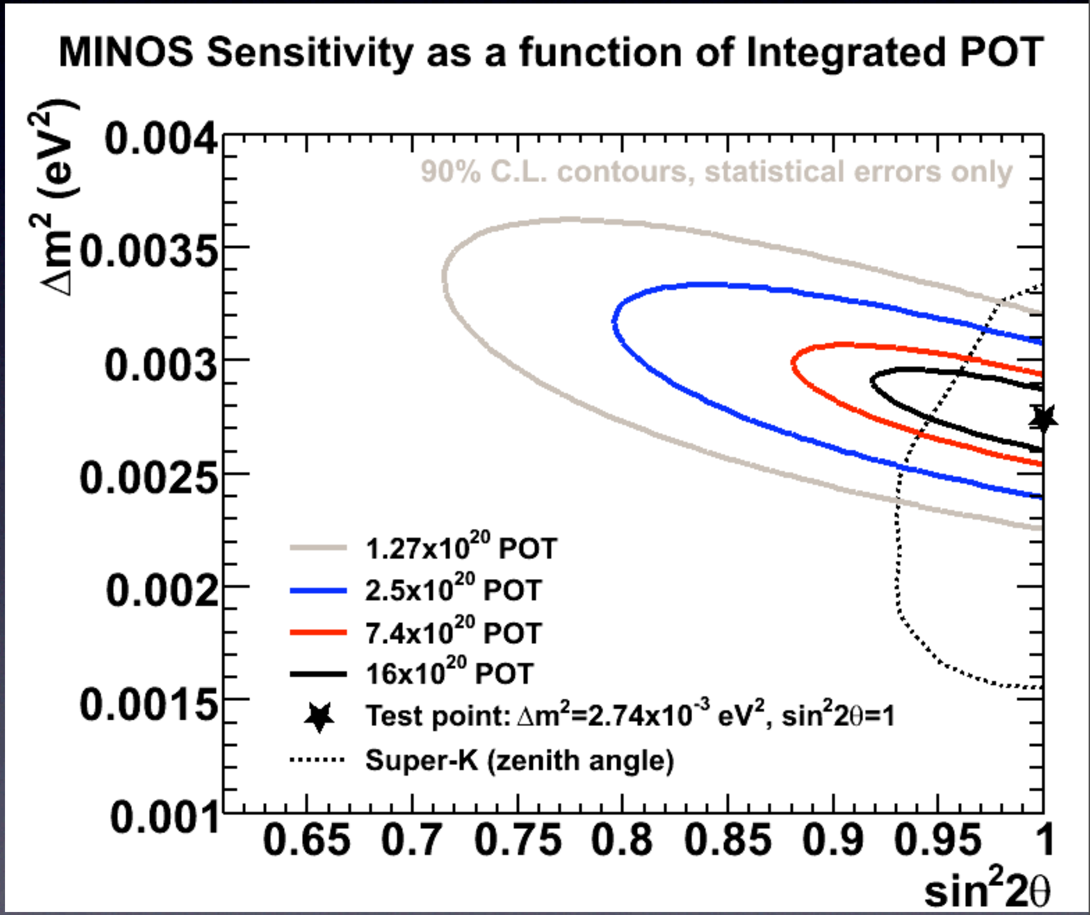
MINOS Allowed Region

MINOS Allowed Region

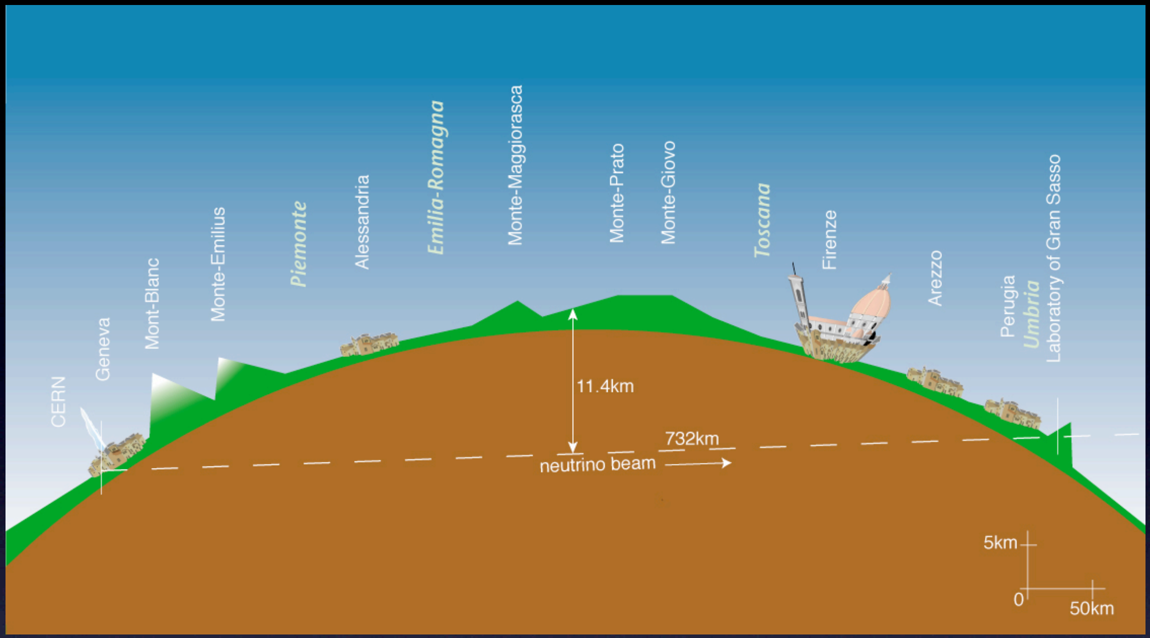
For 1.27x10^{20} protons



Presently accumulated 3x10^{20} protons

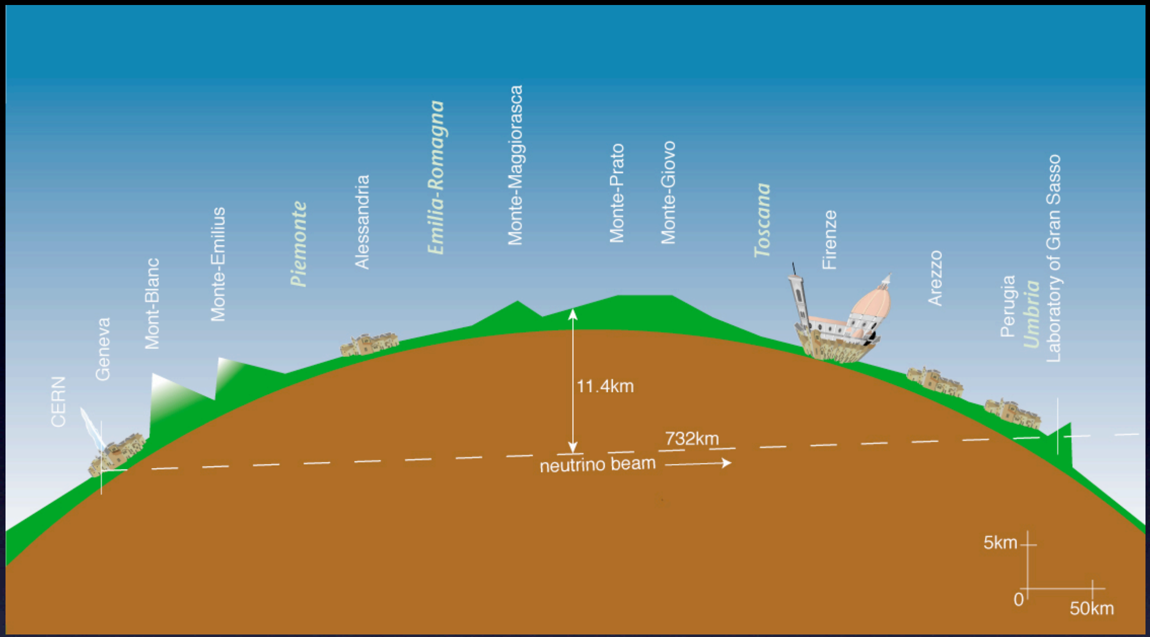


CNGS, CERN to Gran Sasso beam



- L = 732 Km
- 17 GeV average ν_μ energy, optimized for $\nu_\mu \rightarrow \nu_\tau$ appearance experiment

CNGS, CERN to Gran Sasso beam



- L = 732 Km
- 17 GeV average ν_μ energy, optimized for $\nu_\mu \to \nu_\tau$ appearance experiment

- 400 GeV protons from SPS, 4.8×10^{13} protons per 6 s cycle
- 200 days x 60% SPS sharing x 55% efficiency

⇒ 4.5×10^{19} pot/year, 500 kW peak power, 1.8×10^{22} GeV/year on target

- compare with NuMI, 3×10^{20} pot/year design value, achieved 1.5×10^{20} POT/year equivalent to 1.8×10^{22} GeV/year on target

OPERA detector

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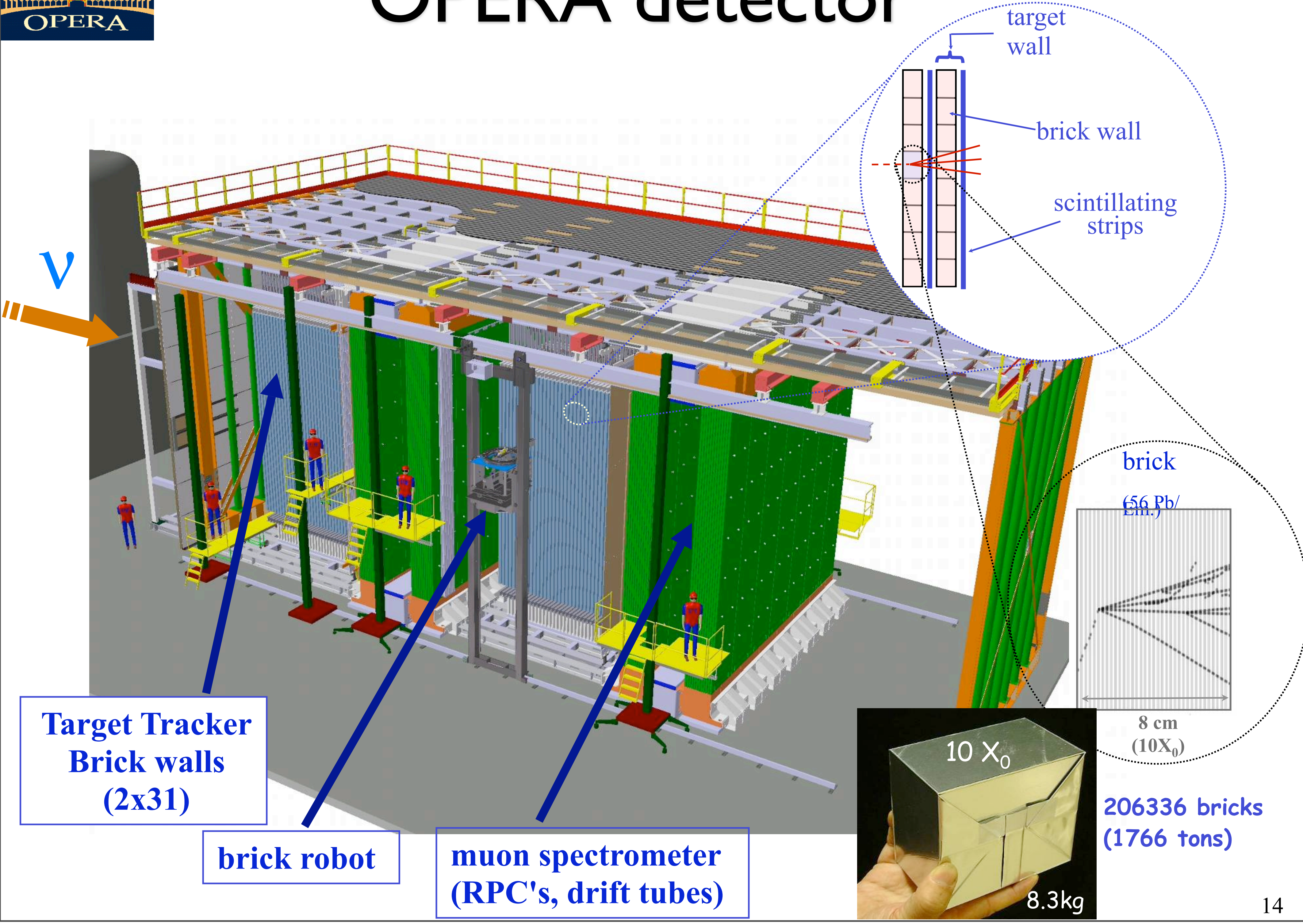
OPERA detector



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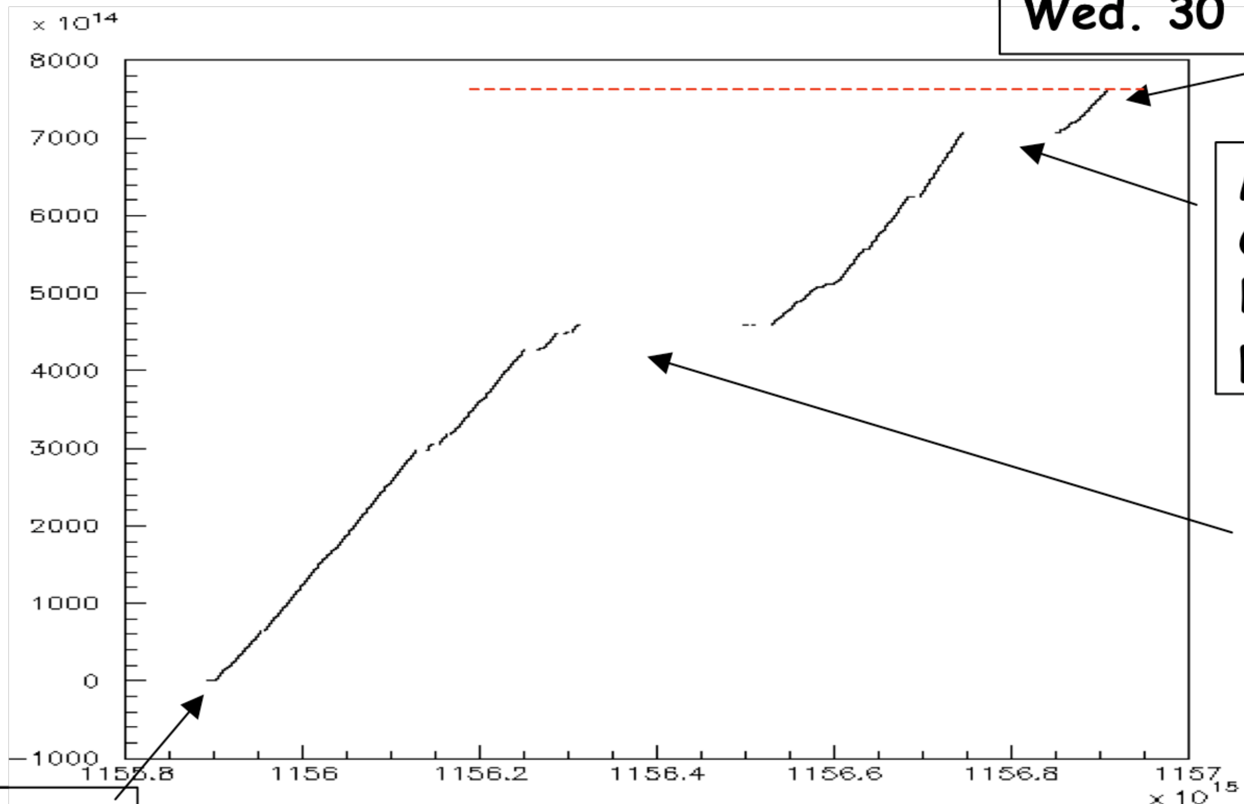
Integrated POT @Aug '06 RUN

TOTAL:
7.6 E17 pot

EXT1: 3.81 E17 pot
EXT2: 3.79 E17 pot

Wed. 30 Aug. 2006 5:00



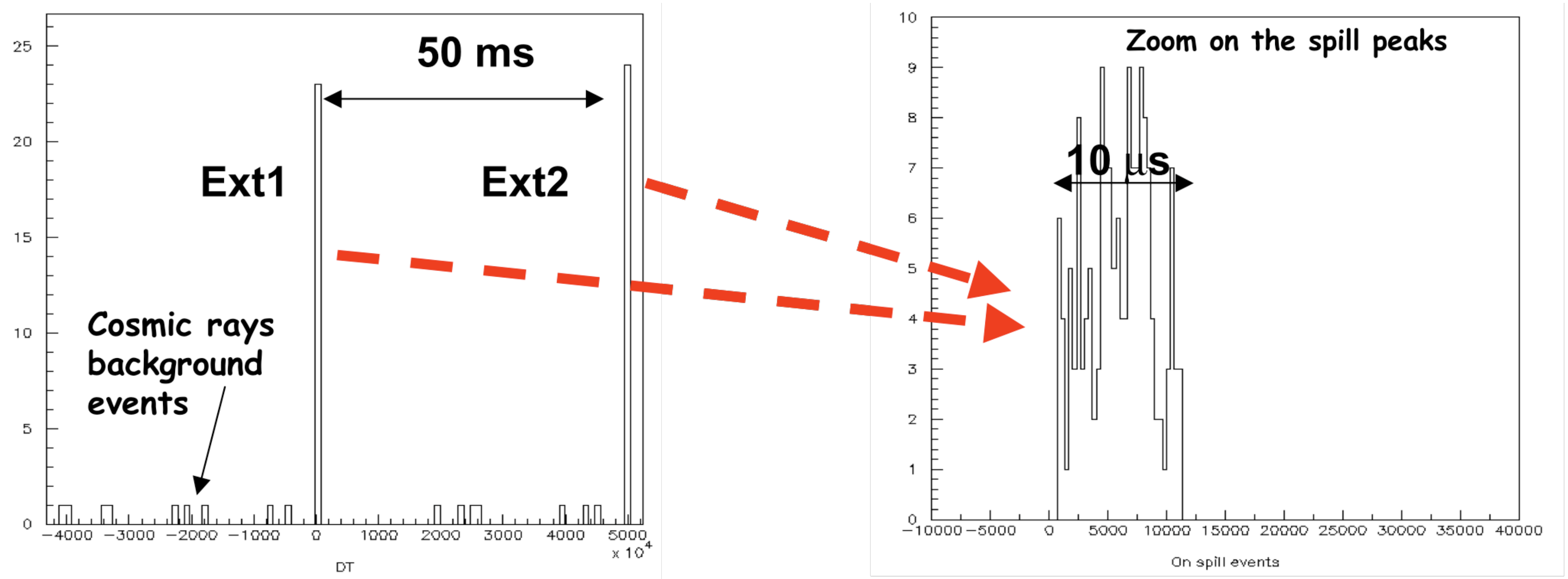
MD Monday + CNGS smoke Detection system problem

2 days MD + problems On Friday 25

Fri 18 Aug. 2006 13:40

Unix time

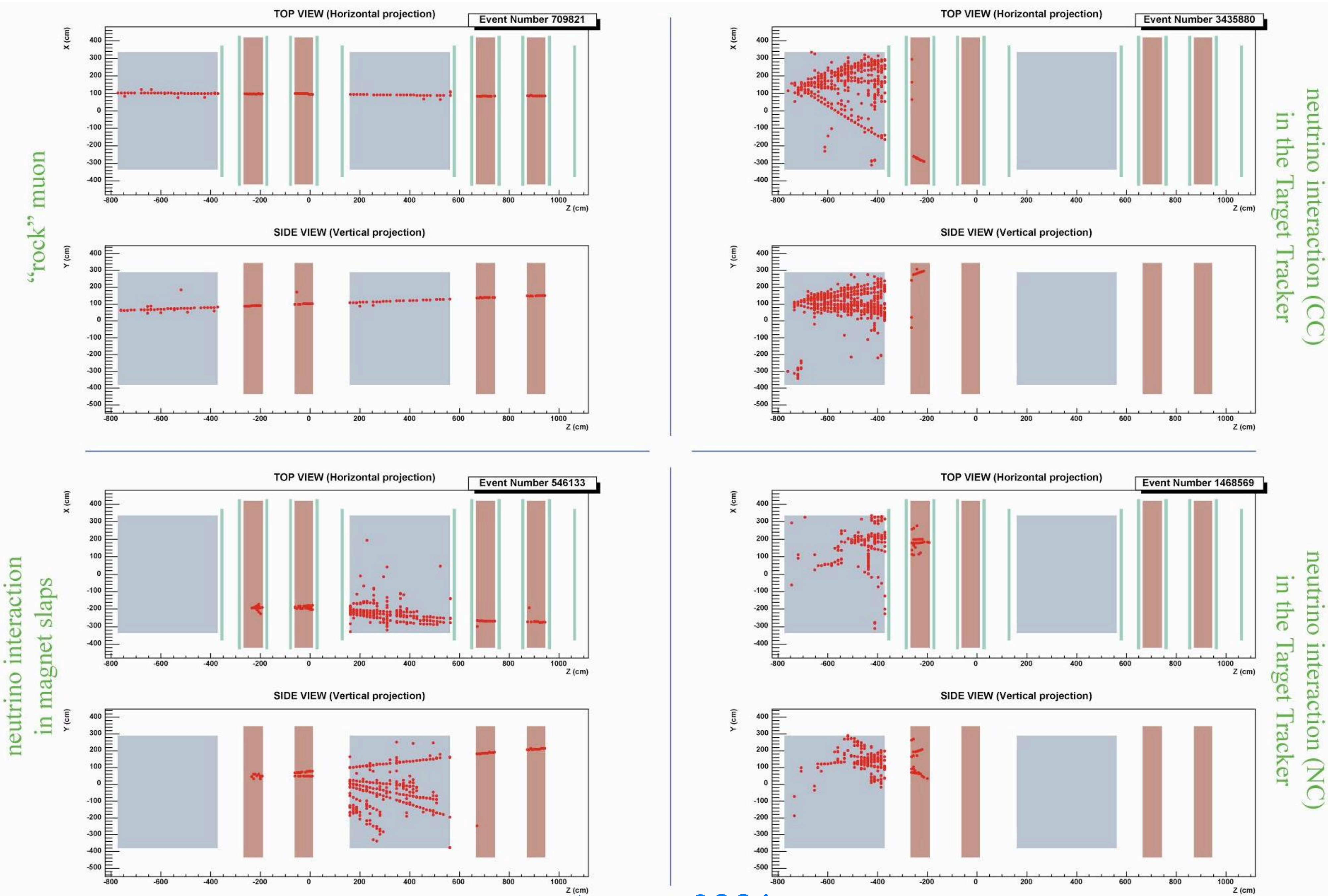
Timing : Event vs Extraction
Aug '06 RUN



Time to first extraction (ns)

Closest time to extraction (ns)

CNGS events



August 2006

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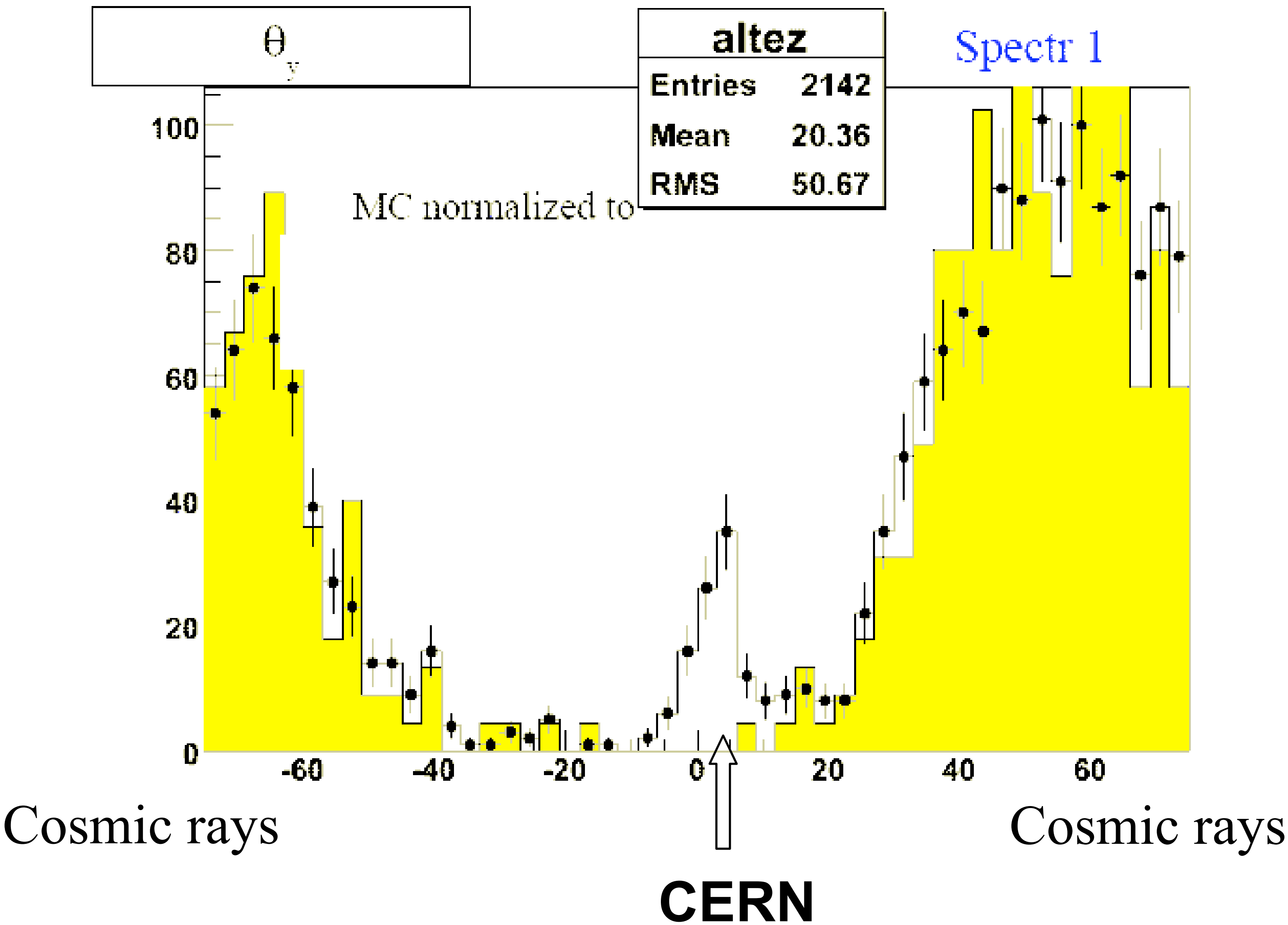
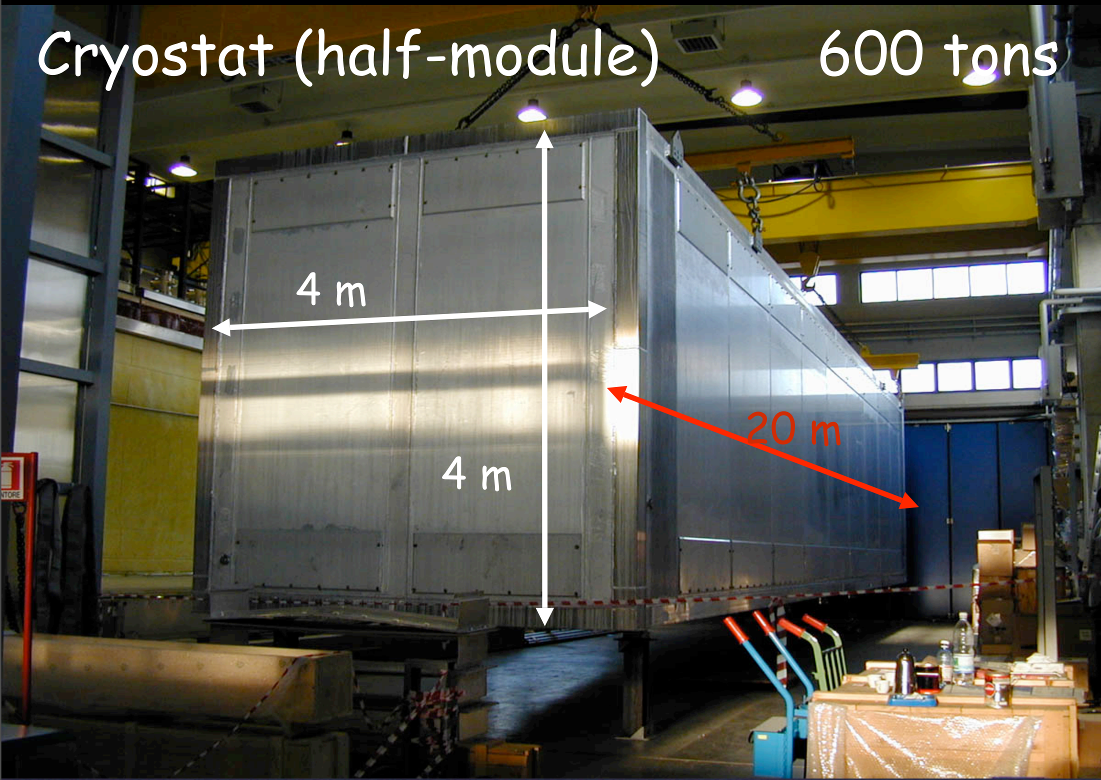
CERN direction observed by muons

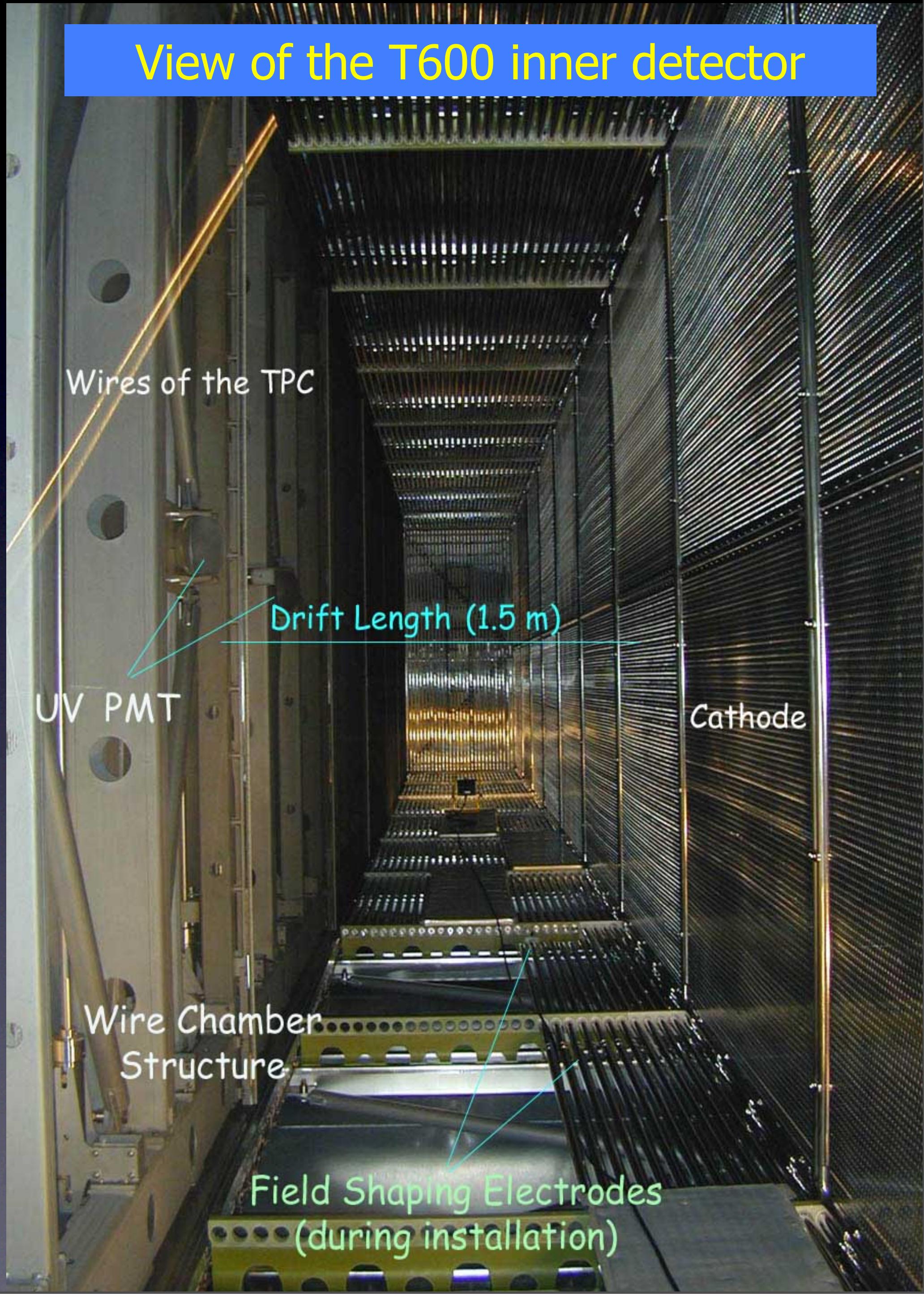


CNGS water leak

Today we have removed one shielding block of the side shielding of the CNGS reflector. The radiation was low enough to stay beside the reflector for some minutes and to have a direct look to the possible leak locations. The leak in the closed water cooling circuit of the reflector was located immediately: The insulating ceramic part of the most downstream tube connecting the outer conductor with the water drain pipe is broken (see attached picture). The reason for this rupture has to be understood. Most likely is due to additional clamps that provide vapor tightness (a condition that could be negotiated), which might overconstrain the system. These clamps could be removed quite easily, an operation that we would then like to do at all the other connecting tubes of the reflector and also the horn.
We are investigating the possibility for repair of the connecting tube in-situ, i.e. without moving the reflector, but just the side shielding. In the next days we will prepare a detailled plan of the interventions during this shut-down, such that CNGS is ready for the 2007 re-start.

The ICARUS T600 detector





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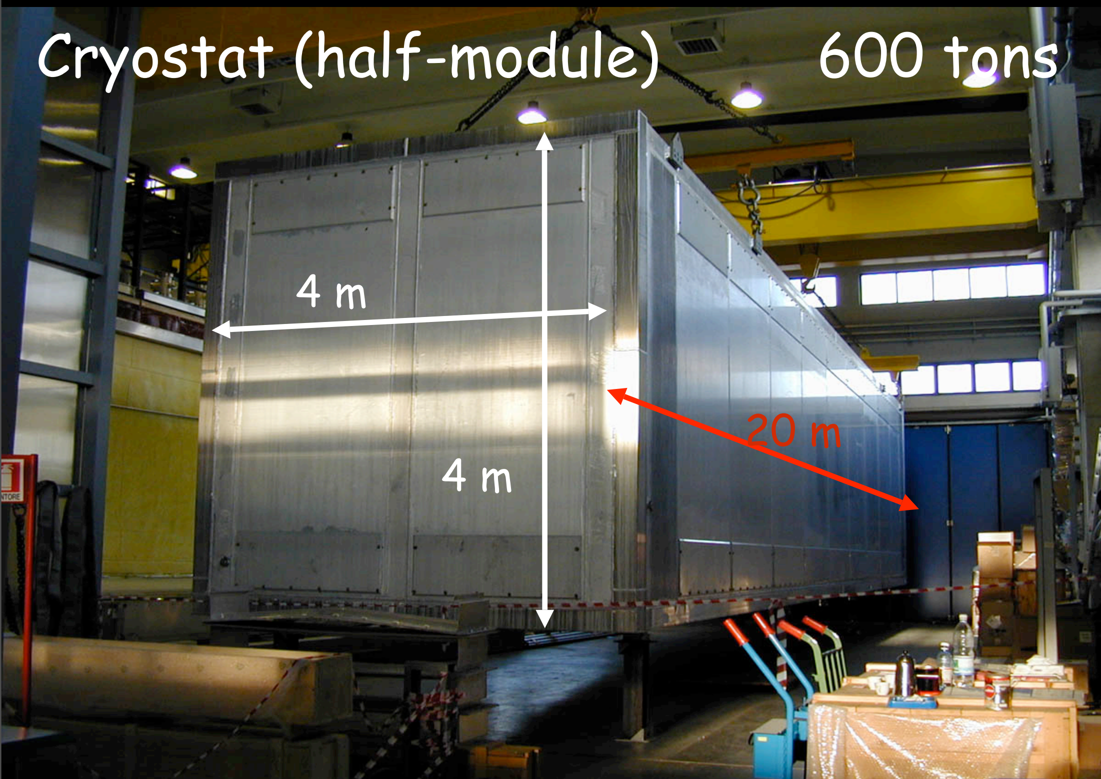
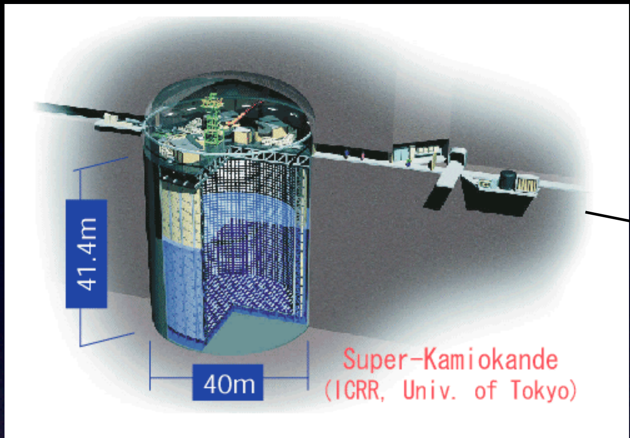
The ICARUS T600 detector



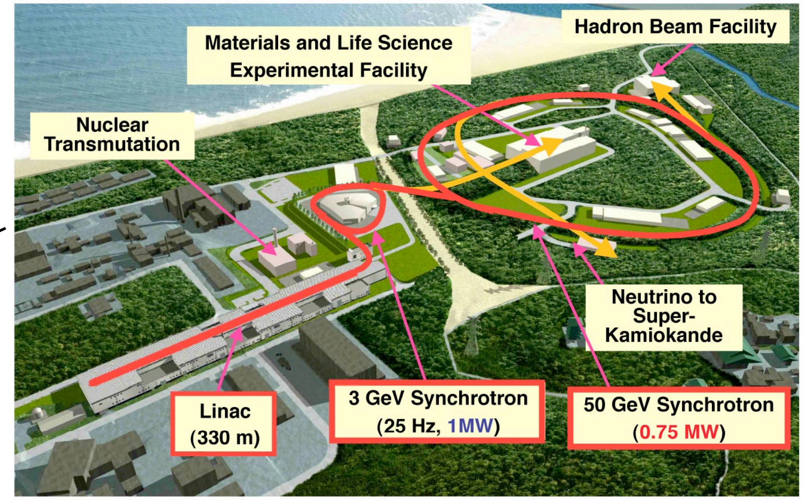
- Built between years 1997 and 2001
- Completely assembled on surface
- Full scale demonstration test run on surface conditions of one half-module in summer 2001
- Full unit assembly terminated in 2002
- Results published
- Transportation to LNGS in 12/2004
- **Planned T600 commissioning in 2007 ?**
- INFN contemplates construction of bigger modules in new nearby LNGS site (off-axis CNGS)

See arXiv:0704.1422 (April 2007)

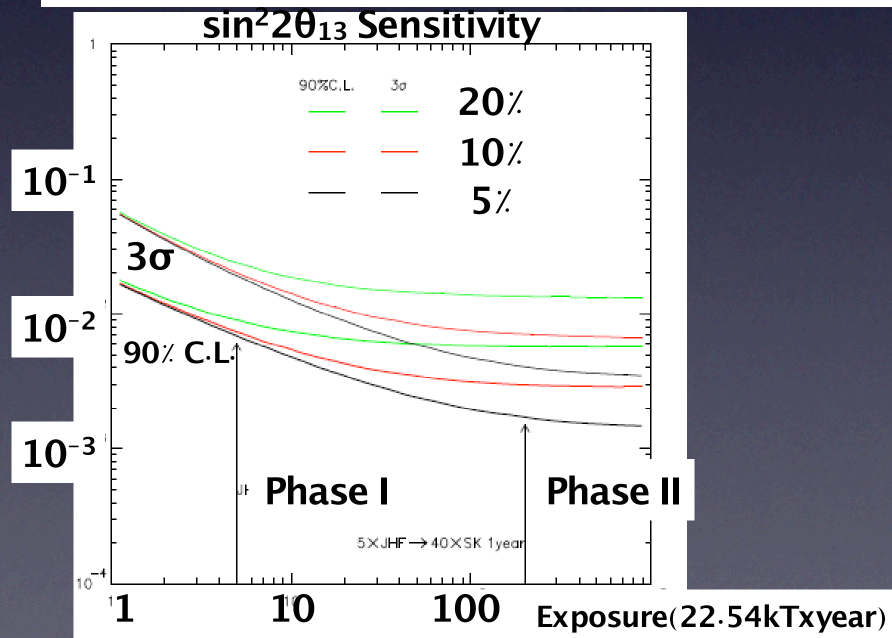
Tokai to Kamioka (T2K)



Far detector : Super Kamiokande



ν beam : J-PARC facility



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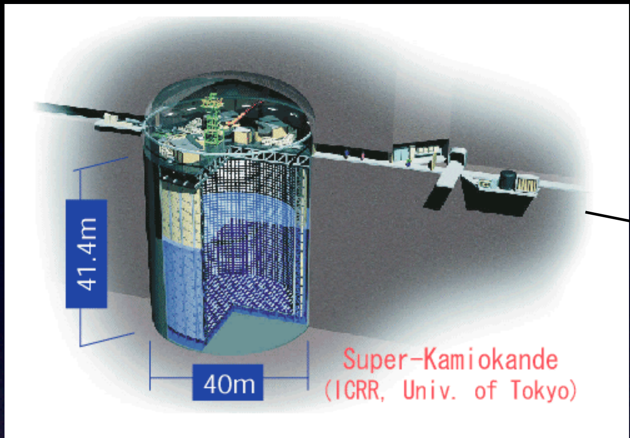

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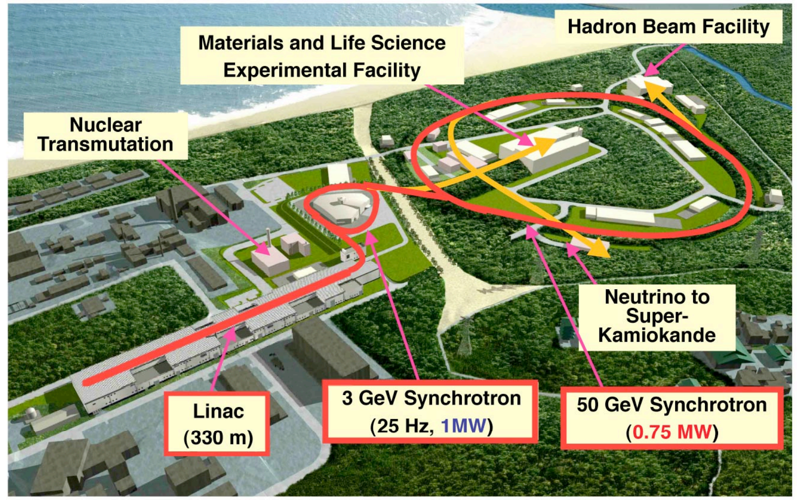
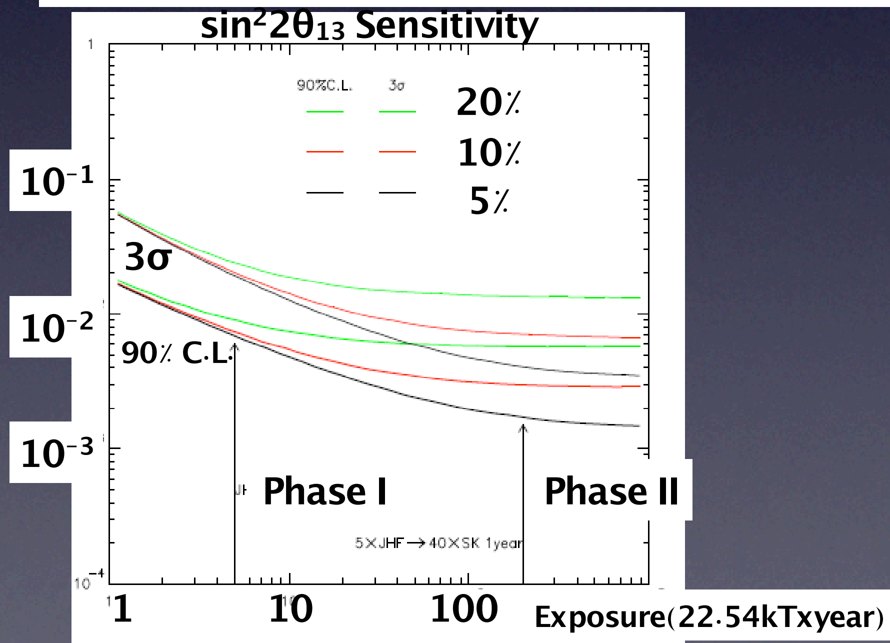


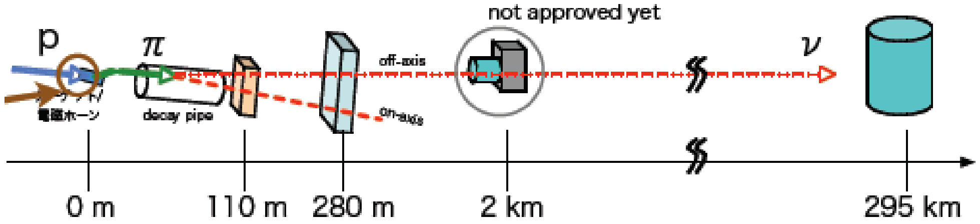
ν beam : J-PARC facility

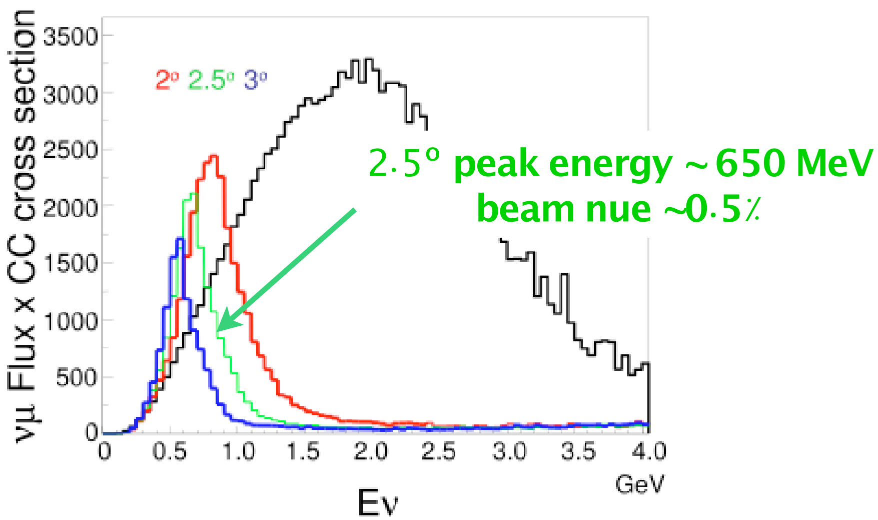
- ➡ **2009 Phase I : θ_{13}, θ_{23}, Δm^2_{23}**
  - J-PARC : 0.75 MW @ 30 GeV
  - SK-III : 22.5 kT FV, full PMT coverage
- ➡ **2015 Phase II : θ_{13}, δ_{CP} ?**
  - J-PARC : 4MW @ 50 GeV (?)
  - HyperK : 1 MT scale



A. Rubbia

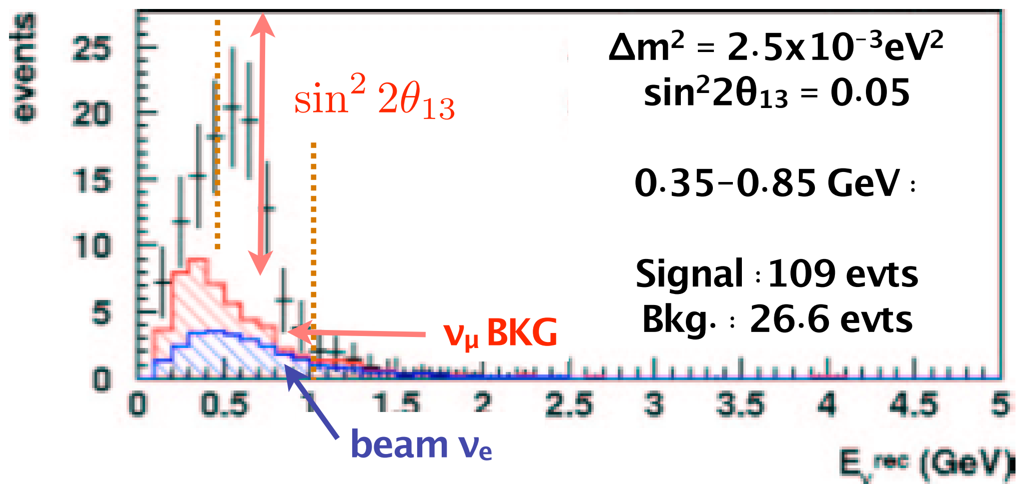
T2K measurements



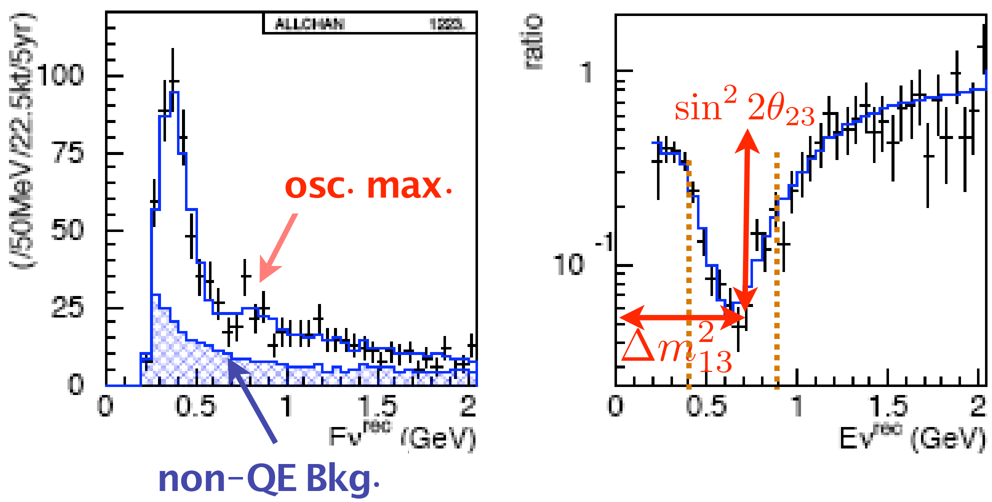


5x 10²¹ pots

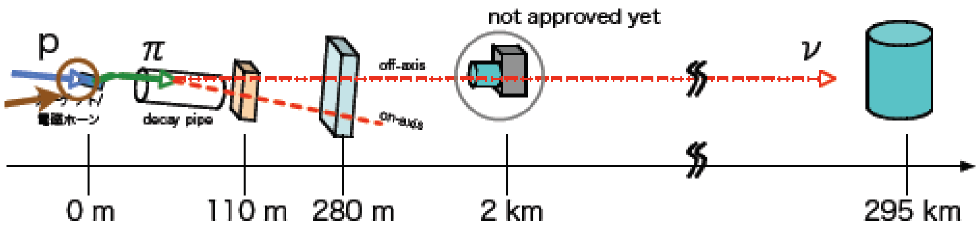
SuperK selected e-LIKE evts



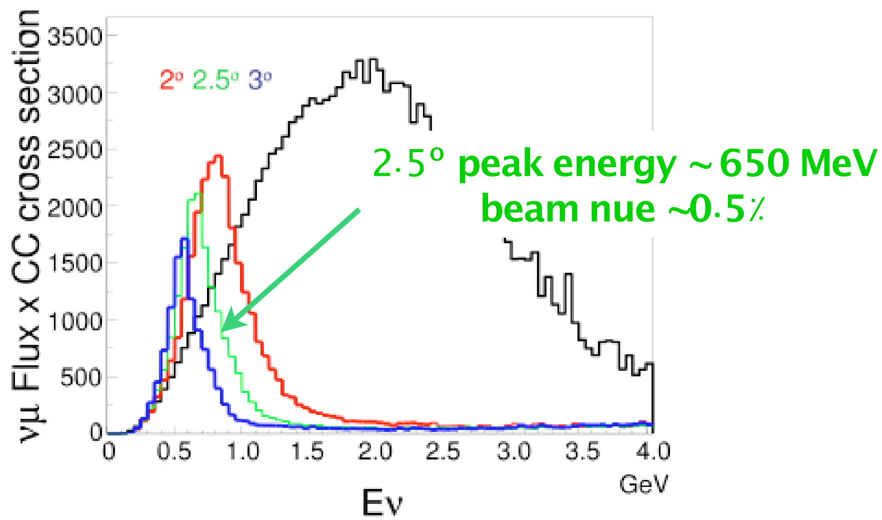
SuperK selected μ-LIKE evts



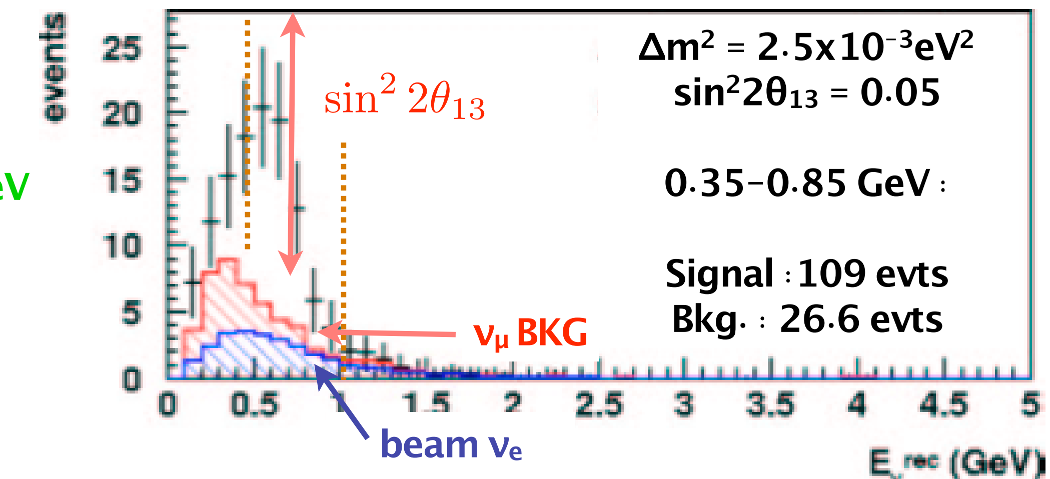
T2K measurements



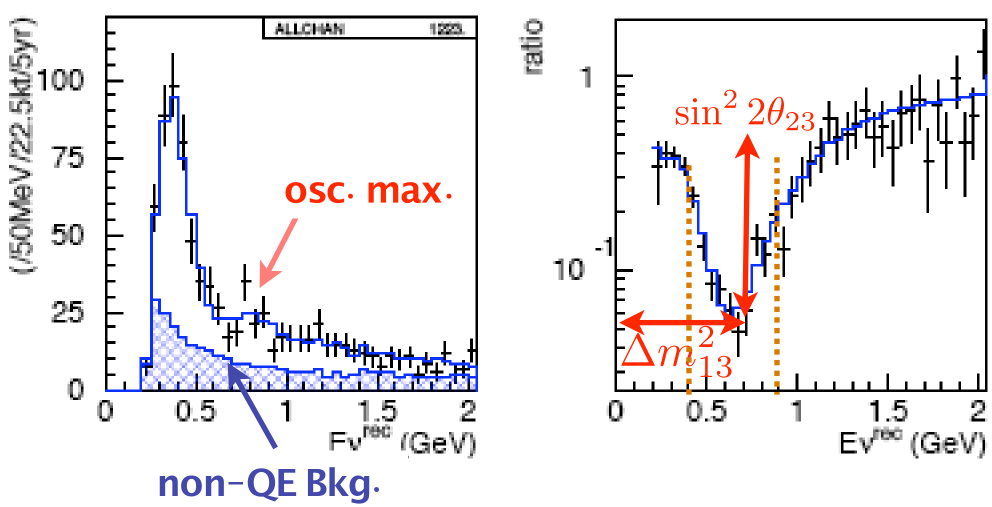
$5x\,10^{21}$ pots



SuperK selected e-LIKE evts



SuperK selected μ-LIKE evts



- ➡ Appearance

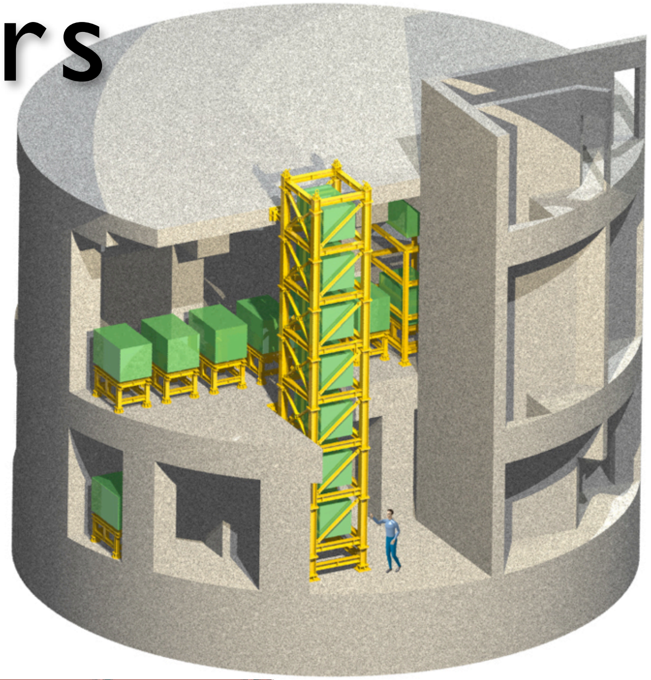
$$\sin^2 2\theta_{13} > 0.01$$

- ➡ Disappearance

$$\delta(\sin^2 2\theta_{23}) \approx 0.01$$

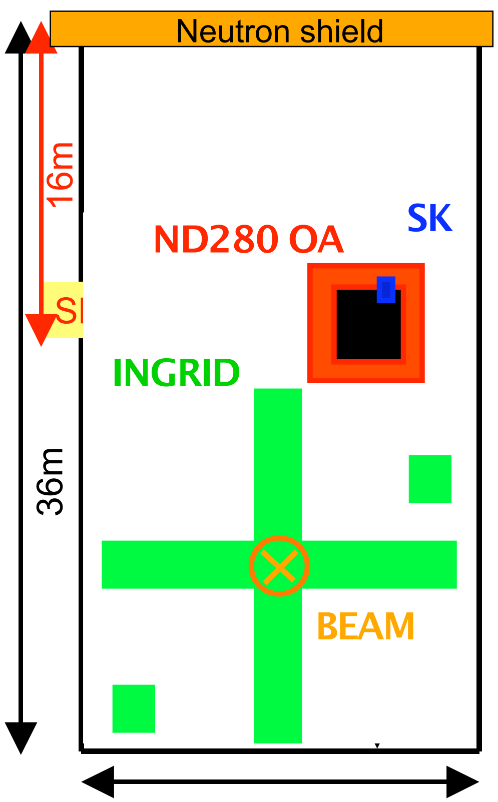
$$\delta(\Delta m^2_{13}) < 10^{-4}\ \mathrm{eV}^2$$

ND280 Near Detectors



- ➡ To be measured before oscillation: Beam flux, Beam νe contamination, non-QE background
- ➡ Near detector tasks :
  - SuperK νe background < 10%
  - νμ event normalisation < 5%
  - Energy scale <2%
  - Beam linear distortion < 20%
  - Width < 10%
  - non-QE/CCQE at 5-10%

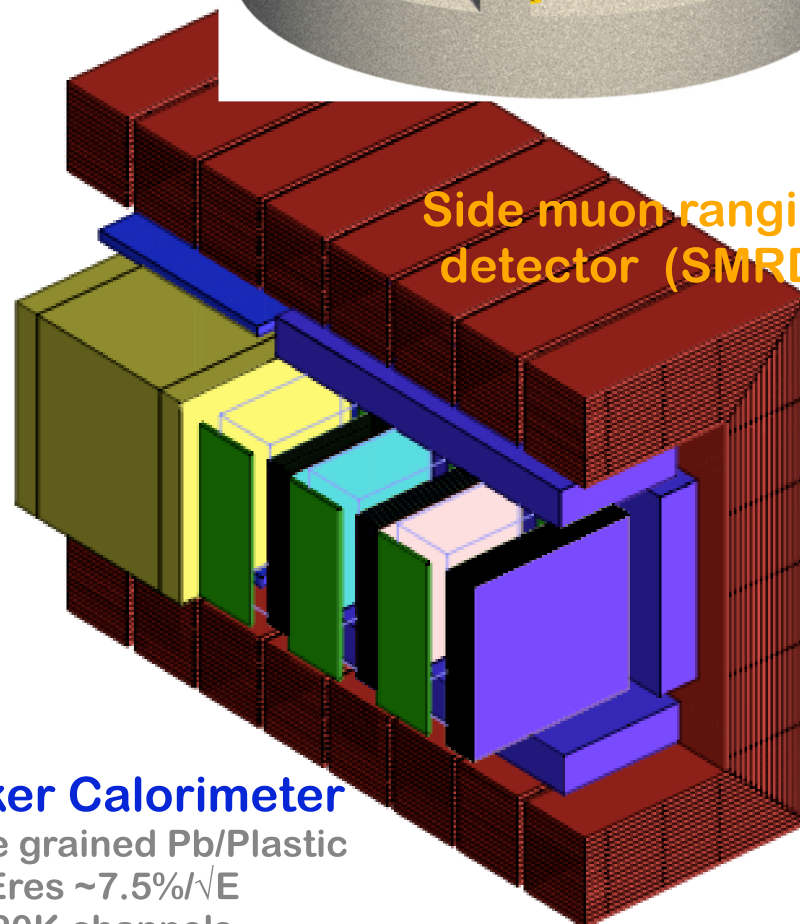
ND280 Pit



UA1/NOMAD magnet
B=0.2 T

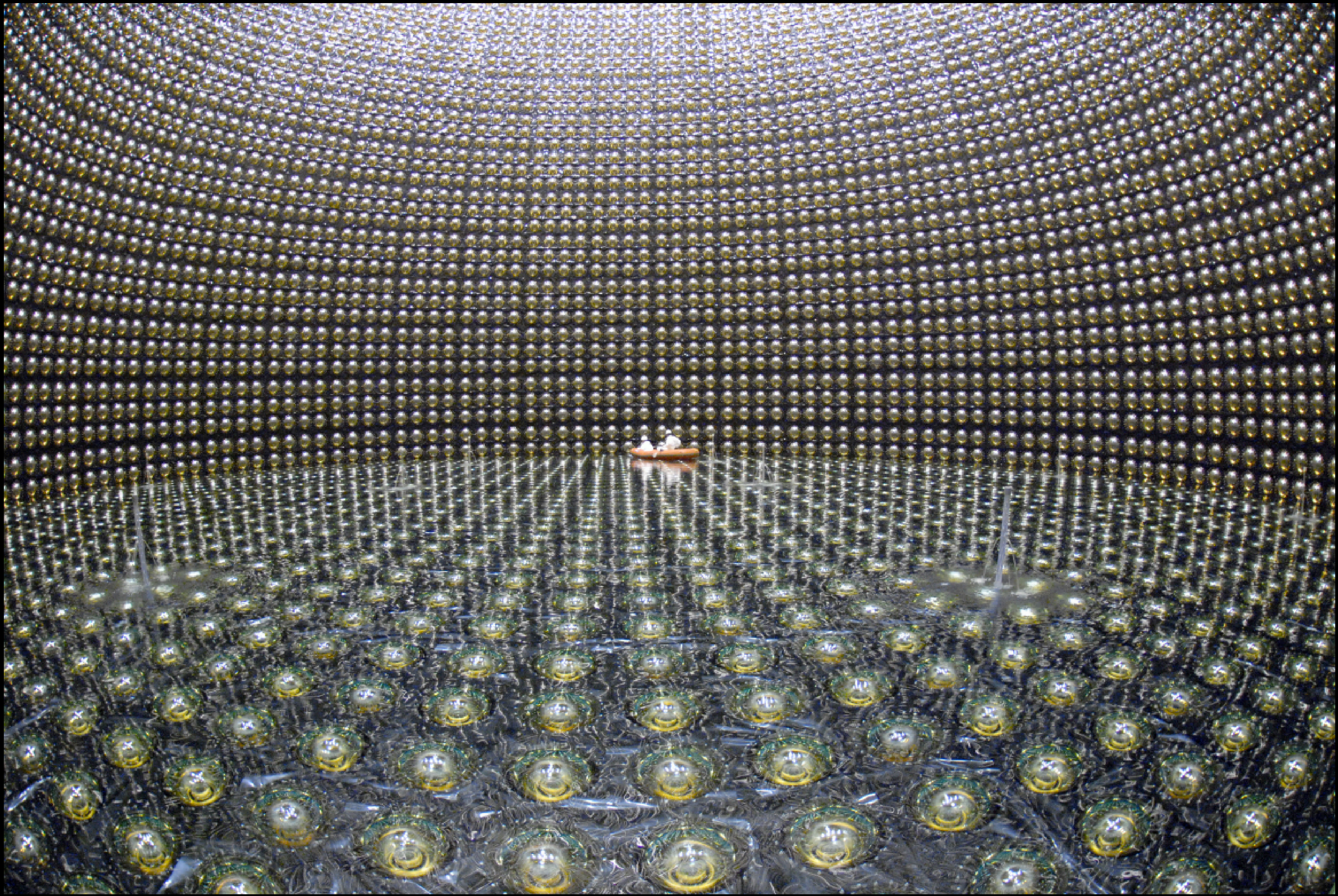
3 TPC modules
MicroMegas pads
Position resolution < 0.8 mm
Mom resolution to 1GeV <7-8%

2 Fine Grained 2x1.3t target detectors (FGD)
FGD1(C): X-Y plastic
FGD2(H20): X-Y plastic
+passive water target
8k channels



Tracker Calorimeter
X-Y fine grained Pb/Plastic
Eres ~7.5%/√E
20K channels

T2K Far detector: SK-III

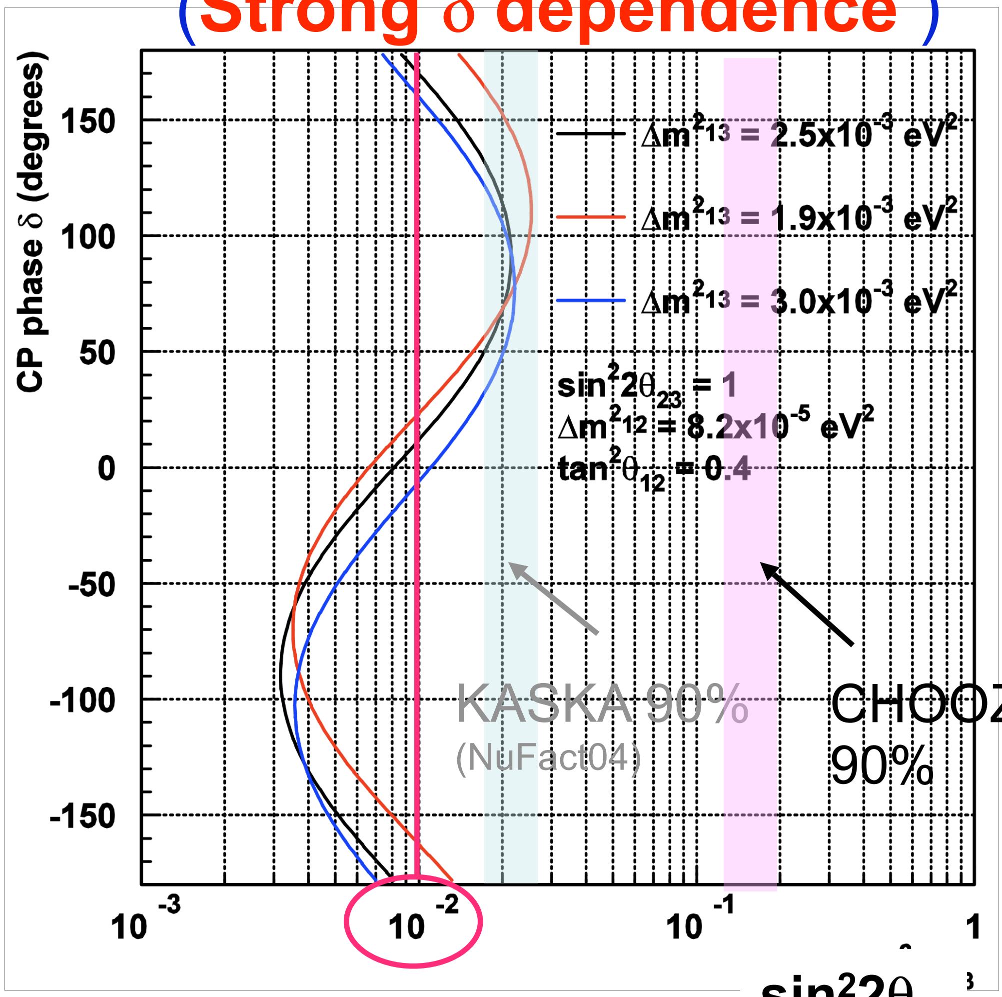


T2K Physics Sensitivity

5x 10^{21} pots

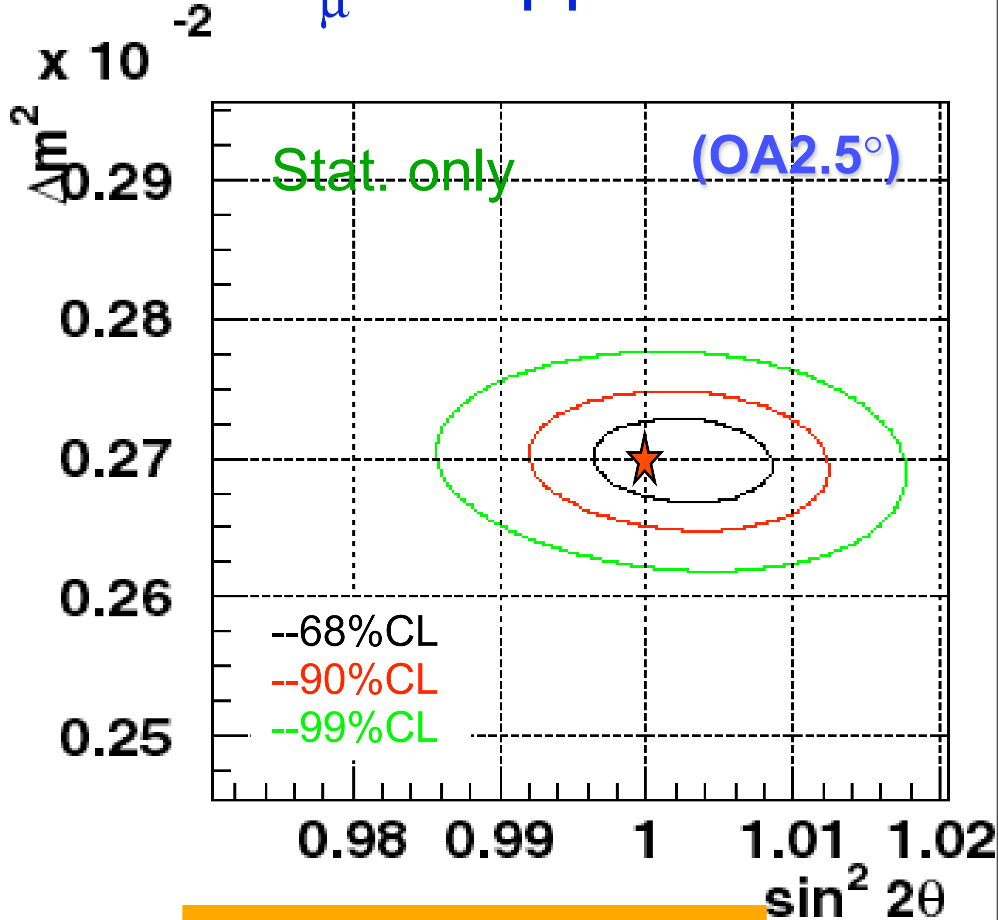
ν_e appearance

(Strong δ dependence)



>10 times improvement from CHOOZ

ν_μ disappearance



Goal

$\delta(\sin^2 2\theta_{23}) \sim 0.01$

$\delta(\Delta m_{23}^2) \sim < 1\times10^{-4}$

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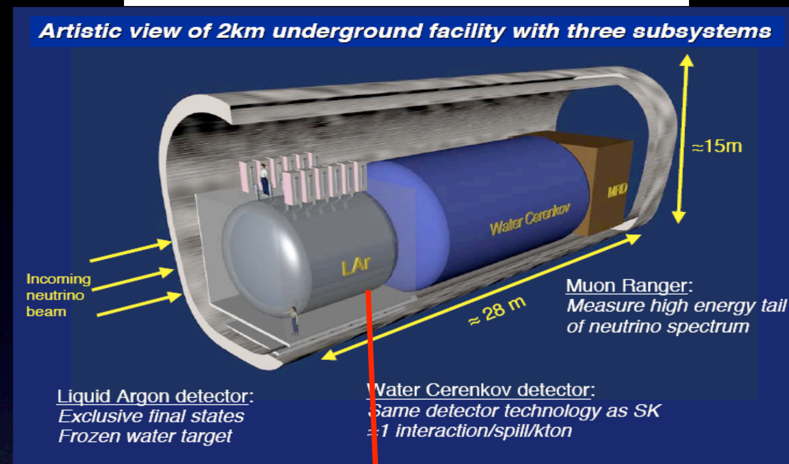
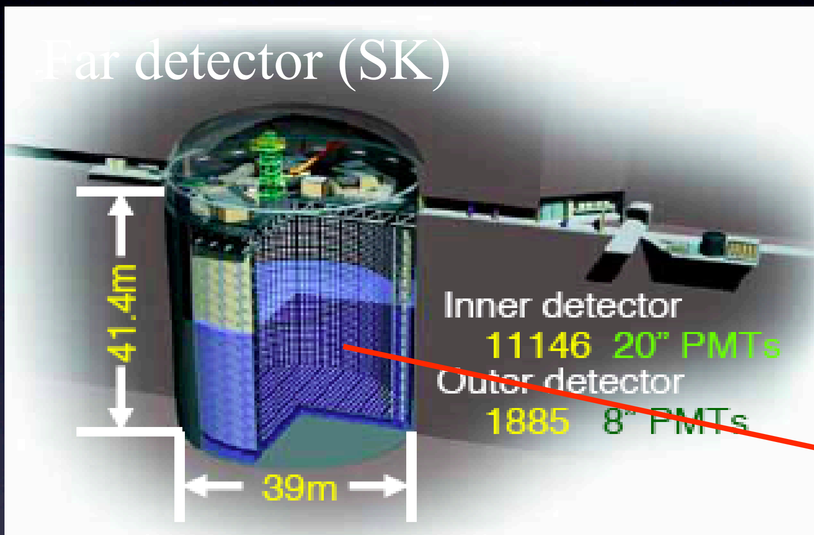
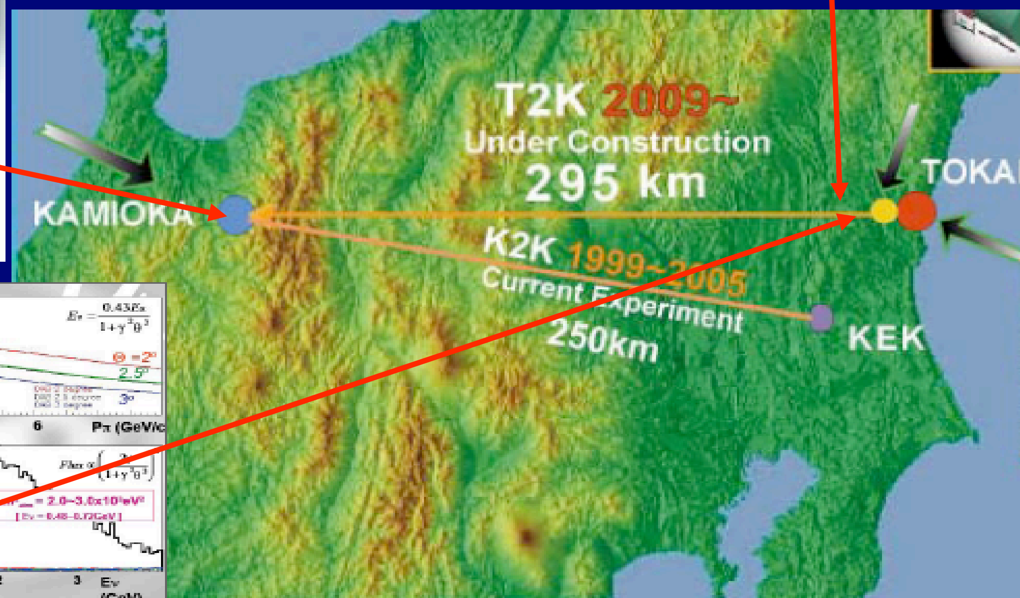
Possible extension of T2K experiment

Internal discussions within Collaboration concerning possible extension at 2km site

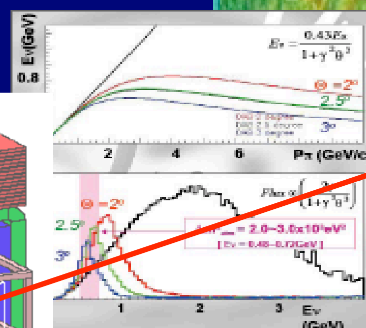
1 kt WC+ 150 ton LAr



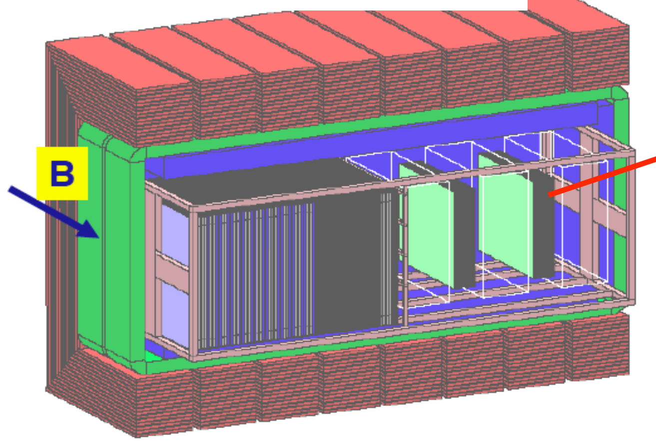




0.75 MW or >2x CERN SPS power

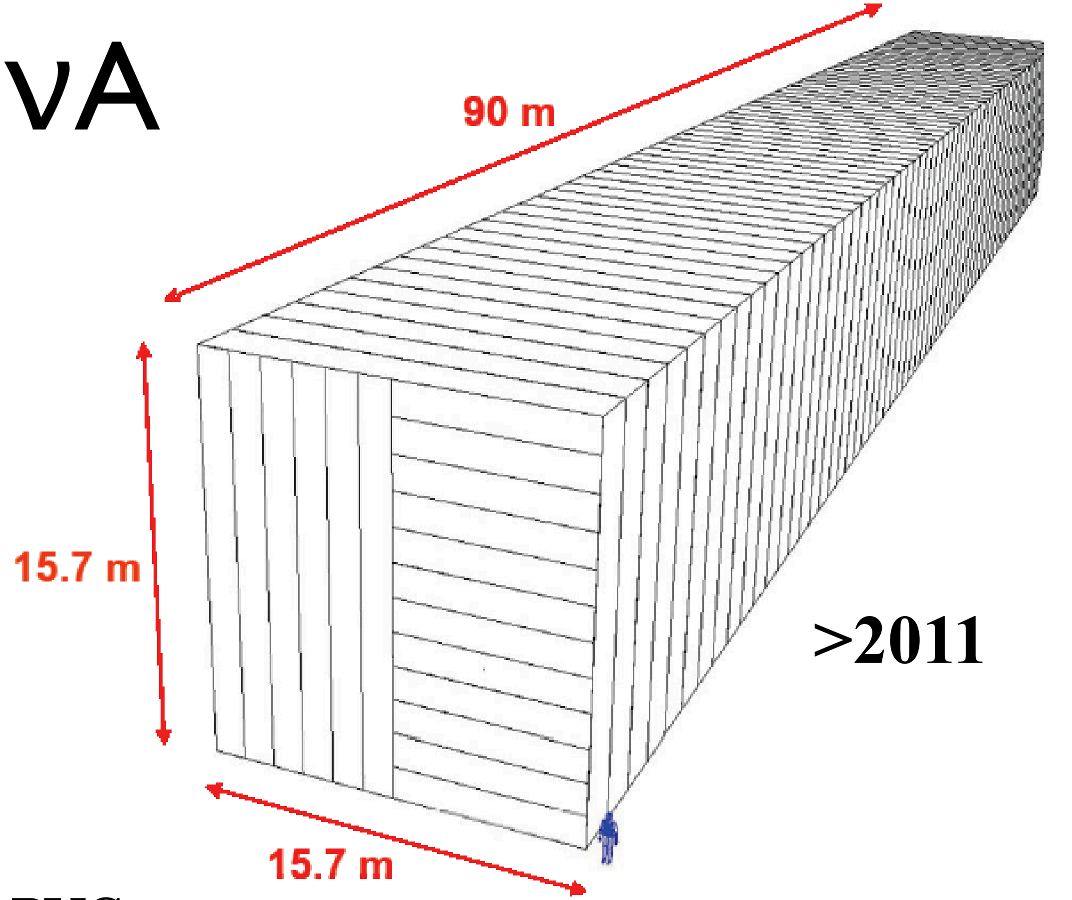


Near 280m detector



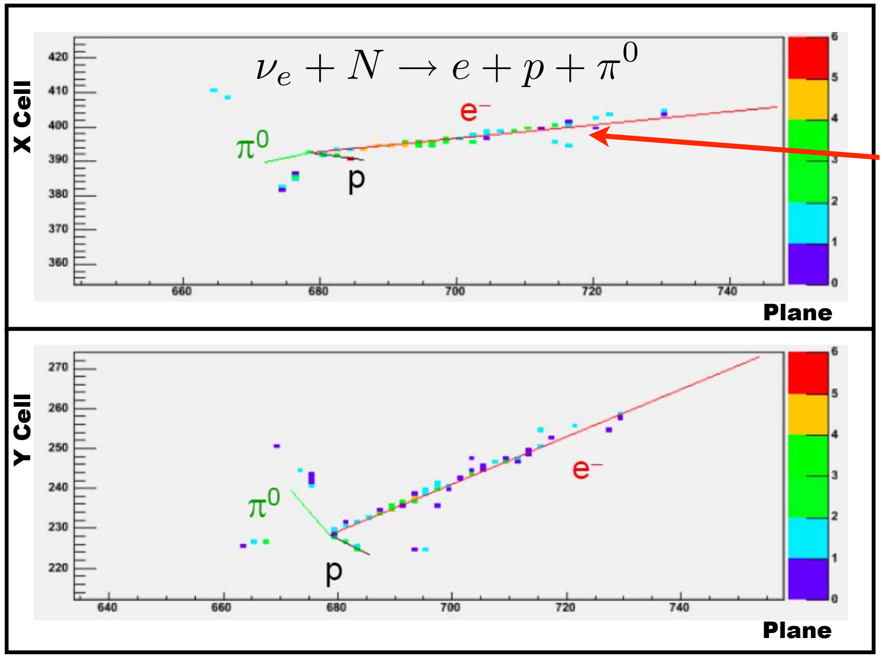
- Low energy neutrino superbeam (less than 1 GeV) from Tokai to Super-Kamiokande starting in 2009 and reaching power of 1.35 MW by 2012 from 40 GeV proton synchrotron (>10^{21} p.o.t./year). Off-axis by 2.5°.
- Foreseen upgrades: 4 MW power and (eventually) 1000 kton Hyper-K
- Very interesting ideas: LBL detector in Korea → **T2KK**

NOvA

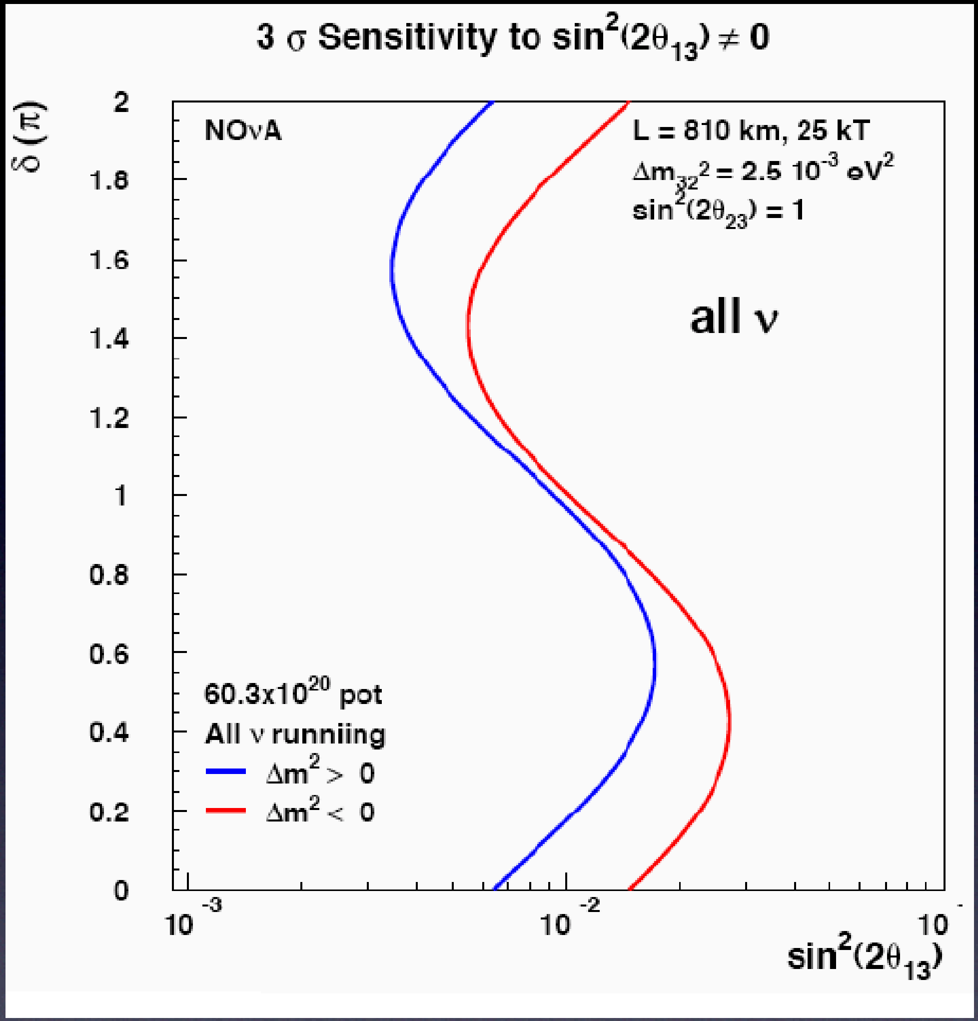


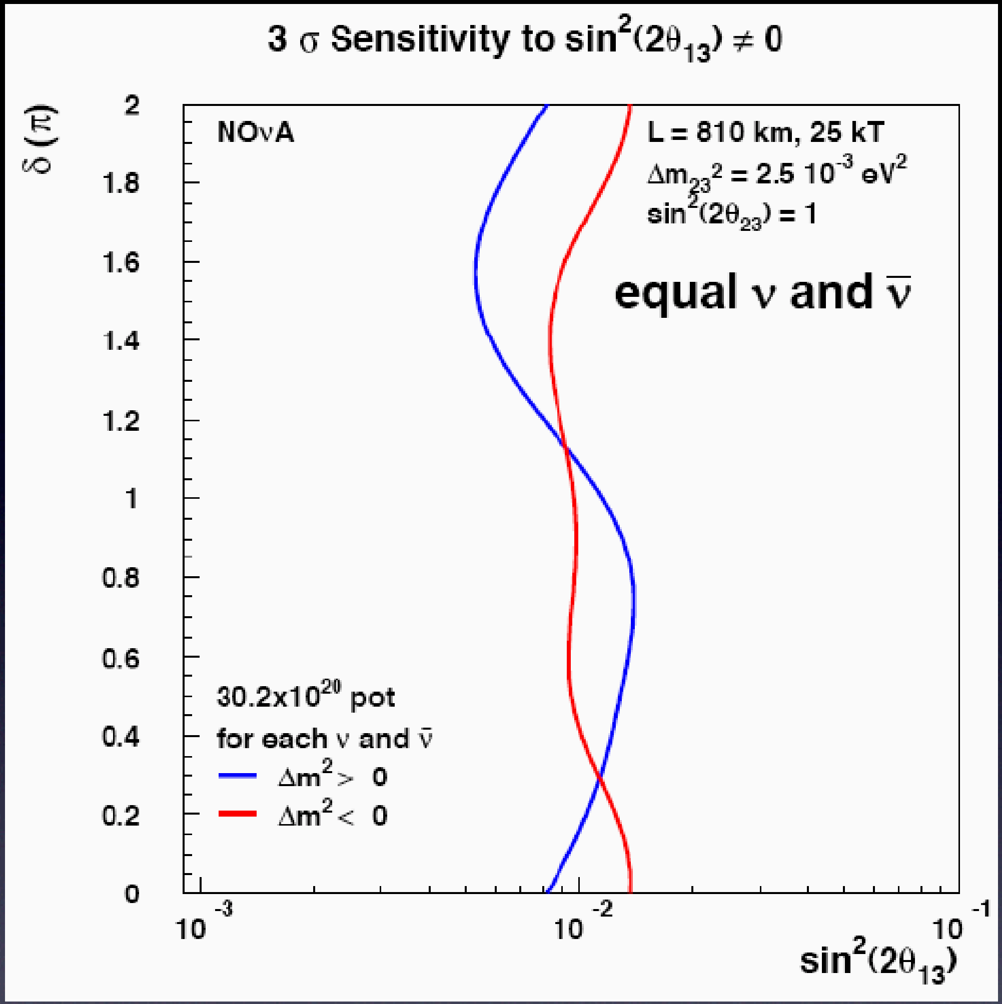
O(20) kton tracking calorimeter

- alternating horizontal and vertical cells of liquid scintillator contained in PVC
  - 80% scintillator, 20% PVC
- 32 cells/extrusion, 12 extrusions/plane
  - cell dimensions: 3.9 cm x 6 cm x 15.7 m
- U-shaped 0.7 mm WLS fiber into APD
- Longitudinal granularity 0.15 X_0
- Efficiency for ~2 GeV ν_e events ~25%
  - background fraction for ν_μ NC ~$2\text{x}10^{-3}$
  - background fraction for ν_μ CC ~$4\text{x}10^{-4}$



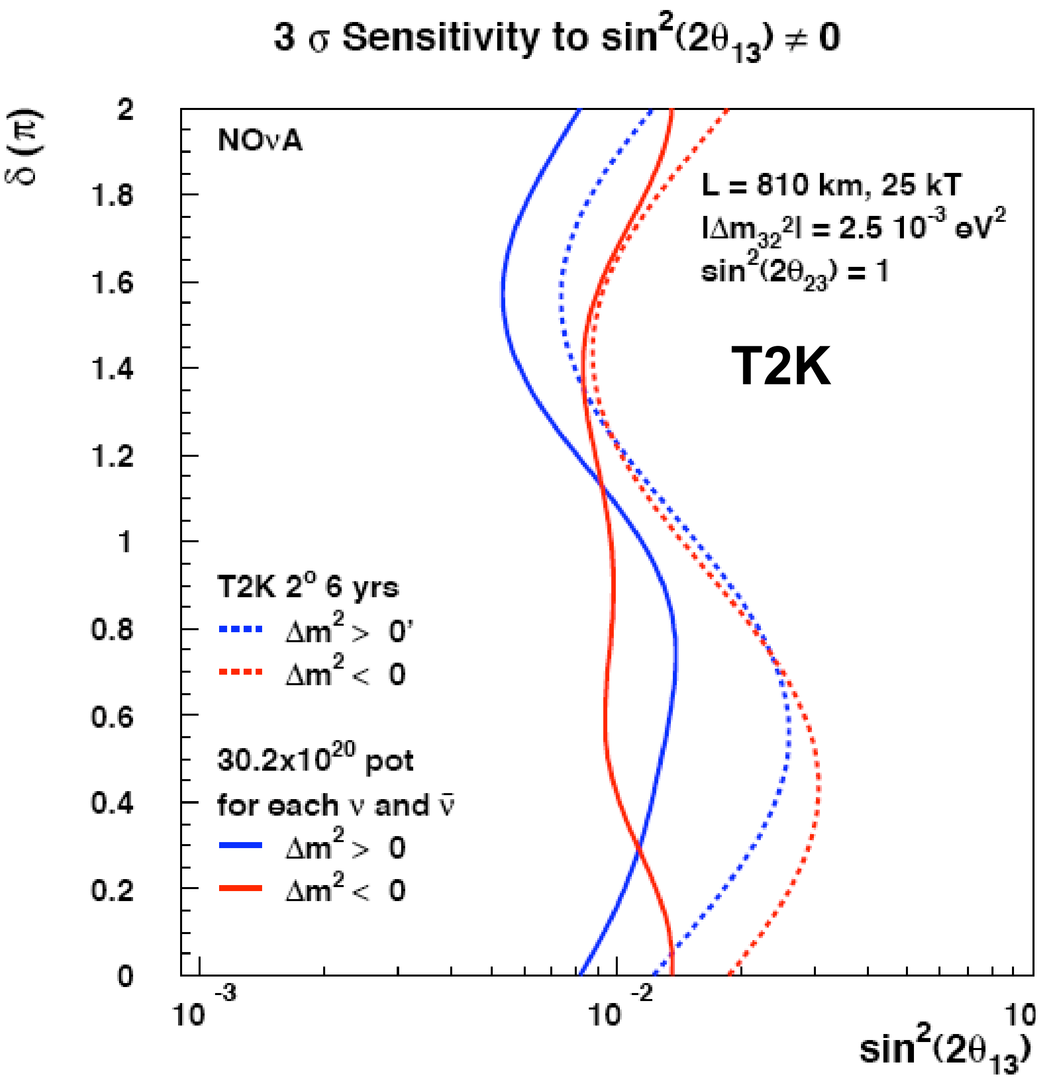
3 σ Sensitivity to θ_{13} # 0

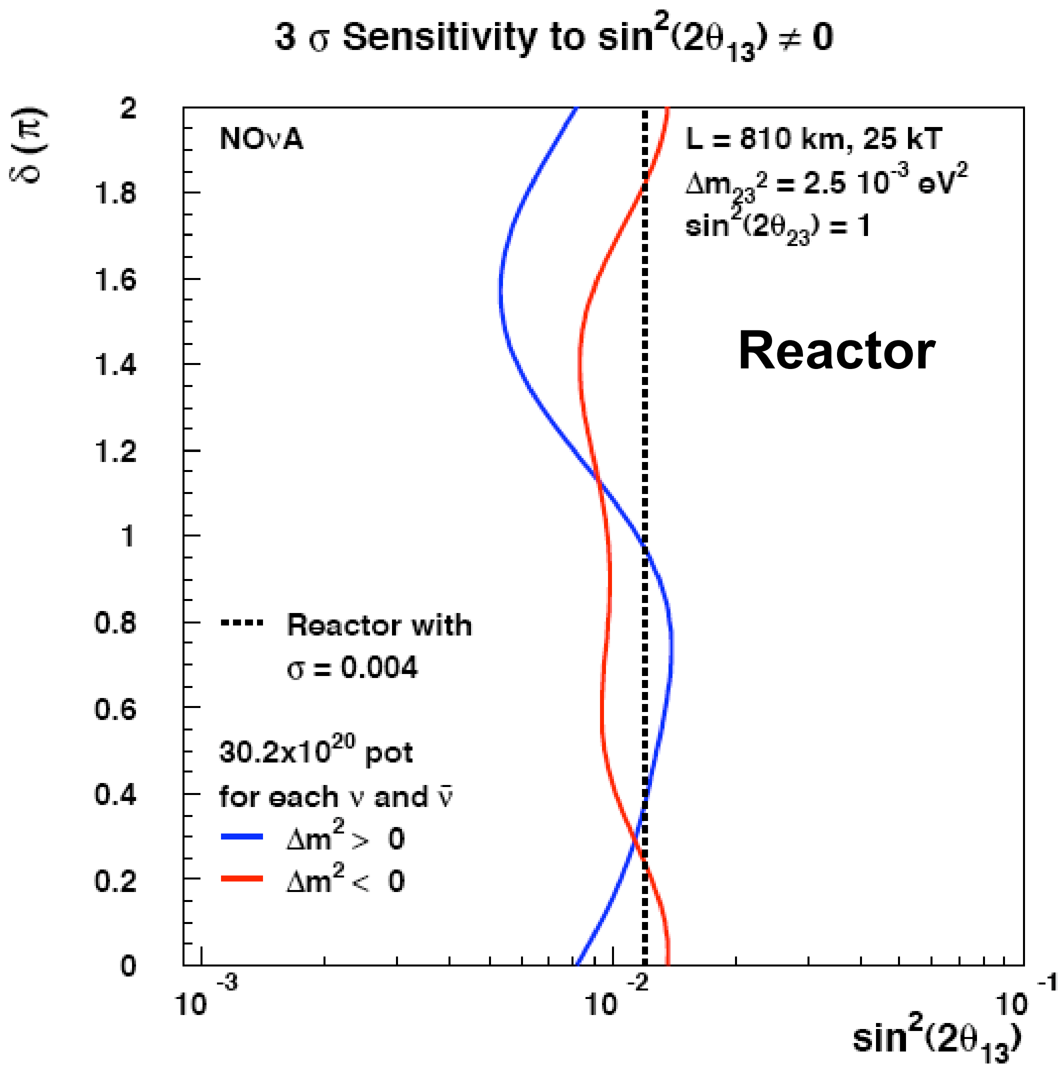




- As part of the NOνA project, the NuMI neutrino line will be upgraded to 6×10^{20} POT/year, with a beam power of 700 kW
- Assumed total protons = 60×10^{20} pots (2006: 1.5×10^{20} pot/year)
- NoVA is a "single measurement" experiment.

Comparison to T2K and a Reactor Experiment





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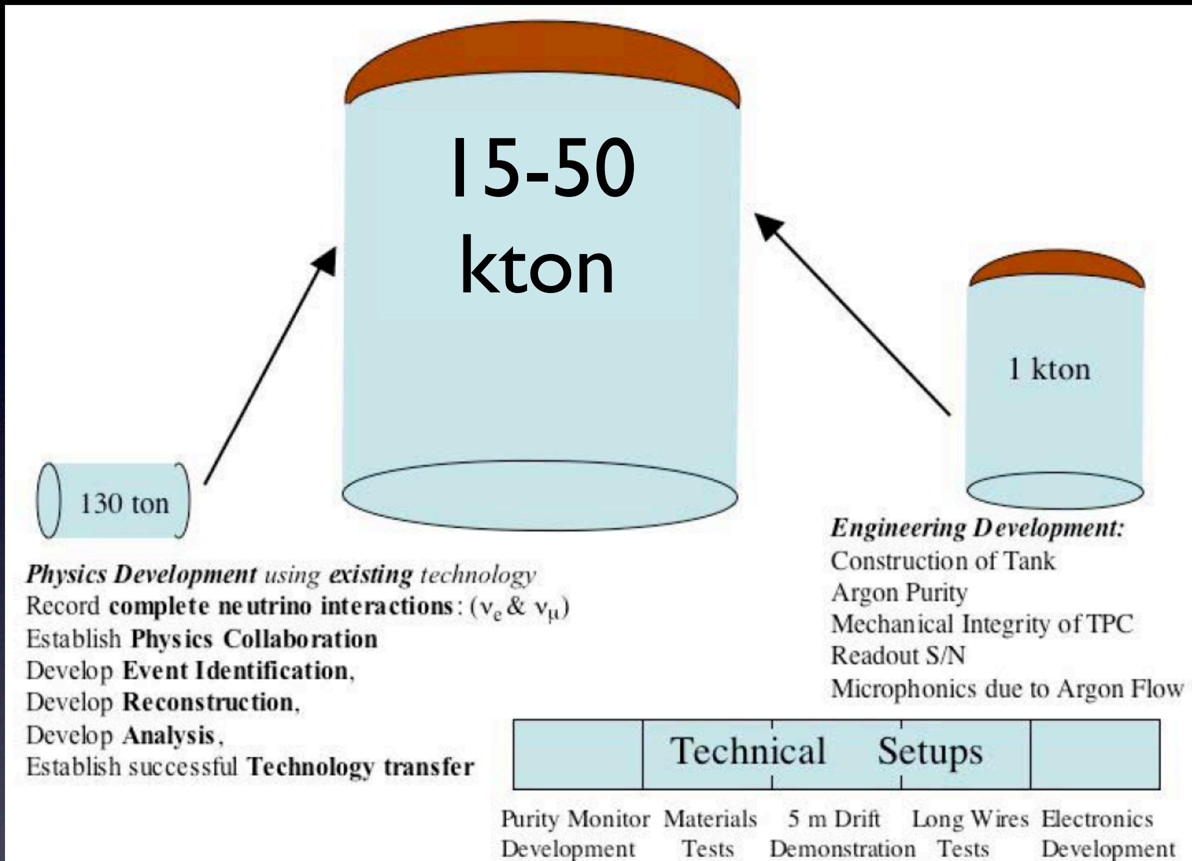
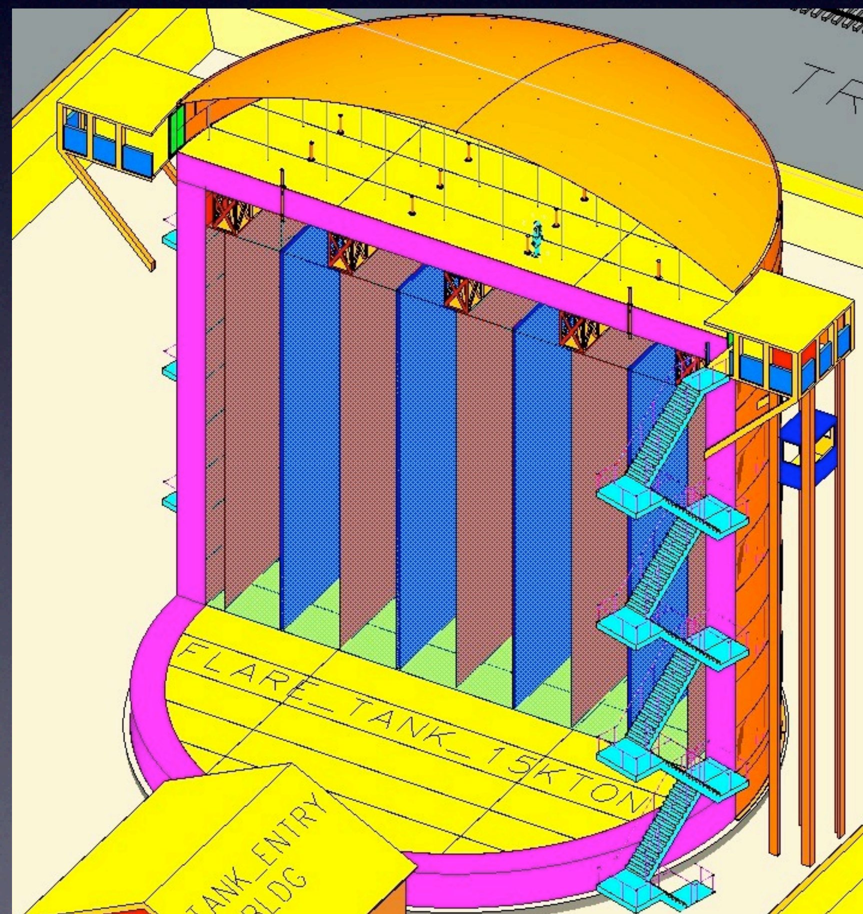
FLARE / LAr TPC (FNAL)

L. Bartoszek et al. FERMILAB-PROPOSAL-0942, Aug 2004.



Aimed at (S)NUMI long-baseline program



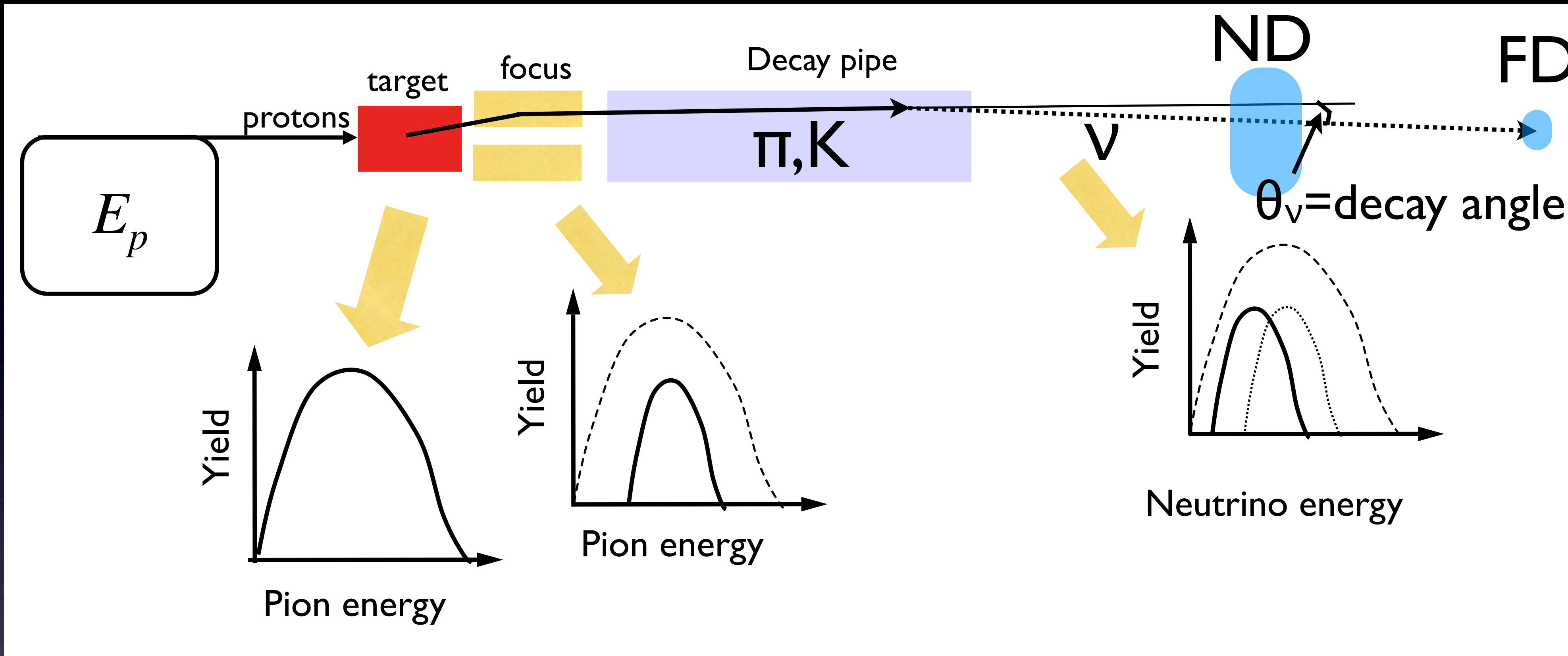
- Starting point: ICARUS-design
- R&D on argon purity, long wires, cold electronics, ...
- Detector on surface (challenging!)

AN UPGRADED CNGS ?

JHEP 0611:032,2006

A. Rubbia

More superbeams ?



- Conventional neutrino beams are nowadays relatively straight-forward
- Main issues are related to power on target, radiation damage and radiation protection in the target/decay region
- If the far neutrino detector (FD) is on axis ($\theta_\nu = 0$) & far away:
  - ★Neutrino energy ≈ 0.43 × pion energy
  - ★Lorentz-boost gives a factor E_ν^2 on solid angle

A. Rubbia

Off-axis neutrino beam configuration

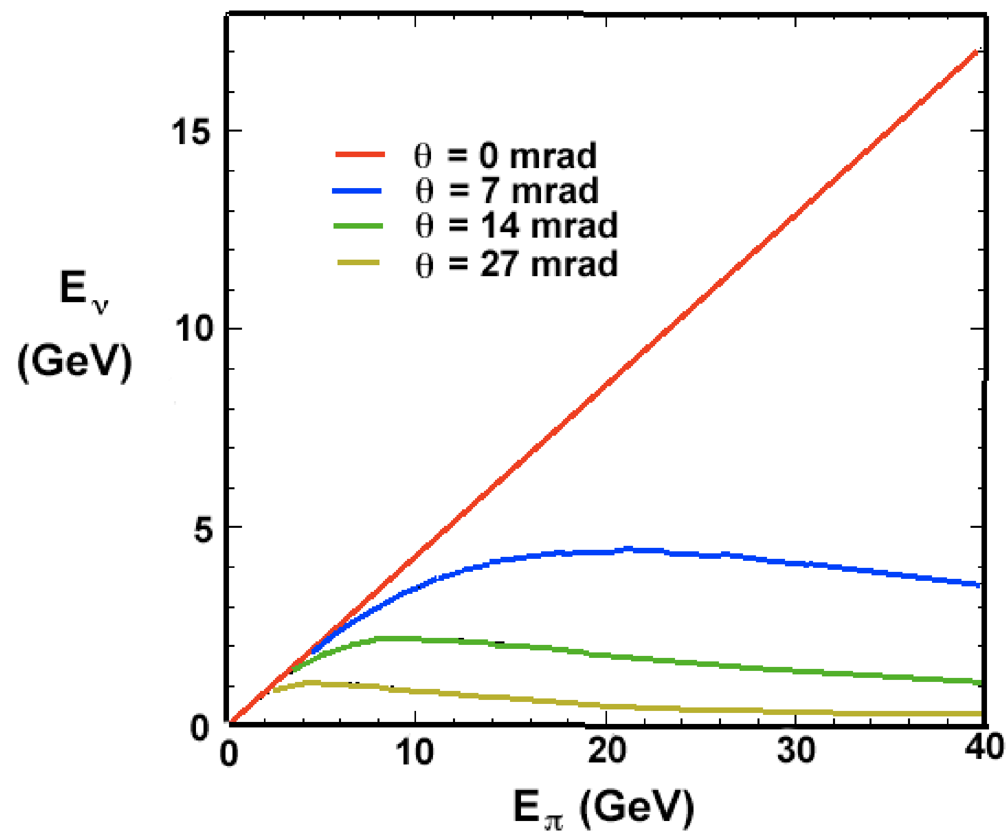
$$E_\nu = \frac{m_M^2 - m_\mu^2}{2(E_M - p_M \cos\theta_\nu)} \approx E_\nu^{max} \frac{1}{2\left(\frac{1}{1+\beta} + \frac{1}{2}\beta\gamma^2\theta_\nu^2\right)}$$

$$\approx E_\nu^{max} \frac{1}{(1+\gamma^2\theta_\nu^2)}$$

$E_\nu^{max} = 0.427\gamma m_\pi$ for pions and $E_\nu^{max} = 0.954\gamma m_K$ for kaons.

Idea pioneered by E889 Collaboration, "Long Baseline Neutrino Oscillation Experiment", Physics Design Report, BNL no 52455 (1995).

For a given $\theta_\nu \neq 0$, a large range of pion (kaon) energies contributes to a small range of neutrino energies



A. Rubbia

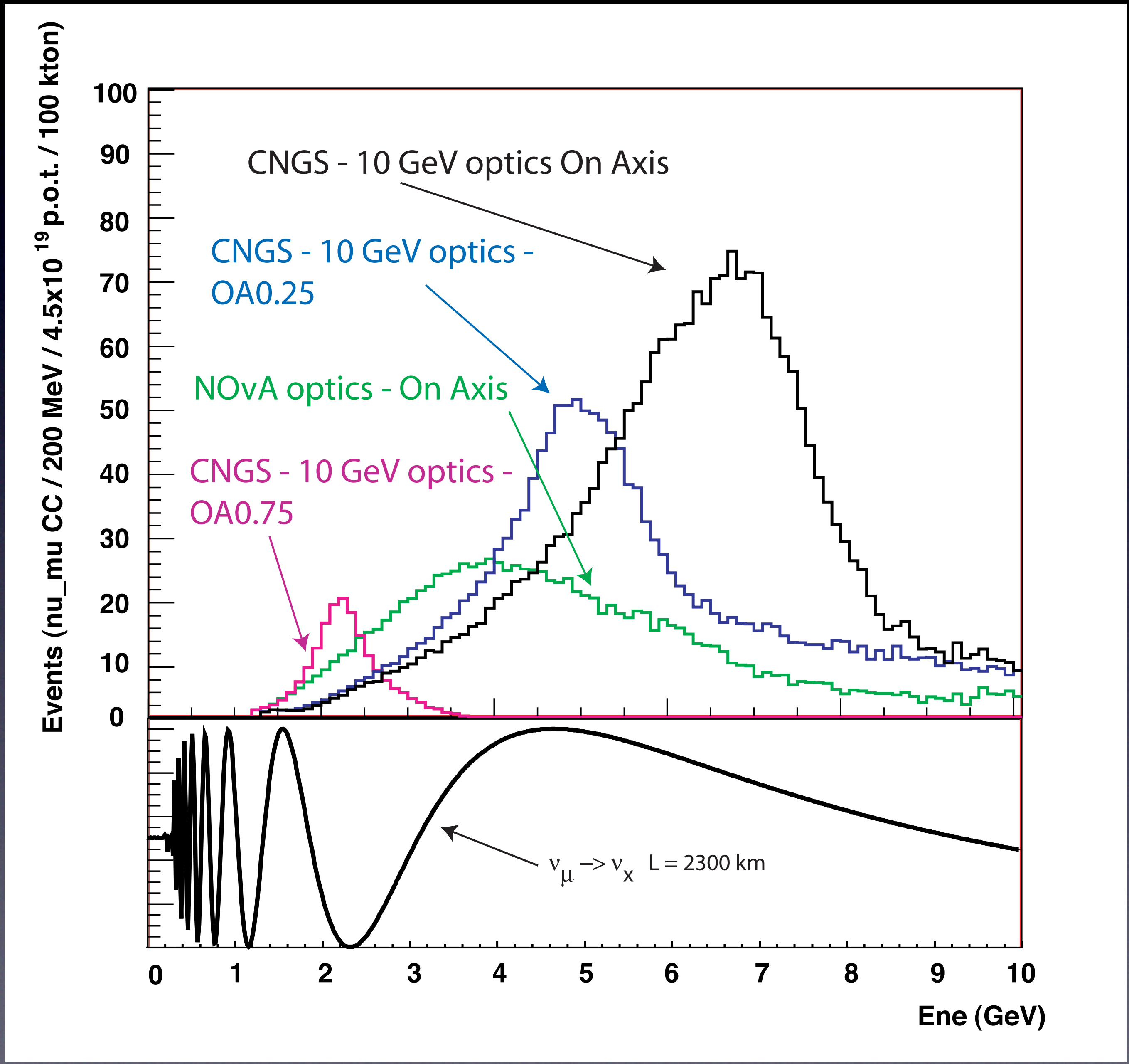
"On" vs "Off"-axis configurations

Full simulation focusing optics for various typical configurations

★CNGS-like 10 GeV/c
★NOvA L.E. optics

★On-Axis
★Off-axis OA0.25 deg
★Off-axis OA0.75 deg

★Normalized to 4.5e19 pots, 100 kton, L=2300km



A. Rubbia

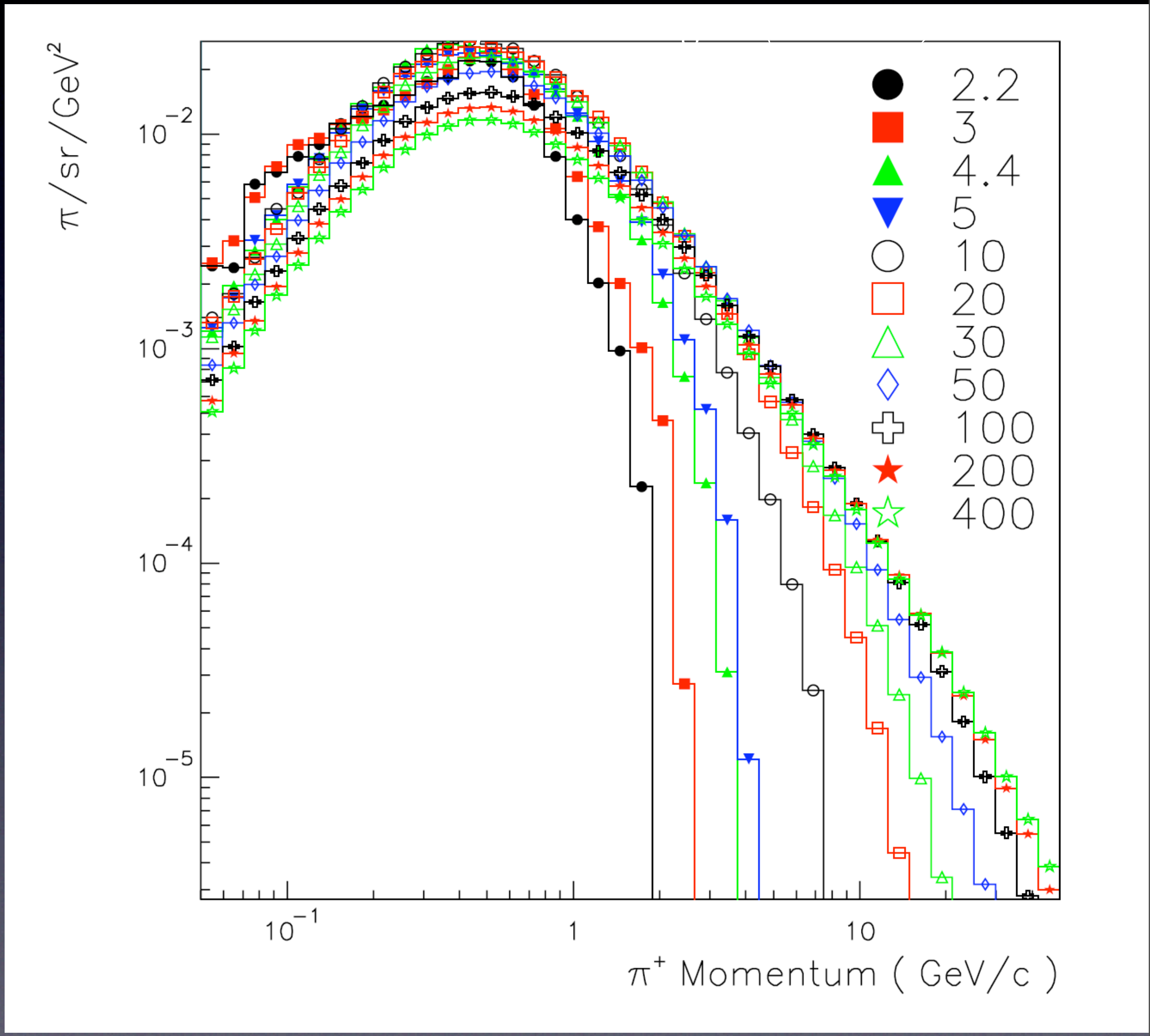
Superbeam: scaling of pion production

Scaling: in order to compare spectra at different proton energies, we divide by the proton energy E_p

All normalized spectra have similar shapes, with maximum yield around $p_\pi \approx 500\ MeV/c$
Departure from "scaling" consist in difference at low energy, and harder spectra at high E_p

These means that the relevant figure is the number of protons x energy of protons on target

Estimated positive pion yields for different



A. Rubbia

CERN neutrino complex (CN)

- The main focus of the CERN accelerator complex will soon shift to LHC. However, it is known that the integrated luminosity in the LHC experiments will directly depend upon the performance and reliability of the injectors, namely Linac2, PSB, PS and SPS.
- The CERN working group on Proton Accelerators for the Future (PAF) has reviewed the situation and elaborated a baseline scenario for the upgrades of the CERN accelerators.
- In the first stage, a new Linac4 would be built to simplify the operation of the PS complex for LHC and help investigate the SPS capability to handle very high brightness beams. In a second stage, the PS would be replaced by a new PS (PS+) with a beam power of approximately 200 kW available at 50 GeV/c.
- If the proton beam from the new PS could be efficiently post-accelerated to 400 GeV/c and extracted to the CNGS target area, a MW-class neutrino beam would be possible.

Beam parameters

JHEP 0611:032,2006

	JPARC design	JPARC upgrade	FNAL w/o PD	FNAL w PD	CERN CNGS dedicated	CERN CNGS'	CERN CNGS+
Proton energy E_p	40 GeV/c		120 GeV/c		400 GeV/c		
$ppp(\times 10^{13})$	33	> 33	9.5	15	4.8	7	14
T_c (s)	3.64	< 3.64	1.6	1.467	6	6	6
Efficiency	1.0	1.0	1.0	1.0	0.55	0.55	0.83
Running (d/y)	130	130	230	230	200	200	200
N_{pot} / yr $(\times 10^{19})$	100	$\simeq 700$	120	200	7.6	11	33
Beam power (MW)	0.6	4	1.1	2.0	0.3	0.4	1.2
$E_p \times N_{pot}$ $(\times 10^{22}$ GeV$\times$pot/yr)	4	28	14.4	24	3	4.4	13.2

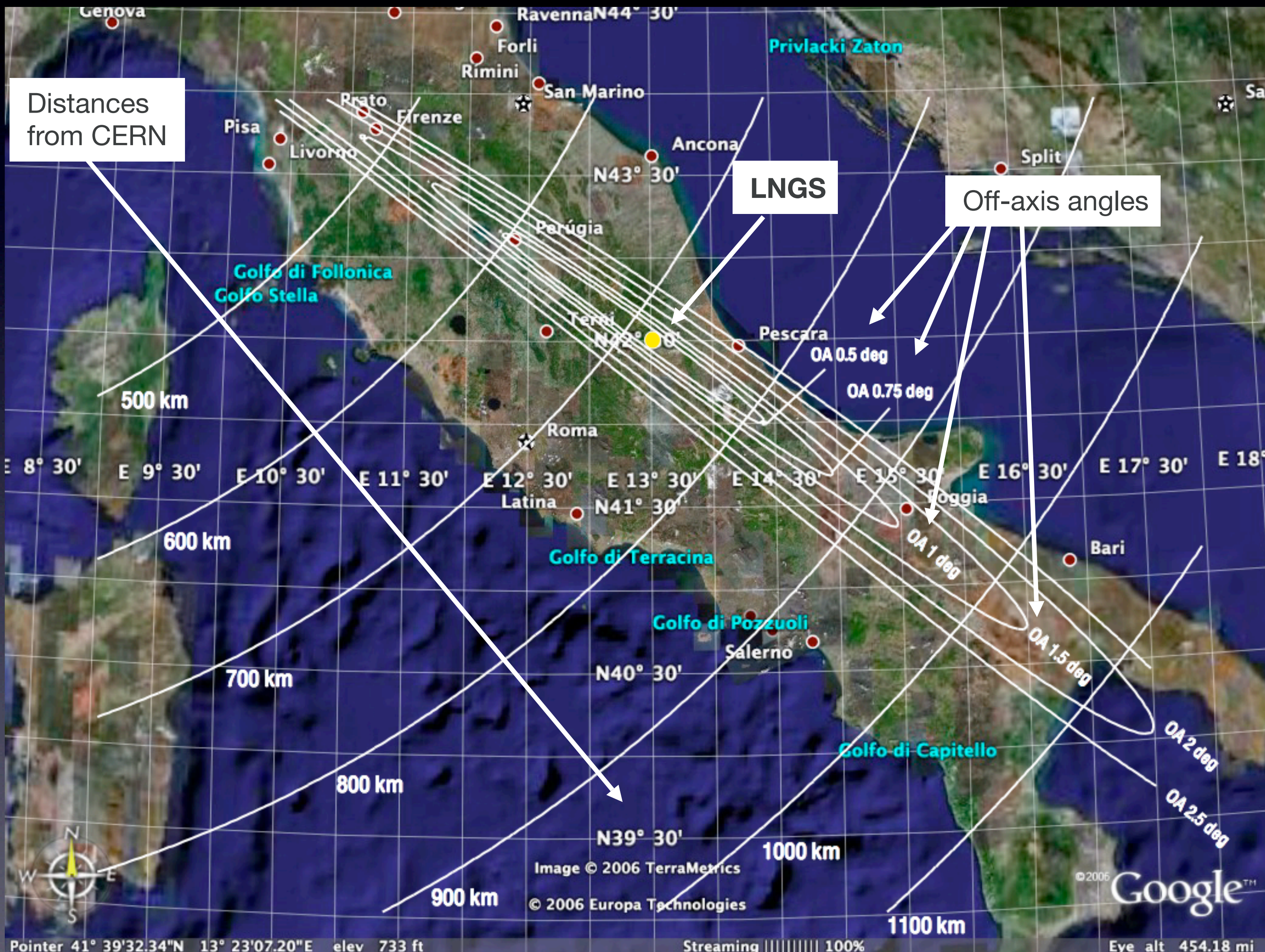
CNGS "shared" 4.5×10^{19} pot/yr

CERN: compensate less protons/year (Npot) by higher proton energy (Ep)

➠ competitive Ep x Npot !!

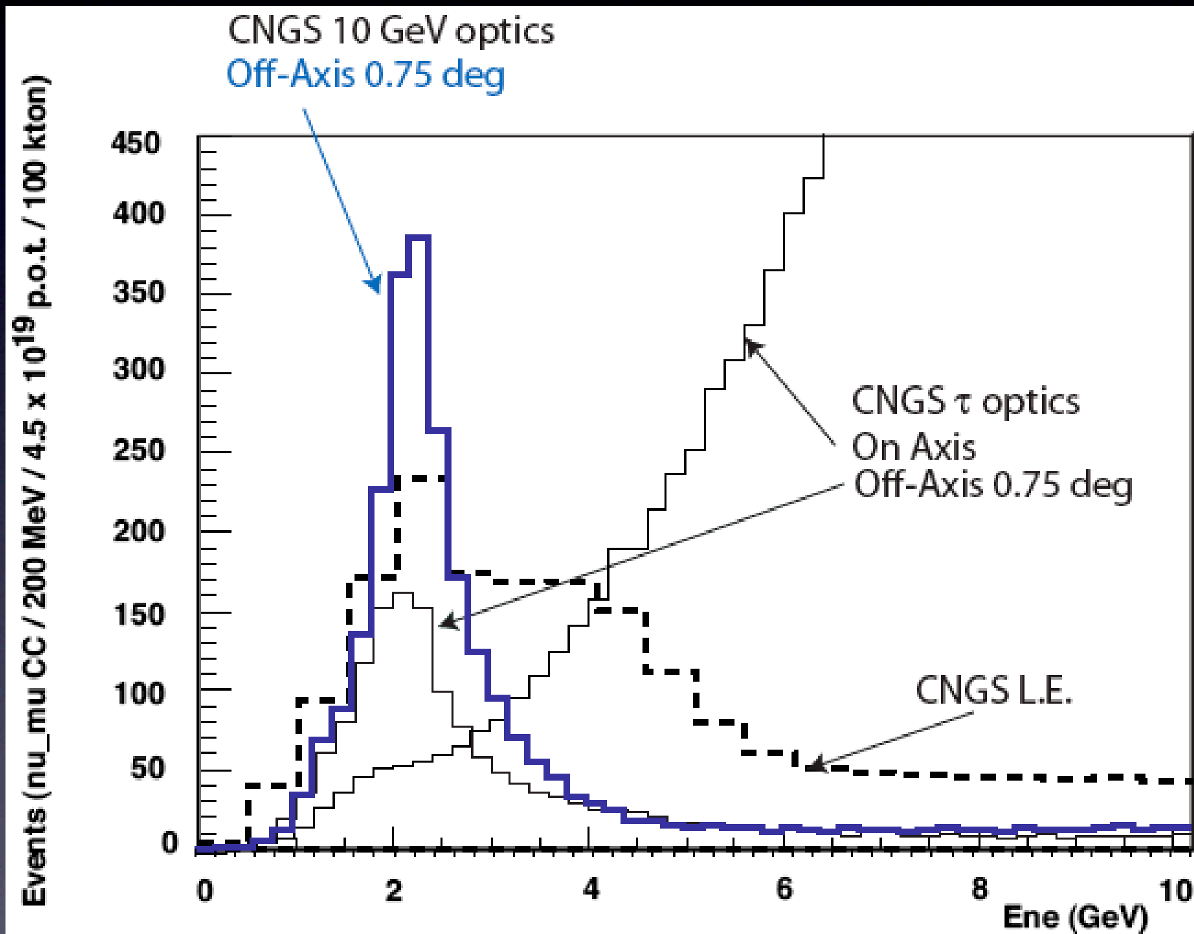
A. Rubbia

CNGS beam profile



- The beam is aimed on-axis towards the Gran Sasso Laboratory.
- The energy is tuned in order to observe τ-neutrino appearance (about 35 GeV mesons).
- The location of a new detector would have a baseline between 500 km and 1050 km. The limits on the maximal off-axis angle are related to the baseline considered.

CNGS beam optimisation



- In order to use the CNGS beam to perform ν_e appearance measurements, we need to increase the spectrum at low energy.
- Optics was re-designed to have on-axis low energy neutrino beam (CNGS L.E.) (July 2002, JHEP 0209:004,2002)
- With the original (τ) optics and using the off-axis technique similar results are achieved (30% less below 2 GeV compared to CNGS L.E. but less high energy tail).
- A factor of 2 can be gained with a new optics to focus pions of 10 GeV.

CNGS beam optics

JHEP 0209:004,2002 → CNGS L.E.

JHEP 0611:032,2006 → CNGS 10 GeV

	CNGS τ	CNGS L.E.	CNGS 10 GeV
Target			
Material	Carbon	Carbon	Carbon
Total target length	2 m	1 m	2 m
Number of rods	13	1	8
Rod spacing	first 8 with 9 cm dist.	none	9 cm
Diameter of rods	first 2 5 mm, then 4 mm	4mm	2 mm
Horn			
Distance beginning of target-horn entrance	320 cm	25 cm	100 cm
Length	6.65 m	4 m	6.65 m
Outer conductor radius	35.8 cm	80 cm	37.2 cm
Inner conductor max. radius	6.71 cm	11.06 cm	11.4 cm
Inner conductor min. radius	1.2 cm	0.2 cm	0.15 cm
Current	150kA	300kA	140kA
Reflector			
Distance beginning of target-reflector entrance	43.4 m	6.25 m	11 m
Length	6.65 m	4 m	6.45 m
Outer conductor radius	55.8 cm	90 cm	56.6 cm
Inner conductor max. radius	28 cm	23.6 cm	24 cm
Inner conductor min. radius	7cm	5 cm	6 cm
Current	180kA	150kA	180kA
Decay tunnel			
Distance beginning of target-tunnel entrance	100 m	50 m	100 m
Length	992 m	350 m	1100 m*
Radius	122 cm	350 cm	122 cm

CNGS 10 GeV "optimized"

- Meson production parameterized with M. Bonesini, Eur. Phys. J. C20, 13 (2001)

- Individual particle tracking from target through optics system and decay tunnel

- Secondary interactions taken into account

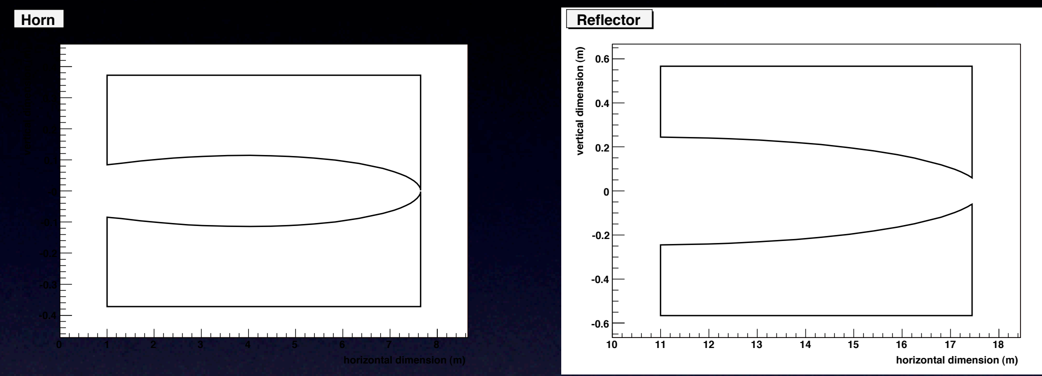
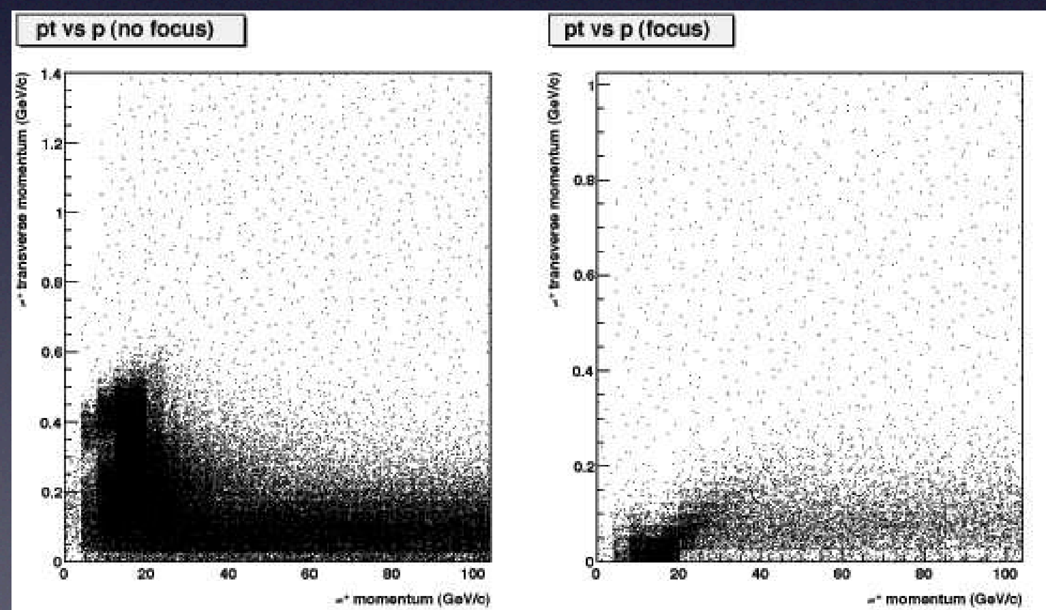


Figure 3: Geometry of horn and reflector for CNGS 10 GeV optics.



Optimal off-axis kinematics

A) Well-known kinematics formula

$$E_\nu = \frac{m_M^2 - m_\mu^2}{2(E_M - p_M \cos\theta_\nu)} \approx E_\nu^{max} \frac{1}{2\left(\frac{1}{1+\beta} + \frac{1}{2}\beta\gamma^2\theta_\nu^2\right)}$$

$$\approx E_\nu^{max} \frac{1}{(1+\gamma^2\theta_\nu^2)}$$

B) Condition for energy to observe 1st maximum and minimum:

$$1.27 \frac{L(km)}{E_{max}(GeV)} \Delta m^2(eV^2) \simeq \frac{\pi}{2}$$

$$1.27 \frac{L(km)}{E_{min}(GeV)} \Delta m^2(eV^2) \simeq \pi$$

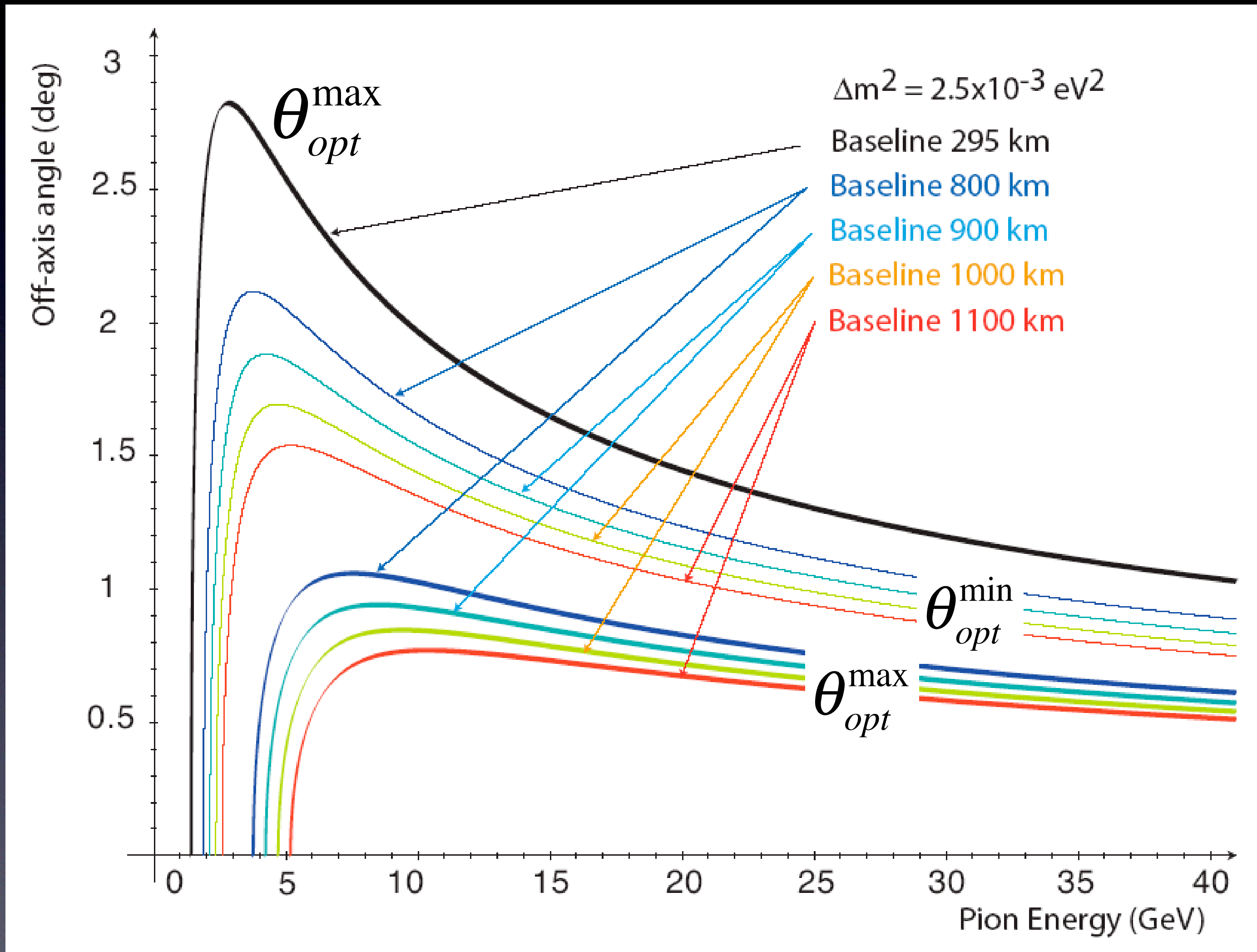
C) Combining expressions A)&B), one finds optimal off-axis angle for observing 1st maximum or minimum. For example for pion decays:

$$\theta_\nu^{opt,max} \approx \sqrt{\left(\frac{\pi}{2.54} \frac{E_\nu^{max}(GeV)}{L(km)\Delta m^2(eV^2)} - 1\right)\frac{1}{\gamma^2}} \approx \sqrt{\left(\frac{\pi}{2.54} \frac{0.427 E_\pi(GeV)}{L(km)\Delta m^2(eV^2)} - 1\right)\left(\frac{m_\pi}{E_\pi}\right)^2}$$

$$\theta_\nu^{opt,min} \approx \sqrt{\left(\frac{\pi}{1.27} \frac{0.427 E_\pi(GeV)}{L(km)\Delta m^2(eV^2)} - 1\right)\left(\frac{m_\pi}{E_\pi}\right)^2} \quad ($$

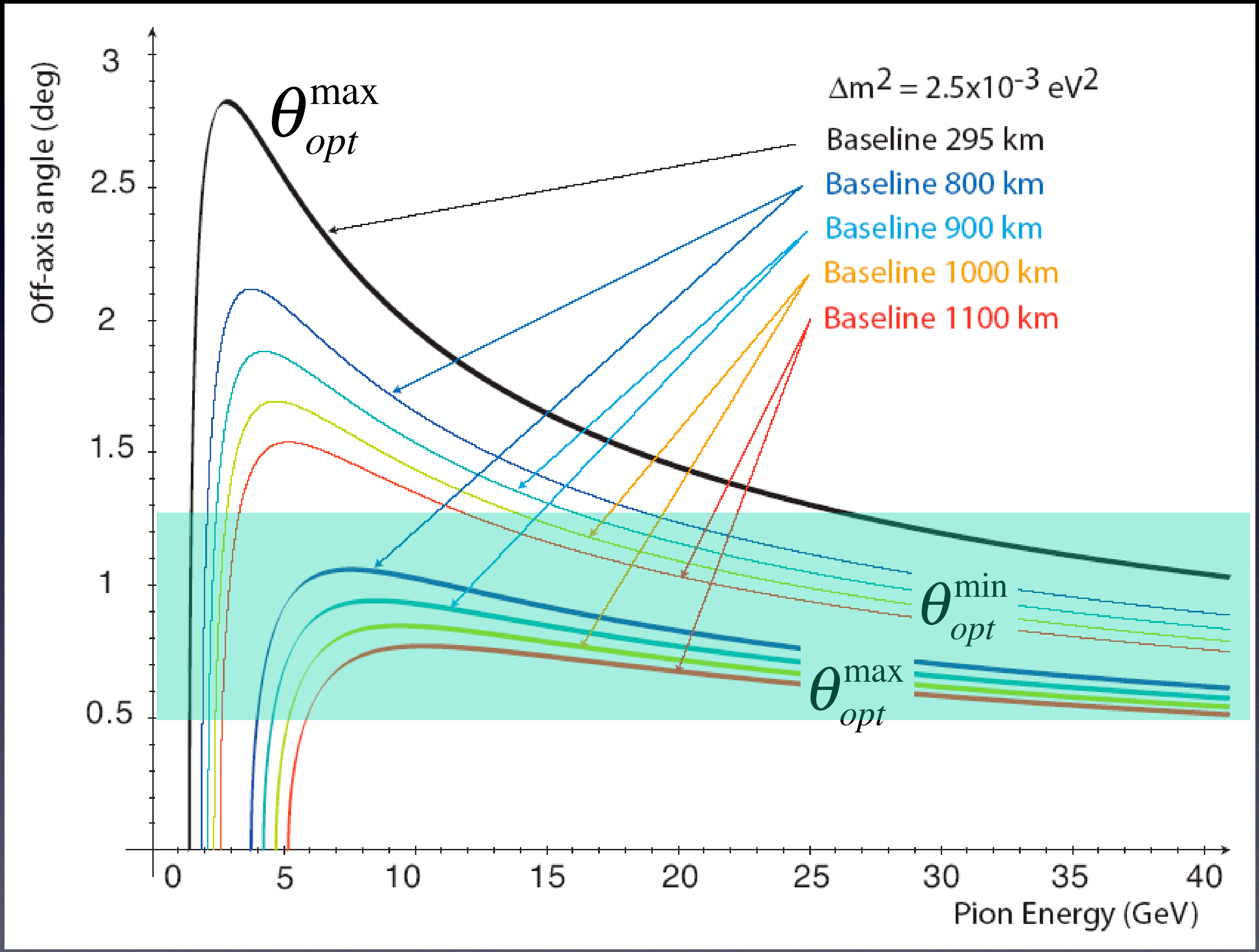
A. Rubbia

Optimal off-axis angle for first maximum (minimum) at several baselines



A. Rubbia

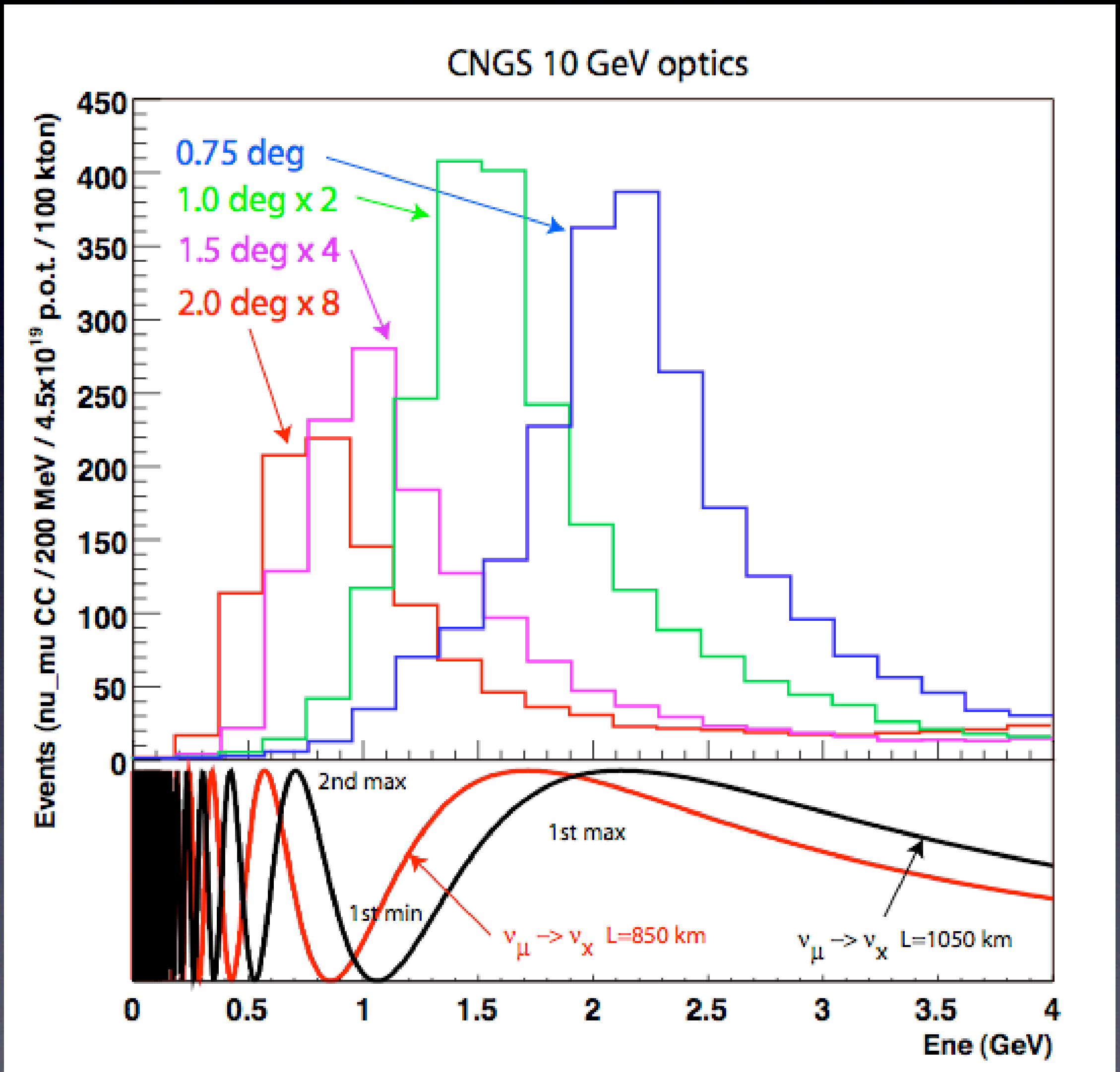
Optimal off-axis angle for first maximum (minimum) at several baselines



≈0.75°

A. Rubbia

CNGS beam: location selection



- We selected two locations on the CNGS beam.
- The first option is 0.75 degrees off-axis at 850 km, to optimize the rate at the first maximum of oscillation (good for θ_{13} sensitivity).
- The second option is 1.5 degrees off-axis at 1050 km, to optimize the rate at the first minimum and second maximum of oscillation (good for CP-Violation and mass hierarchy sensitivity).
- A combination of the 2 was also considered where the total 100 kton mass was split into 30 kton at 850 km and 70 kton at 1050 km.

Detector technology

- When searching for ν_e appearance there will be both an irreducible intrinsic ν_e background and a background due to event misidentification.
- In a next generation experiment one should aim at reducing the backgrounds from event misidentification as much as possible in order to profit at most from the increased statistics. Eventually, the limiting factor will be the knowledge of the intrinsic ν_e background so other sources of backgrounds should be suppressed below this contamination, which is generally at the level of the percent in the region of the oscillation maximum.
- This is not the case in T2K and NoVA where a ratio ν_e:NC $\pi^0 \approx 1:1$ is achieved at the cost of efficiency ($\epsilon \approx 40\%$ for T2K, $\approx 20\%$ for NoVA).
- We note that thanks to the progress in predicting neutrino fluxes and cross-sections given the extended campaigns of hadro-production measurements and the running of, or plans for, dedicated neutrino cross-section-measurement experiments, we can expect that the systematic error on the prediction of the intrinsic ν_e background (≈ the number of background events) will be below 5%.
- Our analysis assumes the concept of a liquid Argon TPC with mass order of 100 kton, as proposed in hep-ph/0402110.
- We note that the physics potentials of the upgraded CNGS could also be considered with other detector technologies. In particular, a NoVA-type or a large Water Cerenkov detectors could offer complementary options, however, in those cases a detailed analysis of the π^0 backgrounds should be performed to estimate their sensitivity. On the other hand, the liquid Argon TPC should reduce this source below the intrinsic ν_e background.

Liquid Argon TPC (I)

- Detector features and performance:
  - Liquid detector
  - Scalable
  - Fully and continuously sensitive
  - Higher detection efficiency for multiGeV events
  - Better and „Gaussian“ neutrino energy resolution
  - Clean event selection and background suppression
  - Better electron identification and NC suppression also in MultiGeV region
  - Magnetic field possible, useful for neutrino/antineutrino separation

Liquid Argon TPC (II)

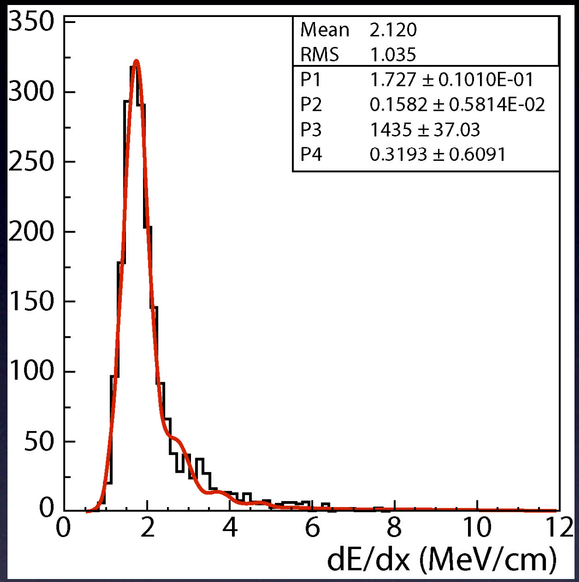
- Physics performance:
  - Rich and multipurpose accelerator & non-accelerator physics program
  - Possibly at shallow depths (not at surface!)
  - Complementary to Water Cerenkov detectors
  - Compensate "smaller" mass by higher efficiency and higher cross-section for MultiGeV events
  - Well matched to "Wide Band neutrino Beam" to cover 1st max, min, 2nd max,... with unbiased selection and good energy resolution, important for future θ_{13}-δ, sgn(Δm^2) studies
  - Technology ready for future next generation facilities (e.g. NF if magnetized) up to high energies (10-20 GeV)

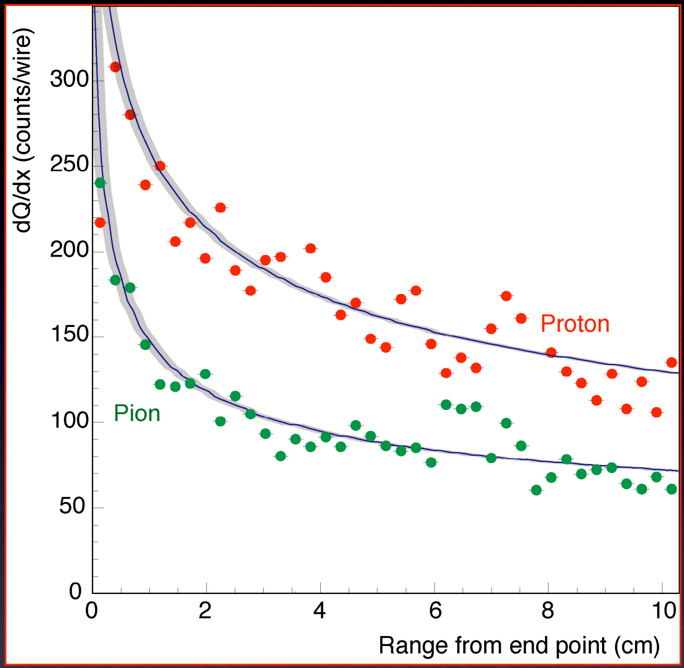
A tracking calorimeter

- High granularity: readout pitch ≈3 mm, local energy deposition measurement, particle type identification

$$T_{kin} = \int \frac{dE}{dx} dx$$

$$\frac{\sigma_{T_{kin}}}{T_{kin}} \approx 4\%$$



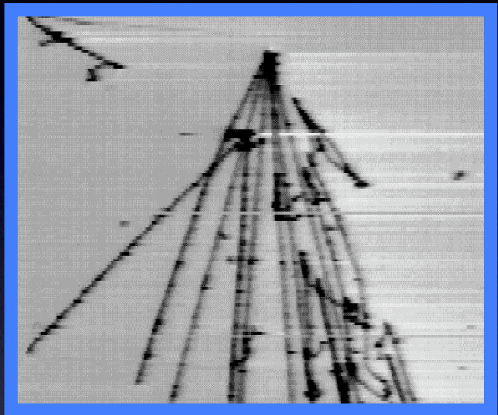


- Fully homogenous, full sampling calorimeter
  - ✦ Low energy electrons: $$\frac{\sigma(E_e)}{E_e} = \frac{11\%}{\sqrt{E_e(MeV)}} \oplus 2.5\%$$
  - ✦ Electromagnetic shower: $$\frac{\sigma(E_{em})}{E_{em}} = \frac{3\%}{\sqrt{E_{em}(GeV)}} \oplus 1.5\%$$
  - ✦ Hadronic shower: $$\frac{\sigma(E_{had})}{E_{had}} \simeq \frac{30\%}{\sqrt{E_{had}(GeV)}} \oplus 10\%$$

Full imaging

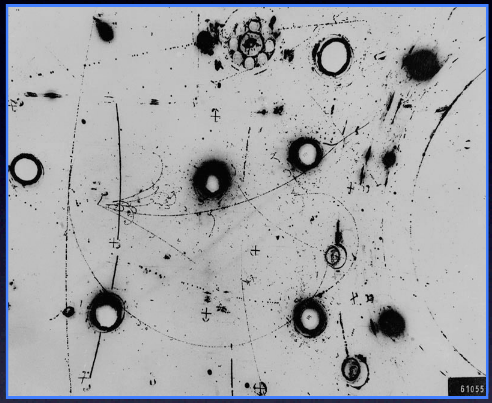
- Fully active, homogeneous, high-resolution device: **high statistics neutrino interaction studies with bubble chamber accuracy**.
- Reconstruction of low momentum hadrons (below Cerenkov threshold), especially recoiling protons: a proton of 1070 MeV/c (Cerenkov threshold in Water) travels 1 metre in LAr.
- Exclusive measurement of νNC events with clean π^0 identification and a very good e/π^0 discrimination.

Real event in ICARUS

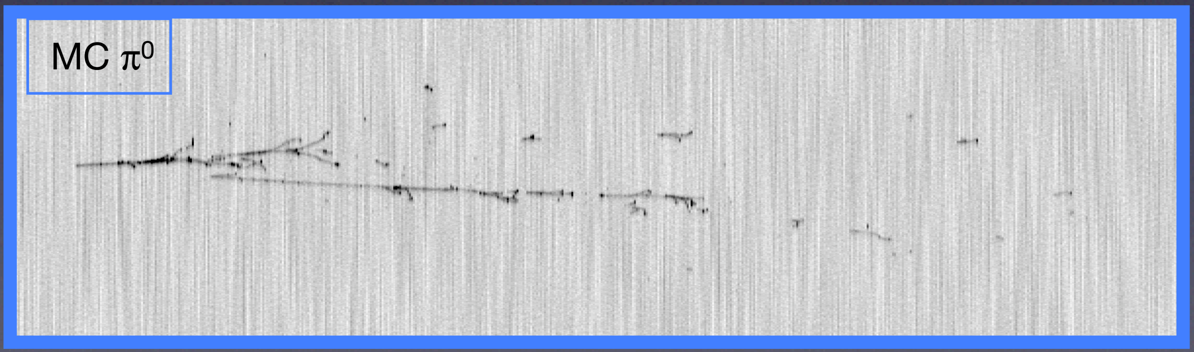


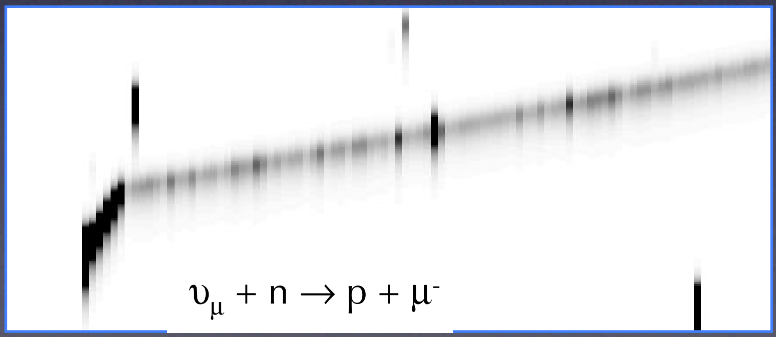
High granularity: Sampling = $0.02\ X_0$
"bubble" size $\approx 3\times3\times0.4\ mm^3$

Gargamelle bubble chamber



bubble diameter ≈3mm

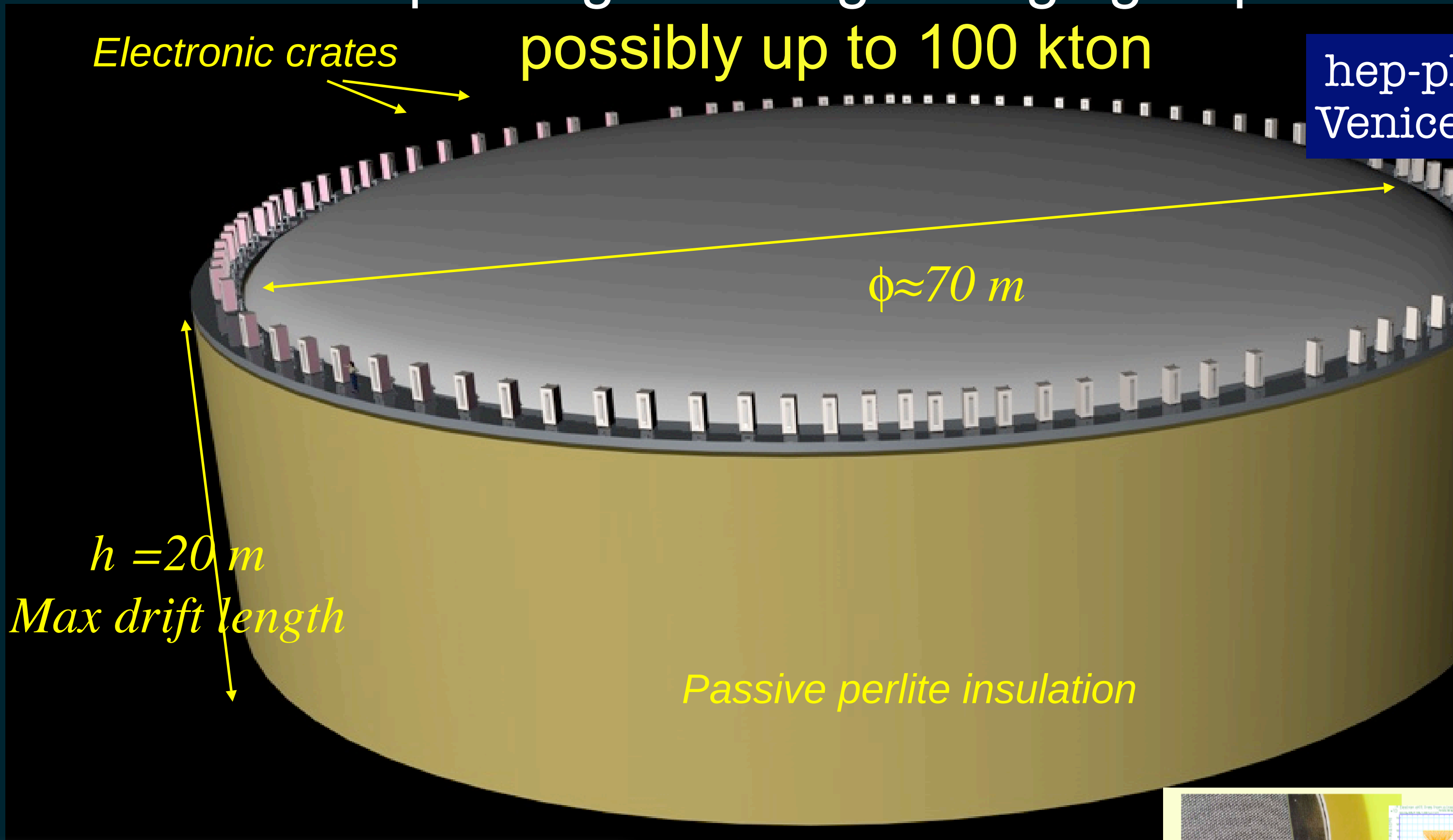




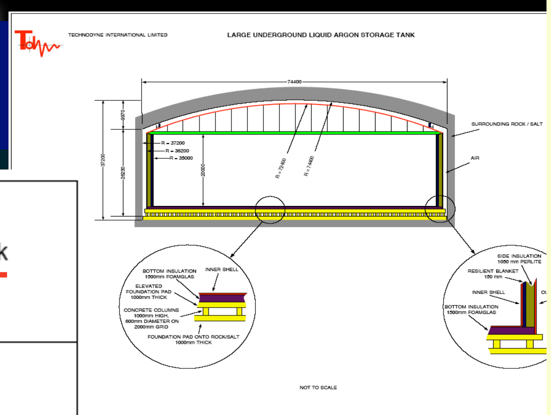
MC QE event, p momentum = 490 MeV/c

GLACIER: scalable ("non-ModuLAr") design

Giant Liquid Argon Charge Imaging ExpeRiment

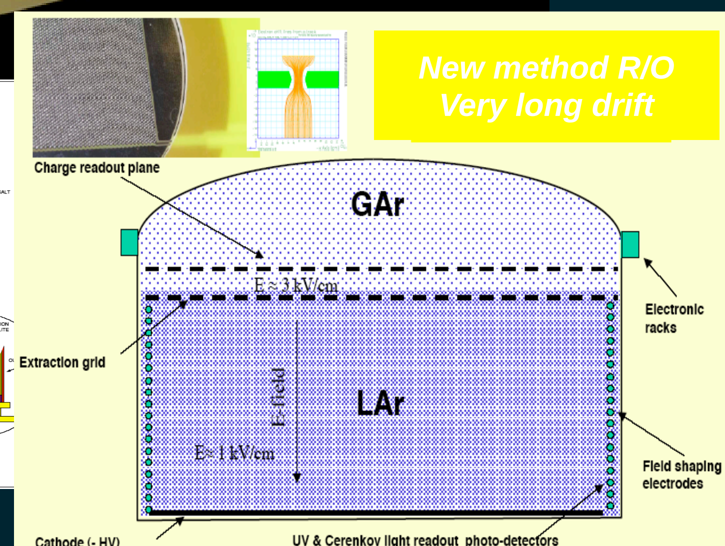


Single module cryo-tanker based on industrial LNG technology

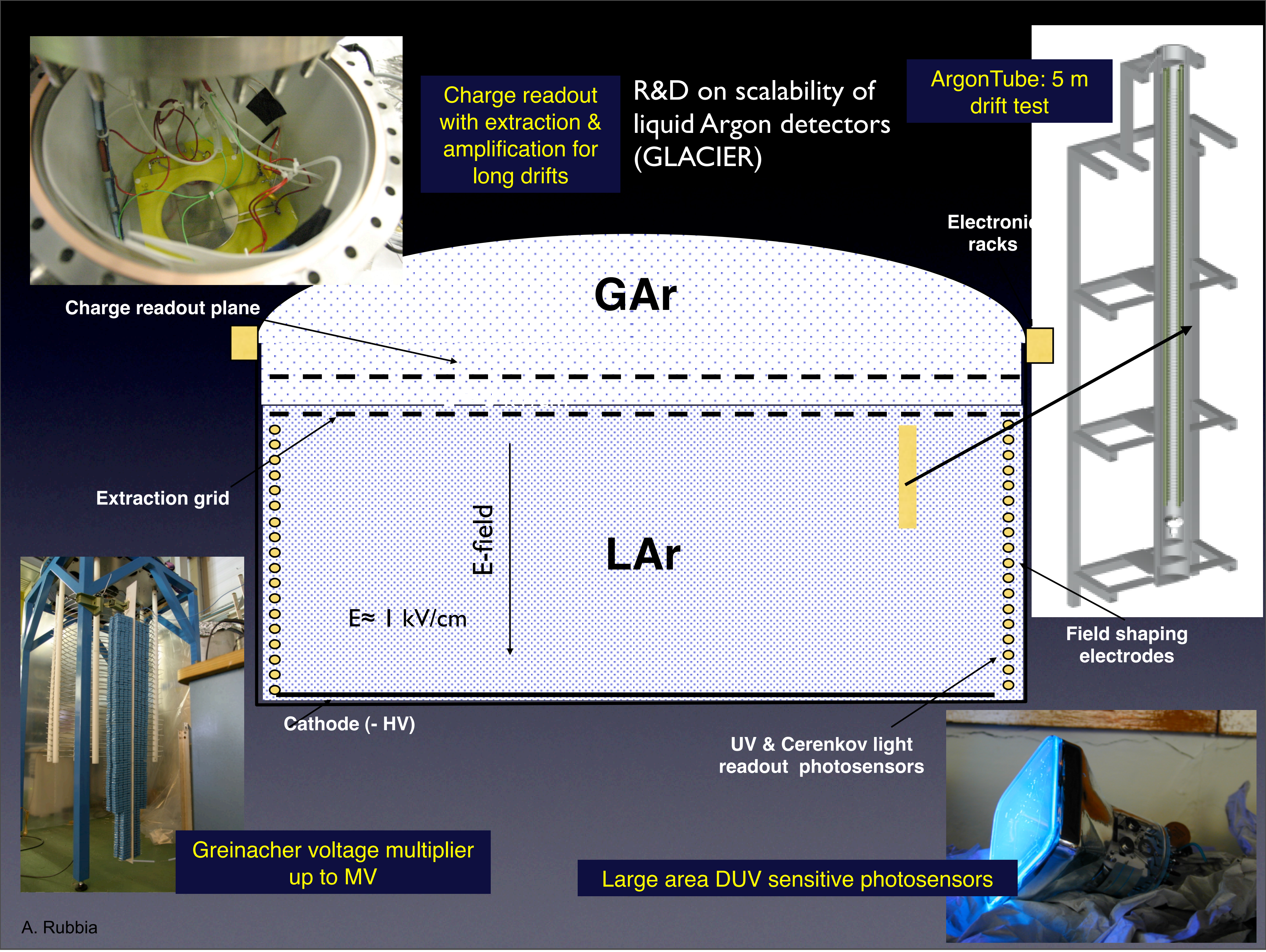


Project: Large Underground Argon Storage Tank

A feasibility study mandated to Technodyne Ltd (UK): Feb-Dec 2004



A. Rubbia


R&D on scalability of liquid Argon detectors (GLACIER)
Charge readout with extraction & amplification for long drifts
ArgonTube: 5 m drift test
Electronic racks
Charge readout plane
GAr
Extraction grid
E-field
LAr
E≈ 1 kV/cm
Field shaping electrodes
Cathode (- HV)
UV & Cerenkov light readout photosensors
Greinacher voltage multiplier up to MV
Large area DUV sensitive photosensors
A. Rubbia

The concepts for a scalable design

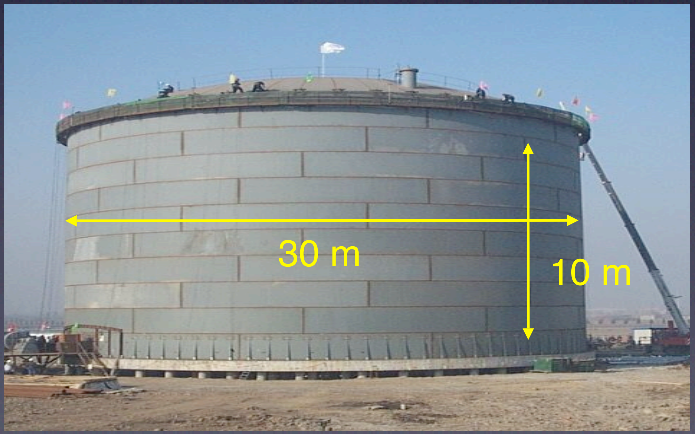
- LNG tank, as developed for many years by petrochemical industry
  - Certified LNG tank with standard aspect ratio
  - Smaller than largest existing tanks for methane, but underground
  - Vertical electron drift for full active volume
- A new method of readout (Double-phase with LEM)
  - to allow for a very long drift paths and cheaper electronics
  - to allow for low detection threshold (≈50 keV)
  - to avoid use of readout wires, which can be hardly mechanically and electrically scaled up and with disfavored use in conjunction with magnetic fields
  - A path towards pixelized readout for 3D images.
- Voltage multiplier to extend drift distance
  - High drift field of 1 kV/cm by additional of stages, w/o VHV feed-through
- Very long drift path
  - Minimize channels by increasing active volume with longer drift path
- Light readout on surface of tank
- Possibly immersed superconducting solenoid for B-field

Scaling parameters

100 kton:

Dewar	$\phi \approx$ 70 m, height $\approx$ 20 m, perlite insulated, heat input $\approx$ 5 W/m^2
Argon storage	Boiling Argon, low pressure (<100 mbar overpressure)
Argon total volume	73000 m^3, ratio area/volume $\approx$ 15%
Argon total mass	102000 tons
Hydrostatic pressure at bottom	3 atmospheres
Inner detector dimensions	Disc $\phi \approx$70 m located in gas phase above liquid phase
Charge readout electronics	100000 channels, 100 racks on top of the dewar
Scintillation light readout	Yes (also for triggering), 1000 immersed 8" PMTs with WLS
Visible light readout	Yes (Cerenkov light), 27000 immersed 8" PMTs of 20% coverage, single γ counting capability

10 kton:



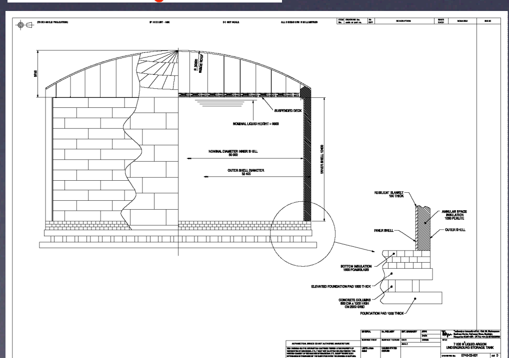
Dewar	$\phi \approx$ 30 m, height $\approx$10 m, perlite insulated, heat input $\approx$ 5 W/m^2
Argon storage	Boiling Argon, low pressure (<100 mbar overpressure)
Argon total volume	7000 m^3, ratio area/volume $\approx$ 33%
Argon total mass	9900 tons
Hydrostatic pressure at bottom	1.5 atmospheres
Inner detector dimensions	Disc $\phi \approx$30 m located in gas phase above liquid phase
Charge readout electronics	30000 channels, 30 racks on top of the dewar
Scintillation light readout	Yes (also for triggering), 300 immersed 8" PMTs with WLS

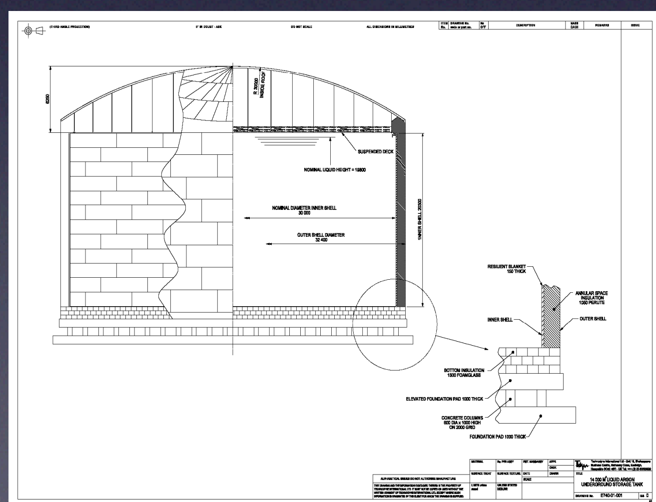
1 kton: 1% prototype: engineering detector, $\phi \approx$ 10m, h $\approx$ 10m, shallow depth?

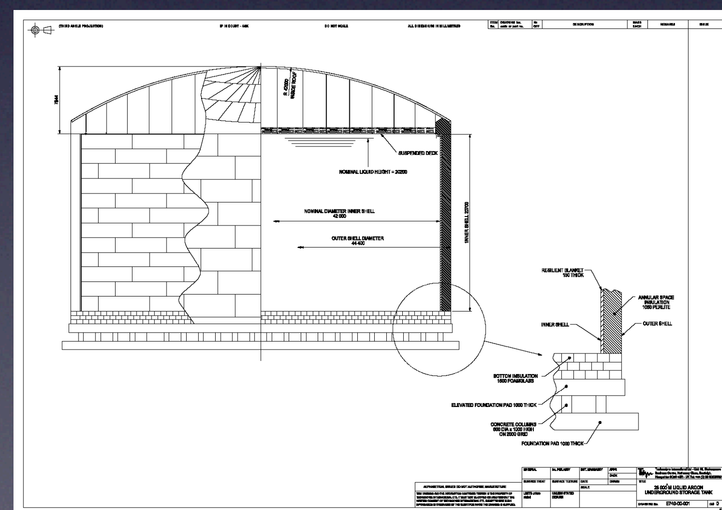
A. Rubbia

Scaling: three options to reach 40 kton

	1 unit of	2 units of	4 units of
Liquid Argon mass (per unit)	39.2 kton	19.6 kton	9.8 kton
Fiducial volume m^3 (per unit)	28000	14000	7000
Total liquid Argon mass	39.2 kton	39.2 kton	39.2 kton







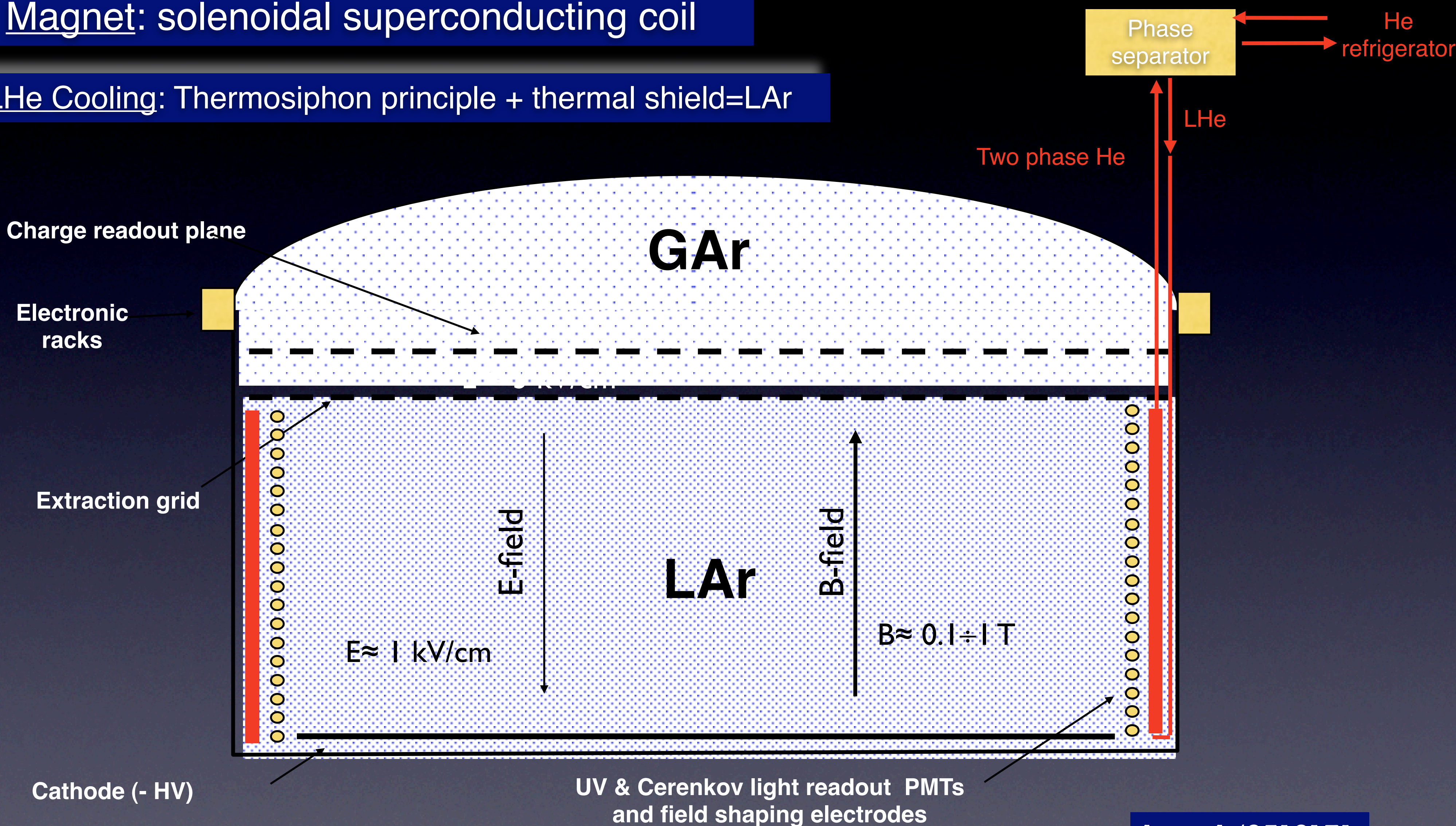
Φ=30 m, h=10 m → Φ=30 m, h=20 m → Φ=40 m, h=20 m

A. Rubbia

Layout for a magnetized detector

Magnet: solenoidal superconducting coil

LHe Cooling: Thermosiphon principle + thermal shield=LAr

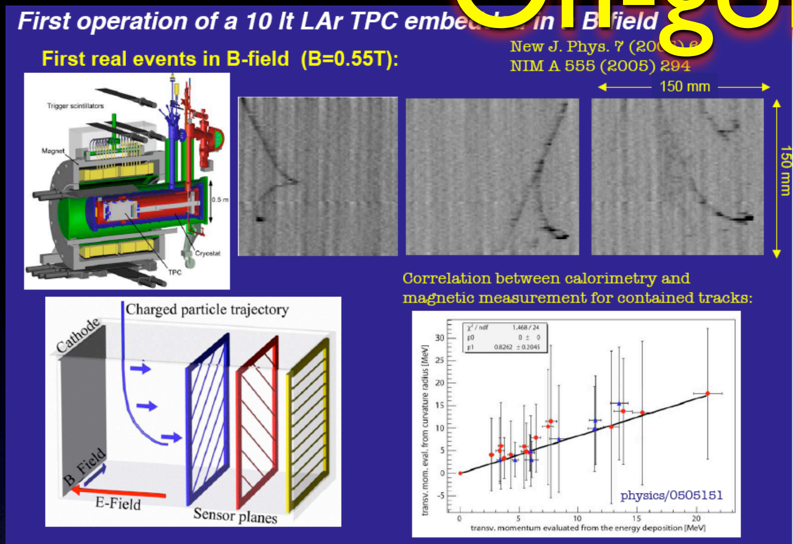


hep-ph/0510131
Frascati, 2005

Magnet: HTS coil also considered

A. Rubbia

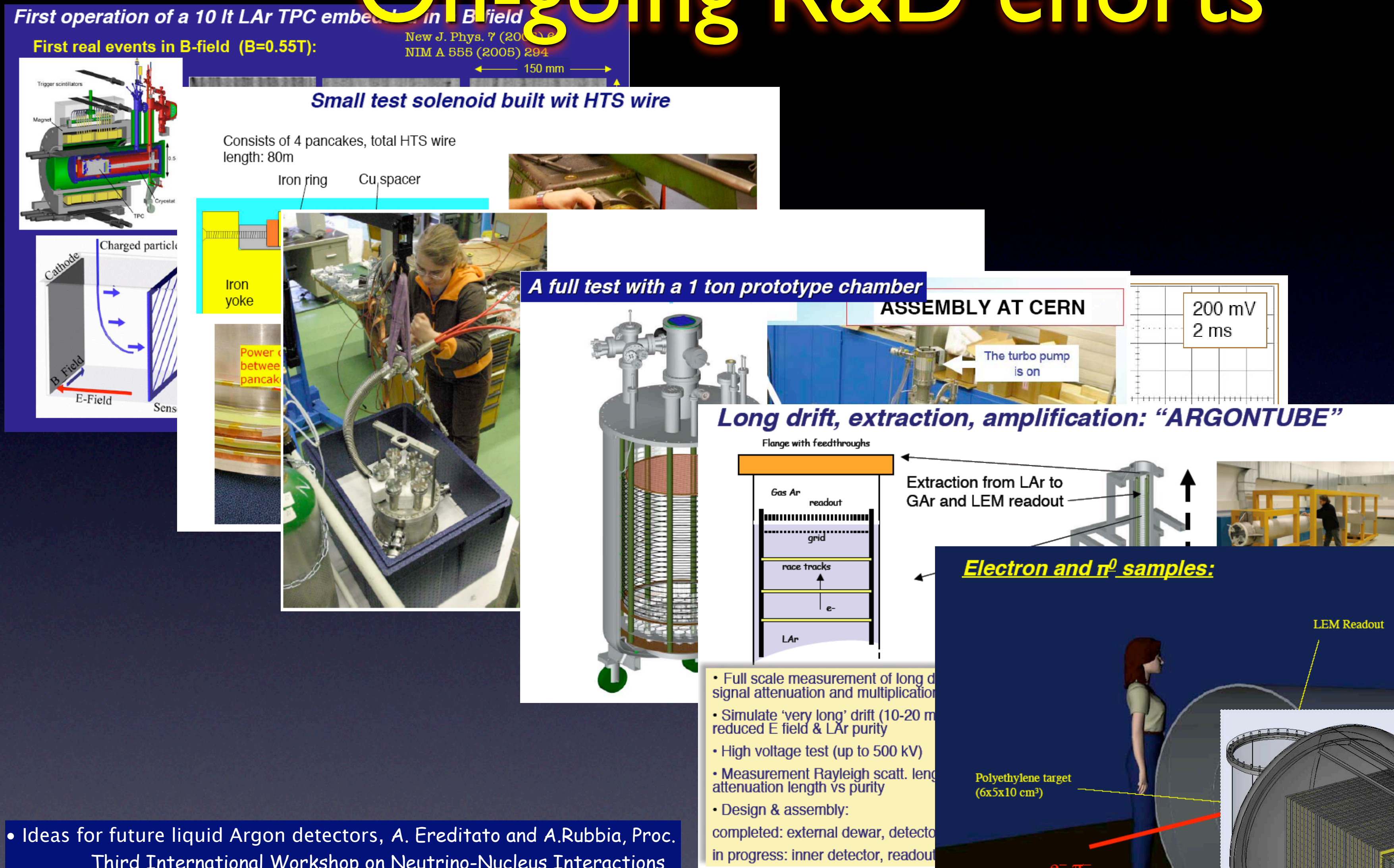
On-going R&D efforts

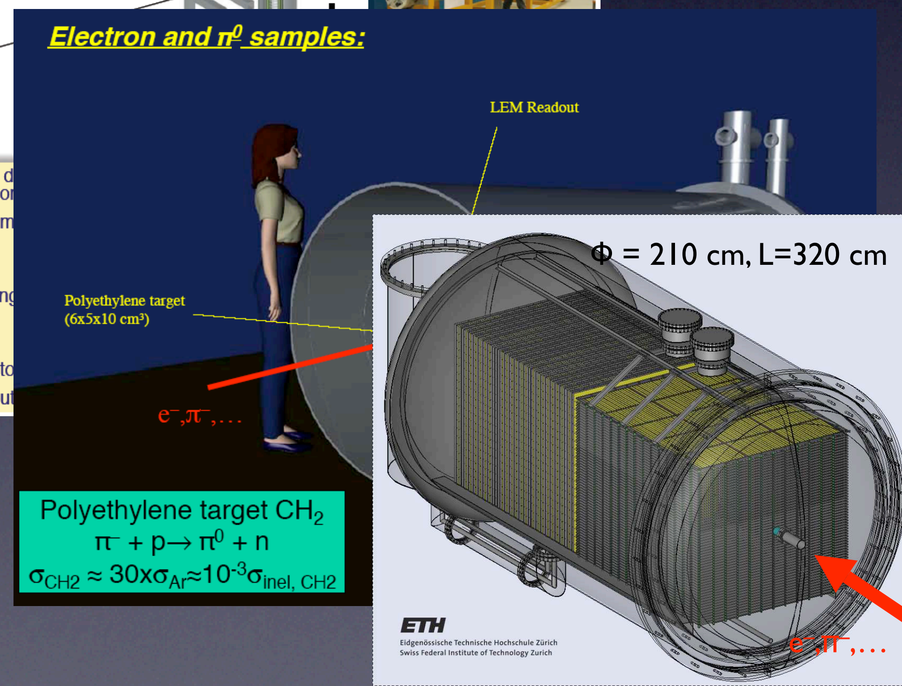


- Ideas for future liquid Argon detectors, A. Ereditato and A.Rubbia, Proc. Third International Workshop on Neutrino-Nucleus Interactions in the Few GeV Region, NUINT04, March 2004, Gran Sasso, Italy, **Nucl.Phys.Proc.Suppl.139:301-310,2005**, hep-ex/0409034
- Liquid Argon TPC: mid & long term strategy and on-going R&D, A.Rubbia, Proc. Int. Conf. on NF and Superbeam, NUFACT04, Osaka, Japan, July 2004
- Liquid Argon TPC: a powerful detector for future neutrino experiments, A.Ereditato and A. Rubbia, HIF05, La Biodola, Italy, May 2005, hep-ph/0509022

A. Rubbia

On-going R&D efforts





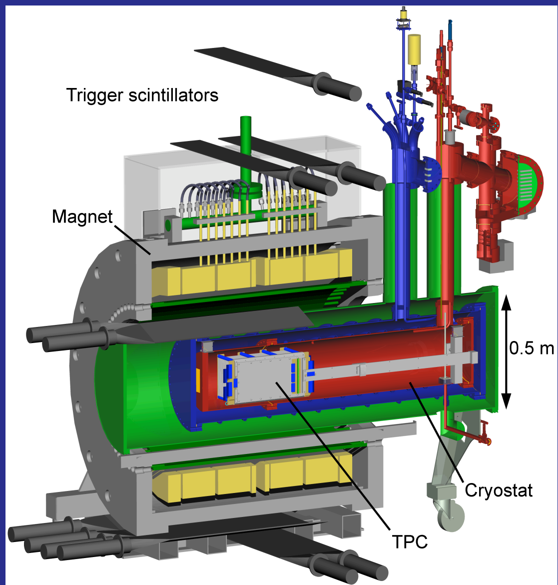
- Ideas for future liquid Argon detectors, A. Ereditato and A.Rubbia, Proc. Third International Workshop on Neutrino-Nucleus Interactions in the Few GeV Region, NUINT04, March 2004, Gran Sasso, Italy, **Nucl.Phys.Proc.Suppl.139:301-310,2005**, hep-ex/0409034
- Liquid Argon TPC: mid & long term strategy and on-going R&D, A.Rubbia, Proc. Int. Conf. on NF and Superbeam, NUFACT04, Osaka, Japan, July 2004
- Liquid Argon TPC: a powerful detector for future neutrino experiments, A.Ereditato and A. Rubbia, HIF05, La Biodola, Italy, May 2005, hep-ph/0509022

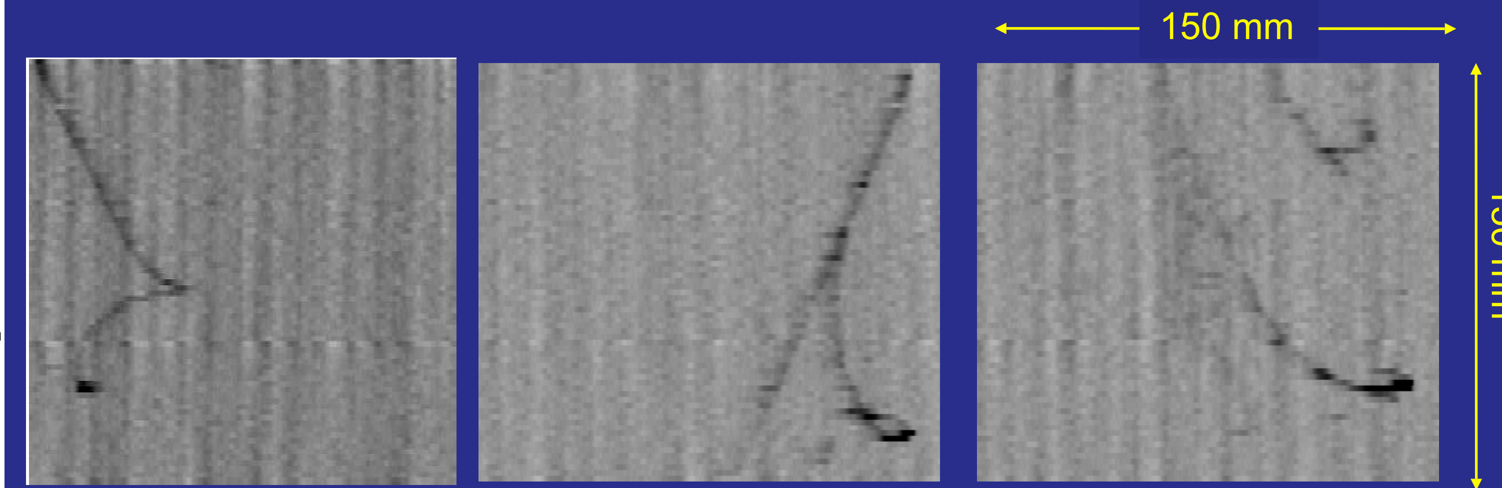
A. Rubbia

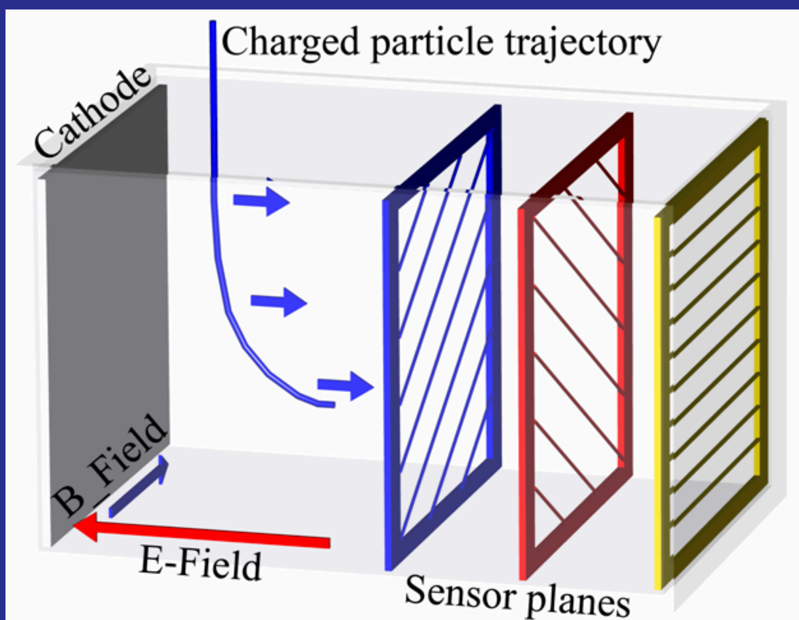
First operation of a LAr TPC embedded in a B-field

First real events in B-field (B=0.55T):

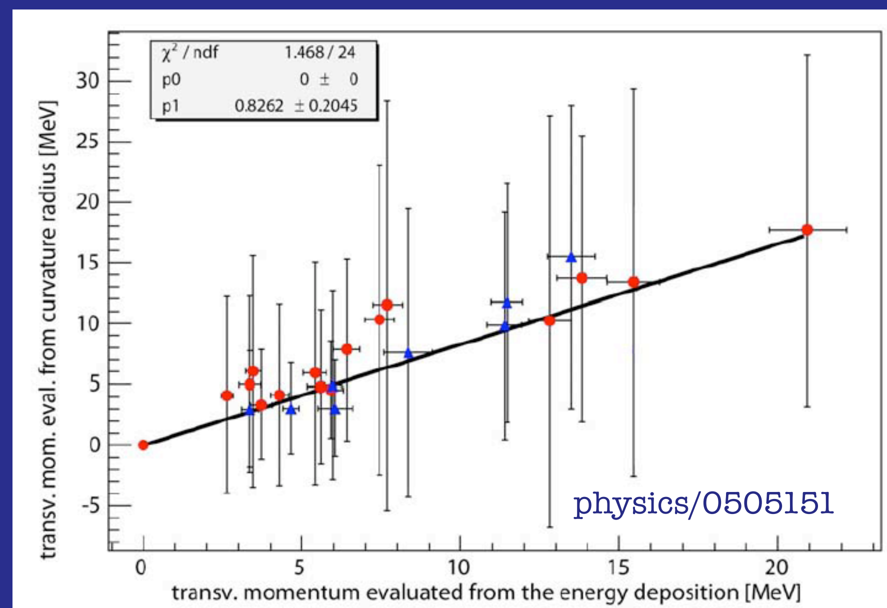
New J. Phys. 7 (2005) 63
NIM A 555 (2005) 294

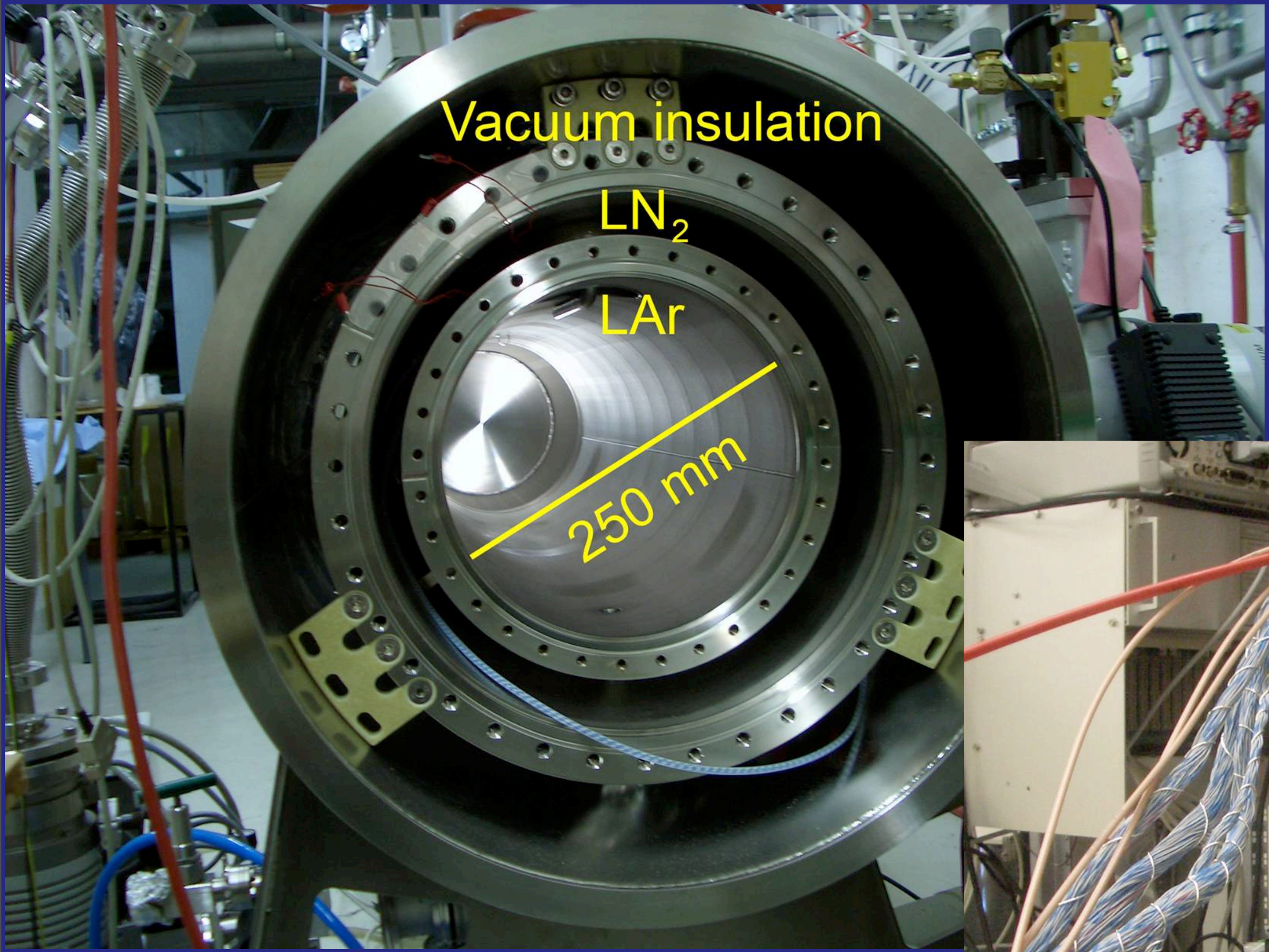




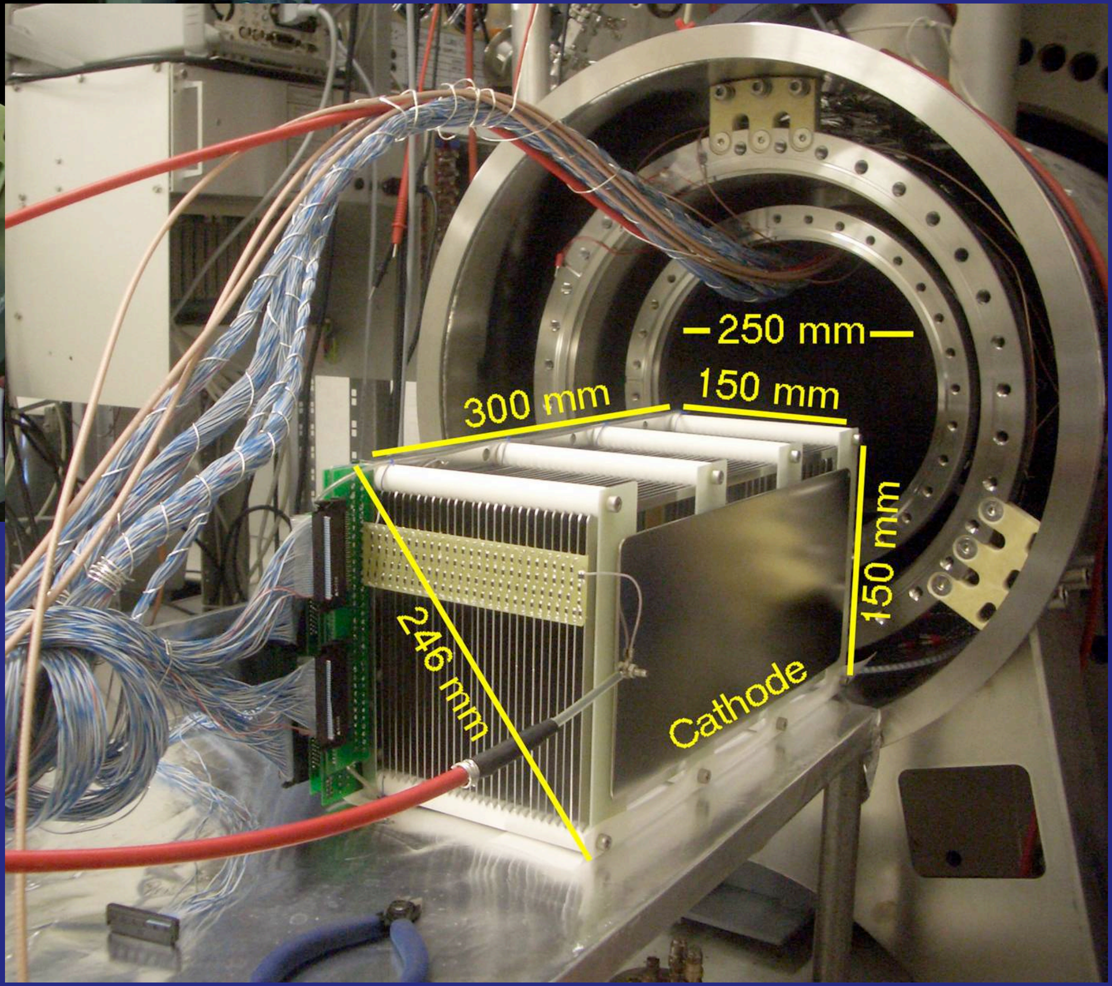


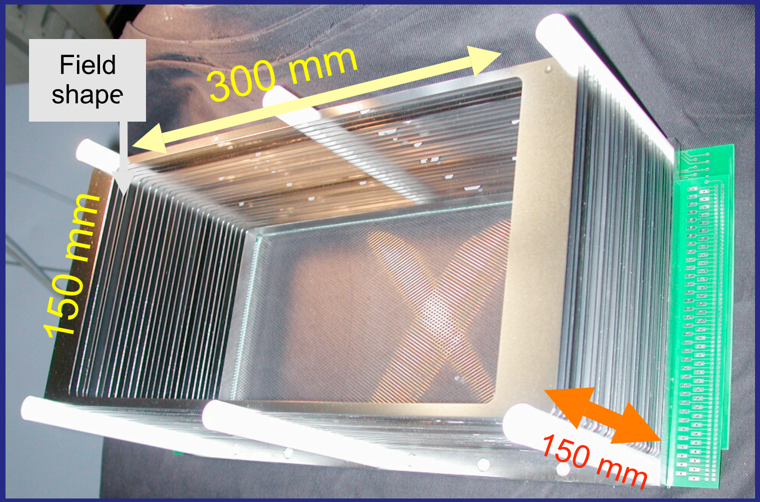
Correlation between calorimetry and magnetic measurement for contained tracks:





NIM A 555 (2005) 294

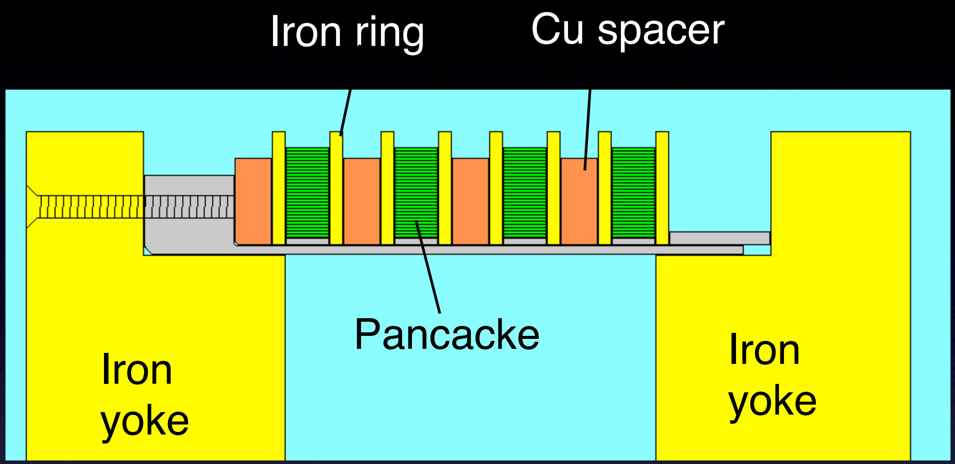


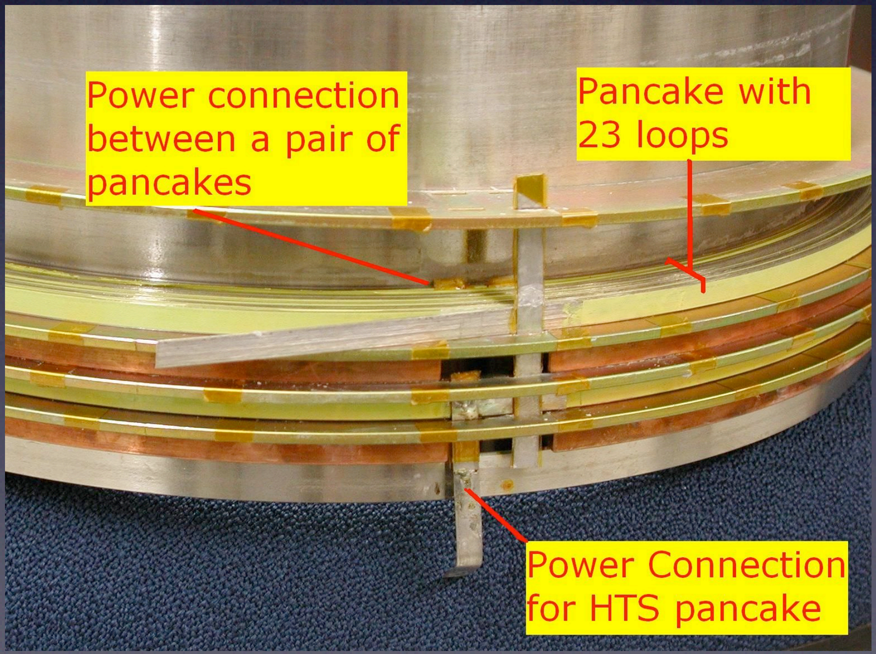


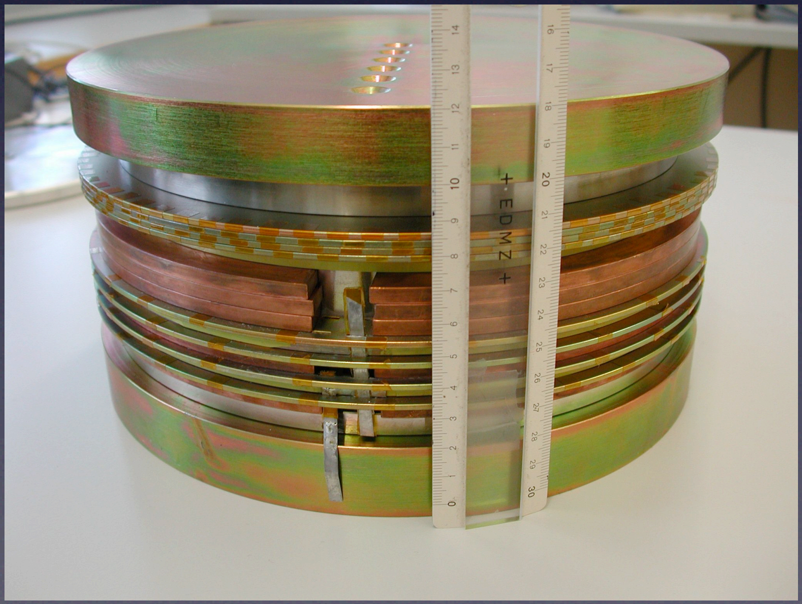
A. Rubbia

Small test solenoid built wit HTS wire

Consists of 4 pancakes, total HTS wire length: 80m





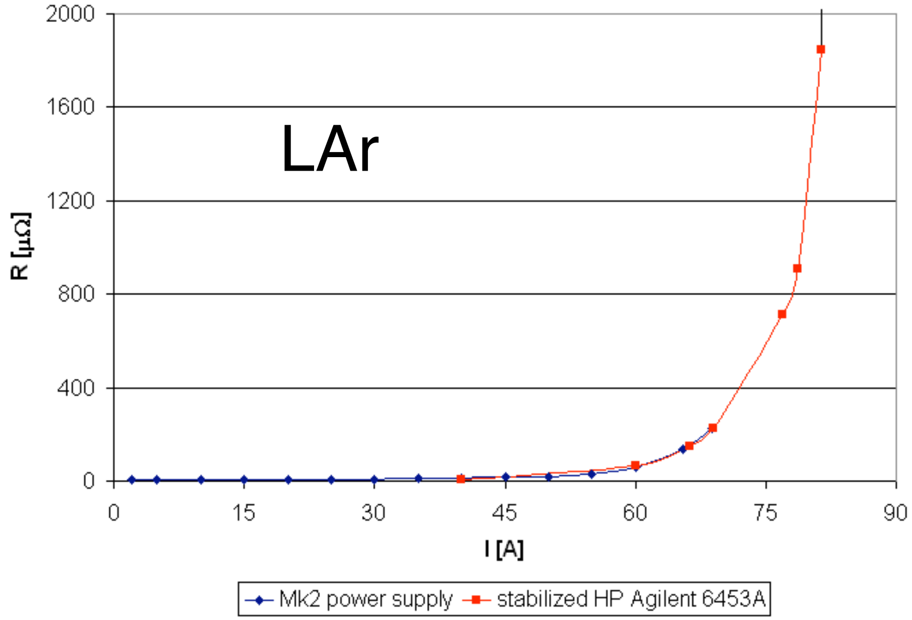


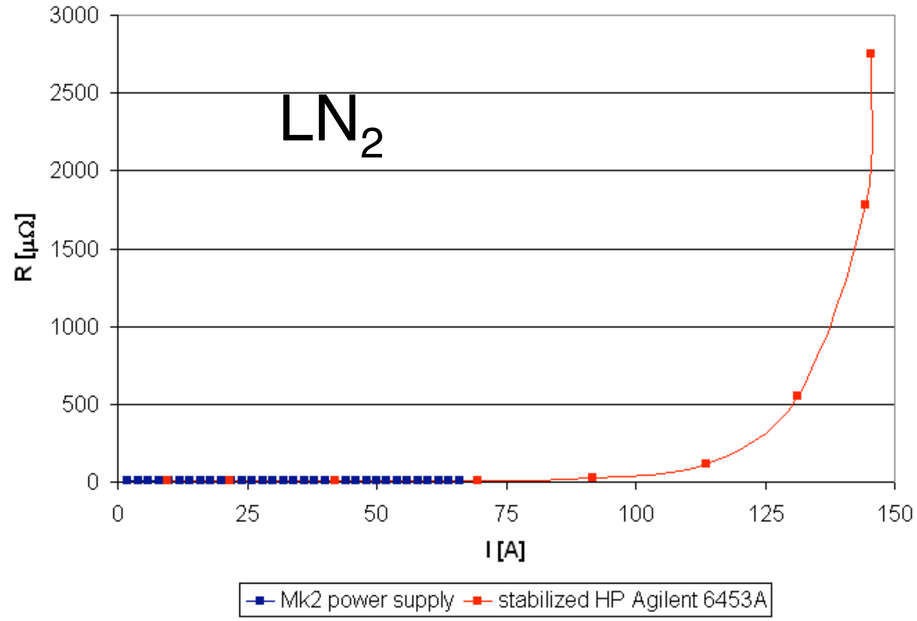
A. Rubbia

Results with the small HTS solenoid

Coil resistance as a function of the applied current

Total HTS wire length: 80 m

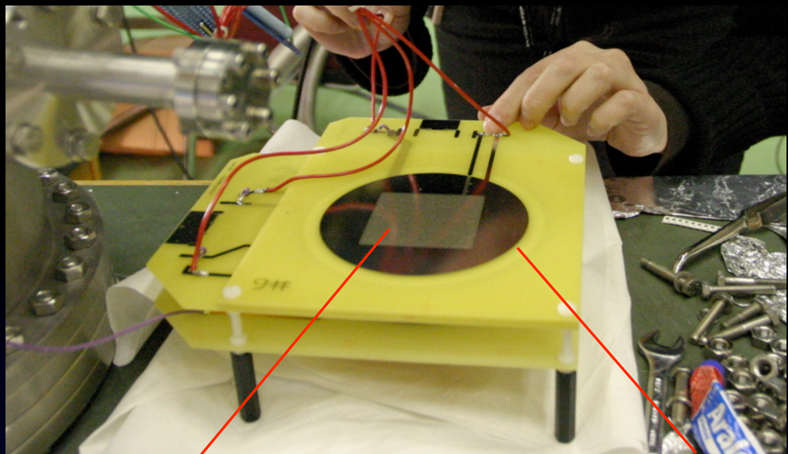


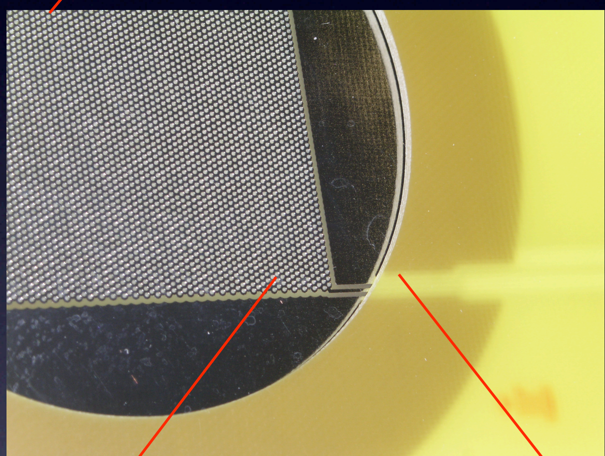


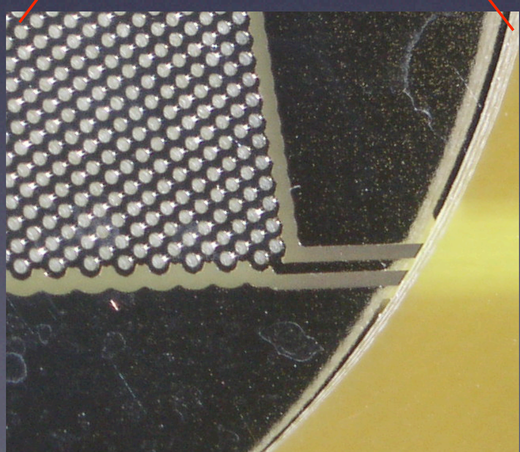
Temperature	LN_2 (77K)	LAr (87K)
Max. applied current	145 A	80 A
On-axis B-field	0.2 T	0.11 T
Coil resistance at 4A	6 μΩ	6 μΩ

A. Rubbia

Charge readout: Thick Large Electron Multiplier (LEM)



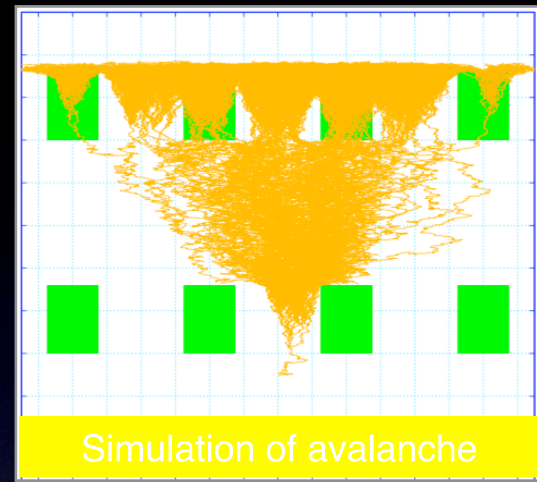




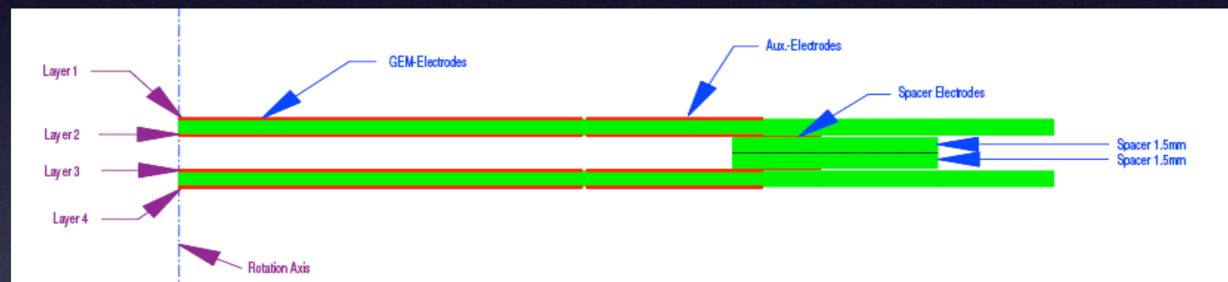
Thick-LEM: Vetronite with holes, coated with copper

- ➡ macroscopic GEM
- ➡ easier to operate at cryogenic temperatures
- ➡ hole dimensions: 500 μm diameter, 800 μm distance

Two consecutive stages



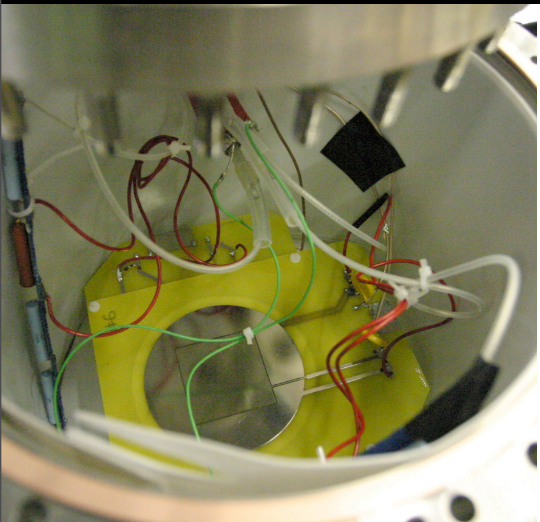
Simulation of avalanche

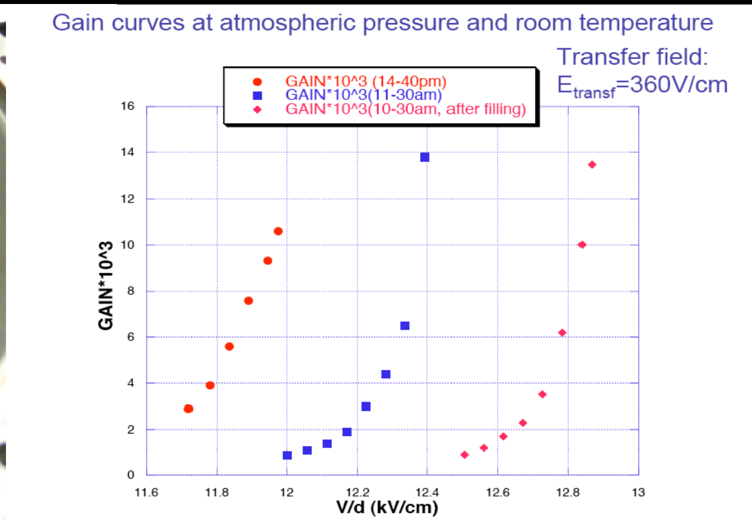


- Single LEM Thickness: 1.5 mm
- Amplification hole diameter = 500 μm
- Distance between centers of neighboring holes = 800 μm
- Distance between stages: 3 mm
- Avalanche spreads into several holes at second stage
- Higher gain reached as with one stage, with good stability

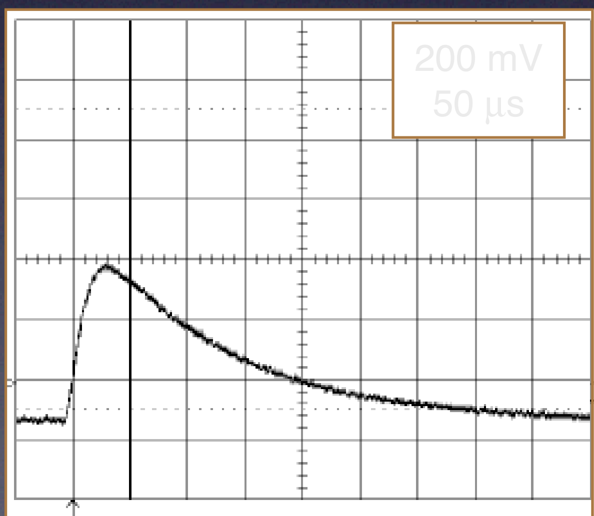
A. Rubbia

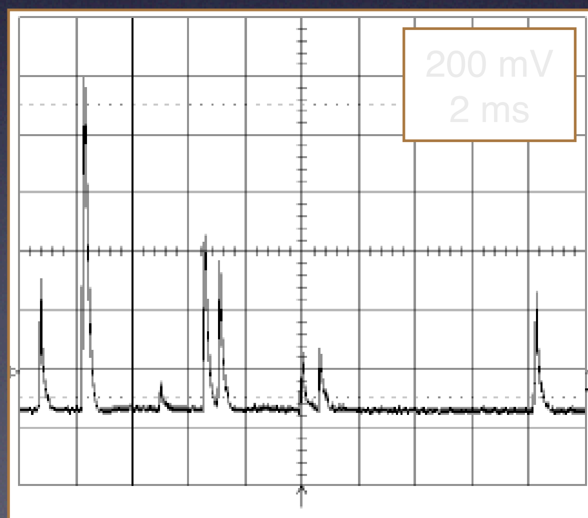
Charge readout: Thick Large Electron Multiplier (LEM)



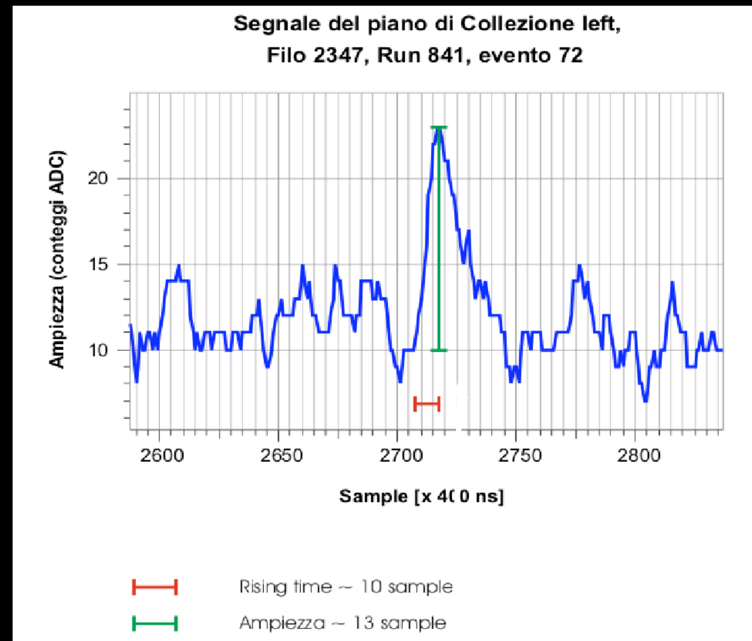


Shapes from Fe^{55} radioactive source (5.8 keV, event rate about 1kHz) of the signals from double-stage LEM system have a very clean S/N ratio.





MIP signal in ICARUS T300

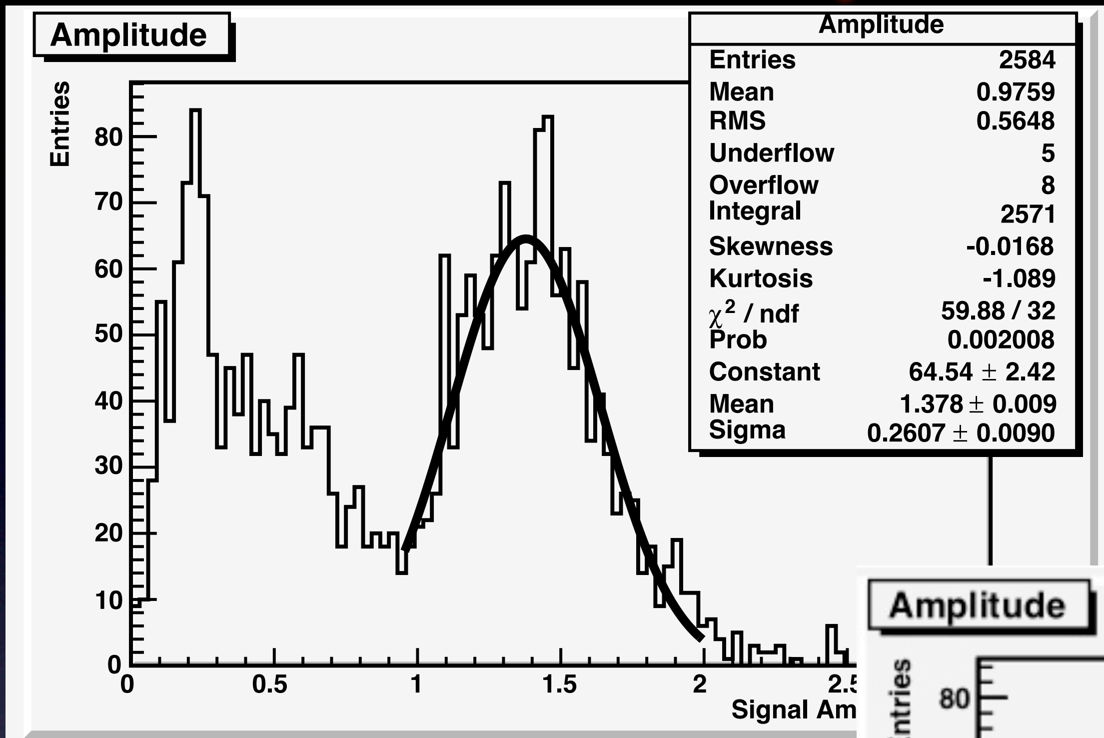


This technique solves the non-scalability of the traditional wire readout used in ICARUS
E.g. MIP signal @ ≈2 MeV/cm has poor S/N !

Full imaging TPC with LEM to be tested in ArDM experiment

A. Rubbia

Fe^{55} spectrum, GAr

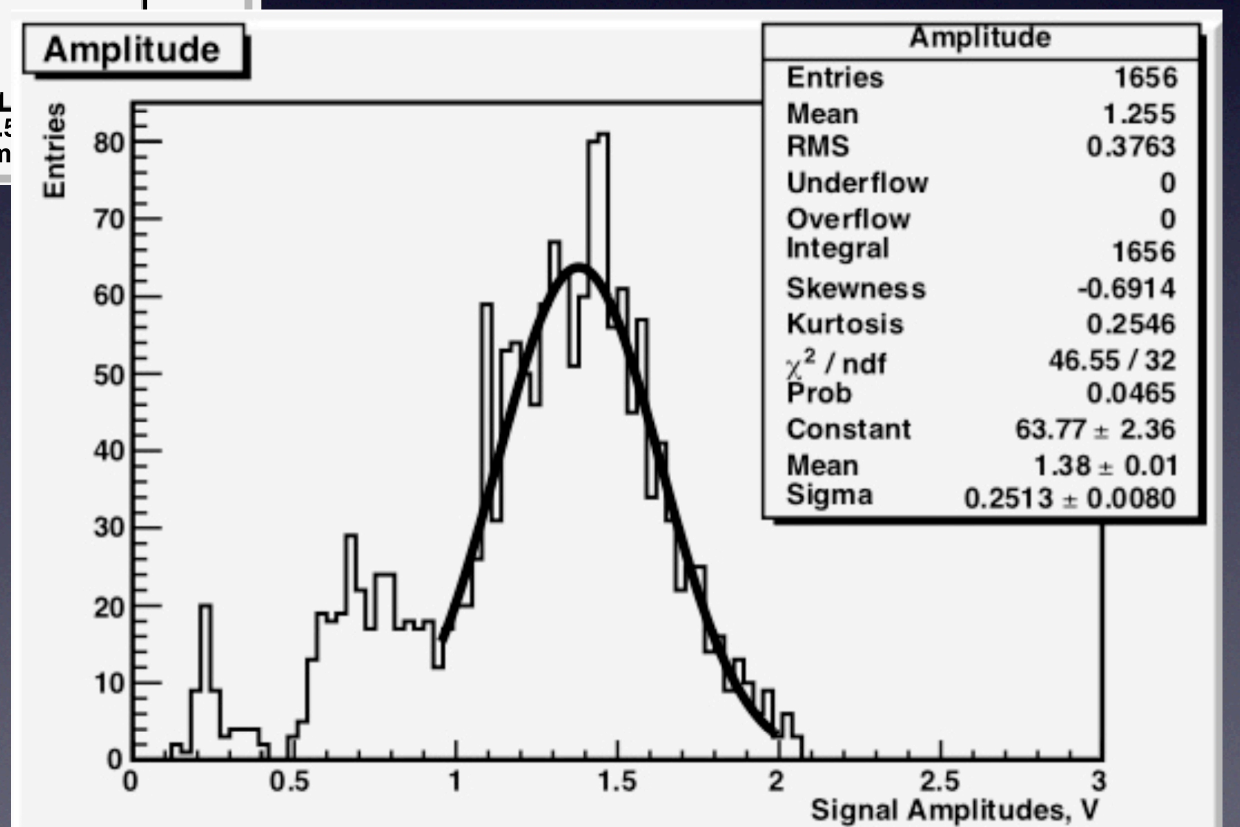


Conditions:
Vlem =2.34kV
Vcath=2.5kV
Electric field:
E=15.6kV/cm
Drift field:
E=0.53kV/cm

Gain ≈ 10^4, FWHM ≈ 45%

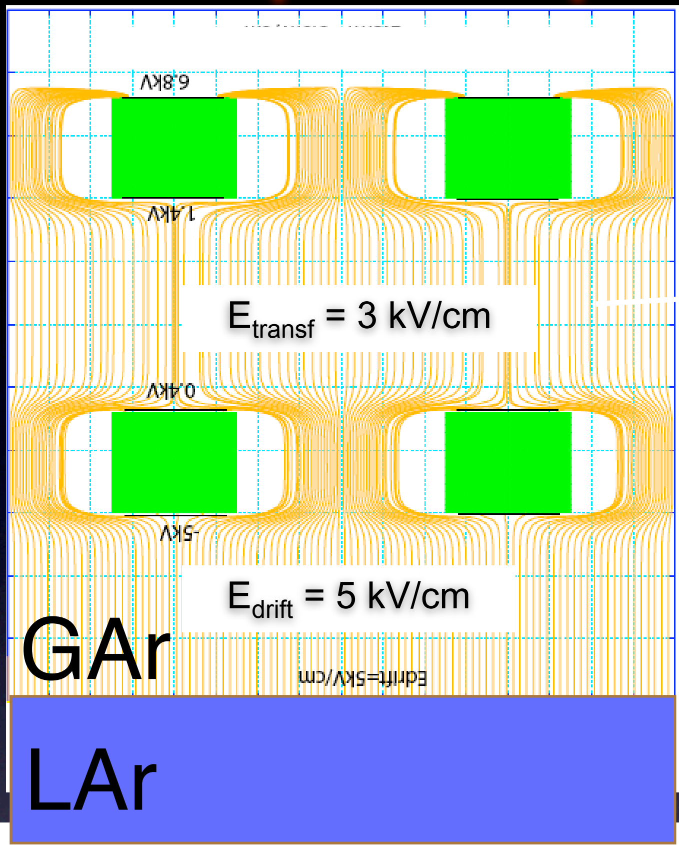
Without cuts

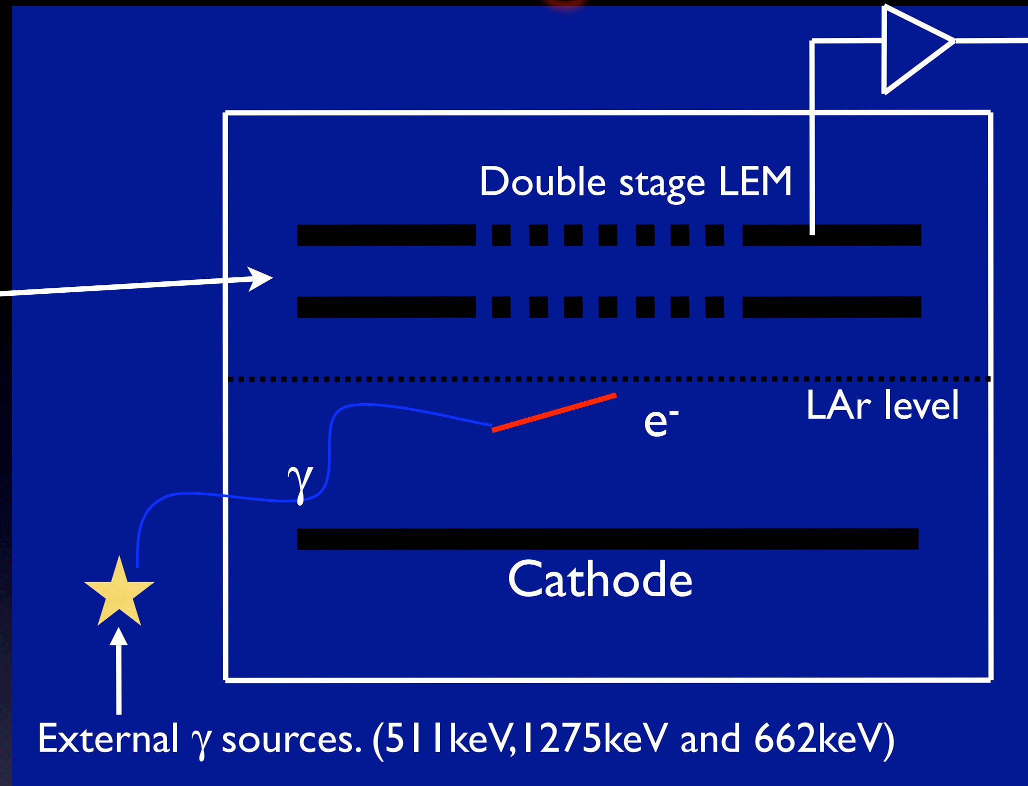
With cut to avoid pile-up:

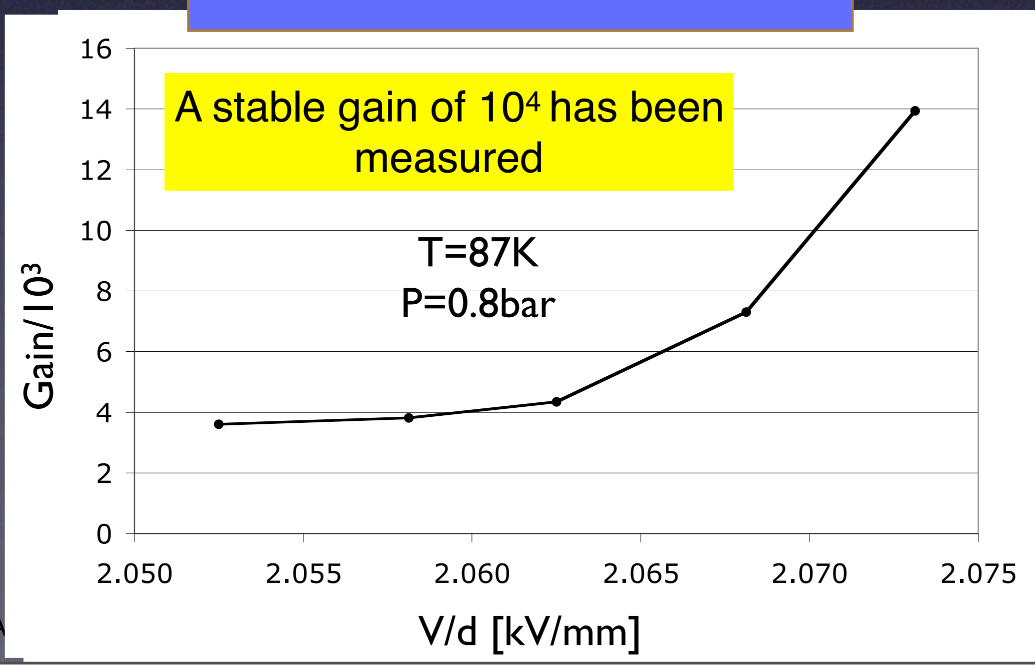


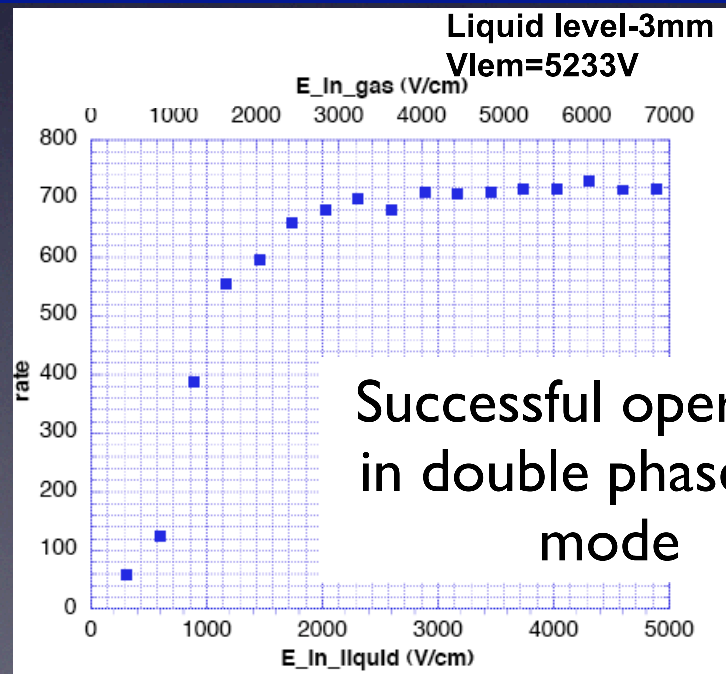
A. Rubbia

Double phase operation with two stages LEM





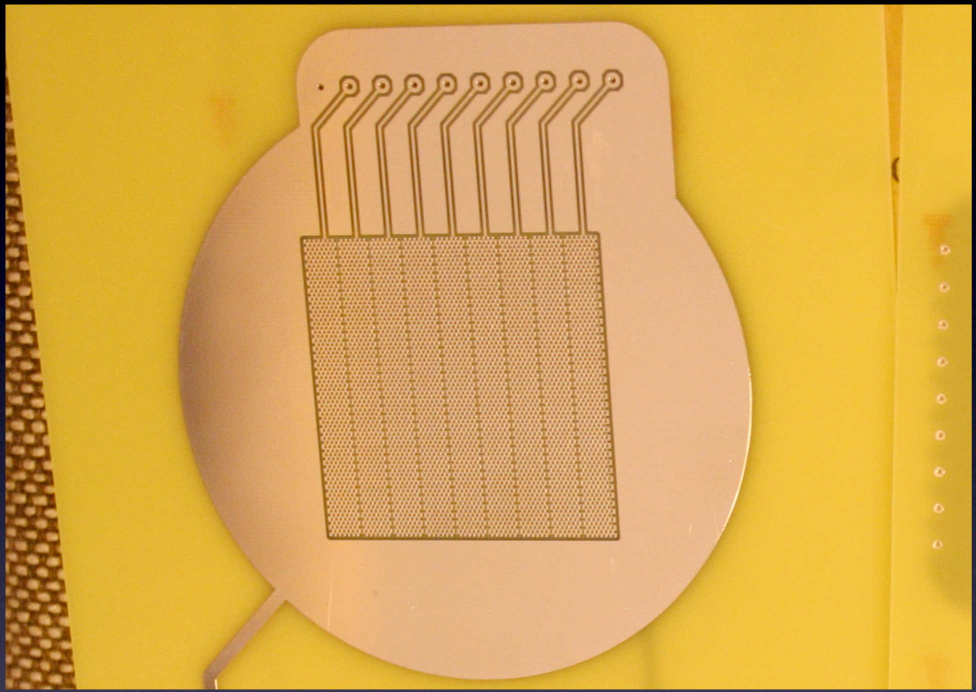




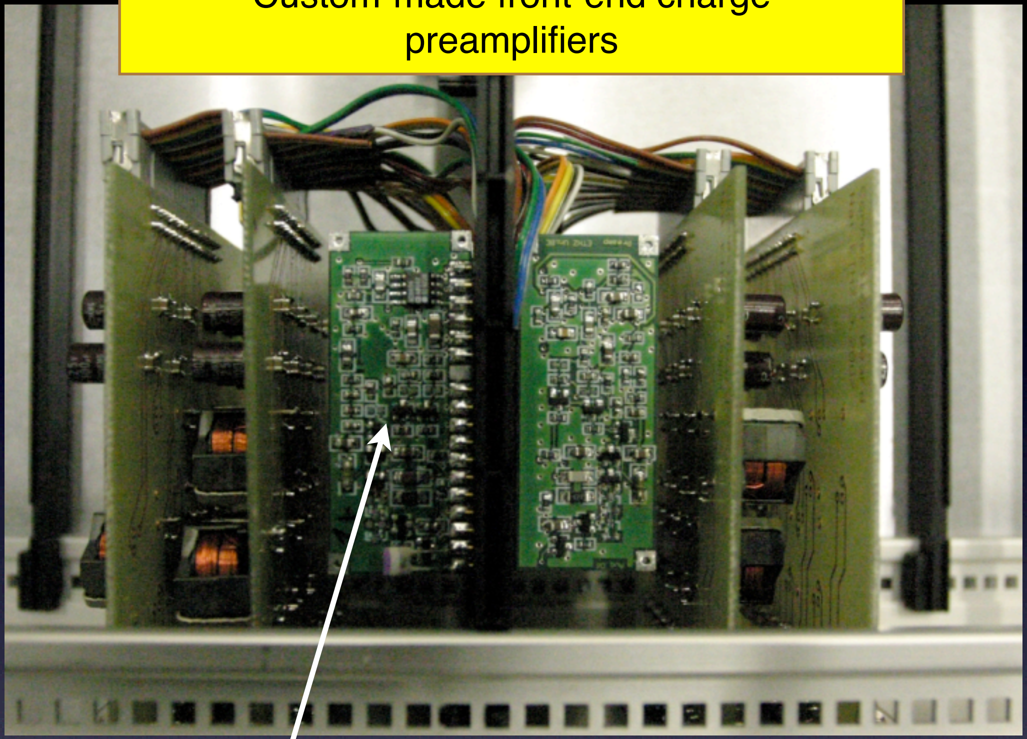
Successful operation in double phase LAr mode

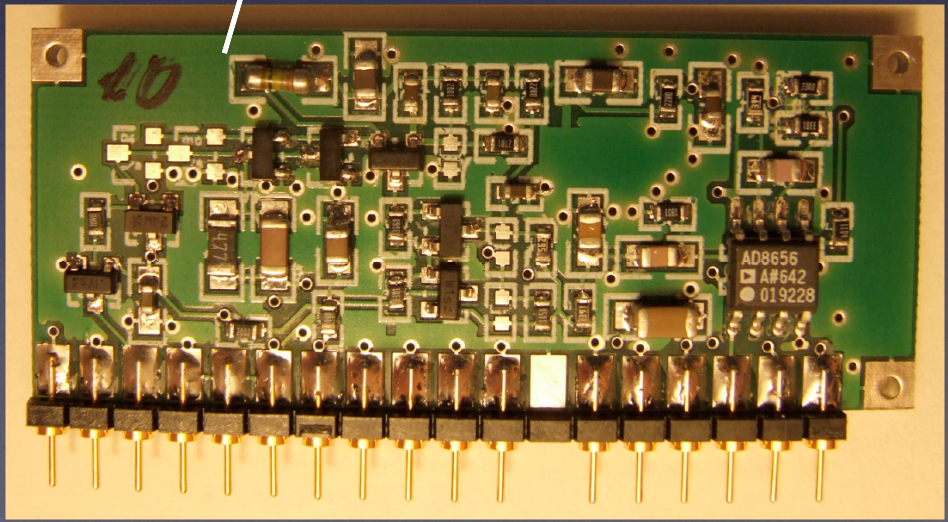
Segmented double stage LEM

9 independent strips



Custom-made front-end charge preamplifiers



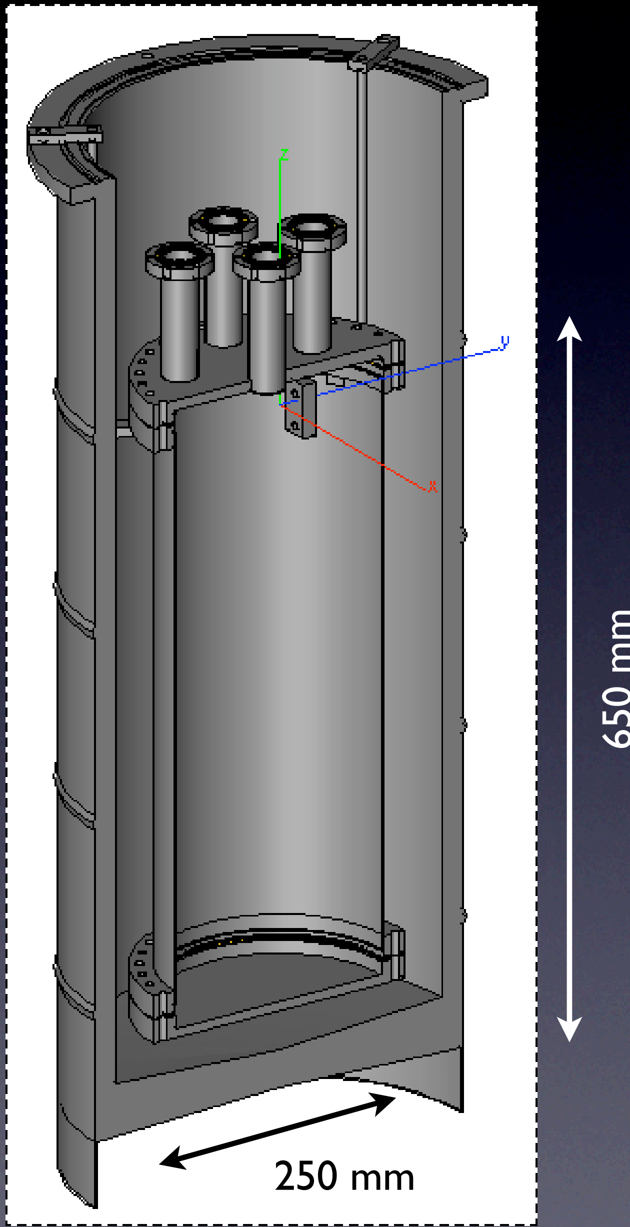


- Development F/E preamplifers + MHz digitizers + DAQ
- Industrial version with CAEN (new module)

LAr TPC with LEM readout for ν's

Bern - ETHZ - IPN Lyon

- Dedicated test of LAr TPC for application to neutrino physics
- ≈5 lt chamber
- LEM or conventional wire readout
- Electronics development in Collab. with IPN Lyon (Autiero, Marteau, Déclais)
  - ASIC version of preamplifiers
  - Possibly cold operation
  - ADC output on Gigabit-Ethernet
- First ASIC test Fall 2007

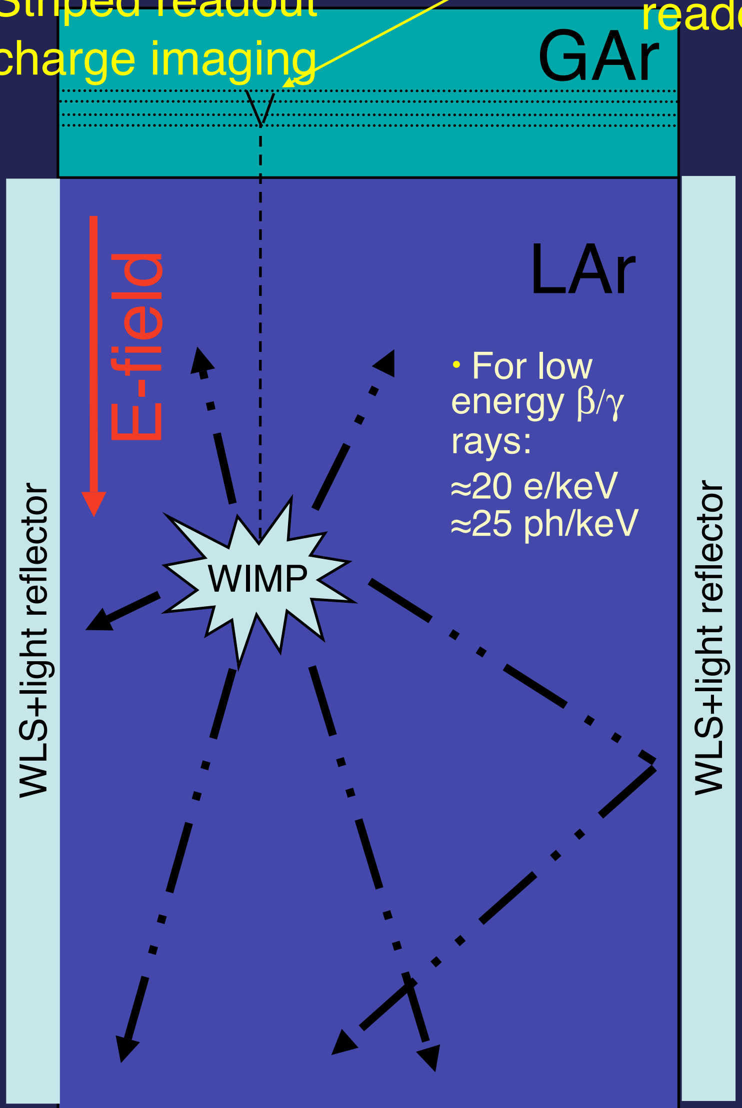


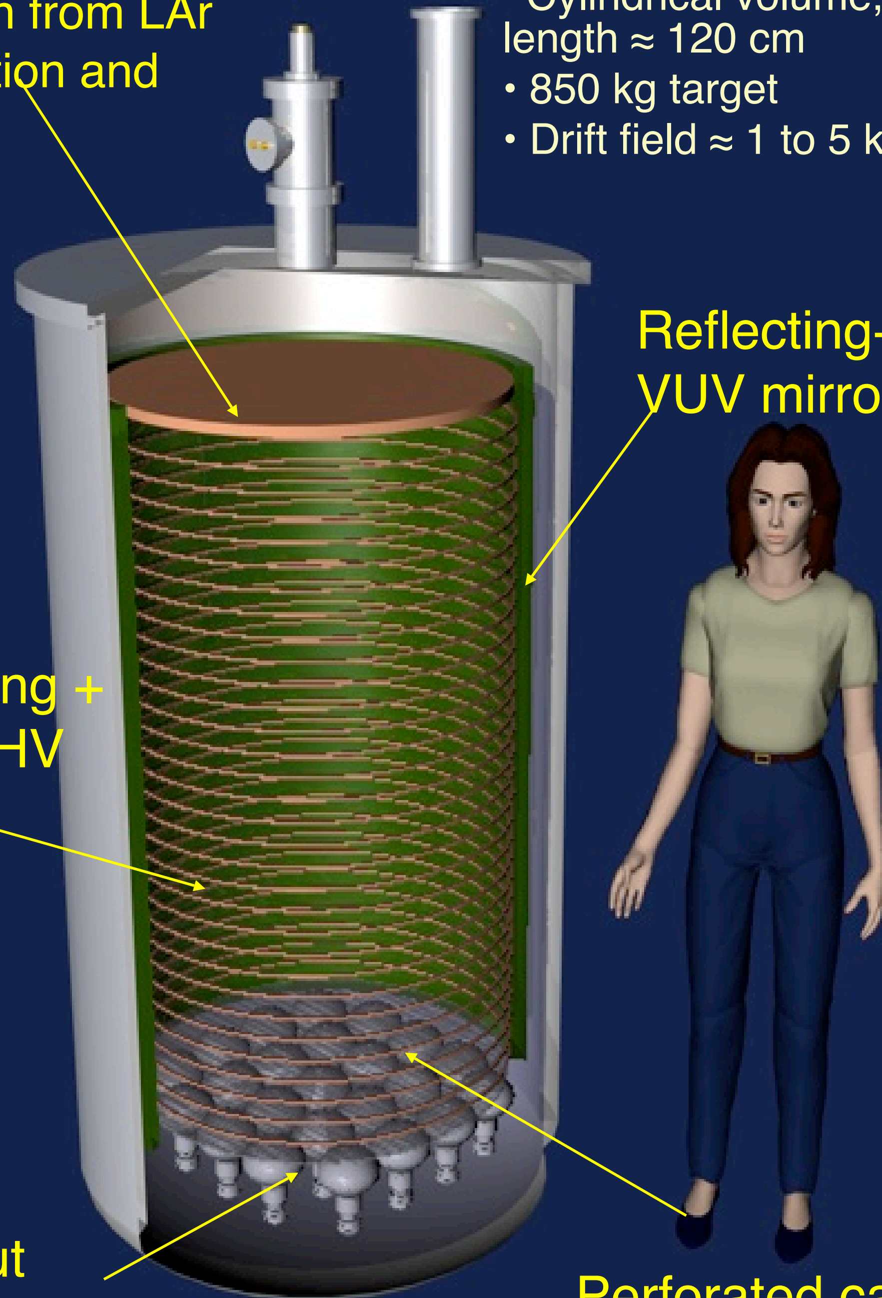
A. Rubbia

ArDM Argon Dark Matter Experiment

CIEMAT - ETHZ -Granada - Sheffield - Warszawa - Zurich

- Cylindrical volume, drift length ≈ 120 cm
- 850 kg target
- Drift field ≈ 1 to 5 kV/cm





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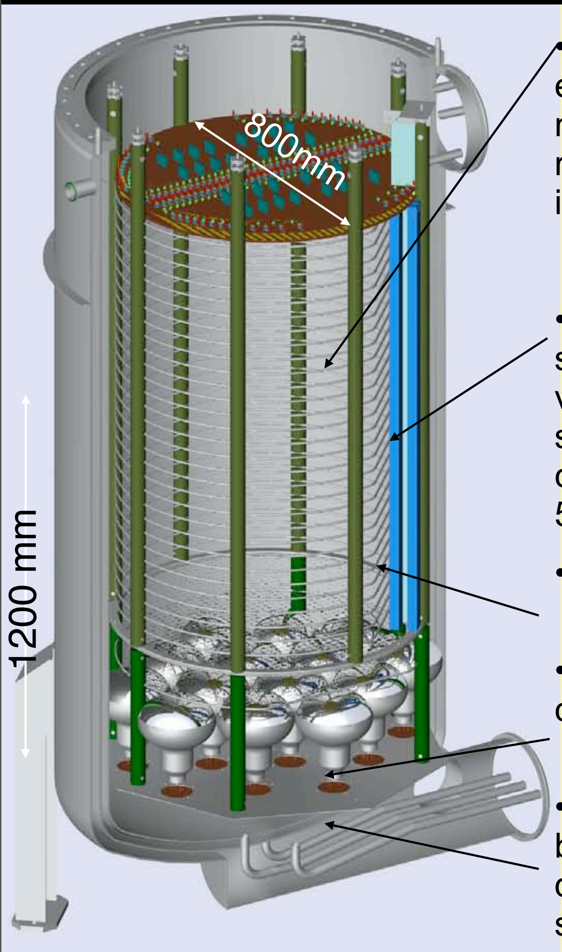
ArDM assembly @ CERN



•Two-stage LEM for electron multiplication and readout to measure ionization charge

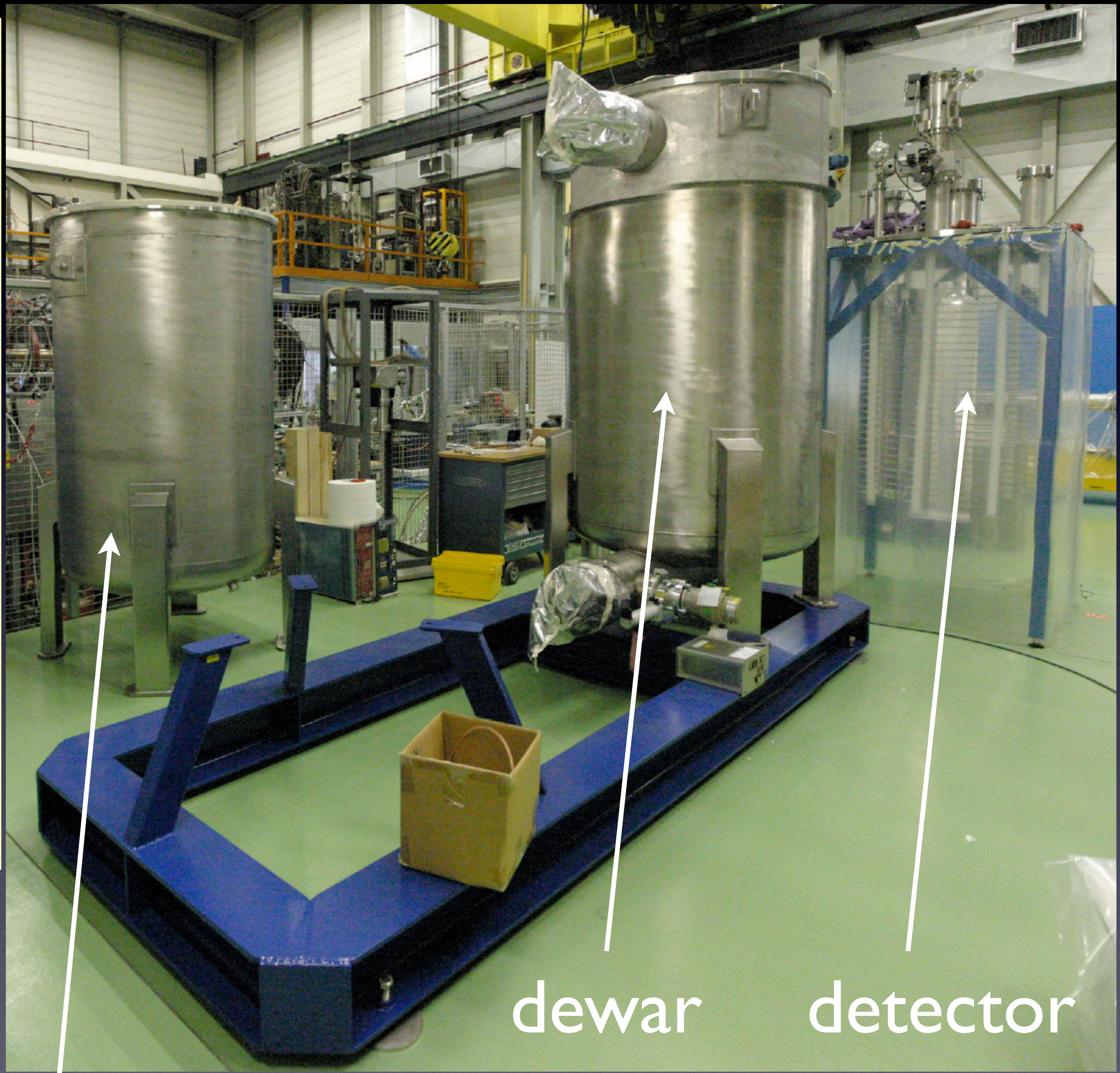
•Greinacher chain: supplies the right voltages to the field shaper rings and the cathode up to 500 kV

•Field shapers

•Transparent cathode

•Photodetectors below the cathode to detect the scintillation light

First tests foreseen in 2007



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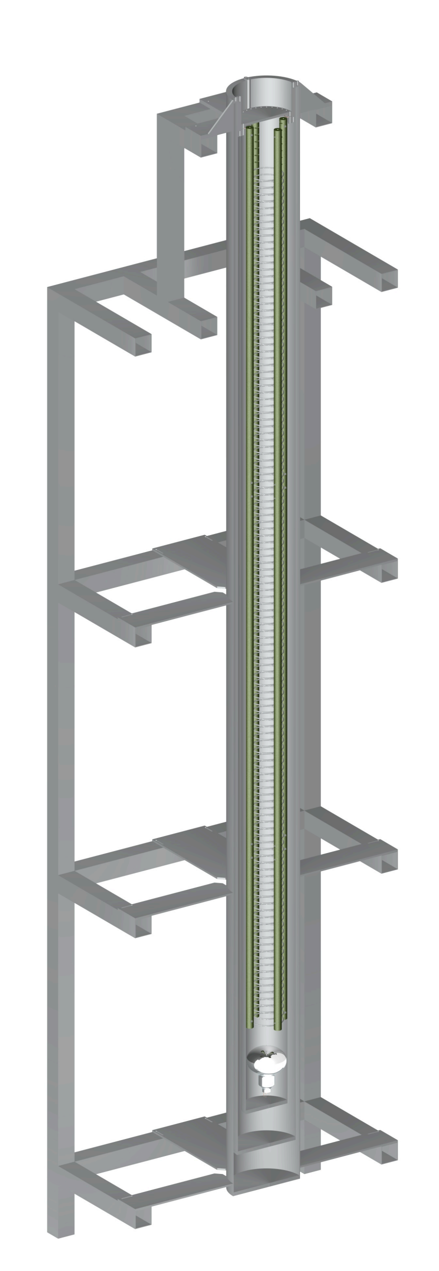
ARGONTUBE

Bern, ETHZ, Granada



Φ = 35 cm, L=585 cm

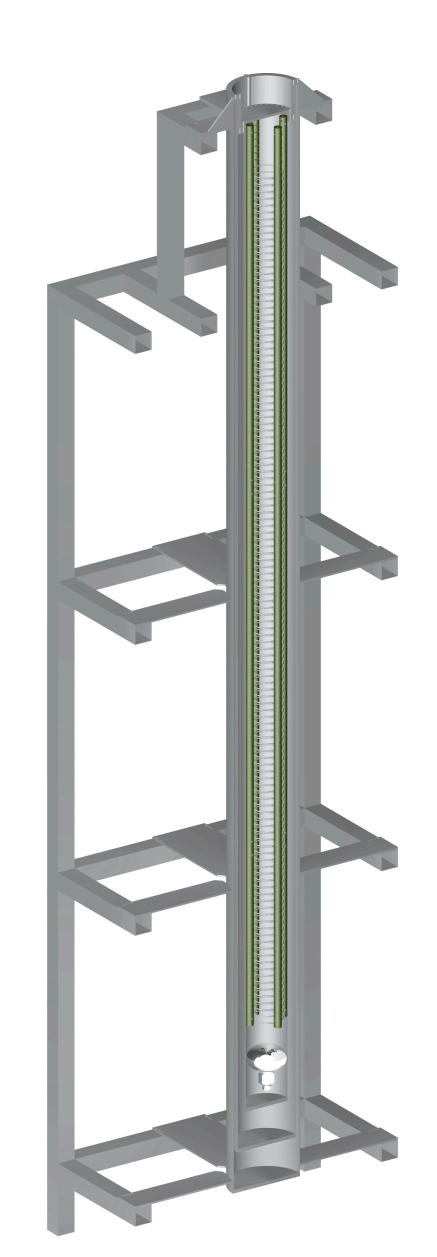
A. Rubbia

ARGONTUBE

Bern, ETHZ, Granada

- Full scale measurement of long drift (5 m), signal attenuation and multiplication, effect of charge diffusion
- Simulate 'very long' drift (10-20 m) by reduced E field & LAr purity
- High voltage test (up to 500 kV)
- Measurement Rayleigh scatt. length and attenuation length vs purity
- Status of design & assembly:
  - ✦external dewar, detector container,inner detector, readout system, …
  - ✦detailed design under preparation

First tests foreseen in 2008



Φ = 35 cm, L=585 cm

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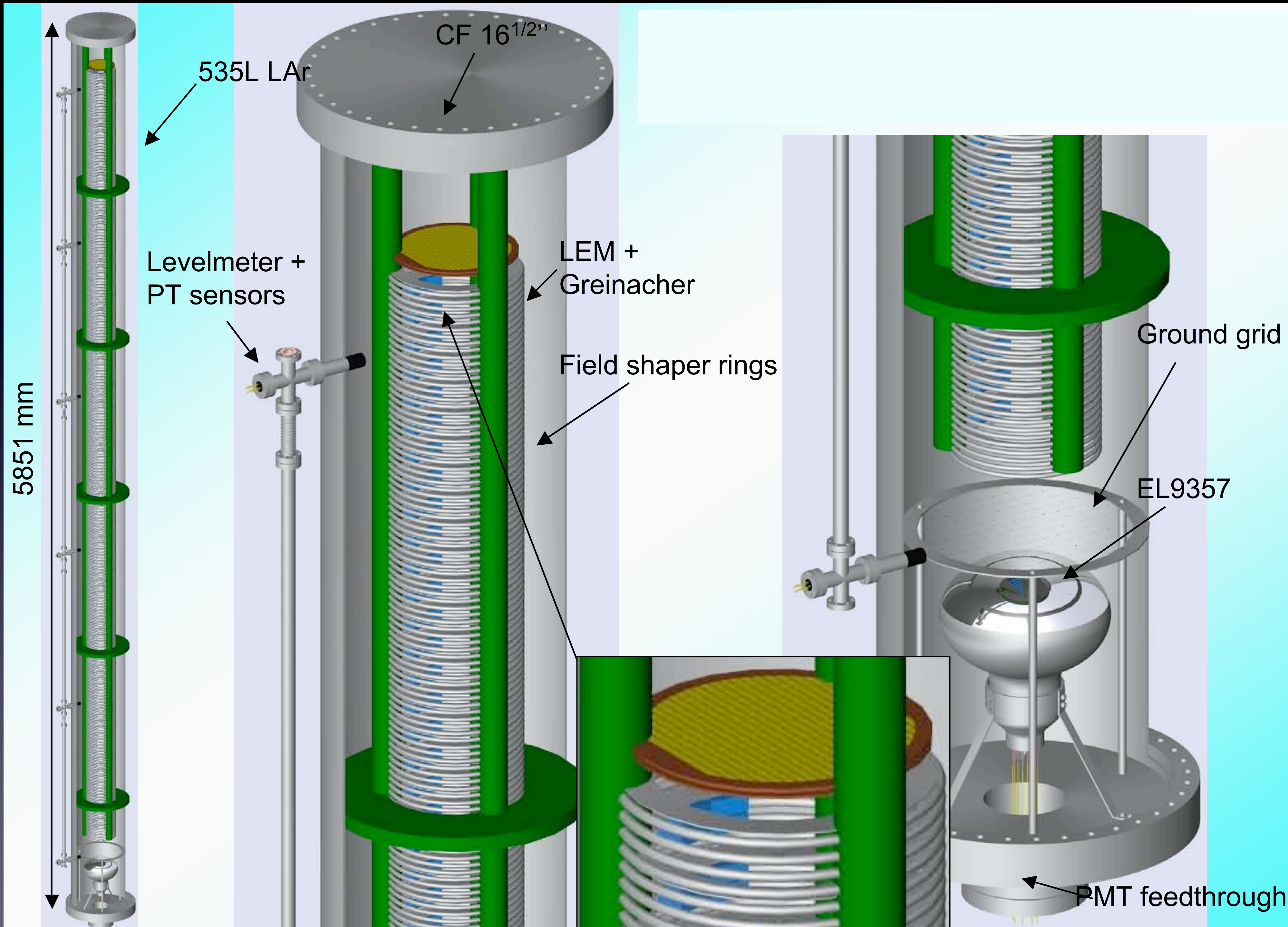
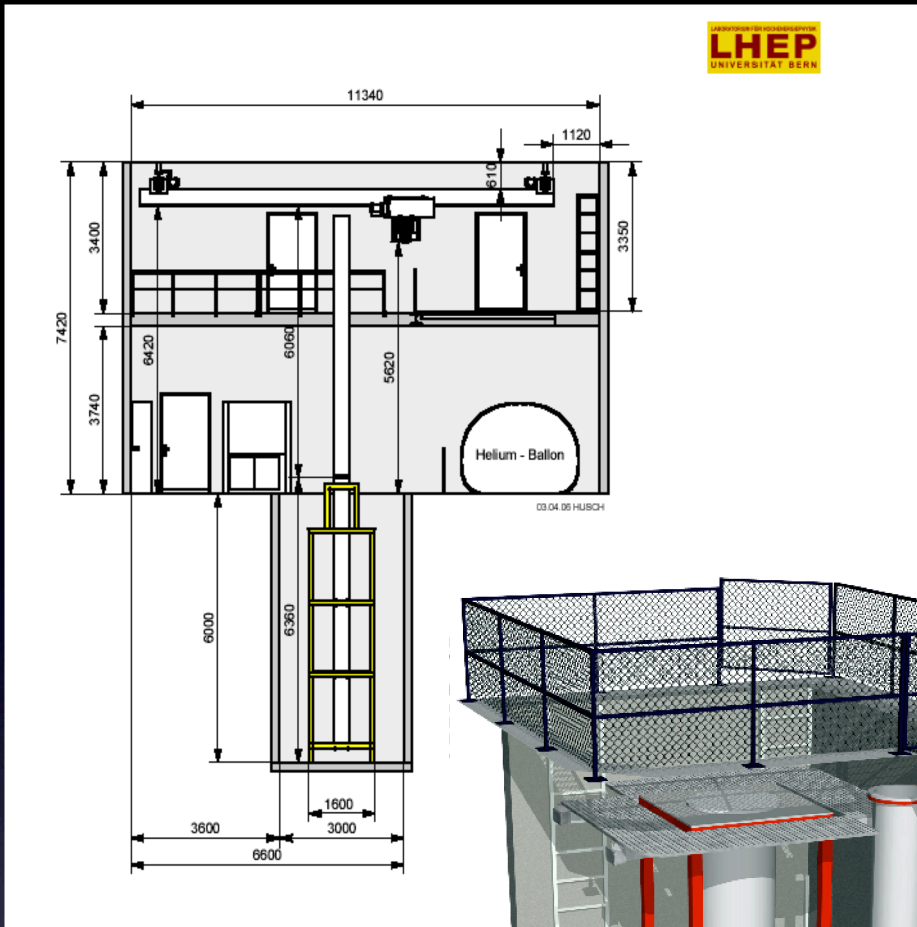
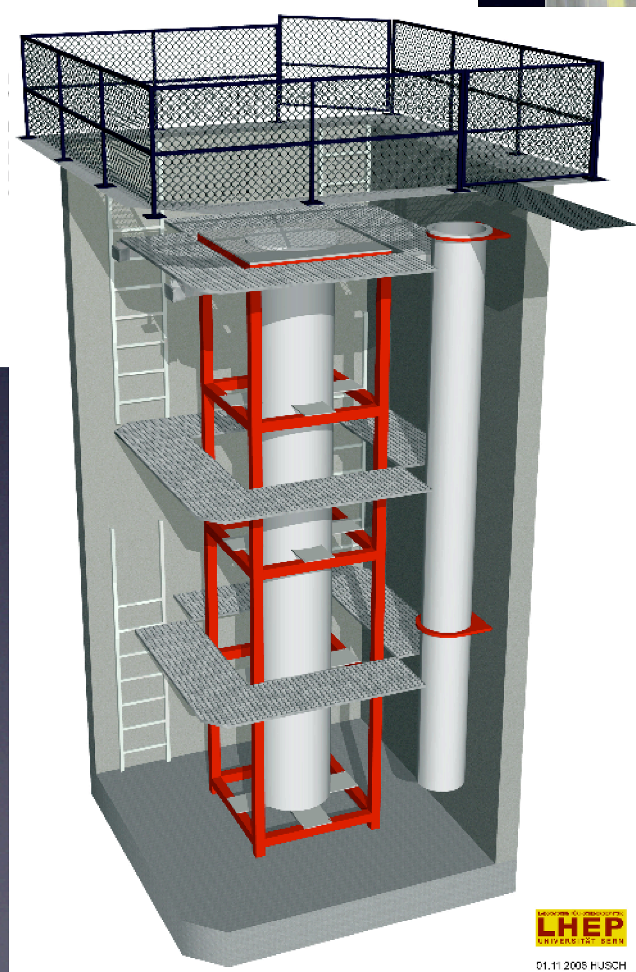
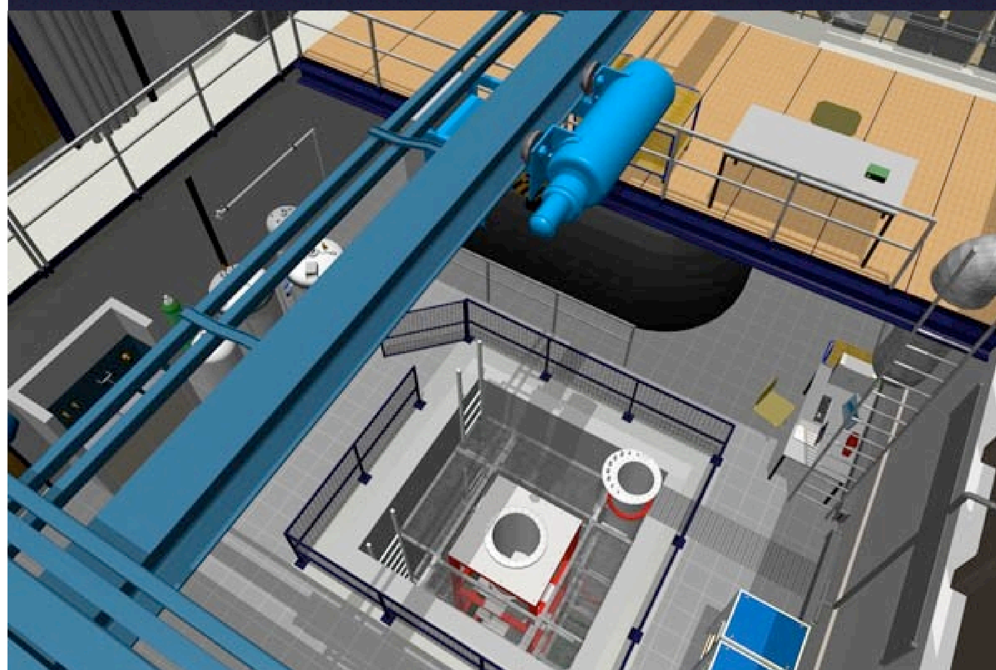
ARGONTUBE inner detector





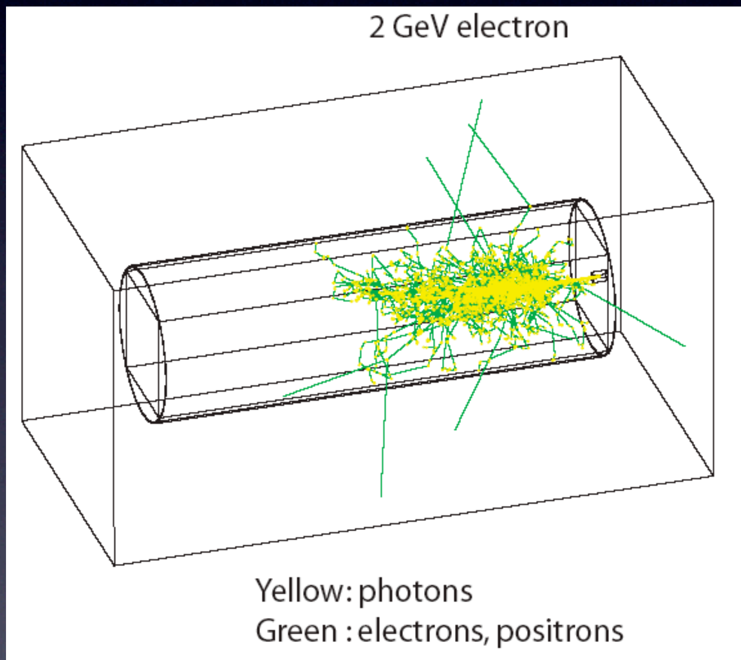




Installation at the University of Bern

Idea: Electron/π^0 separation (EPiLAr)

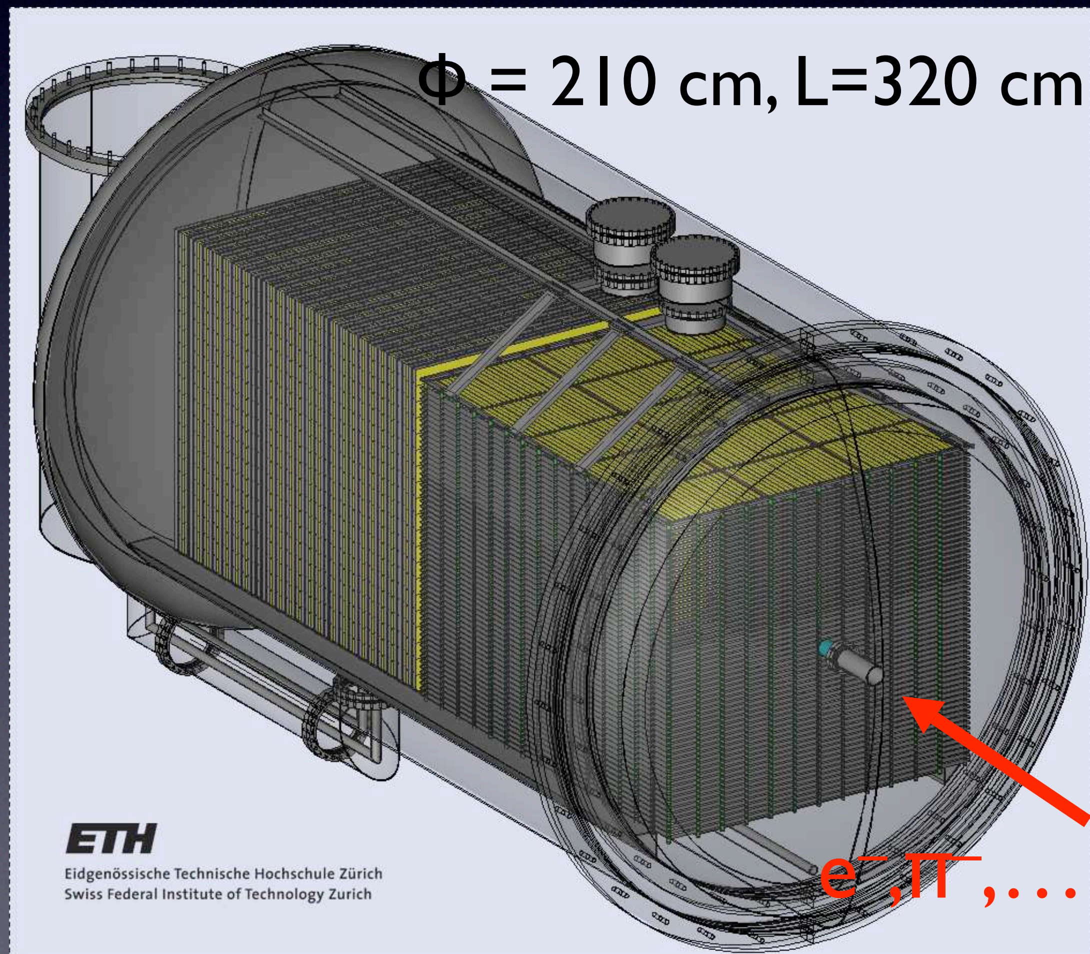
- In order to experimentally verify the result of MC studies which show that an efficiency above 90% for signal can be achieved while suppressing NC background to the permil level. This MC result was shown to be true over a wide range of neutrino energy, typ. between 0 and 5 GeV.



Polyethylene target CH_2

$\pi^- + p \rightarrow \pi^0 + n$

$\sigma_{CH2} \approx 30x\sigma_{Ar} \approx 10^{-3}\sigma_{inel,\, CH2}$



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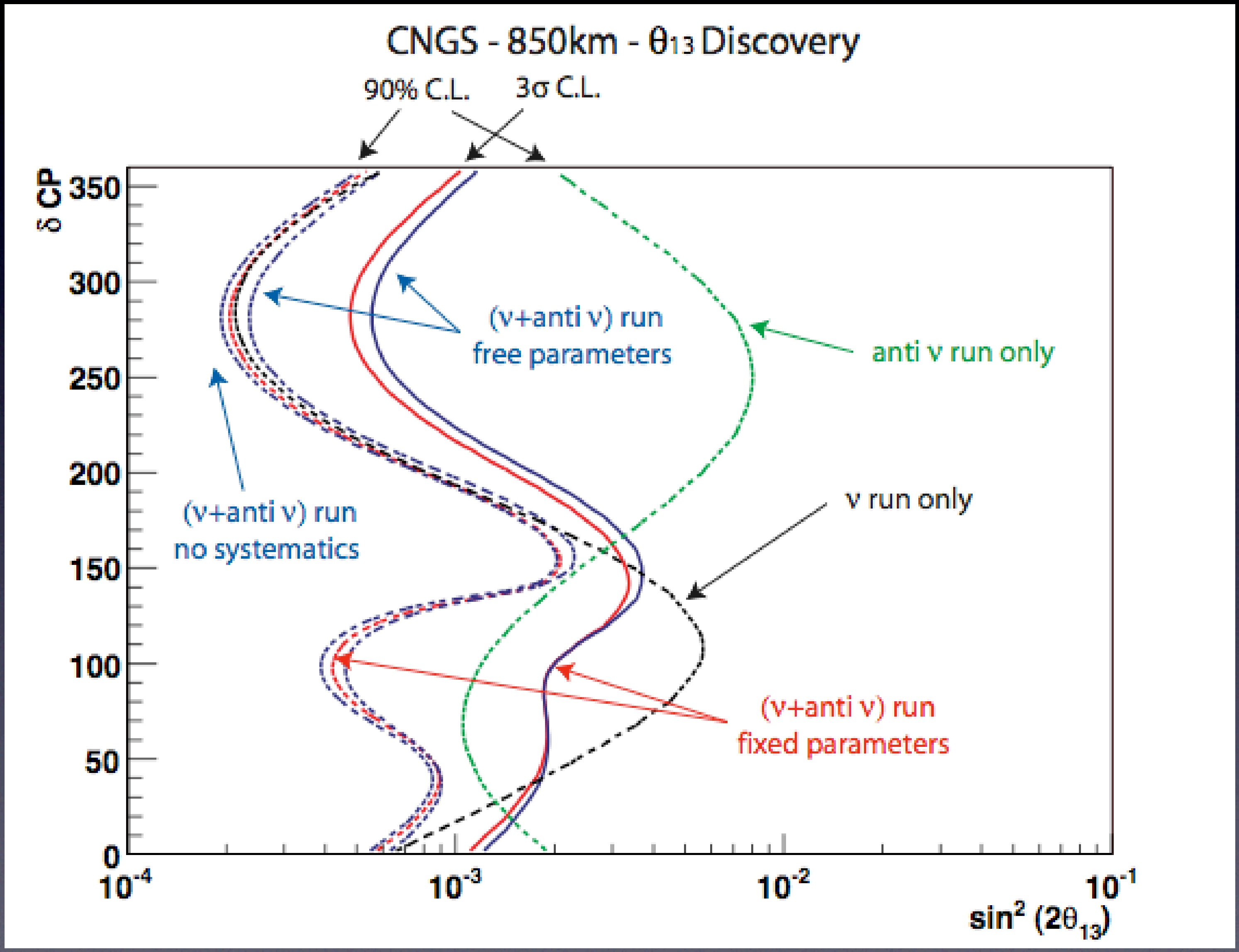
An Upgraded CNGS + Large Liquid Argon TPC

JHEP 0611:032,2006

Results: θ_{13} sensitivity

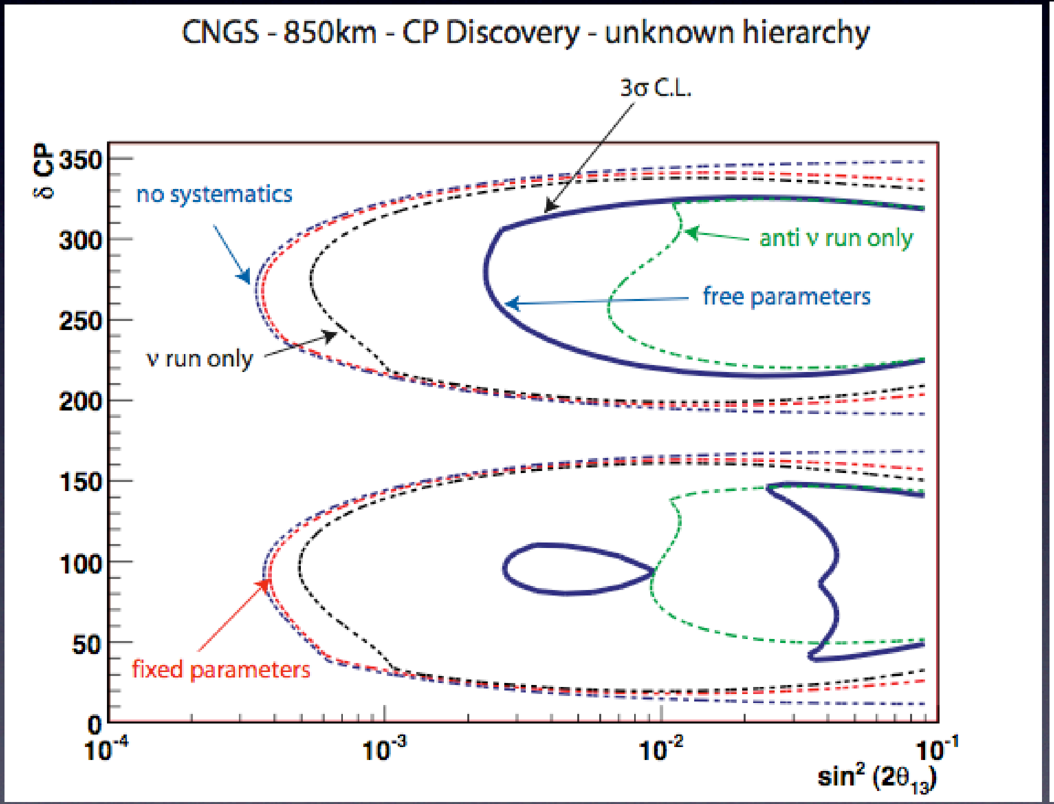
100 kton
5 yrs ν + 5 yrs $\bar{\nu}$
3.3 x 10^{20} pots/yr

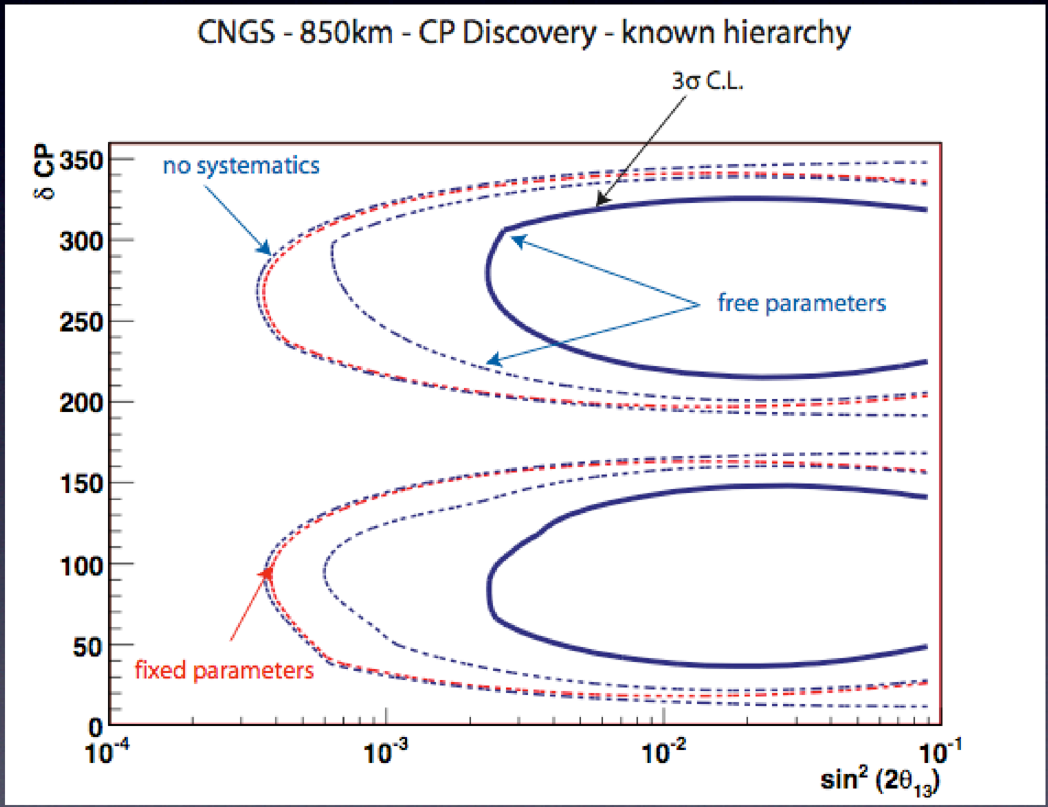


- The fits are performed using the GLoBES software, leaving oscillation parameters free within their priors, and taking into account degeneracies and parameters correlations.

Results: δ_{CP} sensitivity

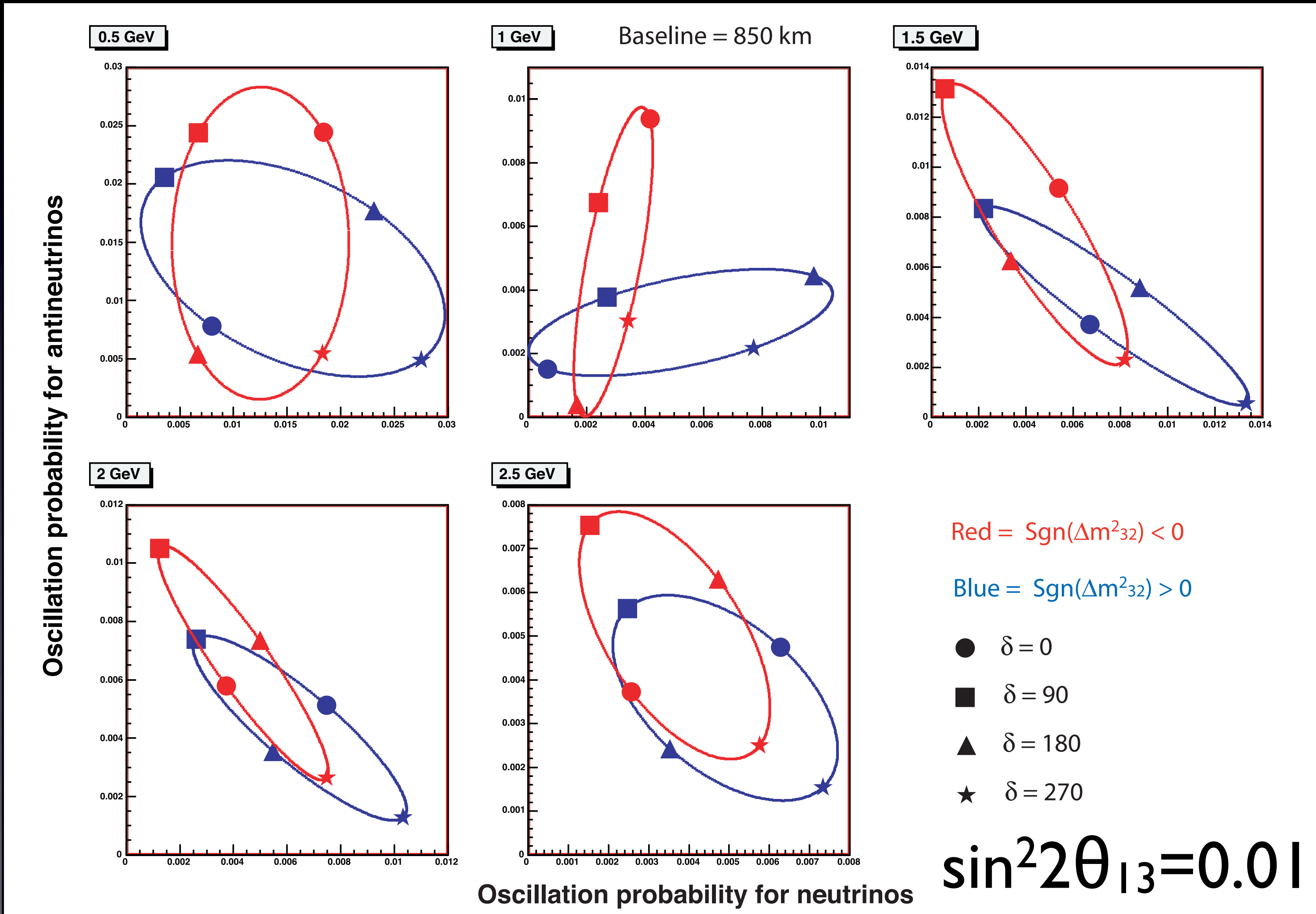
unknown mass hierarchy | *known mass hierarchy*





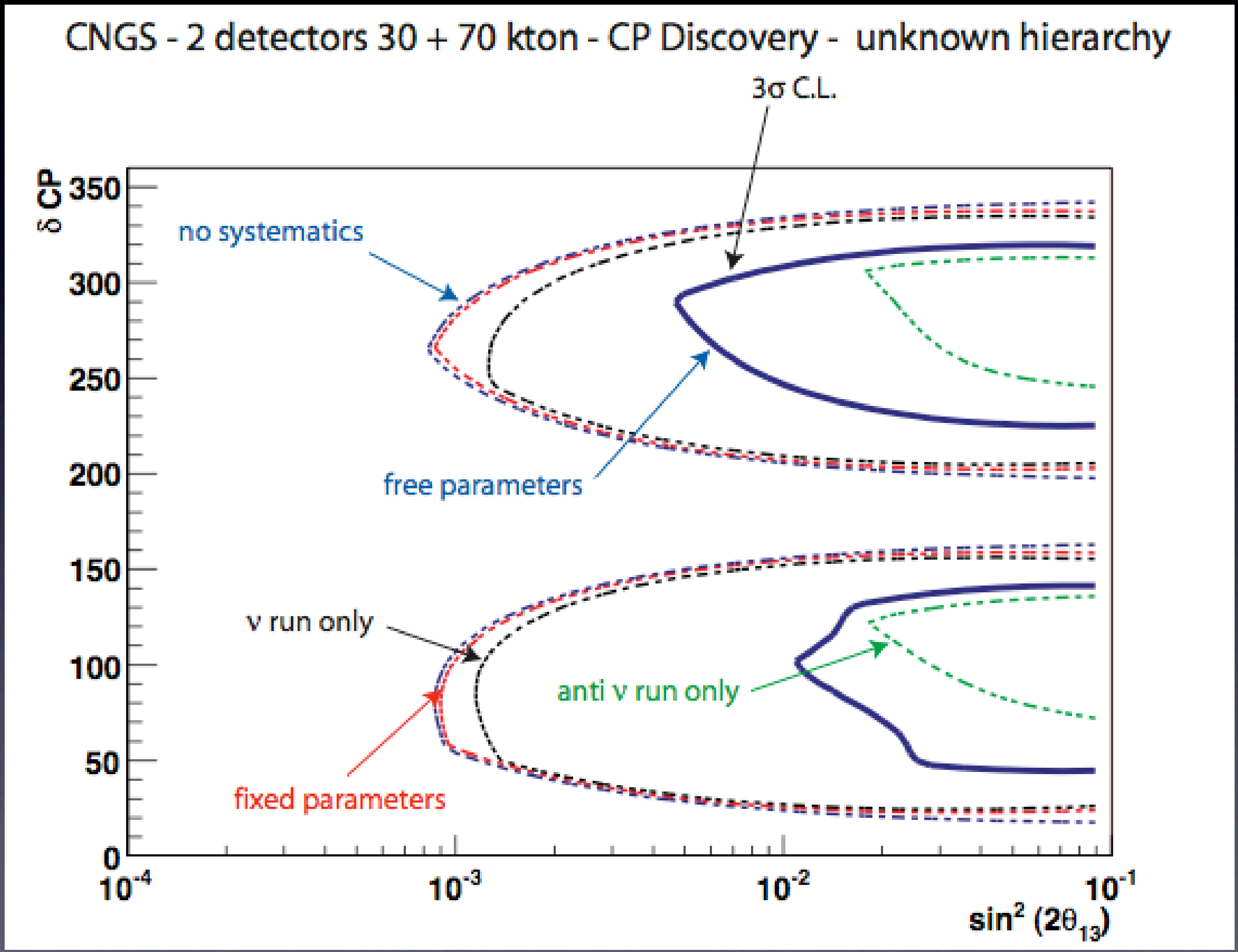
➡ *Parameter degeneracy !*

Neutrinos and antineutrinos



$\sin^2 2\theta_{13} = 0.01$

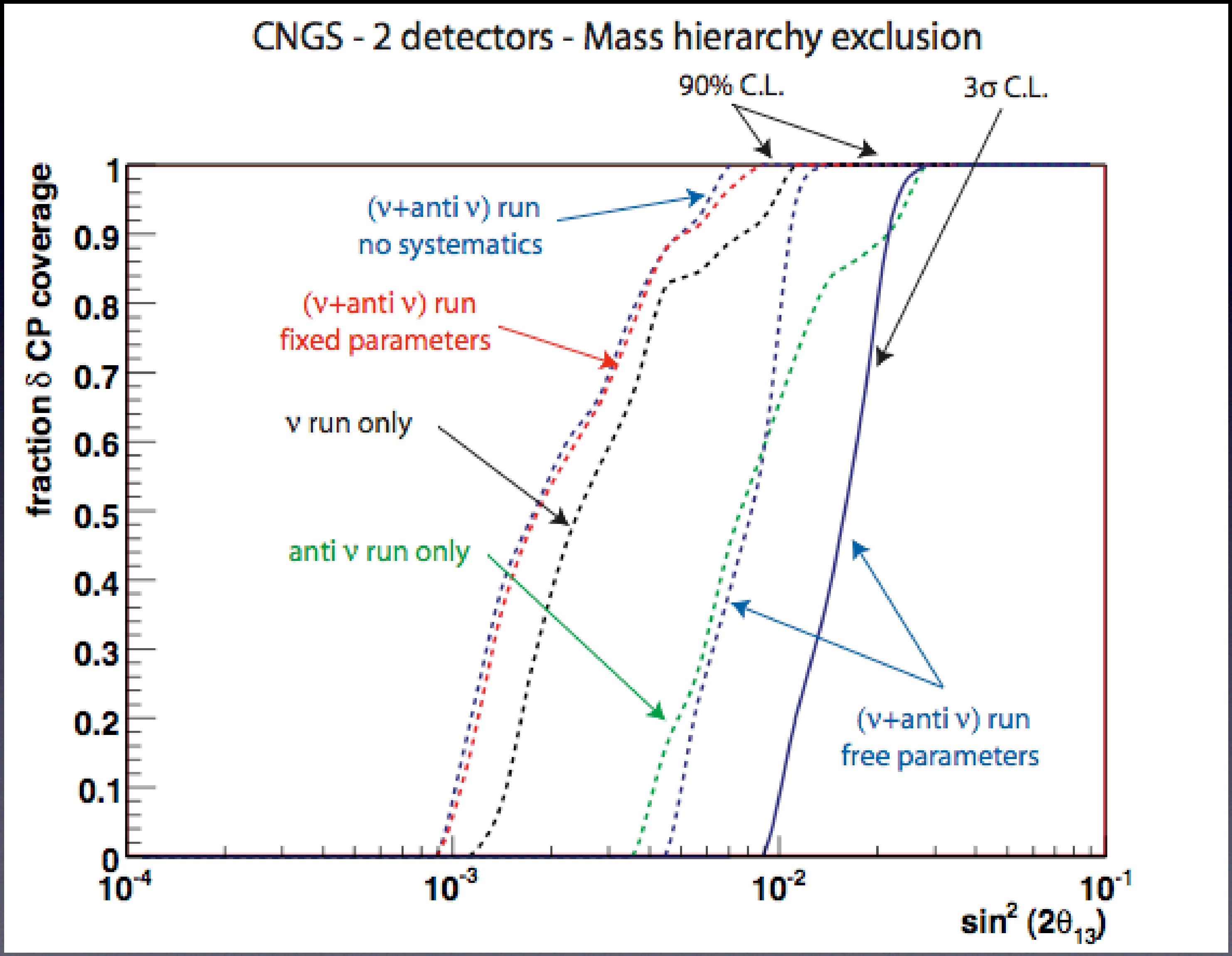
Results: δ_{CP} sensitivity w 2 detectors



A better coverage of the1st maximum, 1st minimum and 2nd maximum of the neutrino oscillation to help solve parameter degeneracy

30 kton @ 850 km
+
70 kton @ 1050 km

Results: mass hierarchy sensitivity



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN — AB DEPARTMENT

Since then...

CERN-AB-2007-013 PAF

April 2007

Analysis of the maximum potential proton flux to CNGS

M. Meddahi, E. Shaposhnikova

for the PAF working group

CERN – Geneva - Switzerland

Abstract

In this note we investigate the limitations to the proton flux which can be sent to the CNGS facility and estimate the maximum that can be attained.

In the first part, the injector chain remains unchanged and the limitations are reviewed for operation up to the so called "ultimate CNGS intensity", $7x10^{13}$ protons per CNGS cycle.

In the second part, the limitations of the SPS accelerator and CNGS facility are described in the scenario of operating with the new injectors - LINAC4, SPL and PS2, as proposed by the PAF working group [PAF].

Upgraded CNGS: CERN-AB report

- With the present injection chain:
  - **up to 1.1 x 10^{20} pots/year**
  - target & horn equipment OK, but difficult to access for potential modifications
  - Possible issues with radioprotection and area classification. New approval required.
- With new injectors (>2016):
  - **up to 2.4 x 10^{20} pots/year**
  - CNGS facility will require rebuild as many beam line components, including target, horn, shielding, decay tube, hadron stop, etc., might require update.
  - New authorizations and area classification ("MW-class", true for any new ν-facility)

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Proton economics

CERN-AB-2007-013 PAF

	SPS cycle length	6 s		4.8 s	
	Injection momentum	14 GeV/c		26 GeV/c	
	Beam sharing / Max SPS intensity @ 400GeV [x10^{13}]	0.45	0.85	0.45	0.85
Present injectors + machines' improvement	4.8 – "Nominal CNGS"	5	9.4		
	5.7- "Max. SPS"	5.9	11.1		
Future injectors + SPS RF upgrade	7 – "Ultimate CNGS"			9	17.1
Future injectors + new SPS RF system + CNGS new equipment design	10 – "Max. PS2"			12.9	24.5

x10^{19}

In the future, there might be enough protons...
We had assumed 3.3×10^{20} pot/yr ➠ rescale by factor 1.3 number of years (5 yrs ➠ 6.7 yrs)

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LAGUNA

Design of a Pan-European Infrastructure for Large Apparatus studying Grand Unification and Neutrino Astrophysics

A. Rubbia

A new infrastructure in Europe ?

A new infrastructure in Europe ?

- Advances in low energy neutrino astronomy and direct investigation of Grand Unification require the construction of very large underground observatories with total active volumes from $O(10^5)$ m^3 up to $O(10^6)$ m^3
- There is currently no such infrastructure in the world able to host underground instruments of this size, although in Europe many national underground laboratories with high technical expertise are currently operated with leading-edge smaller-scale underground experiments.
- A pan-European infrastructure able to host underground instruments of the required size volumes will provide new and unique scientific opportunities in low energy neutrino astronomy and Grand Unification physics.
- This field of research is at the forefront of particle and astro-particle physics and is the subject of intense investigation also in North America and Asia. Such an infrastructure in Europe would interest scientists from all over the world and ensure that Europe will continue to play a leading and innovative role in the field.

ApPEC Roadmap, January 2007

Proton decay and low energy neutrino astrophysics

Field/ Experiments	Cost scale (M€)	Desirable start of construction	Remarks
Dark Matter Search: Low background experiments with 1-ton mass	60-100 M€	2011-2013	2 experiments (different nuclei, different techniques), e.g. 1 bolometric, 1 noble liquid; more than 2 worldwide.
Proton decay and low energy neutrino astronomy: Large infrastructure for p-decay and ν astronomy on the 100kt-1Mton scale	400-800 M€	2011-2013	- multi-purpose - 3 different techniques; large synergy between them. - needs huge new excavation - expenditures likely also after 2015 - worldwide sharing - possibly also accelerator neutrinos in long baseline experiments
The high energy universe: *Gamma rays:* Cherenkov Telescope Array CTA	100 M€ (South) 50 M€ (North)	first site in 2010	Physics potential well defined by rich physics from present gamma experiments
Charged Cosmic Rays: Auger North	85 M€	2009	Confirmation of physics potential from Auger South results expected in 2007
Neutrinos: KM3NeT	300 M€	2011	FP6 design study. Confirmation of physics potential from IceCube and gamma ray telescopes expected in 2008-2010
Gravitational Waves: Third generation interferometer	250-300 M€	Civil engineering 2012	Conceived as underground laboratory

Six national underground science laboratories

IUS

Institute of Underground Science in Boulby mine, UK

CENTRE FOR UNDERGROUND PHYSICS IN PYHÄSALMI MINE

LSM

Laboratoire Souterrain de Modane, France

SUNLAB

Polkowice-Sieroszowice, Poland

LSC

Laboratorio Subterraneo de Canfranc, Spain

LNGS

Laboratori Nazionali del Gran Sasso, Italy

None of these laboratories can host next generation very large volume observatories. Extension are needed.

- What depth?
- What other synergies? (beamline distance from artificial sources at accelerators)
- What is the distance from reactors?

A. Rubbia

Six national underground science laboratories

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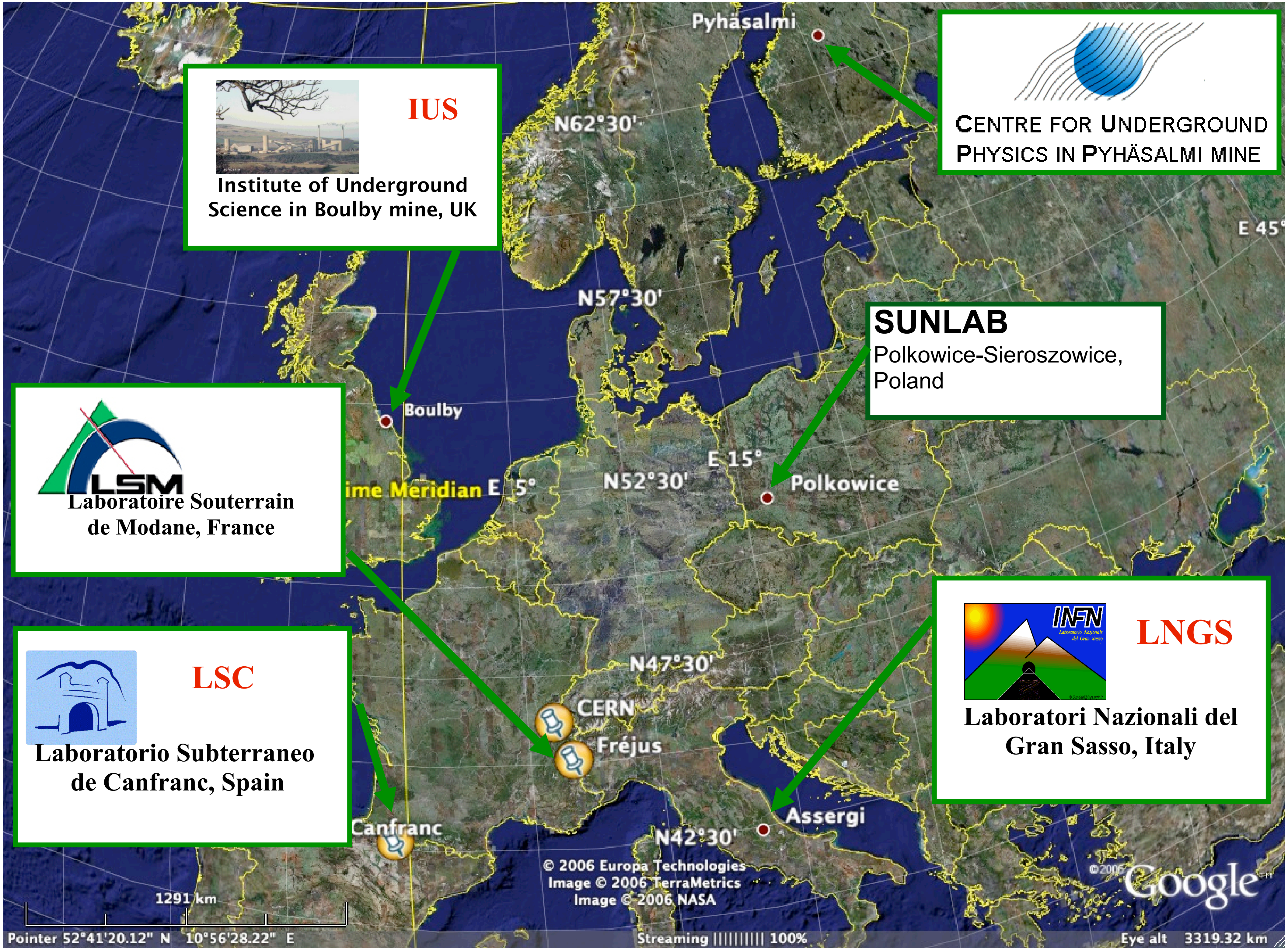
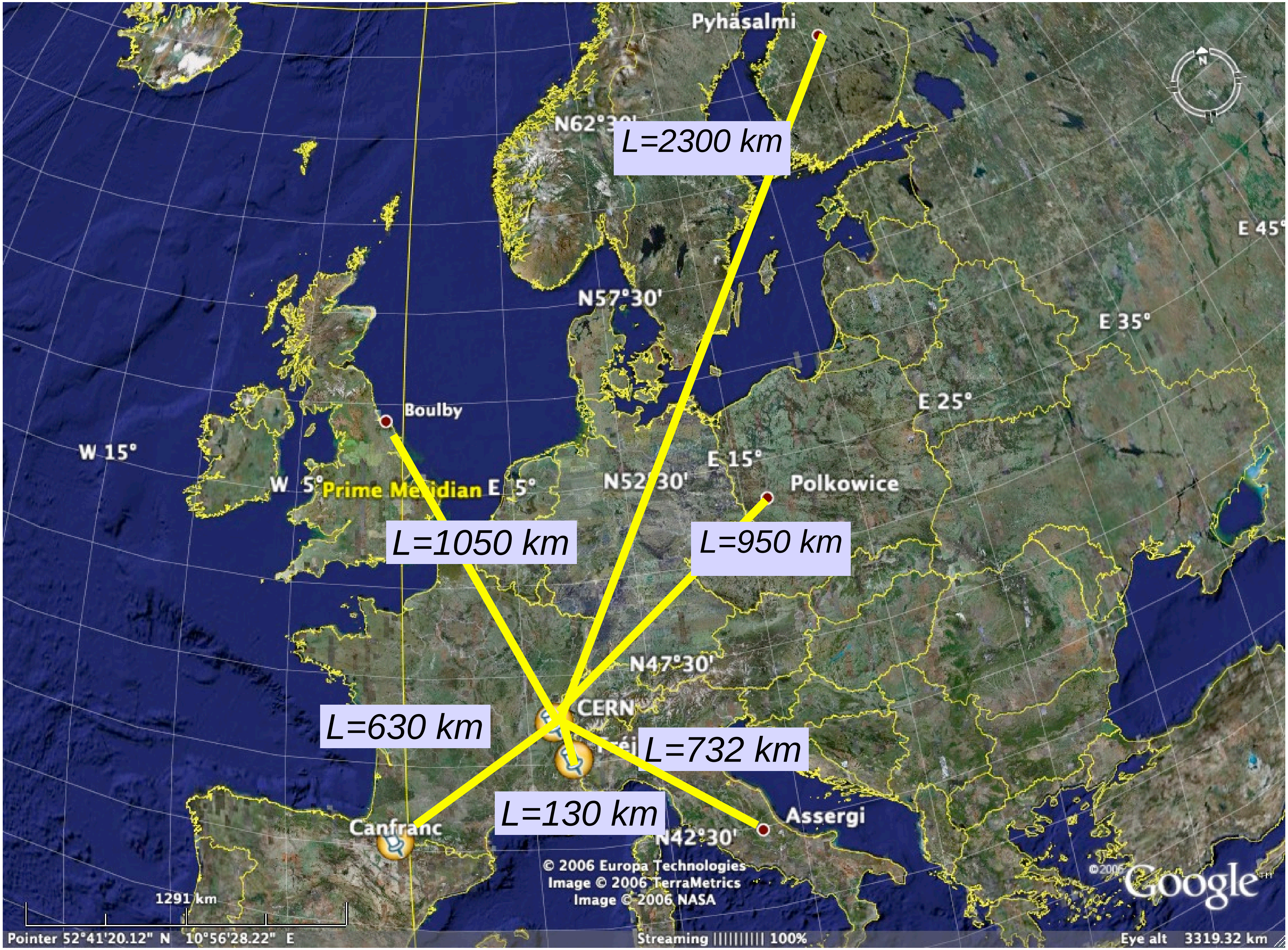
A pan-European Infrastructure for very large volume underground observatories ?

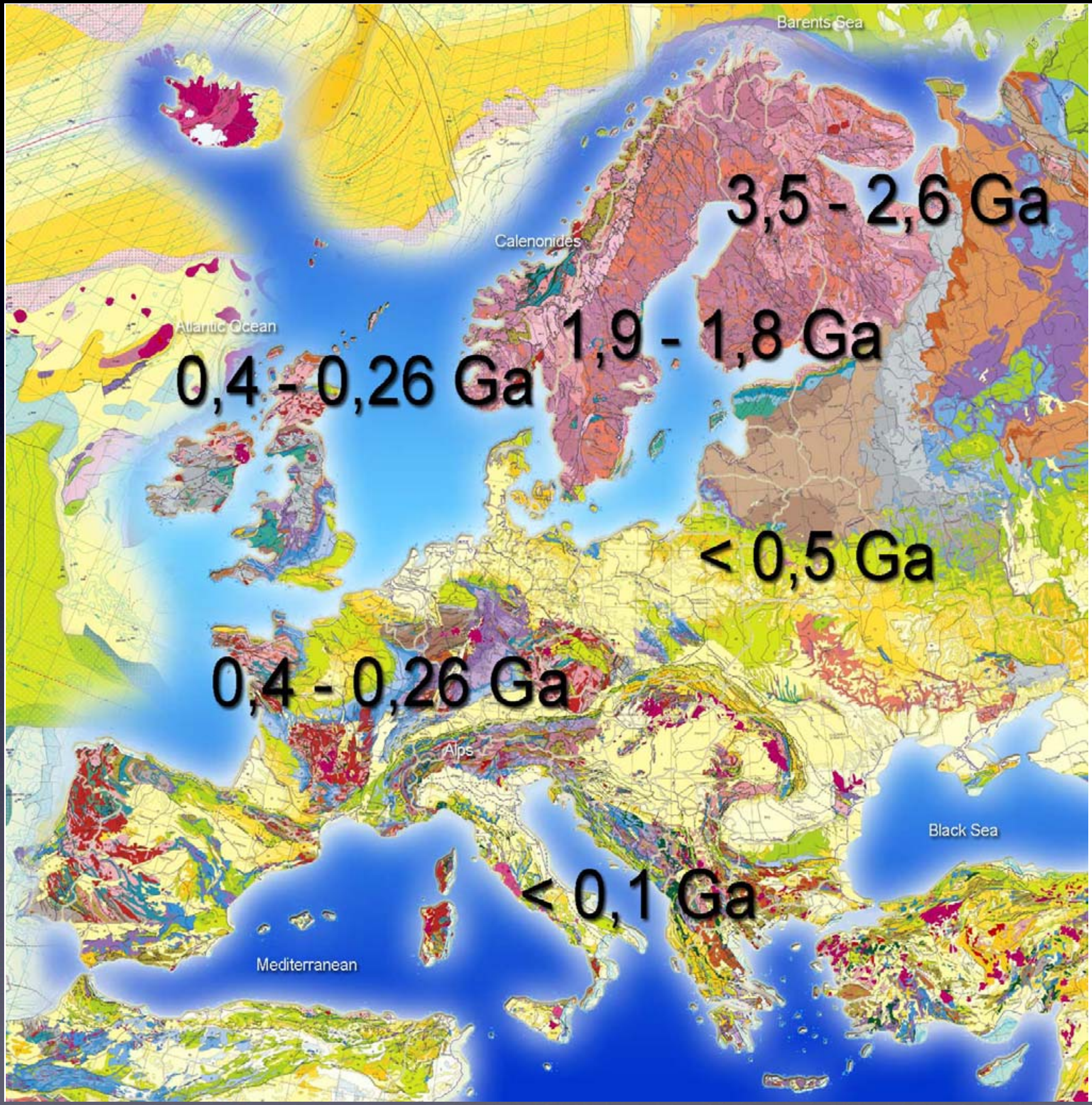
None of these laboratories can host next generation very large volume observatories. Extension are needed.

- What depth?
- What other synergies? (beamline distance from artificial sources at accelerators)
- What is the distance from reactors?


Pyhäsalmi
CENTRE FOR UNDERGROUND PHYSICS IN PYHÄSALMI MINE
IUS
Institute of Underground Science in Boulby mine, UK
N62°30'
E 45°
N57°30'
SUNLAB
Polkowice-Sieroszowice, Poland
Boulby
LSM
Laboratoire Souterrain de Modane, France
ime Meridian E 5°
N52°30'
E 15°
Polkowice
LSC
Laboratorio Subterraneo de Canfranc, Spain
N47°30'
CERN
Fréjus
INFN
LNGS
Laboratori Nazionali del Gran Sasso, Italy
Assergi
Canfranc
N42°30'
© 2006 Europa Technologies
Image © 2006 TerraMetrics
Image © 2006 NASA
1291 km
Google
Pointer 52°41'20.12" N 10°56'28.22" E
Streaming |||||||||| 100%
Eye alt 3319.32 km


Pyhäsalmi
N62°30'
L=2300 km
E 45°
N57°30'
E 35°
E 25°
Boulby
W 15°
E 15°
W 5°
Prime Meridian
E 5°
N52°30'
Polkowice
L=1050 km
L=950 km
N47°30'
CERN
L=630 km
L=732 km
L=130 km
Assergi
Canfranc
N42°30'
© 2006 Europa Technologies
Image © 2006 TerraMetrics
Image © 2006 NASA
1291 km
Pointer 52°41'20.12" N 10°56'28.22" E
Streaming |||||||||| 100%
Eye alt 3319.32 km
Google

Bedrock conditions in Europe



The age of the bedrock in Finland varies between 2 – 3,5 million years
billion

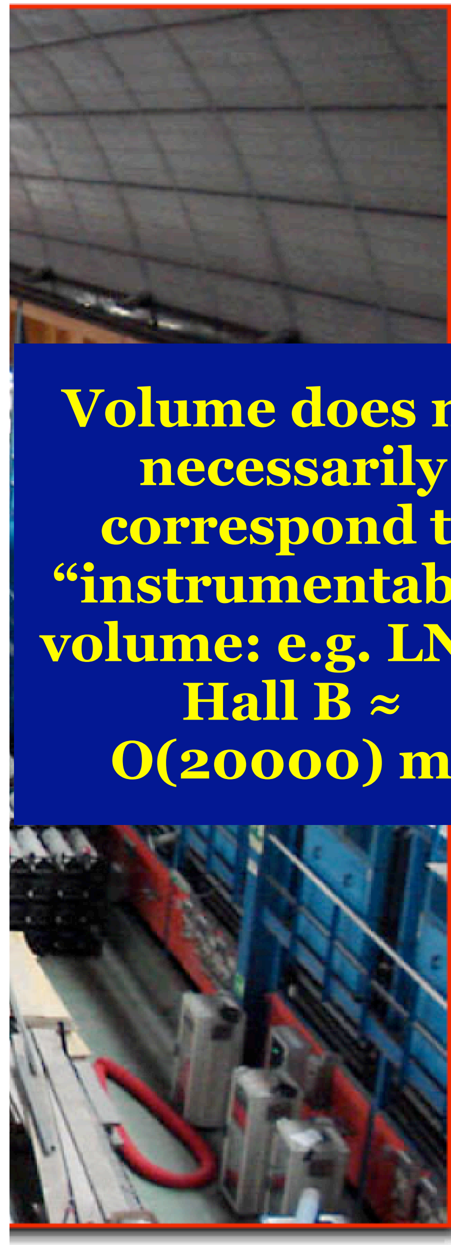
KALLIOSUUNNITTELU OY
ROCKPLAN LTD

University of Helsinki
GTK

Instrumenting underground cavities

Instrumenting underground cavities

Infrastructure ▸	LNGS Gran Sasso	LSM Fréjus	LSC Canfranc	IUS Boulby	BNO Baksan	CUPP Pyhäsalmi
Year of completion	1987	1982	1986, 2005	1989	1977, 1987	1993 (2001)
Area (m^2)	13000	500	150+600	500+1000	550, 600	500-1000
Volume (m^3)	180000	3500	8000	3000	6400, 6500	100-10000
Access	Horizontal	Horizontal	Horizontal	Vertical	Horizontal	Slanted truck road
Depth (m.w.e.)	3700	4800	2450	2800	850, 4800	1050, 1444 up to 4060
Surface profile	Mountain	Mountain	Mountain	Flat	Mountain	Flat
Muon flux (m^{-2} day^{-1})	24	4	406	34	4320, 2.6	8.6 @ 4060m
Neutron flux (>1 MeV) (10^{-6} cm^{-2} s^{-1})	*O* (1)	*O* (1)	*O* (1)	*O* (1)	- , *O* (1)	?
Radon content (Bq/m^3)	*O* (100)	*O* (10)	*O* (100)	*O* (10)	*O* (100)	*O* (100)
Main past and present scientific activities	- DM - ββ - solar ν - SN ν - atmos. ν - monopole - nuclear astrophysics - CRs (μ) - LBL ν's	Eighties: - Proton decay - atmos.ν Now: - DM (Edelweiss) - ββ (NEMO, TGV)	- DM (IGEX-DM, ROSEBUD, ANAIS) - ββ (IGEX)	- DM (Zeplin I,II, III, DRIFT)	*BUST:* - solar ν - SN ν - atmos. ν - CRs (μ) - monopo-les *SAGE:* - solar ν	- CRs (test set-up)
Number of visiting scientists	700	100	50	30	55	15



Volume does not necessarily correspond to "instrumentable" volume: e.g. LNGS Hall B ≈ O(20000) m^3

Worldwide context: very large volumes

A. Rubbia

Worldwide context: very large volumes

Hyper-Kamiokande
Toshibora mine, Japan
>2013 ?

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Worldwide context: very large volumes

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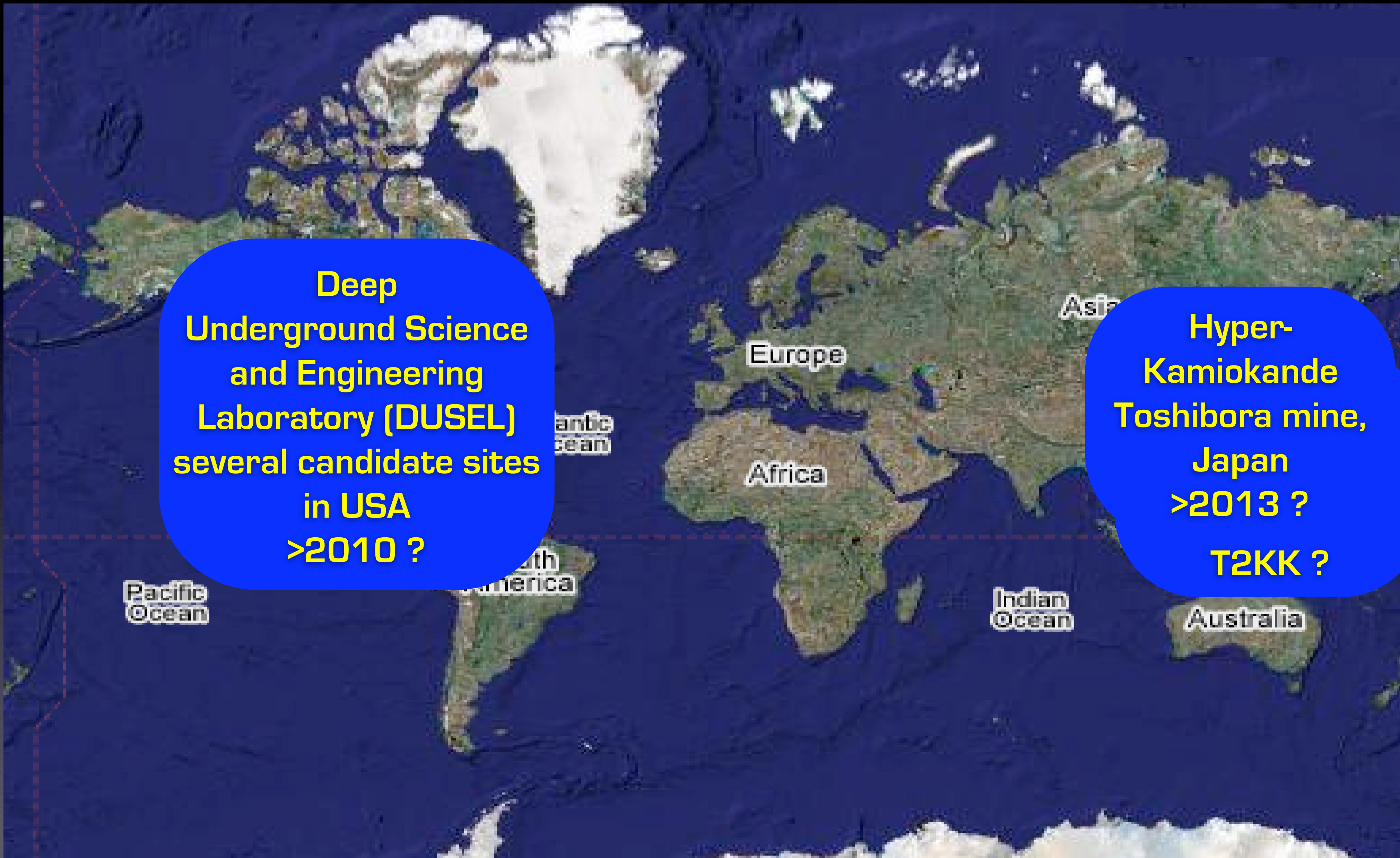
Worldwide context: very large volumes



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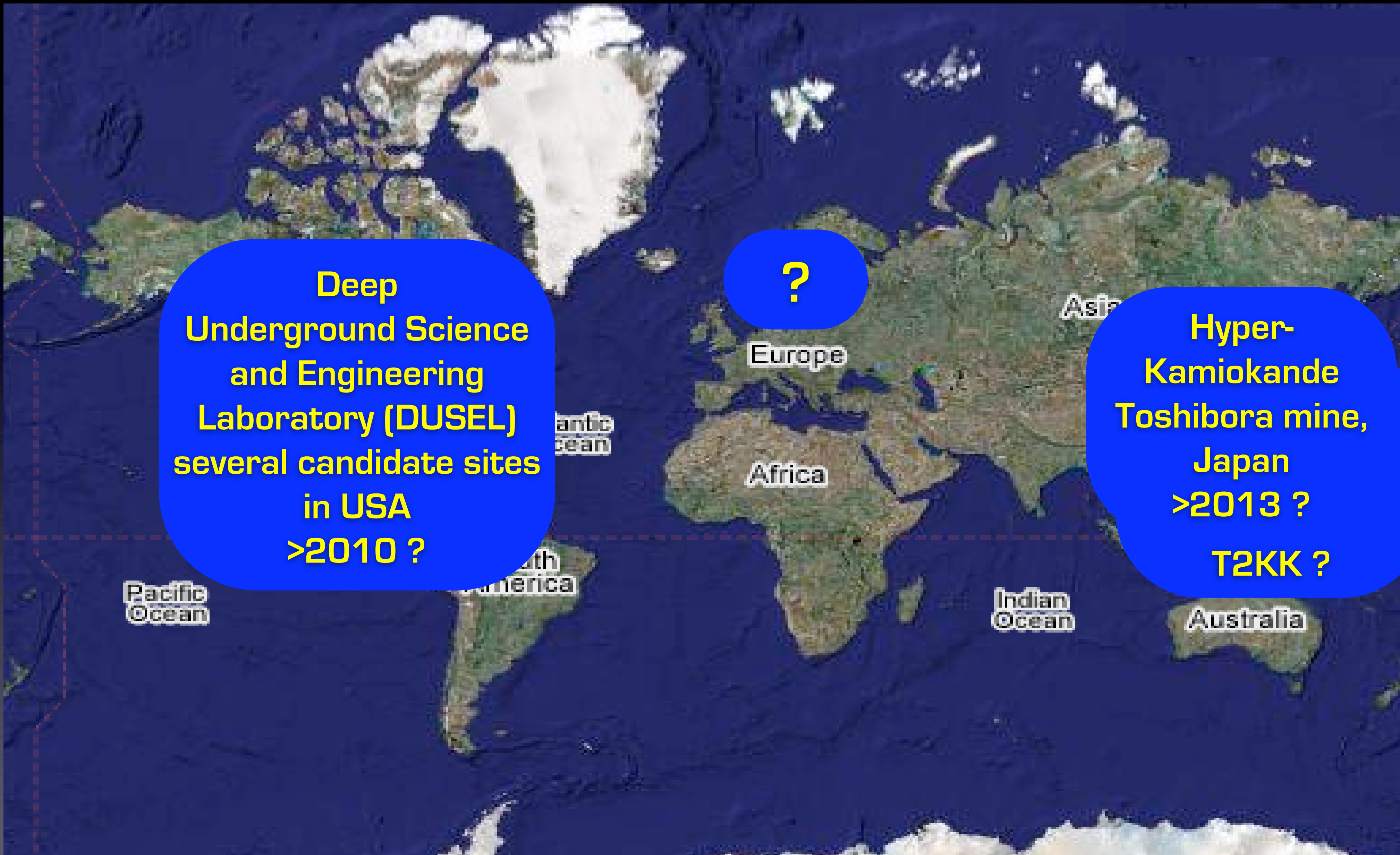
Worldwide context: very large volumes



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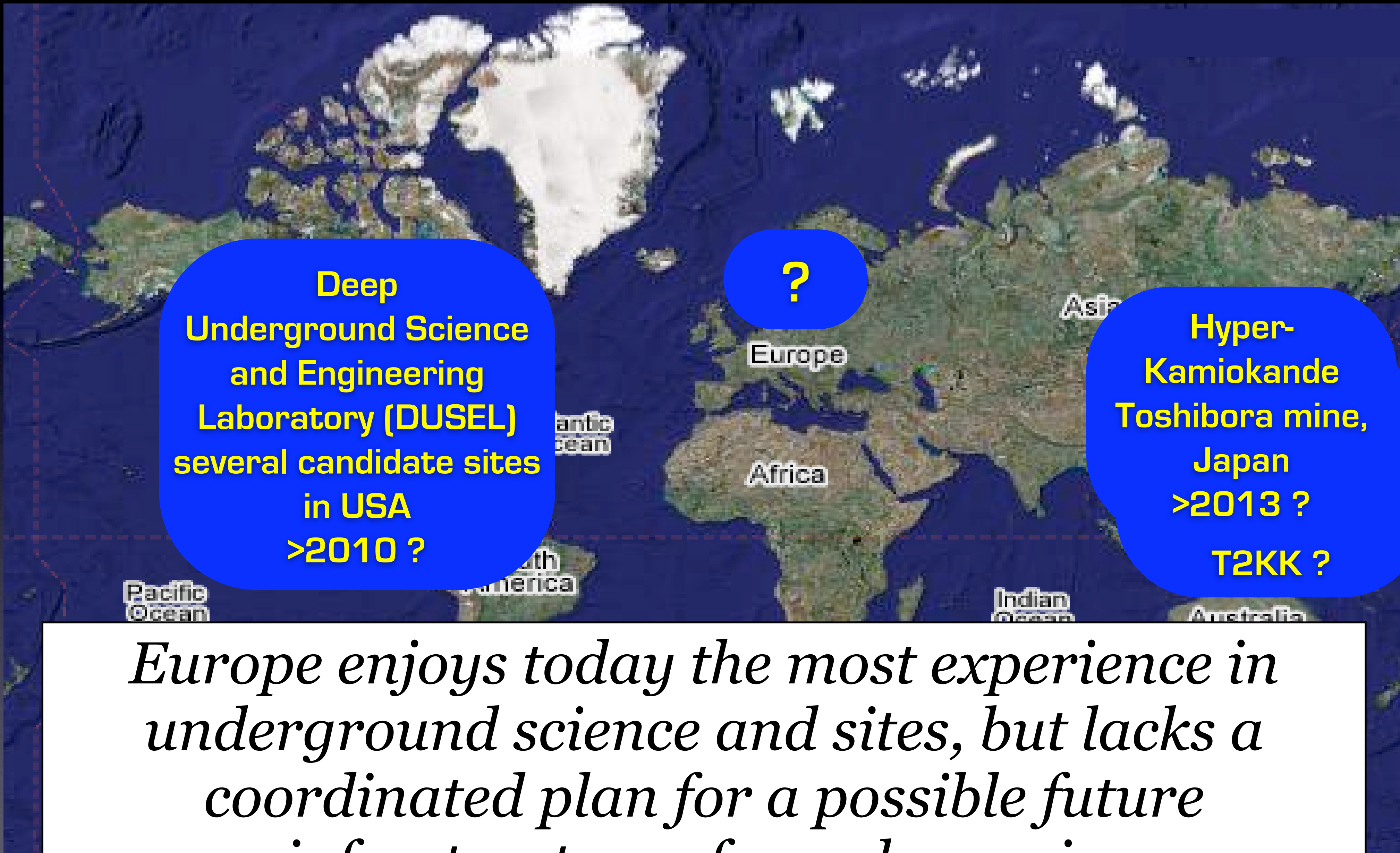
Worldwide context: very large volumes



Deep Underground Science and Engineering Laboratory (DUSEL) several candidate sites in USA >2010 ?

?

Hyper-Kamiokande Toshibora mine, Japan >2013 ?

T2KK ?

Europe enjoys today the most experience in underground science and sites, but lacks a coordinated plan for a possible future infrastructure of very large size

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Worldwide roadmaps...

Worldwide roadmaps...

A neutrino detector optimized for neutrino energies of the order of ~ 1 GeV is also well matched to search for proton decay

- ★ Japan: Super –K (50 kton) ➠ Hyper-K (1 Mton) (T2K phase II)

- ★ US: Report of the US long baseline neutrino experiment study "*A well instrumented very large detector, in addition to its accelerator based neutrino program, could be sensitive to proton decay which is one of the top priorities in fundamental science... Indeed, there is such a natural marriage between the requirements to discover leptonic CP violation and see proton decay that it could be hard to imagine undertaking either effort without being able to do the other*"

- ★ EU: ApPEC recommendation "*We recommend that a new large European infrastructure is put forward as a future international multi-purpose facility on the 100 – 1000 ktons scale for improved studies of proton decay and of low-energy neutrinos from astrophysical origin. The detection techniques ... should be evaluated in the context of a common design study, which should also address the underground infrastructure and the possibility of an eventual detection of future accelerator neutrino beams*"

Primary physics focus of LAGUNA

A. Rubbia

Primary physics focus of LAGUNA

- Direct evidence for Grand Unification (Proton decay)
- Low energy neutrino astronomy
- Long baseline neutrino beam

Primary physics focus of LAGUNA

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Primary physics focus of LAGUNA

- Direct evidence for Grand Unification (Proton decay)
- Low energy neutrino astronomy
- Long baseline neutrino beam

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But also...

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But also...

- Large observatories for detection of dark matter (e.g. directional detection)
- Geophysics, rock science, ...
- Biology
- Extreme conditions underground civil engineering
- etc.

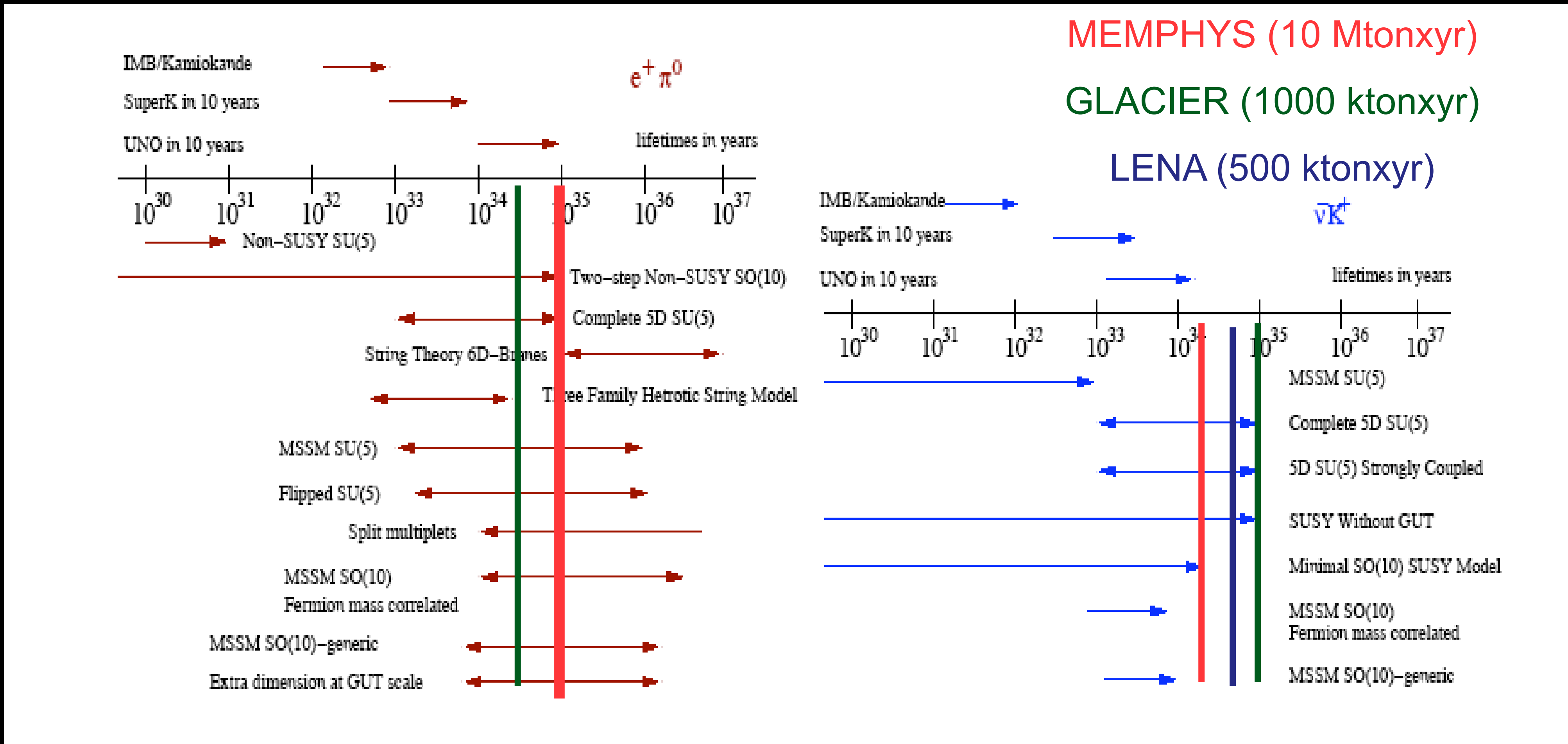
A very rich field !

A. Rubbia

A very rich field !

- Historically a very rich field (SN1987A, solar & atmospheric neutrinos). The physics programme addressed by LAGUNA will span the next 30 years.
  - Testing proton lifetime up to 10^{35} years will provide a very stringent, perhaps ultimate, test of the Grand Unification hypothesis
  - After the optical observation of supernovae by mankind during the last centuries and the SN1987A neutrino detection, the next observable event with neutrinos will occur with high probability in the next decade and with certainty in the next 30 years. Neutrinos will shed more light on the SN explosion mechanisms than optical light!
  - Meanwhile the background flux of neutrinos from relic supernovae can be observed
  - The study of neutrinos properties have shown the first indication of physics beyond the Standard Model of Elementary Particles. New discoveries, like CP-violation in the leptonic sector, are expected in this field.
- High-energy accelerators like the LHC or the planned ILC cannot directly answer these fundamental questions about Nature. This was also recognized in the CERN European roadmap for particle physics: "*A range of very important non-accelerator experiments take place at the overlap between particle and astroparticle physics exploring otherwise inaccessible phenomena; Council will seek to work with ApPEC to develop a coordinated strategy in these areas of mutual interest.*"

Sensitivity to proton decay: comparison with theory



Higher dimension models (eg. 6D SO(10)) not included

Definitively not exhaustive.

Supernova type-II neutrinos

⇒Access supernova and neutrino physics simultaneously

⇒Decouple supernova & neutrino properties via different detection channels

1. Supernova physics:

- Gravitational collapse mechanism
- Supernova evolution in time
- Burst detection
- Cooling of the proto-neutron star
- Shock wave propagation
- Black hole formation?

2. Neutrino properties

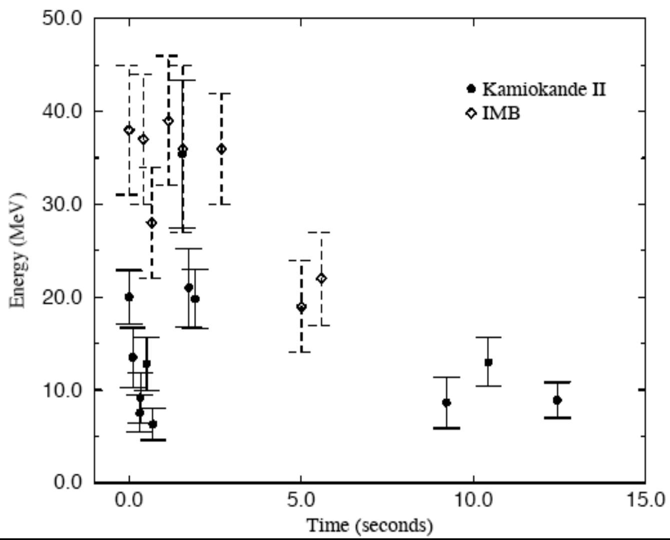
- Neutrino mass (time of flight delay)
- Oscillation parameters (flavor transformation in SN core and/or in Earth): Type of mass hierarchy and θ_{13} mixing angle

3. Early alert for astronomers

- Pointing to the supernova

SN1987A Type II in LMC (~55 kpc)

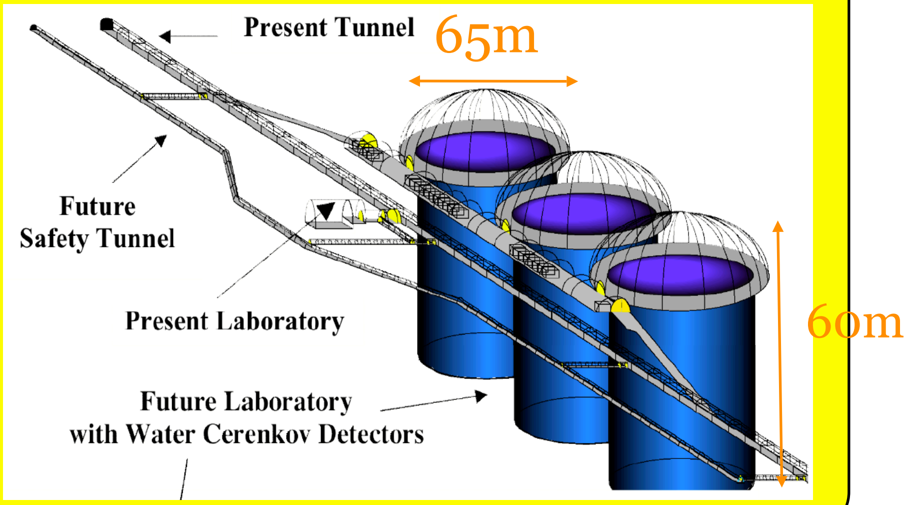
Water Cherenkov:	IMB	E_{th} ~ 29 MeV, 6 kton	8 events
	Kam II	E_{th} ~ 8.5 MeV, 2.4 kton	11 events
Liquid Scintillator:	Baksan	E_{th} ~ 10 MeV, 130 ton	3-5 events
	Mont Blanc	E_{th} ~ 7 MeV, 90 ton	5 events??



Confirmed baseline model... but still many questions

LAGUNA: a proposal for a "Design of a pan-european infrastructure for large apparatus studying Grand Unification and Neutrino Astrophysics"

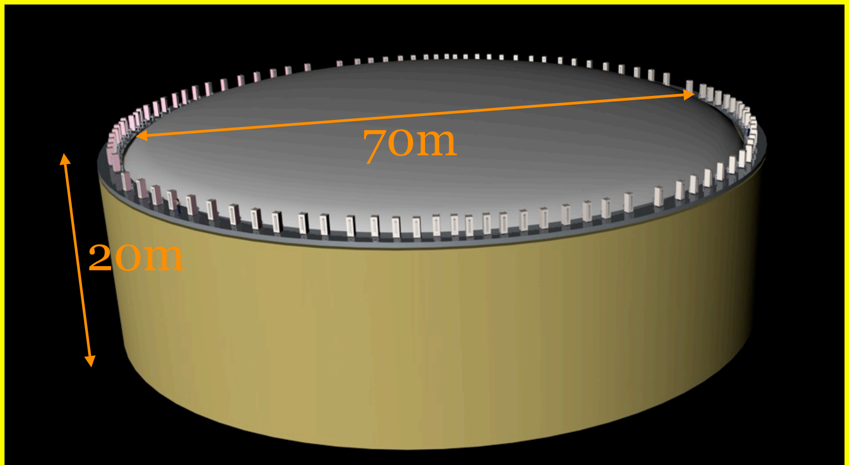
MEMPHYS-like



Water Cherenkov (≈0.5 → 1 Mton)

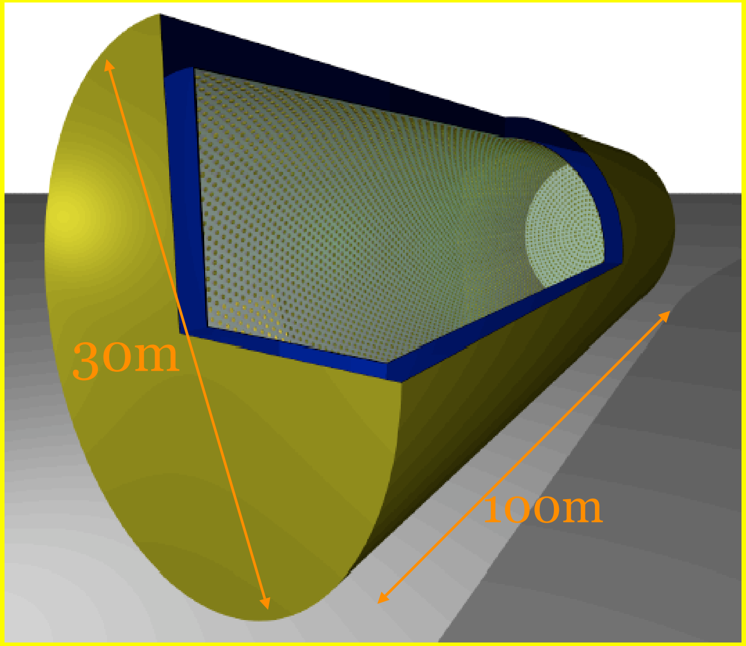
3 detection techniques under considerations

GLACIER-like



Liquid Argon (≈10→100 kton)

LENA-like



Liquid Scintillator (→ 50 kton)

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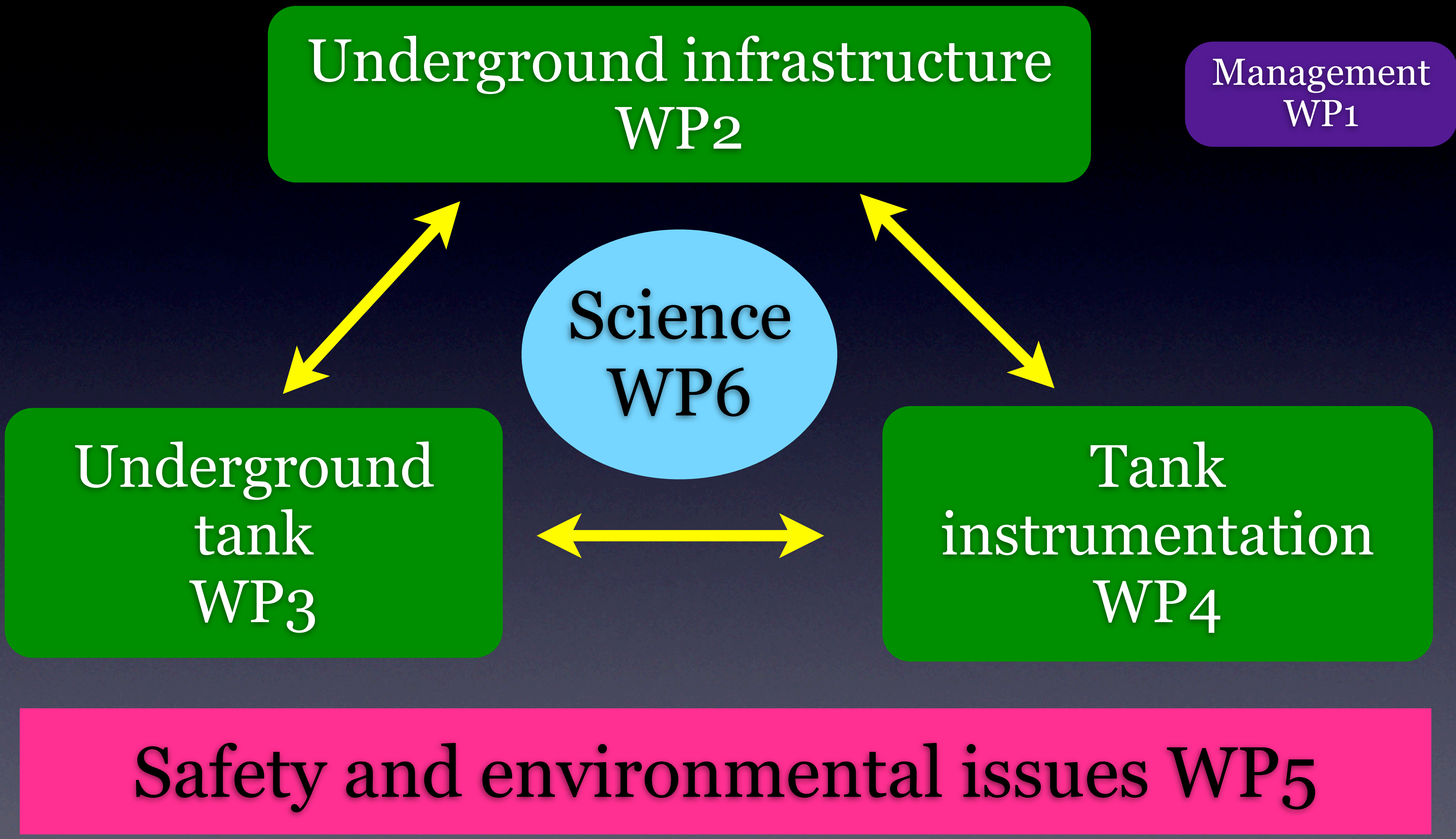
From LAGUNA WG to DS

- During 2006-2007, an effort has been made to consolidate LAGUNA ideas into a format compatible with a potential "design study".
- A series of working meeting were held
  - ☑ Munich, April 24th, 2006
  - ☑ Munich, June 2nd, 2006
  - ☑ Paris, July 21st ,2006
  - ☑ Zurich, October 12th, 2006
  - ☑ Paris, December 18th, 2006
  - ☑ Chambery, March 2nd, 2007
  - ☑ Paris, March 29th, 2007
- Design study ("Collaborative Project FP7-Infrastructures-2007-1") has been submitted on May 2nd 2007.
- ≈ 60 members
- 24 participants: ETH Zürich, Bern, Jyväskylä, Oulu, Rockplan, CEA/DSM/DAPNIA, IN2P3, MPG, TUM, Hamburg, IFJ PAN, IPJ, US, UWr, KGHM CUPRUM, IGSMiE PAN, LSC, Granada, Durham, Sheffield, Technodyne, ETL, Aarhus, AGT
- 9 countries

A. Rubbia

LAGUNA FP7 design study WPs



A. Rubbia

The main “deliverable”

A. Rubbia

The main "deliverable"

- The DS will lead to a "conceptual design report" for a new infrastructure, to allow policy makers and their advisors to prepare the relevant strategic decisions for the development of a new research infrastructure in Europe.

- The deliverables contain the elaboration of "decision factors" like
  (i) technical feasibility (cavern, access, safety, liquid procurement, ...)
  (ii) cost optimization of infrastructure (digging, safety, ...)
  (iii) physics performance (e.g. depth, baseline, ...)
  (iv) ...

An Upgraded CN-"EU" ?

&

LAGUNA

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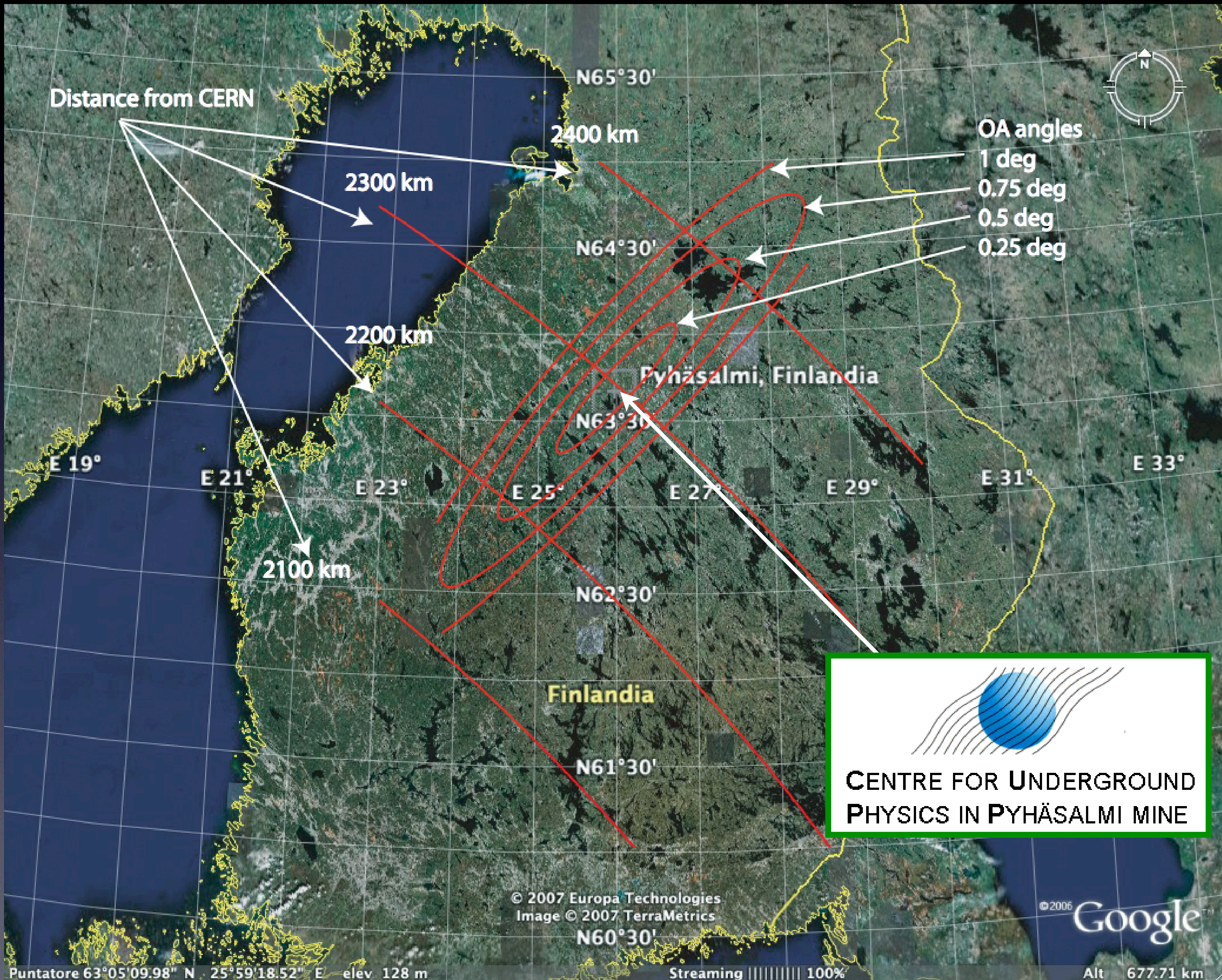
An upgraded CN-"EU" ?

- The pros for CNGS
  - it is there! (for OPERA) : high energy (τ) optimization
- The cons
  - While the new CERN injection chain will provide sufficient protons at the SPS (up to 2.4 x 10^{20} pots/yr), the current CNGS facility will not be able to sustain these intensities
  - The optimization for low energy will require new beam optics
  - There is no near detector
- The LAGUNA DS will study the feasibility of different sites in Europe
  - Part of the physics work will include the optimization of a baseline of possible future beams from CERN
  - A very long baseline L = 2300 km in EU?
    - ➡ to study matter effects and solve mass hierarchy degeneracy ?
    - ➡ improve sensitivity to CP-violation !
  - Work in progress

CN-EU: Finland, L ≈ 2300 km



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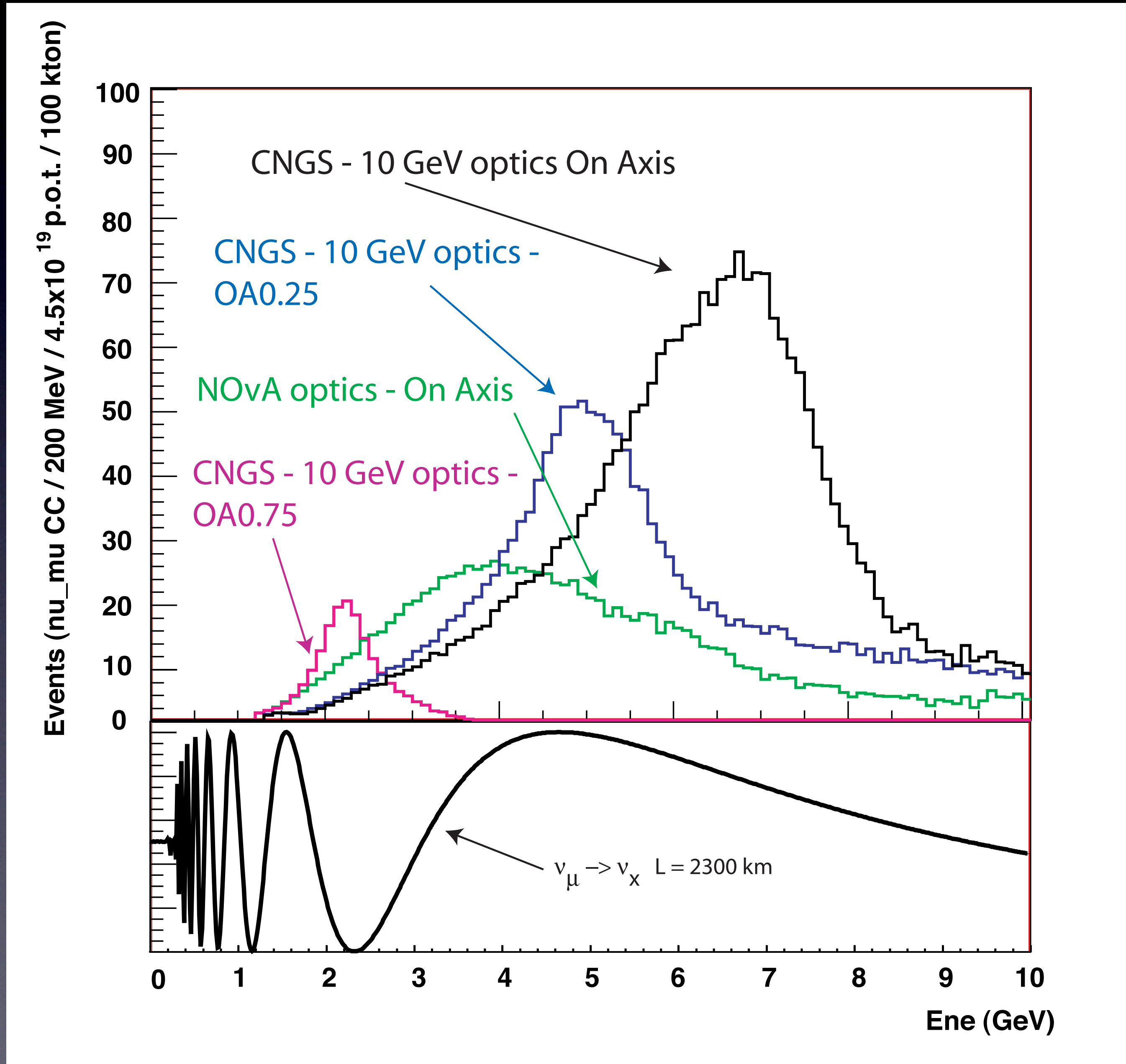
“On” vs “Off”-axis configurations

Full simulation focusing optics for various typical configurations

★CNGS-like 10 GeV/c
★NOvA L.E. optics

★On-Axis
★Off-axis OA0.25 deg
★Off-axis OA0.75 deg

★Normalized to 4.5e19 pots, 100 kton, L=2300km



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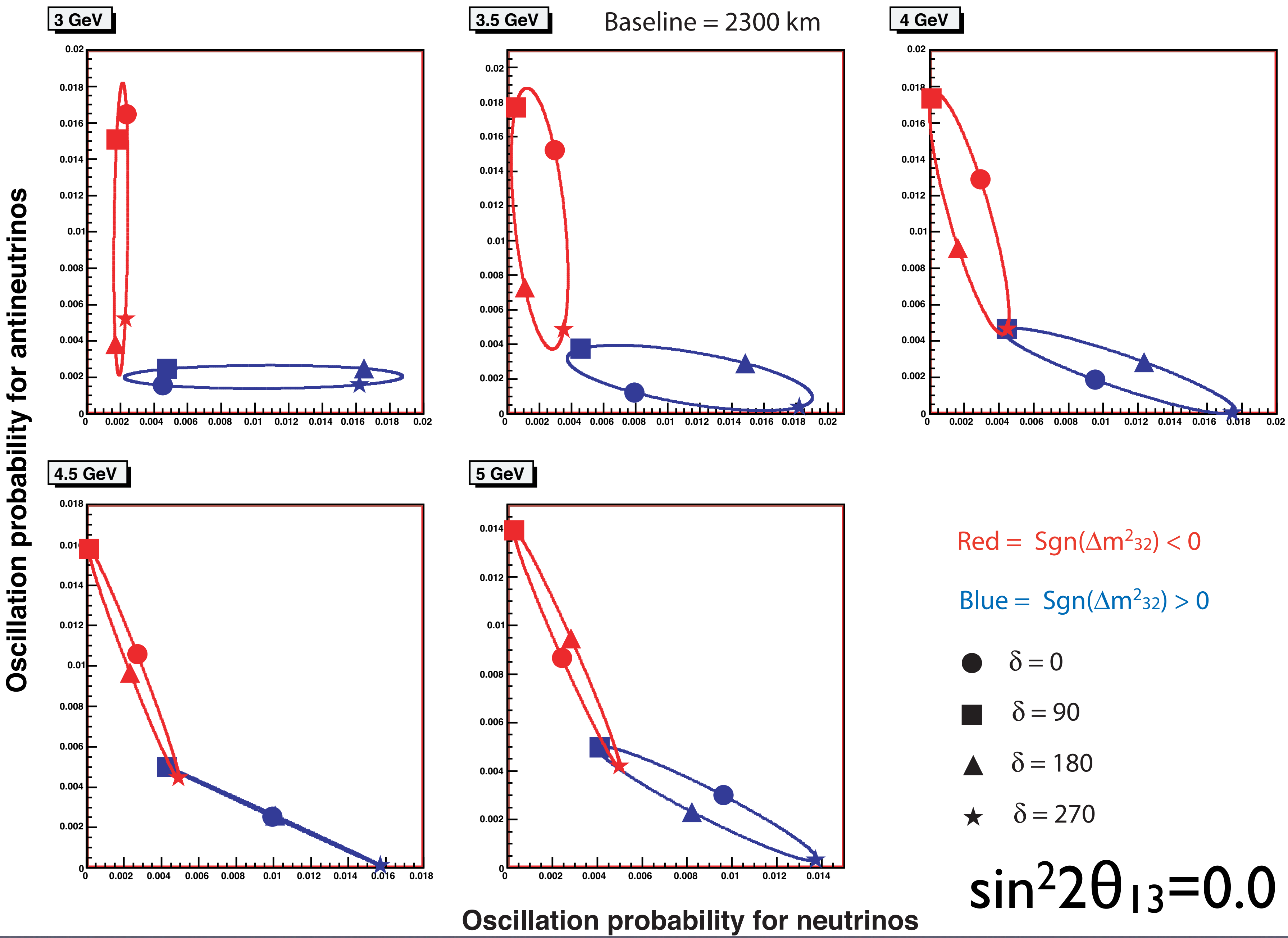
Lifting degeneracies



$\sin^2 2\theta_{13} = 0.01$

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Outlook (I)

- Precise measurements/verifications of neutrino oscillations at the atmospheric Δm^2 presently carried out by the 1st round of long baseline experiments
- Experiments in the next decade (T2K, NOνA) will have a reasonable chance to observe $\nu_\mu \rightarrow \nu_e$ oscillations at the atmospheric scale, opening the way to investigations of CP violation in the leptonic sector
- Coordinated R&D and design studies are required before undertaking the next step:
  - ➡ determination of the best detector technology in conjunction with the requirements on the site
  - ➡ optimization of the baseline taking into account the available sites
  - ➡ optimization of the neutrino beam ⇔ detector technology

Outlook (II)

- The direct evidence for Grand Unification would be one of the most fundamental discoveries in particle physics. This requires new generation very massive detectors.
- An extensive neutrino physics and astronomy programme will be accessible with these new rare event detection instruments, detecting supernova, atmospheric, possibly solar and geo-neutrinos.
- The synergy between precise detectors for long neutrino baseline experiments and proton decay (and astrophysical neutrinos) apparatus is essential for a realistic proposal for a 100-1000 kton fine grain detector
- The LAGUNA design study could provide the means to perform site feasibility studies and to develop mature conceptual design for large volume underground instruments including their infrastructures, with a credible cost estimate. The DS will provide the means to elaborate the scientific and objective information needed to make an optimized choice for site(s) for the pan-European Underground Infrastructure.
- It will hopefully mature around 2010.

The end

Backup Slides

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Rough cost estimates

Item	100 kton	10 kton	1 kton
LNG tank (see notes 1-2)	50÷100	20÷30	8
Inner detector mechanics	10	3	1
Charge readout detectors	15	5	1
Light readout	60 (with Č)	2 (w/o Č)	1
F/E & DAQ electronics	10	5	1
Miscellanea	10	5	1
Detector total	**155 ÷ 205**	**40 ÷ 50**	**13**
Refilling plant	25	10	2
Purification system	10	2	1
Civil engineering + excavation	30	5	2
Forced air ventilation	10	5	1
Safety	10	5	1
Merchant cost of LAr (see note 3)	100	10	1
Grand total	**340 ÷ 390**	**77 ÷ 87**	**21**
Super-conducting magnet	**?**	**60**	**-**

Notes:
(1) Range in cost of tank comes from site-dependence and current uncertainty in underground construction
(2) Cost of tank already includes necessary features for LAr TPC (surface electropolishing, hard roof for instrumentation, feed-throughs,…)
(3) LAr Merchant cost ≠ production cost. Fraction will be furnished from external companies and other fraction will be produced locally (by the refilling plant)