Recent results of measurement of CKM angle γ and CPV in the beauty sector at LHCb

Wojciech Krupa
on behalf of the LHCb collaboration

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Outline

- **The CKM angle γ measurement**
  - Constraints on the CKM angle γ from $B^{\pm} \rightarrow Dh^{\pm}$ decays [LHCb-PAPER-2021-036, submitted to JHEP]
  - Measurement of the CKM angle γ and Δm_s with $B_s^0 \rightarrow D_s^{\mp} h^{\pm} \pi^{\pm} \pi^{\mp}$ decays [JHEP 03(2021) 137]
  - Measurement of the CKM angle γ with $B^{\pm} \rightarrow D[K^{\mp} \pi^{\pm} \pi^{\pm} \pi^{\mp}] h^{\pm}$ decays [LHCb-PAPER-2022-017]
  - The LHCb combination [JHEP 12(2021) 141]
- **CPV in the beauty sector**
  - Observation of the suppressed $\Lambda_b^0 \rightarrow DpK^-$ decay and measurement of its CP asymmetry [JHEP12(2021)141, submitted to PRD]

Other **LHCb** talks during BEACH 2022

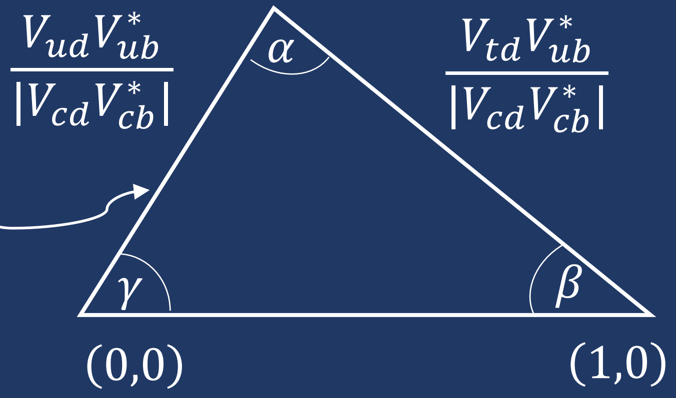
- LHCb physics introductory talk – Chris Parkes
- Rare decays at LHCb, including tests of lepton flavour universality and lepton flavour violation – Marcin Chrząszcz
- Mixing and indirect CP violation in charm mesons at LHCb - Edward Shields
- Direct CPV in charm hadrons at LHCb - Artur Ukleja
- Physics prospects, experimental challenges - LHCb Upgrade 2 – Agnieszka Obłąkowska-Mucha
- Charmed baryons at LHCb - Jakub Ryżka

Introduction to the CKM angle γ

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

CKM quark mixing matrix
Transition's amplitudes

The Unitarity triangle
Graphical representation of Unitarity condition



$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\,\boldsymbol{\lambda}^3\,(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\,\lambda^2 \\ A\,\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\,\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Wolfenstein parameterisation
Transparent parametrisation in terms of 4 parameters

The angle γ is one of the angles of the CKM unitarity triangle:

- It is a Charge-Parity Violation (CPV) parameter.
- It can be measured from tree-level processes only and it is a standard candle measurement in the SM.
- Very small theoretical uncertainties associated with tree-level measurements: $\delta\gamma/\gamma = O(10^{-7})$. [ref]

Introduction to the CKM angle γ

[CKM group]

The angle γ: $\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}\,V_{cb}^*}\right)$ is one of the angles of the CKM unitarity triangle:

- It is studied in the heavy flavour physics experiments like LHCb, Belle, BABAR…
- LHCb indirect measurement:

$$\gamma = 65.4^{+3.8}_{-4.2}{}^{\circ} at\ 68.3\%\ C.L.$$

[JHEP12(2021)141]

- Global indirect constraints:

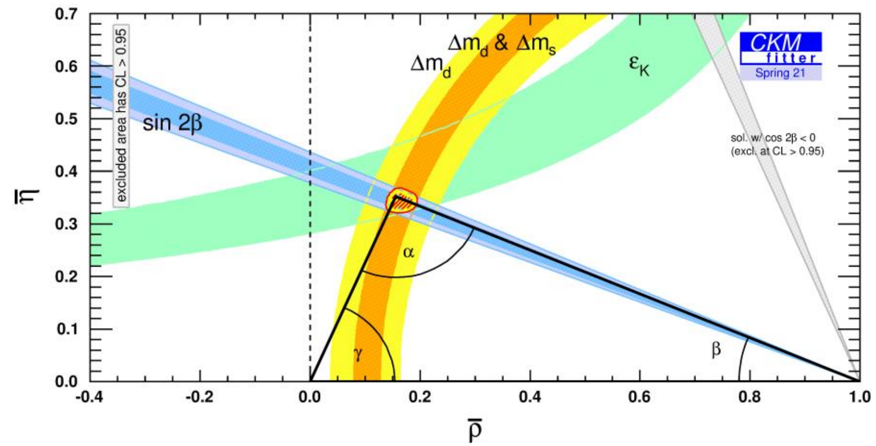
$$\gamma = 65.8 \pm 2.2\,^{\circ}$$

[UT collaboration]

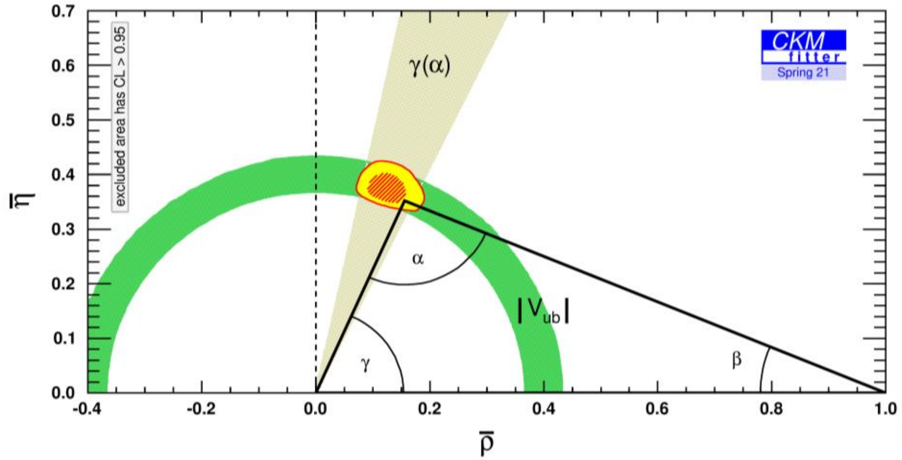
$$\gamma = 65^{+0.9}_{-2.7}{}^{\circ}$$

[CKM group]

Loop (indirect) measurements

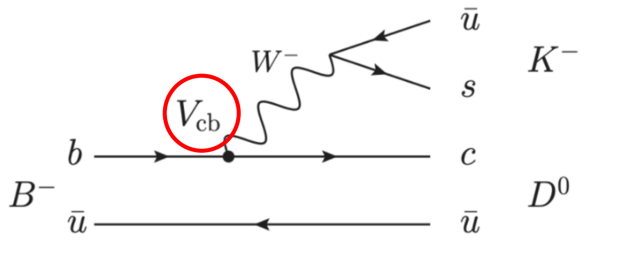


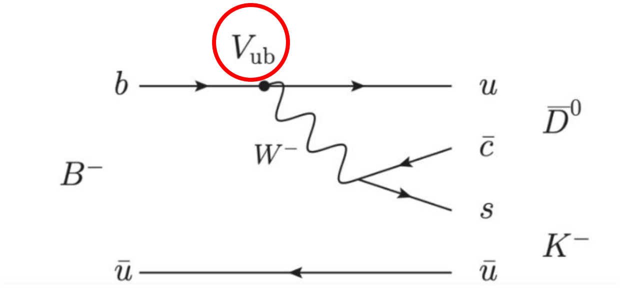
Tree (direct) measurements



Introduction to the CKM angle γ

Measurement of the CKM angle is possible in processes with the interference between the favoured transition $b \to c$ and suppressed transition $b \to u$.

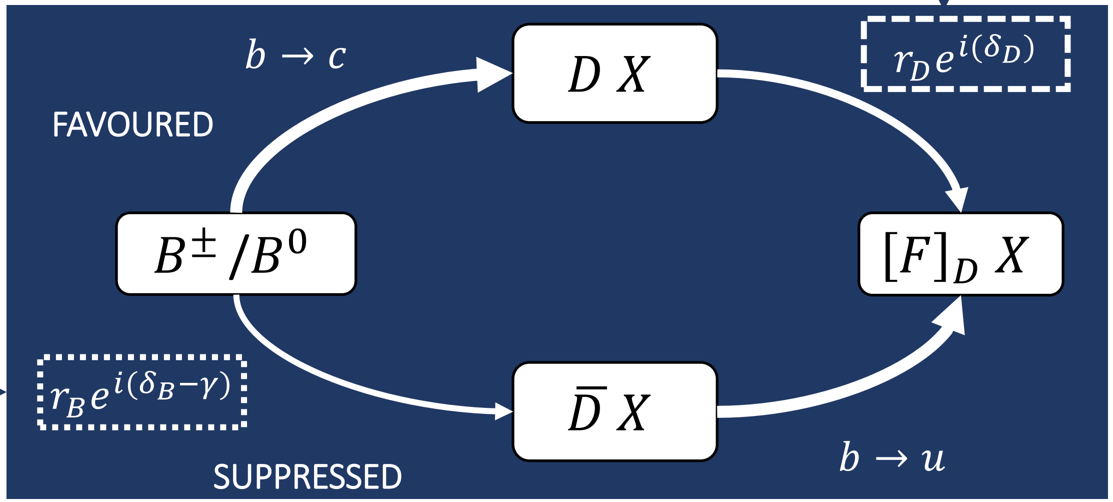




	Method	X	$[F]_D$
$B^0/B^\pm$	ADS (mixed state)	K, π	[Kπ, Kπππ, ...]
$B^0/B^\pm$	GLW (CP e-g)	K, π	[KK, ππ, 4π, ...]
$B^0/B^\pm$	GLS	K, π	[hh]
$B^0/B^\pm$	GGSZ	K^{*0}	$[K^0_s hh]$
B^0/B^0_s	Time-Dependent	$K, K^{*\pm}, K^{*0}$	[hhh, hh]

Ratio of magnitudes and phase difference for D decay amplitudes

Ratio of magnitudes and phase difference for B decay amplitudes

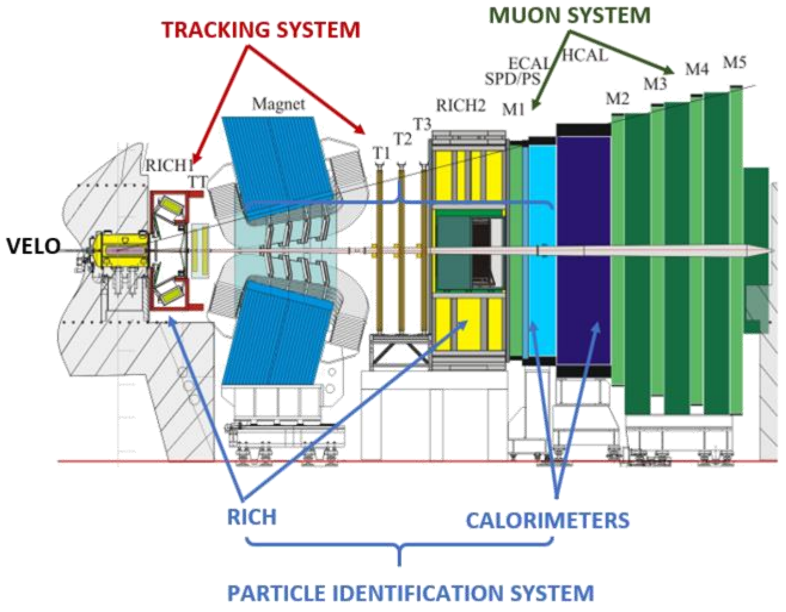


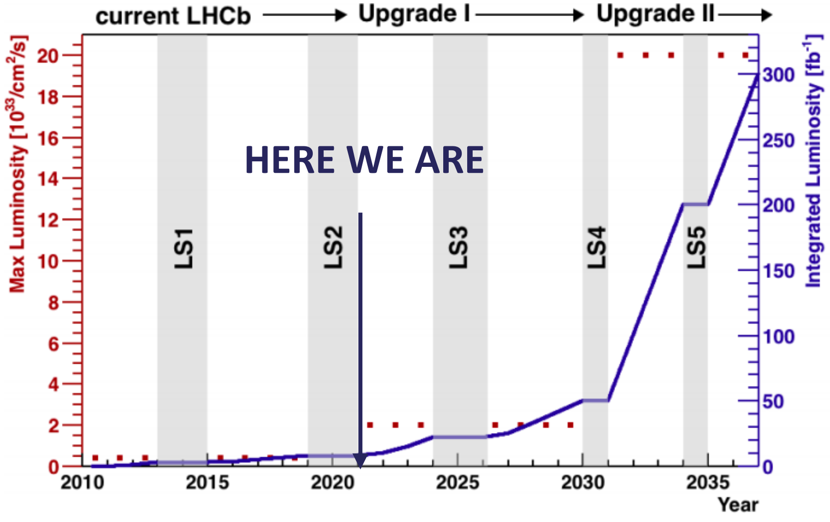
The (former) LHCb spectrometer

[JINST 3 S08005]

LHCb detector designed for decays of hadrons with a b or c quarks:

- Covering the pseudorapidity range ($2<\eta<5$).
- Identification : $\varepsilon(h\rightarrow h)\sim 90\%$: miss $\varepsilon(h\rightarrow h)\sim 5\%$, $\varepsilon_{\mu}\sim 97\%$
- IP resolution : $\sigma_{IP}=20\ \mu\text{m}$
- Momentum resolution: $\Delta p/p=0.5-0.8\ \%$
- Mass resolution : $\sigma(m_{B\rightarrow hh})\approx 22$ MeV
- Time resolution $45-55\ fs$



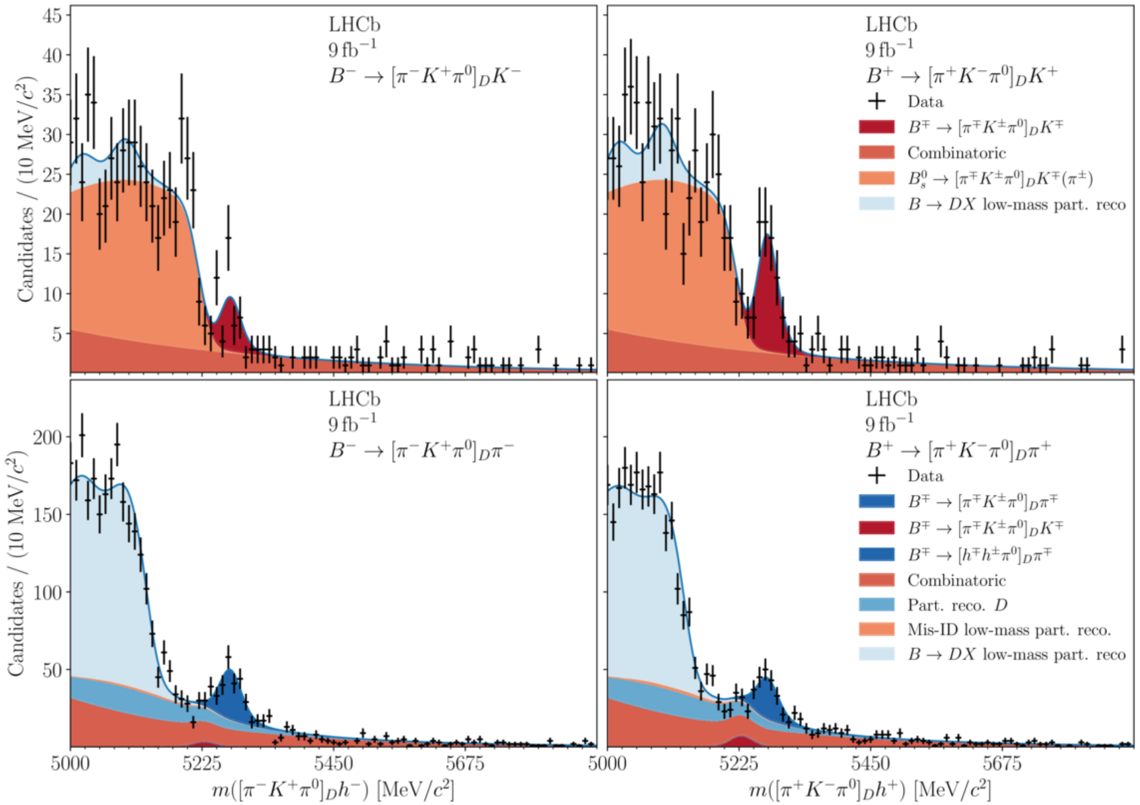


Analysis of $B^{\pm} \to Dh^{\pm}$ $(D \to h^{\pm}h'^{\mp}\pi^0)$

[LHCb-PAPER-2021-036]

- Direct CP measurement using three-body D^0 decay and quasi-GLW(ADS) method
- Full Run 1 + 2 sample (2011-2018)
- h' either kaon or pion
- Simultanious analysis of 8 final states

Mode
$B^{\pm} \to [K^{\pm}K^{\mp}\pi^0]_D\pi^{\pm}$
$B^{\pm} \to [\pi^{\pm}\pi^{\mp}\pi^0]_D\pi^{\pm}$
$B^{\pm} \to [K^{\pm}\pi^{\mp}\pi^0]_D\pi^{\pm}$
$B^{\pm} \to [\pi^{\pm}K^{\mp}\pi^0]_D\pi^{\pm}$
$B^{\pm} \to [K^{\pm}K^{\mp}\pi^0]_DK^{\pm}$
$B^{\pm} \to [\pi^{\pm}\pi^{\mp}\pi^0]_DK^{\pm}$
$B^{\pm} \to [K^{\pm}\pi^{\mp}\pi^0]_DK^{\pm}$
$B^{\pm} \to [\pi^{\pm}K^{\mp}\pi^0]_DK^{\pm}$



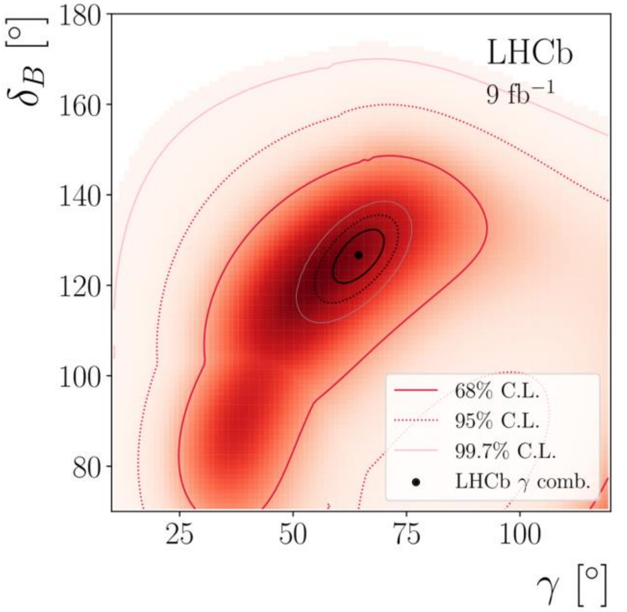
Analysis of $B^{\pm} \to Dh^{\pm}\ (D \to h^{\pm}h'^{\mp}\pi^0)$

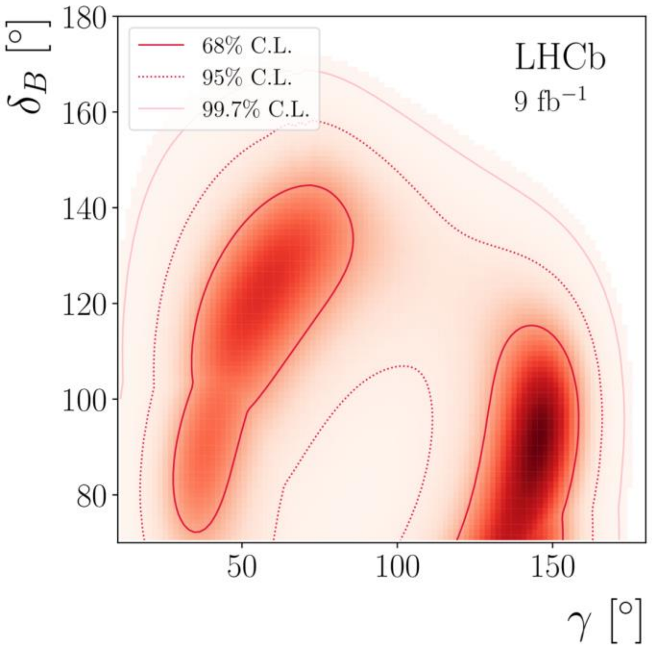
[LHCb-PAPER-2021-036]

- Measurement of over 15 CPV parameters: $R^{KK\pi^0}, A^{K\pi\pi\pi^0}, R_{ADS(K)}$, $A_{ADS(K)}$ and more
- The results are interpreted in terms of γ, δ_B and r_B

Results

- $\gamma = (56^{+24}_{-19})^{\circ}$
- $\delta_B = (122^{+19}_{-23})^{\circ}$
- $r_B = (9.3^{+1.0}_{-0.9}) \times 10^{-2}$



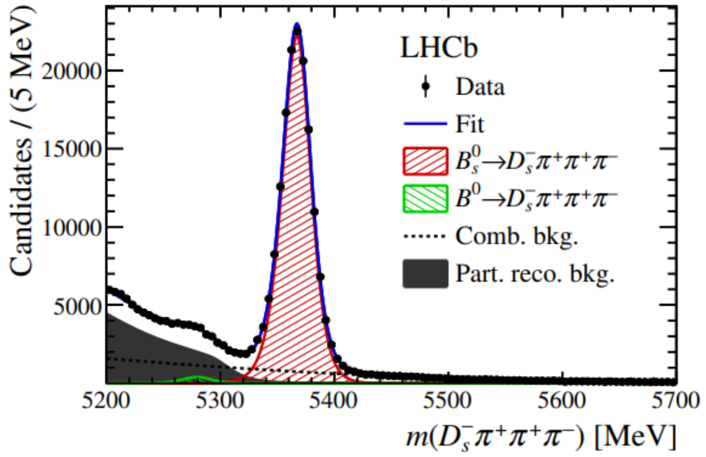


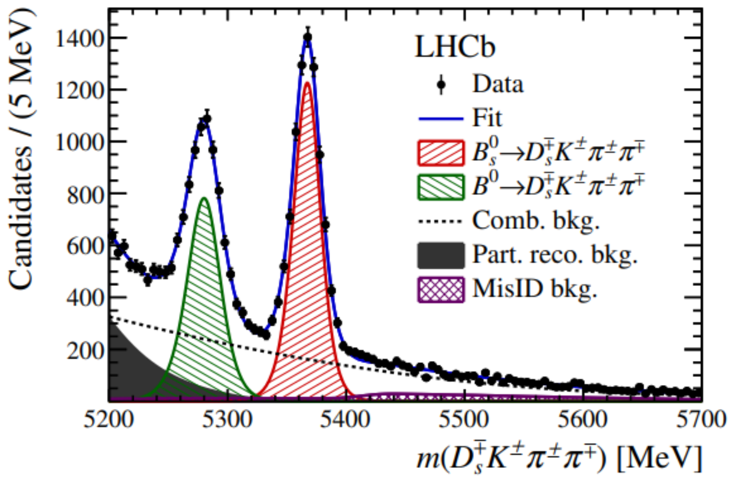
Confidence regions of the strong phase, δ_B versus the CKM angle γ

Analysis of $B_s^0 \to D_s^- h^+ \pi^+ \pi^-$

[JHEP 03 (2021) 137]

- Masurement of the angle γ in $B_s^0 \to D_s^- h^+ \pi^+ \pi^-$
- Full Run 1 + 2 sample (2011-2018)
- **A time-dependent amplitude analysis:** the time-dependent amplitude fit using signal PDF through full-spectrum decay rate $(A^u(x),\ A^c(x))$.
- **A model-independent analysis:** phase-space integrated decay rate, measurement of the CP coefficients: $C_f, A_f^{\Delta\Gamma}, A_{\bar{f}}^{\Delta\Gamma}, S_f, S_{\bar{f}}$
- Simultanious measurement of Δm_s and γ

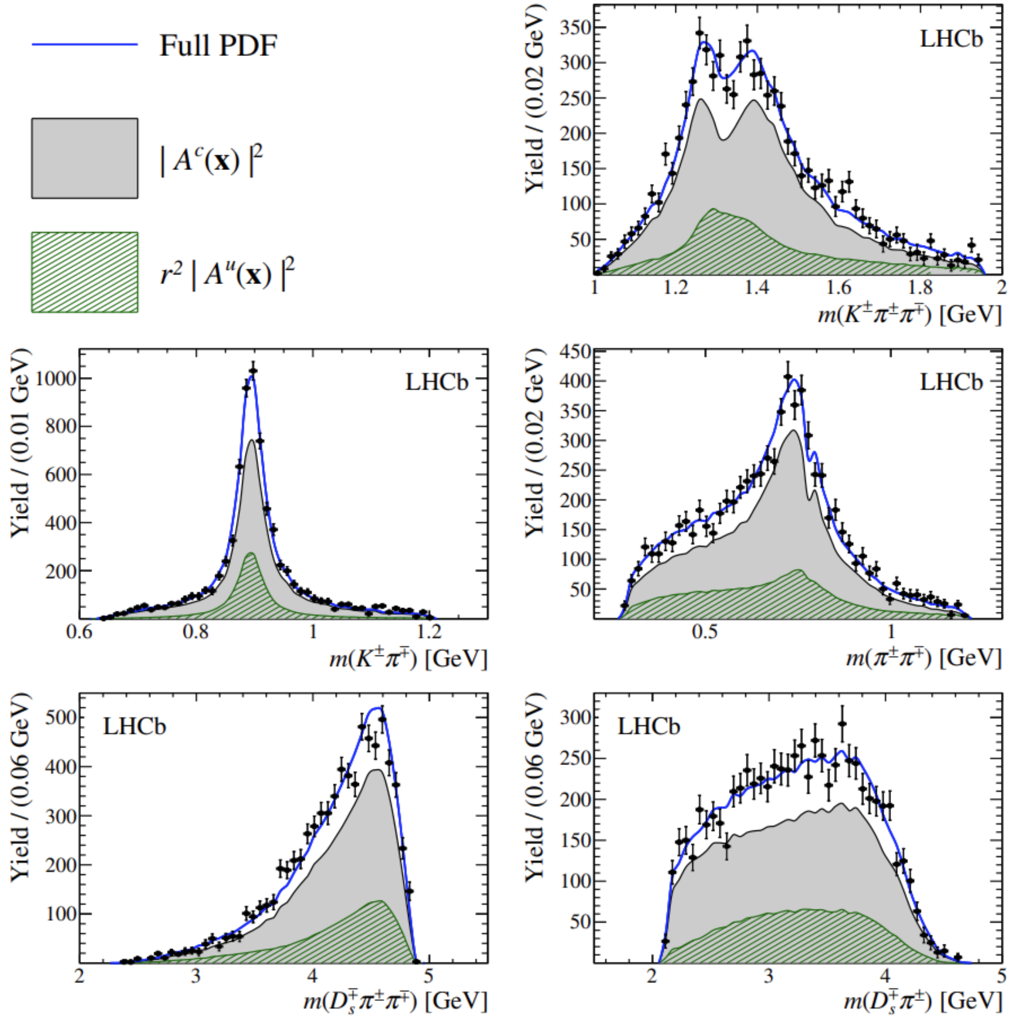




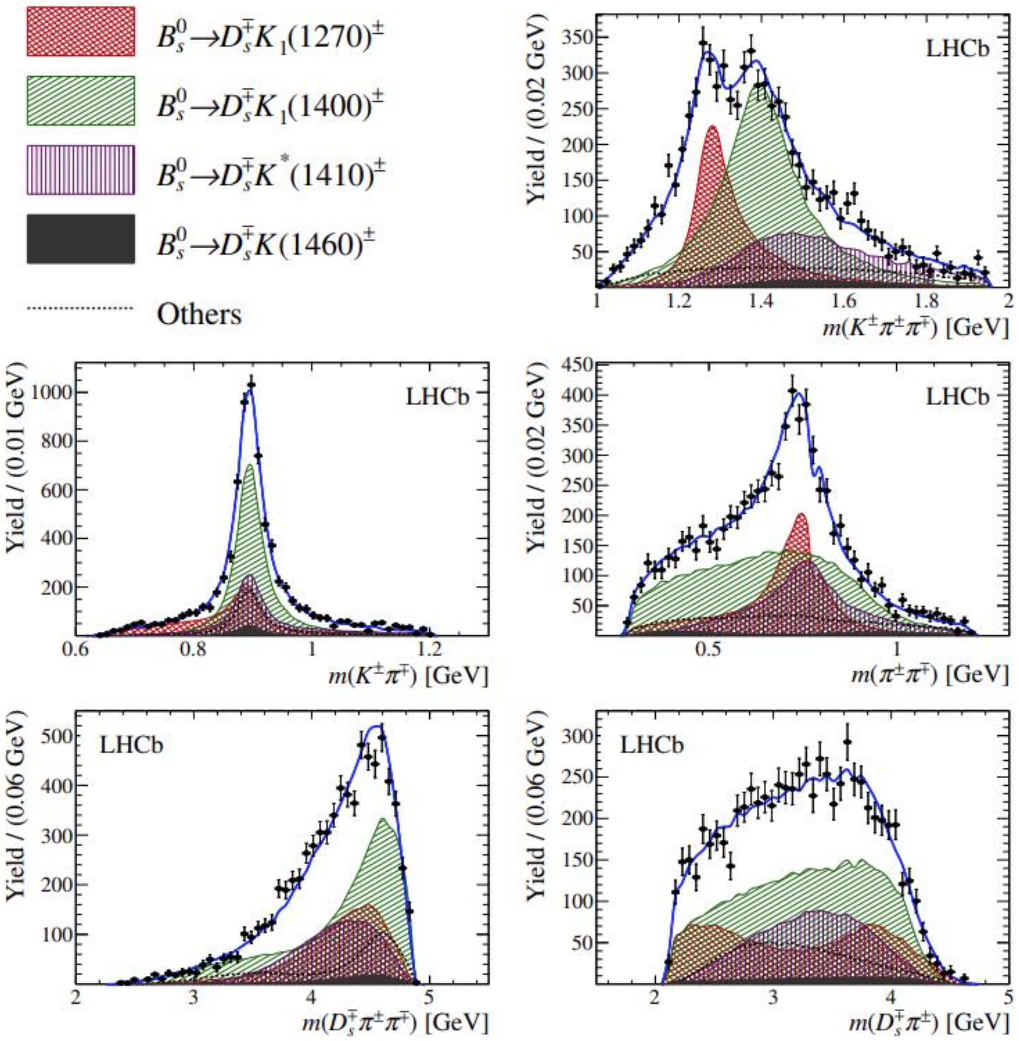
Analysis of $B_s^0 \to D_s^- h^+ \pi^+ \pi^-$

[JHEP 03 (2021) 137]

Contributions from $b \to c$ and $b \to u$ decay amplitudes



Incoherent contributions from intermediate-state components.



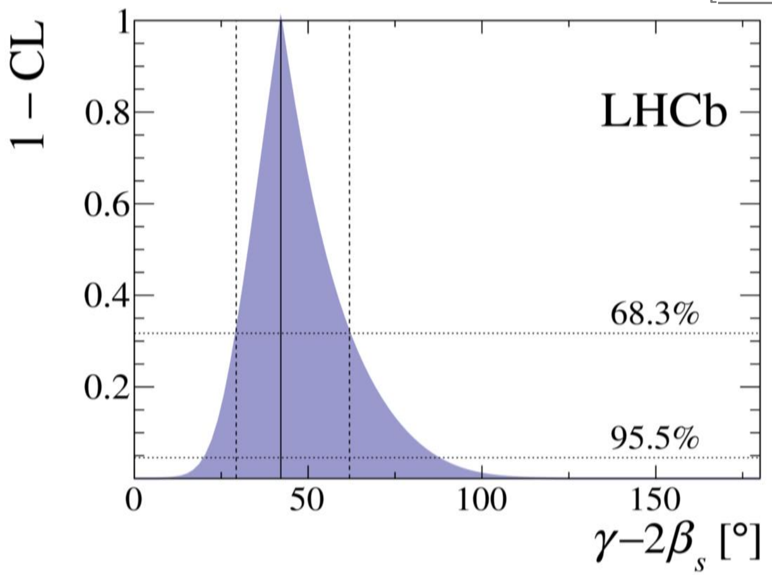
Analysis of $B_s^0 \to D_s^- h^+ \pi^+ \pi^-$

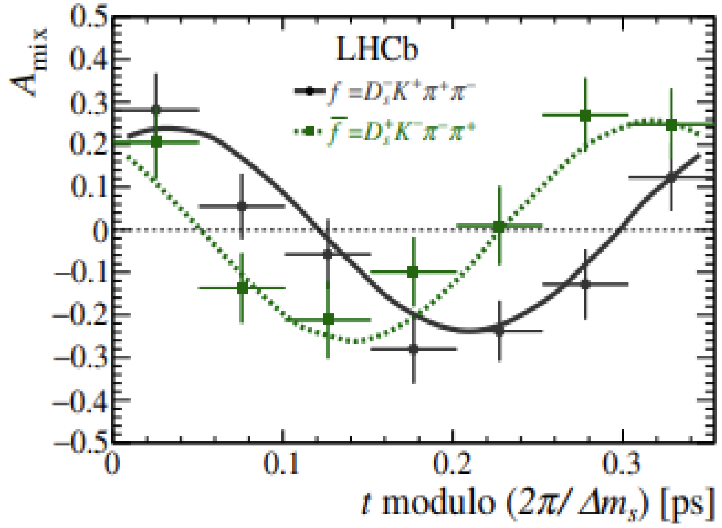
[JHEP 03 (2021) 137]

Results

- $\Delta m_s = \left(17.757 \pm 0.007(stat) \pm 0.008(syst)\right) ps^{-1}$

  the most precise measurement of Δm_s!
- $\gamma = (44 \pm 12)°$ - time-independent amplitude analysis
- $\gamma = (44^{+20}_{-13})°$ - model-independent fit to the phase-space integrated decay-time spectrum





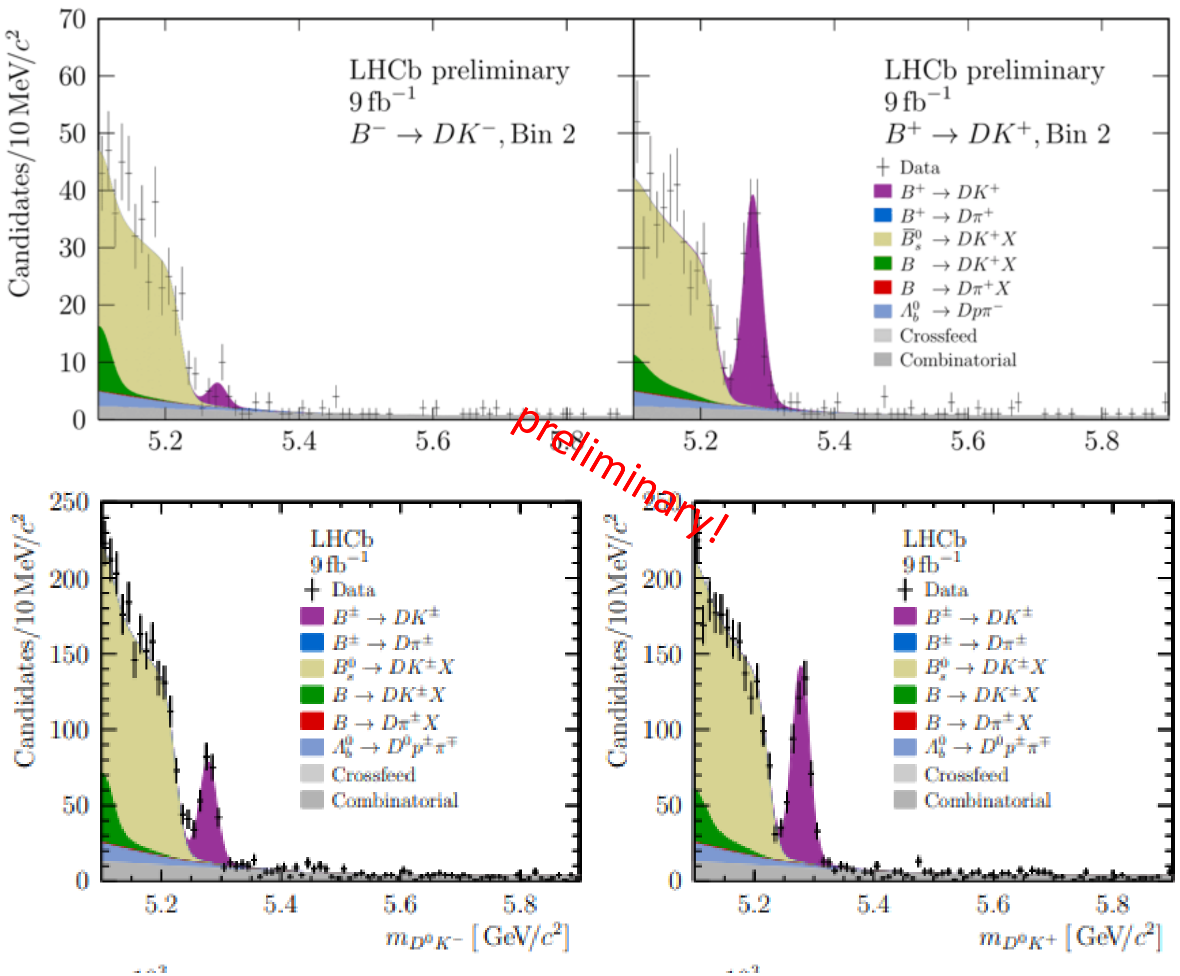
Analysis of $B^{\pm} \to D[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]h^{\pm}$

[LHCb-PAPER-2022-017]

- 4 possible configurations:
  $B^{\pm} \to D[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]h^{\pm}$ (OS) and
  $B^{\pm} \to D[K^{\pm}\pi^{\mp}\pi^{\mp}\pi^{\pm}]h^{\pm}$ (SS)
- Full Run 1 + 2 sample (2011-2018)
- Measurement of γ performered using binned phase-space approach [ref]

Result ▪ $\gamma = (56^{+6.0-0.6+6.7}_{-5.8-0.6+4.3})^{\circ}$

Largest difference between B^{-} and B^{+} ever



LHCb combination to the CKM angle γ

[JHEP12(2021)141]

New LHCb combination (late 2021)

- Including several new and updated results
- For the first time, including results from the beauty **and** charm sectors (simultaneous determination of γ and charm mixing parameters: x, y)
- Grate improvement on the precision of the charm mixing parameters

B decay	D decay	Ref.	Dataset	Status since Ref. [17]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[20]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[21]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[22]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[19]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[23]	Run 1&2	**Updated**
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[20]	Run 1&2	**Updated**
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[24]	Run 1&2(*)	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[24]	Run 1&2(*)	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[25]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[26]	Run 1&2(*)	**Updated**
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[26]	Run 1&2(*)	**New**
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[27]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[28]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	[29]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	[30]	Run 1&2	**New**
D decay	Observable(s)	Ref.	Dataset	Status since Ref. [17]
$D^0 \to h^+h^-$	ΔA_{CP}	[31–33]	Run 1&2	**New**
$D^0 \to h^+h^-$	y_{CP}	[34]	Run 1	**New**
$D^0 \to h^+h^-$	ΔY	[35–38]	Run 1&2	**New**
$D^0 \to K^+\pi^-$ (Single Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[39]	Run 1	**New**
$D^0 \to K^+\pi^-$ (Double Tag)	$R^\pm$, $(x'^\pm)^2$, $y'^\pm$	[40]	Run 1&2(*)	**New**
$D^0 \to K^\pm\pi^\mp\pi^+\pi^-$	$(x^2+y^2)/4$	[41]	Run 1	**New**
$D^0 \to K^0_S\pi^+\pi^-$	x, y	[42]	Run 1	**New**
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[43]	Run 1	**New**
$D^0 \to K^0_S\pi^+\pi^-$	x_{CP}, y_{CP}, Δx, Δy	[44]	Run 2	**New**

LHCb combination to the CKM angle γ

[JHEP12(2021)141]

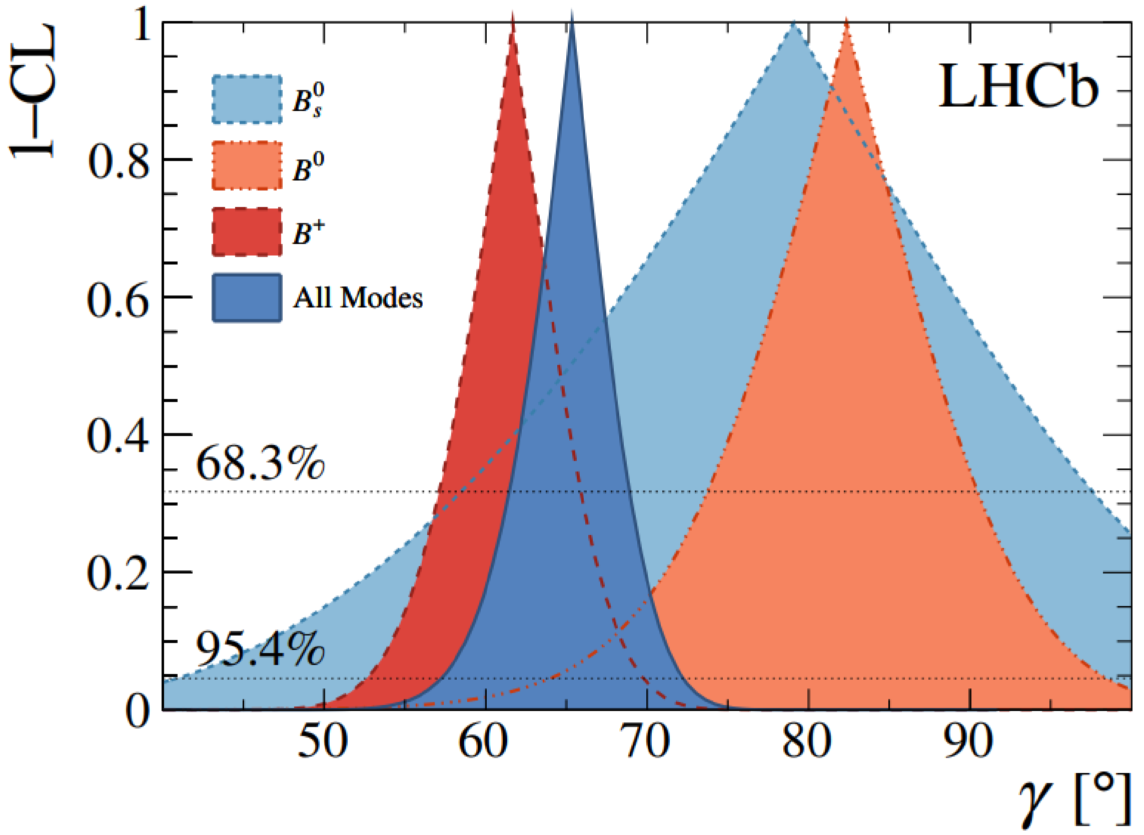
Beauty sector

- The CKM angle γ

$$\gamma = 65.4^{+3.8}_{-4.2}{}^{\circ} \; at \; 68.3\% \; C.L.$$

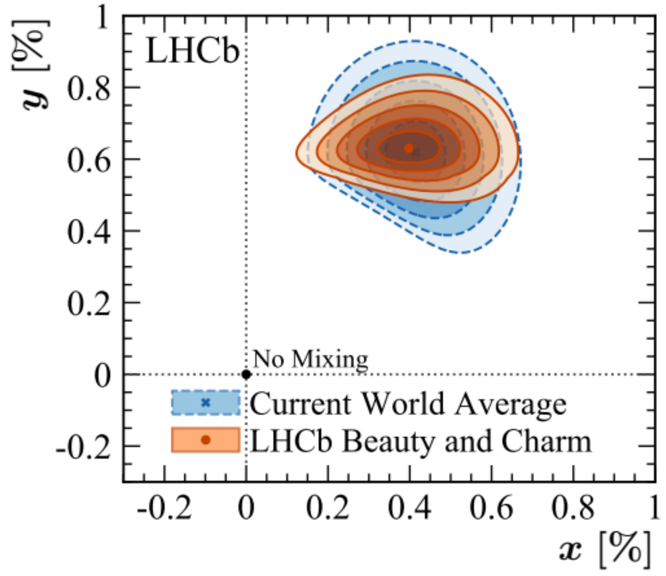
$$\gamma = 65.4^{+7.5}_{-8.7}{}^{\circ} \; at \; 95.5\% \; C.L.$$

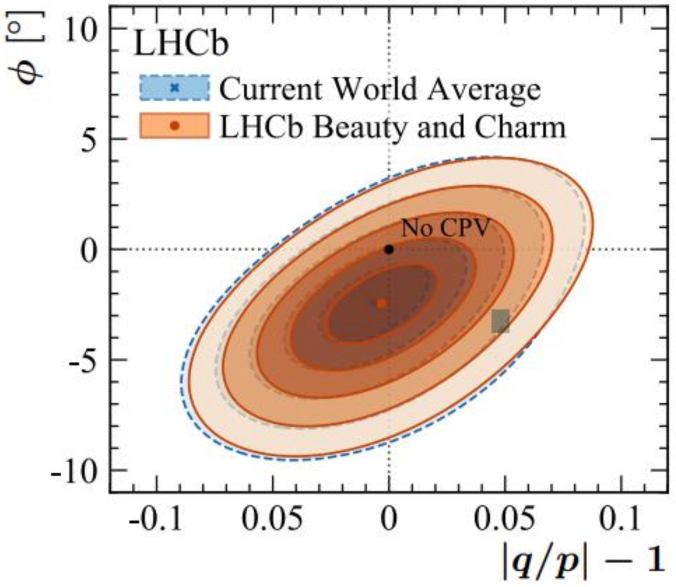
- Most precise by single experiment!
- Around 2σ tension between charged and neutral B mesons



LHCb combination to the CKM angle γ

[JHEP12(2021)141]





*at 68.3% Cl

Charm sector

- The charm mixing parameters*:

$$x = (0.400^{+0.052}_{-0.053}) \qquad y = (0.630^{+0.033}_{-0.030})$$

approximately 2 times more precise than the world average!

$$\phi = (-2.4 \pm 1.2)° \qquad q/p = 0.997 \pm 0.016$$

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D^0}\rangle \; \phi \equiv \arg(q/p)$$
$$x \equiv (m_1 - m_2)/\Gamma \quad y \equiv (\Gamma_1 - \Gamma_2)/2\Gamma$$

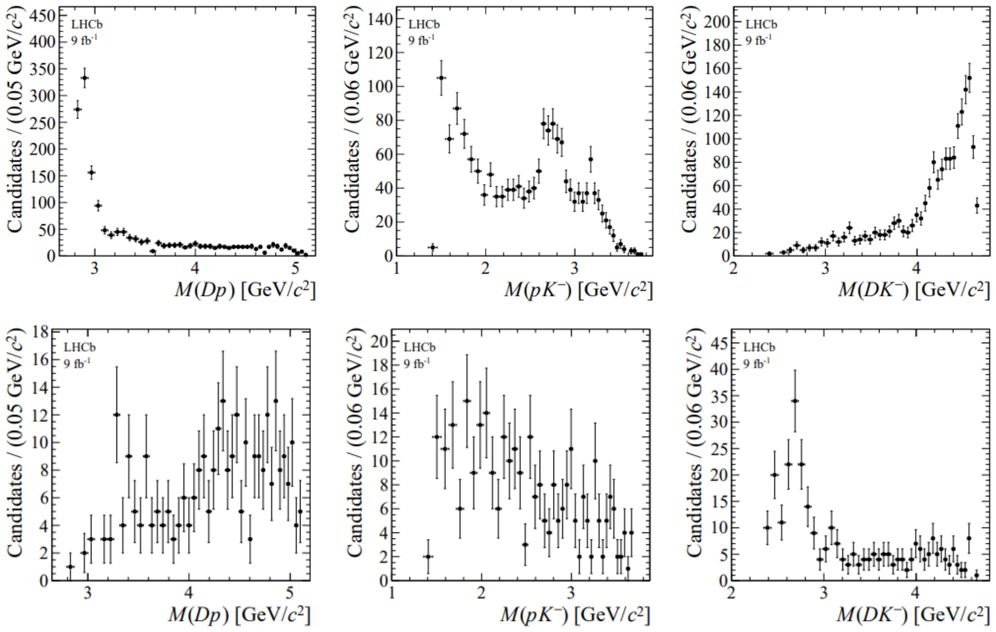
Analysis of $\Lambda_b^0 \to DpK^-(D \to K^\pm\pi^\mp)$

[JHEP12(2021)141]

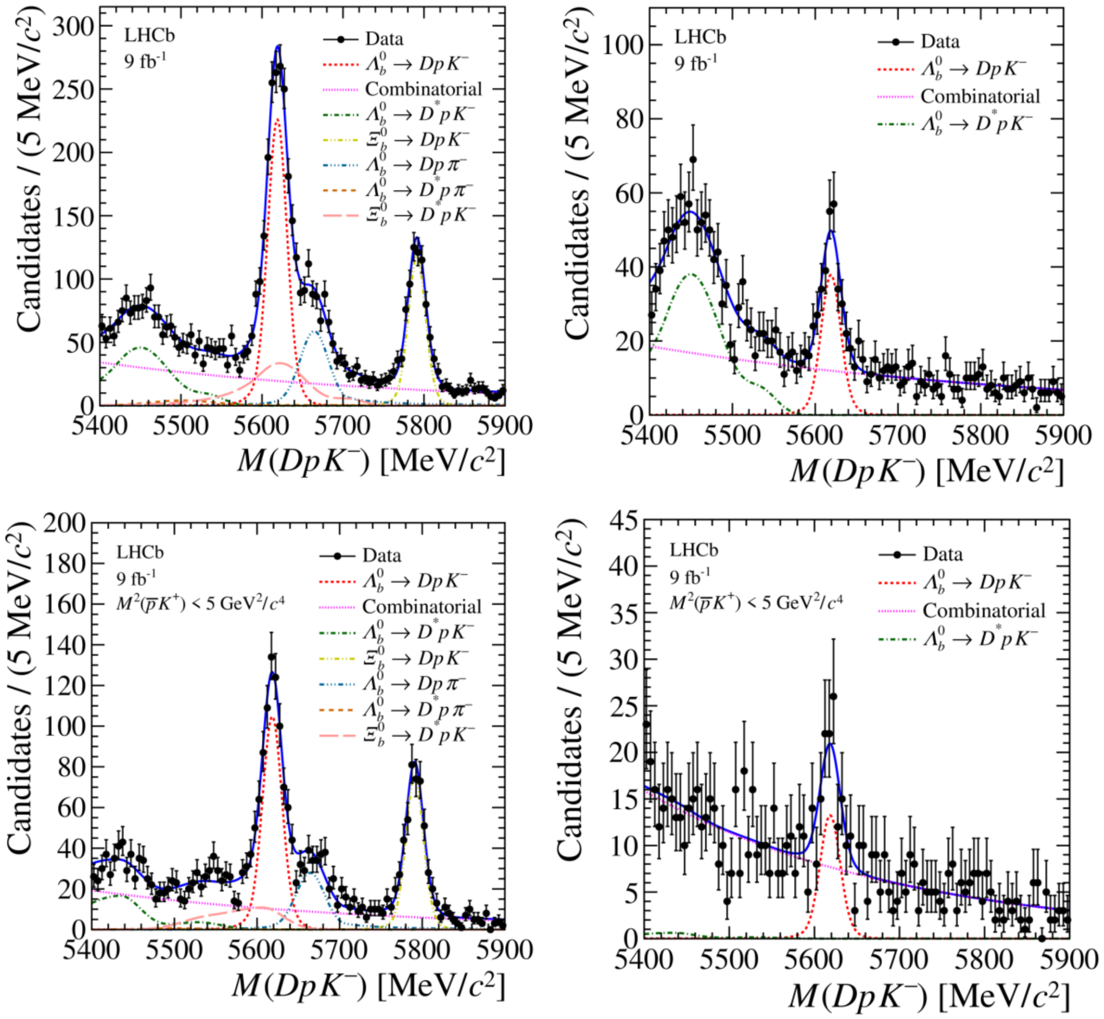
- First observation of $\Lambda_b^0 \to DpK^-(D \to K^+\pi^-)$ (estimated branching fraction 7 times smaller than for favoured mode)
- Full Run 1 + 2 sample (2011-2018)
- The Λ_b^0 resonant structure analysis

Favoured

Suppressed



Favoured $(D \to K^-\pi^+)$ Supressed $(D \to K^+\pi^-)$



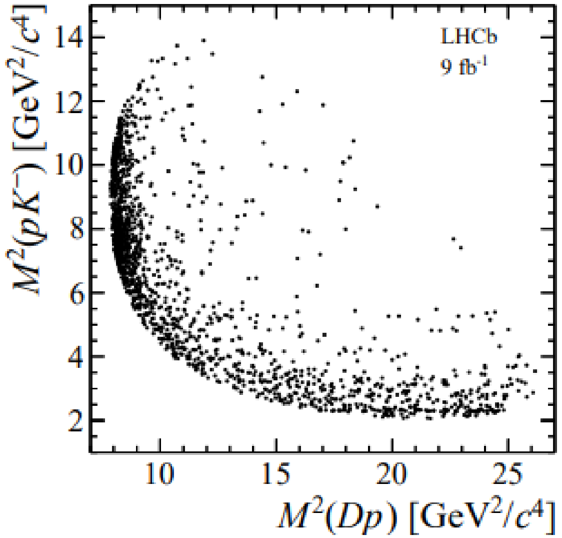
Analysis of $\Lambda_b^0 \to DpK^-(D \to K^\pm\pi^\mp)$

[JHEP12(2021)141]

- Too small signal yield to constrain angle γ
- Good prospect for measurement with a bigger data sample (Run3).

Results

- $R = 7.1 \pm 0.8(\text{stat.})^{+0.4}_{-0.3}(\text{syst.})$
- $A = 0.12 \pm 0.09\ (\text{stat.})^{+0.02}_{-0.03}(\text{syst.})$



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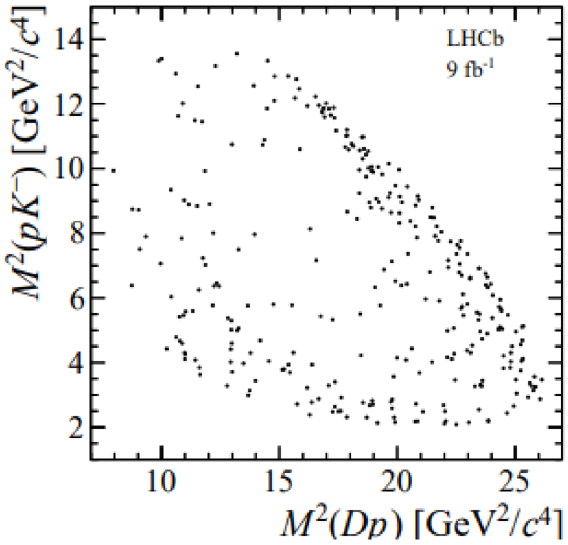
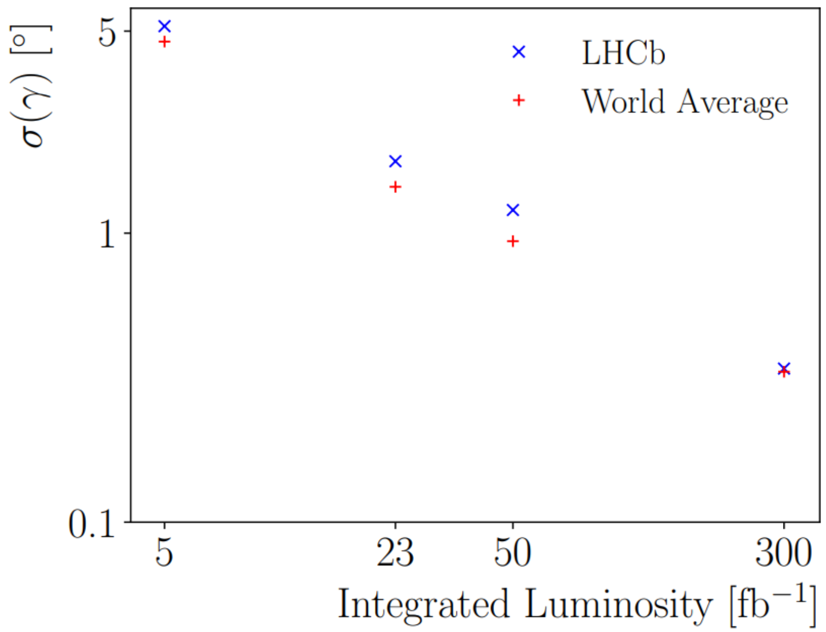


Suppressed

Conclusions

- Many new and updated results on the CPV in the beauty and charm sector!
- Excellent prospects for Run 3 and 4 with the bigger data set.

[CERN-LHCC-2018-027]



Thank you for attention!

$B \to DK$ decays

Several methods of measurements of the angle γ: GLW, ADS, Dalitz plots and time-dependent.

GLW

[PL B253 1991 483]

$$A_{CP}=\frac{\Gamma(\bar{B}^0\to D_{CP}\bar{K}^{*0})-\Gamma(B^0\to D_{CP}K^{*0})}{\Gamma(\bar{B}^0\to D_{CP}\bar{K}^{*0})+\Gamma(B^0\to D_{CP}K^{*0})}$$

$$A_{CP}=\frac{2\kappa r_B^{DK^{*0}}\sin\left(\delta_B^{DK^{*0}}\right)\sin(\gamma)}{1+r_B^2\pm 2r_B\cos(\delta_B)\cos(\gamma)}$$

R_{CP}

$KK/\pi\pi$

ADS

[PRL 78 1997 3257]

$$A_{CP}=\frac{\Gamma\left(\bar{B}^0\to D^0_{K^+\pi^-}\bar{K}^{*0}\right)-\Gamma\left(B^0\to D^0_{K^-\pi^+}K^{*0}\right)}{\Gamma\left(\bar{B}^0\to D^0_{K^+\pi^-}\bar{K}^{*0}\right)+\Gamma\left(B^0\to D^0_{K^-\pi^+}K^{*0}\right)}$$

$$A_{CP}=\frac{2\kappa r_B^{DK^{*0}} r_D^{K^{*0}}\sin\left(\delta_B^{K^{*0}}+\delta_D^{K\pi}\right)\sin(\gamma)}{(r_B^{DK^{*0}})^2+(r_D^{K\pi})^2+2\kappa r_B^{DK^{*0}} r_D^{K^{*0}}\cos\left(\delta_B^{DK^{*0}}+\delta_D^{K\pi}\right)\cos(\gamma)}$$

$\propto R_{CP}$

BPGGSZ

[PRD 68 054018]

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

$$x_{\pm}=r_B\cos(\delta_B\pm\gamma)$$

$$y_{\pm}=r_B\sin(\delta_B\pm\gamma)$$

Time-Dependent

$$\frac{d\Gamma(x,t)}{e^{-\Gamma_s t}dtd\phi_4}$$

$$\propto\left(\left|A_f^c(x)\right|^2+r^2\left|A_f^u(x)\right|^2\right)\cosh\left(\frac{\Delta\Gamma_s t}{2}\right)$$

$$-2Re\left(A_f^c(x)^*r^2A_f^u(x)e^{i\delta-if(\gamma-2\beta_s)}\right)\sinh\left(\frac{\Delta\Gamma_s t}{2}\right)+\ \ldots$$

Analysis of $B_s^0 \to D_s^- h^+ \pi^+ \pi^-$

[JHEP 03 (2021) 137]

Measurement of the angle γ in $B_s^0 \to D_s^- h^+ \pi^+ \pi^-$ decay:

(Full Run 1 & 2: 9 fb^{-1} data sample)

A time-dependent amplitude analysis:

the time-dependent amplitude fit using signal PDF through full-spectrum decay rate.

$$\langle f|B_s^0\rangle = A^c(x) \quad \langle f|\overline{B_s^0}\rangle = re^{i(\delta-\gamma)}A^u(x)$$

$$A^u(x) = \sum_i a_i^u A_i(x)$$

$$A^c(x) = \sum_i a_i^c A_i(x)$$

A model-independent analysis:

(phase-space integrated decay rate)

Measurement of the CP coefficients:

$$C_f, A_f^{\Delta\Gamma}, A_{\bar{f}}^{\Delta\Gamma}, S_f, S_{\bar{f}}$$

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

$$\frac{d\Gamma(x,t)}{e^{-\Gamma_s t}dtd\phi_4} \propto \left(\left|A_f^c(x)\right|^2 + r^2\left|A_f^u(x)\right|^2\right)\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + qf\overbrace{\left(\left|A_f^c(x)\right|^2 r^2\left|A_f^u(x)\right|^2\right)}^{C_f}\cos(\Delta m_s t)$$
$$\underbrace{-\,2Re\left(A_f^c(x)^* r\, A_f^u(x)e^{i\delta-if(\gamma-2\beta_s)}\right)}_{D_f}\sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - 2qf\underbrace{Im\left(A_f^c(x)^* r\, A_f^u(x)e^{i\delta-if(\gamma-2\beta_s)}\right)}_{S_f}\sin(\Delta m_s t)$$