Physics of Neutrino detection

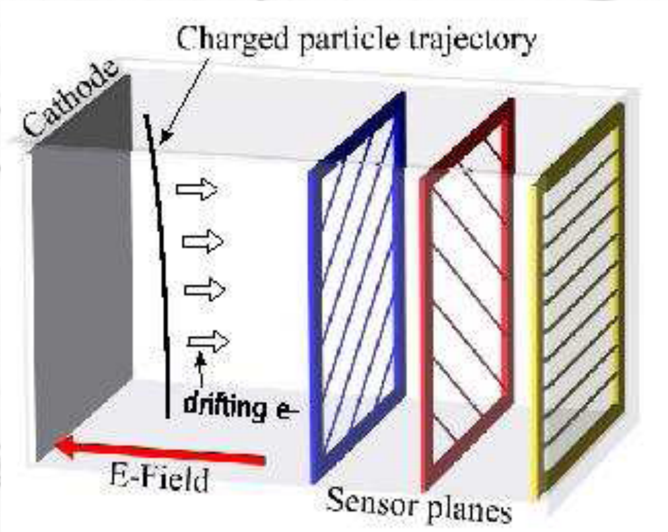
Federico Sánchez
Institut de Física d'Altes Energies (IFAE)
Barcelona

LiqArgon

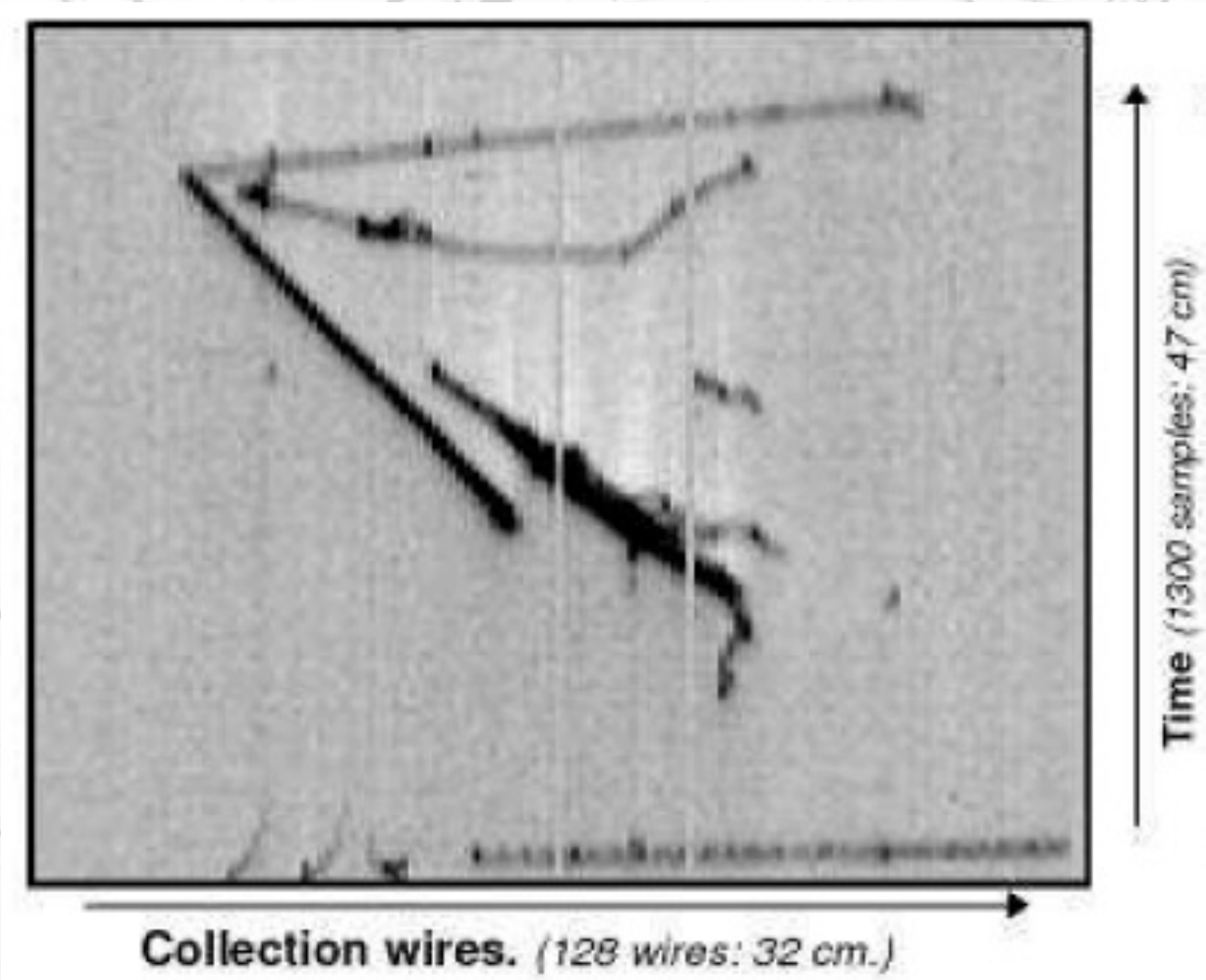
- Liquid Argon TPC has the same principle of operation as gaseous TPCs.
- Electrons are drifted in the liquid:
  - Larger drift voltage.
  - Larger absorption by impurities.
- The target mass is large (larger density).
- It is fully active: low momentum track, good electromagnetic calorimeter.
- The point resolution can be very good → track separation in high multiplicity events and detection of short range particles.

LiqArgon

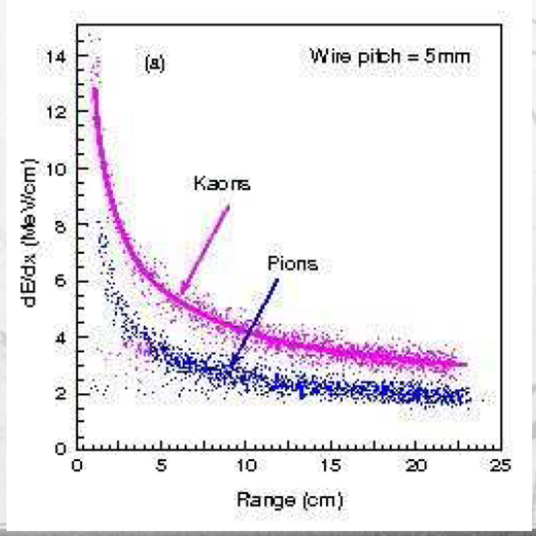
- Liquid Argon TPC has the same principle of operation as gaseous TPCs.
- Electrons are drifted in the liquid:
  - Larger drift voltage.
  - Larger absorption by impurities.
- The target mass is large (larger density).



- It is fully active: low momentum track, good electromagnetic calorimeter.
- The point resolution can be very good → track separation in high multiplicity events and detection of short range particles.

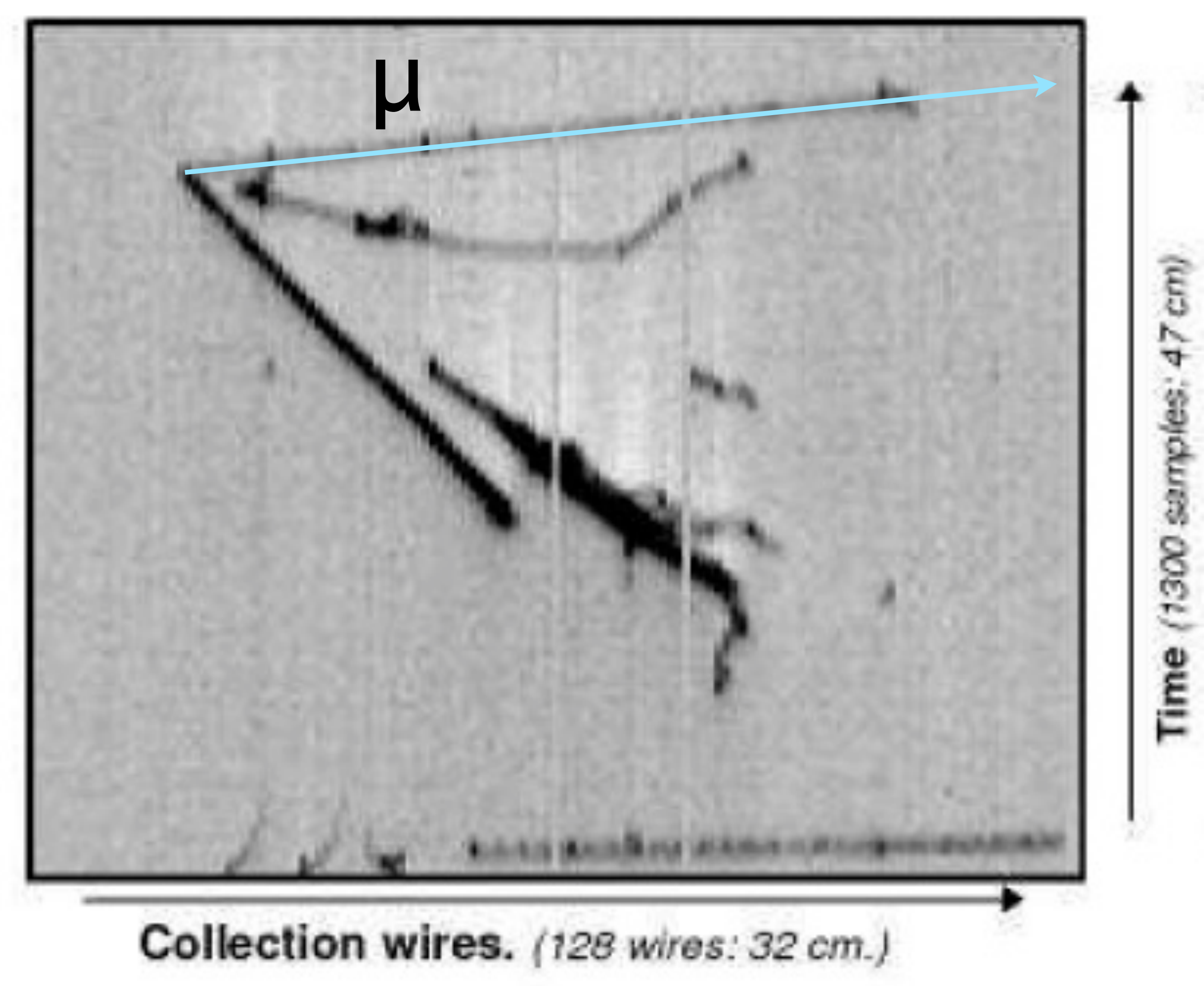


- Liquid Argon TPC is a "modern" electronic bubble chamber.
- A lot of information is available:
  - track length.
  - dE/dx (visible when comparing muon and proton).
  - detached tracks for photon id.
  - calorimetry for gamma energy.

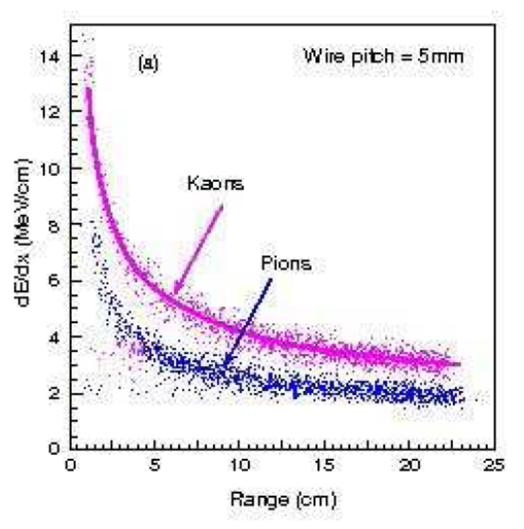


- momentum can be measured by range, curvature or Multiple Scattering.

LiqArgon

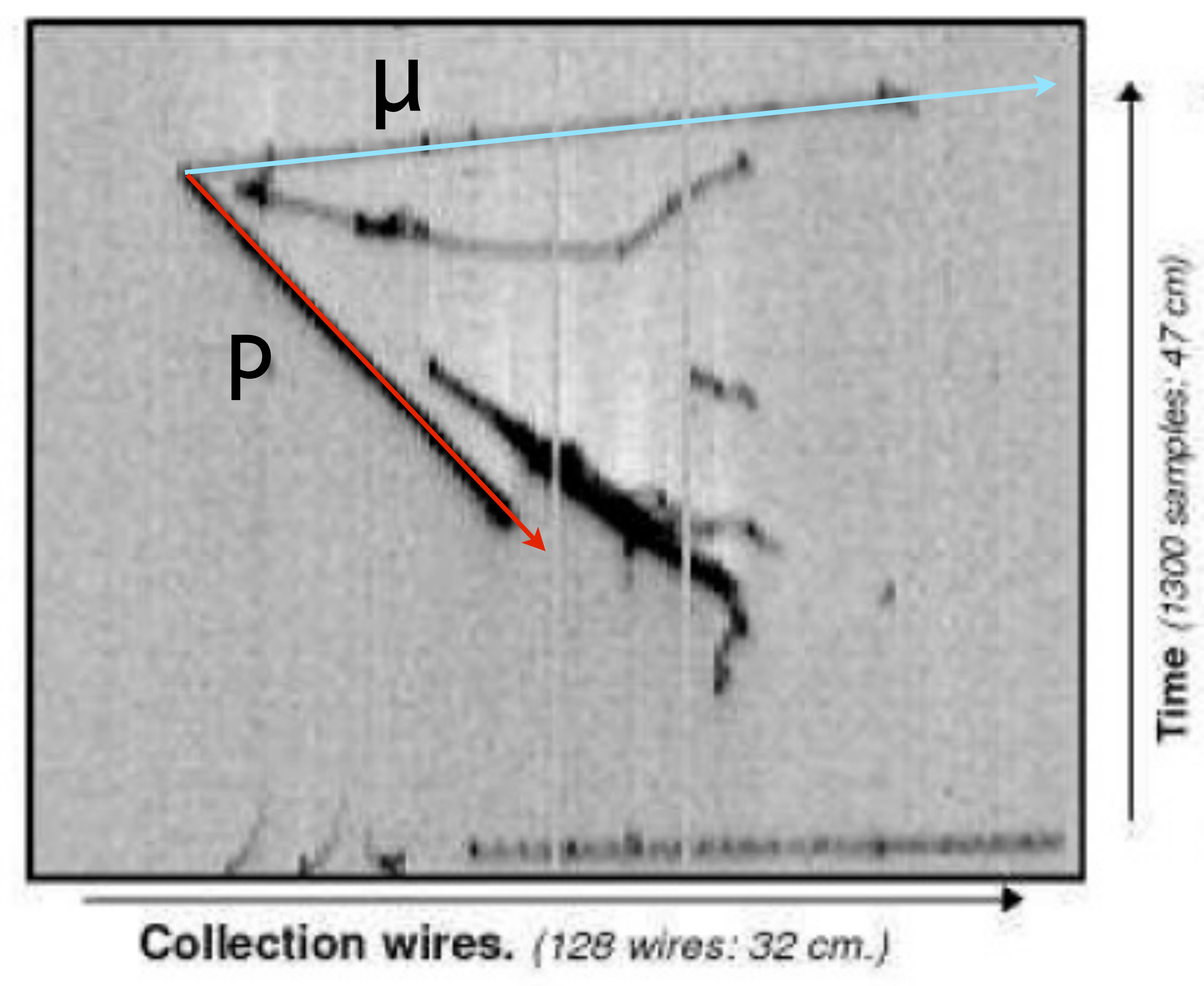


- Liquid Argon TPC is a "modern" electronic bubble chamber.
- A lot of information is available:
  - track length.
  - dE/dx (visible when comparing muon and proton).
  - detached tracks for photon id.
  - calorimetry for gamma energy.

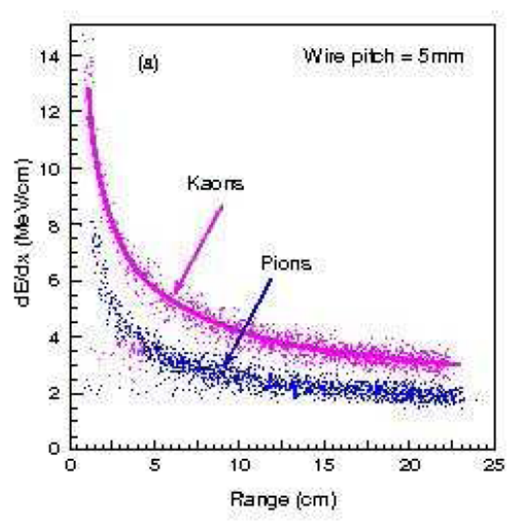


- momentum can be measured by range, curvature or Multiple Scattering.

LiqArgon

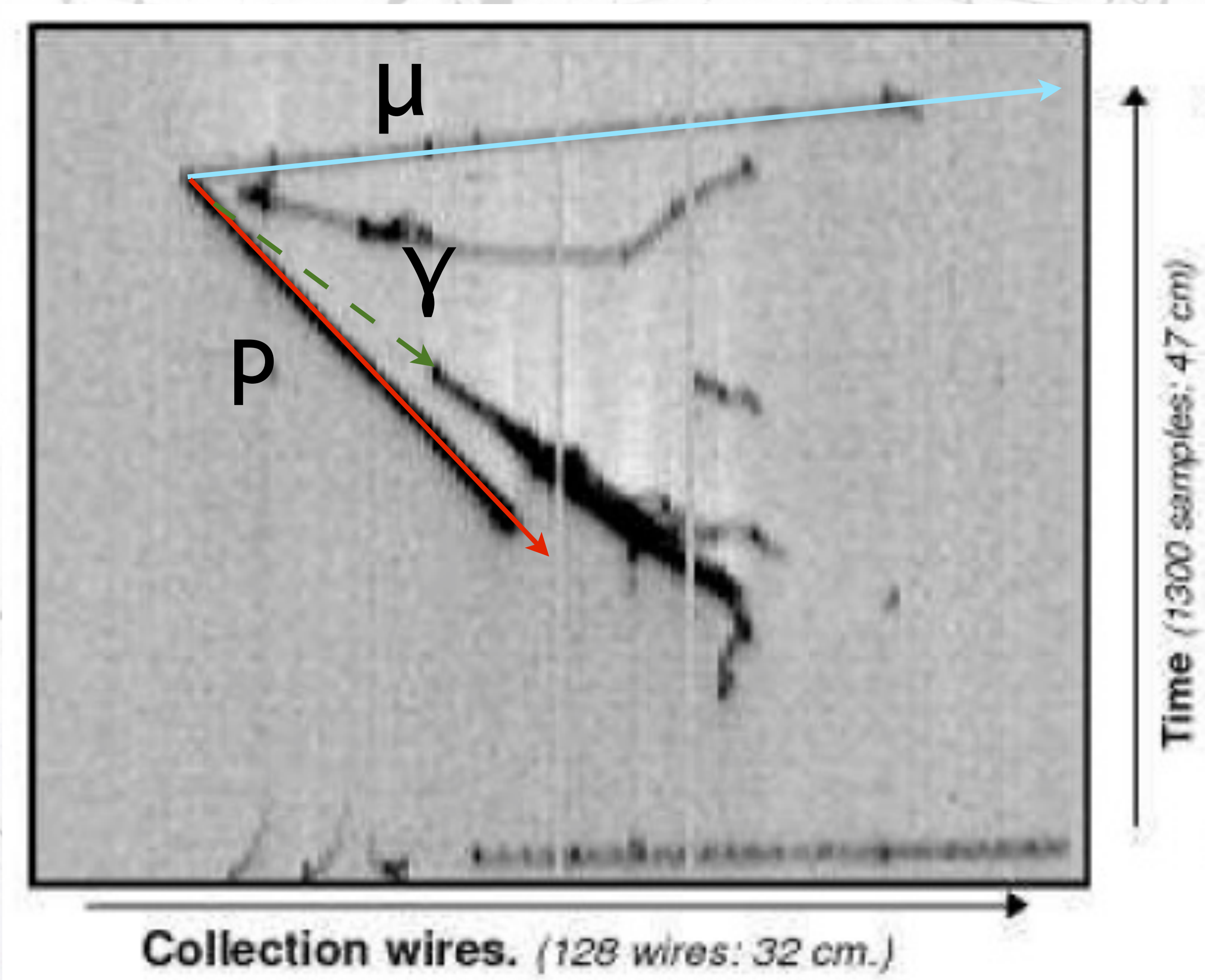


- Liquid Argon TPC is a "modern" electronic bubble chamber.
- A lot of information is available:
  - track length.
  - dE/dx (visible when comparing muon and proton).
  - detached tracks for photon id.
  - calorimetry for gamma energy.

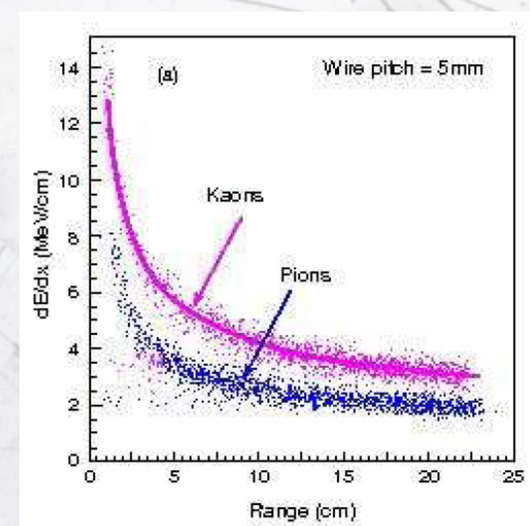


- momentum can be measured by range, curvature or Multiple Scattering.

LiqArgon



- Liquid Argon TPC is a "modern" electronic bubble chamber.
- A lot of information is available:
  - track length.
  - dE/dx (visible when comparing muon and proton).
  - detached tracks for photon id.
  - calorimetry for gamma energy.



- momentum can be measured by range, curvature or Multiple Scattering.

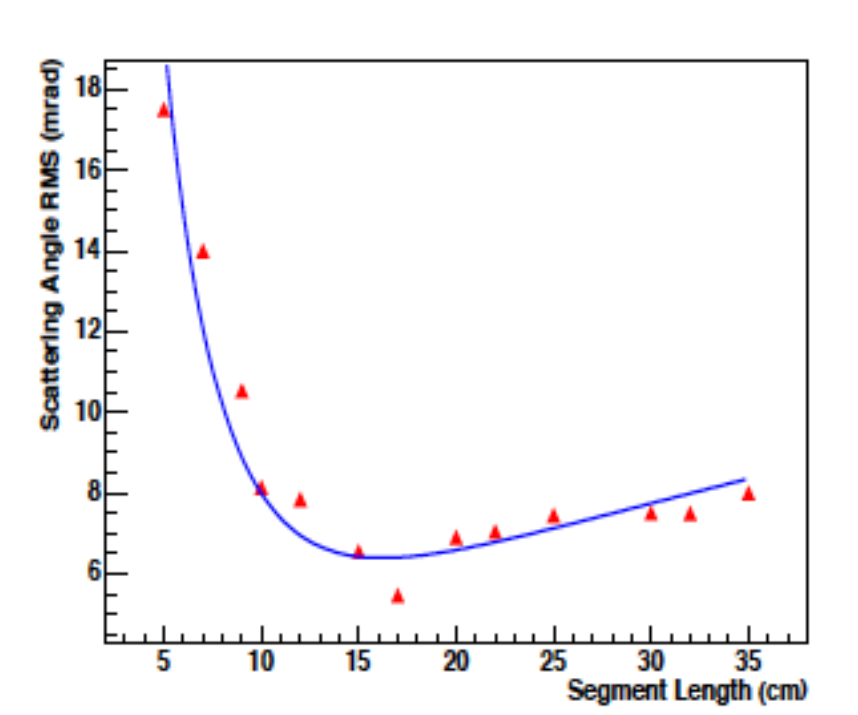
LiqArgon

- Multiple Scattering is normally an annoyance in track properties reconstruction but it can be used in our favour.
- The angular dispersion depends with the momentum:

$$P(\theta) \propto \exp^{\frac{-\theta^2}{2.\theta_0^2}}$$

$$\theta_0 = \frac{13.6MeV}{\beta cp} z \sqrt{x/X_0}[1 + 0.038 \ln(x/X_0)]$$

- Take a track, divide in segment and compute the RMS of the angular differences for consecutive segments after removing large scattering pairs.



- Change the segment length and fit the RMS versus the segment length.

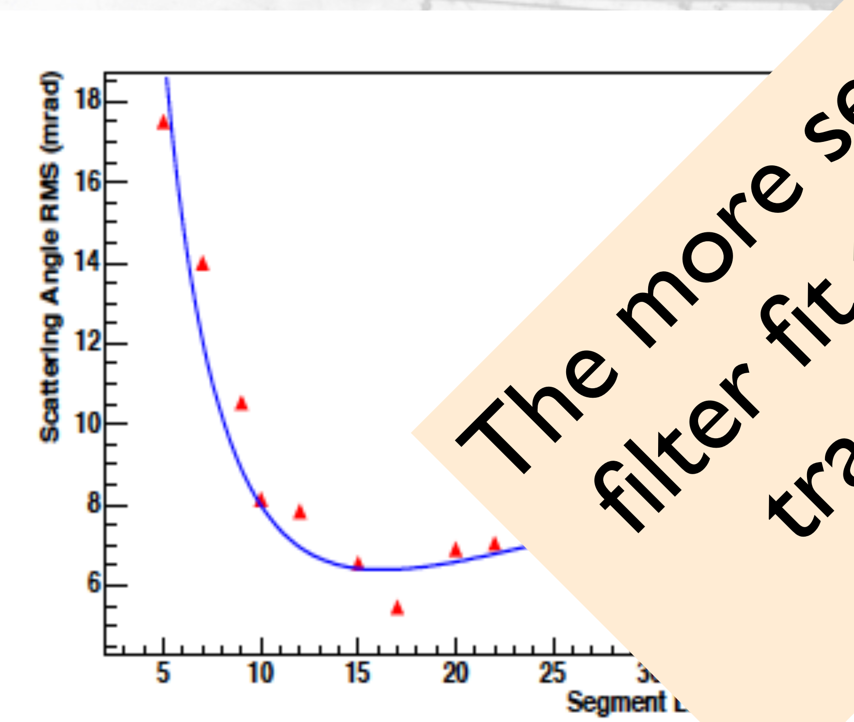
$$\theta^{rms}_{meas} = \sqrt{(\theta_0^{rms})^2 + (\theta^{rms}_{noise})^2}$$

$$= \sqrt{\left(\frac{13.6\ MeV}{\beta c\, p} z \sqrt{\frac{l}{X_0}} \cdot \left[1 + 0.038 \cdot ln\left(\frac{l}{X_0}\right)\right]\right)^2 + (C \cdot l^{-3/2})^2}$$

LiqArgon

- Multiple Scattering is normally an annoyance in trac ... reconstruction but it can be used in our favour.
- The angular dispersion depends with the m ... $\sqrt{x/X_0}[1+0.038\ln(x/X_0)]$

- ... egment and compute the RMS ... nces for consecutive segments ... ge scattering pairs.

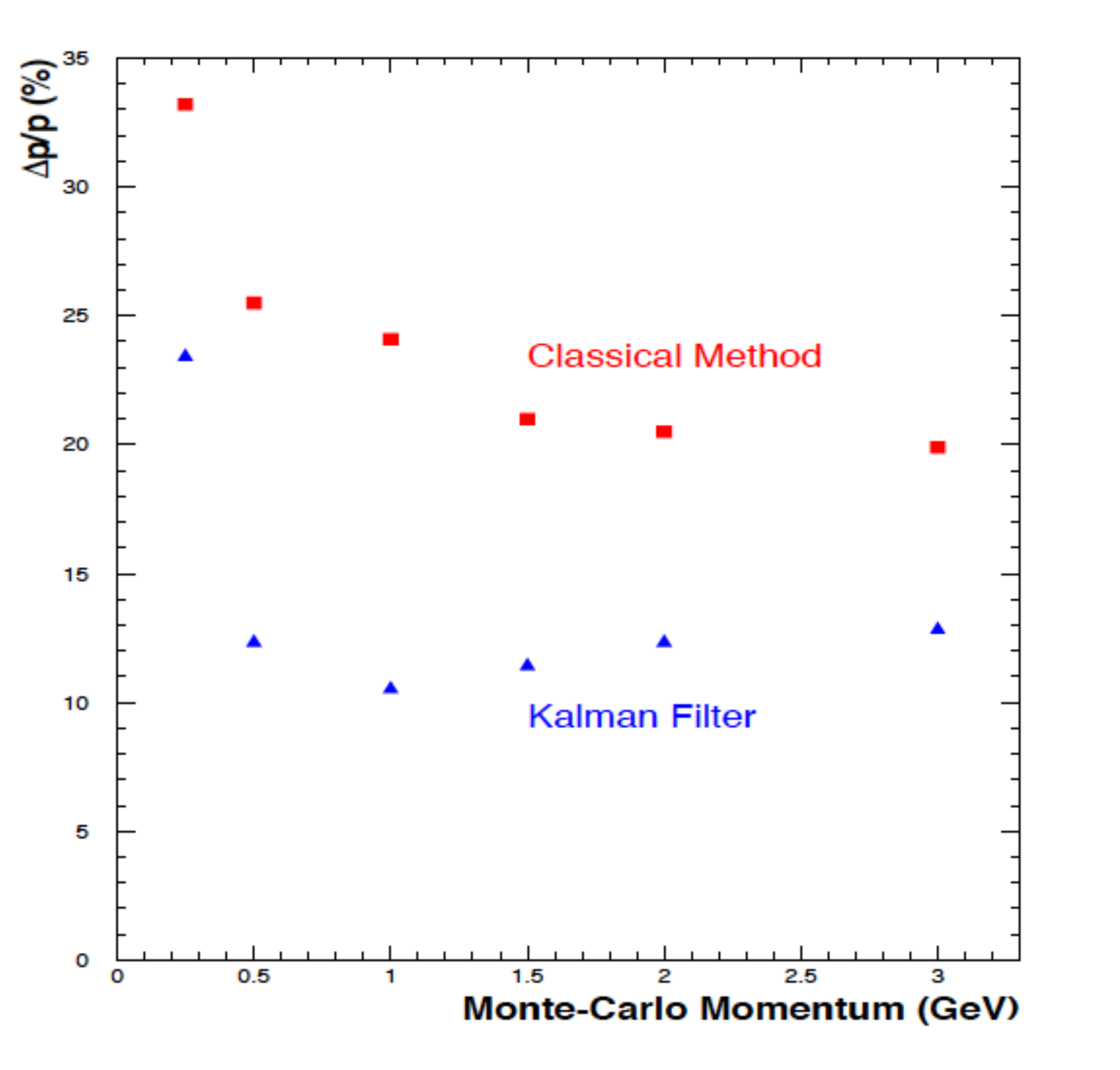


- ... e the segment length and fit the RMS versus the ... ent length.

The more sensitive method uses a Kalman filter fit to the track trajectory with the track momentum and angle as free parameter.

$$\theta^{rms}_{meas} = \sqrt{(\theta^{rms}_{0})^2 + (\theta^{rms}_{noise})^2}$$

$$= \sqrt{\left(\frac{13.6\ MeV}{\beta c\, p} z \sqrt{\frac{l}{X_0}} \cdot \left[1 + 0.038 \cdot ln\left(\frac{l}{X_0}\right)\right]\right)^2 + (C \cdot l^{-3/2})^2}$$

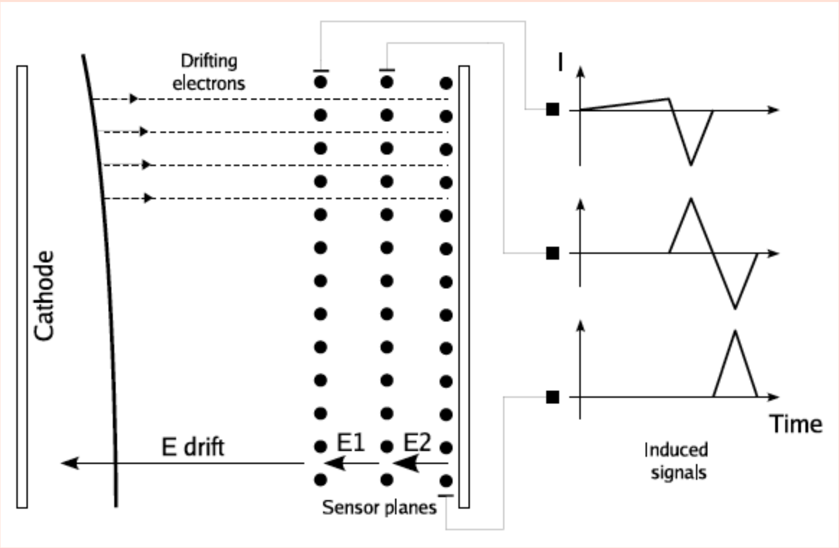


- Momentum resolution is quite reasonable!

LiqAr readouts

- The charge amplification in liquid is a challenging topic. Electrons are not accelerated to the level they initiate a charge avalanche.

Single phase

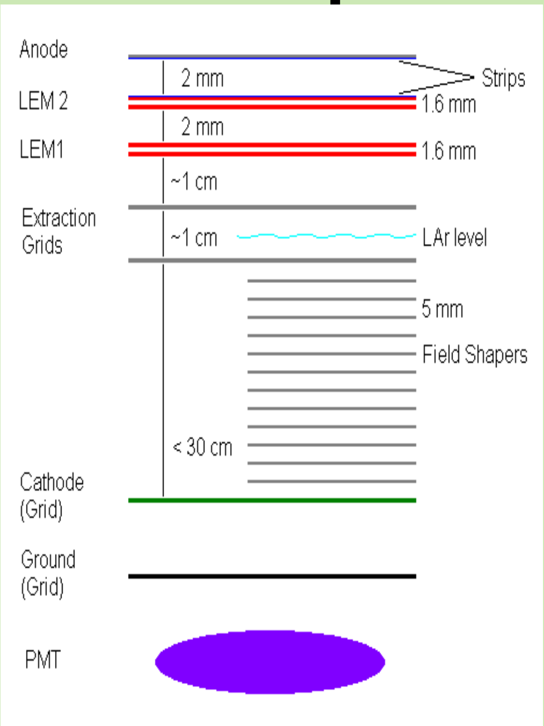


Wires with no amplification

Few electrons collected → noise

Electronics close to wires in LiqAr

Double phase



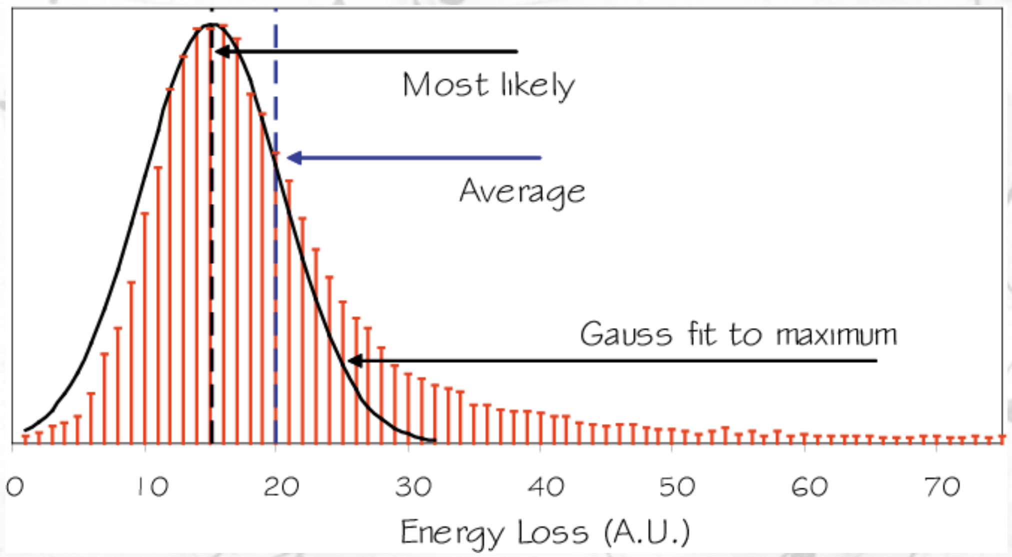
e^- are extracted with strong E field.

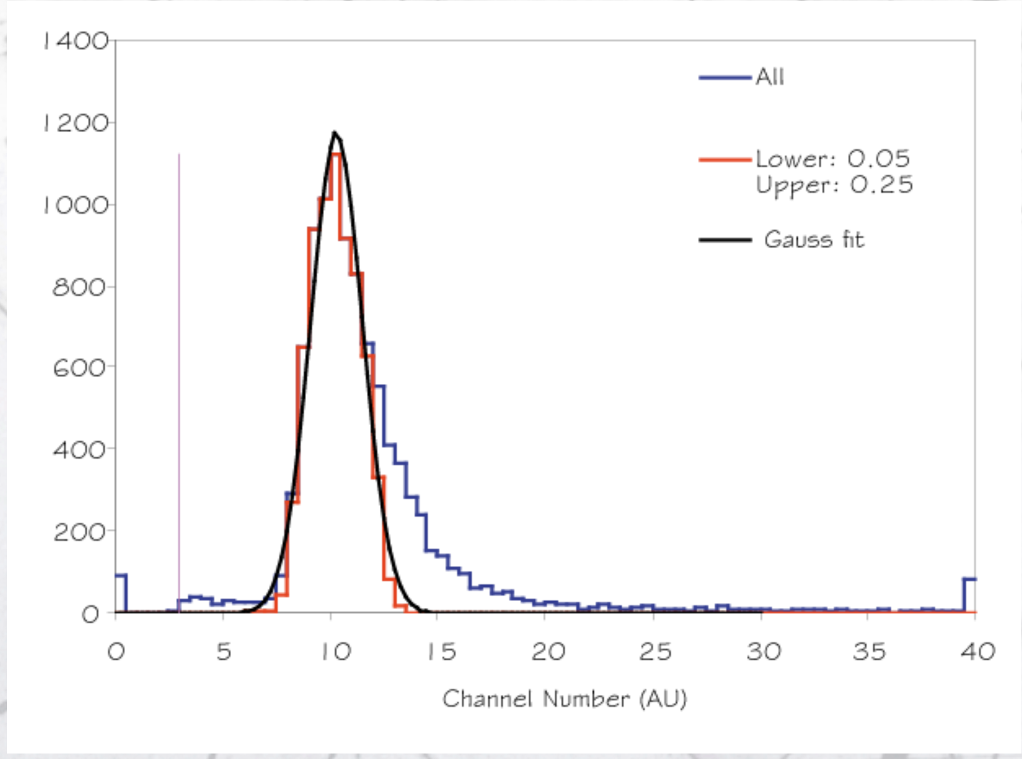
e^- are amplified in pure Ar gas

e^- amplification in pure Ar is not easy

Particle identification

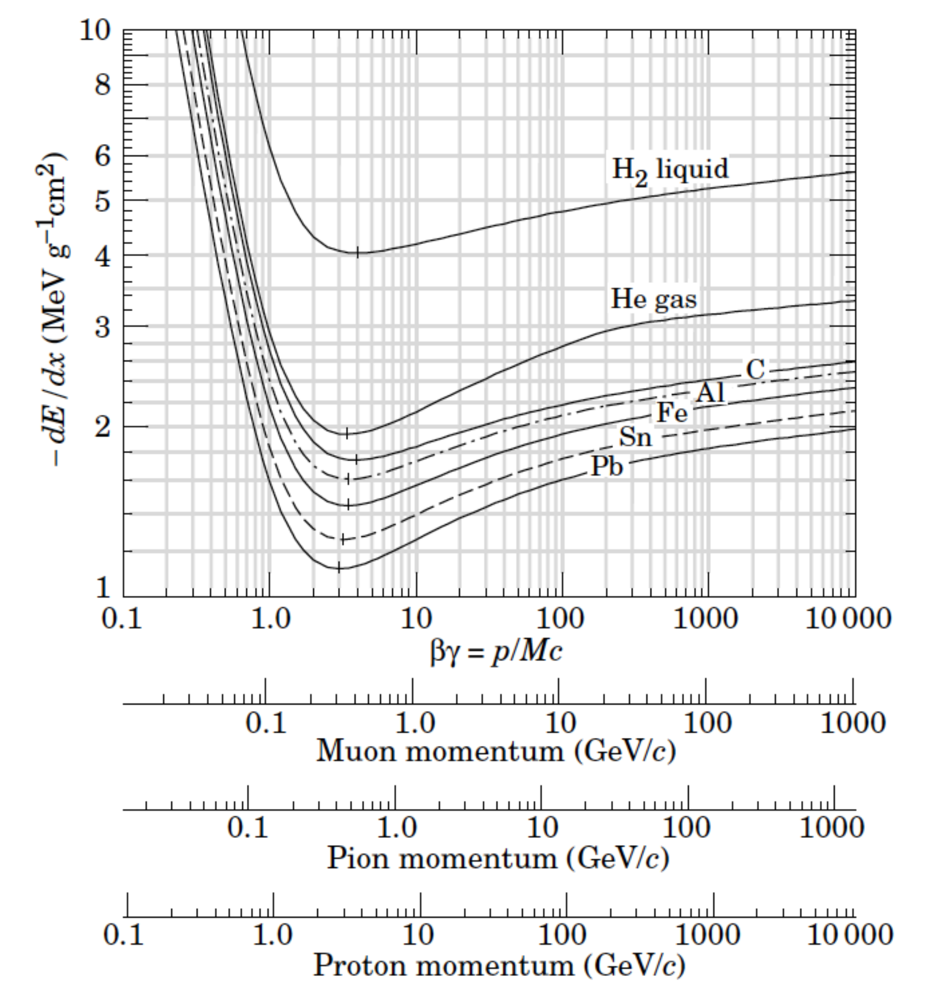
dE/dx

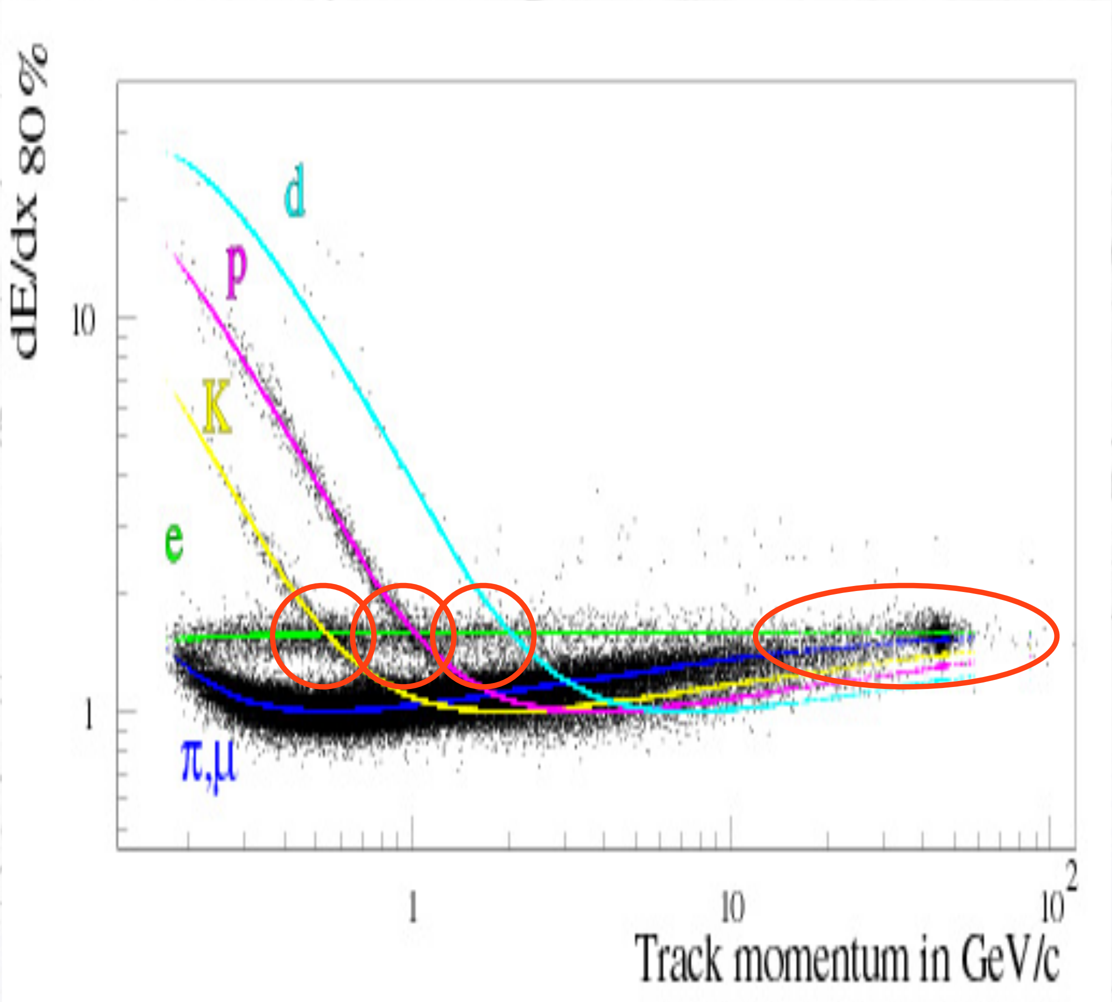




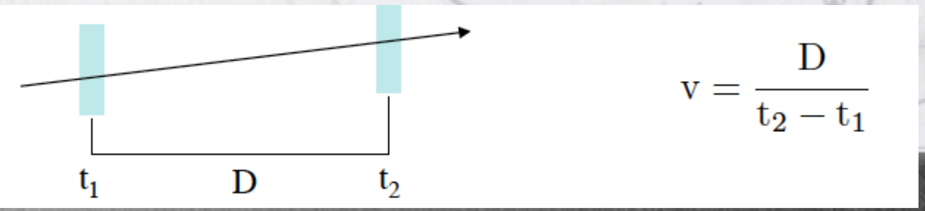
- In proportional gas readouts we can measure the energy released by charge particles.
- The shape of the dE/dx is very asymmetric and depends on the sample length (Central limit theorem)
- Usually the value of the dE/dx is computed:
  - sample several points.
  - take a truncated mean.

Particle identification



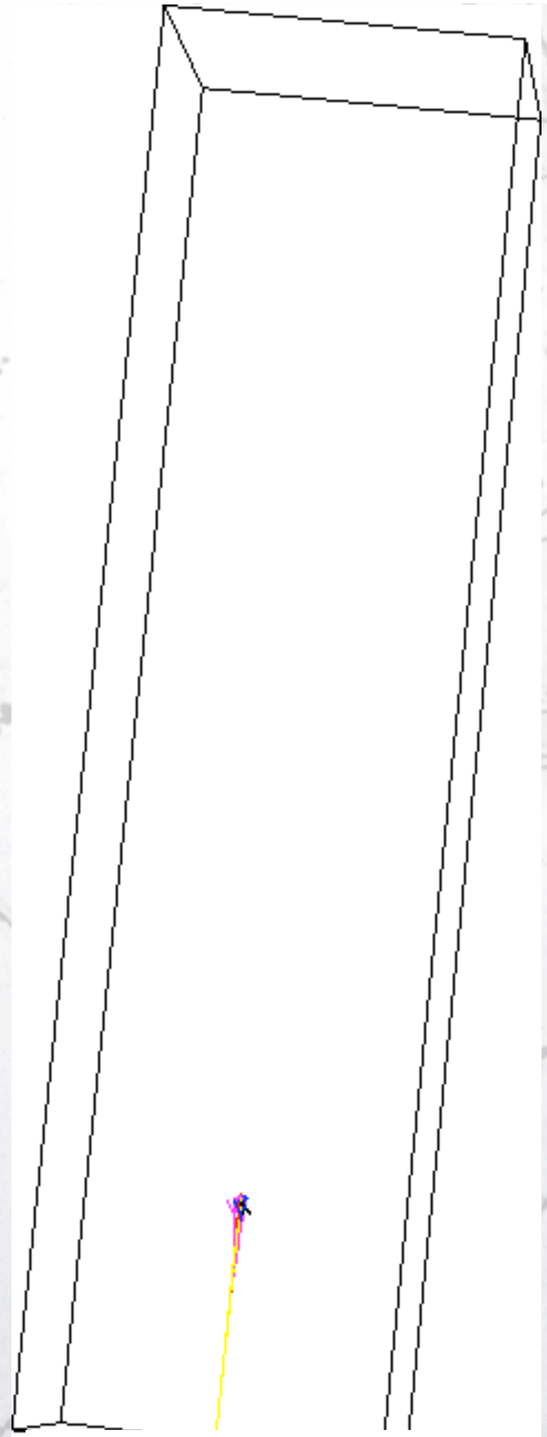


- A combined measurement of momentum (range) and dE/dx allows to identify particles in the regions the dE/dx does not saturate.
- For large momentum, the measurement of the time of flight normally compensate the limitations of the dE/dx.



Particle showers

https://www.mppmu.mpg.de/~menke/elss/



80 GeV electron in Opal

- When the interaction of particles with matter is "inelastic" and increases the number of particles, it tends to create a shower.
  - A shower is a group of particles produced during successive interactions of particles produced in the interactions.
  - The number of particles increases and the energy per particle decreases.
- Electrons / photons and hadrons suffer this kind of interactions, while muons don't (at low energies).

Particle showers

- Electron interactions with matter:
  - Breemstrahlung:
    - dominates at high energies.
  - ionisation.
    - Dominates below a critical energy.
    - The electron deposits the energy without developing the shower.
  - e^-e^+ annihilation at rest.

$$E_c \approx \frac{800MeV}{Z+1.2}$$

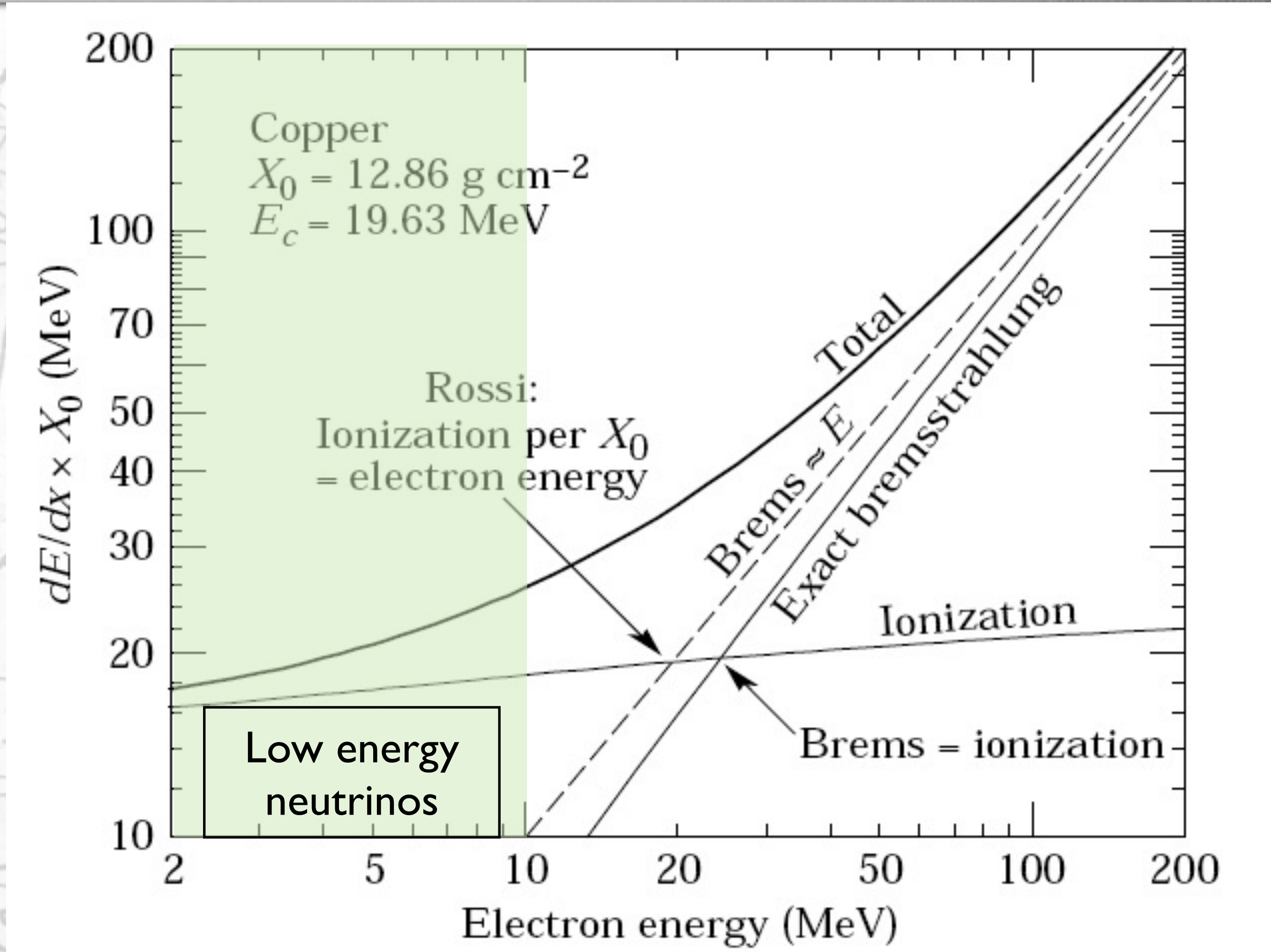
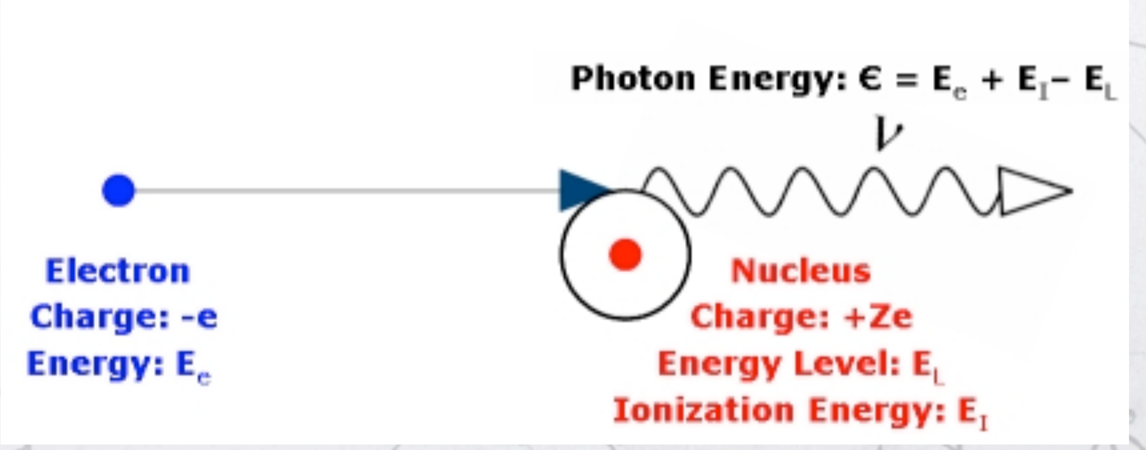


Figure 27.12: Two definitions of the critical energy E_c.

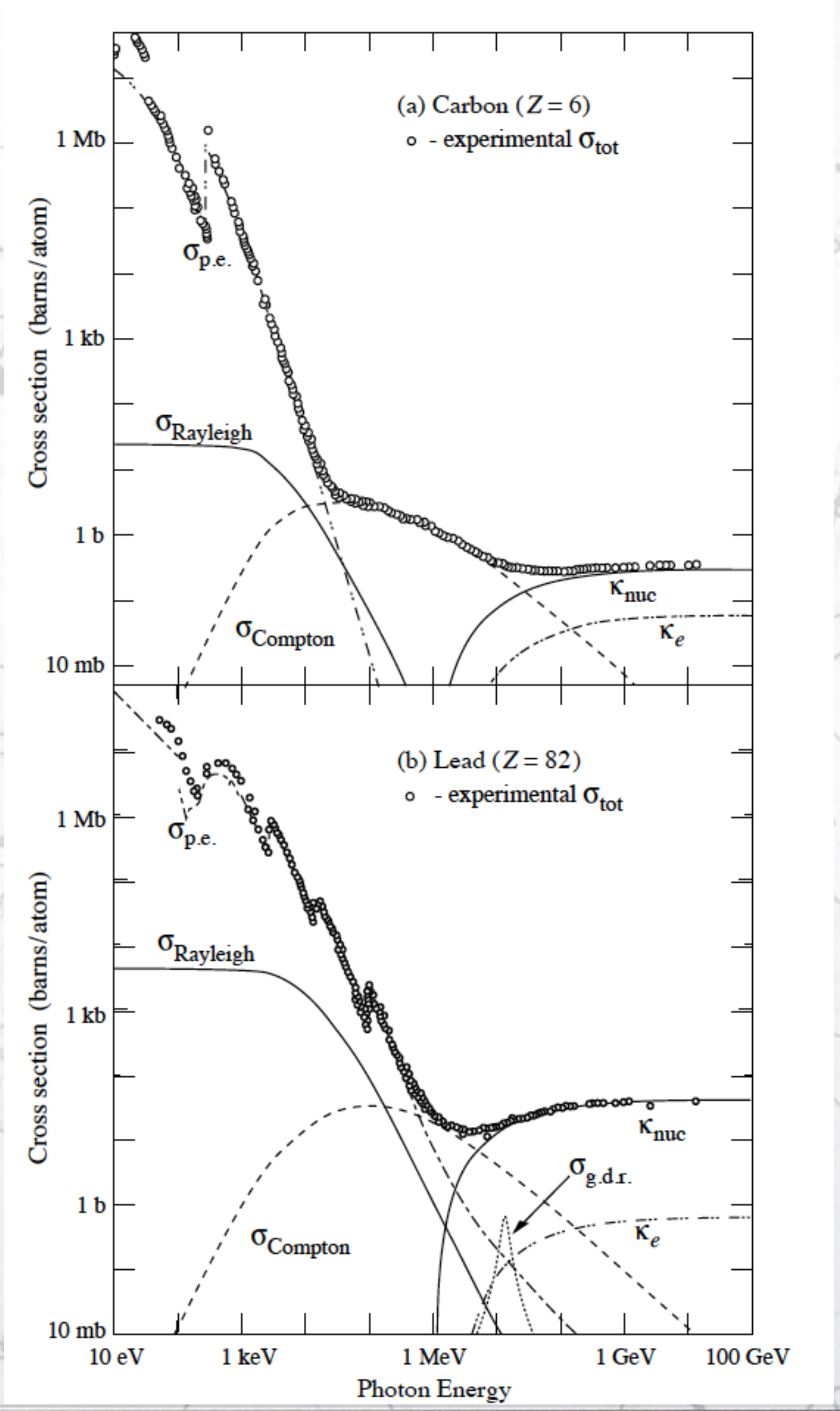


Particle showers

Relevant region of energy

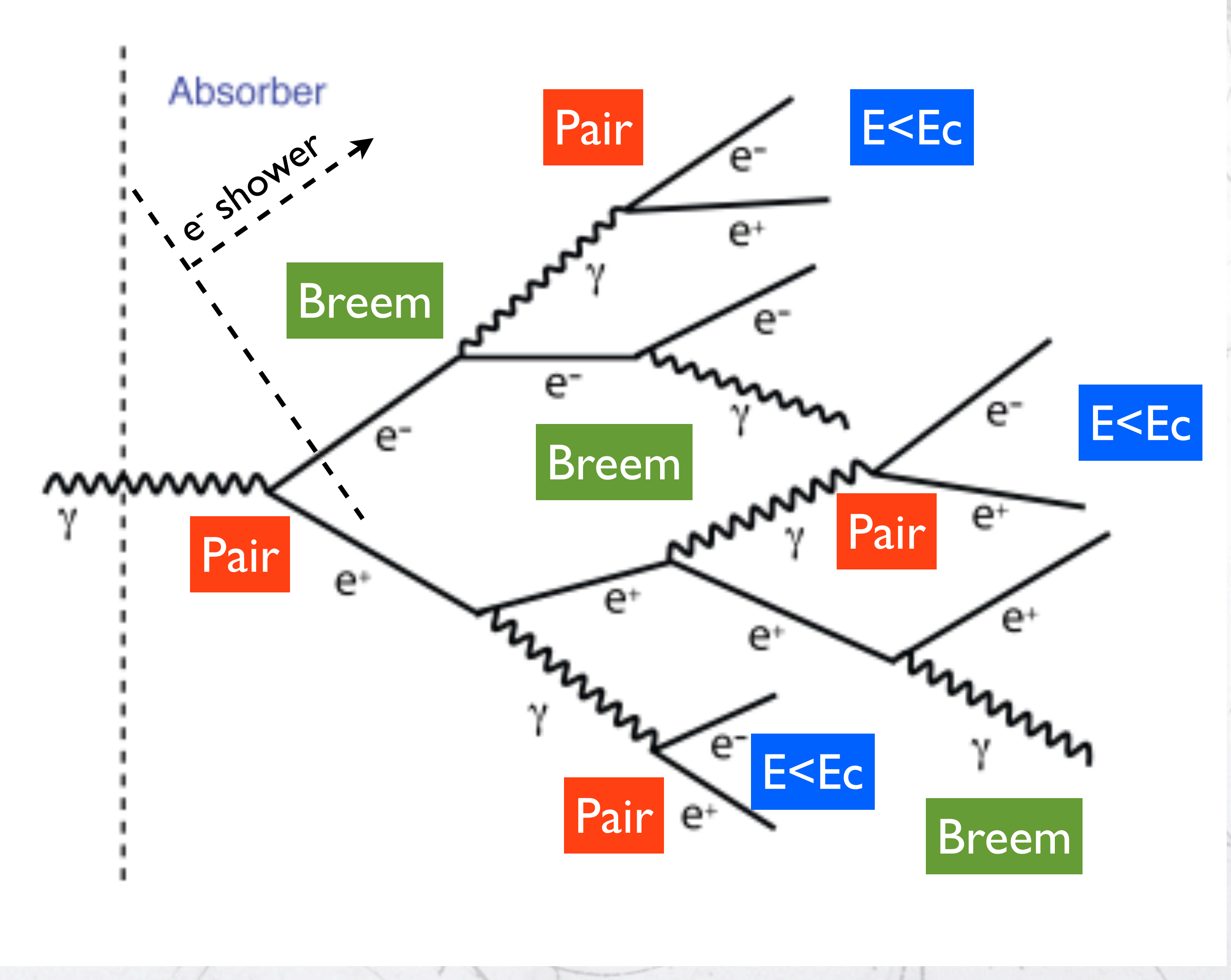
- Photon interactions with matter:
  - Pair production (κ_{nuc},κ_e)
  - Compton scattering ($\sigma_{compton}$)
  - Photoelectric ($\sigma_{p.e.}$)
  - Rayleigh ($\sigma_{Rayleigh}$)
    - Elastic scattering, no energy loss.

- The relative importance of the processes depend strongly on the material Z.



Particle shower

- The processes are chained until eventually the electrons fall below the critical energy and are absorbed by ionisation.
- The energy of all the ionisation is proportional to the incoming photon (electron) particle.
- The number of electrons is also proportional to the incoming particle.



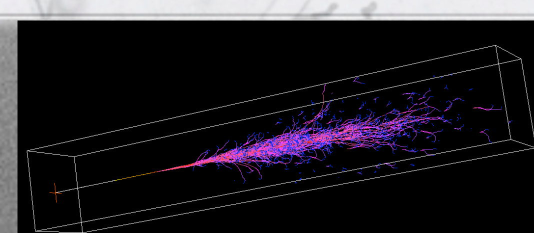
Particle shower

- Electromagnetic showers properties depend on the probability of electrons to produce breemstrahlung and photons produce e^+e^- pair.
  - Radiation length (X_0) is a distance over which:
    - an electron loses 1/e of its energy in radiatio, i.e. emits ~1 breemstrahlung.
    - distance to produce a e^+e^- pair is ~9/7 X_0
  - The interaction probability depends on the Z of the material and its density, the X_0 is defined as density normalized.

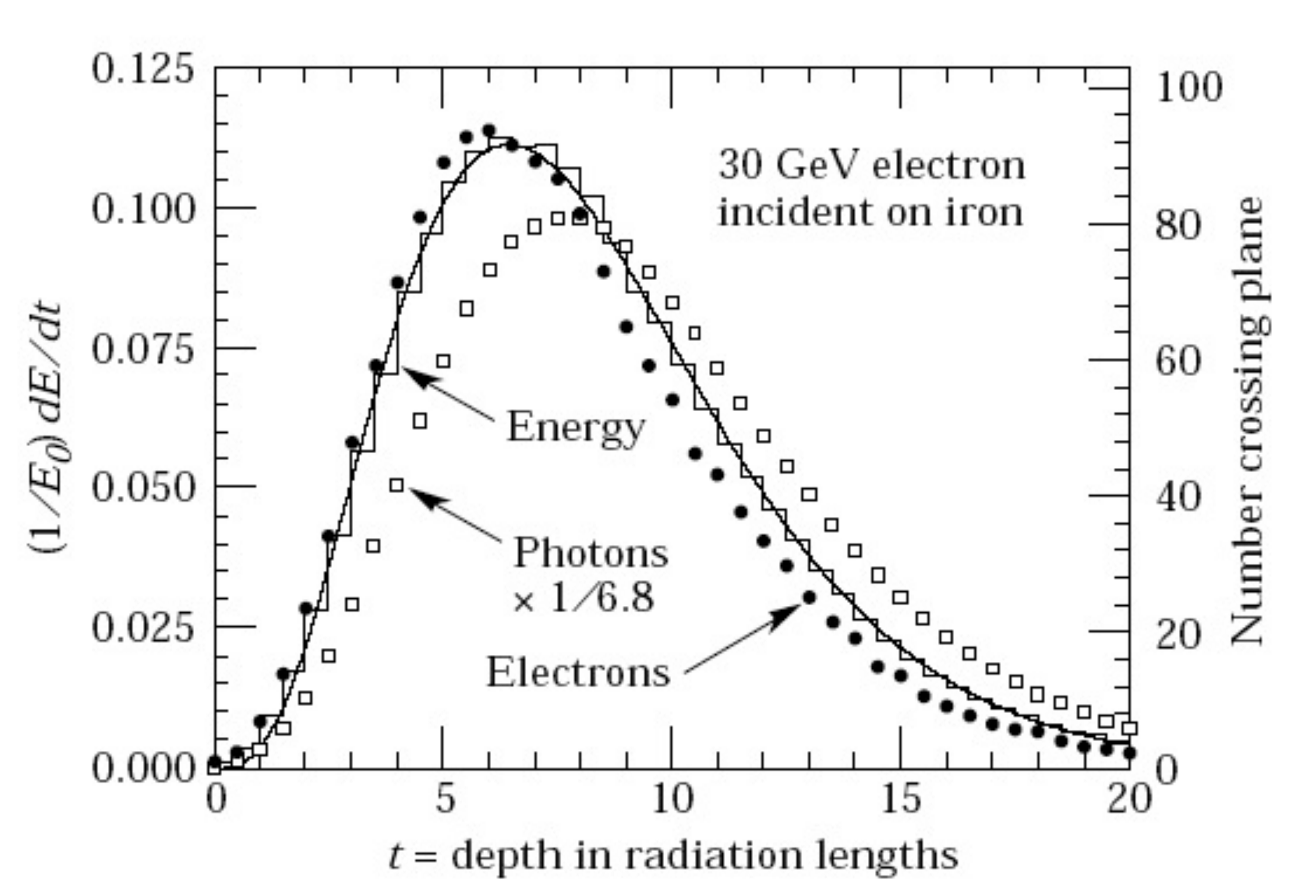
$$X_0 = \frac{716.4A}{Z(Z+1)\ln(287/\sqrt{Z})}[\frac{g}{cm^2}]$$

  - The transverse evolution of the shower also depends on the probability of pair production and breemstrahlung. The control parameter is the Moliere Radius:

$$R_M = \frac{21.2MeV}{E_c}X_0$$



Particle shower

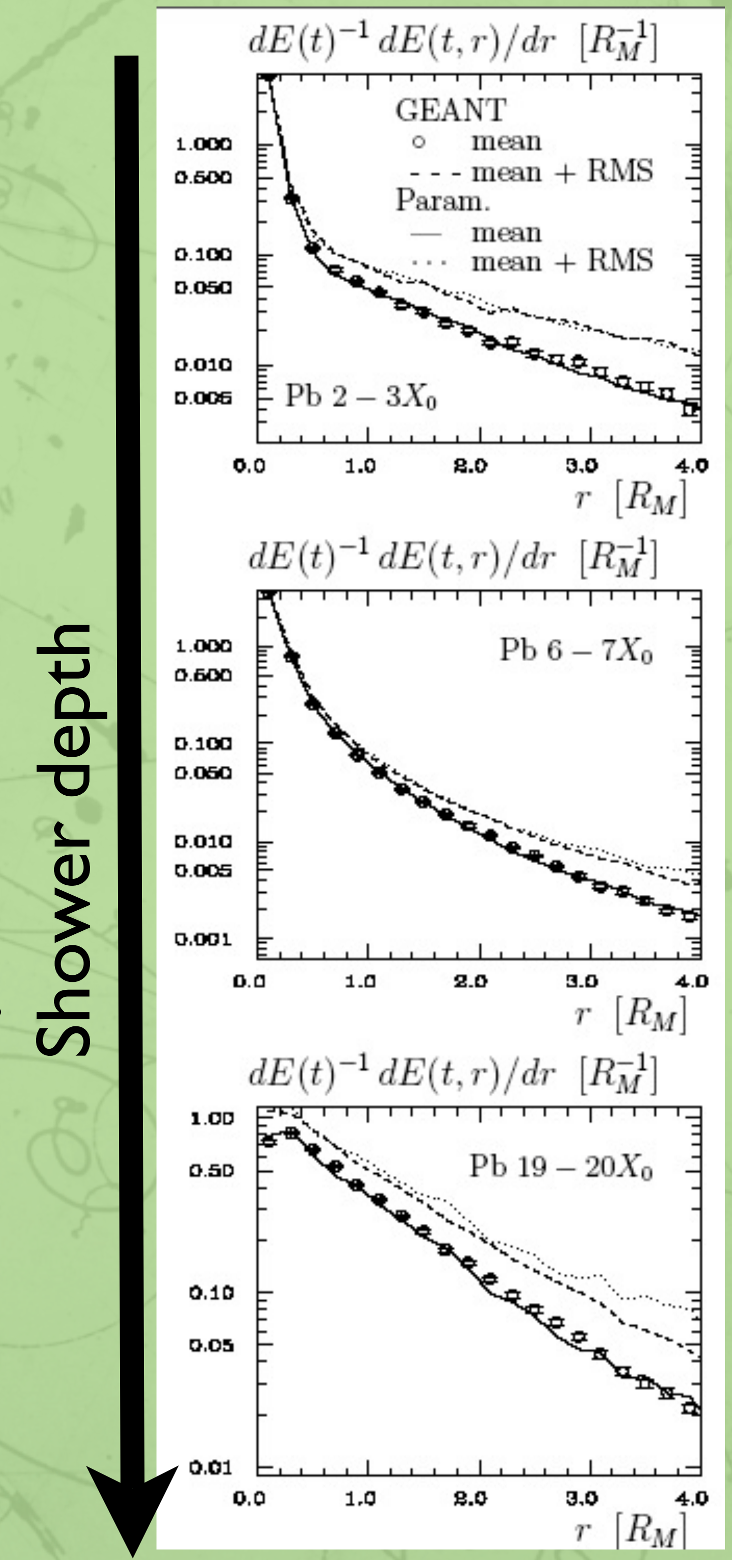


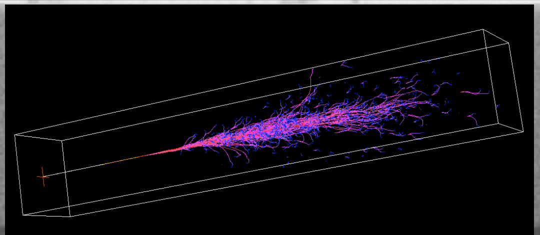
- The longitudinal distribution is described by a Gamma function,

$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

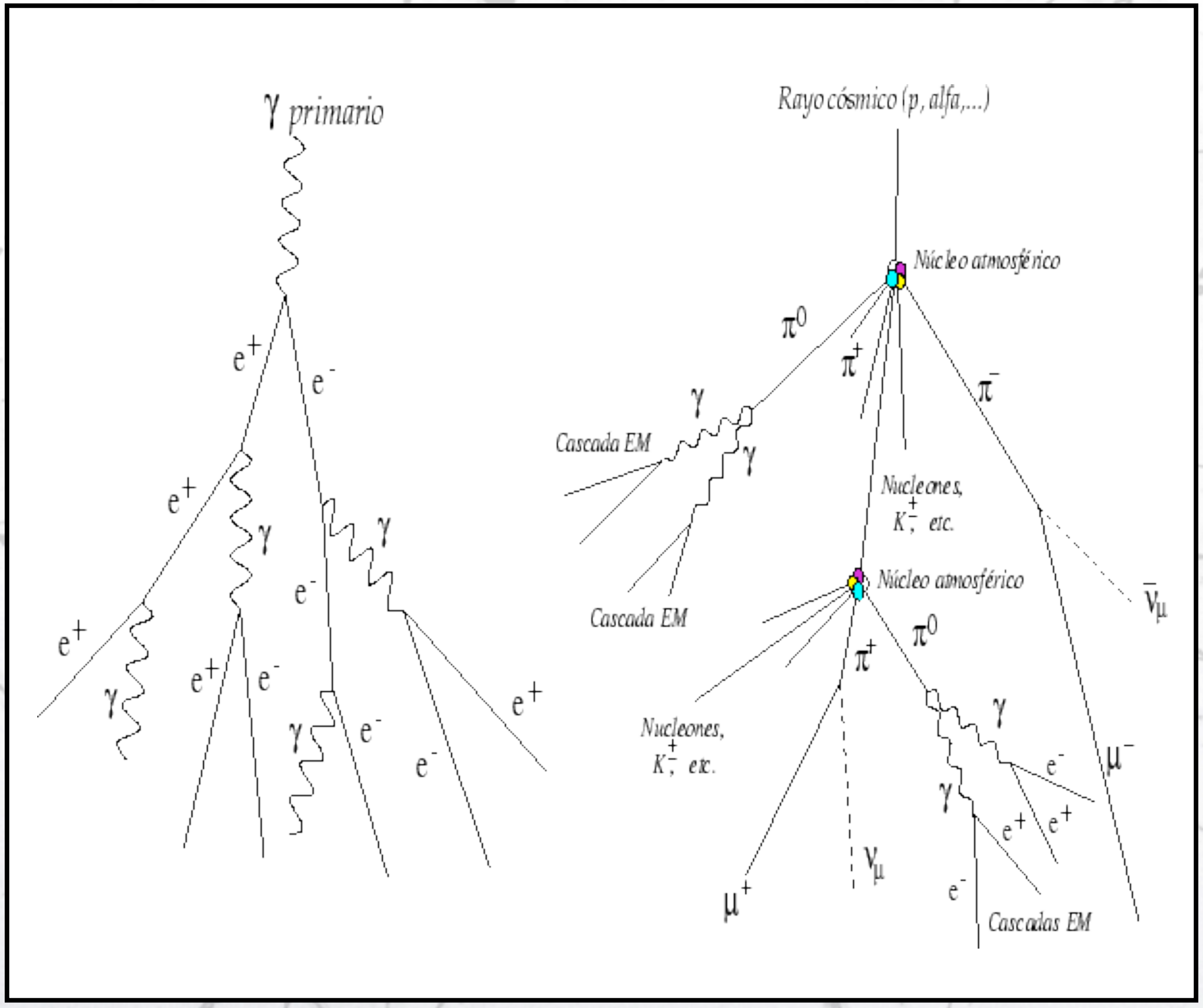
$$t = \frac{x}{X_0}$$

- The transverse distribution is non gaussian.
- It also depends on the shower depth.
- ~90% of the charge is deposited within 1 Moliere radius.
- ~95% of the charge is deposited within 2 Moliere radius



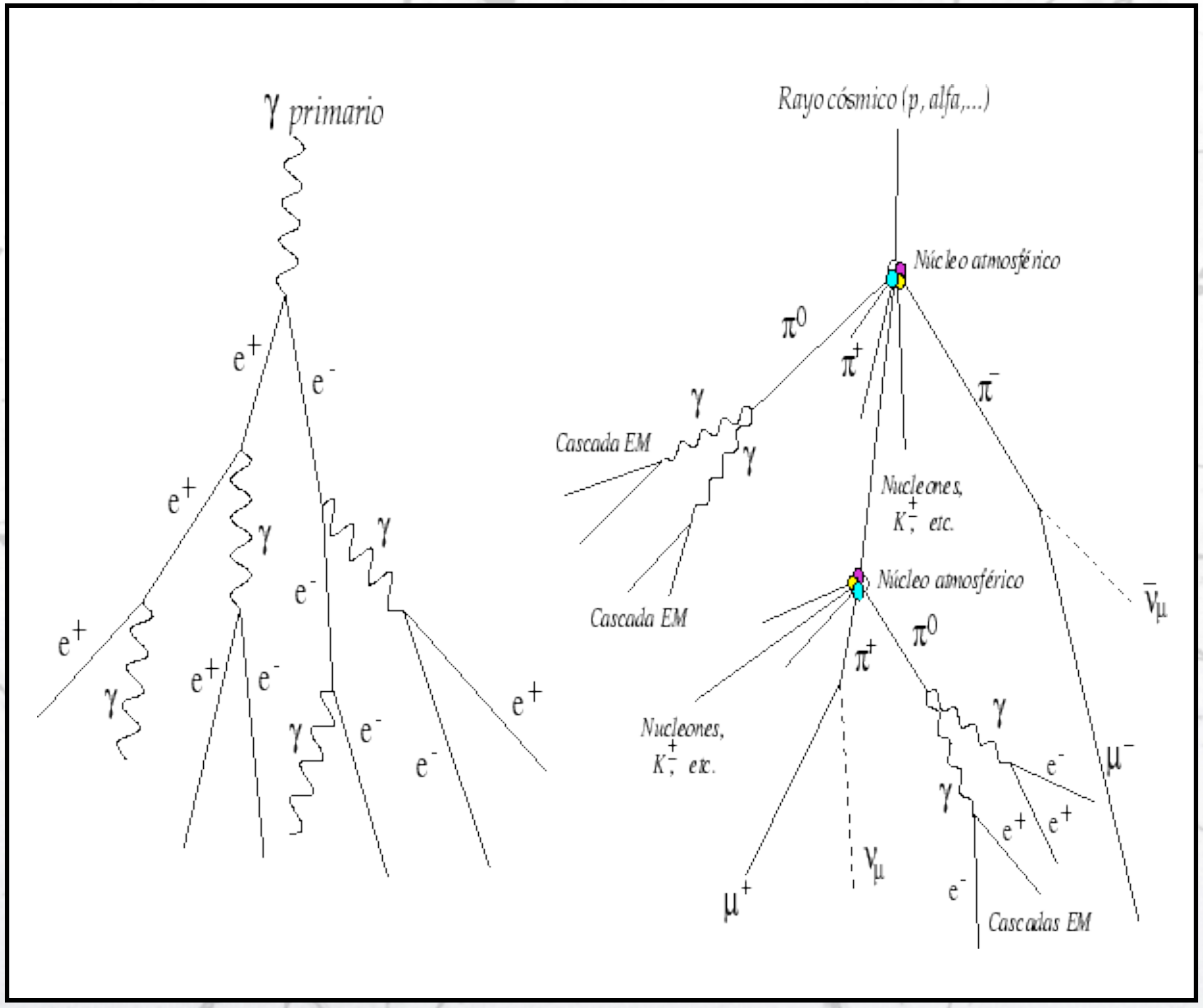


Hadron showers



- Hadronic showers are similar to electromagnetic cascades but more complex:
  - Include hadronic interactions and large variety of particles: photons, electrons, protons, neutrons, kaons, pions, etc….
    - neutrons interact elastically and then thermalise later in the event.
    - Pions, protons and neutrons transfer energy to nucleons, the recoil energy is not visible.

Hadron showers



- The multiplicity of tracks is smaller.
- π^0 are produced in hadronic showers but they decay to photons producing electromagnetic cascades. The fraction of EM in hadronic cascades varies from event to event altering the amount of energy measured.
- In general the hadronic energy is much worse the electromagnetic.
- There are large variations depending on the initial particle (proton, pion, etc…)

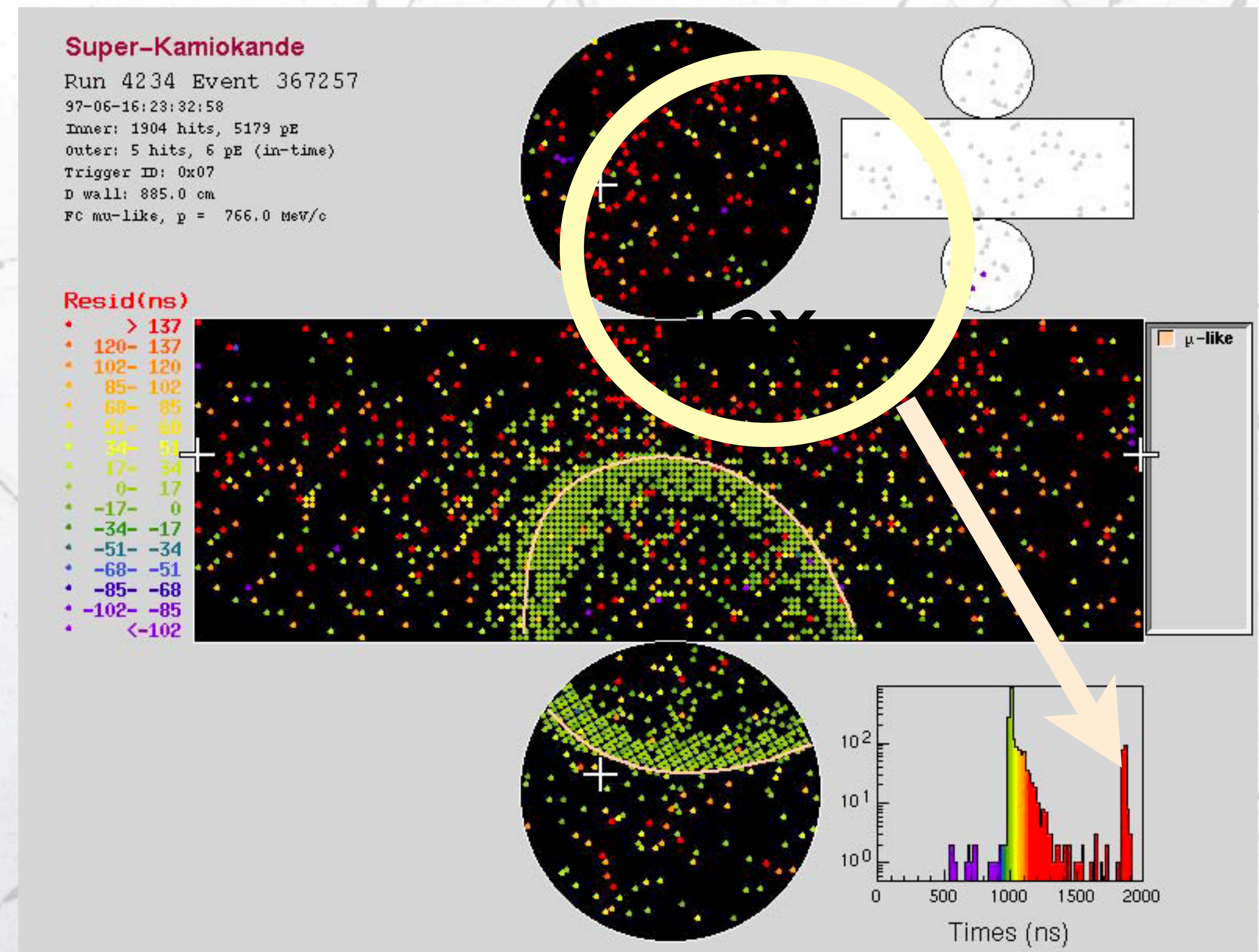
Additional handles

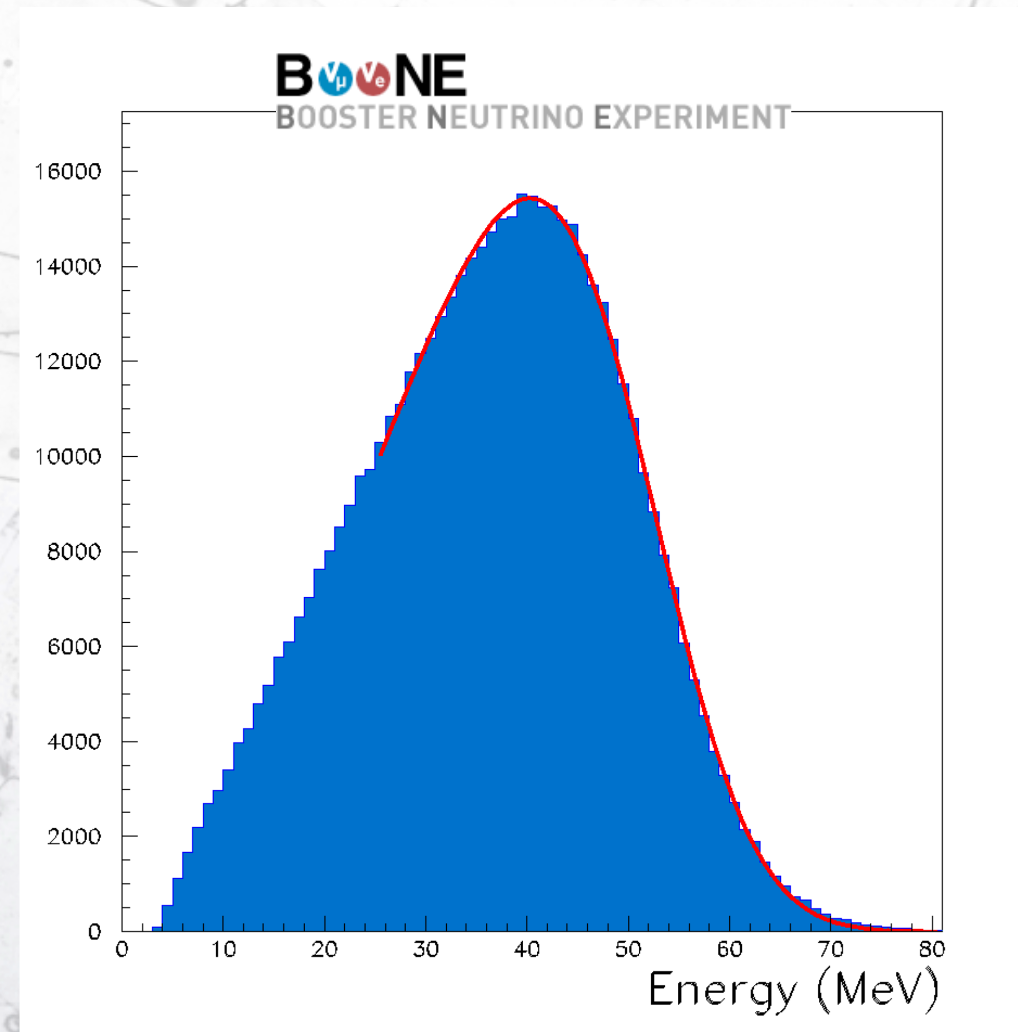
- Muons and pions can be identified in scintillator and Cherenkov detectors by the Michel electron emission after the particle stops.
- Delayed electron-like signal of $E_e < m_\mu/2$

$$\mu \to e\nu\nu$$

$$\pi \to \mu\nu \to e\nu\nu\nu$$

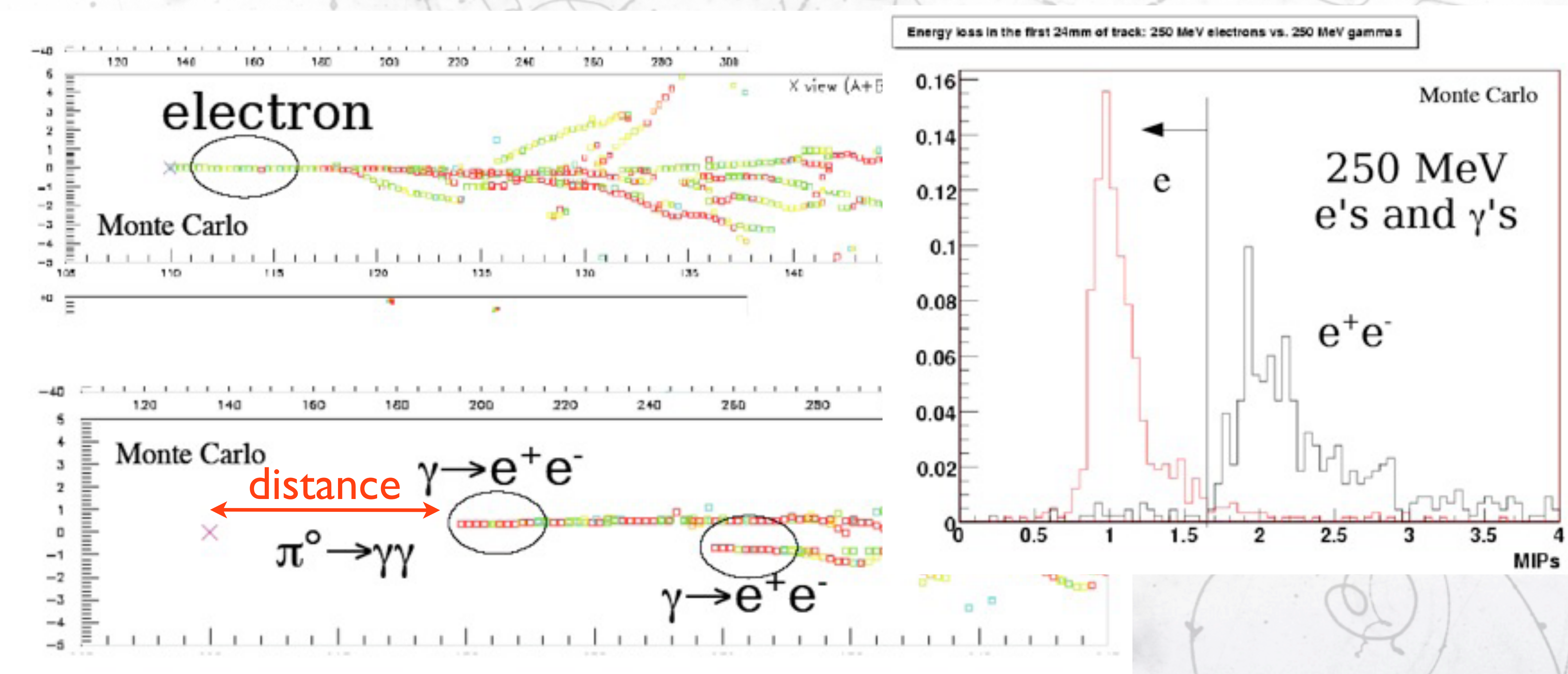
$$\tau_{decay} \approx 2\mu s$$





Additional handles

- γ → e⁺e⁻ can be with two additional handles:



- distance to vertex (when visible).
- double ionization at track start.

Cherenkov

Reminder

- A charged particle radiates if its velocity is greater than the local phase velocity of light (Cherenkov radiation) or if it crosses suddenly from one medium to another with different optical properties (transition radiation).

- This is a negligible energy loss but with interesting properties.

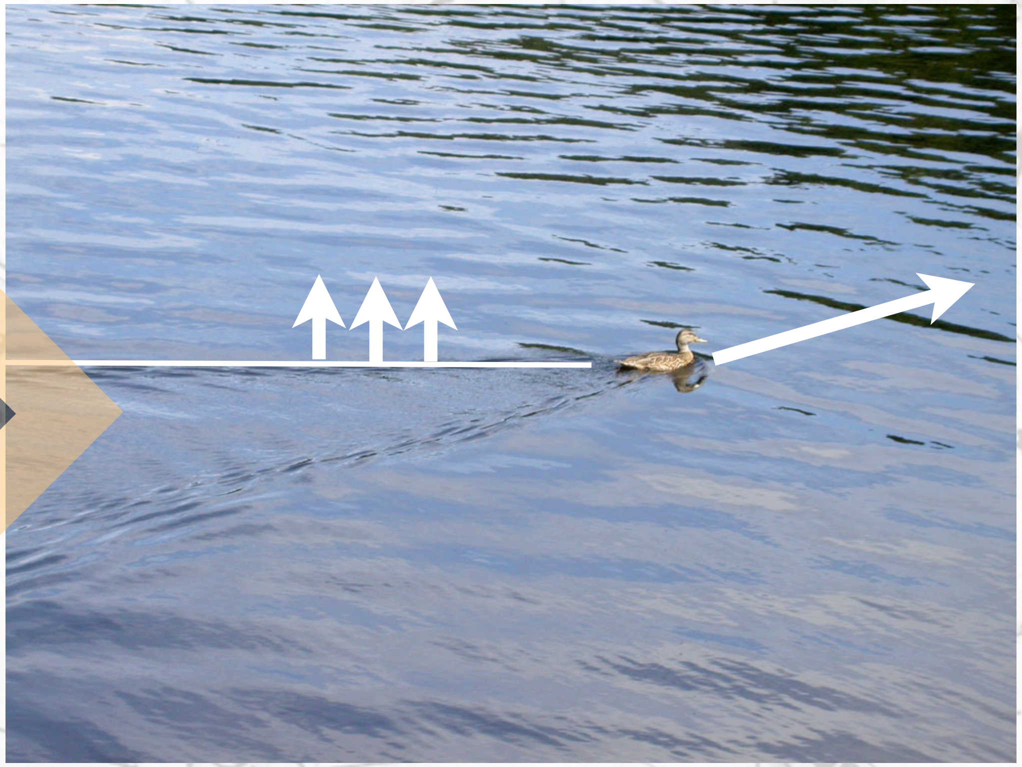
- Light is emitted in a light front with defined angle with respect to the particle direction (directionality):

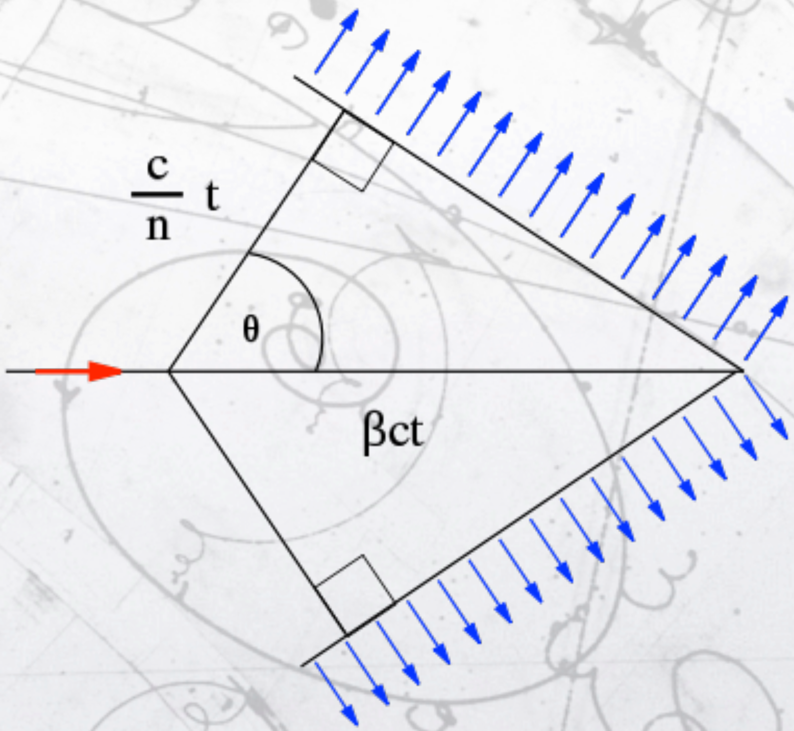
$$\cos\theta = \frac{1}{n\beta}$$

n index of refraction
β particle velocity

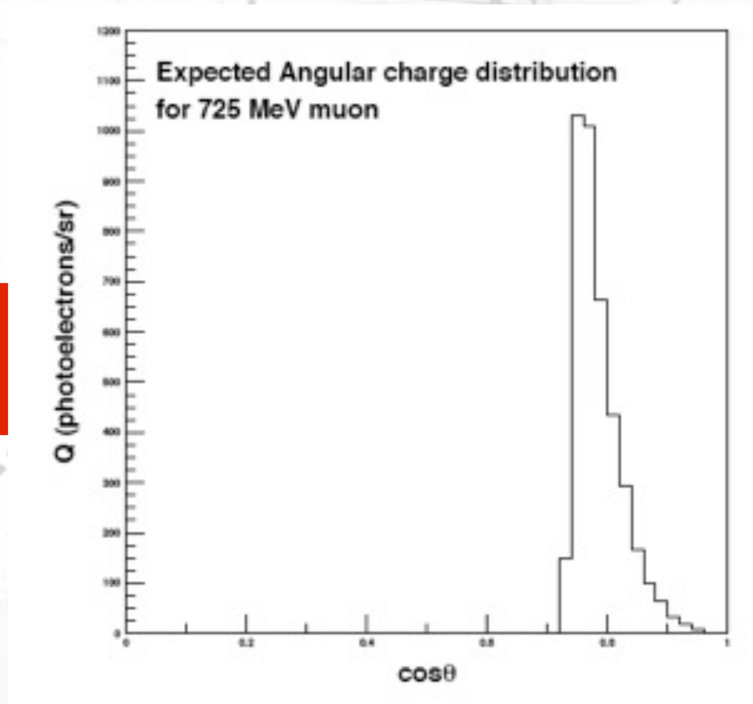
- The threshold is $\beta > 1/n$, $\beta\gamma > 0.75$ in water. In momentum:

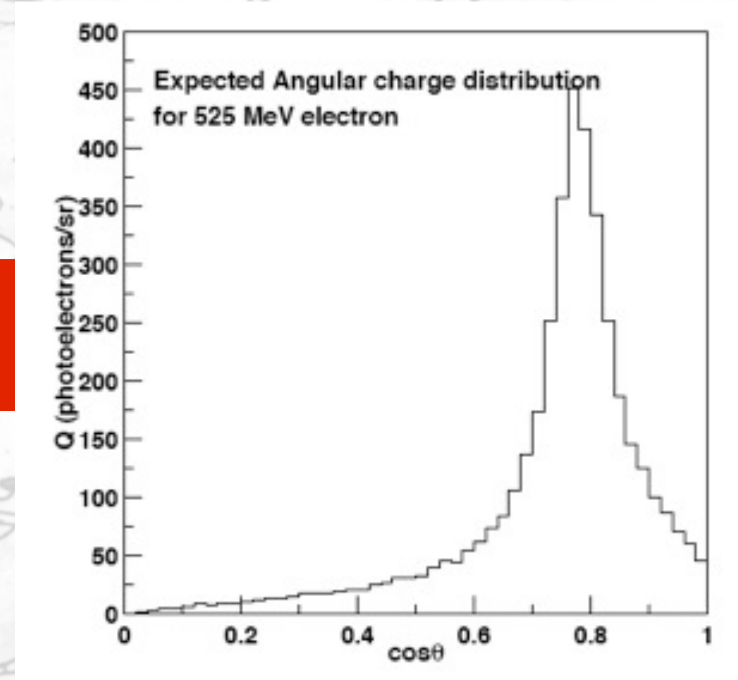
$$p \geq m\sqrt{\frac{1.}{(n^2-1)}}$$

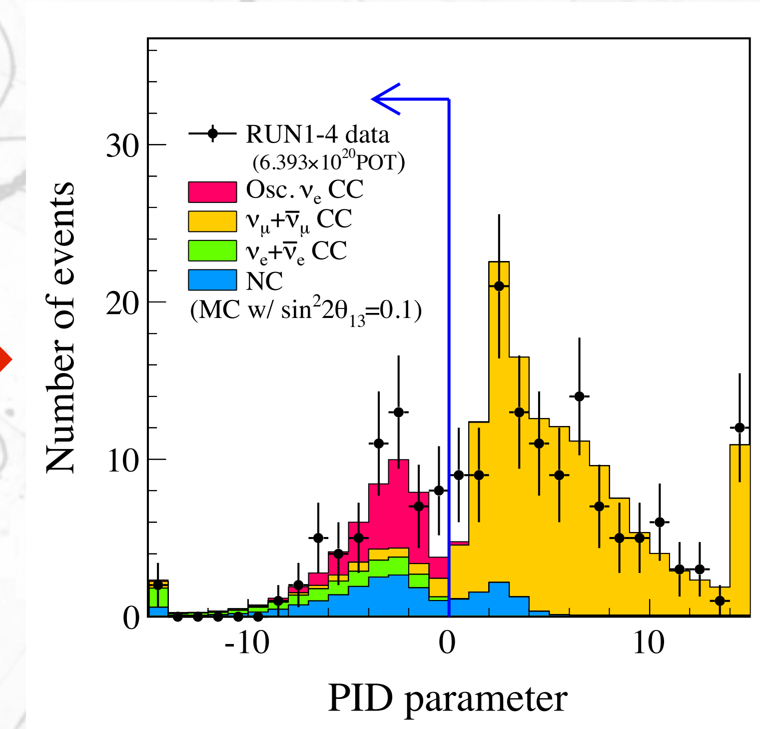




Cherenkov and showers

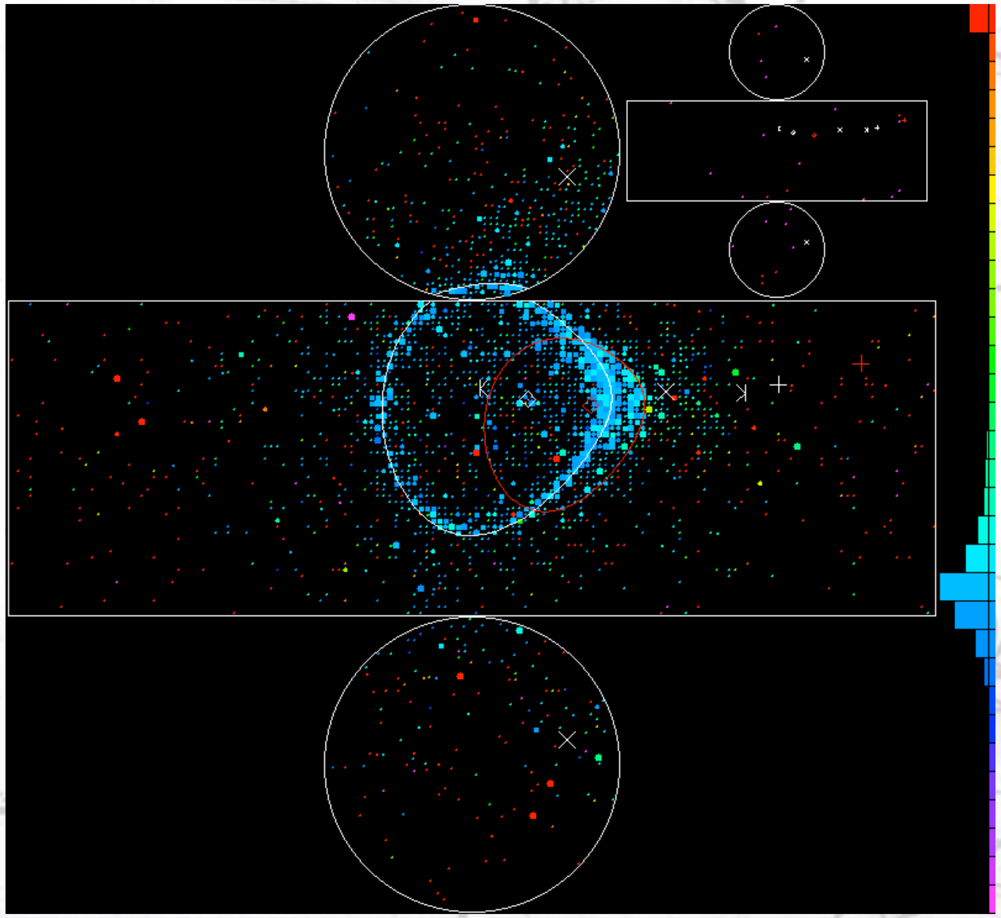


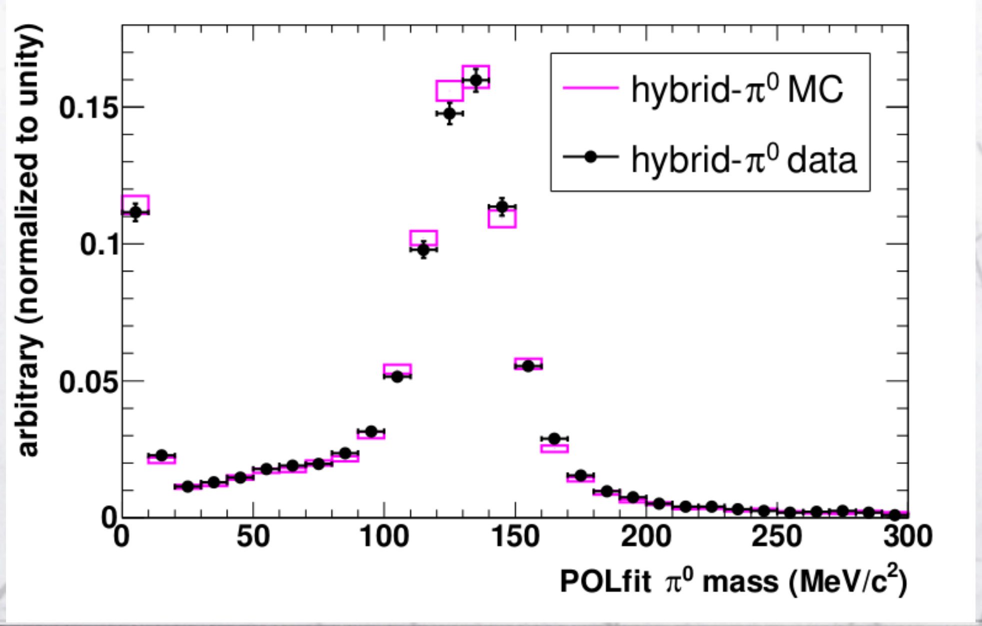




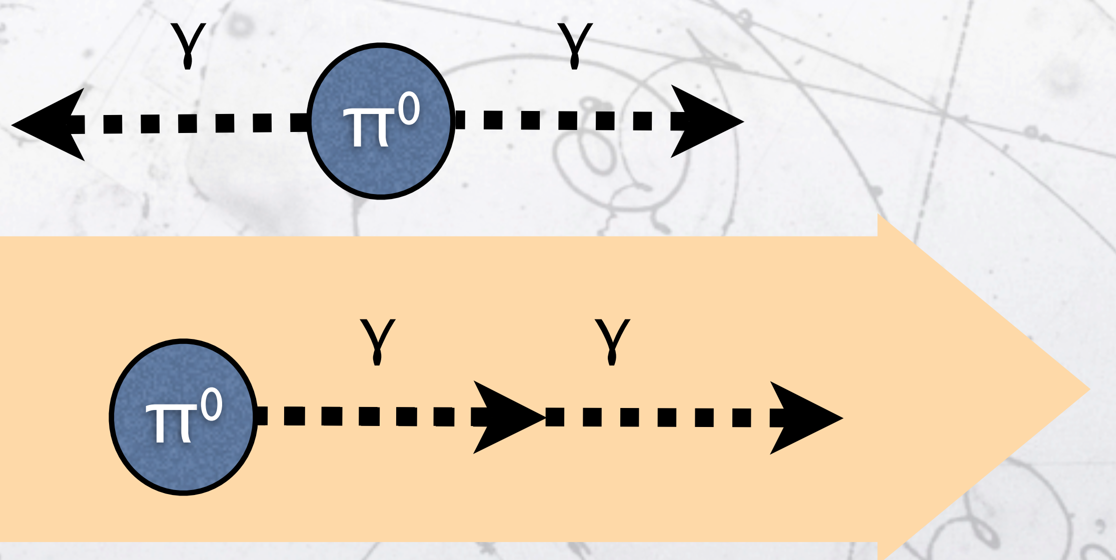
- The expected angular distribution of Cherenkov photons along the primary particle direction is different in electrons and muons:
  - The muon is not sharp due to Multiple Scattering.
- The shape of the distribution can be put into a likelihood and find the id of the original particle.

Cherenkov and showers



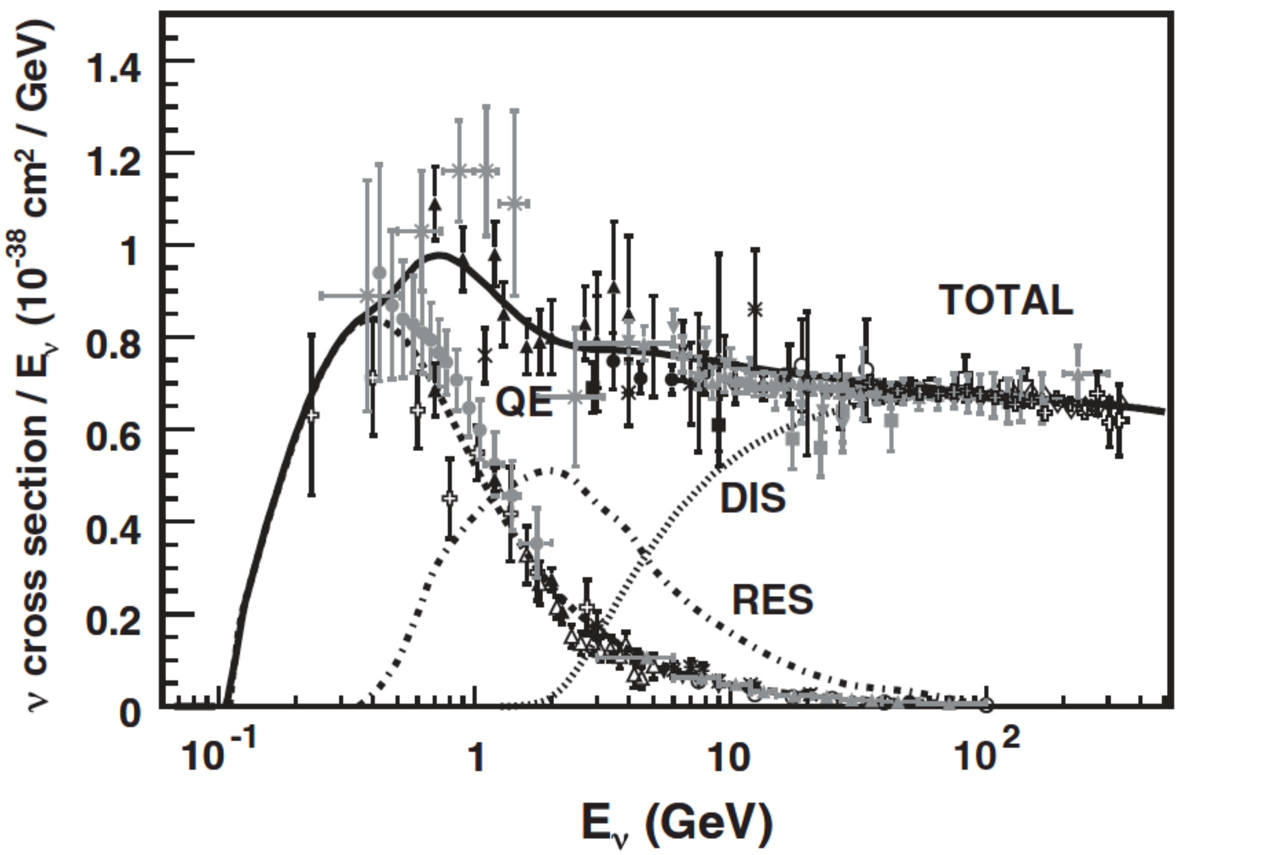


- An important source of background for electron identification are the π^0
  - They are abundantly produced in neutral currents.
  - $\pi^0 \rightarrow \gamma\gamma$. If one γ is missed this can't be distinguished from electrons.
- The detector is able to identify and reject π^0's except in cases where rings overlap.



Neutrino Energy reconstruction

Reminder



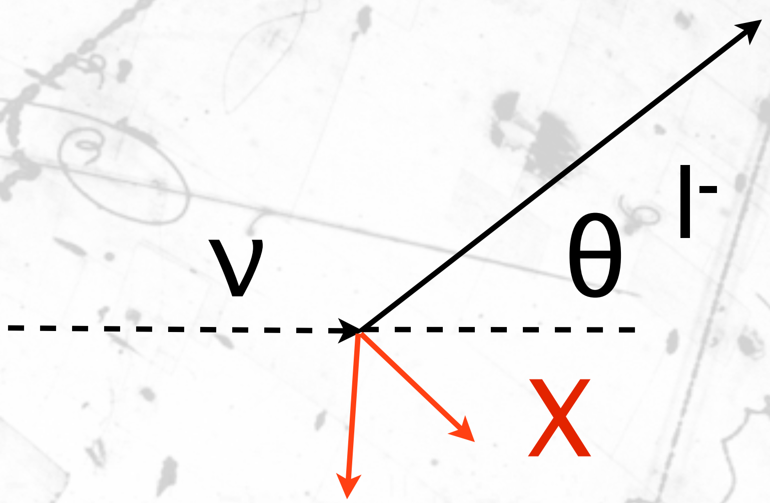
$$(CCQE)\, \nu_l\, n \rightarrow l^- p$$

$$(CCRes)\, \nu_l\, N \rightarrow l^- \Delta^{+,++} \rightarrow l^- N' \pi^+$$

$$(CCDIS)\, \nu_l\, q \rightarrow l^- X$$

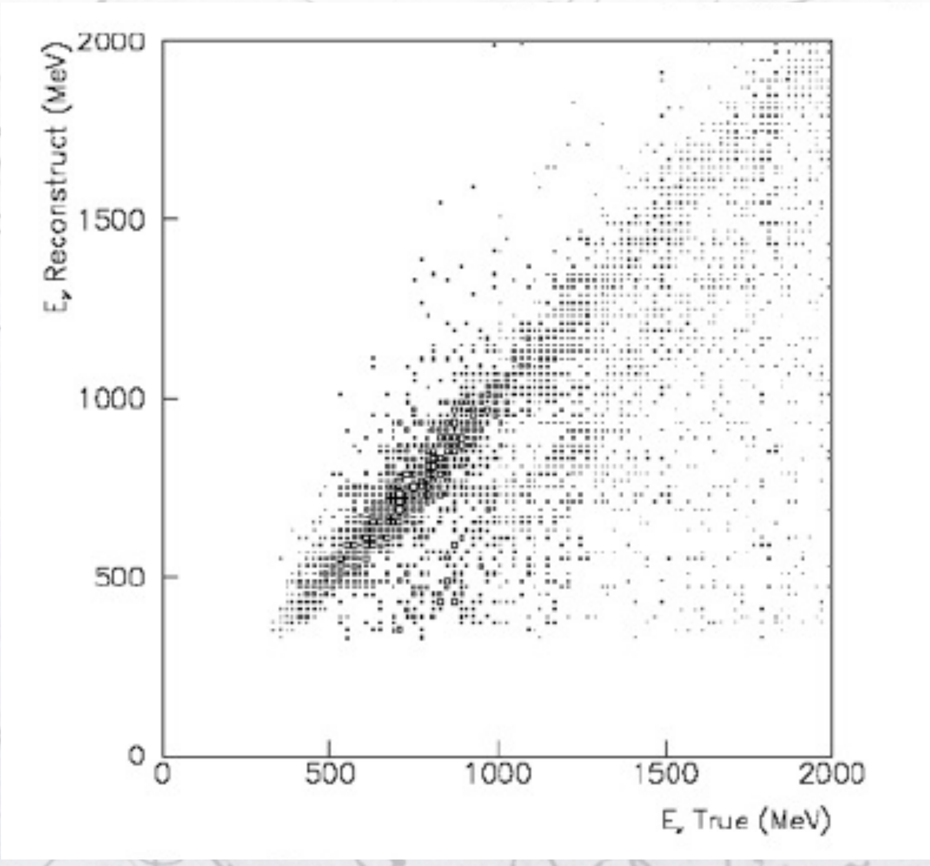
- When the energy of the neutrino is above ~100 MeV, the cross-section with Nuclei dominates.
- There are different interactions when the energy increase.
- In the ideal case, we would like to reconstruct the energy of the neutrino for all these cases.

Lepton kinematics



- Let's assume that we know the direction of the neutrino and the momentum and angle of the lepton.
- Assume the target is at rest (ignore Fermi motion)
- In this case is a two to two body interaction, and conservation of momentum gives:

$$E_\nu = \frac{ME_l - m_l^2/2}{M - E_l + |p_l|\cos\theta_l}$$



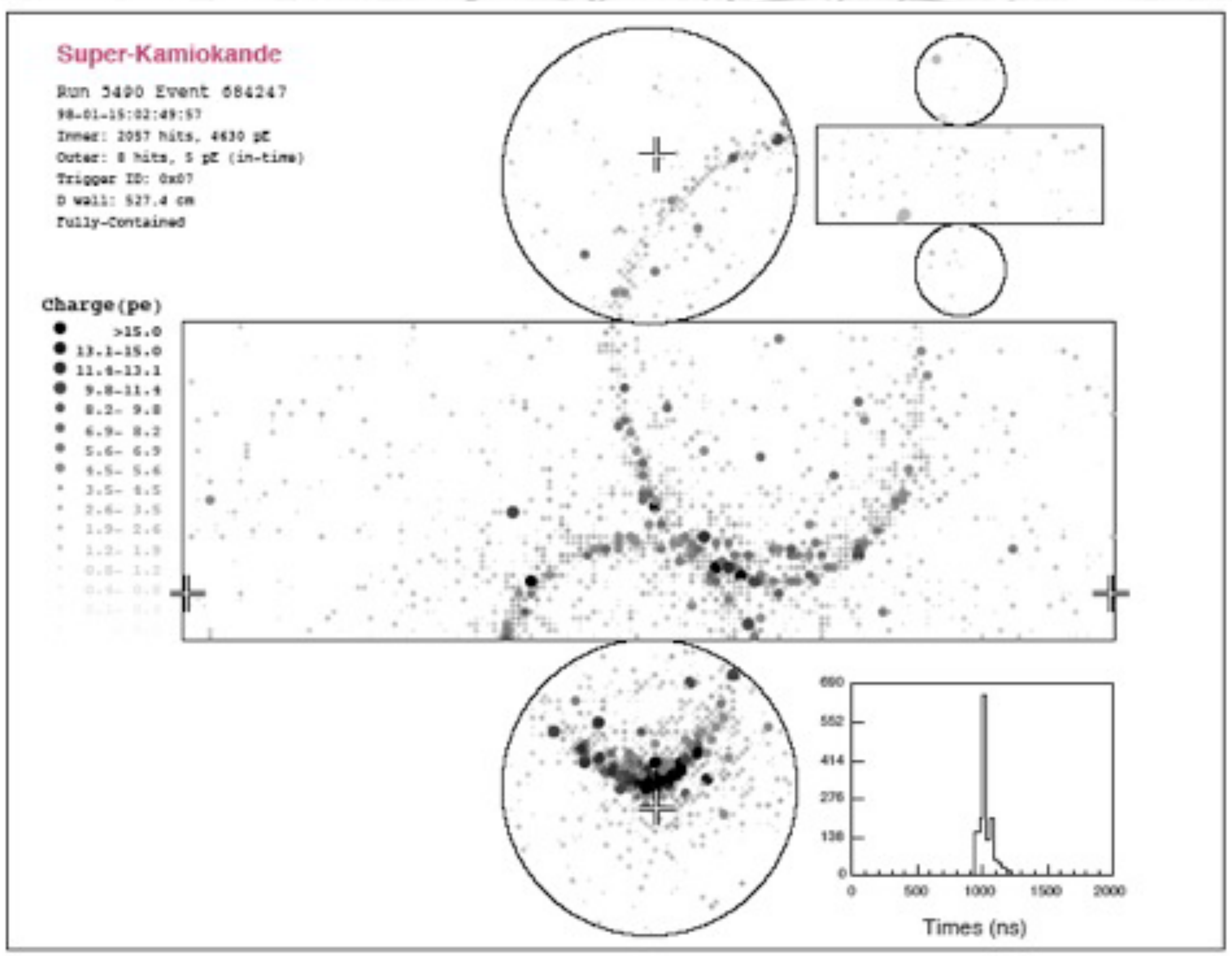
- The equation depends on the final state mass (p, Δ, …) and nuclear effects (Fermi motion).
- We need to identify the channel (only CCQE and CC1π) is possible.

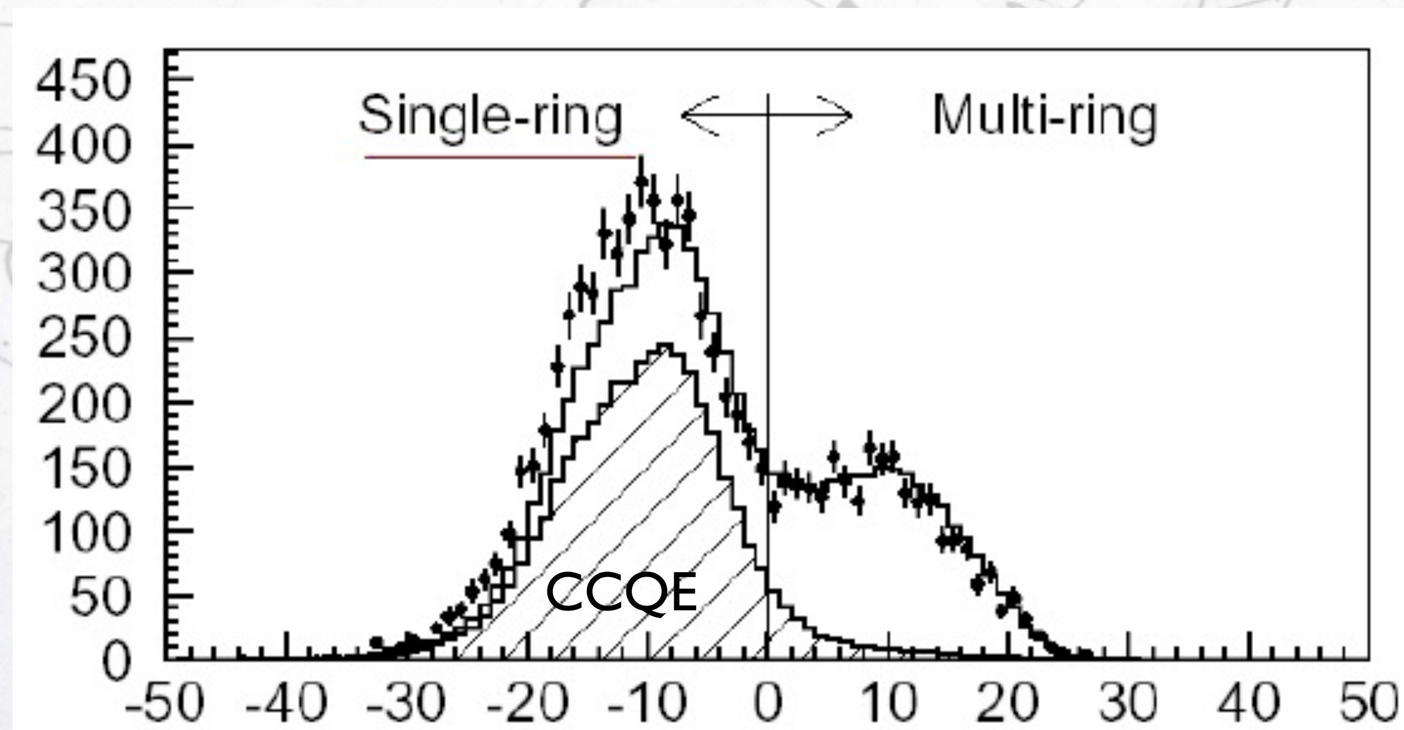
Lepton kinematics

- This is a good, some times mandatory, method:
    - at low energies since dominated by CCQE interactions.
    - water Cherenkov detectors, where the hadron component is below threshold.
    - hadronic particles alter direction, nature and momentum in their way out of the nucleus so it is better to ignore them.
- But, it introduces bias in the energy reconstruction (critical for oscillation physics):
    - Misidentification of the reaction channel.
    - Fermi motion and nuclear effects.

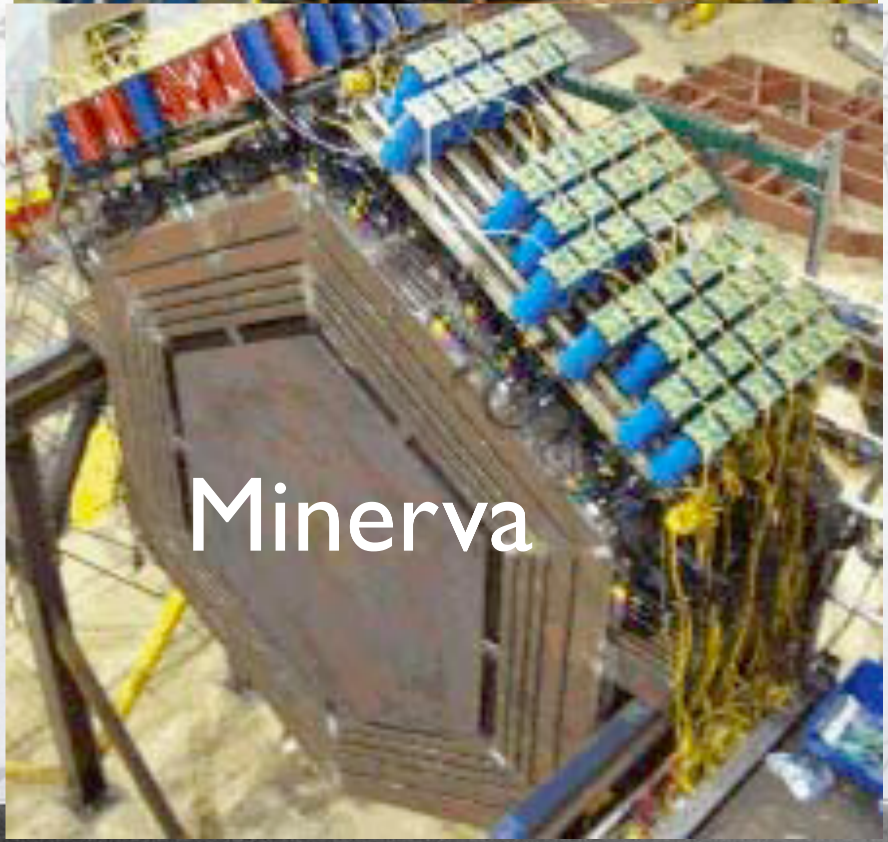
Are there alternatives?

- The Cherenkov detectors has a limiting factor on the detection of low momentum particles due to Cherenkov.
- What is needed is to identify how many rings are seeing in the event to identify CCQE events.

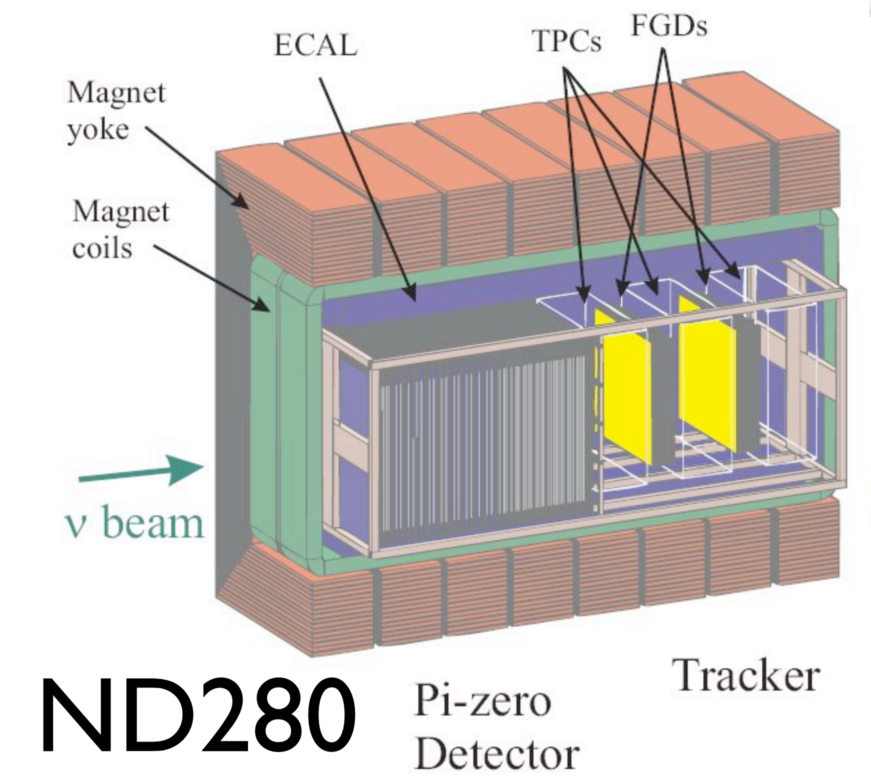


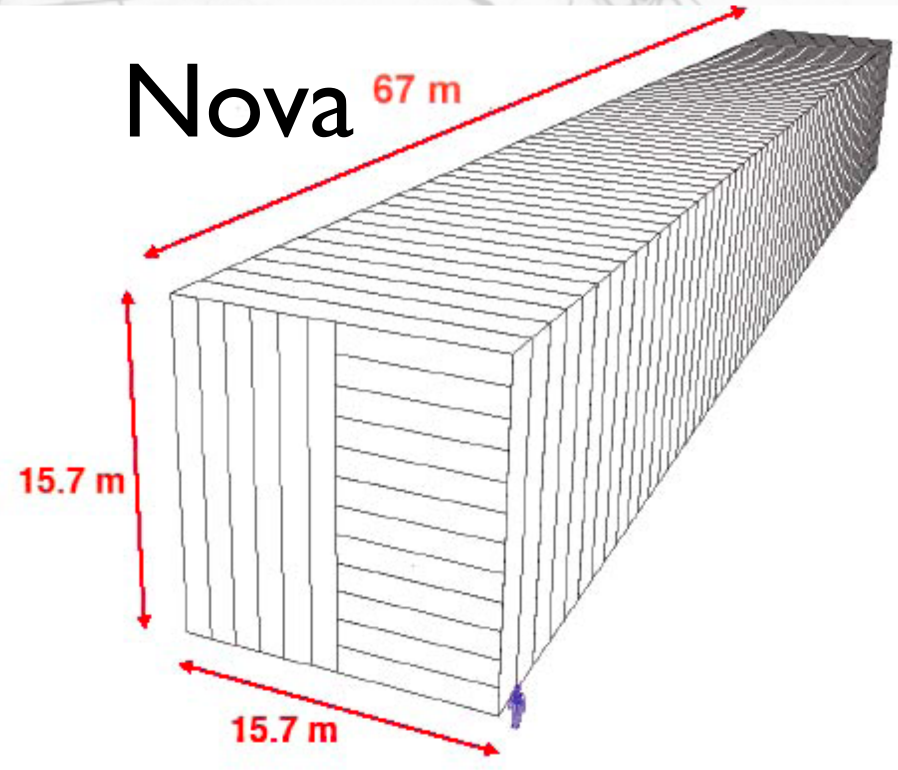


Tracking calorimeters



- Highly segmented active scintillator target.
- Segmentation allow to track particles.
- Energy deposition allows to do calorimetry and particle ID from dE/dx profiles.





Tracking calorimeters

Sampling

- Alternating plates of iron (inactive) and scintillator(active) material.
- It can be "easily" magnetised.
- The iron makes the detector more compact for:
  - electromagnetic and hadronic showers.
  - muons (shorter range)
  - larger target mass per volume.

MINOS

INO

Full active

- Alternating plates of scintillator(active) and/or other active material.
- It can't be "easily" magnetised.
- More sensitive to:
  - short range particles.
  - low energy showers (π^0)

NOVA

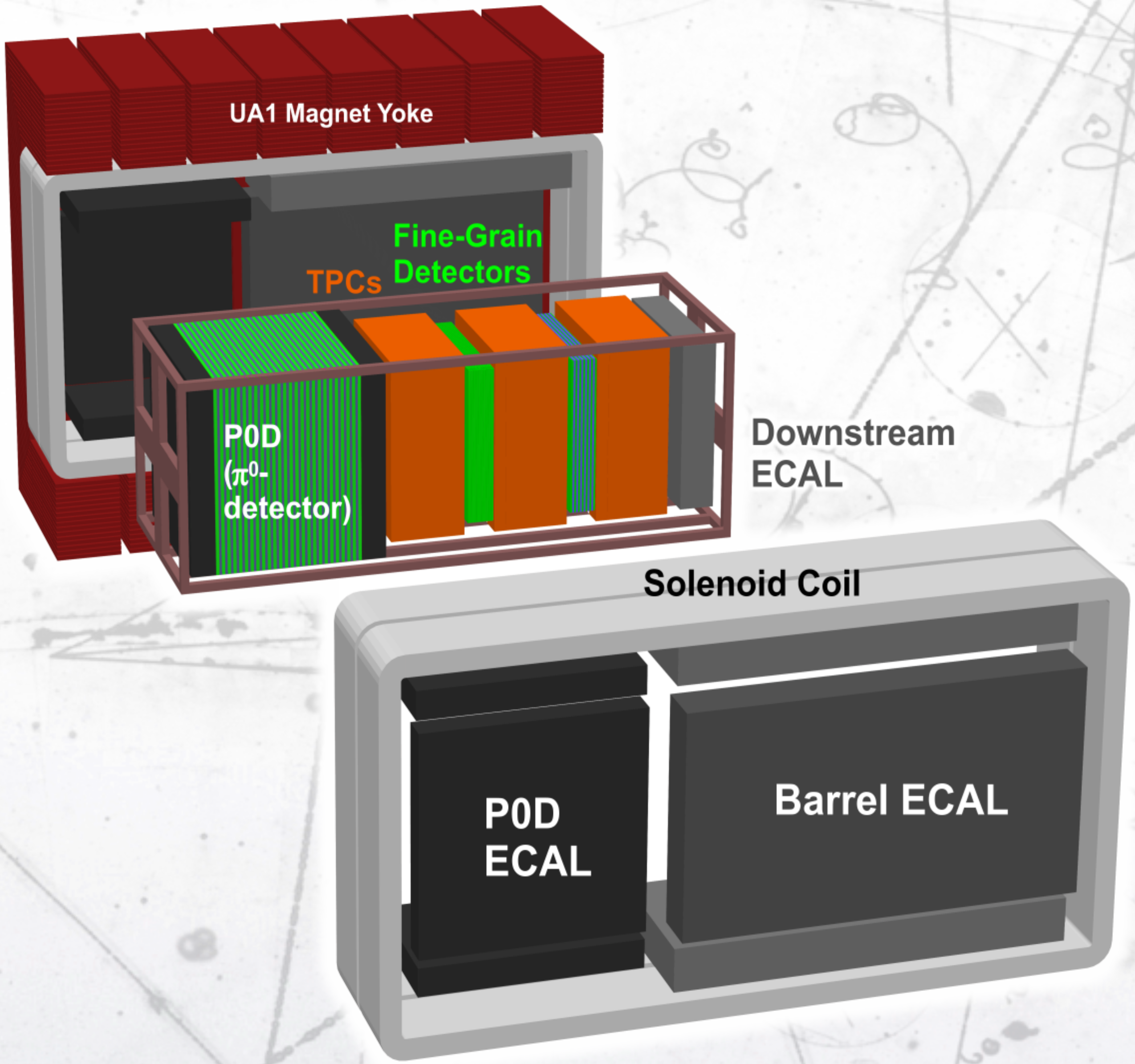
MINERVA

ND280

SCIBOONE

Two special cases

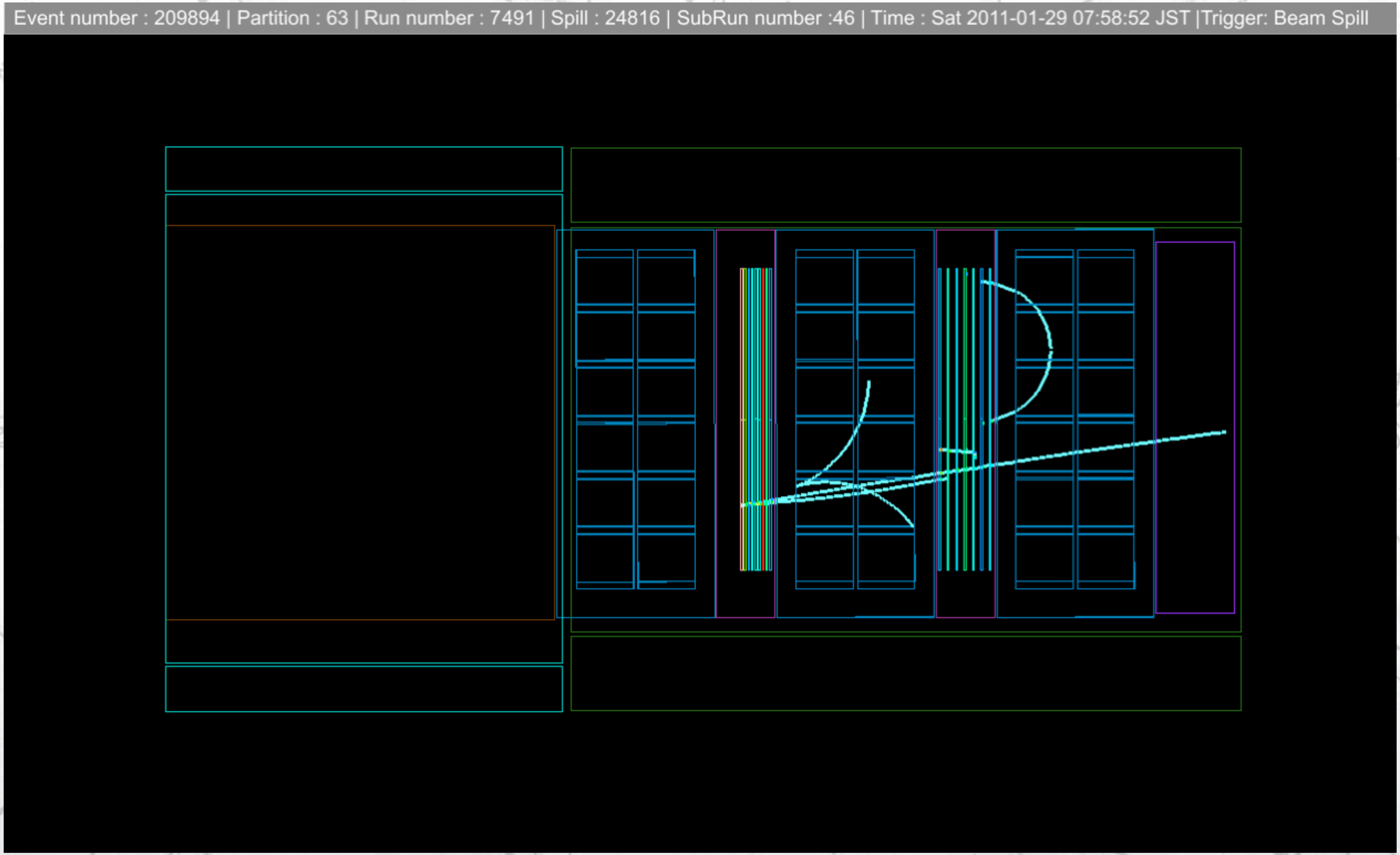
ND280



- Target is fully active (scintillators) for low momentum tracking:
  - thin for tracks (π,μ,p,e,...)
  - thick for π^0
- The TPCs measure the momentum and the PID from dE/dx.
- The neutral particles are catched in the ECAL (sampling calorimeter).
- Muons are tracked in the Magnet for particle ID.

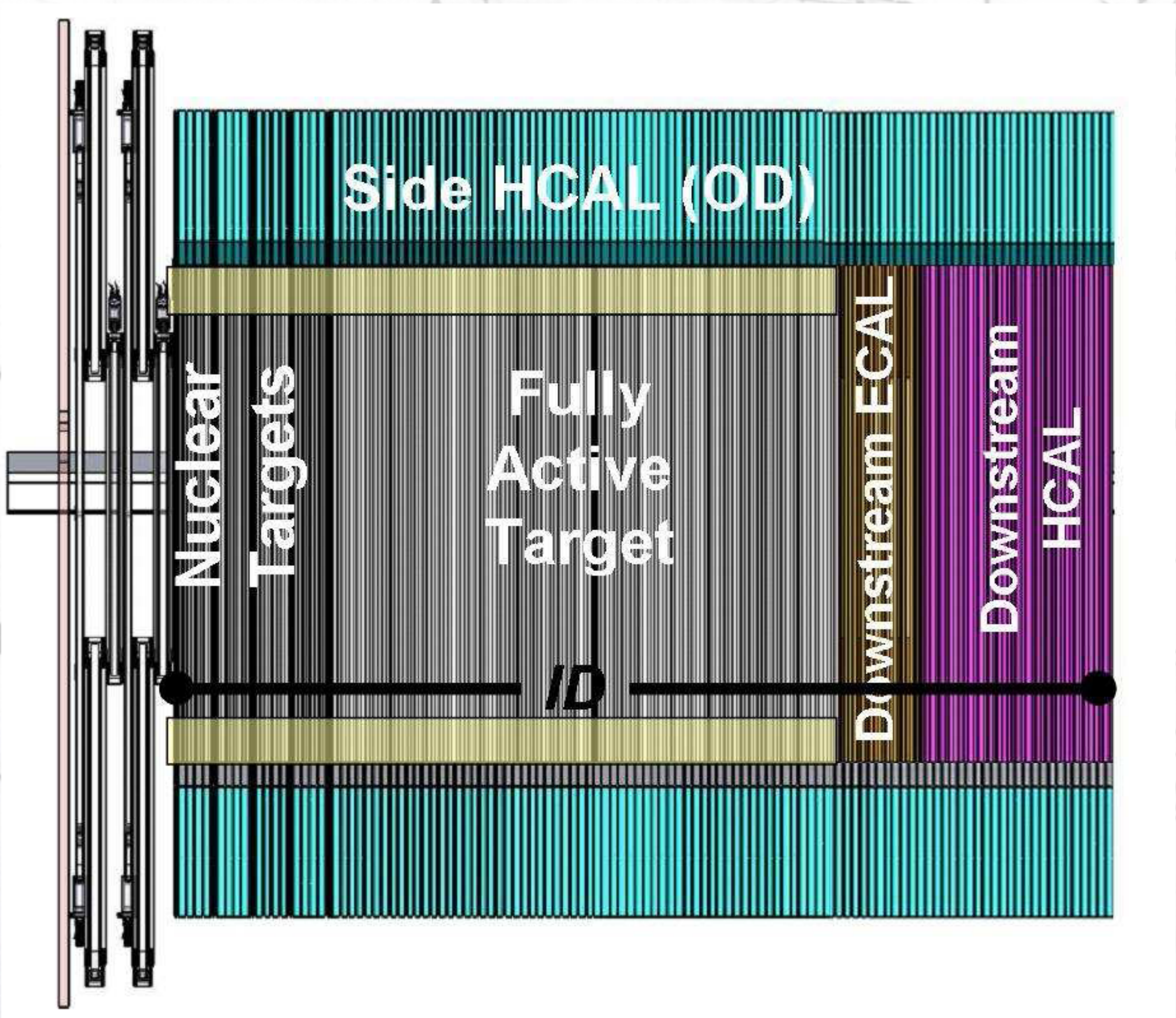
ND280 is closer to the concept of "onion" HEP detectors: several subdetectors with different functions.

Tracking calorimeters



ND280

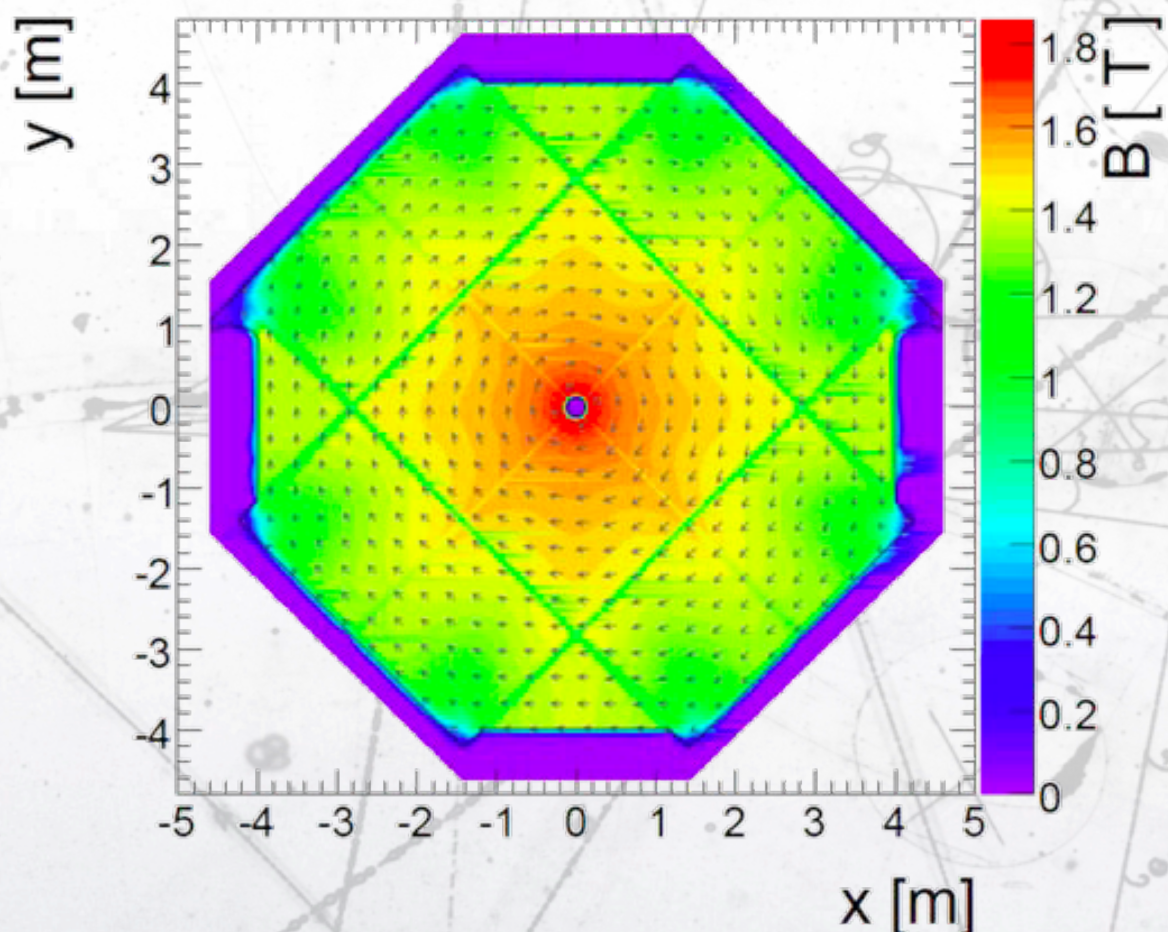
Minerva

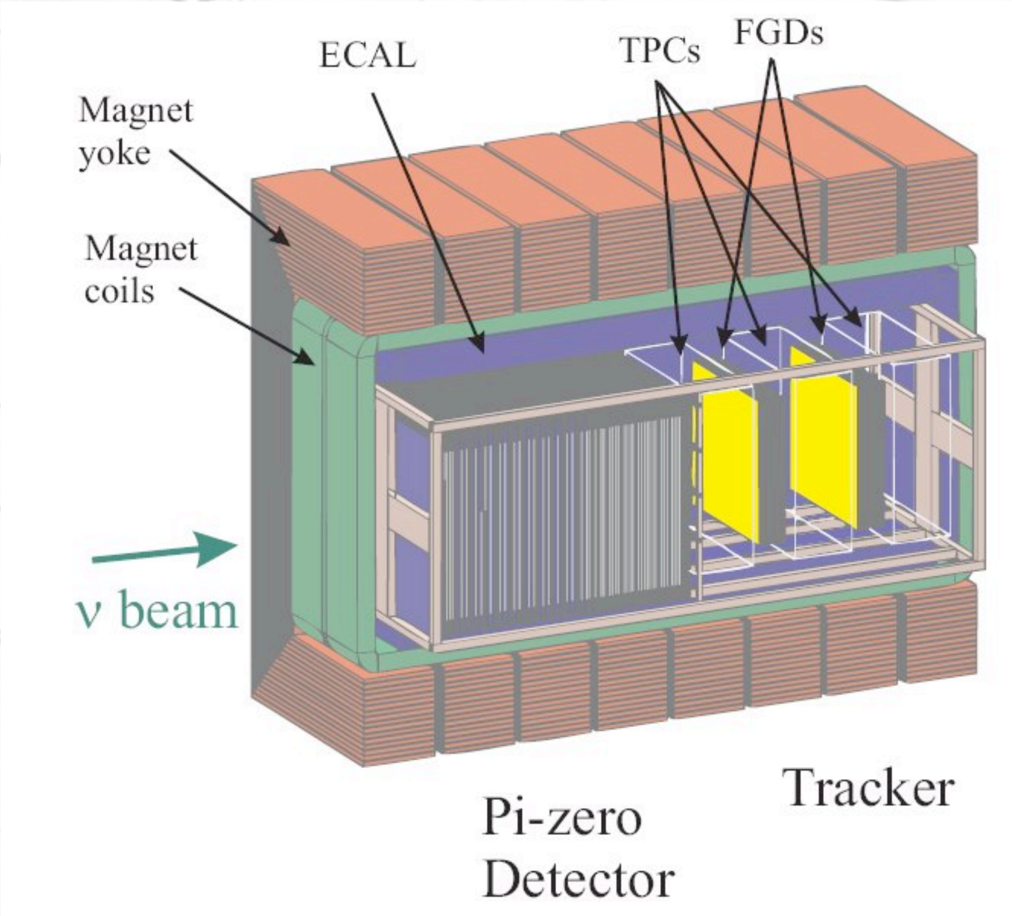


- Target is fully active (scintillators) for low momentum tracking.
- The neutral particles are catched in the ECAL (sampling calorimeter).
- Muons and hadrons are tracked in the HCAL for particle ID.
- It contains several nuclear targets for A dependency studies of cross-sections.

Tracking calorimeters

- Detectors are magnetised for track sign for track charge separation (neutrinos vs antineutrinos), momentum measurement and track containment : MINOS & ND280

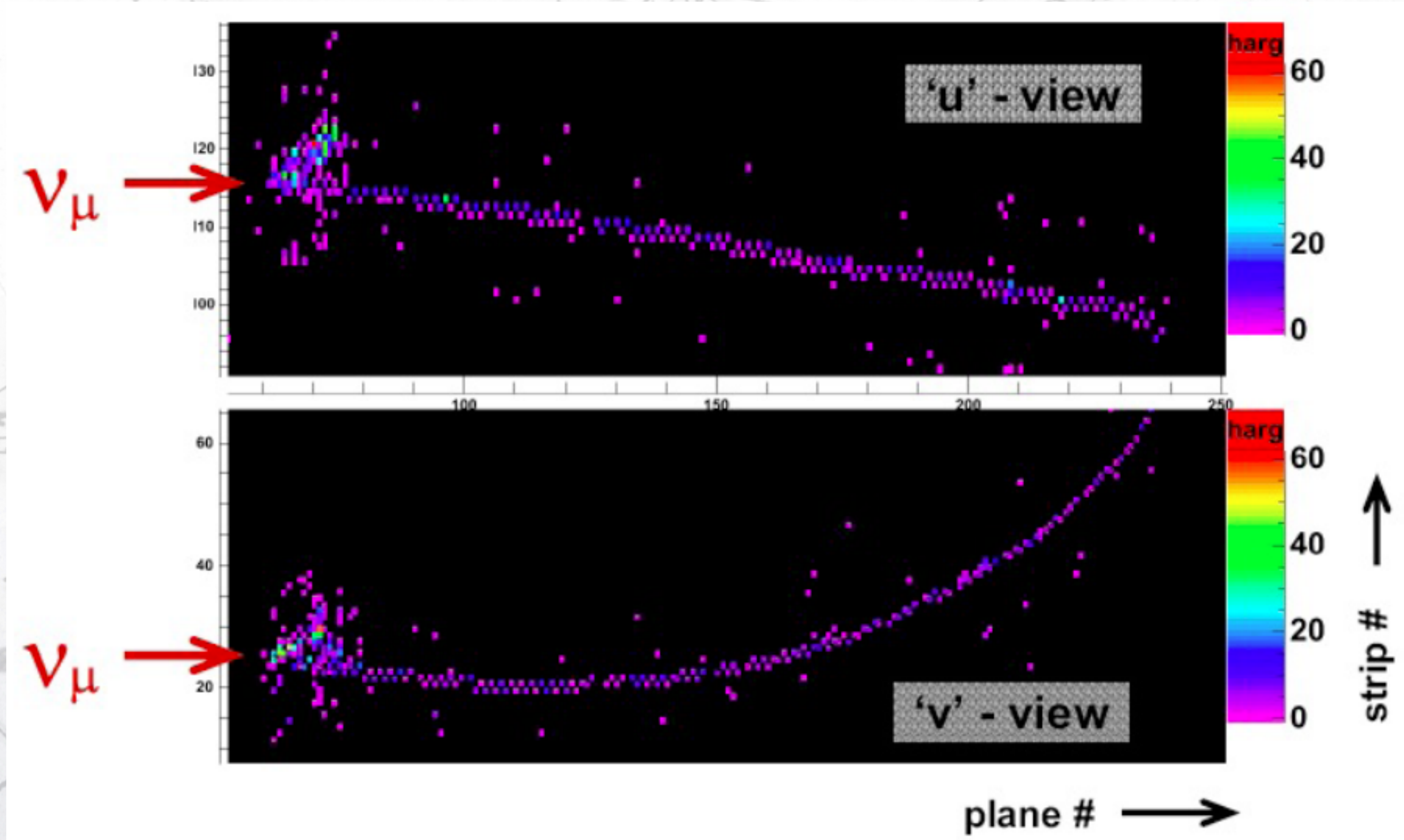




In MINOS the iron plates are magnetised.

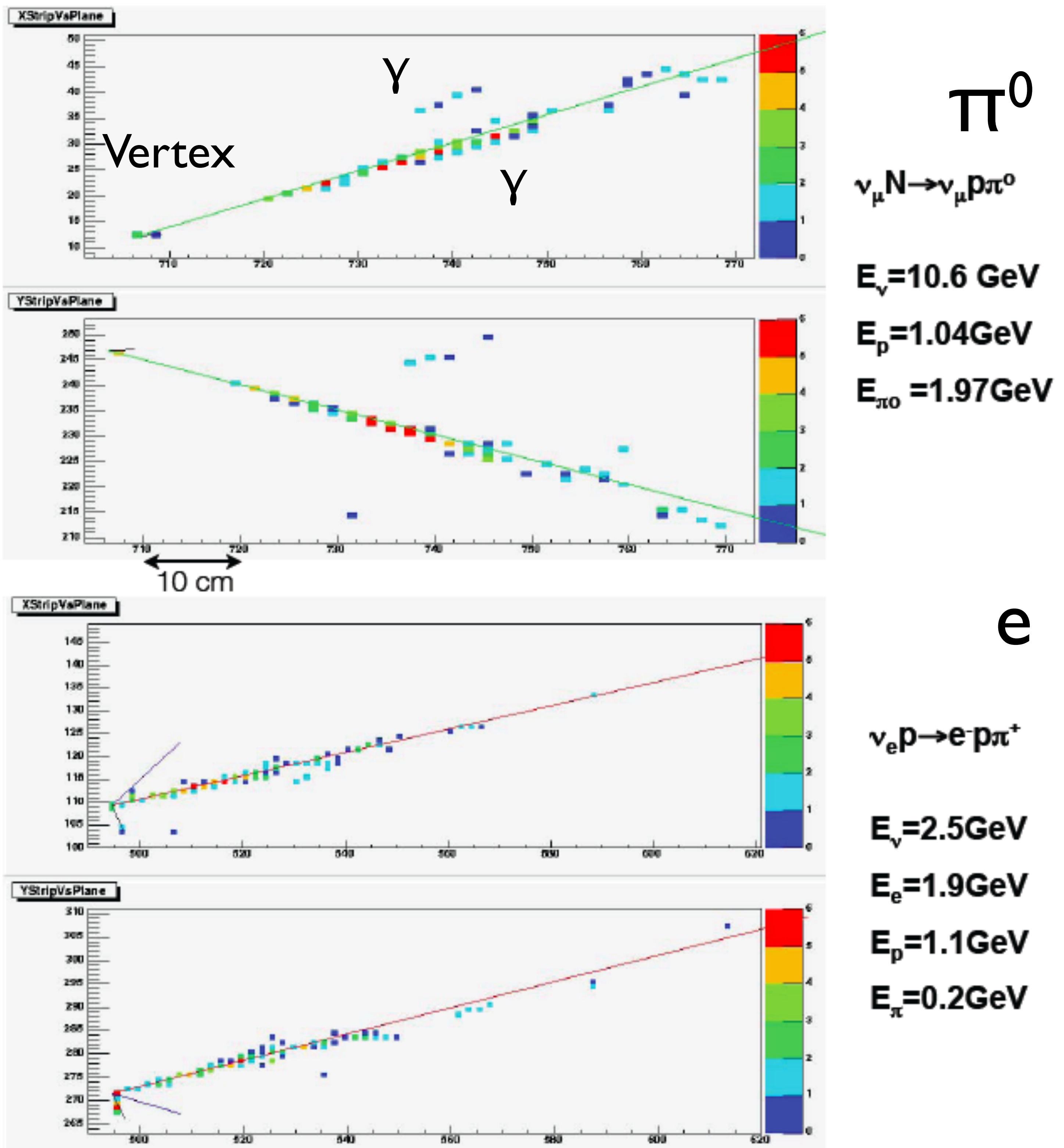
In ND280 the inner volume is magnetised.

Tracking calorimeters



MINOS

Tracking calorimeters



- Nova is designed to detect electron neutrinos in a beam of muon neutrinos.
- The main background is the π^0 misidentification.
- The fully active approach helps in this purpose:
  - full energy collection from photons.
  - larger conversion distances.
  - less density, more separation between photons.

NOVA

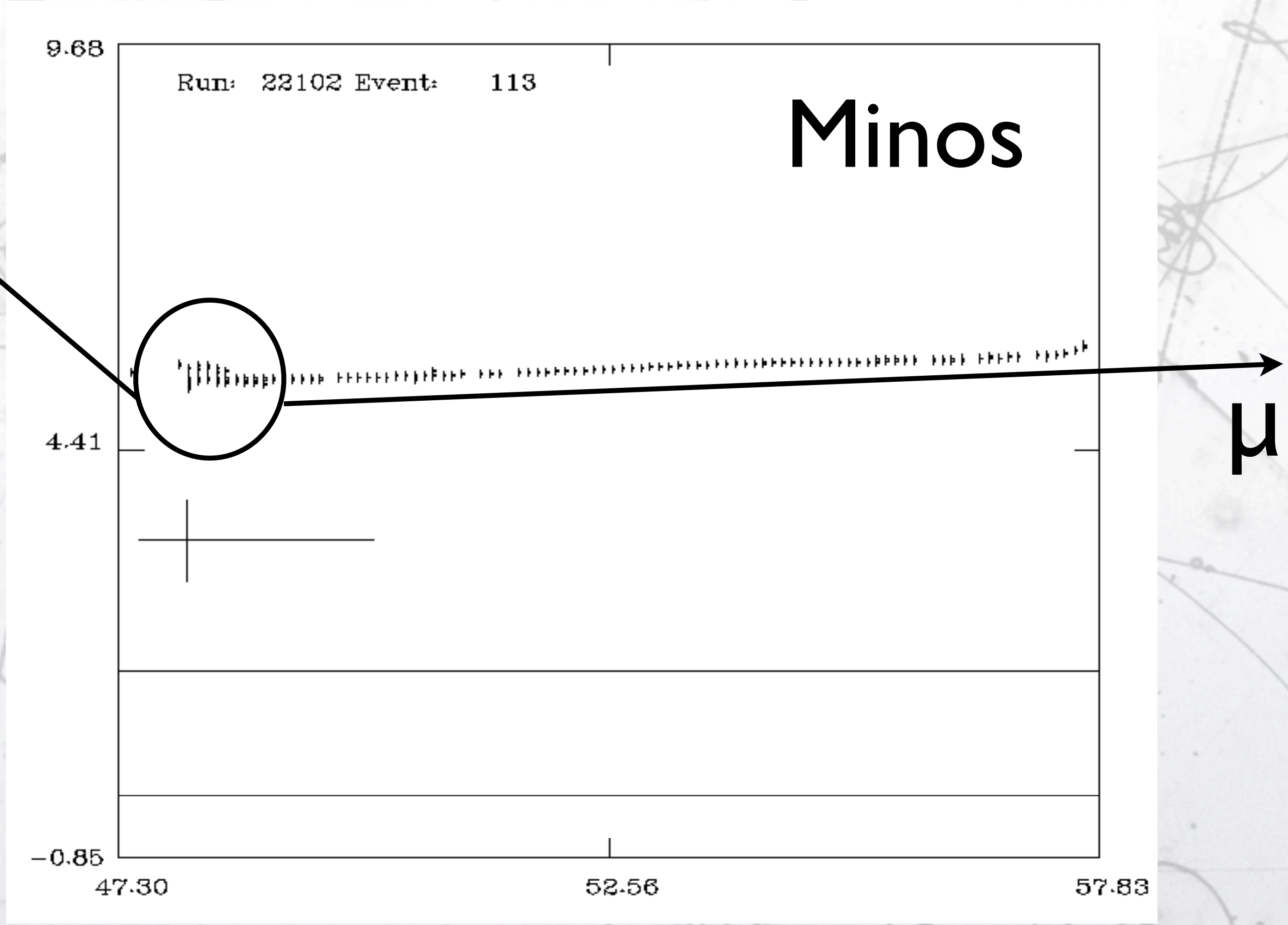
Calorimetry

- Try to reconstruct the total energy through calorimetry methods.

$$E_\nu = E_\mu + E_{had}$$

$$E_\mu = E_{range} || E_{curvature}$$

$$E_{had} = F(\sum_{\forall hits \neq \mu} E_{hits})$$



Detector needs to be calibrated:

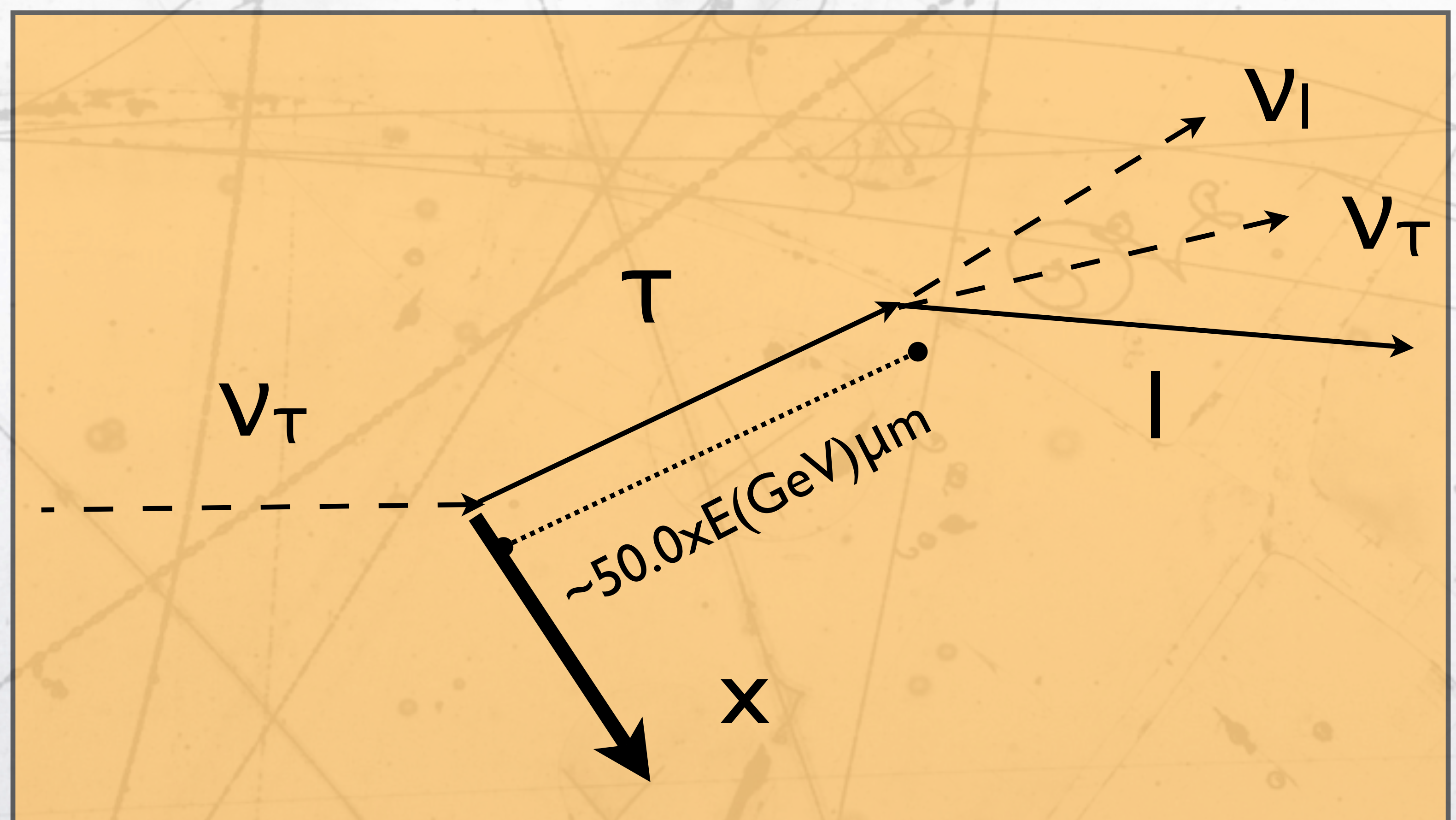
- Response to different particle types.
- Differences in the collection of ionisation and transformation in energy.

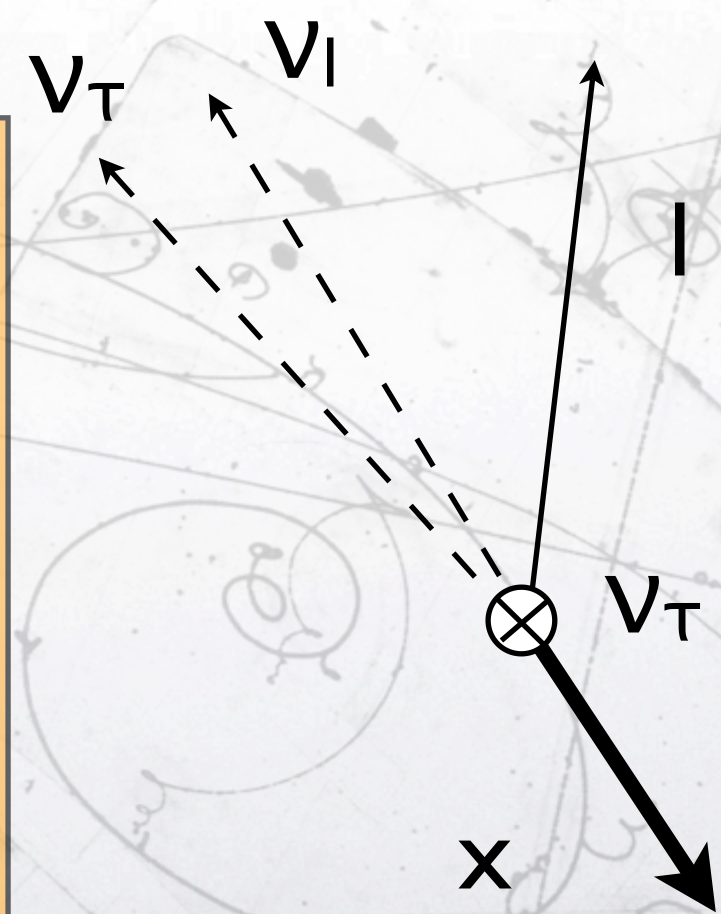
Tau detection

Tau detection basics

- In the ν_τ CC interaction, a tau is produced i the final state.
- The τ lepton is heavy (~1.8 GeV) so the production threshold is large (> M_τ).
- The τ lepton decays fast (2.9×10^{-4}ns) in different channels:
  - leptonic: $\tau \rightarrow \nu_\tau \nu_l l$ (lepton + 2 invisible neutrinos).
  - hadronic: $\tau \rightarrow \nu_\tau h$ (with h = a_1, ρ, etc…)
- The signatures are:
  - Detect the flight of the tau.
  - Detect the missing transverse energy in the decay + event topology.

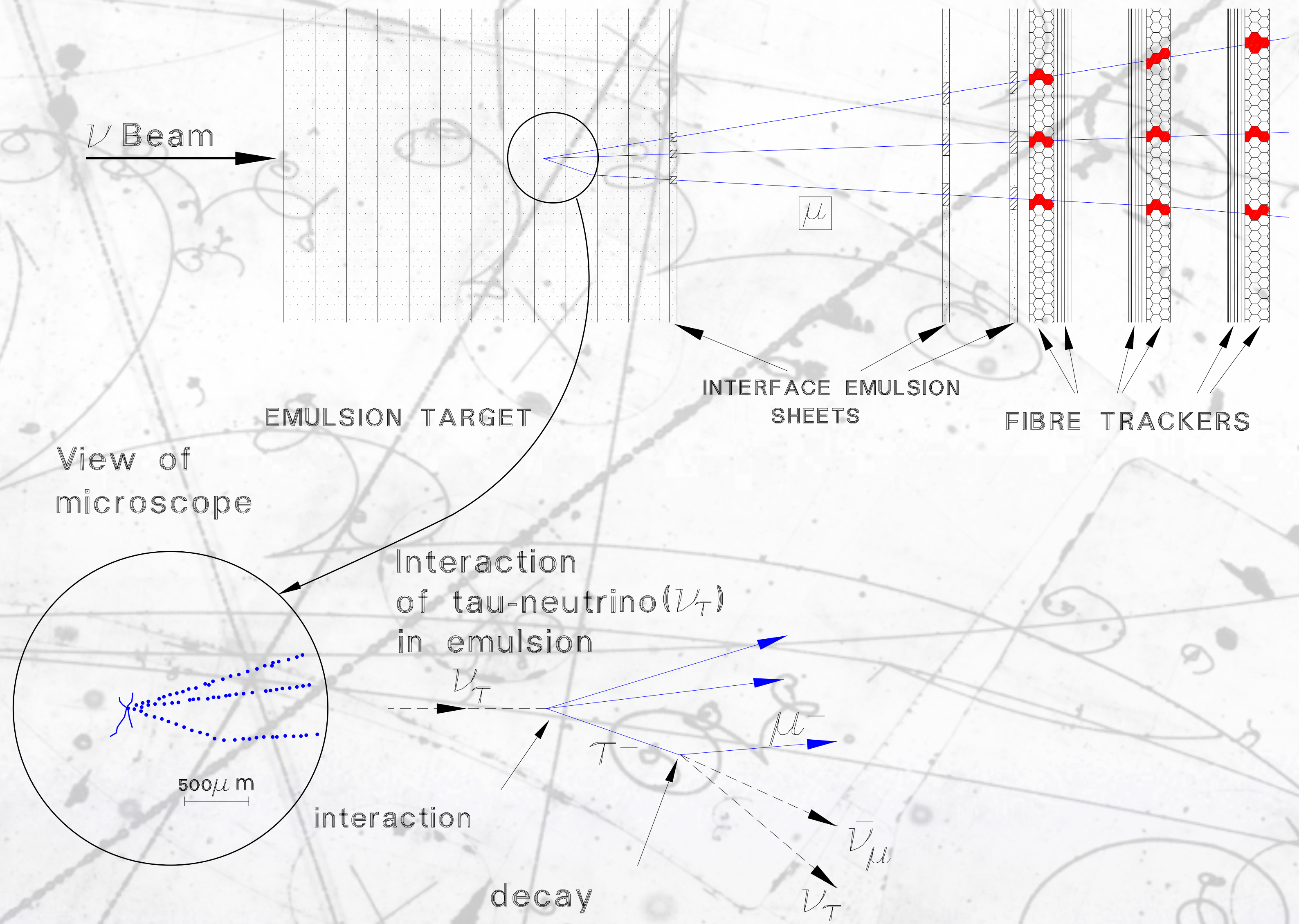
Vertexing





Vertex detector

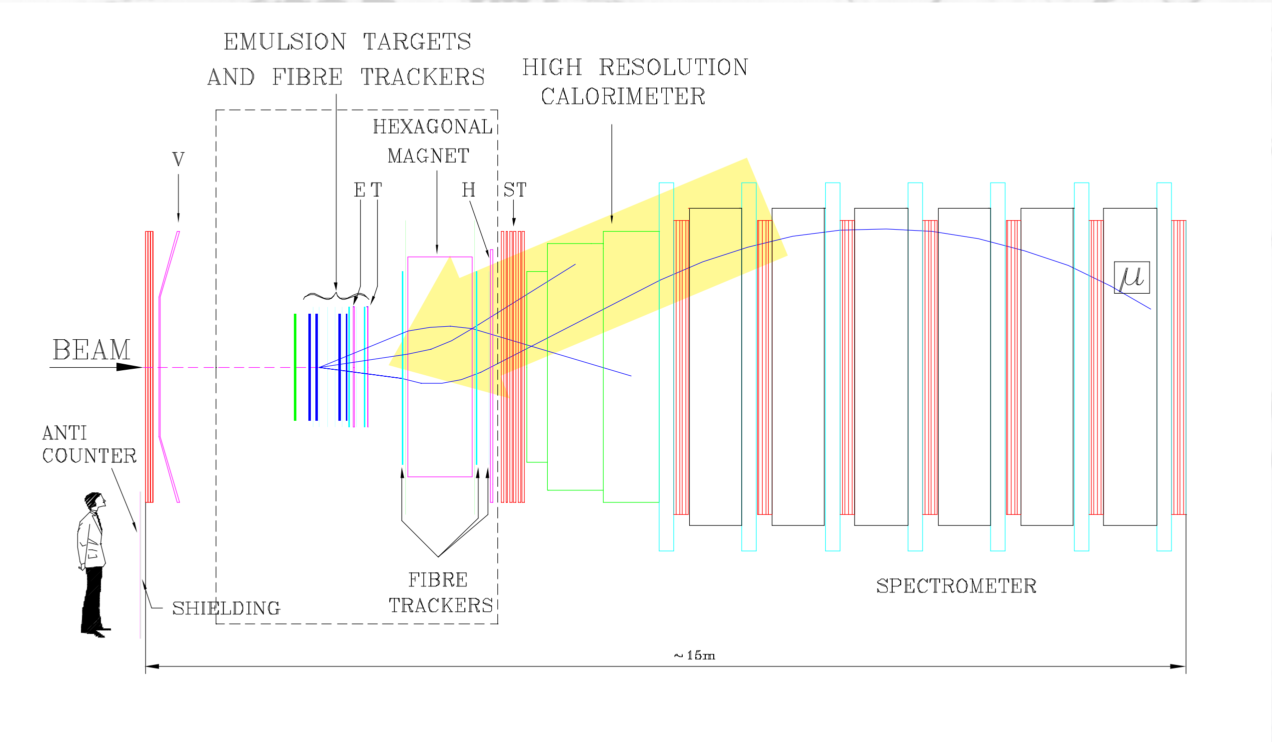
Chorus

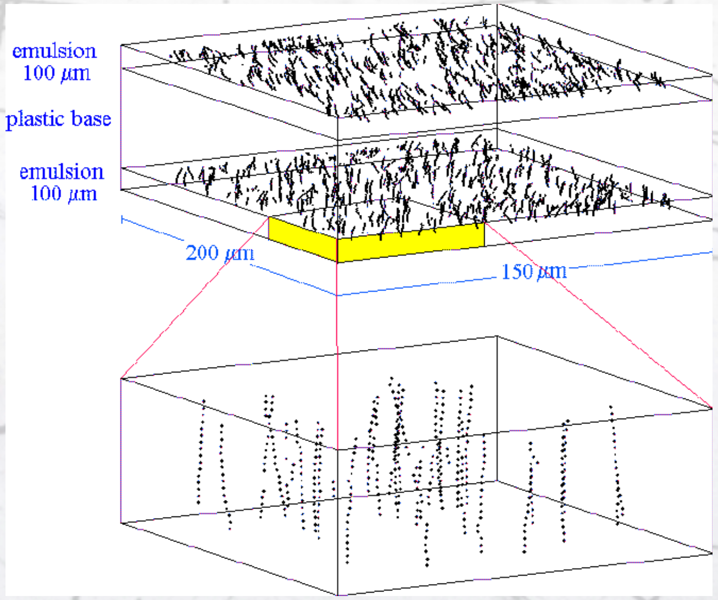


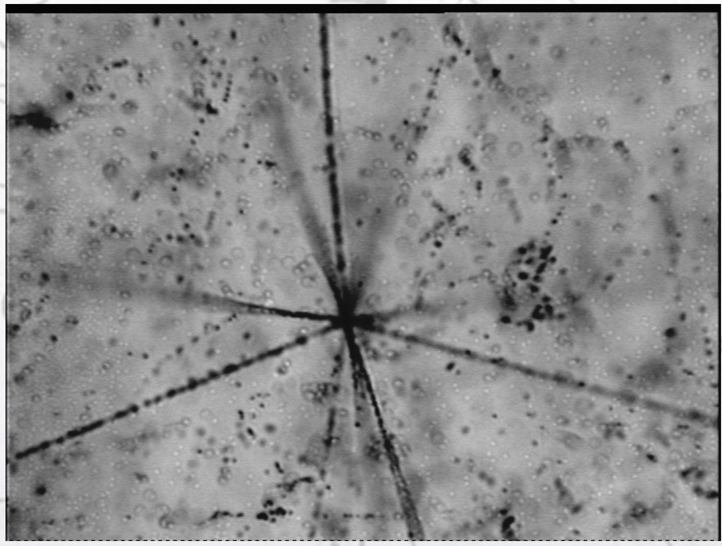
- To detect the tau lepton we need detectors with < 100 μm resolution → emulsions.

Emulsions

- Emulsions are think photographic films with 0.2~0.3 µm grains.
- A minimum ionising particle leaves 30 to 40 hits in 100 µm.
- The photographic emulsion is then developed and reconstructed with the help of an optical microscope.
- Scanning regions are predefined by electronic detectors.

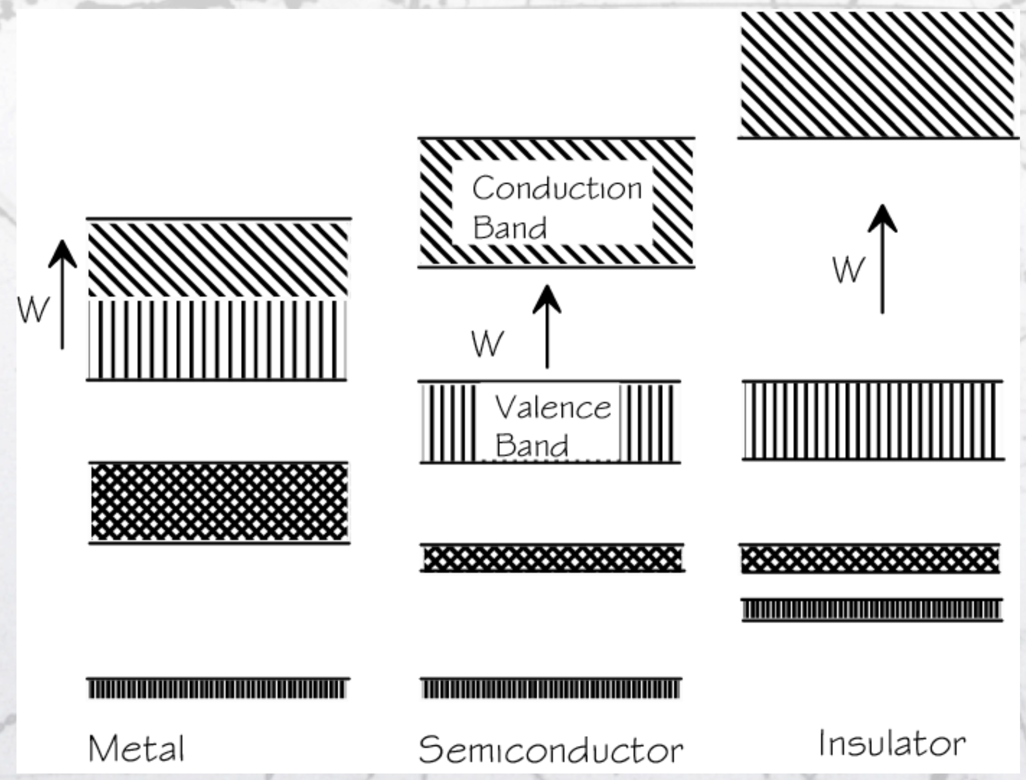


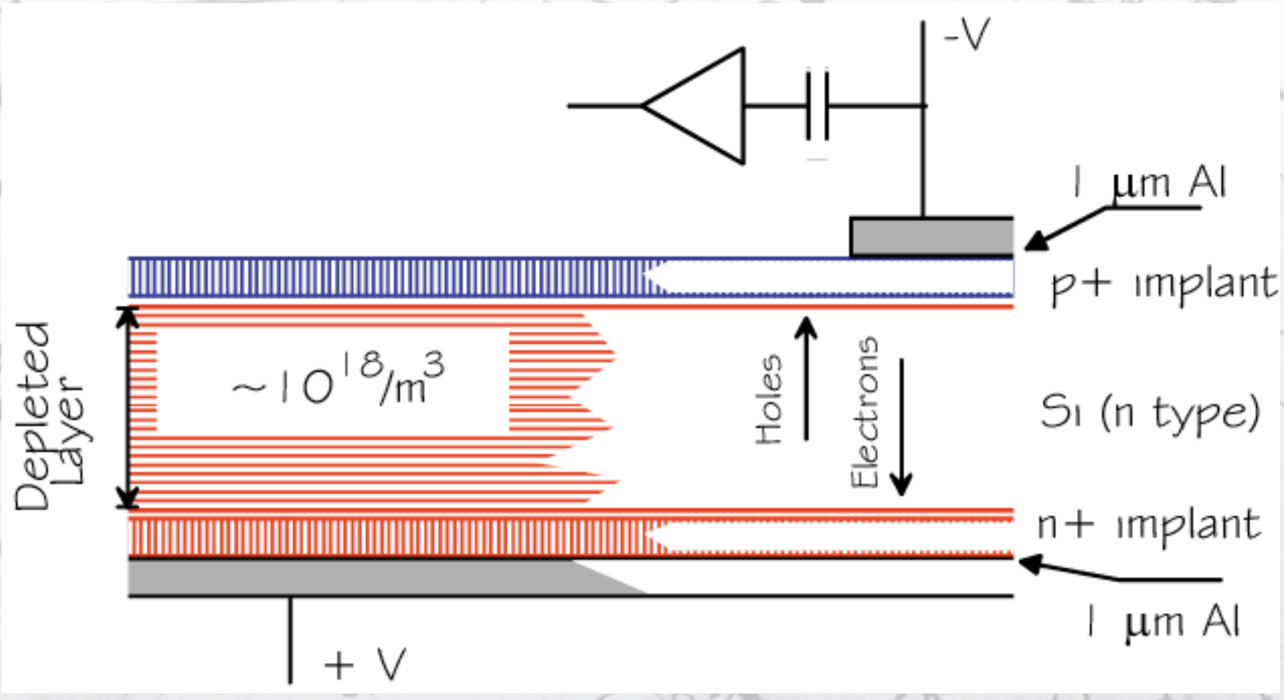




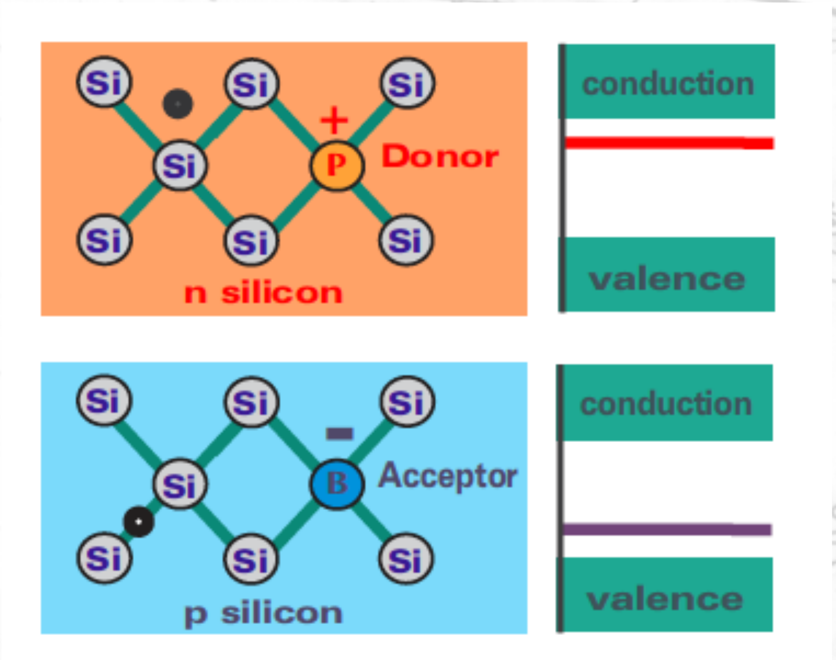
Solid state detectors

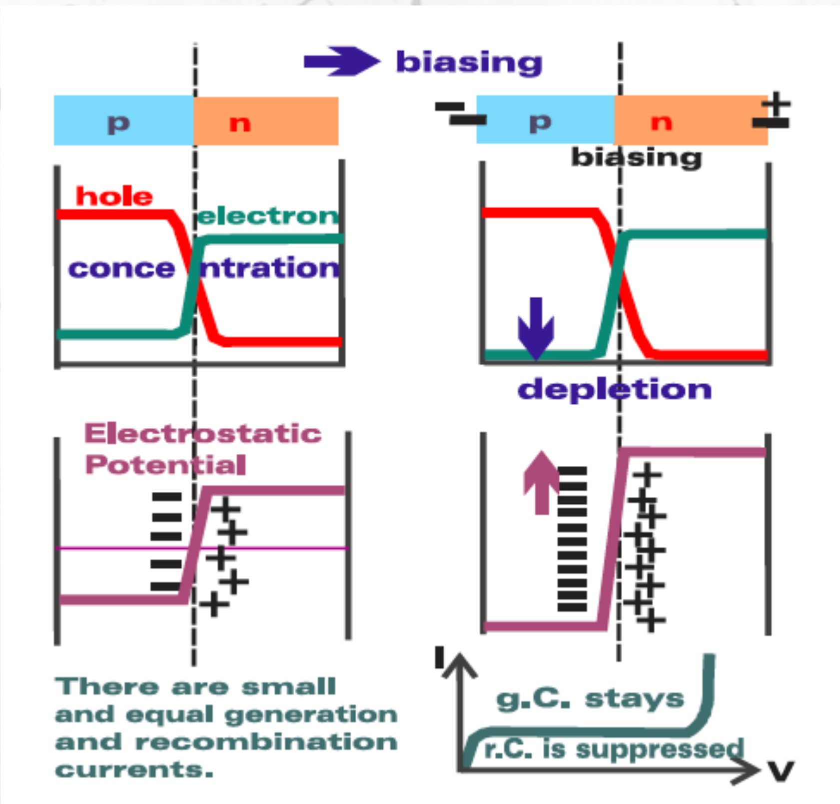
- Solid state detectors are semiconductors: medium gap between the Valence and the conduction bands (→many electrons/deposited energy)
- The passage of particle promote electrons from the valence to the conductive band. Holes and electrons drift to the cathode and anode.
- If anode/cathode are segmented we can determine the track position (<100μm)





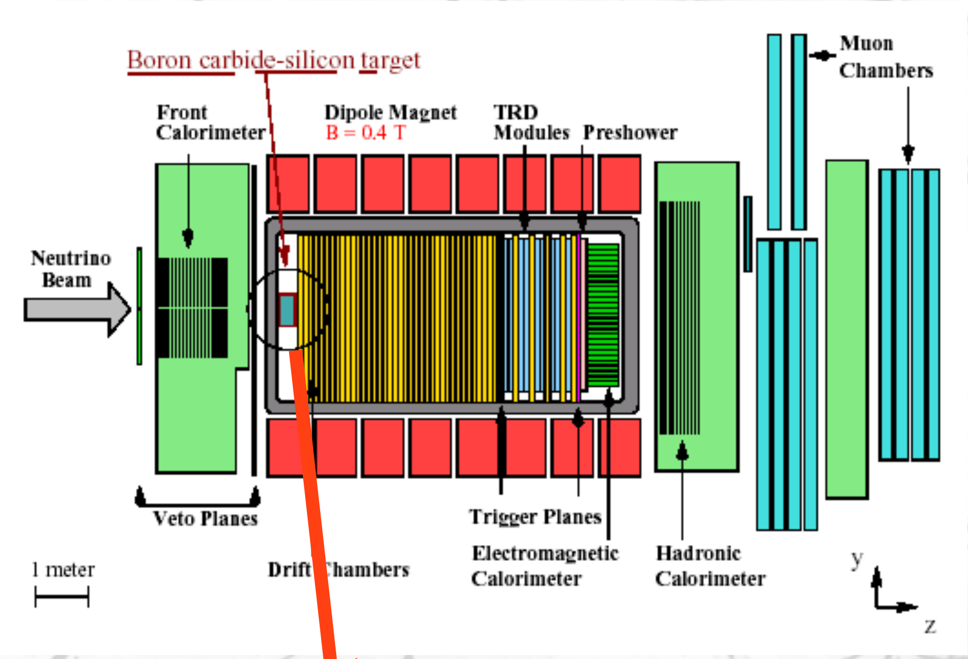
Solid state detectors

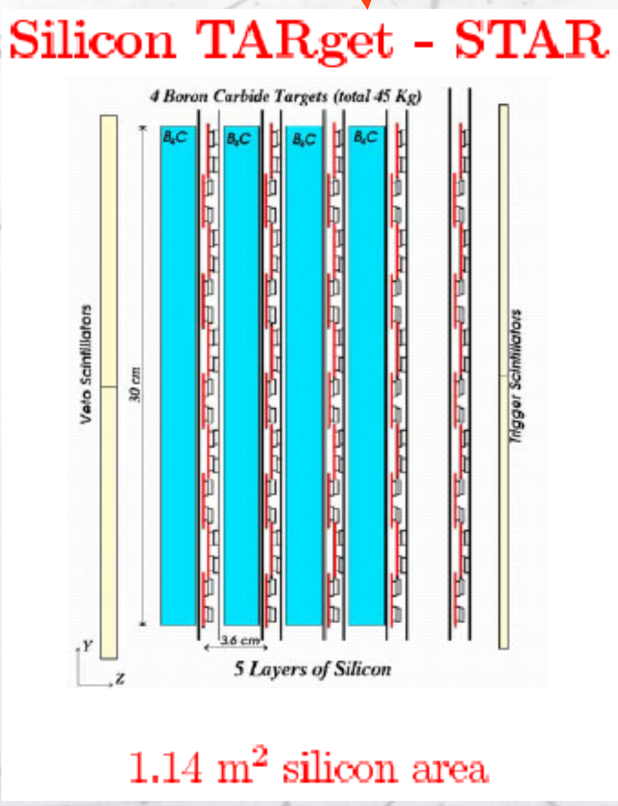




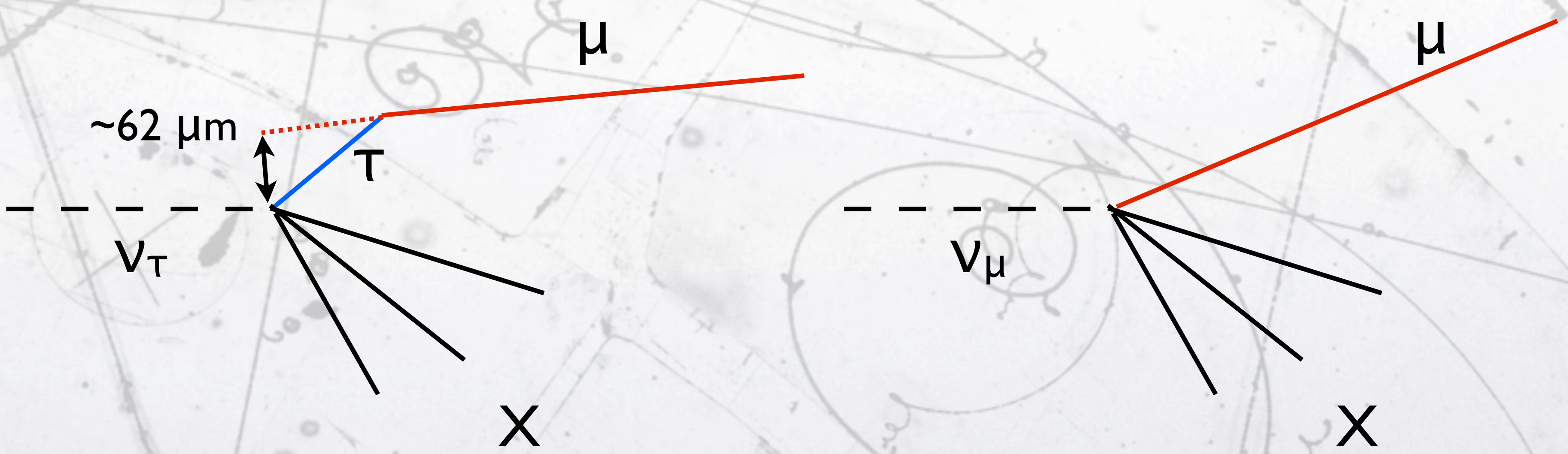
- The solid state detector is actually a diode (pn dopped junction).
- There is always a diffusion of charge from one side to the other where recombines.
- Applying a reverse voltage the potential increases and the diffusion and recombination of electrons/holes decreases.
- Increasing the voltage the region in the detector where this happens increases (depletion).
- A minimum ionising particle creates ~8000 e^-/h^+ per 100 μm.

NOMAD-STAR



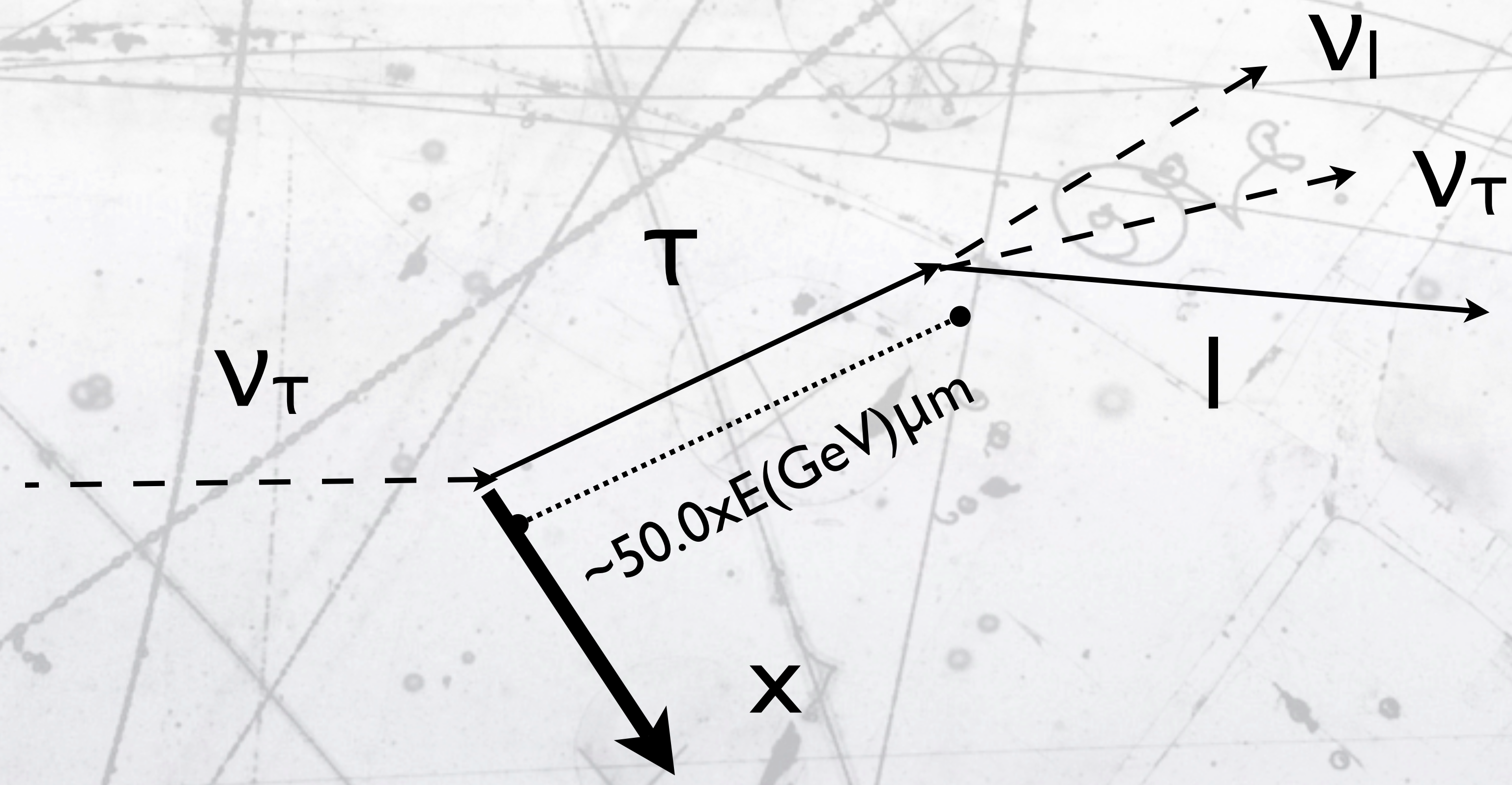


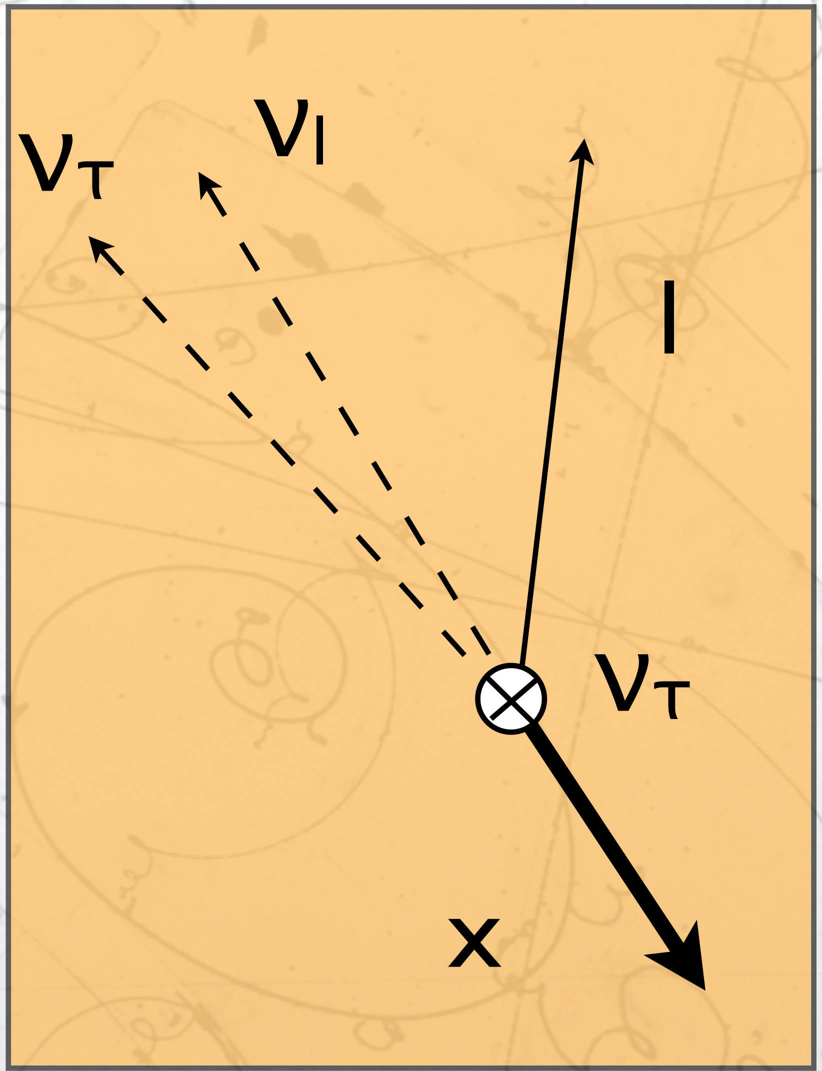
- Nomad placed a silicon detector between layers of passive target made of low Z material (to reduce Multiple Scattering).
- The layers are sepated by 3.6 cm, τ can't be detected. Use the impact parameter.
- Opera use the same technique.



Signal Background

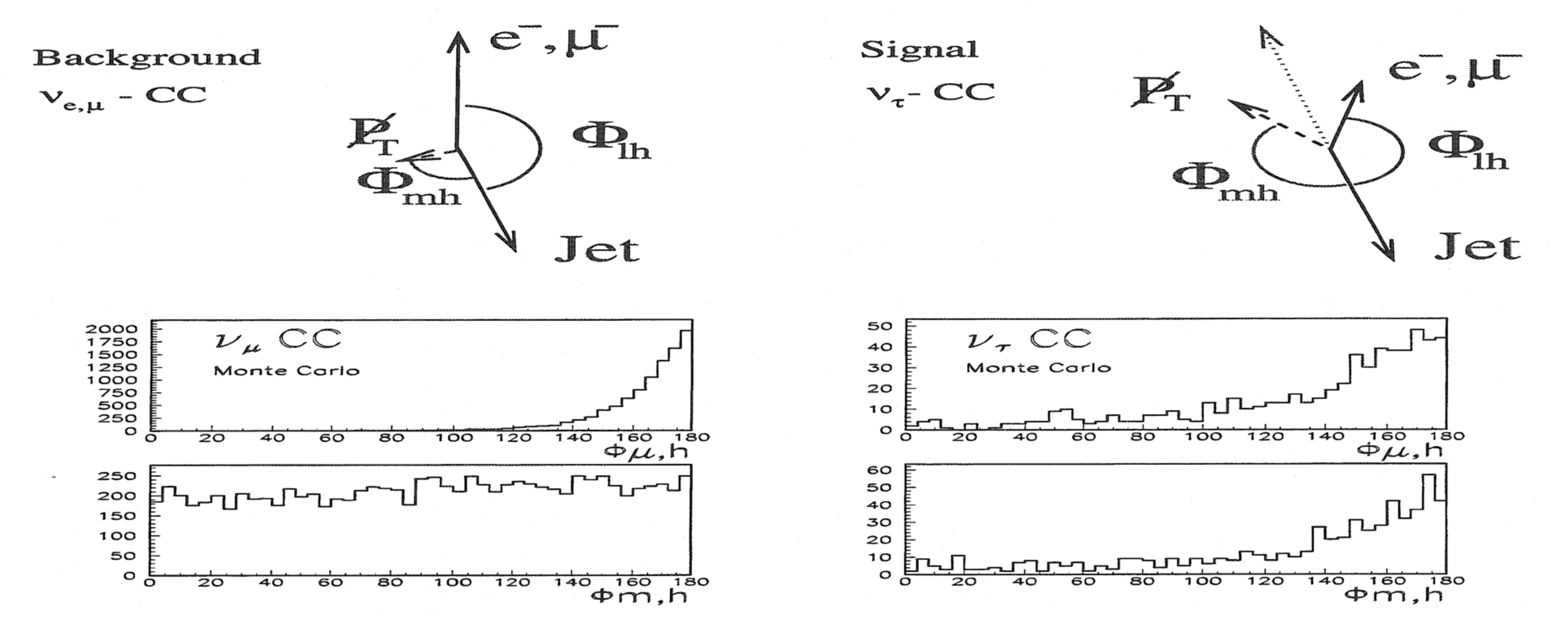
Missing transverse momentum





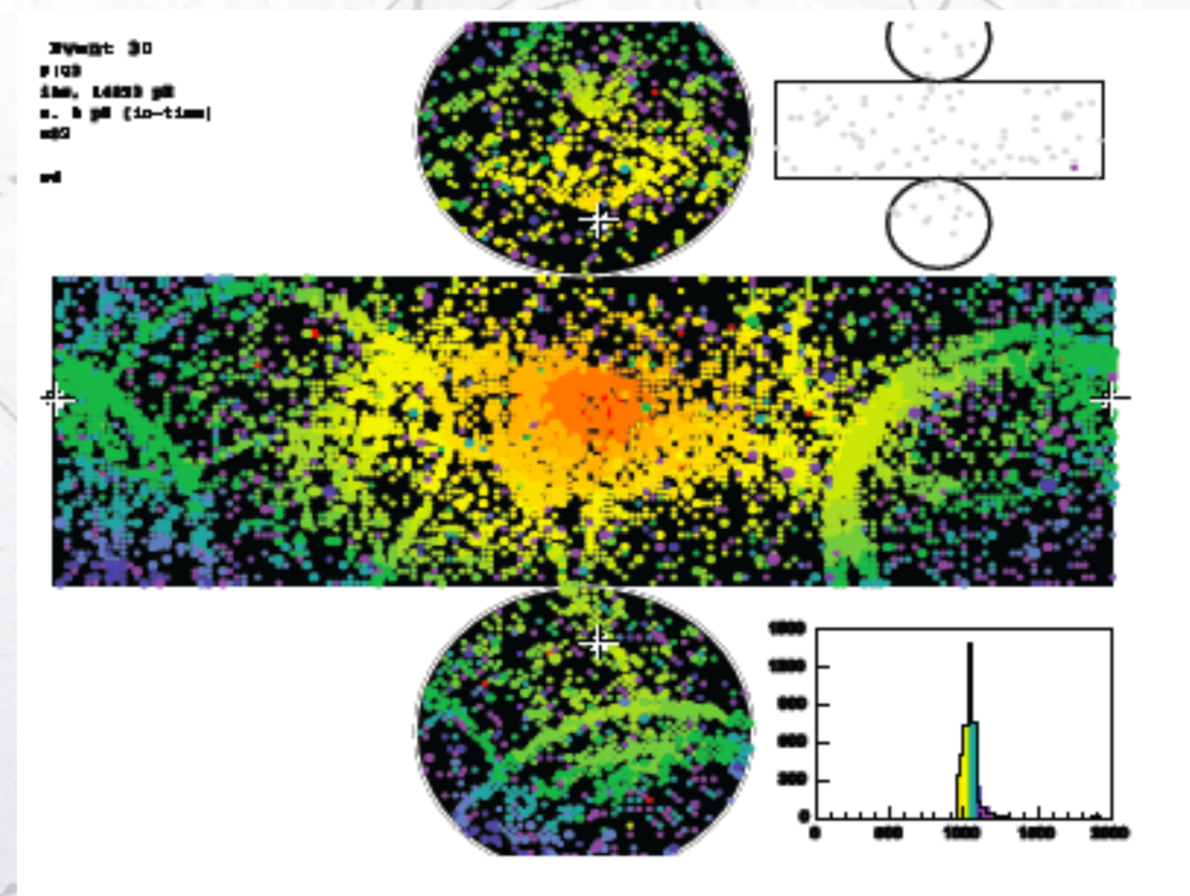
Missing momentum

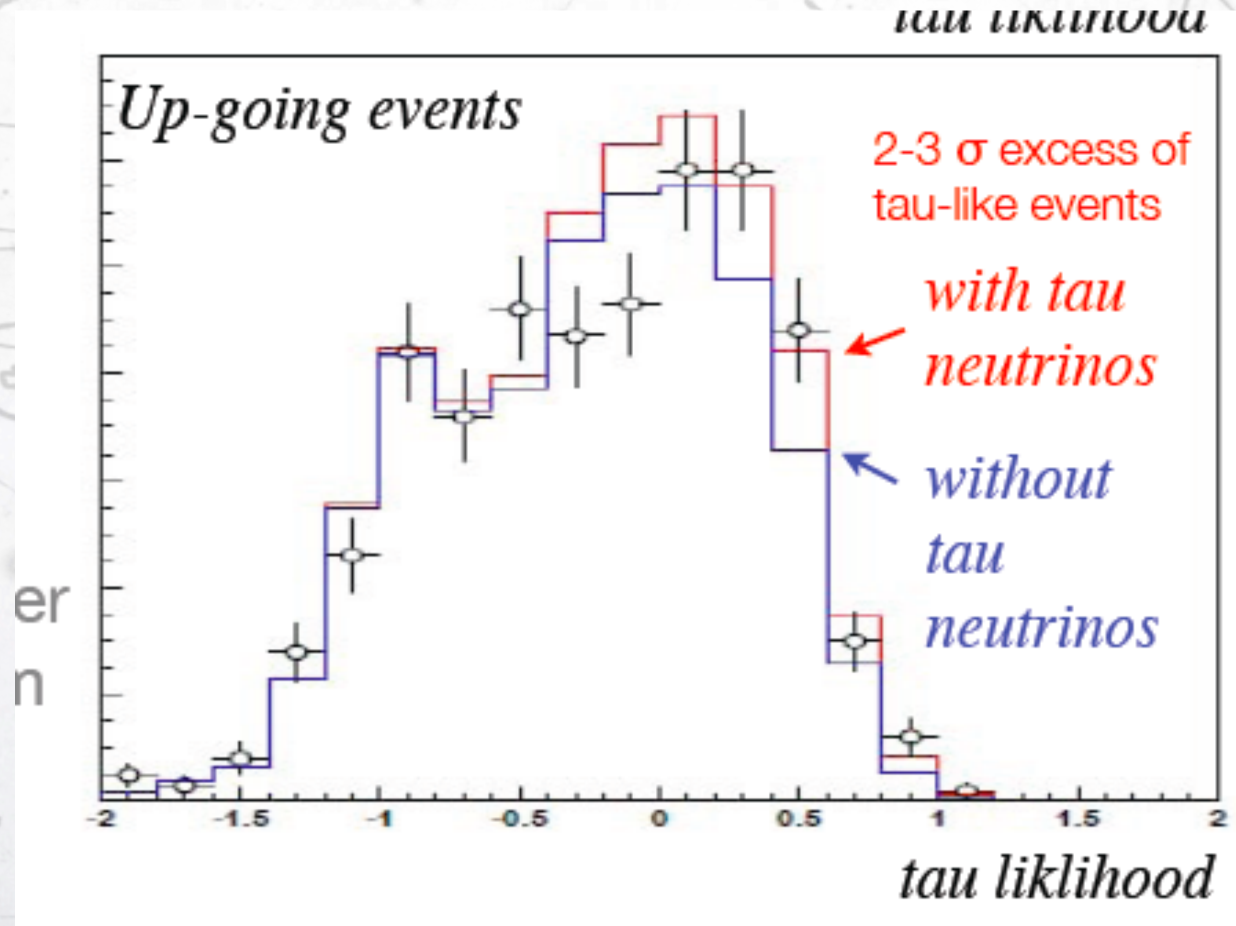
- If we look in the plane transverse to the neutrino direction the momentum of all particles should balance but neutrinos are not visible: missing transverse momentum.
- Need to measure the momentum and direction of all particles in the event and assume the neutrino direction.



Topology

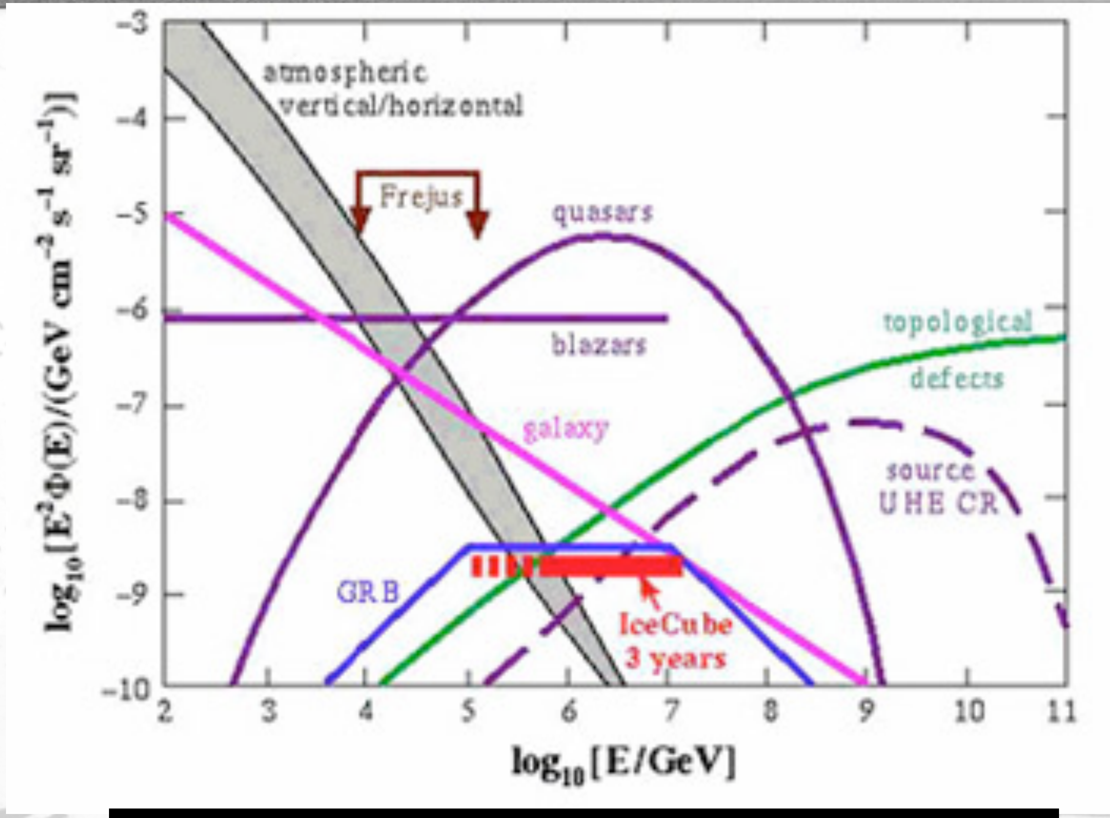
- Another "statistical" method is based on the larger topology of tau events, decays to more than 1 hadron is ~65%.
- Hadrons interact in water and produce additional rings.

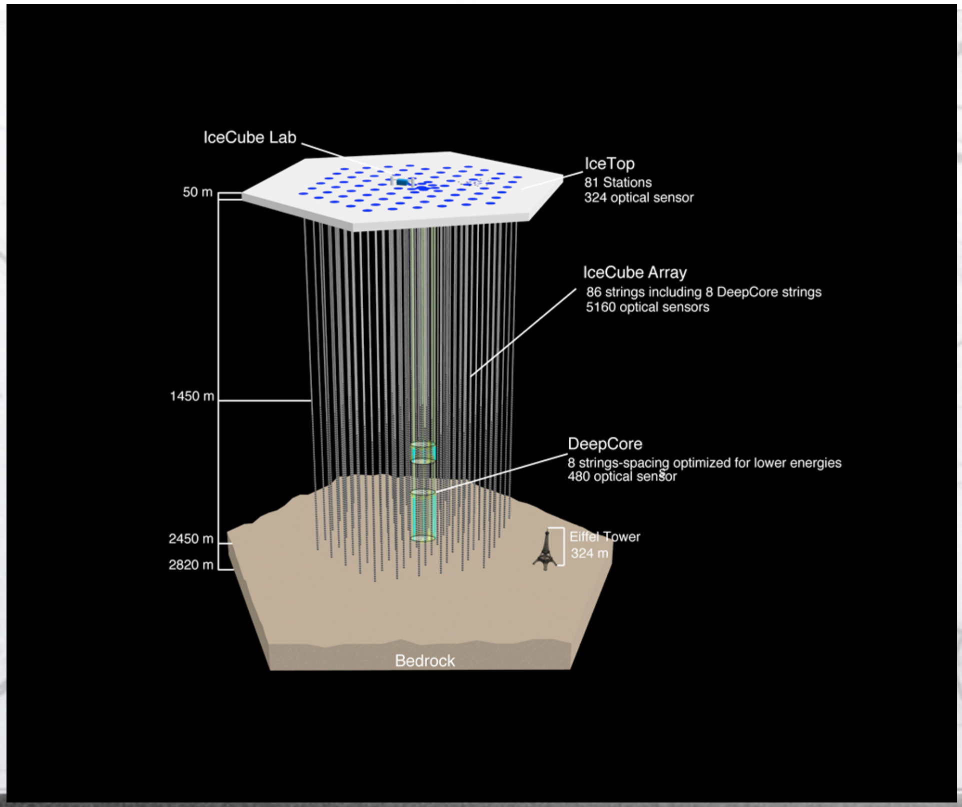




Ultra High energy neutrinos

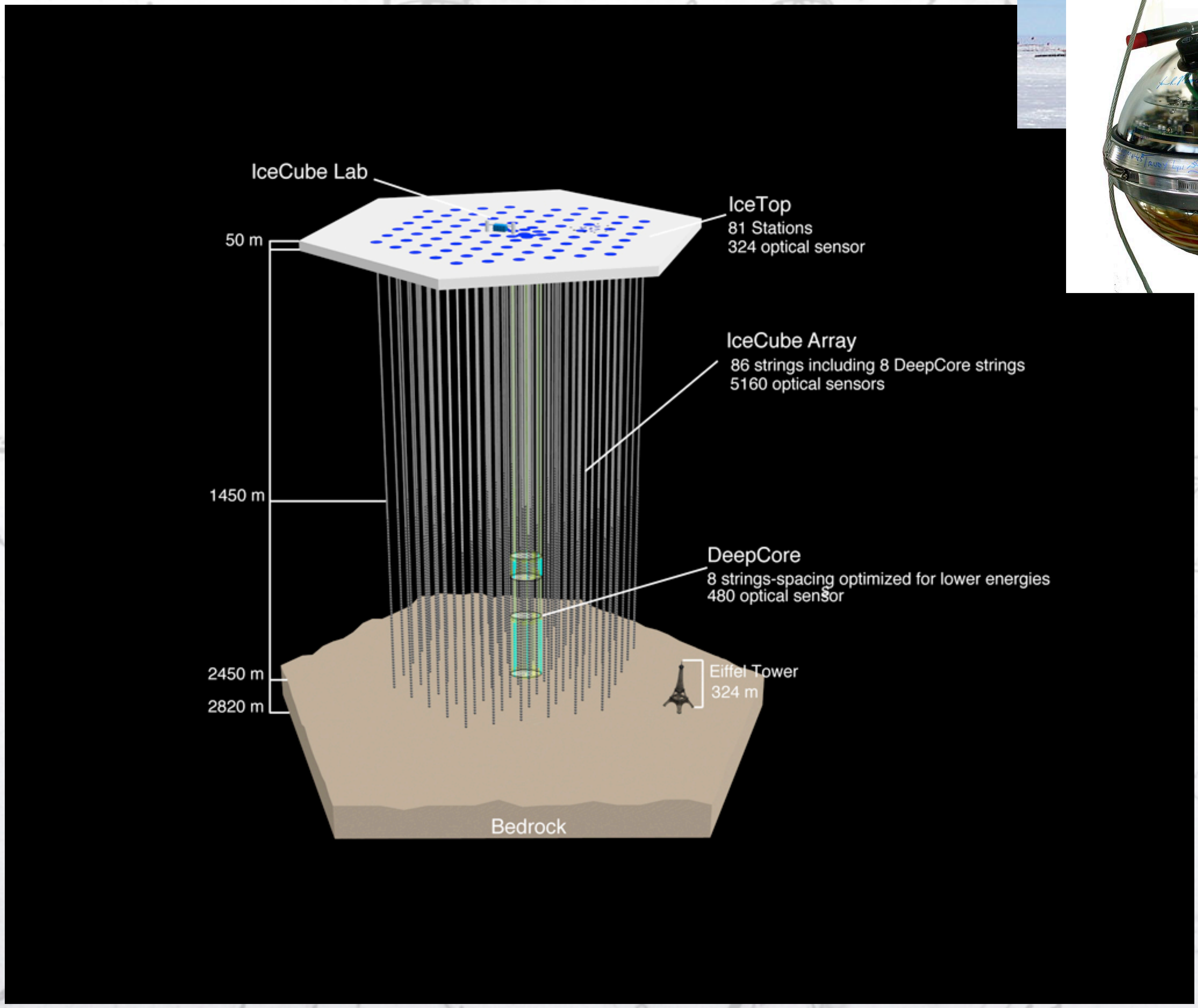
UHE neutrinos





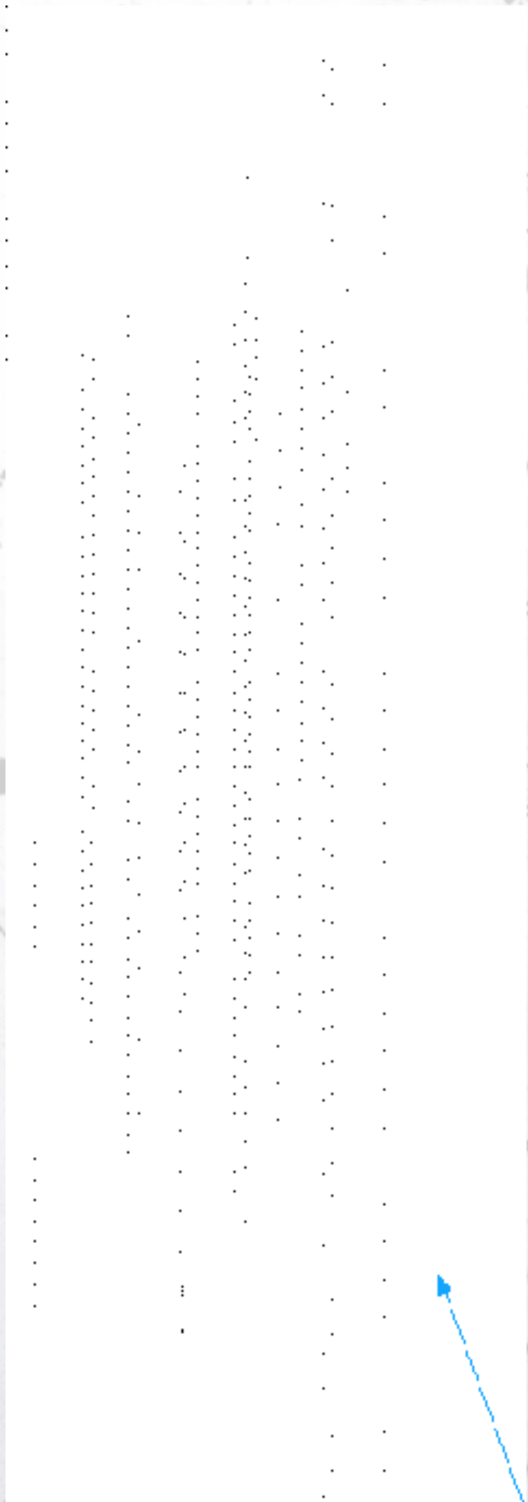
- If neutrinos are produced together with cosmic rays, cosmic neutrinos should be very energetic.
- Cross-section is proportional to E.
- $\sigma\Phi$ decreases by ~9 orders of magnitude between 10^2 GeV and 10^6 GeV.
- We need very large active target mass:
  - Water or ice, with light readout (Cherenkov).
  - Icecube mass is ~50 000 x SK (increase with energy).
- Very large detectors are needed: ~10^9 times exposure than SuperKamiokande.

IceCube

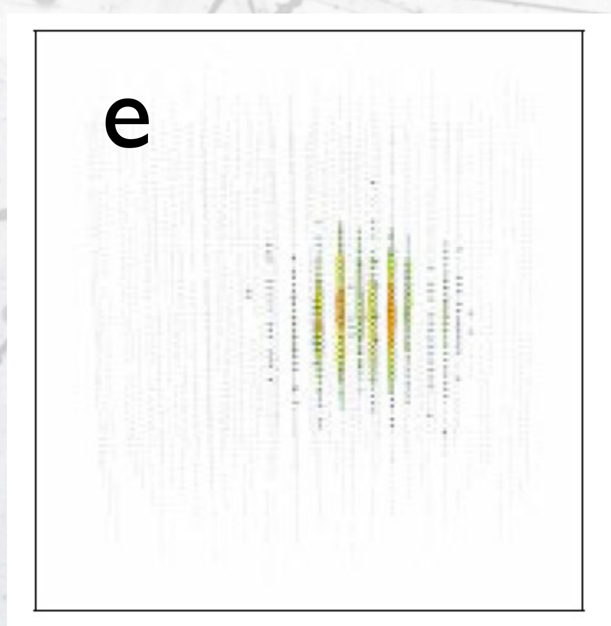


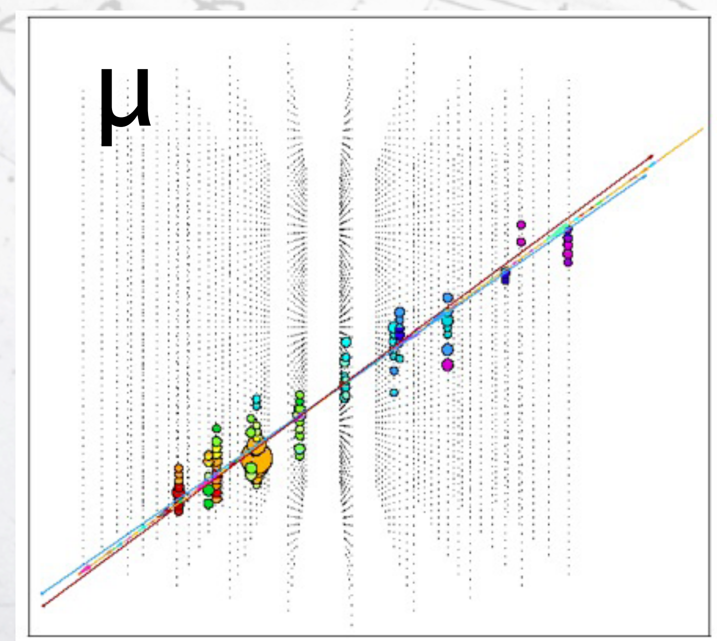
- ~300 sensors point to the ice.
- Particles crossing the ice radiate cherenkov light.

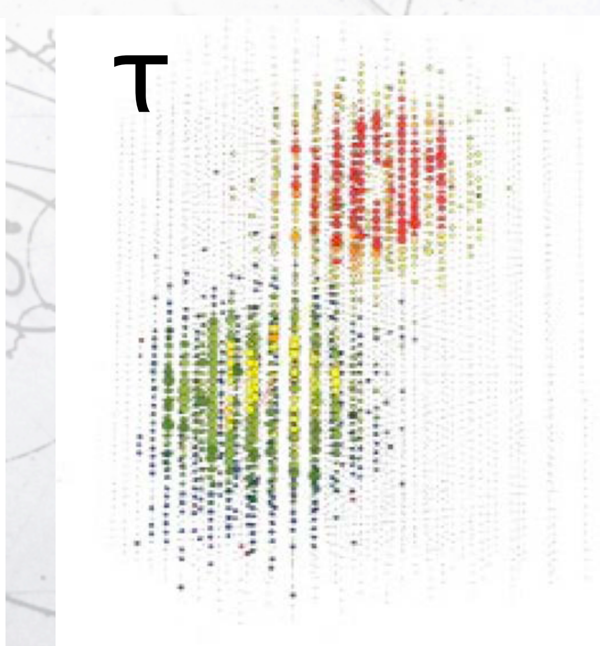
IceCube



- From the arrival time and the position of the signal, it is possible to measure the direction of the track.
- The muon momentum can be computed from the range (limited by the detector side).
- For electromagnetic showers, the total number of photons is proportional to the energy of the electron.
- Tau events can be detected from the double prompt signal.

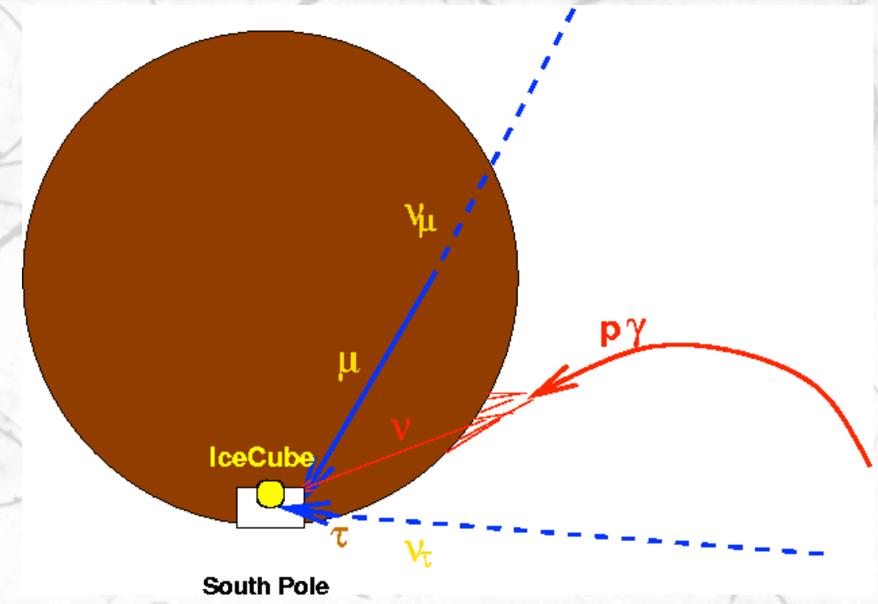


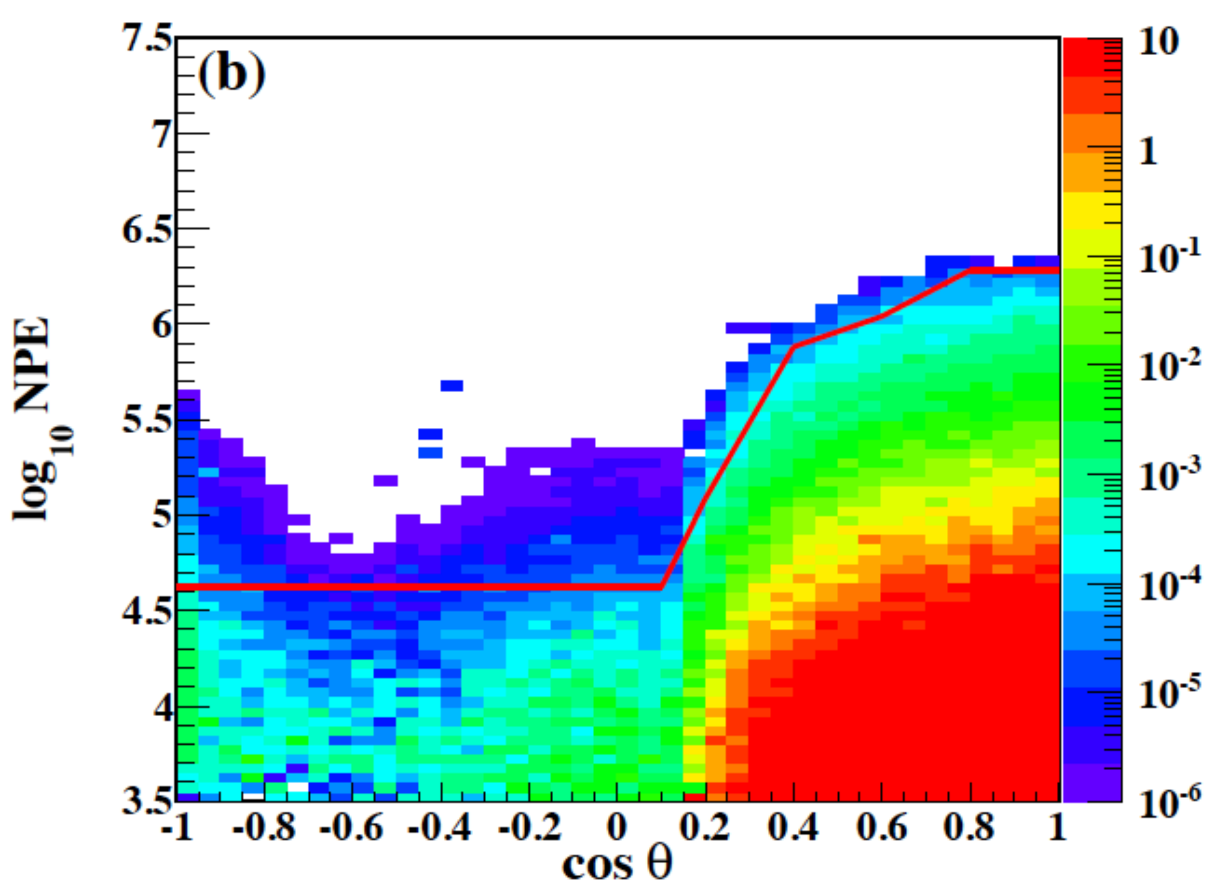


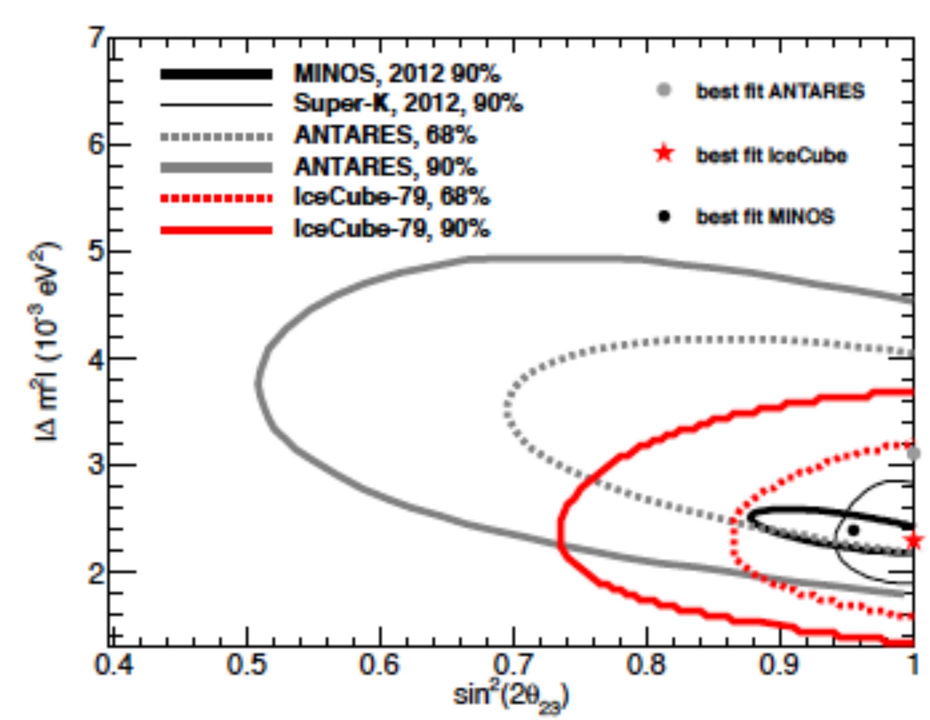


IceCube

- IceCube uses only upward going showers for neutrinos search below certain shower energy.
- The earth blocks charged cosmic rays.



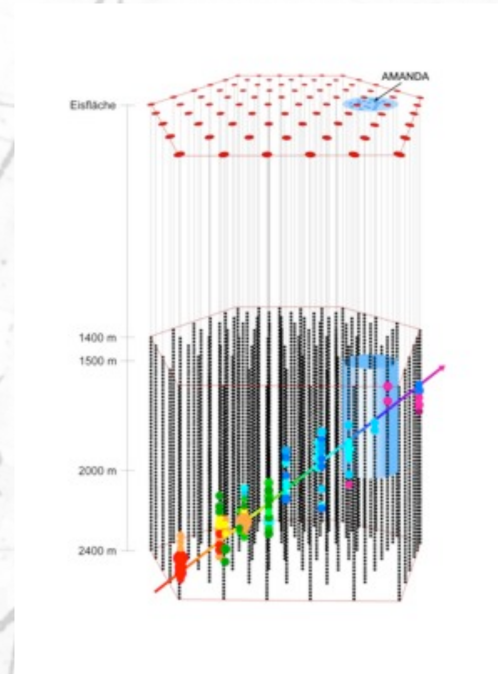


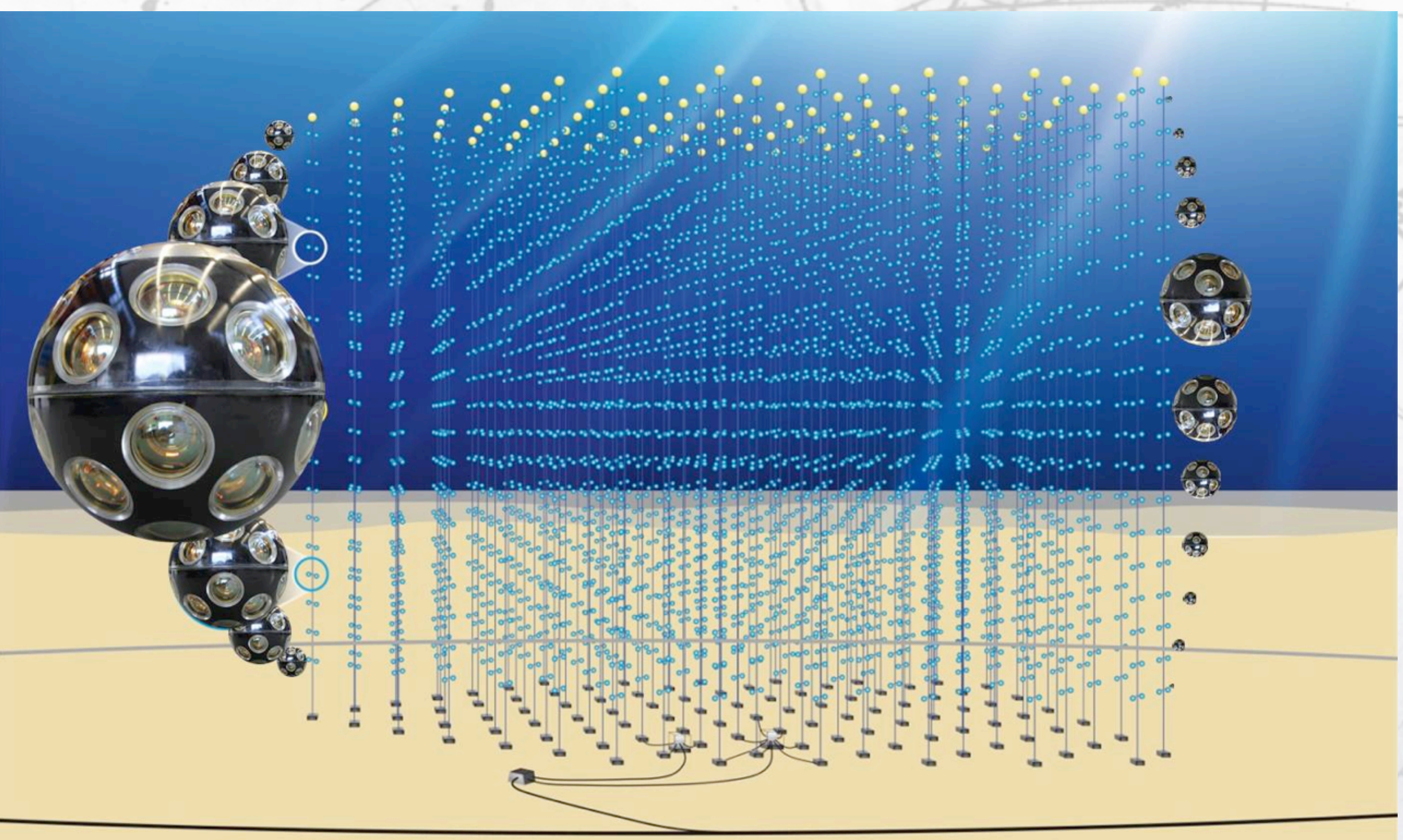


UHE in water

Pioneer: Lake Baikal

using frozen lake as support platform

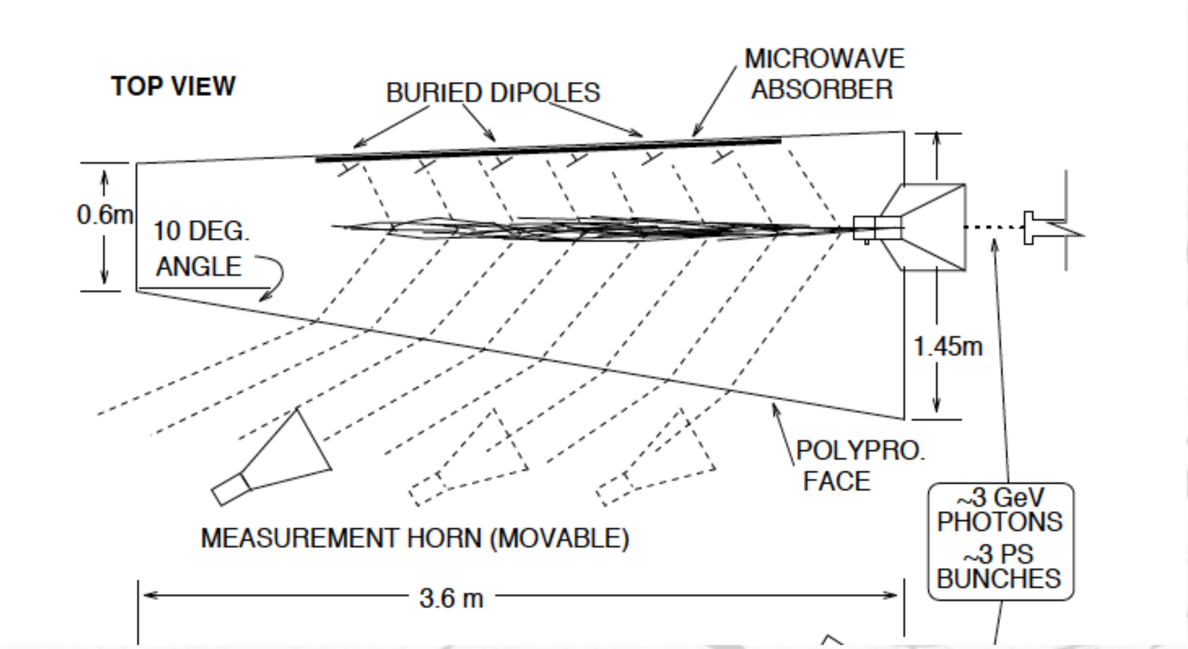




Future: KM3-NET

in the mediterranean sea

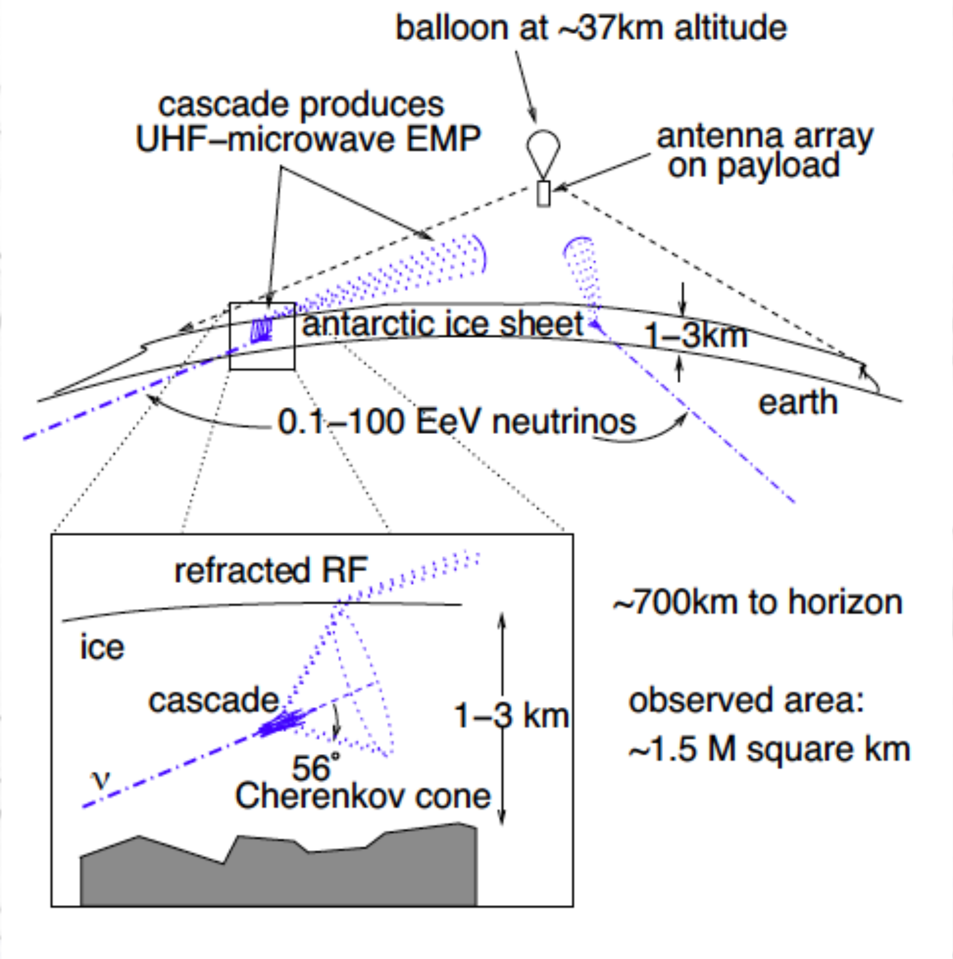
Askaryan Effect

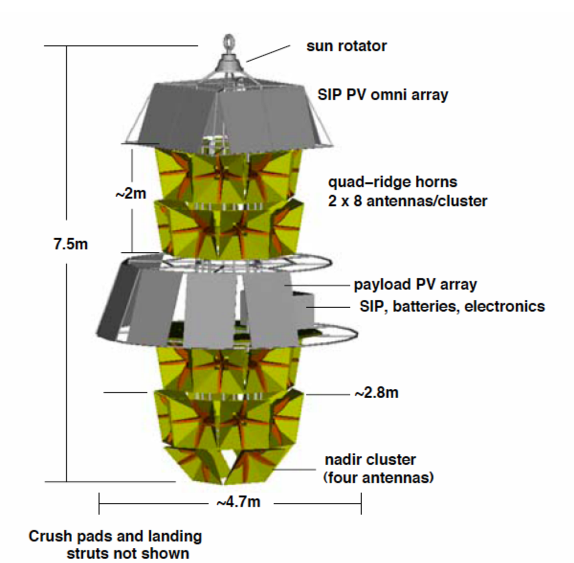


- when a particle shower occurs in a dense, radio transparent medium (ice, sand or salt), positrons, electrons and photons are generated (electromagnetic shower).
- Even with the positron creation electromagnetic showers can be seen as a negative charge asymmetry moving faster than the speed of light in the medium which will emit Cherenkov radiation.
- The emissions will be coherent for wavelengths on the order of the size of the shower, and thus it is enhanced in the radio frequencies.

Radio Cherenkov

- Radio Cherenkov (0.2-1.2 GHz) might be detected by radio-antenas using the ice as a target.
- If the emission points out of the earth, they are most probably neutrinos that crossed earth with no interaction.
- It requires large ν energies (> 10^8 GeV)
- The target volume is also huge (>10^6 km^2) to compensate.





Not science-fiction!

Detecting the invisible

Invisible particles

- The first indication of neutrino particles came from the beta decay where there was missing energy and momentum.
- The missing (invisible) energy and momentum was carried by neutrinos.

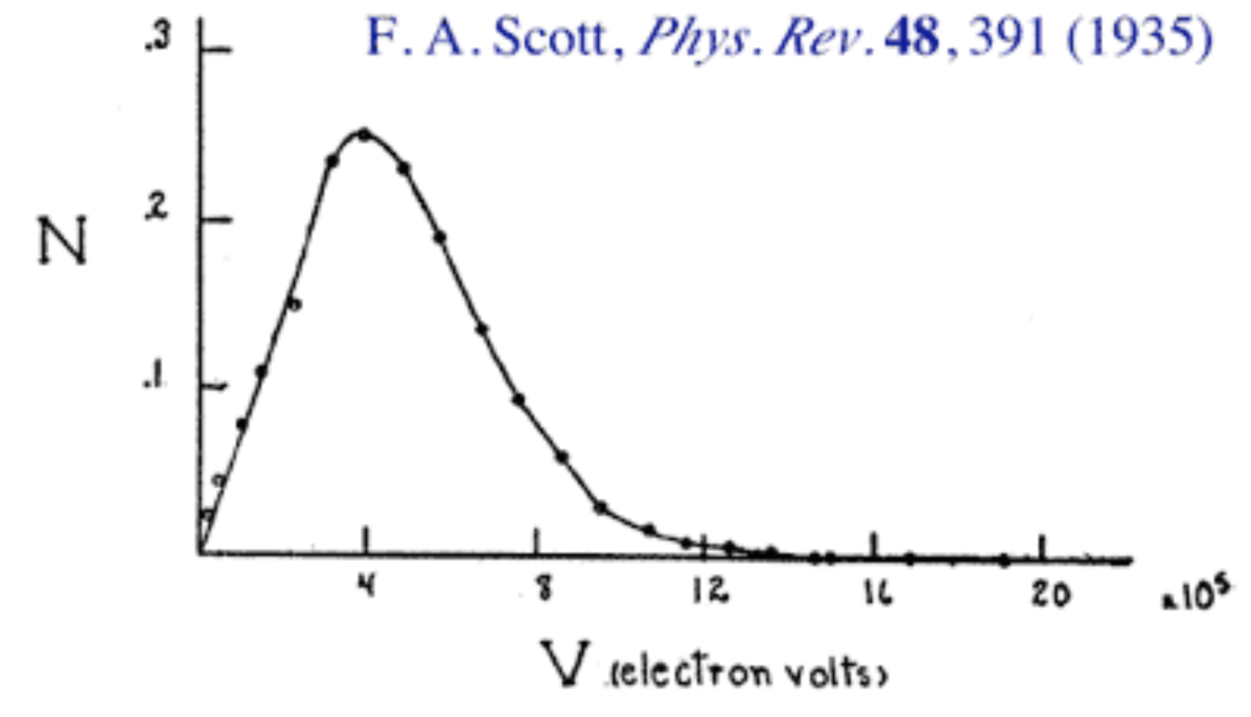
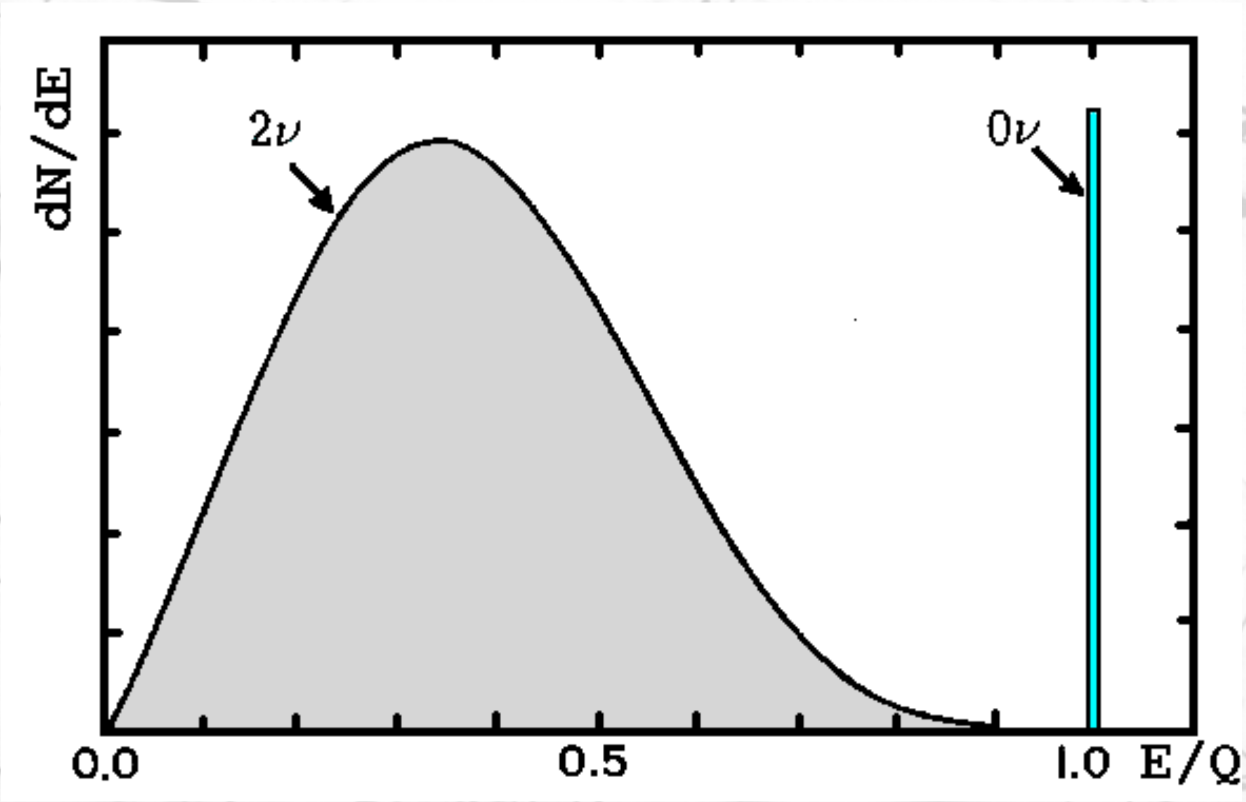


FIG. 5. Energy distribution curve of the beta-rays.

- This primitive idea has been used many times in the future, from LEP & LHC to double beta and mass determination.

Double beta decays

Double beta decay



- The 0ν2β is characterised by a monochromatic 2e emission.
- The experiments are mainly low background underground high resolution calorimeters (ΔE/E ~ 0.2 %)
- New experiments try to get the advantage of the 2 electrons to reduce non 2β background from natural radioactivity: NEMO, NEXT,...

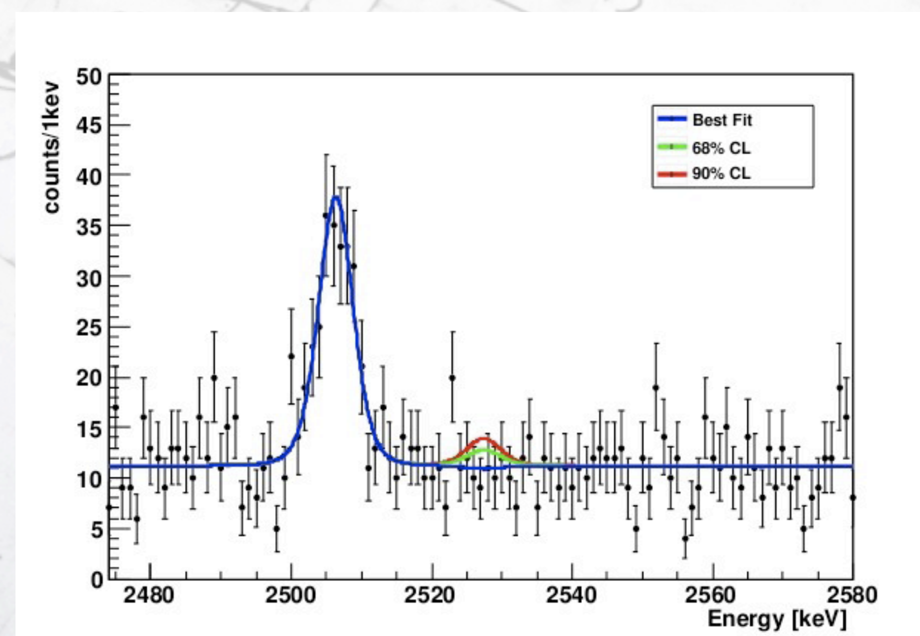
DoubleBeta

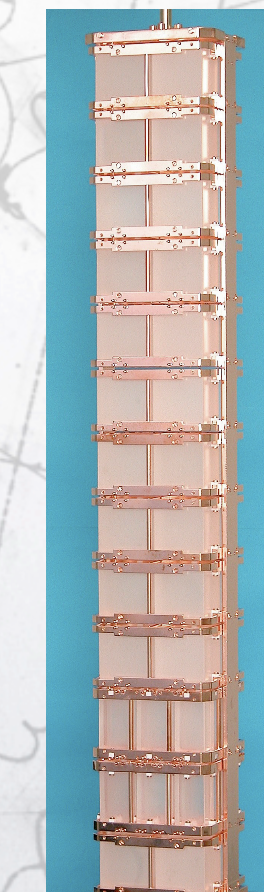
Technology	Pro's	Con's	Isotopes	Experiments
Bolometers	Excellent E resolution isotope = detector	Few isotopes Bckg handling total mass(?)	Ge, Te,	Cuore
Calorimeters	(Very)Large mass isotope = detector	Single isotope	Xe	EXO, Gerda, Kamland + SNO++
Tracking + Calo	Topological bckg reduction many isotopes	Worse E resolution isotope != detector total mass ?	Mo, Ca, Se, Nd	NEMO/SuperNemo.
Calo tracking	Large mass Good E resolution topological bckg reduction isotope = detector	Single isotope	Xe	NEXT, EXO Gas., Cobra, DCBA,..

DoubleBeta

- Ge detector (Klapdor claim) in a large water tank for background reduction.
- Charge in Ge: excellent resolution: 0.2% @ 1 MeV.

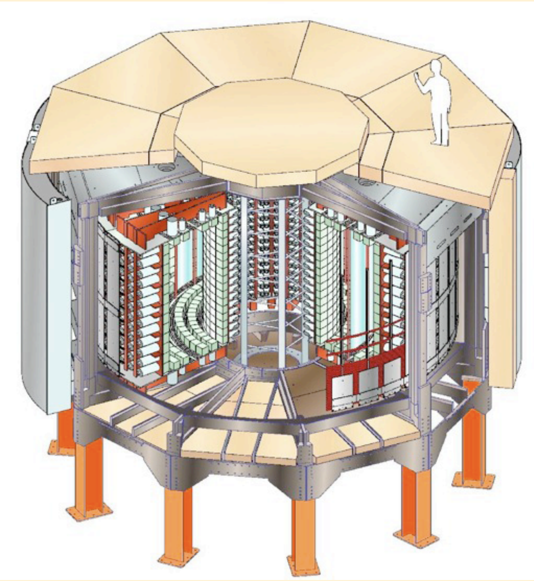
- Te bolometers: measure increase of temperature due to decay products.
- Excellent energy resolution: 0.2% FWHM @ $Q_{\beta\beta}$= 2.6 MeV.

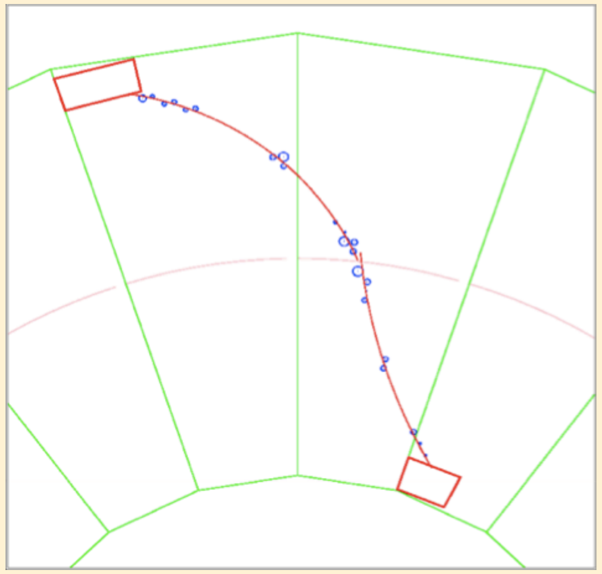




Double Beta

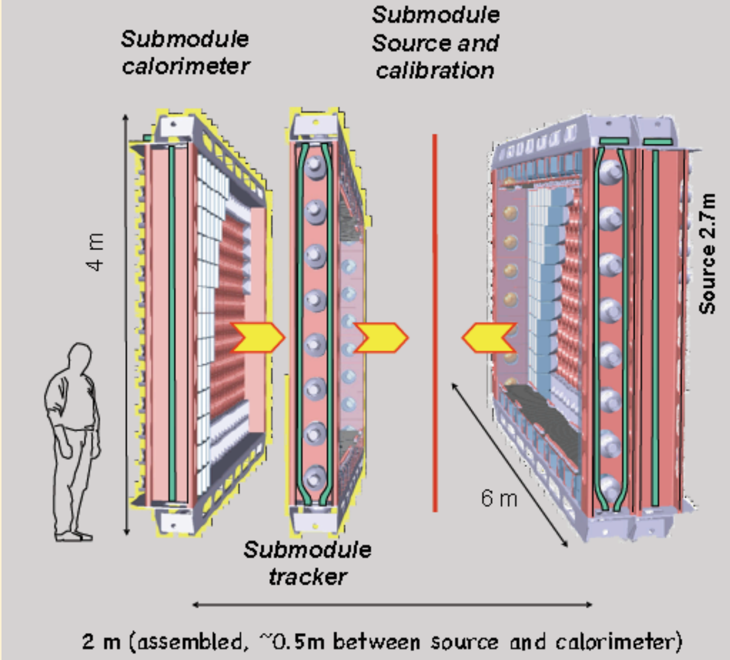
Nemo 3

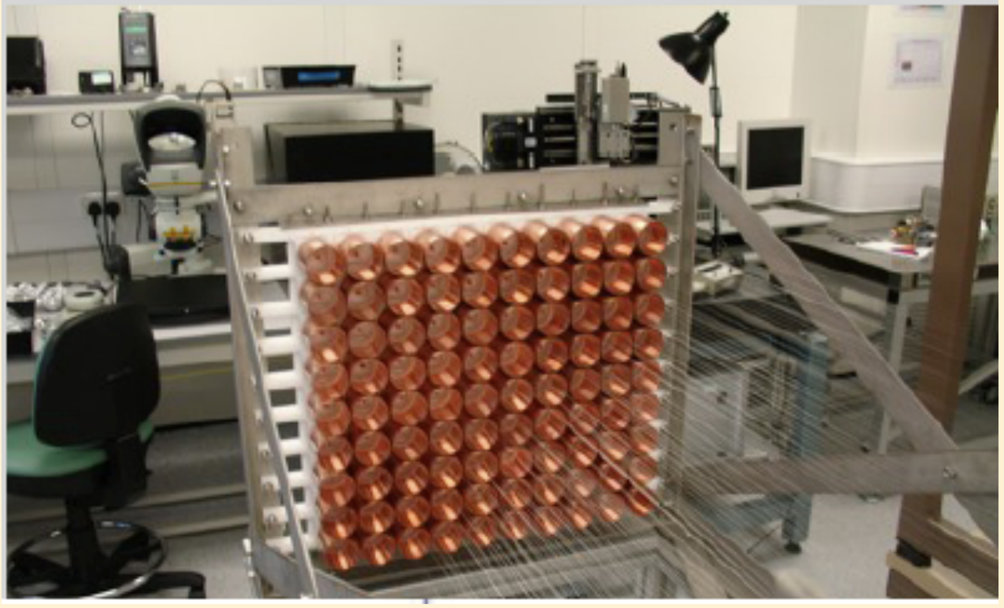




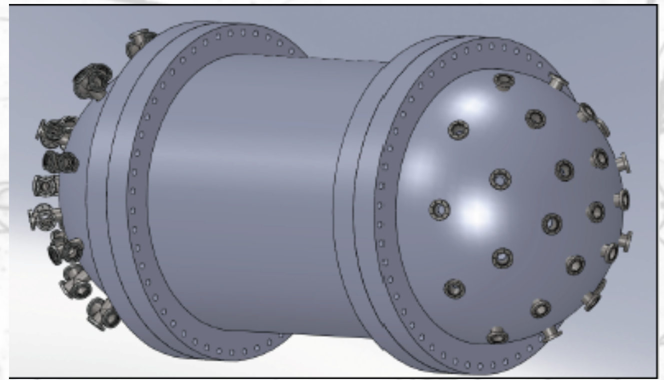
- Topological background reduction:
  - tracking and magnetic field.
  - calorimeter.

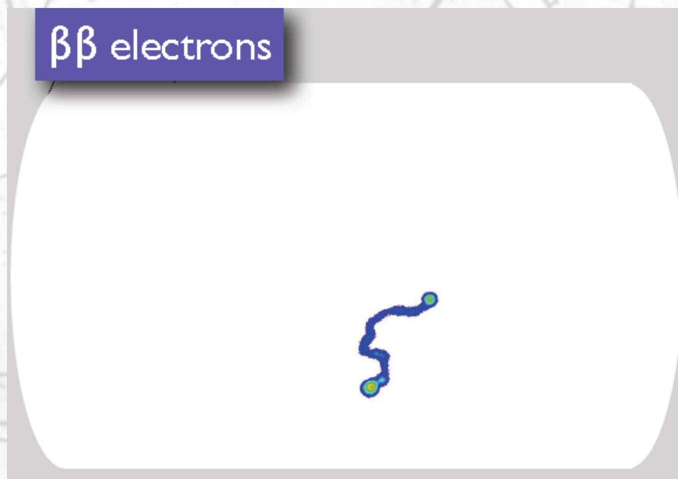
SuperNemo





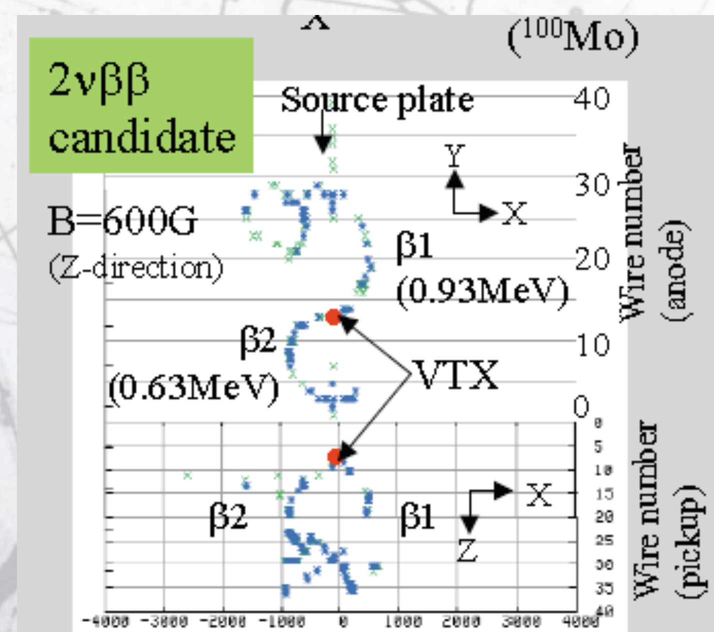
DoubleBeta

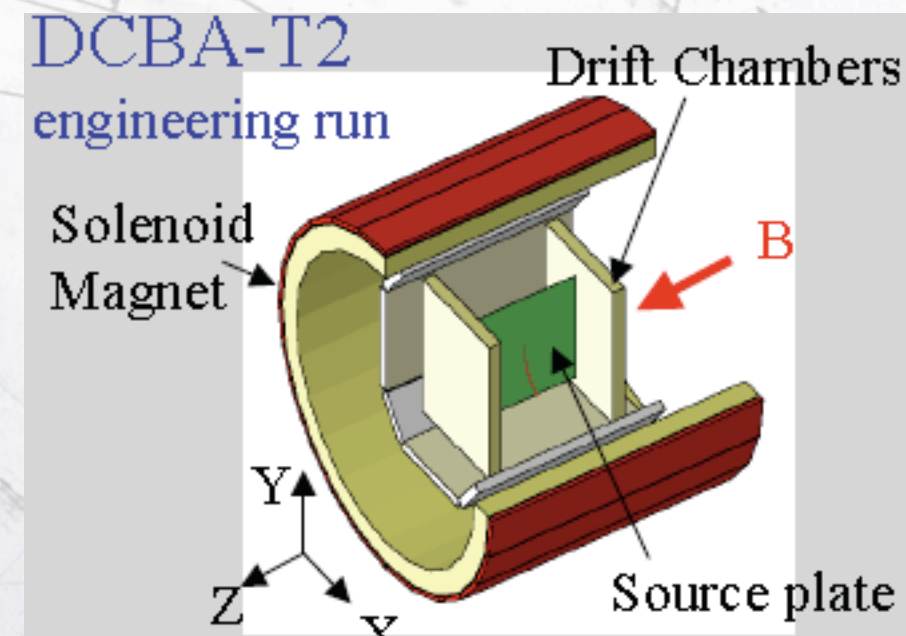




- High pressure Xenon gas TPC: tracking and energy resolution. NEXT & EXO gas. See other talks for reference.
- Topological background reduction.
- Good energy resolution with electroluminiscence.

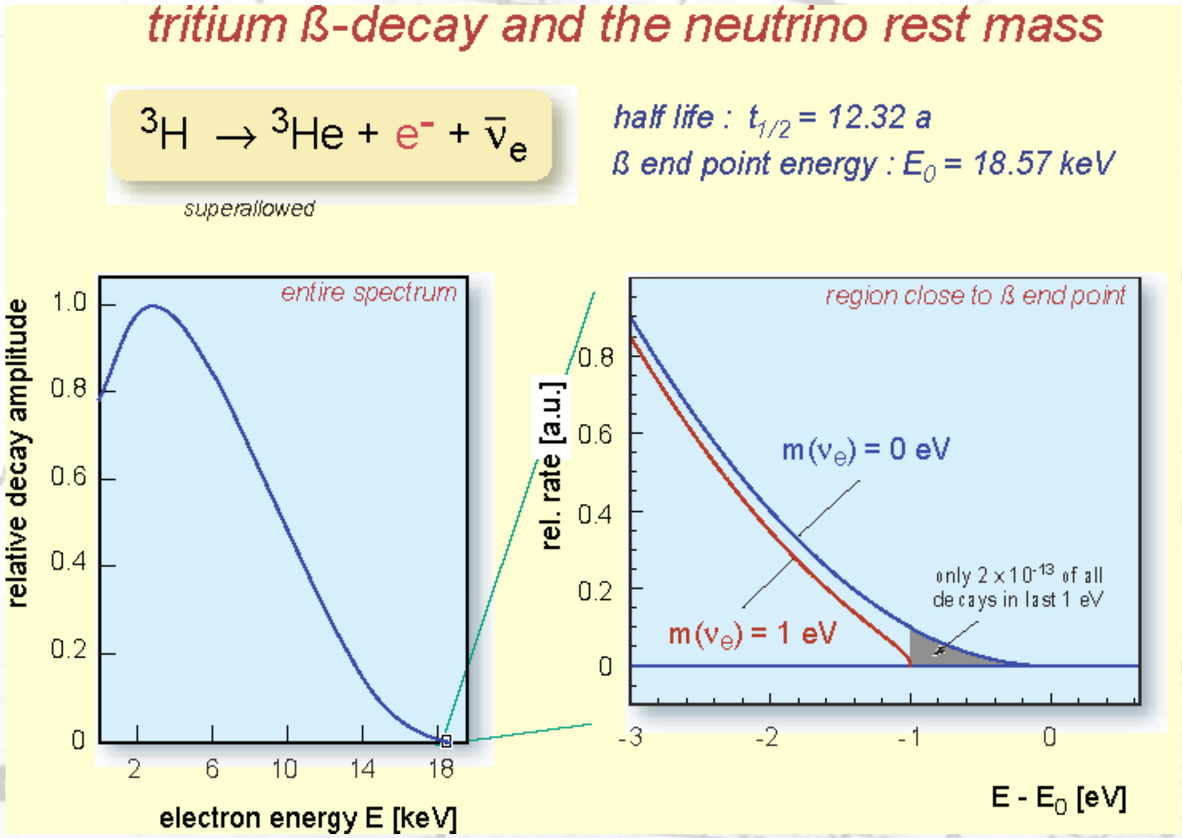
- DCBA-T2. Momentum by electron curvature.
- Foil structure like NEMO3
- topological background reduction.



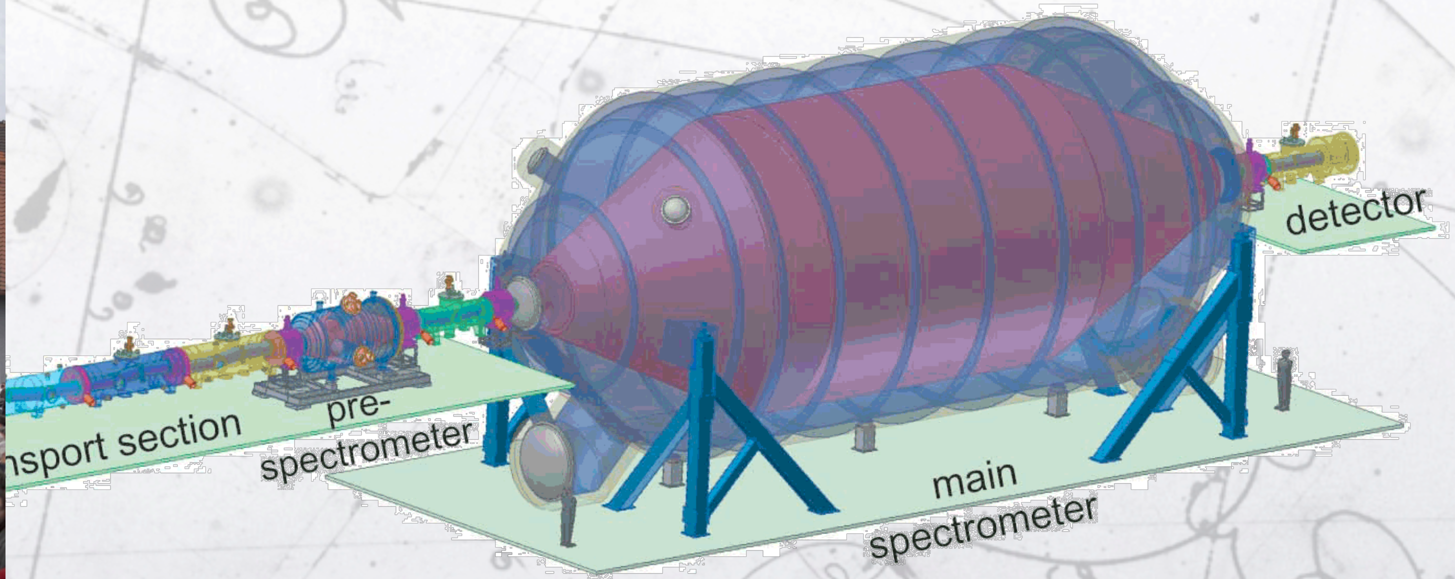


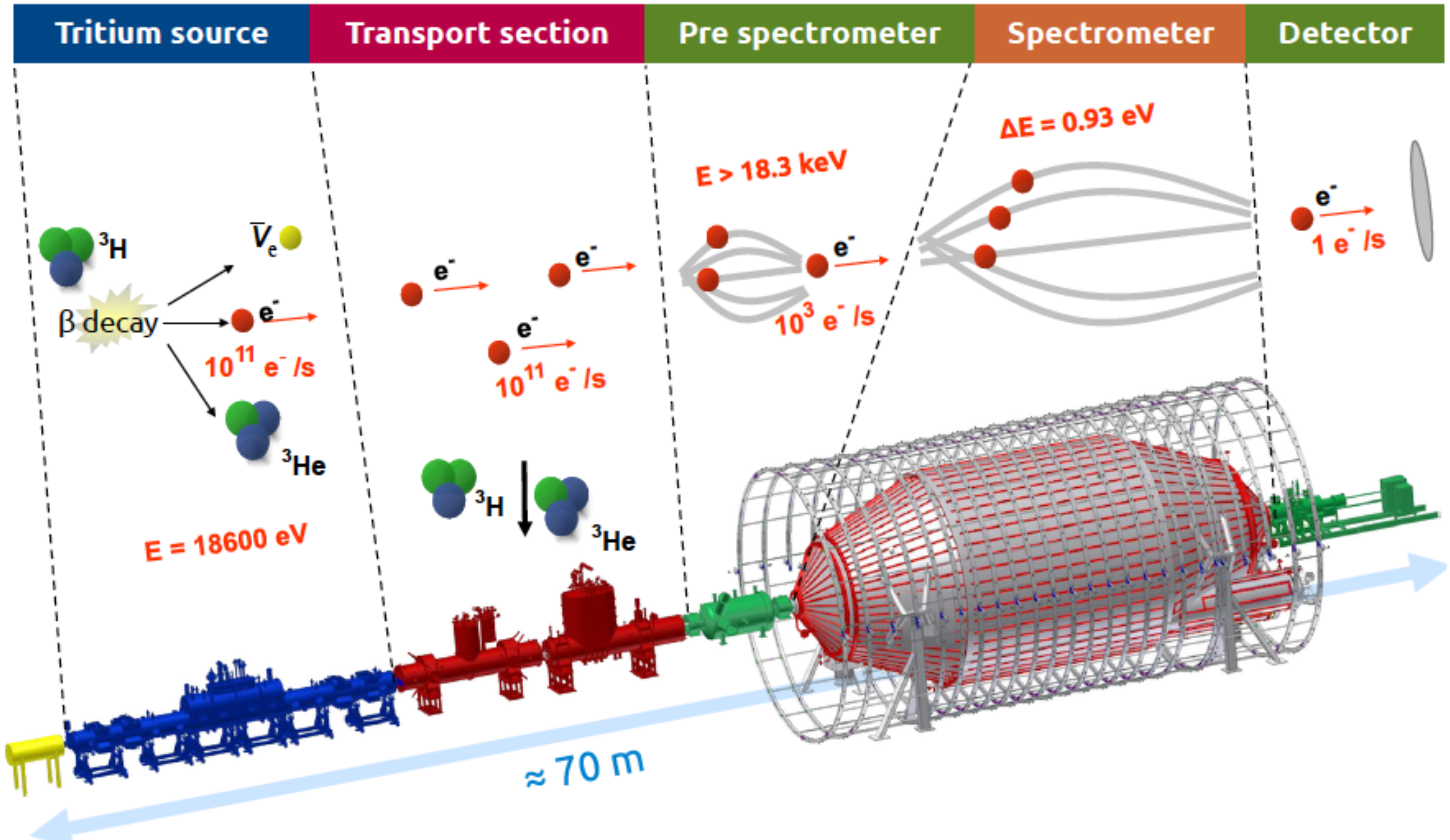
End point for mass determination

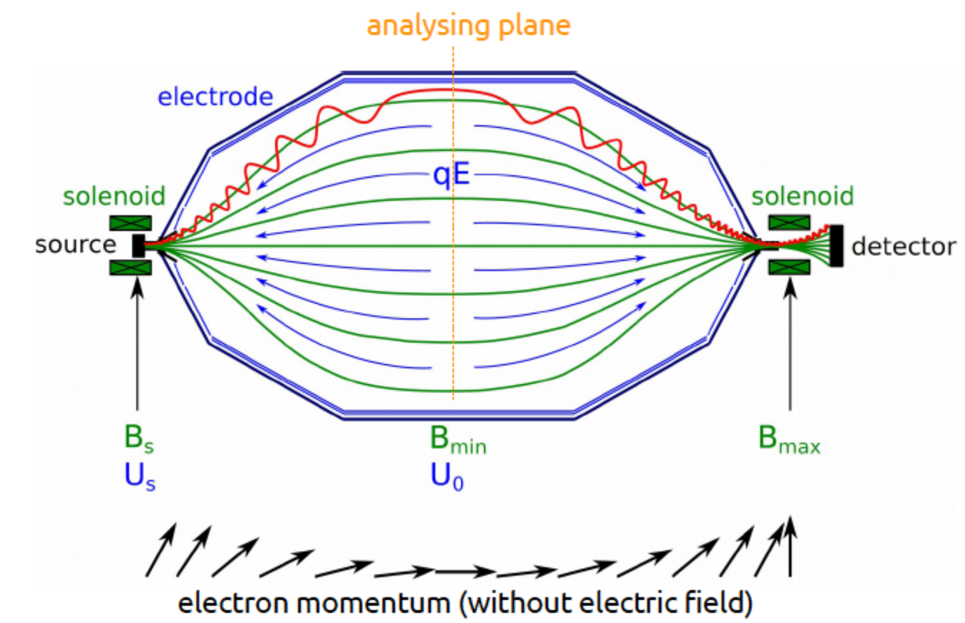
Katrin



- Absolute neutrino mass experiment:
  - ^{3}H β-decay end point.
  - MAC-E filter threshold spectrometer.
  - High resolution: ~0.2eV
- Neutrino properties from "non-observed" neutrinos.





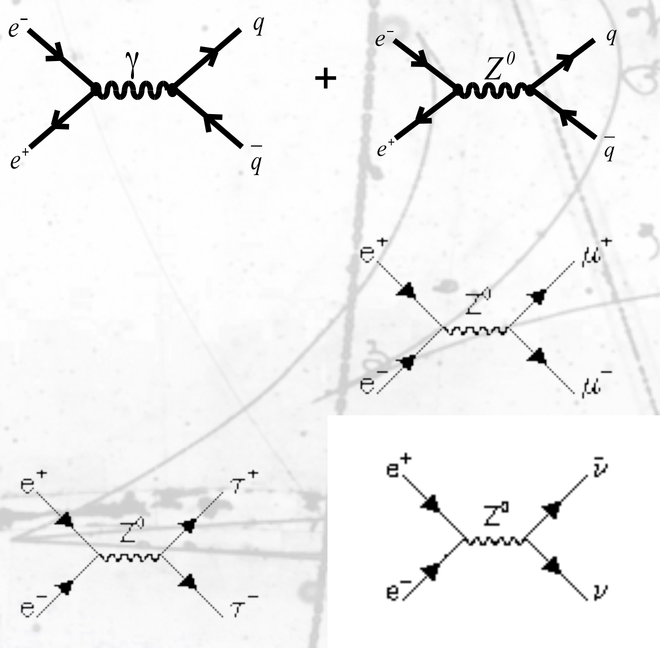


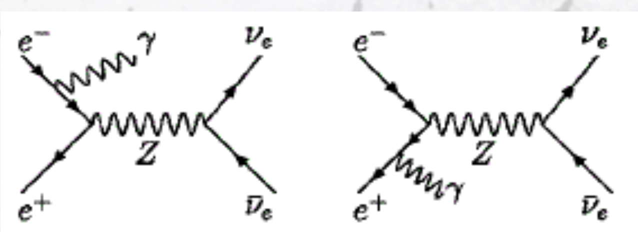
· High pass filter: electrons with $E_{e^- \parallel} > qU_0$ can pass the analysing plane

- The spectrometer counts electrons above a certain cut (pass filter).
- The cut value is varied to provide a very precise beta spectrum.

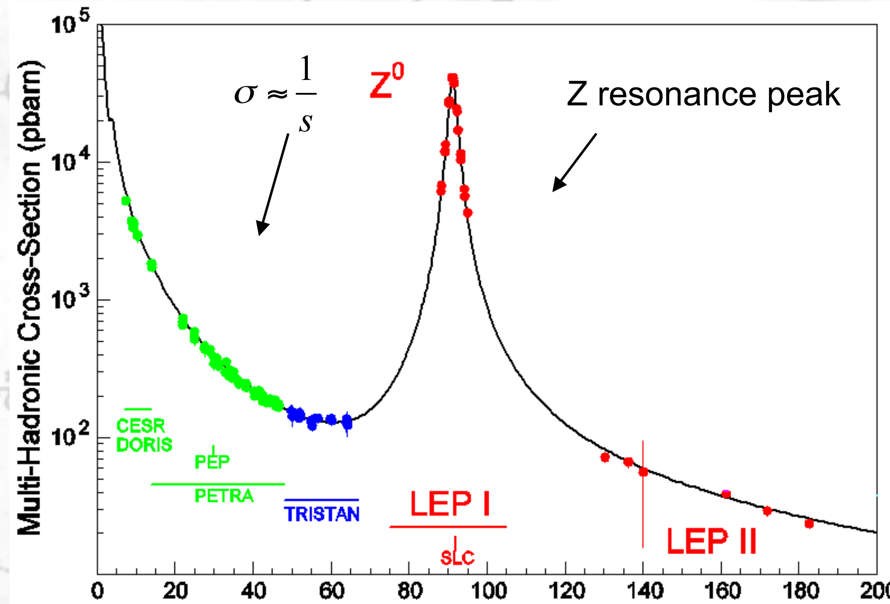
Colliders and the 3 families

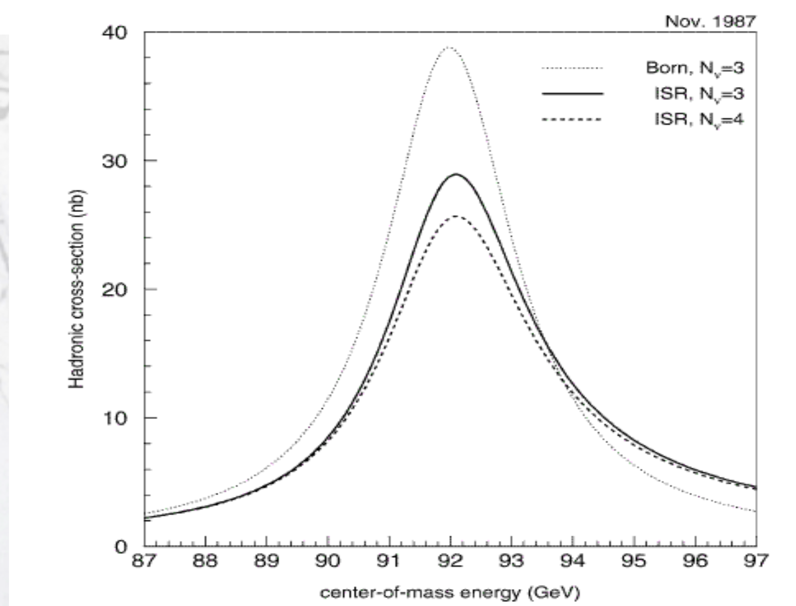
Decay modes





First order QED correction.
Well known process can correct for this.





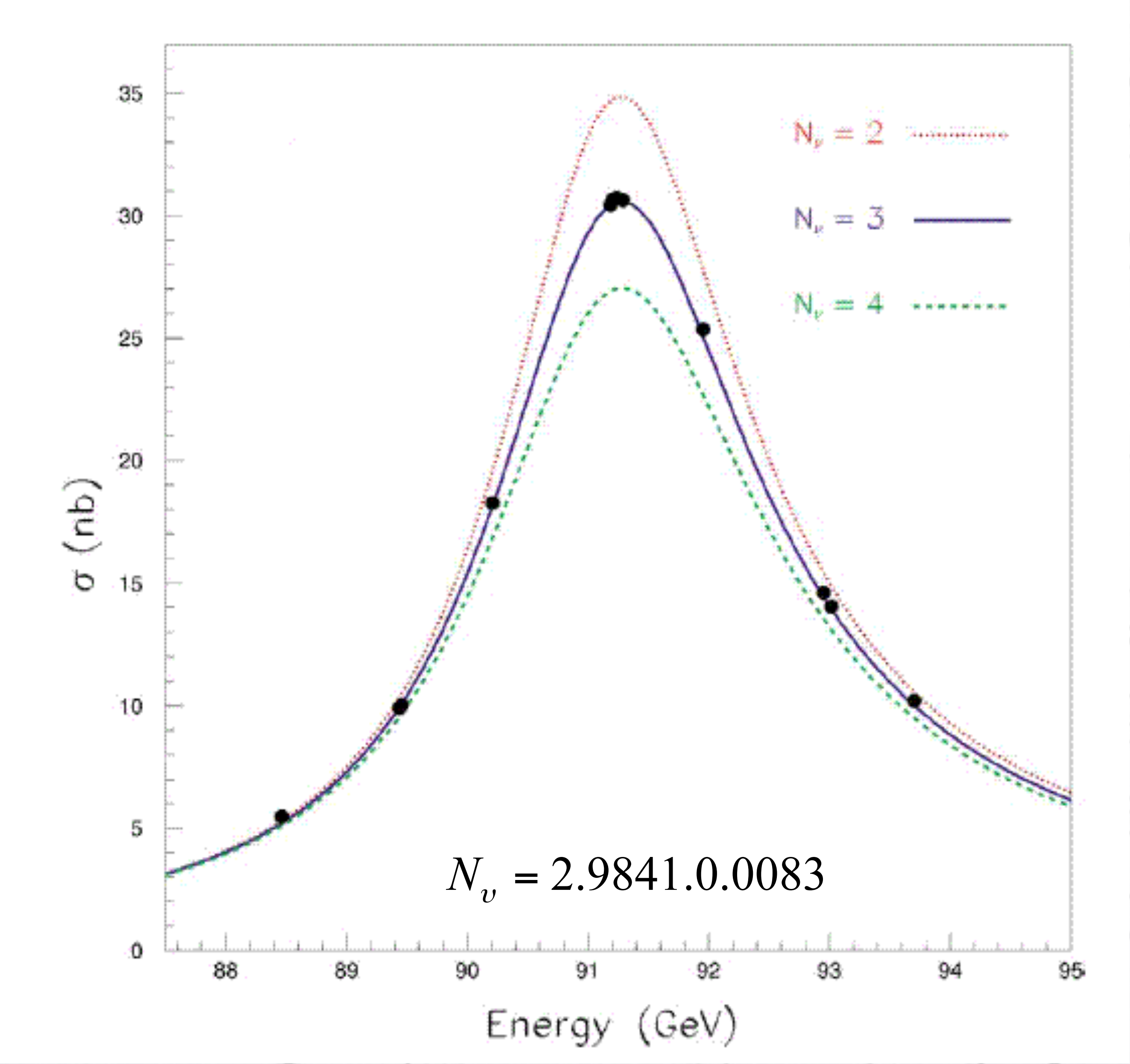
- The width of the Z boson decays depends on the number of possible final states:

$$\Gamma_z = 3\Gamma_l + \Gamma_{had} + N_\nu \Gamma_\nu$$

- Measuring the width contains information about the invisible decays.
- Alternative method, search for 1γ events.

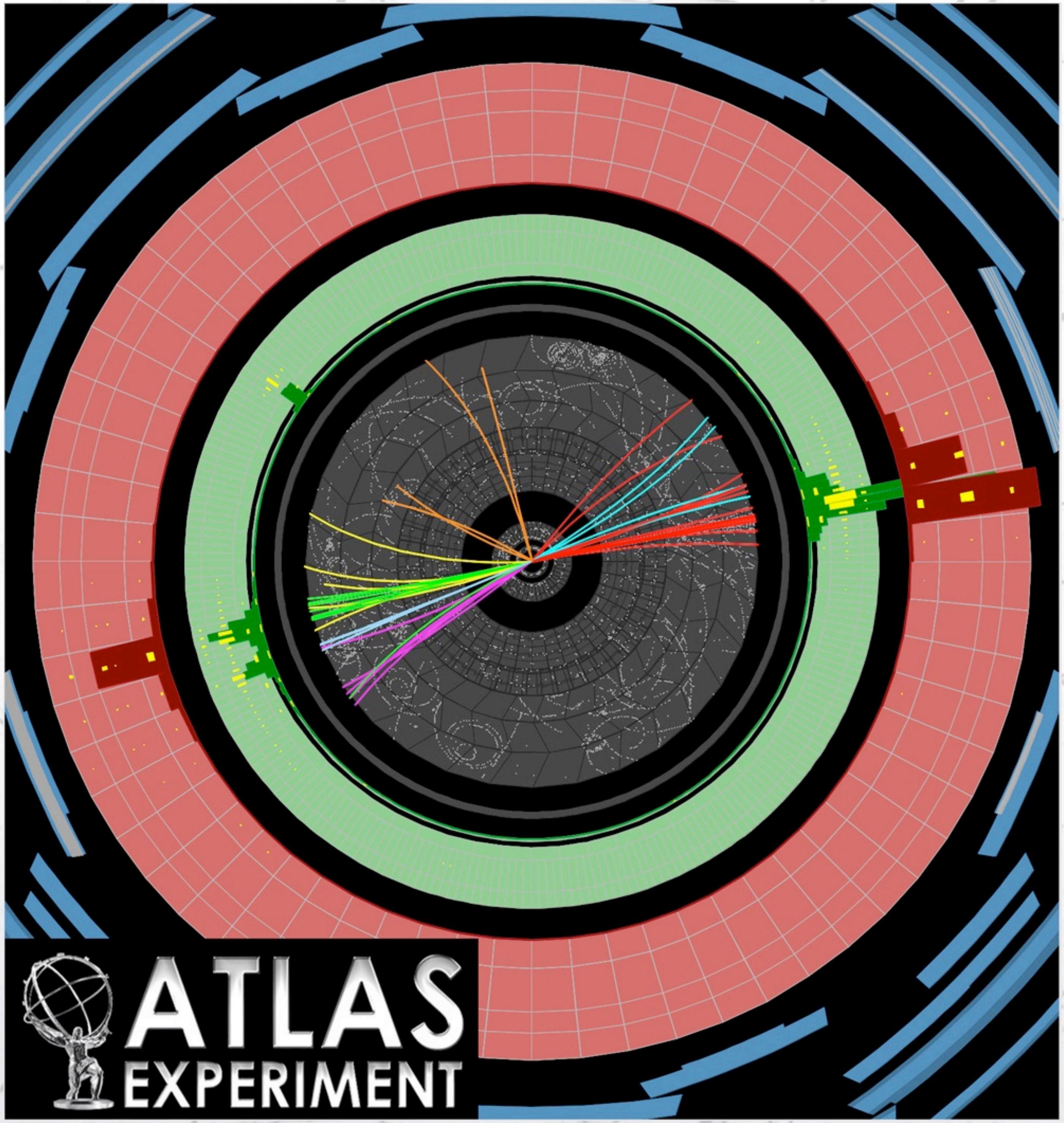
$$e^+e^- \to \gamma\nu\bar{\nu}$$

LEP and 3 families

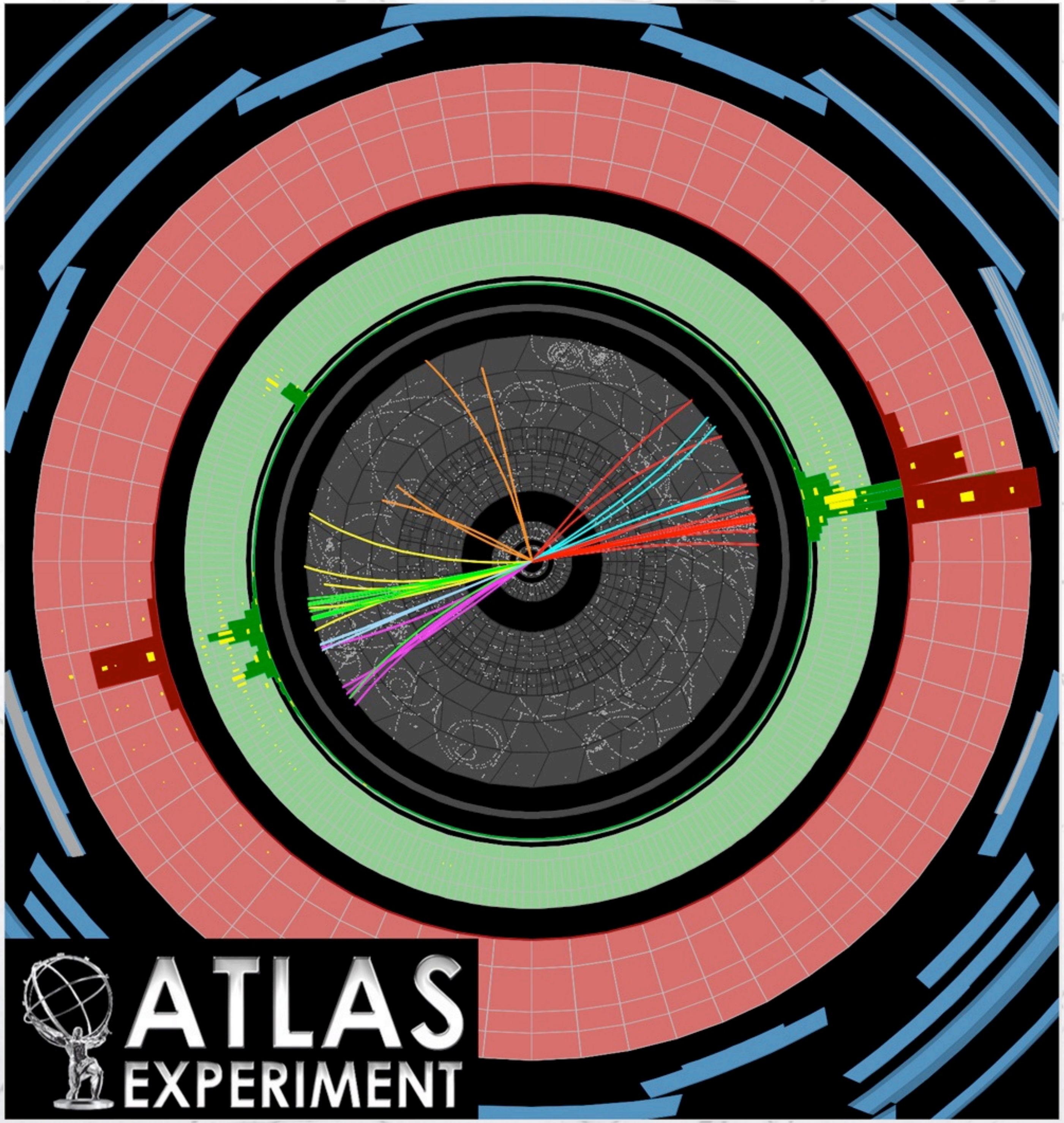


- The number of light neutrinos (m< M_Z/2.) coupling to the Z^0 (active) is ~3.

LHC and new physics

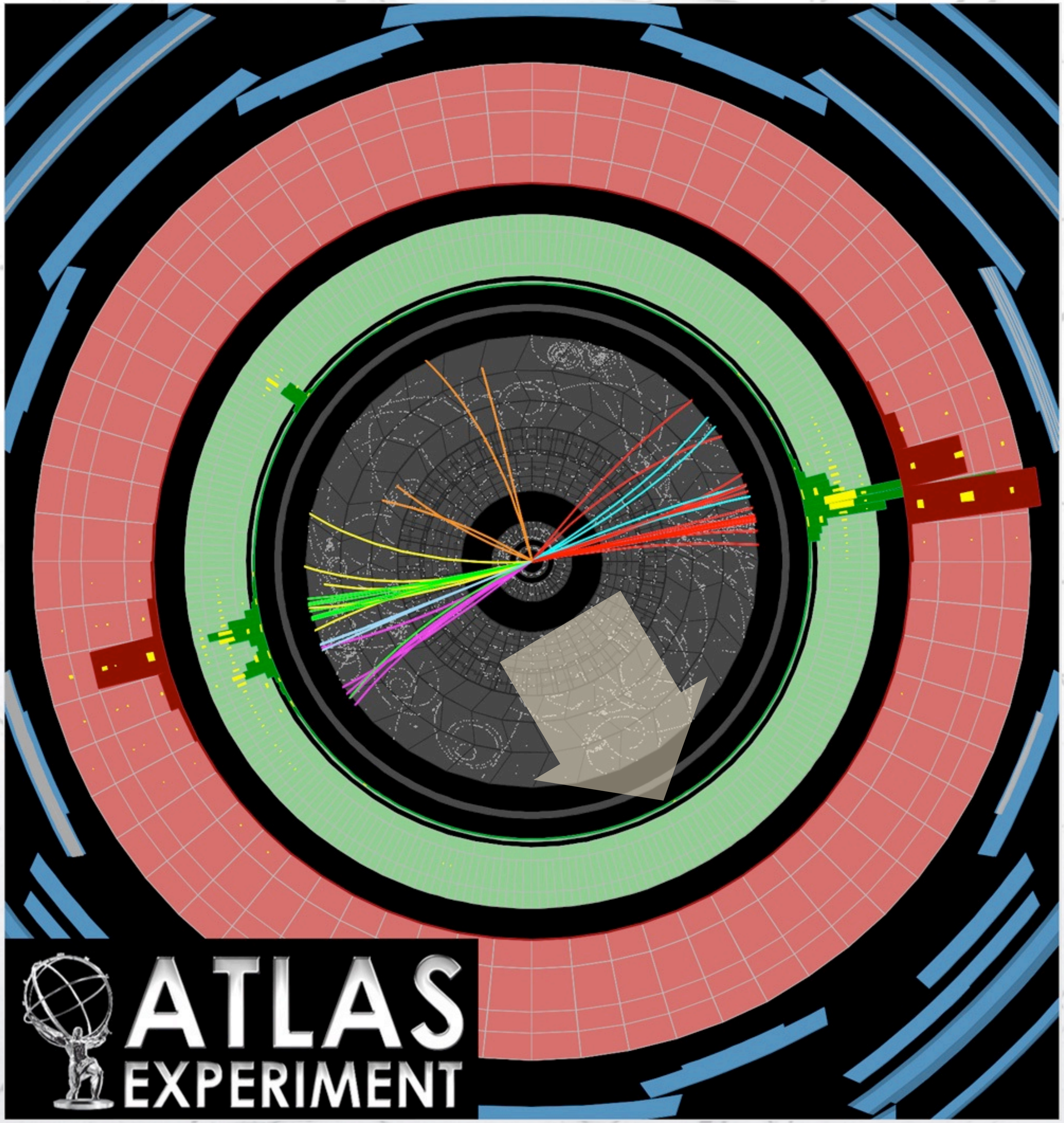


LHC and new physics



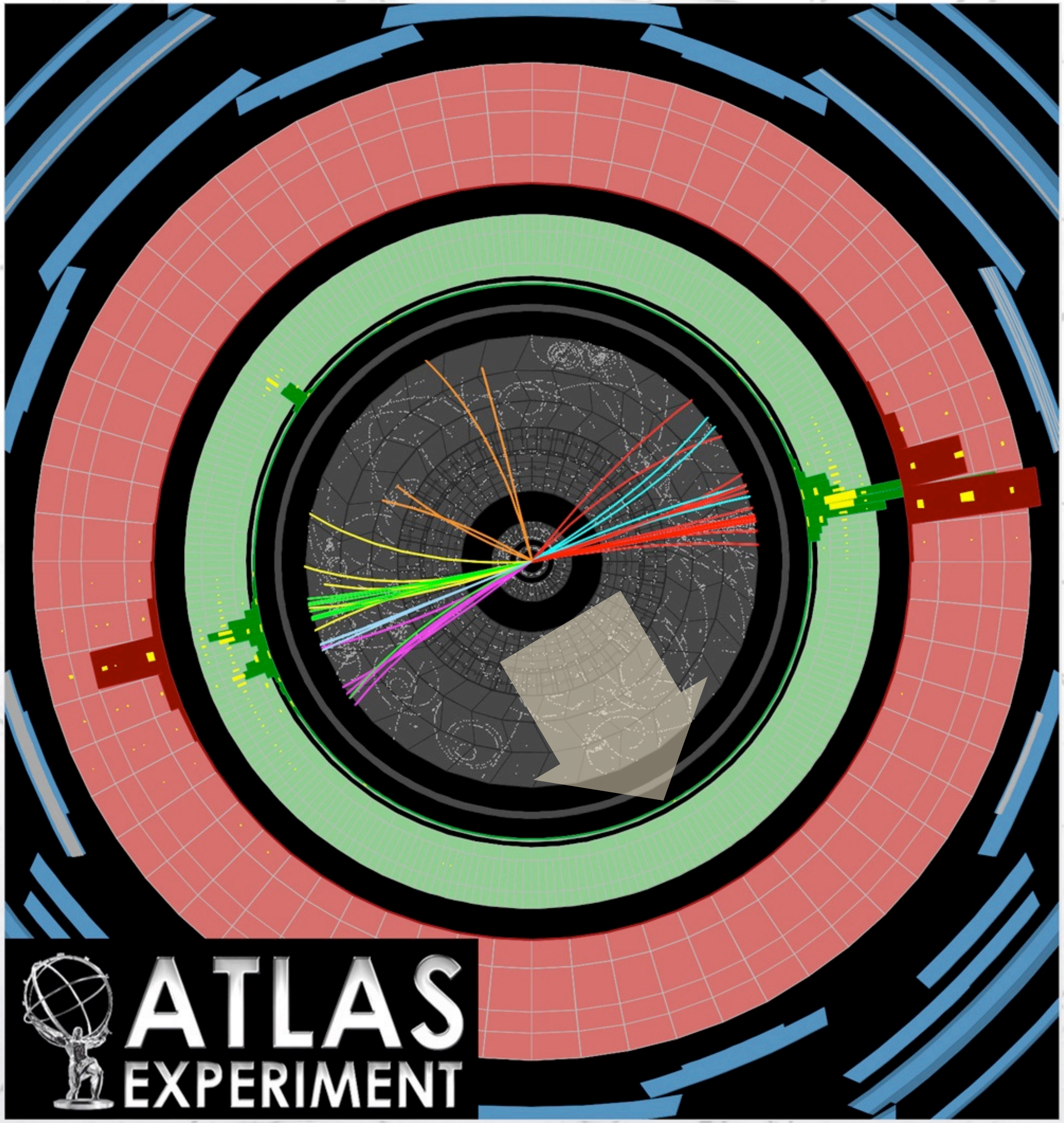
- In LHC the total energy balance is broken by proton remanent in the direction of the beam.
- Transverse momentum is however conserve and it is a powerful tool.

LHC and new physics



- In LHC the total energy balance is broken by proton remanent in the direction of the beam.
- Transverse momentum is however conserve and it is a powerful tool.

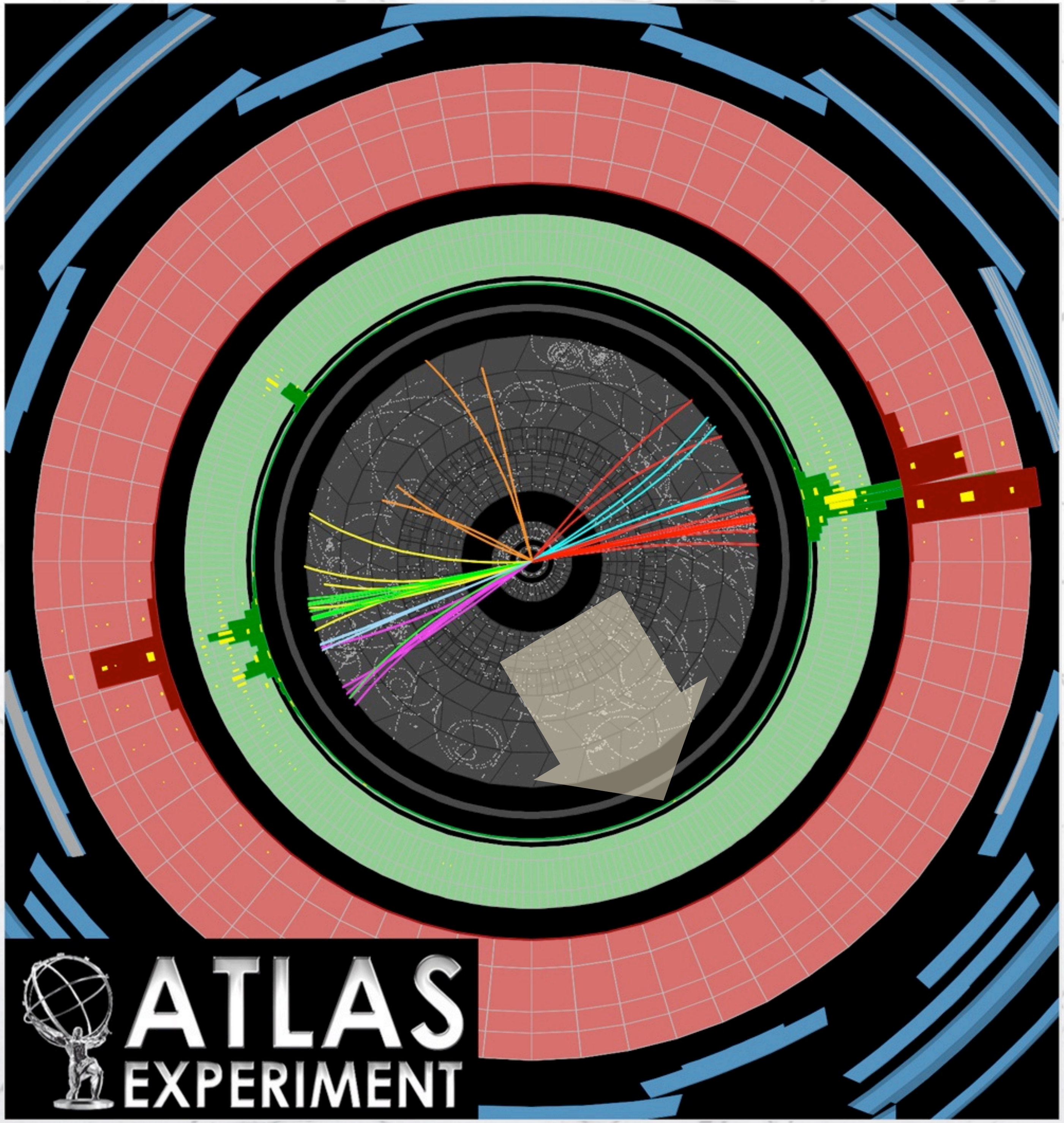
LHC and new physics



- In LHC the total energy balance is broken by proton remanent in the direction of the beam.
- Transverse momentum is however conserve and it is a powerful tool.

- Standard model production of particle decaying to neutrinos: W or Z production → SM physics!

LHC and new physics



- In LHC the total energy balance is broken by proton remanent in the direction of the beam.
- Transverse momentum is however conserve and it is a powerful tool.

- Standard model production of particle decaying to neutrinos: W or Z production → SM physics!

- Weakly interacting particles also produce missing transverse energy → New physics!