The LHCb upgrade

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On behalf of the LHCb Collaboration

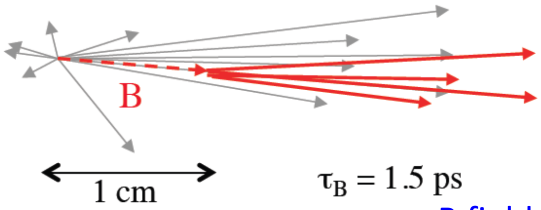
DIS2013, Marseille April 2013.

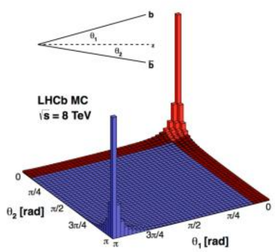
The LHCb detector

Experiment optimized for beauty physics:

– efficient trigger for hadronic and leptonic modes
– precision tracking and vertexing (mass, proper time)
– excellent particle identification

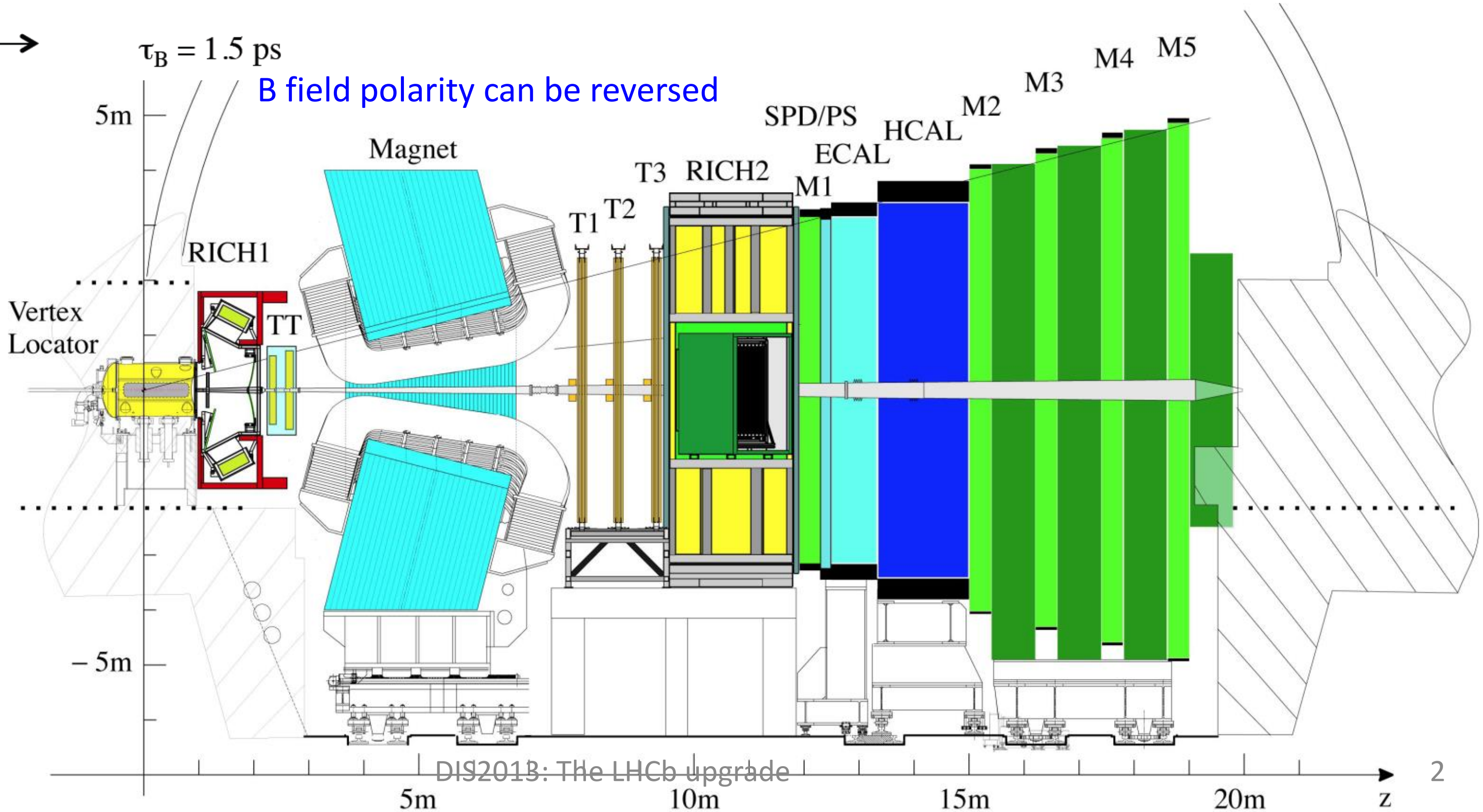
- Decay time resolution **Δ**t: 30-50 fs
- **Δ**p/p = 0.4-0.6%
- **Δ**m = 10-20 MeV/c^2
- Muon ID: **ε**(μ/μ) = 95%, mis-ID **ε**(**π/**μ) ~ 1%
- RICH ID **π**/K: **ε**(K/K) = 95%, mis-ID **ε**(**K/π**) ~ 5%
- CALO ID: : **ε**(e/e)=90%, mis-ID ~ 5%





τ_B = 1.5 ps

B field polarity can be reversed

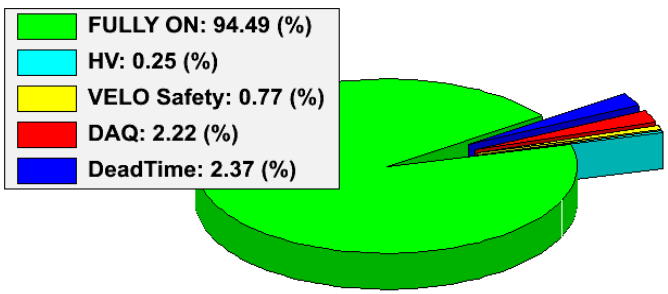


"The LHCb Detector at CERN"; The LHCb Collaboration, JINST 3, S08005 (2008)

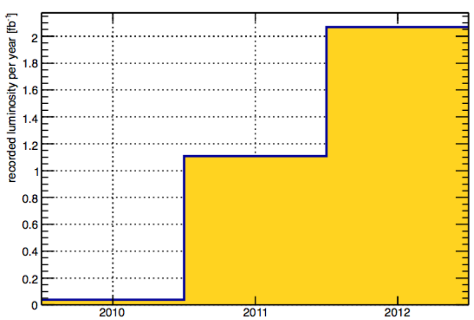
Data taking performance

- LHCb has been taking data quite efficiently: 3.2 fb^{-1} up to now.
- The plan is to record 10 fb^{-1} by 2018.

LHCb data taking efficiency 2012



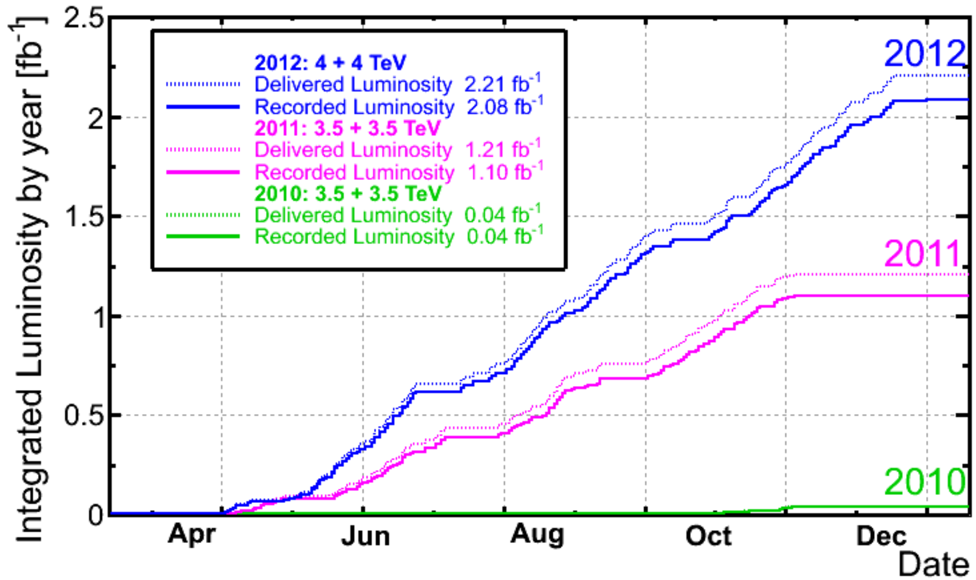
Integrated luminosity
per year of data taking



Delivered luminosity: 3.46 fb^{-1}

Recorded luminosity: 3.21 fb^{-1}

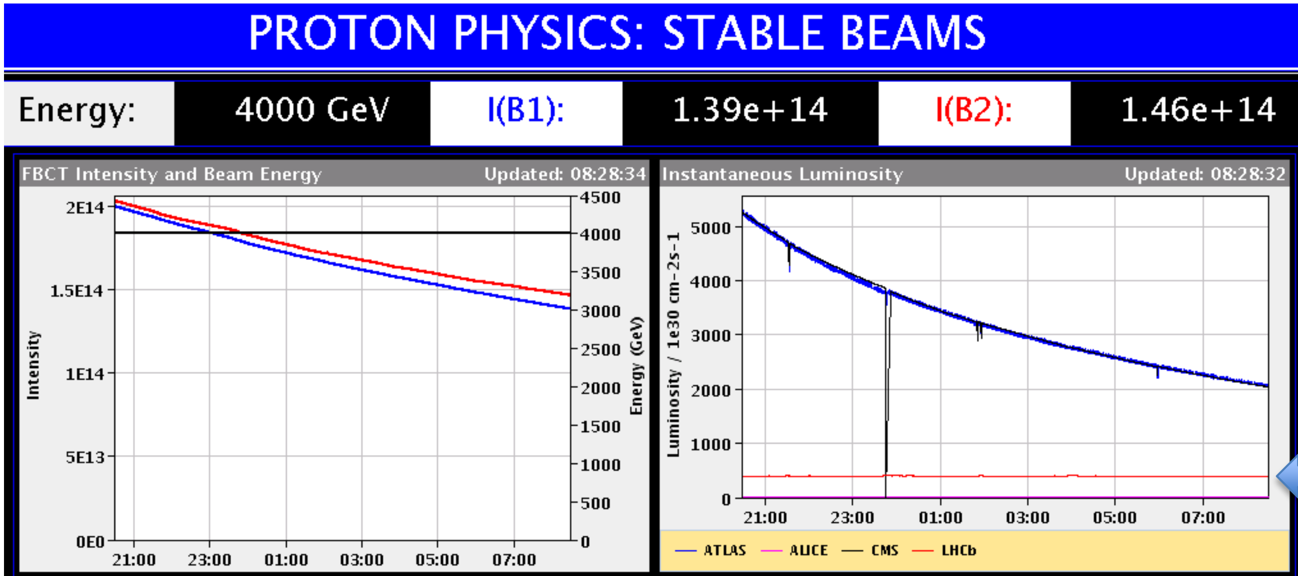
Global Efficiency: 93 %



Instantaneous Luminosity

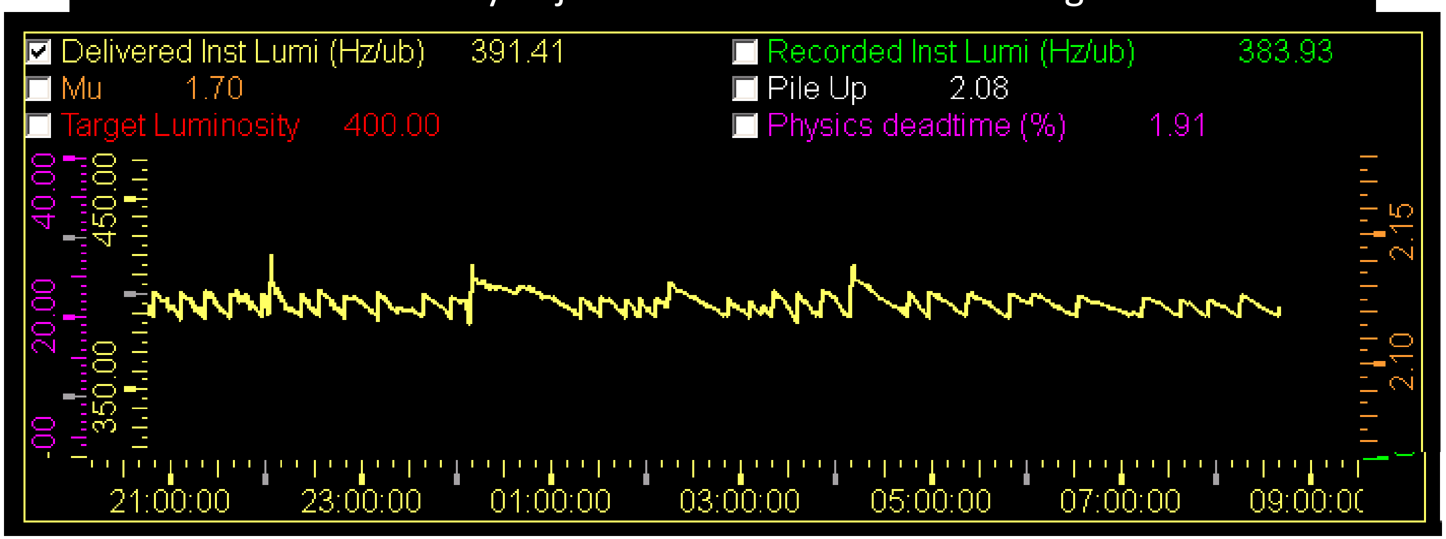
- LHCb was designed to operate with a single collision per bunch crossing, running at a instantaneous luminosity of **$2. \times 10^{32}$ cm^{-2} s^{-1}** (assuming about **2700** circulating bunches).
  - At the time of design there were worries about possible ambiguities in assigning the B decay vertex to the proper primary vertex among many.
- Soon LHCb realized that running at higher multiplicities would have been possible.
  - In 2012 we run at **$4. \times 10^{32}$ cm^{-2} s^{-1}** with only **1262** colliding bunches.
    - 50 ns separation between bunches while the nominal 25 ns (will available by 2015).
  - 4 times more collisions per crossing than planned in the design.
    - The average number of visible collisions per crossing in 2012 raised up to $\mu > 2.5$
- The luminosity is kept constant at the LHCb interaction point by "luminosity levelling": **beam separation is adjusted** few times per hour to maintain the luminosity constant.
  - It is a routine operation since 2011.

Instantaneous Luminosity (II)



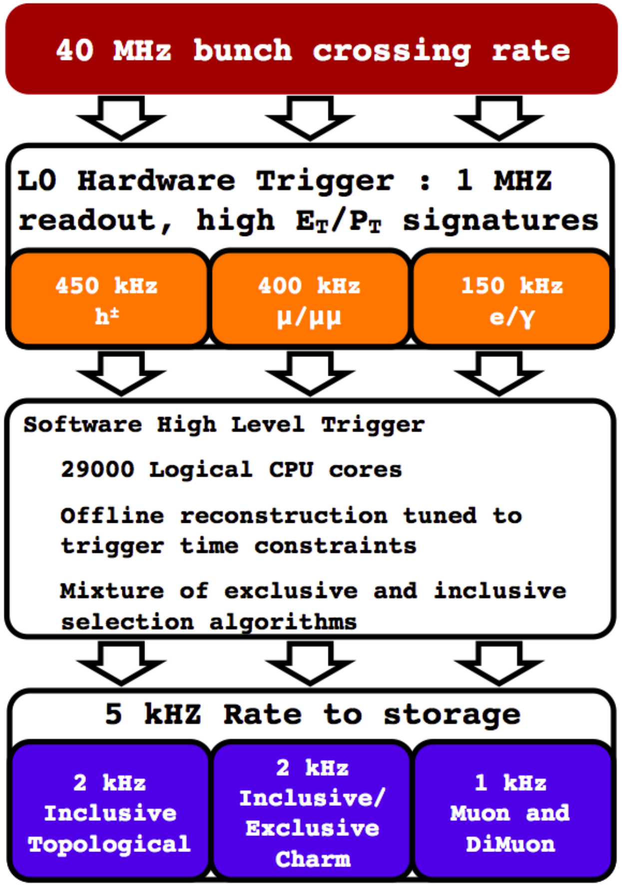
LHCb luminosity

LHCb luminosity adjustment: ±3% around the target value

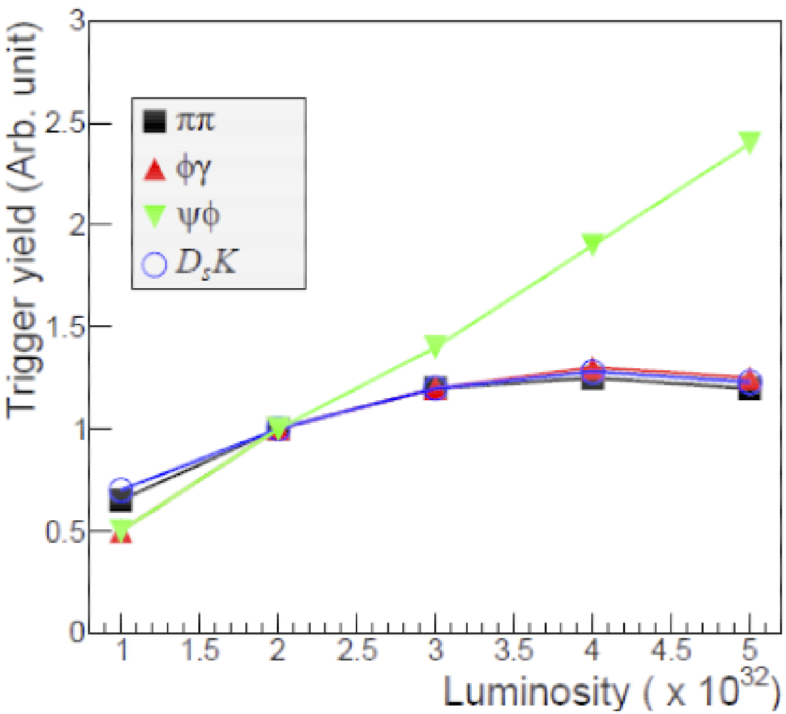


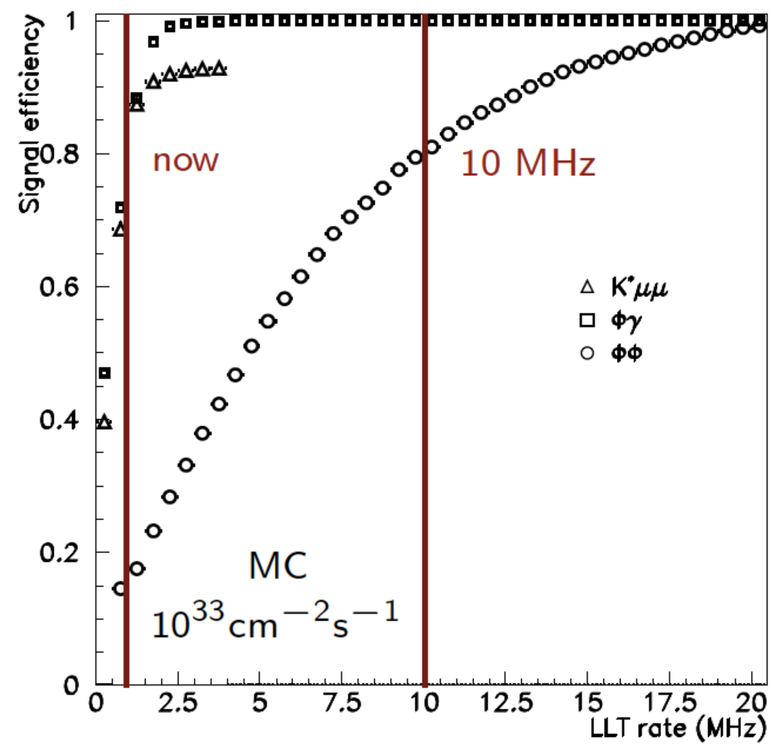
LHCb Trigger

- The **Level-0 trigger** based on the signals from ECAL, HCAL and MUON detectors read at 40 MHz, operates on custom electronics, with a **maximum output rate limited to 1.1 MHz**.
  - Fully pipelined, constant latency of about 4 µs.
  - Bandwidth to the HLT ~ 4 Tb/s, GOL serdes, optical links.
  - High p_T muon (1.4 GeV) or di-muon.
  - High p_T local cluster in HCAL (3.5 GeV) or ECAL (2.5 GeV)
- **HLT1** is a software trigger
  - Reconstruct VELO tracks and primary vertices
  - Select events with at least one track matching **p**, $\mathbf{p_T}$, **impact parameter** and **track quality cuts**.
  - Accept around **50 kHz**.
- **HLT2** performs inclusive or exclusive selections of the events.
  - Full track reconstruction, without particle-id.
  - 25% of the events are **deferred**: temporarily stored on disk and processed during the inter-fills.
  - Total accept rate to disk for offline analysis is around **5 kHz**.



The 1MHz L0 rate limitation





"Framework TDR for the LHCb Upgrade: Technical Design Report"; The LHCb Collaboration,CERN/LHCC-2012-007, LHCb-TDR-12 - 2012

- Due to the available bandwidth and discrimination power of the hadronic L0 trigger LHCb experiences the **saturation of the trigger yield on the hadronic channels**.
- Increasing the first level trigger rate would considerably increase the efficiency on the hadronic channels.

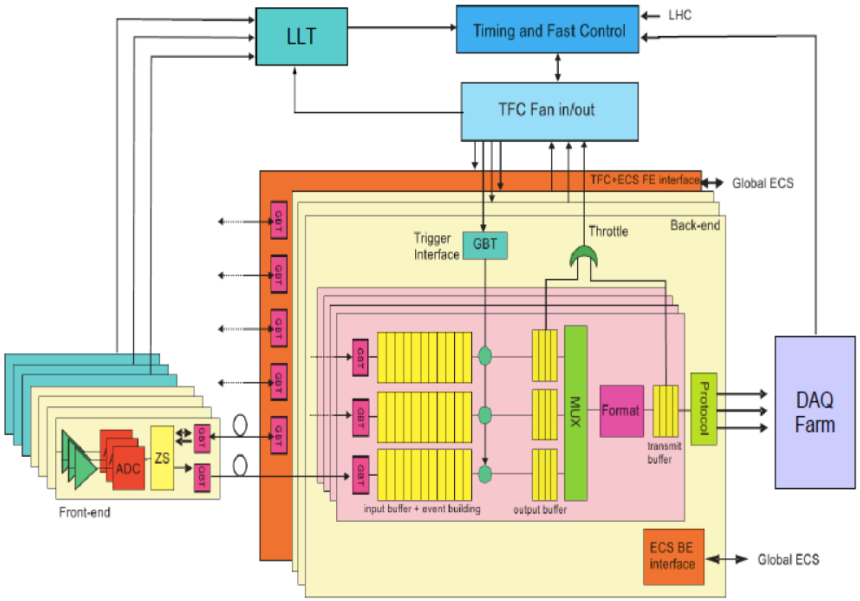
The LHCb upgrade

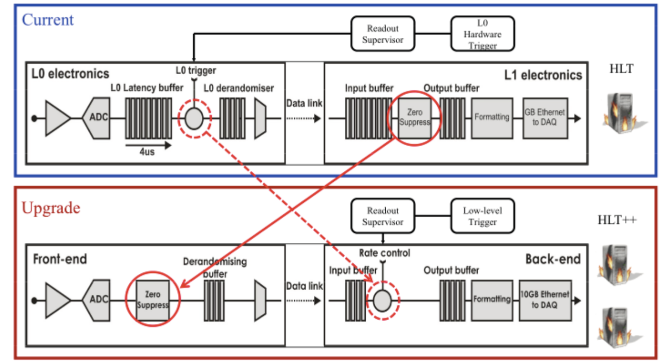
- Readout the whole detector at 40 MHz.
- Use a Low Level Trigger (hardware first level trigger) as a throttle mechanism, while progressively increasing the power of the event filter farm to run the HLT up to 40 MHz.
- Run the experiment at a luminosity of at least **$10. \times 10^{32}$ cm^{-2} s^{-1}** , i.e. 2.5 times the 2012 running value. We have foreseen to reach **$20. \times 10^{32}$ cm^{-2} s^{-1}** and therefore to prepare the sub-detectors on this purpose.
  - At **$10. \times 10^{32}$ cm^{-2} s^{-1}** pile up $\mu \cong 2$ (25 ns time spacing).
  - Increase the yield in the decays with muons by a factor five and the yield of the hadronic channels by a factor ten.
- The upgrade shall take place during the Long Shutdown 2 (LS2) in 2018.
- Collect 50 fb^{-1} of data over ten years.

LHCb upgrade: consequences

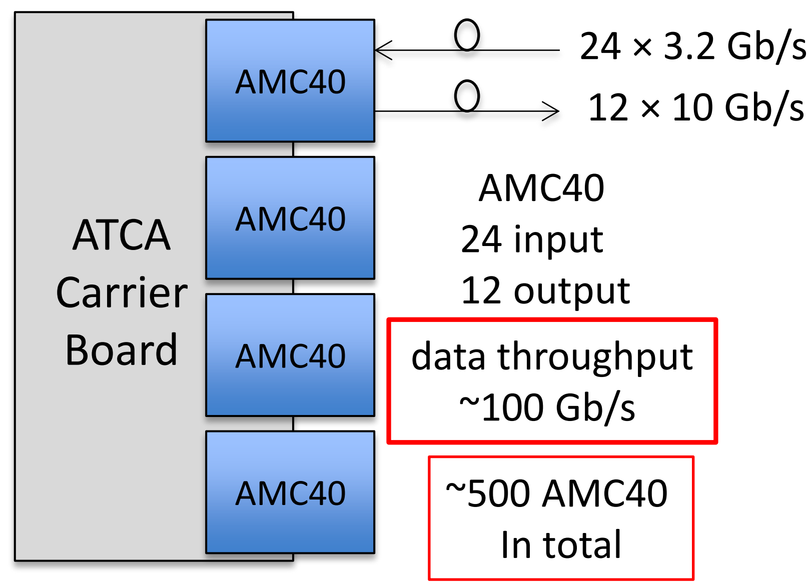
- The detector front-end electronics has to be entirely rebuilt because of the output rate requirements.
  - No more buffering in the front-end electronics boards.
  - A lot more optical links to get the required bandwidth needed to transfer data from the front-end to the read-out boars at 40 MHz.
- New HLT farm and network to be built by exploiting new LAN technologies and powerful many-core processors.
- Rebuild the current sub-detectors equipped with embedded front-end chips.
  - Silicon strip detectors: VELO, TT, IT
  - RICH photo-detectors: front-end chip inside the HPD.
- Consolidate sub-detectors to let them stand the higher foreseen luminosity of $20. \times 10^{32}$ cm^{-2} s^{-1}

Electronics



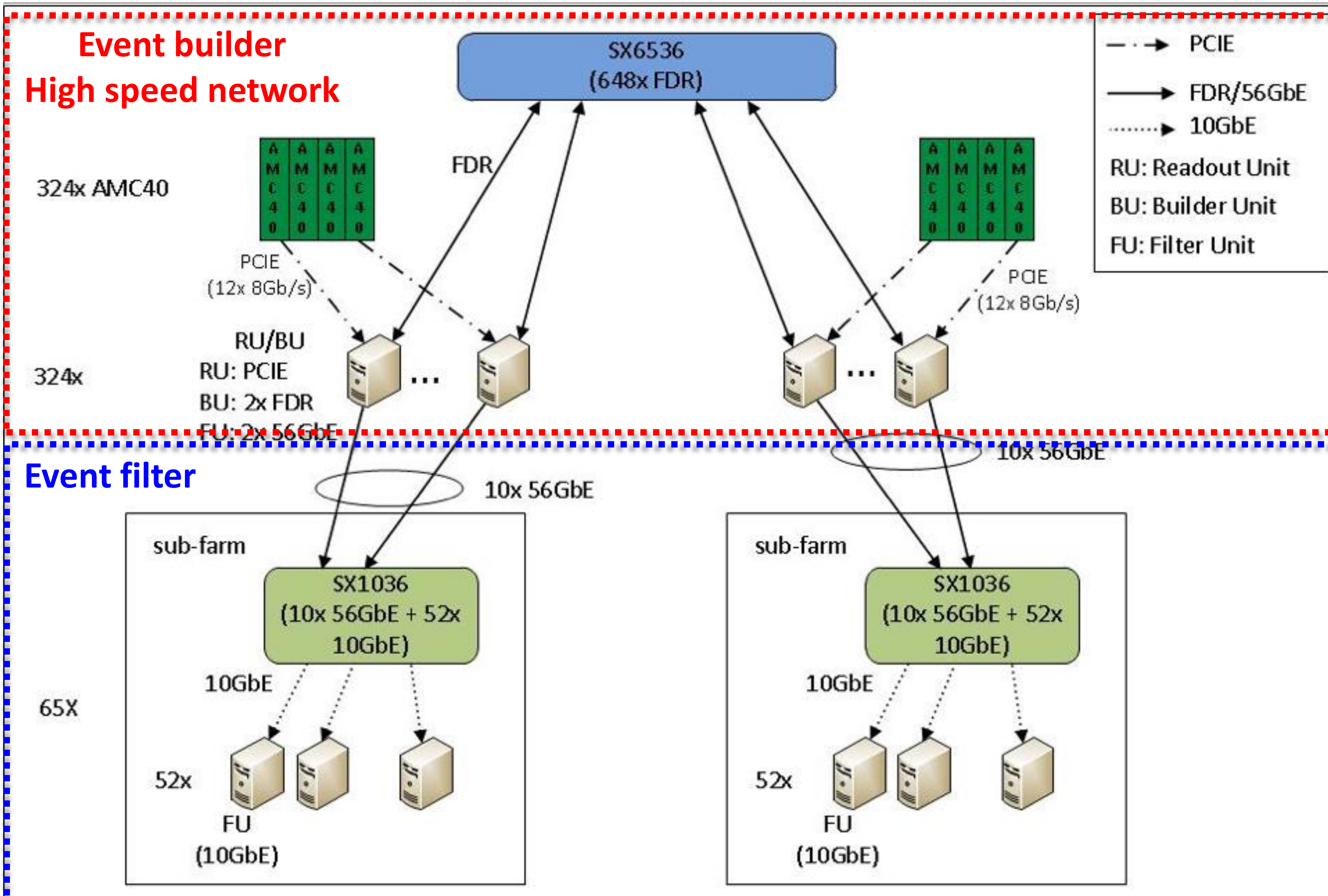


The LHCb readout board



- Data transfer from the frontend boards to the read-out boards at 40 MHz: ~ 40 Tb/s,12000 optical links, using 3.2 Gb/s GBT serializers.
  - Zero suppression performed at the frontend board
- Readout boards for buffering and data format conversion, from custom to industrial standard (LAN protocol).

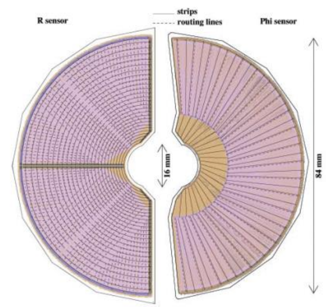
HLT farm and network

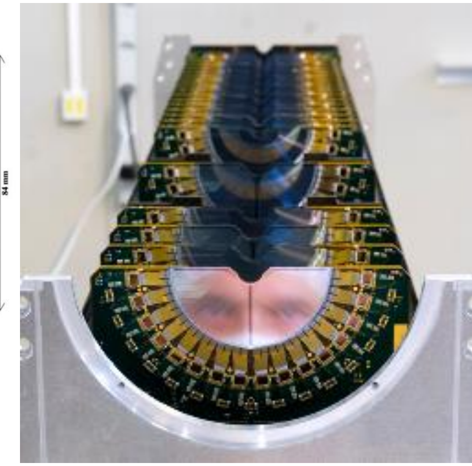


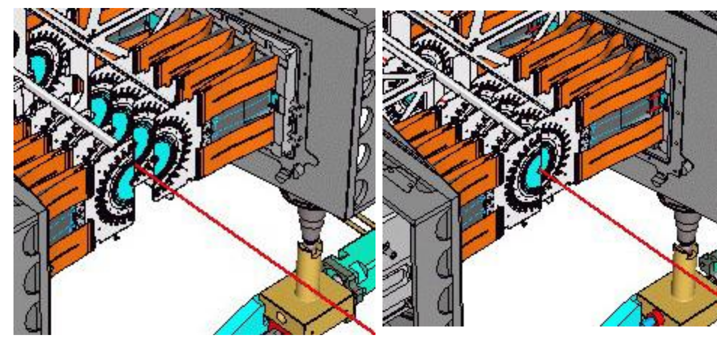
http://lbonupgrade.cern.ch/wiki/index.php/Network-arch

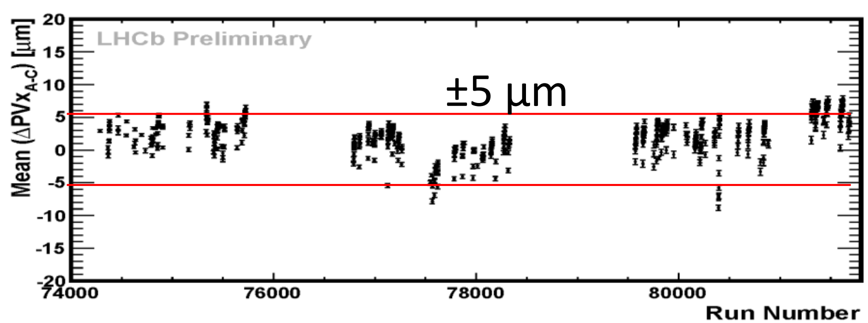
The current VELO

- 21 stations of silicon micro-strip sensors, located nearby the interaction region.
  - R and φ geometry modules
  - 44 mm external radius
- Left and right halves of the **modules can be moved** inward/outward the beam lines: modules open and close at each fill. **Distance from the beam line 5.5 mm**
  - Position centred around the current beam position. Modules do not move during a fill.
  - Positions reproducible within 5 μm: measured as the average distance between right-side PV and left-side PV.
- Primary (beam) and secondary vacuum are separated by a thin Al box (“RF foil”).

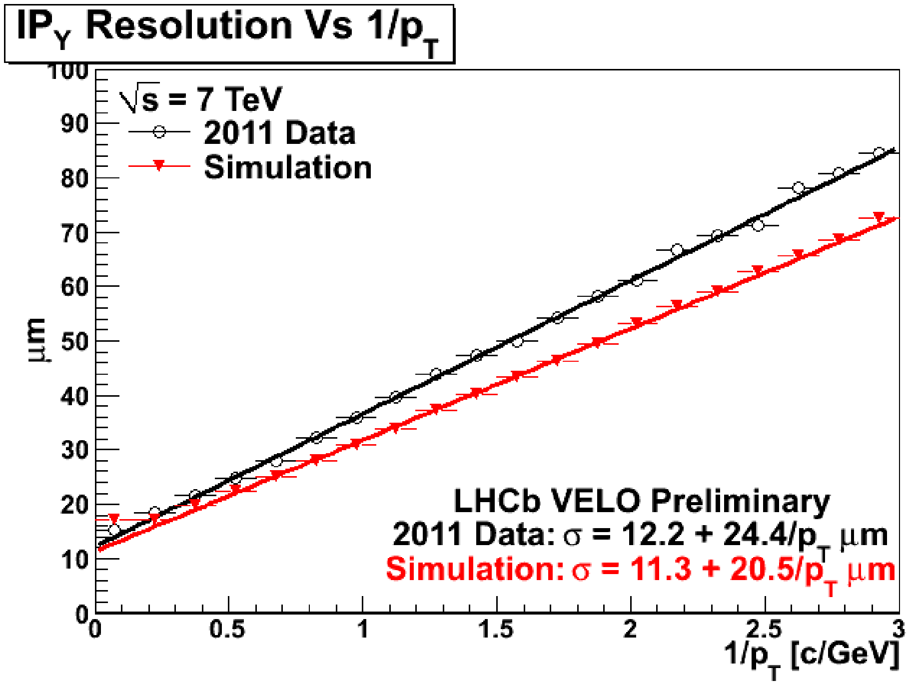








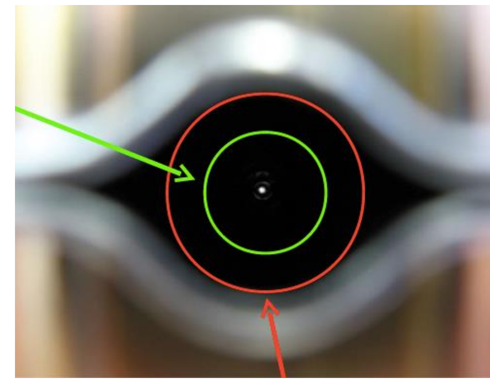
The current VELO (II)



- Impact parameter resolution, essential for heavy flavour physics, is quite good: ~ 20 μm at high p_T (≤ 10 GeV/c in the LHCb acceptance).
- Primary vertex resolution excellent as well:
  ~ 15 μm in the x,y transverse plane.
  ~ 75 μm along the longitudinal z axis (typically with 20 tracks).

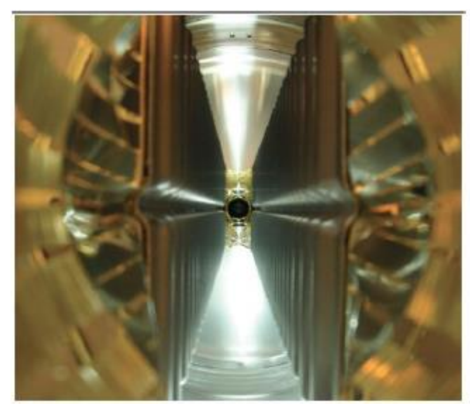
The VELO upgrade

- The VELO upgrade has to maintain or improve the performance of the current detector.



$$\sigma_{IP}^{2} = r_1^2 \left(\frac{13.6\ MeV}{c p_T} \right)^2 \frac{x}{X_0}$$

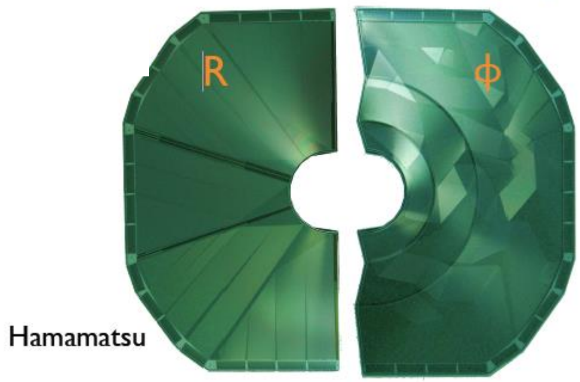
- **Inner radius r$_1$** of RF foil will be **reduced** from 5.5 mm to 3.5 mm.
- The **RF foil** currently contributes with **80%** of the material budget before **r$_1$** and **r$_2$** points: good results in **thinning the thickness** achieved with 1.5 mm instead of the present 4 mm.



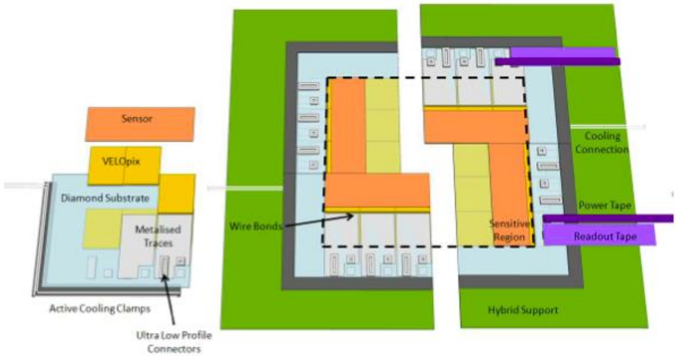
The VELO upgrade (II)

- Electronics will have to withstand 50 fb^{-1} , equivalent to radiation up to 0.3×10^{16} $n_{eq}cm^{-2}$.
- Thickness of the modules has to be reduced to 200 μm to limit the number of produced secondary particles.
- Two options still considered:
- **Microstrip sensors**:
  - Similar to the existing VELO R and φ layout.
  - Finer pitch and segmentation to reduce occupancy, reduced thickness and inner radius.
  - SALT readout ASIC, the same for the IT project.
- **Pixel sensors**:
  - High granularity eases pattern recognition.
  - R&D is focusing on planar silicon sensors 55 μm ×55 μm (256×256).
  - ASIC derived from Timepix/Medipix family.
- Projects review for decision scheduled next May.

Strip sensor prototype



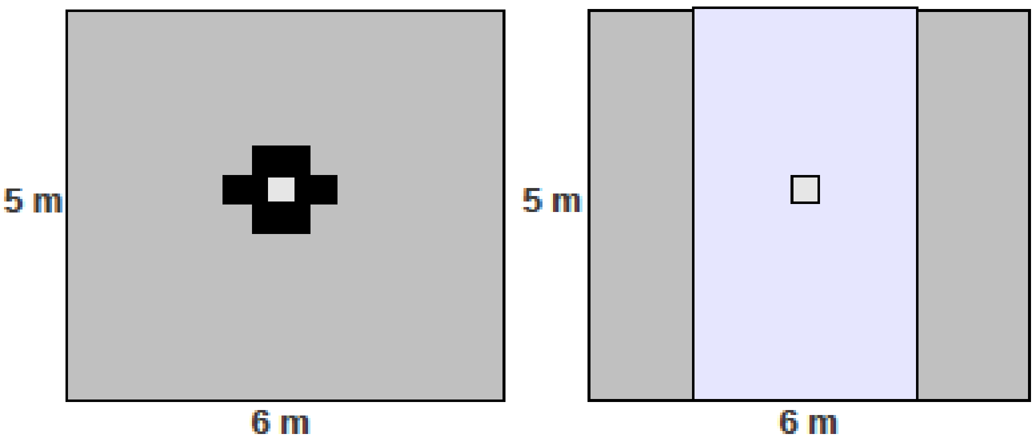
Pixel module layout



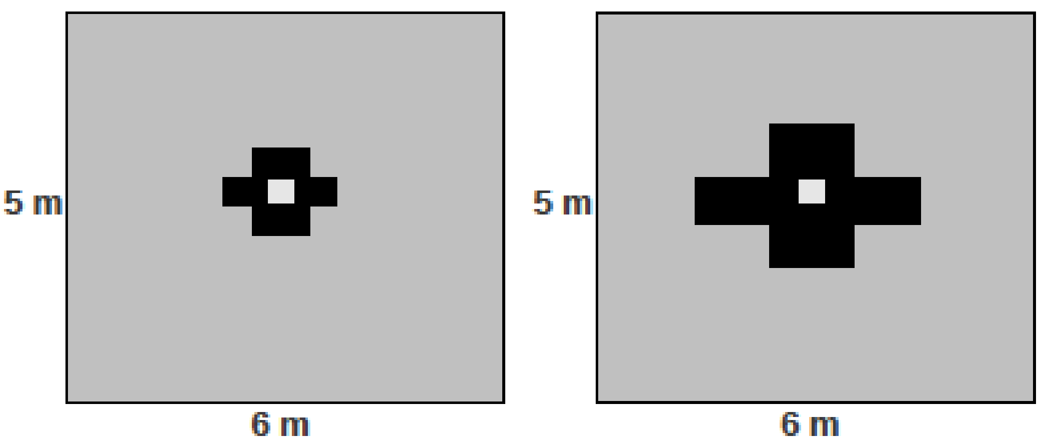
Tracking system upgrade

Replacing the inner tracker of the downstream tracking stations

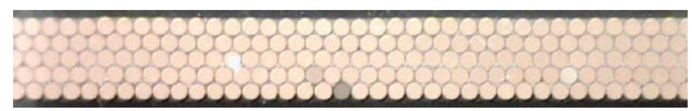
Scintillating Fibers detector



Silicon strip detector



Replacing the straw tubes of the central regions by Scintillating Fibers with Silicon Photo-Multiplier (SiPM) for light collection.
Five layers of 2.5 m long scintillating fibres of 250 μm diameter.
Expected performance: 60 – 100 μm spatial resolution.

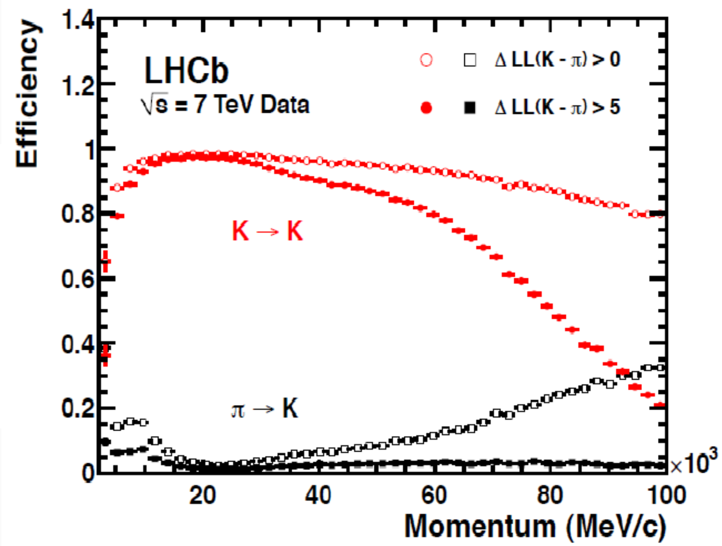


New silicon strip detector with larger coverage, reducing geometry of OT in central region: with shorter straw tubes in central region.

RICH

- Particle identification in the range 2 to ~100 GeV
  - Two RICH, three radiators
  - Readout by HPD
    - ~500, 1024 channels
    - High efficiency
    - Very low noise

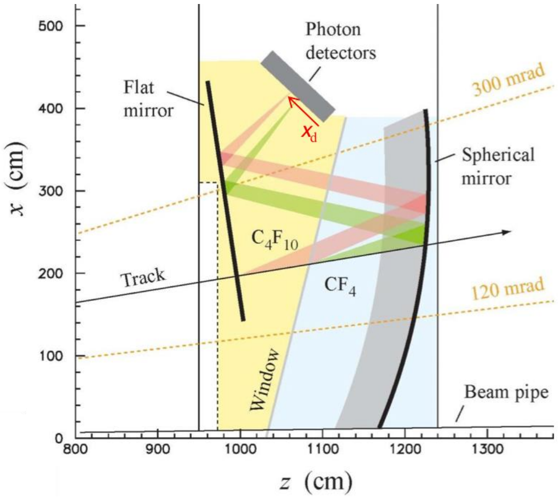
- Particle ID performance
  - ~95% efficiency for 5% contamination
    - Averaged over B daughter tracks
  - Well described by simulation



RICH upgrade

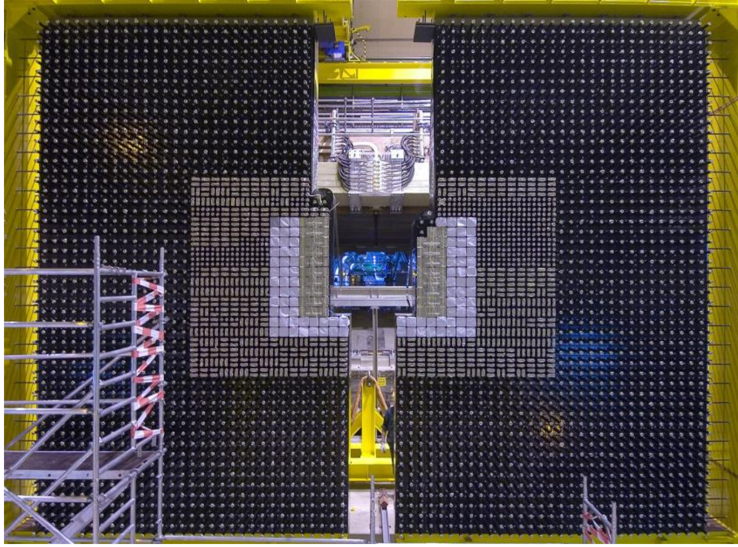
- HPD to be removed due to embedded front-end electronics.
- R&D focused on MaPMT: possible candidate is the Hamamatsu R11265.
- Custom readout ASIC being developed.
- Aerogel will be removed, but occupancy still seems an issue.
- RICH1 upgrade optics with increased mirror radius to spread out the rings.
- Twin-Ring-Identication system (TRIDENT)

TRIDENT

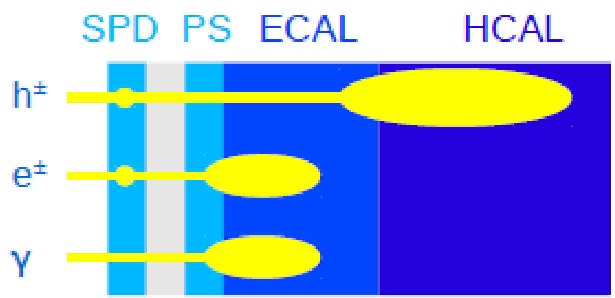


merge both RICHs including complex lens system

Calorimeters

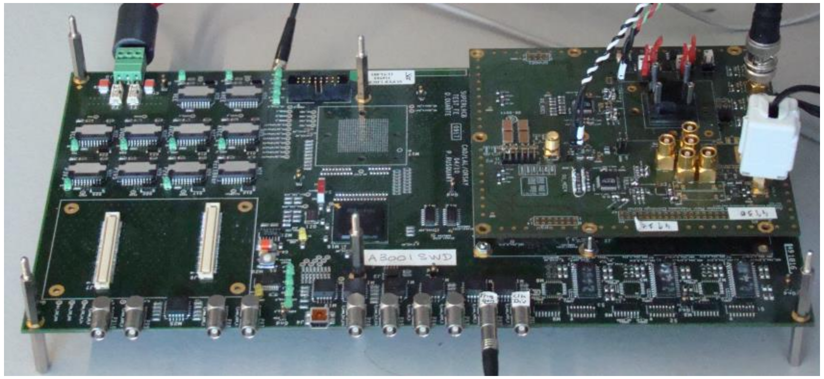


- ECAL made of shashlik blocks
  - Lead - scintillator stack
  - ~6000 channels, readout by PMT
  - $\Delta E/E \sim 10\% / \sqrt{E} + 1\%$
- HCAL: scintillating tiles in iron
  - ~1500 channels, same readout and electronics as ECAL
  - $\Delta E/E \sim 70\% / \sqrt{E} + 9\%$
  - Mainly used for trigger
- PreShower and SPD
  - same geometry as ECAL
  - Scintillator tiles readout by MAPMT
  - Identify electron/photon, used in L0 trigger



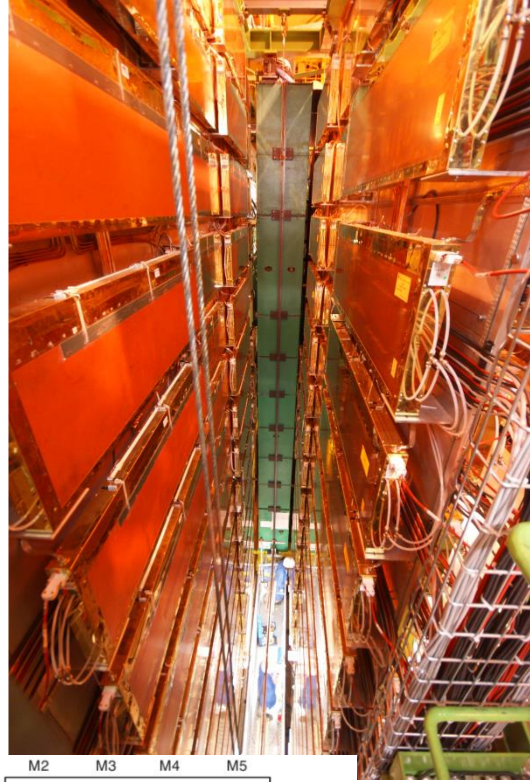
UPGRADE

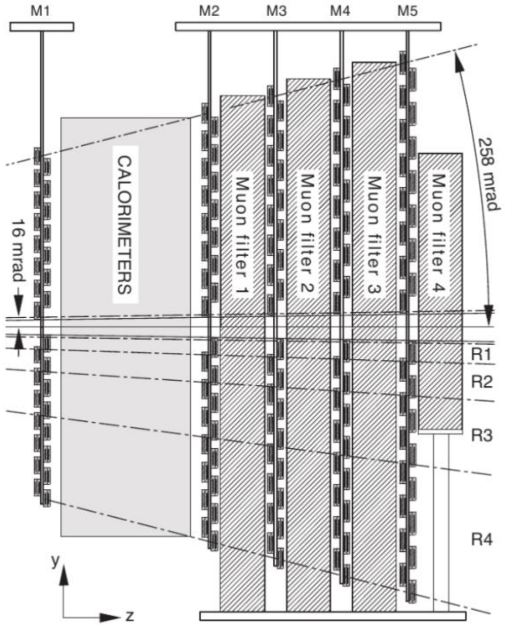
- Removal of SPD and PS due to the high occupancy
- New front-end electronics.
- Some ECAL modules in the inner region might have to be replaced



Muon system

- 5 stations (segmented in four regions) of detectors interleaved with iron walls.
  - 1368 MWPC and 24 GEMs: 435 **m**^{2}
  - First station M1 located before the calorimeters.
  - Projective geometry
    - Allows it to be used in the L0 trigger
  - Muon identification performance
    - ~97% efficiency for 3% miss-ID.





UPGRADE

- M1 will not be needed since of the high occupancy at the higher luminosities.
- Due to the higher rates MWPC may not be adequate anymore in the internal regions close the beam pipe: replaceMWPC internal chambers with triple-GEM.

Performance benchmarks

FTDR CERN/LHCC-2012-007

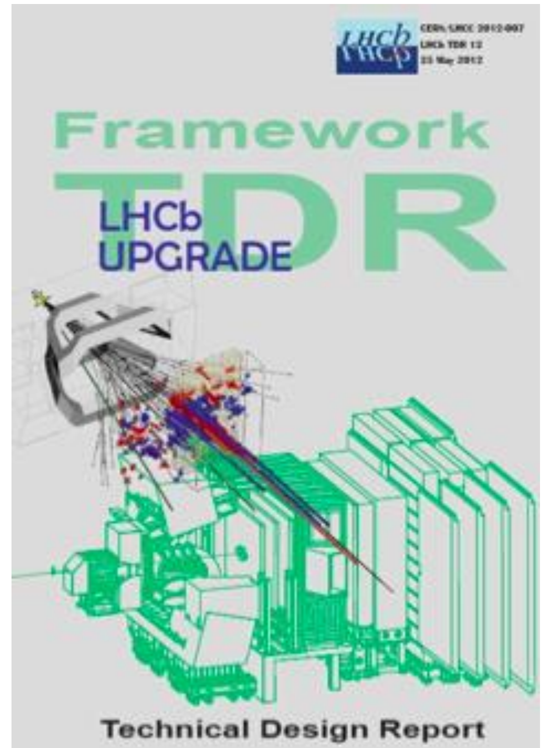
Type	Observable	May 2012	LHCb 2018	Upgrade ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
$\mathrm{B_s}$-mixing	$2\beta_s(\mathrm{B_s^0} \to \mathrm{J}/\Psi\phi)$	0.10	0.025	0.008	∼0.003
	$2\beta_s(\mathrm{B_s^0} \to \mathrm{J}/\Psi\mathrm{f_0}(980))$	0.17	0.045	0.014	∼0.01
	$\mathrm{A_{fs}}(\mathrm{B_s^0})$	$6.4 * 10^{-3}$	$0.6 * 10^{-3}$	$0.2 * 10^{-3}$	$0.03 * 10^{-3}$
Gluonic penguin	$2\beta_s^{\mathrm{eff}}(\mathrm{B_s^0} \to \phi\phi)$	-	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(\mathrm{B_s^0} \to \mathrm{K^{*0}}\overline{\mathrm{K^{*0}}})$	-	0.13	0.02	<0.02
	$2\beta_s^{\mathrm{eff}}(\mathrm{B_s^0} \to \phi\mathrm{K_s^0})$	0.17	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(\mathrm{B_s^0} \to \phi\gamma)$		0.09	0.02	<0.01
	$\gamma^{\mathrm{eff}}(\mathrm{B_s^0} \to \phi\gamma)/\tau_{\mathrm{B^0S}}$	-	5 %	1 %	0.2 %
Electroweak penguin	$\mathrm{S_3}(\mathrm{B^0} \to \mathrm{K^{*0}}\mu^+\mu^-; 1 < \mathrm{q}^2 < 6\,\mathrm{GeV}^2/\mathrm{c}^4)$	0.08	0.025	0.008	0.02
	$\mathrm{S_0A_{FB}}(\mathrm{B^0} \to \mathrm{K^{*0}}\mu^+\mu^-)$	25 %	6 %	2 %	7 %
	$\mathrm{A_I}(\mathrm{K}\mu^+\mu^-; 1 < \mathrm{q}^2 < 6\,\mathrm{GeV}^2/\mathrm{c}^4)$	0.25	0.08	0.025	∼0.02
	$\mathcal{B}(\mathrm{B^+} \to \pi^+\mu^+\mu^-)/\mathcal{B}(\mathrm{B^+} \to \mathrm{K^+}\mu^+\mu^-)$	25 %	8 %	2.5 %	∼10 %
Higgs penguin	$\mathcal{B}(\mathrm{B_s^0} \to \mu^+\mu^-)$	$1.5 * 10^{-9}$	$0.5 * 10^{-9}$	$0.15 * 10^{-9}$	$0.3 * 10^{-9}$
	$\mathcal{B}(\mathrm{B^0} \to \mu^+\mu^-)/\mathcal{B}(\mathrm{B_s^0} \to \mu^+\mu^-)$	-	∼100 %	∼35 %	∼5 %
Unitarity triangle angles	$\gamma(\mathrm{B} \to \mathrm{D^{(*)}K^{(*)}})$	∼10-12°	4°	0.9°	negligible
	$\gamma(\mathrm{B_s^0} \to \mathrm{D_sK})$	-	11°	2.0°	negligible
	$\beta(\mathrm{B^0} \to \mathrm{J}/\Psi\mathrm{K_s^0})$	0.8°	0.6°	0.2°	negligible
Charm CP violation	A_Γ	$2.3 * 10^{-3}$	$0.40 * 10^{-3}$	$0.07 * 10^{-3}$	-
	$\Delta\mathrm{A_{CP}}$	$2.1 * 10^{-3}$	$0.65 * 10^{-3}$	$0.12 * 10^{-3}$	-

Performance benchmarks (II)

- LHCb is unique for NP searches in B_S system and extremely competitive for B_d too.
- LHCb can collect unprecedented charm yields.
- LHCb is also a general purpose experiment with forward geometry.
  - W and Z precision measurements
  - $W \rightarrow \mu\nu$ & $Z \rightarrow \mu\mu$ (2010) differential cross sections and asymmetry in arXiv:1204.1620
  - $Z \rightarrow ee$ (2011) differential cross section arXiv:1212.4620
  - LHCb Z boson measurements, EPJ C71 1600 (2011), LHCb-CONF-2013-007

More information

CERN/LHCC-2011-001



CERN/LHCC-2012-007

LHCb Upgrade fully endorsed by LHCC and approved by CERN Research Board

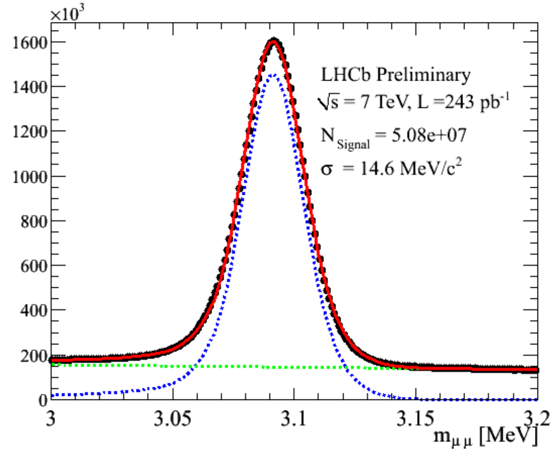
Summary

- Concept of LHCb definitely proved.
  - Dedicated experiment for heavy flavour physics exploiting a forward spectrometer at a hadron collider.
- Many world leading results and many more to come with the 3.2 fb^{-1} full data set.
- Standard Model still survives.
  - Now on probing regions where new physics effects might appear.
- LHCb plan the upgrade to be installed in 2018: Essential next step forward for flavour physics.

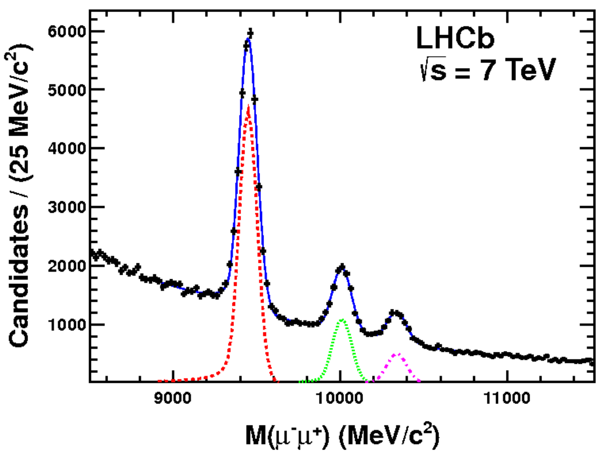
Reconstruction performance

- Momentum resolution excellent
  - From **0.4%** at 5 GeV to **0.6 %** at 100 GeV/c
  - Important ingredient to study narrow states
  - Momentum scale OK, checked by comparing the mass of B mesons to the PDG values.

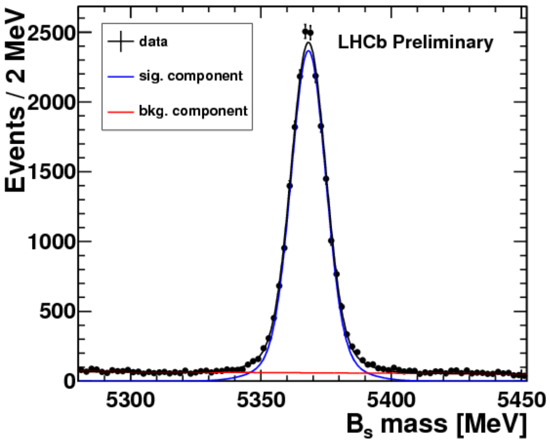
$J/\Psi \rightarrow \mu\mu$: $\sigma \approx 15$ MeV/c²



$\Upsilon(1S) \rightarrow \mu\mu$: $\sigma \approx 54$ MeV/c²



$B_S \rightarrow J/\Psi\Phi$: $\sigma \approx 8$ MeV/c²



- PID is working nicely
  - important to disentangle various de