Past present and future of the LHCb detector

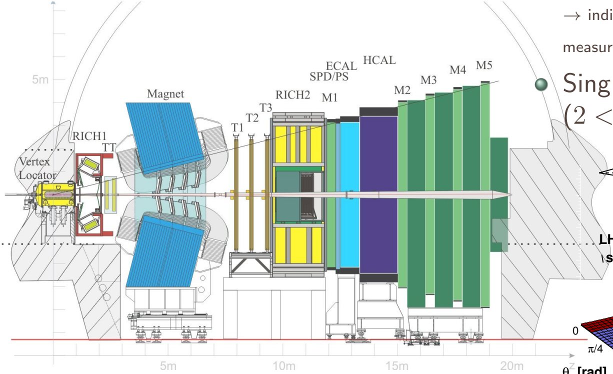
Violetta Cogoni – on behalf of the LHCb collaboration

XXII Cracow EPIPHANY Conference

7–9 January, 2015

Outline

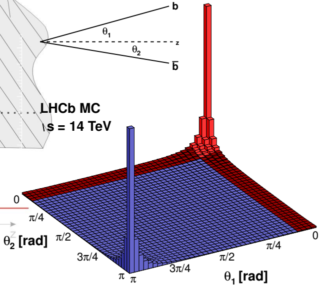
LHCb design



- Optimised to study b- and c-hadrons decays

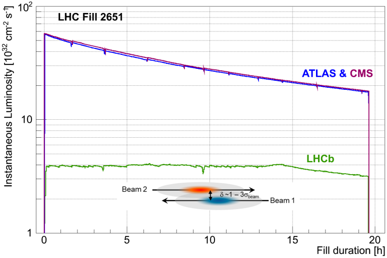
  → indirect searches for New Physics in CPV measurements and rare decays

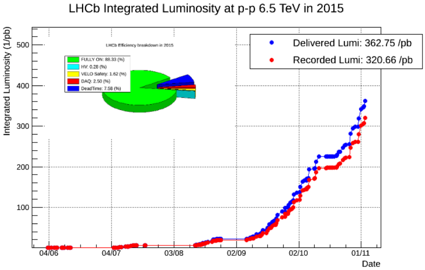
- Single-arm forward spectrometer $(2 < \eta < 5)$



LHCb design

- Operates at leveled luminosity



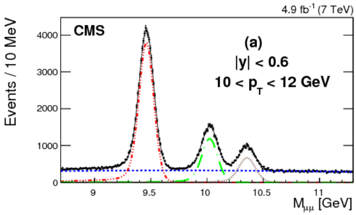


High peaks in luminosity lead to high pile-up which has a deleterious impact on data quality

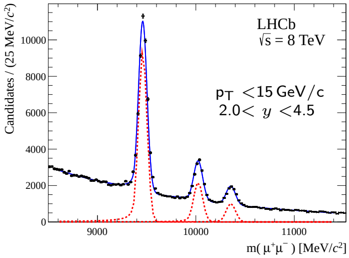
Recorded integrated luminosity at LHCb:

- 2011: $\sim$1 fb^{-1}
- 2012: $\sim$2 fb^{-1}
- 2015: $\sim$320 pb^{-1}

LHCb requirements



[Phys. Lett. B 749 (2015) 14]



[J. High Energy Phys. 06 (2013) 064]

- Excellent resolution
  - → IP resolution 20 μm for high-pT tracks
  - → $\Delta p/p = 0.5\%$ (low p) – 1% (200 GeV/c)
  - → Decay time resolution 45 fs for $B_s \to J/\psi\ \phi$ and $B_s \to D_s\pi$
  - → Mass resolution
    - ∼8 MeV/c^2 for B→J/ψ X decays
    - ∼22 MeV/c^2 for two-body B decays
    - ∼100 MeV/c^2 for $B_s \to \phi\gamma$
- Excellent particle identification capabilities
  - → e: ε_e ∼90% for ∼5% P(e→h)
  - → K: ε_K ∼95% for ∼5% P(π →K)
  - → μ: ε_μ ∼97% for ∼1–3% P($\pi \to \mu$)

The LHCb Upgrade

Aim

- Need to go to very high precision measurements: experimental sensitivity reaches theoretical uncertainty

Type	Observable	Current precision	LHCb 2018	**Upgrade** (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s(B_s^0 \to J/\psi\phi)$	0.10 [139]	0.025	0.008	~0.003
	$2\beta_s(B_s^0 \to J/\psi\, f_0(980))$	0.17 [219]	0.045	0.014	~0.01
	a_{sl}^s	6.4×10^{-3} [44]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{eff}(B_s^0 \to K^{*0}\overline{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{eff}(B^0 \to \phi K_S^0)$	0.17 [44]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{eff}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	<0.01
	$\tau^{eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,GeV^2/c^4)$	0.08 [68]	0.025	0.008	0.02
	$s_0 A_{FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [68]	6 %	2 %	7 %
	$A_I(K\mu^+\mu^-; 1 < q^2 < 6\,GeV^2/c^4)$	0.25 [77]	0.08	0.025	~0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [86]	8 %	2.5 %	~10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~100 %	~35 %	~5 %
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	~10–12° [252, 266]	4°	0.9°	negligible
	$\gamma(B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta(B^0 \to J/\psi K_S^0)$	0.8° [44]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [44]	0.40×10^{-3}	0.07×10^{-3}	–
	$\Delta\mathcal{A}_{CP}$	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–

Eur. Phys. J. C (2013) 73:2373

The LHCb Upgrade

Problem

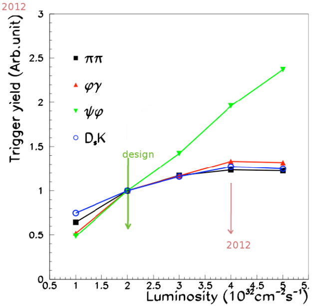
The available bandwidth and the limited discrimination power of hadronic L0 trigger implies **saturation of the trigger for hadronic channels already at** $4 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
⇒ More severe cuts are needed
⇒ Efficiency loss

Strategy

- Luminosity of $2 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- 1 MHz → 40 MHz read-out
- Fully-software trigger
- Plan to collect $50\,\mathrm{fb}^{-1}$

Consequences

- Detector front-end electronics needs to be rebuilt
- Consolidate subdetectors



[CERN-LHCC-2011-001]

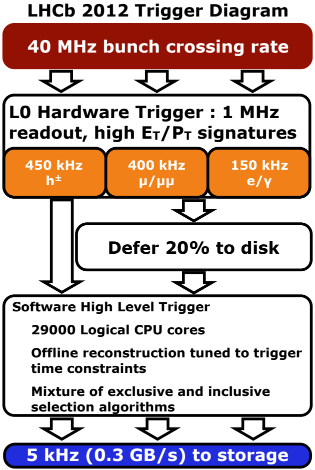
Trigger - Run I

L0

- First level trigger implemented in hardware
- Input from ECAL, HCAL, Muon System
- Reduces rate to 1 MHz
- Maximum latency 4 μs

HLT

- Software stage split into HLT1 and HLT2
- $\sim$30 ms per event reconstruction
- Output rate 5 kHz



Trigger - Run II

∼20% increase in multiplicity
→ more signal
→ trigger has to be more selective

L0

- Maximum readout rate still limited to 1 MHz

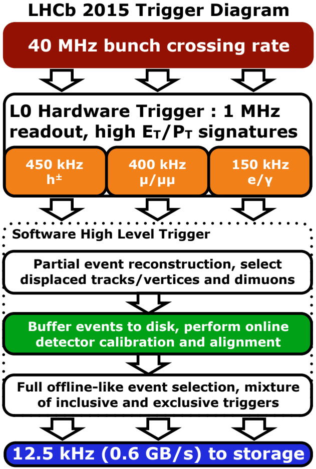
HLT

- Output rate 12.5 kHz
- Buffer 100% events to disk before running HLT2

Online alignment and calibration

Performing the alignment and calibration of the tracking subdetectors in real-time allows to store only candidates (for selected analyses) thus reducing the event size (90% size reduction)⇒ **TURBO stream**

- See Sevda Esen's talk for more details



Trigger - Run III

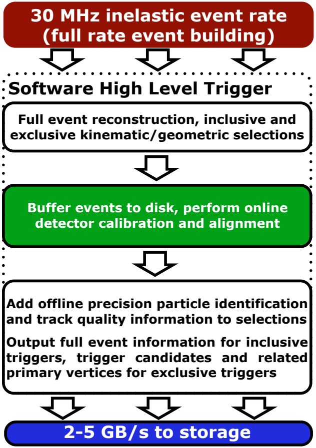
Main limitations

- Collision rate reduced to 1 MHz within fixed latency
- The largest inefficiencies in the trigger chain are introduced with the L0 decision

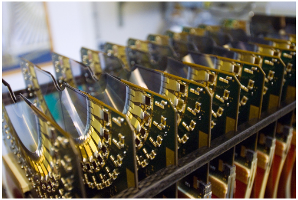
Strategy

- Remove bottleneck readout at 1 MHz → 40 MHz
- L0 replaced by software based Low Level Trigger: trigger as similar as possible to offline selection
- Increased importance of the TURBO stream
- Increased output rate

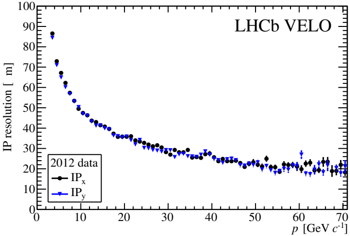
LHCb Upgrade Trigger Diagram

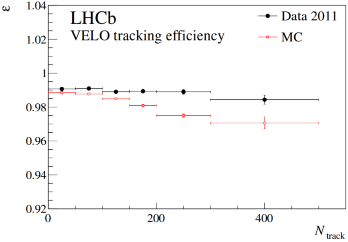


VELO



- Silicon microstrip vertex detector surrounding the collision region
- Two movable detector halves, each with R- and ϕ-segmented sensors
- σ_{IP} ∼20 μm for high-p_T tracks



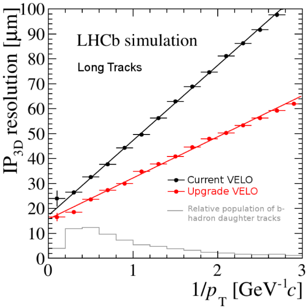


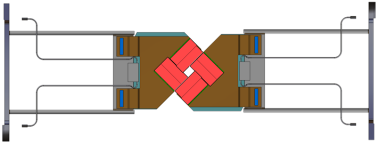
[JINST 9 (2014) 09007]

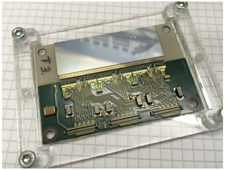
VELO - Run III

Main changes

- Higher track multiplicity→ from strip to pixel detector
- Move closer to the beam: 8.2 mm→5.1 mm
- New microchannel CO_2 cooling system, new air tight RF foil enclosure to separate VELO from primary vacuum
- Sensor thickness: 300 μm→200 μm





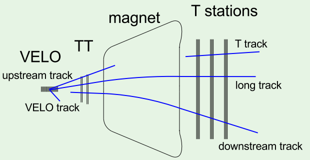


 [LHCB-TDR-013]

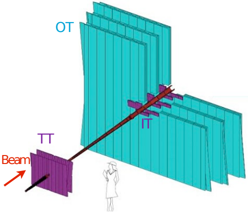
Tracking System - Run I

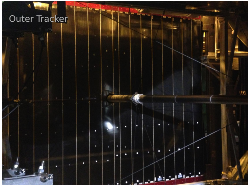
- **TT** - large-area silicon-strip detector - four layers: $0^\circ/+5^\circ/-5^\circ/0^\circ$ ($\sigma_{\text{hit}} \approx 53\,\mu$m, $\varepsilon_{\text{hit}} = 99.8\%$ (2012))
- **T stations** - three stations of four layers each - $0^\circ/+5^\circ/-5^\circ/0^\circ$
  - **Inner Tracker** silicon-strip detectors ($\sigma_{\text{hit}} = 54.9\,\mu$m (2012), $\varepsilon_{\text{hit}} = 99.9\%$ (2012))
  - **Outer Tracker** drift tubes ($\sigma_{\text{hit}} \approx 200\,\mu$m for particles with $p > 10$ GeV/c, $\varepsilon_{\text{hit}} = 99.2\%$)

Pattern recognition



2015 JINST 10 P02007

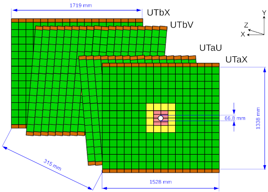




TT → UT - Run III

Main limitations

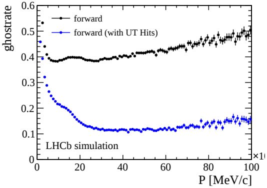
- Insufficient radiation hardness
- Read-out strips of up to four consecutive sensors: unacceptably high occupancies expected at high luminosity
- Read-out Beetle front-end chip not compatible with 40 MHz read-out, cannot be simply replaced



[LHCB-TDR-015]

Upstream Tracker

- Thinner sensors: 500 μm→250 μm
- Finer segmentation: from 183 μm(x)×10 cm(y) to 95 μm×4.9 cm 95 μm×9.7 cm 190 μm×9.7 cm
- Larger coverage: circular cut outs on the UT planes, thinner insulation layer sealed to the beam-pipe
- Lower electronic noise: signal processed at the sensors



[LHCB-TDR-015]

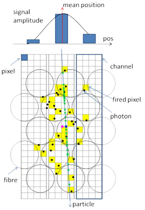
T stations → SciFi Tracker - Run III

Main limitations

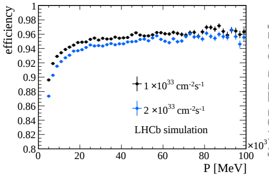
- 40 MHz read-out requires electronics replacement
  ⇒ detector replacement
- Designed for ≈ 10% occupancy at $2 \times 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$
  → currently ≈ 25% occupancy at $5 \times 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$
  ⇒ at $2 \times 10^{33}\,\text{cm}^{-2}\text{s}^{-1}$ the occupancy would be too high

Scintillating Fibers

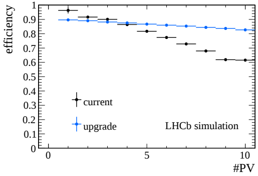
- Fibers allow optical signal transportation outside the acceptance volume
- 2.5 m long fibers with diameter 250 μm read-out by Silicon Photomultipliers (SiPMs)
- Requirements: $\varepsilon_{\text{hit}} \approx 99\%$, $\sigma_{\text{hit}} \approx 100\,\mu$m
- 3 stations of 4 layers each, 0°/+5°/ -5°/0°, circular hole at the center



[LHCB-TDR-015]



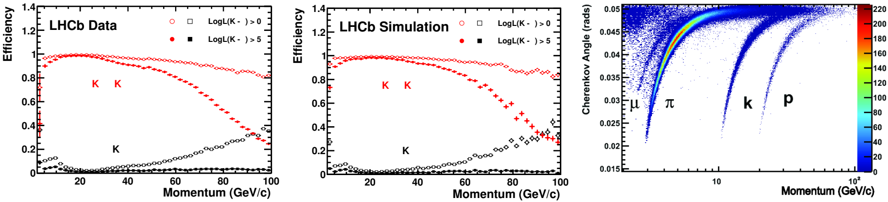
[LHCB-TDR-015]



[LHCB-TDR-015]

RICH

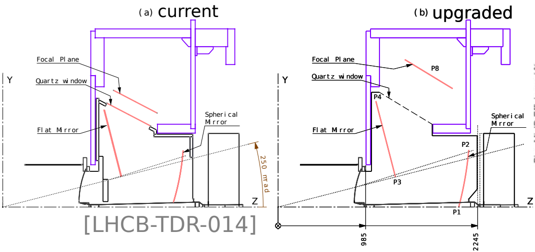
- Two sub-detectors:
  - **RICH 1** 2 GeV/c – 40 GeV/c over 25 mrad – 300 mrad
  - **RICH 2** 30 GeV/c – 100 GeV/c over 15 mrad – 120 mrad
- Particles traversing radiators produce Cherenkov rings on a plane of Hybrid Photon Detectors located outside acceptance



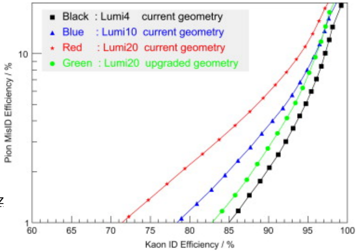
[Int.J.Mod.Phys. A 30 (2015) 1530022]

RICH - Run III

- RICH 1: increasing the focal lenght - increasing the spherical-mirror radius of curvature to lower the occupancies
- RICH 2: occupancy $< 7\%$ no modifications proposed for the optics
- Replace HPDs with 64 ch. multi anode PMTs with CLARO chip



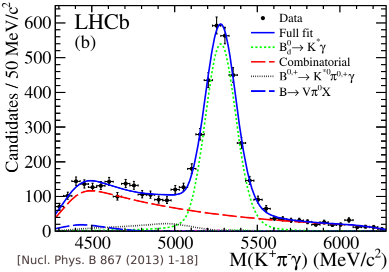
[LHCB-TDR-014]



Calorimeters

Four systems

- **SPD/PS** two planes of scintillator tiles separated by a 12 mm lead layer
  - **Scintillating Pad Detector (SPD)** identifies charged particles for e/γ separation
  - **PreShower (PS)** identifies electromagnetic particles
- **ECAL** "shashlik" technology: 2 mm lead sheets and 4 mm scintillator plates
  Energy resolution
  $\sigma(E)/E = 10\%/\sqrt{E} + 1.5\%$ (E in GeV)
- **HCAL** iron (16 mm)/scintillating (4 mm) tiles parallel to the beam
  Energy resolution
  $\sigma(E)/E = 80\%/\sqrt{E} + 10\%$ (E in GeV)



[Nucl. Phys. B 867 (2013) 1-18]

Here the mass resolution is dominated by ECAL high-energy photon reconstruction performances

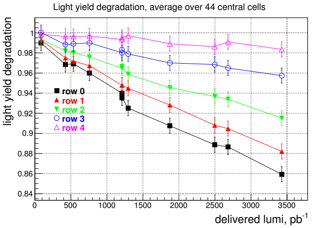
Calorimeters - Run III

Expected radiation damage and high occupancies

- Remove PS and SPD
- HCAL modules ok up to $\sim$50 fb^{-1}
- ECAL modules ok up to $\sim$20 fb^{-1}

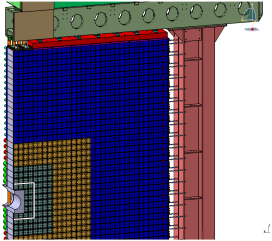
  $\Rightarrow$ Replace of the most irradiated modules foreseen during LS3
- Redesign and rebuilding of the front-end and back-end electronics

  $\uparrow$ this comes also from the decision to reduce the gain of the PMTs



[LHCB-TDR-014]

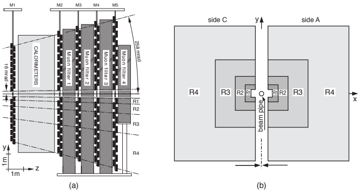
Evidence of radiation ageing in HCAL central module rows during the first three years of operations



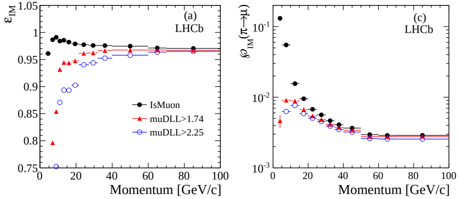
[LHCB-TDR-014]

The modules of the ECAL within the white line will need to be replaced

Muon System - Run I

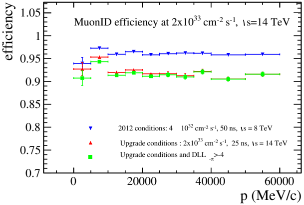


Momentum range	Muon stations
3 GeV/c $< p <$ 6 GeV/c	M2 and M3
6 GeV/c $< p <$ 10 GeV/c	M2 and M3 and (M4 or M5)
$p >$ 10 GeV/c	M2 and M3 and M4 and M5

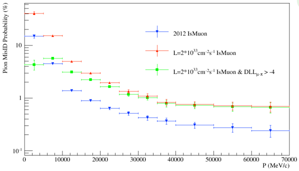


- 5 rectangular stations (M1–M5) interspersed with iron filters
- 4 concentric regions (R1–R4) of decreasing granularity
- Multi-Wire Proportional Chambers (MWPC)
- Triple-GEM detectors (M1R1)
- Offline selection starts from the coincidence of the stations + discriminating variable
- muon ID efficiency $\sim$ 97% for 1–3% $\pi \to \mu$ mis-ID probability

Muon System - Run III



[LHCB-TDR-014]



Upgrade program

- Removal of the first station (M1)
- New off-detector readout electronics compatible with 40 MHz (now limited to 1 MHz) ODE→nODE based on SYNC→nSYNC
- Installation of a new shielding in front of M2 around the beampipe
- **News since LHCB-TDR-014**: new algorithm has been developed which restores the pion rejection performance at high pileup!

	$3<p<6$ GeV/c	$6<p<10$ GeV/c	$p>10$ GeV/c
	Measured at pile-up $\sim$2.3		
IsMuon + muDLL	0.0799 ± 0.007	0.0315 ± 0.0002	0.00666 ± 0.0003
	Extrapolated at pile-up $\sim$7.4		
IsMuonTight + BDT	0.066 ± 0.008	0.031 ± 0.002	0.0068 ± 0.0004
(at 7.4)/(at 2.3)	0.83	0.98	1.0

Conclusions

- LHCb has performed excellently in Run I
- Run II detector performances are similar to those in Run I
- Major changes in Run II trigger strategy with great advantages for an increasing number of analyses
- All TDR for the upgrade have been approved
- Projects for Run III are progressing well, with prototypes under test
- In Run III, broad use of TURBO stream thanks to the success of online alignment and calibration

Backup Slides

Muon System - Run III

performances vs luminosity

Archilli, de Simone, Palutan, Vazquez Gomez

measured at pile-up ∼ 2.3	3< p< 6 GeV/c	6< p< 10 GeV/c	p> 10 GeV/c
IsMuon+muDLL	.0799 ± .0007	.0315 ± .0002	.00666 ± .00003
isMuonTight+muDLL	.0469 ± .0005	.0222 ± .0002	.00611 ± .00003
isMuonTight+BDT	.0348 ± .0005	.0173 ± .0002	.00567 ± .00003

isMuonTight+BDT restores the average π-MisID increase with the pile-up

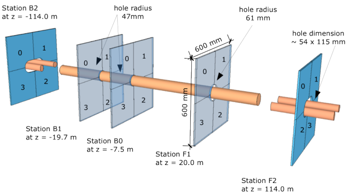
extrapolated at pile-up ∼ 7.4	3< p< 6 GeV/c	6 <p< 10 GeV/c	p> 10 GeV/c
IsMuon+muDLL	.12 ± .01 (1.50)	.048± .003(1.52)	.0091±.0005(1.4)
isMuonTight+muDLL	.088 ±.008 (1.10)	.043±.002 (1.37)	.0076±.0004(1.1)
isMuonTight+BDT	.066 ±.008(0.83)	.031±.002(0.98)	.0068±.0004(1.0)

numbers btw parentheses are the ratios wrt isMuon+muDLL at pile-up∼ 2.3, which represent the benchmark values

Run II → HeRSCheL

Motivation

- LHCb η coverage: some sensitivity in backward region $-1.5 < \eta < -3.5$
- Low pileup in Run II allows Central Exclusive Production (CEP) studies
- Currently: contamination of CEP signal by diffractive events due to high-rapidity particles escaping LHCb acceptance
- Idea: detect very forward activity from showers due to high-rapidity particles hitting the beampipe



- 4 Forward Shower Counters (FSCs) scintillator plates per station with fish tail light guides installed in the tunnel
- FSCs equipped with PMTs

Status

HeRSCheL fully installed - First look at data!