LHCb LS2 Upgrade

R. Jacobsson

on behalf of the LHCb Collaboration

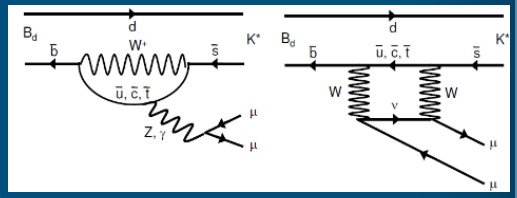
Outline

- LHCb objectives and upgrade motivations
- LHCb features and limitations
- Upgrade strategy
- Physics prospects
- Conclusions

In Praise of Precision Measurements

- Precision measurements likely to have the largest discovery potential for new physics
  - Higgs and top precision physics
  - Flavour precision physics
  - Complemented by direct searches at high scales AND low scales

➔ LHCb focus on measuring *indirect* effects of New Physics in CP violation and rare decays
  - Searching deviations from the SM
  - Virtual effects allow probing energies much higher than E_{cms} of the LHC

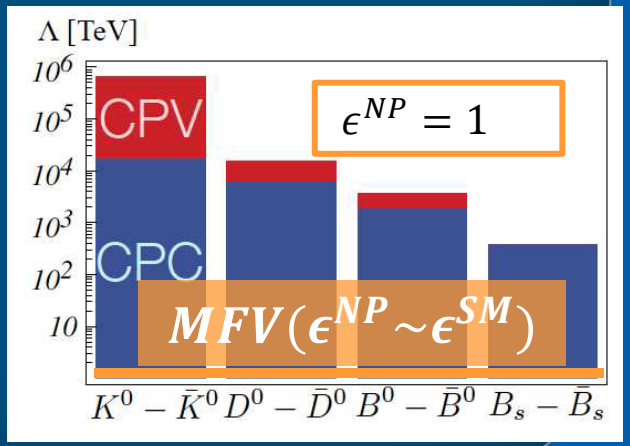


- b and c sector contains large repertoire of decays and topologies
  - New Physics may enter differently in boxes and in penguin contributions
  - ➔ Aim for access to "all" modes

- Upgrade aim: reach experimental sensitivities ≤ theoretical uncertainties

$$\sigma_{stat+sys+th} < \delta C\left[\frac{\epsilon^{NP}}{\Lambda_{NP}^2}\right]$$

  - Not expected to be limited by systematics → often improves with increasing statistics
  - σ_{theory} often decrease with complementary measurements

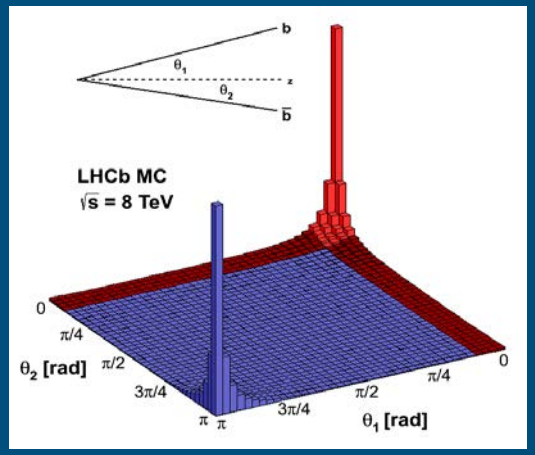


➔ 10-fold our statistics and improve access to hadronic modes
  1. Increase luminosity
  2. Increase efficiency of hadronic channels by factor >2
  3. Improve output bandwidth and lower p_T

  ➔ Gives access to new modes and observables

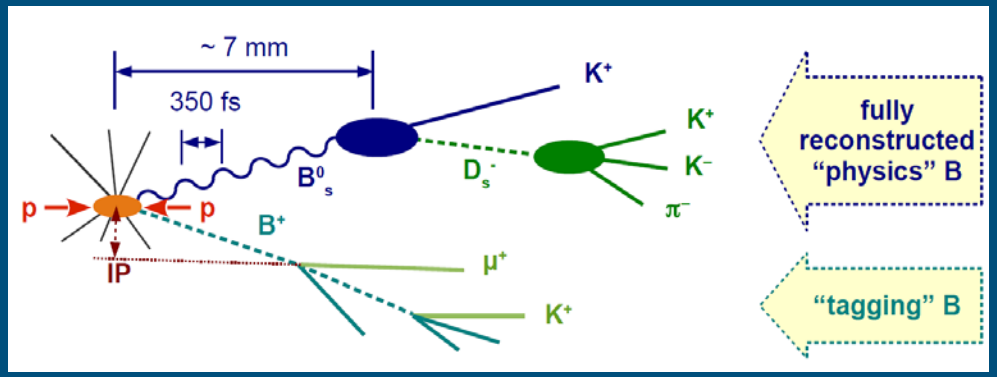
Key features of LHCb at LHC

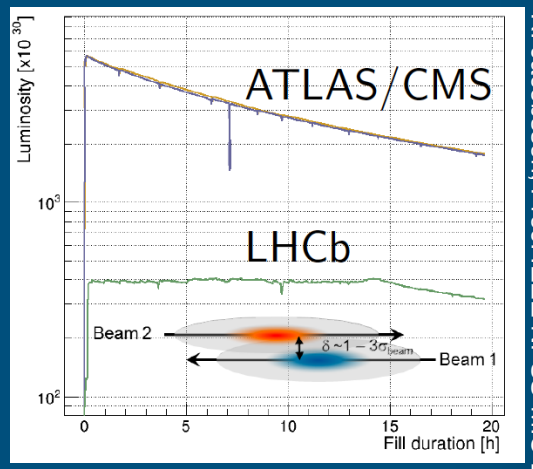
- Large signal cross-sections
  - >100 kHz → 1 MHz of $b\bar{b}$ pairs at LHCb interaction point
  - Access to all b-flavored hadrons B_u (~40%), B_d *(~40%)*, B_s (~10%), and B_c, and *B*-baryons Λ_b *(~10%)* , …
    (arXiv:1111.2357v2, arXiv:1301.5286)
  - $c\bar{c}$ production 20x more



- The final state $b\bar{b}$ / $c\bar{c}$ pair are Lorentz boosted
  - ➔ The B / D hadrons appear in the same hemisphere
  - ➔ Very good proper time resolution

- ➔ Flavor tagging
  - Same side, uses π or *K* emitted together with signal *B* / *D* hadron
  - Opposite side, detects flavor of partner *B* / *D* hadron from decay



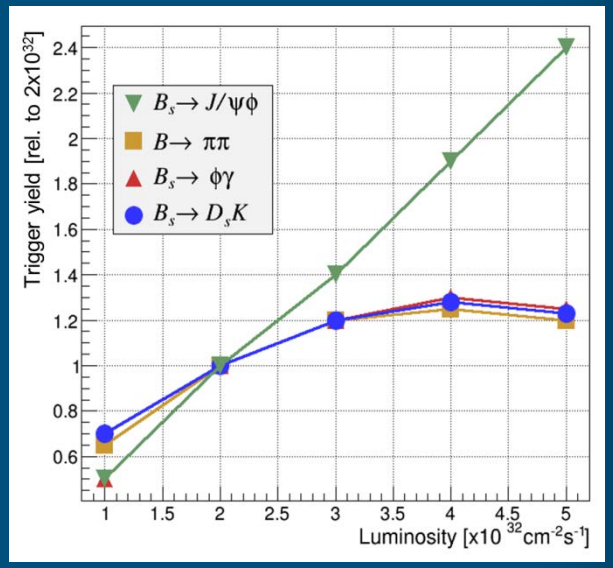


R. Jacobsson, Proc. IEEE NPSS-MIC 2012

- Operating at a controllable levelled luminosity
  - Control detector performance and systematics

Global LHCb Upgrade Strategy

- Current limitation: FE readout time = 900ns ➔ Max 1.1 MHz ensured by L0 trigger
  - At high pileup p_T does not discriminate in hadronic modes
    ➔ Yield of hadronic modes saturates
  - Efficient selection requires full detector
    ➔ IP, p_T of tracks, and PID

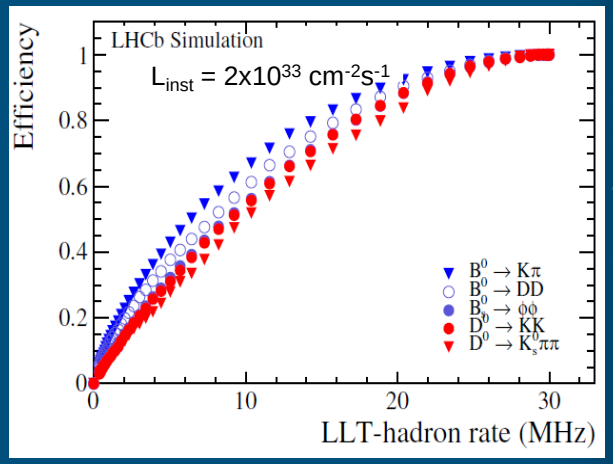


CERN/LHCC 2011-001

<u>Upgrade baseline:</u> Target L= 2×10^{33} $cm^{-2}s^{-1}$

➔ Trigger challenge
- 2% of bunch crossings with b-hadron decay in VELO
- 25% of bunch crossings with c-hadron decay in VELO
- 2 light long-lived hadrons decay in VELO every bunch crossing

➔Background suppression ➔ signal classification



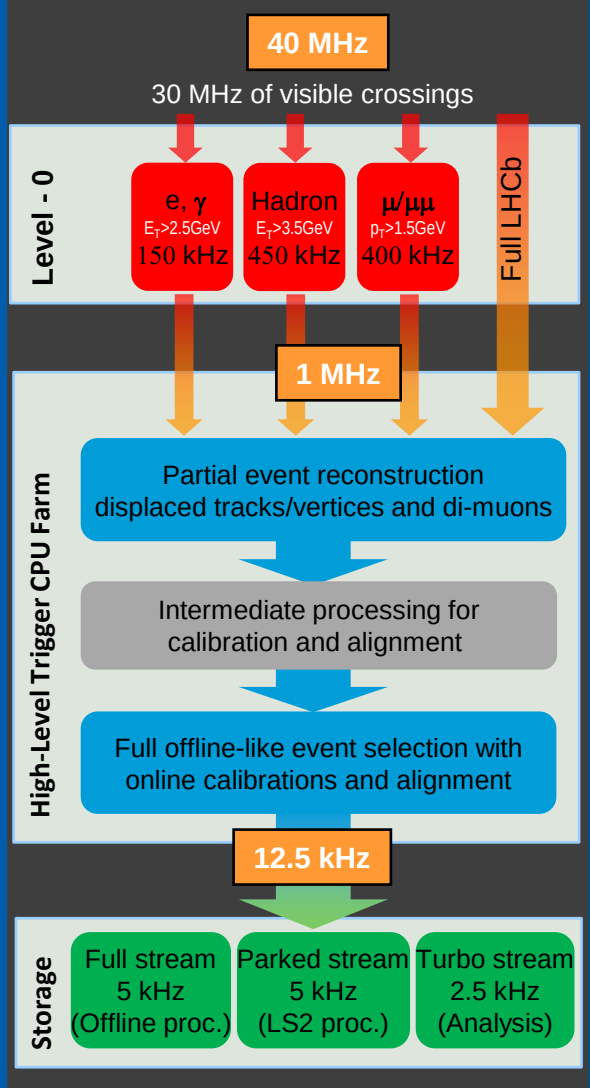
CERN/LHCC 2014-16

1. Remove First Level Trigger
2. Replace all FE/BE for 40 MHz full readout to CPU farm
3. Implement a fast HLT based on full topology
4. Final output bandwidth at >20 kHz
5. Replace main tracking and improvements to PID

- Ultimate trigger flexibility to adjust to physics scene!

Current and Upgraded Trigger

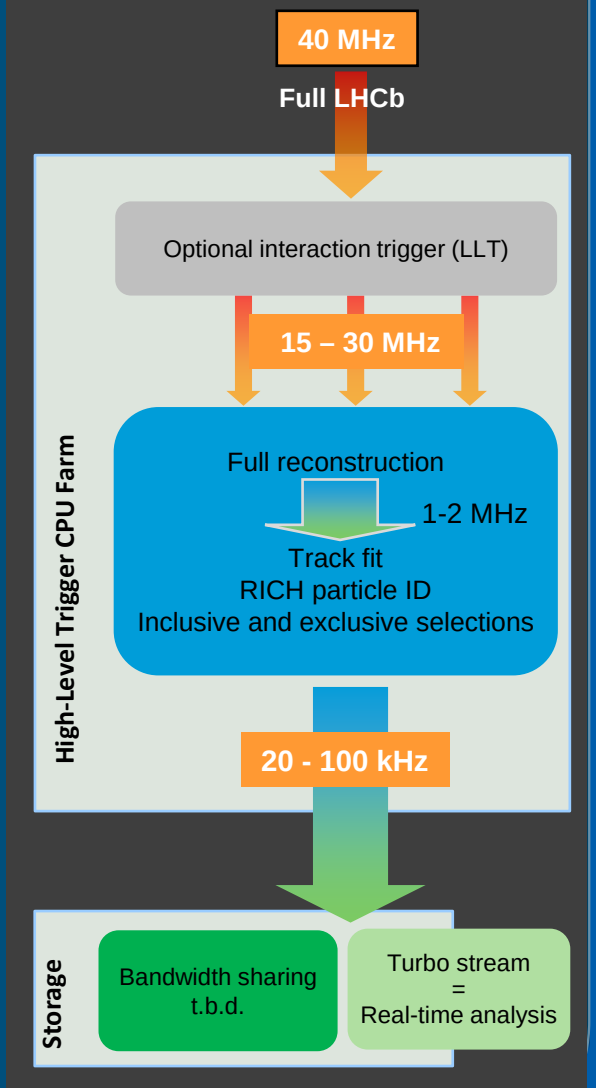
Current trigger scheme



Decay	Run 1 L0xHLT	Upgrade @25kHz
$B^0 \to K^*[K\pi]\mu\mu$	89%	94%
$B_s \to \phi[KK]\phi[KK]$	20%	79%
$B^0 \to D^-[K\pi\pi]\mu\nu$	63%	81%
$\Lambda_b \to p\mu\nu$	54%	59%
$B^+ \to \pi KK$	36%	86%
$B_s \to J/\psi[\mu\mu]\phi[KK]$	91%	93%
$B^0 \to D^+[K\pi\pi]D^-[K\pi\pi]$	18%	56%

CERN/LHCC 2014-16

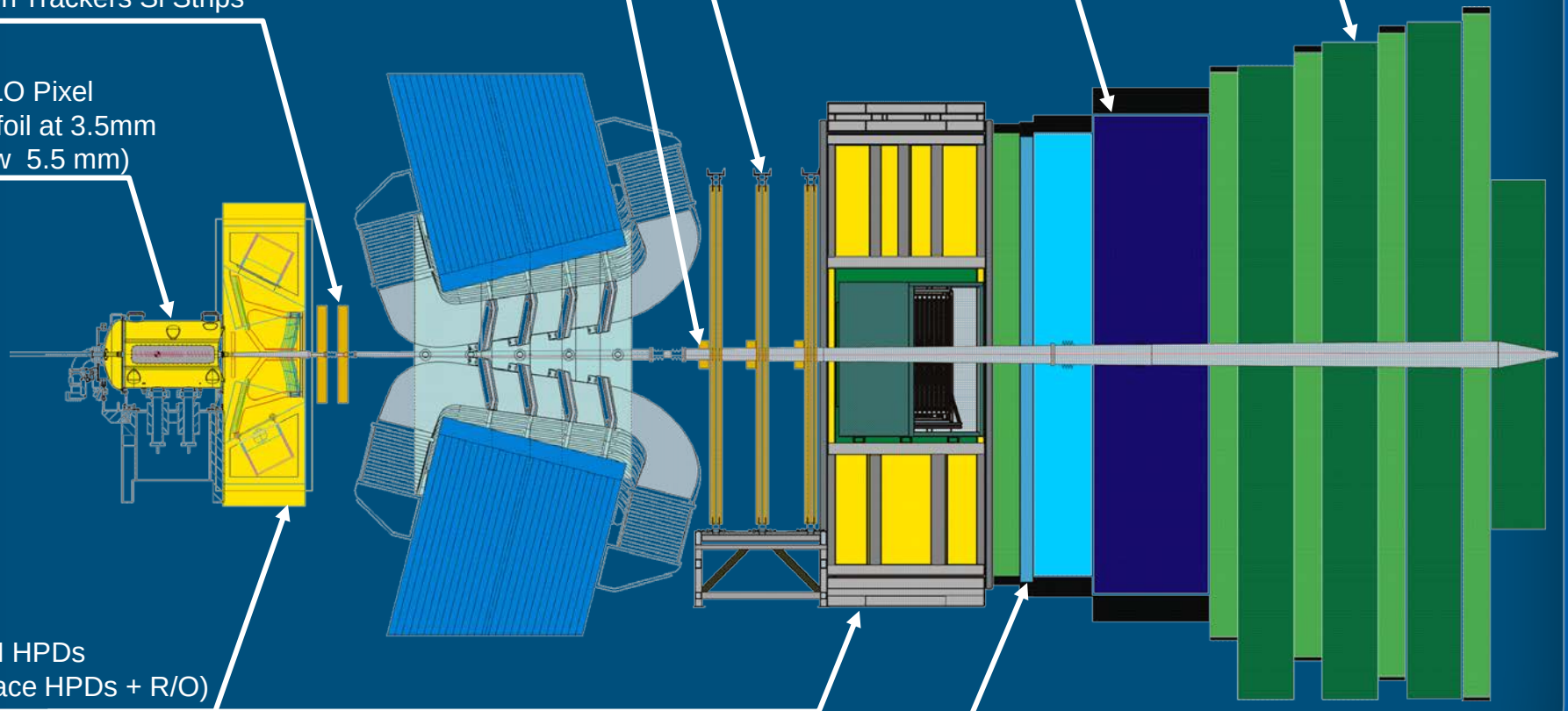
Upgraded trigger scheme



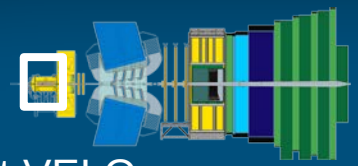
Detector Upgrades

Main detector replacement concern the tracking system

➔ Fast tracking and vertexing will be crucial!



VELO Upgrade

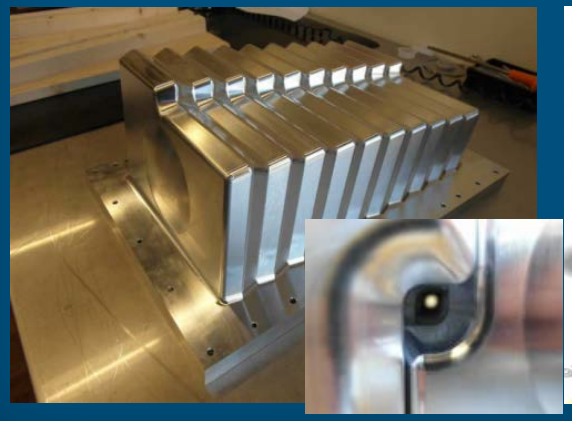


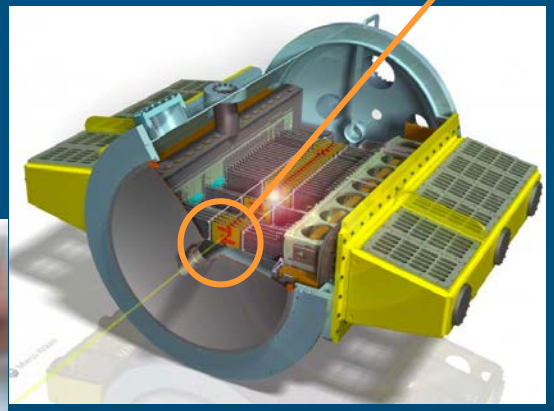
Current VELO:

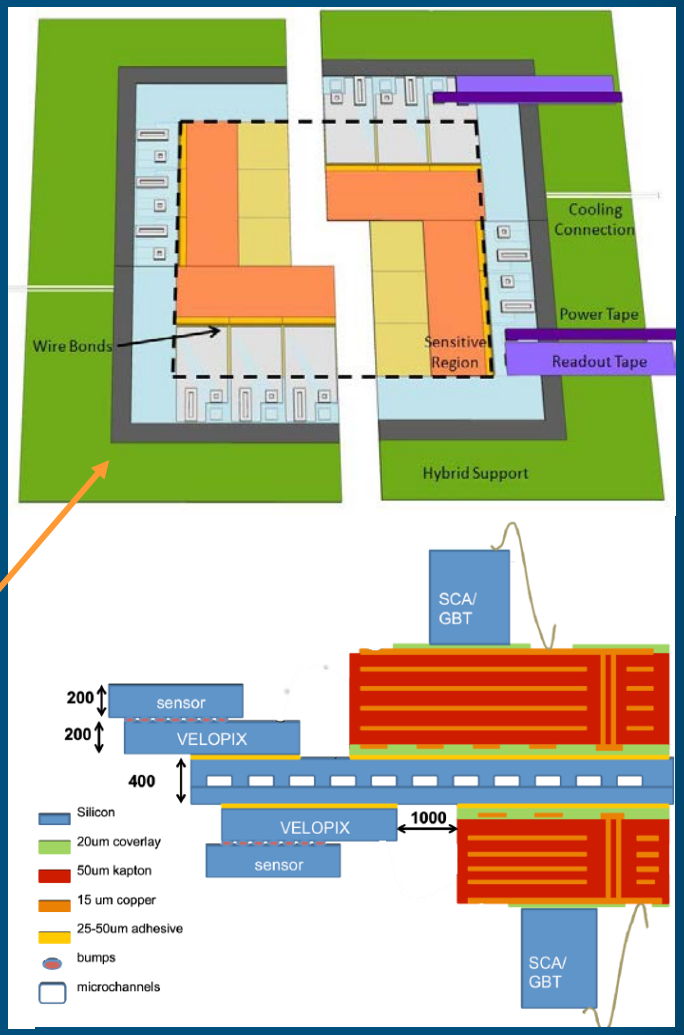
Rϕ silicon micro-strip with pitch 83-101 μm at 8mm from beam with 300μm RF foil

Upgrade:

- Higher granularity and improved resolution
  - ➔ 55×55 μm^2 silicon pixel, 200 μm thickness
  - ➔ Reduced sensor distance to beam (5.1mm)
  - ➔ New RF foil ~150 μm
  - ➔ VeloPix readout chip with 130 nm technology to withstand ~400 MRad
- Cooling challenge
  - Close to beam: ~ 8 × 10^{15} $n_{eq}cm^{-2}$ for 50 fb^{-1}
  - Cool to -20ºC to prevent thermal runaway
  - ➔ Micro-channel CO_2 cooling

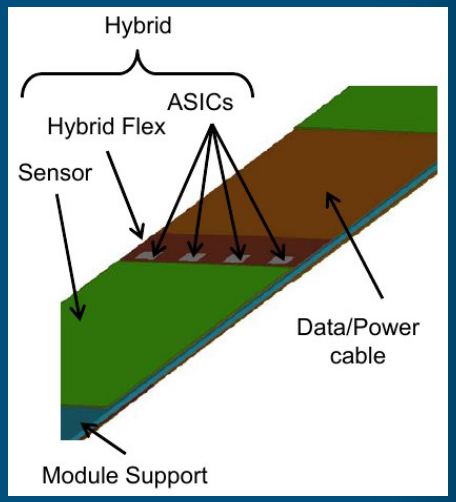


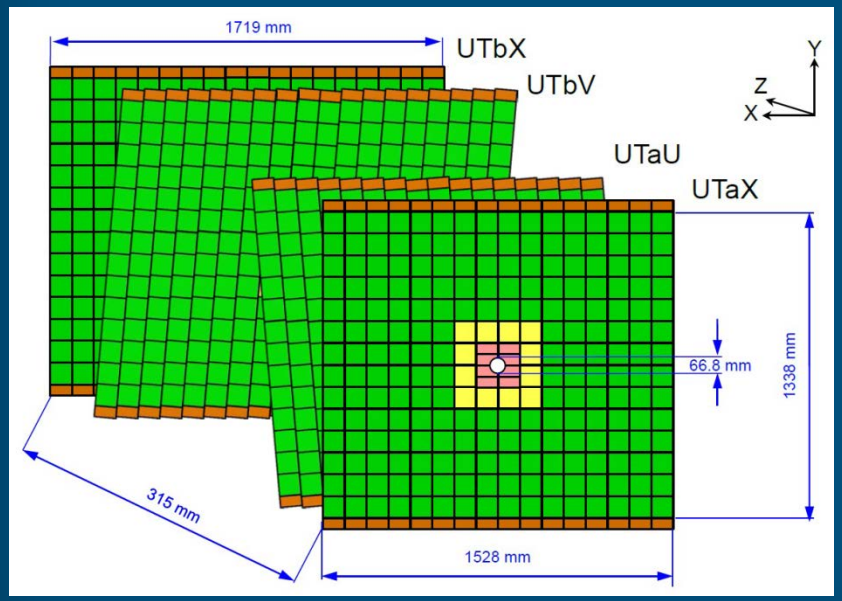


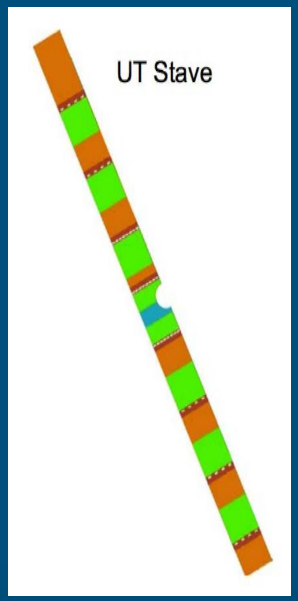


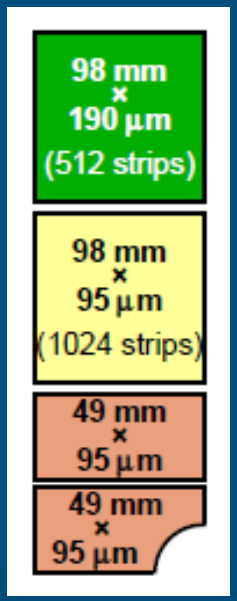
Upstream Tracker

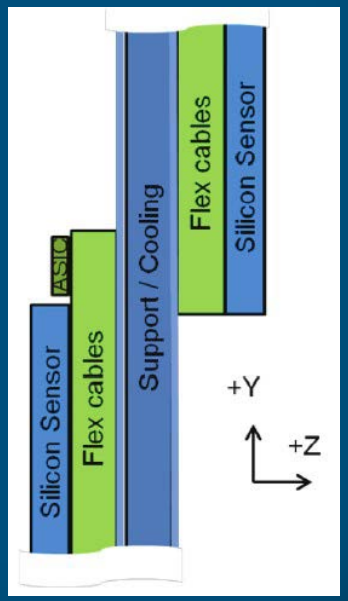
- Redone with Si strip technology: four layers of Si micro-strips
  - Less material with thinner sensors (500 μm → 250 μm)
  - Better coverage by overlapping sensors
  - Readout strip geometry adapted to particle flux
  - Closer to beam pipe improve small-angle acceptance
  - ➔ Fast VELO-UT momentum measurement
  - ➔ Reduce fake VELO-IT/OT tracks
  - Bi-phase CO_2 cooling in stave support









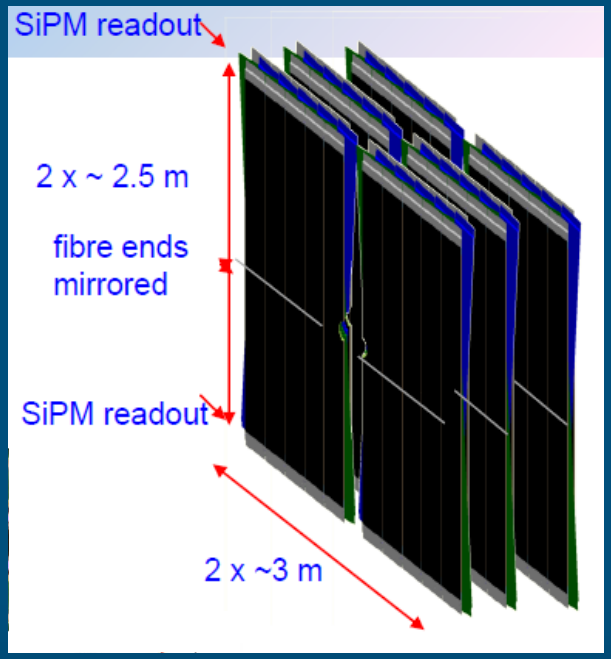


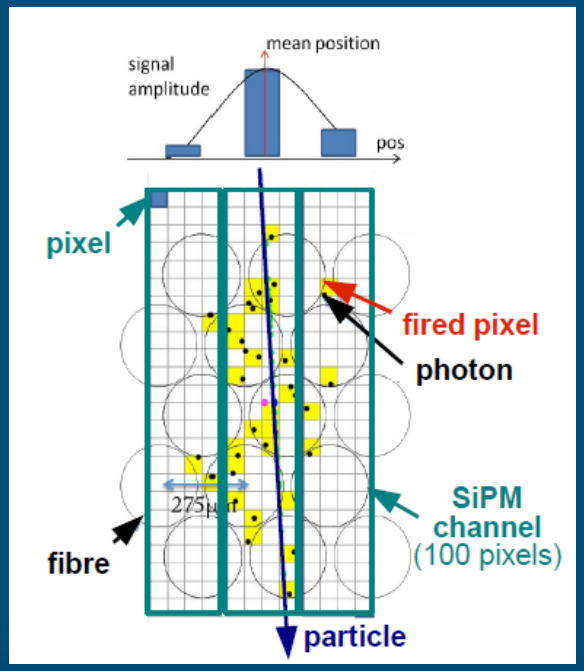
Downstream Tracker

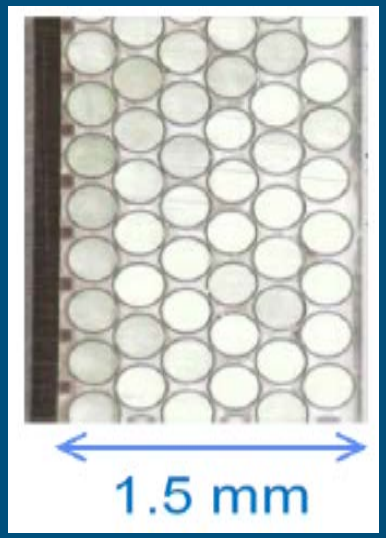
- Replacing completely straw tube and inner Si strips: Scintillating Fibres (SciFi)
  - 6 layers of 2.5 m long scintillating fibres with 250 µm diameter
  - Need to ensure fibres straight to ~50 µm and flat to ~200 µm over 2.5m
  - Silicon Photo-Multiplier (SiPM) readout
  - Neutron damage to SiPM: cooled to –40°C

➔ Expected performance: 50 – 75 µm spatial resolution

➔ Fast track reconstruction in trigger

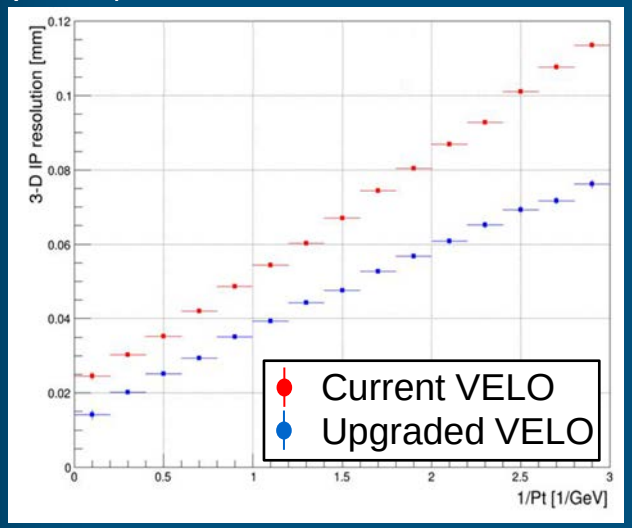


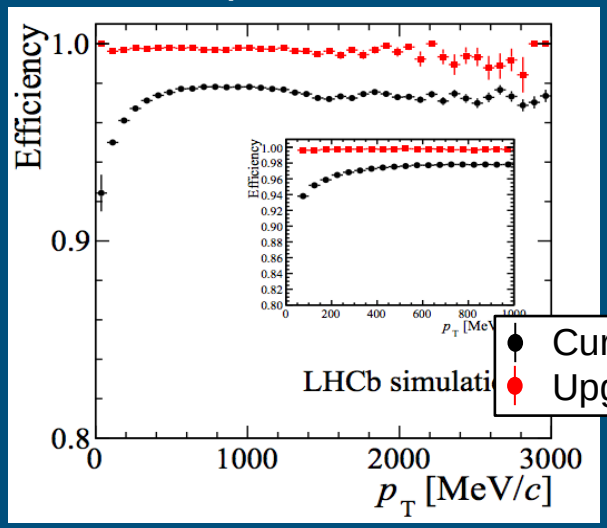


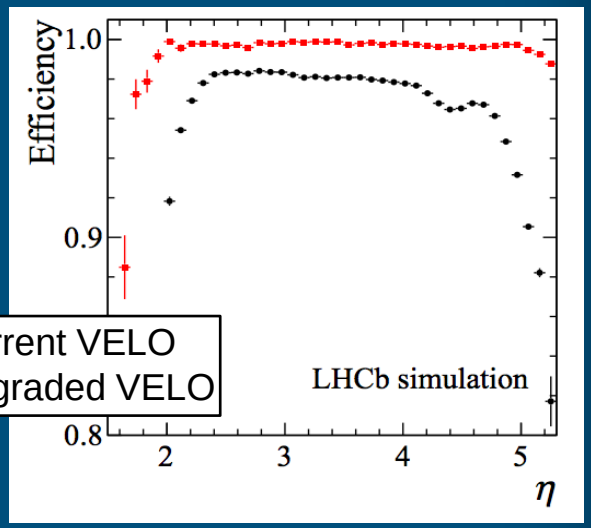


Tracking performance at 2×10^{33} cm^{-2}s^{-1}

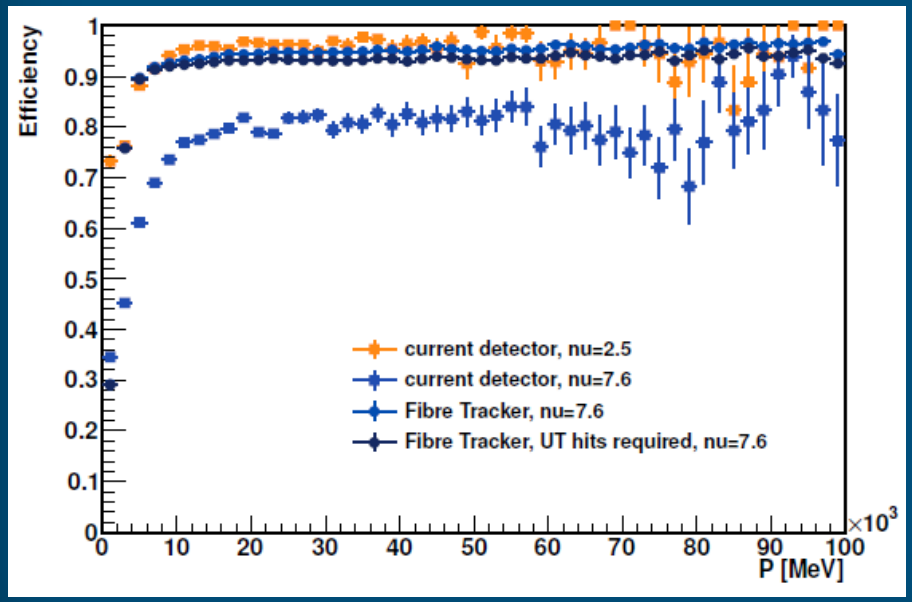
VELO performance

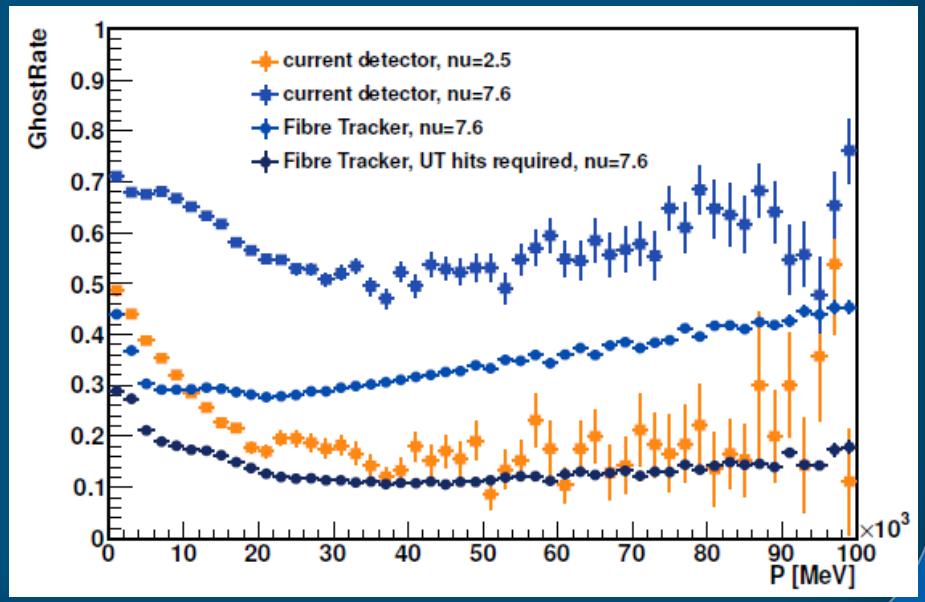






Forward patter recognition performance

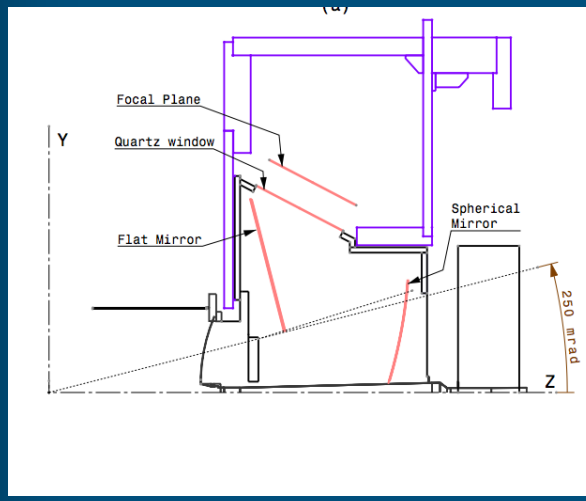




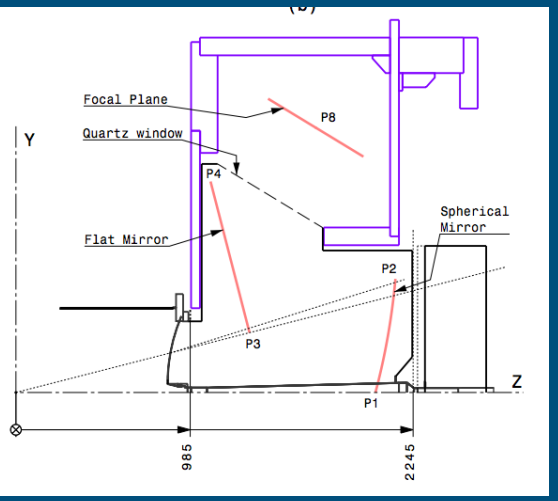
RICH Upgrade

- Partial upgrade of both RICH1 and RICH2:
  - Replace HPDs for 64-channel MAPMT
  - Re-optimize RICH1 mirror optics
  - Spread out rings within current gas enclosure to compensate for higher occupancy

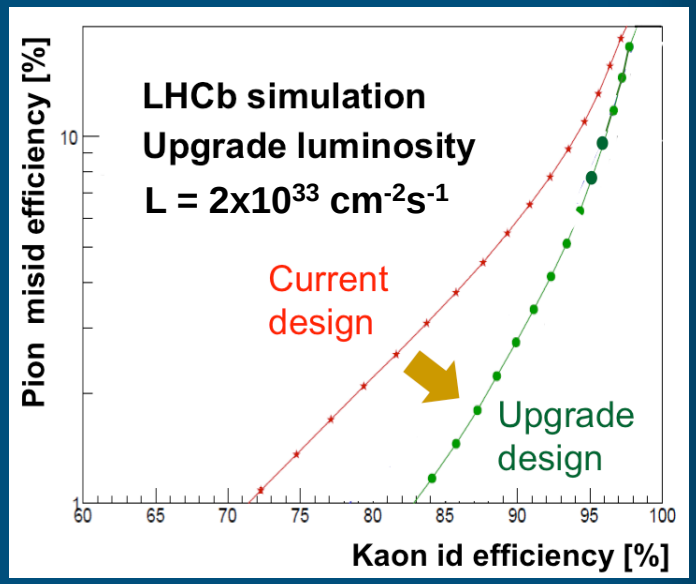
Current RICH1



Upgrade RICH1

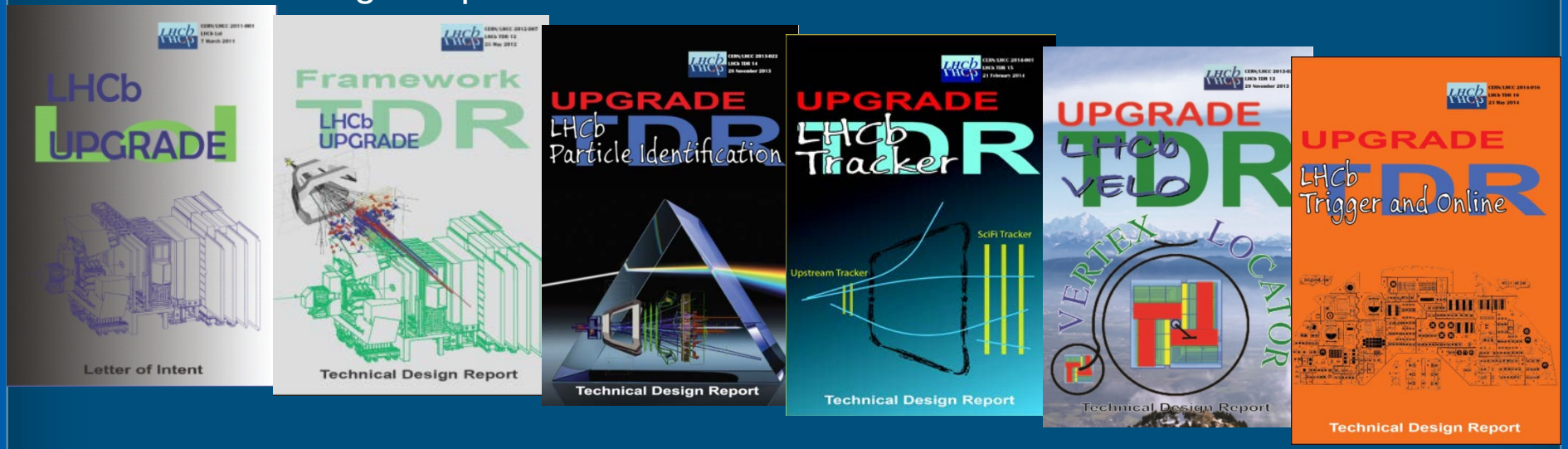


Upgraded K/π performance



Status and schedule

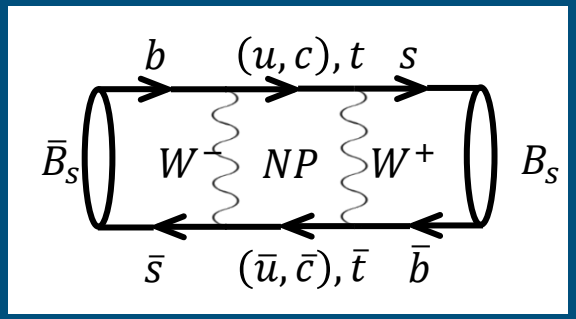
All Technical Design Reports done

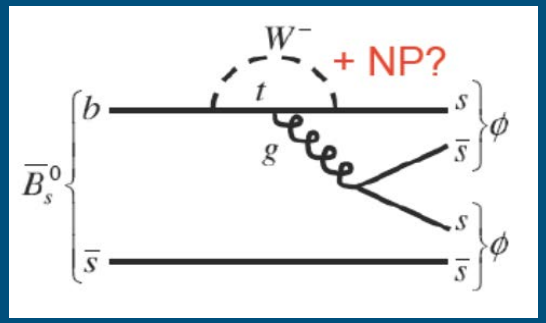


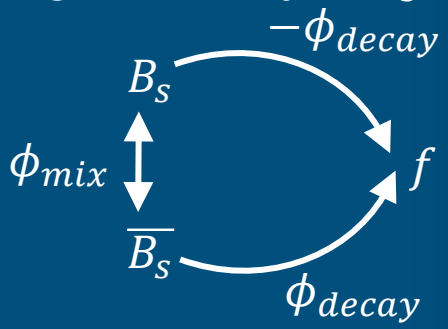
	LHC Era			HL-LHC Era	
Run (Years)	Run 1 (2010 – 2012)	Run 2 (2015 - 2018)	Run 3 (2021 - 2023)	Run 4 (~2027 - 2029)	Run 5 (~2031 -)
Integrated luminosity	**3 fb^{-1}**	**8 fb^{-1}**	**~25 fb^{-1}**	**~50 fb^{-1}**	**~100 fb^{-1}**
	Current LHCb		**Upgraded LHCb**		

Example of prospects: ϕ_s

- CP violating weak phase from the interference between mixing and decay of B_s



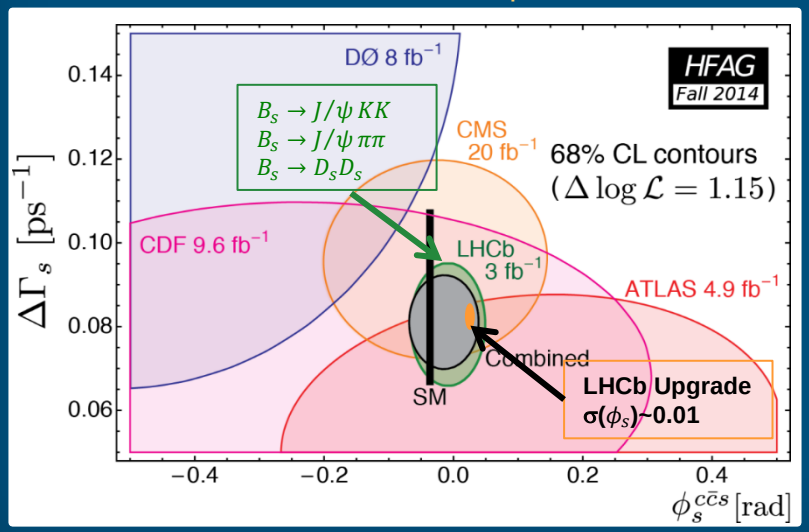


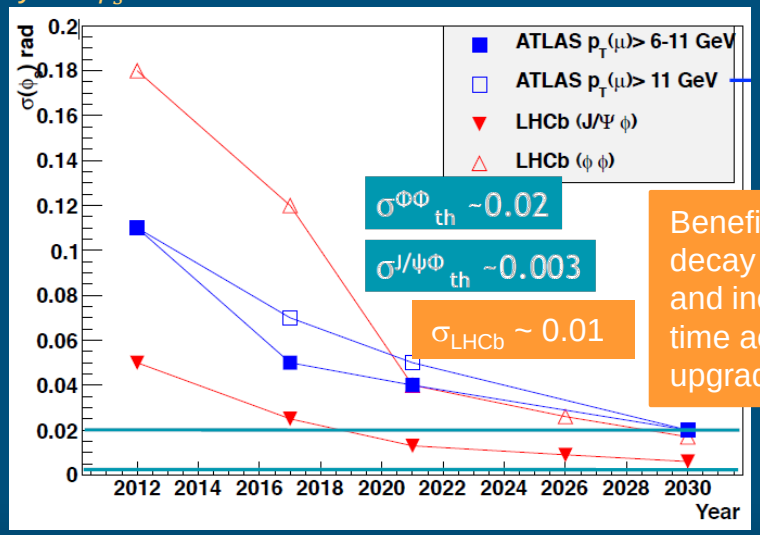


$$\phi_s = \phi_{mix} - 2\phi_{dec}$$

1. Final state with charm: Tree-level decay → $\phi_s^{c\bar{c}s}$
   - Sensitive to NP in mixing: $B_s \to J/\psi\,\phi$ $(B_s \to J/\psi\, f^0,\ B_s \to D_s D_s)$
2. Final state with strange: Gluonic penguin → $\phi_s^{s\bar{s}s}$ = 0 in SM due to cancellation
   - SM null test sensitive to NP in mixing and decay: $B_s \to \phi\phi$ $(B_d \to \phi K_s,\ B_d \to \eta' K_s)$

Expected future sensitivity on ϕ_s with 50 fb^{-1}



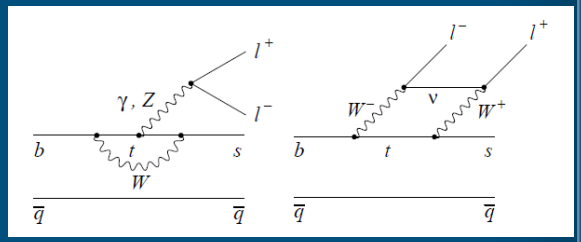


Benefit from better decay time resolution and increased decay time acceptance of the upgraded VELO

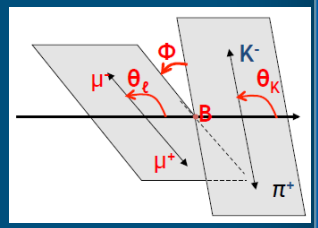
Example of prospects: $b \to s l^+ l^-$

- Electroweak penguin/box diagram sensitive to NP ➔ Helicity structure
  - $B_d \to K^* \mu^+ \mu^-$, $B_s \to \phi \mu^+ \mu^-$
  - 4-body angular analysis as a function of $q^2 = M^2(ll)$

E.g. $A_{FB}(q^2) = \frac{\Gamma(\cos\theta_{Bl^+}>0) - \Gamma(\cos\theta_{Bl^+}<0)}{\Gamma(\cos\theta_{Bl^+}>0) + \Gamma(\cos\theta_{Bl^+}<0)}$, $A_{FB}(q^2) = 0$



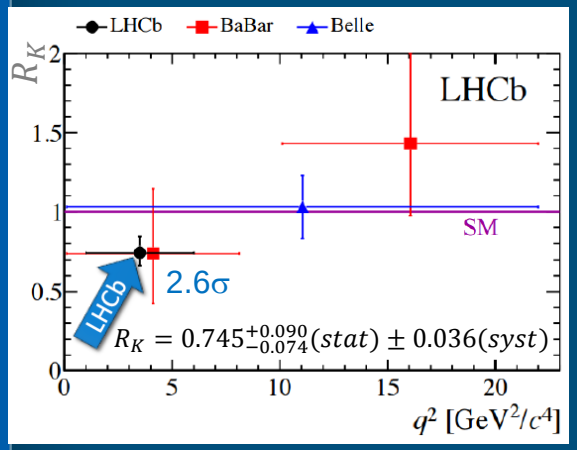
E.g. $A_T^{(2)}(q^2) = \frac{|A_\perp(q^2)|^2 - |A_\parallel(q^2)|^2}{|A_\perp(q^2)|^2 + |A_\parallel(q^2)|^2}$



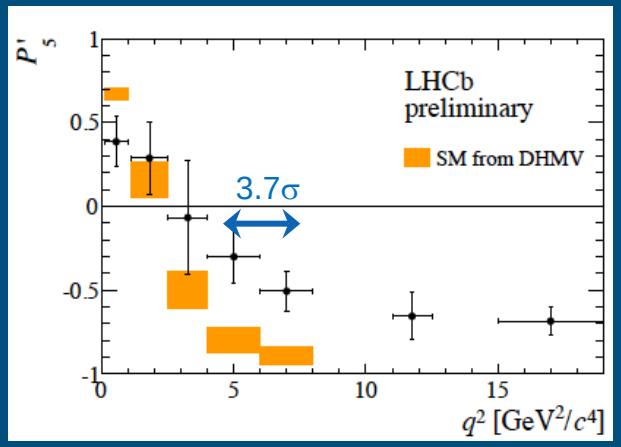
- Currently $b \to s l^+ l^-$ only measurements with some interesting tensions
  - Lepton universality $R_K = \frac{Br(B^+ \to K^+ \mu^+ \mu^-)}{Br(B^+ \to K^+ e^+ e^-)}$ together with P_5' in the differential decay rate in $B_d \to K^* \mu^+ \mu^-$

see talk by D. Martinez Santos

Expected future sensitivity on q_0^2 with 50 fb^{-1}



PRL 113 (2014) 151601



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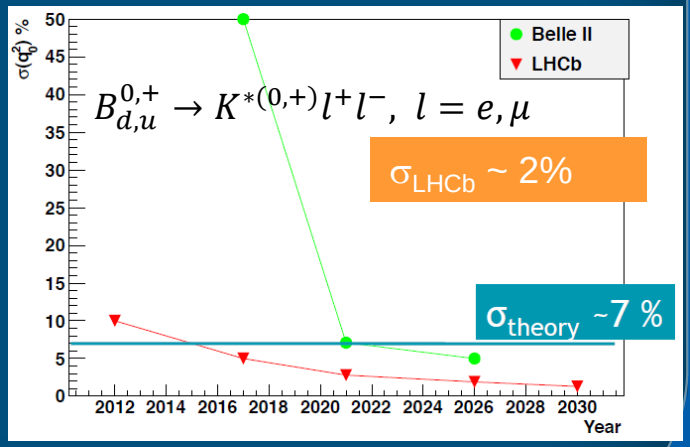
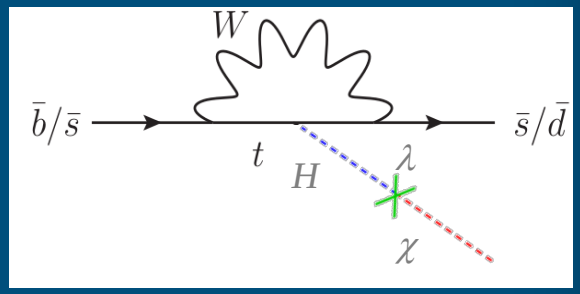


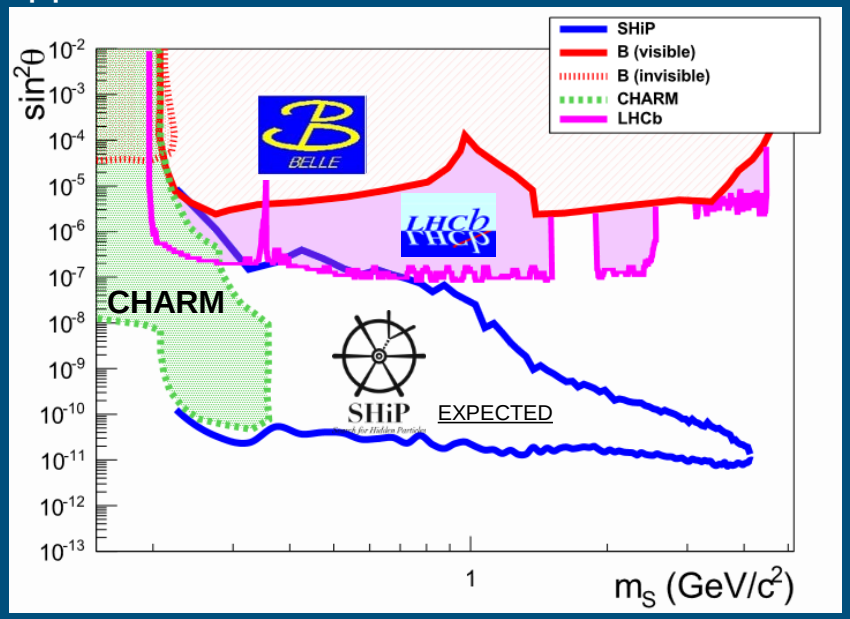
Example of prospects: Long-lived exotics

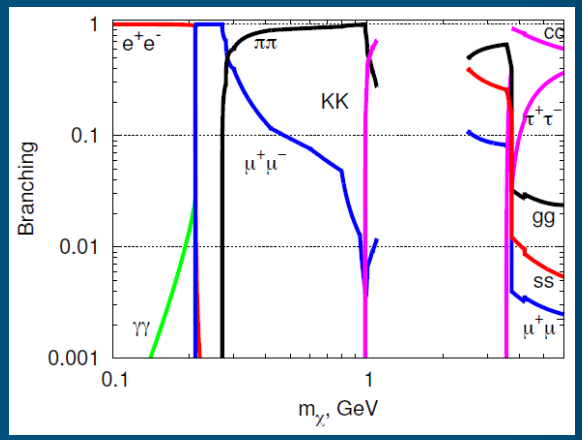
Ex. Search for hidden scalars in $b \to sll$ see talk by F. Redi

- Scalar portal from mixing with Higgs $\mathcal{L} = (g\chi + \lambda\chi^2)H^\dagger H$
  - Lifetime $\tau \propto \sin^{-2}\theta$, e.g. $\tau_\chi \sim 10^{-8} - 10^{-9} s$ for an inflaton
  - ➔ Displaced vertex
  - $b \to s\,\chi(\mu^+\mu^-)$ dominating up to hadronic threshold



- 95% CL upper limit with 3 fb^{-1}:



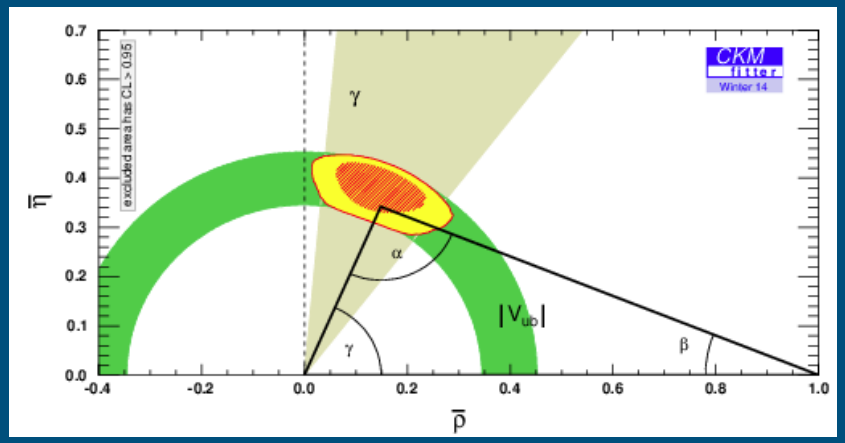


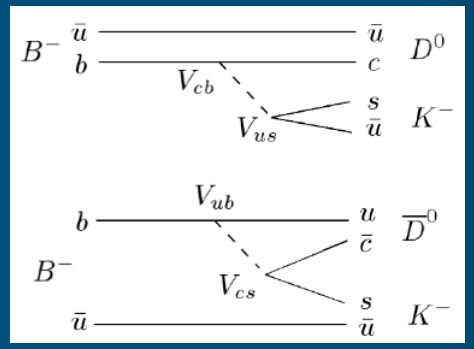
- Results are the most constraining exclusion limit on the process

- Analysis largely background free → sensitivity scales with yield of B

Example of prospects: γ

- On of the largest uncertainties in CKM matric are coming from $\gamma = \frac{|V_{ud}||V_{ub}^*|}{|V_{cd}||V_{cb}^*|}$



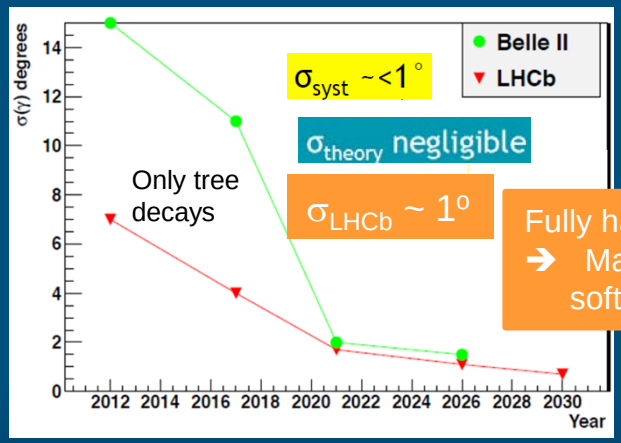


- The angle γ can be measured by comparing V_{cb} and V_{ub} mediated transitions
  - γ from purely trees: $B^{\pm} \to D^{(*)}K^{(*)}$ → SM reference with almost no theory uncertainty
  - $B_s \to D_s K^{\pm}$, loop (mixing) + tree (decay) → sensitive to NP in B_s mixing
  - γ from loop-mediated charmless decays $B \to h^+h^-$, $B^+ \to K^+\pi^+\pi^-$ → penguin sensitive to NP

  → LHCb can do them all

Expected future sensitivity on γ with 50 fb^{-1}

Decay mode	γ sensitivity
$B \to DK$ with $D \to hh'$, $D \to K\pi\pi\pi$	1.3°
$B \to DK$ with $D \to K_S^0\pi\pi$	1.9°
$B \to DK$ with $D \to 4\pi$	1.7°
$B^0 \to DK\pi$ with $D \to hh'$, $D \to K_S^0\pi\pi$	1.5°
$B \to DK\pi\pi$ with $D \to hh'$	$\sim 3^\circ$
Time-dependent $B_s \to D_s K$	2.0°
Combined	$\sim 0.9^\circ$



Fully hadronic B decays
→ Major improvement with software trigger in Upgrade

Example of prospect: Charm CPV

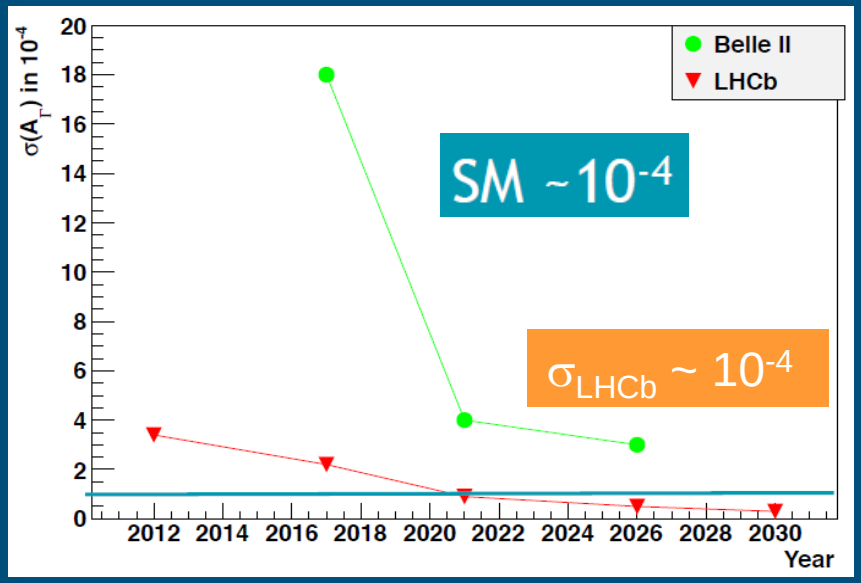
- Indirect CP violation in charm mixing expected to be very small in SM (~10^{-4})
  - D^0 only neutral system with FCNC decays with up type quarks
  - Ex. $A_\Gamma = \frac{\tau(\overline{D^0}\to h^+h^-) - \tau(D^0\to h^+h^-)}{\tau(\overline{D^0}\to h^+h^-) + \tau(D^0\to h^+h^-)}$ with $D^0 \to KK$ and $D^0 \to \pi\pi$

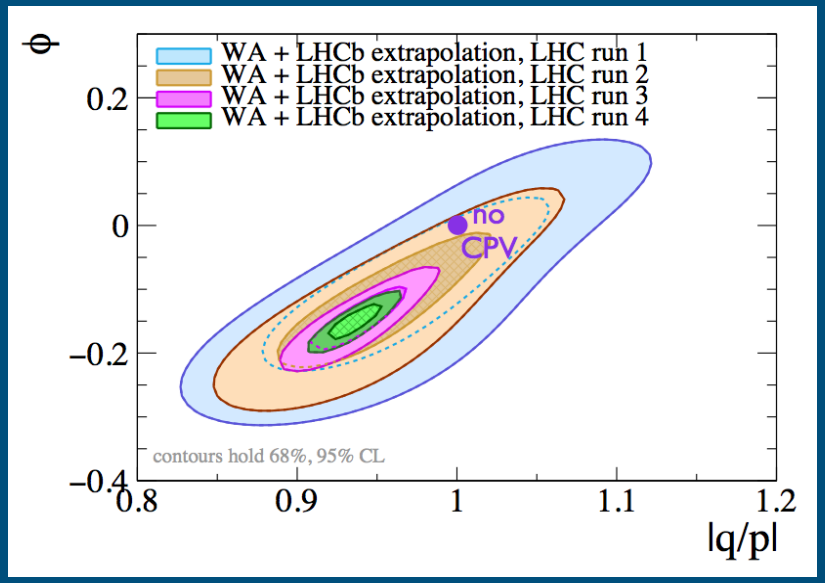
→ $A_\Gamma \neq 0$: indirect CP violation

→ Robust against systematics due to cancellations

The fully hadronic software trigger and the improved impact parameter resolution of the Upgrade are crucial

Expected future sensitivity with 50 fb^{-1}





- Together with ΔA_{CP}, $A_\Gamma(D^0 \to KK) \neq A_\Gamma(D^0 \to \pi\pi)$ may also be used for direct CP violation

Upgrade Physics Prospects

250++ papers and counting

Far from σ_{theory} at end of Run 2

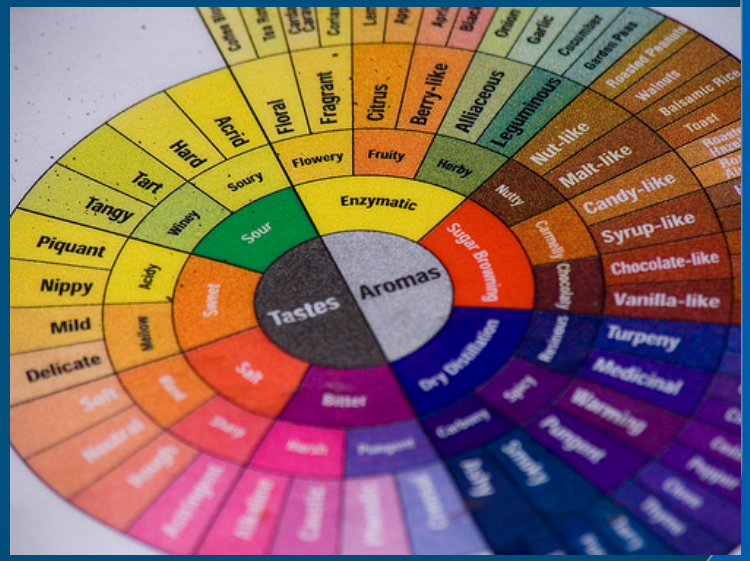
Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory (SM)
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.05	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\ f_0(980))$ (rad)	0.09	0.05	**0.016**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.18	0.12	**0.026**	0.02
	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.14	0.07	**0.024**	~ 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°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	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	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–

+ a wealth of additional physics

- ➔ Diversity and non-spectator effect of the B_c system, and baryons
- ➔ Lepton universality, lepton flavour violation, searches for long-lived "portals"
- Production measurements and spectroscopy, QCD, PDFs, and EW
- …and quarkonium and Z production in pA and possibly also AA collisions

Conclusions

- LHCb has fought hard to earn the title of forward GPD
  - LHCb has demonstrated forward tracking and particle ID in pileup environment
  - A very rich physics precision program
- Folding in efficiencies and luminosity, upgrade get up to 20 times more hadronic events per second !
  - Upgrade allows reaching theoretical uncertainties and opens the door to new observables
- But strength is the full software trigger to tune to any signature that may be popular in 2020!
- The LHCb Upgrade has been fully approved by CERN and is in the production phase.
- In continuous search for new flavours!

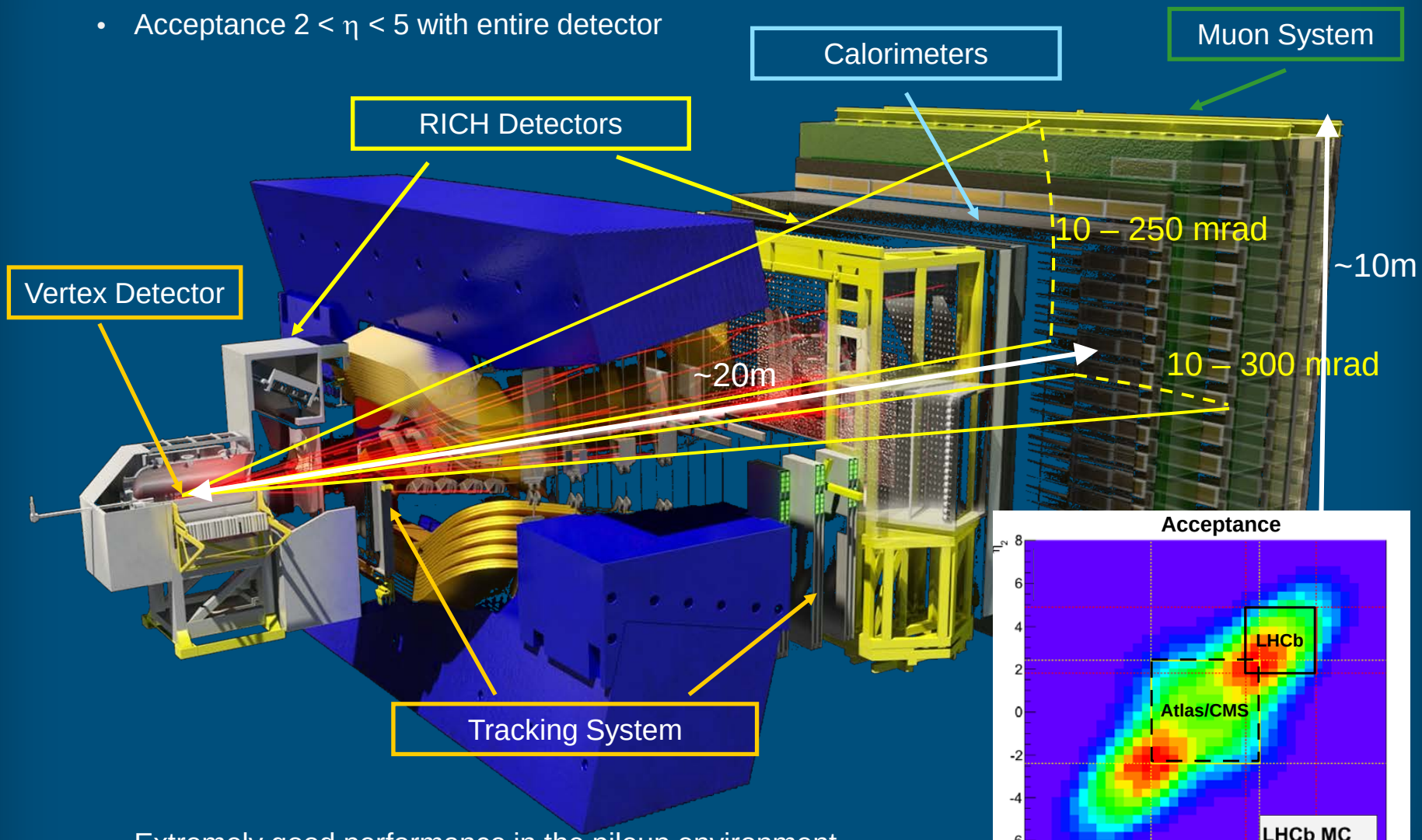


EXTRA SLIDES

LHCb Detector

Covers ~4% of the solid angle, but captures ~40% of the heavy quark production cross-section

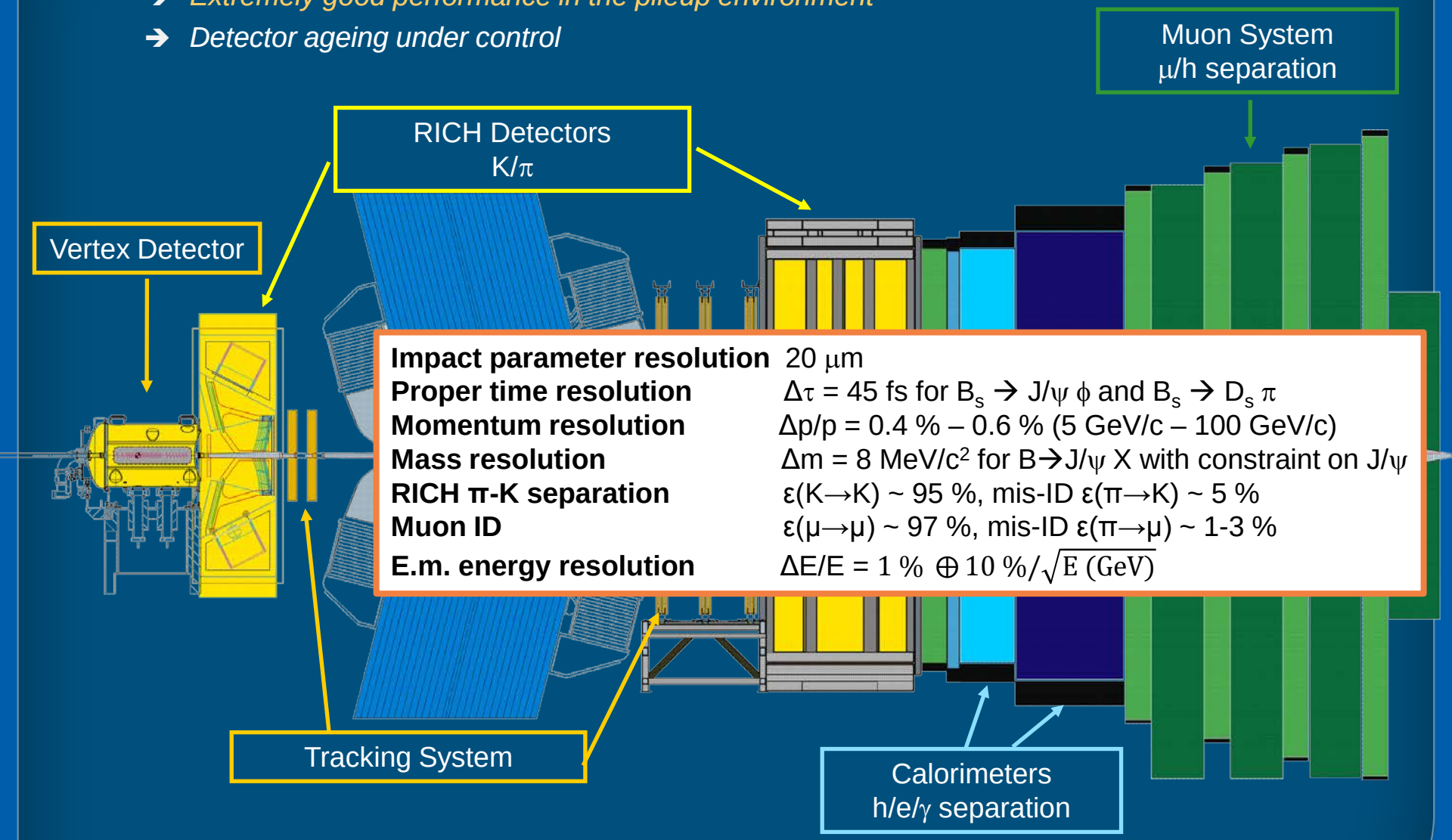
- Acceptance $2 < \eta < 5$ with entire detector



- Extremely good performance in the pileup environment
- Detector ageing under control

Current LHCb Detector Performance

- *Extremely good performance in the pileup environment*
- *Detector ageing under control*



Impact parameter resolution	20 μm
Proper time resolution	$\Delta\tau$ = 45 fs for $B_s \rightarrow J/\psi\ \phi$ and $B_s \rightarrow D_s\ \pi$
Momentum resolution	$\Delta p/p$ = 0.4 % – 0.6 % (5 GeV/c – 100 GeV/c)
Mass resolution	Δm = 8 MeV/c^2 for $B \rightarrow J/\psi$ X with constraint on J/ψ
RICH π-K separation	$\varepsilon(K \rightarrow K)$ ~ 95 %, mis-ID $\varepsilon(\pi \rightarrow K)$ ~ 5 %
Muon ID	$\varepsilon(\mu \rightarrow \mu)$ ~ 97 %, mis-ID $\varepsilon(\pi \rightarrow \mu)$ ~ 1-3 %
E.m. energy resolution	$\Delta E/E = 1\ \% \oplus 10\ \%/\sqrt{E\ (\mathrm{GeV})}$