Summary of WG4: Mixing and mixing-related *CP* violation in B system: Δm, $\Delta\Gamma$, ϕ_s, ϕ_1/β, ϕ_2/α, ϕ_3/γ

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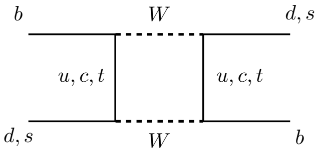
Neutral B meson mixing

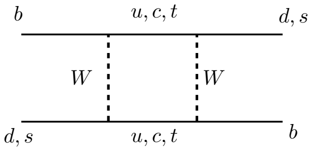
Time evolution of neutral mesons according to the Schrödinger equation

$$i\frac{d}{dt}\begin{pmatrix} a(t)|B^0\rangle \\ b(t)|\bar{B}^0\rangle \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} a(t)|B^0\rangle \\ b(t)|\bar{B}^0\rangle \end{pmatrix}$$

Mixing is determined by 3 parameters: $|M_{12}|$, $|\Gamma_{12}|$, $\phi = \arg(-\Gamma_{12}/M_{12})$, related to 3 observables ΔM, $\Delta\Gamma$, $a_{\mathrm{fs}} = (\Delta\Gamma/\Delta M)\tan\phi$.

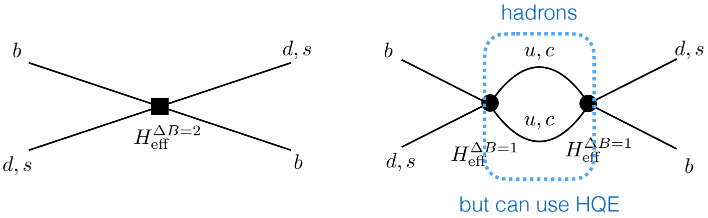
Standard Model mixing is given at leading order by box diagrams:





Effective operators

Compared to hadronic scales, the W and t barely propagate, and can be replaced by local, effective operators

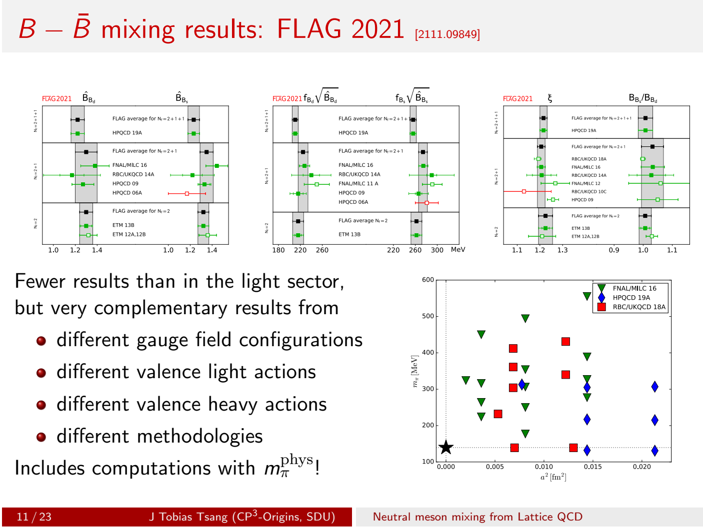


hadrons

but can use HQE

- ΔM: dominated by short distance $\Delta B = 2$ operators
- $\Delta\Gamma$: dominated by intermediate charmonium states. Can use heavy quark expansion (HQE)

Review of LQCD results for $\Delta M_{d,s}$ [J.T.Tsang]



$B-\bar{B}$ mixing results: FLAG 2021 [2111.09849]

Fewer results than in the light sector, but very complementary results from

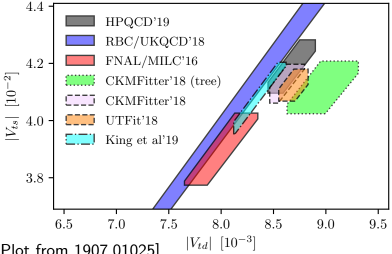
- different gauge field configurations
- different valence light actions
- different valence heavy actions
- different methodologies

Includes computations with $m_\pi^{\rm phys}$!

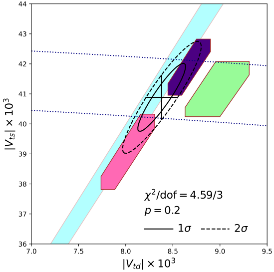
11 / 23 J Tobias Tsang (CP^3-Origins, SDU) Neutral meson mixing from Lattice QCD

Good agreement among groups!

Implications for $|V_{ts}|$ & $|V_{td}|$ [J.T.Tsang]



[Plot from 1907.01025]



[Updated plot, MW, 2103.17224]

- Figures show 1σ regions using lattice matrix elements (or sum rules in cyan, left plot)
- Good fit in right plot (RBC/UKQCD cyan, HPQCD dark blue, FNAL/MILC pink)
- Tension with CKM fit to tree-level observables (green)

Width difference $\Delta\Gamma_s$ [V.Shtabovenko]

[Intro slide from V.Shtabovenko]

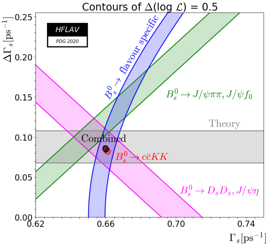
- Our interest: $\Delta\Gamma_s$ from $B_s^0 - \bar{B}_s^0$
- Experimental value (HFLAV 2020 average)

$$\Delta\Gamma^{\text{exp}} = (0.085 \pm 0.004)\ \text{ps}^{-1}$$

- Theory prediction (NLO + n_f-piece of NNLO QCD corrections) [Beneke et al., 1999; Ciuchini et al., 2002, 2003; Lenz & Nierste, 2007; Asatrian et al., 2020, 2017]

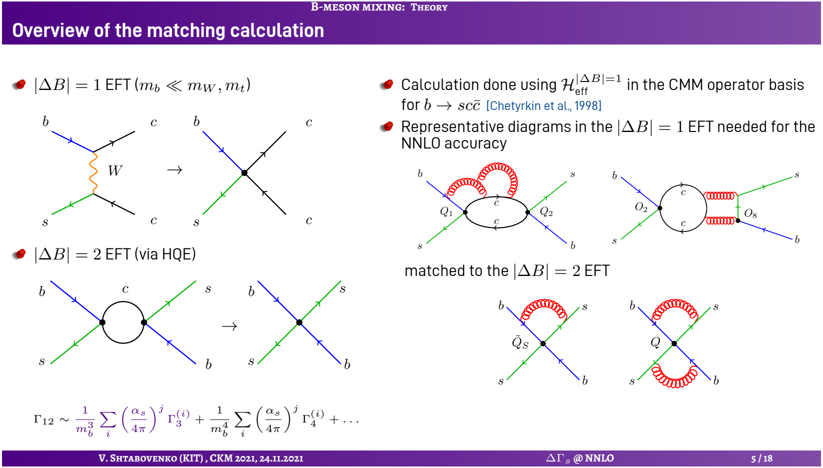
$$\Delta\Gamma_{\text{OS}} = (0.077 \pm 0.015_{\text{pert.}} \pm 0.002_{B,\tilde{B}_S} \pm 0.017_{\Lambda_{\text{QCD}}/m_b})\ \text{ps}^{-1}$$
$$\Delta\Gamma_{\overline{\text{MS}}} = (0.088 \pm 0.011_{\text{pert.}} \pm 0.002_{B,\tilde{B}_S} \pm 0.014_{\Lambda_{\text{QCD}}/m_b})\ \text{ps}^{-1}$$

- Large perturbative uncertainty from the uncalculated NNLO corrections (pert.)
- Can be reduced by including relevant 2- and 3-loop QCD corrections
- Theory under pressure, full NNLO corrections highly desirable



To reduce the theory error: complete NNLO QCD corrections and obtain LQCD determinations of dimension-7 operator matrix elements

Width difference $\Delta\Gamma_s$ [V.Shtabovenko]



B-MESON MIXING: THEORY

Overview of the matching calculation

- $|\Delta B| = 1$ EFT ($m_b \ll m_W, m_t$)
- $|\Delta B| = 2$ EFT (via HQE)

$$\Gamma_{12} \sim \frac{1}{m_b^3} \sum_i \left(\frac{\alpha_s}{4\pi}\right)^j \Gamma_3^{(i)} + \frac{1}{m_b^4} \sum_i \left(\frac{\alpha_s}{4\pi}\right)^j \Gamma_4^{(i)} + \dots$$

- Calculation done using $\mathcal{H}_{\text{eff}}^{|\Delta B|=1}$ in the CMM operator basis for $b \to s c \bar{c}$ [Chetyrkin et al., 1998]
- Representative diagrams in the $|\Delta B| = 1$ EFT needed for the NNLO accuracy

matched to the $|\Delta B| = 2$ EFT

V. SHTABOVENKO (KIT), CKM 2021, 24.11.2021 $\Delta\Gamma_s$ @ NNLO 5 / 18

Tour de force calculation. See V. Shtabovenko's slides for details.

Width difference $\Delta\Gamma_s$ [V.Shtabovenko]

- 2-loop current-penguin matching published [Gerlach, Nierste, Shtabovenko, Steinhauser, arXiv:2106.05979]
- Remaining 2-loop pieces and 3-loop current-current matching underway
- Will yield updated SM theory for $\Delta\Gamma_s$ and a_{fs}^s

Contribution	Literature result	This work
$Q_{1,2} \times Q_{3-6}$	2 loops, z-exact, n_f-part only [Asatrian et al., 2020]	2 loops, $\mathcal{O}(z)$, full
$Q_{1,2} \times Q_8$	2 loops, z-exact, n_f-part only [Asatrian et al., 2020]	2 loops, $\mathcal{O}(z)$, full
$Q_{3-6} \times Q_{3-6}$	1 loop, z-exact, full [Beneke et al., 1996]	2 loops, $\mathcal{O}(z)$, full
$Q_{3-6} \times Q_8$	1 loop, z-exact, n_f-part only [Asatrian et al., 2020]	2 loops, $\mathcal{O}(z)$, full
$Q_8 \times Q_8$	1 loop, z-exact, n_f-part only [Asatrian et al., 2020]	2 loops, $\mathcal{O}(z)$, full
$Q_{1,2} \times Q_{1,2}$	3 loops, $\mathcal{O}(\sqrt{z})$, n_f-part only [Asatrian et al., 2017]	3 loops, $\mathcal{O}(z^0)$, full

- Numerical estimate on the impact of the new 2-loop $O_{1,2} \times O_{3-6}$ contribution [Gerlach, Nierste, VS, Steinhauser, 2021]

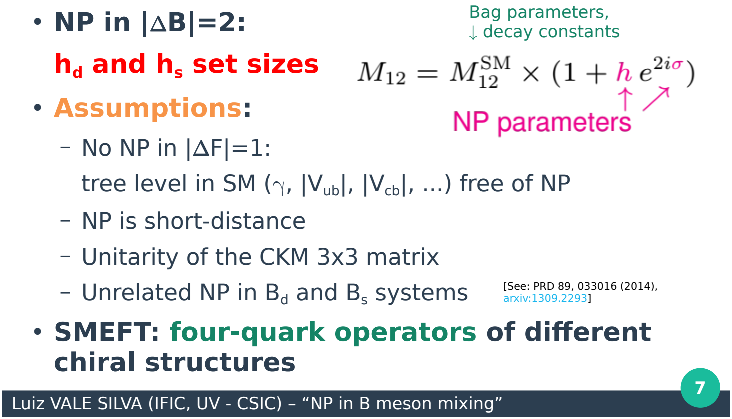
$$\text{1-loop (already known):} \quad \frac{\Delta\Gamma_s^{p,12\times 36,\alpha_s^0}}{\Delta\Gamma_s} = 7.0\% \quad (\text{pole}) \qquad \frac{\Delta\Gamma_s^{p,12\times 36,\alpha_s^0}}{\Delta\Gamma_s} = 6.1\% \quad (\overline{\text{MS}}),$$

$$\text{full 2-loops (new):} \quad \frac{\Delta\Gamma_s^{p,12\times 36,\alpha_s}}{\Delta\Gamma_s} = 0.2\% \quad (\text{pole}), \qquad \frac{\Delta\Gamma_s^{p,12\times 36,\alpha_s}}{\Delta\Gamma_s} = 1.4\% \quad (\overline{\text{MS}}),$$

Lattice results for $\langle B_s | R_{2,3} | \bar{B}_s \rangle$ replace vacuum saturation estimates, firming up LO Λ_{QCD}/m_b contribution [HPQCD, arXiv:1910.00970]

Future sensitivity to NP in Δm_s [L.Vale Silva]

Parameterize deviations from SM by h and σ



- **NP in |ΔB|=2:**

  h_d and h_s set sizes

Bag parameters,
↓ decay constants

$$M_{12} = M_{12}^{\rm SM} \times (1 + h\, e^{2i\sigma})$$

↑ ↗
NP parameters

- **Assumptions:**
  - No NP in |ΔF|=1:
    tree level in SM (γ, $|V_{ub}|$, $|V_{cb}|$, ...) free of NP
  - NP is short-distance
  - Unitarity of the CKM 3x3 matrix
  - Unrelated NP in B_d and B_s systems

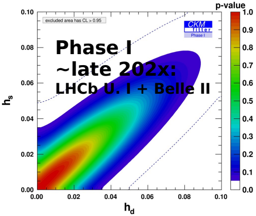
[See: PRD 89, 033016 (2014), arxiv:1309.2293]

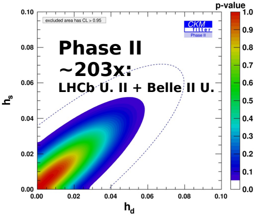
- **SMEFT: four-quark operators of different chiral structures**

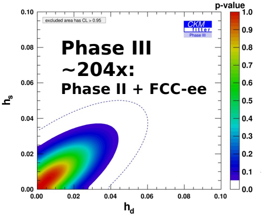
Luiz VALE SILVA (IFIC, UV - CSIC) – “NP in B meson mixing” 7

Future sensitivity to NP in Δm_s [L.Vale Silva]

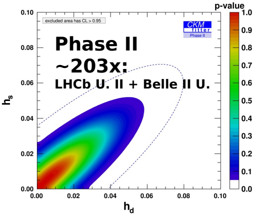
Estimated sensitivity with experimental upgrades

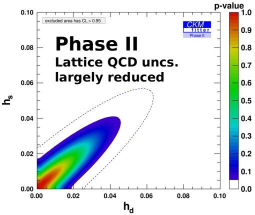


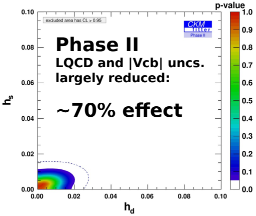




Estimates with order-of-magnitude reduction of LQCD and $|V_{cb}|$ uncertainties

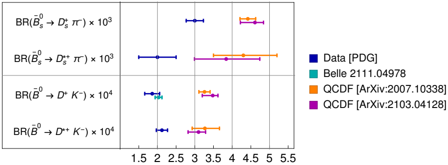






Null test of the Standard Model with flavor-specific CP-asymmetries [A. Rusov] [arXiv: 2111.04478]

There are 2-5.5 σ tensions between SM predictions based on QCD factorization and measured branching fractions.



To address this issue, "flavor-specific decay" of B_q (q=d, s) with following conditions would be theoretically clean null observables:

- For a flavour-specific decay: $\mathcal{A}_{\bar{f}} = 0 = \bar{\mathcal{A}}_f$ [**C1**]

  Examples: $\bar{B}_s \to D_s^+ \ell^- \nu_\ell$, $\bar{B}_d \to D^+ K^-$, $\bar{B}_s \to K^+ \pi^-$

- Absence of direct CP violation: $\bar{\mathcal{A}}_{\bar{f}} = \mathcal{A}_f$ [**C2**]

  In the SM, [**C2**] applies e.g. for $\bar{B}_s \to D_s^+ \pi^-$ and $\bar{B}_d \to D^+ K^-$

$$\begin{pmatrix} \mathcal{A}_f = \langle f|\mathcal{H}_{\text{eff}}|B_q\rangle & \bar{\mathcal{A}}_f = \langle f|\mathcal{H}_{\text{eff}}|\bar{B}_q\rangle \\ \mathcal{A}_{\bar{f}} = \langle \bar{f}|\mathcal{H}_{\text{eff}}|B_q\rangle & \bar{\mathcal{A}}_{\bar{f}} = \langle \bar{f}|\mathcal{H}_{\text{eff}}|\bar{B}_q\rangle \end{pmatrix}$$

Null test of the Standard Model with flavor-specific CP-asymmetries [A. Rusov] [arXiv: 2111.04478]

$B_q - \bar{B}_q$ mixing

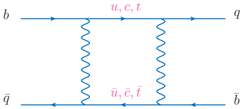
- The meson mass eigenstates $|B_{q,H}\rangle$ and $|B_{q,L}\rangle$

$$\begin{cases} |B_{q,L}\rangle &= p|B_q\rangle + q|\bar{B}_q\rangle \\ |B_{q,H}\rangle &= p|B_q\rangle - q|\bar{B}_q\rangle \end{cases}$$

- The mass difference $\Delta M_q = M_H^q - M_L^q$
- The decay rate difference $\Delta\Gamma_q = \Gamma_L^q - \Gamma_H^q$

$$\Delta M_q \approx 2|M_{12}^q| \qquad \Delta\Gamma_q \approx 2|\Gamma_{12}^q| \cos\phi_{12}^q$$

$$\left|\frac{q}{p}\right| \approx 1 - \frac{a_{\rm fs}^q}{2} \qquad a_{\rm fs}^q \approx \frac{|\Gamma_{12}^q|}{|M_{12}^q|} \sin\phi_{12}^q$$



- The SM predictions

e.g. [Lenz, Tetlalmatzi-Xolocotzi, arXiv: 1912.07621] [HPQCD, arXiv:1910.00970]

$$a_{\rm fs}^d = (-4.73 \pm 0.42) \cdot 10^{-4} \qquad a_{\rm fs}^s = (2.06 \pm 0.18) \cdot 10^{-5}$$

$$\left|\frac{\Gamma_{12}^d}{M_{12}^d}\right| = (4.82 \pm 0.65) \cdot 10^{-3} \qquad \left|\frac{\Gamma_{12}^s}{M_{12}^s}\right| = (4.82 \pm 0.64) \cdot 10^{-3}$$

$$\phi_{12}^d = (-5.6 \pm 1.1)^\circ \qquad \phi_{12}^s = (0.25 \pm 0.05)^\circ$$

Very small values

- Experimental measurements [HFLAV]

(exclusive semi-leptonic decays)

$$a_{\rm sl}^d = a_{\rm fs}^d = (-21 \pm 17) \cdot 10^{-4} \qquad a_{\rm sl}^s = a_{\rm fs}^s = (-60 \pm 280) \cdot 10^{-5}$$

- Expected precision of $\pm 2 \cdot 10^{-4}$ for $a_{\rm sl}^d$ and $\pm 30 \cdot 10^{-5}$ for $a_{\rm sl}^s$ by the LHCb with an integrated luminosity of $300\,{\rm fb}^{-1}$

[LHCb, arXiv: 1808.08865, 1812.07638]

- Projected sensitivity for $a_{\rm sl}^d$ by Belle II?

Null test of the Standard Model with flavor-specific CP-asymmetries [A. Rusov] [arXiv: 2111.04478]

Flavour-specific CP-asymmetry

$$A^q_{\rm fs} = \frac{\Gamma\left(\bar{B}_q(t) \to f\right) - \Gamma\left(B_q(t) \to \bar{f}\right)}{\Gamma\left(\bar{B}_q(t) \to f\right) + \Gamma\left(B_q(t) \to \bar{f}\right)}$$

- For flavour-specific decays (due to [**C1**])

$$\Gamma\left[\bar{B}_q(t) \to f\right] = \frac{1}{2} N_f \left|\mathcal{A}_f\right|^2 (1 + a^q_{\rm fs})\, e^{-\Gamma_q t} \left[\cosh\left(\frac{\Delta\Gamma_q\, t}{2}\right) - \cos\left(\Delta M_q t\right)\right]$$

$$\Gamma\left[B_q(t) \to \bar{f}\right] = \frac{1}{2} N_f \left|\bar{\mathcal{A}}_{\bar{f}}\right|^2 (1 - a^q_{\rm fs})\, e^{-\Gamma_q t} \left[\cosh\left(\frac{\Delta\Gamma_q\, t}{2}\right) - \cos\left(\Delta M_q t\right)\right]$$

- In the SM (due to [**C2**]) $A^q_{\rm fs} = a^q_{fs}$

- Under the presence of general New Physics

$$\begin{aligned} \mathcal{A}_f &= \left|\mathcal{A}_f^{\rm SM}\right| e^{i\phi^{\rm SM}} e^{i\varphi^{\rm SM}} + \left|\mathcal{A}_f^{\rm BSM}\right| e^{i\phi^{\rm BSM}} e^{i\varphi^{\rm BSM}} \\ &=: \left|\mathcal{A}_f^{\rm SM}\right| e^{i\phi^{\rm SM}} e^{i\varphi^{\rm SM}} \left(1 + r e^{i\phi} e^{i\varphi}\right) \end{aligned}$$

$\phi = \phi^{\rm BSM} - \phi^{\rm SM}$ – relative strong phase

$\varphi = \varphi^{\rm BSM} - \varphi^{\rm SM}$ – relative weak phase

$r = |\mathcal{A}_f^{\rm BSM}|/|\mathcal{A}_f^{\rm SM}|$ $r \sim (10 - 20)\%$

- $$A^q_{\rm fs} = \frac{a^q_{\rm fs} - 2r\sin\phi\sin\varphi + 2a^q_{\rm fs} r\cos\phi\cos\varphi + a^q_{\rm fs} r^2}{1 + 2r\cos\phi\cos\varphi + r^2 - 2a^q_{\rm fs} r\sin\phi\sin\varphi} \approx a^q_{\rm fs} - A^q_{\rm dir}$$

with the direct CP asymmetry $A^q_{\rm dir} \approx 2r\sin\phi\sin\varphi$

- Enhancement from $a^q_{fs} \sim 10^{-5}$ (in the SM) up to 40% possible !

Untagged CP asymmetry of time-integrated decay rates is an good observable especially for Bs case:

$$\langle A^q_{\rm untagged}\rangle = \frac{\int_0^\infty dt\left[\Gamma(\bar{B}_q(t) \to \bar{f}) + \Gamma(B_q(t) \to \bar{f})\right] - \int_0^\infty dt\left[\Gamma(\bar{B}_q(t) \to f) + \Gamma(B_q(t) \to f)\right]}{\int_0^\infty dt\left[\Gamma(\bar{B}_q(t) \to \bar{f}) + \Gamma(B_q(t) \to \bar{f})\right] + \int_0^\infty dt\left[\Gamma(\bar{B}_q(t) \to f) + \Gamma(B_q(t) \to f)\right]}$$

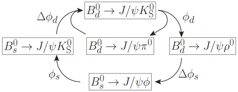
- Experimentally, one measures

$$\langle A^s_{\rm untagged}\rangle = A_{\rm raw} - A_{\rm det} - A_{\rm prod}\frac{\int_{t=0}^\infty e^{-\Gamma_s t}\cos(\Delta M_s t)\epsilon(t)dt}{\int_{t=0}^\infty e^{-\Gamma_s t}\cosh(\frac{\Delta\Gamma_s t}{2})\epsilon(t)dt} - \sum_i f^i_{\rm bkg}\cdot A^i_{\rm bkg}$$

$$A_{\rm raw} = \frac{N(D_s^+\pi^-) - N(D_s^-\pi^+)}{N(D_s^+\pi^-) + N(D_s^-\pi^+)}$$

- ▷ A significant gain in the statistics by not tagging the initial state flavour
- ▷ $A_{\rm det}$ will be reduced by reconstructing $D_s^\pm \to \phi\pi$
- ▷ B_s decays are fully reconstructed in the symmetric $K^\pm K^\mp \pi^\pm \pi^\mp$ final states
- ▷ Due to fast $B_s^0 - \bar{B}_s^0$ oscillations, the impact of $A_{\rm prod}$ is significantly diluted
- ▷ The sources of background are well-understood [LHCb, arXiv: 2104.04412]
- ▷ An expected sensitivity to $\langle A^s_{\rm untagged}\rangle$ is $\mathcal{O}(10^{-3})$ based on Run 1 and Run 2 data (9 fb^{-1}) and anticipated Run 3 data ($\approx$ 15 fb^{-1}) by LHCb

Penguin pollution in $b \to c\bar{c}s$ transitions [K. de Bruyn]



$B_d^0 \to J/\psi K_S^0$

$B_s^0 \to J/\psi K_S^0$

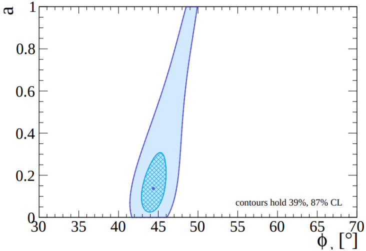
$B_d^0 \to J/\psi \pi^0$

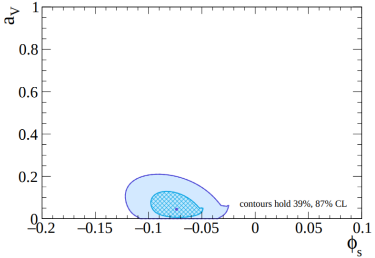
$B_d^0 \to J/\psi \rho^0$

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

Decay Channel	Control Mode	Latest Penguin Analysis
$B_d^0 \to J/\psi K^0$	$B_d^0 \to J/\psi \pi^0$	[M.Barel, KDB, R.Fleischer, E.Malami, `arXiv:2010.14423`]
	$B_s^0 \to J/\psi K_S^0$	[M.Barel, KDB, R.Fleischer, E.Malami, `arXiv:2010.14423`]

Decay Channel	Control Mode	Latest Penguin Analysis
$B_s^0 \to J/\psi \phi$	$B_d^0 \to J/\psi \rho^0$	[M.Barel, KDB, R.Fleischer, E.Malami, `arXiv:2010.14423`]
$B_s^0 \to D_s^- D_s^+$	$B_d^0 \to D_d^- D_d^+$	[L.Bel, KDB, R.Fleischer, M.Mulder, N.Tuning `arXiv:1505.01361`]
$B_s^0 \to J/\psi f_0(980)$	$B_d^0 \to J/\psi f_0(980)$	[R.Fleischer, R.Knegjens. G.Ricciardi `arXiv:1109.1112`]
		Control mode not yet measured
$B_s^0 \to \psi(2S)\phi$	$B_d^0 \to \psi(2S)\rho^0$	None Yet; Control mode not yet measured
$B_s^0 \to J/\psi K^- K^+\|_{m(K^-K^+)>1.05}$		None Yet





$$\phi_d = \left(44.4^{+1.6}_{-1.5}\right)^\circ$$

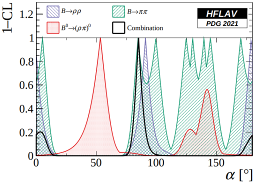
- Compare with $\phi^{\mathrm{eff}}_{d,J/\psi K^0} = (43.6 \pm 1.4)^\circ$

$$\phi_s = -0.074^{+0.025}_{-0.024} = (-4.2 \pm 1.4)^\circ$$

- Compare with $\phi^{\mathrm{eff}}_{s,J/\psi\phi} = -0.071 \pm 0.022 = (-4.1 \pm 1.3)^\circ$

CP violation in $B^0_{(s)} \to hh^{(\prime)}$ [R.Ruíz]

- NEW Measurement of $B^0_{(s)} \to hh^{(\prime)}$ with 1.9 fb^{-1} Run 2 LHCb data [JHEP03(2021)075]
  First observation of time-dependent CP violation in the B^0_s system in $B^0_s \to K^+K^-$ decays



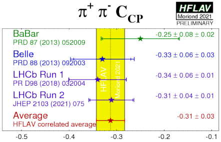
* Isospin analysis using as inputs time dependent CP violation parameters in $B_d \to \pi^+\pi^-, \pi^+\pi^-\pi^0, \rho\pi, \rho\rho$ systems.

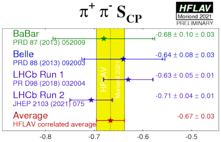
World Average	CKM´18
$(85.4^{+4.8}_{-4.3})^o$	$(84.9^{+5.1}_{-4.5})^o$

Run1+15+16

$$C_{\pi\pi} = -0.320 \pm 0.038$$
$$S_{\pi\pi} = -0.672 \pm 0.034$$
$$C_{KK} = 0.172 \pm 0.031$$
$$S_{KK} = -0.139 \pm 0.032$$
$$A_{KK} = -0.897 \pm 0.087$$
$$A^{B^0}_{CP} = -0.0831 \pm 0.0034$$
$$A^{B^0_s}_{CP} = -0.225 \pm 0.012$$

$> 6.5\sigma$

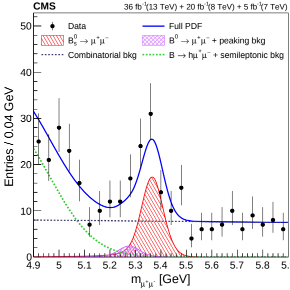


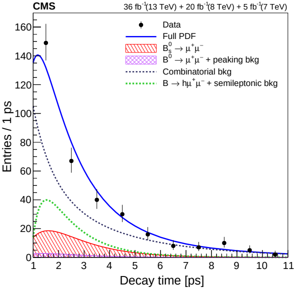


$B_s^0 \to \mu^+\mu^-$ effective lifetime at CMS [A. Mohammad]

- NEW Measurement of the $B_s^0 \to \mu^+\mu^-$ branching fraction and effective lifetime at CMS [JHEP04(2020)188]

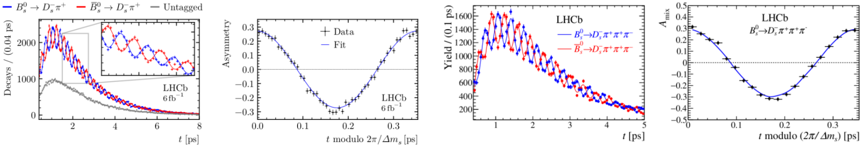
  $\tau_{\mu^+\mu^-} = 1.70^{+0.60}_{-0.43}(\text{stat}) \pm 0.09(\text{syst})$ ps
- Consistent with SM prediction, $\tau_{\mu^+\mu^-} = \tau_{B^0_{sH}} = 1.615 \pm 0.009$ ps [PDG]
- Consistent with LHCb $\tau_{\mu^+\mu^-} = 2.04 \pm 0.44 \pm 0.05$ ps [PRL 118 (2017) 191801]

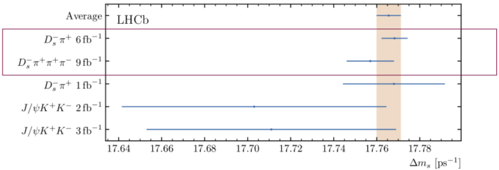




Δm_s at LHCb [A. Lupato]

- NEW Two Δm_s results from LHCb
- $B_s \to D_s^- \pi^+$ [arXiv:2104.04421, accepted by Nature] with full Run 2 data
  $\Delta m_s = 17.7683 \pm 0.0051(\text{stat}) \pm 0.0032(\text{syst}))\text{ps}^{-1}$
- $B_s^0 \to D_s^- \pi^+ \pi^+ \pi^-$ with full Run 1+2 data [JHEP 03 (2021) 137]
  $\Delta m_s = (17.757 \pm 0.007(\text{stat}) \pm 0.008(\text{syst}))\text{ps}^{-1}$



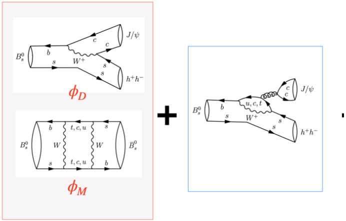


LHCb average

$$\boxed{\Delta m_s = 17.7656 \pm 0.0057 \text{ ps}^{-1}}$$

World average without these two LHCb results
$\Delta m_s = 17.749 \pm 0.020 \text{ ps}^{-1}$ [HFLAV]

CP violation and lifetimes at the LHC [A. Mohammad, L. Novotny, R. Ruíz]



- First Run 2 results by ATLAS, CMS and LHCb of *CP*-violating phase ϕ_s in $b \to c\bar{c}s$ transitions
  [EPJC 81 (2021) 342] [PLB 816 (2021) 136188]
  [EPJC 79 (2019) 706] [PLB 797 (2019) 134789]
- Consistent results in ϕ_s with the SM and between experiments
- Tensions between experiments in Γ_s

$$\phi_s^{meas.} = -2\beta_s + \Delta\phi_s^{peng} + \delta^{NP}$$

LHCb 4.9 fb^{-1}

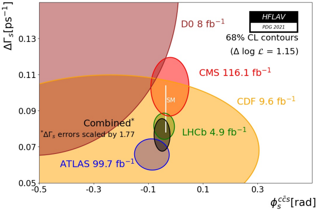
$\phi_s = -0.042 \pm 0.025$ rad
$\Delta\Gamma_s = 0.0813 \pm 0.0048\ \mathrm{ps}^{-1}$
$\Gamma_s = 0.6563 \pm 0.0021\ \mathrm{ps}^{-1}$

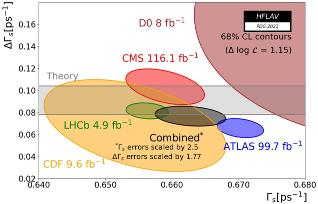
CMS 116 fb^{-1}

$\phi_s = -0.021 \pm 0.044 \pm 0.010$ rad
$\Delta\Gamma_s = 0.1032 \pm 0.0095 \pm 0.0048\ \mathrm{ps}^{-1}$
$\Gamma_s = 0.6590 \pm 0.0032 \pm 0.0023\ \mathrm{ps}^{-1}$

ATLAS 99.7 fb^{-1}

$\phi_s = -0.087 \pm 0.036 \pm 0.021$ rad
$\Delta\Gamma_s = 0.0607 \pm 0.0047 \pm 0.0043\ \mathrm{ps}^{-1}$
$\Gamma_s = 0.6703 \pm 0.0014 \pm 0.0018\ \mathrm{ps}^{-1}$

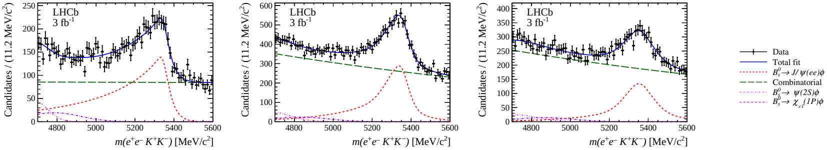




HFLAV

$\phi_s = -0.050 \pm 0.019$ rad
$\Delta\Gamma_s = 0.082 \pm 0.005\ \mathrm{ps}^{-1}$
$\Gamma_s = 0.6628 \pm 0.0035\mathrm{ps}^{-1}$

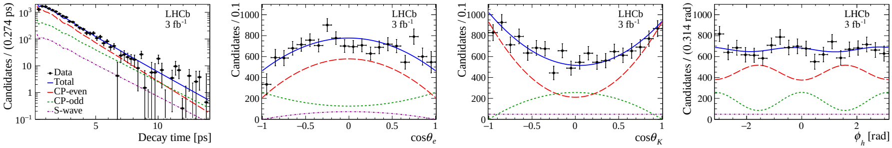
$B_s^0 \to J/\psi[\to e^+e^-]K^+K^-$ at LHCb [R.Ruíz]



- **NEW** First measurement in $B_s^0 \to J/\psi[\to e^+e^-]K^+K^-$ at LHCb (3 fb^{-1}, Run 1) as a proof of principle of a measurement with electrons [LHCb-PAPER-2020-042, arXiv:2105.14738]
- Overall consistent with other measurements, no evidence of *CP* violation

$B_s \to J/\psi(e^+e^-)\phi(K^+K^-)$

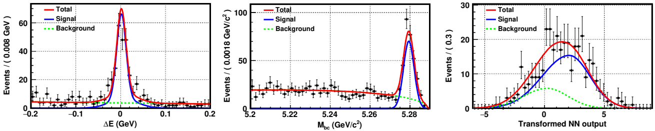
$\phi_s = 0.00 \pm 0.28 \pm 0.07$ rad
$\Delta\Gamma_s = 0.115 \pm 0.045 \pm 0.011\ ps^{-1}$
$\Gamma_s = 0.608 \pm 0.018 \pm 0.012\ ps^{-1}$



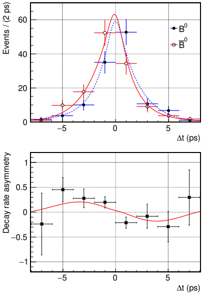
Mixing and mixing related CP violation in the B system [T. Humair]

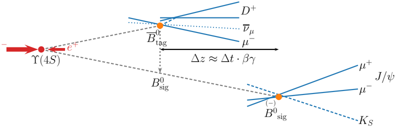
New results using full data set are still coming.

$B^0 \to K_S K_S K_S$



Fit finds 258 ± 17 signal candidates with purity $\approx 74\%$ in the signal region





$$S = -0.71 \pm 0.23\,(\text{stat.}) \pm 0.05\,(\text{syst.}),$$
$$A = \quad 0.12 \pm 0.16\,(\text{stat.}) \pm 0.05\,(\text{syst.}).$$

Result compatible with SM expectation and 2.5 σ away from "no CPV" hypothesis.
$\Rightarrow$ large room for improvement with this mode and other penguin modes with Belle II in future

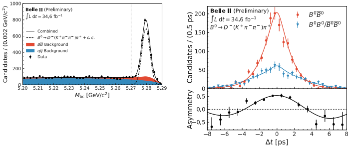
Mixing and mixing related CP violation in the B system [T. Humair]

Results using early data are coming out.

Time-dependent mixing result

BELLE2-NOTE-PL-2020-011

Using 34.6 fb^{-1} Belle II performed mixing frequency measurement using $B^0 \to D^- \pi^+$.



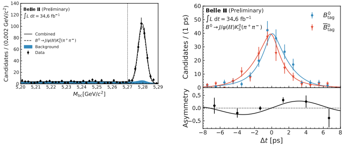
$$\mathbf{\Delta m_d = (0.531\ \pm\ 0.046\ (stat.)\ \pm\ 0.013\ (syst.))\ ps^{-1}}$$

Compatible with PDG: $\Delta m_d = (0.5065\ \pm\ 0.0019)\ \text{ps}^{-1}$.

Time-dependent CP-violation result

BELLE2-NOTE-PL-2020-011

Using the same data, Belle II performed the first Time-Dependent analysis using $B^0 \to J/\psi K_S$.



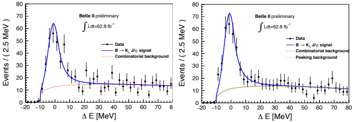
$$\mathbf{\sin(2\phi_1) =\ 0.55\ \pm\ 0.21\ (stat.)\ \pm\ 0.04\ (syst.)}$$

Good early demonstration that Belle II can perform TD analyses.

Many CP-eigenstates are getting ready for time-dependent study.

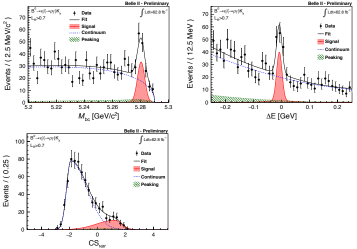
$B^0 \to J/\psi K_L$ reconstruction

CP-even



$B^0 \to \eta' K_S$: branching fraction

b→sq$\bar{\text{q}}$ penguin

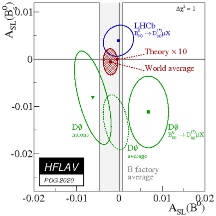


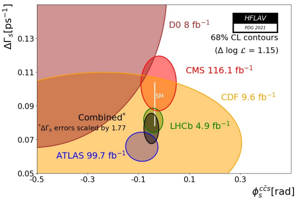
$$\mathcal{B}(B^0 \to \eta' K^0) = (63.4 \pm 3.4\,(\text{stat.}) \pm 3.2\,(\text{syst.})) \times 10^{-6}$$

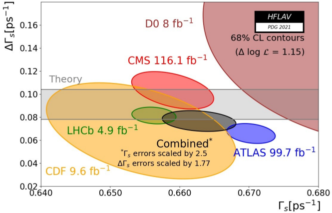
Related topics on global fit

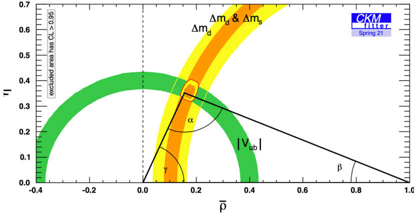
Pick up some highlight related to our WG.

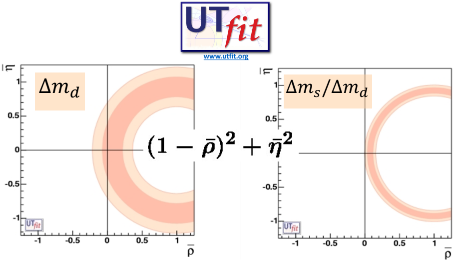
- B lifetime and oscillation parameters: largest impact from ATLAS and CMS.







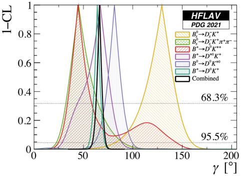


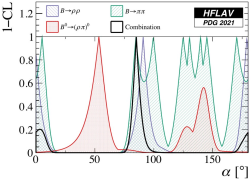


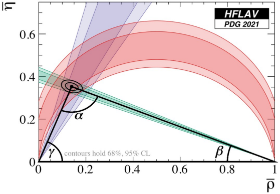
Related topics on global fit

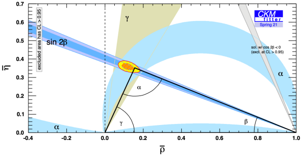
Pick up some highlight related to our WG.

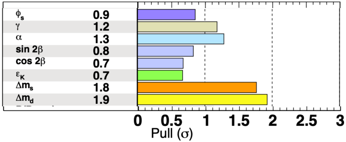
- Unitarity triangle angles: fit to many input channels



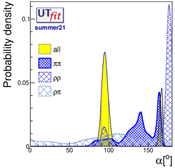








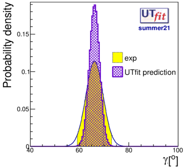
α updated with latest ππ/ρρ BR and C/S results



α from ππ, ρρ, πρ decays:
combined SM: (93.6 ± 4.2)°
UTfit prediction: (90.5 ± 1.9)°

Fabio Ferrari

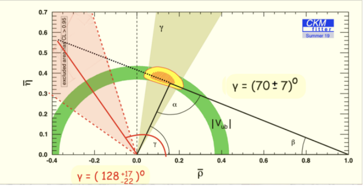
γ updated with all the latest results (LHCb)



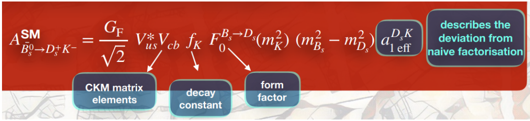
γ from B into DK decays:
HFLAV: (66.2 ± 3.5)°
UTfit prediction: (65.8 ± 1.9)°

CKM workshop 2021

BSM physics in $B_s^0 \to D_s^\mp K^\pm$ [E. Malami] [arXiv:2109.04950, arXiv:2110.04240]



LHCb [JHEP 1803, 059 (2018)]



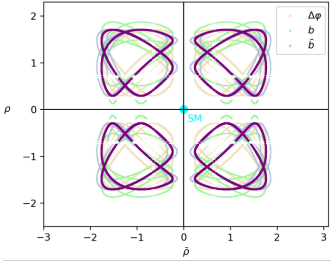
$$A^{\mathrm{SM}}_{\bar B_s^0\to D_s^+K^-} = \frac{G_F}{\sqrt{2}}\, V_{us}^* V_{cb}\, f_K\, F_0^{B_s\to D_s}(m_K^2)\,(m_{B_s}^2 - m_{D_s}^2)\, a_{1\,\mathrm{eff}}^{D_sK}$$

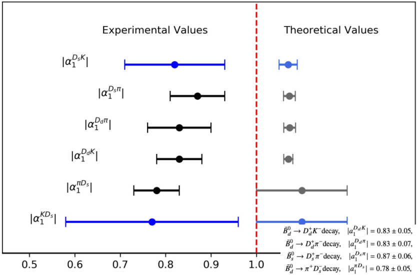
CKM matrix elements

decay constant

form factor

describes the deviation from naive factorisation





$\bar B_d^0 \to D_d^+ K^-$ decay, $|a_1^{D_dK}| = 0.83 \pm 0.05$, differs at 4.8 σ level,
$\bar B_d^0 \to D_d^+ \pi^-$ decay, $|a_1^{D_d\pi}| = 0.83 \pm 0.07$, differs at 3.3 σ level,
$\bar B_s^0 \to D_s^+ \pi^-$ decay, $|a_1^{D_s\pi}| = 0.87 \pm 0.06$, differs at 3.2 σ level,
$\bar B_d^0 \to \pi^+ D_s^-$ decay, $|a_1^{\pi D_s}| = 0.78 \pm 0.05$, differs at 2.9 σ level.

We could now accommodate the data with NP contributions as small as about 30% of the SM amplitudes

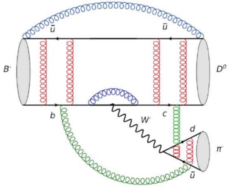
Nonleptonic B decays [T. Huber]

- Generic structure of amplitude for B decays

$$\mathcal{A}(\bar{B} \to f) = \sum_i \left[\lambda_{\rm CKM} \times C \times \langle f|\mathcal{O}|\bar{B}\rangle_{\rm QCD+QED}\right]_i$$

- Interplay between
  - Wilson coefficients C in $\mathcal{H}_{eff}$, known to NNLL in SM
    [Bobeth,Misiak,Urban'99;Misiak,Steinhauser'04,Gorbahn,Haisch'04;Gorbahn,Haisch,Misiak'05;Czakon,Haisch,Misiak'06]
  - CKM factors $\lambda_{\rm CKM}$. Hierarchy of CKM elements, weak phase
  - Hadronic matrix elements $\langle f|\mathcal{O}|\bar{B}\rangle$. Can contain strong phases.
- Interplay offers rich and interesting phenomenology for B decays
  - Plethora of data, numerous observables
  - Test of CKM mechanism and indirect search for New Physics
- BUT: Challenging QCD dynamics in hadronic matrix elements.

  Effects from many different scales !!



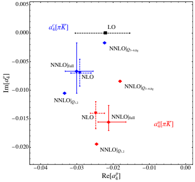
$$\langle \pi^- D^+|Q_i|\bar{B}\rangle \simeq m_B^2\ f_{M_2}\ F_+^{B\to D}(m_\pi^2) \times \int_0^1 du\ T_i^I(u)\ \phi_\pi(u)$$

There are many theory approaches to calculate the amplitudes.

3 hot topics are shown in this presentation.

Penguin amplitudes at two loops

- Direct CP asymmetries to NLO require QCD penguin amplitudes $\alpha_4^{u,c}$ at NNL
  - Complicated calculation: $\mathcal{O}(100)$ diagrams, two loops, two scales, . . .



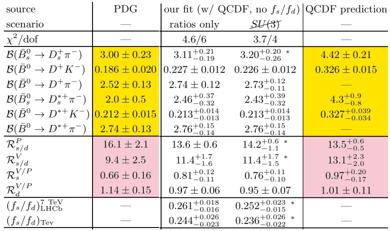
f	NLO	NNLO	NNLO + LD	Exp
$\pi^-\bar{K}^0$	$0.71\,^{+0.13\,+0.21}_{-0.14\,-0.19}$	$0.77\,^{+0.14\,+0.23}_{-0.15\,-0.22}$	$0.10\,^{+0.02\,+1.24}_{-0.02\,-0.27}$	-1.7 ± 1.6
$\pi^0 K^-$	$9.42\,^{+1.77\,+1.87}_{-1.76\,-1.88}$	$10.18\,^{+1.91\,+2.03}_{-1.90\,-2.62}$	$-1.17\,^{+0.22\,+20.00}_{-0.22\,-\ \ 6.62}$	4.0 ± 2.1
$\pi^+ K^-$	$7.25\,^{+1.36\,+2.13}_{-1.36\,-2.58}$	$8.08\,^{+1.52\,+2.52}_{-1.51\,-2.65}$	$-3.23\,^{+0.61\,+19.17}_{-0.61\,-\ \ 3.36}$	-8.2 ± 0.6
$\pi^0\bar{K}^0$	$-4.27\,^{+0.83\,+1.48}_{-0.77\,-2.23}$	$-4.33\,^{+0.84\,+3.29}_{-0.78\,-2.32}$	$-1.41\,^{+0.27\,+5.54}_{-0.25\,-6.10}$	1 ± 10
$\delta(\pi\bar{K})$	$2.17\,^{+0.40\,+1.39}_{-0.40\,-0.74}$	$2.10\,^{+0.39\,+1.40}_{-0.39\,-2.86}$	$2.07\,^{+0.39\,+2.76}_{-0.39\,-4.55}$	12.2 ± 2.2
$\Delta(\pi\bar{K})$	$-1.15\,^{+0.21\,+0.55}_{-0.22\,-0.84}$	$-0.88\,^{+0.16\,+1.31}_{-0.17\,-0.91}$	$-0.48\,^{+0.09\,+1.09}_{-0.09\,-1.15}$	-14 ± 11

$$\delta(\pi\bar{K}) = A_{\rm CP}(\pi^0 K^-) - A_{\rm CP}(\pi^+ K^-)$$

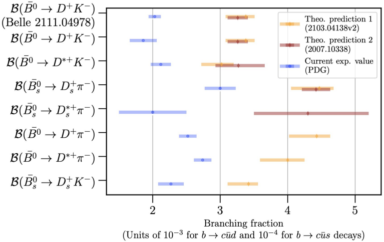
$$\Delta(\pi\bar{K}) = A_{\rm CP}(\pi^+ K^-) + \tfrac{\Gamma_{\pi^-\bar{K}^0}}{\Gamma_{\pi^+K^-}}\, A_{\rm CP}(\pi^-\bar{K}^0) - \tfrac{2\Gamma_{\pi^0K^-}}{\Gamma_{\pi^+K^-}}\, A_{\rm CP}(\pi^0 K^-) - \tfrac{2\Gamma_{\pi^0\bar{K}^0}}{\Gamma_{\pi^+K^-}}\, A_{\rm CP}(\pi^0\bar{K}^0)$$

Nonleptonic B decays [T. Huber]

Two-body heavy-light final states



source	PDG	our fit (w/ QCDF, no f_s/f_d)		QCDF prediction
scenario	—	ratios only	$\cancel{SU(3)}$	—
χ^2/dof	—	4.6/6	3.7/4	—
$\mathcal{B}(\bar{B}_s^0 \to D_s^+\pi^-)$	3.00 ± 0.23	$3.11^{+0.21}_{-0.19}$	$3.20^{+0.20}_{-0.26}$ *	4.42 ± 0.21
$\mathcal{B}(\bar{B}^0 \to D^+K^-)$	0.186 ± 0.020	0.227 ± 0.012	0.226 ± 0.012	0.326 ± 0.015
$\mathcal{B}(\bar{B}^0 \to D^+\pi^-)$	2.52 ± 0.13	2.74 ± 0.12	$2.73^{+0.12}_{-0.11}$	—
$\mathcal{B}(\bar{B}_s^0 \to D_s^{*+}\pi^-)$	2.0 ± 0.5	$2.46^{+0.37}_{-0.32}$	$2.43^{+0.39}_{-0.32}$	$4.3^{+0.9}_{-0.8}$
$\mathcal{B}(\bar{B}^0 \to D^{*+}K^-)$	0.212 ± 0.015	$0.213^{+0.014}_{-0.013}$	$0.213^{+0.014}_{-0.013}$	$0.327^{+0.039}_{-0.034}$
$\mathcal{B}(\bar{B}^0 \to D^{*+}\pi^-)$	2.74 ± 0.13	$2.76^{+0.15}_{-0.14}$	$2.76^{+0.15}_{-0.14}$	—
$\mathcal{R}_{s/d}^P$	16.1 ± 2.1	13.6 ± 0.6	$14.2^{+0.6}_{-1.1}$ *	$13.5^{+0.6}_{-0.5}$
$\mathcal{R}_{s/d}^V$	9.4 ± 2.5	$11.4^{+1.7}_{-1.6}$	$11.4^{+1.7}_{-1.5}$ *	$13.1^{+2.3}_{-2.0}$
$\mathcal{R}_s^{V/P}$	0.66 ± 0.16	$0.81^{+0.12}_{-0.11}$	$0.76^{+0.11}_{-0.10}$	$0.97^{+0.20}_{-0.17}$
$\mathcal{R}_d^{V/P}$	1.14 ± 0.15	0.97 ± 0.06	0.95 ± 0.07	1.01 ± 0.11
$(f_s/f_d)_{\mathrm{LHCb}}^{7\ \mathrm{TeV}}$	—	$0.261^{+0.018}_{-0.016}$	$0.252^{+0.023}_{-0.015}$ *	—
$(f_s/f_d)_{\mathrm{Tev}}$	—	$0.244^{+0.026}_{-0.023}$	$0.236^{+0.026}_{-0.022}$ *	—



2-5 σ discrepancies in branching fractions, ratio s are OK.

- Potential explanations
  - Universal non-factorizable contributions of $\mathcal{O}(-15 - 20\%)$ to amplitude?
  - QED corrections [Beneke,Böer,Finauri,Vos'21]
    - Ease the tension, but are not large enough [See talk by Keri Vos in Monday]
  - Experimental issues? [Recent Belle result 2111.04978 confirms earlier measurements]
  - Shift or larger uncertainties in the input (CKM) parameters?
  - Rescattering effects are also too small [Endo,Iguro,Mishima'21; see Iguro's talk]
  - BSM physics?
  - Combination thereof?

Further developments with BSM are on-going.

New physics searches in B decays are suggested. → see Aleksey's talk.

Nonleptonic B decays [T. Huber]

QCD-factorization and flavour symmetries

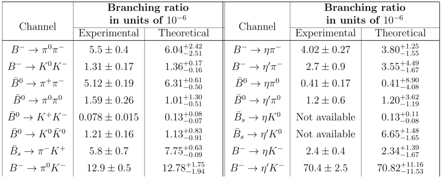
- The amplitudes for $B \to PP$ (P a pseudoscalar meson) can be expressed as

$$\mathcal{A} = i\,\frac{G_F}{\sqrt{2}}\,[\mathcal{T} + \mathcal{P}]$$

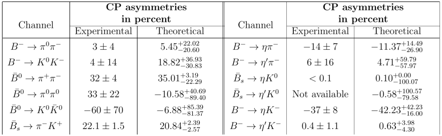
$\mathcal{T}$: Tree sub-amplitudes. $\mathcal{P}$: Penguin sub-amplitudes.

- Determine the SU(3)-invariant amplitudes through a χ^2-fit.
  - 20 complex amplitudes (10 for trees, 10 for penguins)
  - One overall phase and the complex amplitudes A_6^T and A_6^P can be absorbed

$\Longrightarrow$ 35 real parameters.



Channel	Branching ratio in units of 10^{-6}		Channel	Branching ratio in units of 10^{-6}	
	Experimental	Theoretical		Experimental	Theoretical
$B^- \to \pi^0\pi^-$	5.5 ± 0.4	$6.04^{+2.42}_{-2.51}$	$B^- \to \eta\pi^-$	4.02 ± 0.27	$3.80^{+1.25}_{-1.55}$
$B^- \to K^0K^-$	1.31 ± 0.17	$1.36^{+0.17}_{-0.16}$	$B^- \to \eta'\pi^-$	2.7 ± 0.9	$3.55^{+4.49}_{-1.67}$
$\bar{B}^0 \to \pi^+\pi^-$	5.12 ± 0.19	$6.31^{+0.61}_{-0.50}$	$\bar{B}^0 \to \eta\pi^0$	0.41 ± 0.17	$0.41^{+8.90}_{-4.08}$
$\bar{B}^0 \to \pi^0\pi^0$	1.59 ± 0.26	$1.01^{+1.30}_{-0.51}$	$\bar{B}^0 \to \eta'\pi^0$	1.2 ± 0.6	$1.20^{+3.62}_{-1.19}$
$\bar{B}^0 \to K^+K^-$	0.078 ± 0.015	$0.13^{+0.08}_{-0.07}$	$\bar{B}_s \to \eta K^0$	Not available	$0.13^{+0.11}_{-0.08}$
$\bar{B}^0 \to K^0\bar{K}^0$	1.21 ± 0.16	$1.13^{+0.83}_{-0.91}$	$\bar{B}_s \to \eta' K^0$	Not available	$6.65^{+1.48}_{-1.65}$
$\bar{B}_s \to \pi^-K^+$	5.8 ± 0.7	$7.75^{+0.63}_{-0.09}$	$B^- \to \eta K^-$	2.4 ± 0.4	$2.34^{+1.39}_{-1.67}$
$B^- \to \pi^0K^-$	12.9 ± 0.5	$12.78^{+1.75}_{-1.94}$	$B^- \to \eta' K^-$	70.4 ± 2.5	$70.82^{+11.16}_{-11.53}$



Channel	CP asymmetries in percent		Channel	CP asymmetries in percent	
	Experimental	Theoretical		Experimental	Theoretical
$B^- \to \pi^0\pi^-$	3 ± 4	$5.45^{+22.02}_{-20.60}$	$B^- \to \eta\pi^-$	-14 ± 7	$-11.37^{+14.49}_{-26.90}$
$B^- \to K^0K^-$	4 ± 14	$18.82^{+36.93}_{-30.83}$	$B^- \to \eta'\pi^-$	6 ± 16	$4.71^{+59.79}_{-57.97}$
$\bar{B}^0 \to \pi^+\pi^-$	32 ± 4	$35.01^{+3.19}_{-22.29}$	$\bar{B}_s \to \eta K^0$	< 0.1	$0.10^{+0.00}_{-100.07}$
$\bar{B}^0 \to \pi^0\pi^0$	33 ± 22	$-10.58^{+40.69}_{-89.40}$	$\bar{B}_s \to \eta' K^0$	Not available	$-0.58^{+100.57}_{-79.58}$
$\bar{B}^0 \to K^0\bar{K}^0$	-60 ± 70	$-6.88^{+85.39}_{-81.37}$	$B^- \to \eta K^-$	-37 ± 8	$-42.23^{+42.23}_{-16.00}$
$\bar{B}_s \to \pi^-K^+$	22.1 ± 1.5	$20.84^{+2.39}_{-2.57}$	$B^- \to \eta' K^-$	0.4 ± 1.1	$0.63^{+3.98}_{-4.30}$

- Prediction for observables which have not been measured so far

More data will help to reduce uncertainty.

New ideas on measuring ϕ_2 (α) [J. Dalseno][1]

- Recommend transition to amplitude analysis in $B \to \rho\rho$
  - J. Dalseno, JHEP **11** (2018) 193 [INSPIRE]
- Account for isospin-breaking $I = 1$ contributions that distort ϕ_2
- Include $B^0 \to a_1^{\pm}\pi^{\mp}$ region in $B^0 \to \rho^0\rho^0$ analysis
- Understand and reduce dangerous $a_1^{\pm}$ hadronic uncertainty
- Resolve ambiguity in ϕ_2 within next few years without $B^0 \to (\rho\pi)^0$

- $B^0 \to a_1^{\pm}\pi^{\mp}$ amplitude now opens precision SU(3) constraint
  - J. Dalseno, JHEP **10** (2019) 191 [INSPIRE]
- Add charmless amplitude analysis of $B^+ \to K_S^0\pi^+\pi^-\pi^+$
- Gives enough degrees of freedom to constrain non-factorisable SU(3)-breaking
- Consensus on K_1 mixing angle needed to assign proper uncertainty

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[1] slide courtesy of J. Dalseno

New ideas on measuring ϕ_2 (α) [J. Dalseno][2]

- New experimental source of ϕ_2 bias identified
  - J. Dalseno, JHEP **10** (2021) 110 [INSPIRE]
- Fit to ρ mass common to all 3 $B \to \rho\rho$ analyses
- Model systematic uncertainty from ρ pole parameters significant
- Systematic correlations between $B \to \rho\rho$ analyses must be considered
- Eliminates bias and reduces model uncertainty contribution to ϕ_2

- Branching fractions already systematically limited at BaBar/Belle
- Switch to relative branching fractions instead
  - J. Dalseno, arXiv:2110.08183 [hep-ph] [INSPIRE]
- Dominant uncertainty on $N_{B\bar{B}}$ removed, efficiency errors reduced
- Significant improvement to ϕ_2 constraint expected
- Opens new prospects for LHCb, no more limitations from B factories
- $B \to \rho\rho$ system special as isospin triangles very flat
- Take ϕ_2 sensitivity from $B^0 \to \rho^0\rho^0$ instead
- Time-dependent flavour-tagged analysis of $B^0 \to \rho^+\rho^-$ not required!
- Precision in ϕ_2 less than 1° may be possible by Run 5

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[2] slide courtesy of J. Dalseno

Thank you for your attention,
and we'd like to also thank contributions
of all speakers in WG4 session!