Time-integrated measurements of the Unitary Triangle angle $\gamma$

EPS-HEP Conference 2019

Alexandra Rollings on behalf of the LHCb Collaboration

University of Oxford

11th July 2019
Contents

1. Introduction to time independent $\gamma$ measurements
2. How $\gamma$ is measured using tree-level decays
3. The 2018 LHCb combination
4. Update of the $B^0 \rightarrow D K^*0$ ADS/GLW analysis - NEW!
The Unitary Triangle angle $\gamma$

- The CKM matrix can be parameterised to have a single irreducible complex phase, which is the only known source of $CP$ violation within the quark sector:

$$V_{CKM} = \begin{pmatrix}
1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & A\lambda^2 & 1
\end{pmatrix} + \mathcal{O}(\lambda^4)$$
The Unitary Triangle angle $\gamma$

• The CKM matrix can be parameterised to have a single irreducible complex phase, which is the only known source of $CP$ violation within the quark sector:

$$V_{CKM} = \begin{pmatrix}
1 - \lambda^2 /2 & \lambda & A\lambda^3 (\rho - i\eta) \\
-\lambda & 1 - \lambda^2 /2 & A\lambda^2 \\
A\lambda^3 (1 - \rho - i\eta) & A\lambda^2 & 1
\end{pmatrix} + \mathcal{O}(\lambda^4)$$

• The unitary triangle angle $\gamma = \arg \left(-\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*}\right)$
  
  ➢ No top coupling
  ➢ No need for box/loop processes
  ➢ Time independent measurements at tree level!
  ➢ Particularly clean (assuming no enters NP at tree-level)
The Unitary Triangle angle $\gamma$

- The CKM matrix can be parameterised to have a single irreducible complex phase, which is the only known source of $CP$ violation within the quark sector:

$$V_{CKM} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

- The unitary triangle angle $\gamma = \arg \left( -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right)$
  - No top coupling
  - No need for box/loop processes
  - Time independent measurements at tree level!
  - Particularly clean (assuming no enters NP at tree-level)
  - $B \to D X_s: \frac{\Delta \gamma}{\gamma} \sim 10^{-7}$  [JHEP01(2014)051]

To $O(\lambda^3)$, phase only exists in $V_{ub}$: access $\gamma$ using $b \to u$ interfering with $b \to c$ transition
Accessing $\gamma$ with $B \rightarrow DX$ decays

$B = B^-/\bar{B}^0$

$\bar{D}^0X$  $\rightarrow$  $f(D)X$

$D^0X$
Accessing $\gamma$ with $B \rightarrow DX$ decays

$A_B r_B^X e^{i(\delta_B^X - \gamma)}$

$B = B^- / B^0$

$\overline{D}^0 X$ ~ $f(D)X$

$A_B$

$D^0 X$

- $b \rightarrow u$ transition in $B \rightarrow \overline{D}^0 X$ suppressed w.r.t. $b \rightarrow c$ transition in $B \rightarrow D^0 X$
  - 2 possible paths with amplitude ratio $r_B^X$, $CP$ conserving phase $\delta_B^X$ and $CP$ violating phase $\gamma$
Accessing $\gamma$ with $B \to DX$ decays

$A_B r_B^X e^{i(\delta_B^X - \gamma)}$ → $D^0 X$

- $b \to u$ transition in $B \to D^0 X$ suppressed w.r.t. $b \to c$ transition in $B \to D^0 X$
  - 2 possible paths with amplitude ratio $r_B^X$, CP conserving phase $\delta_B^X$ and CP violating phase $\gamma$
- $\gamma$ CP violates $\to$ changes sign under charge conjugation
  - Look for differences in decay rates ($\Gamma \propto |\sum_i A_i|^2$) of $B^{-}(B^0)$ and $B^+ (\bar{B}^0)$ mesons
Accessing $\gamma$ with $B \to DX$ decays

- $b \to u$ transition in $B \to \bar{D}^0X$ suppressed w.r.t. $b \to c$ transition in $B \to D^0X$
  - 2 possible paths with amplitude ratio $r_B^X$, CP conserving phase $\delta_B^X$ and CP violating phase $\gamma$
- $\gamma$ CP violates $\to$ changes sign under charge conjugation
  - Look for differences in decay rates ($\Gamma \propto |\sum_i A_i|^2$) of $B^- (B^0)$ and $B^+ (\bar{B}^0)$ mesons
- Different decay modes have different $r_B^X, \delta_B^X$, but the same $\gamma$!

$A_B r_B^X e^{i(\delta_B^X - \gamma)}$

$B = B^- / \bar{B}^0$

$\bar{D}^0X$

$f(D)X$

$D^0X$

Alexandra Rollings

Time-integrated measurements of the UT angle $\gamma$
• There are several classes of analysis, depending on the final state the $D$ meson is reconstructed in:

1. **GLW**: $D \rightarrow KK, \pi\pi, \pi\pi\pi\pi, KK\pi^0, \pi\pi\pi^0$ [Phys. Lett. B253 (1991) 483] \rightarrow CP or CP-like eigenstates

2. **ADS**: $D \rightarrow \pi K, \pi K\pi\pi, \pi K\pi^0$ [Phys. Lett. D63 (2001) 036005] \rightarrow CF or DCS final state

3. **GGSZ**: $D \rightarrow K_S^0\pi\pi, K_S^0KK$ [Phys. Lett. D68 (2003) 054018] \rightarrow 3-body final state

$B^- \rightarrow [K^0_S h^+ h^-]_D K^- (h = \pi/K):$ the GGSZ Method

$A_B r_B^{DK} e^{i(\delta_B^{DK} - \gamma)}$

$B^-$

$D^0 K^-$

$[K^0_S h^+ h^-]_D K^-$

$A_B$

$D^0 K^-$

Time-integrated measurements of the UT angle $\gamma$
$B^- \rightarrow [K_S^0 h^+ h^-]_D K^- (h = \pi/K)$: the GGSZ Method

- $D = D^0 / \bar{D}^0$ decaying to the same final state have different amplitudes and strong phases
- 3-body $D$ decay $\rightarrow$ measure $B^+ \text{ and } B^-$ yields in Dalitz bins, with axes $m^2_{\pm} = m^2 (K_S^0, h^\pm)$
- Strong phase difference, $\Delta \delta_{D_i} = \delta_{\bar{D}_i} - \delta_{D_i}$ varies across the Dalitz plane

\[
A_B r_B^{DK} e^{i(\delta_B^{DK} - \gamma)} \rightarrow D^0 K^- \quad A_{\bar{D}} e^{-i\delta_{\bar{D}_i}} \rightarrow [K_S^0 h^+ h^-]_{D_i} K^-
\]

\[
B^- \rightarrow [K_S^0 h^+ h^-]_D K^- (h = \pi/K): \text{ the GGSZ Method}
\]
$B^- \rightarrow [K_S^0 h^+ h^-]_D K^- \ (h = \pi/K)$: the GGSZ Method

- $D = D^0/\bar{D}^0$ decaying to the same final state have different amplitudes and strong phases.
- 3-body $D$ decay $\rightarrow$ measure $B^+$ and $B^-$ yields in Dalitz bins, with axes $m_\pm^2 = m^2 (K_S^0, h^\pm)$.
- Strong phase difference, $\Delta \delta_{D_i} = \delta_{\bar{D}_i} - \delta_{D_i}$ varies across the Dalitz plane.
$B^- \rightarrow [K_S^0 h^+ h^-]_D K^- \ (h = \pi/K)$: the GGSZ Method

$A_B r_B^{DK} e^{i(\delta_B^{DK} - \gamma)}$

$\bar{D}^0 K^-$

$A_{\bar{D}_i} e^{-i\delta_{\bar{D}_i}}$

$[K_S^0 h^+ h^-]_{D_i} K^-$

$A_B$

$D^0 K^-$

$A_{D_i} e^{-i\delta_{D_i}}$

- $D = D^0 / \bar{D}^0$ decaying to the same final state have different amplitudes and strong phases
- 3-body $D$ decay $\rightarrow$ measure $B^+$ and $B^-$ yields in Dalitz bins, with axes $m_{\pm}^2 = m^2 (K_S^0, h^\pm)$
- Strong phase difference, $\Delta\delta_{D_i} = \delta_{\bar{D}_i} - \delta_{D_i}$ varies across the Dalitz plane

$D_i$ sits on one side of the $y = x$ axis of symmetry, $\bar{D}_i$ on the other

Alexandra Rollings
Time-integrated measurements of the UT angle $\gamma$

[JHEP 08 (2018) 176]
The model independent GGSZ method

• Look for differences between $B^+$ and $B^-$ yields in each bin $\pm i$:

$$N_{\pm i}^- \propto F_{\pm i} + (x^2 + y^2)F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_- c_{\pm i} + y_- s_{\pm i})$$

$$N_{\pm i}^+ \propto F_{\mp i} + (x^2 + y^2)F_{\pm i} + 2\sqrt{F_i F_{-i}}(x_+ c_{\pm i} - y_+ s_{\pm i})$$
The model independent GGSZ method

• Look for differences between $B^+$ and $B^-$ yields in each bin $\pm i$:

$$N_{\pm i}^- \propto F_{\pm i} + (x_\pm^2 + y_\pm^2)F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_\pm c_{\pm i} + y_\pm s_{\pm i})$$

$$N_{\pm i}^+ \propto F_{\mp i} + (x_\pm^2 + y_\pm^2)F_{\pm i} + 2\sqrt{F_i F_{-i}}(x_\pm c_{\pm i} - y_\pm s_{\pm i})$$

$$c_i = \frac{\int_i |A_{\bar{D}_i}||A_{D_i}| \cos[\delta_{\bar{D}_i} - \delta_{D_i}]}{\sqrt{\int_i |A_{\bar{D}_i}|^2 \int_i |A_{D_i}|^2}}$$

$$s_i = \frac{\int_i |A_{\bar{D}_i}||A_{D_i}| \sin[\delta_{\bar{D}_i} - \delta_{D_i}]}{\sqrt{\int_i |A_{\bar{D}_i}|^2 \int_i |A_{D_i}|^2}}$$

$c_{\pm i}/s_{\pm i}$: strong phase information from CLEO-c measurements [PR: 82:112006]
The model independent GGSZ method

• Look for differences between $B^+$ and $B^-$ yields in each bin $\pm i$:

\[
N_{\pm i}^- \propto F_{\pm i} + (x_-^2 + y_-^2)F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_- c_{\pm i} + y_- s_{\pm i})
\]
\[
N_{\pm i}^+ \propto F_{\mp i} + (x_+^2 + y_+^2)F_{\pm i} + 2\sqrt{F_i F_{-i}}(x_+ c_{\pm i} - y_+ s_{\pm i})
\]

$F_{\pm i}$: Fractional yield of flavour tagged $D$ in bin $\pm i$

Measured using control channel:
$\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu X$

$c_{\pm i}/s_{\pm i}$: strong phase information from CLEO-c measurements
[PR: 82:112006]
The model independent GGSZ method

• Look for differences between $B^+$ and $B^-$ yields in each bin $\pm i$:

\[
N_{\pm i}^- \propto F_{\pm i} + (x_-^2 + y_-^2)F_{\mp i} + 2\sqrt{F_i F_{-i}}(x_- c_{\pm i} + y_- s_{\pm i}) \\
N_{\pm i}^+ \propto F_{\mp i} + (x_+^2 + y_+^2)F_{\pm i} + 2\sqrt{F_i F_{-i}}(x_+ c_{\pm i} - y_+ s_{\pm i})
\]

- $F_{\pm i}$: Fractional yield of flavour tagged $D$ in bin $\pm i$
- Measured using control channel: $\bar{B}^0 \to D^{*+} \mu^- \nu_\mu X$
- $CP$ violating parameters:
  \[
  x_\pm = r_B^{DK} \cos(\delta_B \pm \gamma) \\
y_\pm = r_B^{DK} \sin(\delta_B \pm \gamma)
  \]
- $c_{\pm i}/s_{\pm i}$: strong phase information from CLEO-c measurements

[PR: 82:112006]
Asymmetry in Dalitz bins [JHEP 08 (2018) 176]

- Analysis used 2015 + 2016 data (= 2 fb⁻¹)
- Compare \( B^- \) yields in bin \(+i\) to \( B^+ \) yields in bin \(-i\) (reflection in Dalitz axis of symmetry)

\[
B^- \to D(\to K_S^0\pi^+\pi^-)K^- \quad \text{Bin: +4}
\]

\[
B^+ \to D(\to K_S^0\pi^+\pi^-)K^+ \quad \text{Bin: -4}
\]

LHCb

Difference in peak heights = CP Violation!
• 16 bins for $B^+$ and $B^-$ means 32 observables to measure 4 parameters

• Over-constrained system removes ambiguities present in single-mode analyses (ADS/GLW)

• Opening angle between $(x_+, y_+)$ and $(x_-, y_-)$ gives $\gamma = (87^{+11}_{-12})^\circ$
• The GGSZ results for \((x_\pm, y_\pm)\) is combined with many other LHCb results to extract a combined value of \(\gamma\).

• The world average is currently dominated by the LHCb 2018 combination: \(\gamma = (74.0^{+5.0}_{-5.8})^\circ\)
  - Combined result obtained by minimising a global \(\chi^2\) calculation
  - Uncertainties calculated with a pseudo-experiment approach (Plugin method)
• The GGSZ results for \( (x_\pm, y_\pm) \) is combined with many other LHCb results to extract a combined value of \( \gamma \)

• The world average is currently dominated by the LHCb 2018 combination: \( \gamma = (74.0^{+5.0}_{-5.8})^\circ \)
  - Combined result obtained by minimising a global \( \chi^2 \) calculation
  - Uncertainties calculated with a pseudo-experiment approach (Plugin method)

<table>
<thead>
<tr>
<th>Run 1:</th>
<th>Run 1 &amp; Run 2 (2015 + 2016):</th>
</tr>
</thead>
</table>
| • 3 fb\(^{-1}\) of data at \( \sqrt{s} = 7/8 \) TeV | • 3 fb\(^{-1}\) of data at \( \sqrt{s} = 7/8 \) TeV
• 2 fb\(^{-1}\) of data at \( \sqrt{s} = 13 \) TeV |
| • \( B^- \to DK^- \) ADS & GLS | • \( B^- \to DK^- \) GLW & GGSZ
• \( B^- \to DK^+\pi^-\pi^+ \) GLW & ADS
• \( B^0 \to DK^{*0} \) ADS & GGSZ
• \( B^0 \to DK^+\pi^- \) GLW-Dalitz
• \( B_s^0 \to D_s^{\pm} K^\pm \) TD
• \( B^0 \to D^\pm\pi^\mp \) TD |
| Sevda’s talk | • \( B^- \to D^*K^- \) GLW
• \( B^- \to D^*K^- \) GLW
• \( B^- \to DK^{*-} \) GLW & ADS |
• The GGSZ results for \((x_\pm, y_\pm)\) is combined with many other LHCb results to extract a combined value of \(\gamma\)

• The world average is currently dominated by the LHCb 2018 combination: \(\gamma = (74.0^{+5.0}_{-5.8})^\circ\)
  ➢ Combined result obtained by minimising a global \(\chi^2\) calculation
  ➢ Uncertainties calculated with a pseudo-experiment approach (Plugin method)

Run 1:
- 3 fb\(^{-1}\) of data at \(\sqrt{s} = 7/8\) TeV
- 2017 + 2018 data not yet in the combination. Some way from the full Run1 & Run2 \(\gamma\) result

Run 1 & Run 2 (2015 + 2016):
- 3 fb\(^{-1}\) of data at \(\sqrt{s} = 7/8\) TeV
- 2 fb\(^{-1}\) of data at \(\sqrt{s} = 13\) TeV
- \(B^- \rightarrow DK^-\) ADS & GLS
- \(B^- \rightarrow D K^+ \pi^- \pi^+\) GLW & ADS
- \(B^0 \rightarrow D K^*0\) ADS & GGSZ
- \(B^0 \rightarrow D K^+ \pi^-\) GLW-Dalitz
- \(B^0 \rightarrow D_s^+ K^\pm\) TD
- \(B^0 \rightarrow D^{+\mp}\) TD
- \(B^- \rightarrow D K^-\) GLW & GGSZ
- \(B^- \rightarrow D^* K^-\) GLW
- \(B^- \rightarrow D K^{*-}\) GLW & ADS

Alexandra Rollings

Time-integrated measurements of the UT angle \(\gamma\)
• The combination is currently dominated by analyses of $B^{-}$ decays; increasing focus on developing analyses of $B^{0}$ (next) and $B_{s}^{0}$ mesons (TD):

![Graph showing time-integrated measurements of the UT angle γ](image-url)
$B^0 \rightarrow DK^{*0}$ decays

$B^0 \rightarrow D^0 K^{*0}$

$\bar{D}^0 K^{*0} \rightarrow f(D)K^{*0}$
Both paths are colour suppressed → larger $r_B$ than in $B^-$ decays:

Favoured $b \rightarrow c$: $B^-$

$B^-$
\[
\begin{align*}
\bar u & \quad \bar u \\
\bar u & \quad \bar u \\
r_B^{DK} \sim 0.1
\end{align*}
\]

$V_{cb}$
$B^0 \to D K^{*0}$ decays

$A_B r_B^{DK^{*0}} e^{i(\delta_B^{DK^{*0}} - \gamma)} \quad D^0 K^{*0} \quad A_D \quad f(D)K^{*0}$

$A_B \quad \bar{D}^0 K^{*0} \quad A_D r_D e^{-i\delta_D}$

- $D = D^0 / \bar{D}^0$ decaying 2/4-body final states with amplitude ratio $r_D$ and phase difference $\delta_D$
  - 2 possible paths proceed at a similar rate $\rightarrow$ larger interference effect
The ADS Method

• 2-body: $D^0 \rightarrow K^+\pi^-$, $\bar{D}^0 \rightarrow K^+\pi^-$ and charge conjugates
  • Former is doubly-Cabibbo suppressed w.r.t. the latter ($r_D \sim 0.06$)

• Look for differences in decay rates ($\Gamma \propto |\sum_i A_i|^2$) of $B^0$ and $\bar{B}^0$ mesons:

\[
\Gamma(B^0 \rightarrow DK^{*0}) \propto r_D^2 + r_B^{DK^{*0}}^2 + 2\kappa r_D r_B^{DK^{*0}} \cos(\delta_B^{DK^{*0}} + \delta_D + \gamma)
\]

\[
\Gamma(\bar{B}^0 \rightarrow D\bar{K}^{*0}) \propto r_D^2 + r_B^{DK^{*0}}^2 + 2\kappa r_D r_B^{DK^{*0}} \cos(\delta_B^{DK^{*0}} + \delta_D - \gamma)
\]

Smaller ADS asymmetries than in $B^- \rightarrow DK^-$: interference terms enhanced when $r_D \sim r_B$
The ADS Method

• 2-body: \(D^0 \rightarrow K^+\pi^-, \overline{D}^0 \rightarrow K^+\pi^-\) and charge conjugates
  • Former is doubly-Cabibbo suppressed w.r.t. the latter (\(r_D \sim 0.06\))

• Look for differences in decay rates (\(\Gamma \propto |\sum_i A_i|^2\)) of \(B^0\) and \(\overline{B}^0\) mesons:
  \[
  \begin{align*}
  \Gamma(B^0 \rightarrow DK^{*0}) & \propto r_D^2 + r_B^{DK^{*0}}^2 + 2\kappa r_D r_B^{DK^{*0}} \cos(\delta_B^{DK^{*0}} + \delta_D + \gamma) \\
  \Gamma(\overline{B}^0 \rightarrow D\overline{K}^{*0}) & \propto r_D^2 + r_B^{DK^{*0}}^2 + 2\kappa r_D r_B^{DK^{*0}} \cos(\delta_B^{DK^{*0}} + \delta_D - \gamma)
  \end{align*}
  \]

Smaller ADS asymmetries than in \(B^- \rightarrow DK^-\):
interference terms enhanced when \(r_D \sim r_B\)

• Coherence factor, \(\kappa\), accounts for non-\(K^{*0}\) contributions to \(B^0 \rightarrow DK^+\pi^-\)
  • \(\kappa = 0.958^{+0.005}_{-0.046}\) [PRD 93 (2016) 112018]
The ADS Method

• 2-body: \( D^0 \to K^+\pi^- \), \( \bar{D}^0 \to K^+\pi^- \) and charge conjugates
  - Former is doubly-Cabibbo suppressed w.r.t. the latter (\( r_D \sim 0.06 \))

• Look for differences in decay rates (\( \Gamma \propto |\sum_i A_i|^2 \)) of \( B^0 \) and \( \bar{B}^0 \) mesons:

\[
\Gamma(B^0 \to D K^*) \propto r_D^2 + r_B^{DK^*2} + 2\kappa r_D r_B^{DK^*} \cos(\delta_B^{DK^*} + \delta_D + \gamma)
\]

\[
\Gamma(\bar{B}^0 \to \bar{D} \bar{K}^*) \propto r_D^2 + r_B^{DK^*2} + 2\kappa r_D r_B^{DK^*} \cos(\delta_B^{DK^*} + \delta_D - \gamma)
\]

• Measure ratios of the suppressed decay to their favoured counterparts:

\[
R_{\pi K}^- = \frac{\Gamma(\bar{B}^0 \to [\pi^- K^+]_{D \bar{K}^*0})}{\Gamma(\bar{B}^0 \to [K^- \pi^+]_{D \bar{K}^*0})}
\]

\[
R_{\pi K}^+ = \frac{\Gamma(B^0 \to [\pi^+ K^-]_{D K^*0})}{\Gamma(B^0 \to [K^+ \pi^-]_{D K^*0})}
\]

\( R_{\pi K}^+ \neq R_{\pi K}^- \to CP \) violation!
$B^0 \rightarrow DK^*0, D \rightarrow \pi K$ results [LHCb-PAPER-2019-021] – NEW!

\[ R_{\pi K} = 0.095 \pm 0.021 \pm 0.003 \]

\[ R_+^{\pi K} = 0.064 \pm 0.021 \pm 0.002 \]

- 2011-2016 data (= 5 fb$^{-1}$)

Favoured yield = 786 ± 29
Suppressed yield = 76 ± 16

Favoured yield = 754 ± 29
Suppressed yield = 47 ± 15
$B^0 \rightarrow DK^*0, D \rightarrow \pi K$ results [LHCb-PAPER-2019-021] – NEW!

$R^{\pi K} = 0.095 \pm 0.021 \pm 0.003$

$R^{\pi K} = 0.064 \pm 0.021 \pm 0.002$

- 2011-2016 data (= 5 fb$^{-1}$)
- Suppressed mode significance: 5.8$\sigma$ - first observation!

Favoured yield = 786 ± 29
Suppressed yield = 76 ± 16

Favoured yield = 754 ± 29
Suppressed yield = 47 ± 15
$B^0 \to DK^{*0}, D \to \pi K$ results [LHCb-PAPER-2019-021] – NEW!

- 2011-2016 data (= 5 fb$^{-1}$)
- Suppressed mode significance: 5.8$\sigma$ - first observation!

\[ R^{\pi K} = 0.095 \pm 0.021 \pm 0.003 \]
\[ R^+_{\pi K} = 0.064 \pm 0.021 \pm 0.002 \]
$B^0 \to D K^{*0}, D \to \pi K \pi \pi$ results [LHCb-PAPER-2019-021] – NEW!

- 4-body: coherence factor $\kappa^{K3\pi}_D$ enters as a pre-factor to the interference term [PLB 757 (2016) 520].
  Different $\tau^{K3\pi}_D$ and $\delta^{K3\pi}_D$

- 2011-2016 data (= 5 fb$^{-1}$)
$B^0 \rightarrow DK^{*0}, D \rightarrow \pi K \pi \pi$ results [LHCb-PAPER-2019-021] – NEW!

- 4-body: coherence factor $\kappa_D^{K_3\pi}$ enters as a pre-factor to the interference term [PLB 757 (2016) 520].
- Different $r_D^{K_3\pi}$ and $\delta_D^{K_3\pi}$
- 2011-2016 data (= 5 fb$^{-1}$)
- Suppressed mode significance: $4.4\sigma$

$R_{\pi K \pi \pi} = 0.072 \pm 0.025 \pm 0.003$

$R_{\pi K \pi \pi} = 0.074 \pm 0.026 \pm 0.002$

**Favoured yield = 557 ± 25**
**Suppressed yield = 41 ± 14**

**Favoured yield = 548 ± 25**
**Suppressed yield = 40 ± 14**
The GLW Method

- 2-body: $D$ meson reconstructed in $CP$-even final states $D \to K^+K^-$ and $D \to \pi^+\pi^-$
- $r_D = 1, \delta_D = 0$

\[
\Gamma(B^0 \to D K^{*0}) \propto 1 + r_{D}^{D K^{*0}} + 2\kappa r_{D}^{D K^{*0}} \cos(\delta_B^{D K^{*0}} + \gamma)
\]

\[
\Gamma(\bar{B}^0 \to D \bar{K}^{*0}) \propto 1 + r_{D}^{D K^{*0}} + 2\kappa r_{D}^{D K^{*0}} \cos(\delta_B^{D K^{*0}} - \gamma)
\]

Expect larger interference effect than in $B^- \to D K^-$
decays as $r_{D}^{D K^{*0}}$ is closer to 1
The GLW Method

- 2-body: $D$ meson reconstructed in $CP$-even final states $D \to K^+K^-$ and $D \to \pi^+\pi^-$
  - $r_D = 1, \delta_D = 0$

\[
\Gamma(B^0 \to DK^*) \propto 1 + r_B^{DK^*2} + 2\kappa r_B^{DK^*} \cos(\delta_B^{DK^*} + \gamma)
\]

\[
\Gamma(\bar{B}^0 \to D\bar{K}^*) \propto 1 + r_B^{DK^*2} + 2\kappa r_B^{DK^*} \cos(\delta_B^{DK^*} - \gamma)
\]

- Build up asymmetries and ratios:

\[
A_{CP}^{hh} = \frac{\Gamma(\bar{B}^0 \to [h^+h^-]_D\bar{K}^*) - \Gamma(B^0 \to [h^+h^-]_D K^*)}{\Gamma(\bar{B}^0 \to [h^+h^-]_D\bar{K}^*) + \Gamma(B^0 \to [h^+h^-]_D K^*)}
\]

\[
R_{CP}^{hh} = \frac{\Gamma(\bar{B}^0 \to [h^+h^-]_D\bar{K}^*) + \Gamma(B^0 \to [h^+h^-]_D K^*)}{\Gamma(\bar{B}^0 \to [K^-\pi^+]_D\bar{K}^*) + \Gamma(B^0 \to [K^+\pi^-]_D K^*)} \times \frac{BF(D^0 \to K^-\pi^+)}{BF(D^0 \to h^+h^-)}
\]

Alexandra Rollings

Time-integrated measurements of the UT angle $\gamma$
$B^0 \rightarrow DK^{*0}, D \rightarrow h^+h^-$ results [LHCb-PAPER-2019-021] – NEW!

2011-2016 data (= 5 fb$^{-1}$)

$A_{CP}^{KK} = -0.05 \pm 0.10 \pm 0.01$

$R_{CP}^{KK} = 0.92 \pm 0.10 \pm 0.02$

$A_{CP}^{\pi\pi} = -0.18 \pm 0.14 \pm 0.01$

$R_{CP}^{\pi\pi} = 1.32 \pm 0.19 \pm 0.03$

$KK$ yield = 67 ± 10

$\pi\pi$ yield = 26 ± 6

$KK$ yield = 77 ± 11

$\pi\pi$ yield = 40 ± 7
\( B^0 \rightarrow DK^{*0}, D \rightarrow \pi^+\pi^-\pi^+\pi^- \) results [LHCb-PAPER-2019-021] – NEW!

- 4-body: extend method to quasi-GLW mode by reconstructing the \( D \) meson in the final state \( D \rightarrow \pi^+\pi^-\pi^+\pi^- \)
  - Interference term acquires pre-factor \((2F_{4\pi}^+ - 1)\), where \( F_{4\pi}^+ \) is the fractional \( CP \)-even content of the decay [JHEP 01 (2018) 144]

- Using 2015 + 2016 (= 2 fb\(^{-1}\)) data only
$B^0 \rightarrow DK^{*0}, D \rightarrow \pi^+\pi^-\pi^+\pi^-$ results [LHCb-PAPER-2019-021] – NEW!

- 4-body: extend method to quasi-GLW mode by reconstructing the $D$ meson in the final state $D \rightarrow \pi^+\pi^-\pi^+\pi^-$
  - Interference term acquires pre-factor $(2F^4_+-1)$, where $F^4_+$ is the fractional $CP$-even content of the decay [JHEP 01 (2018) 144]

- Using 2015 + 2016 (= 2 fb$^{-1}$) data only
- Significance 8.4$\sigma$ – first observation!

\[
A^{4\pi}_{CP} = -0.03 \pm 0.15 \pm 0.01 \\
R^{4\pi}_{CP} = 1.01 \pm 0.16 \pm 0.04
\]
Two solutions in the $\gamma - \delta_{B}^{DK*0}$ space are compatible with current LHCb measurement

- No strong $\gamma$ constraint as no significant $CP$ violation observed

Combine the measurements to obtain: $r_{B}^{DK*0} = 0.265 \pm 0.023$

- The uncertainty has been halved compared to the previous measurement
• Two solutions in the $\gamma - \delta_B^{DK^0}$ space are compatible with current LHCb measurement
  • No strong $\gamma$ constraint as no significant $CP$ violation observed

• Combine the measurements to obtain: $r_B^{DK^0} = 0.265 \pm 0.023$
  • The uncertainty has been halved compared to the previous measurement

• Combine with GGSZ analysis of $B^0 \to DK^0$
  ➢ GLW/ADS has higher stats - more precise $r_B^{DK^0}$
  ➢ GGSZ has lower stats but removes degeneracy in $\gamma - \delta_B^{DK^0}$ space
• The $\gamma$ world average is dominated by the 2018 LHCb combination $(74.0^{+5.0}_{-5.8})^\circ$.

• New inputs from the ADS/GLW analysis of $B^0 \to DK^{*0}$ will be added soon, where the uncertainty on $\gamma_B^{DK^{*0}}$ has been halved.

• Reduce width of yellow region!
• The γ world average is dominated by the 2018 LHCb combination \( (74.0^{+5.0}_{-5.8})^\circ \)

• New inputs from the ADS/GLW analysis of \( B^0 \rightarrow DK^{*0} \) will be added soon, where the uncertainty on \( \tau_{B}^{DK^{*0}} \) has been halved
  • Reduce width of yellow region!

• Future prospects for γ precision at LHCb:
  • 4° with Run 2 data (≈ 9 fb\(^{-1}\))
    [arXiv:1709.10308v5]
  • 1.5° by the end of Run 3 (≈ 22 fb\(^{-1}\), 2024)
    [arXiv:1709.10308v5]
  • < 1° by the end of Run 4 (≈ 50 fb\(^{-1}\), 2029)
    [arXiv:1709.10308v5]
  • ≈0.4° in Phase 2 upgrade (≈ 300 fb\(^{-1}\), 2034)
    [CERN-LHCC-2017-003]
Back Up
Measuring $\gamma$ using tree and loop-level decays

- No top quark; accessible via tree-level decays of $B$ mesons
  - $\gamma = (72.1^{+5.4}_{-5.7})^\circ$
  - Theoretically clean

Measuring $\gamma$ using tree and loop-level decays

- No top quark; accessible via tree-level decays of $B$ mesons
  - $\gamma = (72.1^{+5.4}_{-5.7})^\circ$
  - Theoretically clean
Measuring $\gamma$ using tree and loop-level decays

- No top quark; accessible via level decays of $B$ mesons
  - $\gamma = (72.1^{+5.4}_{-5.7})^\circ$
  - Theoretically clean
- $(\bar{\rho}, \bar{\eta})$ apex can be constrain using loop-level decays
  - $\gamma = (65.64^{+0.97}_{-3.42})^\circ$
Measuring $\gamma$ using tree and loop-level decays

- No top quark; accessible via tree-level decays of $B$ mesons
  - $\gamma = (72.1^{+5.4}_{-5.7})^\circ$
  - Theoretically clean
- $(\bar{\rho}, \bar{\eta})$ apex can be constrained using loop-level decays
  - $\gamma = (65.64^{+0.97}_{-3.42})^\circ$

- **Aim**: reduce uncertainty on tree-level measurement in order to verify compatibility or disagreement
- **Method**: combine interference from measurements of $CP$-violating observables from many tree-level $B$ decays

$B^- \to [K_S^0 h^+ h^-]_D K^-$: the GGSZ Method

- Strong phase difference, $\Delta \delta_D = \delta_{\bar{D}} - \delta_D$ varies across the Dalitz plane:
- $s_\pm = m^2_\pm = m^2(K_S^0, h^\pm)$

- Binning schemes chosen to optimize statistical sensitivity to $\gamma$:

$D \to K_S^0 \pi^+ \pi^-:$

$D \to K_S^0 K^+ K^-:$
• An invariant mass fit to the full Dalitz plane ($K_S^0 h^+ h^-$):

![Graphs showing invariant mass distributions for $B^\pm \to DK^\pm$ and $B^\pm \to D\pi^\pm$]
• Likelihood contours for combination with Run 1 analysis [JHEP 10 (2014) 97]:

![Diagram of likelihood contours for combination with Run 1 analysis.](image)
Potential biases on $\gamma$ [arXiv:1904.01129]

- $B^\pm \to [K^0_s h^+ h^-]_D K^-$
  
  \[ \text{Neutral kaon } CPV (\propto \epsilon \approx 10^{-3}) \text{ → source of bias?} \]

- Grossman & Savastio estimated impact on $\gamma$ measurements in global asymmetry measurements [arXiv:1311.3575]
  
  - $\frac{\Delta \gamma}{\gamma} = \mathcal{O} \left( \frac{|\epsilon|}{r_B} \right) \approx 4^\circ$

- Further studies have been performed by Bjørn & Malde
  
  - For Dalitz-plot-based approach of $B^\pm \to [K^0_s \pi^+ \pi^-]_D K^-$ decays
  
  - Including kaon material interaction ($\propto r_\chi = 10^{-3}$)
  
  - Bias is estimated for LHCb and Belle II
Potential biases on $\gamma$ [arXiv:1904.01129]
$B^0 \to DK^{*0}$ 4-body Modes

- $\kappa_D^{K3\pi} = 0.43^{+0.17}_{-0.13}$
- $r_D^{K3\pi} = 0.0549 \pm 0.006$
- $\delta_D^{K3\pi} = (128^{28}_{-17})^\circ$

Measured using studies of charm mixing and quantum correlated $D$-meson decays [PLB 757 (2016) 520]

- $F_+^{4\pi} = 0.769 \pm 0.023$

Measured using quantum correlated $D$-meson decays [JHEP 01 (2018) 144]
Fit components:
1. Signal $B^0 \rightarrow D K^{*0}$
2. $\bar{B}^0_s \rightarrow D K^{*0}$
3. Combinatorial background
4. $B^0 \rightarrow D^{*} K^{*0}$ (part reco)
5. $\bar{B}^0_s \rightarrow D^{*} K^{*0}$ (part reco)
6. $B^+ \rightarrow D K^+ \pi^- \pi^+$ (part reco)
7. $B^0 \rightarrow D \pi^+ \pi^-$ (mis-ID)
Observables

\[ A_{CP} = \frac{2\kappa r_B^{DK*0} \sin \delta_B^{DK*0} \sin \gamma}{R_{CP}} \]

\[ R_{CP} = 1 + \left( r_B^{DK*0} \right)^2 + 2\kappa r_B^{DK*0} \cos \delta_B^{DK*0} \cos \gamma \]

\[ A_{ADS} \approx \frac{R_- - R_+}{R_- + R_+} = \frac{2\kappa r_B^{DK*0} r_D^{K\pi} \sin(\delta_B^{DK*0} + \delta_D^{K\pi}) \sin \gamma}{\left( r_B^{DK*0} \right)^2 + \left( r_D^{K\pi} \right)^2 + 2\kappa r_B^{DK*0} r_D^{K\pi} \cos(\delta_B^{DK*0} + \delta_D^{K\pi}) \cos \gamma} \]

\[ R_{ADS} \approx \frac{R_- + R_+}{2} = \frac{\left( r_B^{DK*0} \right)^2 + \left( r_D^{K\pi} \right)^2 + 2\kappa r_B^{DK*0} r_D^{K\pi} \cos(\delta_B^{DK*0} + \delta_D^{K\pi}) \cos \gamma}{1 + \left( r_B^{DK*0} + r_D^{K\pi} \right)^2 + 2\kappa r_B^{DK*0} r_D^{K\pi} \cos(\delta_B^{DK*0} + \delta_D^{K\pi}) \cos \gamma} \]
Summary of Results [LHCb-PAPER-2019-021]

\[ A_{CP}^{\pi\pi} = -0.18 \pm 0.14 \pm 0.01 \]
\[ R_{CP}^{\pi\pi} = 1.32 \pm 0.19 \pm 0.03 \]
\[ A_{CP}^{KK} = -0.05 \pm 0.10 \pm 0.01 \]
\[ R_{CP}^{KK} = 0.92 \pm 0.10 \pm 0.02 \]
\[ A_{CP}^{4\pi} = -0.03 \pm 0.15 \pm 0.01 \]
\[ R_{CP}^{4\pi} = 1.01 \pm 0.16 \pm 0.04 \]
\[ A_{ADS}^{\pi K} = 0.19 \pm 0.19 \pm 0.01 \]
\[ R_{ADS}^{\pi K} = 0.080 \pm 0.015 \pm 0.002 \]
\[ A_{ADS}^{\pi K\pi\pi} = -0.01 \pm 0.24 \pm 0.01 \]
\[ R_{ADS}^{\pi K\pi\pi} = 0.073 \pm 0.018 \pm 0.002 \]

The dominant systematics are:

- \( A_{CP} \): Production and detection asymmetry corrections
- \( R_{CP} \): Branching fraction normalisation, selection efficiency correction
- \( A_{ADS} \& R_{ADS} \): Fixed parameters in invariant mass fit