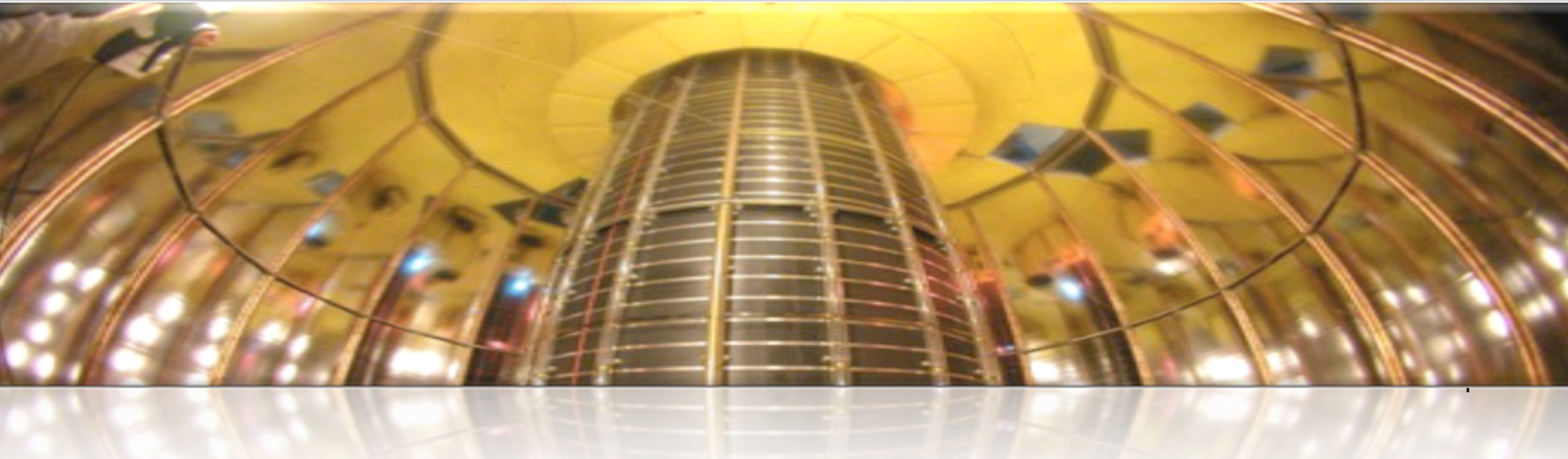
Particle Identification (PID)

distinguishing particle types



Motivation for PID

Two major applications for particle identification:

1) identification of beam particles

2) identification of decay products

If the (vector-)momentum of the particle is known

$$p = m_0 \beta \gamma c$$

(1) selected naturally by the beam-line elements

(2) by means of a magnetic spectrometer

need second observable to identify particle type:

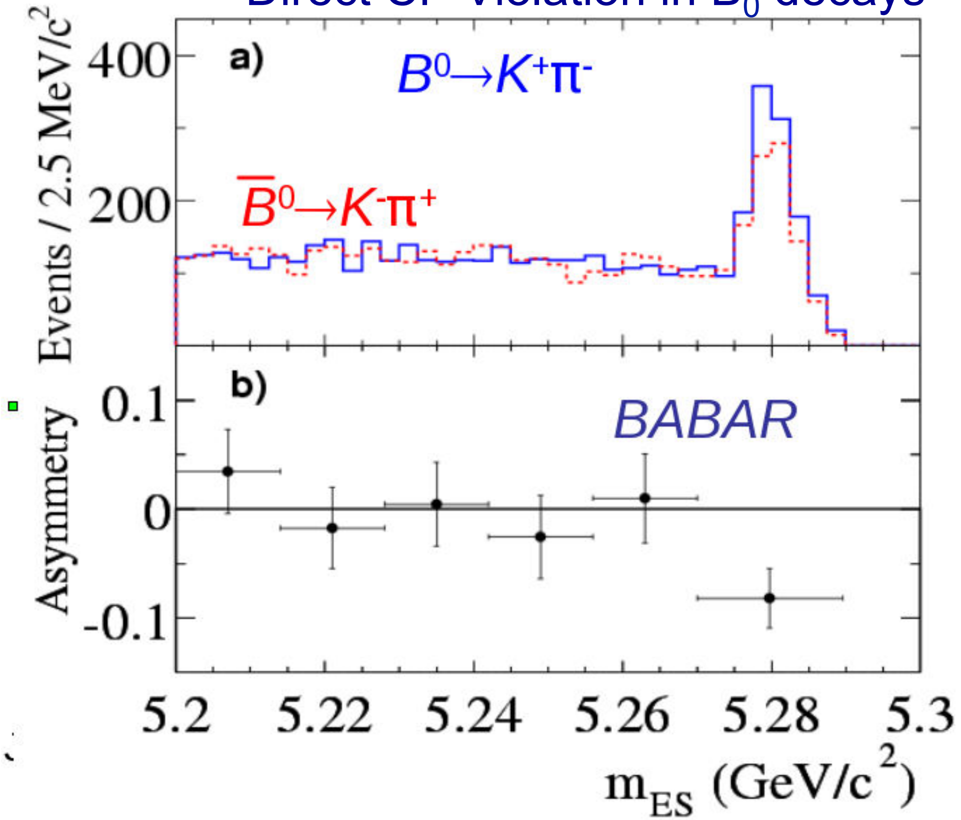
Velocity:	Time-of flight	$\tau \propto 1/\beta$
	Cherenkov angle	$\cos\theta = 1/\beta n$
	Transition radiation	$\gamma \geq 1000$
Energy loss:	Bethe-Bloch	$\frac{dE}{dx} \propto \frac{z^2}{\beta^2} \ln(a\beta\gamma)$
Total energy:	Calorimeter	$E = \gamma m_0 c^2$

Motivation for PID

PID fundamental to many physics studies:

- Hadron physics (COMPASS, PANDA….)
- Flavour physics and CP violation studies (BABAR, BELLE, NA62, LHCb, SuperB…)
- Nucleon structure (HERMES, COMPASS, TJLAB…
- Heavy ion physics (PHENIX, STAR, ALICE…)

Direct CP Violation in B_0 decays



Motivation for PID

To identify long-lived (but still weakly decaying) neutral particles like the hyperons Λ_0 and Ξ_0, and short-lived particles (τ, charm, beauty, resonances), the determination of the 4-vector of all decay products is necessary to be able to calculate the invariant mass of the final state and identify the original particle.

PID reduces to identify all stable particles: **p**, **n**, $\mathbf{K^{\pm}}$, $\mathbf{K^{0}_{L}}$, $\boldsymbol{\pi^{\pm}}$, $\mathbf{e^{\pm}}$, $\boldsymbol{\mu^{\pm}}$, $\boldsymbol{\gamma}$

Special signatures for neutrals:

Photons : Total energy deposited in electromagnetic shower; use energy measurement, shower shape and information on neutrality (e.g. no track)

Neutrons : Energy in calorimeter or scintillator (Li, B, 3He) and information on neutrality (e.g. no track)

K_0, Λ, ... : Reconstruction of invariant masses

Neutrinos : Identify products of charged and neutral current Interactions

Measurement of particle velocity

- Time of flight
- Cherenkov angle
- Transition radiation
- dE/dx – ionization losses

Measurement of particle velocity

- Time of flight

Measure signal time difference between two detectors with good time resolution [start and stop counter]

- Typical detectors:

  Scintillation counter + photodetector

  time resolutions ~50-100 ps (r/o at both ends of the scintillator bar)

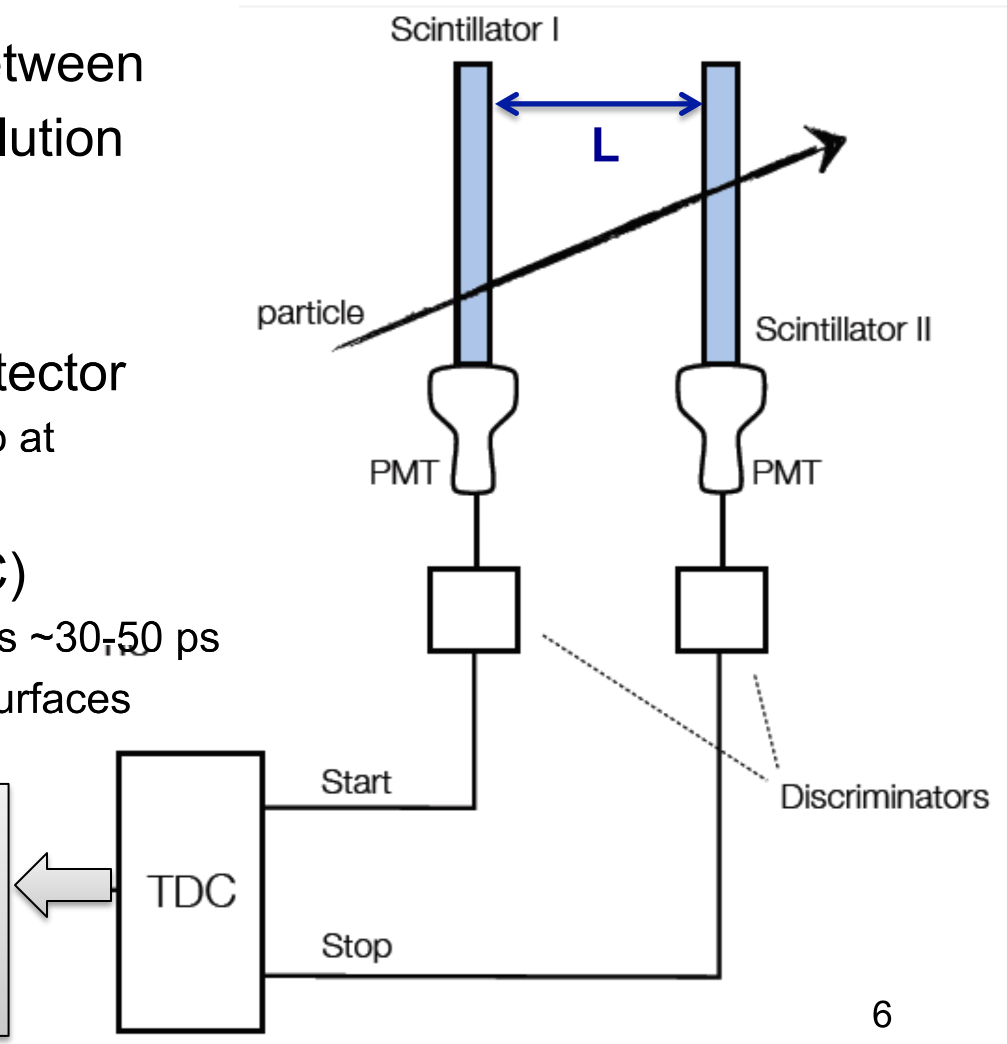
  Resistive Plate Chamber (RPC)

  not sensitive to B, time resolutions ~30-50 ps

  cost effective solution for large surfaces

$$\Delta t = t_2 - t_1 = \frac{L}{c\beta}$$

Multi-channel analyzer t_1 , t_2



Time-of-Flight method

Distinguishing particles with ToF:
[particles have same momentum p]

Particle 1 : velocity v_1, β_1; mass m_1, energy E_1
Particle 2 : velocity v_2, β_2; mass m_2, energy E_2

Distance L : distance between ToF counters

$$\Delta t = L\left(\frac{1}{v_1} - \frac{1}{v_2}\right) = \frac{L}{c}\left(\frac{1}{\beta_1} - \frac{1}{\beta_2}\right)$$

$$= \frac{L}{pc^2}(E_1 - E_2) = \frac{L}{pc^2}\left(\sqrt{p^2c^2 + m_1^2c^4} - \sqrt{p^2c^2 + m_2^2c^4}\right)$$

Relativistic particles, $E \simeq pc \gg m_i c^2$:

$$\Delta t \approx \frac{L}{pc^2}\left[(pc + \frac{m_1^2c^4}{2pc}) - (pc + \frac{m_2^2c^4}{2pc})\right]$$

$$\Delta t = \frac{Lc}{2p^2}\left(m_1^2 - m_2^2\right)$$

For L = 2 m:

Requiring $\Delta t \gtrsim 4\sigma_t$ K/π separation possible up to p = 1 GeV if $\sigma_t \approx 200$ ps ...

Cherenkov counter, RPC : $\sigma_t \approx 40$ ps ...
Scintillator counter : $\sigma_t \approx 80$ ps ...

Example:

Pion/Kaon separation ...
[$m_K \approx 500$ MeV, $m_\pi \approx 140$ MeV]

Assume:
p = 1 GeV, L = 2 m ...

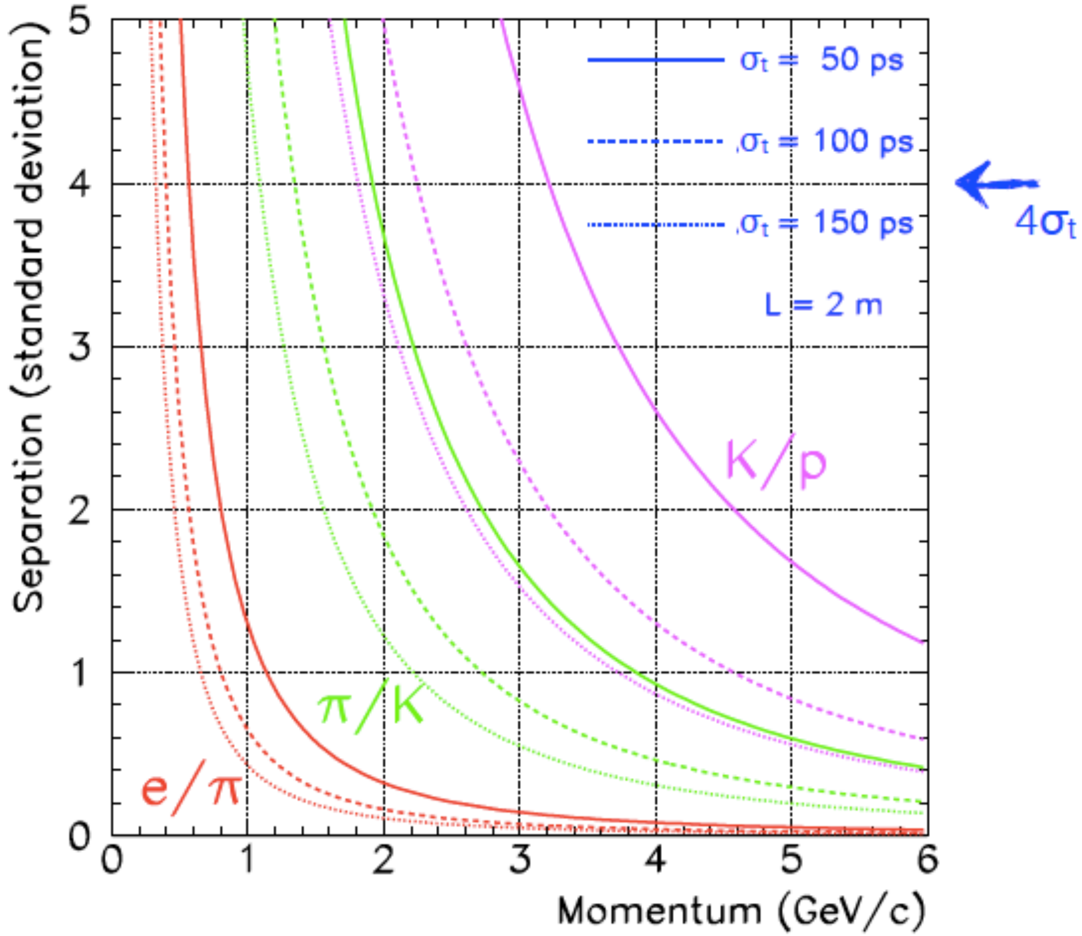
$$\rightarrow \quad \Delta t \approx \frac{2\ \mathrm{m} \cdot c}{2\ (1000)^2\ \mathrm{MeV}^2/c^2}\left(500^2 - 140^2\right)\ \mathrm{MeV}^2/c^4$$

$$\approx 800\ \mathrm{ps}$$

Time of flight performance

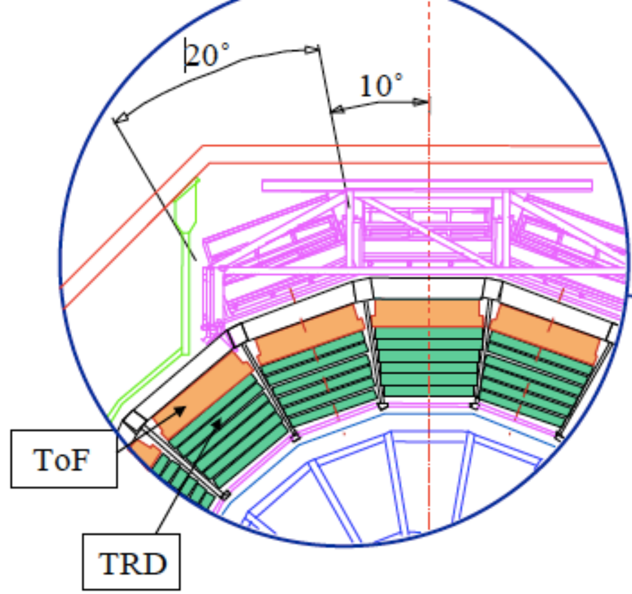
Difference in time-of-flight in σ_t

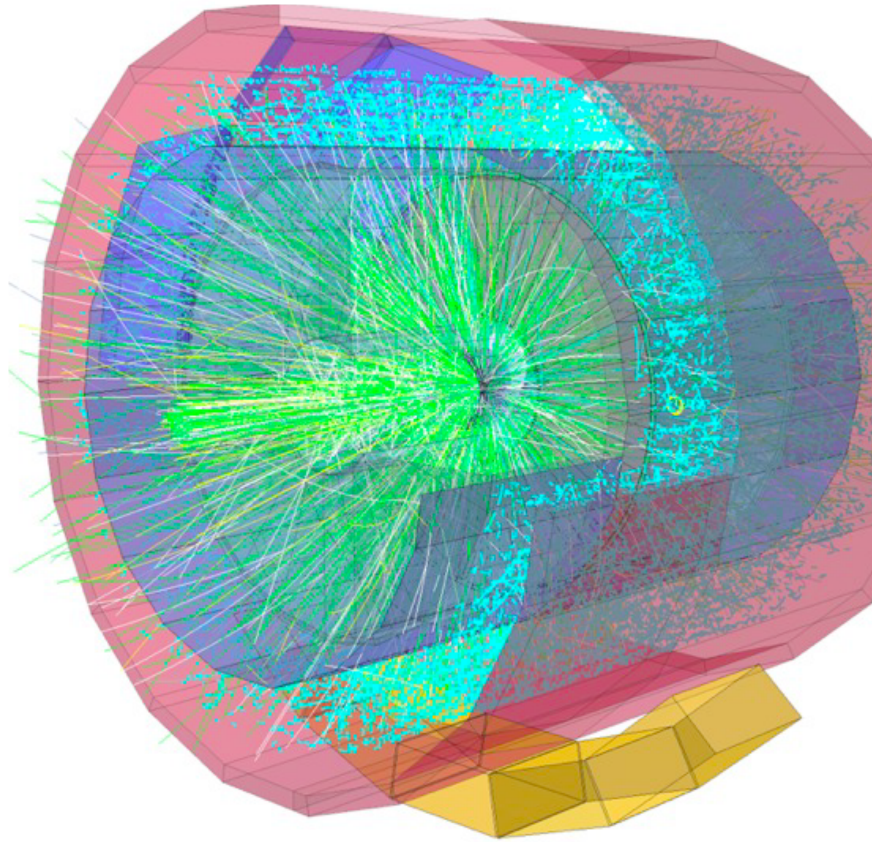
[L = 2 m]



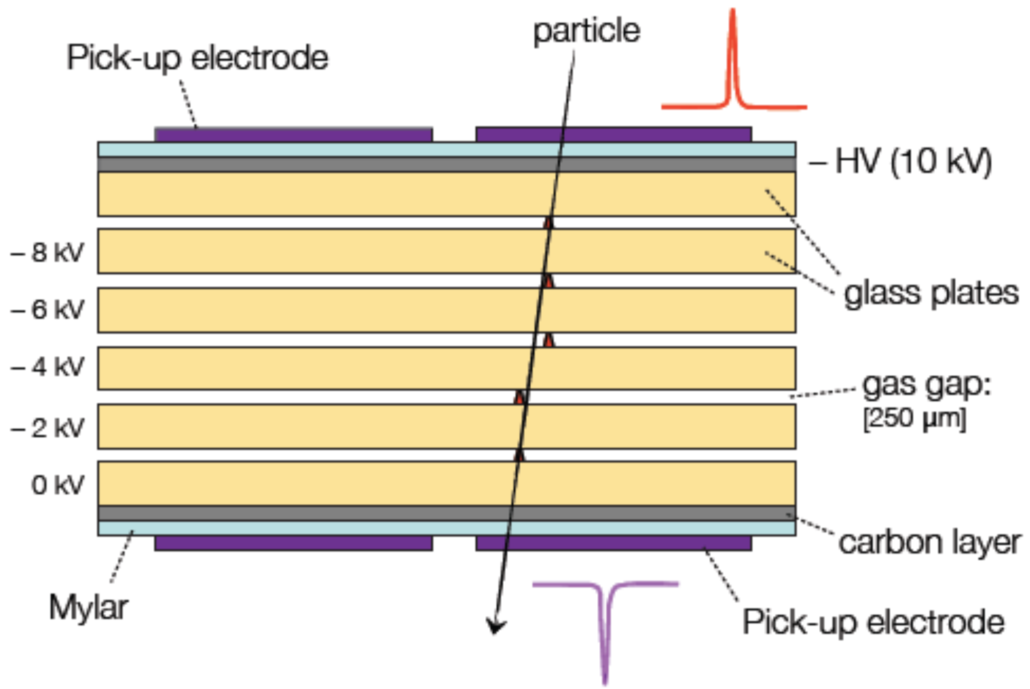
TOF detector - ALICE

ALICE Multi Resistive Plate Chamber
[Time-of-Flight System]
Particle ID in high multiplicity environment
➔ ToF with very high granularity
and coverage of full ALICE barrel
➔ Gas detector is only choice!



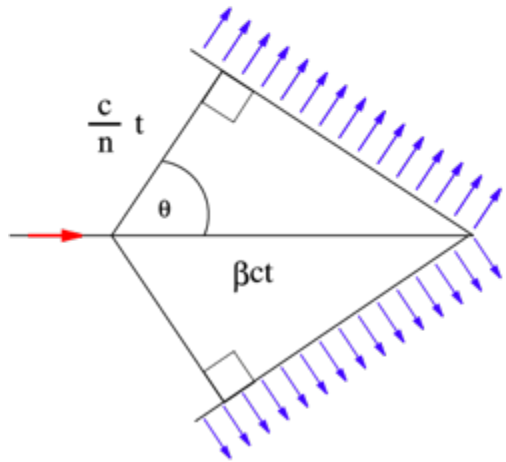


Multi Resistive Plate Chamber



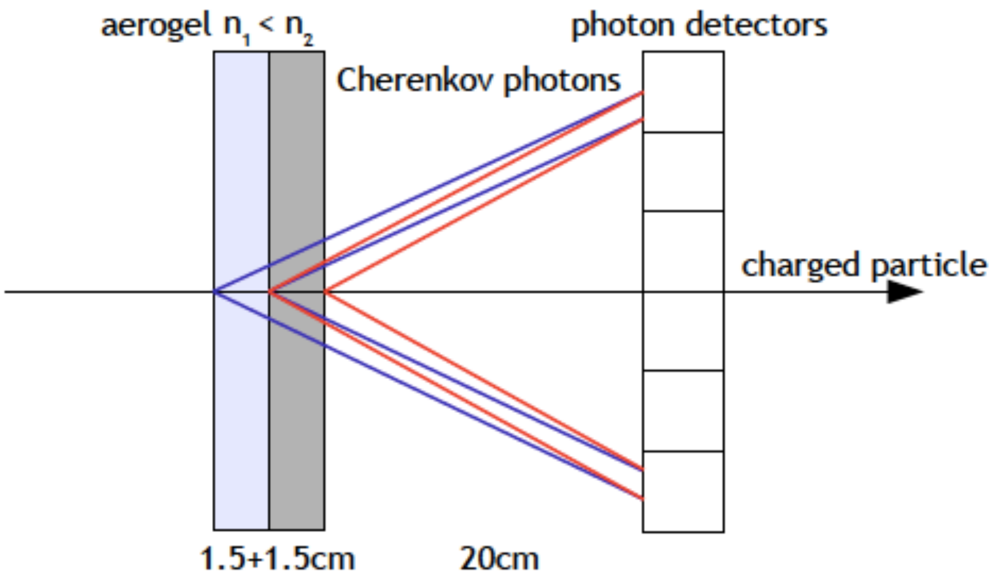
Measurement of particle velocity

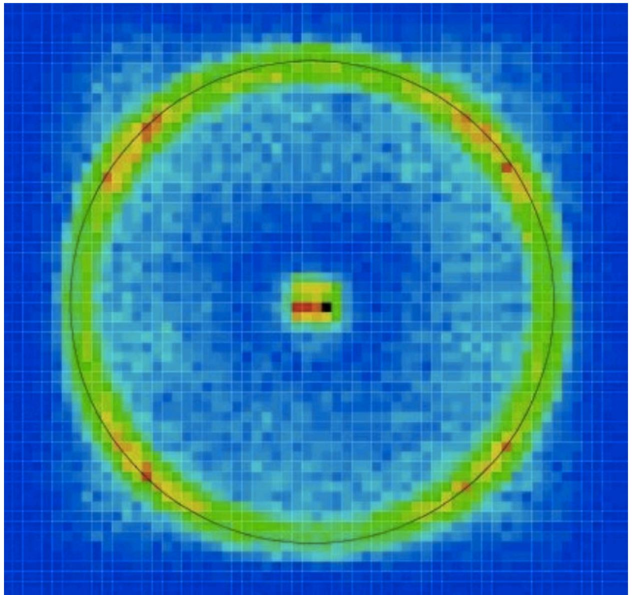
- Cherenkov angle



$$v_{th} \geq \frac{c}{n} \Rightarrow \beta_{th} \geq \frac{1}{n}$$

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

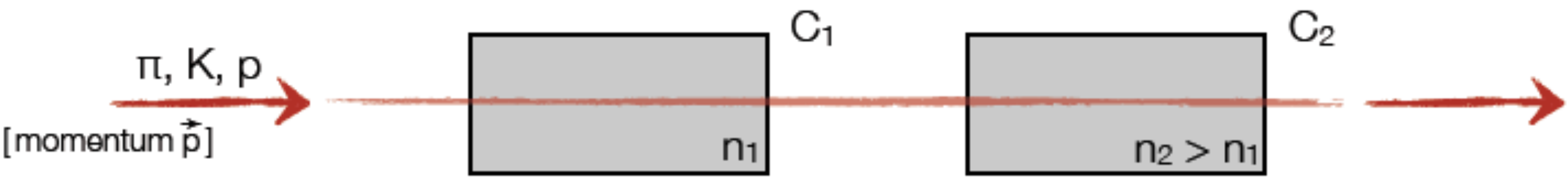




Cherenkov detectors

Threshold detection:

Observation of Cherenkov radiation → $\beta > \beta_{thr}$



Choose n_1, n_2 in such a way that for:

n_2 : $\beta_\pi, \beta_K > 1/n_2$ and $\beta_p < 1/n_2$

n_1 : $\beta_\pi > 1/n_1$ and $\beta_K, \beta_p < 1/n_1$

Note:
e always visible in Cherenkov counters

Light in C_1 and C_2	→	identified pion
Light in C_2 and not in C_1	→	identified kaon
Light neither in C_1 and C_2	→	identified proton

Cherenkov detectors

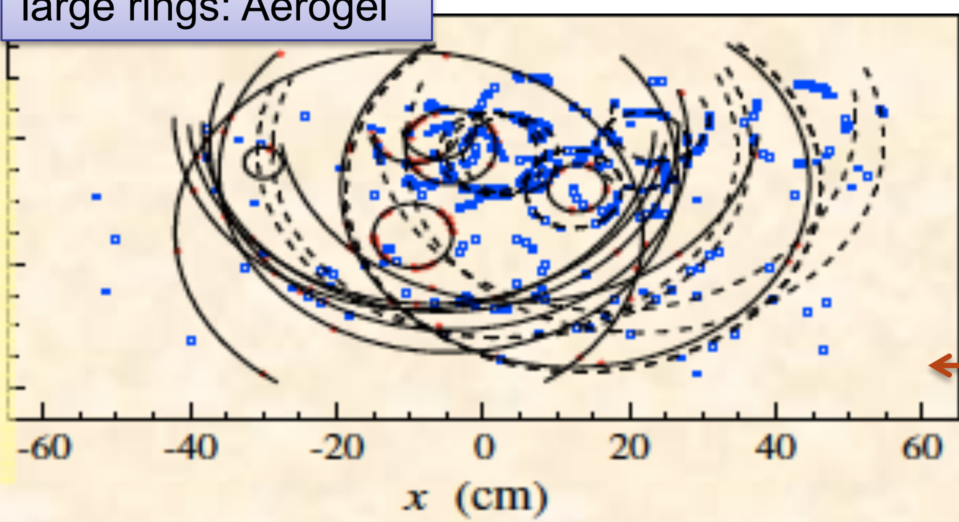
Determination of β from ring radius:

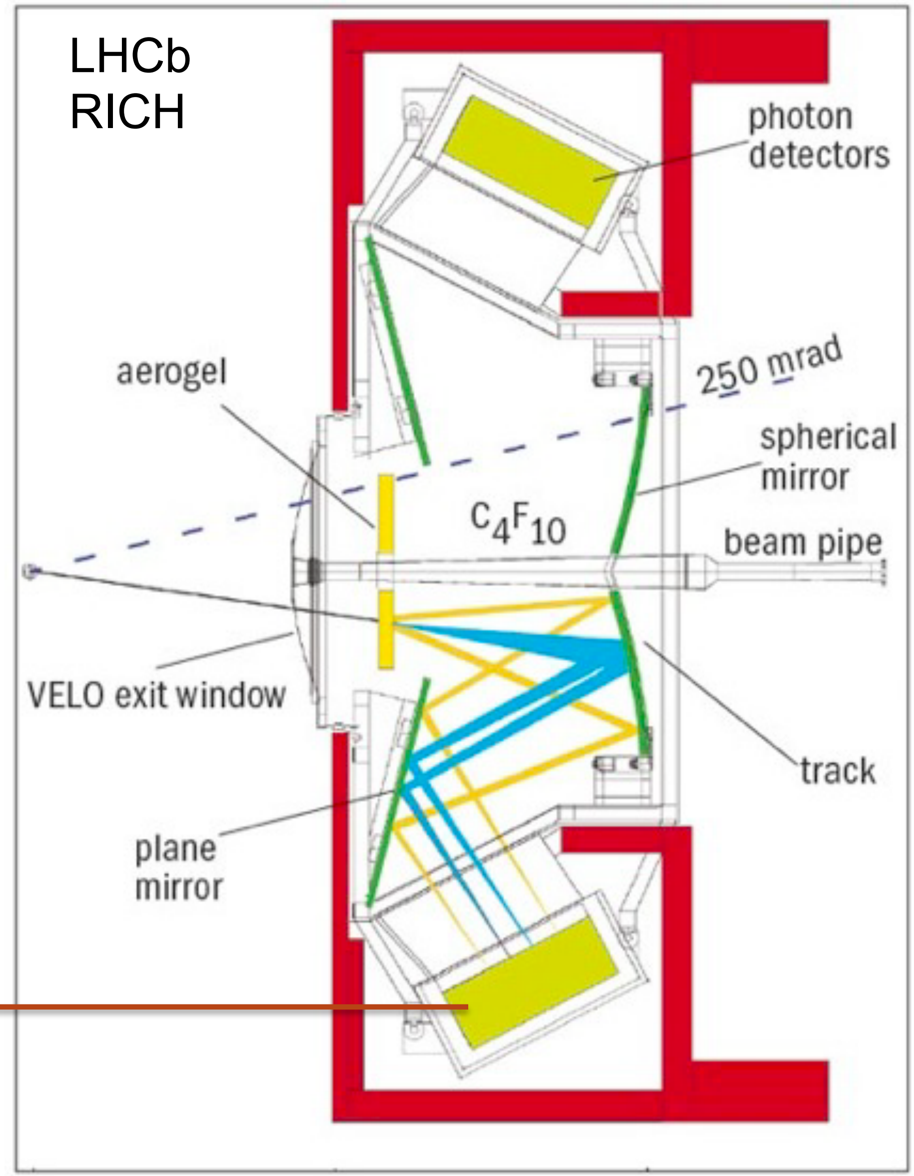
$$\beta = \frac{1}{n\cos(2r/R_s)}$$

R_s : radius of spherical mirror

RICH (Ring Imaging Cherenkov Counter)
DIRC (Detection of Internally Reflected Cherenkov Light)
DISC (special DIRC; e.g. Panda)

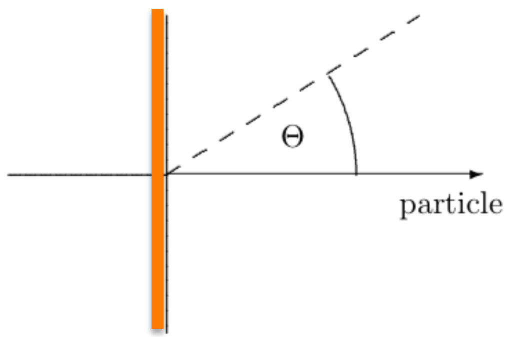
small rings: C_4F_{10}
large rings: Aerogel





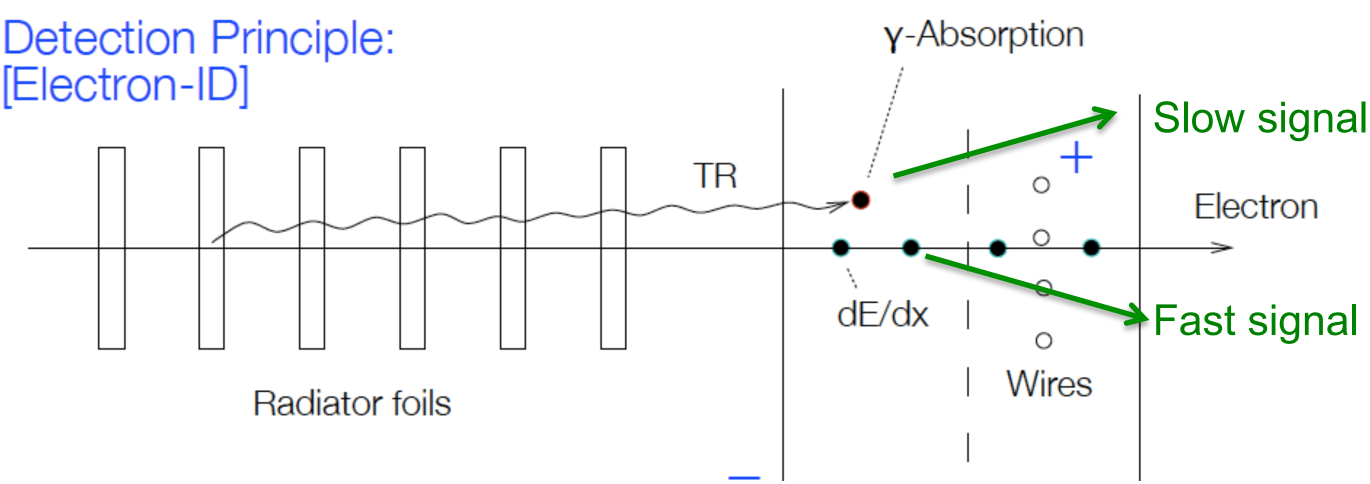
Measurement of particle velocity

- Transition radiation



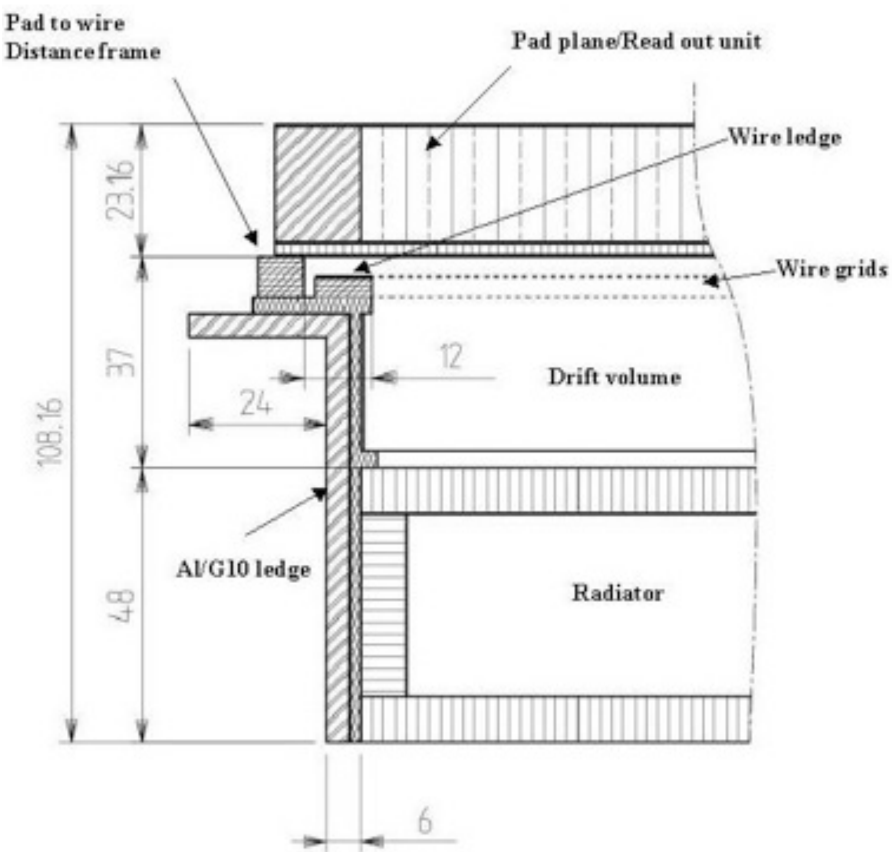
- Typical emission angle: $\Theta = 1/\gamma$
- Energy of radiated photons: $\sim \gamma$
- Number of radiated photons: αz^2
- Effective threshold: $\gamma > 1000$

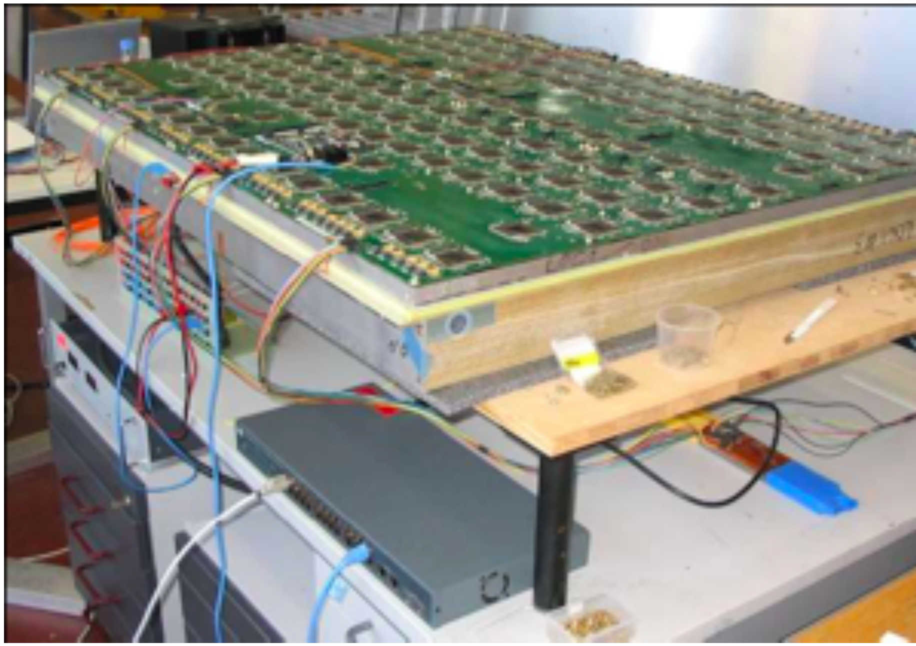
Detection Principle:
[Electron-ID]



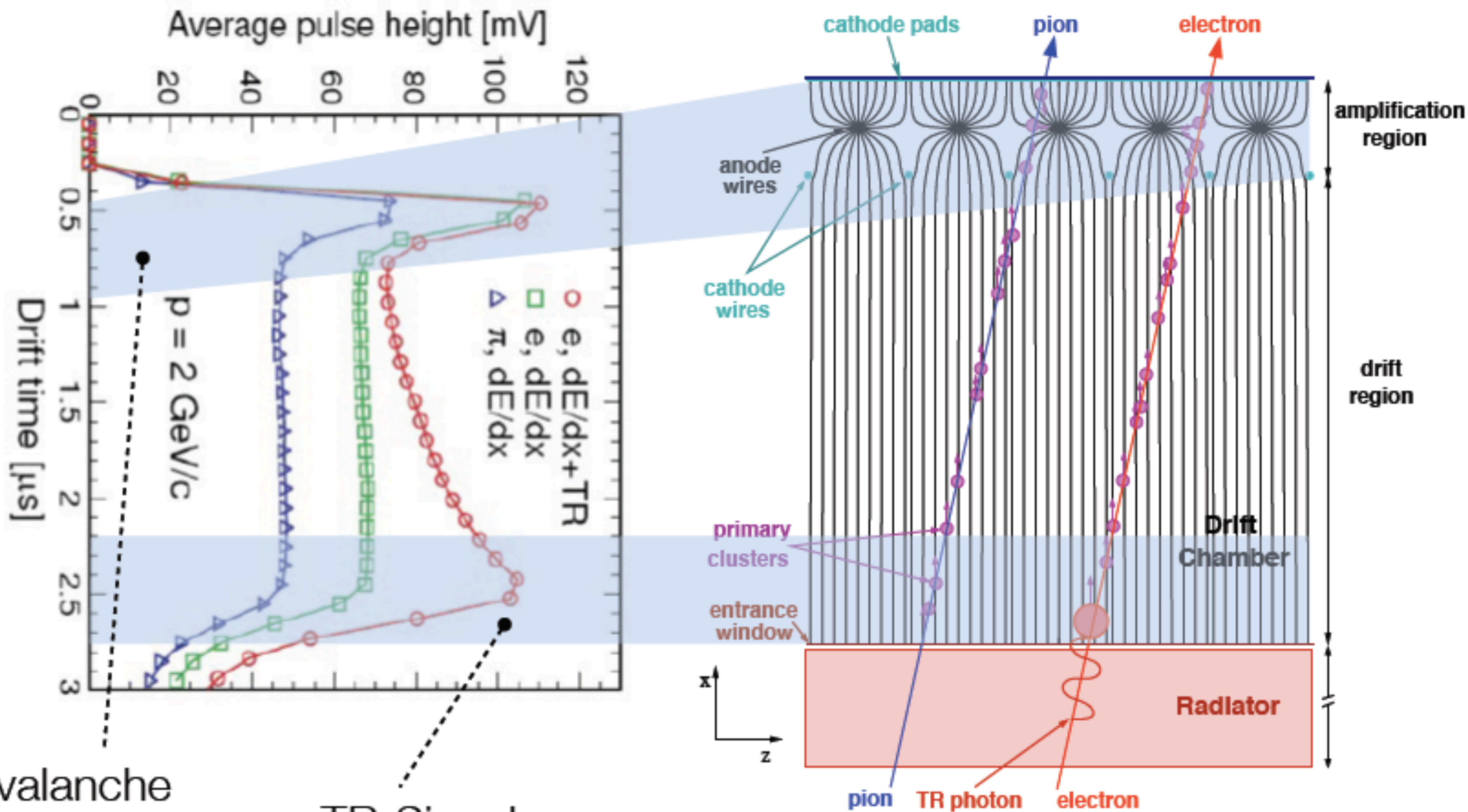
Note: Only X-ray (E>20keV) photons can traverse the many radiators without being absorbed

Transition radiation detectors - ALICE





Transition radiation detectors - ALICE



Avalanche

near anode wires
[high field]

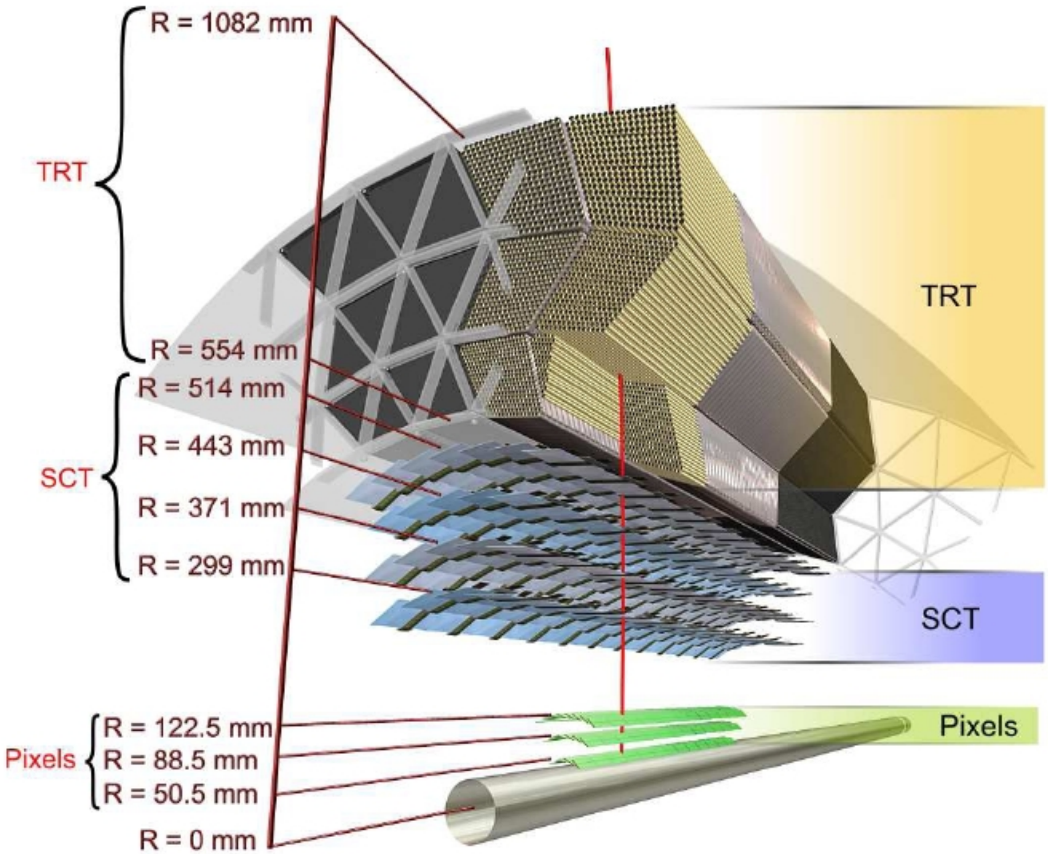
TR-Signal

Gas: Xenon
[High γ-absorption]

Transition Radiation [TR]

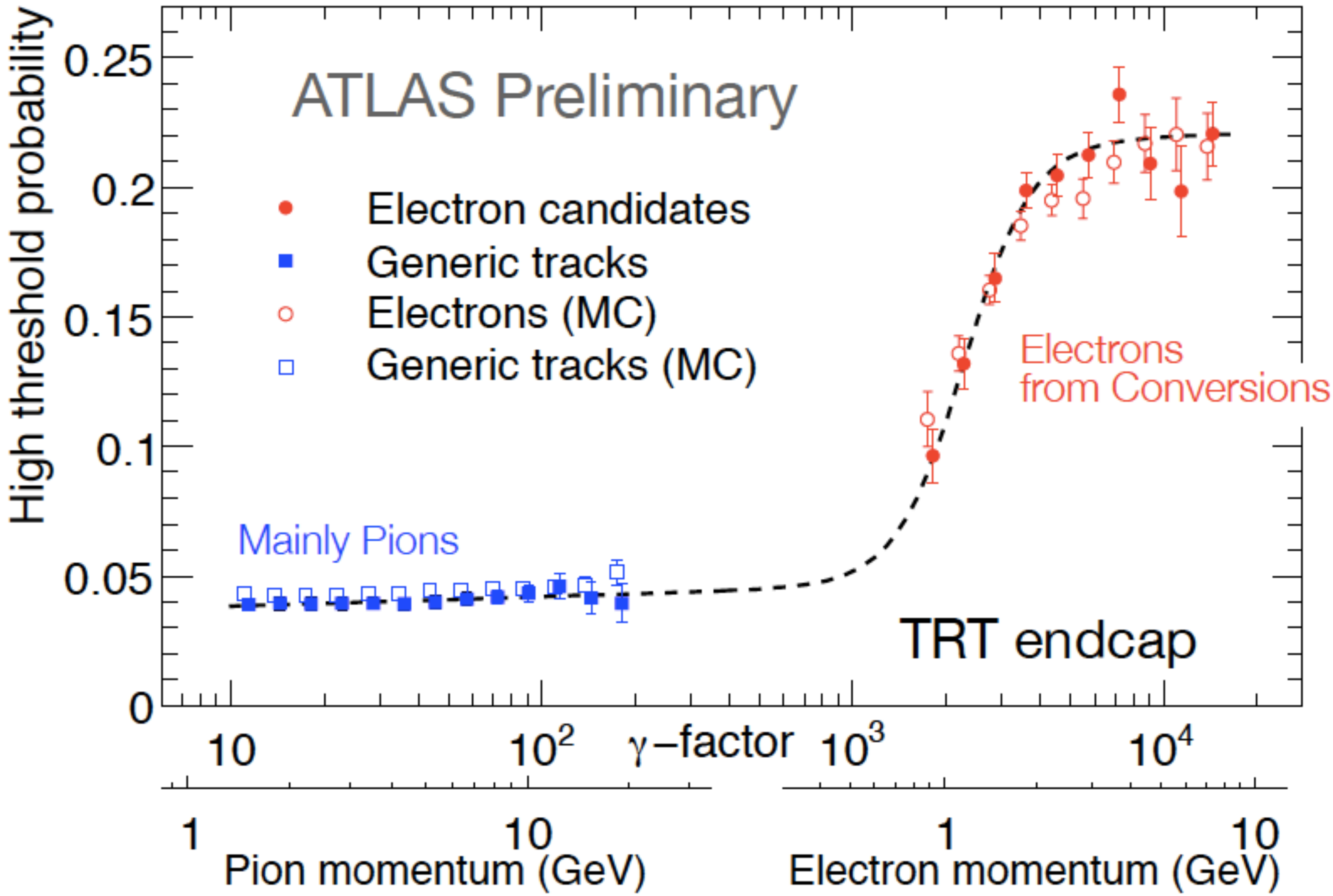
for charged Particles with $\gamma > 1000$

Transition radiation detectors - ATLAS



- straw tubes with xenon-based gas mixture
- 4 mm in diameter, equipped with a 30 μm diameter gold-plated W-Re wire

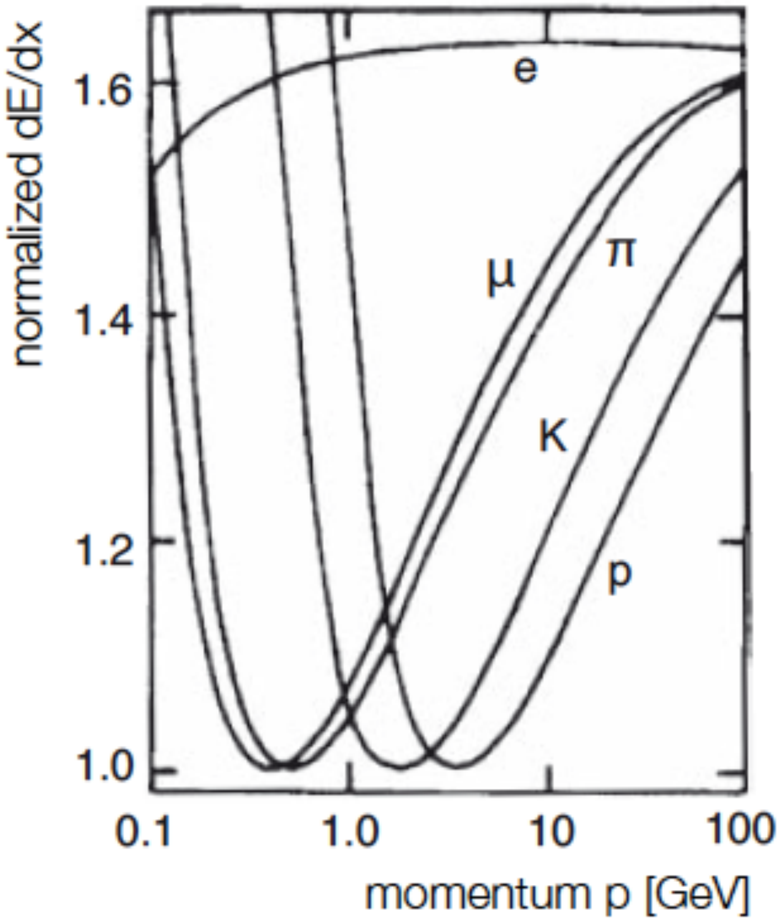
Transition radiation detector (ATLAS)



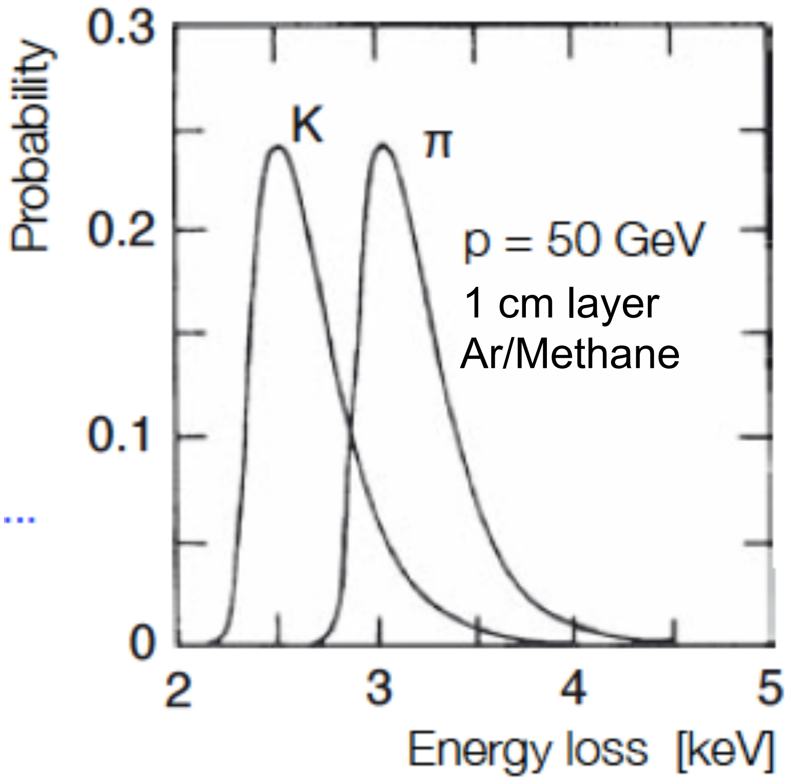
Measurement of particle velocity

- dE/dx – ionization losses

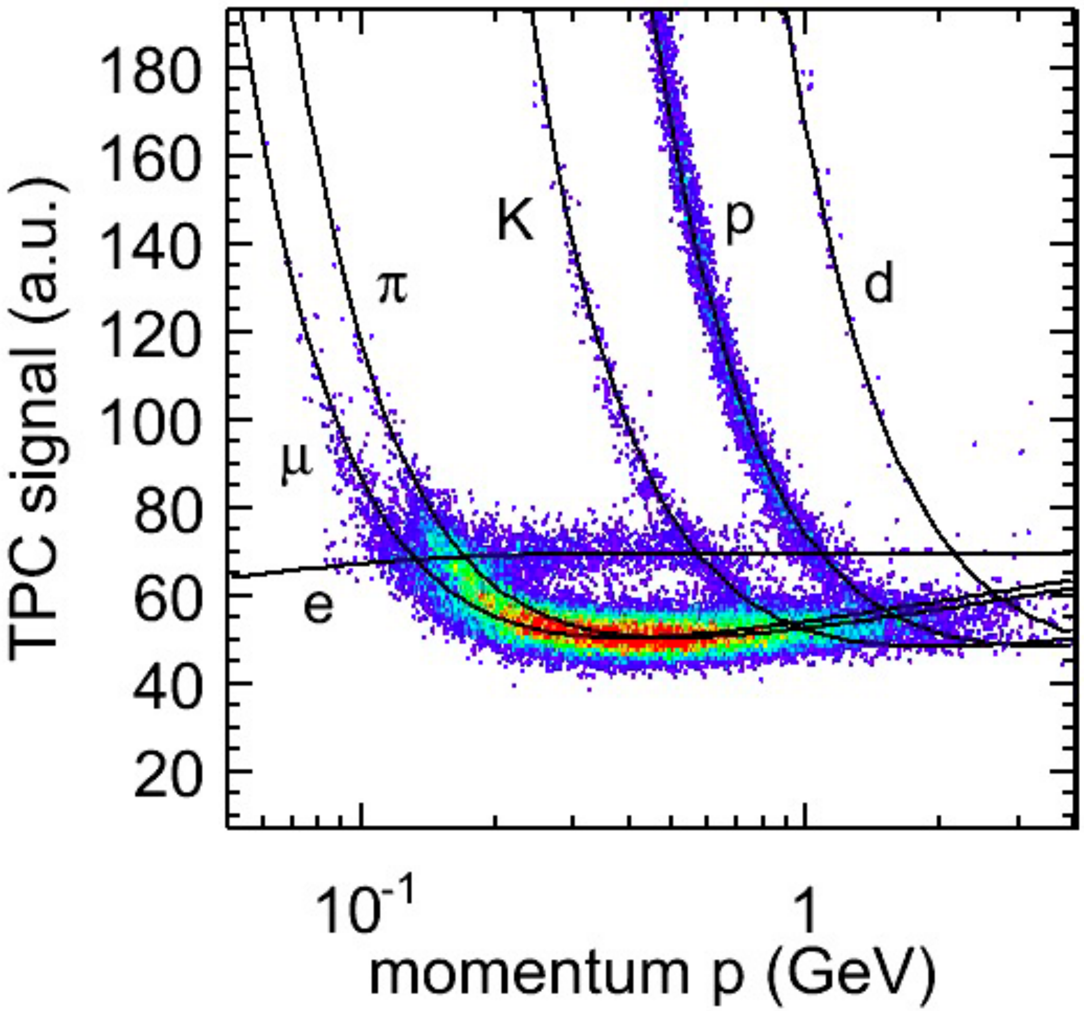
Use relativistic rise of dE/dx for PID
μ/π separation impossible, but
π/K/p generally be achievable
Key problem: Landau fluctuations



...



dE/dx method



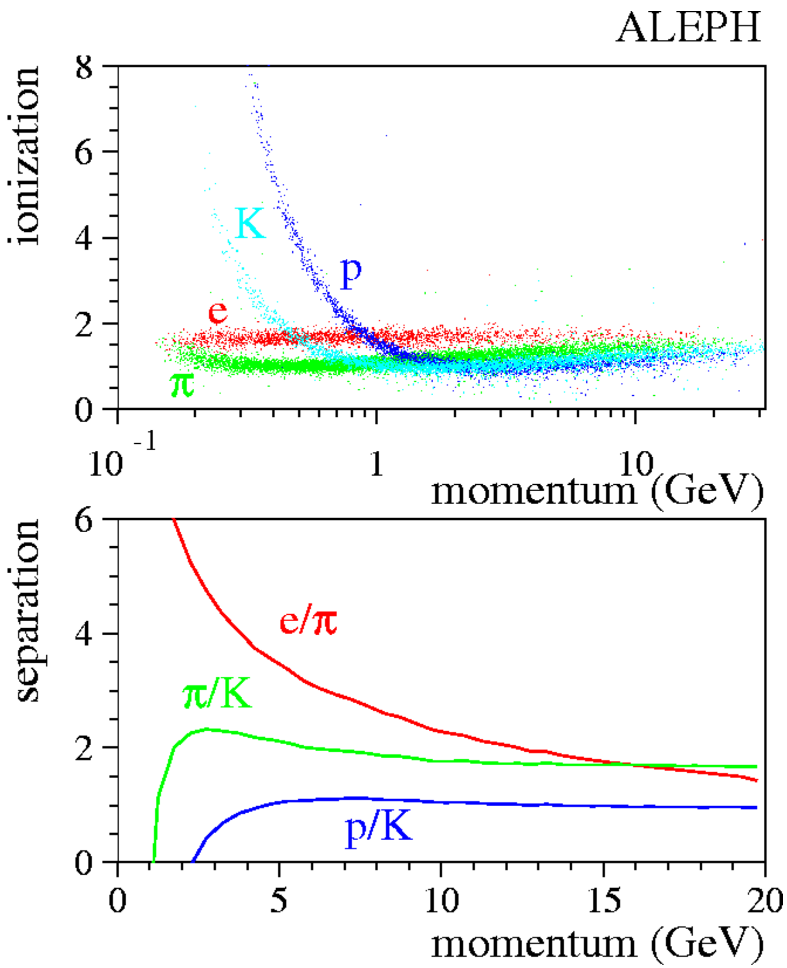
Energy loss measurement in ALICE TPC, 2009

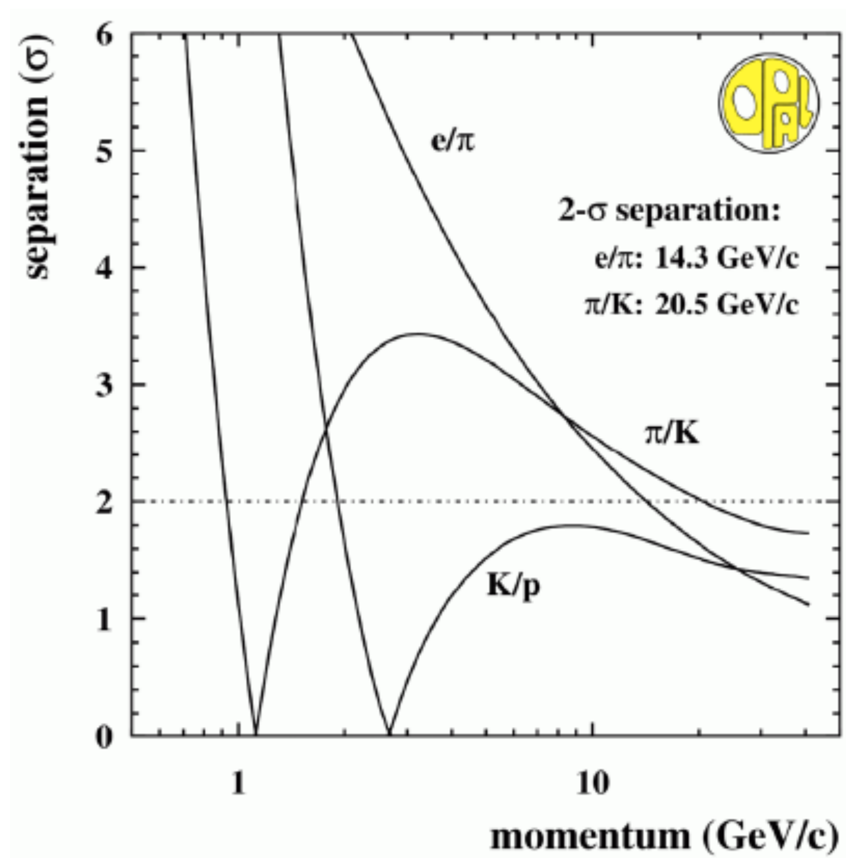
dE/dx is proportional to the particle velocity:

$$\frac{dE}{dx} \propto \frac{Z^2}{\beta^2} \ln\left(a\beta^2\gamma^2\right)$$

dE/dx - separation power

$$W_s = \frac{\left|dE/dx\right|_A - \left|dE/dx\right|_B}{\sigma(dE/dx)}$$

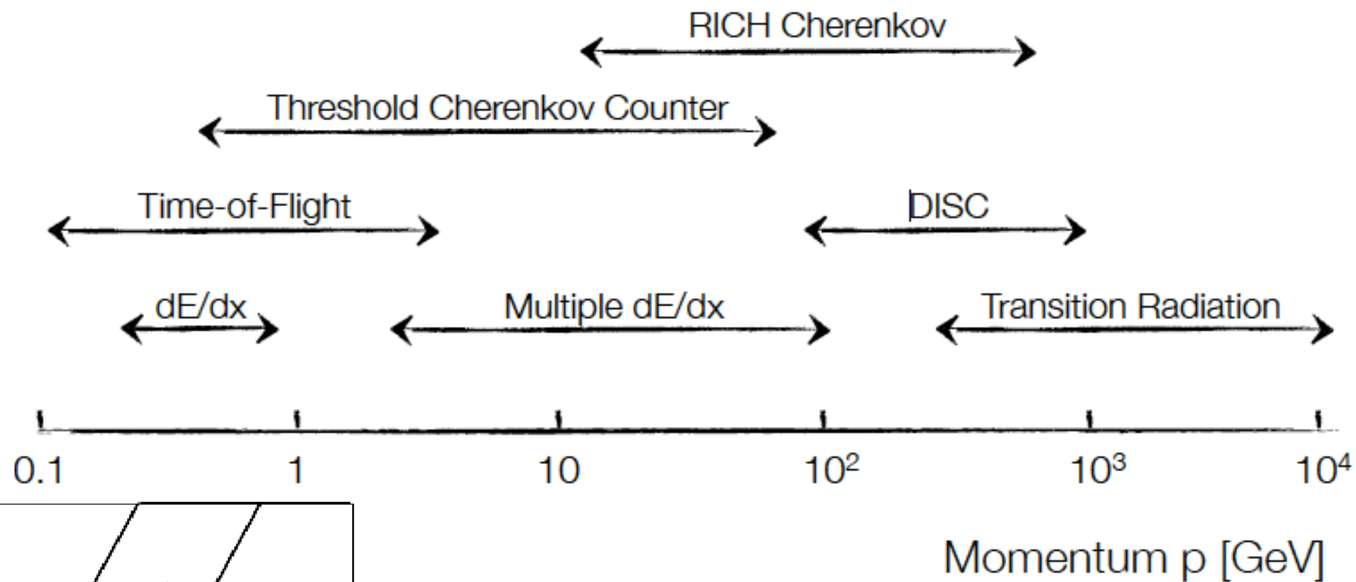


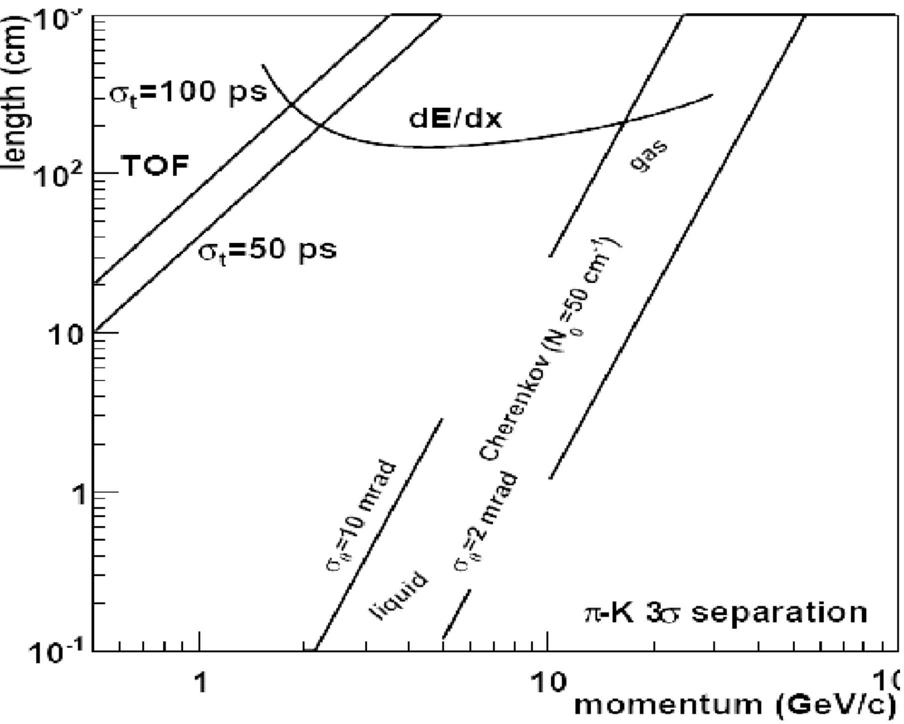


PID by dE/dx never reaches a good particle separation

PID methods - compare

π/K Separation with different PID methods



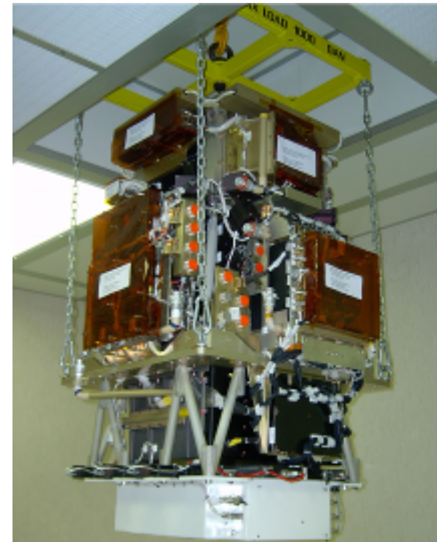


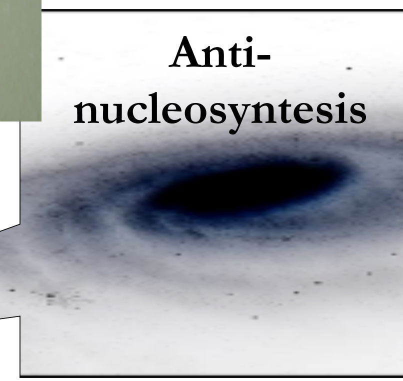
Alternatively topological techniques can be used …

PID in space experiments

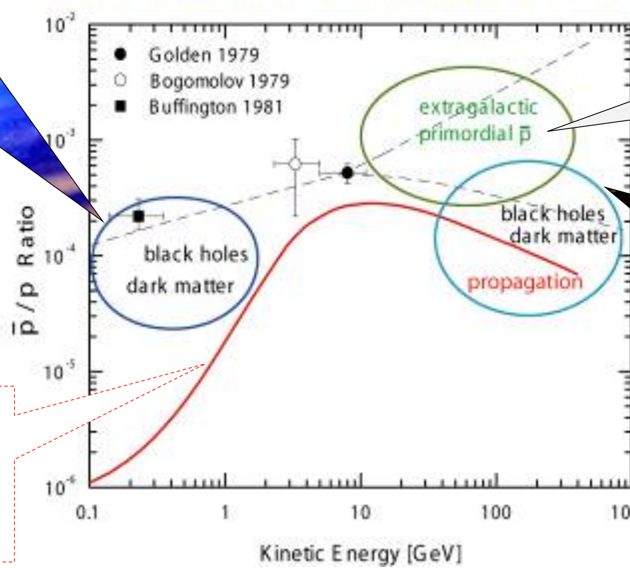
Pamela’s scientific objectives

- ✓ Study antiparticles in cosmic rays
- ✓ Search for antimatter
- ✓ Search for dark matter (e^+ and pbar spectra)
- ✓ Study cosmic-ray propagation
- ✓ Study solar physics and solar modulation
- ✓ Study the electron spectrum (local sources?)





The first historical measurements of the $\bar{p}/p$ - ratio and various Ideas of theoretical Interpretations



Background:
CR interaction with ISM
CR + ISM → p-bar + …

PAMELA milestones

Launch from Baikonur: June 15th 2006, 0800 UTC.

Power On: June 21st 2006, 0300 UTC.

Detectors operated as expected after launch

PAMELA in continuous data-taking mode since commissioning phase ended on July 11th 2006

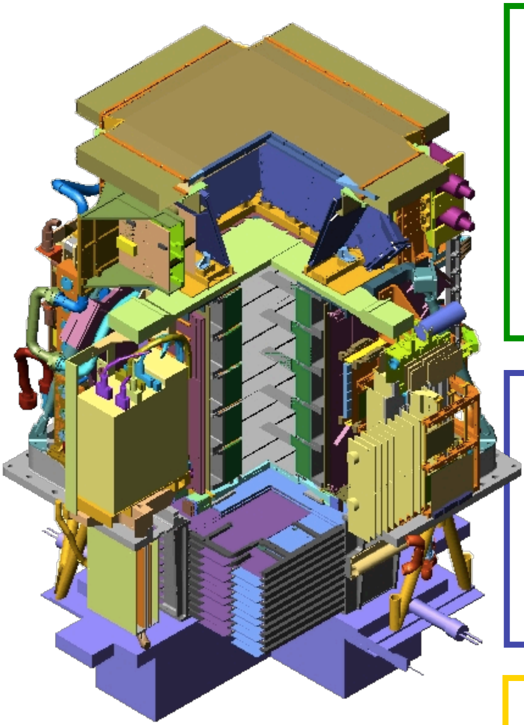
As of now:

- 1128 days in orbit
- Trigger rate ~ 25 Hz
- Data taking ~73% live-time
- >13 TByte of raw data downlinked
- $>10^9$ triggers recorded and under analysis

	Energy range
Antiprotons	80 MeV - 190 GeV
Positrons	50 MeV – 300 GeV

PAMELA detectors

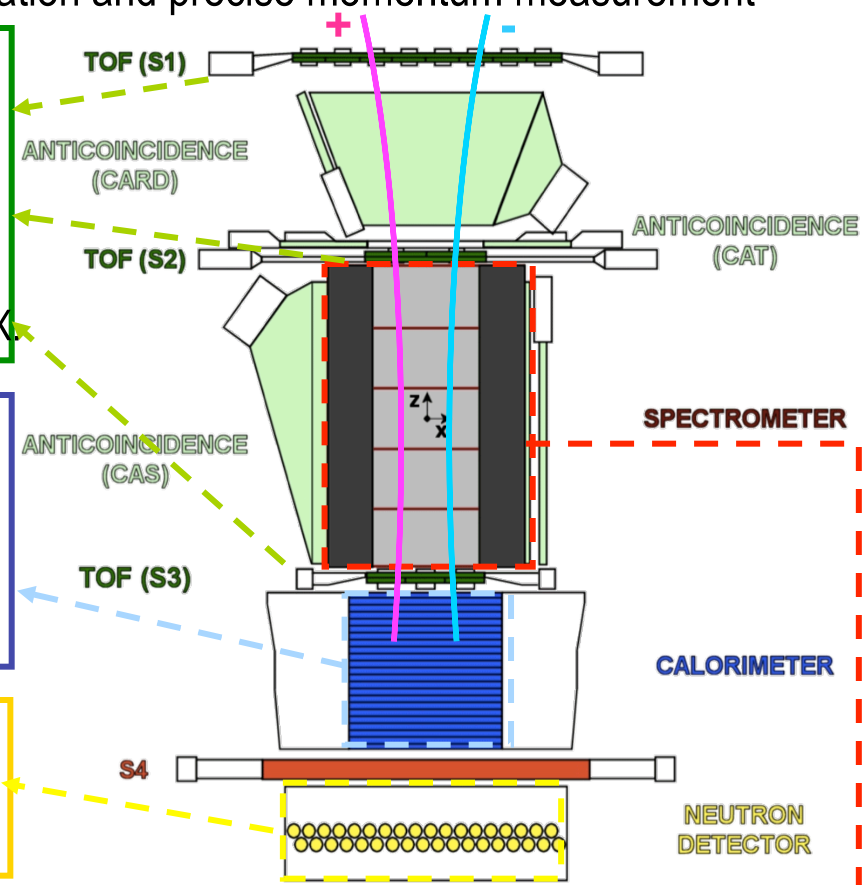
Main requirements → high-sensitivity antiparticle identification and precise momentum measurement



<u>Time-Of-Flight</u>
plastic scintillators + PMT:
- Trigger
- Albedo rejection;
- Mass identification up to 1 GeV;
- Charge identification from dE/dX

<u>Electromagnetic calorimeter</u>
W/Si sampling (16.3 X0, 0.6 λI)
- Discrimination e+ / p, anti-p / e^- (shower topology)
- Direct E measurement for e^-

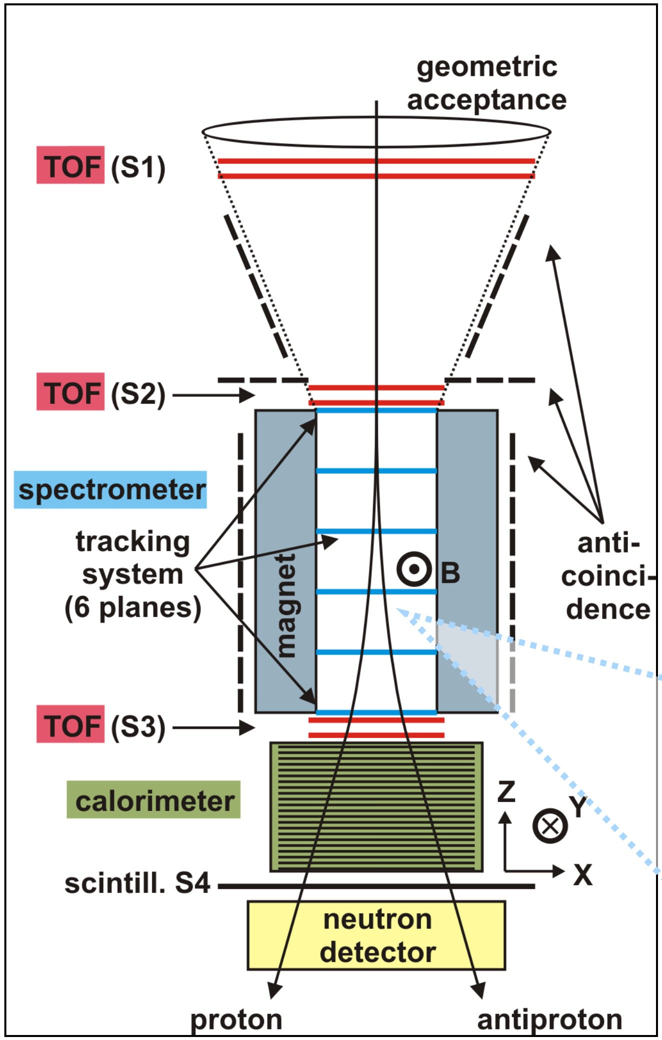
<u>Neutron detector</u>
^{3}He Tubes:
- High-energy e/h discrimination



GF: 21.5 cm^2 sr
Mass: 470 kg
Size: 130x70x70 cm^3
Power Budget: 360W

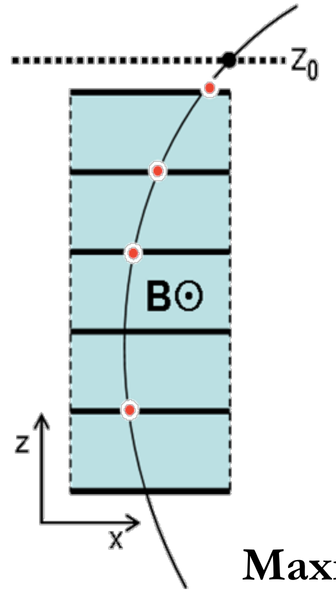
<u>Spectrometer</u>
microstrip silicon tracking system + permanent magnet
It provides:
- ***Magnetic rigidity*** → R = pc/Ze
- ***Charge sign***
- ***Charge value from dE/dx***

Principle of operation



Track reconstruction

$\alpha = (x_0, y_0, \sin\theta, \phi, \eta)$



Iterative χ^2 minimization as a function of track state-vector components α

Magnetic deflection

$|\eta| = 1/R$

R = pc/Ze → **magnetic rigidity**

$\sigma_R/R = \sigma_\eta/\eta$

Maximum Detectable Rigidity (MDR)

def: @ R=MDR ⇒ $\sigma_R/R=1$

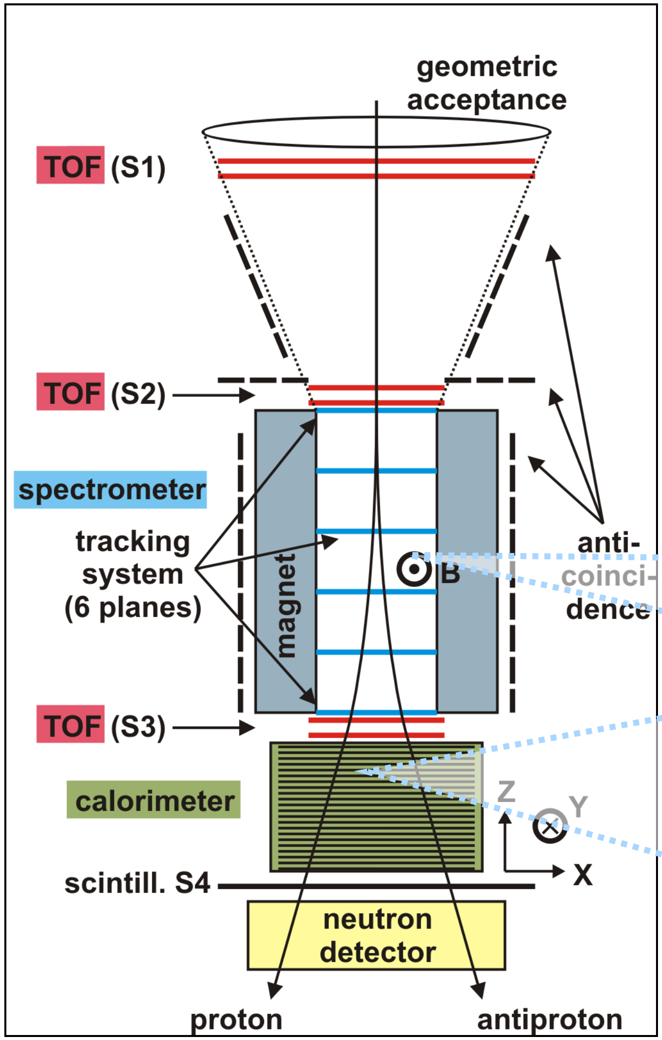
$\mathbf{MDR = 1/\sigma_\eta}$

•Measured @ground with protons of known momentum

→ **MDR~1TV**

•Cross-check in flight with protons (alignment) and electrons (energy from calorimeter)

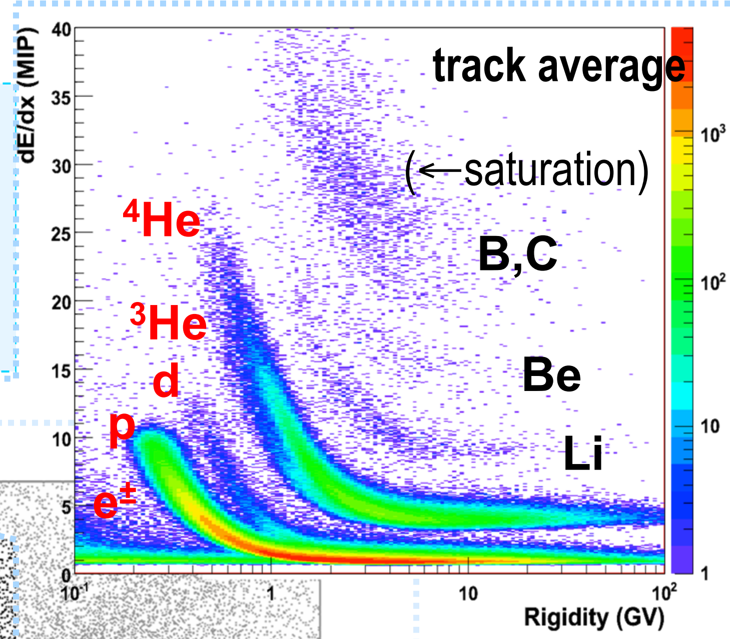
Principle of operation

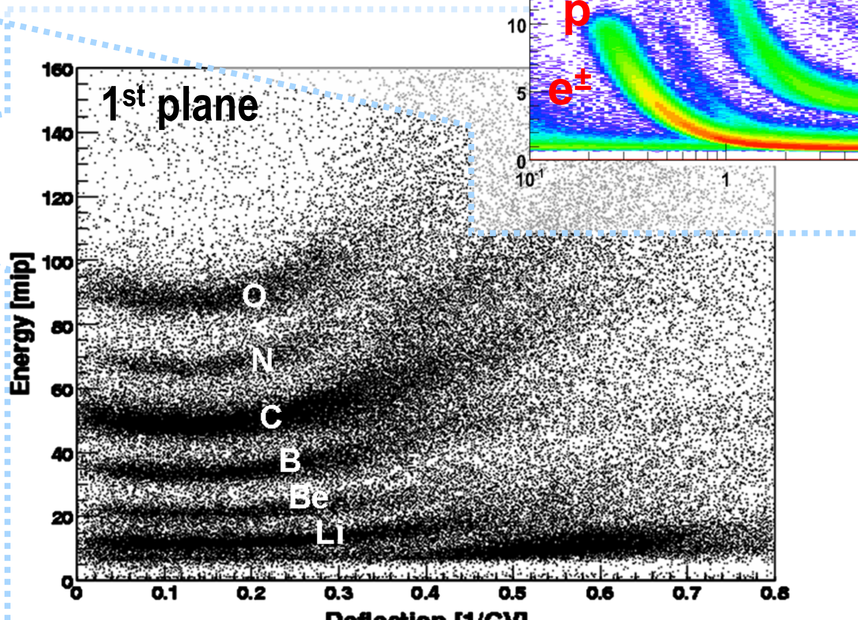


Z measurement

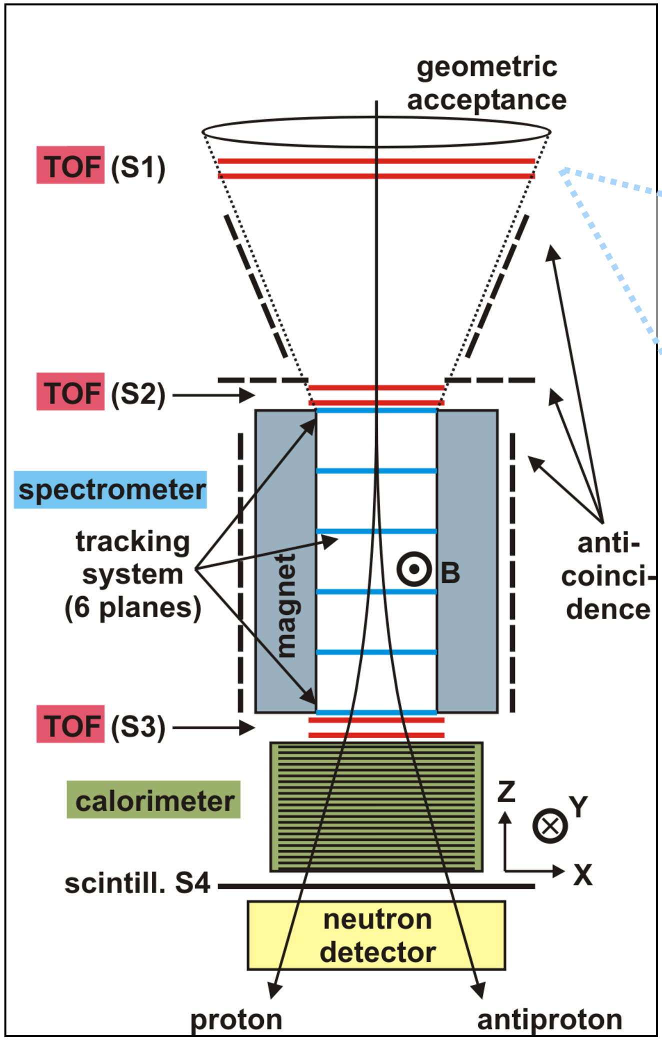
$$-\frac{dE}{dx} = K z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

Bethe Bloch
ionization energy-loss
of heavy (M>>me)
charged particles

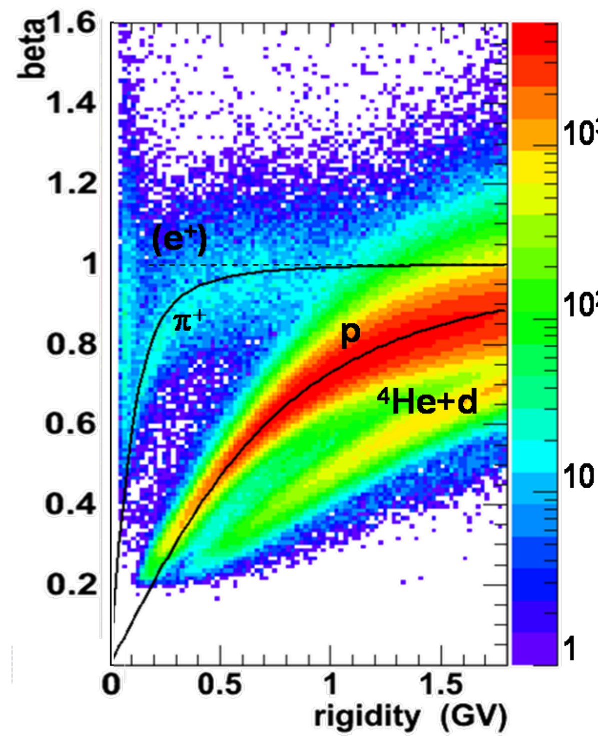




Principle of operation



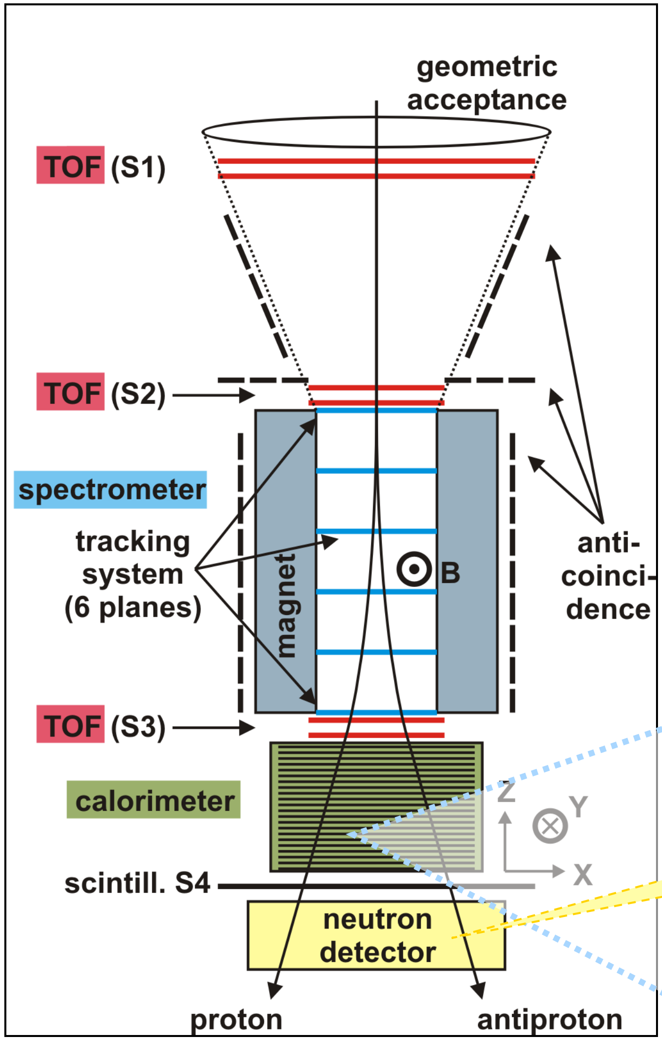
Velocity measurement



- Particle identification @ low energy
- Identify **albedo** (up-ward going particles →**β < 0**)

→ NB! They mimic antimatter!

Principle of operation

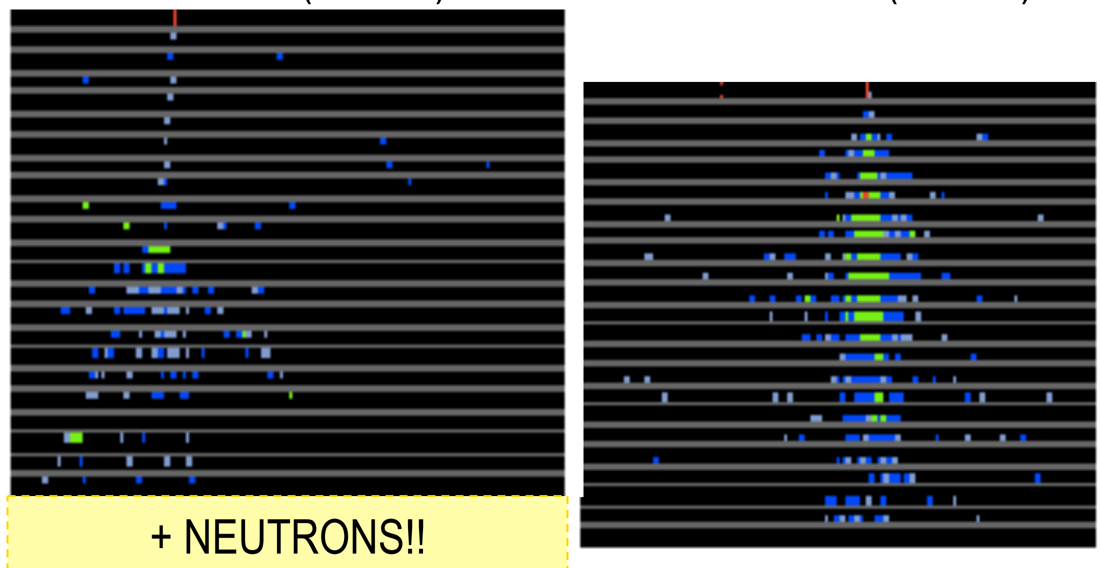


Electron/hadron separation

- **Interaction topology**

e/h separation

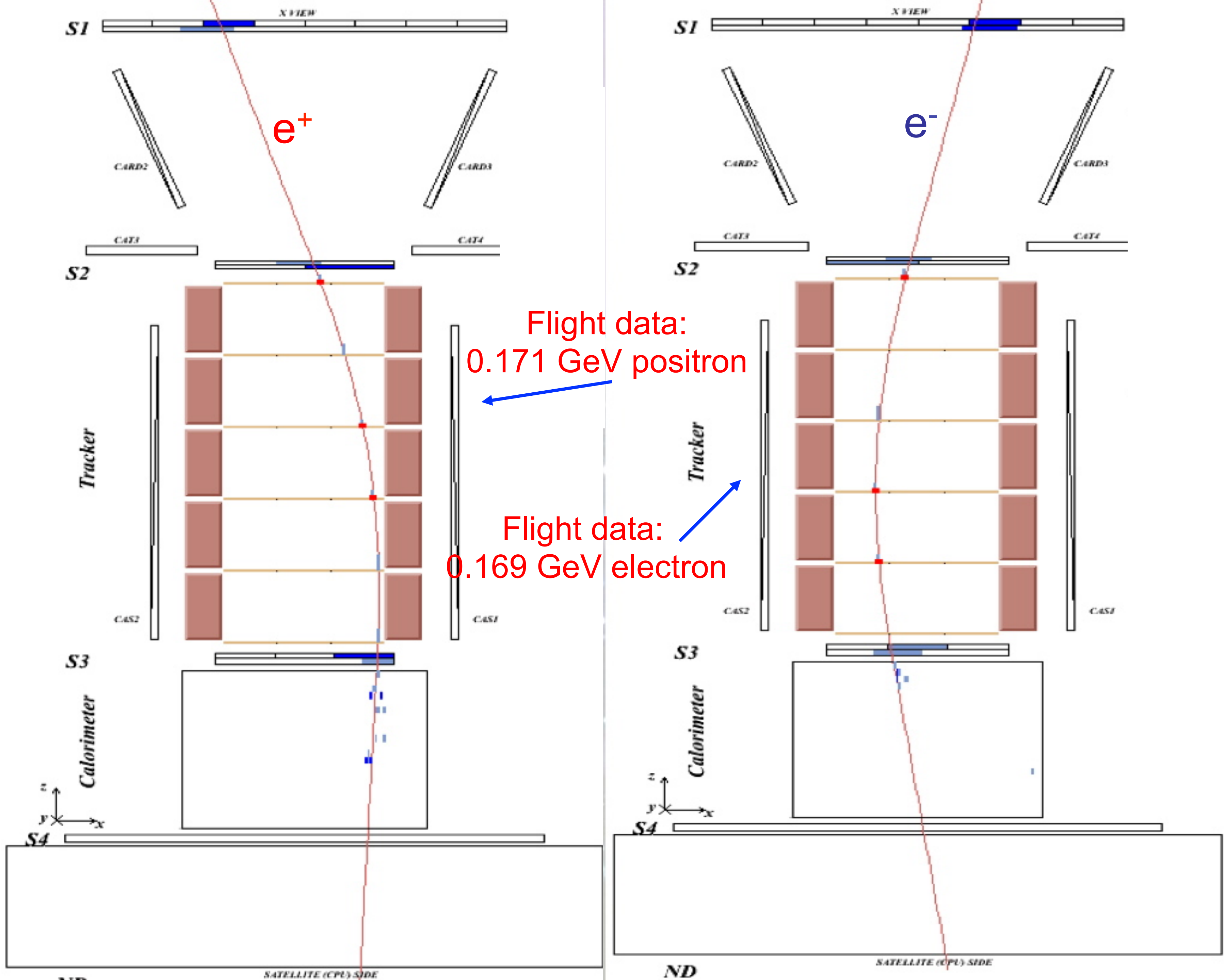
hadron (19GeV) electron (17GeV)



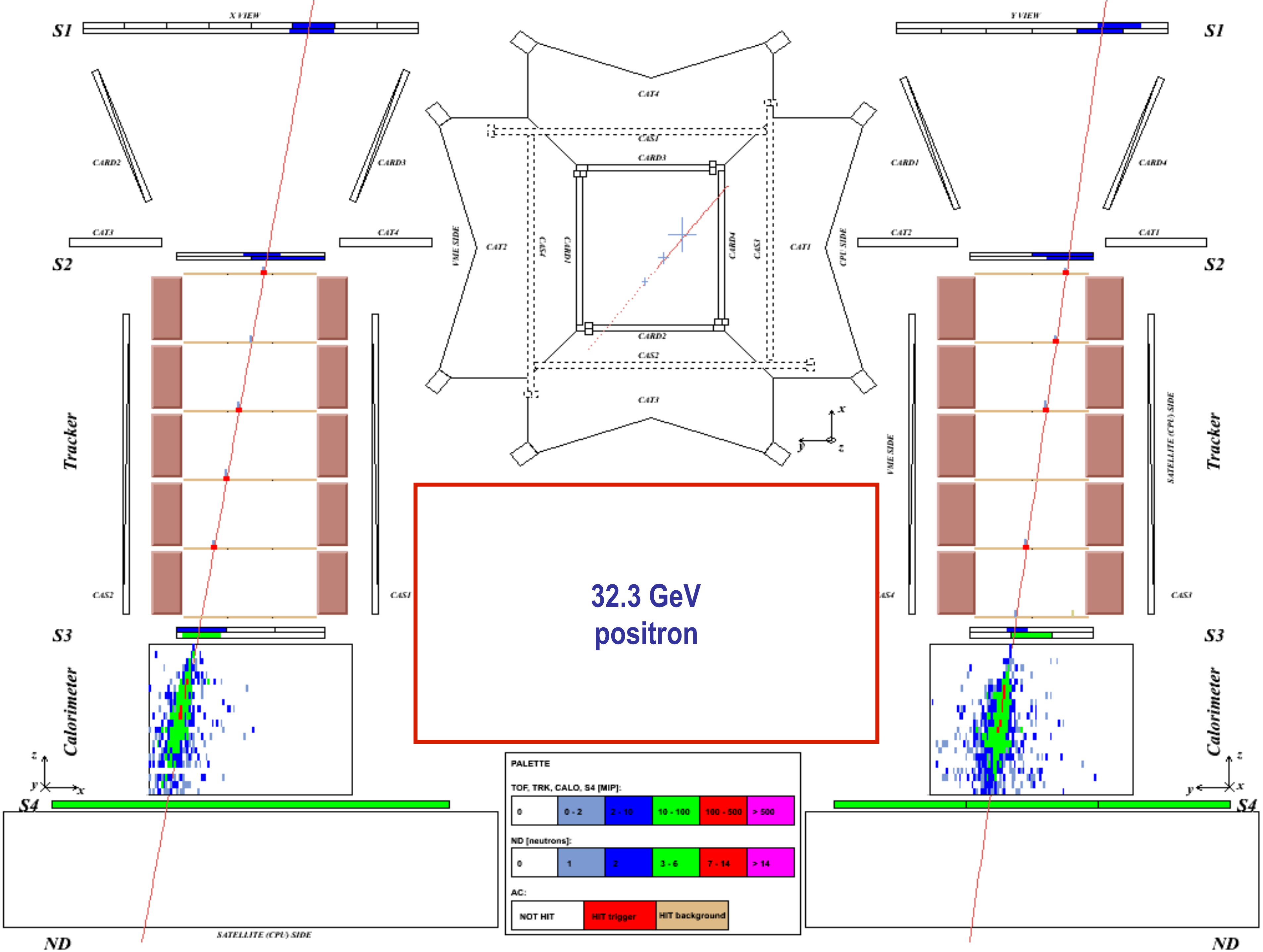
- **Energy measurement of electrons and positrons**

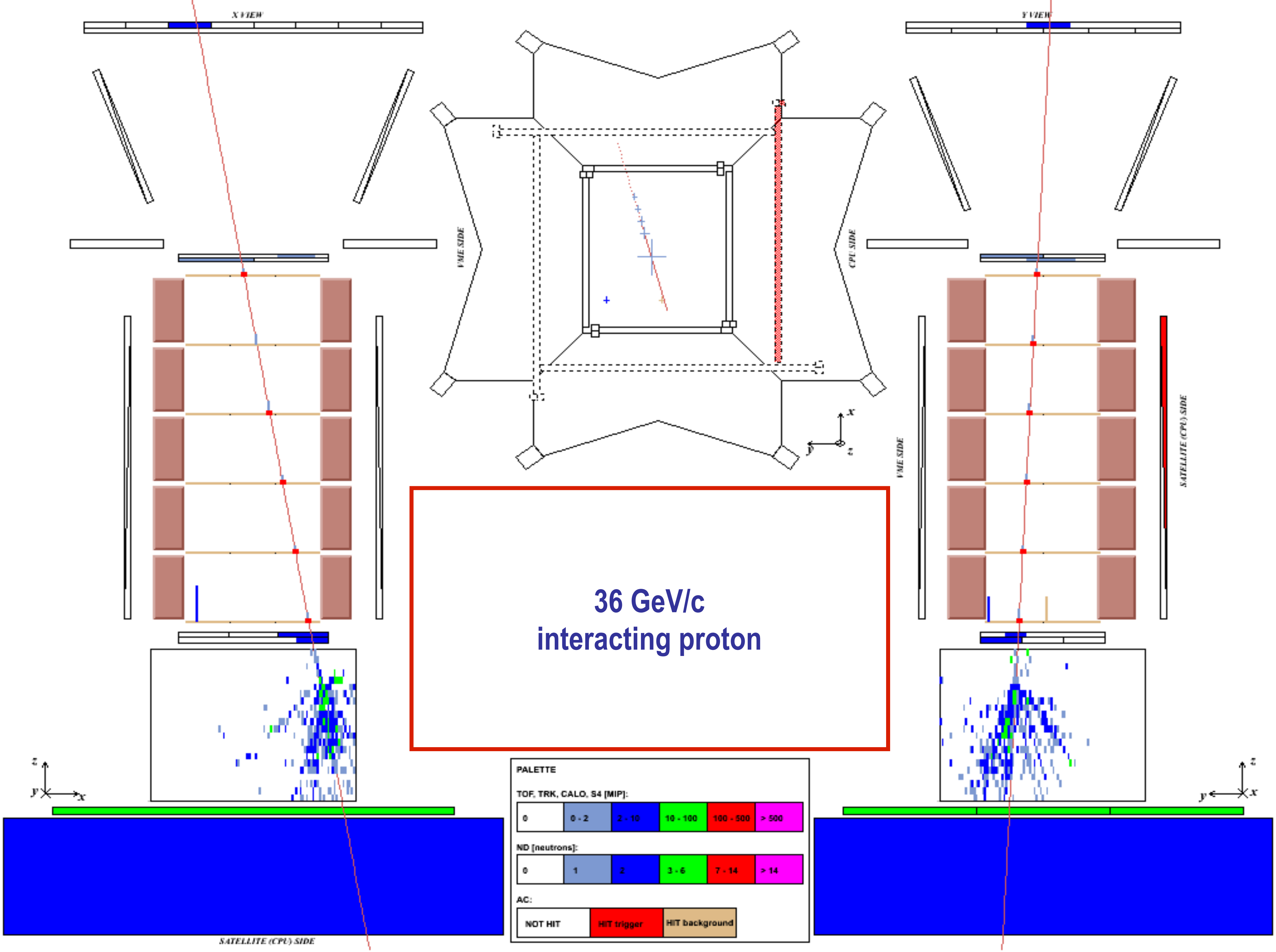
(~full shower containment)

$$\frac{\sigma_E}{E} = a \oplus \frac{b}{\sqrt{E}} \quad \rightarrow a < 5\%$$

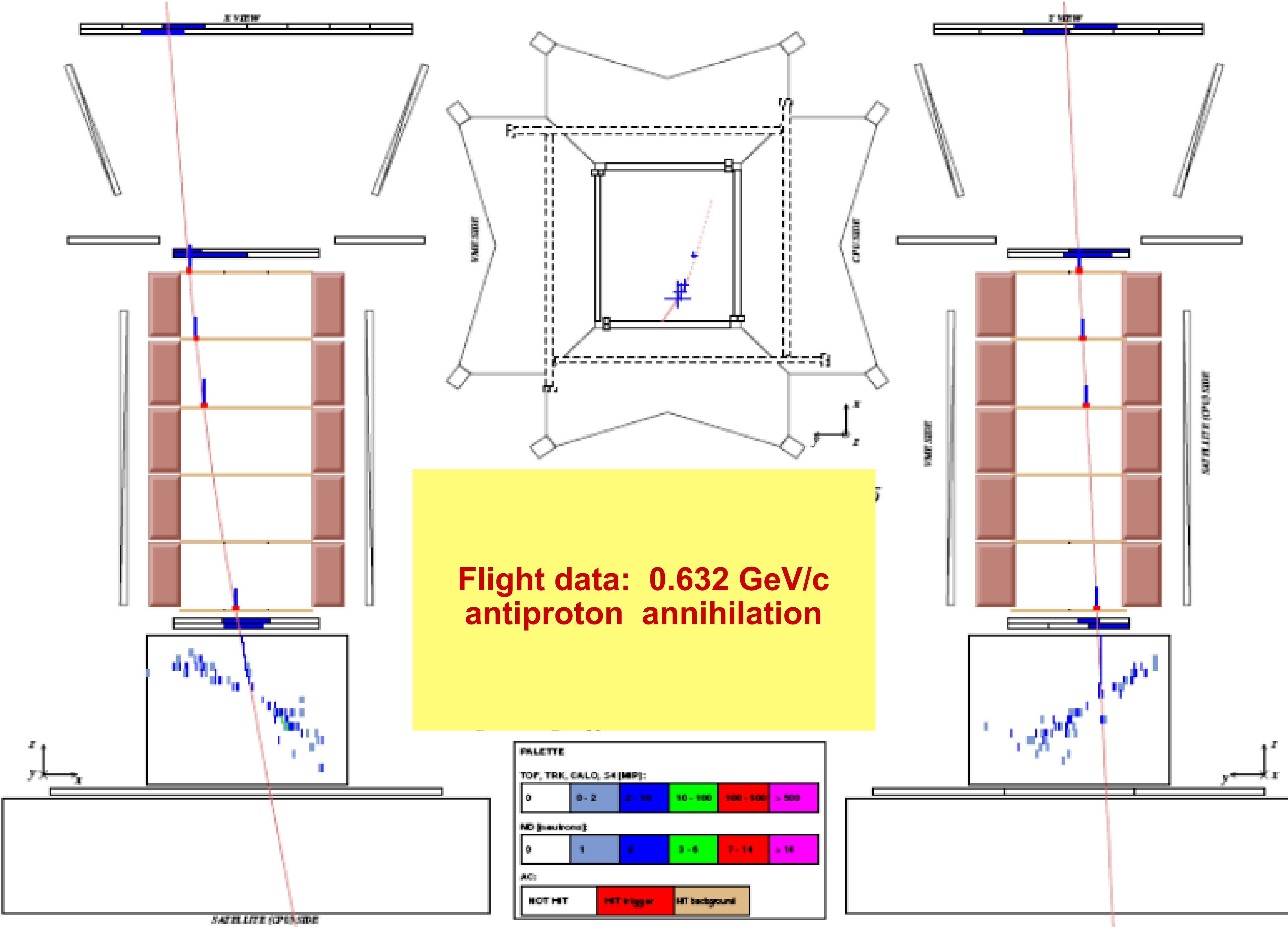


X VIEW
S1
e+
e-
CARD2
CARD3
CAT3
CAT4
S2
Tracker
CAS2
CAS1
S3
Calorimeter
S4
ND
SATELLITE (CPU) SIDE
Flight data:
0.171 GeV positron
Flight data:
0.169 GeV electron


32.3 GeV
positron
X VIEW
Y VIEW
S1
S2
S3
S4
ND
Tracker
Calorimeter
CARD1
CARD2
CARD3
CARD4
CAT1
CAT2
CAT3
CAT4
CAS1
CAS2
CAS3
CAS4
VME SIDE
CPU SIDE
SATELLITE (CPU) SIDE
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background



X VIEW
Y VIEW
VME SIDE
CPU SIDE
VME SIDE
SATELLITE (CPU) SIDE
SATELLITE (CPU) SIDE
36 GeV/c
interacting proton
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background



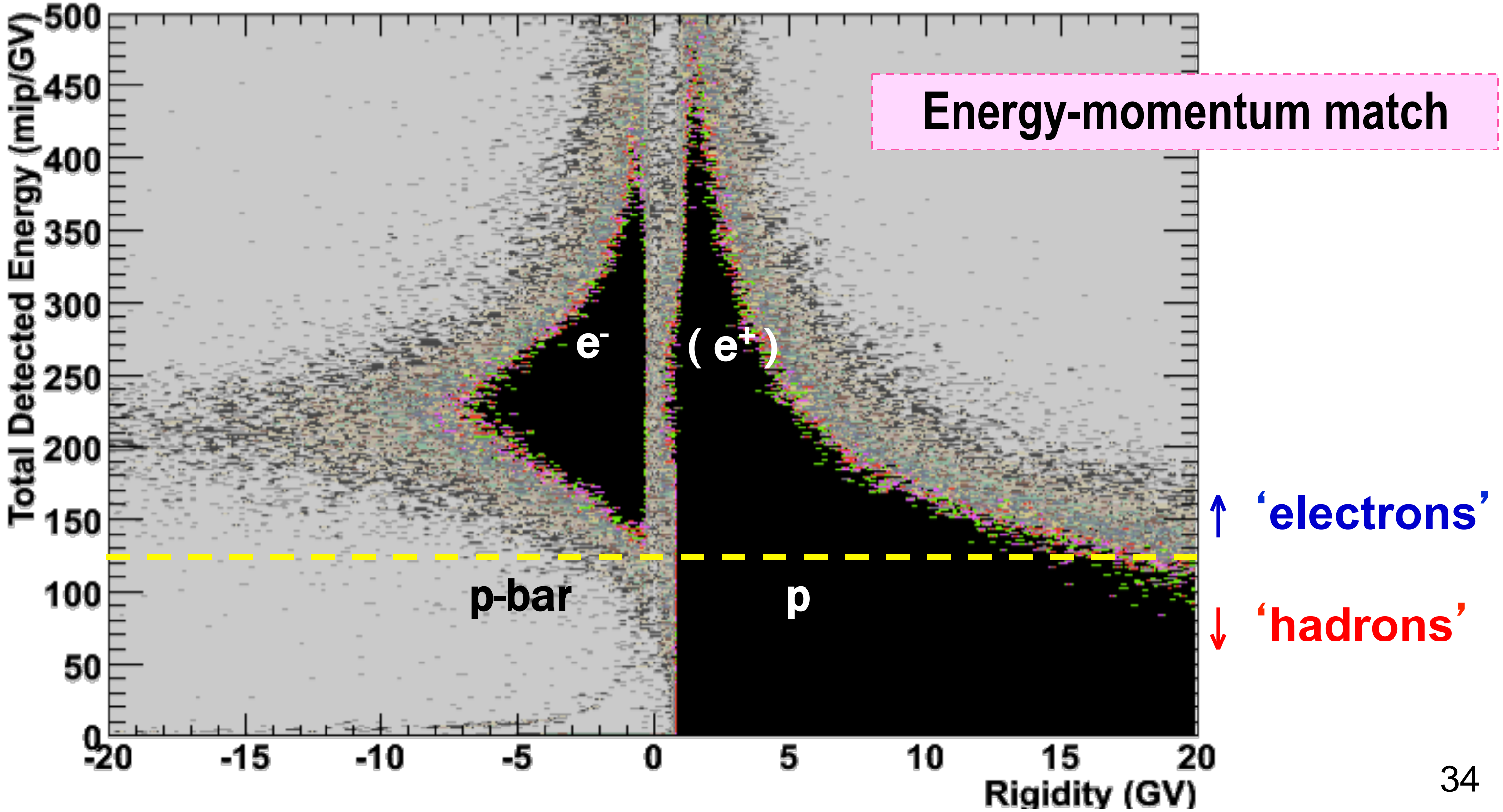
X VIEW
Y VIEW
Flight data: 0.632 GeV/c
antiproton annihilation
PALETTE
TOF, TRK, CALO, S4 [MIP]:
0
0 - 2
2 - 10
10 - 100
100 - 500
> 500
ND [neutrons]:
0
1
2
3 - 6
7 - 14
> 14
AC:
NOT HIT
HIT trigger
HIT background
SATELLITE (CPU) SIDE

Positron identification

The main difficulty for the positron measurement is the **interacting-proton background**:

• fluctuations in hadronic shower development ⇒ $\pi_0 \rightarrow \gamma\gamma$ might mimic pure EM showers

• proton spectrum harder than positron ⇒ p/e^+ increase for increasing energy

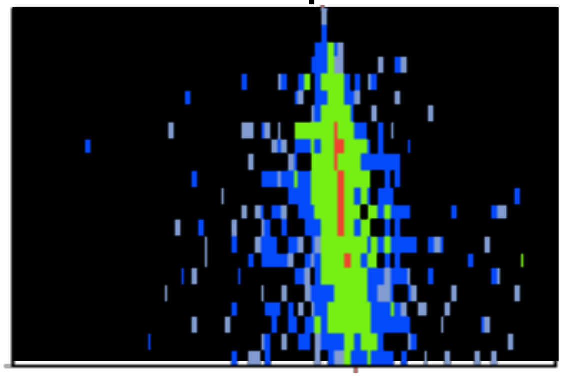


High energy positron analysis

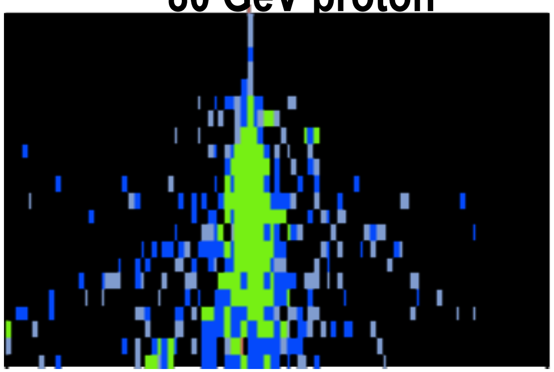
Particle Identification based on calorimeter response:

- **Shower topology**
  - lateral and longitudinal profile
  - shower starting point
- **Total detected energy**
  - energy-rigidity match

51 GeV positron



80 GeV proton



Analysis key points:

- **Tuning/check of selection criteria with:**

  test-beam data / simulation / flight data

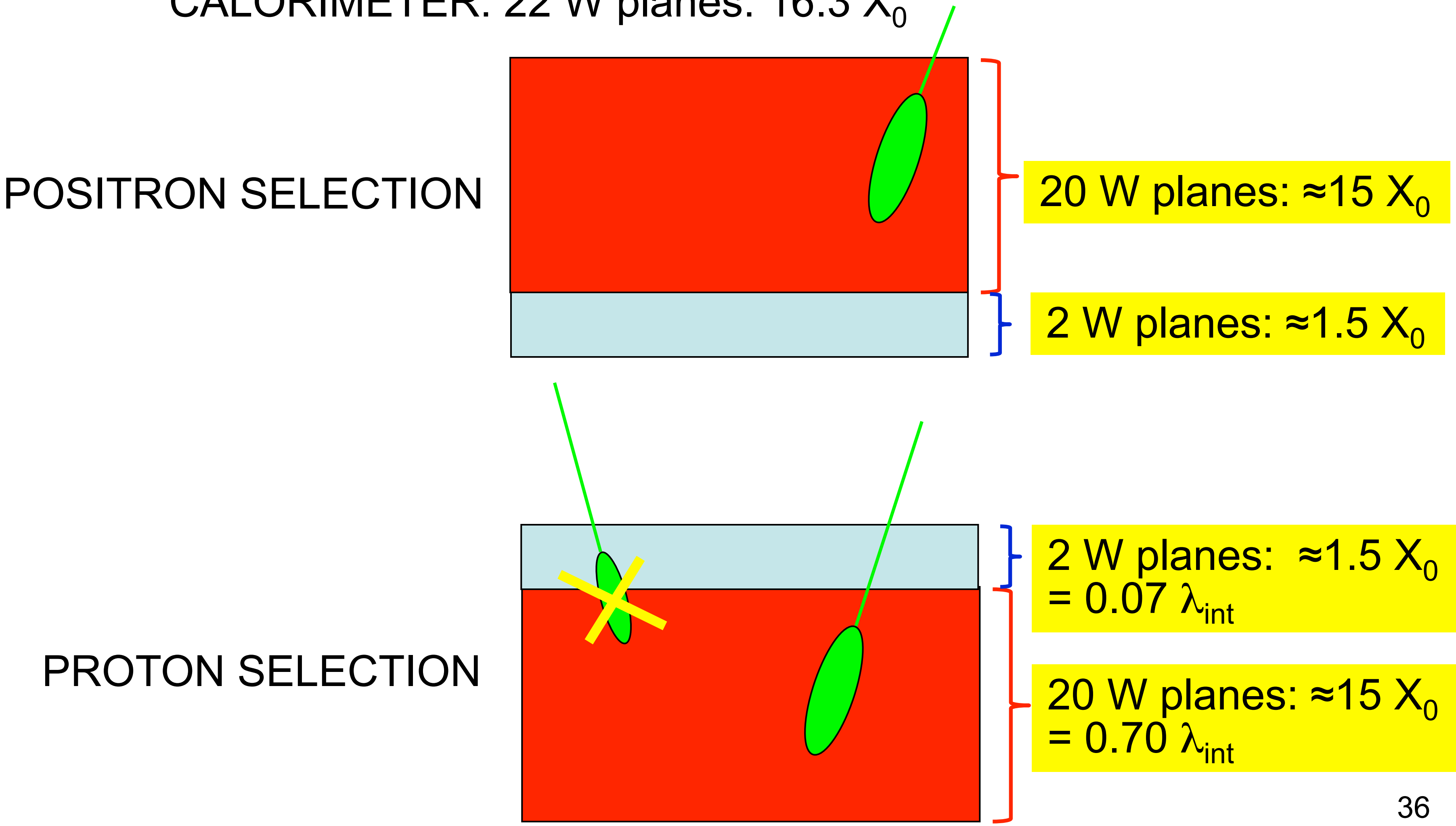
  Selection of pure proton sample from flight data ("pre-sampler" method)

Final results make <u>NO USE</u> of test-beam and/or simulation calibrations.
The measurement is based only on flight data
with the <u>background-estimation</u> method

The “pre-sampler” method

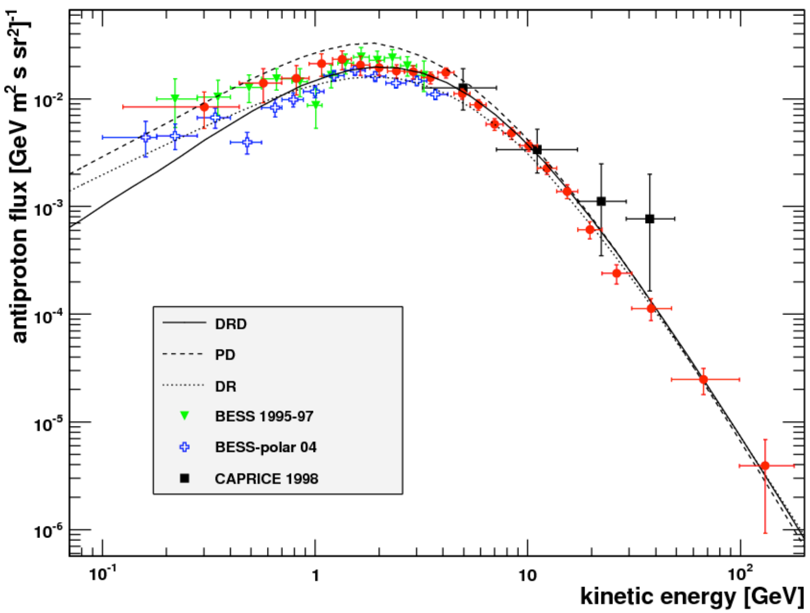
Selection of a pure sample of protons from flight data

CALORIMETER: 22 W planes: 16.3 X_0

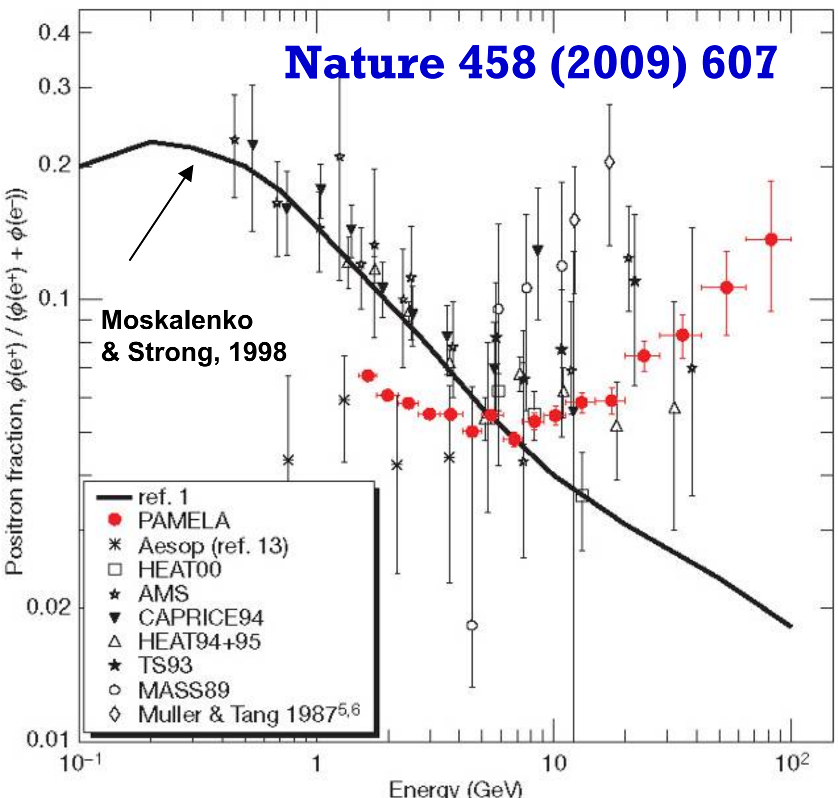


Measuring anti-matter

Antiprotons



Positrons



Antiproton flux (~0.1 GeV ÷180 GeV)

➔ no evident deviations from secondary expectations

Positron charge ratio (~1 GeV ÷100 GeV)

➔ Clear excess with respect to secondary production models

More data to come at lower and higher energies (up to 300 GeV)