CP Violation in $B$ decays

Keri Vos

Universität Siegen
Motivation

- Studies of CP violation are an important part of the flavour program
  - Determining precisely SM inputs (CKM parameters)
  - Search for new physics through sensitivity for new CP violating phases
- Non-leptonic $B$ decays are key players
  - Large data sets from B-factories and LHCb-run I, many observables
  - Already impressive experimental uncertainties
- Foresee unprecedented precision for LHCb upgrade and Belle II
  - Challenges theorists to keep up

→ see also talk by Gilberto T-X
→ see also talk by Stefan de Boer

Focus on recent progress and very selected topics
$B_q - \bar{B}_q$ mixing observables

Leading contribution in the SM

see Buras, Buchalla, Lautenbacher [1995]

Mass eigenstates $H$ and $L$ arise from diagonalization of $\Delta F = 2$ Hamiltonian

Mass difference $\Delta M_q \equiv M_H^q - M_L^q \sim 2|\tilde{M}_{12}^q| > 0$

- Governed by short-distance contributions
- New Physics can have a significant impact see also: di Lucio, Kirk, Lenz [2018]
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**Width difference** $\Delta \Gamma_q \equiv \Gamma^q_L - \Gamma^q_H \sim 2\Gamma^{q\bar{q}}_{12} \cos \phi_q$

- $\Delta \Gamma_s$ sizeable
- Dominated by tree decays, rather insensitive to New Physics
\( \bar{B}_q - B_q \) mixing observables

**Leading contribution in the SM**

Mass eigenstates \( H \) and \( L \) arise from diagonalization of \( \Delta F = 2 \) Hamiltonian

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**Width difference** \( \Delta \Gamma_q \equiv \Gamma_L^q - \Gamma_H^q \sim 2\Gamma_{12}^q \cos \phi_q \)

- \( \Delta \Gamma_s \) sizeable
- Dominated by tree decays, rather insensitive to New Physics [Dunietz, Fleischer, Nierste [2001]; Lenz et al. [2012]; Badin, Gabbiani, Petrov [2007]]

**CP-violating mixing phase** \( \phi_q \equiv \arg \left( -\frac{M_{12}^q}{\Gamma_{12}^q} \right) \)
CP violation in $B_q - \bar{B}_q$ mixing

Flavour-specific semi-leptonic decays probe CP violation in mixing

$$a_{sl}^q = \frac{\Gamma(\bar{B}_q(t) \to f) - \Gamma(B_q(t) \to \bar{f})}{\Gamma(B_q(t) \to f) + \Gamma(B_q(t) \to \bar{f})} = \left(\frac{\Delta \Gamma_q}{\Delta M_q}\right) \tan \phi_q$$

Current Status:

Inclusive SM prediction using HQE

Artuso, Borissov, Lenz [2015]

$$a_{sl}^d|_{SM} = (-4.7 \pm 0.6) \times 10^{-4}$$

$$a_{sl}^s|_{SM} = (2.22 \pm 0.27) \times 10^{-5}$$

see: Jubb, Kirk, Lenz, Tetlalmatzi-Xolocotzi [2017]

- Assumes quark-hadron duality
- Requires lattice calculations of higher-dimensional matrix elements
- Sensitivity to CP violating New Physics
CP violation in $B_s^0 - \bar{B}_s^0$ mixing

New physics would also show up in exclusive determinations of $\phi_s$

$$a_{sl}^s = \left( \frac{\Delta \Gamma_s}{\Delta M_s} \right) \times \tan(\phi_s)$$
**New physics would also show up in exclusive determinations of $\phi_s$**

\[ a_{sl}^s = \left[(0.46 \pm 0.04) \times 10^{-2}\right] \times \tan\left(\langle \phi_s \rangle + \Delta \psi\right) \]

- $a_{sl}^s$ already suppressed by measurements of $\Delta M_s$ and $\Gamma_s$
New physics would also show up in exclusive determinations of $\phi_s$

$$a_{sl}^s = [(0.46 \pm 0.04) \times 10^{-2}] \times \tan (\langle \phi_s \rangle + \Delta \Psi)$$

- $a_{sl}^s$ already suppressed by measurements of $\Delta M_s$ and $\Gamma_s$

Implications of exclusive $\phi_s$ determinations

- Available determinations are all consistent with the SM
- Significantly constrains possible new physics effects
- $\langle \phi_s \rangle$ average of $\phi_f$ with $f = J/\psi \phi, D^- D^+, J/\psi \pi^+ \pi^-, ...$
- Phase $\Delta \Psi$ determined from experimental data

$$\Delta \Psi = \arg \left[ \sum_f \eta_f w_f e^{i(\phi_f^s - \langle \phi_s \rangle)} \right] \quad w_f = \Gamma(B_s^0 \to f) \sqrt{\frac{1 - A_{\text{dir}}^{\text{CP}} (B_s \to f)}{1 + A_{\text{dir}}^{\text{CP}} (B_s \to f)}}$$
**CP violation in $B^0_s$-$\bar{B}^0_s$ mixing**


New physics would also show up in **exclusive determinations** of $\phi_s$

\[ a^s_{sl} = \left[ (0.46 \pm 0.04) \times 10^{-2} \right] \times \tan (\langle \phi_s \rangle + \Delta \Psi) \]

- $a^s_{sl}$ already suppressed by **measurements** of $\Delta M_s$ and $\Gamma_s$

**Exclusive Prediction:**

- Limits the room for new physics
- Interesting to confront with more precise measurements
- Opens also new windows to search for CPV in $D^\pm_s$ decays

Limited by $B_s \rightarrow D_s^- D_s^+$ (small band: upgrade scenario)
CP violation in non-leptonic $B$ decays
Non-leptonic $B$ decays

see Buras, Buchalla, Lautenbacher [1995]

Effective Hamiltonian

$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_{j=u,c} V^*_j q V_{jb} \left( \sum_{i=1,2} C_i(\mu) \, O_{ij}^q(\mu) + \sum_{i=3}^{10} C_i(\mu) \, O_i^q \right)$$

- $C_i(\mu)$ real short-distance coefficient, $\langle O_i \rangle$ long-distance physics

Current-current operators

$$O_{1j}^q = \bar{q}_\alpha \gamma^\mu (1 - \gamma_5) j_\beta \gamma_{\mu} (1 - \gamma_5) b_\alpha$$
$$O_{2j}^q = \bar{q}_\alpha \gamma^\mu (1 - \gamma_5) j_\alpha \gamma_{\mu} (1 - \gamma_5) b_\beta$$

QCD penguin operators ($q' = u, d, s, c, b$)

$$O_3^q = \bar{q}_\alpha \gamma^\mu (1 - \gamma_5) b_\alpha \sum_{q'} \bar{q}'_\beta \gamma_{\mu} (1 - \gamma_5) q'_\beta$$
$$O_4^q = \bar{q}_\alpha \gamma^\mu (1 - \gamma_5) b_\beta \sum_{q'} \bar{q}'_\beta \gamma_{\mu} (1 - \gamma_5) q'_\alpha$$
$$O_5^q = \bar{q}_\alpha \gamma^\mu (1 - \gamma_5) b_\alpha \sum_{q'} \bar{q}'_\beta \gamma_{\mu} (1 + \gamma_5) q'_\beta$$
$$O_6^q = \bar{q}_\alpha \gamma^\mu (1 - \gamma_5) b_\beta \sum_{q'} \bar{q}'_\beta \gamma_{\mu} (1 + \gamma_5) q'_\alpha$$

EW penguin operators

$$O_7^q = \frac{3}{2} \bar{q}_\alpha \gamma^\mu (1 - \gamma_5) b_\alpha \sum_{q'} Q_q' \bar{q}'_\beta \gamma_{\mu} (1 + \gamma_5) q'_\beta$$
$$O_8^q = \frac{3}{2} \bar{q}_\alpha \gamma^\mu (1 - \gamma_5) b_\beta \sum_{q'} Q_q' \bar{q}'_\beta \gamma_{\mu} (1 + \gamma_5) q'_\alpha$$
$$O_9^q = \frac{1}{2} \bar{q}_\alpha \gamma^\mu (1 - \gamma_5) b_\alpha \sum_{q'} Q_q' \bar{q}'_\beta \gamma_{\mu} (1 - \gamma_5) q'_\beta$$
$$O_{10}^q = \frac{3}{2} \bar{q}_\alpha \gamma^\mu (1 - \gamma_5) b_\beta \sum_{q'} Q_q' \bar{q}'_\beta \gamma_{\mu} (1 - \gamma_5) q'_\alpha$$
Non-leptonic $B$ decays

Effective Hamiltonian

$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_{j=u,c} V_{jq}^* V_{jb} \left( \sum_{i=1,2} C_i(\mu) \mathcal{O}_{i}^{jq}(\mu) + \sum_{i=3}^{10} C_i(\mu) \mathcal{O}_{i}^{q} \right)$$

- $C_i(\mu)$ real short-distance coefficient, $\langle \mathcal{O}_i \rangle$ long-distance physics

General non-leptonic $B$ decay (CKM unitarity implies: at most two independent CKM amplitudes)

$$A(B \to f) = e^{i\varphi_1} |A_1| e^{i\theta_1} + e^{i\varphi_2} |A_2| e^{i\theta_2}$$

$$|A_i| e^{i\delta_i} = \sum_k C_k(\mu) \times \langle f | \mathcal{O}_k^i(\mu) | B \rangle$$

Perturbatively calculable
Hadronic matrix element

Hadronic matrix elements theoretically challenging
**QCD dynamics**

**Continuum methods to determine Hadronic Matrix Elements**

- **pQCD**
  - Li, Yu [1995]; Li, Yang [1999]; Keum, Li, Sanda [2000]

- **QCD Factorization**
  - Strong phases generated at $\mathcal{O}(\alpha)$
  - Completion of penguin parameters at NNLO in progress
  - Power corrections challenging to control


- **Soft Collinear Effective Theory (SCET)**
  - Important tool to establish QCDF at higher orders

  Bauer, Pirjol, Stewart [2001]; Bauer, Grinstein, Pirjol, Stewart [2003]; ...

**Flavour symmetries**

- Allow determination of CKM phases
- Permit valuable insights into non-perturbative effects

CP violation in $B$ decays in the SM

Charged $B$ mesons

$$A_{\text{CP}}^{\text{dir}} = \frac{|A(B \to f)|^2 - |A(\bar{B} \to f)|^2}{|A(B \to f)|^2 + |A(\bar{B} \to f)|^2}$$

$$= \frac{2 |A_1||A_2| \sin(\Delta \theta) \sin \Delta \varphi}{|A_1|^2 + |A_2|^2 + 2 |A_1||A_2| \cos(\Delta \theta) \cos \Delta \varphi}$$

Direct CP asymmetry

- Interference between two different decay amplitudes
- Non-trivial CP-conserving strong phase difference $\Delta \theta$
- Non-trivial CP-violating weak phase difference $\Delta \varphi$ (extraction of CKM angle $\gamma$)
**CP violation in $B$ decays in the SM**

Neutral $B_d$ and $B_s$ mesons

\[
A_{\text{CP}}(t) \equiv \frac{\Gamma(B^0_q(t) \to f) - \Gamma(\bar{B}^0_q(t) \to \bar{f})}{\Gamma(B^0_q(t) \to f) + \Gamma(\bar{B}^0_q(t) \to \bar{f})} = \frac{A^\text{dir}_{\text{CP}} \cos(\Delta M_q t) + A^\text{mix}_{\text{CP}} \sin(\Delta M_q t)}{\cosh(\Delta \Gamma_q t/2) + A^\Delta \Gamma_q \sinh(\Delta \Gamma_q t/2)}
\]

\[
A^\text{dir}_{\text{CP}} \equiv \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}, \quad A^\Delta \Gamma \equiv \frac{-2 \text{Re} \lambda_f}{1 + |\lambda_f|^2}, \quad \lambda_f = \frac{q \bar{A}_f}{p A_f}
\]

\[
A^\text{mix}_{\text{CP}} \equiv \frac{-2 \text{Im} \lambda_f}{1 + |\lambda_f|^2} = \frac{2|\lambda_f|^2}{1 + |\lambda_f|^2} \sin \phi_q
\]

**Mixing-induced CP asymmetry**

- Arises from interference between mixing and decay
- Offers an important additional observable
- Can also be sizeable if only one amplitude dominates
Determination of $\gamma$ from $B \rightarrow DK$
Determination of $\gamma$ from $B \rightarrow DK$

\[ \gamma = \arg \left( -\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*} \right) \]

Giri, Grossman, Soffer, Zupan [2003]

- Important parameter: key input of the CKM
- Theoretically extremely clean (no penguin contributions)
  - Electroweak box corrections tiny
  - Incredible precision of $1^\circ$ expected at LHCb upgrade
- New physics contributions in $C_{1,2}$ may cause sizeable shifts in $\gamma$

\[ \propto V_{cb} V_{us}^*(d) \]
\[ \propto V_{ub} V_{cs}^*(d) \]
**γ** determination from $B_s \rightarrow D_s^{\pm} K^{\mp}, \ldots$

Aleksan, Dunietz, Kayser [1990]; de Bruyn, Fleischer, Knegjens, Merk, Schiller, Tuning [2012]; Fleischer [2003]

Another theoretically clean probe

Time-dependent analysis of $B_s \rightarrow D_s^{\pm} K^{\mp}, \ldots$ probes $\phi_s + \gamma$

- Most precise measurement of $\gamma$ from $B_s$ system

$$\gamma = (128^{+17}_{-22})^\circ \quad \text{(using } \phi_s \text{ from } b \rightarrow \bar{c}cs)$$

- Great potential for the LHCb upgrade
- Possible to perform a joint analysis to determine $\gamma$ and $\phi_s$


Similarly $B_d \rightarrow D_s^{\pm} \pi^{\mp}, \ldots$ decays probe $\phi_d + \gamma$

see talk by Greig Cowan
Mixing angles $\phi_s$ and $\phi_d$
Effective mixing angles $\phi_d$ and $\phi_s$

CP asymmetries determine the “effective” mixing angle

$$\sin \phi_q^{\text{eff}} = \frac{A_{\text{CP}}^{\text{mix}}(B^0_q \to f)}{\sqrt{1 - A_{\text{CP}}^\text{dir}(B^0_q \to f)^2}} = \sin \left( \phi_q^{\text{SM}} + \Delta \phi_q + \phi_q^{\text{NP}} \right)$$

- New era of precision physics: reach of $\mathcal{O}(0.5^\circ)$ foreseen
- Subleading terms are doubly Cabibbo suppressed
- Controlling hadronic effects crucial
- Penguin shift $\Delta \phi_q$ decay is mode specific

Non-perturbative effects

- $B \to J/\psi M$ factorizes in $N_c \to \infty$, but large corrections
- Flavour symmetries provide valuable insights into hadronic parameters
Controlling penguin effects in $B_d \rightarrow J/\psi K_S$

Fleischer [1999]; Ciuchini, Pierini, Silvestrini [2005, 2011];
Faller, Fleischer, Jung, Mannel [2008]; Jung [2012];
de Bruyn, Fleischer [2015]

\[ \phi_d^{SM} \equiv 2\beta = 2 \arg \left( -\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right) \]

Penguin suppressed golden mode:

\[ A(B_d^0 \rightarrow J/\psi K_S) = \left( 1 - \frac{\chi^2}{2} \right) C' \left[ 1 + \epsilon a' e^{i\theta'} e^{i\gamma} \right] , \quad \epsilon = \frac{\chi^2}{1 + \chi^2} \sim 0.05 \]

Penguin enhanced control mode:

\[ A(B_s^0 \rightarrow J/\psi K_S) = -\chi C \left[ 1 - ae^{i\theta} e^{i\gamma} \right] \]

- Extract penguin parameters $(a, \theta)$ using $\gamma$ as input
- Decays are related via $U$-spin ($s$-quark $\leftrightarrow$ $d$-quark)
- Only sensitive to non-factorizable $U$-spin breaking de Bruyn, Fleischer [2015]
Controlling penguin effects in $B_d \rightarrow J/\psi K_S$

Penguin effects can be controlled!

Current data

- Current data gives $\Delta \phi_d^{J/\psi K_S} = (-0.71^{+0.56}_{-0.65})^\circ$ Some theoretical assumptions
- Benchmark scenario matches experimental precision in upgrade era

Benchmark scenario (LHCb upgrade)
Controlling penguin effects in $B_s \rightarrow J/\psi \phi$

Faller, Fleischer, Jung, Mannel [2008]; Jung [2013]
de Bruyn, Fleischer [2015]; Fleischer [2007]; Jung, Schacht [2014]

\[ \phi_{s}^{SM} \equiv 2\beta_{s} = 2\text{arg} \left( -\frac{V_{ts}V_{tb}^{*}}{V_{cs}V_{cb}^{*}} \right) \]

See Talk by Greig Cowan

**Penguin suppressed golden mode:**

$B_{s}^{0} \rightarrow J/\psi \phi$ (requires polarization measurements)

**Penguin enhanced control mode:**

$B_{d}^{0} \rightarrow J/\psi \rho^{0}$ (but also $B_{s} \rightarrow J/\psi \bar{K}^{*0}$)

- Implement *U*-spin symmetry and use $\gamma$ as input
- CP asymmetries measurements are key inputs
- Already implemented by LHCb
  [LHCb, JHEP 1511 (2015) 082]
- **Penguin effects under control** $\rightarrow$ additional tests of QCD possible

Similar strategy allows extraction of $\phi_{s}$ from $B_{s} \rightarrow D_{s} \bar{D}_{s}$
CP violation in $B_s^0 \rightarrow K^- K^+$
Flavor symmetries in $B^0_s \rightarrow K^- K^+$ and $B_d \rightarrow \pi^- \pi^+$

- $B^0_s \rightarrow K^- K^+$ dominated by QCD Penguin topologies
- Related to $B^0_d \rightarrow \pi^- \pi^+$ via $U$-spin symmetry
- Extract $\gamma$ and $\phi_s$ from direct and mixing-induced CP asymmetries

$$\gamma = (63.5^{+7.2}_{-6.7})^\circ \quad \phi_s = -(6.9^{+9.2}_{-8.0})^\circ$$

- Allows comparison between pure tree and penguin determinations
- Quickly limited by dominant $U$-spin breaking corrections
Flavor symmetries in $B^0_s \rightarrow K^- K^+$ and $B_d \rightarrow \pi^- \pi^+$

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$\gamma = (63.5^{+7.2}_{-6.7})^\circ \quad \phi_s = -(6.9^{+9.2}_{-8.0})^\circ$

Controlling $SU(3)$ breaking effects

- $\gamma$ and $\phi_d$ input parameters; extract $\phi_s$
- Split U-spin corrections: factorizable and non-factorizable effects
- Semileptonic ratios provide additional input

$$R_K \equiv \frac{\Gamma(B_s \rightarrow K^- K^+)}{|d\Gamma(B_s \rightarrow K^- \ell^+ \nu_\ell)/dq^2|_{q^2=m^2_K}}$$
Controlling $SU(3)$ breaking effects

Gronau, Rosner [1995]; Fleischer, Jaarsma, and KKV[2016]

Non-factorizable $U$-spin breaking probed by

\[
\xi a_{NF} \equiv \left| \frac{a_{NF}}{a'_{NF}} \right| = \left| \frac{a^T_{NF}}{a'^T_{NF}} \right| \frac{1+r_P}{1+r'_P} \frac{1+x}{1+x'}
\]

- Very favourable and robust structure
- Use data-driven methods to quantify $U$-spin breaking corrections

\[
r_P \equiv \frac{p(ut)}{T} \sim O(\lambda)
\]

\[
x \equiv \frac{E+P_A(ut)}{T+P(ut)} \sim O(\lambda)
\]
Controlling \textit{SU}(3) breaking effects

Gronau, Rosner [1995]; Fleischer, Jaarsma, and KKV[2016]

Non-factorizable \textit{U}-spin breaking probed by

\[
\xi a \equiv \left| \frac{a_{\text{NF}}}{a'_{\text{NF}}} \right| = \left| \frac{a^T_{\text{NF}}}{a'^T_{\text{NF}}} \right| \left| \frac{1+r_P}{1+r'_P} \right| \left| \frac{1+x}{1+x'} \right|
\]

- Very favourable and robust structure
- Use data-driven methods to quantify \textit{U}-spin breaking corrections

Hadronic uncertainties

- QCDF probes the tree-level contributions $a^T_{\text{NF}}$ Beneke, Huber, Li [2010]
- More insights from future measurements of CP asymmetries
  - Pure penguin (P) $B_d^0 \to K^0 \bar{K}^0, B_s^0 \to K^0 \bar{K}^0$
  - Pure exchange (E) and penguin annihilation (PA) topologies
    $B_d^0 \to K^+ K^-, B_s^0 \to \pi^+ \pi^-$

\[
\begin{align*}
  r_P & \equiv \frac{p(ut)}{T} \sim O(\lambda) \\
  x & \equiv \frac{E+PA(ut)}{T+P(ut)} \sim O(\lambda)
\end{align*}
\]
Matching the experimental precision of 0.5° requires

- 5% precision on differential rate of $B_s \rightarrow K^- \ell^+ \nu_\ell$ not yet measured
- 5% precision $SU(3)$-breaking corrections achievable
The $B \rightarrow \pi K$ Puzzle
The $B \to \pi K$ puzzle

$B \to \pi K$ decays have been in the spotlight for decades

- Puzzling correlation between CP asymmetries found
- Large discrepancy between experiment and QCDF
- Electroweak penguins (EWP) contribute at the same level as Trees
- EWP sector offers an interesting avenue for NP to enter via

$$qe^{i\phi} e^{i\omega} \equiv - \left( \frac{\hat{P}_{EW} + \hat{P}_{EW}^C}{\hat{T} + \hat{C}} \right)$$
The $B \rightarrow \pi K$ puzzle

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$$\phi e^{i\phi} e^{i\omega} \equiv -\left(\frac{\hat{P}_{EW} + \hat{P}_{EW}^C}{\hat{T} + \hat{C}}\right)$$

**Electroweak penguin parameters**

- $\phi(\omega)$ CP-violating (conserving) phases, $\omega$ model-independently small
- New CP violating physics might enter with large phase $\phi$
**CP asymmetries in** $B \to \pi K$

\[
\Delta_{SR} = A_{\text{CP}}^\text{dir}(\pi^\pm K^\mp) + A_{\text{CP}}(\pi^\pm K^0) \frac{\text{Br}(\pi^\pm K^0)}{\text{Br}(\pi^\pm K^\mp)} \frac{\tau_{B^0}}{\tau_{B^+}} \\
- A_{\text{CP}}^\text{dir}(\pi^0 K^\pm) \frac{2\text{Br}(\pi^0 K^\pm)}{\text{Br}(\pi^\pm K^\mp)} \frac{\tau_{B^0}}{\tau_{B^+}} - A_{\text{CP}}(\pi^0 K_S) \frac{2\text{Br}(\pi^0 K^0)}{\text{Br}(\pi^\pm K^\mp)} = 0 + O(\lambda^2)
\]

**Sum rule provides a Standard Model test**

- Satisfied experimentally $\rightarrow$ still large uncertainties for $B_d^0 \to \pi^0 K^0$
- Predicts $A_{\text{CP}}^\text{dir}(B_d^0 \to \pi^0 K^0) = -0.14 \pm 0.03$ (PDG: $A_{\text{CP}}^{\pi^0 K^0} = 0.00 \pm 0.13$)
- Intriguing opportunites for Belle II

**Mixing-induced CP asymmetry in** $B_d^0 \to \pi^0 K^0$ **provides additional tests**
\[ \sqrt{2}A(B^0 \rightarrow \pi^0 K^0) + A(B^0 \rightarrow \pi^- K^+) \]
\[ = \sqrt{2}A(B^+ \rightarrow \pi^0 K^+) + A(B^+ \rightarrow \pi^+ K^0) \]
\[ = -(\hat{T} + \hat{C}) (e^{i\gamma} - qe^{i\phi} e^{i\omega}) \equiv 3A_{3/2} = 3|A_{3/2}|e^{i\phi_{3/2}} , \]

- QCD penguin and colour-suppressed EWPs cancel
- Gives a clean correlation between the CP asymmetries in \( B_d \rightarrow \pi^0 K_S \)
- Minimal \( SU(3) \) input

\[ |\hat{T} + \hat{C}| = R_{T+C} |V_{us}/V_{ud}| \sqrt{2}|A(B^+ \rightarrow \pi^+ \pi^0)| \]

\[ R_{T+C}|_{\text{fact}} = f_K/f_\pi = 1.2 \pm 0.2 \]

Uncertainty accounts for non-factorizable \( SU(3) \) breaking
Hints towards New Physics in the EWP sector?
Pinning down New Physics in EWP sector

see Poster by Ruben Jaarsma

Fleischer, Jaarsma, KKV [2018]; Fleischer, Jaarsma, Malami, KKV [2018]

Additional constraint from mixing-induced CP asymmetry

Current data

Benchmark scenario

Exciting prospects for Belle-II
CP violation in multibody decays
CP violation in multibody decays

- Large part of the non-leptonic $B$ decays
- Rich structure of CP violation
  - Especially for $B \rightarrow \pi\pi\pi$

Theoretically challenging:
- T-odd correlations Durieux, Grossman [2015]; Gronau, Rosner [2015]
- Using flavour symmetries Bhattacharya, Gronau, Imbeault, Rosner, London, Bediaga, Guerrer, de Miranda
- Applying CPT-invariance Nogueira, Bediaga, Cavalcante, Frederico, Lourenco [2015]; ...
- Using heavy meson chiral perturbation theory Cheng, Chua, Soni [2007]; Cheng, Chua, Zhang [2017]
QCD Factorization in three-body decays

Kraenkl, Mannel, Virto [2015]; Klein, Mannel, Virto, KKV [2017]

Factorization theorem at the phase space edge

\[
\langle \pi^+ \pi^+ \pi^- | O_i | B \rangle = T^i \otimes F_{B \rightarrow \pi^+} \otimes \Phi_{\pi^+ \pi^-} + T^i \otimes F_{B \rightarrow \pi^+ \pi^-} \otimes \Phi_{\pi^+}
\]

- Improvement over quasi-two body interpretation
- Introduces new non-perturbative strong phases
  - Light-cone sum rules for $B \rightarrow hh$ form factors Khodjamirian, Cheng, Virto [2017]; Khodjamirian, Descotes-Genon, Virto, KKV [wip]
- Challenge: Reach the same level as two-body QCDF
Summary
Summary

- Extraction of $\gamma$ from $B \rightarrow DK$ is theoretically clean
  - Impressive 1° precision in the upgrade era expected
  - Will play an increasingly important role as input parameter

- Penguin pollution in $\phi_s$ determinations under control

- Penguin dominated $B_s \rightarrow KK$ offers additional probe of $\phi_s$
  - Requires analyses of $B_s^0 \rightarrow K^- \ell^+ \nu_\ell$

- $B \rightarrow \pi K$ decays remain puzzling → good prospects
  - Improved CP asymmetries in $B_d \rightarrow \pi^0 K_S$ needed
  - Crucial to distinguish New Physics from QCD effects

- Three-body decays still offer many interesting avenues to explore
  - Study QCDF in $B^0 \rightarrow D^{-} \pi^{+} \pi^{0}$
Summary

- Extraction of $\gamma$ from $B \to DK$ is theoretically clean
  - Impressive $1^\circ$ precision in the upgrade era expected
  - Will play an increasingly important role as input parameter

- Penguin pollution in $\phi_s$ determinations under control

- Penguin dominated $B_s \to KK$ offers additional probe of $\phi_s$
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- $B \to \pi K$ decays remain puzzling → good prospects
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- Three-body decays still offer many interesting avenues to explore
  - Study QCDF in $B^0 \to D^- \pi^+ \pi^0$

Thank you for your attention
Back up
Constraints on new physics from the sum rule

- Limited sensitivity to $q$ and $\phi$ for $q < 3$
Correlation between CP asymmetries in $B^0_d \rightarrow \pi^0 K^0$

Fleischer, Jaeger, Pirjol, Zupan [2008]; Fleischer, Jaarsma, KKV [2018]

New element: constraint on angle $\phi_{\pm} = \arg(\bar{A}_\pm A^*_\pm)$

$$\phi_{\pm}|_{SM,\phi=0} = 2r \cos \delta \sin \gamma + \mathcal{O}(\lambda^2) = (8.7 \pm 3.5)^\circ$$
Pinning down New Physics in EWP sector

- Complement the isospin analysis with $S_{CP}^{\pi^0 K_S}$

$$\tan \phi_{00} = 2(r \cos \delta - r_c \cos \delta_c) \sin \gamma + 2r_c (\cos \delta_c - 2\tilde{a}_C/3) q \sin \phi + \mathcal{O}(\lambda^2)$$

- $r, \delta, r_c$ and $\delta_c$ hadronic parameters determined from $B \rightarrow \pi\pi$
- Only cosines of small phases, low sensitivity to variations
- Includes color-suppressed EWPs $\tilde{a}_C = a_C \cos(\Delta_C + \delta_c)$
- Effects included in a data-driven way

$$R \equiv \frac{\text{Br}(\pi^- K^+)}{\text{Br}(\pi^+ K^0)} = 0.89 \pm 0.04 = 1 - 2r \cos \delta \cos \gamma + 2r_c \tilde{a}_C q \cos \phi + \mathcal{O}(\lambda^2)$$
Controlling penguin effects in $B_s \to J/\psi\phi$

$A_{\text{dir}}^{\text{CP}}(B_d \to J/\psi\rho^0)$

$A_{\text{mix}}^{\text{CP}}(B_d \to J/\psi\rho^0)$

$a_f, \theta_f$

$\Delta \phi_s^{(\psi\phi)}$

$A_{\text{dir}}^{\text{CP}}(B_s \to J/\psi\phi)$

$A_{\text{mix}}^{\text{CP}}(B_s \to J/\psi\phi)$

$\phi_s$

Minimal Fit

$B(B_d \to J/\psi\rho^0)$

$B(B_s \to J/\psi K^*0)$

$A_{\text{dir}}^{\text{CP}}(B_s \to J/\psi K^*0)$

$|A'_f/A_f|$ New Link $|A'_f/A_f|$ Extended Fit

Test Old Input

QCD Calculations