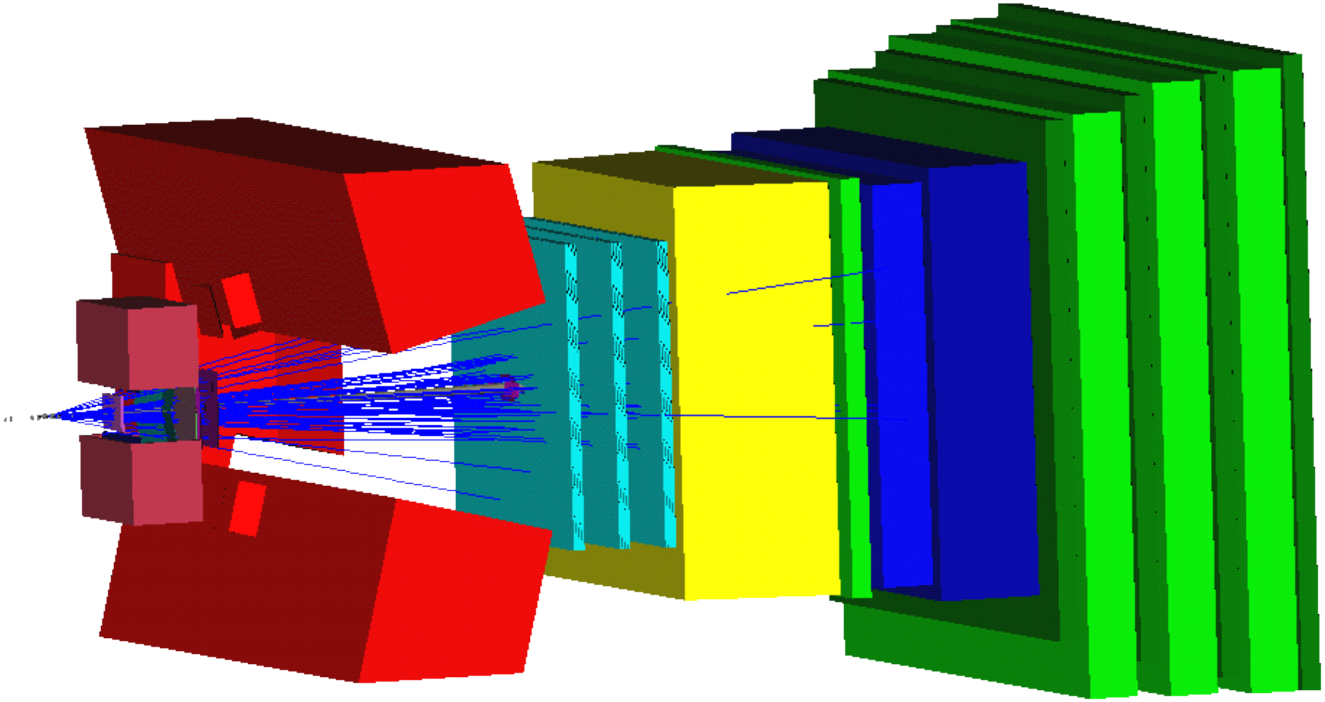
Introduction to LHCb



Preface

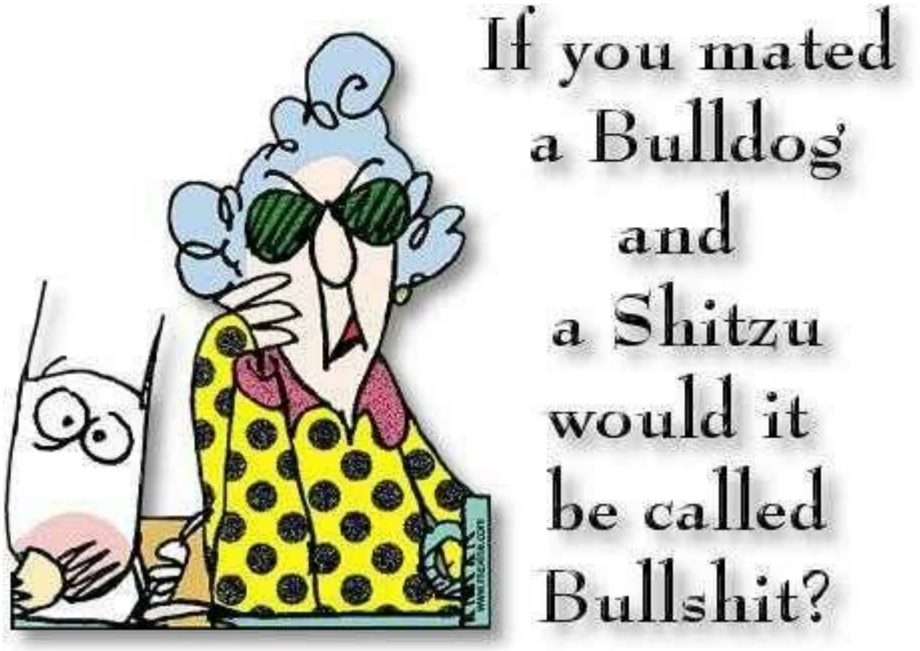
Next four lectures:

1. Introduction to LHCb
2. Overview of flavour physics
3. Recent CP violation measurements
4. Recent results from rare decays

Today:

- Starting with some detector physics (bottom-up approach)
- Aimed to give overview of detector aspects important for LHCb
- Assumes some prior knowledge of detector physics....
- …but if I go to fast…..

Please ask questions



Not that I know all the answers…

Or if you become bored…

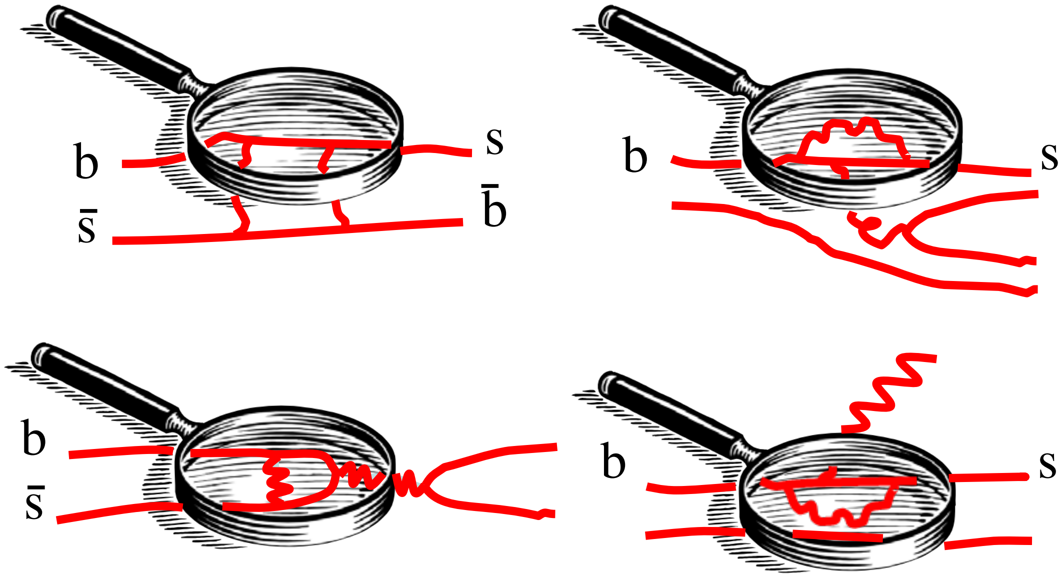
Don’t hesitate to tell me.

Heavy flavour physics (next week)

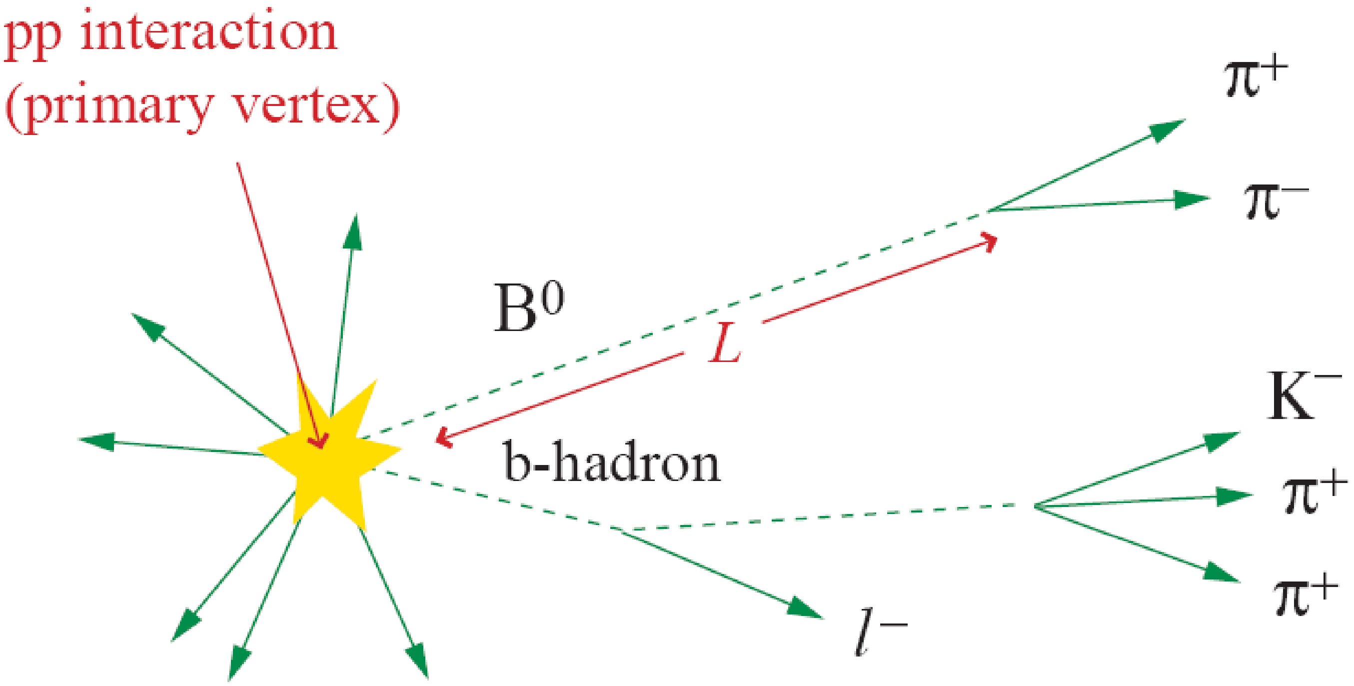
The aim of heavy flavour physics is to study *B* and *D* decays to look for anomalous effects beyond the Standard Model.

- New particles can appear as virtual particles in loop and penguin diagrams.
- Indirect searches have a high sensitivity to effects from new particles.
  - Can see NP effects before the direct searches.
  - Indirect measurements can access higher scales.
- Possible to measure the phases of the new couplings
  - New physics at TeV scale must have a flavour structure to provide suppression of FCNC.

→ Complementary to direct searches at ATLAS and CMS.

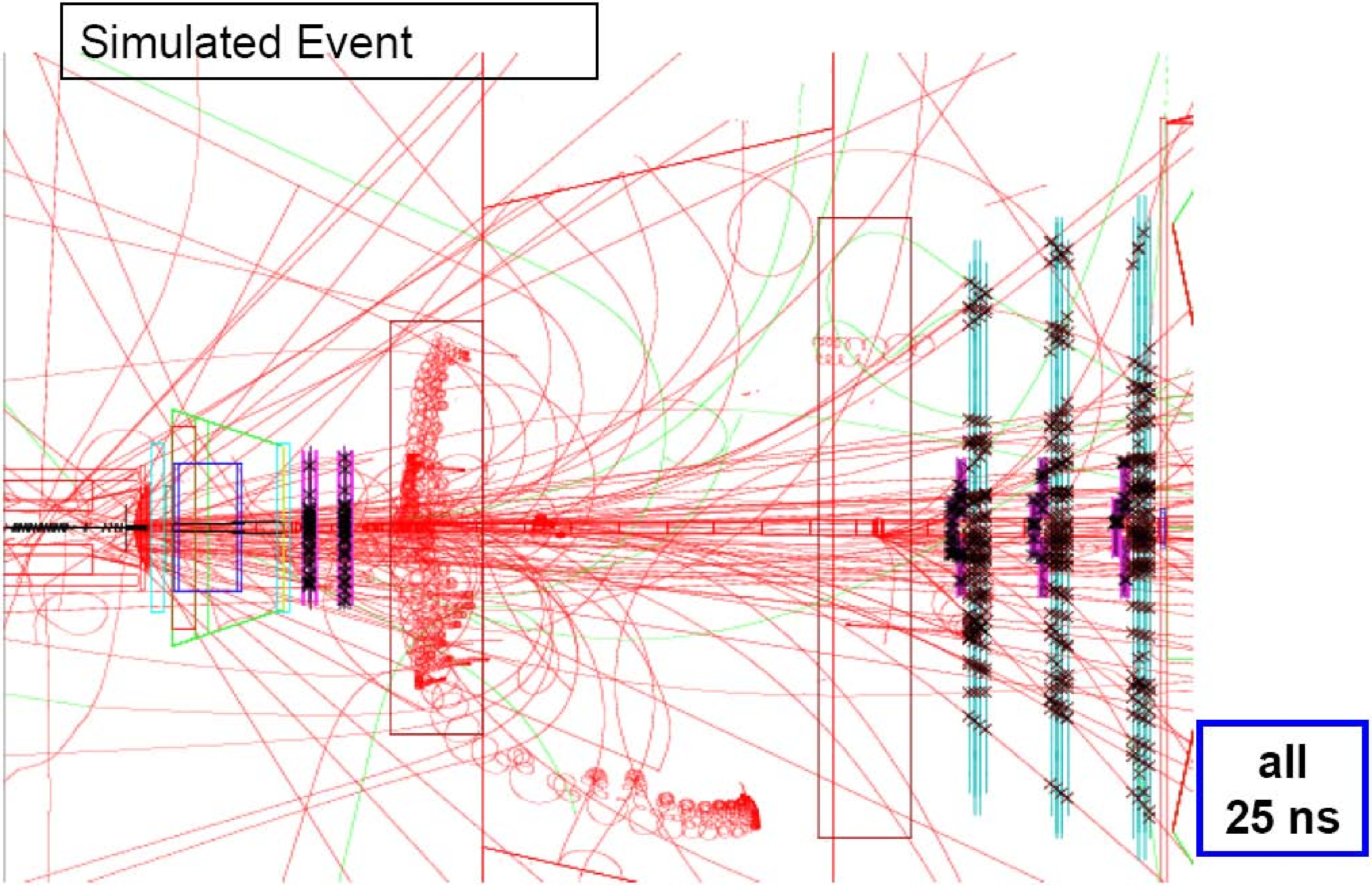


Typical *B* decay event

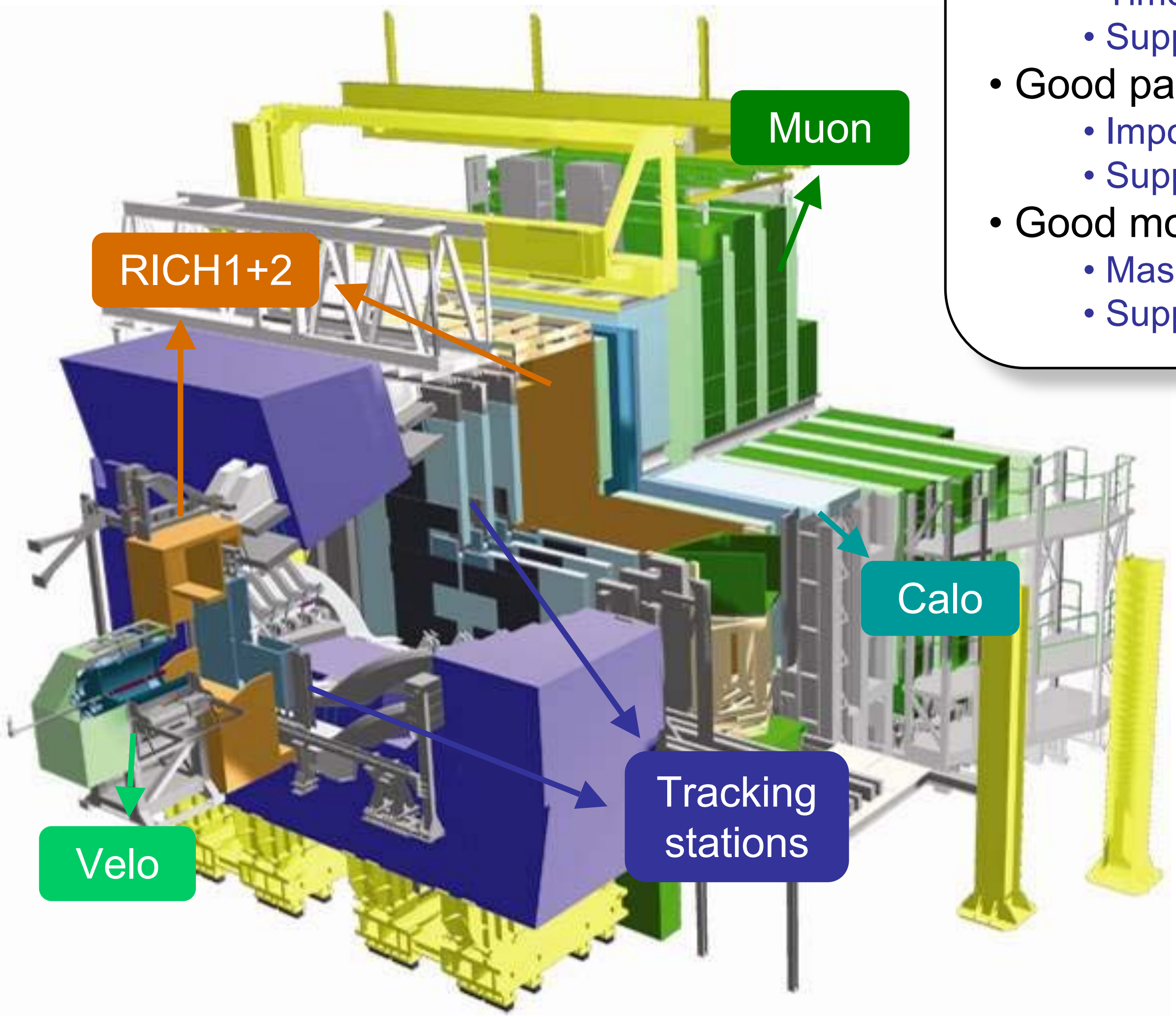


- Typical decay length of *B* hadron ~ 7 mm
- Decay products with p ~ 1 – 200 GeV

Simulated event



LHCb detector



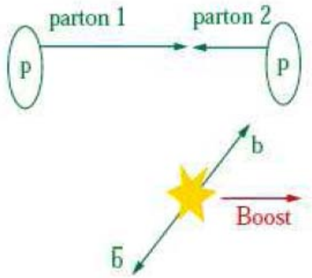
LHCb made for Heavy Flavour physics

- Good vertex resolution
  - Time-dependent measurements.
  - Suppress background from prompt decays.
- Good particle identification
  - Important for trigger, flavour tagging
  - Suppress background.
- Good momentum resolution
  - Mass resolution of heavy flavours.
  - Suppress background.

Forward detector

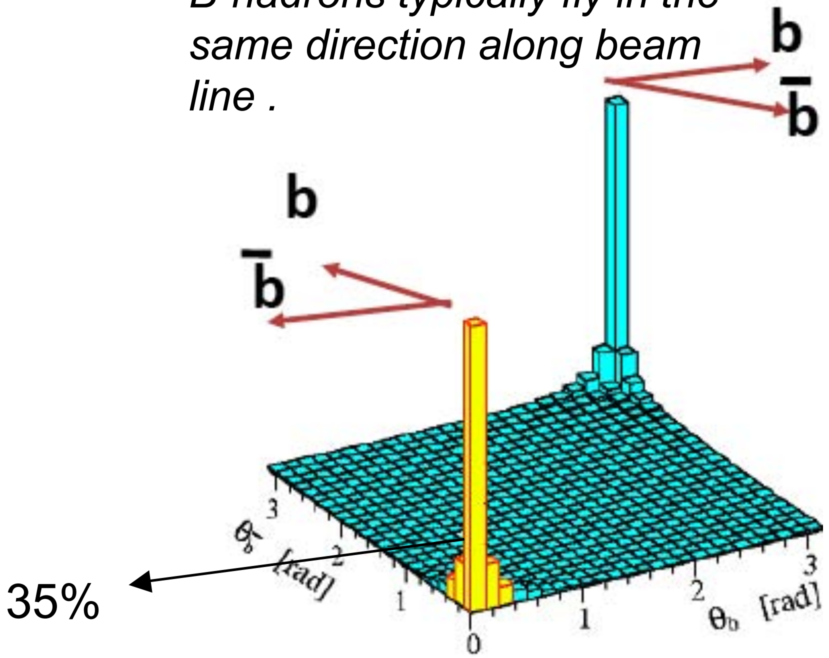
Why is LHCb not built like ATLAS or CMS?

Most B (and D) hadrons are produced either in forward or backward direction
→ Due to boost of the $b\bar{b}$ pair
→ m(b) relatively light compared to high centre-of mass energy of LHC



Build LHCb as a forward detector
(backward direction not covered: only one LHCb fits in the cavern ☺)

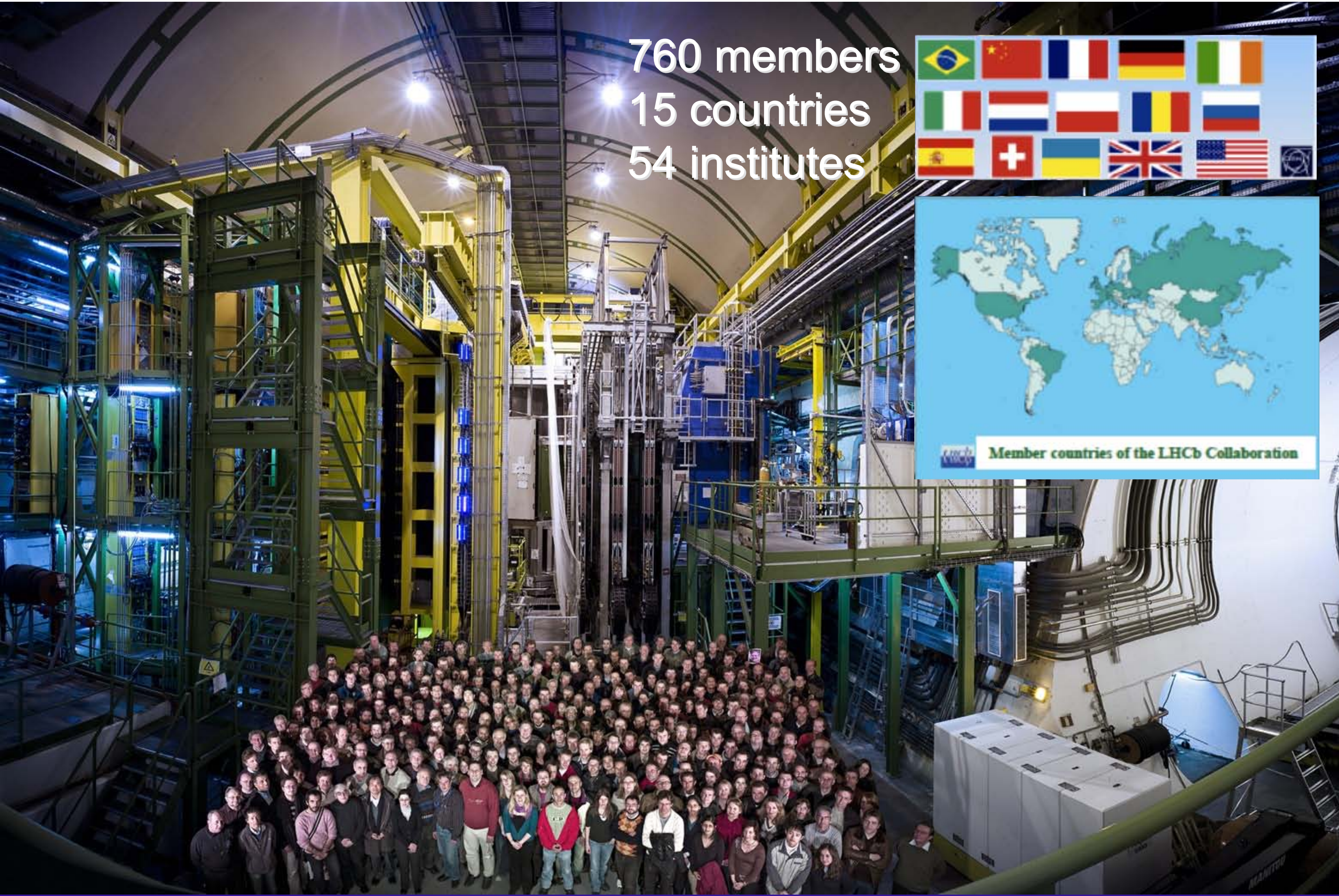
B-hadrons typically fly in the same direction along beam line .



Advantages:
- High yield of B and D hadrons
- Place vertex detector close to beam
- Modular design (easy maintenance)
- Large integrated magnetic field: high momentum resolution.

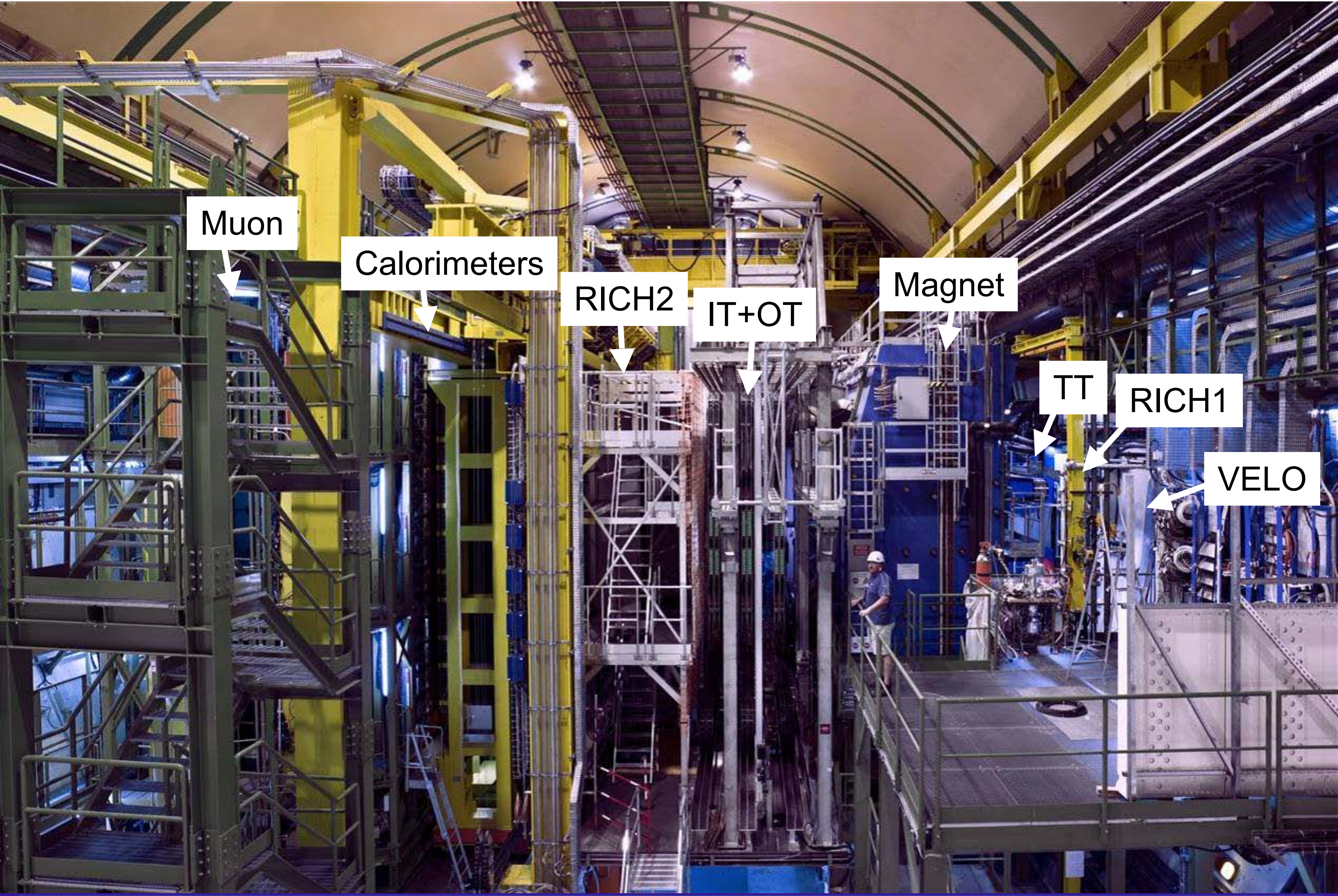
Disadvantage
- Very high particle flux (radiation, reconstruction)

Collaboration

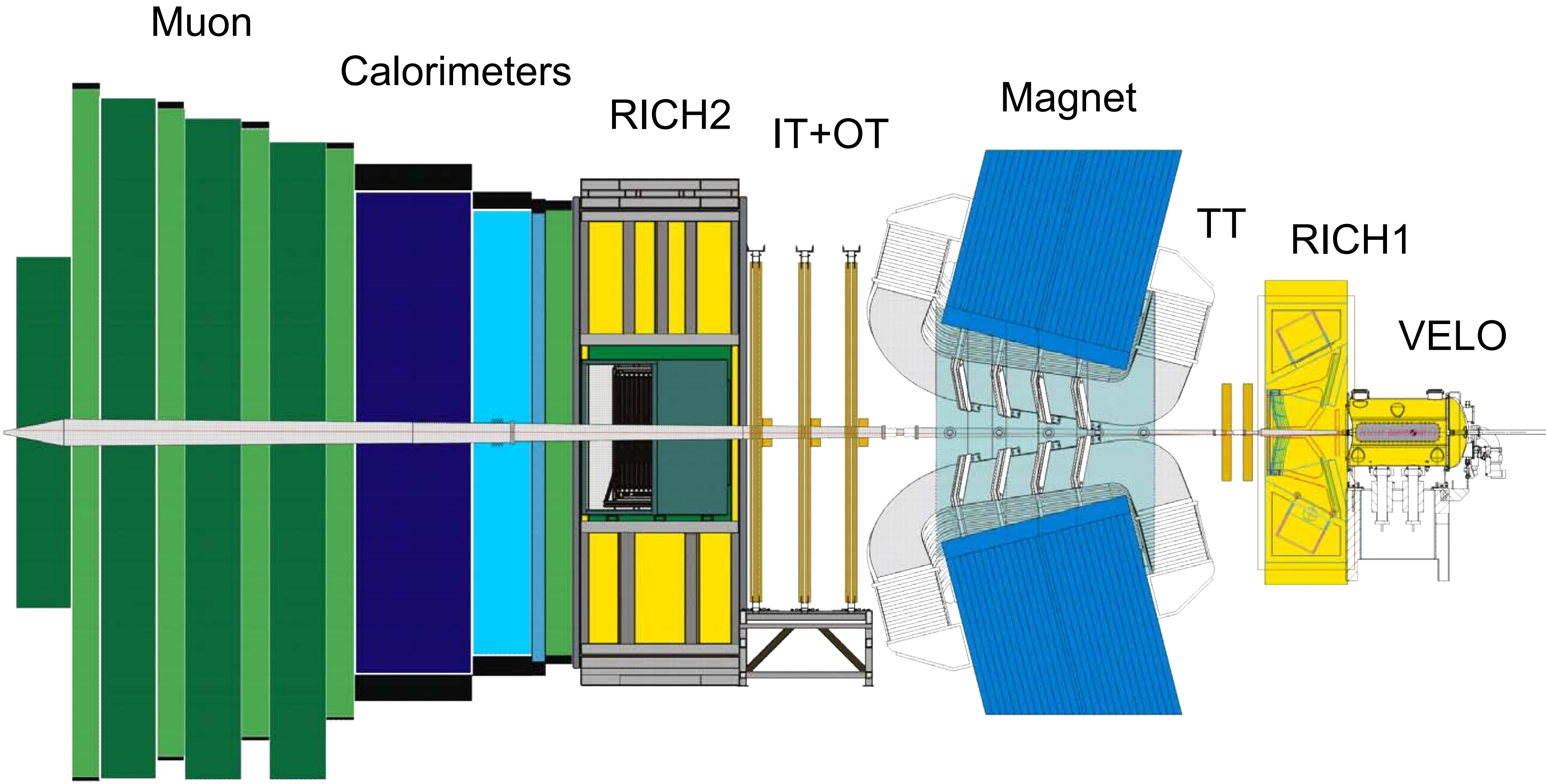


760 members
15 countries
54 institutes

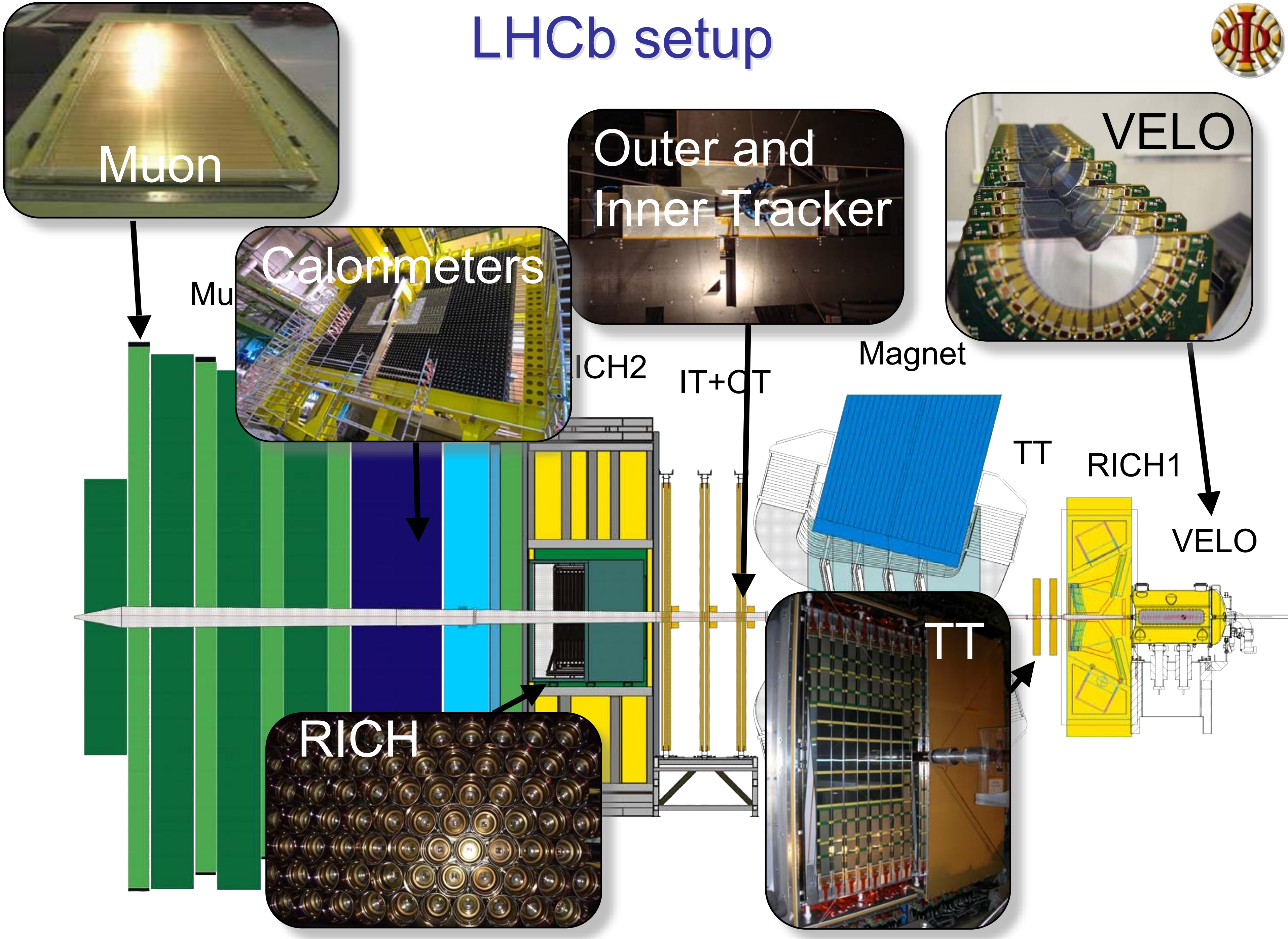
LHCb in the cavern



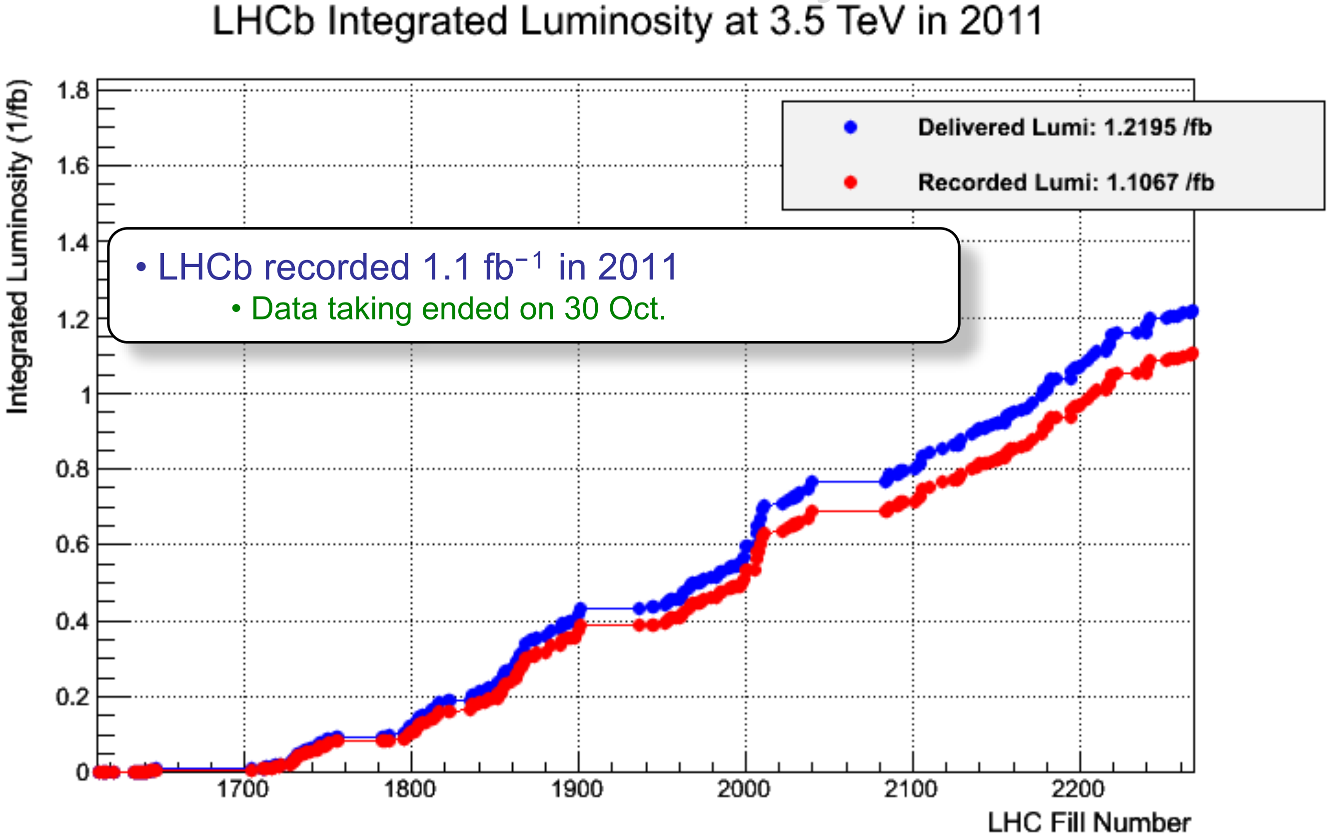
LHCb setup



LHCb setup


Muon
Outer and Inner Tracker
VELO
Calorimeters
Mu
RICH2
IT+OT
Magnet
TT
RICH1
VELO
TT
RICH

Luminosity



- LHCb recorded 1.1 fb^{-1} in 2011
  - Data taking ended on 30 Oct.

But what does this mean? How many B's are produced?

$$\boxed{N_{b\bar{b}} = \sigma_{b\bar{b}} \int \mathcal{L} \mathrm{d}t}$$

B cross section:

- σ_{bb} = 284 ± 53 μb (√s = 7 TeV) [PLB **694** 209]

→ 3.1 x 10^{11} $b\bar{b}$ pairs already produced at LHCb!

Cross sections at 14 TeV:

Total	100 mb
Inelastic	80 mb
$c\bar{c}$	3.5 mb
$b\bar{b}$	500 μb

In 1 in every 200 collisions a bb pair is produced

Reminder

Luminosity

Nb. Of protons per bunch for beam 1

Nb. Of protons per bunch for beam 2

Nb. Of bunches per beam which participate in the interactions

$$L = \frac{N_1 N_2 n_b f}{4\pi\sigma_x\sigma_y}$$

Revolution frequency for a single bunch

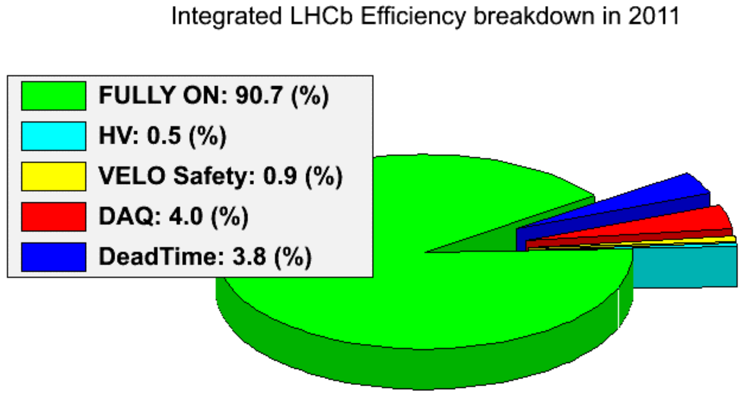
Width of the bunches in x,y - direction

$$\sigma_{x,y} = \sqrt{\beta_{x,y}\varepsilon_{x,y}}$$

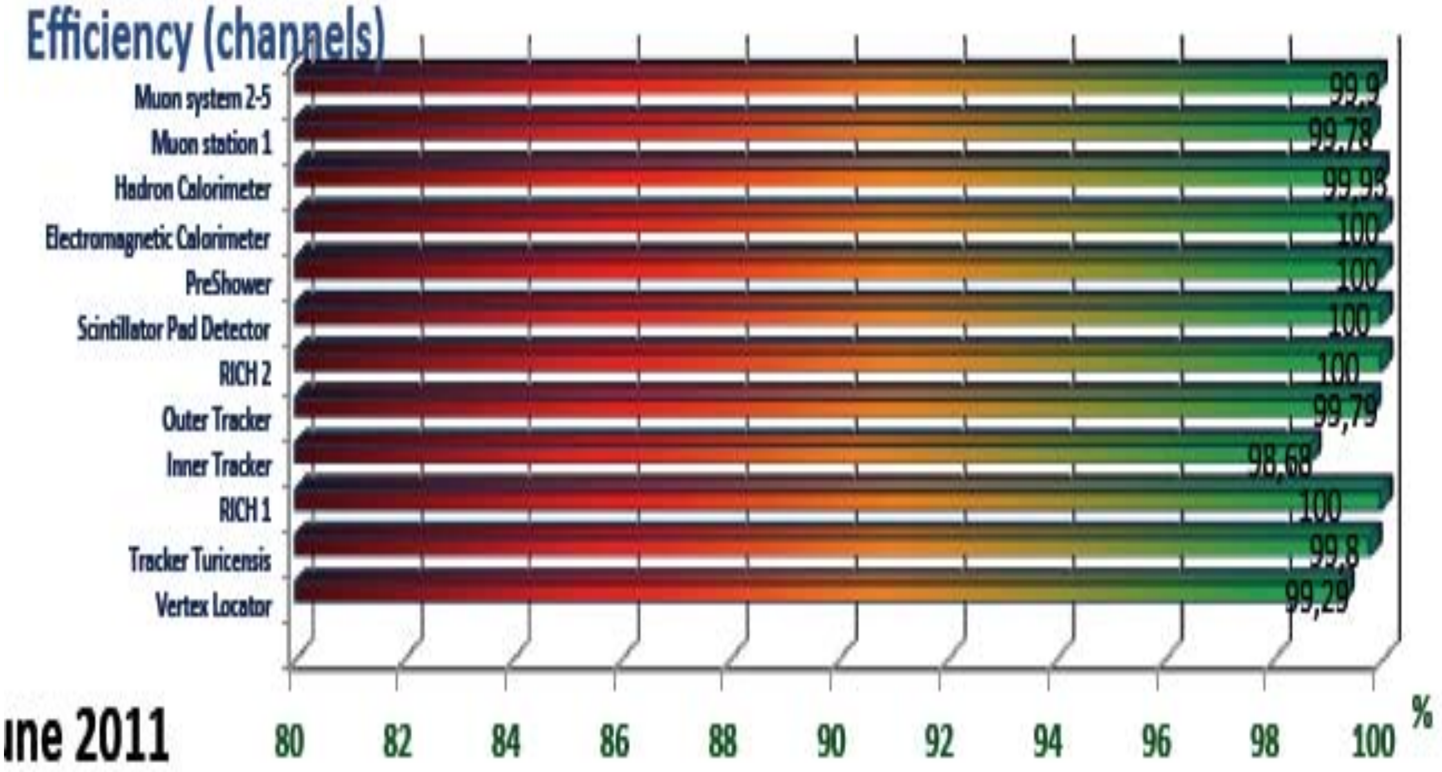
ε– emittance (determined by beam quality from pre accelerators)

β - beta function, i.e. Strength of the focussing magnets

Data taking efficiency



- Data taken with high efficiency ~90%
- Offline data quality rejects < 1%
- Sub-detectors all with > 98% active channels.



Pushing LHCb to its limits

Parameters:	**Design**	**2011**	units
• LHC Beam energy	7.0	3.5	GeV
• Number of bunches in LHC	2808	1300	
• Number of interactions per BX:	0.5	1.5	
• Instantaneous luminosity	2.0	3.0	10^{32} cm^{-2}s^{-1} = 10^{2} μb^{-1}s^{-1}
• Running time	10^{7}	$0.4 \cdot 10^{7}$	seconds
• Integrated luminosity per year	2.0	1.1	fb^{-1}

Performance of LHC in 2011

- Lower beam energy: b cross section only half.
- Fewer number of bunches
- Effective running time LHC in 2011 only 1.5 month.

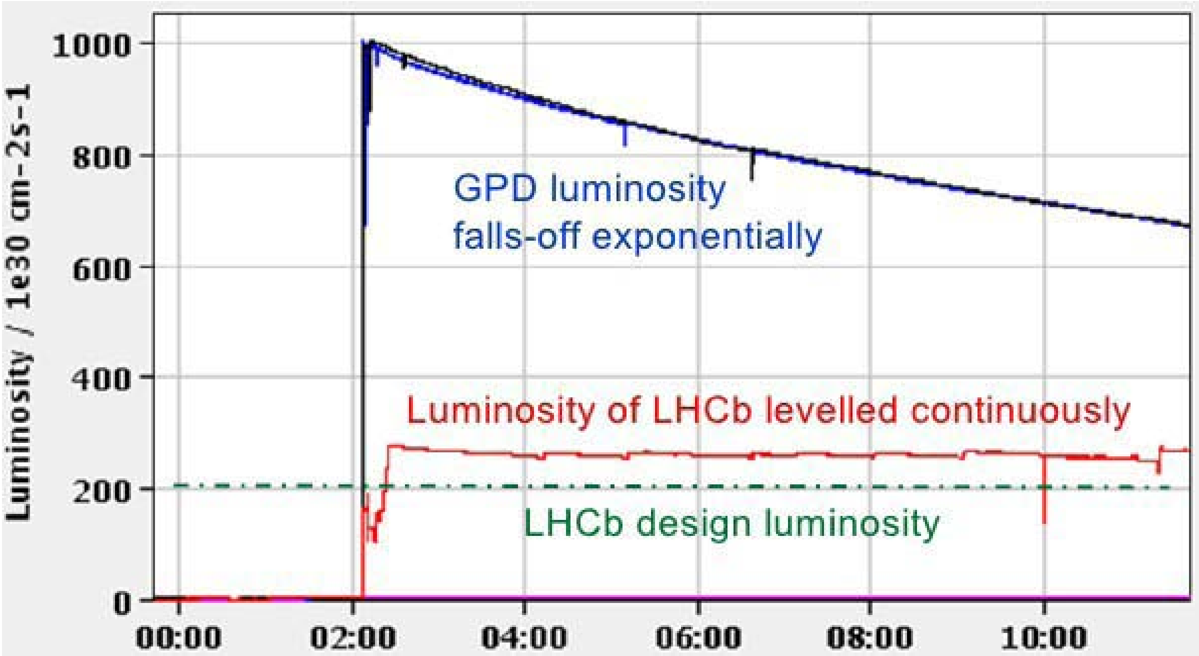
Solution LHCb:

- Run at higher instantaneous luminosity

→ Trigger and reconstruction must cope with higher multiplicities

- Luminosity leveling (see next slide)

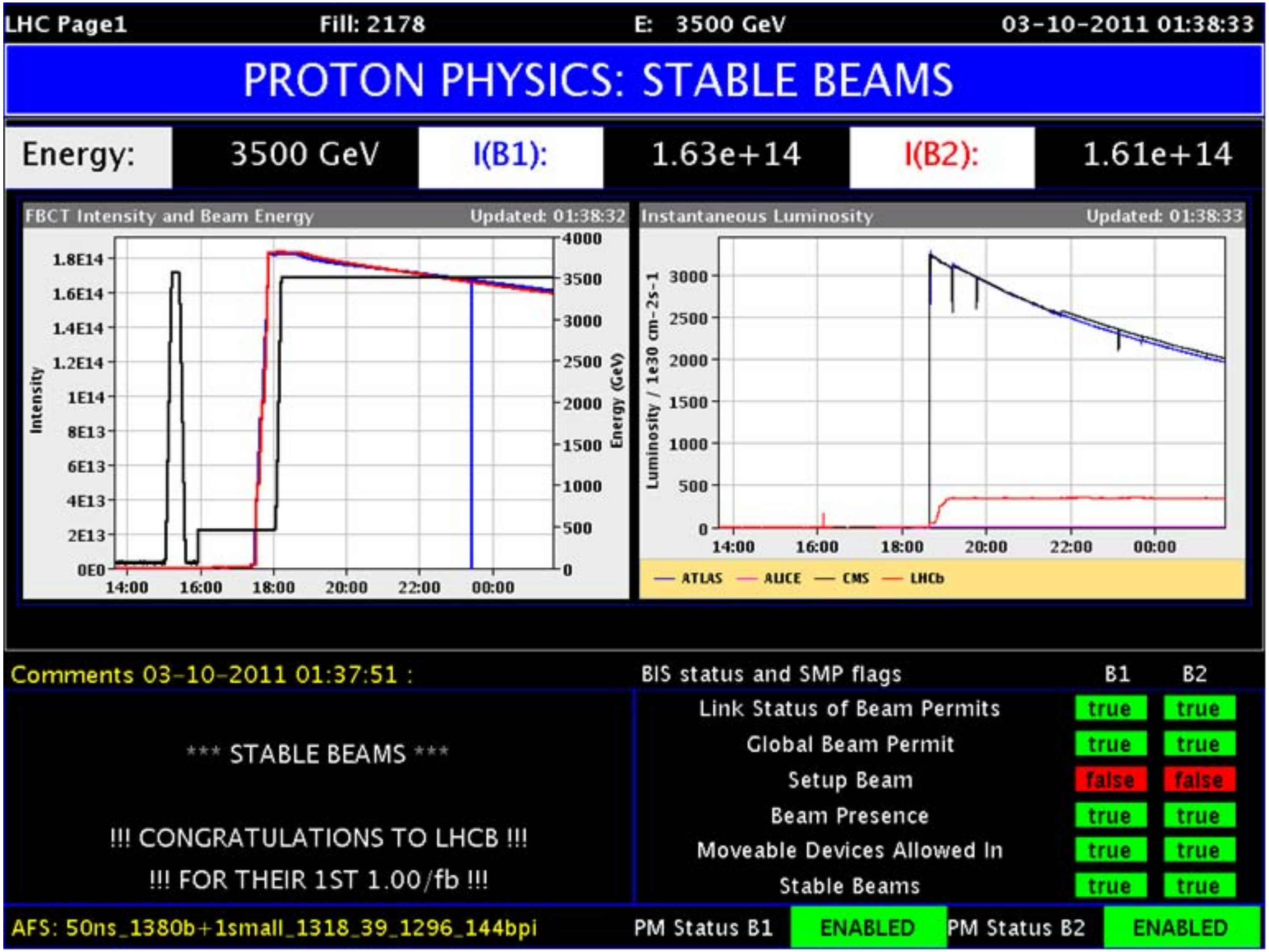
Luminosity leveling



Luminosity leveling

- LHCb already running above design lumi
  - Average L~$3\times10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (nominal 2×10^{32})
- Need to cope with higher occupancies
  - More pile-up: average μ~1.5 (nominal 0.5)
- Continuous, automatic adjustment of offset of colliding beams.
- Allows optimal conditions throughout a fill.
- Very new technique. Not all LHC experts were convinced it would work.
- Allows to take data much more efficiently.

Follow actual status on “LHC page 1”



LHC Page1 Fill: 2178 E: 3500 GeV 03-10-2011 01:38:33

PROTON PHYSICS: STABLE BEAMS

Energy:	3500 GeV	I(B1):	1.63e+14	I(B2):	1.61e+14

FBCT Intensity and Beam Energy Updated: 01:38:32

Instantaneous Luminosity Updated: 01:38:33

Comments 03-10-2011 01:37:51 :

*** STABLE BEAMS ***

!!! CONGRATULATIONS TO LHCB !!!

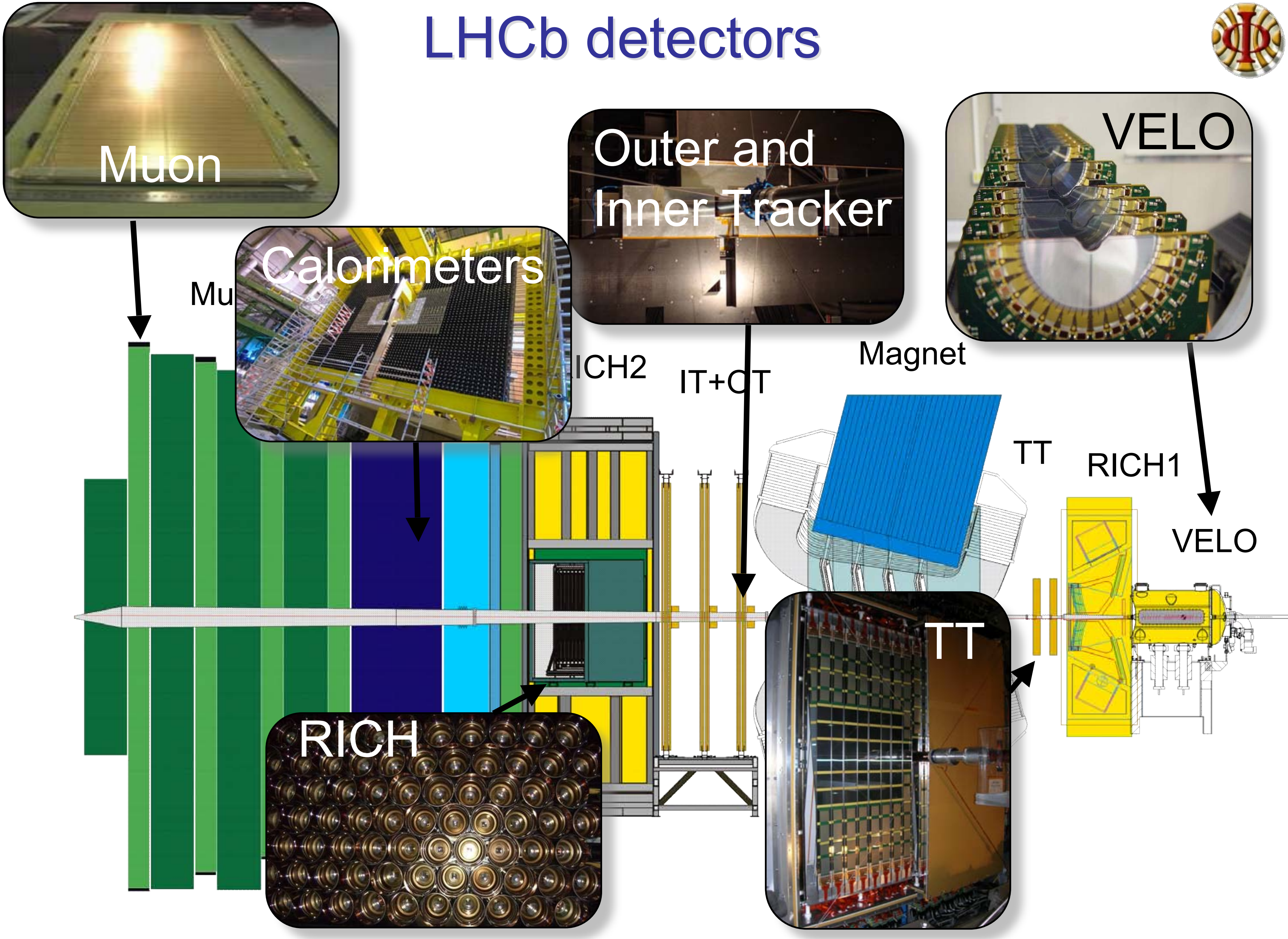
!!! FOR THEIR 1ST 1.00/fb !!!

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: 50ns_1380b+1small_1318_39_1296_144bpi

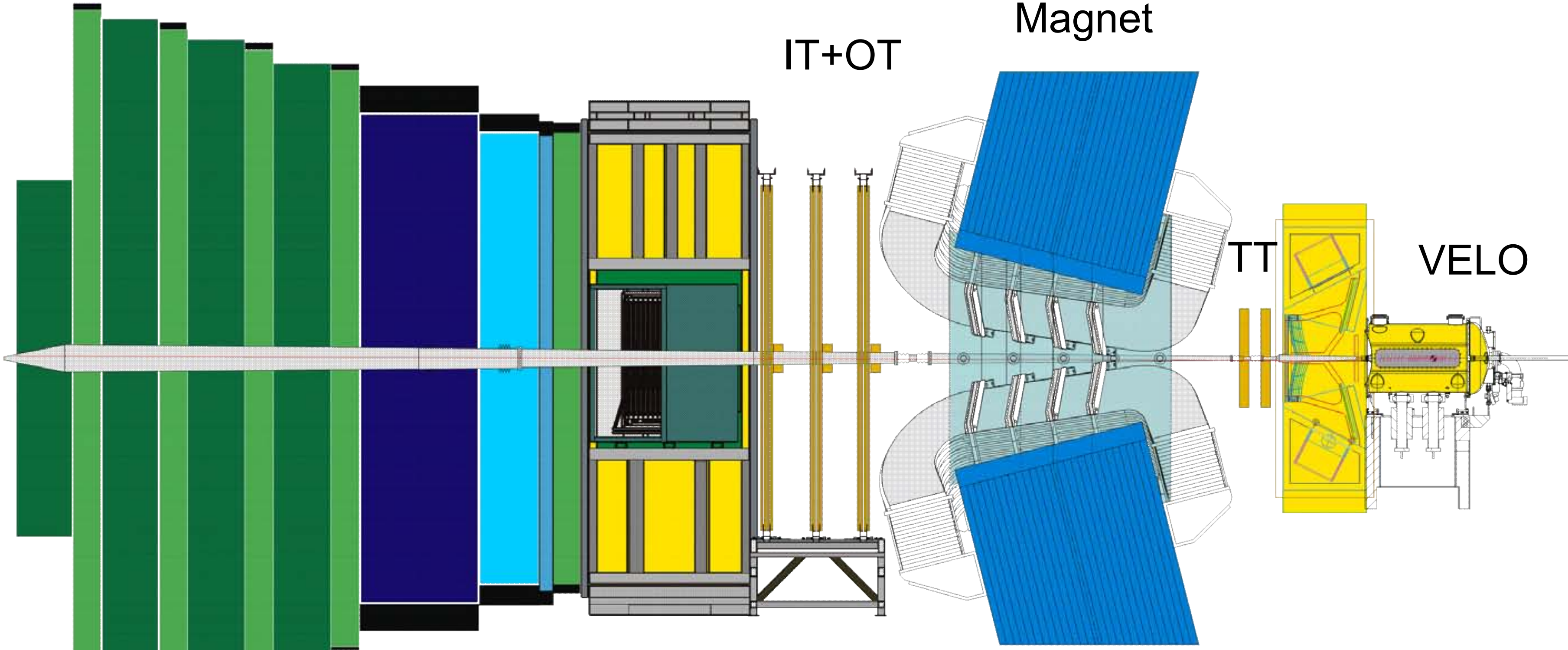
PM Status B1 ENABLED PM Status B2 ENABLED

LHCb detectors



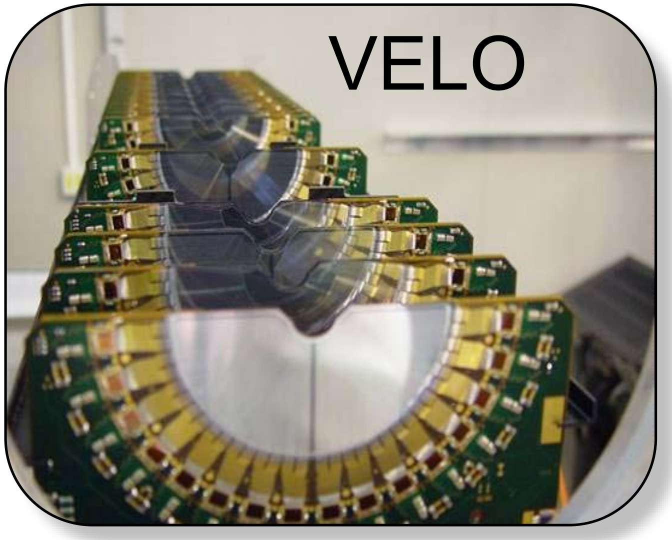
LHCb from a tracking point of view

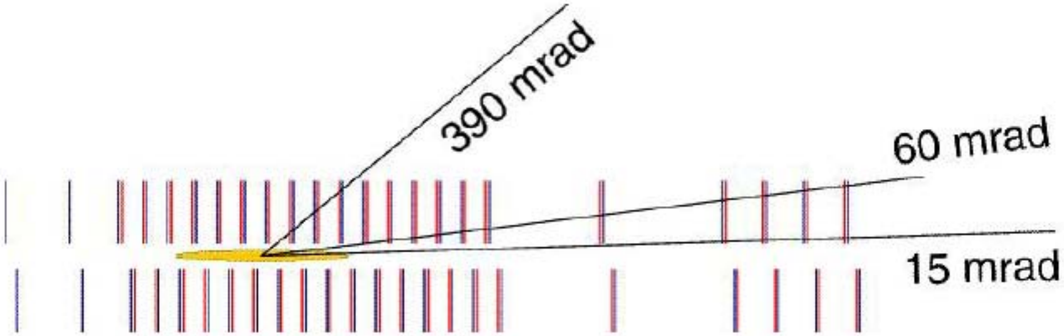
Goal	**Purpose**	**Solution**
1. Measure **proper time** of decaying particles	Identify *B* hadrons and time-dependent analysis.	Vertex detector: **VELO** (+tracking stations)
2. Measure **mass** of decaying particles	Identify signal and separate from background.	Magnet + tracking stations: **TT, IT, OT** (+VELO).



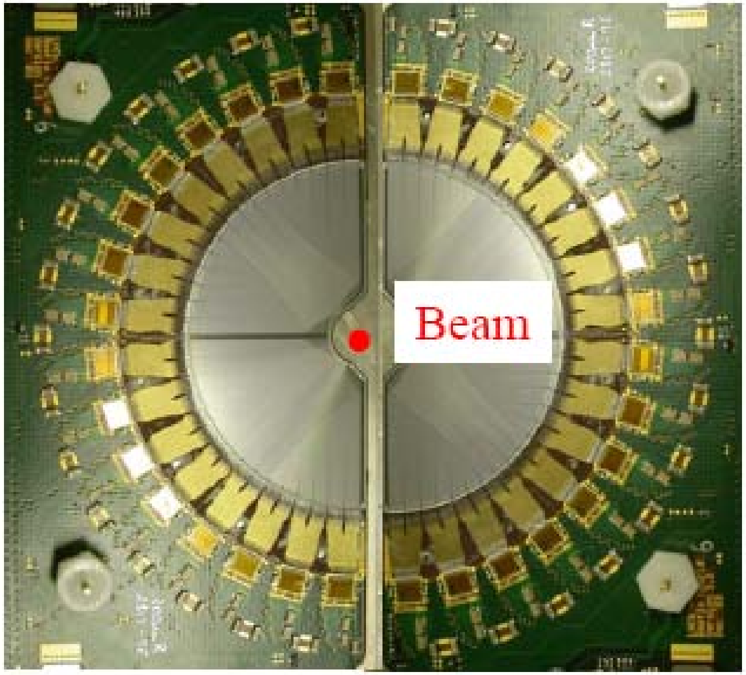
LHCb has extremely good mass and proper time resolution

Vertex detector

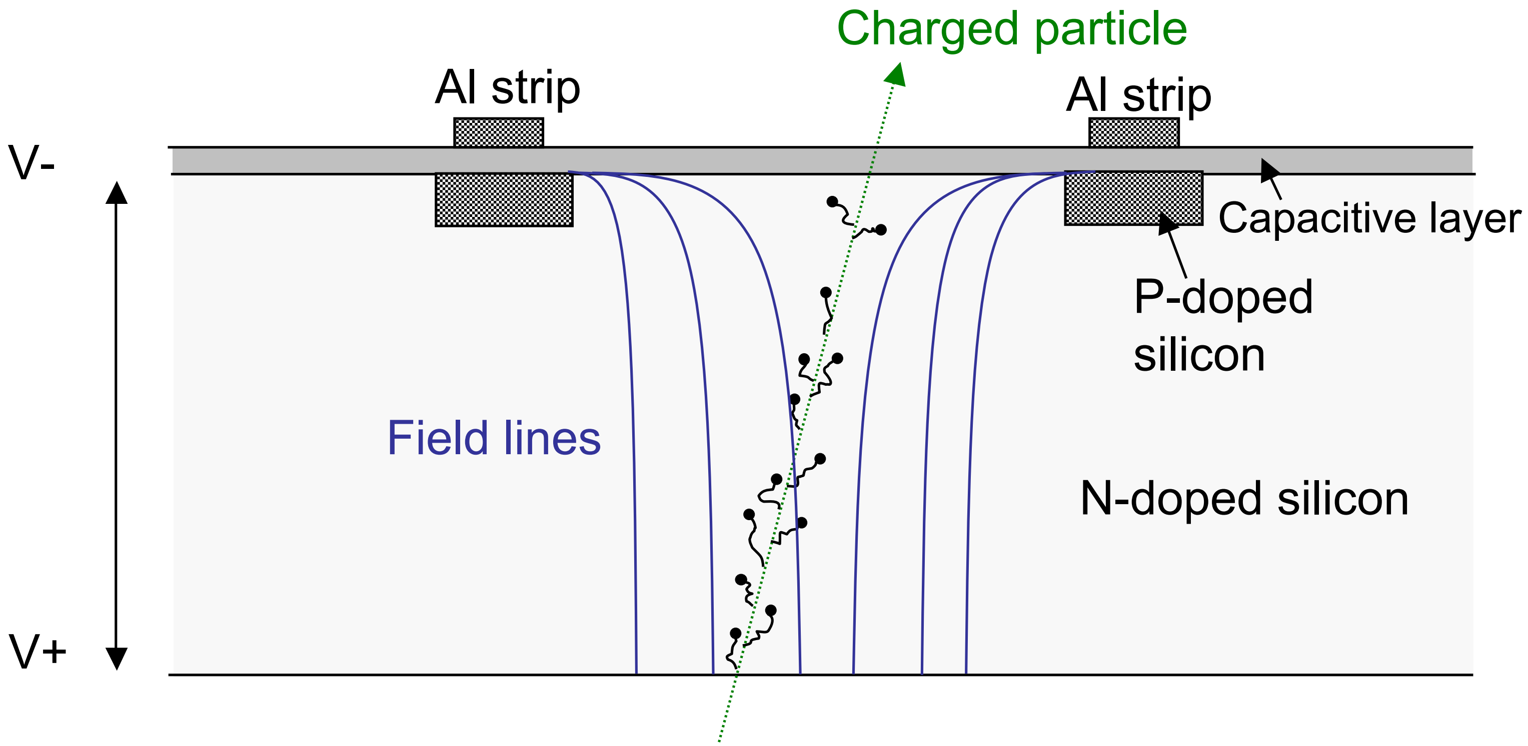




- ☐ Two retractable halves.
- ☐ 21 modules, each with a r- and φ-measuring sensor.
- ☐ Strip pitch: 36–102 μm.
- ☐ S/N > 20



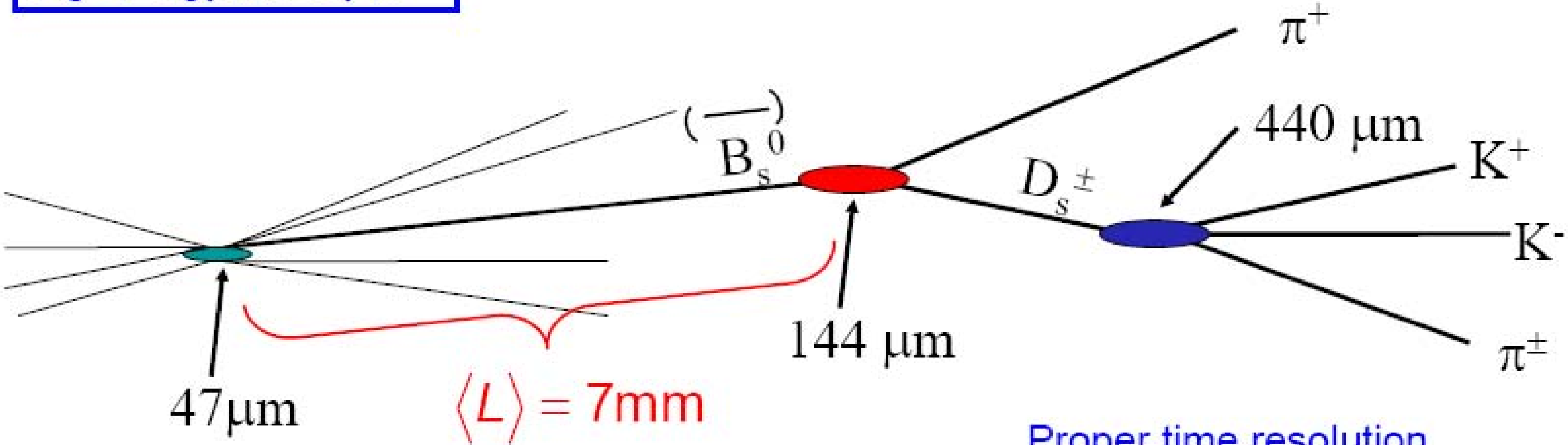
(Reminder) Silicon detectors



- Bias voltage between backplane and strips.
- Bias voltage such that silicon is depleted of charge carriers (depletion voltage).
- Traversing charged particle creates electron-hole pairs.
- Holes and electrons generated along path (only showing holes)
- Holes attracted by strips, electrons by the backplane.

Vertex reconstruction

$B_s \to D_s(K\,K\,\pi)\,\pi$

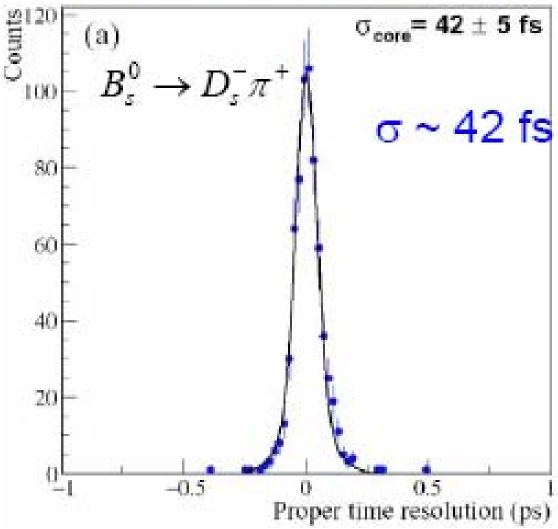


$$L = c\beta\gamma t$$

$$t = \frac{Lm}{p}$$

→

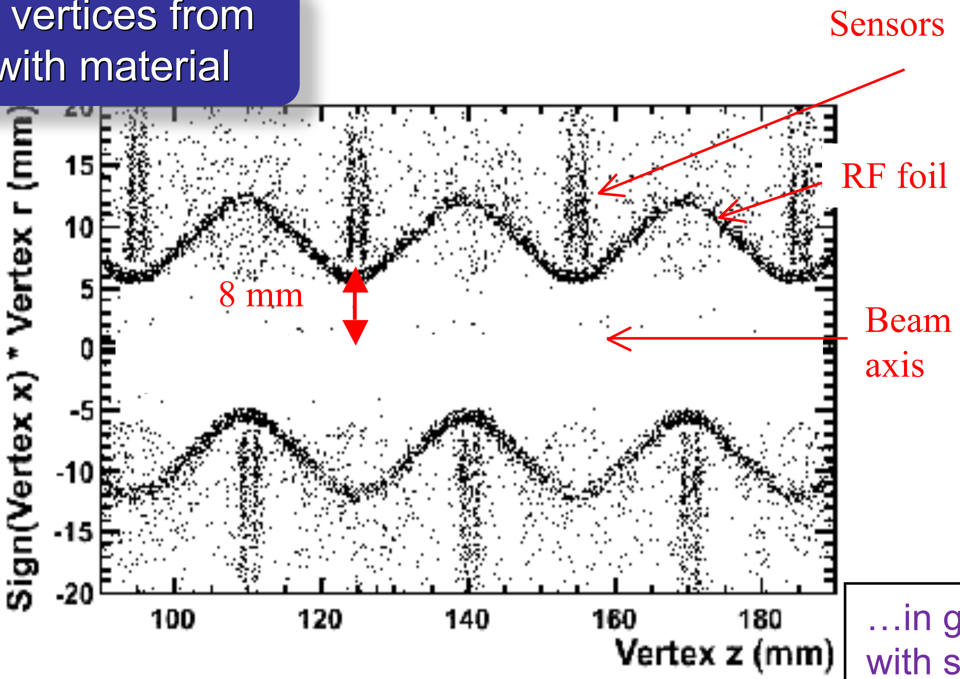
Proper time resolution



Vertex reconstruction

- VELO sensors only 8 mm from beam.
- Impact parameter resolution = 12 μm for high p_T tracks.
- Good primary and secondary vertex resolution.
  - Suppress background from prompt decays.
- Good proper-time resolution
  - Important for time-dependent measurements.

VELO “tomography” with vertices from secondary interactions with material

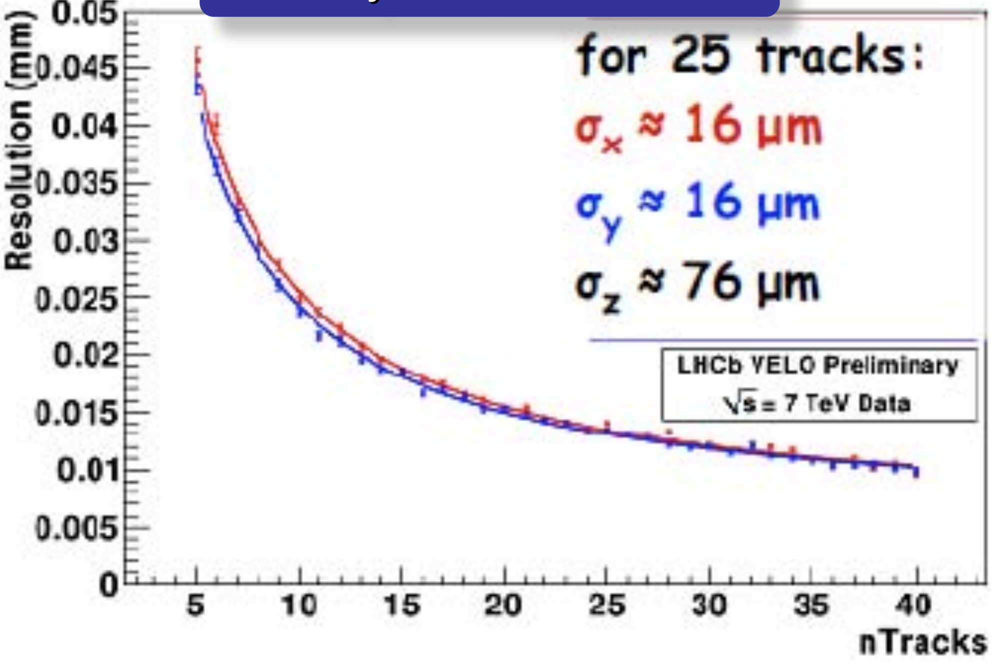


RF-foil must be as thin as possible to reduce error on the vertex position

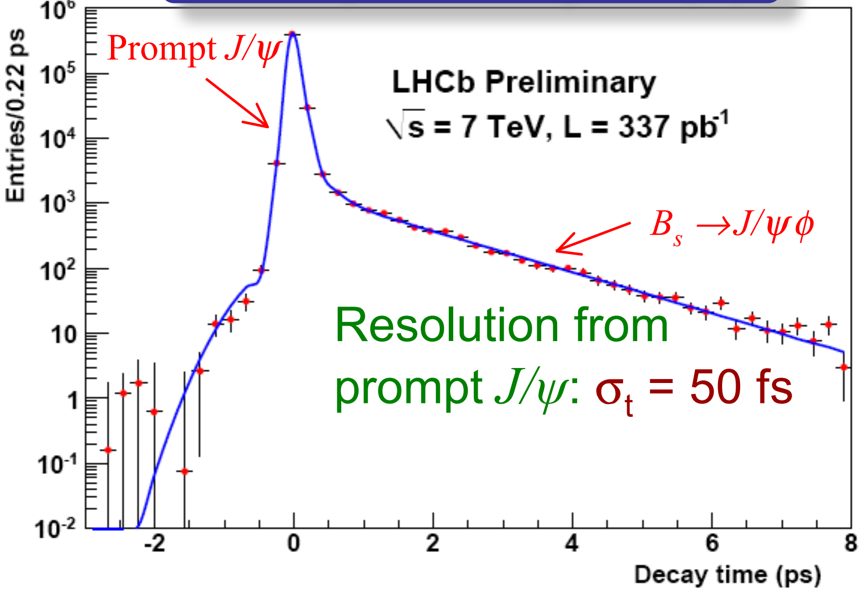
…in good agreement with simulation

Vertex reconstruction

Primary vertex resolution

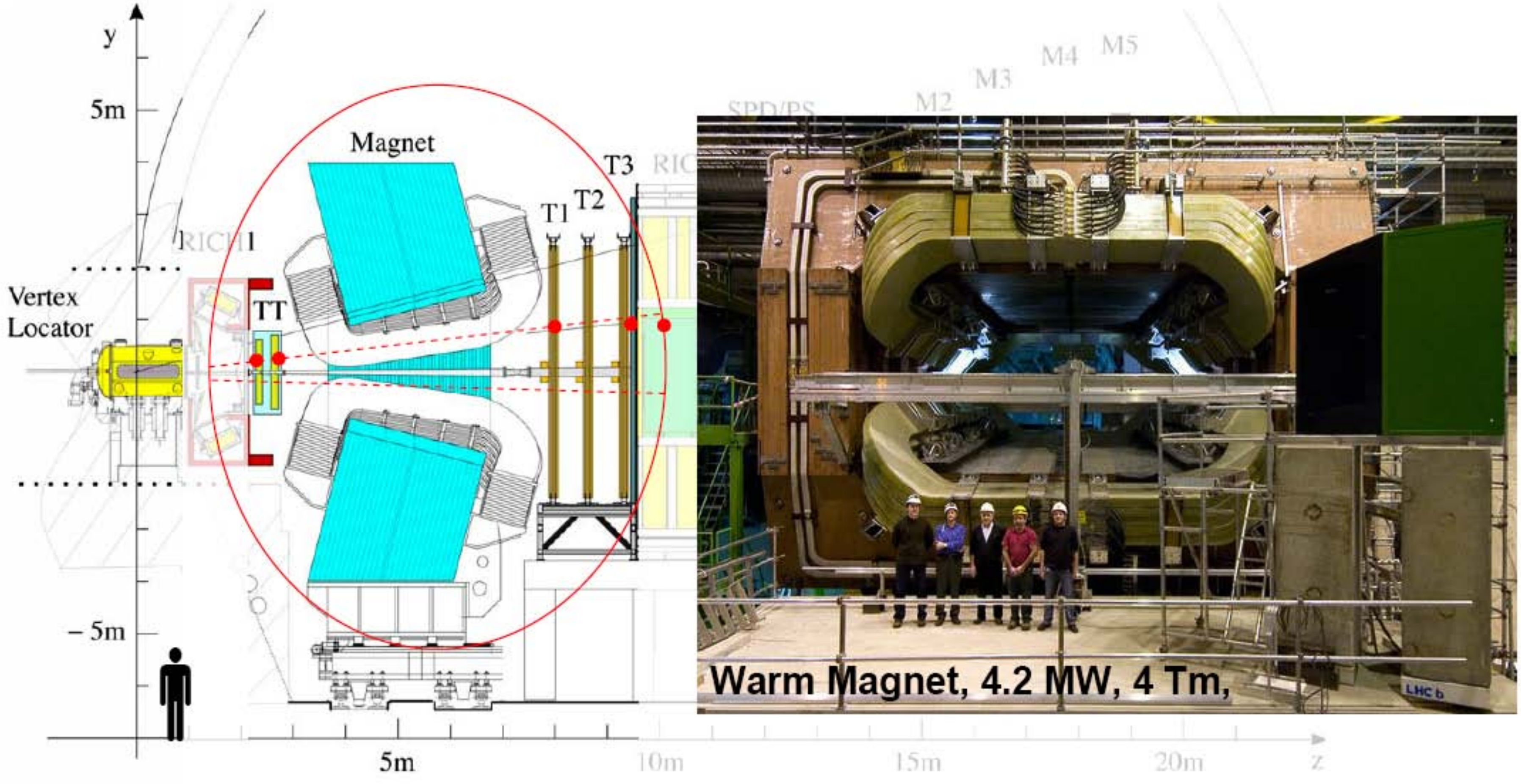


Decay time in $B_s \rightarrow J/\psi\ \phi$



Resolution from prompt J/ψ: σ_t = 50 fs

Magnet



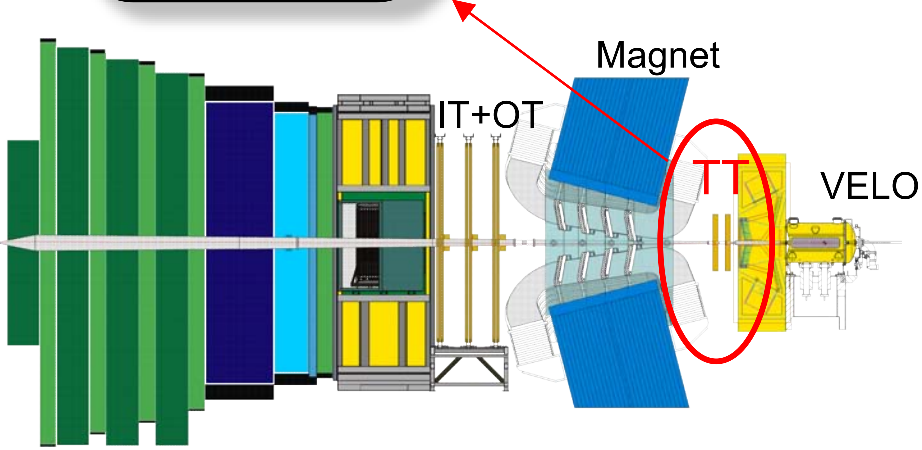
Warm Magnet, 4.2 MW, 4 Tm,

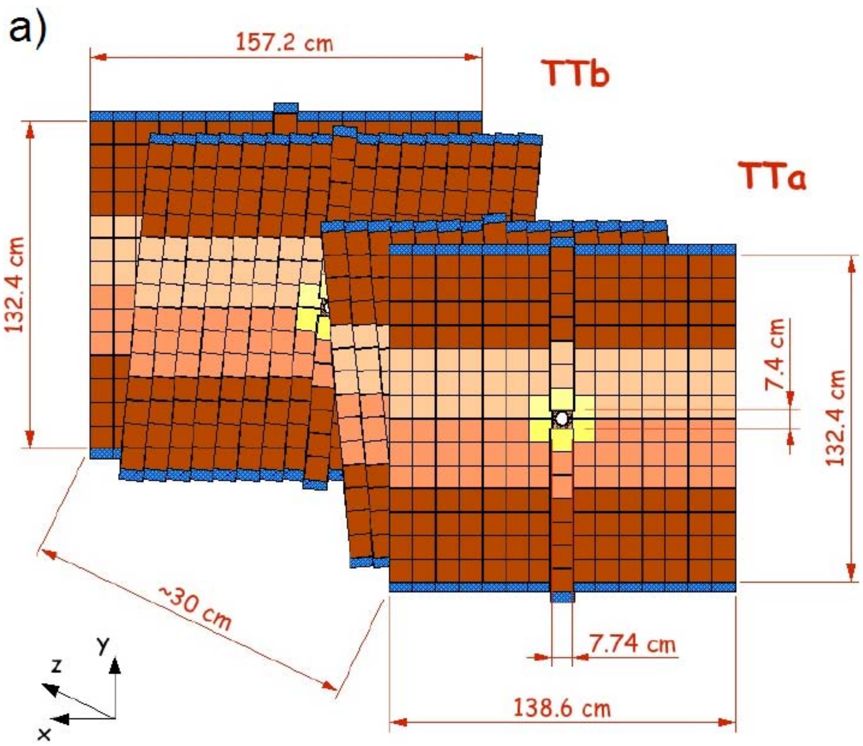
Tracking system and dipole magnet to measure angles and momenta

$\Delta p/p$ ~ 0.4 %, mass resolution ~ 14 MeV (for $B_s \to D_sK$)

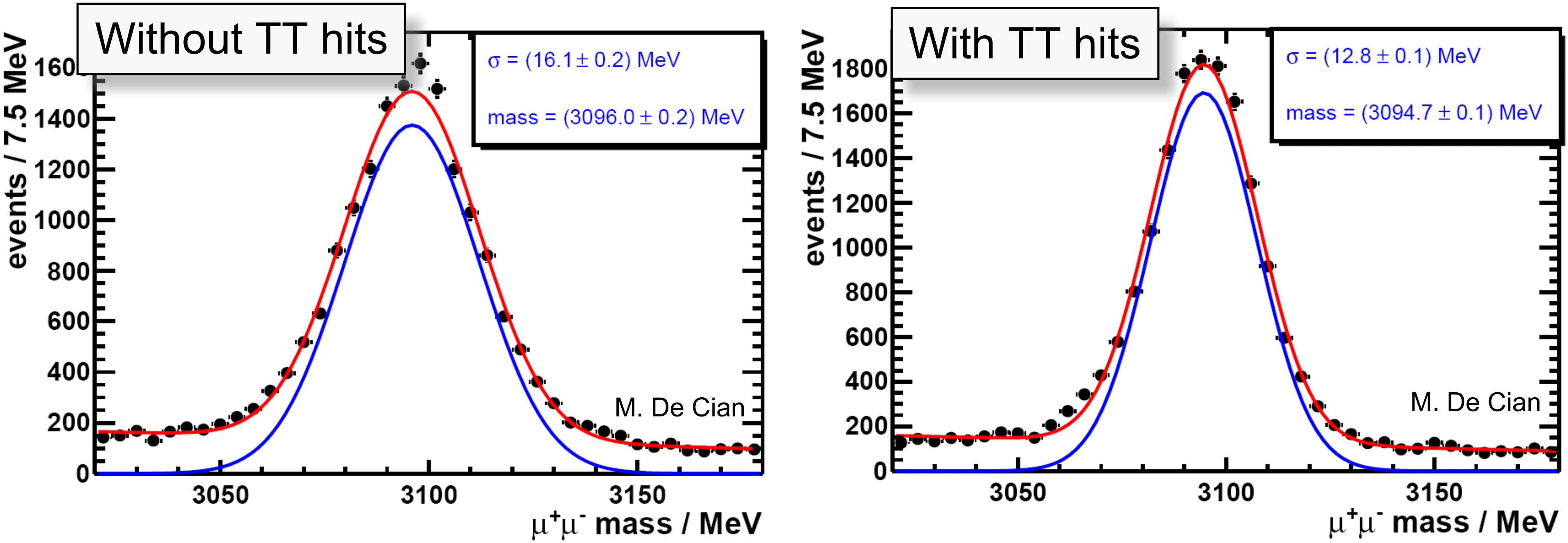
Tracking system: TT

- Just after RICH1 and before the magnet
- Four layers (0º,+5º,−5º,0º) of 150 x 130 cm.
- Strip pitch: 183 μm.
- S/N ~ 13
- 64 modules with 14 sensors each.
- Hit resolution about 50 μm.





Tracking system: TT

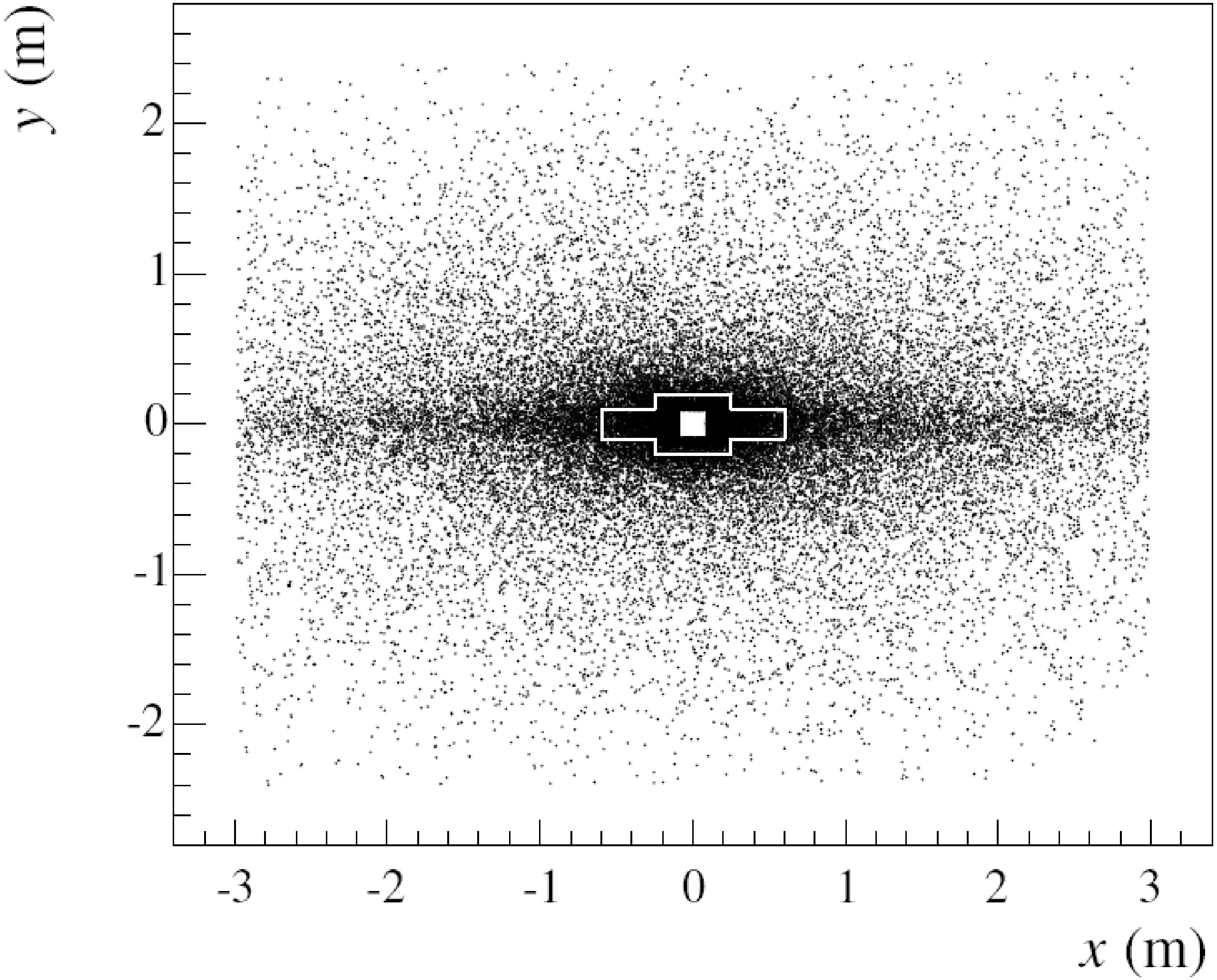


→TT needed to compensate scattering of RICH1.

→ Improves mass resolution by about 25-30%.

T stations

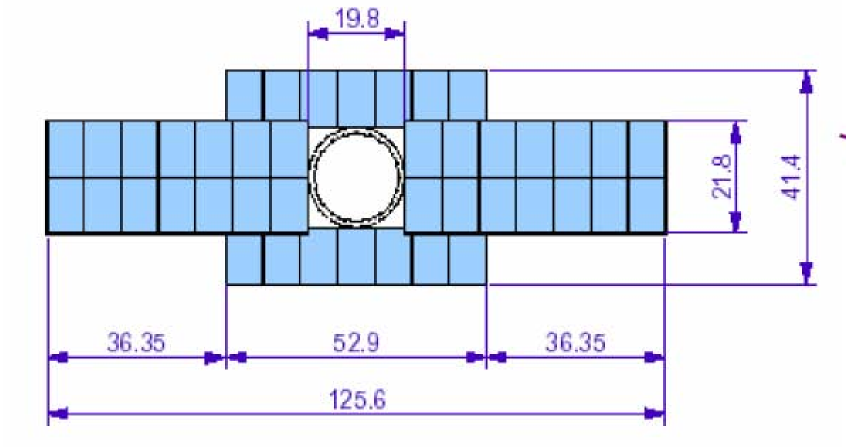
Why do the tracking stations after the magnet consist of two detectors?

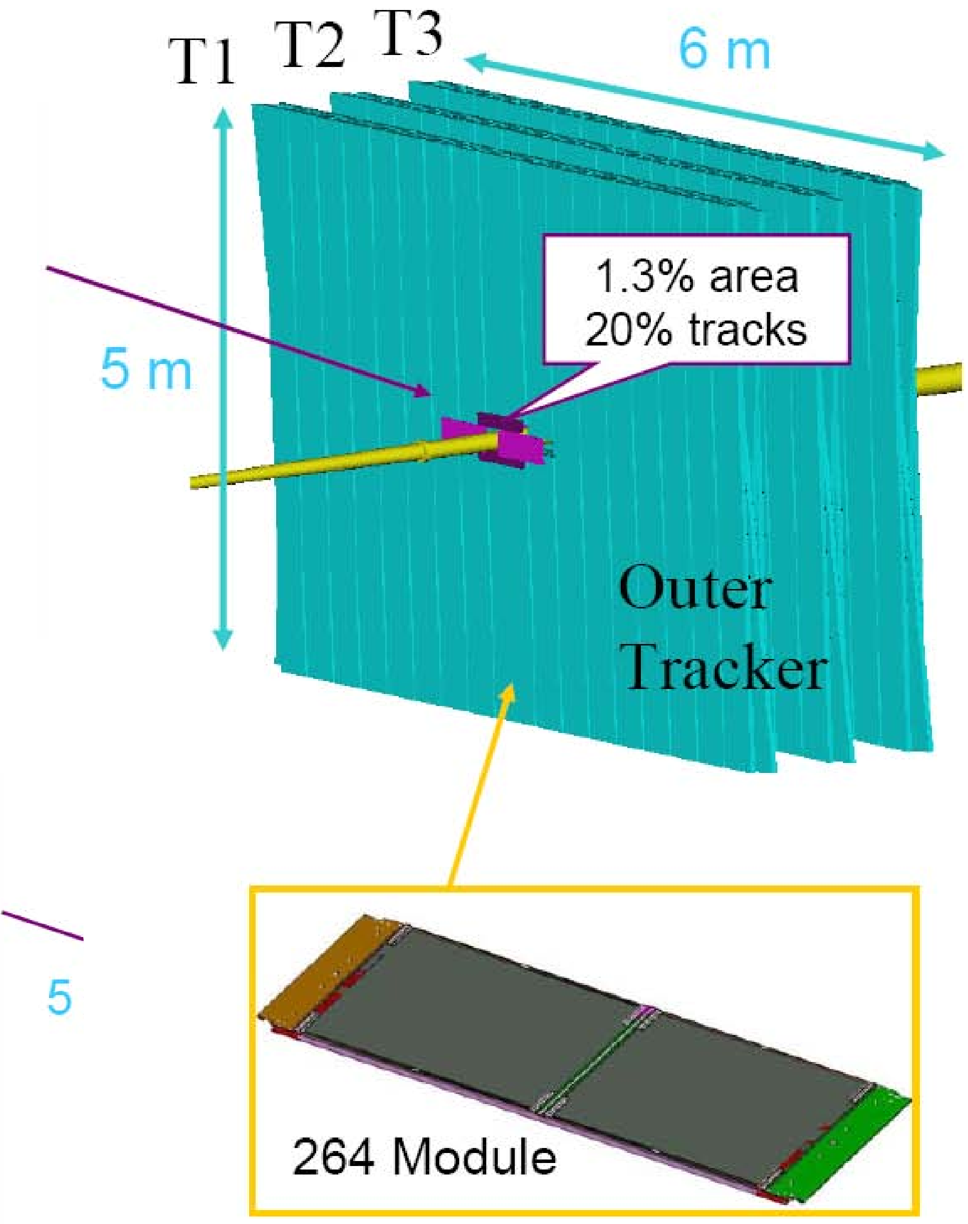


Tracking system: IT

- 3 stations with 4 boxes each.
- Each box has 4 layers (0º,+5º,−5º,0º).
- Strip pitch: 198 μm.
- S/N ~ 16
- Hit resolution about 50 μm.

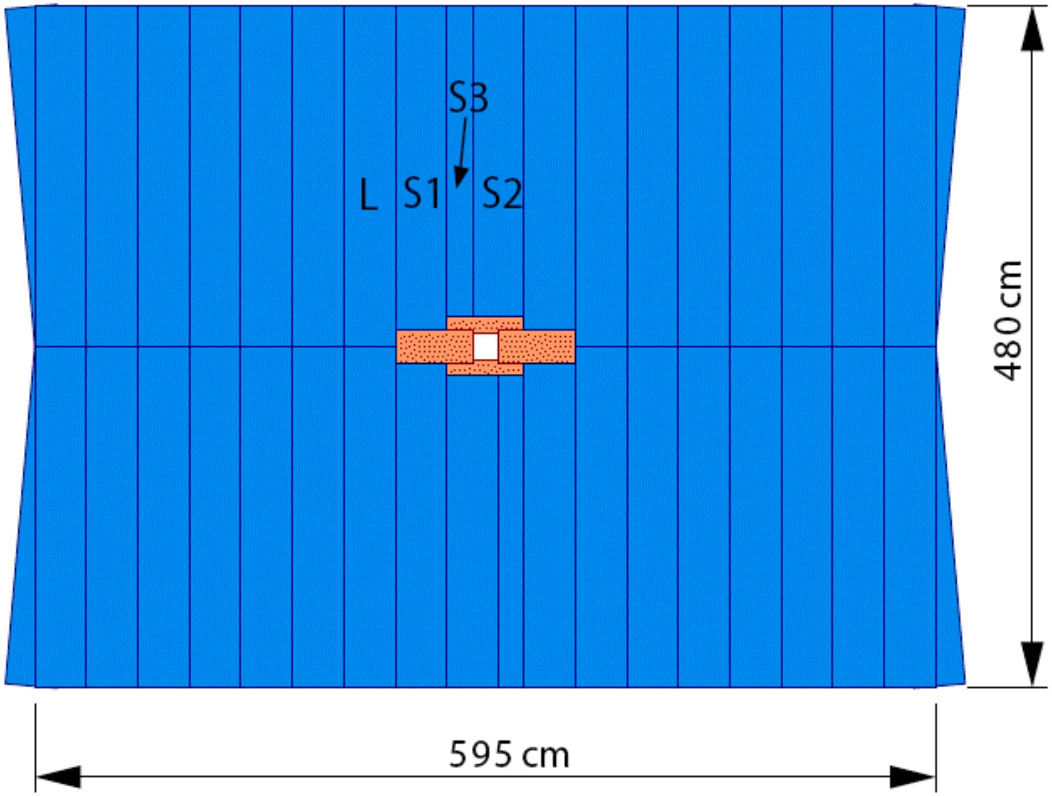
Inner Tracker: Silicon sensors



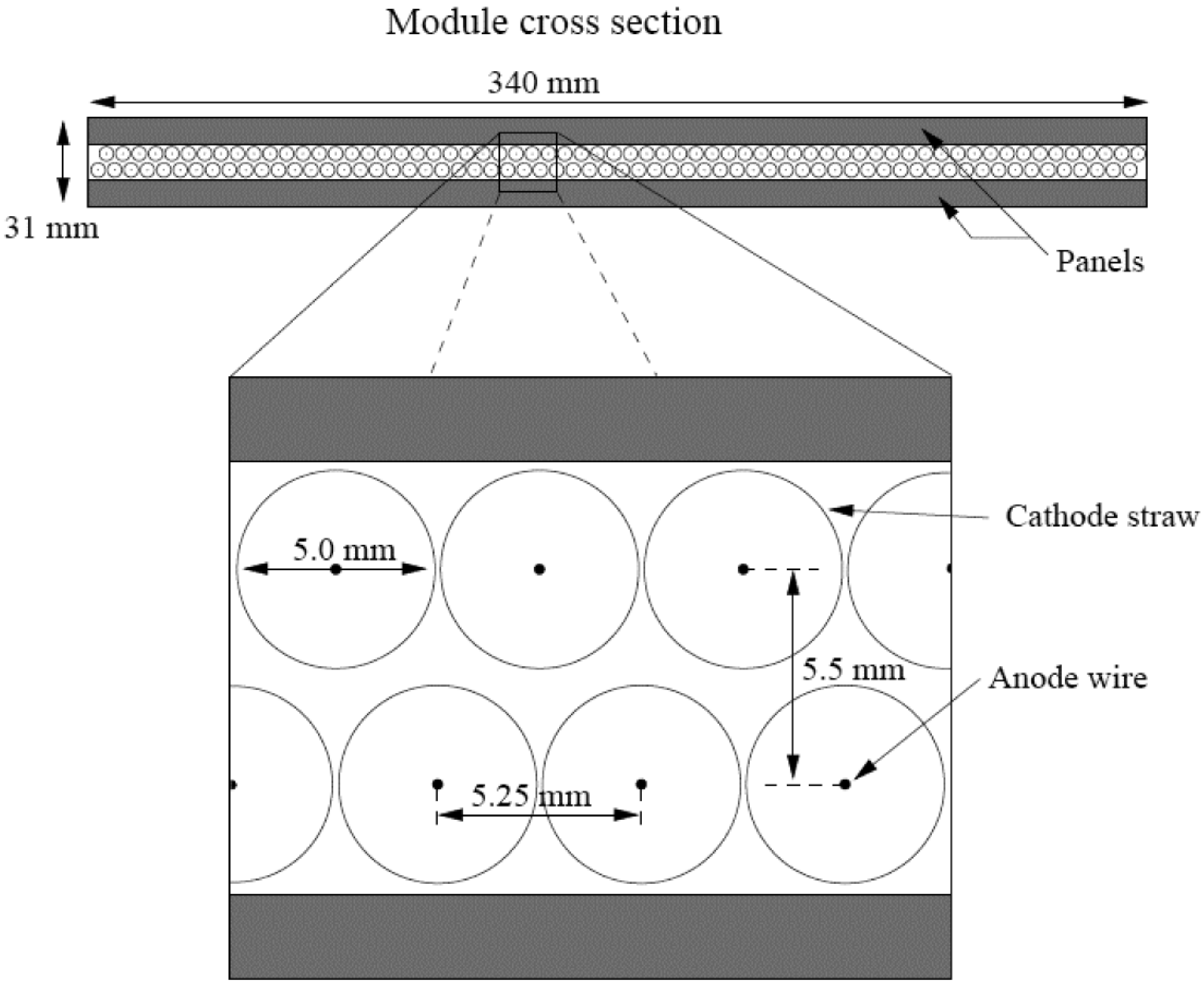


Tracking system: OT

- ❑ 3 stations of modules with straw tubes
- ❑ Each station has 4 layers (0º,+5º,−5º,0º).
- ❑ Straw pitch: 5 mm
- ❑ Resolution: ~200 micron

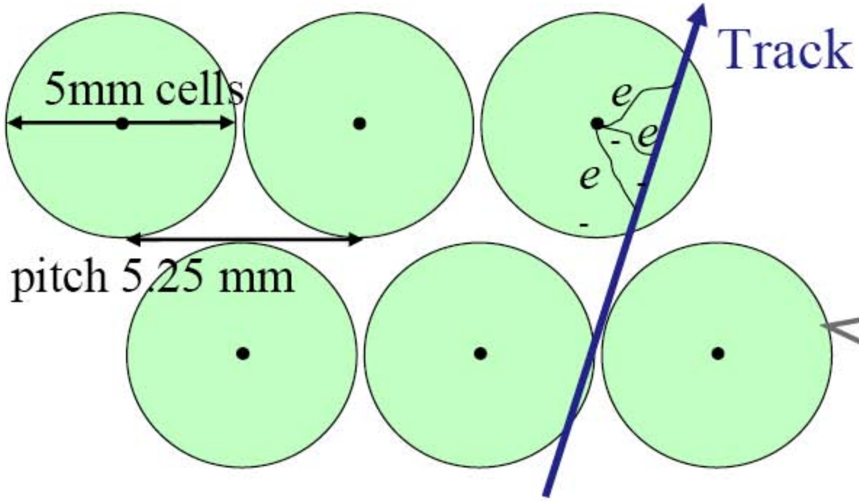


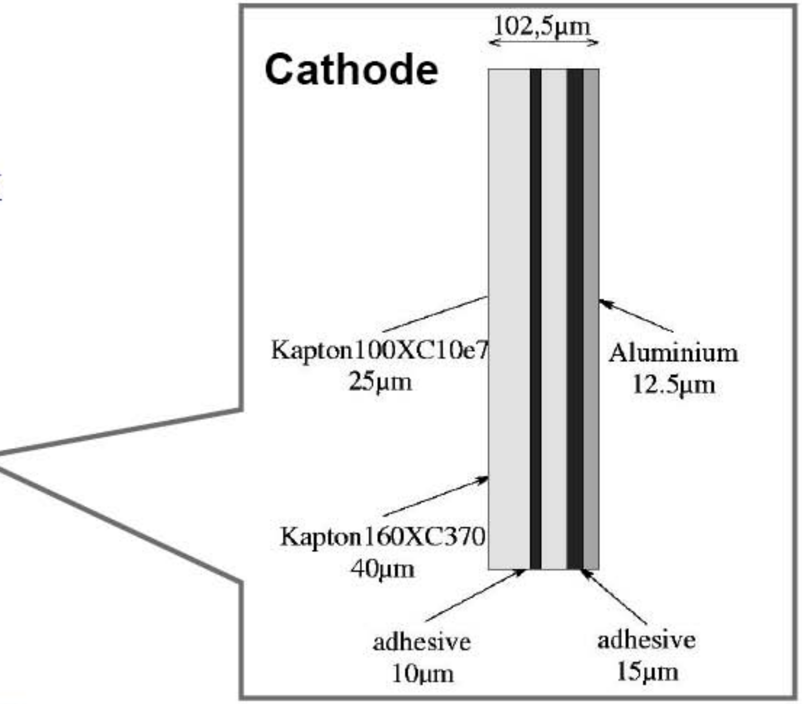
Tracking system: OT

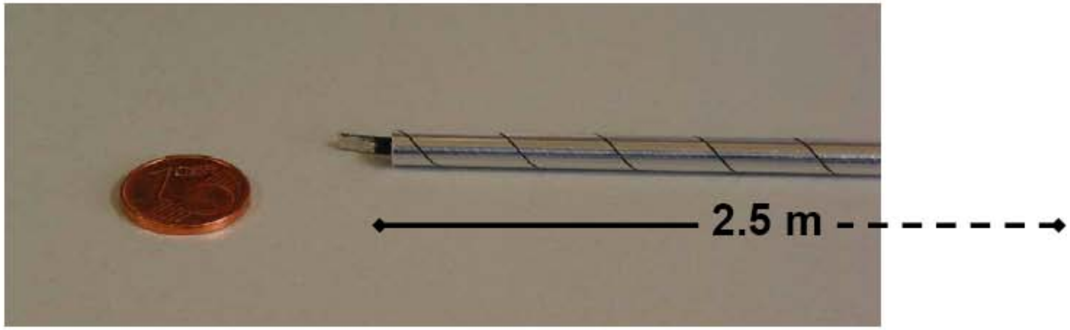


Tracking system: Outer Tracker

Straw tube drift chamber modules

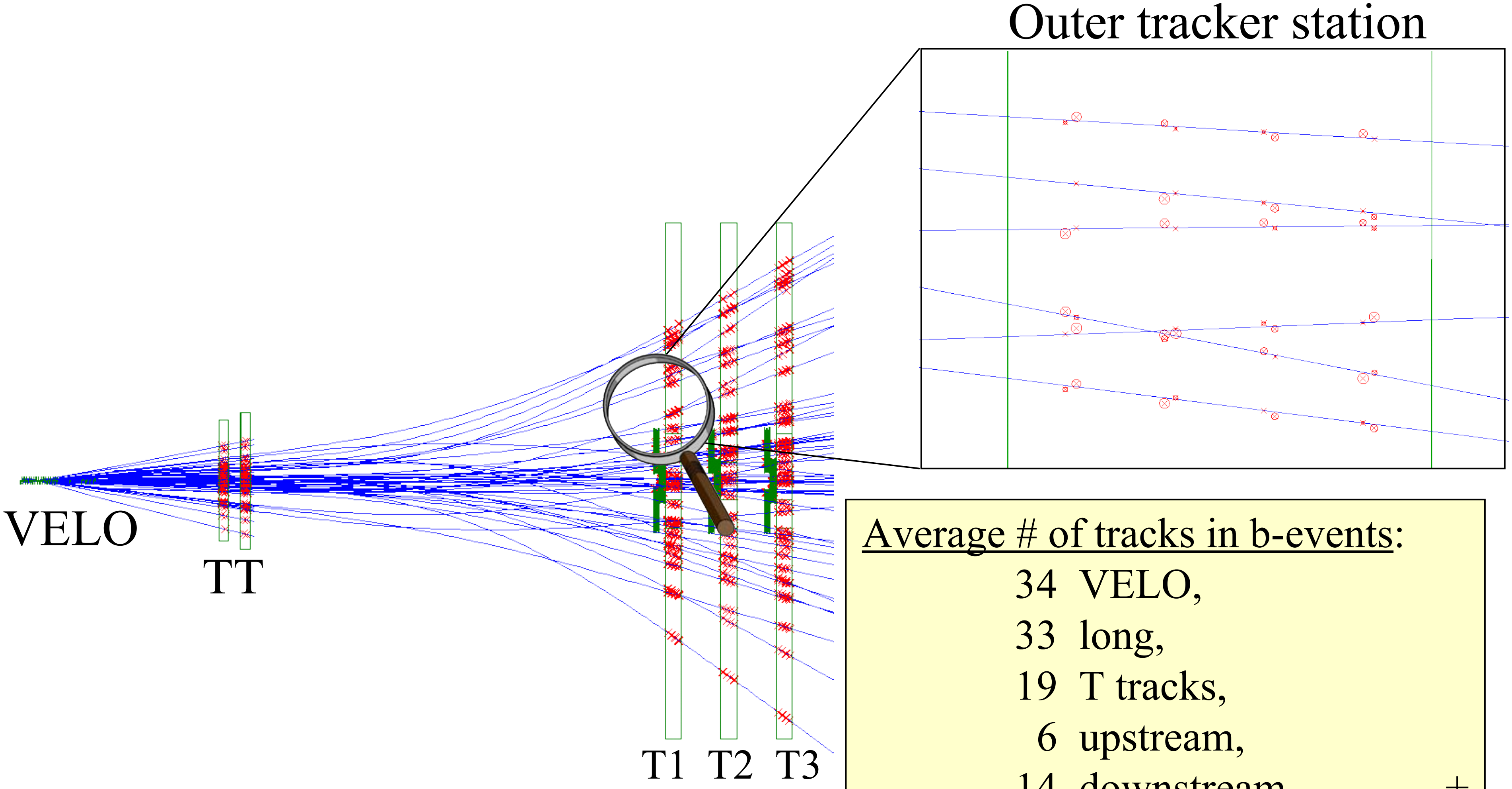






Outer Tracker

Track reconstruction



Average # of tracks in b-events:

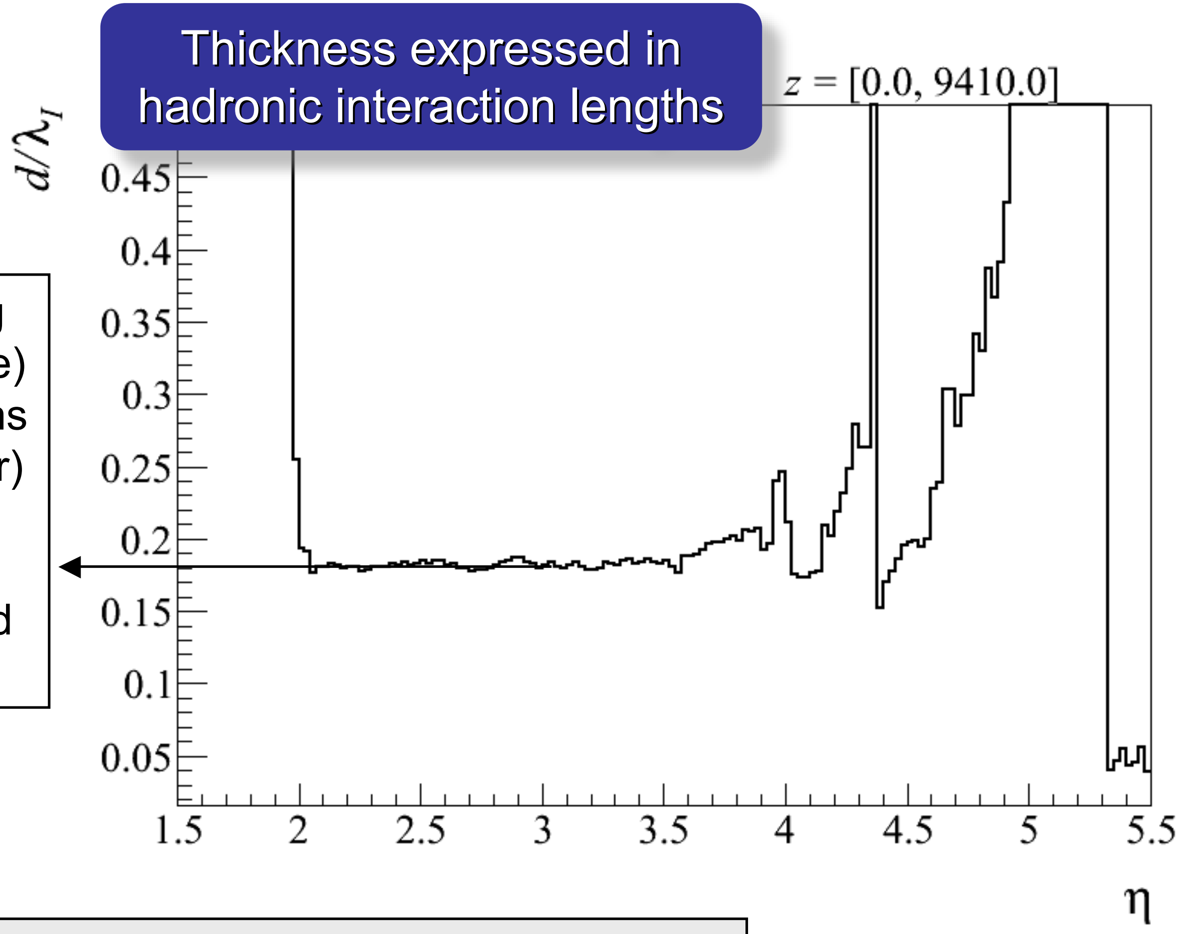
34 VELO,
33 long,
19 T tracks,
6 upstream,
14 downstream +

Total 106 reconstructed tracks

Track reconstruction

Why should the tracking detectors be light?

Reason 1: Otherwise they will stop the particles (hadronic showers)



Thickness expressed in hadronic interaction lengths

- Thickness of material in tracking system: 18% (over 9m of distance)
- That means ~18% of the hadrons have hadronic interaction (shower) in detector.
- Hadronic interactions only important for hadrons (muons and electrons not affected).

18% thickness corresponds to 8 cm of aluminium

Track fitting

Definition (Merriam-Webster)
Track [trak]: Detectable evidence (as the wake of a ship, a line of footprints, or a wheel rut) that something has passed.

Definition (High-energy physics)
Path of a charged particle through a detector.

Track is a collection of track states along this path
→ conveniently parameterized in z positions (LHCb).

Track state:

- State vector

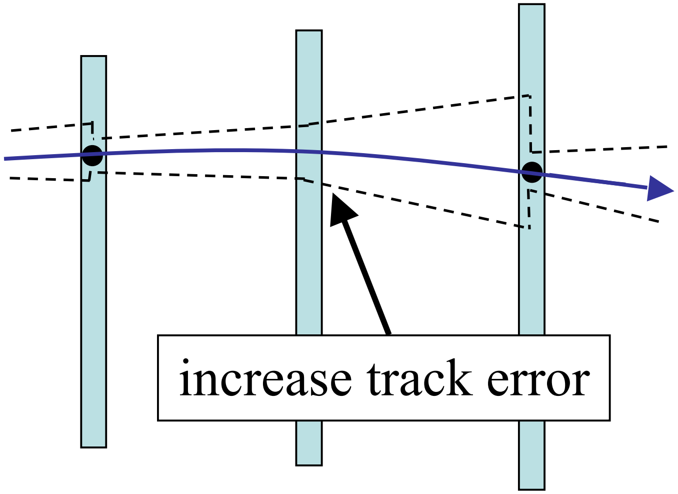
$$\vec{x} = \begin{pmatrix} x \\ y \\ t_x \\ t_y \\ q/p \end{pmatrix}$$ at a given z-position, where $t_x = \frac{\partial x}{\partial z}$ and $t_y = \frac{\partial y}{\partial z}$.

- Plus corresponding covariance matrix (5x5).

Track fitting

Track fit issues:

- Many parameters.
  - 5n free parameters (n = number of states)
- Need to incorporate material effects (see below)
  - More free parameters to fit



Solution

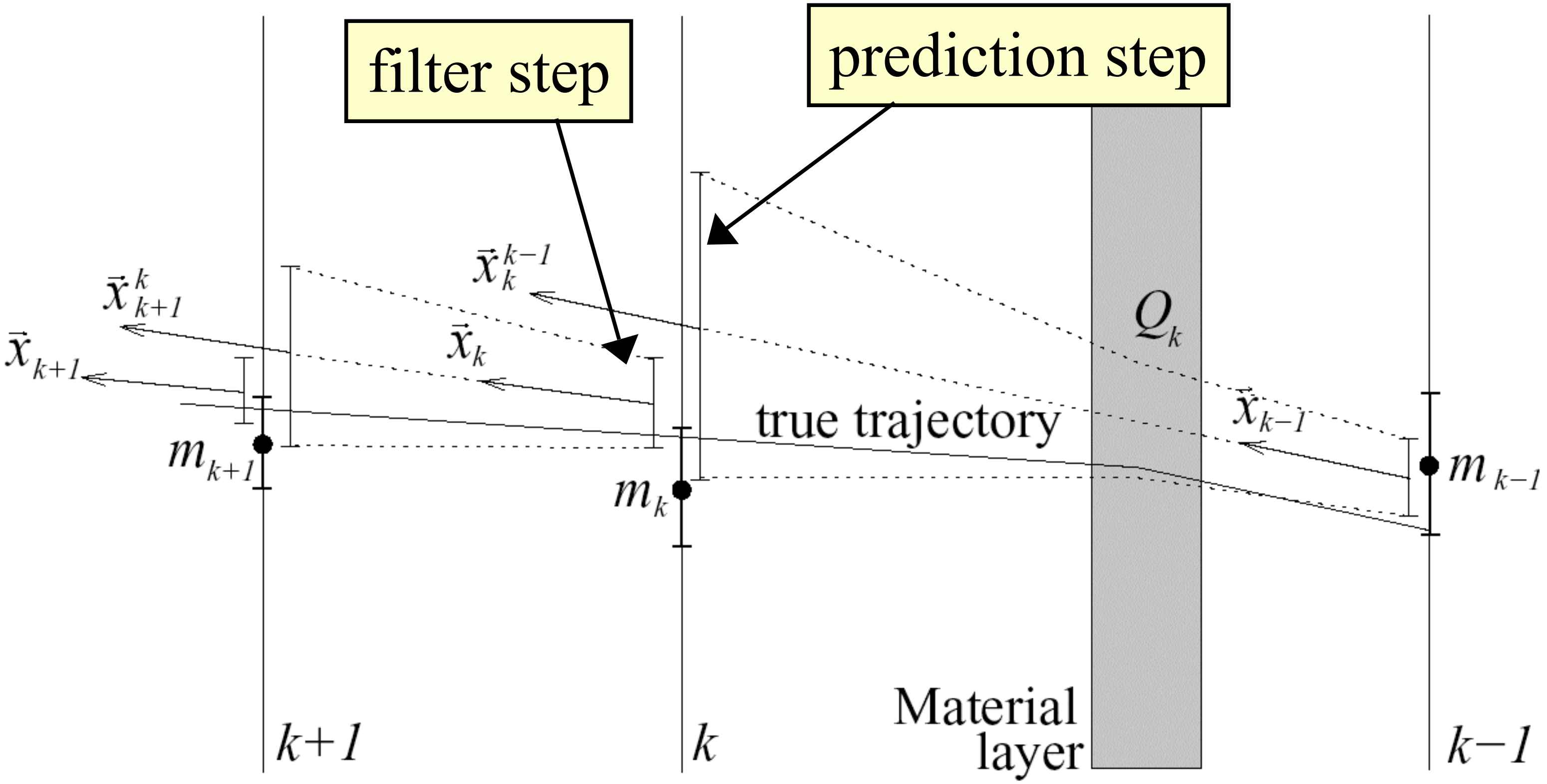
- Run track fit recursively: add measurements one by one. Fit only the state at the current measurement.

→ This is the Kalman filter.

Two material effects included in stepping through matter:

1. Energy loss
2. Multiple scattering

Track fitting



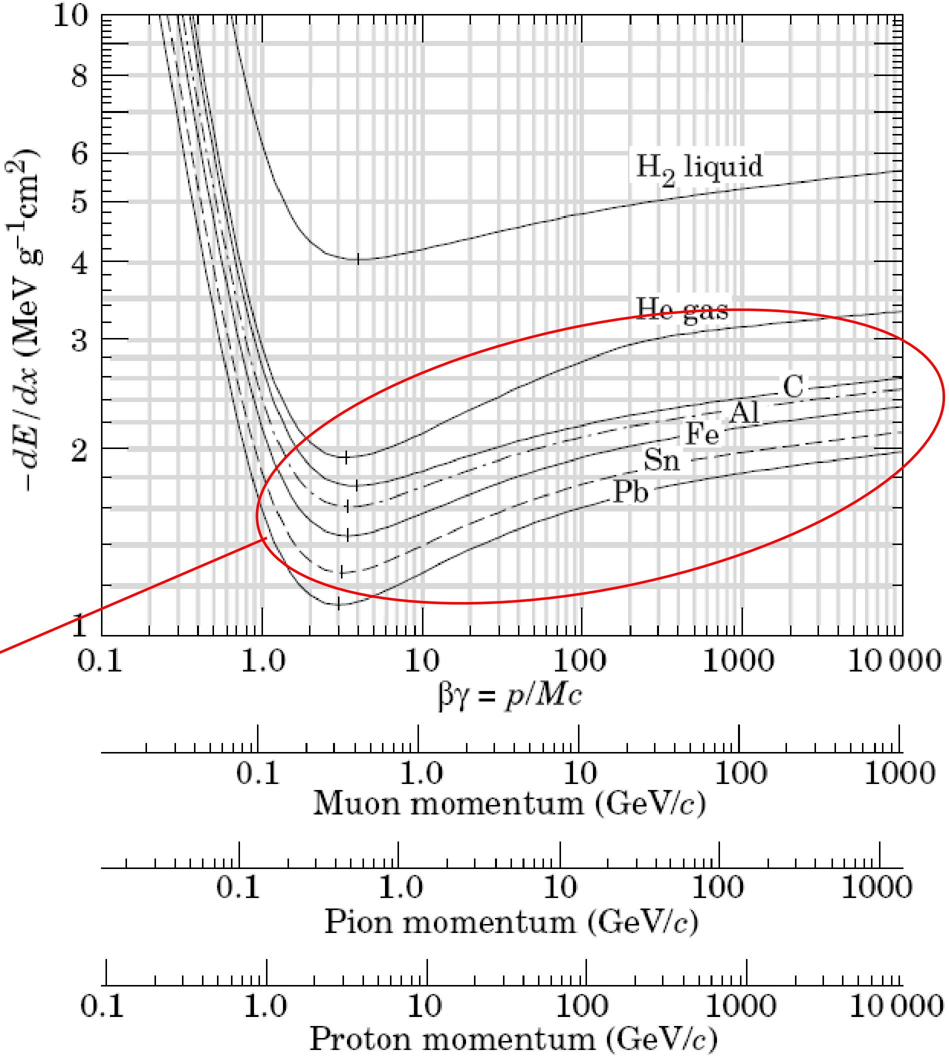
x: track states
m: measurements

Material effects in track fit

1. **Energy loss** (all charged particles except electrons)
   - Caused by ionization of the medium.
   - Note that this effect is actually needed to measure the particles (hits)!

Uses Bethe Bloch formula (depends on density, thickness, and Z/A)

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2 T_{\max}}{(1-\beta^2)I^2} - \beta^2 - \frac{\delta}{2}\right]$$



- MIP looses about 40 MeV in 8 cm of aluminium: small effect in the LHCb tracking system (typical momentum is 2-200 GeV).
- But still larger than momentum resolution (10-30 MeV).

Electrons and photons

Electrons

- Electrons loose their energy not by ionization but by bremsstrahlung.
- For bremsstrahlung energy loss is inversely proportional to mass of particle.
- Electrons loose 30% of their energy before magnet due to bremsstrahlung:

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{E}{X_0}$$

Radiation length:
In LHCb about 60% in tracking system.

- Therefore, momentum (and mass) resolution worse compared to muons

Photons

- Related to bremsstrahlung is photon conversion $\gamma \longrightarrow e^+e^-$
- Mean free path is 7/9 X_0
- Converted photons before the magnet cannot be reconstructed.
  - After magnet they still form single cluster in calorimeters.

Material effects in track fit

Why should the tracking detectors be light?

Reason 2: Otherwise they will scatter more (worse momentum resolution)

2. Multiple scattering

- Modeled by increasing covariance (error) matrix (not predictive).
- Uses Molière angular distribution: depends mainly on momentum, density, thickness.
- Significant effect for low momentum particles (depends on spatial resolution)
  - In case of LHCb: particles below p < 80 GeV.

Multiple scattering (Moliere angular distribution):

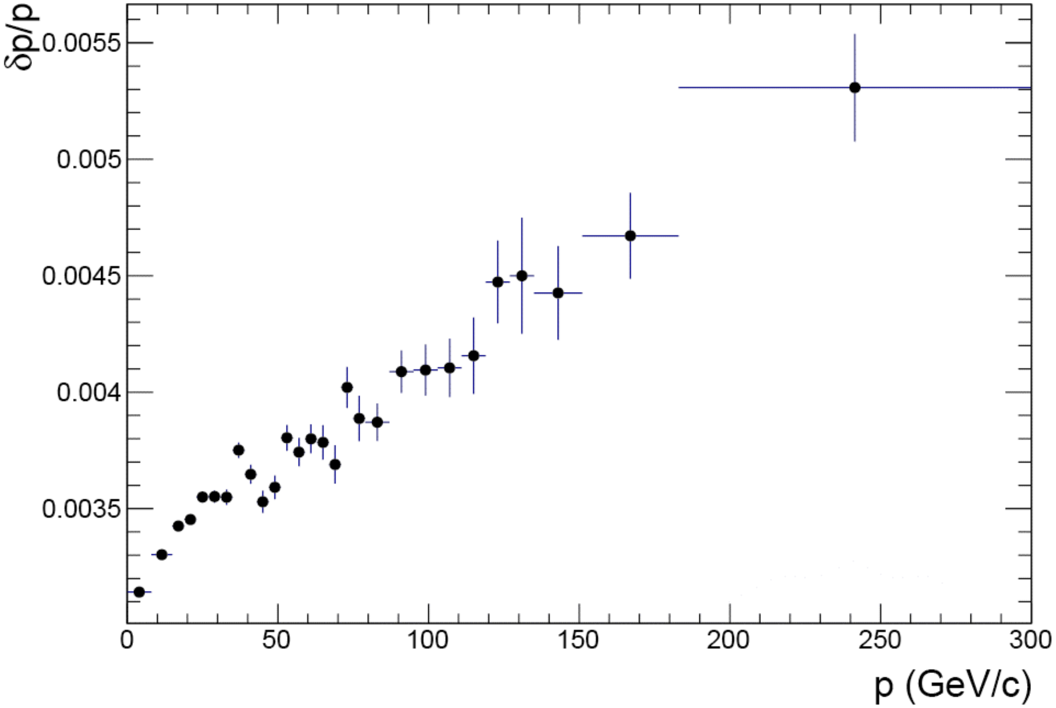
$$\theta_0 = \frac{13.6\,\mathrm{MeV}}{\beta c p} z \sqrt{\frac{x}{X_0}} \left[1 + 0.038 \ln \frac{x}{X_0} \right]$$

Thickness/radiation length: taken from detector description (simulation)

Momentum resolution

- Integrated Bdl ~ 4 Tm
- Accurate field map and alignment
- Momentum resolution 0.4-0.6 %
- Mass resolution J/ψ: 13 MeV
  - MC: 10 MeV

→ Accurate mass measurements.



Momentum resolution

The momentum kick from the magnet (~1 GeV) depends on integrated magnetic field:

$$\Delta\vec{p} = q\int \mathrm{d}\vec{l} \times \vec{B}$$

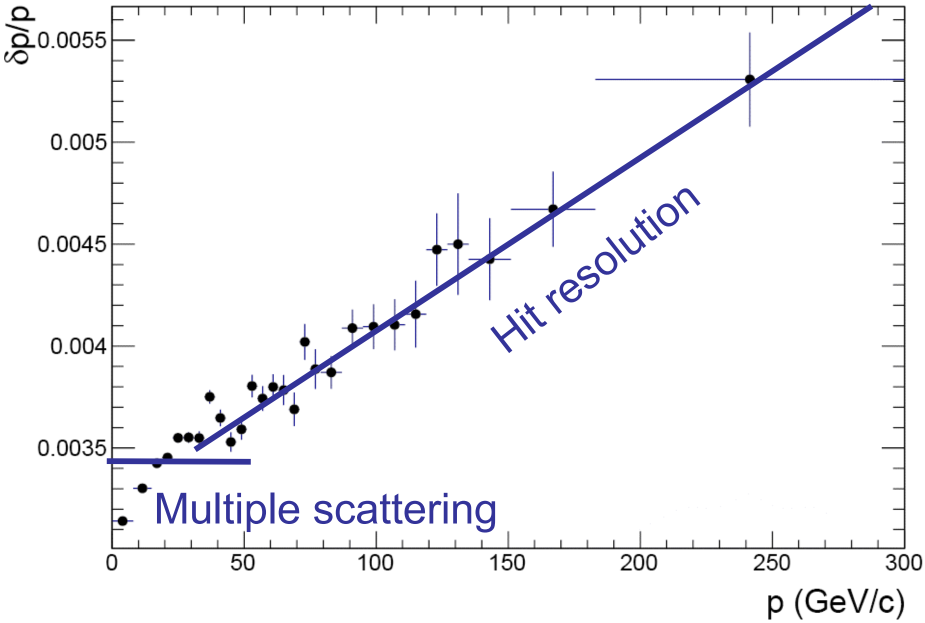
The main component can be written as

$$\Delta p_x = p_{x,f} - p_{x,i} = p\left(\frac{t_{x,f}}{\sqrt{1+t_{x,f}^2+t_{y,f}^2}} - \frac{t_{x,i}}{\sqrt{1+t_{x,i}^2+t_{y,i}^2}}\right) = q\int \left|\mathrm{d}\vec{l} \times \vec{B}\right|_x$$

Where t_x is the slope (dx/dz) of the particle.

Using the multiple scattering formula and the expected hit resolution one obtains the following parameterization:

$$\frac{\partial p}{p} = A \oplus B \cdot p$$



Very simplified model. In particular it does not describe:

- different resolutions of IT and OT
- different amounts of material seen by different particles
- non-Gaussian effects

Invariant mass

Invariant mass formula (2 body decay):

$$m_M^2 = m_1^2 + m_2^2 + 2\left(\sqrt{\vec{p}_1^{\,2} + m_1^2}\sqrt{\vec{p}_2^{\,2} + m_2^2} - |\vec{p}_1||\vec{p}_2|\cos\Theta\right)$$

Assuming $m_{1,2} << p_{1,2}$

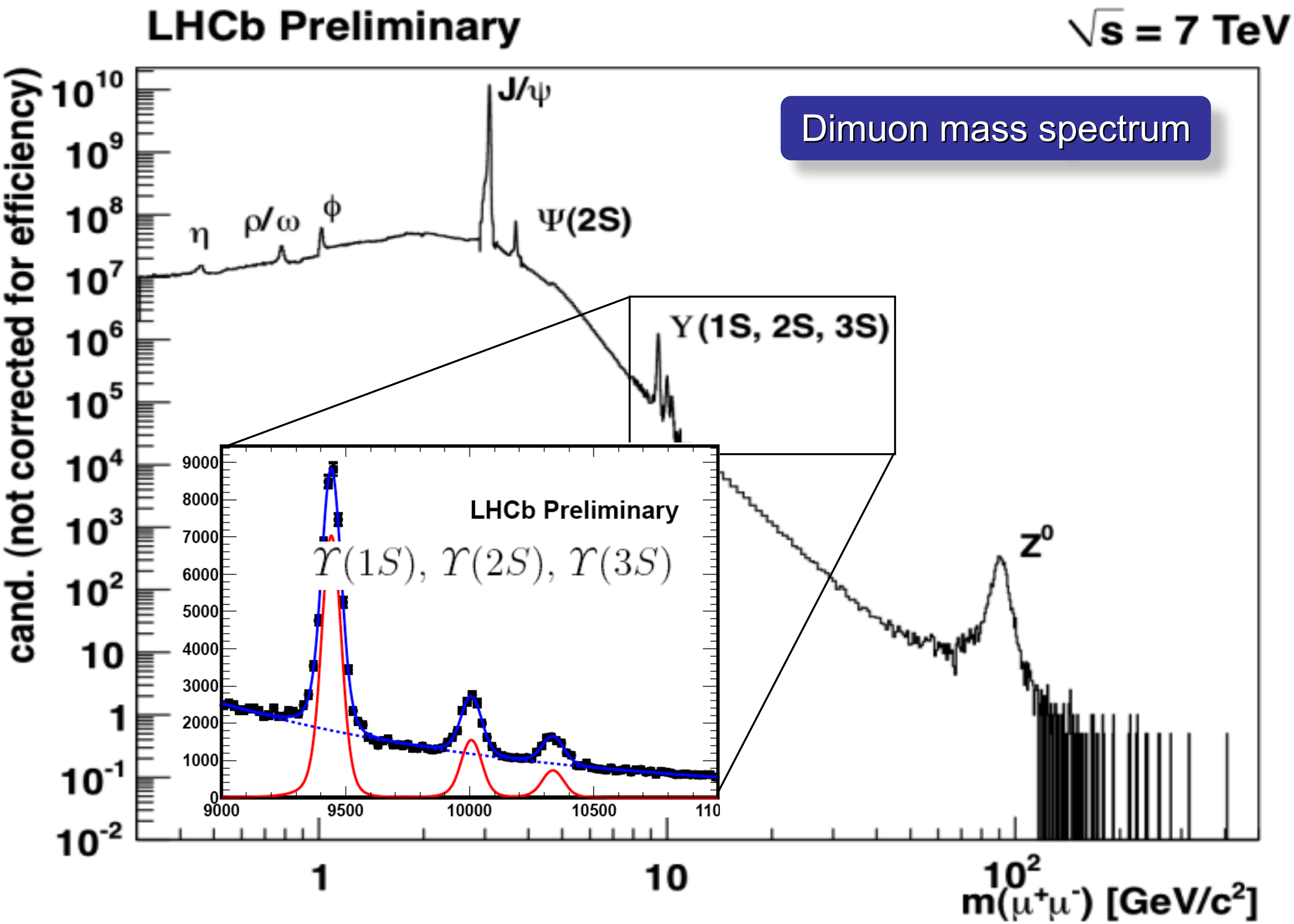
$$m_M^2 = m_1^2 + m_2^2 + 2|\vec{p}_1||\vec{p}_2|(1 - \cos\Theta)$$

Opening angle term

In LHCb error on opening angle term typically much smaller than momentum error.

Mass resolution mainly determined by momentum resolution

Full mass spectrum

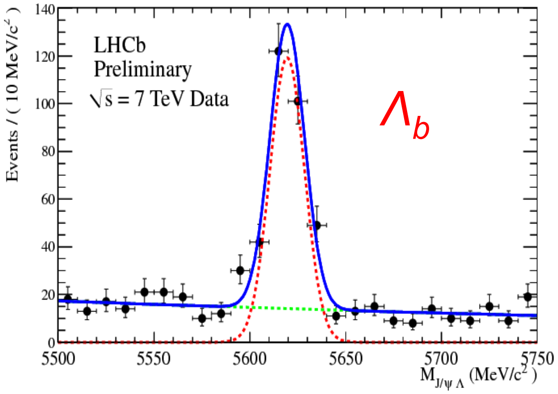


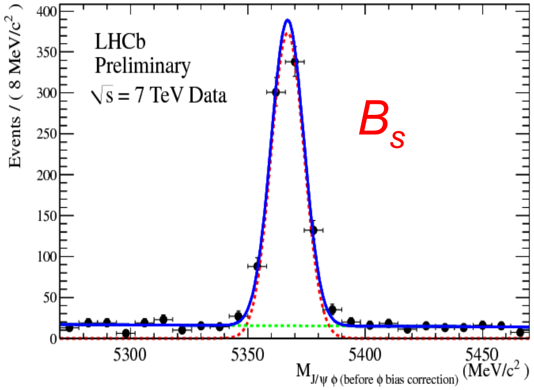
Dimuon mass spectrum

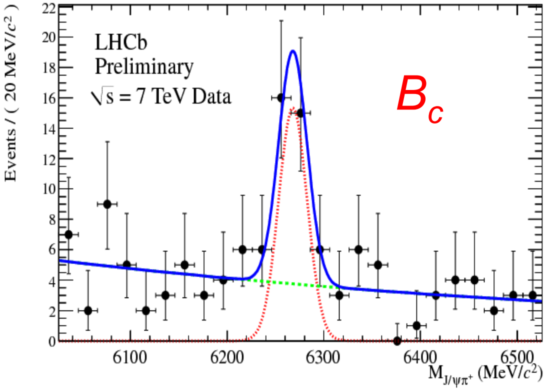
Measurement of B masses

LHCb-CONF-2011-027: B masses [MeV/c^2]	PDG
$M(B^+ \to J/\psi K^+) = 5279.27 \pm 0.11\,(\text{stat}) \pm 0.20\,(\text{syst})$	5279.17 ± 0.29
$M(B^0 \to J/\psi K^{*0}) = 5279.54 \pm 0.15\,(\text{stat}) \pm 0.16\,(\text{syst})$	5279.50 ± 0.30
$M(B^0 \to J/\psi K^0_S) = 5279.61 \pm 0.29\,(\text{stat}) \pm 0.20\,(\text{syst})$	5279.50 ± 0.30
$M(B^0_s \to J/\psi \phi) = 5366.60 \pm 0.28\,(\text{stat}) \pm 0.21\,(\text{syst})$	5366.30 ± 0.60
$M(\Lambda_b \to J/\psi \Lambda) = 5619.49 \pm 0.70\,(\text{stat}) \pm 0.19\,(\text{syst})$	5620.2 ± 1.6
$M(B^+_c \to J/\psi \pi^+) = 6268.0 \pm 4.0\,(\text{stat}) \pm 0.6\,(\text{syst})$	6277 ± 6

More precise than PDG values!







World-best mass measurements! (2010 data only)

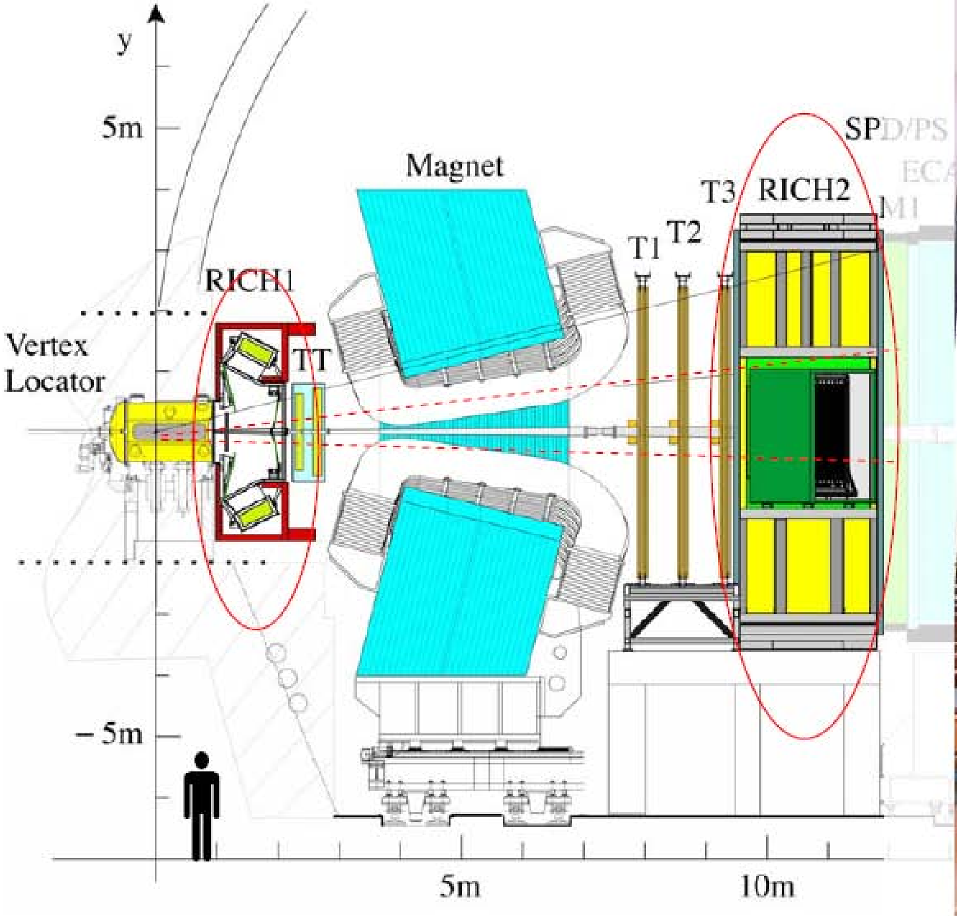
Particle ID

Which particles travel through LHCb?

- Electrons (e^+, e^-)
- Muons (μ^+, μ^-)
- Photons (neutral; detected in calorimeter)
- Pions (π^+, π^-)
- Kaons (K^+, K^-, K_S^0 decays after 2 m in $\pi\pi$)
- Protons (p^+, p^-)
- Neutrons (neutral; detected in calorimeters)
- Lambda's (neutral; decay after ~2m into p π)
- + small fraction of other long-lived strange baryons

PID detectors used to separate the different species.
Note that the tracking detector only detect charged particles!

RICH detectors

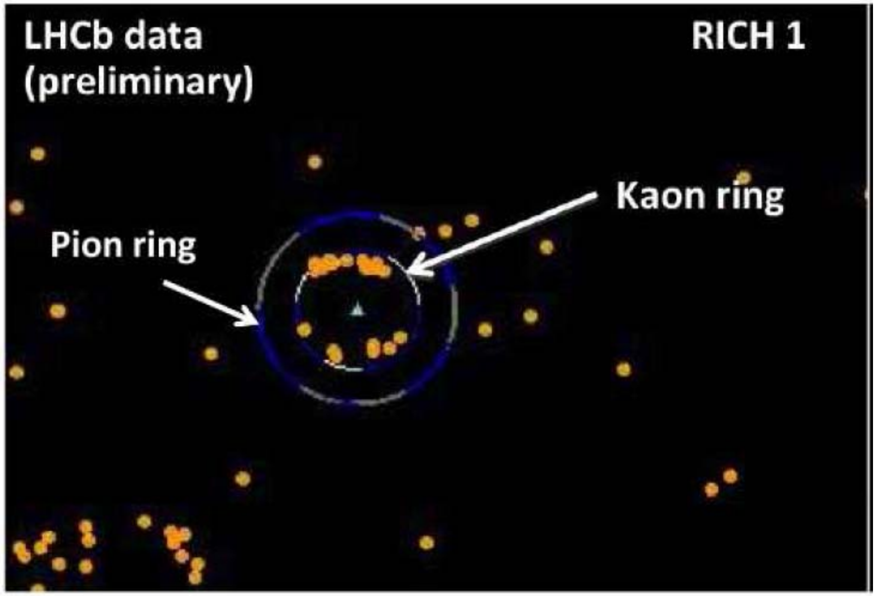


Two **RICH** detectors for charged hadron identification

RICH=Ring Imaging CHerenkov detector

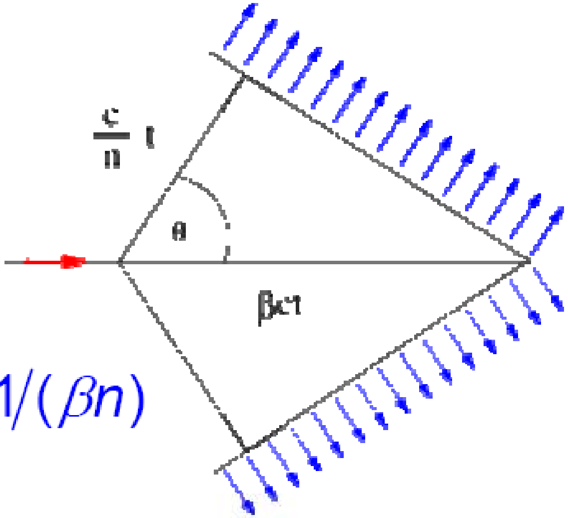
RICH detectors are the specialized detectors to allow charged hadron (π, K, p) identification.

Important for B physics, as there are many hadronic decay modes
e.g.: $B_s \rightarrow D_s^- K^+ \rightarrow (K^+ K^- \pi^-) K^+$



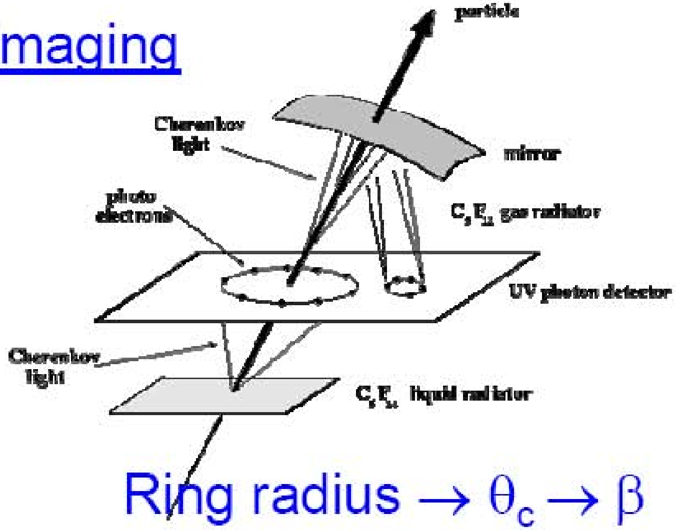
Cherenkov Radiation

if $\beta > \frac{c}{n}$



$$\cos\theta_c = 1/(\beta n)$$

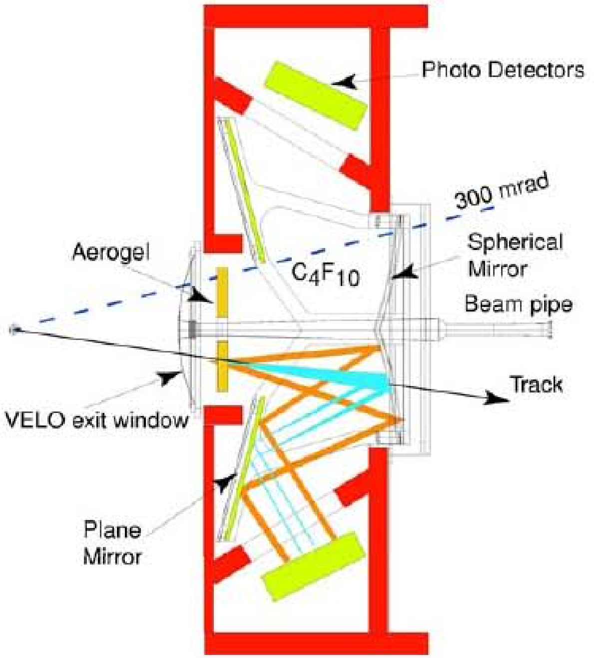
Ring Imaging

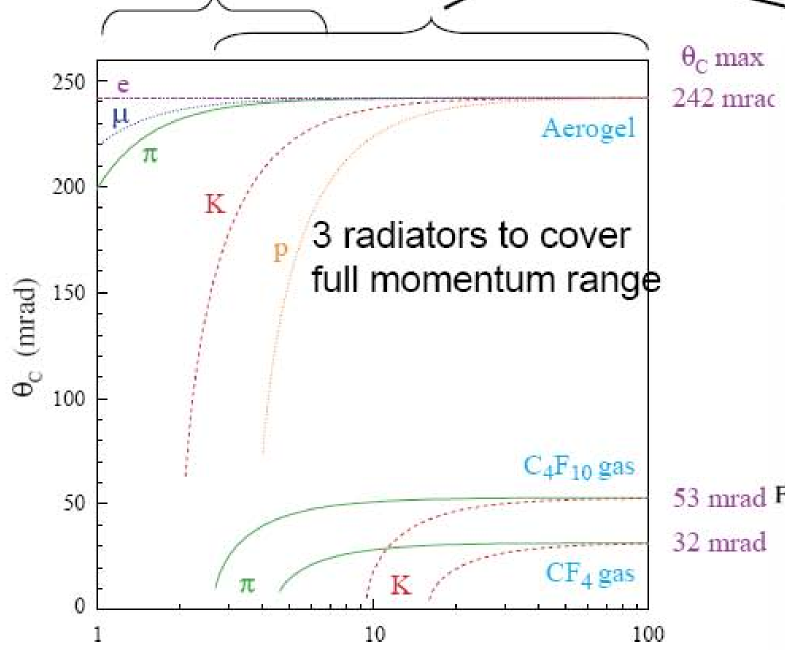


Ring radius → $\theta_c \rightarrow \beta$

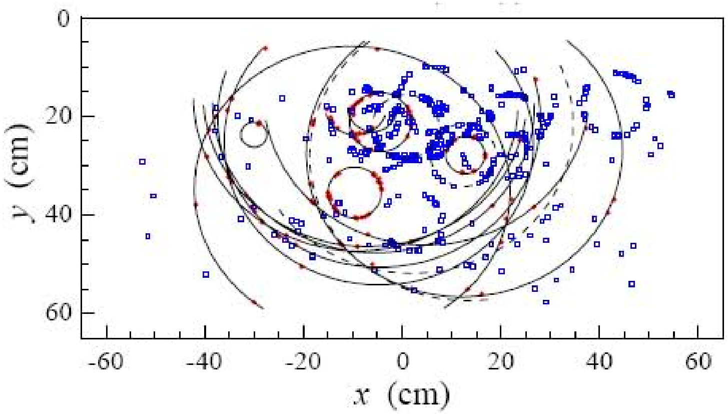
RICH detectors

RICH 1

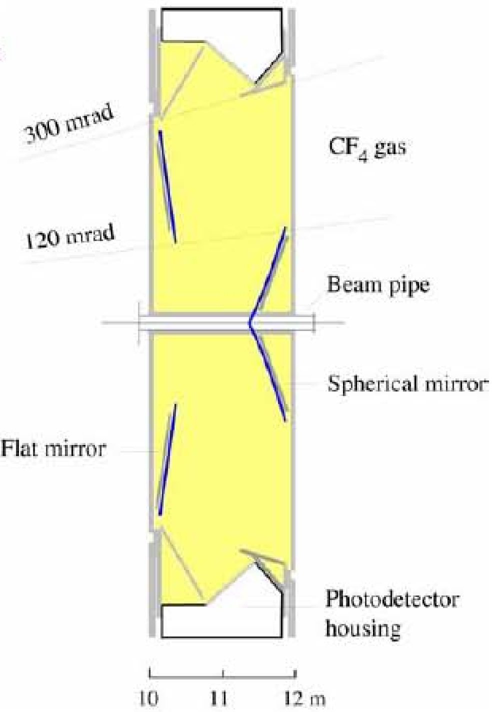




3 radiators to cover full momentum range



RICH 2

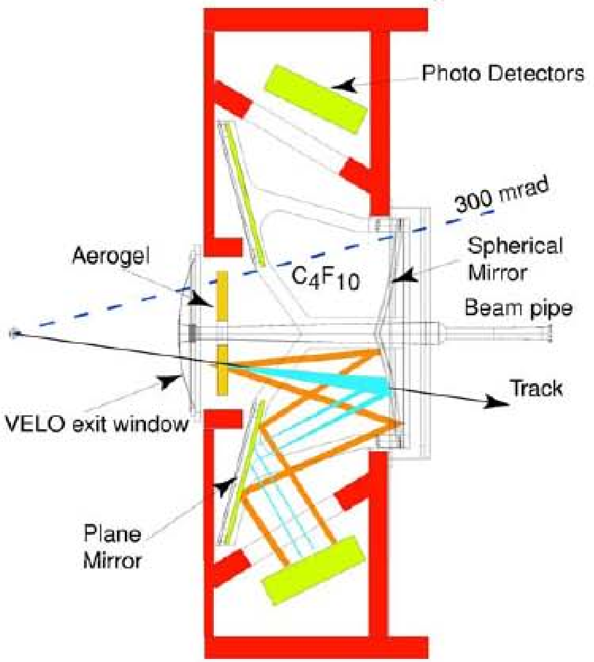


Radiator:
Aerogel **n=1.03**
C_4F_{10} **n=1.0014**

Radiator: CF_4
n=1.0005

RICH detectors

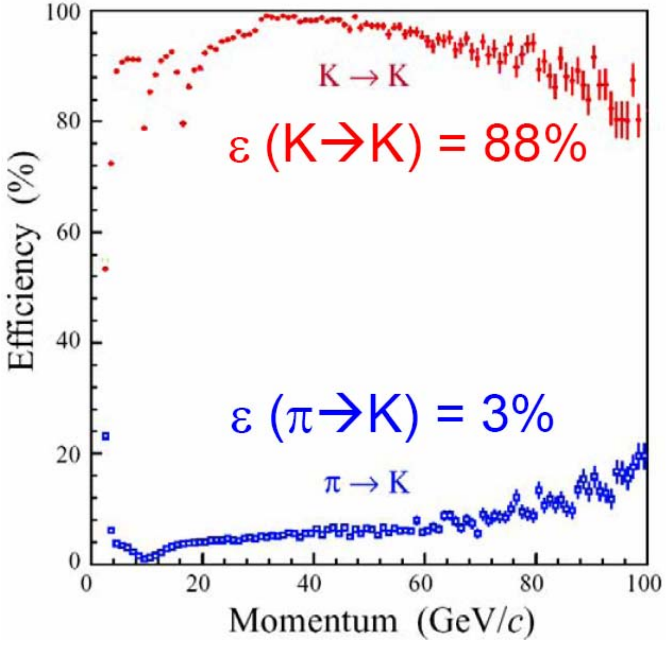
RICH 1



Radiator:

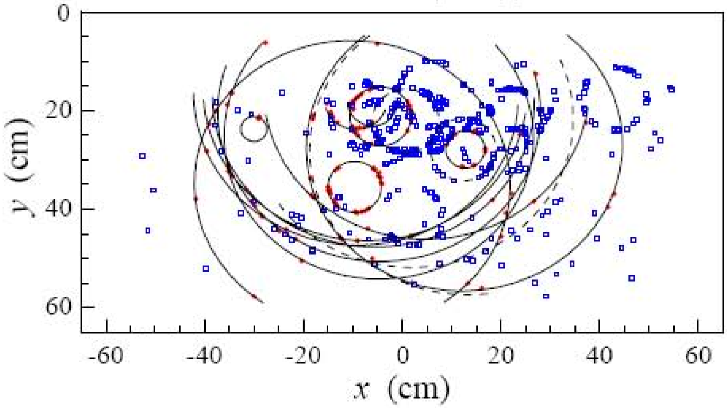
Aerogel n=1.03

C_4F_{10} n=1.0014

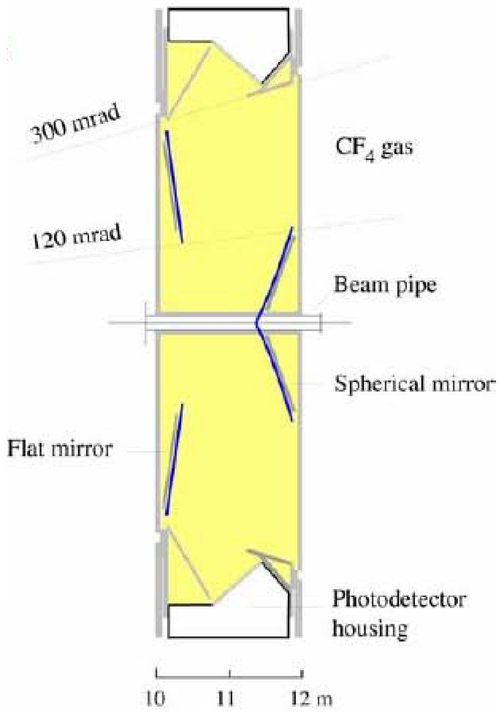


ε (K→K) = 88%

ε (π→K) = 3%



RICH 2



Radiator: CF_4

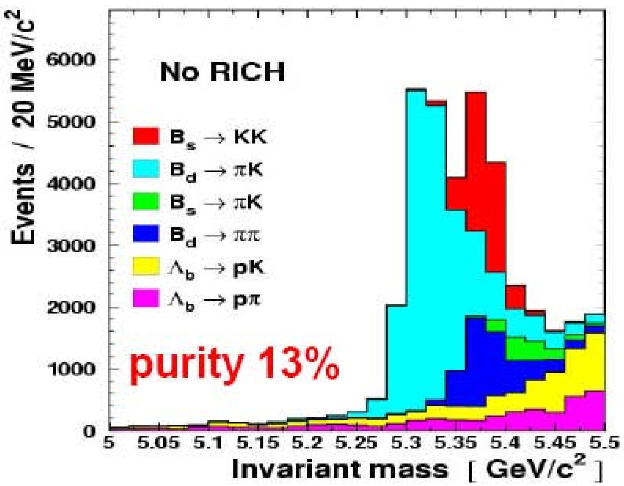
n=1.0005

RICH performance

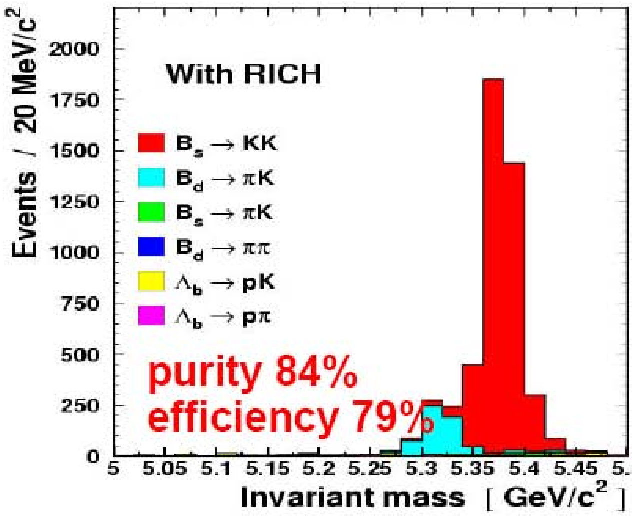
No RICH

With RICH

$B_s \to K K$

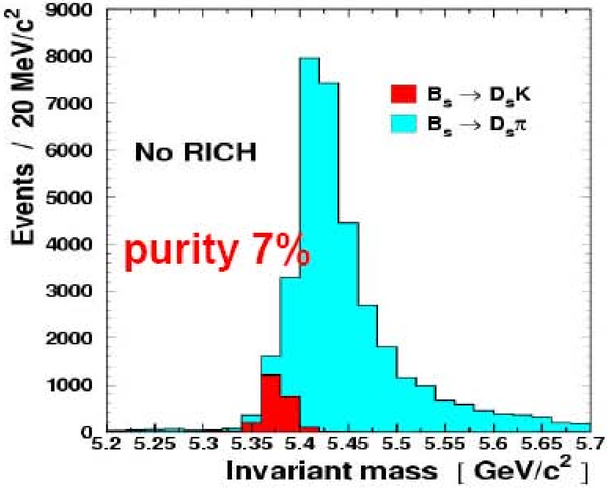


purity 13%

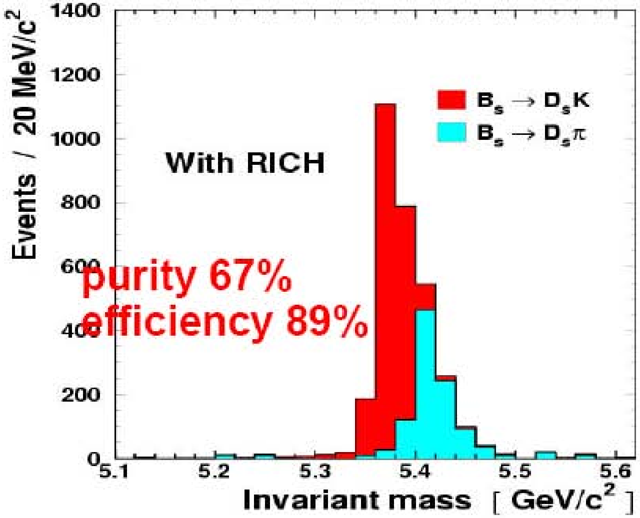


purity 84%
efficiency 79%

$B_s \to D_s K$

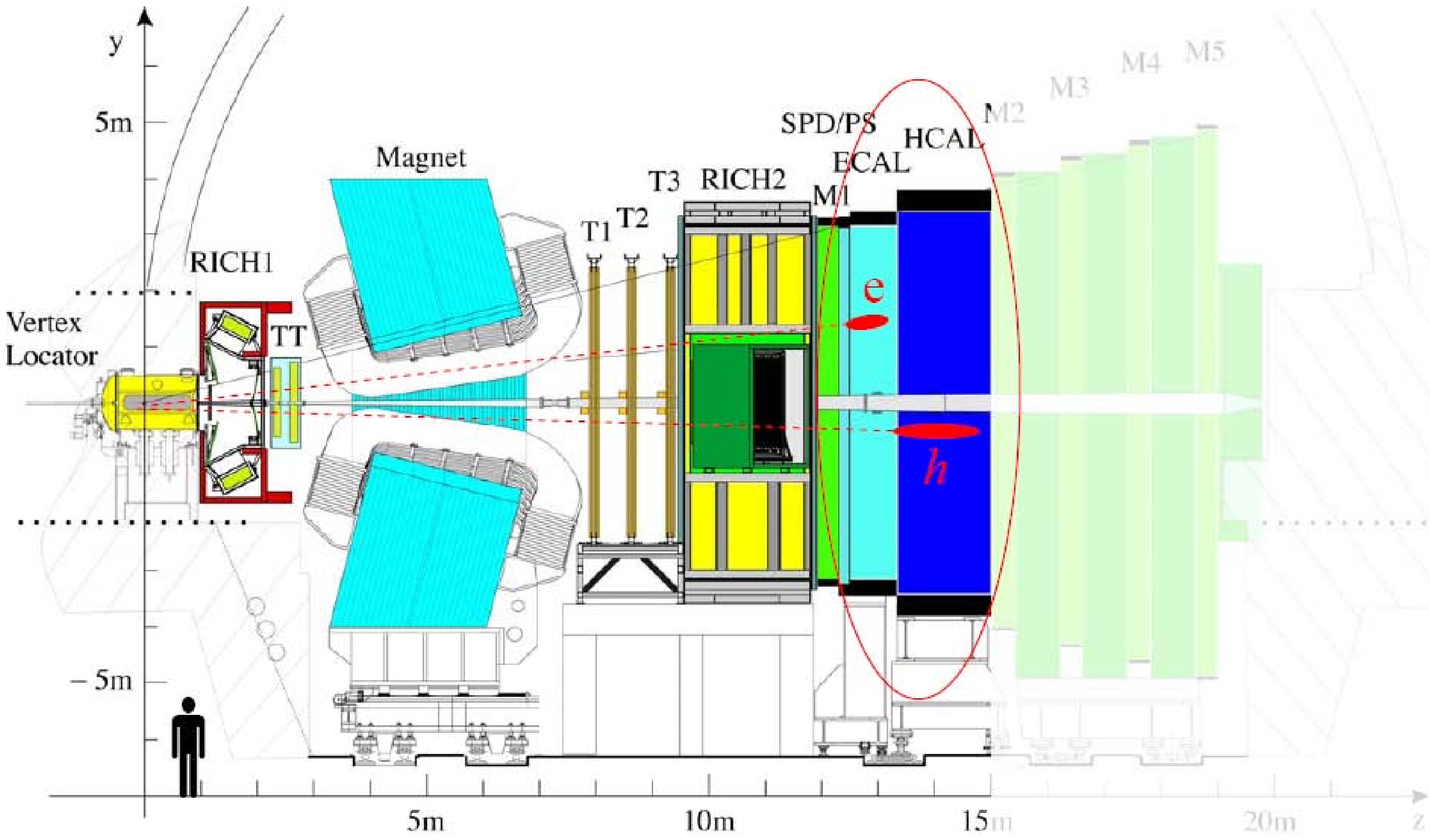


purity 7%



purity 67%
efficiency 89%

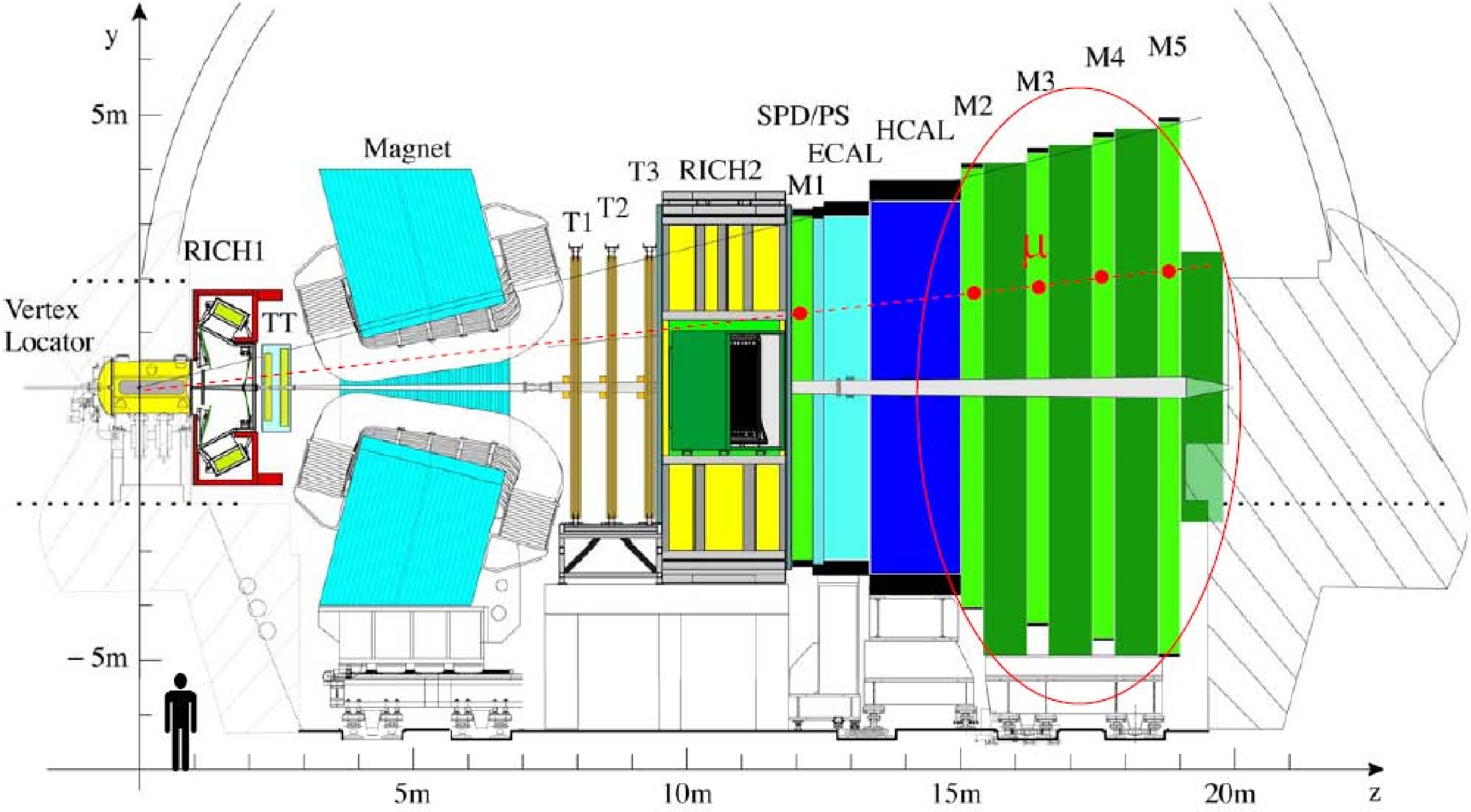
Calorimeters



Calorimeter system to identify electrons, hadrons and neutrals

Important for the first level (Level 0) of the trigger.

Muon detectors



Muon system to identify muons, also used in first level (L0) of the trigger

Calorimeters and Muon detectors

Calorimeters:
- Goal is to stop the particles and measure their energy (heavy detectors).
- Particles produce shower of secondary particles.
- Amount of scintillation light is measure for energy of incoming particle.
- Electrons and photons give electromagnetic shower in first part of calorimeters: ECAL
- Hadrons give hadronic shower in second part of calorimeters: HCAL
- Calorimeter is only place where neutral particles are detected.

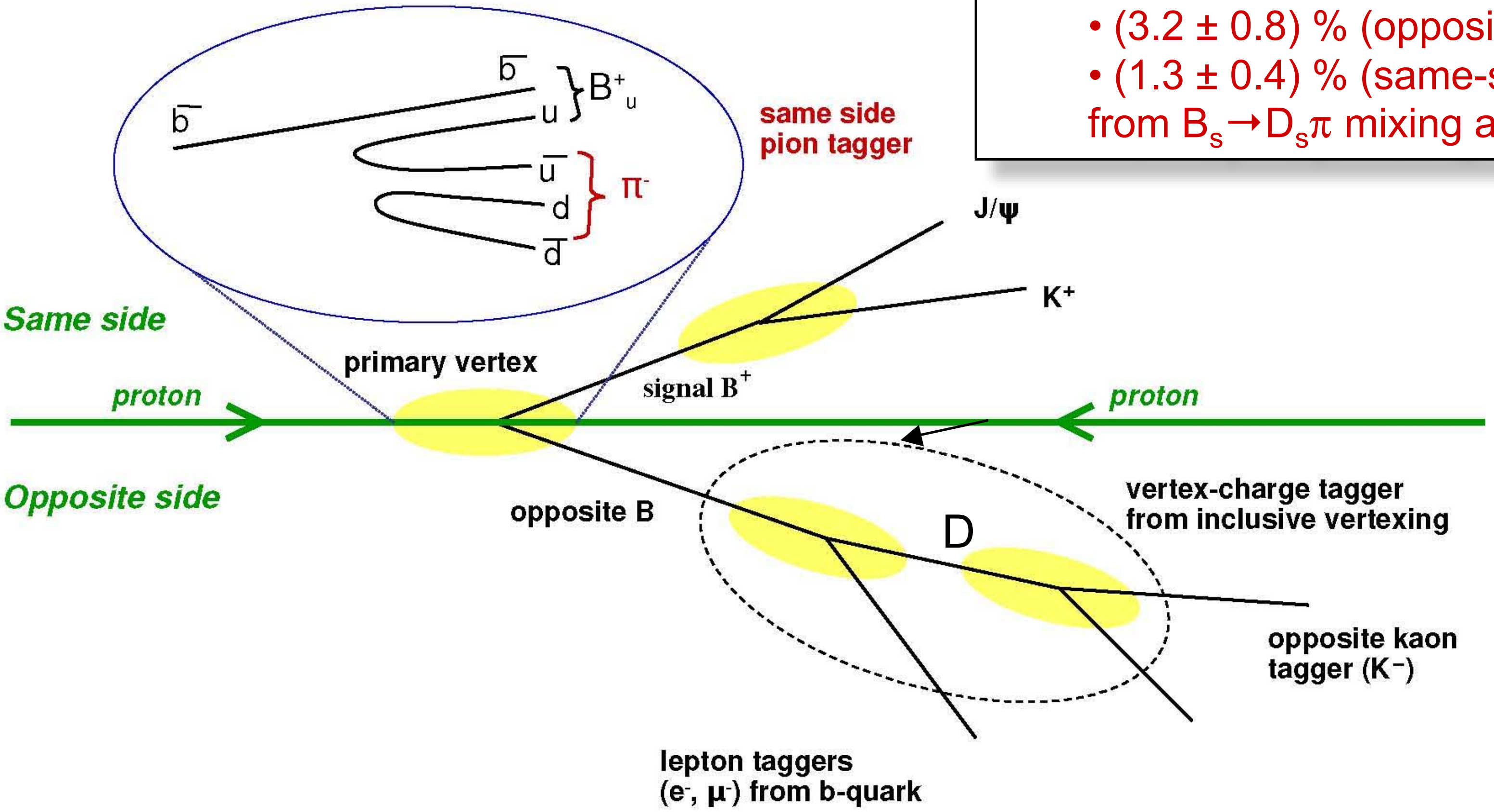
Muon detectors:
- Muons are not so much affected by material in calorimeters.
  - They cannot have hadronic interaction, only electromagnetic.
- Muon detectors interleaved with iron wall to remove any non-muon.
- Anything that traverses through the muon detector must be a muon.

PID performance: flavour tagging

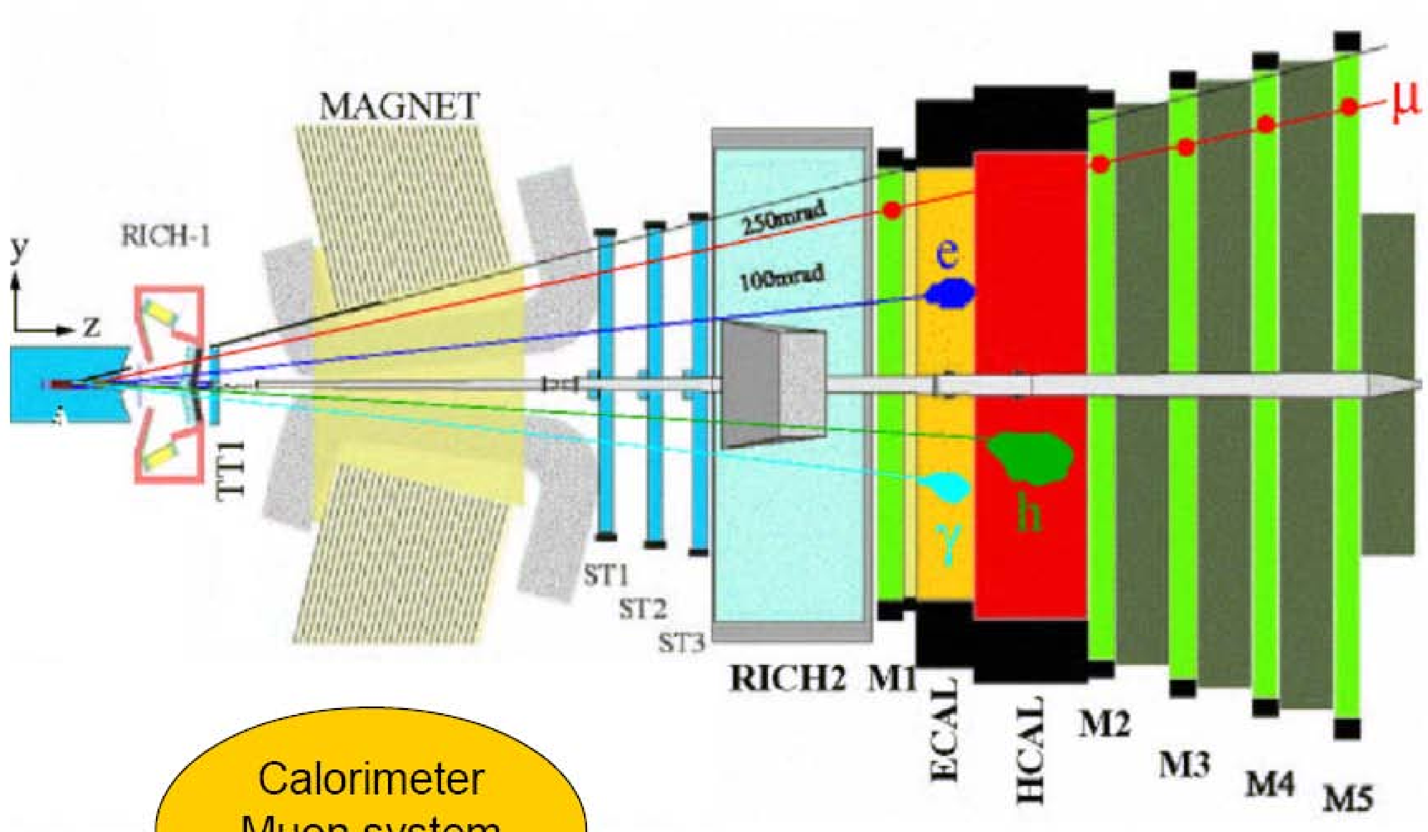
Flavour tagging

- Tagging of production flavour (B or $\overline{B}$)
- Important for mixing & CP analyses.
- Performance calibrated using control channels such as $B^+ \rightarrow J/\psi\, K^+$
- Tagging power: $\varepsilon(1\text{-}2\omega)^2$ =
  - (3.2 ± 0.8) % (opposite-side tag)
  - (1.3 ± 0.4) % (same-side tag)

  from $B_s \rightarrow D_s\pi$ mixing analysis.



Trigger: Level-0 trigger



Calorimeter
Muon system
Pile-up system

40 MHz

Level-0 Hardware: (4μs)
High p_T μ, e, h, γ signatures
1.1, 2.8, 3.6, 2.6 GeV

1 MHz

PC Farm:

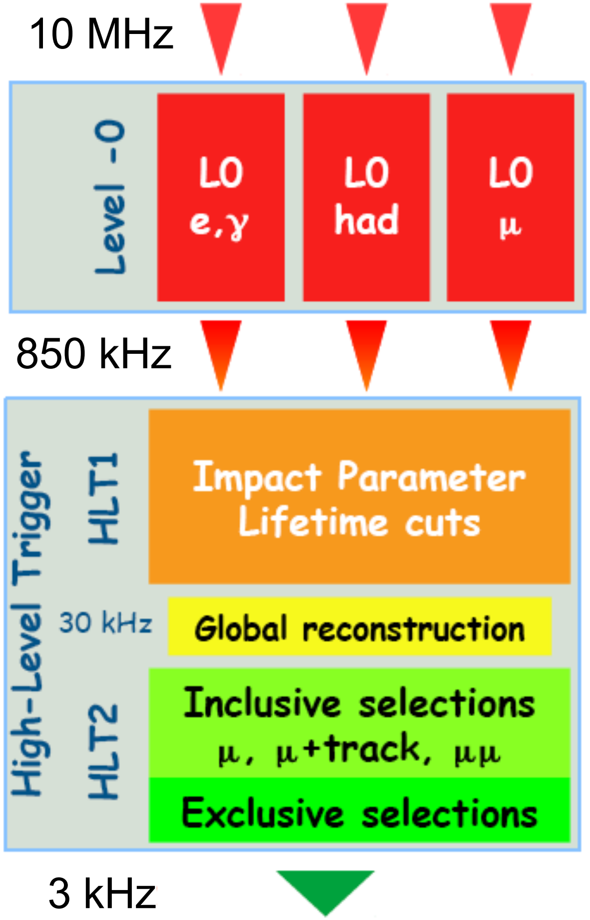
Higher Level Trigger
(full event info)

Trigger: High-level trigger

Hardware Level-0 trigger followed by two-stage software High Level Trigger, HLT1 and HLT2

- HLT1 performs partial reconstruction, confirms L0 objects: associates them with reconstructed tracks, especially with those displaced from the PV
- HLT2: full reconstruction; uses reconstructed objects for exclusive selections with clear signature

Depending on luminosity, the L0 and HLT thresholds can be tuned such that not to exceed maximal throughput of the systems.



Average event size ~35 kB

Trigger: High-level trigger

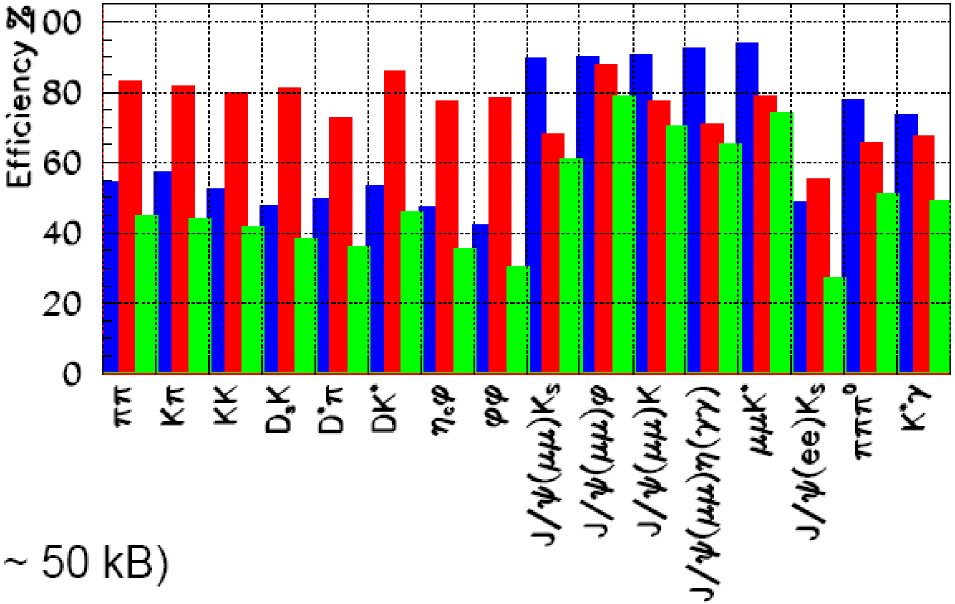
1 MHz

Higher Level Trigger (Software)

Stepwise event reconstruction:

- Confirmation of trigger signature using tracking chambers
- Secondary vertex reconstruction
- Full event reconstruction

2 KHz Storage (event size ~ 50 kB)


L0, HLT and L0×HLT efficiency

HLT rate	Event type	Calibration	Physics
200 Hz	Exclusive B candidates	Tagging	B (core program)
600 Hz	High mass di-muons	Tracking	J/ψ, b→J/ψX (unbiased)
300 Hz	D* candidates	PID	Charm (mixing & CPV)
900 Hz	Inclusive b (e.g. b→μ)	Trigger	B (data mining)

LHCb Upgrade

- Main limitation that prevents exploiting higher luminosity is the Level-0 (hardware) trigger

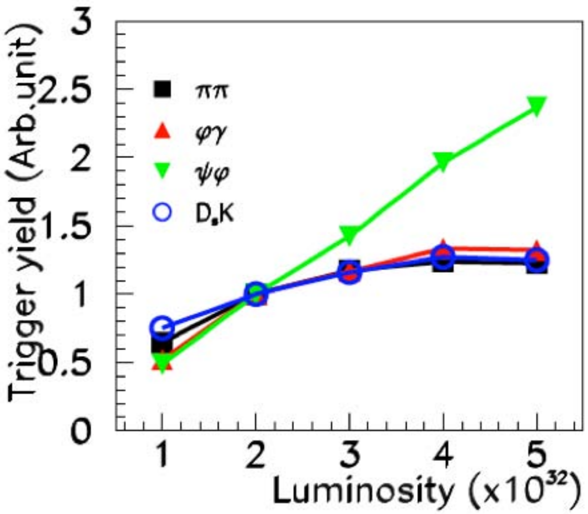
- To keep output rate < 1 MHz requires raising thresholds → hadronic yields reach plateau

- Proposed upgrade is to *remove* hardware trigger read out detector at 40 MHz (bunch crossing rate) Trigger fully in software in CPU farm.

- Will allow to increase luminosity by factor ~ 5 to 1–2 × 10^{33} cm^{-2} s^{-1}

- Requires replacing front-end electronics and part of tracking system. Planned for the long shutdown in 2018. Running for 10 years will then give ~ 50 fb^{-1}

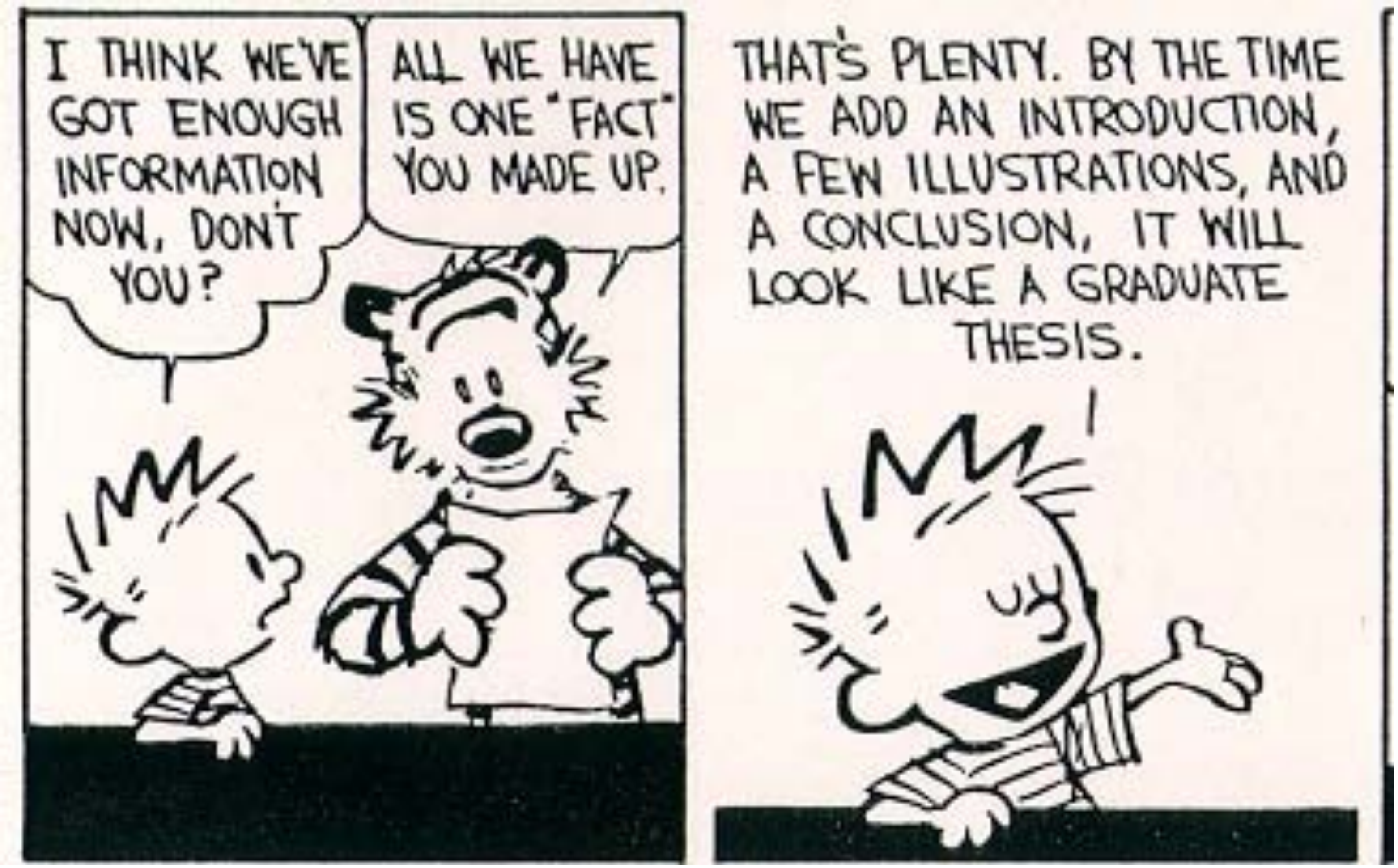
- Letter of Intent recently submitted to the LHCC Physics case endorsed, detector R&D underway (*e.g.* scintillating-fibre tracking, TOF, …)




CERN/LHCC 2011-001
LHCb LoI
7 March 2011

LHCb
UPGRADE

Letter of Intent


I THINK WE'VE GOT ENOUGH INFORMATION NOW, DON'T YOU?
ALL WE HAVE IS ONE "FACT" YOU MADE UP.
THAT'S PLENTY. BY THE TIME WE ADD AN INTRODUCTION, A FEW ILLUSTRATIONS, AND A CONCLUSION, IT WILL LOOK LIKE A GRADUATE THESIS.

Conclusion

- LHCb has just collected 1.1 fb^{-1} of data.
- Waiting for you to be analysed!