ICARUS T3000 (CNGS-2): A second-generation Proton Decay Experiment and Neutrino Observatory at the Gran Sasso Laboratory

André Rubbia (ETHZ)
CERN AB seminar

CERN-CDS

Outline of talk

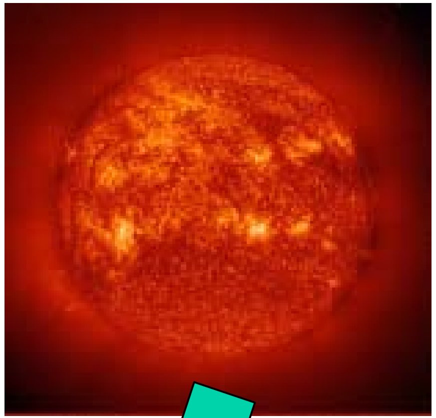
- ICARUS is a large underground experiment which is based on the new liquid Argon TPC technology, originally proposed at CERN by Carlo Rubbia (CERN-EP/77-08 (1977)) and supported by INFN over many years of R&D
- ICARUS T3000 acts as a sort of observatory for the study of neutrinos and the instability of matter at the Gran Sasso Underground Laboratory
- The Liquid Argon TPC is a new kind of detector, effectively an electronic bubble-chamber
  - ➥ ICARUS T3000 at Gran Sasso is an important milestone for this technology and acts as a full-scale test-bed with a total of 3 kton of liquid Argon to be located a difficult underground environment
  - ➥ This technology has also great potentials in other applications, such as future very large underground experiments
- In this talk:
  - ➥ Physics aims
  - ➥ Technology
  - ➥ Status
  - ➥ What kind of CERN neutrino beams could take advantage liquid Ar detectors? (this is a seminar, not a proposal, meant for discussions…)

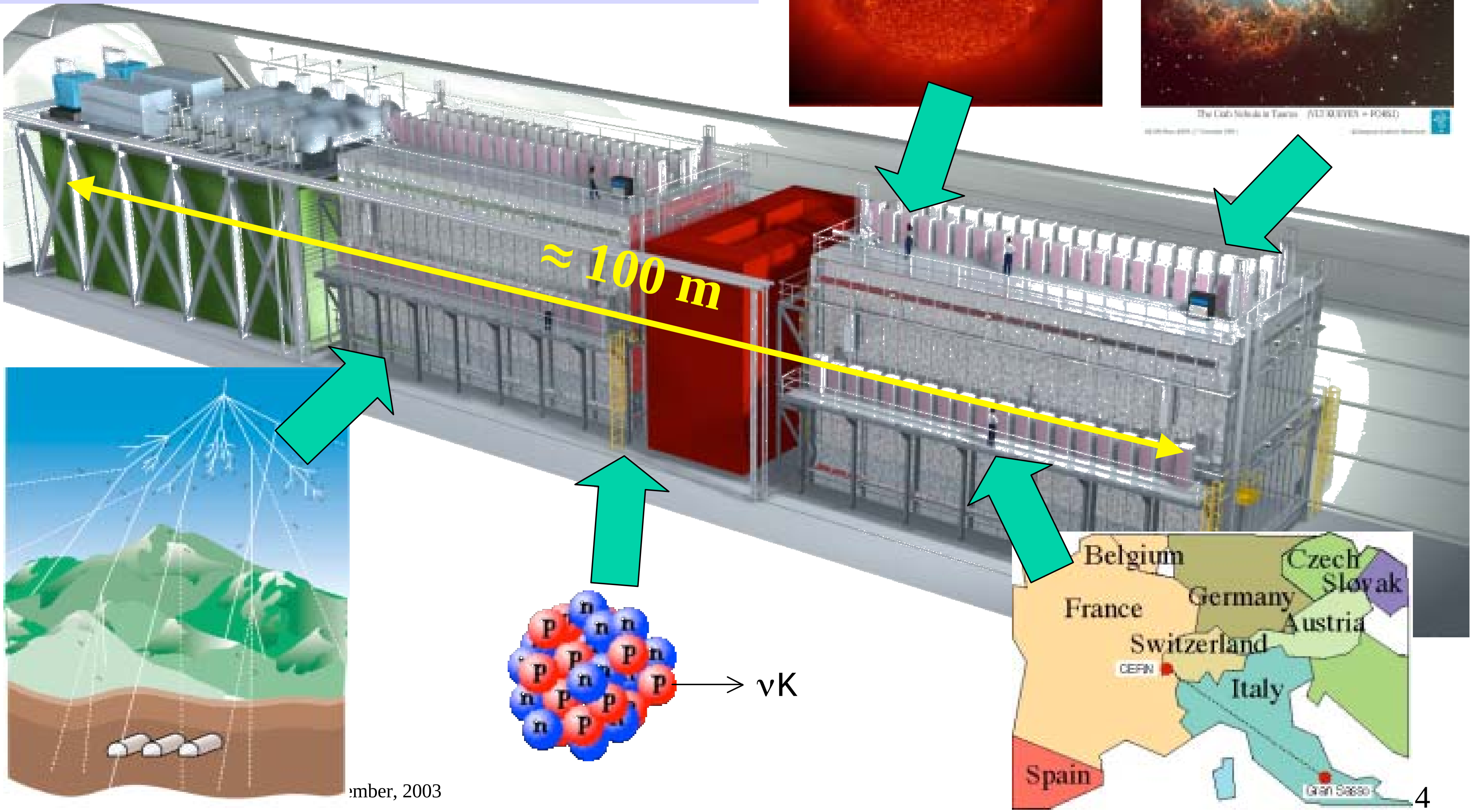
The ICARUS collaboration (25 institutes, ≈150 physicists)

M. Aguilar-Benitez, S. Amoruso, Yu. Andreew, P. Aprili, F. Arneodo, B. Babussinov, B. Badelek, A. Badertscher, M. Baldo-Ceolin, G. Battistoni, B. Bekman, P. Benetti, E. Bernardini, A. Borio di Tigliole, M. Bischofberger, R. Brunetti, R. Bruzzese, A. Bueno, C. Burgos, E. Calligarich, D. Cavalli, F. Cavanna, F. Carbonara, P. Cennini, S. Centro, M. Cerrada, A. Cesana, R. Chandrasekharan, C. Chen, D. B. Chen, Y. Chen, R. Cid, D. Cline, P. Crivelli, A.G. Cocco, A. Dabrowska, Z. Dai, M. Daniel, M. Daszkiewicz, C. De Vecchi, A. Di Cicco, R. Dolfini, A. Ereditato, M. Felcini, A. Ferrari, F. Ferri, G. Fiorillo, M.C. Fouz, S. Galli, D. Garcia, Y. Ge, D. Gibin, A. Gigli Berzolari, I. Gil-Botella, S.N. Gninenko, N. Goloubev, A. Guglielmi, K. Graczyk, L. Grandi, K. He, J. Holeczek, X. Huang, C. Juszczak, D. Kielczewska, M. Kirsanov, J. Kisiel, L. Knecht, T. Kozlowski, H. Kuna-Ciskal, N. Krasnikov, P. Ladron de Guevara, M. Laffranchi, J. Lagoda, Z. Li, B. Lisowski, F. Lu, J. Ma, N. Makrouchina, G. Mangano, G. Mannocchi, M. Markiewicz, A. Martinez de la Osa, V. Matveev, C. Matthey, F. Mauri, D. Mazza, A. Melgarejo, G. Meng, A. Meregaglia, M. Messina, C. Montanari, S. Muraro, G. Natterer, S. Navas-Concha, M. Nicoletto, G. Nurzia, C. Osuna, S. Otwinowski, Q. Ouyang, O. Palamara, D. Pascoli, L. Periale, G. Piano Mortari, A. Piazzoli, P. Picchi, F. Pietropaolo, W. Polchlopek, T. Rancati, A. Rappoldi, G.L. Raselli, J. Rico, L. Romero, E. Rondio, M. Rossella, A. Rubbia, C. Rubbia, P. Sala, N. Santorelli, D. Scannicchio, E. Segreto, Y. Seo, F. Sergiampietri, J. Sobczyk, N. Spinelli, J. Stepaniak, M. Stodulski, M. Szarska, M. Szeptycka, M. Szeleper, M. Terrani, R. Velotta, S. Ventura, C. Vignoli, H. Wang, X. Wang, C. Willmott, M. Wojcik, J. Woo, G. Xu, Z. Xu, X. Yang, A. Zalewska, J. Zalipska, C. Zhang, Q. Zhang, S. Zhen, W. Zipper.

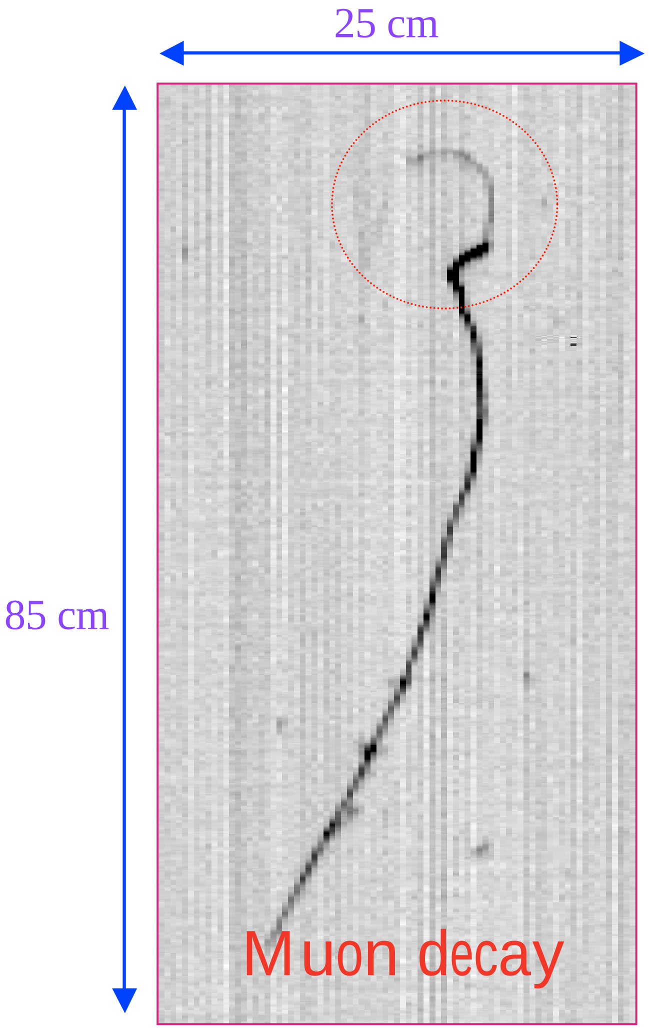
ITALY: L'Aquila, LNF, LNGS, Milano, Napoli, Padova, Pavia, Pisa, CNR Torino, Torino Univ., Politec. Milano.
SWITZERLAND: ETH/Zürich.
CHINA: Academia Sinica Beijing.
POLAND: Univ. of Silesia Katowice, Univ. of Mining and Metallurgy Krakow, Inst. of Nucl. Phys. Krakow, Jagellonian Univ. Krakow, Univ. of Technology Krakow, A.Soltan Inst. for Nucl. Studies Warszawa, Warsaw Univ., Wroclaw Univ.
USA: UCLA Los Angeles.
SPAIN: Univ. of Granada, CIEMAT
RUSSIA: INR (Moscow)

ICARUS T3000: “A Second-Generation Proton Decay Experiment and Neutrino Observatory at the Gran Sasso Laboratory”

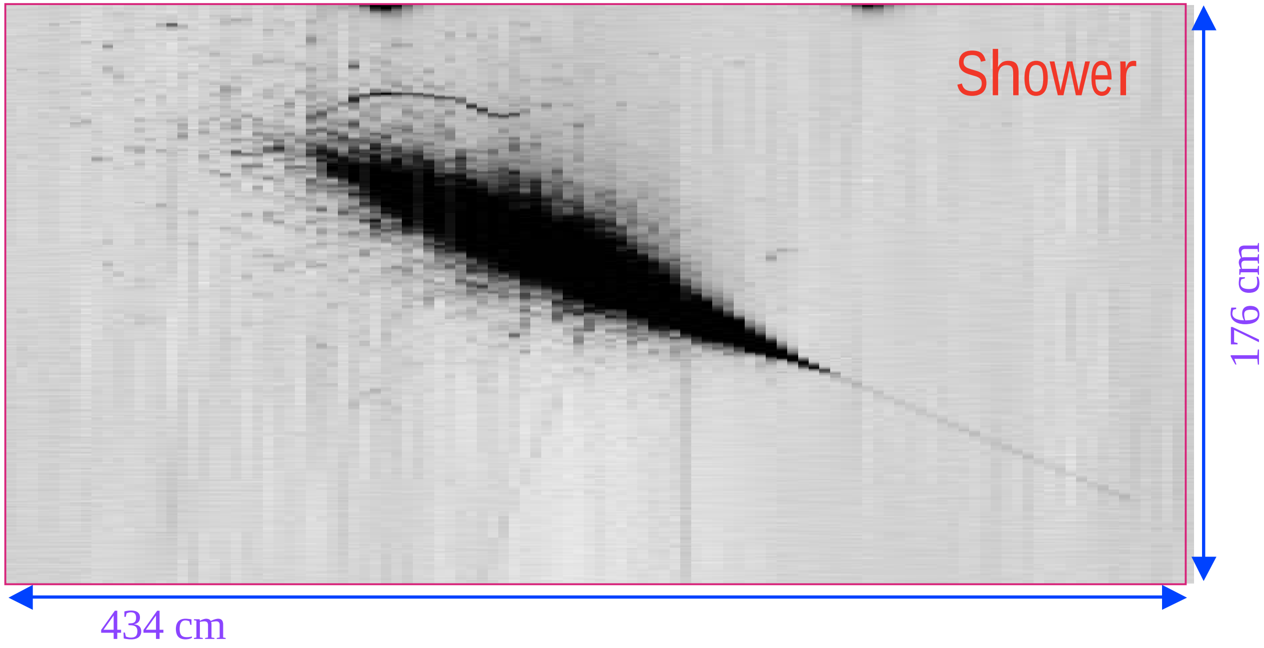


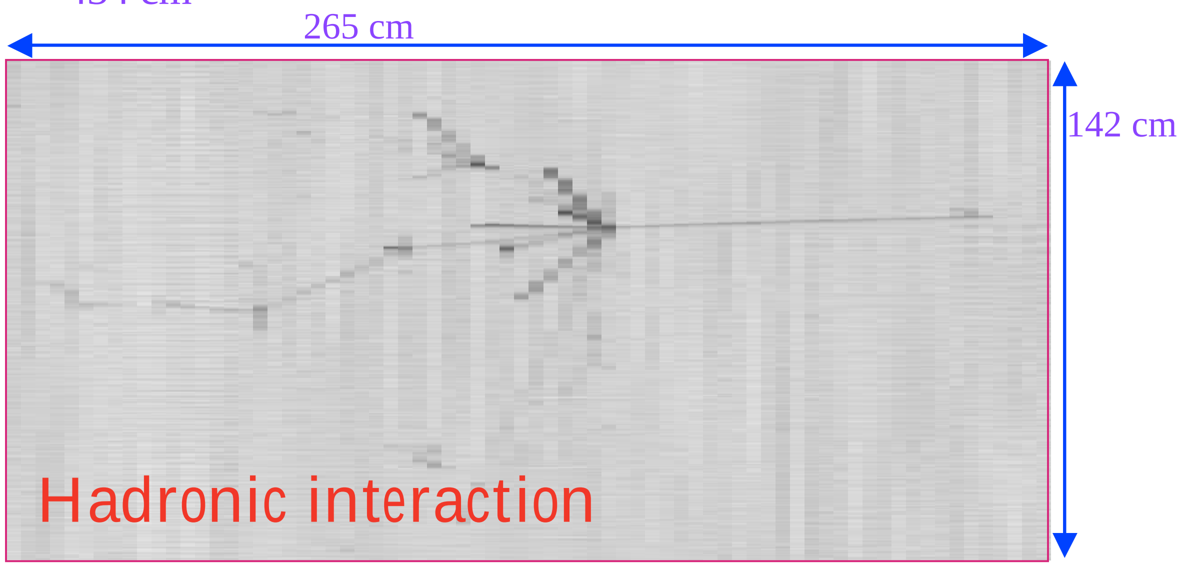


Electronic bubble chamber



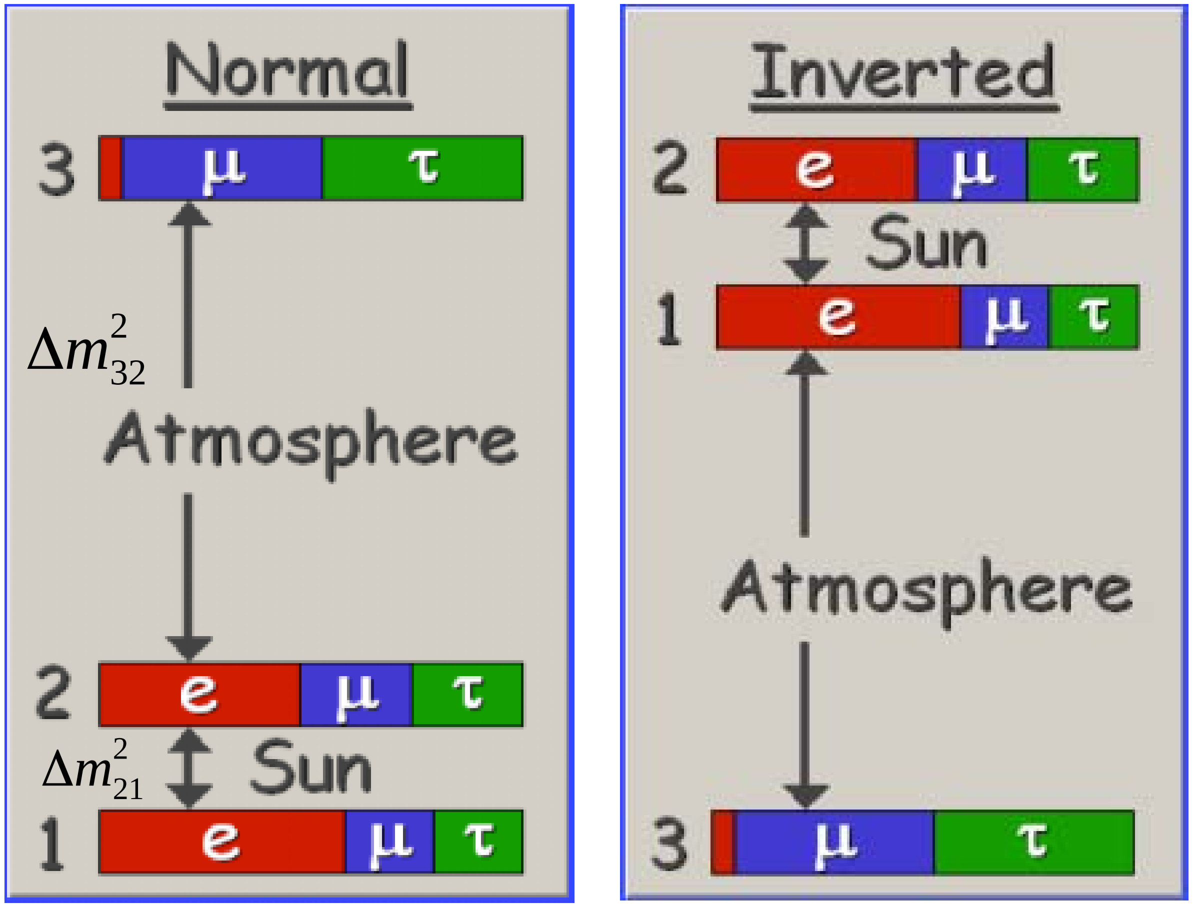
Run 960, Event 4   Collection Left





Run 308, Event 160   Collection Left

Neutrino masses and mixing: the standard view



Figures from G. Raffelt

Weak eigenstates

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

Mass eigenstates

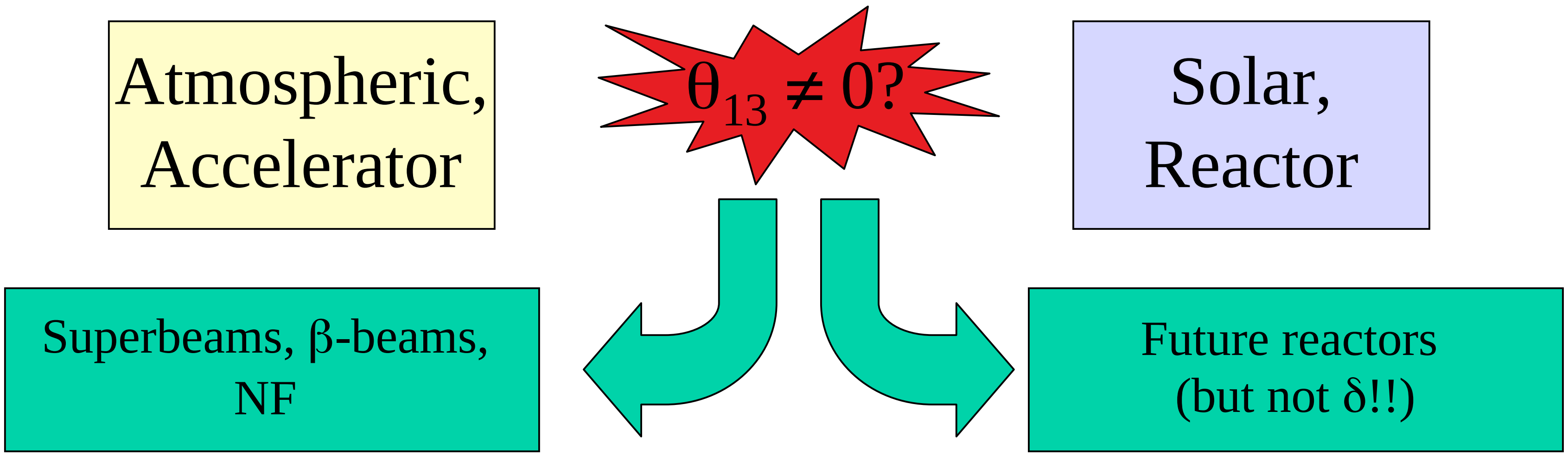
<u>*Normal hierarchy:*</u> $\Delta m^2_{21} \approx 7 \times 10^{-5} eV^2$, $\Delta m^2_{32} \approx 2.5 \times 10^{-3} eV^2$

"small" *"large"*

Studying the leptonic mixing matrix

- The leptonic mixing matrix (MNSP) can be parameterized as the product of several rotation matrices, that turn out to be experimentally accessible in different experiments
- Note: the quark mixing matrix (CKM) has been studied for more than 50 years and there are still planned experiments, like LHCb, to study it in the future
- The complex phase δ could play a fundamental role in the matter-antimatter asymmetry of the Universe

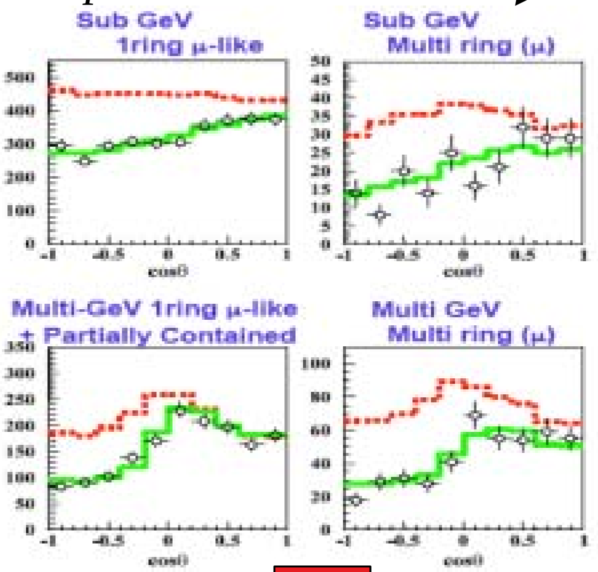
$$U_{MNSP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot diag(1, e^{i\alpha}, e^{i\beta})$$



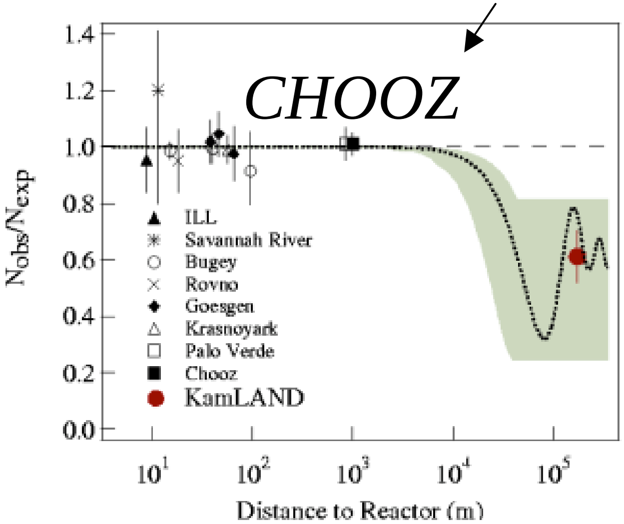
“Large” Δm^2 data

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



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



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

?

?

Appearance:

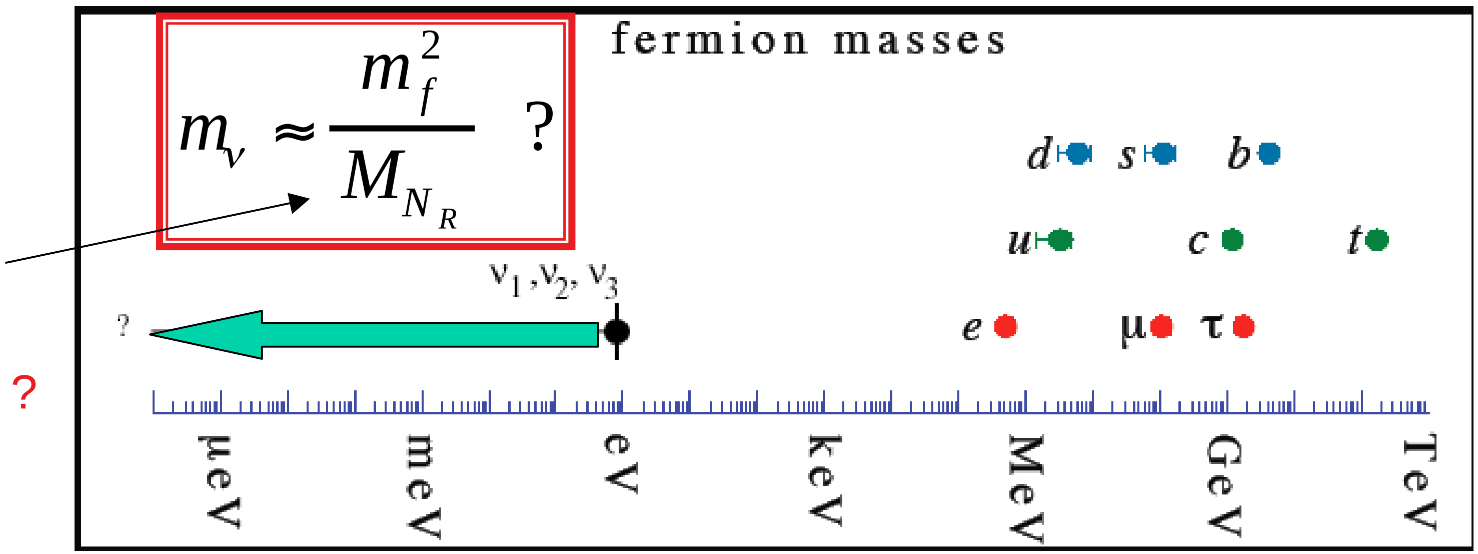
$$P(\nu_\mu \xrightarrow{?} \nu_\tau) = \cos^4\theta_{13} \sin^2 2\theta_{23} \sin^2\left(\Delta m^2_{32} \frac{L}{4E}\right)$$

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

And

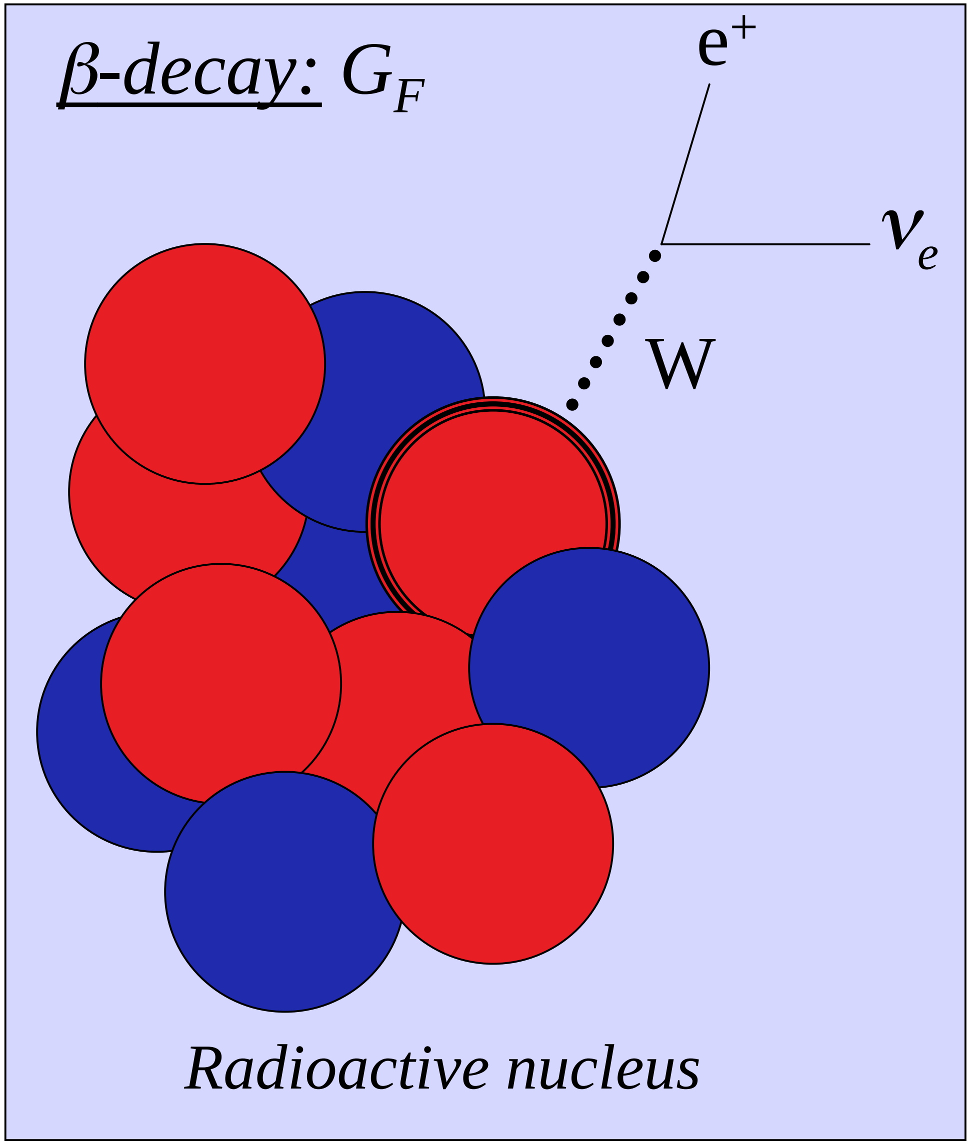
Neutrino masses: viewpoint from fundamental theory

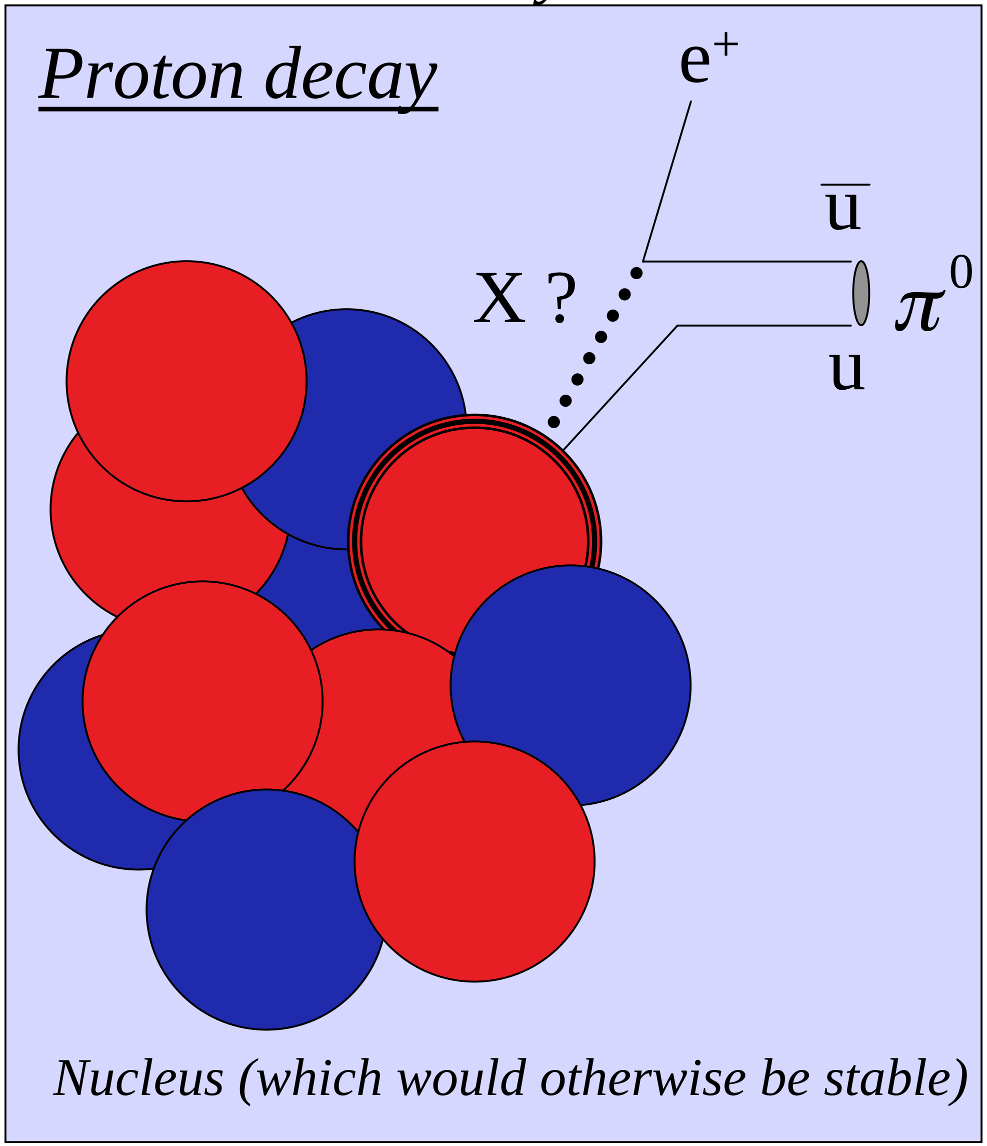
- Non-vanishing neutrino masses are a clear indication of new physics beyond the Standard Model (so far the only one)
  - Dirac mass: Even if Higgs boson is discovered at LHC, Higgs mechanism cannot explain neutrino masses unless we postulate the existence of right-handed neutrinos
  - Majorana mass: 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



Matter instability: radioactive decays

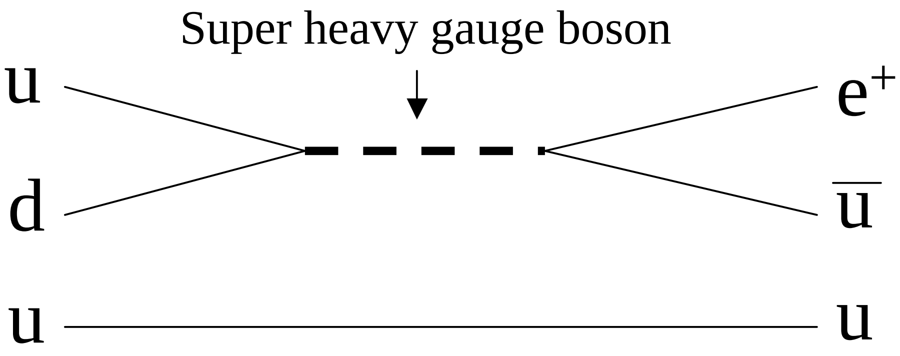
$\tau > 10^{33} years$?



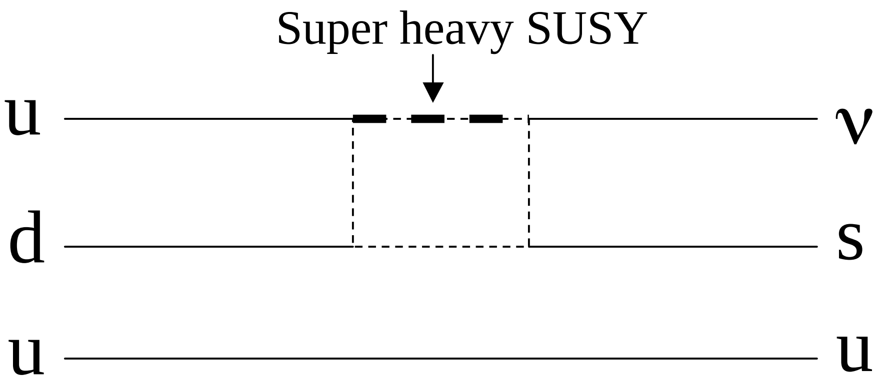


Proton decay: baryon number violation

- The baryon number violation could be mediated through very heavy particles. This would make this process possible, but rare at low energy.

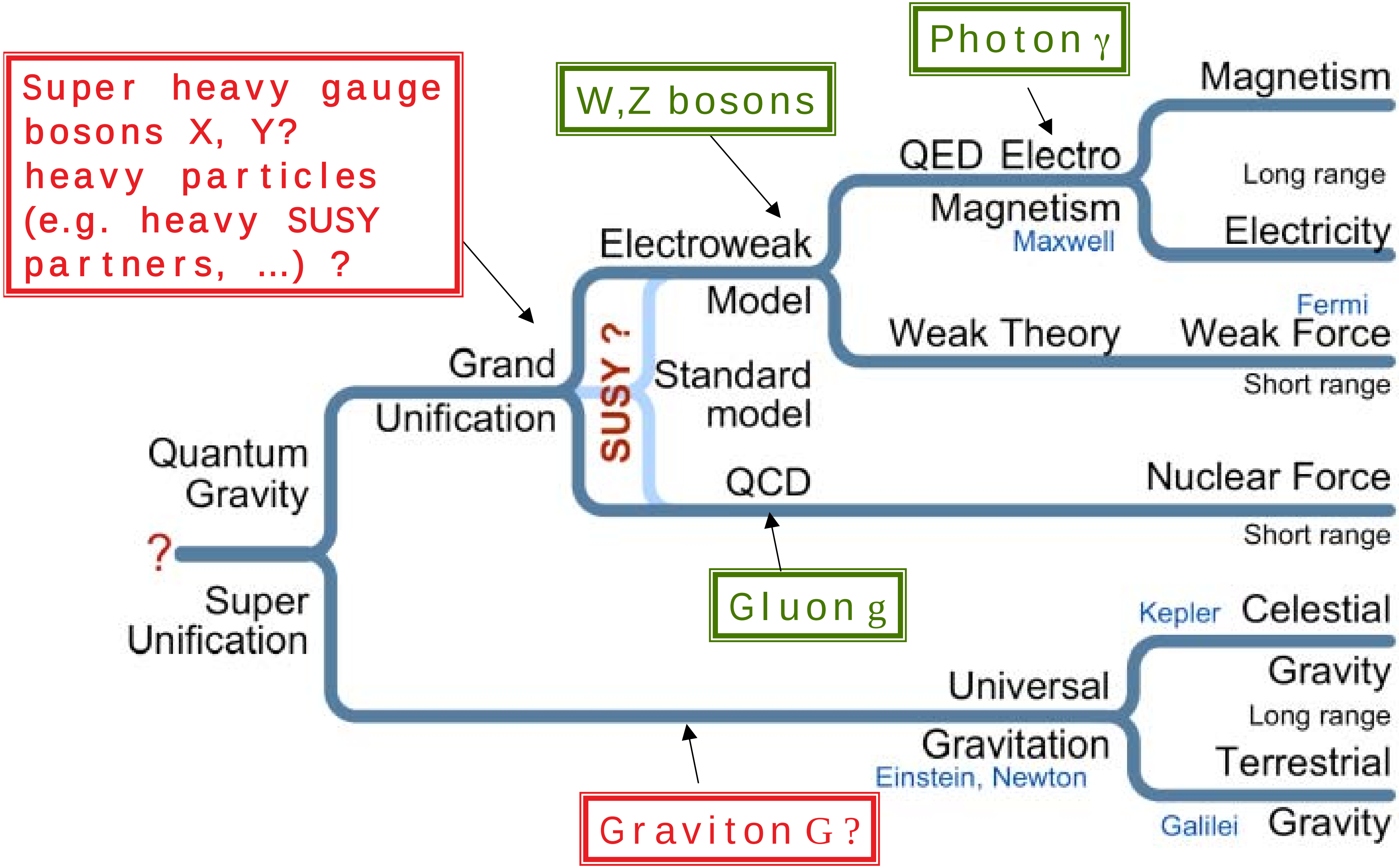


$$p \to e^{+}\pi^{0}$$



$$p \to \bar{\nu} K^{+}$$

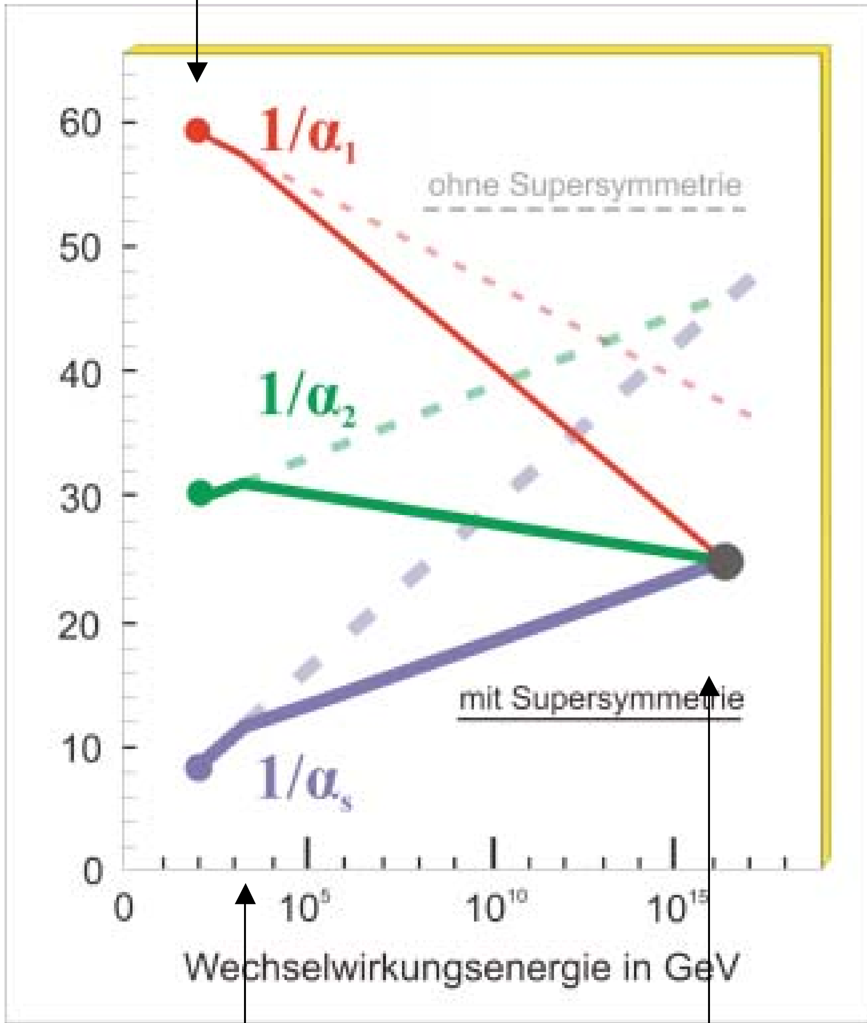
Force unifications: GUT physics



Grand Unification of forces: coupling constants

- Even though we do not know whether GU is actually occurring, there are experimental “hints” which support it
- The forces seem to unify at an energy that will not be reachable by accelerator techniques (at least for a long time)
- Extreme precision measurements or extremely rare decay searches (sometimes called “propagator” physics) are the only way to probe the GUT scale
- Complementary to high energy accelerator physics frontier

LEP precision measurements

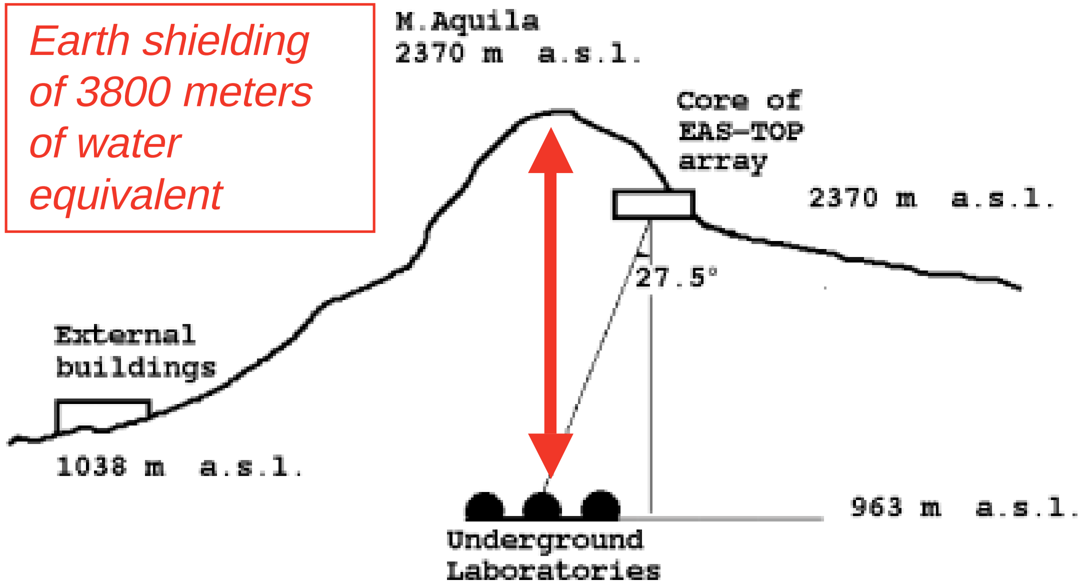


LHC domain $\approx 10^3$ GeV

Unification ? $\approx 10^{17\pm1}$ GeV

Gran Sasso Underground Laboratory

Earth shielding of 3800 meters of water equivalent



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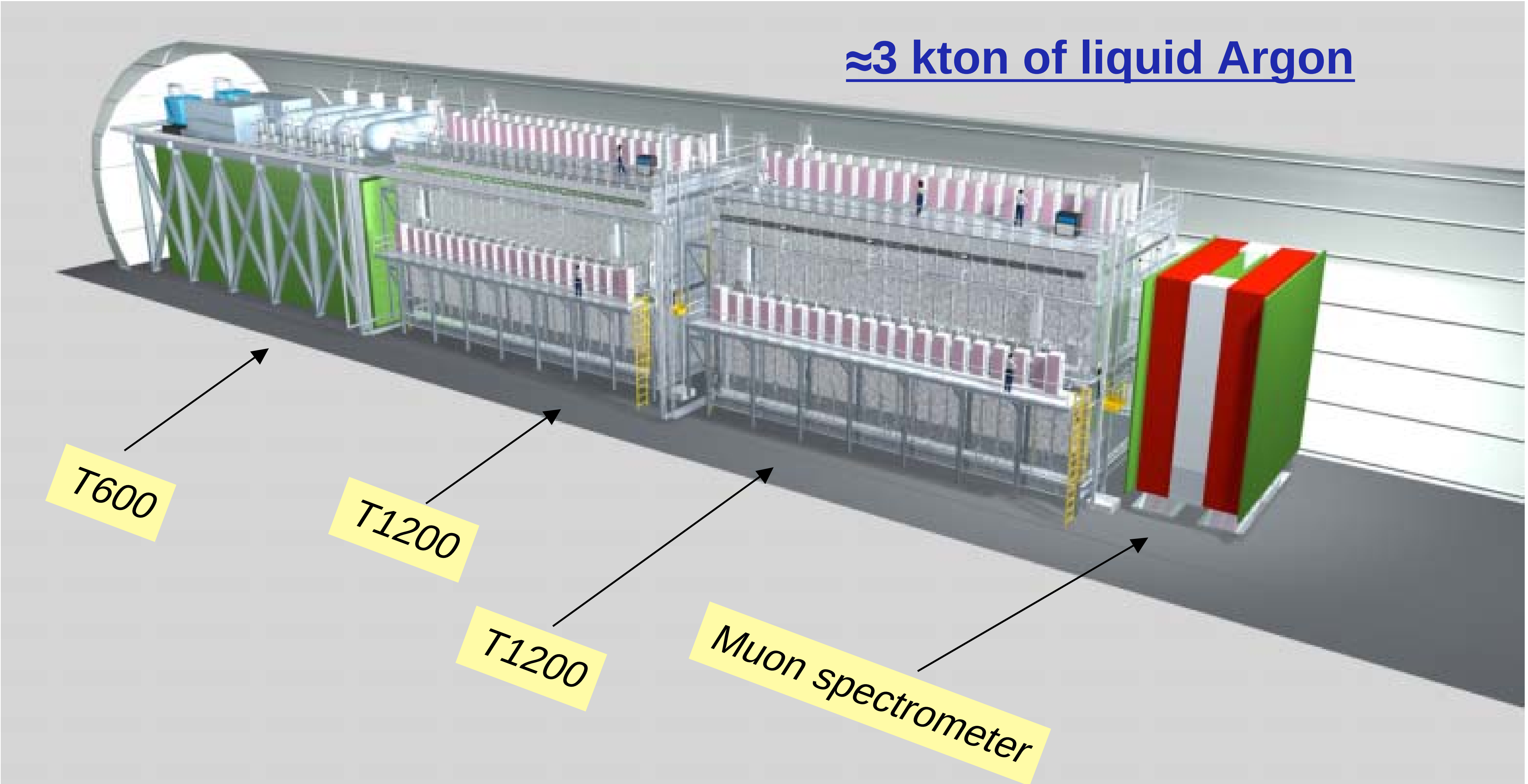
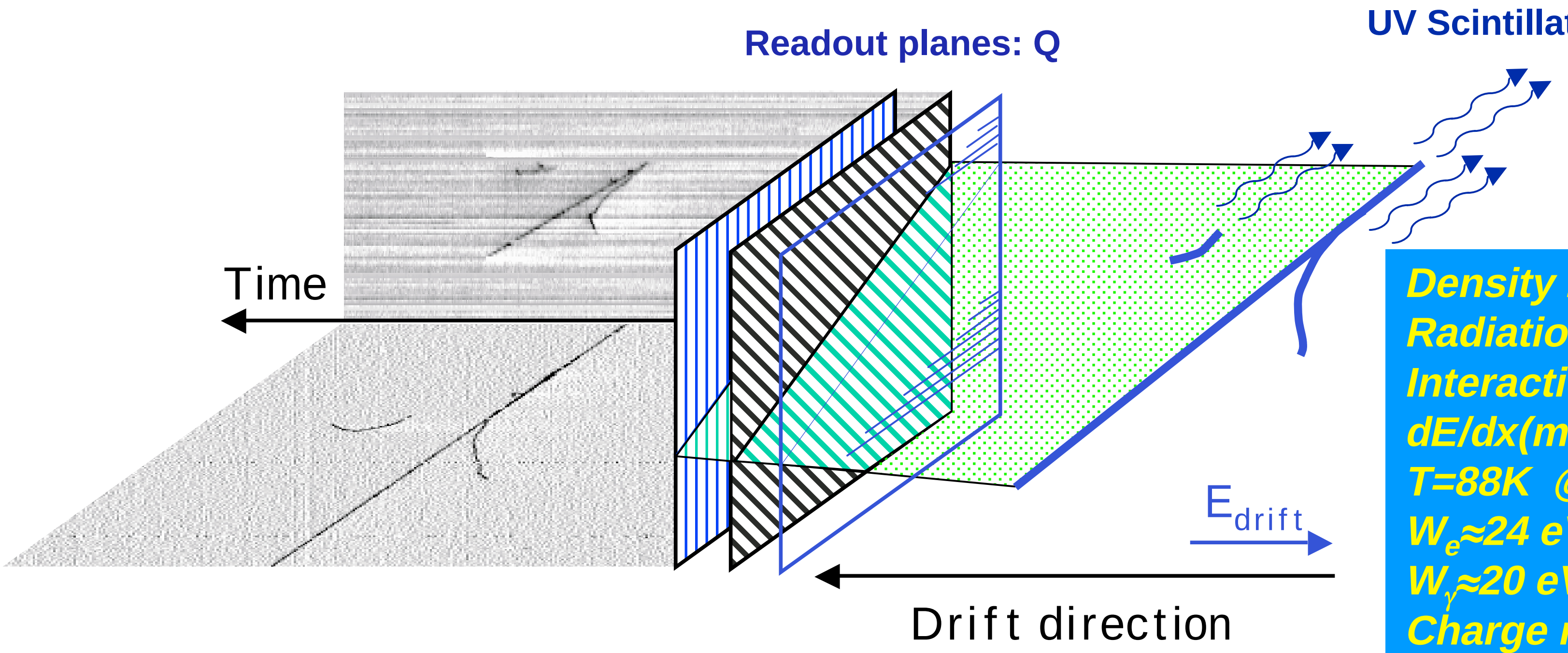
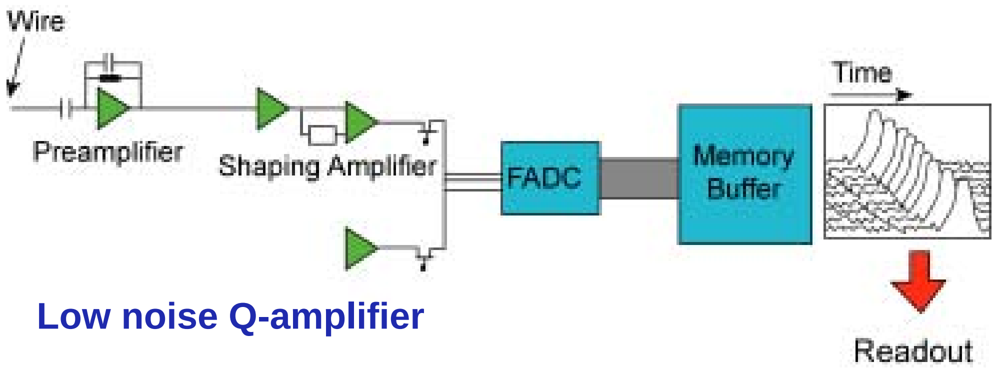


The Liquid Argon TPC (I)



Density 1.4 g/cm³
Radiation length 14 cm
Interaction length 80 cm
dE/dx(mip) = 2.1 MeV/cm
T=88K @ 1 bar
$W_e \approx 24$ eV
$W_\gamma \approx 20$ eV
Charge recombination (mip) @ E = 500 V/cm ≈ 40%



Low noise Q-amplifier

Continuous waveform recording

- High density
- Non-destructive readout
- Continuously sensitive
- Self-triggering
- Very good scintillator: T_0

The Liquid Argon TPC (II)

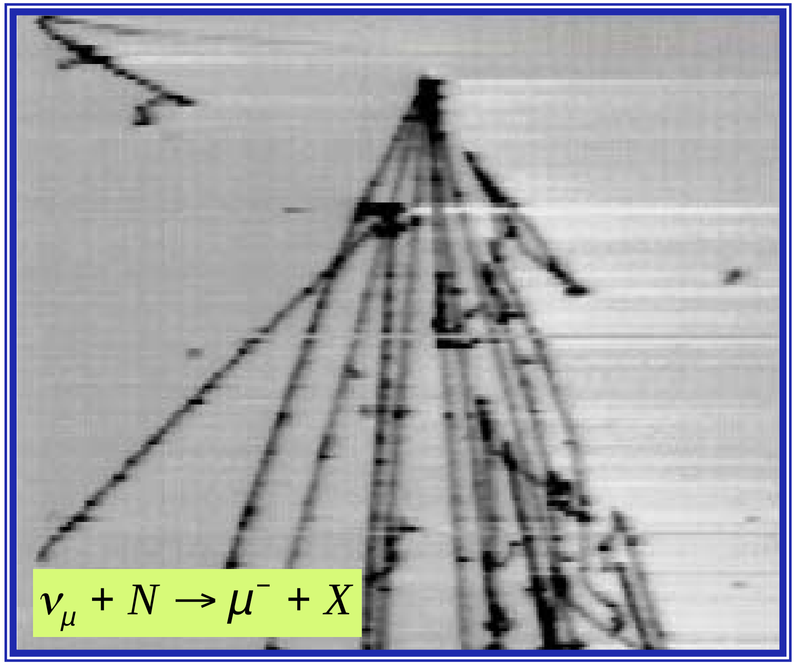
- Cryogenics: Detector must be maintained at cryogenic temperatures, safety issues must be addressed for large detectors, in particular underground
- LAr Purity: Ionization tracks can be transported practically undistorted, by a uniform electric field, for distances of the order of several meters in a highly purified (electronegative impurities < 0.1 ppb O_2 equiv.) liquid argon (LAr).
- Charge Readout: A set of electrodes (wires) placed at the end of the drift path senses the ionization charges and provides a two-dimensional view of the event (wire co-ordinate vs drift co-ordinate)
  - ➥ No charge multiplication occurs in LAr ➔➔ several wire planes can be installed with the wires having different orientations ➔➔ non-destructive charge readout ➔➔ multiple views ➔➔ 3D reconstruction
- UV light Readout: LAr is also a very good scintillator ➔➔ scintillation light (λ = 128 nm) provides a prompt signal to be used for triggering purposes and for absolute event time measurement ➔➔ immersed pmt coated with WLS

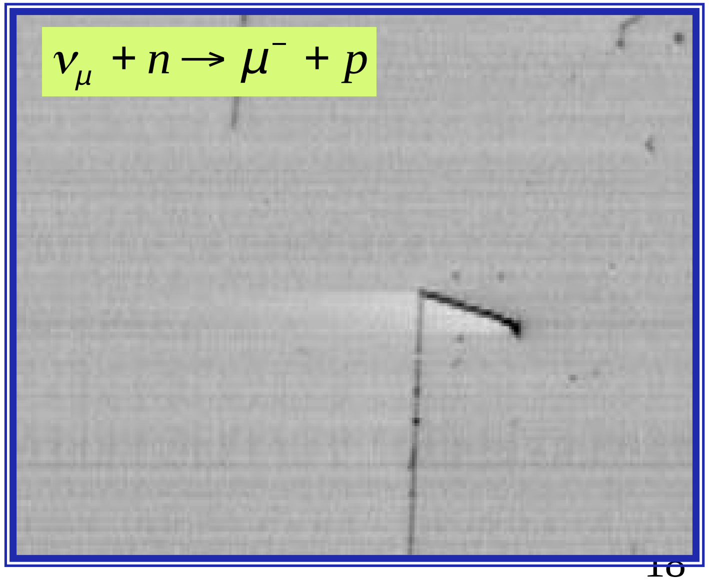
Past experience and results - 50 liter prototype in CERN WANF

- Active volume : 50 liters
- Readout planes: 2 (0°,90°)
- Max drift distance: 45cm

✓Reconstruction of vertices of ν-interactions
✓Fermi-motion
✓Track direction by δ-rays
✓dE/dx versus range for K,π,p discrimination
✓Max. electron lifetime > 10 ms

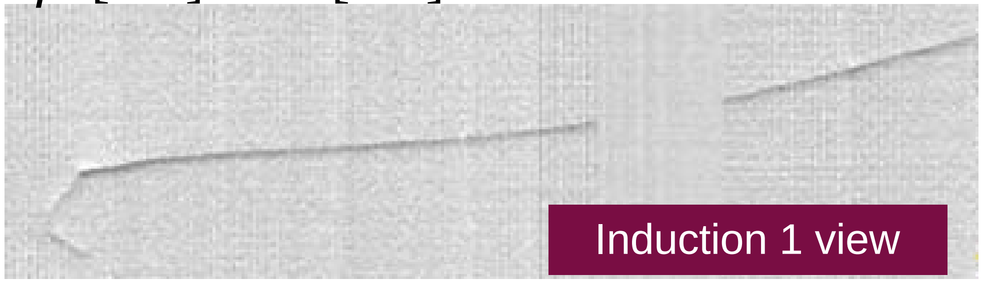
- LAr purification by Ar vapour filtering and re-condensation
- LAr purity monitors
- Optimization of front-end electronics for induction and collection planes
- Warm and cold electronics
- Readout chain calibration studies
- Signal treatment
- Collection of scintillation light
- 1.4 m drift length (special test)

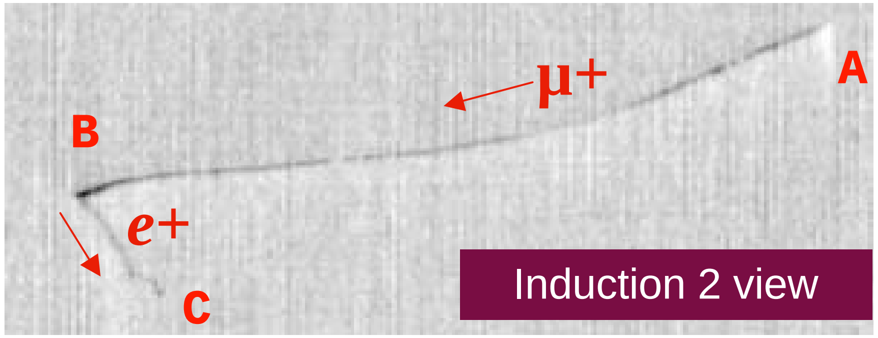


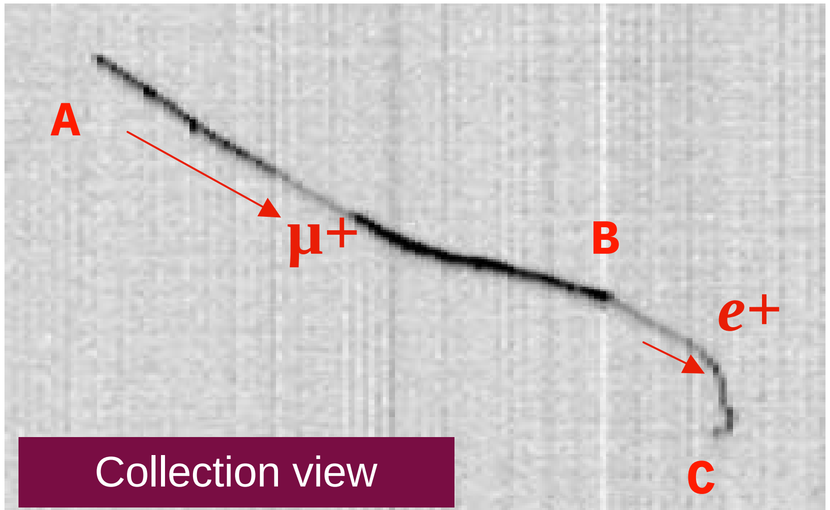


3D reconstruction stopping muon with first T600 unit

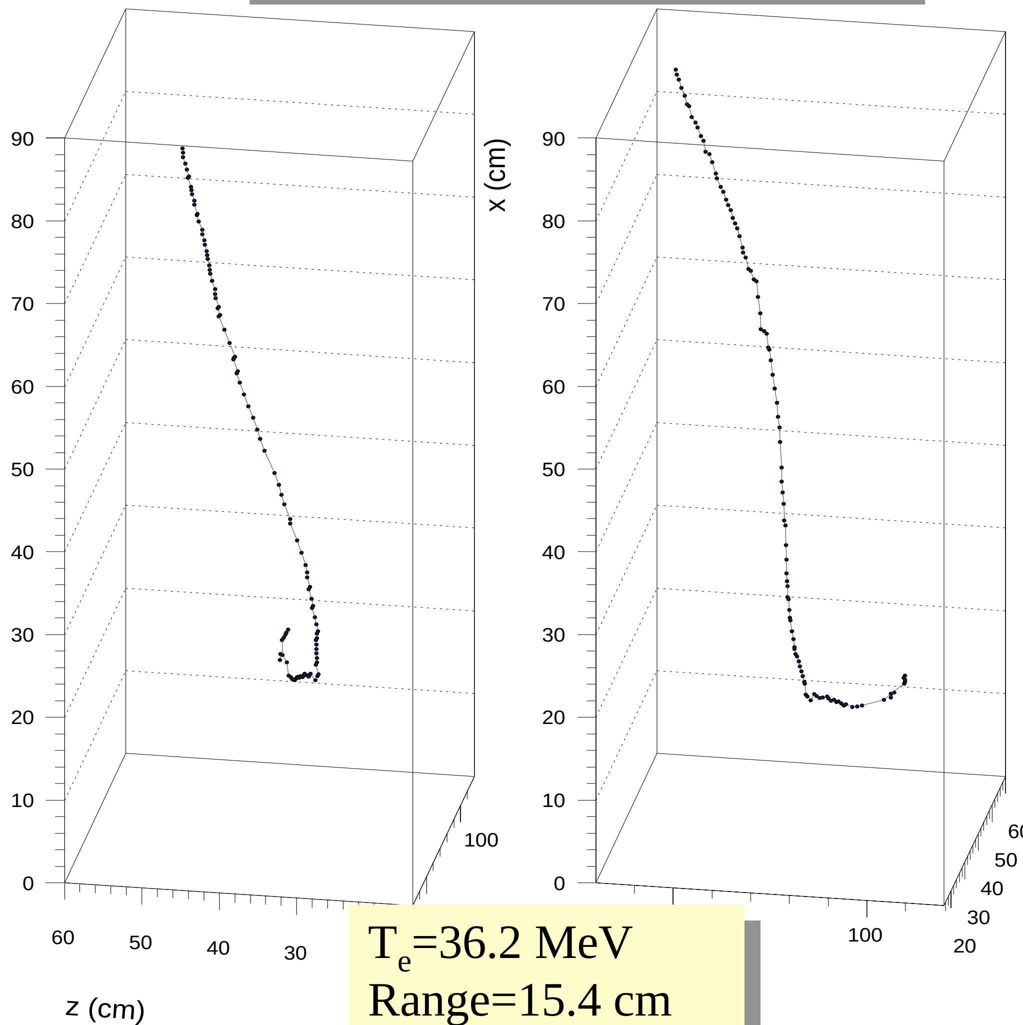
$\mu^{+}[AB] \rightarrow e^{+}[BC]$





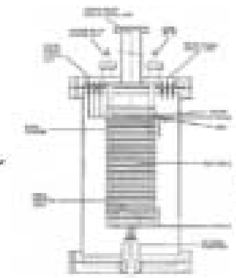


Run 939 Event 95 Right chamber



T_e=36.2 MeV
Range=15.4 cm

The path to massive liquid argon detectors

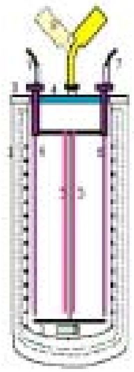


24 cm drift wires chamber

CERN

1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

3 ton prototype



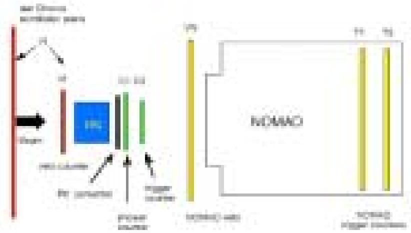
1991-1995: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.

CERN

Lab activities:

50 litres prototype
1.4 m drift chamber

CERN



1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

10 m^3 industrial prototype

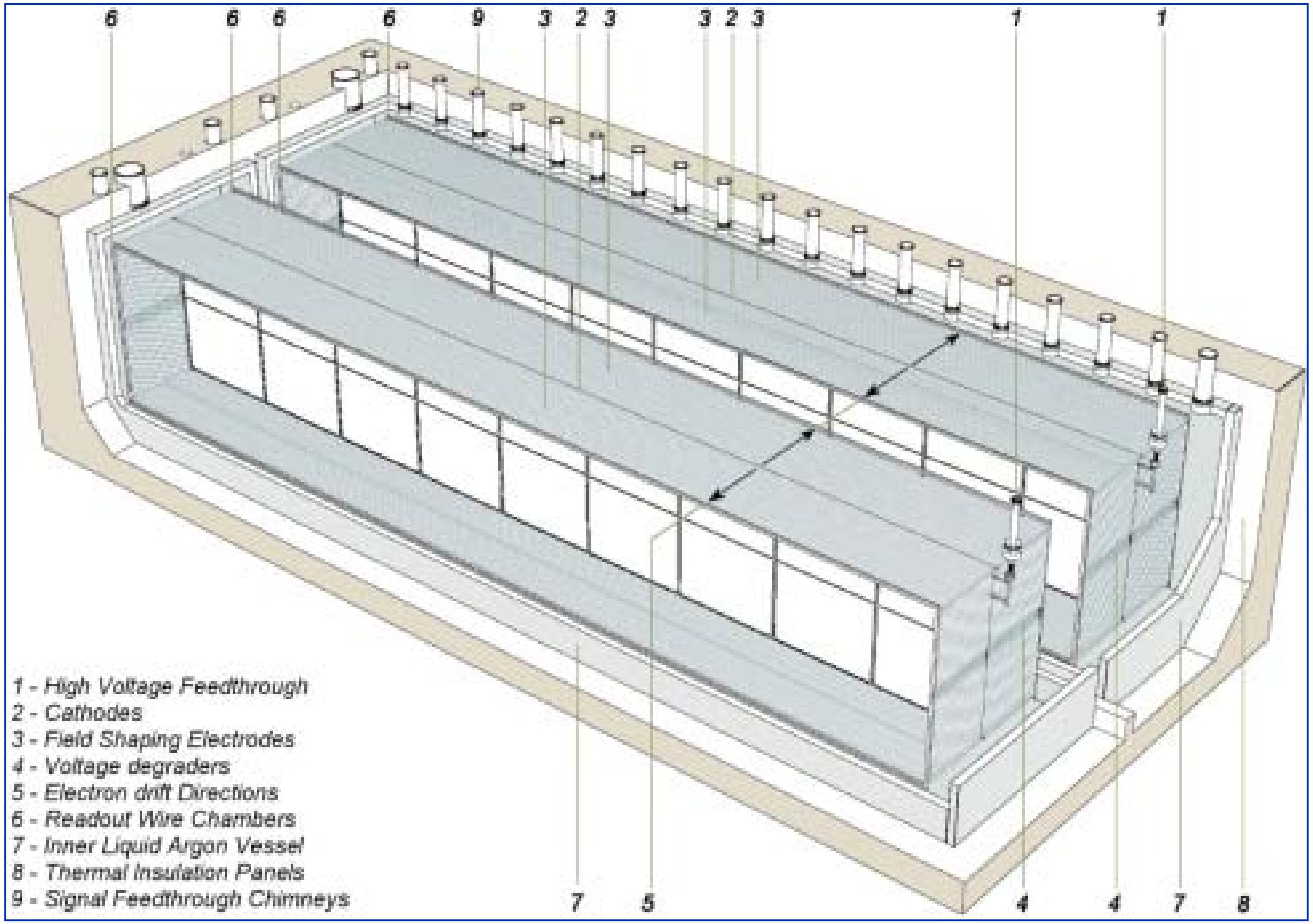
1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

T600 detector

2001: First T600 module

Cooperation with industry

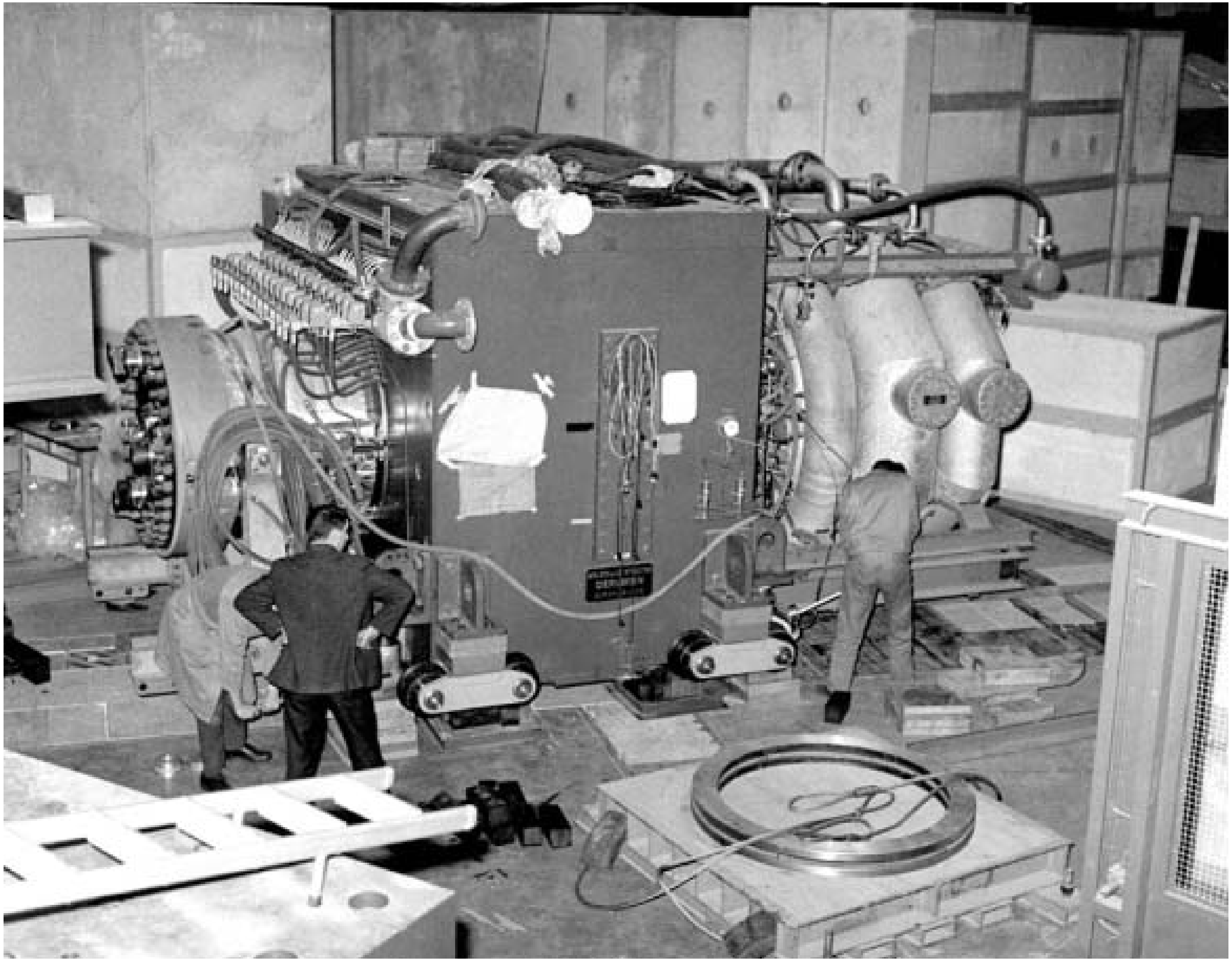
The “first unit”: T600 Module



- Two separate containers
  - ➥inner volume/cont. = **3.6 x 3.9 x 19.6 m^3**
- Sensitive mass = 476 ton
- 4 wire chambers with 3 readout planes at 0°, ±60° (two chambers / container)
  - ➥≈ 54000 wires None broke during test
- Maximum drift = 1.5 m
  - ➥HV = -75 kV @ 0.5 kV/cm
- Scintillation light readout with 8” VUV sensitive PMTs

First T300 cryostat during construction (2001)

HLBC 500 liter @ CERN (1963)



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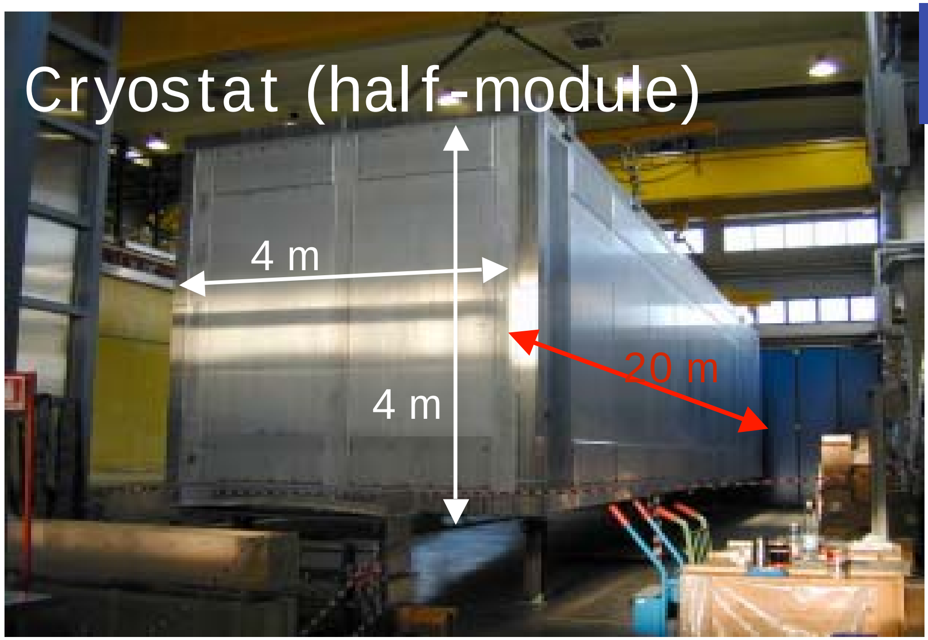
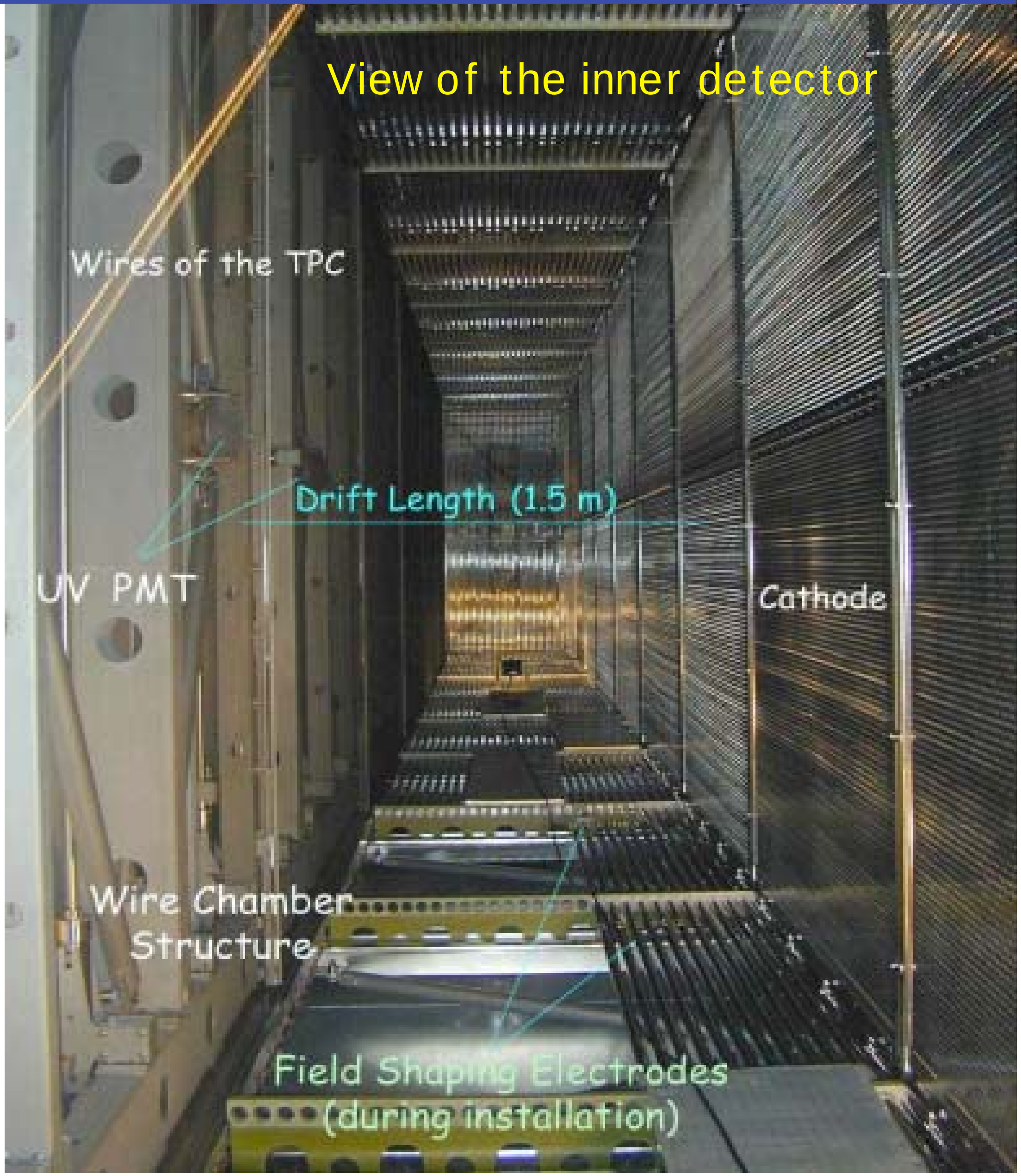
ICARUS T300 prototype

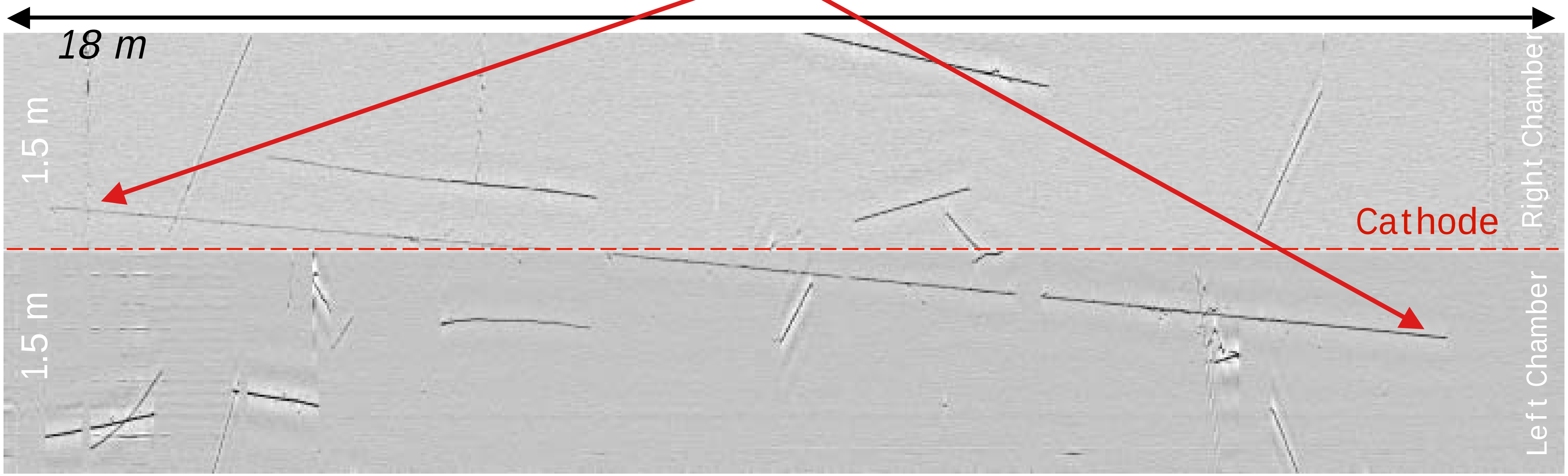


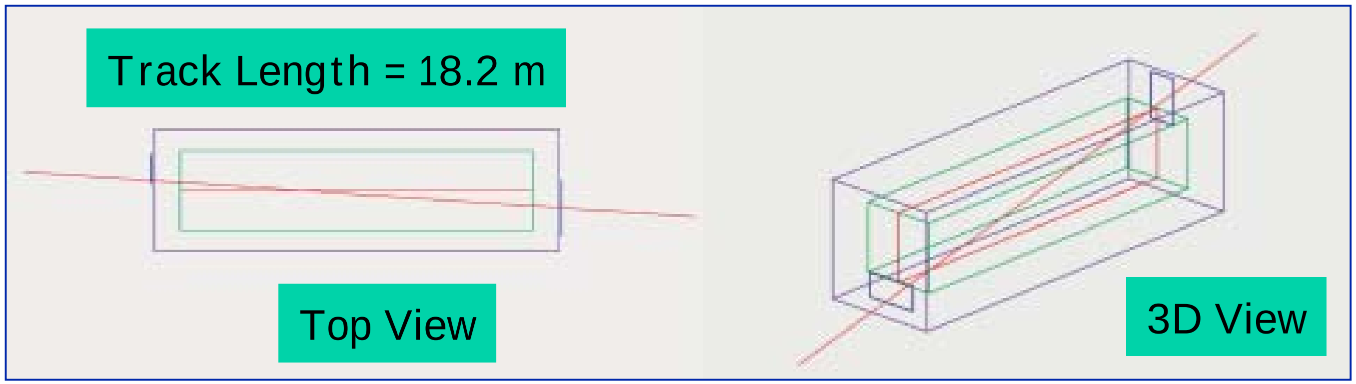


The T600 module

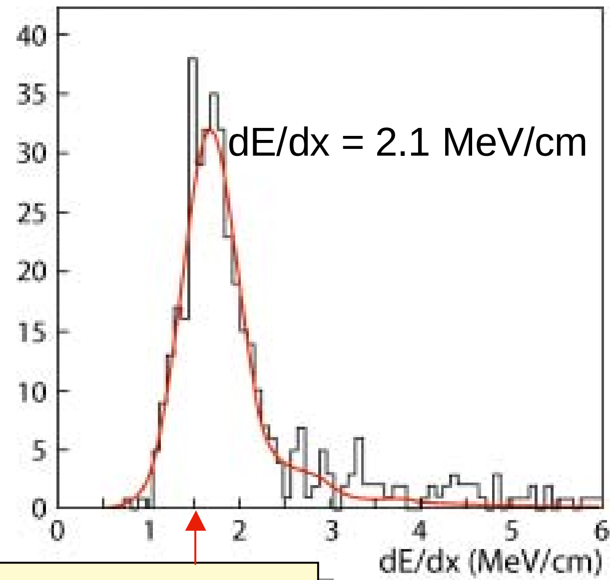
- Approved and funded in 1996
- Built between years 1997 and 2002
- Completely assembled in the INFN assembly hall in Pavia
- Full scale Demonstration test run of half-unit during first half 2001
  - ➥Three months duration
  - ➥Completely successful
  - ➥Data taking with cosmic rays
  - ➥Detector performance
  - ➥Full scale analyses
- Full unit Assembly terminated in 2002
- Waiting to be installed at LNGS

Long longitudinal muon track crossing the cathode plane



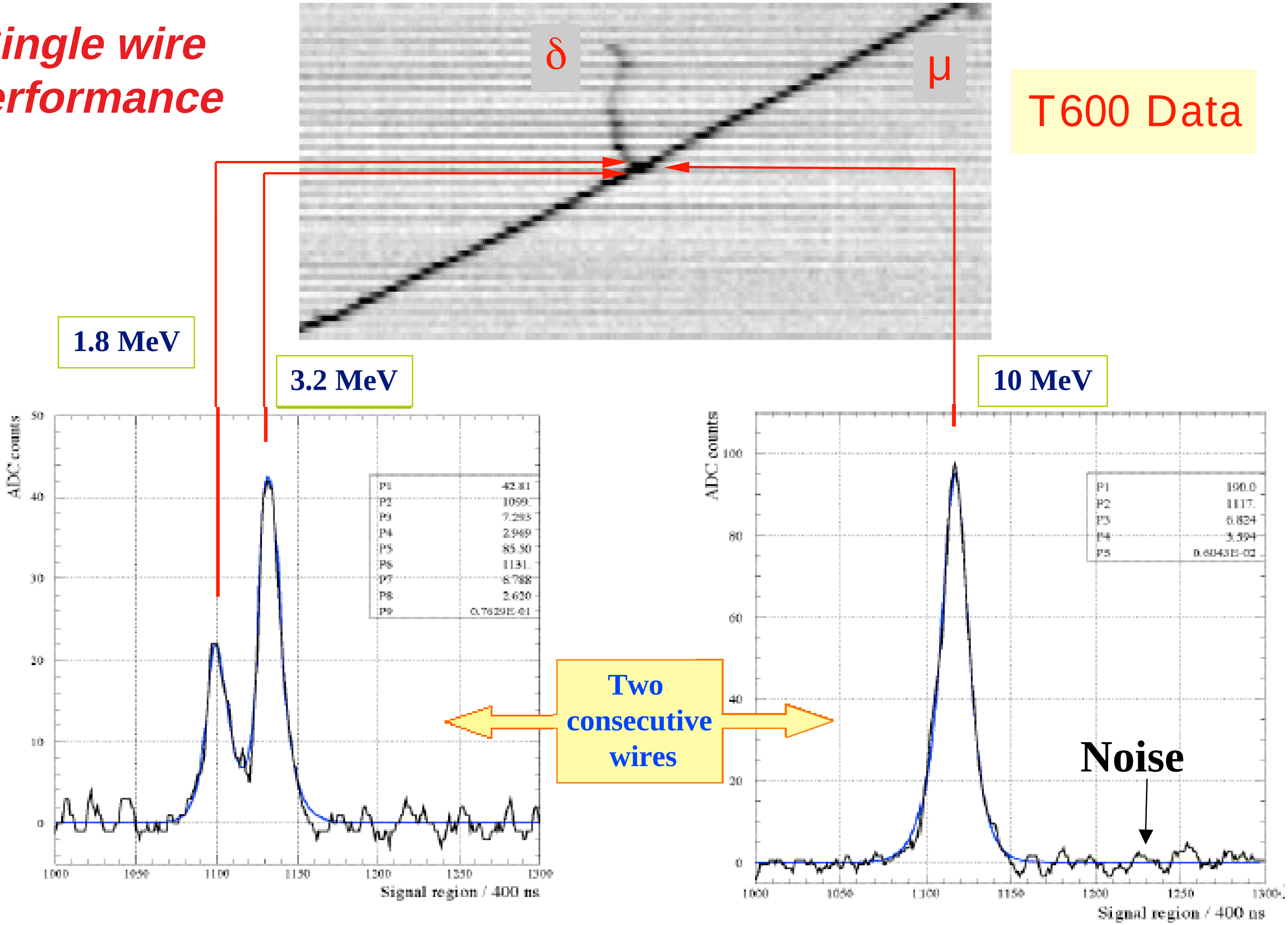


3-D reconstruction of the long track



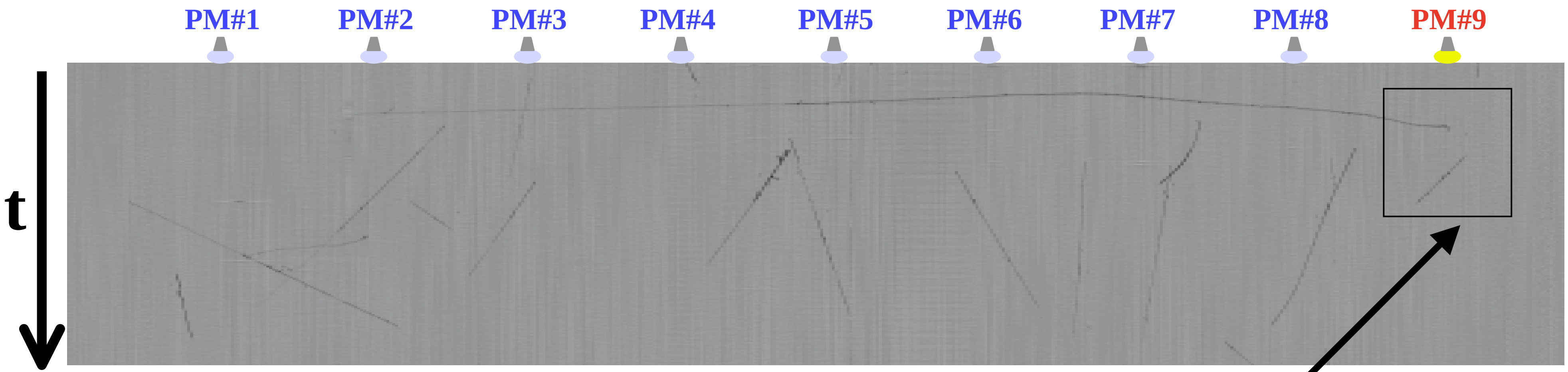
dE/dx distribution along the track

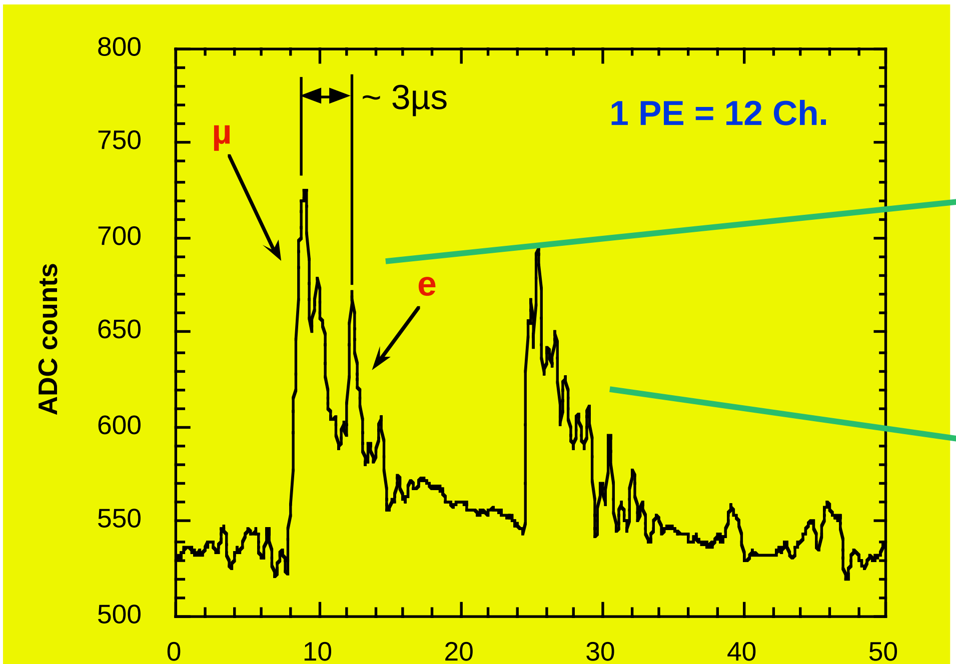
Single wire performance



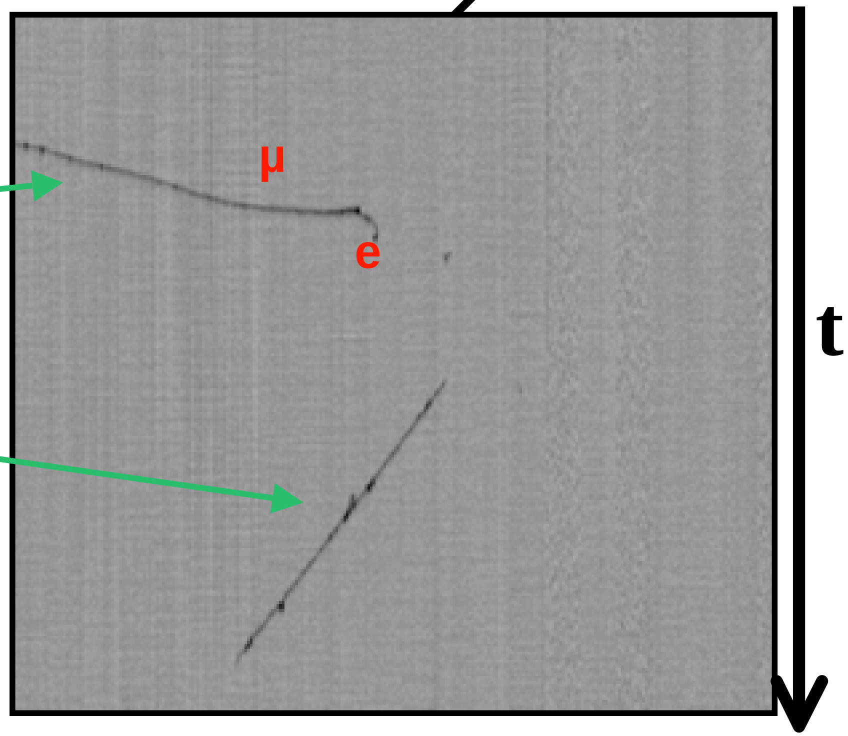
Threshold above noise ≈ 200 KeV

Scintillation light readout

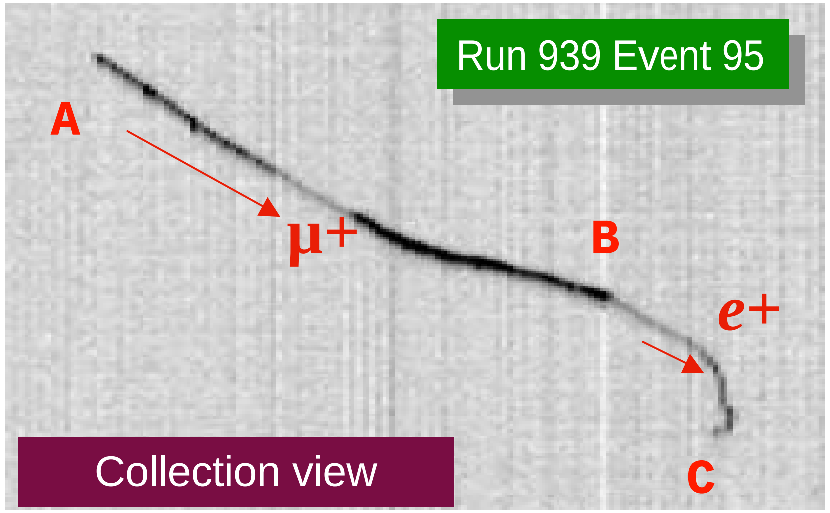




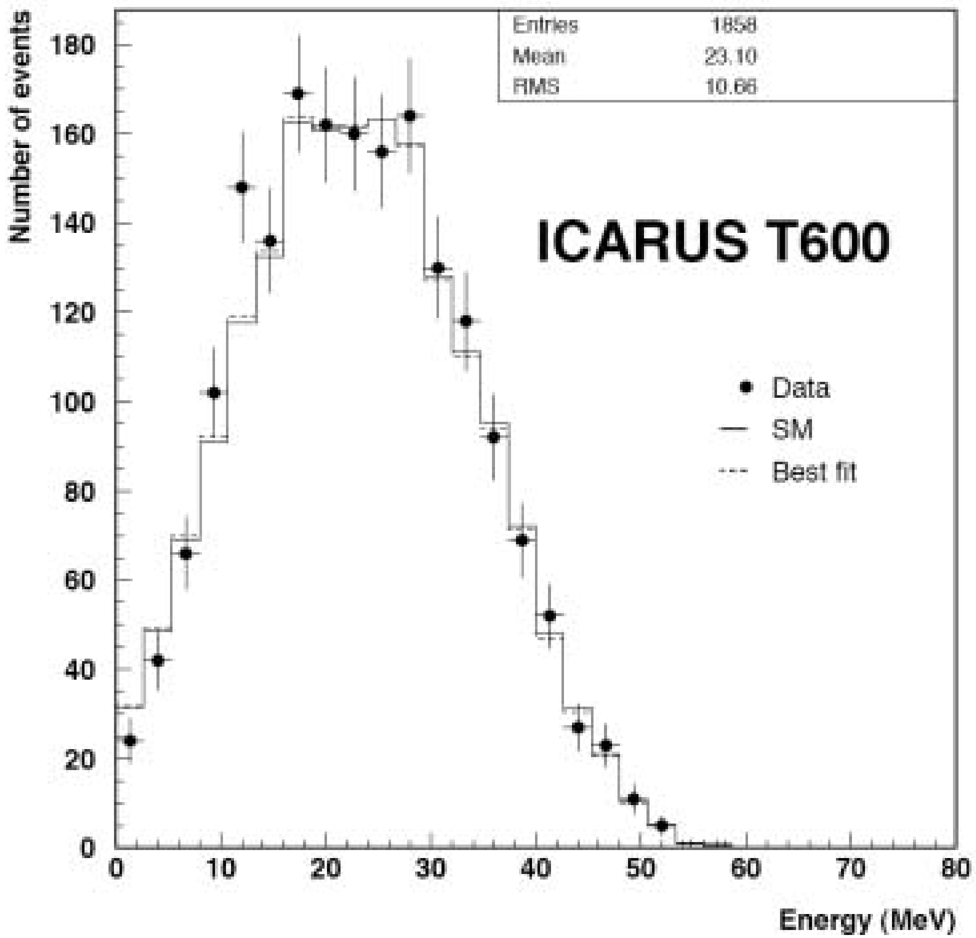
Signal PMT#9



Measurement of the muon decay spectrum and ρ parameter



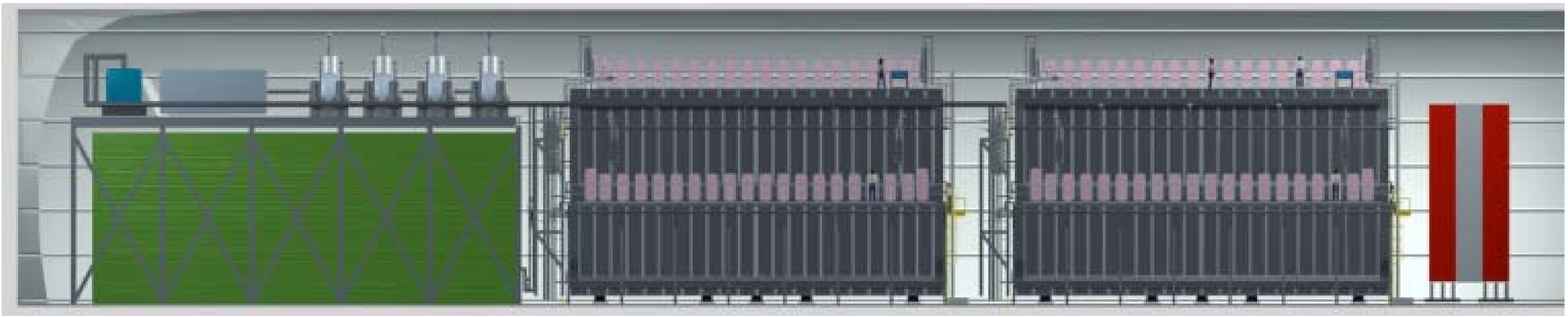
Author	Value	Assumption
Peoples	0.750 ± 0.003	$\eta \equiv 0$
Sherwood	0.760 ± 0.009	$\eta \equiv 0$
Fryberger	0.762 ± 0.008	$\eta \equiv 0$
Derenzo	0.752 ± 0.003	$-0.13 < \eta < 0.07$
SLD	$0.72 \pm 0.09 \pm 0.03$	lepton univers.
CLEO	$0.747 \pm 0.010 \pm 0.006$	lepton univers.
ARGUS	0.731 ± 0.031	lepton univers.
L3	$0.72 \pm 0.04 \pm 0.02$	lepton univers.
OPAL	$0.78 \pm 0.03 \pm 0.02$	lepton univers.
DELPHI	$0.78 \pm 0.02 \pm 0.02$	lepton univers.
ALEPH	0.742 ± 0.016	lepton univers.
This analysis	$0.72 \pm 0.06 \pm 0.08$	$-0.020 < \eta < 0.006$



$$\frac{\sigma_E}{E} = (11 \pm 1)\% / \sqrt{E(MeV)} \oplus (1.97 \pm 0.05)\%$$

ICARUS detector configuration in LNGS Hall B (T3000)

First Unit T600 + Auxiliary Equipment	T1200 Unit (two T600 superimposed)	T1200 Unit (two T600 superimposed)	Magnet

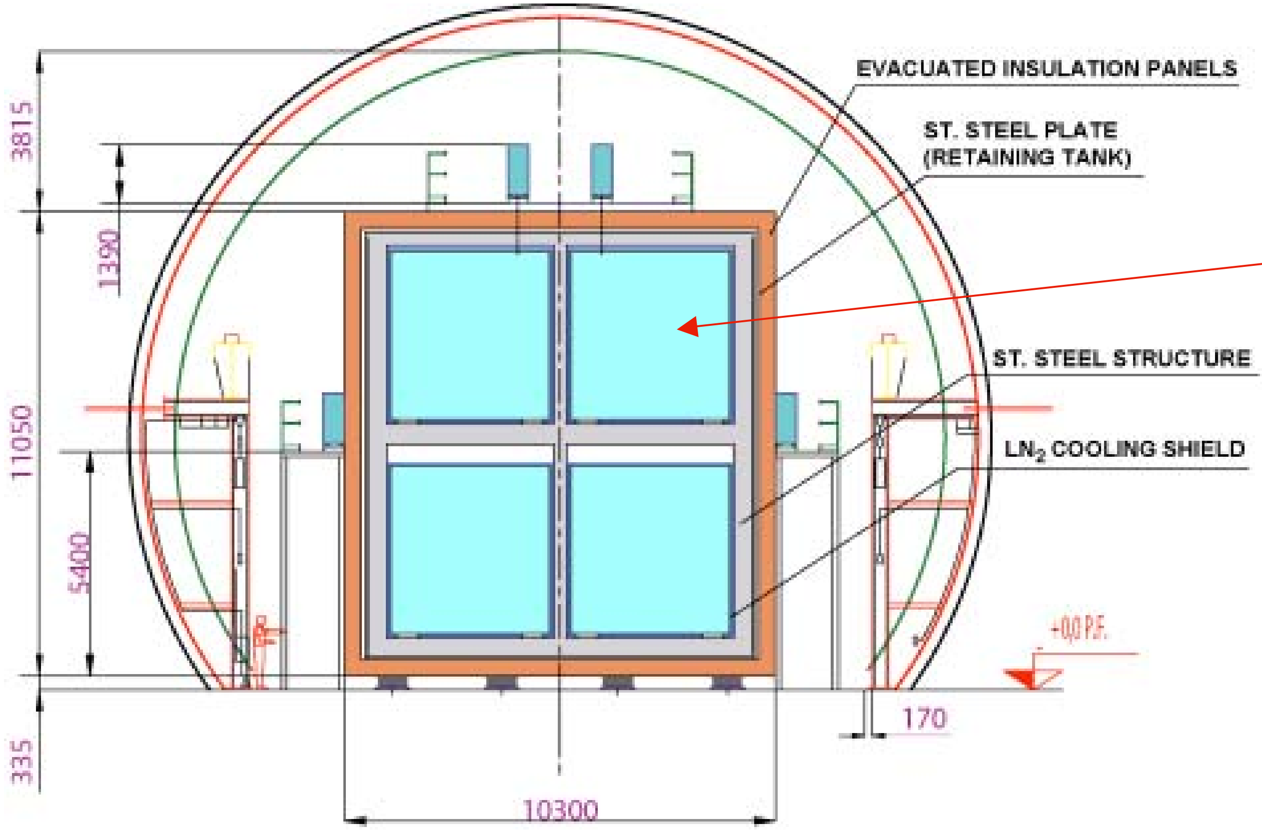


≈ 35 Metres

≈ 60 Metres

(final co-location of magnet not yet finalized)

The T1200 "Unit"



Detailed engineering project was produced by Air Liquide (June 2003)

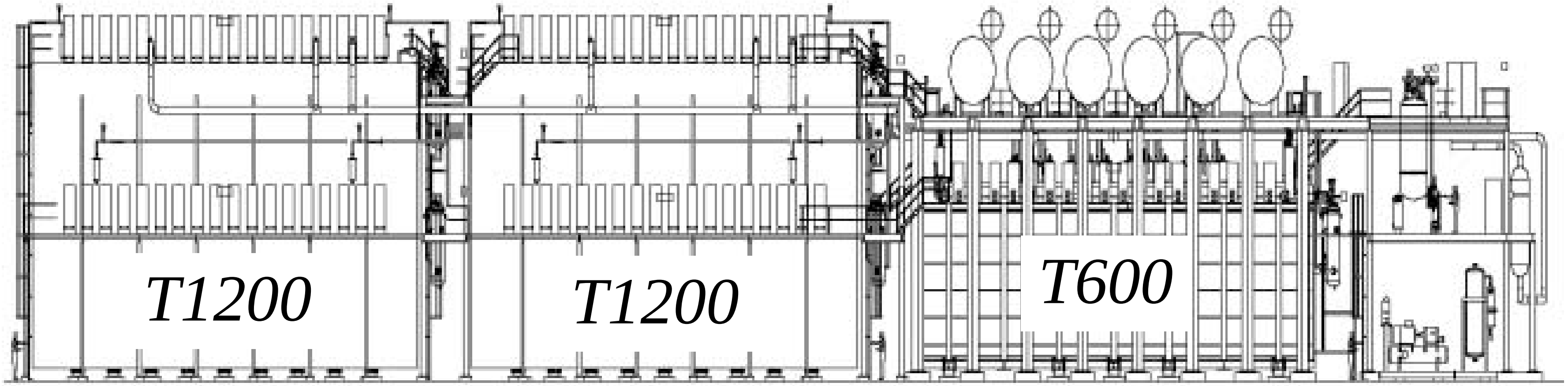
T1200 cryostat ready for tendering

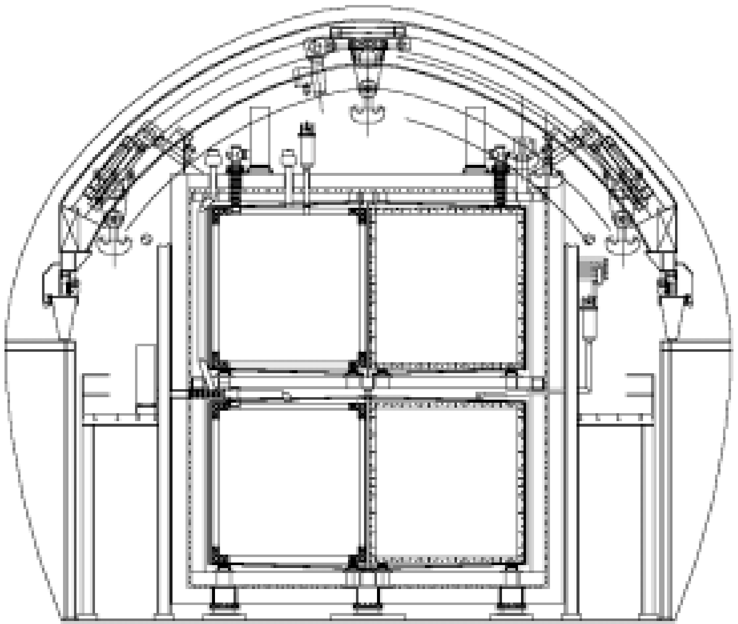
- Based on cloning the present T600 containers
  - ➥ A cost-effective solution given tunnel access conditions
- Preassembled modules outside tunnel are arranged in supermodules of about 1200 ton each (4 containers)
  - ➥ Time effective solution (parallelizable)
- Drift doubled 1.5 m ➔ 3 m
  - ➥ sensible solution given past experience
- Built with large industrial support (AirLiquide, Breme-Tecnica, Galli-Morelli, CAEN, …)
  - ➥ "order as many as you need" solution

Safe installation of T3000 @ LNGS

- Safe installation *is* possible even though it takes time to design in concordance with safety and laws. This is a very sensitive subject given the Borexino accident (the justice has been ceased against the LNGS laboratory).
  - ➥ Iterations needed, close cooperation between safety experts, risk analysts and engineers
- Basic guidelines
  - ➥ A full Definitive Project of installation of T3000 was prepared by industry
  - ➥ In parallel, LNGS subcontracted a specialized company to provide a Safety Risk Analysis Document (SRA)
- Status:
  - ➥ **The "definitive project" of the T600 installation at LNGS has been approved in March, 2003**
  - ➥ **Installation foreseen in 2004 (installation contract (1.6m€) should be signed by infn by end of 2003)**
  - ➥ **In the meantime, a new director has been appointed at LNGS**
  - ➥ **A new working group led by A.Scaramelli (CERN/ST) has been formed to <u>re-assess</u> the safety aspects. Expect answer by end of 2003.**

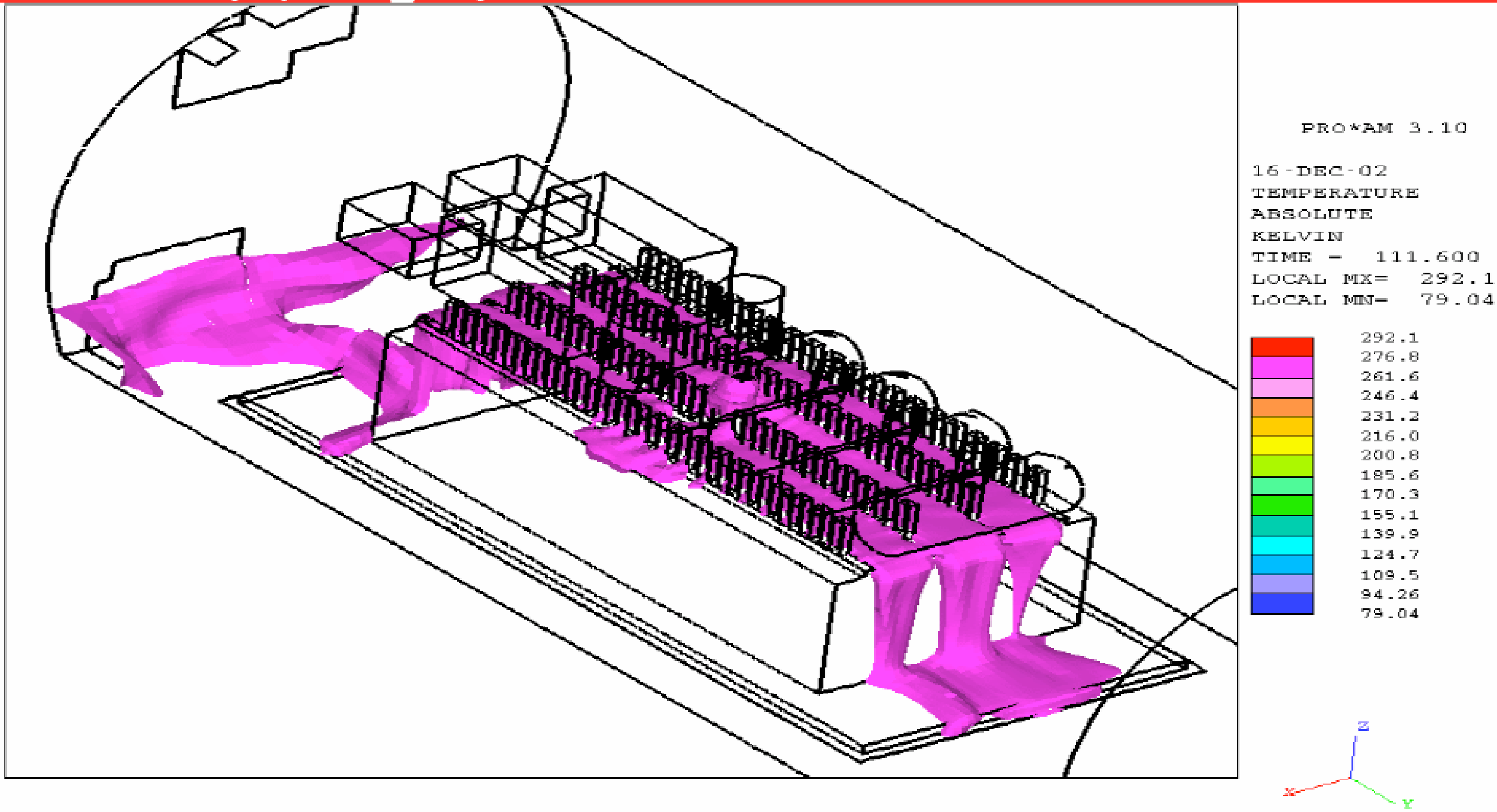
T3000 “definitive” project at LNGS Hall B





Complete engineering

LN2 release from broken connections of storage tank (Q=2Kg/s) – Isotherm 0°C after 2 min

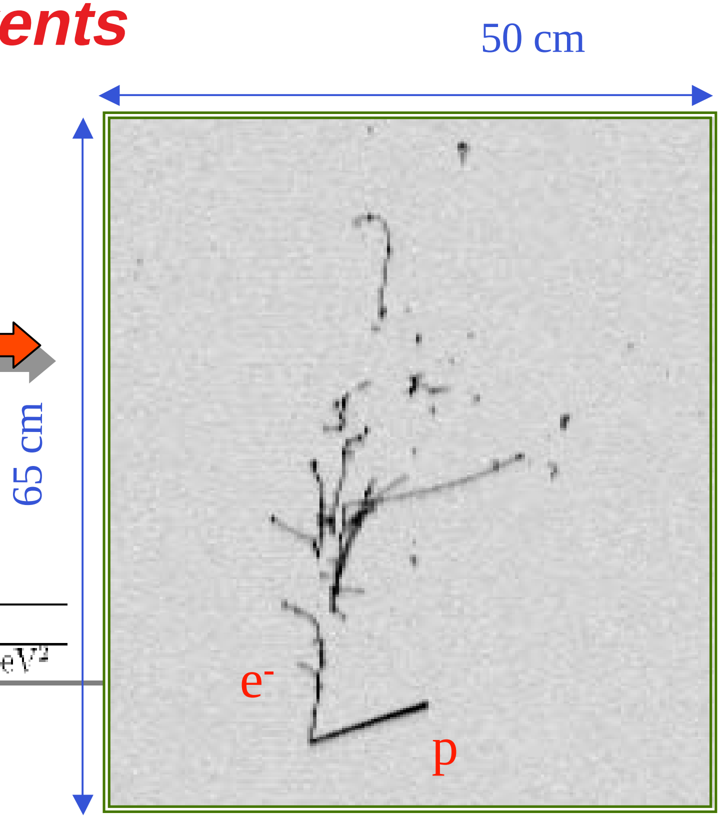


11/6/2003 A. Scaramelli

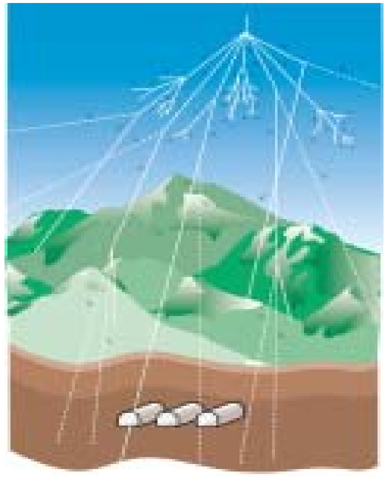
Atmospheric neutrino events

Mass is not the only issue!

In 1 year of T600 running ICARUS will collect about 100 events of this quality (in presence of oscillations)

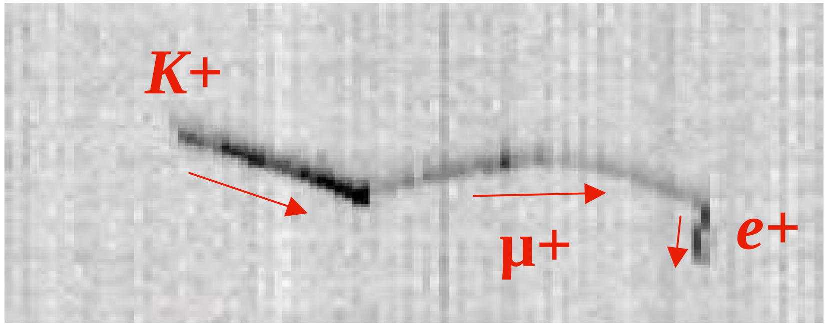


	2 kton×year			
	Solar minimum		Solar maximum	
	No osc.	$\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2	No osc.	$\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2
Muon-like	266 ± 16	182 ± 13	249 ± 16	171 ± 13
$\mu + p$	59 ± 8	39 ± 6	71 ± 8	35 ± 6
$P_{lepton} < 400$ MeV	114 ± 11	69 ± 8	98 ± 10	63 ± 8
$\mu + p$	32 ± 2	20 ± 4	28 ± 5	18 ± 4
Electron-like	150 ± 12	150 ± 12	138 ± 12	138 ± 12
$e + p$	35 ± 6	35 ± 6	40 ± 6	40 ± 6
$P_{lepton} < 400$ MeV	74 ± 9	74 ± 9	66 ± 8	66 ± 8
$e + p$	20 ± 4	20 ± 4	18 ± 4	18 ± 4
NC-like	192 ± 14	192 ± 14	175 ± 13	175 ± 13
TOTAL	608 ± 25	524 ± 23	562 ± 24	484 ± 22



Proton decay

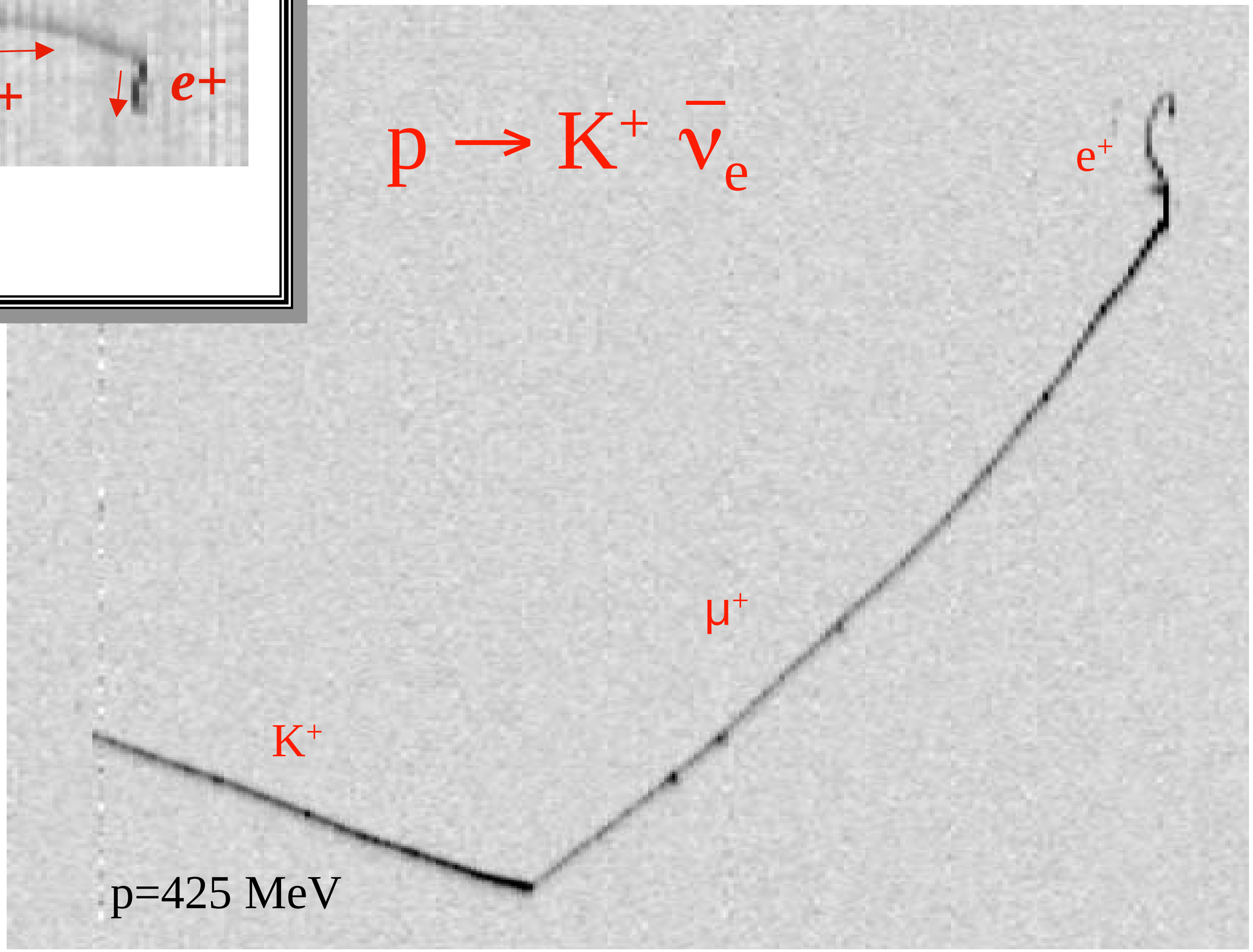
$$K^+[AB] \rightarrow \mu^+[BC] \rightarrow e^+[CD]$$

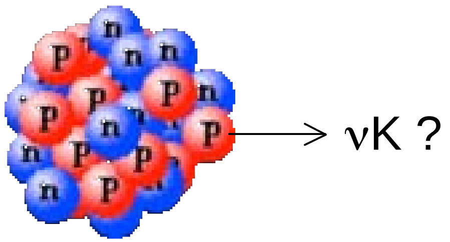


Run 939 Event 46

65 cm

53 cm





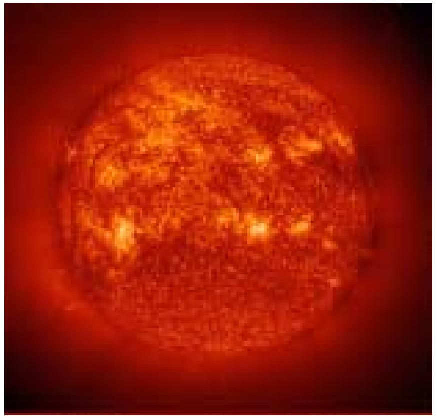
Test of GUT

Supernova and solar neutrinos

- Four distinct signatures (see **JCAP 0310:009,2003**)

$$\overset{(-)}{\nu}_x + e^- \rightarrow \overset{(-)}{\nu}_x + e^- \qquad \overset{(-)}{\nu}_x + {}^{40}Ar \rightarrow {}^{40}Ar^* + \overset{(-)}{\nu}_x$$

$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^- \qquad \bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+$$



Reaction		Scenario I: No oscillation	Oscillation (n.h.) Large θ_{13}	Oscillation (n.h.) Small θ_{13}	Oscillation (i.h.) Large θ_{13}	Oscillation (i.h.) Small θ_{13}
Elastic						
	$\nu_e\, e^-$	20	20	20	20	20
	$\bar{\nu}_e\, e^-$	8	8	8	8	8
	$(\nu_\mu + \nu_\tau)\, e^-$	7	7	7	7	7
	$(\bar{\nu}_\mu + \bar{\nu}_\tau)\, e^-$	6	6	6	6	6
	total $\nu\, e^-$	41	41	41	41	41
Absorption						
CC	$\nu_e\ {}^{40}\mathrm{Ar}$	188	962	730	730	730
	$\bar{\nu}_e\ {}^{40}\mathrm{Ar}$	15	33	33	75	33
NC	$\nu\ {}^{40}\mathrm{Ar}$	492	492	492	492	492
	$\bar{\nu}\ {}^{40}\mathrm{Ar}$	419	419	419	419	419
Total		1155	1947	1715	1757	1715

Type II SN
D=10 kpc (galactic)
$E_B = 3 \times 10^{53}$ erg
Rate: ≈1 every 30 years!

ICARUS and CERN-LBL program

- ICARUS as a LBL neutrino oscillations experiment between CERN and LNGS using SPS was discussed in the 1993 proposal already
  - ➥ ICARUS-II. A Second Generation Proton Decay Experiment And Neutrino Observatory At The Gran Sasso Laboratory Proposal, VOL I (1993) & II (1994), LNGS-94/99.
- The final proposal for T3000 has been written and submitted to
  - ➥ INFN directorate and Comm. II in November 2001
  - ➥ LNGS SC in November 2001
  - ➥ CERN SPSC in March 2002 **(SPSC-P-323)**
- It was recommended/approved by:
  - ➥ Italian “Direttivo INFN” (December 2001),
  - ➥ LNGS SC (for the atmospheric, solar neutrino and proton decay physics program, March 2002),
  - ➥ Italian “Commissione Scientifica II” (for the whole scientific physics program, June 2002),
  - ➥ CERN SPS Committee (for the CNGS neutrino beam physics program, September 2002).
  - ➥ CERN RB approval: CNGS-2 (March 2003)

Main reactions at the CNGS

Expected ν_e and ν_τ contamination (in absence of oscillations) is of the order of 10^{-2} and 10^{-7} relative to the main ν_μ component

$\nu_\mu \to \nu_\tau$

$$\nu_\tau + Ar \to \tau + jet; \quad \tau \to \begin{cases} e\nu\nu & 18\% \\ \mu\nu\nu & 18\% \\ h^- n h^0 \nu & 50\% \\ h^- h^+ h^- n h^0 \nu & 14\% \end{cases}$$

Charged current (CC)

$\nu_\mu \to \nu_e$

$$\nu_e + Ar \to e + jet$$

(CC)

$\nu_\mu \to \nu_s$

$$\nu_x + Ar \to \nu_x + jet$$

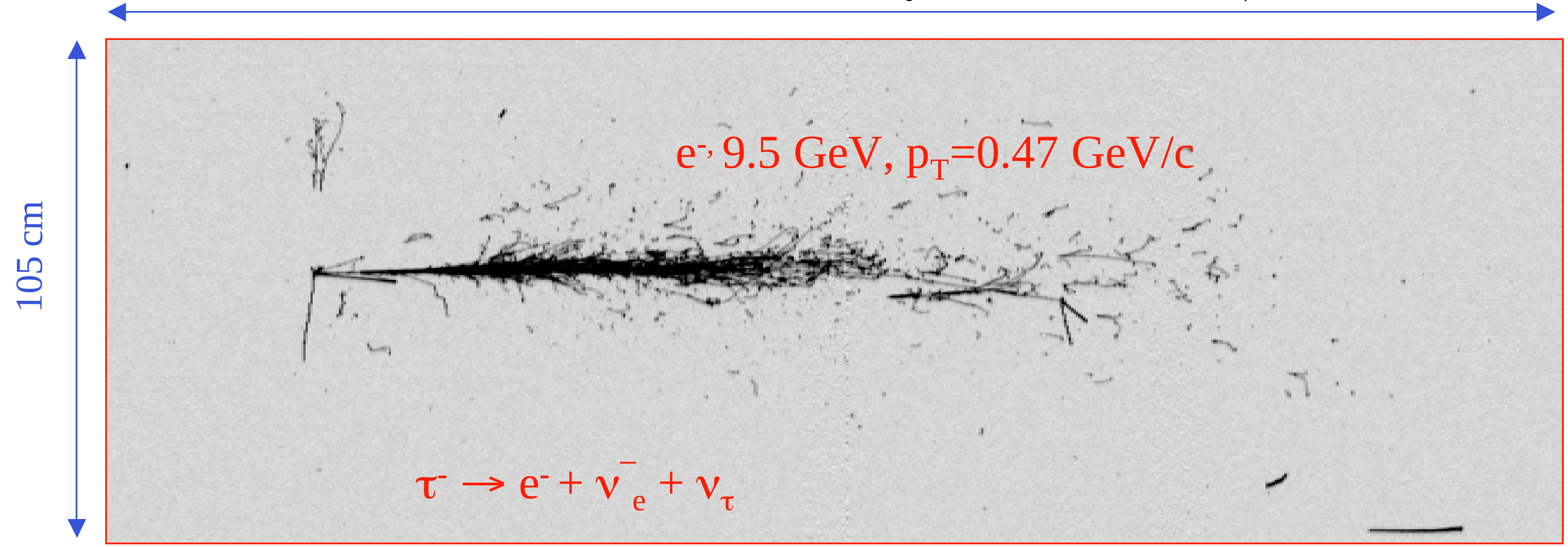
Neutral current (NC)

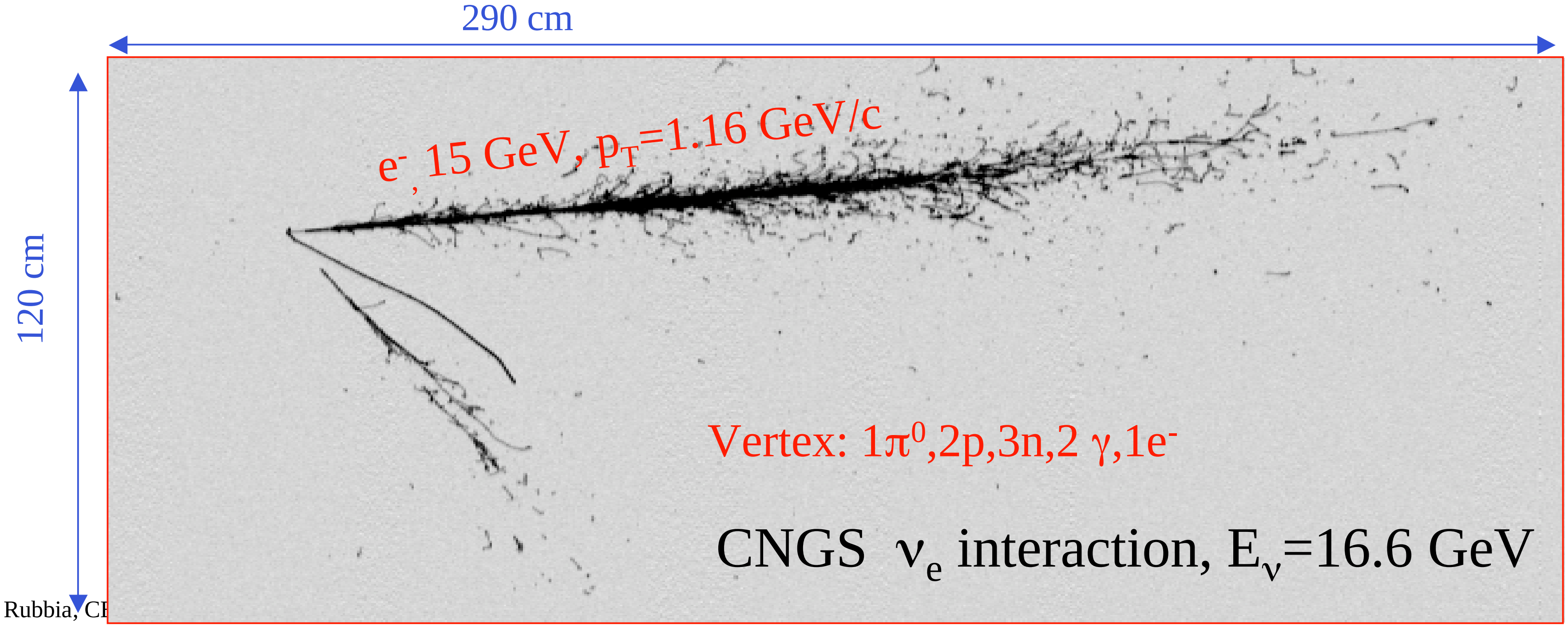
Control sample

$$\nu_\mu + Ar \to \mu + jet$$

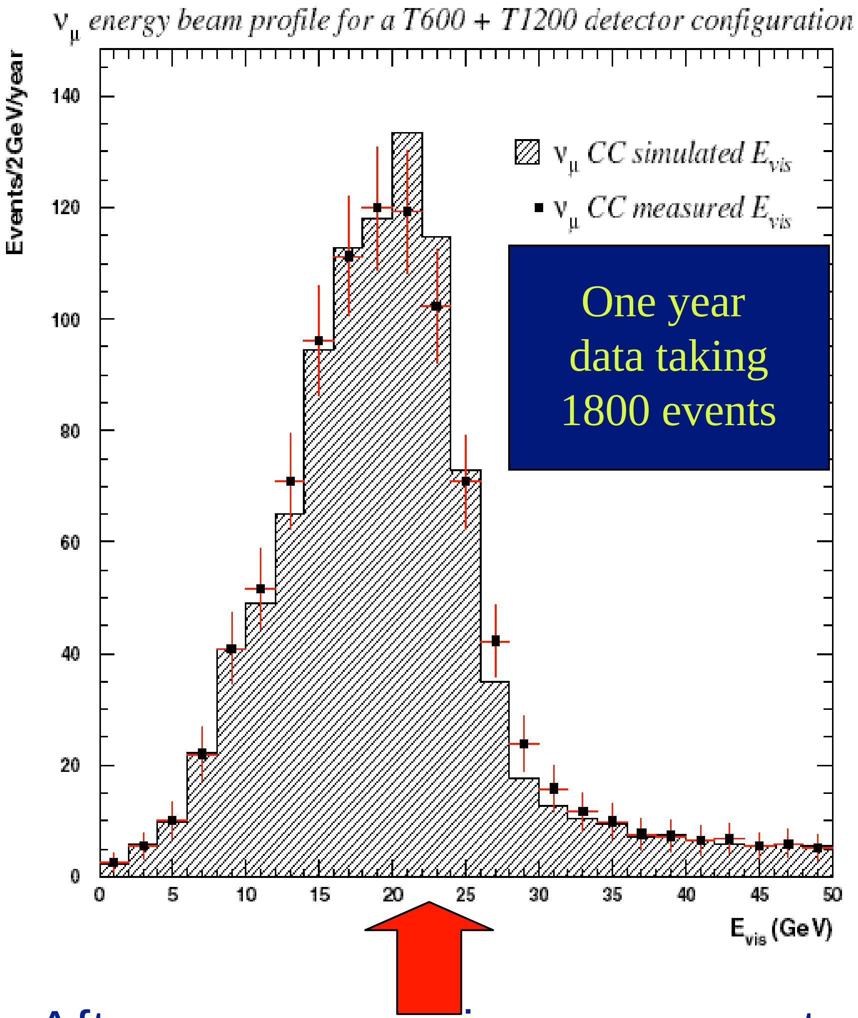
(CC)

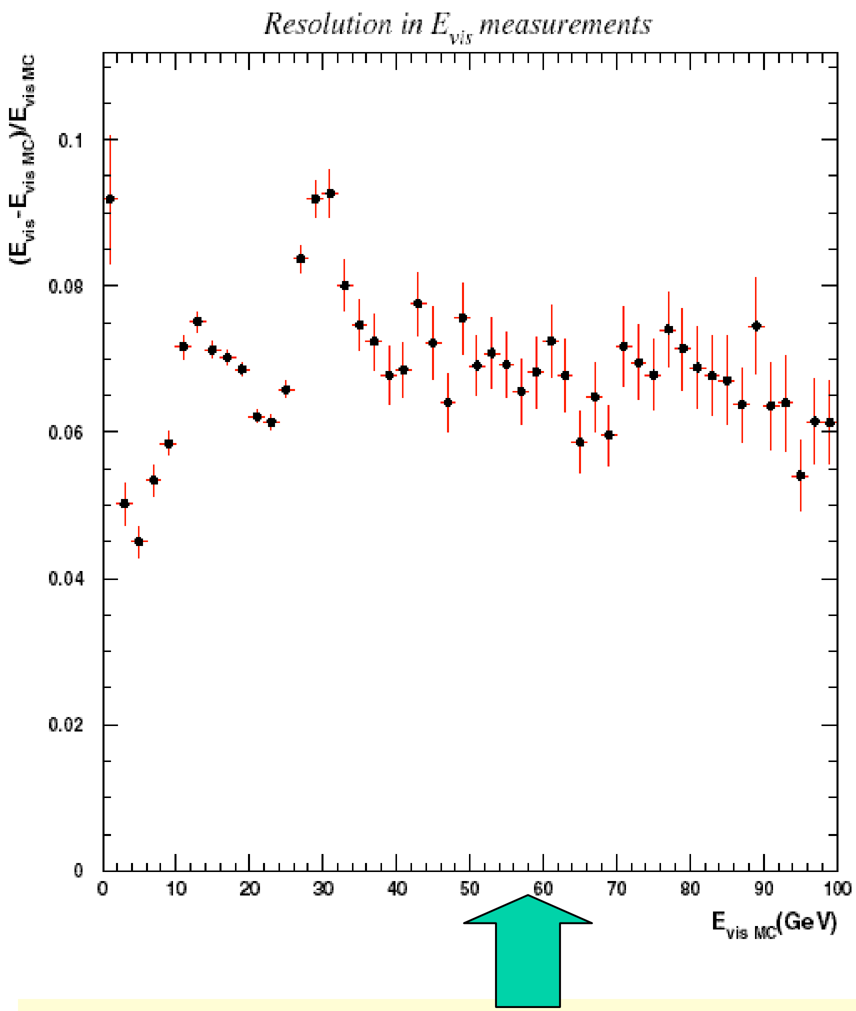
CNGS ν_τ interaction, E_ν=18.7 GeV





CNGS beam profile measurement





After one year, precise measurement of

The CNGS beam profile

Average neutrino energy resolution

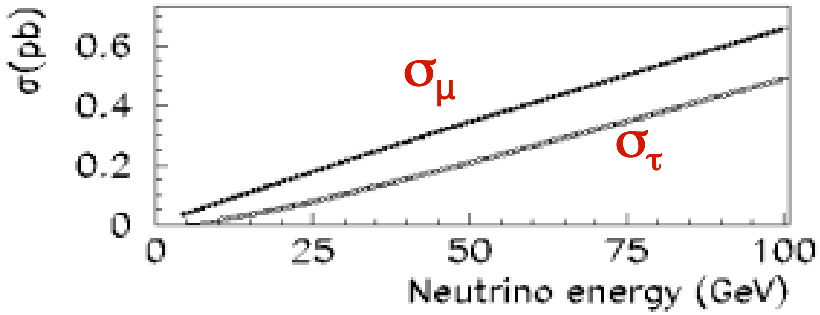
around 7%

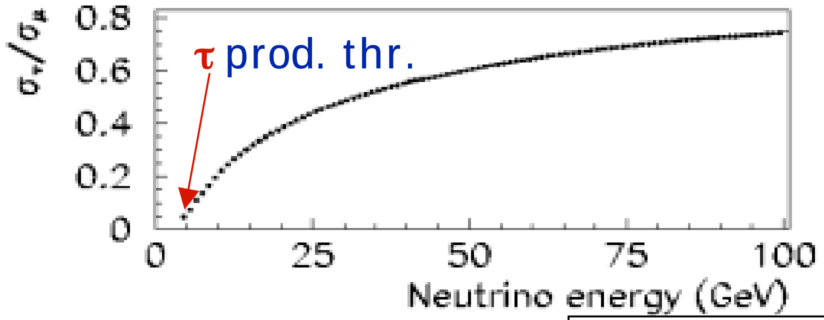
CNGS Optimization for ν_τ Appearance

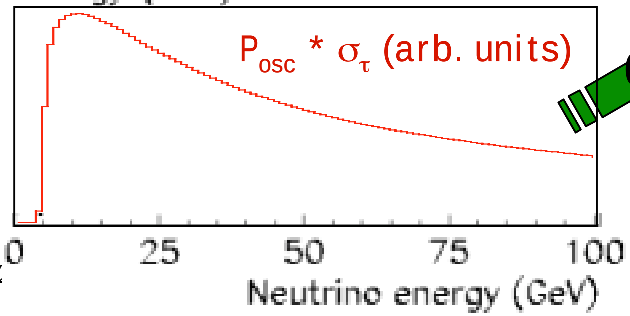
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

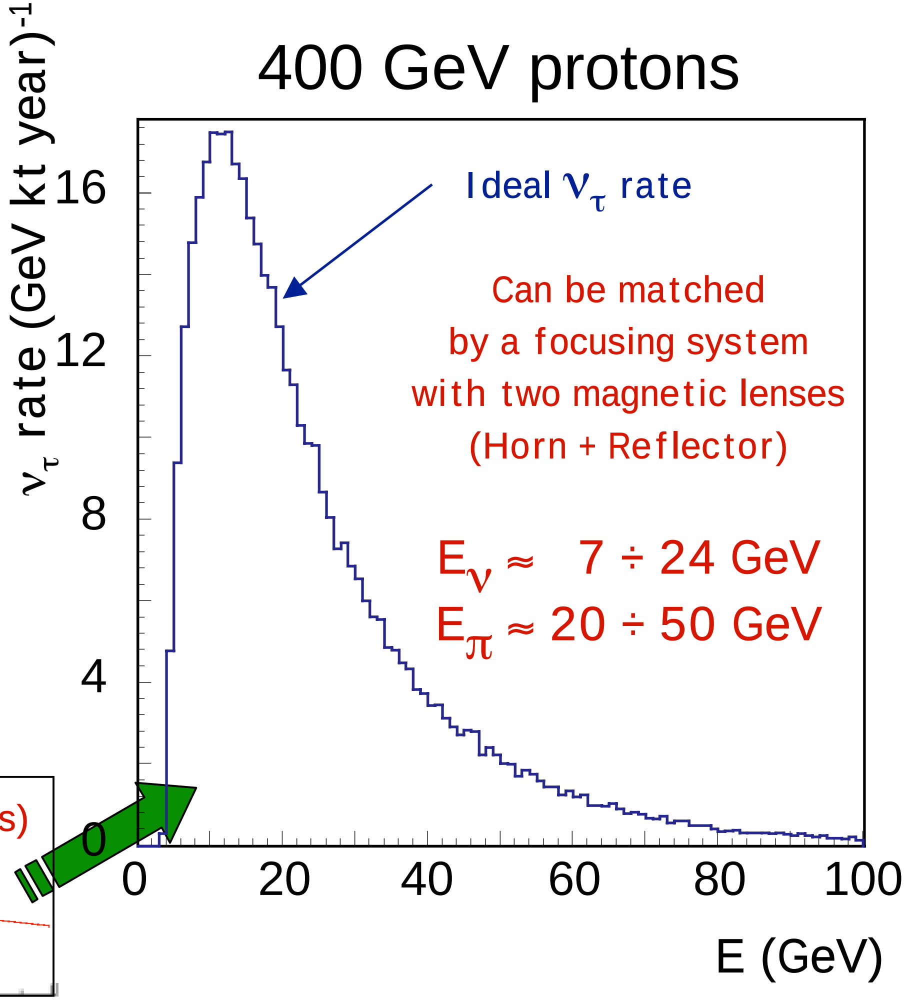
P_{osc} ↓ E_ν ↑

σ_τ/σ_μ CC increases with energy (kin. suppr. due to τ mass)









Total rates with T3000 @ CNGS

- Detector configuration
  - ➥ T3000
  - ➥ Active LAr: 2.35 ktons
- 5 years of CNGS running
  - ➥ Shared mode
  - ➥ 4.5 x 10^{19} p.o.t./year (conservative?)
- 280 ν_τ CC expected for Δm^2_{23}=3 x 10^{-3} eV^2 and maximal mixing

Process	Expected Rates
ν_μ CC	32600
$\overline{\nu}_\mu$ CC	652
ν_e CC	262
$\overline{\nu}_e$ CC	17
ν NC	10600
ν NC	243
ν_τ CC, Δm^2 (eV^2)	
1 x 10^{-3}	31
2 x 10^{-3}	125
3 x 10^{-3}	280
5 x 10^{-3}	750

$\nu_\mu \rightarrow \nu_\tau$ appearance search summary

- T3000 detector (2.35 kton active, **1.5 kton fiducial**)
- **Integrated pots "nominal"= $5 \times 4.5 \times 10^{19}$ = 2.25×10^{20} pots**
- Several decay channels are exploited (electron = golden channel)

Super-Kamiokande: $1.6 < \Delta m^2 < 4.0$ at 90% C.L.

τ decay mode	Signal $\Delta m^2 = 1.6 \times 10^{-3}$ eV^2	Signal $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2	Signal $\Delta m^2 = 3.0 \times 10^{-3}$ eV^2	Signal $\Delta m^2 = 4.0 \times 10^{-3}$ eV^2	BG
$\tau \rightarrow e$	3.7	9	13	23	0.7
$\tau \rightarrow \rho$ DIS	0.6	1.5	2.2	3.9	< 0.1
$\tau \rightarrow \rho$ QE	0.6	1.4	2.0	3.6	< 0.1
Total	**4.9**	**11.9**	**17.2**	**30.5**	**0.7**

- **Straight-forward kinematical analyses à la NOMAD experiment @ CERN, however with typically factor 100 less background rejection required**
- **Backgrounds measured in situ (main background is ν_e CC)**
- High sensitivity to signal, and oscillation parameters determination

Kinematical criteria: the NOMAD experience

- In NOMAD it was demonstrated that kinematical criteria provide a powerful way to separate tau signal from backgrounds
- It was also realized that kinematical closure depends on many subtle effects
  - ➥ Nuclear effects at vertex
  - ➥ Hadronization
  - ➥ Detector ineffiencies
  - ➥ …
- NOMAD never managed to reproduce exactly the kinematics of the events
  - ➥ NOMAD had a good muon measurement and relied on the "data simulator" technique

NOMAD

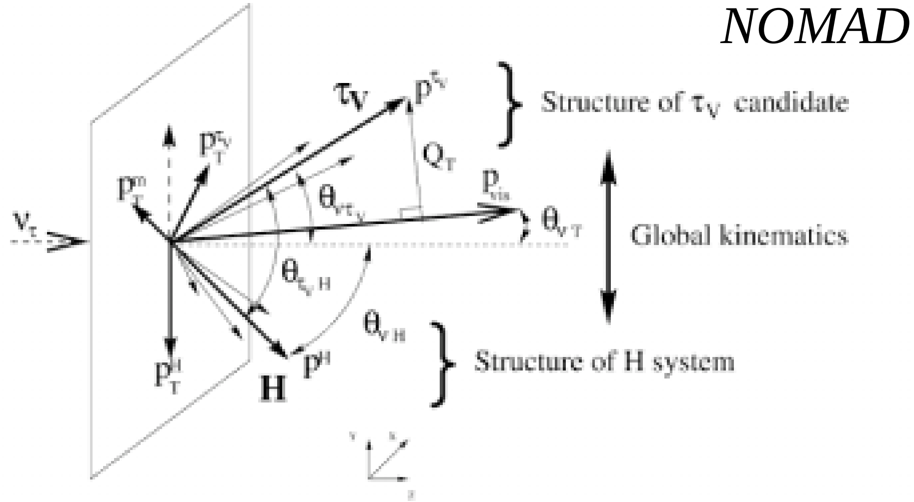
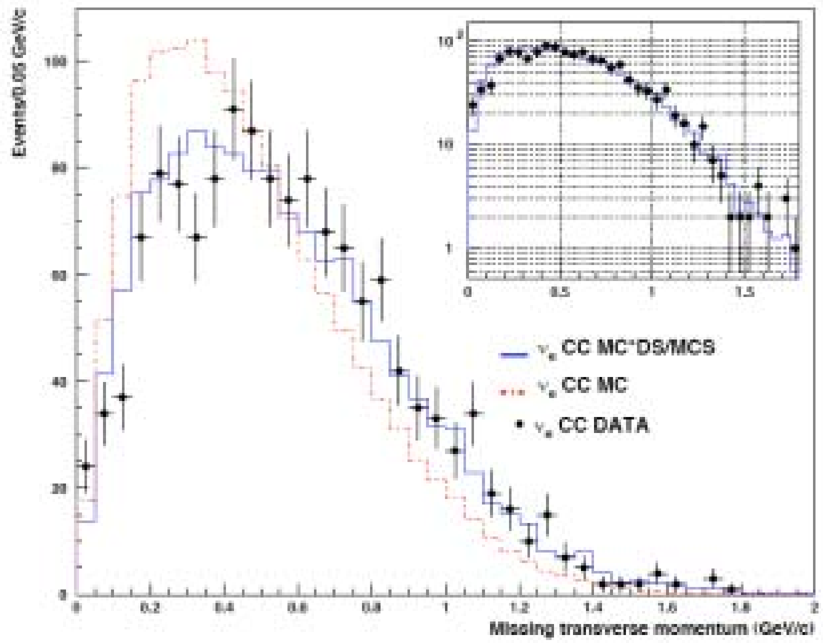
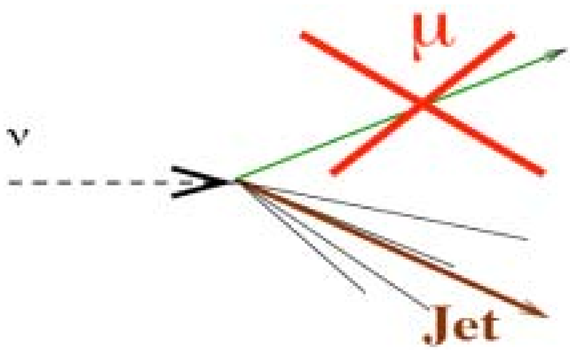


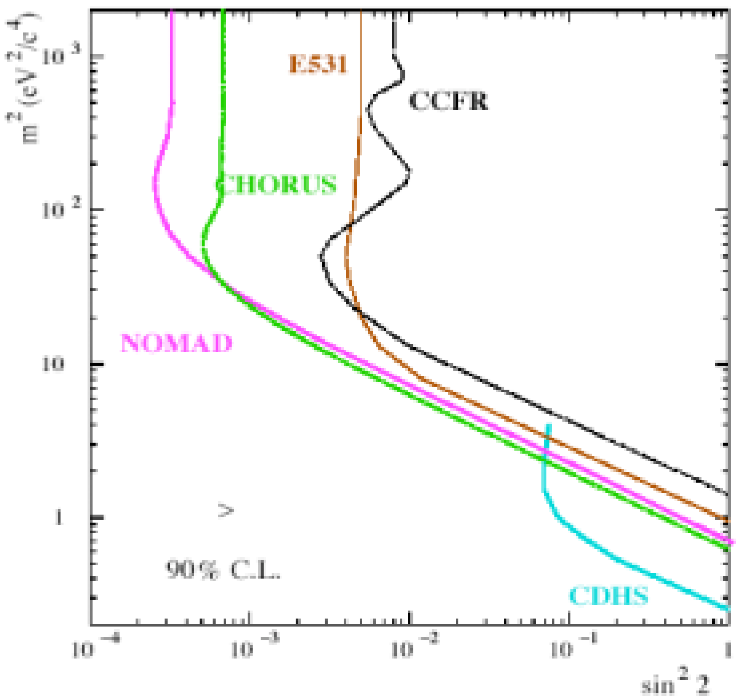
Fig. 16. Definition of the NOMAD kinematics for a ν_τ CC event.



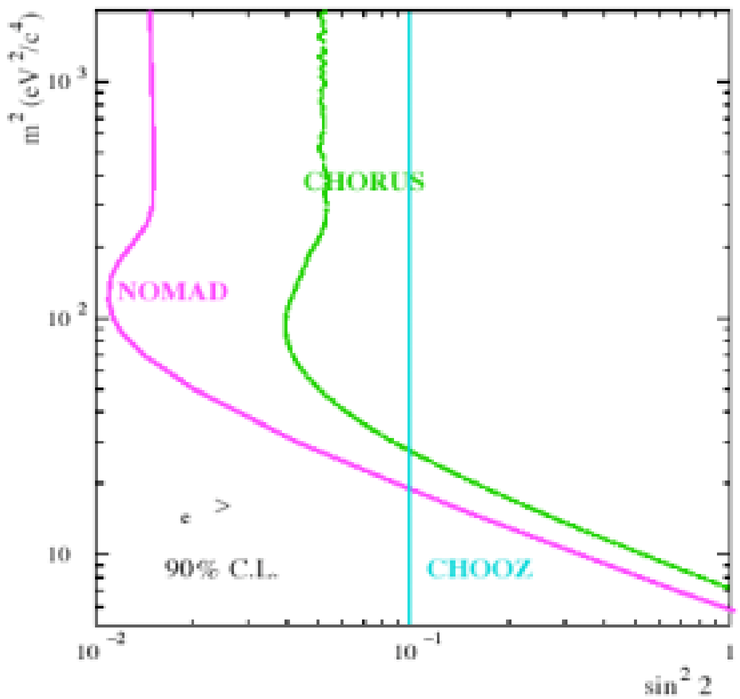


Kinematical vs emulsion: NOMAD vs CHORUS

- $\nu_\mu \longrightarrow \nu_\tau$:



- $\nu_e \longrightarrow \nu_\tau$:



Final results with F&C published in Nucl. Phys. B 611 (2001) 3-39:

$$\begin{cases} S_{\nu_\mu\to\nu_\tau} & = & 2.50\times10^{-4} \;\; 90\%\text{CL} \\ L_{\nu_\mu\to\nu_\tau} & = & 1.63\times10^{-4} \;\; 90\%\text{CL} \\ P(\leq L) & = & 37\% \end{cases}$$

$$\begin{cases} S_{\nu_e\to\nu_\tau} & = & 1.10\times10^{-2} \;\; 90\%\text{CL} \\ L_{\nu_e\to\nu_\tau} & = & 0.74\times10^{-2} \;\; 90\%\text{CL} \\ P(\leq L) & = & 39\% \end{cases}$$

CHORUS limit: $\sin^2 2\theta < 7\times10^{-4}$ 90% C.L. (Phys.Lett.B497:8-22,2001)

$\nu_\mu \rightarrow \nu_e$ *appearance: θ_{13} search*

- T3000 detector (**2.35 kton fiducial**)
- **Integrated pots "nominal"= $5 \times 4.5 \times 10^{19} = 2.25 \times 10^{20}$ pots**
- Profits from unique e/π^0 separation in ICARUS

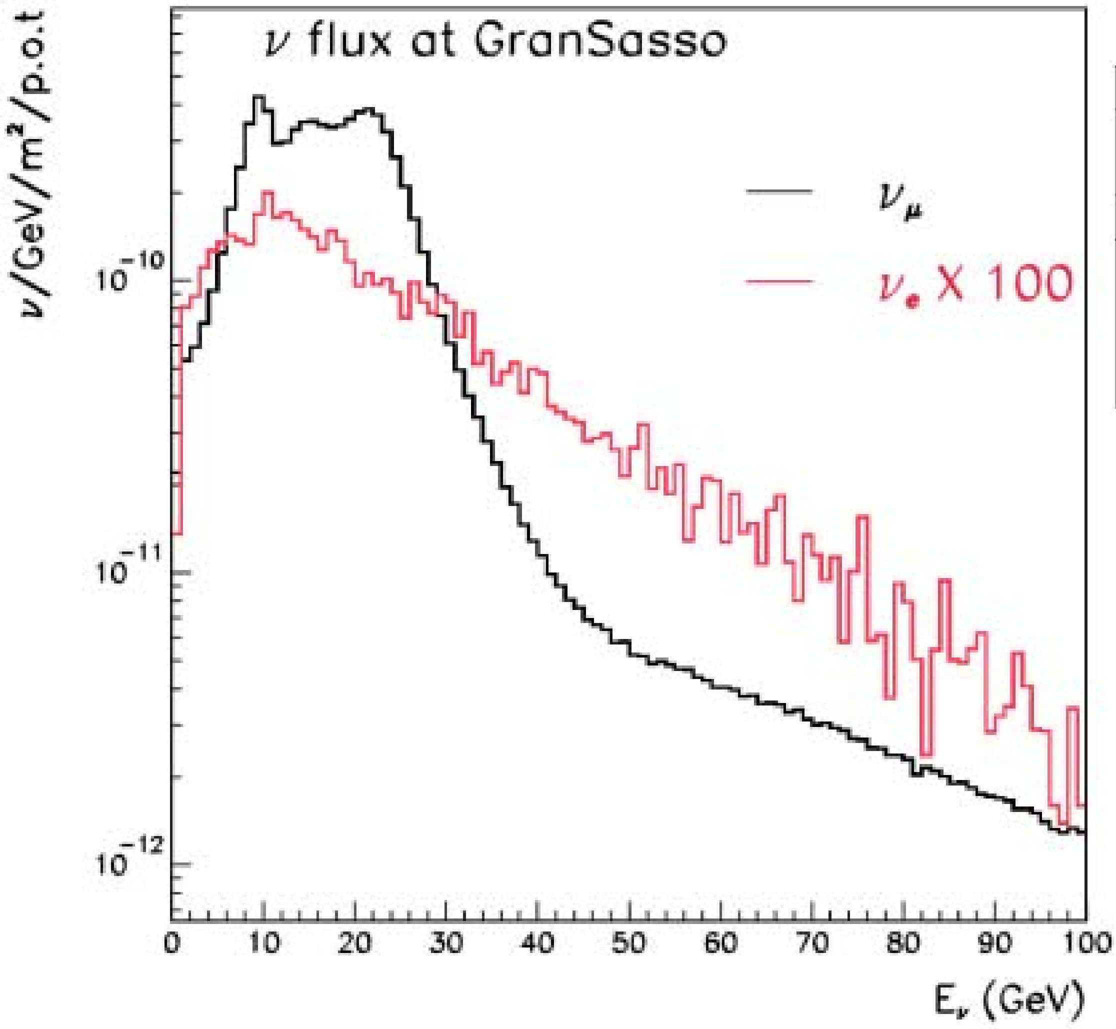
"intrinsic" → $\nu_e + Ar \rightarrow e + jet$

"intrinsic" → $\nu_x + Ar \rightarrow \nu_x + \pi^0 + jet$, with π^0 → "e"

\+ $\nu_\mu \rightarrow \nu_e$ → $\nu_e + Ar \rightarrow e + jet$

Excess…

CNGS neutrino fluxes and rates



CERN SL-note 2000-063 EA

Energy region E_{ν_μ} [GeV]	1 - 30	1 - 100
ν_μ [m^{-2}/pot] ν_μ CC events/pot/kt	7.36×10^{-9} 5.05×10^{-17}	7.78×10^{-9} 5.85×10^{-17}
$\langle E \rangle_{\nu_\mu\,fluence}$ [GeV]		17.7
fraction of other neutrino events: ν_e/ν_μ $\overline{\nu}_\mu/\nu_\mu$ $\overline{\nu}_e/\nu_\mu$	0.8 % 2.1 % 0.07 %	

- Small ν_e contamination

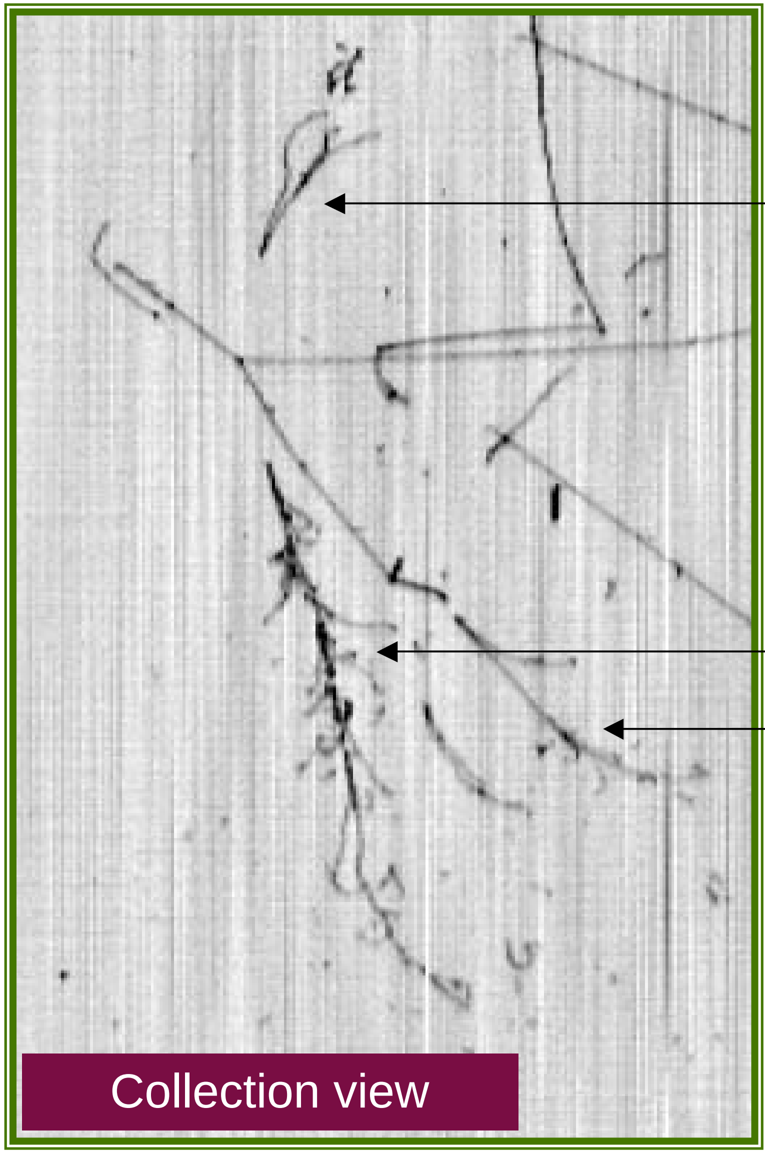
$$\nu_e / \nu_\mu = 0.8\%$$

- Error on knowledge relative to ν_μ

$$\Delta\nu_e / \nu_\mu \approx \left(\pm 5\% \nu_e\right) / \nu_\mu$$

$$\approx \pm 4 \times 10^{-4}$$

Pi zero candidate (preliminary)



Run 975, Event 151

- Reconstruction of γ-showers

T600

158 MeV

752 MeV

140 MeV

$\theta = 141^{o}$

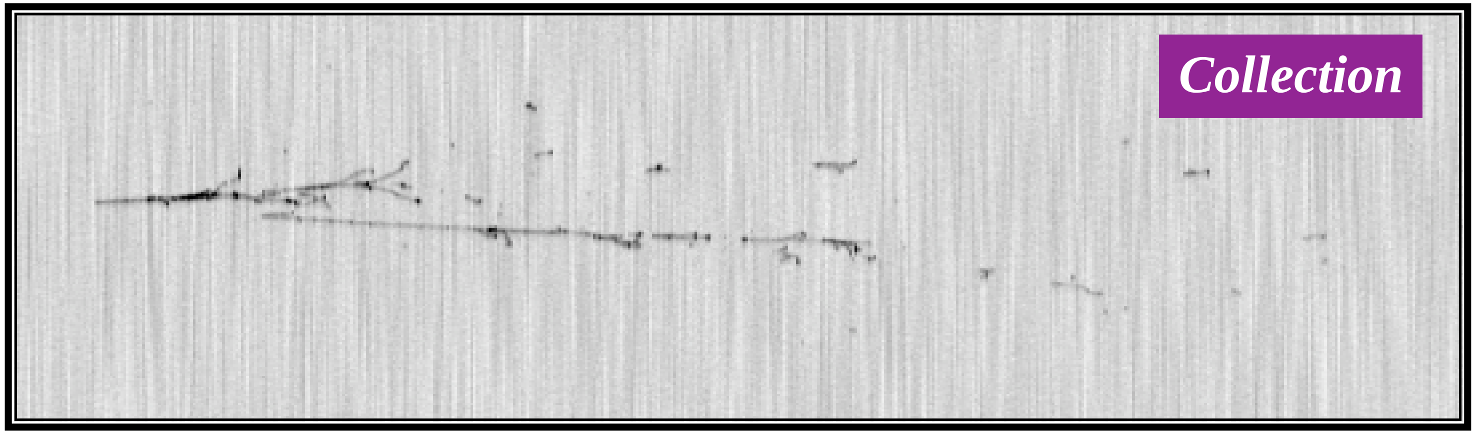
$M_{inv} = 650$ MeV

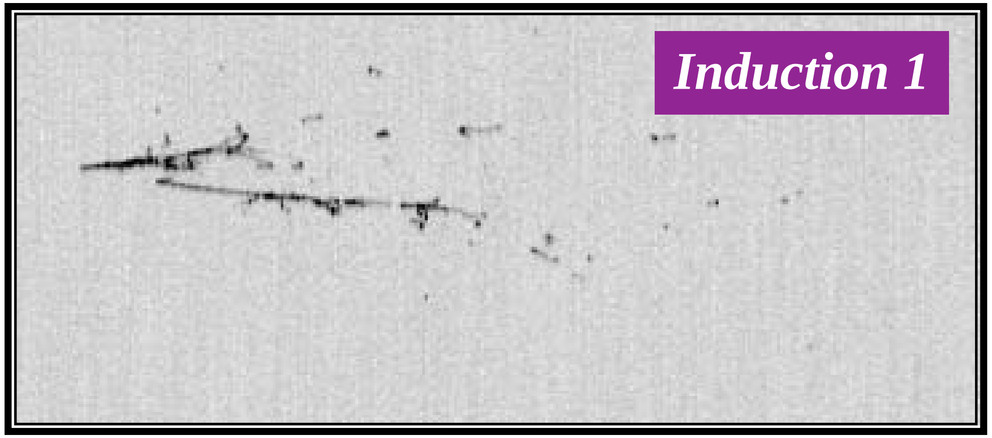
$\theta = 25^{o}$

$M_{inv} = 140$ MeV

(error evalulation in progress)

A fully simulated and digitized π^0 event

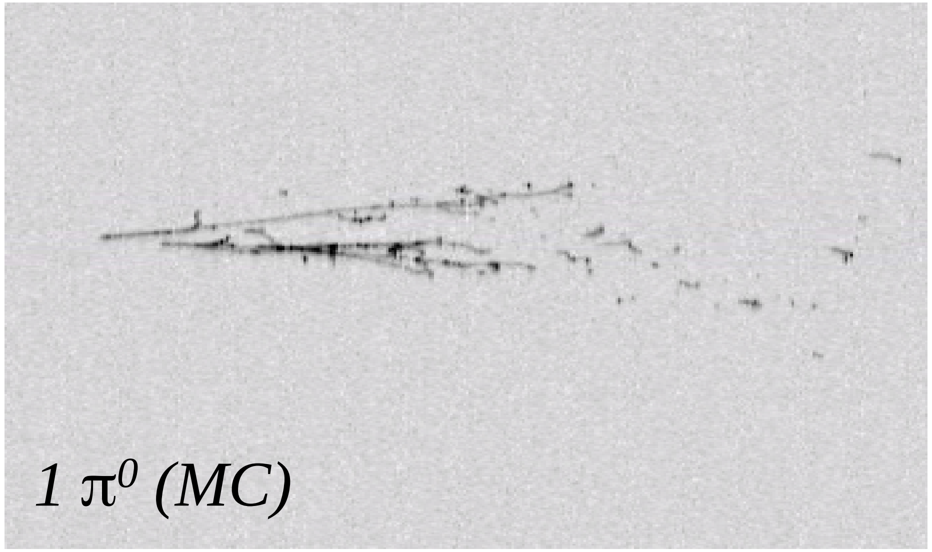


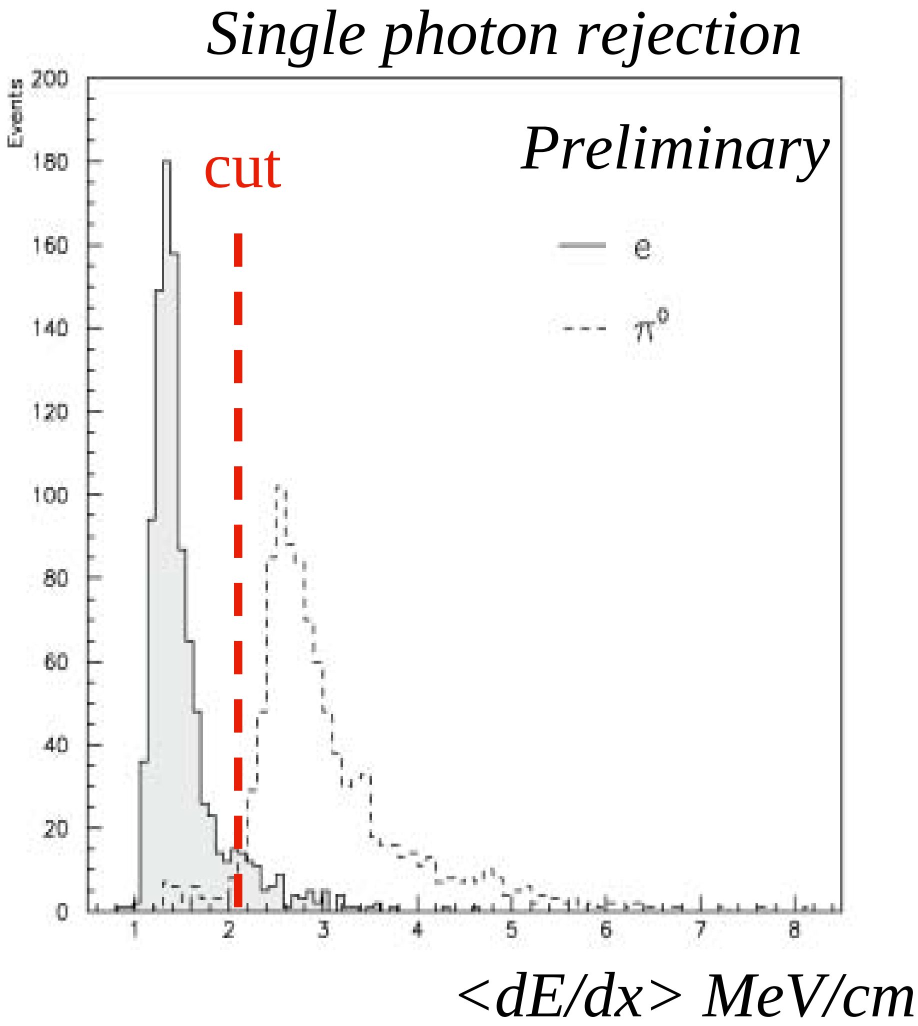


full simulation,digitization, and noise inclusion

Rejection π_0 based on imaging

- Based on full simulation, digitization, noise and automatic reconstruction of events
- Algorithm: cut for 90% eff. electrons
  1. Events with vertex: conversion within 1cm (3 wires) of vertex $R_1 \approx 19$
  2. Single/double mip $R_2 \approx 30$ (preliminary)

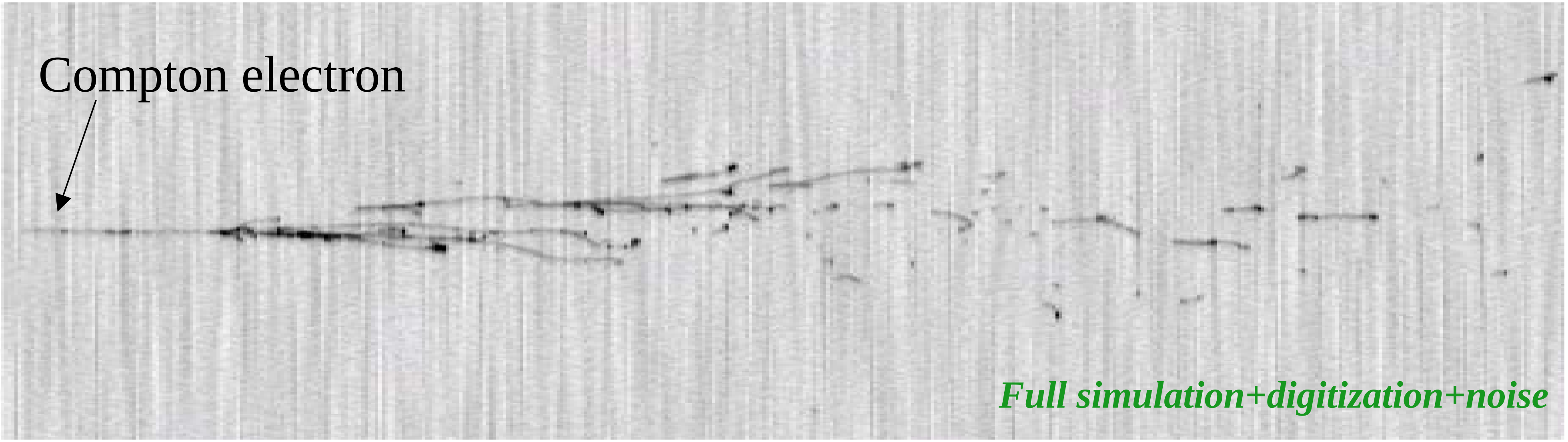




Imaging provides $\approx 2 \times 10^{-3}$ efficiency for single π_0

Rejection π_0 based on imaging

- π^0 surviving dE/dx separation cut (total 31 events out of 1000 1GeV π^0)
  - ➥ 21 events: Compton scattering
  - ➥ 5 events: Asymmetric decays (partners have less than 4 MeV)
  - ➥ 2 events: positron annihilation immediately
  - ➥ 1 event: positron make immediate Bremsstrahlung taking >90% of energy
- π^0 rejection improves with energy: 5% @ 0.25 GeV, 4% @ 0.5 GeV, 3% @ 1 GeV, 2% @ 2 GeV

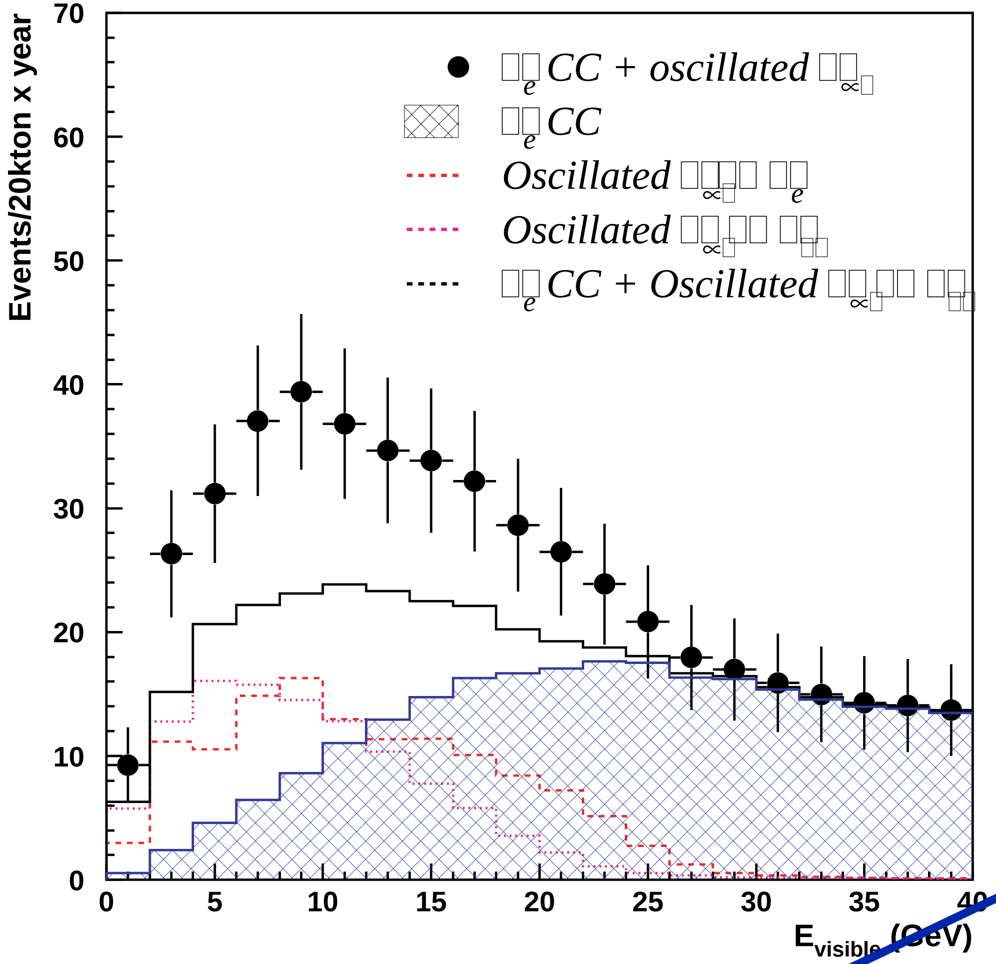


- Further rejection by kinematical cuts (depends on actual beam energy profile)
  - ➥ E.g. $\nu n \rightarrow \nu \pi^0 n$: precise mass reconstruction

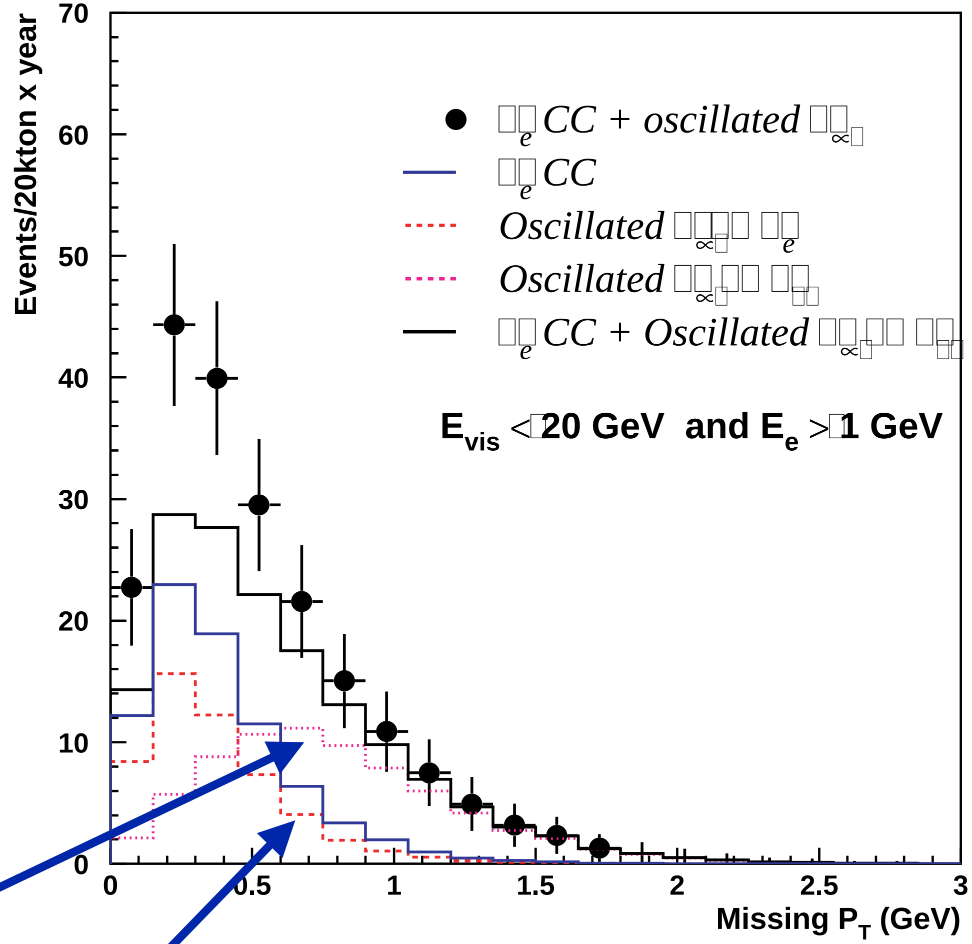
Finally: NC EVENT rejection: $F(NC) <\approx 1\times10^{-3}$

Δm^2_{32}=3.5x10^{-3} eV^2; $\sin^2 2\theta_{23}$ = 1 ; $\sin^2 2\theta_{13}$ = 0.05

Total visible energy



Transverse missing P_T



$$P(\nu_\mu \to \nu_\tau) = \cos^4\theta_{13}\sin^2 2\theta_{23}\Delta^2_{32}$$

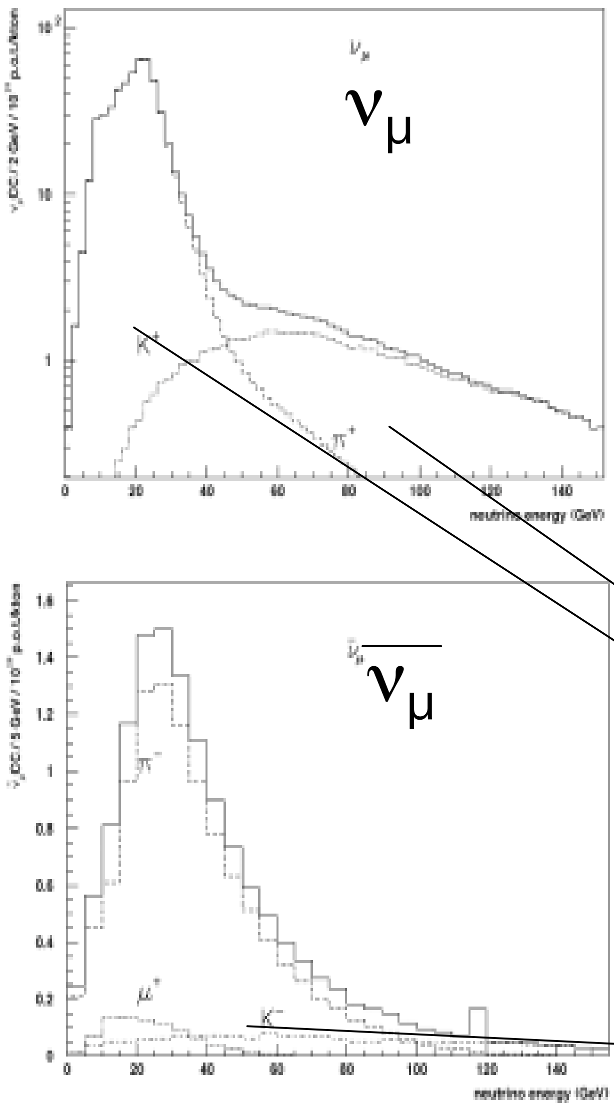
$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{13}\sin^2\theta_{23}\Delta^2_{32}$$

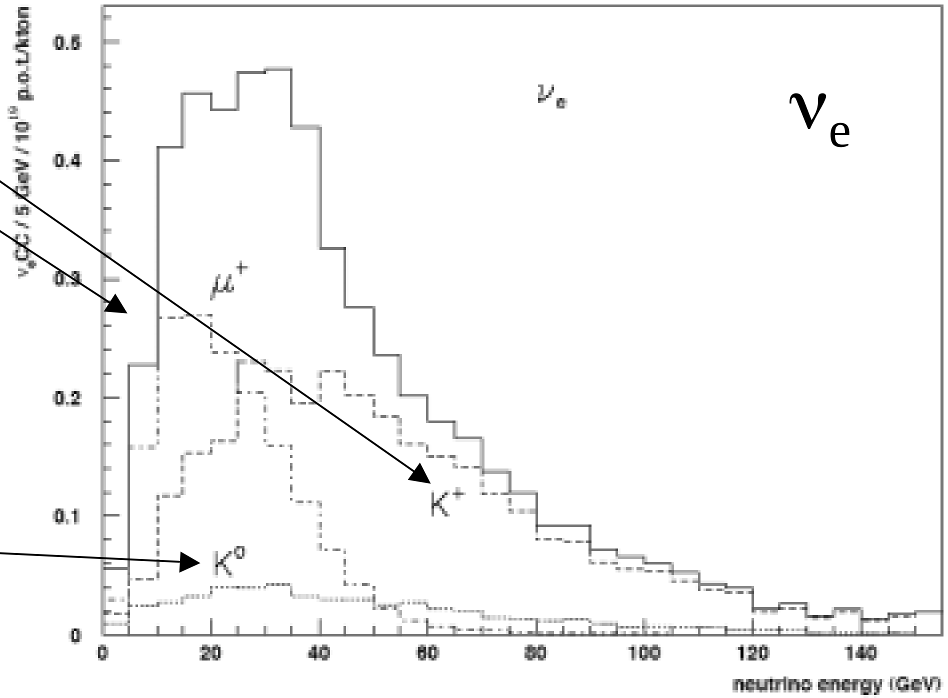
Predicting beam components (I)

- CERN-NGS has no "near station"
  - ➥ Beam components cannot be "measured" in absence of oscillations (near/far comparison)
  - ➥ Note however that near/far also relies heavily on MC calculations since near/far spectra are different
- Neutrino beam components must be calculated
  - ➥ Precise knowledge of all elements in beam line
  - ➥ Precise monitoring of proton beam impinging on target (beam spot position + tails)
  - ➥ Precise alignment of elements and monitoring of geometry (A.E.Ball et al., CERN-EP-2001-037/CERN-SL-2001-016 EA)
  - ➥ Muon monitors
  - ➥ Dedicated hadron-production experiment : **NA56/SPY experiment**
  - ➥ A good MC program (FLUKA)
- Preliminary estimate (Guglielmi et al., INFN note):
  - ➥ systematic error at CNGS: **3% on ν_e/ν_μ**

Predicting beam components (II): in situ

- 10% of ν_μ CC events have E_ν>50 GeV
- Precise measurement for *p* above 50 GeV and charge discrimination help in the prediction of the ν_e component
- See **PREDICTION OF NEUTRINO FLUXES IN THE NOMAD EXPERIMENT.** By NOMAD Collaboration (P. Astier *et al.*). CERN-EP-2003-032, Jun 2003. 43pp. Submitted to NIMA e-Print Archive: **hep-ex/0306022**





For $\Delta m^2_{23} = 2.5 \times 10^{-3}$

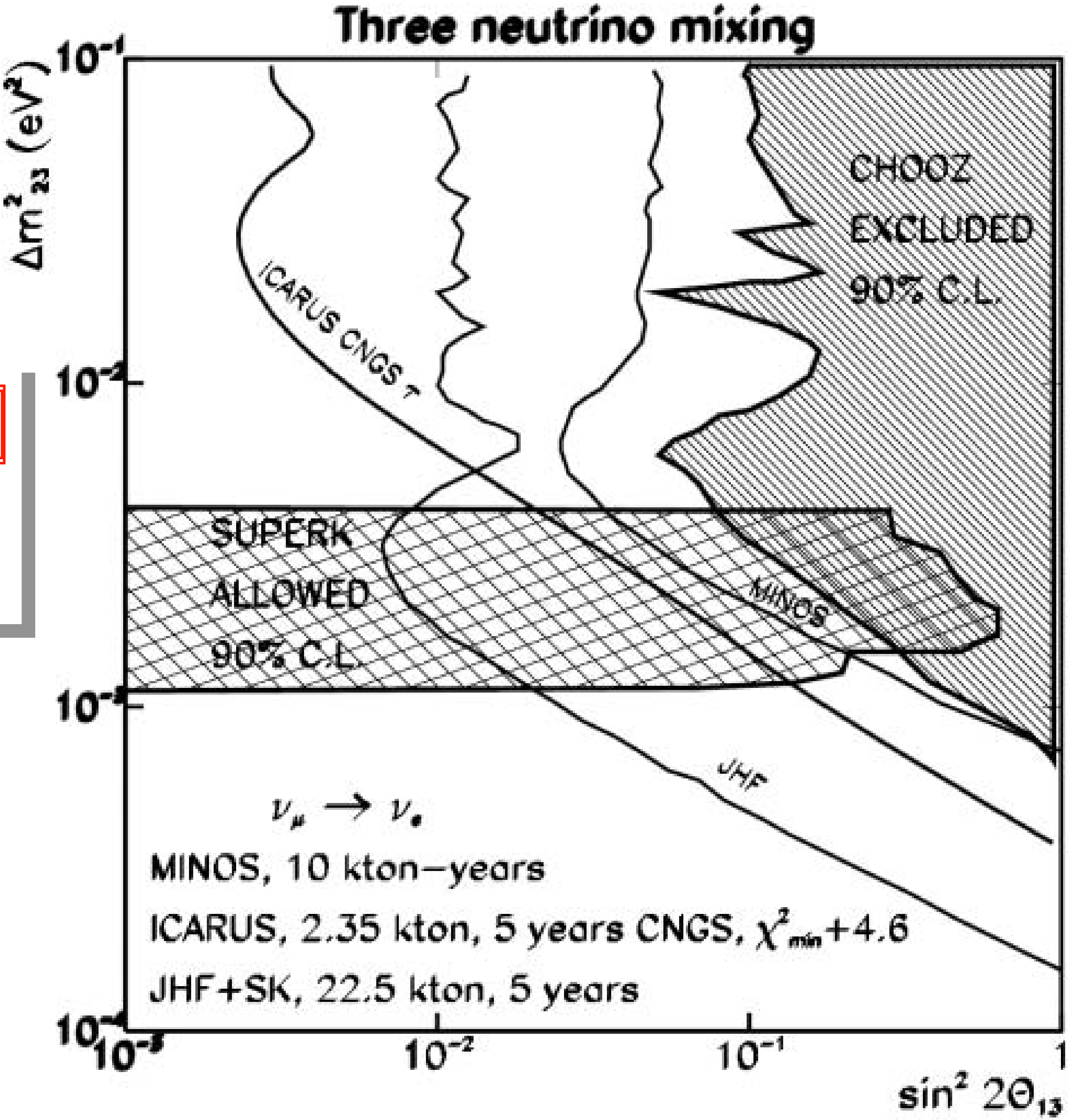
$$(\sin^2 2\theta_{13})_{CNGS,\tau} < 0.04 \quad \text{or} \quad \theta_{13} < 6^\circ$$

$$(\sin^2 2\theta_{13})_{CHOOZ} < 0.14 \quad \text{or} \quad \theta_{13} < 11^\circ$$

$$(\sin^2 2\theta_{13})_{MINOS} < 0.06 \quad \text{or} \quad \theta_{13} < 7^\circ$$

pots “nominal”= $5 \times 4.5 \times 10^{19}$ = 2.25×10^{20} pots

Limited by statistics of CNGS!



SPS-CNGS beam optimization for θ_{13} (I): what?

- We have investigated the possibility to improve the CNGS beam performance for θ_{13} searches
- We showed that by an appropriate optimization of the target and focusing optics, we could increase the flux of low energy neutrinos by about a factor 5 compared to the current optimization
- This turns out to be the *most sensitive setup for θ_{13} searches* of the currently approved long-baseline experiments and is competitive with the proposed JHF superbeam
- PLEASE NOTE: this is not a proposal, it is a study by “physicists” trying to optimize “physics” output. In particular, technical feasibility, cost, cost vs physics optimization have NOT been addressed.
- More details in:
  - ➥ *A Low-energy Optimization Of The CERN-NGS Neutrino Beam For A Theta(13) Driven Neutrino Oscillation Search, JHEP 0209:004,2002*

SPS-CNGS beam optimization for θ_{13} (II): Motivations

- The confirmation that $\nu_\mu \rightarrow \nu_\tau$ oscillations will be an important milestone
  - ➥ However, the main focus of neutrino physics is shifting towards the subleading $\nu_\mu \rightarrow \nu_e$ oscillations driven by the so-called θ_{13} angle
- The measurement of a non-vanishing θ_{13} would
  - ➥ Be a discovery, proving that the mixing matrix is 3x3 and opening the door to search for CP-violation searches in the leptonic sector !

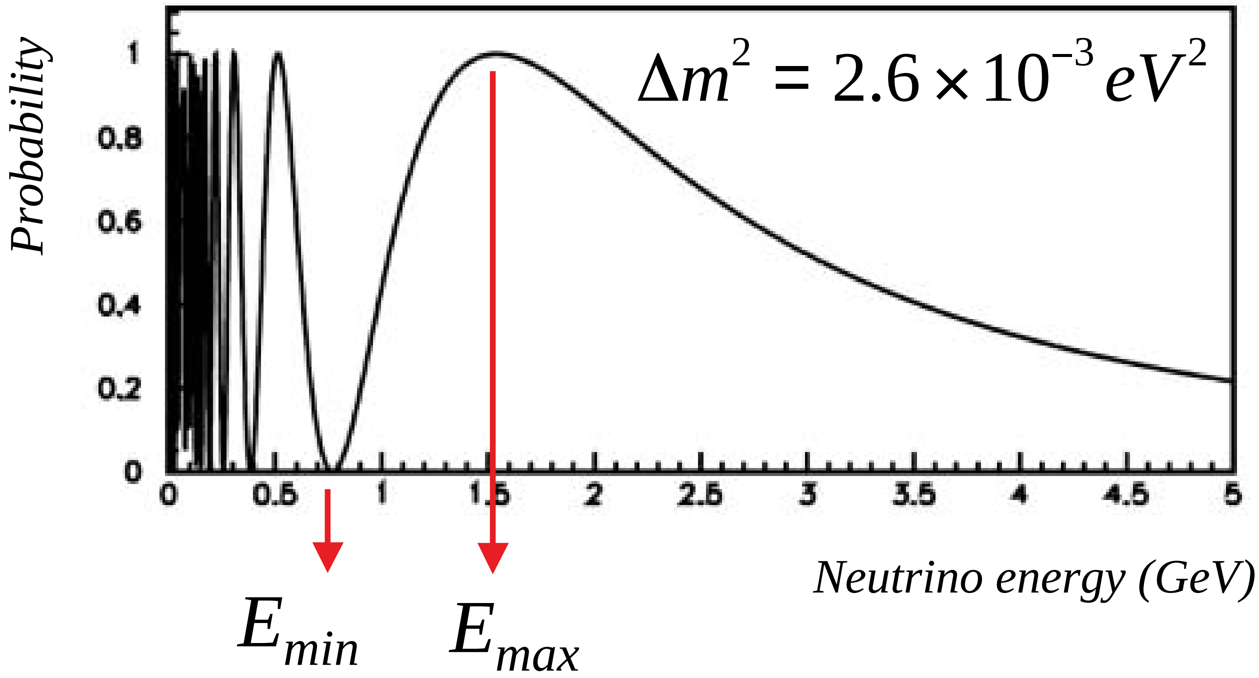
    (note that CP-violation effects will only be visible for relatively large θ_{13})
- The advantage of a "general purpose" detector like ICARUS
  - ➥ Can fully exploit a low energy beam !
  - ➥ Profits from unique e/π^0 separation in ICARUS

	$\Delta m^2 (\text{eV}^2)$							
L (km)	1×10^{-3}		2×10^{-3}		3×10^{-3}		4×10^{-3}	
	E_{max} MeV	E_{min} MeV	E_{max} MeV	E_{min} MeV	E_{max} MeV	E_{min} MeV	E_{max} MeV	E_{min} MeV
730	590	295	1180	590	1771	885	2361	1180

Maximize flux between 0 and 2.5 GeV !

Maximum & minimum of oscillation

L=730 km



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

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

Low energy CNGS optimization

The current CNGS optimization for τ appearance is not optimal for the search for subleading $\nu_\mu \rightarrow \nu_e$ oscillation. Try to optimize

Maximize flux between 0 and 2.5 GeV

E_p GeV	focus	decay tunnel length (m)	ν_μ flux ν/cm^2	ν_e flux ν/cm^2	10^{19} p.o.t. ν_μ CC ev/kton	10^{19} p.o.t. ν_e CC ev/kton	$< E_\nu >$, CC ν_μ GeV	$< E_\nu >$, CC ν_e GeV	ν_μ / ν_e CC
400	p.f	350	$1.3 \cdot 10^{-13}$	$2.6 \cdot 10^{-15}$	**9.0**	0.12	1.8	1.8	1.3%
400	horn	350	6.10^{-14}	$9.0 \cdot 10^{-16}$	**4.5**	$4.2 \cdot 10^{-2}$	1.8	1.4	0.9%
400	p.f †	CNGS	$1.6 \cdot 10^{-14}$	$3.2 \cdot 10^{-16}$	**1.8**	$2.2 \cdot 10^{-2}$	2.1	1.7	1.2%
400	$\tau^\dagger$	CNGS	$1 \cdot 10^{-14}$	$9.4 \cdot 10^{-17}$	**0.9**	$8.7 \cdot 10^{-3}$	1.8	1.8	0.9%

Table 3: Neutrino beam parameters for the CNGS baseline, with $E_\nu < 2.5$ GeV. The † cases correspond to the *present CNGS design* for target, acceptance and focusing system.

Factor of 5 improvement at low energy

Low energy CNGS target and optics

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

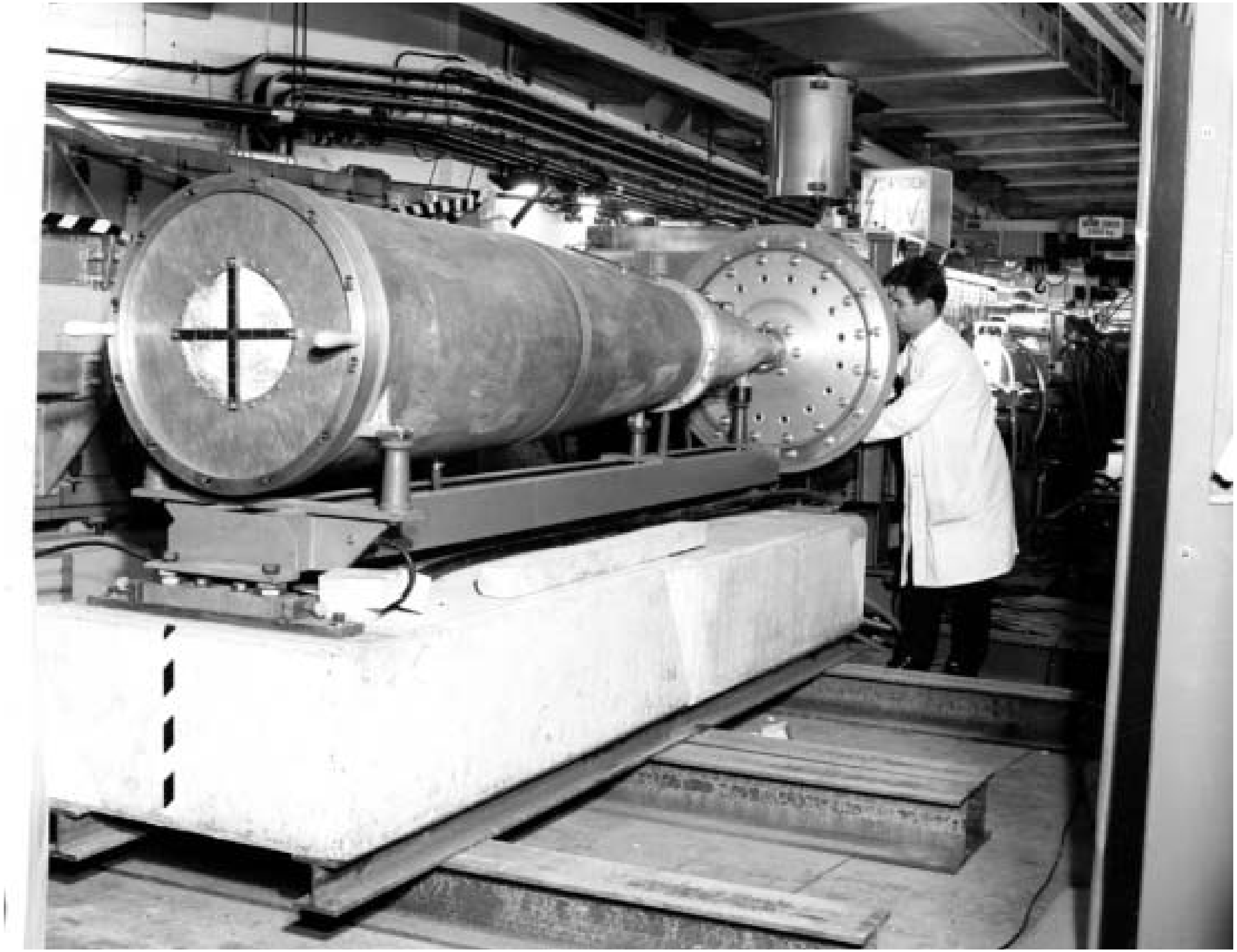
Table 2: Parameter list for the present CNGS design and the "new" beam for low energy ν . For the parameters flagged with a †, a full optimization has not been performed and possible improvements have not been studied yet.

New compact target

New focusing

Decay tunnel

Focusing horn (1963)

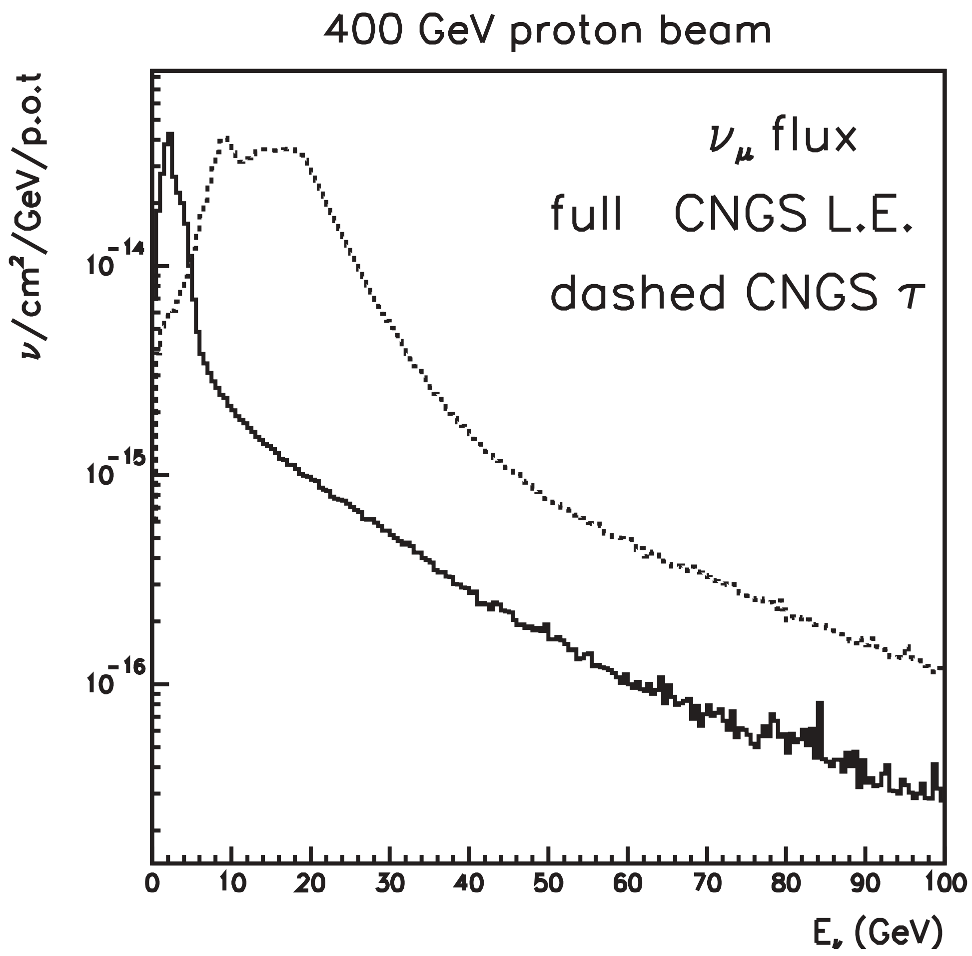


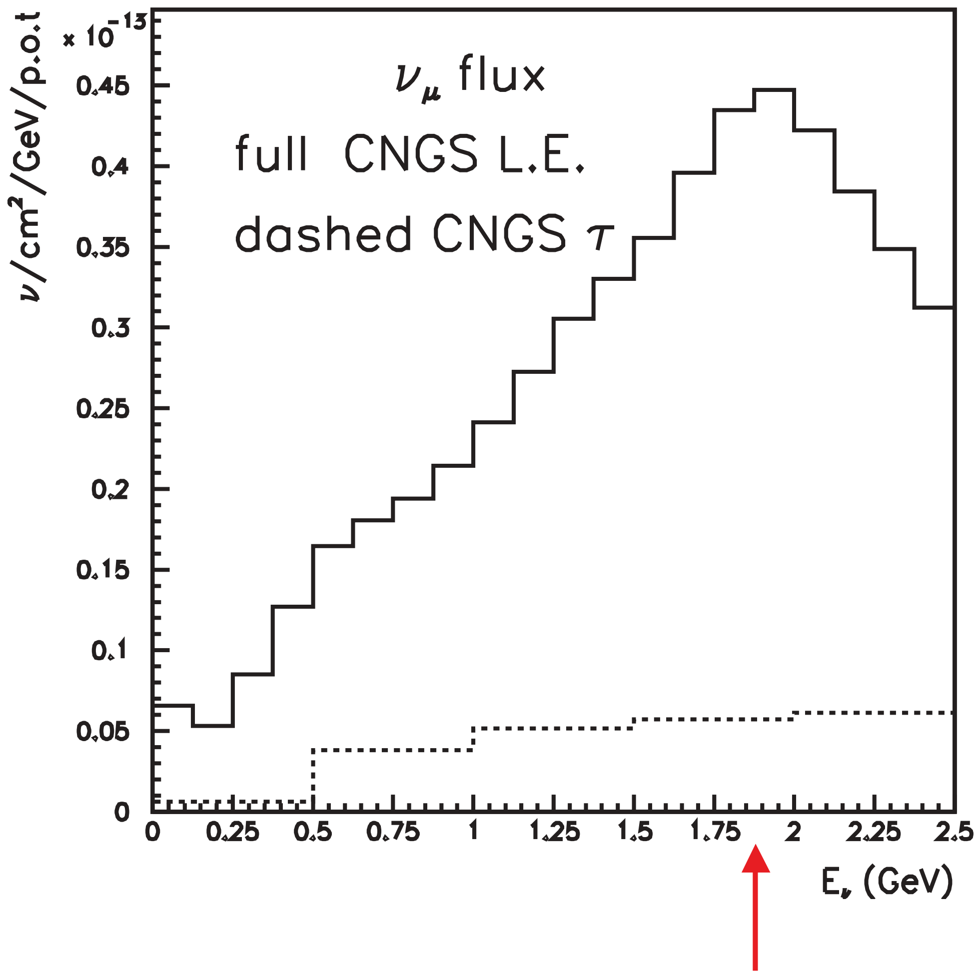
CERN-CDS

Reflector (1966)

CERN-CDS

Predicted neutrino fluxes





- Full FLUKA simulation
- Factor 5 improvement at low energy

Maximum oscillation
For $\Delta m^2 = 3\times10^{-3}$ eV^2

Expected number of events

θ_{13} (degrees)	$\sin^2 2\theta_{13}$	ν_e CC		$\nu_\mu \to \nu_e$	
		$E_\nu < 4$ GeV	$E_\nu < 50$ GeV	$E_\nu < 4$ GeV	$E_\nu < 50$ GeV
9	0.095	5	44	16	22.
8	0.076	5	44	13	18.
7	0.059	5	44	10	13
5	0.030	5	44	5	7
3	0.011	5	44	1.8	2.5
2	0.005	5	44	0.8	1.1
1	0.001	5	44	0.2	0.3

CNGS L.E.

Table 4: Events from the CNGS L.E. beam, assuming $\Delta m^2_{23} = 3 \times 10^{-3} eV^2$, $\theta_{23} = 45°$, 5 years of operation and 2.35 kton fiducial mass.

θ_{13} (degrees)	$\sin^2 2\theta_{13}$	ν_e CC		$\nu_\mu \to \nu_e$	
		$E_\nu < 4$ GeV	$E_\nu < 50$ GeV	$E_\nu < 4$ GeV	$E_\nu < 50$ GeV
9	0.095	1.5	150	4	42
8	0.076	1.5	150	3.1	34
7	0.059	1.5	150	2.4	26
5	0.030	1.5	150	1.2	14
3	0.011	1.5	150	0.4	5
2	0.005	1.5	150	0.2	2.2
1	0.001	1.5	150	0.1	0.5

CNGS τ

Table 5: Events from the CNGS τ beam, assuming $\Delta m^2_{23} = 3 \times 10^{-3} eV^2$, $\theta_{23} = 45°$, 5 years of operation and 2.35 kton fiducial mass.

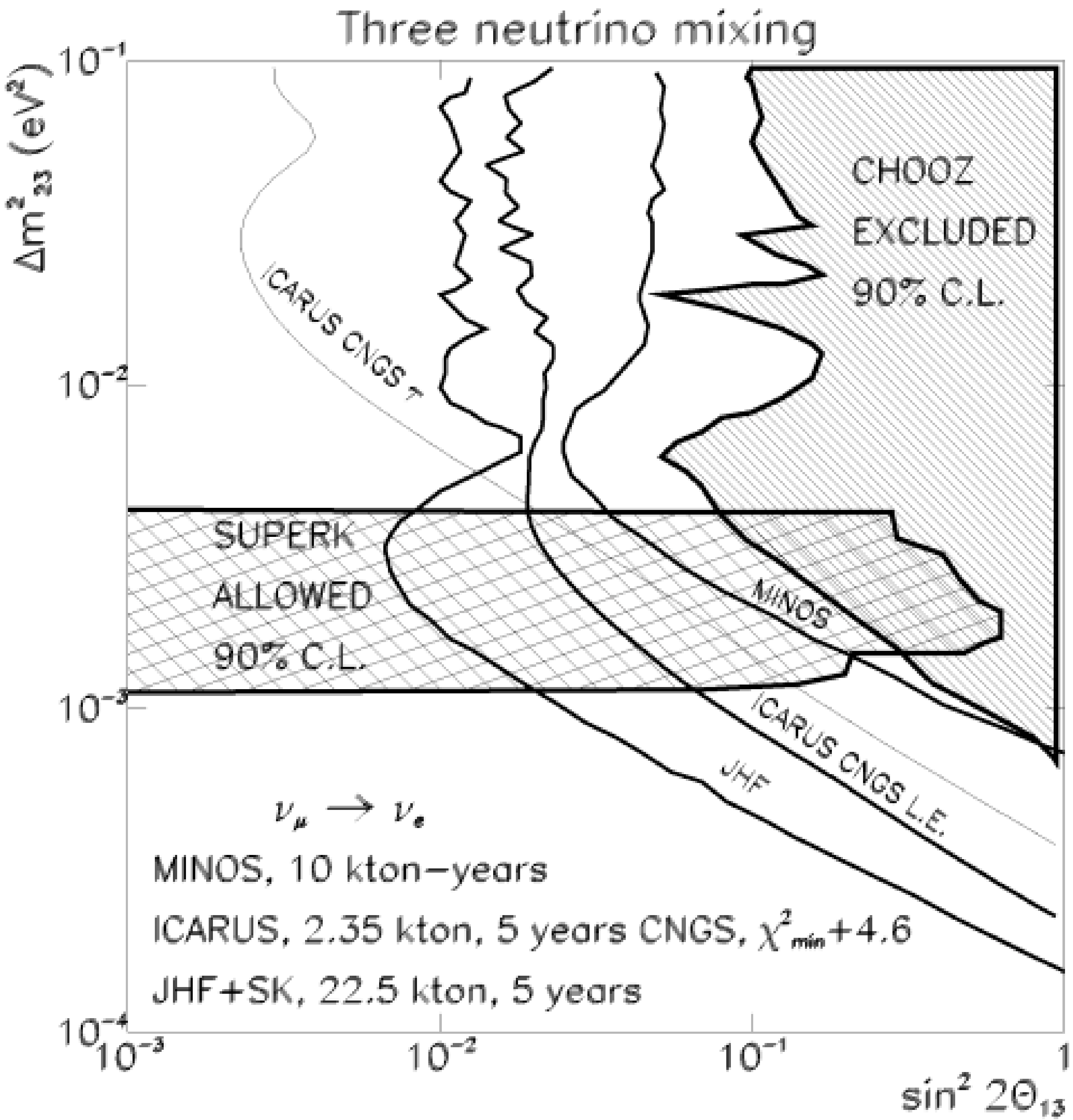
For $\Delta m^2_{23} = 2.5 \times 10^{-3}$

$$(\sin^2 2\theta_{13})_{\mathrm{CNGS,L.E.}} < 0.02\,,$$

$$\text{or} \qquad \theta_{13} < 4^o\,.$$

pots “nominal”= $5 \times 4.5 \times 10^{19}$ = 2.25×10^{20} pots

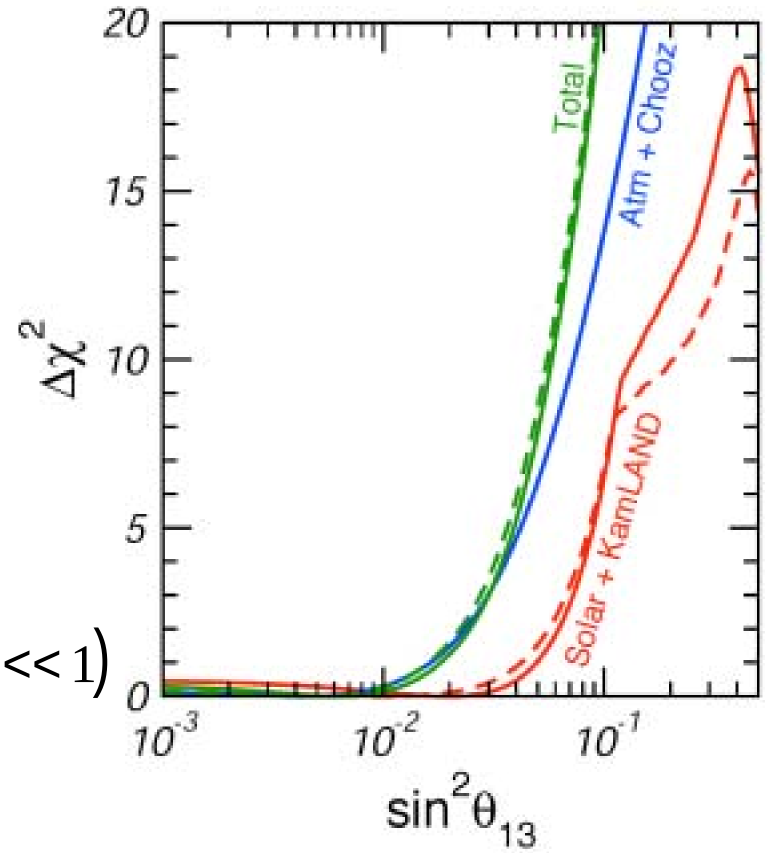
(Still) Limited by statistics of CNGS but optimized



Overall fit of oscillation parameters

Maltoni et al., hep-ph/0309130

parameter	best fit	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	6.9	6.0–8.4	5.4–9.5
Δm^2_{31} $[10^{-3}\mathrm{eV}^2]$	2.6	1.8–3.3	1.4–3.7
$\sin^2\theta_{12}$	0.30	0.25–0.36	0.23–0.39
$\sin^2\theta_{23}$	0.52	0.36–0.67	0.31–0.72
$\sin^2\theta_{13}$	0.006	≤ 0.035	≤ 0.054



Warning: $\sin^2 2\theta_{13} \approx 4\sin^2\theta_{13}$ $(\theta_{13} << 1)$

Assumptions:

- Only 3-mixing neutrinos
- Ignore LSND result
- Atmospheric oscillation is tau appearance

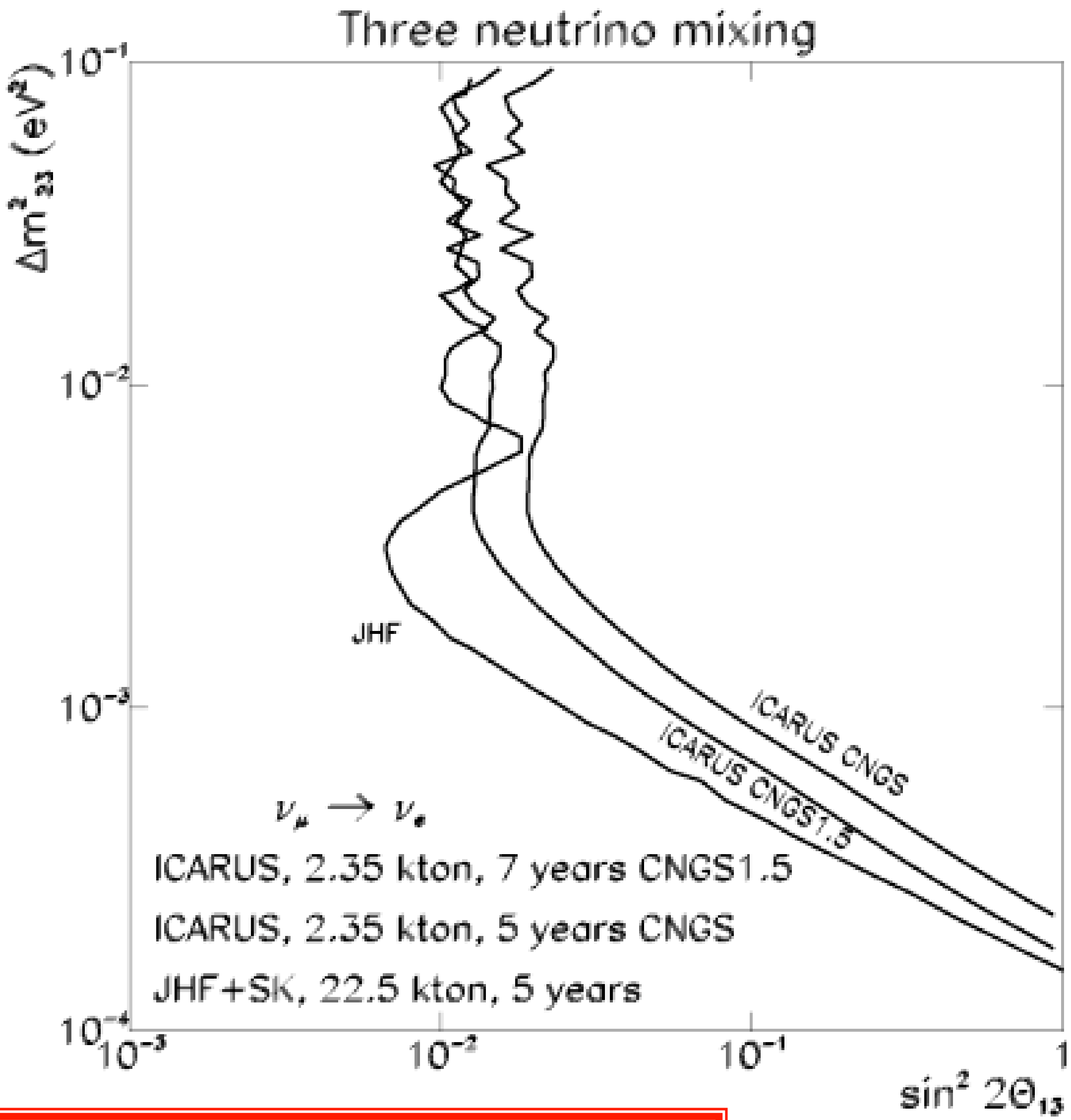
- Combine solar, atmospheric, reactors

$$\left(\sin^2 2\theta_{13}\right)_{best} \approx 0.025$$

Sensitivity of CNGS L.E. optimization

Increasing the proton intensity of PS and SPS, (R. Cappi et al., CERN-PS-2001-041-AE)

pots "upgrade"= $1.5 \times 7 \times 4.5 \times 10^{19}$ = 4.7×10^{20} pots



For $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2:

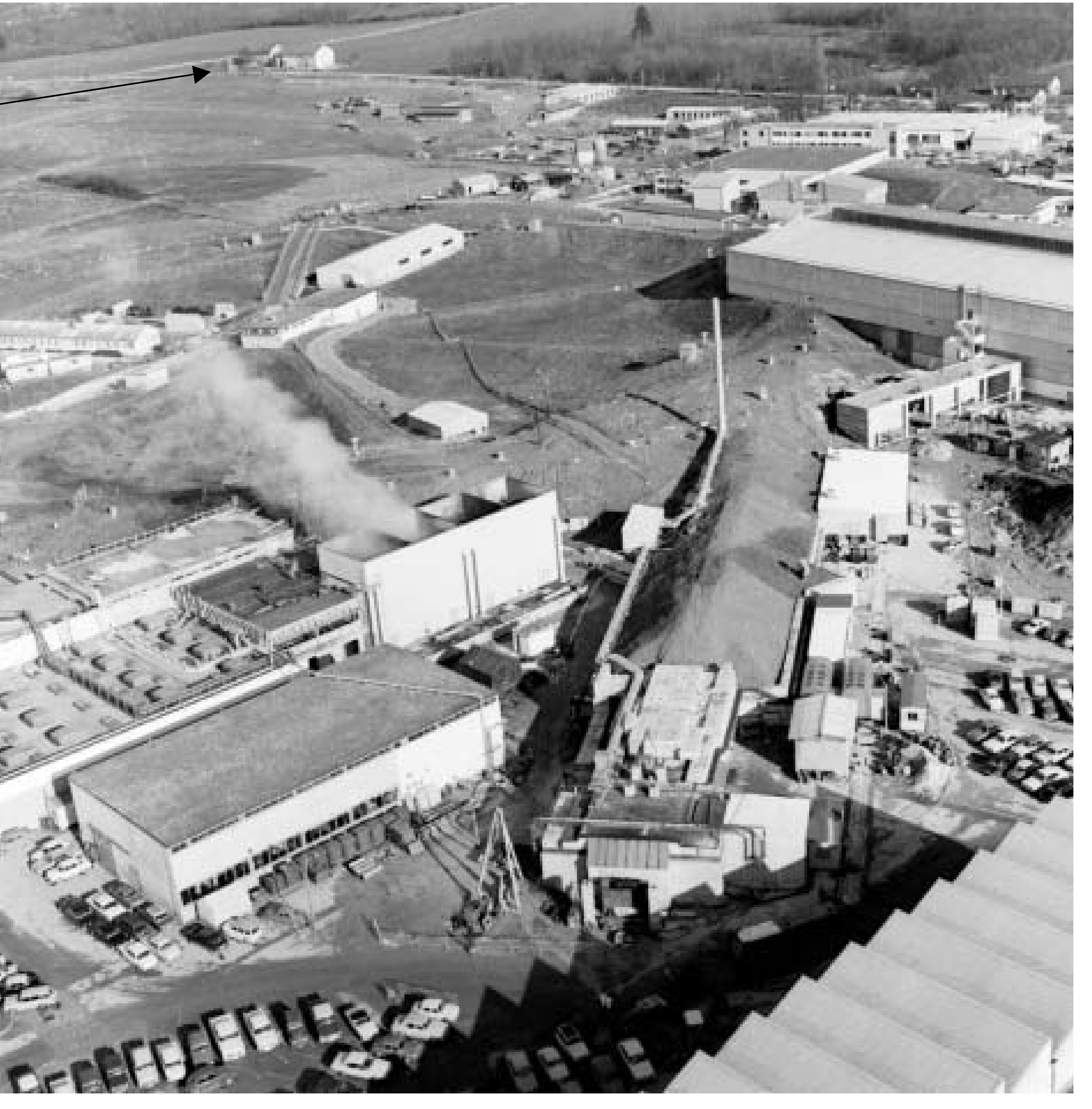
$$(\sin^2 2\theta_{13})_{CNGS1.5,L.E.} < 0.015 \quad \text{or} \quad \theta_{13} < 3.5^\circ$$

Proton beam optimization for θ_{13}

- Upgraded proton driver intensity ??? YES!
  - In case of evidence for non vanishing θ_{13} at CNGS, a more intense "superbeam" will be required to gain more statistics to understand better the phenomenon
  - In case of negative result, more sensitivity will be required…
- New types of neutrino beams have been proposed
  - Neutrino factories (mu ring) require high intensity proton source (+ €'s)
  - β-beams ("Zuc-beams")
  - "Conventional low energy" using high intensity SPL @ E_p=2.2 GeV
  - All are very good match to large underground ICARUS-like detectors
- We ask a question concerning conventional pion beams:
  - Given the oscillation parameters and a given baseline, is there a best proton energy from the point of view of proton "economics"?
- More details in:
  - *"Proton Driver Optimization For New Generation Neutrino Superbeams To Search For Subleading $\nu_\mu \to \nu_e$ Oscillations (Theta(13) Angle)", New J.Phys.4:88,2002*

View of the neutrino area (1967)

Swiss-French border



CERN-CDS

Baselines…


CERN
L=130 km
Fréjus
L=730 km
LNGS
France
Austria
Slovenia
Italy
Andorra
Bosnia and Herzegovina
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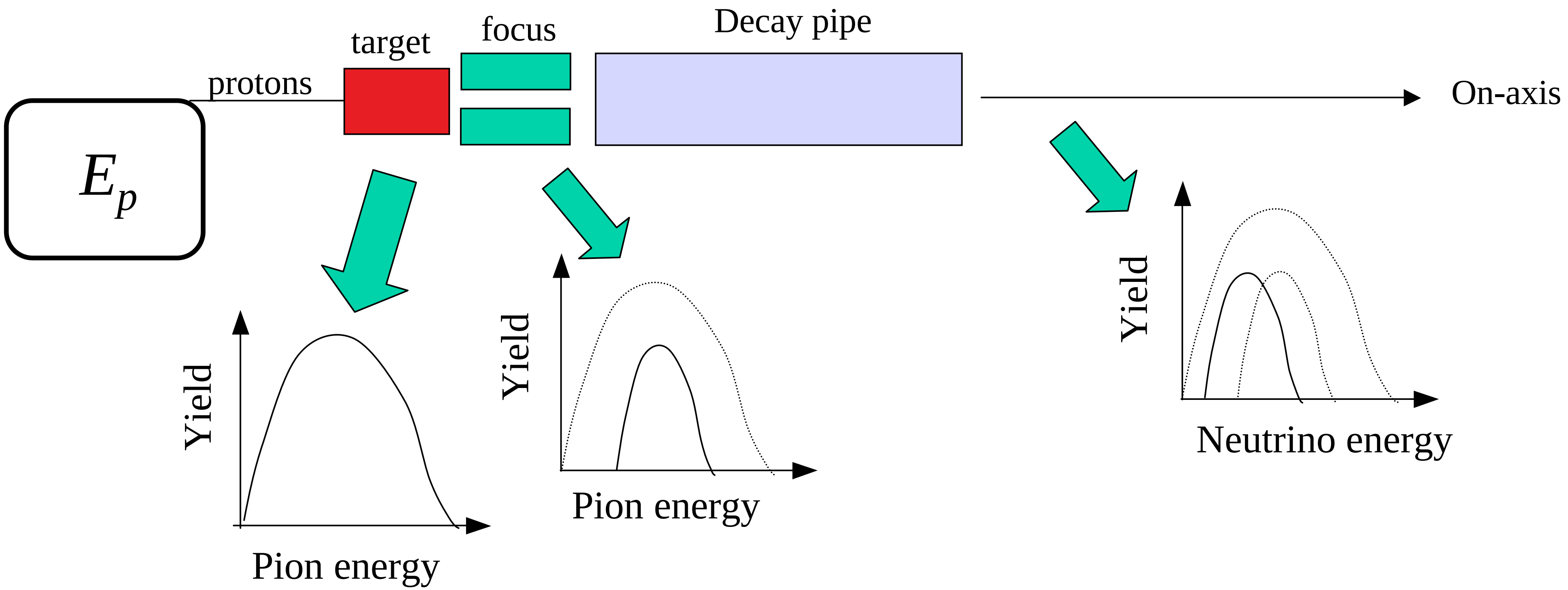
…neutrinos do not care, provided they have the right energy

	Δm^2 (eV^2)							
	1×10^{-3}		2×10^{-3}		3×10^{-3}		4×10^{-3}	
L (km)	E_{max} (MeV)	E_{min} (MeV)	E_{max} (MeV)	E_{min} (MeV)	E_{max} (MeV)	E_{min} (MeV)	E_{max} (MeV)	E_{min} (MeV)
100	81	40	162	81	243	121	323	162
150	121	61	243	121	364	182	485	243
200	162	81	323	162	485	243	647	323
300	243	121	485	243	728	364	970	485
400	323	162	647	323	970	485	1294	647
500	404	202	809	404	1213	606	1617	809
600	485	243	970	485	1455	728	1940	970
730	590	295	1180	590	1771	885	2361	1180

Proton driver optimization



If the neutrino detector is far away:

- neutrino energy ≈ 0.43 × pion energy
- Lorentz-boost gives a factor E_ν^2 on solid angle

For E_p, we consider LE (2.2, 4.4 GeV), ME (20÷50 GeV), HE (400 GeV)

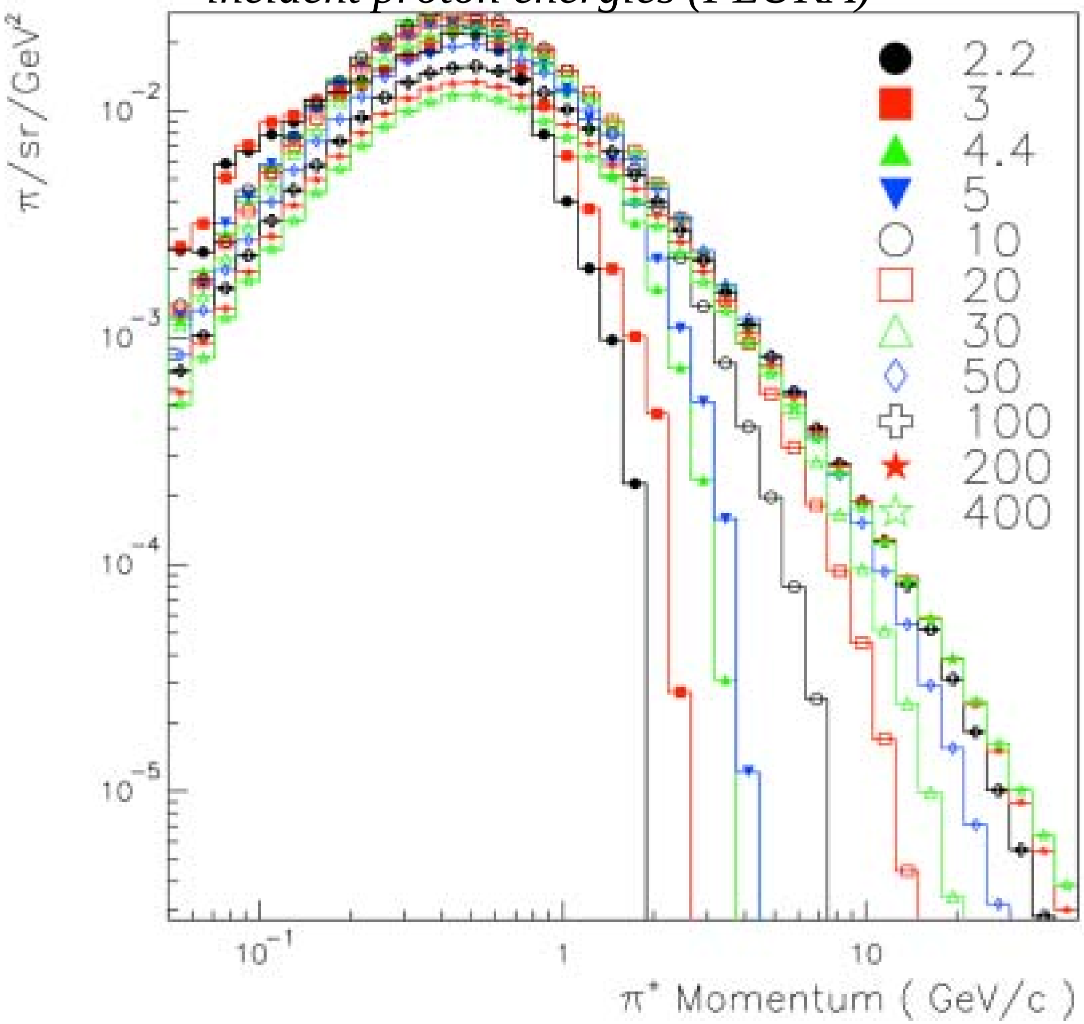
(SPL) *("PS")* *(SPS)*

Neutrino beam: 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

Estimated positive pion yields for different incident proton energies (FLUKA)



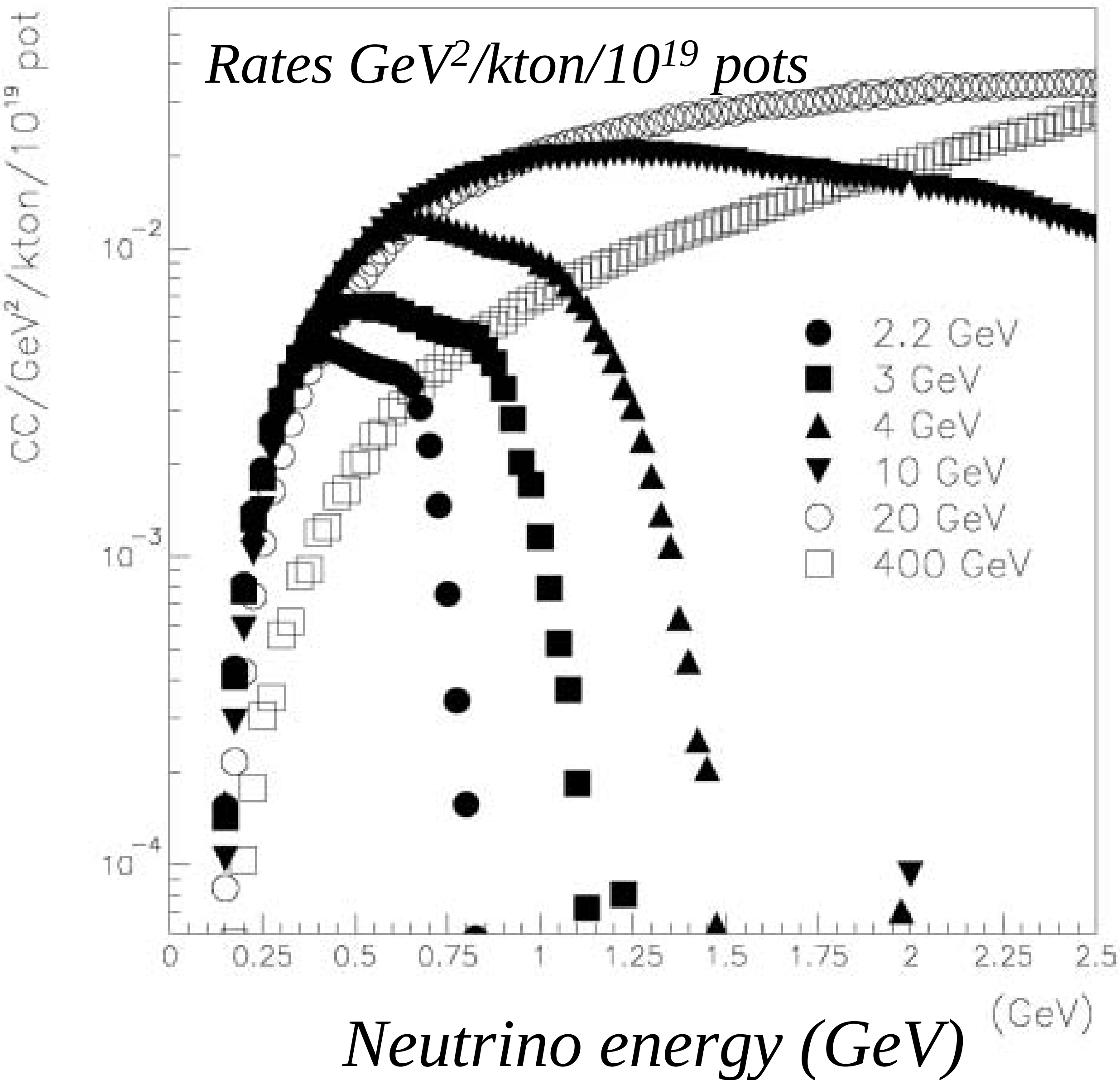
Neutrino beam: scaling of neutrino production

Muon-neutrino charged current interactions at L=732 km for different incident proton energies

The superposition of the curves at the lowest energies (expect for 400 GeV) is impressive.
<u>The neutrino rate at low energy is simply proportional to E_p!</u>

The **power factor**:

$$F \equiv E_p \times N_{pot}$$



Neutrino beam: scaling of oscillated events

- We can now compute the number of $\nu_\mu \rightarrow \nu_e$ oscillated neutrino events

$$N_e \propto N_{pot} \times \int dE_\nu \sigma(E_\nu) \phi(E_\nu) P(E_\nu, L, \Delta m^2, \theta_{13})$$

- One assumes for the moment "perfect focusing" with efficiency ε=20% and an acceptance of 1 rad
- We compute the needed proton on target (N_{pot}) in order to have N_e=5 in a detector of 2.35 km for various proton energies and **$\sin^2 2\theta_{13}$ = 0.001**
- Similarly, we can also compute the number of ν_μ charged current events in the region of oscillation

$$N^0_{\mu,CC} \propto \int_{E_{\min}}^{E_{\max}} dE_\nu \sigma(E_\nu) \phi(E_\nu)$$

Results
proton energy

baseline

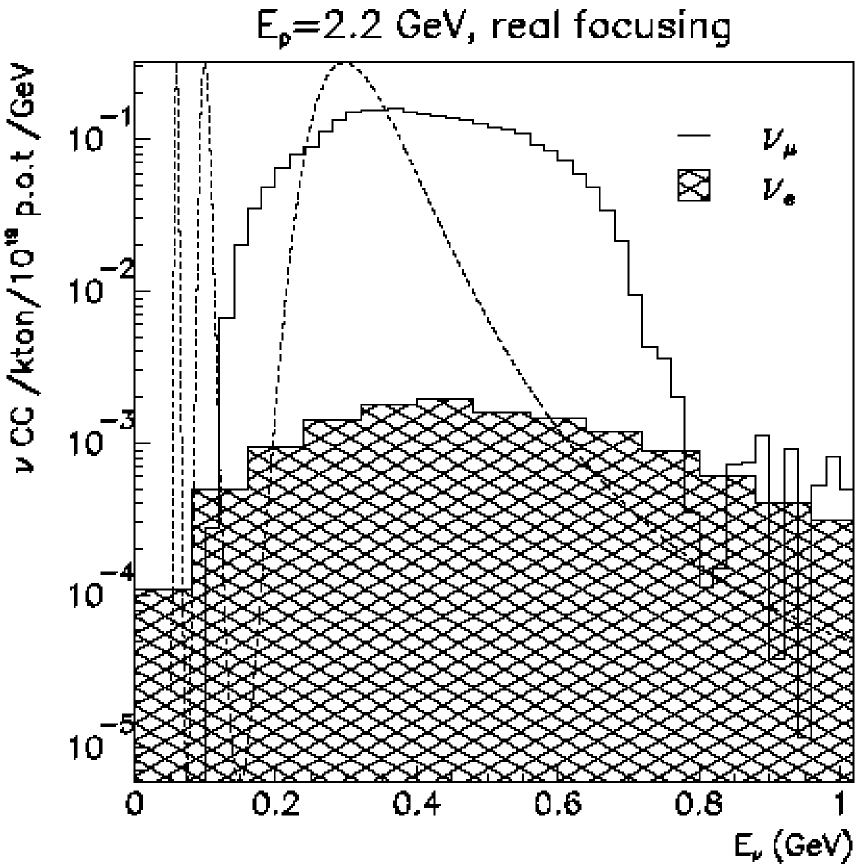
L (km)	2.2 GeV $N^0_{\mu,CC}$	2.2 GeV N_{pot}	4.4 GeV $N^0_{\mu,CC}$	4.4 GeV N_{pot}	20 GeV $N^0_{\mu,CC}$	20 GeV N_{pot}	50 GeV $N^0_{\mu,CC}$	50 GeV N_{pot}	400 GeV $N^0_{\mu,CC}$	400 GeV N_{pot}
100	0.035	2.9×10^{24}	0.048	2.1×10^{24}	0.20	5.1×10^{23}	0.3	3.4×10^{23}	1.0	1.0×10^{23}
150	0.052	$\mathbf{1.9 \times 10^{24}}$	0.098	1.0×10^{24}	0.45	2.2×10^{23}	0.7	1.4×10^{23}	2.3	4.4×10^{22}
200	0.046	2.2×10^{24}	0.122	$\mathbf{8.2 \times 10^{23}}$	0.65	1.5×10^{23}	1.1	9.5×10^{22}	3.5	2.9×10^{22}
300	0.023	4.3×10^{24}	0.112	8.9×10^{23}	0.90	1.1×10^{23}	1.6	6.4×10^{22}	5.4	1.9×10^{22}
400	0.013	7.7×10^{24}	0.081	1.2×10^{23}	0.97	$\mathbf{1.0 \times 10^{23}}$	1.8	5.6×10^{22}	6.4	1.6×10^{22}
500	0.008	1.2×10^{25}	0.055	1.8×10^{24}	0.96	$\mathbf{1.0 \times 10^{23}}$	1.9	5.3×10^{22}	7.1	1.4×10^{22}
600	0.006	1.8×10^{25}	0.038	2.7×10^{24}	0.91	1.1×10^{23}	1.9	$\mathbf{5.2 \times 10^{22}}$	7.5	$\mathbf{1.3 \times 10^{22}}$
730	0.003	2.9×10^{25}	0.025	4.0×10^{24}	0.83	1.2×10^{23}	1.9	$\mathbf{5.2 \times 10^{22}}$	7.8	$\mathbf{1.3 \times 10^{22}}$

For each baseline there is an optimal proton energy $E_p^{optimal}$, which minimizes the required integrated proton on targets

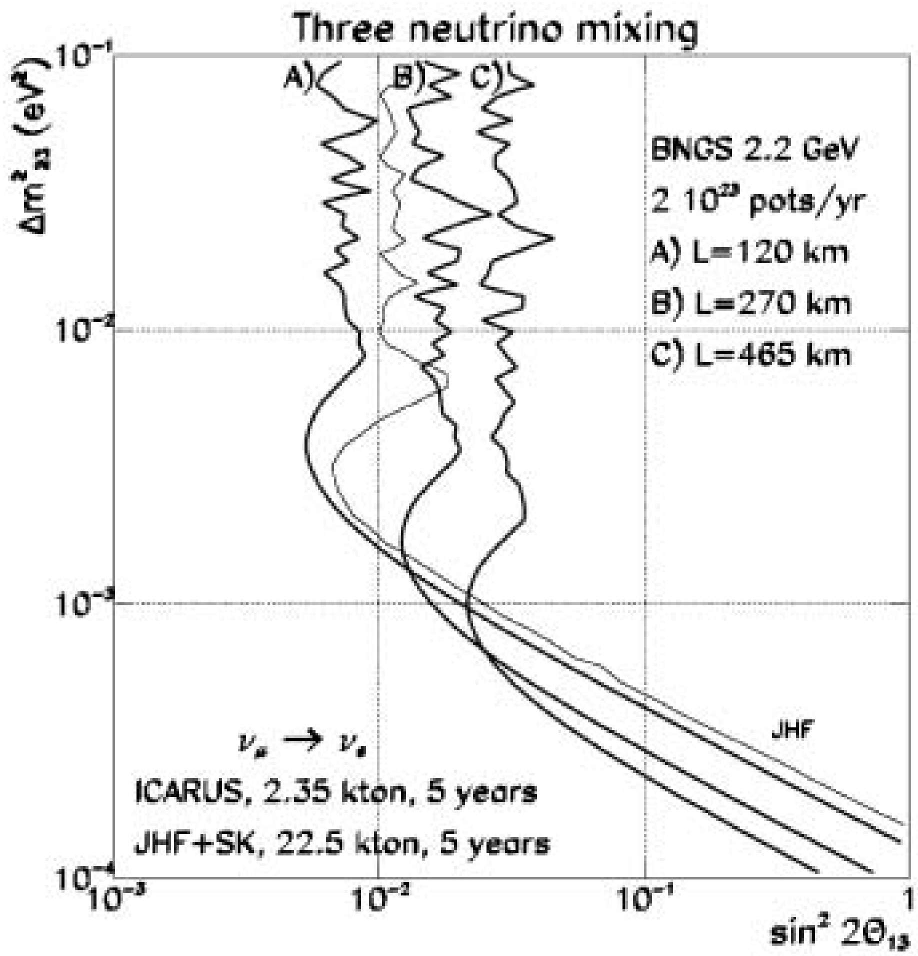
Conversely, for each proton energy there is an optimal baseline L_{opt}, which maximizes the integrated neutrino oscillation probability in the neutrino energy region which corresponds to the largest weighted pion yield at that proton energy

These results hold also in "real" focusing (see *New J.Phys.4:88,2002*)

Example I: 2.2 GeV SPL



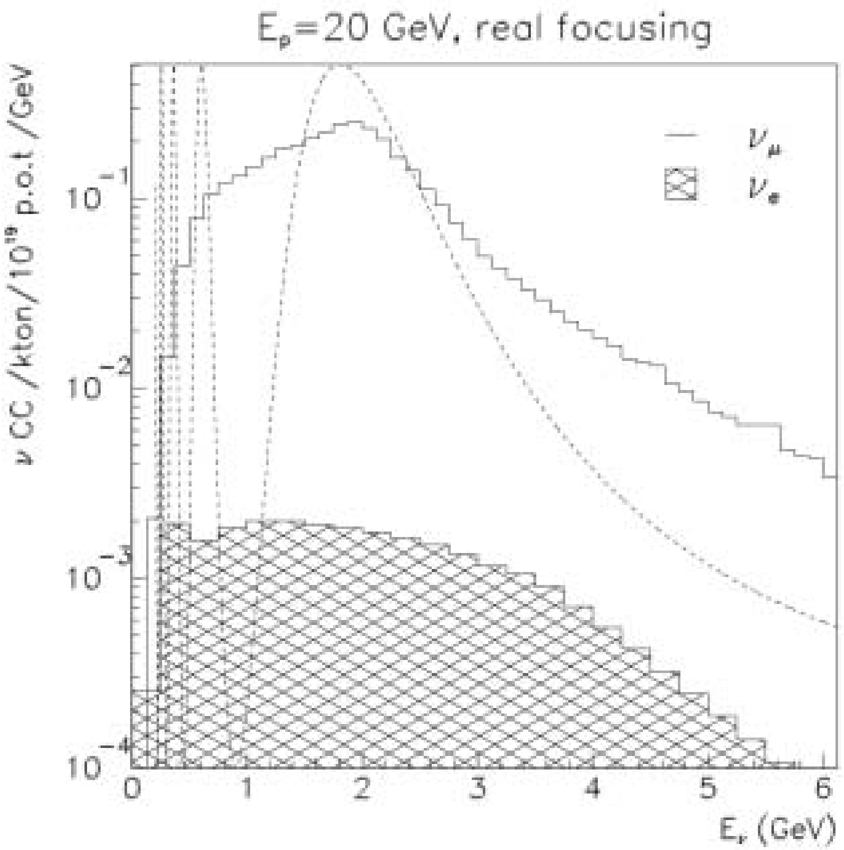
2x10^23 pots/yr @ 2.2 GeV
L=120 km and 2.35 kton



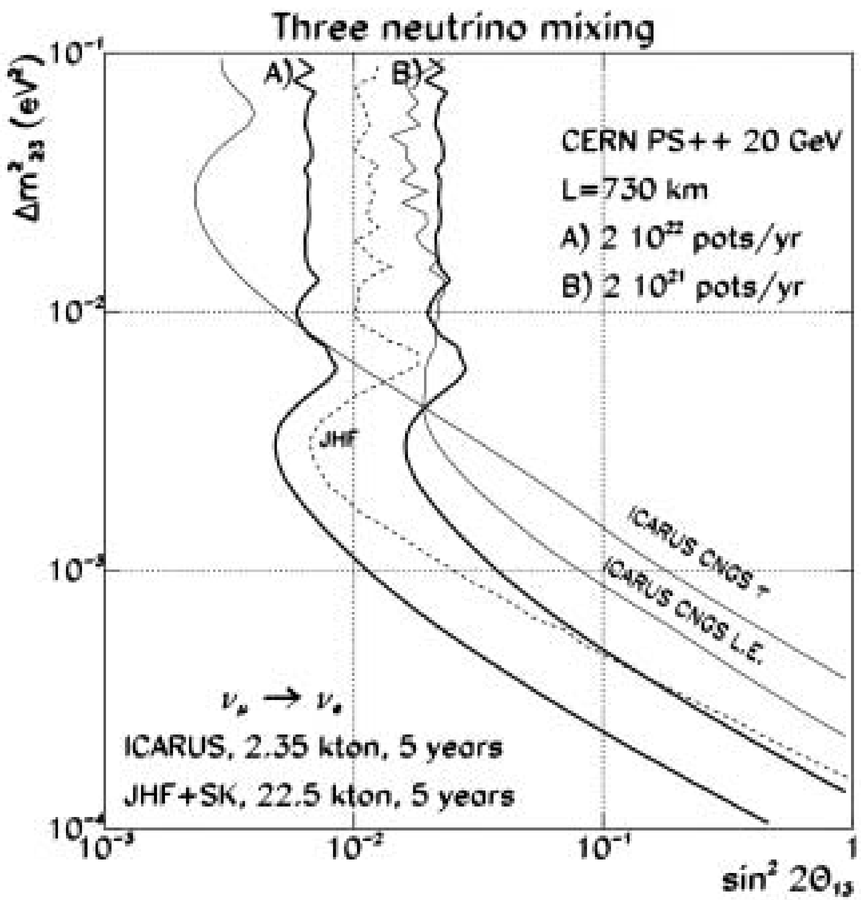
For $\Delta m^2 = 2.5\times10^{-3}$ eV^2:

$$(\sin^2 2\theta_{13})_{BNGS,120\ \mathrm{km}} < 0.006$$
$$(\sin^2 2\theta_{13})_{BNGS,270\ \mathrm{km}} < 0.015$$
$$(\sin^2 2\theta_{13})_{BNGS,465\ \mathrm{km}} < 0.03$$

Example III: a new high intensity 20 GeV PS



2x10²² pots/yr @ 20 GeV
L=732 km and 2.35 kton



<u>*For $\Delta m^2 = 2.5\times10^{-3}$ eV^2:*</u>

$$(\sin^2 2\theta_{13})_{PS++,2\times10^{21}\ pot/year} < 0.016$$
$$(\sin^2 2\theta_{13})_{PS++,2\times10^{22}\ pot/year} < 0.005$$

Conclusion

- The Liquid Argon TPC is a new kind of detector, effectively an electronic bubble-chamber
  - ➥ ICARUS T3000 at Gran Sasso is an important milestone for this technology and acts as a full-scale test-bed in a difficult underground environment
  - ➥ This technology has large potentials for future programs
- ICARUS T3000 acts as a sort of observatory for the study of neutrinos and the instability of matter at the Gran Sasso Underground Laboratory
  - ➥ ICARUS has a vast physics program in the domain of neutrinos and proton decay searches which is highly complementary to collider physics (LHC).
  - ➥ It will take advantage of the CERN-NGS neutrino beam
  - ➥ For $\nu_\mu \rightarrow \nu_e$ searches, the maximum intensity will be required (8×10^{19} pots/year would be welcome). It could be worth it. A low energy focusing could optimize the sensitivity per p.o.t.
- Beyond CNGS, high intensity proton beams with x10-x100 the present intensities will be fundamental to stay at the forefront of accelerator neutrino physics.