III. Physikalisches Institut A | RWTH AACHEN UNIVERSITY

Experimental Techniques in Particle Physics (WS 2020/2021)

Particle Identification

Prof. Alexander Schmidt

02.02.2021

schedule

- the time slots of the GEANT4 course on

  - Thursday 4th February and
  - Thursday 11th February

  will be used for the ongoing exercise (CMS data analysis tutorial).
  We will use the usual zoom link of the lecture:
  https://rwth.zoom.us/j/94827607276?pwd=RGYvRzdUbWhzNFZOb0szSUpDOXQ4UT09

- the last lecture will be Tuesday 9th February (topic: “some example applications and alternative particle detection techniques”)

- the written exam (Klausur) will take place **as planned** on 16. March at 14:00

- the planned location for the exam is still the physics lecture hall at Campus Melaten (28D001)

- we will notify you through Email (through moodle) in case location or date need to be changed

- the regulations may change on short notice 😕

- **you must be registered for the exam in RWTH online**

motivation for particle ID

- without knowing the type of particle, we don't know it's mass
- without the mass, we can't determine the full four-vector, and therefore not reconstruct decay chains

- methods for particle ID:

topological

- geometrical matchings
- event topology
- global properties of events

- not through a dedicated detector interaction

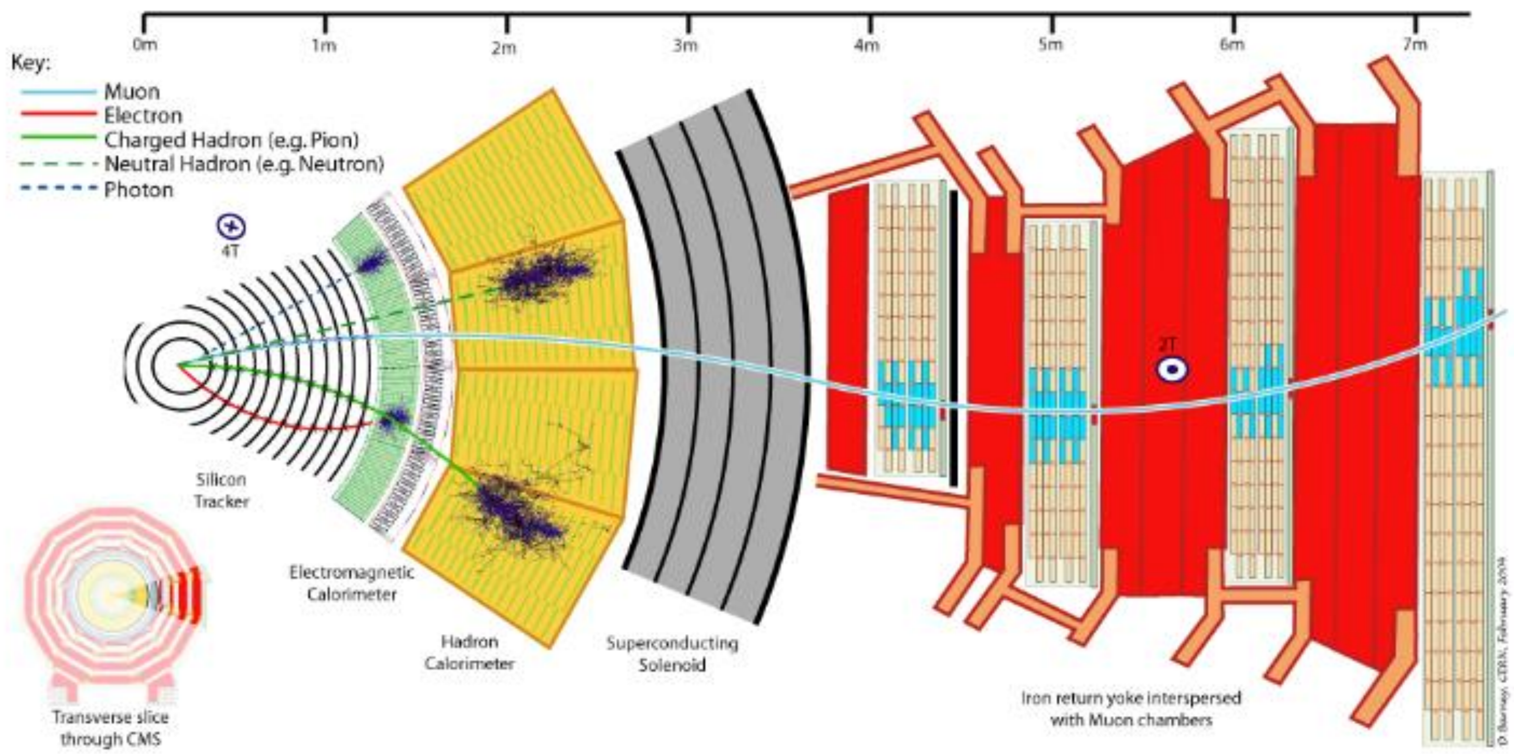
by means of certain properties

- time of flight
- ionisation properties
- Cerenkov radiation
- transition radiation

- these proceed through dedicated detector interactions

- these are understood as the classical "PID" methods

Particle Identification:



CMS-Collaboration

Multi-purpose detectors

- Tracking chamber
- Calorimeters
- Muon chamber

→ Identification of

- Photon: no track, electromagnetic cluster in calorimeters
- Electron: track, electromagnetic cluster in calorimeters
- Hadron: track, hadronic cluster in calorimeters
- Muon: track in muon chamber

all topological

But no distinction between pion, kaons and protons

The identification of these hadrons is here called PID („Particle ID")
In other detectors (e.g. neutrino detectors) also the PID
of other particles is needed (e.g. electron-muon distinction)

basic ingredients

~~All~~ methods for the PID of charged particles use their mass
Mass determination is possible by measuring two kinematic variables
Example: p and β

$$\Rightarrow m = p\sqrt{\frac{1}{\beta^2} - 1}$$

1. Momentum

Always one of the two kinematic parameters.

$\frac{\sigma_p}{p} \propto p$ Resolution $\sim 1\%$ at $10\ GeV$

Energy? $mc^2 = \sqrt{E^2 - p^2c^2}$

But calorimetric measurements much too unprecise for this purpose

2.a Velocity β

Usefull as long as particle is non relativistic:

- Time of flight: $\Delta t \propto 1/\beta$
- Specific ionisation: $dE/dx \propto 1/\beta^2$
- Cerenkov radiation: $\cos\theta_c \propto 1/\beta$

2.b Lorentz boost γ

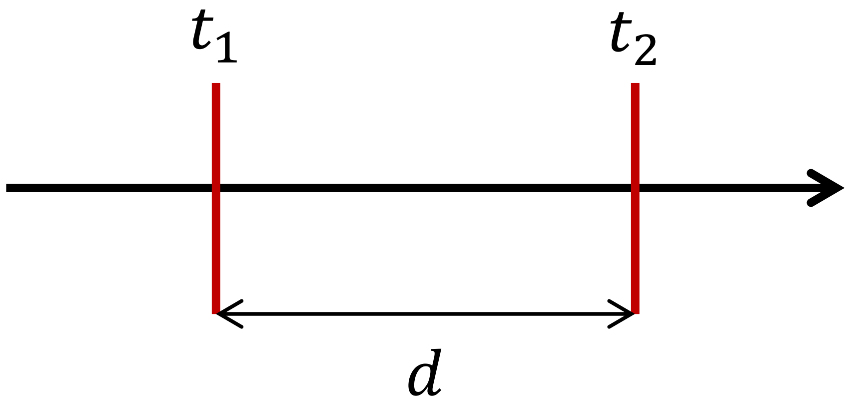
For relativistic particles

- Specific ionisation: $dE/dx \propto \ln\gamma$
- Transition radiation: $E_\gamma \propto \gamma$

time of flight

Time-of-flight measurement to determine β

Precision proportional to detector distance $\frac{\sigma_t}{t} \propto d$



In collider experiments often only one counter, because start time known from bunch crossing

Very good time resolution of detectors needed:

- Plastic scintillators
- Resistive plate chambers (RPC)
  → large area gas filled detectors in streamer mode

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)

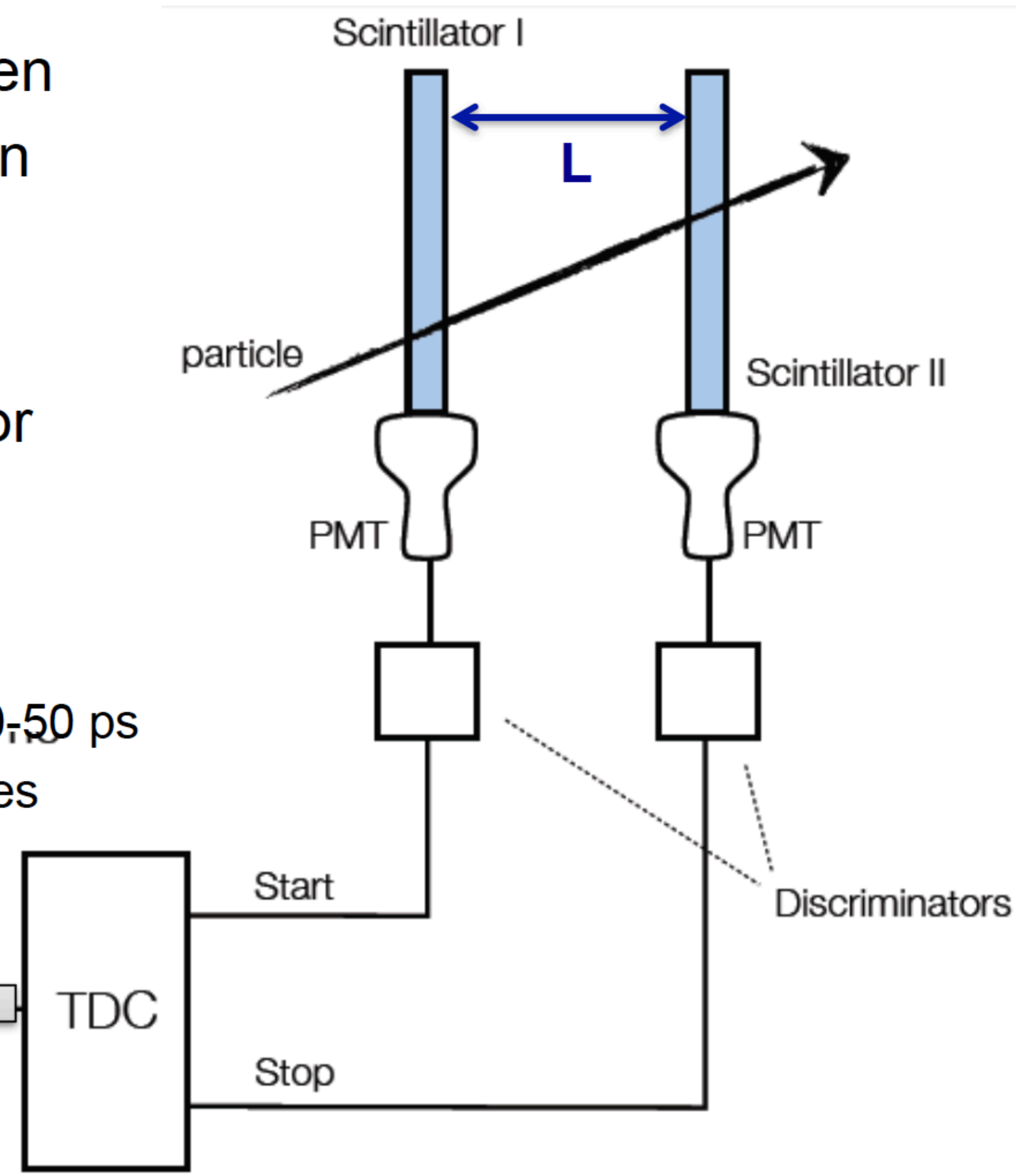
  Resistive Plate Chamber (RPC)

  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, $\boldsymbol{\beta}_1$; mass m_1, energy E_1
Particle 2 : velocity v_2, $\boldsymbol{\beta}_2$; 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, $E \simeq pc \gg m_i c^2$:

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

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

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:

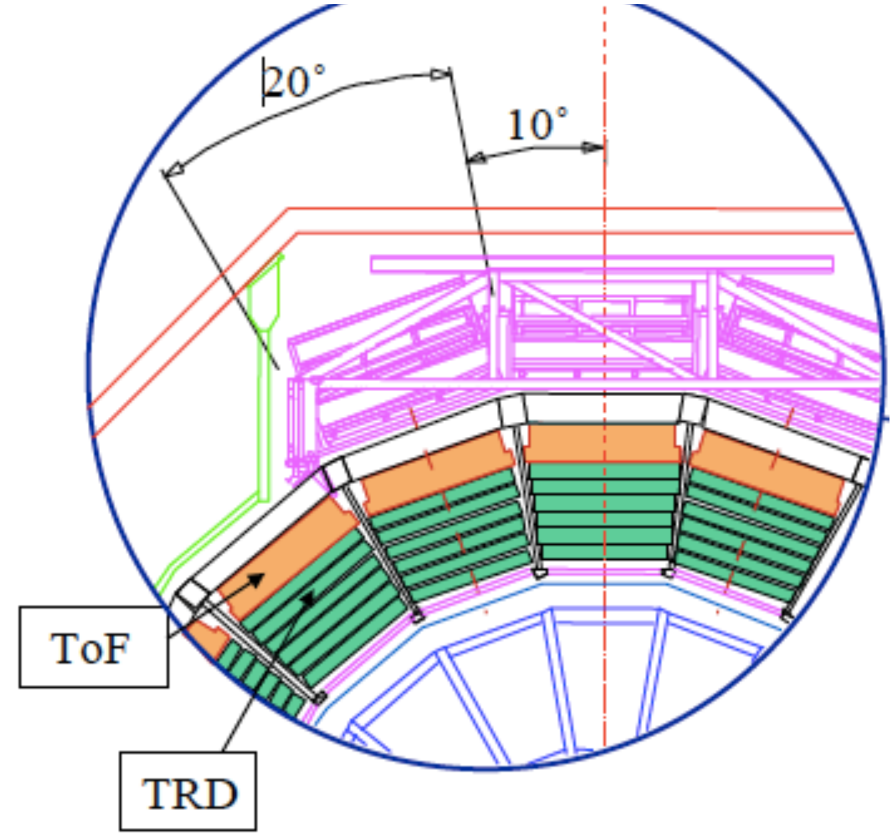
Pion/Kaon separation ...
[$m_K \approx 500$ MeV, $m_\pi \approx 140$ MeV]

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

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

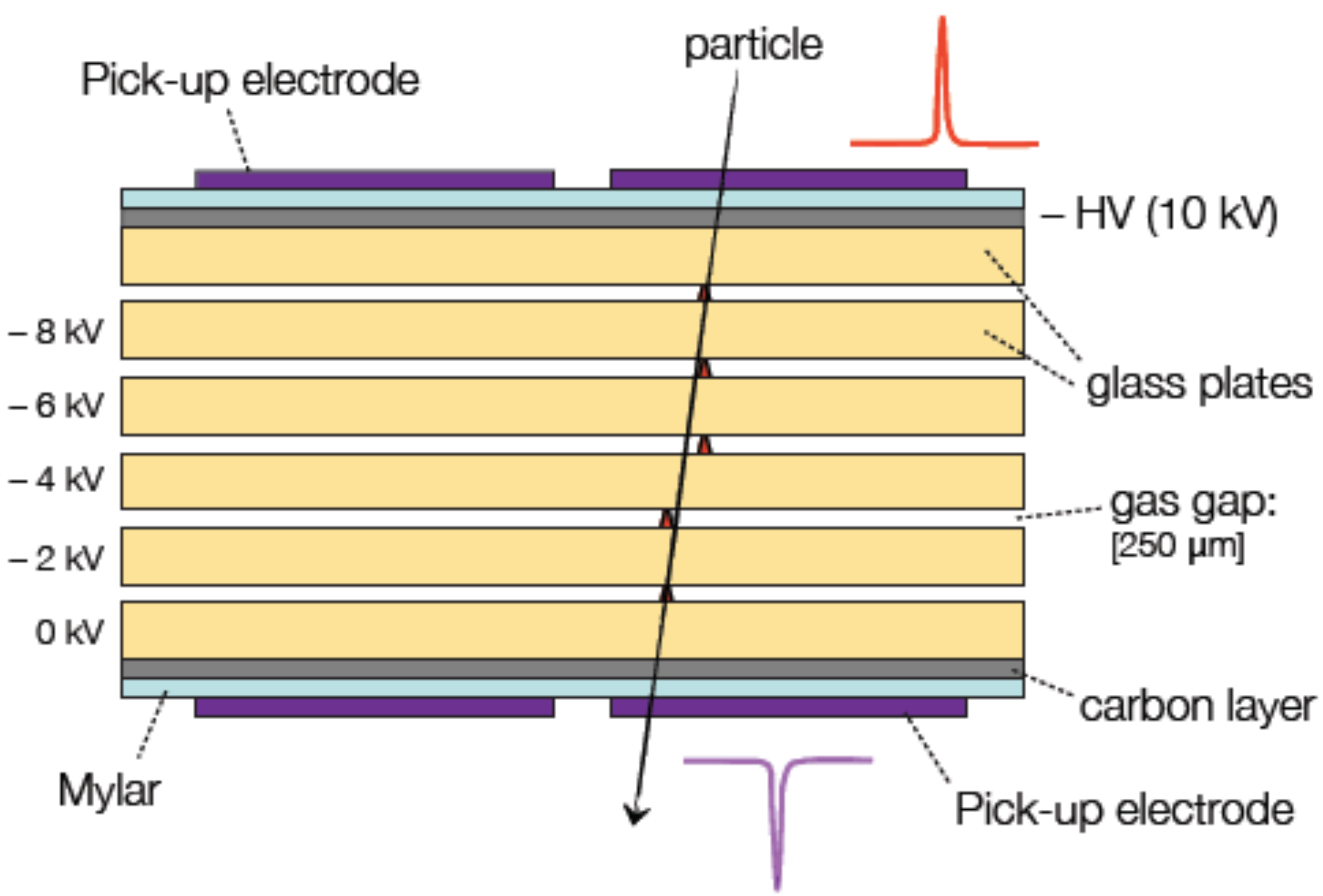
$$\approx 800\ \mathrm{ps}$$

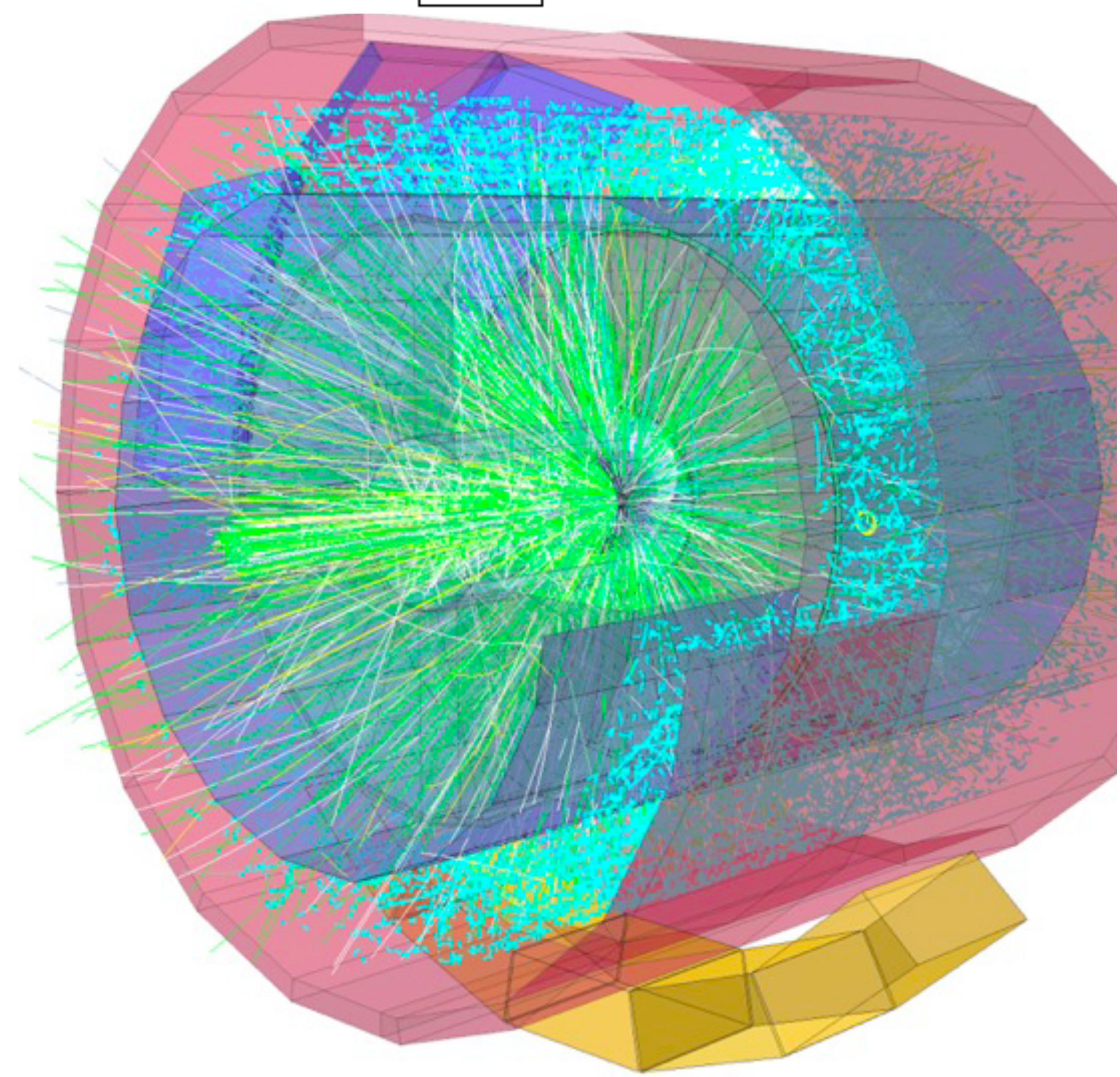
TOF detector - ALICE



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





Specific Ionisation dE/dx to determine β

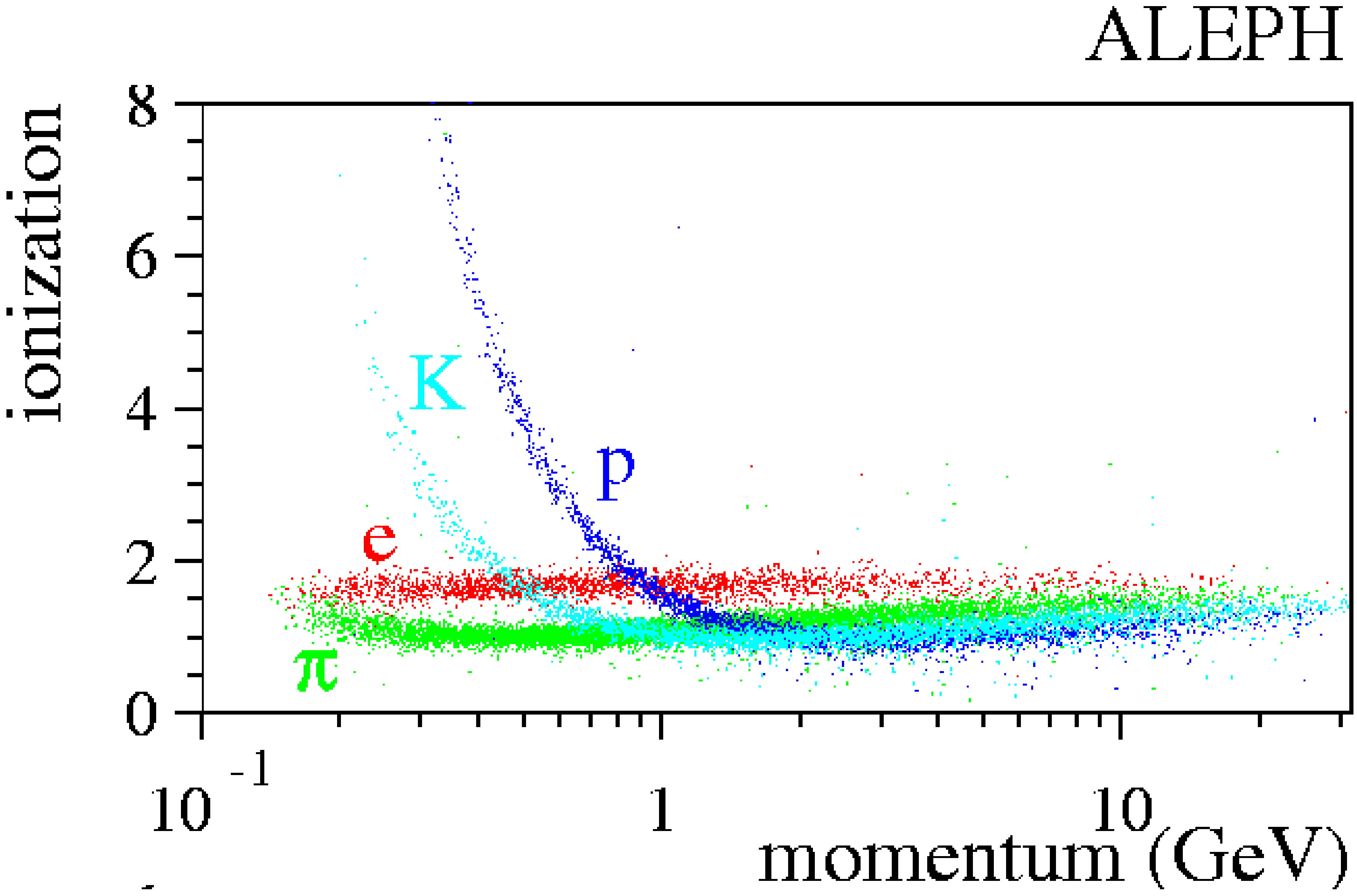
$$\frac{dE}{dx} \propto \frac{1}{\beta^2} \qquad \text{(non-relativistic region)}$$

- Measured with gas ionisation detectors
- Measure mean energy loss, but take care of Landau fluctuations!
  - For one track measure $\frac{dE}{dx}$ several times (30-300x)
  - Extract $\langle\frac{dE}{dx}\rangle$ from the measured distribution
  - „Truncated Mean“: Remove measurements with high values

    i.e. δ-electrons and Landau tails
- Precision for argon:

$$\sigma \approx 10\% \sqrt{\frac{100}{N}} \sqrt{\frac{1\,m}{l}} \sqrt{\frac{1\,bar}{p}}$$

N: Measurements ($\lesssim 100$)
l: Track length
p: Pressure

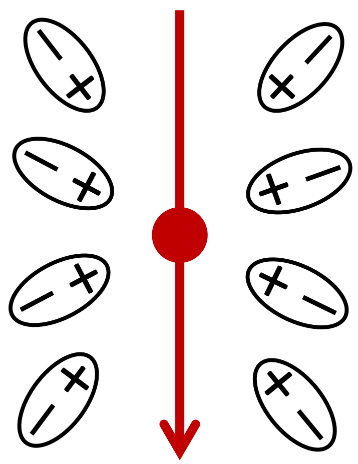

ALEPH
ionization
8
6
4
2
0
K
p
e
π
10^{-1}
1
10
momentum (GeV)

Cerenkov Radiation to determine β

The speed of the propagation of light in water is only $0.75c$. Matter can be accelerated beyond this speed easily.

A charged particle passes a medium faster than the speed of light in this medium

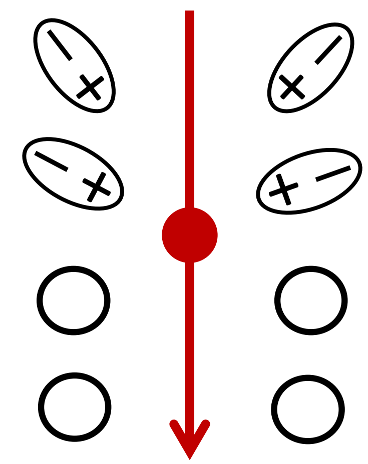
$$v < \frac{c}{n}$$



Symmetric
charge distribution

- ➢ Dipol moment vanishes
- ➢ No radiation

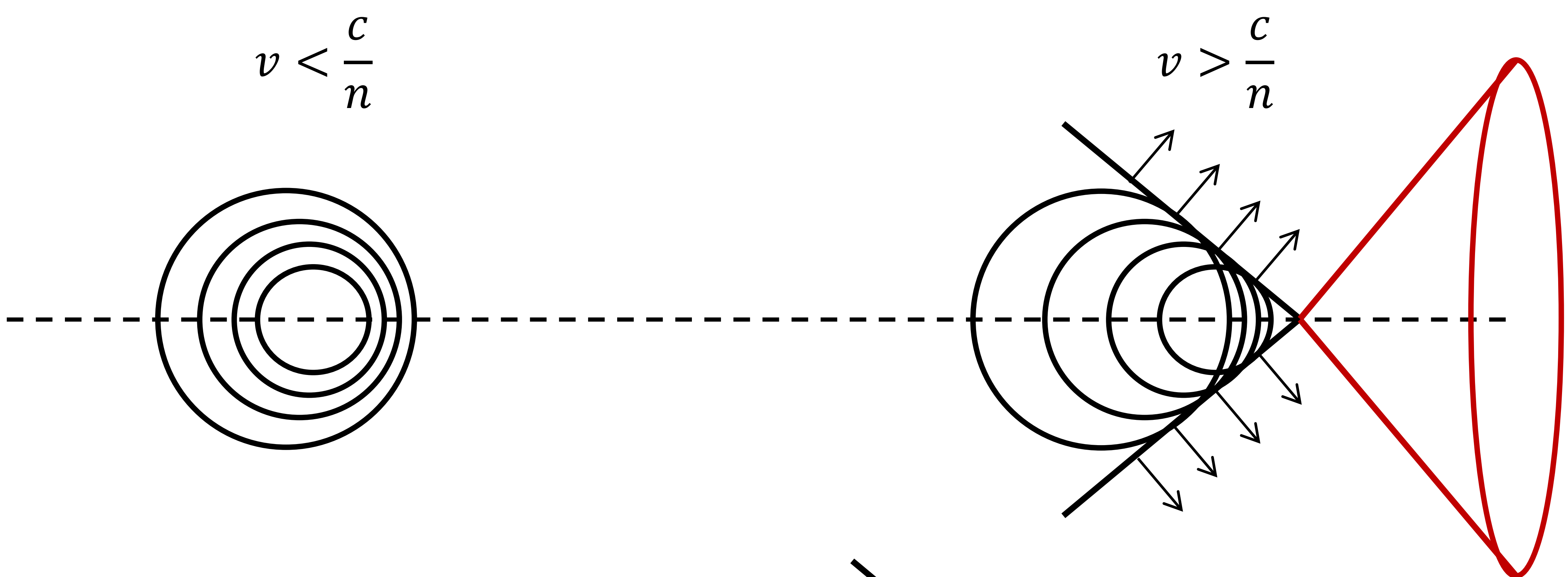
$$v > \frac{c}{n}$$



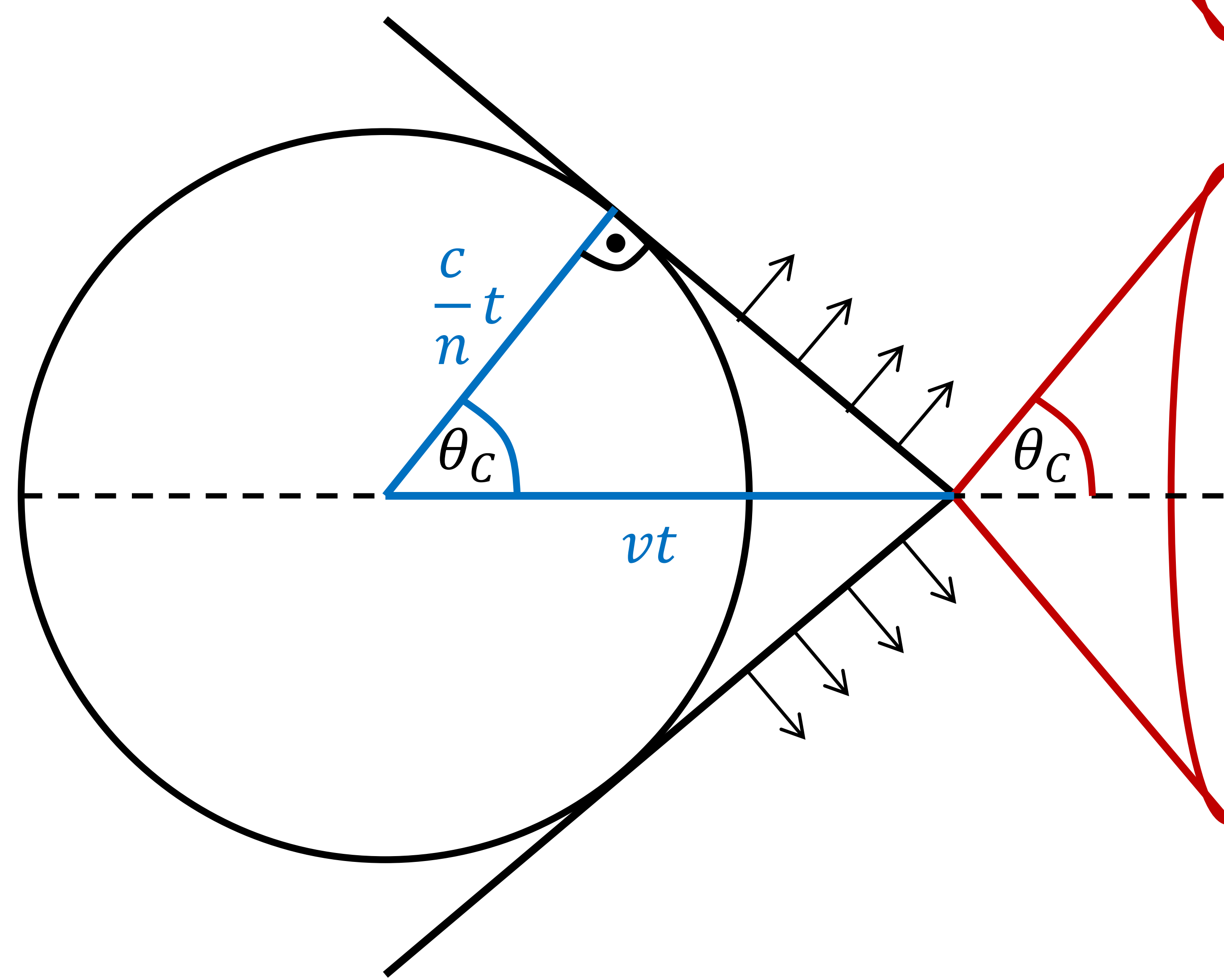
Asymmetric
charge distribution

- ➢ Moving dipol moment
- ➢ Radiation of Cerenkov light

Cerenkov radiation



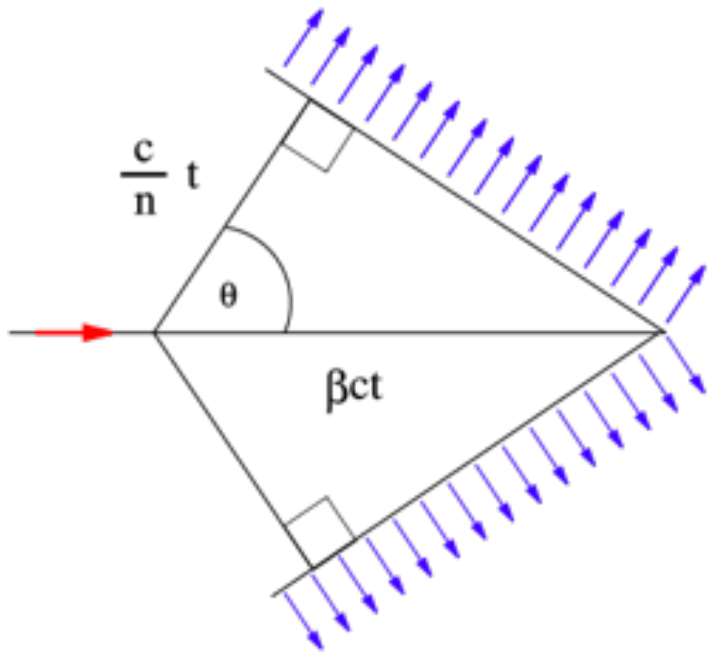
$$\cos\theta_C = \frac{\frac{c}{n}t}{vt} = \frac{c}{n\,v} = \frac{1}{\beta n}$$



Light cone with
half opening angle θ_C

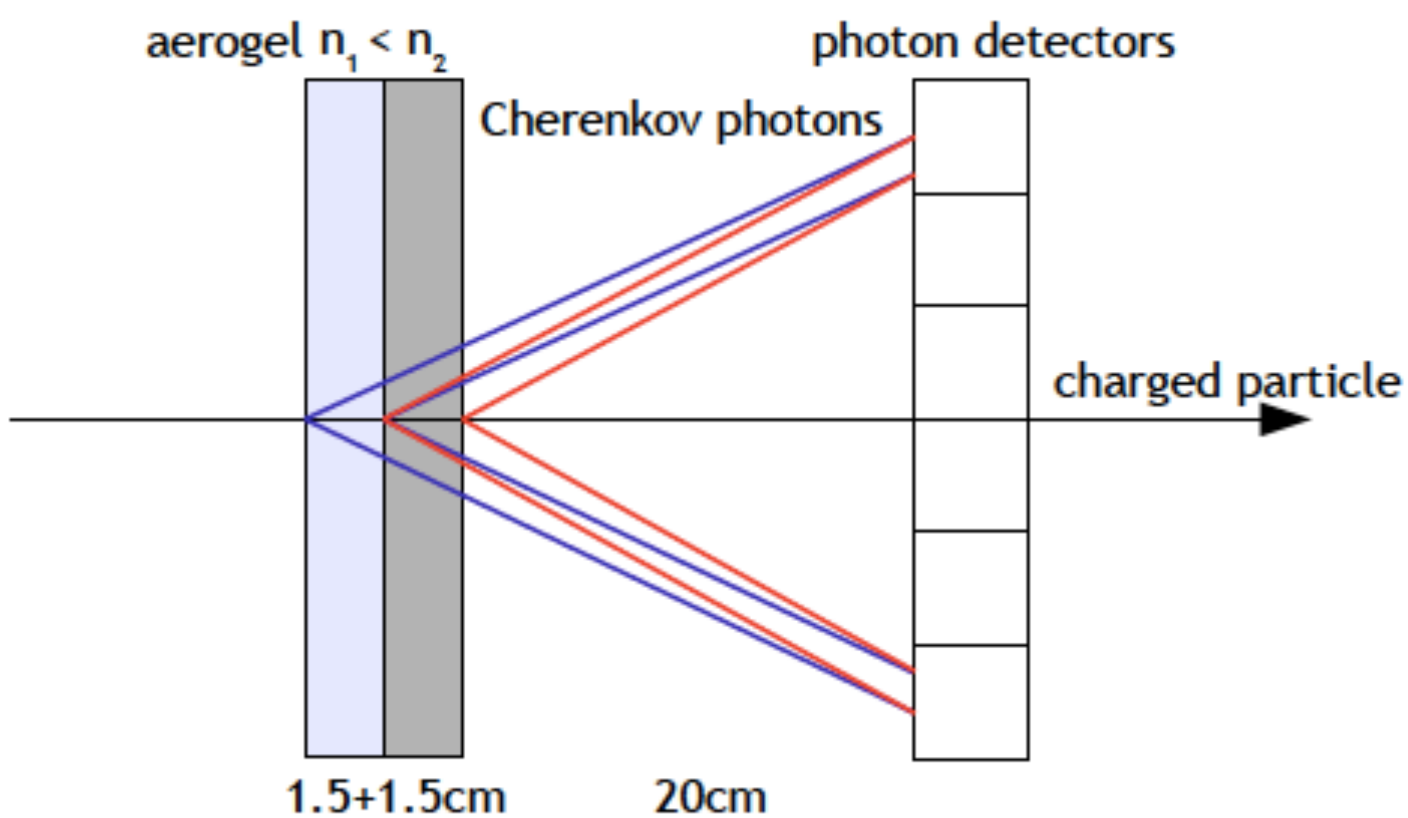
Measurement of particle velocity

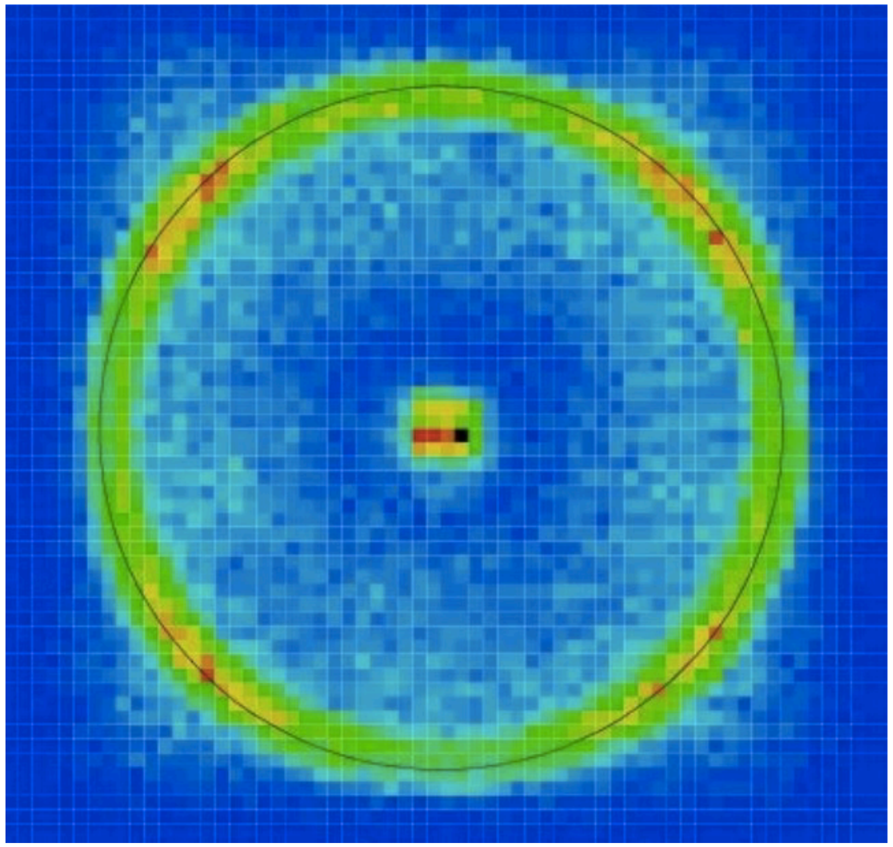
- Cherenkov angle



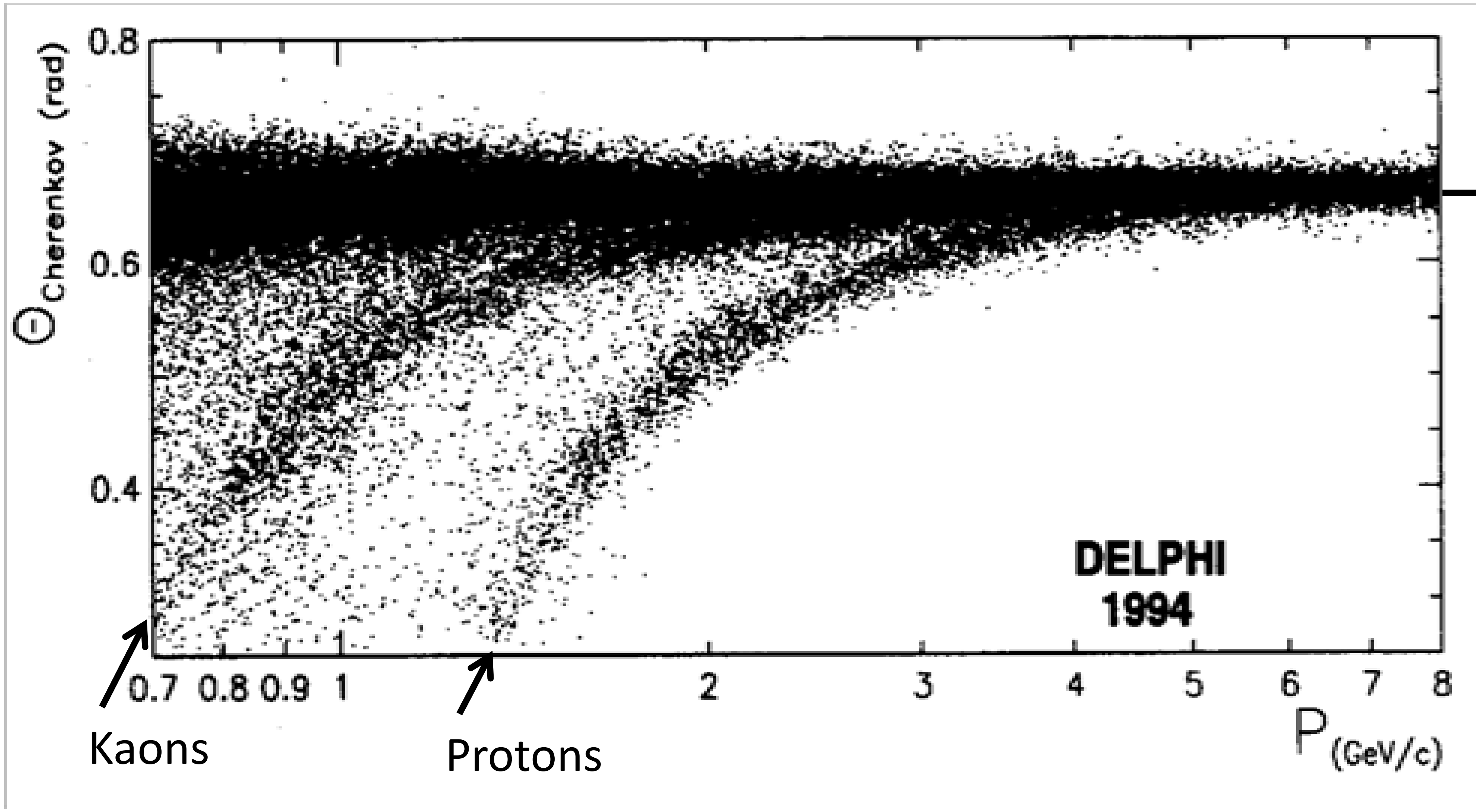
$$v_{th} \geq \frac{c}{n} \Rightarrow \beta_{th} \geq \frac{1}{n}$$

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





- Diameter of ring → Cerenkov angle $\theta_C \rightarrow \beta$



$\beta \approx 1$

$$\cos\theta_C = \frac{1}{\beta n} \;\Rightarrow\; \cos 0.68 = \frac{1}{n} \;\Rightarrow\; n \approx 2$$

Cherenkov detectors

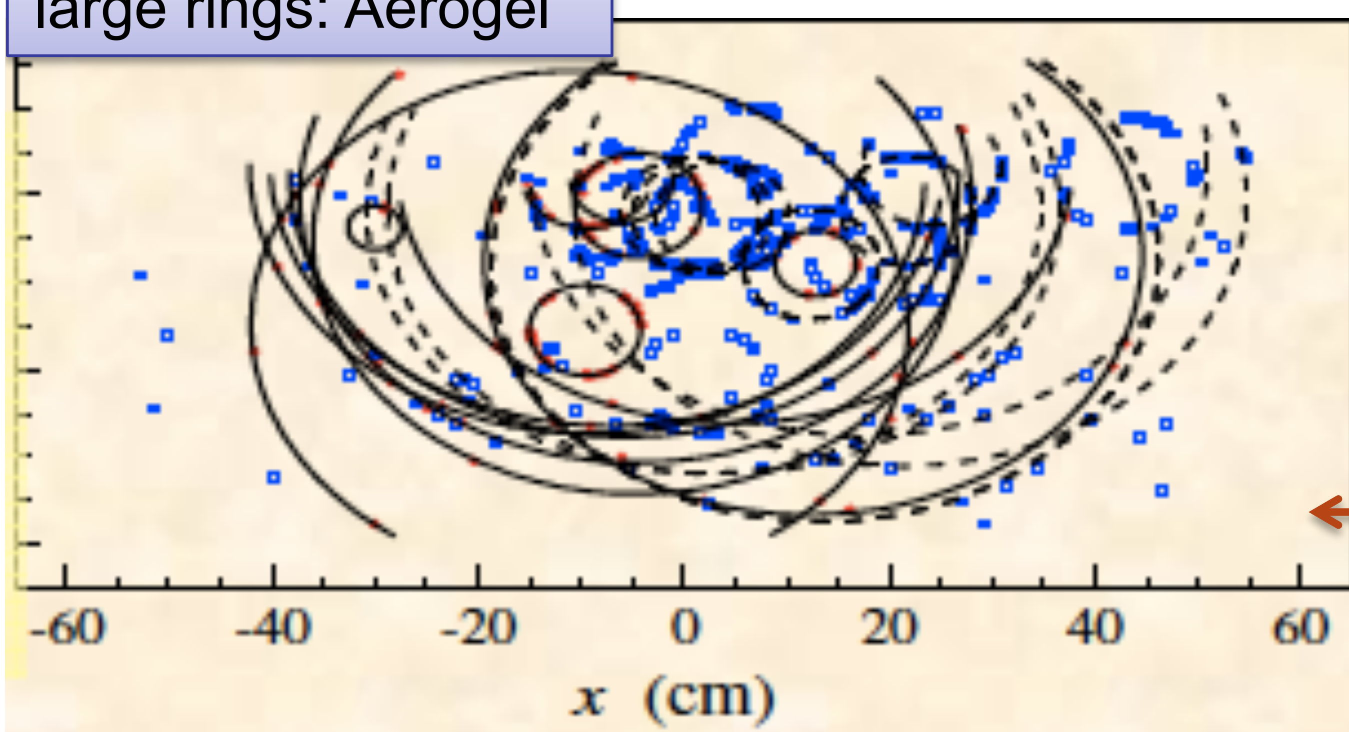
Determination of β from ring radius:

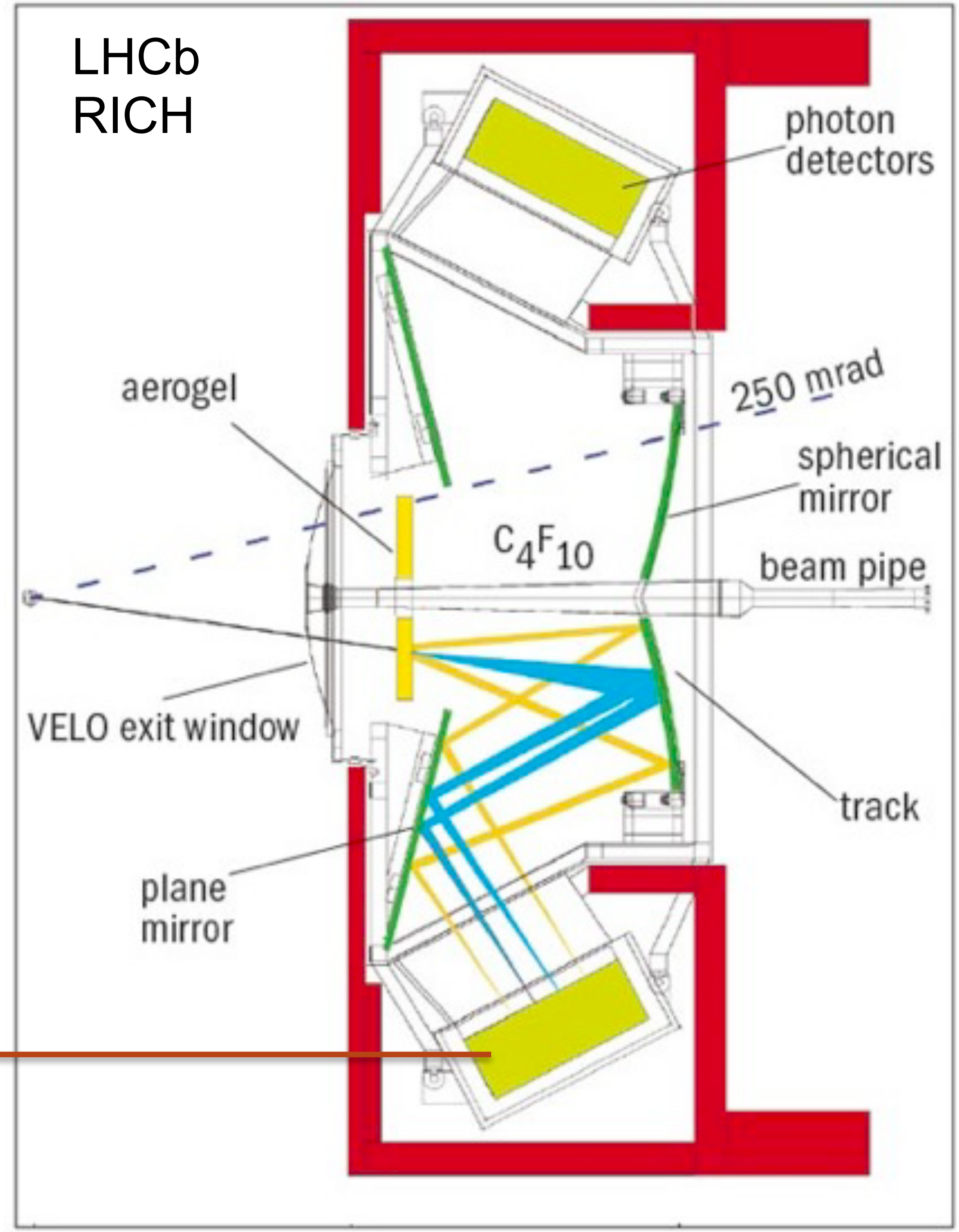
$$\beta = \frac{1}{n\cos(2r/R_s)}$$

R_s : radius of spherical mirror

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

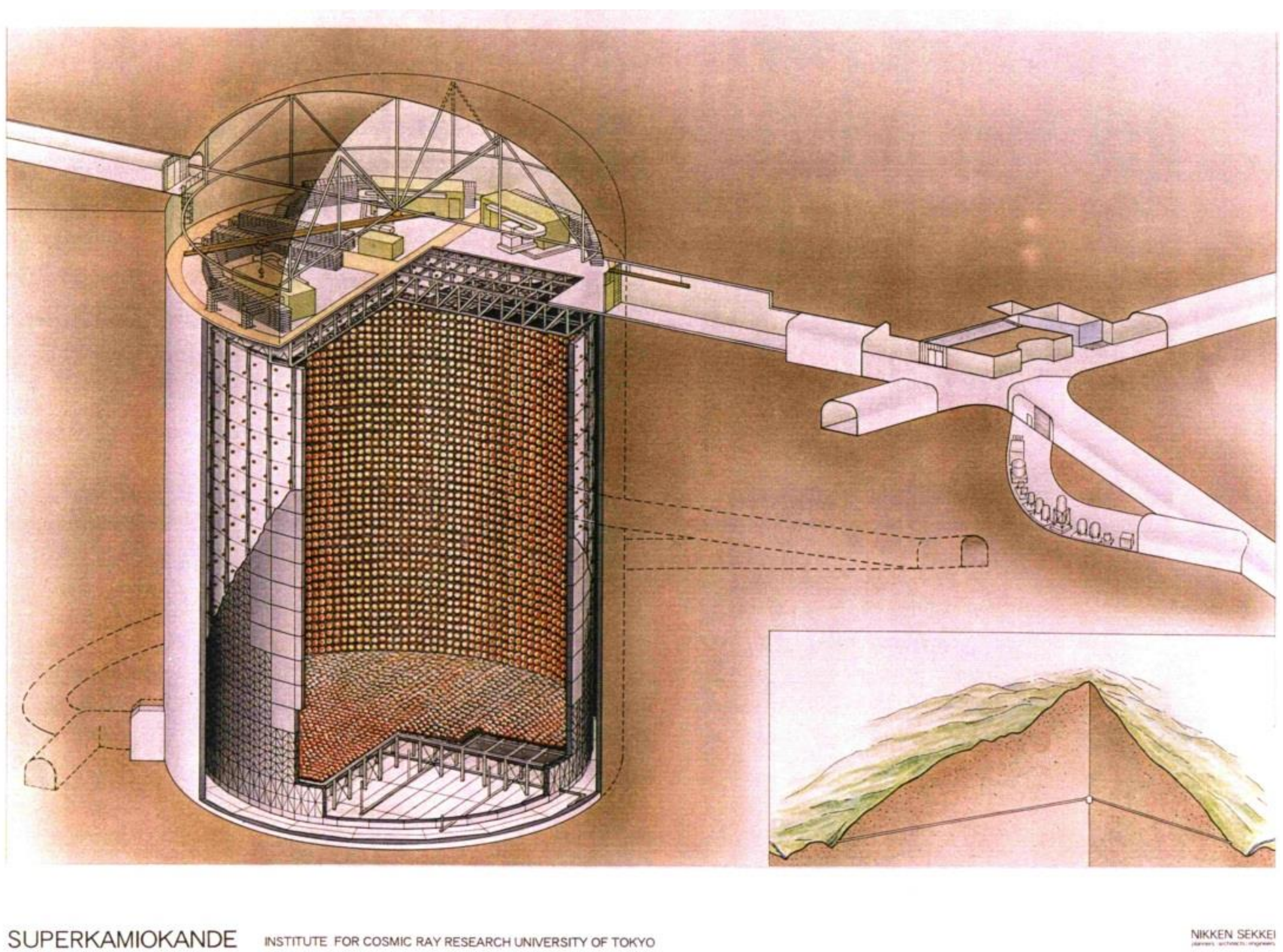
small rings: C_4F_{10}
large rings: Aerogel

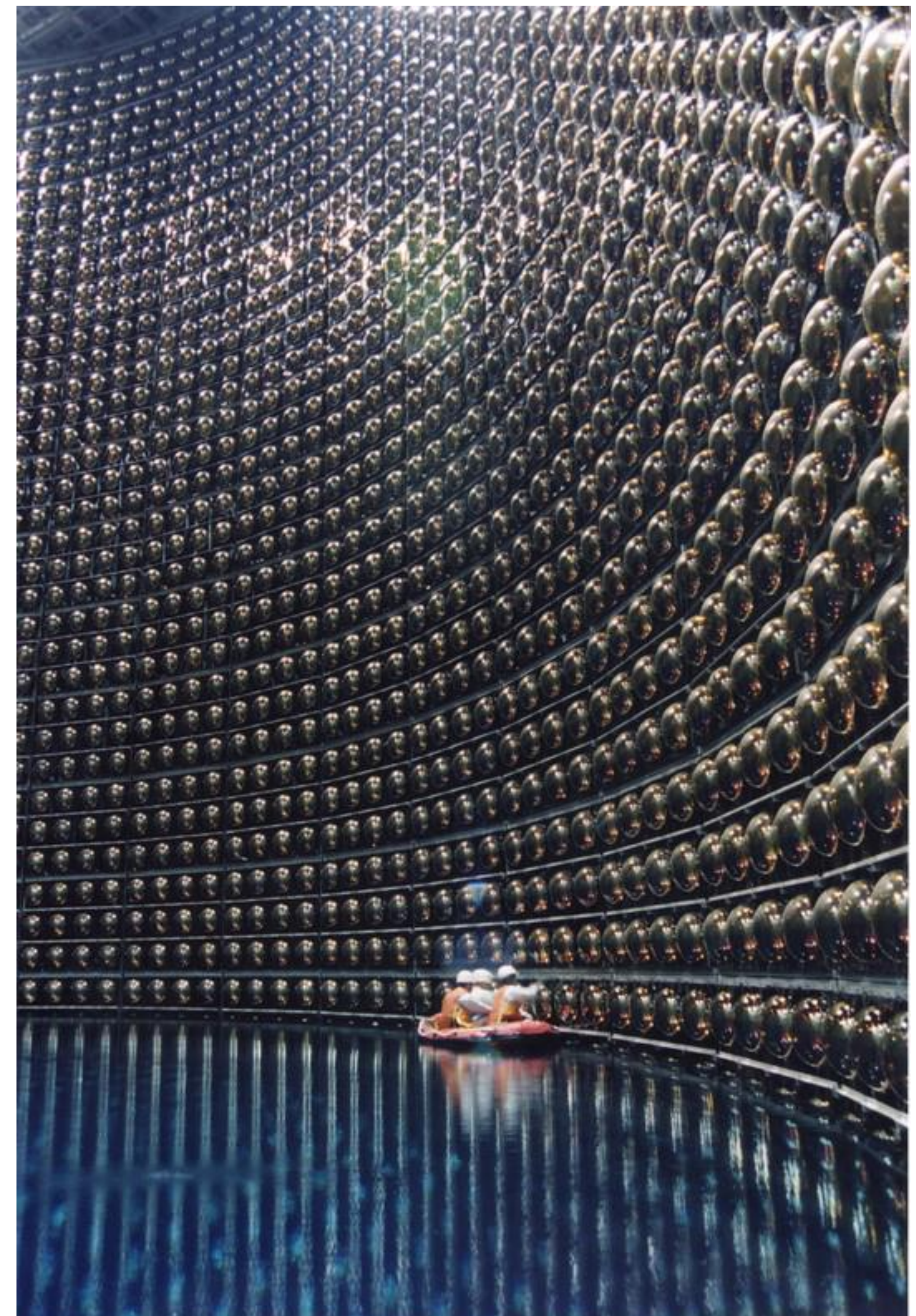




Insertion: Cerenkov cones in neutrino detectors

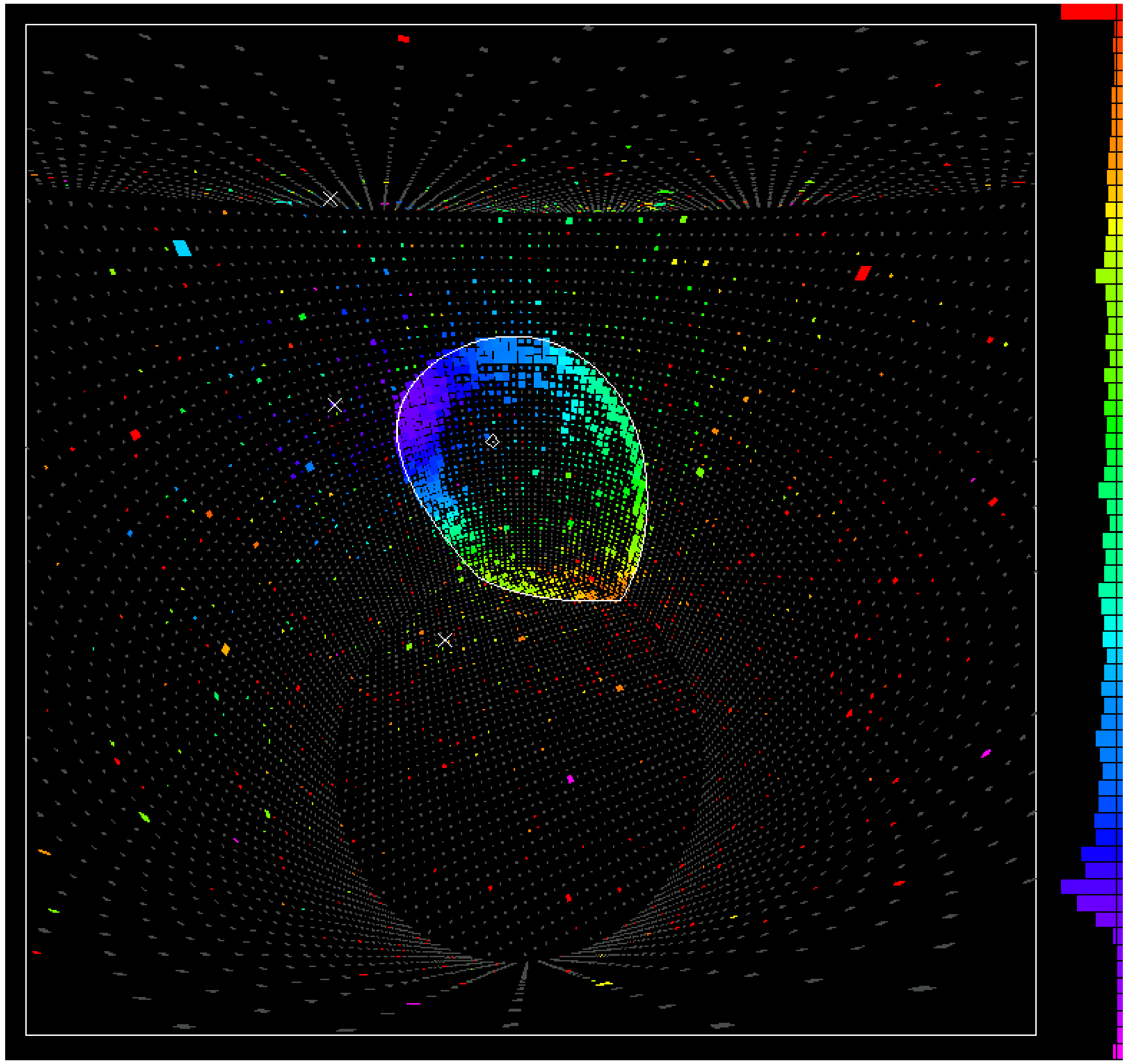
Super-Kamiokande is a 50,000 ton water Cherenkov detector, with 11,000 photomultiplier tubes, which started observation in 1996 after 5 years of construction



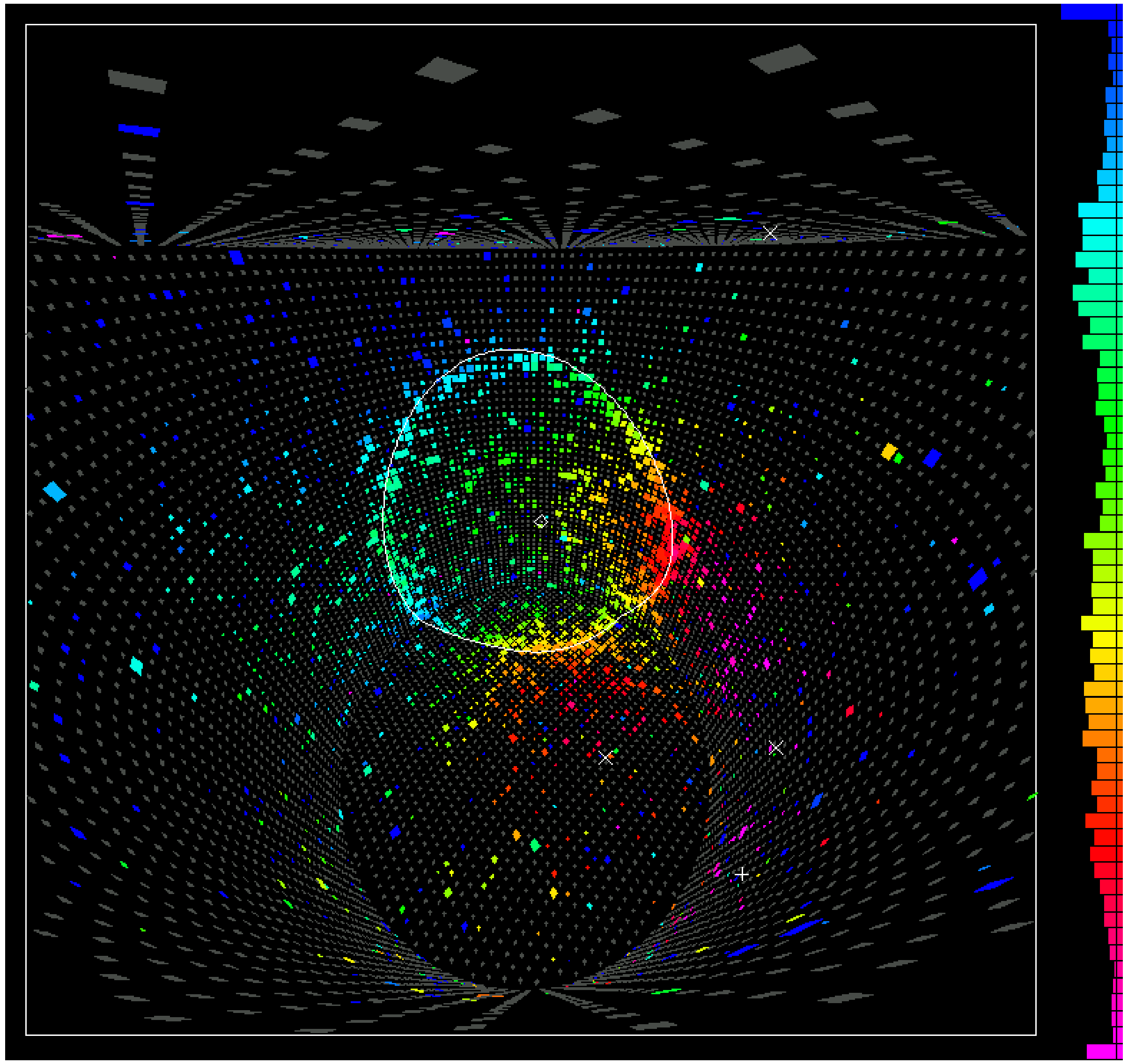


Insertion: Cerenkov cones in neutrino detectors

Muon



Electron



- Rings on tank walls, because particle tracks very short (otherwise discs)
- Sharp ring for muons $\leftrightarrow$ fuzzy ring for electrons due to bremsstrahlung
- Different kind of particle ID! → Has nothing to do with a measurement of β

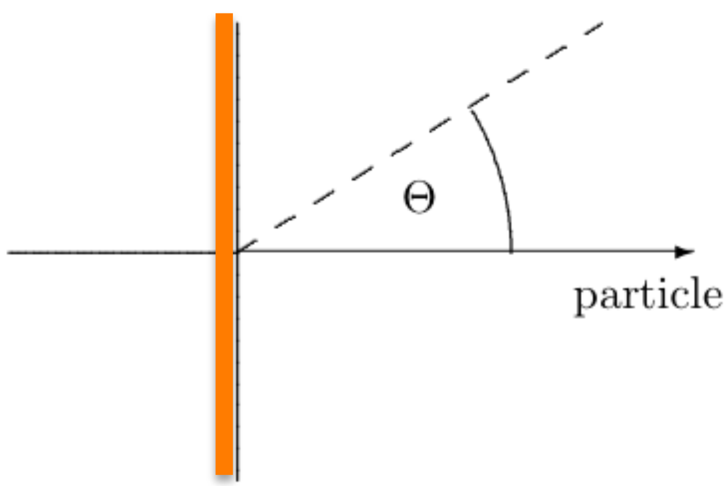
Transition radiation (**TR**)

is a form of electromagnetic radiation emitted when a charged particle passes through inhomogeneous media, such as a boundary between two different media. This is in contrast to Cherenkov radiation, which occurs when a charged particle passes through a homogeneous dielectric medium at a speed greater than the phase velocity of electromagnetic waves in that medium.

Since the electric field of the particle is different in each medium, the particle has to "shake off" the difference when it crosses the boundary. The total energy loss of a charged particle on the transition depends on its Lorentz factor $\gamma = E/mc^2$ and is mostly directed forward, peaking at an angle of the order of $1/\gamma$ relative to the particle's path.

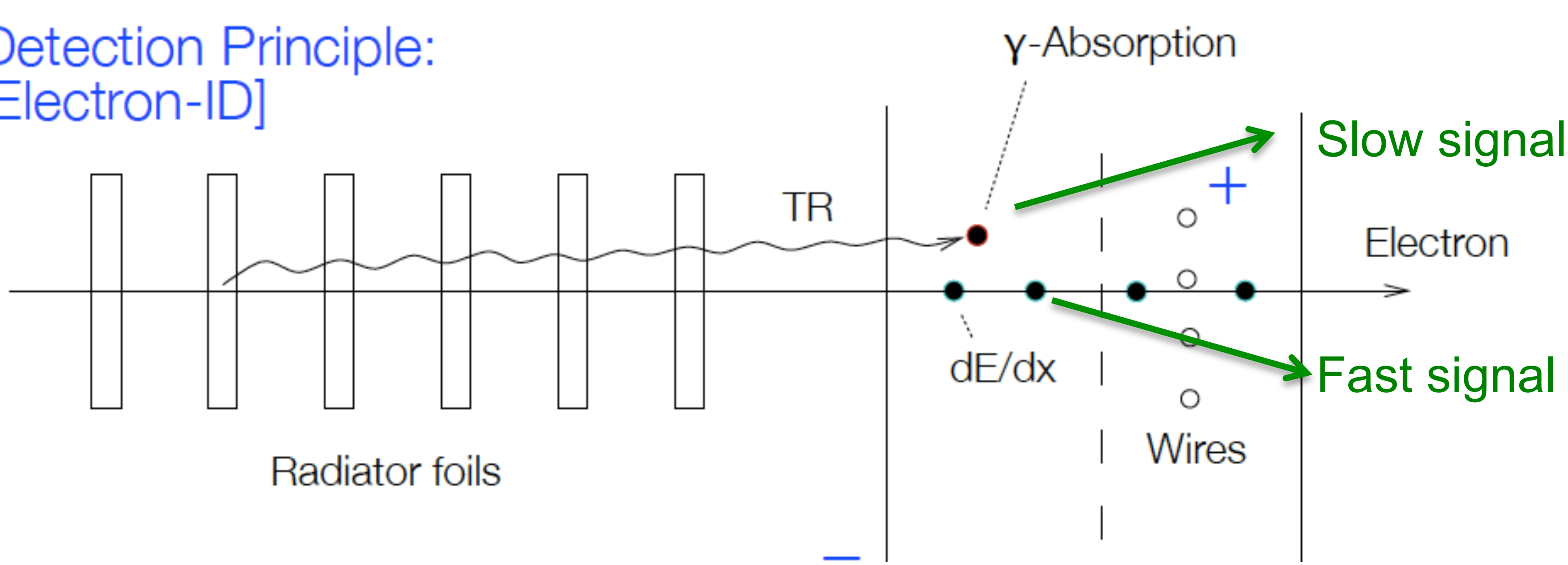
Measurement of particle velocity

- Transition radiation



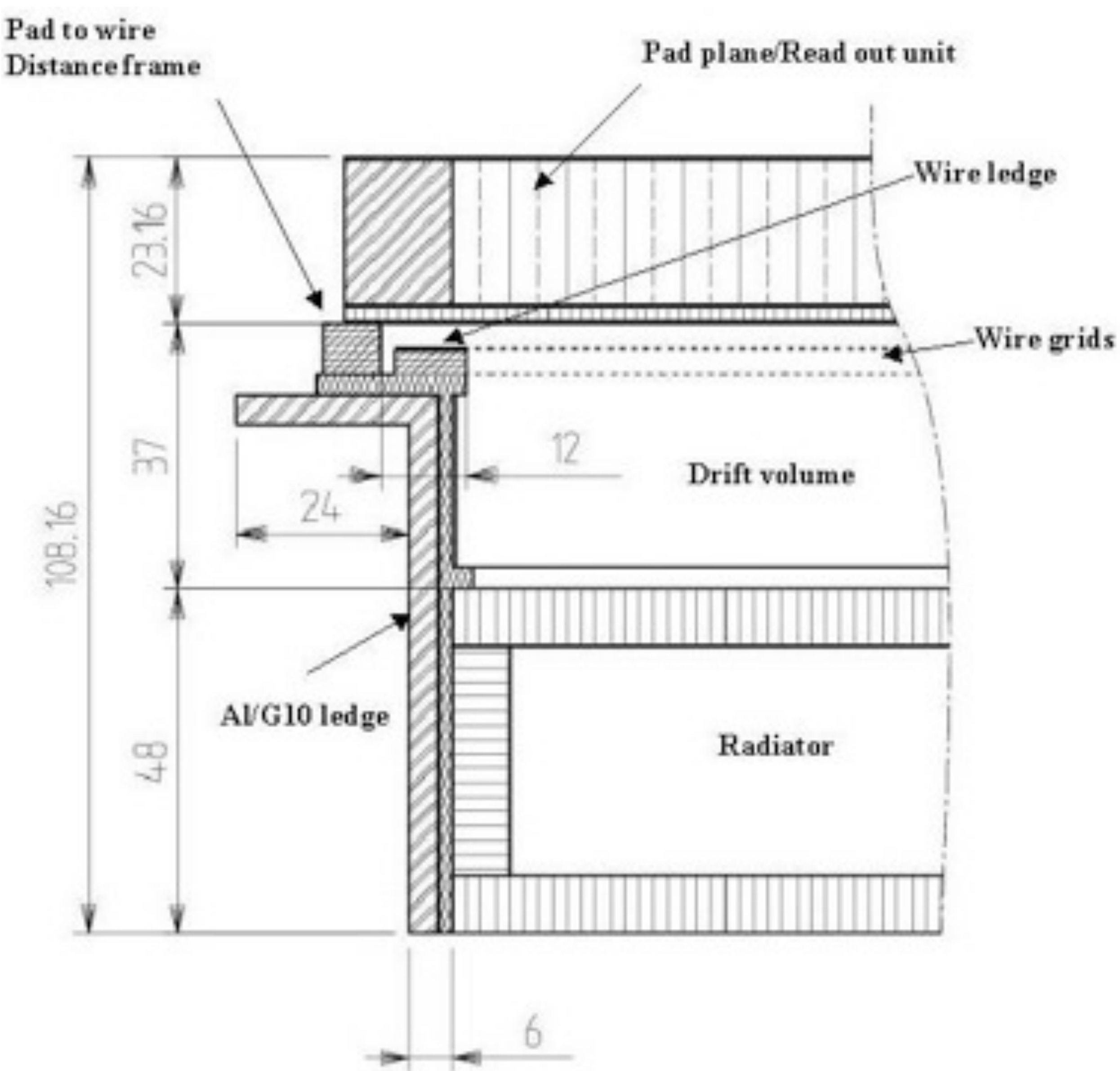
- Typical emission angle: $\Theta = 1/\gamma$
- Energy of radiated photons: $\sim \gamma$
- Number of radiated photons: αz^2
- Effective threshold: $\gamma > 1000$

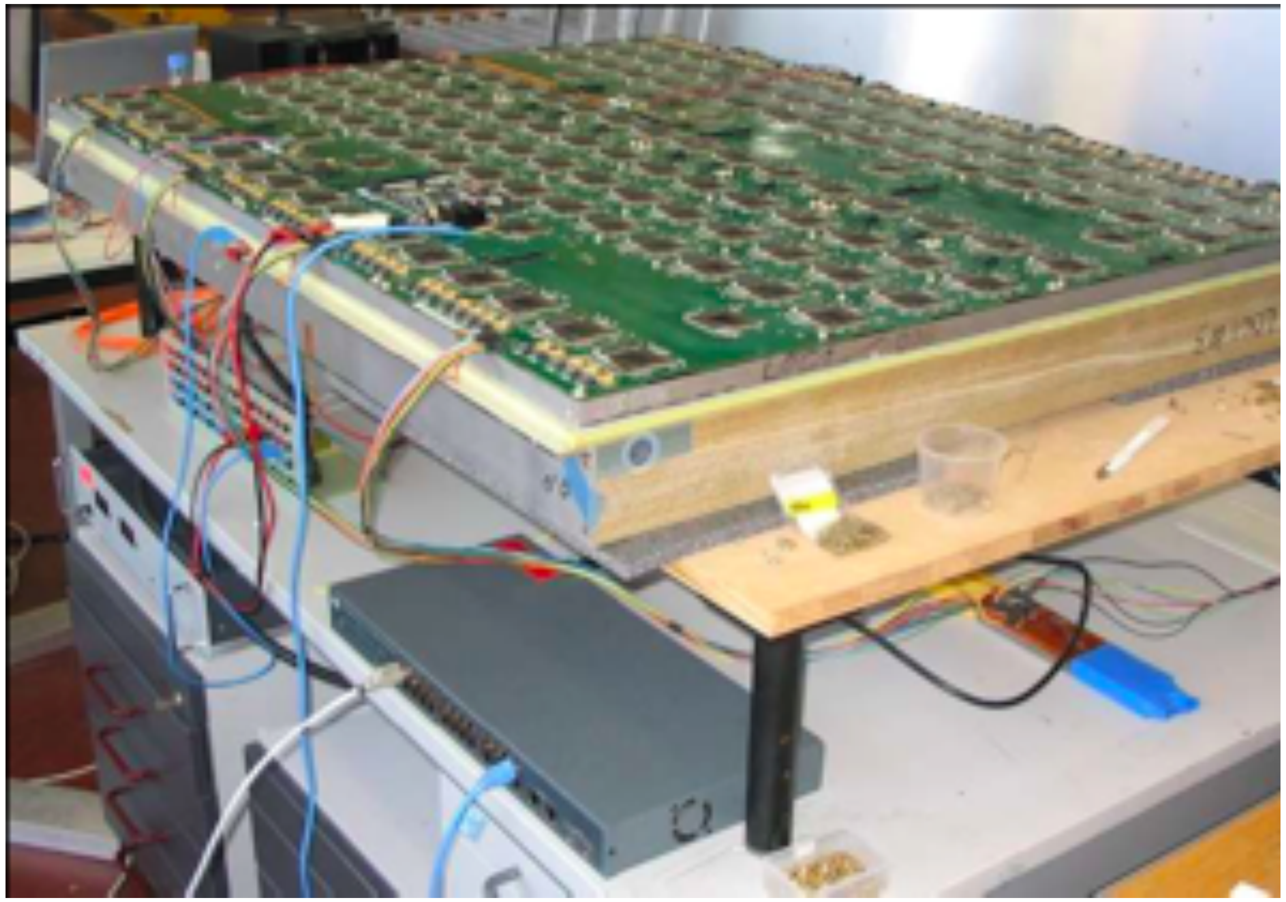
Detection Principle:
[Electron-ID]



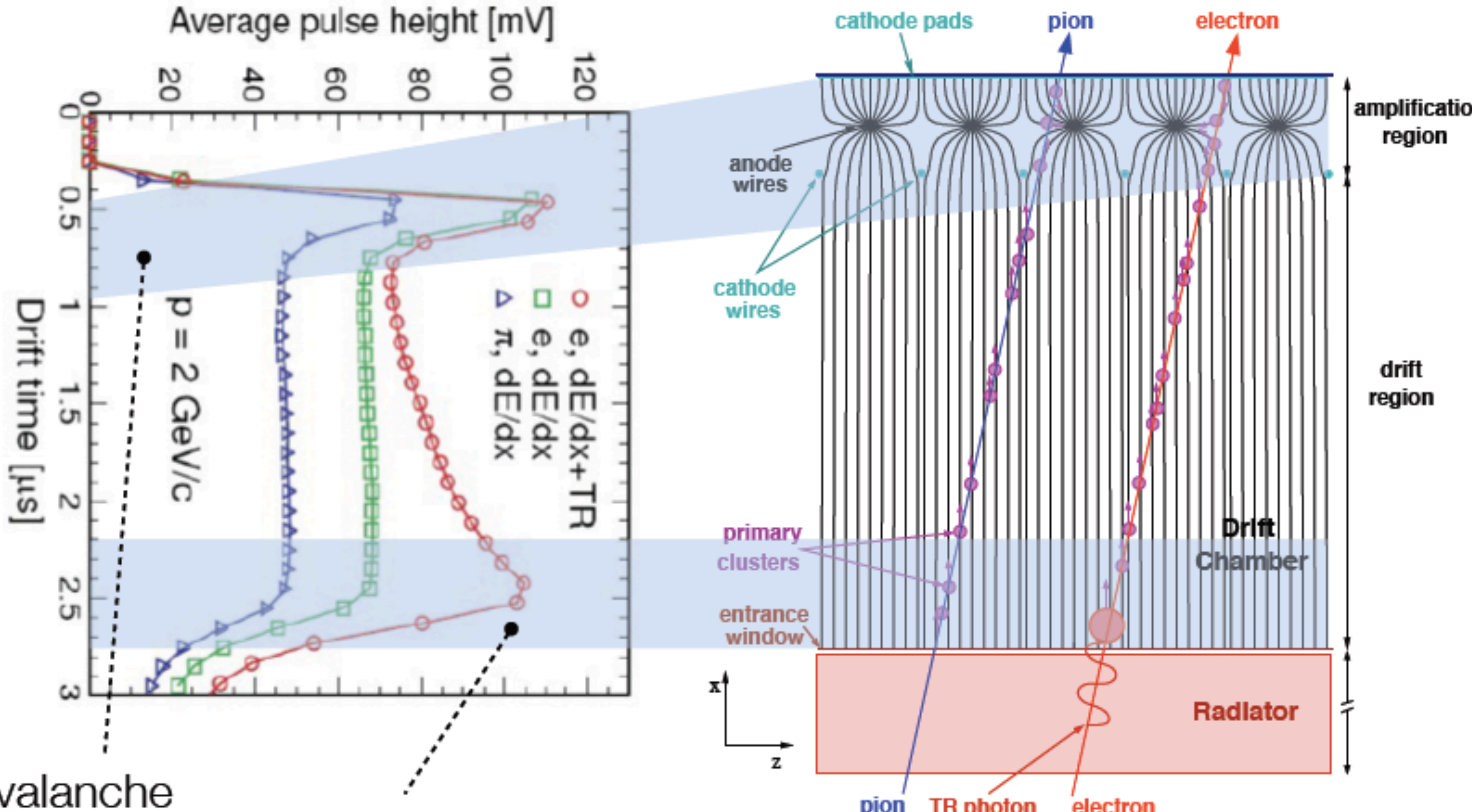
Note: Only X-ray (E>20keV) photons can traverse the many radiators without being absorbed

Transition radiation detectors - ALICE





Transition radiation detectors - ALICE



Avalanche

near anode wires
[high field]

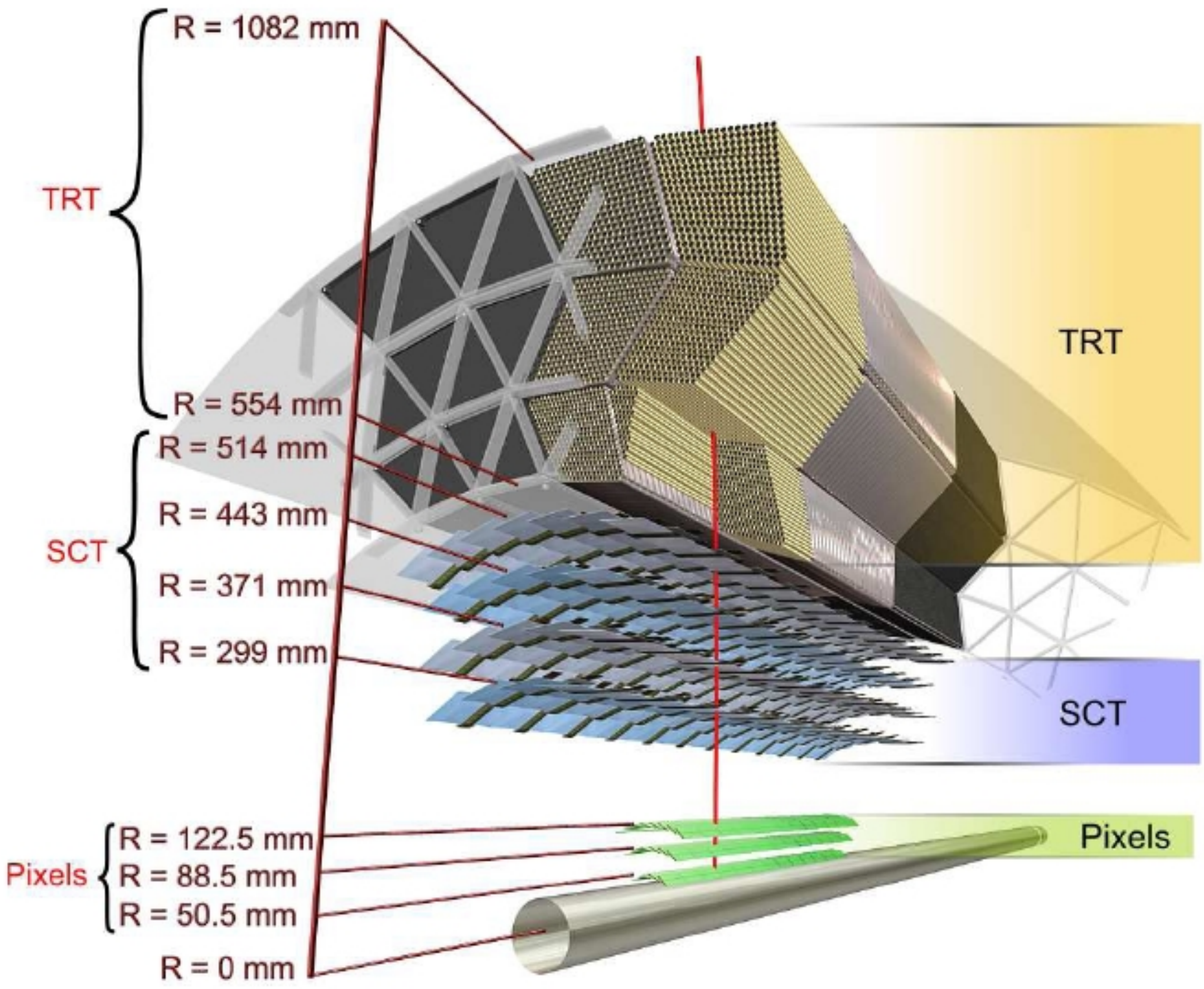
TR-Signal

Gas: Xenon
[High γ-absorption]

Transition Radiation [TR]

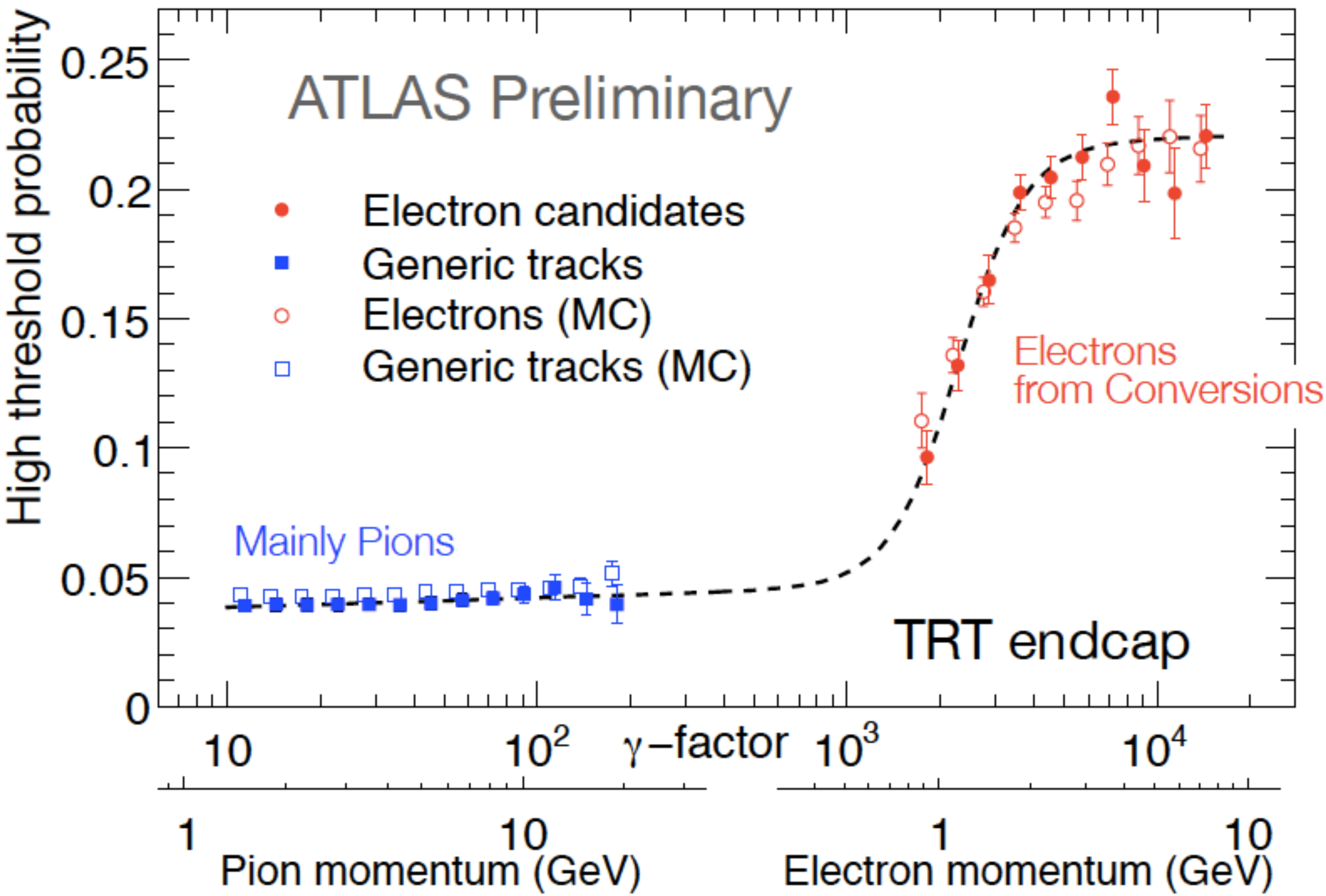
for charged Particles with γ > 1000

Transition radiation detectors - ATLAS



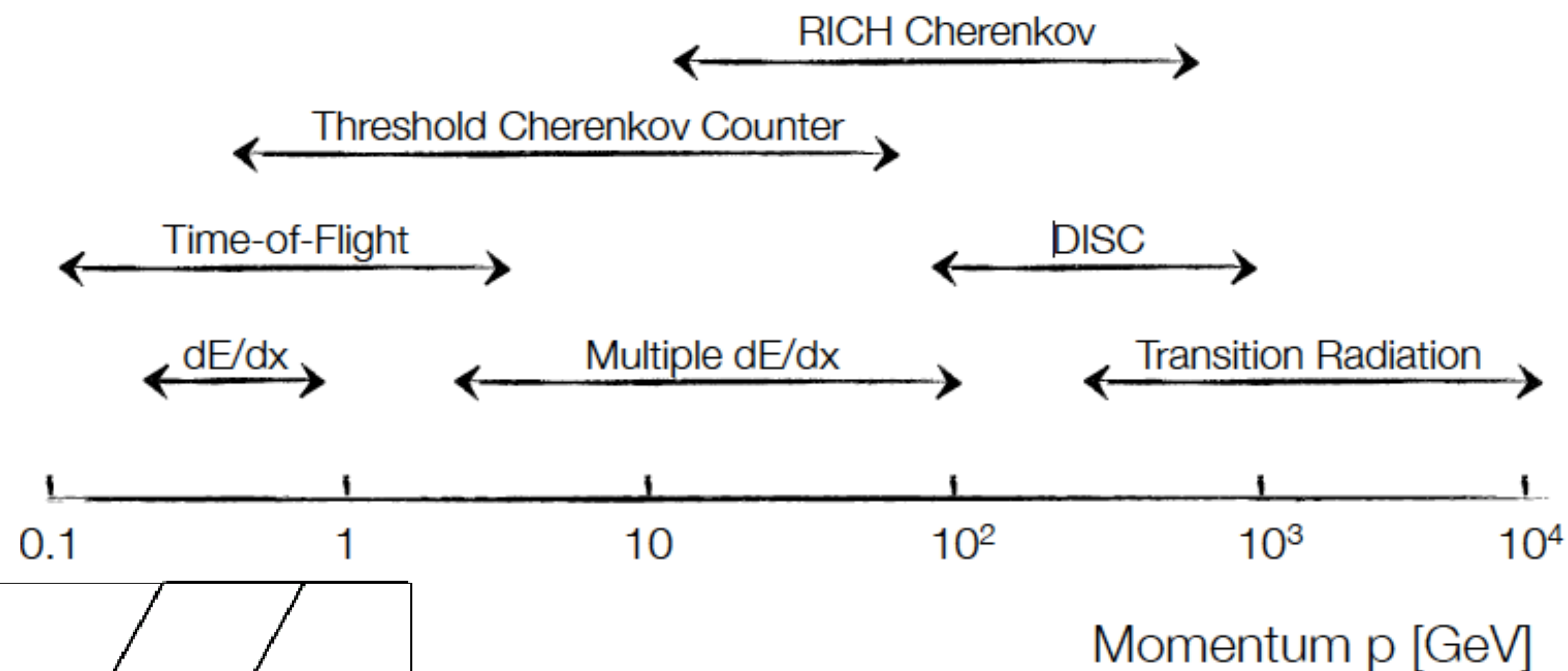
- straw tubes with xenon-based gas mixture
- 4 mm in diameter, equipped with a 30 μm diameter gold-plated W-Re wire

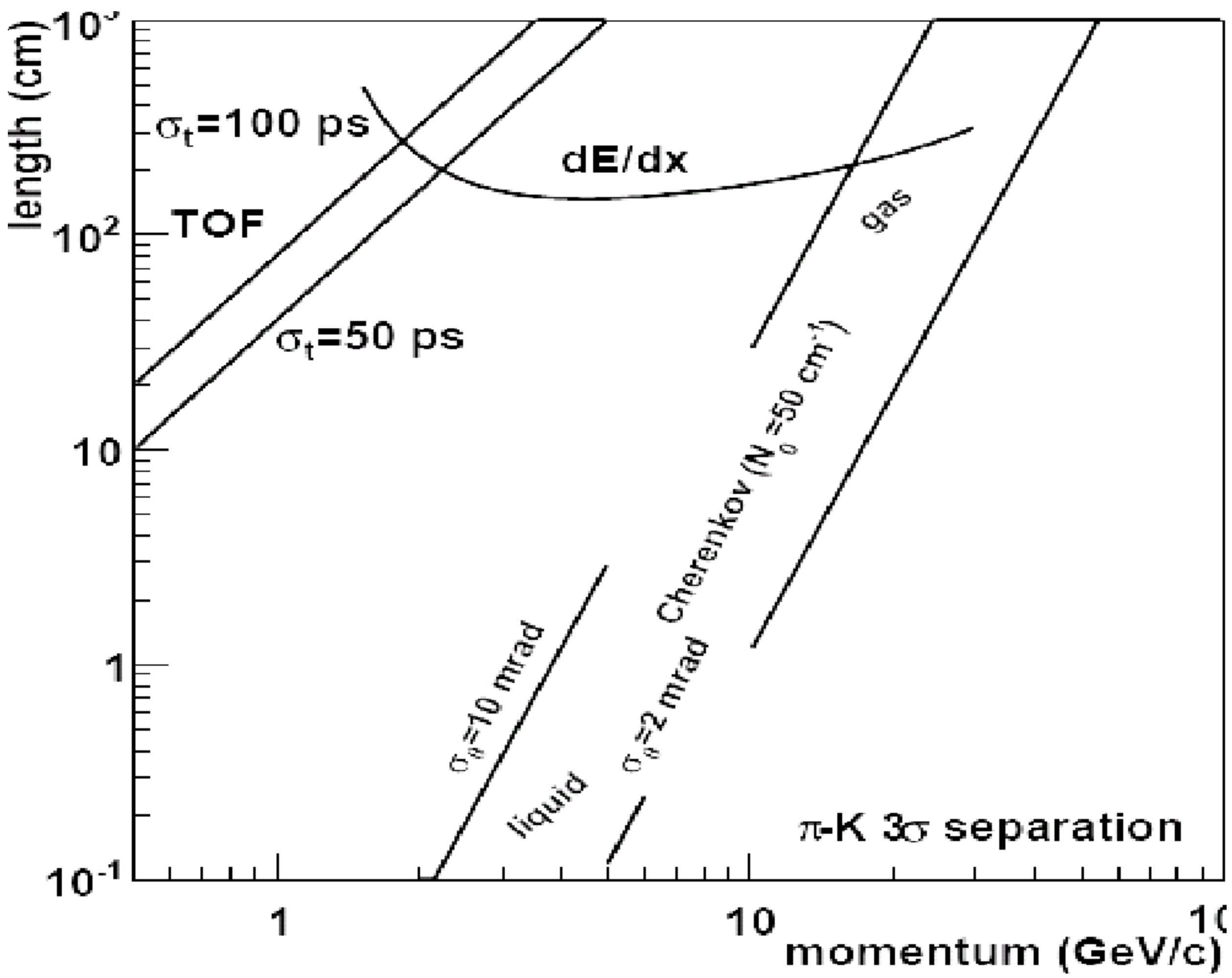
Transition radiation detector (ATLAS)



PID methods - compare

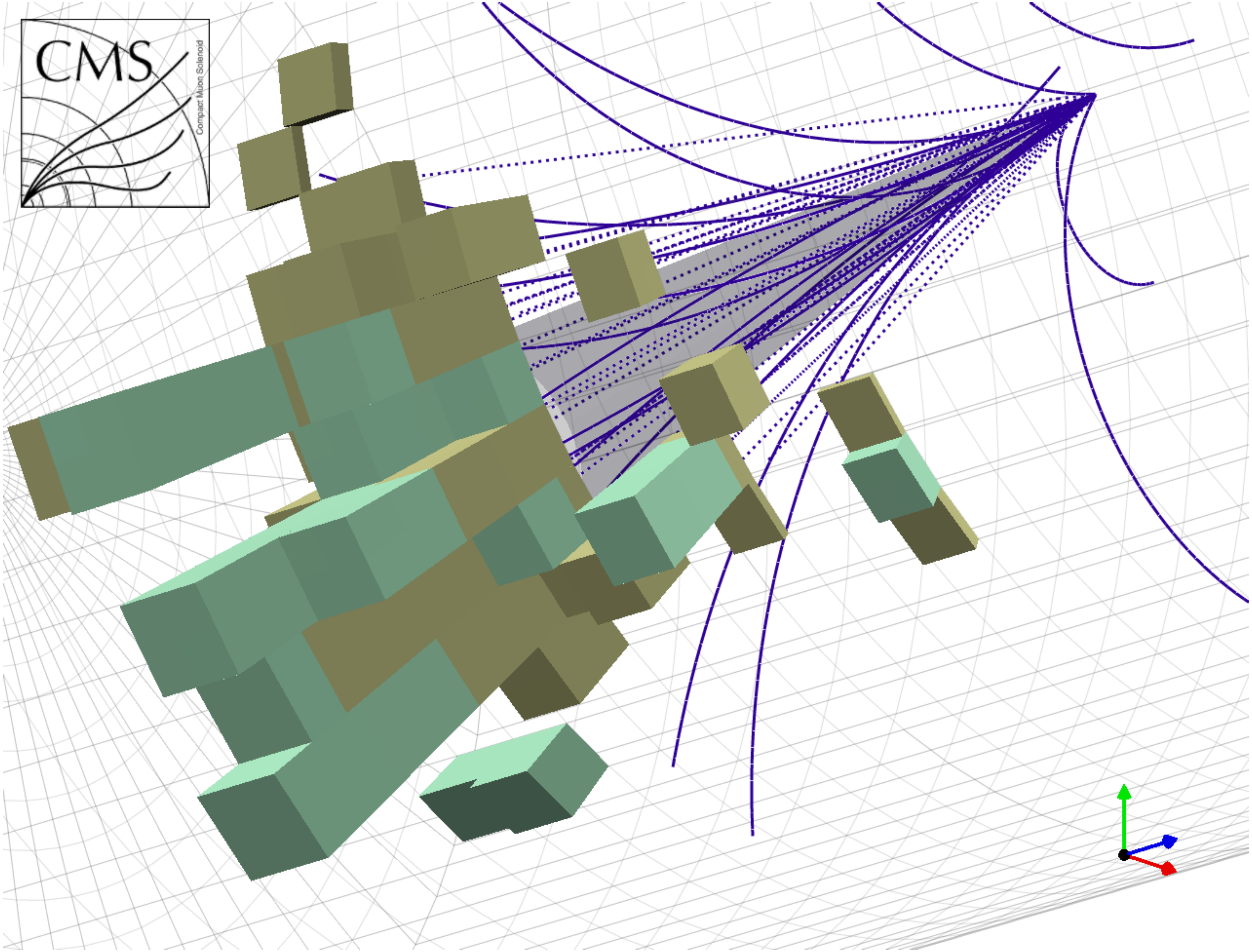
π/K Separation with different PID methods





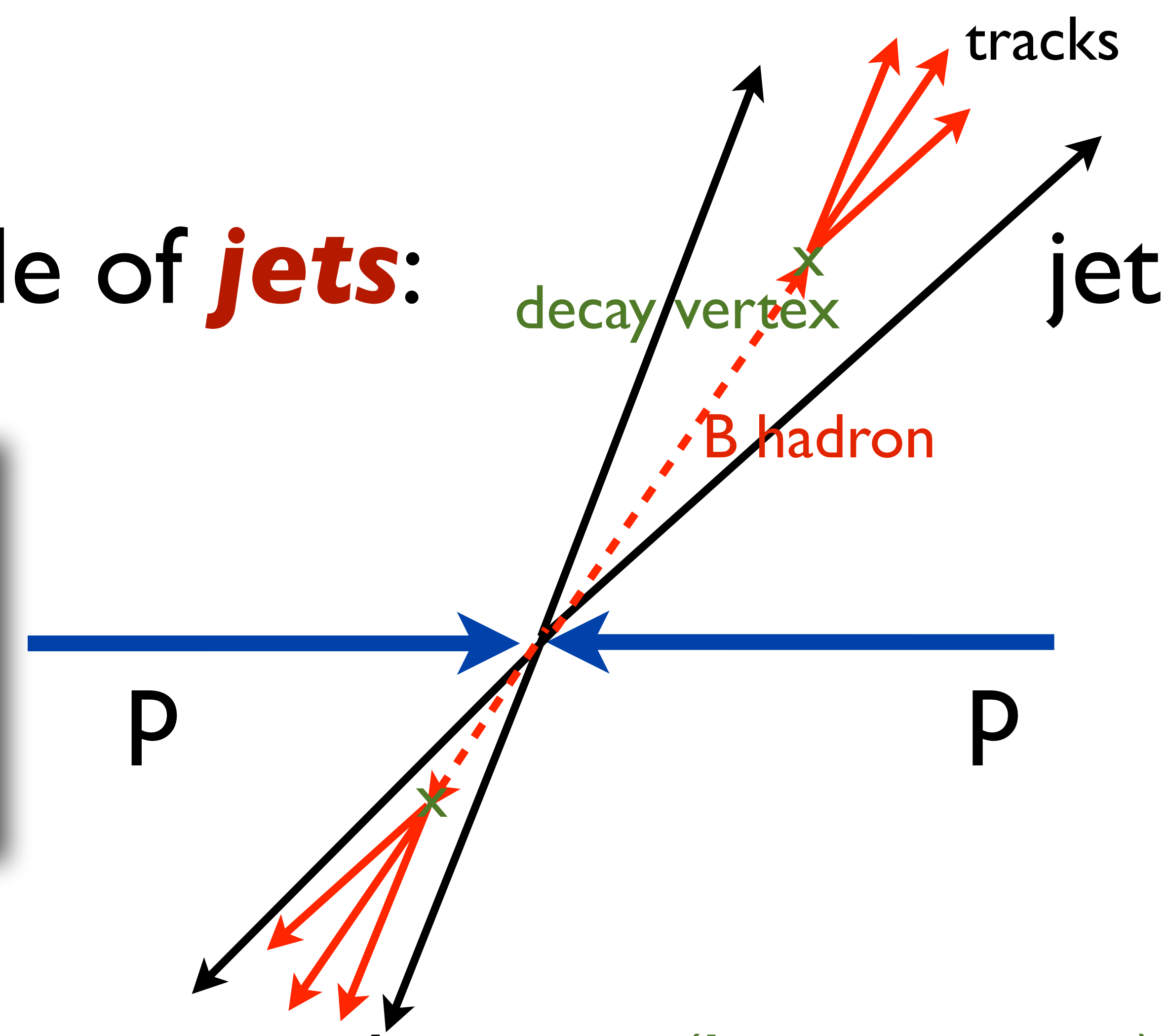
topological particle ID methods:

- extreme variety
- combination of information from different detectors


CMS
Compact Muon Solenoid

example: b-quarks

at hadron colliders (LHC)
B-hadrons are produced inside of ***jets***:



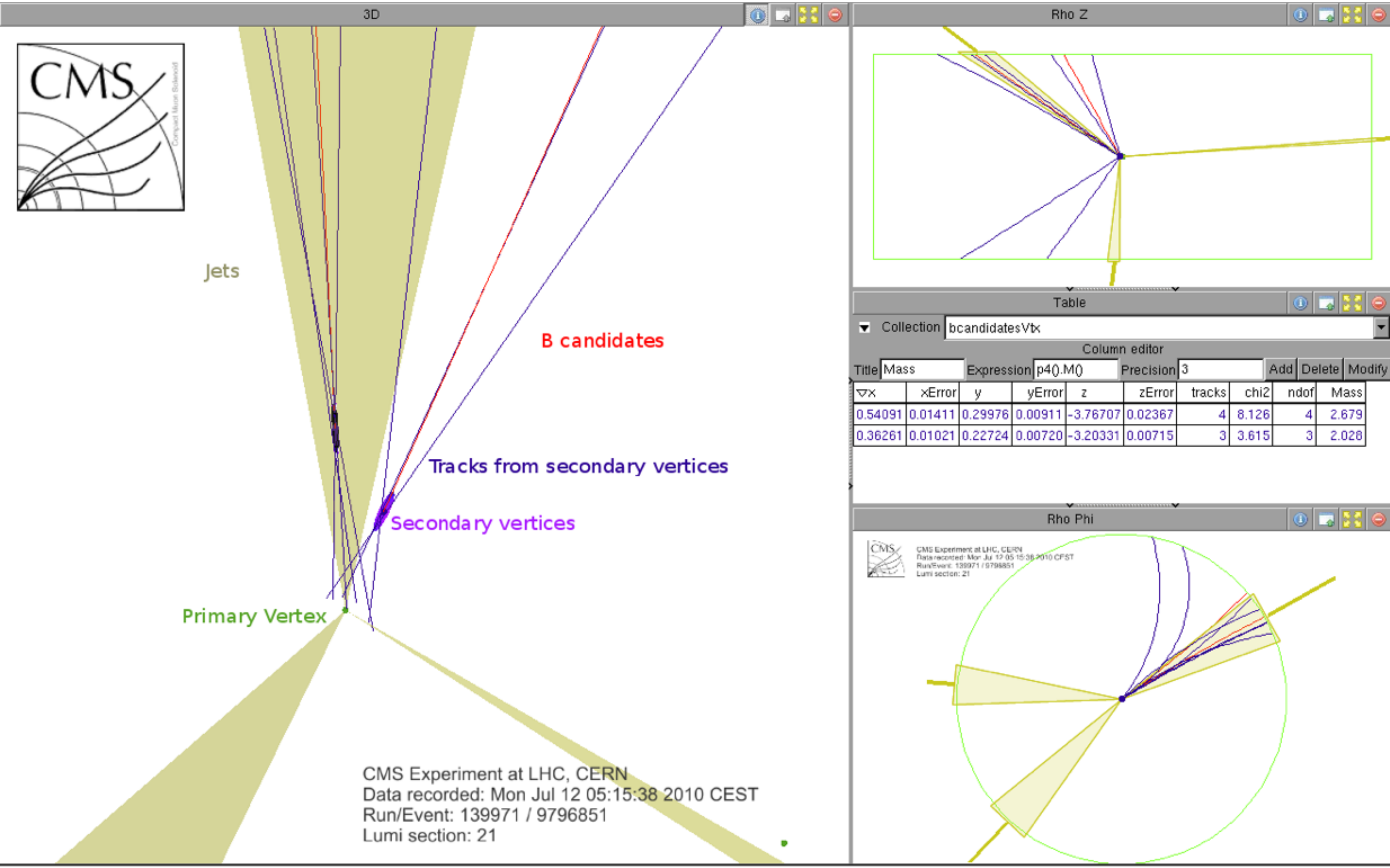
their ***lifetime*** (1.5ps) and the Lorentz boost lead to displaced decay vertices

inclusive:

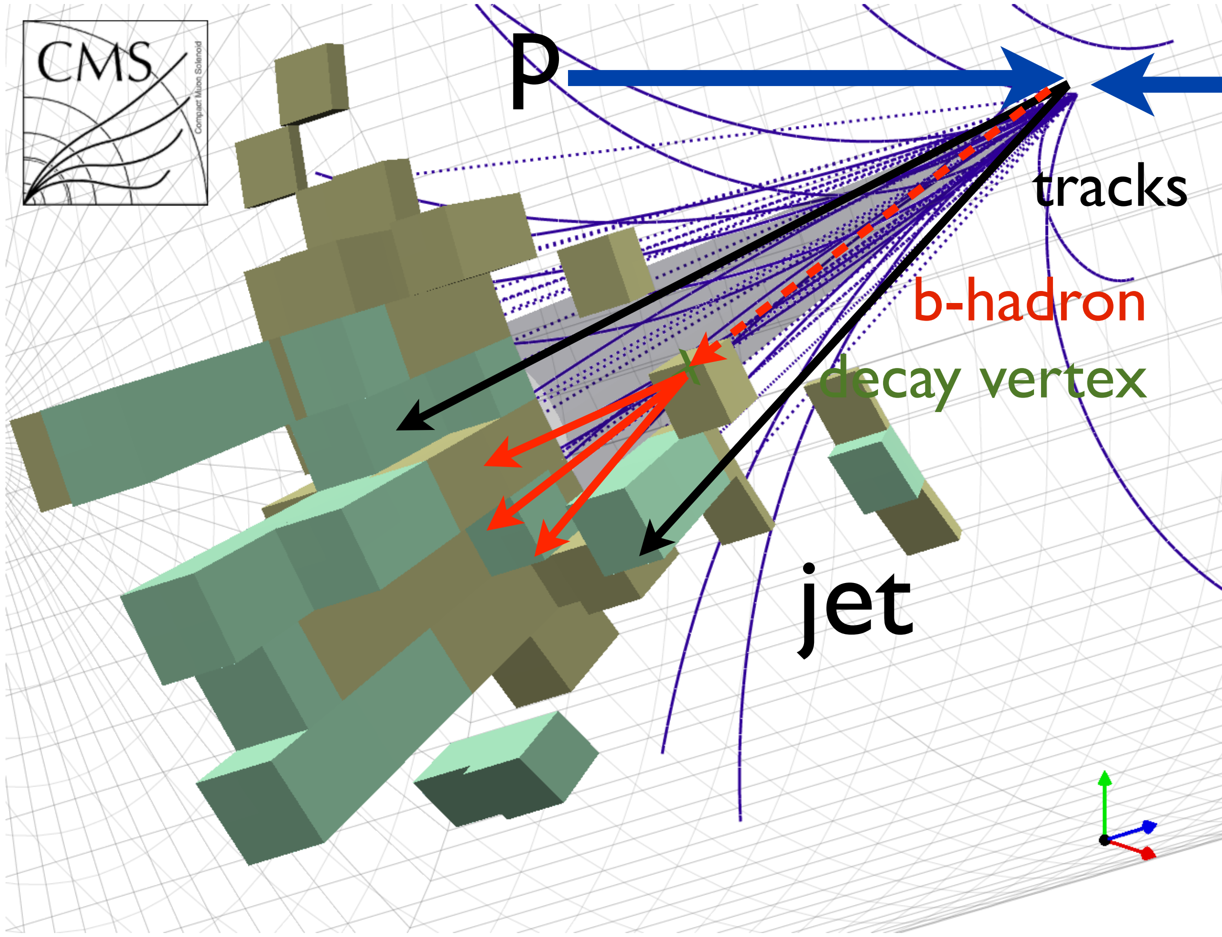
look for **displaced** tracks and vertices within jets *(b-jet tagging)*

exclusive:

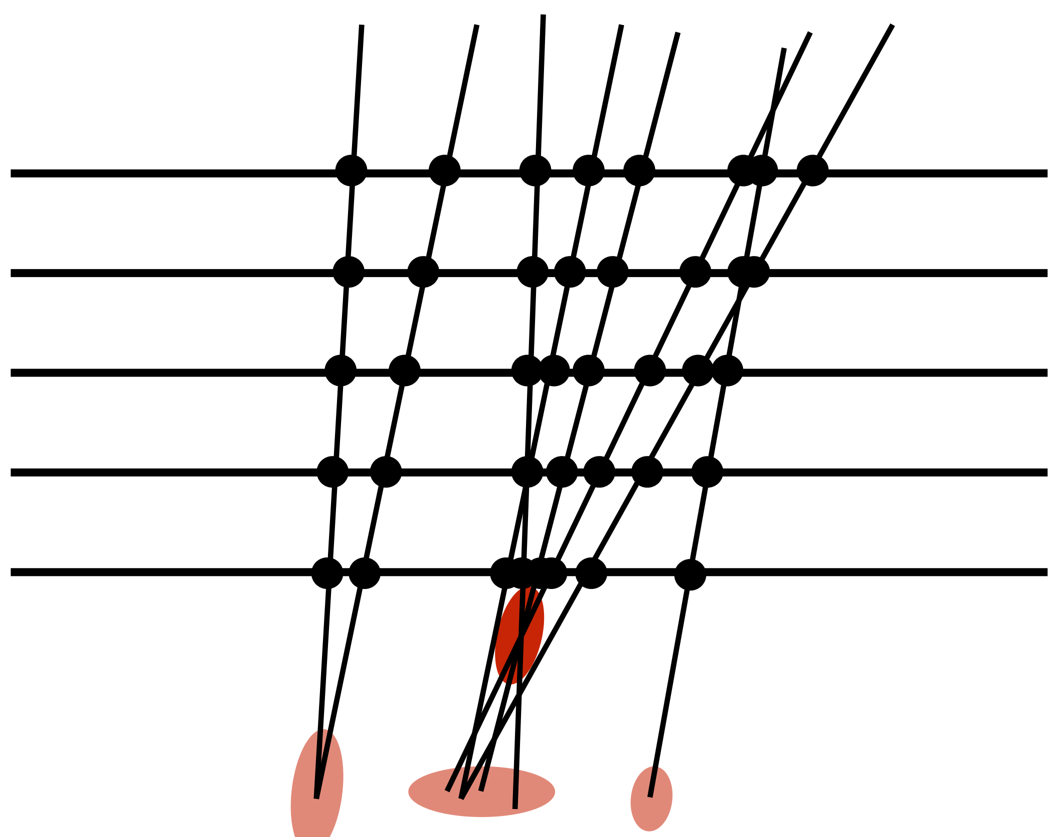
full reconstruction of the B meson four-vector using decays with $B \rightarrow J/\psi\ X$ with $J/\psi \rightarrow \mu^+\mu^-$



3D
Rho Z
Table
Rho Phi
CMS
Jets
B candidates
Tracks from secondary vertices
Secondary vertices
Primary Vertex
CMS Experiment at LHC, CERN
Data recorded: Mon Jul 12 05:15:38 2010 CEST
Run/Event: 139971 / 9796851
Lumi section: 21
Collection bcandidatesVtx
Column editor
Title Mass Expression p4().M() Precision 3 Add Delete Modify
x xError y yError z zError tracks chi2 ndof Mass
0.54091 0.01411 0.29976 0.00911 -3.76707 0.02367 4 8.126 4 2.679
0.36261 0.01021 0.22724 0.00720 -3.20331 0.00715 3 3.615 3 2.028



- **exploit properties** of b/c-flavoured hadrons in jets:
  - lifetime **(decay vertex)**
  - mass
  - momentum fraction
  - decay modes

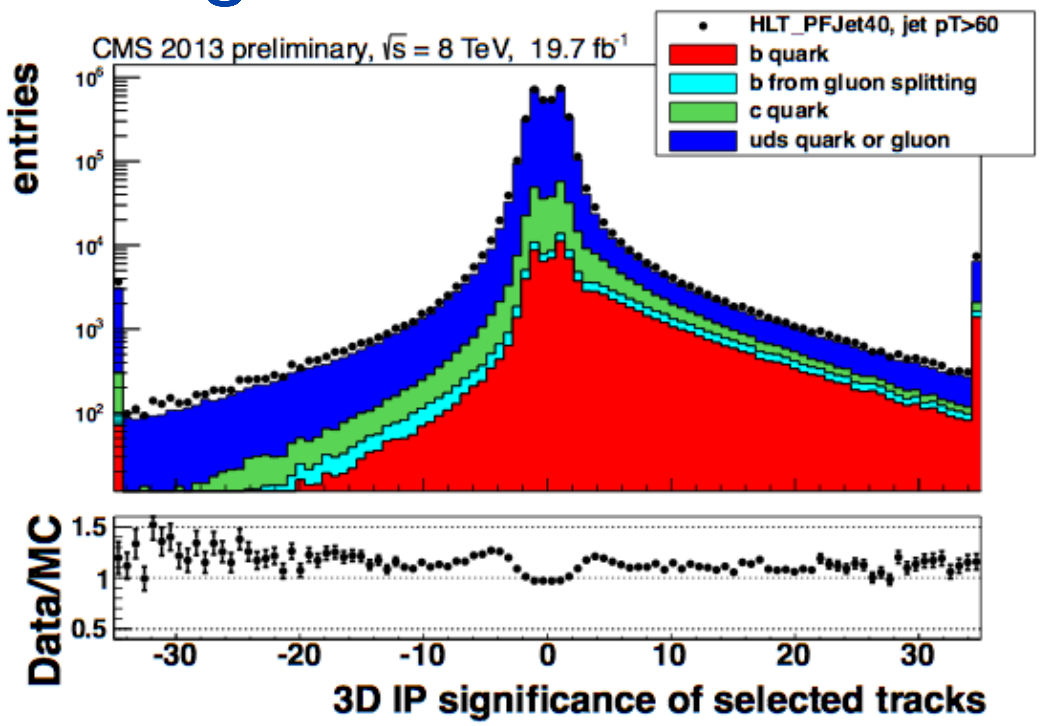


- combine information with deep learning methods

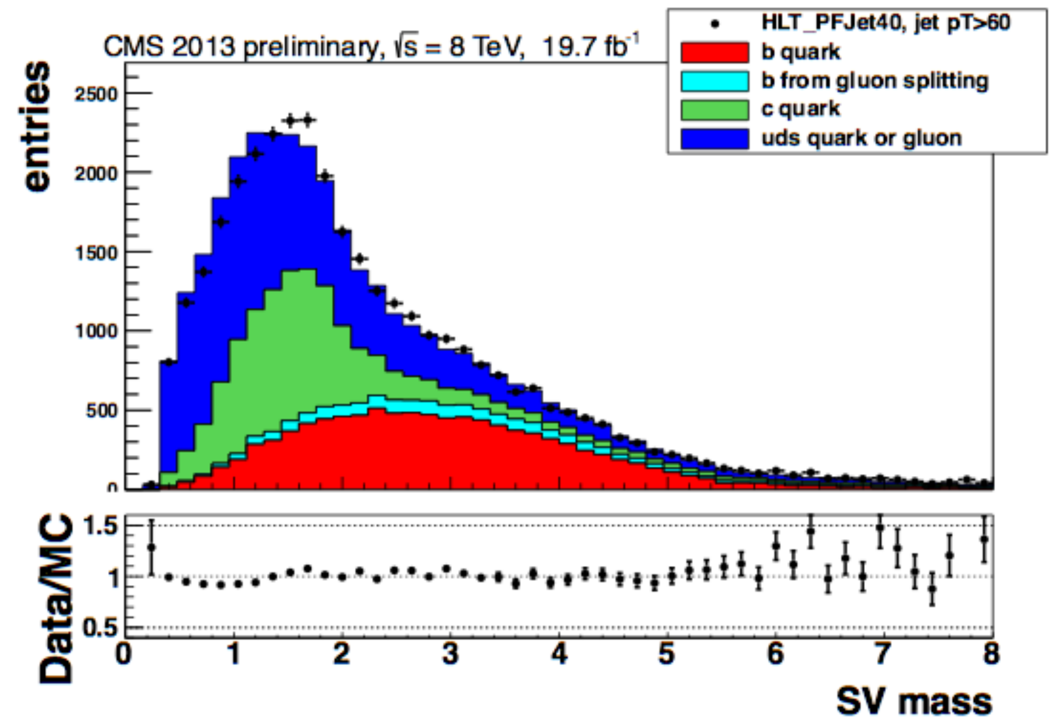
jet flavour identification

- characteristic properties to separate b-jets from non-b-jets:

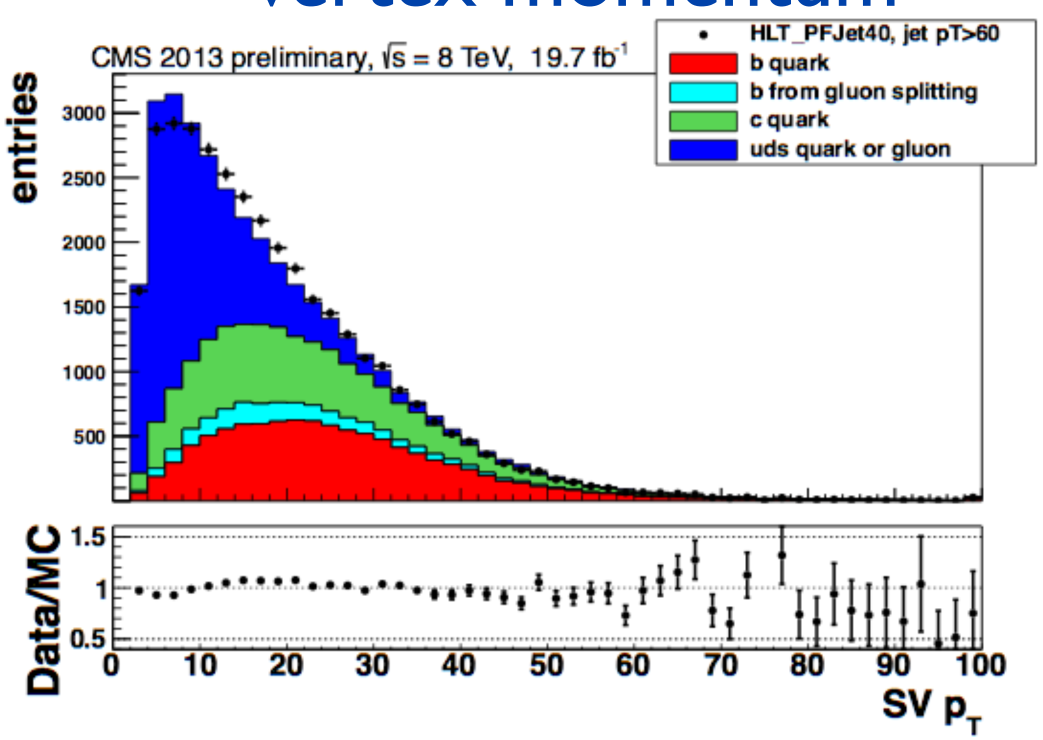
IP significance == IP/error



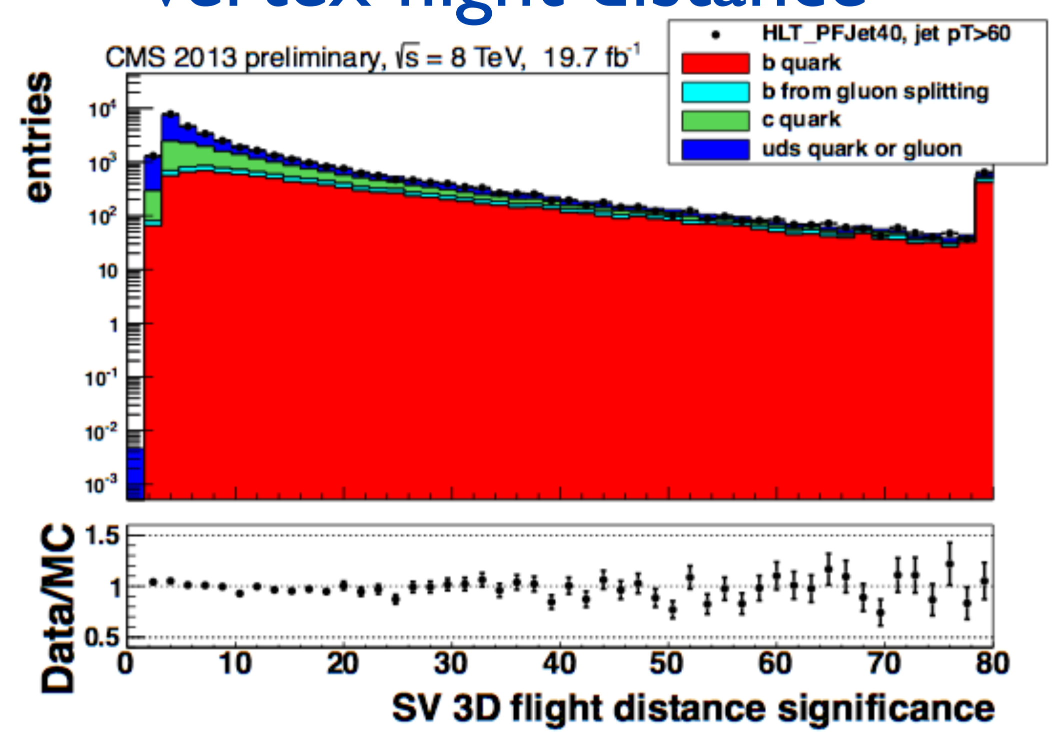
invariant mass of vertex



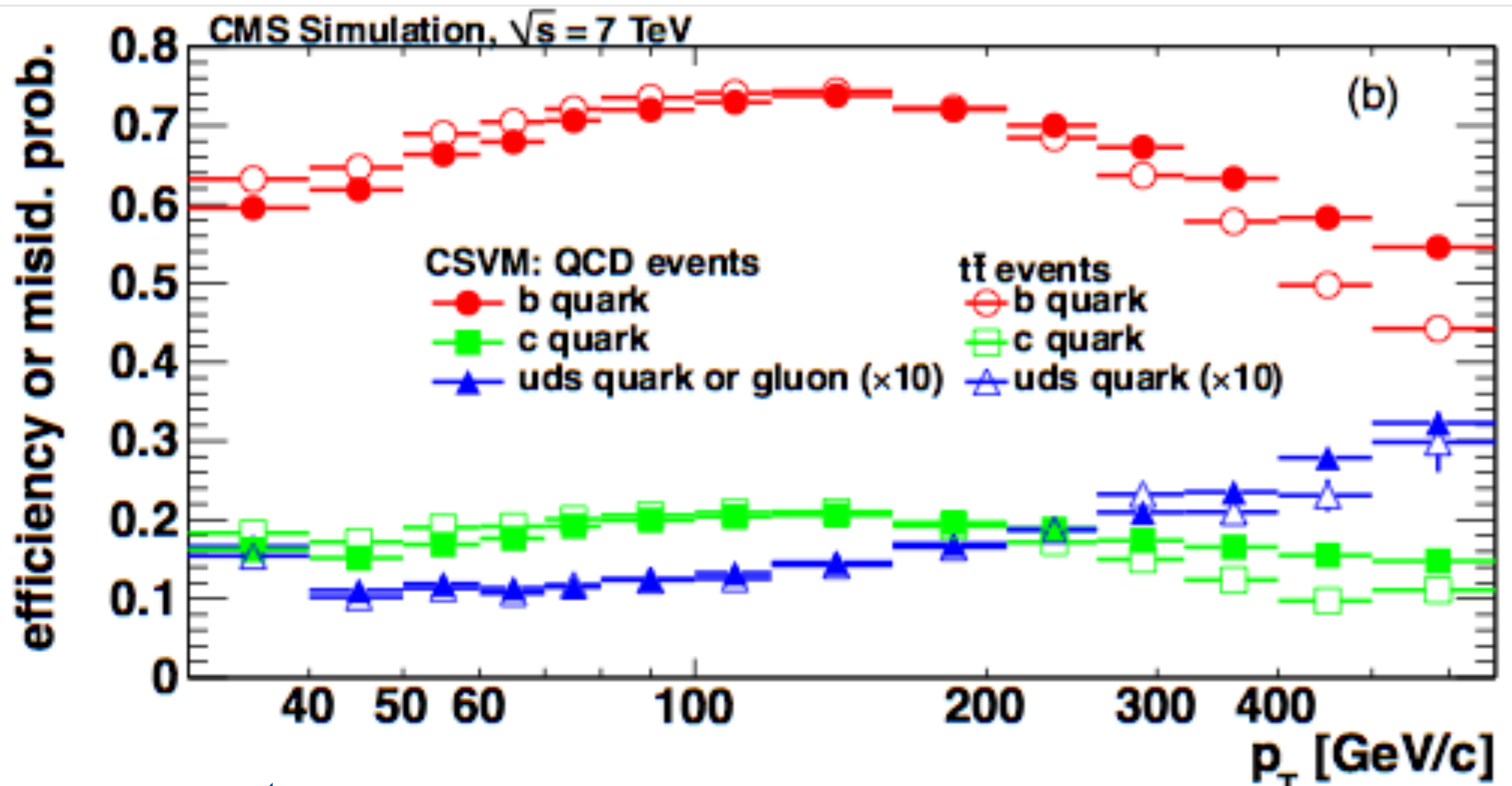
vertex momentum



vertex flight distance



example: b-quarks



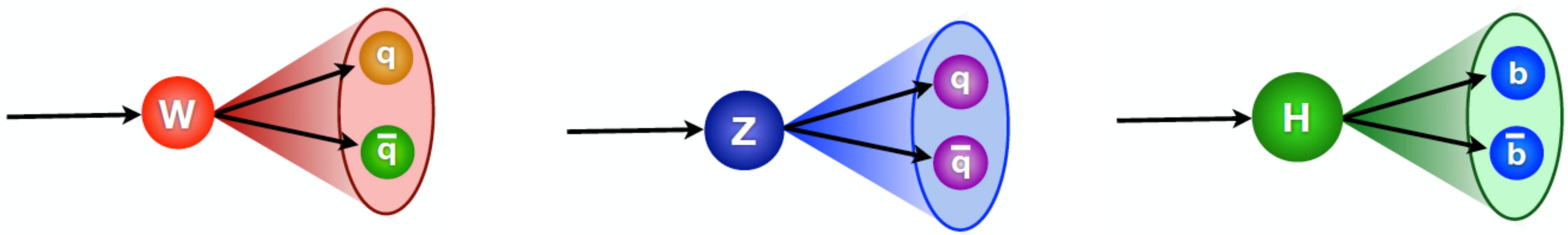
low-momentum:

- more multiple coulomb scattering
- smaller Lorentz factor → B hadron decays closer to primary vertex (more difficult to resolve)

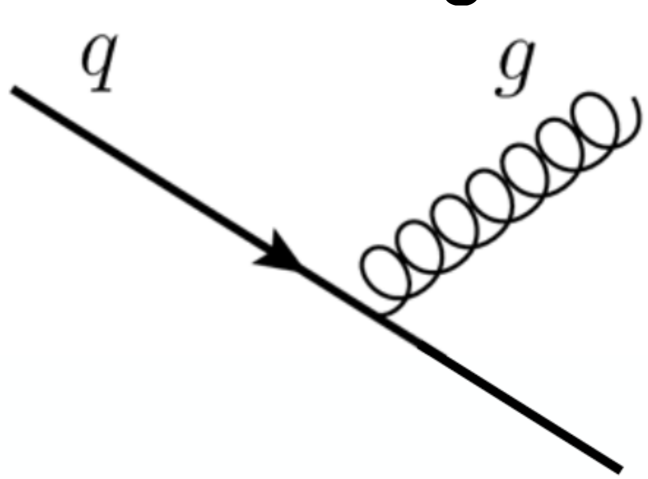
high-momentum:

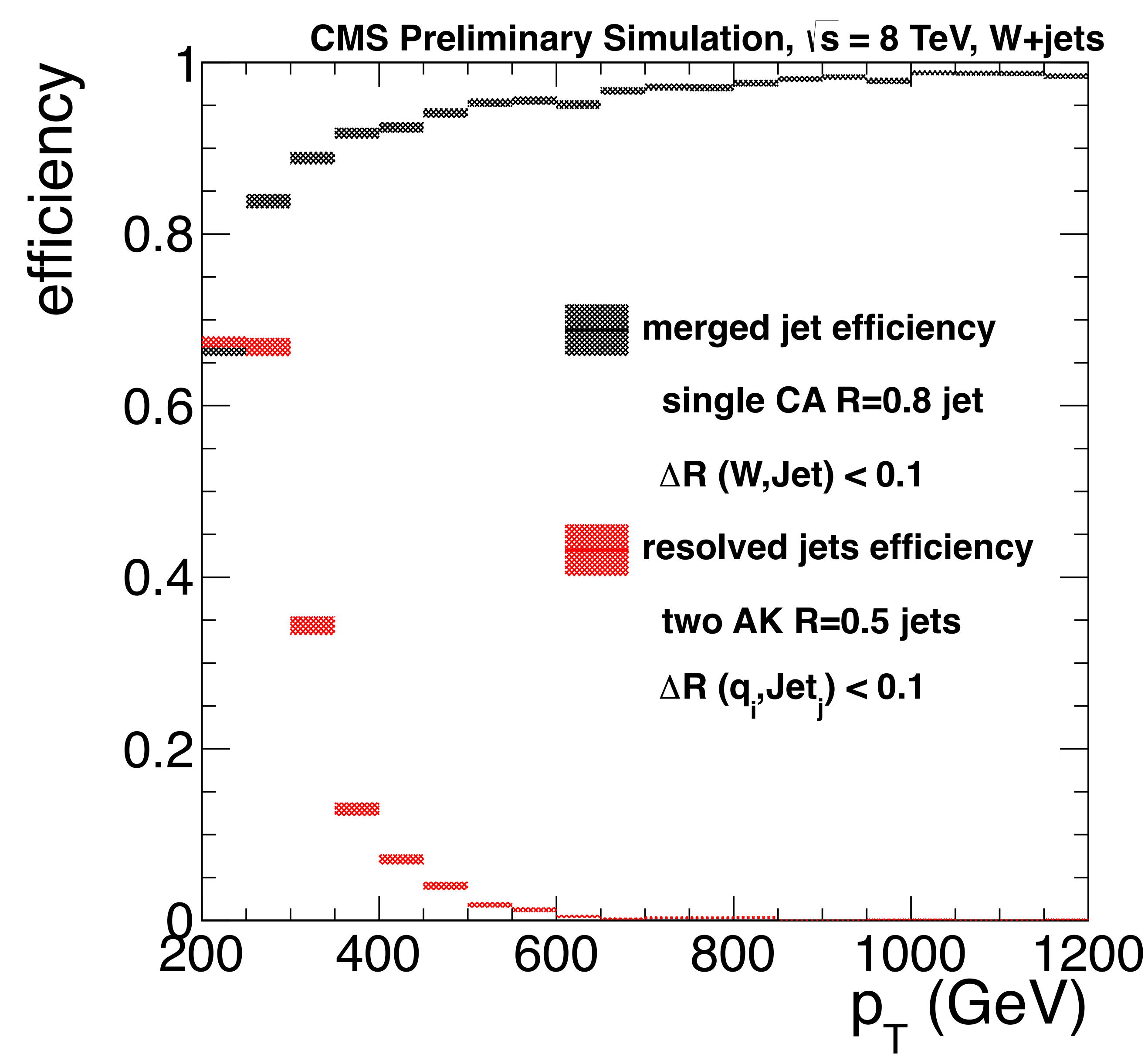
- more collimated jets
- dense environment difficult for tracking
- smaller track curvature
- close-by-tracks create overlapping hits in the detector

2-body decay

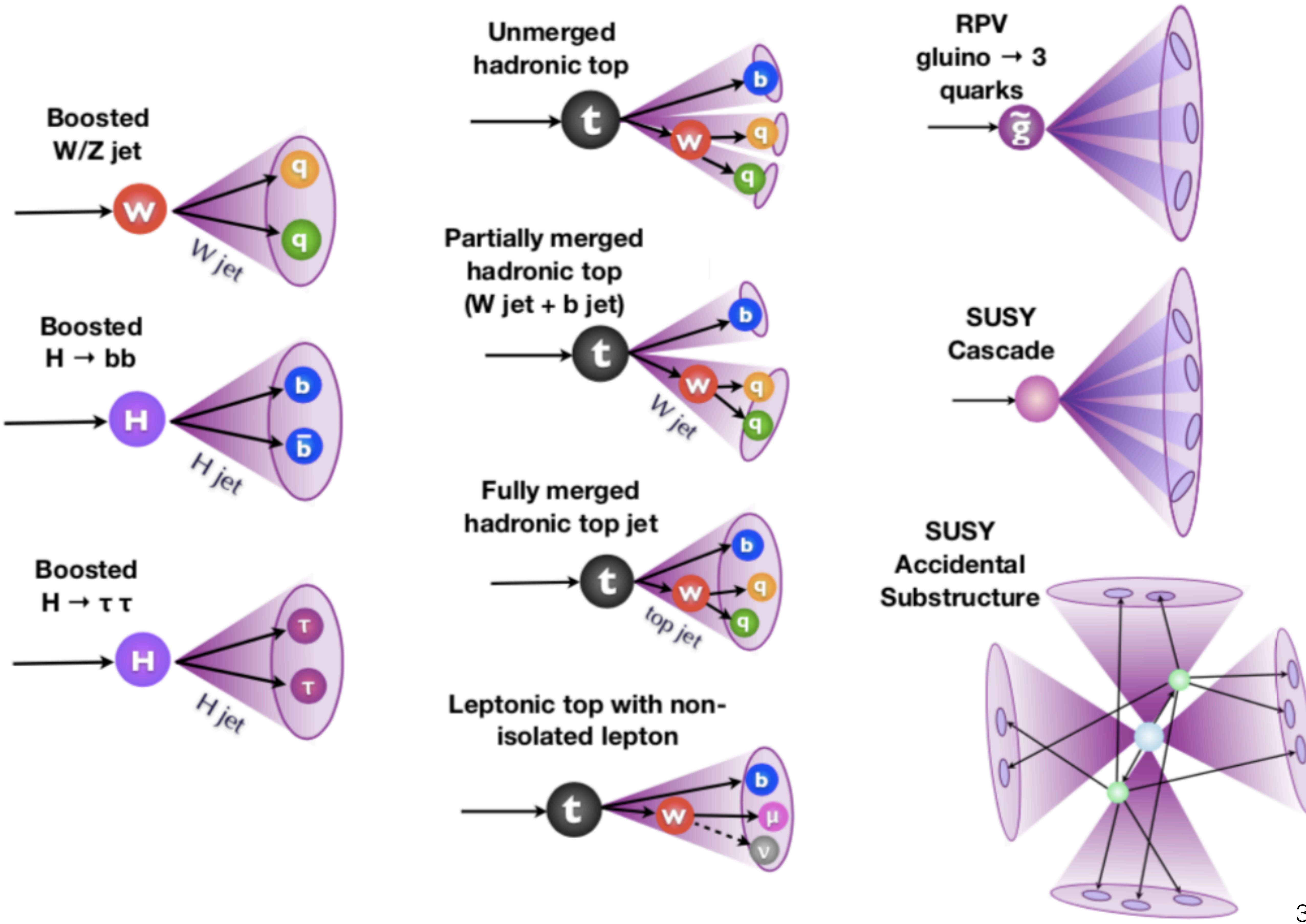


- angular separation
  $\Delta R \approx 2M/p_T$
- efficiency for 2 jets drops with p_T
- how to distinguish from QCD:

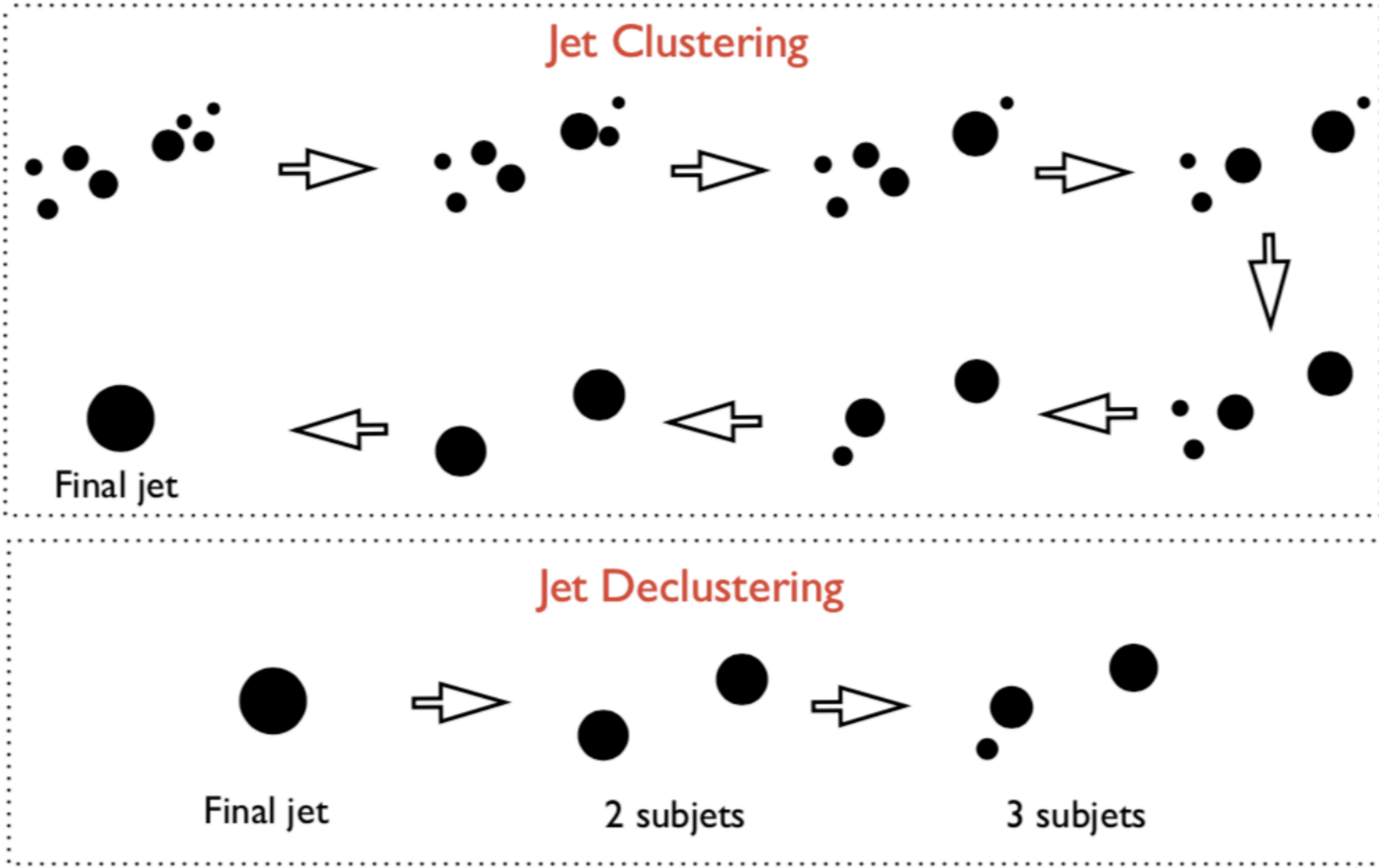




boosted topologies



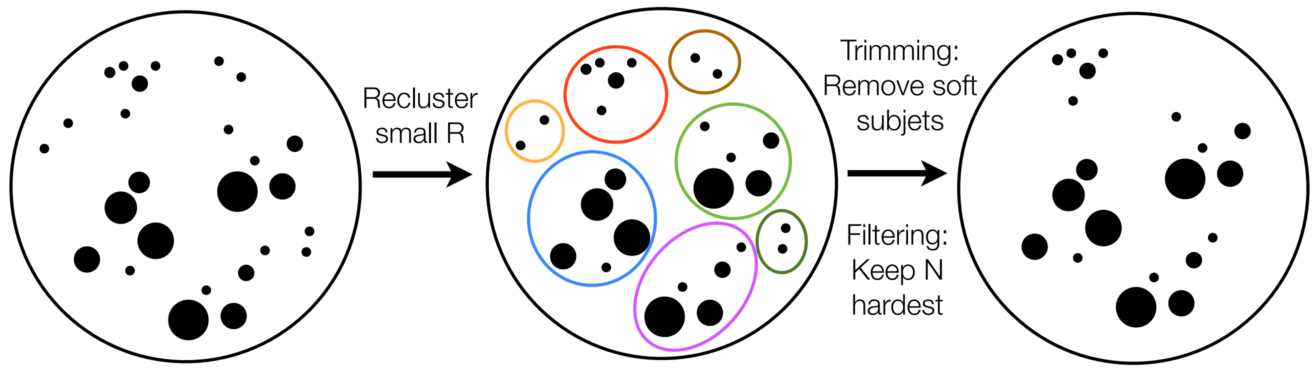
jet substructure: declustering



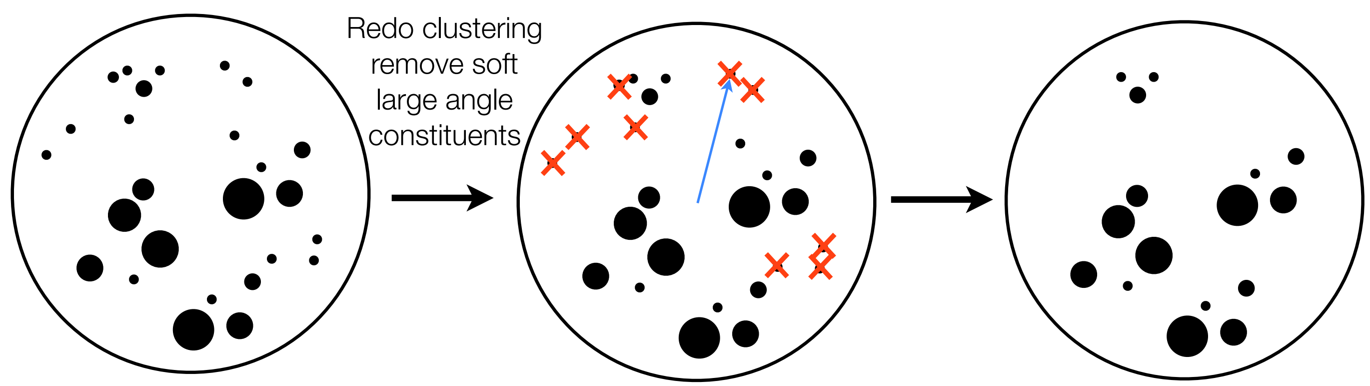
boosted topologies: jet grooming

J. Dolen

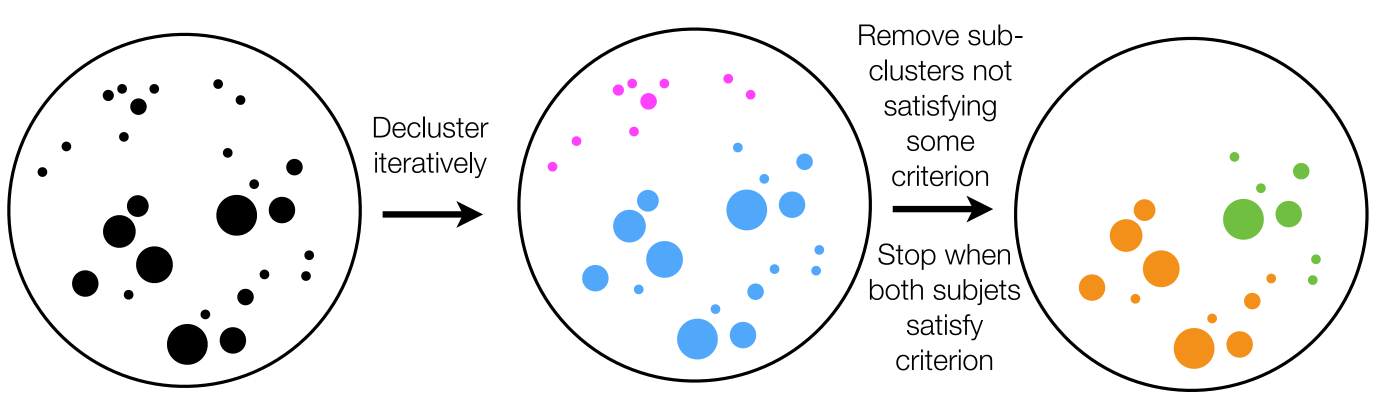
Trimming, Filtering - Recluster jet with smaller distance parameter. Condition based subjet removal.



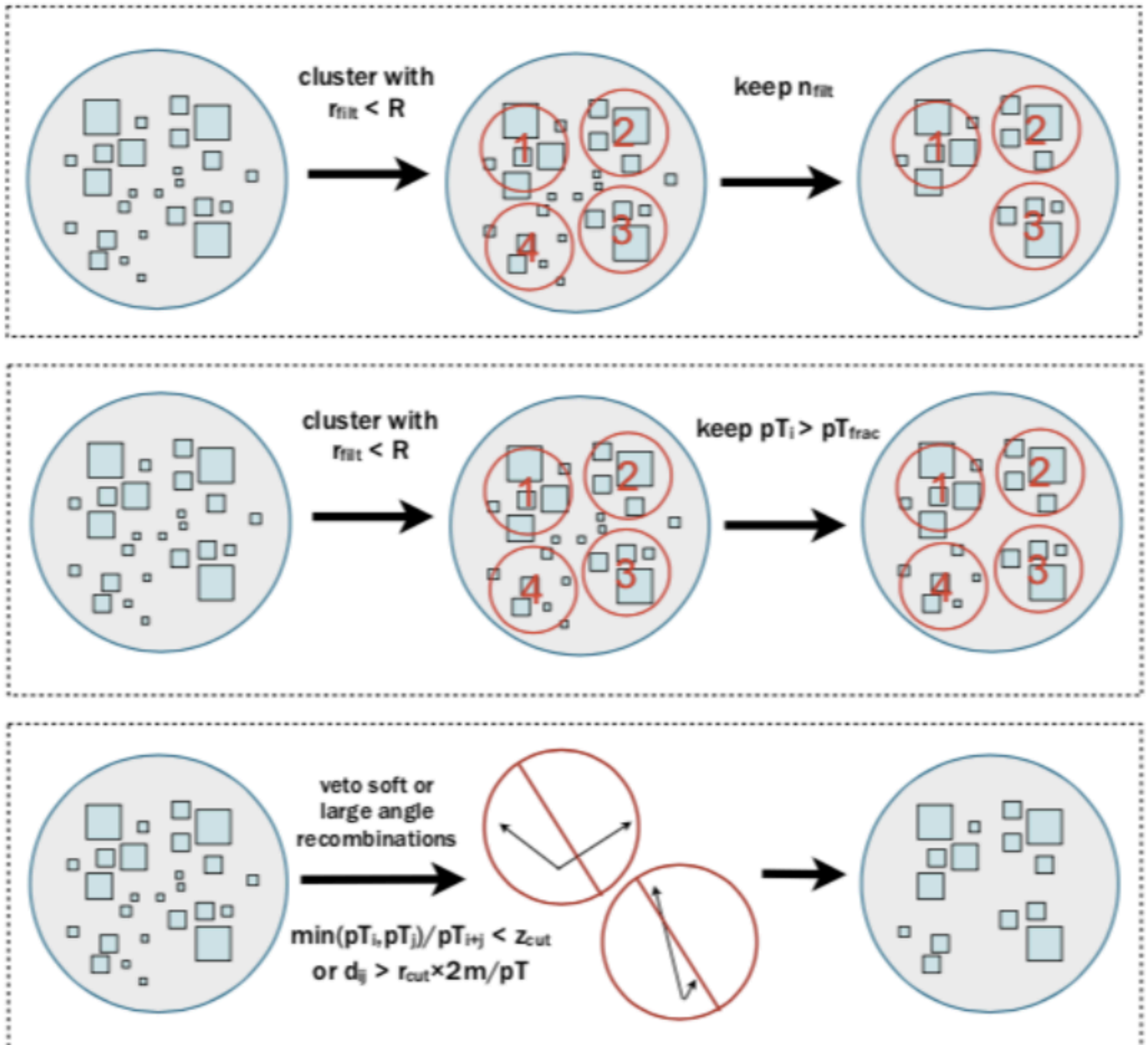
Pruning - Recluster jet. Remove soft large angle particles.



BDRS, MMDT, Soft Drop, JHU top tagger, CMSTT - Recursively decluster jet. Remove sub-clusters not satisfying algorithm condition. Stop declustering when both subjets satisfy condition.



boosted topologies: jet grooming



filtering — default: $r_{filt} = 0.3$, $n_{filt} = 3$

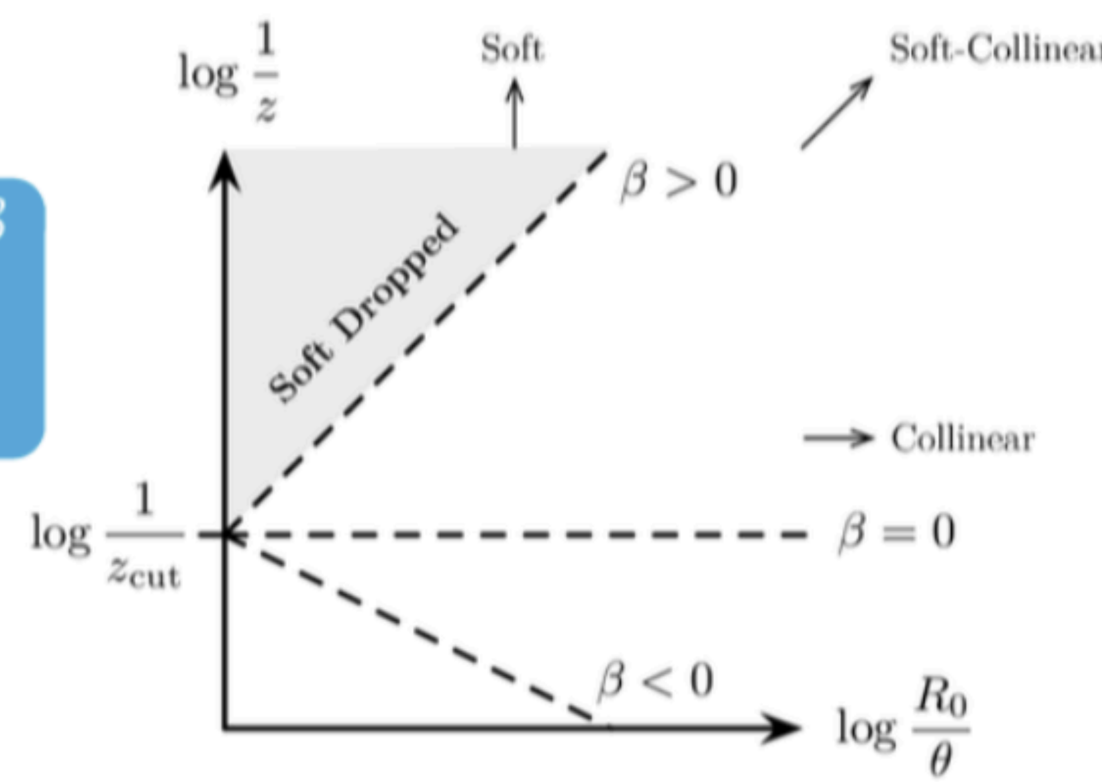
trimming — default: $r_{filt} = 0.2$, $pT_{frac} = 0.03$

pruning — default: $z_{cut} = 0.1$, $r_{cut} = 0.5$

boosted topologies: jet grooming

soft-drop algorithm:

1. Undo last stage of CA clustering tree and label two subjets j_1, j_2 of jet j.
2. If
$$z_g = \frac{\min(p_{t,1}, p_{t,2})}{p_{t,1} + p_{t,2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0} \right)^{\beta}$$
then j is the soft-dropped jet.
3. Otherwise define j to be the harder subjet and iterate.



- For $\beta = 0$, drops soft radiation entirely.
- Provides handle on UE and PU, identifying hard substructure.

boosted topologies: jet grooming