Some future possibilities with the CKM angle γ average

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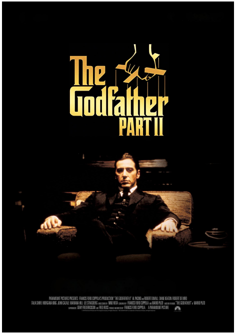
Towards the Ultimate Precision in Flavour Physics II, Durham

3rd April 2019

Sequels that are better than the original?

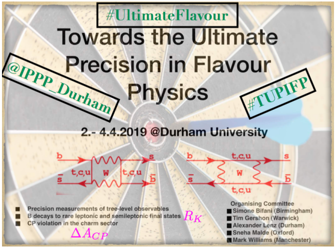
The Godfather Part II



The Empire Strikes Back

Common Market 2.0?

TUPIFP II?



CKM angle γ

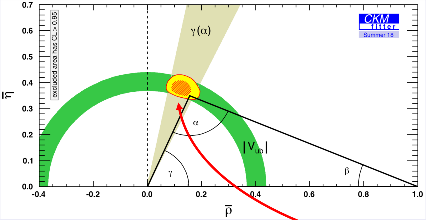
- One of the only really theoretically clean CKM parameters (*disclaimer - see later slides)
- Precision measurements of γ will set a SM benchmark to test CPV in the quark sector

Direct: $\gamma = (72.1^{+5.4}_{-5.7})^\circ$

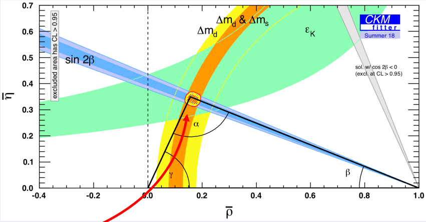
Indirect: $\gamma = (65.6^{+1.0}_{-3.4})^\circ$

Currently a $\sim 2\sigma$ tension

Tree-level constraints



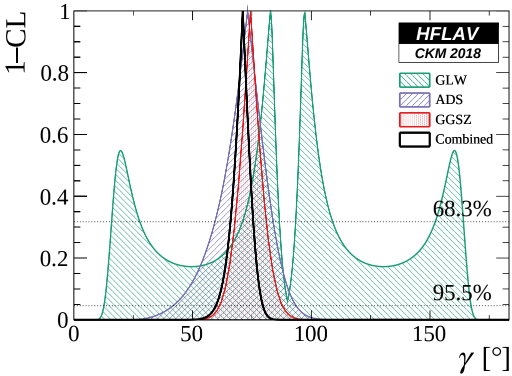
Loop-level constraints



NP?

CKM angle γ

- One of the few CKM constraints that will actually improve at $\sqrt{N}$ without the need for developments in theory
- Understanding of experimental systematics will be crucial for this
  - PID, background shape modelling, background rates, strong phases
  - Time acceptance and time resolution
- But we have a nice handle on this via comparison of different methods



Overview

1. 1. World average prospects

2. 2. Combined fits with charm and beauty data

3. 3. Probing new physics at tree-level

1. World average prospects

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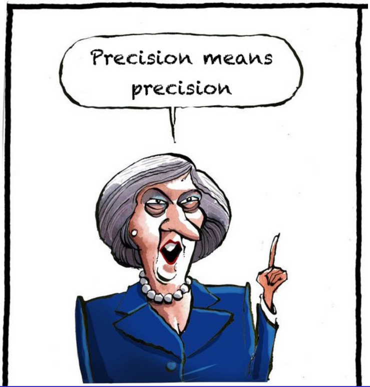
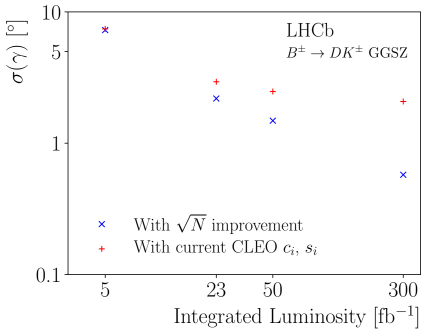
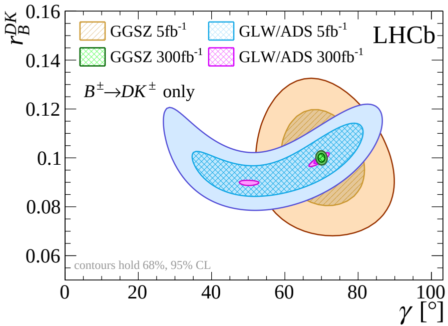


World average prospects

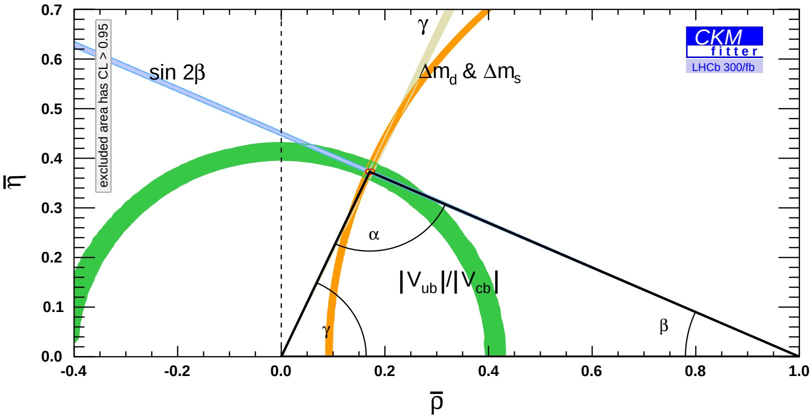
- Since the last TUPIFP meeting LHCb have published Phase-II Upgrade Physics case [arXiv:1808.08865] and there is also the Belle-II Physics Book [arXiv:1808.10567]
- Lots of preliminary results shown previously have been formalised
- With 300 fb^{-1} at LHCb and 50 ab^{-1} at Belle-II we get to $\mathcal{O}(0.4^\circ)$
- Requires improved knowledge of charm strong phases





World average prospects

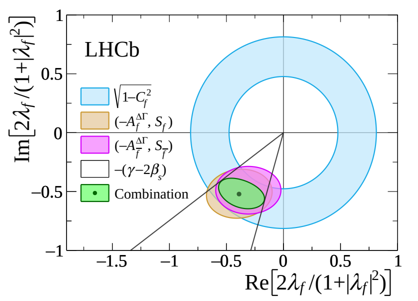
- LHCb only UT constraints at $300\,\text{fb}^{-1}$



What can we do with a precision $< 1^\circ$?

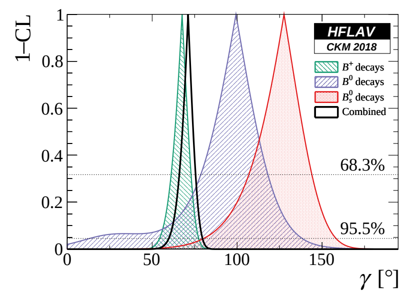
In 20 years time we will know γ to $< 1^\circ$ precision in B^+, B^0 and B_s^0 systems independently

Penguin free measurement of ϕ_s?



- See Mark Whitehead's talk on Thursday for more

Comparison between initial states?



- Can different decay topologies (B^+ vs B^0/B_s^0) allow us to probe NP effects?

- Combined fits across beauty and charm
- Probing for NP effects directly

2. Combined fits with beauty and charm datasets

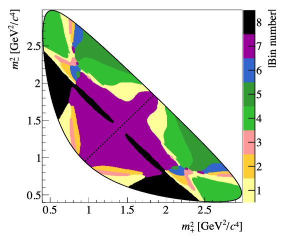
2. Combined fits with beauty and charm datasets

This shows a summary of studies performed by **Rizwaan Mohammed** (a Masters student at Cambridge) who will start a PhD at Oxford in October. Currently being written up for a project report, considering a future publication.

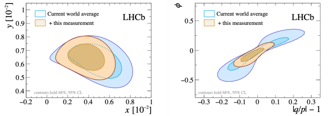
Combined fits in charm and beauty sectors

- Currently strong phase measurements in $D^0 \to K^0_S hh$ are used as inputs for:
  - Mixing / CPV measurements in charm (values are Gaussian constrained)
  - GGSZ measurements of γ (values are fixed)
- At present use measurements from CLEO-c, in the future these will come from BESIII

CLEO / BES-III measurements of c_i and s_i

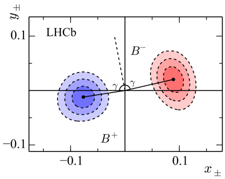


LHCb bin-flip method for x_D, y_D, Δx, Δy



$$R_{bj}^{\pm} = r_b - \langle t \rangle_j \sqrt{r_b}\,[(1-r_b)c_b y - (1+r_b)s_b x]$$

LHCb GGSZ method for γ



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

Beauty and Charm combined fit inputs

Generated toys for projected future luminosities at LHCb

1. Charm strong phases in $D \to K^0_\mathrm{S}\pi\pi$, c_b and s_b
   - Use CLEO central values and uncertainties
   - Use CLEO central values with projected BES-III uncertainties ($\times 10\mathcal{L}$)
2. Charm Bin Flip method in decay-time bins (j) and Dalitz bins (b) for $D \to K^0_\mathrm{S}\pi\pi$
   - Use toys with "Optimal-Binning" estimating both Prompt and SL yields

$$R^{\pm}_{bj} \approx \frac{r_b \left[1 + \frac{1}{4}\langle t^2\rangle_j \,\mathrm{Re}(z^2_{CP} - \Delta z^2)\right] + \frac{1}{4}\langle t^2\rangle_j \,|z_{CP} \pm \Delta z|^2 + \sqrt{r_b}\langle t\rangle_j \mathrm{Re}\left[X^*_b(z_{CP} \pm \Delta z)\right]}{\left[1 + \frac{1}{4}\langle t^2\rangle_j \,\mathrm{Re}(z^2_{CP} - \Delta z^2)\right] + r_b \frac{1}{4}\langle t^2\rangle_j \,|z_{CP} \pm \Delta z|^2 + \sqrt{r_b}\langle t\rangle_j \mathrm{Re}\left[X_b(z_{CP} \pm \Delta z)\right]}$$

   - With $r_b = F_{-b}/F_b$, $X_b = c_i - is_i$, $z = -(y_D + ix_D)$, $(q/p)^{\pm 1} z = z_{CP} + \Delta z$
3. Beauty GGSZ control mode $B^0 \to D^{*+}\mu^-\nu$ for F_b
   - Estimated from LHCb GGSZ values
4. Beauty GGSZ yields in $B^\pm \to DK^\pm$
   - Toys with "Optimal-Binning"

$$N^+_{\pm b} = h_{B^+}\left[F_{\mp b} + (x^2_+ + y^2_+)F_{\pm b} + 2\sqrt{F_i F_{-b}}(x_+ c_{\pm b} - y_+ s_{\pm b})\right]$$
$$N^-_{\pm b} = h_{B^-}\left[F_{\pm b} + (x^2_- + y^2_-)F_{\mp b} + 2\sqrt{F_i F_{-b}}(x_- c_{\pm b} - y_- s_{\pm b})\right]$$

Beauty and Charm combined fit parameters

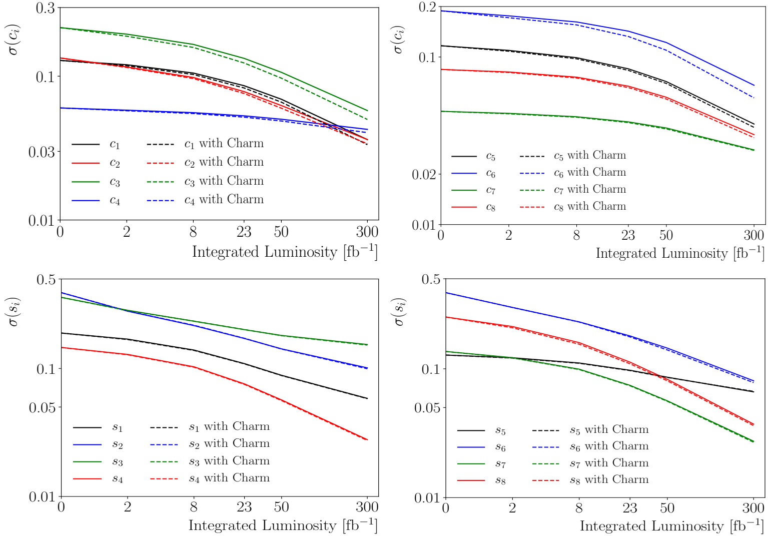
1. Charm strong phases in $D \to K^0_S\pi\pi$, c_b and s_b
   - c_b, s_b
2. Charm Bin Flip method in decay-time bins (j) and Dalitz bins (b) for $D \to K^0_S\pi\pi$
   - Physics parameters: x_D, y_D (charm-mixing), Δx, Δy (CPV in charm-mixing)
   - Nuisance paramters: $r_b = F_{-b}/F_b$ (ratio of fractions of $D^0/\bar{D}^0$ in each bin where time-acceptance cancels)
3. Beauty GGSZ control mode $B^0 \to D^{*+}\mu^-\nu$ for F_b
   - Nuisance parameters: $F_{\pm b}$ (fraction of $D^0/\bar{D}^0$ in each bin including LHCb acceptance)
4. Beauty GGSZ yields in $B^\pm \to DK^\pm$
   - Physics parameters: $x_\pm$, $y_\pm$ (CPV in beauty) i.e. (r_B, δ_B, γ)

Question:

How much does the LHCb charm and beauty data improve our knowledge of the strong phases and how much does this effect our knowledge of mixing and CP parameters?

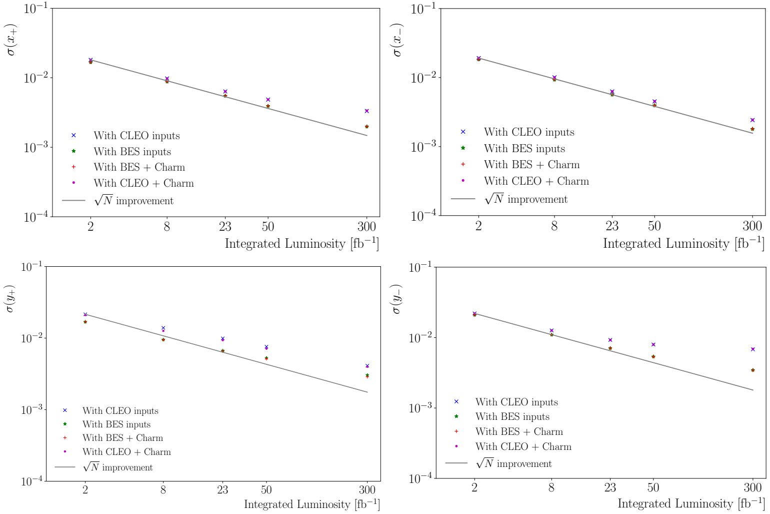
Beauty and Charm combined fit results (strong phases)

- Shows the impact on the CLEO uncertainties of adding LHCb b and c datasets
- For context BESIII expects $\sim 10\times$ more data than CLEO



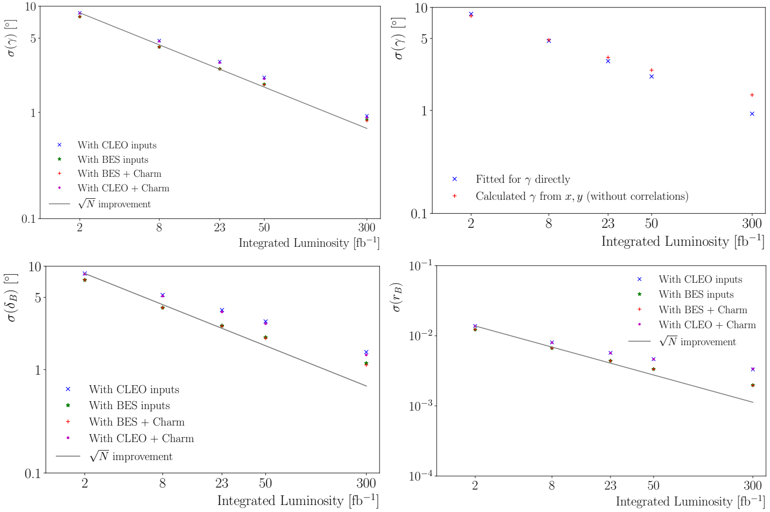
Beauty and Charm combined fit results (b parameters)

- Need for BESIII uncertainties in the future is clear
- Usefulness of combined fit seems negligible for $(x_\pm, y_\pm)$ however ...



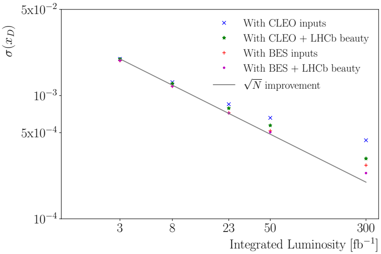
Beauty and Charm combined fit results (b parameters)

- When interpreting in (r_B, δ_B, γ) instead of $(x_\pm, y_\pm)$ **correlations are vital**
- A small gain when performing a combined fit



Beauty and Charm combined fit results (c parameters)

- Inclusion of beauty data is helpful for the charm mixing parameters



3. Probing new physics at tree-level

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Some preliminary studies in the process of being written up for publication.

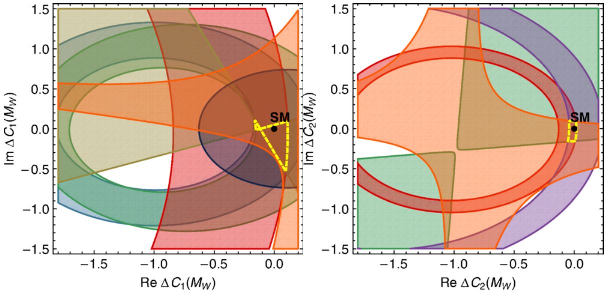
Sensitivity to tree-level Wilson coefficients

- We always say CKM angle γ is a SM benchmark with negligible theoretical uncertainty - $\mathcal{O}(10^{-7})^\circ$
- This is only true **if we assume no NP at tree-level**
- Brod, Lenz et. al [Phys. Rev. D92 (2015) 033002] show how much "wiggle" room is in this assumption

$$\mathcal{H}_{\text{eff}}^{u_1 \bar{u}_2 d_1} = \frac{G_f}{\sqrt{2}} V_{u_1 b} V^*_{u_2 d_1} \left[C_1 \mathcal{Q}_1^{u_1 \bar{u}_2 d_1} + C_2 \mathcal{Q}_2^{u_1 \bar{u}_2 d_1} \right]$$

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

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



Sensitivity to tree-level Wilson coefficients

- A NP contribution to C_1 or C_2 gives a modification to our amplitude ratio:

Modification of amplitude ratio

$$r_B e^{i(\delta_B \pm \gamma)} \to r_B e^{i(\delta_B \pm \gamma)} \left[1 + (r_{A'} - r_A) \frac{\Delta \mathcal{C}_1^{NP}}{\mathcal{C}_2} \right]$$

In particular note that:

$$\gamma \to \gamma \left[1 + (r_A - r_{A'}) \frac{\mathrm{Im}(\Delta \mathcal{C}_1^{NP})}{\mathcal{C}_2} \right]$$

where r_A ($r_{A'}$) are hadronic unknowns representing the favoured (suppressed) colour singlet / rearranged amplitude ratio

- Can redefine all GLW/ADS/GGSZ relations shifting by a single complex NP contribution $A = (r_{A'} - r_A)\Delta \mathcal{C}_1^{NP} / \mathcal{C}_2$

Modification of decay rate

$$\Gamma(B^\pm \to DK^\pm) \to \left| r_D e^{-i\delta_D} + r_B e^{i(\delta_B \pm \gamma)}(1 + A) \right|^2$$

Sensitivity to tree-level Wilson coefficients

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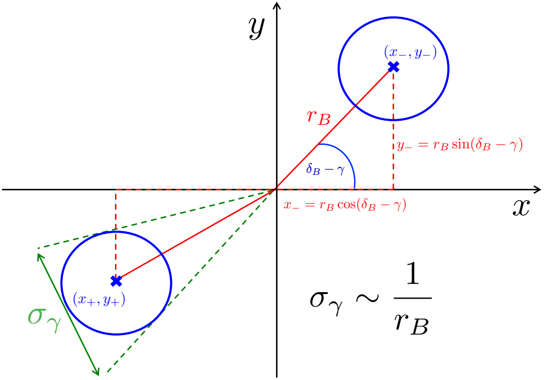

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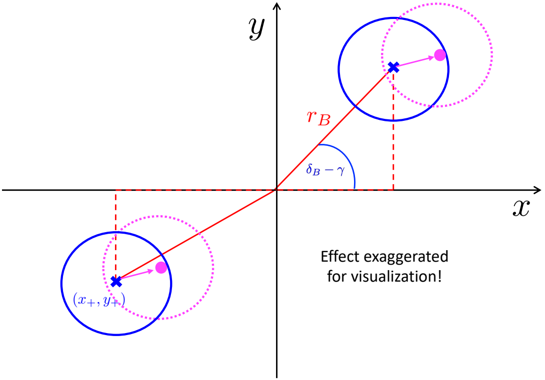
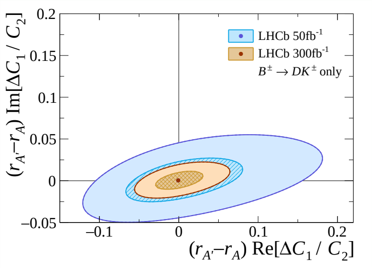


Sensitivity to tree-level Wilson coefficients

Sensitivity to generic NP contribution in complex number A

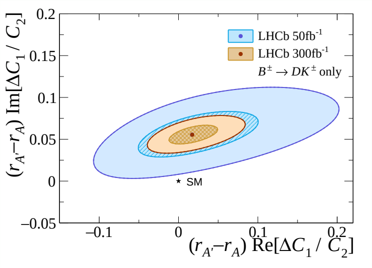
$$A = (r_{A'} - r_A) \frac{\Delta \mathcal{C}_1^{NP}}{\mathcal{C}_2}$$

Future exclusion profile for A



- What values of A can be excluded in the future

Using "still allowed" NP contribution



- Estimate $\Delta r = r_{A'} - rA \approx 0.6$ and allow $\text{Im}(\Delta \mathcal{C}_1^{NP}(m_b)) \sim \mathcal{O}(10\%)$

Can do even more by including rates from other $b \to c/u$ processes:

$$B \to D\pi,\ B \to D^{*0}h^0,\ B \to X_{d(s)}\gamma,\ a_{sl}^{d(s)},\ B \to \pi\pi$$

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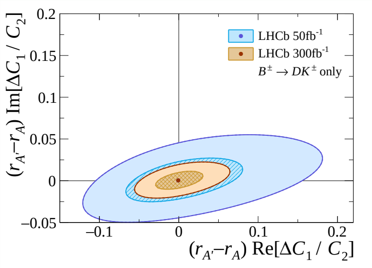

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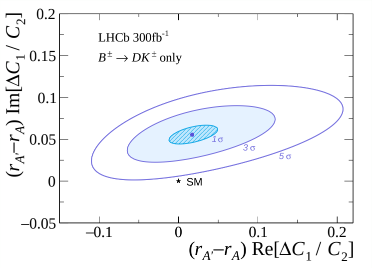

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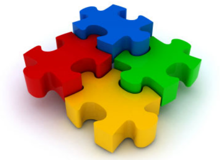
Summary

- If LHCb collects $\geq 300\,\text{fb}^{-1}$ γ will reach $\mathcal{O}(0.4^\circ)$ precision
- Will have $< 1^\circ$ precision independently in B^+, B^0 and B_s^0 modes
- Will allow for penguin free measurement of ϕ_s with $\sim 0.02\,\mathrm{rad}$ precision
- Fitting charm and beauty datasets in a combined way offers some benefit to charm mixing measurements with $D^0 \to K_\mathrm{S}^0\pi\pi$ but not much for beauty parameters
- Carefully considering correlations will be crucial
- BESIII inputs will be vital for the ultimate precision on γ
- Can eventually set limits on / directly probe generic new physics contributions at tree-level
- Have the potential to be even more sophisticated than this when including additional inputs



THANK YOU!