Liquid Argon TPC and R&D

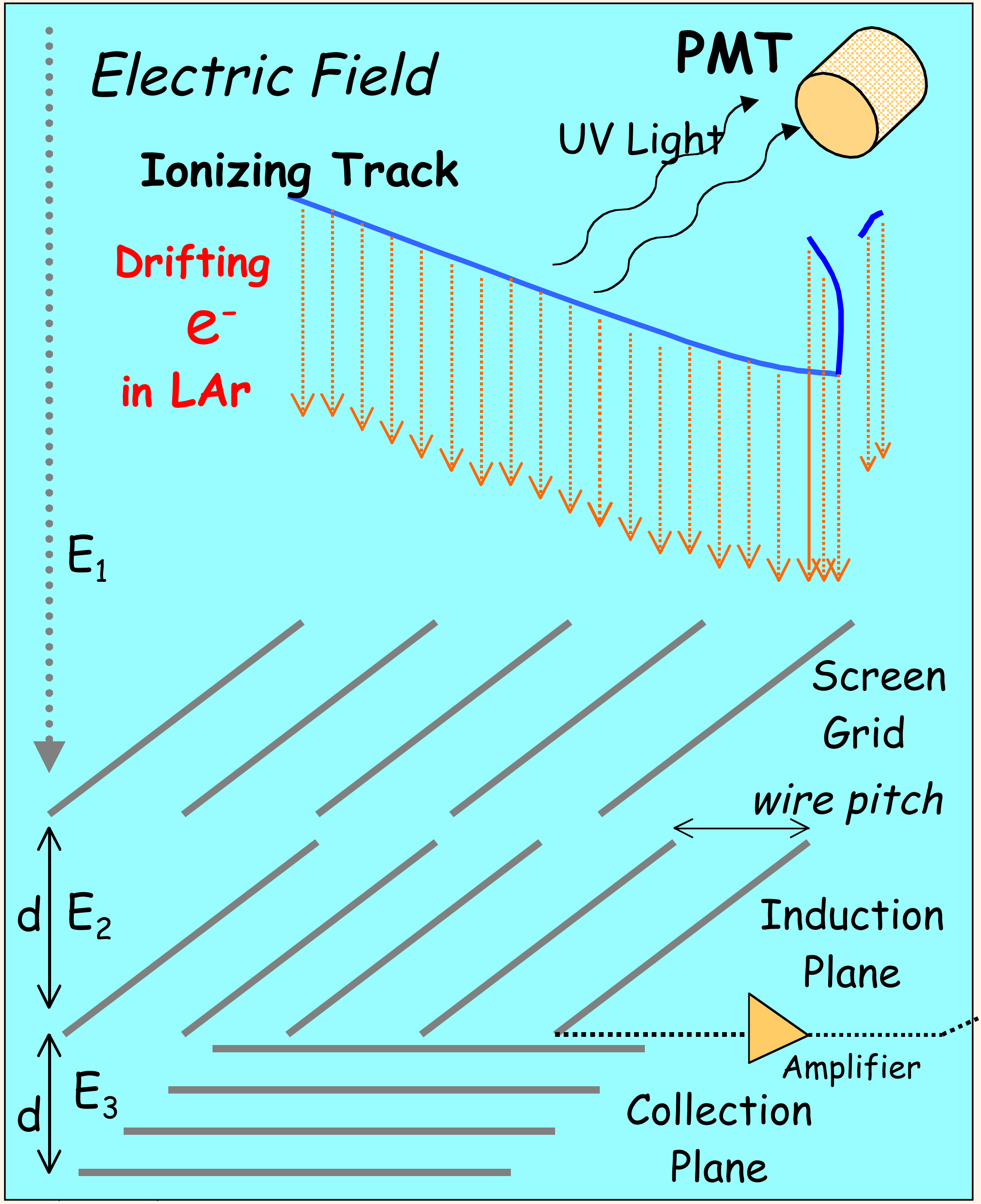
André Rubbia (*ETH Zürich*)
ICARUS Collaboration

Special thanks to A. Bueno, I. Gil-Botella, S. Navas-Concha, C. Rubbia, P. Sala

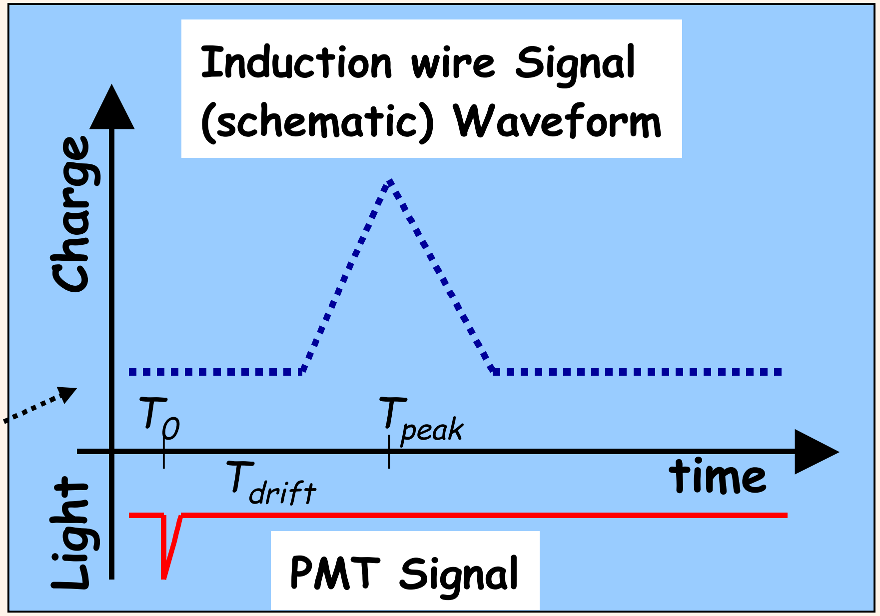
Large detectors for proton decay, supernovae and atmospheric neutrinos and low energy neutrinos from high intensity beam

January 16-18, 2002, CERN, Geneva, Switzerland

ICARUS Liquid Argon TPC



The LAr TPC technique is based on the fact that ionization electrons can drift over large distances (meters) in a volume of purified liquid Argon under a strong electric field. If a proper readout system is realized (i.e. a set of fine pitch wire grids) it is possible to realize a massive "electronic bubble chamber", with superb 3-D imaging.



Liquid Argon TPC properties

- **High density, heavy ionisation medium**
    - $\rho = 1.4$ g/cm^3, X_0=14 cm, λ_{int} = 80 cm
- **Extremely high resolution detector**
    - – 3D image 3x3x0.6 mm^3 (400 ns sampling)
- **Continuously sensitive**
- **Self-triggering or through prompt scintillation light**
- **Stable and safe**
    - – Inert gas/liquid
    - – High thermal inertia (230 MJ/m^3)
- **Relatively cheap detector**
    - – Liquid argon is cheap, it is “stored” not “used” in the experiment
    - – TPC : no of channels proportional to surface
- **Cryogenic temperature**
    - – T = 88K at 1 bar
- **High purity required for long-drift time**
    - – 0.1 ppb of O_2 equivalent for 3 ms drift
- **No signal amplification in liquid**
    - – 1 m.i.p. over 2 mm yields 10000 electrons

Cryogenic plant

Argon purification

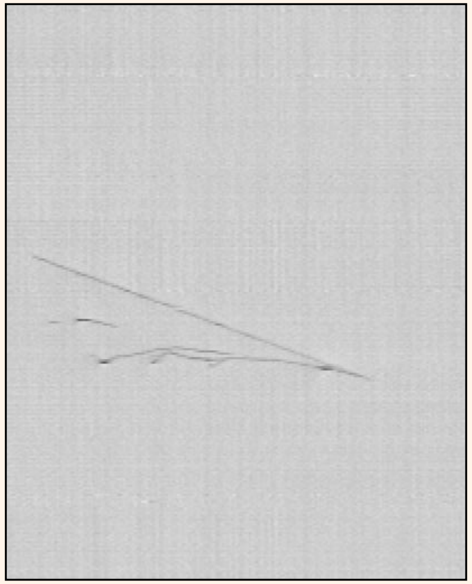
Low noise electronics

ICARUS bibliography

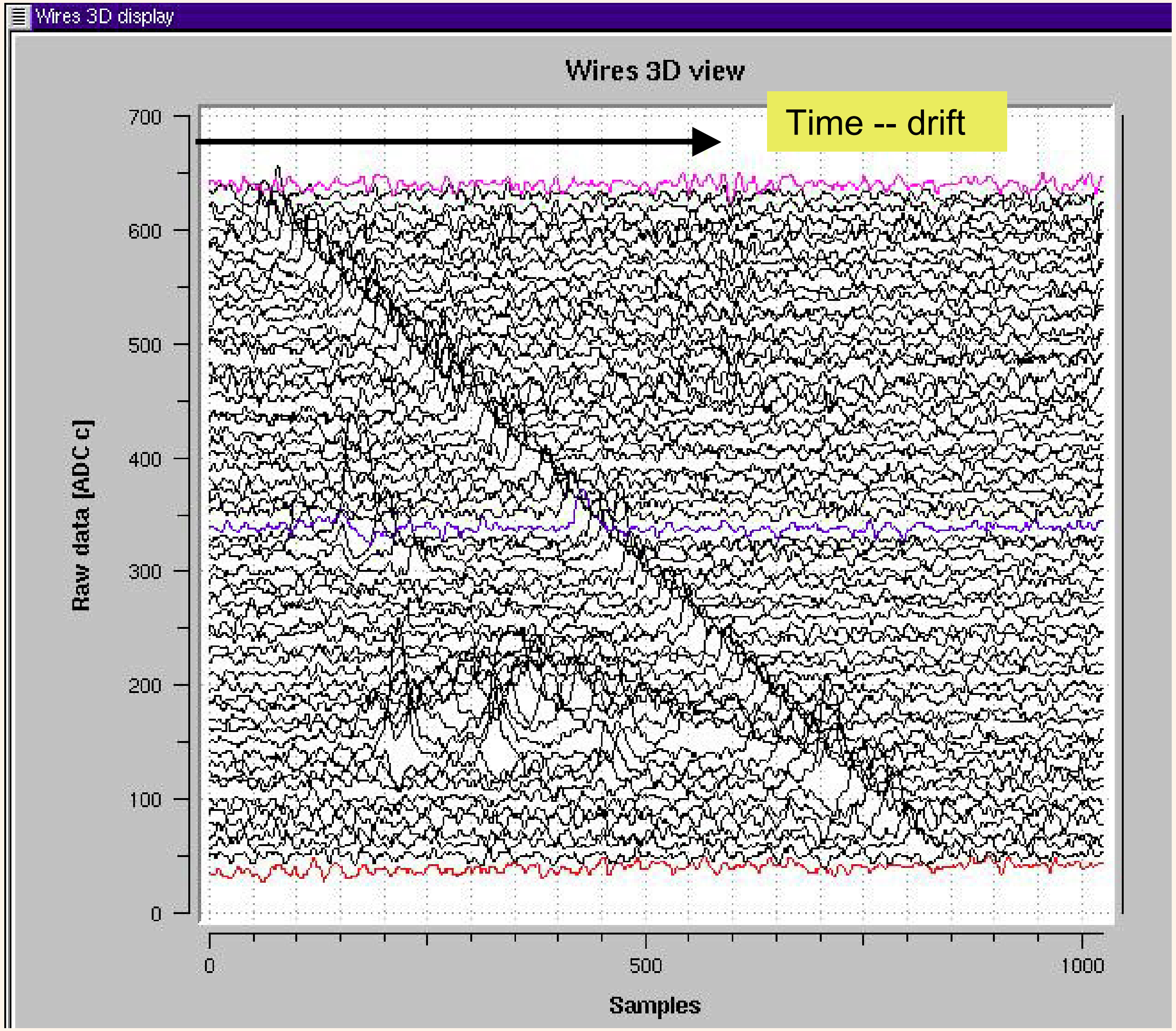
1. The ICARUS Collaboration:*ICARUS: a proposal for the Gran Sasso Laboratory* Experiment proposal, **INFN/AE-85/7**, Frascati (Italy, 1985).
2. M.˚Baldo-Ceolin *et al.* (32 authors):*ICARUS I: an optimized, real-time detector of solar neutrinos,* Experiment proposal, **LNF-89/005 (R)**, 10 Feb. 1989.
3. P.˚Cennini *et al.* (53 authors), *ICARUS II: second generation proton decay experiment and neutrino observatory at the Gran Sasso laboratory (Volume I),* Experiment proposal, **LNGS-94/99-I**, Sept. 1993.
4. P.˚Cennini *et al.* (57 authors), *ICARUS II: second generation proton decay experiment and neutrino observatory at the Gran Sasso laboratory (Volume II),* Experiment proposal, **LNGS-94/99-II**, May 1994.
5. P.˚Cennini *et al.* (59 authors):, *A first 600 ton ICARUS detector installed at the Gran Sasso laboratory,* Addendum to proposal, **LNGS-95/10**, May 1995.
6. P.˚Cennini *et al.* (70 authors):, *A search programme for explicit neutrino oscillations at long and medium baselines with the ICARUS detector,* Experiment proposal, **CERN/SPSLC/96-58, SPSLC/P304**, Dec. 1996.
7. P.˚Cennini *et al.* (70 authors):, *ICARUS-Like technology for long baseline neutrino oscillations,* Experiment proposal, **CERN/SPSC 98-33**, Oct. 1998.
8. F.˚Arneodo *et al.* (112 authors), *ICANOE: a proposal for a CERN-GS long baseline and atmospheric neutrino oscillation experiment,* Experiment proposal, **INFN/AE-99-17, CERN/SPSC 99-25, SPSC/P314**, Sep. 1999.
9. F.˚Arneodo *et al.* (109 authors), *ICANOE: preliminary techincal design & cost estimate,* Addendum to proposal, **LNGS-P21/99-ADD1, CERN/SPSC 99-39, SPSC/P314 Add.1**, Nov. 1999.
10. F.˚Arneodo *et al.* (123 authors), *ICANOE: answers to questions and remarks concerning the ICANOE project,* Addendum to proposal, **LNGS-P21/99-ADD2, CERN/SPSC 99-40, SPSC/P314 Add.2**, Nov. 1999.
11. F.˚Arneodo *et al.*, THE ICARUS EXPERIMENT: A Second-Generation Proton Decay Experiment and Neutrino Observatory at the Gran Sasso Laboratory., INITIAL PHYSICS PROGRAM, **ICARUS-TM/2001-03 LNGS P28/01 LNGS-EXP 13/89 add.1/01**

ICARUS liquid argon imaging TPC

Detector is readout with a wave-form analyser and is continuously sensitive...



Real event



ICARUS T600 prototype

First cryostat delivery
Pavia (Feb 29, 2000)

The developed technology allows (relatively) easy transportability

The *ICARUS T600* module (cryostat & internal detector) can be fully assembled and then shipped to the defined experimental beam site

Ext. insulation, Electronic & DAQ installation

LAr filling, RUN

ICARUS T600: the existing detector

¥A first semimodule of the T600 prototype has been built (97- 00) and fully successfully tested (on surface, Apr.-Aug. 2001).

¥ Complete T600 detector layout currently being finalized (2002):

Cryogenics:

cryostat divided in 2 half-modules (about 20X4X4 m^3)
passive insulation (LN_2 cooling system)
LAr purifier (forced LAr re-circulation) + GAr purifier

Internal detector : LAr TPC (4 chambers), tot. 58.000 wires

TPC: 3 planes at 60°, 3 mm pitch, 3 mm space between planes
1.5 m max drift distance (TPC-Cathode)
[i.e. 1 ms drift time at nominal E.F. of 500 V/cm]
60 PMT s per half-module (UV sensitive by w.l.s. deposition, 10 fl, Q.E. 10%, 5 MeV min. detectable energy deposition).

Slow-control

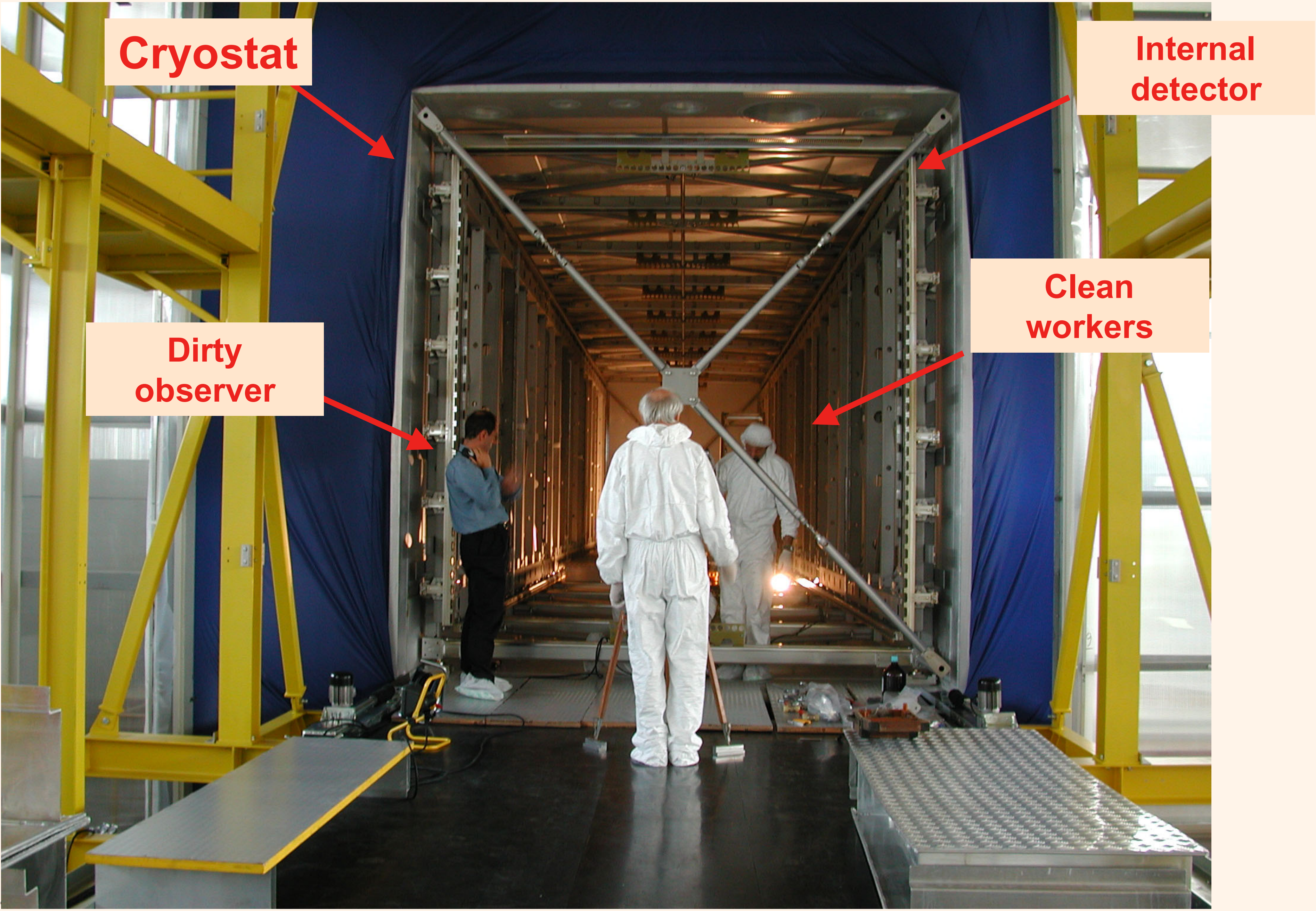
High-voltage system

Readout electronics: individual wire waveform recorder

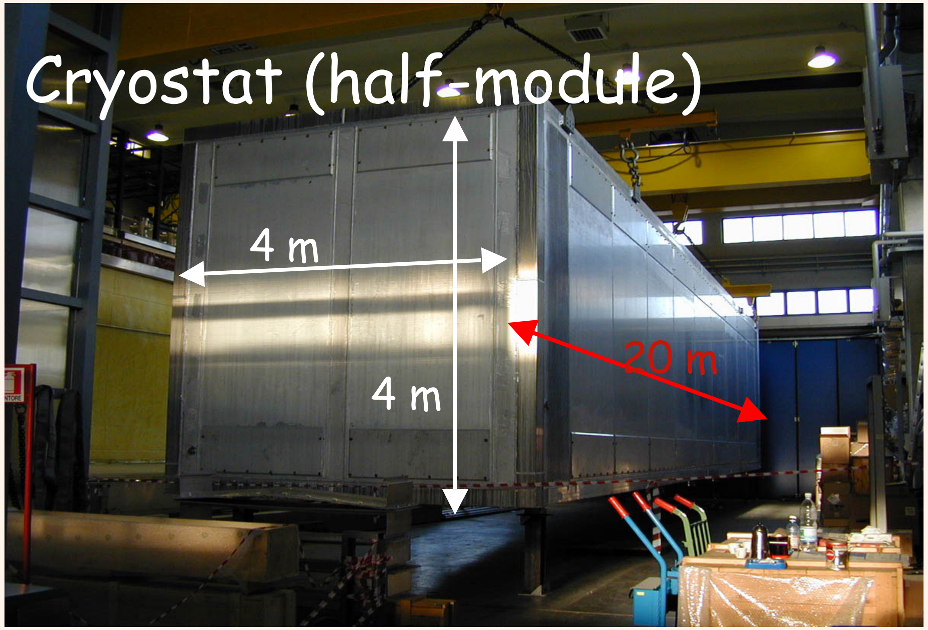
Analog Board (Amplifiers) + Digital Board (ADC conv. & hit finding)

DAQ

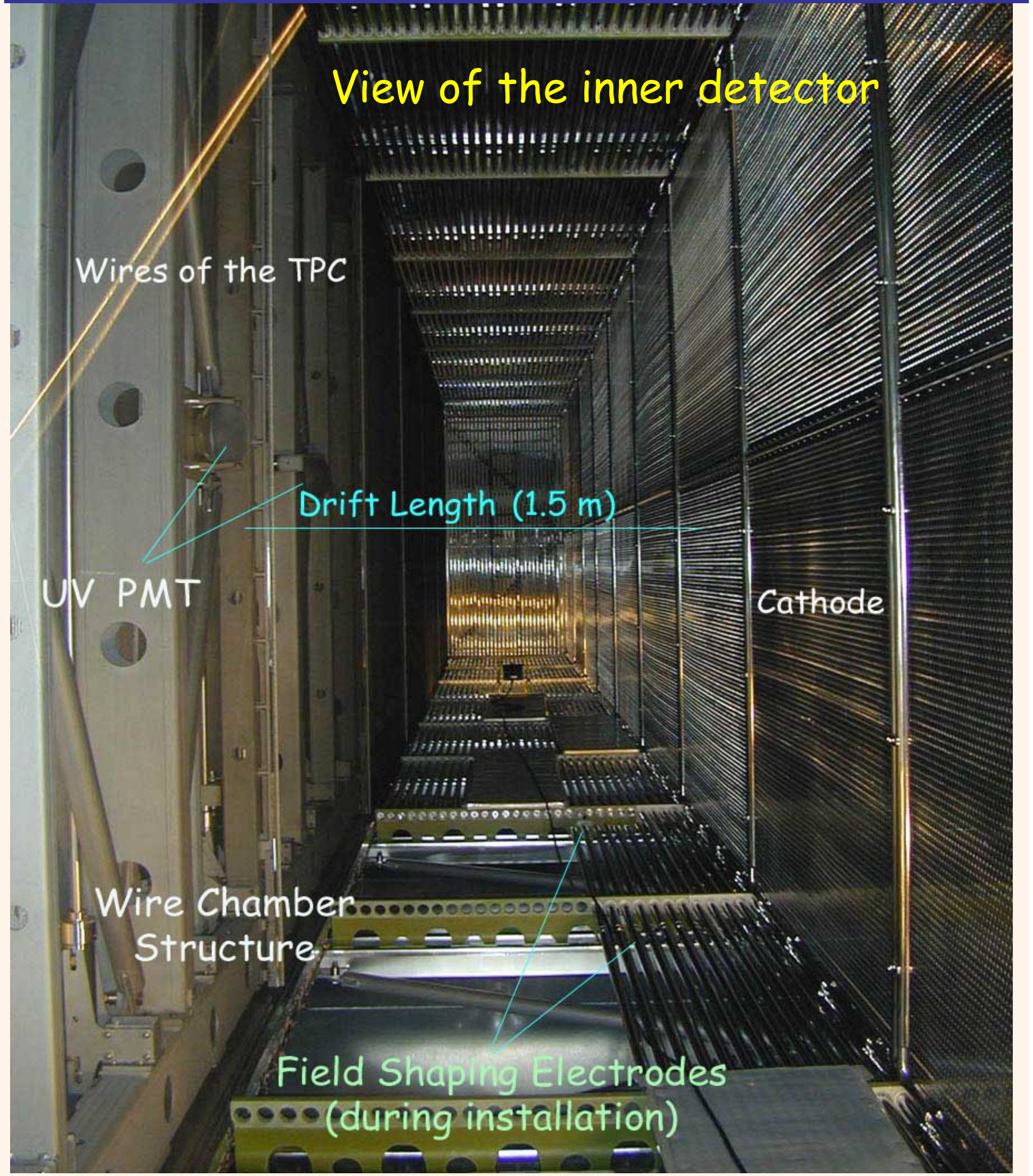
Assembly of the T600 internal detector (Mar-Jul 2000)



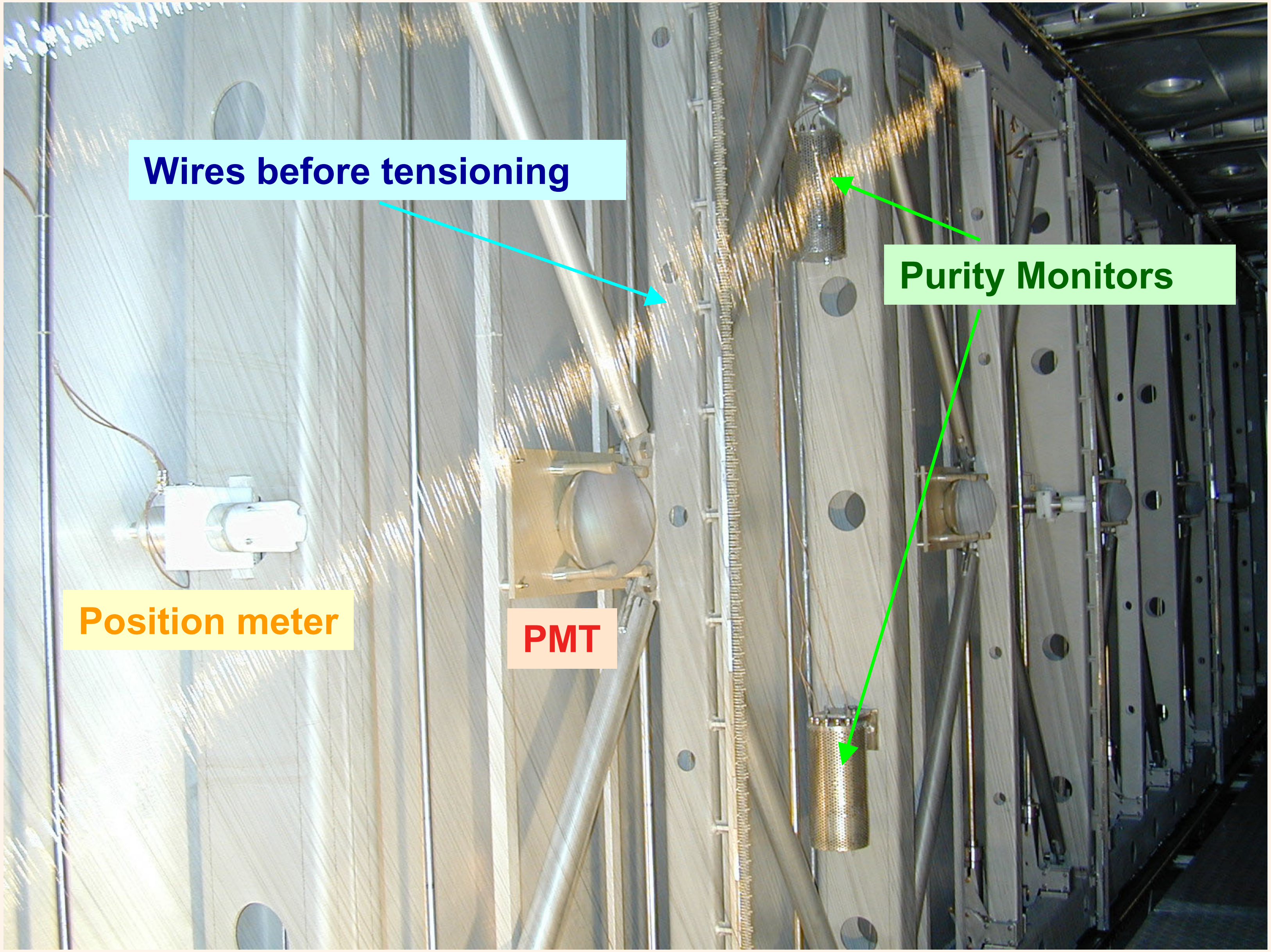
ICARUS T600 prototype



Detector during construction

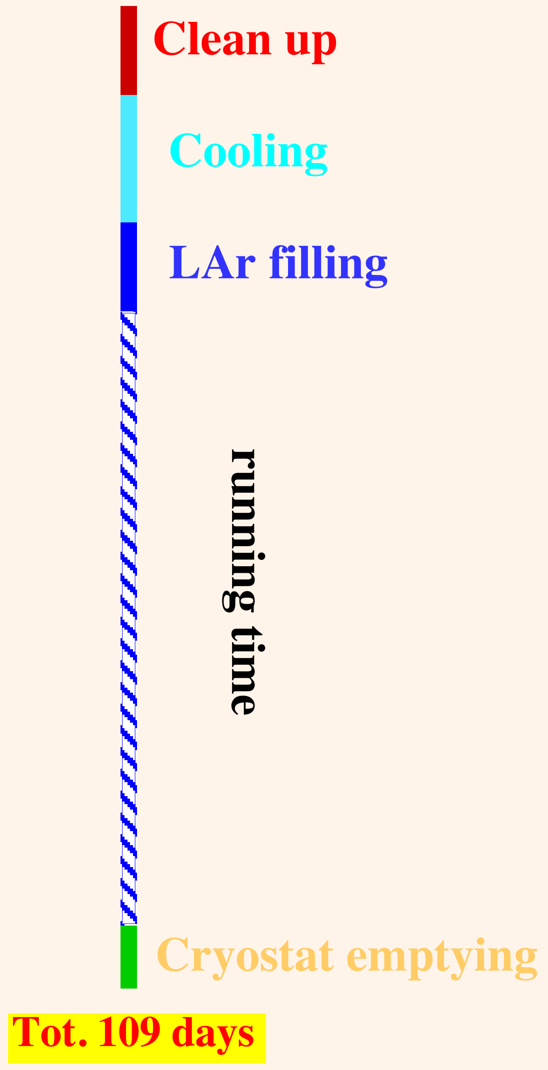


Slow control sensor (behind wire planes)

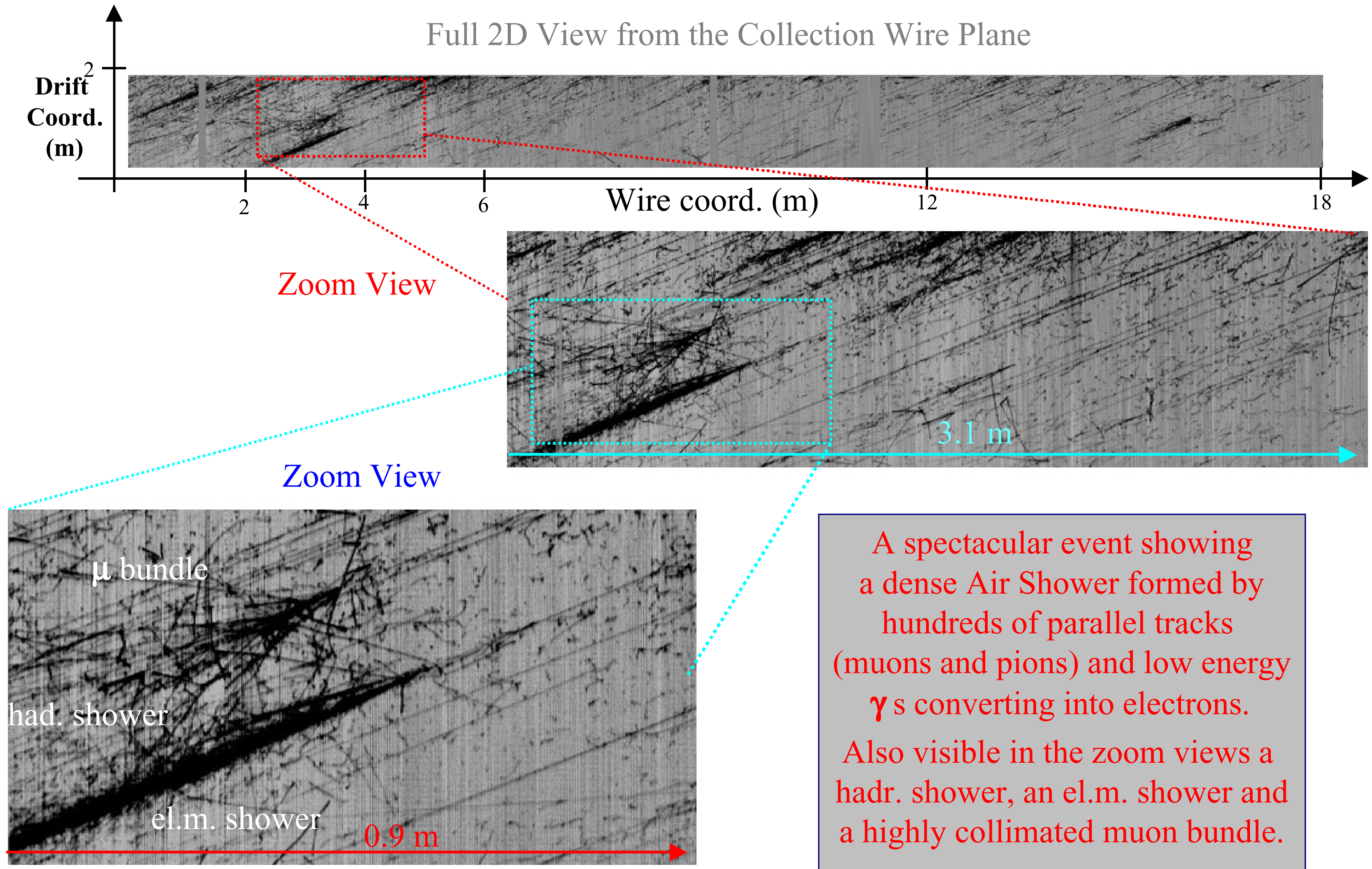


T600 half-module technical run (2001)

- **Clean up (vacuum): 10 days**
  - ✶ 7 days to find and recover the leaks
  - ✶ 3 days to reach 10^{-4} mbar□
- **Cooling: 14 days**
  - ✶ 11 days for pre-cooling (down to -50 °C)
  - ✶ 3 days to reach -178 °C□
- **LAr filling: 10 days**
- **True running time: 68 days**
- **Cryostat emptying: 7 days**



Detector has been carefully monitored during all phases of running and demonstrated to behave as expected !



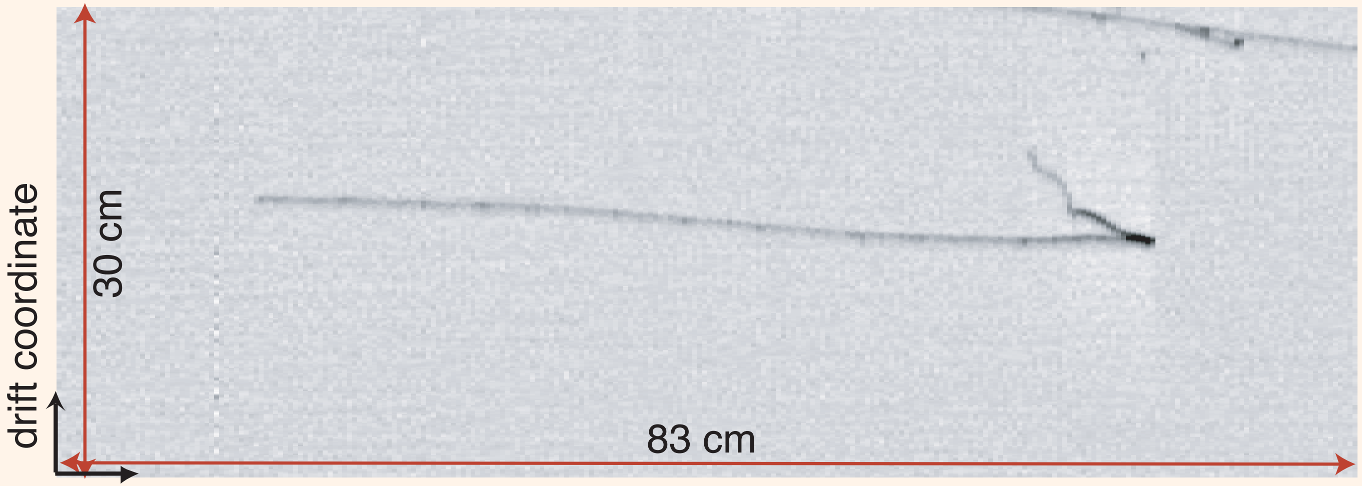
A spectacular event showing a dense Air Shower formed by hundreds of parallel tracks (muons and pions) and low energy γ s converting into electrons.

Also visible in the zoom views a hadr. shower, an el.m. shower and a highly collimated muon bundle.

T600 test @ Pv: Run 308 - Evt 4 (July 2nd, 2001)

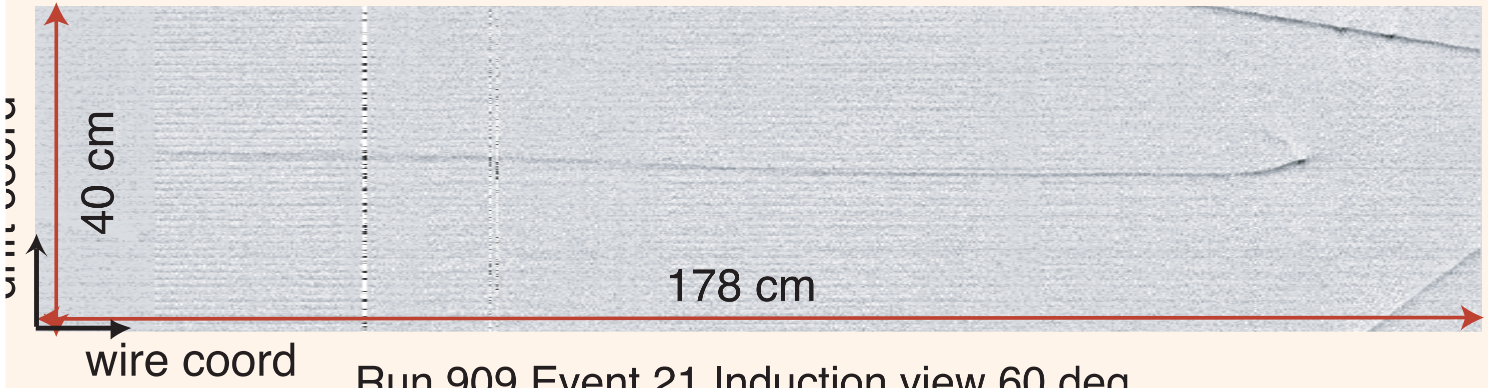
Multiple plane readout

Run 909 Event 21 Collection view



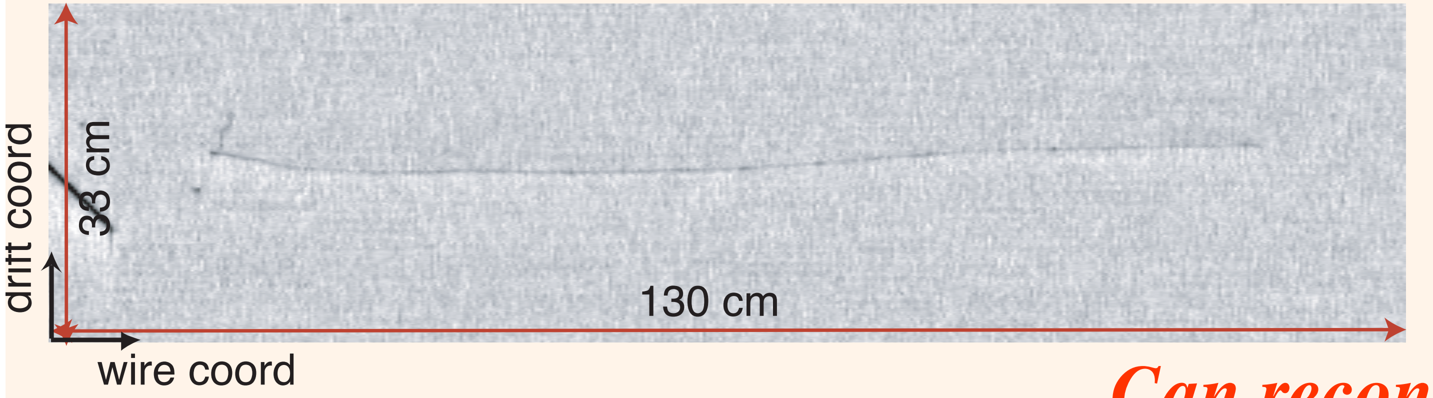
collection

Run 909 Event 21 Induction view 0 deg



Induction 1

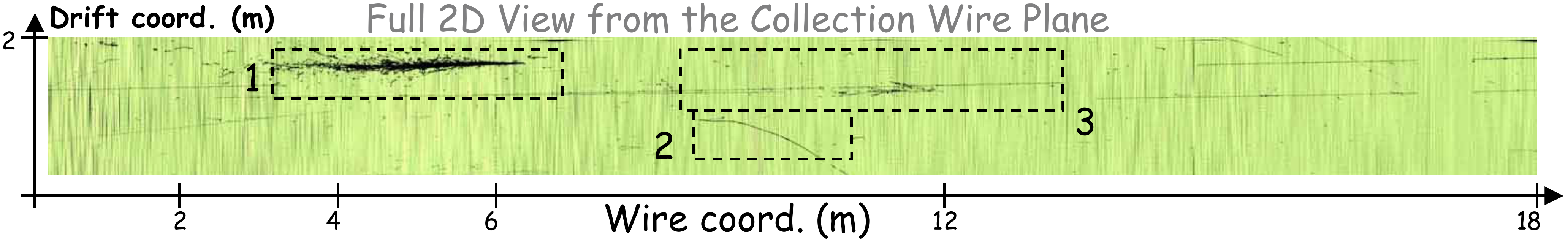
Run 909 Event 21 Induction view 60 deg



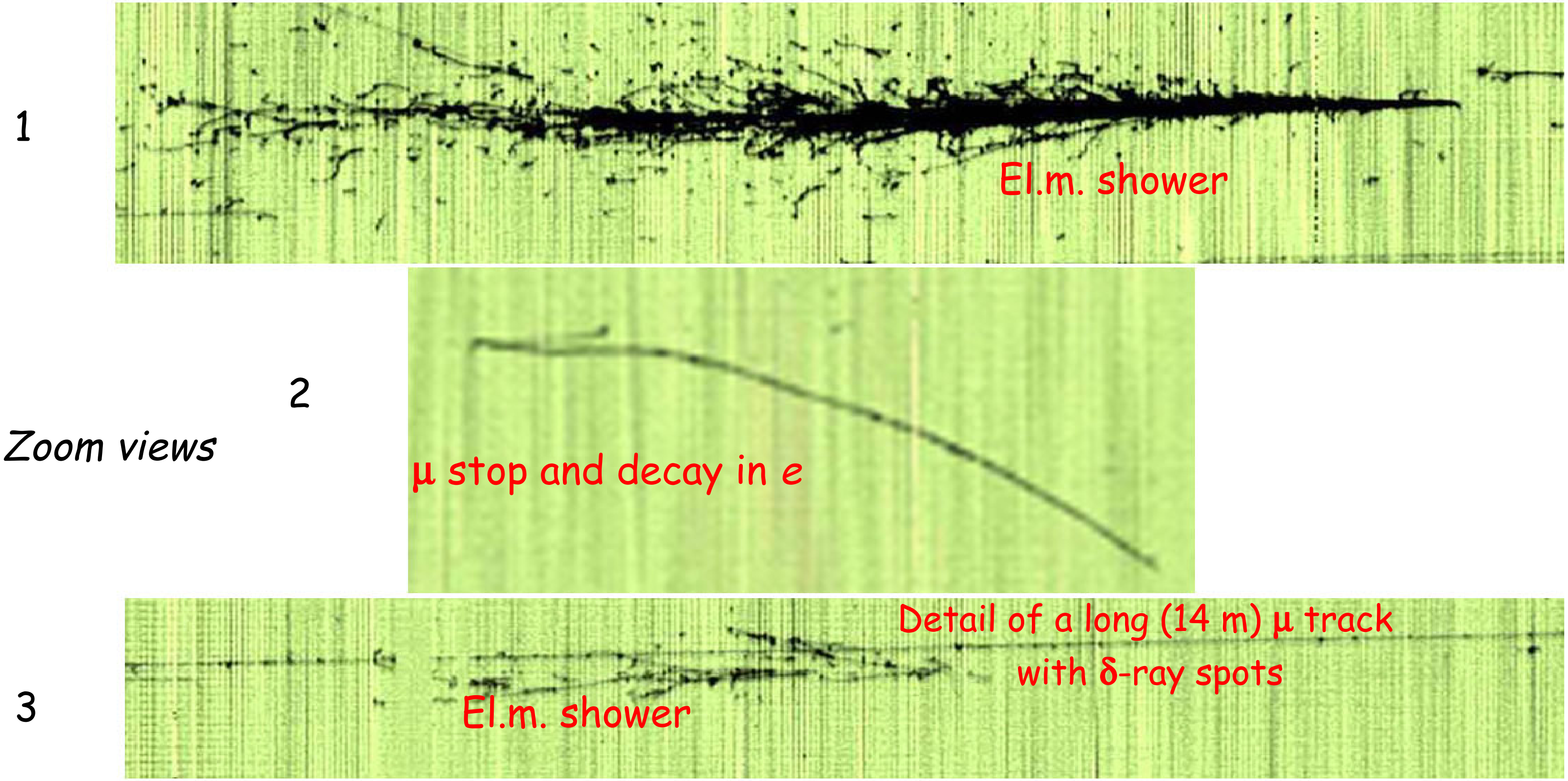
Induction 2

Can reconstruct 3D images !

Full 2D View from the Collection Wire Plane

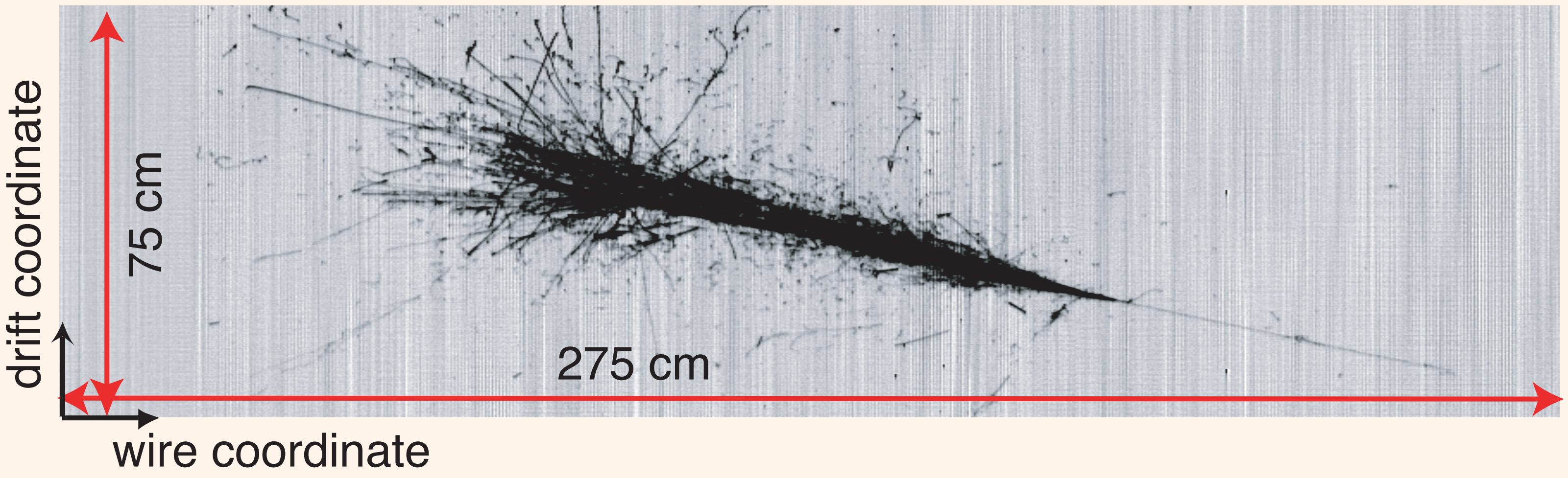


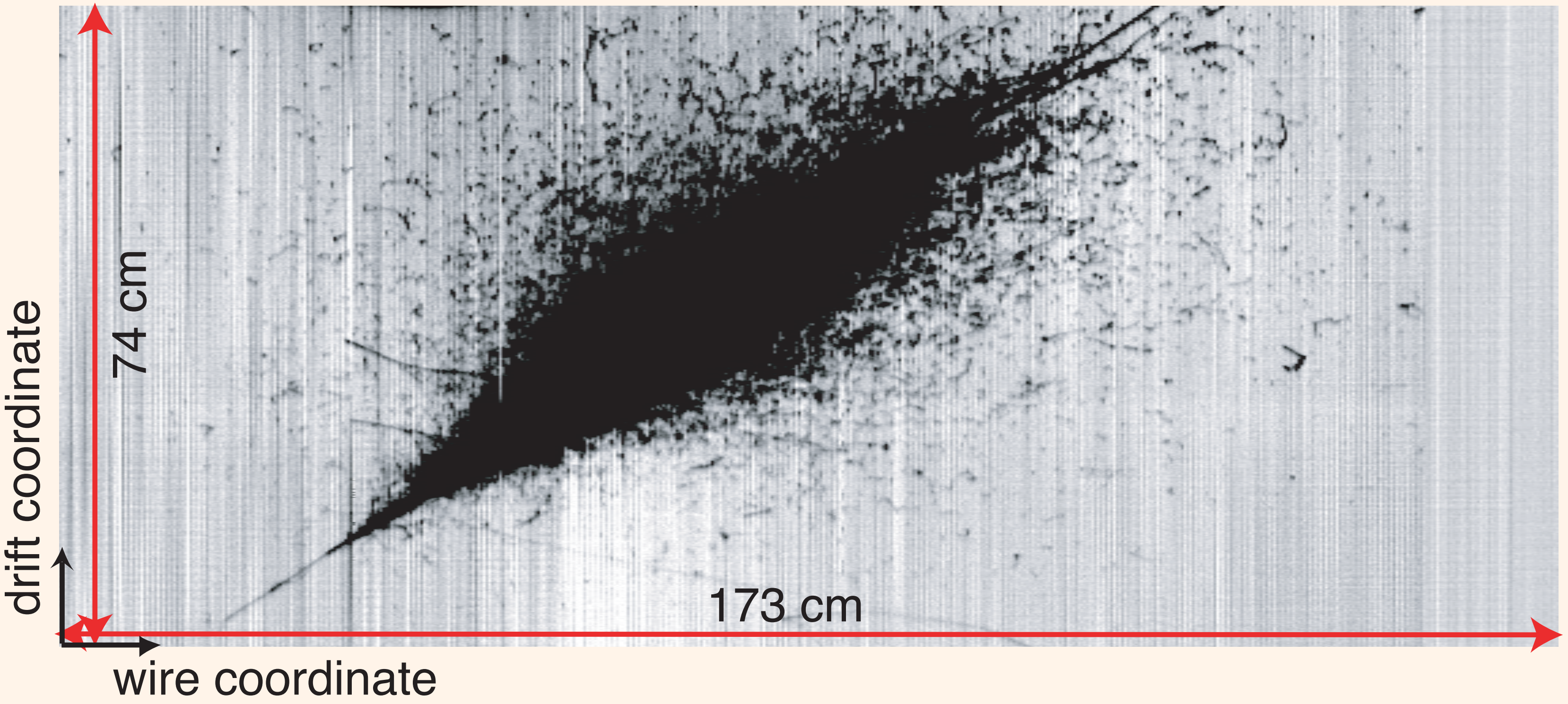
Zoom views



T600 test @ Pv: Run 201 - Evt 12

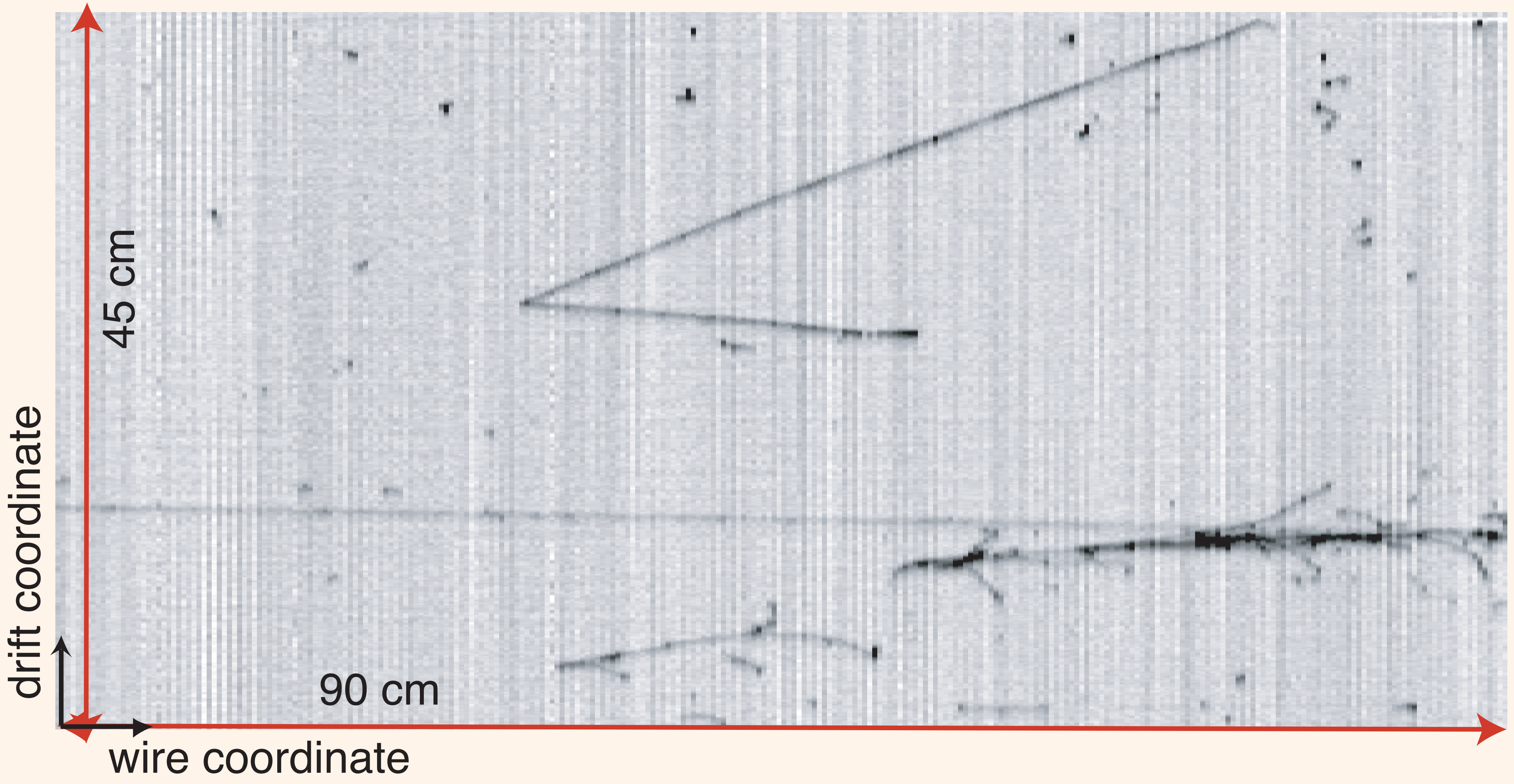
Showers


Run 308 Event 7 Collection view


Run 308 Event 332 Collection view

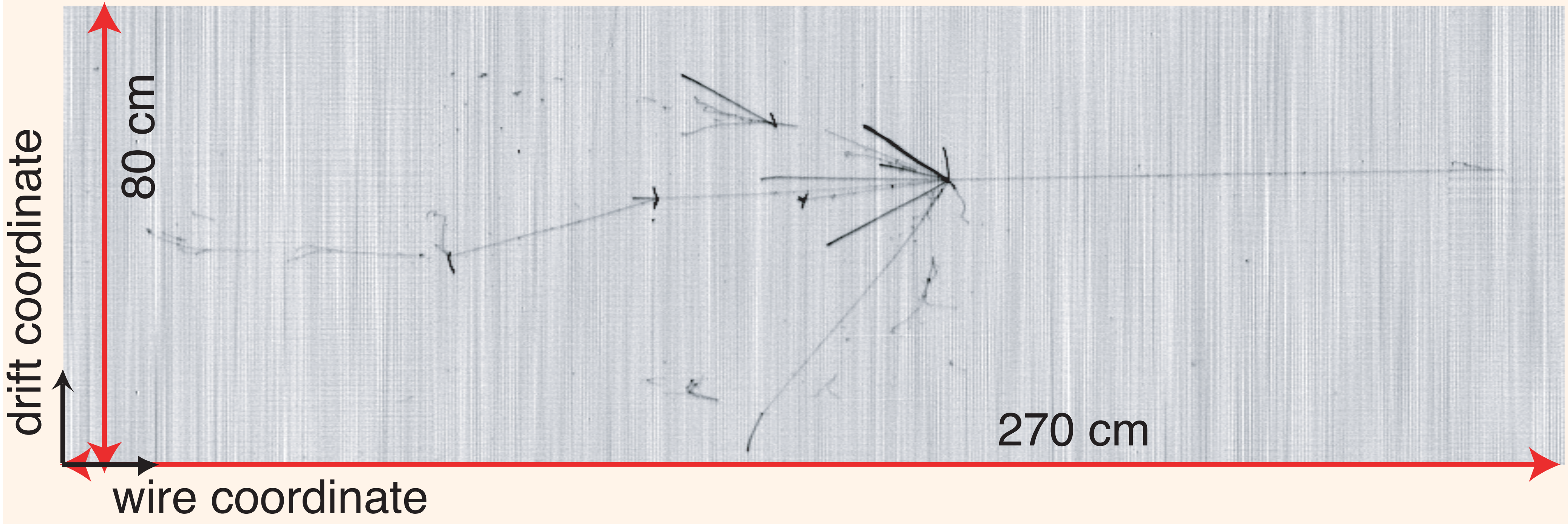
V0 candidate

Run 969 Event 18 Collection view

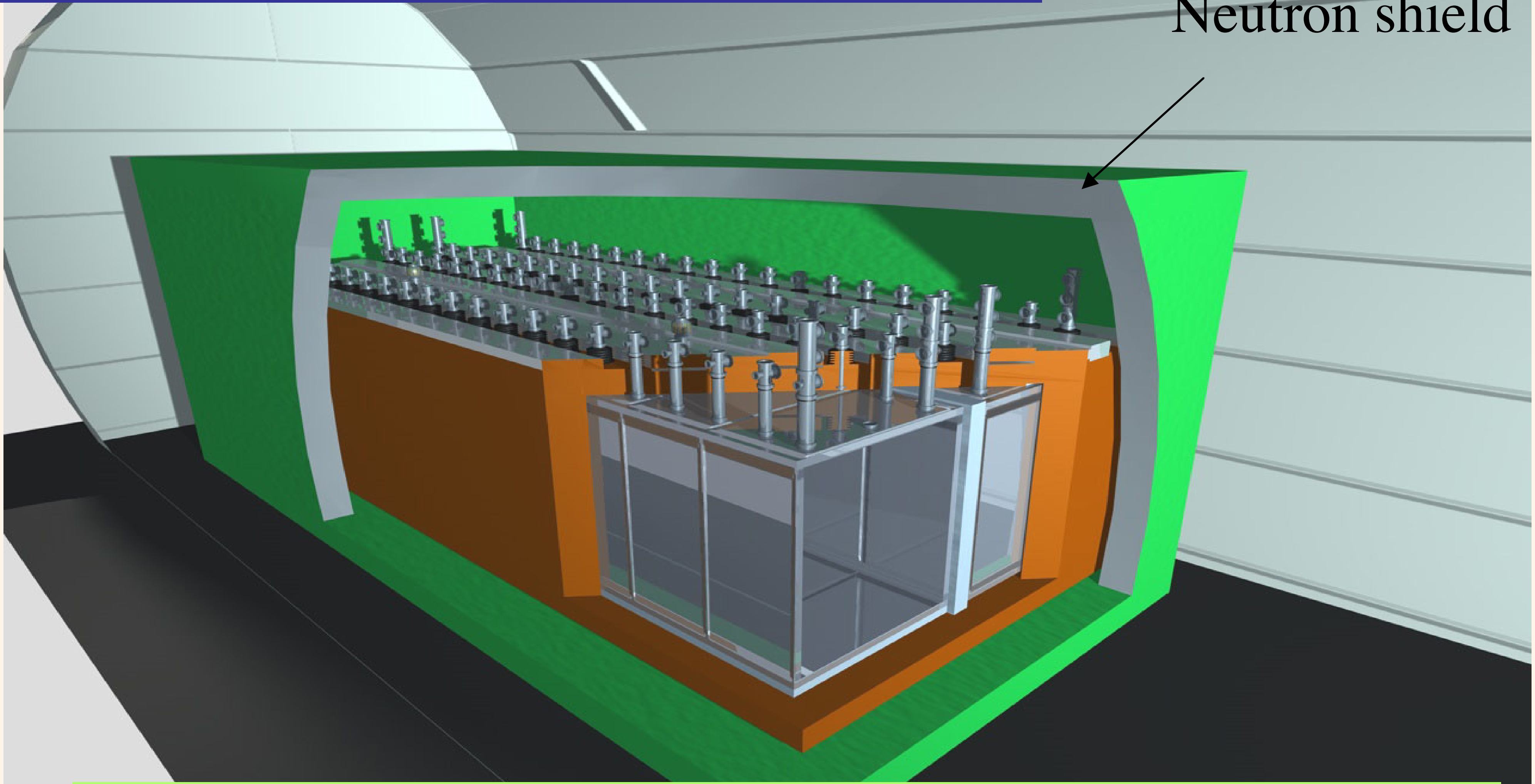


Hadron interaction

Run 308 Event 160 Collection view



ICARUS T600 installation in LNGS

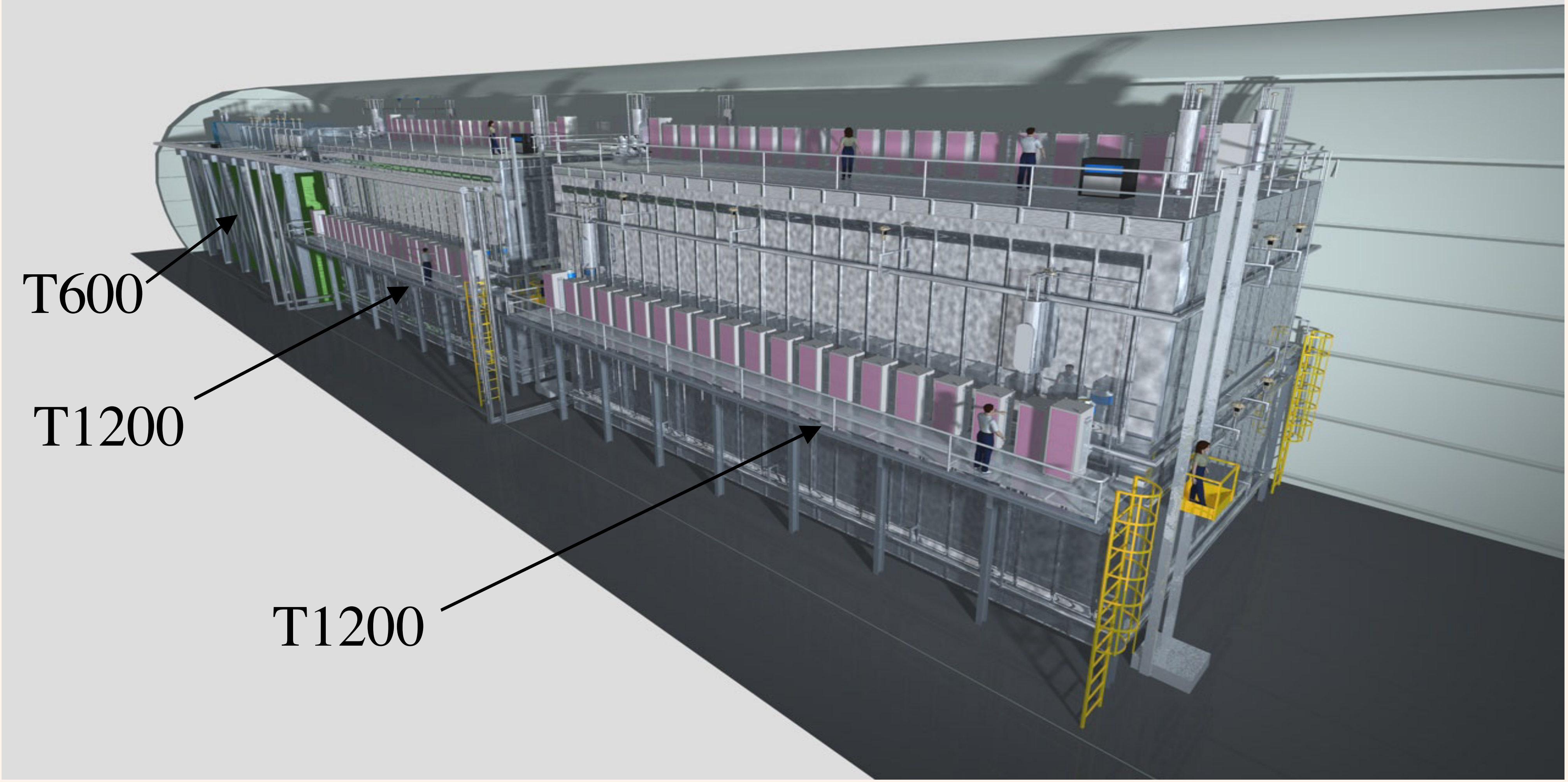


Transportation and re-mounting at GranSasso underground facility during 2002.

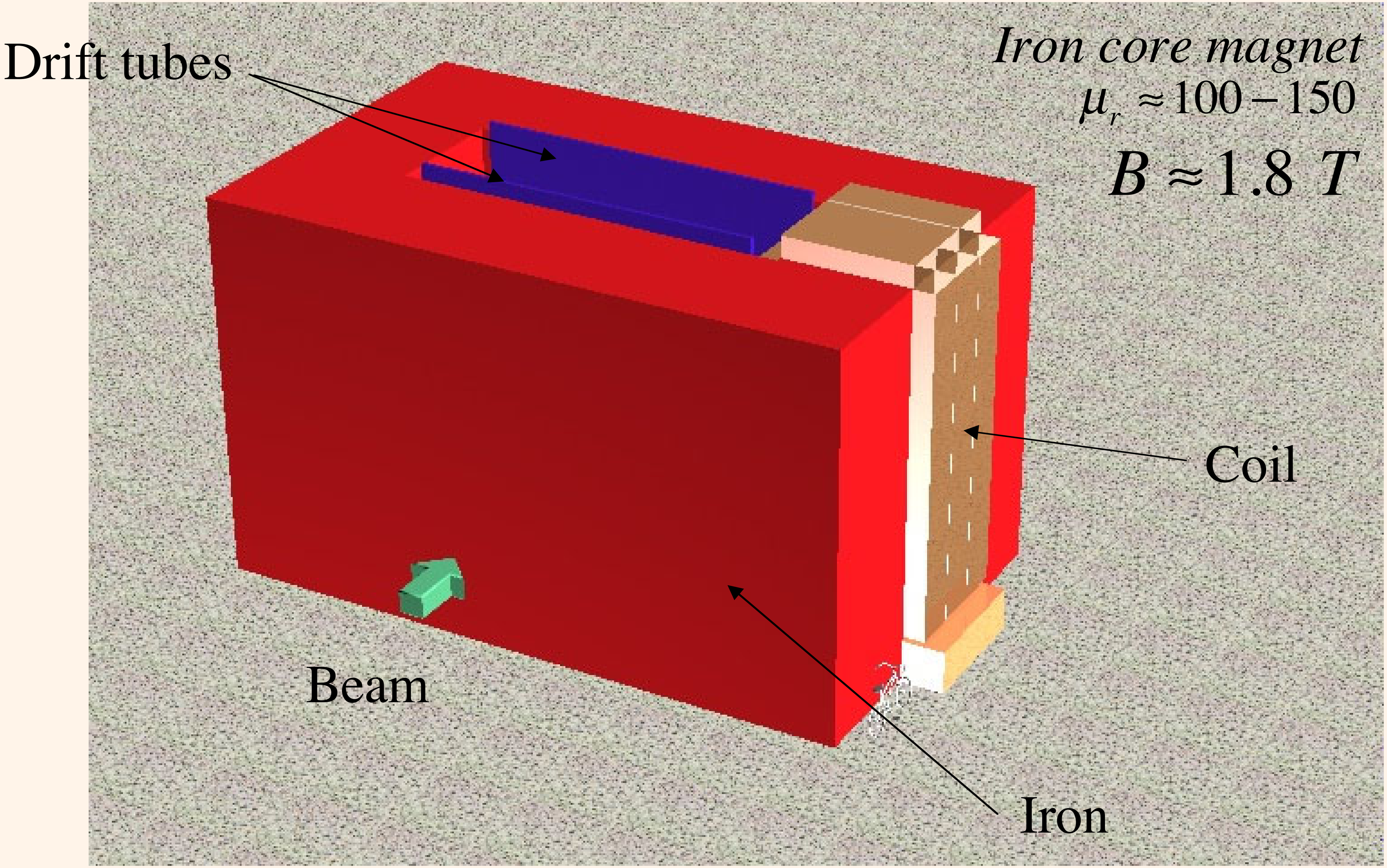
Initial physics program: **hep-ex/0103008**

ICARUS T600+2xT1200 in LNGS proposal

LNGS-EXP 13/89 add.2/01



External muon spectrometer



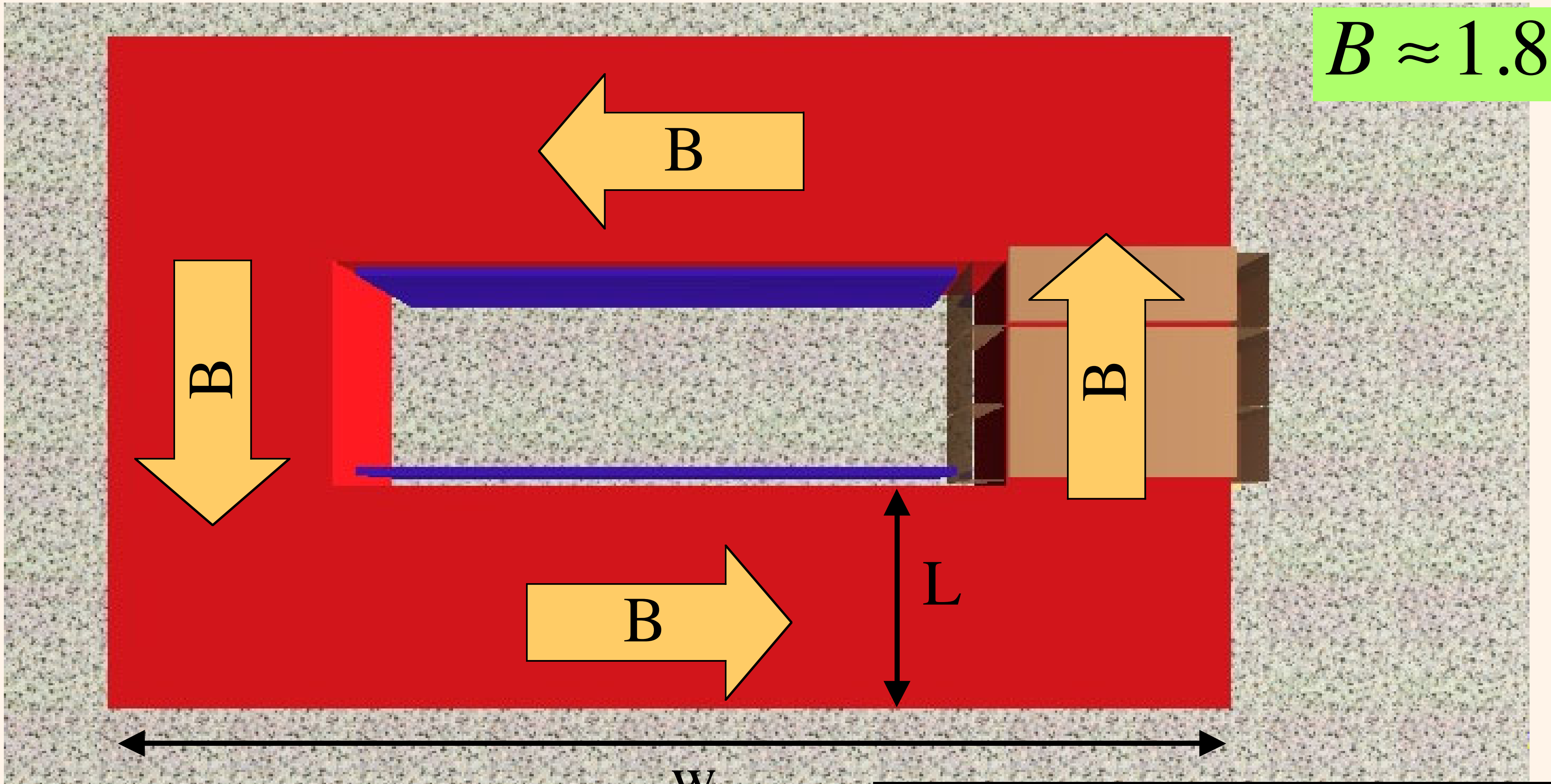
Iron core magnet

$\mu_r \approx 100-150$

$B \approx 1.8\ T$

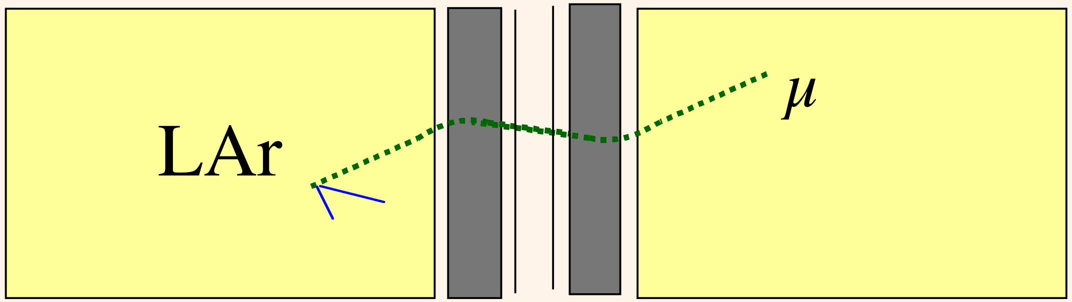
External muon spectrometer (top view)

$B \approx 1.8\ T$



Length L	**2 or 3 meters**
Width w	**8 m matched to LAr transverse dimensions**

Muon momentum resolution

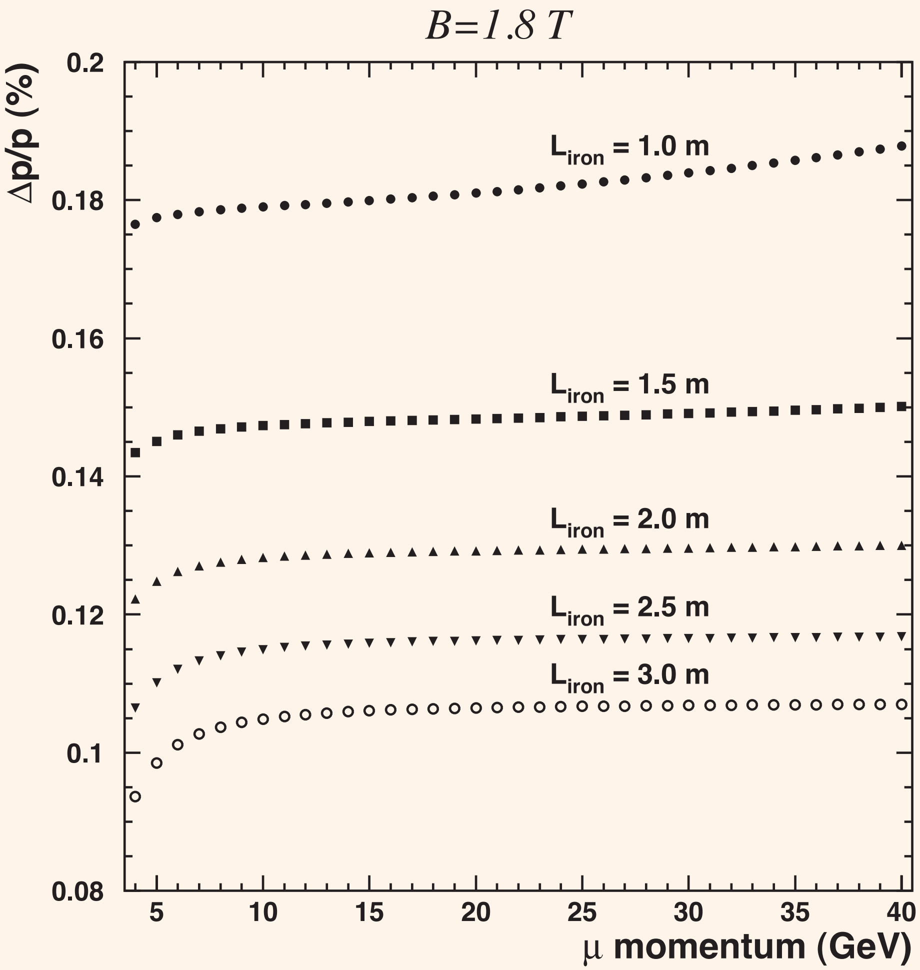


Resolution multiple scattering dominated $\sigma_x = 0.5 \ \ mm$

$$\frac{\Delta p}{p} \approx 13\% \quad for \quad L = 2m$$

Estimated wrong sign confusion:

$$ws\mu \approx 10^{-5}$$

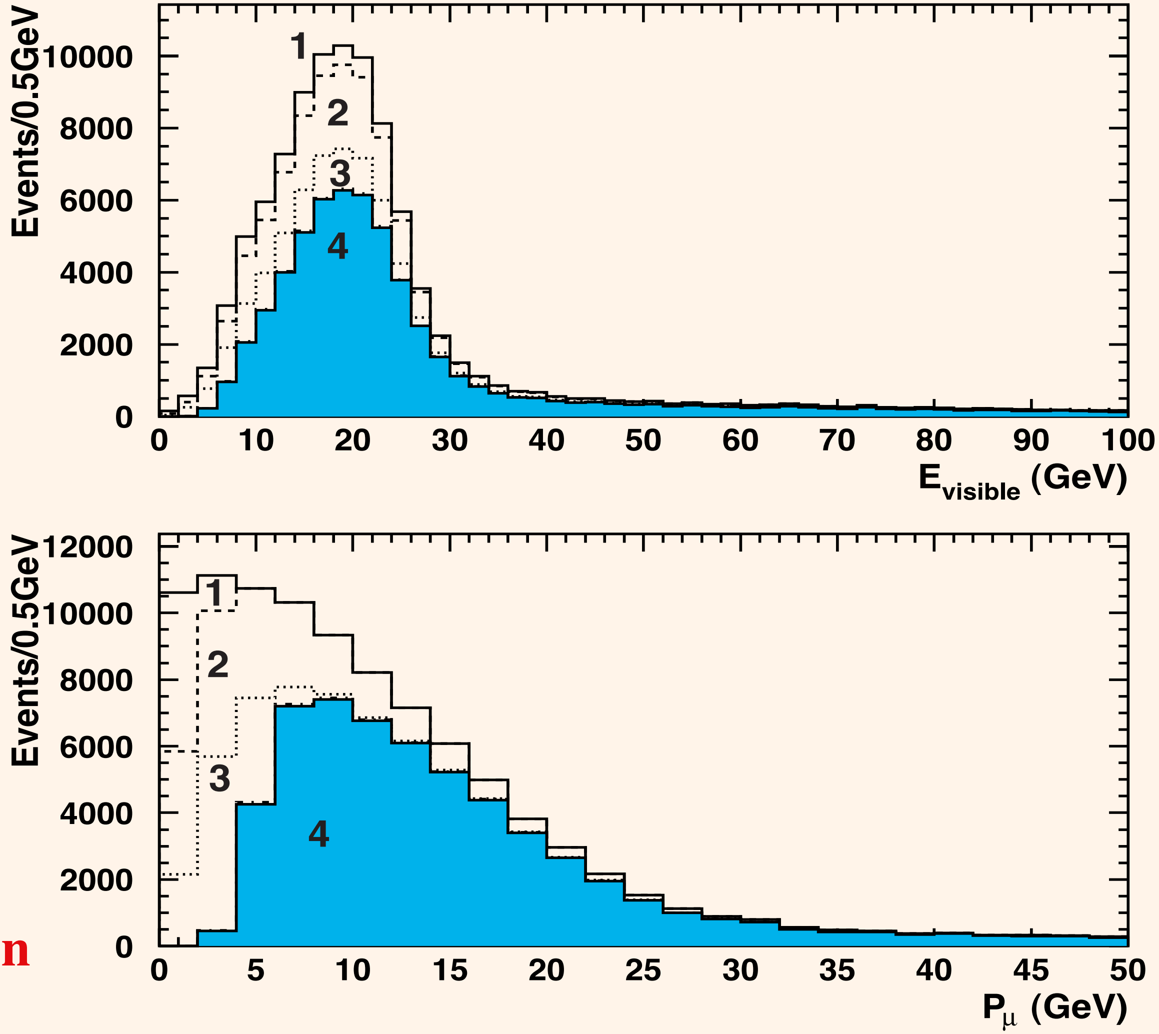


Muon acceptance

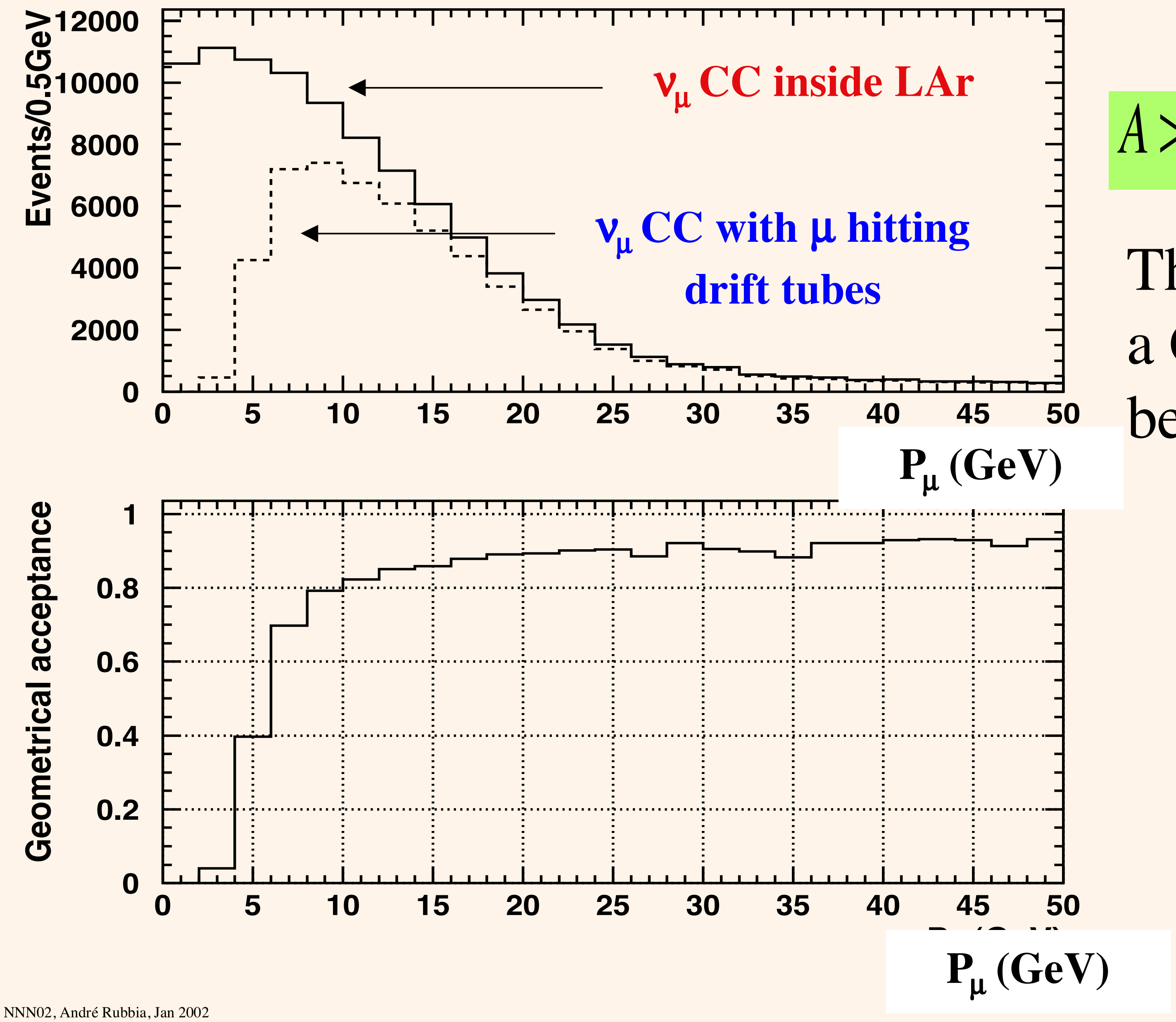
- ➢ν_μ CC events generated uniformly inside one T1200 module with spectrum from CNGS

- ➢Muon spectrometer: two 8x8 m^2, 3 m long Fe blocks with two middle drift tubes planes

1. **Initial sample inside LAr**
2. **Muons that do not stop inside LAr**
3. **Muon inside Fe spectrometer transverse dimensions**
4. **Muon that do not stop inside iron**



Muon acceptance



$A > 50\% \quad for \quad P_\mu > 5 \ GeV$

This is optimized for a CNGS-type of beam.

Is this the subject of the workshop?

- ***Large detectors…***
  - *T600 in 2002, 3 kton planned for 2005*
  - ***Bigger masses envisageable for >2005***
- ***for proton decay…***
  - *Background free searches, unbiased in all decay channels*
  - *Linear gain in sensitivity with exposure up to 1 Megaton×yr*
  - *The right way to go into the unkown…*
- ***supernovae (and solar!)…***
  - *Sensitive to* ν_e*(anti-*ν_e*) only via CC reaction and all other flavors via ES*
  - *Instrinsic threshold down to 150 KeV deposited energy, actual threshold for solar (≈5 MeV on primary electron) dictated by backgrounds*
- ***and atmospheric neutrinos…***
  - *All neutrino flavors (including* ν_τ*) down to kinematical thresholds*
  - *Excellent event classification, NC/CC, L/E resolution*
- ***and low energy neutrinos from high intensity beams***
  - *Excellent e and* μ *identification*
  - *Excellent* π^0 *background rejection*
  - *Electron charge accessible if LAr embedded in B-field*

Scaling the ICARUS modules

- As already discussed in the SuperI document (CERN/SPSC 98-33, SPSC/M620) the ICARUS modules could be scaled up in order to more easily and affordably reach larger masses
- For example, scaling up the ICARUS T1200 module proposed for LNGS by a factor 2 in each direction, we obtain

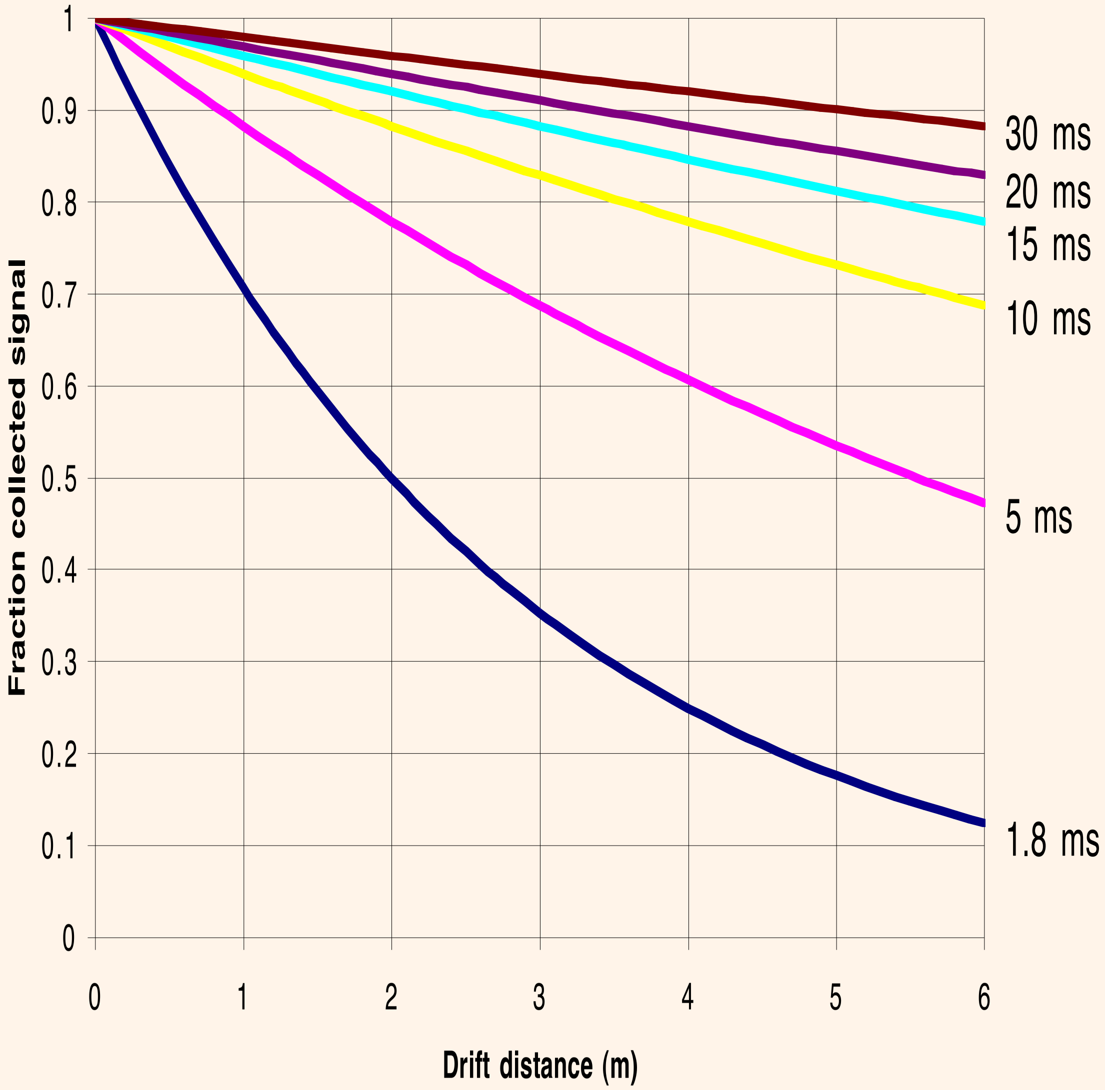
$$2^3 \times T1200 \approx T10000$$

i.e. a 10 kton basic building block module (3t → T15 → T600 → T1200 → …).

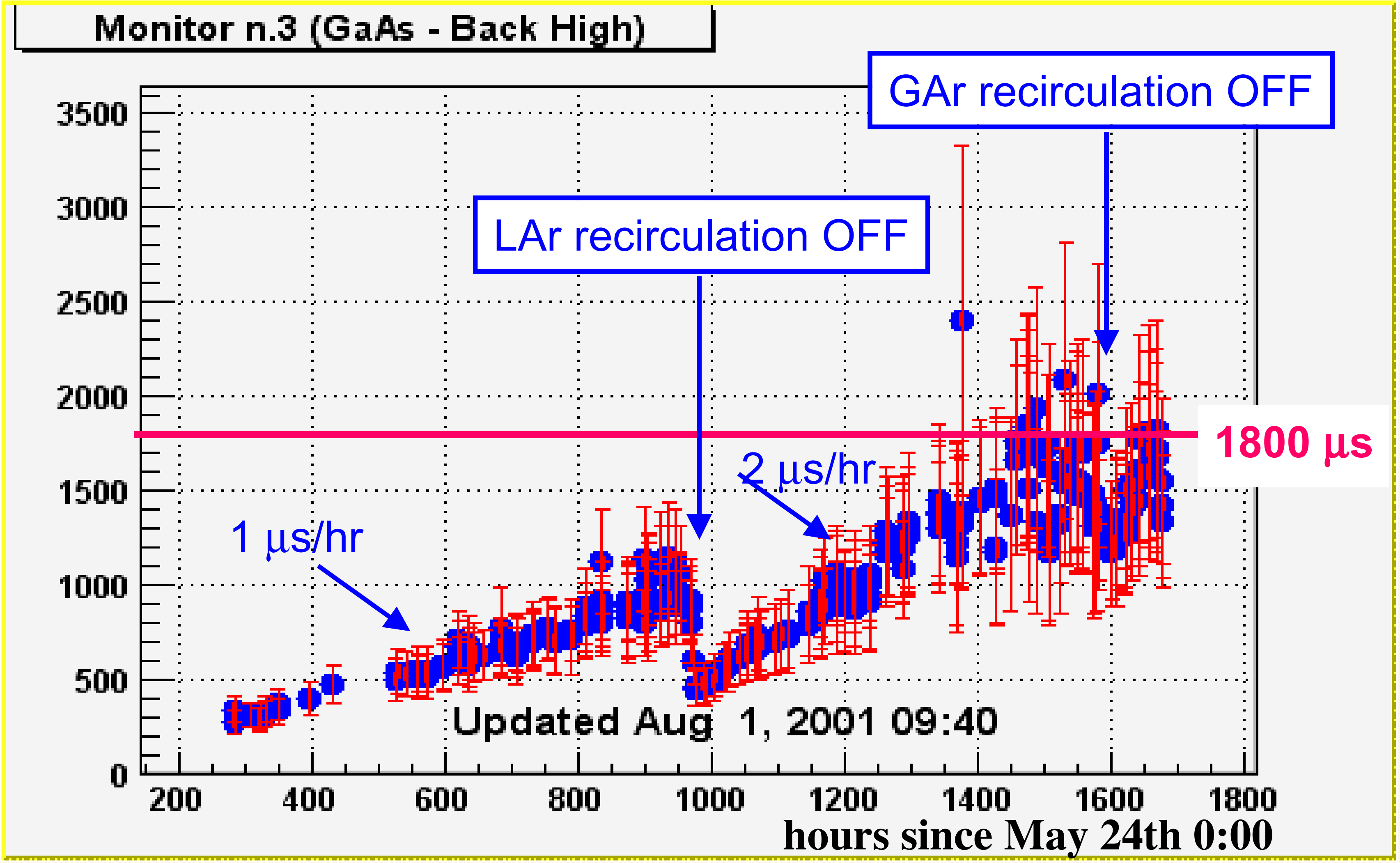
- **This extrapolation seems conceivable within a timescale beyond 2005**.

Drift velocity, H.V. and signal attenuation

- Working drift field
  E=500 V/cm ⇒ drift velocity
  v_d=1.6 mm/μs
- For a 6 meter drift:
  - H.V_{drift}=300kV,
    maximum drift time
    t_{max}=3.75 ms
- Requires high level of purity in order to avoid charge attenuation
- Measured electron lifetime:
  50 liter TPC $\tau > 10$ ms, T600 prototype (after ≈10 weeks): $\tau > 1.8$ ms, was still growing



Achieved electron lifetime in T600



Maximum electron lifetime: 1800 µs

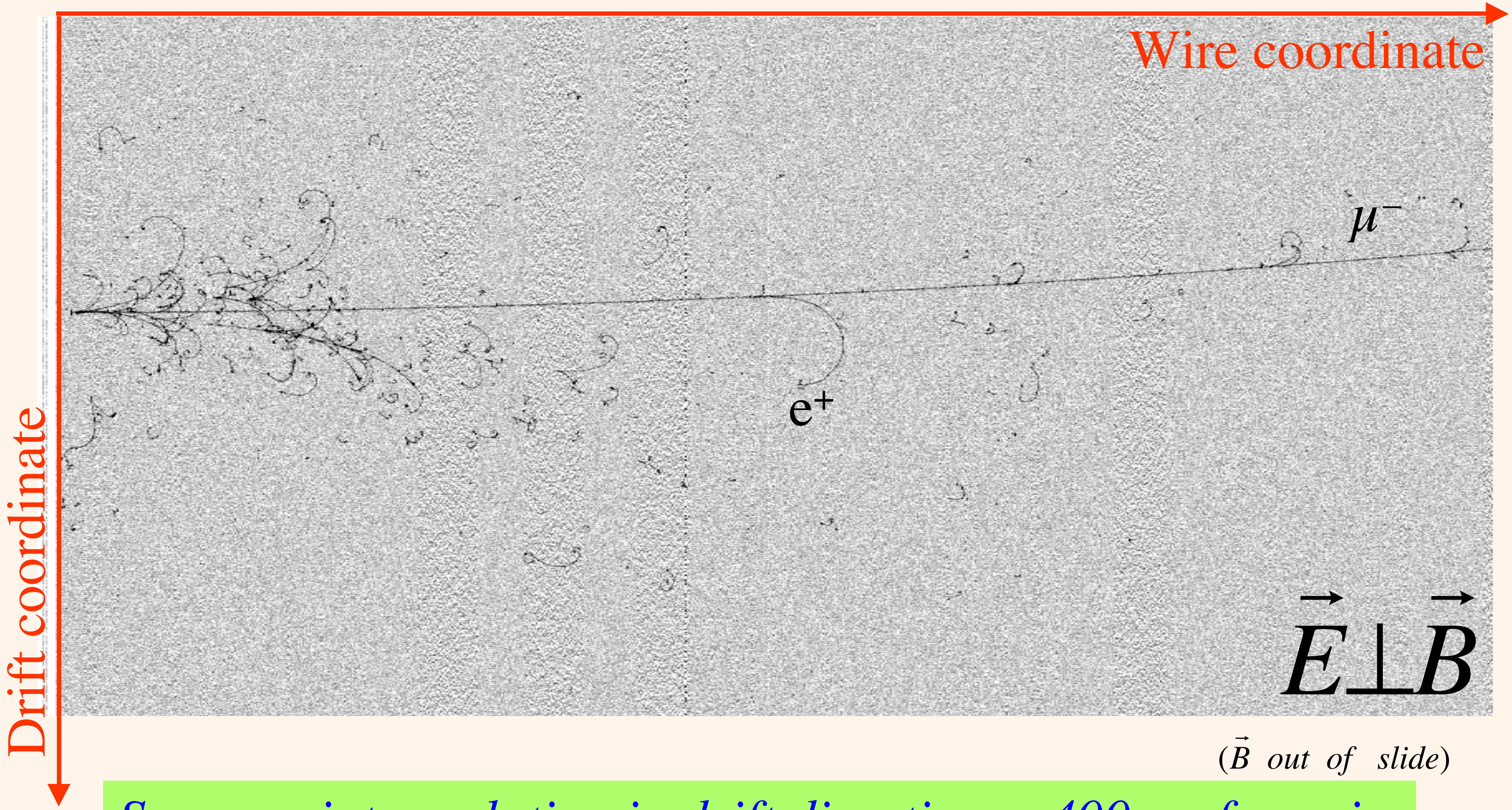
Which type of design ?

- Bigger LAr masses and three possible layouts:
  - A) LAr only
  - B) LAr + external spectrometer
  - C) Magnetized LAr
- LAr in magnetic field was already discussed in the past, as part of the original ICARUS proposals
- The building of the magnetized LAr is essentially an engineering and cost problem
  - L3 magnet could roughly enclose an ICARUS T1200
  - CMS and ATLAS are building very large magnets
  - Superconducting or standard is an engineering choice

Which detector configuration ?

- We can a priori conceive the « do it all » detector.
  - See LANNDD
- Realistically, we can consider different detector configurations, depending on **the kind of physics** we want to achieve, e.g.
  - Non-accelerator physics,
    - proton decay, atmospheric, SN, solar
      - ✶3xT10000, magnetic field not mandatory
  - Accelerator physics:
    - Superbeam or Neutrino factory
      - ✶2xT10000 with external spectrometer,
    - Neutrino factory and *electron charge* for direct T-violation search
      - ✶1xT10000 immersed in B-field

Simulated ν_μ CC event in B=0.1 T

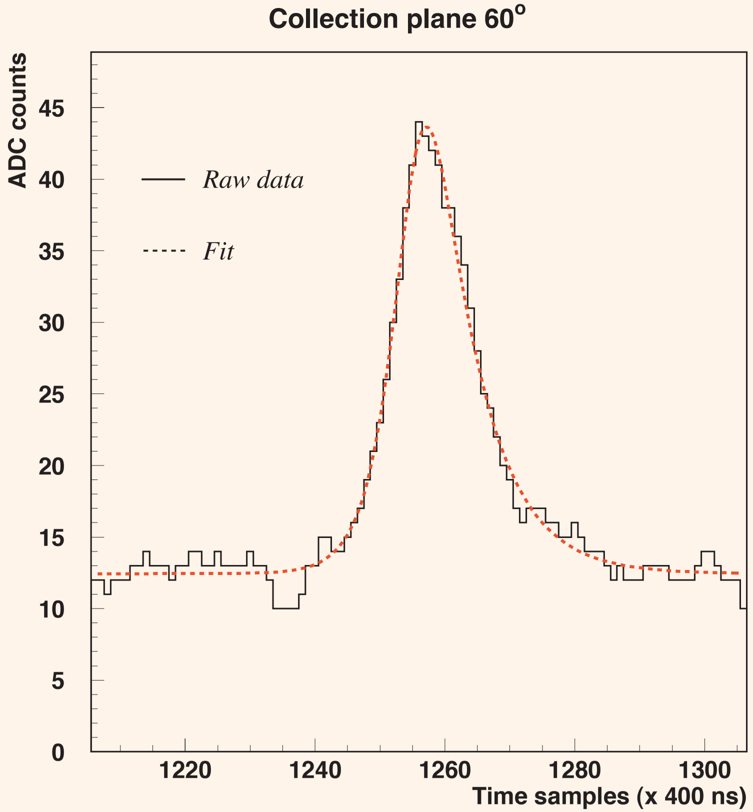


($\vec{B}$ *out of slide*)

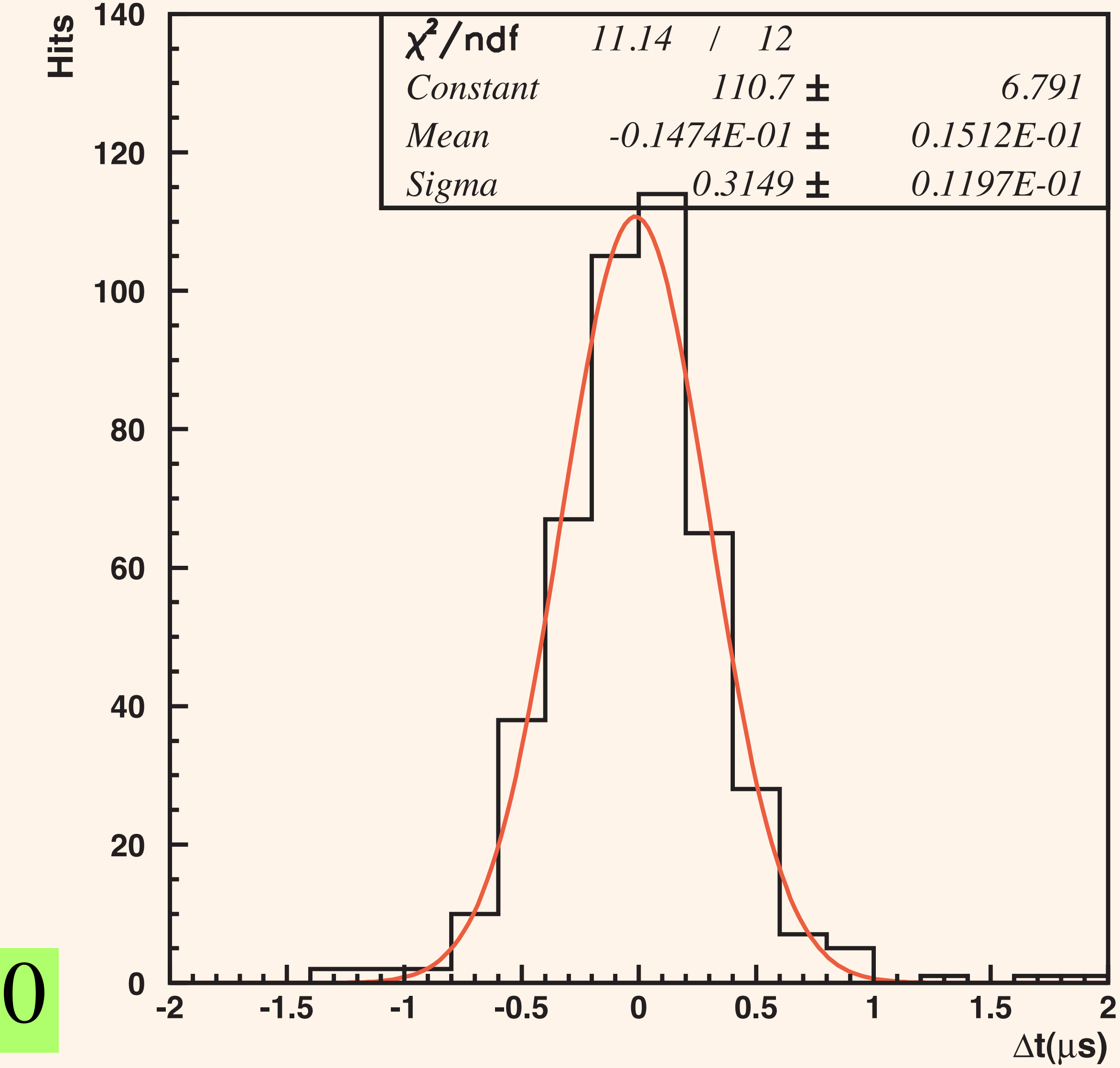
Space point resolution in drift direction: ≃400μm for m.i.p

Measured space point resolution

Fit of T600 signal data (C.R. muons)



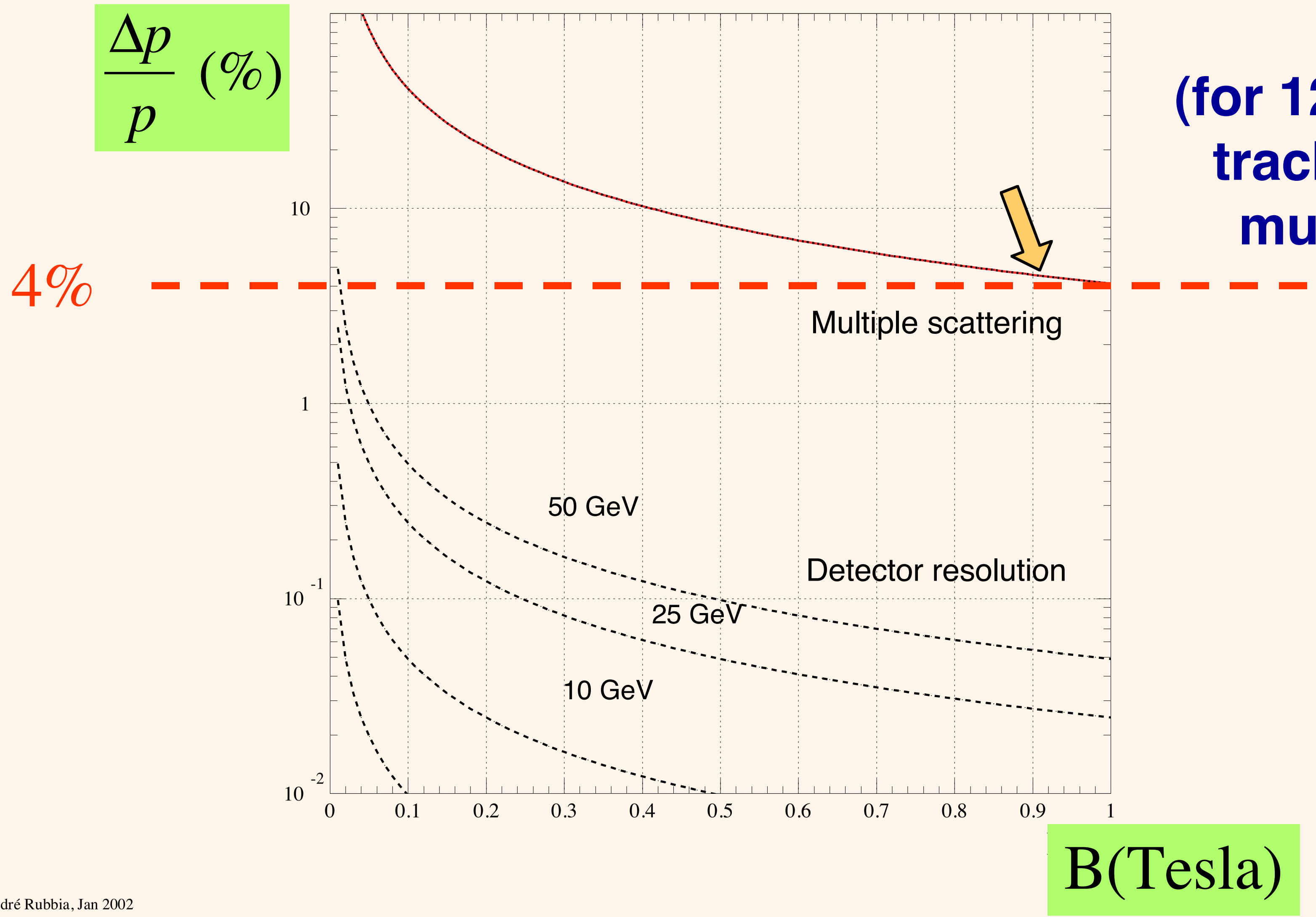
$\sigma_d \approx 400\mu m \;\; in \;\; T600$



Time residuals (C.R. muons in T600)

Track momentum resolution

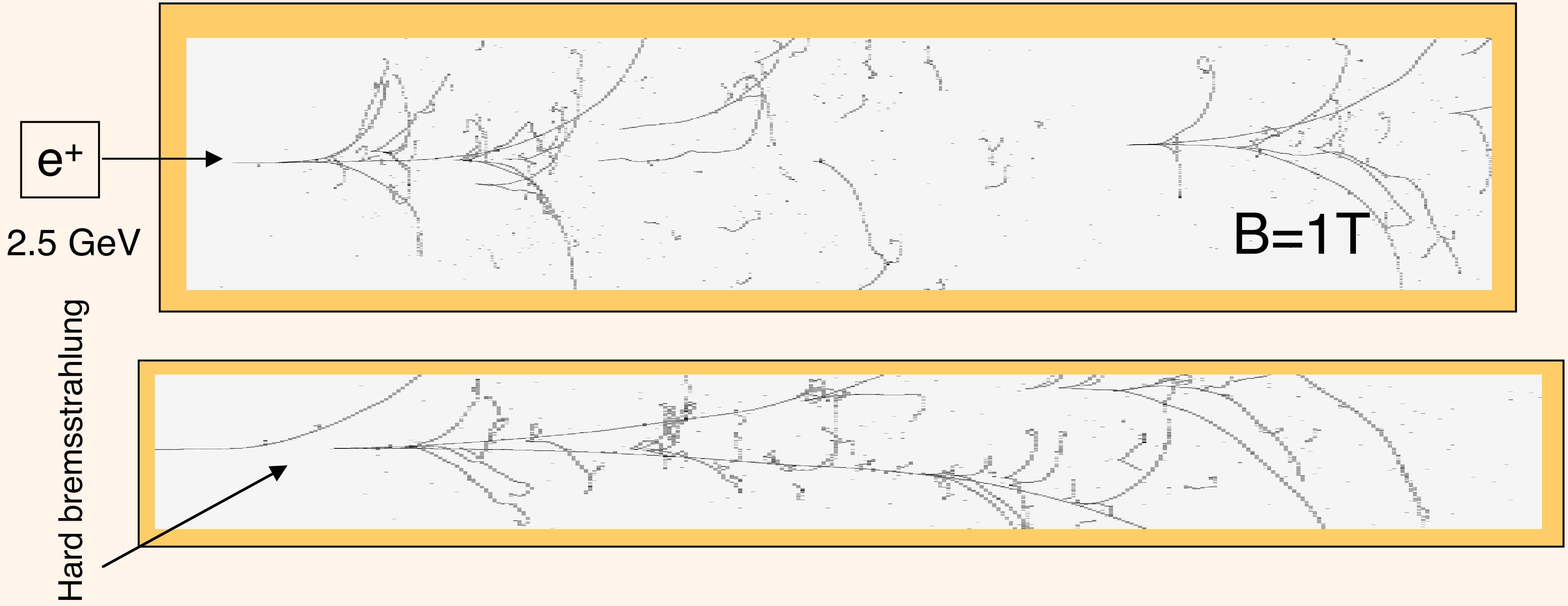
Track momentum determination by magnetic deflection in Liquid Argon dominated by multiple scattering



(for 12m long tracks, i.e. muons!)

Measuring the electron charge

A. Rubbia, hep-ph/0106088

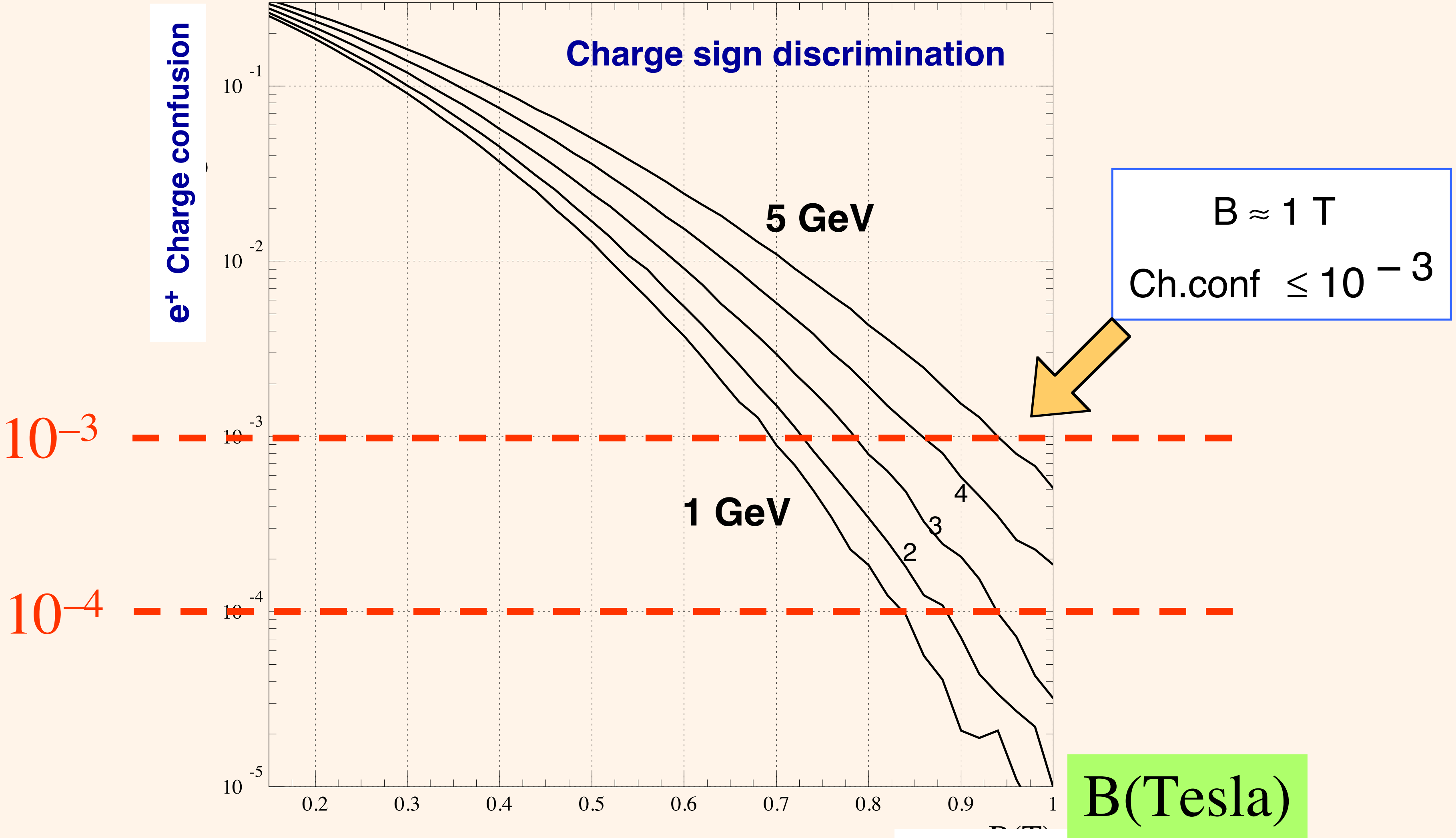


a) Primary electron momentum … curvature radius obtained by the calorimetric energy measurement

b) Soft bremsstrahlung γ's … the primary electron remembers its original direction → long effective x for bending

c) Hard initial bremsstrahlung γ's … the energy is reduced → low P → small curvature radius

Electron charge discrimination



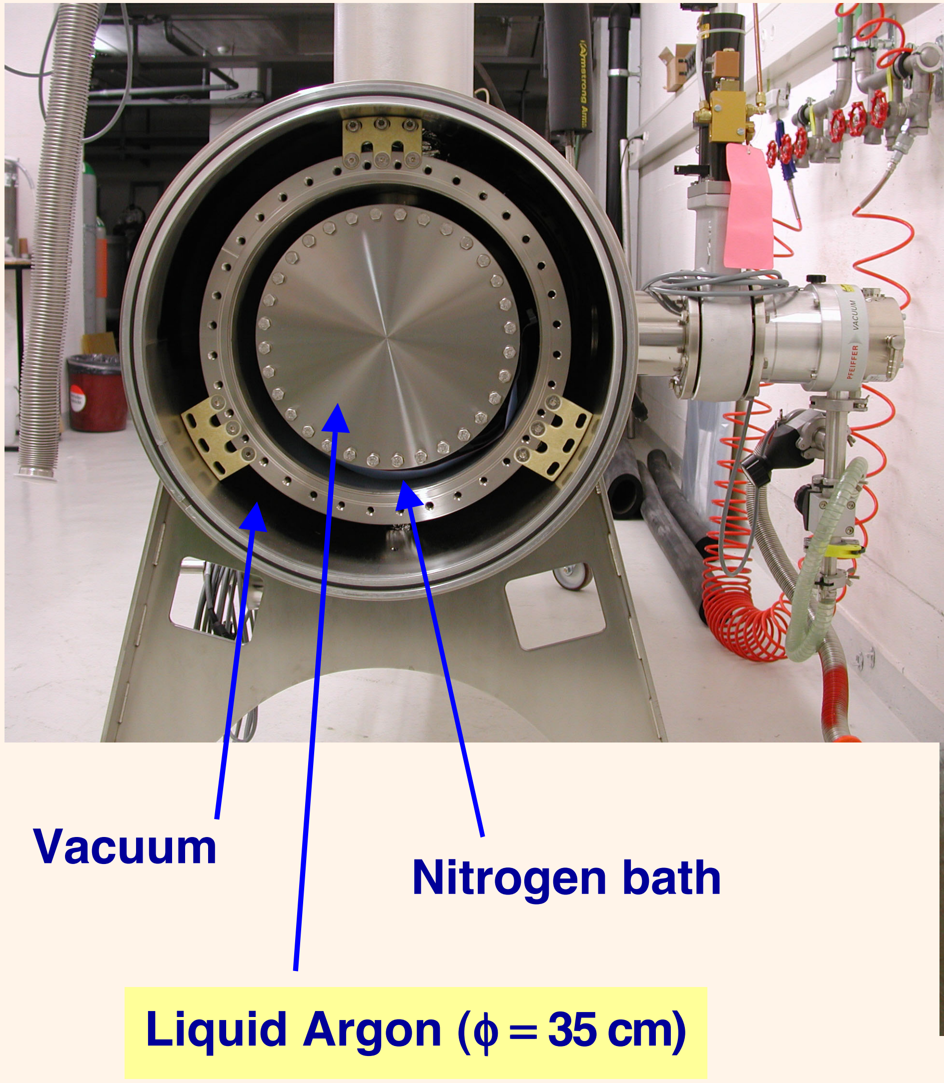
B ≈ 1 T

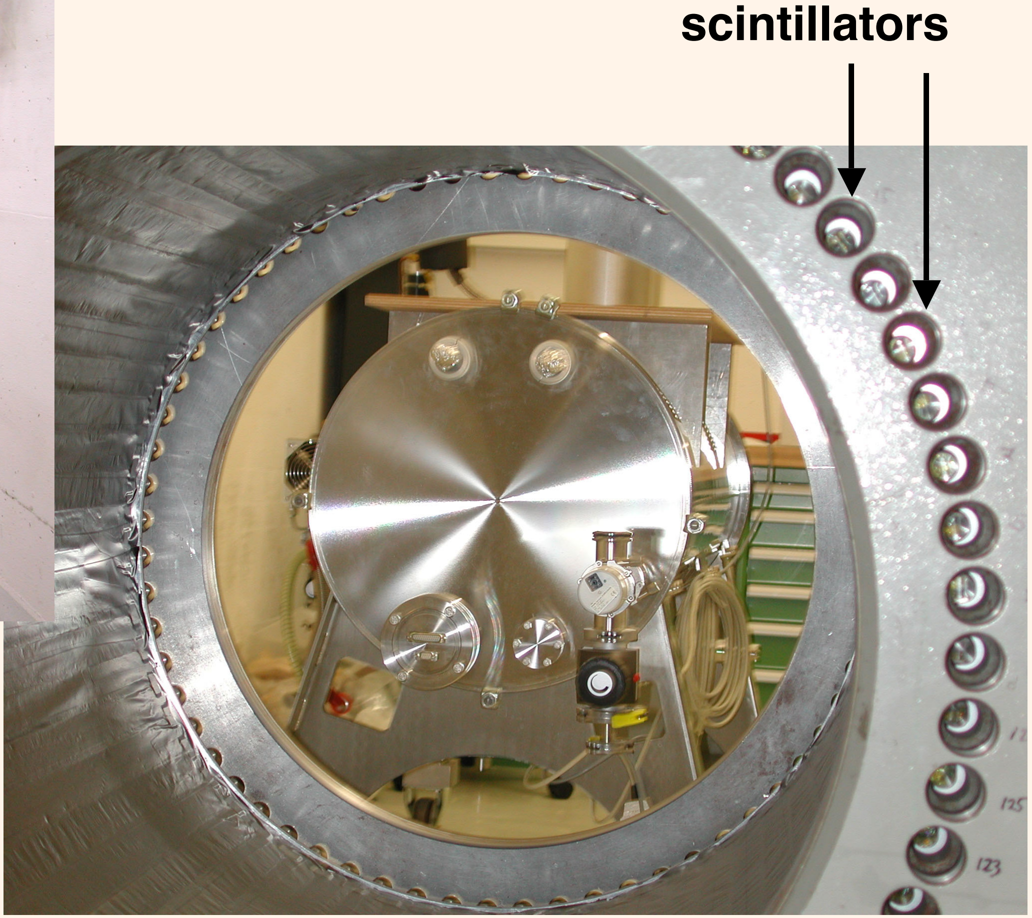
Ch.conf $\leq 10^{-3}$

Given the interesting level of charge confusion required (see later), this appears to be only practically conceivable for electron energies <≈ 5 GeV and requires a field of ≈ 1 T

TPC in magnetic field

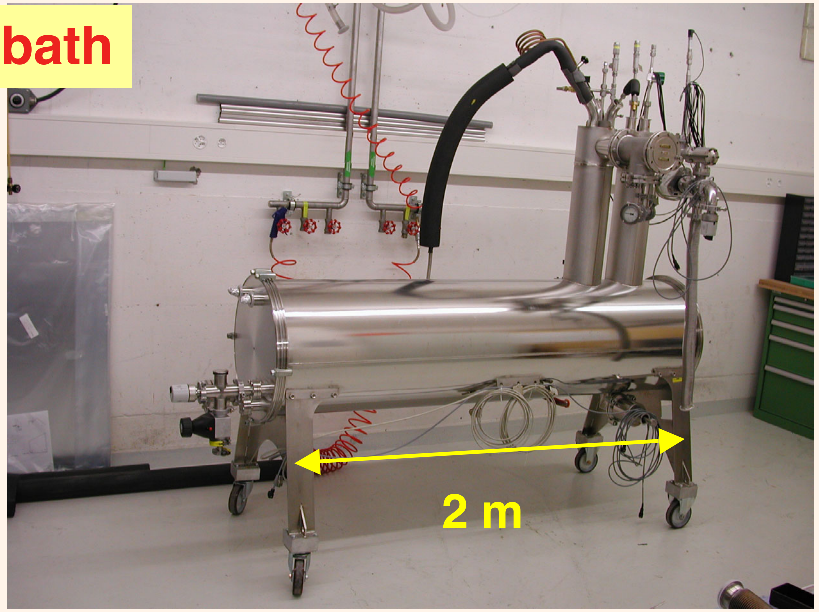
We are building a prototype of Liquid Argon TPC in a magnetic field. Uses a 0.5 T magnetic field and a 2 m x 0.35 m Liquid Argon cylinder to understand the performance of liquid Argon imaging TPC in a magnetic field (free electron drift properties, ability to measure sagitta, etc)



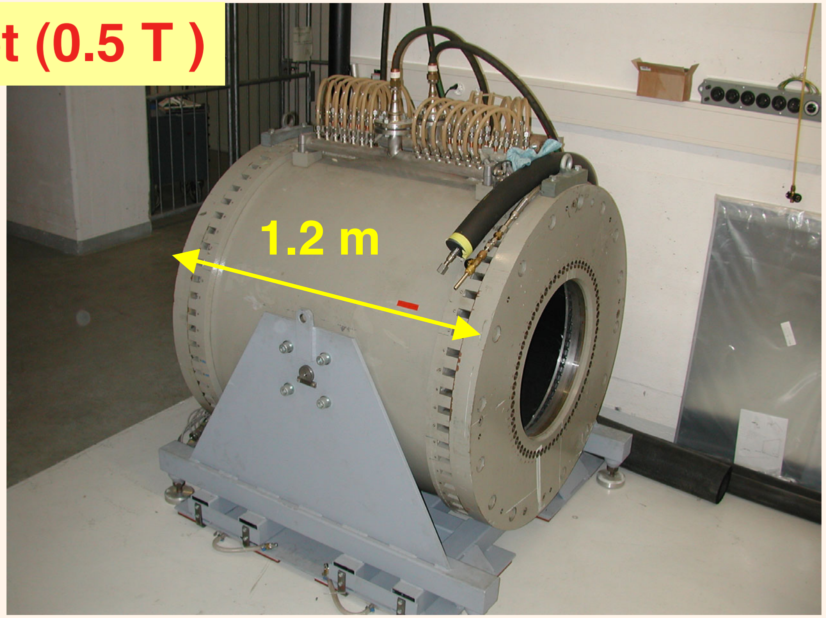


TPC in magnetic field

LAr bath

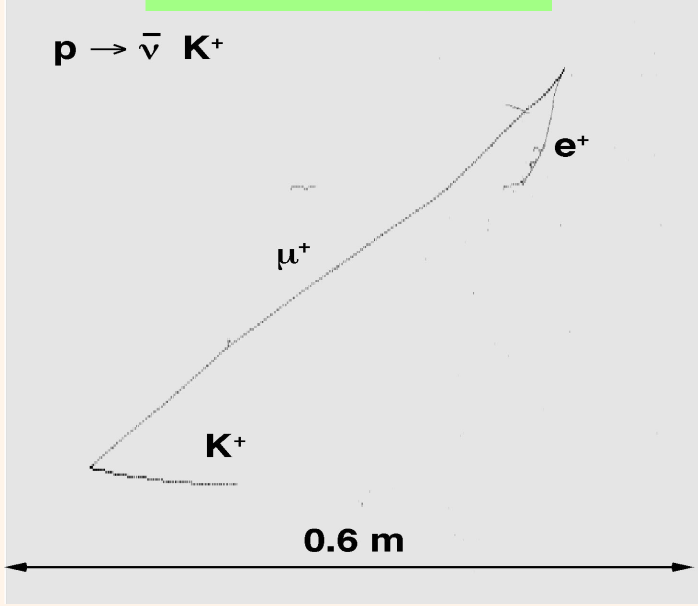


Magnet (0.5 T)

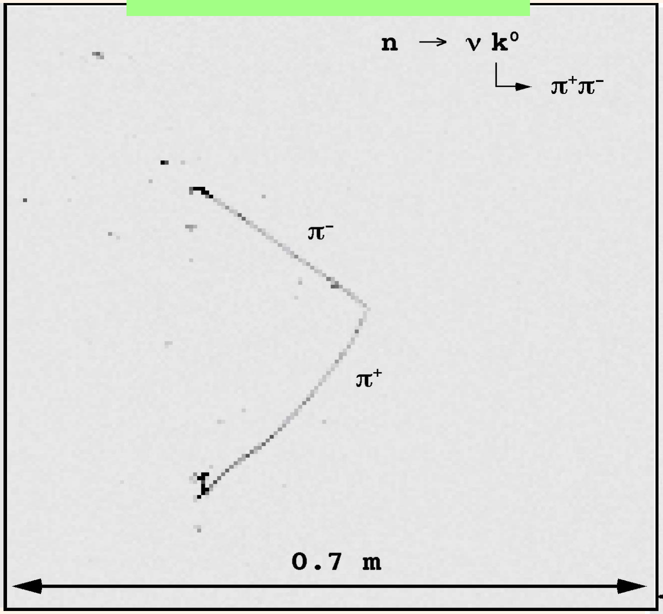


Nucleon decay searches

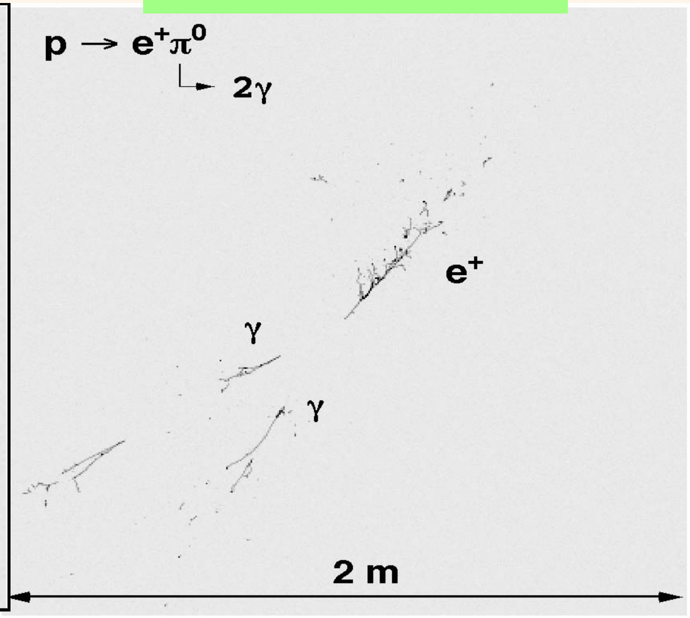
$p \to \nu K^+$ decay



$n \to \nu K^0$ decay



$p \to e^+\ \pi^0$ decay



Thanks to excellent tracking and particle *id* capabilities

LAr unique tool for

Extremely efficient background rejection

High detection efficiency

Bias-free, fully exclusive channel searches!

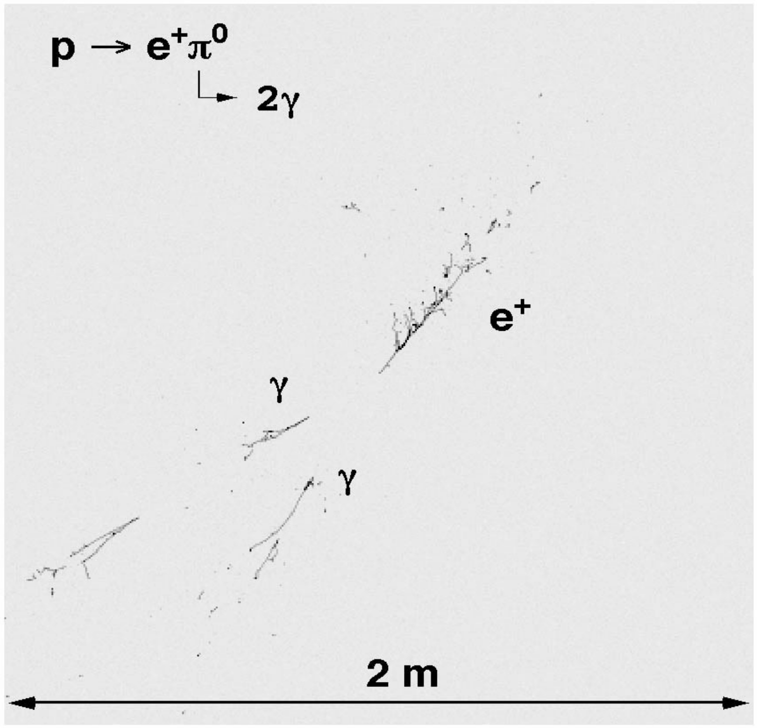
Nucleon decay analyses

See ICARUS-TM/2001/04 for details

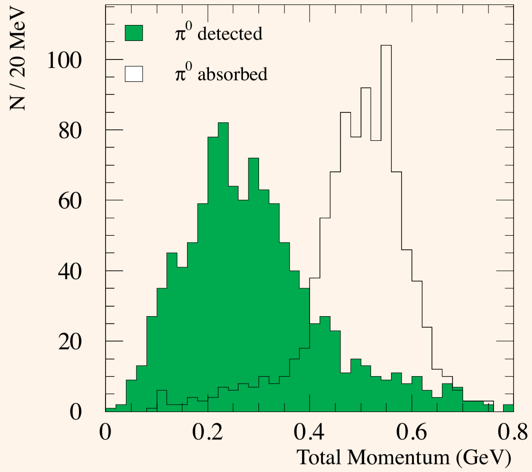
- **Nucleon decay searches are an integral part of ICARUS physics program.**
- **Detailed simulation of nucleon decays in Argon, including nuclear effects**
- **Full simulation of the atmospheric neutrino background up to the megaton-year exposure**
- **Nuclear effects are important as**
  - They change the exclusive final state configuration
  - They introduce a distortion in the apparent kinematics of the event
- **They are included in signal and background**
  - Based on FLUKA nuclear model.
- **Neutrino background estimates based on NUX-FLUKA generator**

See A. Rubbia et al., NUINT01, Tsukuba, Japan 2001.

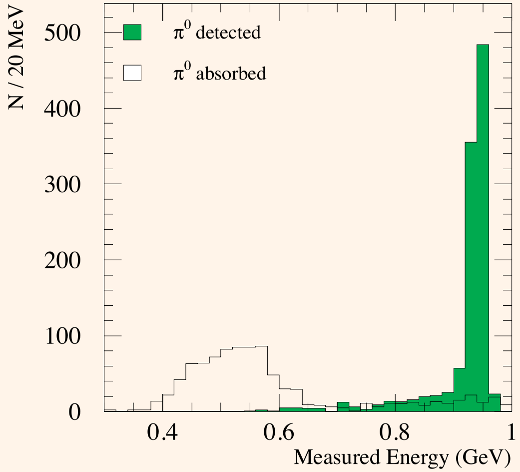
$p \rightarrow e^+ \pi^0$ decay kinematics



Total mom.



Meas. energy



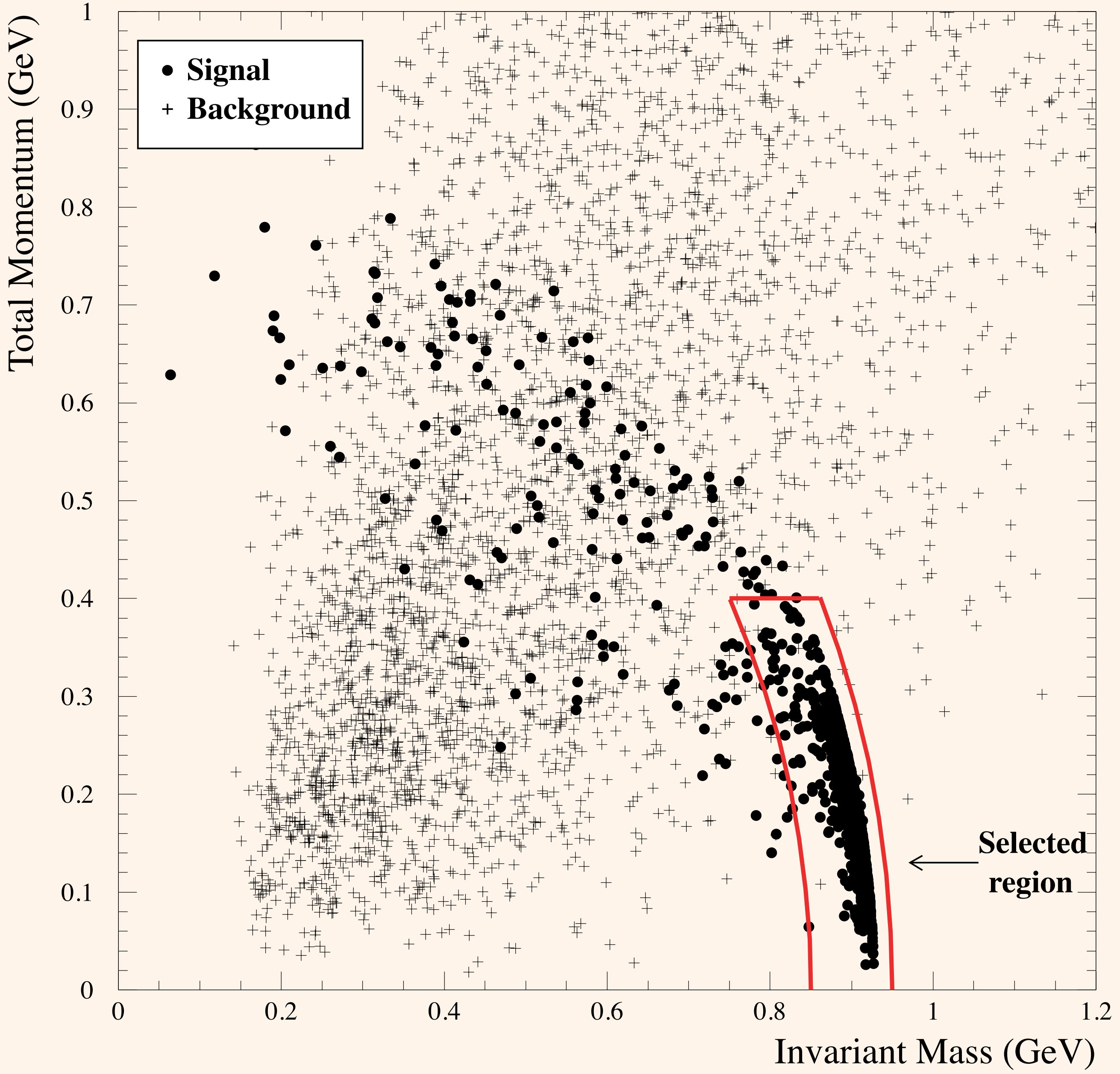
15 MeV width at peak

≈45% π^0 absorbed in Ar nucleus

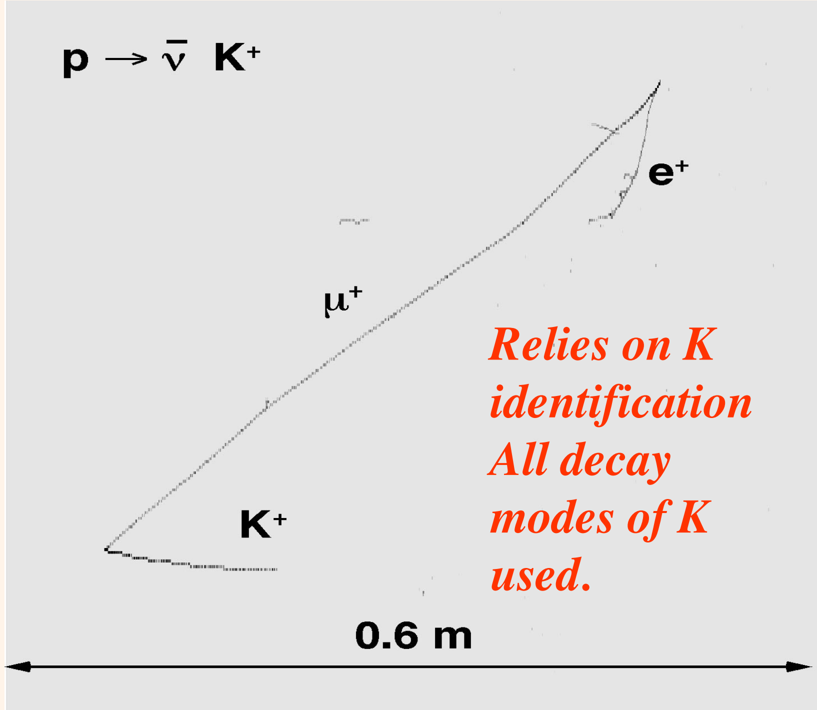
Exclusive Channel Cuts	$p \rightarrow e^+ \pi^0$	ν_e **CC**	$\bar{\nu}_e$ **CC**	ν_μ **CC**	$\bar{\nu}_\mu$ **CC**	ν **NC**	$\bar{\nu}$ **NC**
One π^0	54.00%	6604	2135	15259	5794	8095	3103
One positron	54.00%	6572	2125	20	0	0	0
No charged pions	53.90%	3605	847	5	0	0	0
No protons	50.85%	1188	656	1	0	0	0
Total Momentum < 0.4 GeV	46.70%	454	127	0	0	0	0
0.86 GeV < Total E < 0.95 GeV	45.30%	1	0	0	0	0	0

Exposure: 1000 kton x year

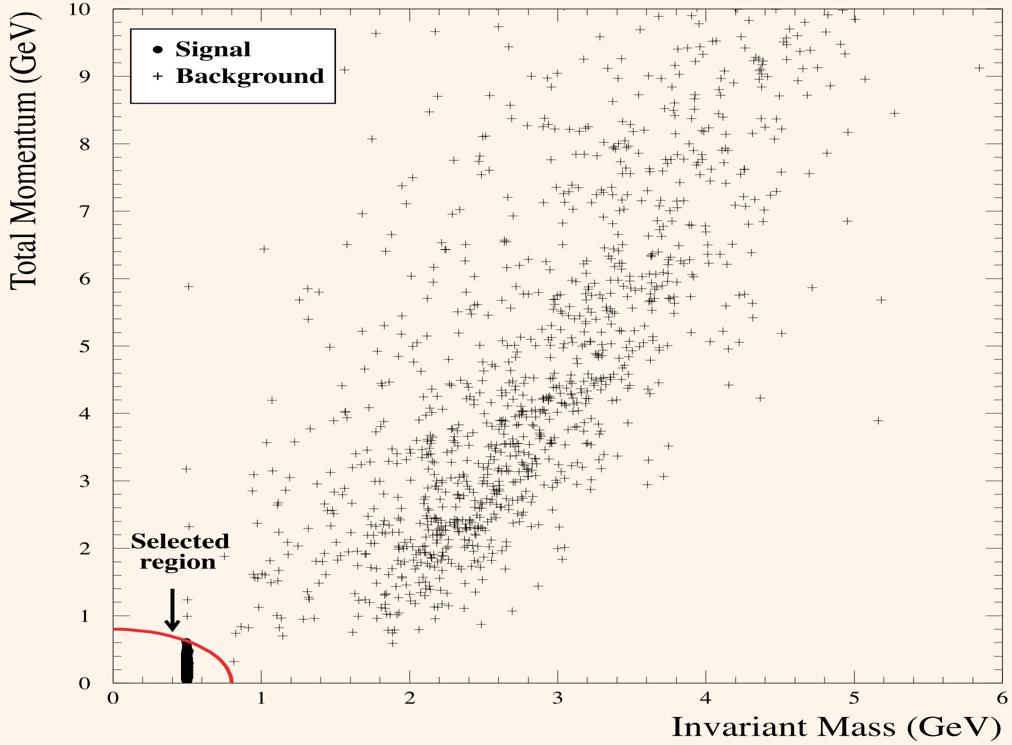
$p \to e^+ \pi^0$


Total Momentum (GeV)
Invariant Mass (GeV)
● Signal
+ Background
Selected region
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.2
0.4
0.6
0.8
1
1.2

$p \rightarrow K^+ \nu$ decay kinematics



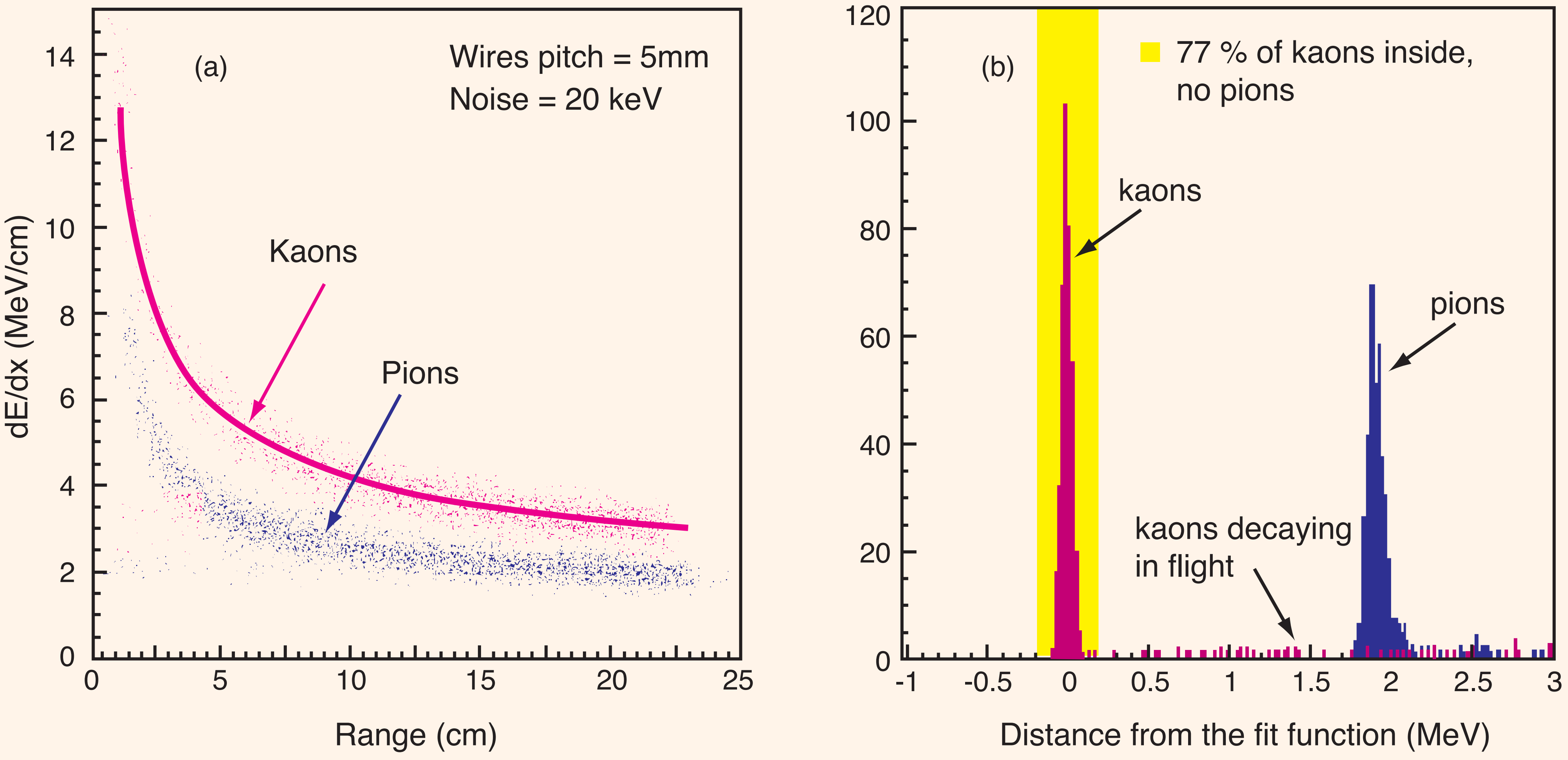
Relies on K identification
All decay modes of K used.



Cuts	$p \rightarrow K^+\bar{\nu}$	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν NC	$\bar{\nu}$ NC
One Kaon	96.75%	308	36	871	146	282	77
No π^0	96.75%	143	14	404	56	138	25
No positrons	96.75%	0	0	400	56	138	25
No muons	96.75%	0	0	0	0	138	25
No charged pions	96.75%	0	0	0	0	57	9
Total Energy < 0.8 GeV	96.75%	0	0	0	0	1	0

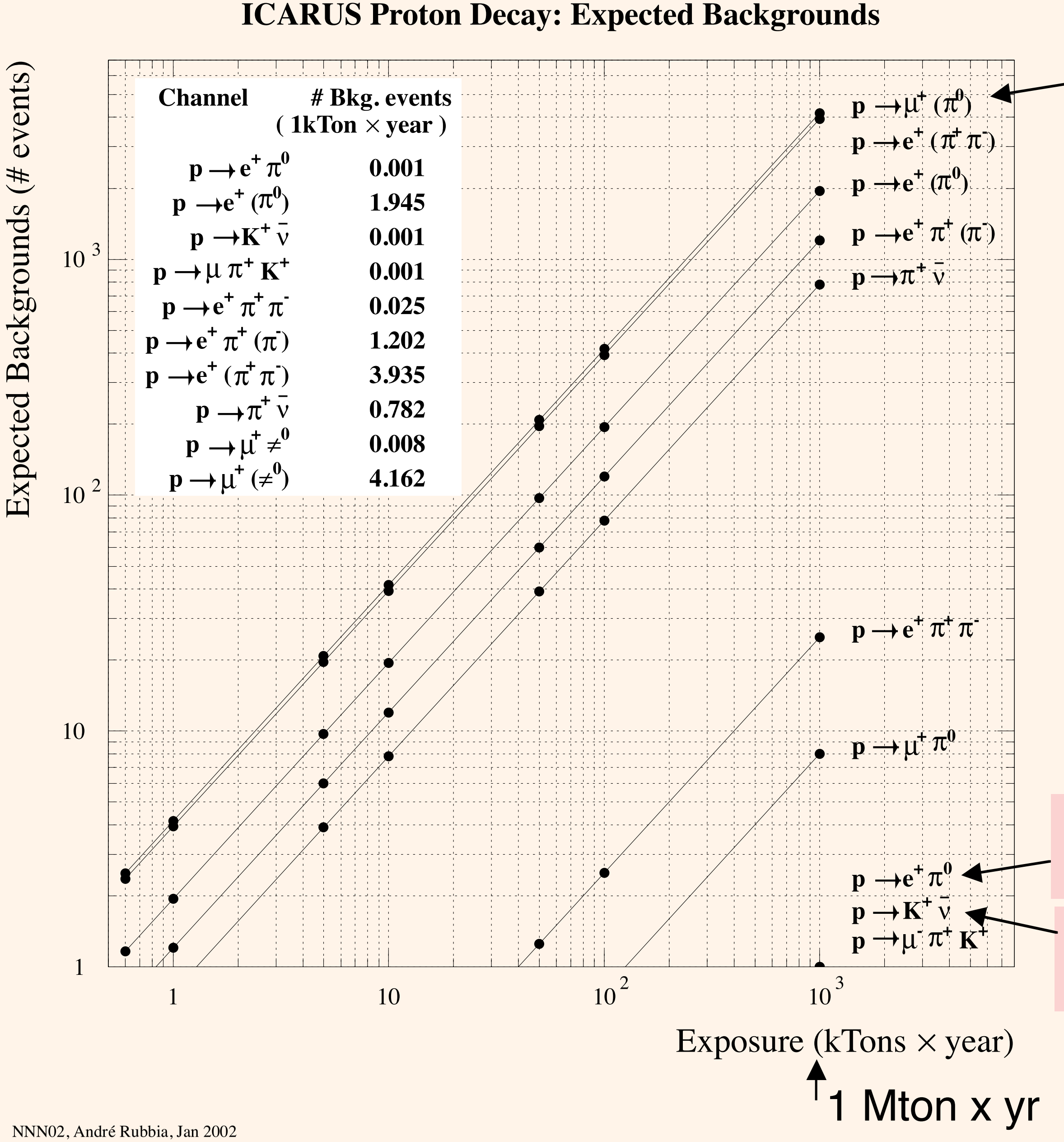
Exposure: 1000 kton x year

Kaon identification



Energy loss profile along kaon and pion tracks and distribution of the distance from the kaon fit function along pion and kaon tracks.

Proton decay: expected backgrounds vs channel



Channel	# Bkg. events (1kTon × year)
$p \to e^+ \pi^0$	0.001
$p \to e^+ (\pi^0)$	1.945
$p \to K^+ \bar{\nu}$	0.001
$p \to \mu\, \pi^+ K^+$	0.001
$p \to e^+ \pi^+ \pi^-$	0.025
$p \to e^+ \pi^+ (\pi^-)$	1.202
$p \to e^+ (\pi^+ \pi^-)$	3.935
$p \to \pi^+ \bar{\nu}$	0.782
$p \to \mu^+ \neq^0$	0.008
$p \to \mu^+ (\neq^0)$	4.162

$p \to e^+X$

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

$p \to K^+\nu$

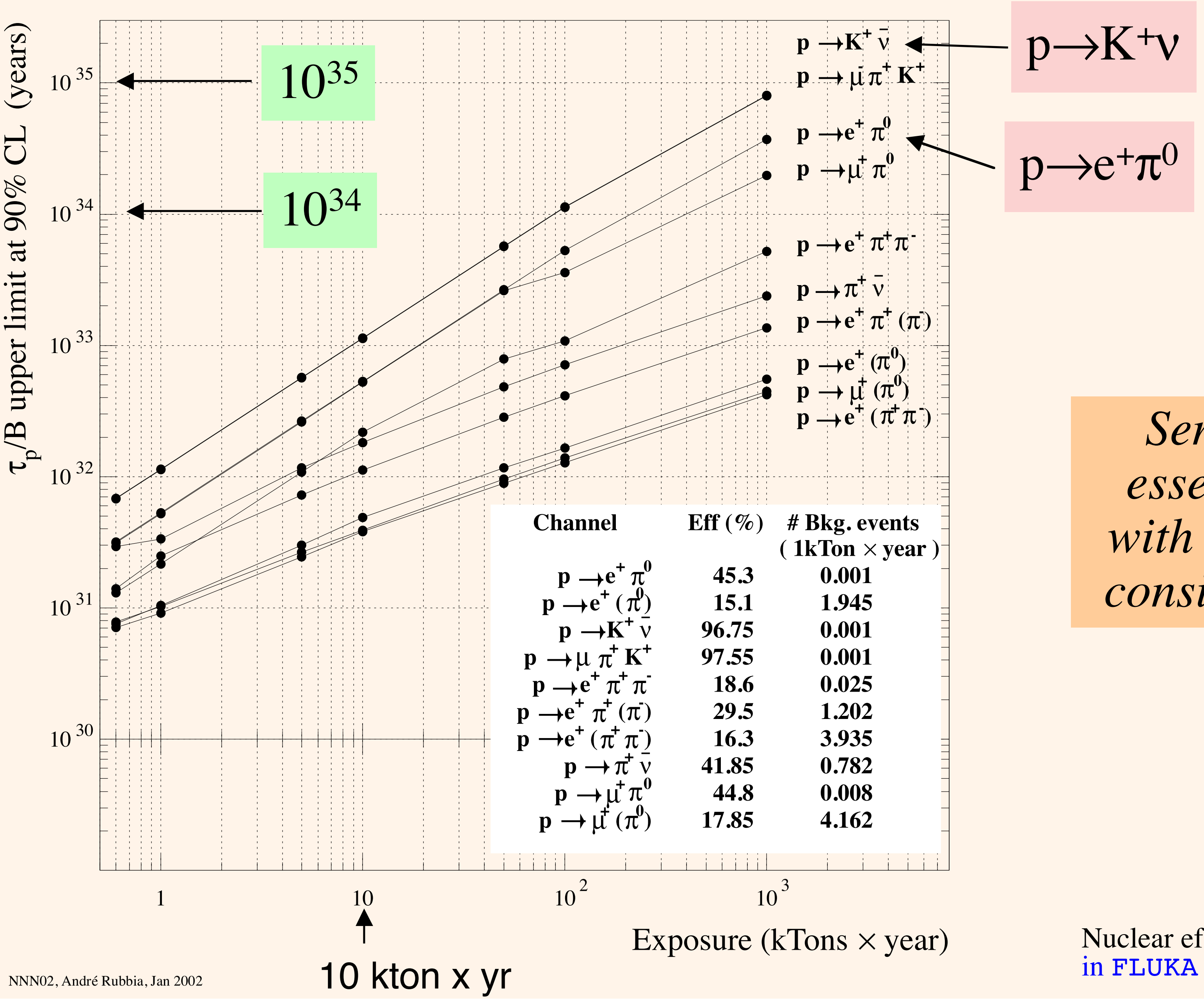
Extremely good exclusive signal signatures

⇒ Excellent background rejection

Discovery with a single event!

Nuclear effects in backgrounds: fully embedded in FLUKA nuclear model

Sensitivity vs exposure



Channel	Eff (%)	# Bkg. events (1kTon × year)
$p \rightarrow e^+ \pi^0$	45.3	0.001
$p \rightarrow e^+ (\pi^0)$	15.1	1.945
$p \rightarrow K^+ \bar{\nu}$	96.75	0.001
$p \rightarrow \mu\ \pi^+ K^+$	97.55	0.001
$p \rightarrow e^+ \pi^+ \pi^-$	18.6	0.025
$p \rightarrow e^+ \pi^+ (\pi^-)$	29.5	1.202
$p \rightarrow e^+ (\pi^+ \pi^-)$	16.3	3.935
$p \rightarrow \pi^+ \bar{\nu}$	41.85	0.782
$p \rightarrow \mu^+ \pi^0$	44.8	0.008
$p \rightarrow \mu^+ (\pi^0)$	17.85	4.162

Sensitivity grows essentially linearly with exposure for all considered channels.

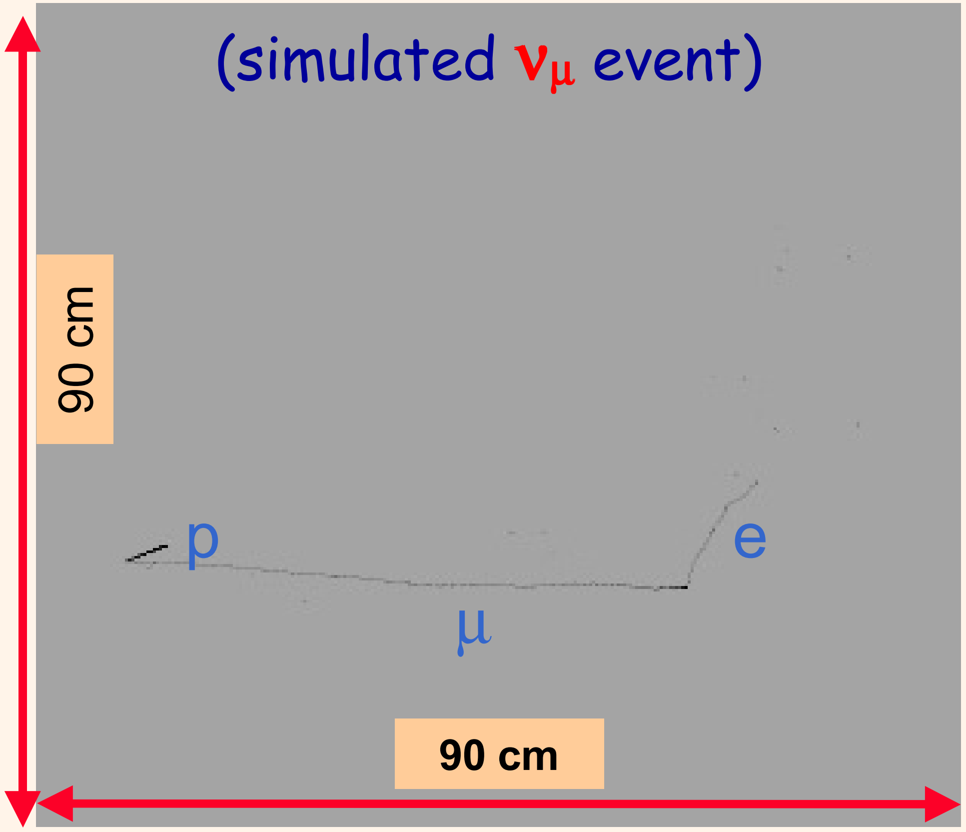
Nuclear effects in signal: fully embedded in FLUKA nuclear model

Understanding atmospheric neutrinos

- **ICARUS thanks to its unprecedented imaging properties will provide**
  - An observation of atmospheric neutrino events with very high quality.
  - An unbiased, mostly systematic free, observation of atmospheric neutrino events
    - ⇒CC/NC separation, clean e/μ discrimination, all final states accessible, excellent e/π^0 separation, particle identification (p/K/π) for slow particles
  - An excellent reconstruction of incoming neutrino properties (energy and direction)

A tool to understand atmospheric neutrinos, in terms of their basic properties (flux, flavor) & of the physics of neutrinos (oscillations)

Atmospheric ν events

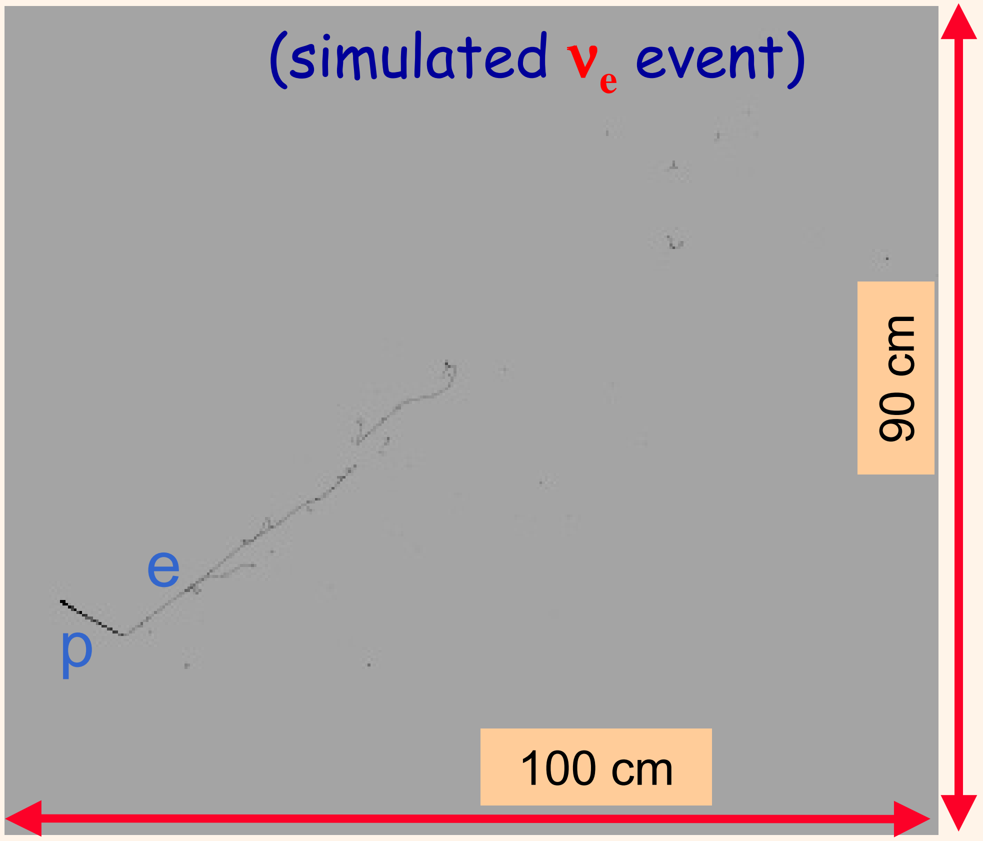


ν_μ quasi-elastic interaction

E_ν = 370 MeV

P_μ = 250 MeV

T_p = 90 MeV



ν_e quasi-elastic interaction

E_ν = 450 MeV

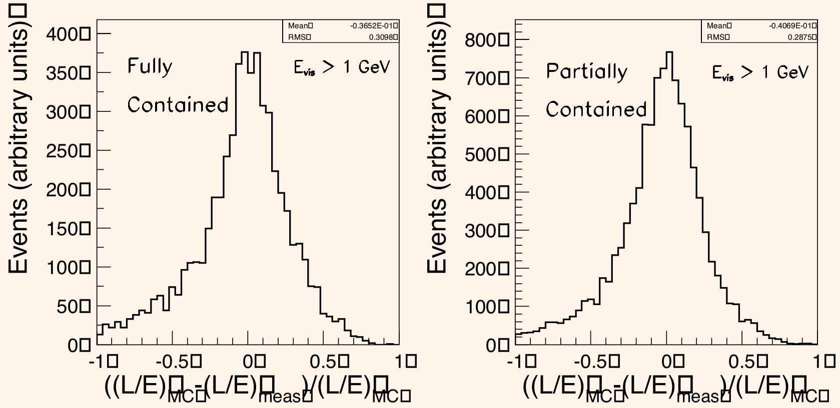
P_e = 200 MeV

T_p = 240 MeV

L/E distribution

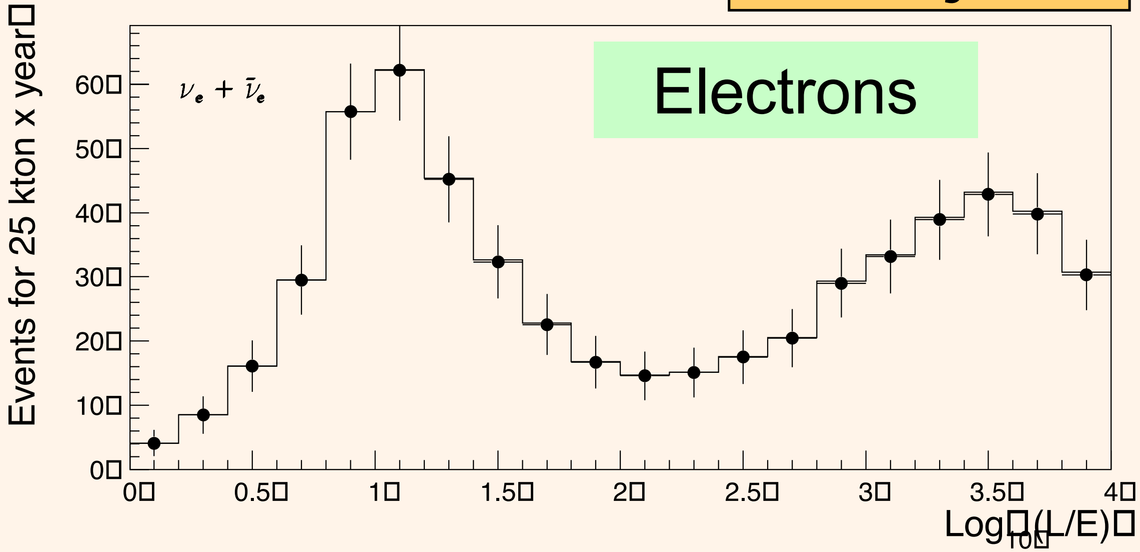
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

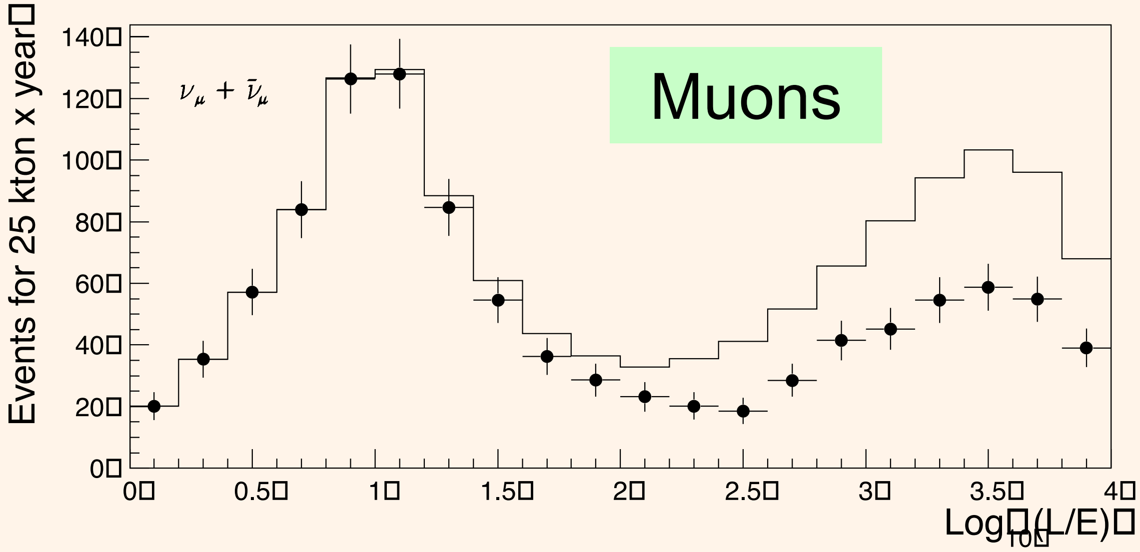
25 kt year



$$\Delta(L/E)_{RMS} \approx 30\%$$

- **Oscillation parameters:**
  $\Delta m^2_{32} = 3.5 \times 10^{-3}$ eV^2
  - $\sin^2 2\Theta_{23} = 0.9$
  - $\sin^2 2\Theta_{13} = 0.1$
- *Electron sample can be used as a reference for no oscillation case*



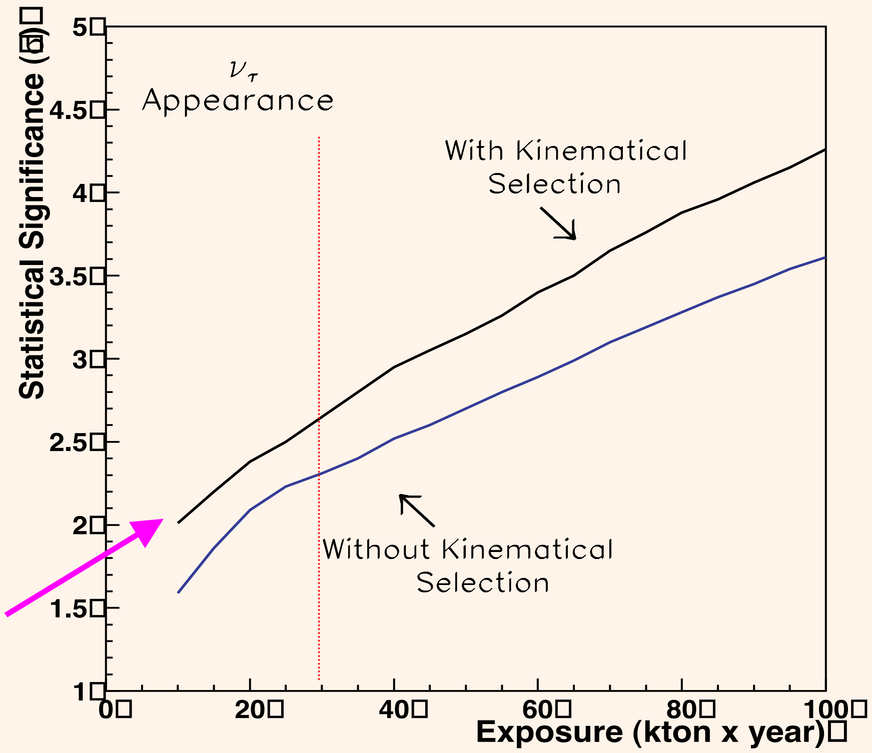


Atmospheric direct τ appearance

- Search for *ν_τCC at high energy*
  - –30 *ν_τCC/year expected*
- Compare NC(top) to NC(bottom) at high energy
  - –Requires good discrimination of NC event direction
- Exploit precise measurement of all final state particles
  - – Count events as a function of visible energy
  - –Improved discrimination by a study of the event kinematical properties

>3σ effect

after **40 kt x year exposure**



Solar and SN neutrinos detection

- Real-time detection of low energy i.e. solar and supernovae neutrinos through two independent reactions:

Elastic scattering on atomic electron

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

ν absorption on Argon nuclei (CC reaction)

$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$$

- Double signature for CC events: primary electron track eventually surrounded by **low energy secondary tracks** ($^{40}K^*$ de-excitation).
- Electron detection threshold = 5 MeV (needed to reduce background contribution and to establish the e$^-$ direction in elastic scattering).
- Sensitive to ^{8}B and *hep* components of the solar neutrino spectrum.

<u>Supernova:</u>

$$\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+$$

Solar neutrino event rates

New solar model:
BP2000 ν flux used

^8B $5.15 \times 10^6/cm^2/s$

hep $9.3 \times 10^3/cm^2/s$
(BP98: 2.10)

(No oscillation hypothesis)

Electron energy threshold (MeV)	Solar neutrino events (1kton × year)		
	Elastic	**Fermi**	**Gamow-Teller**
0.0	782806	2011	4541
1.0	4560	1978	3287
2.0	1854	1848	3111
3.0	1465	1588	2762
4.0	1114	1212	2250
5.0	809	784	1644
5.5	676	579	1336
6.0	557	397	1042
6.5	450	247	774
7.0	358	135	540
7.5	278	63	349
8.0	212	26	205
8.5	156	10	107
9.0	112	5	49
9.5	77	3	20
10.0	51	2	8
10.5	32	2	4
11.0	19	1	3

$T_{thresh} = 5\ MeV$

Solar neutrino analysis

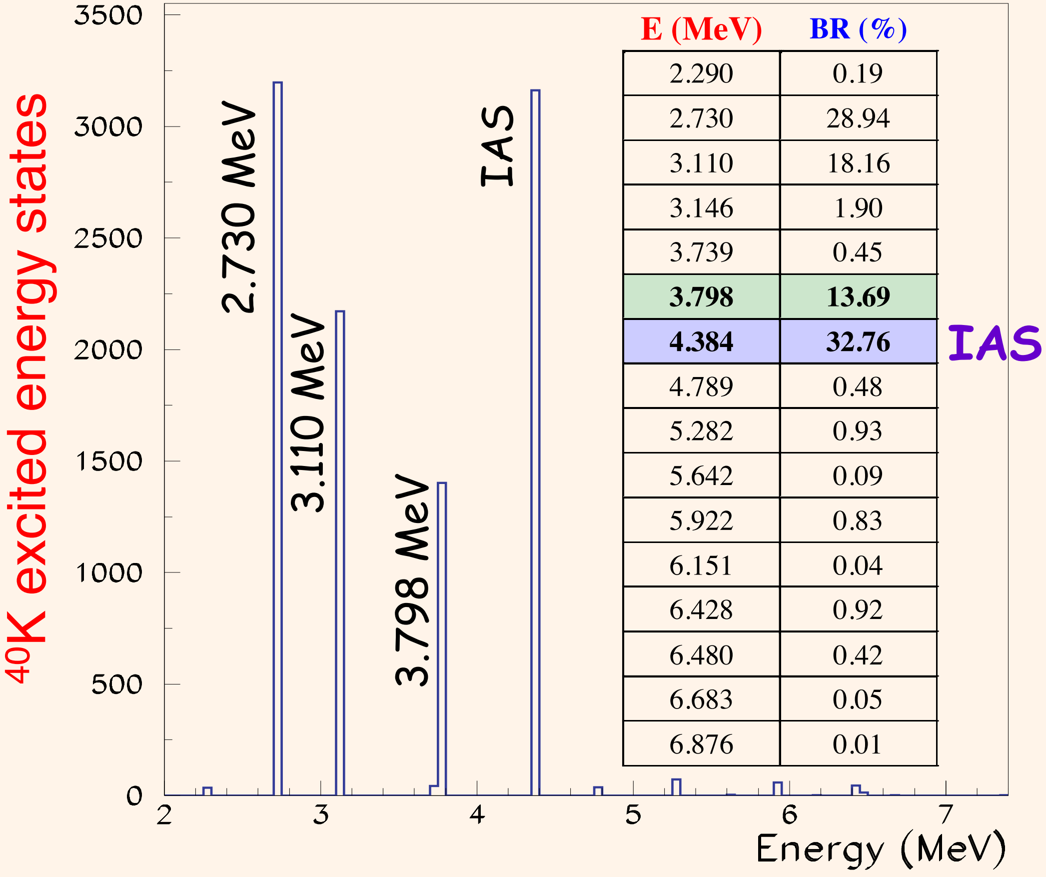
$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^{*} + e^{-}$$

- Elastic scattering
  - → σ precisely known <1%
- Fermi (F) transition **to 4.38 MeV IAS ^{40}K**
  - → σ precisely known <1%

    Bahcall, J.N. Rev. Mod. Phys., 50, 881(1978).
- Gamov-Teller (GT) **to various ^{40}K levels**
  - → σ less precisely known ¯ 10%

    Ormand et.al, PLB 345 (1995) 343.
  - → $\sigma_{GT} \approx 2\sigma_F$

K deexcitation

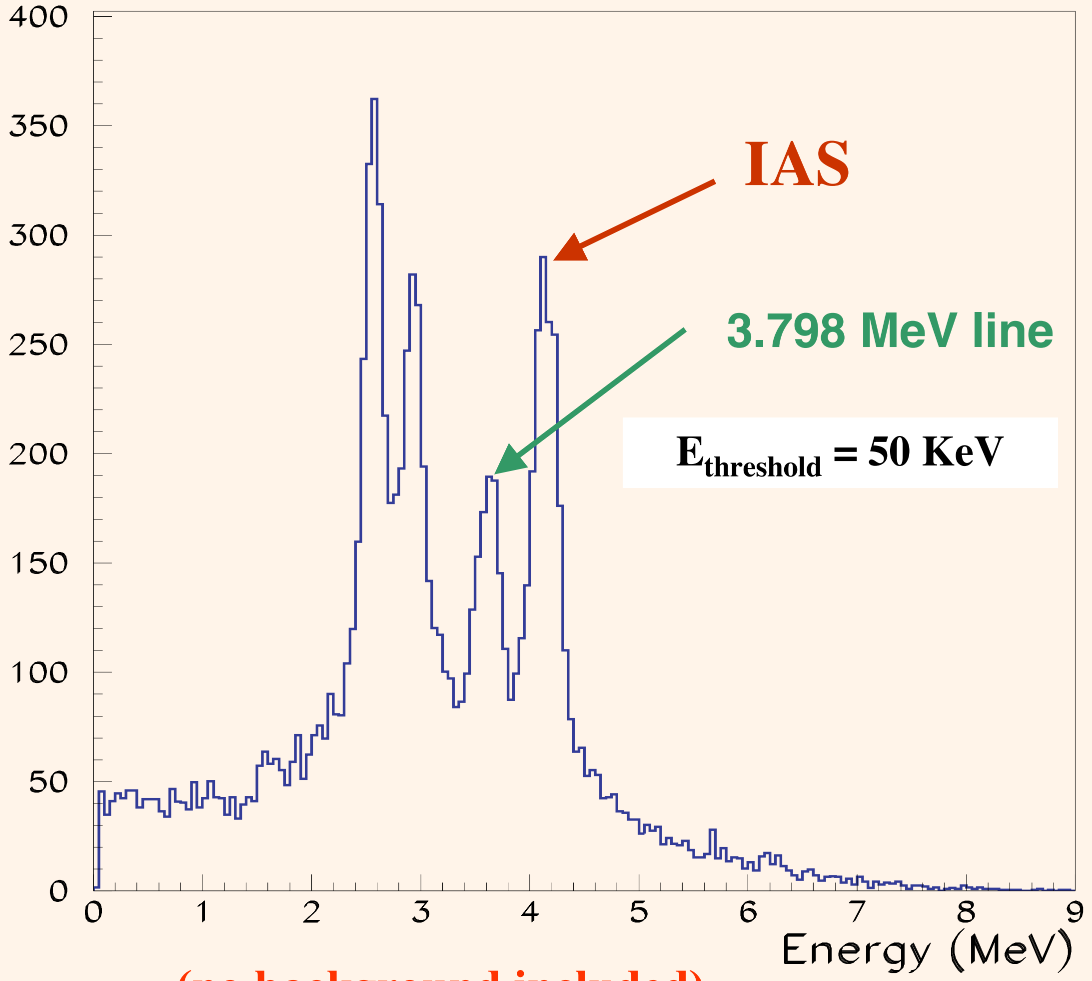


E (MeV)	BR (%)
2.290	0.19
2.730	28.94
3.110	18.16
3.146	1.90
3.739	0.45
3.798	**13.69**
4.384	**32.76**
4.789	0.48
5.282	0.93
5.642	0.09
5.922	0.83
6.151	0.04
6.428	0.92
6.480	0.42
6.683	0.05
6.876	0.01

IAS

Precise measurement of the CC rate

Reconstructed photon spectrum



IAS

3.798 MeV line

$E_{threshold}$ = 50 KeV

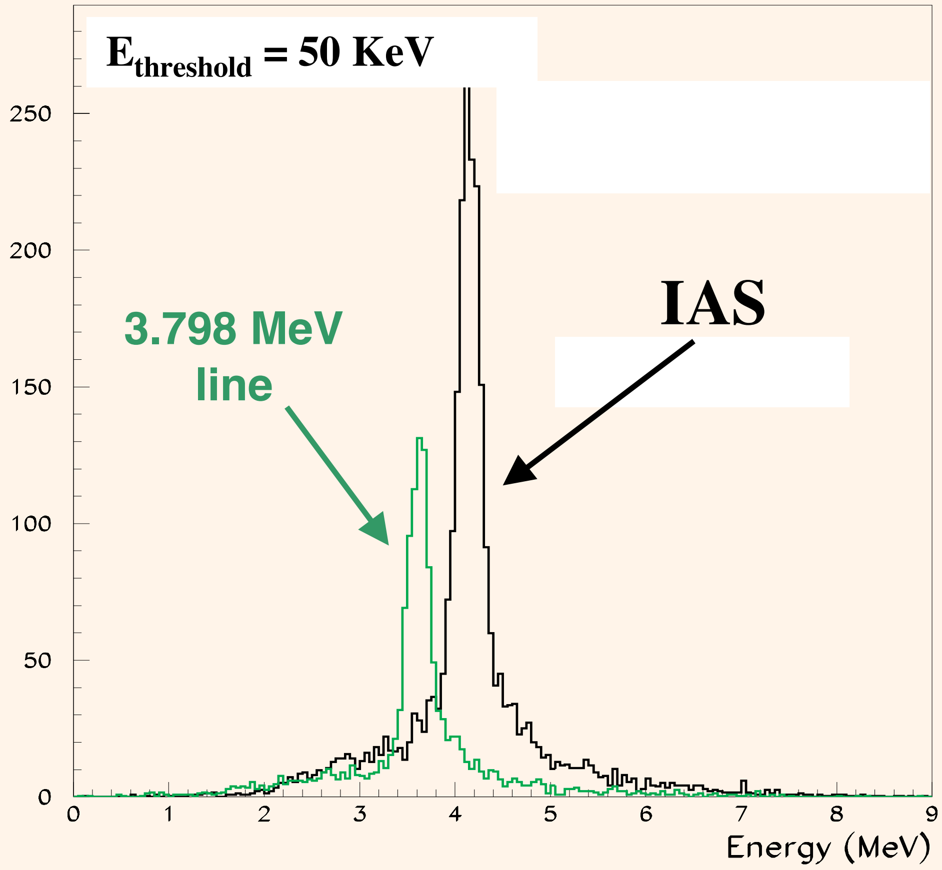
(no background included)

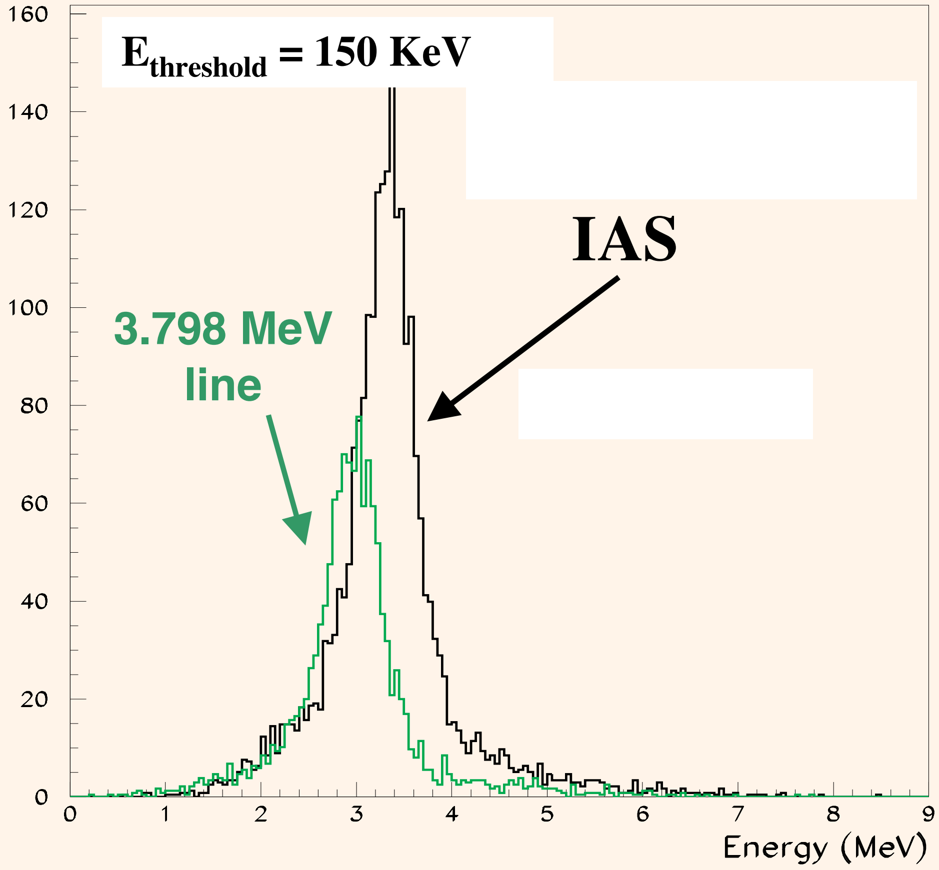
A precise measurement of the solar flux can be obtained by distinguishing the superallowed Fermi transition among the other excited states

An accurate calibration of the detector energy response is fundamental

IAS discrimination vs energy threshold

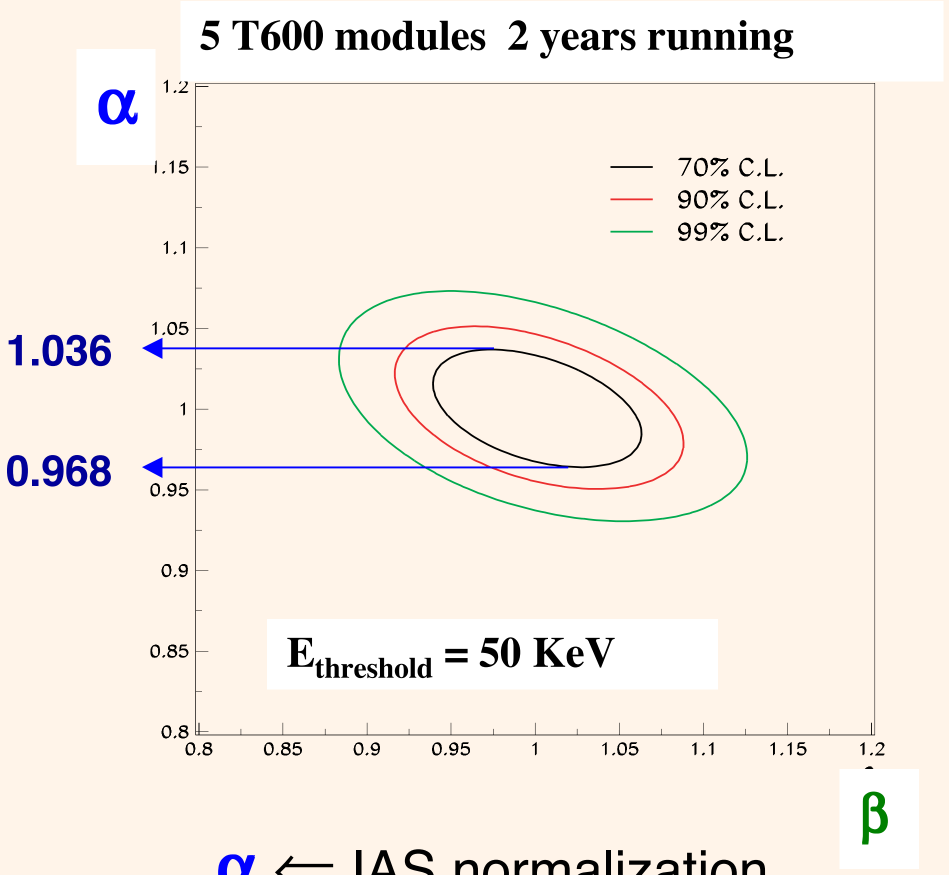
Line resolution depends on energy detection threshold



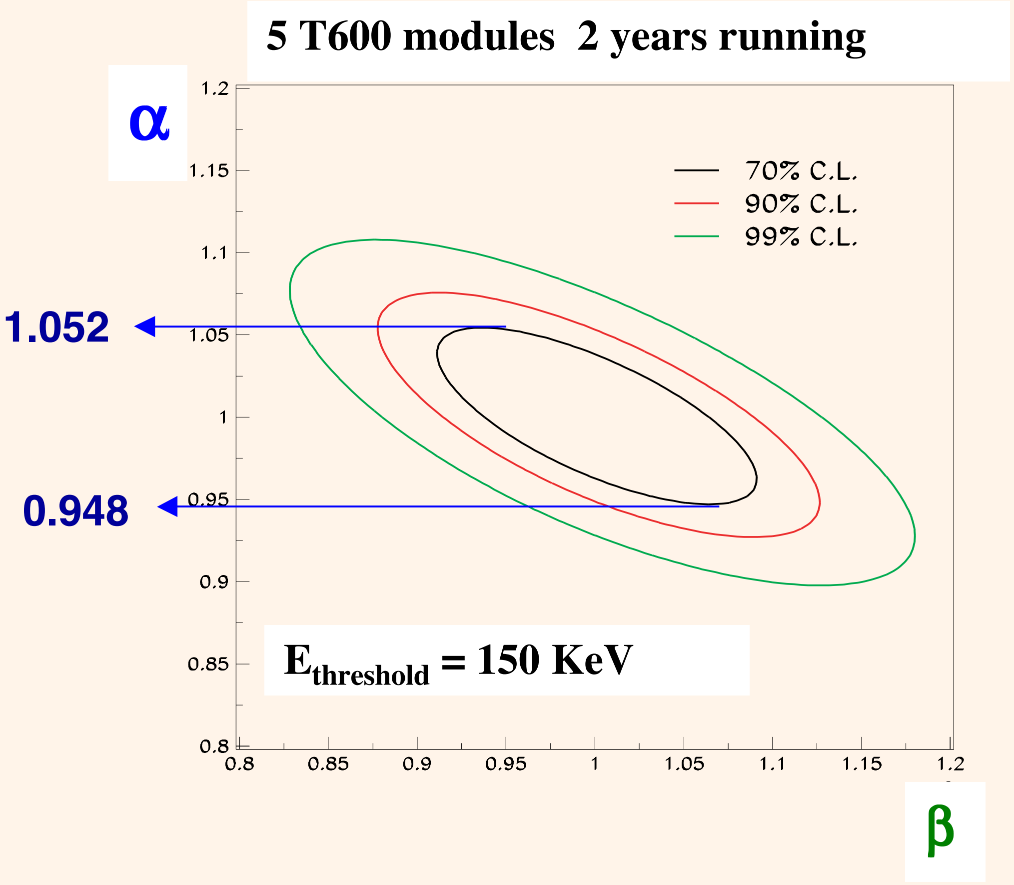


Plots normalized to 2 years running of 5 T600 modules

Precision solar flux determination



5 T600 modules 2 years running



5 T600 modules 2 years running

(no background included)

α ⇐ IAS normalization

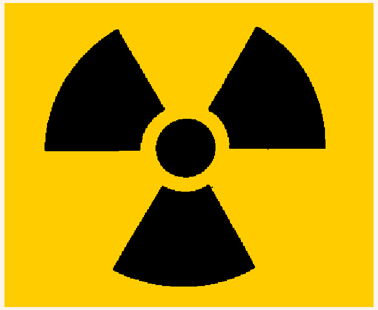
β ⇐ GT (3.798 MeV) normalization

At **70% C.L.**, **α** could be determined with **5% precision**

($E_{threshold}$ = 150 KeV) in 2 years with 3 kton

Main background source

neutrons → Able to generate **electrons** in the region $E_{e-} > 5$ MeV



- **External source**: **natural radioactivity** present in the rock (^{40}K, Uranium, Thorium,…).
- **Internal source**: radioactive **contamination** of structural materials.

Solar ν's background events in T600

Natural radioactivity

Spontaneous fission or (α,n) reactions

n flux

Captures in the detector (^{40}Ar, ^{27}Al, ^{56}Fe,…)

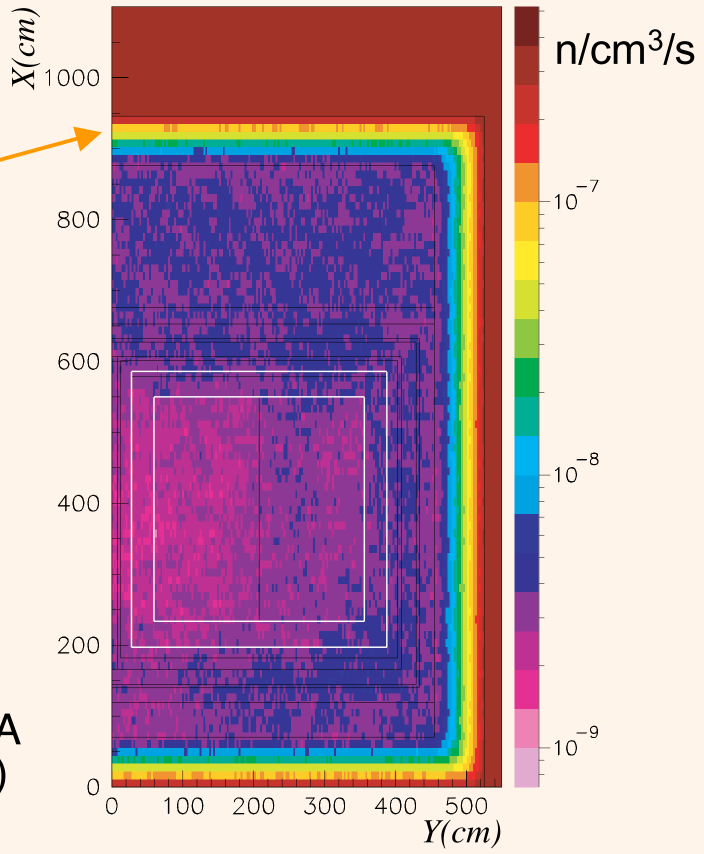
γ-rays

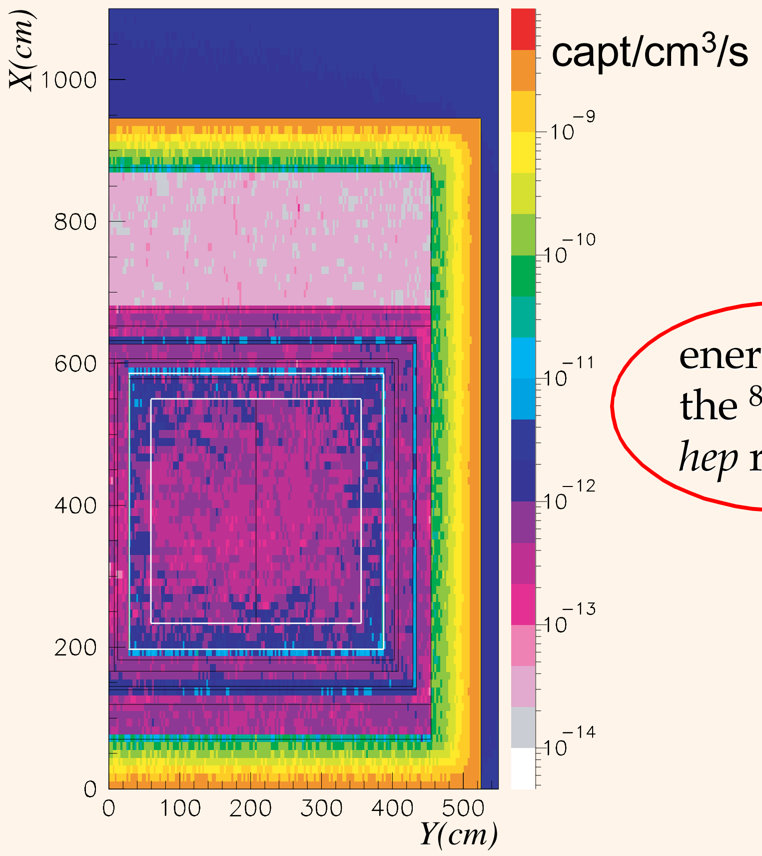
e^-

energies in the ^{8}B and *hep* range

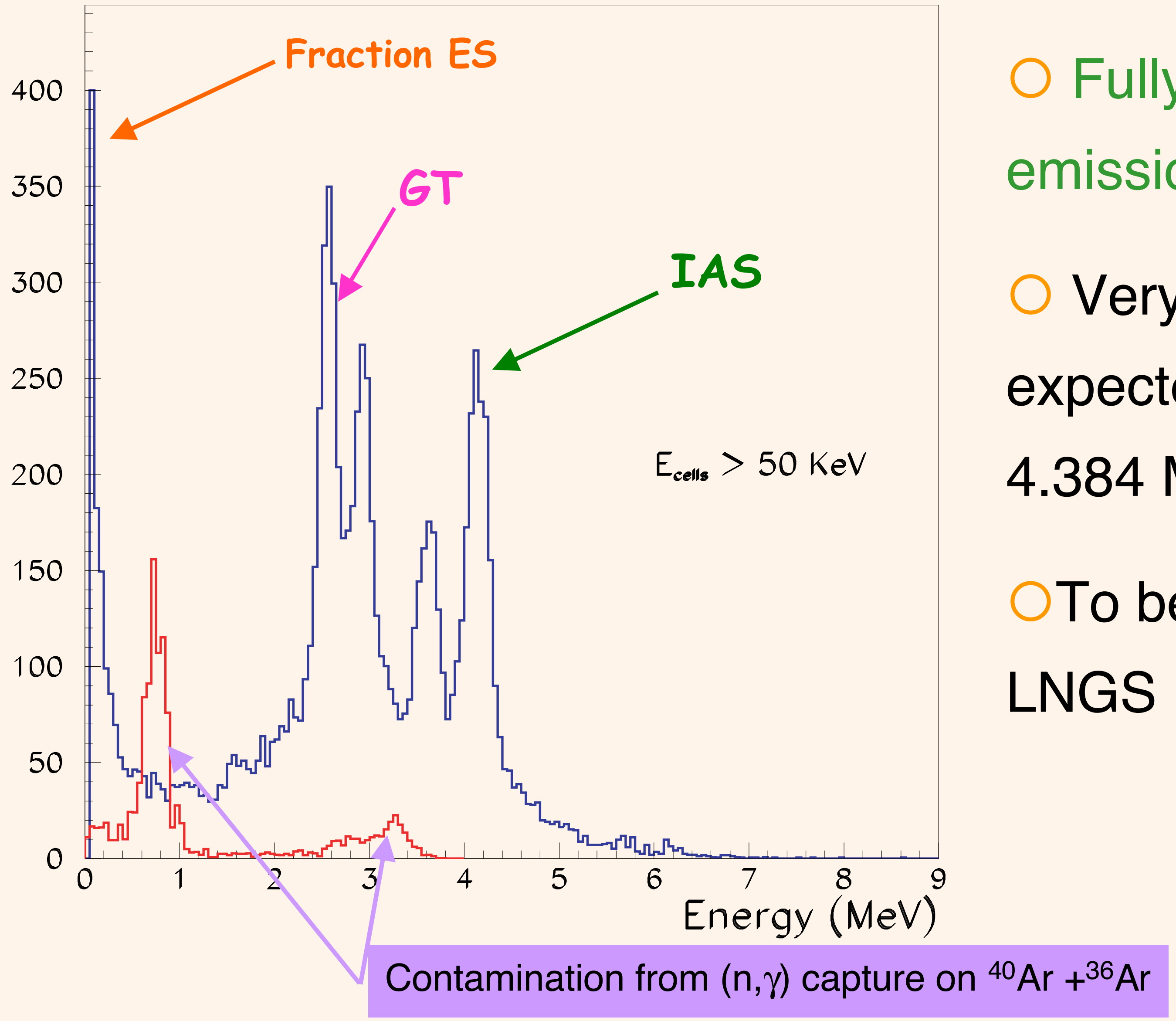
Neutron shield

(Full FLUKA simulation)





Background in T600



Contamination from (n,γ) capture on ^{40}Ar +^{36}Ar

- ○ Fully correlated photon emission.
- ○ Very little background expected for IAS photon at 4.384 MeV.
- ○ To be tested in situ at LNGS

Supernova rates

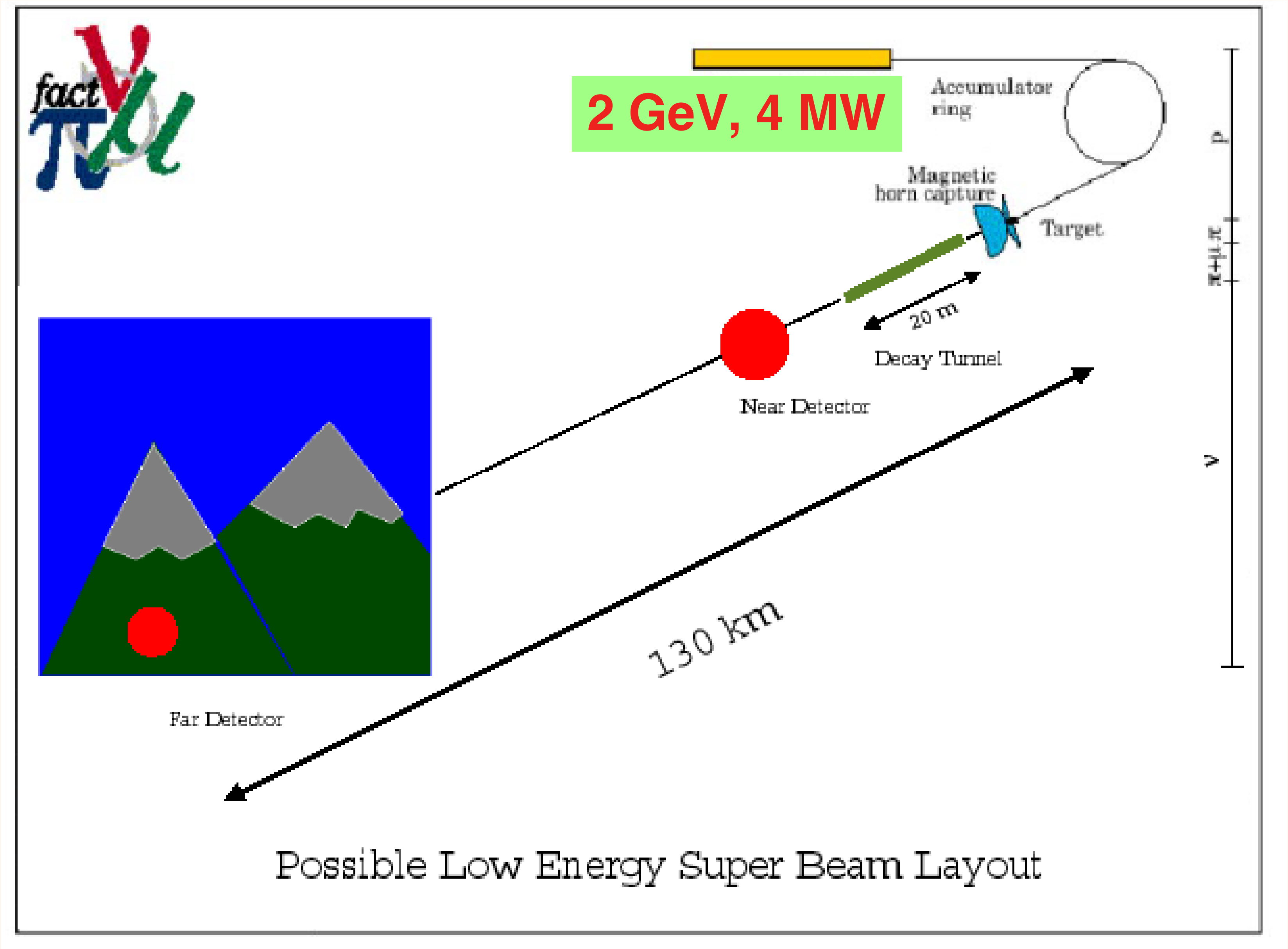
Assume Fermi-Dirac energy spectra and no oscillations.

$$\left\langle E_{\nu_e} \right\rangle = 11 MeV,\ \left\langle E_{\bar{\nu}_e} \right\rangle = 16 MeV,\ \left\langle E_{\nu_{\mu,\tau}} \right\rangle = 25 MeV,\ \left\langle E_{\bar{\nu}_{\mu,\tau}} \right\rangle = 25 MeV$$

Reaction		T (MeV)	$< E_\nu >$ (MeV)	Event rate **30 ktons**
Elastic				
	$\nu_e\, e^-$	3.5	11	198
	$\bar{\nu}_e\, e^-$	5	16	84
	$(\nu_\mu + \nu_\tau)\, e^-$	8	25	66
	$(\bar{\nu}_\mu + \bar{\nu}_\tau)\, e^-$	8	25	54
	total $\nu\, e^-$			402
Absorption				
	$\nu_e\ {}^{40}\mathrm{Ar}$ (Fermi)	3.5	11	708
	$\nu_e\ {}^{40}\mathrm{Ar}$ (GT)	3.5	11	1020
Total				2130

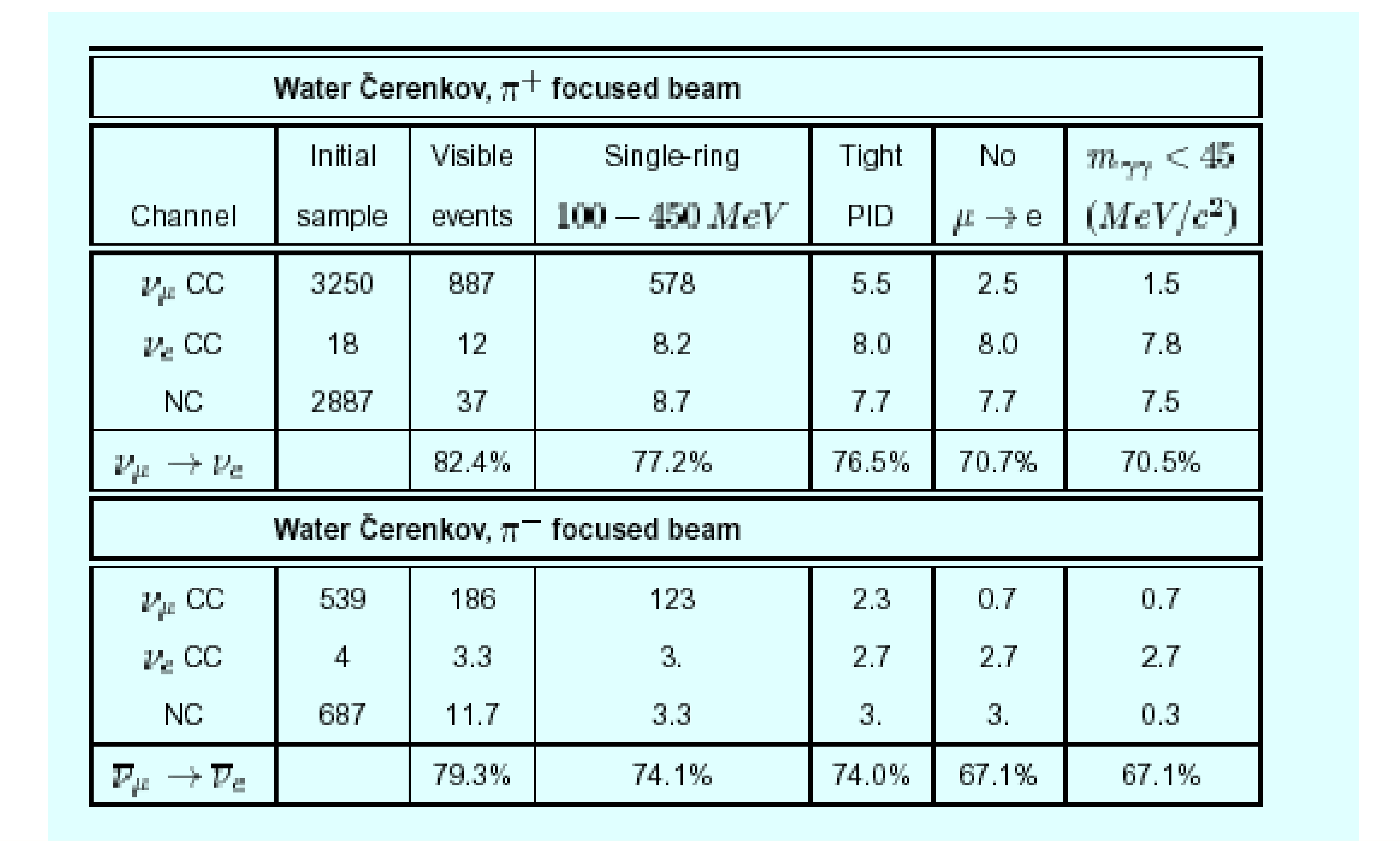
Antineutrino electron absorption not yet included.

CERN superbeam option: SPL (Superconducting Proton Linac)


2 GeV, 4 MW

Mezzetto, NUFACT01

Expected event rate for 200 kt x year exposure:



Channel	Initial sample	Visible events	Single-ring $100 - 450\ MeV$	Tight PID	No $\mu \to$ e	$m_{\gamma\gamma} < 45$ (MeV/c^2)
Water Čerenkov, π^+ focused beam						
ν_μ CC	3250	887	578	5.5	2.5	1.5
ν_e CC	18	12	8.2	8.0	8.0	7.8
NC	2887	37	8.7	7.7	7.7	7.5
$\nu_\mu \to \nu_e$		82.4%	77.2%	76.5%	70.7%	70.5%
Water Čerenkov, π^- focused beam						
ν_μ CC	539	186	123	2.3	0.7	0.7
ν_e CC	4	3.3	3.	2.7	2.7	2.7
NC	687	11.7	3.3	3.	3.	0.3
$\overline{\nu}_\mu \to \overline{\nu}_e$		79.3%	74.1%	74.0%	67.1%	67.1%

Mezzetto, NUFACT01

SPL neutrino superbeam

- **Signal: $\nu_\mu \rightarrow \nu_e$ appearance (Ue3)**
  - Expected to appear at the ν_μ disappearance dip
- **Backgrounds:**
  - ν_μ misidentification $< 10^{-5}$
  - π^0 (Neutral currents) background <0.001
  - ν_e contamination dominant: ≈ 0.002-0.003
- **Problem: recomputed neutrino flux rate : disagreement!**

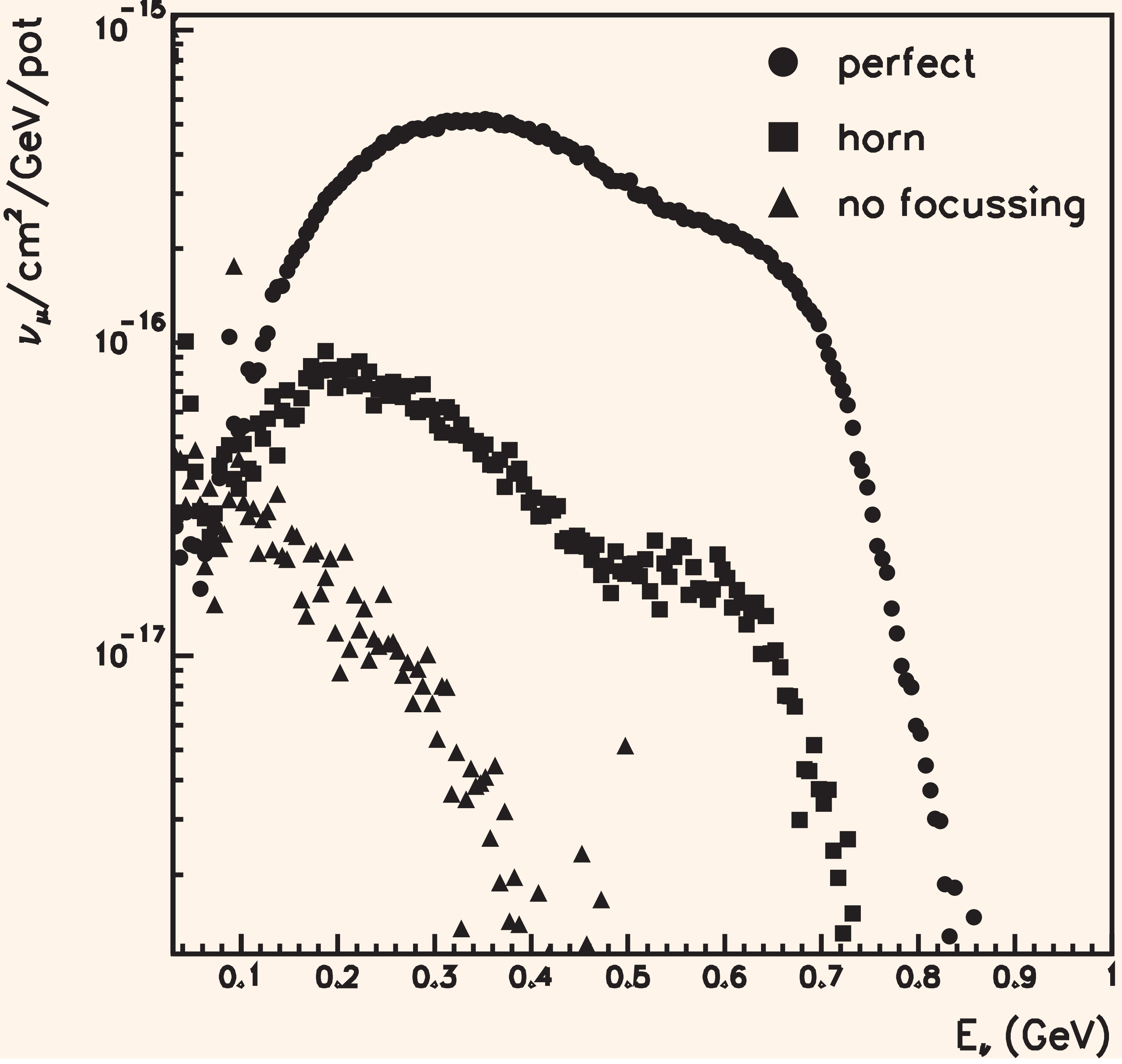
Comparison of rates: no focus, preliminary horn, ideal focusing

	no focus	horn focus	perfect focus
730 km			
ν_μ flux (ν/cm^2/p.o.t.)	$7.0 \cdot 10^{-18}$	$3.5 \cdot 10^{-17}$	$2.1 \cdot 10^{-16}$
$< E > \nu_\mu$ flux (MeV)	80.	218.	370.
ν_μ CC /kton 10^{23} pot	0.25	3.3	41
$< E > \nu_\mu$ CC (MeV)	300.	418	473
130 km			
ν_μ flux (ν/cm^2/pot)	$2.2 \cdot 10^{-16}$	$1.1 \cdot 10^{-15}$	$6.6 \cdot 10^{-15}$
ν_μ CC / kton 10^{23} pot	7.9	104	1290

PRELIMINARY

Full FLUKA simulation (including horn)

Spectrum at L=732 km: ν_μ Flux at Gran Sasso PRELIMINARY



An isotropic SPL neutrino beam?

$$\phi_{isotropic} = \frac{Y_{\pi^+}}{4\pi R^2} \approx \frac{0.3\ \pi^+ / pot}{4\pi(50km)^2} \approx 10^{12} \nu / m^2 / 10^{23}\, pot$$

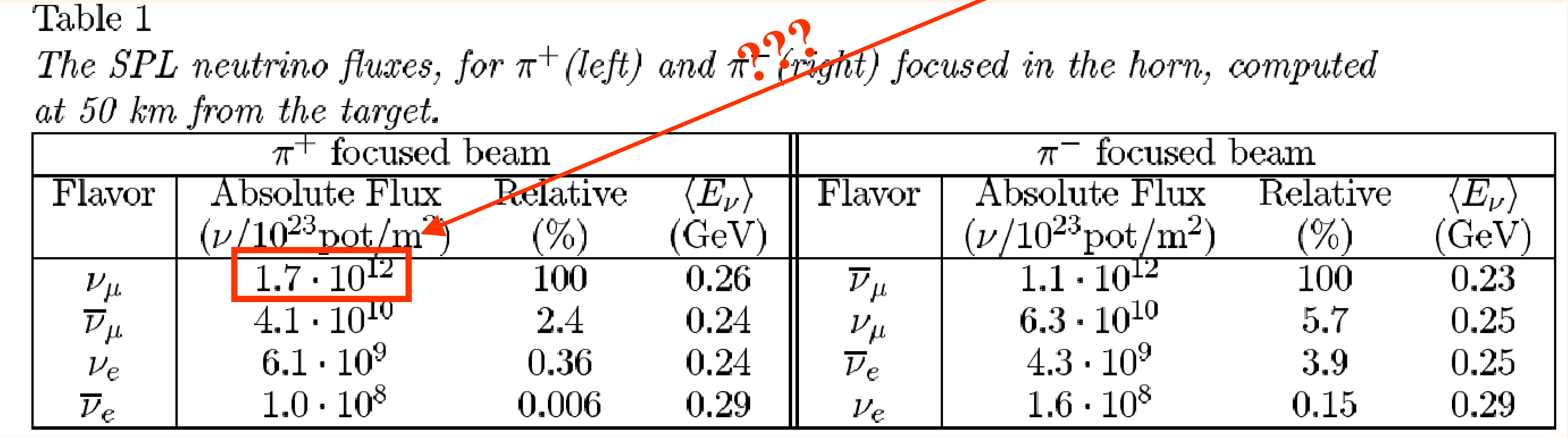


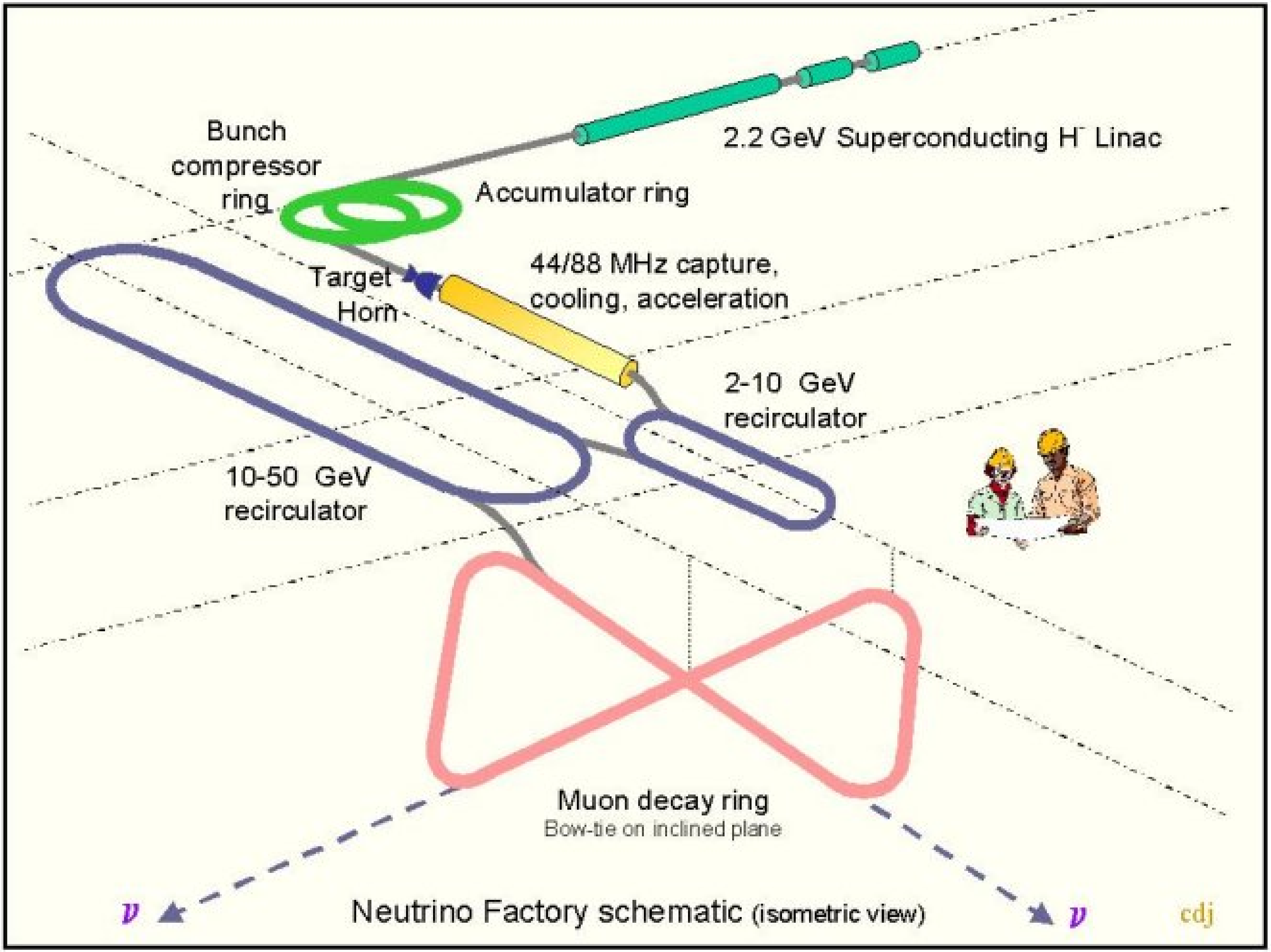
Table 1
The SPL neutrino fluxes, for π^+ (left) and π^- (right) focused in the horn, computed at 50 km from the target.

???

π^+ focused beam				π^- focused beam			
Flavor	Absolute Flux ($\nu/10^{23}$pot/m^2)	Relative (%)	$\langle E_\nu \rangle$ (GeV)	Flavor	Absolute Flux ($\nu/10^{23}$pot/m^2)	Relative (%)	$\langle E_\nu \rangle$ (GeV)
ν_μ	$\boxed{1.7 \cdot 10^{12}}$	100	0.26	$\overline{\nu}_\mu$	$1.1 \cdot 10^{12}$	100	0.23
$\overline{\nu}_\mu$	$4.1 \cdot 10^{10}$	2.4	0.24	ν_μ	$6.3 \cdot 10^{10}$	5.7	0.25
ν_e	$6.1 \cdot 10^{9}$	0.36	0.24	$\overline{\nu}_e$	$4.3 \cdot 10^{9}$	3.9	0.25
$\overline{\nu}_e$	$1.0 \cdot 10^{8}$	0.006	0.29	ν_e	$1.6 \cdot 10^{8}$	0.15	0.29

A. Blondel, J. Burguet-Castell, D. Casper, M. Donega, S. Gilardoni, J.J. Gomez-Cadenas, P. Hernandez, M. Mezzetto, Nufact Note 95, October 2001

CERN neutrino factory option:



Neutrino Factory schematic (isometric view)

The oscillation physics program at the NF

$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$

$\nu_\mu \rightarrow \nu_e$	appearance
ν_μ	disappearance
$\nu_\mu \rightarrow \nu_\tau$	appearance
$\bar{\nu}_e$	disappearance
$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$	appearance
$\bar{\nu}_e \rightarrow \bar{\nu}_\tau$	appearance

Plus their charge conjugates with μ^+ beam

Ideal detector should be able to measure **12 different processes as a function of L and E_ν**

$$\begin{cases} \nu_\ell N \rightarrow \ell^- + hadrons \\ \bar{\nu}_\ell N \rightarrow \ell^+ + hadrons \end{cases} \qquad \begin{cases} \nu_\ell N \rightarrow \nu_\ell + hadrons \\ \bar{\nu}_\ell N \rightarrow \bar{\nu}_\ell + hadrons \end{cases}$$

1. ***Particle ID***: *charged lepton tags* ***incoming neutrino flavor***
2. ***Charge ID***: *sign of lepton charge tags* ***helicity*** *of incoming neutrino*
3. ***Energy resolution***: *Reconstructed event energy is* $E_\nu = E_l + E_{had}$

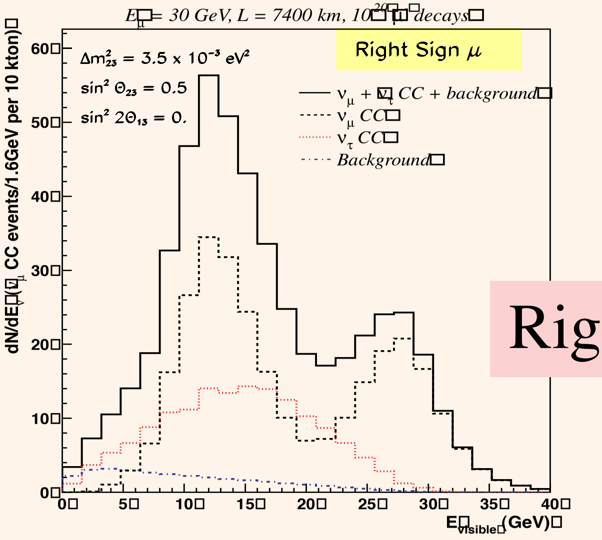
The physics programme at the NF

- **With a <u>magnetized liquid argon TPC</u>, we can do the measurements proposed with magnetized F_e calorimeter**
  - Since muons are very well measured:
    - Momentum threshold in LAr TPC can be very low ($dE/dx \approx 200$ MeV/m)
    - Muon well separated from jet thanks to detailed imaging
- **This means**
  - Precise determination of Δm^2_{23} and θ_{23}
  - Stringent limit/precise measurement of θ_{13}
  - Determination of Δm^2_{23} sign
  - Study matter effects
  - Search for CP violation
- **However, the better granularity offers in addition new possibilitities! :**
  - Detection of $\nu_e \rightarrow \nu_\tau$ oscillations
  - Over-constrain the oscillation parameters (matrix unitarity)
  - Study the δ phase by direct search of T violation

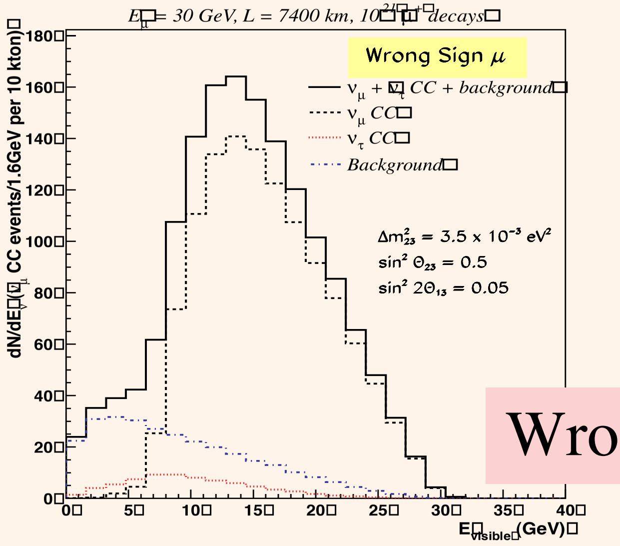
A. Bueno, M. Campanelli, S. Navas-Concha, A. Rubbia, hep-ph/0112297, Dec 2001

Study four event classes

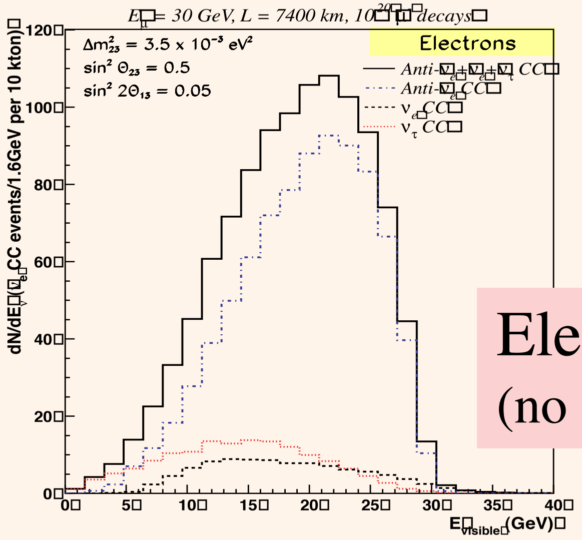
A. Bueno, M. Campanelli, A. Rubbia. , Nucl.Phys.B589 (2000) 577



Right sign μ

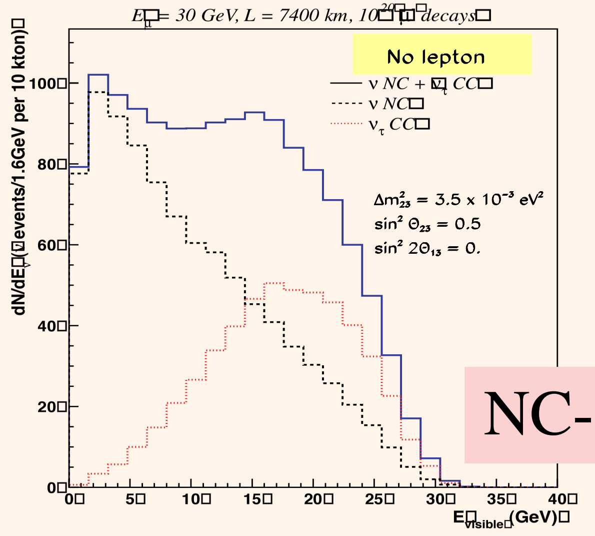


Wrong sign μ



Electrons

(no charge info)



NC-like

Combining all classes$\Rightarrow$ (over-constrained) sensitivity to all oscillations!

How to experimentally observe the δ-phase?

- $\Delta\delta \equiv P(\nu_e \rightarrow \nu_\mu; \delta=\pi/2) - P(\nu_e \rightarrow \nu_\mu; \delta=0)$

Compares oscillation probabilities as a function of E_ν measured with wrong-sign muon event spectra, to MonteCarlo predictions of the spectrum in absence of CP violation

- $\Delta CP(\delta) \equiv P(\nu_e \rightarrow \nu_\mu; \delta) - P(\overline{\nu}_e \rightarrow \overline{\nu}_\mu; \delta)$

Compares oscillation probabilities measured using the appearance of ν_μ and $\overline{\nu_\mu}$, running the storage ring with a beam of stored μ^+ and μ^-, respectively. Matter effects are dominant at large distances

- $\Delta T(\delta) \equiv P(\nu_e \rightarrow \nu_\mu; \delta) - P(\nu_\mu \rightarrow \nu_e; \delta)$

Compares the appearance of ν_μ and ν_e in a beam of stored μ^+ and μ^-. As opposite to the previous case, matter effects are the same, thus cancel out in the difference

- $\Delta\overline{T}(\delta) \equiv P(\overline{\nu}_e \rightarrow \overline{\nu}_\mu; \delta) - P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e; \delta)$

Same as previous case, but with antineutrinos. This effect is usually matter-suppressed with respect to the neutrino case.

A. Bueno, M. Campanelli, S. Navas-Concha, A. Rubbia, hep-ph/0112297

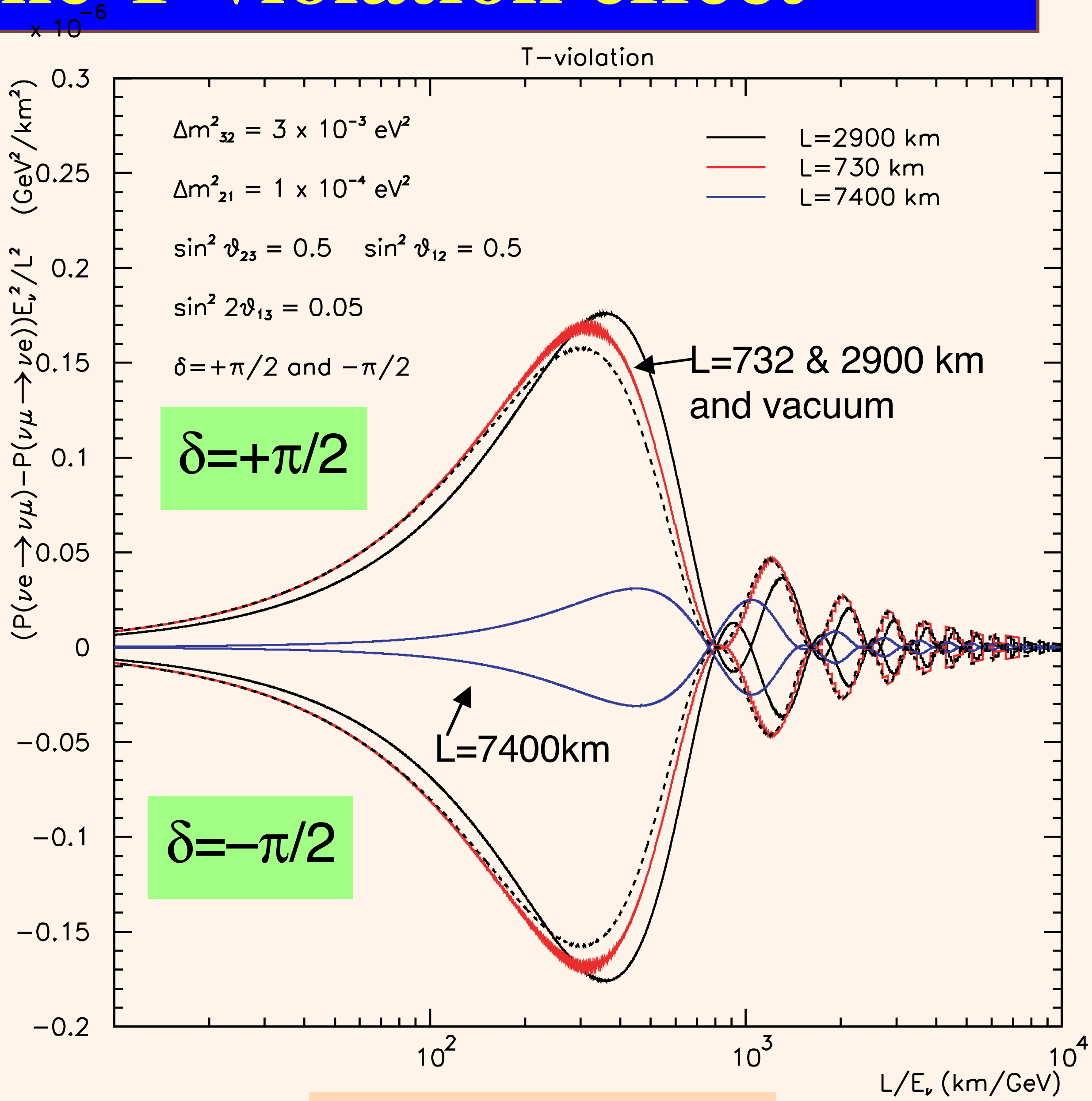
Scaling of the T-violation effect

$$\left[P\left(\nu_e \rightarrow \nu_\mu\right) - P\left(\nu_\mu \rightarrow \nu_e\right)\right] \times E_\nu^2 / L^2$$

- **The effect as function of L/E is the approximately the same at L=732 or 2900 km and in vacuum.**

- The dependence to the δ-phase is reduced by matter at L=7400 km

See A. Bueno, M. Campanelli, S. Navas-Concha, A. Rubbia, hep-ph/0112297, Dec 2001



$L / E \ (km / GeV)$

Binned ΔT discriminant

$$\Delta_T(i) \equiv P_i(\nu_\mu \to \nu_e) - P_i(\nu_e \to \nu_\mu)$$

and similar for $\overline{\Delta}_T(i)$ *for antineutrinos*

The difference in probability for wrong-sign muons and wrong-sign electrons is a **direct proof of T-violation**.

Matter effects are the same, and cancel out in the difference.

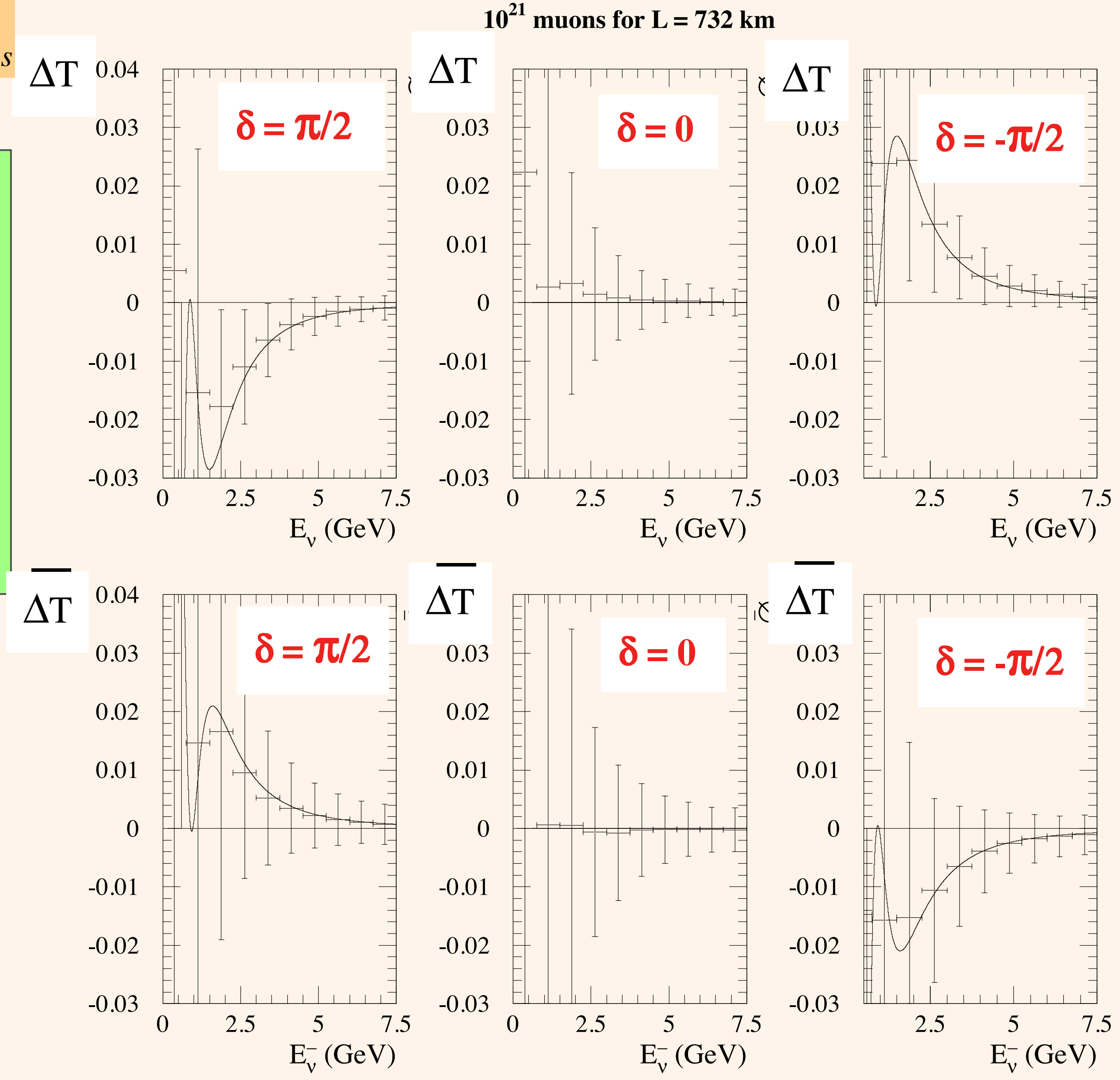
L=732 km,

E_μ = 7.5 GeV

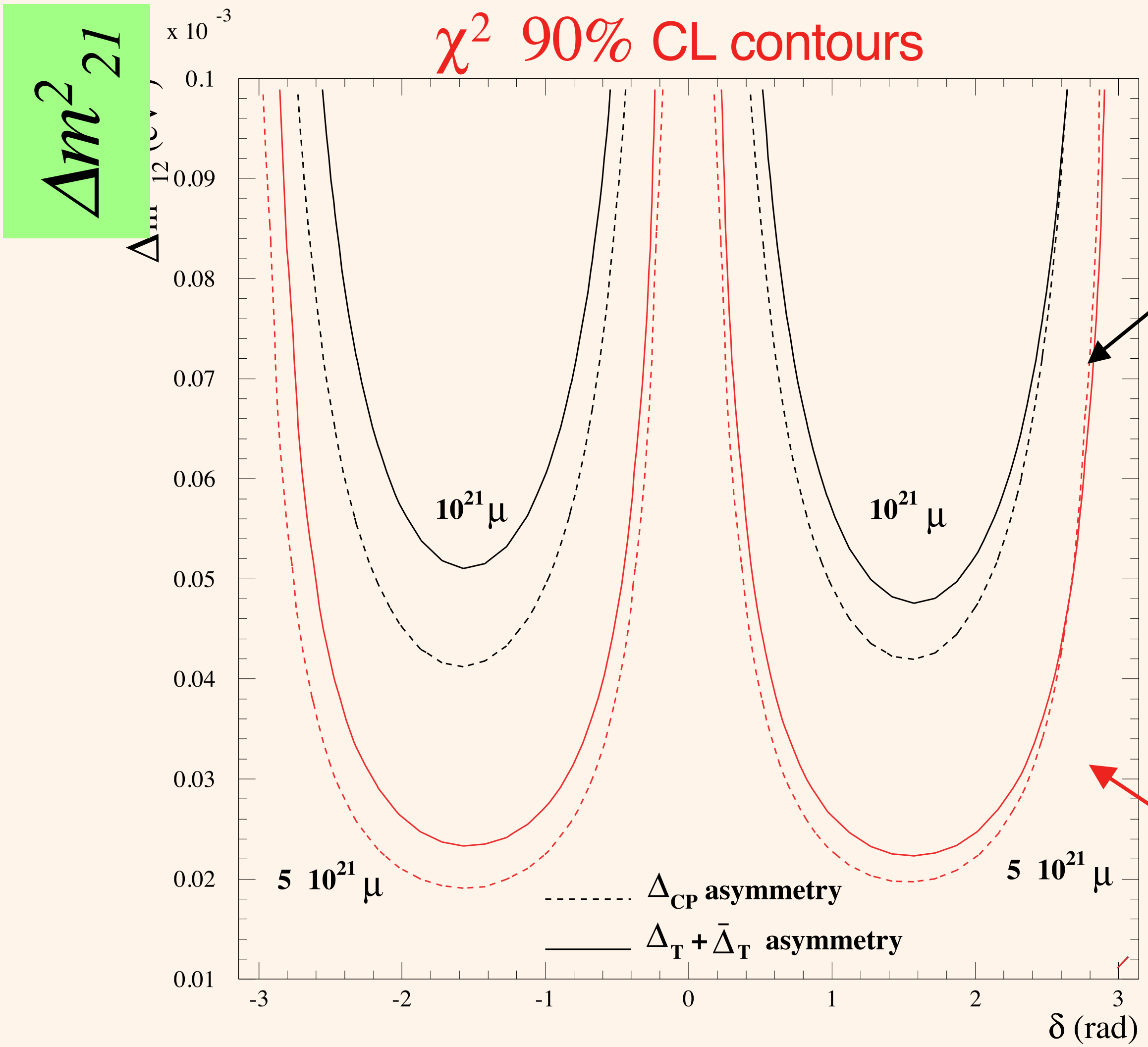
10^{21} μ decays

10 kTon detector

Expected statistical errors only



Direct T/CP-violation sensitivity



δ

10^{21} μ decays

5×10^{21} μ decays

CP violation
and
T-violation
measurements

L = 732 km

E_μ = 7.5 GeV

ε_e = 20%

10 kton detector

10^{21} μ decays required to cover LMA solution !

A. Bueno, M. Campanelli, S. Navas-Concha, A. Rubbia, hep-ph/0112297

Conclusion

- The excellent properties of liquid Argon imaging provide a vast physics program of **extremely high quality**.
- The ICARUS Liquid Argon TPC has moved from basic proof of principle to large kton scale devices.
  - **T600 in 2002 at LNGS**
  - **3 kton proposed for ≈2005**
- This is the proof that kton-scale LAr can be built and operated underground.
- R&D for magnetized LAr ongoing.