Towards precision phenomenology in non-leptonic and rare B decays

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Outline

- Exclusive nonleptonic B decays
  - Charmless two-body decays [Bell,Beneke,Li,TH'15]
  - Heavy-light final states [Kränkl,TH'15; Kränkl,Li,TH'16]
  - Three-body decays
- Inclusive rare B decays
  - $\bar{B} \to X_s\, \ell^+ \ell^-$ [Hurth,Lunghi,TH'15]
  - $\bar{B} \to X_d\, \ell^+ \ell^-$ [Hurth,Lunghi,Jenkins,Vos,Qin,TH w.i.p.]

Introduction to non-leptonic *B* decays

- Non-leptonic *B* decays offer a rich and interesting phenomenology
  - Large data sets from *B*-factories, Tevatron, LHCb, in future Belle II
  - $\mathcal{O}(100)$ final states
  - Numerous observables:
    - branching ratios
    - CP asymmetries
    - polarisations
    - Dalitz plot analyses
    - Combinations thereof
- Test of CKM mechanism (CP violation)
- Indirect search for New Physics
  - Not as sensitive as rare or radiative *B* decays, but large data sets

Introduction to non-leptonic *B* decays

- Theoretical description complicated by purely hadronic initial and final state
  - QCD effects from many different scales

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; ...]

- Soft-collinear effective theory (SCET) [Bauer,Fleming,Pirjol,Stewart'01; Beneke,Chapovsky,Diehl,Feldmann'02]
  - Similar to QCDF, factorises spectator part further

[Wang,Wang,Yang,Lü'08; Wang,Zhou,Li,Lü'17]

Introduction to non-leptonic *B* decays

- 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]

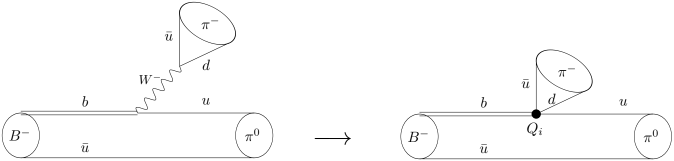
  Isospin, U-Spin ($d \leftrightarrow s$), V-Spin ($u \leftrightarrow s$), Flavour SU(3)

  [see e.g. Chiang,Gronau,Rosner'08; Chiang,Zhou'06'08; Cheng,Chiang,Kuo'14'16]
  - Only few a priori assumptions about scales needed
  - Implementation of symmetry breaking difficult [Jung,Mannel'09; Cheng,Chiang'12]
- Combination: Factorization-assisted topological-amplitude approach (FAT)

  [Li,Lü,Yu'12; Li,Lü,Qin,Yu'13; Wang,Zhang,Li,Lü'17]
- Dalitz plot analysis. Applied to 3-body decays
  - Mostly a fit to data, but also QCD-based predictions possible

    [Kränkl,Mannel,Virto'15; Klein,Mannel,Virto,Vos'17]

Effective theory for B decays



- $M_W,\, M_Z,\, m_t \gg m_b$: integrate out heavy gauge bosons and t-quark

- Effective Hamiltonian: [Buras,Buchalla,Lautenbacher'96; Chetyrkin,Misiak,Münz'98]

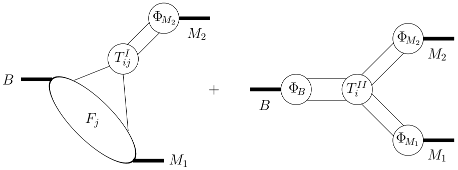
$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \left[C_1 Q_1^p + C_2 Q_2^p + \sum_{k=3}^{6} C_k Q_k + C_8 Q_8 \right] + \text{h.c.}$$

$$Q_1^p = (\bar{d}_L \gamma^\mu T^a p_L)(\bar{p}_L \gamma_\mu T^a b_L) \qquad Q_4 = (\bar{d}_L \gamma^\mu T^a b_L) \textstyle\sum_q (\bar{q} \gamma_\mu T^a q) \qquad Q_8 = -\dfrac{g_s}{16\pi^2}\, m_b\, \bar{d}_L\, \sigma_{\mu\nu} G^{\mu\nu} b_R$$

$$Q_2^p = (\bar{d}_L \gamma^\mu p_L)(\bar{p}_L \gamma_\mu b_L) \qquad Q_5 = (\bar{d}_L \gamma^\mu \gamma^\nu \gamma^\rho b_L) \textstyle\sum_q (\bar{q} \gamma_\mu \gamma_\nu \gamma_\rho q)$$

$$Q_3 = (\bar{d}_L \gamma^\mu b_L) \textstyle\sum_q (\bar{q} \gamma_\mu q) \qquad Q_6 = (\bar{d}_L \gamma^\mu \gamma^\nu \gamma^\rho T^a b_L) \textstyle\sum_q (\bar{q} \gamma_\mu \gamma_\nu \gamma_\rho T^a q) \qquad \lambda_p = V_{pb} V_{pd}^*$$

QCD factorisation



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

$$\langle M_1 M_2 | Q_i | \bar{B} \rangle \simeq m_B^2 \, F_+^{B\to M_1}(0) \, f_{M_2} \int_0^1 du \;\; T_i^I(u) \, \phi_{M_2}(u)$$

$$+ f_B \, f_{M_1} \, f_{M_2} \int_0^1 d\omega dv du \;\; T_i^{II}(\omega, v, u) \, \phi_B(\omega) \, \phi_{M_1}(v) \, \phi_{M_2}(u)$$

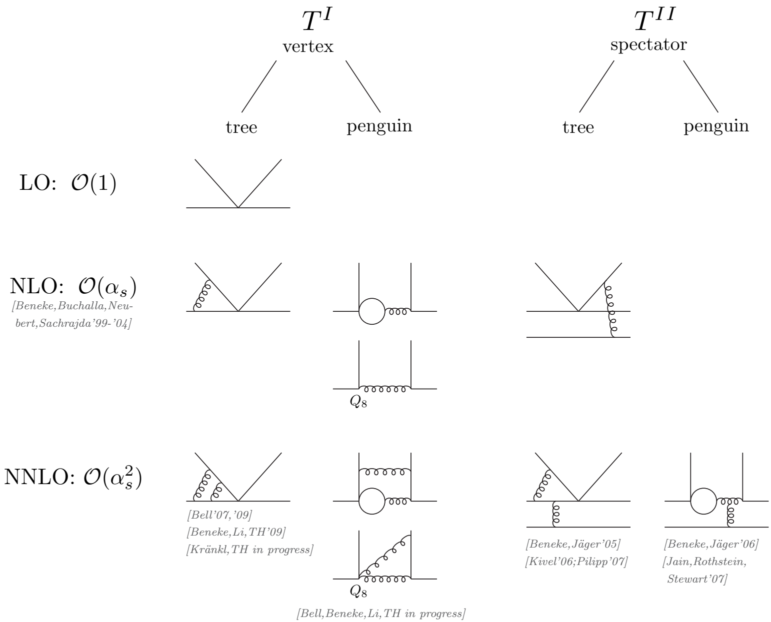
- $T^{I,II}$: Hard scattering kernels, perturbatively calculable

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

  } Universal. From Sum Rules, Lattice

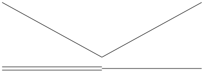
- Strong phases are $\mathcal{O}(\alpha_s)$ and/or $\mathcal{O}(\Lambda_{\rm QCD}/m_b)$

Anatomy of QCD factorisation

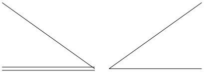


Classification of amplitudes

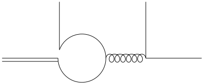
- α_1 : colour-allowed tree amplitude



- α_2 : colour-suppressed tree amplitude



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



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

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

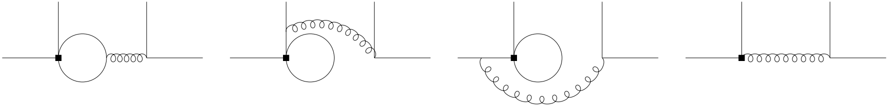
[Beneke,Neubert'03]

- Tree amplitudes α_1 and α_2 known analytically to NNLO

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

Penguin amplitudes a_4^u and a_4^c to NLO

- NLO:



$$\alpha_4^u(\pi\pi) = -0.029 - [0.002 + 0.001i]_V + [0.003 - 0.013i]_P + [?? \; + \; ?? \; i]_{\mathcal{O}(\alpha_s^2)}$$

$$+ \left[\frac{r_{\rm sp}}{0.485}\right] \left\{[0.001]_{\rm LO} + [0.001 + 0.000i]_{HV+HP} + [0.001]_{\rm tw3}\right\}$$

$$= (-0.024^{+0.004}_{-0.002}) + (-0.012^{+0.003}_{-0.002})i$$

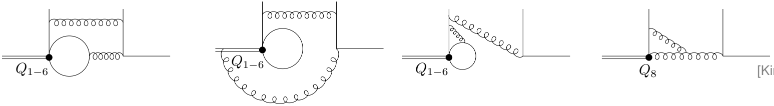
$$\alpha_4^c(\pi\pi) = -0.029 - [0.002 + 0.001i]_V - [0.001 + 0.007i]_P + [?? \; + \; ?? \; i]_{\mathcal{O}(\alpha_s^2)}$$

$$+ \left[\frac{r_{\rm sp}}{0.485}\right] \left\{[0.001]_{\rm LO} + [0.001 + 0.001i]_{HV+HP} + [0.001]_{\rm tw3}\right\}$$

$$= (-0.028^{+0.005}_{-0.003}) + (-0.006^{+0.003}_{-0.002})i$$

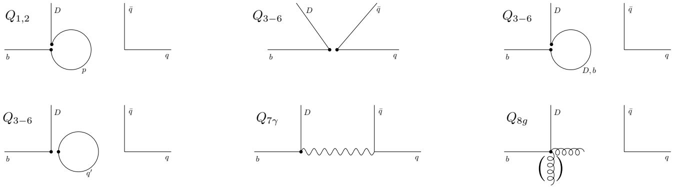
Penguin amplitudes at two loops

- $\mathcal{O}(70)$ diagrams at NNLO.



[Kim,Yoon'11]

- Quite some book-keeping due to various insertions



- Focus on $Q_1^{u,c}$ and $Q_2^{u,c}$ insertions first
  - Only $\sim$ 25 diagrams contribute
  - However: Genuine two-loop two-scale problem with threshold
  - Apply state-of-the-art multi-loop techniques
  - Perform matching from QCD onto SCET

Results: Penguin Amplitudes

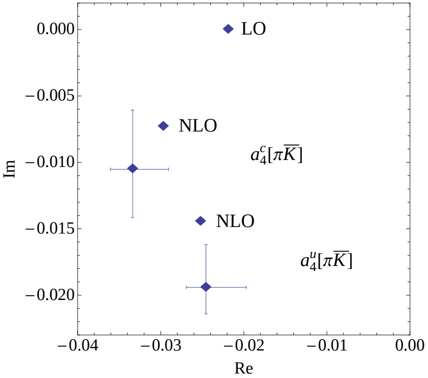
- Only $Q_{1,2}$ contribution. Inputs from [Beneke,Li,TH'09]

$$
\begin{aligned}
a_4^u(\pi\bar{K})/10^{-2} &= -2.87 - [0.09 + 0.09i]_{\mathrm{V}_1} + [0.49 - 1.32i]_{\mathrm{P}_1} - [0.32 + 0.71i]_{\mathrm{P}_2} \\
&\quad + \left[\frac{r_{\mathrm{sp}}}{0.434}\right] \left\{ [0.13]_{\mathrm{LO}} + [0.14 + 0.12i]_{\mathrm{HV}} - [0.01 - 0.05i]_{\mathrm{HP}} + [0.07]_{\mathrm{tw3}} \right\} \\
&= (-2.46^{+0.49}_{-0.24}) + (-1.94^{+0.32}_{-0.20})i\,,
\end{aligned}
$$

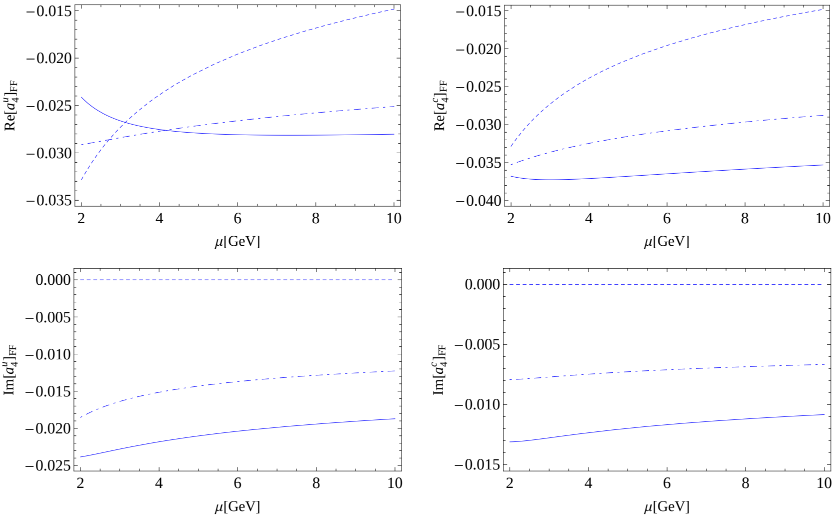
$$
\begin{aligned}
a_4^c(\pi\bar{K})/10^{-2} &= -2.87 - [0.09 + 0.09i]_{\mathrm{V}_1} + [0.05 - 0.62i]_{\mathrm{P}_1} - [0.77 + 0.50i]_{\mathrm{P}_2} \\
&\quad + \left[\frac{r_{\mathrm{sp}}}{0.434}\right] \left\{ [0.13]_{\mathrm{LO}} + [0.14 + 0.12i]_{\mathrm{HV}} + [0.01 + 0.03i]_{\mathrm{HP}} + [0.07]_{\mathrm{tw3}} \right\} \\
&= (-3.34^{+0.43}_{-0.27}) + (-1.05^{+0.45}_{-0.36})i\,.
\end{aligned}
$$

- NNLO correction sizable, but no breakdown of perturbative expansion

Results: Penguin Amplitudes



Results: Scale dependence



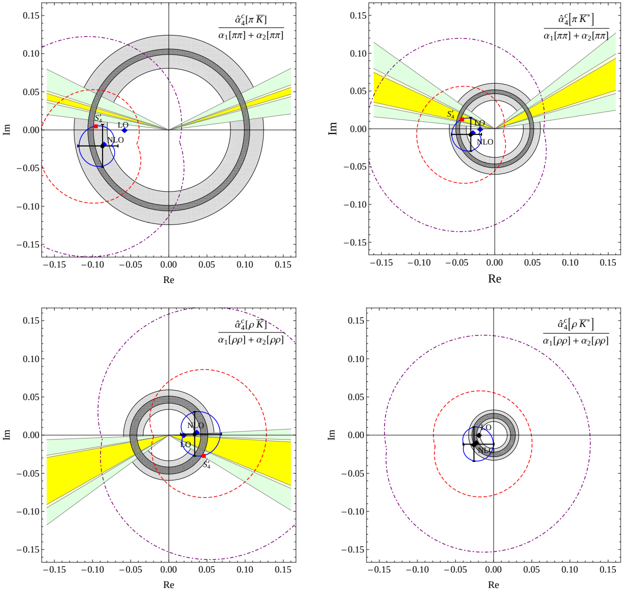
- Only form factor term, no spectator scattering

Results: Amplitude ratios

Ratio	NLO	NNLO
$\frac{P_{\pi\pi}}{T_{\pi\pi}}$	$-0.121-0.021i$	$-0.124^{+0.031}_{-0.060}+(-0.026^{+0.045}_{-0.046})i$
$\frac{P_{\rho\rho}}{T_{\rho\rho}}$	$-0.035-0.009i$	$-0.041^{+0.020}_{-0.016}+(-0.014^{+0.019}_{-0.018})i$
$\frac{P_{\pi\rho}}{T_{\pi\rho}}$	$-0.038-0.005i$	$-0.040^{+0.016}_{-0.030}+(-0.009^{+0.026}_{-0.026})i$
$\frac{P_{\rho\pi}}{T_{\rho\pi}}$	$0.040+0.002i$	$0.036^{+0.042}_{-0.023}+(-0.001^{+0.033}_{-0.033})i$
$\frac{C_{\pi\pi}}{T_{\pi\pi}}$	$0.317-0.040i$	$0.320^{+0.255}_{-0.142}+(-0.030^{+0.150}_{-0.091})i$
$\frac{C_{\rho\rho}}{T_{\rho\rho}}$	$0.165-0.064i$	$0.176^{+0.187}_{-0.133}+(-0.054^{+0.142}_{-0.104})i$
$\frac{C_{\pi\rho}}{T_{\pi\rho}}$	$0.219-0.064i$	$0.212^{+0.197}_{-0.112}+(-0.062^{+0.114}_{-0.079})i$
$\frac{C_{\rho\pi}}{T_{\rho\pi}}$	$0.092-0.080i$	$0.112^{+0.189}_{-0.144}+(-0.065^{+0.152}_{-0.115})i$
$\frac{T_{\rho\pi}}{T_{\pi\rho}}$	$0.821+0.016i$	$0.810^{+0.262}_{-0.200}+(\ 0.010^{+0.062}_{-0.062})i$
$\frac{\alpha_4^c(\pi K)}{\alpha_1(\pi\pi)+\alpha_2(\pi\pi)}$	$-0.085-0.019i$	$-0.087^{+0.022}_{-0.036}+(-0.021^{+0.029}_{-0.029})i$
$\frac{\alpha_4^c(\pi K^*)}{\alpha_1(\pi\pi)+\alpha_2(\pi\pi)}$	$-0.029-0.005i$	$-0.030^{+0.015}_{-0.026}+(-0.007^{+0.023}_{-0.023})i$
$\frac{\alpha_4^c(\rho K)}{\alpha_1(\rho\rho)+\alpha_2(\rho\rho)}$	$0.037+0.004i$	$0.034^{+0.039}_{-0.021}+(\ 0.001^{+0.030}_{-0.030})i$
$\frac{\alpha_4^c(\rho K^*)}{\alpha_1(\rho\rho)+\alpha_2(\rho\rho)}$	$-0.023-0.010i$	$-0.027^{+0.027}_{-0.016}+(-0.012^{+0.024}_{-0.023})i$

- Unpublished numbers. Only $Q_{1,2}$ contribution. Inputs from [Beneke,Li,TH'09].

Results: Amplitude ratios



Results: Direct CP asymmetries I

- Direct CP asymmetries in percent.

  Errors are CKM and hadronic, respectively.

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

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

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

Results: Direct CP asymmetries II

- Direct CP asymmetries in percent

f	NLO	NNLO	NNLO + LD	Exp
$\pi^- \bar{K}^{*0}$	$1.36\,^{+0.25}_{-0.26}\,^{+0.60}_{-0.47}$	$1.49\,^{+0.27}_{-0.29}\,^{+0.69}_{-0.56}$	$0.27\,^{+0.05}_{-0.05}\,^{+3.18}_{-0.67}$	-3.8 ± 4.2
$\pi^0 K^{*-}$	$13.85\,^{+2.40}_{-2.70}\,^{+5.84}_{-5.86}$	$18.16\,^{+3.11}_{-3.52}\,^{+7.79}_{-10.57}$	$-15.81\,^{+3.01}_{-2.83}\,^{+69.35}_{-15.39}$	-6 ± 24
$\pi^+ K^{*-}$	$11.18\,^{+2.00}_{-2.15}\,^{+9.75}_{-10.62}$	$19.70\,^{+3.37}_{-3.80}\,^{+10.54}_{-11.42}$	$-23.07\,^{+4.35}_{-4.05}\,^{+86.20}_{-20.64}$	-23 ± 6
$\pi^0 \bar{K}^{*0}$	$-17.23\,^{+3.33}_{-3.00}\,^{+7.59}_{-12.57}$	$-15.11\,^{+2.93}_{-2.65}\,^{+12.34}_{-10.64}$	$2.16\,^{+0.39}_{-0.42}\,^{+17.53}_{-36.80}$	-15 ± 13
$\delta(\pi \bar{K}^*)$	$2.68\,^{+0.72}_{-0.67}\,^{+5.44}_{-4.30}$	$-1.54\,^{+0.45}_{-0.58}\,^{+4.60}_{-9.19}$	$7.26\,^{+1.21}_{-1.34}\,^{+12.78}_{-20.65}$	17 ± 25
$\Delta(\pi \bar{K}^*)$	$-7.18\,^{+1.38}_{-1.28}\,^{+3.38}_{-5.35}$	$-3.45\,^{+0.67}_{-0.59}\,^{+9.48}_{-4.95}$	$-1.02\,^{+0.19}_{-0.18}\,^{+4.32}_{-7.86}$	-5 ± 45

$$\hat{\alpha}_4^p(M_1 M_2) = a_4^p(M_1 M_2) \pm r_\chi^{M_2} a_6^p(M_1 M_2) + \beta_3^p(M_1 M_2)$$

Results: Branching ratios

- Unpublished numbers. Only $Q_{1,2}$ contribution. Inputs from [Beneke,Li,TH'09].
- Branching ratios in 10^{-6}.

	NNLO	NLO	Experiment
$B^- \to \pi^-\pi^0$	$5.43\,^{+2.66}_{-2.14}\,^{+2.05}_{-1.73}\,^{+1.27}_{-0.57}\,^{+0.52}_{-0.50}$	5.33	$5.48\,^{+0.35}_{-0.34}$
$\bar{B}^0_d \to \pi^+\pi^-$	$7.47\,^{+3.15}_{-2.61}\,^{+3.36}_{-2.76}\,^{+0.30}_{-0.60}\,^{+1.18}_{-0.66}$	7.30	$5.10\,^{+0.19}_{-0.19}$
$\bar{B}^0_d \to \pi^0\pi^0$	$0.35\,^{+0.14}_{-0.11}\,^{+0.19}_{-0.11}\,^{+0.33}_{-0.09}\,^{+0.20}_{-0.10}$	0.33	$1.33\,^{+0.46}_{-0.46}$
$B^- \to \pi^-\bar{K}^0$	$16.03\,^{+0.79}_{-0.77}\,^{+9.66}_{-6.68}\,^{+0.87}_{-1.28}\,^{+13.51}_{-5.61}$	14.94	$23.79\,^{+0.75}_{-0.75}$
$B^- \to \pi^0 K^-$	$9.57\,^{+0.79}_{-0.74}\,^{+5.00}_{-3.50}\,^{+0.18}_{-0.39}\,^{+7.15}_{-3.01}$	8.97	$12.94\,^{+0.52}_{-0.51}$
$\bar{B}^0_d \to \pi^+K^-$	$14.01\,^{+1.09}_{-1.03}\,^{+8.43}_{-5.76}\,^{+0.12}_{-0.26}\,^{+11.92}_{-4.92}$	12.88	$19.57\,^{+0.53}_{-0.52}$
$\bar{B}^0_d \to \pi^0\bar{K}^0$	$5.82\,^{+0.31}_{-0.31}\,^{+4.05}_{-2.72}\,^{+0.07}_{-0.16}\,^{+5.58}_{-2.26}$	5.31	$9.93\,^{+0.49}_{-0.49}$

- Errors are CKM, scale and inputs (masses, decay constants, FFs), Gegenbauer moments, power corrections

The decays $B \to D^{(*)} L$

[Kränkl,TH'15; Kränkl,Li,TH'16]

- $L \in \{\pi, \rho, K^{(*)}, a_1(1260)\}$
- Only colour-allowed tree amplitude
  - No colour-suppressed tree amplitude, no penguins
  - Spectator scattering and weak annihilation power suppressed

$$BR(\bar{B}_0 \to D^+\pi^-) = \frac{G_F^2(m_B^2 - m_D^2)^2|\vec{q}|}{16\pi m_B^2}\tau_{\bar{B}^0}|V_{ud}^* V_{cb}|^2 \, |a_1(D\pi)|^2 \, f_\pi^2 \, F_0^2(m_\pi^2) + O\left(\frac{\Lambda_{QCD}}{m_b}\right)$$

- Applications
  - Ratios of non-leptonic decay widths

$$\frac{\Gamma(\bar{B}_d \to D^+\pi^-)}{\Gamma(\bar{B}_d \to D^{*+}\pi^-)} = \frac{(m_B^2 - m_D^2)^2|\vec{q}\,|_{D\pi}}{4m_B^2|\vec{q}\,|^3_{D^*\pi}} \left(\frac{F_0(m_\pi^2)}{A_0(m_\pi^2)}\right)^2 \left|\frac{a_1(D\pi)}{a_1(D^*\pi)}\right|^2$$

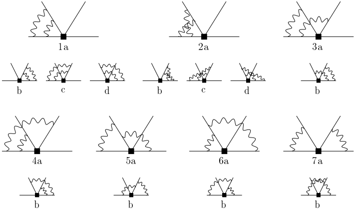
  - Test of factorisation via ratios to semi-leptonic decay

$$\frac{\Gamma(\bar{B}_d \to D^{(*)+}\pi^-)}{d\Gamma(\bar{B}_d \to D^{(*)+}l^-\bar{\nu})/dq^2\big|_{q^2=m_\pi^2}} = 6\pi^2|V_{ud}|^2 \, f_\pi^2 \, |a_1(D^{(*)}\pi)|^2$$

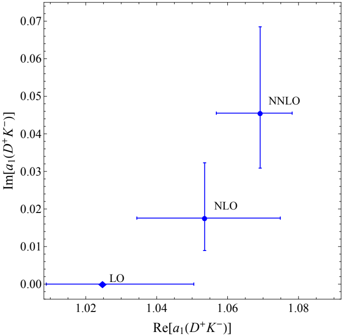
  - Estimate size of power corrections, test of QCD factorisation

NNLO calculation and result for $a_1(\bar{B}^0 \to D^+ K^-)$

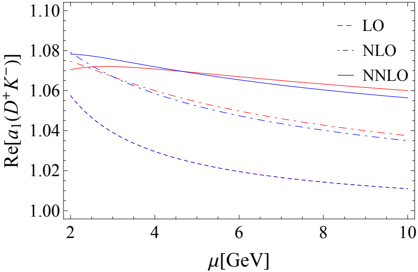
- NLO correction small
  - Colour suppression
  - Small Wilson Coefficient
- At NNLO
  - Again around 70 diagrams

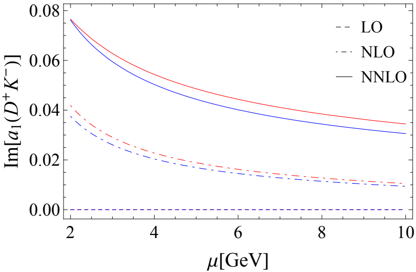


$$
\begin{aligned}
a_1(D^+K^-) &= 1.025 + [0.029 + 0.018i]_{\rm NLO} \\
&\quad + [0.016 + 0.028i]_{\rm NNLO} \\
&= (1.069^{+0.009}_{-0.012}) + (0.046^{+0.023}_{-0.015})i
\end{aligned}
$$



Scale dependence





Branching ratios in QCD factorisation I

$$\mathrm{BR}(\bar{B}^0 \to D^+\pi^-) = \frac{G_F^2 (m_B^2 - m_D^2)^2 |\vec{q}|_{D\pi}}{16\pi m_B} \tau_{\bar{B}^0} |V_{ud}^* V_{cb}|^2 \, |a_1(D\pi)|^2 f_\pi^2 F_0^2(m_\pi^2)$$

- Form factor parametrization from CLN [Caprini,Lellouch,Neubert'97]

  [For more recent $B \to D$ form factor analysis see Wang,Wei,Shen,Lü'17]

  - Slope and normalization from fit to semileptonic data (HFAG)
- Calculation applies equally well to other $\bar{B}^0 \to D^{*+} L^-$ decays
- Branching ratios in 10^{-3}

Decay	Theory (NNLO)	Experiment
$\bar{B}^0 \to D^+\pi^-$	$3.93^{+0.43}_{-0.42}$	2.68 ± 0.13
$\bar{B}^0 \to D^{*+}\pi^-$	$3.45^{+0.53}_{-0.50}$	2.76 ± 0.13
$\bar{B}^0 \to D^+\rho^-$	$10.42^{+1.24}_{-1.20}$	7.5 ± 1.2
$\bar{B}^0 \to D^{*+}\rho^-$	$9.24^{+0.72}_{-0.71}$	6.0 ± 0.8

- NNLO central values about $20 - 30\%$ larger than experimental ones

Branching ratios in QCD factorisation II

Decay mode	LO	NLO	NNLO	Exp.
$\bar{B}_d \to D^+\pi^-$	3.58	$3.79^{+0.44}_{-0.42}$	$3.93^{+0.43}_{-0.42}$	2.68 ± 0.13
$\bar{B}_d \to D^{*+}\pi^-$	3.15	$3.32^{+0.52}_{-0.49}$	$3.45^{+0.53}_{-0.50}$	2.76 ± 0.13
$\bar{B}_d \to D^+\rho^-$	9.51	$10.06^{+1.25}_{-1.19}$	$10.42^{+1.24}_{-1.20}$	7.5 ± 1.2
$\bar{B}_d \to D^{*+}\rho^-$	8.45	$8.91^{+0.74}_{-0.71}$	$9.24^{+0.72}_{-0.71}$	6.0 ± 0.8
$\bar{B}_d \to D^+K^-$	2.74	$2.90^{+0.33}_{-0.31}$	$3.01^{+0.32}_{-0.31}$	1.97 ± 0.21
$\bar{B}_d \to D^{*+}K^-$	2.37	$2.50^{+0.39}_{-0.36}$	$2.59^{+0.39}_{-0.37}$	2.14 ± 0.16
$\bar{B}_d \to D^+K^{*-}$	4.79	$5.07^{+0.65}_{-0.62}$	$5.25^{+0.65}_{-0.63}$	4.5 ± 0.7
$\bar{B}_d \to D^{*+}K^{*-}$	4.30	$4.54^{+0.41}_{-0.40}$	$4.70^{+0.40}_{-0.39}$	–
$\bar{B}_d \to D^+a_1^-$	10.82	$11.44^{+1.55}_{-1.48}$	$11.84^{+1.55}_{-1.50}$	6.0 ± 3.3
$\bar{B}_d \to D^{*+}a_1^-$	10.12	$10.66^{+1.11}_{-1.06}$	$11.06^{+1.10}_{-1.07}$	–

- Branching ratios in 10^{-3} for $b \to c\bar{u}d$ and 10^{-4} for $b \to c\bar{u}s$ transitions
- Have also B_s and Λ_b decays
- Non-negligible W-exchange contributions in $\bar{B}_d \to D^{(*)+}\pi^- \,/\, \rho^-$ decays? (not present in $\bar{B}_d \to D^{(*)+}K^{(*)-}$)

Tests of QCD factorisation

- Ratios of non-leptonic decay widths
  - Within error bars, no significant tension

Decay	Theory (NNLO)	Experiment
$\Gamma(\bar{B}^0 \to D^{*+}\pi^-)/\Gamma(\bar{B}^0 \to D^+\pi^-)$	$0.878^{+0.162}_{-0.150}$	1.03 ± 0.07
$\Gamma(\bar{B}^0 \to D^+\rho^-)/\Gamma(\bar{B}^0 \to D^+\pi^-)$	$2.653^{+0.163}_{-0.158}$	2.80 ± 0.47

- Extraction of $|a_1|$ from ratios of non-leptonic and semi-leptonic BRs

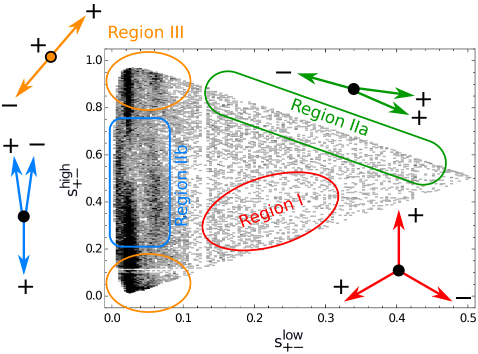
$$\frac{\Gamma(\bar{B}_d \to D^{(*)+}\pi^-)}{d\Gamma(\bar{B}_d \to D^{(*)+}l^-\bar{\nu})/dq^2\big|_{q^2=m_\pi^2}} = 6\pi^2|V_{ud}|^2\, f_\pi^2\, |a_1(D^{(*)}\pi)|^2$$

Decay	$\lvert a_1\rvert$ Theory (NNLO)	$\lvert a_1\rvert$ Experiment
$\bar{B}^0 \to D^+\pi^-$	1.07 ± 0.01	0.89 ± 0.05
$\bar{B}^0 \to D^{*+}\pi^-$	1.07 ± 0.01	0.96 ± 0.03
$\bar{B}^0 \to D^+\rho^-$	1.07 ± 0.01	0.91 ± 0.08
$\bar{B}^0 \to D^{*+}\rho^-$	1.07 ± 0.01	0.86 ± 0.06

  - Quasi-universal value $|a_1| \sim 1.07$ at NNLO. Experiment favors lower $|a_1|$.
- Leaves room for (negative) power corrections to the amplitude of $\sim 10 - 15\%$

Three-body nonleptonic B-decays

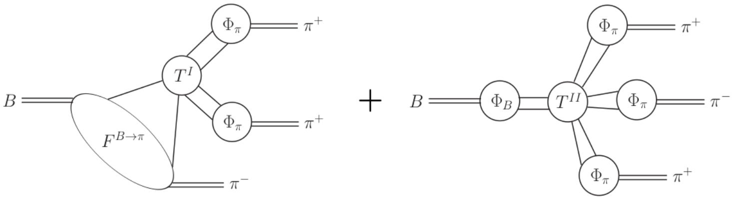
- Three-body nonleptonic B-decays provide another fertile testing-ground to study CP violation
- Events populate a Dalitz plot, wealth of data
- Focus on $B^+ \to \pi^+\pi^-\pi^+$ in a factorisation approach [Kränkl,Mannel,Virto'15]
  - Identify different regions in Dalitz plot
  - Each region obeys its own factorisation formula



[Plots courtesy by K. Vos]

Central region

[Kränkl,Mannel,Virto'15]



- Factorisation formula

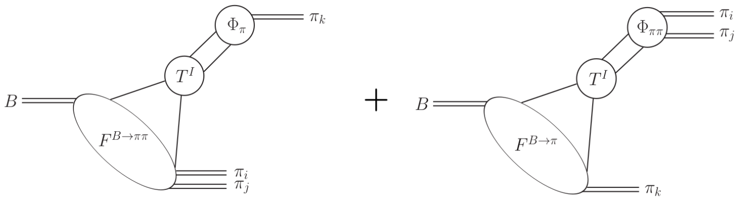
$$\langle \pi^+\pi^+\pi^- | \mathcal{Q}_i | B^+ \rangle_c = T_i^I \otimes F^{B\to\pi} \otimes \Phi_\pi \otimes \Phi_\pi + T_i^{II} \otimes \Phi_B \otimes \Phi_\pi \otimes \Phi_\pi \otimes \Phi_\pi$$

- At tree-level all convolutions are finite
- $1/m_b^2$ and α_s suppressed compared to two-body case

Edges of Dalitz plot

[Kränkl,Mannel,Virto'15]

- Resonances close to the edges



- Factorisation formula

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

- Always an improvement over quasi-two-body decays, reduces to $B \to \rho\pi$ for ρ dominance and zero-width approximation
- New nonperturbative input (source of strong phases): 2πLCDA, $B \to \pi\pi$ form factor

New nonperturbative input

- New nonperturbative input from data or model [Klein,Mannel,Virto,Vos'17]
- 2πLCDA [Polyakov'99]

$$\phi^q_{\pi\pi}(u,\zeta,s) = \int \frac{dx^-}{2\pi} e^{iu(k^+_{12}x^-)} \left\langle \pi^+(k_1)\pi^-(k_2)|\bar{q}(x^-n_-)\not{n}_+ q(0)|0\right\rangle$$

$$s = (k_1+k_2)^2,\ \zeta = k_1/s$$

- Both isoscalar ($I=0$) and isovector ($I=1$) contribute
- At leading order only normalization needed

$$\int du\ \phi^{I=1}_{\pi\pi}(u,\zeta,s) = (2\zeta-1)F_\pi(s) \qquad \int du\ \phi^{I=0}_{\pi\pi}(u,\zeta,s) = 0$$

- Time-like pion formfactor $F_\pi(s)$ from $e^+e^- \to \pi\pi(\gamma)$ data
  - Magnitude well constrained, phase not [Shekhovtsova,Przedzinski,Roig,Was'12; Hanhart'12]
  - Also isoscalar part F^S_π needed [Celis,Cirigliano,Passemar'13; Daub,Hanhart,Kubis'15]

New nonperturbative input

- $B \to \pi\pi$ form factor [Klein,Mannel,Virto,Vos'17]
  - Was studied in $B \to \pi\pi\,\ell\,\nu$ decays
    [Faller,Feldmann,Khodjamirian,Mannel,van Dyk'13; Böer,Feldmann,van Dyk'16]
- For $B^+ \to \pi^+\pi^-\pi^+$ only vector form factor relevant

$$k_{3\mu} \left\langle \pi^+(k_1)\pi^-(k_2)|\bar{b}\gamma^\mu\gamma^5 u|B^+(p)\right\rangle = i\, m_\pi\, F_t(s,\zeta)$$

- Both isoscalar (S-wave) and isovector (P-wave) contributions

$$F_t = F_t^{I=0} + F_t^{I=1}$$

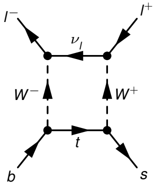
  - Isovector $F_t^{I=1}$ part studied with QCD Light-Cone Sum Rules
    [Hambrock,Khodjamirian'15; Cheng,Khodjamirian,Virto'17]
  - Assumption / model for $F_t^{I=1}$ [Klein,Mannel,Virto,Vos'17]
    - Decay $B \to \pi\pi$ proceeds only resonantly through $B \to \rho \to \pi\pi$
  - Model for $F_t^{I=0}$. Fit β and ϕ from data [Klein,Mannel,Virto,Vos'17]

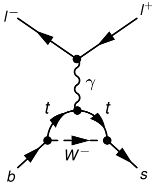
$$F_t^{I=0}(q^2) = \frac{m_B^2}{m_\pi f_\pi}\beta e^{i\phi} F_\pi^S(q^2)$$

[Celis,Cirigliano,Passemar'13; Daub,Hanhart,Kubis'15]

Introduction to inclusive $\bar{B} \to X_s \ell^+ \ell^-$

- Inclusive $\bar{B} \to X_s \ell^+ \ell^-$
  - Rare decay, FCNC process
  - Probes SM directly at the loop level
  - Sensitivity to new physics
- Complementary to $\bar{B} \to X_s \gamma$
  - More observables
  - Box and penguin diagrams
  - Besides C_7, also sensitivity to $C_{9,10}$
- Complementary to $\bar{B} \to K^{(*)} \mu^+ \mu^-$
  - Complementarity in experimental analysis: LHCb vs. BaBar, Belle (II)
  - Handling of power corrections
  - Sensitivity to different (combinations of) operators
  - Probing different theoretical approaches when measuring e.g. C_9



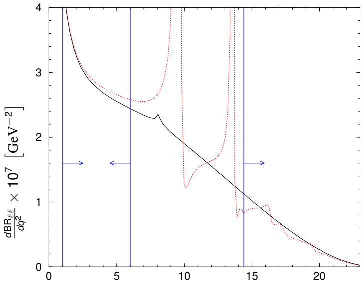


Observables

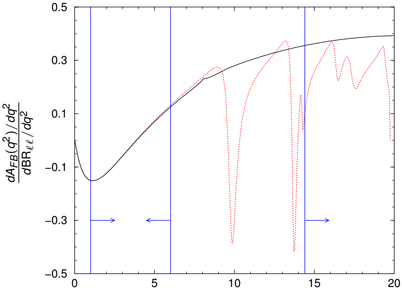
- Double differential decay width ($z = \cos\theta_\ell$) [Lee,Ligeti,Stewart,Tackmann'06]

$$\frac{d^2\Gamma}{dq^2\,dz} = \frac{3}{8}\left[(1+z^2)\,H_T(q^2) + 2\,z\,H_A(q^2) + 2\,(1-z^2)\,H_L(q^2)\right]$$

Note: $$\frac{d\Gamma}{dq^2} = H_T(q^2) + H_L(q^2)\,, \qquad \frac{dA_{\rm FB}}{dq^2} = 3/4\,H_A(q^2)$$



[Ghinculov,Hurth,Isidori,Yao]



[Ghinculov,Hurth,Isidori,Yao]

- Low-q^2 region: $1\,\mathrm{GeV}^2 < q^2 < 6\,\mathrm{GeV}^2$
- High-q^2 region: $q^2 > 14.4\,\mathrm{GeV}^2$

Observables

- Dependence of the H_i on WCs

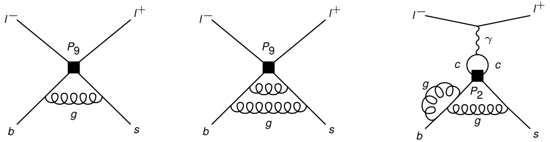
$$H_T(q^2) \propto 2s(1-s)^2\left[\left|C_9 + \frac{2}{s}C_7\right|^2 + |C_{10}|^2\right]$$
$$H_A(q^2) \propto -4s(1-s)^2 \ \mathrm{Re}\left[C_{10}\left(C_9 + \frac{2}{s}C_7\right)\right]$$
$$H_L(q^2) \propto (1-s)^2\left[\left|C_9 + 2\,C_7\right|^2 + |C_{10}|^2\right]$$

- Consider integrals of H_i over two bins 1 – 3.5 GeV^2 and 3.5 – 6 GeV^2
  - H_T suppressed at low-q^2: Factor "s" and small $\left|C_9 + \frac{2}{s}C_7\right|^2$
- Moreover: zero of H_A in low-q^2 region
- High-q^2 region:
- Introduction of the ratio $\mathcal{R}(s_0) = \dfrac{\int_{\hat{s}_0}^1 \mathrm{d}\hat{s}\ d\Gamma(\bar{B} \to X_s \ell^+\ell^-)/d\hat{s}}{\int_{\hat{s}_0}^1 \mathrm{d}\hat{s}\ d\Gamma(\bar{B}^0 \to X_u \ell\nu)/d\hat{s}}$ [Ligeti,Tackmann'07]
  - Normalize to semileptonic $\bar{B}^0 \to X_u \ell\nu$ rate with the same cut
    Need differential semi-leptonic $b \to u$ rate

Perturbative and non-perturbative corrections

$$\Gamma(\bar{B} \to X_s \ell\ell) = \Gamma(b \to X_s \ell\ell) \ + \ \text{power corrections}$$

- Pert. corrections at quark level are known to NNLO QCD + NLO QED
  [Misiak,Buras,Münz,Bobeth,Urban,Asatrian,Asatryan,Greub,Walker,Bobeth,Gambino,Gorbahn,Haisch,Blokland]
  [Czarnecki,Melnikov,Slusarczyk,Bieri,Ghinculov,Hurth,Isidori,Yao,Greub,Pilipp,Schüpbach,Lunghi,TH]
  - Involves diagrams up to three loops



  - Fully differential QCD corrections at NNLO for $P_{9,10}$ also known
    [Brucherseifer,Caola,Melnikov'13]

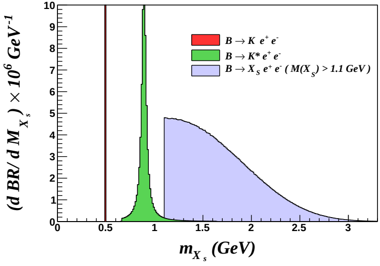
- $1/m_b^2$, $1/m_b^3$ and $1/m_c^2$ non-pert. corrections
  [Falk,Luke,Savage'93]
  [Ali,Hiller,Handoko,Morozumi'96]
  [Bauer,Burrell'99; Buchalla,Isidori,Rey'97]

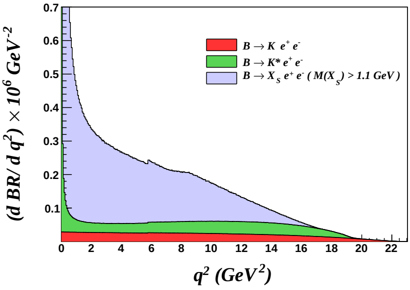
- Factorizable $c\bar{c}$ contributions implemented via KS approach [Krüger, Sehgal'96]

Collinear photons

- Rate differential in q^2 is not IR safe w.r.t. energetic, collinear photon radiation off leptons
- Gives rise to log-enhanced QED corrections $\propto \alpha_{\rm em} \log(m_b^2/m_\ell^2)$
- Size of logs depends on experimental setup
  - $q^2 = (p_{\ell^+} + p_{\ell^-})^2$ vs. $q^2 = (p_{\ell^+} + p_{\ell^-} + p_{\gamma,\rm coll})^2$
  - To compare to BaBar electron channel our numbers need to be modified

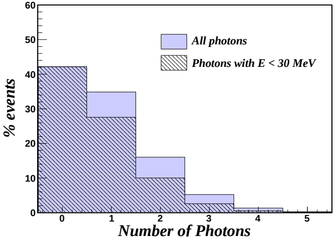
$$\frac{\left[\mathcal{B}_{ee}^{\rm low}\right]_{q=p_{e^+}+p_{e^-}+p_{\gamma_{\rm coll}}}}{\left[\mathcal{B}_{ee}^{\rm low}\right]_{q=p_{e^+}+p_{e^-}}} - 1 = 1.65\% \qquad \frac{\left[\mathcal{B}_{ee}^{\rm high}\right]_{q=p_{e^+}+p_{e^-}+p_{\gamma_{\rm coll}}}}{\left[\mathcal{B}_{ee}^{\rm high}\right]_{q=p_{e^+}+p_{e^-}}} - 1 = 6.8\%$$

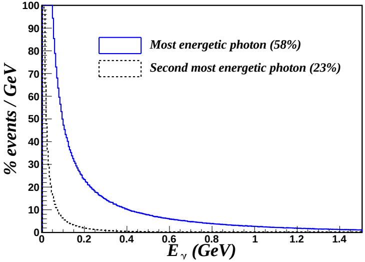


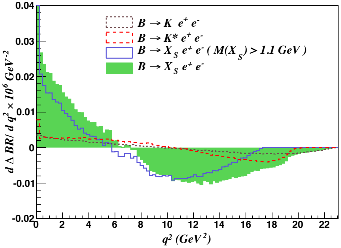


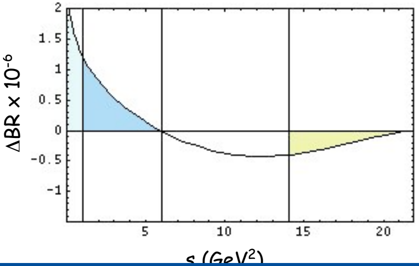
Collinear photons

- Validation
  - Generate events (EVTGEN), hadronise (JETSET), add EM radiation (PHOTOS)









H_T

- Results for H_T, integrated over bins in low-q^2 region, in units of 10^{-6}
  - Electron channel

$$H_T[1,3.5]_{ee} = 0.29 \pm 0.02$$
$$H_T[3.5,6]_{ee} = 0.24 \pm 0.02$$
$$H_T[1,6]_{ee} = 0.53 \pm 0.04$$

  - Muon channel

$$H_T[1,3.5]_{\mu\mu} = 0.21 \pm 0.01$$
$$H_T[3.5,6]_{\mu\mu} = 0.19 \pm 0.02$$
$$H_T[1,6]_{\mu\mu} = 0.40 \pm 0.03$$

- Total error $\mathcal{O}(5-8\%)$. Still dominated by scale uncertainty.

H_L

- Results for H_L, integrated over bins in low-q^2 region, in units of 10^{-6}
  - Electron channel

$$H_L[1,3.5]_{ee} = 0.64 \pm 0.03$$
$$H_L[3.5,6]_{ee} = 0.50 \pm 0.03$$
$$H_L[1,6]_{ee} = 1.13 \pm 0.06$$

  - Muon channel

$$H_L[1,3.5]_{\mu\mu} = 0.68 \pm 0.04$$
$$H_L[3.5,6]_{\mu\mu} = 0.53 \pm 0.03$$
$$H_L[1,6]_{\mu\mu} = 1.21 \pm 0.07$$

- Again total error $\mathcal{O}(5-7\%)$.

Branching ratio, low-q^2 region

- Branching ratio, integrated over bins in low-q^2 region, in units of 10^{-6}
  - Electron channel

$$\mathcal{B}[1,3.5]_{ee} = 0.93 \pm 0.03_{\rm scale} \pm 0.01_{m_t} \pm 0.03_{C,m_c} \pm 0.01_{m_b} \pm 0.002_{\alpha_s} \pm 0.003_{\rm CKM} \pm 0.01_{\rm BR_{sl}}$$
$$= 0.93 \pm 0.05$$

$$\mathcal{B}[3.5,6]_{ee} = 0.74 \pm 0.04_{\rm scale} \pm 0.01_{m_t} \pm 0.03_{C,m_c} \pm 0.01_{m_b} \pm 0.003_{\alpha_s} \pm 0.002_{\rm CKM} \pm 0.01_{\rm BR_{sl}}$$
$$= 0.74 \pm 0.05$$

$$\mathcal{B}[1,6]_{ee} = 1.67 \pm 0.07_{\rm scale} \pm 0.02_{m_t} \pm 0.06_{C,m_c} \pm 0.02_{m_b} \pm 0.01_{\alpha_s} \pm 0.005_{\rm CKM} \pm 0.02_{\rm BR_{sl}}$$
$$= 1.67 \pm 0.10$$

  - Muon channel

$$\mathcal{B}[1,3.5]_{\mu\mu} = 0.89 \pm 0.03_{\rm scale} \pm 0.01_{m_t} \pm 0.03_{C,m_c} \pm 0.01_{m_b} \pm 0.002_{\alpha_s} \pm 0.002_{\rm CKM} \pm 0.01_{\rm BR_{sl}}$$
$$= 0.89 \pm 0.05$$

$$\mathcal{B}[3.5,6]_{\mu\mu} = 0.73 \pm 0.04_{\rm scale} \pm 0.01_{m_t} \pm 0.03_{C,m_c} \pm 0.01_{m_b} \pm 0.003_{\alpha_s} \pm 0.002_{\rm CKM} \pm 0.01_{\rm BR_{sl}}$$
$$= 0.73 \pm 0.05$$

$$\mathcal{B}[1,6]_{\mu\mu} = 1.62 \pm 0.07_{\rm scale} \pm 0.02_{m_t} \pm 0.05_{C,m_c} \pm 0.02_{m_b} \pm 0.01_{\alpha_s} \pm 0.005_{\rm CKM} \pm 0.02_{\rm BR_{sl}}$$
$$= 1.62 \pm 0.09$$

- Again total error $\mathcal{O}(5-7\%)$, dominated by scale uncertainty.

H_A

- Results for H_A, integrated over bins in low-q^2 region, in units of 10^{-6}
  - Electron channel

$$H_A[1,3.5]_{ee} = -\,0.103 \pm 0.005$$
$$H_A[3.5,6]_{ee} = +\,0.073 \pm 0.012$$
$$H_A[1,6]_{ee} = -\,0.029 \pm 0.016$$

  - Muon channel

$$H_A[1,3.5]_{\mu\mu} = -\,0.110 \pm 0.005$$
$$H_A[3.5,6]_{\mu\mu} = +\,0.067 \pm 0.012$$
$$H_A[1,6]_{\mu\mu} = -\,0.042 \pm 0.016$$

- Single bins much better behaved than entire low-$\hat{s}$ region, owing to cancellations due to zero crossing

Zero of H_A (FBA)

- Forward-backward asymmetry (or H_A) has a zero in low-q^2 region
- Electron channel

$$(q_0^2)_{ee} = (3.46 \pm 0.10_{\text{scale}} \pm 0.001_{m_t} \pm 0.02_{C,m_c} \pm 0.06_{m_b} \pm 0.02_{\alpha_s})\ \text{GeV}^2$$
$$= (3.46 \pm 0.11)\ \text{GeV}^2$$

- Muon channel

$$(q_0^2)_{\mu\mu} = (3.58 \pm 0.10_{\text{scale}} \pm 0.001_{m_t} \pm 0.02_{C,m_c} \pm 0.06_{m_b} \pm 0.02_{\alpha_s})\ \text{GeV}^2$$
$$= (3.58 \pm 0.12)\ \text{GeV}^2$$

High-q^2 region

- Branching ratio, integrated over high-q^2 region, in units of 10^{-7}
  - Electron channel

$$
\begin{aligned}
\mathcal{B}[>14.4]_{ee} =& 2.20 \pm 0.30_{\text{scale}} \pm 0.03_{m_t} \pm 0.06_{C,m_c} \pm 0.16_{m_b} \pm 0.003_{\alpha_s} \pm 0.01_{\text{CKM}} \pm 0.03_{\text{BR}_{\text{sl}}} \\
& \pm 0.12_{\lambda_2} \pm 0.48_{\rho_1} \pm 0.36_{f_s} \pm 0.05_{f_u} \\
=& 2.20 \pm 0.70
\end{aligned}
$$

  - Muon channel

$$
\begin{aligned}
\mathcal{B}[>14.4]_{\mu\mu} =& 2.53 \pm 0.29_{\text{scale}} \pm 0.03_{m_t} \pm 0.07_{C,m_c} \pm 0.18_{m_b} \pm 0.003_{\alpha_s} \pm 0.01_{\text{CKM}} \pm 0.03_{\text{BR}_{\text{sl}}} \\
& \pm 0.12_{\lambda_2} \pm 0.48_{\rho_1} \pm 0.36_{f_s} \pm 0.05_{f_u} \\
=& 2.53 \pm 0.70
\end{aligned}
$$

- Total error $\mathcal{O}(30\%)$
- Significantly lower values compared to earlier works [Greub,Pilipp,Schüpbach'08]
  - Main reaons: Power corrections, QED corrections, different q^2_{min}
  - To lesser extend: Input parameters, normalisation
  - Perfect agreement if we switch to prescription by Greub et. al.

High-q^2 region

- Ratio $\mathcal{R}(q^2_{\rm min})$, integrated over high-$q^2$ region, in units of 10^{-3}
  - Electron channel

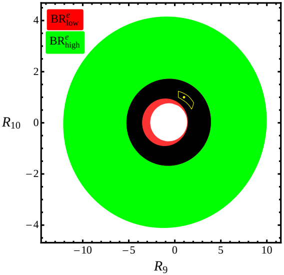
$$
\begin{aligned}
\mathcal{R}(14.4)_{ee} =& 2.25 \pm 0.12_{\rm scale} \pm 0.03_{m_t} \pm 0.02_{C,m_c} \pm 0.01_{m_b} \pm 0.01_{\alpha_s} \pm 0.20_{\rm CKM} \\
& \pm 0.02_{\lambda_2} \pm 0.14_{\rho_1} \pm 0.08_{f_u^0+f_s} \pm 0.12_{f_u^0-f_s} \\
=& 2.25 \pm 0.31
\end{aligned}
$$

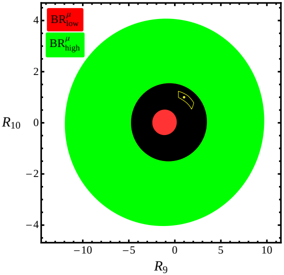
  - Muon channel

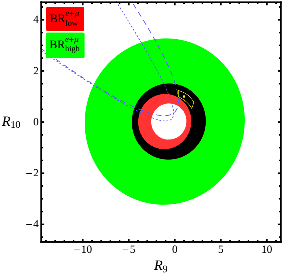
$$
\begin{aligned}
\mathcal{R}(14.4)_{\mu\mu} =& 2.62 \pm 0.09_{\rm scale} \pm 0.03_{m_t} \pm 0.01_{C,m_c} \pm 0.01_{m_b} \pm 0.01_{\alpha_s} \pm 0.23_{\rm CKM} \\
& \pm 0.0002_{\lambda_2} \pm 0.09_{\rho_1} \pm 0.04_{f_u^0+f_s} \pm 0.12_{f_u^0-f_s} \\
=& 2.62 \pm 0.30
\end{aligned}
$$

- Total error $\mathcal{O}(10-15\%)$.
  - Uncertainties due to power corrections significantly reduced
  - Largest source of error are CKM elements (V_{ub})

- Model-independent constraints on high-scale WCs





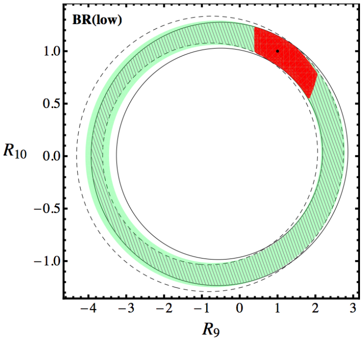


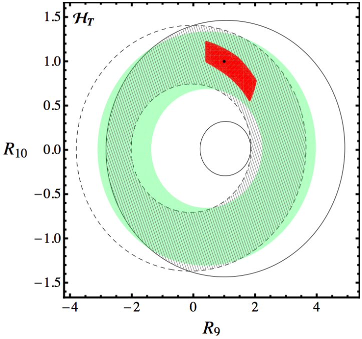
[Hurth,Lunghi,TH'15 [1503.04849]]

Inclusive $\bar{B} \to X_s \ell^+ \ell^-$

[Hurth,Lunghi,TH'15 [1503.04849]]

- Model-independent constraints on high-scale WCs
- Extrapolation to the full Belle-II statistics (50 ab^{-1})

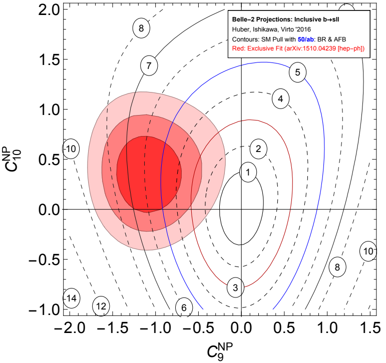




Inclusive vs. exclusive $b \to s\ell^+\ell^-$

[Ishikawa,Virto,TH w.i.p., preliminary]

- If the *true* values for the NP contributions are $C_9^{\rm NP}$ and $C_{10}^{\rm NP}$, with which significance will the Belle II measurements exclude the SM ($C_9^{\rm NP} = C_{10}^{\rm NP} = 0$)?
- For each point ($C_9^{\rm NP}$, $C_{10}^{\rm NP}$), we consider hypothetical measurements of *BR* and $A_{\rm FB}$, with central values given by the theory predictions at the corresponding NP point, and errors given by the experimental sensitivity study plus an extra 5% to account for non-perturbative effects[Hurth,Fickinger,Turczyk,Benzke'17].
- Complementarity study: We also consider the one-, two-, and three-sigma regions obtained from the current global fit, which is dominated by the *exclusive* $b \to s\mu\mu$ measurements at LHCb (red regions).

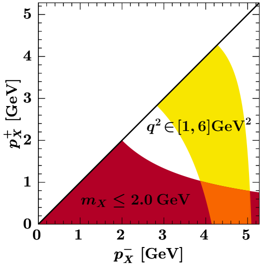


[See also Hurth,Mahmoudi'13; Hurth,Mahmoudi,Neshatpour'14]

Cuts on M_{X_s}

- The suppression of background from $b \to c\ (\to s\ell\nu)\ \ell\nu$ requires a cut on M_{X_s}. Have $M_{X_s} < 1.8\ (2.0)$ GeV at BaBar (Belle).
- Usually taken into account on experimental side
- This puts kinematics at low-q^2 into the shape function region

  $\Rightarrow$ SCET applicable, define
  $p_X^{\pm} = E_X \mp |\vec{p}_X|$ [Lee,Ligeti,Stewart,Tackmann'06]
- High-q^2 region hardly affected by the cut



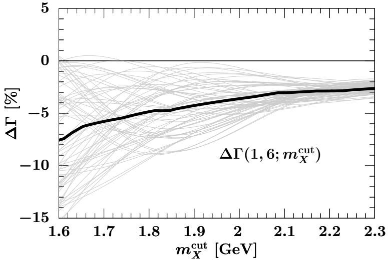
Cuts on M_{X_s}

- Compute non-perturbative corrections of leading and subleading order in $\Lambda_{\rm QCD}/m_b$ [Lee,Tackmann'08]

- Use different models for subleading SF

- Effect on H_i and Γ is ~ -5 to -10%

- Shift of zero of FBA is ~ -0.05 to -0.10 GeV^2



- Add NNLO QCD-corrections to heavy-light currents in shape function region [Bell,Beneke,Li,TH'10]

- Zero of FBA

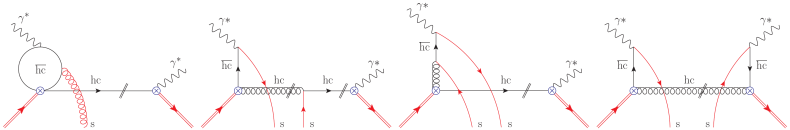
$$q_0^2 = \left[(3.34 \ldots 3.40)^{+0.22}_{-0.25}\right] \,\text{GeV}^2 \qquad \text{for} \qquad m_X^{\rm cut} = (2.0 \ldots 1.8)\,\text{GeV}$$

  - In same region as inclusive result
  - Significantly smaller than exclusive result [Beneke,Feldmann,Seide'01]

Cuts on M_{X_s}

[Hurth,Fickinger,Turczyk,Benzke'17]

- Recent analysis of factorization to subleading power in $\bar{B} \to X_s \ell^+ \ell^-$ in presence of a cut on M_{X_s}
- Systematic analysis of resolved power corrections at $\mathcal{O}(1/m_b)$
- Compute so-called resolved contributions, explore numerical impact



- Numerical impact

$$\mathcal{F}_{17} \in [-0.5, +3.4]\,\%, \quad \mathcal{F}_{78} \in [-0.2, -0.1]\,\%, \quad \mathcal{F}_{88} \in [0, 0.5]\,\%$$

(normalized to OPE result)

$$\mathcal{F}_{1/m_b} \in [-0.7, +3.8]$$

$$\mathcal{F}_{19}: \quad O(1/m_b^2) \text{ but } |C_{9/10}| \sim 13|C_{7\gamma}|$$

- Resolved contributions stay nonlocal when the hadronic mass cut is released
  - Represents irreducible uncertainty independent of the hadronic mass cut

Inclusive $\bar{B} \to X_s \ell^+ \ell^-$ and $\bar{B} \to X_d \ell^+ \ell^-$

[Qin,Vos,TH w.i.p. and Hurth,Jenkins,Lunghi,Qin,Vos,TH w.i.p.]

- Further improvements in $\bar{B} \to X_s \ell^+ \ell^-$
  - Update inclusion of charm resonances:
    Replace Krüger-Sehgal functions by fit to latest BES-III data
- In $\bar{B} \to X_d \ell^+ \ell^-$ transitions, sides of UT are democratic in size (all $\propto \lambda^3$)
  - Expect measurable CP asymmetries in this channel
  - Latest theory prediction from 2003 [Asatrian,Bieri,Greub,Walker'03]
  - Update in progress
    - Inclusion of matrix elements of $\mathcal{O}^u_{1/2}$
    - Inclusion of new perturbative corrections (especially log-enhanced QED)
    - Inclusion of all available power corrections
    - Inclusion of 5-body contribution of type $b \to d\, q\bar{q}\, \ell^+ \ell^-$ [Qin,Vos,TH w.i.p.]
    - Inclusion of effects from $u\bar{u}$ resonances

Conclusion

- Two-body nonleptonic B decays have entered era of precision physics
  - Many sophisticated approaches
  - BRs and direct CP asymmetries for charmless two-body decays at NNLO in QCDF almost complete
    - Perturbative series under control, but sizable uncertainties due to unknown power corrections
  - Heavy-light final states allow to test factorization approach
  - Also QCDF analysis of three-body decays under study
- Inclusive $\bar{B} \to X_s \ell^+ \ell^-$ is an unsung hero
  - Complementarity to $\bar{B} \to X_s \gamma$ and $\bar{B} \to K^{(*)} \mu^+ \mu^-$ can help in the search for NP
  - Complete phenomenological analysis to NNLO QCD + NLO QED for all angular observables
    - Careful investigation of treatment of energetic collinear photons
    - Most observables have parametric + perturbative errors of $\mathcal{O}(5 - 10\%)$
  - Also $\bar{B} \to X_d \ell^+ \ell^-$ under study ($\longrightarrow$ CP observables)

Backup slides

Some definitions

$$A_{\pi\pi} = i\,\frac{G_F}{\sqrt{2}}\, m_B^2 F_+^{B\to\pi}(0) f_\pi$$

$$r_{\rm sp} = \frac{9 f_\pi \hat{f}_B}{m_b \lambda_B F_+^{B\to\pi}(0)}$$

$$\lambda_B^{-1} = \int_0^\infty \frac{d\omega}{\omega}\,\phi_B(\omega,\mu)$$

Results: Direct CP asymmetries III

- Direct CP asymmetries in percent

f	NLO	NNLO	NNLO + LD	Exp
$\rho^- \bar{K}^0$	$0.38\,^{+0.07\,+0.16}_{-0.07\,-0.27}$	$0.22\,^{+0.04\,+0.19}_{-0.04\,-0.17}$	$0.30\,^{+0.06\,+2.28}_{-0.06\,-2.39}$	-12 ± 17
$\rho^0 K^-$	$-19.31\,^{+3.42\,+13.95}_{-3.61\,-\;\,8.96}$	$-4.17\,^{+0.75\,+19.26}_{-0.80\,-19.52}$	$43.73\,^{+7.07\,+\;\,44.00}_{-7.62\,-137.77}$	37 ± 11
$\rho^+ K^-$	$-5.13\,^{+0.95\,+6.38}_{-0.97\,-4.02}$	$1.50\,^{+0.29\,+\;\,8.69}_{-0.27\,-10.36}$	$25.93\,^{+4.43\,+25.40}_{-4.90\,-75.63}$	20 ± 11
$\rho^0 \bar{K}^0$	$8.63\,^{+1.59\,+2.31}_{-1.65\,-1.69}$	$8.99\,^{+1.66\,+3.60}_{-1.71\,-7.44}$	$-\;0.42\,^{+0.08\,+19.49}_{-0.08\,-\;\,8.78}$	6 ± 20
$\delta(\rho\bar{K})$	$-14.17\,^{+2.80\,+7.98}_{-2.96\,-5.39}$	$-5.67\,^{+0.96\,+10.86}_{-1.01\,\;\,-9.79}$	$17.80\,^{+3.15\,+19.51}_{-3.01\,-62.44}$	17 ± 16
$\Delta(\rho\bar{K})$	$-8.75\,^{+1.62\,+4.78}_{-1.66\,-6.48}$	$-10.84\,^{+1.98\,+11.67}_{-2.09\,-\;\,9.09}$	$-\;2.43\,^{+0.46\,+\;\,4.60}_{-0.42\,-19.43}$	-37 ± 37