Measurements of the Unitarity Triangle angle γ at LHCb

Anton Poluektov

Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

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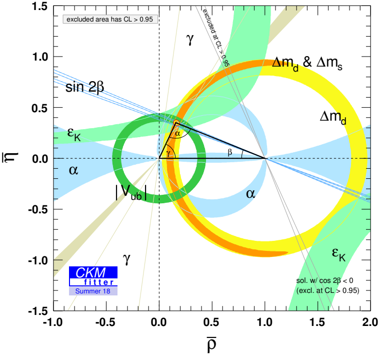
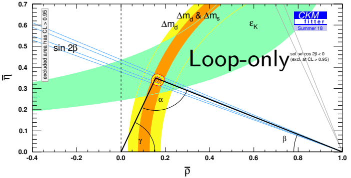
Unitarity Triangle measurements

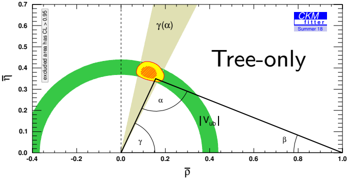
Cabibbo-Kobayashi-Maskawa matrix

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

Sensitivity to BSM effects from the global consistency of various measurements







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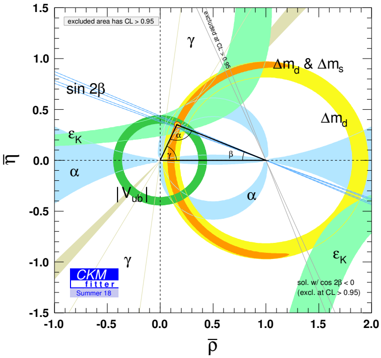
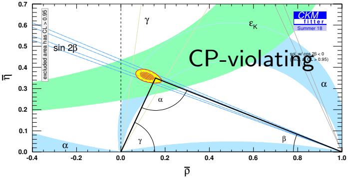
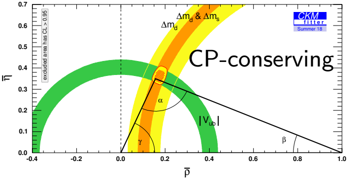


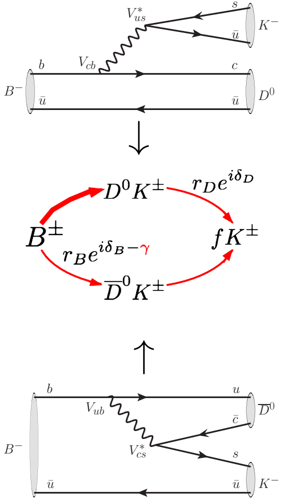




SM reference measurement: γ from trees

Unitarity Triangle angle γ/ϕ_3

- Measured entirely in tree-level 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 $B \to DK$, $B \to DK^*$ ("Dalitz" or "BPGGSZ")
  - Time-dependent analyses, e.g. $B^0_s \to D_s K$, $B^0 \to D\pi$



CP-asymmetric rates and experimental observables

Rate for $B \to DX$, $D \to f$ decay chain or its CP-conjugate:

$$\Gamma \propto r_D^2 + r_B^2 + 2\kappa r_D r_B \cos(\delta_B - \delta_D \pm \gamma)$$

Experimental observables:

r_B : ratio of $b \to u$ and $b \to c$ amplitudes

r_D : ratio of $D^0 \to f$ and $\overline{D}^0 \to f$ amplitudes ($\equiv 1$ for D_{CP})

δ_B and δ_D: corresponding strong phase differences

κ : coherence factor:

$\equiv 1$ for 2-body decays

< 1 if integrating over (non-constant) amplitude

Take M $B \to DX$ modes, N $D \to f$ modes:

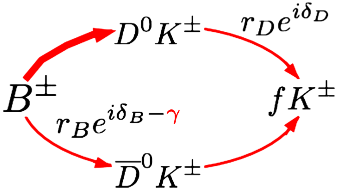
- $\sim (M \times N)$ measurements
- $\sim (M + N)$ unknowns (factorisation!)

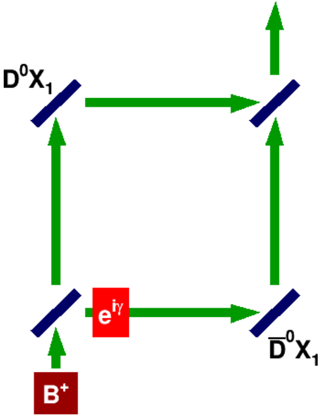
$\Rightarrow$ system of equations solvable w/o any theory input!

For multibody decays, can consider different kinematic regions as different decays, so γ measurement possible with only a single mode

Coherence factor

Optical analogy: double-slit interferometer





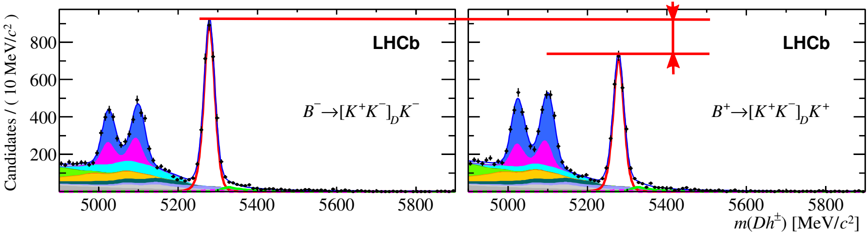
Accuracy depends on the *contrast of interference pattern*

- Determined by the ratio of two amplitudes, and by the coherence factor κ.
- Even if two amplitudes are large, $\kappa \simeq 0 \Rightarrow$ no sensitivity to γ.
  - Can happen *e.g.* if amplitudes are oscillating in the region of integration
- Want to keep two amplitudes as coherent as possible.

γ from *CP*-asymmetric rates (GLW, ADS)

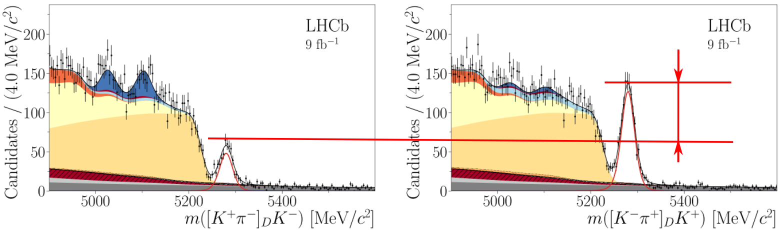
GLW mode: $D \to CP$ eigenstate [PLB 777 (2018) 16]

$r_B \simeq 0.1$, $r_D = 1$



ADS mode: $D \to$ doubly Cabibbo-suppressed state. [JHEP 04 (2021) 081]

$r_B \simeq 0.1$, $r_D \simeq 0.06$. *Higher contrast*

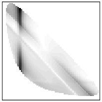
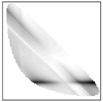


Dalitz plot density: $d\sigma(m_+^2, m_-^2) \sim |A|^2 dm_+^2 dm_-^2$, where $m_\pm^2 = m^2_{K_S\pi^\pm}$

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

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

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

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

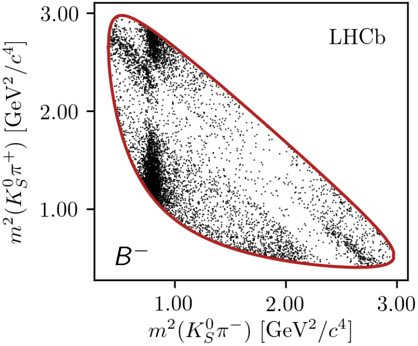
- $B^+ \to DK^+$ modes: $r_B \simeq 0.1$. Need to know the strong phase difference between D^0 and $\overline{D}^0$
  - From A_D model $\Rightarrow$ uncertainty
  - From B data themselves: low precision
- Quantum-coherent $D^0\overline{D}^0$ pairs at CLEO, BESIII: $|D_1^0\overline{D}_2^0 - \overline{D}_1^0 D_2^0|$
  - Maximal possible coherence $\Rightarrow$ precisely constrain the strong phase.
  - Need to use external information from low-energy e^+e^- experiment.
- Intermediate case: neutral $B^0 \to DK\pi$, $r_B \simeq 0.3$ [talk by Yuya Shimizu]
  - Correlated 3-body decays of both B and D: double Dalitz plot analysis!

$B \to DK$, $D \to K^0_S \pi^+ \pi^-$ Dalitz plots

[JHEP 02 (2021) 169]

Full LHCb dataset: 2011–2018 (Run I + II), $\int \mathcal{L} dt = 9$ fb^{-1} at $\sqrt{s} = 7, 8, 13\,\mathrm{TeV}$

Samples used: $B^{\pm} \to Dh^{\pm}$ ($h = K, \pi$) with $D \to K^0_S \pi^+ \pi^-$ and $D \to K^0_S K^+ K^-$



Larger admixture of opposite-flavour amplitude, $r_B \simeq 0.1$.

CP asymmetry now visible by eye.

[JHEP 02 (2021) 169]

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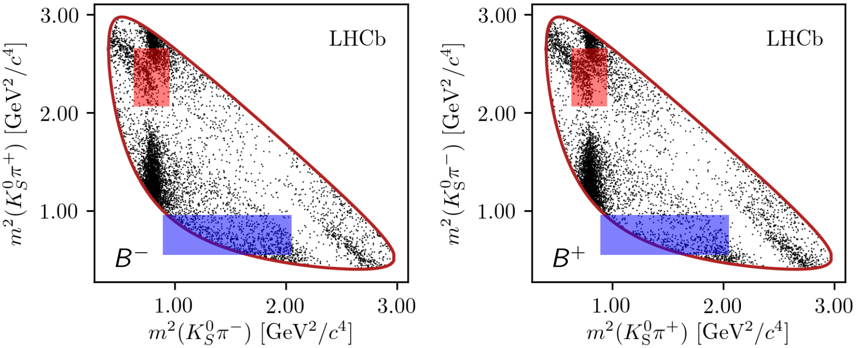

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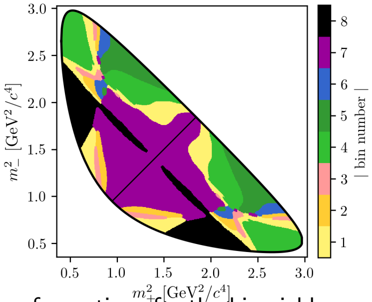
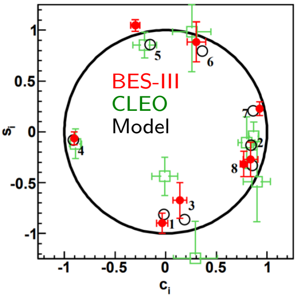
Binned model-independent fit

[PRL 124, 241802 (2020)]





System of equations for the bin yields:

$$N_i^{\pm} = h_{\pm}\left[F_i + (x_{\pm}^2 + y_{\pm}^2)F_{-i} + 2\sqrt{F_i F_{-i}}(x_{\pm}c_i + y_{\pm}s_i)\right]$$

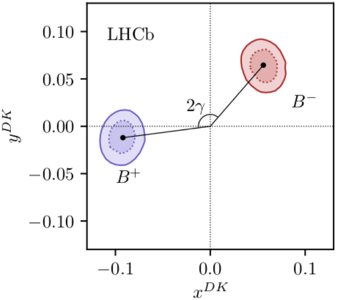
- Physics parameters: $x_{\pm} = r_B \cos(\delta_B \pm \gamma)$, $y_{\pm} = r_B \sin(\delta_B \pm \gamma)$,
- Strong phase parameters: c_i, s_i measured by CLEO and BES-III from quantum correlations in $e^+e^- \to D\overline{D}$ decays.
  - BES-III measurement [PRL 124, 241802 (2020)] used for the 1st time, $\times 4$ stats of CLEO
- Flavour-specific bin yield fractions: F_i, shared between $B \to DK$ and $B \to D\pi$

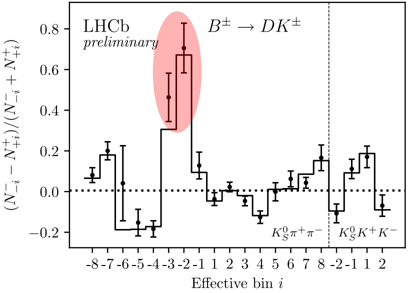
Coherence in bin i is determined by $s_i^2 + c_i^2$

Results

[JHEP 02 (2021) 169]

Binned fit results and constraints on physics parameters:





- Most precise single measurement of γ.
- Using full Run I + Run II sample by LHCb, $B^\pm \to Dh^\pm$, $D \to K^0_S h^+ h^-$ ($h = K, \pi$)
- New strong phase measurement by BES-III used
- Statistically dominated, $\sigma(syst) \sim 1^\circ$, σ(CLEO+BES)$\sim 1^\circ$.

Results

[JHEP 02 (2021) 169]

Binned fit results and constraints on physics parameters:

$$x_-^{DK} = (\ \ 5.6 \pm 1.0 \pm 0.2 \pm 0.3) \times 10^{-2},$$
$$y_-^{DK} = (\ \ 6.5 \pm 1.1 \pm 0.3 \pm 0.4) \times 10^{-2},$$
$$x_+^{DK} = (-9.2 \pm 1.0 \pm 0.2 \pm 0.2) \times 10^{-2},$$
$$y_+^{DK} = (-1.2 \pm 1.2 \pm 0.3 \pm 0.3) \times 10^{-2},$$
$$x_\xi^{D\pi} = (-5.3 \pm 2.0 \pm 0.3 \pm 0.2) \times 10^{-2},$$
$$y_\xi^{D\pi} = (\ \ 1.0 \pm 2.3 \pm 0.5 \pm 0.3) \times 10^{-2},$$

exp. syst CLEO, BES-III

$$\gamma = (69 \pm 5)^\circ,$$
$$r_B^{DK} = 0.089^{+0.008}_{-0.007},$$
$$\delta_B^{DK} = (118 \pm 6)^\circ,$$
$$r_B^{D\pi} = 0.0048^{+0.0017}_{-0.0016},$$
$$\delta_B^{D\pi} = (287^{+26}_{-27})^\circ.$$

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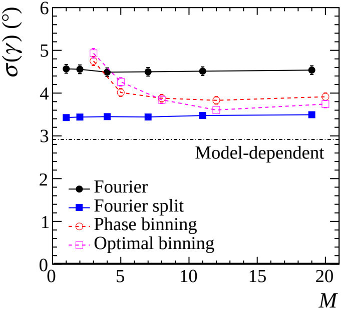
$B \to DK$, $D^0 \to K^0_S\pi^+\pi^-$: can we do better with the same stats?

[Ongoing project in LHCb+BESIII (Oxford, IHEP, CPPM)]

Binned approach reduces statistical precision compared to unbinned fit.

Carefully optimised binning has $\simeq 80\%$ power of the unbinned fit (*coherence!*)

Can we do better? [AP, EPJC (2018) 78: 121]



Weight functions instead of **bins**:

$$\int_{\mathcal{D}_i} \ldots dz \quad \to \quad \int_{\mathcal{D}} \ldots \times w_i(z)\, dz$$

E.g. **Fourier expansion** of strong phase difference:

$$w_{2n}(z) = \cos\left(n\Delta\delta_D(z)\right);$$
$$w_{2n+1}(z) = \sin\left(n\Delta\delta_D(z)\right)$$

Somewhat better results (in toy MC) than binned approach, fewer free parameters

Still does not reach the model-dependent precision.

Can we find a better set of basis functions?

[Ongoing project in LHCb+BESIII (Oxford, IHEP, CPPM)]

If the function $p(\mathbf{z})$ fully lies in the subspace spanned by the set of basis functions $w_\alpha(\mathbf{z})$, the information contained in the projections p_α will be maximal.

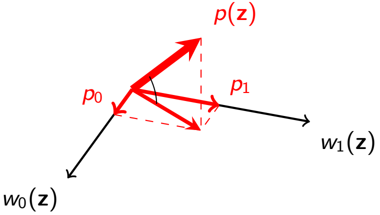
Density over $D \to K^0_S\pi^+\pi^-$ Dalitz plot from $B \to DK$ decays:

$$p_B(\mathbf{z}) = h_B\{p_D(\mathbf{z}) + r_B^2\bar{p}_D[\mathbf{z}) + 2(xC(\mathbf{z}) + yS(\mathbf{z})]\}$$

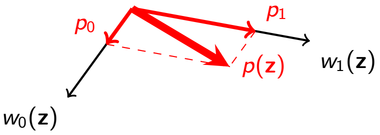
The density $p_B(\mathbf{z})$ is a **linear combination** of 4 functions:

$$p_D(\mathbf{z}),\quad \bar{p}_D(\mathbf{z}),\quad C(\mathbf{z}) = \sqrt{p_D\bar{p}_D\sin\delta},\quad S(\mathbf{z}) = \sqrt{p_D\bar{p}_D\cos\delta}$$

Density functions are **model-dependent**, but the measurement is **model-independent** (wrong model $\Rightarrow$ p_B not fully contained in the span of basis functions, less coherence but no bias)

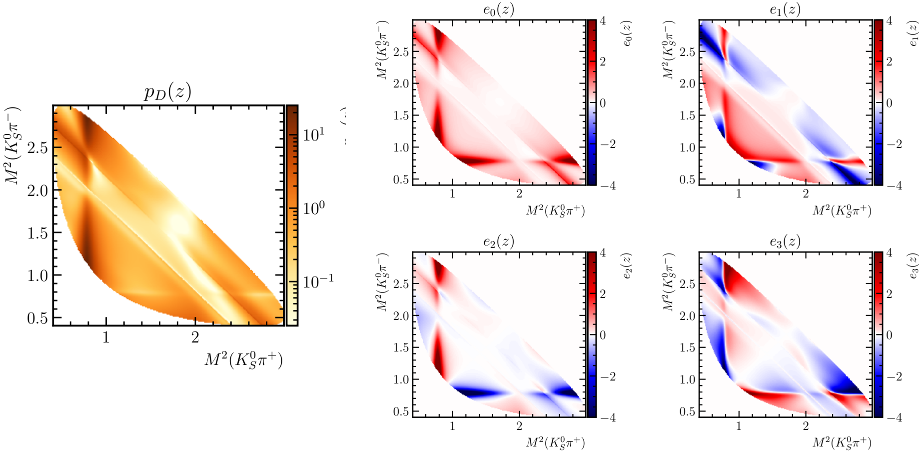


$p(\mathbf{z})$ not fully contained in w_α span



$p(\mathbf{z})$ fully contained in w_α span

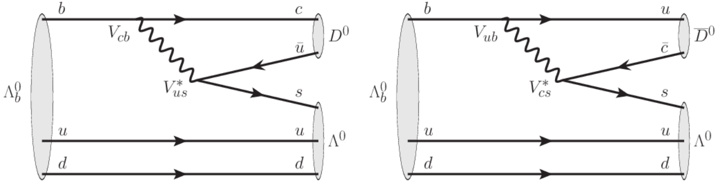
Basis functions



- Result of orthogonalisation of the set $p_D(\mathbf{z})$, $\bar{p}_D(\mathbf{z})$, $C(\mathbf{z})$, $S(\mathbf{z})$
- Only 4 unknown strong phase parameters
- γ sensitivity expected to be **equal** to model-dependent fit
- Further improvement possible: > 4 functions for model-dependent-equivalent sensitivity for a family of models

$\Lambda_b^0 \to DpK^-$ decays

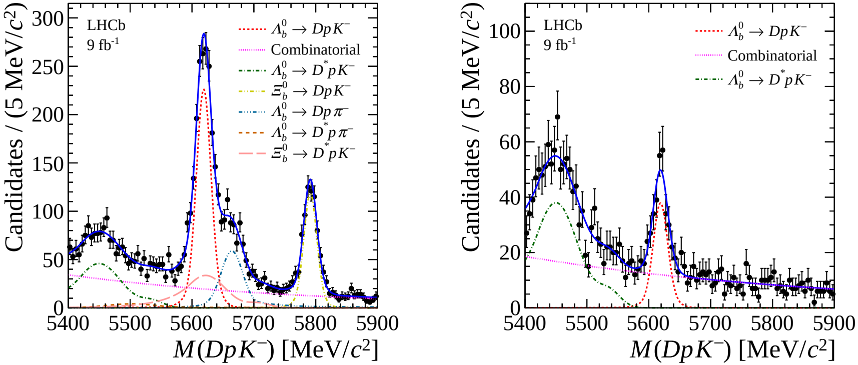
γ-sensitive modes in the case of Λ_b^0:



$\Lambda_b^0 \to D\Lambda^0_{\to p\pi^-}$ mode affected by low efficiency to reconstruct long-lived Λ^0.
Trying with excited, strongly decaying $\Lambda^{*0} \to pK^-$ instead

- Favoured $\Lambda_b^0 \to DpK^-$ with $D \to K^-\pi^+$ is observed in Run 1 [PRD 89, 032001 (2014)]
- Now:
  - Search for suppressed mode $\Lambda_b^0 \to DpK^-$ with $D \to K^+\pi^-$ with enhanced $b \to c$ and $b \to u$ interference term
  - Measure CP asymmetry

Signal with full Run 1+Run 2 LHCb data sample



First observation of the suppressed mode!

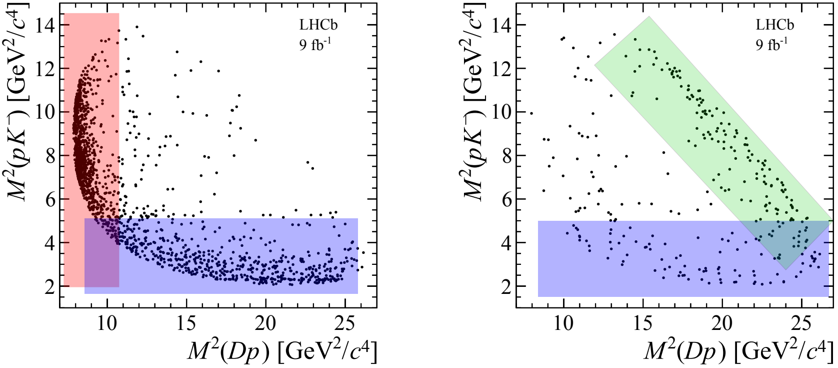
- Yields: 1437 ± 92 (favoured), 241 ± 22 (suppressed)
- Favoured-to-suppressed $\mathcal{B}$ ratio $R = 7.1 \pm 0.8(\text{stat})^{+0.4}_{-0.3}(\text{syst})$

[arXiv:2109.02621]

$\Lambda_b^0 \to DpK^-$ decay amplitude

Favoured: $\Lambda_c^{*+} \to D^0 p$ and $\Lambda^{*0} \to pK^-$

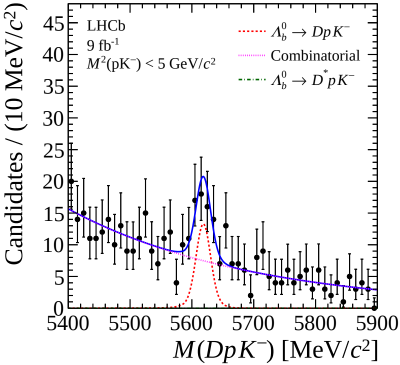
Suppressed: $D_s^{*-} \to \bar{D}^0 K^-$ and $\Lambda^{*0} \to pK^-$

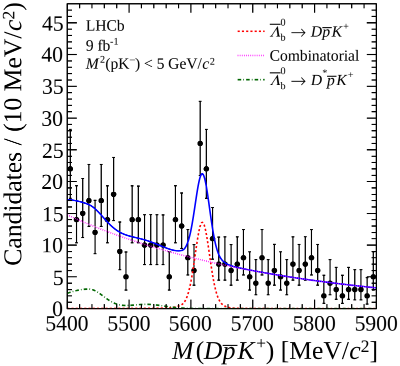


- $\Lambda_b^0 \to \Lambda_c^{*+} K^-$ $(b \to c)$ and $\Lambda_b^0 \to D_s^{*-} p$ $(b \to u)$ amplitudes are flavour-specific
- Taking only $\Lambda_b^0 \to D\Lambda^{*0}$ ($M^2(pK^-) < 5\,\mathrm{GeV}^2/c^4$) should enhance CPV term

[arXiv:2109.02621]

CP asymmetry in the $\Lambda^{*0} \to pK^-$ region ($M^2(pK^-) < 5\,\mathrm{GeV}^2/c^4$)





$$R = 8.6 \pm 1.5\,(\text{stat.})^{+0.4}_{-0.3}\,(\text{syst.}),$$
$$A = 0.01 \pm 0.16\,(\text{stat.})^{+0.03}_{-0.02}\,(\text{syst.}).$$

[arXiv:2109.02621]

- ADS-like mode measured
- GLW-like mode (D_{CP}): analysis in progress [IJCLab]

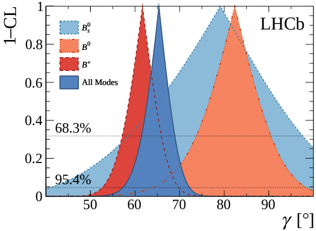
Even provided that we measure nonzero CP asymmetry in $\Lambda_b^0 \to DpK^-$, can we extract γ?

- Λ_b^0 decays are more complex because of overlapping helicity states
  - Each Λ^{*0} helicity has, in general, its own strong phase
  - Sum up over polarisations of initial and final states
  - $\Rightarrow$ effectively, low and unknown coherence factor κ.
- $\Lambda_b^0 \to D\Lambda^0$ case with weak $\Lambda^0 \to p\pi^-$ decay:
  - Can measure Λ^0 polarisation and resolve γ
  - See e.g. [Giri, Mohanta, Khanna, PRD 65 (2002) 073029]
- $\Lambda_b^0 \to D\Lambda^{*0}$ is different because $\Lambda^{*0} \to pK^-$ is strong (P-conserving)
  - Unfortunately, Λ_b^0 are produced not polarised in pp. Can we *make* them polarised?
  - Could exploit correlations of two b baryons [Yu. Grossman, private communication]. Mostly should be in $L = 1$. *Polarisation tagger?*

Summary

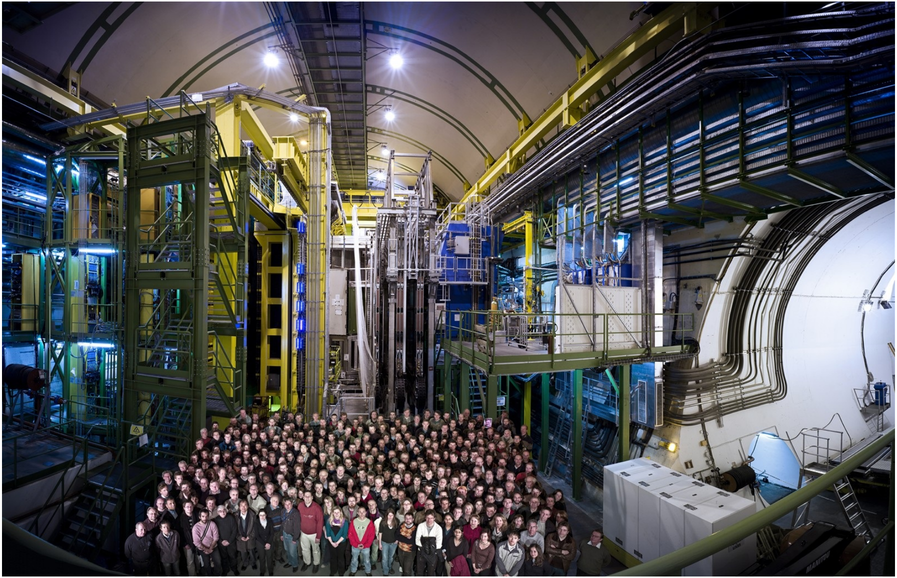
- Combination of all LHCb measurements: $\gamma = 65.4^{+3.8}_{-4.2}{}^{\circ}$.
- Many contributing modes $\Rightarrow$ more robust measurement.
- Ideas to improve precision even with the current dataset
  - Improve coherence in Dalitz plot modes
  - Double Dalitz [talk by Yuya Shimizu]
  - Time-dependent measurements
  - Other B mesons and b-baryons?
- Aim at precision $\simeq 1.5^{\circ}$ after Run 3.

[arXiv:2110.02350]



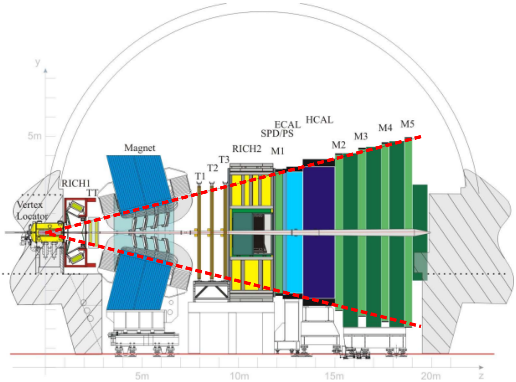
Backup

LHCb experiment



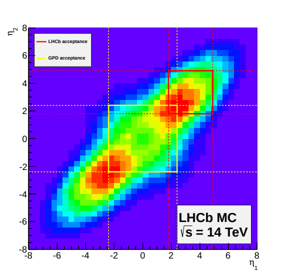
[JINST 3 (2008) S08005]

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



Rapidity coverage

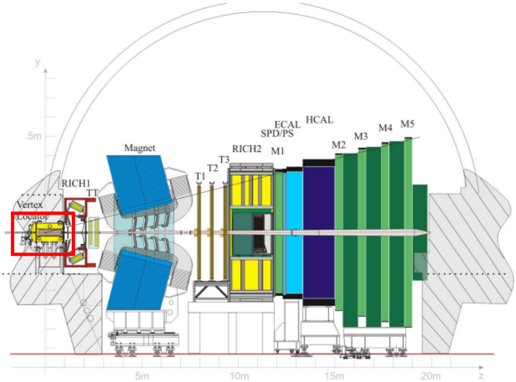
$$2 < \eta < 5$$



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

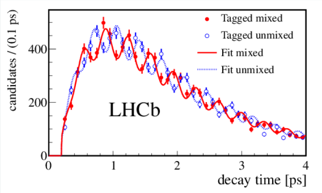
[JINST 3 (2008) S08005]

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



Vertexing

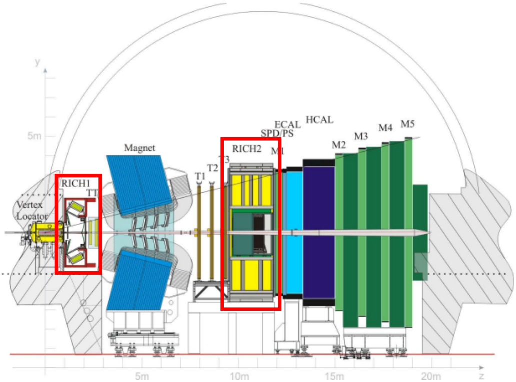
B_s^0 oscillations with $B_s^0 \to D_s\pi$



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

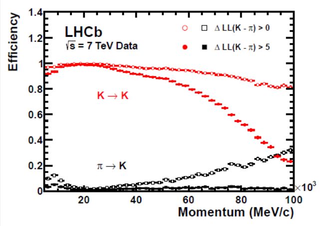
- Covers forward region (maximum of c and b production)
- Good vertexing: measure B^0 and B_s^0 oscillations, reject prompt background

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



PID

K/π ID efficiency and misID rate



[EPJ C73 (2013) 2431]

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LHCb

[JINST 3 (2008) S08005]

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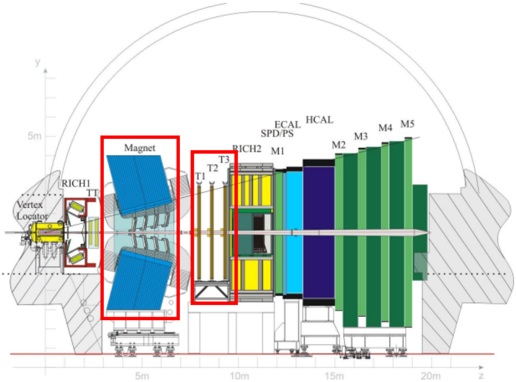
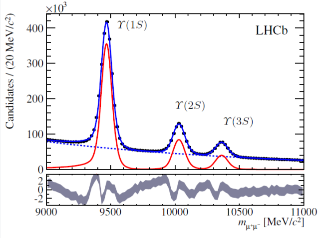


Tracking

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



[PRL 111 (2013) 101805]

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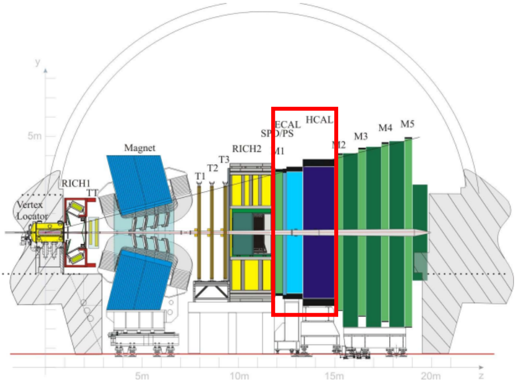
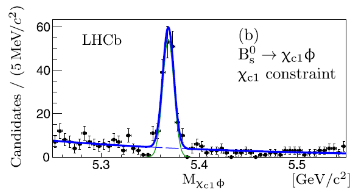


Calorimetry

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



[Nucl. Phys. B874 (2013) 663]

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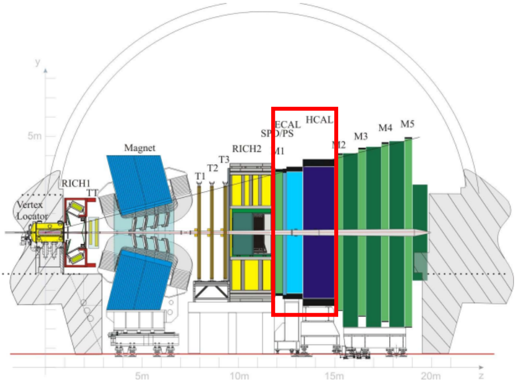

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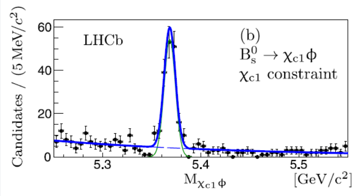

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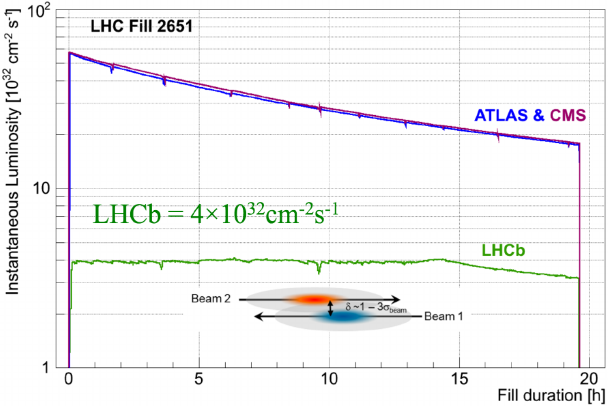
- Efficient trigger, including fully hadronic modes

LHCb operation



$3\,\mathrm{fb}^{-1}$ in 2011 and 2012 (Run I, $\sqrt{s} = 7, 8\,\mathrm{TeV}$)

$6\,\mathrm{fb}^{-1}$ in 2015-2018 (Run II, $\sqrt{s} = 13\,\mathrm{TeV}$, higher b CS): Analyses ongoing

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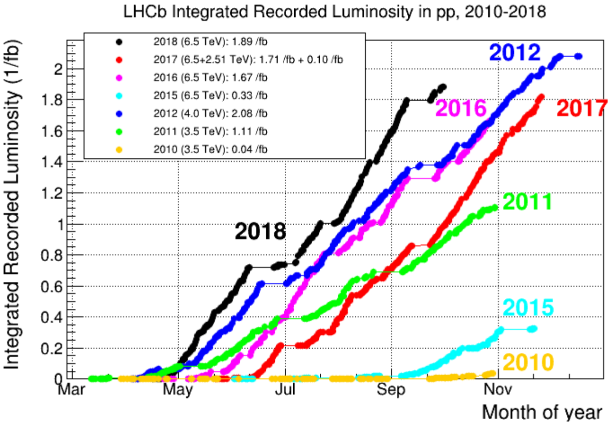

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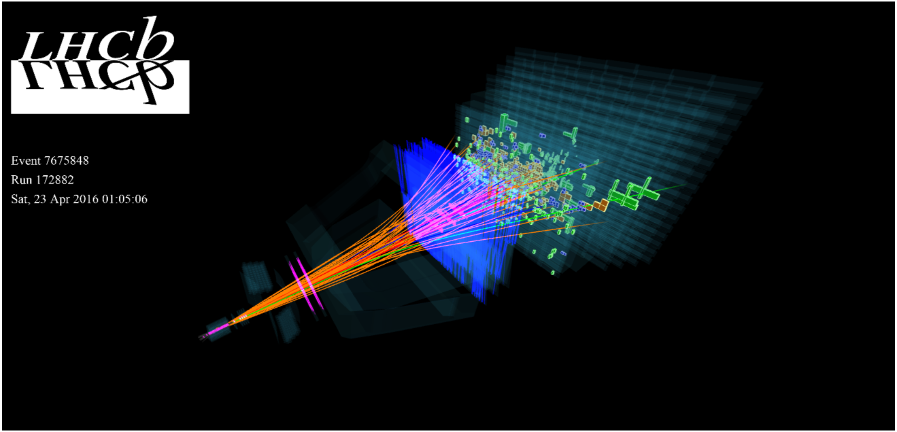
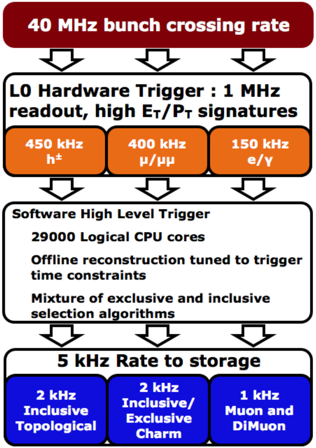
Proton-proton collision



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.



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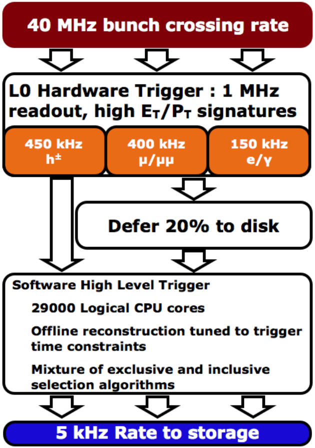

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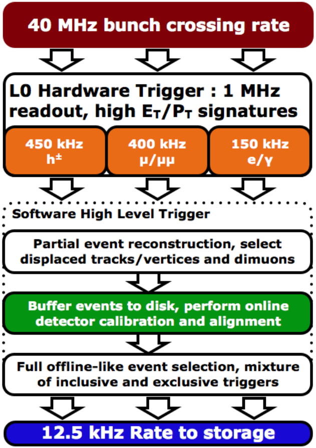


- 2011 and early 2012: increased trigger bandwidth (compared to design 2 kHz) to accommodate charm
- 2012: *deferred trigger* configuration: keep the trigger farm busy between fills
- Since 2015: *split trigger*
  - All 1st stage (HLT1) output stored on disk
  - Used for real-time calibration and alignment
  - 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

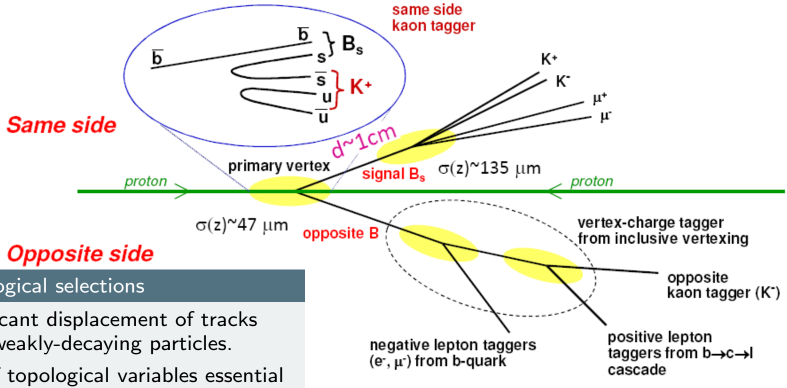
Measure lifetime based on vertex displacement from the primary vertex of *pp* interaction.

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 $\epsilon_{\rm tag} D^2 = 3.7\%$.

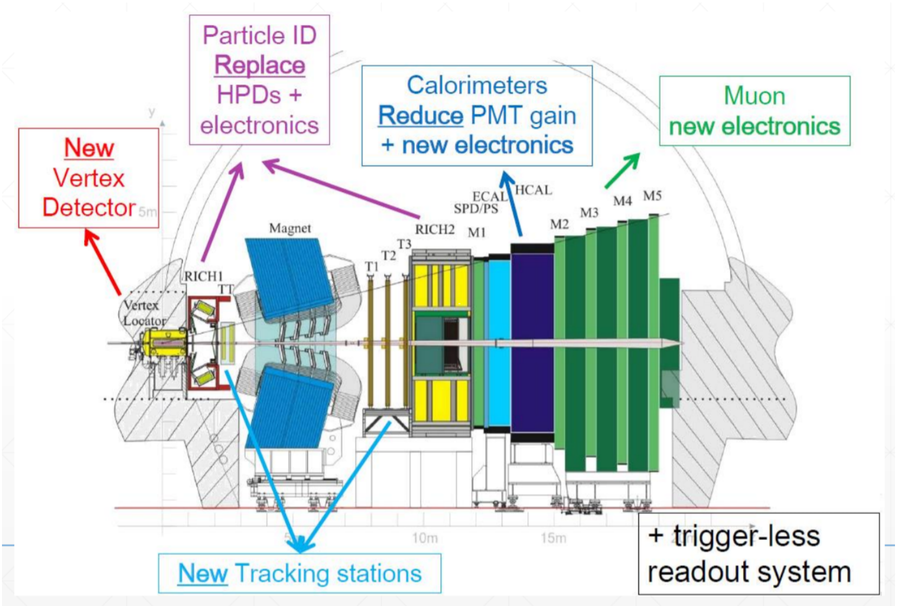


Topological selections

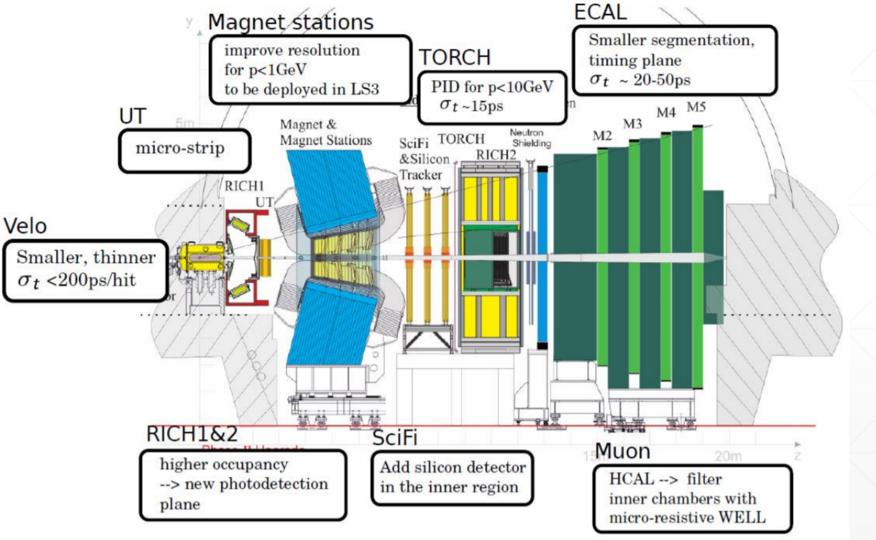
Significant displacement of tracks from weakly-decaying particles.

Use of topological variables essential to reduce combinatorial background.

LHCb upgrade I

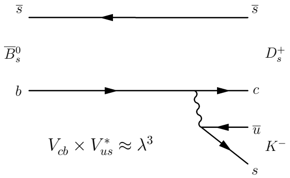


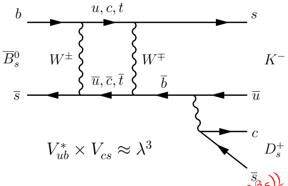
LHCb upgrade II



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 $\overline{f}$)

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

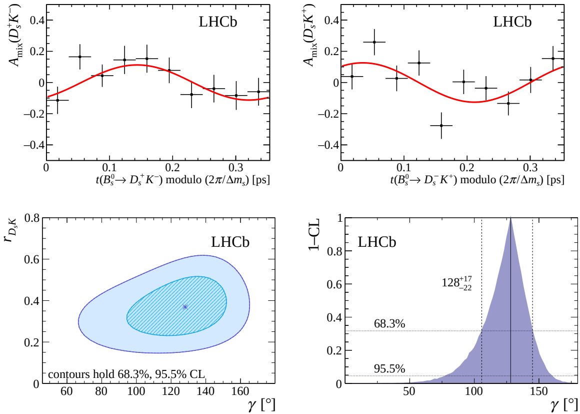
$A_f^{\Delta\Gamma} = -\frac{2r\cos(\delta-(\gamma-2\beta_s))}{1+r^2}$, $C_f = \frac{1-r^2}{1+r^2}$, $S_f = \frac{2r\sin(\delta-(\gamma-2\beta_s))}{1+r^2}$

Measure $\gamma - 2\beta_s$, δ, r

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 $SU(3)$ $B^0 \to D_s\pi$)

[JHEP 03 (2018) 059]

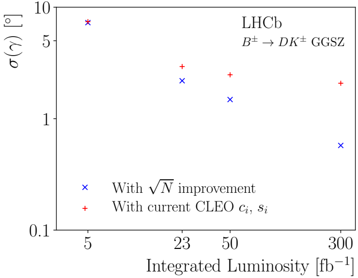


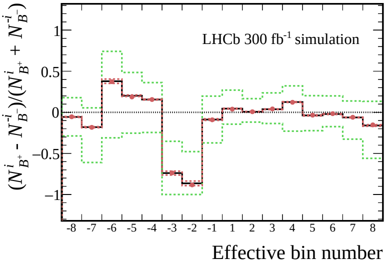
Relies on input $-2\beta_s = -0.030 \pm 0.033 \Rightarrow$ $\gamma = (128^{+17}_{-22})^\circ$ (stat-limited).

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

Prospects for γ: $B \to DK$ GGSZ

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





- Critical uncertainty: measurement of strong phase difference in bins. Currently: $\simeq 1^{\circ}$ (CLEO, BES-III).
- Further reduction is possible:
  - Expect BES-III to contribute with larger dataset.
  - Technique to obtain $D^0 - \overline{D}^0$ 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.

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

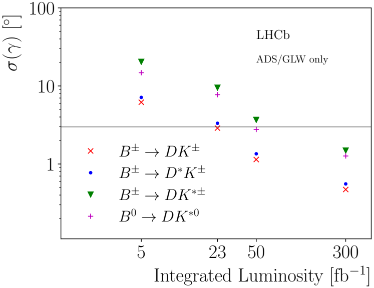
Main systematic uncertainties with rate and asymmetry measurements:

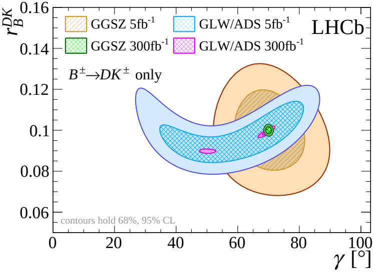
- Production and instrumentation asymmetries
- Backgrounds and their asymmetries.

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





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 $B^0_s \to D^+_s K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K^0_S$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B^0_s \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B^0_s \to D^+_s D^-_s$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B^0_s \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a^s_{sl}	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$\boldsymbol{B^0_s, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B^0_s \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B^0_s \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **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}	$(K^0_S\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–