Two-body charmless decays in QCD Factorisation: status and prospects

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Based on

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Outline

- Introduction
- Theory approaches to charmless non-leptonic *B*-decays
- Status of two-body charmless decays in QCD Factorisation
- Prospects
- Conclusion

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

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; . . .]

- 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]

Theory approaches

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:

  - Recently: factorization-assisted topological-amplitude approach (FAT)

    [Li,Lü,Yu'12; Li,Lü,Qin,Yu'13; Wang,Zhang,Li,Lü'17]

  - Many more analysis

  [Descotes-Genon,Matias,Virto'06; Ciuchini,Silvestrini et al.; Datta,London,Imbeault'03,'12]
  [Fleischer'99+; Fleischer,Jaarsma,Vos'16-'18; Nandi,Soni'10; . . .]

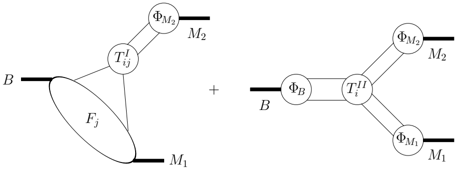
  $\rightarrow$ See also Jaarsma's talk later this session

Theory approaches

More theory approaches

- 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]
  - Also Flavour-symmetry analyses
    [e.g. Bhattacharya,Gronau,Imbeault,London,Rosner'14; Bhattacharya,London'15]
  - Important for phenomenology
    $\rightarrow$ see talks by Bhattacharya and Magalhães in WG 5 on Tue

QCD factorisation



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

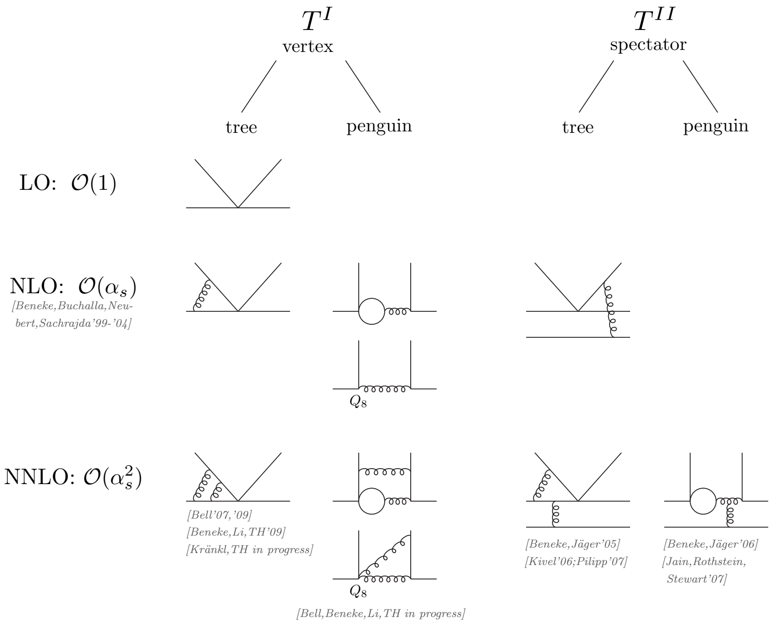
$$\langle M_1 M_2 | Q_i | \bar{B} \rangle \simeq m_B^2 \, F_+^{B\to M_1}(0) \, f_{M_2} \int_0^1 du \;\; T_i^I(u) \, \phi_{M_2}(u)$$
$$+ f_B \, f_{M_1} \, f_{M_2} \int_0^1 d\omega dv du \;\; T_i^{II}(\omega, v, u) \, \phi_B(\omega) \, \phi_{M_1}(v) \, \phi_{M_2}(u)$$

- $T^{I,II}$: 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

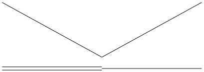
- Strong phases are $\mathcal{O}(\alpha_s)$ and/or $\mathcal{O}(\Lambda_{\mathrm{QCD}}/m_b)$

Anatomy of QCD factorisation

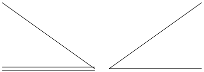


Classification of amplitudes

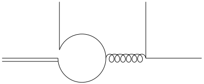
- α_1 : colour-allowed tree amplitude



- α_2 : colour-suppressed tree amplitude



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



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

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

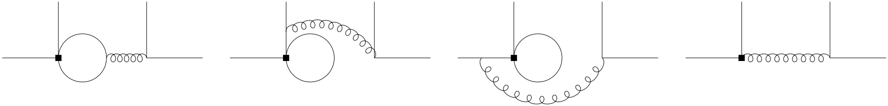
[Beneke,Neubert'03]

- 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:



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

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

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

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

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

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

Motivation for NNLO

- Direct CP asymmetries start at $\mathcal{O}(\alpha_s)$
  - Large (scale) uncertainties
  - NNLO is only first perturbative correction
  - NNLO is NLO for direct CP asymmetries!

- NLO results for tree amplitudes

$$\alpha_1(\pi\pi) = 1.009 + [0.023 + 0.010\, i]_{\rm NLO} - \left[\frac{r_{\rm sp}}{0.445}\right] \left\{[0.014]_{\rm LOsp} + [0.008]_{\rm tw3}\right\} = 1.010 + 0.010 i$$

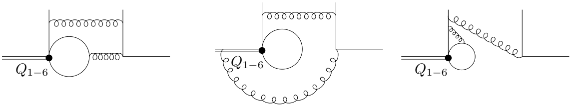
$$\alpha_2(\pi\pi) = 0.220 - [0.179 + 0.077\, i]_{\rm NLO} + \left[\frac{r_{\rm sp}}{0.445}\right] \left\{[0.114]_{\rm LOsp} + [0.067]_{\rm tw3}\right\} = 0.222 - 0.077 i$$

  - Large cancellation in LO + NLO in α_2. Particularly sensitive to NNLO

- Problems with colour-suppressed, tree-dominated decays (e.g. $\bar{B}^0 \to \pi^0\pi^0$)
  - However: Recent prelim. result by Belle: $\mathcal{B}(\bar{B}^0 \to \pi^0\pi^0) = (0.90 \pm 0.16) \cdot 10^{-6}$
- Does factorisation hold at NNLO?

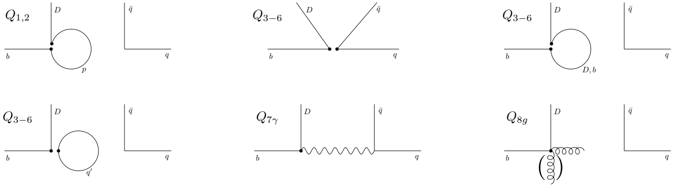
Penguin amplitudes at two loops

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



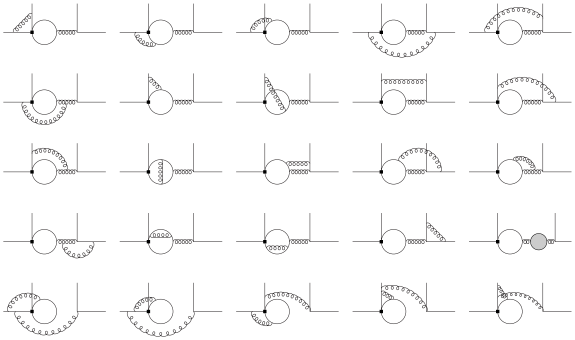
[Kim,Yoon'11]

- Quite some book-keeping due to various insertions



Penguin amplitudes at two loops

- For $Q_{1,2}^{u,c}$ only a subset of $\sim$ 25 diagrams contributes



- Technical diffculties:
  - 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

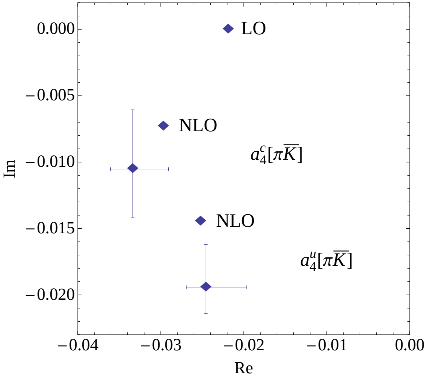
- Only $Q_{1,2}$ contribution. Inputs from [Beneke,Li,TH'09]

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

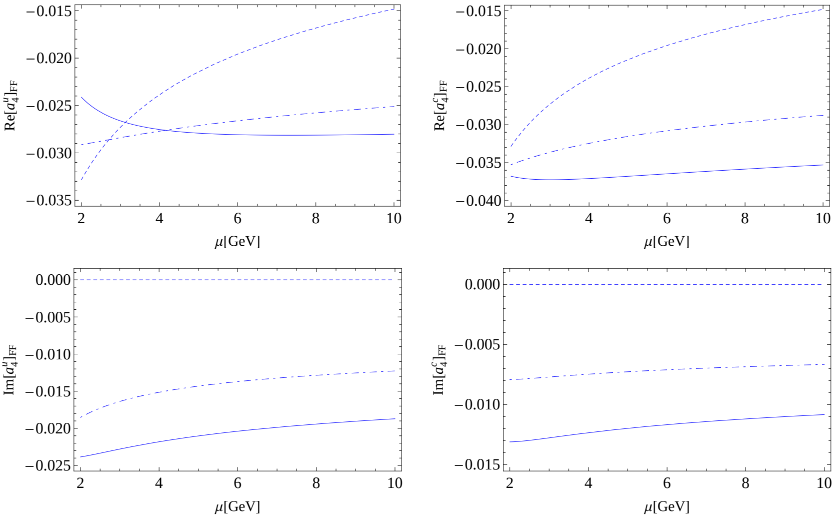
$$\begin{aligned} a_4^c(\pi\bar{K})/10^{-2} &= -2.87 - [0.09 + 0.09i]_{\mathrm{V}_1} + [0.05 - 0.62i]_{\mathrm{P}_1} - [0.77 + 0.50i]_{\mathrm{P}_2} \\ &\quad + \left[\frac{r_{\mathrm{sp}}}{0.434}\right]\left\{[0.13]_{\mathrm{LO}} + [0.14 + 0.12i]_{\mathrm{HV}} + [0.01 + 0.03i]_{\mathrm{HP}} + [0.07]_{\mathrm{tw3}}\right\}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

- NNLO correction sizable, but no breakdown of perturbative expansion

Results: Penguin Amplitudes



Results: Scale dependence



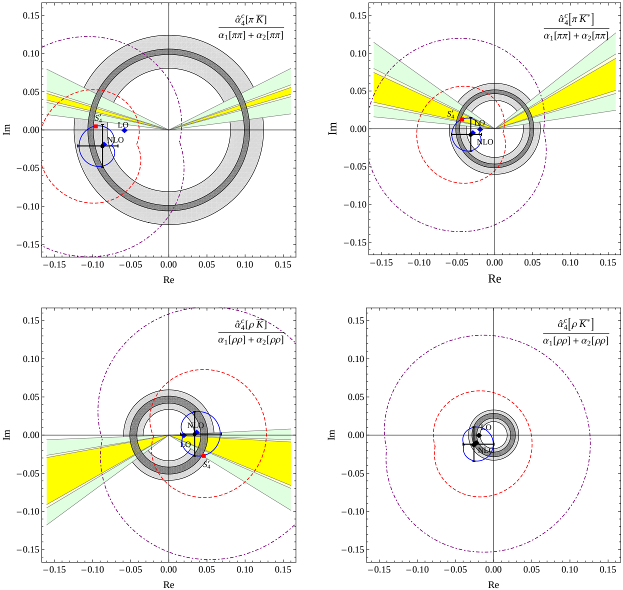
- Only form factor term, no spectator scattering

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

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

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

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	$23.79\,^{+0.75}_{-0.75}$
$B^- \to \pi^0K^-$	$9.57\,^{+0.79}_{-0.74}\,^{+5.00}_{-3.50}\,^{+0.18}_{-0.39}\,^{+7.15}_{-3.01}$	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

Prospects I

- Perturbative QCD corrections
  - Compute scalar penguin amplitude a_6 to NNLO
    - Power-suppressed, but chirally enhanced contribution
    - Factorises at NLO

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

$$r_\chi^\pi = \frac{2 m_\pi^2}{m_b(\mu)\, 2 m_q(\mu)}\,, \qquad r_\chi^K = \frac{2 m_K^2}{m_b(\mu)\,(m_q + m_s)(\mu)}\,, \qquad m_q = (m_u + m_d)/2$$

- QED corrections
  - Relevant for observables that are sensitive to isospin-violating effects
  - Formulation of factorisation theorem not straightforward

- Make connection to QCDF in three-body decays
  - New nonperturbative input: $B \to \pi\pi$ FF, 2πLCDA
  - Would benefit from $\bar{B}^0 \to D^+(\pi\pi)^-$ data!

Prospects II

- Power corrections
  - Were argued to be small based on NLO analysis of $\bar{B}^0 \to D^+\pi^-$ [BBNS'00]
    - NNLO analysis gives hints for natural size ($\sim 10 - 15\%$) [Kränkl,Li,TH'16]
  - To date: Parametrisation of the unknown [BBNS'01] or using data [Bobeth,Gorbahn,Vickers'14]
  - Optimal solution: Understanding of power corrections on field-theoretic grounds
    - Complicated, but ideas in this direction exist based on the 'collinear anomaly' [Becher,Neubert'10; Chiu,Jain,Neill,Rothstein'12]
  - Until then: Attempt to combine Flavour-symmetries with QCDF, e.g.

$$
\begin{aligned}
P^{s0} \;=\; & f P^{d0}\Big[1 + (A^d_{KK}/P^{d0})\Big\{\delta\alpha^c_4 - \delta\alpha^c_{4EW}/2 \\
& +\delta\beta^c_3 + 2\delta\beta^c_4 - \delta\beta^c_{3EW}/2 - \delta\beta^c_{4EW}\Big\}\Big]
\end{aligned}
$$

[Descotes-Genon,Matias,Virto'06]

- Aim for comprehensive analysis for all channels and observables

Conclusion and Outlook

- QCDF at leading power and NNLO QCD is established and almost complete
- Yet many improvements possible in the future
- Aim at comprehensive pheno analysis and precise predictions for plethora of observables
  - Hope to be able to disentangle perturbative, parametric and hadronic uncertainties from potential (small) NP effects

Backup slides

- Topological tree amplitudes at NNLO [Beneke,Li,TH '09]

$$\alpha_1(\pi\pi) = 1.009 + [0.023 + 0.010\,i]_{\rm NLO} + [0.026 + 0.028\,i]_{\rm NNLO} - \left[\frac{r_{\rm sp}}{0.445}\right]\left\{[0.014]_{\rm LOsp} + [0.034 + 0.027\,i]_{\rm NLOsp} + [0.008]_{\rm tw3}\right\} = 1.000^{+0.029}_{-0.069} + (0.011^{+0.023}_{-0.050})\,i$$

$$r_{\rm sp} = \frac{9 f_{M_1} \hat{f}_B}{m_b \lambda_B f_+^{B\pi}(0)}$$

$$\alpha_2(\pi\pi) = 0.220 - [0.179 + 0.077\,i]_{\rm NLO} - [0.031 + 0.050\,i]_{\rm NNLO} + \left[\frac{r_{\rm sp}}{0.445}\right]\left\{[0.114]_{\rm LOsp} + [0.049 + 0.051\,i]_{\rm NLOsp} + [0.067]_{\rm tw3}\right\} = 0.240^{+0.217}_{-0.125} + (-0.077^{+0.115}_{-0.078})\,i$$

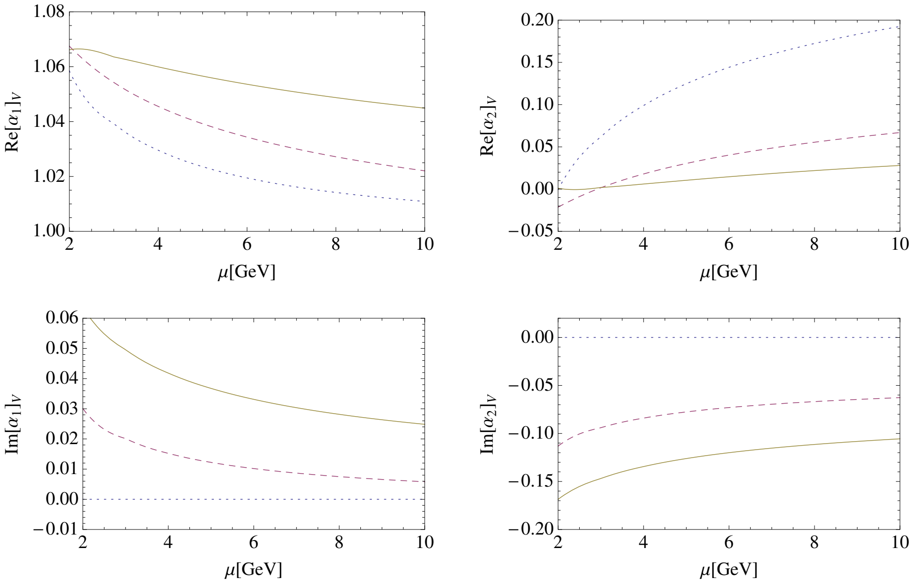
- In agreement with G. Bell [Bell'09]

- NNLO corrections to vertex and spectator terms significant but tend to cancel! ☹

Renormalization scale dependence

- Only vertex correction, no spectator scattering

[Beneke,Li,TH '09]



Some definitions

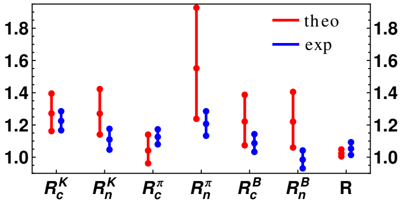
$$A_{\pi\pi} = i\,\frac{G_F}{\sqrt{2}}\,m_B^2 F_+^{B\to\pi}(0) f_\pi$$

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

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

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

$$\Delta A_{\rm CP}^{0}(\pi K) = A_{\rm CP}(B^- \to \pi^- \bar{K}^0) - A_{\rm CP}(\bar{B}^0 \to \pi^0 \bar{K}^0)$$



Results: Direct CP asymmetries III

- Direct CP asymmetries in percent

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

More on theory approaches to nonleptonic B-decays

- Perturbative QCD (PQCD) approach based on k_T-factorisation

  [see e.g. Keum,Li,Sanda'01]

  - Factorises amplitudes according to

    $$A(B \to M_1 M_2) = \phi_B \otimes H \otimes J \otimes S \otimes \phi_{M_1} \otimes \phi_{M_2}$$

  - Generates larger strong phases. Avoids endpoint divergences.
  - However: Organises amplitude differently
  - Introduces additional infrared prescriptions, e.g. exponentiation of Sudakov logs, phenomenological model for transverse momentum effects
  - Discussion of theoretical uncertainties difficult, since no complete NLO ($\mathcal{O}(\alpha_s^2)$) analysis available
  - Independent information on hadronic input functions not available