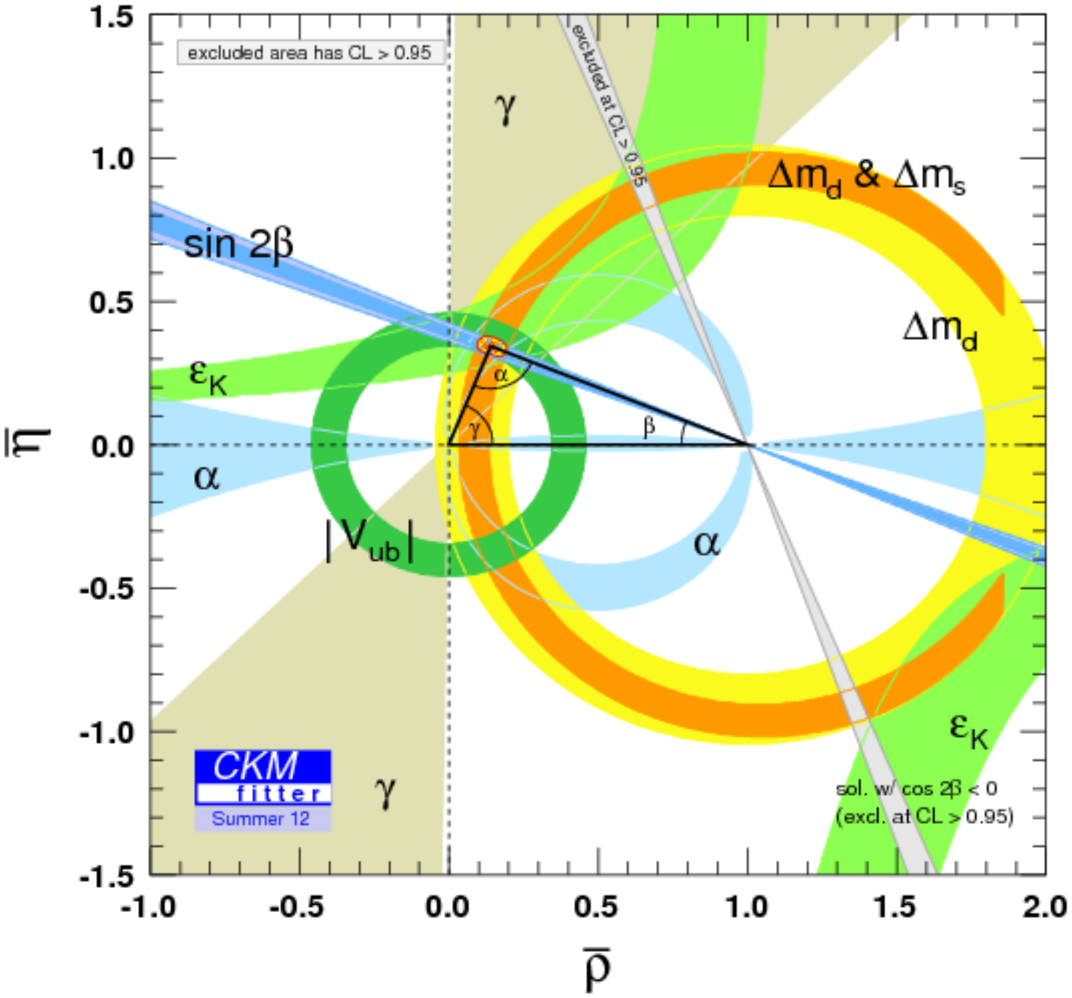
Heavy flavour physics



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:

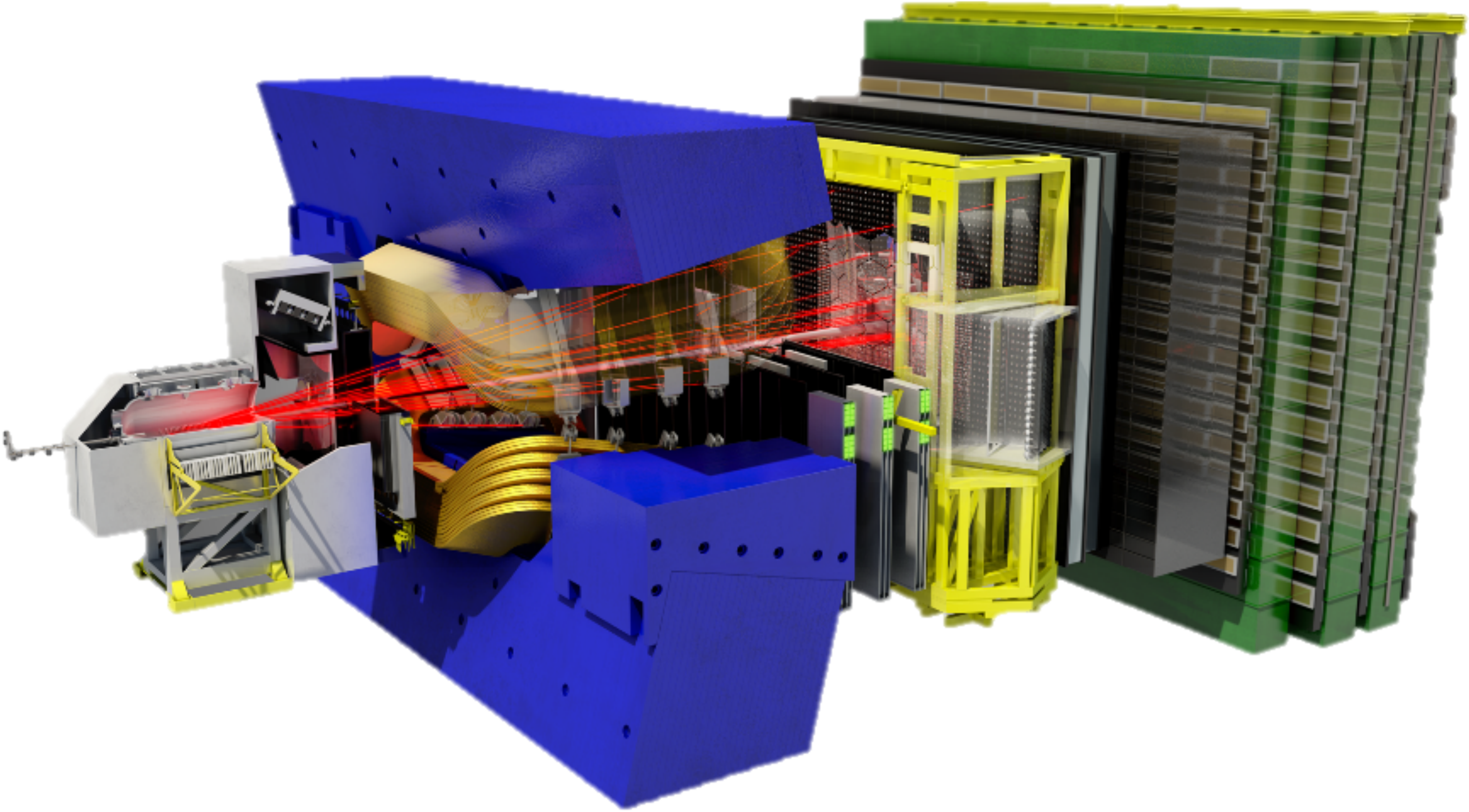
- Starting with some detector physics (bottom-up approach)
- Aimed to give overview of detector aspects important for LHCb
- Assumes some prior knowledge of detector physics....
- …but if I go to fast…..

Please ask questions

Or if you become bored…

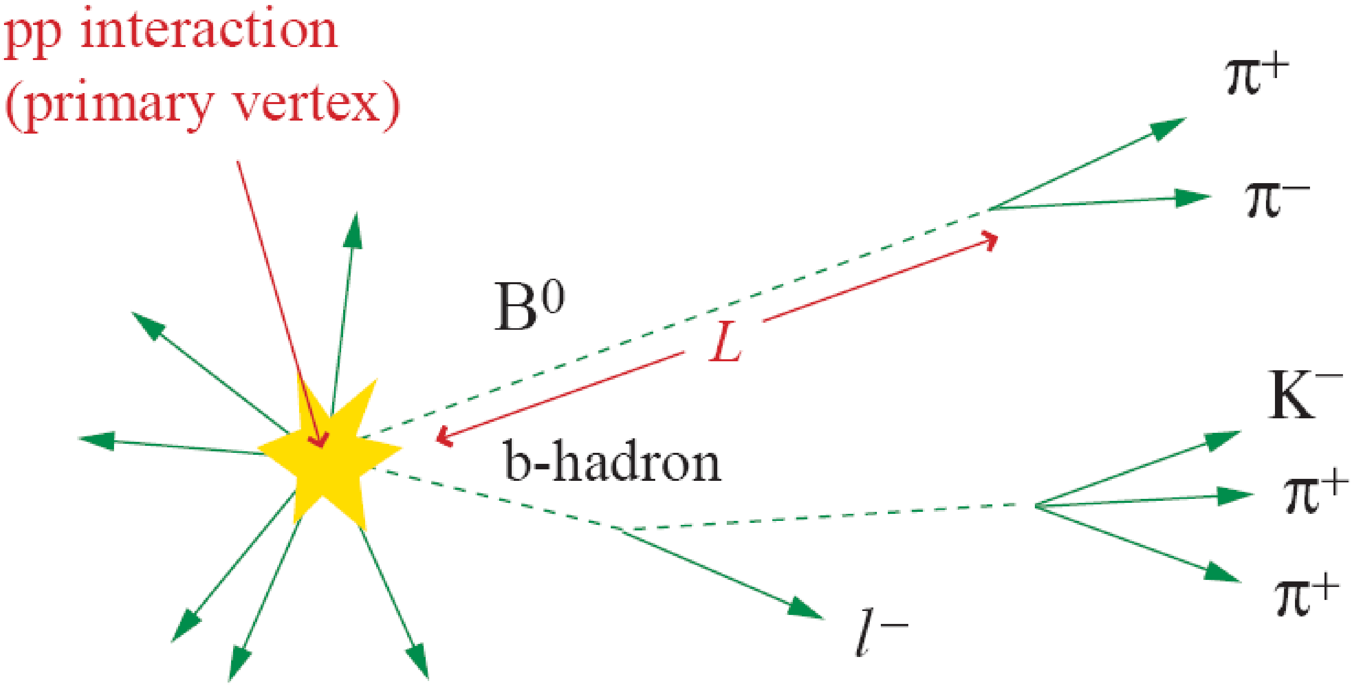
Don’t hesitate to tell me.

Introduction to LHCb



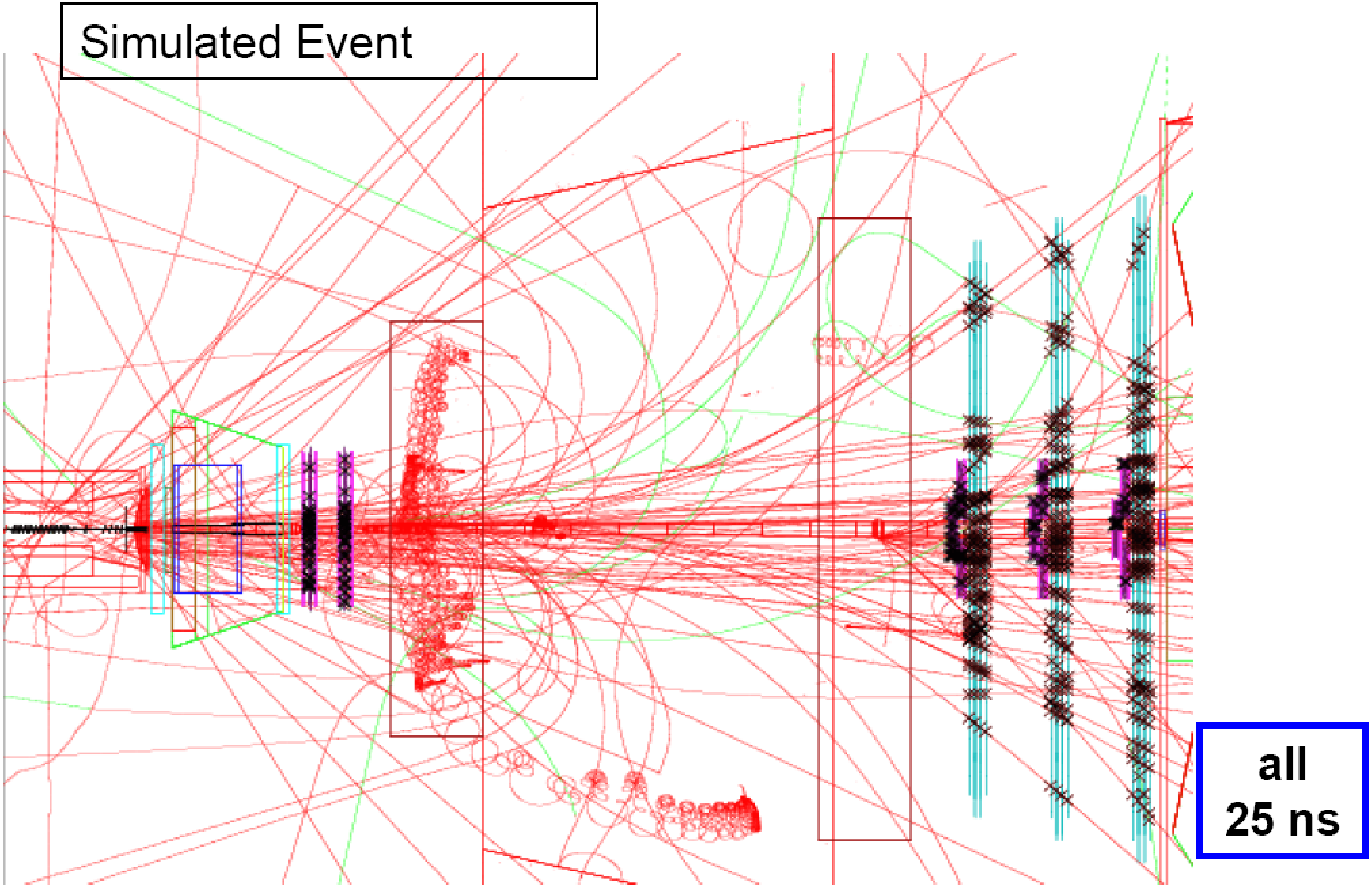
Typical *B* decay event

"*A B is the elephant of the particle zoo: it is very heavy and lives a long time*" – T. Schietinger

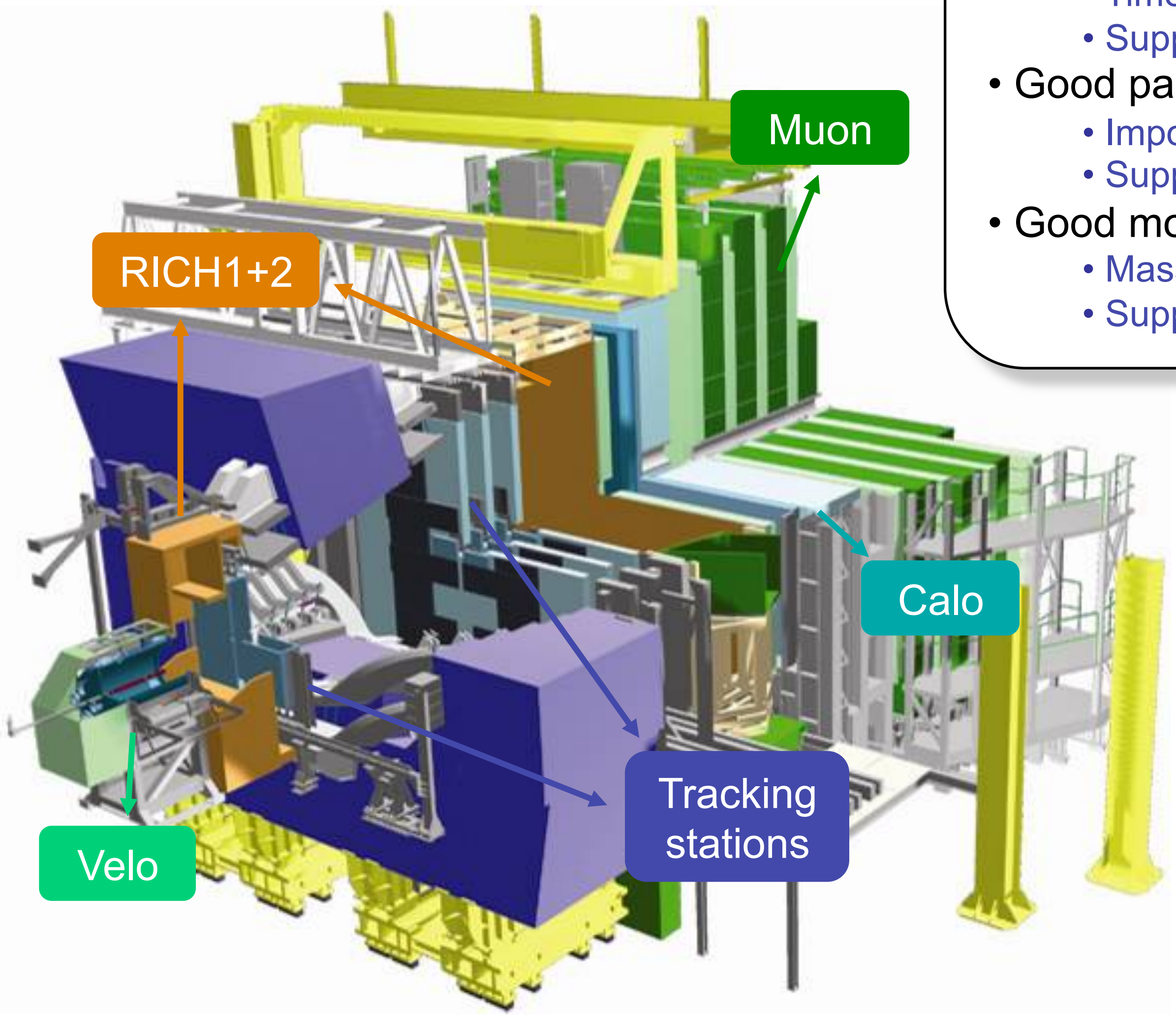


- Typical decay length of *B* hadron ~ 7 mm
- Decay products with p ~ 1 – 200 GeV

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.

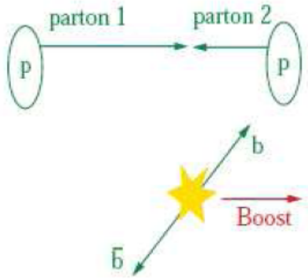
Forward detector

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

→ b mass relatively light compared to high centre-of mass energy of LHC



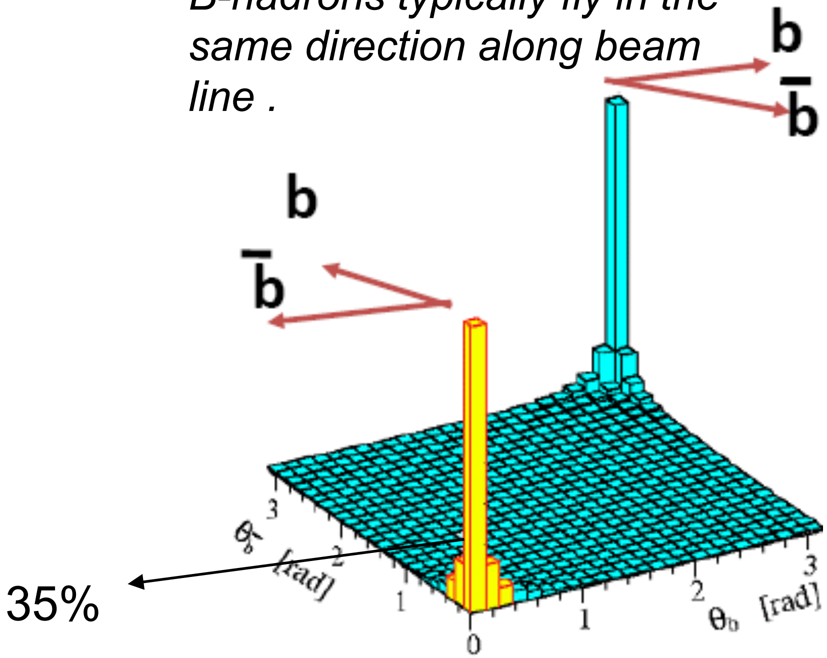
Build LHCb as a forward detector
(backward direction not covered: only one LHCb fits in the cavern ☺)

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.

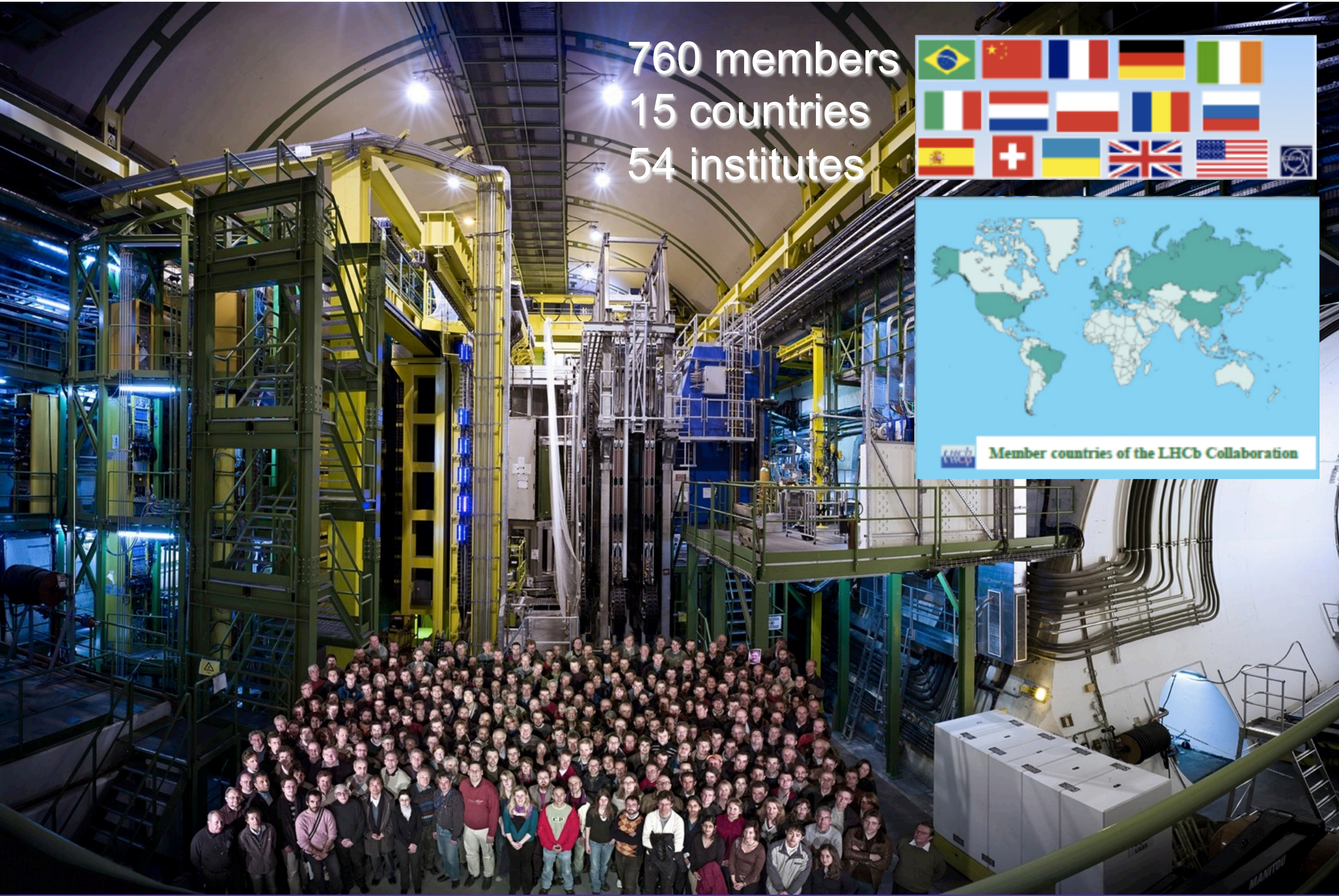
Disadvantage
- Very high particle flux (radiation, reconstruction)

→ need to run at lower luminosity

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

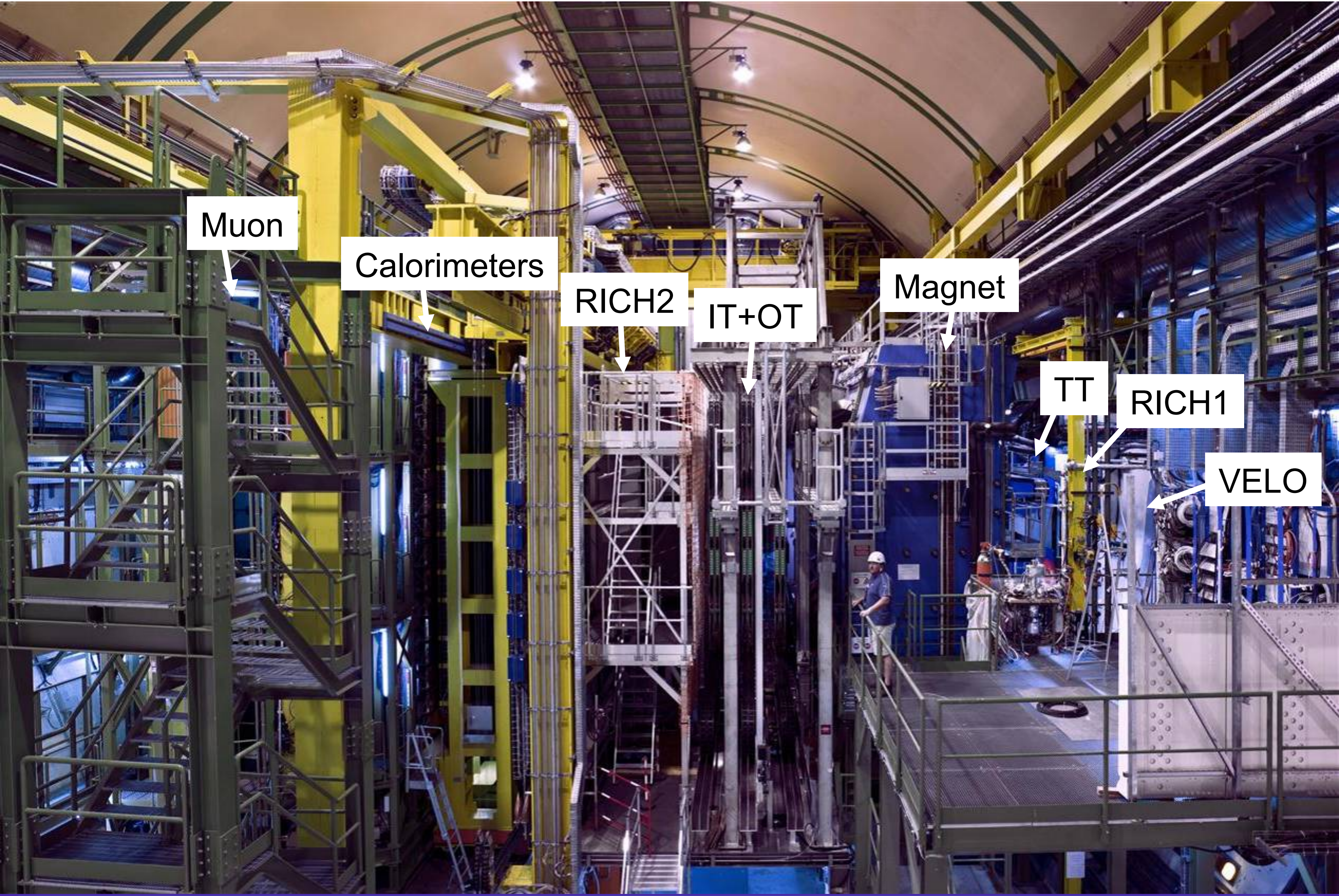


Collaboration

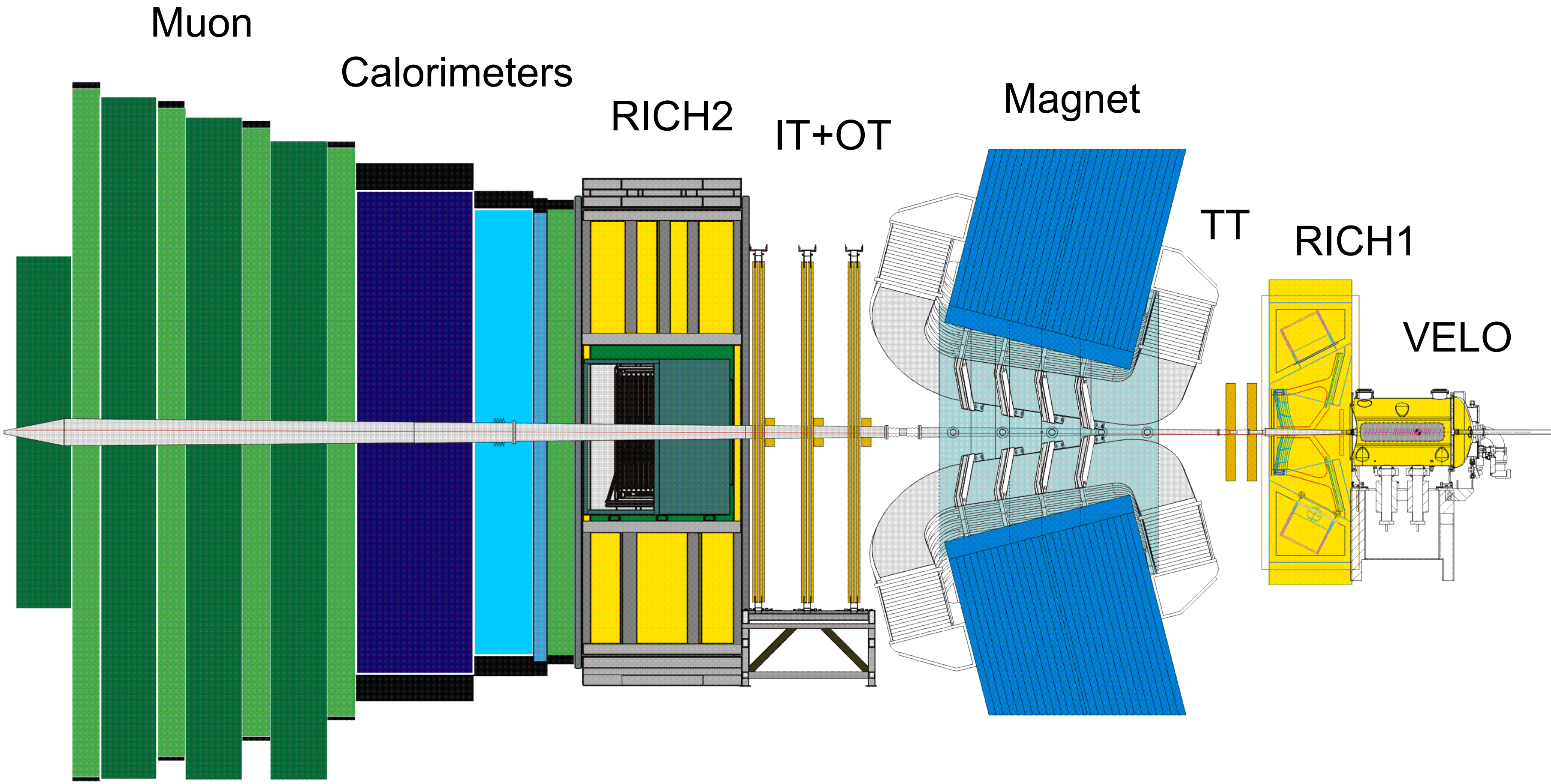


760 members
15 countries
54 institutes

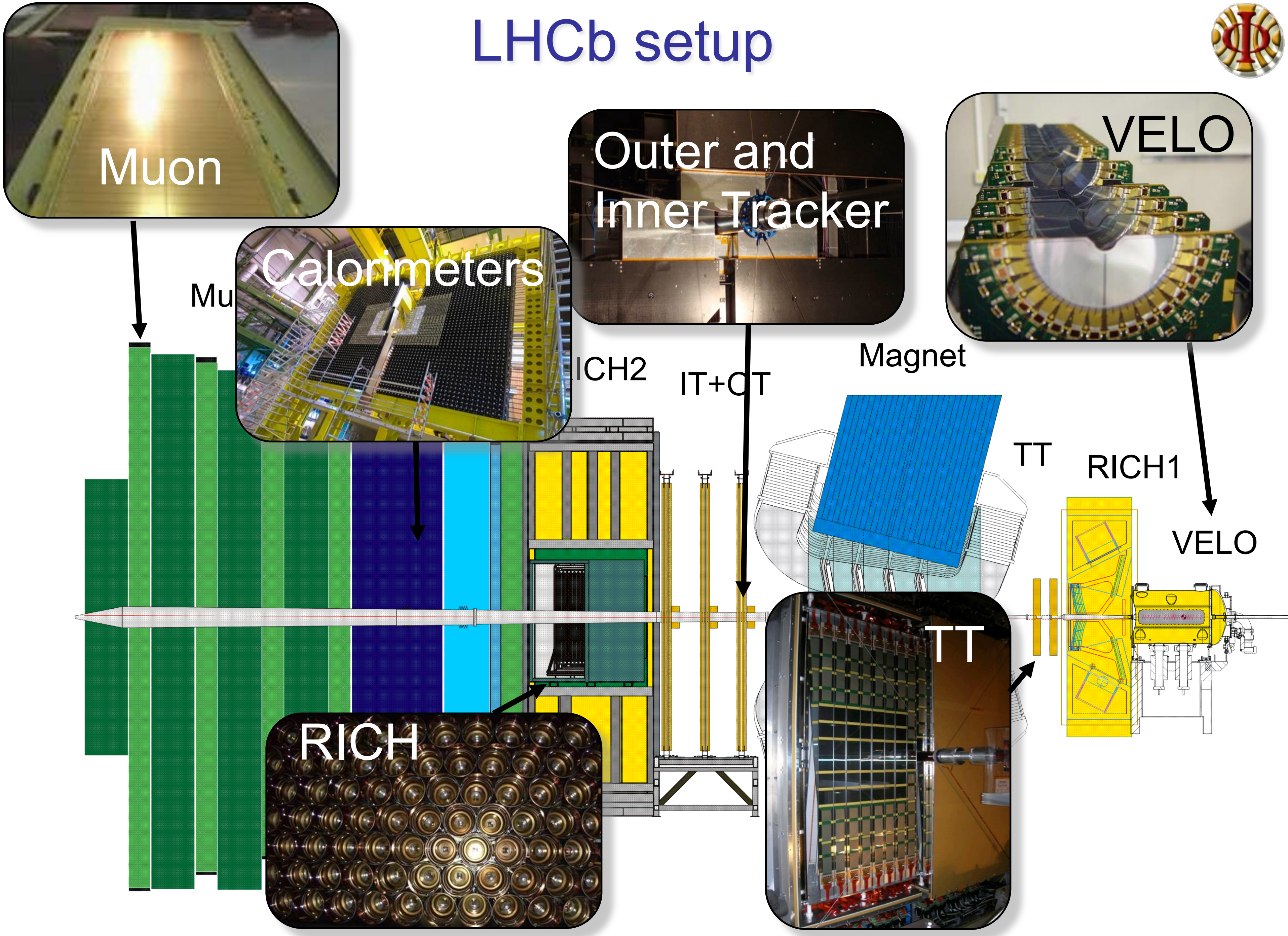
LHCb in the cavern



LHCb setup

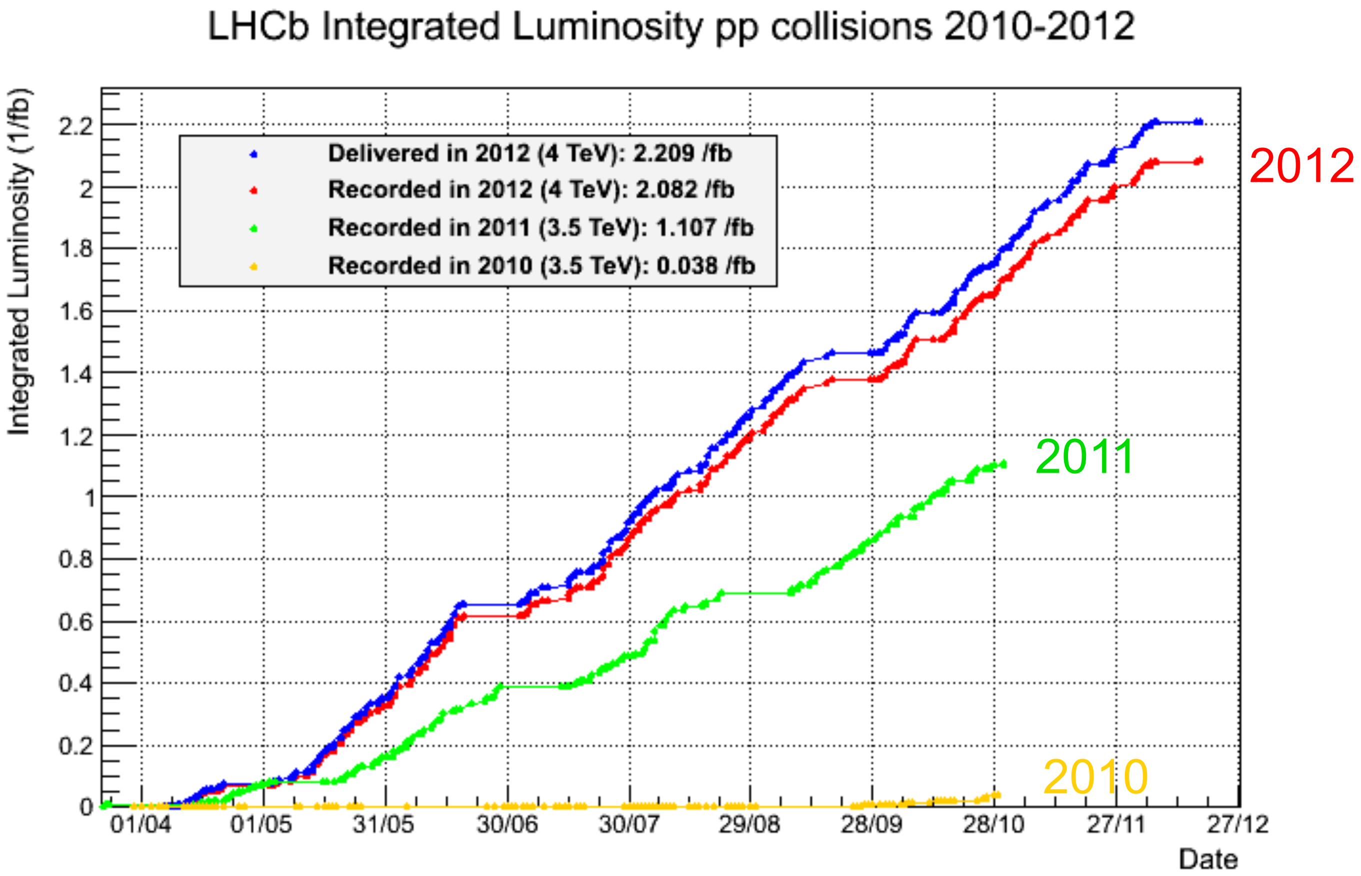


LHCb setup


Muon
Calorimeters
Outer and Inner Tracker
VELO
Mu
ICH2
IT+OT
Magnet
TT
RICH1
VELO
RICH
TT

Luminosity

- LHCb recorded 3.2 fb^{-1} in 2011-2012
  - Data taking ended on 16 Dec 2012.



Luminosity

- LHCb recorded 3.2 fb^{-1} in 2011-2012
  - Data taking ended on 16 Dec 2012.

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

B cross section:

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

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

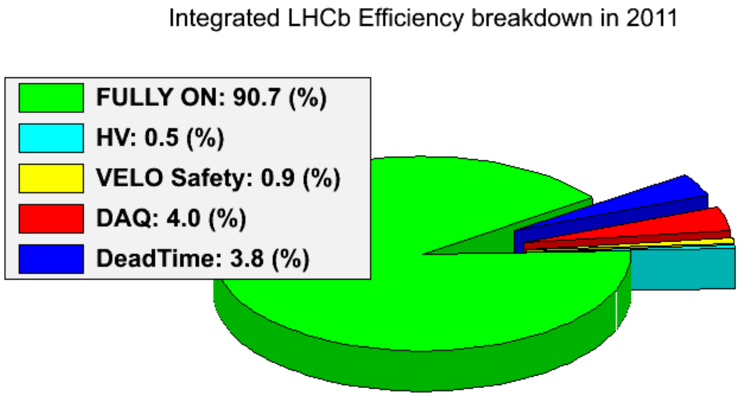
→ 9.0 x 10^{11} $b\bar{b}$ pairs already produced at the LHCb interaction point!

Cross sections at 14 TeV:

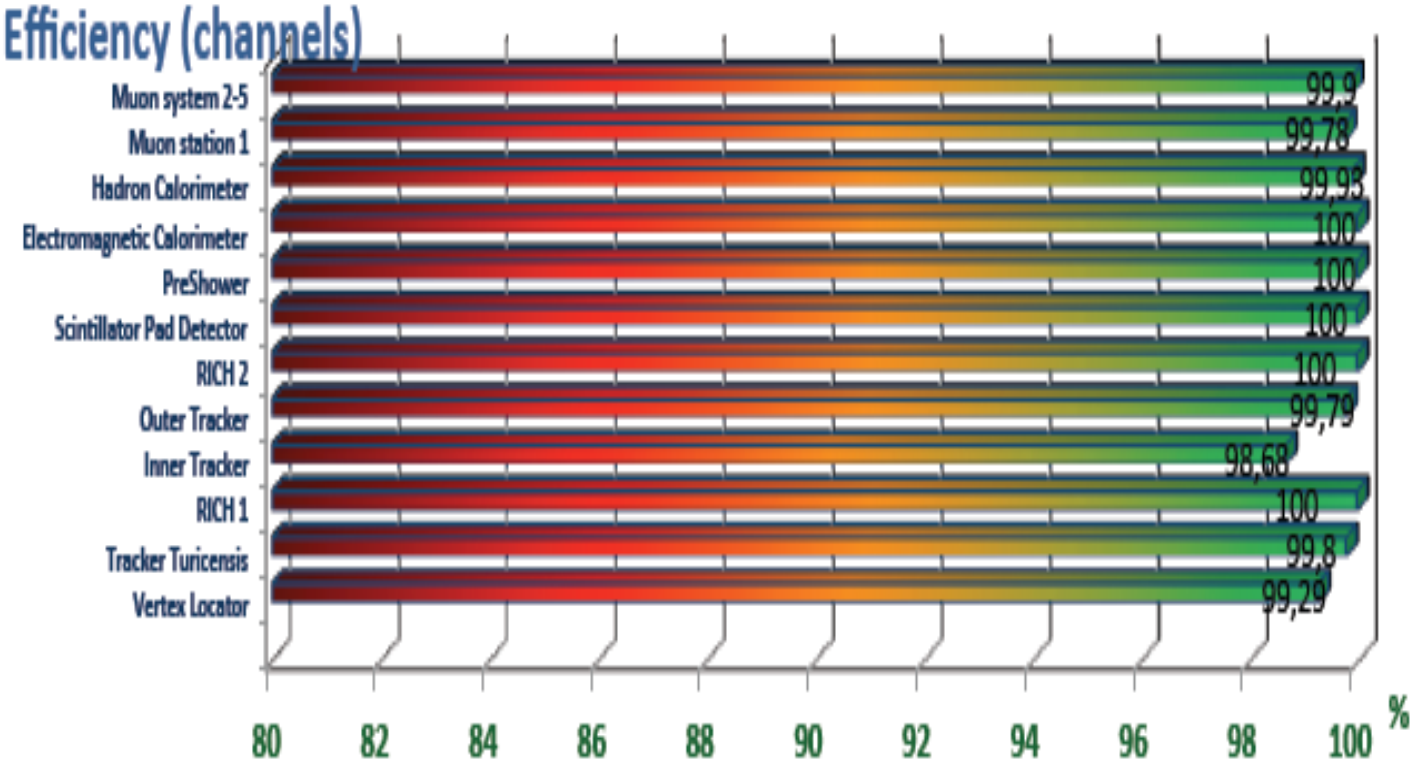
Total	100 mb
Inelastic	80 mb
$c\bar{c}$	3.5 mb
$b\bar{b}$	500 μb

In 1 in every 200 collisions a bb pair is produced

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**	**2012**	units
• LHC Beam energy	7.0	3.5	4.0	TeV
• Number of bunches in LHC	2808	1300	1300	
• Running time	1.0	0.4	0.5	10^7 seconds
• Number of interactions per BX (μ):	0.5	1.5	2.0	←
• Instantaneous luminosity	2.0	3.0	4.0	$10^{32}\ \mathrm{cm^{-2}s^{-1}} = 10^{2}\ \mu\mathrm{b^{-1}s^{-1}}$
• Integrated luminosity per year	2.0	1.1	2.1	fb^{-1}

Performance of LHC in 2011-2012

☹ Lower beam energy: b cross section only half.

☹ Fewer number of bunches

☹ Effective running time LHC in 2011-12 only 3.5 month (out of 24).

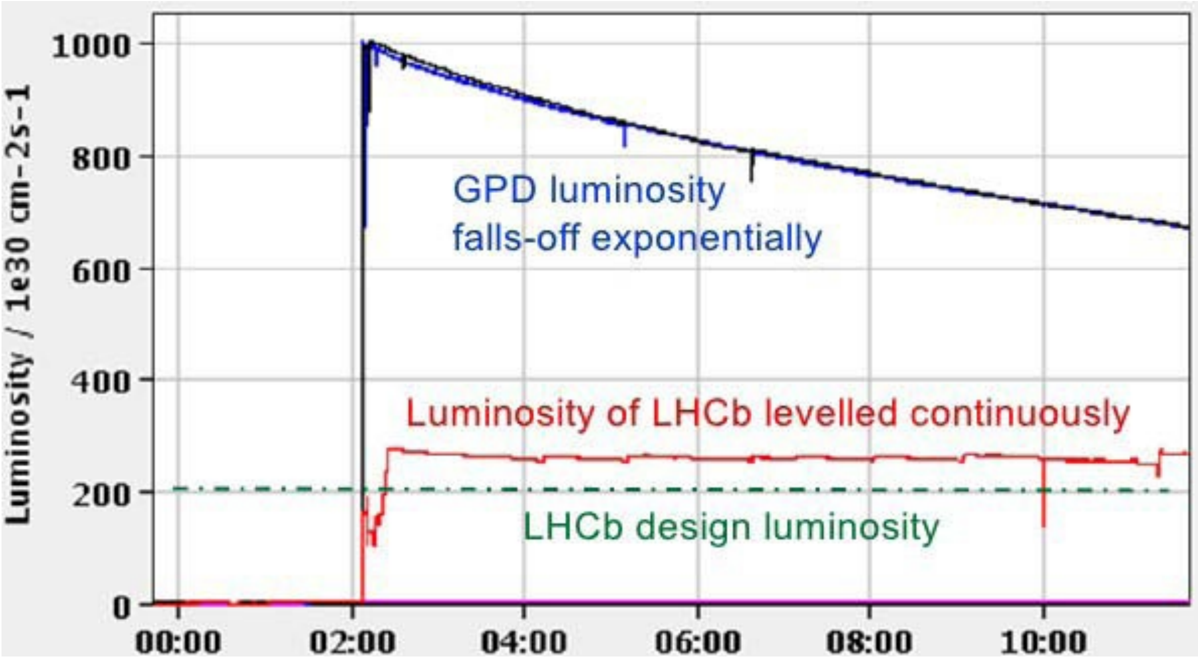
Solution LHCb:

☺ Run at higher instantaneous luminosity

→ Trigger and reconstruction must cope with higher multiplicities

☺ Luminosity leveling and deferred trigger (see next slides)

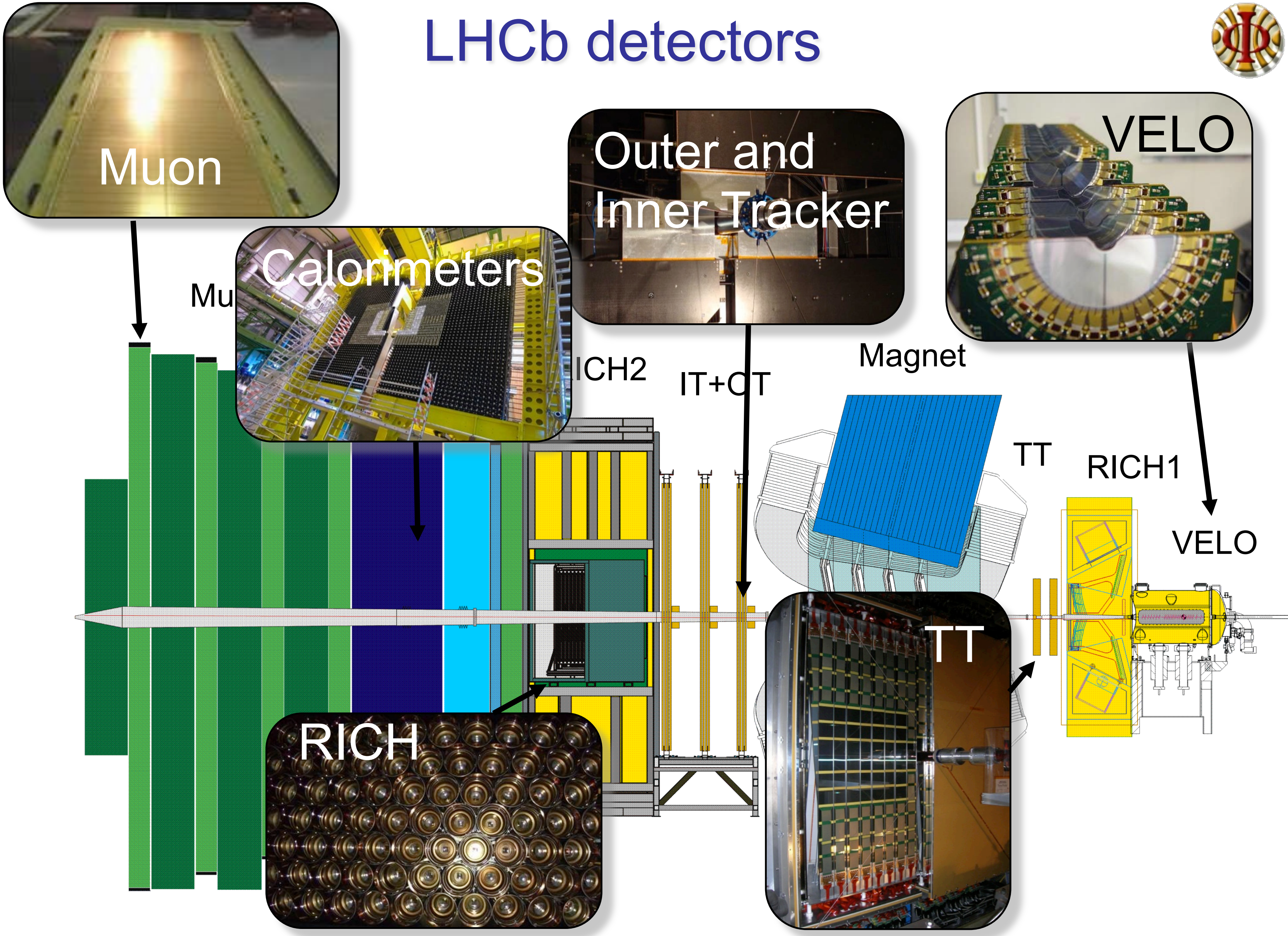
Luminosity leveling



<u>Luminosity leveling</u>

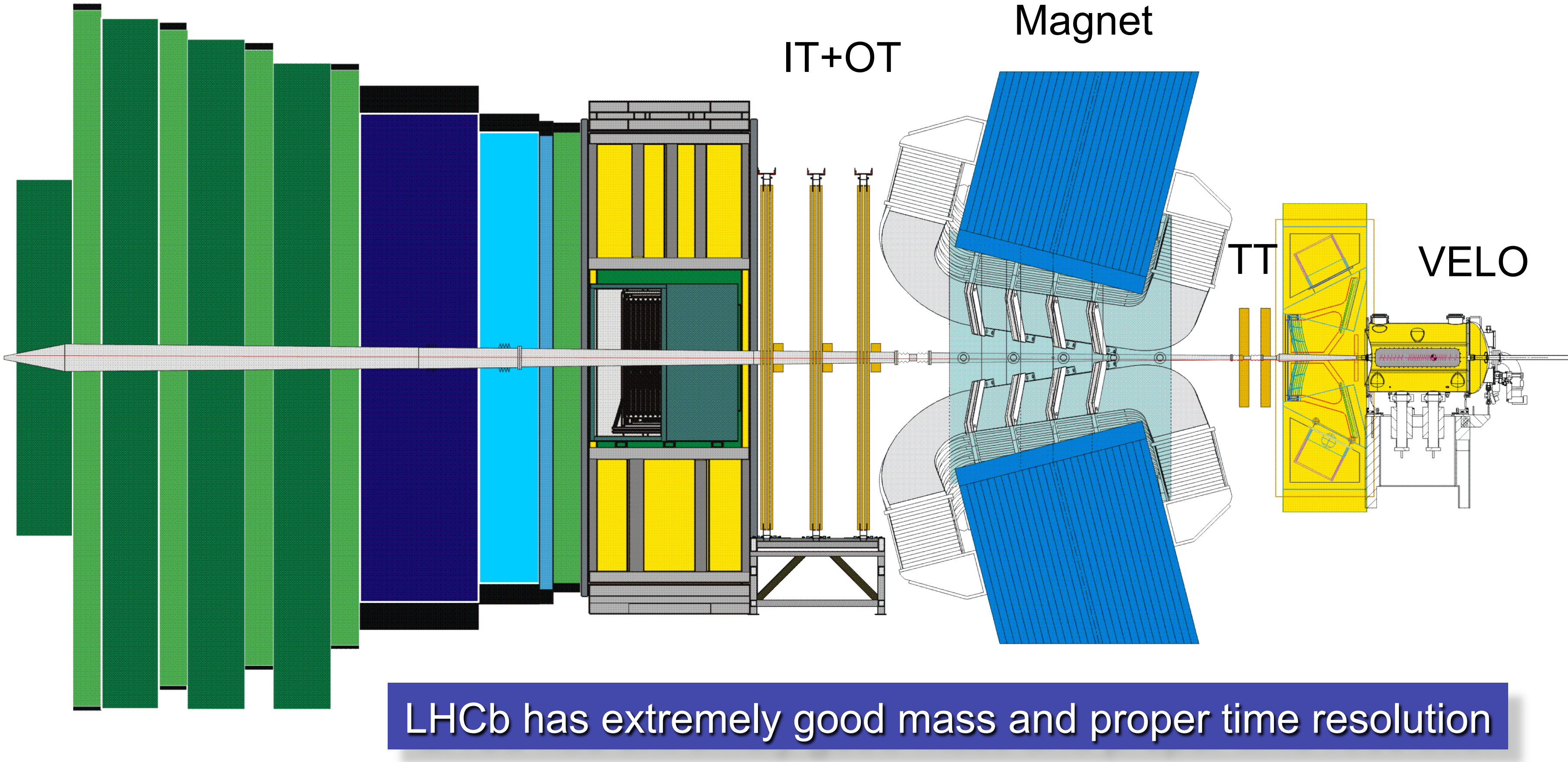
- LHCb already running twice above design lumi
    - Average L~4×10^{32} $cm^{-2}s^{-1}$ (nominal 2×10^{32})
- Need to cope with higher occupancies
    - More pile-up: average μ~2.0 (nominal 0.5)
- Continuous, automatic adjustment of offset of colliding beams.
- Allows optimal conditions throughout a fill.
- Very new technique. Not all LHC experts were convinced it would work.
- Allows to take data much more efficiently.

LHCb detectors



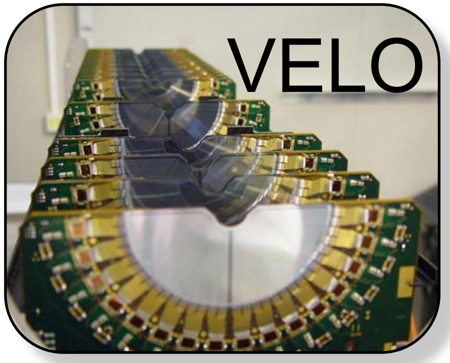
LHCb from a tracking point of view

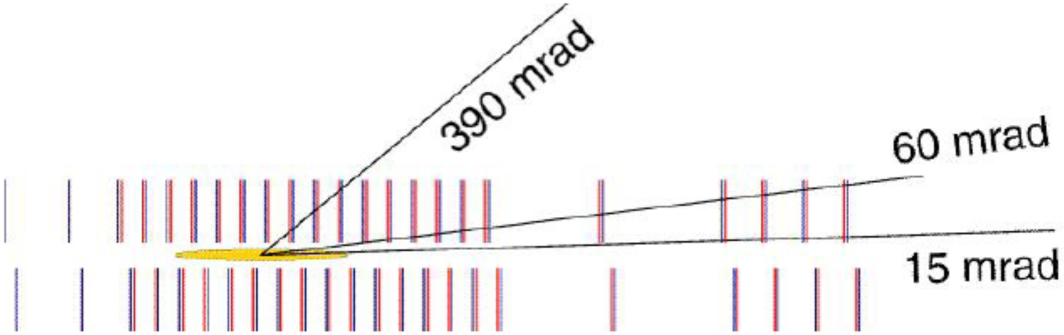
Goal (Remember the elephant)	**Purpose**	**Solution**
1. Measure **proper time** of decaying particles	Identify *B* hadrons and time-dependent analysis.	Vertex detector: **VELO** (+tracking stations)
2. Measure **mass** of decaying particles	Identify signal and separate from background.	Magnet + tracking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



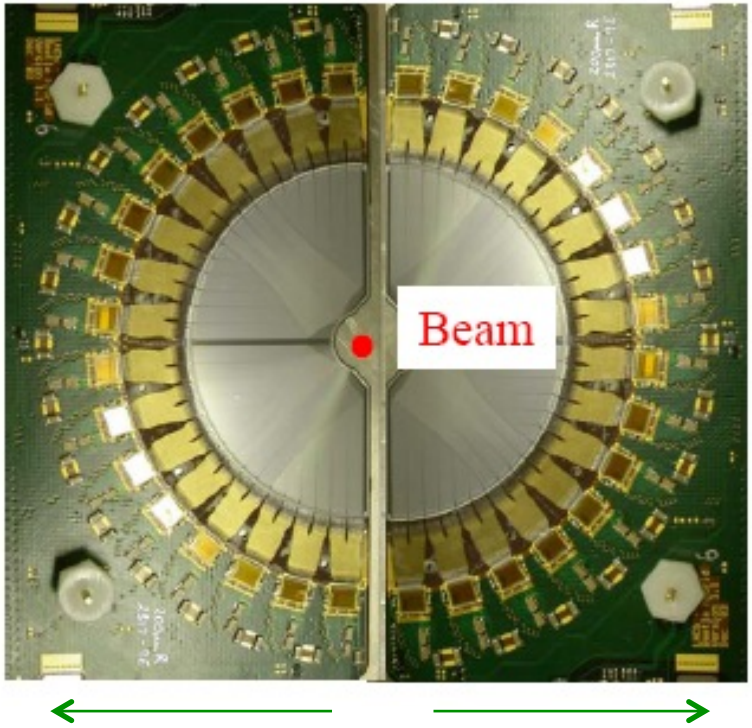
LHCb has extremely good mass and proper time resolution

Vertex detector



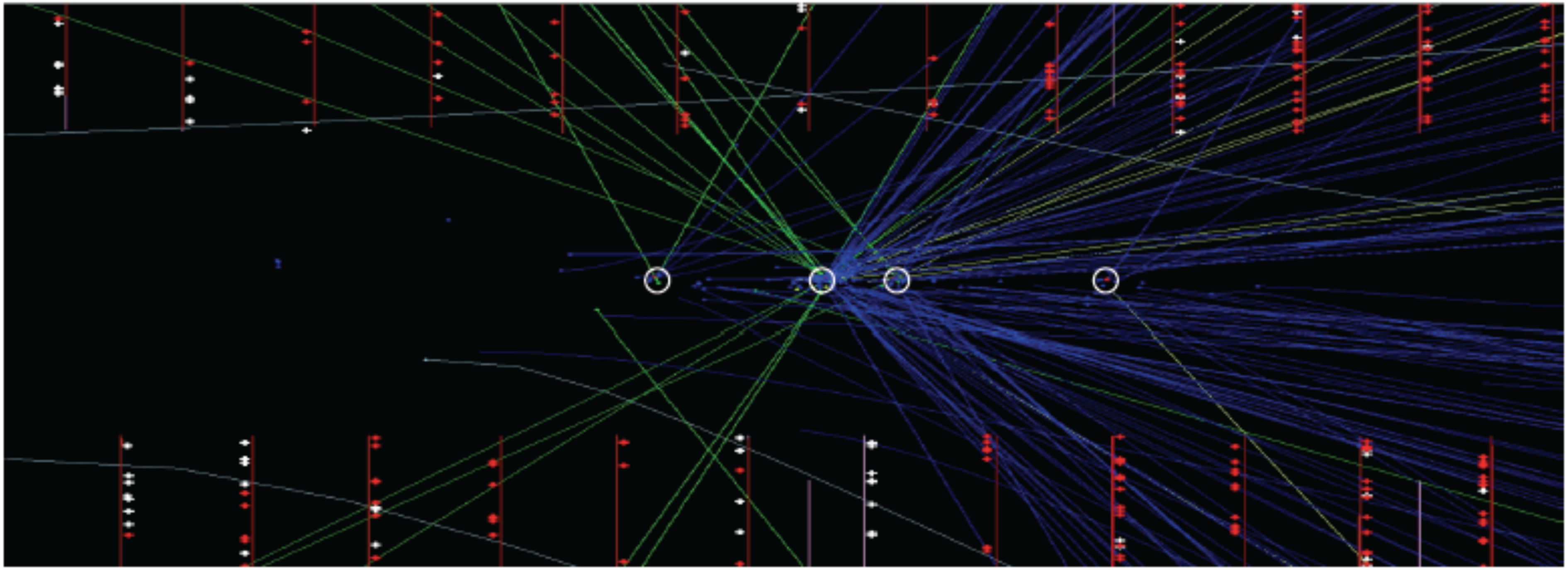


- 21 modules, each with a r- and φ-measuring sensor.
- Strip pitch: 36–102 μm.
- Velo sensors (active area) only 8 mm from beam…



→ Velo sensors need to be retracted during LHC injection and ramp.

Pile-up vertices

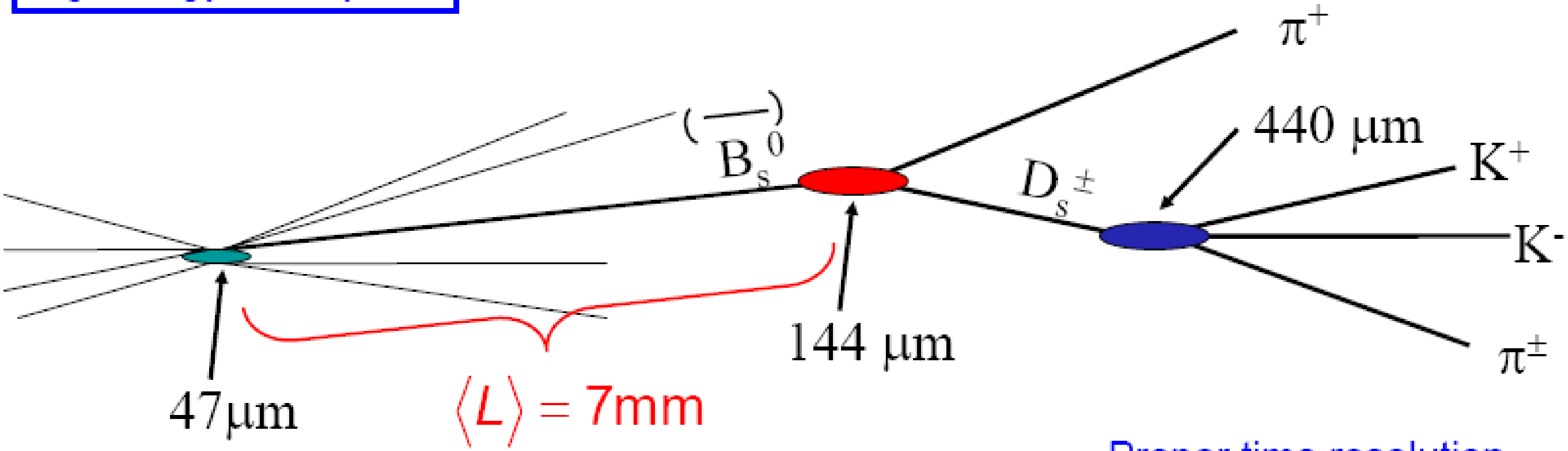


VELO rz view

20 MHz of bunch crossings with an average of 2 proton-proton interactions per bunch crossing, and about 30 particles produced per interaction

Vertex reconstruction

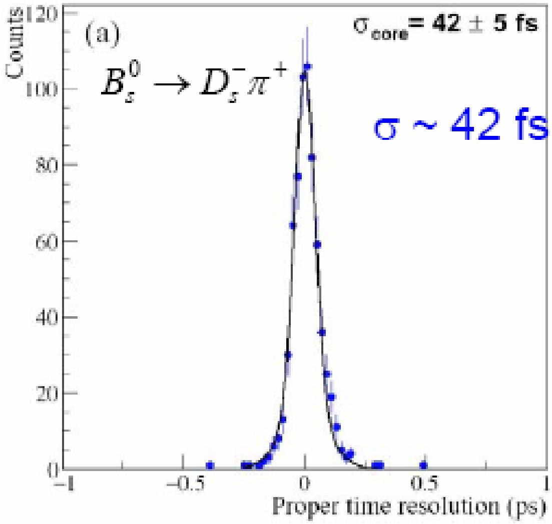
$B_s \rightarrow D_s(K\,K\,\pi)\,\pi$



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

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

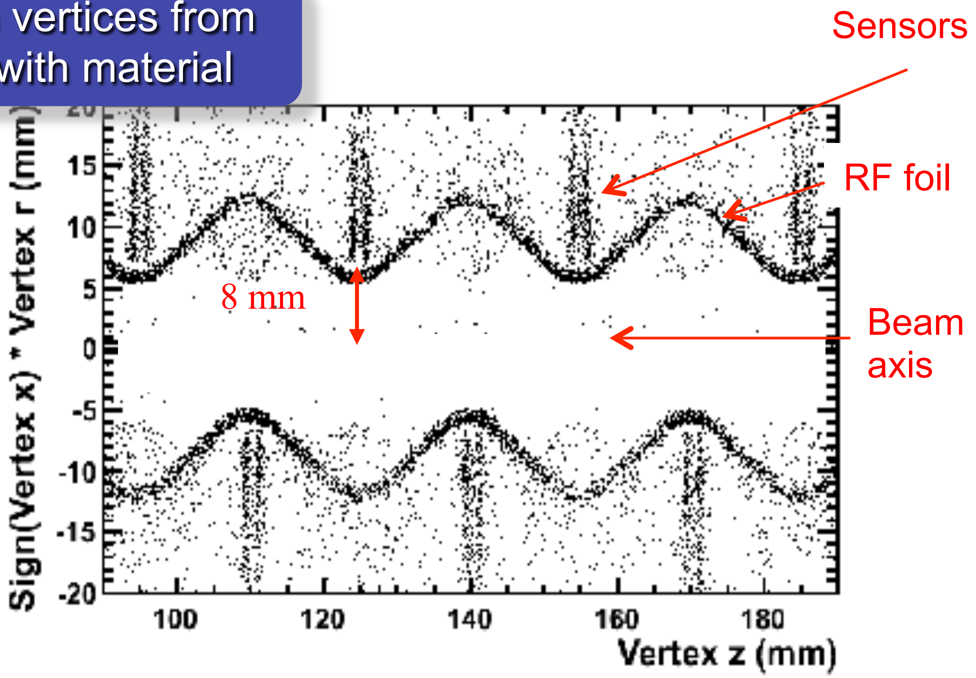
Proper time resolution



Vertex reconstruction

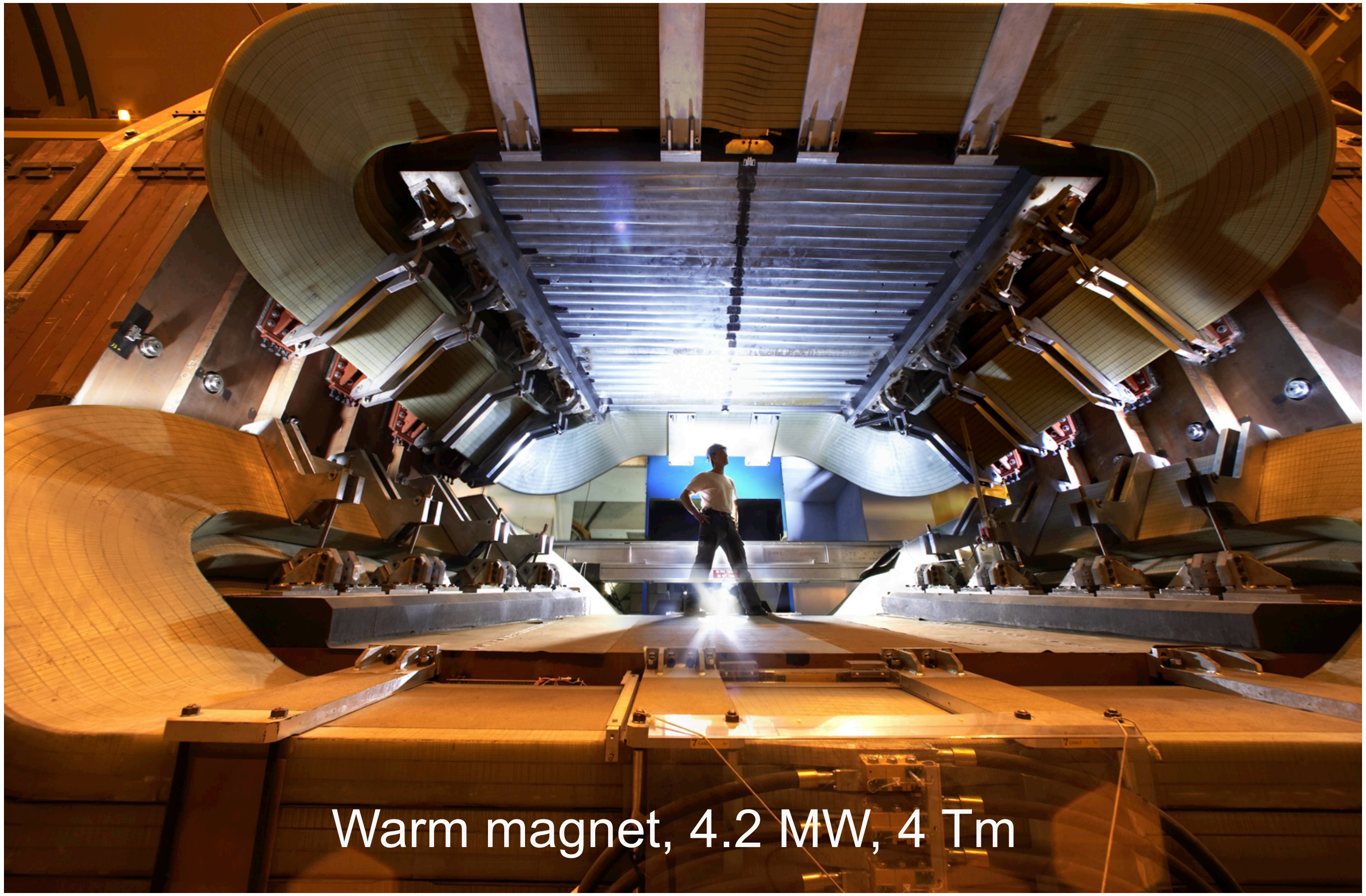
- VELO sensors only 8 mm from beam.
- Impact parameter resolution = 12 μm for high p_T tracks.
- Good primary and secondary vertex resolution.
  - Suppress background from prompt decays.
- Good proper-time resolution
  - Important for time-dependent measurements.

VELO "tomography" with vertices from secondary interactions with material



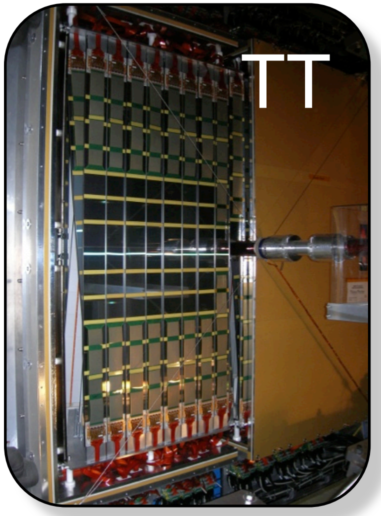
RF-foil must be as thin as possible to reduce error on the vertex position

Magnet

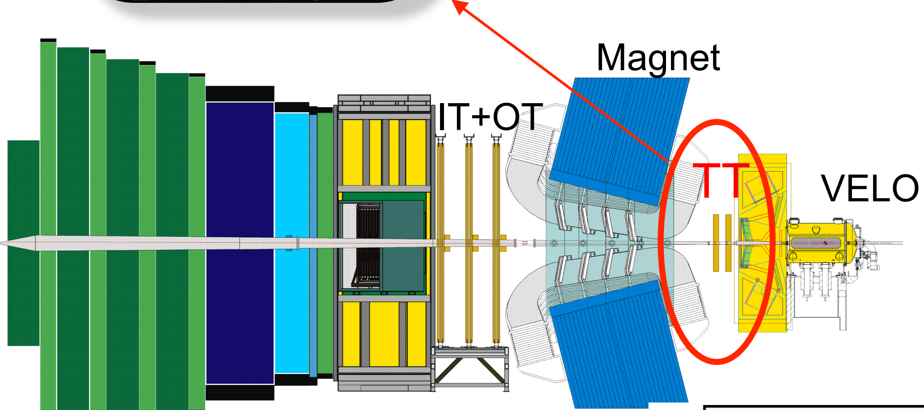

Warm magnet, 4.2 MW, 4 Tm

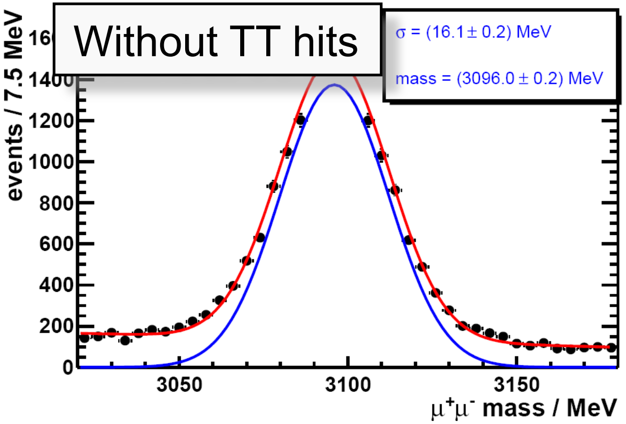
Magnet bends the particles to measure their momentum
Momentum resolution: $\Delta p/p \sim 0.4$ %
Determines the mass resolution

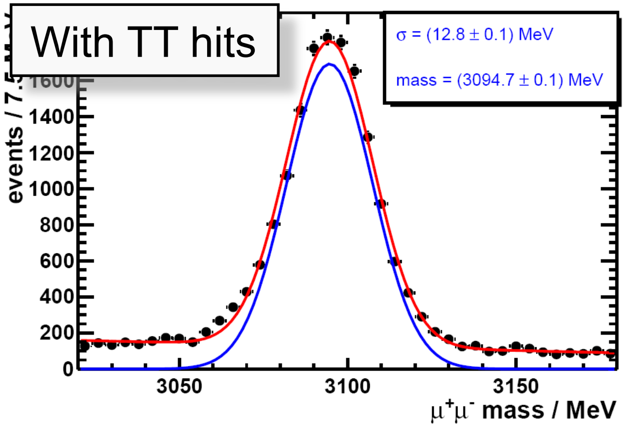
Tracking system: TT



- ☐ Just after RICH1 and before the magnet
- ☐ Four layers (0°,+5°,−5°,0°) of 150 x 130 cm.
- ☐ Strip pitch: 183 μm.
- ☐ 64 modules with 14 sensors each.
- ☐ Hit resolution about 50 μm.
- ☐ Important for K_S reconstruction.
- ☐ Improves mass resolution.

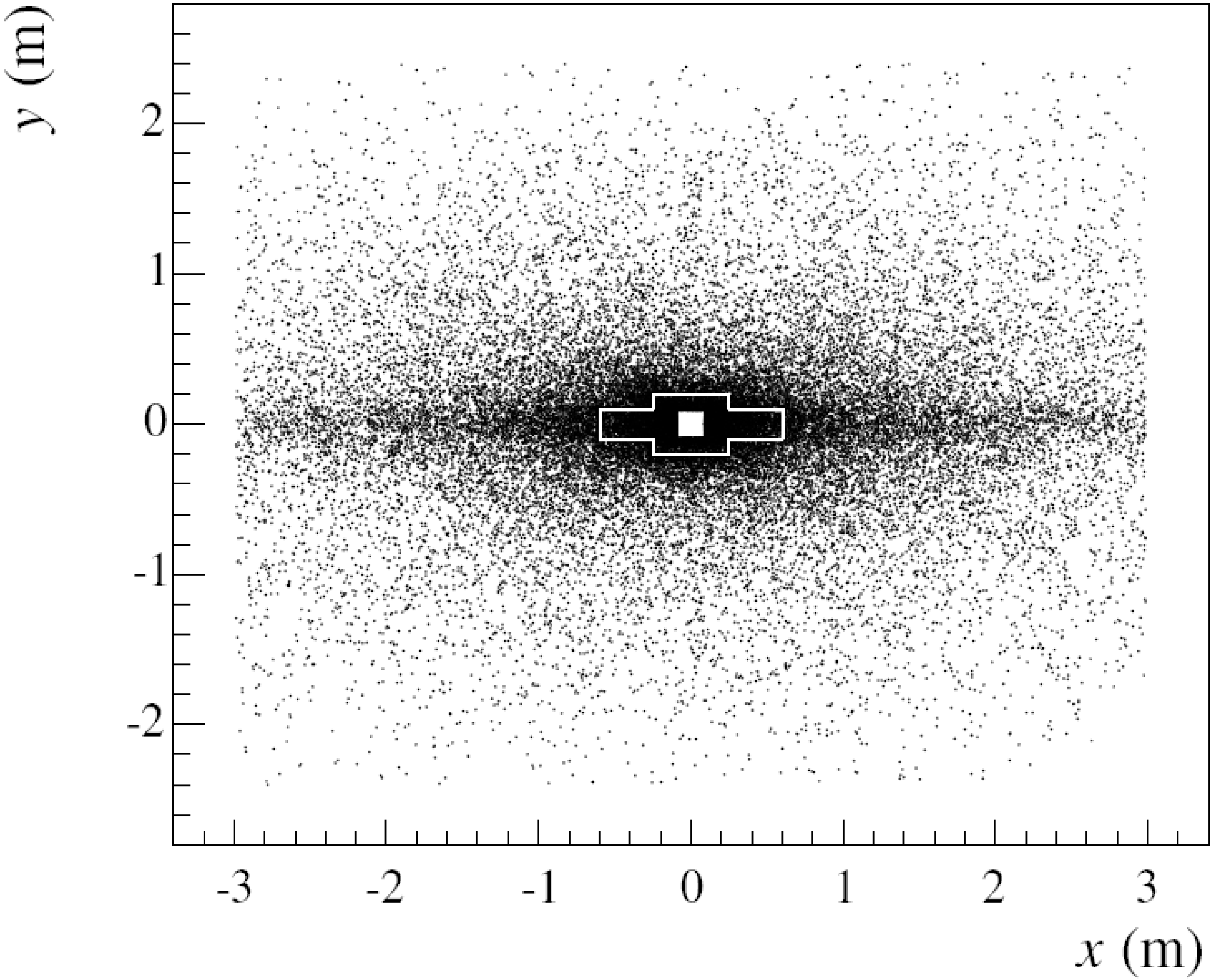






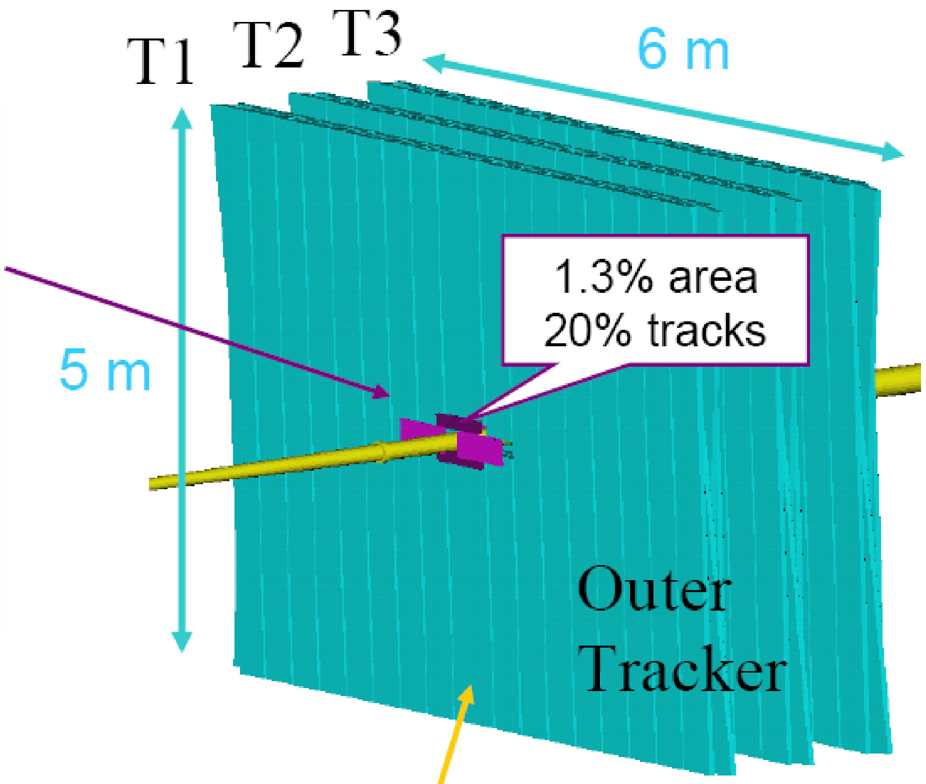
T stations: Inner and Outer Tracker

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

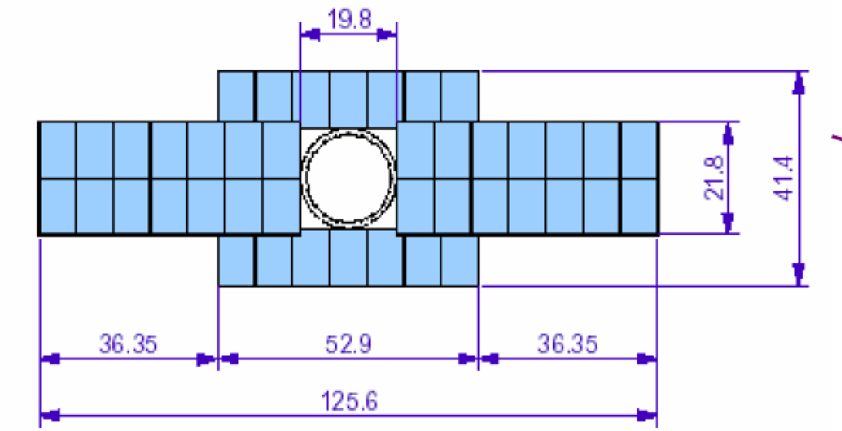


Tracking system: IT

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



Inner Tracker: Silicon sensors



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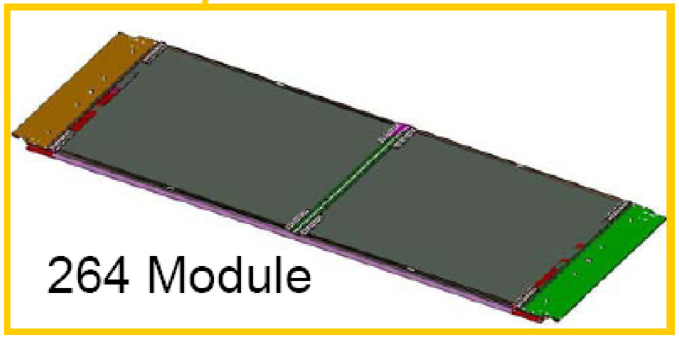
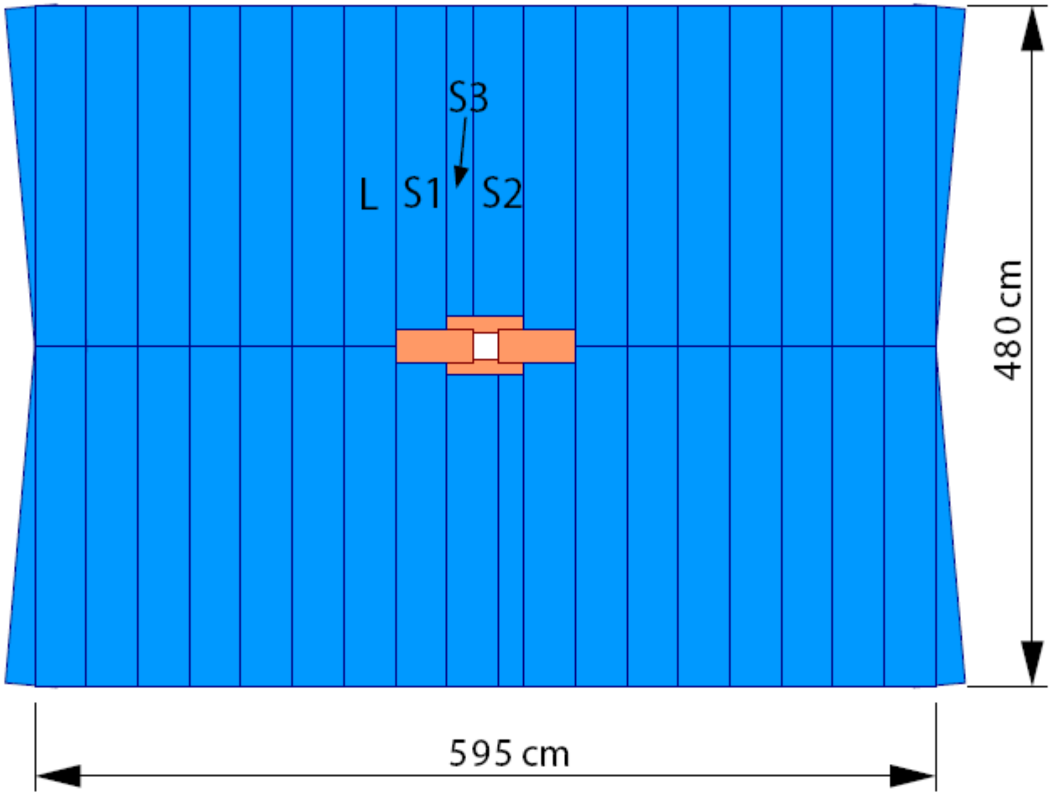
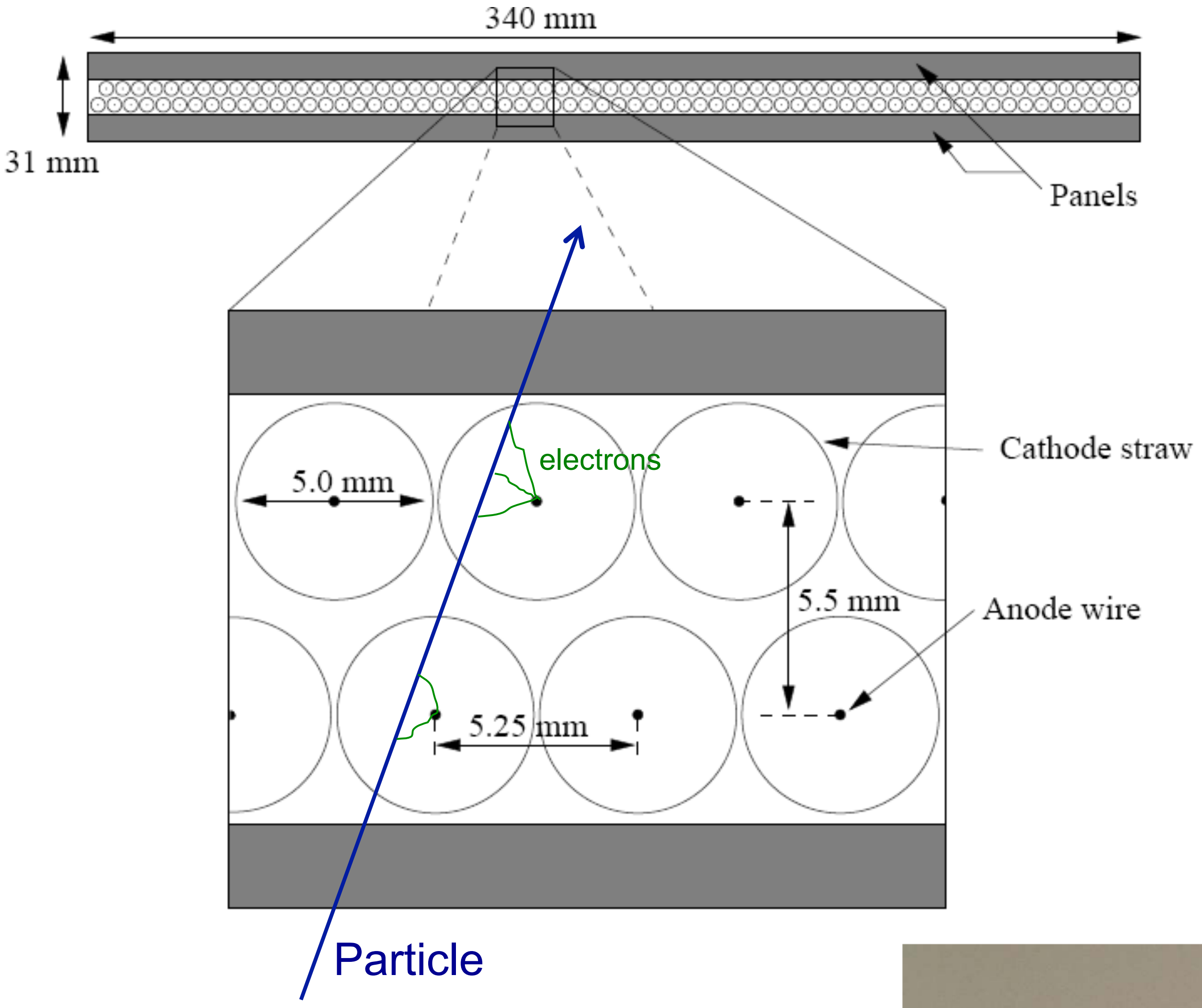


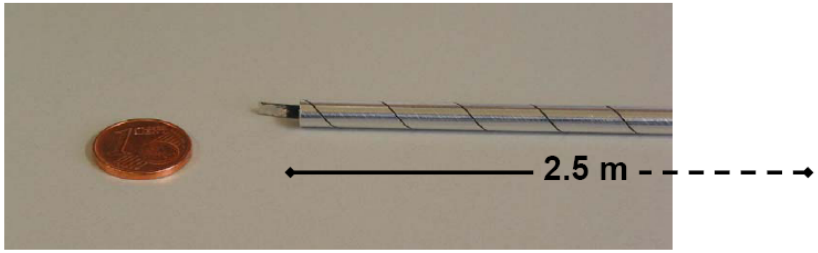
Tracking system: OT

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

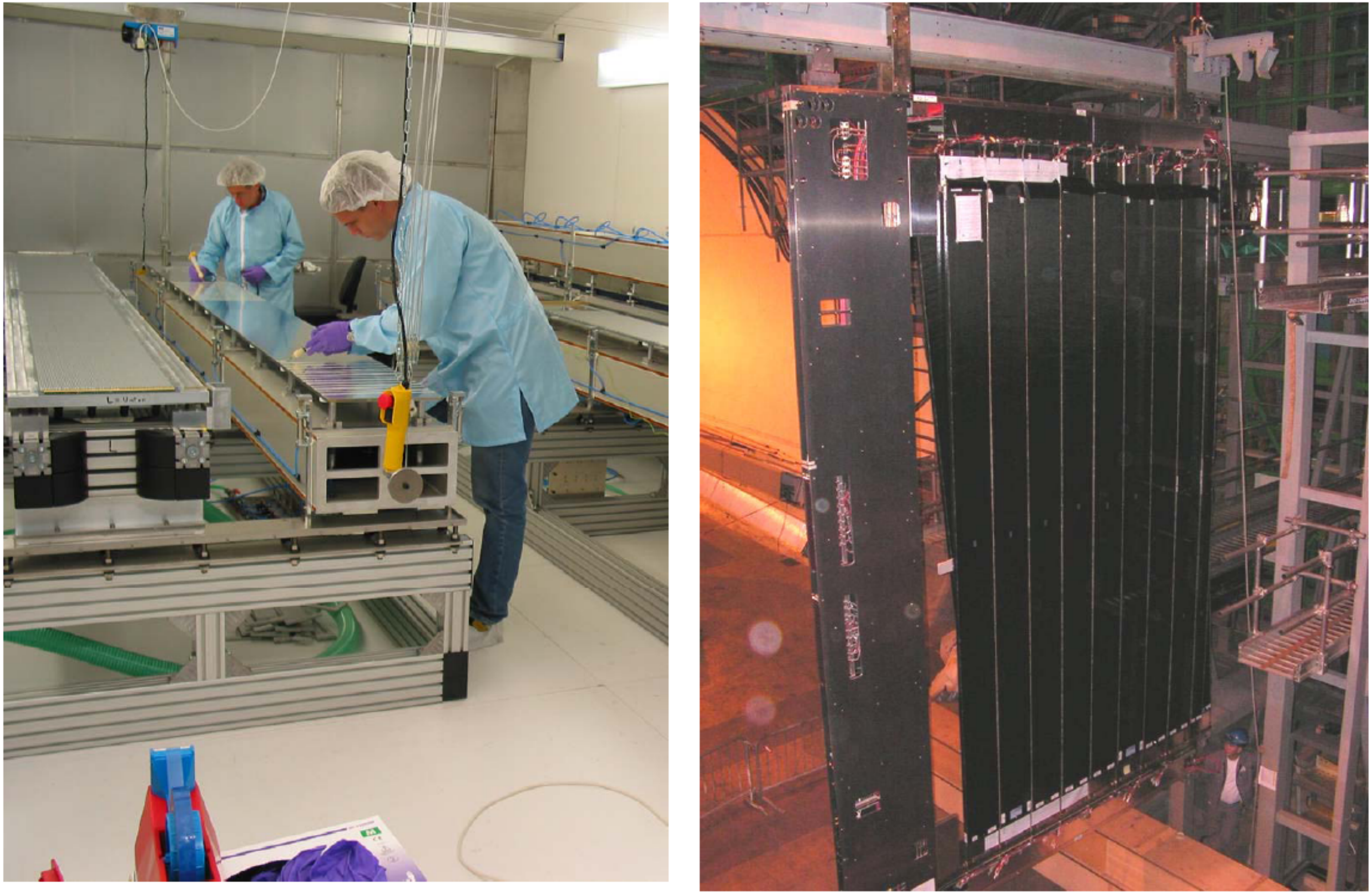


Tracking system: OT

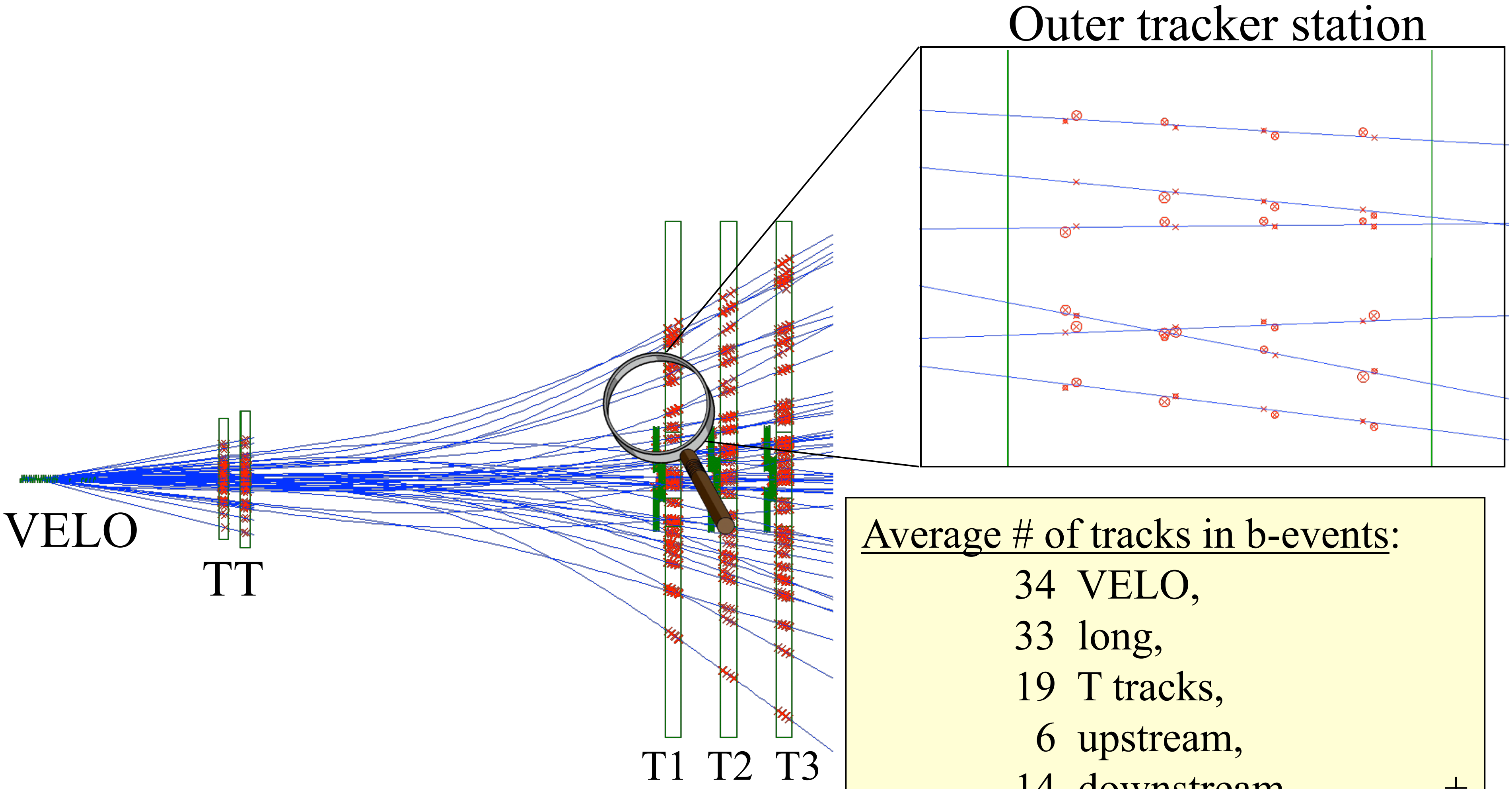




Outer Tracker



Track reconstruction



Average # of tracks in b-events:

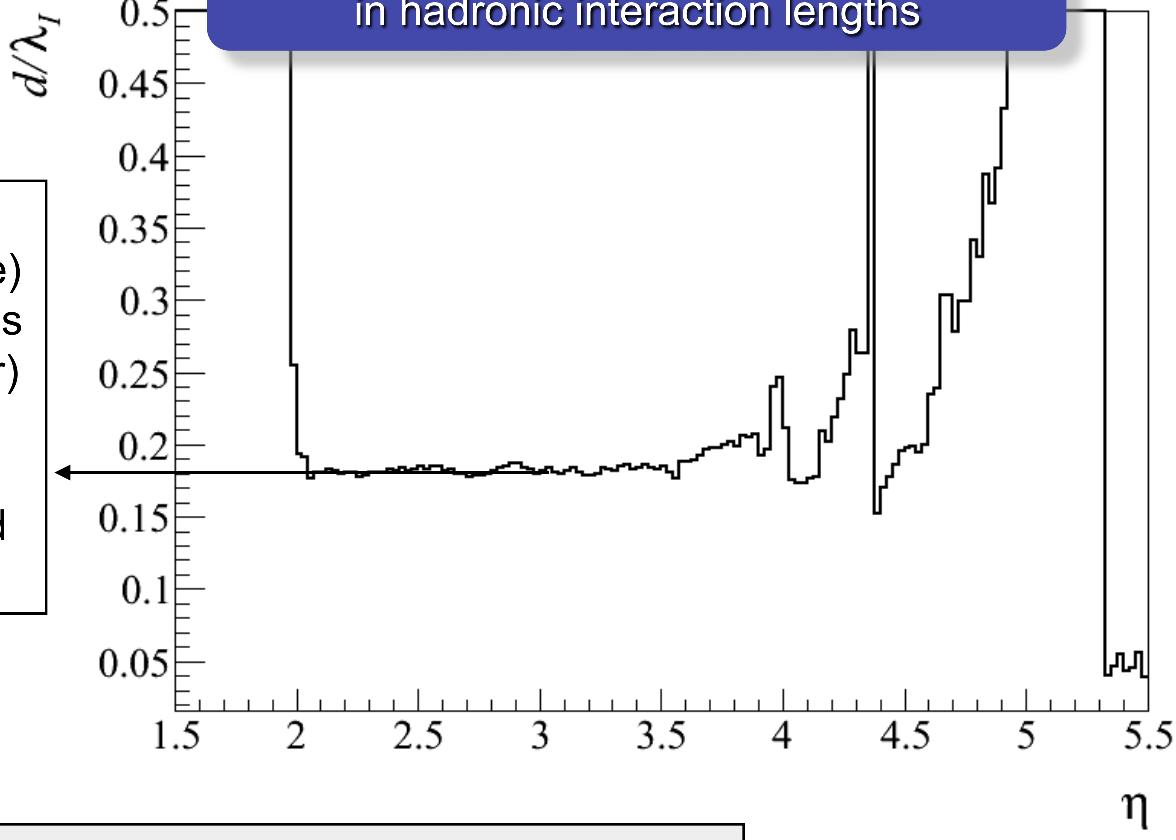
34	VELO,
33	long,
19	T tracks,
6	upstream,
14	downstream +
Total 106	reconstructed tracks

Track reconstruction

Why should the tracking detectors be light?

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

- Thickness of material in tracking system: 18% (over 9m of distance)
- That means ~17% of the hadrons have hadronic interaction (shower) in tracking system.
- Hadronic interactions only important for hadrons (muons and electrons not affected).



Thickness of tracking detectors expressed in hadronic interaction lengths

18% thickness corresponds to 8 cm of aluminium

Track reconstruction

Why should the tracking detectors be light?

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

Will cause that particles move outside search windows in track reconstruction.
Significant effect for particles below $p < 80$ GeV

(basically all particles of interest).

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 in radiation length: taken from detector description (simulation)

Scattering is mainly an electromagnetic effect.

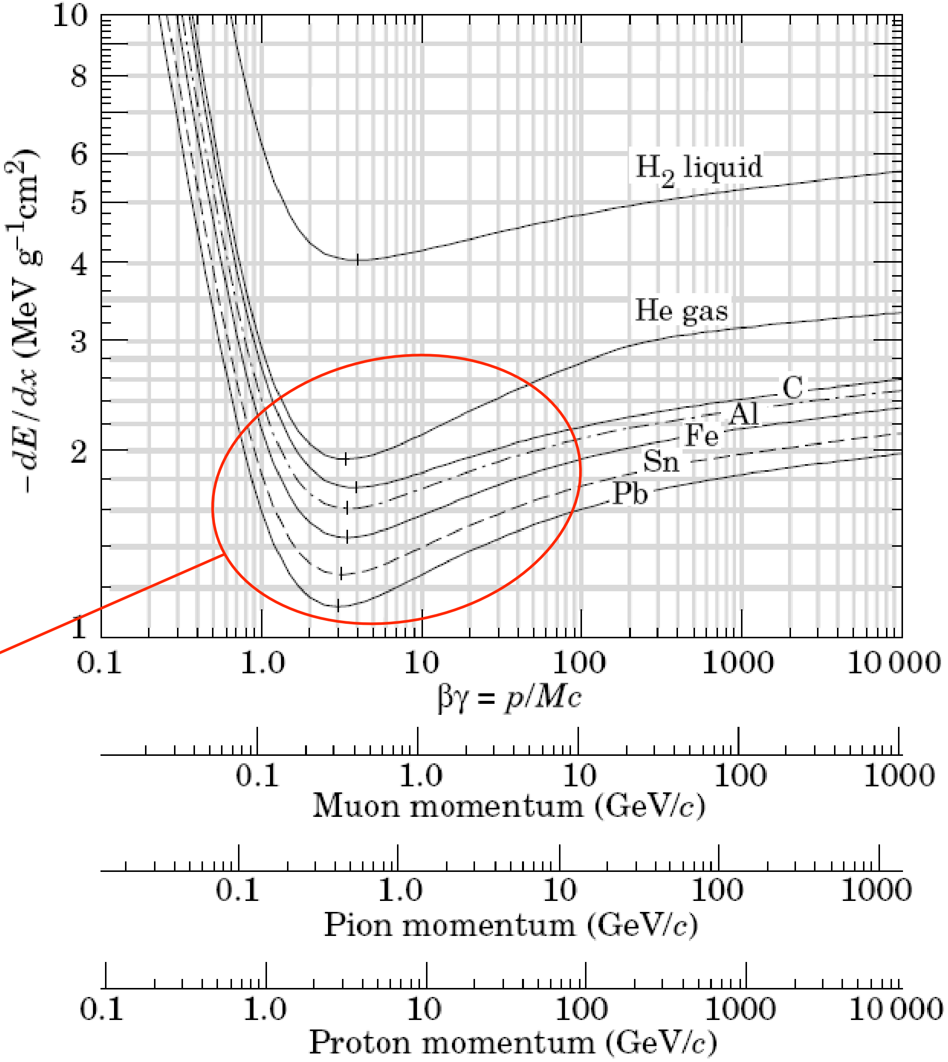
Other material effects: energy loss

Energy loss

- Caused by ionization of the medium (electromagnetic).
- Note that this effect is actually needed to measure the particles (hits)!

See Bethe Bloch formula

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



What's a MIP?

Minimum ionizing particle

- 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 mass resolution (10-30 MeV).

Electrons and photons

Electrons

- Electrons loose their energy mainly 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 much worse compared to muons

Photons

- Related to bremsstrahlung is photon conversion $\gamma \rightarrow e^+e^-$
- 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.

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

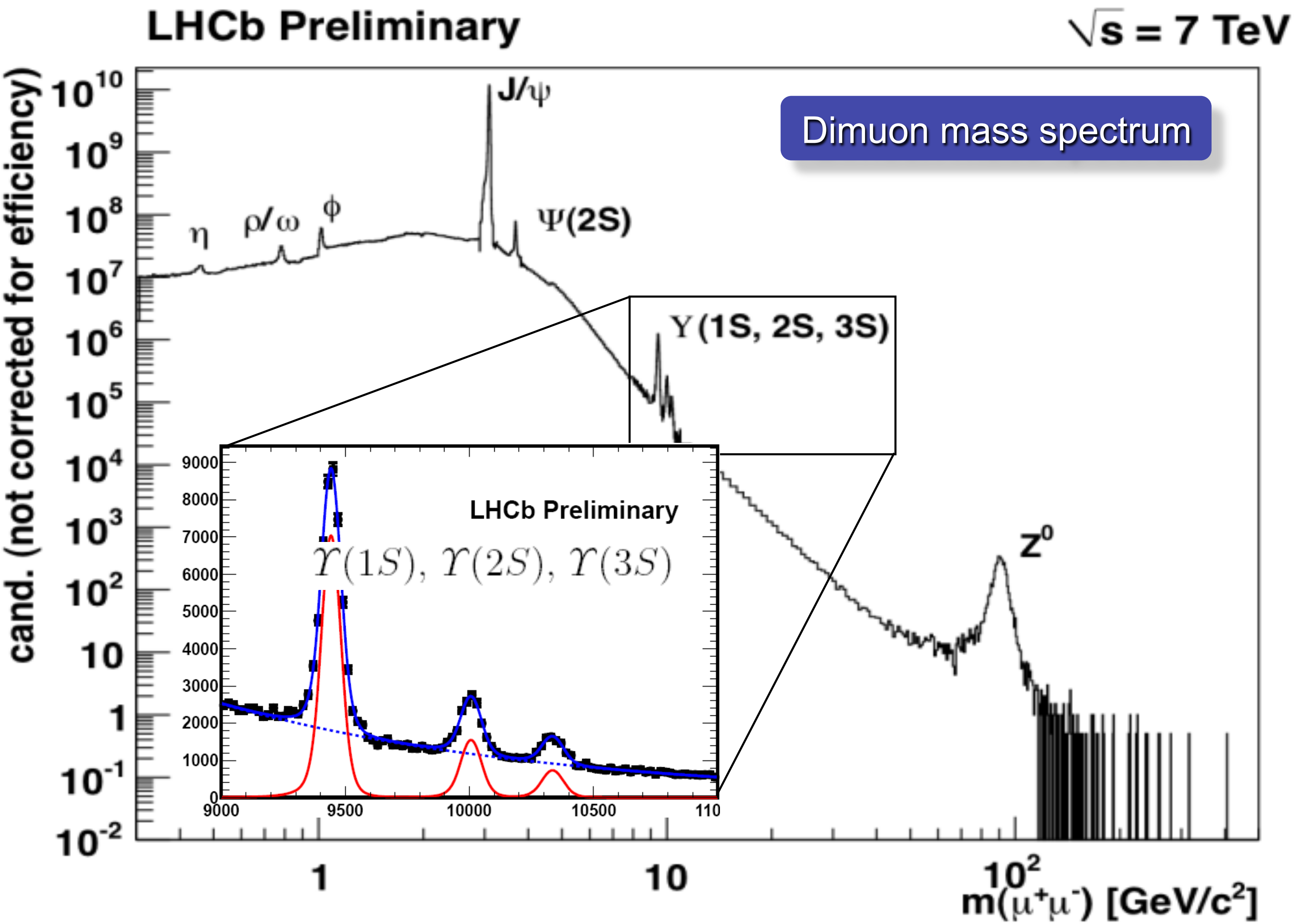
$$m_M^2 = m_1^2 + m_2^2 + 2|\vec{p}_1||\vec{p}_2|\boxed{(1 - \cos\Theta)}$$

Opening angle term

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

Mass resolution mainly determined by momentum resolution

Full mass spectrum

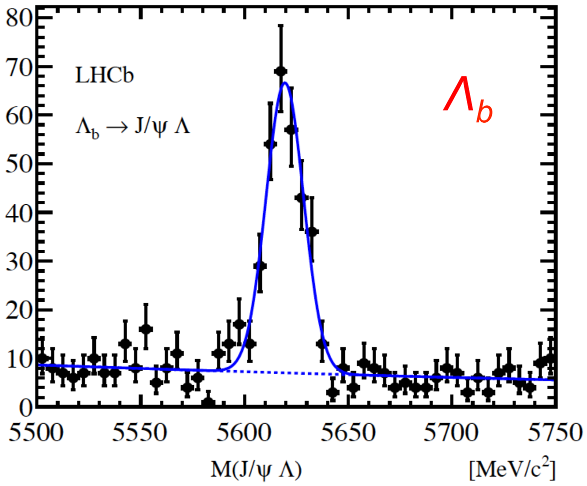


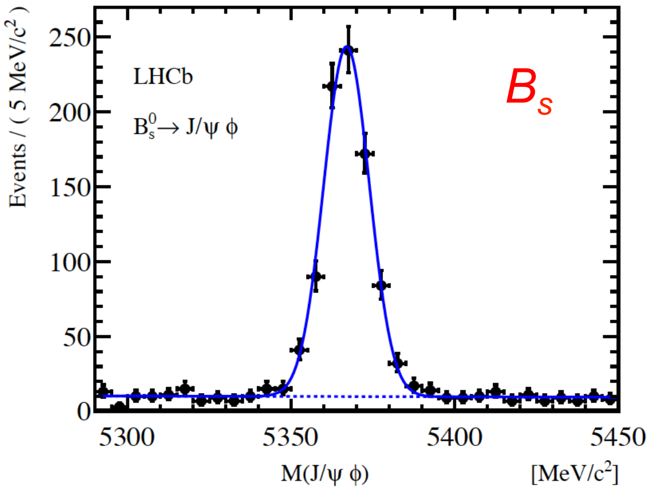
Measurement of *B* masses

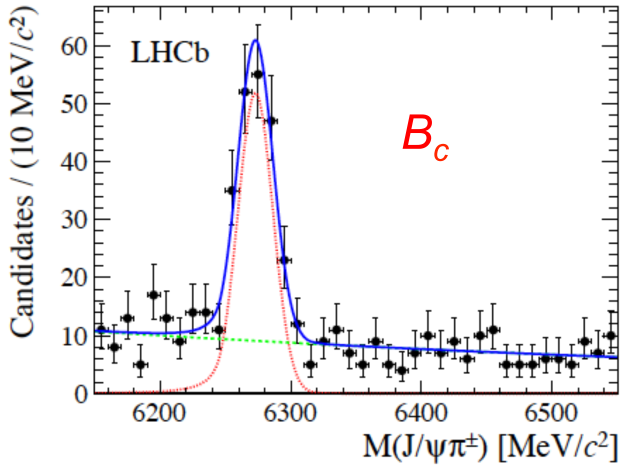
Quantity	LHCb measurement	Best previous measurement	
$M(B^+)$	5279.38 ± 0.35	5279.10 ± 0.55	[4]
$M(B^0)$	5279.58 ± 0.32	5279.63 ± 0.62	[4]
$M(B^0_s)$	5366.90 ± 0.36	5366.01 ± 0.80	[4]
$M(\Lambda^0_b)$	5619.19 ± 0.76	5619.7 ± 1.7	[4]
$M(B_c^+)$	6273.7 ± 2.1	6275.6 ± 3.8	

Phys. Lett. B 708 (2012) 241-248

Phys. Rev. Lett. 109 (2012) 232001







World-best mass measurements!

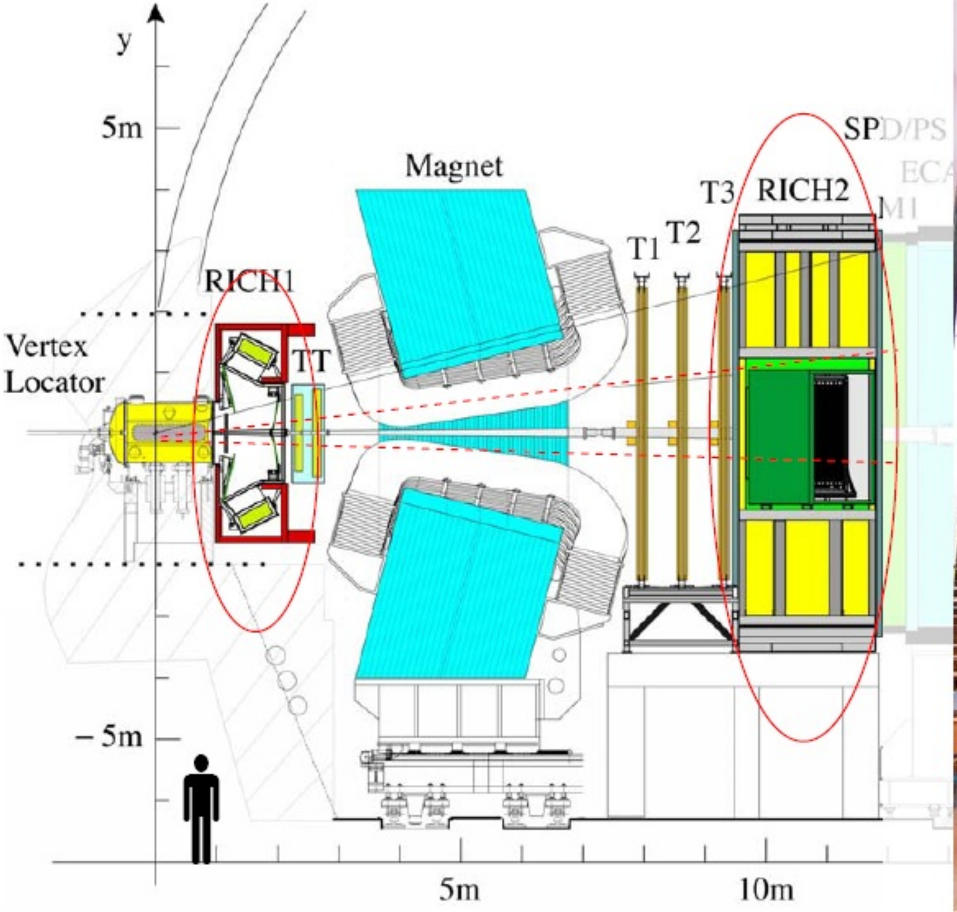
Particle ID

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 $\pi\pi$, K_L^0 stops in HCAL)
- **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
- + anything that we do not detect (e.g. neutrino's)

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

RICH detectors

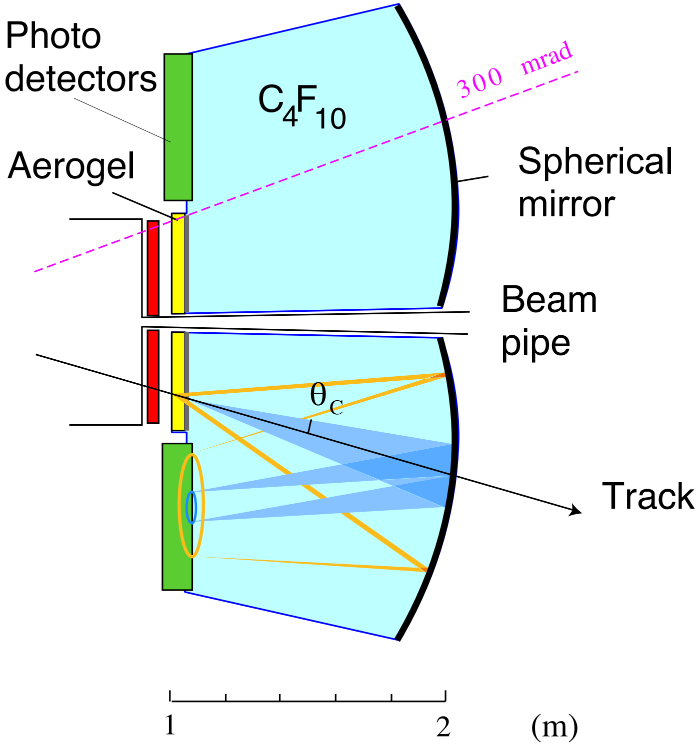


Two **RICH** detectors for charged hadron identification

RICH=Ring Imaging CHerenkov detector

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

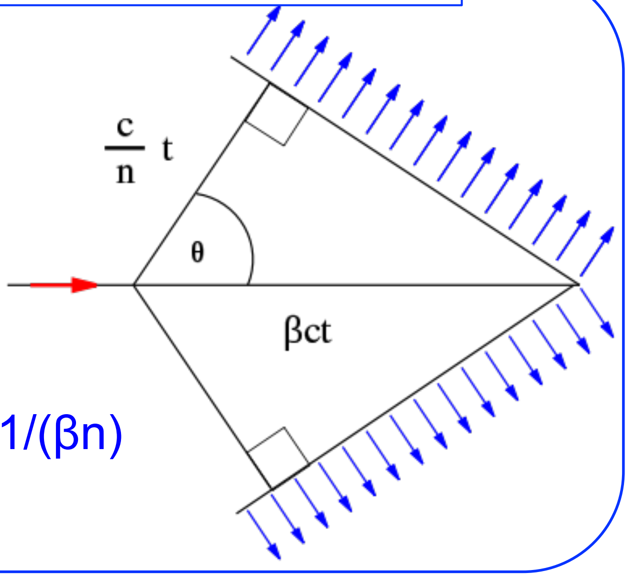
Important for B physics as there are many hadronic decay modes.

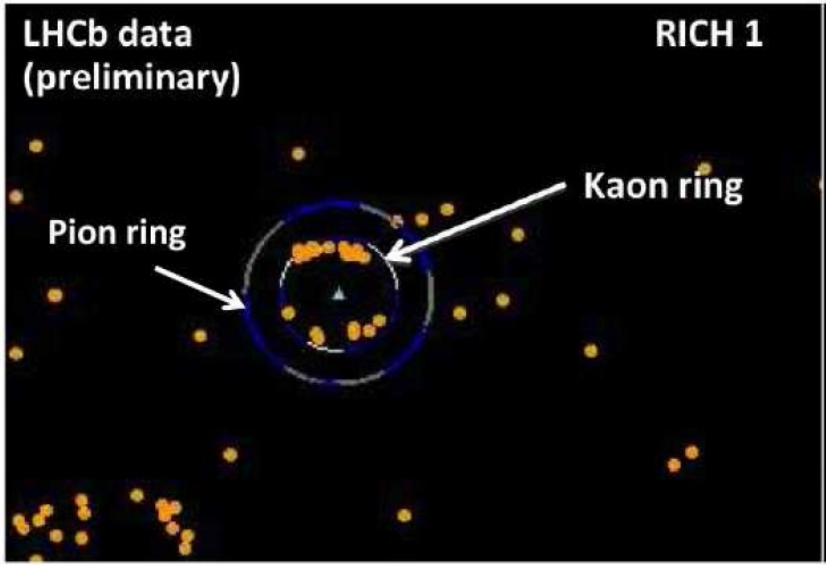


Cherenkov radiation

If β > c/n

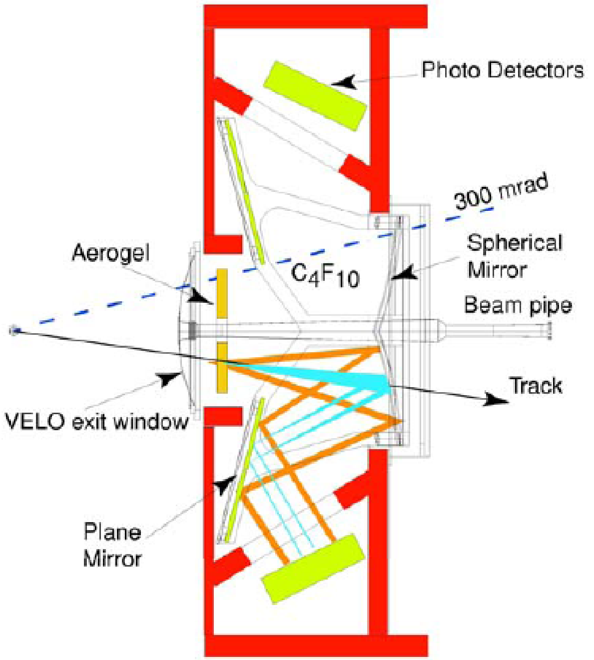
$\cos\theta_c = 1/(\beta n)$





RICH detectors

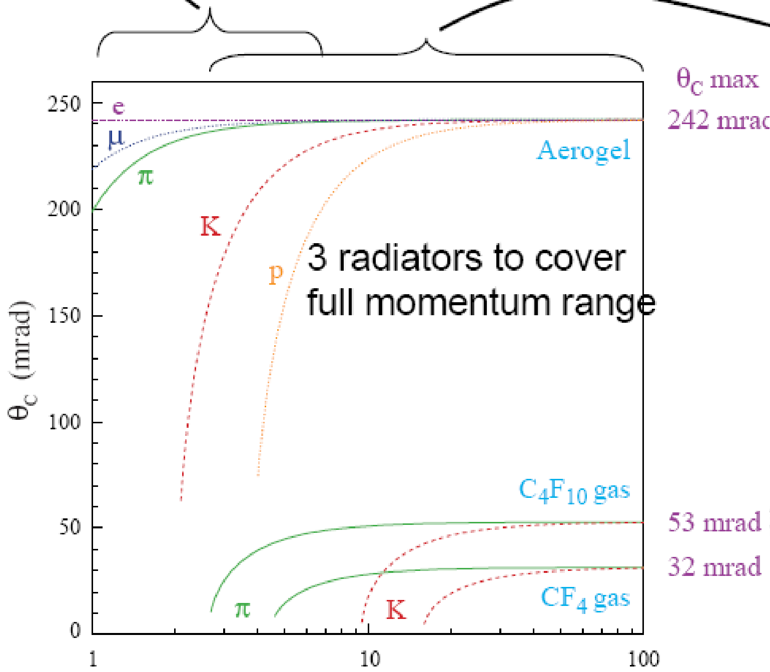
RICH 1



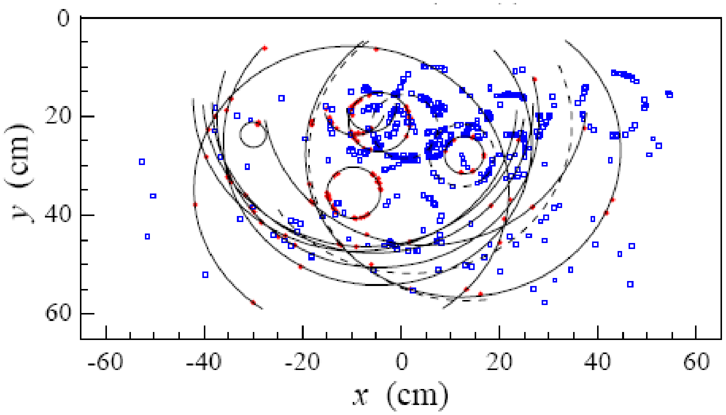
Radiator:

Aerogel **n=1.03**

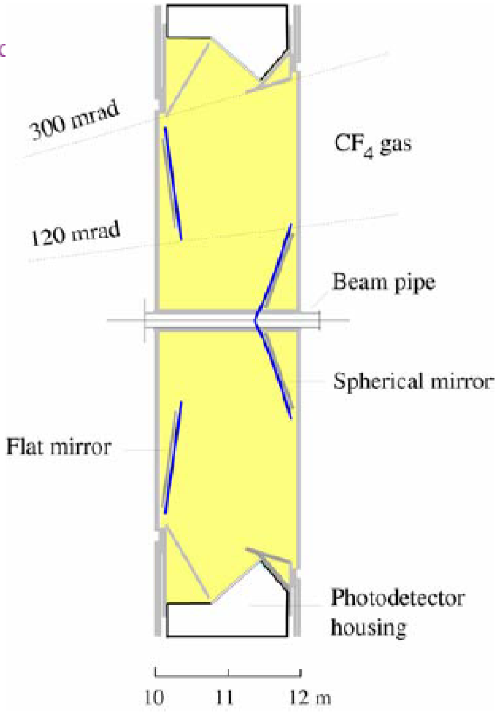
C_4F_{10} **n=1.0014**



3 radiators to cover full momentum range



RICH 2

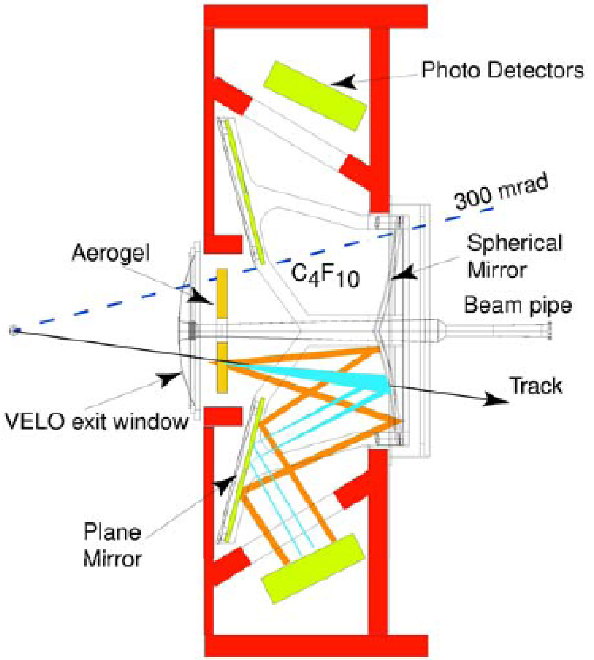


Radiator: CF_4

n=1.0005

RICH detectors

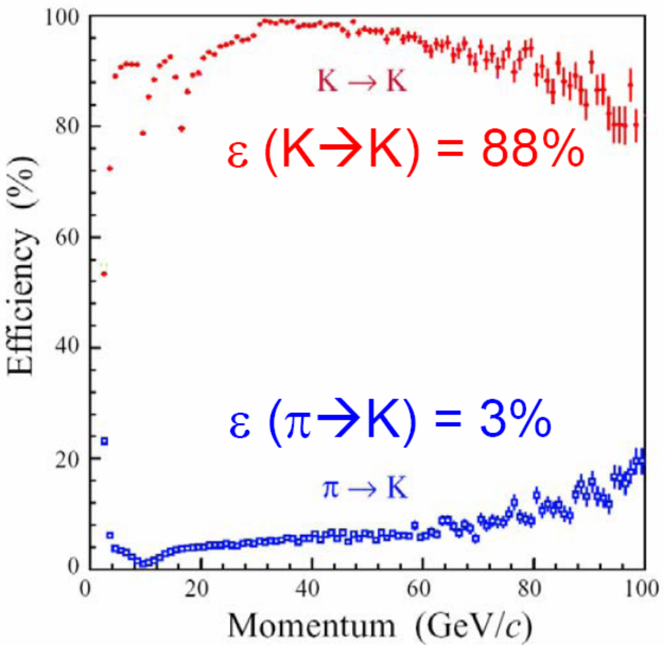
RICH 1



Radiator:

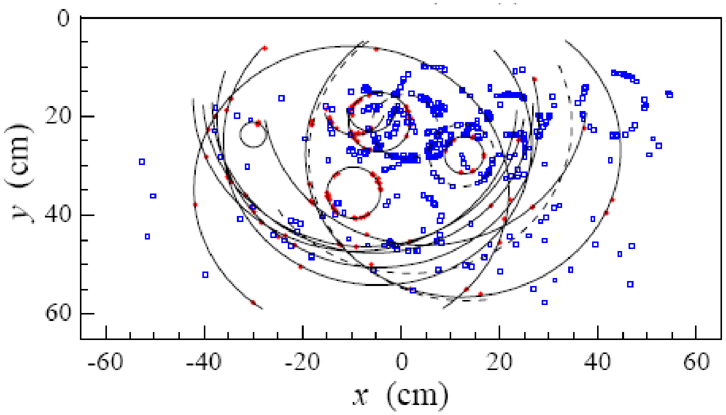
Aerogel n=1.03

C_4F_{10} n=1.0014

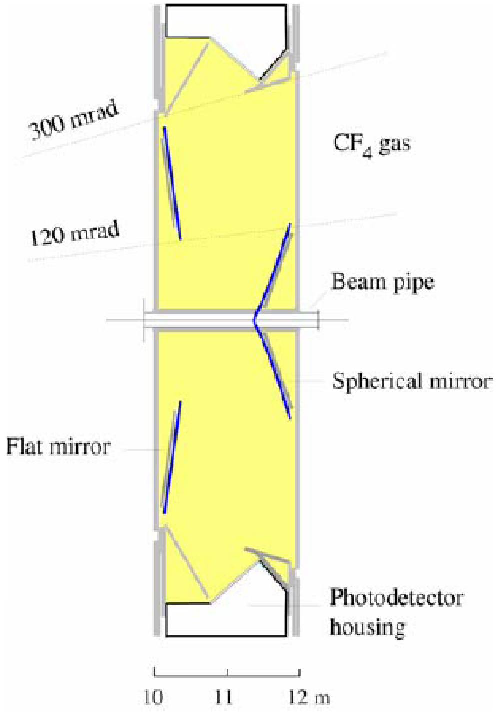


ε (K→K) = 88%

ε (π→K) = 3%



RICH 2



Radiator: CF_4

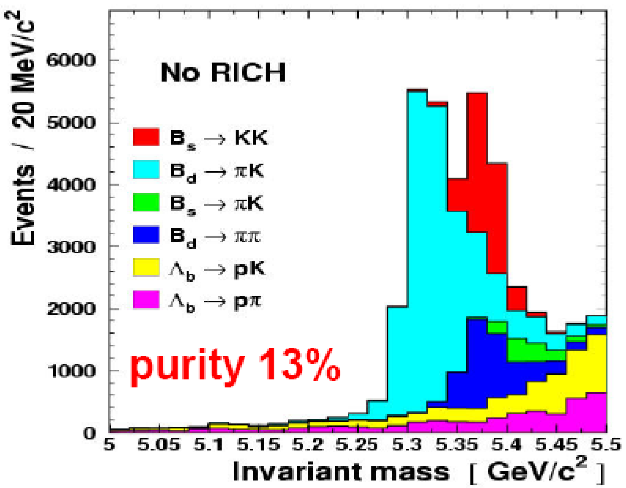
n=1.0005

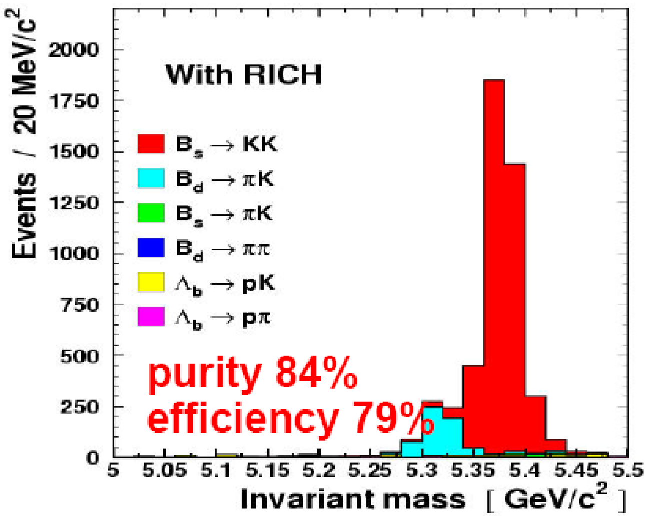
RICH performance

No RICH

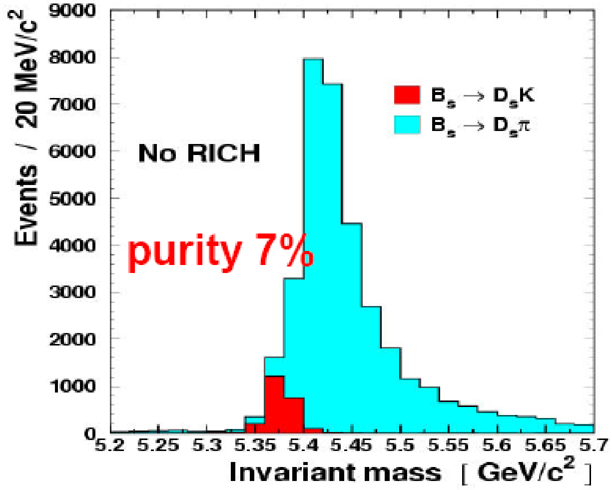
With RICH

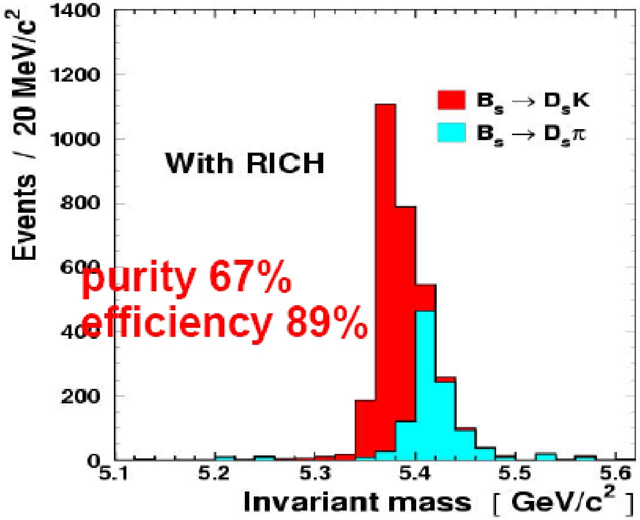
$B_s \rightarrow KK$



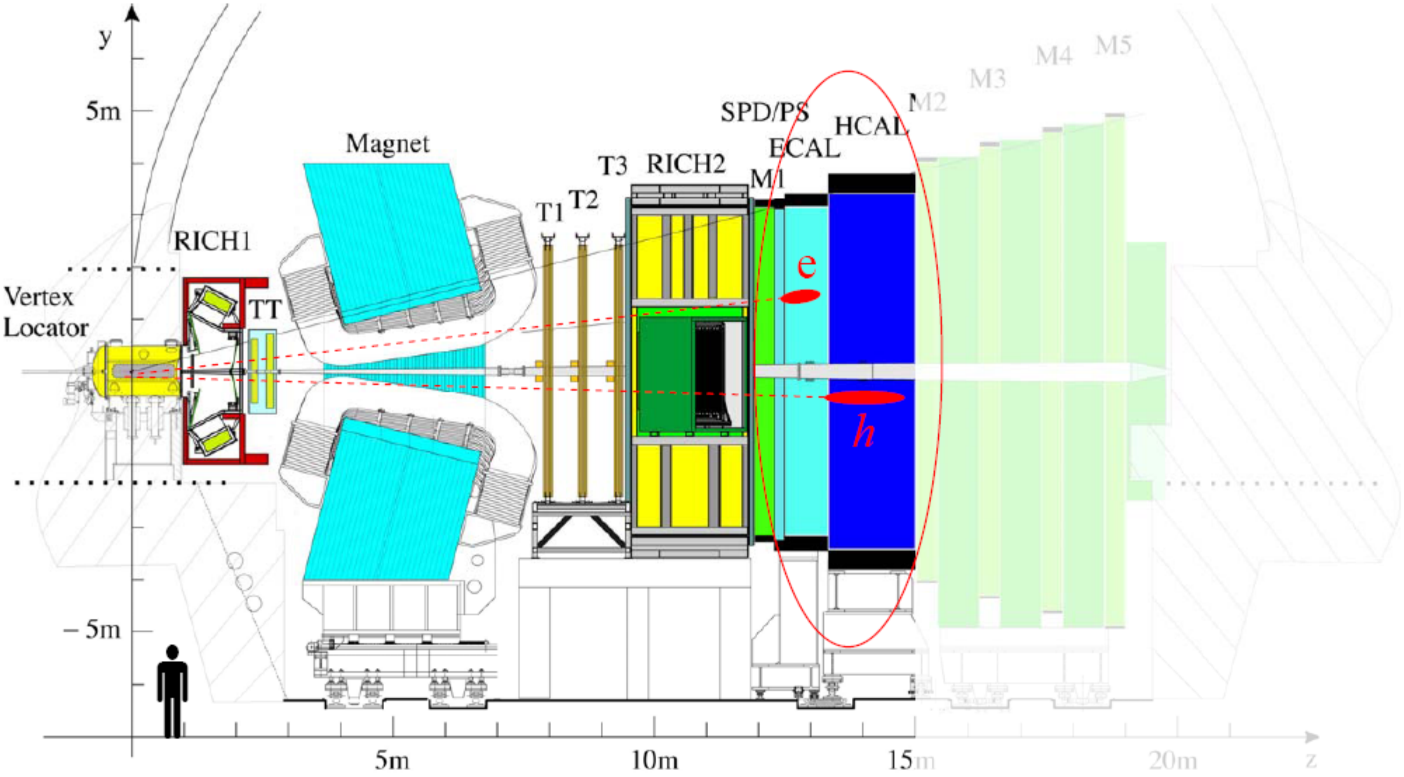


$B_s \rightarrow D_s K$



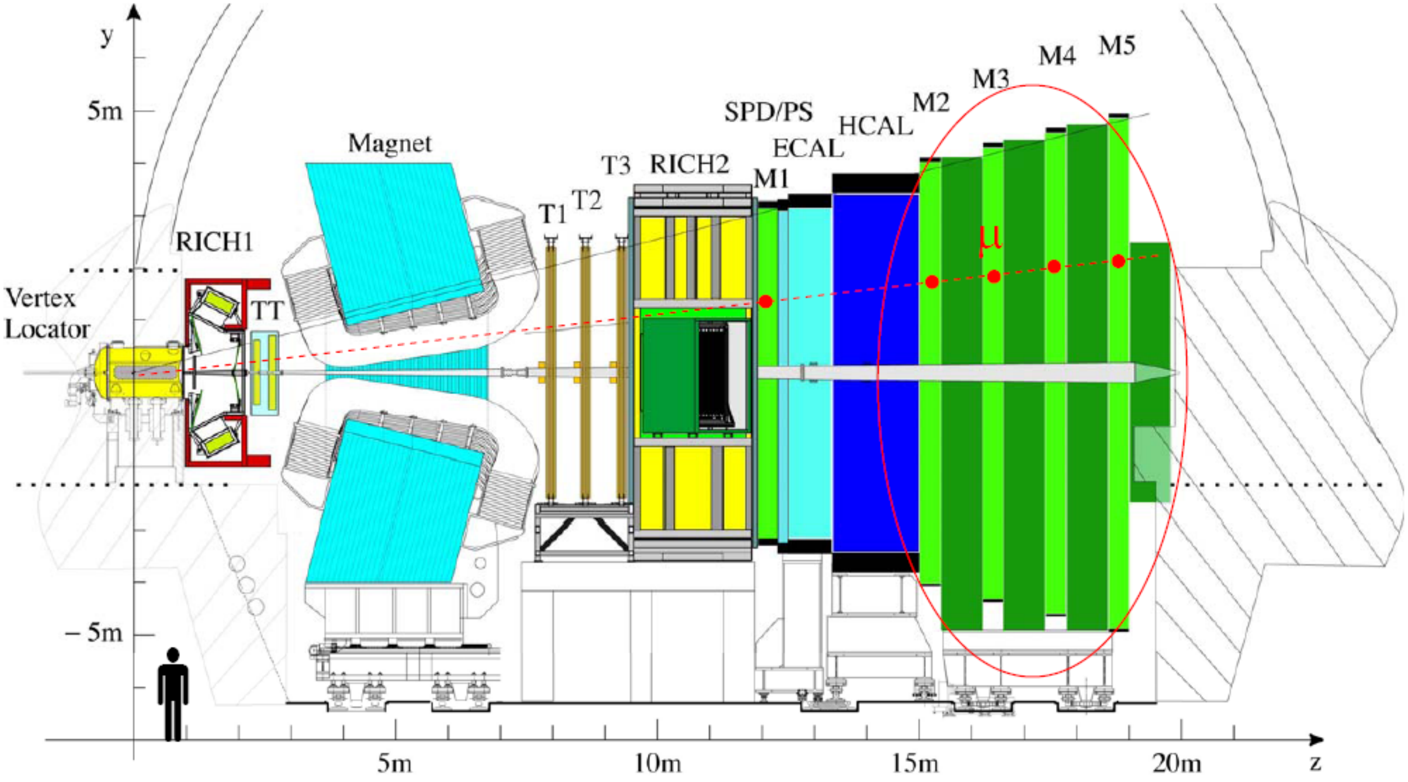


Calorimeters



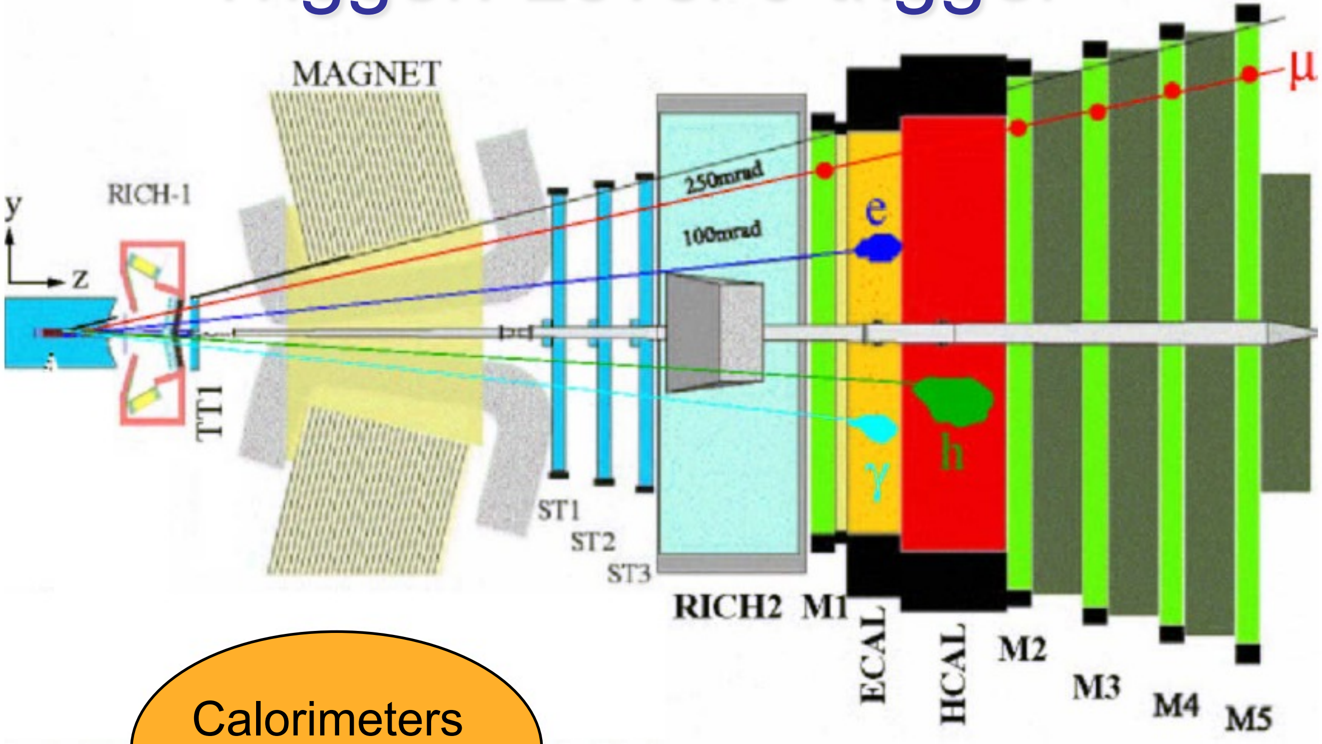
- Goal is to stop the particles and measure their energy (heavy detectors).
- Particles produce shower of secondary particles.
- Amount of scintillation light is measure for energy of incoming particle.
- Electrons and photons give electromagnetic shower in first part of calorimeters: ECAL
- Hadrons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

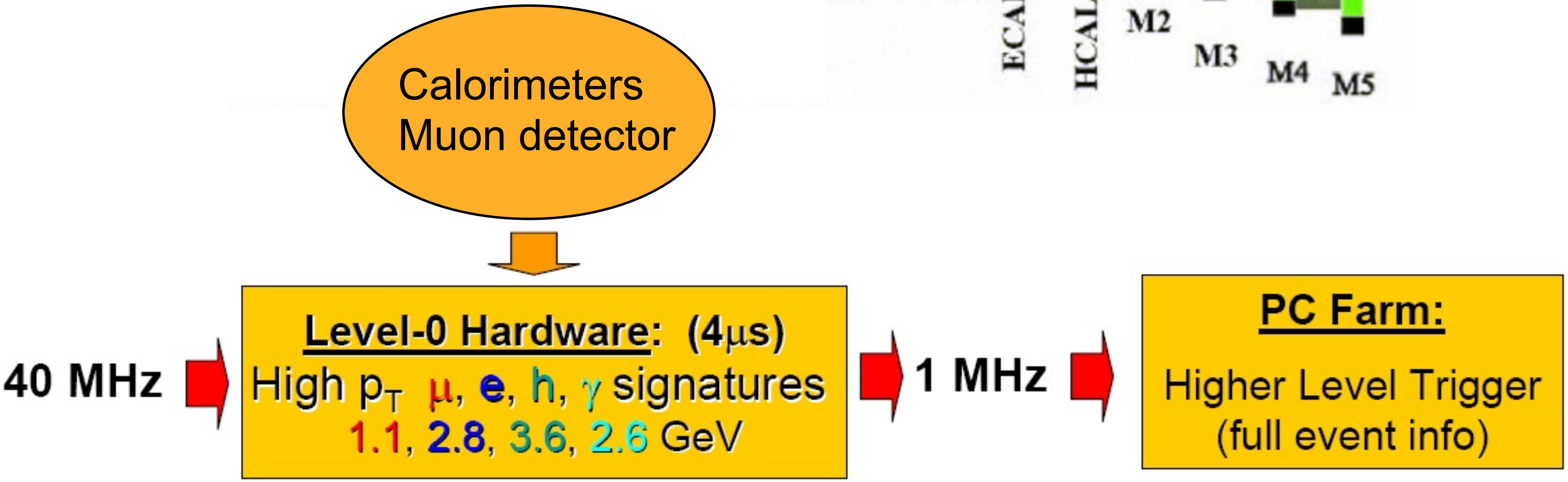
Muon detectors



- Muons are not so much affected by material in calorimeters.
  - No hadronic interaction, only electromagnetic.
- Muon detectors are interleaved with iron walls to remove any non-muon.
- Anything that traverses through the muon detector must be a muon.

Trigger: Level-0 trigger





Calorimeters
Muon detector

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)

All subdetectors store their data in hardware buffers for 4 μs.
Only when positive L0 decision data is sent to farm.

Trigger: High-level trigger

The PC farm

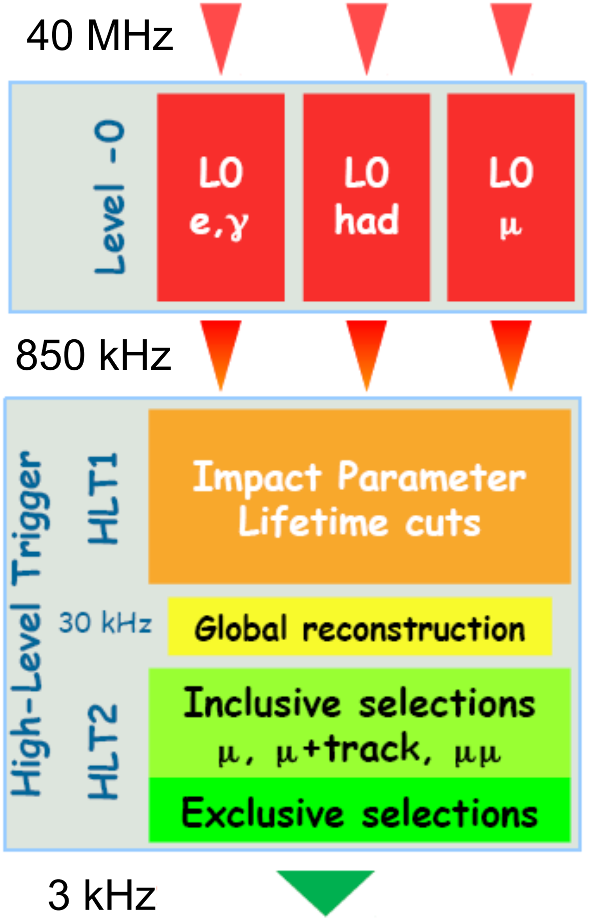
(15k of CPUs)

- Each CPU in the farm gets an event.
- A CPU has about 30 ms to reconstruct the event.
  - Offline reconstruction takes about 2 s per event

Two-stage software 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.



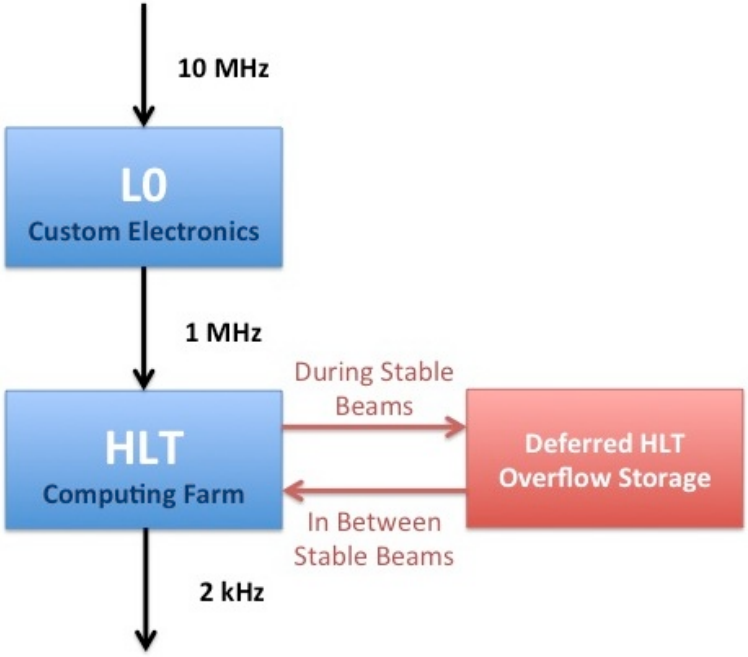
Average event size ~35 kB

Deferred trigger

- HLT runs only 20% of the time
  - Due to technical stops and gaps between LHC fills.

Idea: Use interfill gaps to process events collected during fill.

- Temporarily store about 20% of the L0 triggered events during a fill.
  - About 200 TB of storage available on CPU farm.
- Process them directly after the fill.
- One of the keys to LHCb's successes!


10 MHz

L0
Custom Electronics

1 MHz

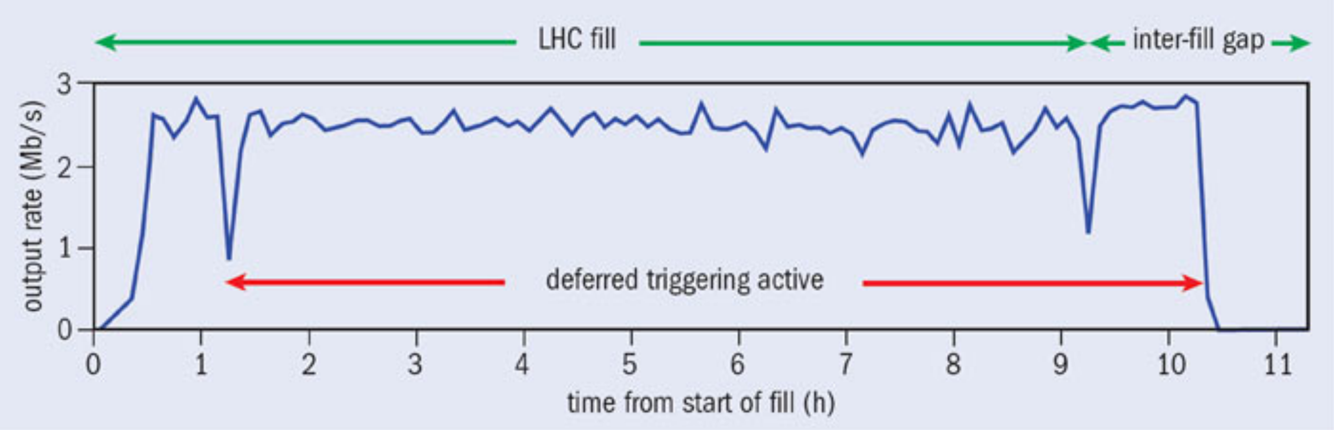
HLT
Computing Farm

During Stable Beams

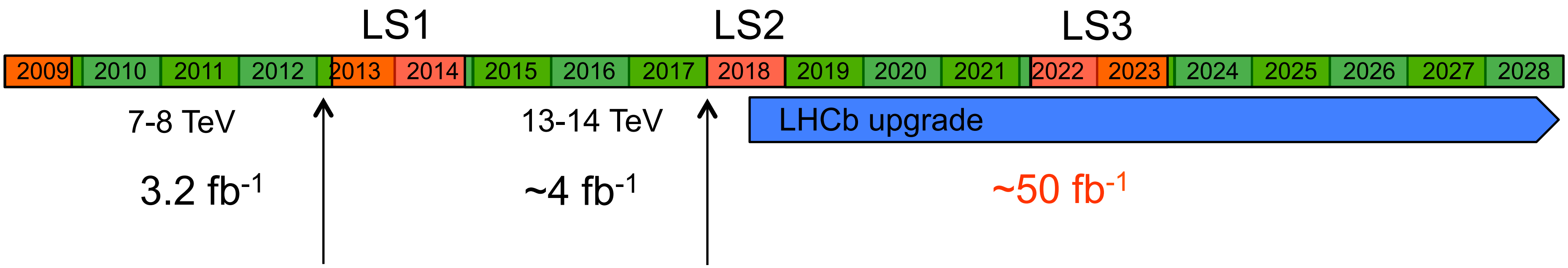
Deferred HLT Overflow Storage

In Between Stable Beams

2 kHz



LHCb timeline



LS1 LS2 LS3

2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028

7-8 TeV

13-14 TeV

LHCb upgrade

3.2 fb^{-1}

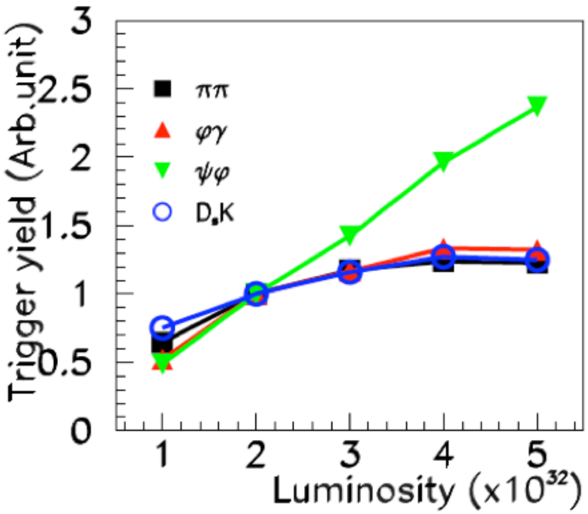
~4 fb^{-1}

~50 fb^{-1}

- LHCb has now collected 3.2 fb^{-1}.
  - Long shutdown 1 (LS1) will start soon.
- LHCb will collected another 4 fb^{-1} before LS2.
- What then? Collect another 4 fb^{-1} before LS3?
- No, LHCb will upgrade in 2018 to go to higher luminosities.
- Goal: collect 50 fb^{-1} in the following 10 years.

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} $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
- 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}

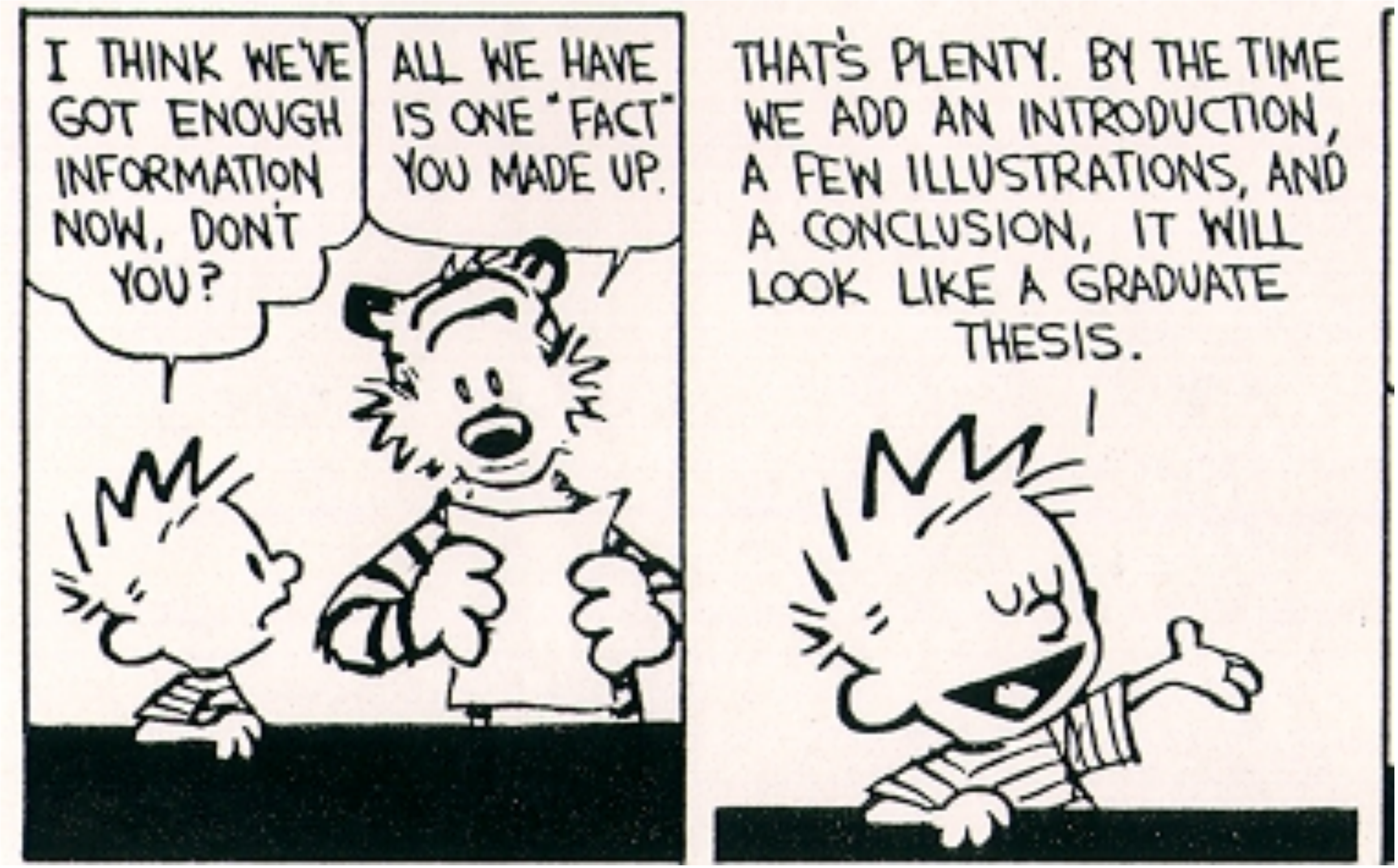


CERN/LHCC 2011-001
LHCb LoI
7 March 2011

LHCb
UPGRADE

Letter of Intent

Conclusion


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.