Example 3: fixed target and forward spectrometer experiments

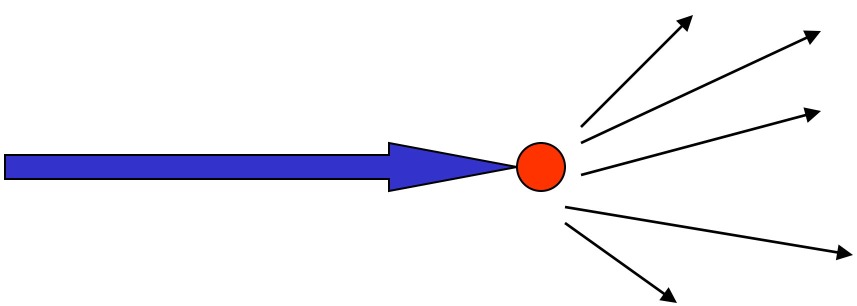
Peter Križan

Particle physics experiments

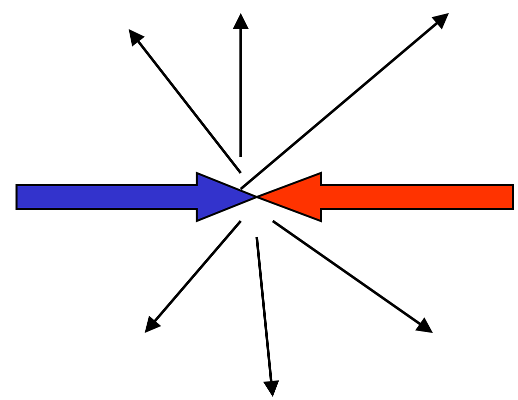
Accelerate elementary particles, let them collide →
energy released in the collision is converted into mass of new particles, some of which are unstable

Two ways how to do it:

Fixed target experiments

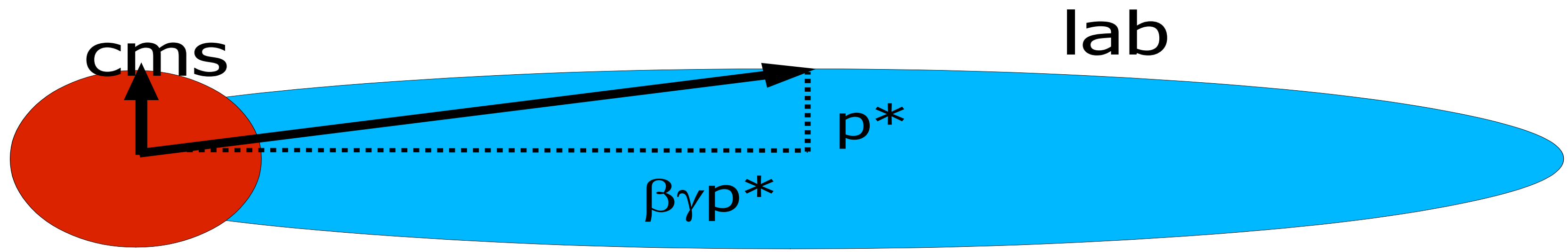


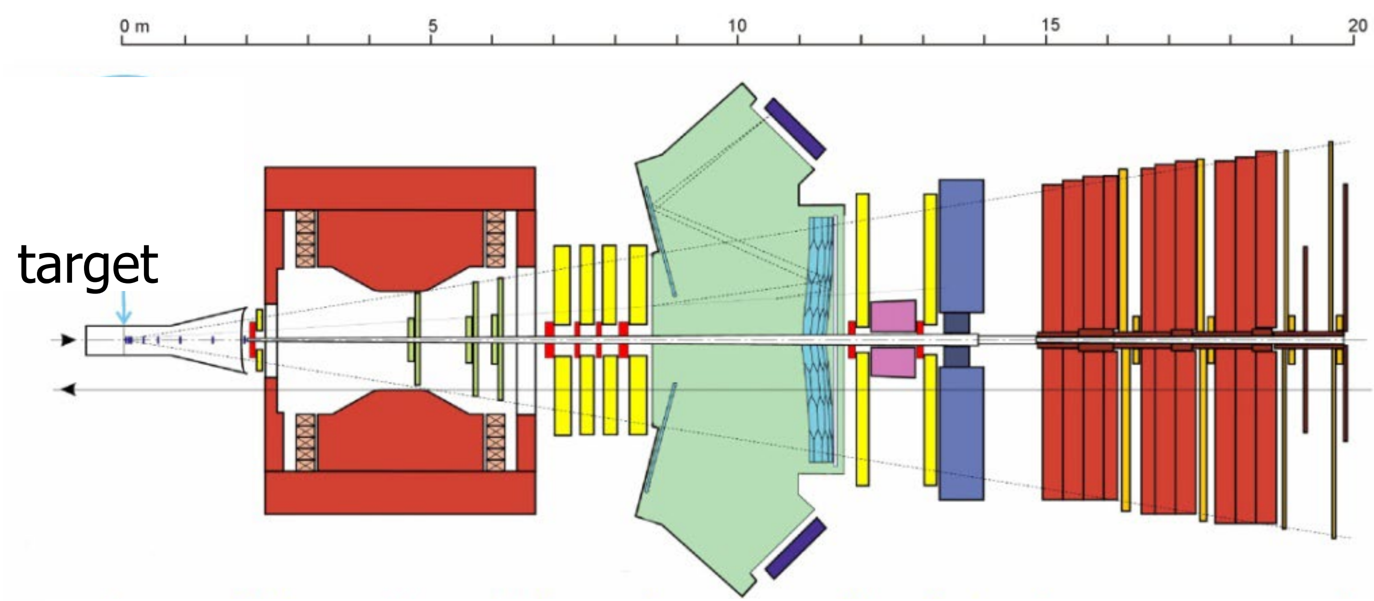
Collider experiments



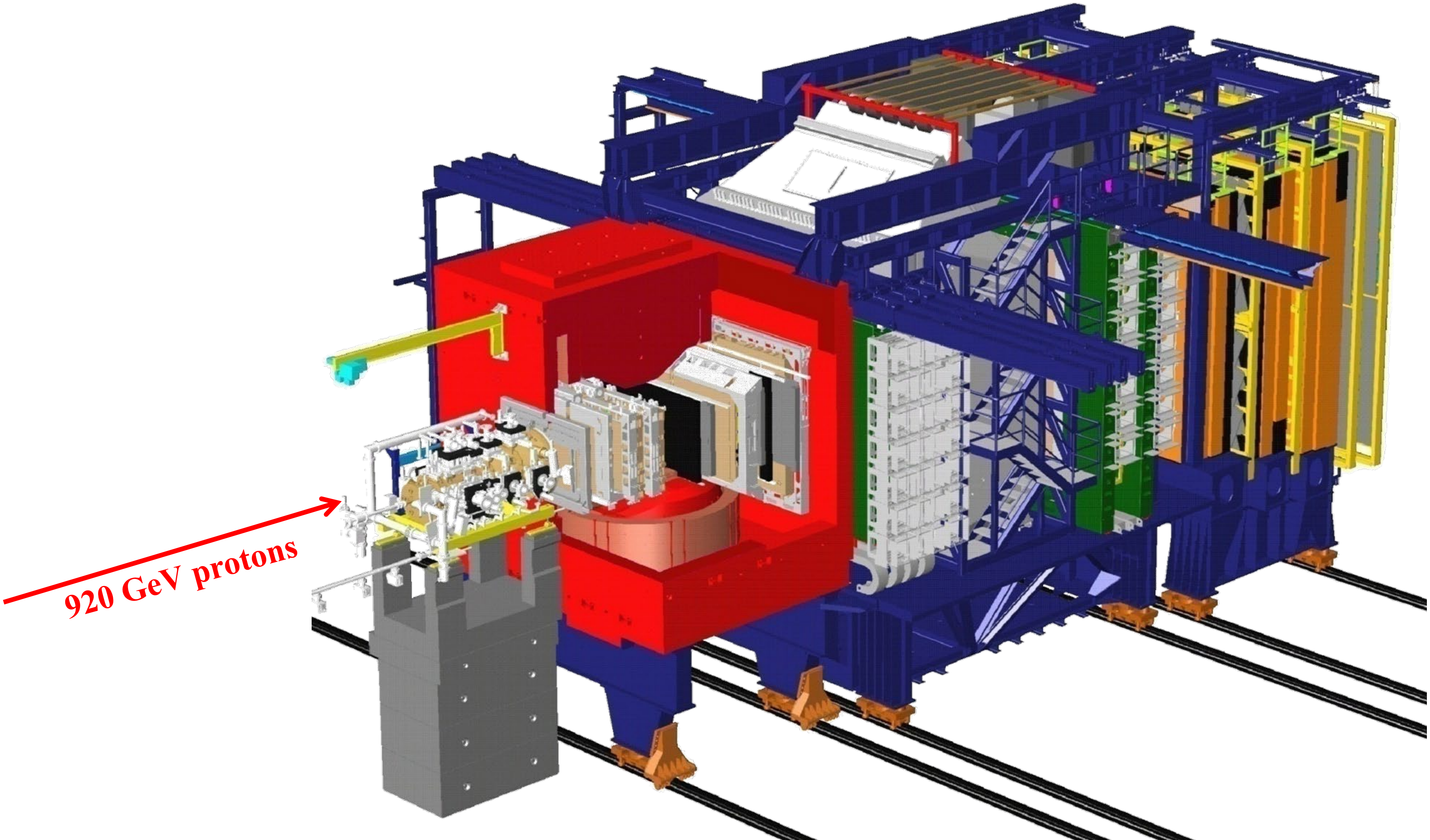
Experimental aparatus

Detector form: symmetric for colliders with symmetric energy beams; extended in the boost direction for an asymmetric collider; very forward oriented in fixed target experiments.

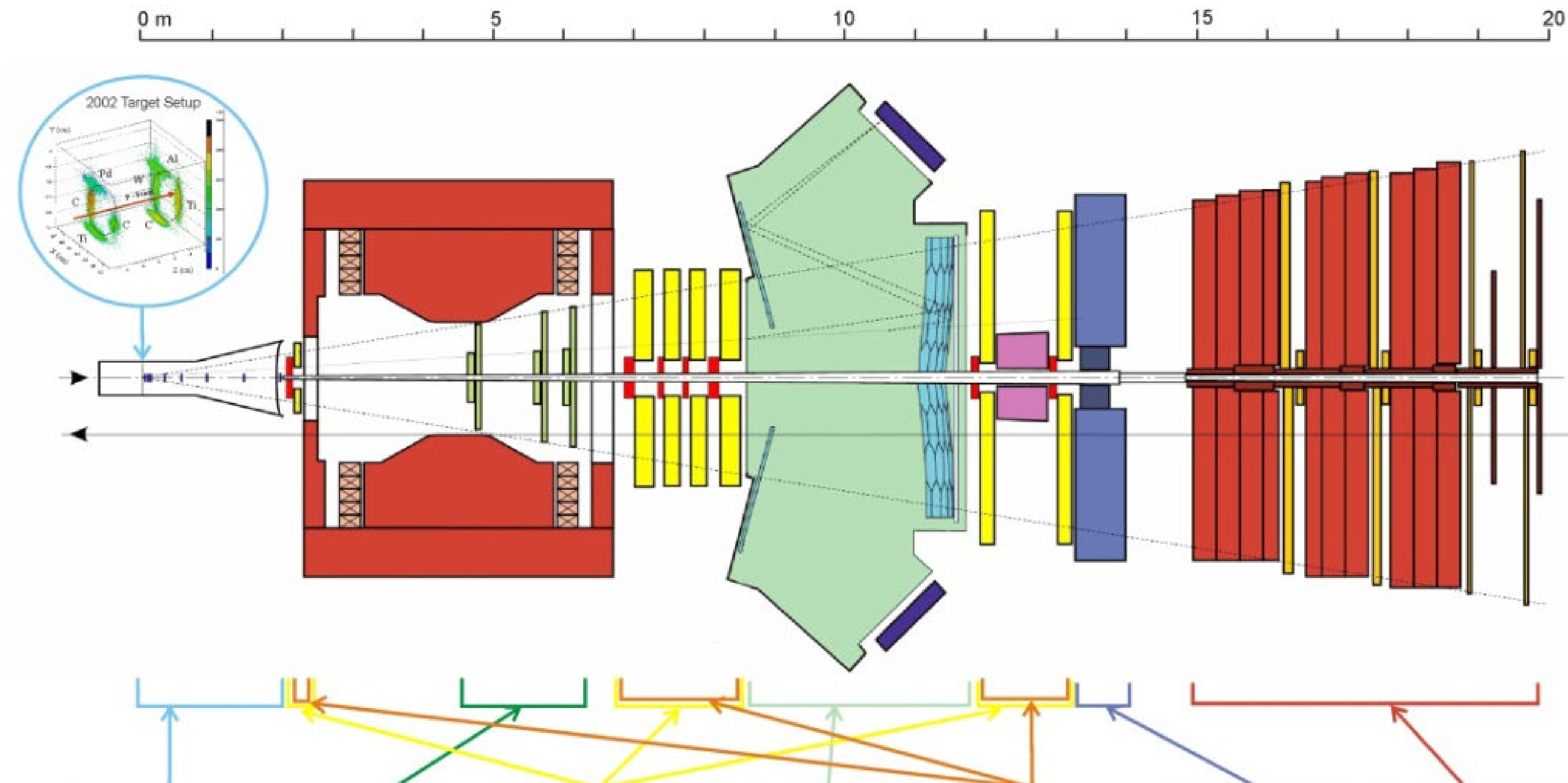




Example of a fixed target experiment: HERA-B



Example of a fixed target experiment: HERA-B



Target & Vertex
8 layers of double-sided Si-microstrips, movable on Roman-Pots; 8 wire-target (see above)

High p_T
3 superlayers gas, pixel and pad chambers; pre-trigger for high p_T tracks

Outer Tracker
7 superlayers of honeycomb drift chambers, 5 and 10mm cells

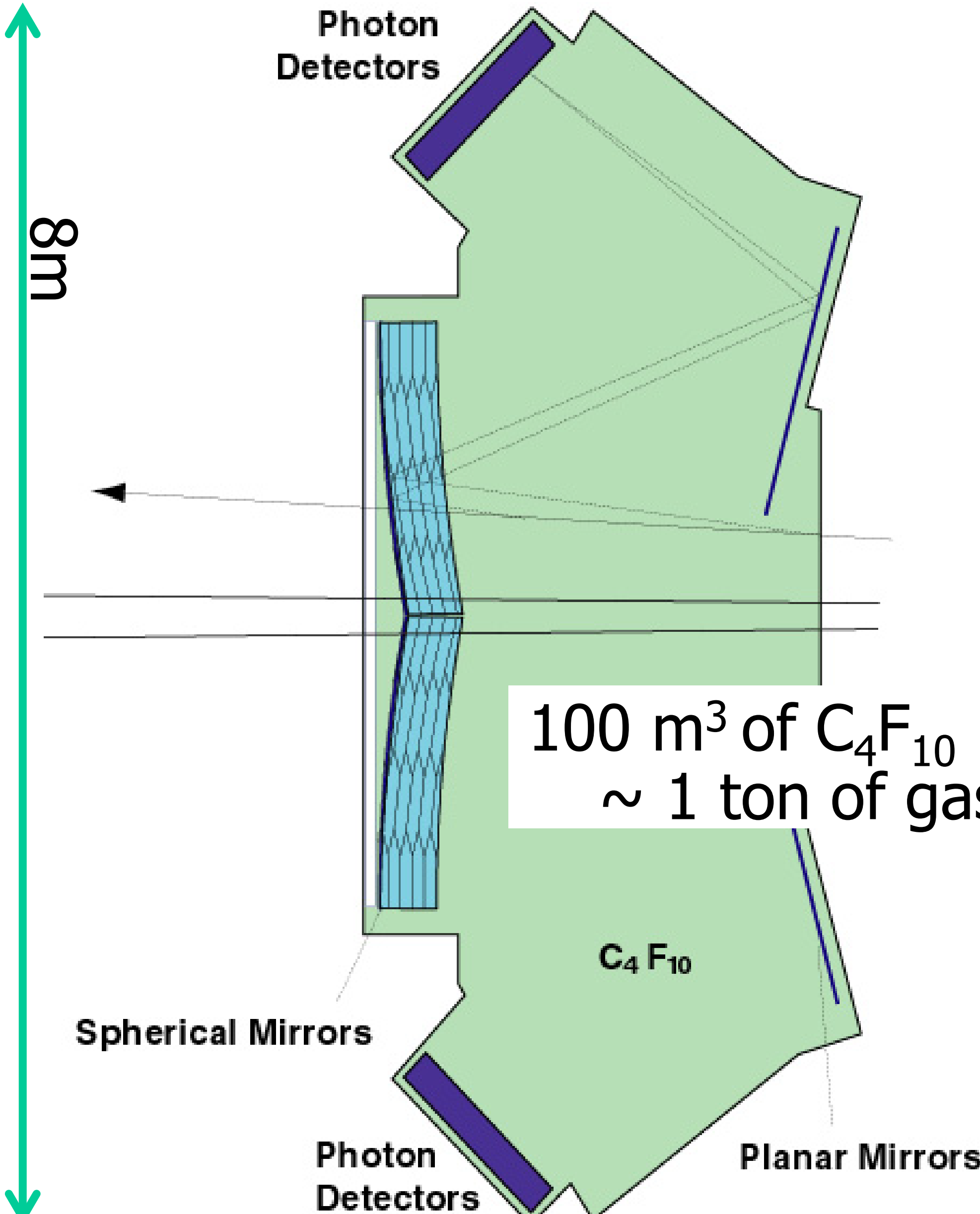
RICH
Spherical mirror inside C_4F_{10} radiator, Lens-enhanced multianode PMT focal plane.

Inner Tracker
7 superlayers of Micro Strip Gas Chambers with GEM-foil

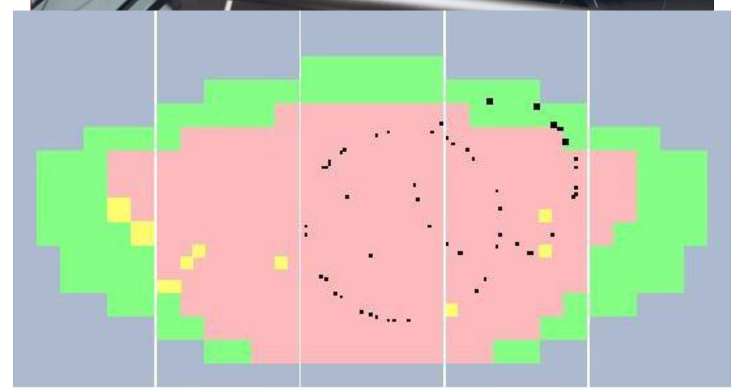
Electromagnetic Calorimeter
W/Pb scintillator sandwich, shashlik WLS readout with PMTs; energy-cluster pre-trigger

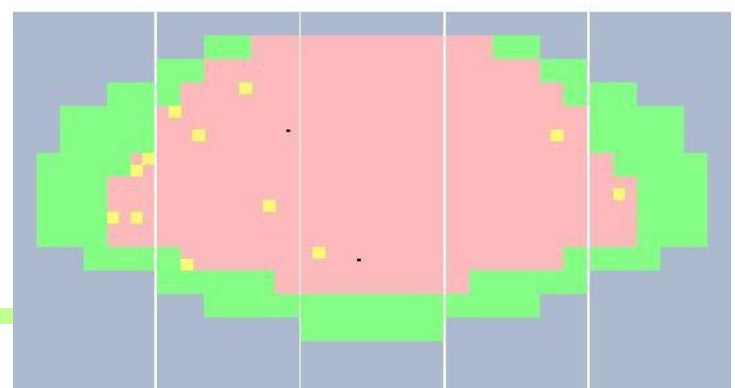
Muon System
4 superlayers of gas-pixel, tube & pad chambers; pad-coincidence pre-trigger

HERA-B RICH

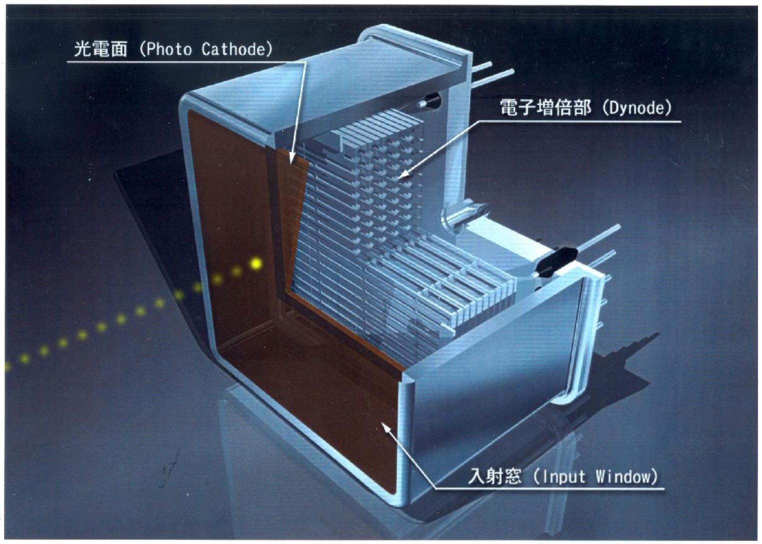


100 m^3 of C_4F_{10}
~ 1 ton of gas

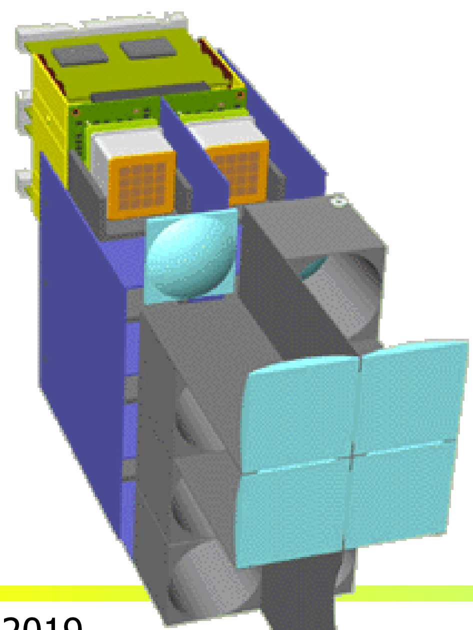


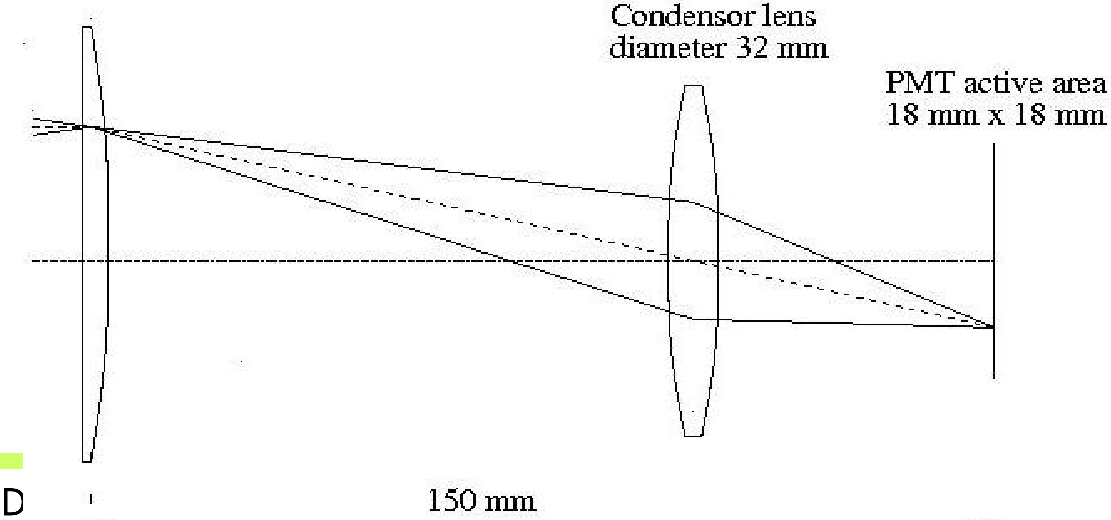


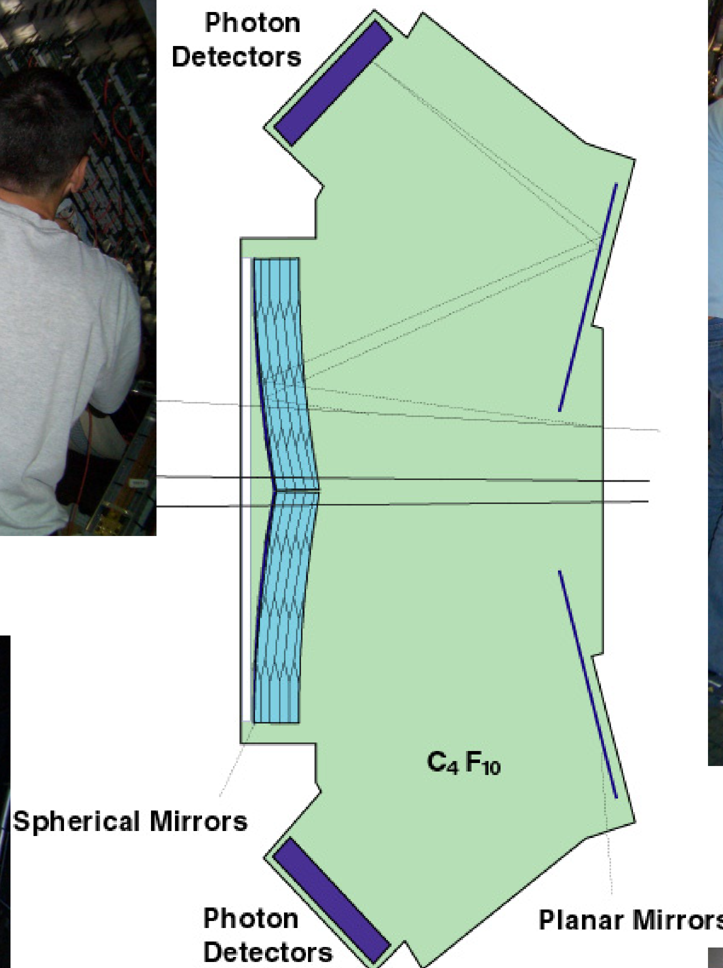
RICH: multianode PMTs as photosensors



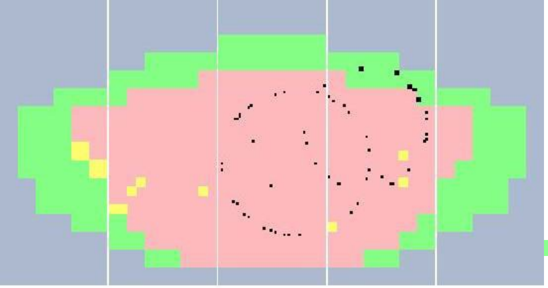
Multianode PMTs with metal foil dynodes and 2x2, 4x4 or 8x8 anodes Hamamatsu R5900 (and follow up types 7600, 8500)

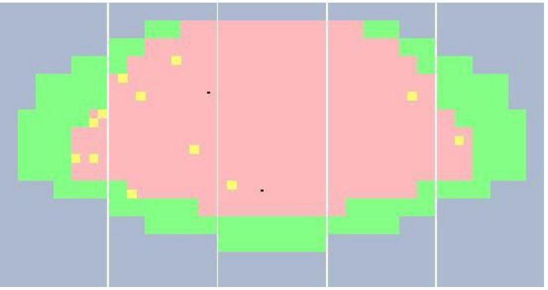




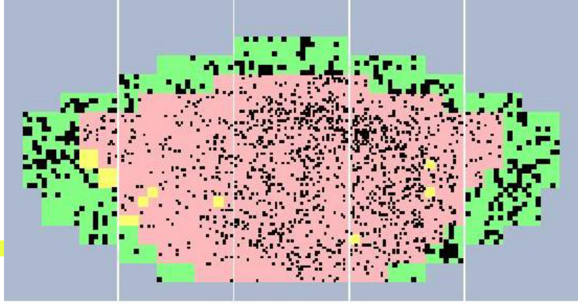

Photon Detectors
$C_4 F_{10}$
Spherical Mirrors
Photon Detectors
Planar Mirrors

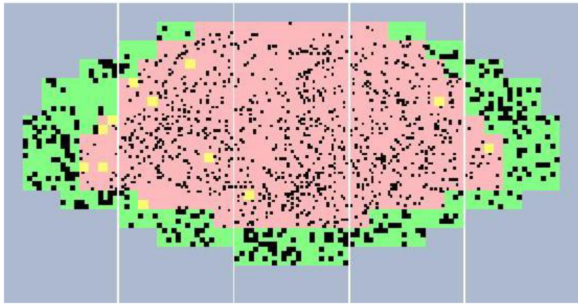
HERA-B RICH





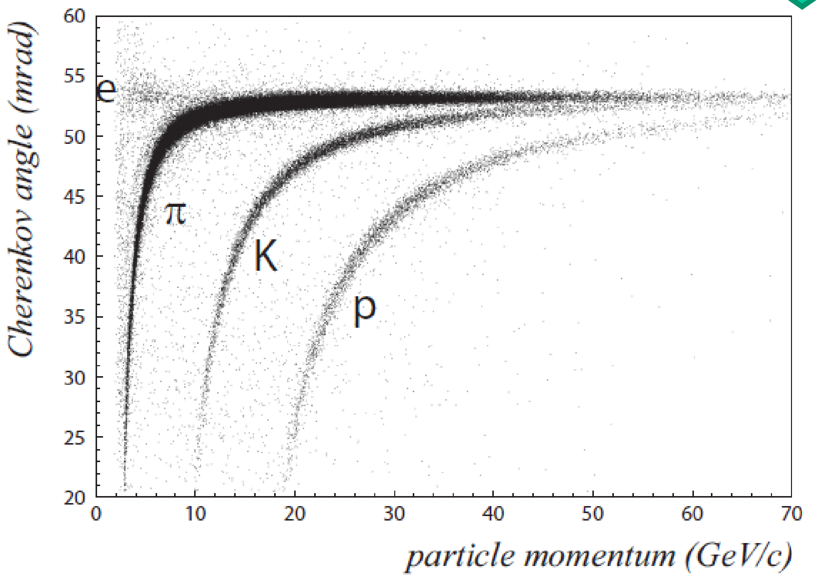
← Little noise, ~30 photons per ring

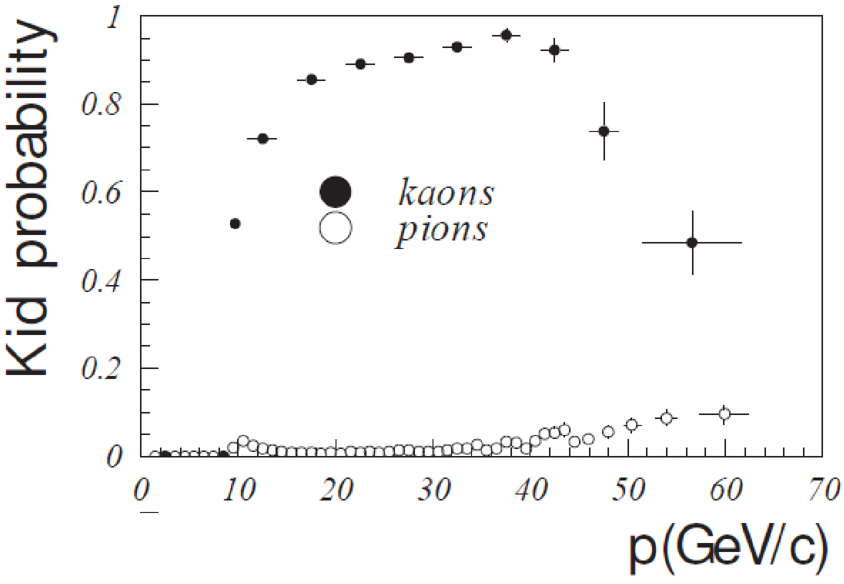




Typical event →

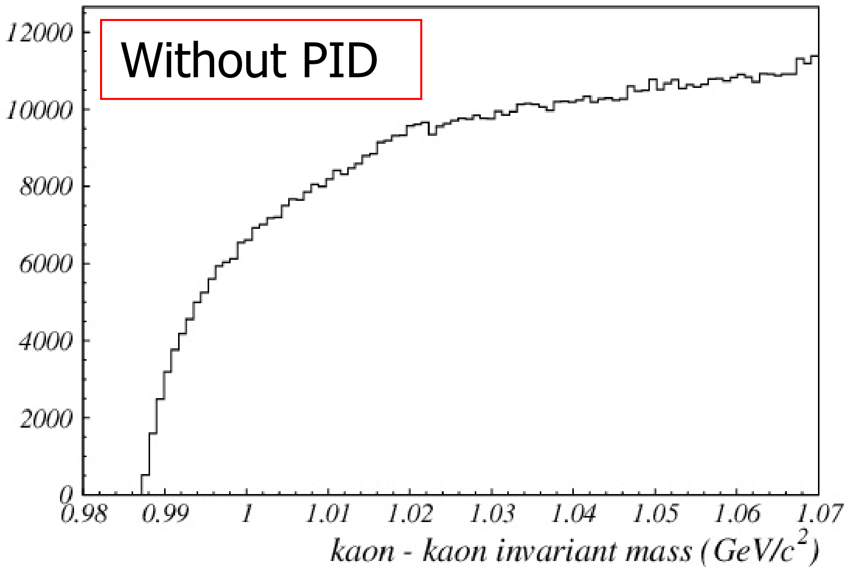
Worked very well!

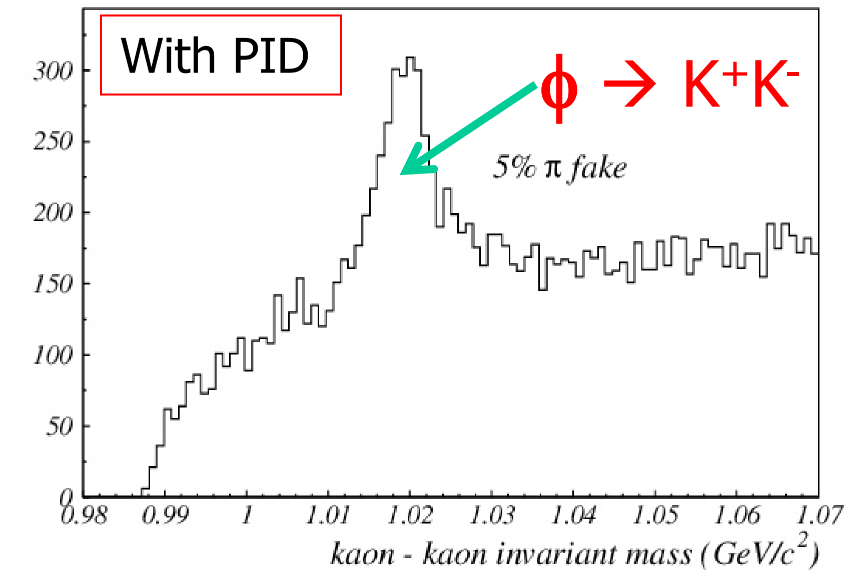




Kaon efficiency and pion fake probability

Importance of PID





K^+K^- invariant mass

- For all pairs of oppositely charged particles

- For those that were identified as kaons

The $\phi \rightarrow K^+K^-$ decay only becomes visible after particle identification is taken into account.

B physics at LHC: b-production in pp collisions at LHC

- Pairs of $b\bar{b}$ quarks are mostly produced in the forward/backward direction:

$$\boxed{\sigma_{b\bar{b}} = 500\mu b}$$

$10^{12}\, b\bar{b}$ produced per year

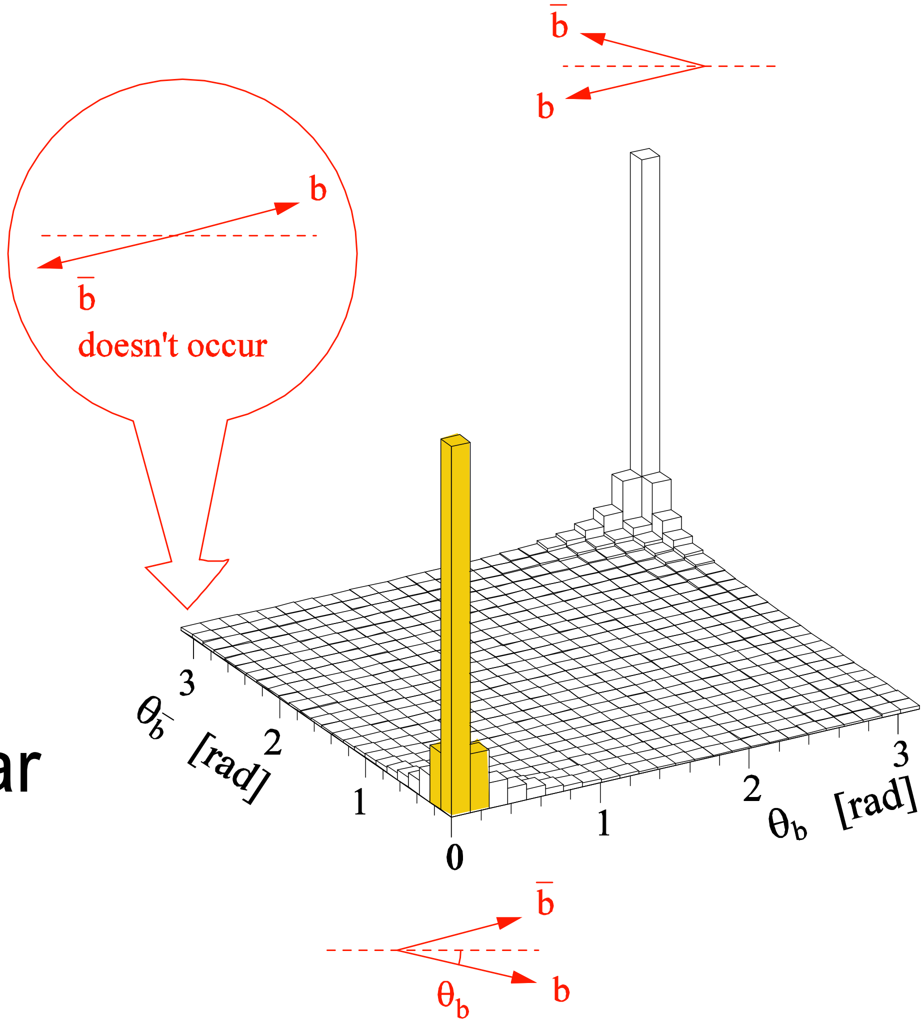
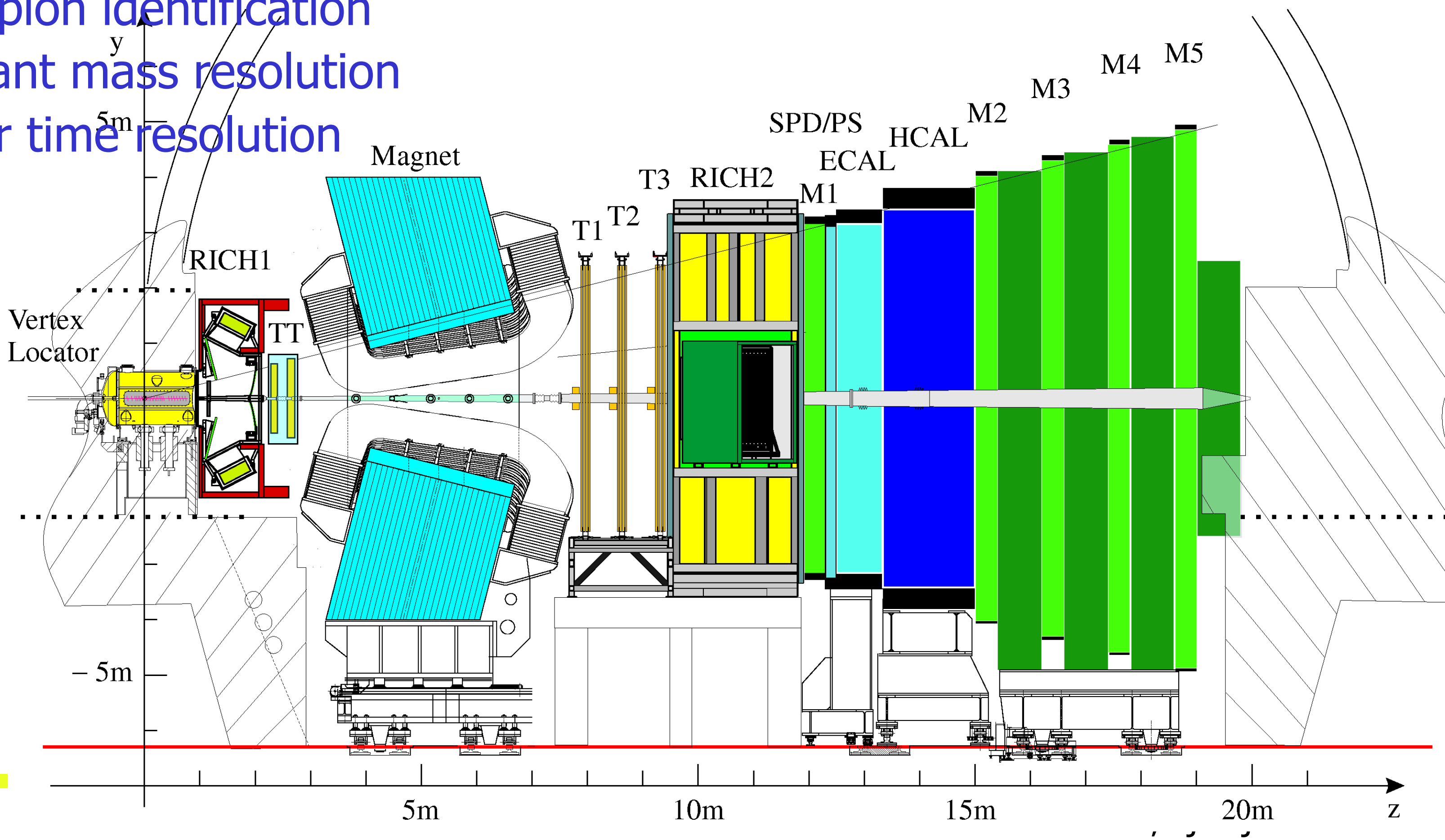


Figure 2.1: Polar angles of the b- and $\bar{b}$-hadrons calculated by the PYTHIA event generator.

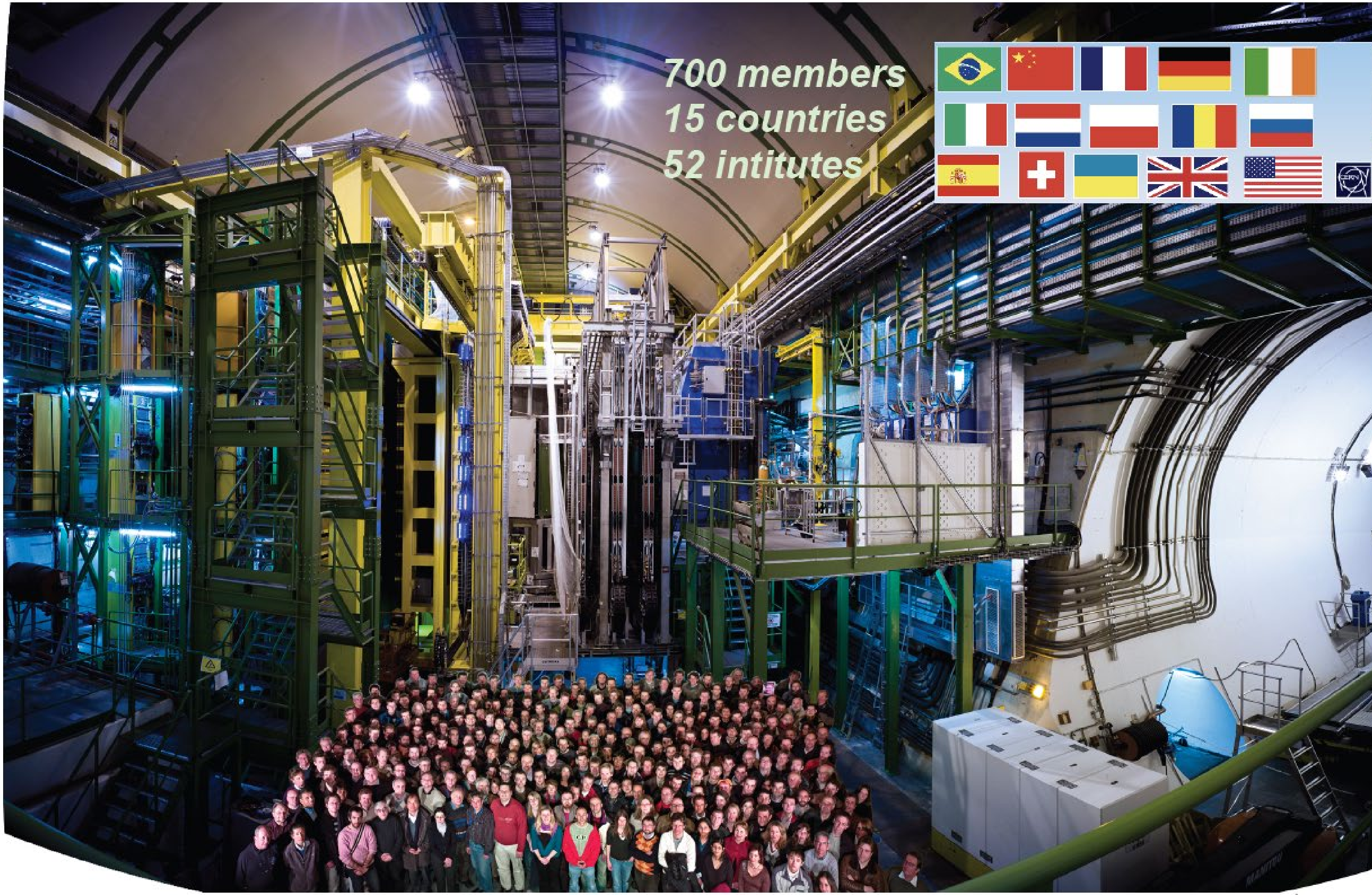
LHCb

LHCb is a forward spectrometer:

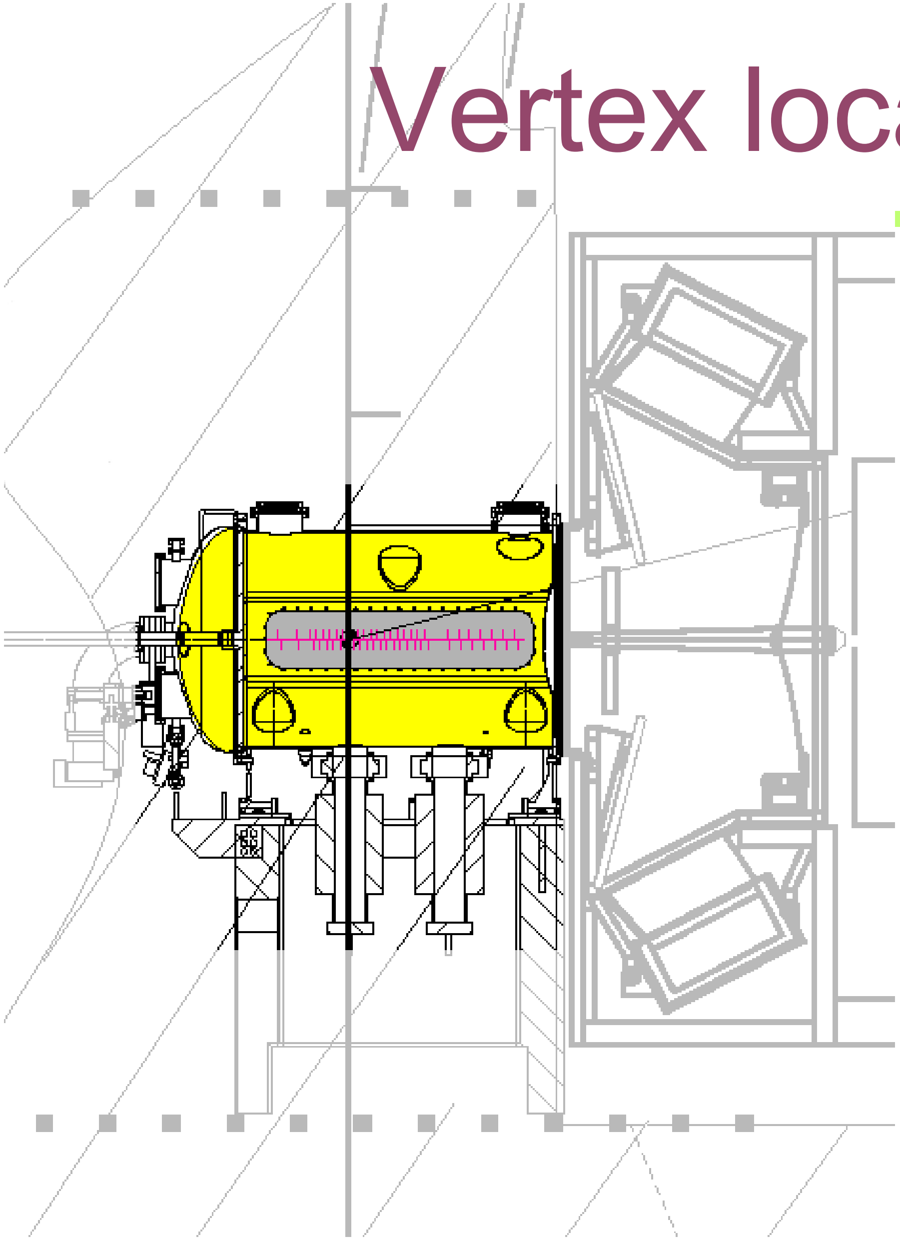
- Acceptance 10-300 mrad
- Efficient B-mesons trigger
- Good Kaon/pion identification
- Good invariant mass resolution
- Good proper time resolution



LHCb Collaboration



Vertex locator - VELO



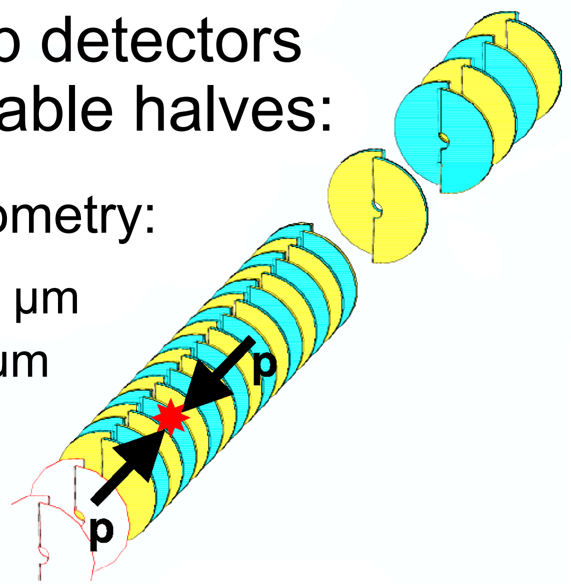
Vertex detector

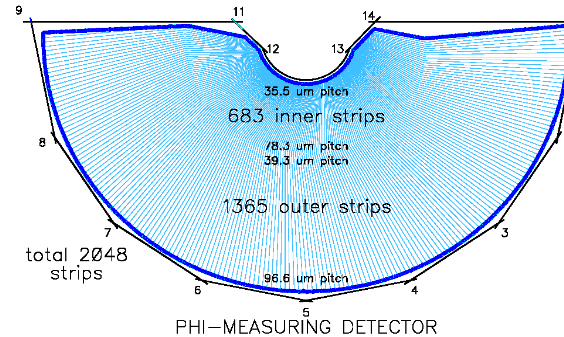
Key element surrounding the IP:

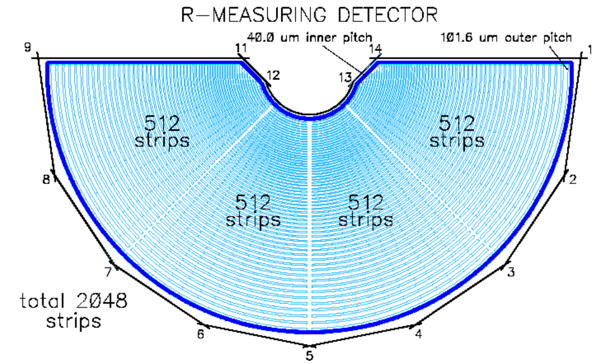
- Measure the position of the primary and the $B_{d,s}$ vertices
- Used in L1 trigger.

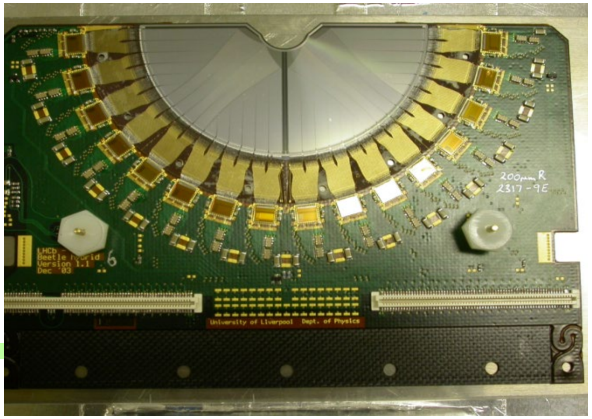
Vertex locator

- 21 pairs of silicon strip detectors arrange in two retractable halves:
  - Strips with an R-φ geometry:
    - R strip pitch: 40-102 μm
    - φ strip pitch: 36-97 μm
  - 172k channels.



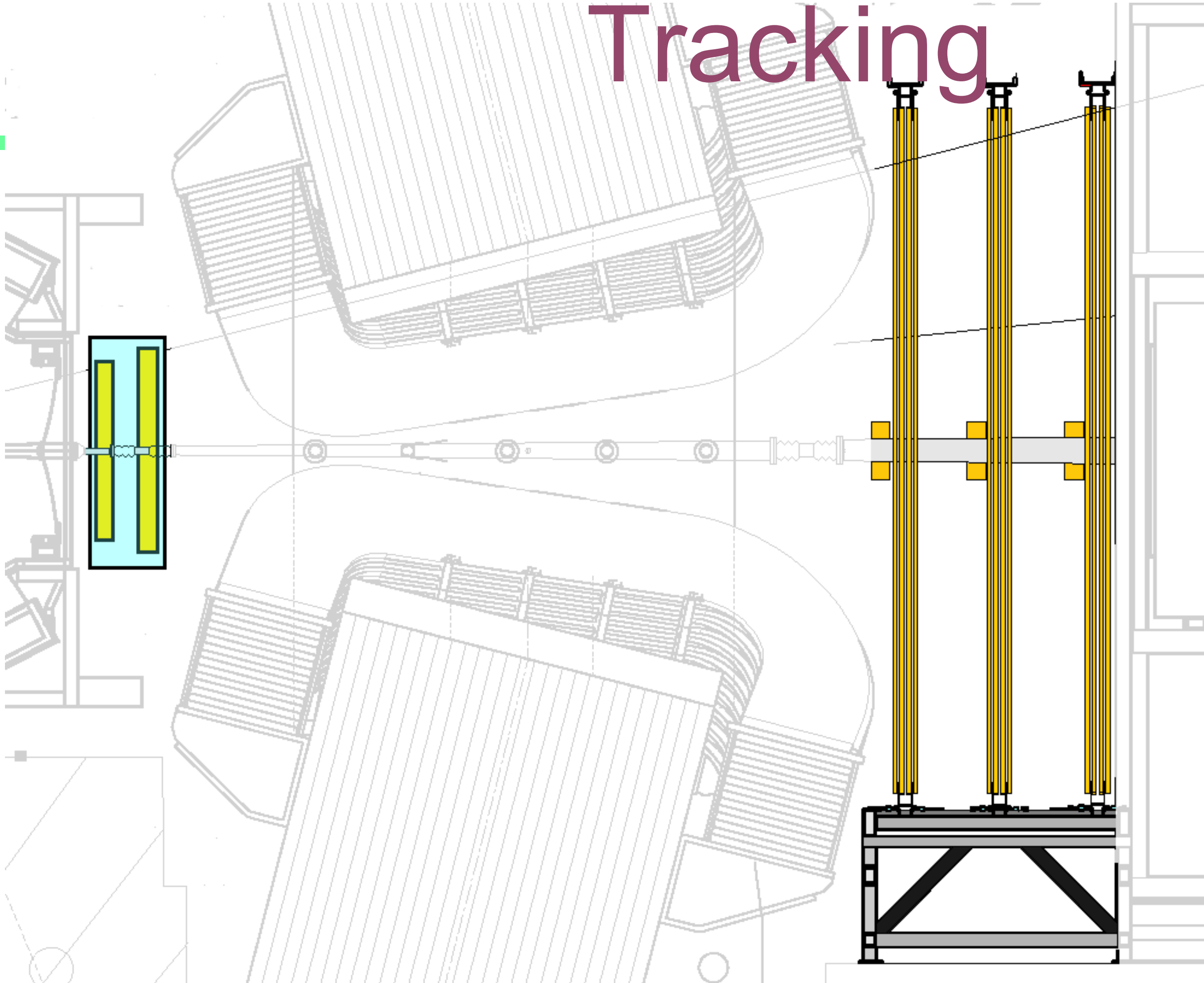






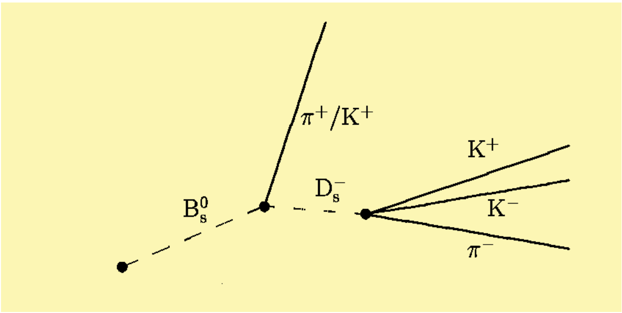
- Operated:
  - In vacuum, separated from beam vacuum by an Al foil
  - Close to the beam line (7 mm)
  - Radiation ≤ 1.5×10^{14} n_{eq}/cm^2 per year
  - Cooled at -5 °C

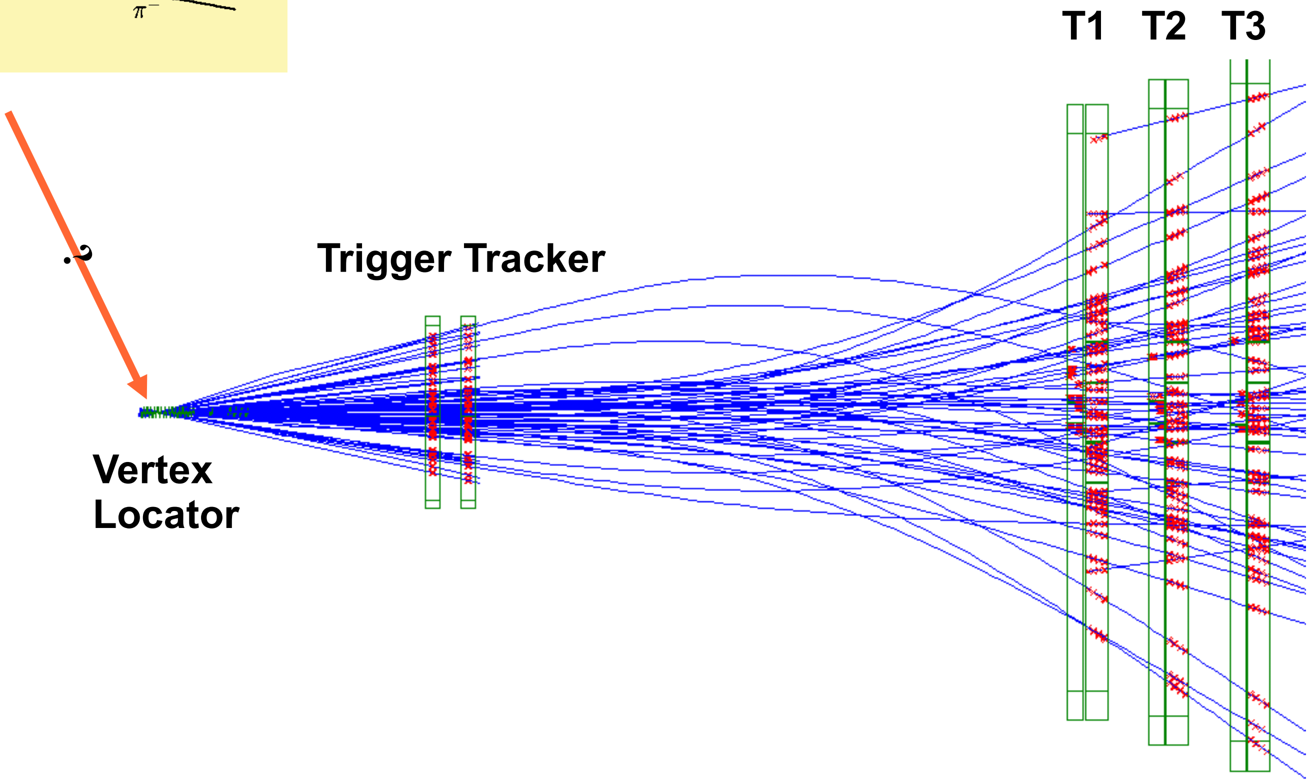
Tracking



Key elements to find tracks and to measure their momentum.

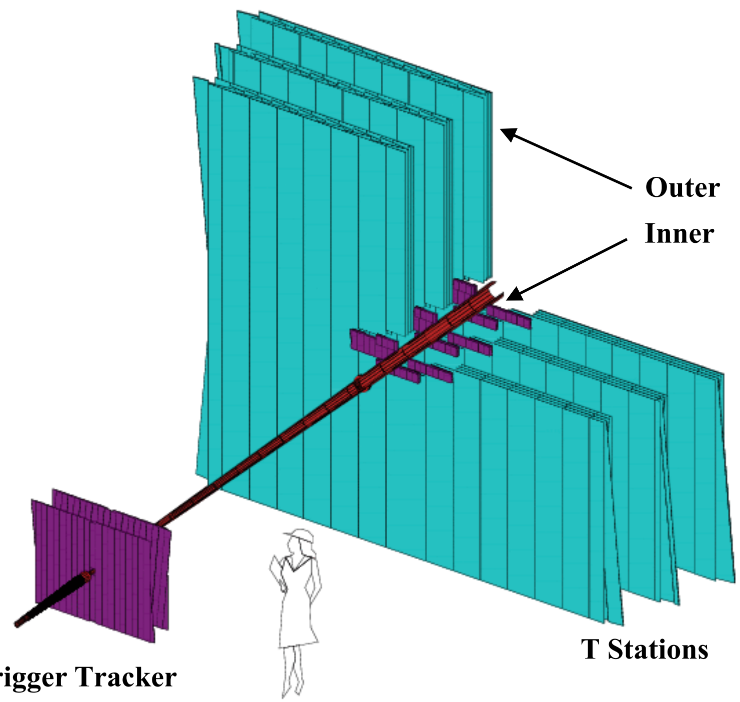
$$B_s \to D_s^{\pm} K^{\mp} \to \left(K^{+} K^{-} \pi^{\pm}\right) K^{\mp}$$





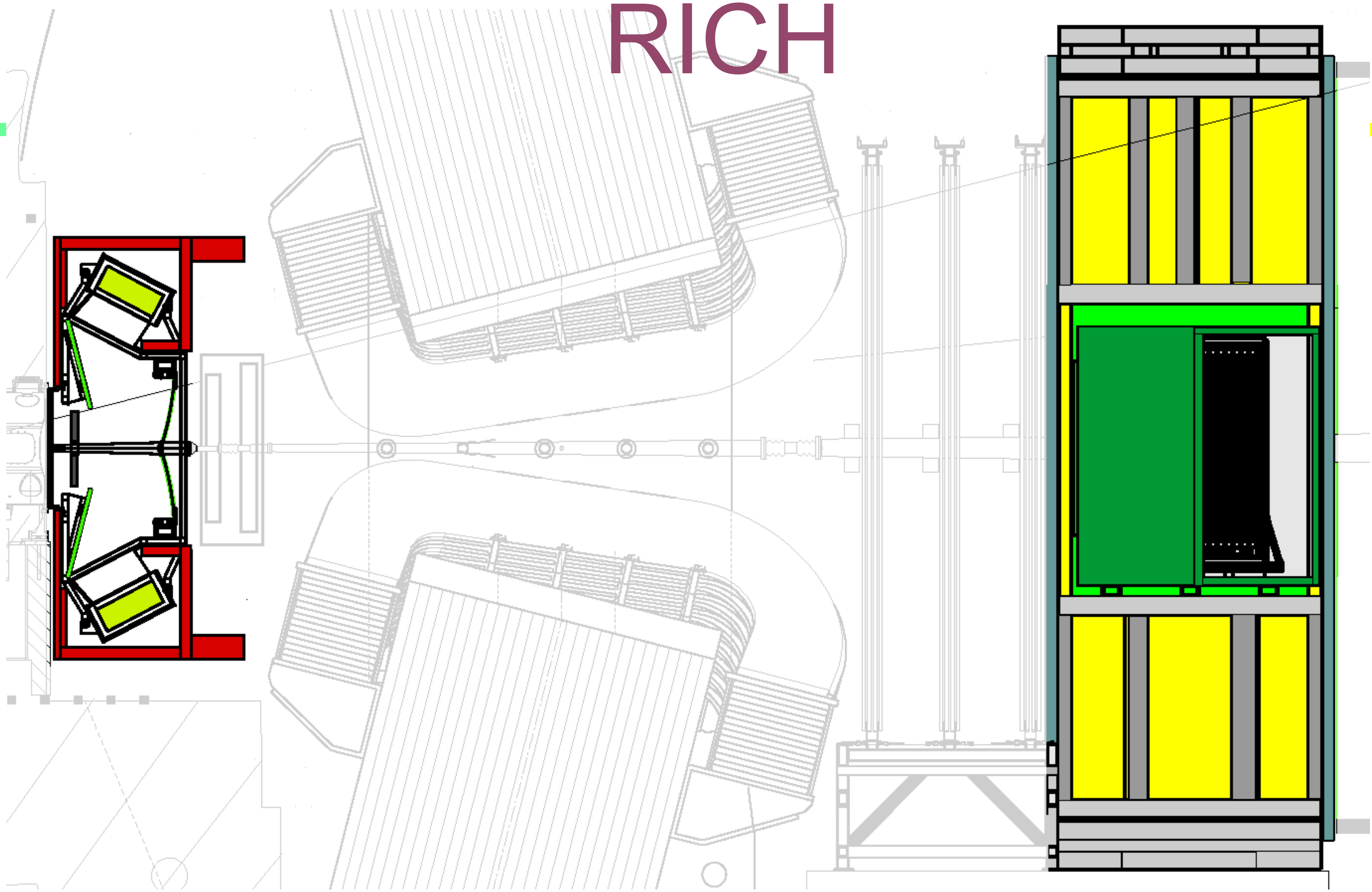
Reconstructed event: ~72 tracks

Tracking system



- Trigger Tracker:
  - Microstrip silicon detector
  - 144k channels
- Three T stations:
  - Inner tracker:
    - Microstrip Silicon detector
    - 130k channels
  - Outer tracker:
    - Straw tubes (5 mm)
    - 56k channels

RICH



Key elements to identify pions and kaons in the momentum range $p \in [2, 100]\,\mathrm{GeV}/c$

LHCb RICHes

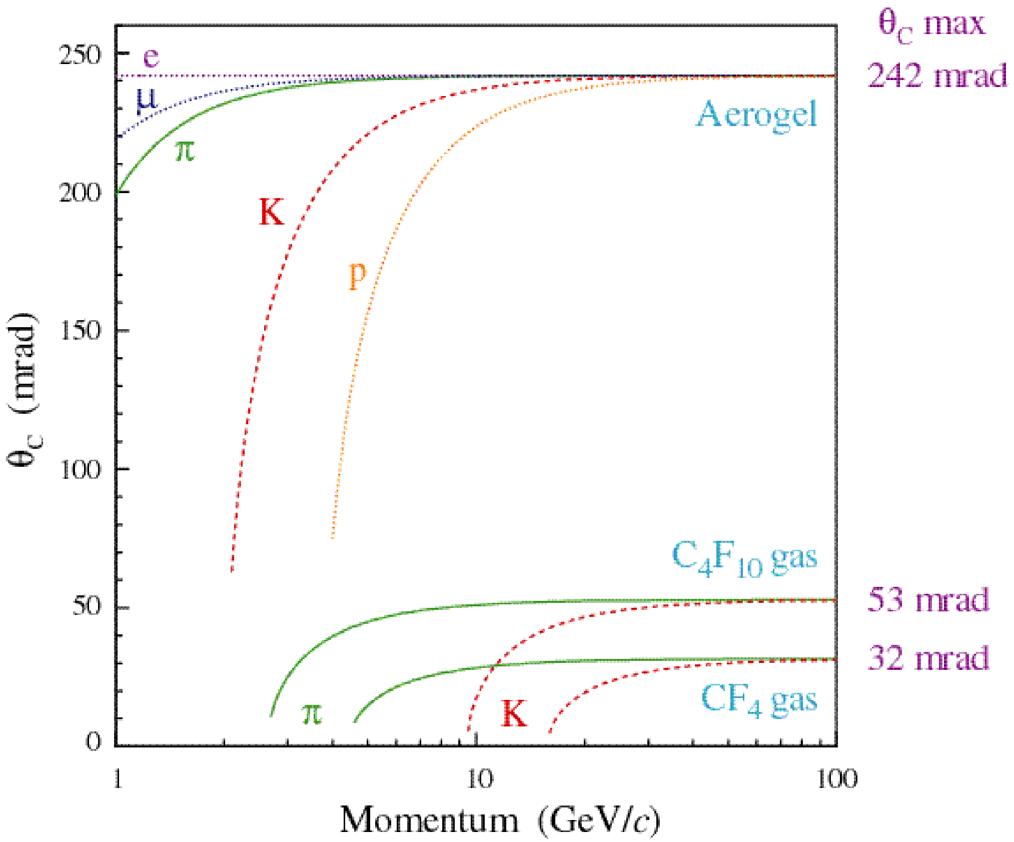
RICH system divided into two detectors equipped with 3 radiators to cover the full acceptance and momentum range:

•from a few GeV (tagging kaons)

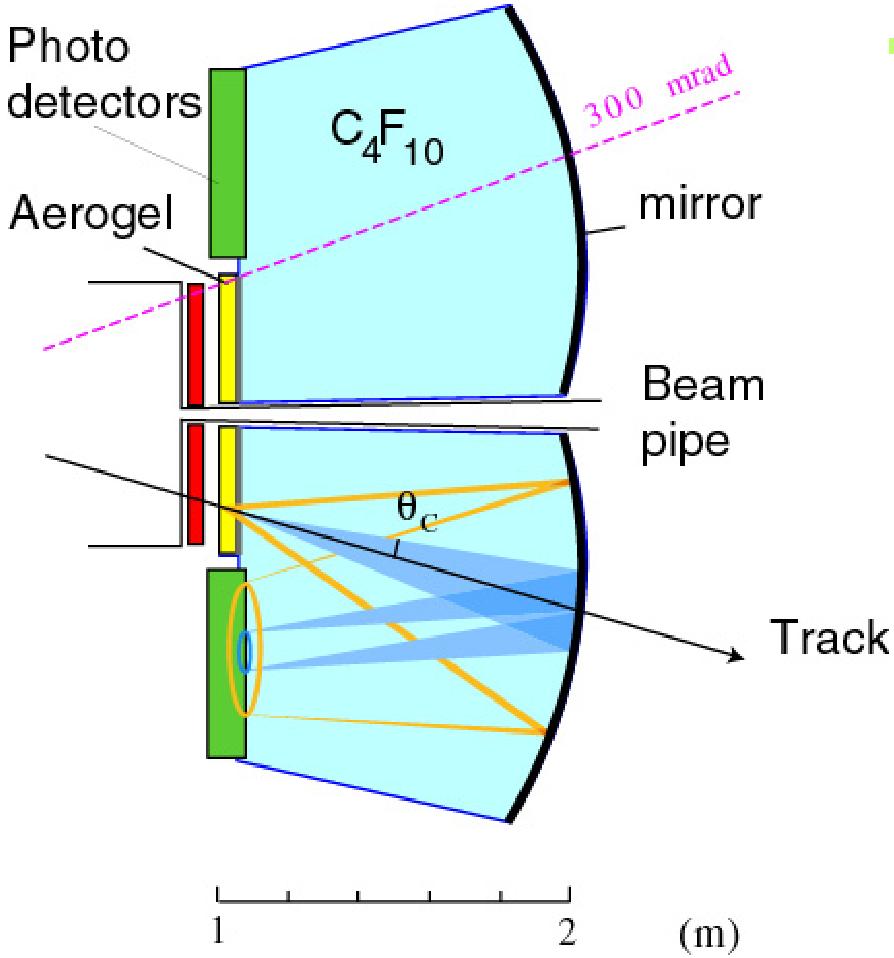
•up to 100 GeV: two body B decays

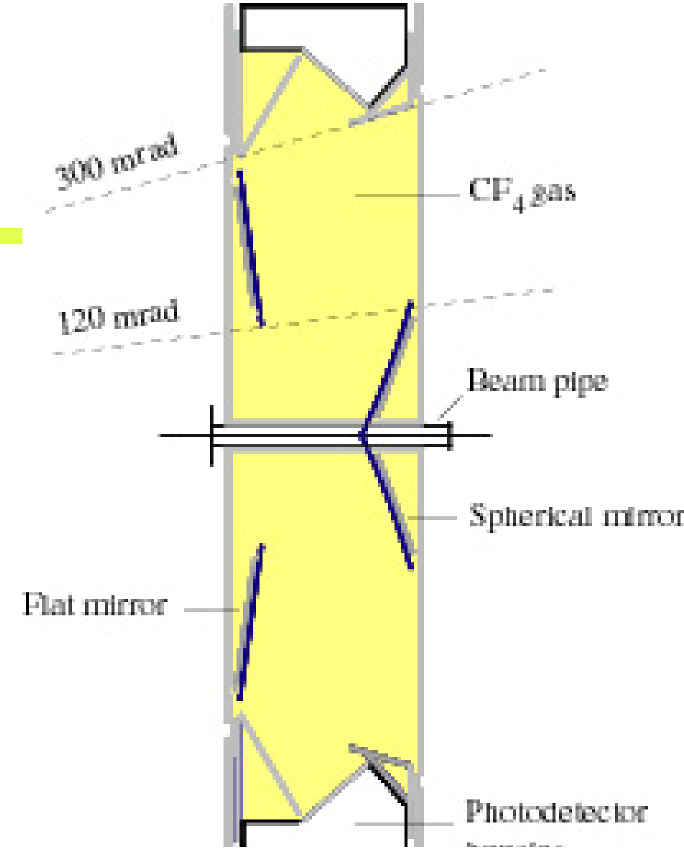
General rule: for 3σ separation, a RICH with a single radiator can cover a factor of 4-7 in momentum from threshold to the maximal momentum.

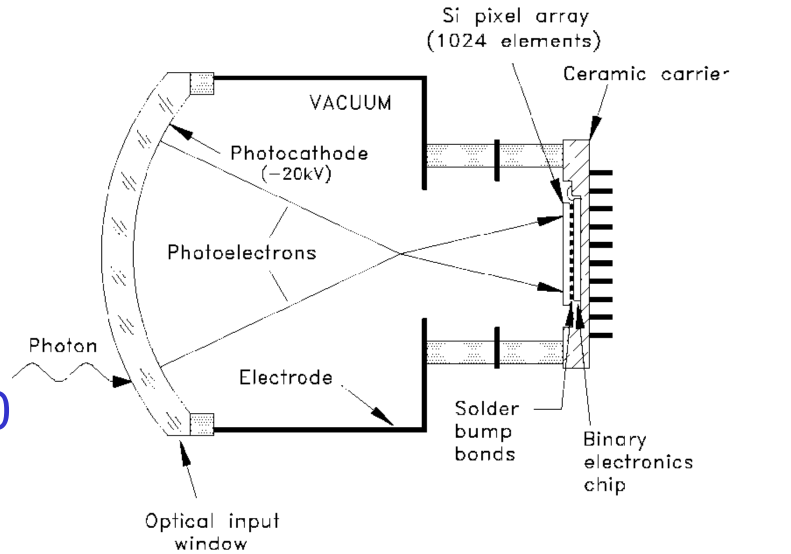
Larger momentum region → need more radiators!



RICH with three radiators



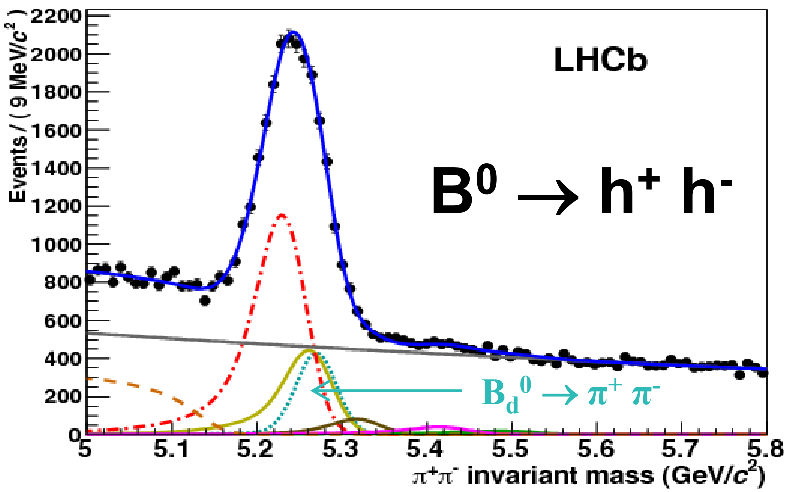




Hybrid photodetector:

32×32 pixel sensor array (500×500 μm²), 20 kV operation voltage, demagnification factor ~5

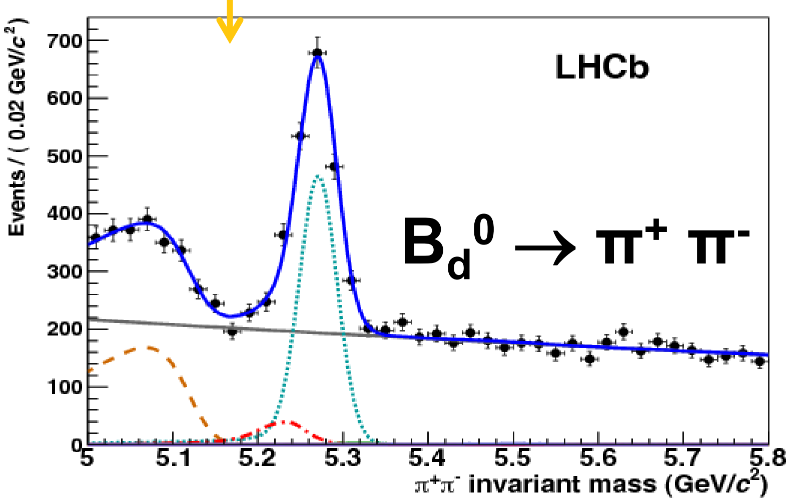
Particle ID with RICH



Efficient particle ID of π, K, p essential for selecting rare beauty and charm decays

K-identification and π-misidentification efficiencies vs. particle momentum

particle identification of 2 pions



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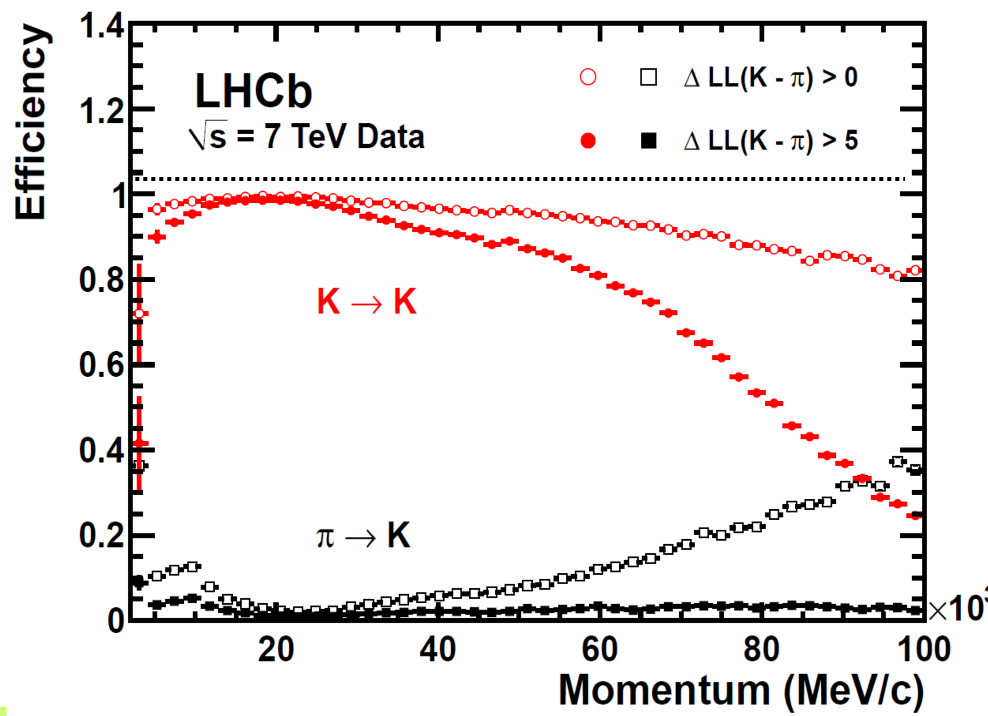
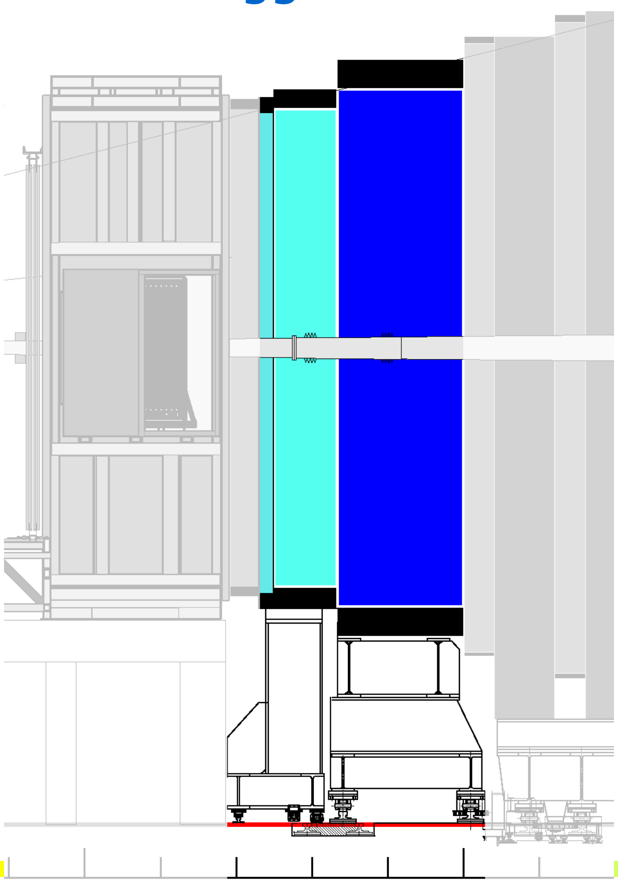
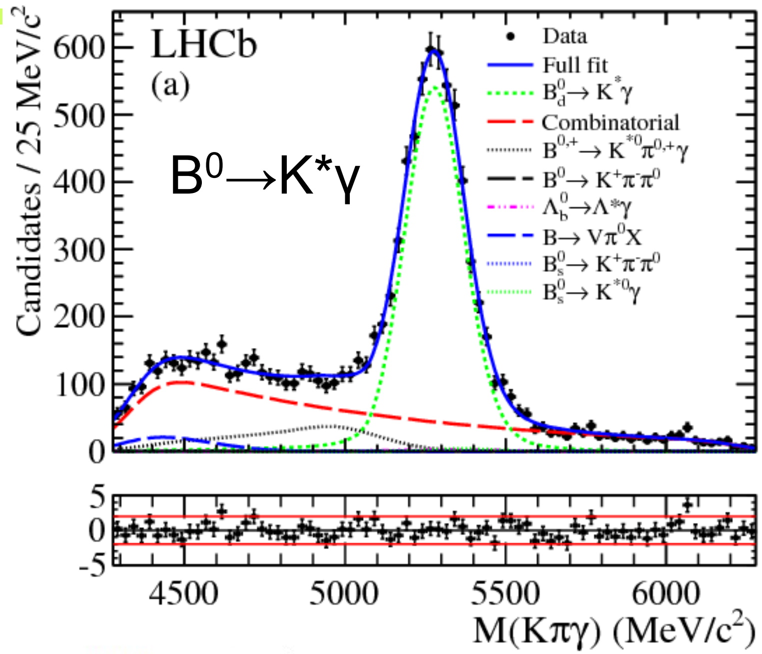


Calorimeters

Key element to identify γ, π^0
and to measure their energy.

Used in L0 trigger.





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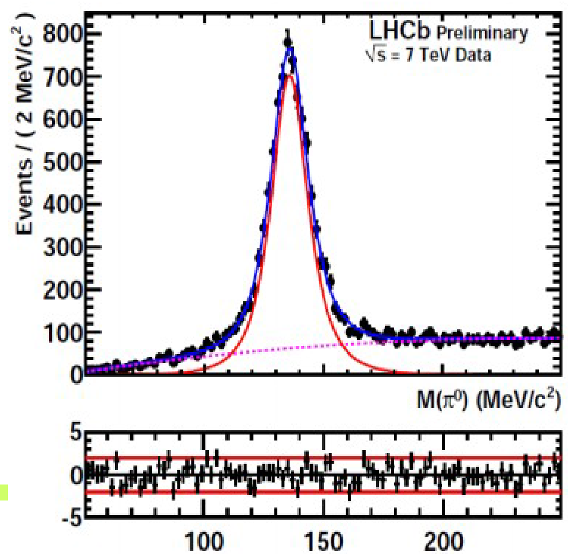


$\pi^0 \rightarrow \gamma\gamma$

LHCb calorimeters

- System subdivided into 3 parts:

  Scintillating Pad Detector (SPD) and Preshower:

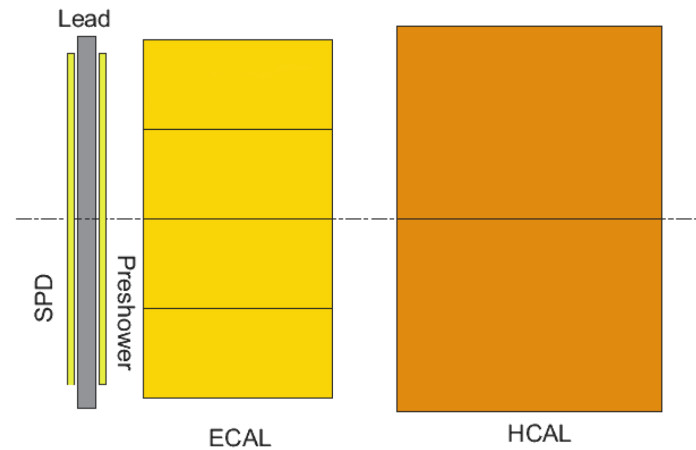
  - Two layers of scintillator pads separated by a 1.5cm lead converter

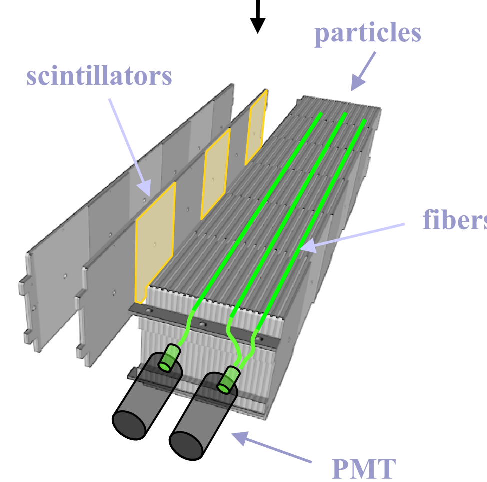
  Electromagnetic Calorimeter (ECAL):

  - Shashlik types,
  - Lead+ scintillator tiles
  - 25 X_0

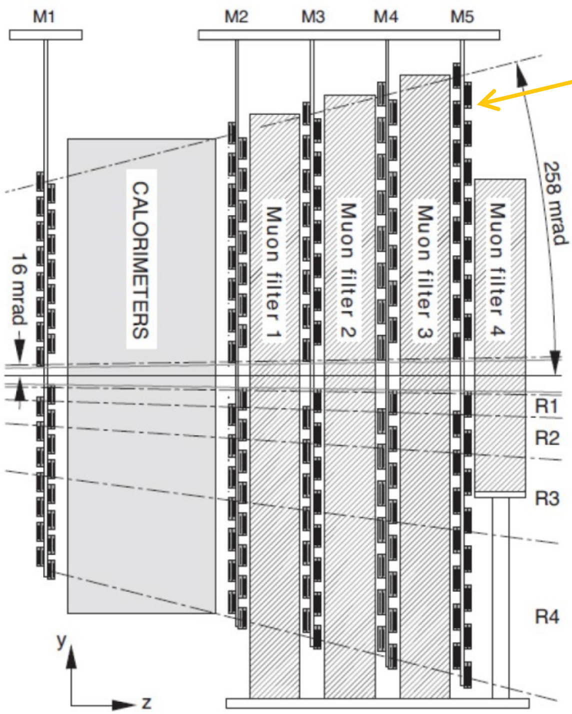
- Hadronic calorimeter (HCAL):
  - Iron + scintillator tiles
  - 5.6 λ_I

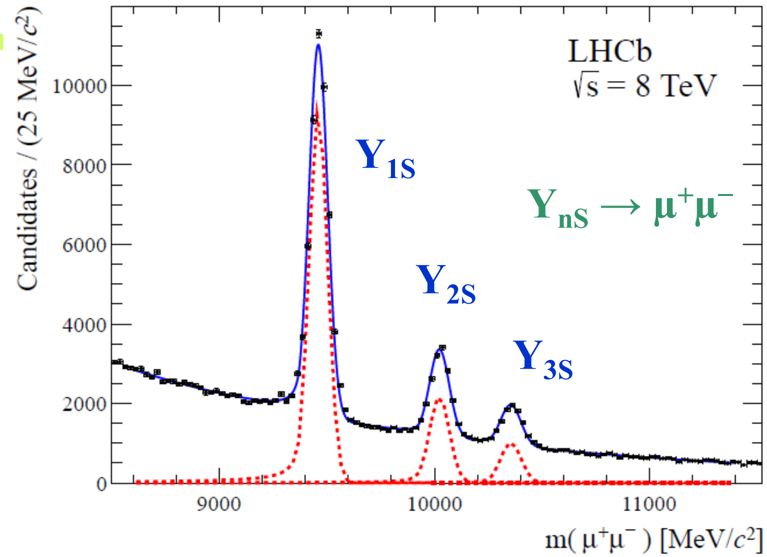
- A total of 19k channels readout by Wave Length Shifter fibres connected to PMs or MaPMTs.





Particle ID with the Muon System





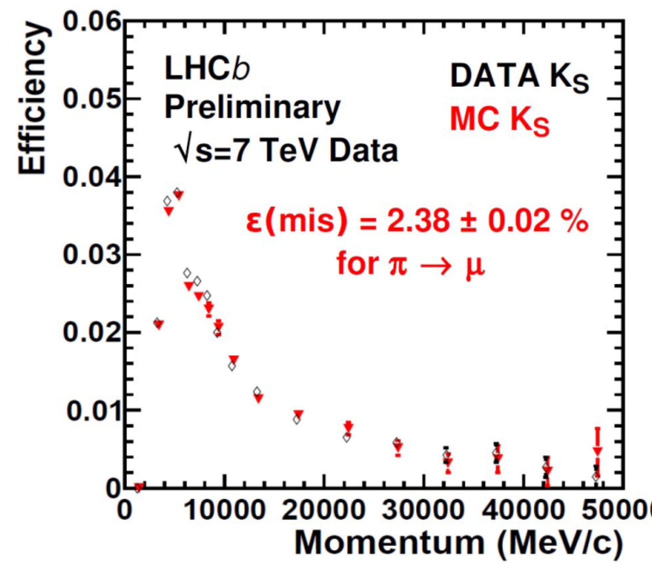
High detection efficiency: $\varepsilon(\mu) = (97.3 \pm 1.2)\%$

Low misidentification rates:

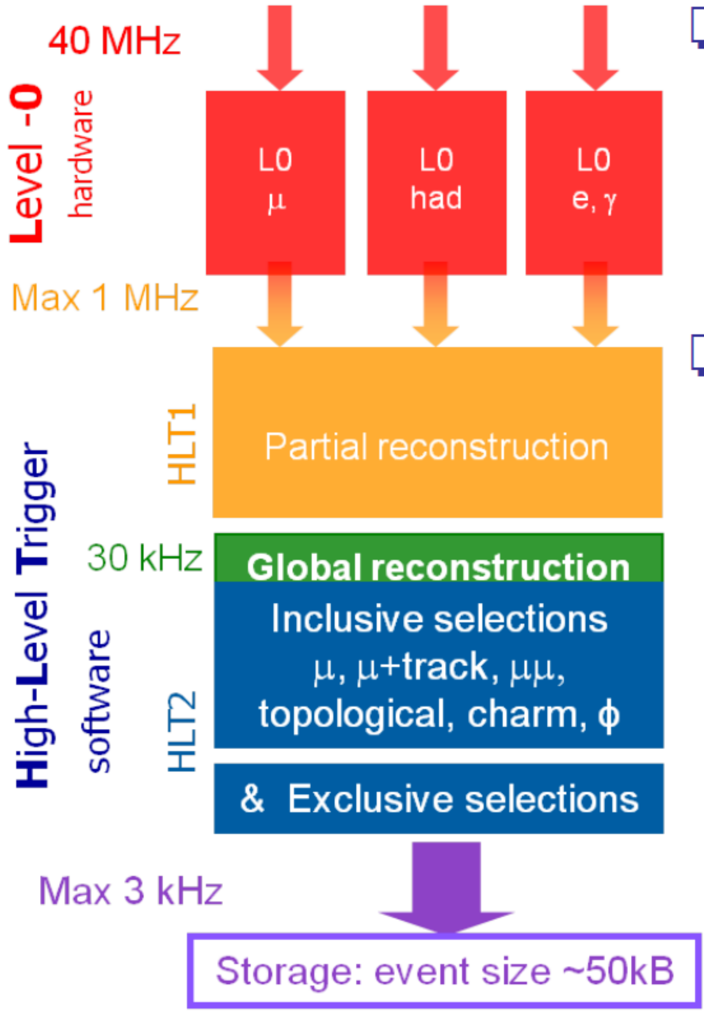
$\varepsilon(p \rightarrow \mu) = (0.21 \pm 0.05)\%$

$\varepsilon(\pi \rightarrow \mu) = (2.38 \pm 0.02)\%$

$\varepsilon(K \rightarrow \mu) = (1.67 \pm 0.06)\%$



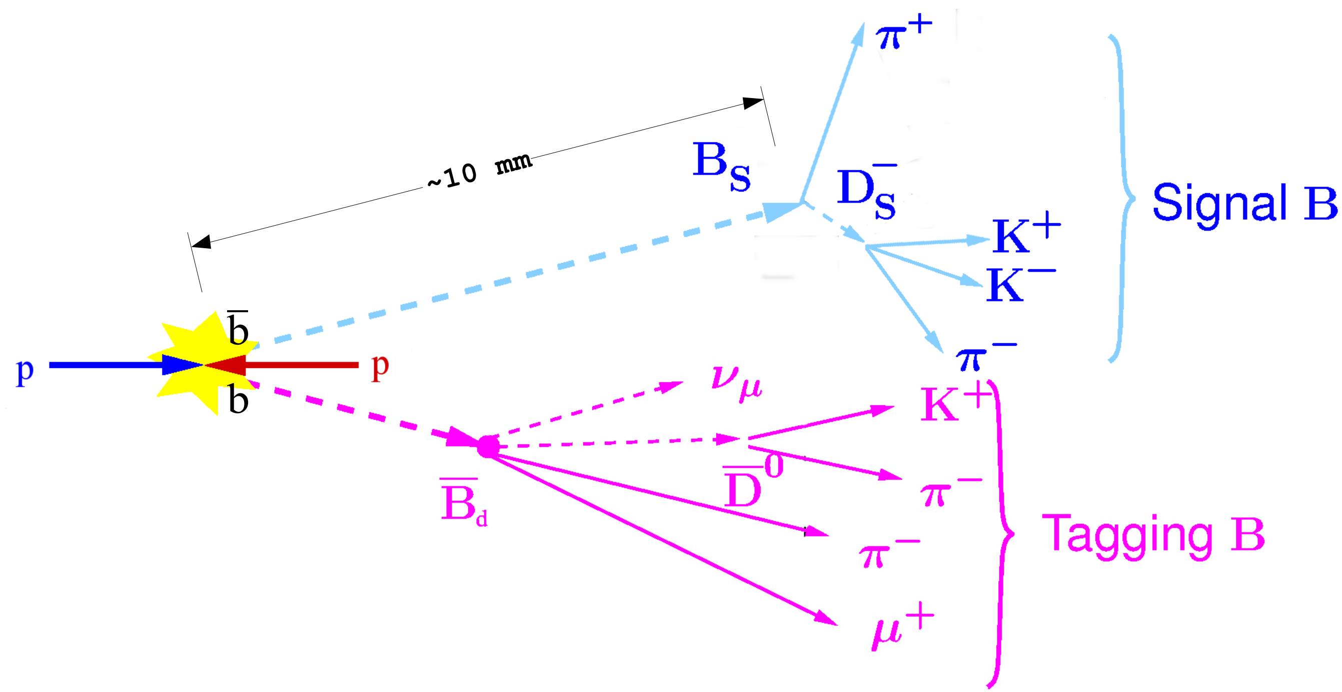
Triggers



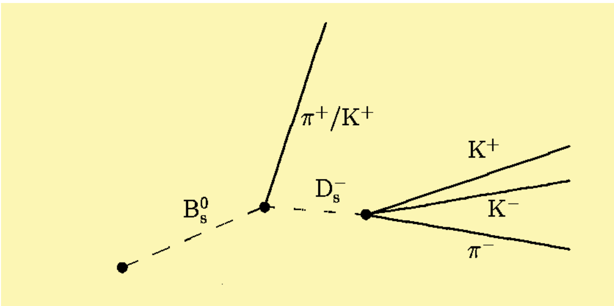
- **Level-0:**
  - fully synchronous custom electronics at 40 MHz
    - 11 MHz of visible interactions reduced to max. 1 MHz
    - select single objects with large p_T (E_T), typically $p_T(\mu) > 1$ GeV/c and $E_T(h,e,\gamma,\pi^0) > 3$–$4$ GeV
- **High-level trigger**
  - Farm of 1500 multi-processor boxes
  - Stage 1: add tracking info, impact parameter cuts
  - Stage 2: full reconstruction + selections
  - Output:
    - ~1 kHz charm, ~ 1 kHz B, ~1 kHz others

	Typical efficiencies
B decays with μμ	70–90%
Fully hadronic B decays	20–45%
Fully hadronic charm decays	10–20%

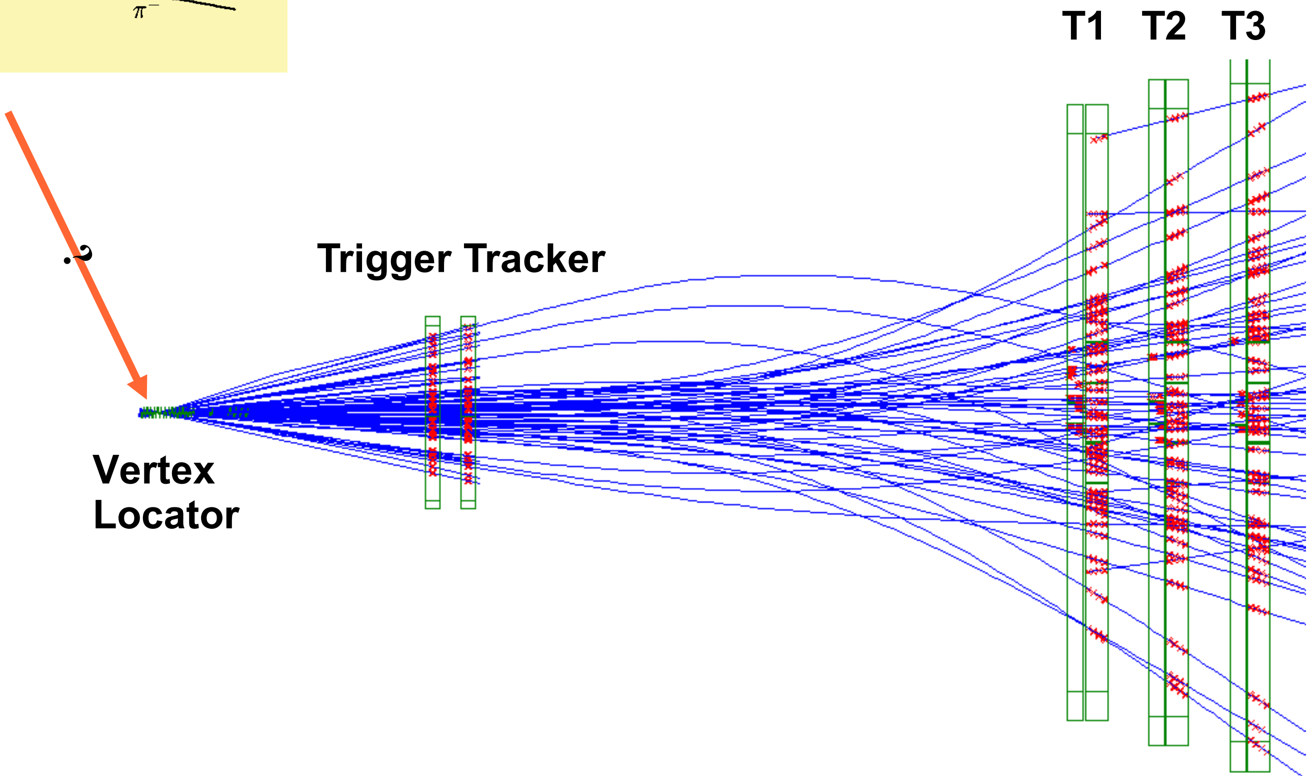
Time dependent measurements at LHCb



- The proper time of the signal B decay is measured via:
  - the position of the primary and secondary vertexes;
  - the momentum of the signal B state from its decay products.

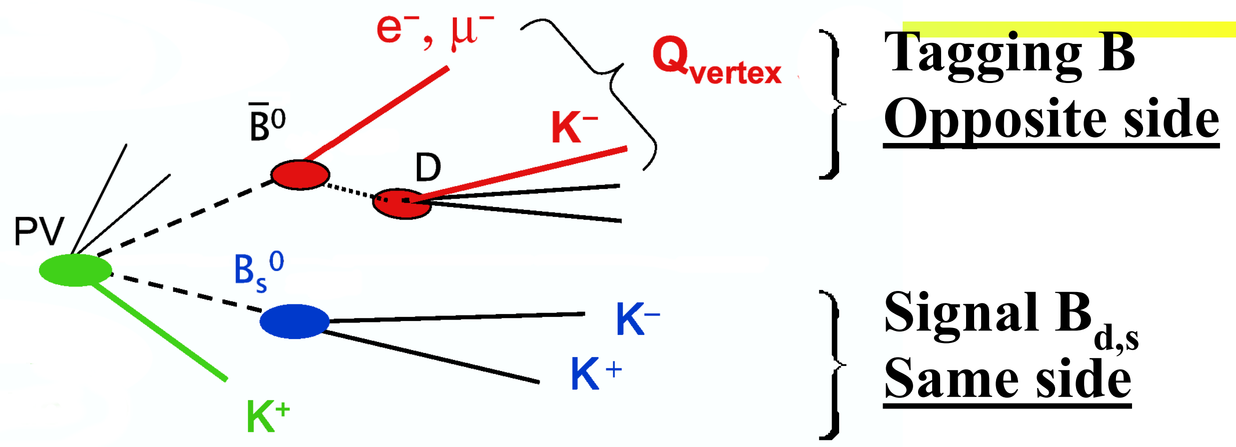


$$B_s \rightarrow D_s^{\pm} K^{\mp} \rightarrow \left(K^+ K^- \pi^{\pm}\right) K^{\mp}$$



Reconstructed event: ~72 tracks

Flavour Tagging



Opposite side:

- e, μ from semileptonic b decays;
- $K^\pm$ from b decays chain;
- Inclusive vertex charge.

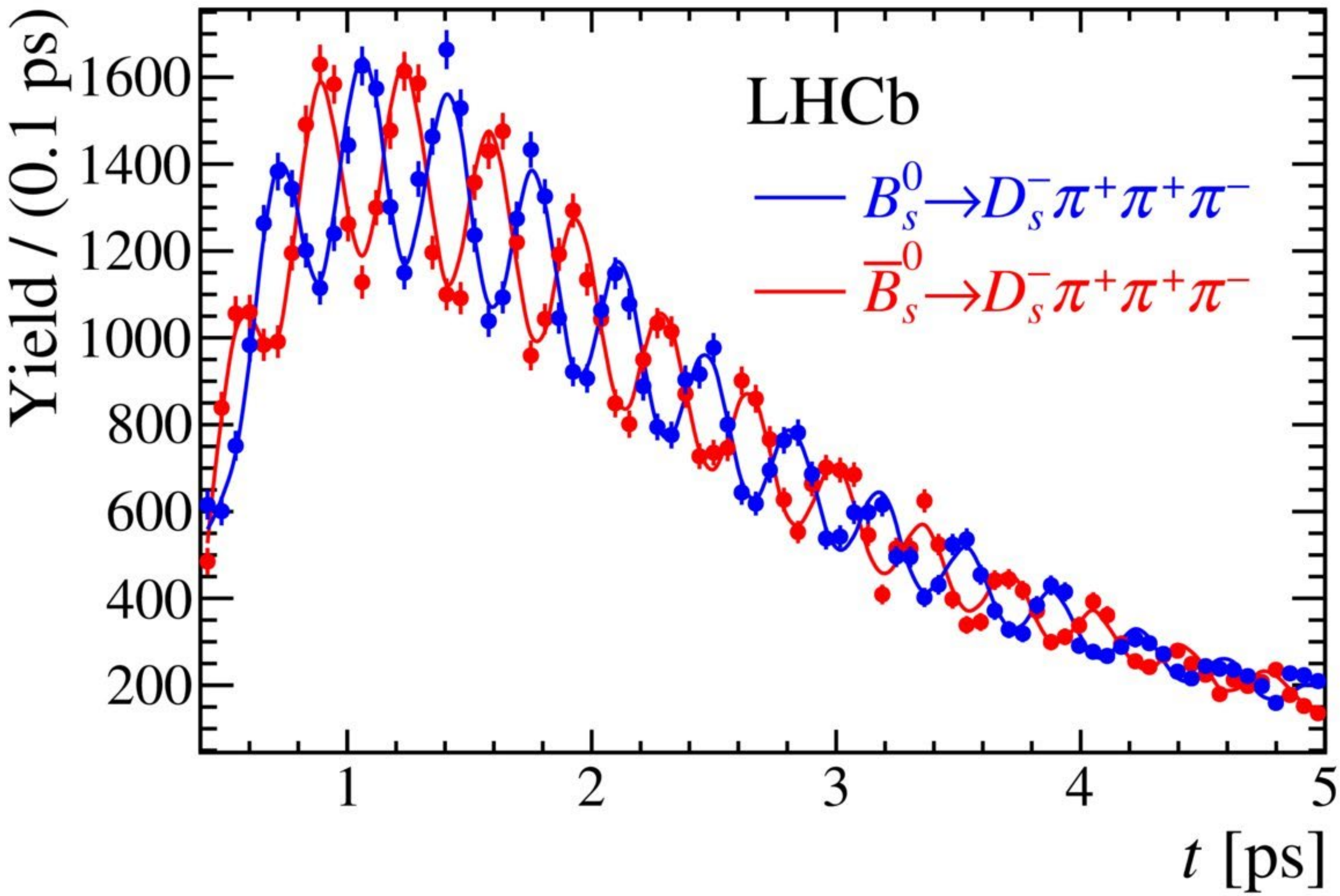
Same side:

- $K^\pm$ from fragmentation accompanying B_s meson.

Effective tagging efficiencies vary between 3% and 9% depending on the final state.

N.B. Effective tagging efficiencies is **>30%** at B factories, ~2% at CDF/D0

B_s mixing: B_s ←→ anti-B_s



Excellent timing precision: B_s turn into anti-B_s in 0.3 ps, 3 10^{12} per second