CP Violation in Non-leptonic B Decays as a Portal to New Physics

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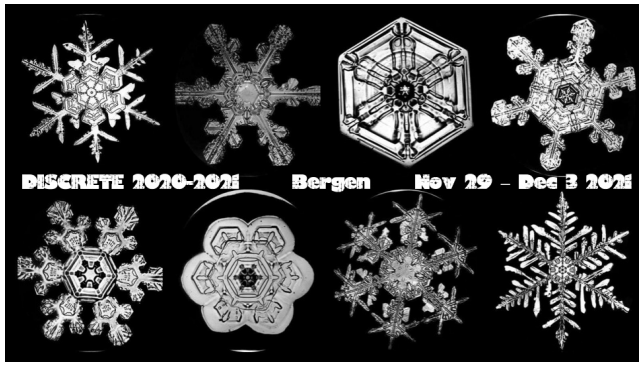


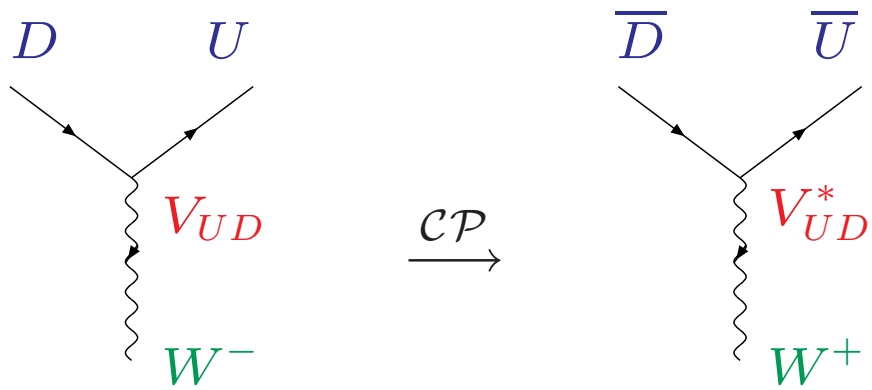
Setting the Stage

The Quark-Flavour Code

- Quark flavour physics and CP violation in the Standard Model (SM):

$$\left.\begin{matrix}\text{flavour}\\ \text{eigen-}\\ \text{states}\end{matrix}\right\} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{\text{quark-mixing matrix, also known as the Cabibbo–Kobayashi–Maskawa (CKM) matrix}} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix} \left\{\begin{matrix}\text{mass}\\ \text{eigen-}\\ \text{states}\end{matrix}\right.$$

$\rightarrow$ *unitary* matrix; *complex* phase $\rightarrow$ CP violation



- New Physics (NP): $\rightarrow$ typically new sources for flavour and CP violation.

$$\Rightarrow \boxed{\textit{encoded in weak decays of } K,\ D \textit{ and } B \textit{ mesons} \ldots}$$

Hope for New Physics (NP) ...

- We have indications that the SM *cannot* be complete:
  - Neutrino masses $\neq 0$: suggest see-saw mechanism, GUT scenarios ...
  - Baryon asymmetry of the Universe (SM cannot generate it ...)
  - The long-standing problem of dark matter (?)
- Fundamental theoretical questions/problems:
  - Hierarchy problem
  - Fine-tuning problem

  $\rightarrow$ suggest NP in the TeV regime (!?)
- Popular specific models for physics beyond the SM:
  - Supersymmetry (SUSY)
  - Universal extra dimension (UED)
  - Warped extra dimension (WED)
  - Little Higgs models (LH, with T parity LHT)
  - Z' models
  - ...

  $\rightarrow$ new sources of flavour & CP violation

Where Do We Stand?

- Data taking @ LHC: $\rightarrow$ discovery of "Higgs-like" particle, but ...
  - No SM deviations seen @ ATLAS/CMS.
  - CP violation & flavour sector globally consistent with the CKM picture.
  - But "anomalies" are emerging in B-meson decays [$+ (g-2)_\mu$]:
    - Semi-leptonic B decays: $\rightarrow$ talk by Wolfgang Altmannshofer
    - Non-leptonic B decays: $\rightarrow$ this talk ...
- Implications for the structure of NP:

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm NP}(\varphi_{\rm NP}, g_{\rm NP}, m_{\rm NP}, ...)$$

  - Large characteristic NP scale $\Lambda_{\rm NP}$, i.e. not just $\sim$ TeV, which would be challenging for direct searches at ATLAS and CMS, or / and ...
  - Symmetries prevent large NP effects in FCNCs and the flavour sector.
- Much more is yet to come: LHC run II data + run III + ... Belle II ...

Hierarchy of Scales

$$\underbrace{\Lambda_{\rm NP} \sim 10^{(0\ldots?)}\,\text{TeV} \gg \Lambda_{\rm EW} \sim 10^{-1}\,\text{TeV}}_{\text{(very) short distances}} \gg\gg \underbrace{\Lambda_{\rm QCD} \sim 10^{-4}\,\text{TeV}}_{\text{long distances}}$$

- Powerful theoretical concepts/techniques:

$\rightarrow$ "Effective Field Theories"

  - Heavy degrees of freedom (NP particles, top, Z, W) are "integrated out" from appearing explicitly: $\rightarrow$ *short-distance loop functions.*
  - Calculation of *perturbative QCD corrections.*
  - *Renormalization group* allows the summation of large $\log(\mu_{\rm SD}/\mu_{\rm LD})$.

- Applied to the SM and various NP scenarios, such as the following:
  - MSSM, UED, WED, LH, LHT, Z' models, ...

Standard Model Effective Theories (SMEFT): very popular ...

Theoretical Tool: Low-Energy Effective Hamiltonians

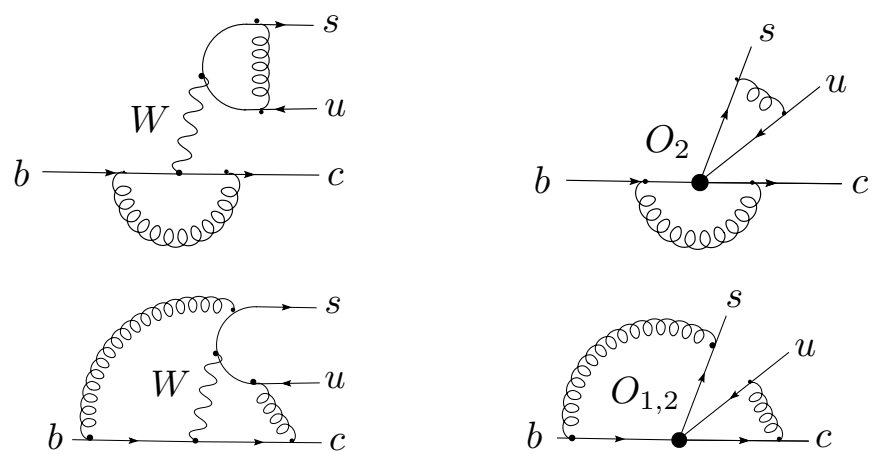
- Separation of short-distance from long-distance contributions (OPE):

$$\boxed{\langle \overline{f}|\mathcal{H}_{\text{eff}}|\overline{B}\rangle = \frac{G_{\rm F}}{\sqrt{2}} \sum_j \lambda^j_{\rm CKM} \sum_k C_k(\mu)\, \langle \overline{f}|Q^j_k(\mu)|\overline{B}\rangle}$$

[$G_{\rm F}$: Fermi's constant, $\lambda^j_{\rm CKM}$: CKM factors, μ: renormalization scale]

- Short-distance physics: [Buras *et al.*; Martinelli *et al.* ('90s); ...]

$\rightarrow$ Wilson coefficients $C_k(\mu)$ $\rightarrow$ *perturbative* quantities $\rightarrow$ known!



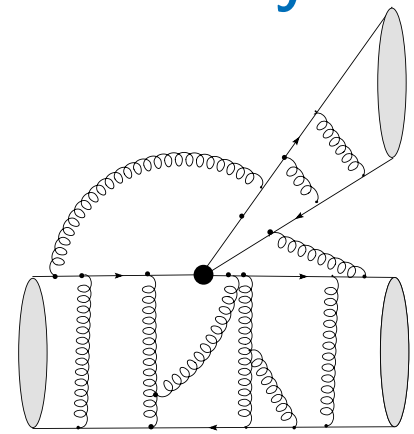
- Long-distance physics:

$\rightarrow$ matrix elements $\langle \overline{f}|Q^j_k(\mu)|\overline{B}\rangle$ $\rightarrow$ *non-perturbative* $\rightarrow$ "unknown"!?

[Lattice QCD: impressive recent progress, but still challenging for non-leptonic B decays]

Key Player for CP Violation: Non-Leptonic B Decays

$$|A_j|e^{i\delta_j} \propto \sum_k \underbrace{C_k(\mu)}_{\text{pert. QCD}} \times \boxed{\langle \overline{f}|Q_k^j(\mu)|\overline{B}\rangle}$$



- QCD factorization (QCDF):

  Beneke, Buchalla, Neubert & Sachrajda (1999–2001); Beneke & Jäger (2005); ...
  Huber *et al.* (2016); Bell *et al.* (2020); Bordone *et al.* (2020); Beneke *et al.* (2001)

- Perturbative Hard-Scattering (PQCD) Approach:

  Li & Yu ('95); Cheng, Li & Yang ('99); Keum, Li & Sanda ('00); ...

- Soft Collinear Effective Theory (SCET):

  Bauer, Pirjol & Stewart (2001); Bauer, Grinstein, Pirjol & Stewart (2003); ...

- QCD sum rules:

  Khodjamirian (2001); Khodjamirian, Mannel & Melic (2003); ...

Lots of progress, still generally a theoretical challenge ...

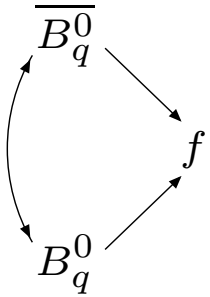
Circumvent the $\langle \overline{f} | Q_k^j(\mu) | \overline{B} \rangle$ in CP-B Studies:

- Amplitude relations allow us in fortunate cases to eliminate the hadronic matrix elements ($\rightarrow$ typically strategies to determine the UT angle γ):
  - *Exact* relations: class of pure "tree" decays (e.g. $B \rightarrow DK$).
  - *Approximate* relations, which follow from the *flavour symmetries* of strong interactions, i.e. $SU(2)$ isospin or $SU(3)_{\rm F}$:

$$B \rightarrow \pi\pi,\ B \rightarrow \pi K,\ B_{(s)} \rightarrow KK.$$

- Decays of neutral B_d or B_s mesons:

Interference effects through B_q^0–$\overline{B_q^0}$ mixing:



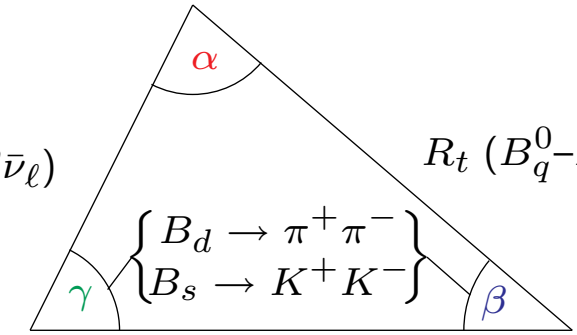
  - Lead to "mixing-induced" CP violation $S(f)$, in addition to "direct" CP violation $C(f)$ (caused by interference between decay amplitudes).
  - If one CKM amplitude dominates:

$$\Rightarrow \textit{ hadronic matrix elements cancel in } S(f), \textit{ while } C(f) = 0.$$

CP Violation B-Decay Benchmark Processes

- Unitarity Triangle:

$B \to \pi\pi$ (isospin), $B \to \rho\pi$, $B \to \rho\rho$



R_b ($b \to u, c\ell\bar{\nu}_\ell$)

R_t (B_q^0–$\bar{B}_q^0$ mixing)

$B \to \pi K$ (penguins)

$B_d \to \psi K_S$ ($B_s \to \psi\phi$: $\phi_s \approx 0$)

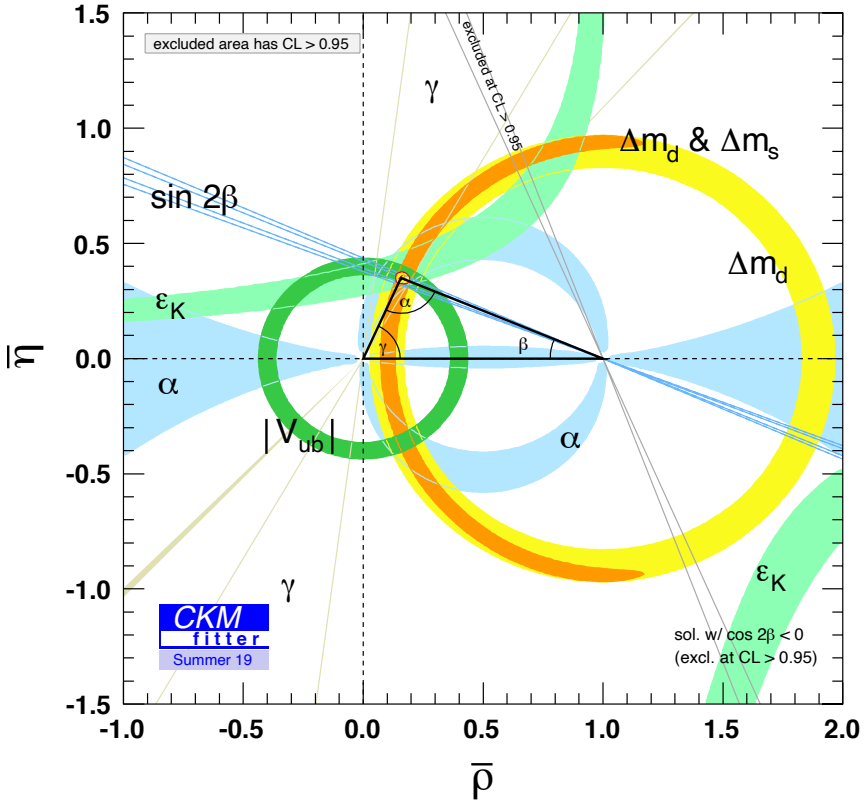
$B_d \to \phi K_S$ (pure penguin)

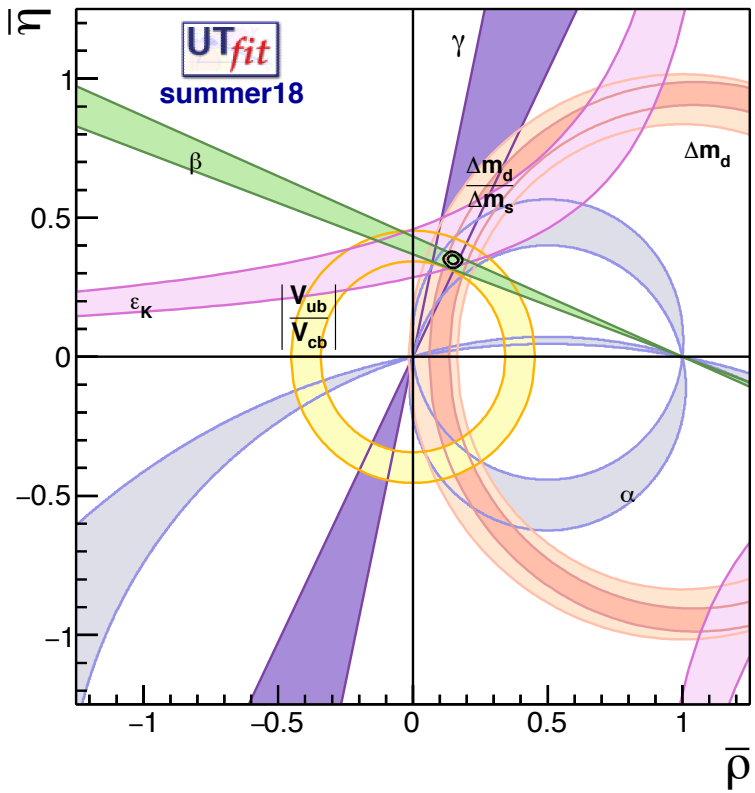
$$\left.\begin{array}{l} B_u^\pm \to K^\pm D \\ B_d \to K^{*0} D \\ B_c^\pm \to D_s^\pm D \end{array}\right\} \text{only trees}$$

$$\left.\begin{array}{l} B_d \to D^{(*)\pm}\pi^\mp : \ \gamma + 2\beta \\ B_s \to D_s^\pm K^\mp : \ \gamma + \phi_s \end{array}\right\} \text{only trees}$$

$\boxed{\text{New Physics}} \Rightarrow \boxed{\text{Discrepancies (!?)}}$

Current Status of the Unitarity Triangle

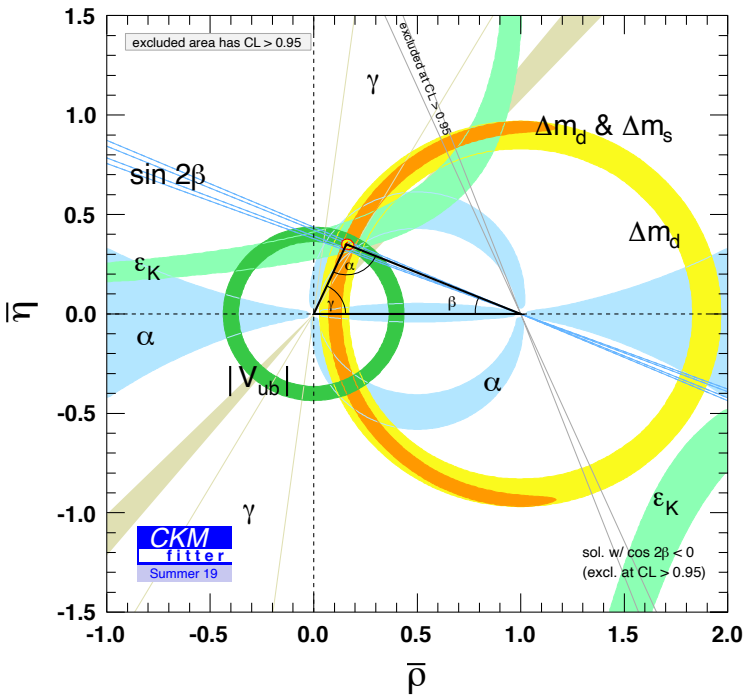


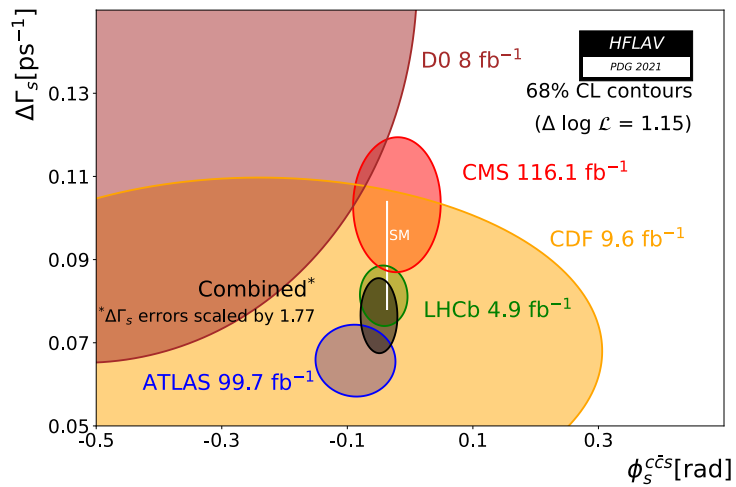


Precision Measurements of the B_q^0–$\bar{B}_q^0$ Mixing Phases

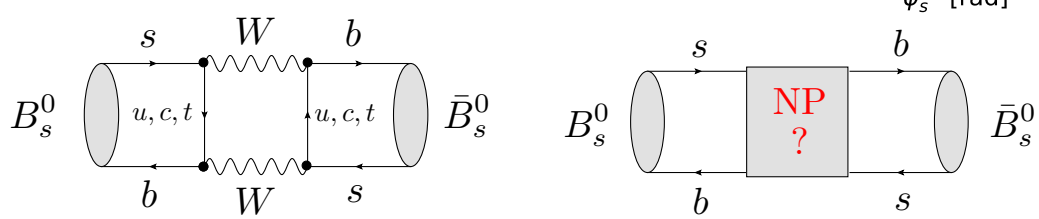
[Many thanks to Kristof De Bruyn for updating the plots; see also his talk @ CKM 2021]

Current Experimental Situation





- B_s^0–$\bar{B}_s^0$ mixing phase:



$$\boxed{\phi_s^{c\bar{c}s} \equiv \phi_s = \phi_s^{\rm SM} + \phi_s^{\rm NP} = -2\lambda^2\eta + \phi_s^{\rm NP}}$$

- HFLAV *average* of the experimental data from various decay channels:

$$\phi_s = -(2.86 \pm 1.09)^\circ \quad \text{vs.} \quad \phi_s^{\rm SM} = -\left(2.120^{+0.046}_{-0.040}\right)^\circ$$

Towards New Frontiers ...

- Crucial for resolving smallish effects of New Physics:
  - Have a critical look at theoretical analyses and their approximations:

    $\rightarrow$ key issue: $\boxed{\text{strong interactions: } \rightarrow \text{ “hadronic” effects}}$
  - Match the experimental and theoretical precisions.

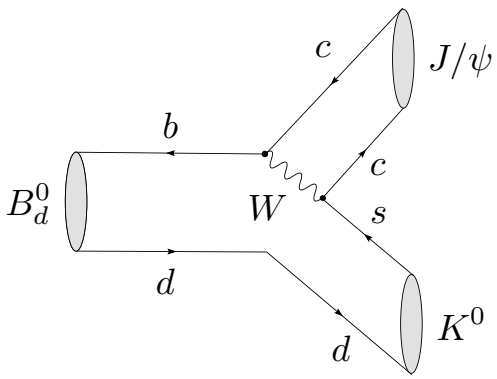
- Benchmark decays for exploring CP violation:

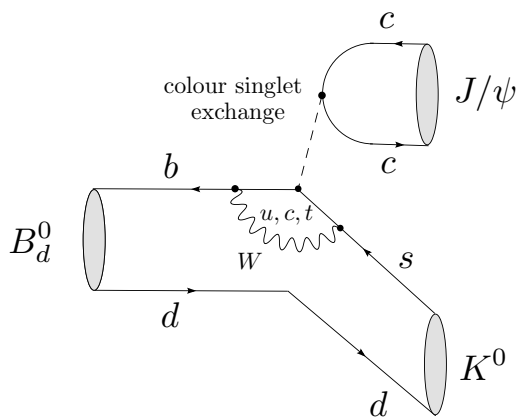
$$B_d^0 \rightarrow J/\psi K_{\rm S}, \quad B_s^0 \rightarrow J/\psi \phi$$

  - Allow measurements of the $B_{d,s}^0$–$\bar{B}_{d,s}^0$ mixing phases $\phi_{d,s}$.
  - Uncertainties from doubly Cabibbo-suppressed *penguin* contributions.
  - These effects are usually neglected ...

$$\Rightarrow \boxed{\textit{How big are they and how can they be controlled?}}$$

CP Violation in $B_d^0 \to J/\psi K_S$





- SM corrections: $\to$ *doubly Cabibbo-suppressed penguins*

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

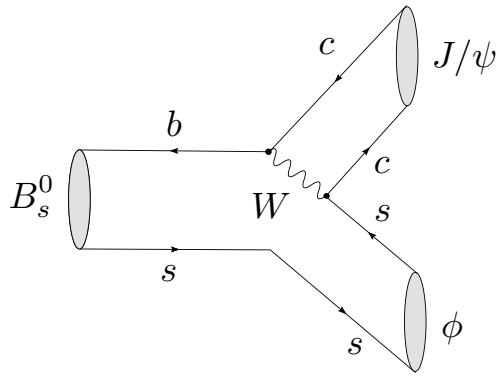
- Generalized expression for mixing-induced CP violation: $[\phi_d = 2\beta + \phi_d^{\rm NP}]$

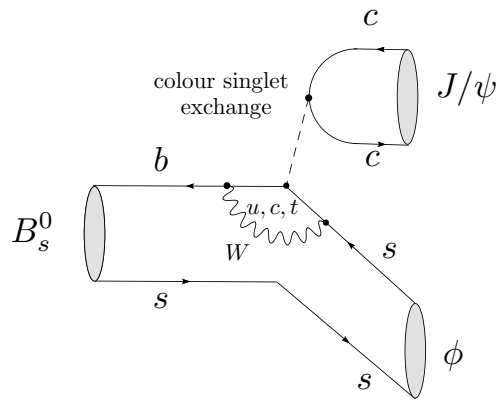
$$\frac{S(B_d \to J/\psi K_S)}{\sqrt{1 - C(B_d \to J/\psi K_S)^2}} = \sin(\phi_d + \Delta\phi_d)$$

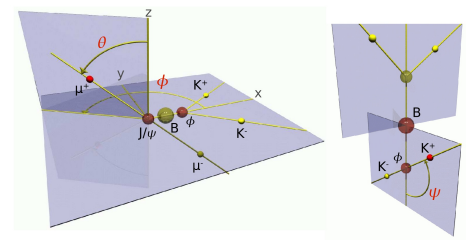
$$\begin{aligned} \sin\Delta\phi_d &\propto 2\epsilon a' \cos\theta' \sin\gamma + \epsilon^2 a'^2 \sin 2\gamma \\ \cos\Delta\phi_d &\propto 1 + 2\epsilon a' \cos\theta' \cos\gamma + \epsilon^2 a'^2 \cos 2\gamma \end{aligned}$$

[S. Faller, R.F., M. Jung & T. Mannel (2008)]

The $B_s^0 \to J/\psi\phi$ Decay







- Final state is mixture of CP-odd and CP-even states:

  $\to$ disentangle through $J/\psi[\to \mu^+\mu^-]\phi[\to\ K^+K^-]$ angular distribution

- Impact of SM penguin contributions: $f \in \{0, \|, \perp\}$

$$A\left(B_s^0 \to (J/\psi\phi)_f\right) = \left(1 - \frac{\lambda^2}{2}\right) \mathcal{A}'_f \left[1 + \epsilon a'_f e^{i\theta'_f} e^{i\gamma}\right]$$

  $\star$ CP-violating observables $\Rightarrow$ $\phi_{s,(\psi\phi)_f}^{\rm eff} = \phi_s + \Delta\phi_s^{(\psi\phi)_f}$

- Smallish B_s^0–$\bar{B}_s^0$ mixing phase ϕ_s (as following from the data):

  $\Rightarrow$ $\Delta\phi_s^{(\psi\phi)_f} \equiv \Delta\phi_s^f$ at the 1° level would have a significant impact ...

[Faller, R.F. & Mannel (2008)]

Towards High-Precision Analyses

- Era of Belle II and the LHCb upgrades:
  - Experimental precision requires the control of the penguin corrections to reveal possible CP-violating NP contributions to B_d^0–$\bar{B}_d^0$ mixing.
  - The topic receives long-standing interest in the theory community:
    R.F., (99); Ciuchini, Pierini & Silvestrini (05, 11); Faller, R.F., Jung & Mannel (08); Gronau & Rosner (08); De Bruyn, R.F., Koppenburg; Jung (2012); De Bruyn, R.F. (15); Frings, Nierste & Wiebusch (15); Barel, De Bruyn, R.F., Malami (2020).
- The hadronic phase shifts $\Delta\phi_d$, $\Delta\phi_s^f$ *cannot* be reliably calculated:

$\Rightarrow$ *use "control channels"* $B_s^0 \to J/\psi K_{\rm S}$, $B_d^0 \to J/\psi\pi^0$, $B_s^0 \to J/\psi\rho^0$*:*

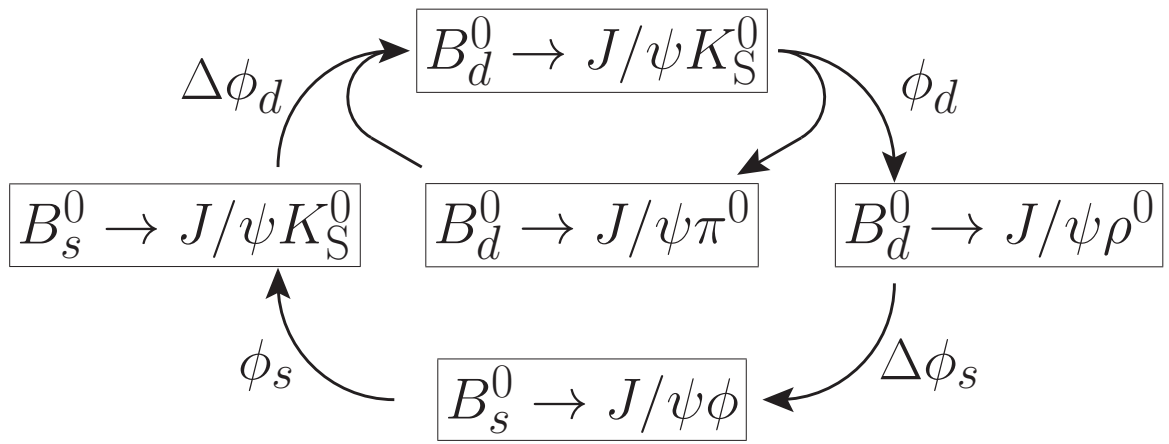
  - Key feature: $\to$ *"magnified" penguin parameters (no ϵ suppression)*

Example: $$\boxed{A(B_s^0 \to J/\psi K_{\rm S}) \propto \left[1 - a e^{i\theta} e^{i\gamma}\right]}$$

  - U-spin flavour symmetry: $$\boxed{a e^{i\theta} = a' e^{i\theta'}}$$

Combined Analysis

- Interplay between the control channels:



Assumptions:

– Neglect exchange and penguin-annihilation topologies.

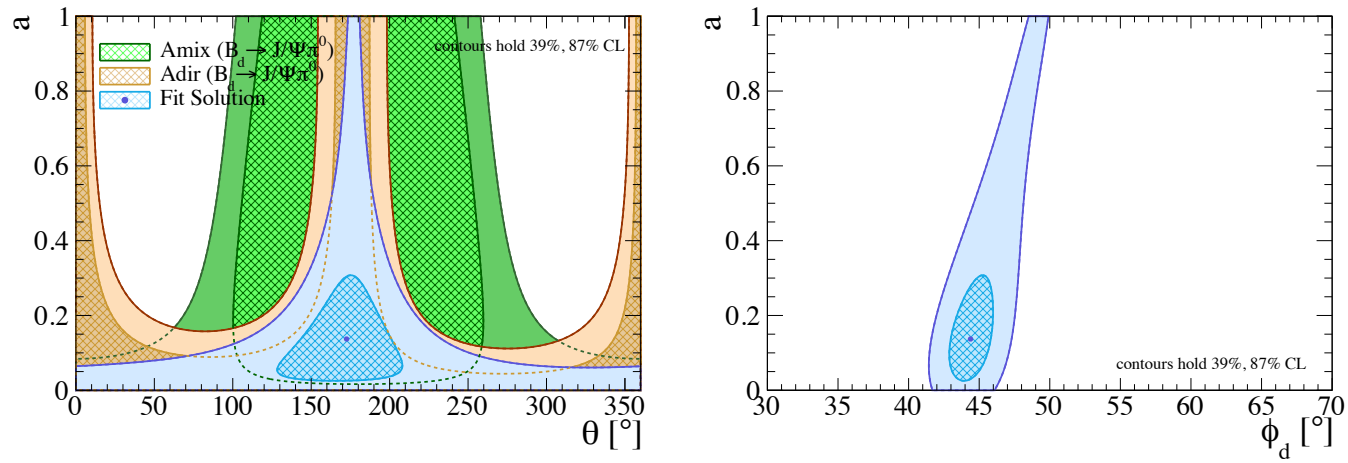
– Ignore polarisation-dependent effects in $B_{(s)} \to J/\psi V$ modes:

current lack of data $\to$ future measurements...

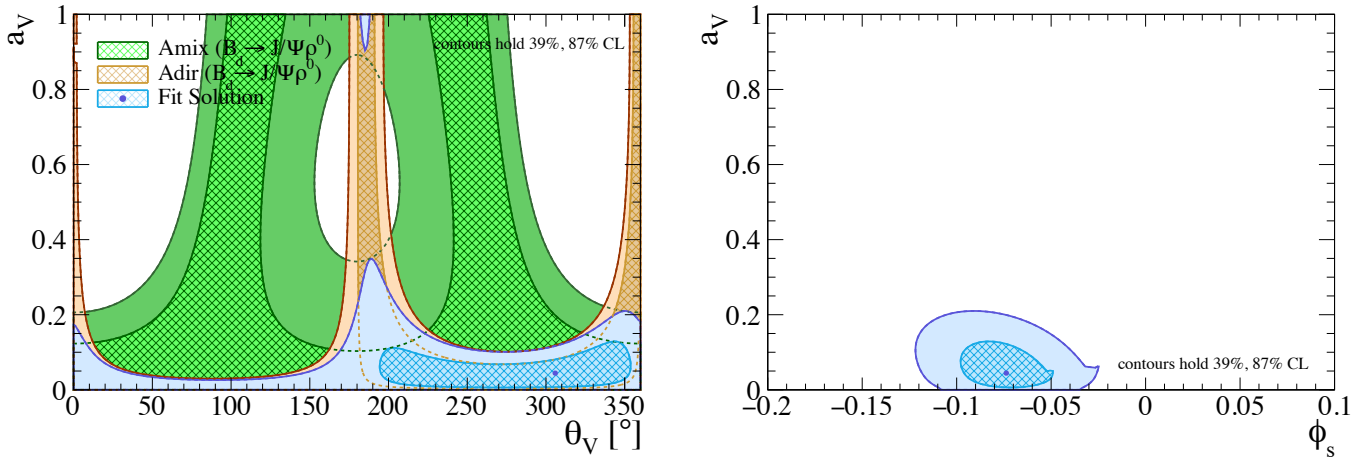
– Assume $SU(3)$ flavour symmetry relations.

[Barel, R.F., De Bruyn, Malami (2021)]

Picture from Current Data

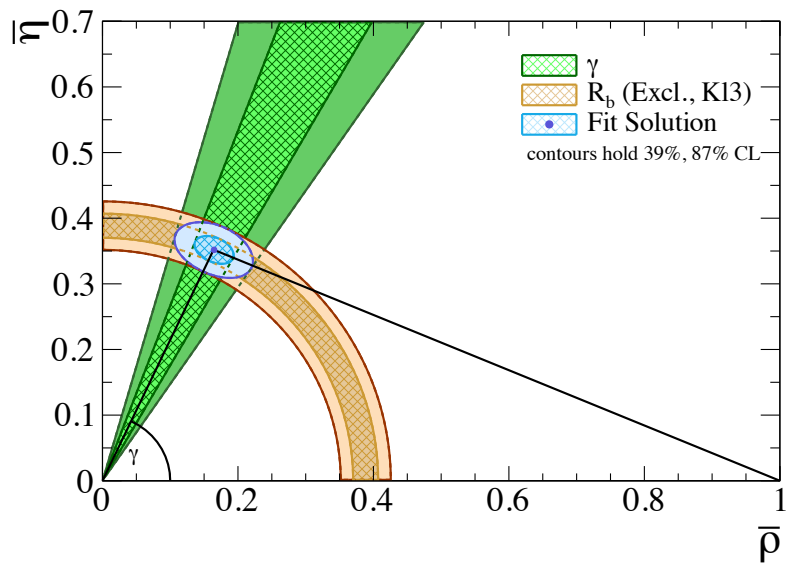


$$a = 0.14^{+0.17}_{-0.11},\ \theta = \left(173^{+35}_{-45}\right)^{\circ},\ \phi_d = \left(44.4^{+1.6}_{-1.5}\right)^{\circ}$$



$$a_V = 0.044^{+0.0.085}_{-0.038},\ \theta_V = \left(306^{+48}_{-112}\right)^{\circ},\ \phi_s = -\left(4.2 \pm 1.4\right)^{\circ}$$

Searching for New Physics



- Experimental value: $\phi^{\rm eff}_{d,J/\psi K^0} = (43.6 \pm 1.4)^\circ$

- Taking penguin effects into account:

$$\Delta\phi_s = \left(0.14^{+0.54}_{-0.70}\right)^\circ, \quad \phi_s = \phi_s^{\rm SM} + \phi_s^{\rm NP} = -\,(4.2 \pm 1.4)^\circ$$

- UT as determined above: $\phi_s^{\rm SM} = -2\lambda^2\eta = -\,(2.01 \pm 0.12)^\circ$

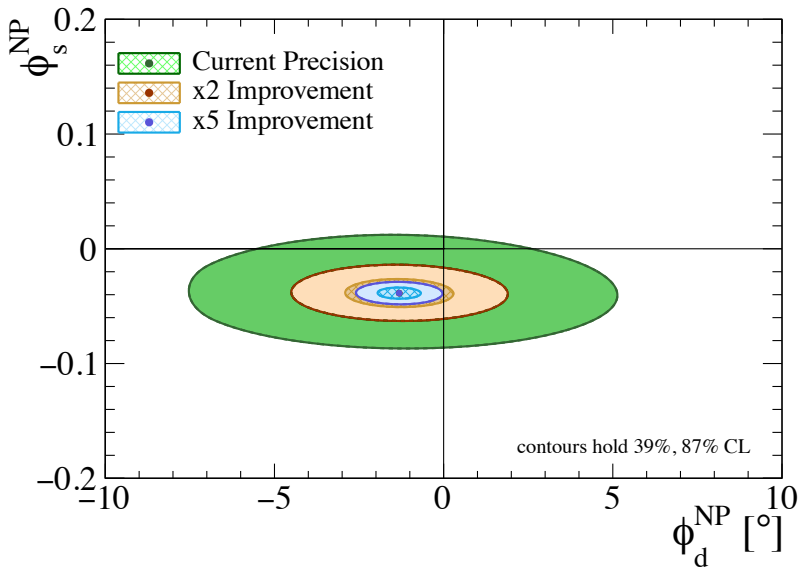
$$\Rightarrow \quad \boxed{\phi_s^{\rm NP} = -\,(2.2 \pm 1.4)^\circ}$$

Illustration of Future Prospects

- Inputs and assumptions:
  - Mixing phases:

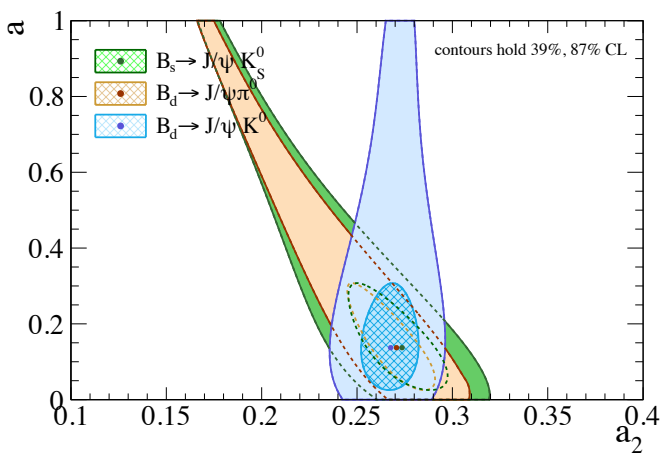
$$\phi_d^{\rm SM} = 2\beta = (45.7 \pm 2.8)^\circ\,, \quad \phi_s^{\rm SM} = -\,(2.01 \pm 0.12)^\circ$$

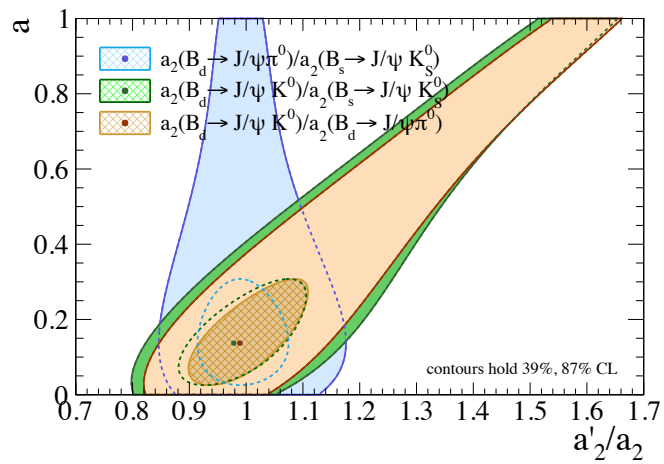
  - Similar experimental improvements in $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi\rho^0$:



- Observations:
  - We could reveal CP-violating NP effects with 5σ significance.
  - The SM prediction of ϕ_d is a limiting factor, making ϕ_d less favourable.

Insights into Hadronic Physics





$$\sqrt{2}A(B_d^0 \to J/\psi\pi^0) = \frac{G_F}{\sqrt{2}} V_{cd}^* V_{cb}^* m_{J/\psi} f_{J/\psi} f^+_{B_d\to\pi}(m^2_{J/\psi})(p_{B\mu}+p_{K\mu})\cdot\varepsilon^\mu_{J/\psi}$$
$$\times \left(1 - a e^{i\theta} e^{i\gamma}\right) \times a_2(B_d^0 \to J/\psi\pi^0)$$

- Effective colour-suppression factor: $a_2(B_d^0 \to J/\psi\pi^0)$

  $\to$ agrees (surprisingly) well with "naive factorization": $a_2 = 0.21 \pm 0.05$

  [Buras & Silvestrini (1998)]

- Non-factorizable $SU(3)$-breaking effects:

  – Deviations from factorisation at (30-40)% level, with $SU(3)$-breaking effects at 20% level $\Rightarrow$ non-fact. $SU(3)$-breaking effects at 5 % level :

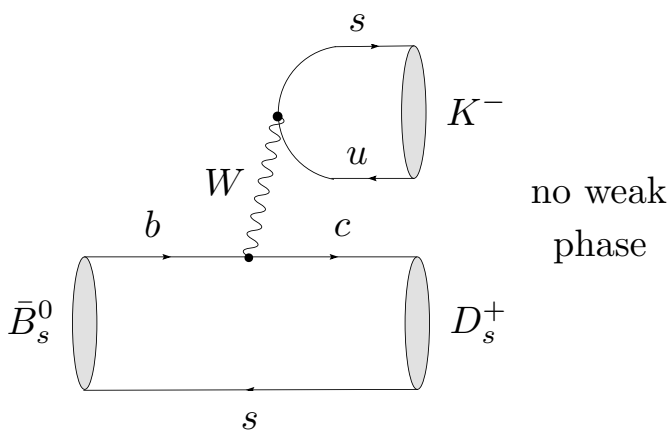
  $\to$ supported by plot on the right-hand side panel $\to$ *robust method!*

The $B_s^0 \to D_s^\mp K^\pm$ Puzzle

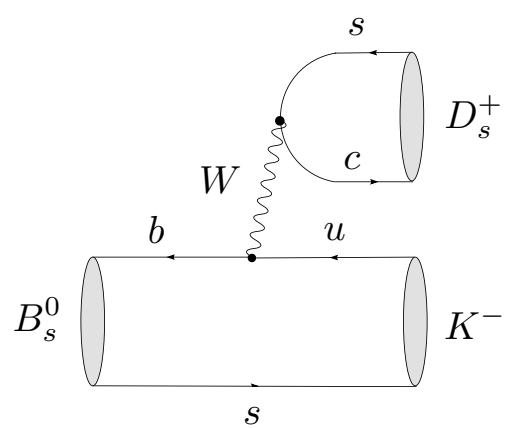
[R.F. and Eleftheria Malami (2021); see also Eleftheria's talk @ CKM 2021]

Toplogies & Interference

- Colour-allowed tree topologies in the Standard Model:



no weak phase

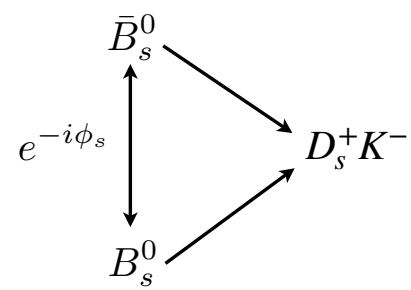


$\propto e^{i\gamma}$

- Time-dependent rate asymmetry:

$$\frac{\Gamma(B_s^0(t) \to D_s^+ K^-) - \Gamma(\bar{B}_s^0(t) \to D_s^+ K^-)}{\Gamma(B_s^0(t) \to D_s^+ K^-) + \Gamma(\bar{B}_s^0(t) \to D_s^+ K^-)}$$

$$= \frac{C\,\cos(\Delta M_s\, t) + S\,\sin(\Delta M_s\, t)}{\cosh(y_s\, t/\tau_{B_s}) + \mathcal{A}_{\Delta\Gamma}\,\sinh(y_s\, t/\tau_{B_s})}$$



- Decay width difference: $y_s \equiv \Delta\Gamma_s/(2\,\Gamma_s) = 0.062 \pm 0.004$
- Similar structure for CP-conjugate final state $D_s^- K^+$: $\overline{C}$, $\overline{S}$ and $\overline{\mathcal{A}}_{\Delta\Gamma}$

Closer Look at Observables

- Observables of the time-dependent rate asymmetries:

$$C = \frac{1-|\xi|^2}{1+|\xi|^2}, \quad S = \frac{2\,\mathrm{Im}\,\xi}{1+|\xi|^2}, \quad \mathcal{A}_{\Delta\Gamma} = \frac{2\,\mathrm{Re}\,\xi}{1+|\xi|^2}$$

$\Rightarrow$ ξ (and $\bar{\xi}$) can be *unambiguously* determined from the data.

- Interference effects are described by the following observables:

$$\xi = -e^{-i\phi_s}\left[e^{i\phi_{\rm CP}}\frac{A(\overline{B}^0_s \to D_s^+ K^-)}{A(B^0_s \to D_s^+ K^-)}\right] = -e^{-i(\phi_s+\gamma)}\underbrace{\left[\frac{1}{x_s e^{i\delta_s}}\right]}_{\text{hadronic}}$$

$$\bar{\xi} = e^{-i\phi_s}\left[e^{i\phi_{\rm CP}}\frac{A(\overline{B}^0_s \to D_s^- K^+)}{A(B^0_s \to D_s^- K^+)}\right] = -e^{-i(\phi_s+\gamma)}\underbrace{\left[x_s e^{i\delta_s}\right]}_{\text{hadronic}}$$

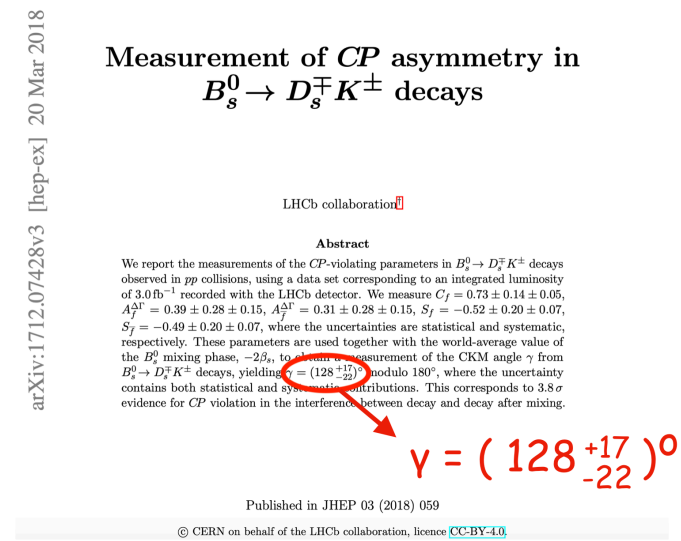
$\Rightarrow$ $\boxed{x_s,\ \delta_s \text{ cancel in } \xi \times \bar{\xi} = e^{-i2(\phi_s+\gamma)} \Rightarrow \textit{clean} \text{ extraction of } \phi_s + \gamma}$

[Aleksan, Dunietz, Kayser (1992); R.F. (2003); De Bruyn *et al.* (2012)]

LHCb Analysis

- Measurements of the CP-violating observables and fit to the data:

$$\boxed{\text{Assume Standard Model relations: } |\bar{\xi}| = 1/|\xi| \;\Rightarrow\; C + \overline{C} = 0}$$



arXiv:1712.07428v3 [hep-ex] 20 Mar 2018

Measurement of *CP* asymmetry in $B_s^0 \to D_s^{\mp} K^{\pm}$ decays

LHCb collaboration[1]

Abstract

We report the measurements of the *CP*-violating parameters in $B_s^0 \to D_s^{\mp} K^{\pm}$ decays observed in pp collisions, using a data set corresponding to an integrated luminosity of $3.0\,\mathrm{fb}^{-1}$ recorded with the LHCb detector. We measure $C_f = 0.73 \pm 0.14 \pm 0.05$, $A_f^{\Delta\Gamma} = 0.39 \pm 0.28 \pm 0.15$, $A_{\bar{f}}^{\Delta\Gamma} = 0.31 \pm 0.28 \pm 0.15$, $S_f = -0.52 \pm 0.20 \pm 0.07$, $S_{\bar{f}} = -0.49 \pm 0.20 \pm 0.07$, where the uncertainties are statistical and systematic, respectively. These parameters are used together with the world-average value of the B_s^0 mixing phase, $-2\beta_s$, to obtain a measurement of the CKM angle γ from $B_s^0 \to D_s^{\mp} K^{\pm}$ decays, yielding $\gamma = (128\,^{+17}_{-22})^{\circ}$ modulo 180°, where the uncertainty contains both statistical and systematic contributions. This corresponds to $3.8\,\sigma$ evidence for *CP* violation in the interference between decay and decay after mixing.

$\gamma = (128\,^{+17}_{-22})^{\circ}$

Published in JHEP 03 (2018) 059

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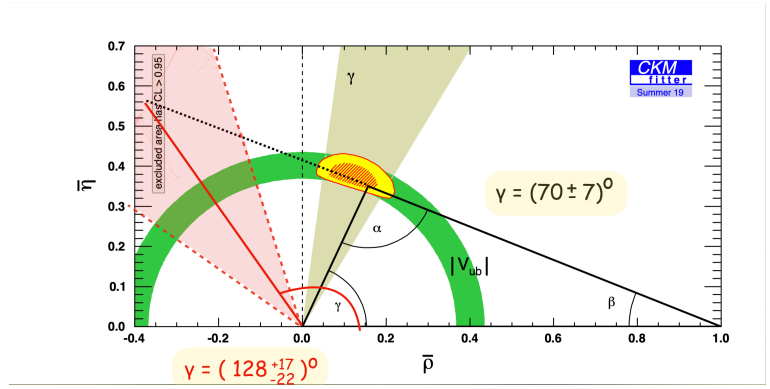
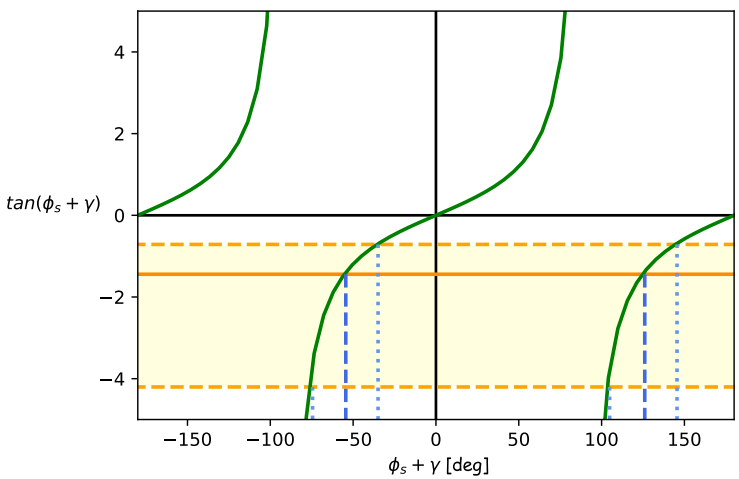


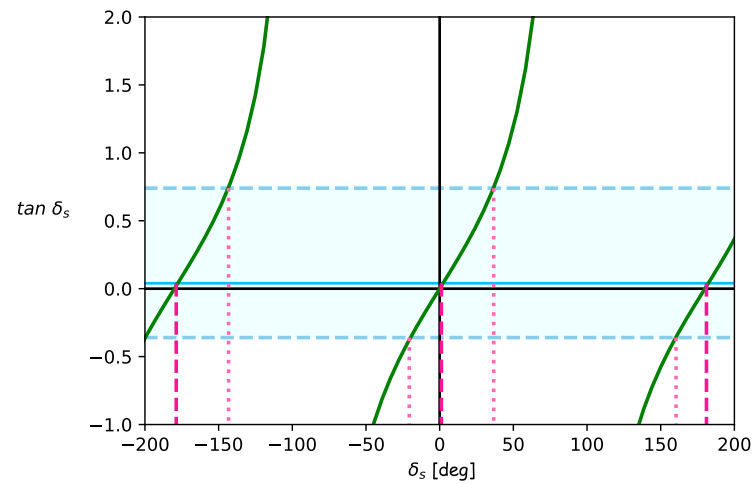
$\Rightarrow$ $\boxed{\text{Puzzling situation!?}}$ $\rightarrow$ R.F. and Eleftheria Malami (2021)

Transparent Determination of Parameters

- We use the following relations:

$$\tan(\phi_s+\gamma) = -\left[\frac{\overline{S}+S}{\overline{\mathcal{A}}_{\Delta\Gamma}+\mathcal{A}_{\Delta\Gamma}}\right], \quad \tan\delta_s = \left[\frac{\overline{S}-S}{\overline{\mathcal{A}}_{\Delta\Gamma}+\mathcal{A}_{\Delta\Gamma}}\right] \quad \Rightarrow$$





$$\Rightarrow \quad \phi_s+\gamma = \underbrace{\left[(-55^{+22}_{-18})^\circ\right]}_{\text{excluded(fact.)}} \vee (125^{+22}_{-18})^\circ, \quad \delta_s = \underbrace{\left[(182^{+34}_{-22})^\circ\right]}_{\text{excluded(fact.)}} \vee (2^{+34}_{-22})^\circ$$

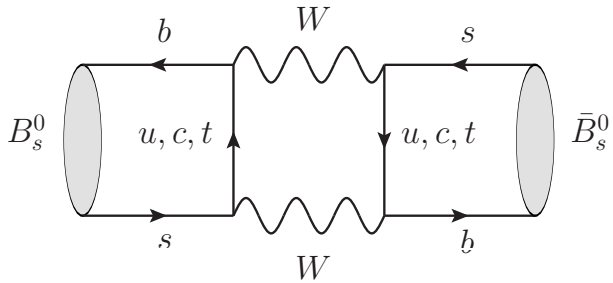
$$|\xi| = \sqrt{\frac{1-C)}{1+C}} \Rightarrow |\xi| = 2.53^{+1.43}_{-0.59}, \ |\bar{\xi}| = 0.40 \pm 0.13$$

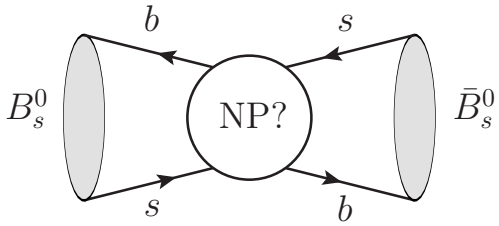
- LHCb fit (without the solutions mod 180°): $\rightarrow$ $\boxed{\textit{excellent agreement:}}$

$$\phi_s+\gamma = \left(126^{+17}_{-22}\right)^\circ, \quad \delta_s = (-2^{+13}_{-14})^\circ, \quad x_s = |\bar{\xi}| = 0.37^{+0.10}_{-0.09}$$

How Could New Physics Enter?

- New Physics in B_s^0–$\bar{B}_s^0$ mixing:





  - Mixing parameters ΔM_s and $\Delta\Gamma_s$: time evolution $\rightarrow$ measured.
  - New sources of CP violation may affect the mixing phase ϕ_s:

    $\rightarrow$ *included through* $B_s^0 \rightarrow J/\psi\phi$ *(and penguin control modes):*

$$\textit{Data (see above)} \Rightarrow \phi_s = \phi_s^{\rm SM} + \phi_s^{\rm NP} \Rightarrow \boxed{\gamma = \left(131^{+17}_{-22}\right)^\circ}$$

- New Physics in decay amplitudes:

  - The puzzling value of γ would require NP contributions with new sources of CP violation at the decay amplitude level:

$$\Rightarrow \boxed{\text{explore the } \bar{B}_s^0 \rightarrow D_s^+ K^- \text{ and } B_s^0 \rightarrow D_s^+ K^- \text{ branching ratios}}$$

Branching Ratios

- "Theoretical" branching ratios: $\rightarrow$ *B_s^0–$\bar{B}_s^0$ mixing is "switched off":*

$$\mathcal{B}_{\rm th} \equiv \frac{1}{2}\left[\mathcal{B}(\bar{B}_s^0 \to D_s^+ K^-)_{\rm th} + \mathcal{B}(B_s^0 \to D_s^+ K^-)_{\rm th}\right]$$

  – Observable ξ allows us to disentangle the decay paths:

$$\mathcal{B}(\bar{B}_s^0 \to D_s^+ K^-)_{\rm th} = 2\left(\frac{|\xi|^2}{1+|\xi|^2}\right)\mathcal{B}_{\rm th}$$

$$\mathcal{B}(B_s^0 \to D_s^+ K^-)_{\rm th} = 2\left(\frac{1}{1+|\xi|^2}\right)\mathcal{B}_{\rm th}$$

- Standard Model relations:

$$\mathcal{B}(\bar{B}_s^0 \to D_s^+ K^-)_{\rm th} \stackrel{\rm SM}{=} \mathcal{B}(B_s^0 \to D_s^- K^+)_{\rm th}$$

$$\mathcal{B}(B_s^0 \to D_s^+ K^-)_{\rm th} \stackrel{\rm SM}{=} \mathcal{B}(\bar{B}_s^0 \to D_s^- K^+)_{\rm th}$$

$$\Rightarrow \quad \mathcal{B}_{\rm th} \stackrel{\rm SM}{=} \bar{\mathcal{B}}_{\rm th}.$$

- "Experimental" branching ratios: $\rightarrow$ *time-integrated quantities:*

$$\mathcal{B}_{\rm exp} = \frac{1}{2}\int_0^\infty \left[\Gamma(\bar{B}_s^0(t) \to D_s^+ K^-) + \Gamma(B_s^0(t) \to D_s^+ K^-)\right] {\rm d}t$$

$$\mathcal{B}_{\rm th} = \left[\frac{1-y_s^2}{1+\mathcal{A}_{\Delta\Gamma_s} y_s}\right] \mathcal{B}_{\rm exp}$$

- Unfortunately, only a measurement of the following average is available:

$$\mathcal{B}_\Sigma^{\rm exp} \equiv \mathcal{B}_{\rm exp} + \bar{\mathcal{B}}_{\rm exp} \equiv 2\,\langle \mathcal{B}_{\rm exp}\rangle = (2.27 \pm 0.19)\times 10^{-4}$$

- Assuming the SM (as LHCb), we have the following relation:

$$\mathcal{B}_{\rm th} = \bar{\mathcal{B}}_{\rm th} = \left[\frac{1-y_s^2}{1+y_s\langle \mathcal{A}_{\Delta\Gamma}\rangle_+}\right] \langle \mathcal{B}_{\rm exp}\rangle \quad \text{with} \quad \langle \mathcal{A}_{\Delta\Gamma}\rangle_+ \equiv \frac{\overline{\mathcal{A}}_{\Delta\Gamma} + \mathcal{A}_{\Delta\Gamma}}{2}$$

- Finally, we obtain the following branching ratios from the data:

$$\begin{aligned} \mathcal{B}(\bar{B}_s^0 \to D_s^+ K^-)_{\rm th} &= (1.94 \pm 0.21)\times 10^{-4} \\ \mathcal{B}(B_s^0 \to D_s^+ K^-)_{\rm th} &= (0.26 \pm 0.12)\times 10^{-4} \end{aligned}$$

Theoretical Interpretation

- Factorization provides the theoretical framework:. $b \to c\bar{u}s$ process:

$$A(\bar{B}_s^0 \to D_s^+ K^-)\big|_{\rm SM} = \frac{G_{\rm F}}{\sqrt{2}} V_{us}^* V_{cb} f_K F_0^{B_s \to D_s}(m_K^2)(m_{B_s}^2 - m_{D_s}^2) a_{1\,\rm eff}^{D_s K}$$

[$V_{us}^* V_{cb}$: CKM factor; f_K: kaon decay constant; $F_0^{B_s \to D_s}(m_K^2)$: form factor]

- Deviation from naive factorization:

$$a_{1\,\rm eff}^{D_s K} = a_1^{D_s K} \left(1 + \frac{E_{D_s K}}{T_{D_s K}}\right)$$

  – Non-factorizable effects in the color-allowed tree amplitude $T_{D_s K}$:

    "Show-case" example for factorization: $\boxed{|a_1^{D_s K}| = 1.07 \pm 0.02}$

  – Moreover, non-factorizable exchange topology $E_{D_s K}$:

$$\textit{Experimental data:} \quad r_E^{D_s K} \equiv \left|1 + \frac{E_{D_s K}}{T_{D_s K}}\right| = 1.00 \pm 0.08$$

- Amplitude with similar structure for the $b \to u\bar{c}s$ mode $\bar{B}_s^0 \to K^+ D_s^-$:

  – Here factorization appears on less solid ground: $\boxed{|a_1^{K D_s}| = 1.1 \pm 0.1}$

Minimizing CKM and Form Factor Uncertainties

- Introduce ratios with appropriate semileptonic decay information:

$$R_{D_s^+K^-} \equiv \frac{\mathcal{B}(\bar{B}_s^0 \to D_s^+ K^-)_{\rm th}}{\mathrm{d}\mathcal{B}\left(\bar{B}_s^0 \to D_s^+ \ell^- \bar{\nu}_\ell\right)/\mathrm{d}q^2|_{q^2=m_K^2}} = 6\pi^2 f_K^2 |V_{us}|^2 |a_{1\,\rm eff}^{D_sK}|^2 X_{D_sK}$$

$$X_{D_sK} \equiv \Phi_{\rm ph}\left[F_0^{B_s\to D_s}(m_K^2)/F_1^{B_s\to D_s}(m_K^2)\right]^2$$

  - $|V_{cb}|$ cancels: discrepancy between inclusive/exclusive determinations.
  - $\Phi_{\rm ph}$ is a calculable phase-space factor, very close to 1.
  - Impact of non-perturbative hadronic form factors is minimal due to

$$F_0^{B_s\to D_s}(0) = F_1^{B_s\to D_s}(0)$$

  - Implementation using experimental data: $\Rightarrow$ $\boxed{|a_1^{D_sK}| = 0.82 \pm 0.11}$

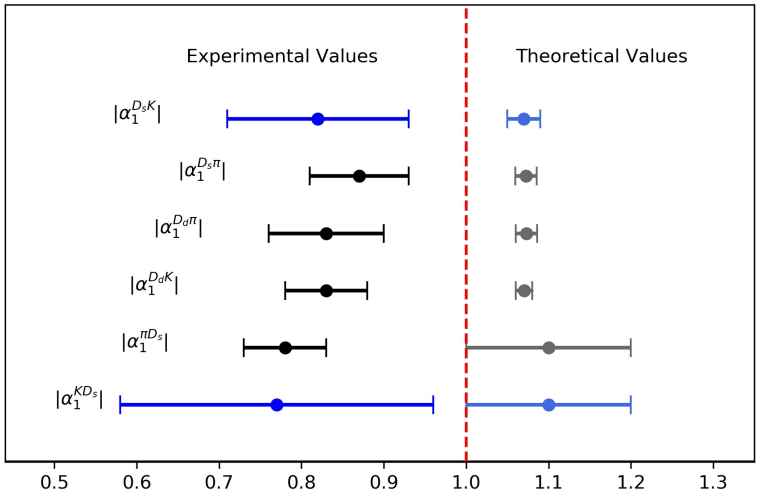
- Similar analysis for $\bar{B}_s^0 \to K^+ D_s^-$, where the partner is $\bar{B}_s^0 \to K^+ \ell \bar{\nu}_\ell$:

  - $\bar{B}_s^0 \to K^+ \ell^- \bar{\nu}_\ell$ observed but no differential rate measurement reported.
  - Use $\bar{B}_d^0 \to \pi^+ \ell^- \bar{\nu}_\ell$ with $SU(3)$ flavour symmetry:

$$\Rightarrow \quad \boxed{|a_1^{KD_s}| = 0.77 \pm 0.19}$$

Compilation of $|a_1|$ Parameters

- Using analogous ratios with respect to semileptonic decays, we have performed a detailed analysis of $B_{(s)}$ decays with similar dynamics:



Similar pattern!

  - $\bar{B}_d^0 \to D_d^+ K^-$ stands out, showing a discrepancy of $4.8\,\sigma$ significance.
  - Surprisingly small branching ratios of some channels noted before:
    R.F., Tuning, Serra (2011); De Bruyn *et al.* (2012); Bordone *et al.* (2020).
  - Detailed analyses within NP scenarios:
    Iguro & Kitahara (2020); Cai *et al.* (2021); Bordone, Greljo & Marzocca (2021)
  - General NP effects in tree decays:
    Brod *et al.* (2015); Lenz & Tetlalmatzi-Xolocotzi (2019)

- Pattern of $|a_1|$ parameters complements CPV puzzle in $B_s^0 \to D_s^\mp K^\pm$:

$\Rightarrow$ Exciting new puzzle: manifestation of New Physics!?

New Physics: Amplitudes and Observables

- Generalization of the decay amplitudes:

$$A(\bar{B}_s^0 \to D_s^+ K^-) = A(\bar{B}_s^0 \to D_s^+ K^-)_{\rm SM} \left[1 + \bar{\rho}\, e^{i\bar{\delta}} e^{+i\bar{\varphi}}\right]$$

$$\bar{\rho}\, e^{i\bar{\delta}} e^{i\bar{\varphi}} \equiv \frac{A(\bar{B}_s^0 \to D_s^+ K^-)_{\rm NP}}{A(\bar{B}_s^0 \to D_s^+ K^-)_{\rm SM}}$$

[δ: CP-conserving strong phase; φ: CP-violating NP phase]

  – $\bar{B}_s^0 \to D_s^- K^+$ channel: $\to$ analogous expression with ρ, φ and δ.

- Useful to introduce the following quantities:

$$\bar{b} \equiv \frac{\langle R_{D_s K}\rangle}{6\pi^2 f_K^2 |V_{us}|^2 |a_{1\,\rm eff}^{D_s K}|^2 X_{D_s K}} = 1 + 2\,\bar{\rho}\cos\bar{\delta}\cos\bar{\varphi} + \bar{\rho}^2 = 0.58 \pm 0.16$$

$$b \equiv \frac{\langle R_{K D_s}\rangle}{6\pi^2 f_{D_s}^2 |V_{cs}|^2 |a_{1\,\rm eff}^{K D_s}|^2 X_{K D_s}} = 1 + 2\,\rho\cos\delta\cos\varphi + \rho^2 = 0.50 \pm 0.26$$

[$\langle R\rangle$: CP-averaged quantities]

- New Physics contributions may generate direct CP violation:

$$\mathcal{A}_{\rm CP}^{\rm dir} \equiv \frac{|A(B_s^0 \to D_s^+ K^-)|^2 - |A(\bar{B}_s^0 \to D_s^- K^+)|^2}{|A(B_s^0 \to D_s^+ K^-)|^2 + |A(\bar{B}_s^0 \to D_s^- K^+)|^2} = \frac{2\,\rho \sin\delta \sin\varphi}{1 + 2\,\rho\cos\delta\cos\varphi + \rho^2}$$

[Similar for the CP-conjugate asymmetry $\bar{\mathcal{A}}_{\rm CP}^{\rm dir}$, involving $\bar{\rho}$ with $\bar{\delta}$ and $\bar{\varphi}$]

- Generalisations for the observables $\bar{\xi}$ and ξ:

$$\bar{\xi} = \bar{\xi}_{\rm SM} \left[\frac{1 + \rho\, e^{i\delta} e^{+i\varphi}}{1 + \bar{\rho}\, e^{i\bar{\delta}} e^{-i\bar{\varphi}}}\right] = -|\bar{\xi}| e^{+i\delta_s} e^{-i(\phi_s+\gamma)} e^{i\Delta\bar{\varphi}}$$

[Similar expression for ξ: interchange $\bar{\rho}$, $\bar{\delta}$, $\bar{\varphi}$ and ρ, δ, φ]

$$\xi \times \bar{\xi} = e^{-i2(\phi_s+\gamma)} \left[\frac{1 + \rho\, e^{i\delta} e^{+i\varphi}}{1 + \rho\, e^{i\delta} e^{-i\varphi}}\right] \left[\frac{1 + \bar{\rho}\, e^{i\bar{\delta}} e^{+i\bar{\varphi}}}{1 + \bar{\rho}\, e^{i\bar{\delta}} e^{-i\bar{\varphi}}}\right]$$

$$\frac{1 + \rho\, e^{i\delta} e^{+i\varphi}}{1 + \rho\, e^{i\delta} e^{-i\varphi}} = e^{-i\Delta\Phi} \sqrt{\frac{1 - \mathcal{A}_{\rm CP}^{\rm dir}}{1 + \mathcal{A}_{\rm CP}^{\rm dir}}}$$

$$\left|\xi \times \bar{\xi}\right|^2 = \left[\frac{1 - \mathcal{A}_{\rm CP}^{\rm dir}}{1 + \mathcal{A}_{\rm CP}^{\rm dir}}\right] \left[\frac{1 - \bar{\mathcal{A}}_{\rm CP}^{\rm dir}}{1 + \bar{\mathcal{A}}_{\rm CP}^{\rm dir}}\right]$$

Constraining NP Parameters

- New Physics generalization of the "master equation":

$$\xi \times \bar{\xi} = \sqrt{1 - 2\left[\frac{C + \bar{C}}{(1+C)\left(1+\bar{C}\right)}\right]} e^{-i[2(\phi_s + \gamma_{\rm eff})]}$$

$$\gamma_{\rm eff} \equiv \gamma + \frac{1}{2}\left(\Delta\Phi + \Delta\bar{\Phi}\right) = \gamma - \frac{1}{2}\left(\Delta\varphi + \Delta\bar{\varphi}\right)$$

$$\tan\Delta\Phi = -\left[\frac{2\rho\cos\delta\sin\varphi + \rho^2\sin 2\varphi}{1 + 2\rho\cos\delta\cos\varphi + \rho^2\cos 2\varphi}\right]$$

$\Rightarrow$ UT angle γ enters as an "effective" angle with a NP phase shift!

- Takes possible direct CP violation into account: $C + \bar{C}\big|_{\rm SM} = 0$

$$\frac{C + \bar{C}}{(1+C)\left(1+\bar{C}\right)} = \mathcal{A}_{\rm CP}^{\rm dir} + \bar{\mathcal{A}}_{\rm CP}^{\rm dir} + \mathcal{O}((\mathcal{A}_{\rm CP}^{\rm dir})^2)$$

$$\boxed{\text{Assume } \delta = \bar{\delta} = 0^\circ \text{ to be consistent with LHCb, i.e. } C + \bar{C} = 0}$$

- Branching ratios:

$\Rightarrow$ $\bar{b}$ and b give $\bar{\rho}$ and ρ as functions of $\bar{\varphi}$ and φ, respectively.

- CP violation:

$$\Rightarrow \quad \Delta\varphi = \Delta\bar{\varphi} = \gamma - \gamma_{\rm eff} = -(61 \pm 20)^\circ,$$

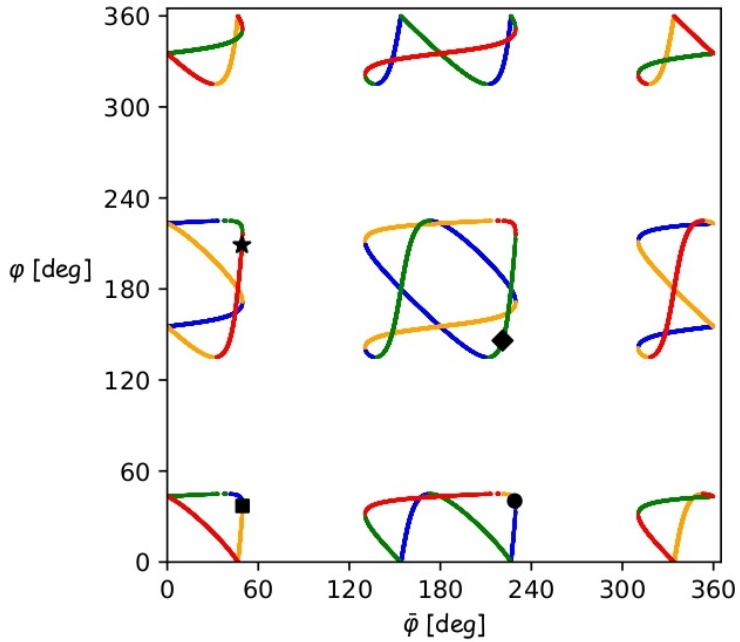
where we used $\gamma = (70 \pm 7)^\circ$ and $\gamma_{\rm eff} = \left(131^{+17}_{-22}\right)^\circ$, and

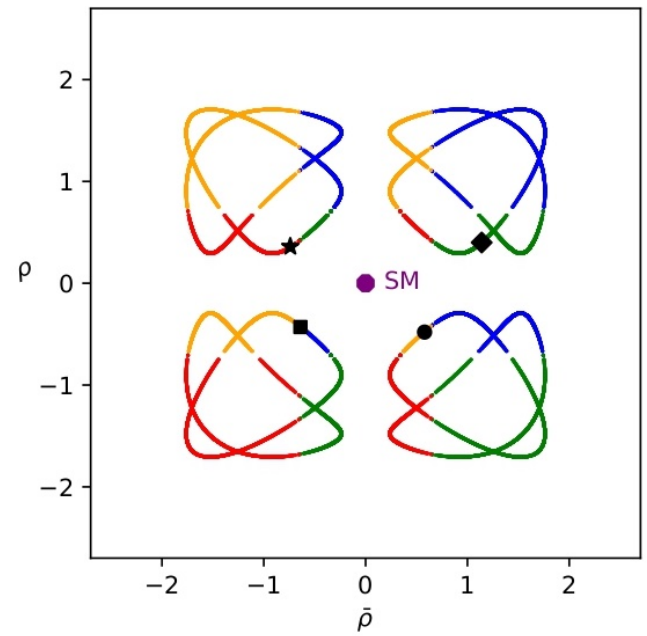
$$\tan\Delta\varphi = \frac{\rho\sin\varphi + \bar{\rho}\sin\bar{\varphi} + \bar{\rho}\rho\sin(\bar{\varphi}+\varphi)}{1 + \rho\cos\varphi + \bar{\rho}\cos\bar{\varphi} + \bar{\rho}\rho\cos(\bar{\varphi}+\varphi)}.$$

- Correlations between the NP parameters:

b, $\bar{b}$ and $\Delta\varphi$ $\Rightarrow$ $\boxed{\varphi \text{ as function of } \bar{\varphi}\text{, and } \rho \text{ as function of } \bar{\rho}}$

- Central values of current measurements:

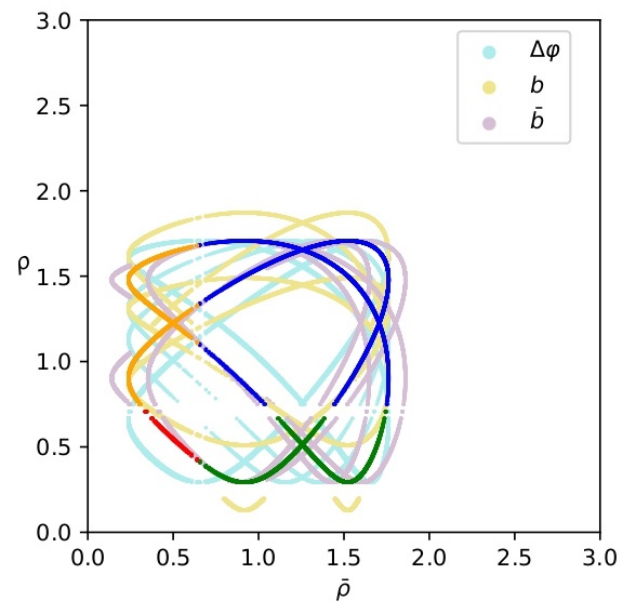




- Impact of uncertainties:

Interestingly, NP amplitudes in the (30-50)% range of the SM amplitudes could accommodate the data.

Intriguing situation: stay tuned...

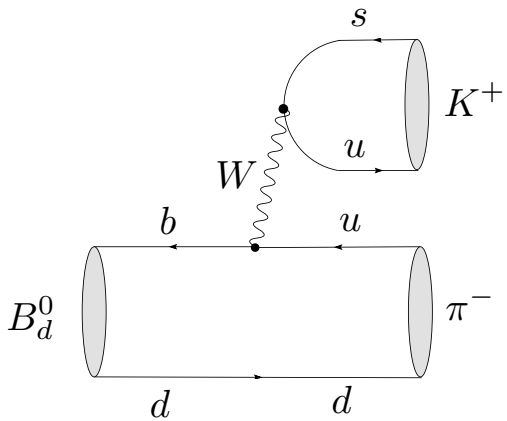


The $B \to \pi K$ Puzzle

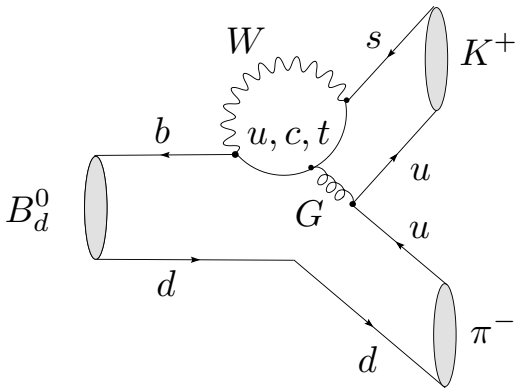
[R.F., Jäger, Pirjol & Zupan (2008); R.F., Jaarsma, Malami & Vos (2016)]

Closer Look at $B \to \pi K$ Decays

- Example:



$\propto A\lambda^4 R_b e^{i\gamma}$



$\propto A\lambda^2$

$$\lambda^2 R_b = \mathcal{O}(0.02) \quad \Rightarrow \quad \boxed{\text{QCD penguins } \textit{dominate}}$$

- As can straightforwardly be seen:

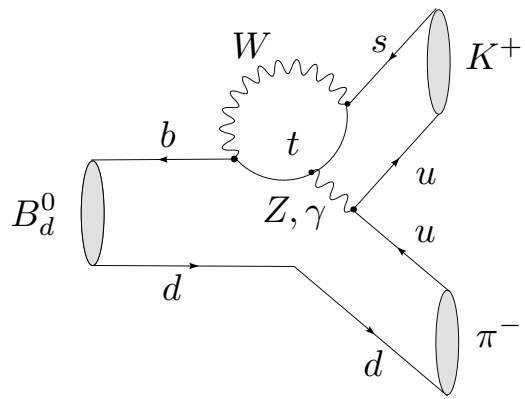
This feature holds, in fact, for *all other* $B \to \pi K$ decays:

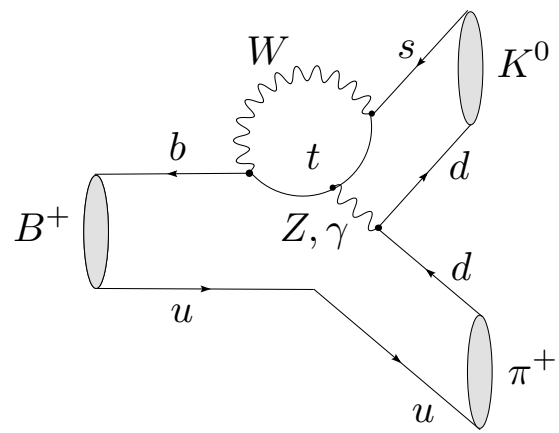
$$B^+ \to \pi^+ K^0,\ B_d^0 \to \pi^0 K^0,\ B^+ \to \pi^0 K^+.$$

Electroweak Penguins

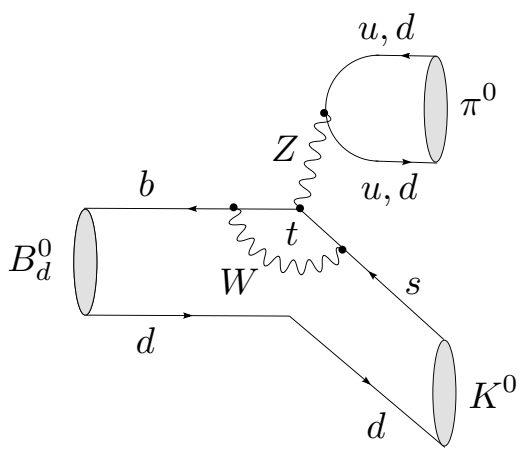
$\rightarrow$ allow us to divide the $B \rightarrow \pi K$ system into two classes:

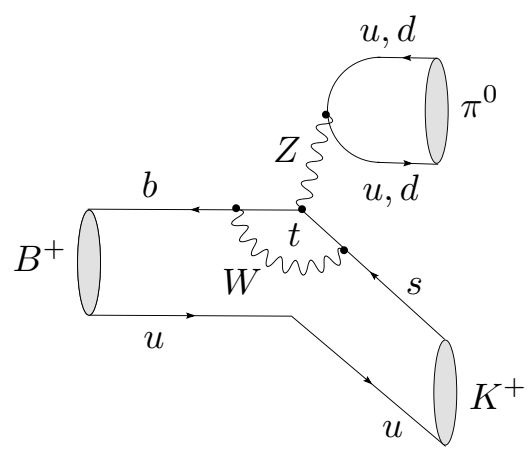
- EW penguins are *colour-suppressed*: $\rightarrow$ *tiny* contributions ...





- EW penguins are *colour-allowed*: $\rightarrow$ *sizeable*, competing with trees!





[Gronau, London, Rosner (1995); R.F. (1995); Buras, R.F., Recksiegel, Schwab (2003); ...]

Puzzle in CP Violation in $B_d^0 \to \pi^0 K_{\rm S}$

- CP-violating rate asymmetry:

$$\frac{\Gamma(\bar{B}_d^0(t) \to \pi^0 K_{\rm S}) - \Gamma(B_d^0(t) \to \pi^0 K_{\rm S})}{\Gamma(\bar{B}_d^0(t) \to \pi^0 K_{\rm S}) + \Gamma(B_d^0(t) \to \pi^0 K_{\rm S})}$$

$$= A_{\rm CP}^{\pi^0 K_{\rm S}} \cos(\Delta M_d t) + S_{\rm CP}^{\pi^0 K_{\rm S}} \sin(\Delta M_d t)$$

- Isospin relation:

$$\sqrt{2} A(B_d^0 \to \pi^0 K^0) + A(B_d^0 \to \pi^- K^+) \equiv 3 A_{3/2}$$

$$3 A_{3/2} = -(\hat{T} + \hat{C}) e^{i\gamma} + (\hat{P}_{EW} + \hat{P}_{EW}^{\rm C}) = -(\hat{T} + \hat{C}) \left(e^{i\gamma} - q e^{i\phi} e^{i\omega}\right)$$

- $SU(3)$ flavour symmetry:
  - Determination of $|\hat{T} + \hat{C}|$ from the $B^+ \to \pi^+ \pi^0$ branching ratio:

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

  - Electroweak penguin parameter:

$$q e^{i\phi} e^{i\omega} \equiv - \left[\frac{\hat{P}_{EW} + \hat{P}_{EW}^{\rm C}}{\hat{T} + \hat{C}} \right] \stackrel{\rm SM}{=} \frac{-3}{2\lambda^2 R_b} \left[\frac{C_9 + C_{10}}{C_1 + C_2} \right] R_q = (0.68 \pm 0.05) R_q$$

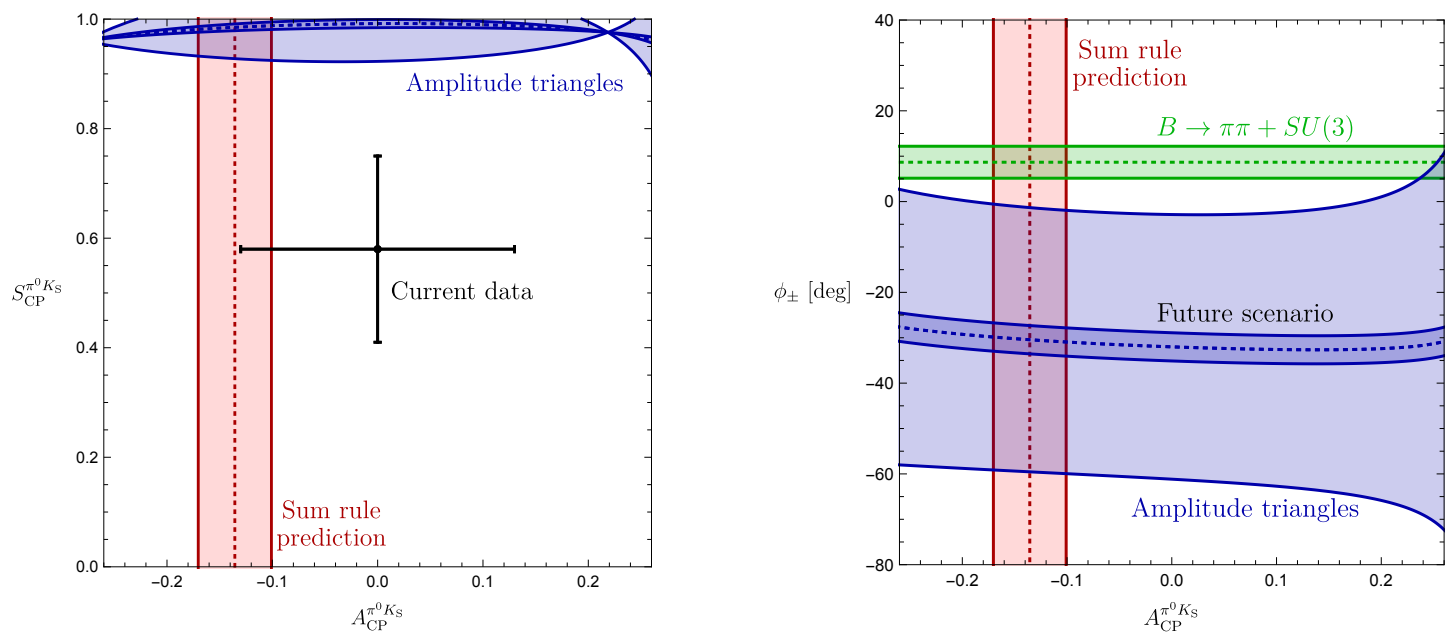
($R_{T+C} = f_K / f_\pi$ and R_q describe $SU(3)$-breaking effects)

Correlation between CP asymmetries of $B_d^0 \to \pi^0 K_S$*:*

- Introduce the angle $\phi_{00} \equiv \arg(\bar{A}_{00} A_{00}^*)$ between the decay amplitude $A_{00} \equiv A(B_d^0 \to \pi^0 K^0)$ and its CP-conjugate $\bar{A}_{00}$:

$$S_{\rm CP}^{\pi^0 K_S} = \sin(\phi_d - \phi_{00})\sqrt{1 - (A_{\rm CP}^{\pi^0 K_S})^2}$$

- Isospin amplitude triangle relation and (minimal) $SU(3)$ input: $\Rightarrow$



$[\phi_\pm \equiv \arg(\bar{A}_\pm A_\pm^*)]$

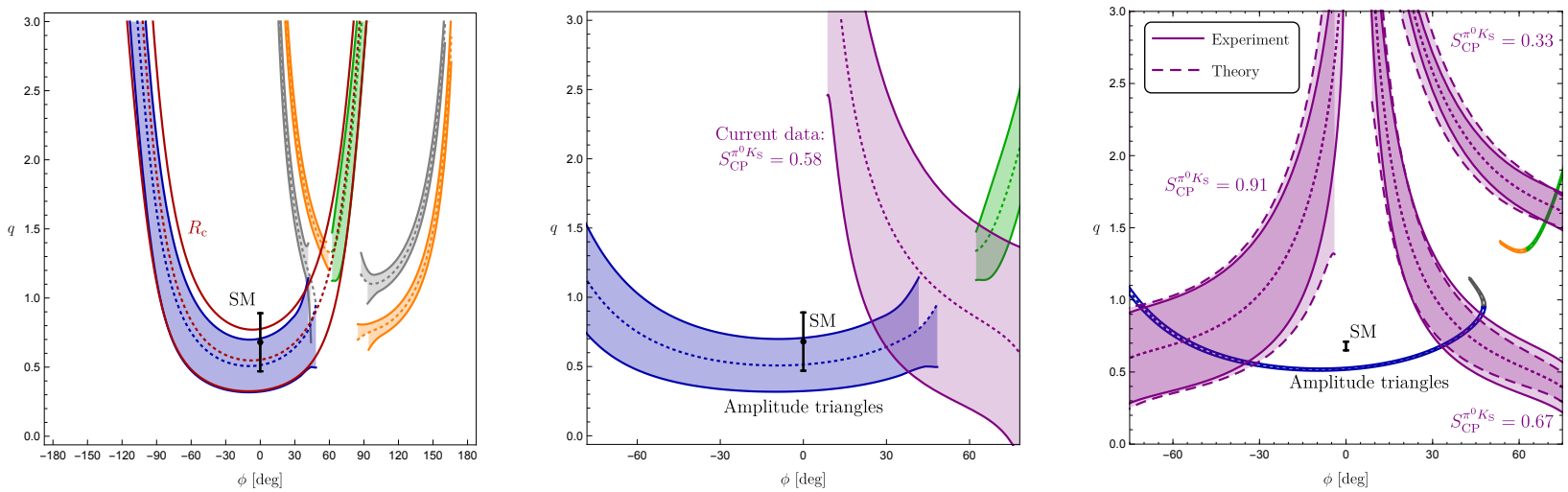
$\Rightarrow$ *Puzzling pattern!?*

Modified Electroweak Penguin Sector

- Use further information from charged $B \to \pi K$ decays:
  - Satisfy also an isospin relation:

$$\sqrt{2}A(B^+ \to \pi^0 K^+) + A(B^+ \to \pi^+ K^0) = 3A_{3/2}$$

  - Implies correlations in the ϕ–q plane of EW penguin parameters:



- Intriguing situation:
  - Yet another signal for new sources of CP violation?
  - Interesting playground for Belle II $\to$ look forward to data...

[R.F., Jaarsma, Malami & Vos (2016)]

Conclusions and Outlook

Towards New Frontiers with Non-Leptonic B Decays

- $B_d^0 \to J/\psi K_{\rm S}$ and $B_s^0 \to J/\psi\phi$ decays: $\to$ $\boxed{\phi_d \text{ and } \phi_s}$
  - Strategy to include doubly Cabibbo-suppressed penguins through "control channels" where these contributions are not suppressed.
  - Crucial in view of very impressive future precision for ϕ_d and ϕ_s ...
  - Interesting insights into hadronic physics: factorization...
  - ϕ_s may still result in NP effects larger than 5σ significance.

- $B_s^0 \to D_s^\mp K^\pm$ decays: $\to$ $\boxed{Puzzle}$
  - Intriguing CP-violating observables...
  - Complemented through puzzling patterns in the $B_s^0 \to D_s^\mp K^\pm$ branching ratios: consistent with other modes!
  - Model-independent framework to include and constrain NP effects.

- $B \to \pi K$ decays: $\to$ $\boxed{Puzzle}$
  - Isospin relations with minimal $SU(3)$ input give intriguing correlations.
  - Mixing-induced CP violation in $B_d^0 \to \pi^0 K_{\rm S}$ plays a key role.
  - Modified electroweak penguin sector!?

Intriguing Situation: Questions

- Could the puzzling patterns in the $B_s^0 \to D_s^{\mp} K^{\pm}$ and $B \to \pi K$ decays actually be manifestations of the same kind of New Physics?

- Could there be links with the "B decay anomalies" in semi-leptonic and leptonic rare B decays receiving currently a lot of attention?

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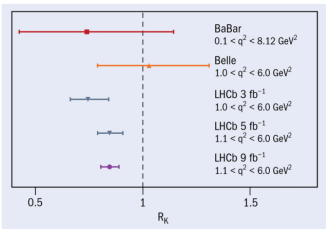
FLAVOUR PHYSICS NEWS

New data strengthens R_K flavour anomaly

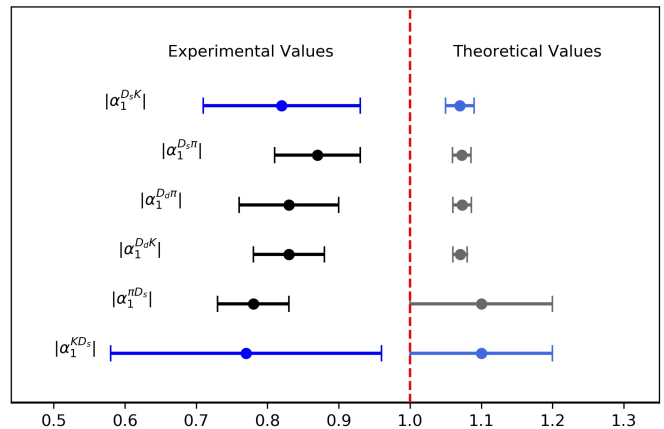
23 March 2021

A report from the LHCb experiment



Comparison between R_K measurements In addition to the LHCb result, the measurements by the BaBar and Belle collaborations, which combine $B^+ \to K^+ \ell^+ \ell^-$ and $B^0 \to K_S^0 \ell^+ \ell^-$ decays, are also shown. Credit: LHCb

The principle that the charged leptons have identical electroweak interaction strengths is a distinctive feature of the Standard Model (SM). However, this lepton-flavour universality (LFU) is an accidental symmetry in the SM, which may not hold in theories beyond the SM (CERN Courier May/June 2019 p33). The LHCb collaboration has used a number of rare decays mediated by flavour-changing neutral currents, where the SM contribution is suppressed, to test for deviations from LFU. During the past few years, these and other measurements, together with results from B-factories, hint at possible departures from the SM.



- Specific models and links with collider physics and direct NP searches?

$\Rightarrow$ $\boxed{\textit{Exciting times: stay tuned ...}}$

Greetings from the Nikhef Theory Group