Nonleptonic B decays

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Outline

- Introduction to nonleptonic decays
- Direct CP asymmetries to NLO
- Puzzles in tree-level color-allowed decays
- QCD factorisation and flavour symmetries
- Conclusion

Not covered: 3-body decays [see talk by D. Torres Machado, also Zou et al. 2003.03754; Mannel,Olschewsky,Vos 2003.12053; Fan,Wang 2006.08223; Li et al. 2007.13629; Cheng,Chiang,Chua 2011.03201,2011.07468; Virto,Vos,TH 2007.08881; Lü et al. 2107.11079; Chai et al. 2109.00664; Bediaga et al. 2109.01625; . . .]

CPV in mixing, lifetimes [see talks by V. Shtabovenko, L. Vale Silva and in WG4 on Tuesday, also Lenz,Rauh et al. 1711.02100,1904.00940,1909.11087,1911.07856; Nierste et al. 1709.02160,2006.13227,2106.05979; . . .]

Anatomy of nonleptonic B decays

- Generic structure of amplitude for B decays

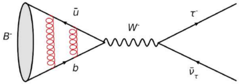
$$\mathcal{A}(\bar{B} \to f) = \sum_i \left[\lambda_{\rm CKM} \times C \times \langle f|\mathcal{O}|\bar{B}\rangle_{\rm QCD+QED}\right]_i$$

- 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 !!

Exclusive B decays, generalities

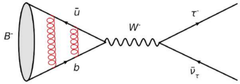
- Leptonic decays



$$\langle 0|\bar{u}\gamma^\mu\gamma_5 b|B^-(p)\rangle = i\, f_B\, p^\mu$$

Exclusive B decays, generalities

- Leptonic decays



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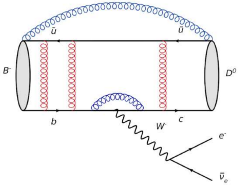
- Semi-leptonic decays

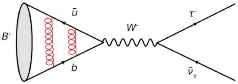


$$\langle D(p')|\bar{c}\gamma^\mu b|\bar{B}(p)\rangle$$

$$= F_+(q^2)\left[(p+p')^\mu - \frac{m_B^2 - m_D^2}{q^2}\, q^\mu\right]$$

$$+ F_0(q^2)\,\frac{m_B^2 - m_D^2}{q^2}\, q^\mu$$

- Leptonic decays



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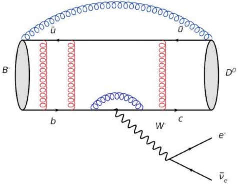

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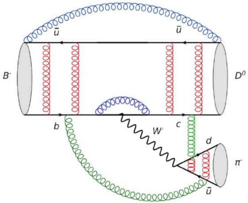
- Non-leptonic decays



$$\langle \pi^- D^+|Q_i|\bar{B}\rangle \simeq m_B^2\; f_{M_2}\; F_+^{B\to D}(m_\pi^2)$$

$$\times \int_0^1 du\;\; T_i^I(u)\;\phi_\pi(u)$$

Theory approaches

Theory approaches based on factorisation

- Disentangle long and short distances

- QCD Factorisation [Beneke,Buchalla,Neubert,Sachrajda'99-'01]
  - Systematic framework to all orders in α_s and leading power in Λ/m_b
  - Problems with factorisation of power suppressed and annihilation contributions. Endpoint divergences.
  - Countless pheno applications

[Beneke,Neubert'03; Cheng,Yang'08; Cheng,Chua'09; Bell,Pilipp'09; Beneke,Li,TH'09; Bobeth,Gorbahn,Vickers'14; Bell,Beneke,Li,TH'15'20]
[Beneke,Böer,Toelstede/Finauri,Vos'20'21, . . .]

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[Beneke,Böer,Toelstede/Finauri,Vos'20'21, . . .]

- PQCD [Keum,Li,Sanda'00; Lü,Ukai,Yang'00]
  - Based on k_T-factorisation. Organises amplitude differently
  - Generates larger strong phases. Avoids endpoint divergences.
  - Discussion of theoretical uncertainties difficult since no complete NLO ($\mathcal{O}(\alpha_s^2)$) analysis available
  - Also countless pheno applications [e.g. Ali,Kramer,Li, Lü,Shen,Wang,Wang'07]

More theory approaches

- Flavour symmetries: [Zeppenfeld'81]

  Isospin, U-Spin ($d \leftrightarrow s$), V-Spin ($u \leftrightarrow s$), Flavour SU(3)

  [e.g. Savage,Wise'89; Gronau,Hernandez,London,Rosner'95; Chiang,Gronau,Rosner'08; Chiang,Zhou'06'08; Grossman,Ligeti,Robinson'13]
  [Cheng,Chiang,Kuo'14'16, Hsiao,Chang,He'15; . . .]

  - Only few a priori assumptions about scales needed
  - Implementation of symmetry breaking difficult

  [Jung,Mannel'09; Cheng,Chiang'12; Grossman,Robinson'12]

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- Combination:
  - Recently: factorization-assisted topological-amplitude approach (FAT)
    [Li,Lü,Yu'12; Li,Lü,Qin,Yu'13; Wang,Zhang,Li,Lü'17]
  - Many more analysis [Ali,Kramer,Lü'98; Descotes-Genon,Matias,Virto'06; Ciuchini,Silvestrini et al.; Nandi,Soni'10;]
    [Fleischer et al.'99+; Fleischer,Jaarsma,Malami,Vos'16+; Datta,London,Imbeault'03,'12; Cheng,Chua'09; Tetlalmatzi,TH'21 . . .]

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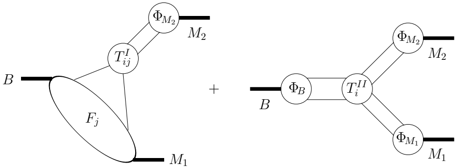
- Dalitz plot analysis. Applied to 3-body decays. Important for phenomenology.
  - Mostly data-driven, but also QCD-based predictions possible

    [Kränkl,Mannel,Virto'15; Klein,Mannel,Virto,Vos'17]
  - Also Flavour-symmetry analyses

    [e.g. Bhattacharya,Gronau,Imbeault,London,Rosner'14; Bhattacharya,London'15; Bediaga,Magalhaes et al. . . .]

QCD factorisation for nonleptonic decays



- Amplitude in the limit $m_b \gg \Lambda_{\rm QCD}$ [Beneke,Buchalla,Neubert,Sachrajda'99-'04]

$$\langle M_1 M_2 | Q_i | \bar{B} \rangle \simeq m_B^2 \, F_+^{B\to M_1}(0) \, f_{M_2} \int_0^1 du \; T_i^I(u) \, \phi_{M_2}(u) \; + \; (M_1 \leftrightarrow M_2)$$
$$+ f_B \, f_{M_1} \, f_{M_2} \int_0^\infty d\omega \int_0^1 dv \, du \; T_i^{II}(\omega, v, u) \, \phi_B(\omega) \, \phi_{M_1}(v) \, \phi_{M_2}(u) \; + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}}{m_b}\right)$$

- $T^{I,II}$: Hard scattering kernels, perturbatively calculable

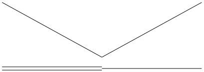
- F_+ : $B \to M$ form factor
  f_i : decay constants
  ϕ_i : light-cone distribution amplitudes

  } Universal. From Sum Rules, Lattice

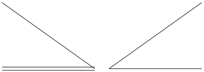
- Strong phases are $\mathcal{O}(\alpha_s)$ and/or $\mathcal{O}(\Lambda_{\rm QCD}/m_b)$

Classification of amplitudes

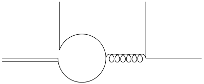
- α_1 : colour-allowed tree amplitude



- α_2 : colour-suppressed tree amplitude



- $\alpha_4^{u,c}$: QCD penguin amplitudes



$$\begin{aligned}
\sqrt{2}\,\langle\pi^-\pi^0|\,\mathcal{H}_{eff}\,|B^-\rangle &= A_{\pi\pi}\;\lambda_u\Big[\alpha_1(\pi\pi)+\alpha_2(\pi\pi)\Big] \\
\langle\pi^+\pi^-|\,\mathcal{H}_{eff}\,|\bar{B}^0\rangle &= A_{\pi\pi}\;\Big\{\lambda_u\Big[\alpha_1(\pi\pi)+\alpha_4^u(\pi\pi)\Big]+\lambda_c\,\alpha_4^c(\pi\pi)\Big\} \\
-\,\langle\pi^0\pi^0|\,\mathcal{H}_{eff}\,|\bar{B}^0\rangle &= A_{\pi\pi}\;\Big\{\lambda_u\Big[\alpha_2(\pi\pi)-\alpha_4^u(\pi\pi)\Big]-\lambda_c\,\alpha_4^c(\pi\pi)\Big\}
\end{aligned}$$

$$\begin{aligned}
\langle\pi^-\bar{K}^0|\,\mathcal{H}_{eff}\,|B^-\rangle &= A_{\pi\bar{K}}\;\Big[\lambda_u^{(s)}\;\alpha_4^u+\lambda_c^{(s)}\;\alpha_4^c\Big] \\
\langle\pi^+K^-|\,\mathcal{H}_{eff}\,|\bar{B}^0\rangle &= A_{\pi\bar{K}}\Big[\lambda_u^{(s)}\;(\alpha_1+\alpha_4^u)+\lambda_c^{(s)}\;\alpha_4^c\Big]
\end{aligned}$$

[Beneke,Neubert'03]

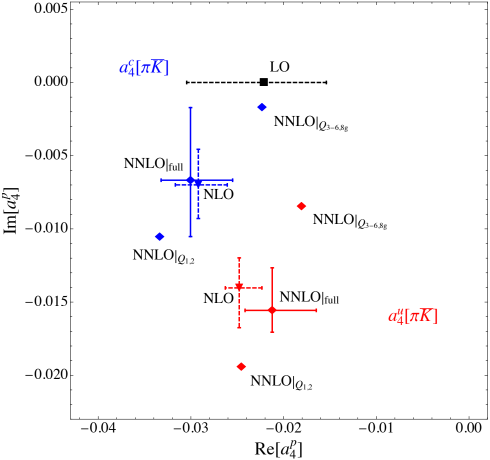
- Tree amplitudes α_1 and α_2 known analytically to NNLO

[Bell'07'09; Beneke,Li,TH'09]

Penguin amplitudes at two loops

[Bell,Beneke,Li,TH'20]

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



- Recently, also QED corrections became available

[Beneke,Böer,Toelstede,Vos'20]

Results: Direct CP asymmetries

[Bell,Beneke,Li,TH'15]

- Direct CP asymmetries in percent.

  Errors are CKM and hadronic, respectively.

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

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

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

[For QED corrections see Beneke,Böer,Finauri/Toelstede,Vos'20'21 and Keri Vos' talk on Monday]

[For a first number on $A_{\rm CP}(B^0 \to \pi^0\bar{K}^0)$ see 2104.14871 + talk by Hazra]

Two-body heavy-light final states

[Bordone,Gubernari,Jung,van Dyk,TH'20]

- Determine b-quark fragmentation fractions f_s/f_d from hadronic two-body decays into heavy-light final states
- Requires ratio $$\mathcal{R}_{s/d}^{P(V)} \equiv \frac{\mathcal{B}(\bar{B}_s^0 \to D_s^{(*)+}\pi^-)}{\mathcal{B}(\bar{B}^0 \to D^{(*)+}K^-)}$$

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- QCD factorization for $\bar{B}_q^0 \to D_q^{(*)+}L^-$ decays

[Beneke,Buchalla,Neubert,Sachrajda'99-'04]

$$\langle D_q^{(*)+}L^- |\, \mathcal{Q}_i \,|\bar{B}_q^0\rangle = \sum_j F_j^{\bar{B}_q \to D_q^{(*)}}(M_L^2) \int_0^1 du\, T_{ij}(u)\phi_L(u) + \mathcal{O}\left(\frac{\Lambda_{\text{QCD}}}{m_b}\right)$$

- Particularly clean: Only colour-allowed tree amplitude
  - No colour-suppressed tree amplitude, no penguins
  - Spectator scattering and weak annihilation power suppressed
  - Weak annihilation absent if all final-state flavours distinct
    - as in $\bar{B}_s^0 \to D_s^+\pi^-$ and $\bar{B}^0 \to D^+K^-$ but not in $\bar{B}^0 \to D^+\pi^-$

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- Hard function known to $\mathcal{O}(\alpha_s^2)$

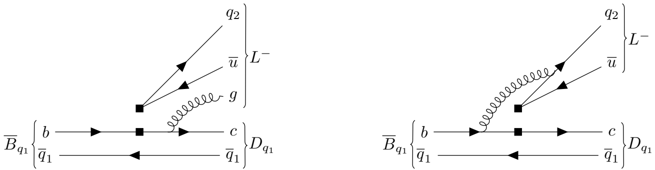
[Kränkl,Li,TH'16]

- Form factors from recent precision study

[Bordone,Gubernari,Jung,van Dyk'19]

Subleading power

[Bordone,Gubernari,Jung,van Dyk,TH'20]



- Power corrections arise from several effects
  - Higher twist effects to the light-meson LCDA
  - Hard-collinear gluon emission from the spectator quark q
  - Hard-collinear gluon emission from the heavy quarks b and c
  - Soft-gluon exchange between $B \to D$ and light-meson system

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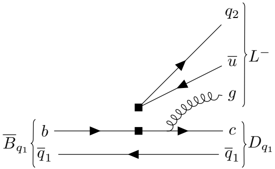

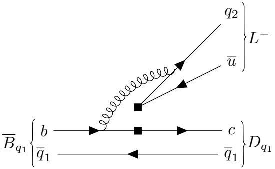

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Estimate of total size of power corrections

$$\mathcal{R}^P_{s/d}\Big|_{\text{NLP}}/\mathcal{R}^P_{s/d}\Big|_{\text{LP}} - 1 \approx -1.7‰ \qquad \mathcal{R}^V_{s/d}\Big|_{\text{NLP}}/\mathcal{R}^V_{s/d}\Big|_{\text{LP}} - 1 \approx -1.7‰$$

- Supports the picture of these decays being very clean

Results

source	PDG	our fit (w/ QCDF, no f_s/f_d)		QCDF prediction
scenario	—	ratios only	~~$SU(3)$~~	—
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
$(f_s/f_d)_{\text{LHCb}}^{7\text{ TeV}}$	—	$0.261^{+0.018}_{-0.016}$	$0.252^{+0.023}_{-0.015}$ *	—
$(f_s/f_d)_{\text{Tev}}$	—	$0.244^{+0.026}_{-0.023}$	$0.236^{+0.026}_{-0.022}$ *	—

- BR discrepancies

$$\bar{B}_s^0 \to D_s^+\pi^- \quad \to 4\sigma$$
$$\bar{B}^0 \to D^+K^- \quad \to 5\sigma$$
$$\bar{B}_s^0 \to D_s^{*+}\pi^- \quad \to 2\sigma$$
$$\bar{B}^0 \to D^{*+}K^- \quad \to 3\sigma$$

- Ratios OK

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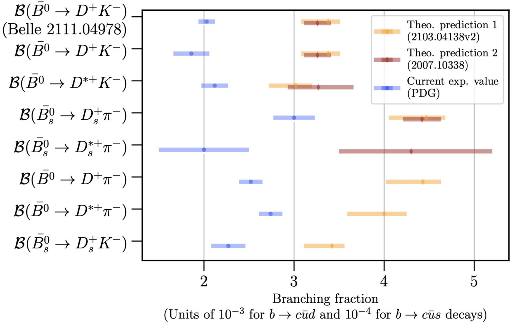
scenario	—	ratios only	~~$SU(3)$~~	—
χ^2/dof	—	4.6/6	3.7/4	—
$\mathcal{B}(\bar{B}_s^0 \to D_s^+\pi^-)$	3.00 ± 0.23	$3.11^{+0.21}_{-0.19}$	$3.20^{+0.20}_{-0.26}$ *	4.42 ± 0.21
$\mathcal{B}(\bar{B}^0 \to D^+K^-)$	0.186 ± 0.020	0.227 ± 0.012	0.226 ± 0.012	0.326 ± 0.015
$\mathcal{B}(\bar{B}^0 \to D^+\pi^-)$	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
$(f_s/f_d)_{\text{LHCb}}^{7\text{ TeV}}$	—	$0.261^{+0.018}_{-0.016}$	$0.252^{+0.023}_{-0.015}$ *	—
$(f_s/f_d)_{\text{Tev}}$	—	$0.244^{+0.026}_{-0.023}$	$0.236^{+0.026}_{-0.022}$ *	—

- BR discrepancies

$$\bar{B}_s^0 \to D_s^+\pi^- \quad \to 4\sigma$$
$$\bar{B}^0 \to D^+K^- \quad \to 5\sigma$$
$$\bar{B}_s^0 \to D_s^{*+}\pi^- \quad \to 2\sigma$$
$$\bar{B}^0 \to D^{*+}K^- \quad \to 3\sigma$$

- Ratios OK



[Plot courtesy of N. Skidmore]

Interpretation

- 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]
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  - Combination thereof?

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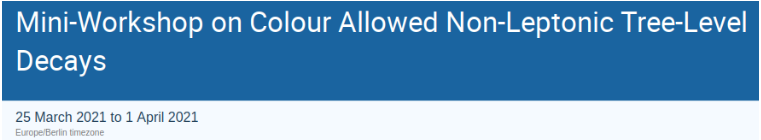

https://indico.scc.kit.edu/event/2352/

Further developments, BSM

- Tension can be partially explained by a left-handed W' model, compatible with other flavor and collider bounds [Iguro,Kitahara'20; see Iguro's talk]

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  - Some of them can explain the data at the 1σ-level
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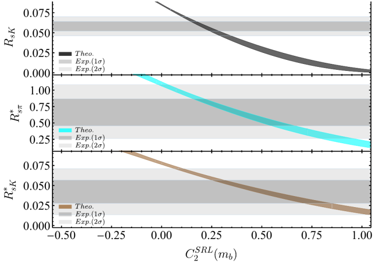

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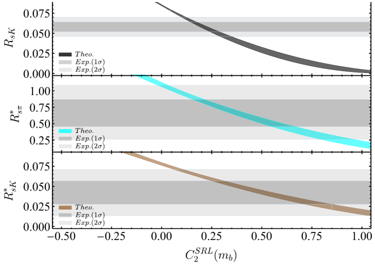
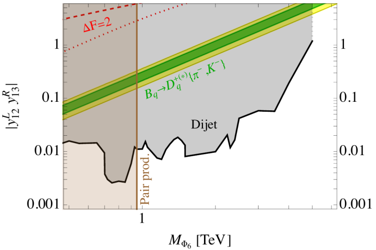


- Combine with dijet searches

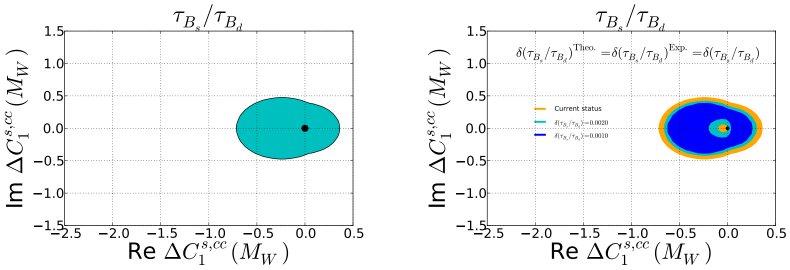
  [Bordone,Greljo,Marzocca'21]

  - Consider mediators with various $SU(3) \times SU(2) \times U(1)$ quantum numbers



- Combine nonleptonics and lifetimes

[Tetlalmatzi,Lenz'19]



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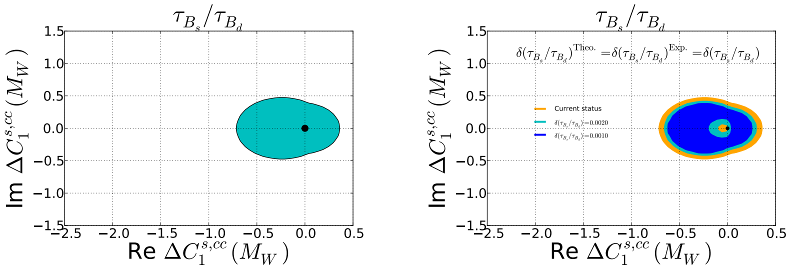


- New-physics searches using $B_s^0 \to D_s^{\mp} K^{\pm}$ [Fleischer,Malami'21; see Malami's talk this session]
- Flavour-specific nonleptonic decays are sensitive to CP violation in $B^0_{(s)} - \bar{B}^0_{(s)}$ mixing [Gershon,Lenz,Rusov,Skidmore'21; see Rusov's talk]
  - BSM contributions to nonleptonic decay amplitudes could give significant enhancements to flavour-specific CP asymmetries

$$A_{\text{fs}}^q = \frac{\Gamma\left(\bar{B}_q(t) \to f\right) - \Gamma\left(B_q(t) \to \bar{f}\right)}{\Gamma\left(\bar{B}_q(t) \to f\right) + \Gamma\left(B_q(t) \to \bar{f}\right)}$$

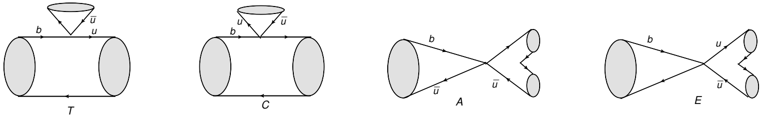
- The amplitudes for $B \to PP$ (P a pseudoscalar meson) can be expressed as

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

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

- Topological decomposition of the sub-amplitudes [He,Wang'18]

$$\begin{aligned}
\mathcal{T}^{TDA} \;=\;& T\; B_i (M)^i_j \bar{H}^{jl}_k (M)^k_l + C\; B_i (M)^i_j \bar{H}^{lj}_k (M)^k_l + A\; B_i \bar{H}^{il}_j (M)^j_k (M)^k_l \\
&+ E\; B_i \bar{H}^{li}_j (M)^j_k (M)^k_l + T_{ES} B_i \bar{H}^{ij}_l (M)^l_j (M)^k_k + T_{AS} B_i \bar{H}^{ji}_l (M)^l_j (M)^k_k \\
&+ T_S B_i (M)^i_j \bar{H}^{lj}_l (M)^k_k + T_{PA} B_i \bar{H}^{li}_l (M)^j_k (M)^k_j + T_P B_i (M)^i_j (M)^j_k \bar{H}^{lk}_l \\
&+ T_{SS} B_i \bar{H}^{li}_l (M)^j_j (M)^k_k
\end{aligned}$$



QCD-factorization and flavour symmetries

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$$(B_i) = (B^+, B^0_d, B^0_s)$$

$$(M^i_j) = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_q}{\sqrt{2}} + \frac{\eta'_q}{\sqrt{2}} & \pi^- & K^- \\ \pi^+ & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_q}{\sqrt{2}} + \frac{\eta'_q}{\sqrt{2}} & \bar{K}^0 \\ K^+ & K^0 & \eta_s + \eta'_s \end{pmatrix}$$

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- The $\bar{H}^{ij}_k$ are contain the CKM elements, e.g.

$$\bar{H}^{12}_1 = \lambda_u^{(d)}, \qquad \bar{H}^{13}_1 = \lambda_u^{(s)}.$$

QCD-factorization and flavour symmetries

- SU(3)-irreducible decomposition of the sub-amplitudes

$$\begin{aligned}\mathcal{T}^{IRA} \;=\; & A_3^T B_i(\bar{H}_{\bar{3}})^i (M)_k^j (M)_j^k + C_3^T B_i (M)_j^i (M)_k^j (\bar{H}_{\bar{3}})^k + B_3^T B_i (\bar{H}_3)^i (M)_k^k (M)_j^j \\ & + D_3^T B_i (M)_j^i (\bar{H}_{\bar{3}})^j (M)_k^k + A_6^T B_i (H_6)_k^{ij} (M)_j^l (M)_l^k + C_6^T B_i (M)_j^i (\bar{H}_6)_k^{jl} (M)_l^k \\ & + B_6^T B_i (\bar{H}_6)_k^{ij} (M)_j^k (M)_l^l + A_{15}^T B_i (\bar{H}_{\overline{15}})_k^{ij} (M)_j^l (M)_l^k + C_{15}^T B_i (M)_j^i (\bar{H}_{\overline{15}})_l^{jk} (M)_k^l \\ & + B_{15}^T B_i (\bar{H}_{\overline{15}})_k^{ij} (M)_j^k (M)_l^l .\end{aligned}$$

- $SU(3)$ decomposition:

$$H_k^{ij} = \frac{1}{8}\left(H_{\overline{15}}\right)_k^{ij} + \frac{1}{4}\left(H_6\right)_k^{ij} - \frac{1}{8}\left(H_{\overline{3}}\right)^i \delta_k^j + \frac{3}{8}\left(H_{\overline{3}'}\right)^j \delta_k^i$$

- Gives linear relations between topological and $SU(3)$-invariant amplitudes, e.g.

[He,Wang'18]

$$A_3^T = -\frac{A}{8} + \frac{3E}{8} + T_{PA}, \qquad B_3^T = T_{SS} + \frac{3T_{AS} - T_{ES}}{8},$$

$$A_6^T = \frac{1}{4}(A - E), \qquad B_6^T = \frac{1}{4}(T_{ES} - T_{AS})$$

QCD-factorization and flavour symmetries

[Tetlalmatzi-Xolocotzi,TH'21]

- 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 [Paz'02]

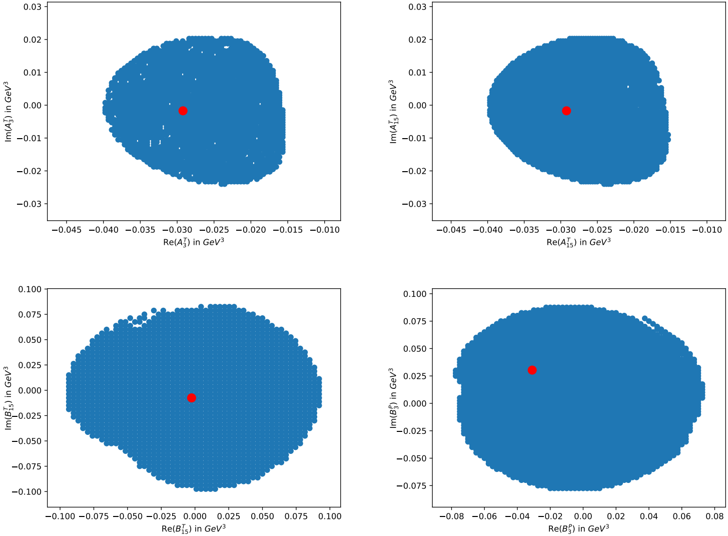
  $\Longrightarrow$ 35 real parameters.

- Use the following experimental input for branching fractions and CP asymmetries
  - Branching fractions : 23 measurements plus 6-upper bounds
  - CP Asymmetries: 17 measurements plus 1-upper bound

- Implement η-η' mixing in the FKS scheme (a single mixing angle) [Feldmann,Kroll,Stech'98]
- Determine uncertainties through likelihood ratio test, determine p value from Wilk's theorem with 2 degrees of freedom.

[Tetlalmatzi-Xolocotzi,TH’21]

- Good overall fit quality: $\chi^2/d.o.f. = 0.851$



SU(3) fit: Results

[Tetlalmatzi-Xolocotzi,TH'21]

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

QCD-factorization and flavour symmetries

- Investigate connection to QCD factorization (QCDF)
- Amplitudes for two body non-leptonic B-meson decays in QCDF [Beneke,Neubert'03]

$$
\begin{aligned}
\mathcal{A}^{\rm QCDF} = \sum_{p=u,c} A_{M_1M_2} \Big\{ & BM_1 \left(\alpha_1\delta_{pu}\hat{U} + \alpha_4^p\hat{I} + \alpha_{4,\rm EW}^p\hat{Q}\right) M_2\,\Lambda_p \\
& + BM_1\Lambda_p \cdot \text{Tr}\left[\left(\alpha_2\delta_{pu}\hat{U} + \alpha_3^p\hat{I} + \alpha_{3,\rm EW}^p\,\hat{Q}\right) M_2\right] \\
& + B\left(\beta_2\delta_{pu}\hat{U} + \beta_3^p\hat{I} + \beta_{3,\rm EW}^p\,\hat{Q}\right) M_1M_2\Lambda_p \\
& + B\Lambda_p \cdot \text{Tr}\left[\left(\beta_1\delta_{pu}\hat{U} + \beta_4^p\hat{I} + b_{4,\rm EW}^p\,\hat{Q}\right) M_1M_2\right] \\
& + B\left(\beta_{S2}\delta_{pu}\hat{U} + \beta_{S3}^p\hat{I} + \beta_{S3,\rm EW}^p\,\hat{Q}\right) M_1\Lambda_p \cdot \text{Tr}M_2 \\
& + B\Lambda_p \cdot \text{Tr}\left[\left(\beta_{S1}\delta_{pu}\hat{U} + \beta_{S4}^p\hat{I} + b_{S4,\rm EW}^p\,\hat{Q}\right) M_1\right] \cdot \text{Tr}M_2 \Big\}
\end{aligned}
$$

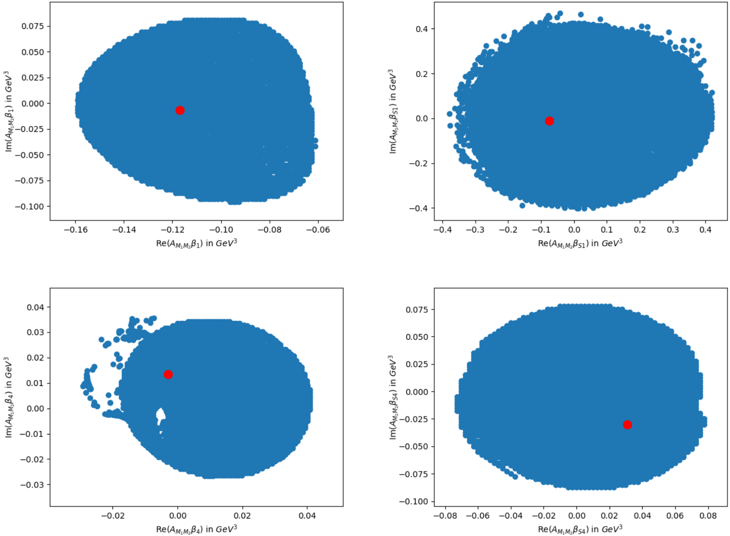
- Establish transformation rules between the different approaches [Tetlalmatzi-Xolocotzi,TH'21]

$$
T = A_{M_1M_2}\left[\alpha_1 + \frac{3}{2}\alpha^u_{4,EW} - \frac{3}{2}\alpha^c_{4,EW}\right], \quad C = A_{M_1M_2}\left[\alpha_2 + \frac{3}{2}\alpha^u_{3,EW} - \frac{3}{2}\alpha^c_{3,EW}\right],
$$
$$
E = A_{M_1M_2}\left[\beta_1 + \frac{3}{2}b^u_{4,EW} - \frac{3}{2}b^c_{4,EW}\right], \quad A = A_{M_1M_2}\left[\beta_2 + \frac{3}{2}\beta^u_{3,EW} - \frac{3}{2}\beta^c_{3,EW}\right]
$$

- Translate fit results into constraints on QCDF amplitudes
  - Quantify the size of the annihilation amplitudes β_i and b_i as dictated by data

QCDF amplitudes: Results

[Tetlalmatzi-Xolocotzi,TH'21]



- Annihilation amplitudes get constrained between the $\mathcal{O}(0.04)$ and $\mathcal{O}(0.3)$ level

Conclusion, Outlook

- Interesting patterns in data vs. theory for color-allowed, tree-level nonleptonic decays
  - Data consistently below theory, discrepancy up to $\sim 5\sigma$
  - We will learn something from this situation: power corrections in QCDF, input parameters, new physics, ...

- Precision in charmless nonleptonic decays must be further increased
  - Get power corrections / flavour symmetry breaking better under control
  - More data will help, in particular on direct CP asymmetries $A_{\rm CP}(B^0 \to \pi^0 \bar{K}^0)$ [2104.14871 + talk by Hazra], $A_{\rm CP}(B^0_{(s)} \to \eta P), \ldots$