LHCb prospects for measurements of UT angles

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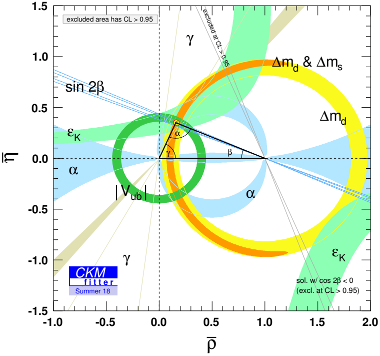
On behalf of the LHCb collaboration

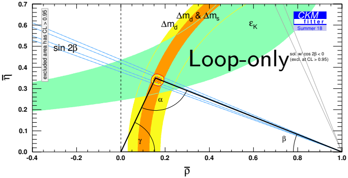
Unitarity Triangle measurements

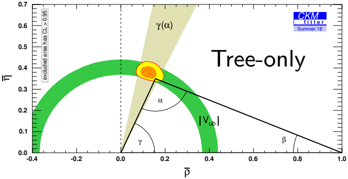
Cabibbo-Kobayashi-Maskawa matrix

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Sensitivity to NP comes from the global consistency of various measurements







Unitarity Triangle measurements

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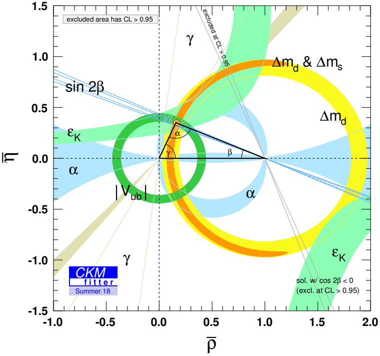
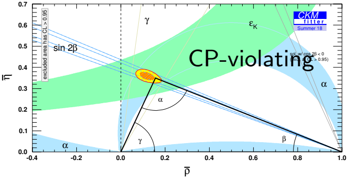
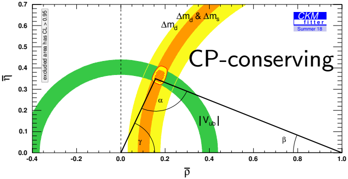
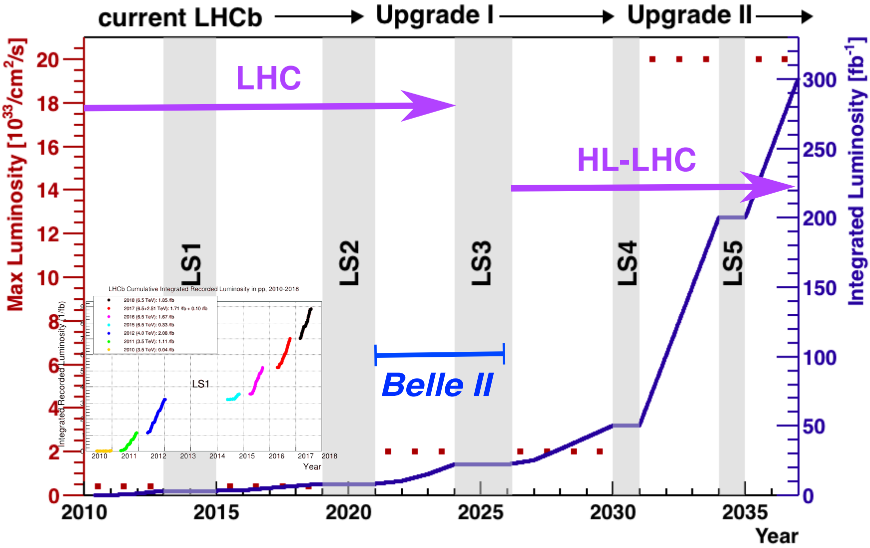


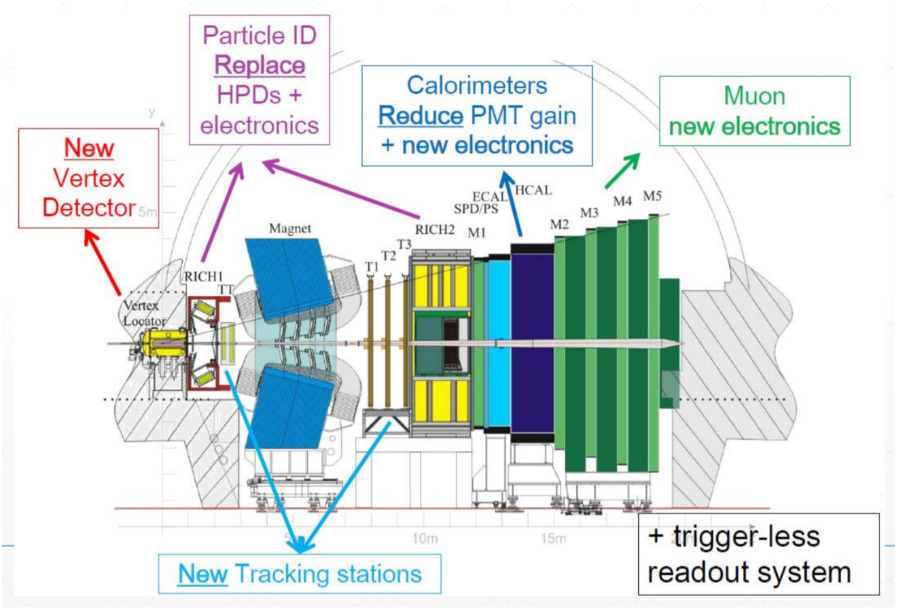




LHCb timeline



LHCb upgrade I



New Vertex Detector

Particle ID
Replace HPDs + electronics

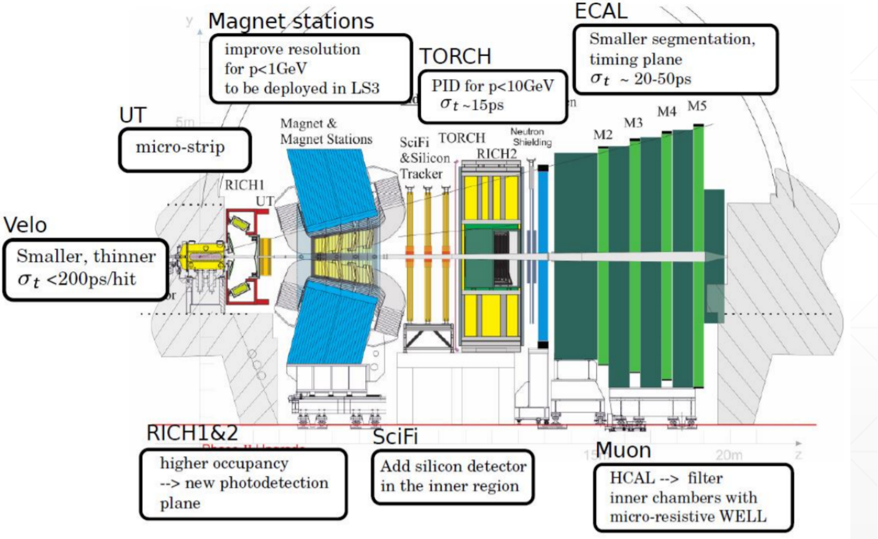
Calorimeters
Reduce PMT gain
+ new electronics

Muon
new electronics

New Tracking stations

+ trigger-less readout system

LHCb upgrade II



Magnet stations
improve resolution
for p<1GeV
to be deployed in LS3

TORCH
PID for p<10GeV
$\sigma_t \sim$15ps

ECAL
Smaller segmentation,
timing plane
σ_t ~ 20-50ps

UT
micro-strip

Velo
Smaller, thinner
σ_t <200ps/hit

RICH1&2
higher occupancy
--> new photodetection
plane

SciFi
Add silicon detector
in the inner region

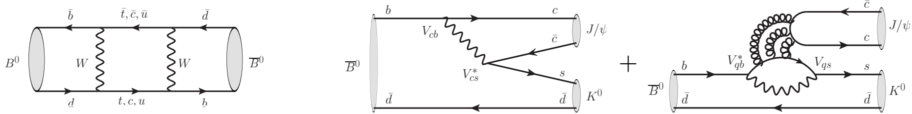
Muon
HCAL --> filter
inner chambers with
micro-resistive WELL

$$\beta$$

Time-dependent *CP* violation

Interference between the decays with and without mixing

$$\begin{tikzcd}
B^0 \arrow[rr, bend left, "A_f"] \arrow[dr, bend right, "q/p"'] & & J/\psi K^0_S \\
& \overline{B}^0 \arrow[ur, bend right, "\overline{A}_f"'] &
\end{tikzcd}$$



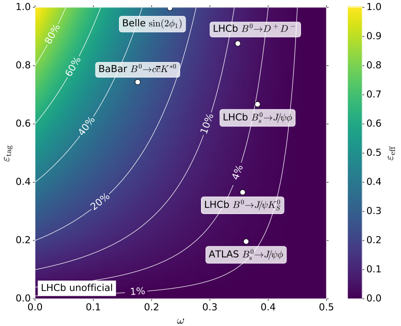
Time-dependent CP asymmetry

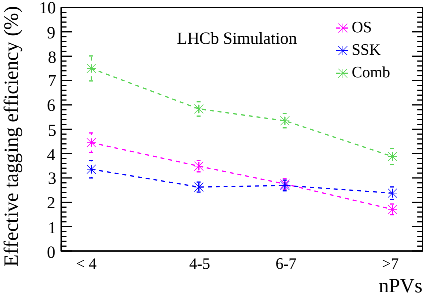
$$A_{CP}(t) = \frac{\Gamma(\overline{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\overline{B}^0(t) \to f) + \Gamma(B^0(t) \to f)} = \frac{\overset{= \sin 2\beta}{S} \sin(\Delta m\, t) + \overset{\simeq 0}{C} \cos(\Delta m\, t)}{\underset{\to 1}{\cosh(\frac{1}{2}\Delta\Gamma\, t)} + \underset{\to 0}{A_{\Delta\Gamma} \sinh(\frac{1}{2}\Delta\Gamma\, t)}}$$

Flavour tagging

Performance critically depends on flavour tagging performance.

$$\sigma \propto \frac{1}{\sqrt{\epsilon_{eff} N}}; \quad \epsilon_{eff} = \epsilon_{tag}(1-2\omega); \quad \epsilon_{tag} = \frac{N_{tagged}}{N_{tagged}+N_{untagged}}; \quad \omega = \frac{N_{right}}{N_{right}+N_{wrong}}$$





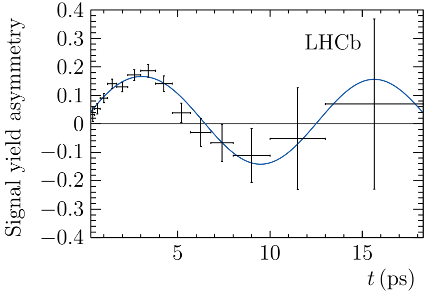
With Upgrade II: expect $\langle N_{PV} \rangle \sim 50$.

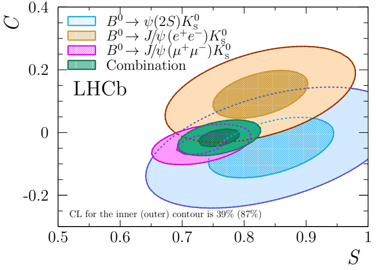
Timing in VELO/tracker is essential to recover Run I performance.
~ 50 ps will be needed to reach reasonable track-PV mis-association rate.

Current $\sin 2\beta$ measurements

[PRL 115, 031601 (2015)] [JHEP 11 (2017) 170]

Measured in $B^0 \to J/\psi\, K^0_\mathrm{S}$ with $J/\psi \to \mu^+\mu^-$ and e^+e^-, and $B^0 \to \psi(2S)K^0_\mathrm{S}$, $\psi(2S) \to \mu^+\mu^-$.



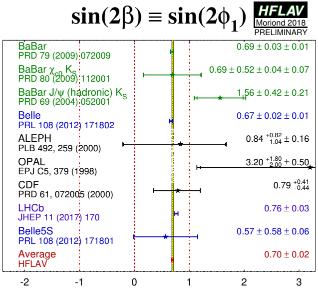


Combined result:

$$S_{c\bar{c}K^0_\mathrm{S}} = 0.760 \pm 0.034$$

$$C_{c\bar{c}K^0_\mathrm{S}} = -0.017 \pm 0.029$$

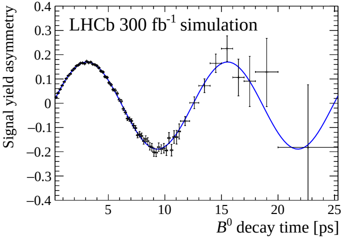
Precision similar to B factories. Dominated by statistics.

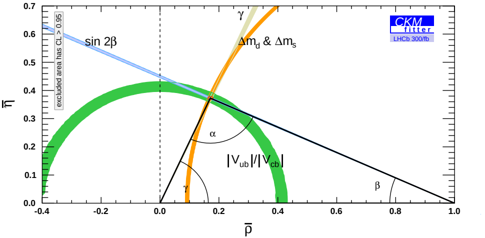


Upgrade prospects

[LHCb-PUB-2018-009: "Physics case for an LHCb Upgrade II"]

Assuming FT performance can be kept at Run I level: $\sigma(\sin 2\beta) = 0.003$ for 300 fb^{-1}.



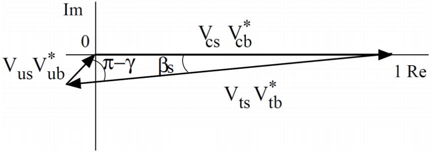


Penguin contribution becomes a major systematic uncertainty.

- $SU(3)$ symmetry to constrain penguin contribution, *e.g.* $B_s \to J/\psi K^0_S$.
- $B^0 \to D\pi^+\pi^-$ mode: tree-level process; no penguin pollution. In addition, measures $\sin 2\beta$ and $\cos 2\beta$ independently.
  - $D \to KK, \pi\pi$: TD Dalitz plot analysis (model uncertainty)
    $\sigma(\sin 2\beta) \sim 0.007$, $\sigma(\cos 2\beta) \sim 0.017$ for 300 fb^{-1} [JPG 36 (2009) 025006]
  - $D \to K^0_S hh$: MI approach, TD analysis of two correlated Dalitz plots
    Estimated $\sigma(\beta) \sim (2-3)^\circ$ with 50 fb^{-1} [JHEP 03(2018) 195]

ϕ_s

Another unitarity triangle and β_s



β_s: similar to β, but in B_s^0 system.

Measurable phase between mixing and decay:

$$\phi_s = \phi_M - 2\phi_D = -2\beta_s + \Delta\phi_s^{peng} + \delta_s^{NP}$$

- Sensitivty to New Physics
- Input measurement for other CKM studies (e.g. $B_s^0 \to D_s K$, see later)

Similar TD formalism, but more complicated because of finite $\Delta\Gamma_s$:

$$\frac{d\Gamma_{B_s^0(\bar{B}_s^0)\to f}(t)}{dt} \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + \overset{= -\frac{2|\lambda_f|\cos\phi_s}{1+|\lambda_f|^2}}{A_f^{\Delta\Gamma}} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right.$$
$$\left. \pm \underset{= \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}}{C_f} \cos(\Delta m_s t) \mp \underset{= \frac{2|\lambda_f|\sin\phi_s}{1+|\lambda_f|^2}}{S_f} \sin(\Delta m_s t)\right]$$

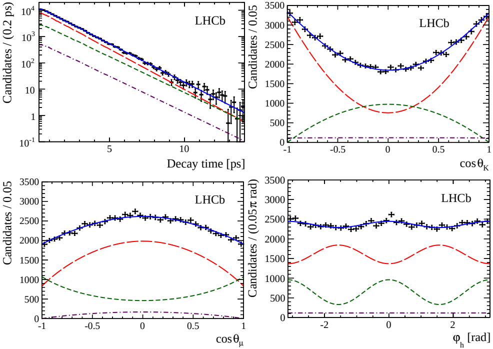
Mixing-induced CP violation in $B_s \to J/\psi K^+K^-$

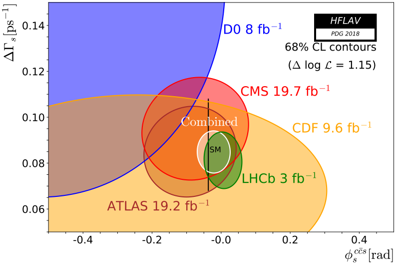
[PRL 114, 041801 (2015)]

- K^+K^- can be in P wave (ϕ) or S wave
- 3 P waves ($\mathcal{CP}$-odd or $\mathcal{CP}$-even), angular analysis to distinguish them
- Ambiguity $\varphi_s \leftrightarrow \pi - \varphi_s$ is resolved by measuring the P wave strong phase as a function of m_{KK}.
- Combined with $B_s^0 \to J/\psi\pi^+\pi^-$, $B_s^0 \to \psi(2S)K^+K^-$

$$
\begin{aligned}
\phi_s &= -58 \pm 49 \pm 6 \text{ mrad}\\
\Gamma_s &= 0.6603 \pm 0.0027 \pm 0.0015\\
\Delta\Gamma_s &= 0.0805 \pm 0.0091 \pm 0.0032\\
\Delta m_s &= 17.711^{+0.055}_{-0.057} \pm 0.0032\\
|\lambda| &= 0.964 \pm 0.019 \pm 0.007
\end{aligned}
$$

Decay time and helicity distributions:



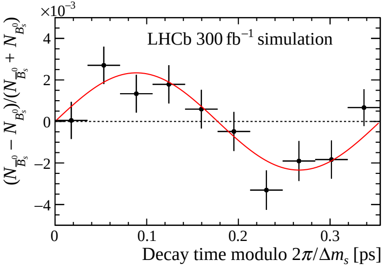


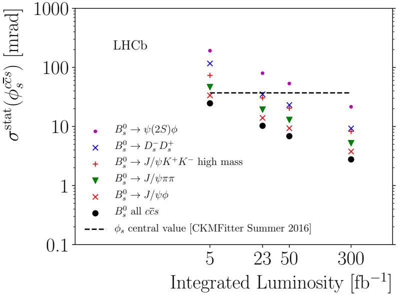
ϕ_s prospects

[LHCb-PUB-2018-009: "Physics case for an LHCb Upgrade II"]

Important to combine several $b \to c\bar{c}s$ modes to control systematic uncertainties and penguin contribution.

Several modes are expected to measure non-zero $-2\beta_s^{SM} = -36.4 \pm 1.2$ mrad.





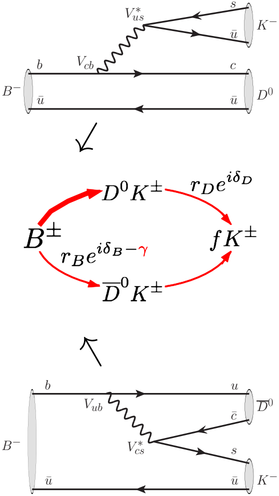
Expected sensitivity with 300 fb^{-1}: 4 mrad for $B_s^0 \to J/\psi\,\phi$ and 3 mrad for all modes combined

$$\gamma$$

SM reference measurement: γ from trees

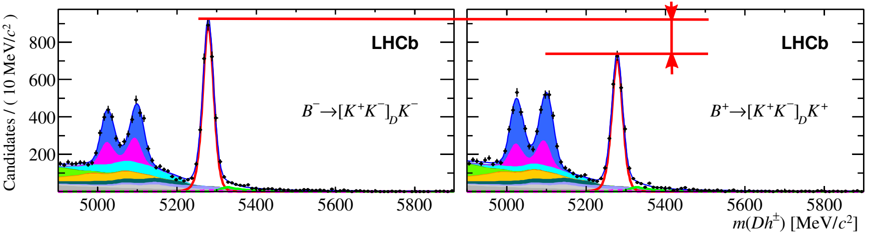
- Measured entirely from tree decays.
- All hadronic parameters can be constrained from experiment $\Rightarrow$ theoretically very clean (uncertainty $< 10^{-7}$[Brod, Zupan, JHEP 1401 (2014) 051])
- Combination of many different modes:
  - Time-integrated asymmetries in $B \to DK$, $B \to DK^*$, $B \to DK\pi$ with $D \to hh, hhhh$ ("ADS", "GLW")
  - Dalitz plot analyses of $D^0 \to K^0_S h^+ h^-$ from $B \to DK$, $B \to DK^*$ ("GGSZ")
  - Time-dependent analyses of $B^0_s \to D_s K$, $B^0 \to D\pi$
- Experimentally, just entering precision measurement regime ($< 10\%$)

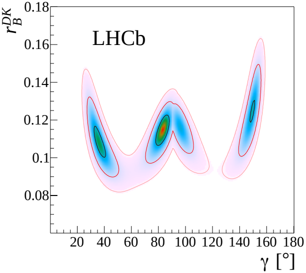
[LHCb-CONF-2016-001]



State of the art: γ from CP-asymmetric rates

[PLB 777 (2018) 16]





CP-violating rate for $B^\pm \to D(\to f)K^\pm$ decays:

$$\Gamma(B^\pm \to D(\to f)K^\pm) = r_D^2 + r_B^2 + 2\kappa r_D r_B \cos(\delta_B - \delta_D \pm \gamma)$$

r_B : ratio of $b \to u$ and $b \to c$ amplitudes
r_D : ratio of $D^0 \to f$ and $\bar{D}^0 \to f$ amplitudes ($\equiv 1$ for D_{CP})
δ_B and δ_D: corresponding strong phase differences
κ : coherence factor ($\equiv 1$ for 2-body decays)

Combination of several D and B decay modes to constrain γ

γ from $B^\pm \to DK^\pm$, $D \to K^0_S\pi^+\pi^-$

[GGSZ, 2003; Bondar, 2002]

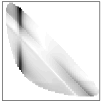
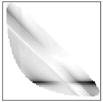
Information on γ from Dalitz plot analysis of $D \to K^0_S\pi^+\pi^-$ from $B^\pm \to DK^\pm$.

Dalitz plot density: $d\sigma(m^2_+, m^2_-) \sim |A|^2 dm^2_+ dm^2_-$, where $m^2_\pm = m^2_{K_S\pi^\pm}$

Flavour D amplitude: $A_D(m^2_+, m^2_-)$

Amplitude of $D \to K^0_S\pi^+\pi^-$ from $B^+ \to DK^+$:

$$A_B(m^2_+, m^2_-) = A_D(m^2_+, m^2_-) + r_B e^{i\delta_B + i\gamma} A_D(m^2_-, m^2_+)$$

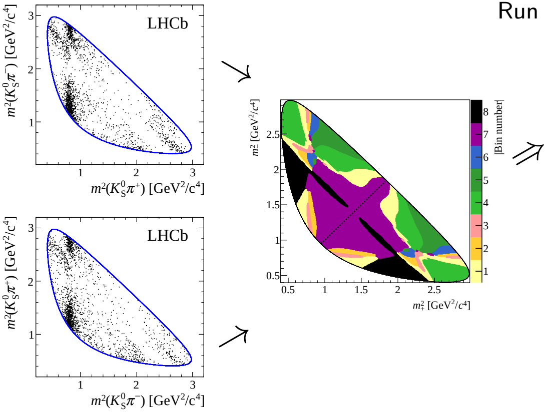
$=$  $+ r_B e^{i\delta_B + i\gamma}$ 

Need to know $A_D(m^2_+, m^2_-)$, both amplitude and phase (or, more precisely, phase difference between (m^2_+, m^2_-) and (m^2_-, m^2_+)).

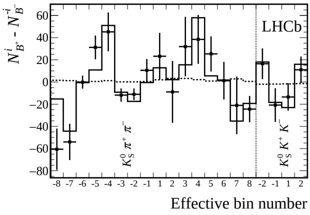
Model-dependent: obtain A_D from $D \to K^0_S\pi^+\pi^-$ fit to the isobar model ⇒ model uncertainty

Model-independent: obtain phase difference info from $e^+e^- \to D^0\overline{D}^0$ decays (CLEO, BES-III)

State of the art: γ from Dalitz plot analyses



Run II (2015, 2016): [JHEP 08 (2018) 176]



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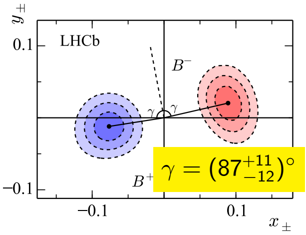


$\gamma = (87^{+11}_{-12})^\circ$

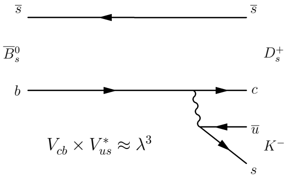
Combination with Run I: $\gamma = (80^{+10}_{-9})^\circ$

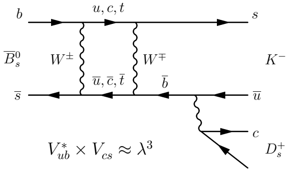
Main syst uncertainties (total ∼ 30% of stat):

- Strong phase measurement (CLEO)
- Dalitz plot efficiency correction
- Mass fit shapes

γ from time-dependent analyses

Interference between $b \to u$ and $b \to c$ amplitude from B_s^0 mixing.
Comparable magnitudes $r = |\frac{p}{q}\frac{A_f}{A_{\overline{f}}}| \simeq 0.4$.





Time-dependent decay rates for $B_s^0(\overline{B}_s^0) \to f$ (similarly for $\overline{f}$)

$= -\frac{2r\cos(\delta-(\gamma-2\beta_s))}{1+r^2}$

$$\frac{d\Gamma_{B_s^0(\bar{B}_s^0)\to f}(t)}{dt} \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + A_f^{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)\right.$$
$$\left.\pm C_f\cos(\Delta m_s t) \mp S_f\sin(\Delta m_s t)\right]$$

Measure $\gamma - 2\beta_s$, δ, r

$= \frac{1-r^2}{1+r^2}$

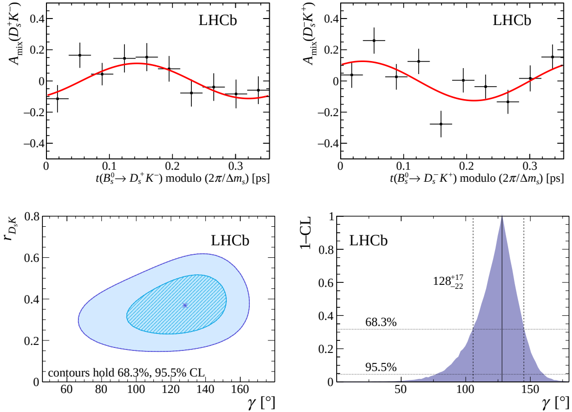
$= \frac{2r\sin(\delta-(\gamma-2\beta_s))}{1+r^2}$

Similar technique with $B^0 \to D\pi$ (but negligible $\Delta\Gamma_d$, small $r \simeq 0.02 \Rightarrow$ only two observables $S_f, S_{\overline{f}}$).

Measure $2\beta + \gamma$ with the external input for r (from $SU(3)$ $B^0 \to D_s\pi$)

γ from time-dependent analyses

[JHEP 03 (2018) 059]



Relies on input $-2\beta_s = -0.030 \pm 0.033 \Rightarrow \gamma = (128^{+17}_{-22})^\circ$ (stat-limited).

Systematic uncertainties: background, Δm_s, time acceptance, resolution, flavour tagging. All data-driven.

Safe to assume $1/\sqrt{N}$ scaling $\Rightarrow \sim 1^\circ$ with 300 fb^{-1}.

[LHCb-PUB-2018-009: "Physics case for an LHCb Upgrade II"]

State of the art: γ combination

Many modes are combined to constrain γ: [LHCb-CONF-2018-002]

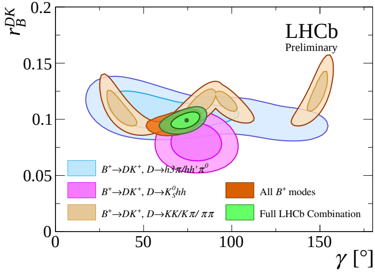
B decay	D decay	Method	Ref.	Dataset[†]	Status since last combination [3]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[16]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[17]	Run 1	As before
$B^+ \to DK^+$	$D \to K^0_S h^+h^-$	GGSZ	[18]	Run 2	New
$B^+ \to DK^+$	$D \to K^0_S K^+\pi^-$	GLS	[19]	Run 1	As before
$B^+ \to D^*K^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^{*+}$	$D \to h^+h^-$	GLW/ADS	[20]	Run 1 & 2	Updated results
$B^+ \to DK^{*+}$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[20]	Run 1 & 2	New
$B^+ \to DK^+\pi^+\pi^-$	$D \to h^+h^-$	GLW/ADS	[21]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^+\pi^-$	ADS	[22]	Run 1	As before
$B^0 \to DK^+\pi^-$	$D \to h^+h^-$	GLW-Dalitz	[23]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	GGSZ	[24]	Run 1	As before
$B^0_s \to D_s^\mp K^\pm$	$D_s^+ \to h^+h^-\pi^+$	TD	[25]	Run 1	Updated results
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^+\pi^-\pi^+$	TD	[26]	Run 1	New

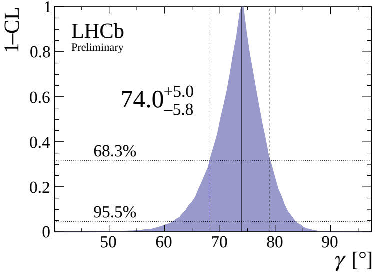
[†] Run 1 corresponds to an integrated luminosity of 3 fb^{-1} taken at centre-of-mass energies of 7 and 8 TeV . Run 2 corresponds to an integrated luminosity of 2 fb^{-1} taken at a centre-of-mass energy of 13 TeV .

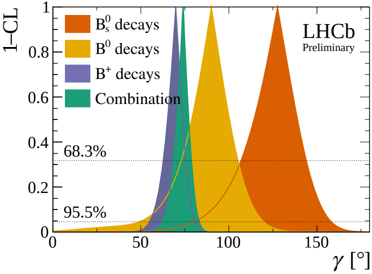
State of the art: γ combination

- $D \to hh$ (ADS/GLW) provide strong constraints in r_B, δ_B, γ space, but ambiguities and non-gaussian uncertainties.
- $D \to K^0_S hh$ modes break ambiguities
- Different correlation patterns result in combined γ uncertainty better than just plain average.
- Different analysis approaches (rates, Dalitz, time-dep) allow better control of systematic uncertainties.

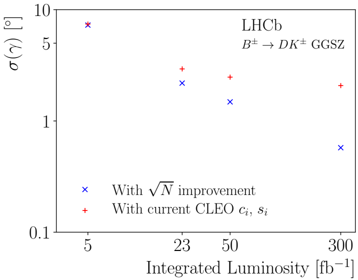
[LHCb-CONF-2018-002]



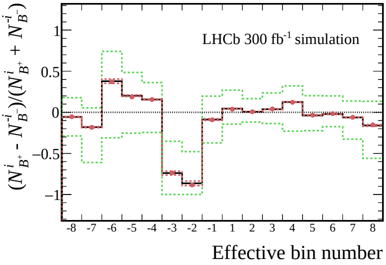




Prospects for γ: GGSZ



[LHCb-PUB-2018-009: "Physics case for an LHCb Upgrade II"]



- Critical uncertainty: CLEO measurement of strong phase difference in bins. Currently: $\simeq 2^\circ$.
- Further reduction is possible:
  - Expect BES-III to contribute with around ×4 larger dataset.
  - Technique to obtain $D^0 - \bar{D}^0$ phase difference from charm mixing fits at LHCb [JHEP 10 (2012) 185]
  - Use other $B \to DX$ decays to overconstrain phase difference, such as $B \to DK\pi$, $D \to K^0_S\pi\pi$ [PRD 97, 056002 (2018)]
  - $B \to DK$ decays themselves constrain phase difference for sufficiently large dataset [preliminary toy MC studies]
- Other uncertainties depend on control or MC samples.

Assume that $1/\sqrt{N}$ scaling is valid: $\sigma(\gamma) < 1^\circ$ with 300 fb^{-1}

[LHCb-PUB-2018-009: "Physics case for an LHCb Upgrade II"]

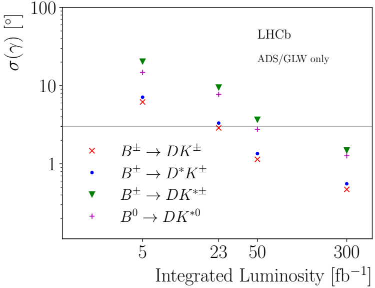
Main systematic uncertainties with rate and asymmetry measurements:

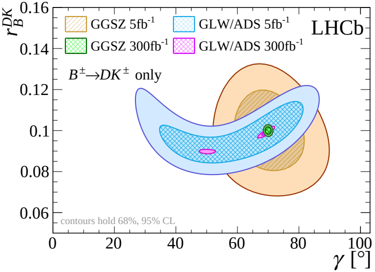
- Production and instrumentation asymmetries
- Backgrounds and their asymmetries.

All data-driven, so assumed to scale with data sample.

Additional subtle point to be taken into account:

- Charm mixing and *CP* violation in charm
- Matter effects for K^0_S final states





Estimated $\sigma(\gamma) \simeq 0.35°$ with 300 fb^{-1} (!)

Prospects for γ: beyond $1/\sqrt{N}$

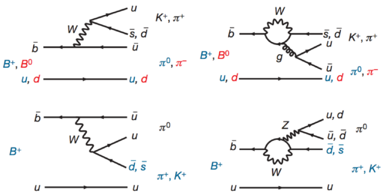
- New modes not used in the combination yet:
  - Multibody B and D decays
  - Modes with neutrals, both fully and partially-reconstructed.
  - $B_c \to DD_s$: Large CPV with $r_B \simeq 1$, but very low yields (~ 1 event in Run 1)
  - b baryons, e.g. $\Lambda_b^0 \to D\Lambda$, DpK: complication due to S and P-wave amplitudes with possibly different strong parameter. Precision depends on Λ_b^0 polarisation.
- New strategies with existing modes:
  - "Unified" approach for GLW/ADS/GGSZ with common treatment of systematic uncertainties [arXiv:1804.05597]
  - Fourier analysis instead of binning for model-independent GGSZ approach: squeeze last bits of statistical power [EPJC (2018) 78: 121]

α, $\beta_{(s)}$, γ from charmless decays

γ from charmless processes

[PRD 98, 032004 (2018)]

- Extraction of γ and β_s from time-dependent asymmetries of $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$
- Use U-spin symmetry to disentangle contributions from different topologies



Data sample	$C_{\pi^+\pi^-}$	$S_{\pi^+\pi^-}$	$C_{K^+K^-}$	$S_{K^+K^-}$	$A^{\Delta\Gamma}_{K^+K^-}$
Run 1 ($3\,\mathrm{fb}^{-1}$ [112])	$-0.34 \pm 0.06 \pm 0.01$	$-0.63 \pm 0.05 \pm 0.01$	$0.20 \pm 0.06 \pm 0.02$	$0.18 \pm 0.06 \pm 0.02$	$-0.79 \pm 0.07 \pm 0.10$
			σ (stat.)		
Run 1-3 ($23\,\mathrm{fb}^{-1}$)	0.015	0.013	0.015	0.015	0.018
Run 1-6 ($300\,\mathrm{fb}^{-1}$)	0.004	0.004	0.004	0.004	0.005

Are an input to global analysis which allows to measure γ and $-2\beta_s$.
Other charmless measurements:

- $\alpha = \pi - \beta - \gamma$ from $B \to \pi\pi, B \to \rho\rho$: main sensitivity will come from Belle II (neutral final states)
- $B60 \to \pi^+\pi^-\pi^0$ TD Dalitz plot analysis, measure α. Expect large yields at LHCb.
- $B^0_{(s)} \to K^0_S hh$: determine CP violating parameters for resonant contributions, related to γ and β_s

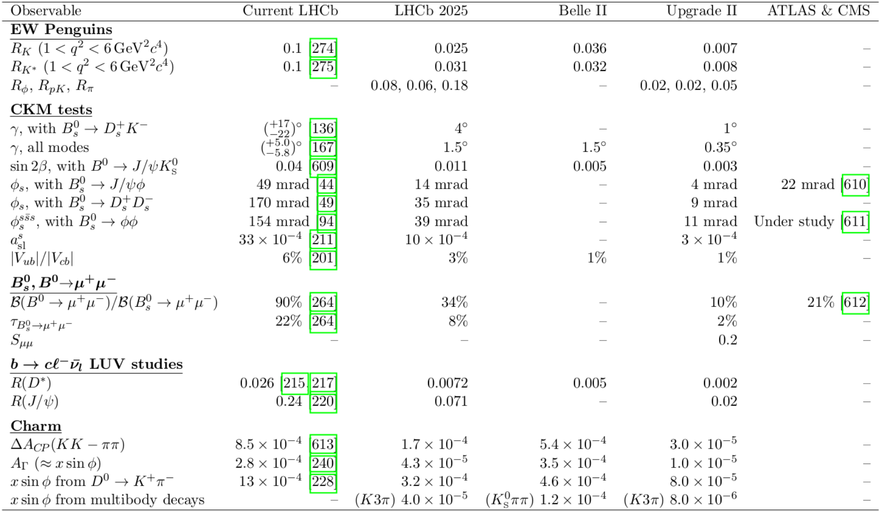
Conclusions

- UT angle measurements provide essential information about CP violation mechanism, together with other CKM measurements, a sensitive probe for physics beyond SM.
- No major show-stopper for LHCb Upgrade I and Upgrade II.
- But **a lot** of efforts will be needed to make use of huge statistics of 300 fb^{-1}.
  - Computing, storage, bookkeeping
  - Analysis infrastructure
  - Personpower for many additional modes
  - Subtle systematic effects at sub-% level
  - Combination with cross-feed between tens (or hundreds) of modes

All of that is doable, but again, **a lot** of efforts will be needed.

LHCb upgrade prospects for benchmark measurements

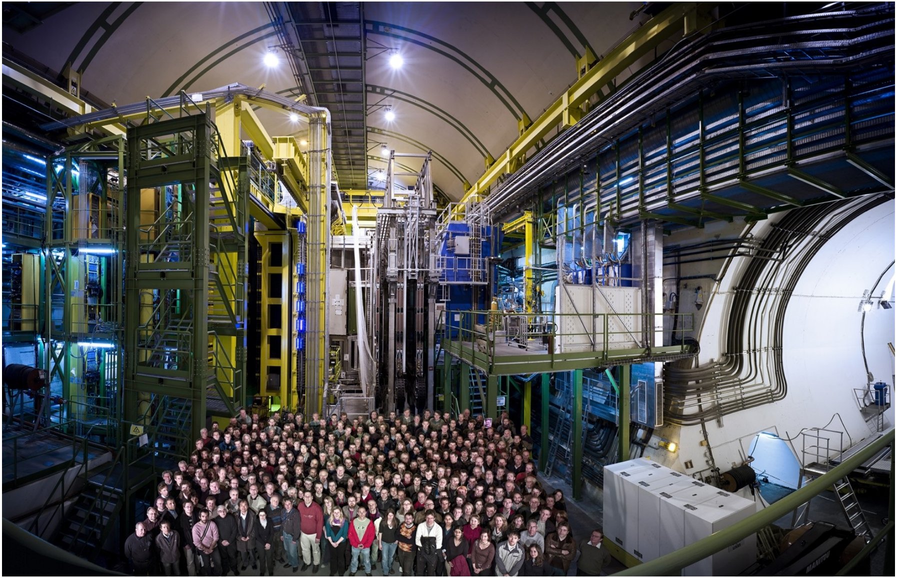
[LHCb-PUB-2018-009: "Physics case for an LHCb Upgrade II"]



Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K ($1 < q^2 < 6\,\mathrm{GeV}^2c^4$)	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} ($1 < q^2 < 6\,\mathrm{GeV}^2c^4$)	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ LUV studies					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ ($\approx x \sin\phi$)	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

Backup

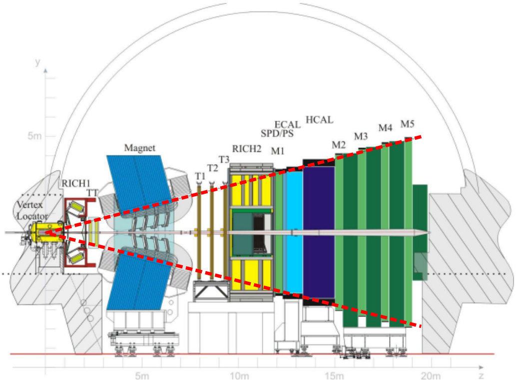
LHCb experiment



LHCb

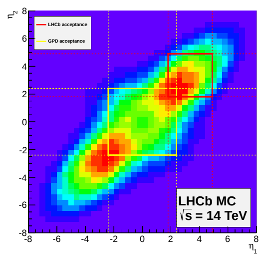
[JINST 3 (2008) S08005]

One-arm spectrometer optimised for studies of beauty and charm decays at LHC



Rapidity coverage

$2 < \eta < 5$



- Covers forward region (maximum of c and b production)

LHCb

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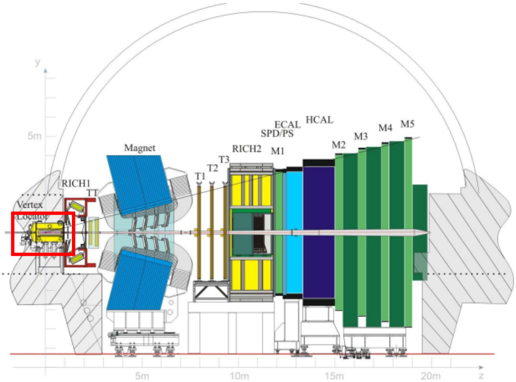
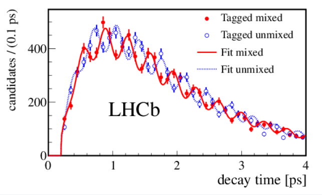


Vertexing

B_s^0 oscillations with $B_s^0 \to D_s\pi$



[New J. Phys. 15 (2013) 053021]

- Covers forward region (maximum of c and b production)
- Good vertexing: measure B^0 and B_s^0 oscillations, reject prompt background

LHCb

[JINST 3 (2008) S08005]

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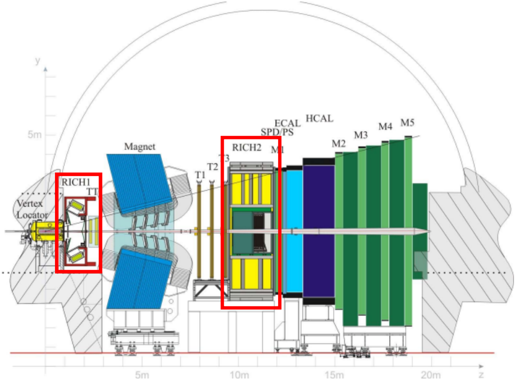
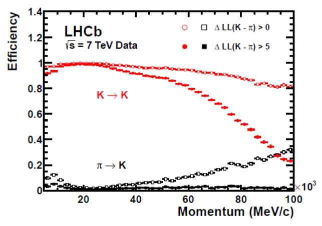


PID

K/π ID efficiency and misID rate



[EPJ C73 (2013) 2431]

- Covers forward region (maximum of c and b production)
- Good vertexing: measure B^0 and B^0_s oscillations, reject prompt background
- Particle identification: flavour tagging, misID background

LHCb

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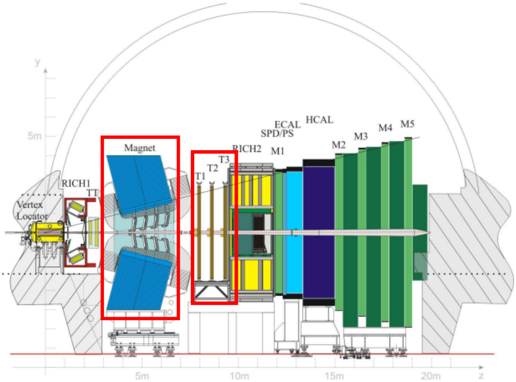
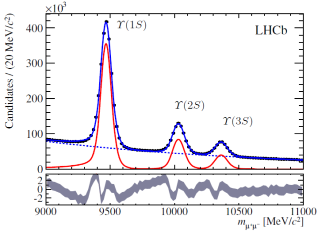


Tracking

$\mu^+\mu^-$ mass spectrum



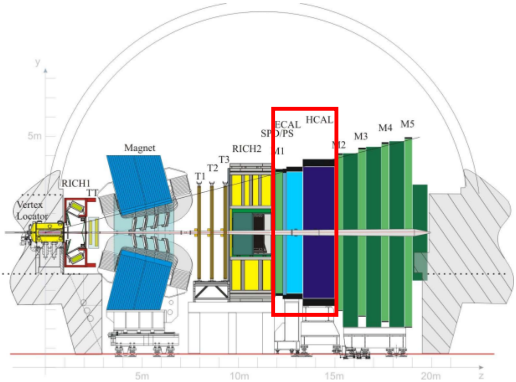
[PRL 111 (2013) 101805]

- Covers forward region (maximum of c and b production)
- Good vertexing: measure B^0 and B_s^0 oscillations, reject prompt background
- Particle identification: flavour tagging, misID background
- High-resolution tracking

LHCb

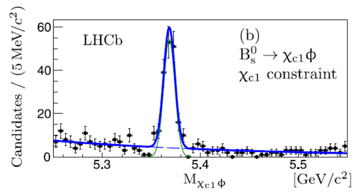
[JINST 3 (2008) S08005]

One-arm spectrometer optimised for studies of beauty and charm decays at LHC



Calorimetry

$B_s^0 \to \chi_{c1}\phi,\ \chi_{c1} \to J/\psi\gamma$



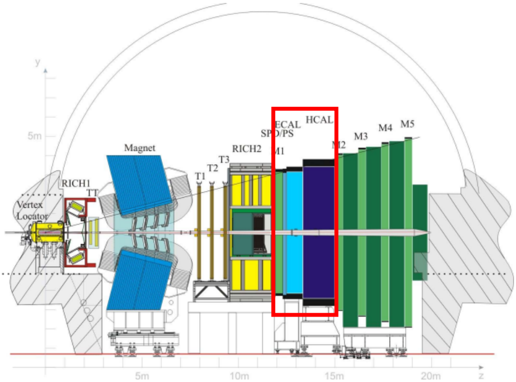
[Nucl. Phys. B874 (2013) 663]

- Covers forward region (maximum of *c* and *b* production)
- Good vertexing: measure B^0 and B_s^0 oscillations, reject prompt background
- Particle identification: flavour tagging, misID background
- High-resolution tracking
- Calorimetry: reconstruct neutrals (π^0, γ) in the final state

LHCb

[JINST 3 (2008) S08005]

One-arm spectrometer optimised for studies of beauty and charm decays at LHC



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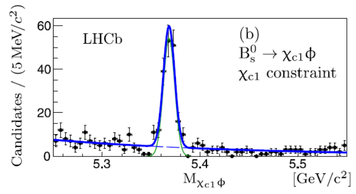
$B_s^0 \to \chi_{c1}\phi$, $\chi_{c1} \to J/\psi\gamma$



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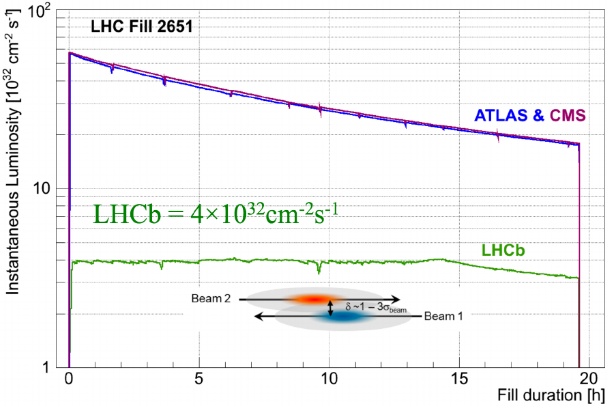
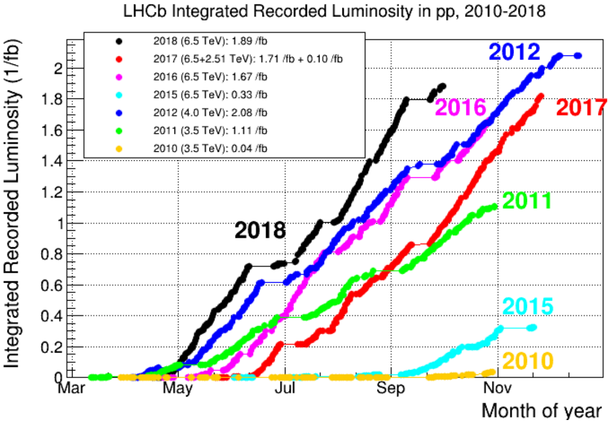
- Particle identification: flavour tagging, misID background
- High-resolution tracking
- Calorimetry: reconstruct neutrals (π^0, γ) in the final state
- Efficient trigger, including fully hadronic modes

LHCb operation



$3\,\mathrm{fb}^{-1}$ in 2011 and 2012 (Run 1, $\sqrt{s} = 7, 8\,\mathrm{TeV}$): Most of results in this talk
$2\,\mathrm{fb}^{-1}$ in 2015 and 2016 (Run 2, $\sqrt{s} = 13\,\mathrm{TeV}$, higher b CS): Analyses ongoing
$1.71\,\mathrm{fb}^{-1}$ (2017) and $1.89\,\mathrm{fb}^{-1}$ (2018 so far) at $13\,\mathrm{TeV}$

LHCb operation



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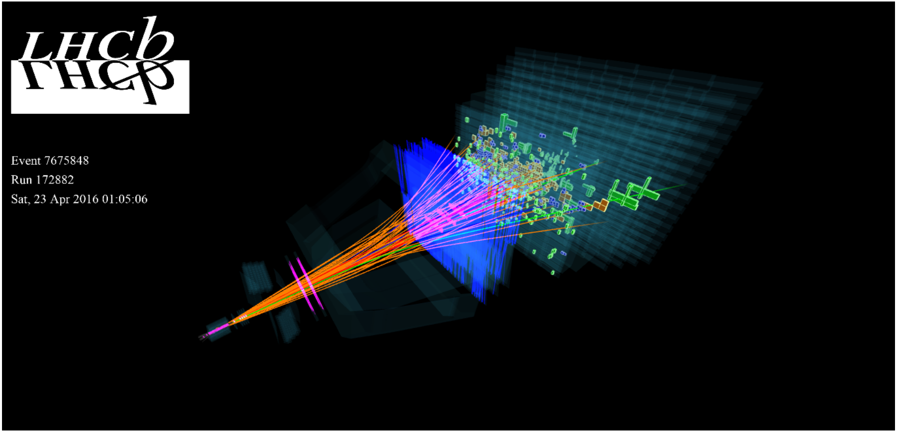
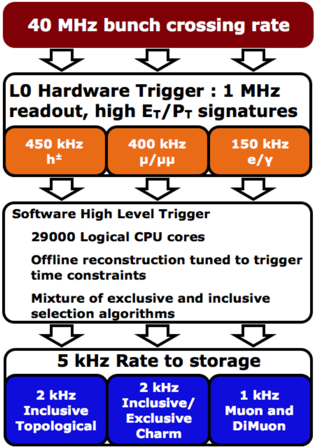
$1.71\,\mathrm{fb}^{-1}$ (2017) and $1.89\,\mathrm{fb}^{-1}$ (2018 so far) at $13\,\mathrm{TeV}$

Proton-proton collision



LHCb trigger

Trigger is a crucial elements in experiments at hadron machines. Need to work in a very difficult environment with hundreds of tracks in each beam crossing.



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

29000 Logical CPU cores

Offline reconstruction tuned to trigger time constraints

Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage

2 kHz Inclusive Topological

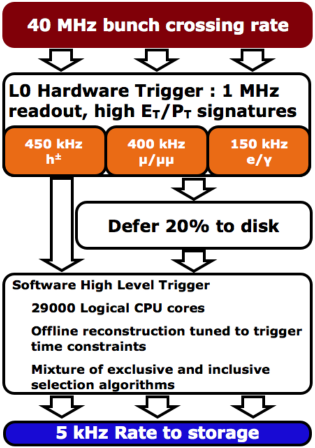
2 kHz Inclusive/ Exclusive Charm

1 kHz Muon and DiMuon

- 2011 and early 2012: increased trigger bandwidth (compared to design 2 kHz) to accommodate charm

LHCb trigger

Trigger is a crucial elements in experiments at hadron machines. Need to work in a very difficult environment with hundreds of tracks in each beam crossing.



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

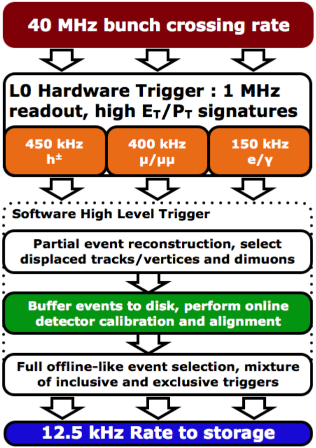
Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage

- 2011 and early 2012: increased trigger bandwidth (compared to design 2 kHz) to accommodate charm
- 2012: *deferred trigger* configuration: keep the trigger farm busy between fills

LHCb trigger

Trigger is a crucial elements in experiments at hadron machines. Need to work in a very difficult environment with hundreds of tracks in each beam crossing.



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

- 2011 and early 2012: increased trigger bandwidth (compared to design 2 kHz) to accommodate charm
- 2012: *deferred trigger* configuration: keep the trigger farm busy between fills
- Since 2015: *split trigger*
  - All 1st stage (HLT1) output stored on disk
  - Used for real-time calibration and alignment
  - 2nd stage (HLT2) uses offline-quality calibration
  - 5 kHz of 12 kHz to Turbo stream:
    - Candidates produced by trigger are stored
    - No raw event ⇒ smaller event size
    - Used for high-yield channels (charm, J/ψ, ...)

Analysis techniques

Time-dependent measurements

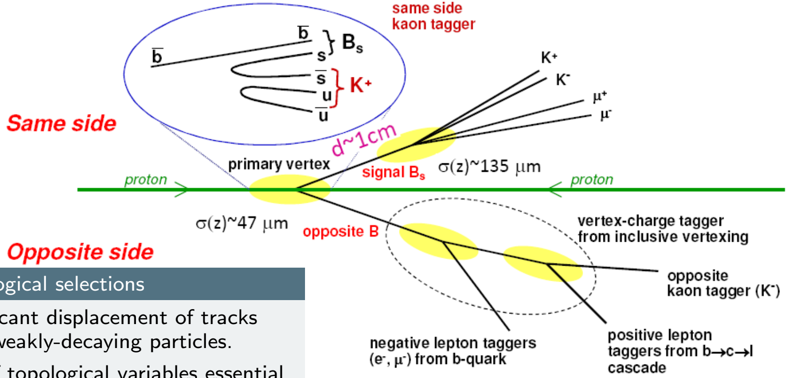
Measure lifetime based on vertex displacement from the primary vertex of *pp* interaction.

Large boost provides excellent time resolution ($\sigma_t \simeq 45$ fs)

Flavor tagging

Need to identify B flavour *at production time* (different from flavour at decay time due to oscillations).
Use decay products of the opposite-side B (OS) and π, K associated with same-side B (SS).

Effective tagging power $\epsilon_{\text{tag}} D^2 = 3.7\%$.



Topological selections

Significant displacement of tracks from weakly-decaying particles.

Use of topological variables essential to reduce combinatorial background.