Ideas for future liquid Argon TPC detectors

Antonio Ereditato (INFN Naples)

André Rubbia (ETH Zürich)

Special thanks to

Anselmo Meregaglia, Marcello Messina, Paola Sala (ETH Zürich)

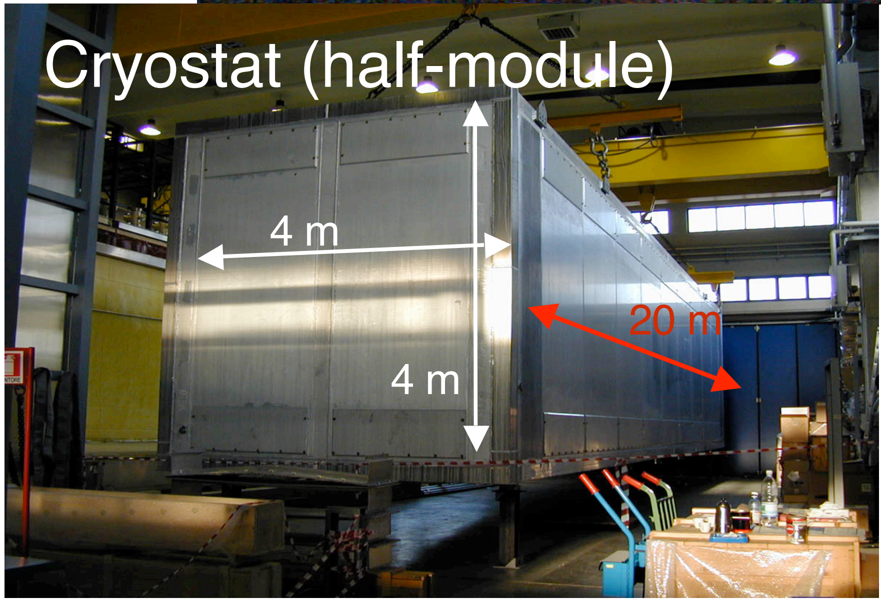
NuInt04

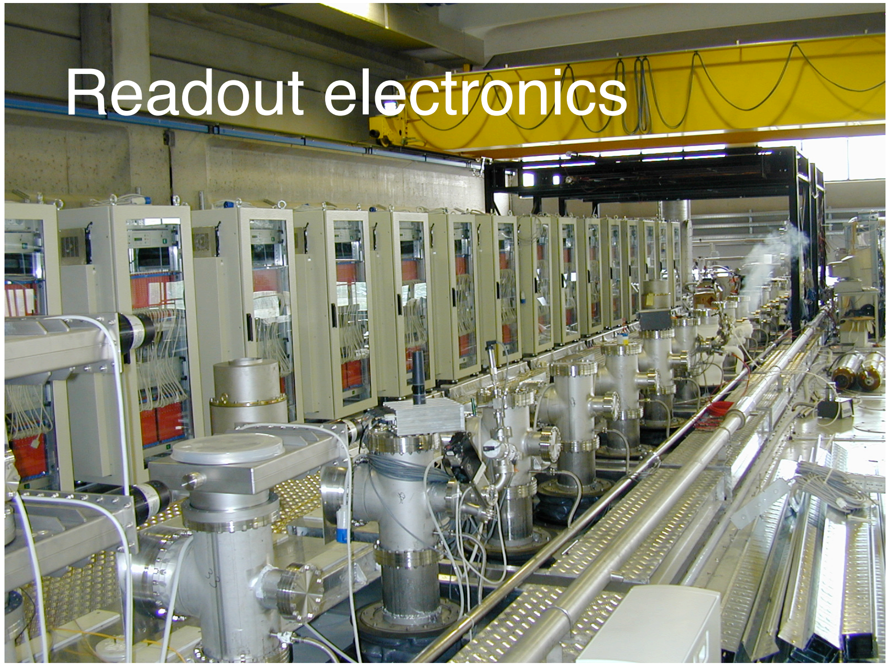
March 17- 21, 2004 LNGS, Italy

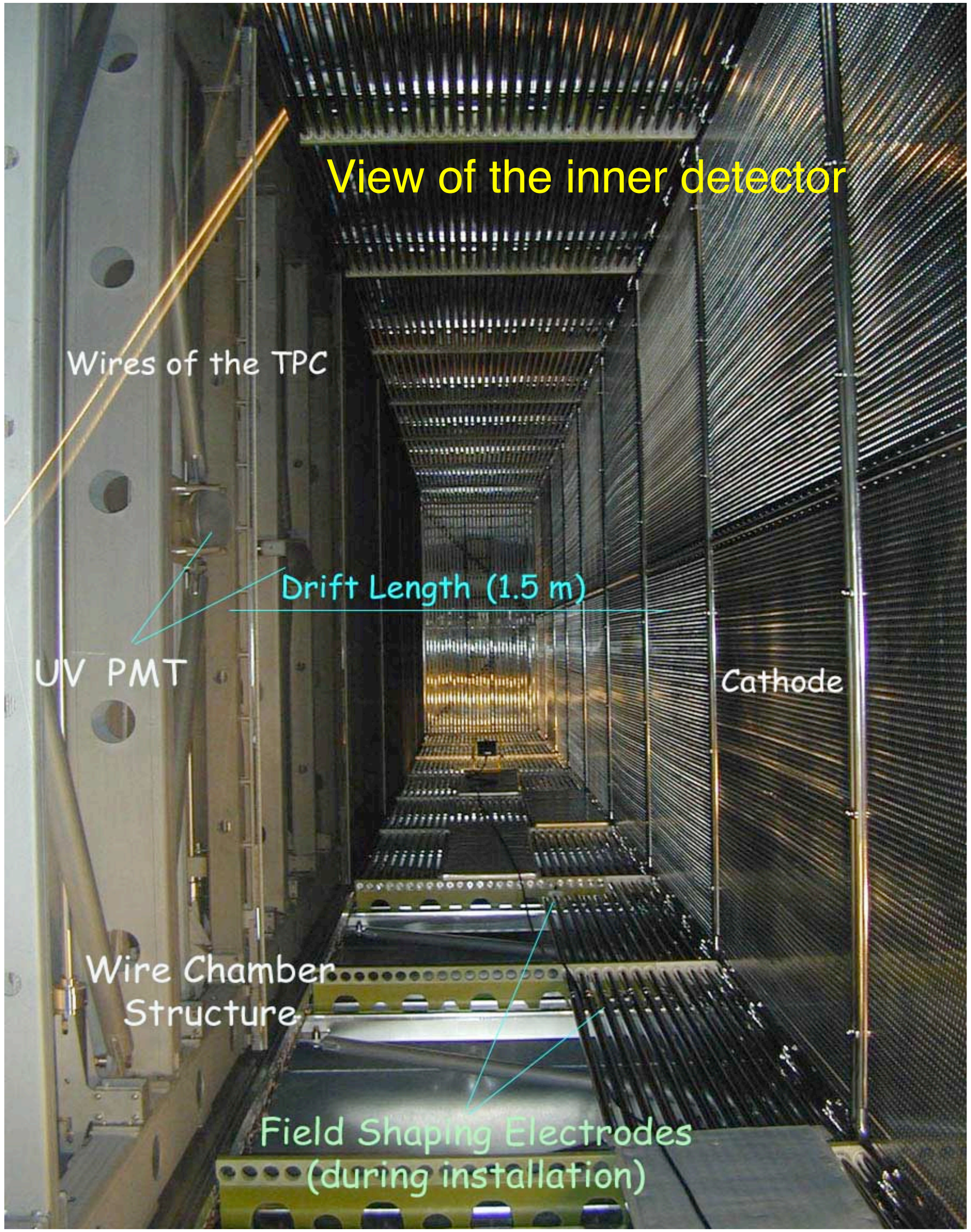
Introduction

- **The liquid Argon TPC imaging has reached a high level of maturity thanks to many years of R&D effort conducted by the ICARUS collaboration**
  - ➥ This programme has made possible the successful operation of a 300 ton module on surface.
  - ➥ The operation of the T600 @ LNGS is in good prospect and will represent a fundamental milestone for the technique.
- **There is the proposal to reach the kton mass scale at LNGS (T3000)**
- **As of today, physics is calling for at least two applications of this technique at two different mass scales with a high degree of interplay:**
  - ➥ ≈100 ktons: proton decay, high statistics astrophysical & accelerator neutrinos, …
  - ➥ ≈100 tons: systematic study of neutrino interactions, …
- **Synergy between small & large scales (i.e. short & long baselines)**
- **Work is in progress along these lines of thoughts**
  - ➥ We present here a brief overview of our current ideas & activities
- **As far as NUINT is concerned, we think that the contribution of a liquid Argon TPC would be substantial**

ICARUS T300 prototype







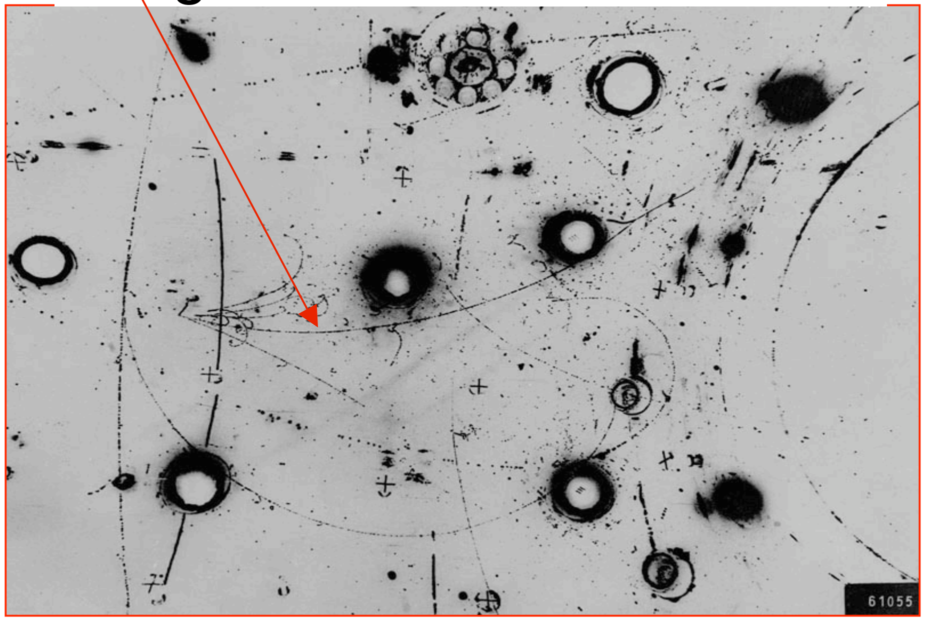
Liquid Argon TPC
Overview

Electronic bubble chamber

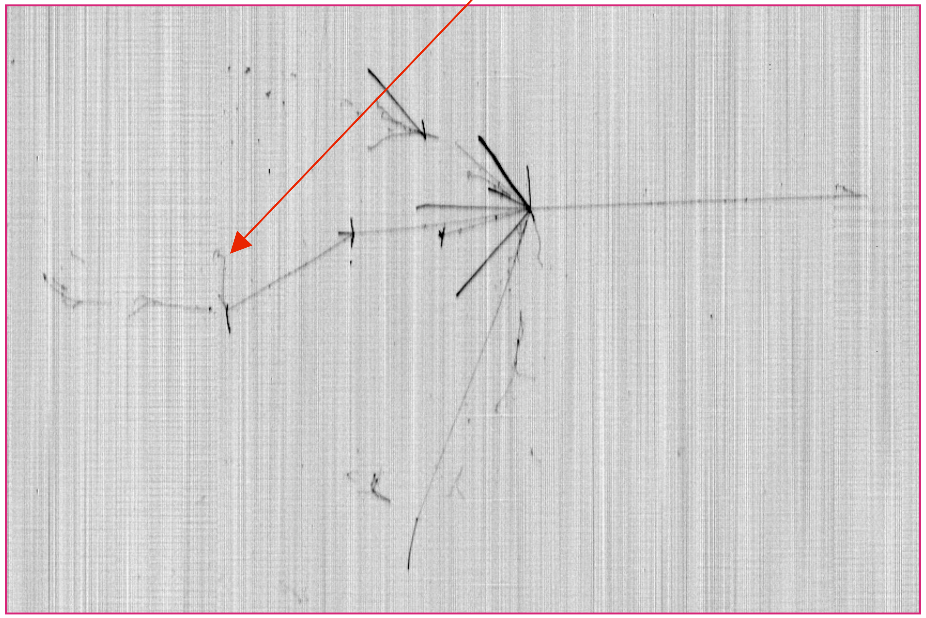
Bubble diameter ≈ 3 mm
(diffraction limited)

Bubble size ≈ 3x3x0.4 mm^3

Gargamelle bubble chamber



ICARUS electronic chamber



Medium	*Heavy freon*	
Sensitive mass	3.0	ton
Density	1.5	g/cm3
Radiation length	11.0	cm
Collision length	49.5	cm
dE/dx	2.3	MeV/cm

Medium	*Liquid Argon*	
Sensitive mass	Many ktons	
Density	1.4	g/cm3
Radiation length	14.0	cm
Collision length	54.8	cm
dE/dx	2.1	MeV/cm

Liquid Argon medium properties

	Water	Liquid Argon
Density (g/cm^3)	1	1.4
Radiation length (cm)	36.1	14.0
Interaction length (cm)	83.6	83.6
dE/dx (MeV/cm)	1.9	2.1
Refractive index (visible)	1.33	1.24
Cerenkov angle	42°	36°
Cerenkov $d^2N/dEdx$ (β=1)	≈160 eV^{-1} cm^{-1}	≈130 eV^{-1} cm^{-1}
Muon Cerenkov threshold (p in MeV/c)	120	140
Scintillation (E=0 V/cm)	No	Yes (≈50000 γ/MeV @ λ=128nm)
Long electron drift	Not possible	Possible (μ=500 cm^2/Vs)
Boiling point (@ 1 bar)	373 K	87 K

When a charged particle traverses liq. Argon:

- **Ionization process**
  - ➥ W_e = 23.6 ± 0.3 eV
- **Scintillation (luminescence)**
  - ➥ W_γ = 19.5 eV
  - ➥ UV spectrum "line" (λ=128 nm ⇔ 9.7 eV)
  - ➥ Not energetic enough to further ionize, hence, argon is transparent
  - ➥ Only Rayleigh-scattering
- **Cerenkov light (if relativistic particle)**

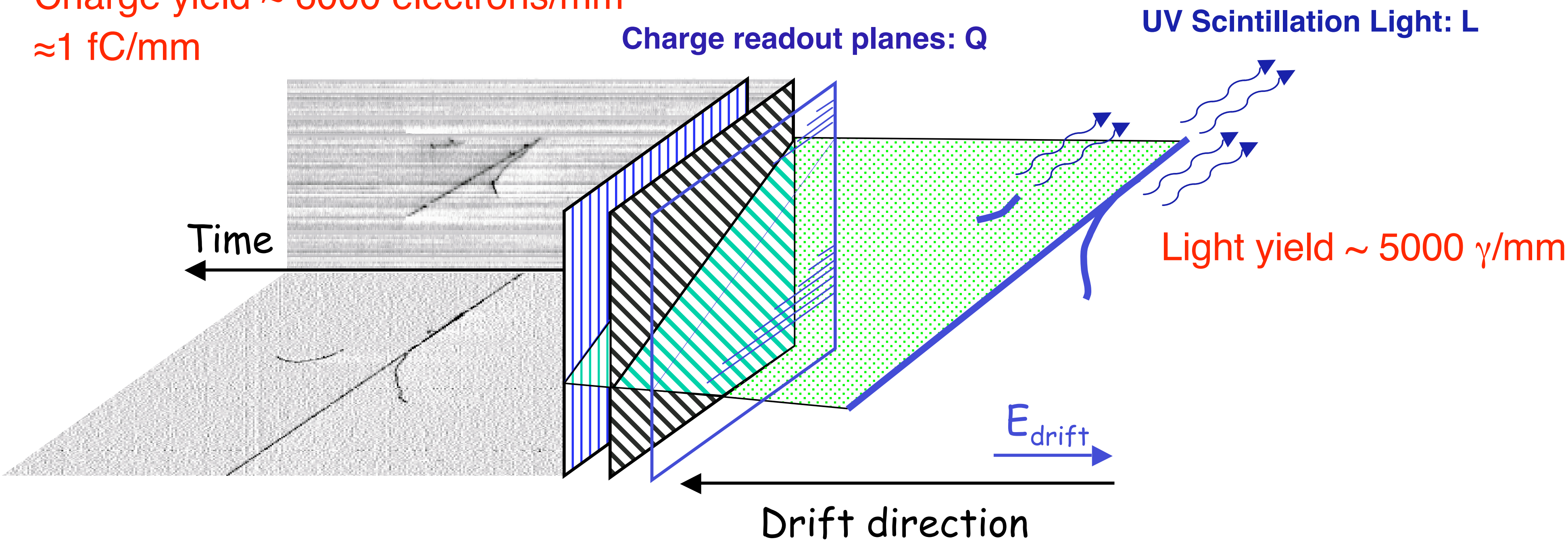
☞ ***Charge***

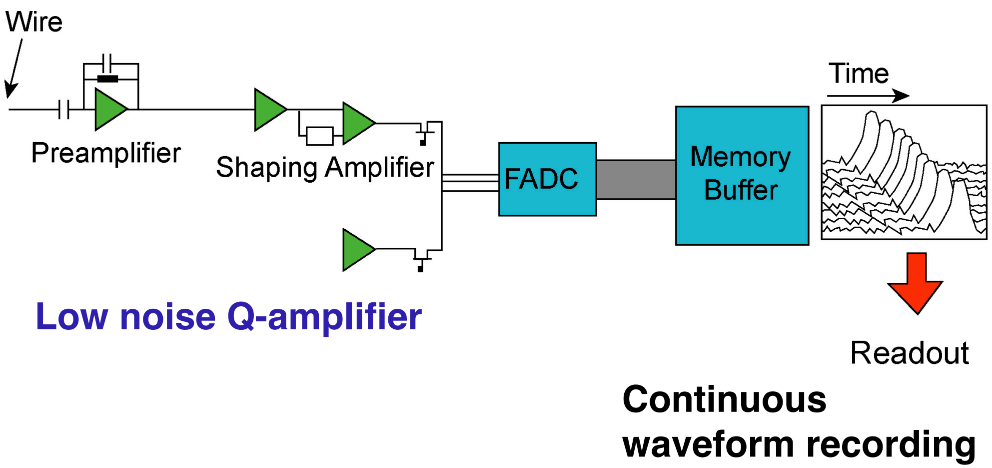
☞ ***Scintillation light (VUV)***

☞ ***Cerenkov light (if β>1/n)***

The Liquid Argon TPC

Charge yield ~ 6000 electrons/mm
≈1 fC/mm

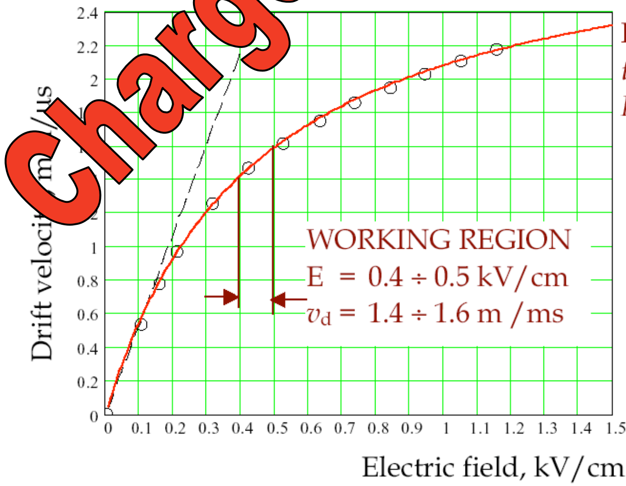




- High density
- Non-destructive readout
- Continuously sensitive
- Self-triggering
- T_0 available (scintillation)

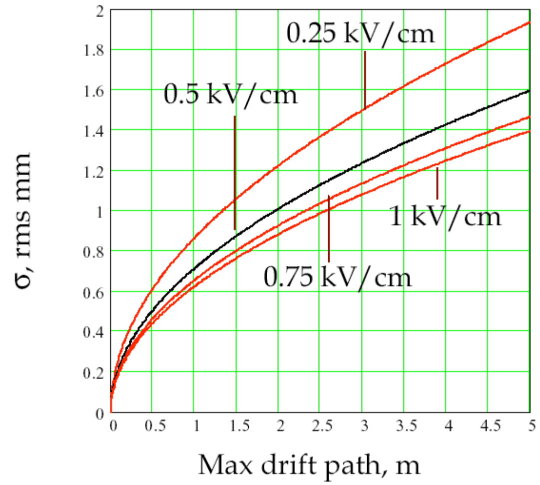
Electron drift properties in liquid Argon

Charge



Drift velocity versus electric field in liquid argon

FOR 5 m MAX. DRIFT:
t_{max} = 3.6 ÷ 3.1 ms
HV_{max} = 200 ÷ 250 kV



Longitudinal rms diffusion spread versus drift paths at different electric field intensities

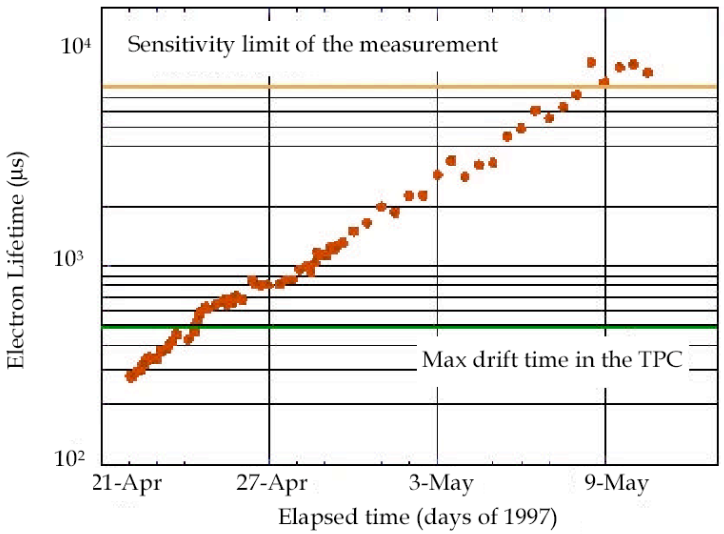
$$\sigma_D = \sqrt{2 \cdot D \cdot \frac{x}{v_d}}$$
$$D = 4.06\ cm^2/s$$

$\sigma_D = 0.9\ mm \cdot \sqrt{T_D[ms]}$

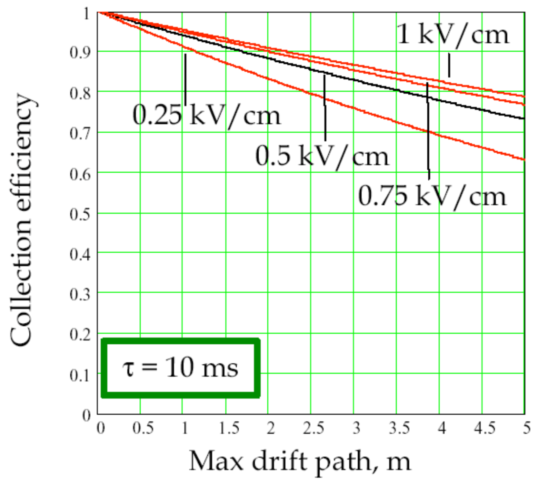
Longitudinal rms diffusion spread at 0.5 kV/cm

Average $\langle\sigma_D\rangle$ = 1.1 mm

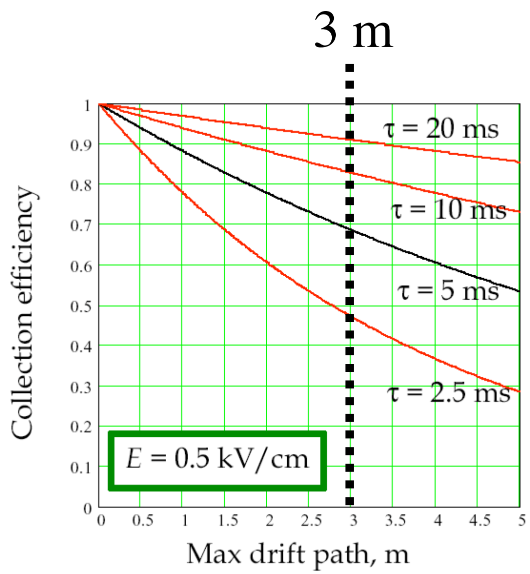
Maximum σ_{Dmax} = 1.6 mm



Purification rate for the 50L TPC



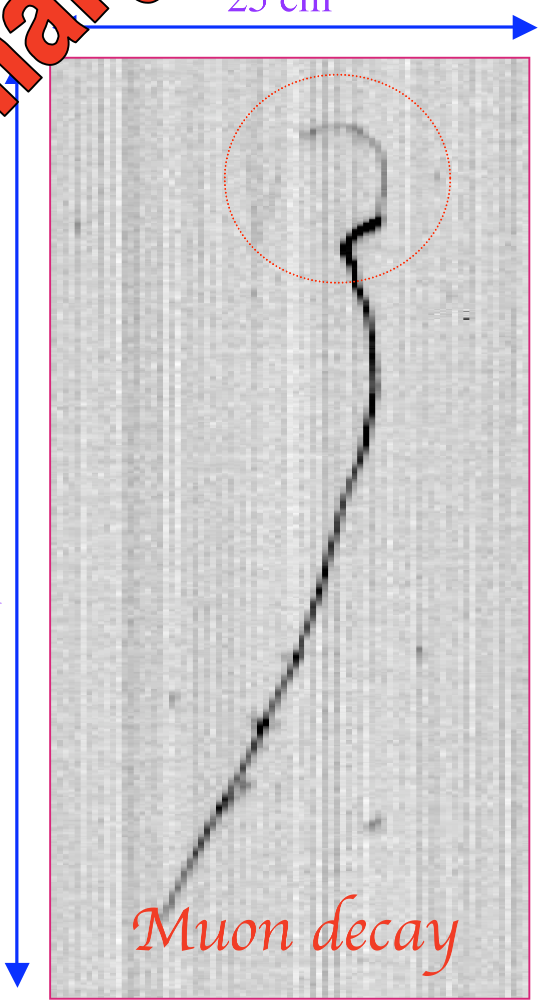
Drifting charge attenuation versus drift paths at different electric field intensities (τ = 10 ms)



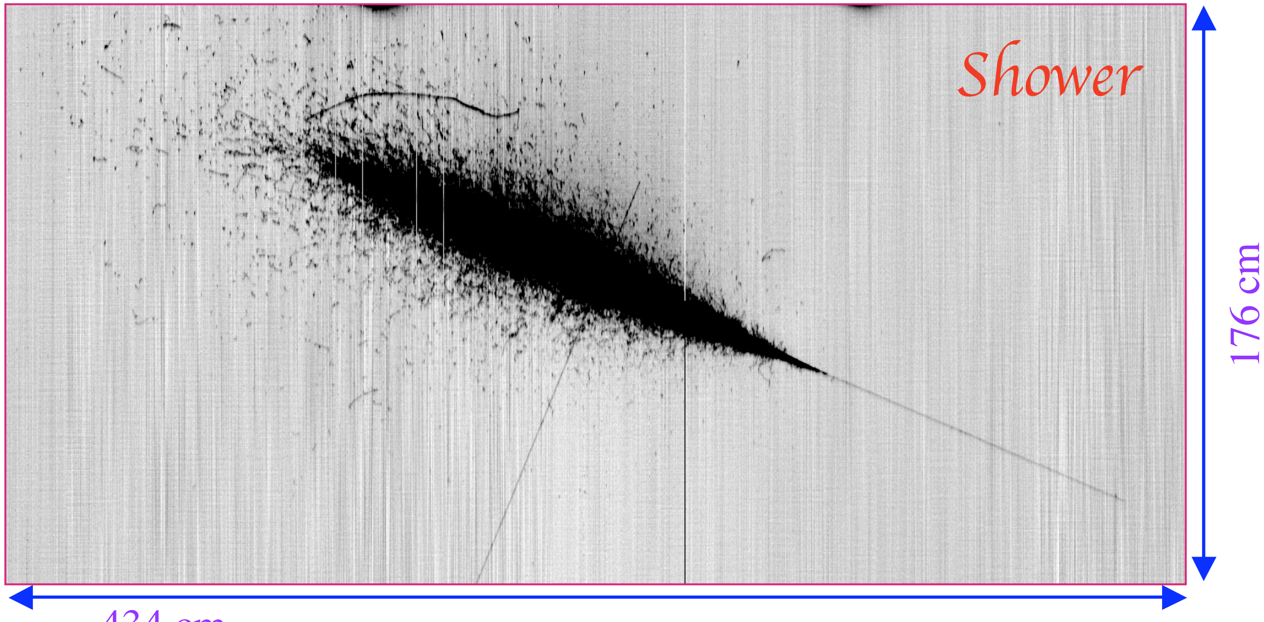
Drifting charge attenuation versus drift path at different electron lifetimes (*E* = 0.5 kV/cm)

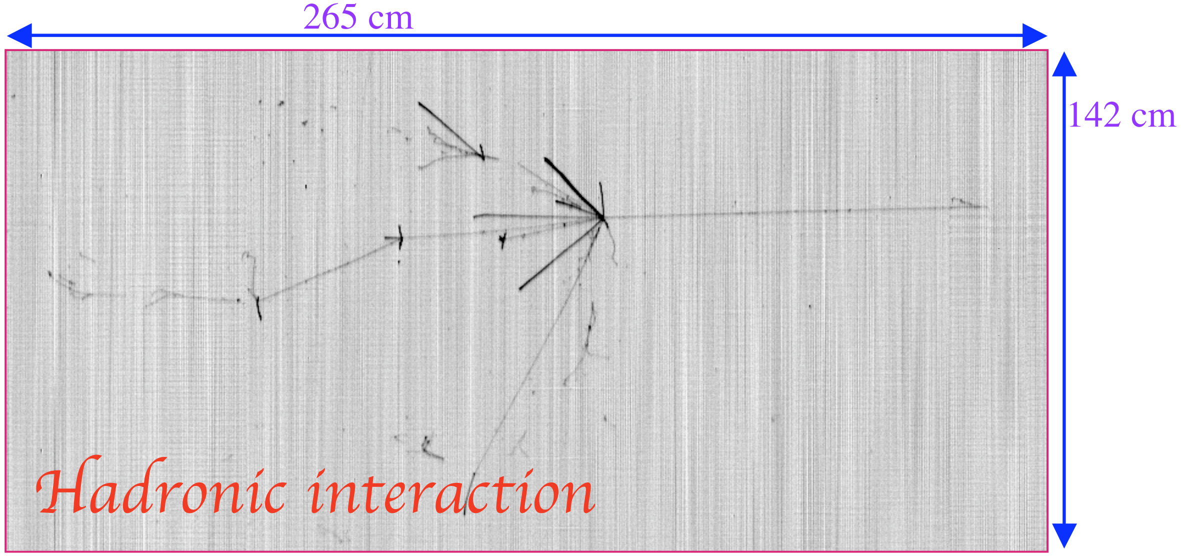
(Real) cosmic rays events in T300

Charge



Run 960, Event 4   Collection Left





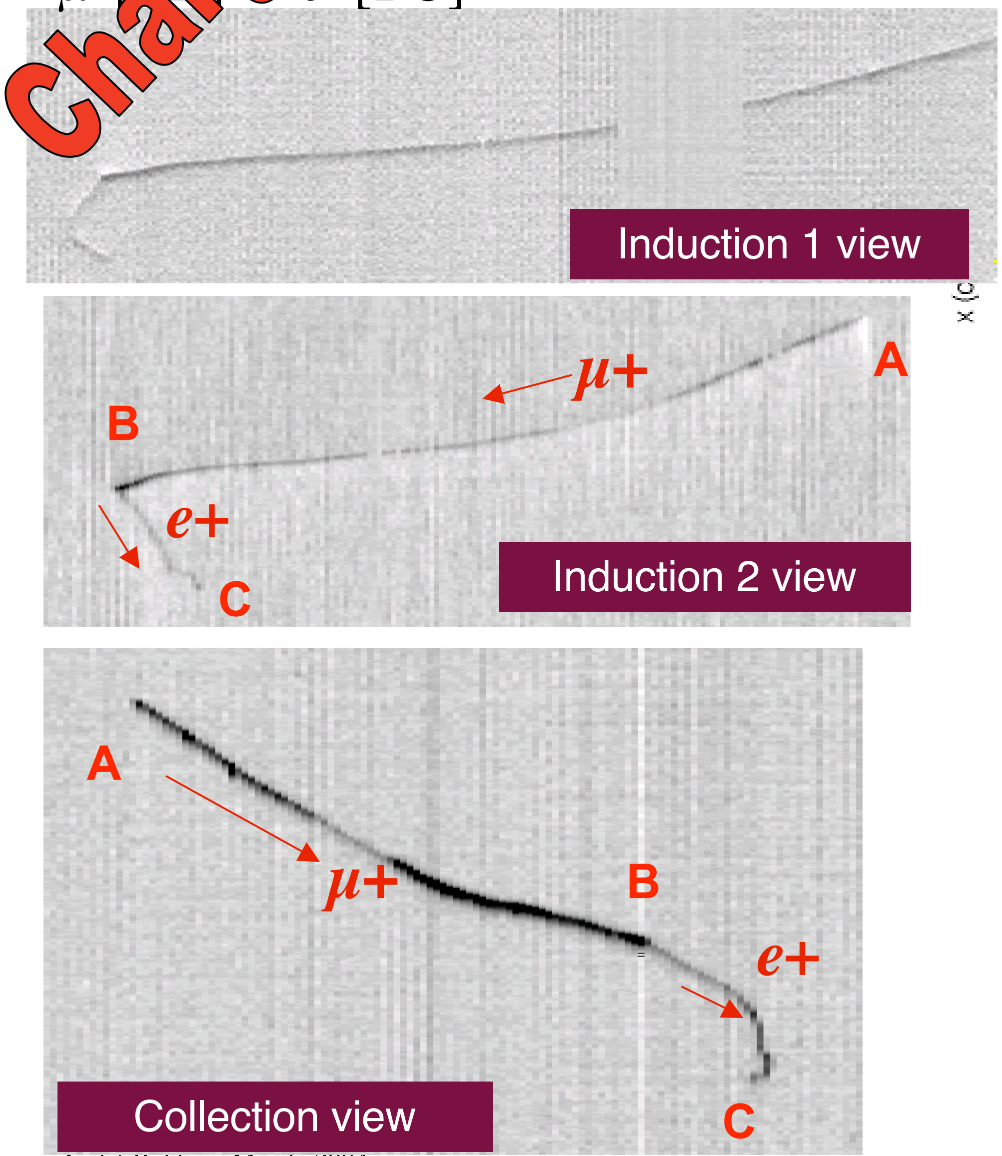
Run 308, Event 160   Collection Left

(Real) 3D reconstruction stopping muon

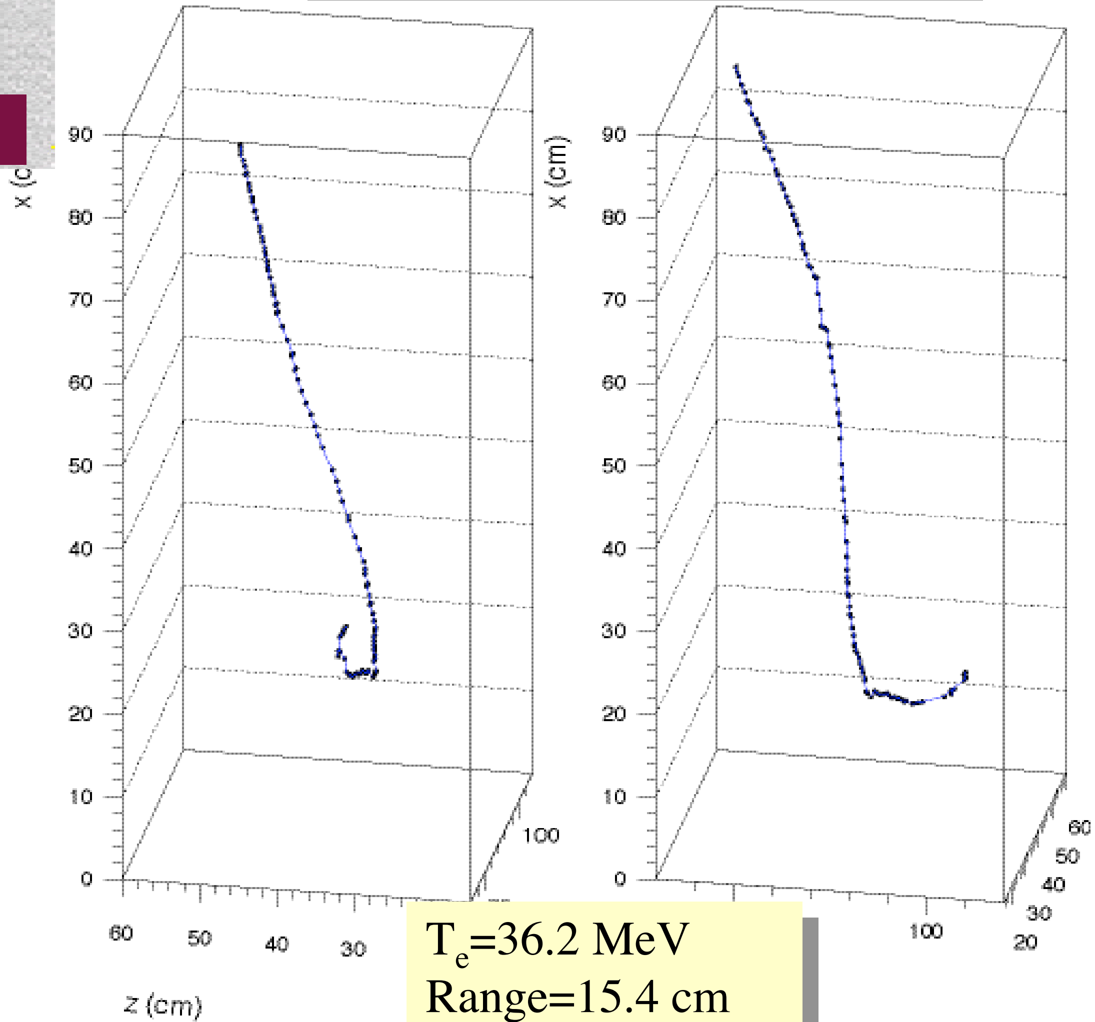
Charge

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

(Reconstruction is automatic)



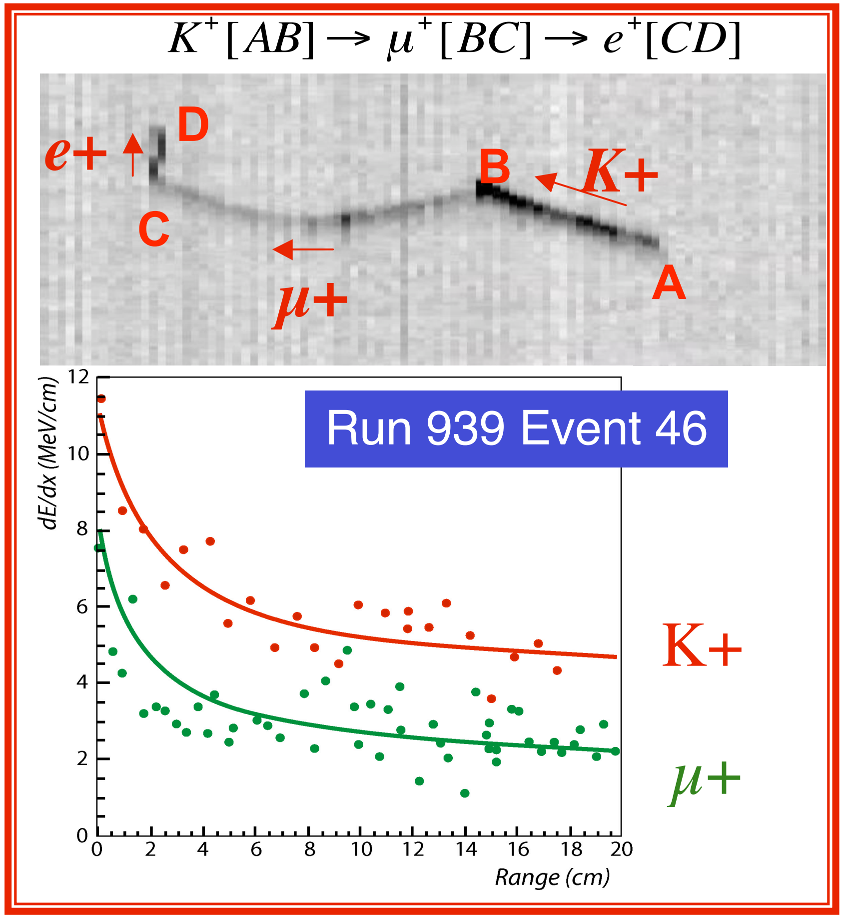
Run 939 Event 95 Right chamber

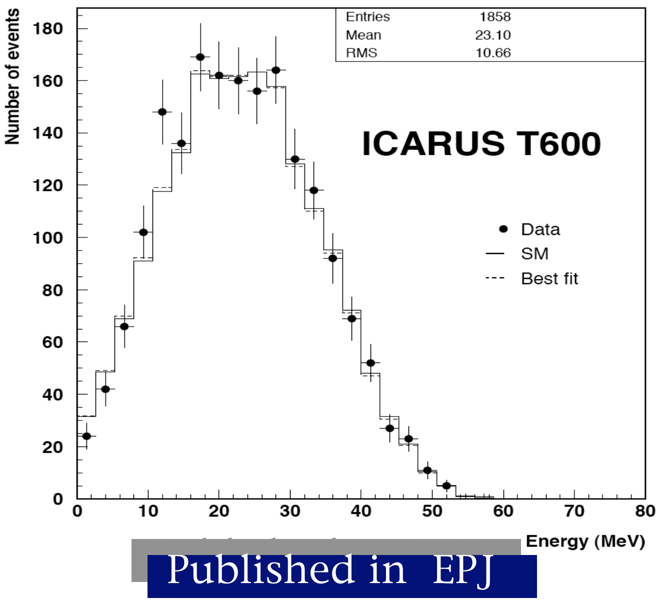


T_e=36.2 MeV
Range=15.4 cm

Charge readout performance: summary

- **Tracking device**
  - ➥ Precise event topology
  - ➥ Momentum via multiple scattering
- **Measurement of local energy deposition dE/dx**
  - ➥ e / γ separation (2%X_0 sampling)
  - ➥ Particle ID by means of dE/dx vs range measurement
- **Total energy reconstruction (calorimeter)**
  - ➥ Full sampling, homogeneous calorimeter with excellent accuracy for contained events



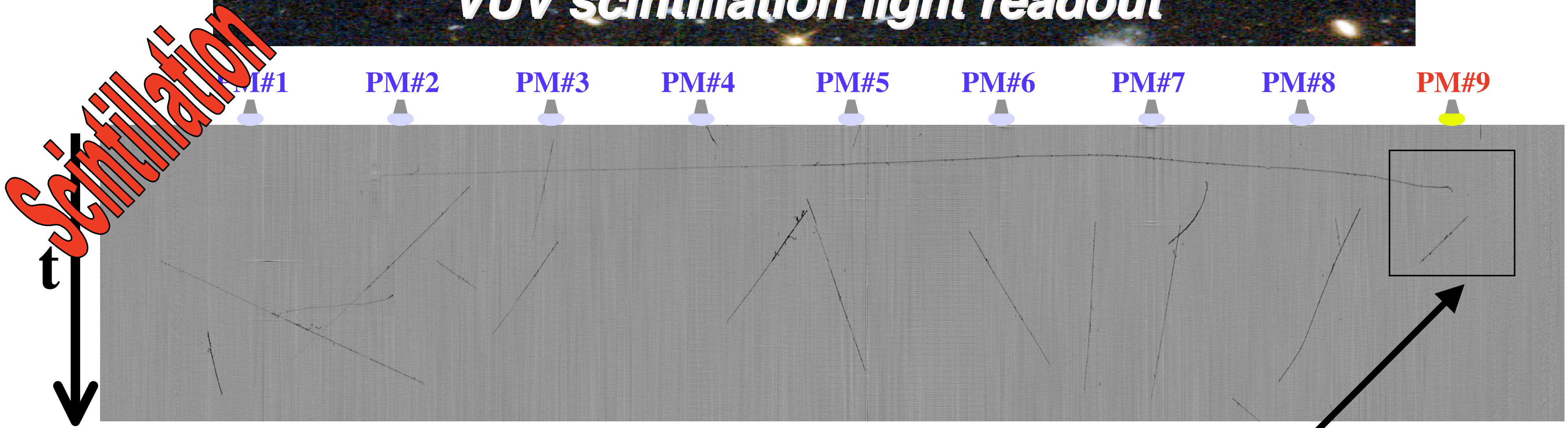


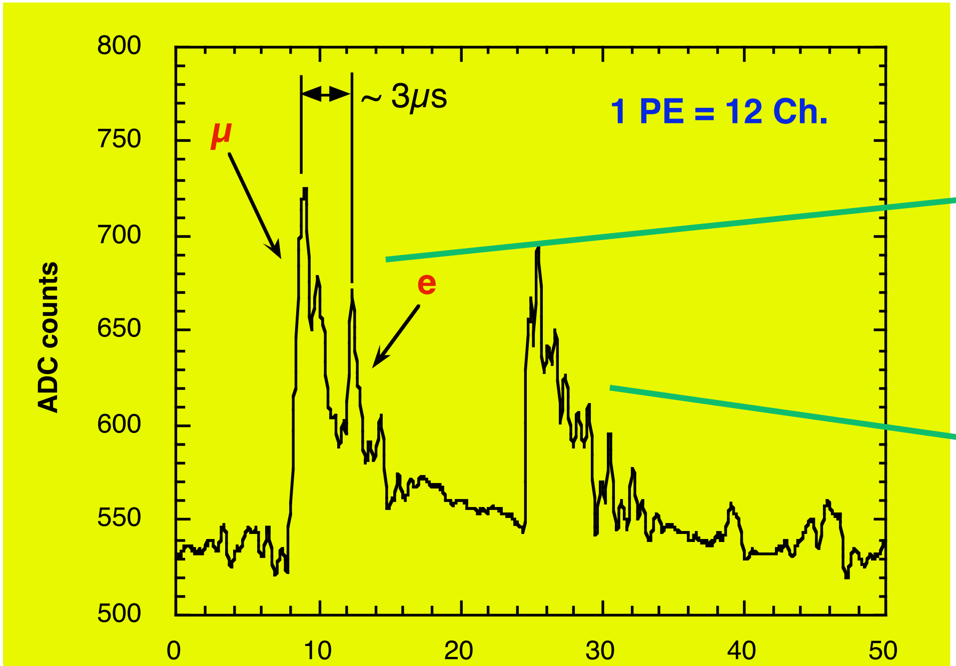
RESOLUTIONS

Low energy electrons:	$\sigma(E)/E = 11\% / \sqrt{E(MeV)} + 2\%$
Electromagn. showers:	$\sigma(E)/E = 3\% / \sqrt{E(GeV)}$
Hadron shower (pure LAr):	$\sigma(E)/E \approx 30\% / \sqrt{E(GeV)}$ +…
Hadron shower (+TMG):	$\sigma(E)/E \approx 17\% / \sqrt{E(GeV)}$ +…

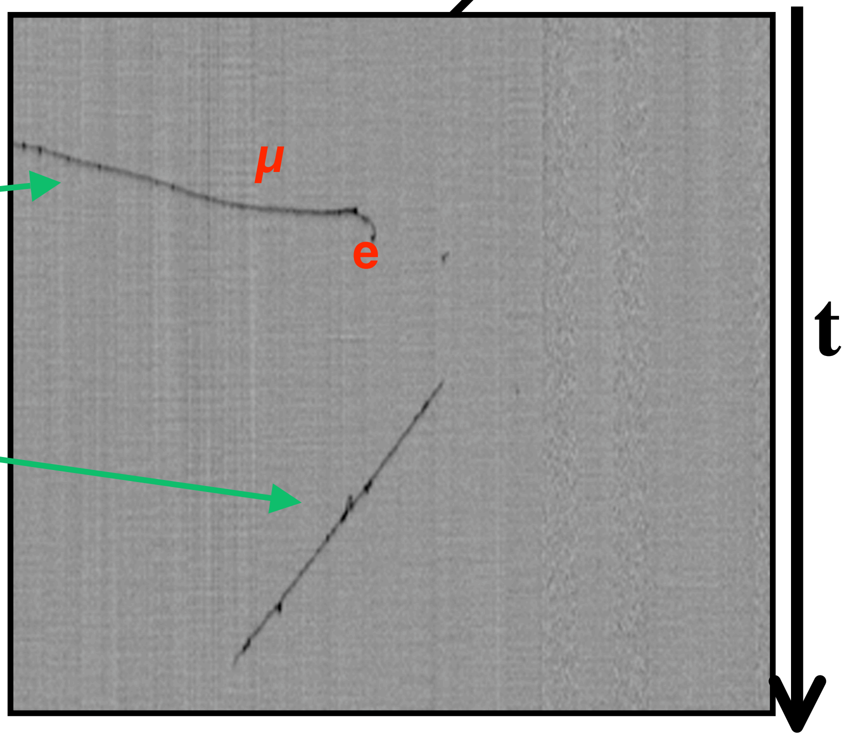
(hadronic energy includes offline SW compensation, MC study)

VUV scintillation light readout



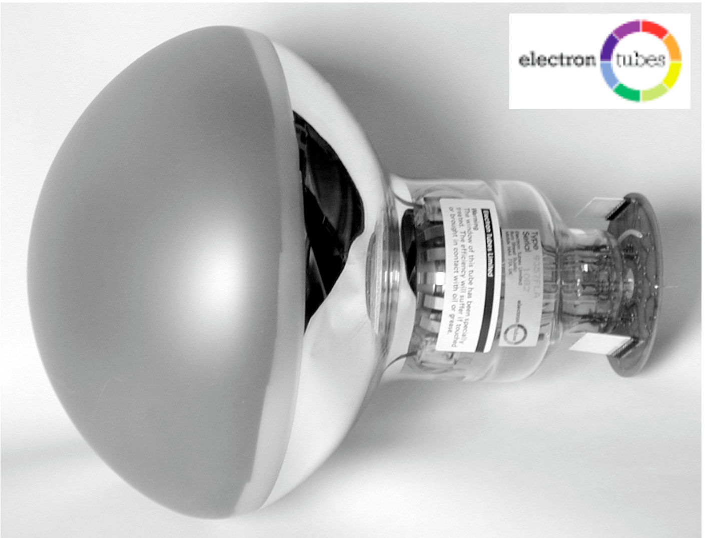


Signal PMT#9



VUV light readout

- Commercial PMT with large area
  - ➥Glass-window
- For scintillation VUV $\lambda = 128$ nm
  - ➥Wavelength-shifter
- Immersed T(LAr) = 87 K



Electron Tubes 9357FLA

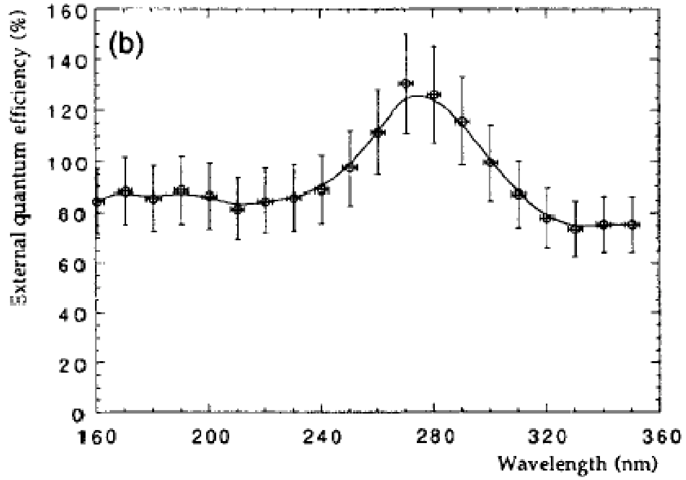
8" PMT (bialkali with Pt deposit)

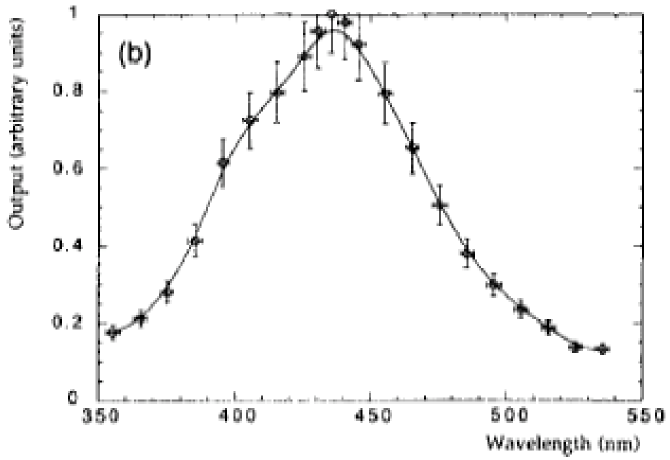
$G = 1 \times 10^7$ @ ~1400 V

peak Q.E. (400-420 nm) ~ 18 % (≈10% cold)

T_{rise} ~ 5 ns, FWHM ~ 8 ns

With TPB as WLS



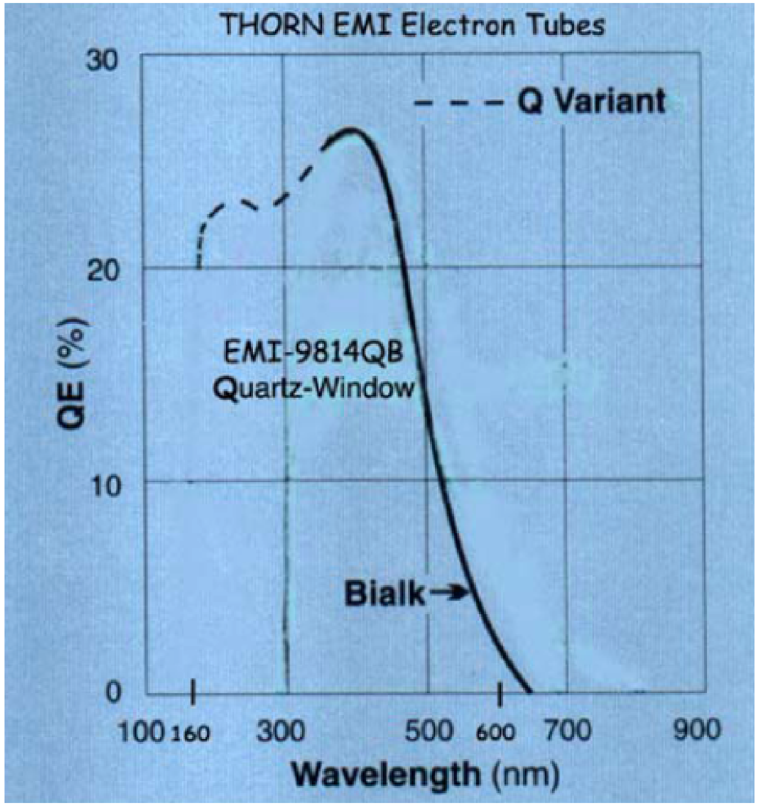


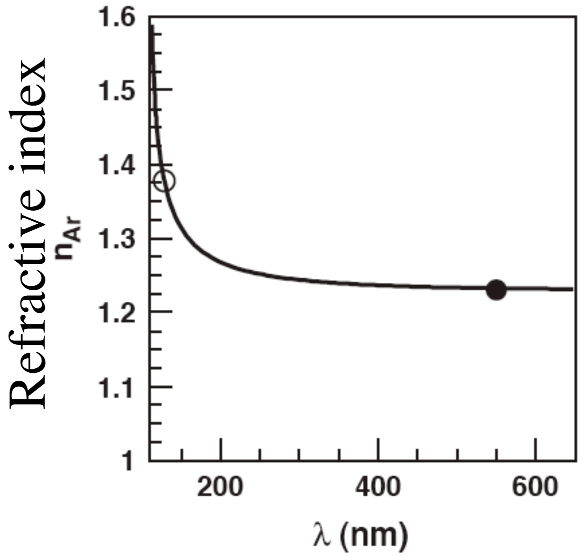
Lally et al., NIMB 117 (1996) 421

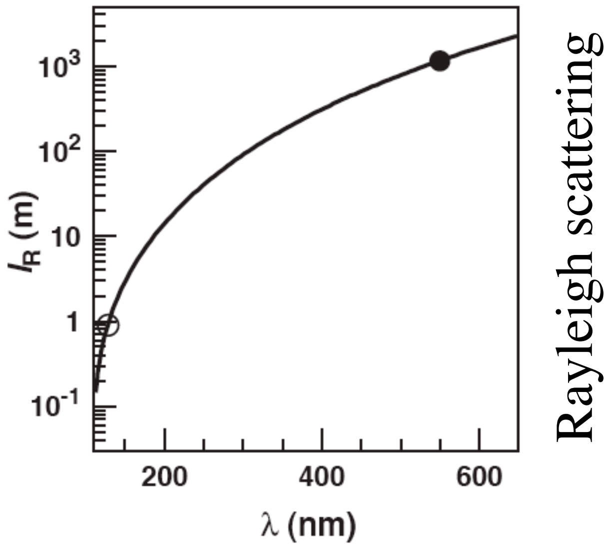
Cerenkov light readout

Cerenkov

- M. Antonello et al., ICARUS Collab., *"Detection of Cerenkov light emission in liquid Argon"* NIMA, published
- Immersed PMT 2" EMI-9814 BQ (sensitivity up to 160 nm)







Data consistent with Cerenkov emission:

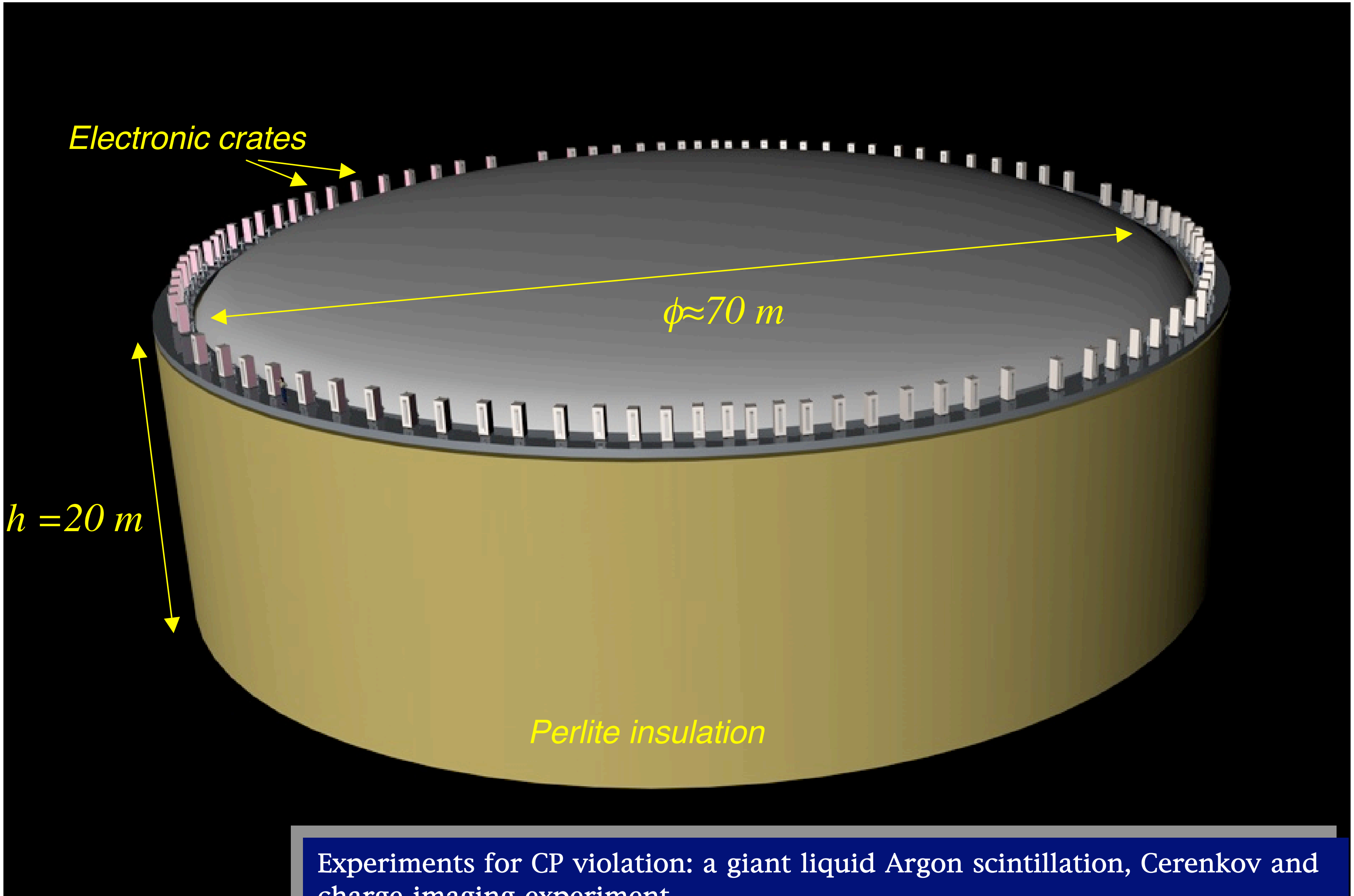
$$dN/dx(160\text{-}600\,\text{nm}) \approx 700\ \gamma/\text{cm}\ (\beta \approx 1)$$

Liquid Argon TPC:
Application to different mass scales

100 ton

100 <u>k</u>ton

100 kton liquid Argon detector



Experiments for CP violation: a giant liquid Argon scintillation, Cerenkov and charge imaging experiment.

A.Rubbia, Proc. II Int. Workshop on Neutrinos in Venice, 2003, hep-ph/0402110

Events for 100 kton detector mass

Number of targets for nucleon stability:

6×10^{34} nucleons $\Rightarrow \tau_p / Br > 10^{34}$ years $\times$ T(yr) $\times \varepsilon$ @ 90 CL

Low energy Super-Beams or beta-beams:

460 ν_μ CC per 10^{21} 2.2 GeV protons (real focus) @ L = 130 km

15000 ν_e CC per 10^{19} ^{18}Ne decays with γ=75

Atmospheric:

10000 atmospheric events/year

100 ν_τ CC /year from oscillations

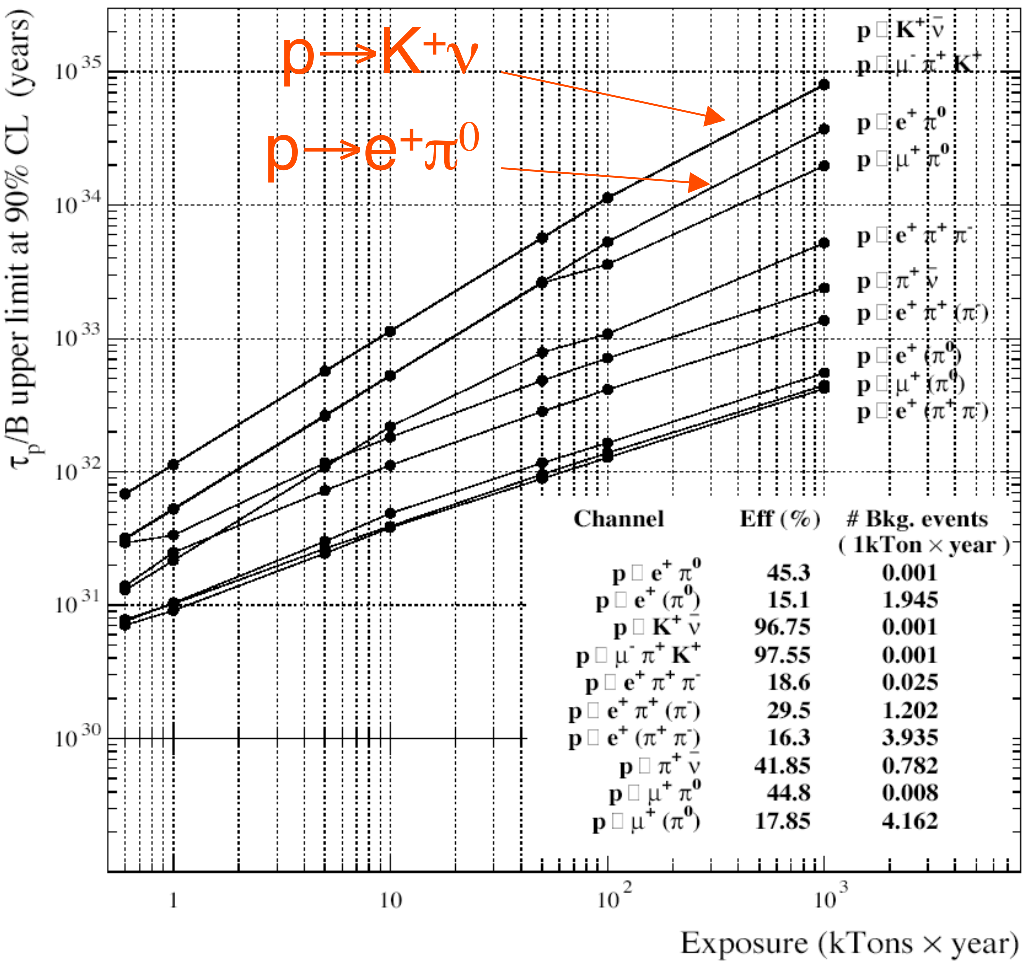
Solar:

324000 solar neutrinos/year @ $E_e > 5$ MeV

Supernova type-II:

≈20000 events @ D=10 kpc

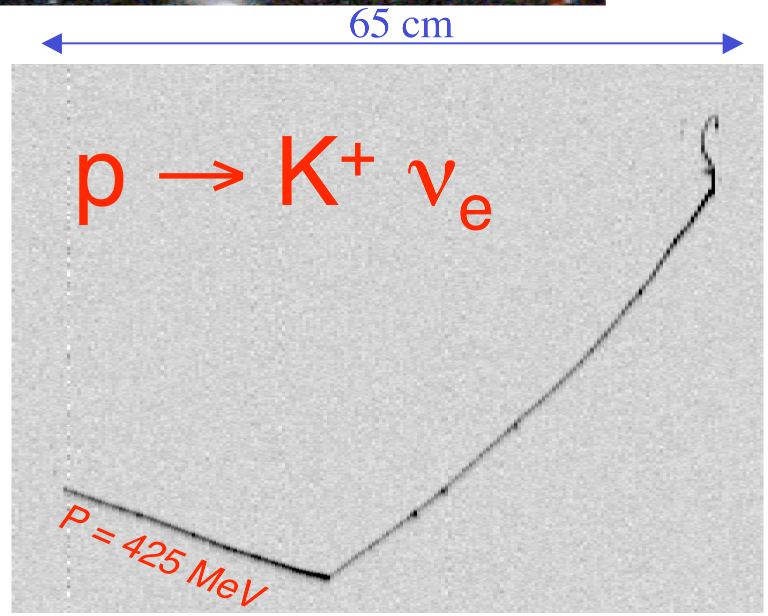
Proton decay: sensitivity vs exposure



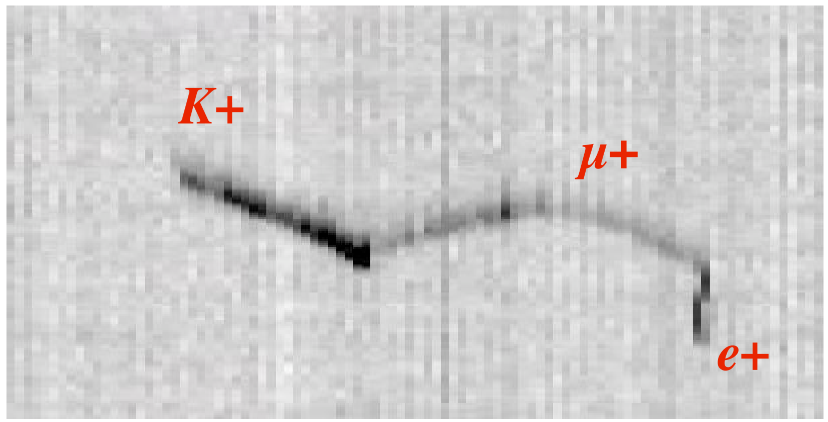
Channel	Eff (%)	# Bkg. events (1kTon × year)
$p \rightarrow e^+ \pi^0$	45.3	0.001
$p \rightarrow e^+ (\pi^0)$	15.1	1.945
$p \rightarrow K^+ \bar{\nu}$	96.75	0.001
$p \rightarrow \mu^- \pi^+ K^+$	97.55	0.001
$p \rightarrow e^+ \pi^+ \pi^-$	18.6	0.025
$p \rightarrow e^+ \pi^+ (\pi^-)$	29.5	1.202
$p \rightarrow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

6×10^{34} nucleons $\Rightarrow$

τ_p/Br > ≈10^{34} years × T(yr) × ε @ 90 CL



"Single" event detection capability

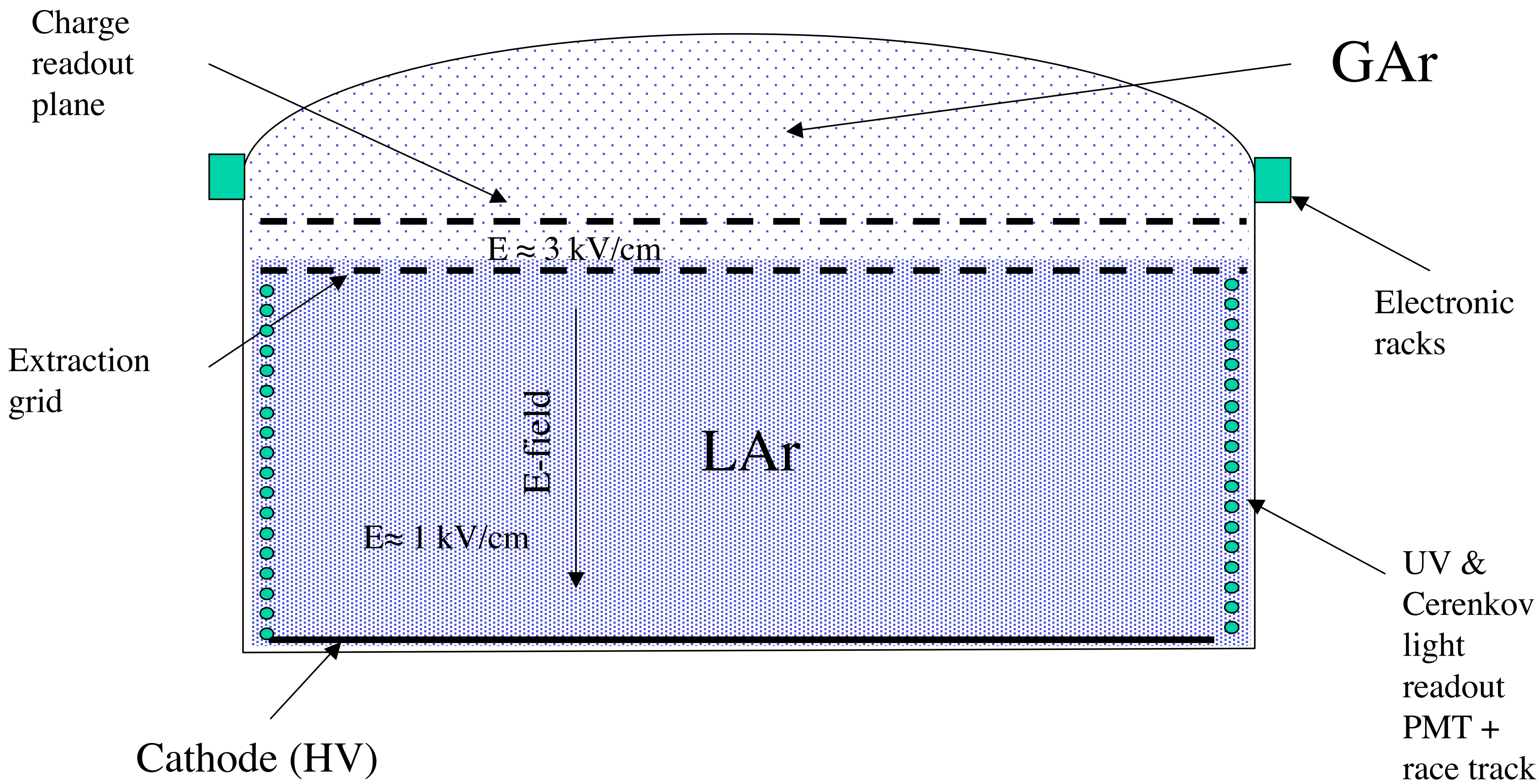


T600: Run 939 Event 46

A tentative detector layout... and name: GLACIER

***G**iant **L**iquid **A**rgon **C**harge **I**maging **E**xpe**R**iment*

Single detector: charge imaging, scintillation, Cerenkov light



Tentative parameter list: to be further studied

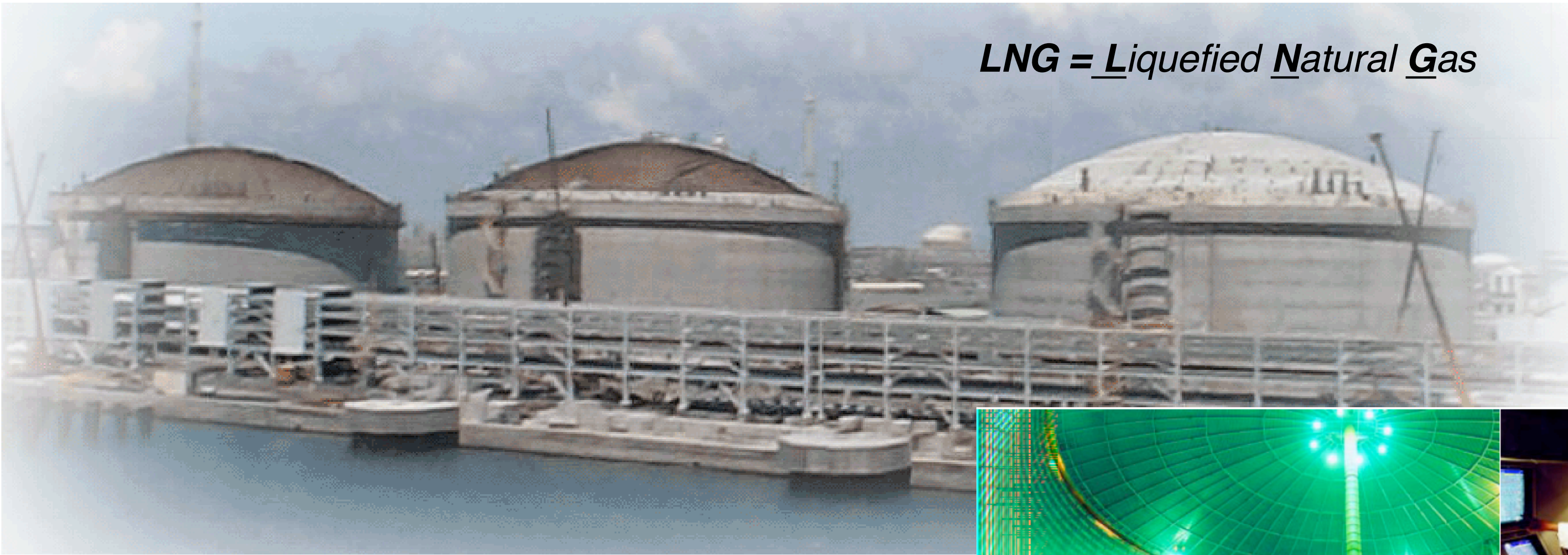
Dewar	φ≈70 m, height ≈ 20 m, passive perlite insulated, heat input ≈5W/m^2
Argon storage	Boiling argon, low pressure (<100 mbar overpressure)
Argon total volume	73118 m^3 (height = 19 m), ratio area/volume≈15%
Argon total mass	102365 tons
Hydrostatic pressure at bottom	≈3 atm
Inner detector dimensions	Disc φ ≈70 m located in gas phase above liquid phase
Electron drift in liquid	20 m maximum drift, HV=2 MV for *E*=1KV/cm, *v_d≈2 mm/μs, max drift time ≈10 ms*
Charge readout view	2 independent perpendicular views, 3mm pitch, in gas phase (electron extraction) with charge amplification (typ. x100)
Charge readout channels	≈100000
Readout electronics	100 racks on top of dewar (1000 channels per crate)
Scintillation light readout	Yes (also for triggering), 1000 immersed 8“ PMT with WLS (TPB)
Visible light readout	Yes (Cerenkov light), 27000 immersed 8“ PMTs or 20% coverage, single photon counting capability

Charge extraction, amplification, readout

- **Detector is running in BI-PHASE MODE**
  - ➥ XXL drift (≈20 m) ⇒ charge attenuation to be compensated by charge amplification near anodes located in gas phase
  - ➥ Amplification operates in proportional mode
  - ➥ After max drift of 20 m @ 1 KV/cm, diffusion ≈ readout pitch ≈ 3 mm

Electron drift in liquid	**20 m maximum drift, HV=2 MV for *E*=1KV/cm, *v_d≈2 mm/μs, max drift time ≈10 ms***
Charge readout view	**2 independent perpendicular views, 3mm pitch**
Maximum charge diffusion	**σ≈2.8 mm ($\sqrt{2Dt_{max}}$ for D=4 cm^2/s)**
Maximum charge attenuation	***$e^{-(tmax/\tau)}$≈ 1/150* for τ=2 ms electron lifetime**
Needed charge amplification	**10^2 to 10^3**
Methods for amplification	**Extraction to and amplification in gas phase**
Possible solutions	**Thin wires (ϕ≈30μm)+pad readout, GEM, LEM, …**

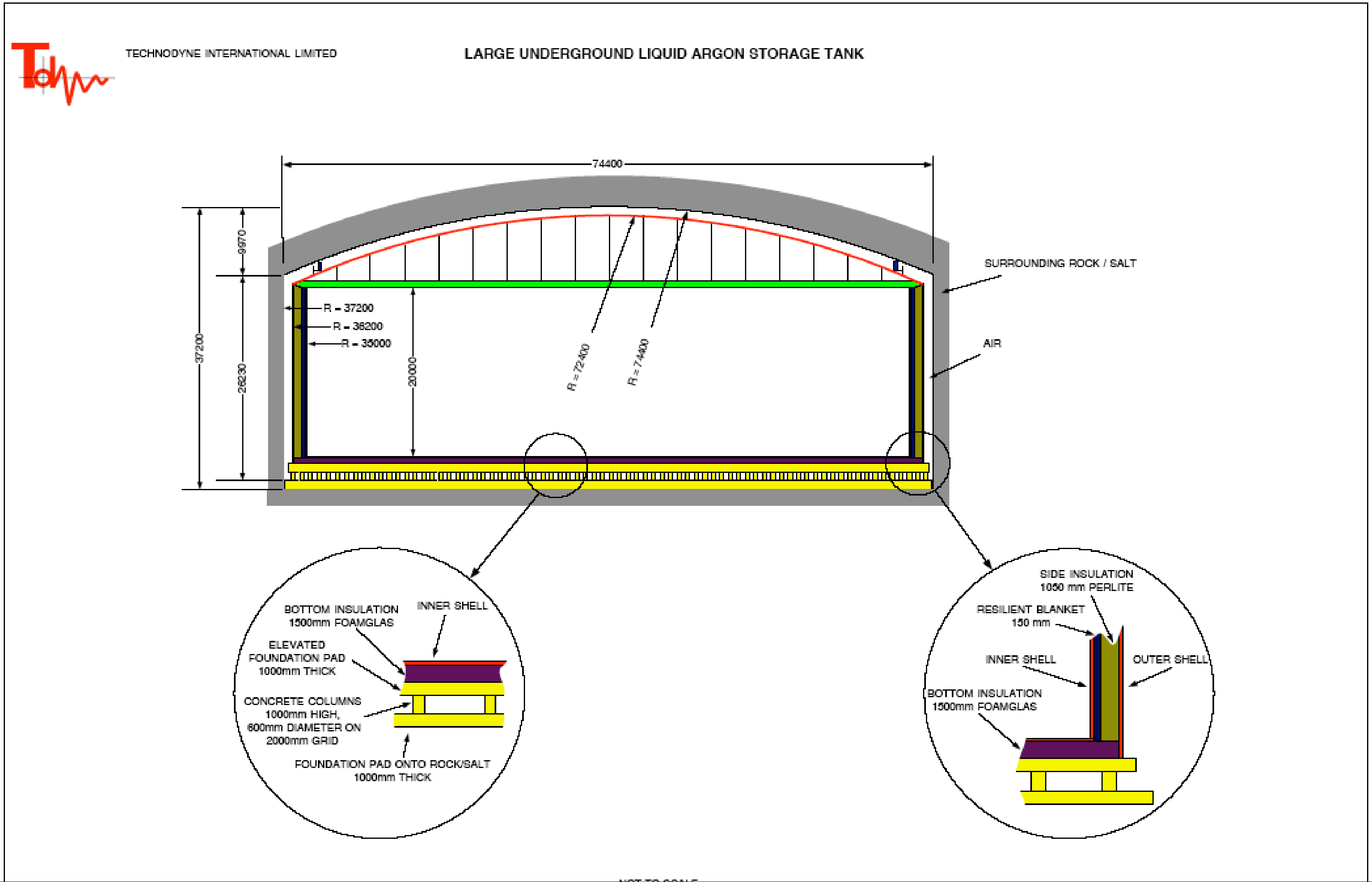
Cryogenic storage tanks for LNG



LNG = Liquefied Natural Gas

- About 200 cryo-tankers exist in the world… up to ≈200’000 m^3
- Process, design and safety issues already solved by petrochemical industry !

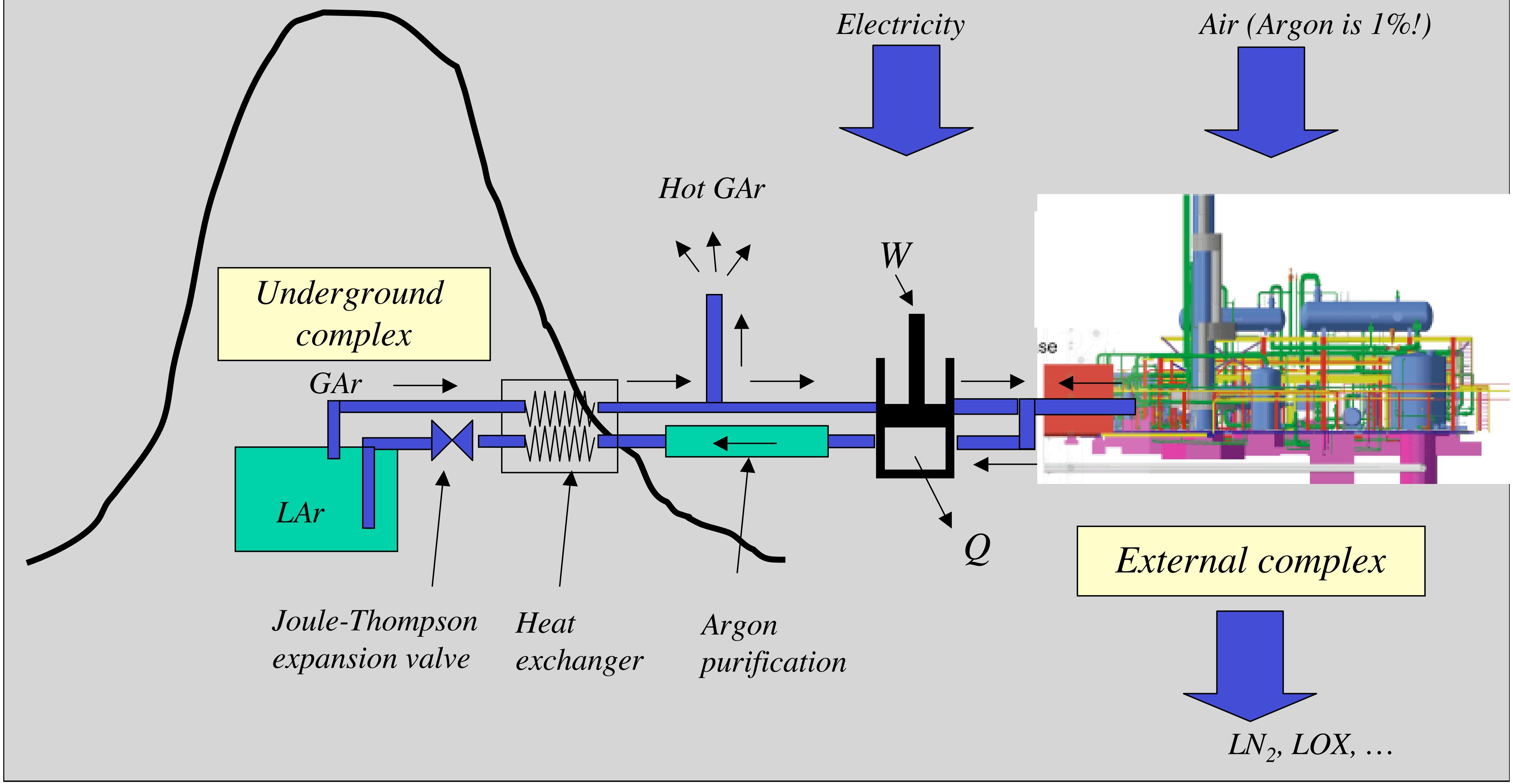
Technodyne feasibility study



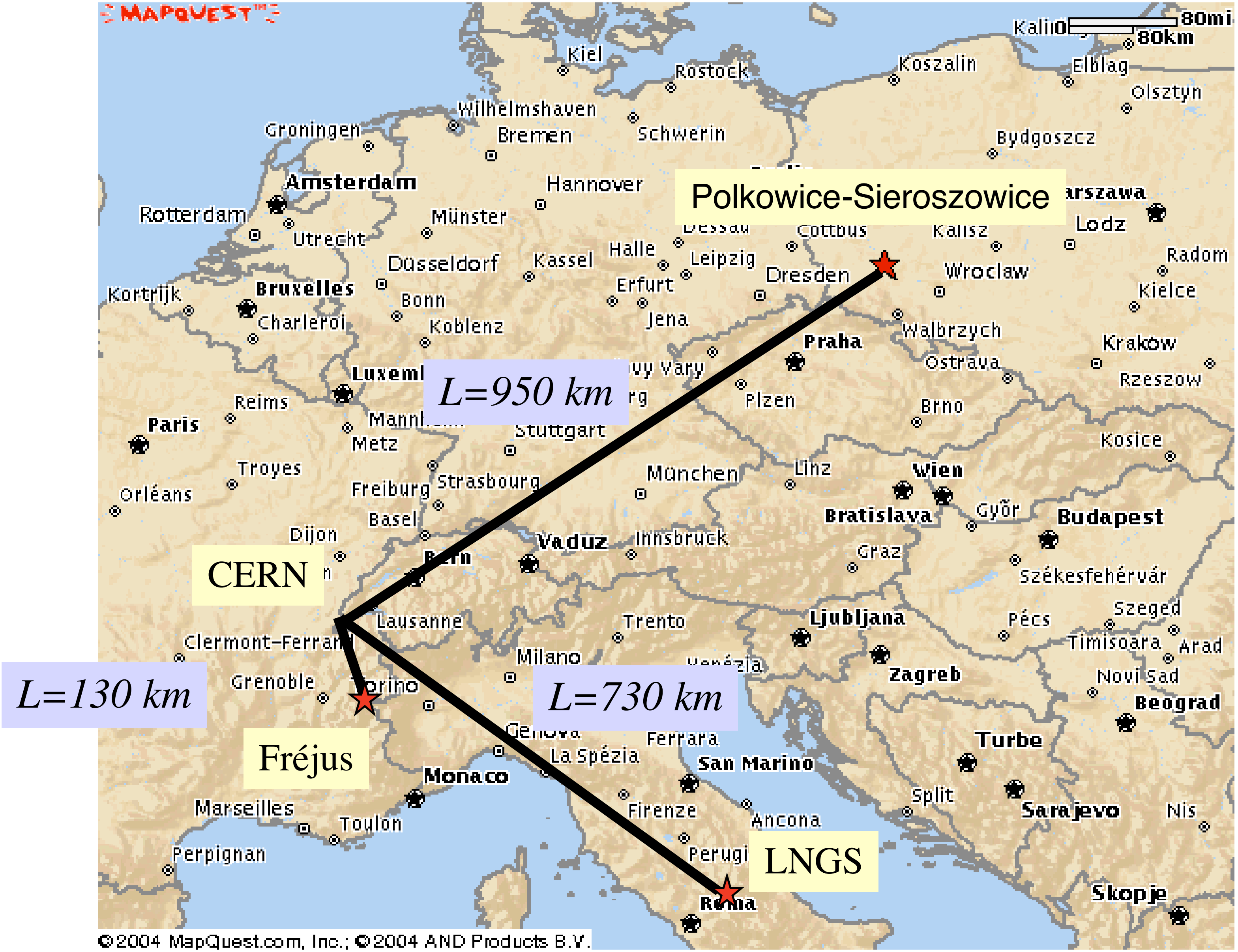
Work in progress: Underground storage, engineering issues, process system & equipment, civil engineering consulting, safety, cost & time

Process system & equipment

- In situ cryogenic plant: tanker 5 W/m² heat input, continuous re-circulation (purity)
- Filling speed (100 kton): 150 ton/day → 2 years to fill, 9 years to evaporate !!

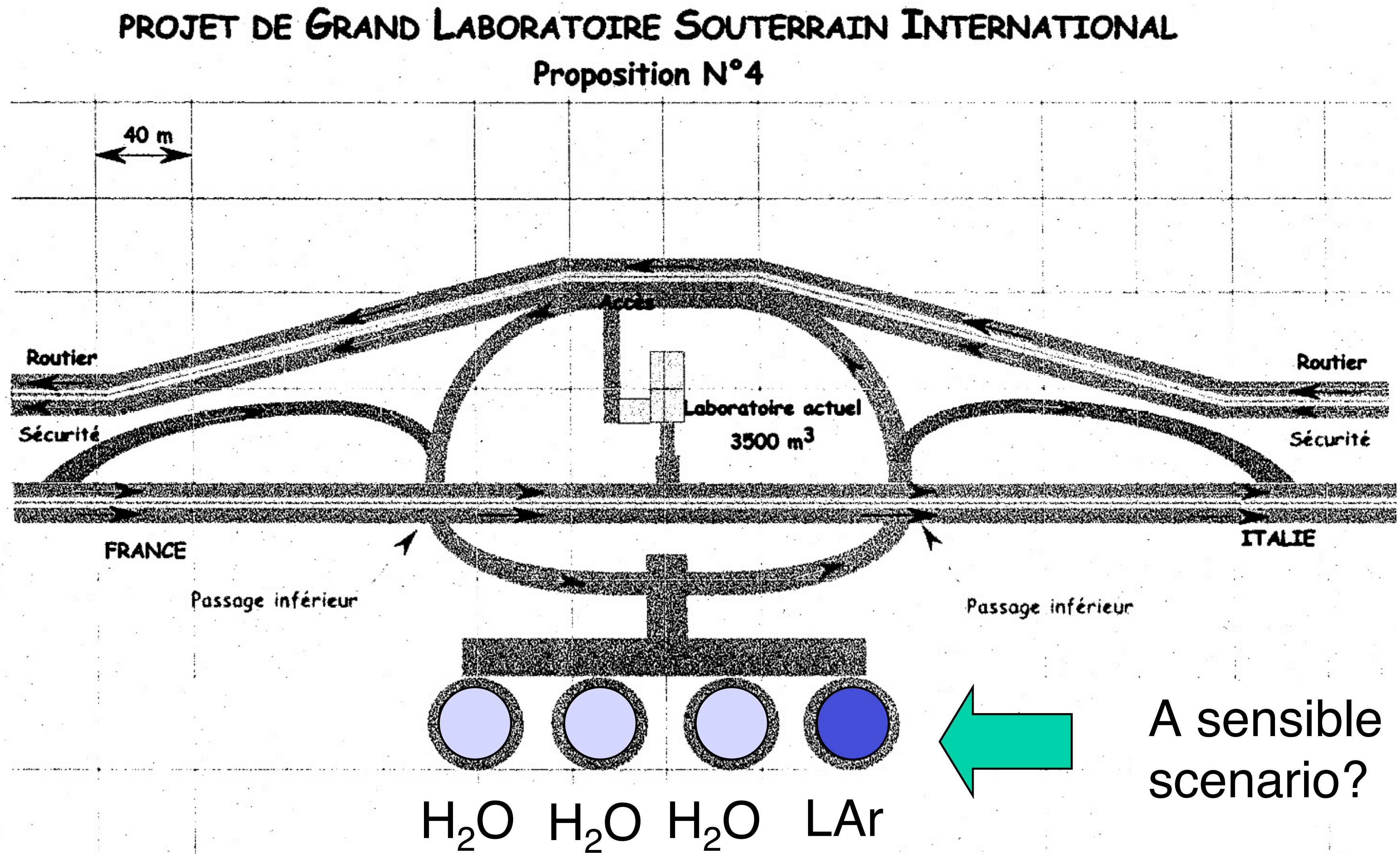


Long baselines Europe



Fréjus laboratory project

Cooperation agreement between IN2P3/CNRS/DSM/CEA & INFN



A sensible scenario?

“CUPRUM mines” Polkowice-Sieroszowice

Contact with Mining and Metallurgy department (Krakow University of Technology and Science) and with mining companies (A. Zalewska)

Copper mines (owned by KGHM, one of the largest producers of copper and silver in the world)

Salt layer at ≈1000 m underground (dry)

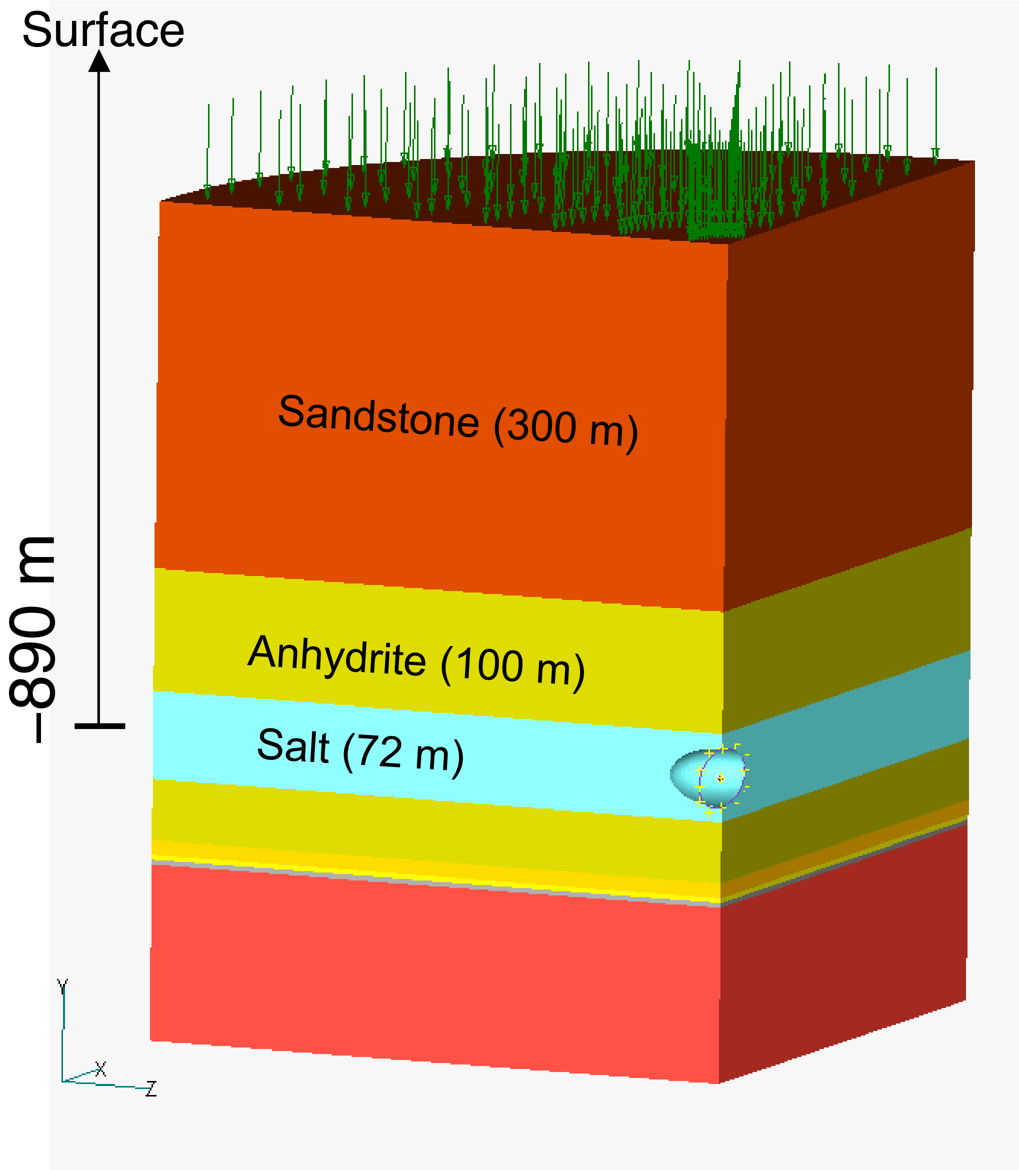
<u>**Very large caverns already exist**</u> (from mine exploitation)

Possibility to host ≈80’000 m^3 detector (O(100kton LAr)) in salt cavern: geophysics under study

Feasibility of large underground cavern

- **Geophysical instabilities limit the size of the underground cavern**
- **Actual size limit depends on details of rock and depth and on the wished cavern geometry**
- **Finite element analysis**
- **Calculation for Polish mine courtesy of** Witold Pytel, CBPM "Cuprum" OBR, Wroclaw

Cavern ≈ 100'000 m^3
or
Tunnel-like geometry



Finite element analysis for Polish mine

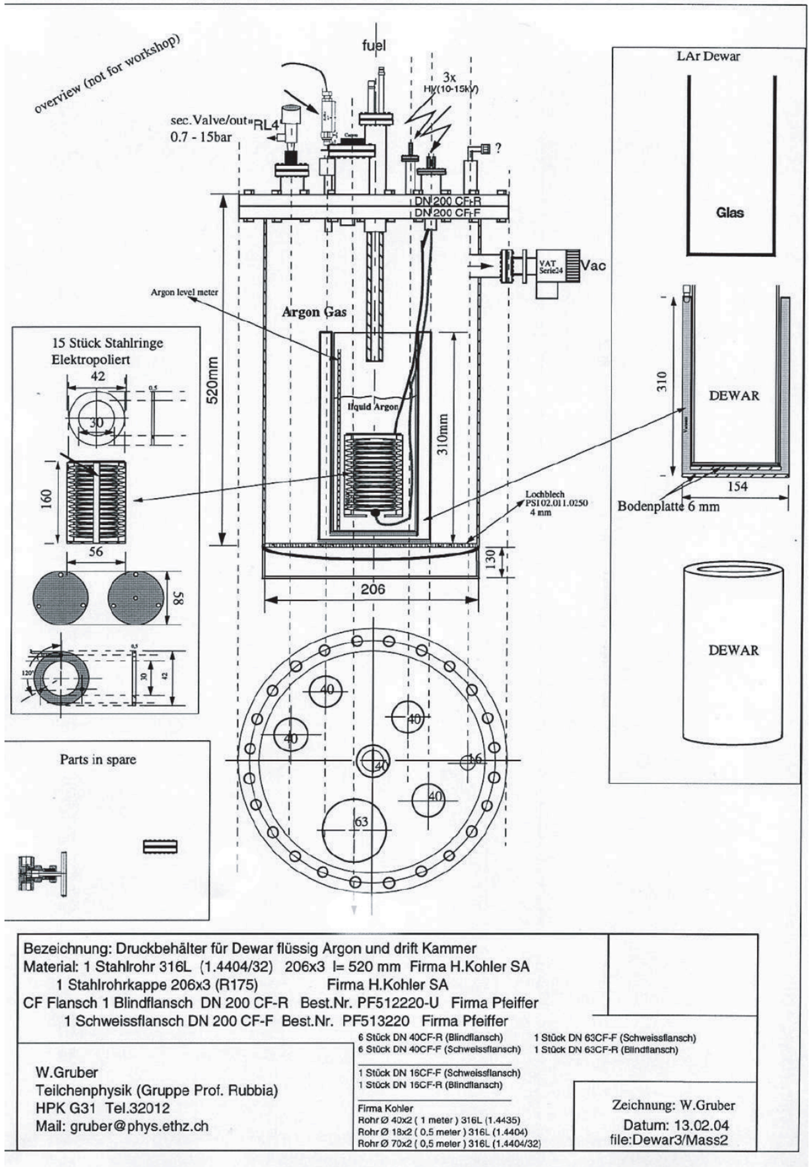
100 kton detector: milestones

- **Nov 2003: Venice workshop**
  - ➥ Basic concept based on LNG tanker, signal amplification, single detector for charge imaging, scintillation and Cerenkov light readout
  - ➥ Design presented for proton decay, astrophysics ν's, superbeams, betabeams
  - ➥ Stressed need of detailed physics comparison: 1 Mton water versus 100 kton liquid argon detector
- **Feb 2004: Feasibility study launched for underground liquid Argon storage**
  - ➥ Industry: Technodyne (UK) mandated for study (expert in LNG design)
  - ➥ Design provided as input to the Fréjus underground lab study
  - ➥ Salt mine in Poland being investigated
- **May 2004: Multi-MW physics workshop at CERN**
- **September 2004 : CERN SPSC special session (Villars)**
- **…**

- **Engineering studies, dedicated test measurements, detector prototyping, simulation, physics performance studies in progress**

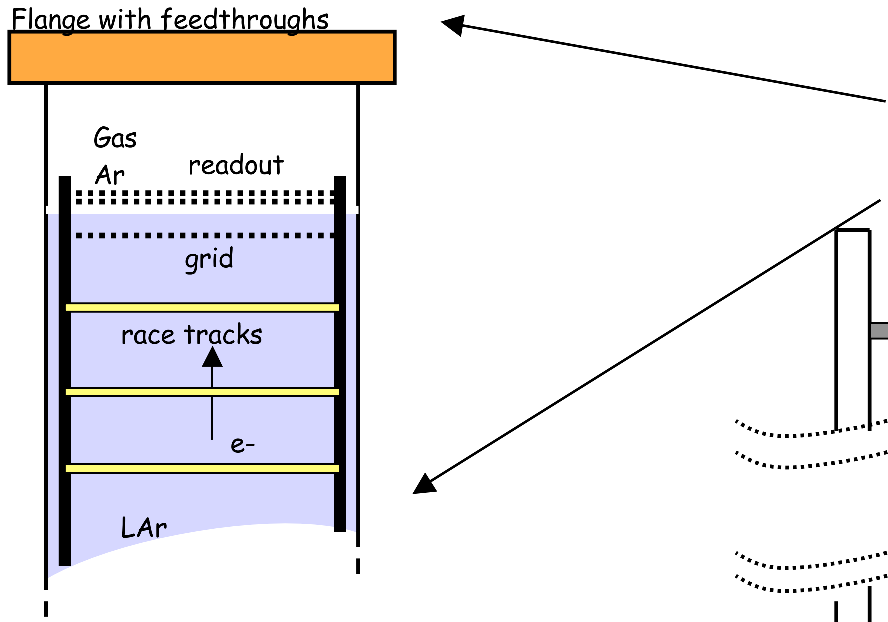
High pressure drift properties

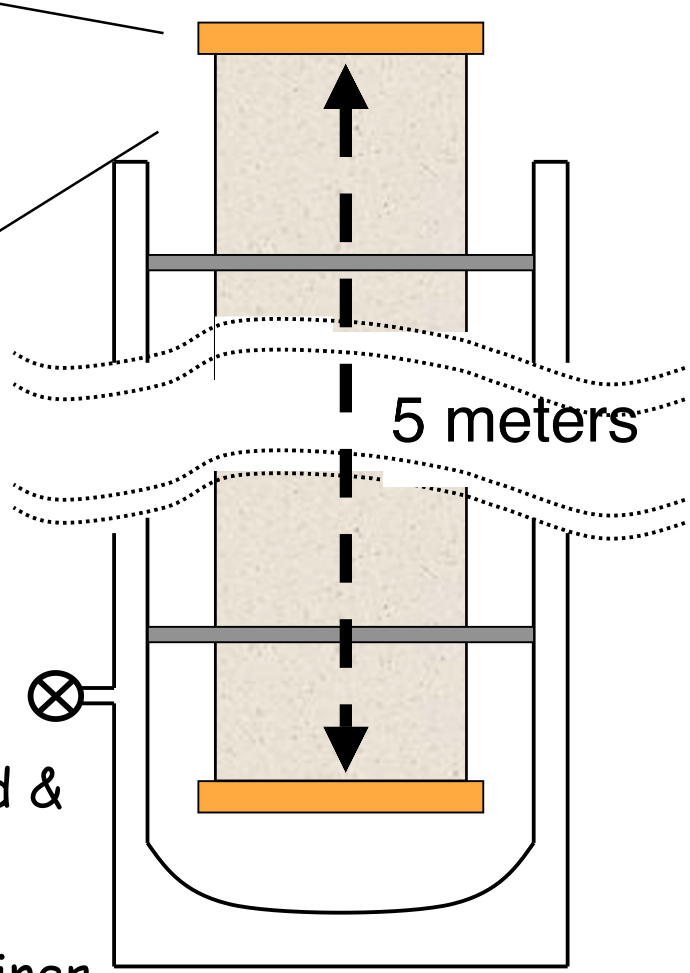
- **Future large tankers:**
  - ➥ Hydrostatic pressure could be quite significant (3-4 atmosphere at the bottom of the tanker).
- **Test of electron drift properties in high pressure liquid argon**
  - ➥ important to understand if the electron drift properties and imaging under high pressure
- **Study in progress**
  - ➥ Prototype designed



R&D in progress

Long drift, extraction, amplification: test module





- A full scale measurement of long drift (5 m), signal attenuation and multiplication is planned.

- Simulate 'very long' drift (10-20 m): reduced E field & LAr purity

- Design in progress: external dewar, detector container, inner detector, readout system, …

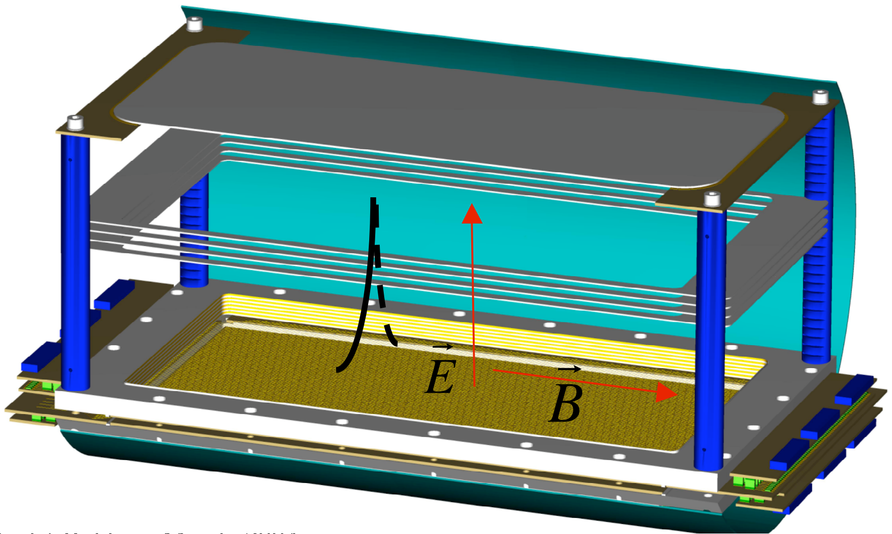
R&D in progress

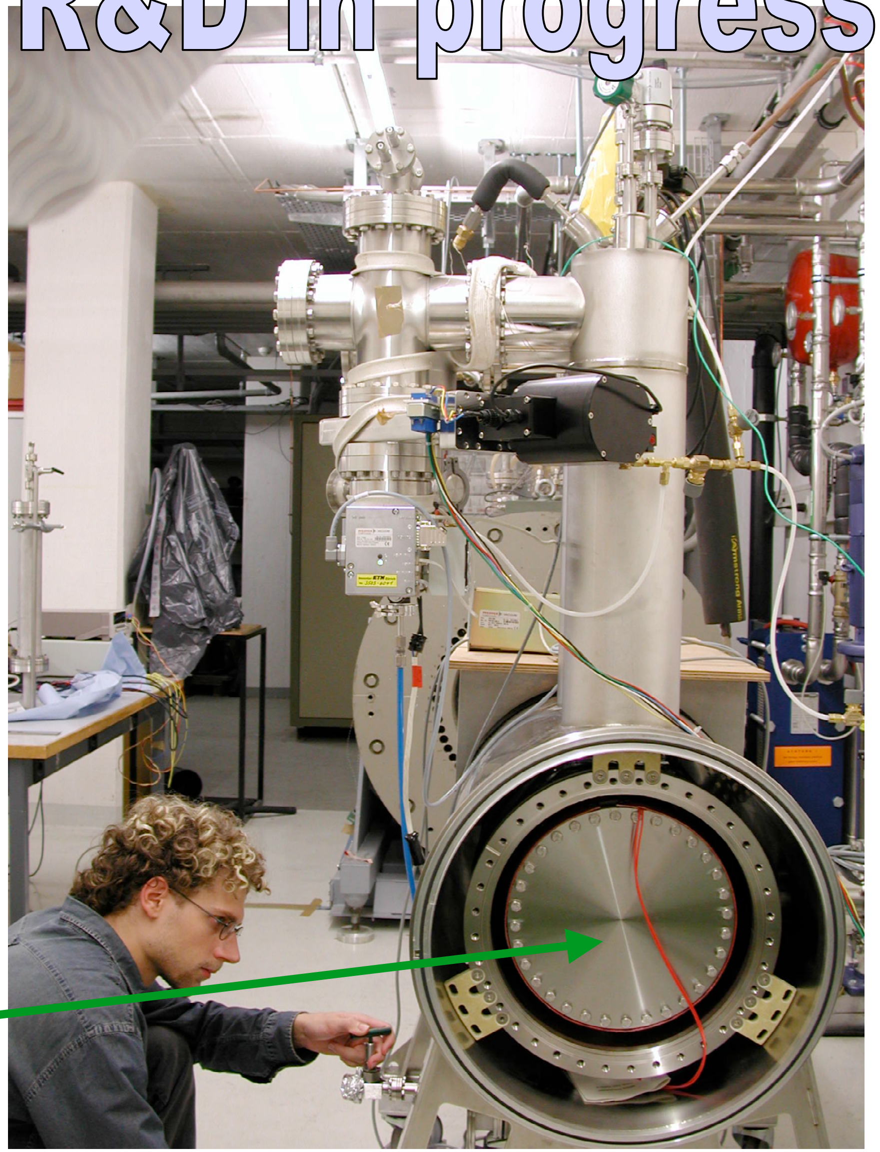
Test of liquid Argon imaging in B-field

R&D in progress

- **Small chamber in SINDRUM-I recycled magnet up to B=0.5T (230KW) given by PSI, Villigen**
- **Test program:**
  - ➥ Check basic imaging in B-field
  - ➥ Measure traversing and stopping muons bending
  - ➥ Charge discrimination
  - ➥ Check Lorentz angle ($\alpha \approx 30$mrad @ E=500 V/cm, B=0.5T)

Width 300mm, height 150mm, drift length 150mm

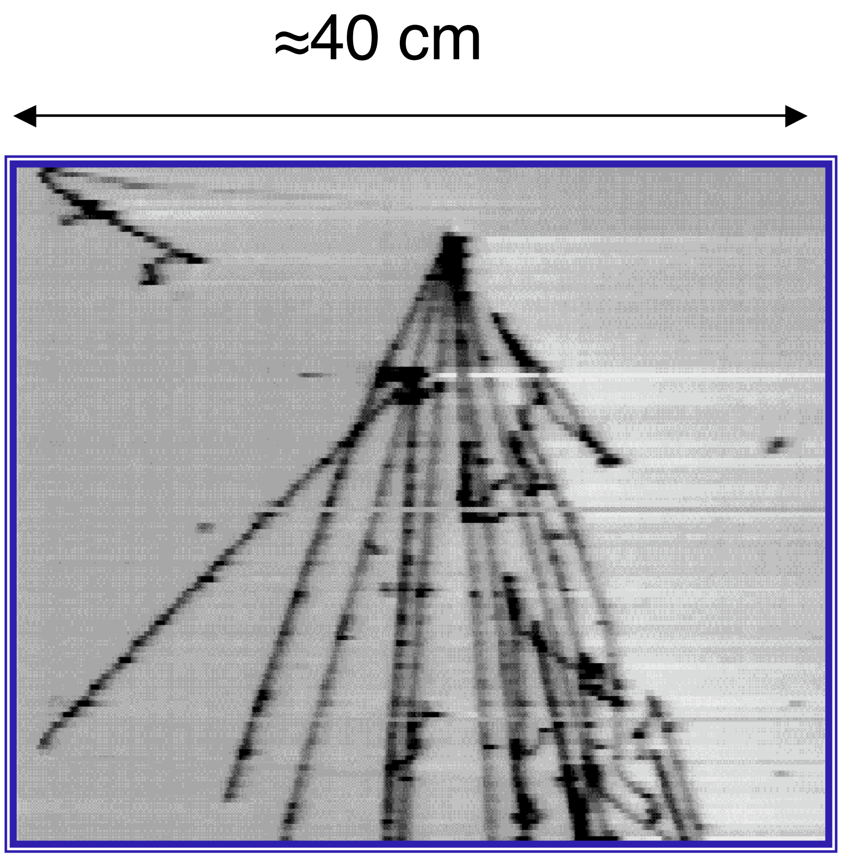




100 ton

Neutrino physics program @ near site

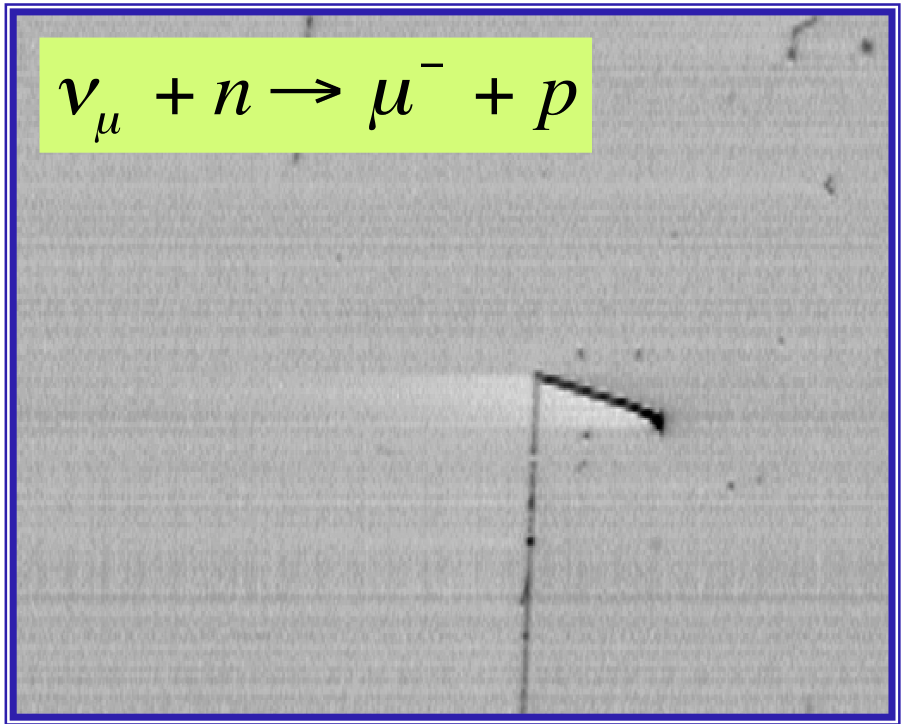
- **Take maximum advantage of high granularity imaging (tracking) and excellent energy resolution (calorimeter) properties of liquid Argon TPC**
- **"Standard model" neutrino physics**
  - ➥ DIS+resonances modeling
  - ➥ QE modeling
  - ➥ Binding, Fermi-motion, Pauli-exclusion, NN-correlations, PDF modifications, other nuclear effects, form factors, …
- **Provide "near" or "intermediate" detector measurements**
  - ➥ Flux determination
  - ➥ Precise measurement of intrinsic ν_e component
  - ➥ Precise measurement of π^0 production
    - ☛ π^0 background at far detector



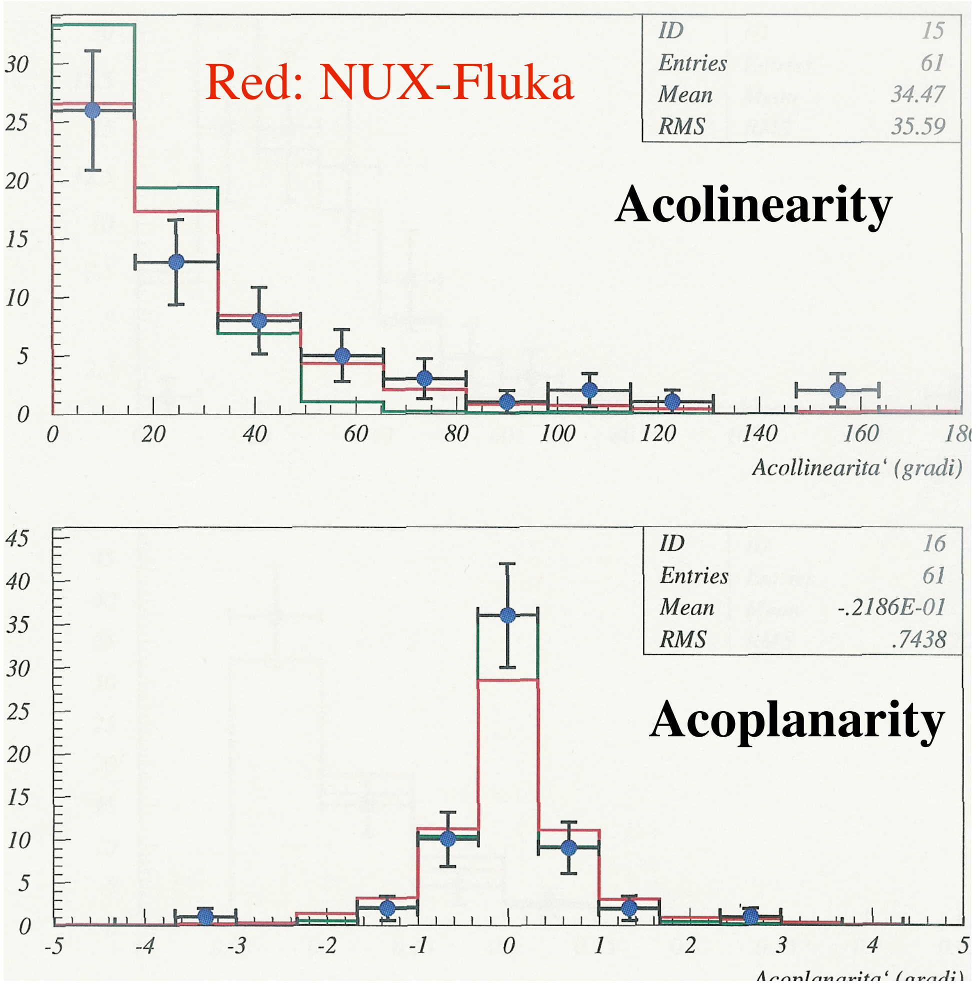
(Real) neutrino event in 50 liter prototype @ CERN WA beam (1998)

Study of quasi-elastic interactions

- **Selection of pure lepton-proton final state with exactly one proton $T_P>50$ MeV (range > 2 cm) and any number protons $T_P<50$ MeV**

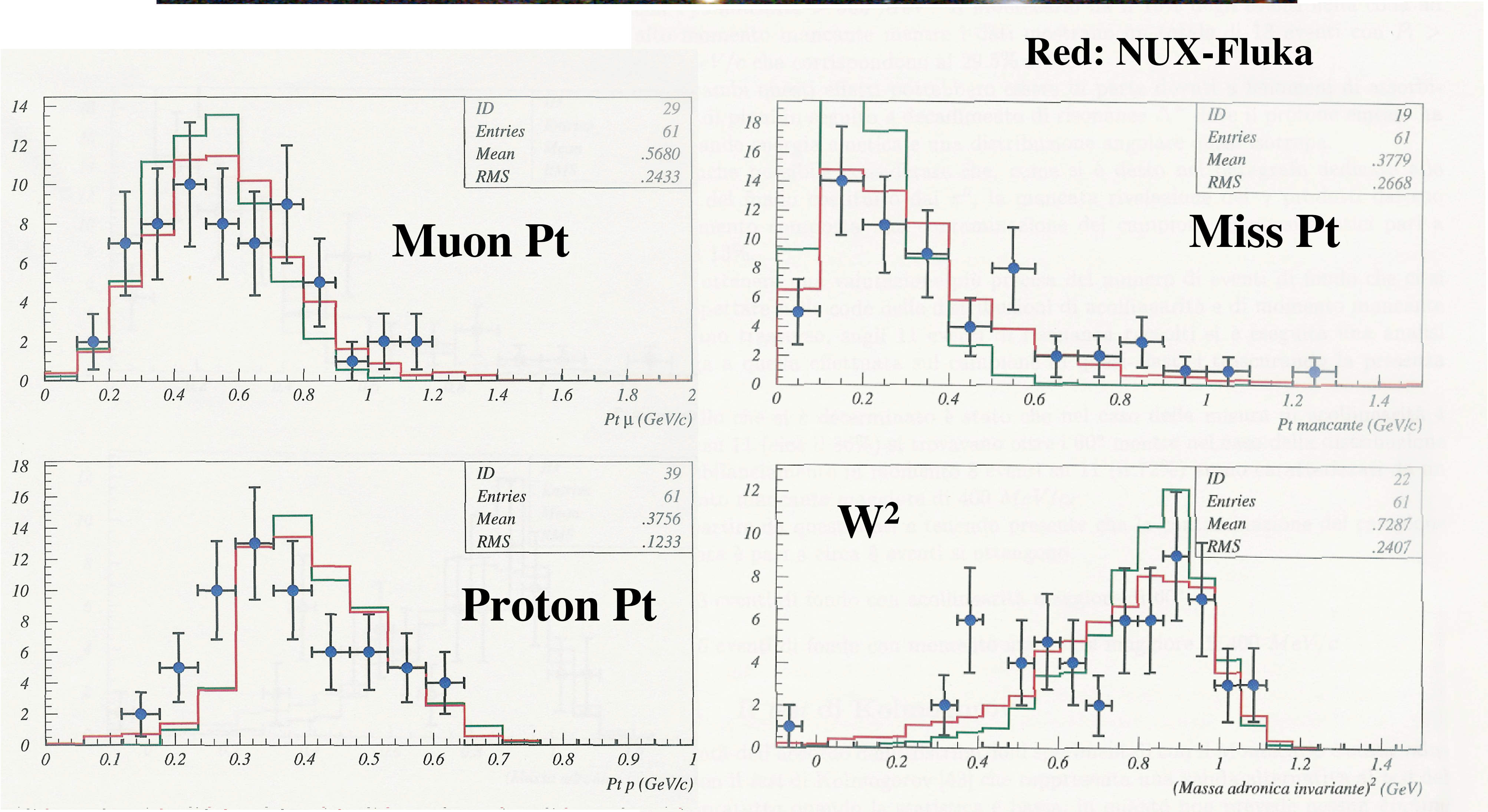


Real neutrino event in 50 liter prototype @ CERN



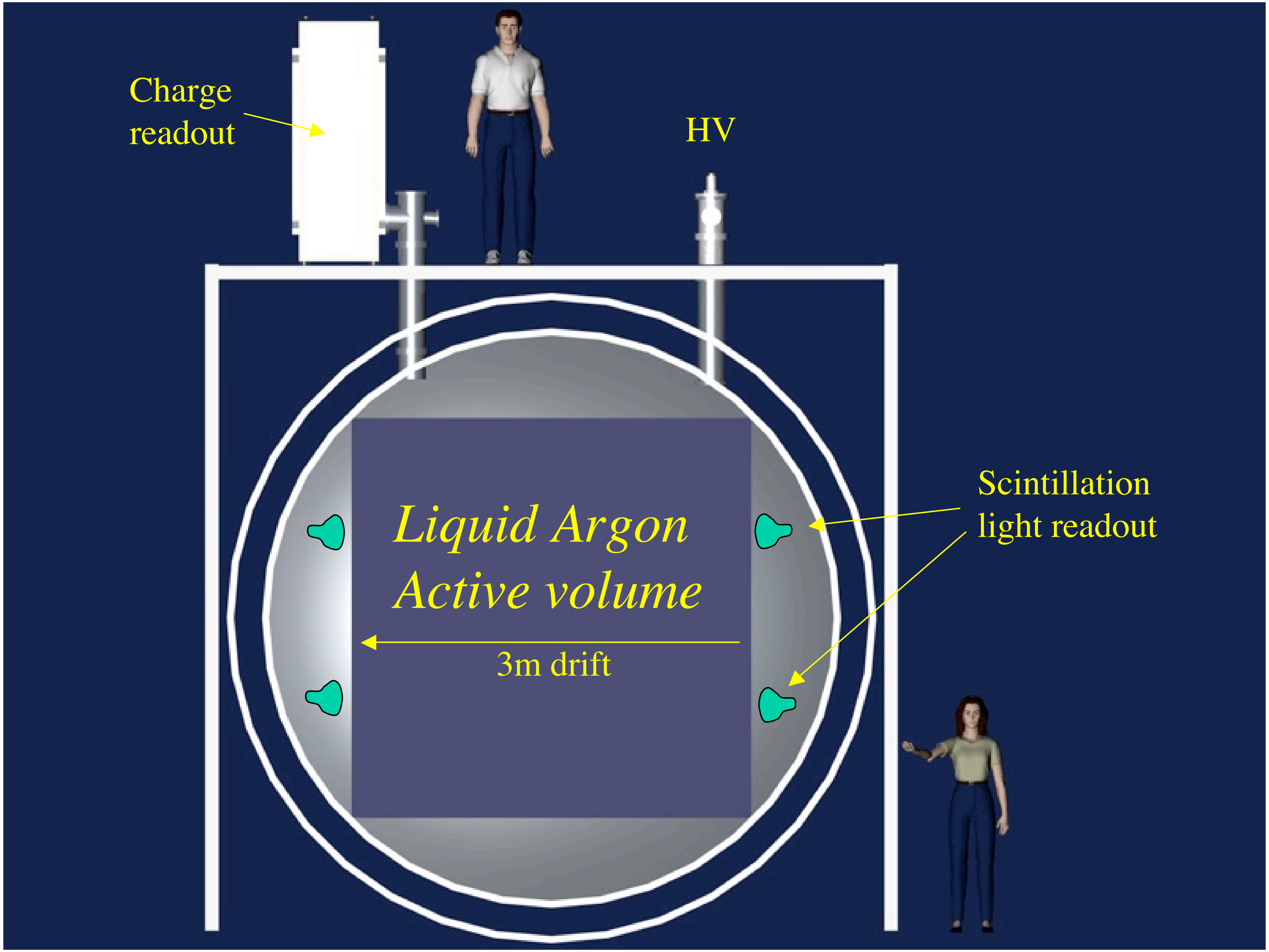
B. Boschetti's thesis (Milano, 1998)

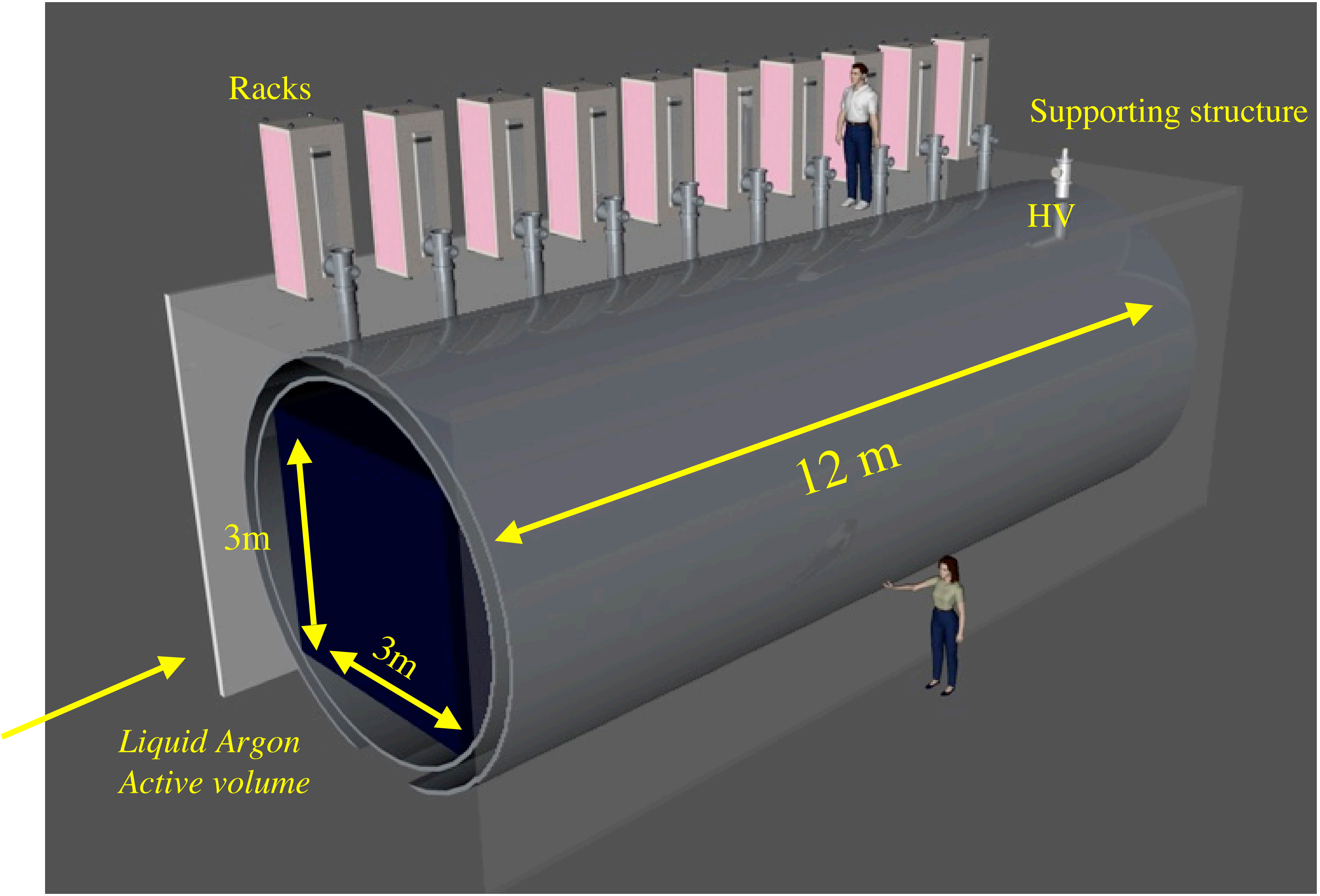
Events (50 liter exposed at CERN)



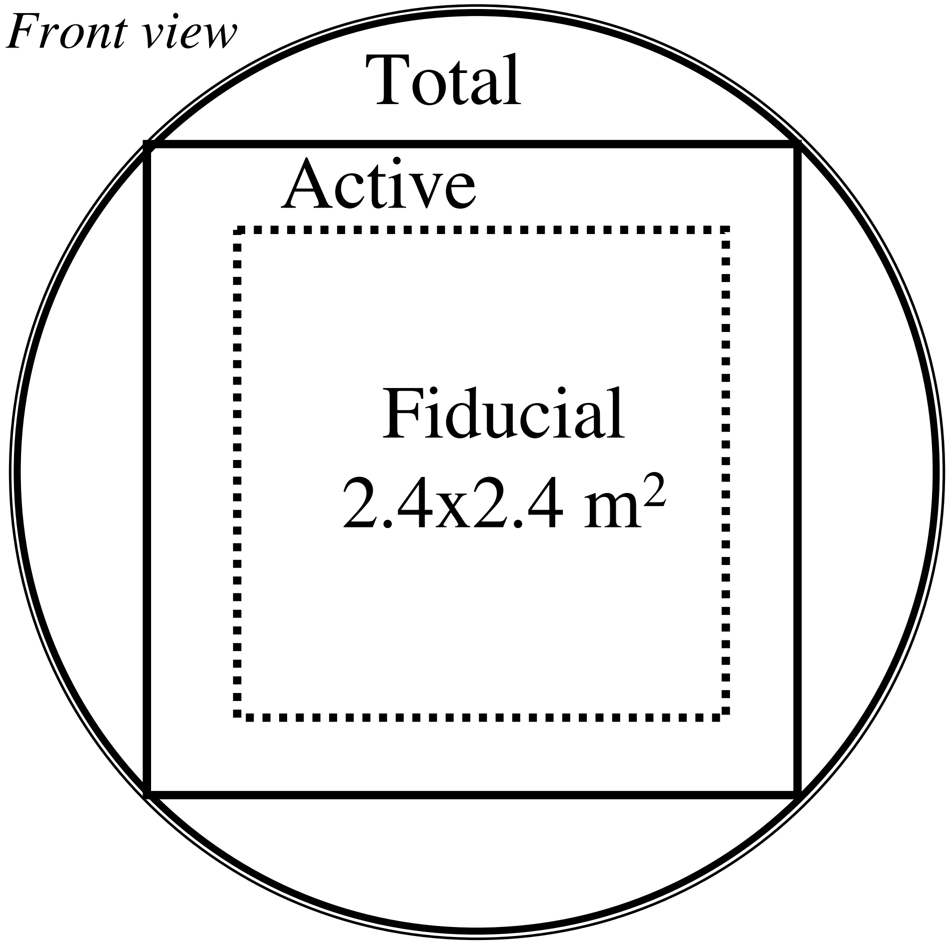
- Good agreement with NUX-FLUKA expectations → **NEED MORE STATISTICS!!**

Conceptual design study of a 150 ton active LAr detector:




Racks
Supporting structure
HV
12 m
3m
3m
Liquid Argon
Active volume

Basic design parameters



Radius = 2,12 m

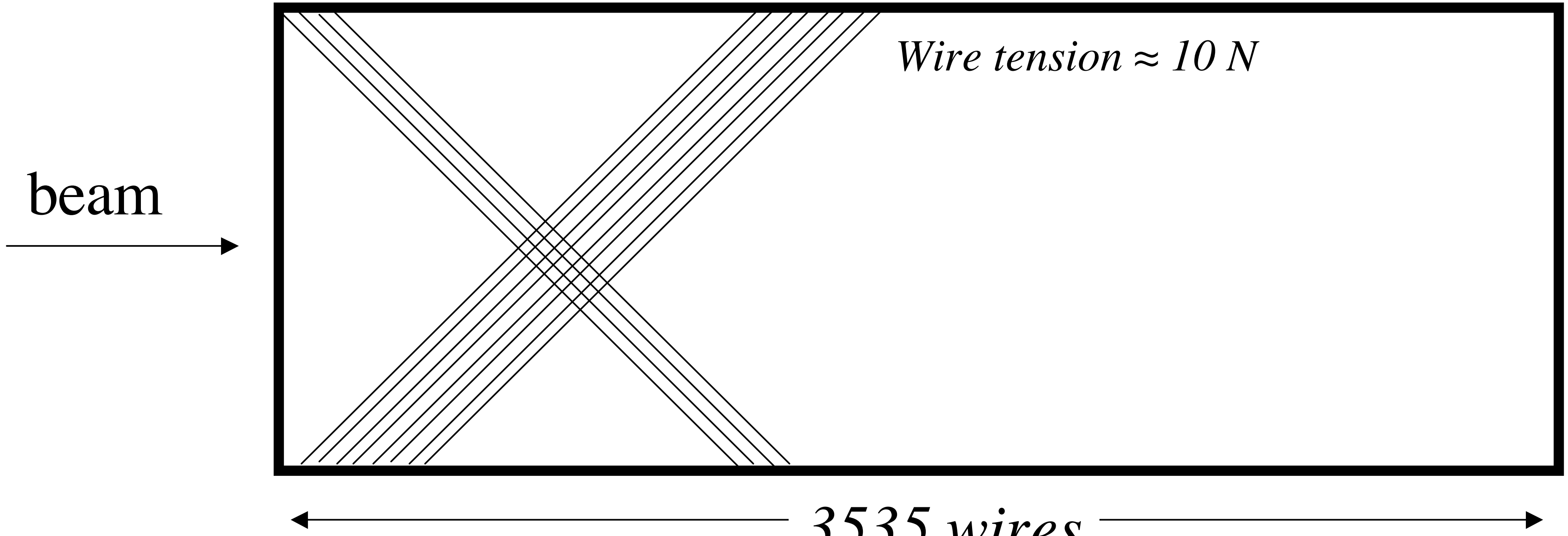
Length = 12 m

Dewar outer vessel	φ ≈5 m, length ≈ 13 m, thickness 15 mm, weight ≈22 tons
Dewar inner vessel	φ = 4,2 m, length=12 m, vacuum insulated, thickness 8 mm, ≈10 tons
Liquid Argon	Total: ≈ 240 tons Active: 150 tons Fiducial ≈100 tons
Inner detector dimensions	3x3 m^2, length 12 m
Electron drift	3 m maximum drift, HV=150 KV for E=500 V/cm, v_d≈1.6 mm/μs
Charge readout view	2 independent views, ±45°, 2 or 3mm wire pitch
Readout wires	Total ≈10000 or 7000 wires, ϕ = 150 μm
Readout electronics	Racks on top of dewar
Scintillation light readout	Yes (also for triggering)

Readout chamber

Baseline assumptions:

*Two wire planes, ±45°, **3 mm pitch**, ϕ 150 μm*

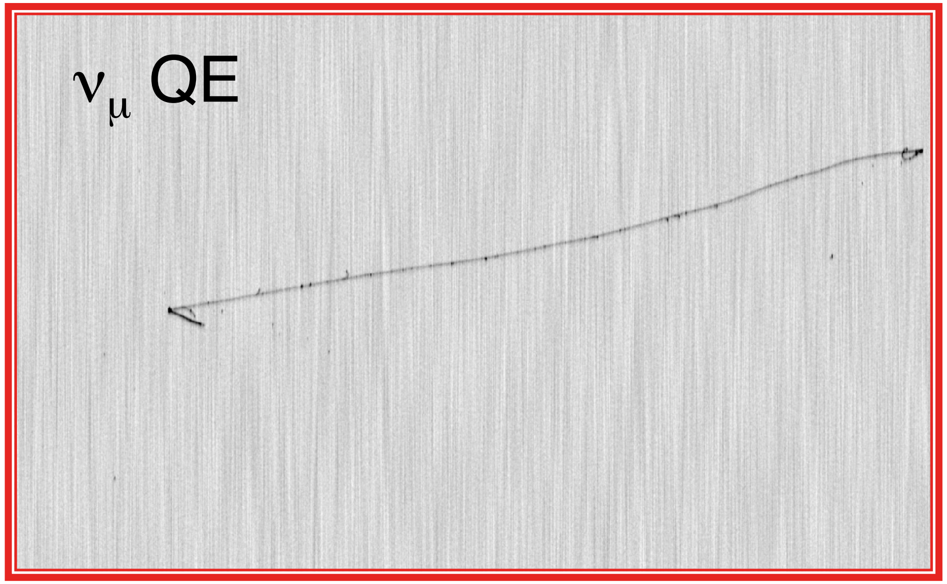


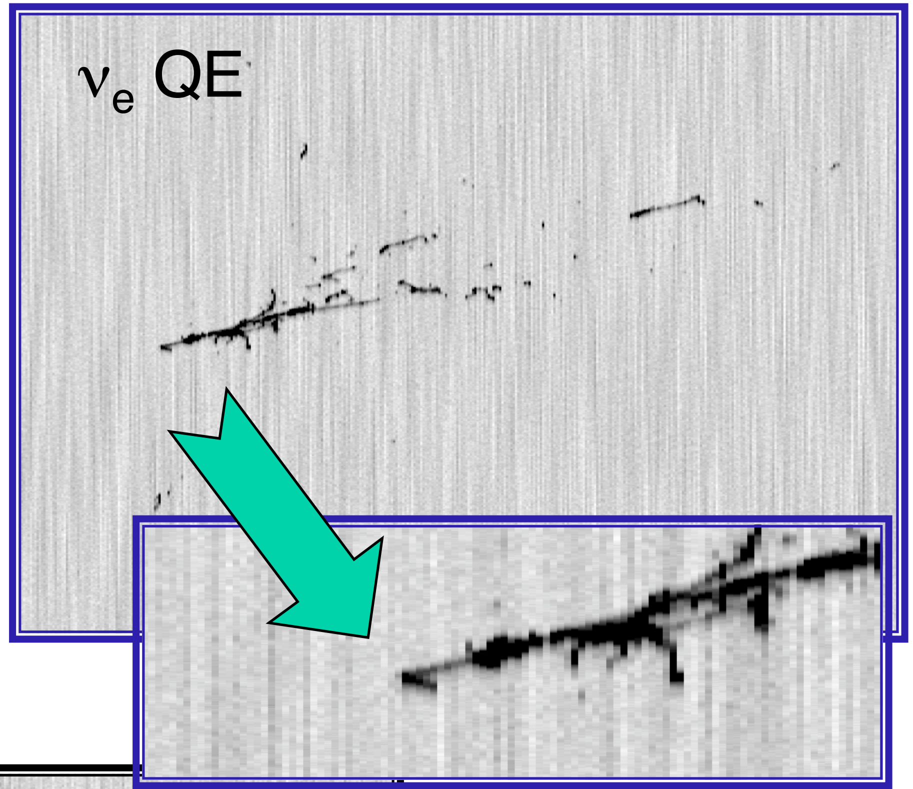
7071 wires in total

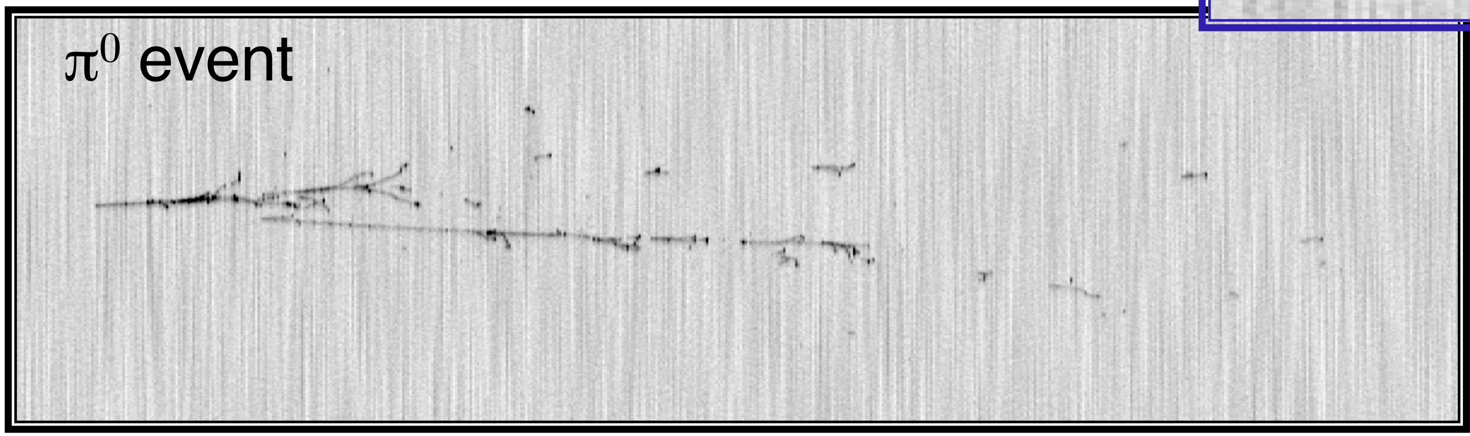
2121 long
1414 short

221 units of 32 wires

Typical events at 1 GeV



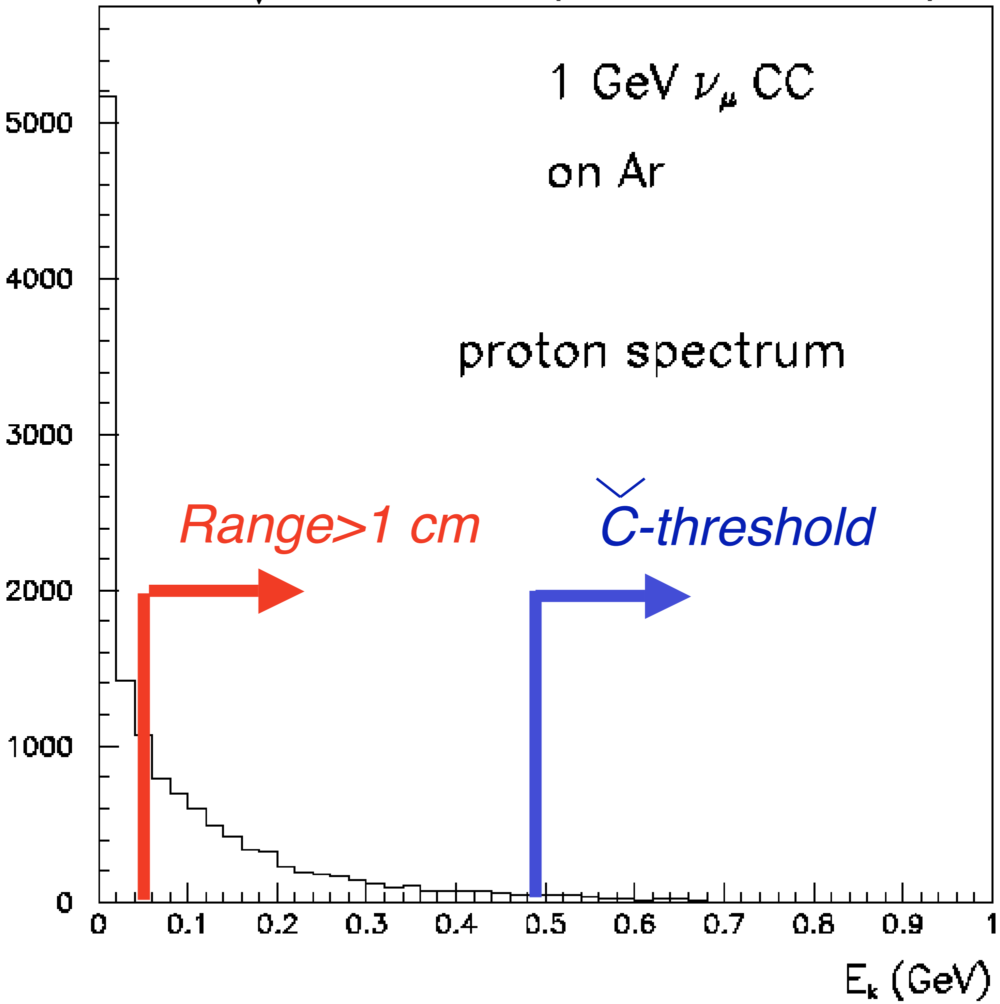




full simulation, digitization, and noise inclusion

Particle detection thresholds

E_ν = 1 GeV (NUX-FLUKA)



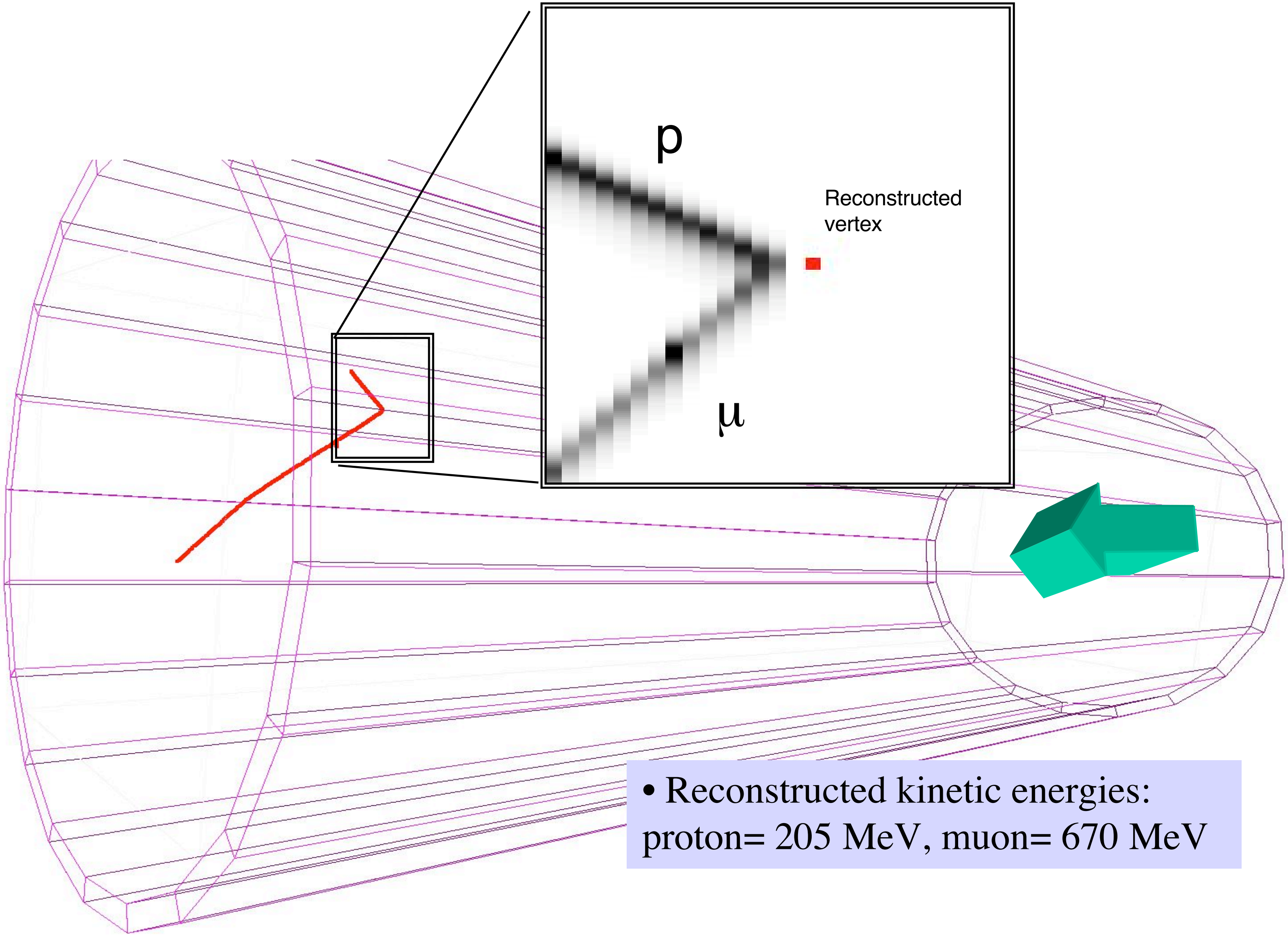
Protons

Kinetic energy T (MeV)	Momentum p (MeV/c)	Range in LAr (cm)
10	43	0.14
40	280	0.93
70	370	4.19
100	446	7.87
300	813	51.9
500	1094	116

Particle	Cerenkov thr. in H_2O MeV/c	range in LAr cm
e	0.6	0.07
μ	120	12
π	159	16
K	568	59
p	1070	110

Automatic reconstruction in liquid Argon TPC

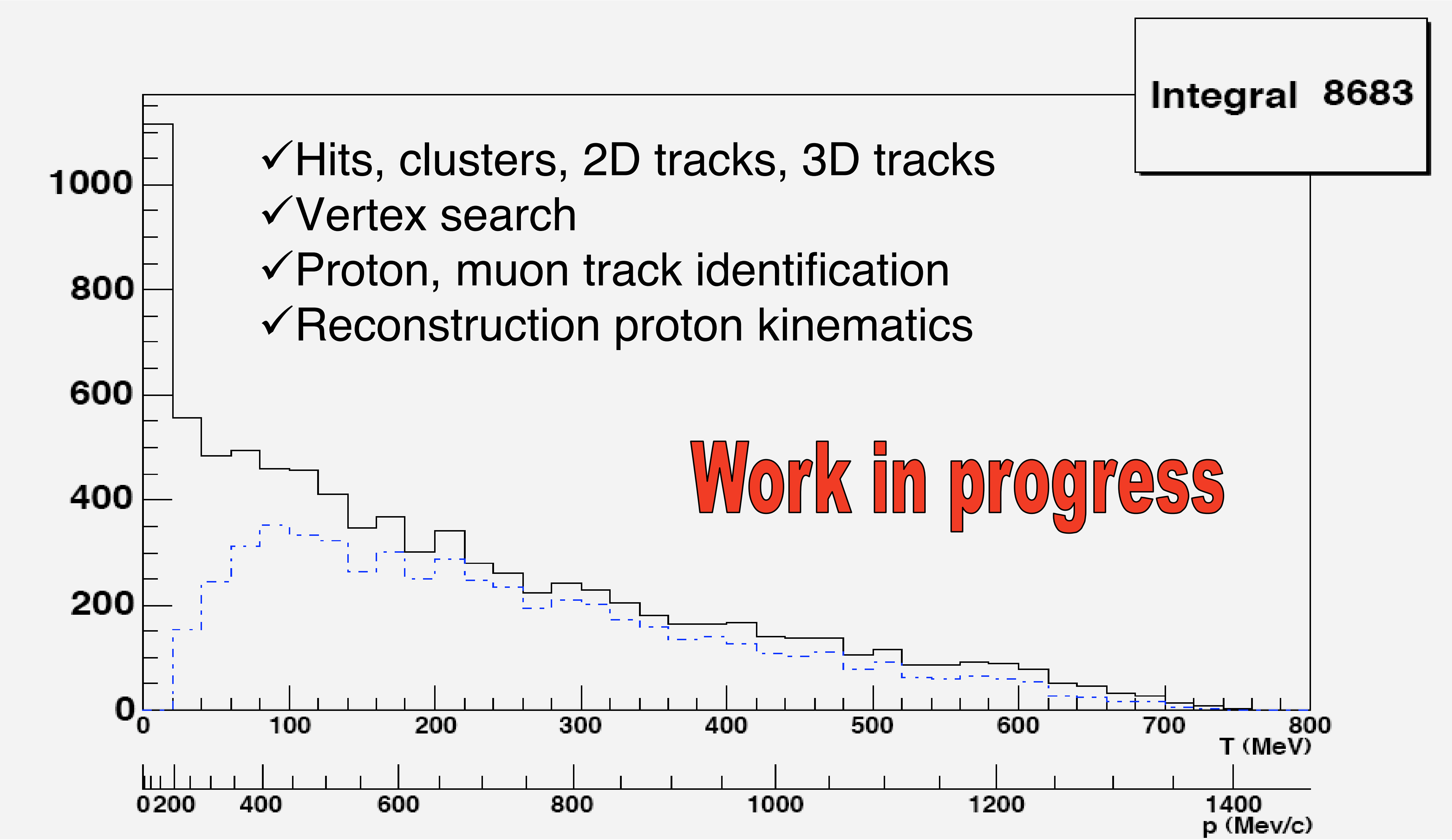
The excellent imaging capabilities allow for fully automatic event reconstruction
⇒ ***high statistics experiment !***



• Reconstructed kinetic energies:
proton= 205 MeV, muon= 670 MeV

Fully automatized event reconstruction

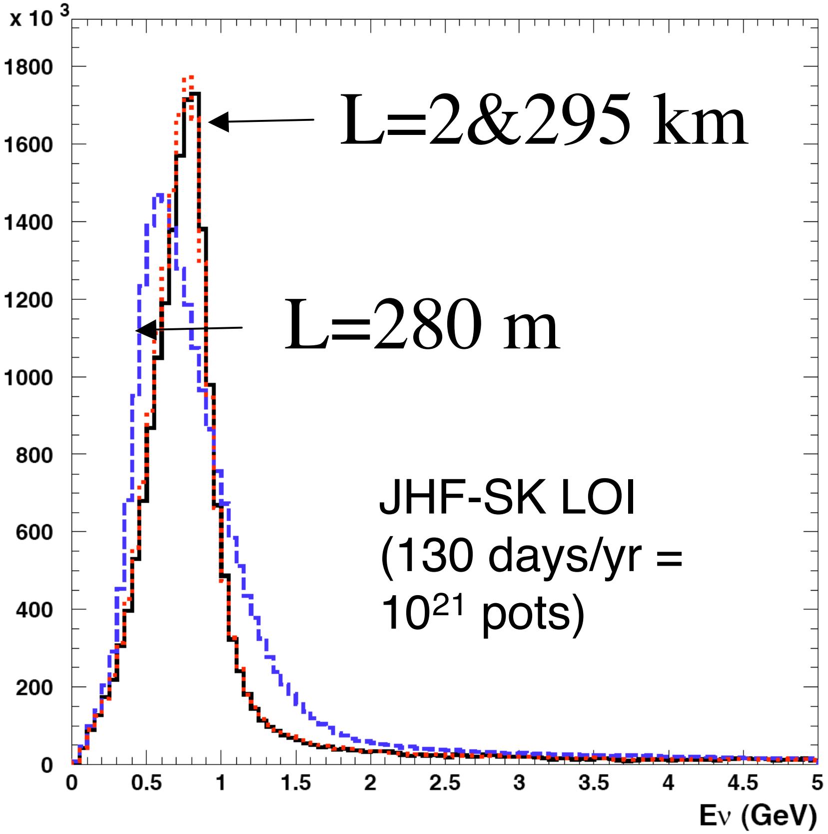
- ✓Hits, clusters, 2D tracks, 3D tracks
- ✓Vertex search
- ✓Proton, muon track identification
- ✓Reconstruction proton kinematics



- **Solid black line: MC kinetic energy of all protons**
- **Blue dashed line: MC kinetic energy of reconstructed protons**

Study for application as a near detector

Newly approved T2K project would provide an ideal & high intensity beam for a ≈100 ton liquid Argon detector



For example: 100 ton @ L=2000 m

Beam	E_{peak}(GeV)	ν_μ	ν_e
OA2	0.7	300000/yr 0.1/spill	5800/yr 45/day

Outlook

- **The liquid Argon TPC imaging has reached a high level of maturity thanks to many years of R&D effort conducted by the ICARUS collaboration. The kton mass scale will be reached at LNGS with the ICARUS T3000.**

- **Today, physics is calling for applications at two different mass scales:**
  - ➥≈100 ktons: proton decay, high statistics astrophysical & accelerator neutrinos
  - ➥≈100 tons: systematic study of neutrino interactions

- **We presented here an overview of our current thinking & activities. We will further pursue work along these lines of thoughts and hope to stimulate feed-back from the community.**