Challenging the CKM picture of CP violation at LHCb

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on behalf of the LHCb Collaboration

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Qui Nhon, July 10-16, 2016
**CKM: before & after LHC**

- 4x smaller area
- 4x better $\sigma(J)$
- 2x on angles
  (4x on $\gamma$ )

**Most of the improvement due to LHCb !**

Further improvements after this plot (EPS'15)
The LHCb experiment

- Large LHC yields in hi-η region ~100μb
- Great mass/momentum resolution
- Great I.P. resolution resolves Bs oscillations
- Great K/π/p/μ separation
- Lum. Leveling and L0 μ/h/γ trigger
- Large online PC farm and high rate to storage
LHCb signals

LHCb's large yields balance the larger background and worse tagging power relative to e+e- experiments → today's similar sensitivity on tagged measurements: e.g. $B^0 \rightarrow J/\psi K_s$

(LHCb even better positioned for untagged measurements, and time-dependent $B_s$)

LHCb 41,500 (J/psi Ks only)

BaBar 8,400

PRD 79, 072009

Belle 15,500

PRL 108, 171802

PRL 115, 031601

Candidates / (1 MeV/c^2)

5240 5260 5280 5300 5320

m (MeV/c^2)
Flavor Tagging @ LHCb

- Same-side pion (kaon for Bs)
- Opposite side Vertex Charge, lepton, kaon, or charm
- Total performance $\varepsilon D^2 = 3\div5\%$ depending on channel
  - Compare to $\sim30\%$ at “B-factories”
**Status of sin(2\(\beta\)) @ LHCb**

Tagged time-dependent analysis

- Exploit OS and for first time SS\(\pi\) tag. \(\epsilon D^2 = 2.99 \pm 0.03\%\)

\[
\sin(2\beta) \equiv \sin(2\phi_1) \quad \text{HFAF Moriond 2015 PRELIMINARY}
\]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Year</th>
<th>Reference</th>
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<tbody>
<tr>
<td>BaBar</td>
<td>2009</td>
<td>PRD 79, 072009</td>
</tr>
<tr>
<td>BaBar (\chi, K)</td>
<td>2009</td>
<td>PRD 80, 112001</td>
</tr>
<tr>
<td>BaBar (J/\psi) (hadronic) (K)</td>
<td>2004</td>
<td>PRD 69, 052001</td>
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<td>Belle</td>
<td>2012</td>
<td>PRL 108, 171802</td>
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<td>ALEPH</td>
<td>1998</td>
<td>PLB 492, 259</td>
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<tr>
<td>OPAL</td>
<td>1998</td>
<td>EPJ C5, 379</td>
</tr>
<tr>
<td>CDF</td>
<td>2000</td>
<td>PRD 61, 072005</td>
</tr>
<tr>
<td>LHCb</td>
<td>2015</td>
<td>PRL 115, 031601</td>
</tr>
<tr>
<td>BelleSS</td>
<td>2012</td>
<td>PRL 108, 171801</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td></td>
<td><strong>0.69 \pm 0.02</strong></td>
</tr>
</tbody>
</table>

\[ S = 0.731 \pm 0.035 \pm 0.020 \]

\[ S_{\text{Belle}} \frac{J/\psi}{K_S} = 0.670 \pm 0.029 \pm 0.013 \]

\[ S_{\text{BaBar}} \frac{J/\psi}{K_S} = 0.662 \pm 0.039 \pm 0.012 \]

- Precision of LHCb 3fb\(^{-1}\) result ~ Babar/Belle
NEW: Best measurement of $\Delta m_d$
Submitted Apr 12, 2016

- Use semileptonic (self-tagging) decays $B^0 \to D^{(*)-} \mu X$
- $\Delta m_d = 505.0 \pm 2.1 \pm 1.0$ ns\(^{-1}\)
- This measurement alone improves the WA from $510 \pm 3 \to 506.4 \pm 1.9$ [HFAG]
Another new semileptonic result: $a_{SL}$

Submitted June 1, 2016

ArXiv:1605.09768

- Use semileptonic (self-tagging) decays $B_s^0 \to D_s^{(*)} \mu X$ to measure mixing CPV

$$a_{sl} = \frac{N(\bar{B} \to B \to f) - N(B \to \bar{B} \to \bar{f})}{N(\bar{B} \to B \to f) + N(B \to \bar{B} \to \bar{f})} = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

- Fast $B_s$ oscillations wash out effects of the production asymmetry

- World's best single measurement: $a_{sl} = 0.43 \pm 0.26{\text{(stat)}} \pm 0.20{\text{(syst)}} \%$

Brings the WA back towards the SM !
No need to ask about Bs mixing

- Measuring the $CP$-violating phase $\varphi_{s}^{c\bar{c}s}$:
  
  $-2\beta_{s} \equiv -2 \arg \left( -V_{ts}V_{tb}^{*}/V_{cs}V_{cb}^{*} \right) = -0.0363 \pm 0.0013$ in SM

- 100x zoom relative to B0 plot (50 fs bins)... (thanks to the VELO)

\[
\varphi_{s} = -0.058 \pm 0.049 \pm 0.006 \text{ rad}, \]
\[
|\lambda| = 0.964 \pm 0.019 \pm 0.007, \]
\[
\Gamma_{s} = 0.6603 \pm 0.0027 \pm 0.0015 \text{ ps}^{-1}, \]
\[
\Delta\Gamma_{s} = 0.0805 \pm 0.0091 \pm 0.0033 \text{ ps}^{-1} \]
No need to ask about $B_s$ mixing

Measuring the $CP$-violating phase $\phi^{c\bar{c}s}_s$:

$$-2\beta_s \equiv -2 \arg \left( -\frac{V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*} \right) = -0.0363 \pm 0.0013 \text{ in SM}$$

68% CL contours ($\Delta \log L = 1.15$)

CDF 9.6 fb$^{-1}$

CMS 19.7 fb$^{-1}$

ATLAS 19.2 fb$^{-1}$

DO$\delta$ 8 fb$^{-1}$
\( \phi_s \) penguin corrections from data

- With increasing levels of precision, cannot anymore neglect contribution of penguin diagrams.

- It is however possible to obtain corrections from \( B_s \to J/\psi K^*0 \) data, by measuring BR/polarization.

\( \phi_s \) penguin corrections from data

\[ \Delta \phi_{s,0} = 0.000^{+0.009}_{-0.011} \text{ (stat)} \pm 0.004 \text{ (syst)} \text{ rad}, \]
\[ \Delta \phi_{s,||} = 0.001^{+0.010}_{-0.014} \text{ (stat)} \pm 0.008 \text{ (syst)} \text{ rad}, \]
\[ \Delta \phi_{s,\perp} = 0.003^{+0.010}_{-0.014} \text{ (stat)} \pm 0.008 \text{ (syst)} \text{ rad}. \]

→ Obtained that shifts from penguin pollution are small:
Recent developments on CKM Angle Gamma
\[ \gamma = \text{arg} \left( -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right) \]

- A family of $B \rightarrow D K$ decays receive contributions from both $b \rightarrow u$ and $b \rightarrow c$ tree-level processes.
- Interference ($A_{\text{CP}}$) measures $\gamma$ cleanly – different ways:
  - GLW: $D \rightarrow \text{CP eigenstates}$ [PLB 265 (1991) 172]
  - ADS: $D \rightarrow \text{DCS mode}$ [PRL 78 (1997) 3257]
  - GGSZ: $D \rightarrow \text{n-body, via Dalitz}$ [PRD 68 (2003) 054018]

Still least known CKM angle
**D^0K^{*0} GGSZ**

- B sign tagged by flavor-specific decay $K^{*0} \rightarrow K+\pi^-$
- $D^0 \rightarrow 3$-body Dalitz amplitude
  - $A_D = |A_D(m_-,m_+)| e^{i\delta_D}$
- Parametrize interference with
  - $x_\pm = r_{B^0} \cos(\delta_{B^0} \pm \gamma)$
  - $y_\pm = r_{B^0} \sin(\delta_{B^0} \pm \gamma)$

**Recent results from LHCb**
- JHEP06(2016)13
- ArXiv:1605.0108
Hot from the press: $D^0K^{*0}$ GGSZ

JHEP06(2016)131, published 21/6/2016

Model-independent fit of Dalitz plot of $D^0 \rightarrow K_S \pi^+\pi^- (+ K_S KK)$

$N_i(B^0) = n_{B^0} \left[ F_i + (x_i^2 + y_i^2)F_{-i} + 2 \kappa \sqrt{F_iF_{-i}} (x_i c_i + y_i s_i) \right]$

- Divide Dalitz plot in wide bins
- Correct for local efficiency $F_i$ using semileptonic B data
  - $B^0 \rightarrow D^*+ \mu X$
  - $D^0$ decay phase shifts from CLEO data [PRD 82 112006]
    - fit for $x^\pm y^\pm$
**Hot from the press: $D^0K^{*0}$ GGSZ**

**model-independent**

JHEP06(2016)131, published 21/6/2016

**model-dependent**

ArXiv:1605.01082 posted 1/7/2016

$\gamma = 71 \pm 20 \, \text{deg}$

$\gamma = 80^{+21}_{-20} \, \text{deg}$
Other recent results: ADS


Note large asymmetry (first \( >5\sigma \) effect in a single mode)

\[
A_{\text{ADS}(K)}^{\pi K} = -0.403 \pm 0.056 \pm 0.011
\]

\[
A_{\text{ADS}(\pi)}^{\pi K} = 0.100 \pm 0.031 \pm 0.009
\]

Analysis also performed in 4-body D\(^0\) final states
Other recent results: GLW


\[ A_{GLW(K)}^{KK} = 0.087 \pm 0.020 \pm 0.008 \]

\[ A_{GLW(K)}^{\pi\pi} = 0.128 \pm 0.037 \pm 0.012 \]

\[ A_{GLW(K)}^{\pi\pi\pi\pi} = 0.100 \pm 0.034 \pm 0.018 \]

Novelty: \( D^0 \rightarrow 4\pi \) final state
LHCb Gamma combination

LHCb-CONF-2016-001 (Mar 14, 2016)

- $B^+ \rightarrow DK^+, D \rightarrow h^+h^-, \text{GLW/ADS, } 3 \text{ fb}^{-1}$ [ArXiv:1603.0899]
- $B^+ \rightarrow DK^+, D \rightarrow h^+\pi^-\pi^+\pi^-, \text{quasi-GLW/ADS, } 3 \text{ fb}^{-1}$ [ArXiv:1603.0899]
- $B^+ \rightarrow DK^+, D \rightarrow h^+h^-\pi^0, \text{quasi-GLW/ADS, } 3 \text{ fb}^{-1}$ [PRD 91 (2015) 112014]
- $B^+ \rightarrow DK^+, D \rightarrow K^0_S h^+h^-, \text{model-independent GGSZ, } 3 \text{ fb}^{-1}$ [JHEP 10 (2014) 097]
- $B^+ \rightarrow DK^+, D \rightarrow K^0_S K^+\pi^-, \text{GLS, } 3 \text{ fb}^{-1}$ [PLB 733 (2014) 36]
- $B^0 \rightarrow DK^+\pi^-, D \rightarrow h^+h^-, \text{GLW-Dalitz, } 3 \text{ fb}^{-1}$ [PRD 93 (2016) 112018]
- $B^0 \rightarrow DK^{*0}, D \rightarrow K^+\pi^-, \text{ADS, } 3 \text{ fb}^{-1}$ [PRD 90 (2014) 112002]
- $B^0 \rightarrow DK^{*0}, D \rightarrow K^0_S \pi^+\pi^-, \text{model-dependent GGSZ, } 3 \text{ fb}^{-1}$ [ArXiv:1605.0108]
- $B^+ \rightarrow DK^+\pi^+\pi^-, D \rightarrow h^+h^-, \text{GLW/ADS, } 3 \text{ fb}^{-1}$ [PRD 92 (2015)]
- $B^0_s \rightarrow D^+_s K^-, \text{time-dependent, } 1 \text{ fb}^{-1}$ [JHEP 11 (2014) 060]
**LHCb angle $\gamma$ combination**

Combined: $\gamma = (70.9^{+7.1}_{-8.5})^\circ$

- Most precise measurement from a single experiment!
- Latest: not yet in this plot
Angle $\gamma$ “beyond the trees”

- Results from tree-level measurements can be compared to gamma (and $\beta_s$) results from penguin processes in search for deviations.
- Analysis of 1fb$^{-1}$ of $B^0 \to \pi^+\pi^-$ and $B_s \to KK$ data already provide interesting sensitivity (in agreement with tree-level).


$$\gamma = (63.5^{+7.2}_{-6.7})^\circ$$

$$-2\beta_s = -0.12^{+0.14}_{-0.16} \text{ rad}$$
Prospects
CKM: does it fit the SM?

- As of today, no statistically significant deviation from CKM scheme has been seen.
- Still there are good reasons to expect CPV effects beyond the SM/CKM scheme.
- Potentially sensitive to very high E scales - while, in spite of the accuracy of current CKM fit, O(20%) NP effects could still be hiding in data.

→ We are definitely NOT at the end of this game.

The LHCb upgrade: detector

- Substantial upgrades to most detectors
- Higher granularity + faster electronics to handle higher L
The LHCb DAQ upgrade

- Detector readout and trigger at 40 MHz + higher rate to storage will be the drivers to handle 5x luminosity and collect larger samples
  - Plan for 50 fb⁻¹ integrated luminosity by the end of Run 4 (2028)
- Based on new front-end electronics, large PC-based event-builder network, and large expansion of online CPU farm
- Real-time data calibration and reconstruction

L_{\text{max}} = 2 \times 10^{33}

Increase \varepsilon(\text{hadron})

L_{\text{max}} = 4 \times 10^{32}
Future NP sensitivity in B-mixing

- LHCb with 50 fb\(^{-1}\) will continue to dominate in HL-LHC era:
  \[ \sigma(\phi_s) = 0.045 \rightarrow 0.009 \]

  Also extrapolate:
  \[ \sigma(\beta) = 0.2 \text{ deg (~Belle II)} \]

- Sensitivity to NP at 2 TeV (10^3 TeV) level, independent of phase
  \[ \rightarrow \text{gluino sensitivity in the same ballpark of direct searches} \]
CKM plots of the future

M. Bona CKM 2014

Errors from tree-only fit on $\rho$ and $\eta$:
- $\sigma(\rho) = 0.008$ [currently 0.051]
- $\sigma(\eta) = 0.010$ [currently 0.050]

Errors from 5-constraint fit on $\rho$ and $\eta$:
- $\sigma(\rho) = 0.005$ [currently 0.034]
- $\sigma(\eta) = 0.004$ [currently 0.015]
**LHCb is not just about Beauty...**

Unprecedented access to clean samples of **Billions** of charm hadron decays
Prospects in Charm CPV

- LHCb the first single experiment to observe D⁰ mixing \[\text{[PRL 110 (2013) 10180]}\]
- **World best** $A_{\text{CP}}$ measurements already from the first 1 fb⁻¹
- CPV in charm not yet observed. Indirect CPV not theory limited. Related to top FCNC.
- 50 fb⁻¹ yield interesting sensitivities → unique probe of up-quark sector

Recently publ. 3 fb⁻¹ $D \rightarrow \pi\pi$/KK DCPV:

$\Delta A_{\text{CP}} = [-0.10 \pm 0.08(\text{stat}) \pm 0.03(\text{syst})] %$

\[\text{PRL 116, 191601 (2016)}\]
# LHCb projections to 50 fb$^{-1}$ – and still room for improvement...

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>LHC Run 1</th>
<th>LHCb 2018</th>
<th>LHCb upgrade</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0$ mixing</td>
<td>$\phi_s(B_s^0 \rightarrow J/\psi \phi)$ (rad)</td>
<td>0.049</td>
<td>0.025</td>
<td>0.009</td>
<td>$\sim$ 0.003</td>
</tr>
<tr>
<td></td>
<td>$\phi_s(B_s^0 \rightarrow J/\psi f_0(980))$ (rad)</td>
<td>0.068</td>
<td>0.035</td>
<td>0.012</td>
<td>$\sim$ 0.01</td>
</tr>
<tr>
<td></td>
<td>$A_{sl}(B_s^0)$ (10$^{-3}$)</td>
<td>2.8</td>
<td>1.4</td>
<td>0.5</td>
<td>0.03</td>
</tr>
<tr>
<td>Gluonic penguin</td>
<td>$\phi_s^{\text{eff}}(B_s^0 \rightarrow \phi\phi)$ (rad)</td>
<td>0.15</td>
<td>0.10</td>
<td>0.018</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$\phi_s^{\text{eff}}(B_s^0 \rightarrow K^{*0}K^{*0})$ (rad)</td>
<td>0.19</td>
<td>0.13</td>
<td>0.023</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td></td>
<td>$2\beta^{\text{eff}}(B_s^0 \rightarrow \phi K_S^0)$ (rad)</td>
<td>0.30</td>
<td>0.20</td>
<td>0.036</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed currents</td>
<td>$\phi_s^{\text{eff}}(B_s^0 \rightarrow \phi\gamma)$ (rad)</td>
<td>0.20</td>
<td>0.13</td>
<td>0.025</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td></td>
<td>$\tau^{\text{eff}}(B_s^0 \rightarrow \phi\gamma)/\tau_{B_s^0}$</td>
<td>5%</td>
<td>3.2%</td>
<td>0.6%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Electroweak penguin</td>
<td>$S_3(B_s^0 \rightarrow K^{*0}\mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{GeV}^2/c^4)$</td>
<td>0.04</td>
<td>0.020</td>
<td>0.007</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$q_0^2 A_{FB}(B_s^0 \rightarrow K^{*0}\mu^+\mu^-)$</td>
<td>10%</td>
<td>5%</td>
<td>1.9%</td>
<td>$\sim$ 7%</td>
</tr>
<tr>
<td></td>
<td>$A_1(K\mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{GeV}^2/c^4)$</td>
<td>0.09</td>
<td>0.05</td>
<td>0.017</td>
<td>$\sim$ 0.02</td>
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<tr>
<td></td>
<td>$\mathcal{B}(B_s^+ \rightarrow \pi^+\mu^+\mu^-)/\mathcal{B}(B_s^0 \rightarrow K^+\mu^+\mu^-)$</td>
<td>14%</td>
<td>7%</td>
<td>2.4%</td>
<td>$\sim$ 10%</td>
</tr>
<tr>
<td>Higgs penguin</td>
<td>$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$ (10$^{-9}$)</td>
<td>1.0</td>
<td>0.5</td>
<td>0.19</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$</td>
<td>220%</td>
<td>110%</td>
<td>40%</td>
<td>$\sim$ 5%</td>
</tr>
<tr>
<td>Unitarity triangle angles</td>
<td>$\gamma(B \rightarrow D^{(<em>)}K^{(</em>)})$</td>
<td>7°</td>
<td>4°</td>
<td>0.9°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\gamma(B_s^0 \rightarrow D_{s0}^{(<em>)}K^{(</em>)})$</td>
<td>17°</td>
<td>11°</td>
<td>2.0°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\beta(B_s^0 \rightarrow J/\psi K_S^0)$</td>
<td>1.7°</td>
<td>0.8°</td>
<td>0.31°</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>$A_F(D^0 \rightarrow K^+K^-)$ (10$^{-4}$)</td>
<td>3.4</td>
<td>2.2</td>
<td>0.4</td>
<td>large</td>
</tr>
<tr>
<td></td>
<td>$\Delta A_{CP}$ (10$^{-3}$)</td>
<td>0.8</td>
<td>0.5</td>
<td>0.1</td>
<td>large</td>
</tr>
</tbody>
</table>

- More obs
- x3
- x8
- large
- negligible
LHCb Future Upgrade Studies

- Due to the exciting prospects, LHCb recently started considering further improvements to its program:
  - Small improvements/consolidations for Run 4 (“Phase-1B”)
  - Further upgrades for Run 5, to accept up to \( L = 300 \text{ fb}^{-1} \)

[→ see "Beyond the LHCb Phase-1 Upgrade" workshop, 6/4/2016]
Conclusions

- LHCb run I brought significant improvement to the precision of our CKM picture

- An exciting path to further results in the coming years at LHC