Measurements of CKM angle γ at LHCb

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The CKM matrix and CP violation

- CP violation (CPV) of quarks in SM originates from the weak phase in Cabibbo-Kobayashi-Maskawa (CKM) matrix

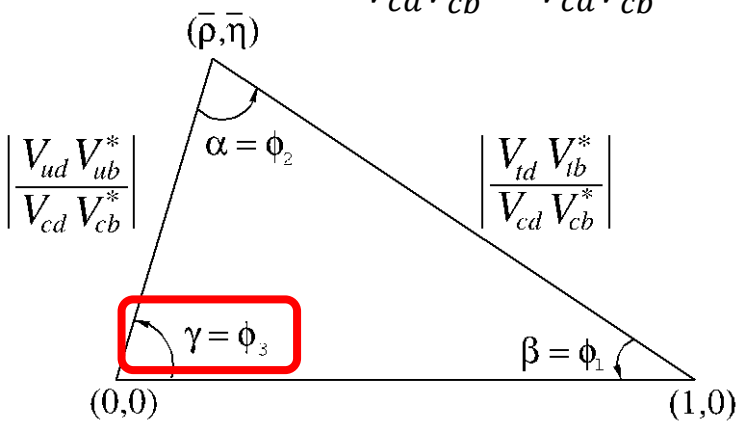
[Phys.Rev.Lett. 10 (1963) 531]
[Prog.Theor.Phys. 49 (1973) 652]

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = V_{\mathrm{CKM}} \begin{bmatrix} d \\ s \\ b \end{bmatrix} = \begin{bmatrix} |V_{ud}| & |V_{us}| & \boxed{|V_{ub}|e^{-i\gamma}} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

- Unitarity of CKM matrix $\Longrightarrow$ the unitarity triangle (UT)

$$1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} + \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} = 0$$

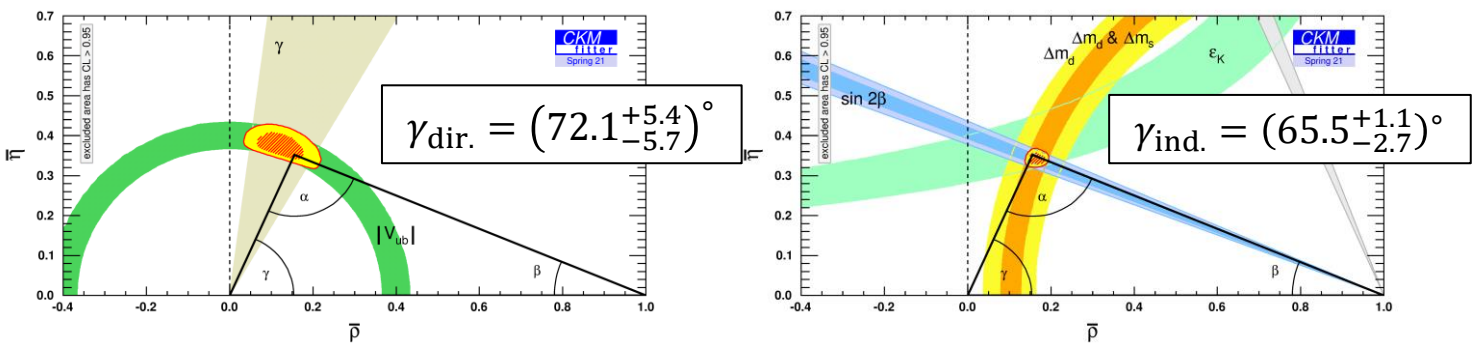
- Area of UT indicates the magnitude of CPV in SM
- CPV in SM not sufficient
  - probe BSM physics indirectly by overconstraining CKM parameters



The CKM angle γ

$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

- γ is the only angle accessible in tree-level
- SM benchmark value – effectively no theory uncertainty [JHEP 01 (2014) 051]
- Search for BSM: direct vs. indirect measurement
  - direct: measure γ from tree-level decays
  - indirect: assume UT is closed and infer γ from other processes



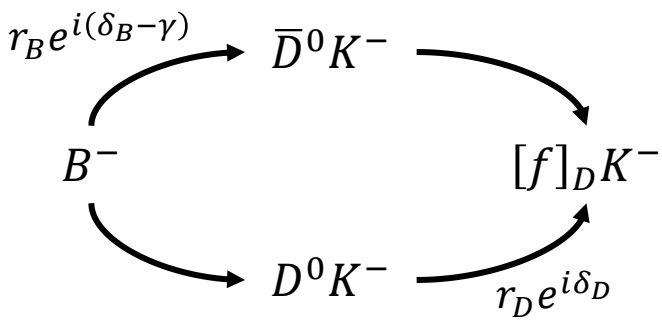
CKMfitter, Preliminary results as of spring 2021

- a sub-degree precision is needed

Approaches to probe γ

- γ can be accessed via interference between $b \to cW$ and $b \to uW$ transitions
- Textbook case: $B^{\pm} \to [f]_D K^{\pm}$

$$\Gamma \propto r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D - \gamma)$$
$$\overset{CP}{\Leftrightarrow} \bar{\Gamma} \propto r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D + \gamma)$$



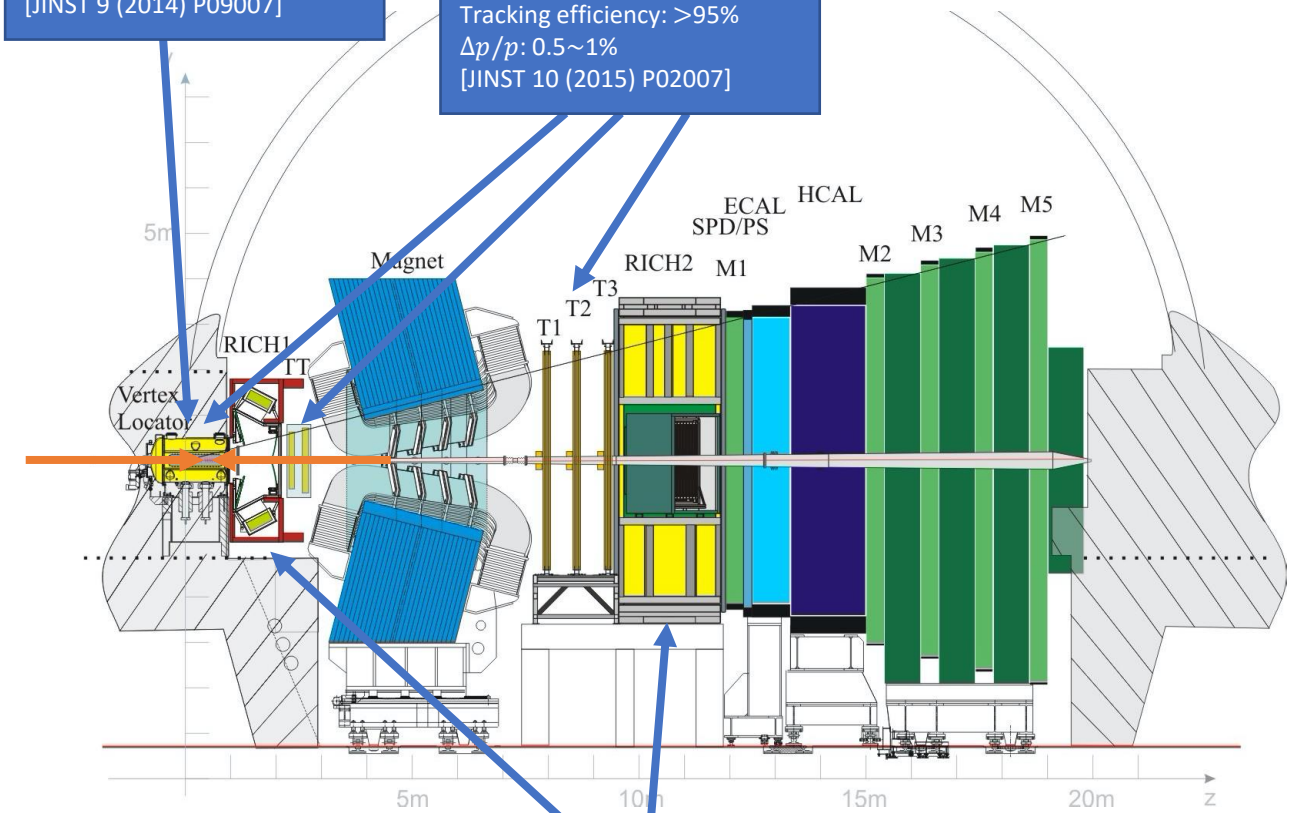
  - GLW method: $f = K^+K^-, \pi^+\pi^-$, etc. [Phys.Lett.B 253 (1991) 483], [Phys.Lett.B 265 (1991) 172]
  - ADS method: $f = K^{\mp}\pi^{\pm}(\pi^{\pm}\pi^{\mp})$, etc. [Phys.Rev.Lett. 78 (1997) 3257], [Phys.Rev.D 63 (2001) 036005]
  - BPGGSZ method: $f = K_S^0\pi\pi, K_S^0 KK$, etc. [Phys.Rev.D 68 (2003) 054018]
- Time-dependent (TD) method: $B_s^0 \to D_s^{\mp} K^{\pm}$, etc.

The LHCb detector [JINST 3 (2008) S08005]

$2 < \eta < 5$

Decay time resolution: ~50 fs
IP resolution: ~35 μm
[JINST 9 (2014) P09007]

Tracking efficiency: >95%
$\Delta p/p$: 0.5~1%
[JINST 10 (2015) P02007]

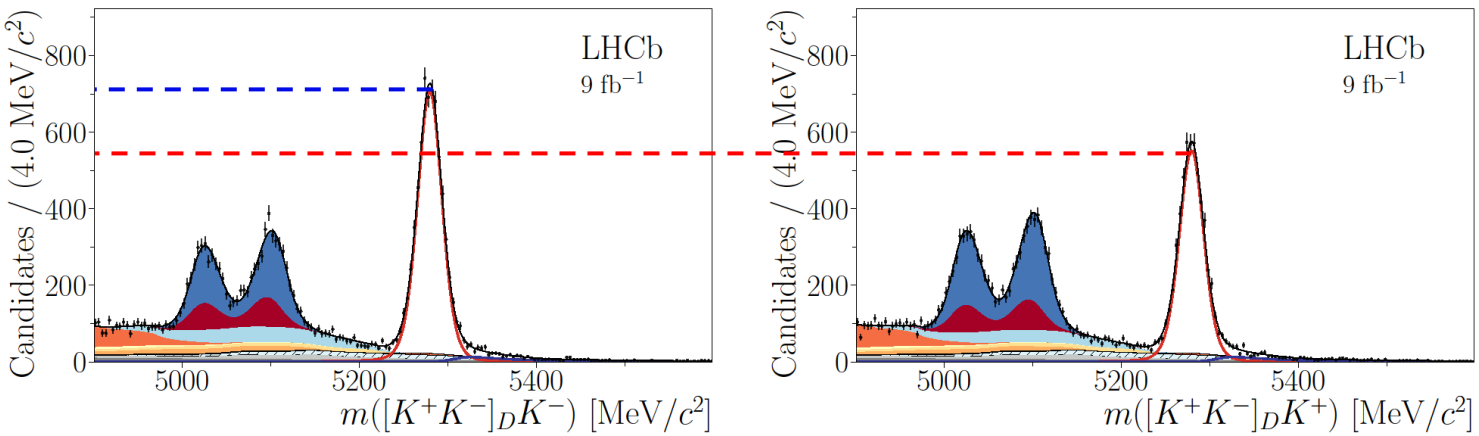


Hadron identification:
$\epsilon(K \to K) \sim 95\%$ with $\epsilon(\pi \to K) \sim 10\%$
[Phys. J. C73 (2013) 2431]

GLW/ADS analysis of $B^{\pm} \to [h^+h^-]_D h^{\pm}$ [JHEP 04 (2021) 081]

- GLW mode: $B^{\pm} \to [\pi^+\pi^-]_D h^{\pm}$, $B^{\pm} \to [K^+K^-]_D h^{\pm}$
- Asymmetry

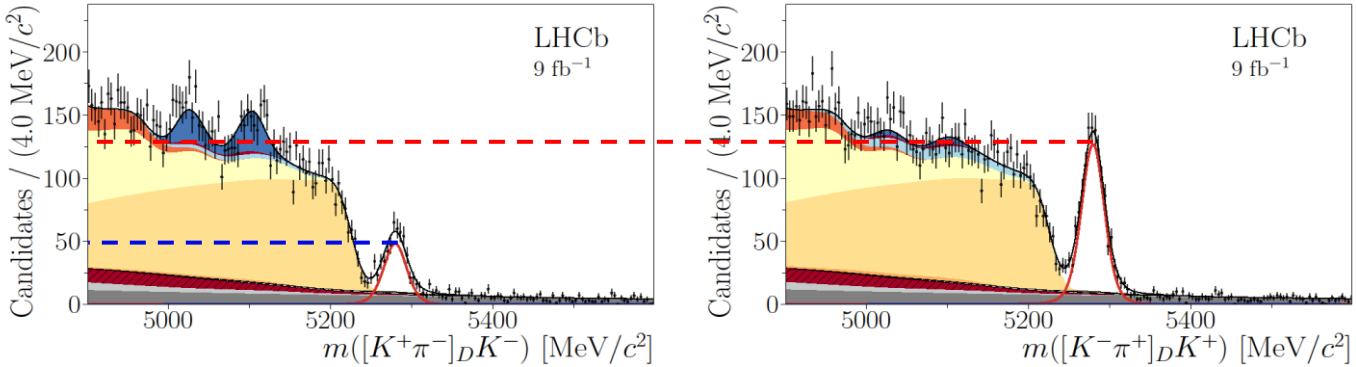
$$A_h^{CP} = \frac{\Gamma\left(B^- \to D_{CP}^{(*)} h^-\right) - \Gamma\left(B^+ \to D_{CP}^{(*)} h^+\right)}{\Gamma\left(B^- \to D_{CP}^{(*)} h^-\right) + \Gamma\left(B^+ \to D_{CP}^{(*)} h^+\right)}$$



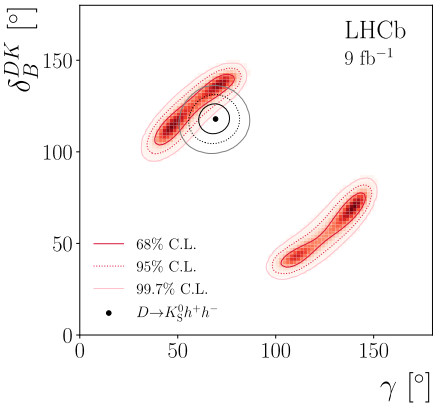
$$A_K^{CP} = 0.136 \pm 0.009 \pm 0.001$$
$$A_K^{CP,\gamma} = 0.123 \pm 0.054 \pm 0.031$$
$$A_K^{CP,\pi^0} = -0.115 \pm 0.019 \pm 0.009$$

GLW/ADS analysis of $B^{\pm} \to [h^+h^-]_D h^{\pm}$ [JHEP 04 (2021) 081]

- ADS mode: $B^{\pm} \to \left[K^{\mp}\pi^{\pm}\right]_D h^{\pm}$, larger interference between
  - favored B decay + DCS D decay ($r_D^{K\pi} \sim 0.06$)
  - suppressed B decay ($r_B^{DK} \sim 0.1$) + CF D decay



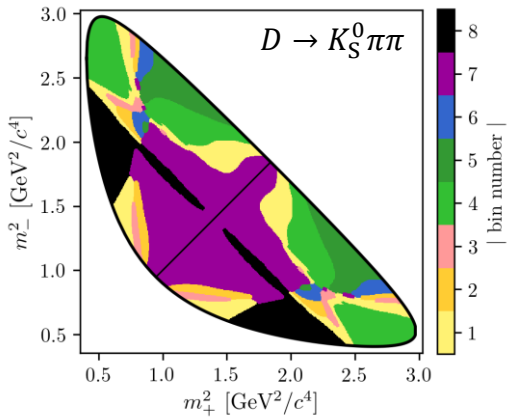
$$A_K^{\pi K} = -0.451 \pm 0.026$$
$$A_K^{\pi K,\gamma} = -0.558 \pm 1.349$$
$$A_K^{\pi K,\pi^0} = 0.717 \pm 0.286$$

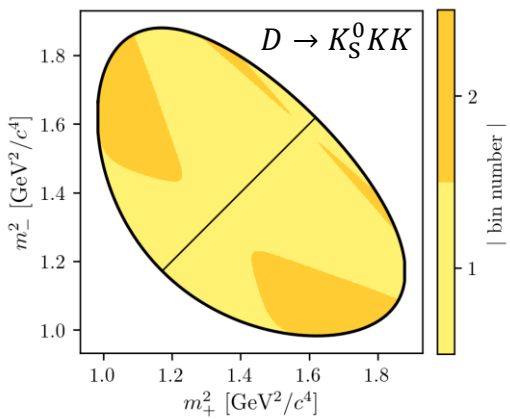


BPGGSZ analysis of $B^{\pm} \to \left[K_S^0 h^+ h^-\right]_D h^{\pm}$

[JHEP 02 (2021) 169]

- D decays to self-conjugated state $K_S^0 h^+ h^-$
  - each point on the 3-body phase space contribute different r_D, δ_D – different sensitivity to γ on the Dalitz plot
- In practice, the Dalitz plots are split into different bins
  - binning schemes are optimized for maximum statistical sensitivity



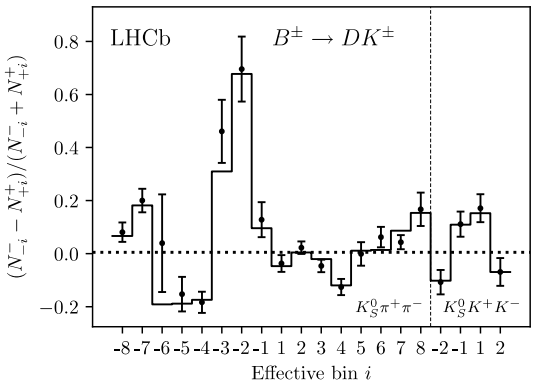


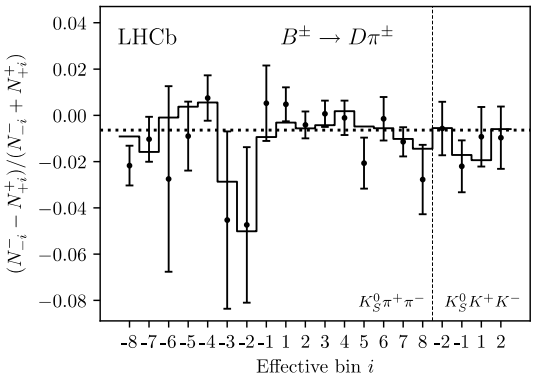
  - charm parameters in each bin are measured by BESIII & CLEO experiment – independent of $K_S^0 hh$ amplitude model

[Phys.Rev.D 82 (2010) 112006]
[Phys.Rev.D 101 (2020) 11, 112002]
[Phys.Rev.D 102 (2020) 5, 052008]

BPGGSZ analysis of $B^{\pm} \to \left[K_S^0 h^+ h^-\right]_D h^{\pm}$

[JHEP 02 (2021) 169]

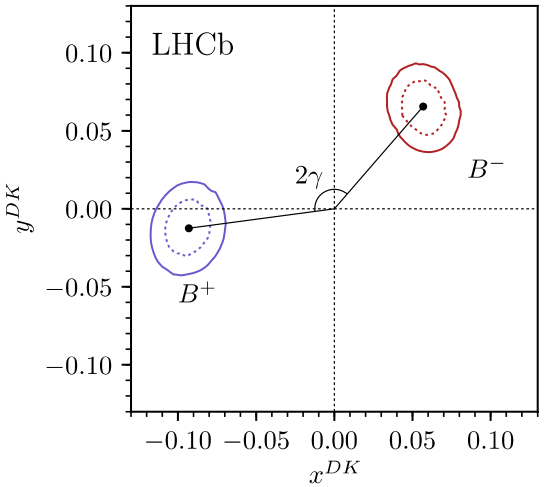




- CP violation is clearly observed in $B^{\pm} \to DK^{\pm}$
- Data insufficient to see CPV in $B^{\pm} \to D\pi^{\pm}$

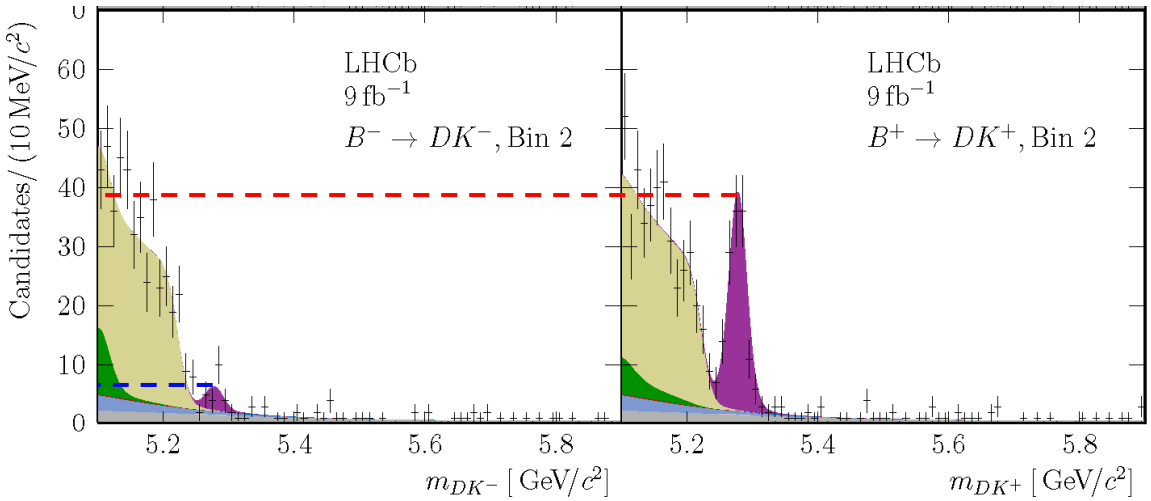
$$\boxed{\gamma = \left(68.7^{+5.2}_{-5.1}\right)^{\circ}}$$

- So far the most precise single measurement on γ
- $B^{\pm} \to D\pi^{\pm}$ parameters also measured



γ from $B^{\pm} \to \left[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}\right]_D h^{\pm}$ [arXiv:2209.03692]

- ADS decay of D meson, but also has phase space dependent sensitivity to γ – measured in a binned approach
  - binning phase space on D decay strong phase $\delta_D^{K3\pi}$
  - D decay parameters measured by BESIII experiment [JHEP 05 (2021) 164]



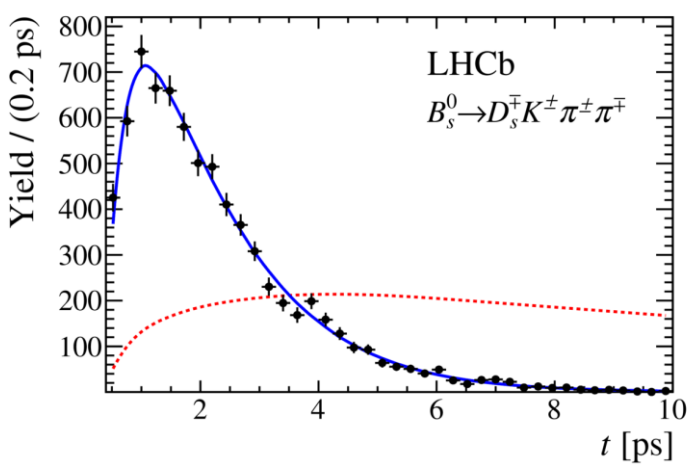
- Large bin-dependent CPV – up to 85% asymmetry

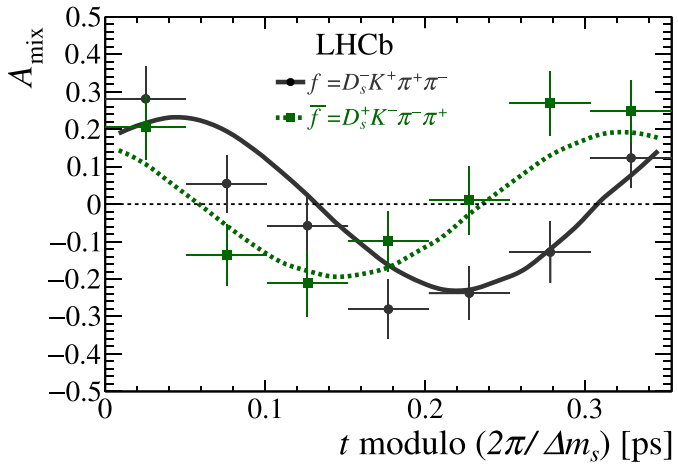
$$\boxed{\gamma = \left(54.8^{+6.0\ +0.6\ +6.7}_{-5.8\ -0.6\ -4.3}\right)^{\circ}}$$

- Stat. uncertainty compatible with $B^{\pm} \to DK^{\pm}$ BPGGSZ analysis

TD analysis of $B_s^0 \to D_s^{\mp} h^{\pm} \pi^+ \pi^-$ [JHEP 03 (2021) 137]

- Two processes at same order in terms of CKM matrix elements
- Time-dependent decay rates provide info on CPV during $B_s^0 - \bar{B}_s^0$ mixing and decay

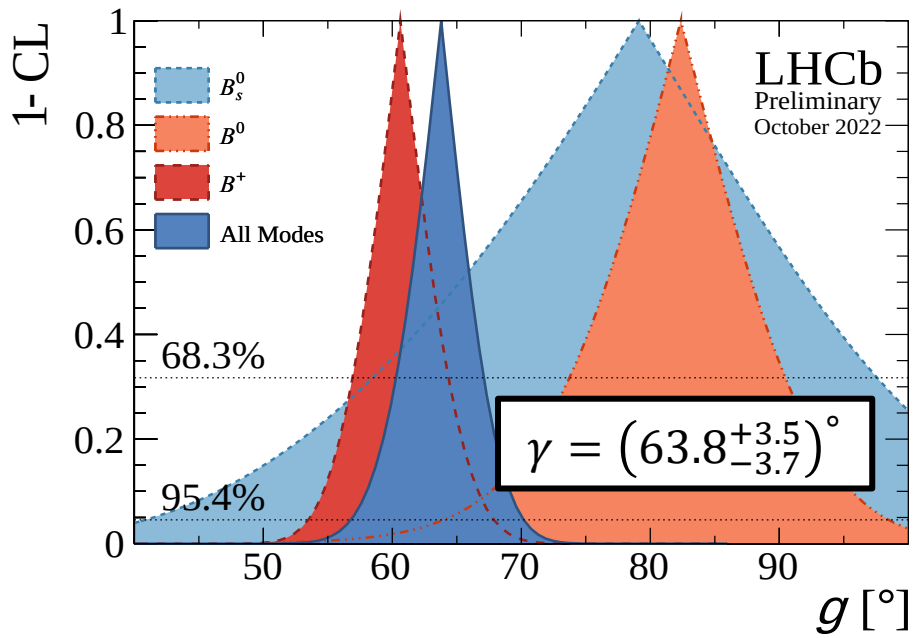




$$\gamma = (44 \pm 12)^\circ$$

- An important contribution to γ from B_s^0 decays

γ combination [LHCb-CONF-2022-003]



- Most precise direct measurement on γ from a single experiment
  - reached $< 4°$, got closer to indirect determination $\gamma_{\text{ind.}} = (65.5^{+1.1}_{-2.7})°$
- γ was improved by $\sim 10\%$ compared to previous combination [JHEP 12 (2021) 141]
  - biggest improvement comes from $B^\pm \to [K^\mp\pi^\pm\pi^\pm\pi^\mp]_D h^\pm$ result
- $\sim 2\sigma$ tension between different B categories

Summary & prospects

- 10 years of measurements from LHCb has significantly improved our knowledge to γ
- γ is no longer the least well-determined weak phase
- LHCb already achieved a precision of $< 4^\circ$, with many analyses to be added. Possible to reach 3° in Run1&2?
- Aiming for $< 1^\circ$ in Upgrade I era
  - $\sim 1.5^\circ$ after Run3 ($23\ \mathrm{fb}^{-1}$, 2025)
  - $\sim 1^\circ$ after Run4 ($50\ \mathrm{fb}^{-1}$, 2030)
  - sub-degree precision may come sooner than we expect!

Stay Tuned

Backup

GLW/ADS analysis of $B^{\pm} \to [h^+h^-]_D h^{\pm}$ [JHEP 04 (2021) 081]

- Asymmetry

$$A_h^f = \frac{\Gamma\left(B^- \to D_f^{(*)} h^-\right) - \Gamma\left(B^+ \to D_f^{(*)} h^+\right)}{\Gamma\left(B^- \to D_f^{(*)} h^-\right) + \Gamma\left(B^+ \to D_f^{(*)} h^+\right)}$$

- GLW mode

$$A_K^{CP\pm} = \frac{\pm 2 r_B^{DK} \sin\delta_B^{DK} \sin\gamma}{1 + (r_B^{DK})^2 + 2 r_B^{DK} \cos\delta_B^{DK} \cos\gamma}$$

- ADS mode

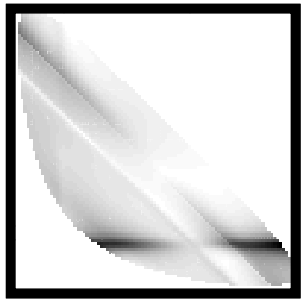
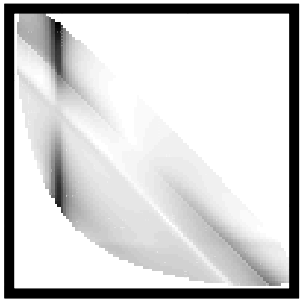
$$A_K^{\pi K} = \frac{2 r_B^{DK} r_D^{K\pi} \sin(\delta_B^{DK} + \delta_D^{K\pi}) \sin\gamma}{(r_B^{DK})^2 + (r_D^{K\pi})^2 + 2 r_B^{DK} r_D^{K\pi} \cos(\delta_B^{DK} + \delta_D^{K\pi}) \cos\gamma}$$

BPGGSZ analysis of $B^{\pm} \to \left[K_S^0 h^+ h^-\right]_D h^{\pm}$

[JHEP 02 (2021) 169]

- Amplitude of $B^- \to \left[K_S^0 \pi^+ \pi^-\right]_D K^-$

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

$=$  $+ r_B^{DK} e^{i(\delta_B^{DK} - \gamma)}$ 

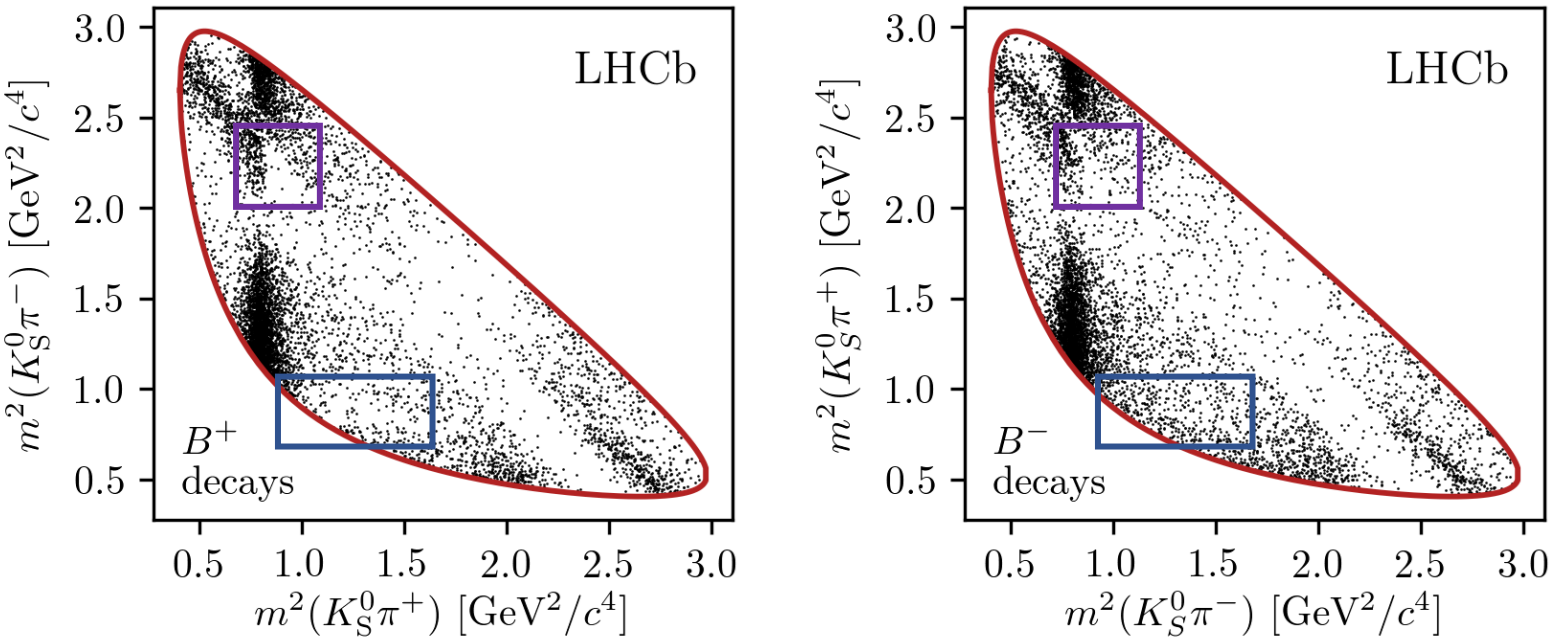
- Binned equation

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

  - $N_i^{\pm}$: number of $B^{\pm}$ signal in bin i
  - F_i: fraction of D^0 events in bin i
  - c_i, s_i: strong phase parameters, measured by CLEO and BESIII
  - $x_{\pm}, y_{\pm}$: CP observables, $x_{\pm} + i y_{\pm} = r_B^{DK} e^{i(\delta_B^{DK} \pm \gamma)}$

BPGGSZ analysis of $B^{\pm} \to \left[K_S^0 h^+ h^-\right]_D h^{\pm}$

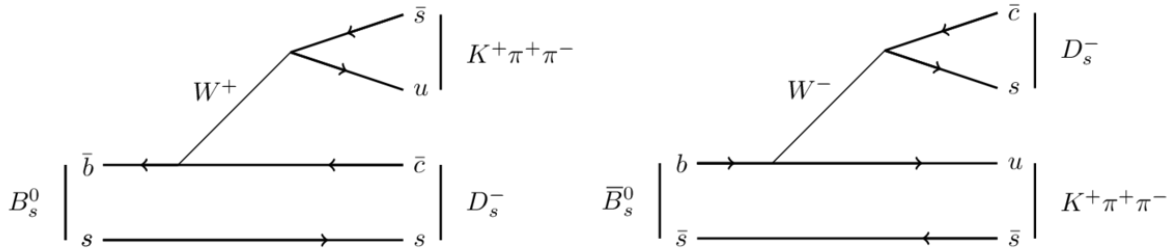
[JHEP 02 (2021) 169]



- Visible CP asymmetry in $B^{\pm} \to DK^{\pm}$

TD analysis of $B_s^0 \to D_s^{\mp} h^{\pm} \pi^+ \pi^-$ [JHEP 03 (2021) 137]

- Two processes at same order in terms of CKM matrix elements $|V_{cb}||V_{us}|$ vs. $|V_{ub}||V_{cs}|$



- Time-dependent decay rate, phase space integrated

$$\frac{\mathrm{d}\Gamma(B_s^0 \to f)}{\mathrm{d}t} \propto \left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + C_f \cos(\Delta m_s t) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_s t}{2}\right) - S_f \sin(\Delta m_s t)\right] e^{-\Gamma_s t},$$

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

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

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

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

γ combination [LHCb-CONF-2022-003]

B decay	D decay	Ref.	Dataset	Status since Ref. [14]
$B^\pm \to Dh^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to h^+\pi^-\pi^+\pi^-$	[30]	Run 1	As before
$B^\pm \to Dh^\pm$	$D \to K^\pm\pi^\mp\pi^+\pi^-$	[18]	Run 1&2	**New**
$B^\pm \to Dh^\pm$	$D \to h^+h^-\pi^0$	[19]	Run 1&2	**Updated**
$B^\pm \to Dh^\pm$	$D \to K^0_S h^+h^-$	[31]	Run 1&2	As before
$B^\pm \to Dh^\pm$	$D \to K^0_S K^\pm\pi^\mp$	[32]	Run 1&2	As before
$B^\pm \to D^*h^\pm$	$D \to h^+h^-$	[29]	Run 1&2	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+h^-$	[33]	Run 1&2(*)	As before
$B^\pm \to DK^{*\pm}$	$D \to h^+\pi^-\pi^+\pi^-$	[33]	Run 1&2(*)	As before
$B^\pm \to Dh^\pm\pi^+\pi^-$	$D \to h^+h^-$	[34]	Run 1	As before
$B^0 \to DK^{*0}$	$D \to h^+h^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to h^+\pi^-\pi^+\pi^-$	[35]	Run 1&2(*)	As before
$B^0 \to DK^{*0}$	$D \to K^0_S\pi^+\pi^-$	[36]	Run 1	As before
$B^0 \to D^\mp\pi^\pm$	$D^+ \to K^-\pi^+\pi^+$	[37]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	[38]	Run 1	As before
$B^0_s \to D^\mp_s K^\pm\pi^+\pi^-$	$D^+_s \to h^+h^-\pi^+$	[39]	Run 1&2	As before

- Lots of analyses to be updated with full LHCb Run1&2 data set