Detector Basics III

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Summary of lecture II

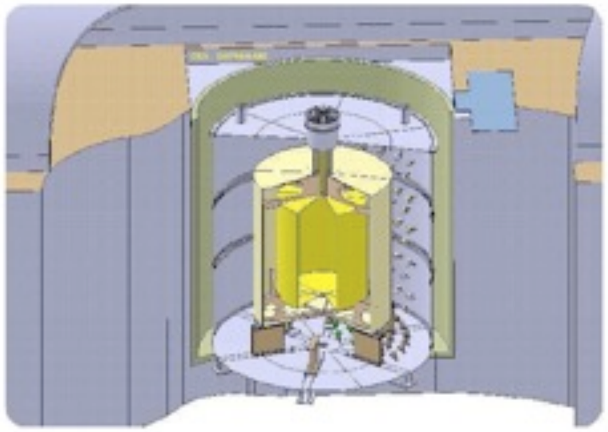
	Cherenkov counters	**Tracking calorimeters**
	unsegmented	segmented
	requires low rates, relatively low multiplicity events	can operate at high rates and relatively high multiplicity events
	cannot be magnetized	can be magnetized
	best at ~1 GeV and below	best at ~1 GeV and above
	solar, super-nova, atmospheric, accelerator neutrinos	super-nova, atmospheric, accelerator, accelerator neutrinos
	e-like/mu-like particle ID	e/γ/μ/π/p separation possible
	muons, pions, protons potentially below threshold	all kinetic energy visible in principle
electron neutrino efficiency	40% (@ 0.7 GeV)	35% (@ 2 GeV)
NC rejection	90%	99%
channel counts	0.5 channels/kt [SK]	20 channels/kt [NOvA]
<cost/kt>	~$8M [SK,2009]	~$15M [NOvA,2009]

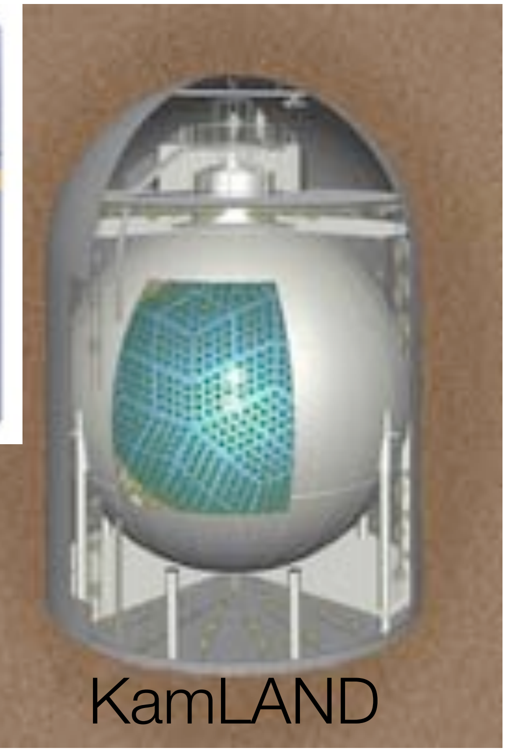
Today: A bit of a mash up of some remaining topics

- Low energy scintillator detectors
- Tau neutrino detection
- Time projection chambers

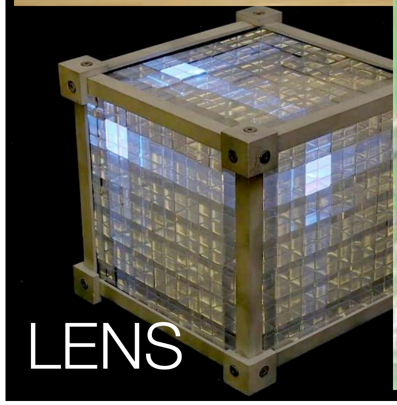
Unsegmented liquid scintillator detectors

- Large volume of liquid scintillator viewed by PMT’s
- Anti-electron neutrino detection from reactors at ~3.5 MeV
- Electron neutrino detection via elastic scattering from Sun at 0.7 MeV
- Scintillator allows for larger light collection (~200 photons/MeV) than water
- Used for detection of anti-neutrinos from reactor experiments (CHOOZ/KamLAND/Double CHOOZ/Daya Bay/Reno) and neutrinos from the Sun (Borexino)
- At these low energies the name of the game is background suppression from naturally occurring radioactive sources


Double CHOOZ


KamLAND


Borexino


LENS

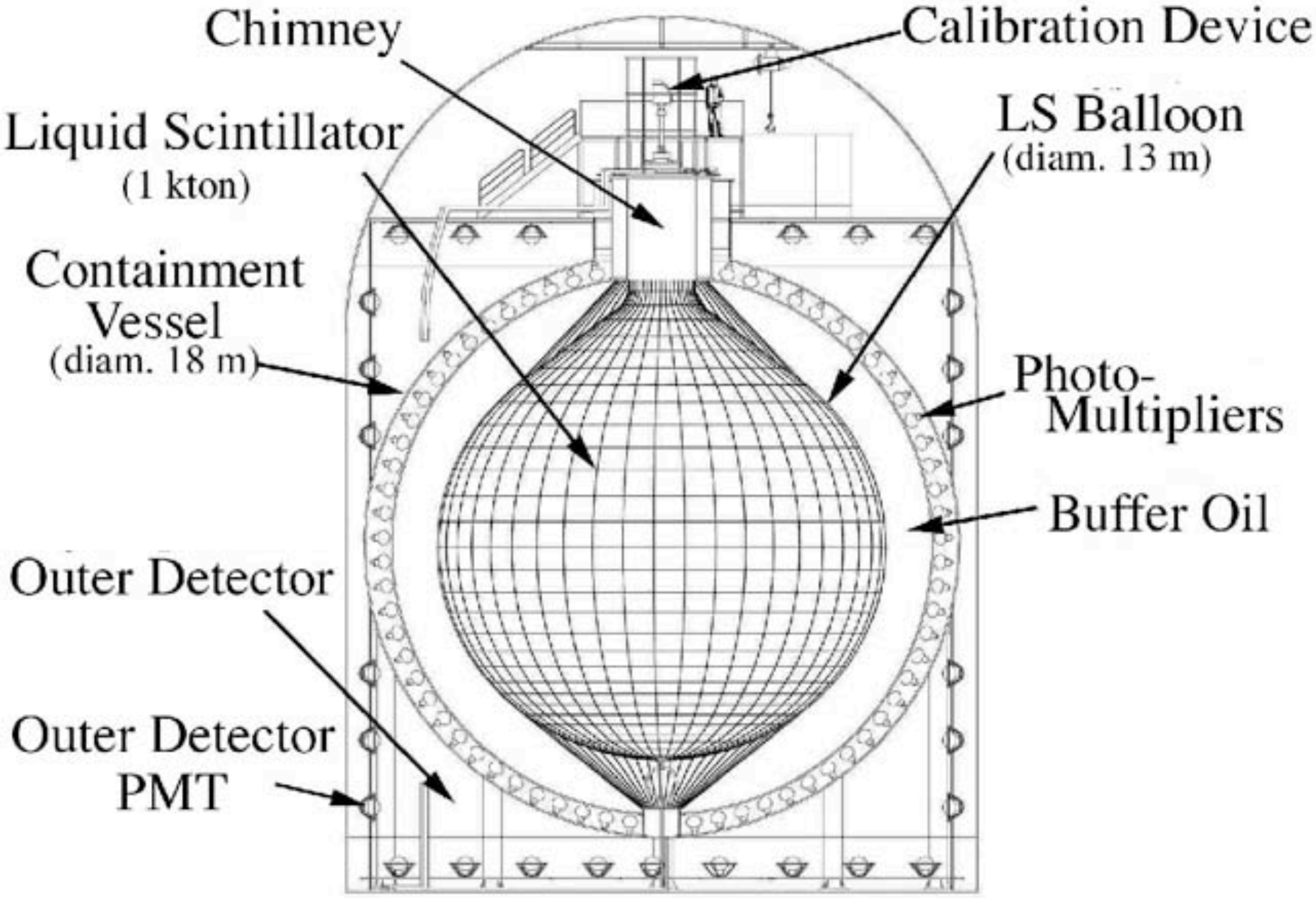
Daya Bay


Reno

Building for low background: Buffer zones

- For these low energy detectors it is common to build the detector in layers of buffer zones with careful control of components that go into the central most zones

- “Dirty” components, for example PMT glass which contains lots of U and Th, are kept away from the central regions.



KamLAND

Background rejection: Coincidence

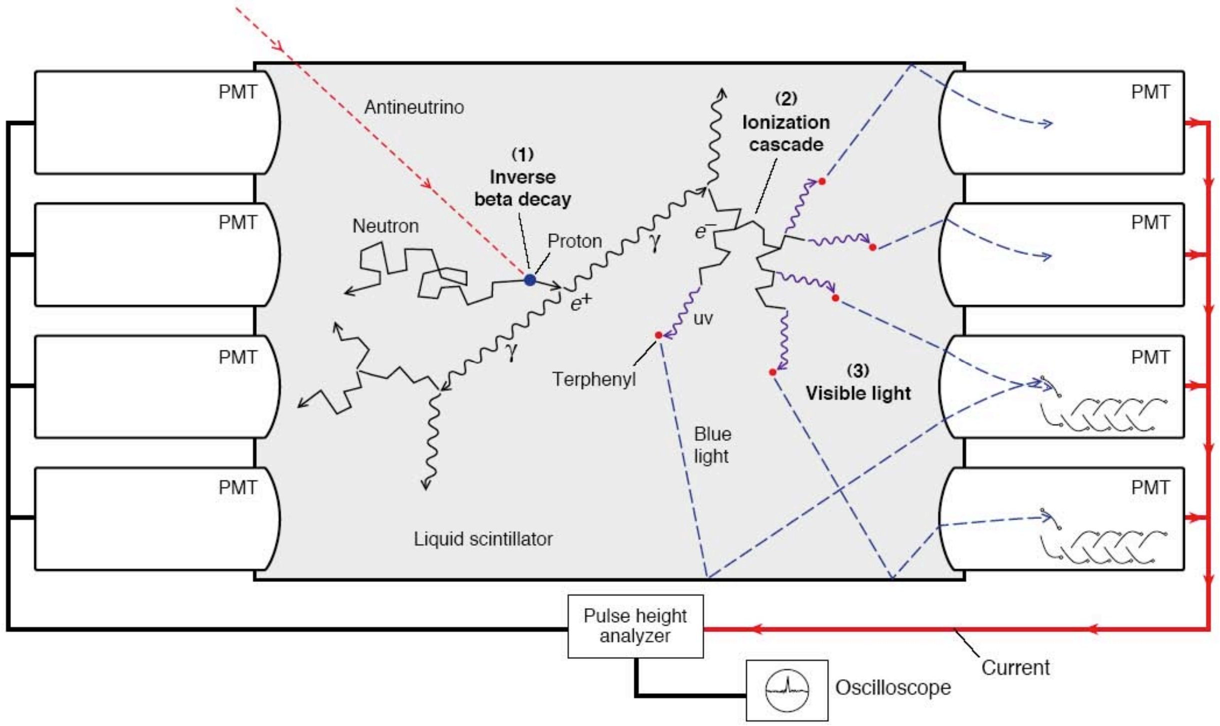
- For reactor neutrino experiment the detection channel is:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

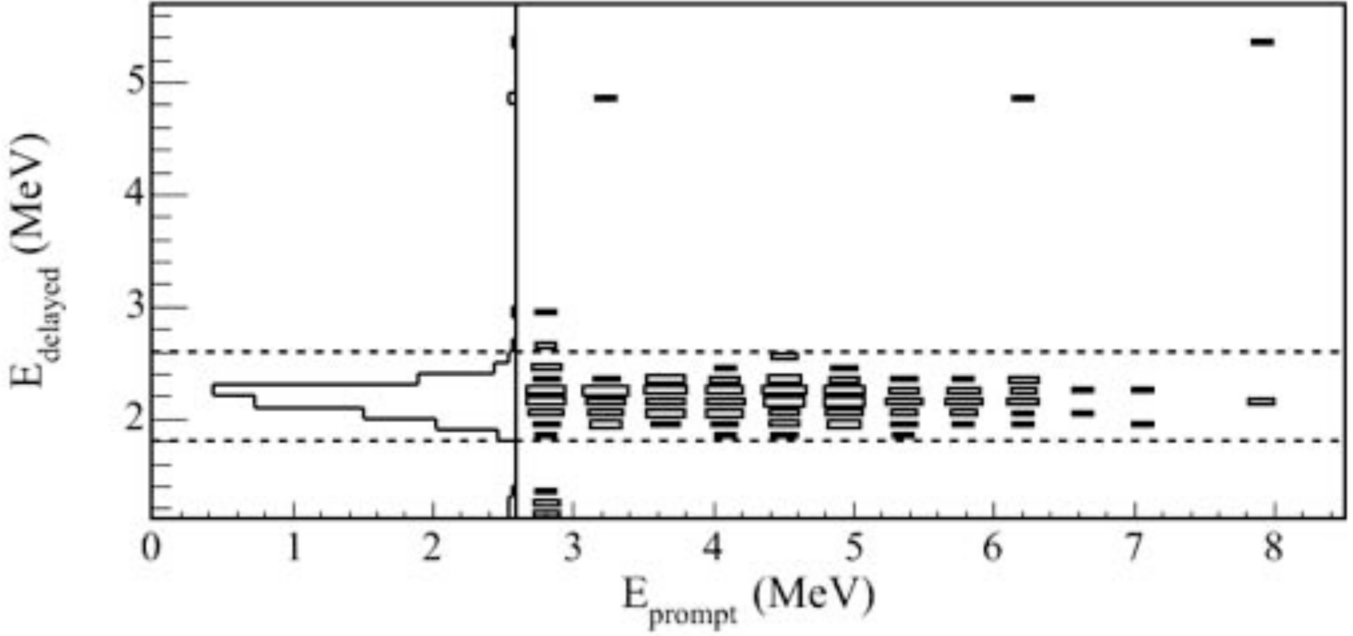
- Positron deposits its kinetic energy and annihilates promptly

$$E_{e^+} = E_{\bar{\nu}_e} - (M_n - M_p) + m_e$$

- Neutron wanders around for ~5 ms and is captured about 5 cm away from interaction vertex (on Gd or Cd dissolved in scintillator) releasing 2.2 MeV in gamma rays (in case of KamLAND shown here)
- This energy-time double coincidence signal dramatically beats the background down

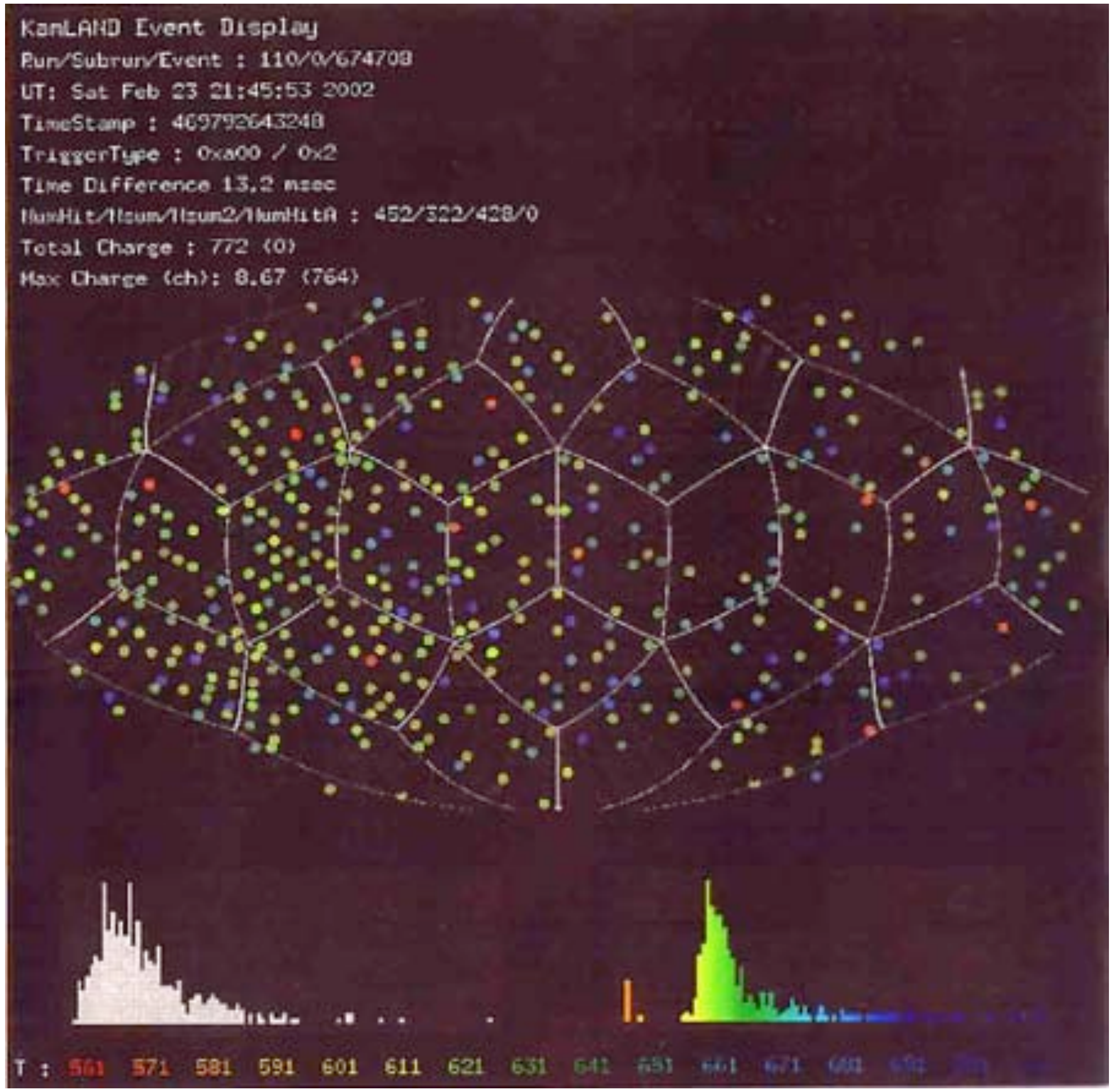


KamLAND



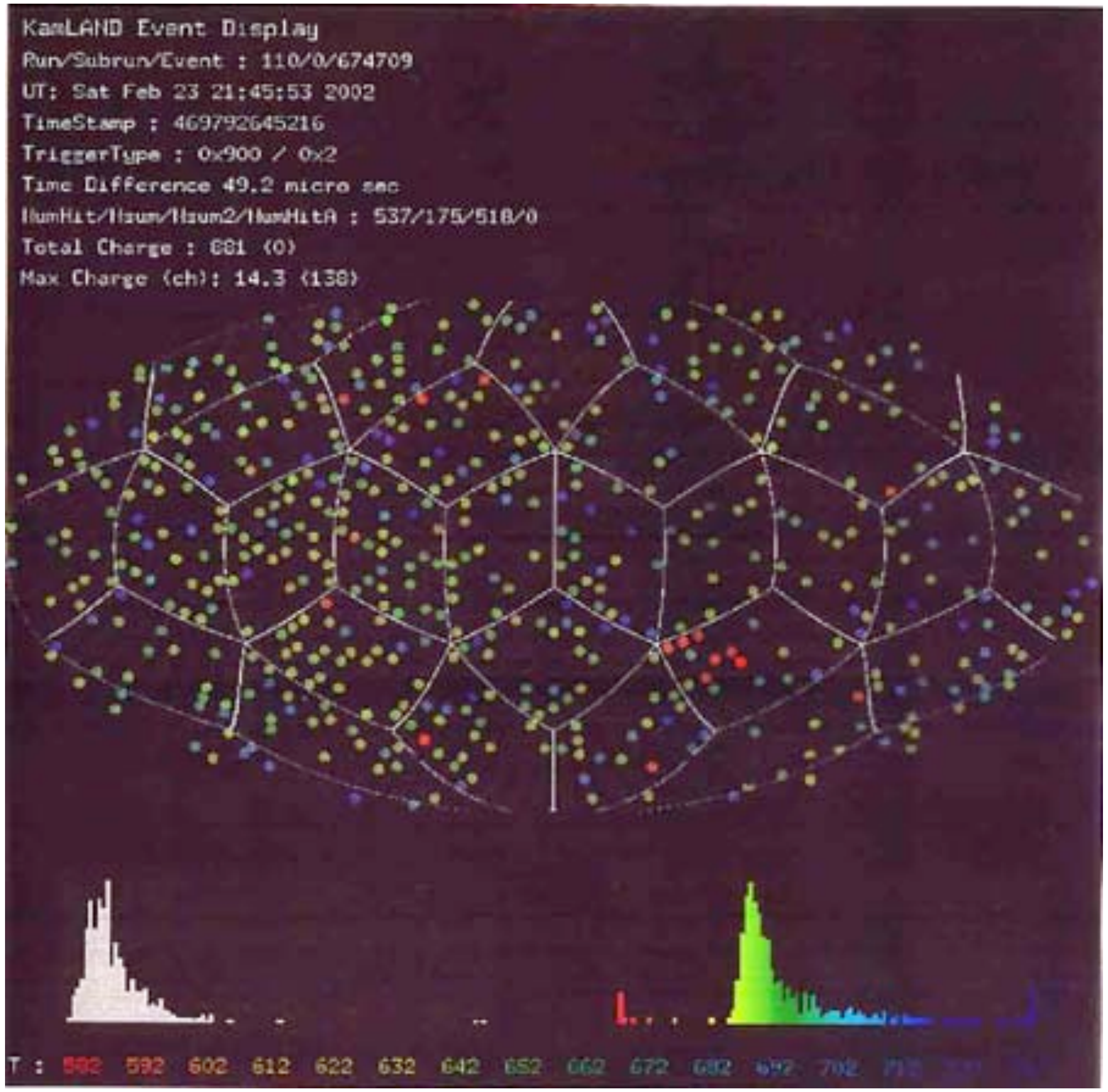
KamLAND’s signal

Feb 23 21:45:32 2002 469792643248



```
KamLAND Event Display
Run/Subrun/Event : 110/0/674708
UT: Sat Feb 23 21:45:53 2002
TimeStamp : 469792643248
TriggerType : 0xa00 / 0x2
Time Difference 13.2 msec
NumHit/Nsum/Nsum2/NumHitA : 452/322/428/0
Total Charge : 772 (0)
Max Charge (ch): 8.67 (764)
```

Feb 23 21:45:32 2002 469792645216

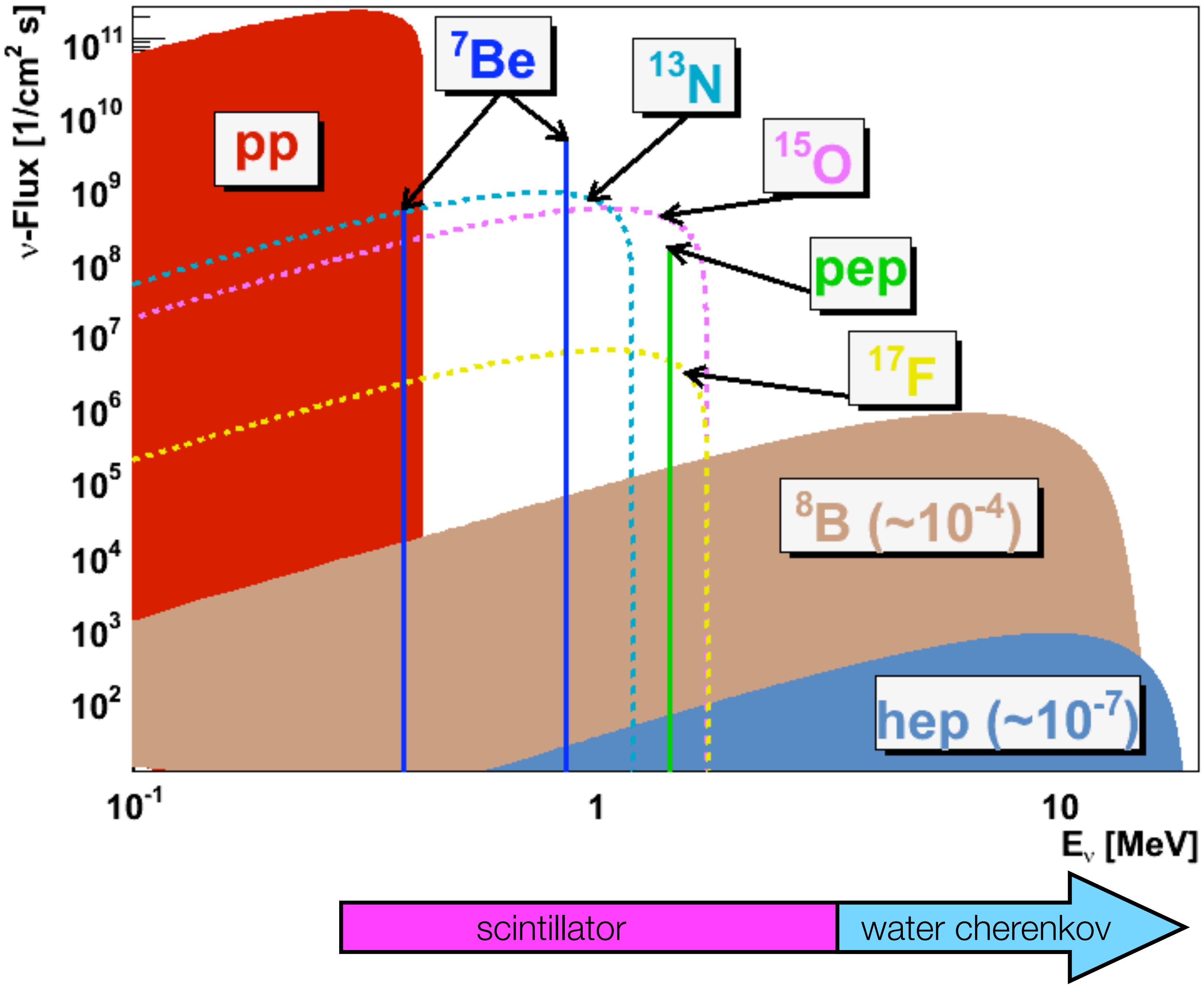


```
KamLAND Event Display
Run/Subrun/Event : 110/0/674709
UT: Sat Feb 23 21:45:53 2002
TimeStamp : 469792645216
TriggerType : 0x900 / 0x2
Time Difference 49.2 micro sec
NumHit/Nsum/Nsum2/NumHitA : 537/175/518/0
Total Charge : 881 (0)
Max Charge (ch): 14.3 (138)
```

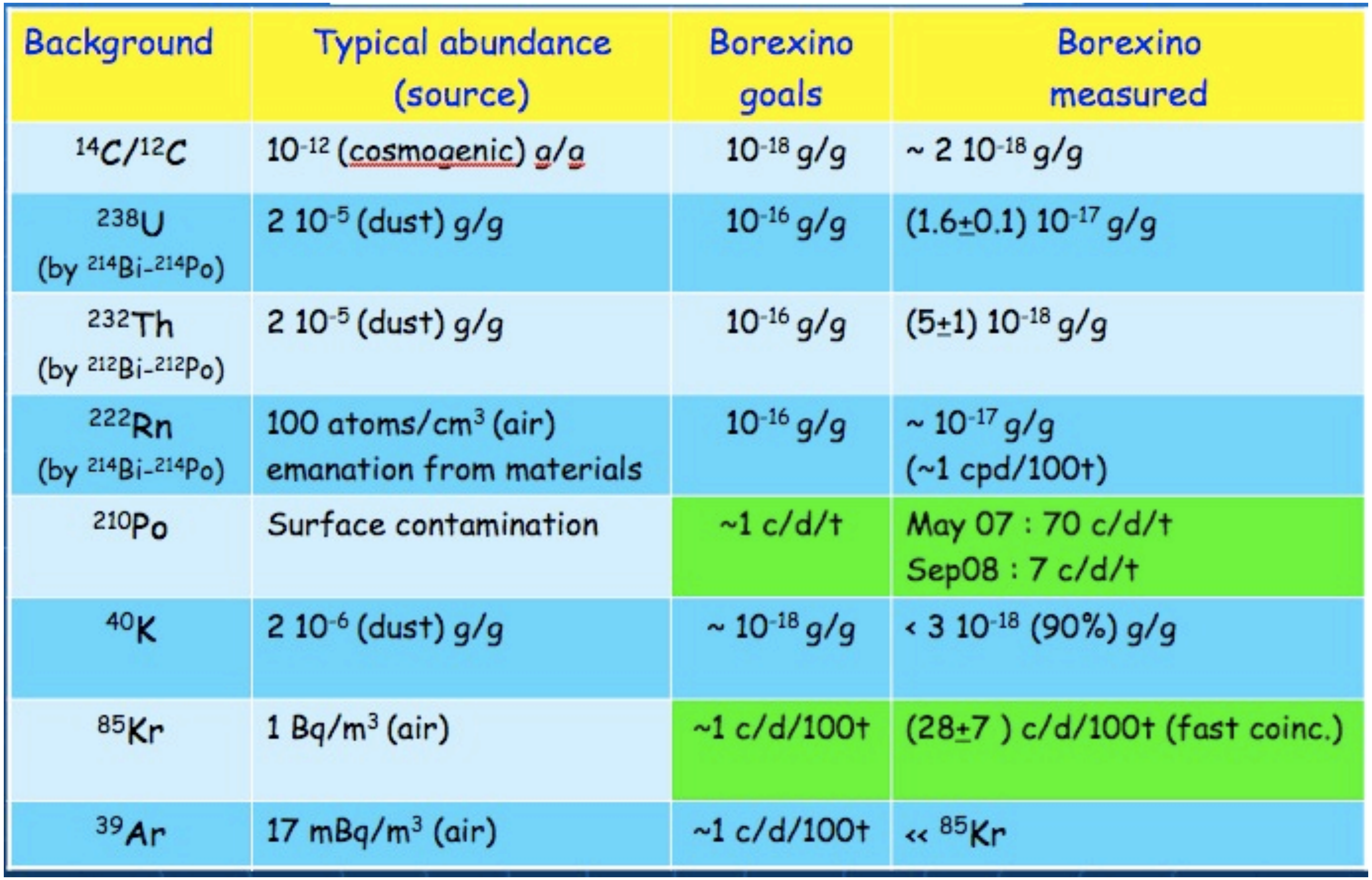
Times differ by ~2000 ticks of a 25 ns clock

Low energy solar neutrinos

- Water Cherenkov runs out of light around 4 MeV
- Switch to scintillator at lower energies
- Scintillation light is emitted isotropically. Gives up directional information - can't rely on pointing events to Sun
- Unlike inverse-beta decay, elastic scattering does not provide an energy-time coincidence signal.



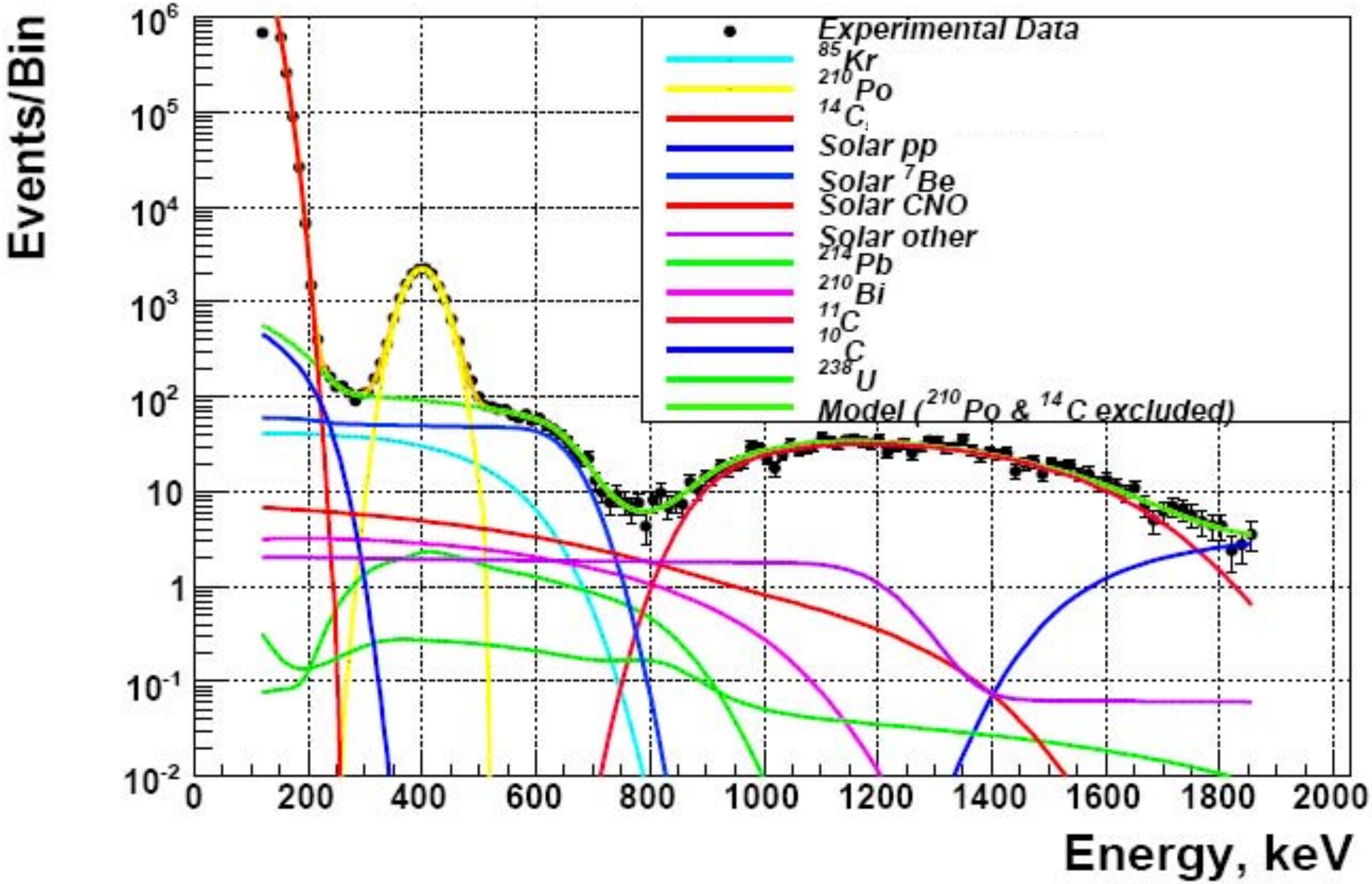
Radio-pure scintillator: Borexino



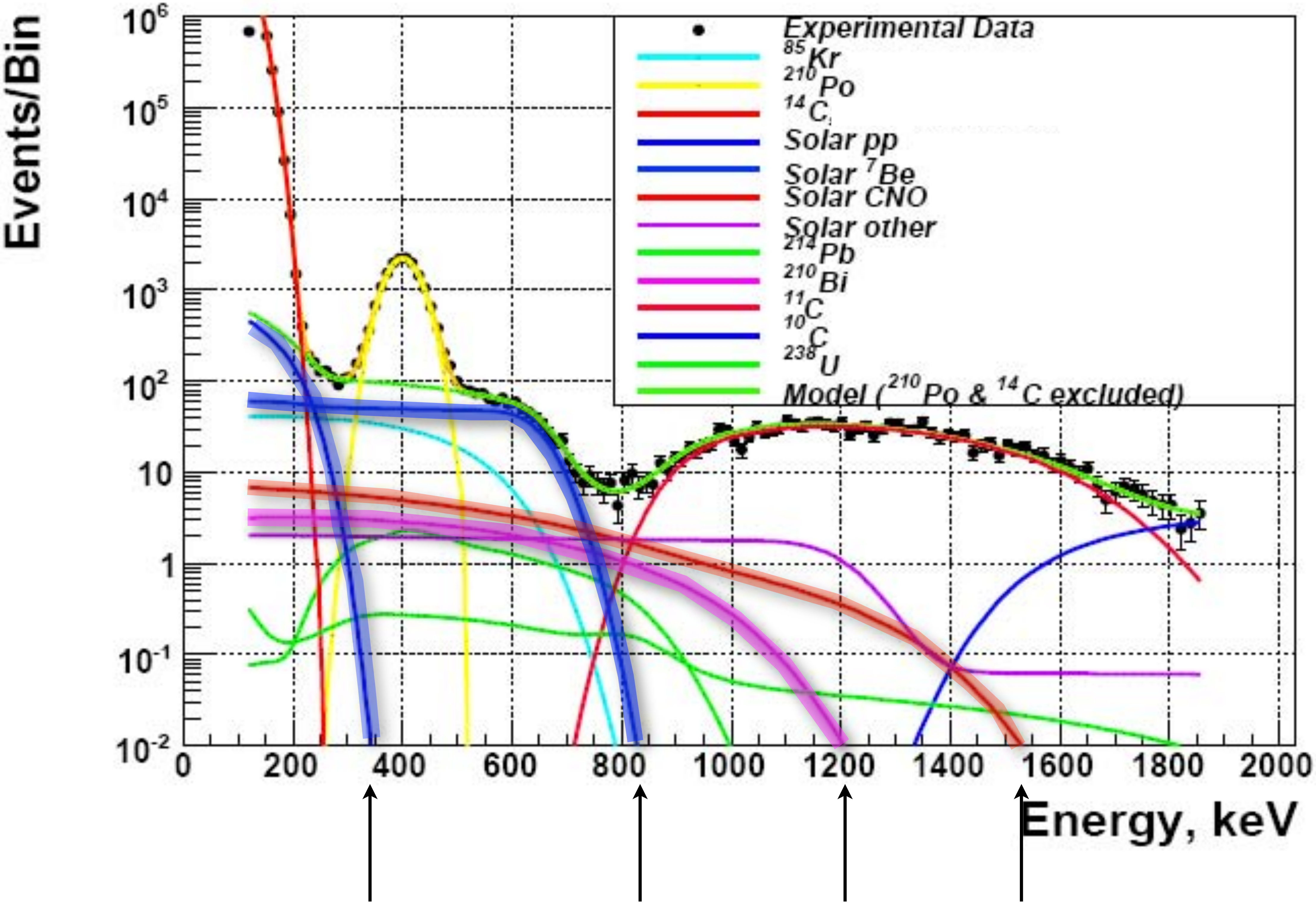
Background	Typical abundance (source)	Borexino goals	Borexino measured
$^{14}C/^{12}C$	10^{-12} (cosmogenic) g/g	10^{-18} g/g	~ 2 10^{-18} g/g
^{238}U (by ^{214}Bi-^{214}Po)	2 10^{-5} (dust) g/g	10^{-16} g/g	(1.6±0.1) 10^{-17} g/g
^{232}Th (by ^{212}Bi-^{212}Po)	2 10^{-5} (dust) g/g	10^{-16} g/g	(5±1) 10^{-18} g/g
^{222}Rn (by ^{214}Bi-^{214}Po)	100 atoms/cm^3 (air) emanation from materials	10^{-16} g/g	~ 10^{-17} g/g (~1 cpd/100t)
^{210}Po	Surface contamination	~1 c/d/t	May 07 : 70 c/d/t Sep08 : 7 c/d/t
^{40}K	2 10^{-6} (dust) g/g	~ 10^{-18} g/g	< 3 10^{-18} (90%) g/g
^{85}Kr	1 Bq/m^3 (air)	~1 c/d/100t	(28±7) c/d/100t (fast coinc.)
^{39}Ar	17 mBq/m^3 (air)	~1 c/d/100t	<< ^{85}Kr

Elastic scattering does not provide a double coincidence signal. No choice but to make extremely radio-pure scintillator

Radio-pure scintillator: Borexino

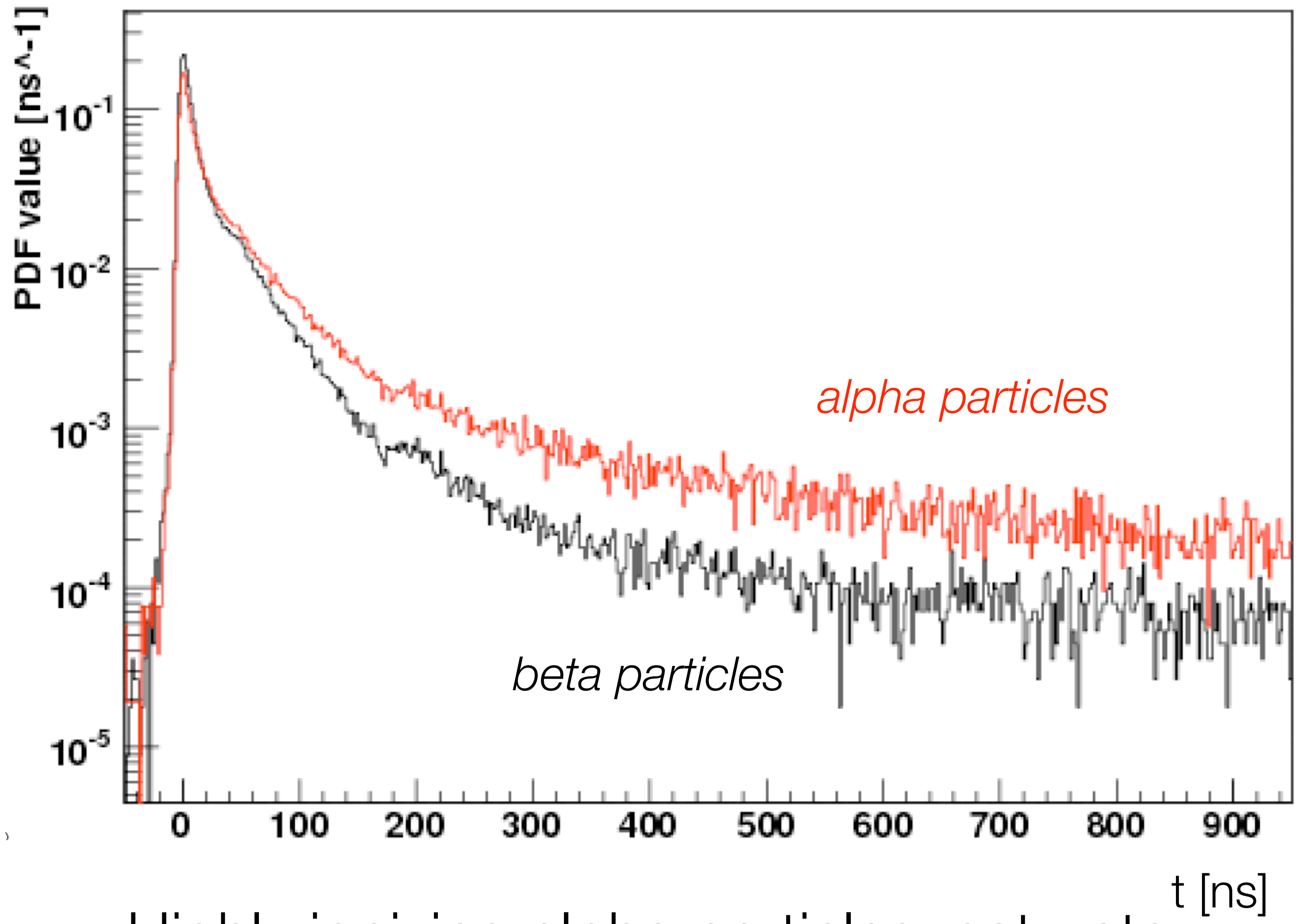


Radio-pure scintillator: Borexino



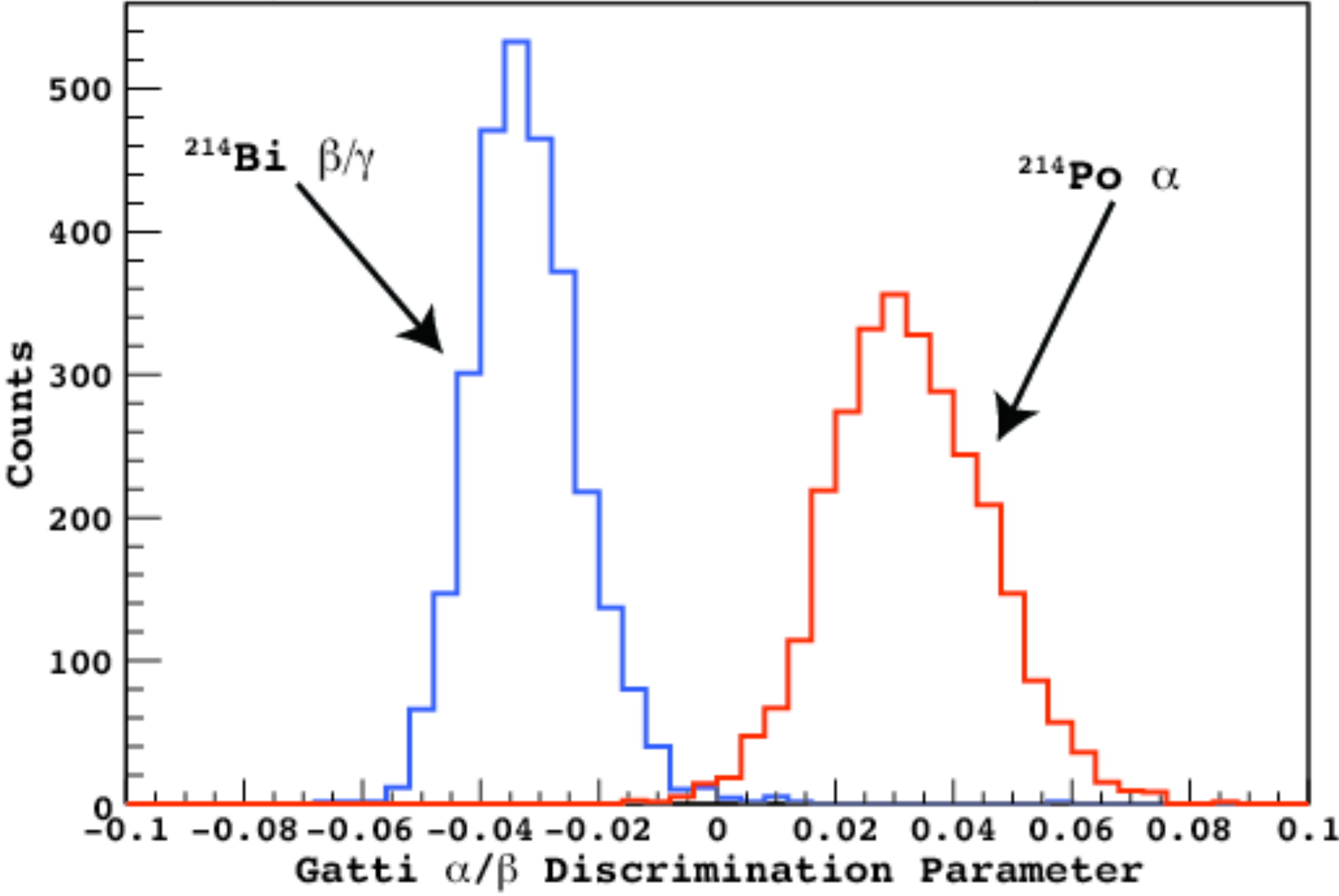
Alpha/Beta discrimination: Borexino

- Can remove events due to alpha emitters based on pulse shape analysis



Highly ionizing alpha particles saturate more of the scintillator and have a longer decay time

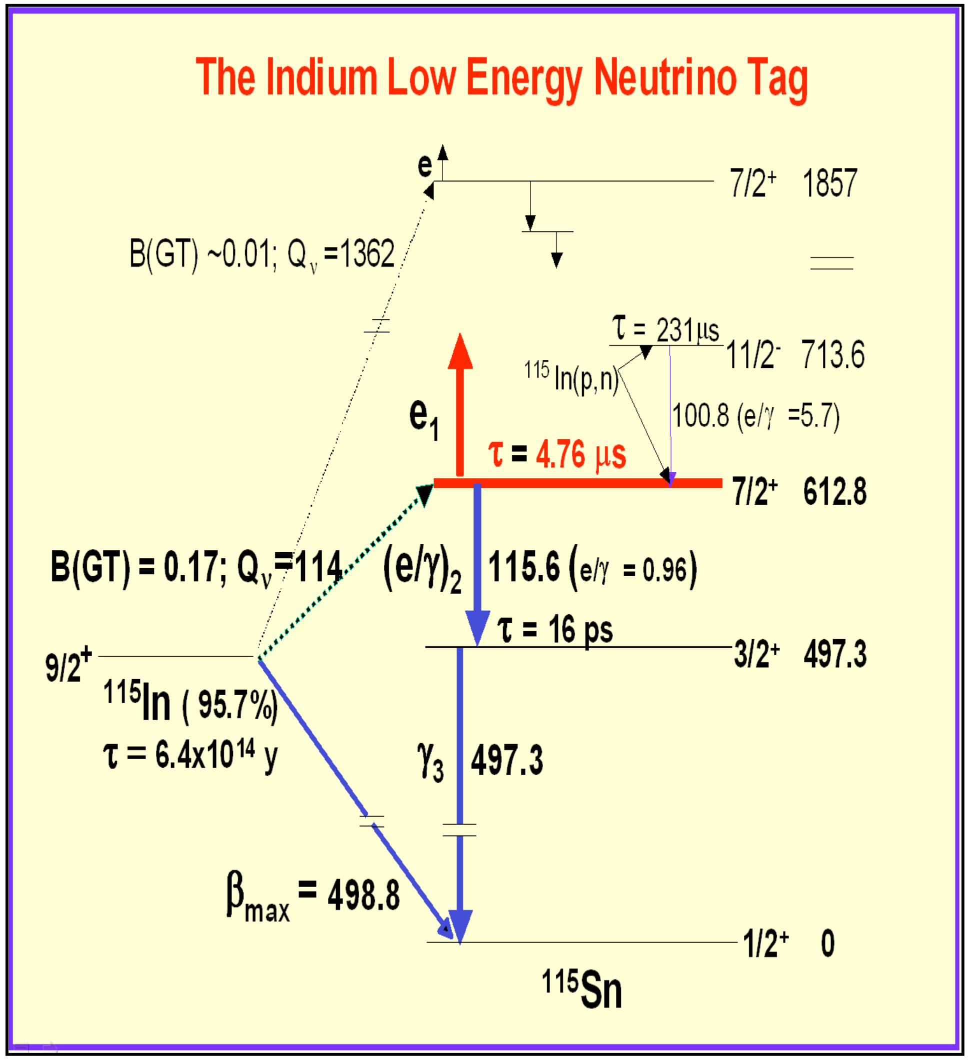
Integrated area between pulse and average pulse

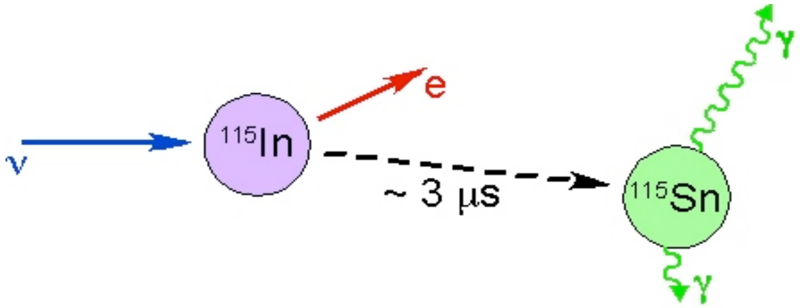


Even lower? LENS

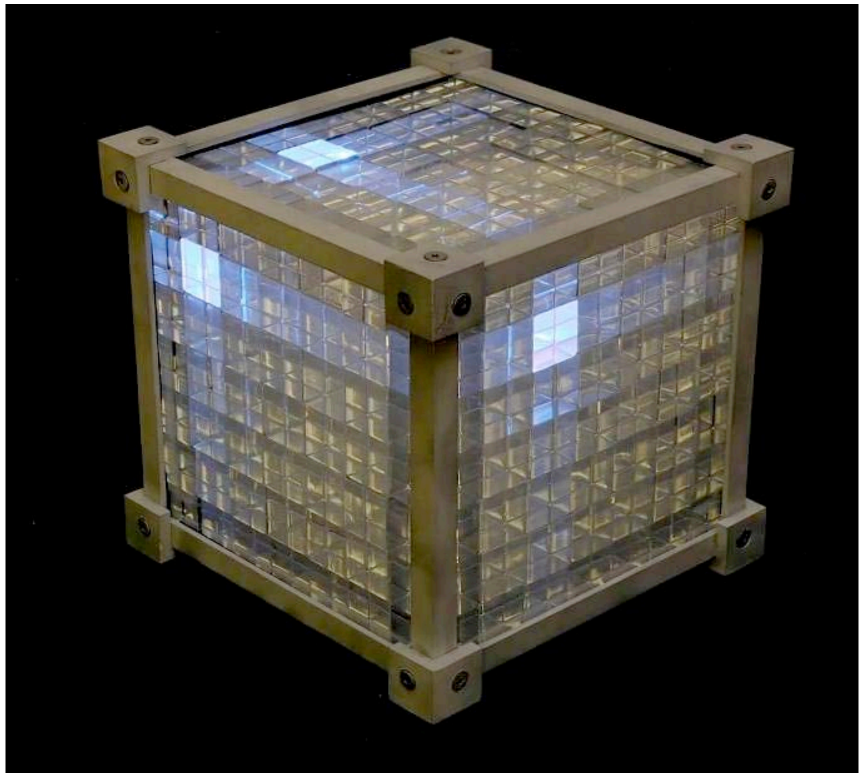
- The LENS experiment proposed to use scintillator loaded with Indium^{115}

$$\nu_e + {}^{115}In \rightarrow \underbrace{e^-}_{\text{solar signal}} + \underbrace{\gamma + (\gamma / e^-)}_{\text{delayed tag } (\tau = 4.76\,\mu s)} + {}^{115}Sn$$



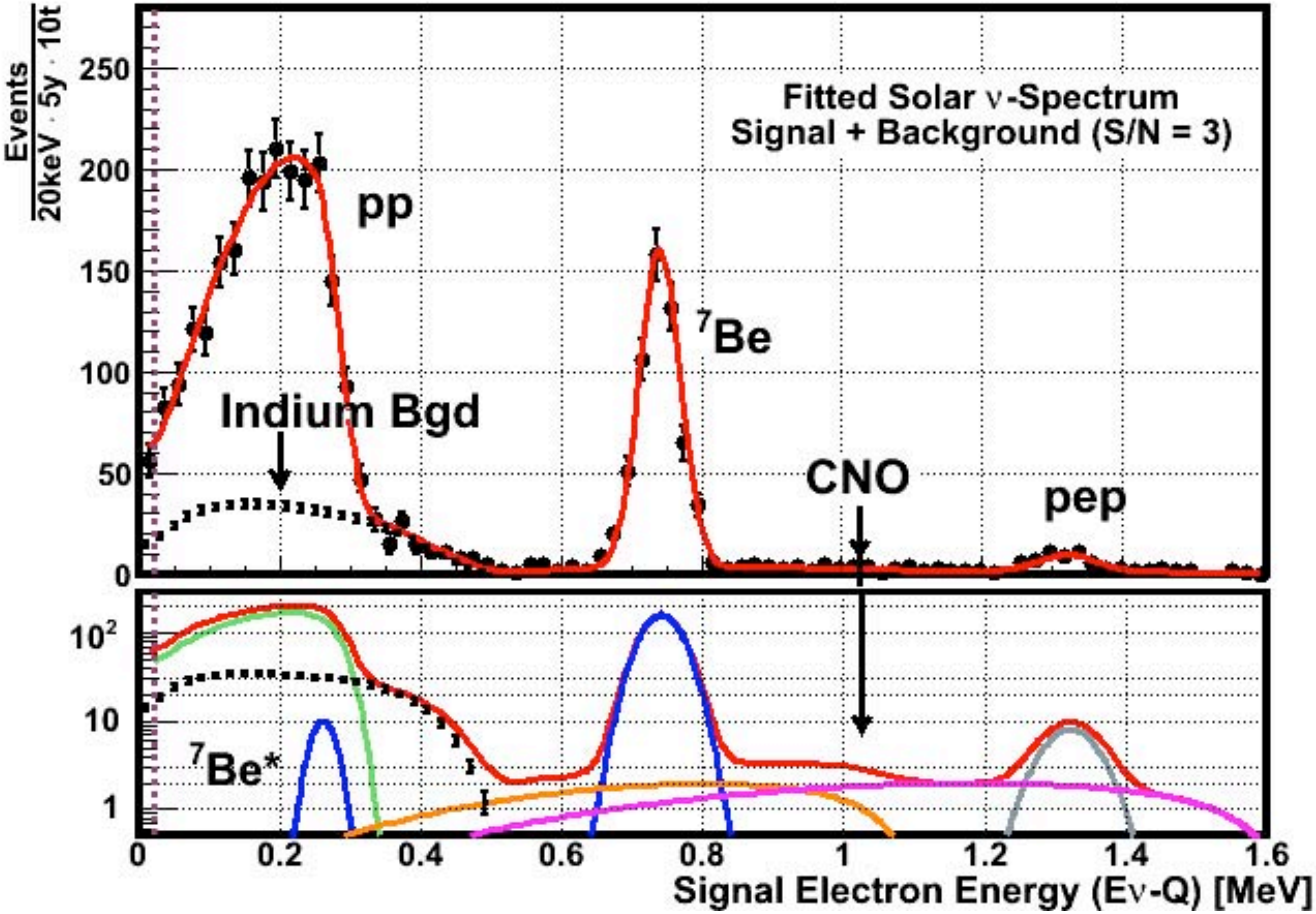


Signature is a triple coincidence in space and time



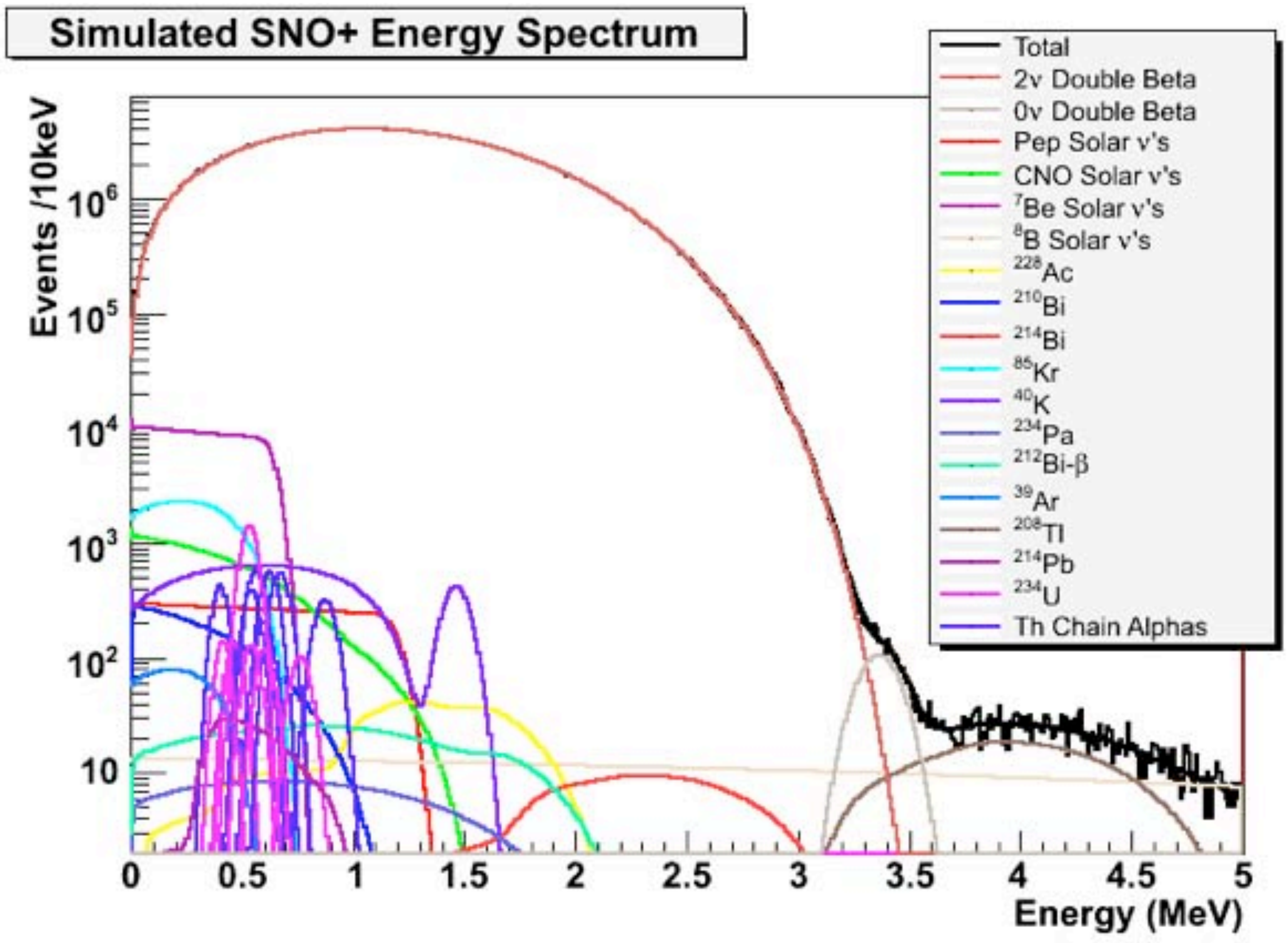
Segment detector and guide light to walls via complete internal reflection

Simulated solar neutrino spectrum in LENS



Liquid scintillator for 0νββ: SNO+

- Reuse SNO cavern but using liquid scintillator instead of D_2O
- Load scintillator with ^{150}Nd
- Overwhelm relatively poor energy resolution with statistics. SNO+ could hold as much as 500 kg of source. Compare to current largest 0νββ experiment which uses roughly 10 kg of isotope.

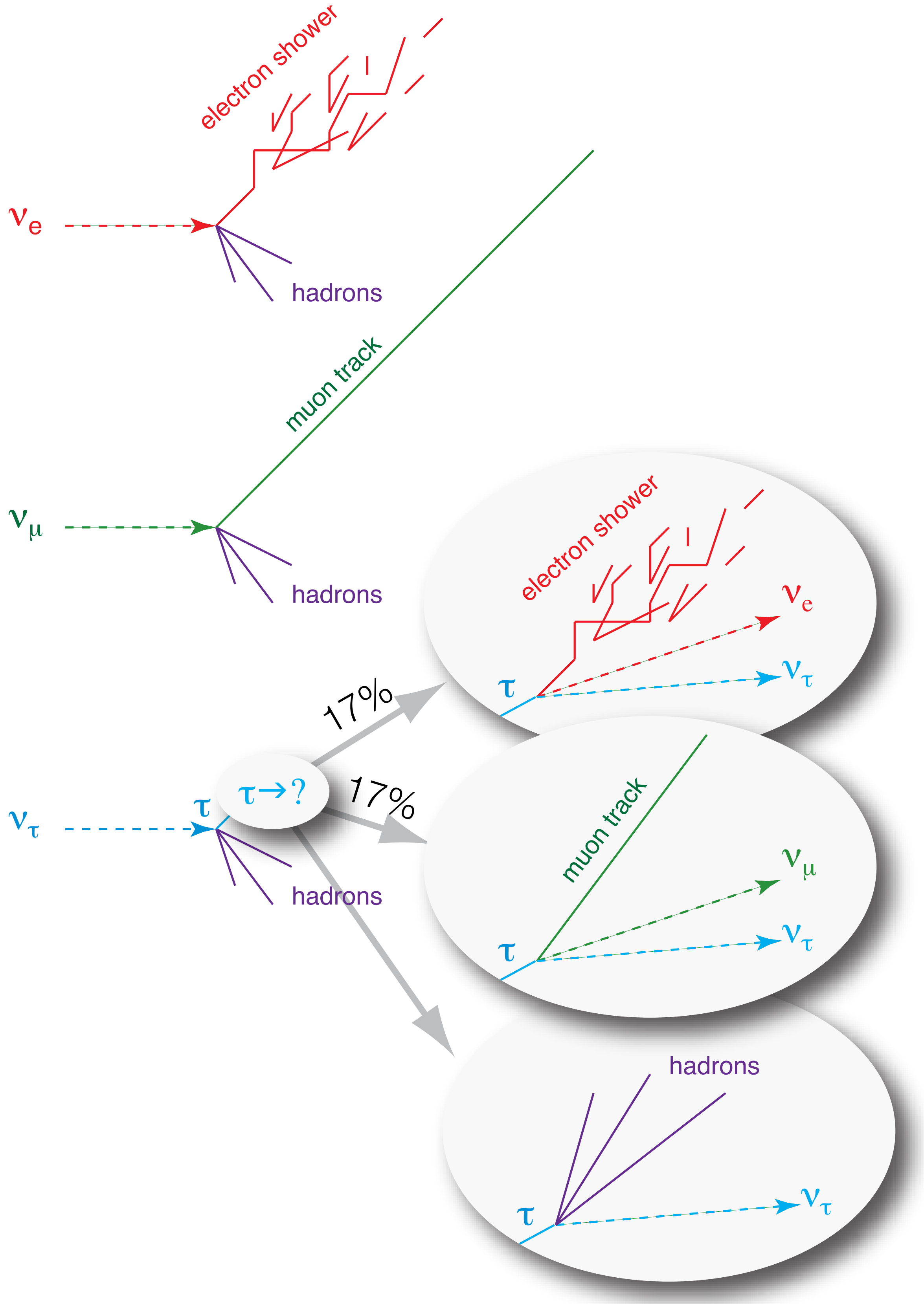


0νββ signal and backgrounds at lower edge of reported observation by Klapdor-Kleingrothaus et al.

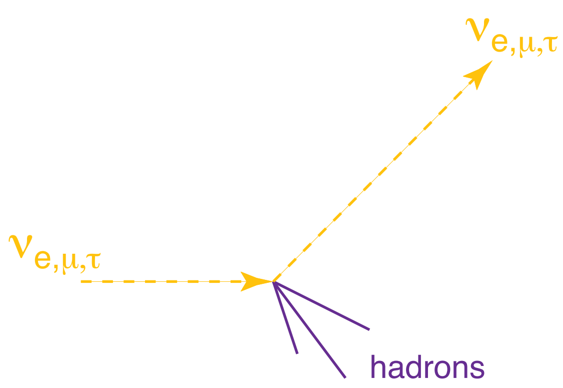
Tau Neutrino Detection

Neutrino detection channels

Charged-current



Neutral-current



- In charged-current (CC) events outgoing lepton tags incoming neutrino flavor.
  - *In the case of ν_τ, the presence of a τ must be deduced from the τ decay products*
- In CC events nearly all the neutrino energy is deposited in the detector
- In neutral-current events, only hadrons are present and no information about the incident neutrino flavor is available
- CC rates are affected by oscillations
- NC rates are not affected by oscillations
  - *In only a few analyses are NC events considered to be signal. In most cases NC events are backgrounds to the CC processes*

Tau neutrinos

- Tau neutrinos are difficult to observe
  - *They are difficult to produce.* First direct observation (DONUT) was via decays of charmed particles in a beam dump.
  - *They are difficult to make interact.* Threshold for tau production is 3.5 GeV. This puts them above the oscillation maximum for most beams designed to study oscillations at the atmospheric mass-squared scale. For example, for L=735 km, Emax = 1.5 GeV, which is below threshold
  - *They are difficult to detect.* The lifetime of the tau is 291 fs; Even when highly boosted, decay length is only a few mm. Required a very finely segmented vertex region.

$$\begin{aligned} c\tau_{\mathrm{LAB}} &= (3\times 10^{11}\ m/\mathrm{s})(290\times 10^{-15}\ \mathrm{s})(\frac{E}{1.7\ \mathrm{GeV}}) \\ &= 0.5\ \mathrm{mm}\times E\ [\mathrm{GeV}] \end{aligned}$$

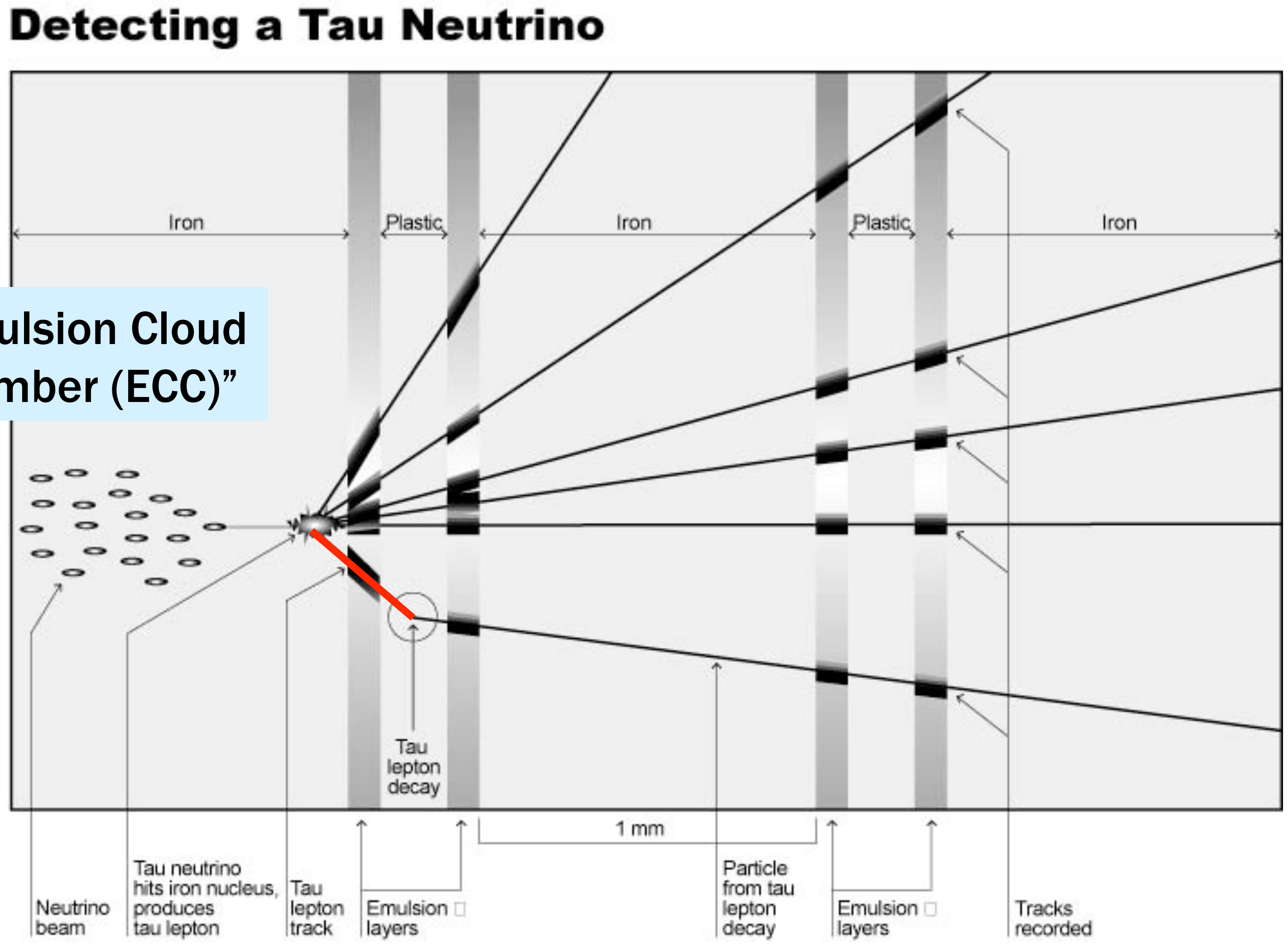
- Tau neutrinos produce backgrounds to electron neutrino searches:

$$\tau \longrightarrow e\ \nu_e\ \nu_\tau$$

Tau Neutrino Detection

- Several experiments look for tau neutrinos
- Observed by DONUT experiment
- Sought from oscillations by CHORUS and OPERA

- All of the above experiments have used thin films of photographic emulsions placed between target layers
- Use of emulsion allows for resolution of short tau track and search for its decay either through a track kink or to multi-prongs
- Emulsion target followed by other detectors which provide tracking and tell you where you had a neutrino interaction and which emulsions you should develop



Detecting a Tau Neutrino

Of one million million tau neutrinos crossing the DONUT detector, scientists expect about one to interact with an iron nucleus.

"Emulsion Cloud Chamber (ECC)"

Layout of the DONUT experiment

Tracking using scintillating fibers interspersed in emulsion target and drift chambers used to locate vertices in emulsion with ~mm accuracy

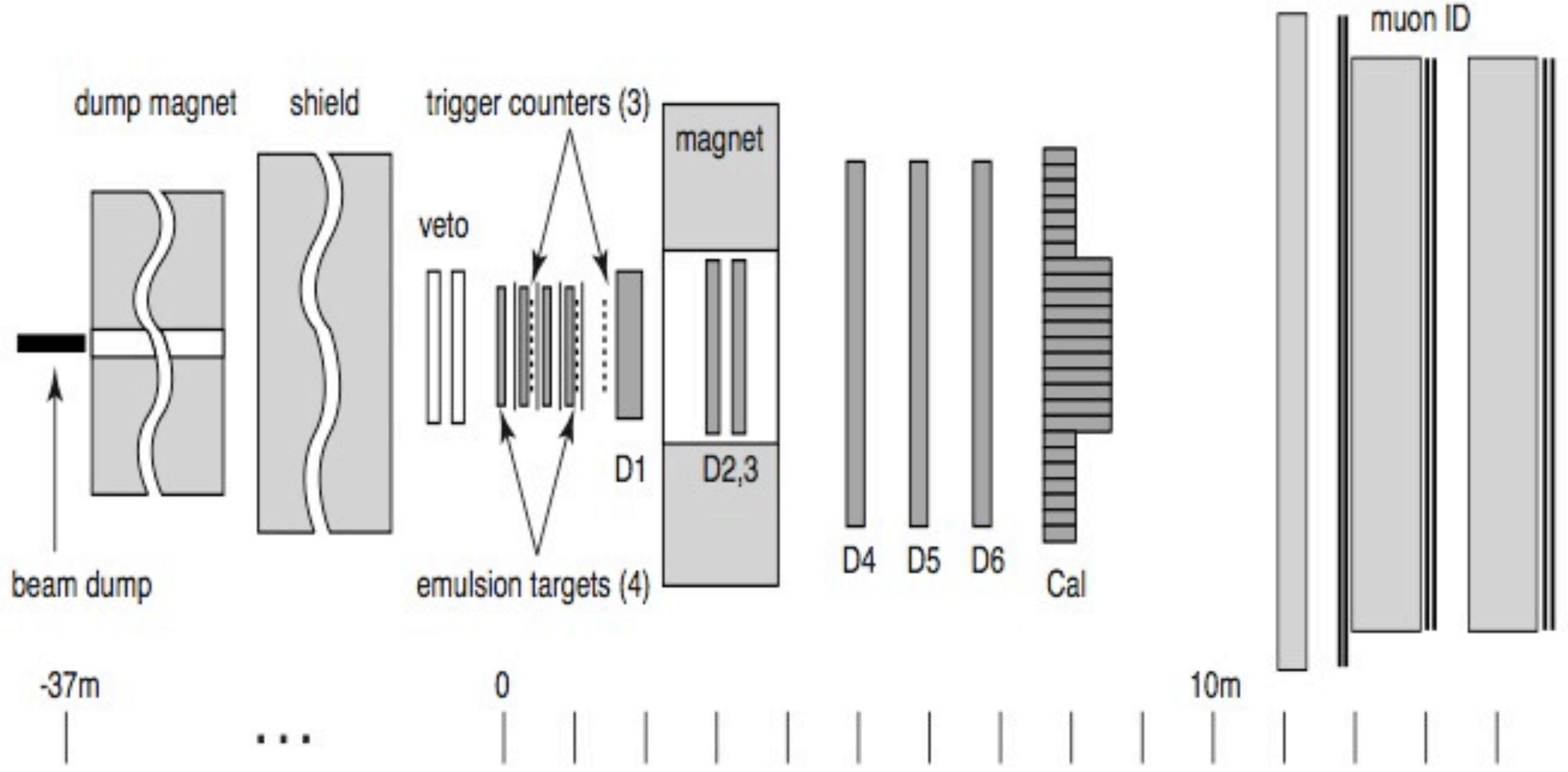


Fig. 1. Experimental beam and spectrometer. At the left, 800 GeV protons were incident on the beam dump, which was 36.5m from the first emulsion target. Muon identification was done by range in the system at the right (downstream).

Tau Neutrino Detection by DONUT Collaboration

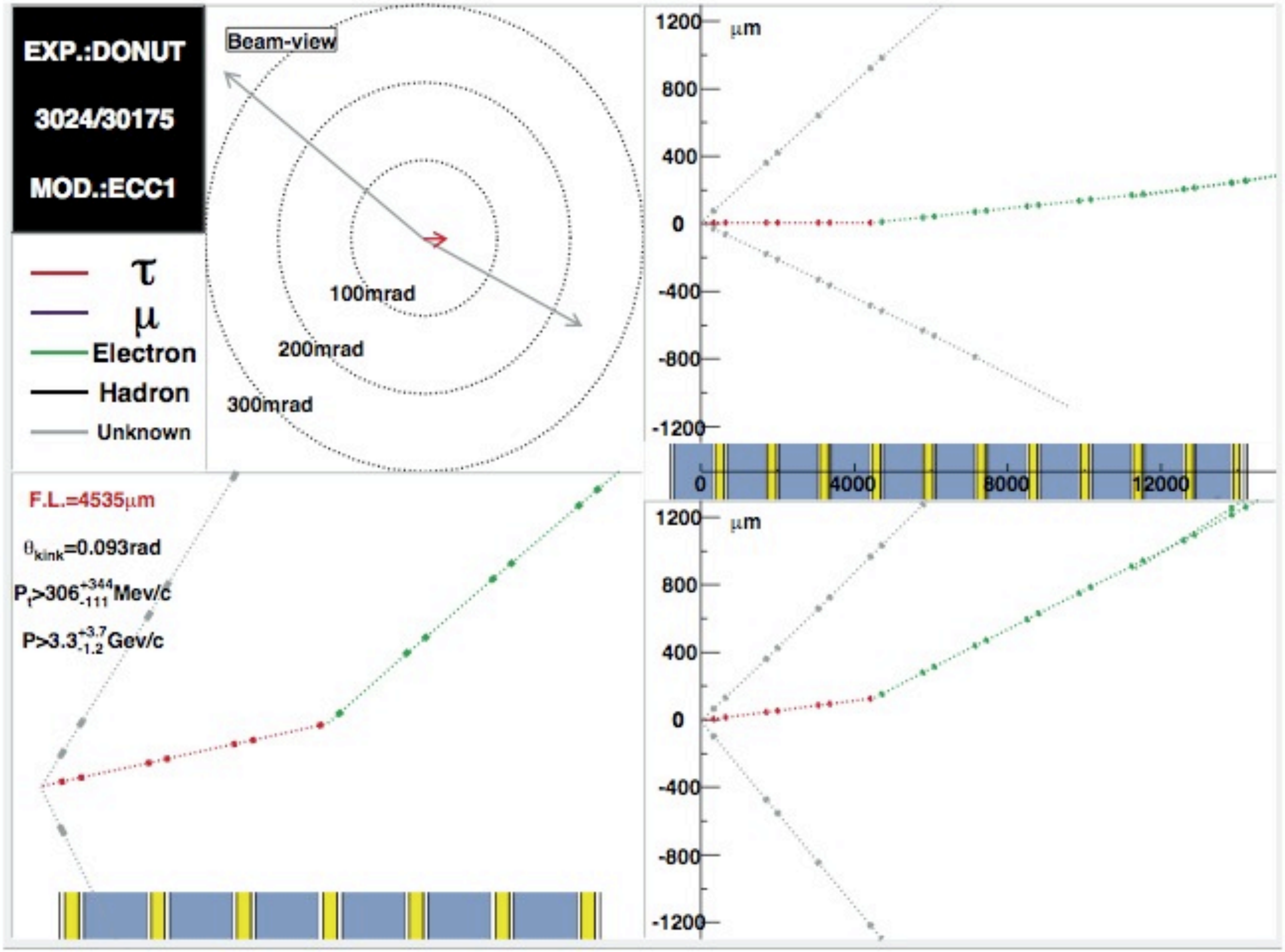
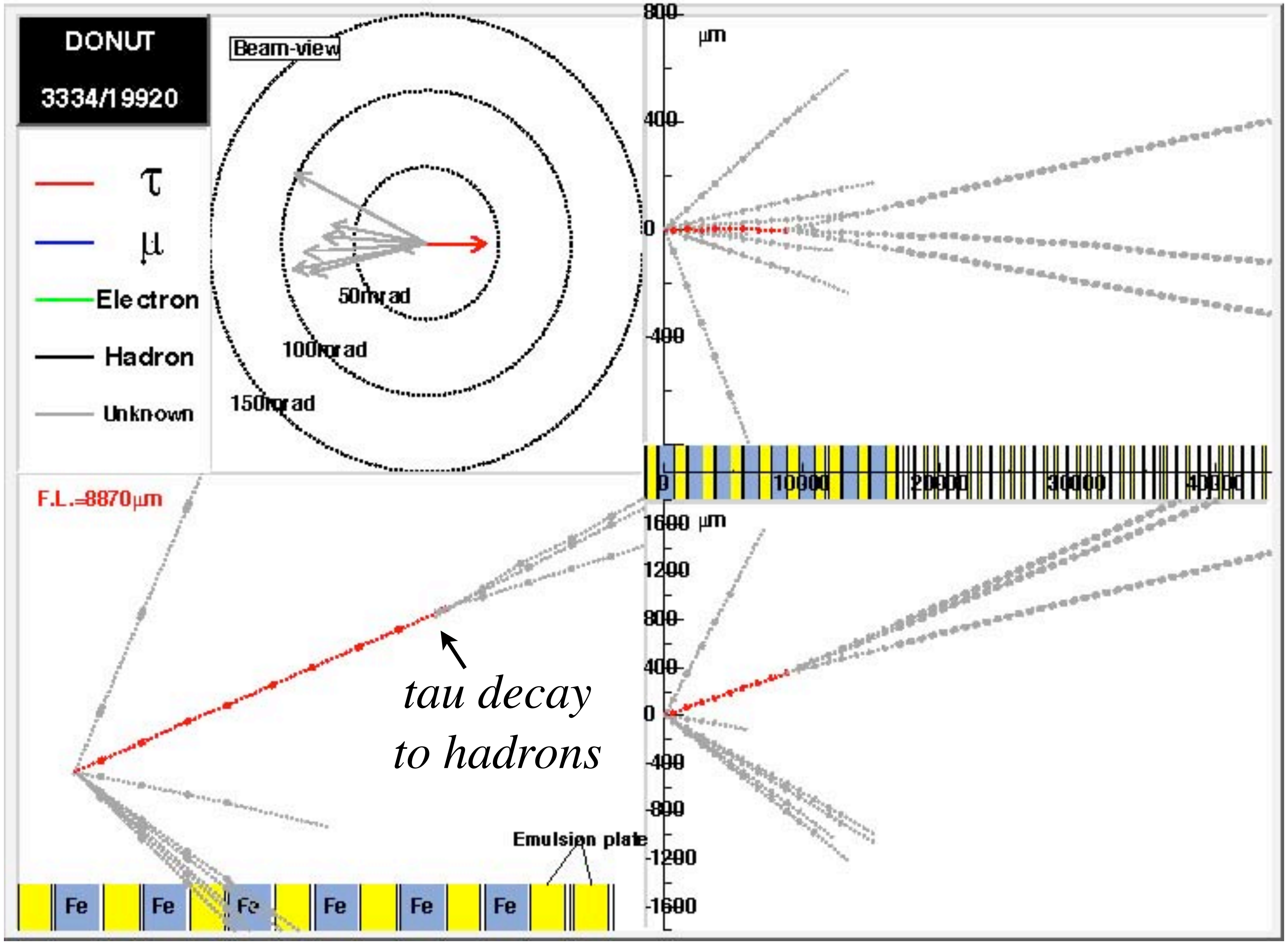


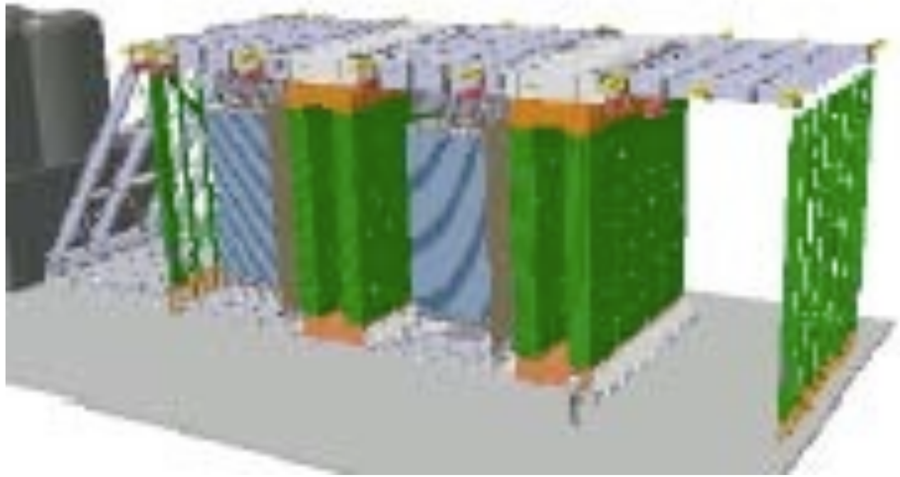
Fig. 18. Event 3024-30175: $\tau \rightarrow e + \nu_\tau + \nu_e$.

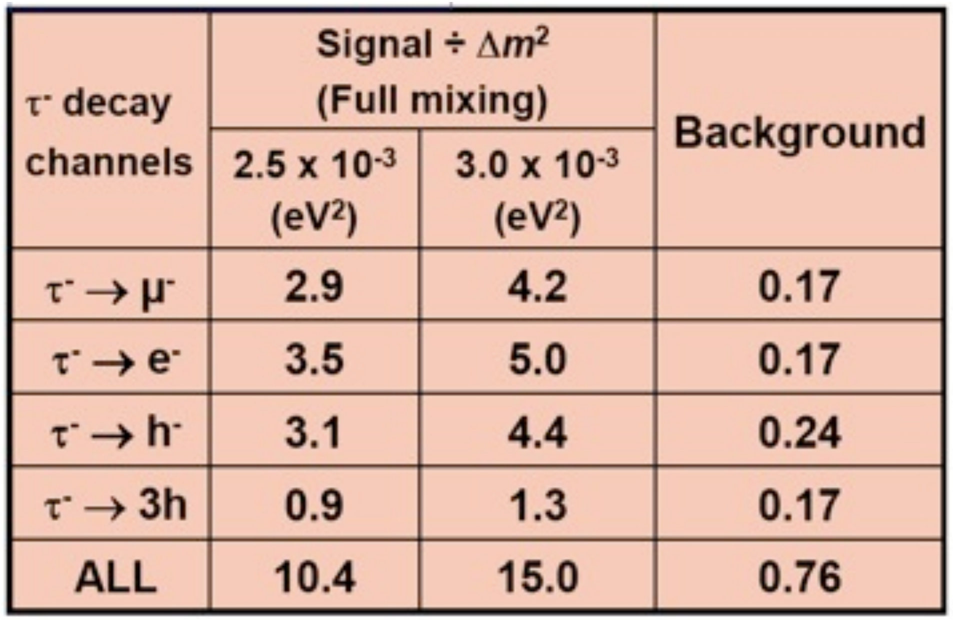
Tau Neutrino Detection by DONUT Collaboration



OPERA Experiment In CNGS beam

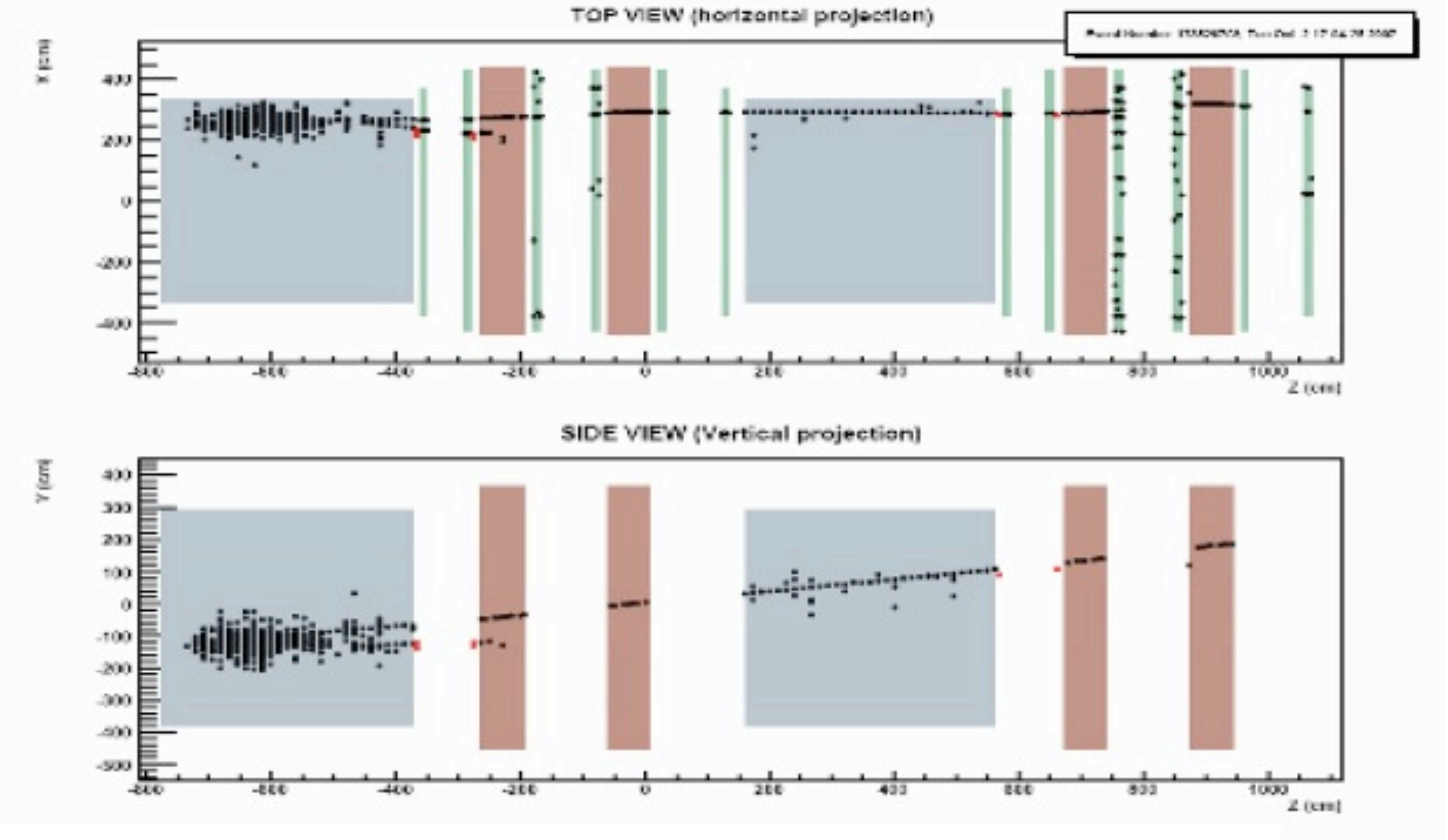
OPERA uses bricks of lead/ emulsion embedded in a solid scintillator-based tracking system + downstream muon spectrometer



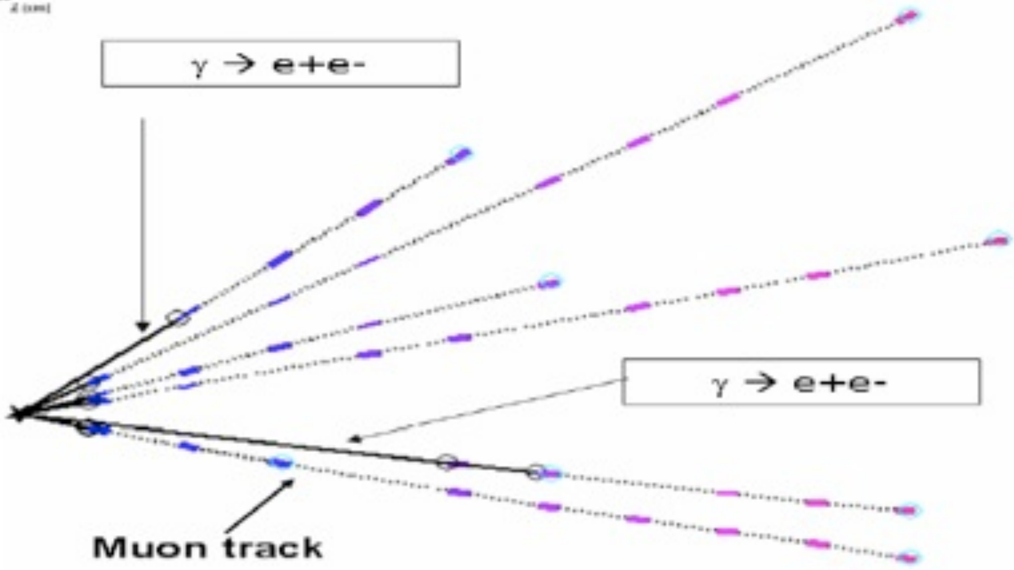


τ^- decay channels	Signal ÷ Δm^2 (Full mixing)		Background
	2.5 x 10^{-3} (eV^2)	3.0 x 10^{-3} (eV^2)	
$\tau^- \to \mu^-$	2.9	4.2	0.17
$\tau^- \to e^-$	3.5	5.0	0.17
$\tau^- \to h^-$	3.1	4.4	0.24
$\tau^- \to 3h$	0.9	1.3	0.17
ALL	10.4	15.0	0.76

First event!

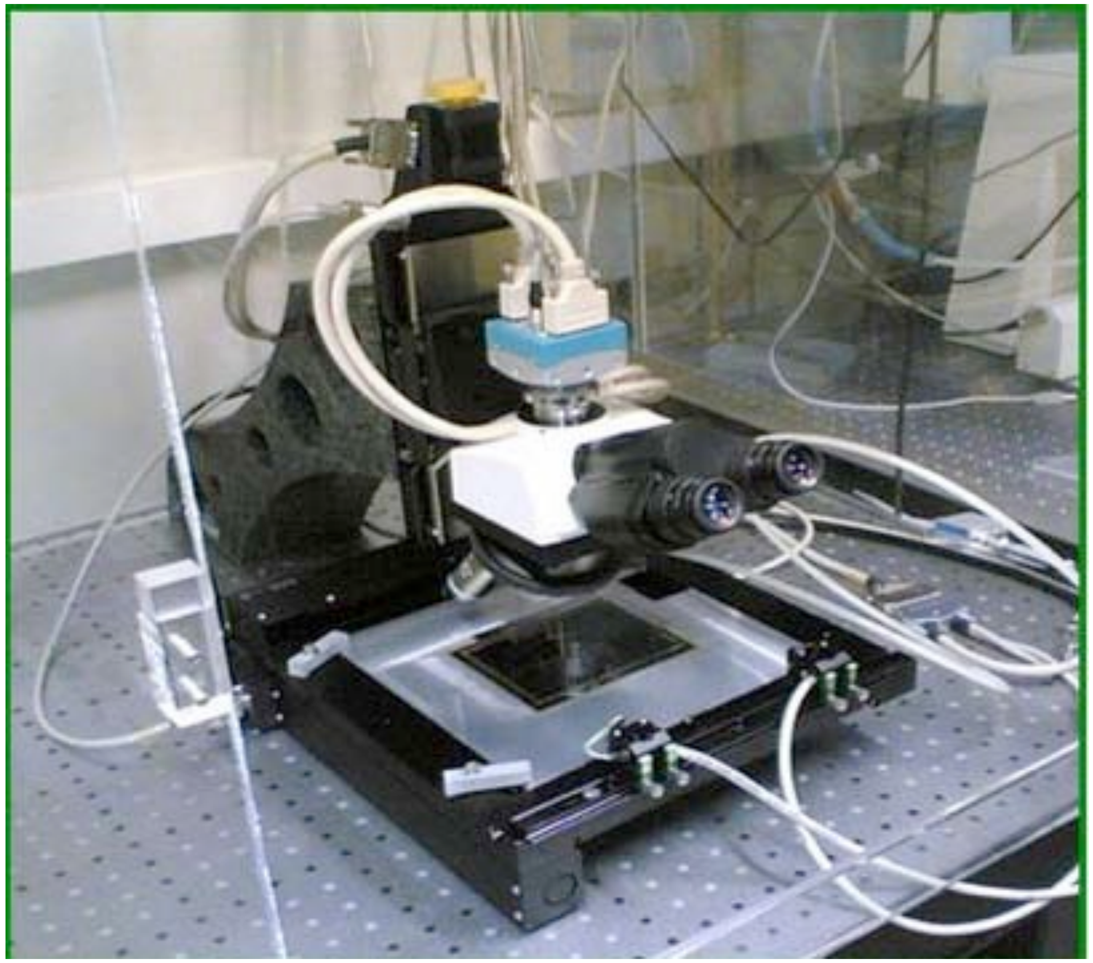


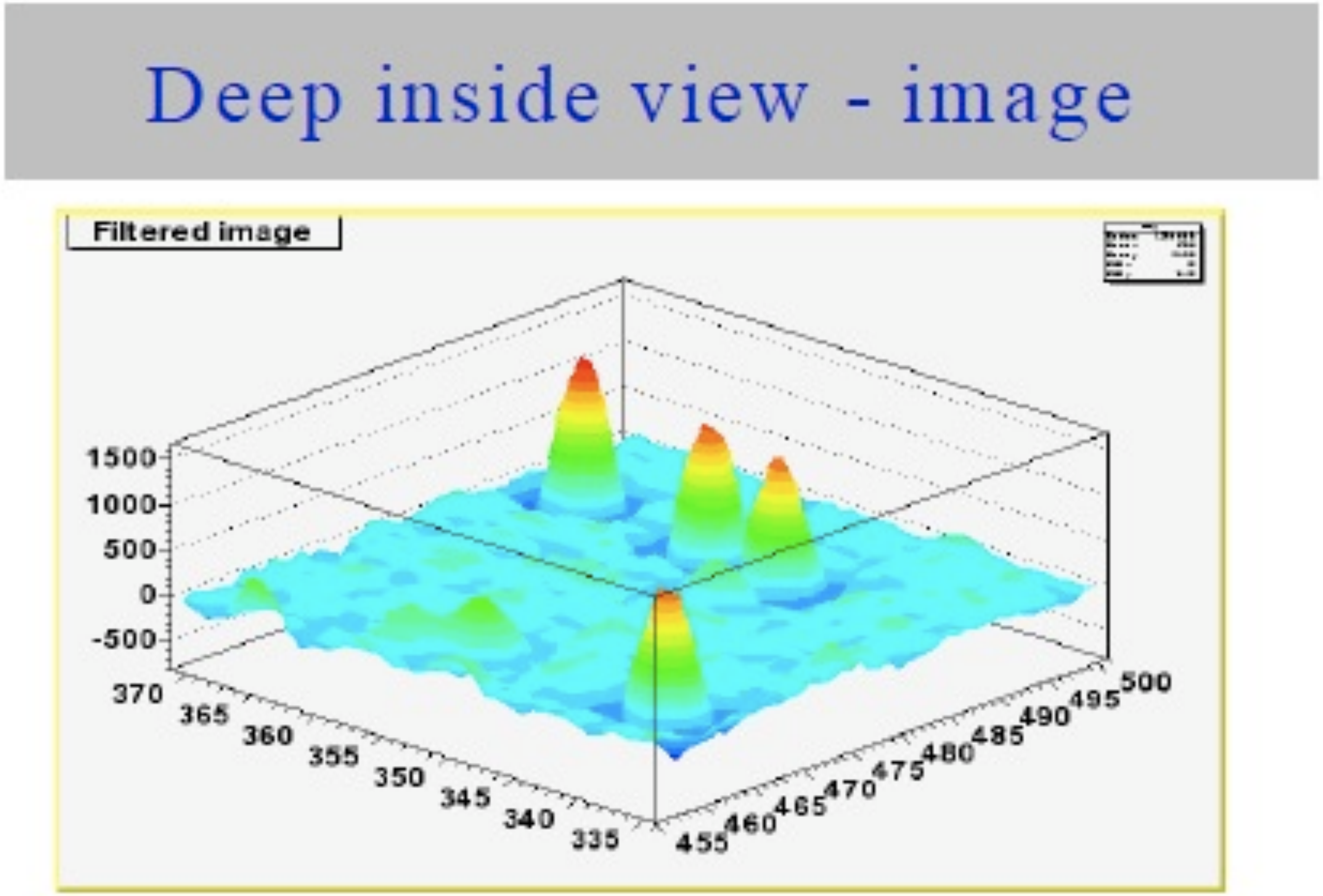
compatible π0 → 2 γ :
π0 mass: 110 ± 30 MeV



Scanning emulsion layers

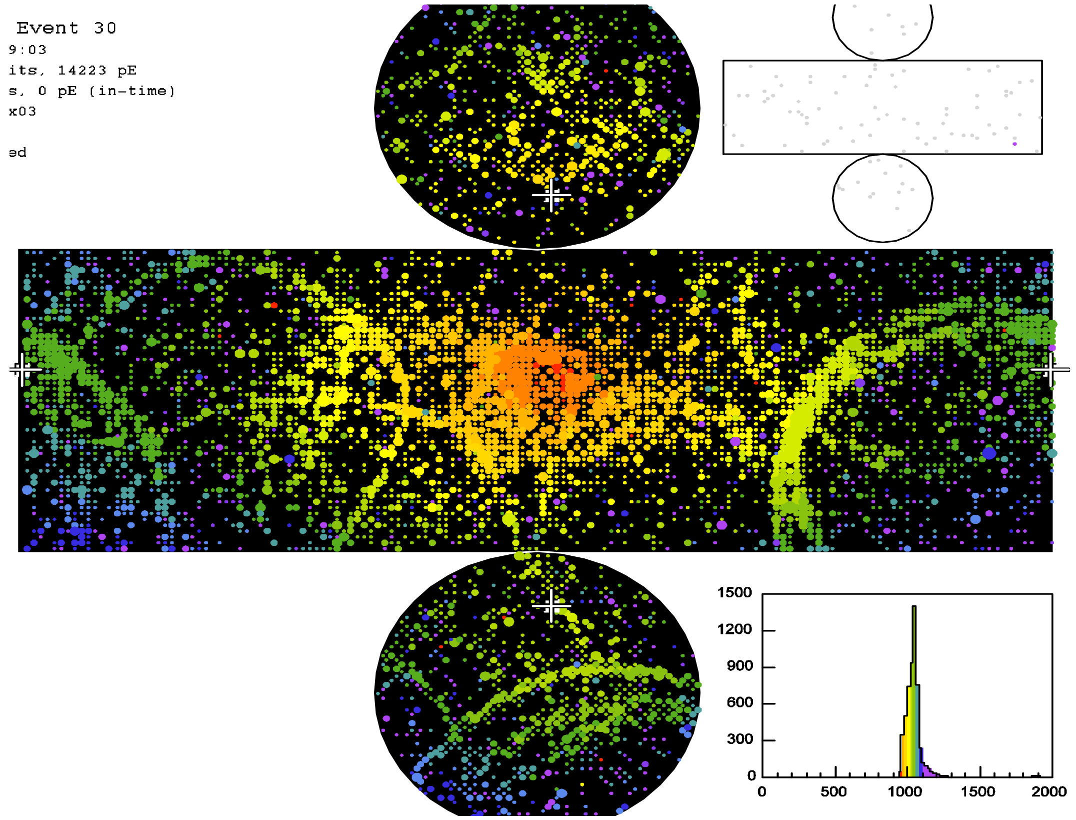
Tracking system is used to identify bricks with interesting events. Those bricks are removed from the detector and the emulsion layers are scanned and digitized.

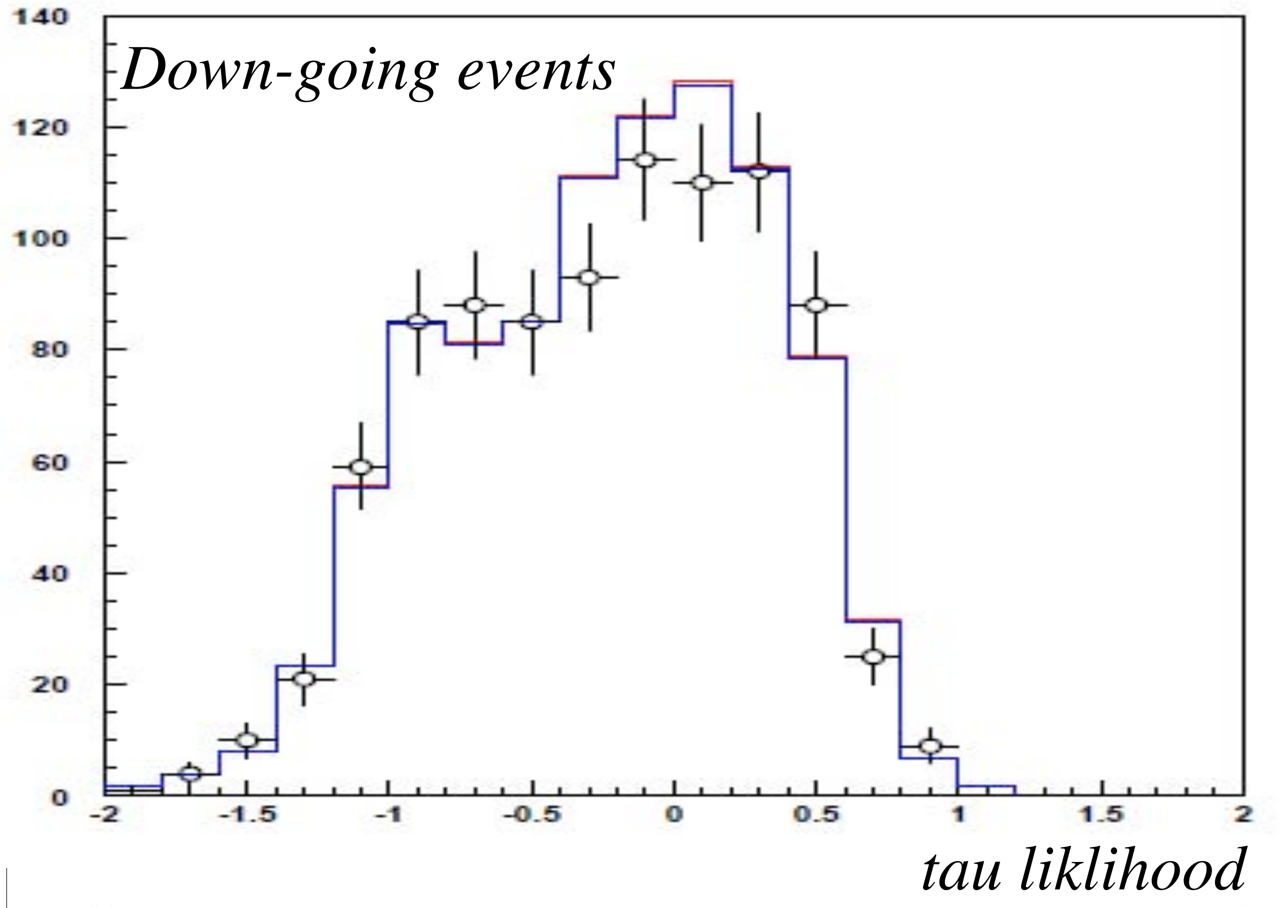


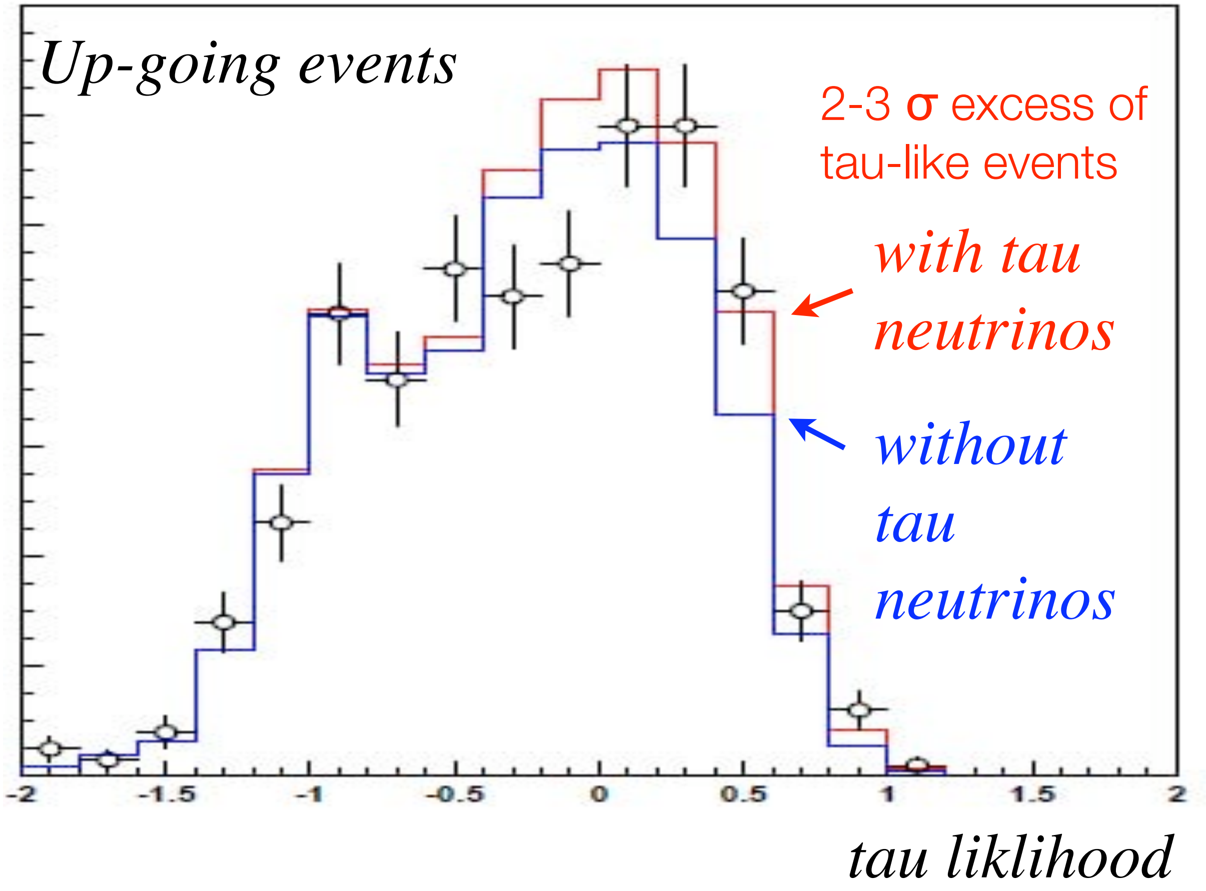


Four tracks in single emulsion layer

Statistical Tau Appearance







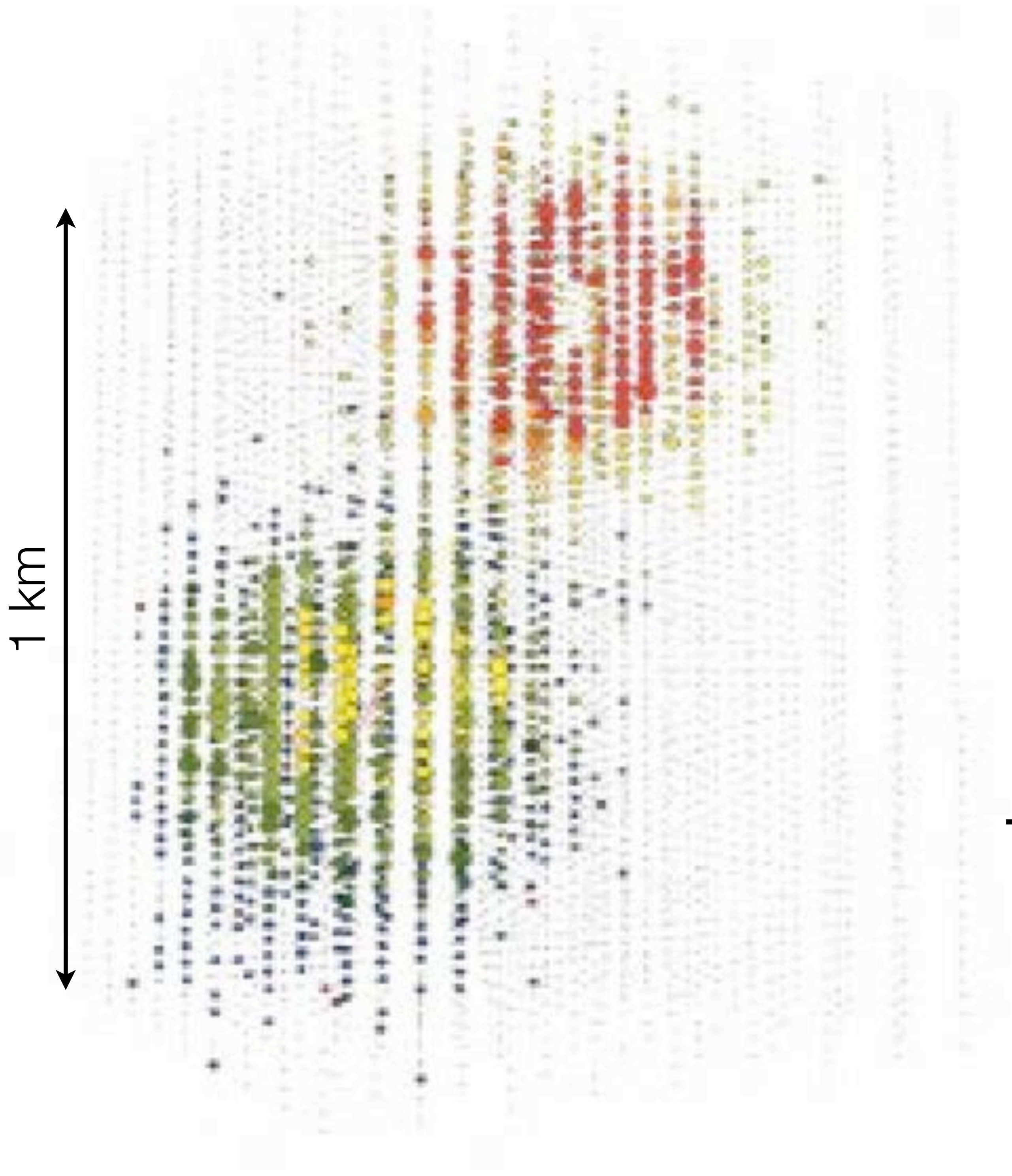
2-3 σ excess of tau-like events

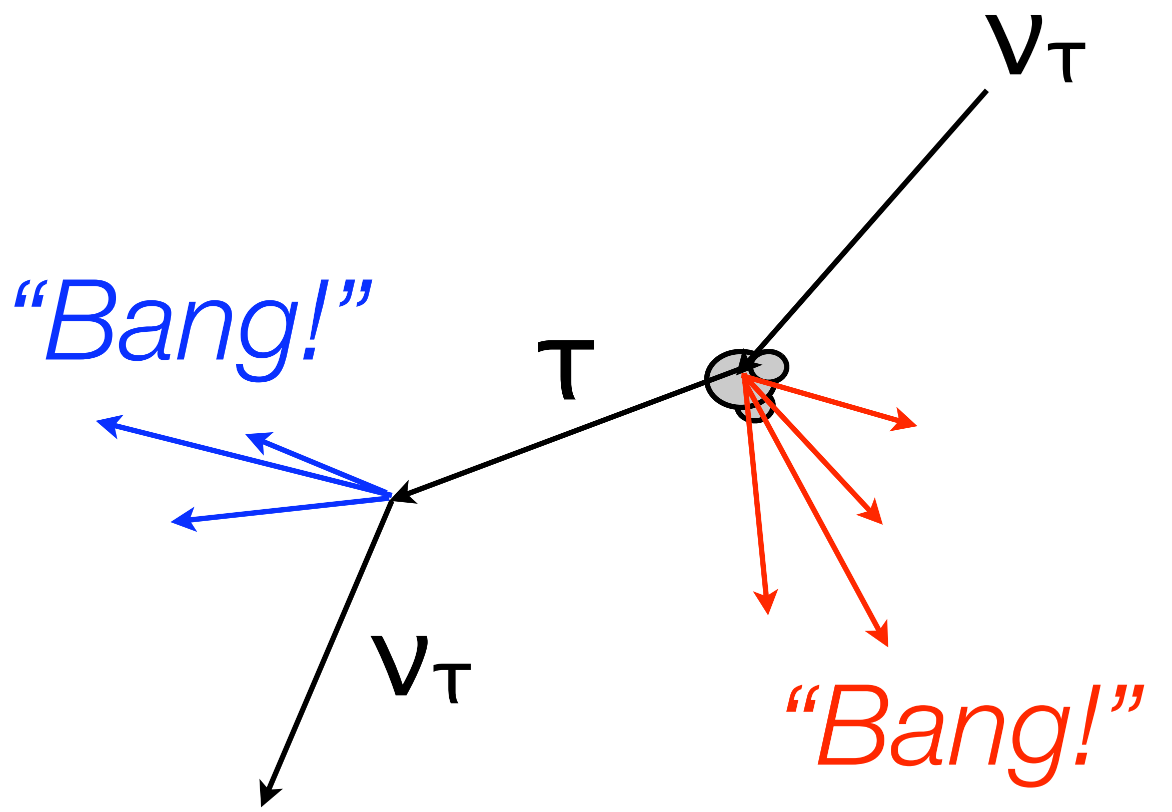
with tau neutrinos

without tau neutrinos

While large detectors may not to be able to identify tau neutrino events one-by-one, they may be able to separate tau neutrino events from other events statistically. In SK hadrons from tau decay travel about 1 interaction length (80 cm) and scatter. Produces large number of thin rings.

Tau neutrinos in Ice Cube: Double bang

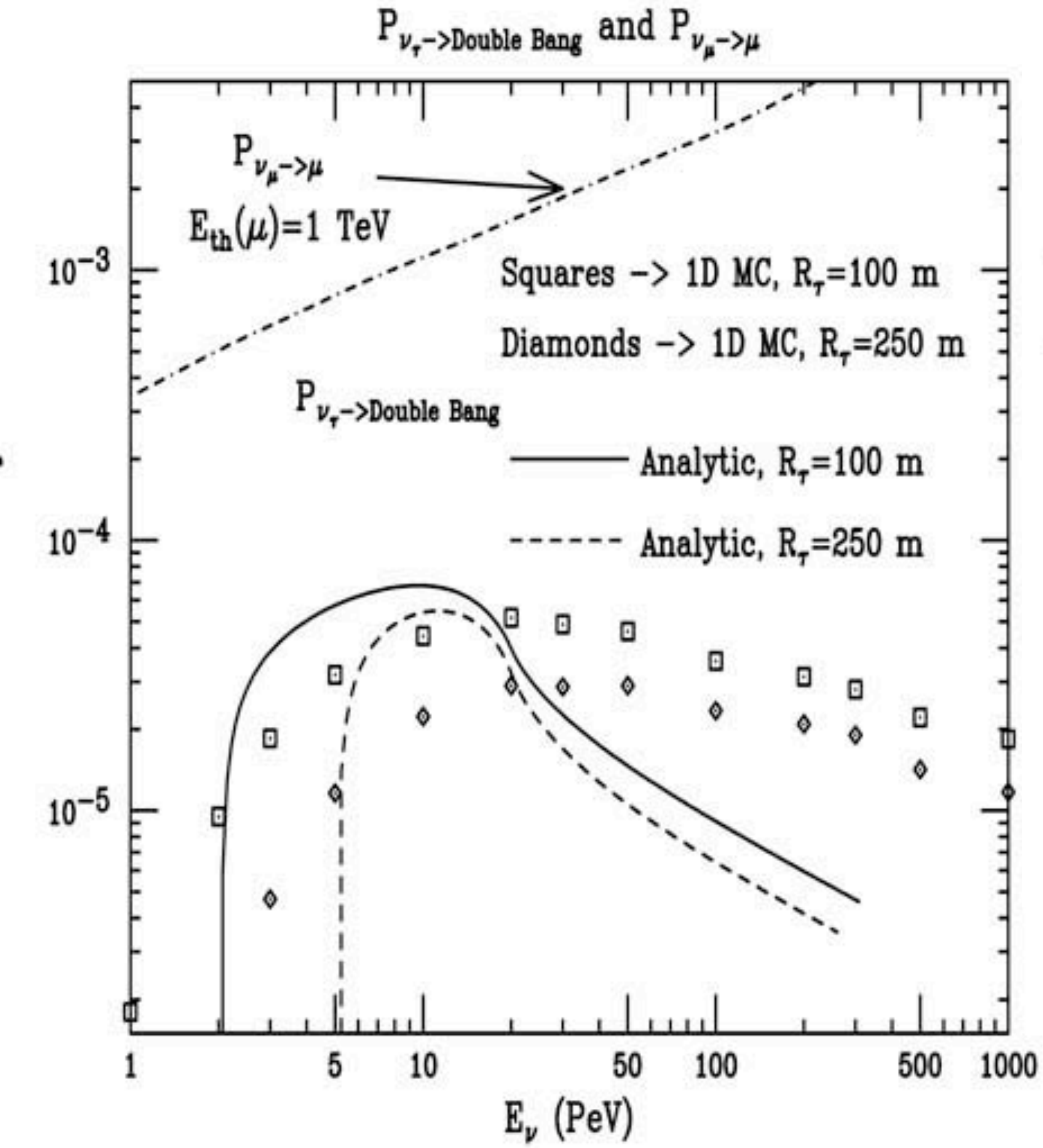




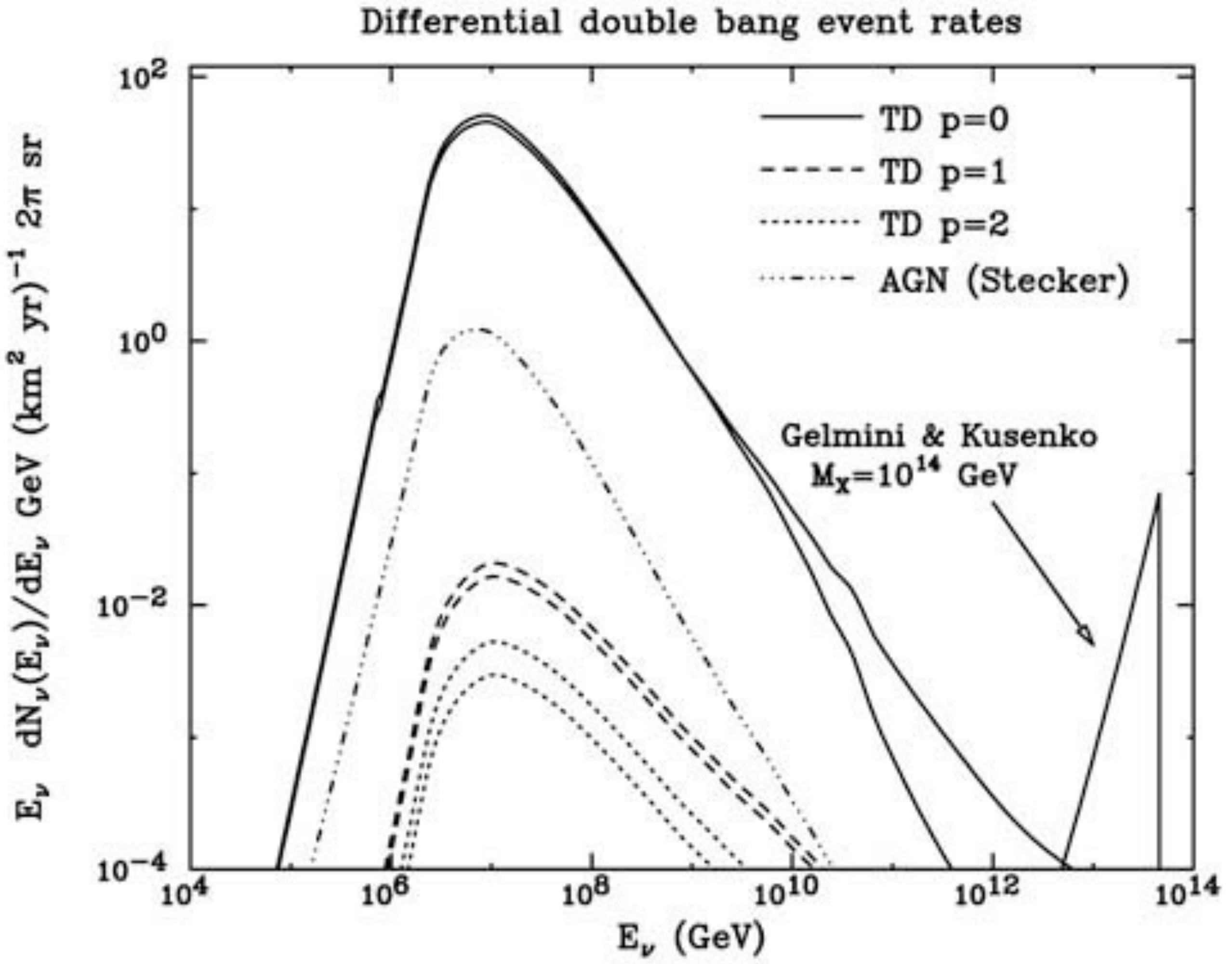
Tau decay length:

$$\begin{aligned}
c\tau_{\mathrm{LAB}} &= (3\times 10^{8}\ \mathrm{m/s})(290\times 10^{-15}\ \mathrm{s})(\frac{E}{1.7\ \mathrm{GeV}}) \\
&= 5\times 10^{-5}\ \mathrm{m}\times E[GeV] \\
&= 50\ \mathrm{m\ for}\ E = 1\ \mathrm{PeV}
\end{aligned}$$

Tau neutrinos in Ice Cube: Double bang



Probability for tau neutrino to produce detectable “double bang” event

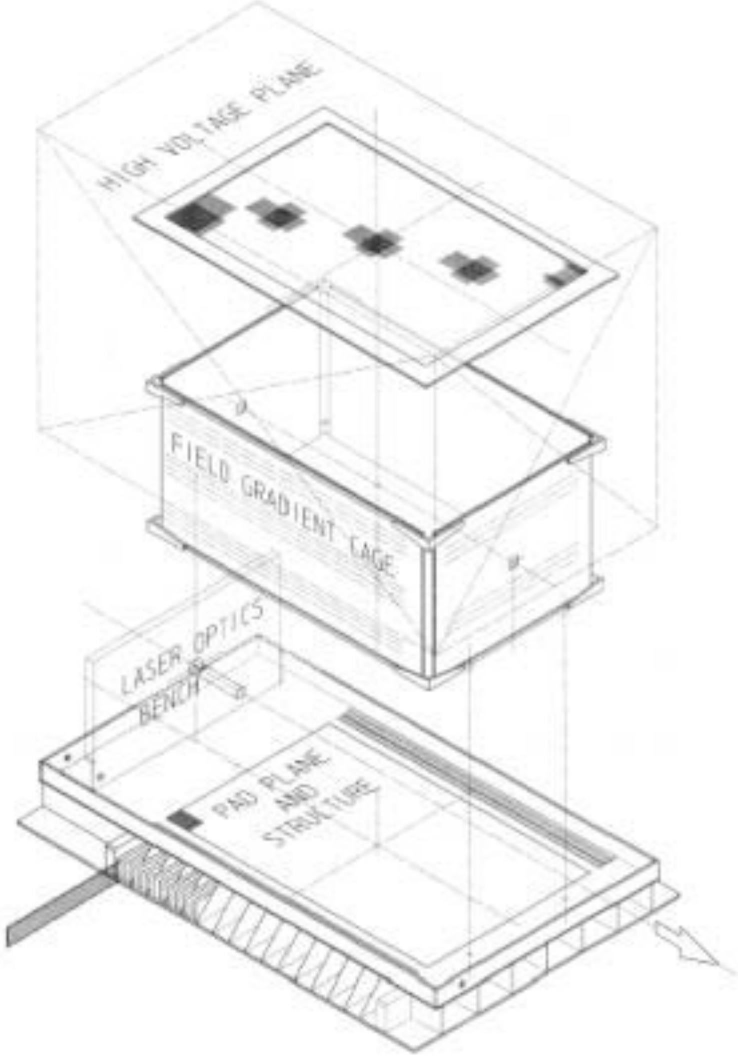


Integrates to ~0.01 or 100 events per year for models of topological defects. ~1 / year from AGNs.

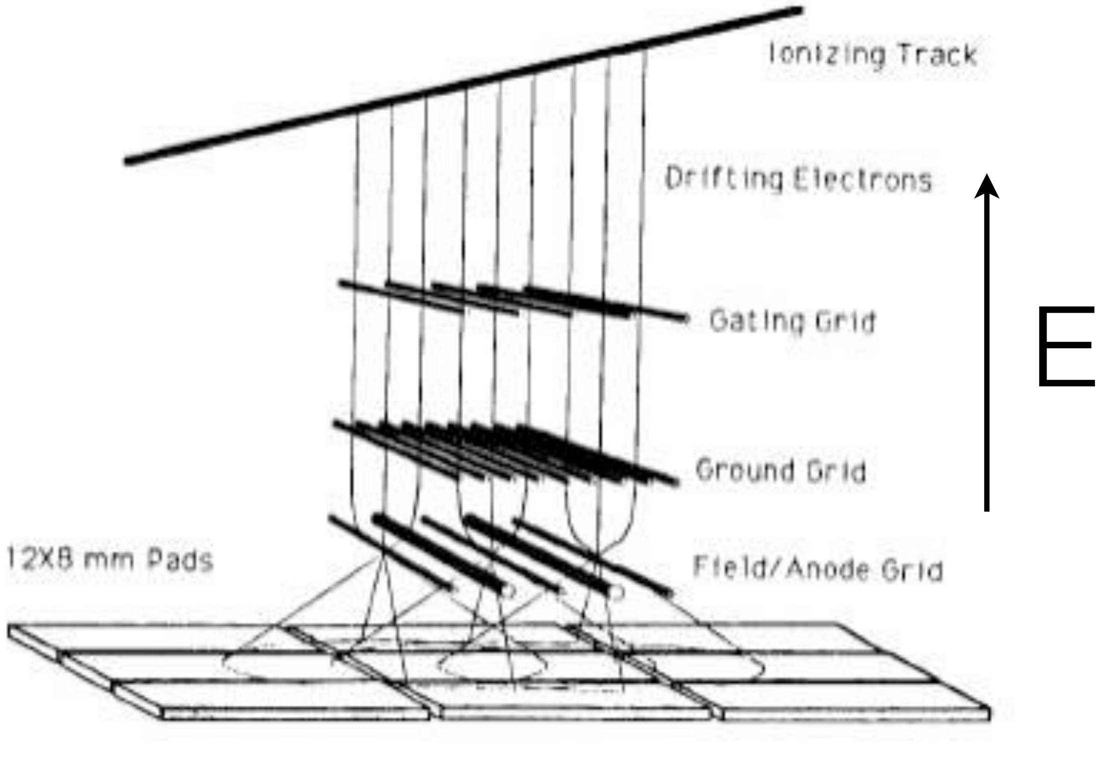
Time Projection Chambers

Time projection chambers (TPCs)

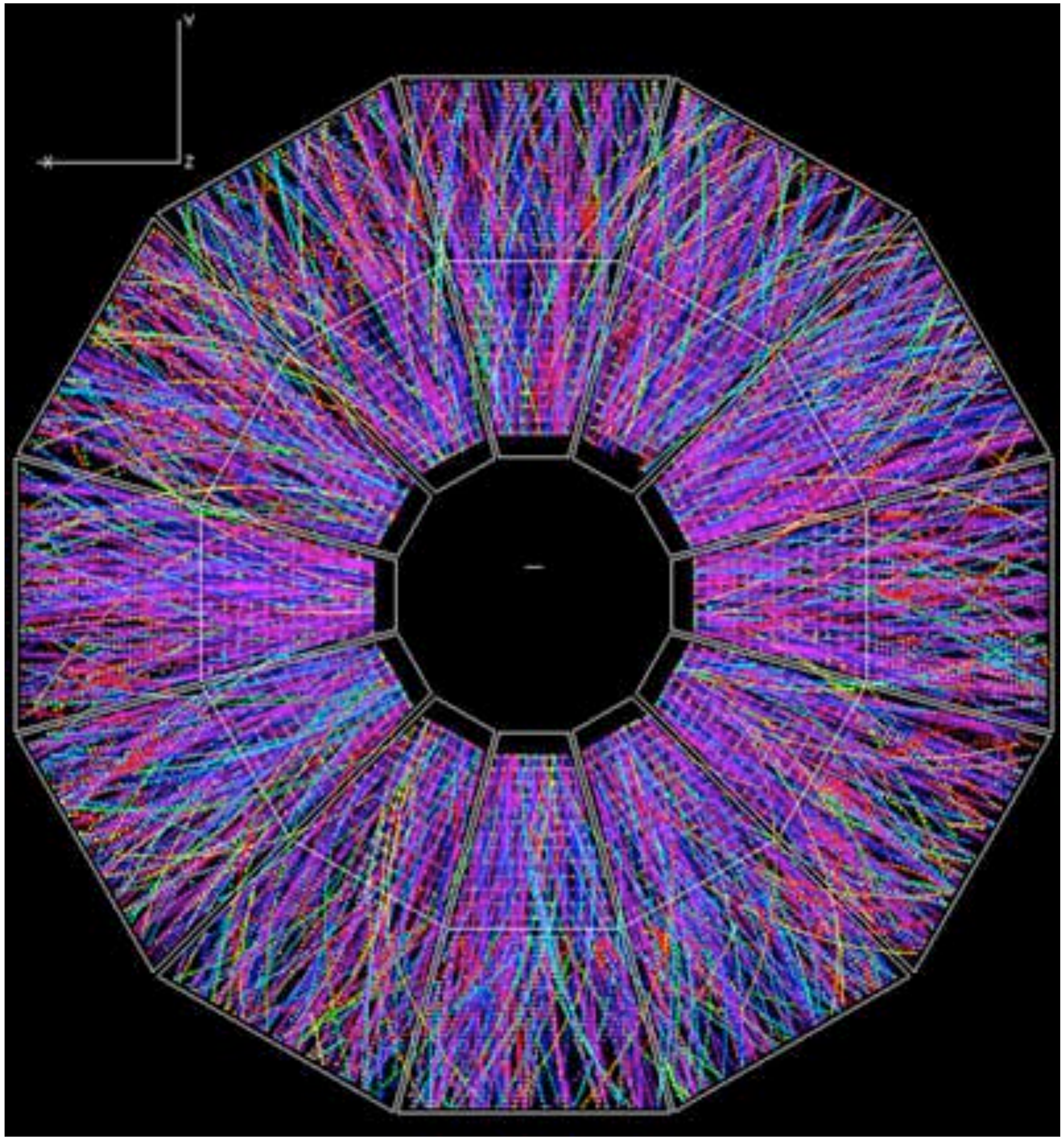
- Gas TPC’s have been widely used by a number of high energy and nuclear experiments
- Provide 3D tracking with ~mm resolution.
- Particle ID possible below 1 GeV using <dE/dx>
- A very common gas Argon-Methane gas mixture. Nobel gas allows for long electron drifts and methane boosts ionization yield.
- Electric fields typically 200 V/cm
- Electron clouds reach terminal velocity at about 5 cm/usec.
- Pads or wire chambers provide 2-D track projection. Arrival times provide 3rd dimension.



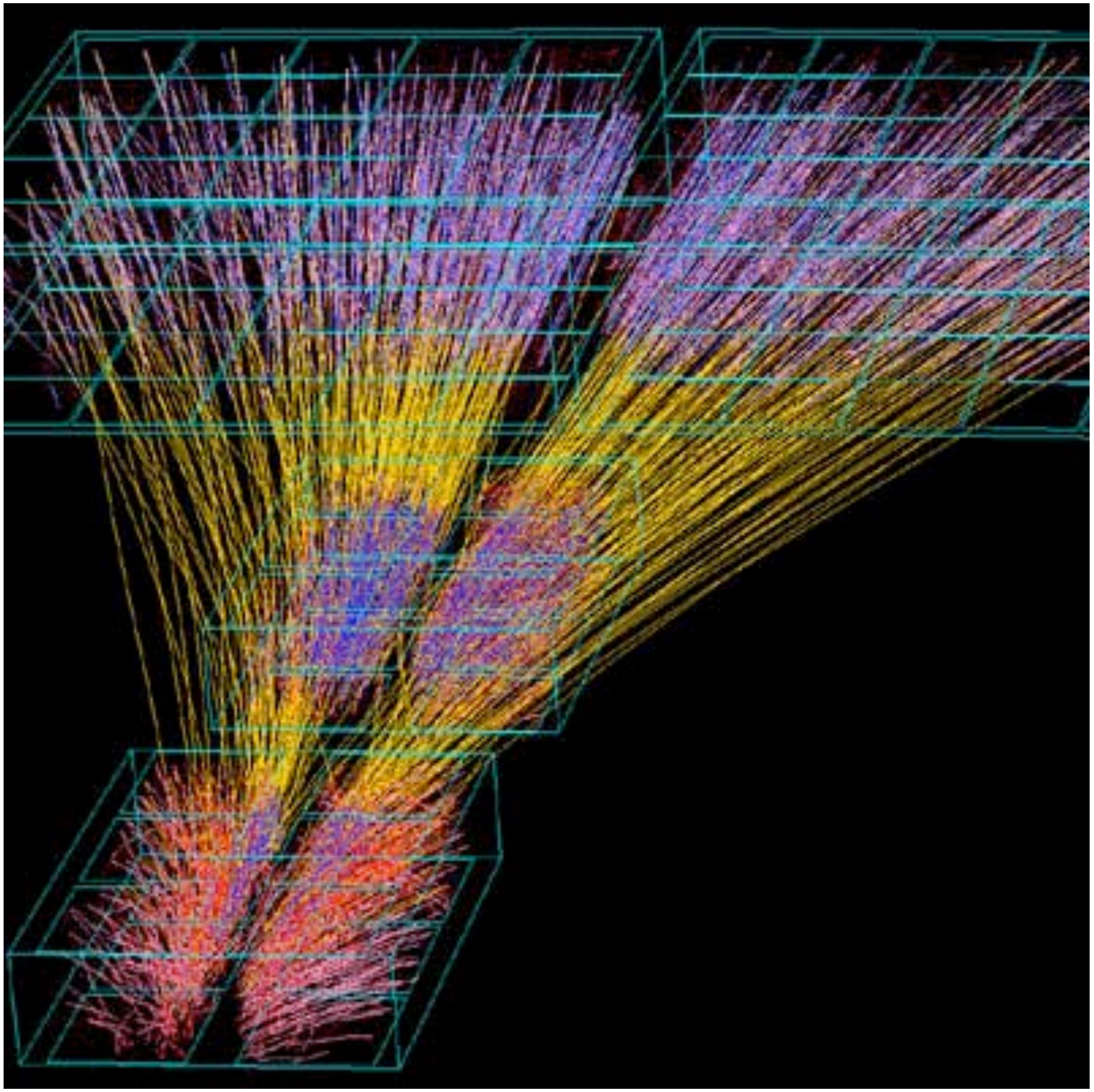
HISS TPC PAD PLANE



TPCs are well suited to high multiplicity environments

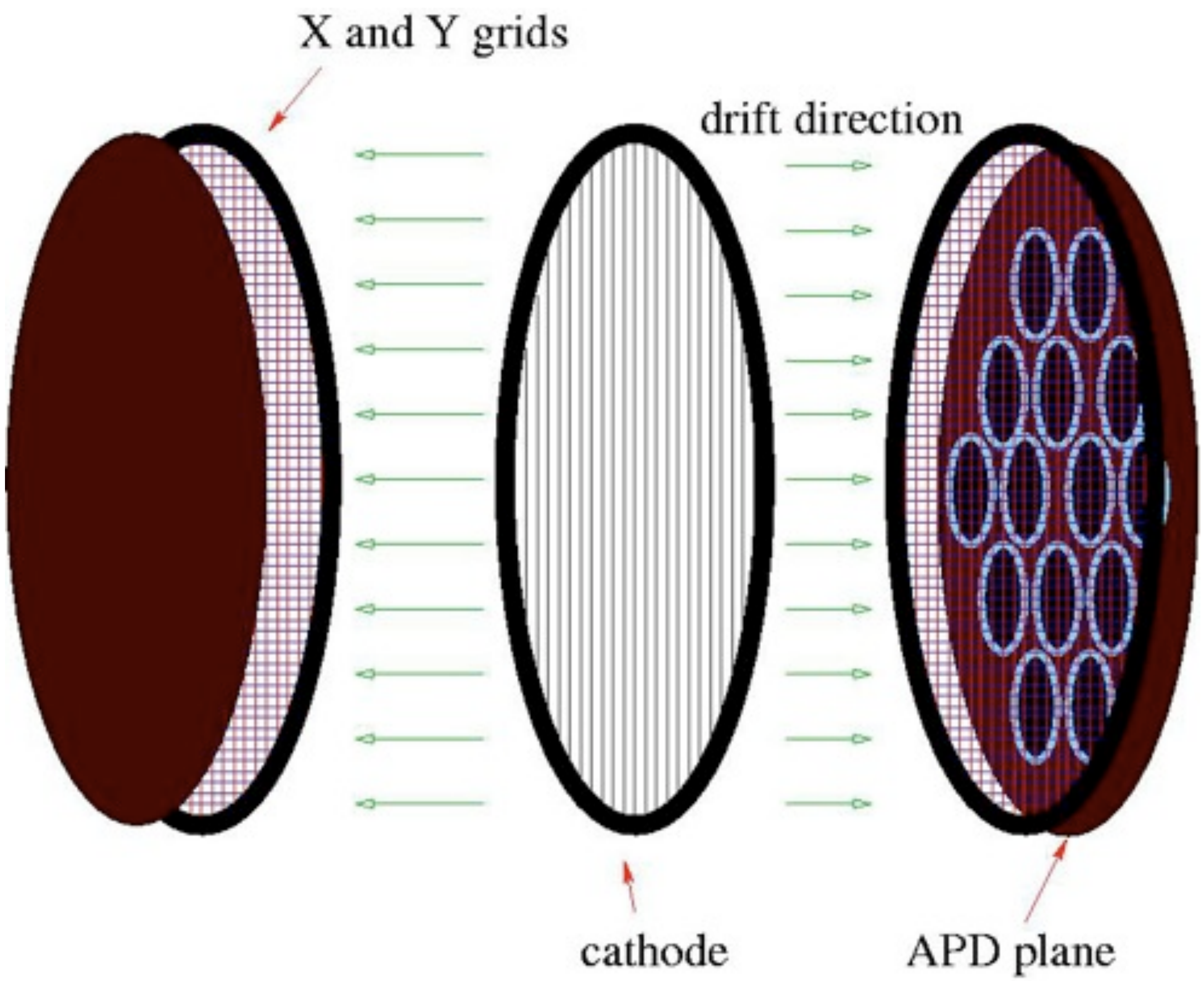


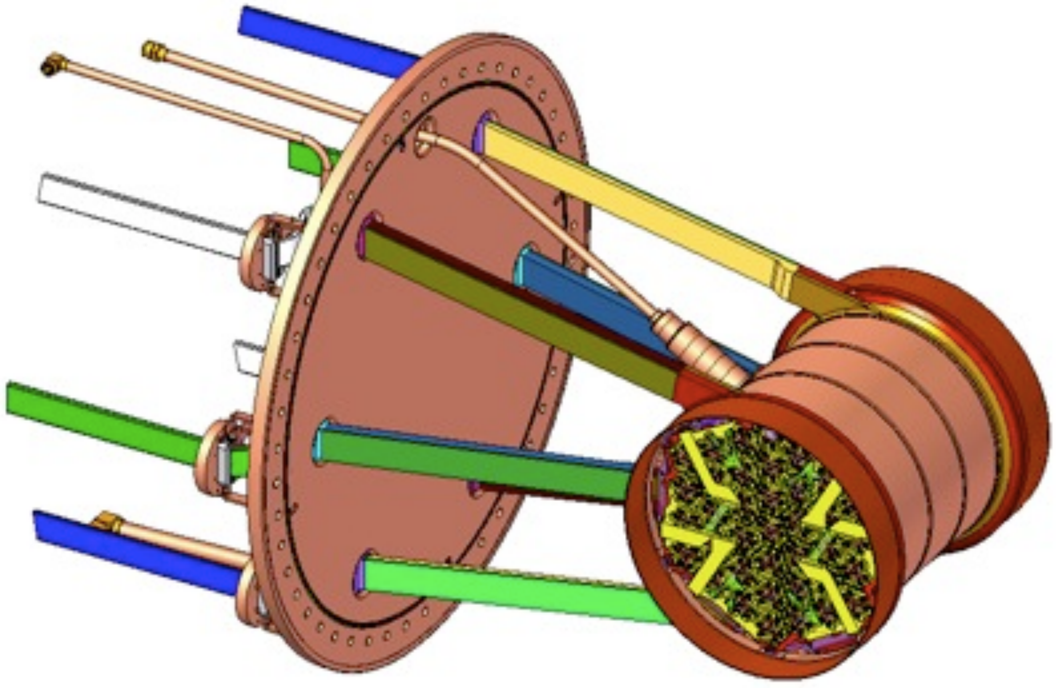
Au + Au at 130 GeV in STAR @ BNL



Pb + Pb at 17 GeV in NA49 @ CERN

Liquid Xe TPC : EXO

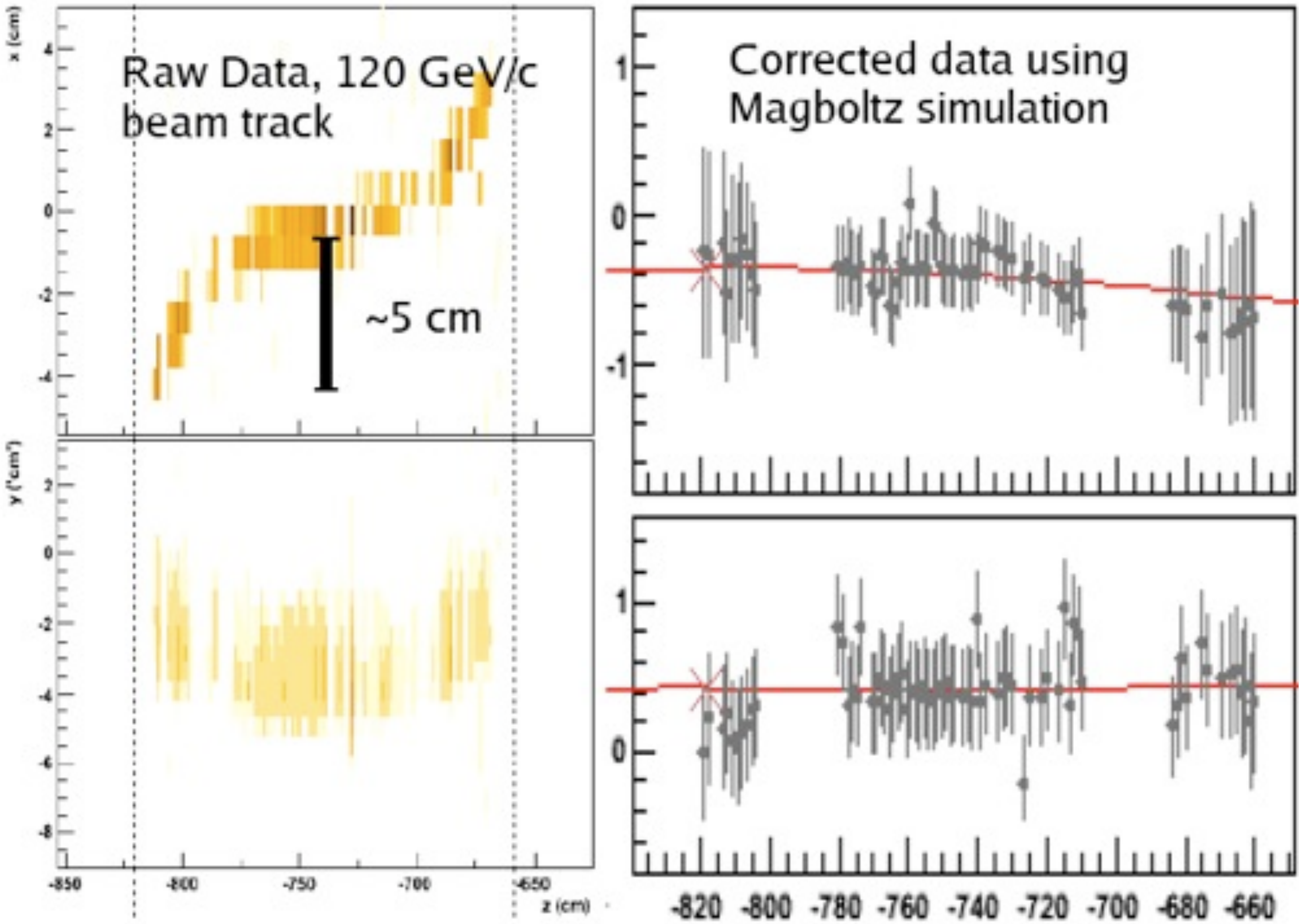




TPC for 0νββ

Operation of TPC in magnetic field

- Very common to operate TPC's in magnetic fields
- Need to minimize $\vec{E} \times \vec{B}$ or electron drifts become extremely complicated
- In general not a problem if size of TPC << aperture of magnet. But, if these are comparable, B field will inevitably have bends.
- If corrections are large, do not trust analytical calculations (eg. Rolandi and Blum) which assume linear "drag" term on electron drift. Rather, learn to use the MAGBOLTZ program.

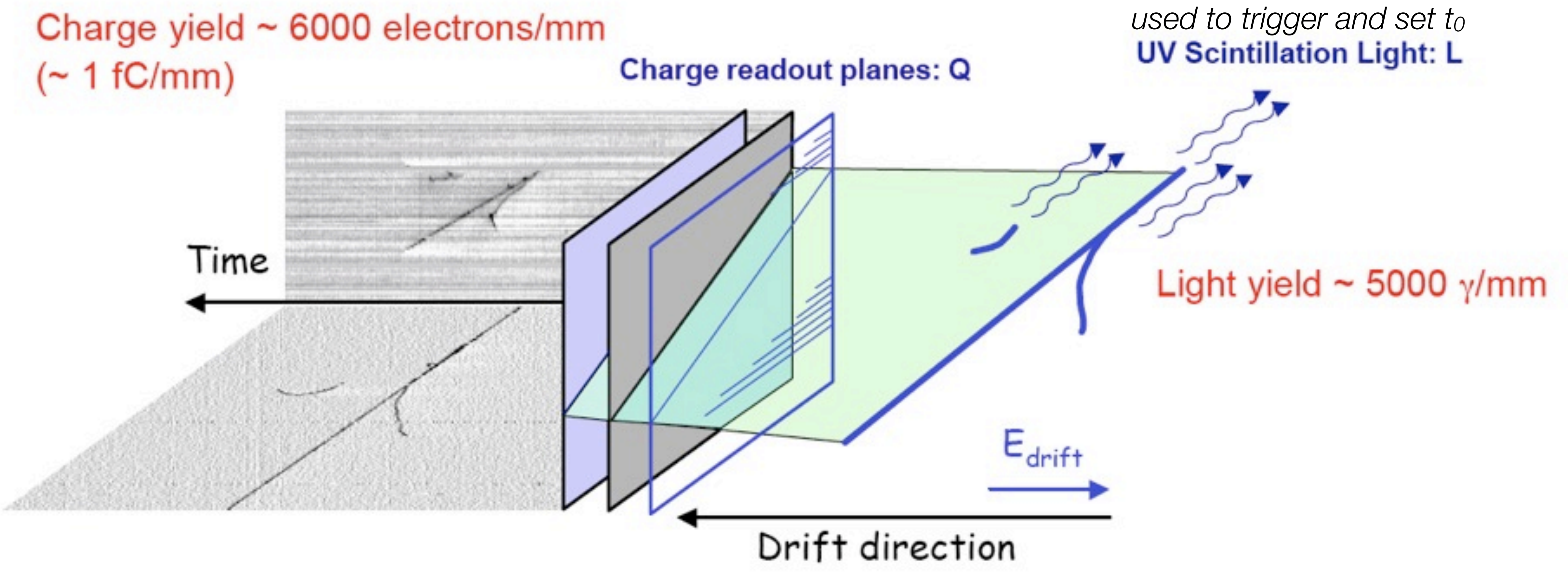


5 cm distortion over ~1 m drift in a gas Ar TPC (MIPP) due to ExB effects

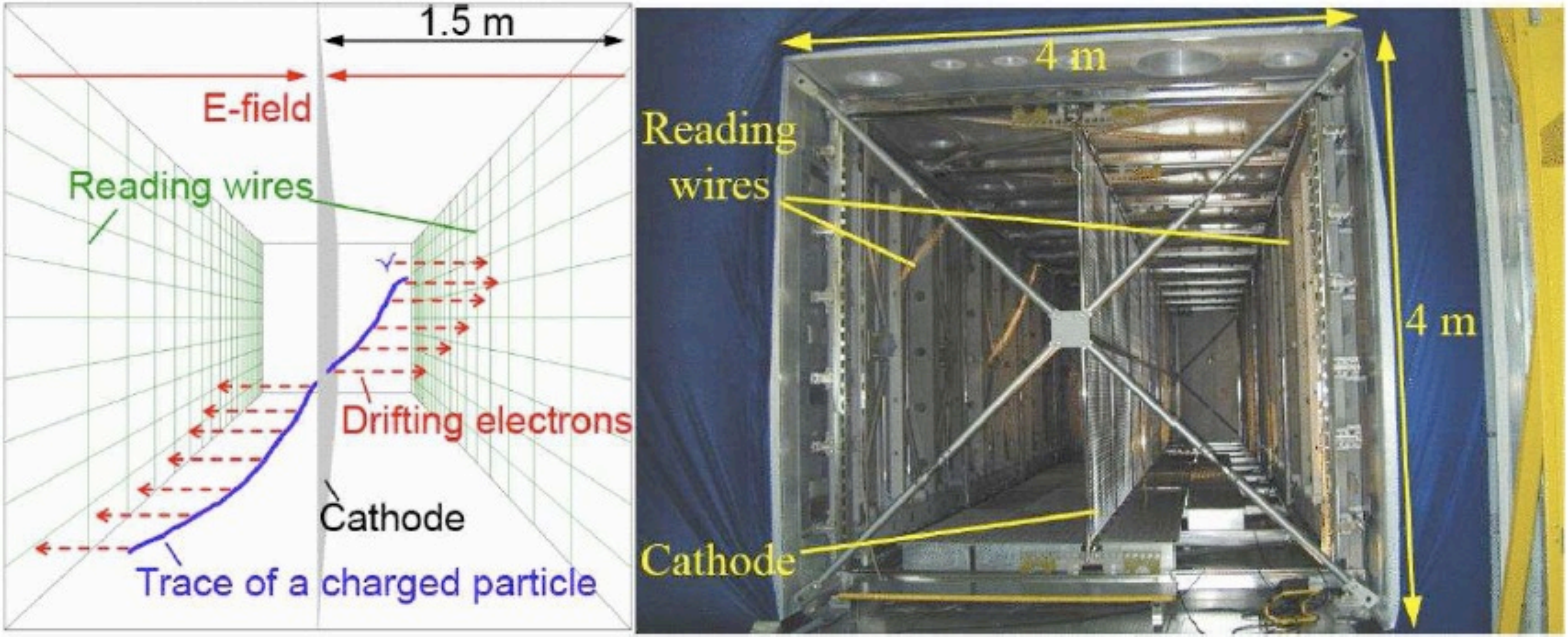
Liquid Argon TPC: Concept

To be applicable to neutrino experiments higher density is required. Use liquid Ar instead of gas. Has potential to reach very large masses (100 kt) with ~mm granularity.

- Boiling point: 87 K (compare to N_2 77 K)
- Density 1.4 g/cc
- Interaction length: 114 cm
- Radiation length: 14 cm
- Moliere radius: 7 cm



The ICARUS LqAr Detector



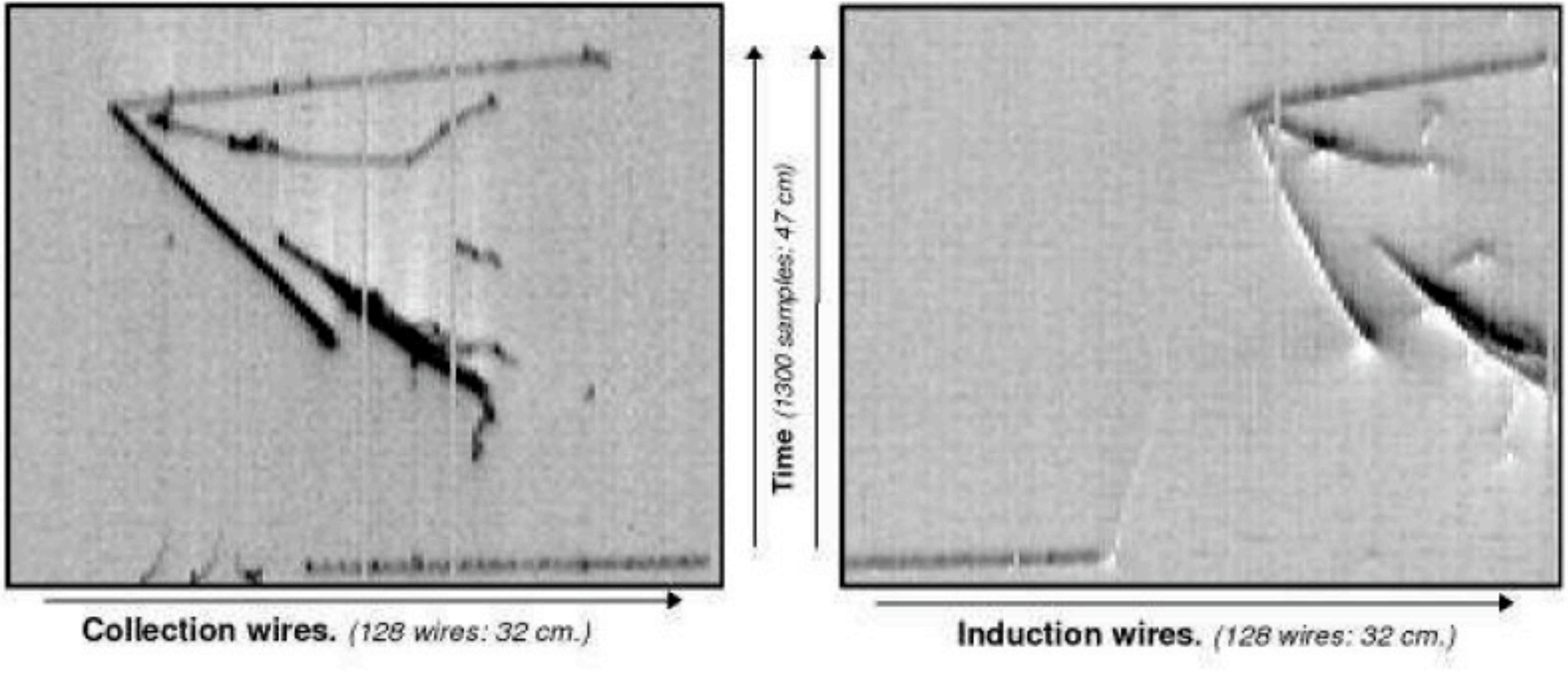
A.M. de la Ossa Romero, hep-ex/0703026

Figure 2.4: Picture of the open T300 ICARUS module during assembly.

What’s going on in this event?

Recorded by 50L LqAr detector in WANF beam

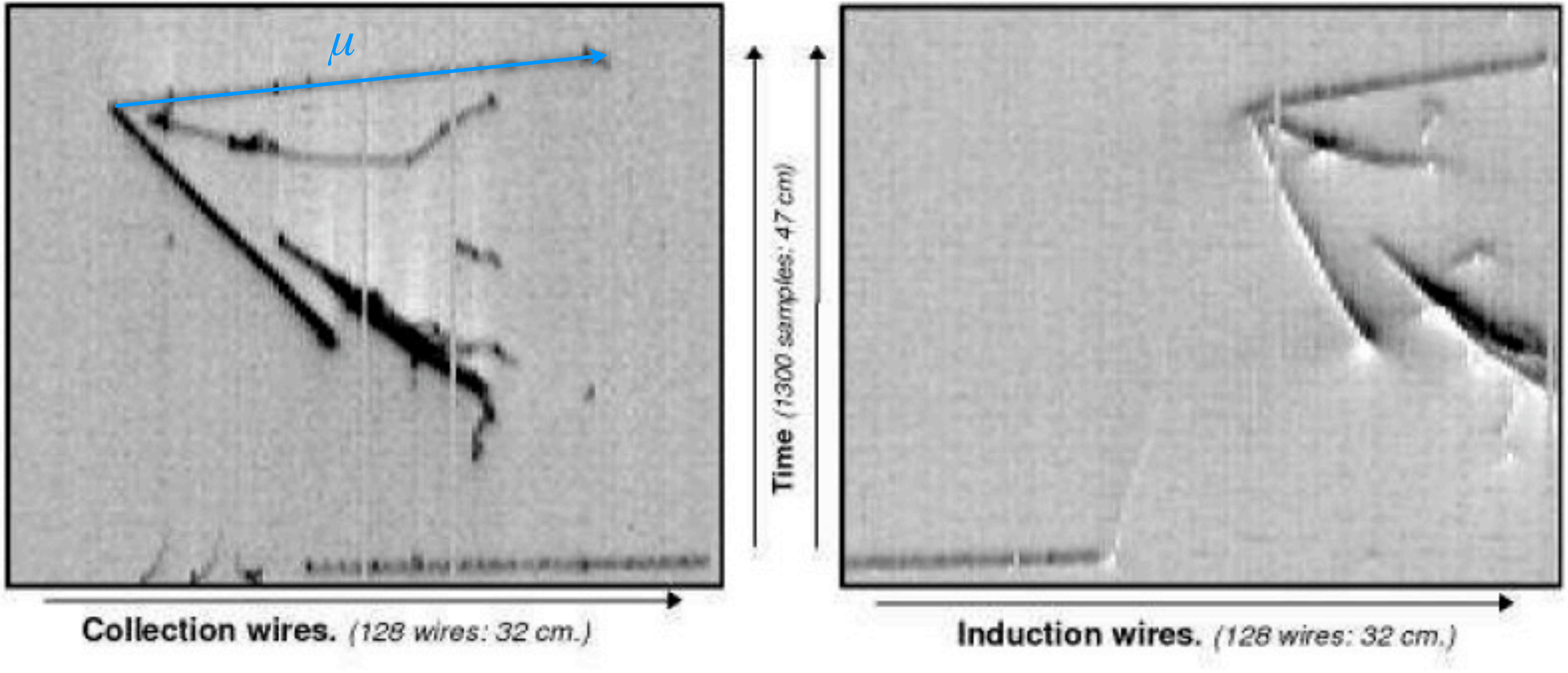
A.M. de la Ossa Romero, hep-ex/0703026



What's going on in this event?

Recorded by 50L LqAr detector in WANF beam

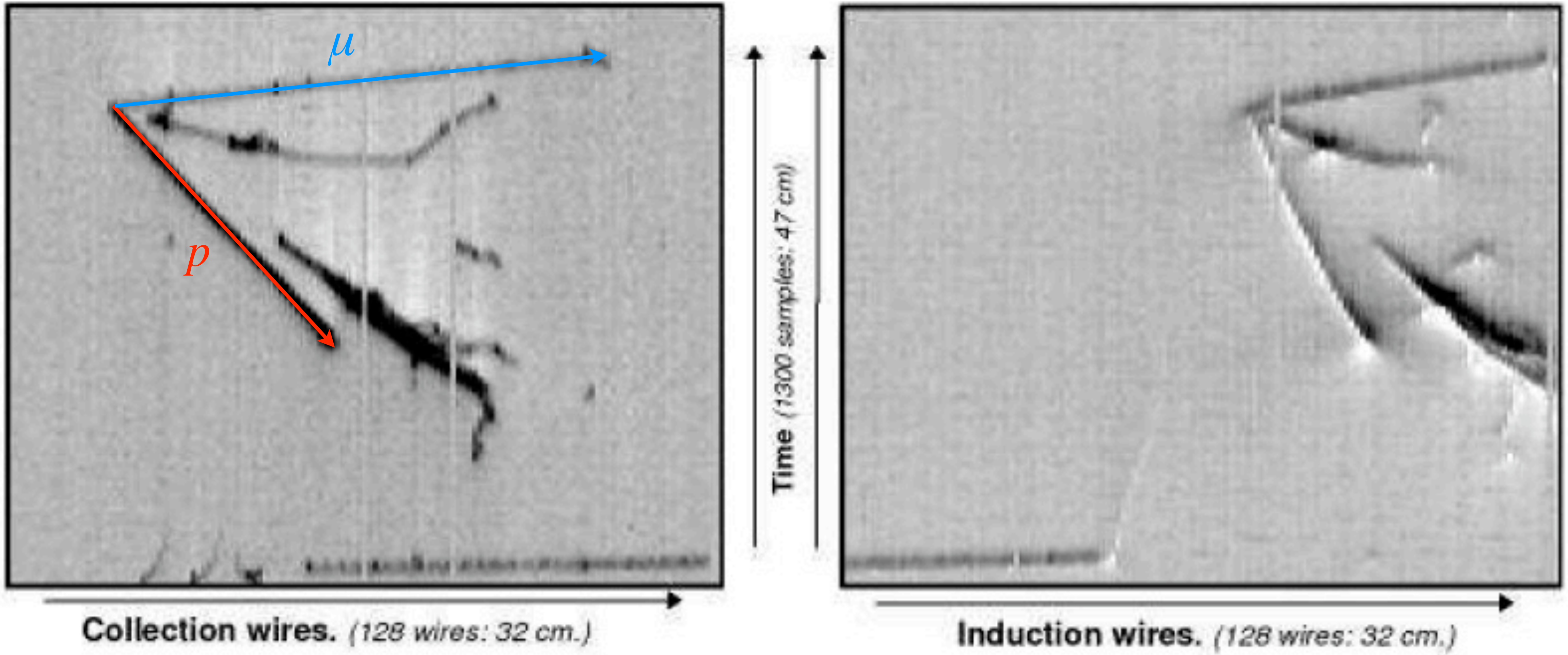
A.M. de la Ossa Romero, hep-ex/0703026



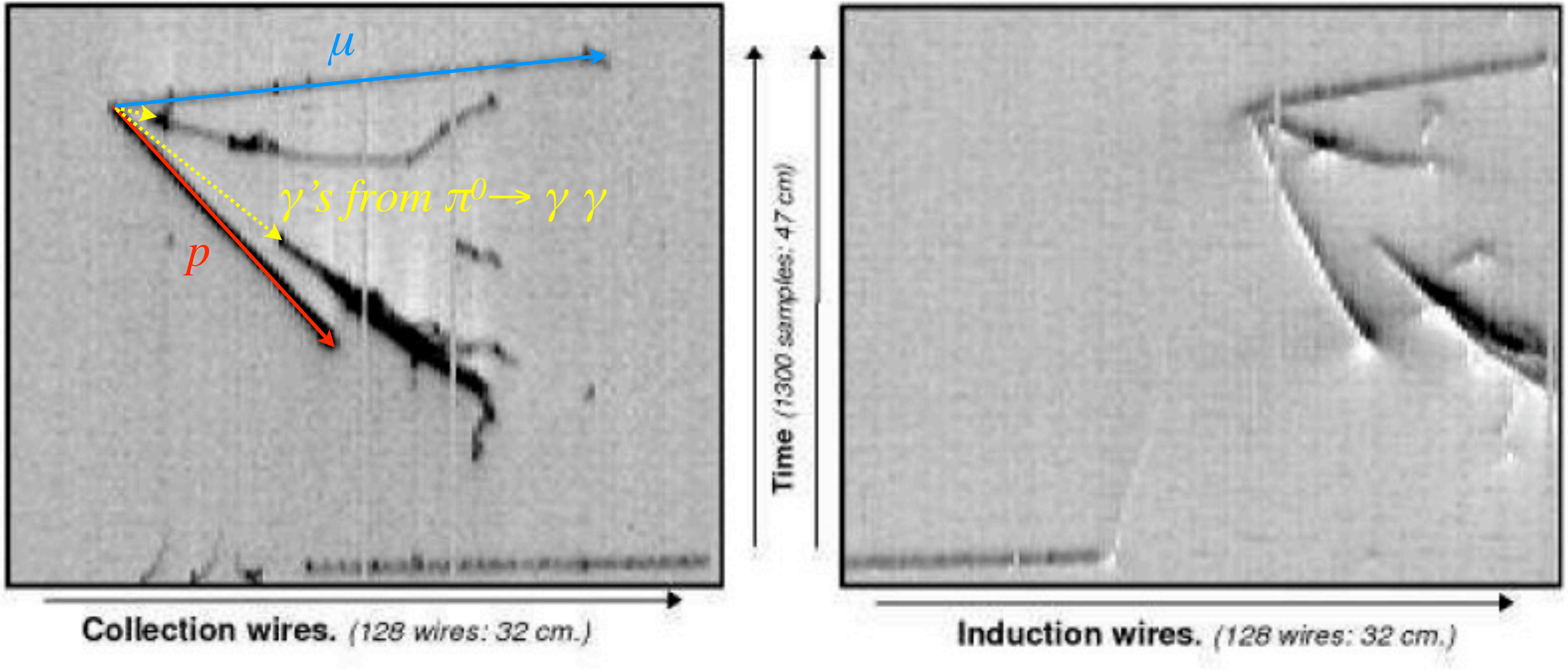
What’s going on in this event?

Recorded by 50L LqAr detector in WANF beam

A.M. de la Ossa Romero, hep-ex/0703026



What’s going on in this event?
Recorded by 50L LqAr detector in WANF beam



A.M. de la Ossa Romero, hep-ex/0703026

What’s going on in this event?

Recorded by 50L LqAr detector in WANF beam

A.M. de la Ossa Romero, hep-ex/0703026

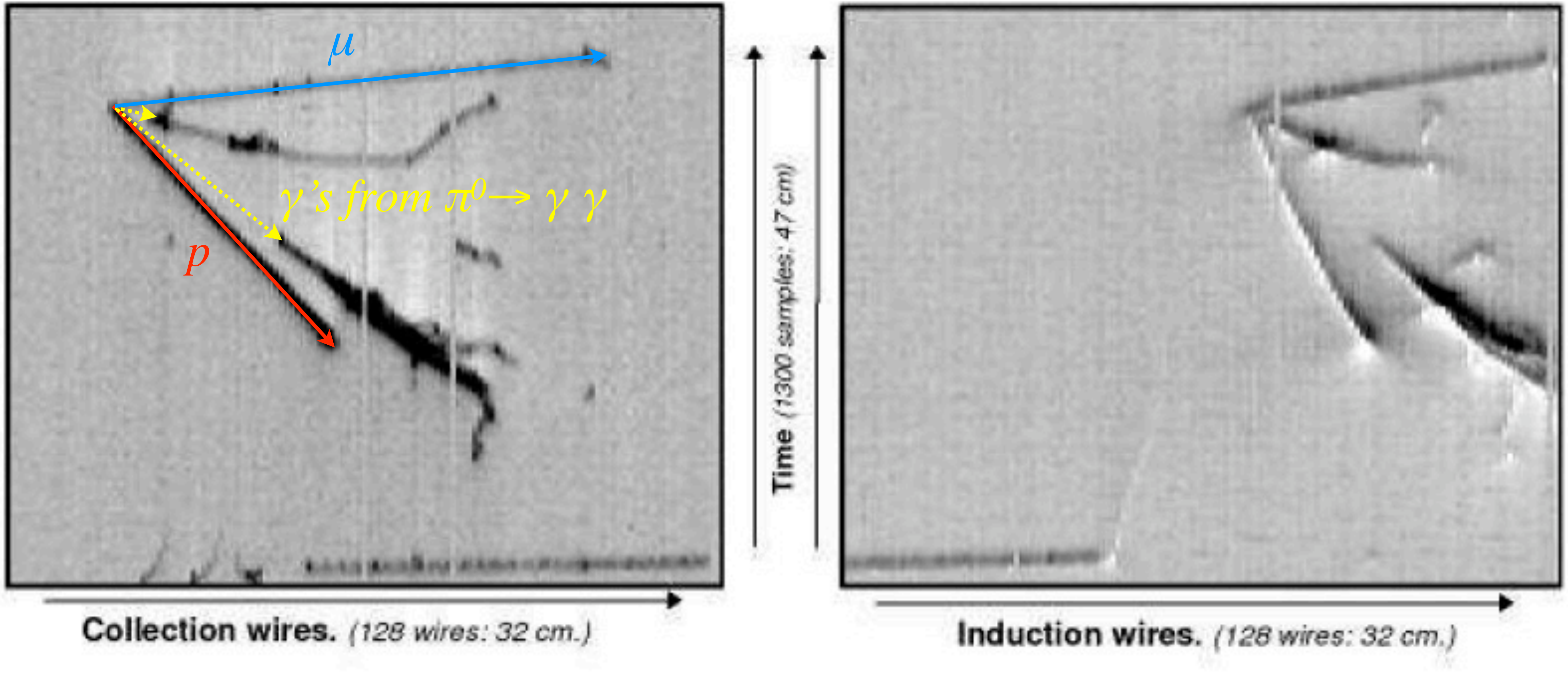
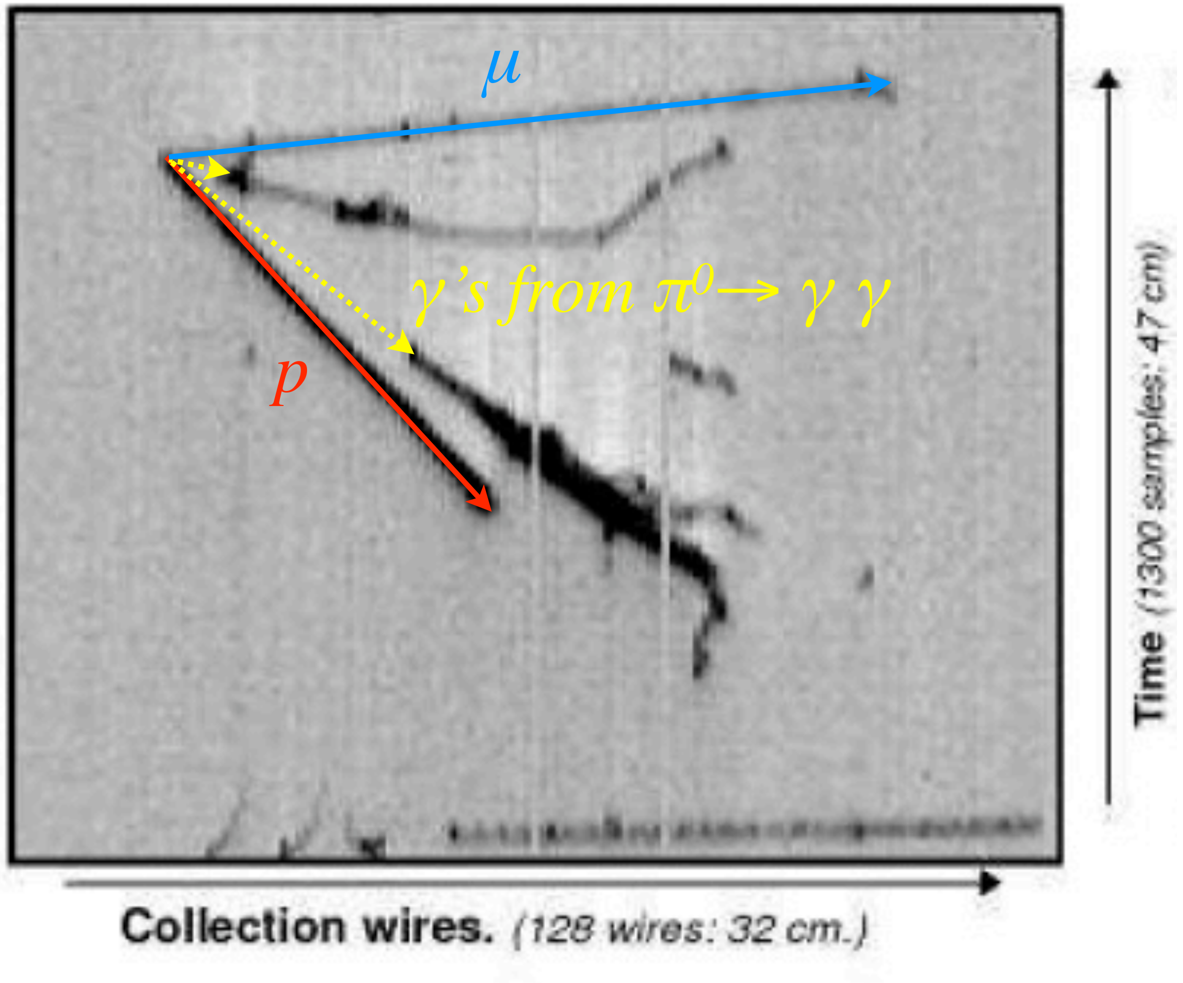


Figure 5.21: The raw image of a low multiplicity real event in the collection (left) and induction plane (right). The event is reconstructed as ($\nu_\mu\ n \rightarrow \mu^- \Delta^+ \rightarrow \mu^-\ p\ \pi^0$) with a mip leaving the chamber, an identified stopping proton and a pair of converted photons from the π^0 decay. When these photons escape from the chamber, the event is tagged as a *golden* event.

What's going on in this event?
Recorded by 50L LqAr detector in WANF beam

A.M. de la Ossa Romero, hep-ex/0703026



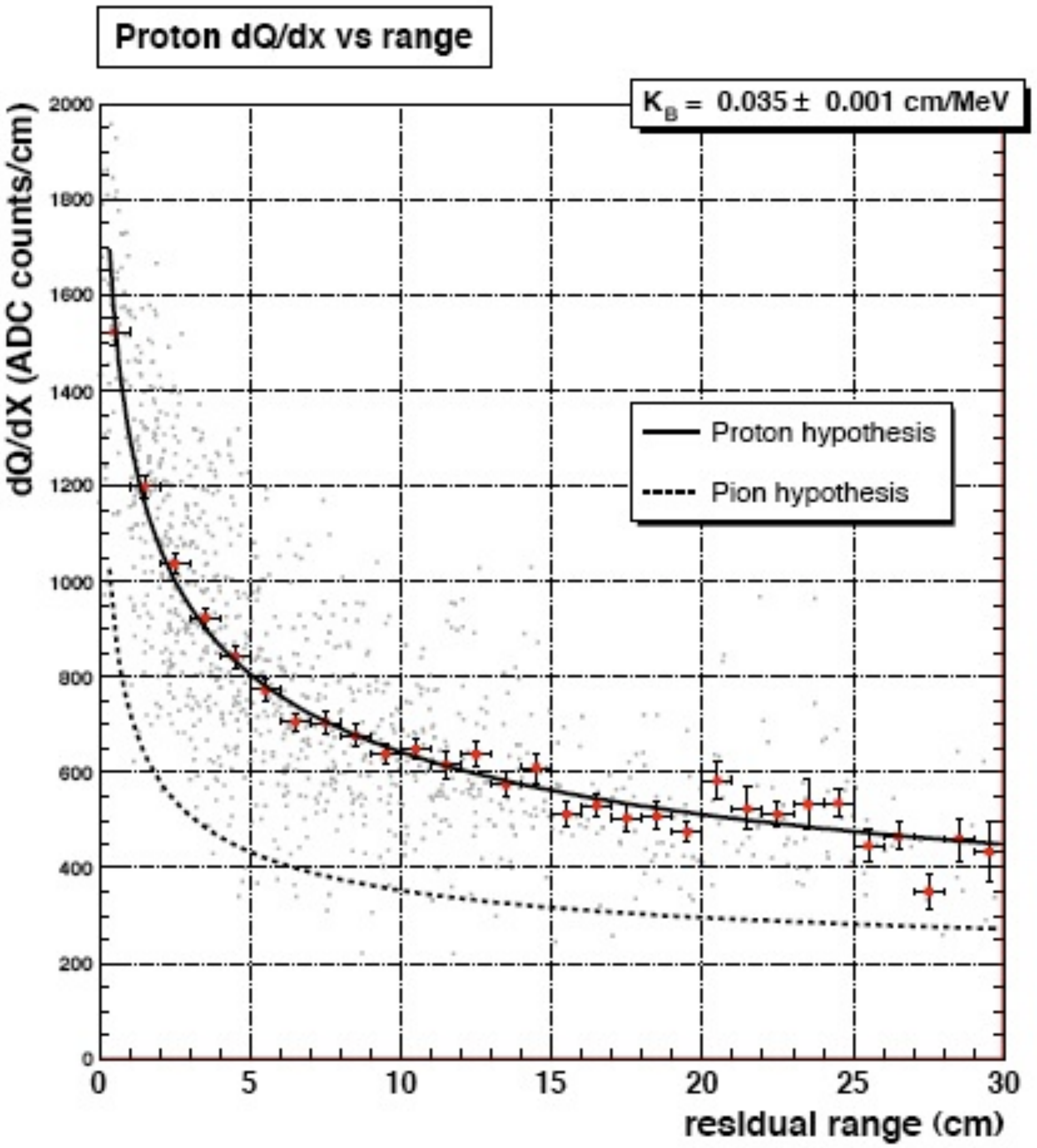
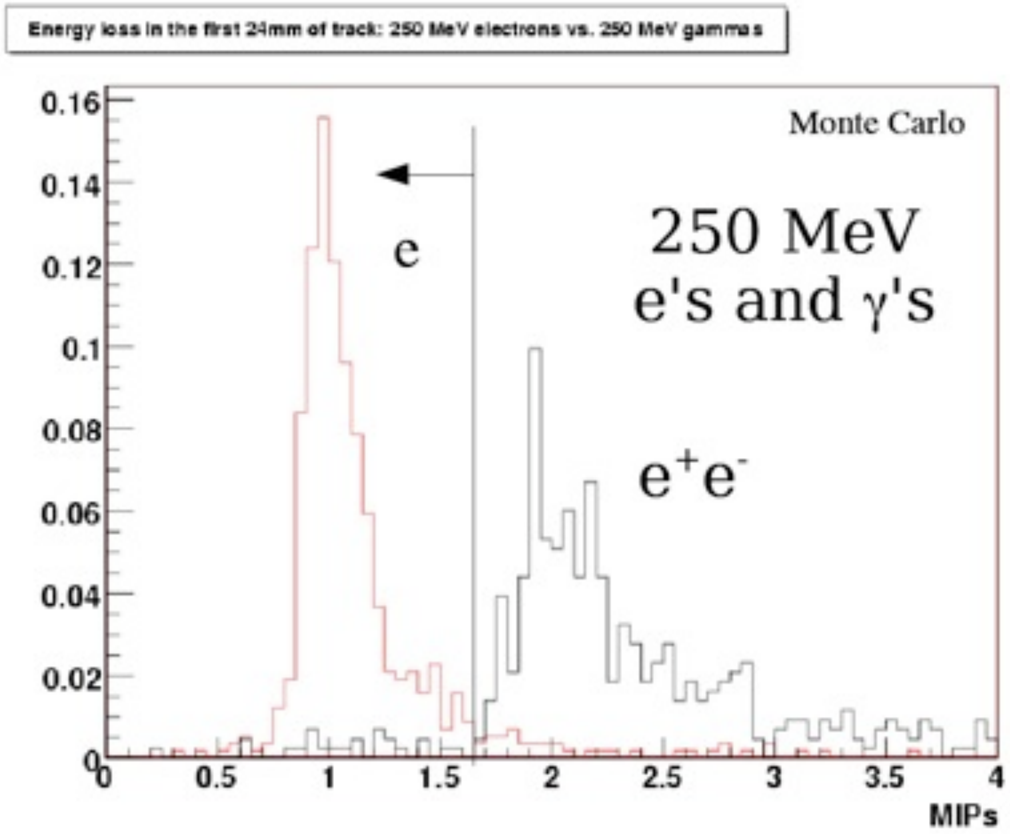
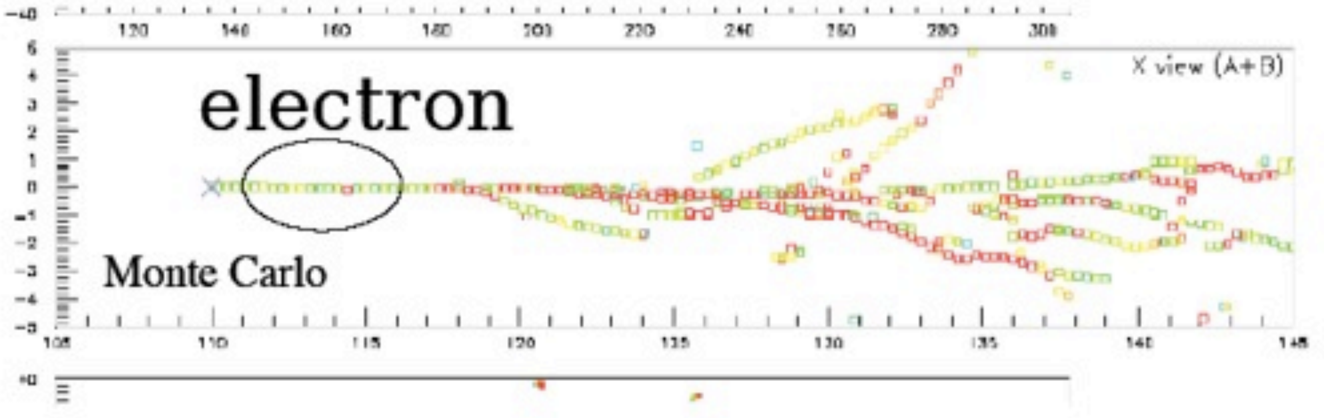


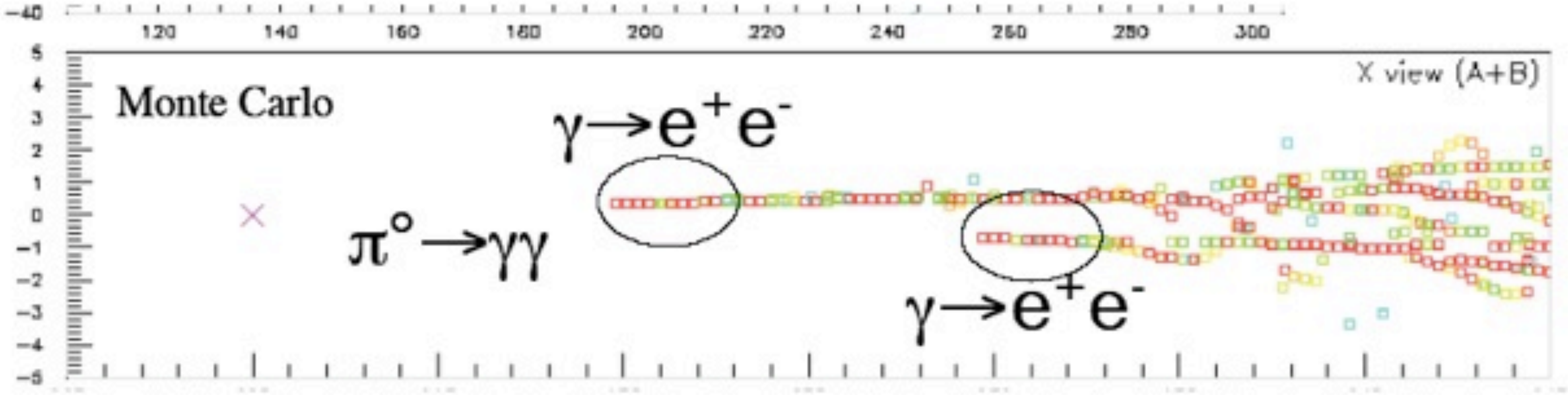
Figure 5.21: The raw image of a low multiplicity … on plane (right). The event is reconstructed as (ν_μ … he chamber, an identified stopping proton and a pair … en these photons escape from the chamber, the event is tagged as a *golden* event.

Electron / Photon Separation

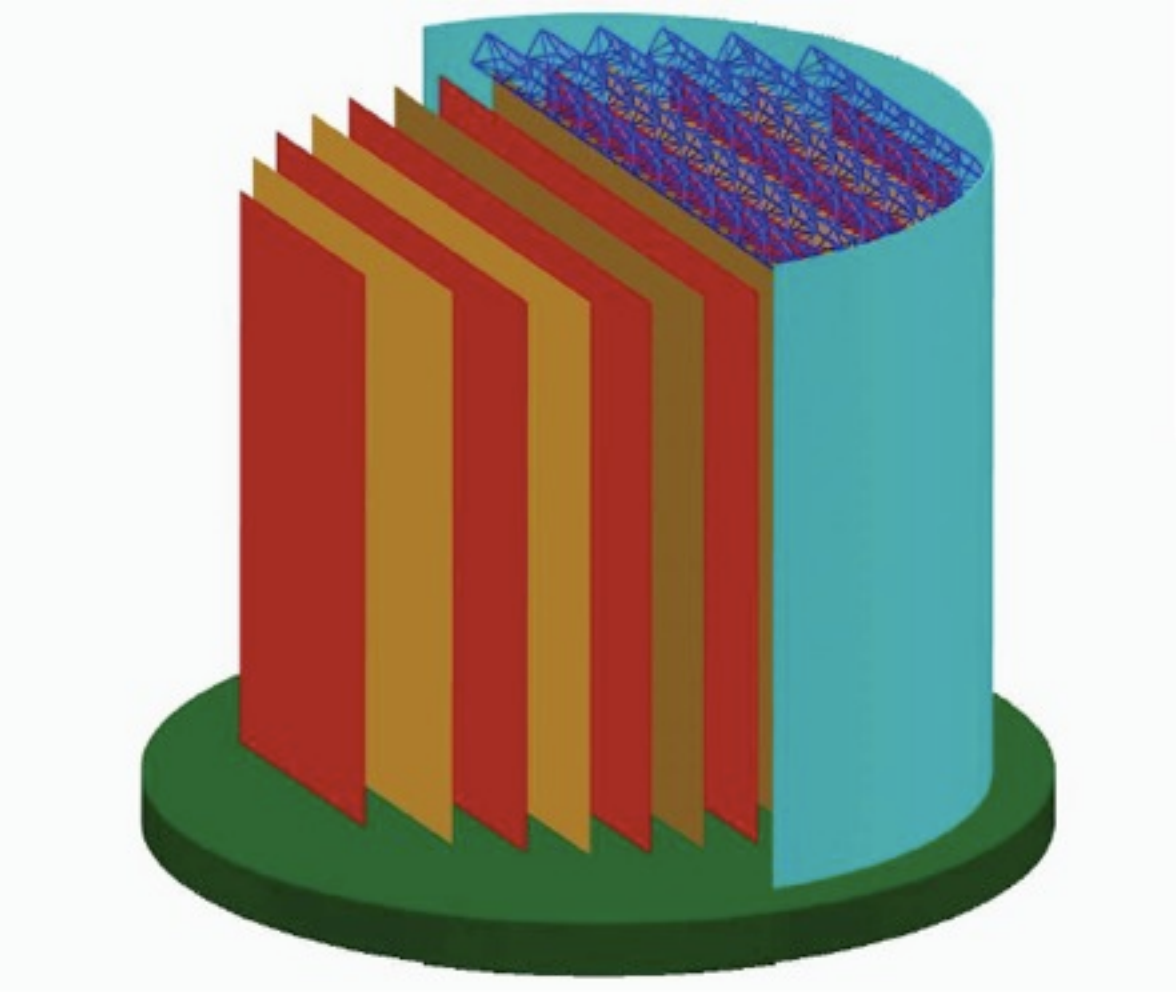
TPC's provide many samples per radiation length. Allows for e/gamma separation by checking dE/dx at start of shower



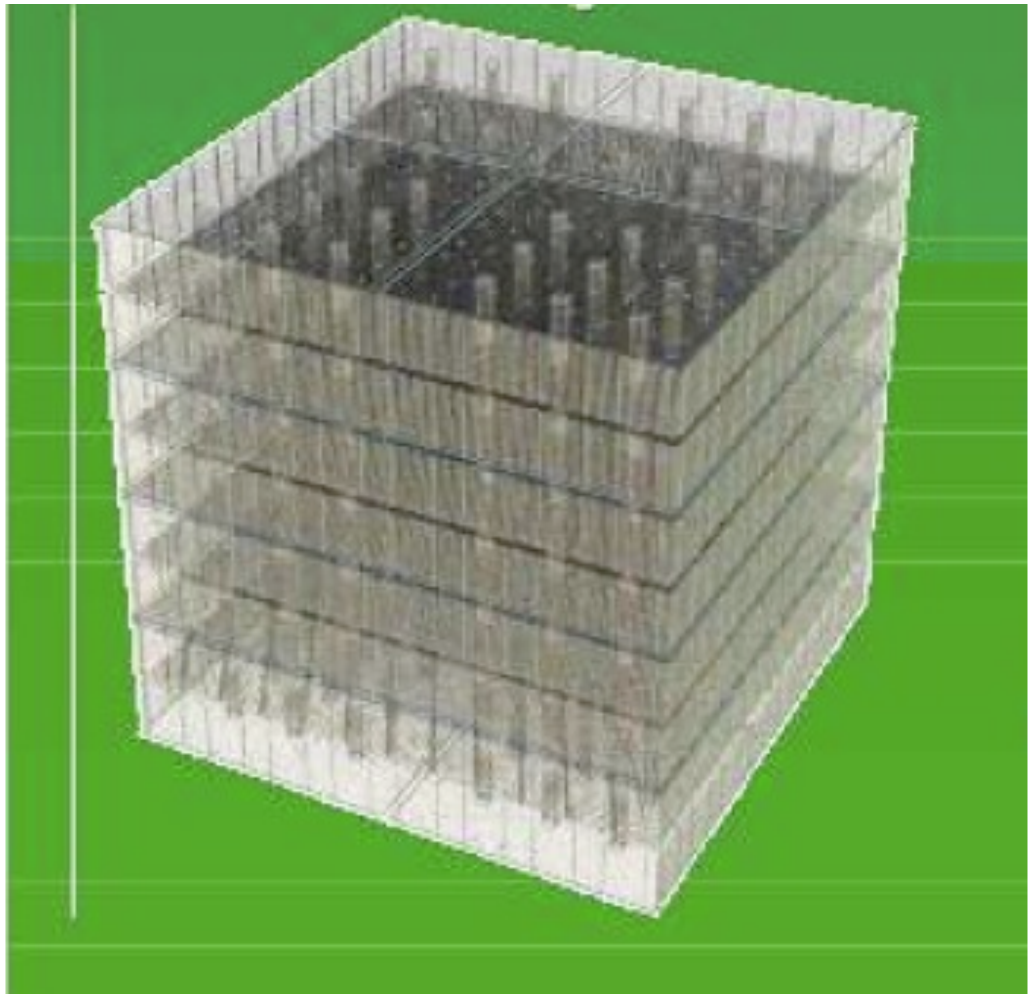




Some possible designs for big detectors

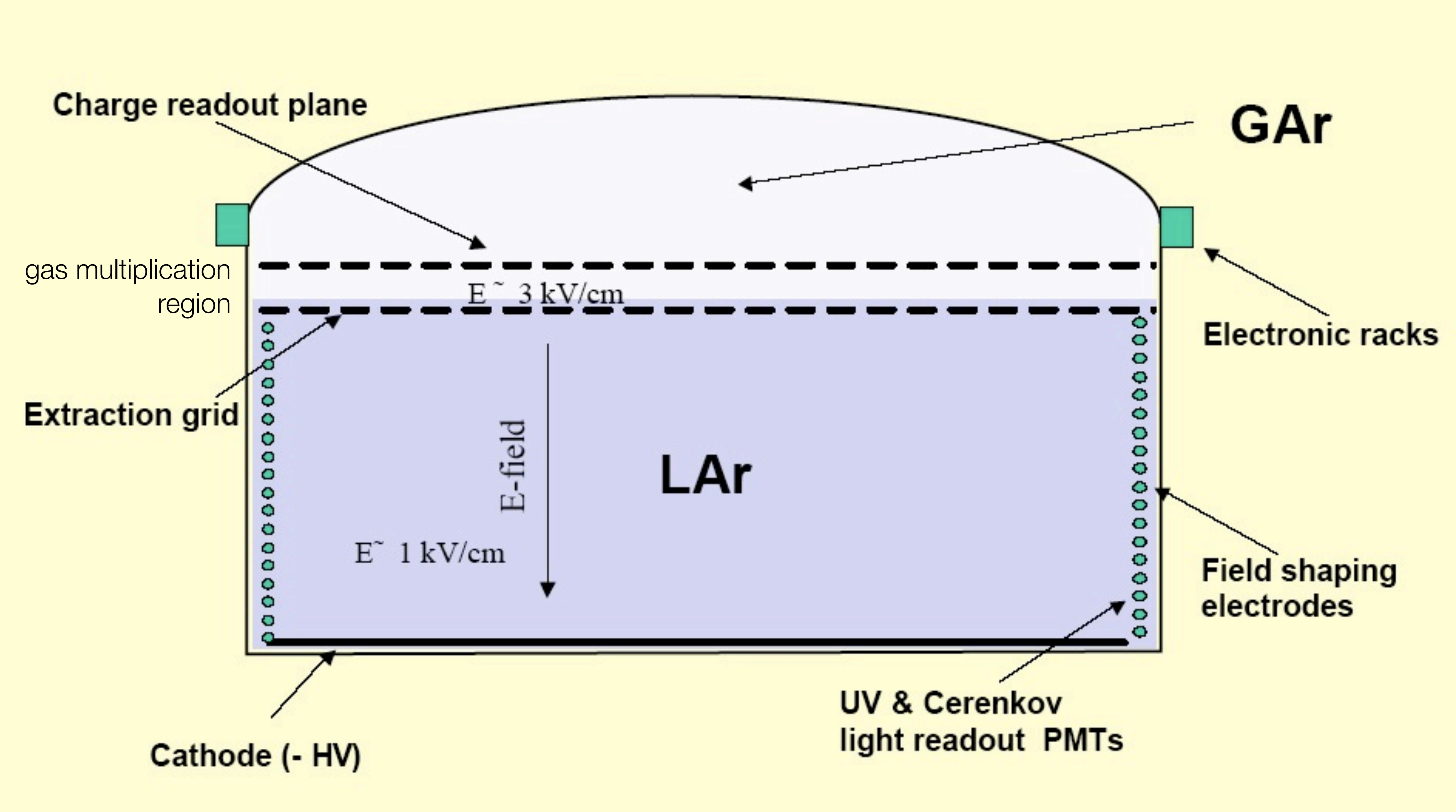


LArTPC: 10-50 kton storage tank. Modular drift regions.



LANDD: Single vessel designed to support vacuum

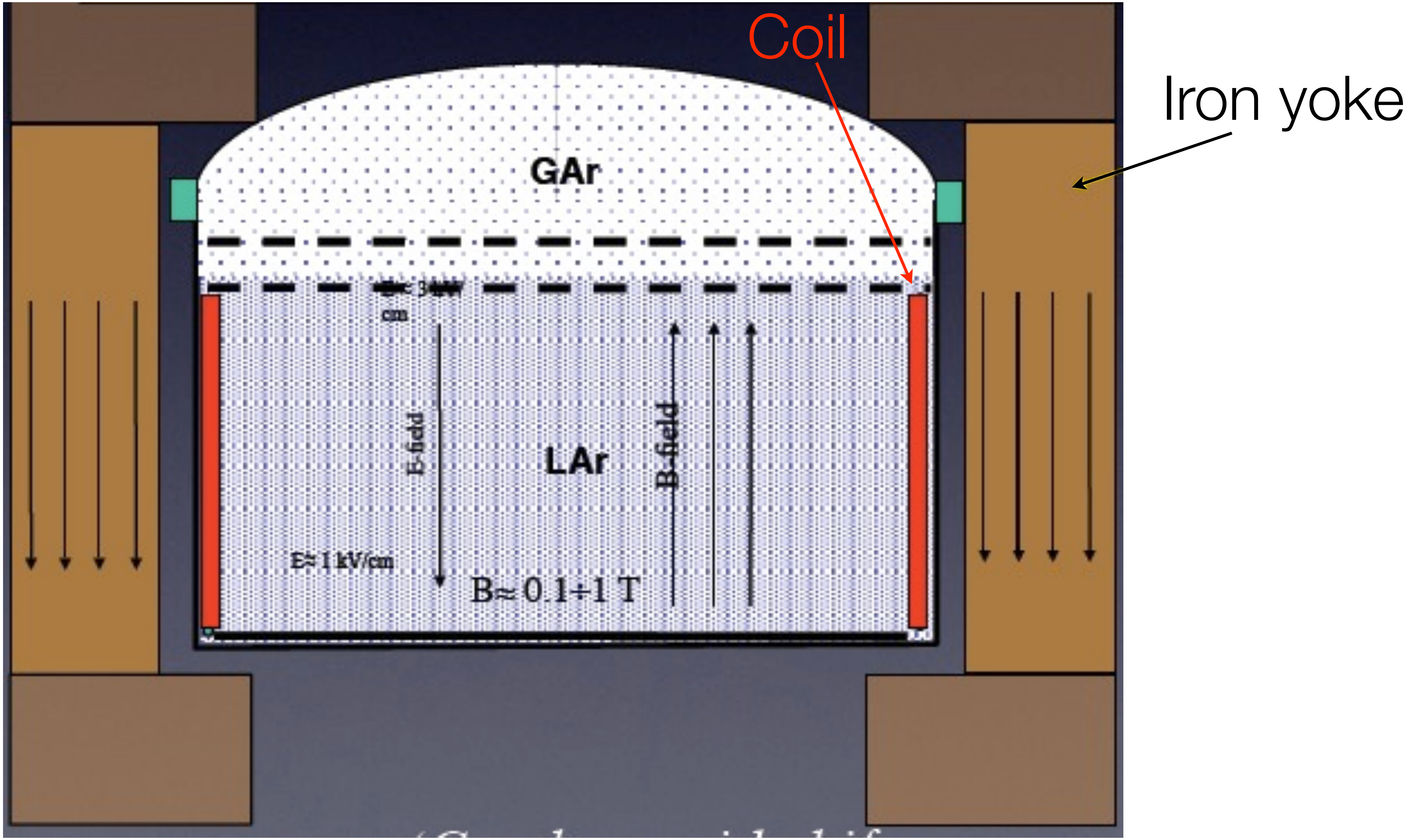
GLACIER Concept



In gas multiplication region, electrons shower in a region of high electric field. Energy/ particle goes up as a result of acceleration in the field.

Concepts for large, magnetized, LqAr detectors

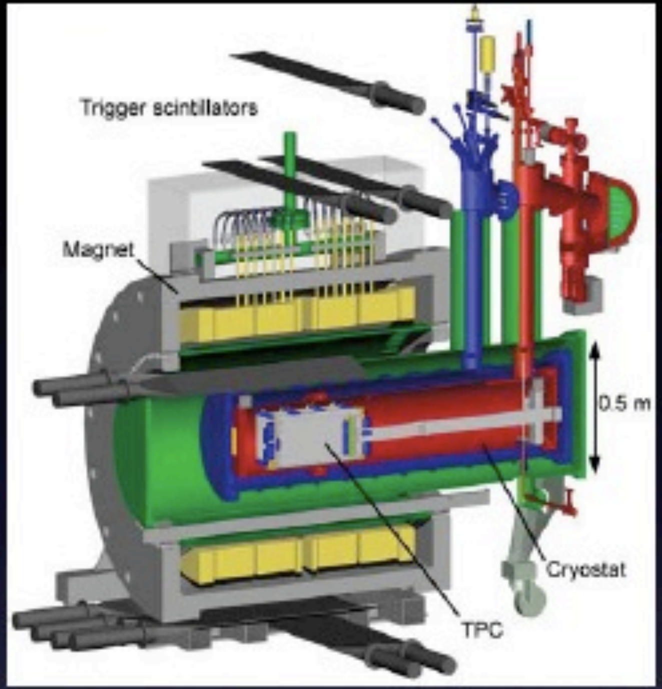
Andre Rubbia, Golden'07

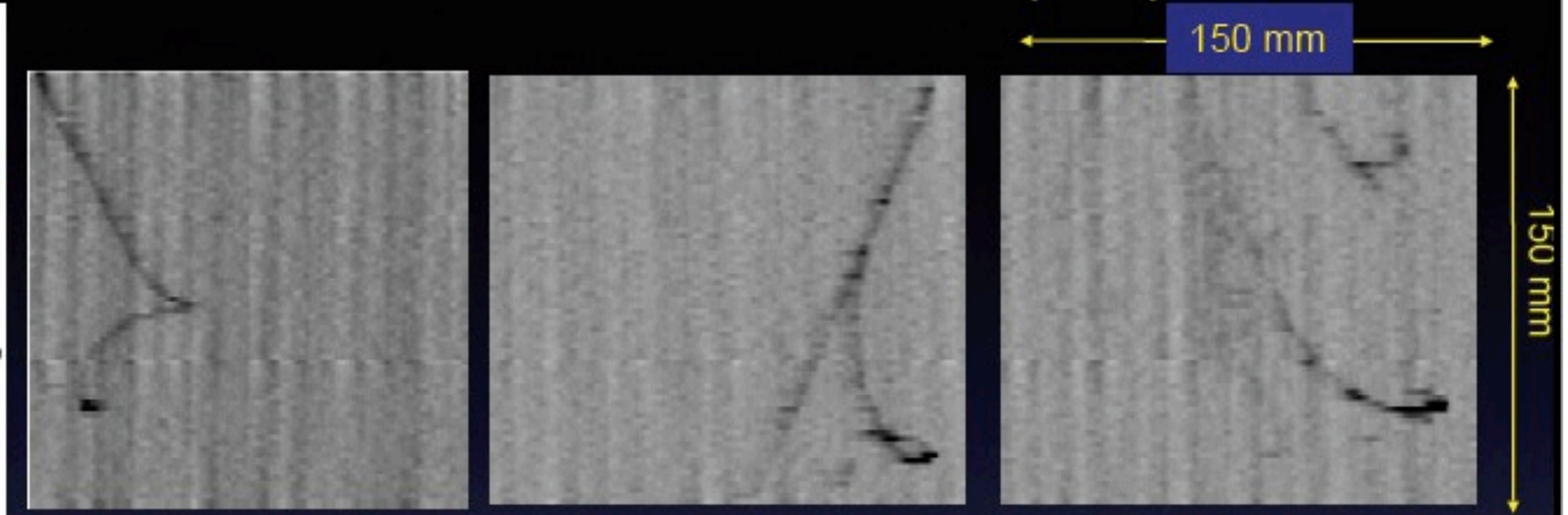


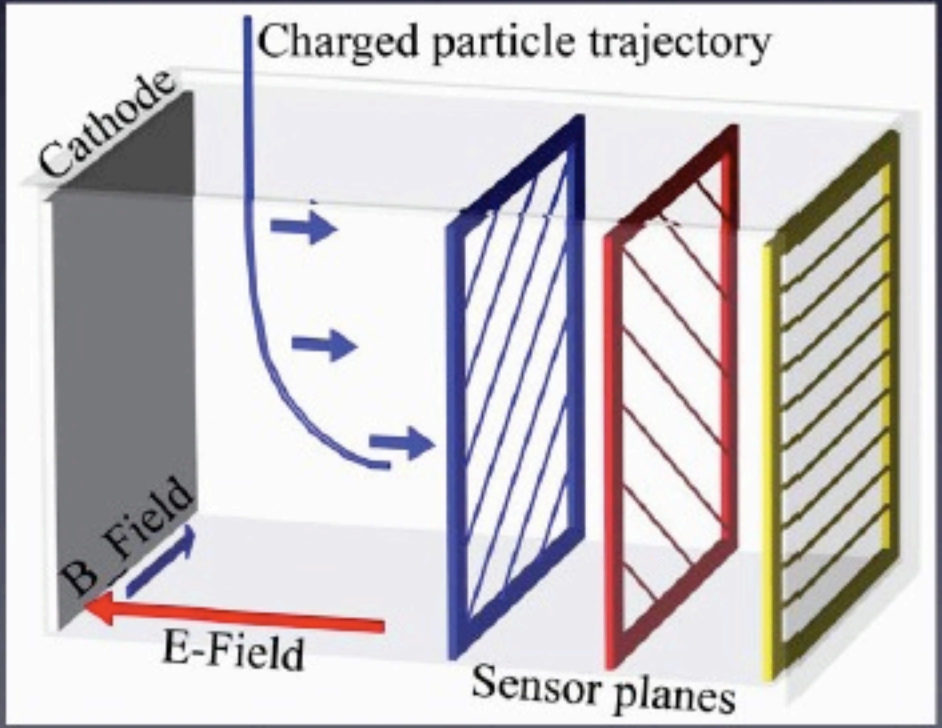
First operation of a LAr TPC embedded in a B-field

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

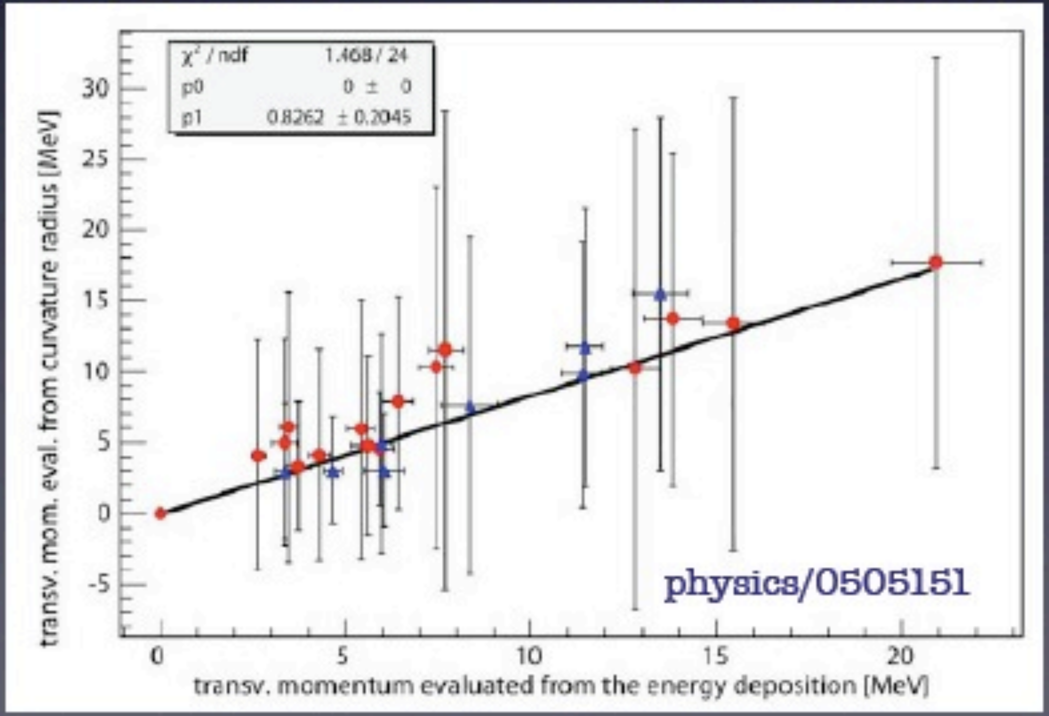
New J. Phys. 7 (2005) 63
NIM A 555 (2005) 294







Correlation between calorimetry and magnetic measurement for contained tracks:



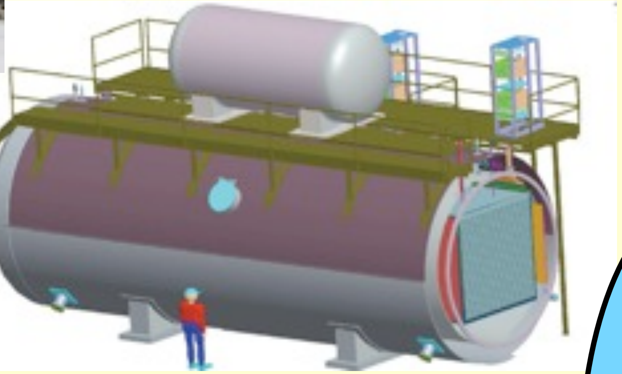
physics/0505151

A. Rubbia

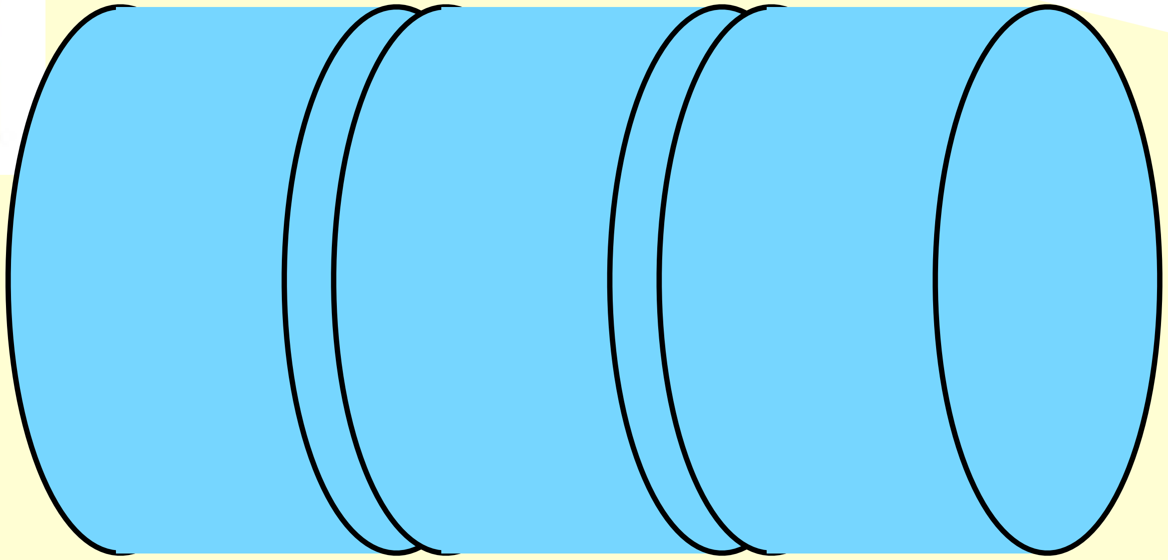
Path to large detectors (U.S.)

0.3 ton → *x600* → *170 ton* → *x30* → *5 kton* → *x20* → *100 kton*

“ArgoNeut” running in front of MINOS now



“MicroBooNE” in 8 GeV beamline at Fermilab



LAr5 in future DUSEL beamline

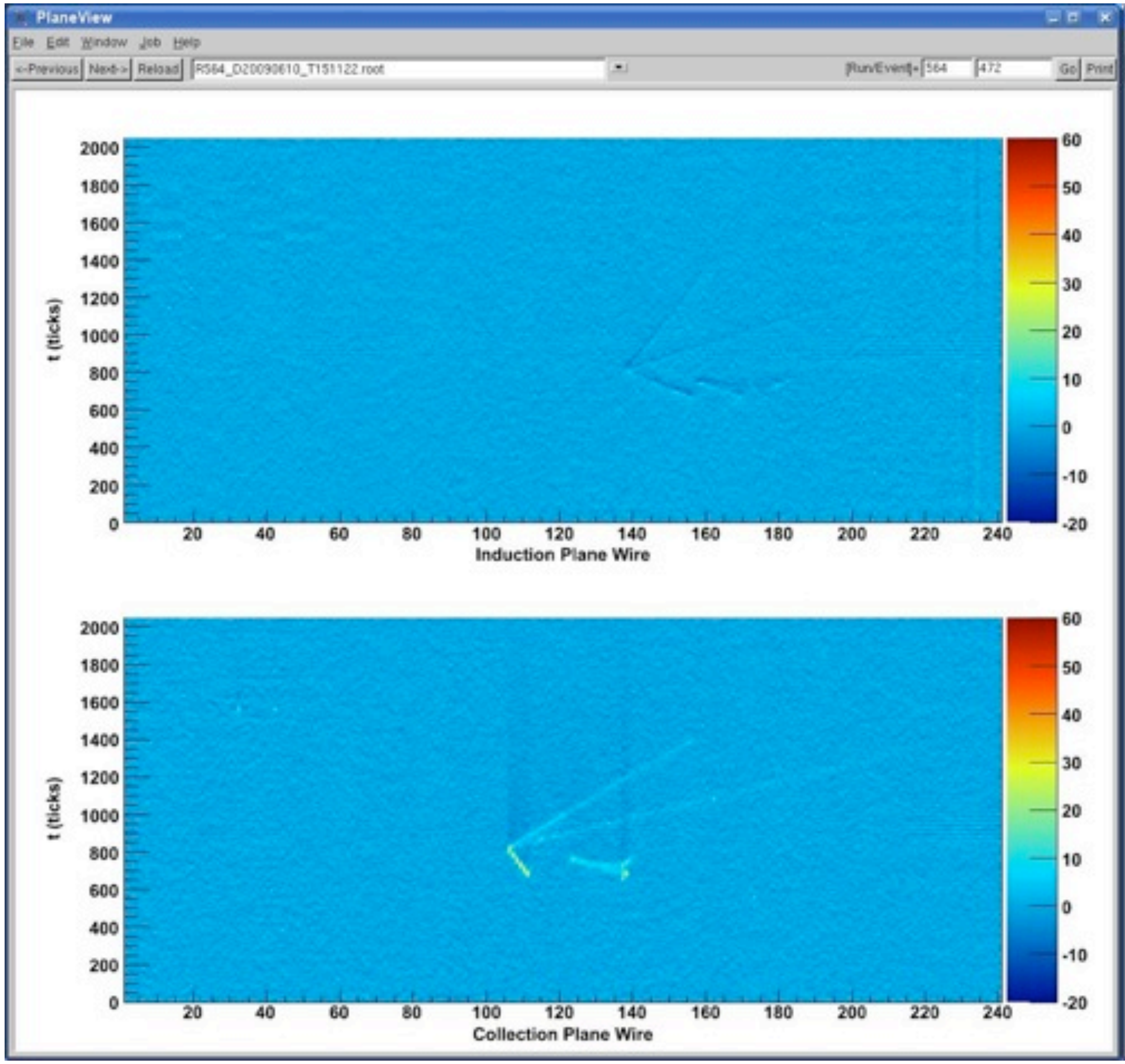
?

Eventual goal:
100 kt

R&D issues

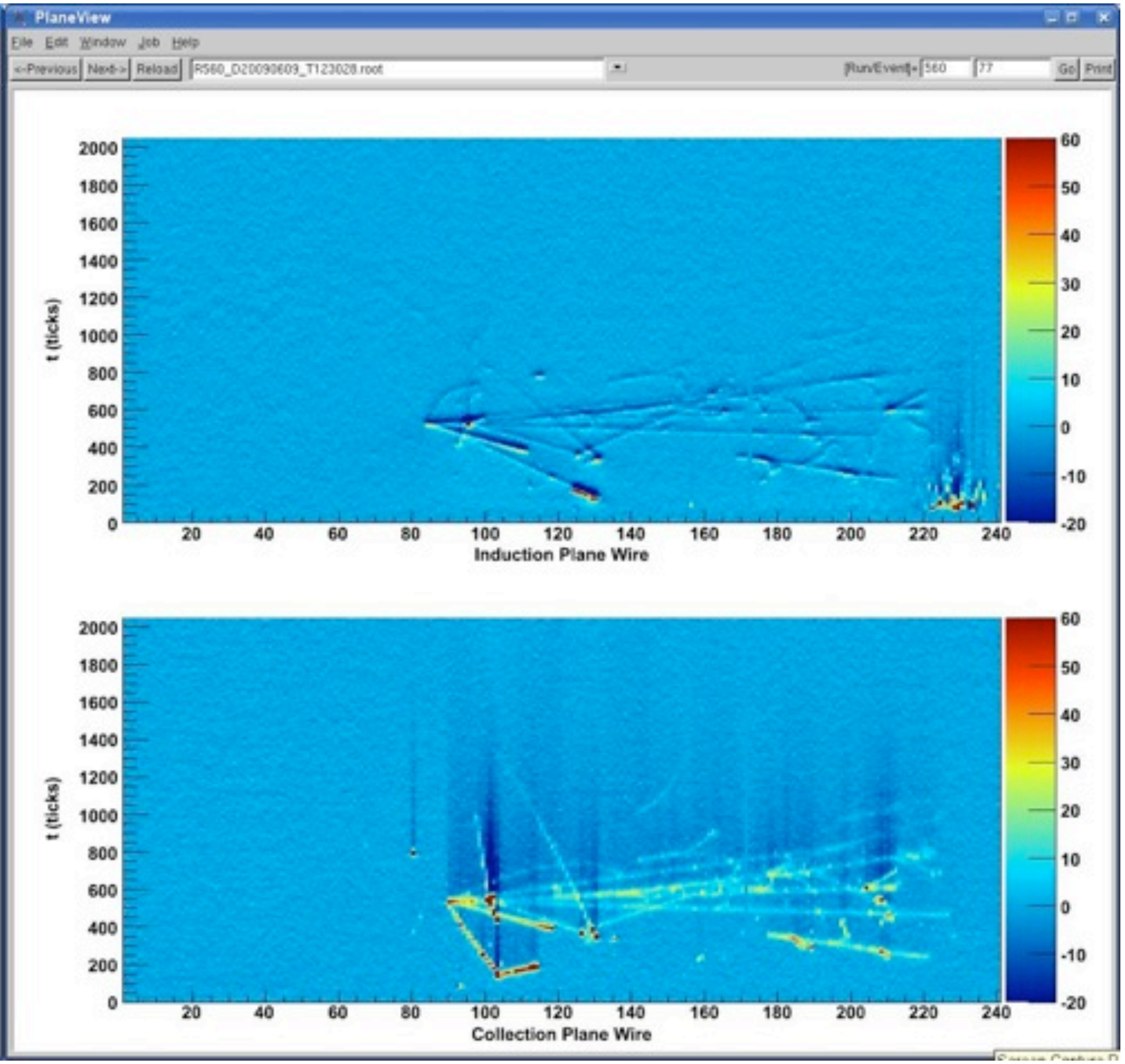
- Are the drift distances required by large detectors achievable in large cryostats?
- Electronic optimization. Multiplexing? Noise?
- Large wire plane construction

First events from ArgoNEUT



R564_D20090610_T151122.root

Run/Event: 564 472



R560_D20090609_T123028.root

Run/Event: 560 77

courtesy of B. Fleming

Summary

Neutrino event topologies

- Muons : Long straight, ~constant energy deposit of 2 MeV cm^2 / g
- Electrons : Create compact showers. Longitudinal size determined by radiation length. Transverse size determined by Moliere radius.
- Photons: Create compact showers after a gap of ~1 radiation length.
- Hadrons : Create diffuse showers. Scale determined by interaction length

Specific technologies:

- *Cherenkov*: Best for low rate, low multiplicity, energies below 1 GeV
- *Tracking calorimeters*: Can handle high rate and multiplicities. Best at 1 GeV and above.
- *Unsegmented scintillator calorimeters*: Large light yields at MeV energies. Background considerations dominate design.
- *TPCs*: Great potential for large mass with high granularity. Lots of activity to realize potential