CP Violation in B decays

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Heavy Quarks and Leptons 2018 Yamagata

Theor. Physik 1

DFG FOR 1873

Motivation

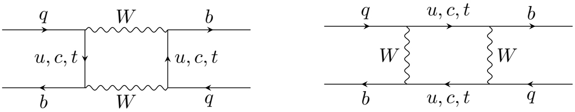
- Studies of CP violation are an important part of the flavour program
  - Determining precisely SM inputs (CKM parameters)
  - Search for new physics through sensitivity for new CP violating phases
- Non-leptonic B decays are key players
  - Large data sets from B-factories and LHCb-run I, many observables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

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 $\Delta M_q \equiv M_H^q - M_L^q \sim 2|M_{12}^q| > 0$

- Governed by short-distance contributions
- New Physics can have a significant impact see also: di Lucio, Kirk, Lenz [2018]

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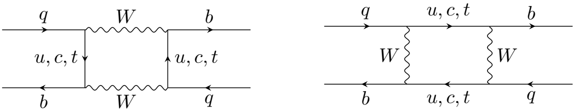

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Width difference $\Delta\Gamma_q \equiv \Gamma_L^q - \Gamma_H^q \sim 2\Gamma_{12}^q \cos\phi_q$

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

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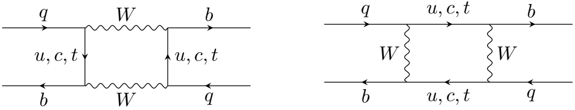

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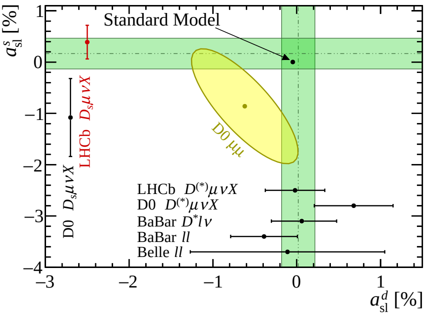
CP-violating mixing phase $\phi_q \equiv \arg\left(-M_{12}^q/\Gamma_{12}^q\right)$

CP violation in B_q-$\bar{B}_q$ mixing

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

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

Current Status:



Artuso, Borissov, Lenz [2015]

Inclusive SM prediction using HQE

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

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

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

Fleischer, KKV, Phys.Lett. B770 (2017) 319

New physics would also show up in exclusive determinations of ϕ_s

$$a_{\rm sl}^s = \left(\frac{\Delta\Gamma_s}{\Delta M_s}\right) \times \tan\left(\phi_s\right)$$

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New physics would also show up in exclusive determinations of ϕ_s

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

- a_{sl}^s already suppressed by measurements of ΔM_s and Γ_s

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Implications of exclusive ϕ_s determinations

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

measurable weight function

$$\Delta\Psi = \arg\left[\sum_f \eta_f w_f e^{i(\phi_s^f - \langle\phi_s\rangle)}\right] \qquad w_f = \Gamma(B_s^0 \to f)\sqrt{\frac{1-\mathcal{A}_{\rm CP}^{\rm dir}(B_s\to f)}{1+\mathcal{A}_{\rm CP}^{\rm dir}(B_s\to f)}}$$

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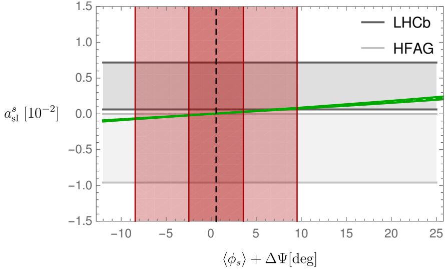
Exclusive Prediction:



- Limits the room for new physcis
- Interesting to confront with more precise measurements
- Opens also new windows to search for CPV in $D_s^\pm$ decays

Limited by $B_s \to D_s^- D_s^+$ (small band: upgrade scenario)

CP violation in non-leptonic B decays

Non-leptonic B decays

see Buras, Buchalla, Lautenbacher [1995]

Effective Hamiltonian

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

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

Current-current operators

$$\mathcal{O}_1^{jq} = \bar{q}_\alpha \gamma^\mu (1-\gamma_5) j_\beta \bar{j}_\beta \gamma_\mu (1-\gamma_5) b_\alpha$$
$$\mathcal{O}_2^{jq} = \bar{q}_\alpha \gamma^\mu (1-\gamma_5) j_\alpha \bar{j}_\beta \gamma_\mu (1-\gamma_5) b_\beta$$

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

$$\mathcal{O}_3^{q} = \bar{q}_\alpha \gamma^\mu (1-\gamma_5) b_\alpha \sum_{q'} \bar{q}'_\beta \gamma_\mu (1-\gamma_5) q'_\beta$$
$$\mathcal{O}_4^{q} = \bar{q}_\alpha \gamma^\mu (1-\gamma_5) b_\beta \sum_{q'} \bar{q}'_\beta \gamma_\mu (1-\gamma_5) q'_\alpha$$
$$\mathcal{O}_5^{q} = \bar{q}_\alpha \gamma^\mu (1-\gamma_5) b_\alpha \sum_{q'} \bar{q}'_\beta \gamma_\mu (1+\gamma_5) q'_\beta$$
$$\mathcal{O}_6^{q} = \bar{q}_\alpha \gamma^\mu (1-\gamma_5) b_\beta \sum_{q'} \bar{q}'_\beta \gamma_\mu (1+\gamma_5) q'_\alpha$$

EW penguin operators

$$\mathcal{O}_7^{q} = \tfrac{3}{2} \bar{q}_\alpha \gamma^\mu (1-\gamma_5) b_\alpha \sum_{q'} Q_{q'} \bar{q}'_\beta \gamma_\mu (1+\gamma_5) q'_\beta$$
$$\mathcal{O}_8^{q} = \tfrac{3}{2} \bar{q}_\alpha \gamma^\mu (1-\gamma_5) b_\beta \sum_{q'} Q_{q'} \bar{q}'_\beta \gamma_\mu (1+\gamma_5) q'_\alpha$$
$$\mathcal{O}_9^{q} = \tfrac{3}{2} \bar{q}_\alpha \gamma^\mu (1-\gamma_5) b_\alpha \sum_{q'} Q_{q'} \bar{q}'_\beta \gamma_\mu (1-\gamma_5) q'_\beta$$
$$\mathcal{O}_{10}^{q} = \tfrac{3}{2} \bar{q}_\alpha \gamma^\mu (1-\gamma_5) b_\beta \sum_{q'} Q_{q'} \bar{q}'_\beta \gamma_\mu (1-\gamma_5) q'_\alpha$$

Non-leptonic B decays

see Buras, Buchalla, Lautenbacher [1995]

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

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

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

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

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

  [Beneke, Buchalla, Neubert, Sachrajda, Bell, Huber, Feldmann, Li, Jaeger, Zupan, ...]

  - Strong phases generated at $\mathcal{O}(\alpha)$
  - Completion of penguin parameters at NNLO in progress

    Beneke, Bell, Huber [in progress]
  - Power corrections challenging to control

- Soft Collinear Effective Theory (SCET)

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

  - Important tool to establish QCDF at higher orders

Flavour symmetries [Gronau, Rosner, London, Buras, Fleischer, Zupan, Pirjol, Jaeger, Mannel, Jung, ...]

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

CP violation in B decays in the SM

Charged B mesons

$$\mathcal{A}_{\rm CP}^{\rm dir} \equiv \frac{|A(B\to f)|^2 - |A(\bar{B}\to f)|^2}{|A(B\to f)|^2 + |A(\bar{B}\to f)|^2}$$
$$= \frac{2|\mathcal{A}_1||\mathcal{A}_2|\sin(\Delta\theta)\sin\Delta\varphi}{|\mathcal{A}_1|^2 + |\mathcal{A}_2|^2 + 2|\mathcal{A}_1||\mathcal{A}_2|\cos(\Delta\theta)\cos\Delta\varphi}$$

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 γ)

CP violation in B decays in the SM

Neutral B_d and B_s mesons

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

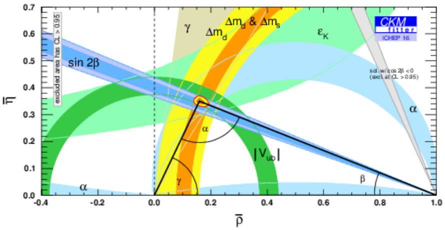
$$\mathcal{A}_{\rm CP}^{\rm dir} \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\,, \quad \mathcal{A}^{\Delta\Gamma} \equiv \frac{-2{\rm Re}\lambda_f}{1+|\lambda_f|^2}\,, \quad \lambda_f = \frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f}$$

$$\mathcal{A}_{\rm CP}^{\rm mix} \equiv \frac{-2{\rm Im}\lambda_f}{1+|\lambda_f|^2} = \frac{2|\lambda_f|}{1+|\lambda_f|^2}\sin\phi_q$$

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 γ from $B \to DK$



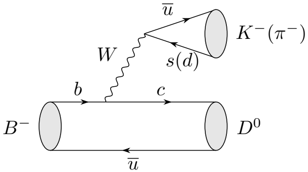
$$\text{Direct } \gamma = (73.5^{+4.3}_{-5.0})^\circ$$

$$\text{Indirect } \gamma = (65.3^{+1.0}_{-2.5})^\circ$$

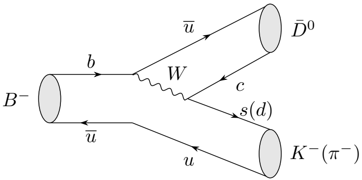
Determination of γ from $B \to DK$

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

Gronau, Wyler [1991]; Gronau, London [1991]; Atwood, Dunietz, Soni [1997]
Giri, Grossman, Soffer, Zupan [2003]



$\propto V_{cb}V_{us(d)}^*$



$\propto V_{ub}V_{cs(d)}^*$

- Important parameter: key input of the CKM
- Theoretically extremely clean (no penguin contributions)
  - Electroweak box corrections tiny Brod, Zupan [2013]; Brod [2014]
- Incredible precision of 1° expected at LHCb upgrade
- New physics contributions in $C_{1,2}$ may cause sizeable shifts in γ
Brod, Lenz, Wiebusch, Tetlalmatzi-Xolocotzi [2014]

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

Another theoretically clean probe

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

- Most precise measurement of γ from B_s system LHCb JHEP 03 [2018] 059

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

- Great potential for the LHCb upgrade
- Possible to perform a joint analysis to determine γ and ϕ_s

Fleischer, Nucl. Phys. B61 (2003) 459

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

Mixing angles ϕ_s and ϕ_d

Effective mixing angles ϕ_d and ϕ_s

CP asymmetries determine the "effective" mixing angle

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

- 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

Frings, Nierste, Wiebush [2015]

- $B \to J/\psi M$ factorizes in $N_c \to \infty$, but large corrections

Fleischer [1999]

- Flavour symmetries provide valuable insights into hadronic parameters

Controlling penguin effects in $B_d \to J/\psi K_S$

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

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

Penguin suppressed golden mode:

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

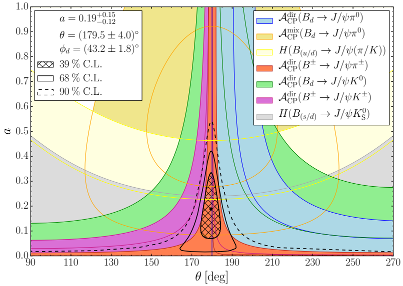
Penguin enhanced control mode:

$$\mathcal{A}(B_s^0 \to J/\psi K_S) = -\lambda\mathcal{C}\left[1 - a e^{i\theta} e^{i\gamma}\right]$$

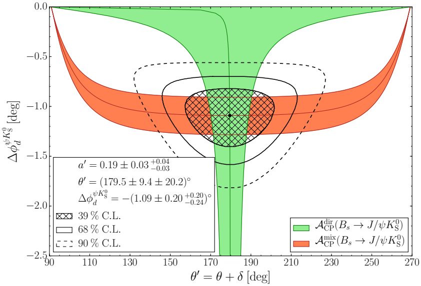
- Extract penguin parameters (a, θ) using γ as input
- Decays are related via U-spin (s-quark $\leftrightarrow$ d-quark)
- Only sensitive to non-factorizable U-spin breaking de Bruyn, Fleischer [2015]

Controlling penguin effects in $B_d \to J/\psi K_S$

de Bruyn, Fleischer, JHEP 1503 [2015] 145



Current data



Benchmark scenario (LHCb upgrade)

- 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

Penguin effects can be controlled!

Controlling penguin effects in $B_s \to J/\psi\phi$

Fleischer [1999]; Ciuchini, Pierini, Silvestrini [2005, 2011]
Faller, Fleischer, Jung, Mannel [2008]; Jung [2013]
de Bruyn, Fleischer [2015]; Fleischer [2007]; Jung, Schacht [2014]

$$\phi_s^{\rm SM} \equiv 2\beta_s = 2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

Penguin suppressed golden mode:

$B_s^0 \to J/\psi\phi$ (requires polarization measurements)

Penguin enhanced control mode:

$B_d^0 \to J/\psi\rho^0$ (but also $B_s \to J/\psi\bar{K}^{*0}$)

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

Similar strategy allows extraction of ϕ_s from $B_s \to D_s\bar{D}_s$

CP violation in $B_s^0 \to K^- K^+$

Flavor symmetries in $B_s^0 \to K^- K^+$ and $B_d \to \pi^- \pi^+$

Fleischer [1999, 2007]; Fleischer, Knegjens [2011]

- $B_s^0 \to K^- K^+$ dominated by QCD Penguin topologies
- Related to $B_d^0 \to \pi^- \pi^+$ via U-spin symmetry
- Extract γ and ϕ_s from direct and mixing-induced CP asymmetries

Fleischer [1999,2007]; Fleischer, Knegjens [2011]; Cuichini, Franco, Mishima, Silvestrini [2012]; LHCb [2015]

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

- Allows comparision between pure tree and penguin determinations
- Quickly limited by dominant U-spin breaking corrections

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Controlling $SU(3)$ breaking effects

- γ and ϕ_d input parameters; extract ϕ_s
- Split U-spin corrections: factorizable and non-factorizable effects
- Semileptonic ratios provide additional input

$$R_K \equiv \frac{\Gamma(B_s \to K^- K^+)}{|d\Gamma(B_s \to K^- \ell^+ \nu_\ell)/dq^2|_{q^2 = m_K^2}}$$

Controlling $SU(3)$ breaking effects

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

Non-factorizable U-spin breaking probed by

$$\xi^a_{\rm NF} \equiv \left|\frac{a_{\rm NF}}{a'_{\rm NF}}\right| = \left|\frac{a^T_{\rm NF}}{a^{T\prime}_{\rm NF}}\right| \left|\frac{1+r_P}{1+r'_P}\right| \left|\frac{1+x}{1+x'}\right|$$

$r_P \equiv P^{(ut)}/T \sim \mathcal{O}(\lambda)$

$x \equiv \frac{E+PA^{(ut)}}{T+P^{(ut)}} \sim \mathcal{O}(\lambda)$

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

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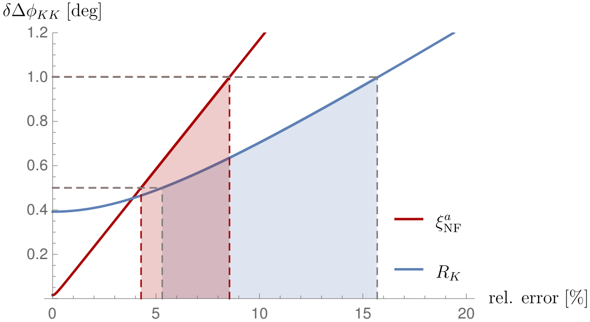
Hadronic uncertainties

- QCDF probes the tree-level contributions $a_{\rm NF}^{T}$ 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 $B_d^0 \to K^+K^-, B_s^0 \to \pi^+\pi^-$

Illustration of the future error on $\Delta\phi_{KK}$

Fleischer, Jaarsma, and KKV[2016]



Matching the experimental precision of 0.5° requires

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

The $B \to \pi K$ Puzzle

The $B \to \pi K$ puzzle

Buras, Fleischer, Recksiegel, Schwab [2004]; Fleischer, Recksiegel, Schwab [2007]; Fleischer, Jaeger, Pirjol, Zupan [2008]
Neubert, Rosner [1998]; Beneke, Neubert [2003]; Beaudry, Datta, London, Rashed, Roux [2018]

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

- Puzzling correlation between CP asymmmetries found
- Large discrepancy between experiment and QCDF
- Electroweak penguins (EWP) contribute at the same level as Trees $\to V_{ub}$ suppressed
- EWP sector offers an interesting avenue for NP to enter via

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

The $B \to \pi K$ puzzle

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- Electroweak penguins (EWP) contribute at the same level as Trees $\to V_{ub}$ suppressed
- EWP sector offers an interesting avenue for NP to enter via

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

Electroweak penguin parameters

Neubert, Rosner [1998]

- $\phi(\omega)$ CP-violating (conserving) phases, ω model-independently small
- New CP violating physics might enter with large phase ϕ

CP asymmetries in $B \to \pi K$

Gronau[2005]; Gronau, Rosner [2006]

$$\Delta_{\rm SR} = \mathcal{A}_{\rm CP}^{\rm dir}(\pi^\pm K^\mp) + \mathcal{A}_{\rm CP}^{\rm dir}(\pi^\pm K^0)\frac{{\rm Br}(\pi^\pm K^0)}{{\rm Br}(\pi^\pm K^\mp)}\frac{\tau_{B^0}}{\tau_{B^+}}$$
$$- \mathcal{A}_{\rm CP}^{\rm dir}(\pi^0 K^\pm)\frac{2{\rm Br}(\pi^0 K^\pm)}{{\rm Br}(\pi^\pm K^\mp)}\frac{\tau_{B^0}}{\tau_{B^+}} - \mathcal{A}_{\rm CP}^{\rm dir}(\pi^0 K_{\rm S})\frac{2{\rm Br}(\pi^0 K^0)}{{\rm Br}(\pi^\pm K^\mp)} = 0 + \mathcal{O}(\lambda^2)$$

Sum rule provides a Standard Model test

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

Mixing-induced CP asymmetry in $B_d^0 \to \pi^0 K^0$ provides additional tests

Isospin Amplitude Triangles

Nir, Quin [1991]; Gronau, Hernandez, London, Rosner [1995]

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

$$\overline{\sqrt{2}A(B^0 \to \pi^0 K^0) + A(B^0 \to \pi^- K^+)}$$
$$= \sqrt{2}A(B^+ \to \pi^0 K^+) + A(B^+ \to \pi^+ K^0)$$
$$\underline{= -(\hat{T} + \hat{C})\left(e^{i\gamma} - q e^{i\phi} e^{i\omega}\right) \equiv 3A_{3/2} = 3|A_{3/2}|e^{i\phi_{3/2}}} \ ,$$

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

$$|\hat{T} + \hat{C}| = R_{T+C} \, |V_{us}/V_{ud}| \, \sqrt{2}|A(B^+ \to \pi^+ \pi^0)|$$

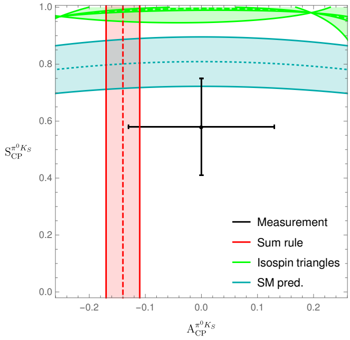
$$R_{T+C}|_{\text{fact}} = f_K/f_\pi = 1.2 \pm 0.2$$

Uncertainty accounts for non-factorizable $SU(3)$ breaking

Isospin Amplitude Triangles

Nir, Quin [1991]; Gronau, Hernandez, London, Rosner [1995]

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

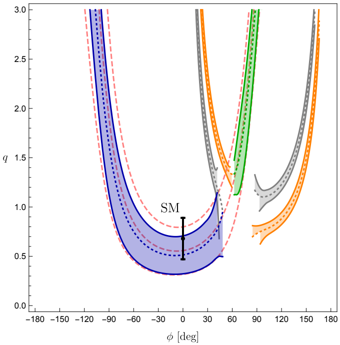


Hints at New Physics in the EWP sector?

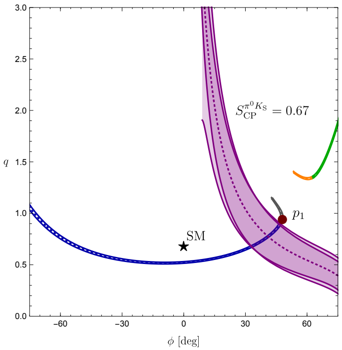
Pinning down New Physics in EWP sector

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

Additional constraint from mixing-induced CP asymmetry



Current data



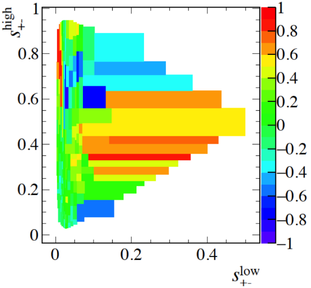
Benchmark scenario

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 $B \to \pi\pi\pi$

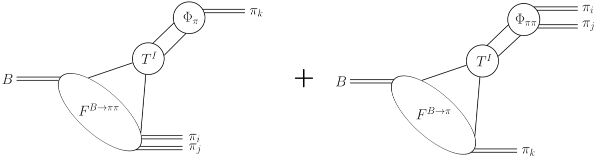


Theoretically challenging:

- 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

$$\langle \pi^+\pi^+\pi^- | \mathcal{O}_i | B \rangle = T_i^I \otimes F^{B\to\pi^+} \otimes \Phi_{\pi^+\pi^-} + T_i^I \otimes F^{B\to\pi^+\pi^-} \otimes \Phi_{\pi^+}$$

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

Summary

Summary

- Extraction of γ from $B \to DK$ is theoretically clean
  - Impressive 1° precision in the upgrade era expected
  - Will play an increasingly important role as input parameter
- Penguin polution in ϕ_s determinations under control
- Penguin dominated $B_s \to KK$ offers additional probe of ϕ_s
  - Requires analyses of $B_s^0 \to K^- \ell^+ \nu_\ell$
- $B \to \pi K$ decays remain puzzling $\to$ good prospects
  - Improved CP asymmetries in $B_d \to \pi^0 K_S$ needed
  - Crucial to distinguish New Physics from QCD effects
- Three-body decays still offer many interesting avenues to explore
  - Study QCDF in $B^0 \to D^- \pi^+ \pi^0$

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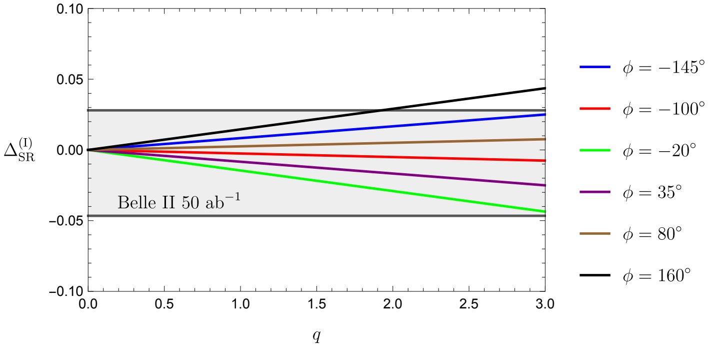
Thank you for your attention

Back up

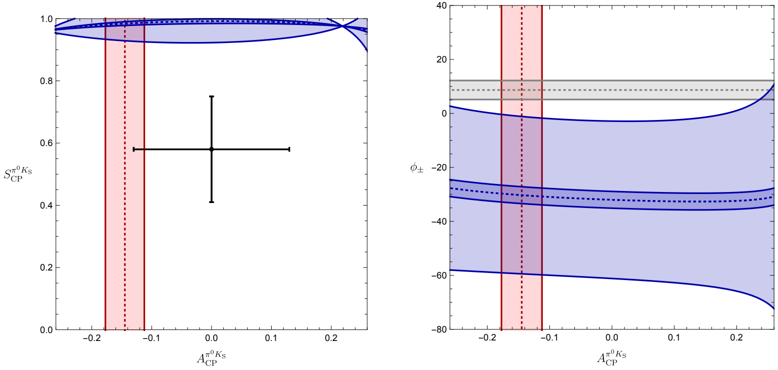
Constraints on new physics from the sum rule

- Limited sensitivity to q and ϕ for $q < 3$



Correlation between CP asymmetries in $B_d^0 \to \pi^0 K^0$

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



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

$$\phi_\pm|_{\mathrm{SM},\phi=0} = 2r\cos\delta\sin\gamma + \mathcal{O}(\lambda^2) = (8.7 \pm 3.5)^\circ$$

Pinning down New Physics in EWP sector

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

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

- r, δ, r_c and δ_c hadronic parameters determined from $B \to \pi\pi$
- Only cosines of small phases, low sensitivity to variations
- Includes color-suppressed EWPs $\tilde{a}_{\text{C}} = a_{\text{C}}\cos(\Delta_{\text{C}} + \delta_c)$
- 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 $B_s \to J/\psi\phi$

de Bruyn, Fleischer, JHEP 1503 [2015] 145