LHCb γ measurements with $B \to D^{(*)}K^{(*)}$

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on behalf of

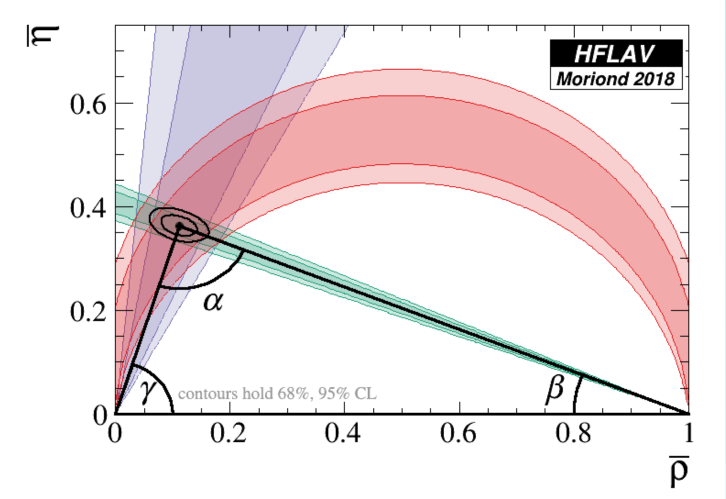
the LHCb collaboration

Implications of LHCb measurements and future prospects – October 2018

The Leverhulme Trust

CKM angle γ

- For many years, least well measured Unitarity Triangle angle; now entering precision measurement era
- Can measure at tree level with $B \rightarrow DX$ decays

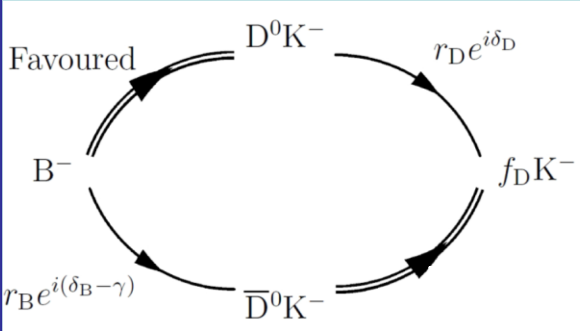


- Exploit weak phase difference γ between $b \rightarrow u$ and $b \rightarrow c$ transitions
- Theoretically clean but room for NP

JHEP 01 (2014) 051 PRD 92 033002 (2015)

- At LHCb, perform
  - **time-integrated measurements**

$B^- \to D^{(*)}K^{(*)-}$, $B^0 \to DK^{*0}$, $B^0 \to DK^+\pi^-$, $B^- \to DK^-\pi^+\pi^-$ PLB 557 198 (2003)



- GLW analysis ($D \to CP$ eigenstate)
  PLB 253 483 (1991) PLB 265 172 (1991)
- ADS analysis ($D \to$ flavour specific)
  PRL 78 3257 (1997) PRD 63 036005 (2001)
- GGSZ analysis ($D \to$ multibody)
  PRD 68 054018 (2003) PRD 70 072003 (2004)
- Dalitz analysis ($B \to$ multibody)
  PRD 79 051301(R) (2009) PRD 80 092002 (2009)

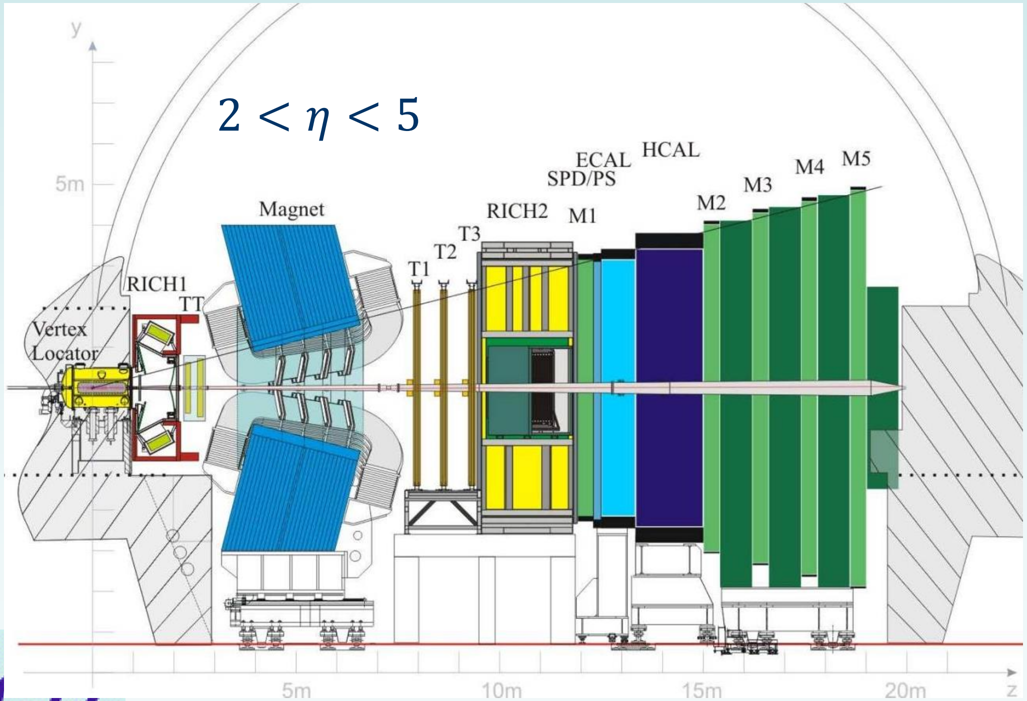
  - **time-dependent measurements** – *see Simon Stemmle's talk*

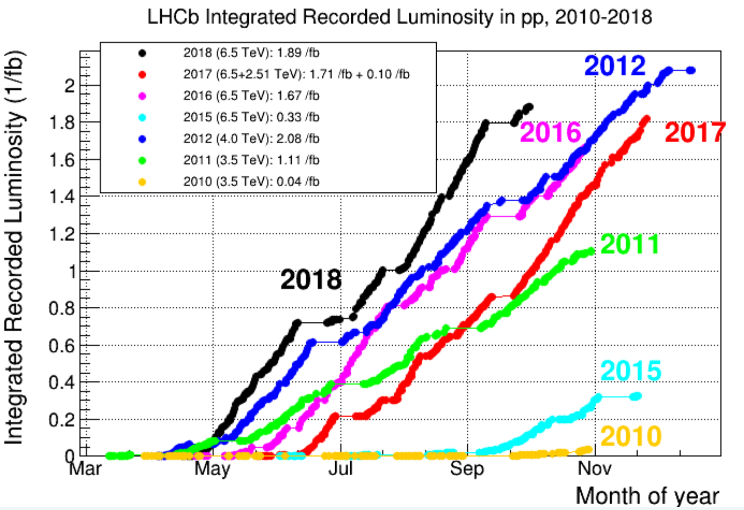
$B_s^0 \to D_s^\mp K^\pm$, $B^0 \to D^\mp\pi^\pm$ PRD 37 3186 (1988) ZPC 54 653 (1992) NPB 671 459 (2003)

  - **combination of LHCb γ measurements**

The LHCb experiment

- Designed for study of particles containing b or c
  - High precision tracking and vertexing
    - Momentum resolution $(0.5 - 1.0)\%$
    - Impact parameter resolution $(15 + 29 / p_T)\ \mu$m
  - RICH detectors for hadron PID ($K - \pi$ separation)



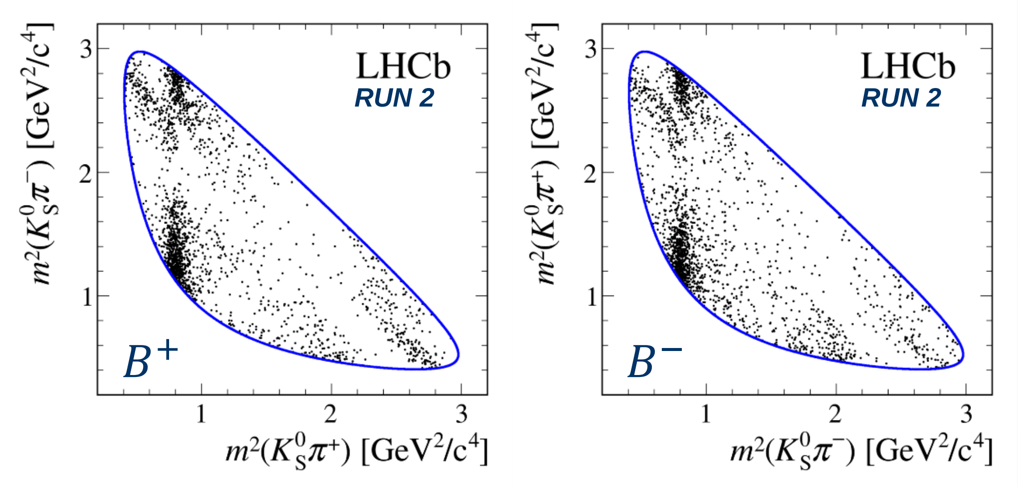


GGSZ analysis of $B^- \to DK^-, D \to K_S^0 h^+ h^-$

- Determine γ using D decay to three-body self-conjugate $K_S^0\pi^+\pi^-$ or $K_S^0K^+K^-$ final state
- One solution for γ in [0, π]
- Requires knowledge of resonant structure of $D \to K_S^0 h^+ h^-$ decay across phase space

$$A_{B^+} \propto \bar{A}_f + r_B e^{i(\delta_B+\gamma)} A_f$$

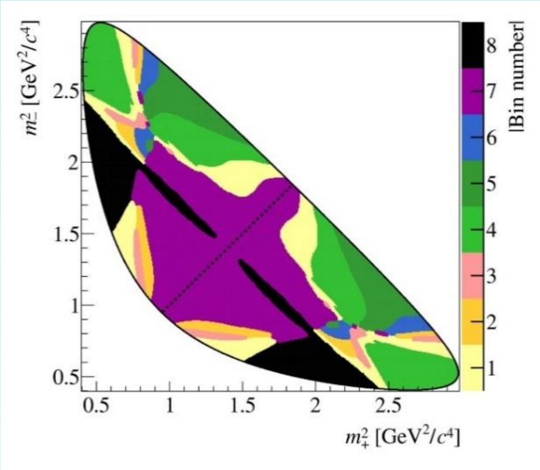
$$A_{B^-} \propto A_f + r_B e^{i(\delta_B-\gamma)} \bar{A}_f$$

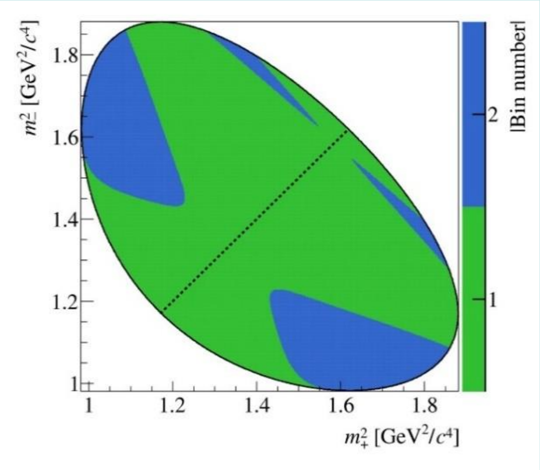


- Observables: $x_\pm = r_B \cos(\delta_B \pm \gamma)$, $y_\pm = r_B \sin(\delta_B \pm \gamma)$

- Model-independent method: bin D decay phase space according to $D^0 - \bar{D}^0$ strong phase difference

$2N$ bins ($i \in [-N, N]$, $i \neq 0$)
$i > 0$ for $m_-^2 > m_+^2$





- Yield in bin i

$$N_{\pm i}^{+} = h_{B^+}\left[F_{\mp i} + \left(x_+^2 + y_+^2\right)F_{\pm i} + 2\sqrt{F_i F_{-i}}\left(x_+ c_{\pm i} - y_+ s_{\pm i}\right)\right]$$

$$N_{\pm i}^{-} = h_{B^-}\left[F_{\pm i} + \left(x_-^2 + y_-^2\right)F_{\mp i} + 2\sqrt{F_i F_{-i}}\left(x_- c_{\pm i} + y_- s_{\pm i}\right)\right]$$

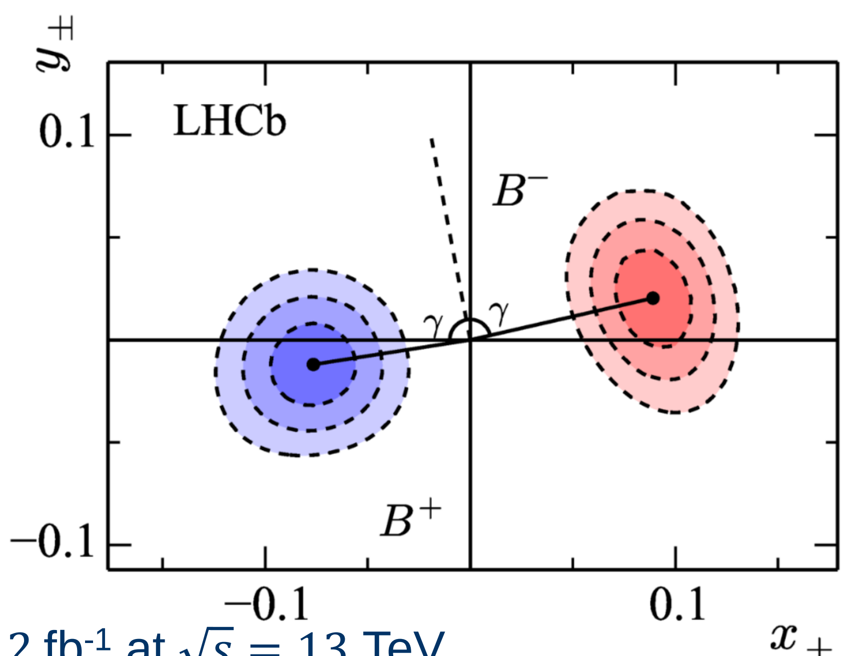
- (c_i, s_i) strong phase difference measurements from CLEO-c

PRD 82 112006 (2010)

- Results with Run 2 data (2 fb^{-1} at $\sqrt{s} = 13$ TeV):

$$x_- = (9.0 \pm 1.7 \pm 0.7 \pm 0.4) \times 10^{-2}$$
$$y_- = (2.1 \pm 2.2 \pm 0.5 \pm 1.1) \times 10^{-2}$$
$$x_+ = (-7.7 \pm 1.9 \pm 0.7 \pm 0.4) \times 10^{-2}$$
$$y_+ = (-1.0 \pm 1.9 \pm 0.4 \pm 0.9) \times 10^{-2}$$

First observation of CP violation in $B^- \to DK^-$, $D \to K_S^0 h^+ h^-$



2 fb^{-1} at $\sqrt{s} = 13$ TeV

Statistical uncertainties only

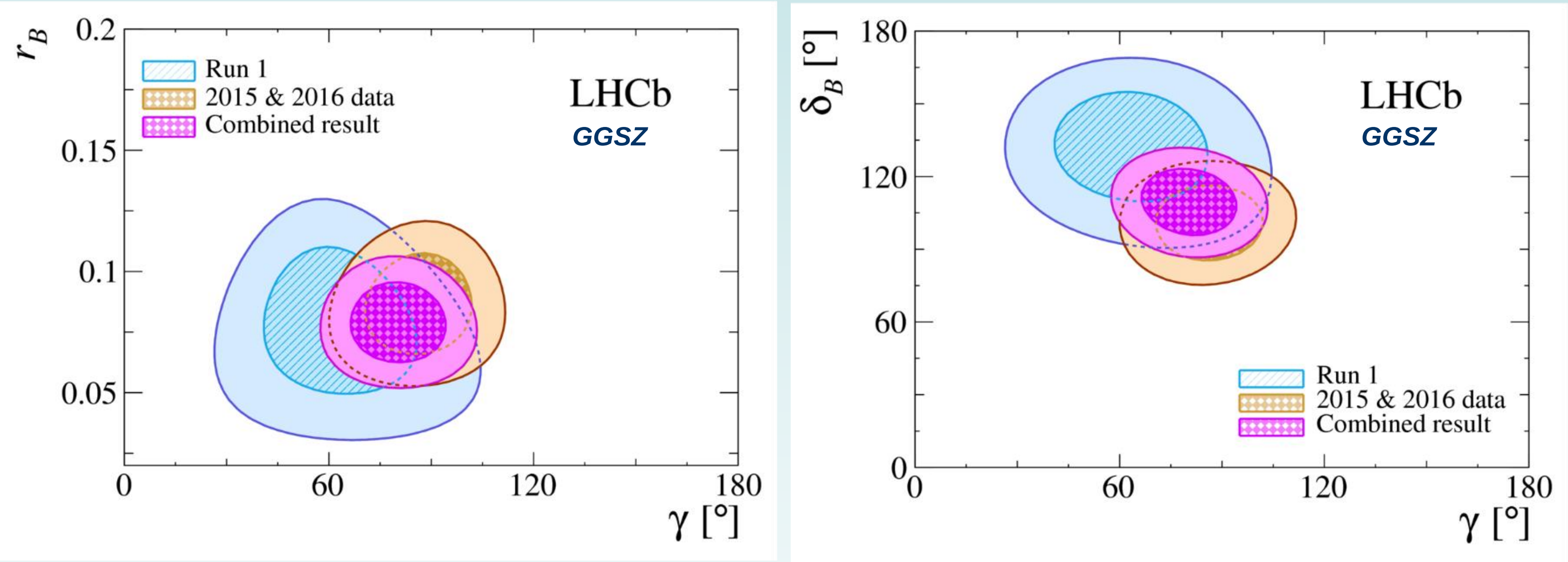
JHEP 08 (2018) 176

- Combine with Run 1 results (3 fb^{-1} at $\sqrt{s} = 7,8$ TeV) to give constraint on γ:

JHEP 10 (2014) 097

$$\gamma = \left(80^{+10}_{-9}\right)^{\circ}$$

GGSZ



Run 1: $\gamma = \left(62^{+15}_{-14}\right)^{\circ}$
2015 & 2016: $\gamma = \left(87^{+11}_{-12}\right)^{\circ}$

LHCb-CONF-2018-002

Combination of LHCb measurements

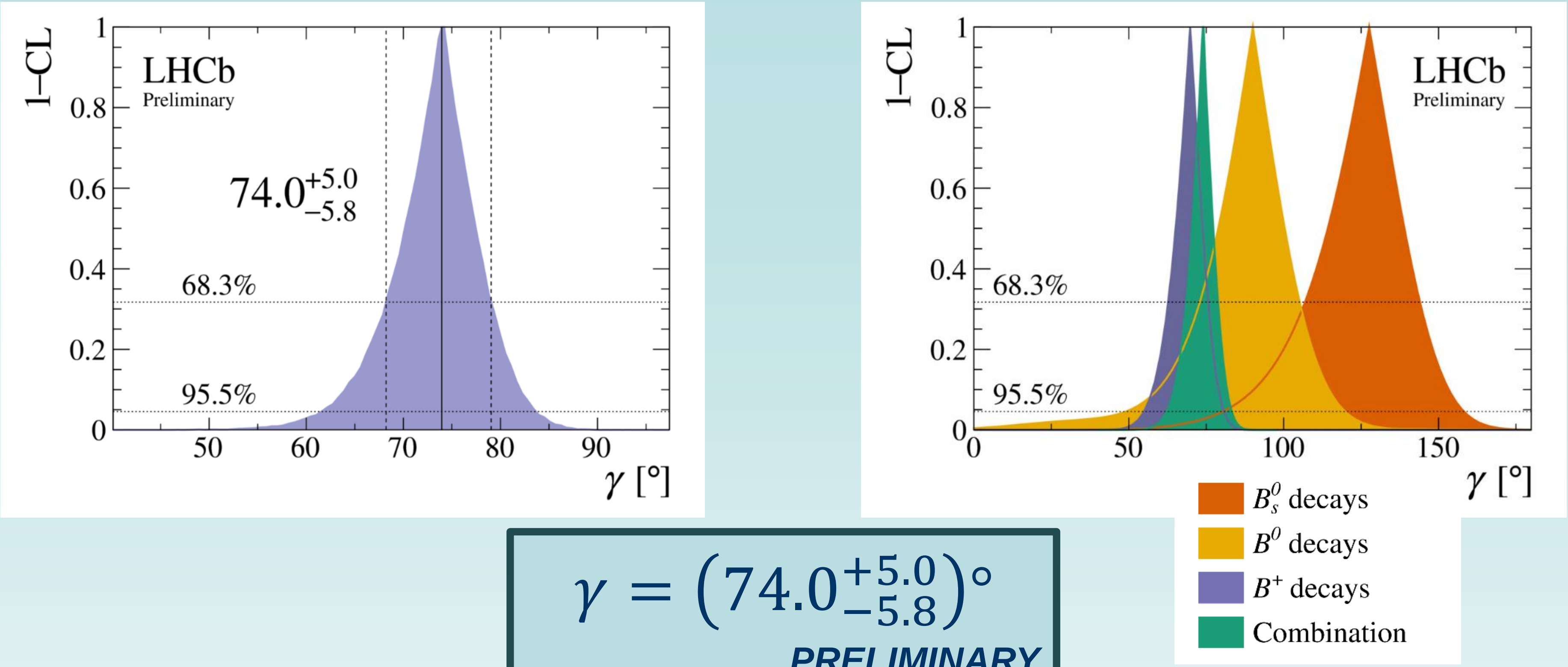
- Combine tree-level LHCb γ measurements:

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
$B^0_s \to D^\mp_s K^\pm$	$D^+_s \to h^+h^-\pi^+$	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 $3\,\text{fb}^{-1}$ taken at centre-of-mass energies of 7 and 8 TeV. Run 2 corresponds to an integrated luminosity of $2\,\text{fb}^{-1}$ taken at a centre-of-mass energy of 13 TeV.

– see Simon Stemmle's talk

- Frequentist approach
- Auxiliary inputs from HFLAV, CLEO and LHCb



$$\gamma = \left(74.0^{+5.0}_{-5.8}\right)^\circ$$

PRELIMINARY

- Most precise determination of γ from a single experiment
- World average: $\gamma = \left(73.5^{+4.2}_{-5.1}\right)^\circ$ HFLAV
- Indirect constraints: $\gamma = \left(65.6^{+1.0}_{-3.4}\right)^\circ$ CKMfitter

Outlook: exploiting existing data

- Run 2 updates
  - $B^- \to DK^-$
    - $D \to h^+h^-$ (ADS), $D \to h^+\pi^-\pi^+\pi^-$, $D \to h^+h^-\pi^0$, $D \to K_S^0 K^+\pi^-$
  - $B^0 \to DK^{*0}$/ $B^0 \to DK^+\pi^-$
    - $D \to h^+h^-$, $D \to K_S^0 h^+h^-$
  - $B^- \to DK^-\pi^+\pi^-$
    - $D \to h^+h^-$
- New possible decay modes
  - $B^- \to DK^-\pi^+\pi^-$, $B^- \to DK^{*-}$
    - $D \to K_S^0 h^+h^-$
  - $B^- \to D^* h^-$
    - $D \to K_S^0 h^+h^-$, $D \to h^+h^-$
  - $D \to K^+K^-\pi^+\pi^-$, $D \to K_S^0\pi^+\pi^-\pi^0$ …

Expect $\sigma(\gamma) = 4°$

EPJ C 73 (2013) 2373

(+ time-dependent analyses)

Outlook: future data

Current LHCb | LHCb Upgrade Ia | LHCb Upgrade Ib | LHCb Upgrade II

3 fb^{-1} | 5 fb^{-1} | 50 fb^{-1} | 300 fb^{-1}

2011-12 *Run 1*

2015-18 *Run 2*

2021-23 *Run 3*

2026-29 *Run 4*

2031- *Run 5*

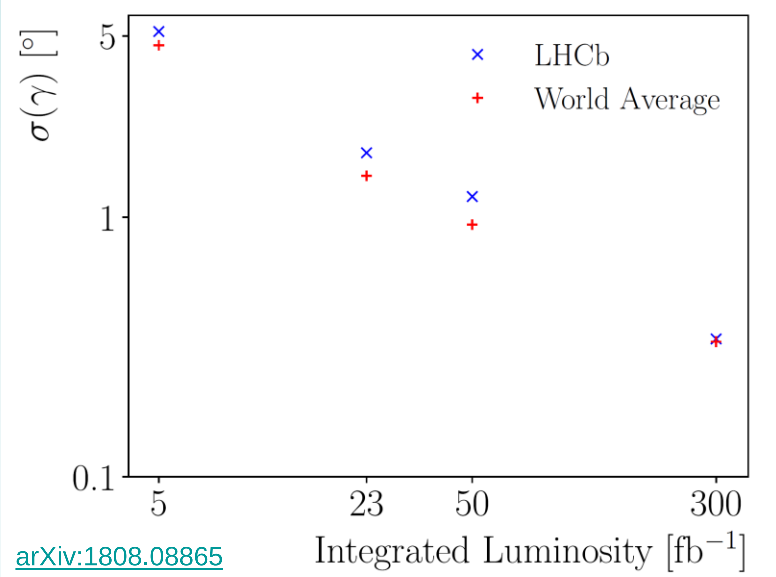
LHC | *HL-LHC*

Outlook: future data

Current LHCb | LHCb Upgrade Ia | LHCb Upgrade Ib | LHCb Upgrade II

Belle II

2011-12	2015-18	2021-23	2026-29	2031-
Run 1	*Run 2*	*Run 3*	*Run 4*	*Run 5*



arXiv:1808.08865

$\sigma(\gamma) = 4°$

EPJ C 73 (2013) 2373

$\sigma(\gamma) = 0.9°$

EPJ C 73 (2013) 2373

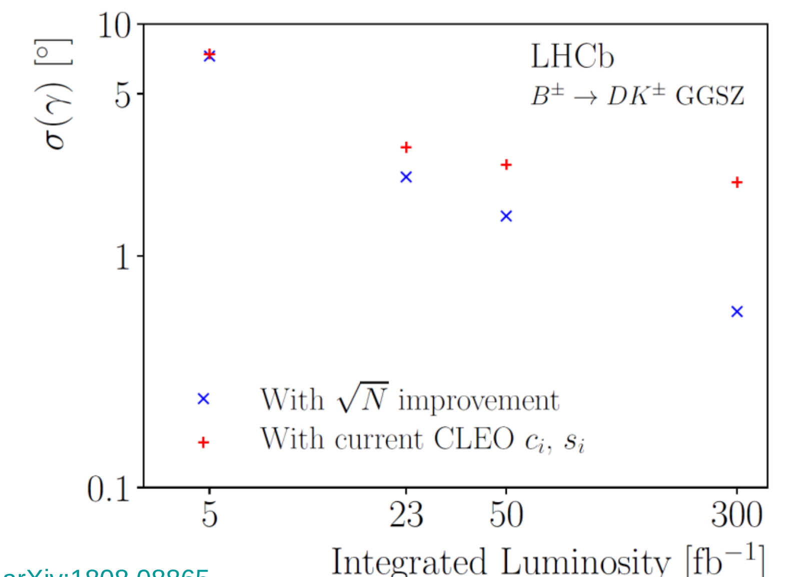
$\sigma(\gamma) = 1.5°$
(Belle II similar)

arXiv:1808.08865
arXiv:1808.10567

$\sigma(\gamma) = 0.35°$

arXiv:1808.08865

- Expect main experimental systematic uncertainties to scale with data/simulation sample sizes
  - Production/instrumentation asymmetries
  - Understanding of backgrounds/control modes and simulation
- For GGSZ, uncertainties from CLEO-c (c_i, s_i) inputs will become limiting in upgrade era ($\sigma(\gamma) \sim 2°$)



arXiv:1808.08865

- Ongoing cooperation between BESIII and LHCb to measure (c_i, s_i) and other charm inputs
  BESIII-LHCb workshop 2018

- Constrain with other decay modes e.g. $B^0 \to DK^+\pi^-$, $D \to K_S^0\pi^+\pi^-$
  PRD 97 056002 (2018)

Outlook: further sensitivity gains

- New possible decay modes?
  - High multiplicity B and D decay modes
  - Modes with neutrals, e.g. $D \to K_S^0 \pi^0$ (Upgrade Ib onwards)
  - γ from B_c or b-baryons
- New strategies?
  - Model-independent unbinned (Fourier analysis) GGSZ approach
    EPJC (2018) 78:121
  - Unified approach – simultaneous GLW/ADS/GGSZ
    arXiv:1804.05597

Conclusions

- Combination of LHCb results, including new GGSZ measurement, gives most precise determination of γ from a single experiment

$$\gamma = \left(74.0^{+5.0}_{-5.8}\right)^\circ$$

PRELIMINARY

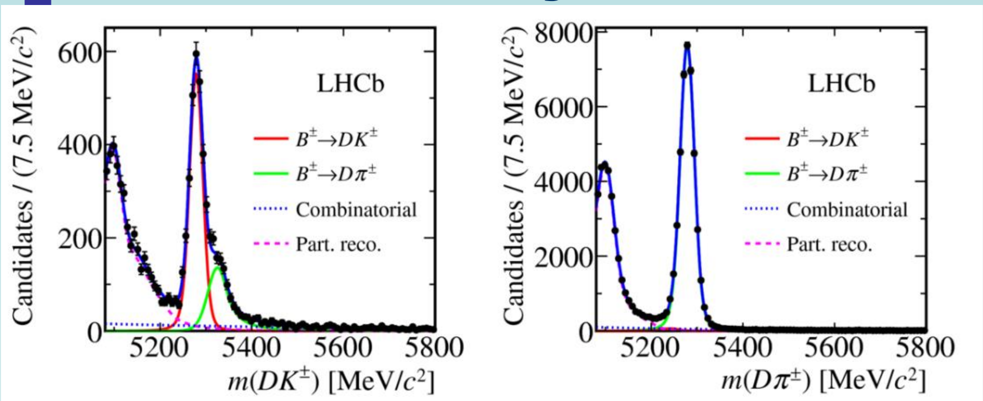
- Coming soon:
  - Further updates including Run 2 data set
  - Studies of new decay modes

Now entering era of precision γ measurement

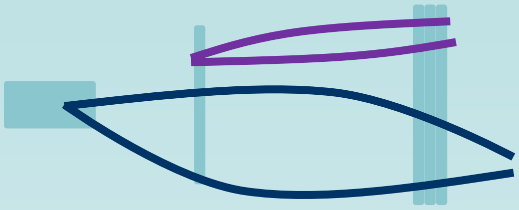
- Expect $\sigma(\gamma) = 1.5°$ in 2025; $\sigma(\gamma) = 0.35°$ with LHCb Upgrade II

JHEP 08 (2018) 176

Backup:
GGSZ analysis of $B^- \to DK^-, D \to K_S^0 h^+ h^-$



K_S^0 without VELO (Si vertex tracker) daughter hits



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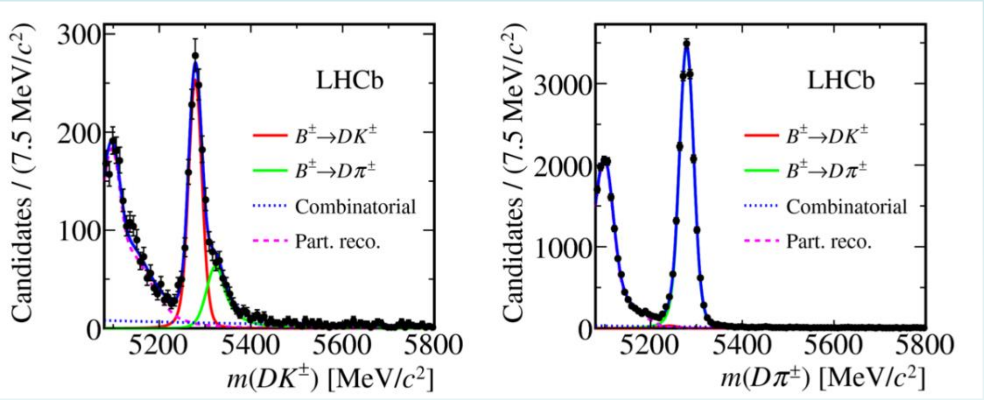
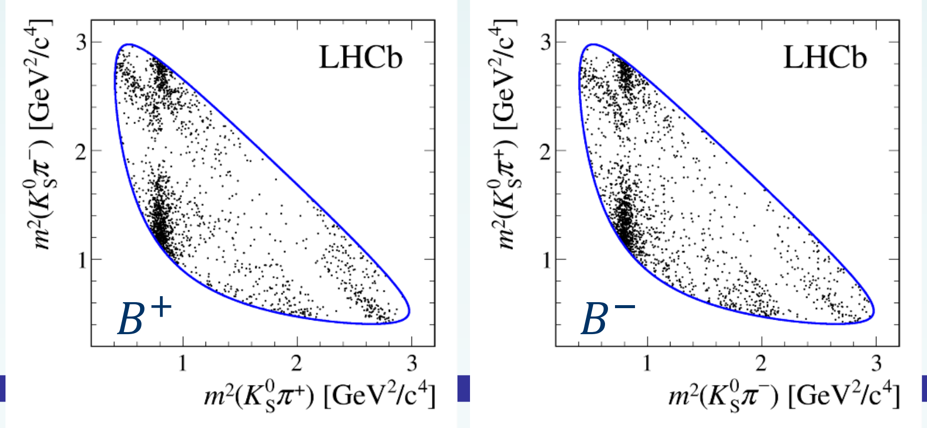
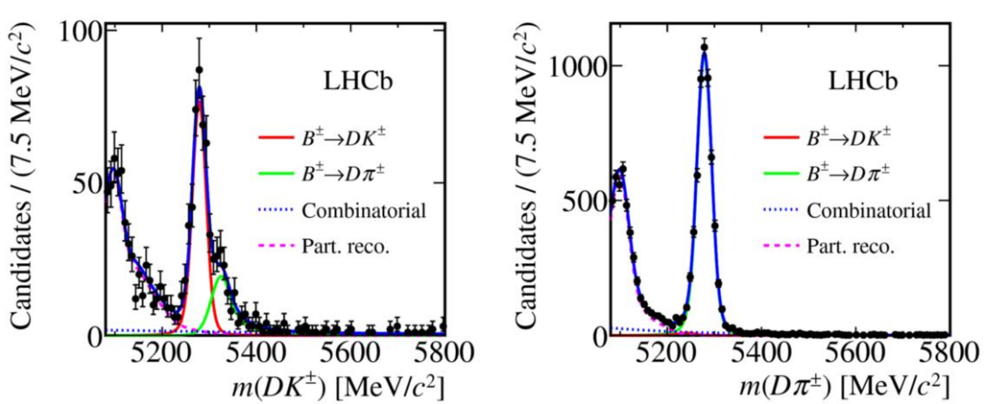


$B^- \to Dh^-$,
$D \to K_S^0 \pi^+ \pi^-$



JHEP 08 (2018) 176



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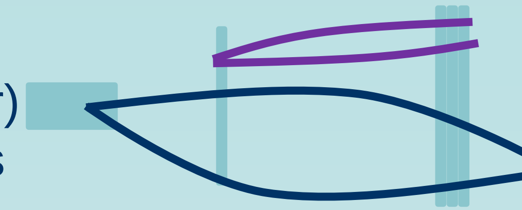

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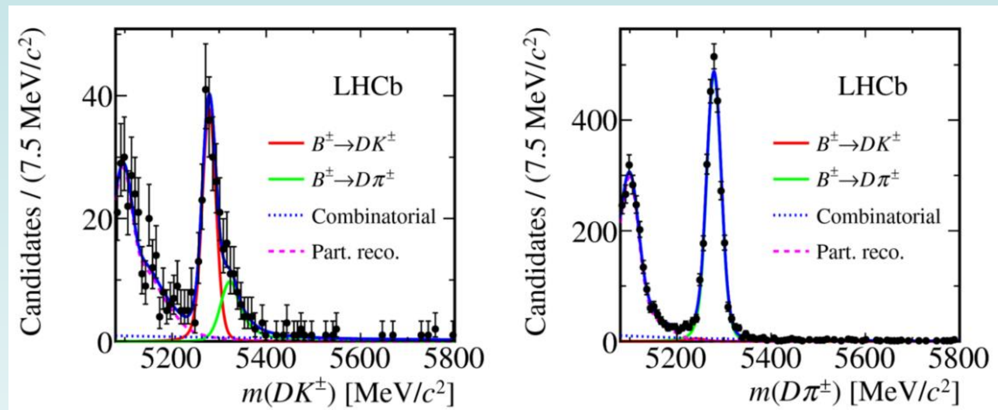
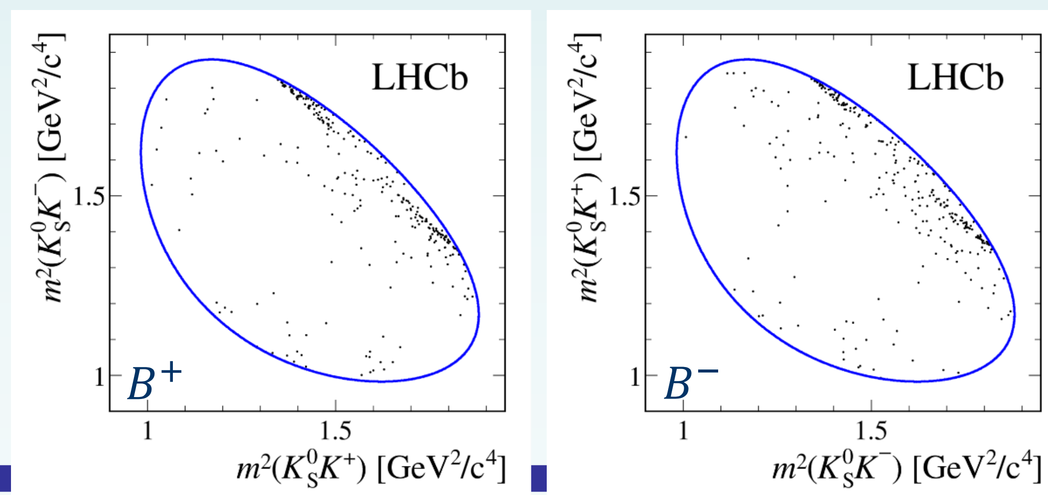


$$B^- \to Dh^-,$$
$$D \to K_S^0 K^+ K^-$$



Backup: Combination of LHCb measurements