ICARUS detectors
Atmospheric neutrinos working group

André Rubbia
ETH Zürich, Switzerland
ICARUS Collaboration

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Introductory remarks

- Current atmospheric data are extremely convincing, in particular that of SuperK.
- However,
  - ❶ ***Only muon "disappearance" has so far been observed***; *convincing signal for flavor oscillation is the detection of an "appearance" effect*; the presence of matter effects disfavors transitions to sterile neutrinos; since maximal $\nu_\mu \rightarrow \nu_e$ is excluded by current data, this means detecting $\nu_\mu \rightarrow \nu_\tau$ appearance.
  - ❷ Given the tau threshold, ***tau appearance is most easily performed with high energy neutrinos produced at accelerators*** $\Rightarrow$ NUMI(high) or CNGS(optimized for tau)
- Nonetheless, there are new measurements that can further improve our **understanding** of the atmospheric oscillation effect. For example:
  - ❸ ***Detecting $\nu_\mu \rightarrow \nu_\tau$ appearance in the atmospheric beam*** $\Rightarrow$ large exposures to accumulate events at sufficiently high energy, good event reconstruction at high energy and good detector granularity to separate tau decays from backgrounds.
  - ❹ ***Observe the predicted L/E dependence of the flavor oscillation (so far only observed with rather poor resolution)***; in particular, models with "exotic" mechanisms (decay,…) cannot be completely excluded; a convincing signal is the ***observation of at least a full L/E "oscillation"*** which requires sufficient L/E "range" and resolution.

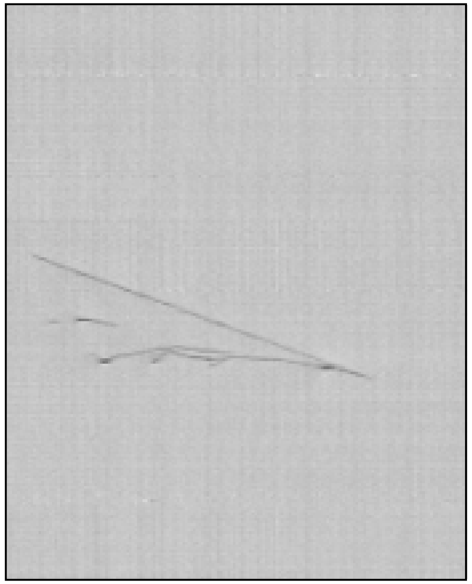
Introductory remarks (II)

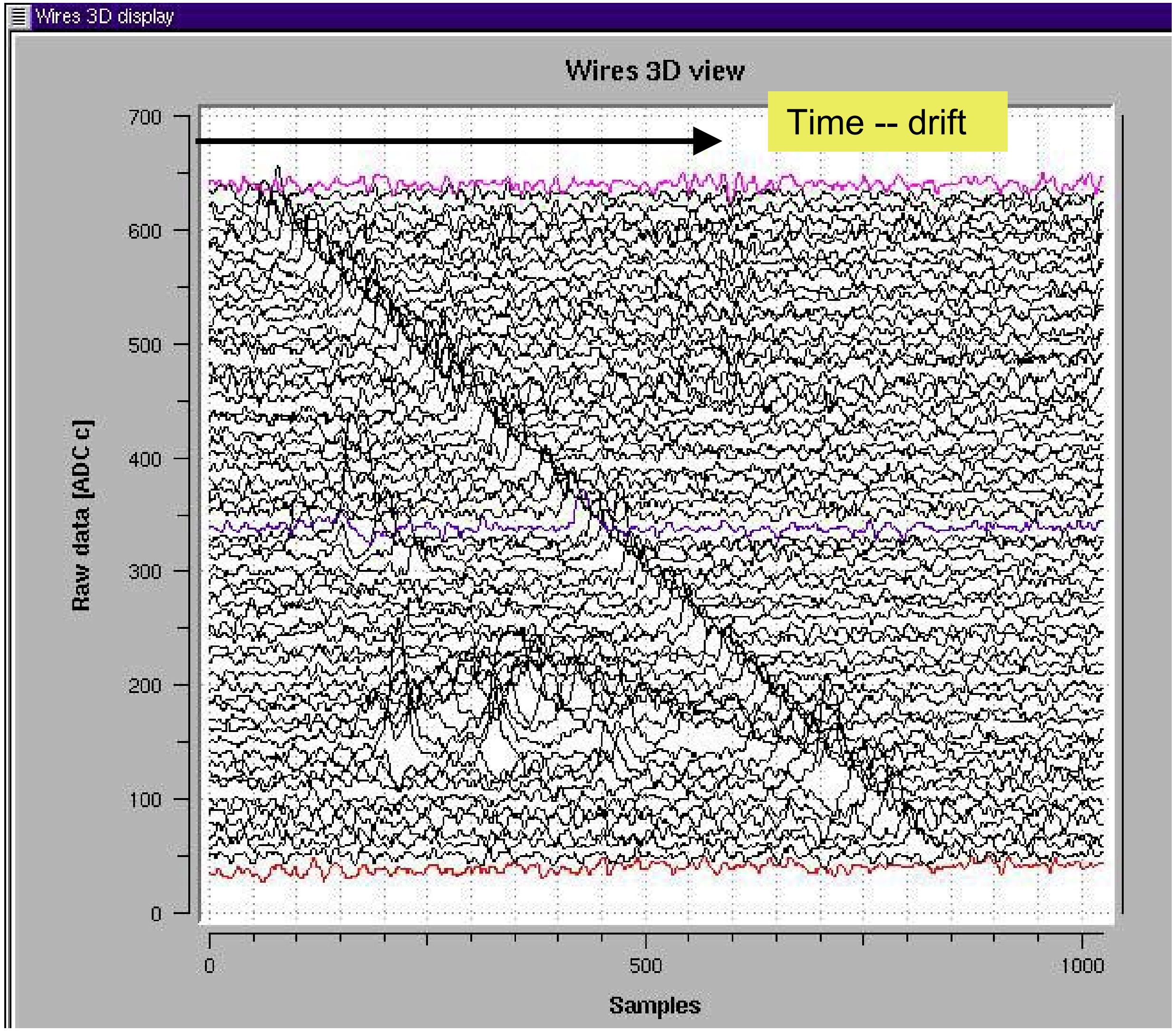
- We expect ICARUS technology to contribute to a better understanding of the atmospheric neutrino phenomenology,
  - ➜ Thanks to its unique performances in terms of ***imaging capabilities***, ***resolution*** and ***precision***
  - ➜ The capability to provide redundant, high precision measurement with ***systematic uncertainties*** of experimental origin ***minimized as much as possible***
  - ➜ Thanks to ***improvements over existing methods*** in
    - **Neutrino event selection**
    - **Identification of muon, electron and tau neutrino flavors**
    - **Identification of neutral currents**
- In addition, the possibility to achieve a ***broad scientific program with the same detector*** is considered fundamental
  - ➜ (a) LBL neutrinos
  - ➜ (b) atmospheric neutrinos
  - ➜ (c) proton decay searches

ICARUS liquid argon imaging TPC

Detector is continuously sensitive, thus allowing to easily simultaneously collect atmospheric, CNGS and other rare events...

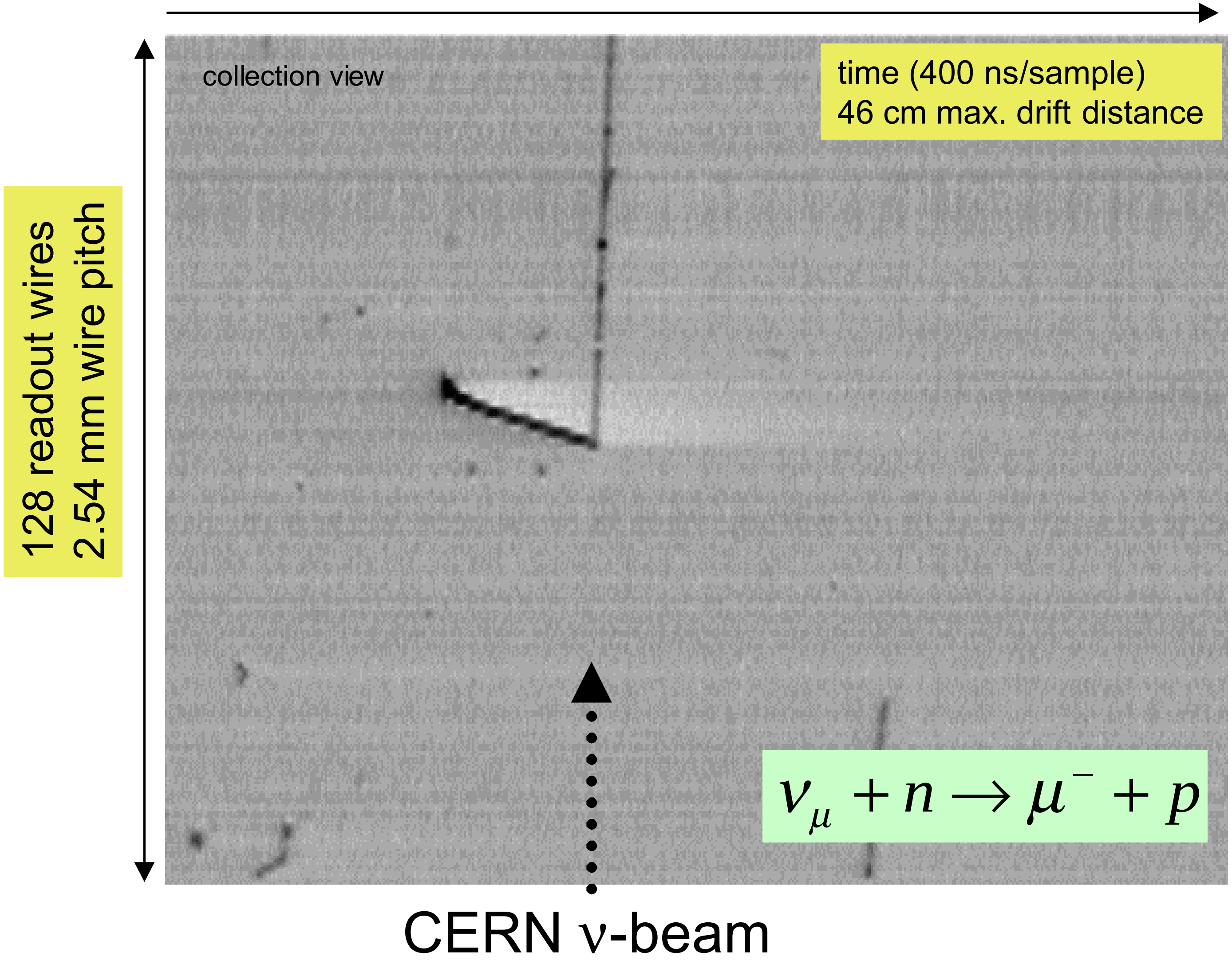
Real event from 15 ton





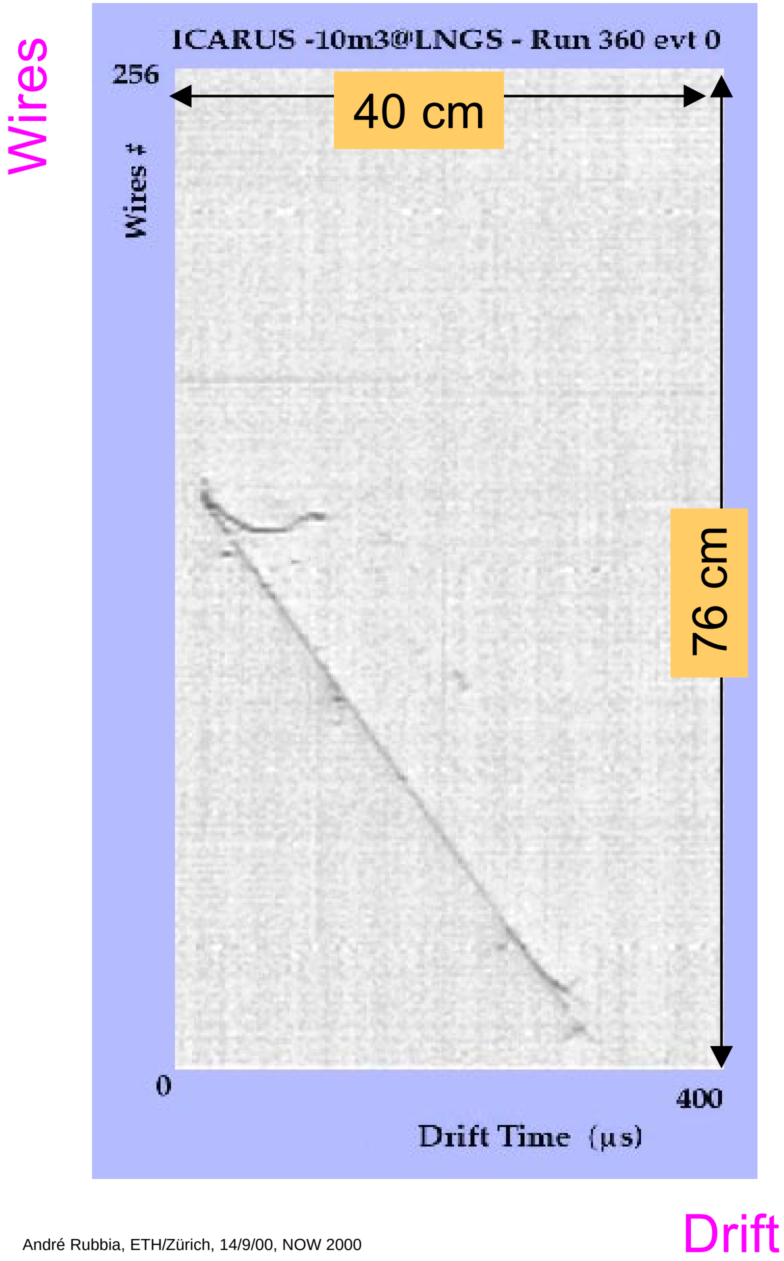
Neutrino event in 50 liter LAr TPC (1998)

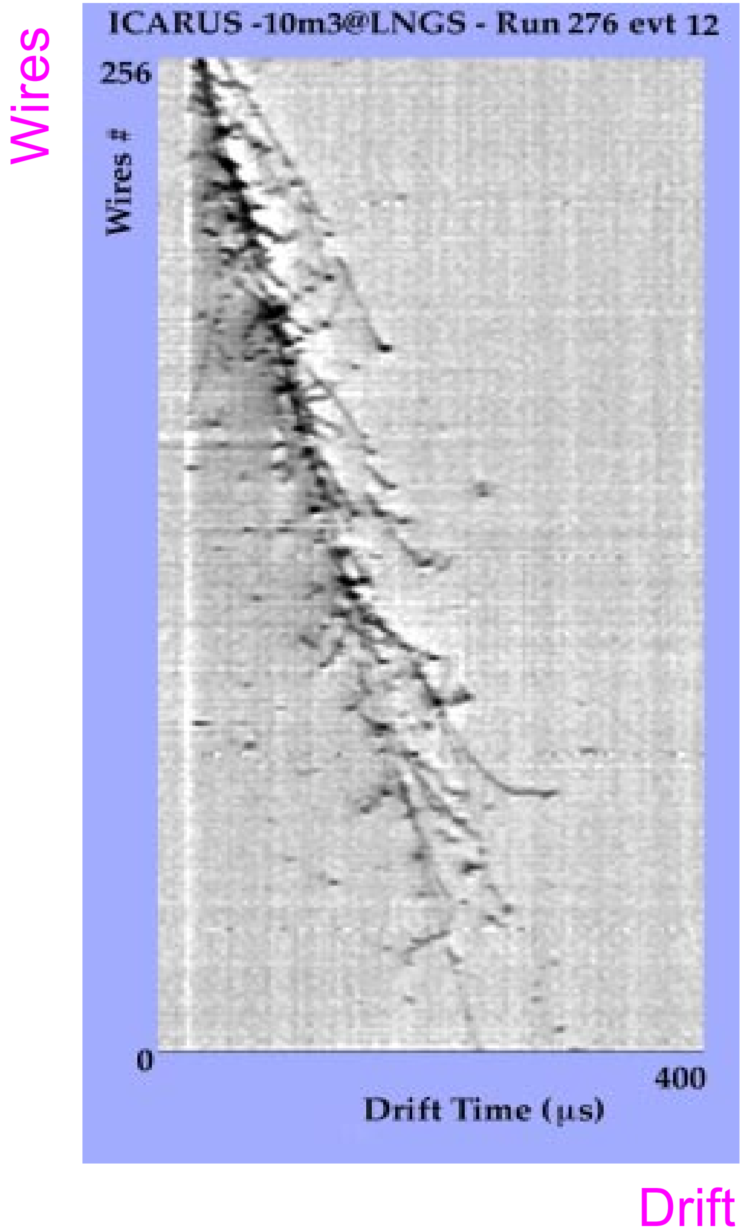
ICARUS-CERN-Milano



(Chamber located in front of NOMAD detector)

Cosmic tracks in 15 ton prototype (2000)





Main characteristics of liquid Argon TPC's

√ **Excellent imaging capabilities**, i.e. a "bubble-chamber" like device

√ Target is fully **isotropic** and **homogeneous**

√ **Tracking device**, capable of **dE/dx measurement**. The high dE/dx resolution allows both good **momentum measurement** and **particle identification** for soft particles

√ **Electromagnetic and hadronic showers are fully sampled**. This allows to have a good energy resolution for both electromagnetic, σ(E)/E≈3/√E(GeV) and hadronic contained showers, σ(E)/E≈20\%/√E(GeV)

√ **Excellent electron identification and e/π^0 discrimination** thanks to the ability to distinguish single and double m.i.p. by ionization and to the bubble chamber quality space resolution

√ Calorimetry allows **full kinematics reconstruction of "contained" events**

√ Muon momentum can be **determined by multiple scattering** $\Delta p/p \approx 20\%$ for long tracks

√ **Continuously sensitive**, **self-triggerable**, **cost effective** and simple to build in **modular form**, sufficiently safe to be located underground.

⇒ ***But physics program requires large mass, of the order of several ktons.***

ICARUS: a graded strategy

- ✯ The partnership of specialized industry already at the level of conceptual design has been crucial to the development of larger detector masses.

Small-scale prototypes → **15 ton** → **2x300 ton** ⇢ **1400 ton** ⇢ **?**

(2x300 ton) ≈2 m max. drift; 4 x 4 m^2 cross section

(1400 ton) ≈4 m max. drift; 8 x 8 m^2 cross section

Full test expected before end of 2000; realistically tracks expected beginning 2001

Cooperation with specialized industries:

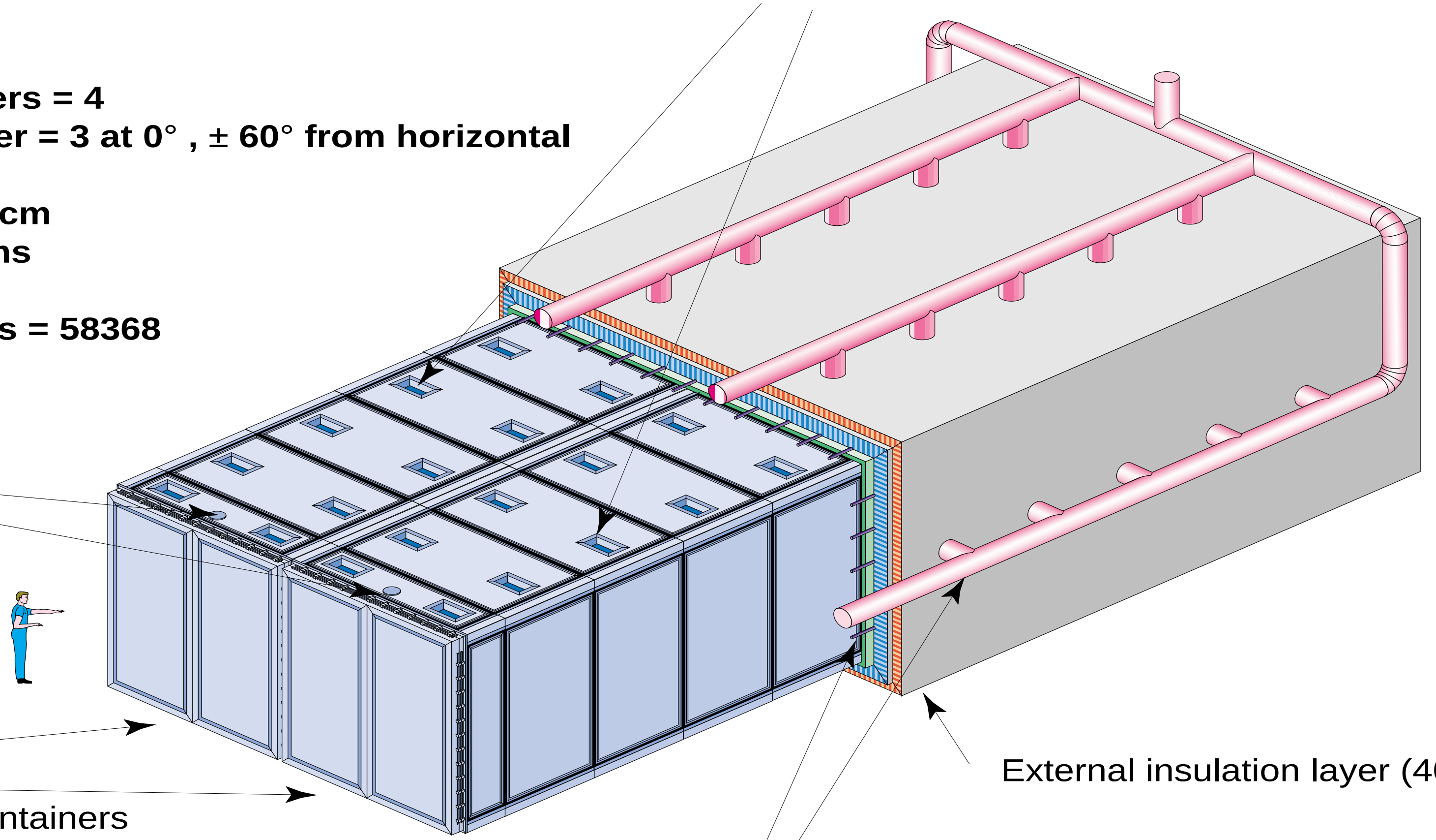
- ➨ **Air Liquide** for Cryostat and Argon purification
- ➨ BREME Tecnica for internal detector mechanics
- ➨ CAEN for readout electronics

The ICARUS T600 module

Under construction

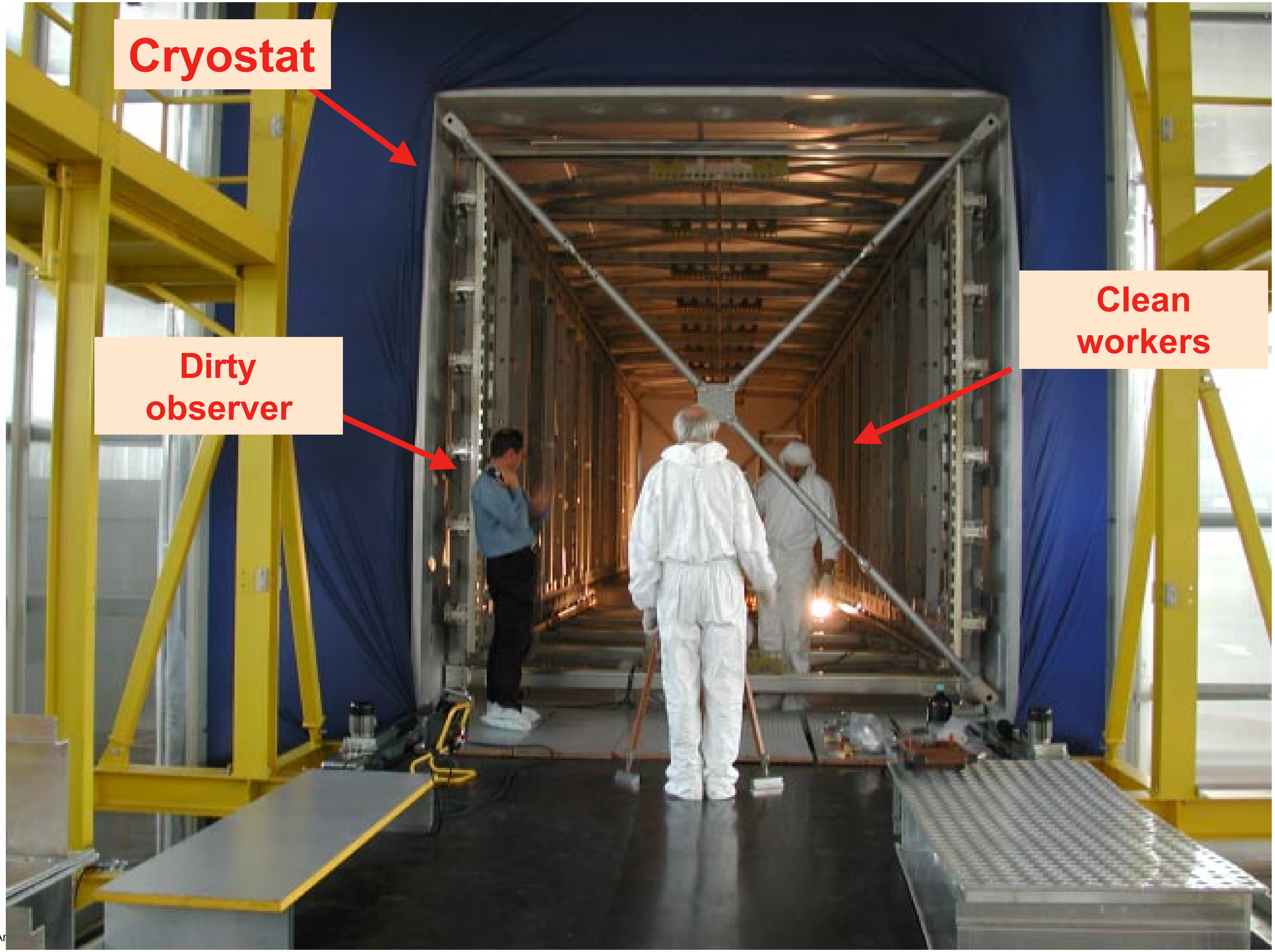
Number of independent containers = 2
Single container Internal Dimensions: Length = 19.6 m , Width = 3.9 m , Height = 4.2 m
Total (cold) Internal Volume = 534 m^3
Sensitive LAr mass = 476 ton

Number of wires chambers = 4
Readout planes / chamber = 3 at 0° , ± 60° from horizontal
Maximum drift = 1.5 m
Operating field = 500 V / cm
Maximum drift time ≈ 1 ms
Wires pitch = 3 mm
Total number of channels = 58368



André Rubbia, ETH/Zürich, 14/9/00, NOW 2000

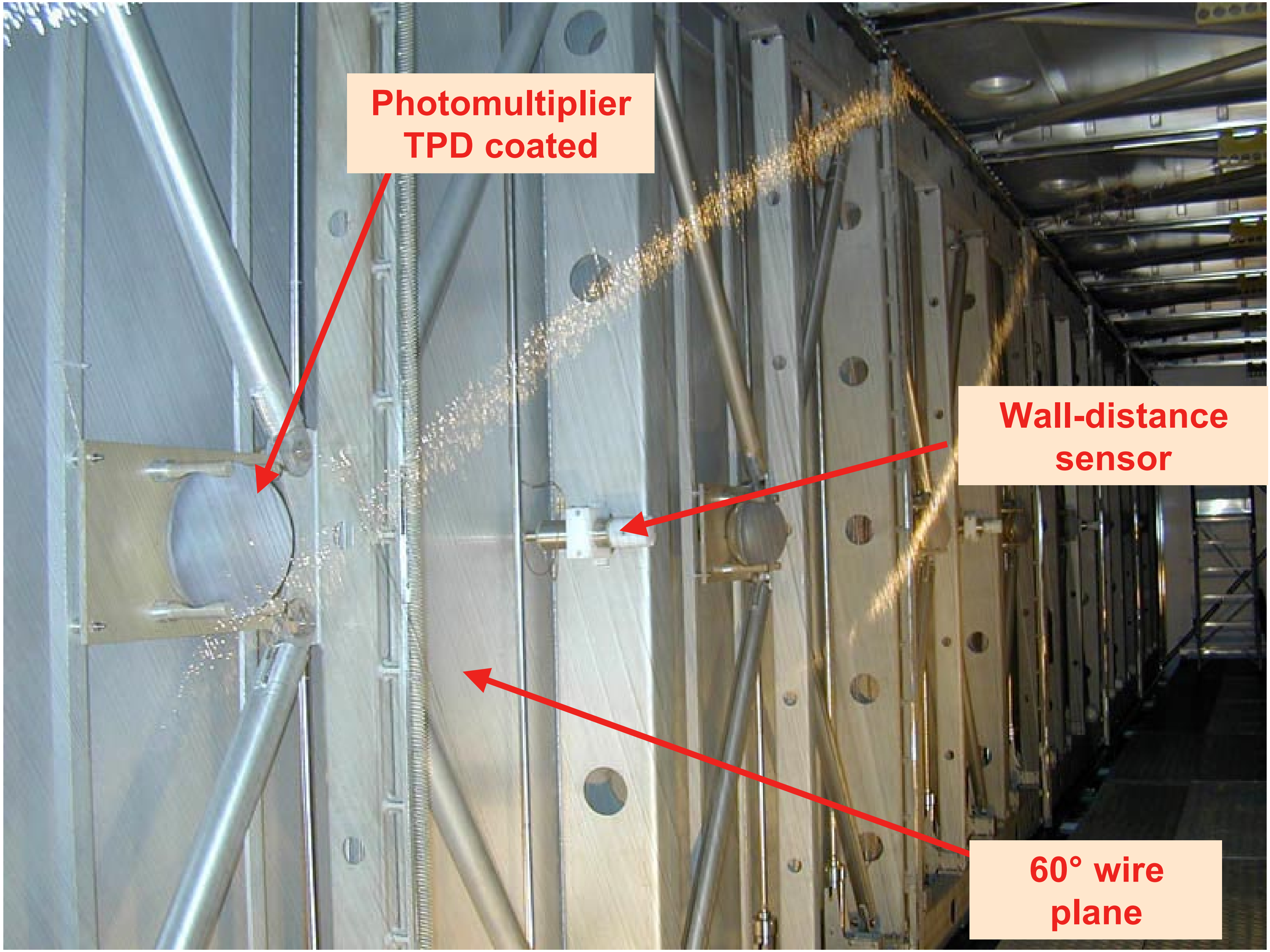
Assembly of the T600 internal detector (clean room)



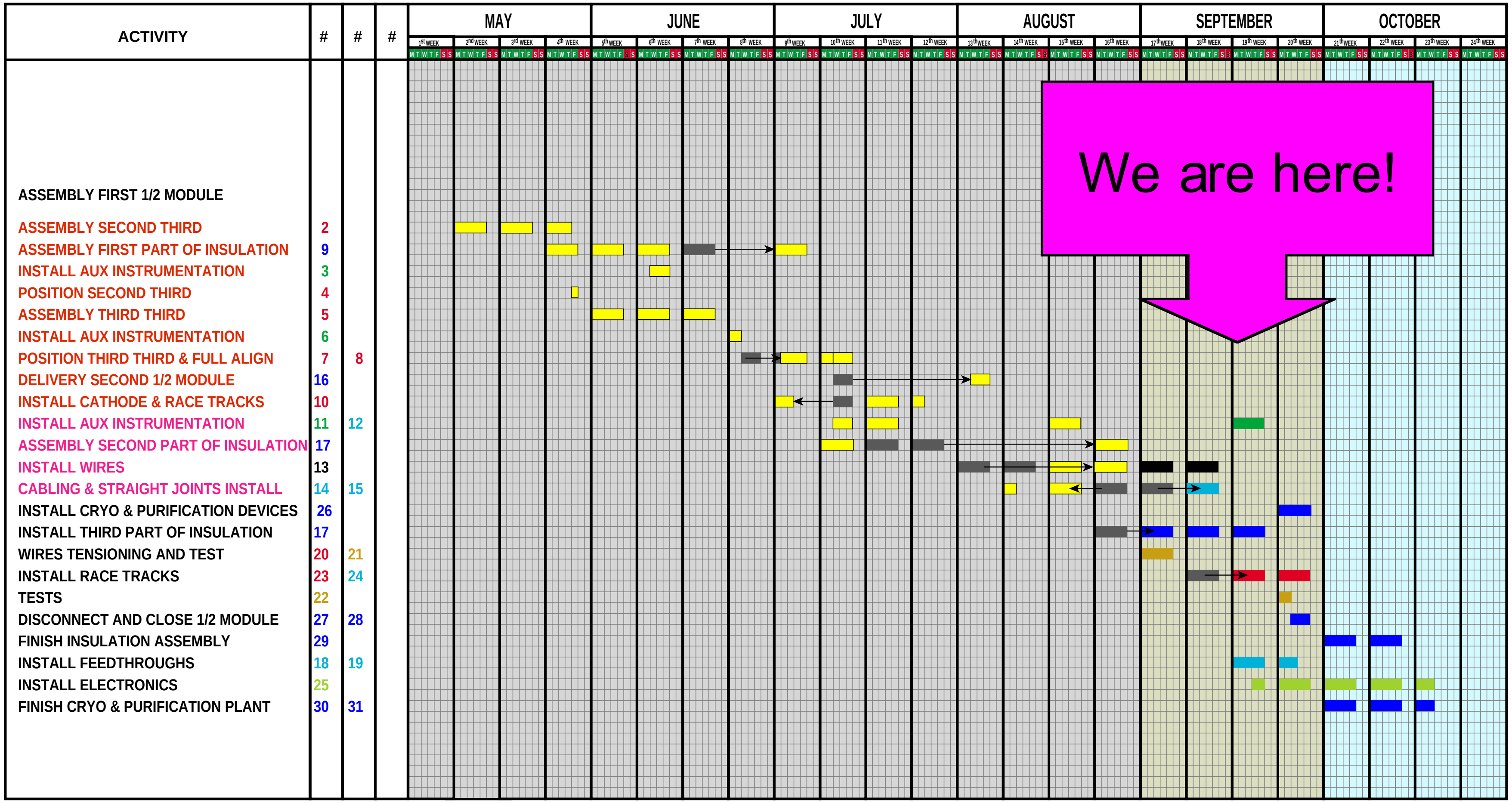
Mounting inside T600 detector (clean room)

Wire installation in T600 internal detector

T600 internal detector (clean room)



Planning for the assembly of the first half-module
- Status at the end of August 2000 -



Color Scheme:

- Completed
- Moved
- Cryogenics & Purification
- Internal Detector Mechanics
- Electronics
- Auxiliary Instrumentation
- Wires Positioning
- Tests

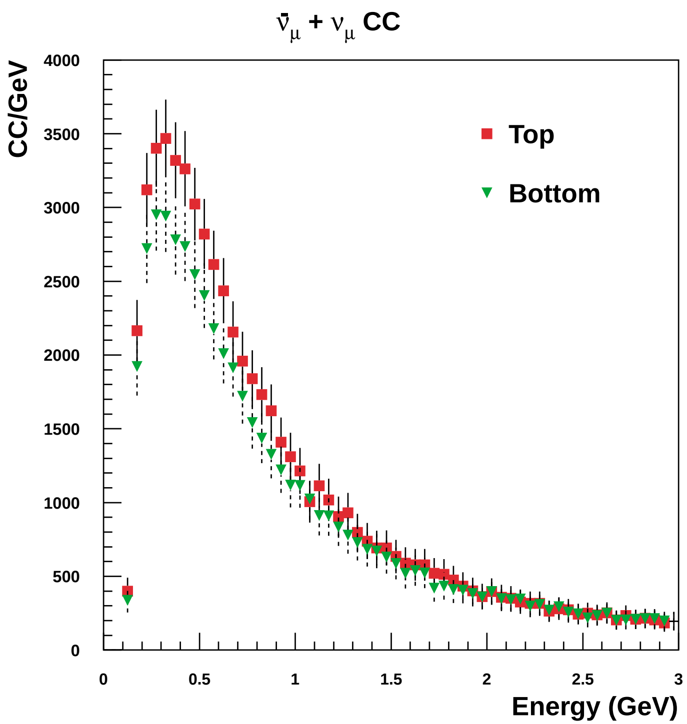
Physics considerations

What we get for 5 ktons:

- **Number of targets for nucleon stability:**
  - – 2×10^{34} nucleons $\Rightarrow$ $\boldsymbol{\tau_p (10^{32}\ \text{years}) > 6 \times T(\text{yr})} \times \varepsilon$ @ 90 C.L.
- **Atmospheric:**
  - – **1000** atm CC events / year
  - – $\approx$**5** ν_τ CC /year from oscillations
- **Solar:**
  - – **8500** solar neutrinos / year @ E > 5 MeV
- **CERN–CNGS:**
  - –**13600** ν_μ CC per year @ L = 730 km
- **Neutrino factory:**
  - – **1200** ν_μ CC per 10^{20} μ @ L = 7400 km

Atmospheric neutrino rates

- Flux: 3D calculation, Battistoni et.al., hep-ph/9907408
- Cross-sections: „NUX“, ICARUS Collab.



Rates per kt/year on Argon

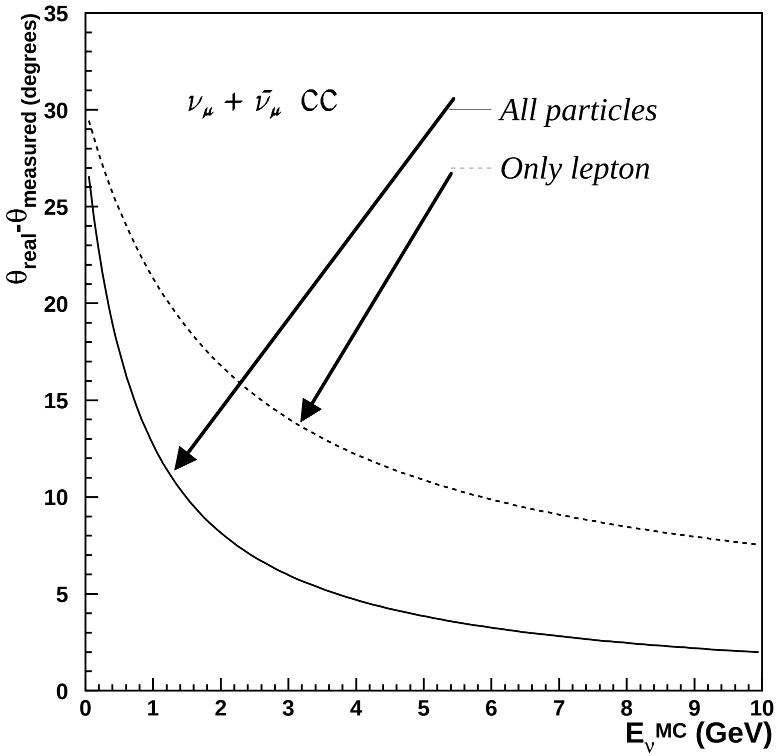
Process	elastic	single-π	inelastic	Total	<E> (GeV)
ν_μ CC	66.7	15.9	24.4	107.0	2.36
$\bar{\nu}_\mu$ CC	12.2	5.3	9.8	27.2	3.34
ν_e CC	39.4	8.4	12.1	59.9	1.60
$\bar{\nu}_e$ CC	5.4	2.1	4.2	11.7	2.36
ν NC	42.9	8.6	13.2	64.8	1.94
$\bar{\nu}$ NC	21.1	3.5	5.0	29.6	2.00

Process	Exposure		
	5 kton$\times$ year	20 kton$\times$year	50 kton$\times$ year
ν_μ CC	535	2140	5350
$\bar{\nu}_\mu$ CC	135	545	1350
ν_e CC	300	1200	3000
$\bar{\nu}_e$ CC	59	235	585
ν NC	325	1300	3250
$\bar{\nu}$ NC	150	590	1500
	1500	***6000***	***15000***

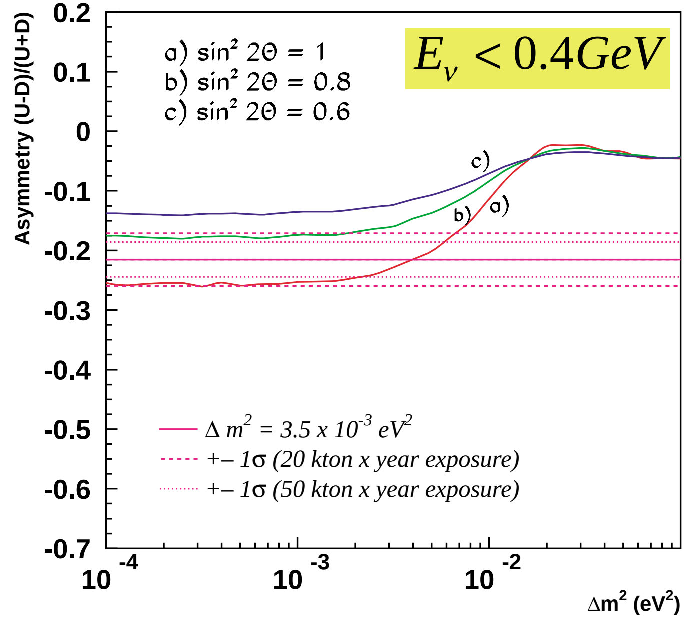
Up/down asymmetry

Benefit from good angular resolution on incoming neutrino direction thanks to reconstruction of all final state particles

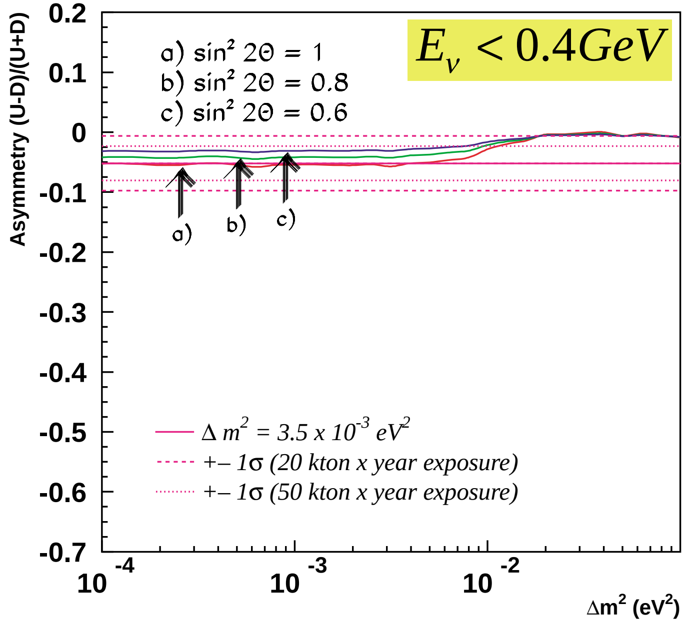
$$\theta_{real} - \theta_{measured}$$



All particles used



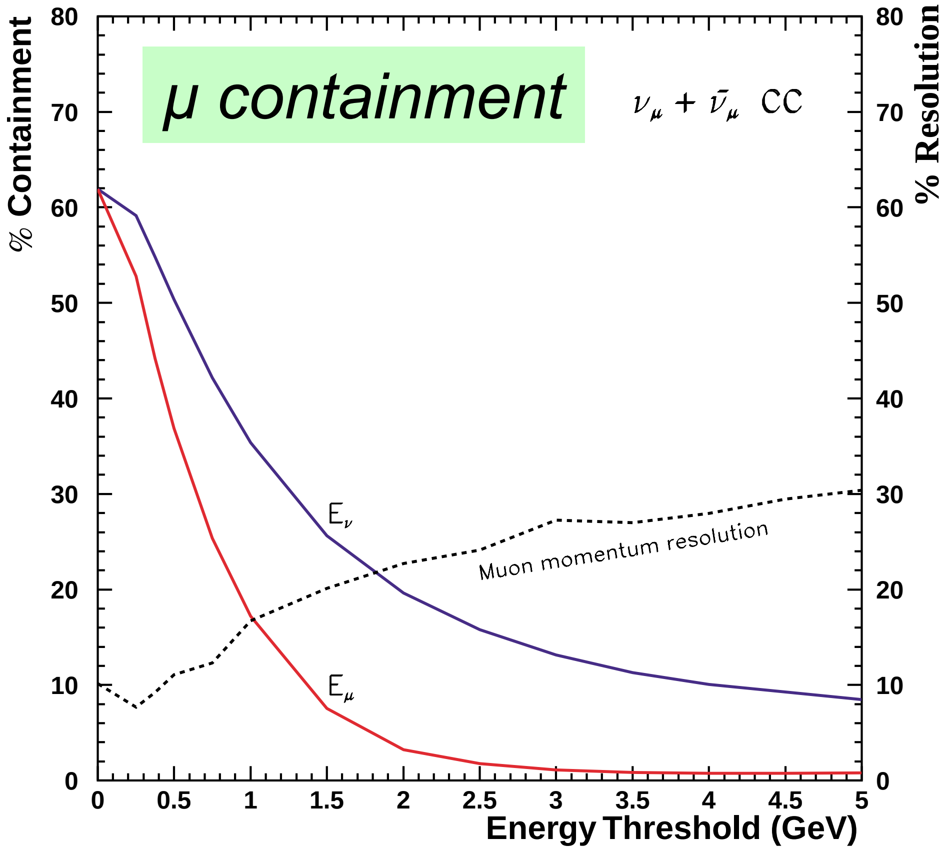
Only lepton used



Important at low energy and to determine mixing angle!

The L/E distribution

- We benefit from
  - → Excellent energy and angular resolution of final state hadrons
  - → Excellent measurement of lepton (electron by shower and muon by multiple scattering)
  - → Overall, very good determination of incoming neutrino L and E



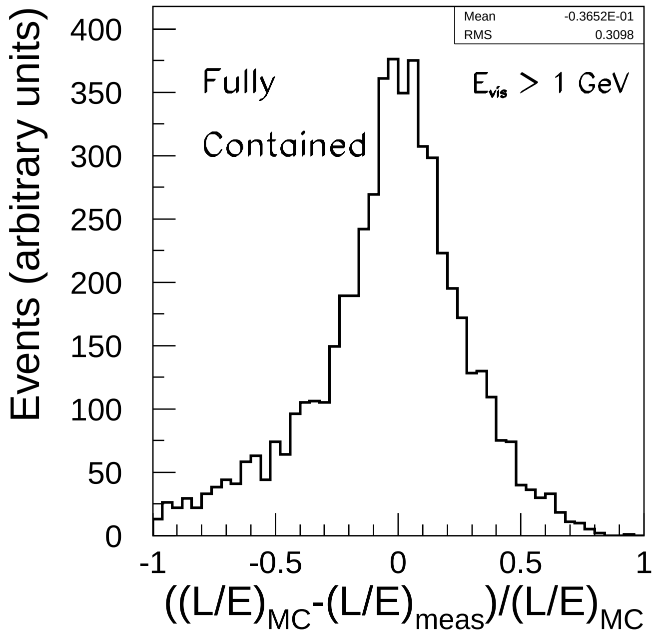
- The selection of events is **clean** and **non-biased**
- The selection is **identical for electron and muon** events ⇒ study both ν_e and ν_μ CC samples

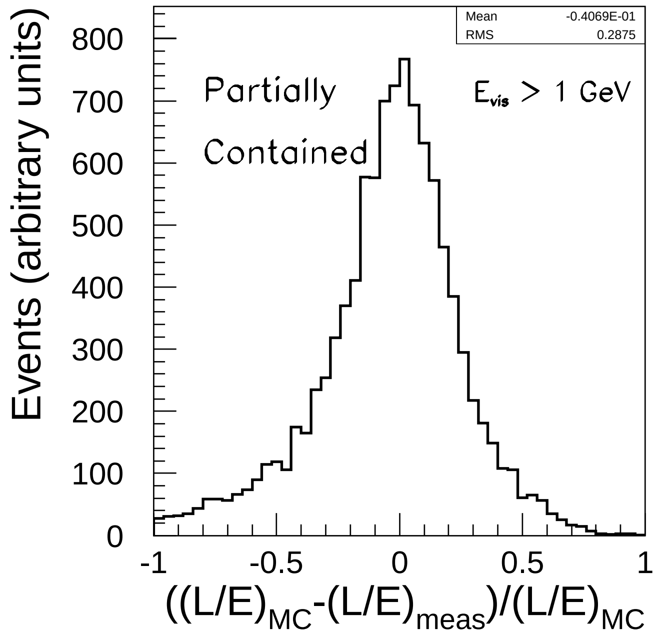
Reconstructed L/E resolution

- Selection cuts to suppress effect of Fermi motion
  - → **$E_{visible}$ > 1 GeV   (efficiency≈40%)**

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

Full simulation





$\nu_\mu + \bar{\nu}_\mu$ CC

Events/year

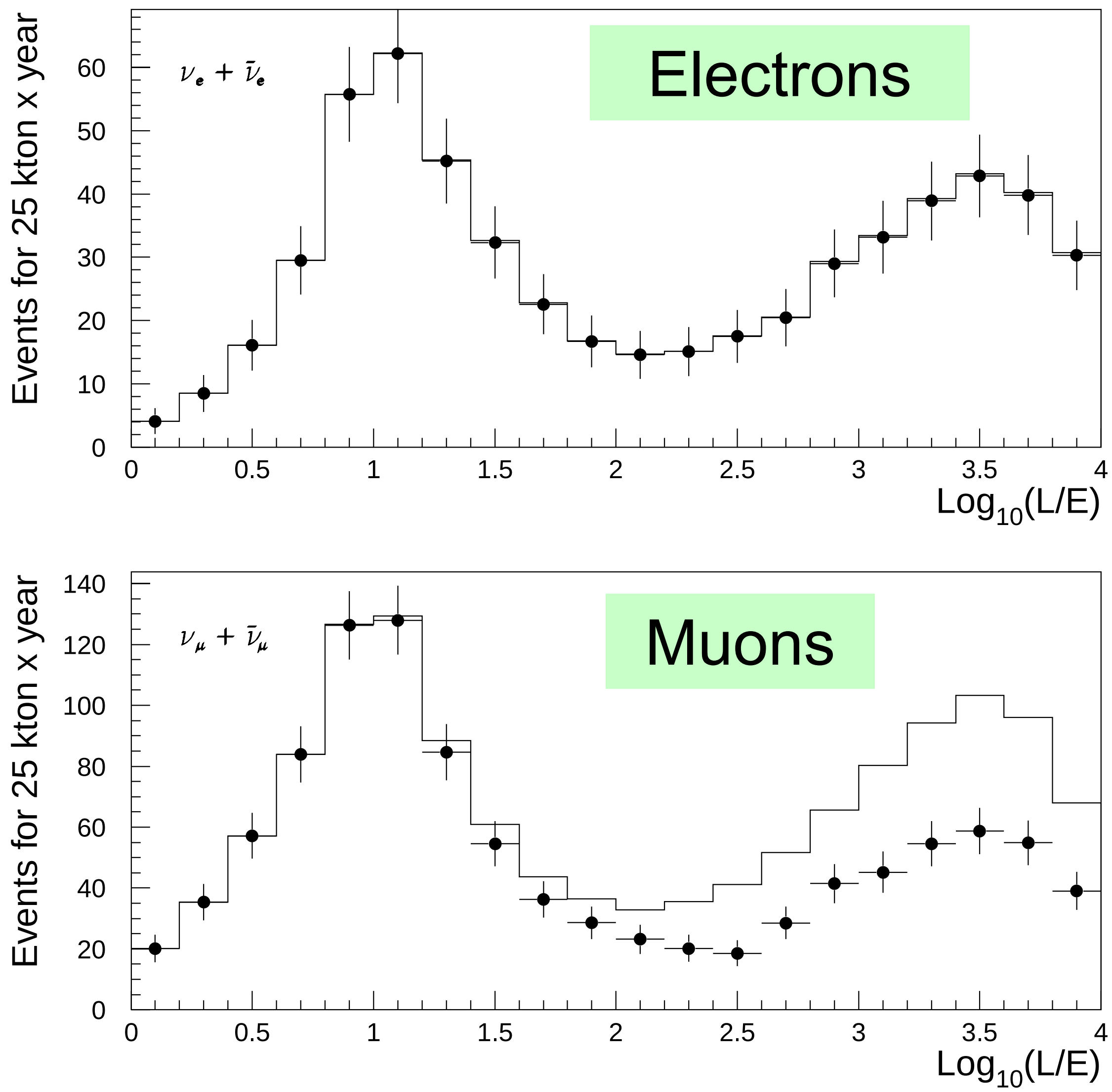
ν_μ CC	**380**
ν_e CC	**160**
ν NC	**400**

L/E distribution: electrons and muons

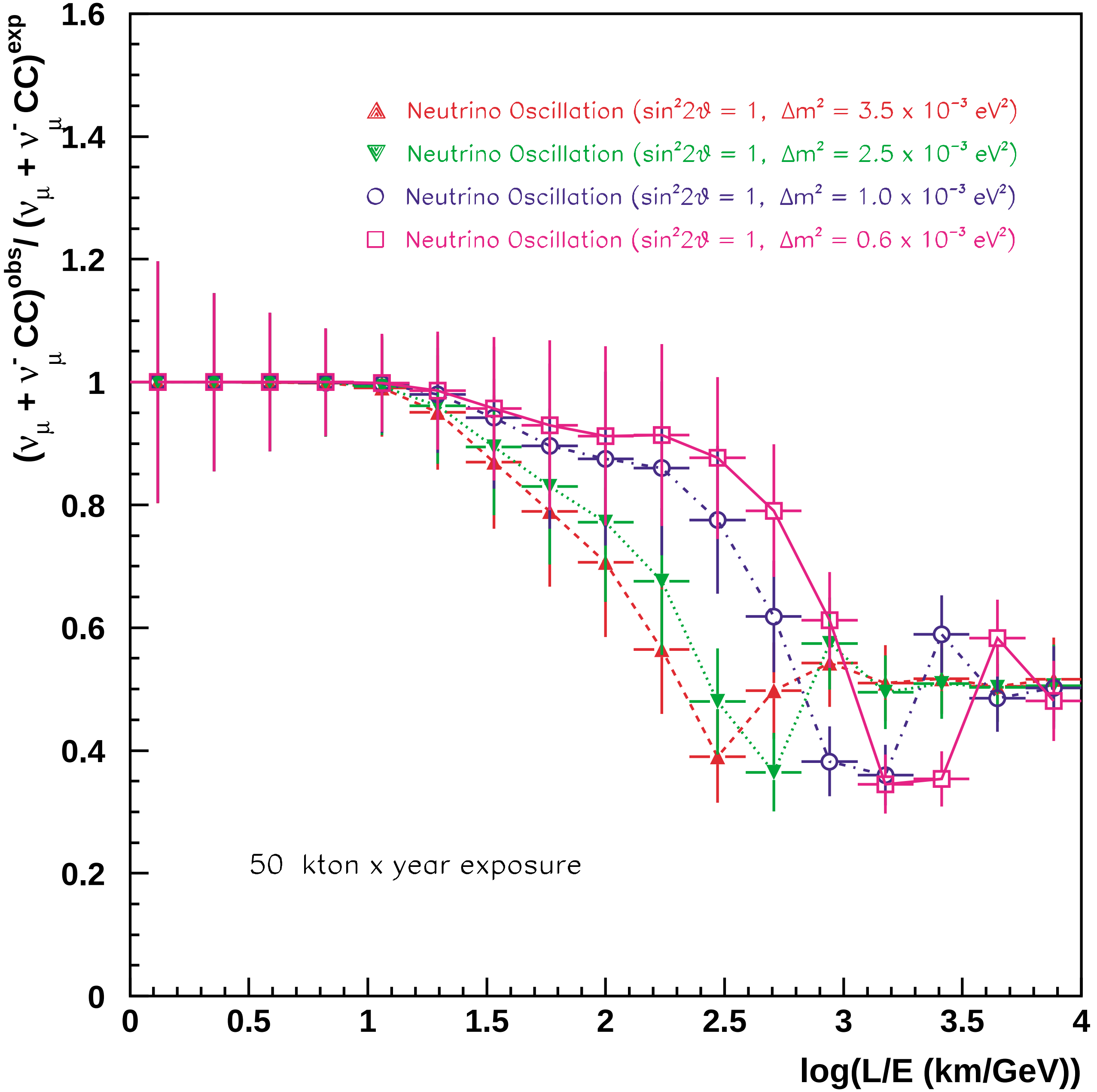
- Oscillation parameters:
  - → $\Delta m^2_{32} = 3.5 \times 10^{-3}$ eV^2
  - → $\sin^2 2\Theta_{23} = 0.9$
  - → $\sin^2 2\Theta_{13} = 0.1$

- ***Electron sample can be used as a reference for no oscillation case***

25 kt year



ν_μ disappearance – L/E distribution



50 kt year

Search for „Tau-like“ atm events (I)

- Discriminate between $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_s$ oscillations by looking for ***excess of „neutral-current-like“ events produced by upward neutrinos*** (large tau branching into hadronic channels)

$$\nu_\mu \xrightarrow{\text{oscillation}} \nu_\tau \rightarrow \tau + X$$

$$\tau \rightarrow \begin{cases} e\nu\nu & 18\% \\ \mu\nu\nu & 18\% \\ h^- n h^0 \nu & 50\% \\ h^- h^+ h^- n h^0 \nu & 14\% \end{cases}$$

- Search for ***ν_τ CC at high energy*** (tau threshold)

$\nu_\tau + \bar{\nu}_\tau$ CC (NUX, Fluka 3D flux)				Relative to Fluka 1D	Relative to Bartol
	Rate (kton× year)				
Δm^2 (eV^2)	DIS	QE	Sum		
5×10^{-4}	0.11	0.11	0.22	0.96	0.81
1×10^{-3}	0.28	0.18	0.46	1.02	0.84
3.5×10^{-3}	0.59	0.21	0.80	1.00	0.81
5×10^{-3}	0.64	0.24	0.88	1.01	0.80
1×10^{-2}	0.70	0.20	0.90	0.99	0.78

≈1 ν_τ CC/kt/year

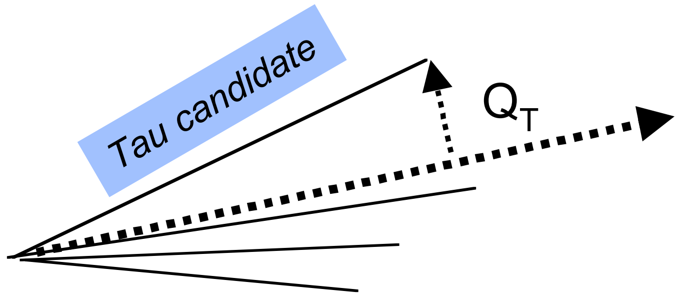
Search for „Tau-like“ atm events (II)

- ✰Consider ***tau decays into hadronic final states (Br ≈ 64%)***
- ✰Compare ***upward/downward neutral currents events*** at high energy
  - ✰Requires good discrimination of NC event direction
- ✰Use the kinematical feature of tau decays to improve over background

Event above an energy cut
$\Delta m^2 = 3.5 \times 10^{-3}\ eV^2$

Cut	ν NC top	τ bottom
$E_{visible} > 1$ GeV	327	22
$E_{visible} > 2$ GeV	150	22
$E_{visible} > 3$ GeV	95	21
$E_{visible} > 4$ GeV	67	20
$E_{visible} > 5$ GeV	51	17
$E_{visible} > 6$ GeV	40	16
$E_{visible} > 7$ GeV	33	14
$E_{visible} > 8$ GeV	28	13
$E_{visible} > 9$ GeV	23	12
$E_{visible} > 10$ GeV	21	11

50 ktxyear

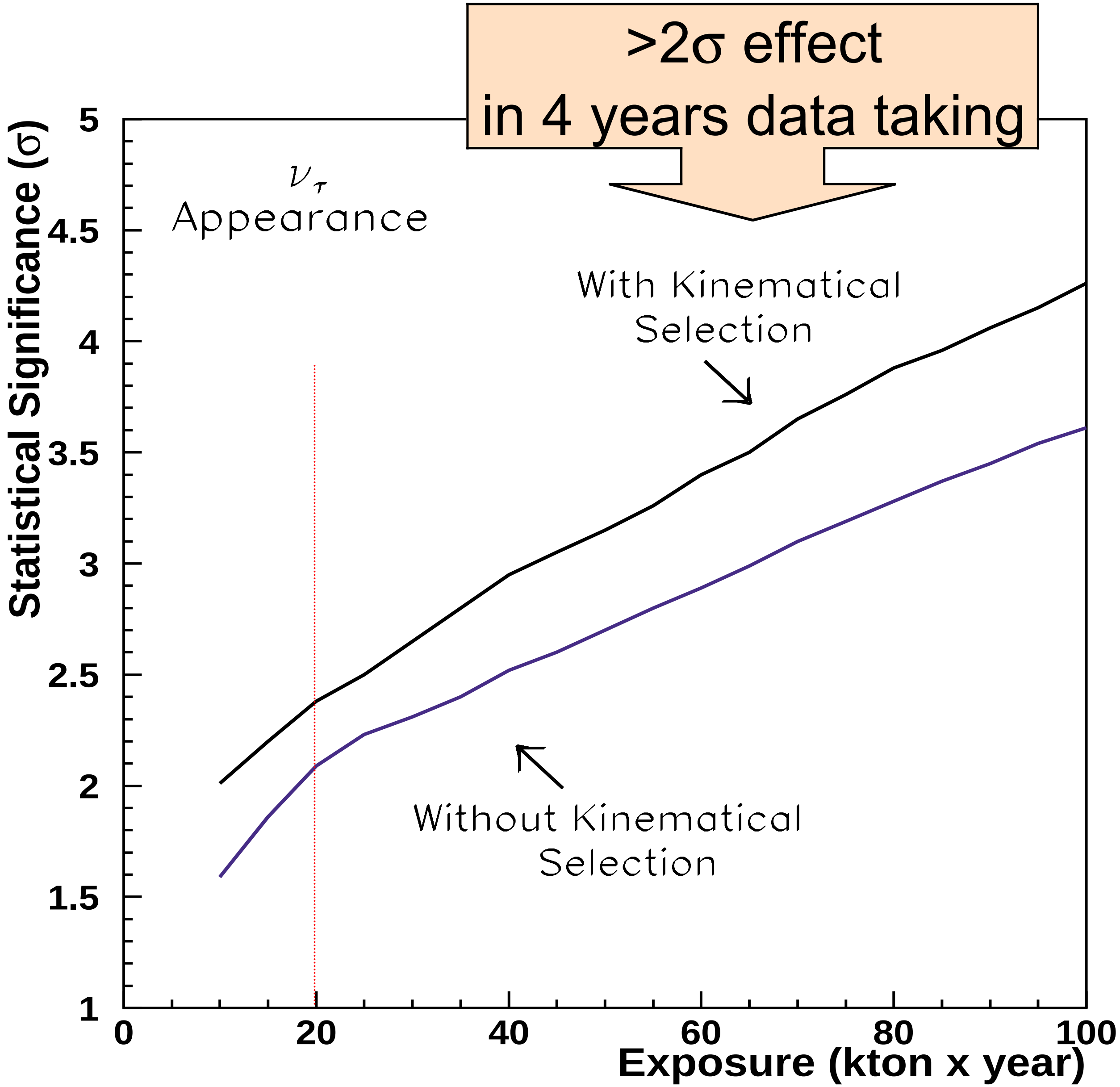


Candidate kinematical isolation:
Q_T = transverse momentum relative to total momentum

Q_T and Evisible combined by likelihood techniques

Search for „Tau-like“ atm events (III)

- Statistical excess for evidence of taus as a function of exposure
- Discrimination between sterile and tau hypothesis more stringent
- Analysis shown with and without kinematical selection



Conclusion

- We are reaching a ***fundamental milestone*** of the liquid Argon imaging TPC technology
- The T600 is expected to realistically produce its first tracks within the ***beginning of next year***
- ***If successful***, it is to be expected that more massive Liquid Argon detectors will be envisaged & constructed
- They will ***provide unique opportunities*** to further detect and study the atmospheric neutrino oscillation phenomenon