The LHCb upgrade

U. Marconi
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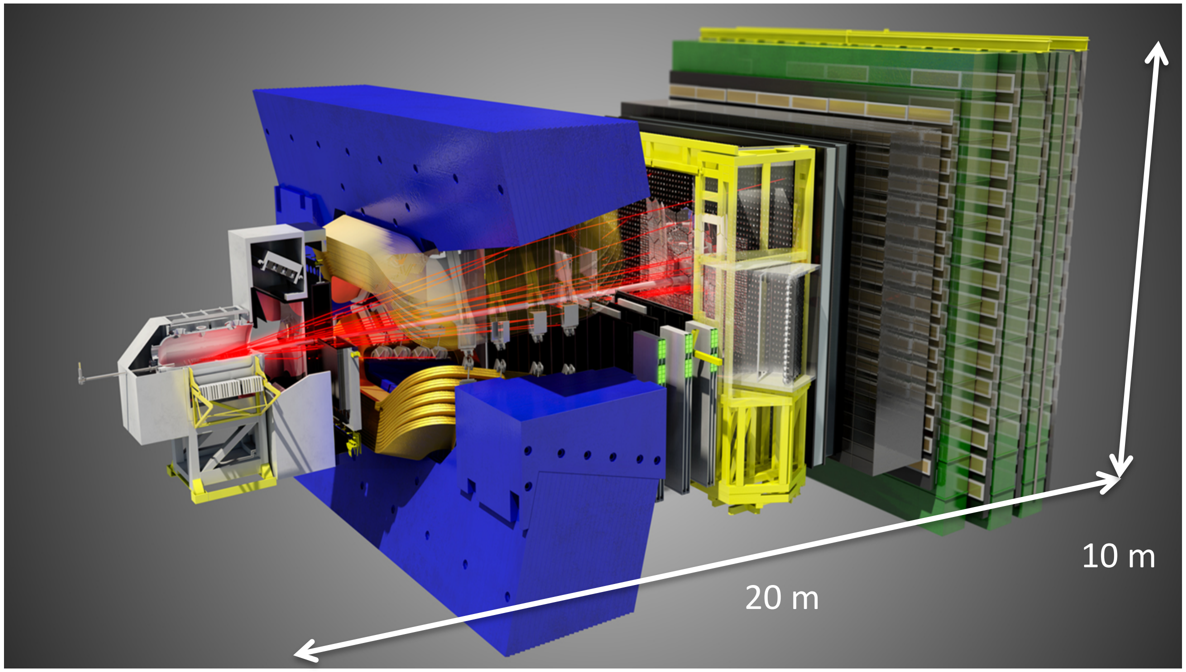
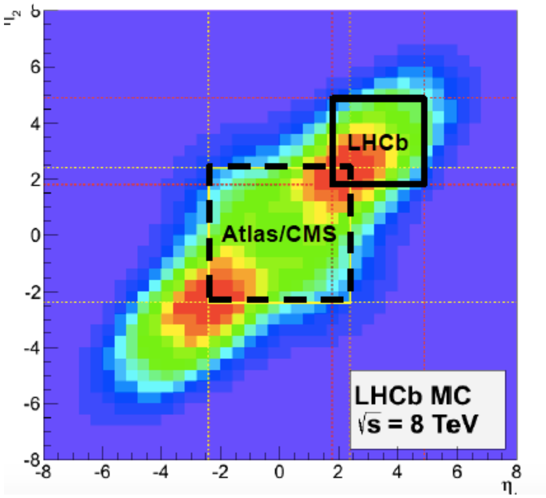
On behalf of the LHCb Collaboration

Single arm forward spectrometer

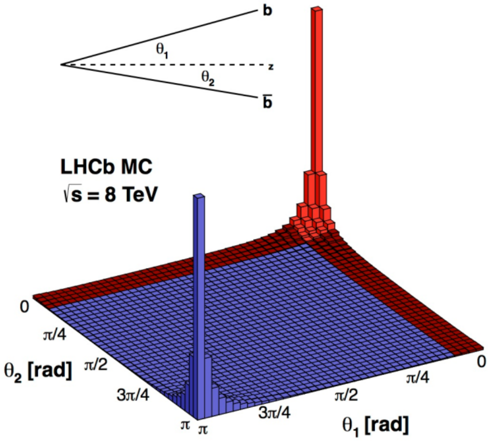
Covering about 4% of the solid angle in the forward region the detector captures 40% of the beauty cross-section.



acceptance $2 < \eta < 5$



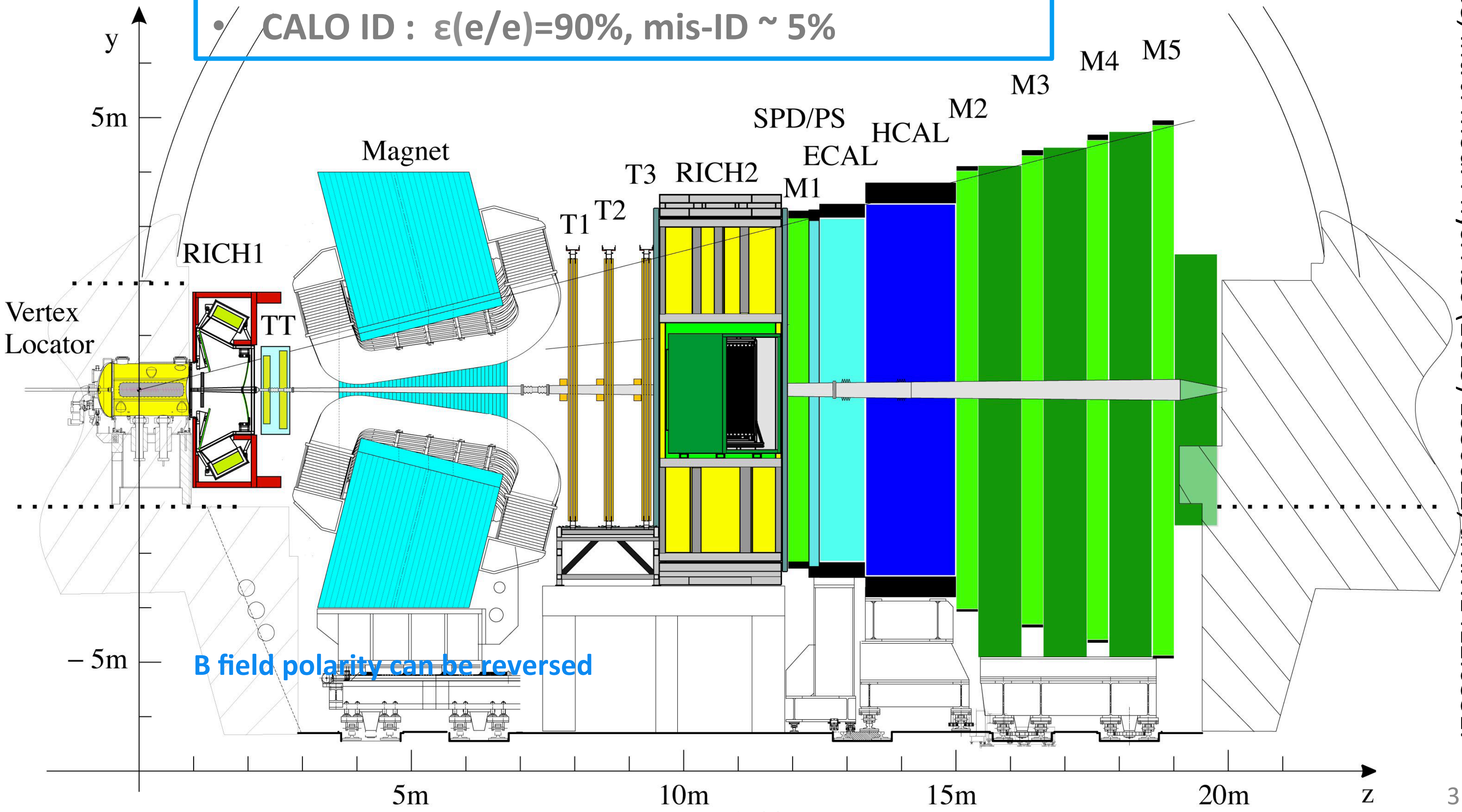
differential cross-section



- $\sigma_{\text{beauty}} = 75$ μb at $\sqrt{s} = 7$ TeV in the LHCb acceptance.
- ~1.5×10^9 beauty pairs per LHC fill.
- Charm cross section 20 times more.

Detector performance

- **Decay time resolution Δt: 30-50 fs**
- **$\Delta p/p$ = 0.4-0.6%**
- **Muon ID : ε(μ/μ) = 95%, ε(π/μ) ~ 1%**
- **RICH ID : ε(K/K) = 95%, ε(K/π) ~ 5%**
- **CALO ID : ε(e/e)=90%, mis-ID ~ 5%**



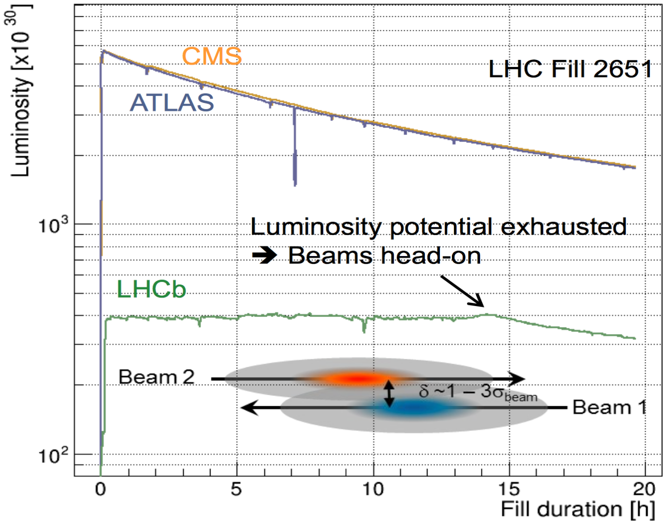
B field polarity can be reversed

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

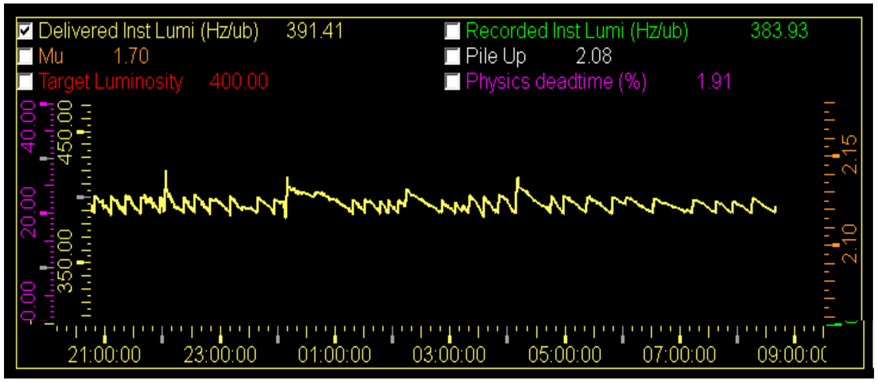
LHCb detector performance, Int. J. Mod. Phys. A30 (2015) 1530022, arXiv:1412.6352.

Instantaneous Luminosity

- **Constant instantaneous luminosity**: leveling at **$4. \times 10^{32}$ cm^{-2}** s^{-}



monitoring instantaneous luminosity



☑ Delivered Inst Lumi (Hz/ub) 391.41
☐ Mu 1.70
☐ Target Luminosity 400.00
☐ Recorded Inst Lumi (Hz/ub) 383.93
☐ Pile Up 2.08
☐ Physics deadtime (%) 1.91

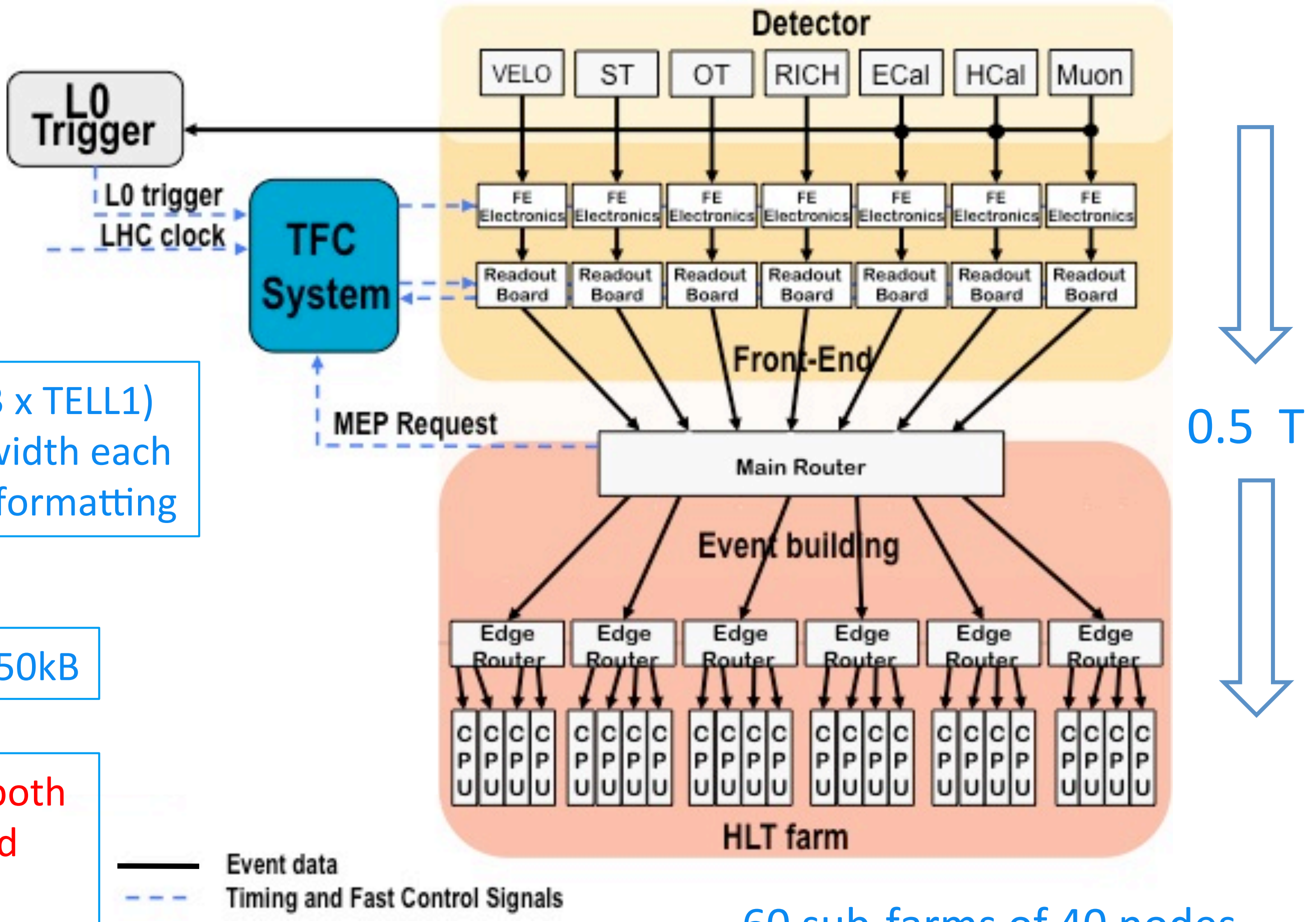
±3% around the target value

- 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.
- We run at **$4. \times 10^{32}$ cm^{-2} s^{-1}** with only **1262** colliding bunches (50 ns time spacing): **4 times more collisions per crossing than planned in the detector design.**

Present DAQ

Push-protocol with centralized flow-control

Trigger rate
1.1 MHz



Readout boards (313 x TELL1)
4 Gb/s output bandwidth each
Buffering and event formatting

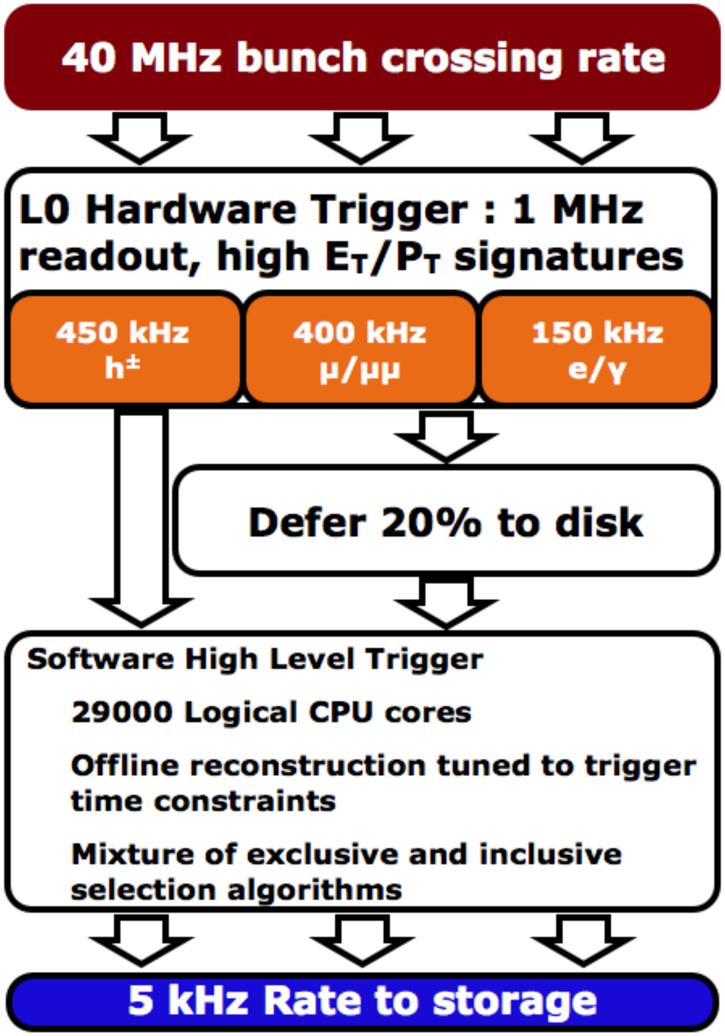
0.5 Tb/s

Event size 50kB

EFF servers perform both the Event Building and the Software Trigger.

60 sub-farms of 40 nodes

Trigger (LS1)



40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^\pm$

400 kHz $\mu/\mu\mu$

150 kHz e/γ

Defer 20% to disk

Software High Level Trigger

29000 Logical CPU cores

Offline reconstruction tuned to trigger time constraints

Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage

- **L0 Trigger**
  - ECAL, HCAL and MUON detectors read out at 40 MHz
  - **20% deferred to disk**
- **HLT is a software trigger**

HLT1

  - Reconstruct VELO tracks and primary vertices
  - Select events with at least one track matching p, p_T , impact parameter and track quality cuts.

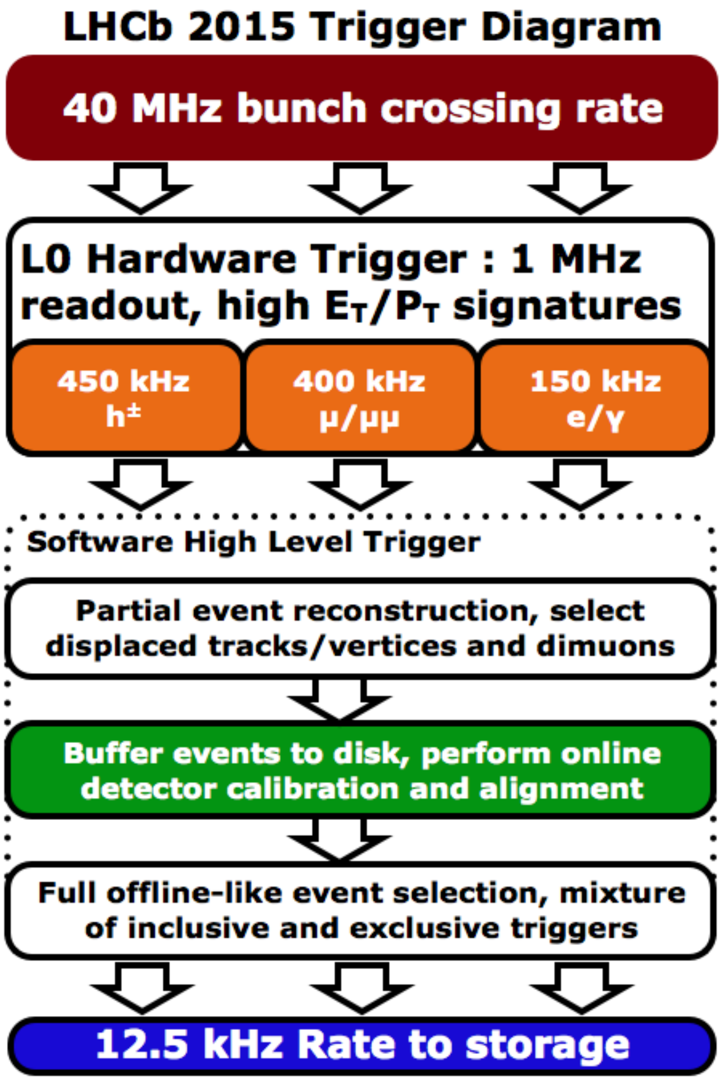
HLT2

  - At around **100 kHz** performs inclusive or exclusive selections of the events.
  - Full track reconstruction, without particle-identification.
  - Total accept rate to disk for offline analysis is around **5 kHz**.

R. Aaij et al. The LHCb trigger and its performance in 2011. *JINST*, 8:P04022,2013

Trigger evolution

- **LHC stable beams during 30% of the running period**:
  70% of the time the CPU of the HLT farm would be idle.
- **Real-time HLT1**:
  HLT1 selects events that are temporarily stored on local disks (farm servers).
  - Staging after the HLT1 filter occurs at a rate of about 100 kHz instead of 1 MHz.
  - An enriched sample to analyse further.
- **Deferred HLT2**:
  Performs the final event filtering, relying on up-to-date calibration constants, with offline quality.
  - Trigger algorithm: ~350 trigger lines
  - Output rate ~**12.5 kHz**.



LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz
$h^\pm$

400 kHz
$\mu/\mu\mu$

150 kHz
e/γ

Software High Level Trigger

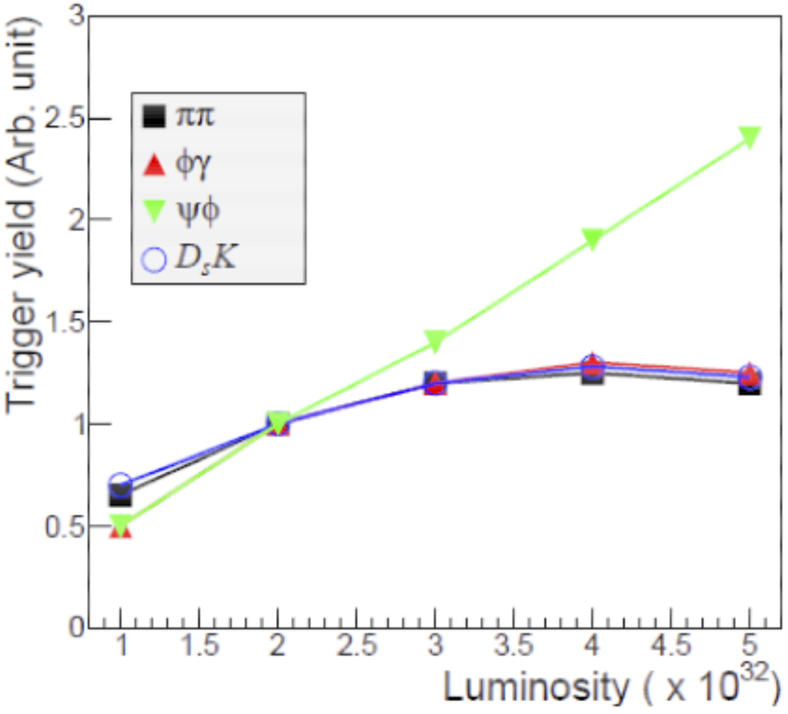
Partial event reconstruction, select displaced tracks/vertices and dimuons

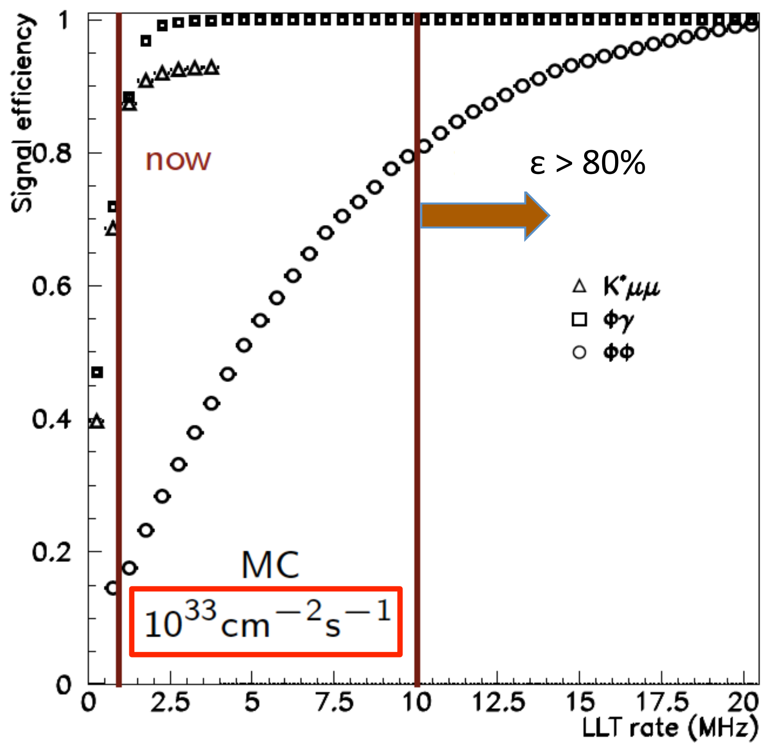
Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz Rate to storage

The 1 MHz readout rate limitation





- Due to the available bandwidth and the limited discrimination power of the hadronic L0 trigger, LHCb experiences the **saturation of the trigger yield on hadronic channels** around 4. ×10^{32} cm^{-2}s^{-1}
- Increasing the first level trigger rate considerably increases the efficiency on the hadronic channels.

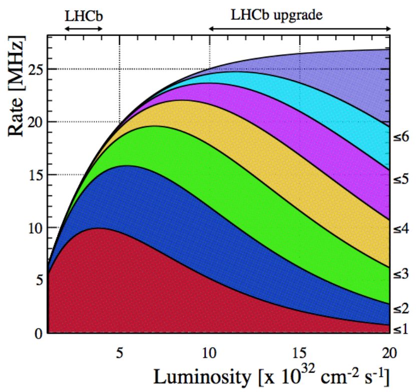
“Framework TDR for the LHCb Upgrade: Technical Design Report”; The LHCb Collaboration,CERN/LHCC-2012-007, LHCb-TDR-12 - 2012

The LHCb upgrade

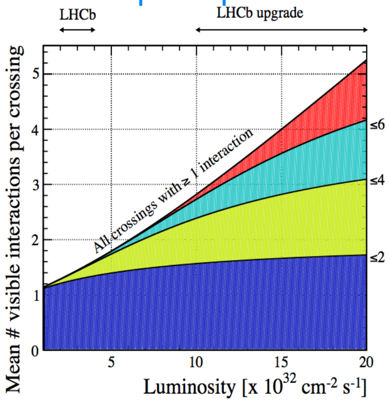
Requirements

- Readout the whole detector at 40 MHz.
- Event selection by HLT software trigger.
- Run the detector at **$2. \times 10^{33}$ cm^{-2}s^{-1}**
  - pp interaction rate 27 MHz
  - Average pile up μ ≅5.2
- Collect **50 fb^{-1}** at 14 TeV over ten years.
- The detector upgrade shall take place during the Long Shutdown 2 (LS2) in 2018-19.

interaction rate



pile up



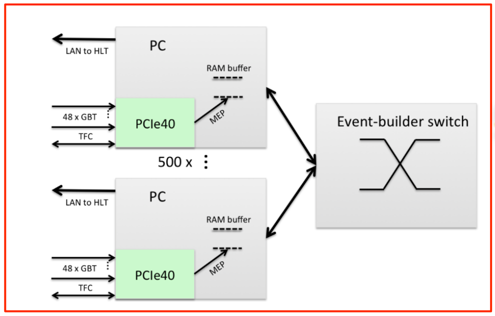
Consequences

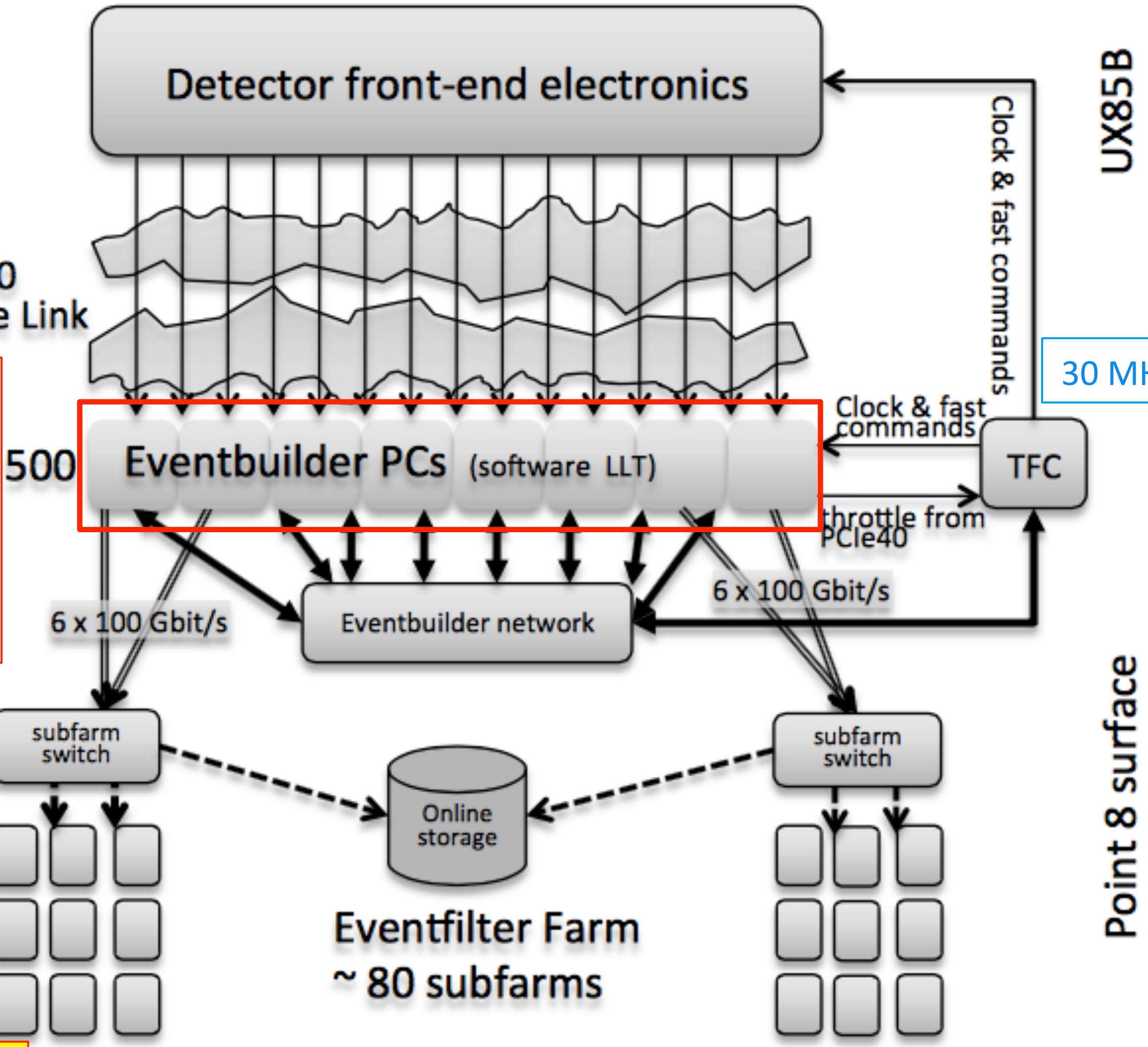
- **The detector front-end electronics has to be entirely rebuilt**
  because of the output rate requirements.
- **New HLT farm and network**
  new LAN technologies and powerful many-core processors.
- **Rebuild the trackers**
- **Consolidate sub-detectors**
  to let them stand the foreseen luminosity.

40 MHz PCIe based readout

5 Gb/s , 300 m long fibres
from the FEE
directly to the Event Builder

Event Builder





30 MHz × 100 kB/evt

CERN-LHCC-2014-016

HLT threads

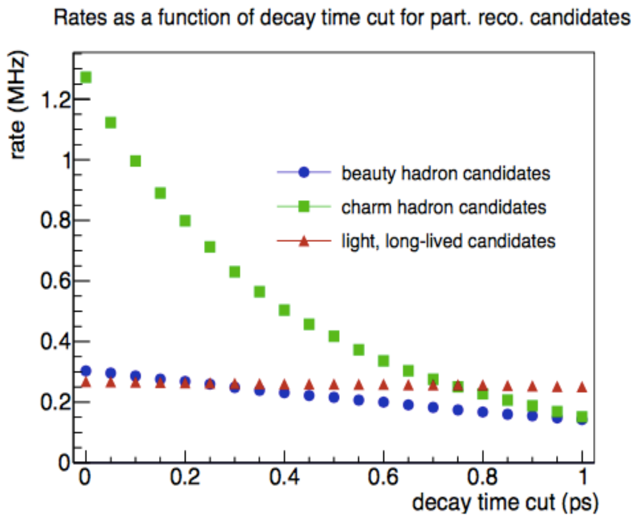
n ~ 30 MHz × 20 ms ~ 6 × 10^5

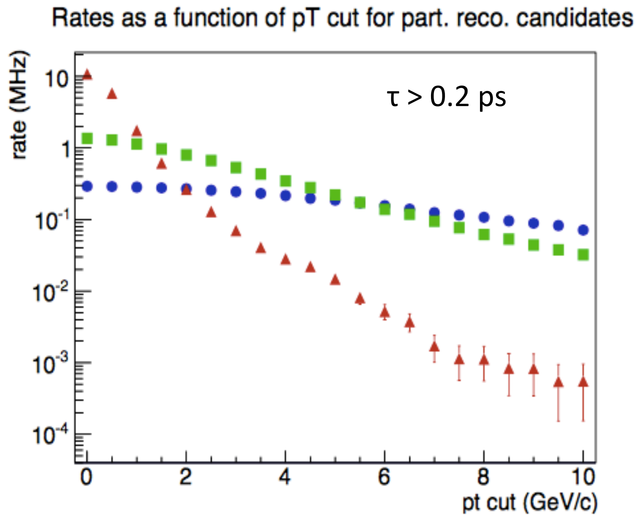
HLT output rate

	b-hadrons	c-hadrons	light, long-lived hadrons
Reconstructed yield	0.032 ± 0.001	0.118 ± 0.001	0.406 ± 0.002
$\epsilon(p_{\mathrm{T}} > 2\,\mathrm{GeV}/c)$	$85.6 \pm 0.6\%$	$51.8 \pm 0.5\%$	$2.3 \pm 0.1\%$
$\epsilon(\tau > 0.2\ \mathrm{ps})$	$88.1 \pm 0.6\%$	$63.1 \pm 0.5\%$	$99.5 \pm 0.1\%$
$\epsilon(p_{\mathrm{T}}) \times \epsilon(\tau) \times \epsilon(\mathrm{LHCb})$	$27.9 \pm 0.3\%$	$22.6 \pm 0.3\%$	$2.2 \pm 0.1\%$
Output rate	$27\ \mathrm{GB\,s^{-1}}$	$80\ \mathrm{GB\,s^{-1}}$	$26\ \mathrm{GB\,s^{-1}}$

Candidates which had at least two tracks from which a vertex could be produced.

max: 10 GB/s

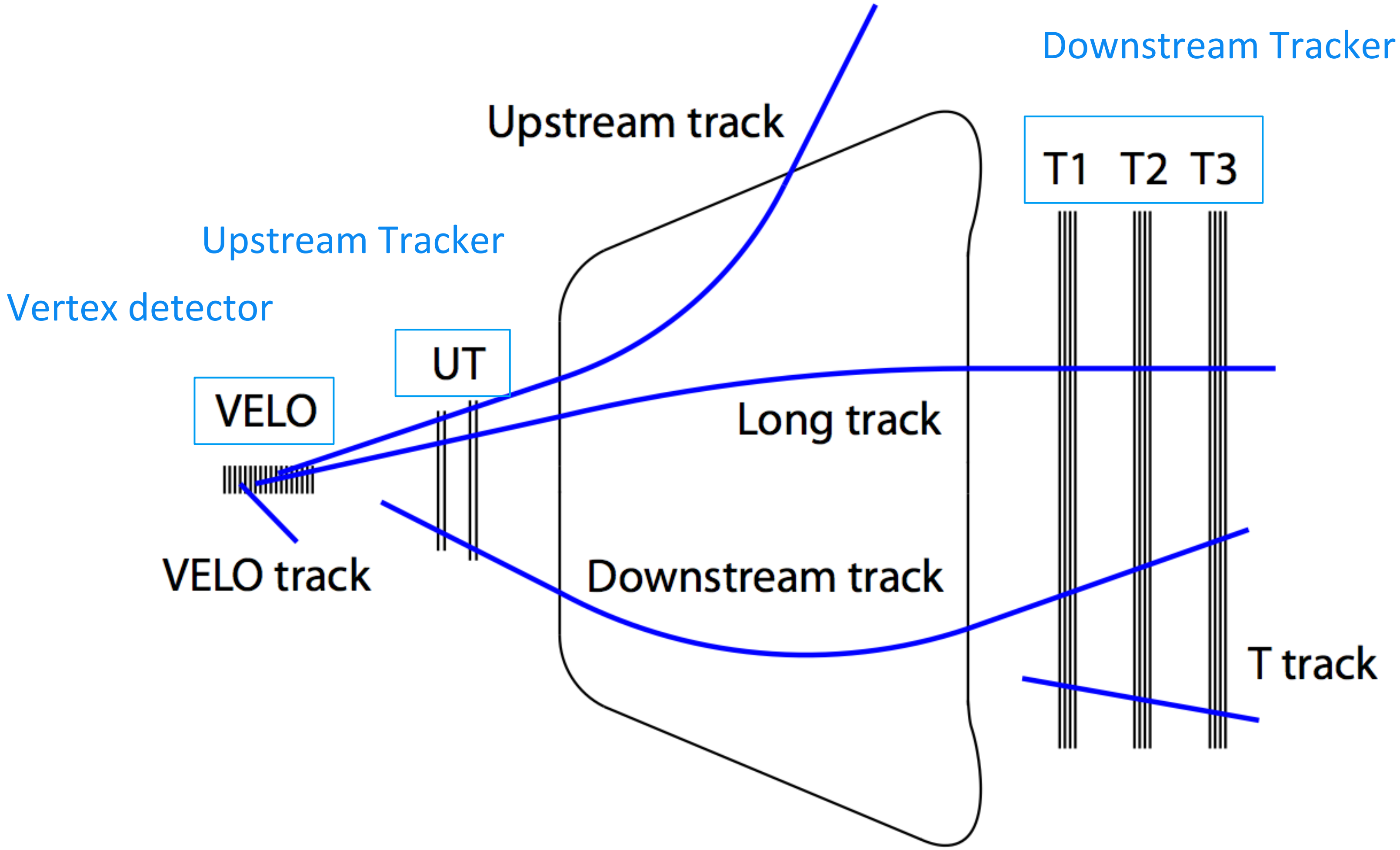




LHCb-PUB-2014-040

"The problem is no longer to find one specific event among billion background events, but **discriminate in a minimally biasing way between various topologically similar signals**". There will be signal modes where 100% pure trigger must be downscaled to fit into the output bandwidth allocated: **the trigger will frequently be the offline event selection**.

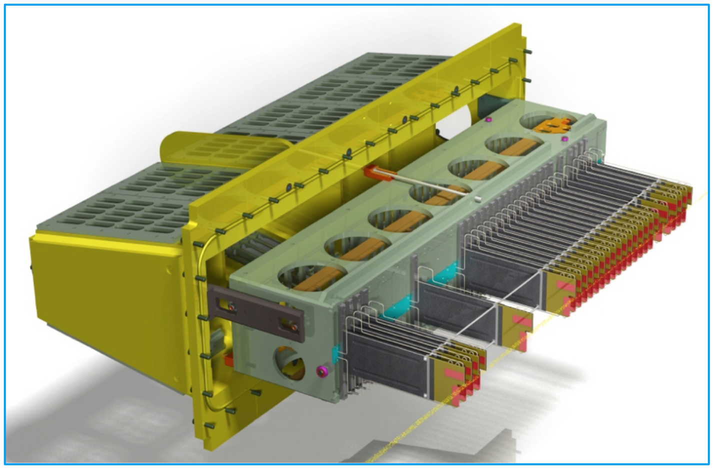
Upgrade of the tracking system



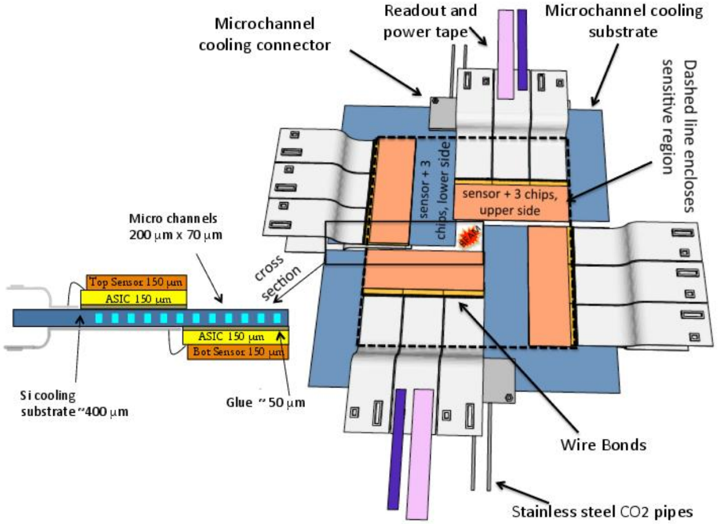
VELO upgrade

- **Higher granularity and improved resolution: Silicon pixels of surface area 55 × 55 μm^2**
- **Reduced material budget:**
  - Sensor thickness: 300 μm → 200 μm
  - Aluminum foil: 300 μm→ ≤ 250 μm
- **Enlarged acceptance:**
  - Edge of detector closer to beam 8.2 mm → 5.1 mm
  - 52 modules in two retractable halves.
- **New readout chip** VeloPix with CMOS 130 nm technology to sustain ~400 MRad
  - Close to beam ~10^{16} $n_{eq}cm^{-2}$ for 50 fb^{-1}
- **Cooling**
  - Cool to -10°C to -15°C to prevent thermal runaway
  - Micro-channel CO_2 cooling

One of the retractable halves



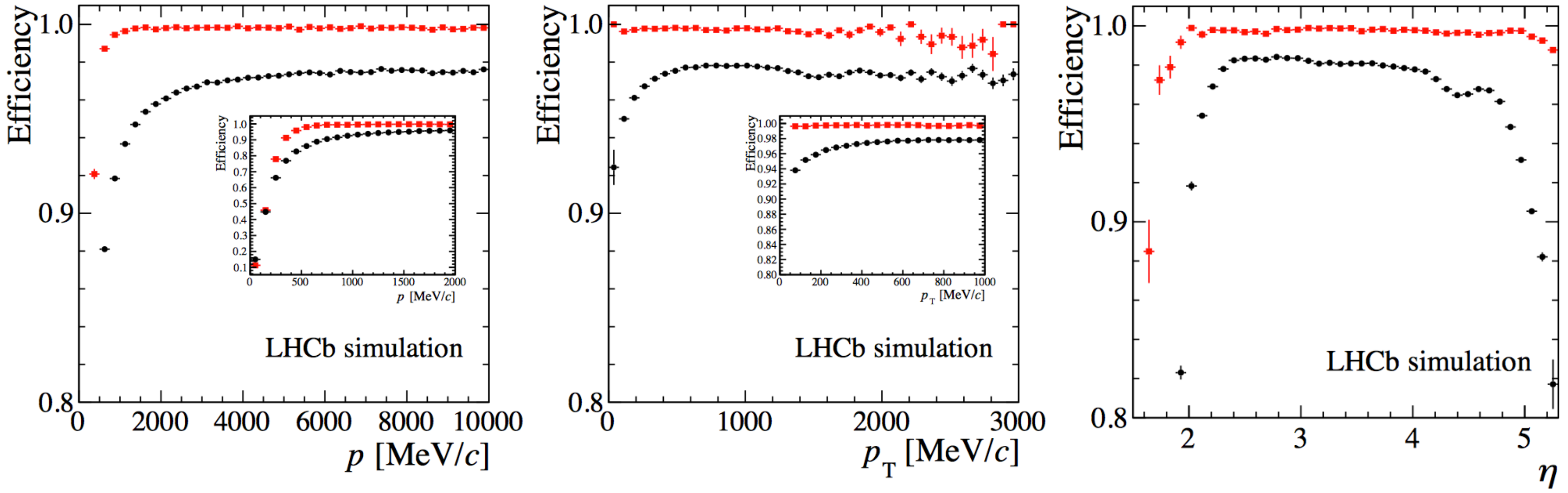
VELO module

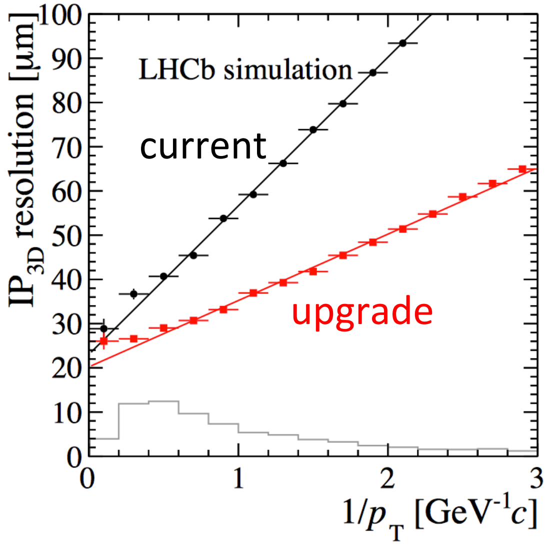


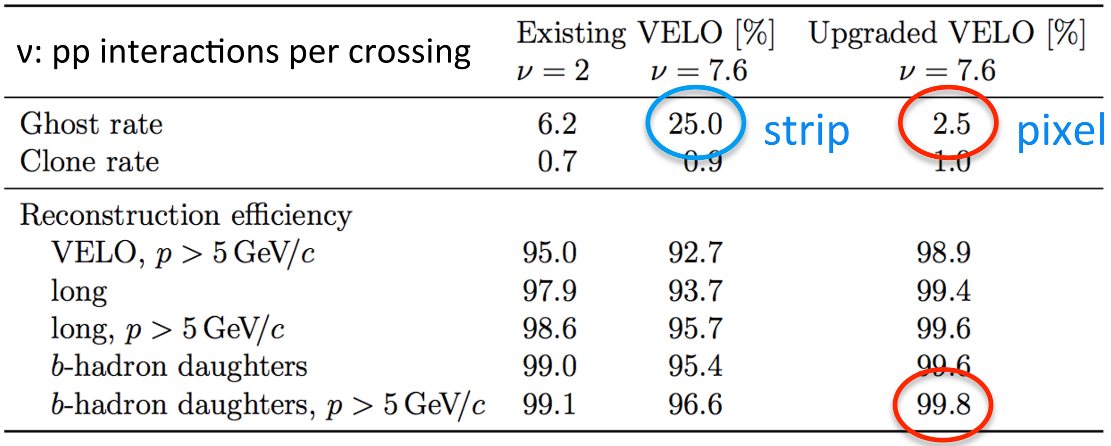
http://cds.cern.ch/record/1624070/files/LHCB-TDR-013.pdf

VELO upgrade (II)

Tracking efficiency







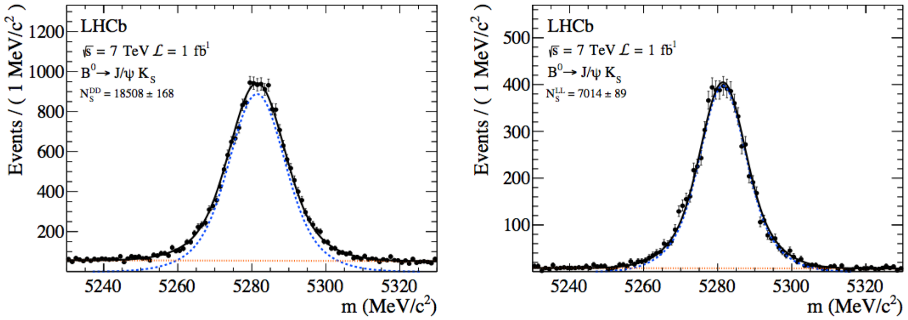
ν: pp interactions per crossing	Existing VELO [%] $\nu = 2$	$\nu = 7.6$	Upgraded VELO [%] $\nu = 7.6$
Ghost rate	6.2	25.0	2.5
Clone rate	0.7	0.9	1.0
Reconstruction efficiency			
VELO, $p > 5\,\mathrm{GeV}/c$	95.0	92.7	98.9
long	97.9	93.7	99.4
long, $p > 5\,\mathrm{GeV}/c$	98.6	95.7	99.6
b-hadron daughters	99.0	95.4	99.6
b-hadron daughters, $p > 5\,\mathrm{GeV}/c$	99.1	96.6	99.8

Expected output data rate: 3 Tb/s

Upstream Tracker

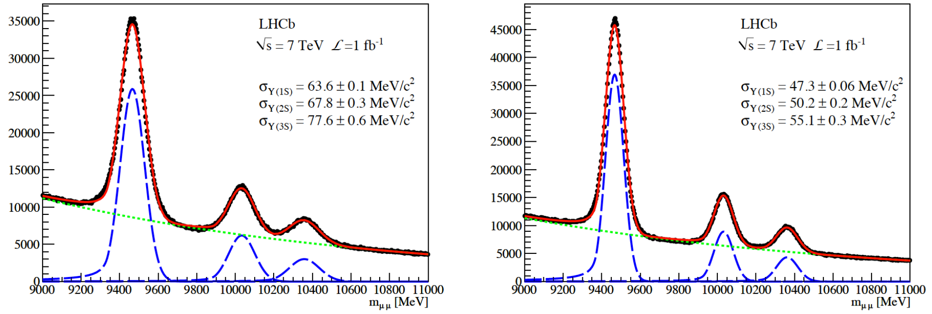
- **Reconstruct downstream tracks** of particles decaying after the VELO ($K_S \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow p\pi$, etc.)
- **Reconstruct upstream tracks**: slow momentum particles that bend out of the acceptance.
- **Improve momentum resolution and signal purity** of long tracks.
- **p_T estimate of charged tracks for fast trigger tracking**
  - $\sigma(p_T)/p_T$~15% in the p_T range of 0.5-10 GeV/c.
  - Decrease the time required by the tracking algorithm by a factor of three.

CERN-LHCC-2014-001 ; LHCB-TDR-015.-2014.


$B_d \rightarrow J/\psi\ K_S$

Downstream Tracks

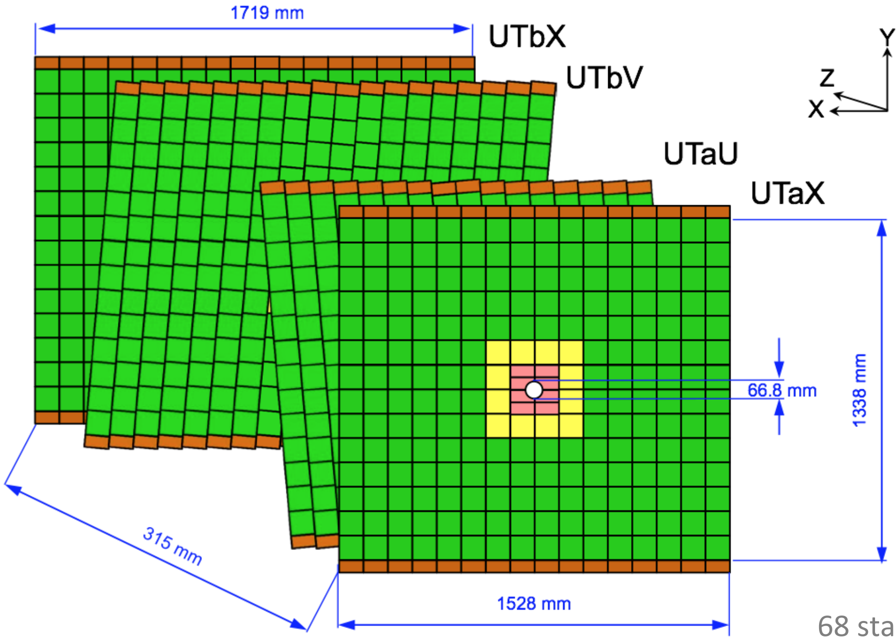
Long Tracks


muon pairs invariant mass

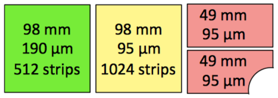
mass resolution improves by about 25%

Upstream Tracker (II)

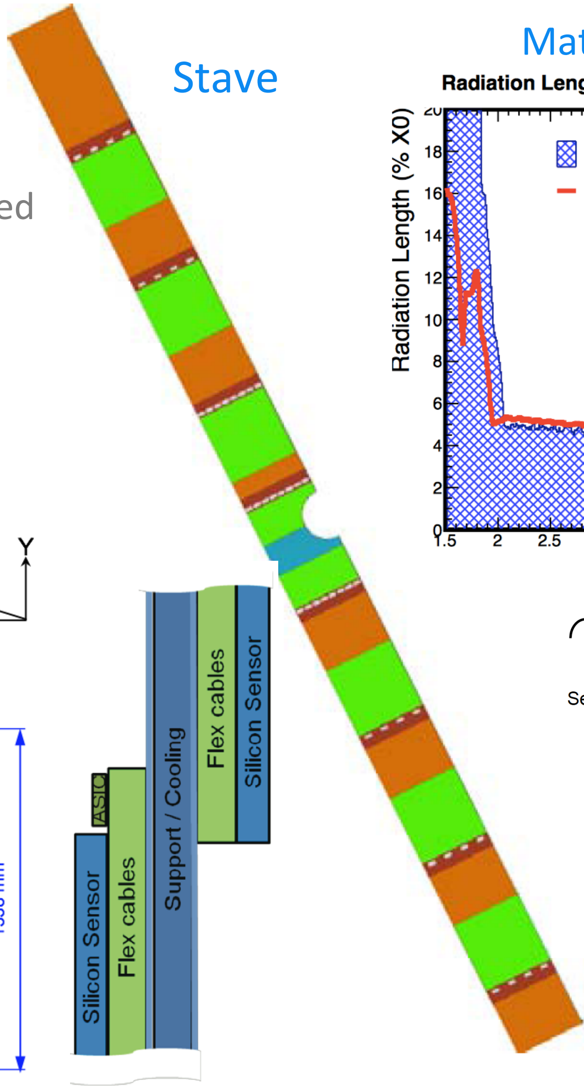
- Material budget kept to minimum: ~1% X_0 per plane. Light mechanics and cooling system.
- Single-sided silicon strip sensors 250 µm thick instead of 500 µm. Strip pitch and length adapted to the particle flux depending on the position.
- Single-hit resolution of 50 µm.
- Improved coverage by overlapping sensors.
- Closer to beam pipe to improve the small-angle acceptance.



Strip pitch and length

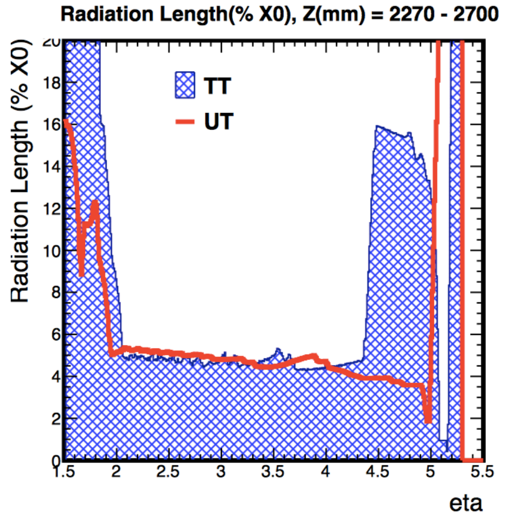


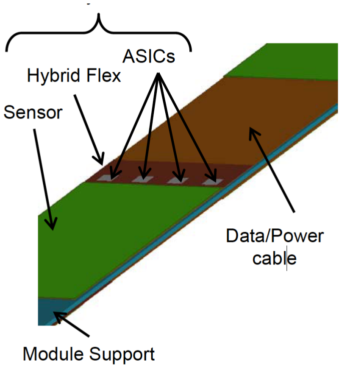
Stave



68 staves, staggered 10 mm in z to provide overlap in x

Material budget



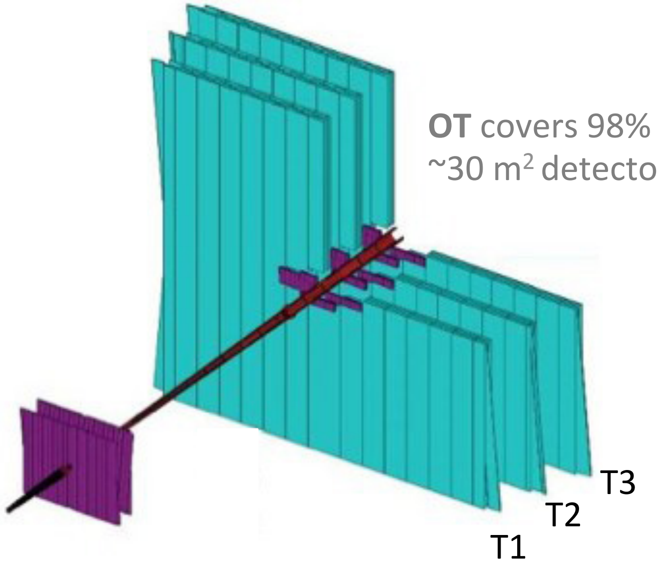


Sensors will be operated at a temperature of -5°C
Bi-phase CO_2 cooling in stave support

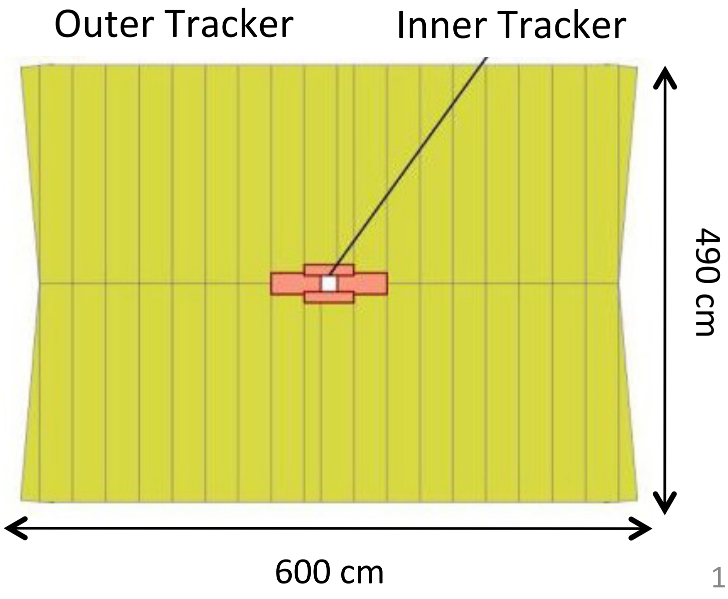
CERN-LHCC-2014-001 ; LHCB-TDR-015.-2014.-196p. (Technical Design Report LHCb ; 15)

Current Downstream Tracker

- Two different sub-detectors: **OT** and **IT**
- **OT** are made of 5mm straw drift tubes (35ns drift time).
  - Resolution is 200 µm
- **IT** is a silicon micro-strip detector covering the high track density region around the beam-pipe.
  - 20% of the tracks impinge on IT
  - Resolution 50 µm
- **At the foreseen luminosity of 2 × 10^{33} $cm^{-2}s^{-1}$ the occupancy in the OT would rise up to 40%: OT can handle up to 25% occupancy levels.**

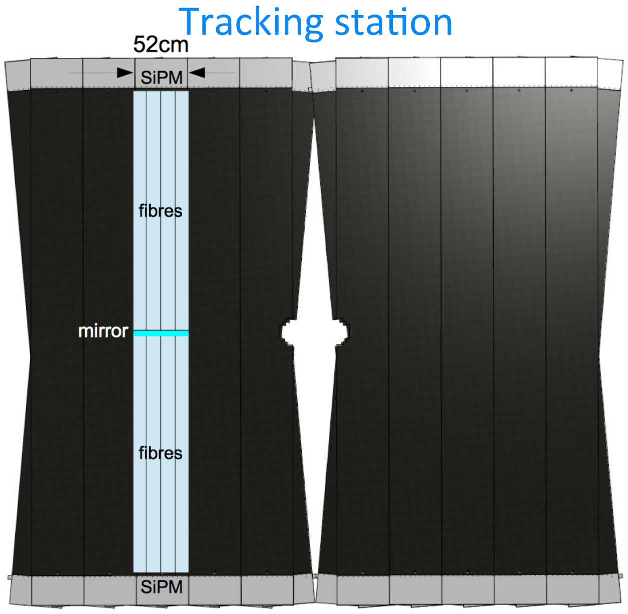


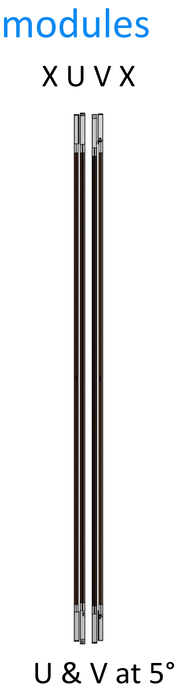
OT covers 98% of the ~30 m^2 detector surface.

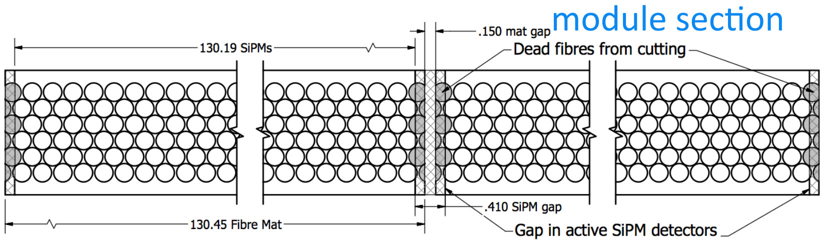


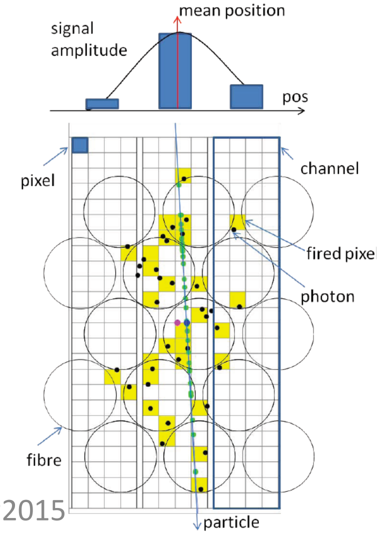
SciFi Downstream Tracker

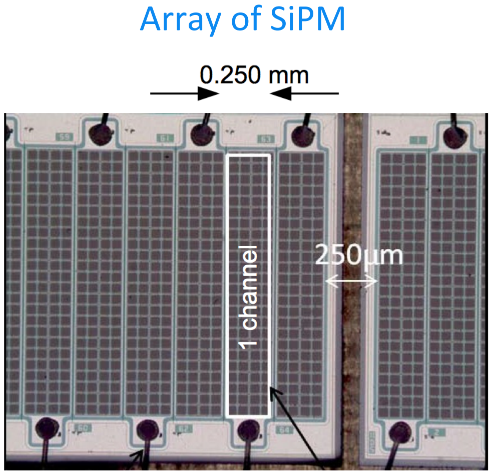
- Scintillating Fibre Trackers covering the full acceptance: 5 × 6 m^2
- A SciFi detector module is made of multiple layers of 2.5 m long scintillating fibres of 250 µm diameter.
- Very light and uniform material distribution: X/X_0 = 2.6% per station.
- The fibres are read by SiPM.
  - The SiPMs need to be cooled to -40°C to mitigate radiation damages.
- Expected 60 – 100 µm spatial resolution.


Tracking station


modules


module section

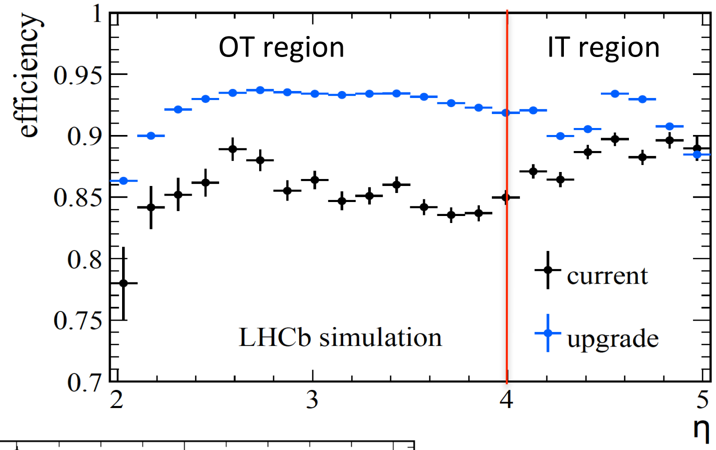



Array of SiPM

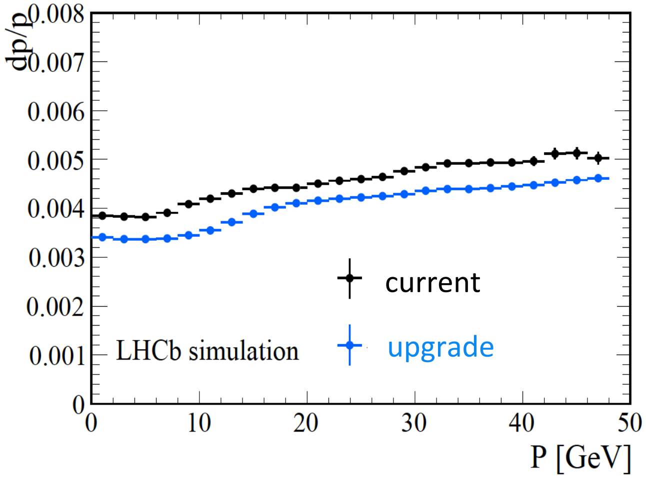
CERN-LHCC-2014-001 ; LHCB-TDR-015.-2014.-196p. (Technical Design Report LHCb ; 15)

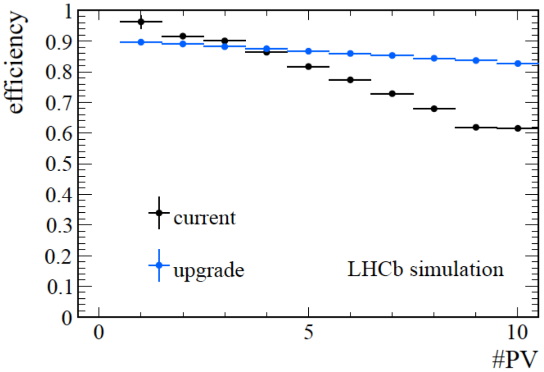
Tracking performance

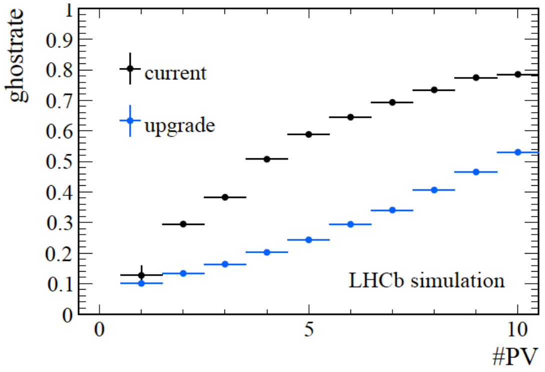
efficiency as function of η



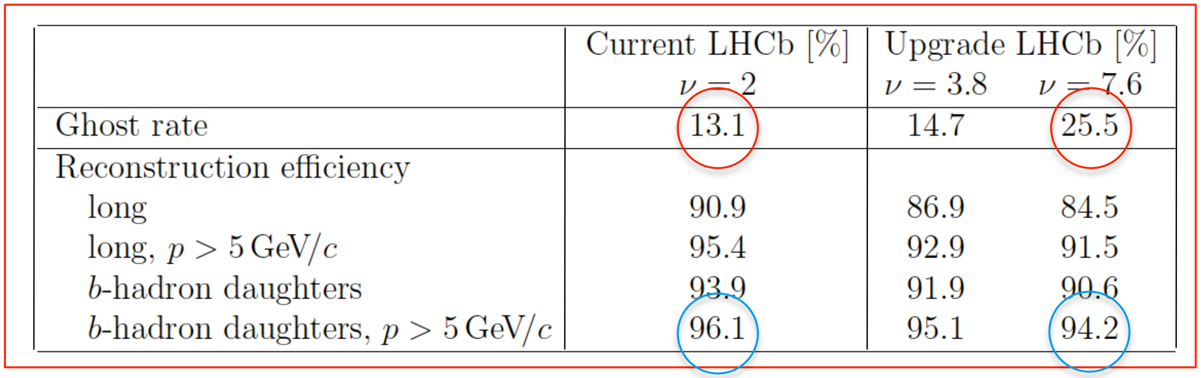
momentum resolution







Performance as function of primary vertices



	Current LHCb [%]	Upgrade LHCb [%]	
	$\nu = 2$	$\nu = 3.8$	$\nu = 7.6$
Ghost rate	13.1	14.7	25.5
Reconstruction efficiency			
long	90.9	86.9	84.5
long, $p > 5\,\mathrm{GeV}/c$	95.4	92.9	91.5
b-hadron daughters	93.9	91.9	90.6
b-hadron daughters, $p > 5\,\mathrm{GeV}/c$	96.1	95.1	94.2

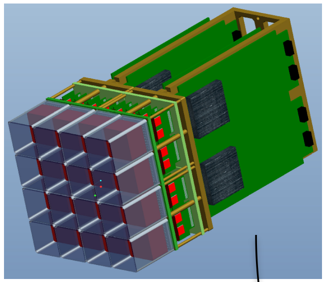
4. × 10^{32} cm^{-2}s^{-1}

2 × 10^{33} cm^{-2}s^{-1}

CERN-LHCC-2014-001 ; LHCB-TDR-015.-2014.-196p. (Technical Design Report LHCb ; 15)

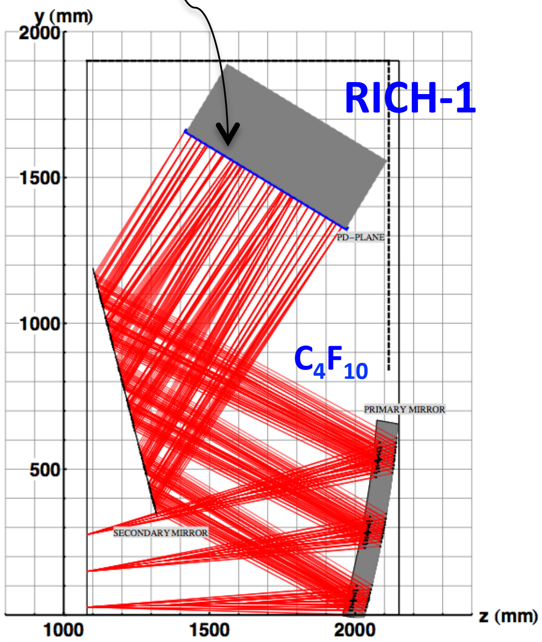
RICH detector

- The overall structure of RICH-1 and RICH-2 unchanged.
- HPD photon detectors will be replaced with MaPMT
  - 1920 in RICH-1 and 2560 in RICH 2
- The optical layout of RICH 1 has to be modified to reduce the hit occupancy.
  - Increasing the focal length of the spherical mirrors halving the occupancy.
- Remove the Aerogel radiator in RICH-1.
  - ~3.5% of X_0
  - The K and π threshold in C_4F_{10} are 9.3 GeV/c and 2.6 GeV/c .



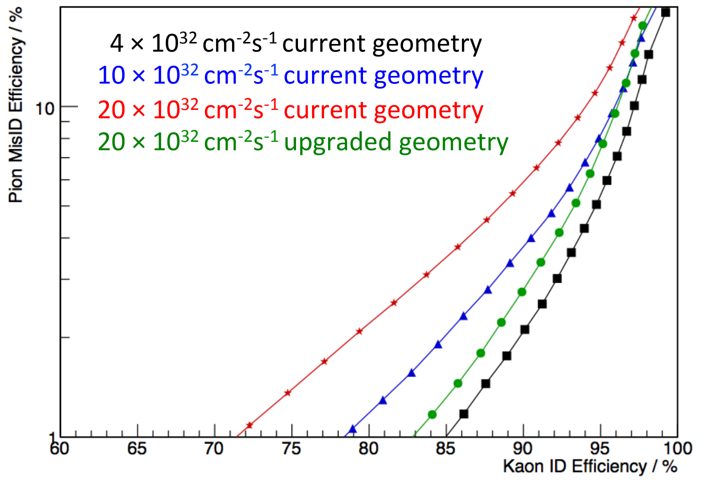
PDM size of 116 × 116 mm^2

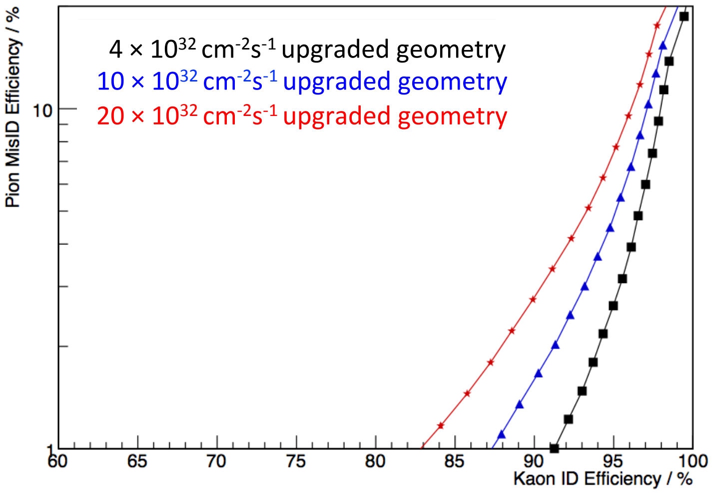
R11265 MaPMT from Hamamatsu.

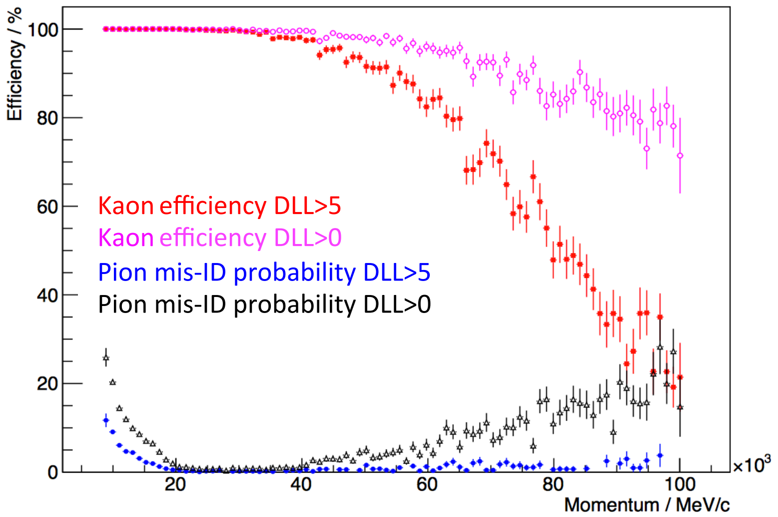


PID performance

Running the full simulation and reconstruction chain in $B_s \to \phi\phi$



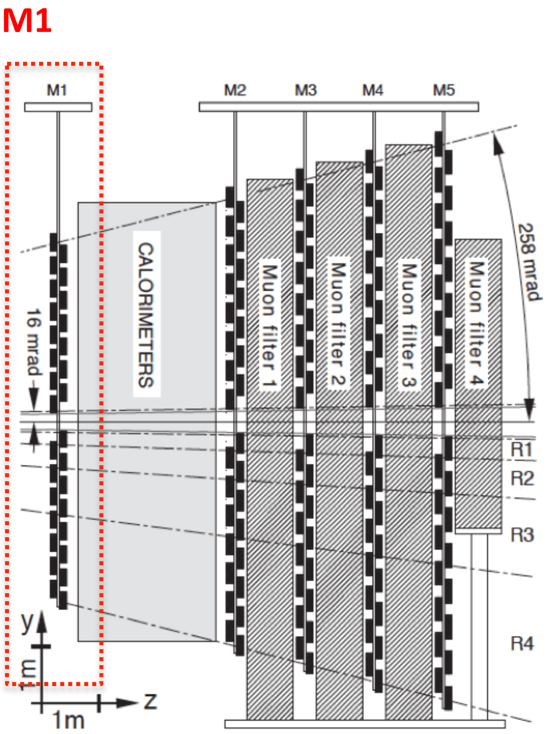




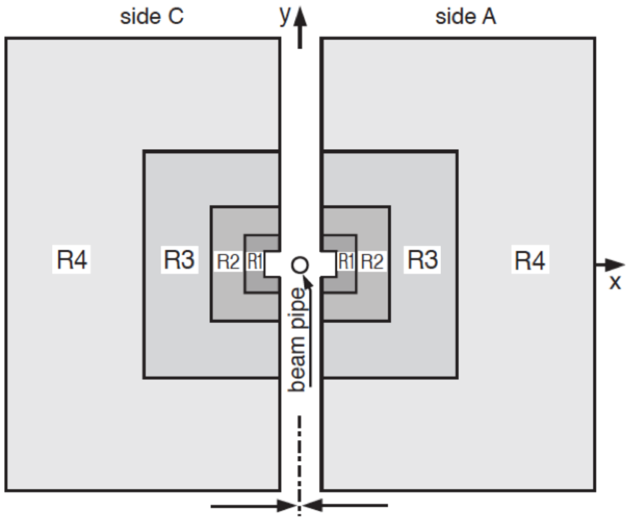
Performance of the LHCb RICH detector at the LHCThe European Physical Journal CMay 2013, 73:2431

CERN-LHCC-2013-022 ; LHCB-TDR-014. - 2013.

MUON system



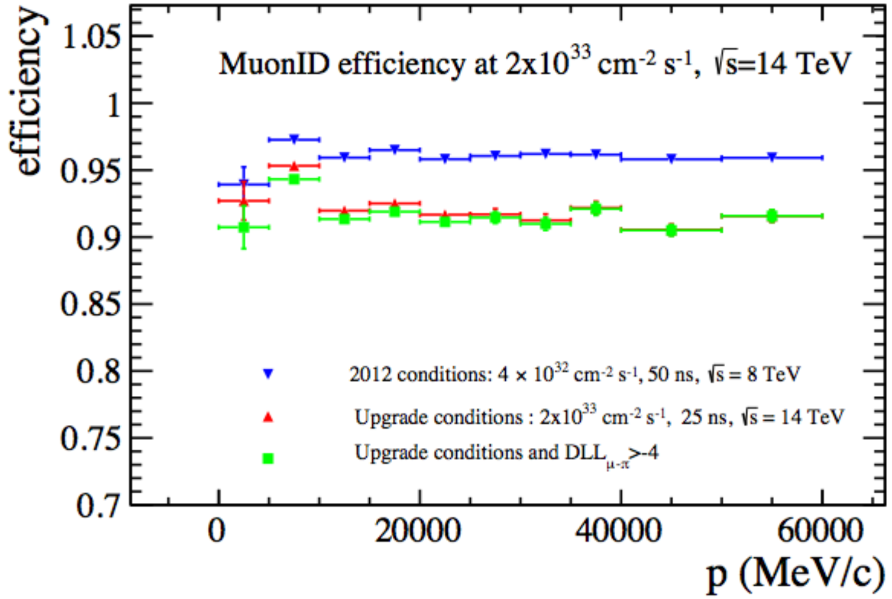
Anode-pad triple-GEM detectors for the R1 regions, MWPCs for the external regions.



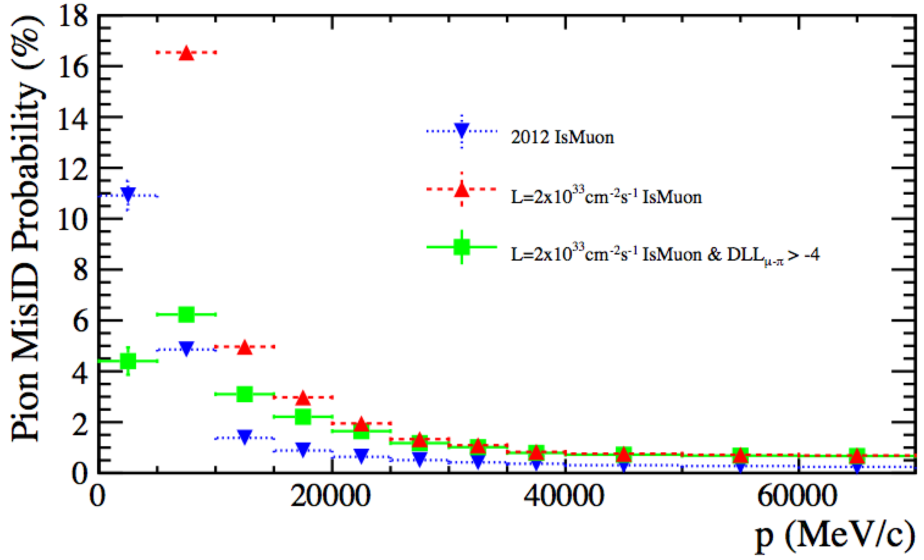
- M1 will be removed: currently used by the L0 trigger.
- High particle flux in the innermost regions of station M2.
  Shielding will be installed around the beam-pipe, behind the HCAL, to reduce the occupancy in these regions.

MUON ID Performance

Efficiency



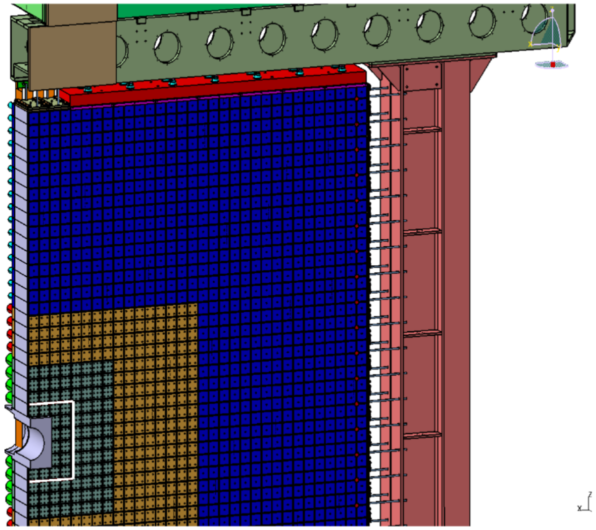
Pion MisID

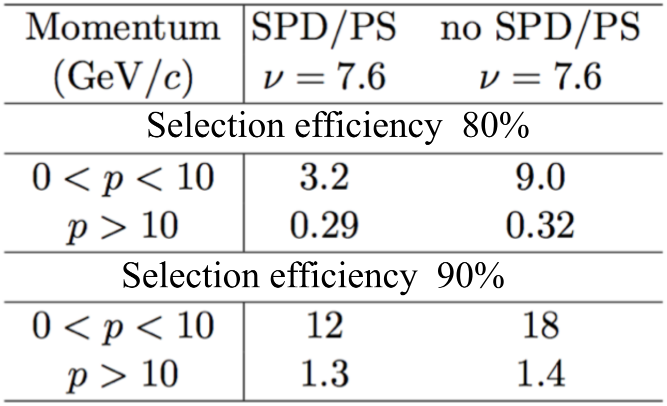


- The efficiency is obtained from a simulated sample of $B_s \rightarrow \mu^+\mu^-$ events and is evaluated for single muon.
- DLL$_{\mu\pi}$ variable: based on the distance of matching hits from the extrapolated track in the muon stations, combined with the information coming from RICH and calorimeter detectors.

Calorimeters

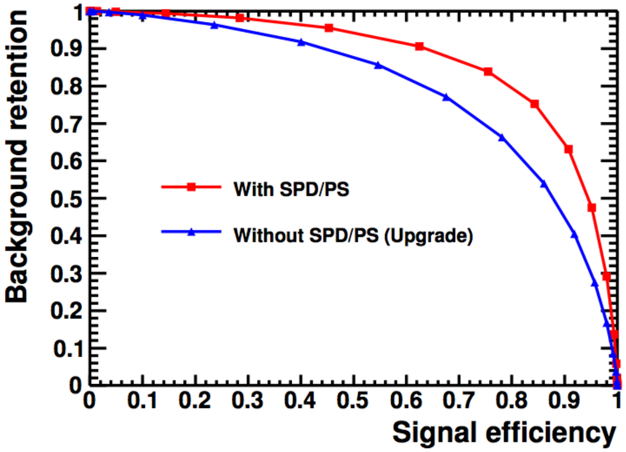
- The scintillating pad detector (SPD) and the pre-shower (PS) will be removed.
- Very little effect for the higher electron momentum sample p > 10 GeV/c
- A reduction of 10 to 15% in the efficiency is observed at a fixed background retention for lower momenta.





Momentum (GeV/c)	SPD/PS $\nu = 7.6$	no SPD/PS $\nu = 7.6$
Selection efficiency 80%		
$0 < p < 10$	3.2	9.0
$p > 10$	0.29	0.32
Selection efficiency 90%		
$0 < p < 10$	12	18
$p > 10$	1.3	1.4

Photon selection



LHCb Upgrade TDRs


LHCb UPGRADE

Letter of Intent

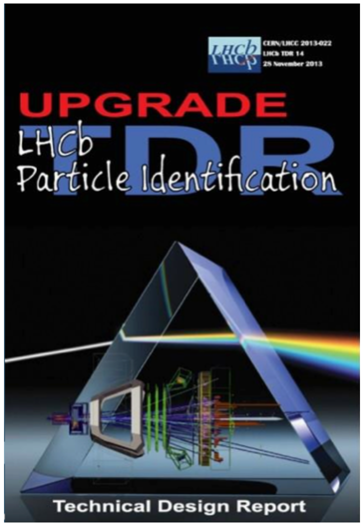
CERN-LHCC-2011-001


Framework TDR

LHCb UPGRADE

Technical Design Report

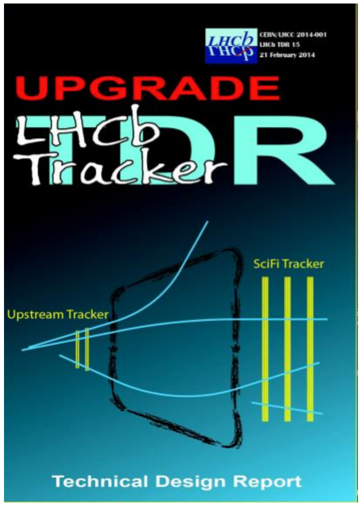
CERN-LHCC-2012-007


UPGRADE TDR

LHCb Particle Identification

Technical Design Report

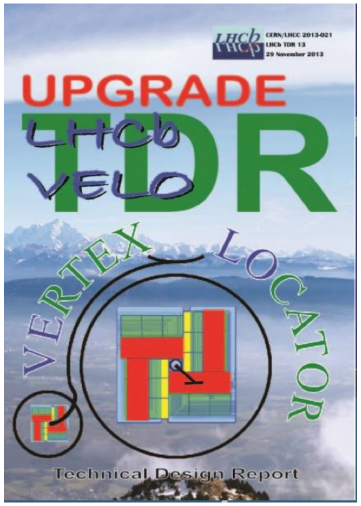
CERN-LHCC-2013-001


UPGRADE TDR

LHCb Tracker

Technical Design Report

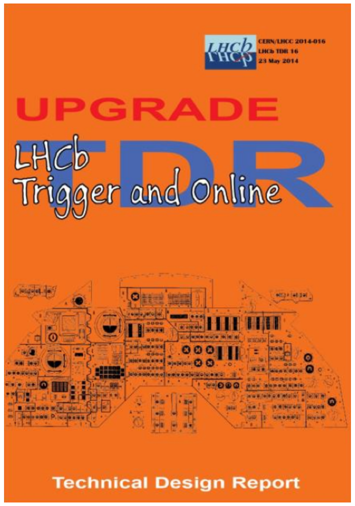
CERN-LHCC-2013-021


UPGRADE TDR

LHCb VELO

Technical Design Report

CERN-LHCC-2014-001


UPGRADE TDR

LHCb Trigger and Online

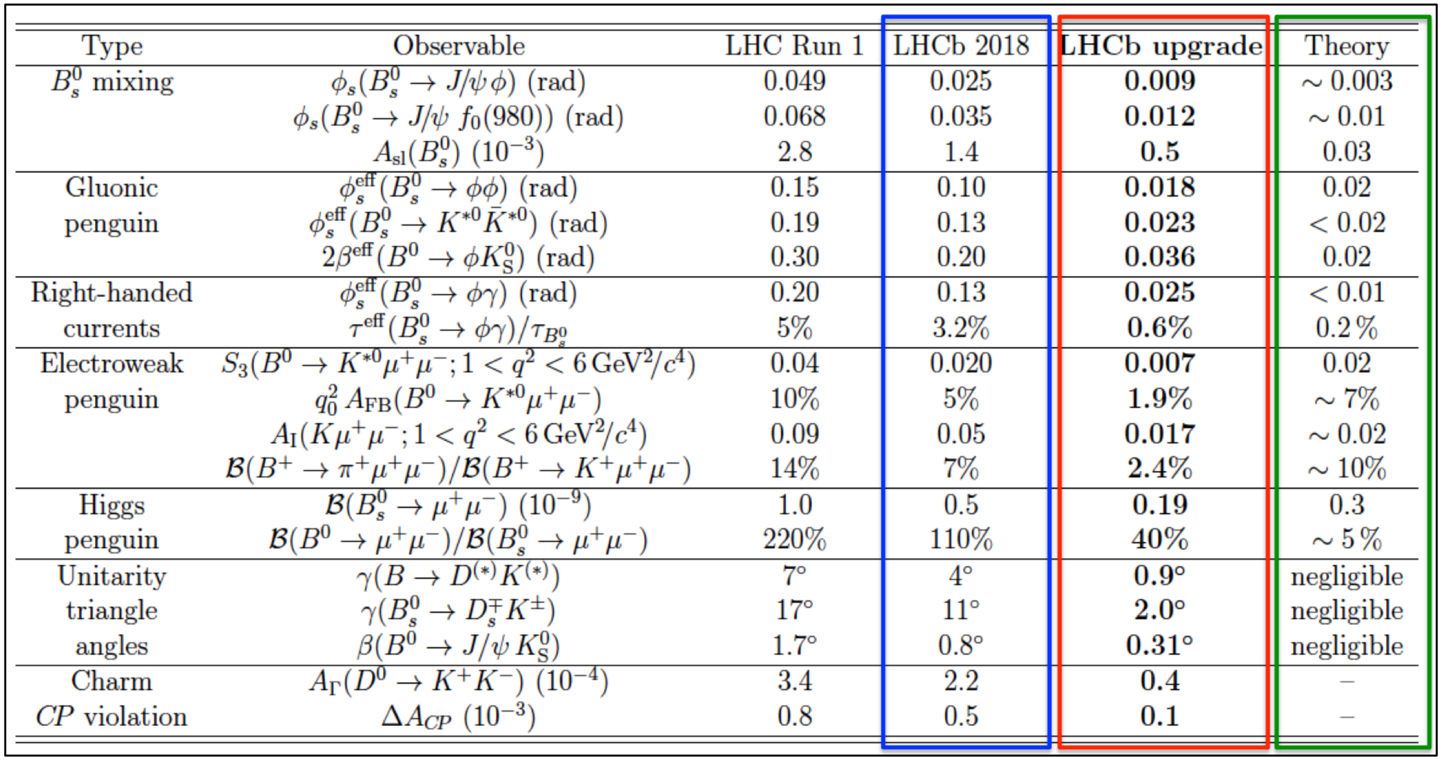
Technical Design Report

CERN-LHCC-2014-016

Examples of prospects

LHC era			**HL-LHC era**	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2020-22)	Run 4 (2025-28)	Run 5+ (2030+)
3 fb^{-1}	8 fb^{-1}	23 fb^{-1}	46 fb^{-1}	100 fb^{-1}

Sensitivity prospects



Type	Observable	LHC Run 1	LHCb 2018	LHCb upgrade	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\mathrm{sl}}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.018**	0.02
	$\phi_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed currents	$\phi_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim$ 7%
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim$ 10%
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim$ 5 %
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**0.9°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm *CP* violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–

LHCb-PUB-2014-040

- Before the upgrade (8 fb^{-1})
- After the upgrade (50 fb^{-1})
- Theory uncertainty (as far as we know today)

The extrapolations assume:

- Precisions scale as √L.
- Gain ×2 on fully hadronic decays removing L0 trigger.
- HLT and analysis performance as in Run I
- Backgrounds as in Run I.

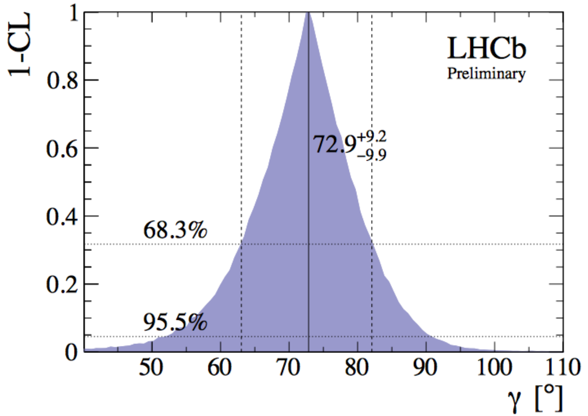
γ from trees

- **Combining several independent decay modes is the key to achieve the ultimate precision.**
- **Time-independent**, $B^{\pm} \rightarrow DK^{\pm}$, $B^{\pm} \rightarrow D\pi^{\pm}$ and $B^0 \rightarrow DK^{*0}$ decays
  - $B^+ \rightarrow Dh^+$, $D \rightarrow hh$, GLW/ADS, Phys. Lett. **B712** (2012) 203
  - $B^+ \rightarrow Dh^+$, $D \rightarrow K\pi\pi\pi$, ADS, Phys. Lett. **B723** (2013) 44
  - $B^+ \rightarrow DK^+$, $D \rightarrow K_S hh$, GGSZ, JHEP **10** (2014) 097 ←
  - $B^+ \rightarrow DK^+$, $D \rightarrow K_S K\pi$, GLS, Phys. Lett. B733 (2014) 36
  - $B^0 \rightarrow DK^{*0}$, $D \rightarrow hh$, GLW/ADS, Phys. Rev. D90 (2014) 112002
- **Time-independent**, $B_S \rightarrow D_S K$, JHEP 11 (2014) 060

$$\boxed{\gamma \equiv Arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)}$$

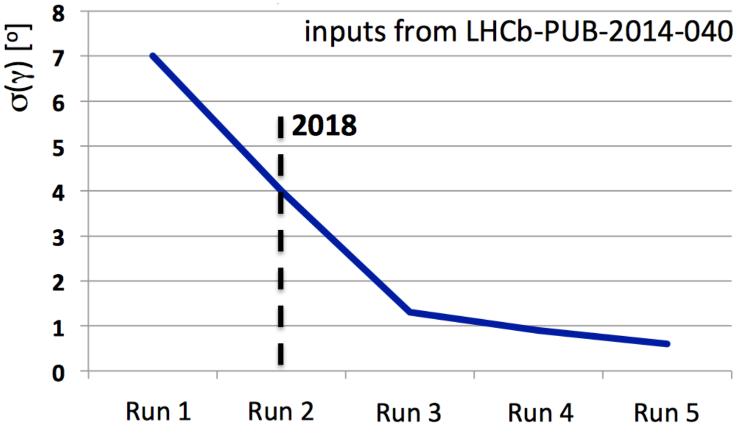
$$\boxed{\gamma = \left(62^{+15}_{-12}\right)^{\circ}}$$

LHCb is now starting to dominate the world average



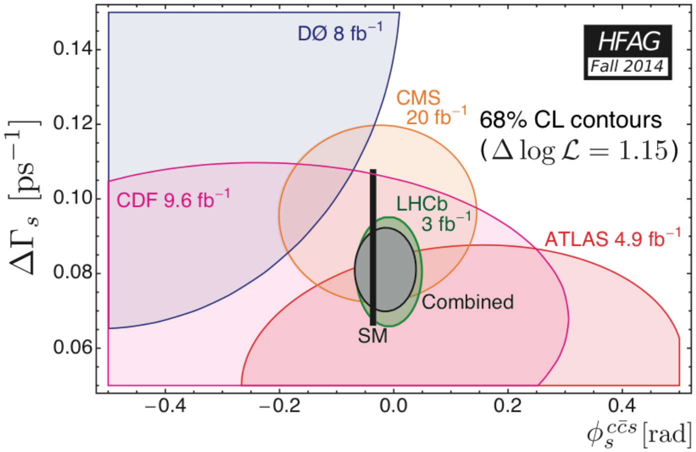
LHCb-CONF-2014-004

σ(γ)≈4° by 2018 and sub-degree precision by the end of the experimental programme



CP induced by B_s mixing: ϕ_s

World average: ϕ_s = – 15 ± 35 mrad

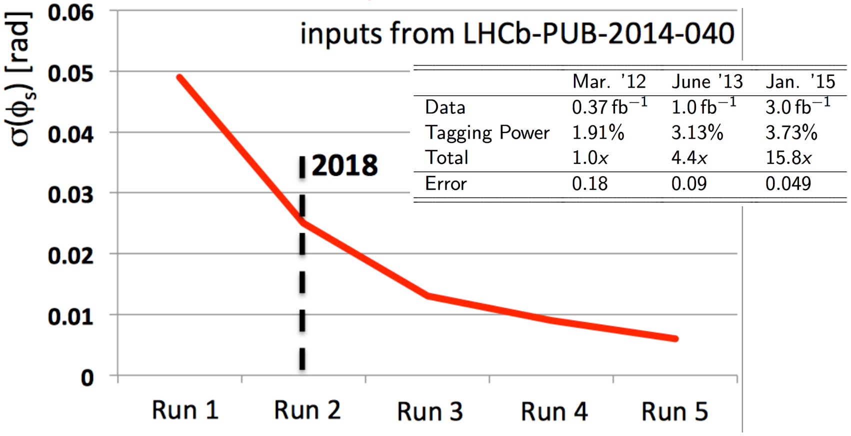


LHCb average: ϕ_s = – 10 ± 40 mrad

- LHCb results with 3 fb^{-1}
- $B_s \rightarrow J/\psi K^+K^-$, ϕ_s = -58 ± 49 ± 6 mrad
  - Phys. Rev. Lett. **114** (2015) 041801
- $B_s \rightarrow J/\psi \pi^+\pi^-$, ϕ_s = 70 ± 68 ± 8 mrad
  - Phys. Lett. **B736** (2014) 186
- $B_s \rightarrow D^+_s D^-_s$ = 20 ± 170 ± 20 mrad
  - Phys. Rev. Lett. **113** (2014) 211801

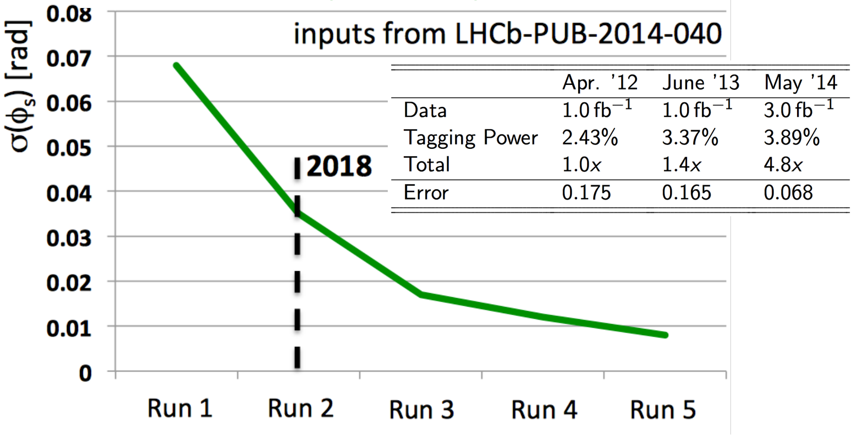
arXiv:1411.3104

$B_s \rightarrow J/\psi\phi$



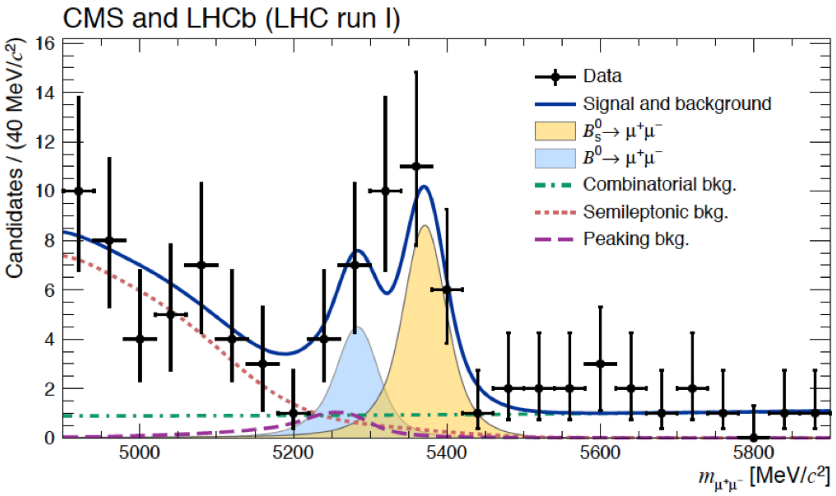
	Mar. '12	June '13	Jan. '15
Data	0.37 fb^{-1}	1.0 fb^{-1}	3.0 fb^{-1}
Tagging Power	1.91%	3.13%	3.73%
Total	1.0*x*	4.4*x*	15.8*x*
Error	0.18	0.09	0.049

$B_s \rightarrow J/\psi f_0$



	Apr. '12	June '13	May '14
Data	1.0 fb^{-1}	1.0 fb^{-1}	3.0 fb^{-1}
Tagging Power	2.43%	3.37%	3.89%
Total	1.0*x*	1.4*x*	4.8*x*
Error	0.175	0.165	0.068

$B_{d,s} \rightarrow \mu^+\mu^-$



Uncertainties include both statistical and systematic: 35% and 18% of the total uncertainty respectively.

Significance of $B_s \rightarrow \mu\mu$:

– First observation at 6.2σ

– Compatibility with the SM at 1.2σ

$B^0 \rightarrow \mu\mu$ hypothesis:

– Excess of events at the 3σ level observed with respect to background.

– Compatible with SM at 2.2σ

CMS & LHCb

$$\mathcal{B}\left(B_s \rightarrow \mu^+\mu^-\right) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

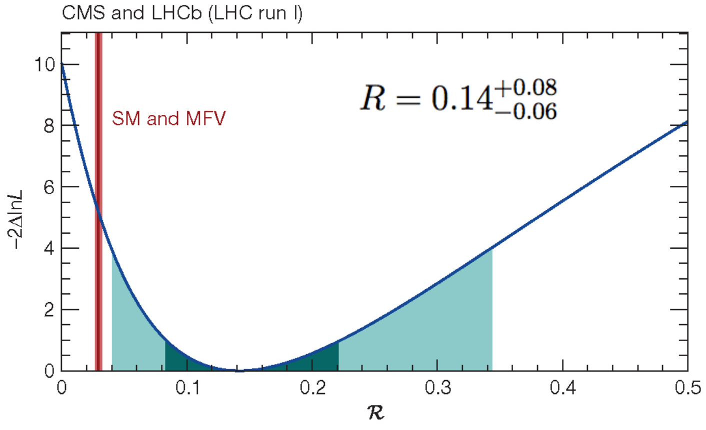
$$\mathcal{B}\left(B^0 \rightarrow \mu^+\mu^-\right) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$$

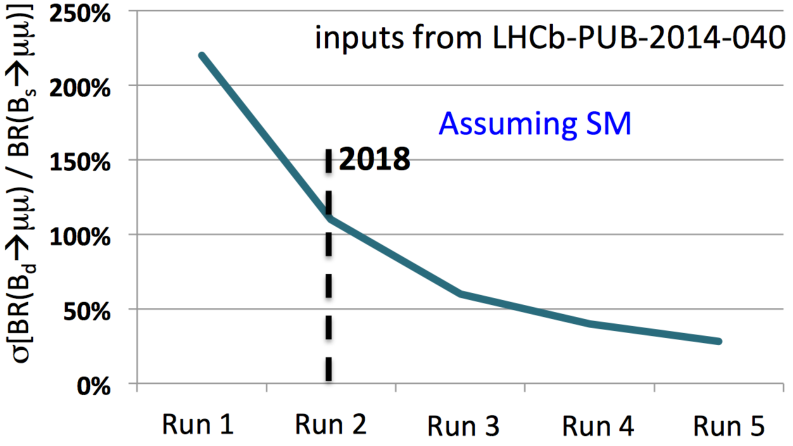
LHCb

$$\mathcal{B}\left(B_s \rightarrow \mu^+\mu^-\right) = 2.9^{+1.1}_{-1.0} \times 10^{-9}$$

$$\mathcal{B}\left(B^0 \rightarrow \mu^+\mu^-\right) < 7.4 \times 10^{-10} \quad 95\%\ C.L.$$

Likelihood of $\mathfrak{B}(B_d \rightarrow \mu^+\mu^-)/\mathfrak{B}(B_s \rightarrow \mu^+\mu^-)$



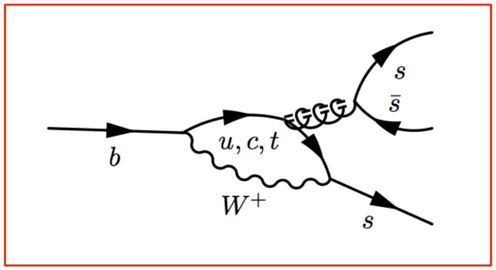


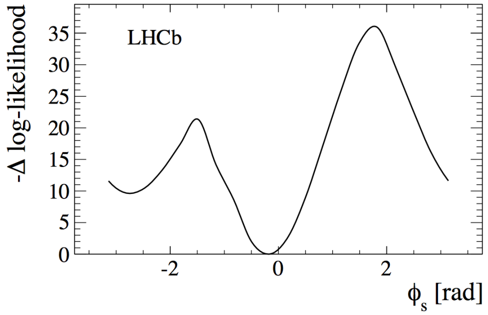
arXiv:1411.4413 Nature (2015) doi:10.1038/nature14474

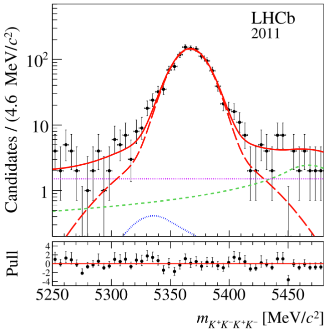
arXiv:1307.5024

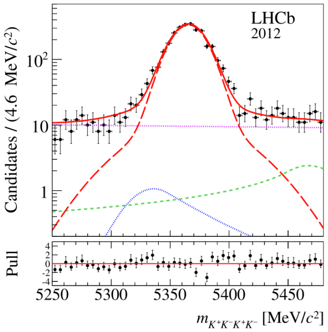
CP violation in $B_s \to \phi\phi$

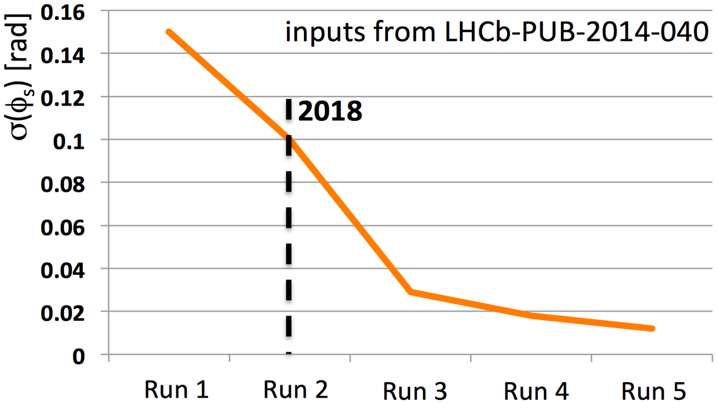
- FCNC gluonic $b \to s\bar{s}s$ penguin
  - Provides an excellent probe of new heavy particles entering the penguin quantum loops.
- Latest LHCb result with full Run 1 data set, with approximately 4000 events: $\phi_s = (-170 \pm 150 \pm 30)$ mrad
- Overall precision comparable to golden $b \to c\bar{c}s$ modes.
- No sign of discrepancy.











Phys. Rev. D90 (2014) 052011, arXiv:1407.2222

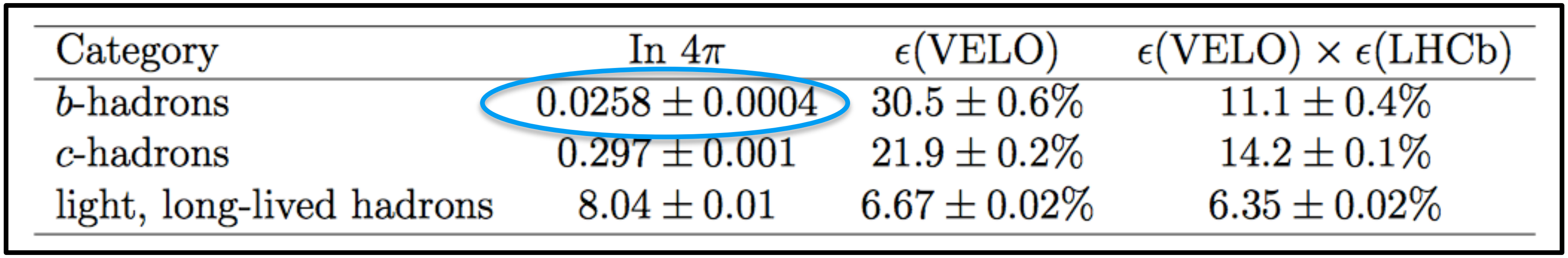
Conclusions

- **LHCb has performed very well in Run 1. Improvements of LHCb results are expected in Run 2**
  Additional 5-6 fb^{-1} at 14 TeV expected by 2018
- **The LHCb upgraded detector will start taking data in 2020**
  New PCIe based read out and full HLT software trigger at 40 MHz.
  Optimized tracking system and good PID.
- **With the upgraded detector LHCb aims to collect 50 fb^{-1} by 2028**
  An order of magnitude more data than Run 1 and Run 2,
  with doubled trigger efficiency on hadronic channels.
- **LHCb prospects look excellent**
  Heavy flavour physics has still large room for improvements.
  Key measurements are far from being limited by systematic uncertainties.
  LHCb has great potential of discovering indirect evidence of NP in future measurements.

The End

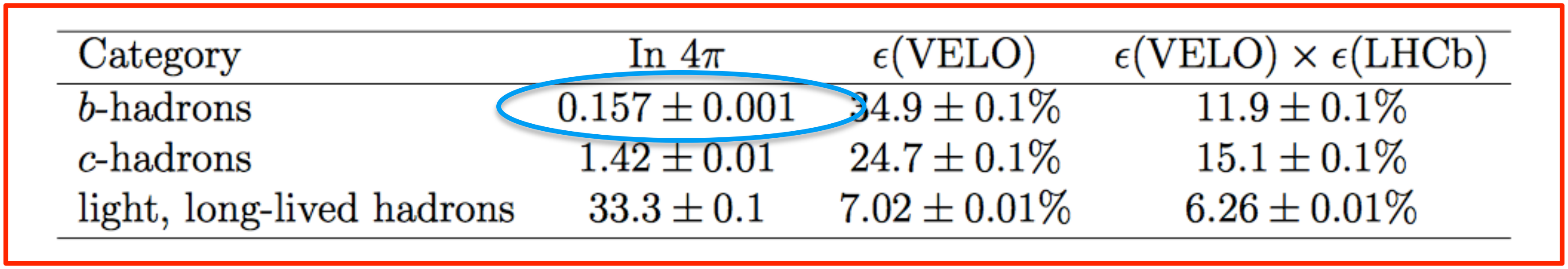
Event yield comparison (generator level)

Current



Category	In 4π	ϵ(VELO)	ϵ(VELO) × ϵ(LHCb)
b-hadrons	0.0258 ± 0.0004	$30.5 \pm 0.6\%$	$11.1 \pm 0.4\%$
c-hadrons	0.297 ± 0.001	$21.9 \pm 0.2\%$	$14.2 \pm 0.1\%$
light, long-lived hadrons	8.04 ± 0.01	$6.67 \pm 0.02\%$	$6.35 \pm 0.02\%$

Upgrade



Category	In 4π	ϵ(VELO)	ϵ(VELO) × ϵ(LHCb)
b-hadrons	0.157 ± 0.001	$34.9 \pm 0.1\%$	$11.9 \pm 0.1\%$
c-hadrons	1.42 ± 0.01	$24.7 \pm 0.1\%$	$15.1 \pm 0.1\%$
light, long-lived hadrons	33.3 ± 0.1	$7.02 \pm 0.01\%$	$6.26 \pm 0.01\%$

A **factor of five** increase in the per-event rate of charm hadrons within the LHCb acceptance; a **factor six** increase in the per-event rate for beauty hadrons; more than two reconstructible SVs from light long-lived particles per event.