CKM angle γ from $B \to DK$ decays

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Towards the Ultimate Precision in Flavour Physics, Warwick

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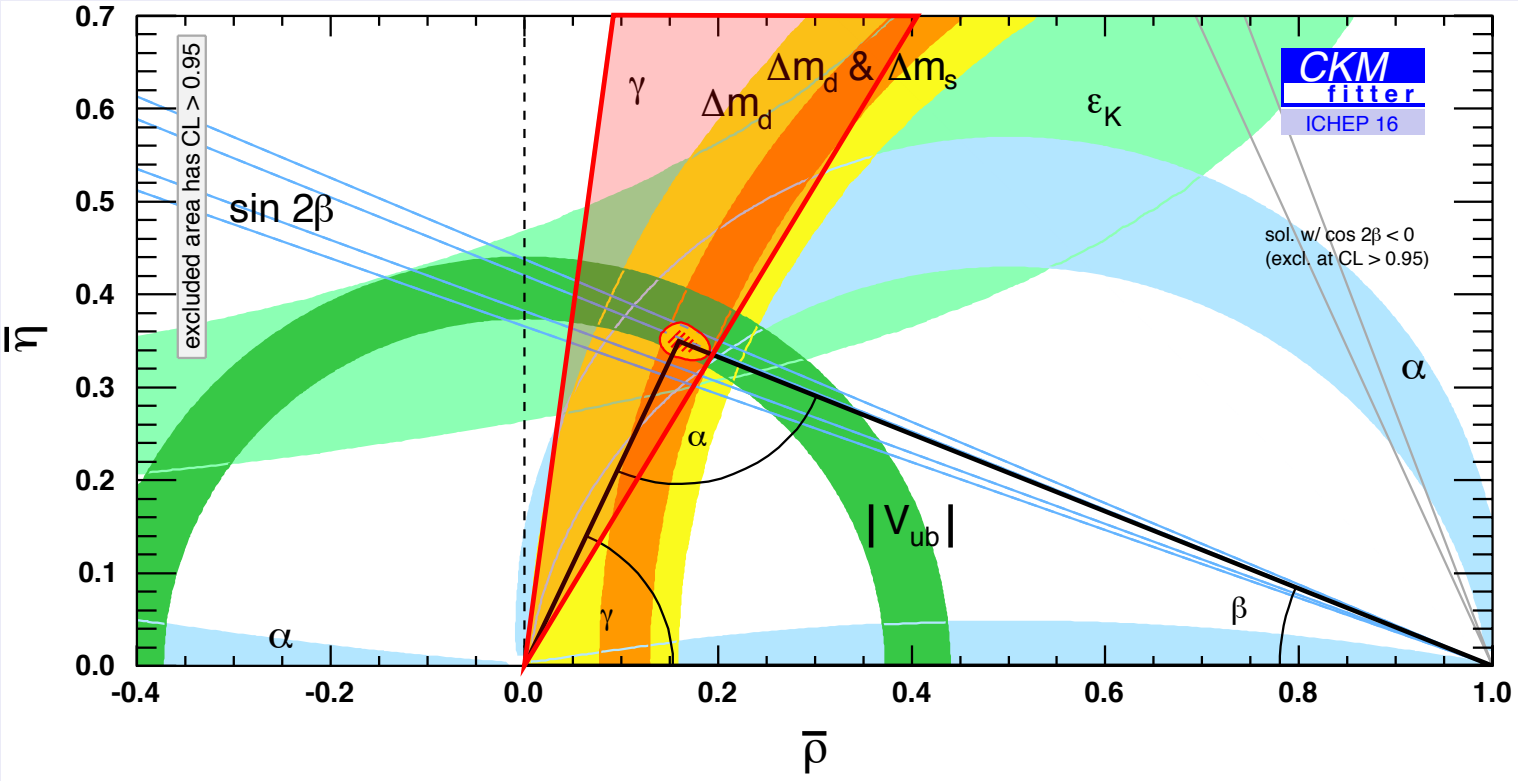
CKM picture is now well verified

- Angle γ is the *least well known* CKM constraint (*although now only just*)
  - **SM benchmark** - only CKM angle accesible at **tree level**

Current Status

Direct: $\gamma = (73.5^{+4.3}_{-5.0})^\circ$ **Indirect:** $\gamma = (65.3^{+1.0}_{-2.5})^\circ$ **Pre-LHCb:** $\gamma = (73^{+22}_{-25})^\circ$

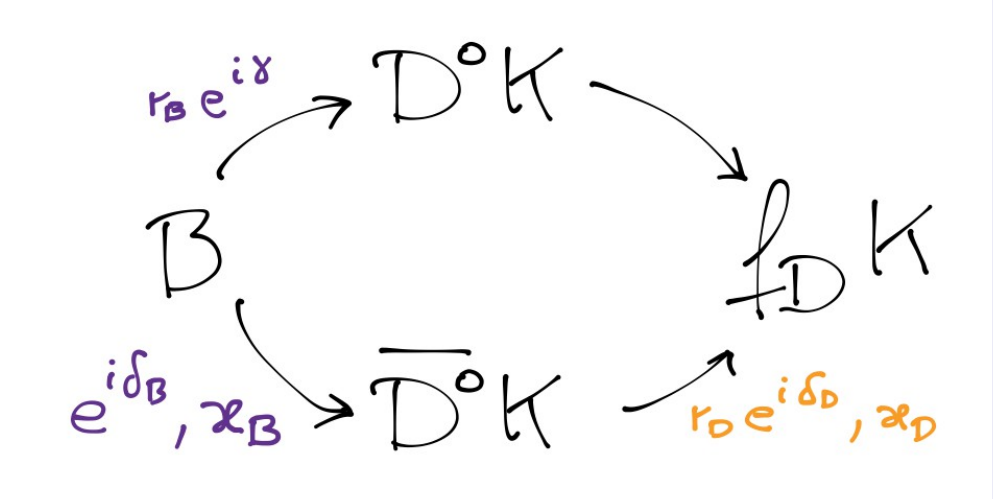


Measuring γ

- γ is the phase between $V_{ub}^* V_{ud}$ and $V_{cb}^* V_{cd}$
  - Require interference between $b \to cW$ and $b \to uW$ to access it
  - No dependence on CKM elements involving the top
  - **Can be measured using tree level B decays**

- The "textbook" case is $B^\pm \to \overset{(-)}{D}{}^0 K^\pm$:
  - Transitions themselves have different final states (D^0 and $\bar{D}^0$)
  - Interference occurs when D^0 and $\bar{D}^0$ decay to the same final state f

Reconstruct the $D^0/\bar{D}^0$ in a final state accesible to both to acheieve interference



- **The crucial feature of these (and similar) decays is that the D^0 can be reconstructed in several different final states** [all have same weak phase γ]

γ from theory

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

- γ is known very well
- Can be determined entirely from tree decays
  - Unique property among all *CP* violation parameters
  - Hadronic parameters can be determined from data
- Neglible theoretical uncertainty (Zupan and Brod 2013)

Theory uncertainty on γ

$$\delta\gamma/\gamma \approx \mathcal{O}(10^{-7})$$ - [arXiv:1308.5663]

- γ can probe for new physics at extrememly high energy scales (Zupan)
  - (N)MFV new physics scenarios: $\sim \mathcal{O}(10^2)$ TeV
  - gen. FV new physics scenarios: $\sim \mathcal{O}(10^3)$ TeV
- NP contributions to $C_{1,2}$ can cause sizeable shifts ($\mathcal{O}(4^\circ)$) in γ (Brod, Lenz et. al 2014) - [arXiv:1412.1446]

γ from experiment

- γ is NOT known very well
- It is quite challenging to measure
- The decay rates are small

Branching ratio for suppressed γ mode

$$BR(B^- \to DK^-, D \to \pi K) \approx 2 \times 10^{-7}$$

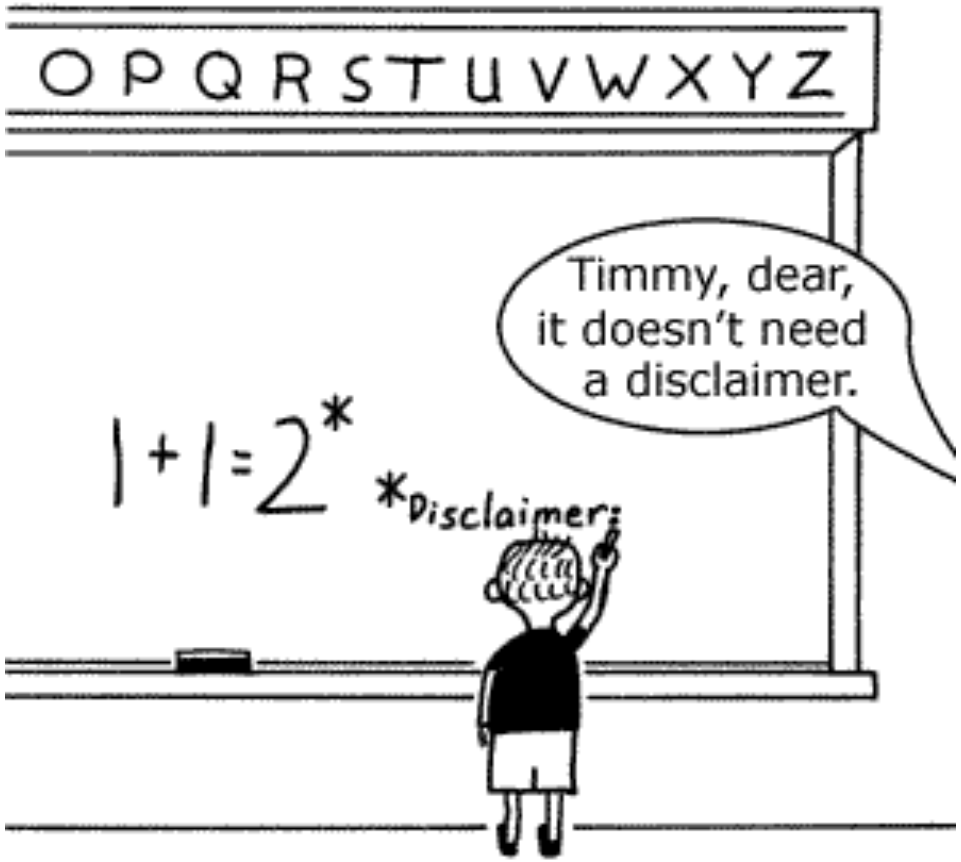
- Small interference effect typically $\sim 10\%$
- Fully hadronic decays - hard to trigger on
- Many channels have a K^0_S or π^0 in the final state - low efficiency at LHCb
- Many different decay channels, many observables and many hadronic unknowns make it statistically challenging

Uncertainty depends on **value** of nuisance parameter

$$\sigma_\gamma \propto \frac{1}{r_B}$$

- External inputs for some beauty and charm parameters are needed

Disclaimer

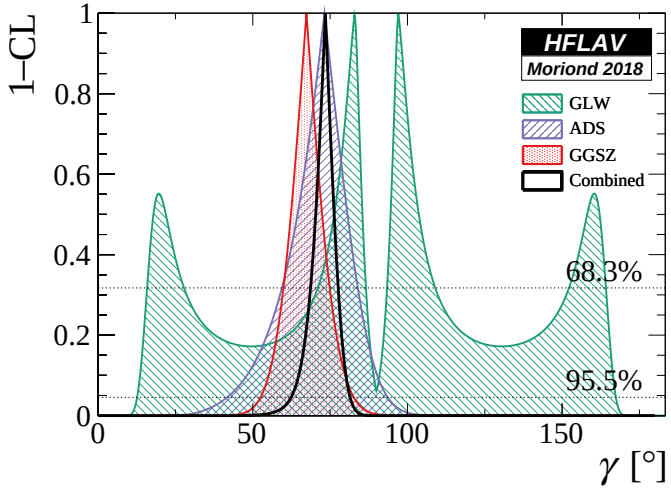


- Many of the numbers shown here for projections are **unofficial**
- They are based on estimates and approximate extrapolations to give a ball park figure

Measuring γ

Categorise decays sensitive to γ depending on the $\overset{(-)}{D}{}^0 \to f$ final state

Optimal sensitivity is only acheived when combining them all together



- GLW
  - CP eigenstates e.g. $D \to KK$, $D \to \pi\pi$
- ADS
  - CF or DCS decays e.g. $D \to K\pi$
- GGSZ
  - 3-body final states e.g. $D \to K^0_S\pi\pi$
- TD (Time-dependent)
  - Interference between mixing and decay e.g. $B^0_s \to D^-_s K^+$ [phase is $(\gamma - 2\beta_s)$]
  - Penguin free measurement of ϕ_s?
- Dalitz
  - Look at 3-body B decays with D^0 or $\bar{D}^0$ in the final state, e.g. $B^0 \to \bar{D}^0 K^+\pi^-$

GLW Method

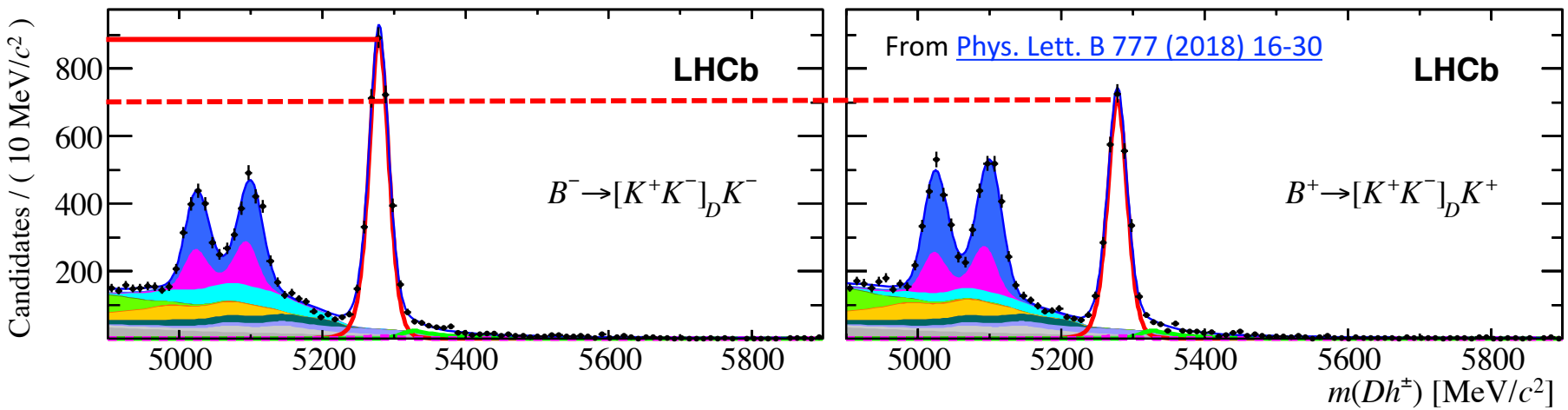
- CP eigenstates e.g. $D \to KK$, $D \to K^0_S \pi^0$
- Gronau, London, Wyler (1991)

- [Phys. Lett. B253 (1991) 483]
- [Phys. Lett. B265 (1991) 172]

GLW observables

$$A_{CP} = \frac{\Gamma(B^- \to D^0_{CP} K^-) - \Gamma(B^+ \to D^0_{CP} K^+)}{\Gamma(B^- \to D^0_{CP} K^-) + \Gamma(B^+ \to D^0_{CP} K^+)} = \frac{\pm 2 r_B \sin(\delta_B)\sin(\gamma)}{1 + r_B^2 \pm 2 r_B \cos(\delta_B)\cos(\gamma)} \quad (1)$$

$$R_{CP} = \frac{\Gamma(B^- \to D^0_{CP} K^-) + \Gamma(B^+ \to D^0_{CP} K^+)}{\Gamma(B^- \to D^0 K^-) + \Gamma(B^+ \to D^0 K^+)} = 1 + r_B^2 \pm 2 r_B \cos(\delta_B)\cos(\gamma) \quad (2)$$



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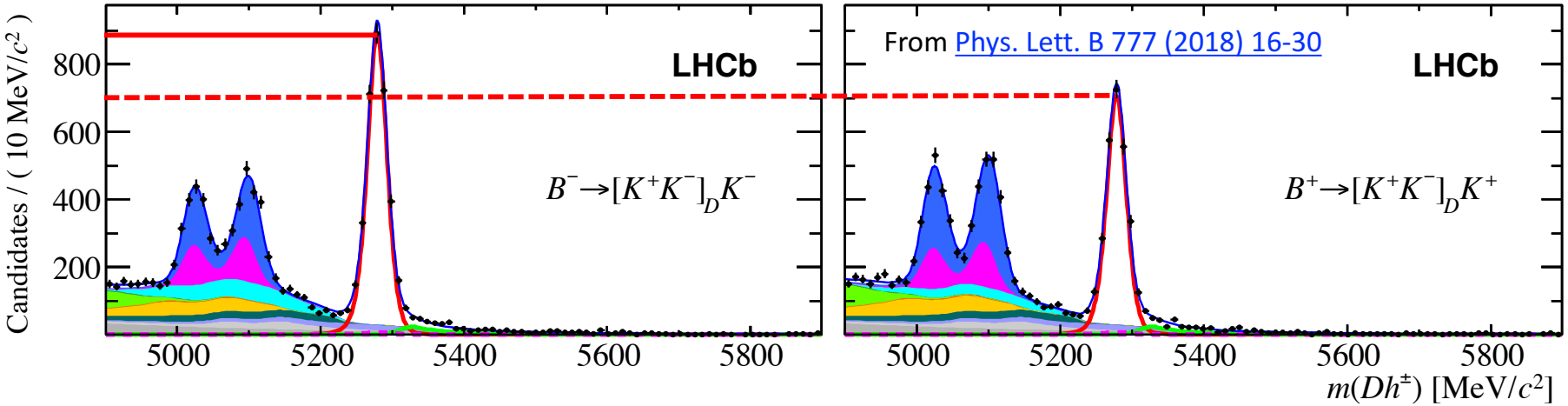

- Can extend to quasi-CP-eigenstates ($D^0 \to KK\pi^0$) if fraction of CP content, F^+, is known

GLW Method

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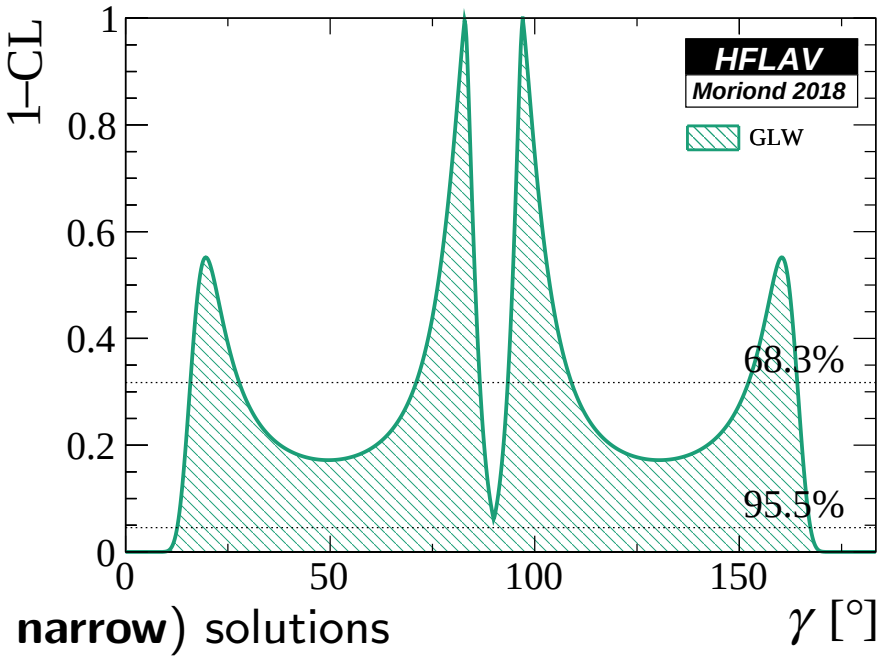

- Multiple (**but very narrow**) solutions
- Require knowledge of F^+ from charm friends

ADS Method

- CF or DCS decays e.g. $D \to K\pi$
- Atwood, Dunietz, Soni (1997,2001)

- [Phys. Rev. D63 (2001) 036005]
- [Phys. Rev. Lett. 78 (1997) 3257]

ADS observables

$$A_{ADS} = \frac{\Gamma(B^- \to [K^+\pi^-]_D K^-) - \Gamma(B^+ \to [K^-\pi^+]_D K^+)}{\Gamma(B^- \to [K^+\pi^-]_D K^-) + \Gamma(B^+ \to [K^-\pi^+]_D K^+)} = \frac{2 r_B r_D \sin(\delta_B + \delta_D)\sin(\gamma)}{r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D)\cos(\gamma)} \quad (3)$$

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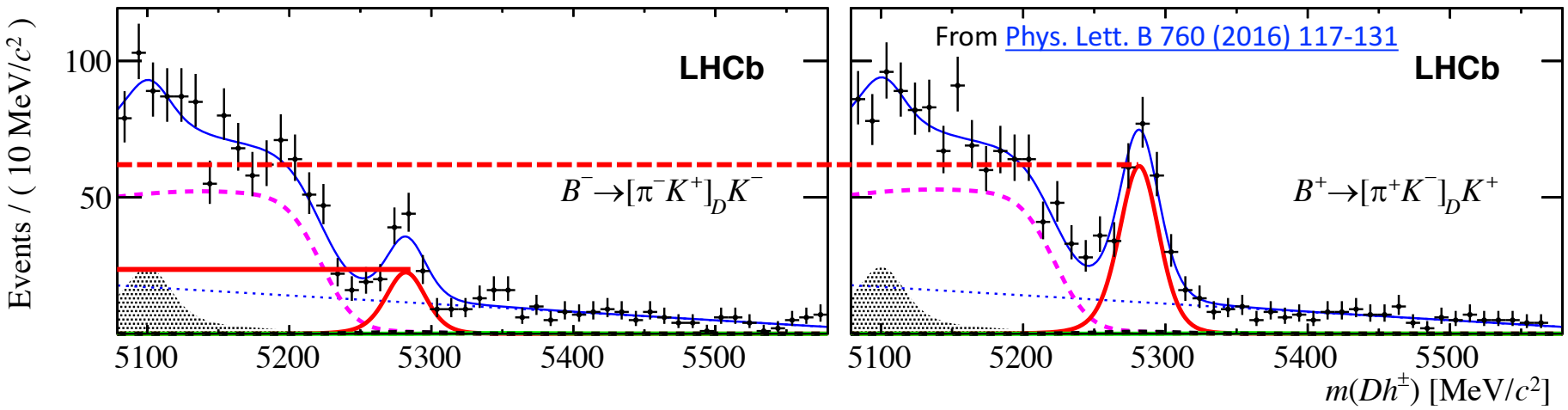

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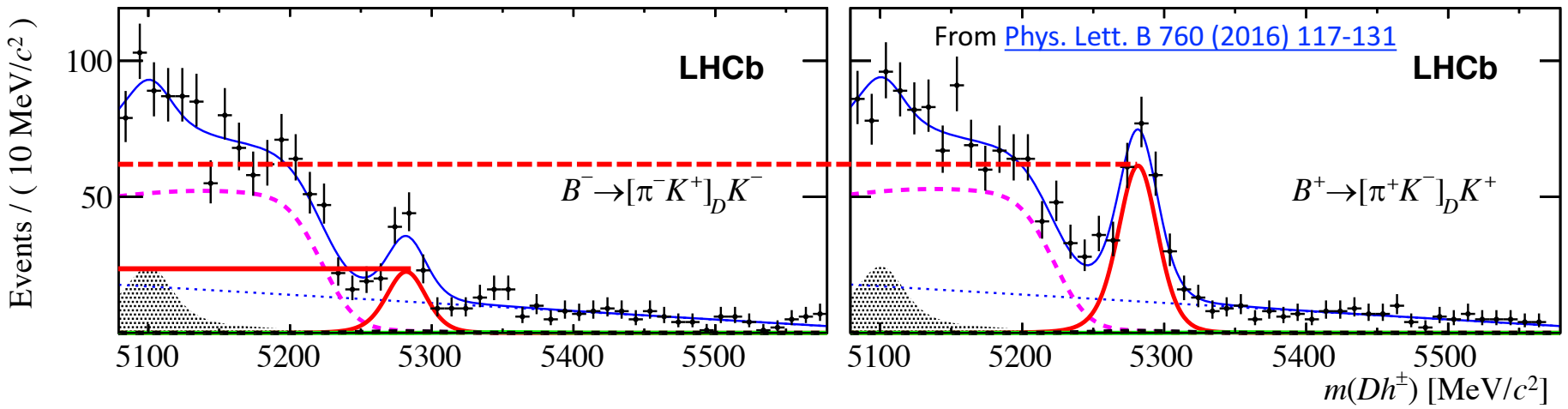

- Can extend to multibody-DCS-decays ($D^0 \to K\pi\pi^0$) if dilution from interference, κ_D, is known

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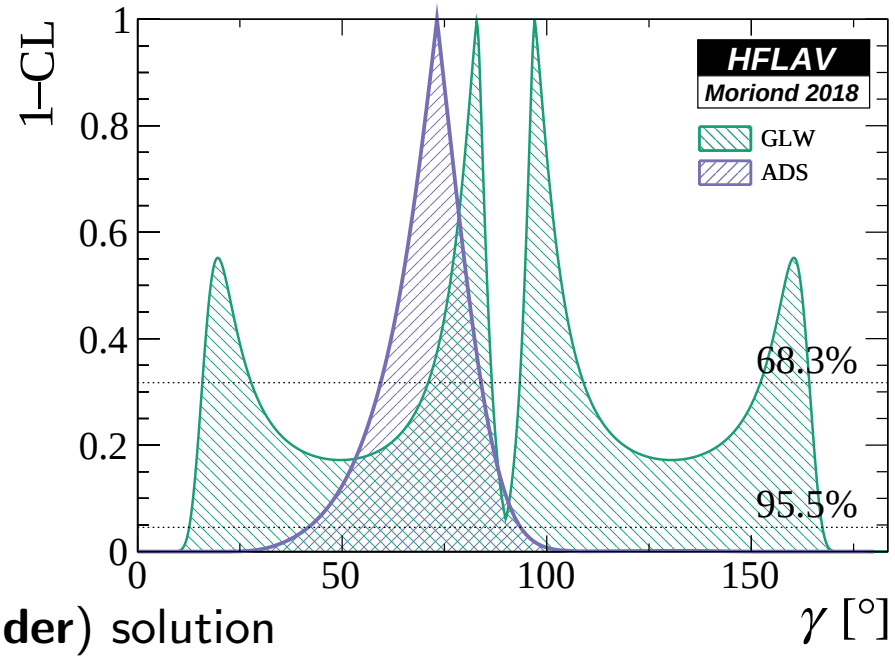


- A single (**yet broader**) solution
- Require knowledge of r_D, δ_D, κ_D from charm friends

GLW/ADS Systematics

- LHCb will dominate GLW/ADS measurements although important for Belle-II to cross check these
  - especially with neutral modes ($B^+ \to D^{*0}[\to D^0\gamma/\pi^0]K^+$, $B^+ \to D^0 K^{*+}[\to K^0_S\pi^+]$) and CP-odd modes with $D^0 \to K^0_S\pi^0$

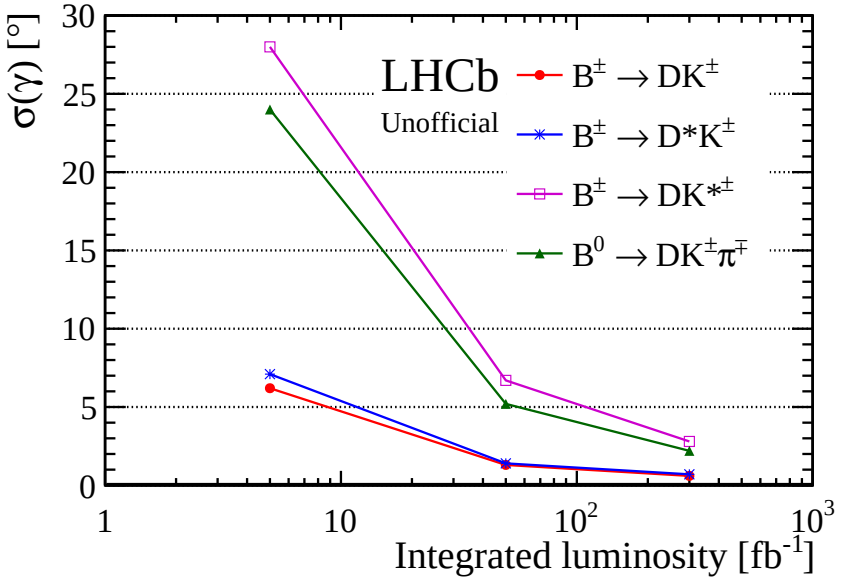
Systematics

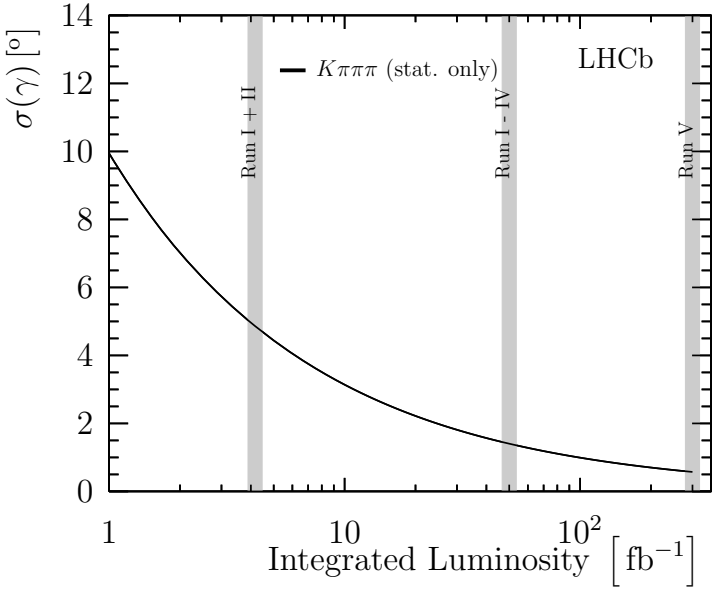
- Measurements are currently statistically limited
- Dominant systematics
  - $B^\pm$ production asymmetry
  - K/π detection asymmetry
  - **Background rates and shape:**
    - particularly $\Lambda^0_b \to \Lambda^+_c K^-$ for GLW
    - particularly $B^0_s \to \overline{D}^0 K^-\pi^+$ for ADS
- These will naturally decrease with larger samples
  - Require accurate knowledge of PID efficiencies and asymmetries
  - Require dedicated studies of background modes (particularly for partially reconstructed modes)
- If systematics become dominant then correlations will be important
  - Requires dedicated studies and/or simultaneous methods

GLW/ADS Prospects

- Large gain from D^{*0} modes
  - Requires accurate knowledge of background rates and shapes
- Excellent potential for $B^+ \to D^0 K^{*+}$ and $B^0 \to D^0 K^{*0}$
  - Better with Dalitz reconstruction of $B^0 \to \bar{D}^0 K^+ \pi^-$ (A. Poluektov and S. Haines talks)
  - Multibody modes also offer equivalent potential at high luminosity (S. Haines talk)

Lumi	$B^- \to D^0 K^-$	$B^- \to D^{*0} K^-$	$B^- \to D^0 K^{*-}$	$B^0 \to D^0 K^+ \pi^-$
50 fb^{-1}	1.3°	1.4°	6.7°	5.2°
300 fb^{-1}	0.6°	0.7°	2.8°	2.2°





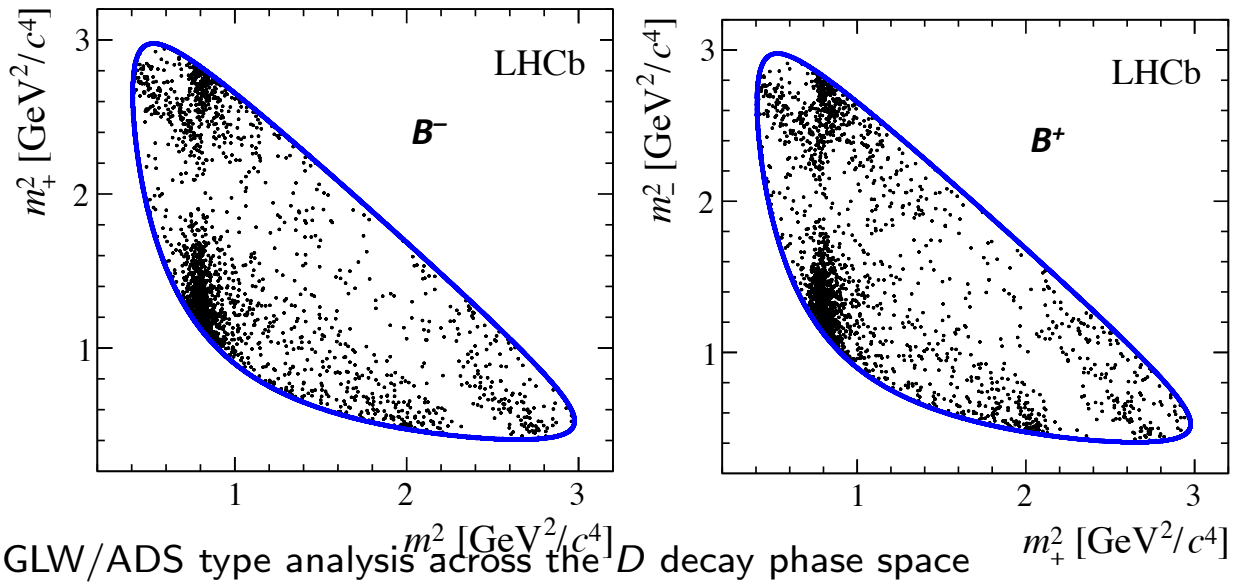
GGSZ Method

- 3-body final states e.g. $D \to K^0_S \pi\pi$
- Giri, Grossman, Soffer, Zupan (2003)
- [Phys. Rev. D68 (2003) 054018]

GGSZ observables (partial rate as function of Dalitz position)

$$d\Gamma_{B^\pm}(\mathbf{x}) = A^2_{(\pm,\mp)} + r_B^2 A^2_{(\mp,\pm)} + 2A_{(\pm,\mp)}A_{(\mp,\pm)}\Big[\underbrace{r_B\cos(\delta_B \pm \gamma)}_{x_\pm}\underbrace{\cos(\delta_{D(\pm,\mp)})}_{c(\pm,\mp)} + \underbrace{r_B\sin(\delta_B \pm \gamma)}_{y_\pm}\underbrace{\sin(\delta_{D(\pm,\mp)})}_{s(\pm,\mp)}\Big] \quad (5)$$

From JHEP 10 (2014) 097



- Essentially a GLW/ADS type analysis across the D decay phase space
- Excellent sensitivity from interference between various contributions

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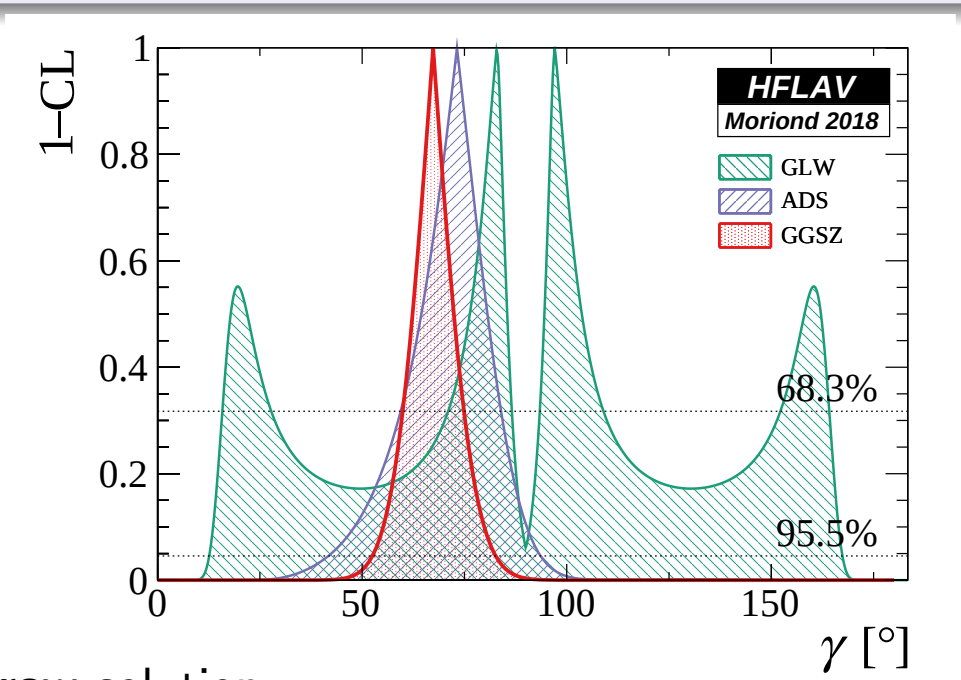


- A **single and narrow** solution
- Again see S. Haines and A. Poluektov talks for more

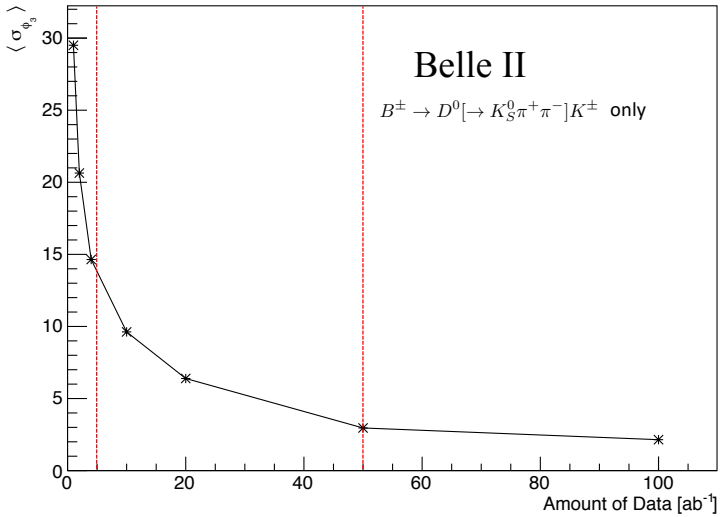
GGSZ Prospects

- Considered the **golden-mode** for γ (certainly true at Belle-II)

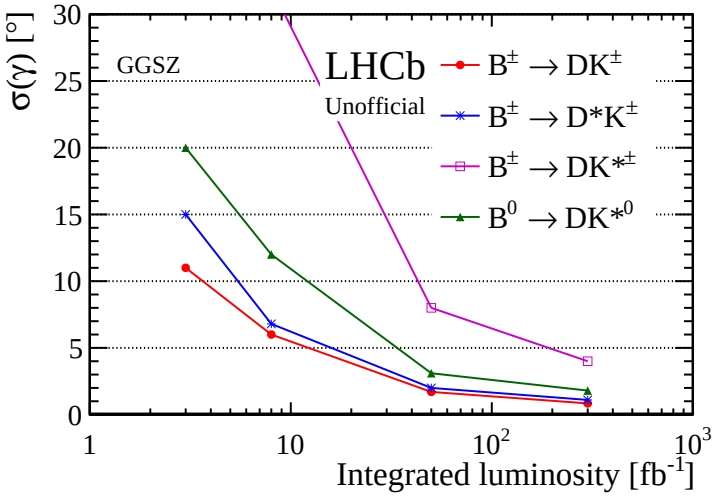
Systematics

- Efficiency correction (mostly data-driven but requires large MC sample for correction)
- Strong phase inputs or model uncertainties (see A. Poluektov, G. Wilkinson and S. Haines talks)
  - $\sqrt{N}$ improvement is much harder to acheieve here

Belle II (DK only)



LHCb (DK only)



- As strong phase uncertainties become dominant incorporating correlation between modes will be essential

TD decays for penguin free measurement of ϕ_s

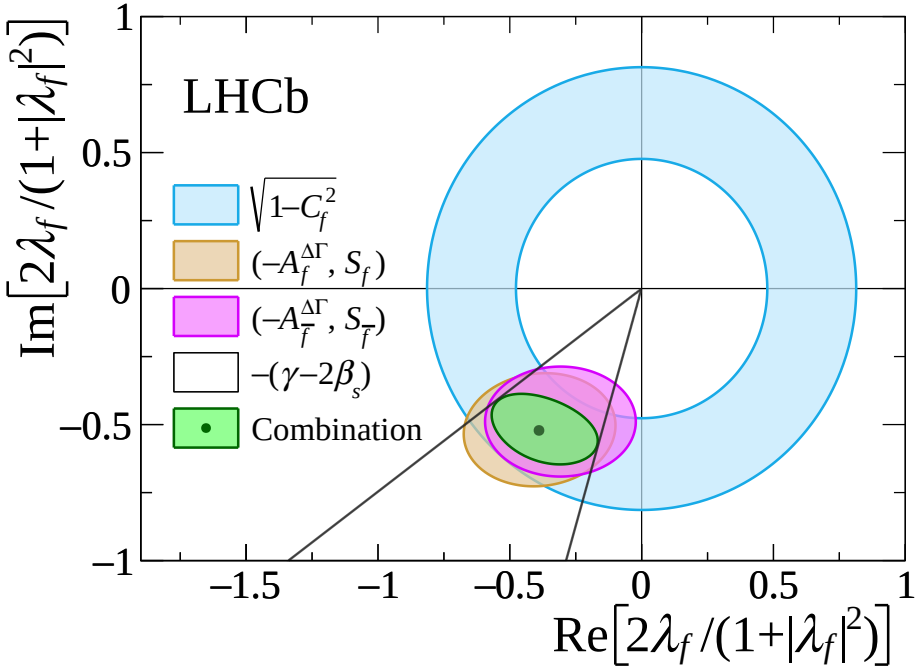
- For decays like $B_s^0 \to D_s^{\mp} K^{\pm}$ interference arises between decay and mixing
- Measures $(\gamma - 2\beta_s)$ at tree level

Variable definitions

$$C_f = -C_{\bar{f}} = \frac{1 - r_B^2}{1 + r_B^2}$$

$$A_{f(\bar{f})}^{\Delta\Gamma_s} = \frac{-2r_B \cos(\gamma - 2\beta_s \mp \delta_B)}{1 + r_B^2}$$

$$S_{f(\bar{f})} = \frac{\pm 2r_B \sin(\gamma - 2\beta_s \mp \delta_B)}{1 + r_B^2}$$



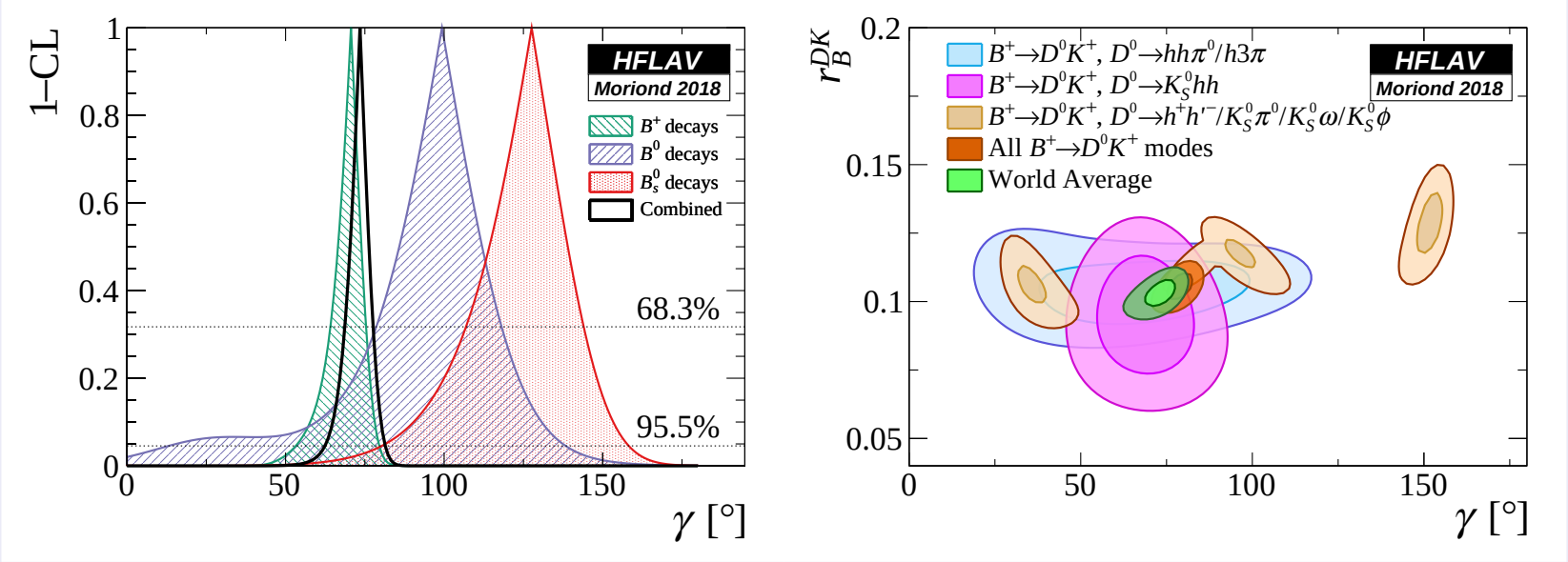
Lumi	8 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$\sigma(\gamma - 2\beta_s) B_s^0 \to D_s^- K^+$	7.8°	1.9°	$\sim 1°$

- Possible penguin free measurement of ϕ_s
  - Systematics: decay-time-acceptance, flavour-tagging, length-scale
- See G. Cowan talk for more

World Average Current Status

World Average (HFLAV)

$$\gamma = (73.5^{+4.3}_{-5.0})^\circ$$



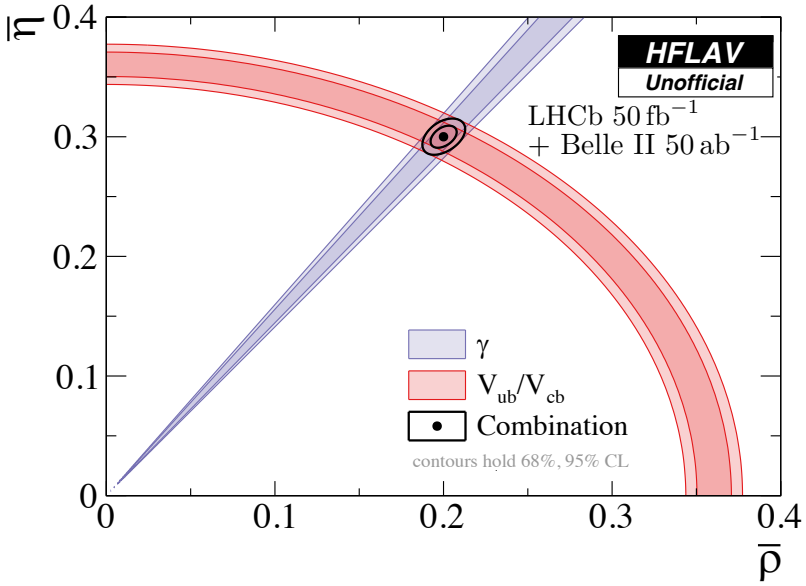
Indirect constraints are: $\gamma = (65.3^{+1.0}_{-2.5})^\circ$ $(\sim 2\sigma)$

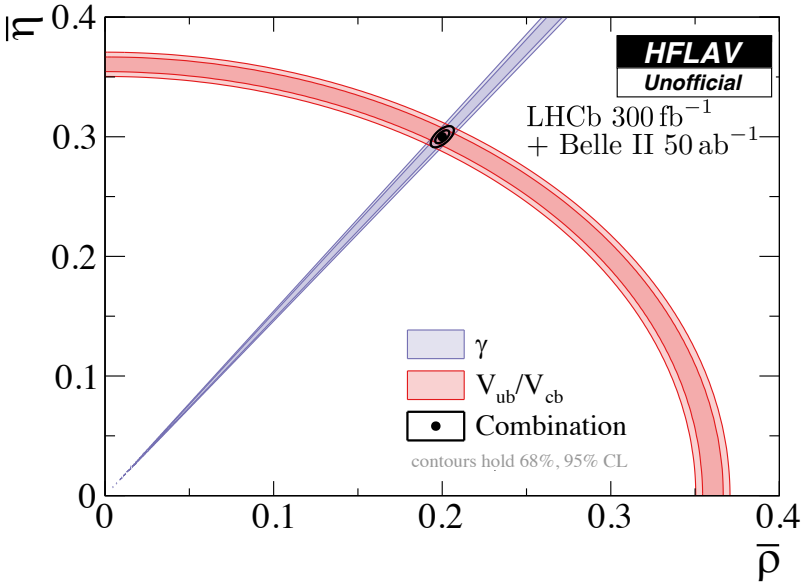
Comparison between B_s^0 and B^+ initial states $\sim 2\sigma$

Ultimate Precision

Can we get to 0.1°?

- Will be hard work
- The studies shown here suggest $\sim 0.7^\circ$ with $50\,\mathrm{fb}^{-1}$ of LHCb and $50\,\mathrm{ab}^{-1}$ of Belle-II (of which $\sim 0.8^\circ$ comes from LHCb)
- With $300\,\mathrm{fb}^{-1}$ at LHCb can get to $\sim 0.35^\circ$ but THIS DOES NOT INCLUDE new kids on the block
  - In particular the double Dalitz ideas with $B^0 \to \overline{D}^0 K^+ \pi^-$
  - Exciting prospects with multibody modes (e.g. full Dalitz analysis of $D \to K3\pi$)
  - Does not consider systematic correlations which may help to reduce overall uncertainty
- Can we become sensitive to differences between B^+, B^0 and B_s^0 initial states?

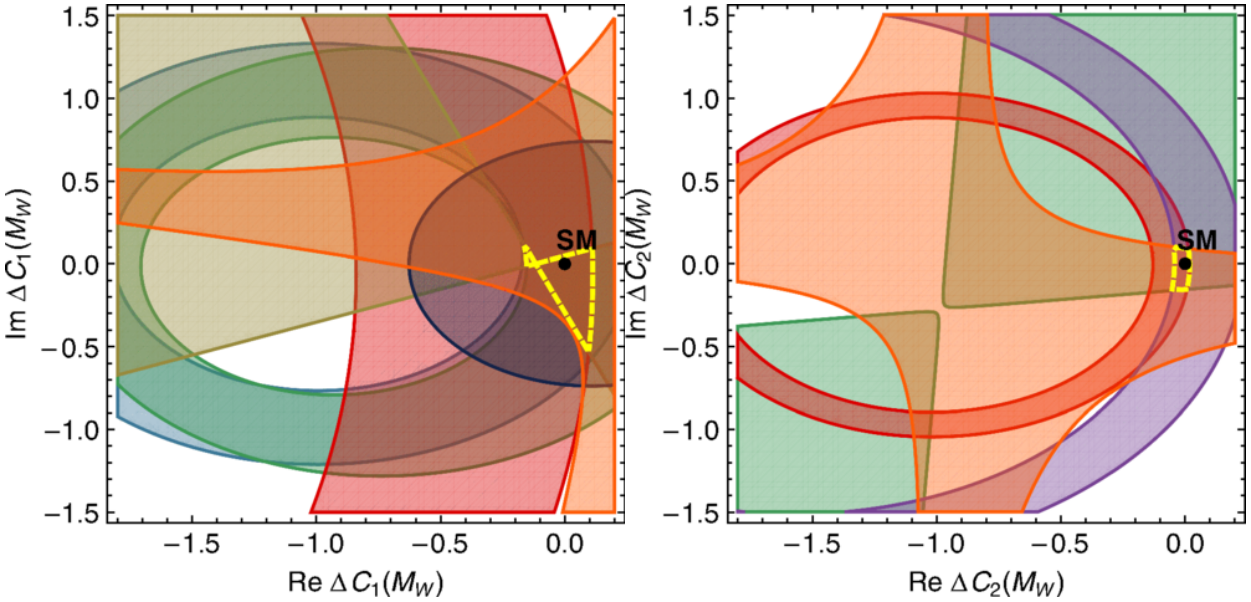




Sensitivity to tree-level Wilson coefficients

- There is still considerable scope in current constraints on tree-level NP in Wilson coefficients $\mathcal{C}_1$ and $\mathcal{C}_2$ - [Phys. Rev. D92 (2015) 033002]

$$\mathcal{C}_1 = \mathcal{C}_1^{SM} + \Delta\mathcal{C}_1^{NP}$$
$$\mathcal{C}_2 = \mathcal{C}_2^{SM} + \Delta\mathcal{C}_2^{NP}$$



- With sufficient precision on γ we can modify our definition of the supressed / favoured amplitude ratio and fit these directly

Modification of $\mathcal{A}(B^- \to \bar{D}^0 K^-)/\mathcal{A}(B^- \to D^0 K^-)$

$$r_B e^{i\delta_B - \gamma} \to r_B e^{i\delta_B - \gamma} \left[\frac{\mathcal{C}_2^{SM} + r_A \mathcal{C}_1^{SM}}{\mathcal{C}_2^{SM} + r_{A'} \mathcal{C}_1^{SM}} \frac{\mathcal{C}_2^{SM} + \Delta\mathcal{C}_2^{NP} + r_{A'}(\mathcal{C}_1^{SM} + \Delta\mathcal{C}_1^{NP})}{\mathcal{C}_2^{SM} + \Delta\mathcal{C}_2^{NP} + r_A(\mathcal{C}_1^{SM} + \Delta\mathcal{C}_1^{NP})} \right] \quad (7)$$

Summary

- CKM angle γ an incredibly **clean** benchmark for the SM
  - A cornerstone of flavour physics experiments' programs
  - Theoretical uncertainty so low the emphasis is on experimental determination
- Sensitive both directly and indirectly to NP
- **Ultimate precision only acheived via combination of multiple decay modes**
- By the end of the current approved LHCb Run ($50\,\mathrm{fb}^{-1}$) with full Belle-II statistics
  - World average can expect precision of $\sim 0.7^{\circ}$
- With $300\,\mathrm{fb}^{-1}$ at LHCb ($+50\,\mathrm{ab}^{-1}$ at Belle-II) can reach even lower
  - World average precision of $\sim 0.35^{\circ}$
  - Control penguin pollution in ϕ_s
  - Become sensitive to differences between topologies (B^+ *vs.* B_s^0 *vs.* B^0)
  - Sufficient precision to fit directly for $\mathcal{C}_1$, $\mathcal{C}_2$

THANK YOU!