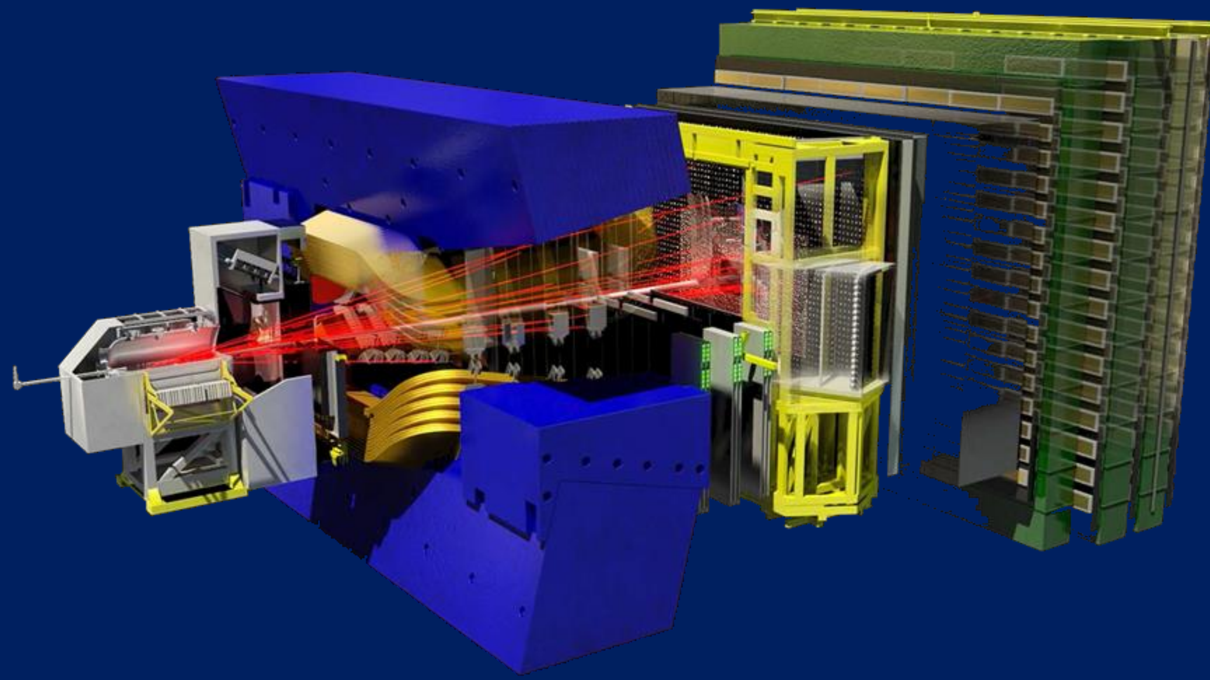


The LHCb upgrade

Burkhard Schmidt, CERN
on behalf of the LHCb Collaboration

Overview

- Introduction to LHCb
- LHCb upgrade
  - Physics Motivation
  - Trigger upgrade
  - Detector upgrade
    - Vertexing and tracking
    - Particle Identification
- Conclusions

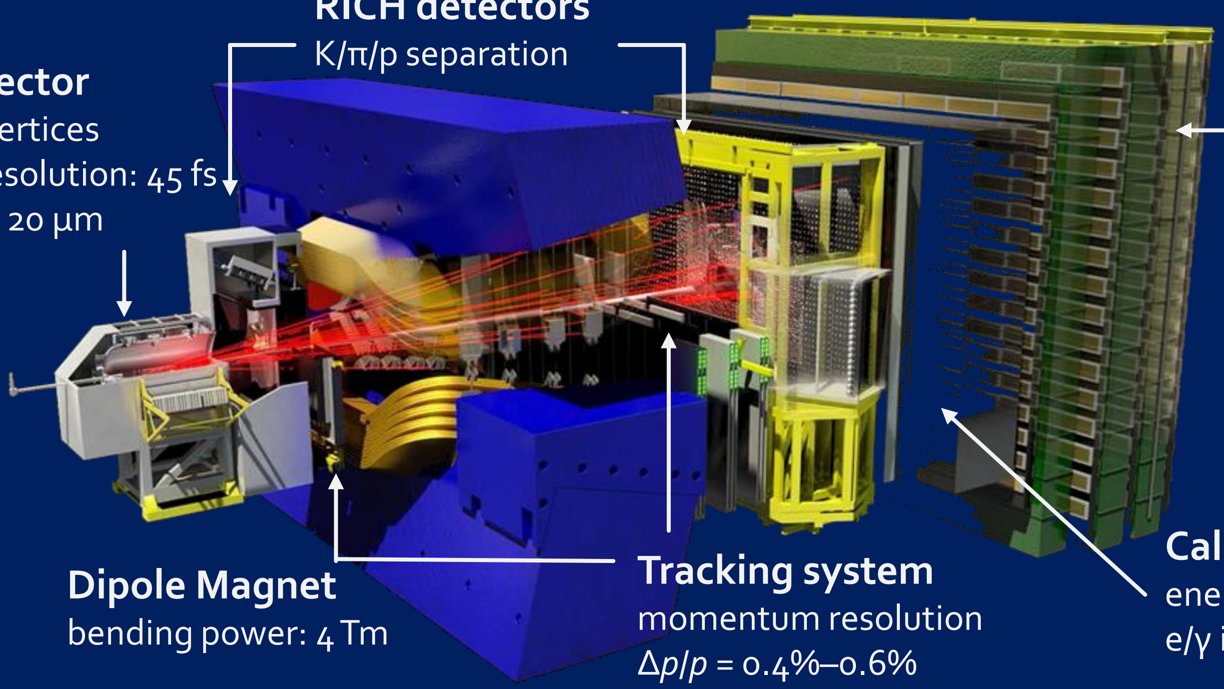
LHCb Collaboration

- ~900 physicists
- 64 universities
- 16 countries

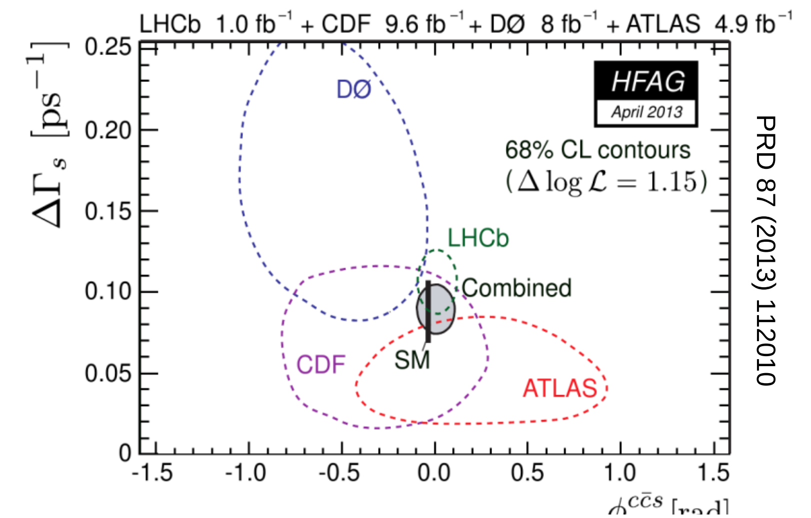
Introduction

LHCb is a high precision experiment devoted to the search for New Physics (NP) beyond the Standard Model (SM)

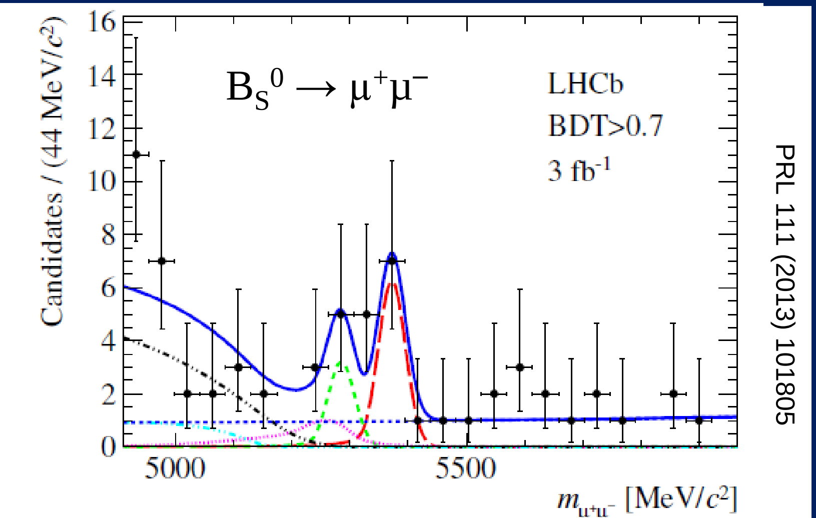
- Study CP violation and rare decays in the b and c-quark sectors
- Search for deviations from the SM due to virtual contributions of new heavy particles in loop diagrams
- Sensitive to new particles above the TeV scale not accessible to direct searches



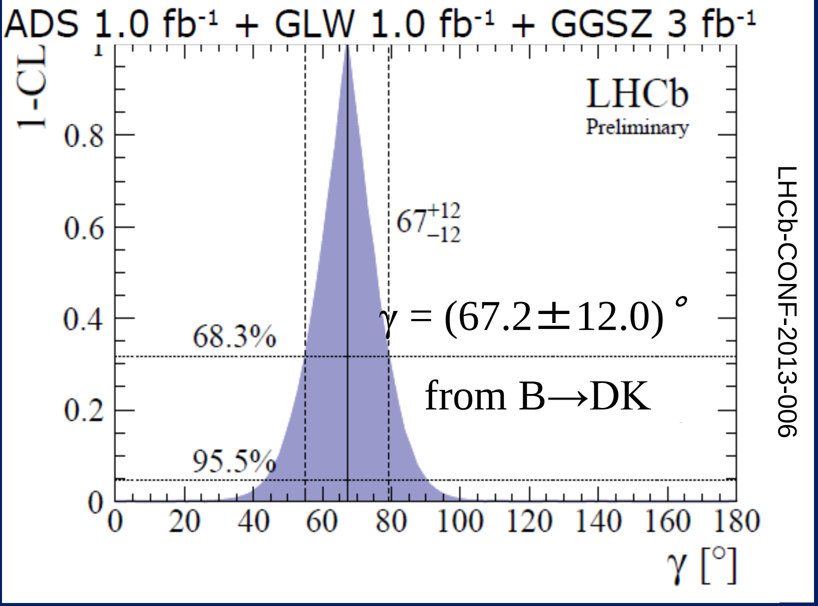
Some highlights of LHCb results

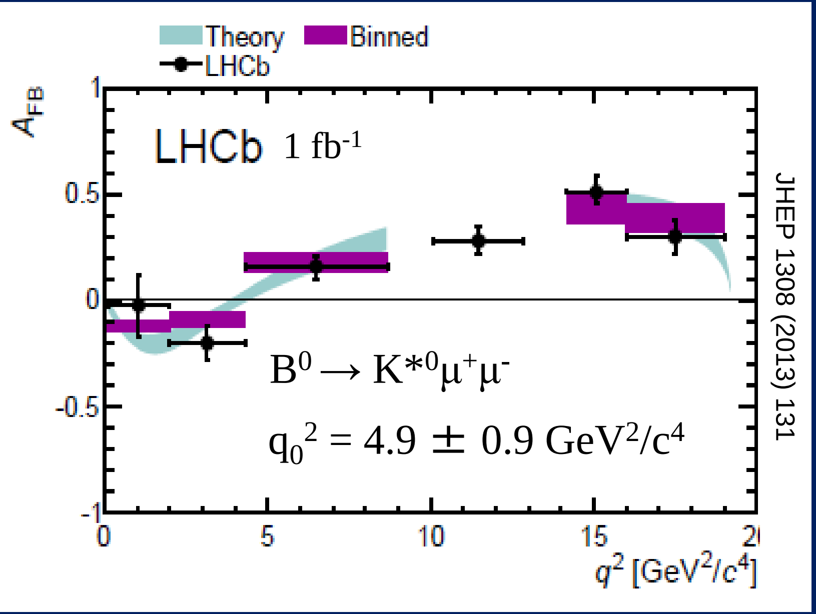


$\Phi_s = 0.01 \pm 0.07(stat) \pm 0.01(syst)$



$BR(B_S^0 \to \mu^+\mu^-) = (2.9^{+1.1}_{-1.0}(stat)^{+0.3}_{-0.1}(syst)) \times 10^{-9}$





Motivation for the LHCb upgrade

Present experimental status:

- flavour changing processes are consistent with the CKM mechanism
- large sources of flavour symmetry breaking are excluded at the TeV scale
- the flavour structure of NP would be very peculiar at the TeV scale (MFV)

Why is the LHCb upgrade important:

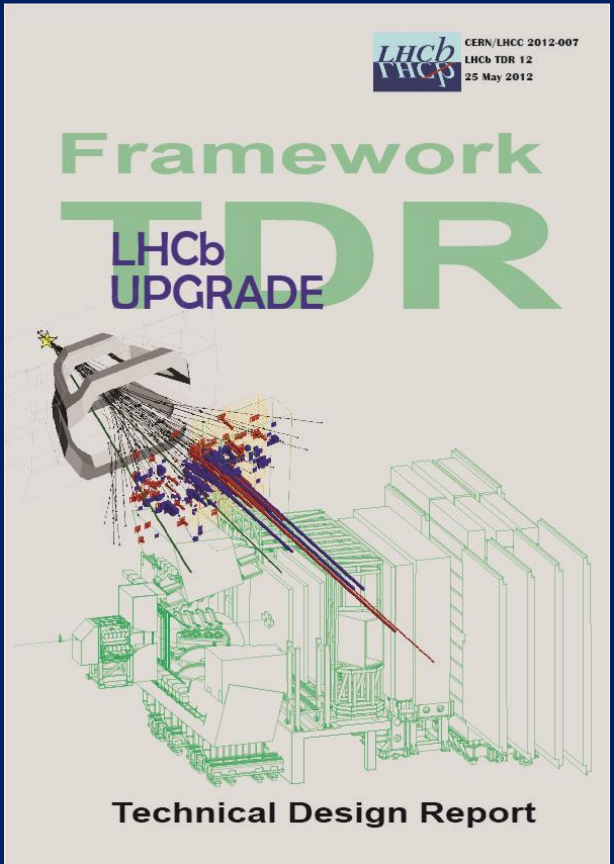
- measurable deviations from the SM are still expected, but should be small
- need to go to high precision measurements to probe clean observables

→ LHCb upgrade essential to increase statistical precision significantly

- Quark flavour physics main component, but physics program includes also:
  - Lepton flavour physics
  - Electroweak physics
  - Exotic searches, proton-ion physics

→ Reinforce LHCb as general purpose forward detector

LHCb upgrade



CERN-LHCC-2011-001

CERN-LHCC-2012-007

Expected luminosity evolution

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

LHC Run I
pp runs with
- 50ns bunch spacing
- E_{CM} 7TeV and 8 TeV

LHCb $\mathcal{L}$~4x10³²/cm²/s
LHCb $\int\mathcal{L}$ ~3/fb

LS1
LHC splice consolidation

LHC Run II
pp runs with
- 25ns bunch spacing,
- E_{CM} 13 TeV

LHCb $\mathcal{L}$>4x10³²/cm²/s
LHCb $\int\mathcal{L}$ >5/fb

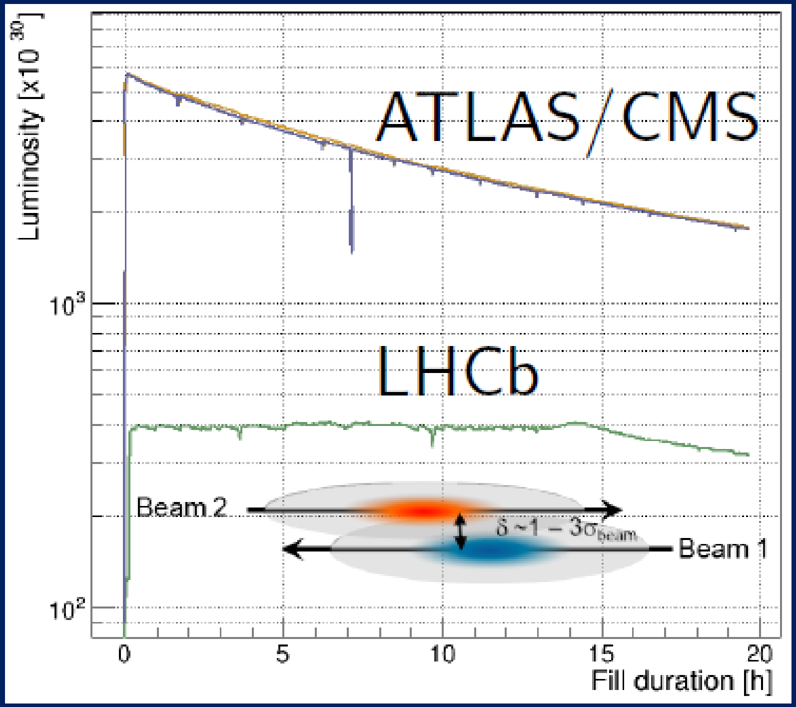
LS 2
LHC injector upgrade
LHCb upgrade

LHC Run III
pp runs with
- 25ns b.spacing
- E_{CM} 14 TeV

$\mathcal{L}$ > 1x10³³/cm²/s
LHCb $\int\mathcal{L}$ > 15/fb

LS3
HL-LHC prep
GPD phase 2 upgrades

LHC Run IV
$\mathcal{L}$=2x10³³/cm²/s
$\int\mathcal{L}$ > 23/fb

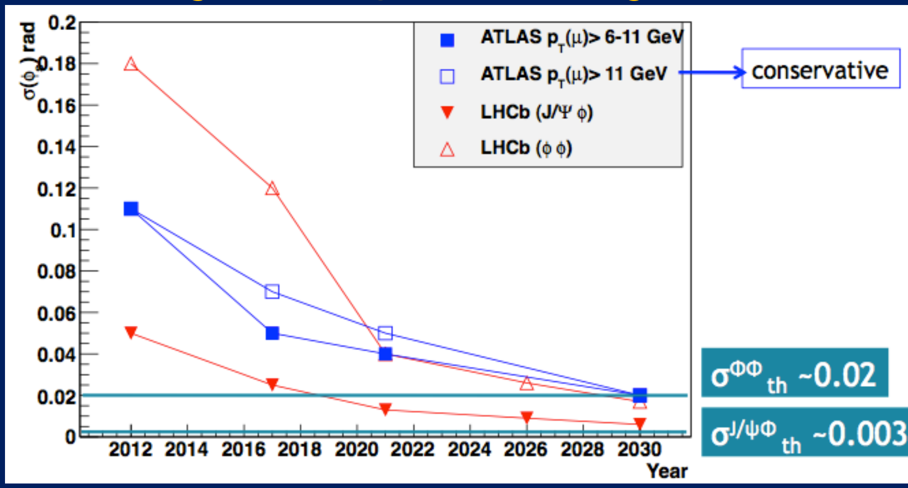


LHCb up to 2018 → ~ 8 fb⁻¹:
- find or rule-out large sources of flavour symmetry breaking at the TeV scale

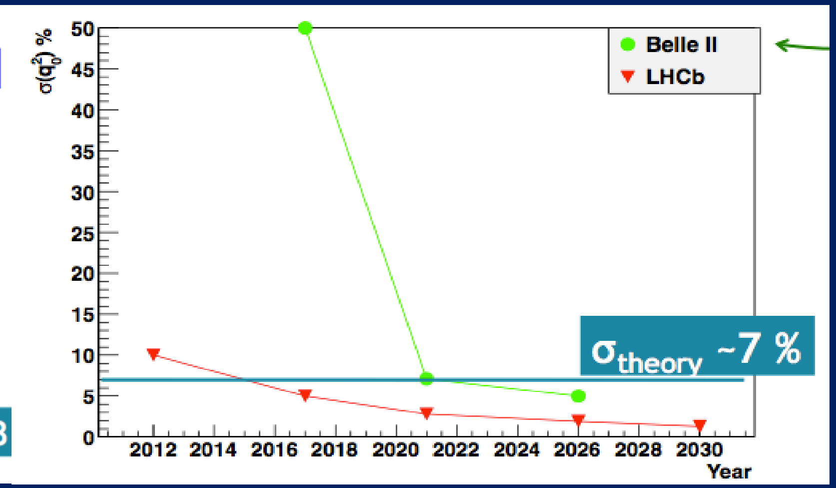
LHCb upgrade → ≥ 50 fb⁻¹:
- increase precision on quark flavour physics observables
- aim at experimental sensitivities comparable to theoretical uncertainties

LHCb upgrade - expected precision

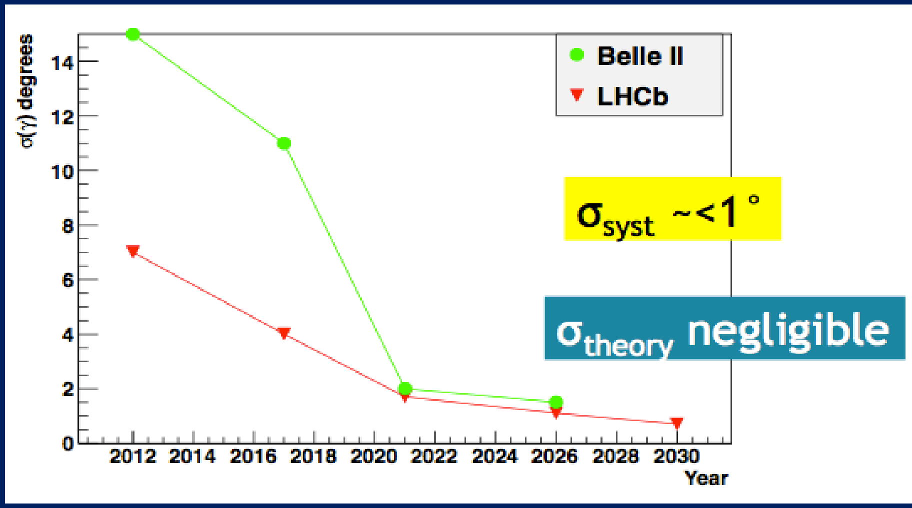
B_s mixing phase ϕ_s



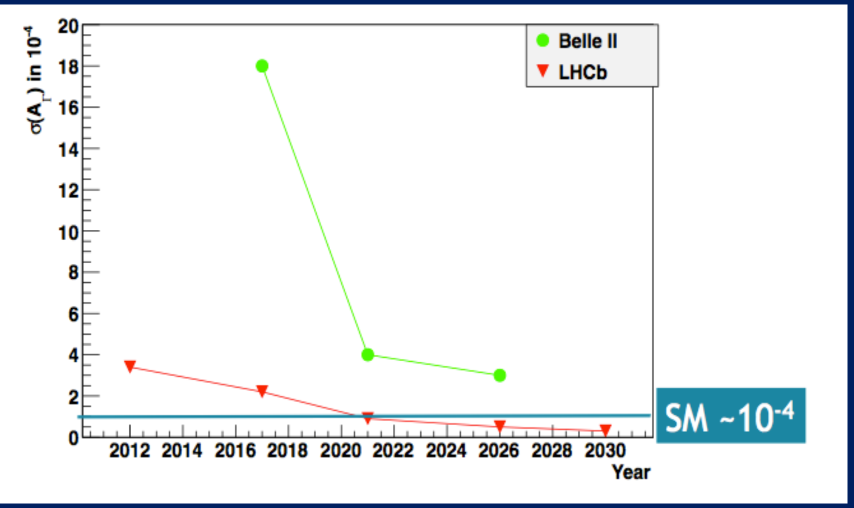
q_o from $B \to K^*ll$



CKM angle γ from trees



A_Γ: CPV in charm



From M.H. Schune, ECFA HL-LHC 2013 workshop

LHCb statistical sensitivity to flavour observables

Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s\ (B_s^0 \to J/\psi\ \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s\ (B_s^0 \to J/\psi\ f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\mathrm{fs}}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\ A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	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–$12°$ [19, 20]	$4°$	$0.9°$	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	$11°$	$2.0°$	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	$0.8°$ [18]	$0.6°$	$0.2°$	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

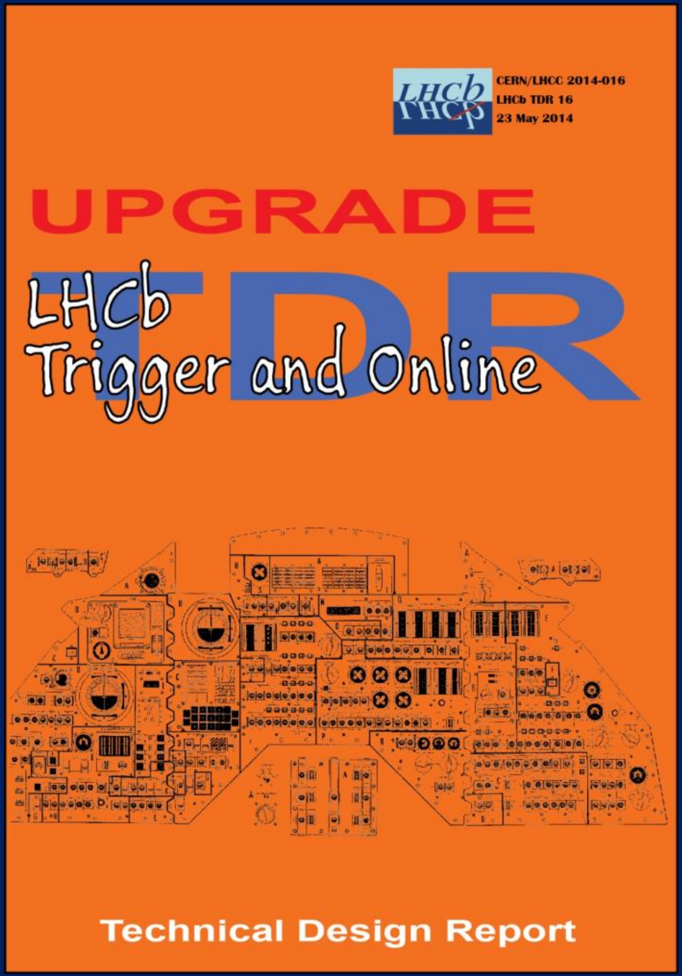
Framework TDR for the LHCb Upgrade
CERN-LHCC-2012-007

Getting close to the theoretical uncertainties

8 fb^{-1} up to 2018

≥ 50 fb^{-1} for the upgrade

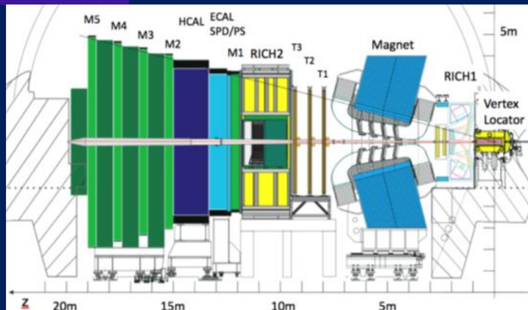
Trigger upgrade

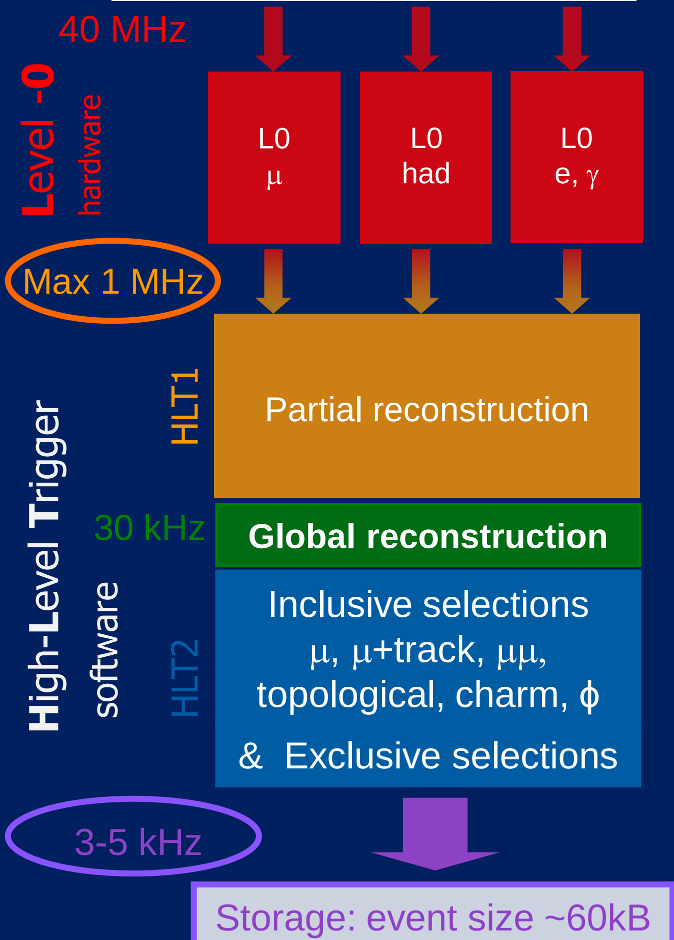


CERN-LHCC-2014-016

- Limitations of the present trigger
- Trigger upgrade

LHCb Trigger – Limitations





- Final states with muons

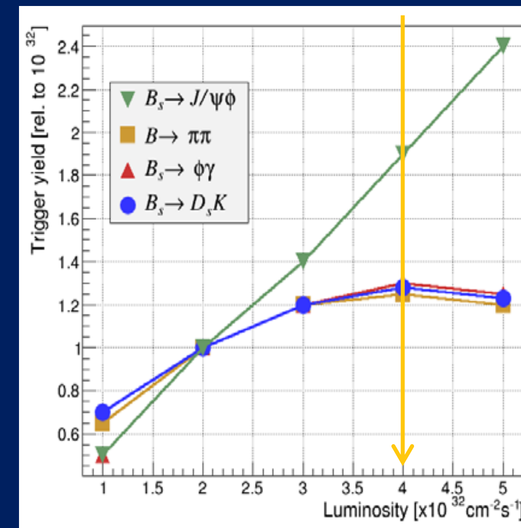
→ Linear gain

- Hadronic final states

→ Yield flattens out

→ Must raise p_T cut to stay within 1 MHz readout limit

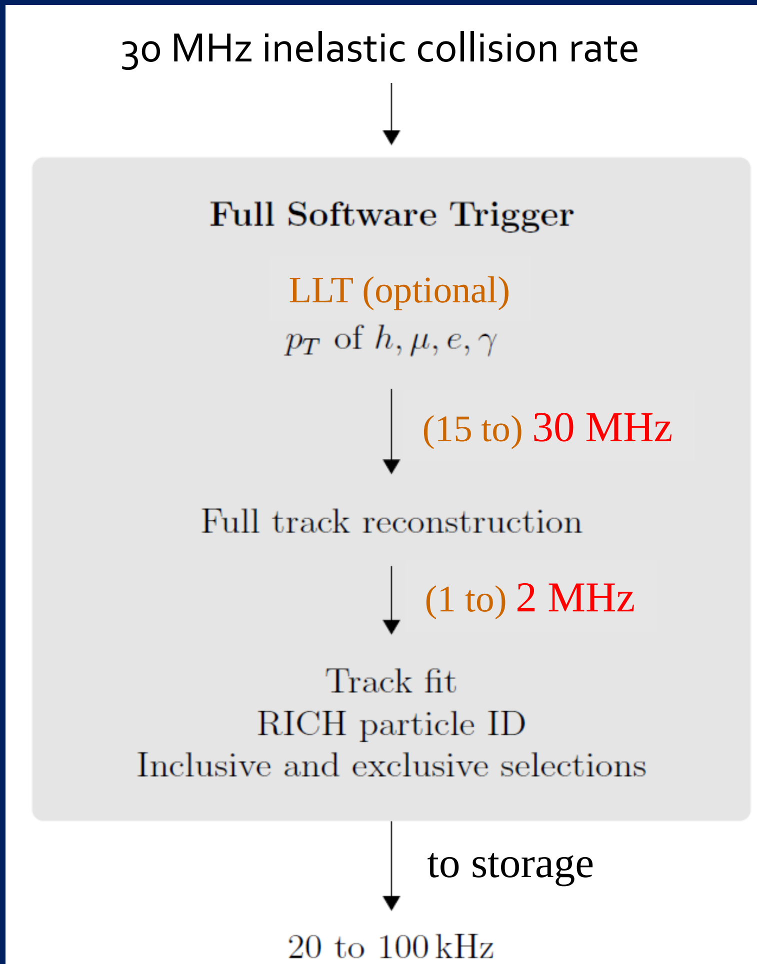
LHCb 2012

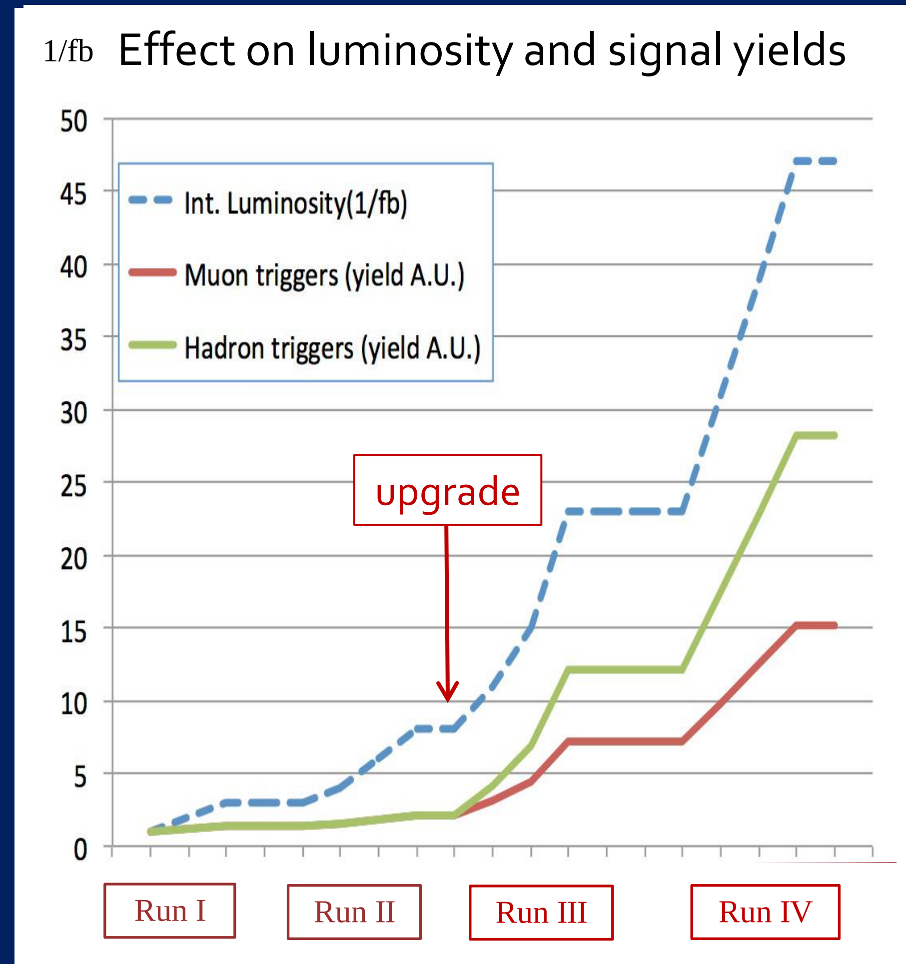


- To profit of a luminosity of $10^{33}cm^{-2}s^{-1}$, information has to be introduced that is more discriminating than E_T.

Upgrade strategy:
40MHz readout rate
Fully software trigger
20kHz output rate

LHCb Trigger Upgrade

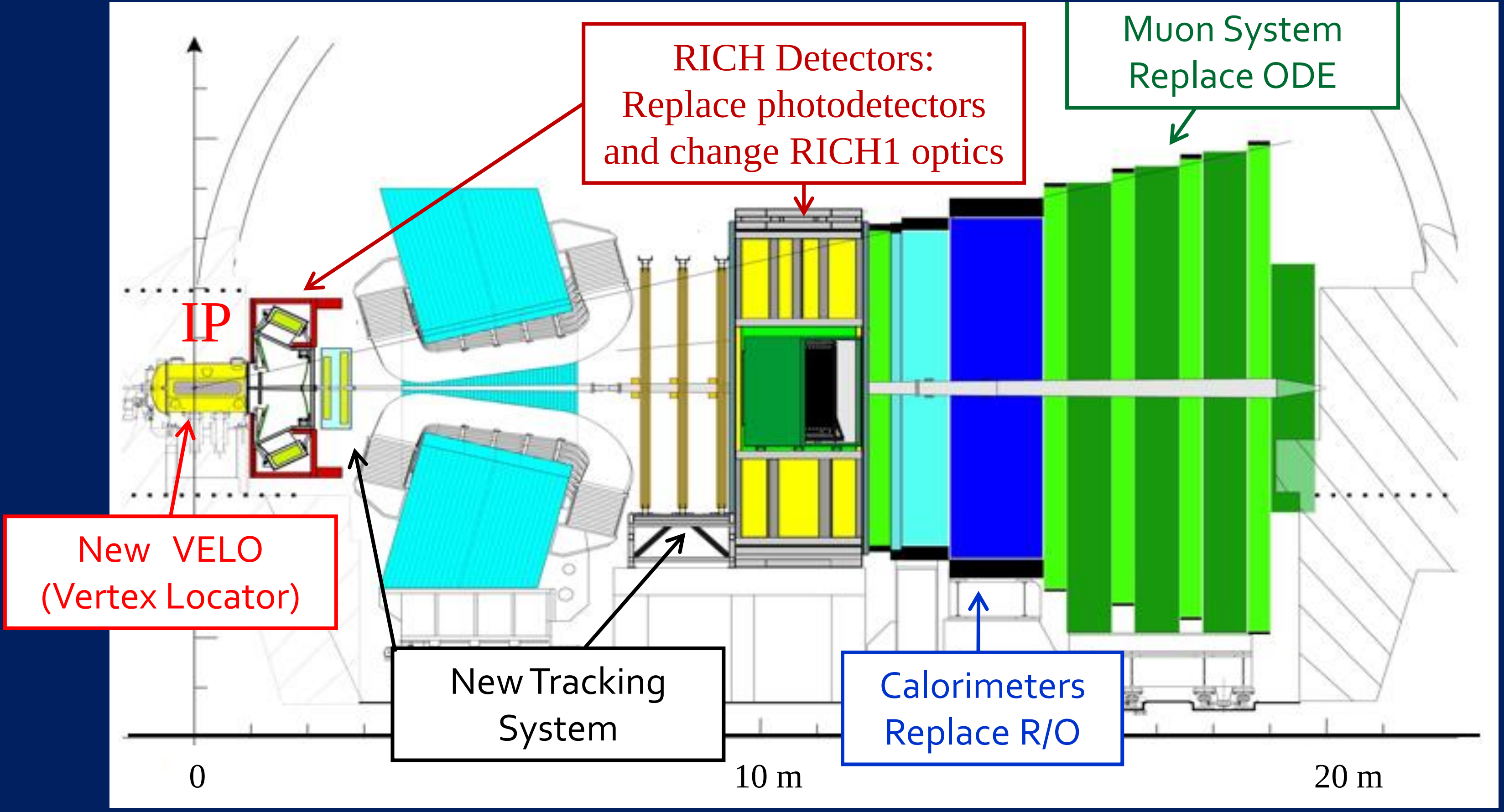




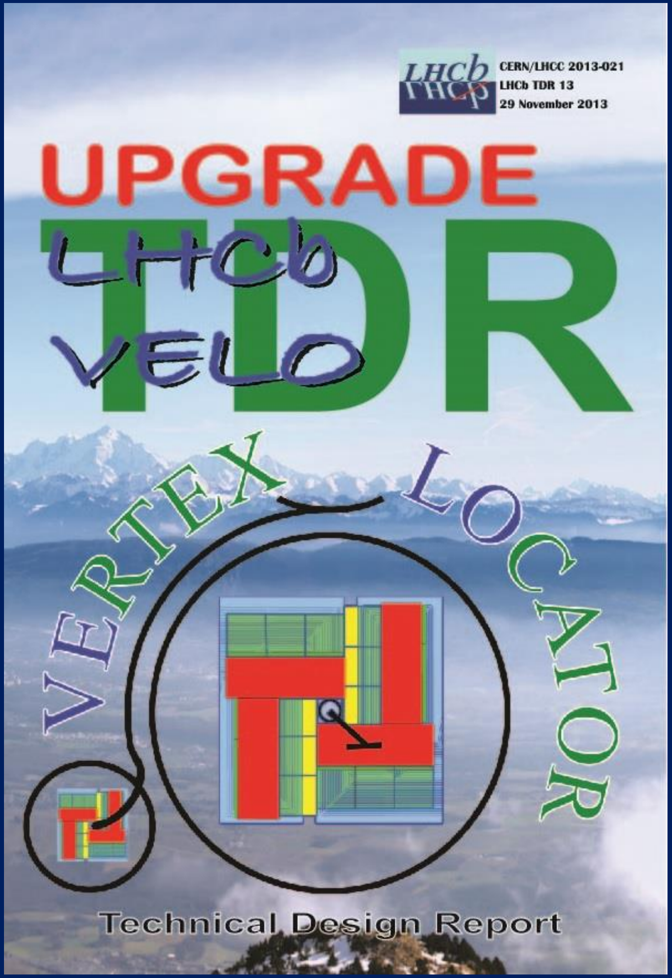
run an efficient and selective software trigger with access to the full detector information at every 25 ns bunch crossing → increase luminosity and signal yields

Detector upgrade to 40 MHz R/O

- upgrade ALL sub-systems to 40 MHz Front-End (FE) electronics
- replace complete sub-systems with embedded FE electronics
- adapt sub-systems to increased occupancies due to higher luminosity
- keep excellent performance of sub-systems with 5 times higher luminosity



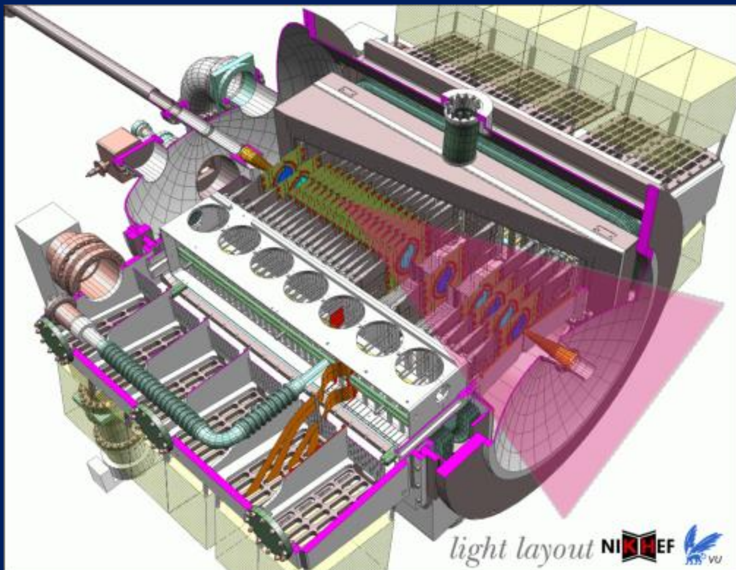
Vertex Detector Upgrade

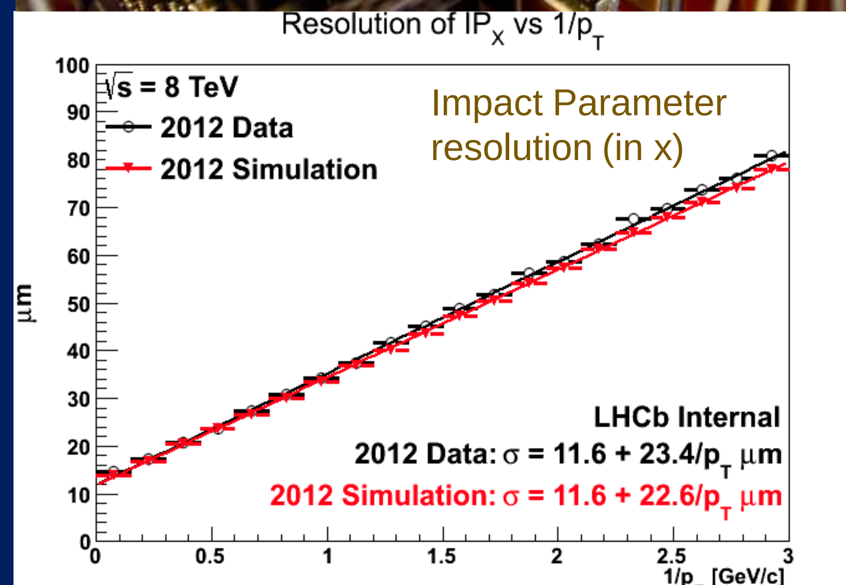


CERN-LHCC-2013-021

- Present detector and its performance
- Detector upgrade
- Expected Performance

Current VErtex LOcator





Two retractable halves

- 5.5 mm from beam when closed
- 30 mm during injection

Operates in secondary vacuum

- 300 μm Al-foils separate detector from beam

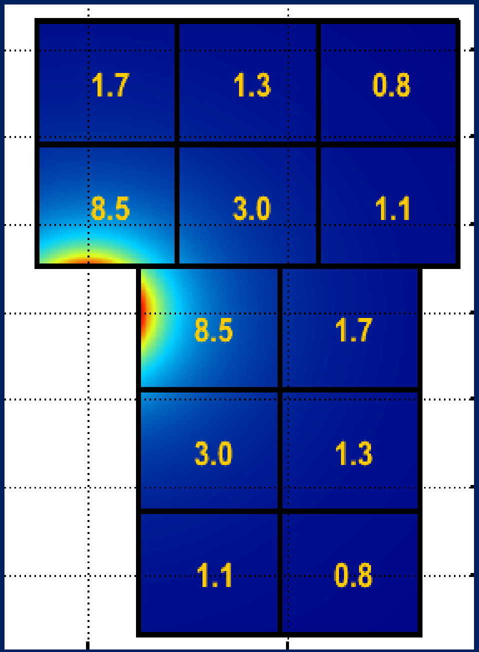
21 R/ Φ modules per half

- Silicon micro-strip sensors
- Pitch 38-101 μm

VELO upgrade

Upgrade challenge:

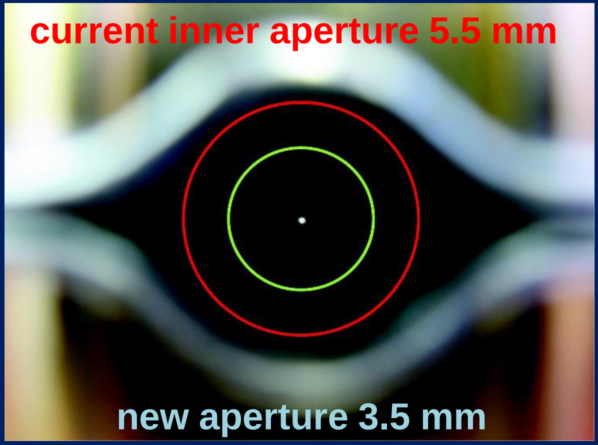
- withstand increased radiation
  - (highly non-uniform radiation of up to $8 \cdot 10^{15}\ n_{eq}/cm^2$ for 50 fb^{-1})
- handle high data volume
- keep (improve) current performance
  - lower materiel budget
  - enlarge acceptance



tracks/chip/event at $L=2 \cdot 10^{33}\ cm^{-2}s^{-1}$

Technical choices :

- 55x55 μm^2 pixel sensors with micro channel CO_2 cooling
- 40 MHz VELOPIX (evolution of TIMEPIX 3, Medipix)
  - 130 nm technology to sustain ~400 MRad in 10 years
- replace RF-foil between detector and beam vacuum
  - reduce thickness from 300 μm ⟶ ≤ 250 μm
- move closer to the beam
  - reduce inner aperture from 5.5 mm ⟶ 3.5 mm



VELO upgrade

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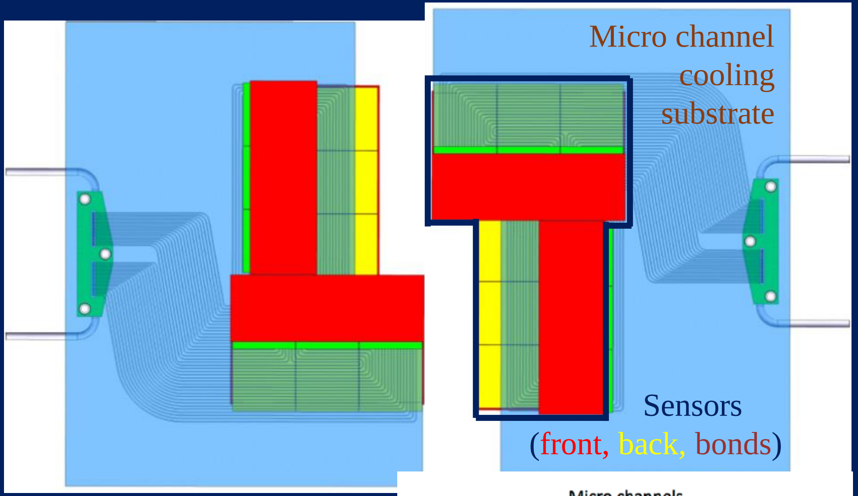

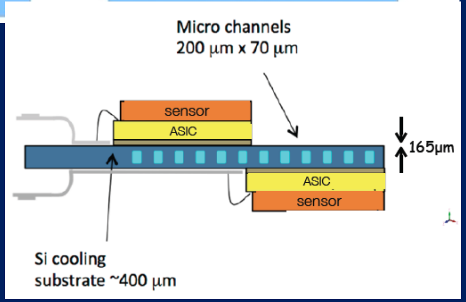

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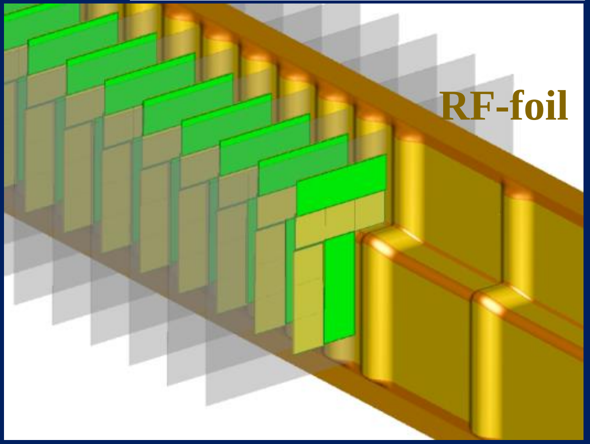
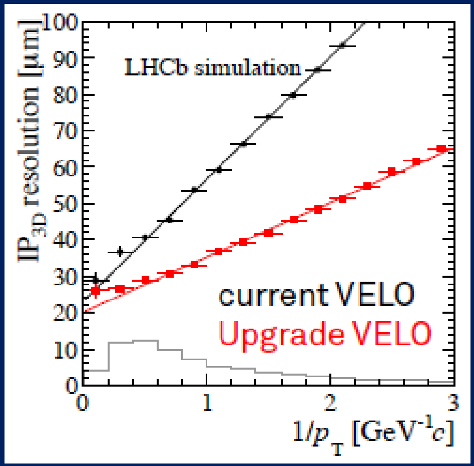
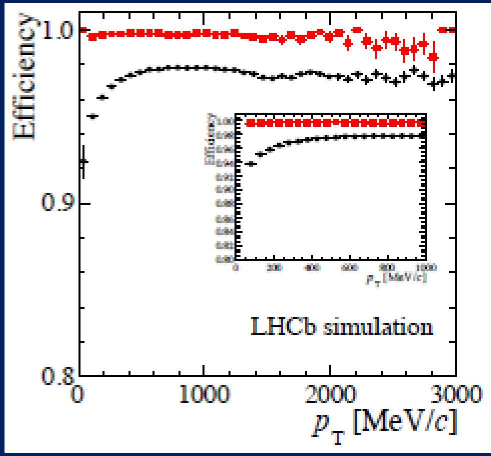


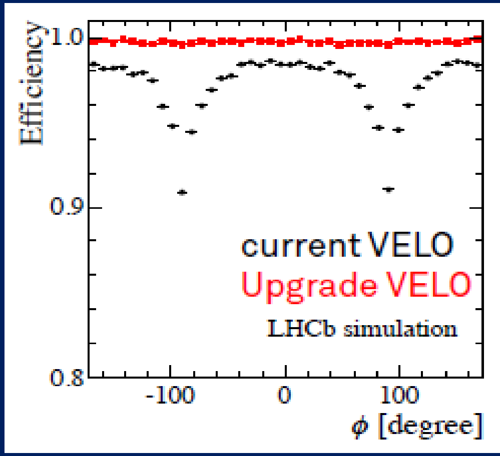
VELO upgrade performance

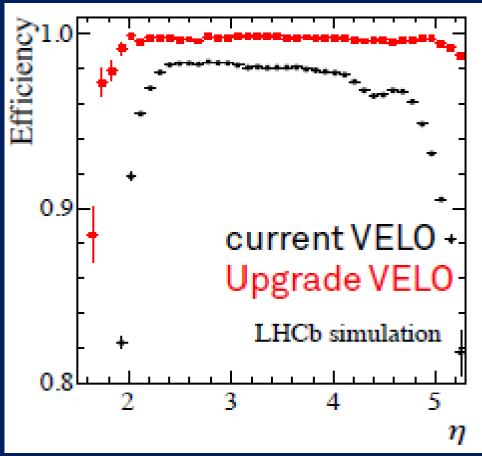
- better impact parameter resolution due to reduced material budget
- reduced ghost rate
- improved efficiency over p_T, ϕ, η



3D IP resolution at $L = 2\cdot10^{33}$ cm^{-2}s^{-1}

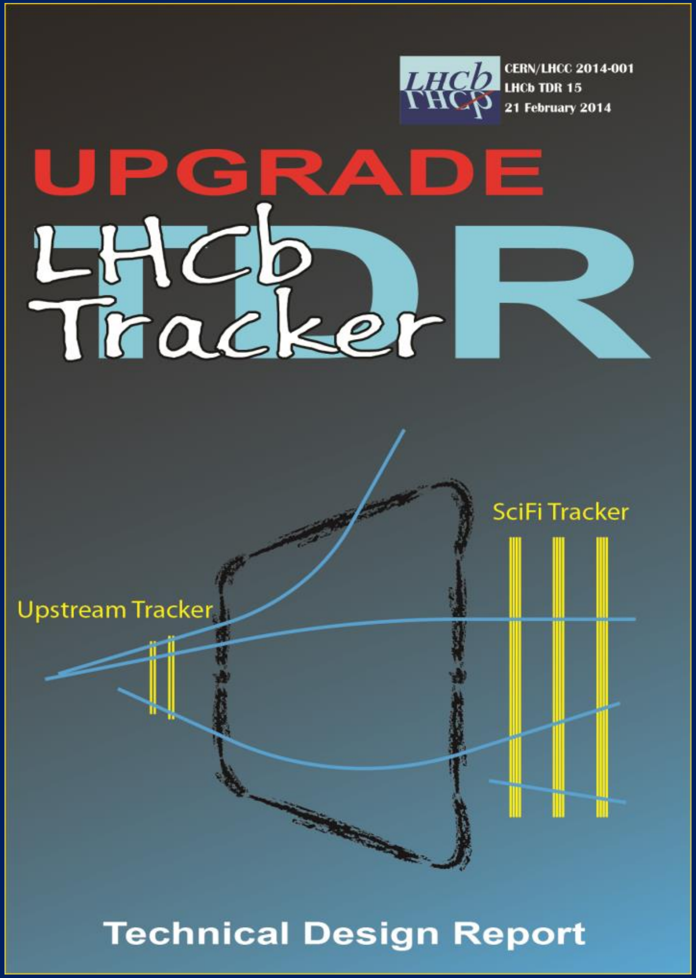






note: full GEANT Monte Carlo with standard LHCb simulation framework

Tracker Upgrade

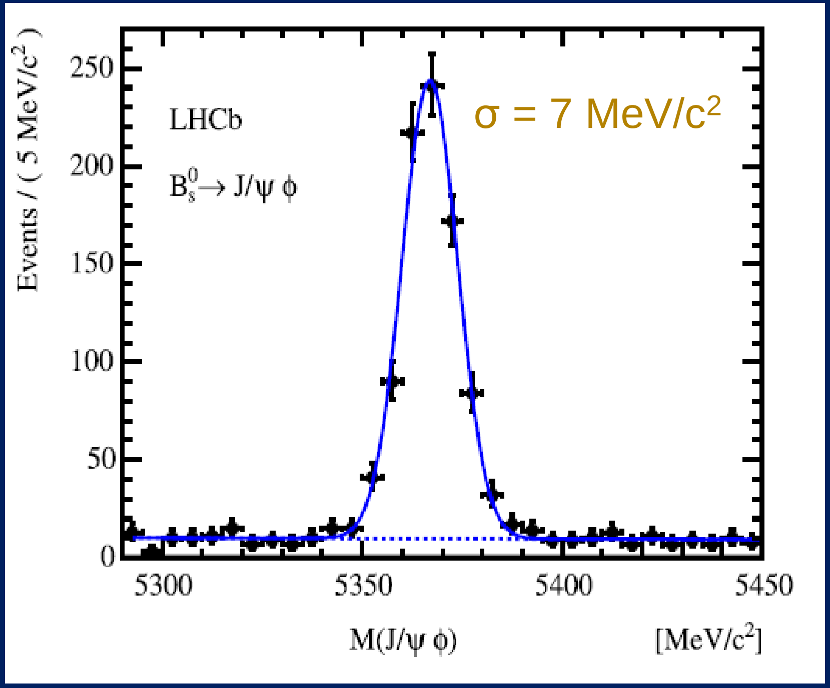


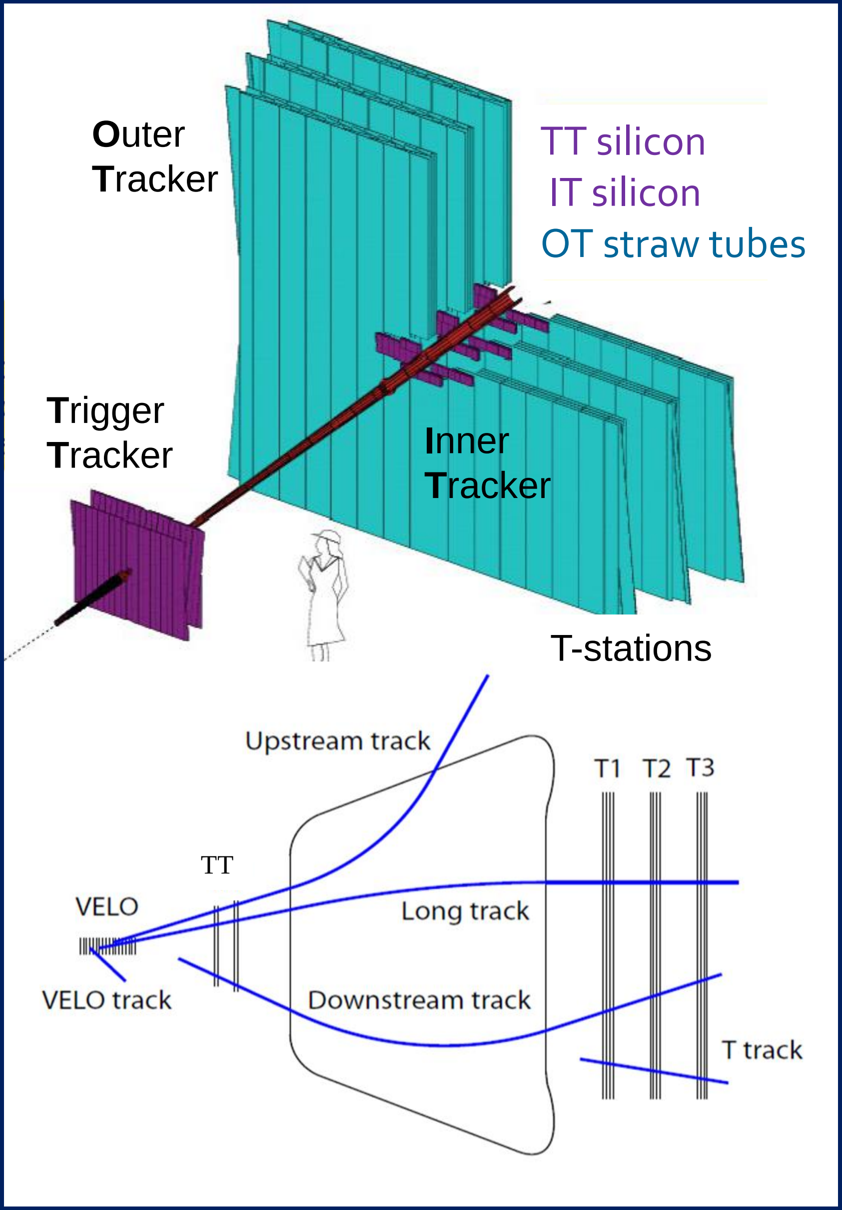
CERN-LHCC-2014-001

- Upstream Tracker
- Scintillating Fibre Tracker

Present Tracking System

- excellent mass resolution
- very low background, comparable to e^+e^- machines
- world's best mass measurements [PLB 708 (2012) 241]

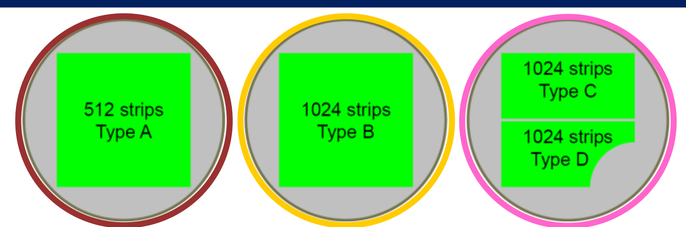




TT upgrade: Upstream Tracker (UT)

silicon strip detector

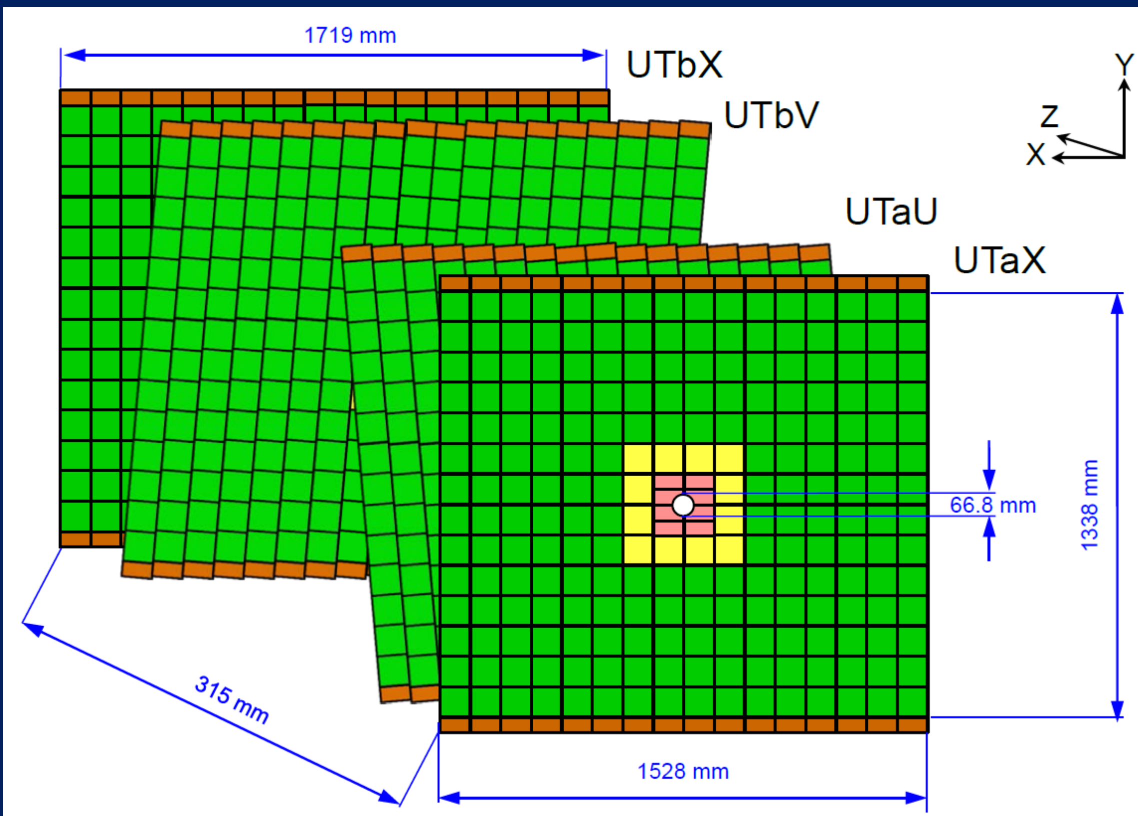
outer middle inner

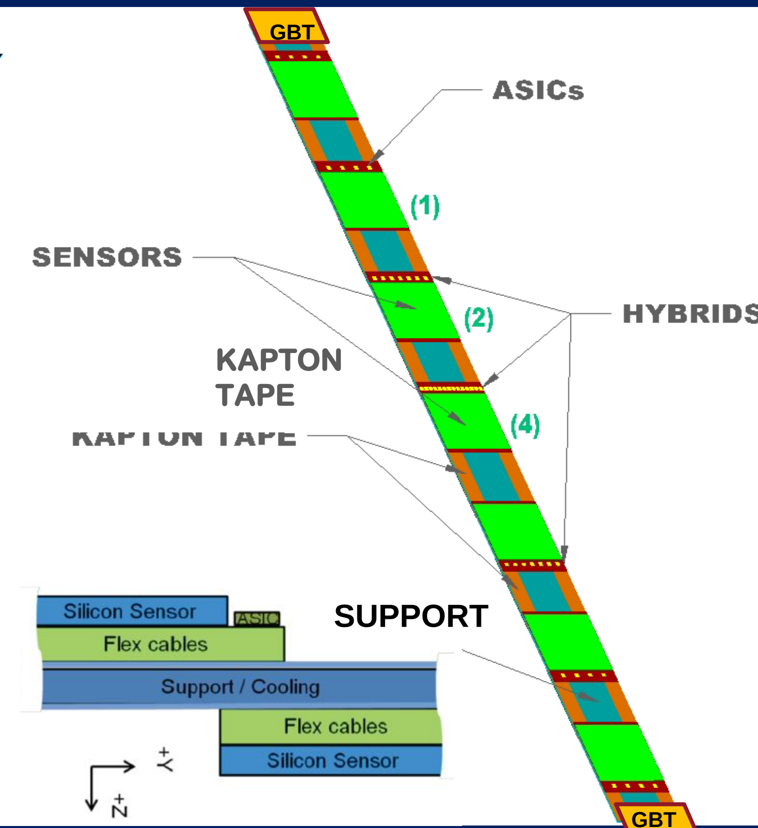


adapt segmentation to varying occupancies (out → in-side):

- 98 → 49 mm long strips
- 190 → 95 µm pitch
- p^+-in-n → n^+-in-p

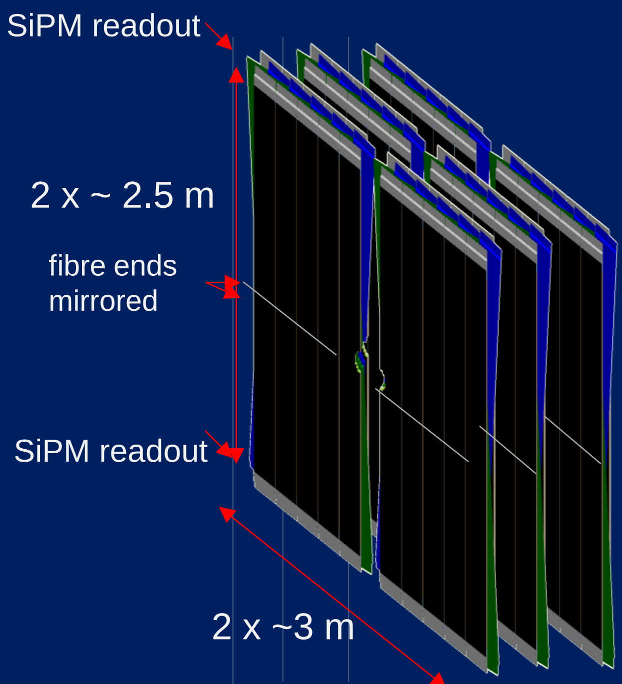
40MHz silicon strip R/O → SALT chip





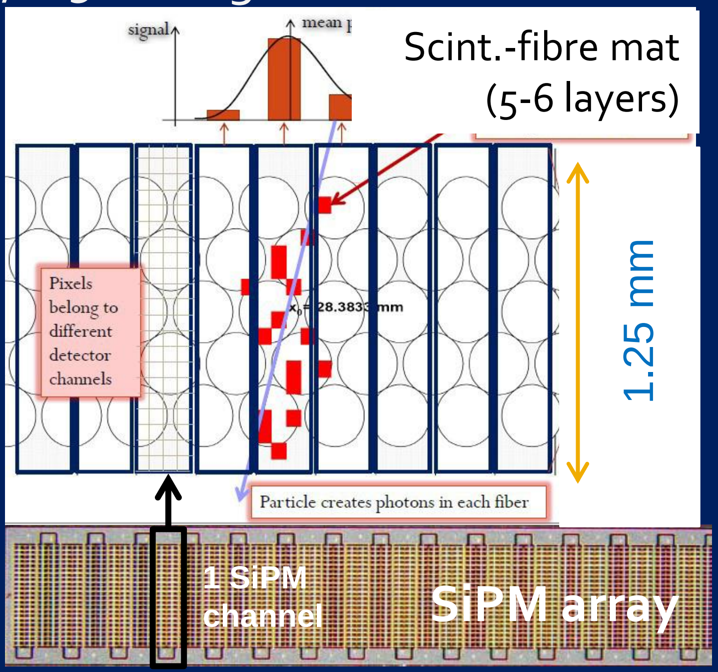
T-stations upgrade: Fibre Tracker

- 3 stations of X-U-V-X (±5° stereo angle) scintillating fibre planes
- every plane made of 5 layers of Ø=250 µm fibres, 2.5 m long
- 40 MHz readout and Silicon PMs at periphery



R/O by dedicated 128 ch.
40 MHz PACIFIC chip

- 3 thresholds (2 bits)
- sum threshold (FPGA)



Challenges: radiation environment

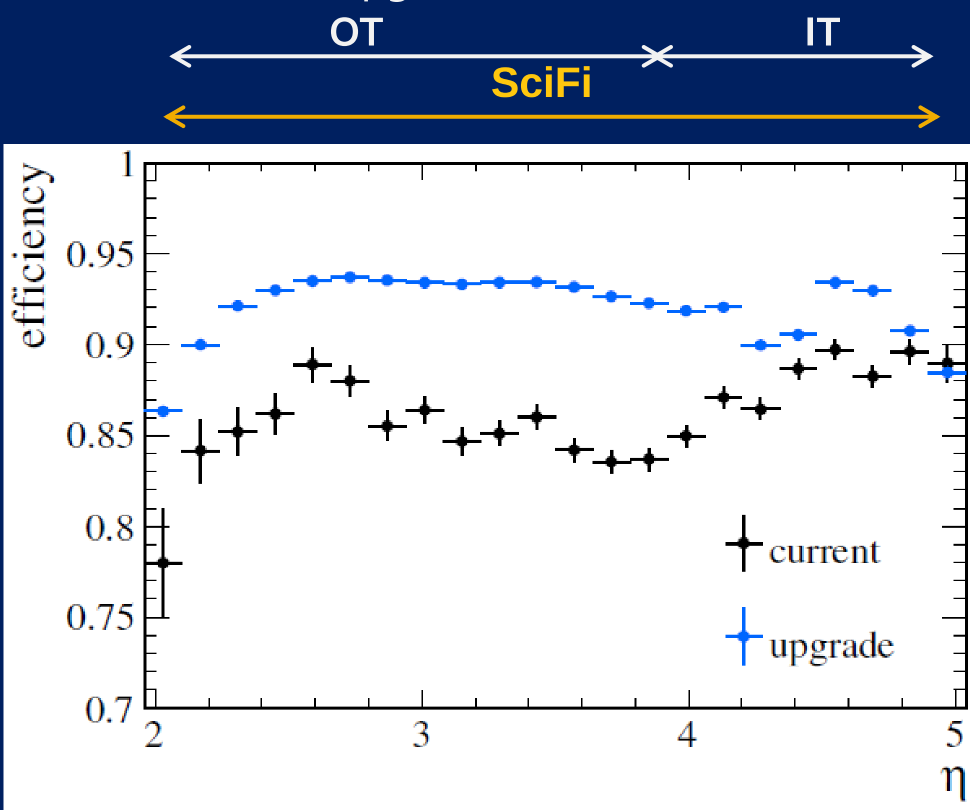
- ionization damage to fibres → tested ok
- neutron damage to SiPM → operate at -40°C
- large size – high precision, O(10'000 km) of fibres

Benefits of SciFi concept:

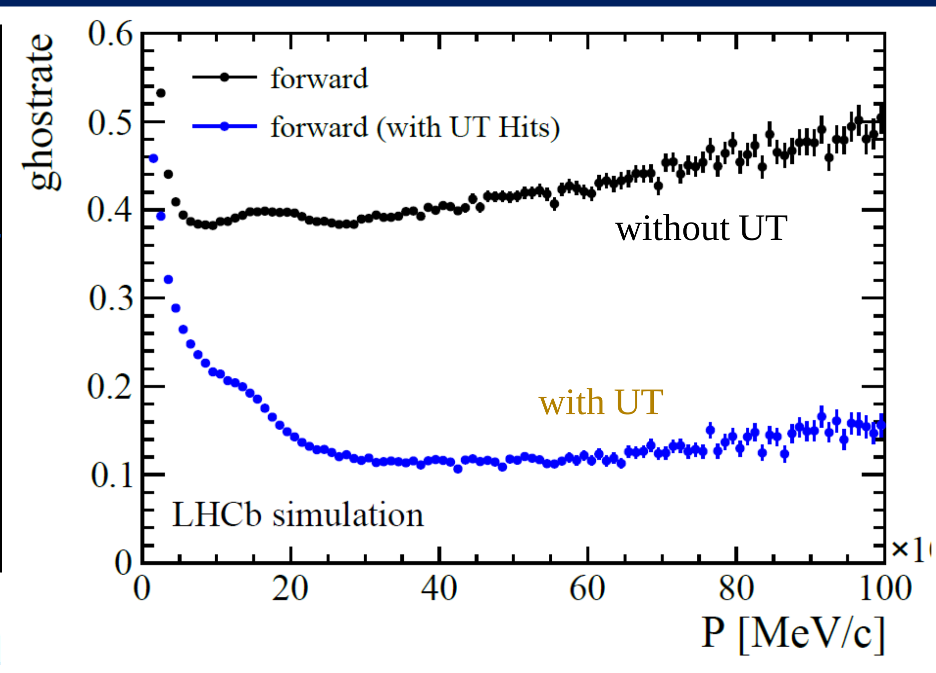
- a single technology to operate
- uniform material budget
- SiPM + infrastructure outside accept.
- x-position resolution of 50 – 75 µm
- fast pattern recognition for HLT

Tracking performance

Efficiency for $B_s \rightarrow \Phi\Phi$ events:
upgrade conditions,
current and upgraded T-stations



Ghost rate for $B_s \rightarrow \Phi\Phi$ events:
long tracks without UT and
with UT (≥ 3hits)



→ improve tracking performance at upgrade luminosity with Fibre Tracker

→ reduce significantly the ghost rate using the Upstream Tracker information

Tracking algorithm for the Trigger

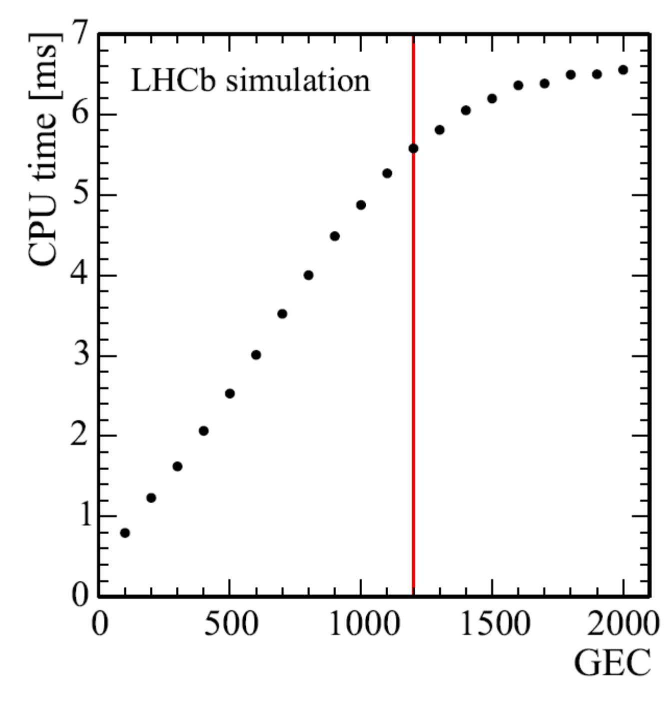
Expected CPU budget with upgraded Event Filter Farm:
~13 ms (10 x current CPU farm)

Performance of HLT tracking with upgraded VELO, UT and FT:

Tracking Algorithm	CPU time[ms] No GEC	CPU time[ms] GEC = 1200
VELO tracking	2.3	2.0
VELO-UT tracking	1.4	1.3
Forward tracking	2.5	1.9
PV finding	0.40	0.38
Total @29 MHz		5.6
Total	6.6	5.4 ms

→ leaves ~ 6-7 ms for a trigger decision

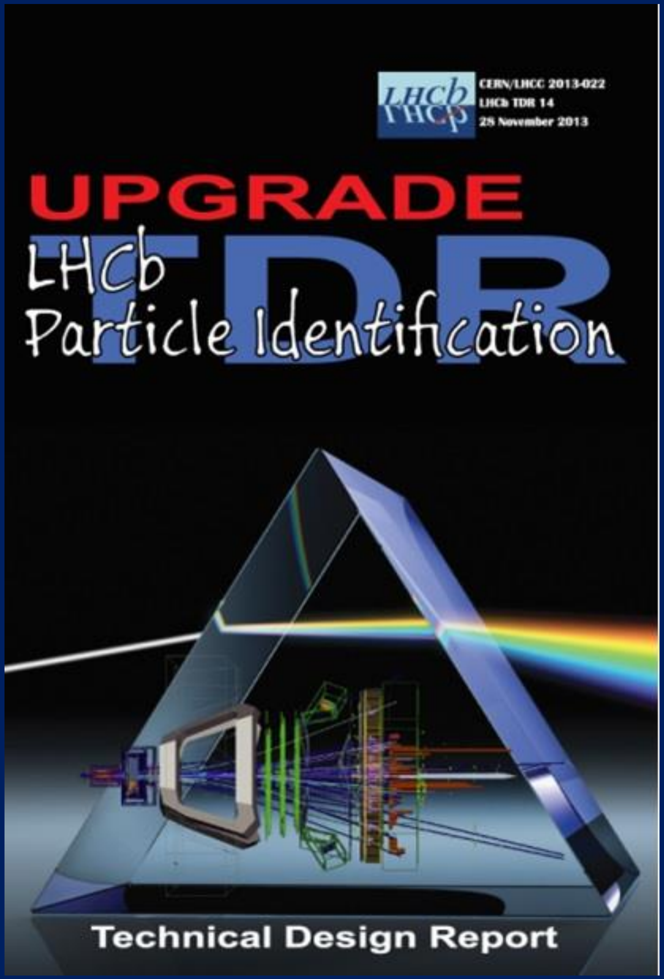
GEC (Global Event Cut) → multiplicity cut to remove pathological events (e.g. hit multiplicity of sub-detector)



	no GEC	GEC< 1200	relative
Ghost rate	10.9%	5.9%	-
long	42.7%	42.9%	50.4%
long, from B	72.5%	72.8%	80.3%
long, $p_T > 0.5\,\mathrm{GeV}/c$	86.9%	87.4%	97.2%
long, from B, $p_T > 0.5\,\mathrm{GeV}/c$	92.3%	92.5%	98.7%

→ high efficiency (even with GEC)

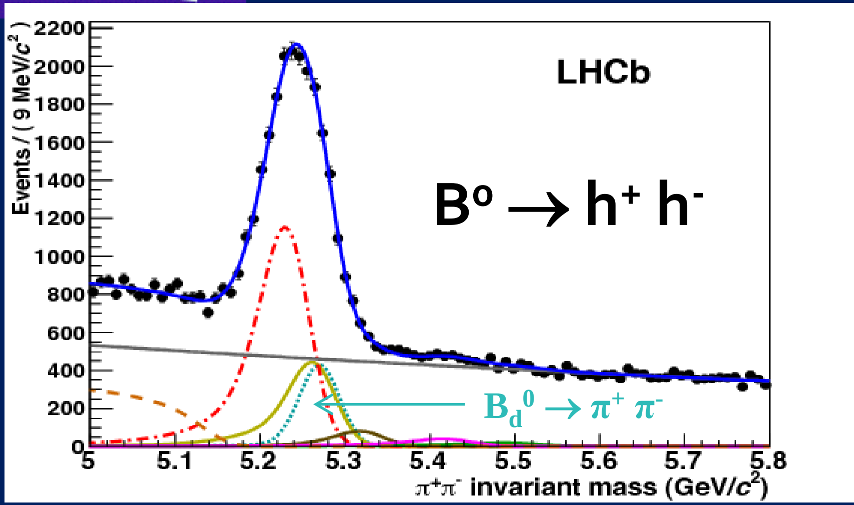
Particle Identification Upgrade



CERN-LHCC-2013-001

- RICH
- Calorimeter
- Muon System

Particle ID with RICH

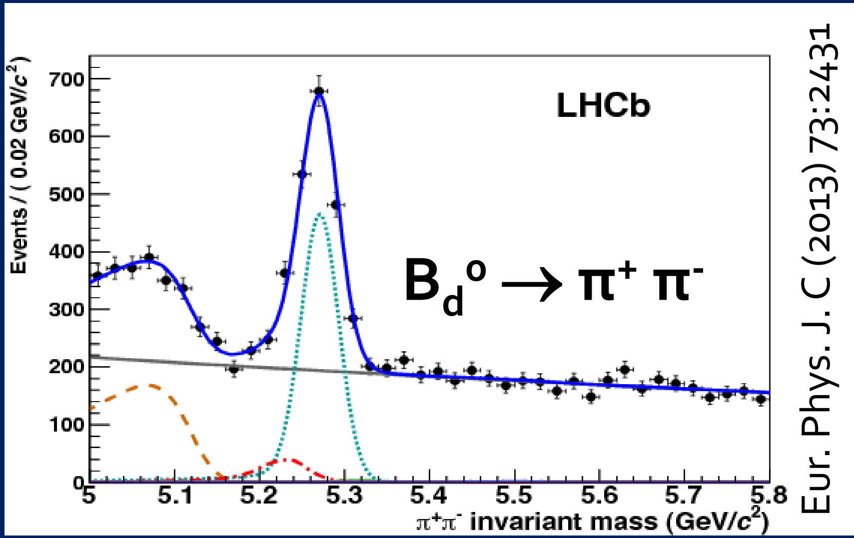


Efficient particle ID of π, K, p essential for selecting rare beauty and charm decays

K-identification and π-misidentification efficiencies vs. particle momentum

↓ particle identification of 2 π

$BR(B \to \pi^+\pi^-) = 5 \times 10^{-6}$!



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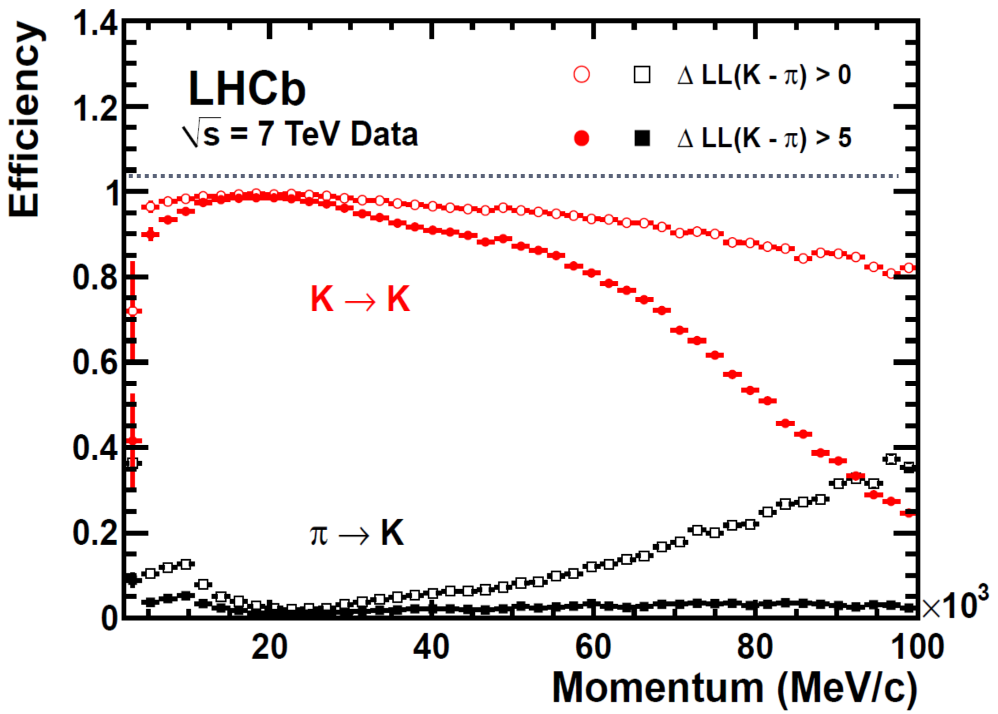
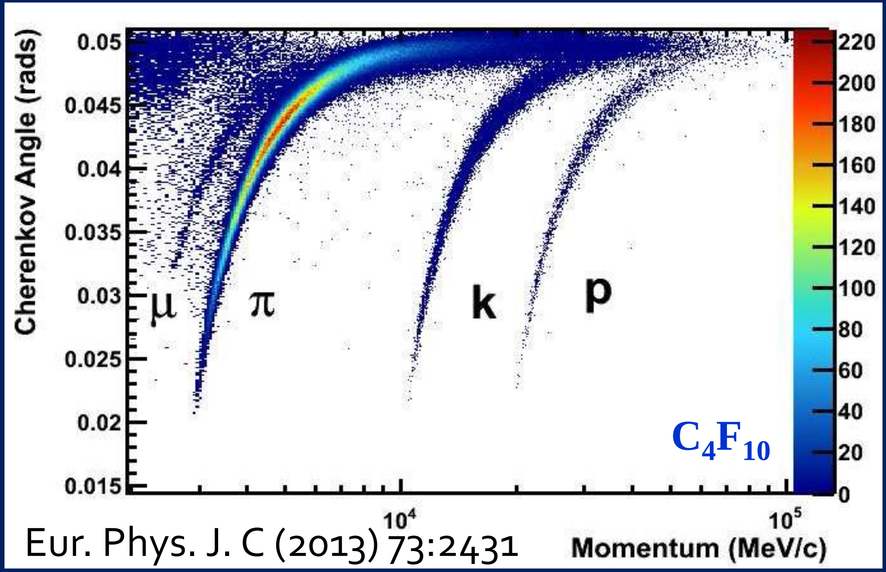


Present RICH 1

Particles traversing radiator produce Cherenkov light rings on an array of HPDs located outside the acceptance



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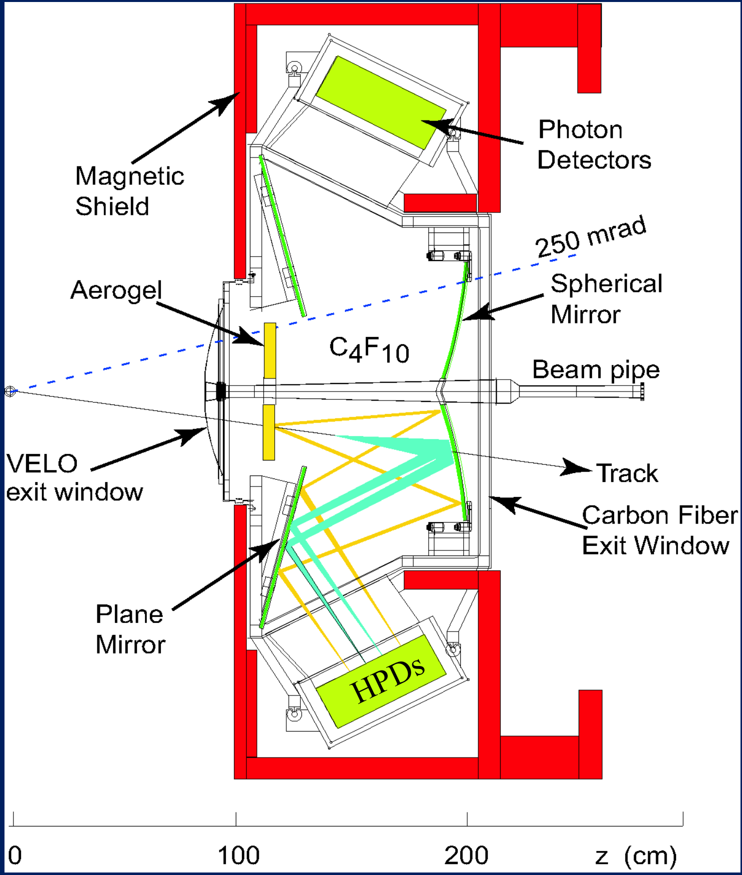
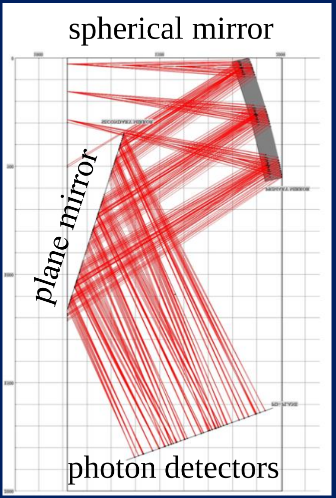
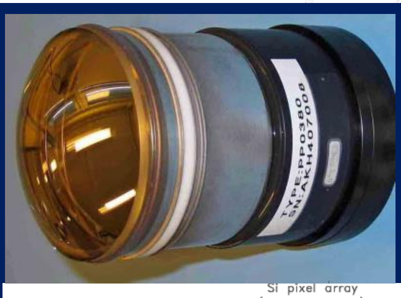
RICH 1

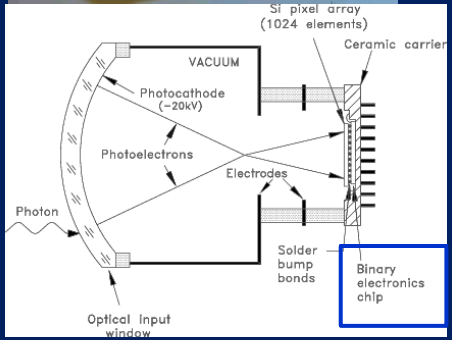




Hybrid Photon Detector

with embedded 1 MHz R/O chip

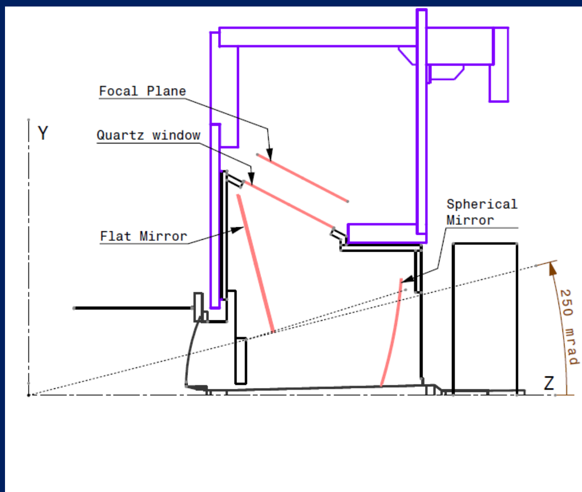




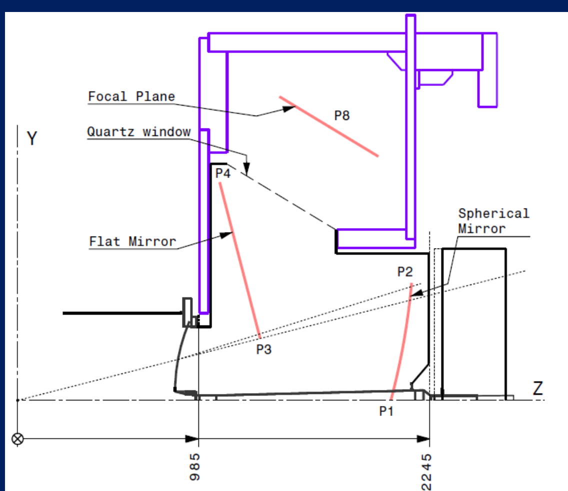
RICH upgrade

optimise RICH1 optics

current



upgrade

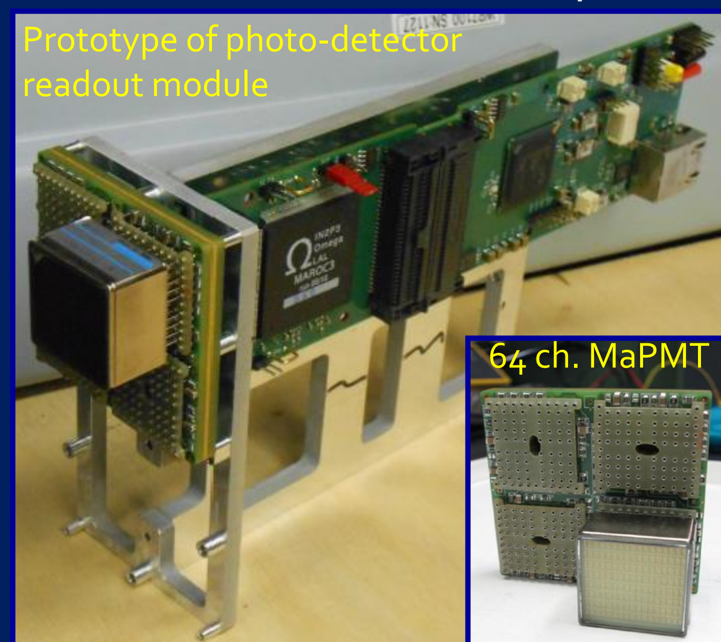


Luminosity of 2·10^{33} cm^{-2}s^{-1} → adapt to high occupancies

- aerogel radiator removed
- modify optics of RICH1 to spread out Cherenkov rings (optimise gas enclosure without modifying B-shield)

40 MHz readout → replace HPDs due to embedded FE

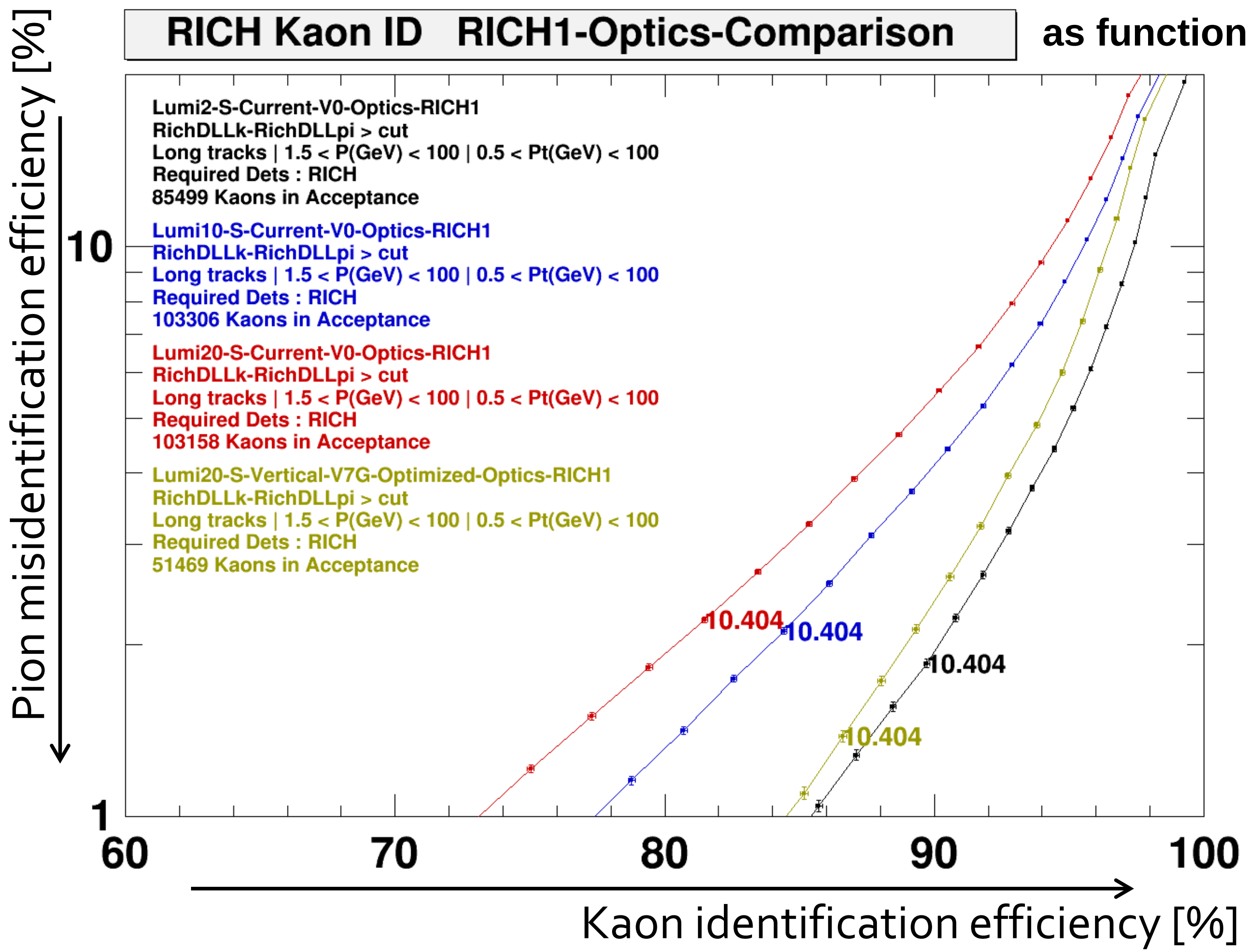
- 64 ch. multi-anode PMTs (baseline)
- 40 MHz Front-End: CLARO chip (or MAROC)



Prototype of photo-detector readout module

64 ch. MaPMT

Performance RICH upgrade



as function of luminosity

Current RICH1

- $2 \cdot 10^{32}\, cm^{-2}s^{-1}$
- $10 \cdot 10^{32}\, cm^{-2}s^{-1}$
- $20 \cdot 10^{32}\, cm^{-2}s^{-1}$

RICH1 upgrade

- $20 \cdot 10^{32}\, cm^{-2}s^{-1}$

note:
full GEANT MC with standard LHCb simulation framework

Particle ID with Calorimeters

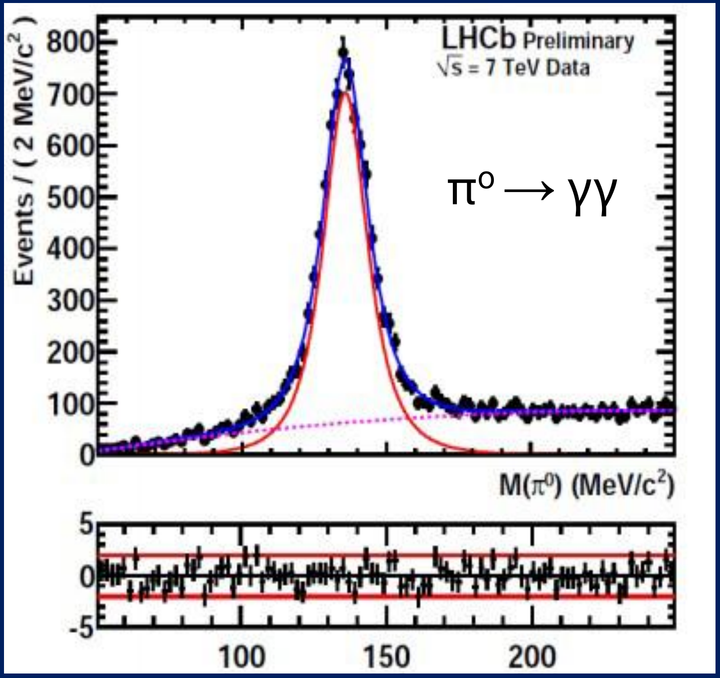
- Calorimeters allow to reconstruct neutral hadrons
- They provide an E_T measurement used in the L0 trigger

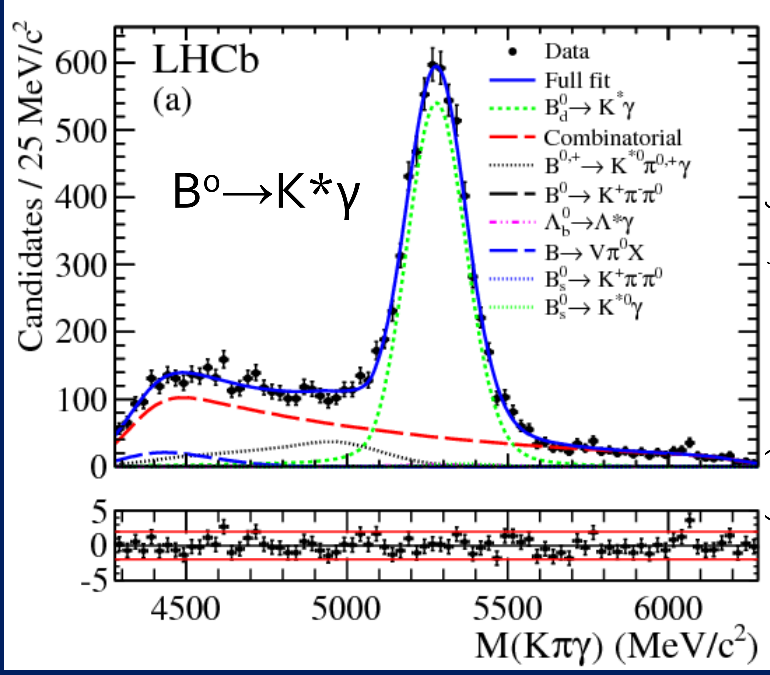
Typical π^0 mass resolution:

~7-10 MeV/c^2 (depending on number of converted photons)

Radiative b→ s γ transitions:

Invariant mass resolution ~ 94 MeV/c^2 dominated by ECAL energy resolution.





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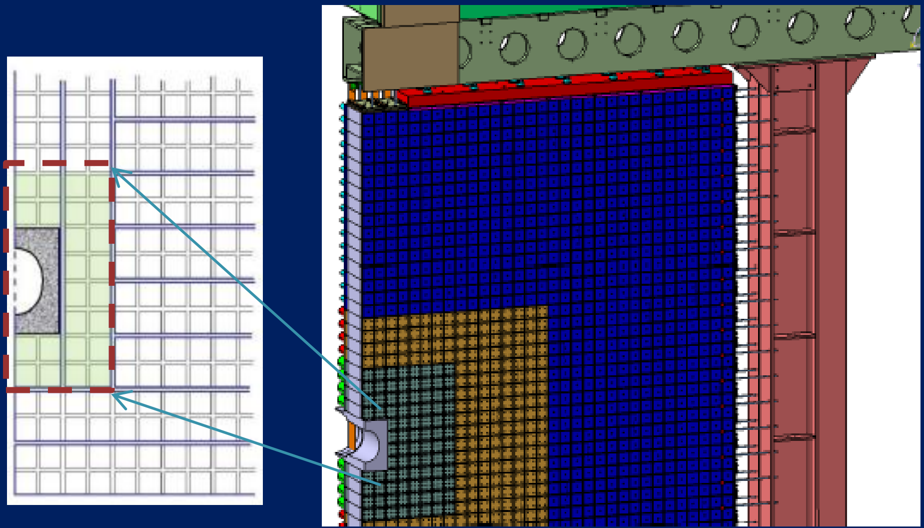
Calorimeter upgrade

40 MHz readout electronics:
- reduce photomultiplier gain
- adopt electronics

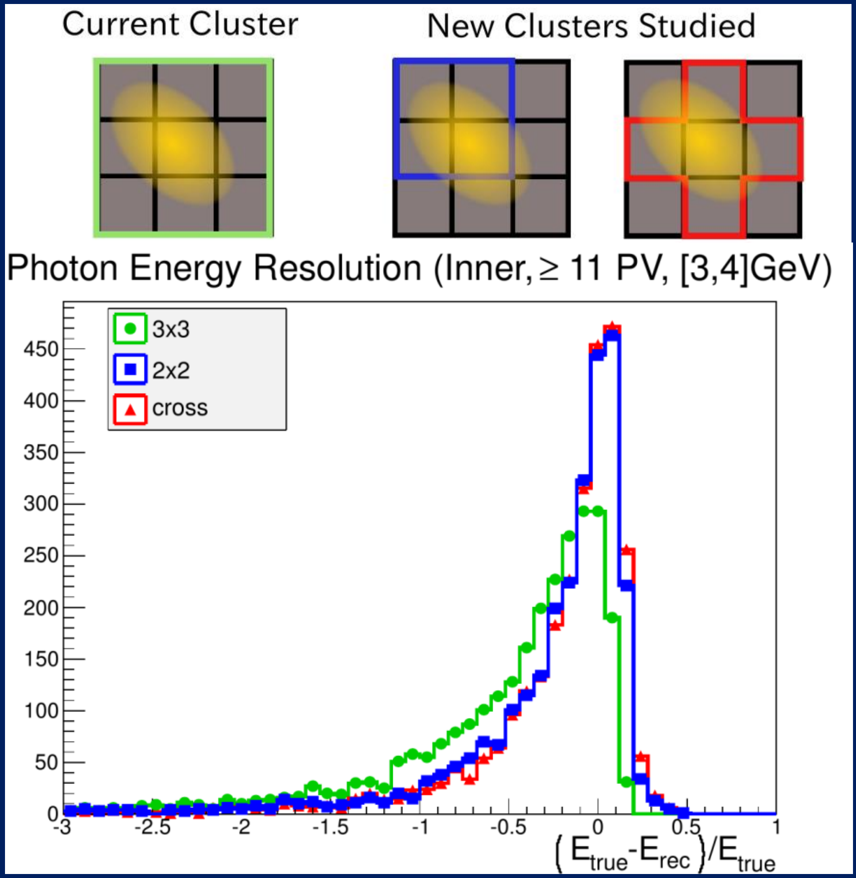
Radiation damage on detectors:
- Preshower and SPD removed
- HCAL modules ok up to ~50 fb^{-1}
- irradiation tests show that most exposed ECAL modules resist up to ~20 fb^{-1} → LS3

Innermost ECAL modules around beam-pipe can be replaced

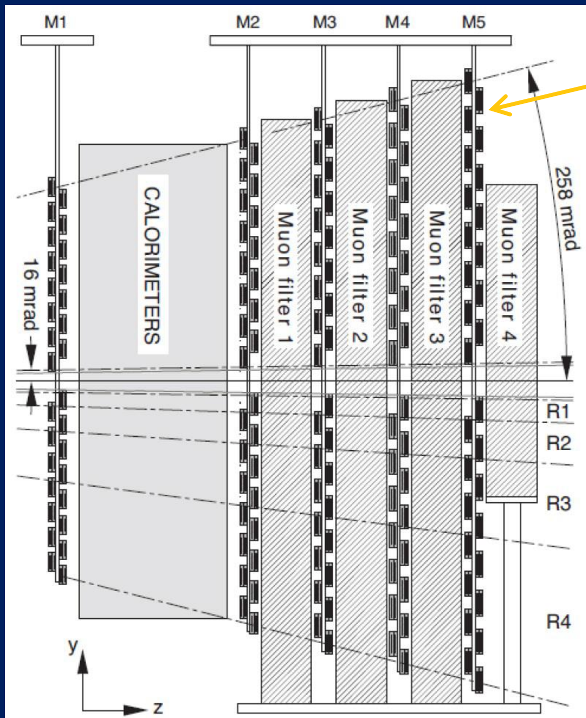


Impact of pile-up on the energy / position measurement:

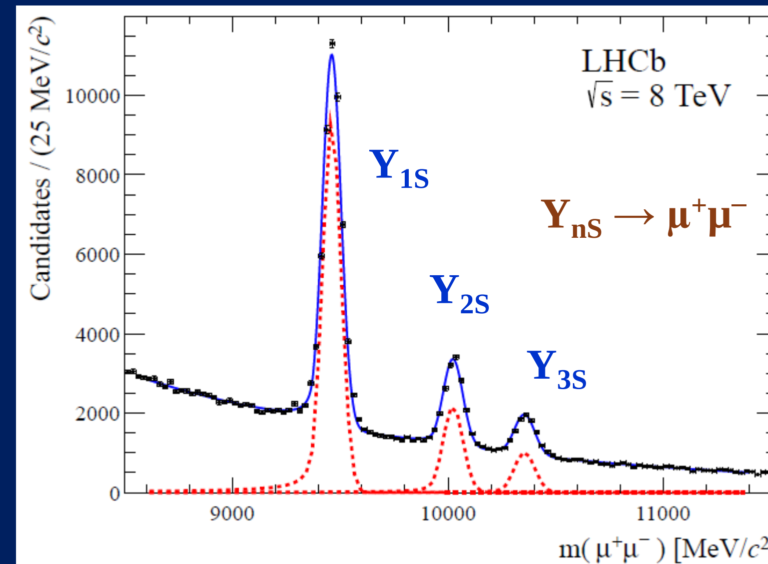
Change the reconstruction and define smaller clusters



Particle ID with the Muon System



MWPC



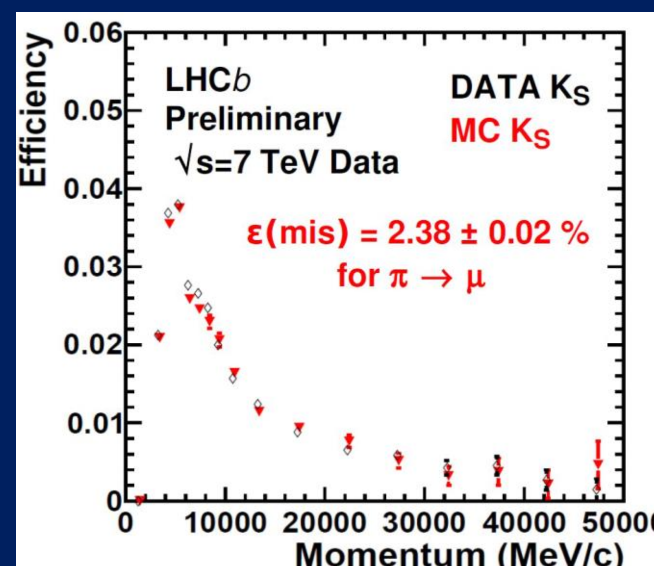
High detection efficiency: $\varepsilon(\mu) = (97.3 \pm 1.2)\%$

Low misidentification rates:

$\varepsilon(p \rightarrow \mu) = (0.21 \pm 0.05)\%$

$\varepsilon(\pi \rightarrow \mu) = (2.38 \pm 0.02)\%$

$\varepsilon(K \rightarrow \mu) = (1.67 \pm 0.06)\%$



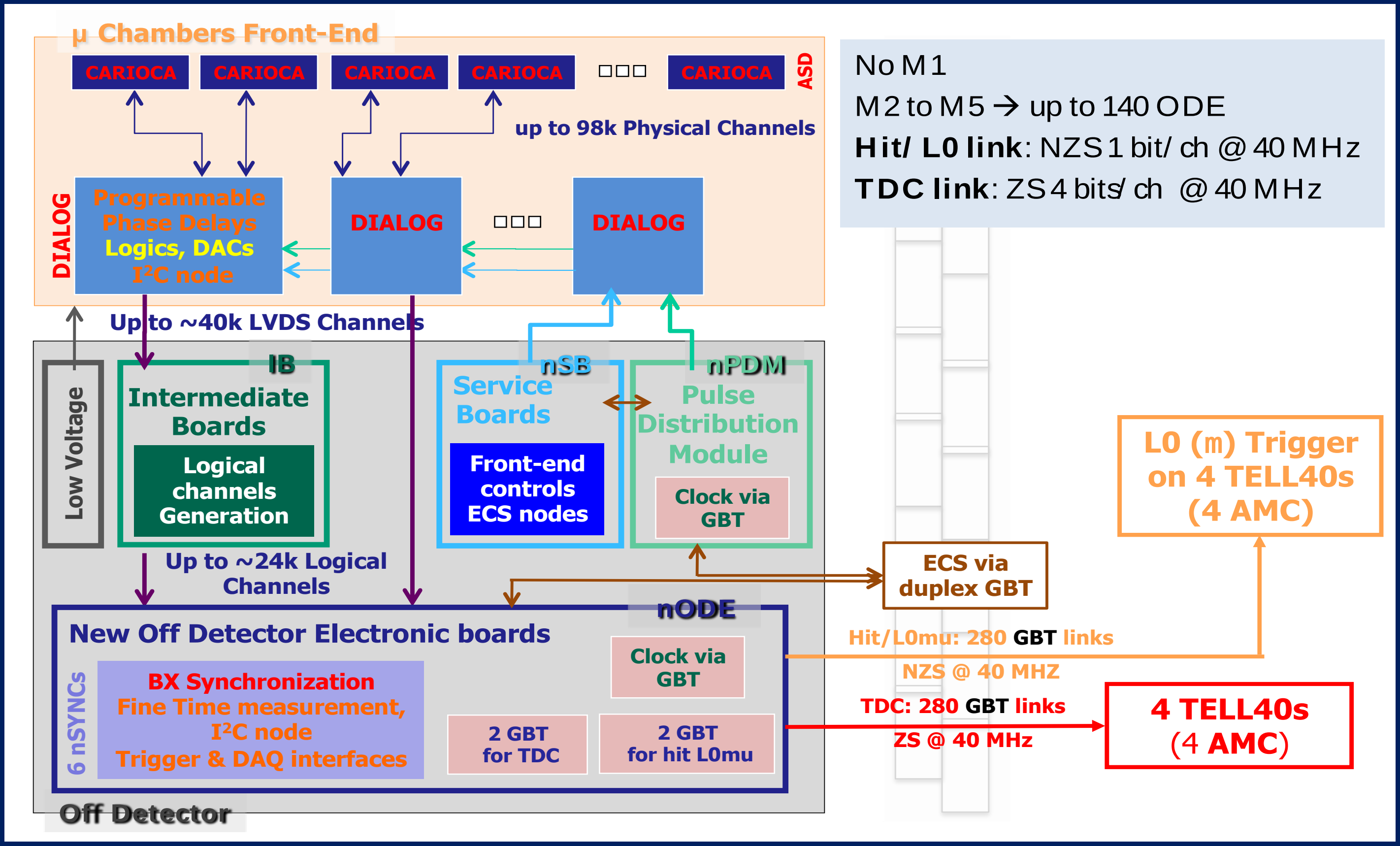
Muon System upgrade

Modifications due to higher luminosity and 40 MHz readout:

- remove M1 due to too high occupancies
- additional shielding behind HCAL to reduce the rate in the inner region of M2
- keep on-detector electronics (CARIOCA); already at 40 MHz readout
- new off-detector electronics for an efficient readout via PCIe40 R/O boards

on-detector electronics

off-detector electronics



Summary and Conclusions

- LHCb is producing world best measurements in the b- and c-quark sector due to its excellent detector performance.
  - By 2018 with ~8 fb^{-1} LHCb will find or rule-out large sources of flavour symmetry breaking at the TeV scale.

- The LHCb upgrade is mandatory to reach experimental precisions of the order of the theoretical uncertainties.
  - An efficient and selective software trigger with access to the full detector information at every 25 ns bunch crossing will allow to collect the necessary ≥50 fb^{-1} within ~10 years.

- The LHCb upgrade is fully approved, with the last TDR under review.
  - The detector upgrade to 40 MHz readout sustaining a levelled luminosity of $2 \times 10^{33}\ cm^{-2}s^{-1}$ at 25 ns bunch spacing is under preparation, to be operational at the beginning of 2020.