Measuring the CKM angle $\gamma$

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The LHCb Spectrometer

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Feinmann diagram for $B_s \rightarrow D_s^+ K^-$

1. Only tree diagrams
2. But: problem of discrete ambiguities
3. Solve by using equivalent decay with $B_d$:
4. But: very small interference effects for $B_d \rightarrow D_s^{\ast\pm} \pi^{\mp}$, and $B_d \rightarrow D^{\pm} \pi^{\mp}$
5. Circumvent problems using assumption of U-spin symmetry $(s \leftrightarrow d)$
6. Simultaneous analysis of $B_s \rightarrow D_s^{\pm} K^{\mp}$ and $B_d \rightarrow D^{\pm} \pi^{\mp}$
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Measuring the CKM angle $\gamma$ from LHCb
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Sensitivity to $\gamma$ through

- matrix element $V_{ub} V_{cs}^*$
- c.f. $\gamma \sim \arg(V_{ub})$
- not enough: need 2nd diagram for interference:
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Diagram for $B_s \to D_s^- K^+$
\[\gamma \text{ from LHCb(II)}\]

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Diagram for \(B_s \to D_s^- K^+\)
\( \gamma \) from LHCb(II)

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- c.f. \( \gamma \sim \text{arg}(V_{ub}) \)
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Diagram for \( B_s \rightarrow D_s^- K^+ \)  
Diagram for \( B_s \rightarrow D_s^+ K^- \)
A Combined $B_s \rightarrow D_s^{\pm} K^{\mp}$ and $B_d \rightarrow D^{\pm} \pi^{\mp}$ Analysis

- Interference through mixing
- CP asymmetries measure $\gamma + \phi_s$
- Tree diagrams only: NO sensitivity to New Physics
- 5400 $B_s \rightarrow D_s K$ events/year at LHCb
- 82000 $B_s \rightarrow D_s \pi$ events/year
\[ A_{CP}(D_s^+K^-) = \frac{B_s \to D_sK^-(t) - \bar{B}_s \to D_sK^-(t)}{B_s \to D_sK^-(t) + \bar{B}_s \to D_sK^-(t)} \]

dependence:

\[ A_{CP}(D_s^+K^-) = \frac{C_s \cos \Delta m_s t + S_s \sin \Delta m_s t}{\cosh(\Delta \Gamma_s t/2) - A_{\Delta \Gamma_s} \sinh(\Delta \Gamma_s t/2)} \]

1. \( \Delta m_s \): mass difference between heavy & light B-meson
2. \( \Delta \Gamma_s \): lifetime difference between heavy & light B-meson
3. \( C_s \) depends on ratio of amplitudes of Feynmann diagrams
4. Similarly done for \( D_s^-K^+ \) analysis
Time-dependent Asymmetries

\[ A_{\text{CP}}(D_s^+K^-) = \frac{B_s \to D_sK^-(t) - \bar{B}_s \to D_sK^-(t)}{B_s \to D_sK^-(t) + \bar{B}_s \to D_sK^-(t)} \]

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Time-dependent Asymmetries

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dependence:

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\[ S_s(\bar{S}_s) \sim \sin(\phi_s + \gamma \pm \delta_s) \]

\[ A_{\Delta \Gamma_s} \sim - \cos(\phi_s + \gamma \pm \delta_s) \]
LHCb Simulated Results

From ~ 5 years of LHCb data:

1. Phase of $D_s^+K^- \delta_s + (\gamma + \phi_s)$
2. Phase of $D_s^-K^+ \delta_s - (\gamma + \phi_s)$
3. $\phi_s$ deduced from $B_s \rightarrow J/\psi\phi$ analysis $\implies$ determine $\gamma$.
4. $\Delta m_s \sim 20$ ps$^{-1}$: $\sigma_{\gamma} \approx 14^\circ$
5. Solve discrete ambiguities with help of $B_d \rightarrow D^+\pi^-$
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γ from $B \rightarrow h^+ h^-$

1. time-dependent CP-asymmetries for $B^0_d \rightarrow \pi^+ \pi^-$ and $B_s \rightarrow K^+ K^-$
2. But: penguin diagram contributes!
3. $A_{\text{dir}}, A_{\text{mix}}$ depend on $\phi_s, \phi_d \& \gamma$
4. and on ratio of penguin to tree amplitudes: $de^{i\theta}$
5. with U-spin symmetry: $d_{\pi \pi} = d_{KK}$, $\theta_{\pi \pi} = \theta_{KK}$
6. $\phi_s$ from $B_s \rightarrow J/\psi \phi$ and $\phi_d$ from $B_d \rightarrow J/\psi K_s$
7. 4 measurements, 3 unknowns $\Rightarrow$ extract $\gamma, \sigma_\gamma = 5^\circ$
\( \gamma \) from \( B \to h^+ h^- \)

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7. 4 measurements, 3 unknowns

8. \( \Rightarrow \) extract \( \gamma, \sigma_\gamma = 5^\circ \)
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1. Time-dependent CP-asymmetries for $B_d^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$.
2. But: penguin diagram contributes!

$$A_{CP}(t) = A_{dir} \cos(\Delta mt) + A_{mix} \sin(\Delta mt)$$

4. $A_{dir}, A_{mix}$ depend on $\phi_s, \phi_d$ & $\gamma$ and on ratio of penguin to tree amplitudes: $de^{i\theta}$

5. With U-spin symmetry: $d_{\pi\pi} = d_{KK}$, $\theta_{\pi\pi} = \theta_{KK}$

6. $\phi_s$ from $B_s \to J/\psi\phi$ and $\phi_d$ from $B_d \to J/\psi K_s$

7. 4 measurements, 3 unknowns $\implies$ extract $\gamma, \sigma_\gamma = 5^\circ$
\( \gamma \) from \( B \to h^+h^- \)

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1. time-dependent CP-asymmetries for \( B^0_d \rightarrow \pi^+ \pi^- \)
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7. \( \phi_s \) from \( B_s \rightarrow J/\psi \phi \) and \( \phi_d \) from \( B_d \rightarrow J/\psi K_s \)
8. 4 measurements, 3 unknowns \( \implies \) extract \( \gamma, \sigma_\gamma = 5^\circ \)
Conclusions

1. **Determine $\gamma$ from tree-diagrams only:**
   $B_s \rightarrow D^\pm_s K^\mp$
   - Use U-spin symmetry to resolve discrete ambiguities
   - Measure time-dependent $CP$-asymmetry
   - $\phi_s$ measured with $B_s \rightarrow J/\psi \phi$ analysis

2. **Determine $\gamma$ from $B_s \rightarrow K^\pm K^\mp$ and $B^0 \rightarrow \pi^+\pi^-$**
   - Measure 2 time-dependent $CP$ asymmetries
   - Problem: penguin diagram contributes
   - Need angles $\phi_s$ and $\phi_d$ from $B_s \rightarrow J/\psi \phi$ and $B^0 \rightarrow J/\psi K_s$

3. $\Rightarrow$ sensitivity to New Physics through Penguin diagram
Conclusions

1. Determine $\gamma$ from tree-diagrams only:
   $B_s \rightarrow D_s^{\pm} K^{\mp}$

   - Use U-spin symmetry to resolve discrete ambiguities

2. Measure time-dependent CP-asymmetry
   $\phi_s$ measured with $B_s \rightarrow J/\psi \phi$ analysis

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   2. Measure time-dependent CP-asymmetry
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   2. Measure time-dependent CP-asymmetry
   3. $\phi_s$ measured with $B_s \rightarrow J/\psi \phi$ analysis

2. Determine $\gamma$ from $B_s \rightarrow K^\pm K^\mp$ and $B^0 \rightarrow \pi^+ \pi^-$
   1. Measure 2 time-dependent CP asymmetries
   2. Problem: penguin diagram contributes
   3. Need angles $\phi_s$ and $\phi_d$ from $B_s \rightarrow J/\psi \phi$ and $B^0 \rightarrow J/\psi K_s$

3. $\Rightarrow$ sensitivity to New Physics through Penguin diagram
Conclusions

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   \[ B_s \rightarrow D_s^{\pm} K^{\mp} \]
   1. Use U-spin symmetry to resolve discrete ambiguities
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Measuring the CKM angle $\gamma$