Some future possibilities with the CKM angle $\gamma$ 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?

Towards the Ultimate Precision in Flavour Physics

2. - 4.4.2019 @Durham University

Matthew Kenzie

Some future possibilities with the CKM angle $\gamma$ average
CKM angle $\gamma$

- One of the only really theoretically clean CKM parameters (*disclaimer - see later slides)
- Precision measurements of $\gamma$ 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

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**Tree-level constraints**

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**Loop-level constraints**

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NP?
CKM angle $\gamma$

- 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

![Graph showing distribution of CKM angle $\gamma$.]
Overview

1. World average prospects

2. Combined fits with charm and beauty data

3. Probing new physics at tree-level
1. World average prospects

Precision means precision
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 $300 \text{ fb}^{-1}$ at LHCb and $50 \text{ ab}^{-1}$ at Belle-II we get to $O(0.4^\circ)$
- Requires improved knowledge of charm strong phases

![Graph](image.png)

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Some future possibilities with the CKM angle $\gamma$ average
1. World average prospects

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

![Graph showing excluded area with CL > 0.95 and CKM fit parameters](image)

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Some future possibilities with the CKM angle $\gamma$ average
What can we do with a precision $< 1^\circ$?

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

### Penguin free measurement of $\phi_s$?

- $\sqrt{1-C_f^2}$
- $(-A_f^{\Delta T}, S_f)$
- $(-A_f^{\Delta T}, S_{-f})$
- $(-\gamma-2\beta_s)$
- Combination

### 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

See Mark Whitehead’s talk on Thursday for more.
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 $\gamma$ (values are fixed)
- At present use measurements from CLEO-c, in the future these will come from BESIII

\[ R^{\pm}_{ij} = r_b - \langle t \rangle \sqrt{r_b} \left[ (1 - r_b)c_b y - (1 + r_b)s_b x \right] \]

\[ N^+_{\pm i} = h_{B^+} \left[ F_{\pm i} + (x_i^2 + y_i^2)F_{\pm i} + 2\sqrt{F_i}F_{\pm i}(x_i - c_{\pm i}) - y_i s_{\pm i} \right] \]

\[ N^-_{\pm i} = h_{B^-} \left[ F_{\pm i} + (x_i^2 + y_i^2)F_{\pm i} + 2\sqrt{F_i}F_{\pm i}(x_i - c_{\pm i}) - y_i s_{\pm i} \right] \]
2. Combined fits with charm and beauty data

**Beauty and Charm combined fit inputs**

### Generated toys for projected future luminosities at LHCb

1. **Charm strong phases in** \( D \to K^0_S\pi\pi, \ c_b \) and \( s_b \)
   - Use CLEO central values and uncertainties
   - Use CLEO central values with projected BES-III uncertainties \((\times10\mathcal{L})\)

2. **Charm Bin Flip method in decay-time bins** \((j)\) and Dalitz bins \((b)\) for \( D \to K^0_S\pi\pi \)
   - Use toys with “Optimal-Binning” estimating both Prompt and SL yields
   
   \[
   R_{bj}^{\pm} \approx \frac{r_b \left[ 1 + \frac{1}{4} \langle t^2 \rangle_j \text{Re}(z_{CP}^2 - \Delta z^2) \right] + \frac{1}{4} \langle t^2 \rangle_j |z_{CP} \pm \Delta z|^2 + \sqrt{r_b} \langle t \rangle_j \text{Re} [X_b^*(z_{CP} \pm \Delta z)]}{1 + \frac{1}{4} \langle t^2 \rangle_j \text{Re}(z_{CP}^2 - \Delta z^2) + r_b \frac{1}{4} \langle t^2 \rangle_j |z_{CP} \pm \Delta z|^2 + \sqrt{r_b} \langle t \rangle_j \text{Re} [X_b(z_{CP} \pm \Delta z)]}
   \]
   - With \( r_b = F_{-b}/F_b \), \( X_b = c_i - is_i \), \( z = -(y_D + ix_D) \), \( (q/p)^{\pm1}z = z_{CP} + \Delta z \)

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”

   \[
   N_{\pm b}^{+} = h_{B^+} \left[ F_{\mp b} + (x_+^2 + y_+^2)F_{\pm b} + 2\sqrt{F_iF_{-b}}(x_+c_{\pm b} - y_+s_{\pm b}) \right]
   \]
   \[
   N_{\pm b}^{-} = h_{B^-} \left[ F_{\pm b} + (x_-^2 + y_-^2)F_{\mp b} + 2\sqrt{F_iF_{-b}}(x_-c_{\pm b} - y_-s_{\pm b}) \right]
   \]
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), $\Delta x$, $\Delta y$ (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. $(r_B, \delta_B, \gamma)$

**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 ...

![Graph 1](image1.png)

![Graph 2](image2.png)
2. Combined fits with charm and beauty data

Beauty and Charm combined fit results ($b$ parameters)

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

![Graphs showing combined fit results](image-url)
2. Combined fits with charm and beauty data

Beauty and Charm combined fit results ($c$ parameters)

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

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![Graph showing combined fits with charm and beauty data](image-url)
3. Probing new physics at tree-level

Some preliminary studies in the process of being written up for publication.
3. Probing new physics at tree-level

Sensitivity to tree-level Wilson coefficients

- We always say CKM angle $\gamma$ is a SM benchmark with negligible theoretical uncertainty - $O(10^{-7})^\circ$
- 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

$$\mathcal{H}_{\text{eff}}^{u_1 \bar{u}_2 d_1} = \frac{G_f}{\sqrt{2}} V_{u_1 b} V_{\bar{u}_2 d_1}^* \left[ C_1 Q_1^{u_1 \bar{u}_2 d_1} + C_2 Q_2^{u_1 \bar{u}_2 d_1} \right]$$

$$C_1 = C_1^{SM} + \Delta C_1^{NP}$$
$$C_2 = C_2^{SM} + \Delta C_2^{NP}$$
3. Probing new physics at tree-level

Sensitivity to tree-level Wilson coefficients

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

\[
\begin{align*}
 r_B e^{i(\delta_B \pm \gamma)} &\rightarrow r_B e^{i(\delta_B \pm \gamma)} \\
 &\quad \times \left[ 1 + (r_{A'} - r_A) \frac{\Delta C_1^{NP}}{C_2} \right]
\end{align*}
\]

In particular note that:

\[
\gamma \rightarrow \gamma \left[ 1 + (r_A - r_{A'}) \frac{\text{Im}(\Delta C_1^{NP})}{C_2} \right]
\]

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 $\Delta A = (r_{A'} - r_A) \Delta C_1^{NP} / C_2$
Sensitivity to tree-level Wilson coefficients

Modification of decay rate

\[ \Gamma(B^\pm \rightarrow DK^\pm) \rightarrow \left| r_D e^{-i\delta_D} + r_B e^{i(\delta_B \pm \gamma)}(1 + A) \right|^2 \]
Sensitivity to tree-level Wilson coefficients

Modification of decay rate

\[ \Gamma(B^{\pm} \rightarrow DK^{\pm}) \rightarrow |r_D e^{-i\delta_D} + r_B e^{i(\delta_B \pm \gamma)}(1 + A)|^2 \]

Effect exaggerated for visualization!
3. Probing new physics at tree-level

Sensitivity to tree-level Wilson coefficients

Sensitivity to generic NP contribution in complex number $A$

$$A = (r_{A'} - r_A) \frac{\Delta C_{1}^{NP}}{C_2}$$

Future exclusion profile for $A$

- What values of $A$ can be excluded in the future

Using “still allowed” NP contribution

- Estimate $\Delta r = r_{A'} - r_A \approx 0.6$ and allow $\text{Im}(\Delta C_{1}^{NP}(m_b)) \sim \mathcal{O}(10\%)$

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

- $B \to D\pi$, $B \to D^{*0} h^0$, $B \to X_{d(s)}\gamma$, $a_{sl}^{d(s)}$, $B \to \pi\pi$
3. Probing new physics at tree-level

Sensitivity to tree-level Wilson coefficients

Sensitivity to generic NP contribution in complex number $A$

$$A = (r_{A'} - r_A) \frac{\Delta C_{1}^{NP}}{C_2}$$

Future exclusion profile for $A$

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Using “still allowed” NP contribution

- Estimate $\Delta r = r_{A'} - r_A \approx 0.6$ and allow $\text{Im}(\Delta C_{1}^{NP}(m_b)) \sim O(10\%)$

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

$$B \to D \pi, B \to D^{*0} h^0, B \to X_{d(s)} \gamma, a_{s,l}^{d(s)}, B \to \pi \pi$$
3. Probing new physics at tree-level

Summary

- If LHCb collects $\geq 300 \text{ fb}^{-1}$ $\gamma$ will reach $O(0.4^\circ)$ precision
- Will have $< 1^\circ$ precision independently in $B^+, B^0$, and $B_s^0$ modes
- Will allow for penguin free measurement of $\phi_s$ with $\sim 0.02 \text{ rad}$ precision
- Fitting charm and beauty datasets in a combined way offers some benefit to charm mixing measurements with $D^0 \rightarrow K_S^0 \pi \pi$ but not much for beauty parameters
- Carefully considering correlations will be crucial
- BESIII inputs will be vital for the ultimate precision on $\gamma$
- 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!