Measurement of the Unitarity Triangle angle γ at LHCb

Anton Poluektov

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

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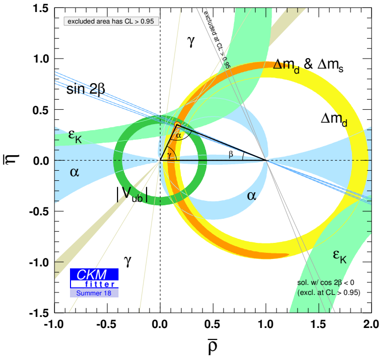
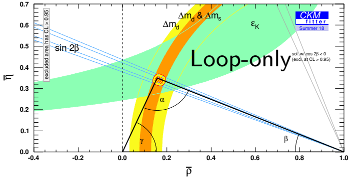
On behalf of the LHCb collaboration

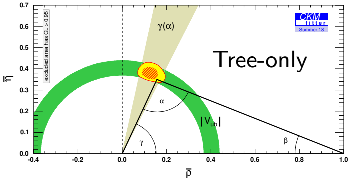
Cabibbo-Kobayashi-Maskawa matrix

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

Sensitivity to BSM effects from the global consistency of various measurements







Unitarity Triangle measurements

Cabibbo-Kobayashi-Maskawa matrix

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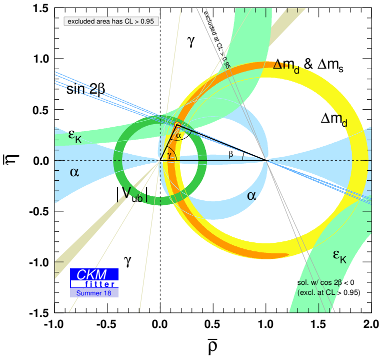
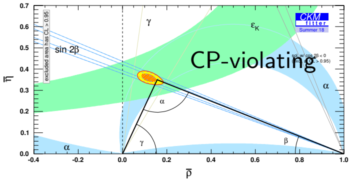
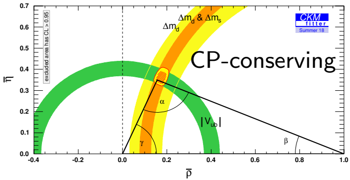


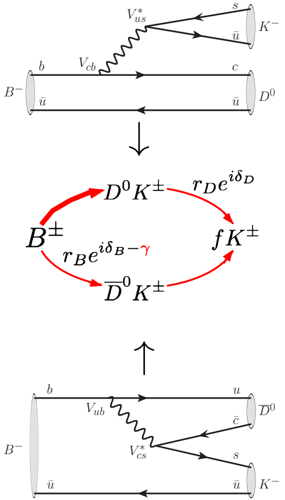




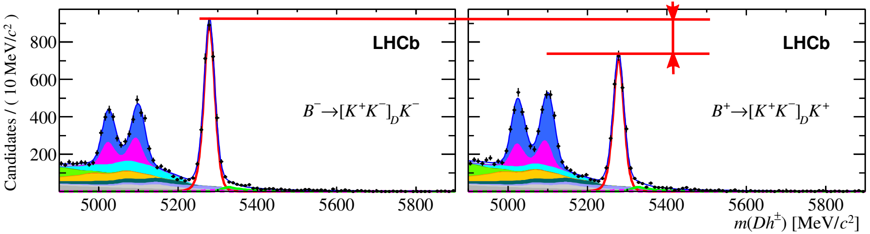
SM reference measurement: γ from trees

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. $B^0_s \to D_s K$, $B^0 \to D\pi$
  [Talk by Stefano Perazzini, $B^0_s \to D^+_s K\pi\pi$]



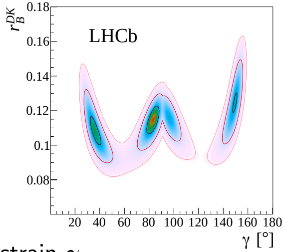
[PLB 777 (2018) 16]



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

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

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 used to constrain γ

γ measurement in $B \to DK$, $D \to K^0_S K^\pm \pi^\mp$ (GLS)

Most of the LHCb measurements are using either Run I data ($3\,\text{fb}^{-1}$, 2011-2012) or including part of Run II ($\sim 5\,\text{fb}^{-1}$ up to 2016) datasets

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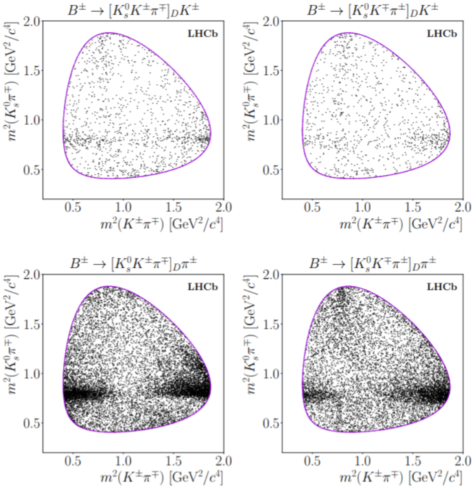
First update with full Run I+II LHCb dataset ($9\,\text{fb}^{-1}$, 2011-2018) [JHEP 06, 40 (2020)]



Two different amplitudes:

- $B^\pm \to D(K^0_S K^\pm \pi^\mp) K^\pm$ ("same sign", SS)
- $B^\pm \to D(K^0_S K^\mp \pi^\pm) K^\pm$ ("opposite sign", OS)

Large coherence around K^{*+} mass measured by CLEO:

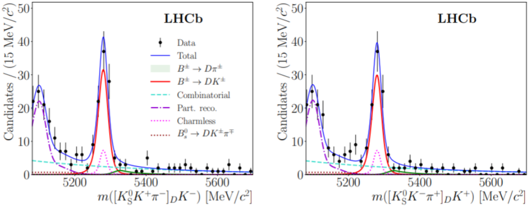
[PRD 85 092016 2012]

$\kappa_D = 0.94 \pm 0.12$ ($\pm 100\,\text{MeV}$)

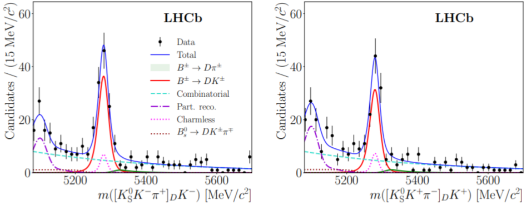
Use K^{*+} region for γ constraints.

[JHEP 06, 40 (2020)]

OS sample, $\pm 100\,\mathrm{MeV}$ region around $K^{*\pm}$:

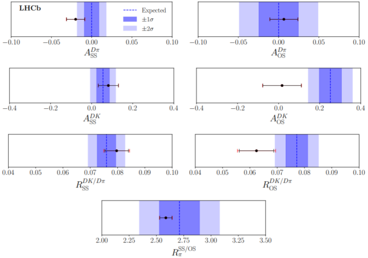


SS sample: $\pm 100\,\mathrm{MeV}$ region around $K^{*\pm}$:



Measured asymmetries and ratios:

$$
\begin{aligned}
A^{D\pi}_{SS} &= -0.020 \pm 0.011 \pm 0.003\,,\\
A^{D\pi}_{OS} &= 0.007 \pm 0.017 \pm 0.003\,,\\
A^{DK}_{SS} &= 0.084 \pm 0.049 \pm 0.008\,,\\
A^{DK}_{OS} &= 0.021 \pm 0.094 \pm 0.017\,,\\
R_{SS/OS} &= 2.585 \pm 0.057 \pm 0.019\,,\\
R^{DK/D\pi}_{SS} &= 0.079 \pm 0.004 \pm 0.002\,,\\
R^{DK/D\pi}_{OS} &= 0.062 \pm 0.006 \pm 0.003\,,
\end{aligned}
$$



No significant CPV observed (yet). To be used as input in γ combination

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

[GGSZ, 2003; Bondar, 2002]

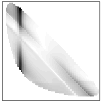
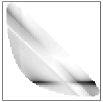
Information on γ from Dalitz plot analysis of $D \to K^0_S\pi^+\pi^-$ from $B^{\pm} \to DK^{\pm}$.

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

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

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

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

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

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)).

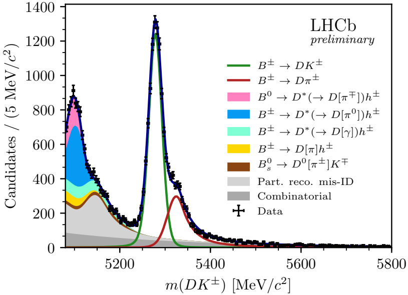
Model-dependent: obtain A_D from $D \to K^0_S\pi^+\pi^-$ fit to the isobar model $\Rightarrow$ model uncertainty

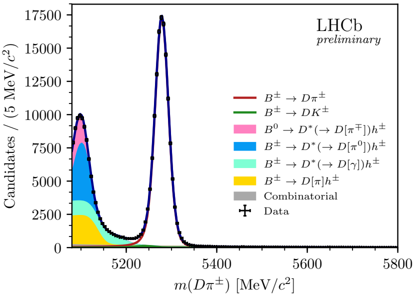
Model-independent: obtain phase difference info from $e^+e^- \to D^0\overline{D}^0$ decays (CLEO, BES-III)

[LHCb-CONF-2020-001]

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

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





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

$\sim 15k$ events

Signal sample with significant CPV

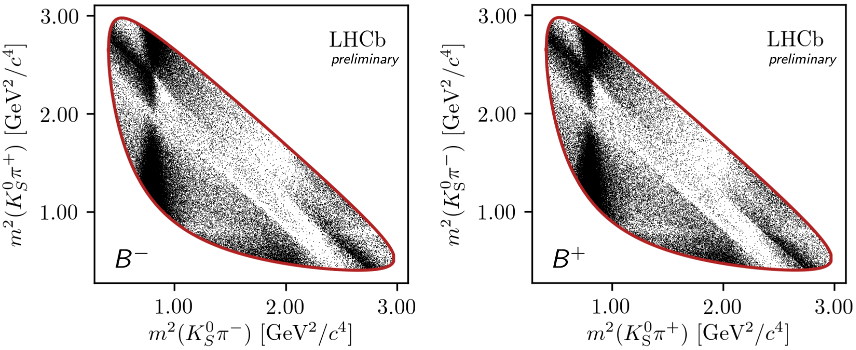
$B \to D\pi,\ D \to K^0_S\pi^+\pi^-$

$\sim 210k$ events

High-stats sample with low CPV for data-driven acceptance

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

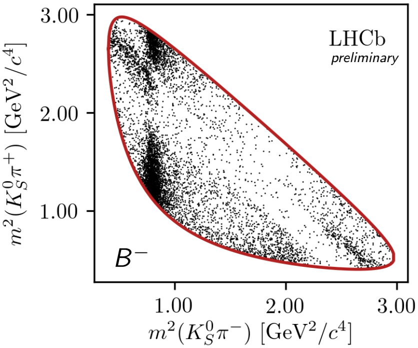
[LHCb-CONF-2020-001]

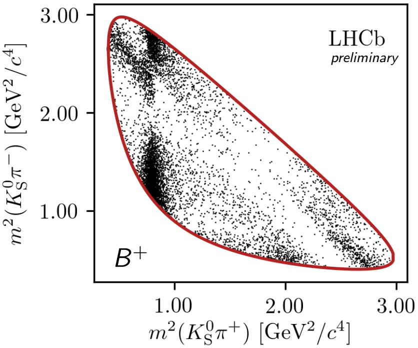


Mostly flavour-specific $D^0 \to K^0_S\pi^+\pi^-$ with very small admixture of opposite flavour $r_B \simeq 0.005$.

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

[LHCb-CONF-2020-001]



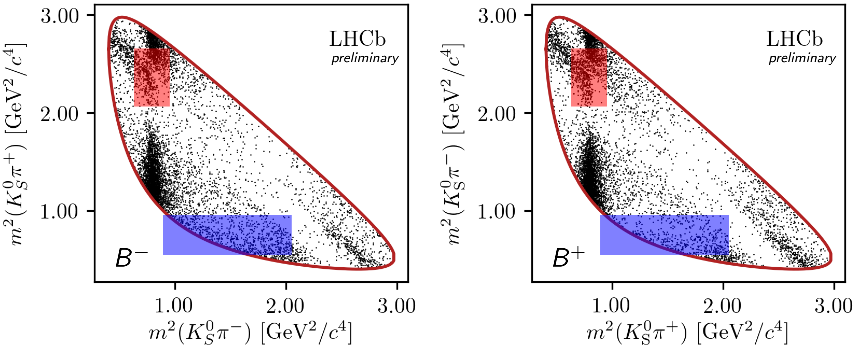


Larger admixture of opposite-flavour amplitude, $r_B \simeq 0.1$.

CP asymmetry now visible by eye.

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

[LHCb-CONF-2020-001]



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

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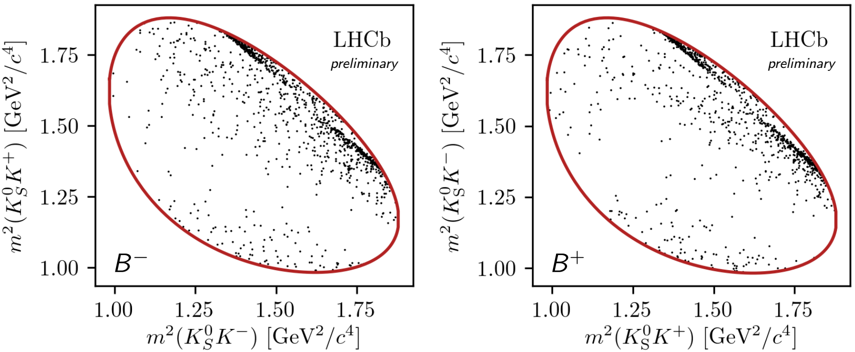
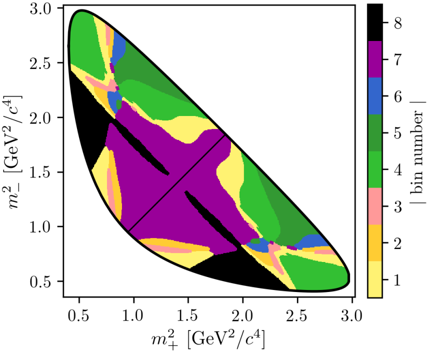
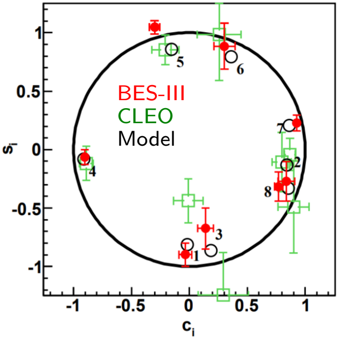


Additional sensitivity from $D \to K^0_S K^+ K^-$ final state.

Binned model-independent fit

[Talk by Jim Libby, PRL 124, 241802 (2020)]



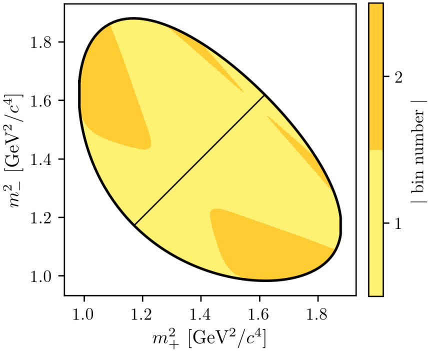


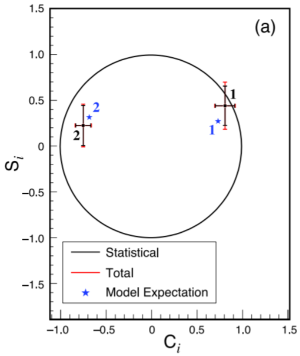
$$N_i^{\pm} = h_{\pm}\left[F_i + (x_{\pm}^2 + y_{\pm}^2)F_{-i} + 2\sqrt{F_i F_{-i}}(x_{\pm}c_i + y_{\pm}s_i)\right]$$

- 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 $B \to D\pi$

Binned model-independent fit

[PRD 82:112006,2010]





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

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Data-driven acceptance

Aim for a few degree precision, experimental systematics can already be a problem.

New fitting technique implemented to reduce syst. uncertainty

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

Bin yield fractions F_i:

- yields of **flavour-specific** $D^0 \to K^0_S \pi^+ \pi^-$ decay in bins.
- Include effects of non-uniform acceptance over Dalitz plot

Previous analysis used $B \to D^0 \mu \nu$ decays

- Trigger and offline selection somewhat different $\Rightarrow$ systematics.

Current analysis:

- Use $B \to D\pi$ decay with identical trigger and offline selection
- Use the same expression as above, account for small opposite-flavour admixture with the same weak phase γ:

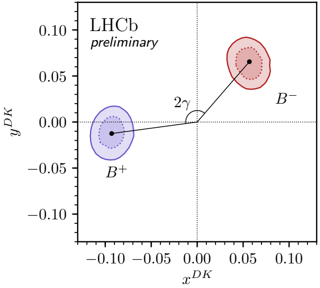
$$x_{\pm}^{D\pi} + iy_{\pm}^{D\pi} = (x_{\pm} + iy_{\pm}) \times \xi^{D\pi}$$

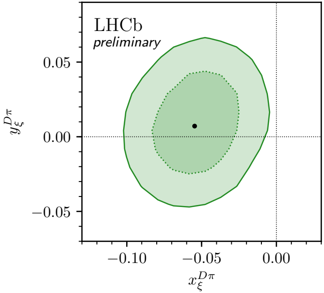
$\equiv x_{\xi}^{D\pi} + iy_{\xi}^{D\pi}$

- F_i and complex $\xi^{D\pi}$ are free parameters

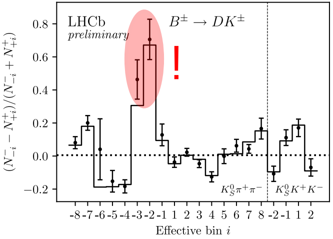
Results

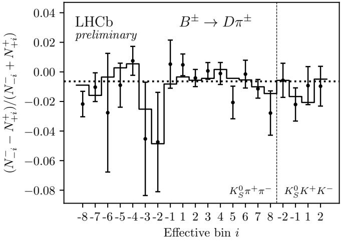
Fit results for CPV observables: [LHCb-CONF-2020-001]





Large CP asymmetry in certain phase space regions:





[LHCb-CONF-2020-001]

Binned fit results and constraints on physics parameters:

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

exp. syst CLEO, BES-III

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

- The most precise single measurement of γ.
- Using full Run I + Run II sample by LHCb, $B^\pm \to Dh^\pm$, $D \to K_S^0 h^+ h^-$ ($h = K, \pi$)
- New data-driven technique to account for non-uniform acceptance
- New strong phase measurement by BES-III used
- Statistically dominated, $\sigma(syst) \sim 1^\circ$, σ(CLEO+BES)$\sim 1^\circ$.

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

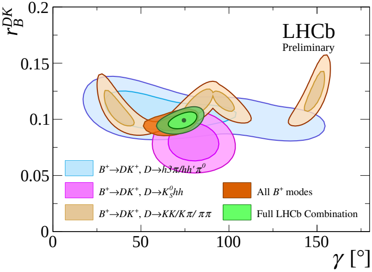
B decay	D decay	Method	Ref.	Dataset†	Status since last combination [3]
$B^+ \to DK^+$	$D \to h^+h^-$	GLW	[14]	Run 1 & 2	Minor update
$B^+ \to DK^+$	$D \to h^+h^-$	ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+\pi^-\pi^+\pi^-$	GLW/ADS	[15]	Run 1	As before
$B^+ \to DK^+$	$D \to h^+h^-\pi^0$	GLW/ADS	[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

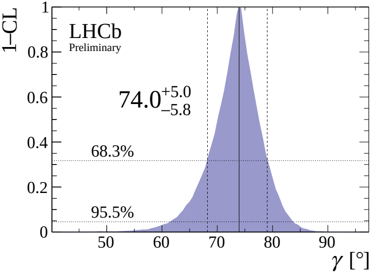
† Run 1 corresponds to an integrated luminosity of 3 fb^{-1} taken at centre-of-mass energies of 7 and 8 TeV . Run 2 corresponds to an integrated luminosity of 2 fb^{-1} taken at a centre-of-mass energy of 13 TeV .

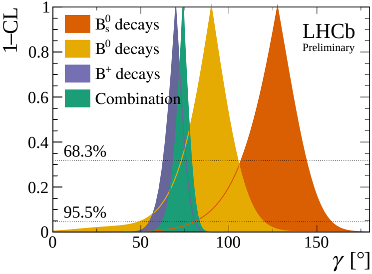
The latest full Run I+II measurements reported above are not yet included!

- $D \to hh$ (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 lower than plain average.
- Different analysis approaches (rates, Dalitz, time-dep) allow for better control of systematic uncertainties.

[LHCb-CONF-2018-002]







Summary

Two new measurements of γ are published employing full Run I+II LHCb dataset (2011–2018).

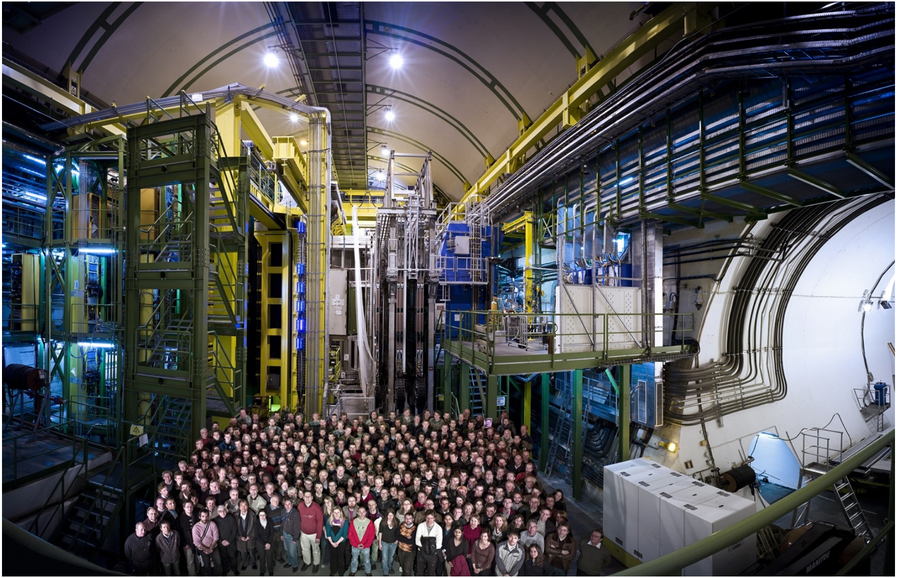
- Dalitz plot analysis of $D \to K^0_S hh$ from $B \to Dh$ ($h = K, \pi$).
  - The most precise single measurement: $\gamma = (69 \pm 5)^\circ$
  - New data-driven technique to reduce systematic uncertainty
  - New measurement of strong phase parameters from BES-III
- CP asymmetry in $B \to DK$, $D \to K^0_S K^\pm \pi^\mp$

LHCb combination of γ measurements will be updated soon, expect $\sigma(\gamma) \sim 4^\circ$.

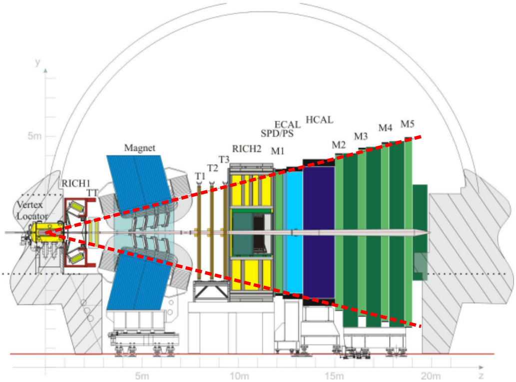
More analyses to be updated with Run I+II dataset (+possibly new analysis techniques), improve precision even further.

Backup

LHCb experiment

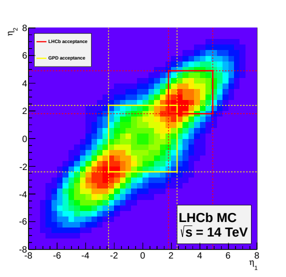


One-arm spectrometer optimised for studies of beauty and charm decays at LHC



Rapidity coverage

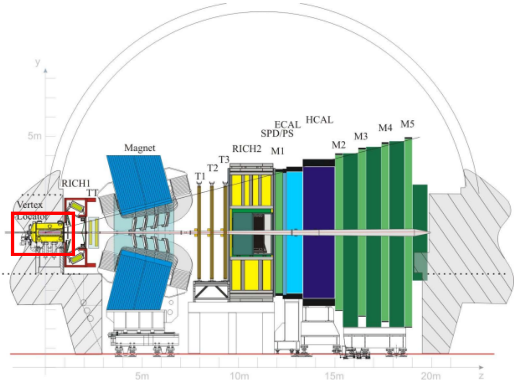
$$2 < \eta < 5$$



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

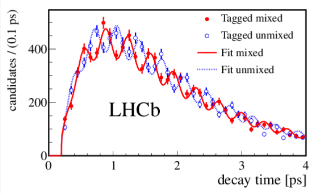
[JINST 3 (2008) S08005]

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



Vertexing

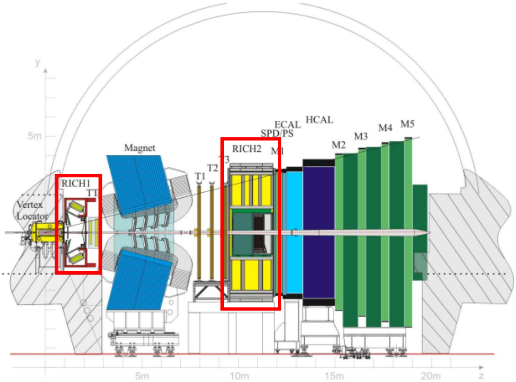
B_s^0 oscillations with $B_s^0 \to D_s\pi$



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

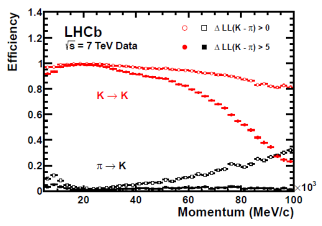
- Covers forward region (maximum of c and b production)
- Good vertexing: measure B^0 and B_s^0 oscillations, reject prompt background

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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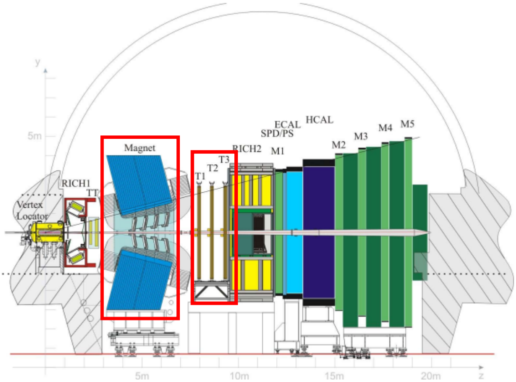
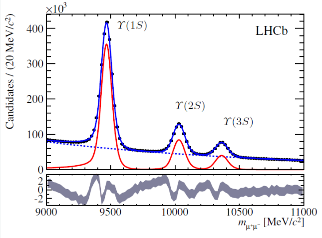


Tracking

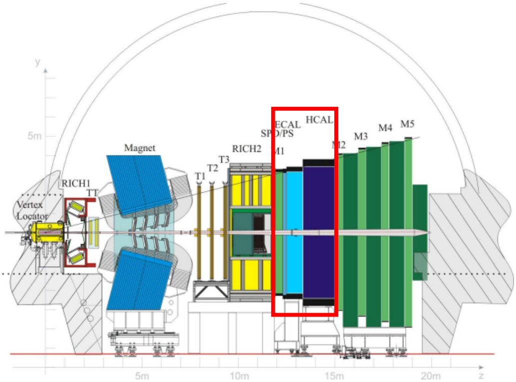
$\mu^+\mu^-$ mass spectrum



[PRL 111 (2013) 101805]

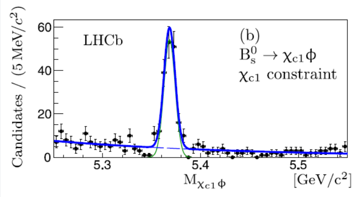
- Covers forward region (maximum of c and b production)
- Good vertexing: measure B^0 and B^0_s oscillations, reject prompt background
- Particle identification: flavour tagging, misID background
- High-resolution tracking

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]

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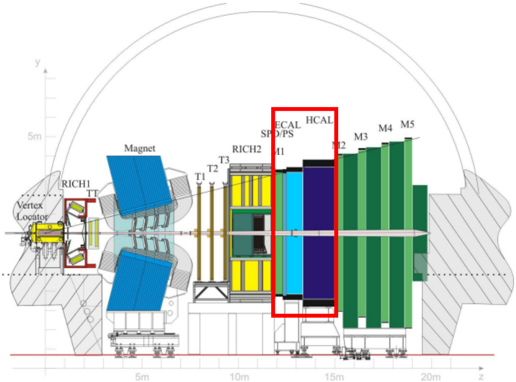

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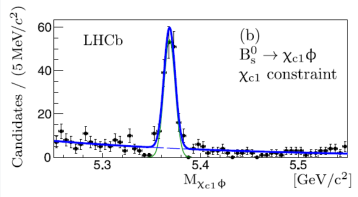

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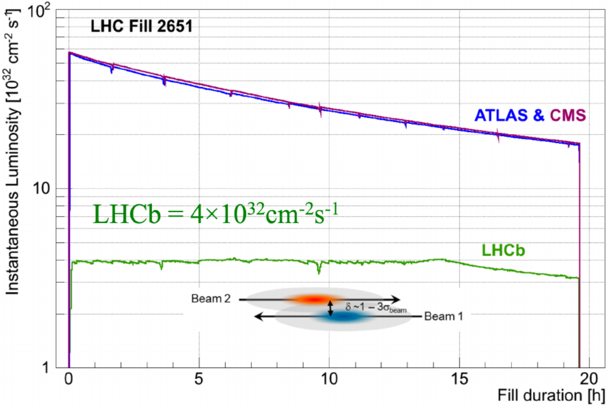
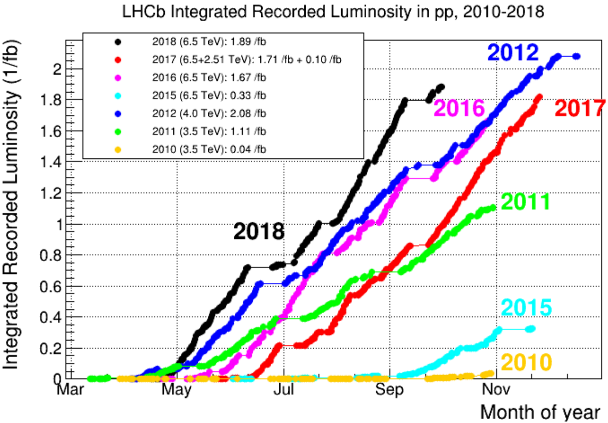
- Efficient trigger, including fully hadronic modes

LHCb operation



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

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



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

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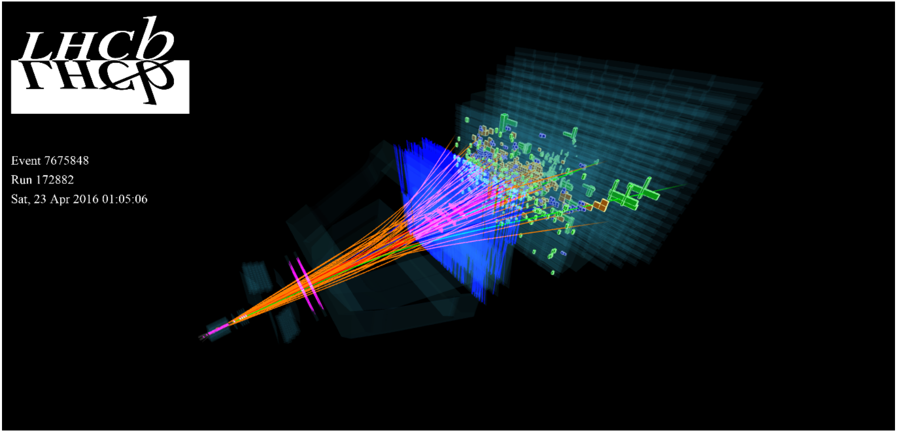
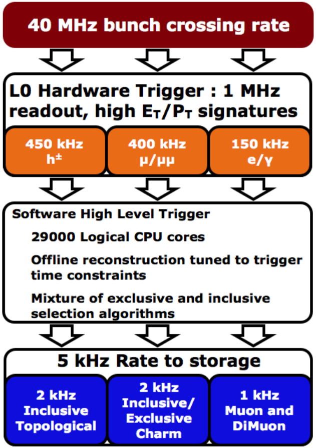
Proton-proton collision



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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LHCb trigger

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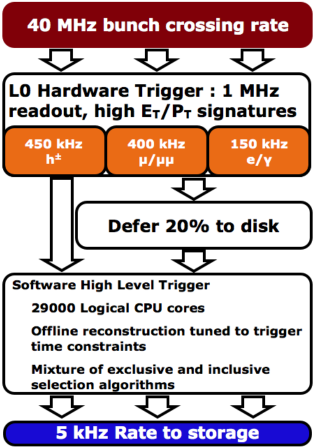

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LHCb trigger

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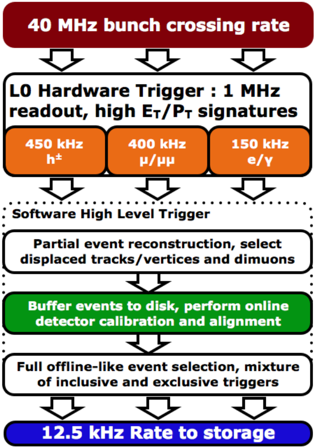


- 2011 and early 2012: increased trigger bandwidth (compared to design 2 kHz) to accommodate charm
- 2012: *deferred trigger* configuration: keep the trigger farm busy between fills
- Since 2015: *split trigger*
  - All 1st stage (HLT1) output stored on disk
  - Used for real-time calibration and alignment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

Time-dependent measurements

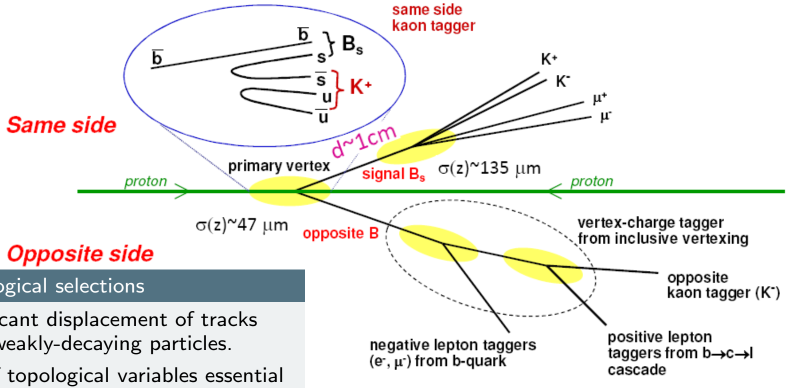
Measure lifetime based on vertex displacement from the primary vertex of *pp* interaction.

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

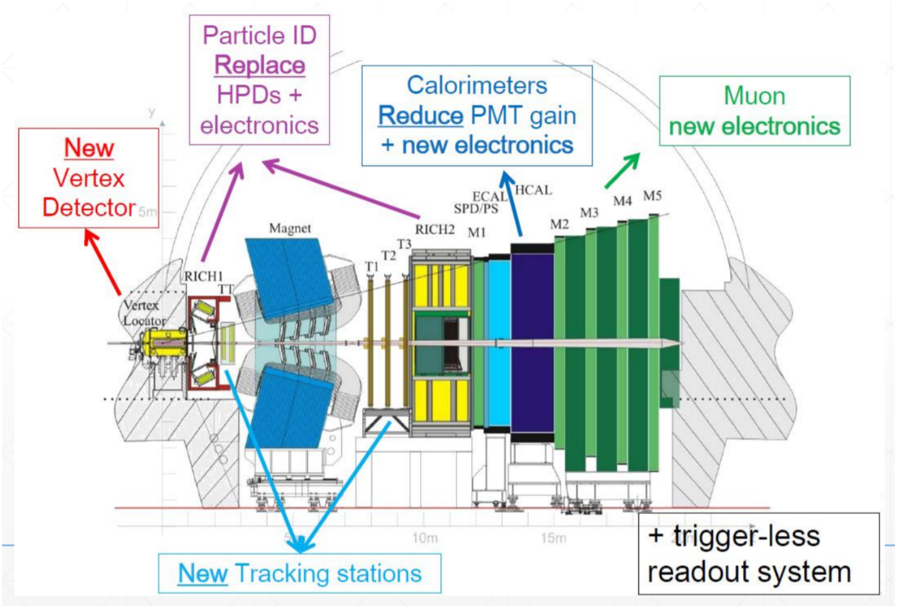


Topological selections

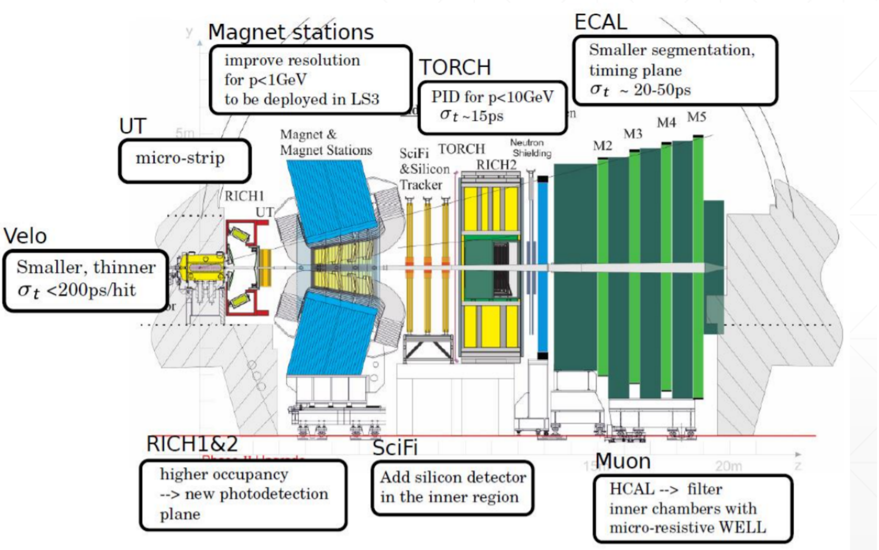
Significant displacement of tracks from weakly-decaying particles.

Use of topological variables essential to reduce combinatorial background.

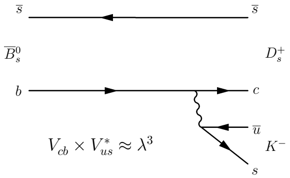
LHCb upgrade I

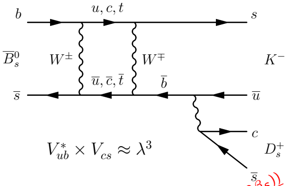


LHCb upgrade II



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 $\overline{f}$)

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

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

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

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

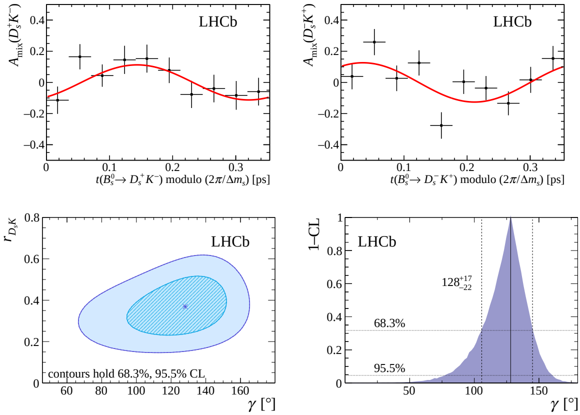
Measure $\gamma - 2\beta_s$, δ, r

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

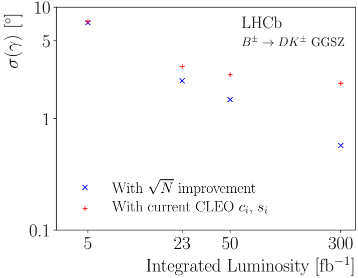
γ from time-dependent analyses

[JHEP 03 (2018) 059]

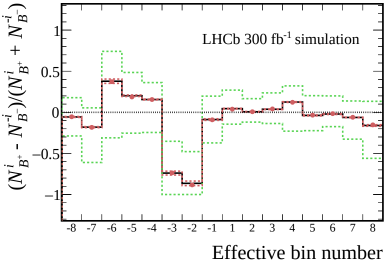


Relies on input $-2\beta_s = -0.030 \pm 0.033 \Rightarrow$ $\gamma = (128^{+17}_{-22})^\circ$ (stat-limited).

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



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



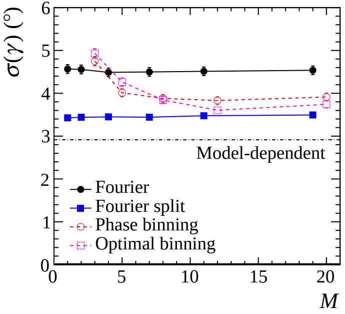
- Critical uncertainty: measurement of strong phase difference in bins. Currently: $\simeq 1^\circ$ (CLEO, BES-III).
- Further reduction is possible:
  - Expect BES-III to contribute with larger dataset.
  - Technique to obtain $D^0 - \overline{D}^0$ phase difference from charm mixing fits at LHCb [JHEP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

Binned approach reduces statistical precision compared to unbinned fit.

Carefully optimised binning has $\simeq 80\%$ power of the unbinned fit.

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
Possible further optimisation of the family of weight functions.

Prospects for γ: ADS/GLW and combination

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

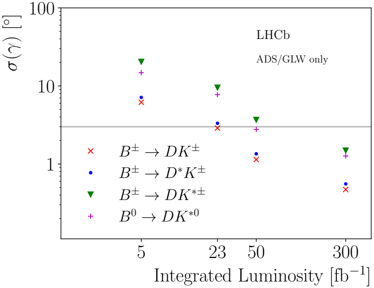
Main systematic uncertainties with rate and asymmetry measurements:

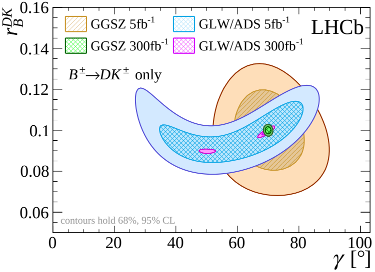
- Production and instrumentation asymmetries
- Backgrounds and their asymmetries.

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 $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [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%	–
$\boldsymbol{B_s^0, B^0 \to \mu^+\mu^-}$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$\boldsymbol{b \to c\ell^-\bar{\nu}_l}$ **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}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–