Polarization fractions and helicity-dependent CP asymmetries in $B_{(s)} \to \rho\rho, \rho K^*$ and $K^* K^*$ decays

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Outline

1. Motivation

2. The perturbative QCD approach
   - Three scale factorization
   - two-body hadronic B decay amplituide
   - Progresses towards to NLO

3. $B_{(s)} \to \rho\rho, \rho K^*$ and $K^* K^*$ revisited
   - Anatomy of the branching fractions
   - Anatomy of the polarization fractions
   - Anatomy of the CP asymmetries

4. Conclusion

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4. Conclusion

Motivation

- **Recent LHCb results** :
  - $f_L(B^0 \to K^{*0}\bar{K}^{*0}) = (60.0 \pm 2.2 \pm 1.7)\%$ PRD113,092002
    $f_L(B_s^0 \to K^{*0}\bar{K}^{*0}) = (15.9 \pm 1.0 \pm 0.7)\%$– anomalously small!

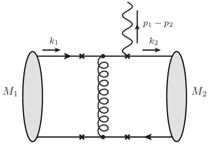
    $f_L(B^+ \to \rho^0 K^{*+}) = (72.0 \pm 2.8 \pm 0.9)\%$ PRL136,021803

  - First observation of CP violation in $B^+ \to \rho^0 K^{*+}$ with 9 σ :
    $A_{CP} = (50.7 \pm 6.4)\%$
    $A_0^{CP}(B^+ \to \rho^0 K^{*+}) = (66.4 \pm 8.4)\%$ – longitudinally dominated
- **Polarization puzzle**: naive factorization predicts $f_L \approx 1$, but experiments show f_L ranges from $\sim 10\%$ to near 100%
- **U-spin ratio**: $f_0(B^0)/f_0(B_s^0) = 3.77 \pm 0.42$ vs. theory ~ 1.1
  $\to > 6\sigma$ tension! highlights the importance role of nonfactorizable contributions
- $B \to VV$ decays: three helicity amplitudes $A_0, A_\parallel, A_\perp$
  $\to$ richer observables: polarization fractions & helicity-dependent CP asymmetries

Outline

Three scale factorization

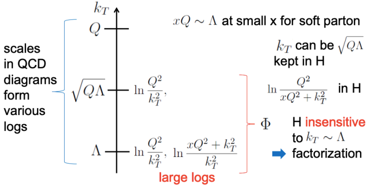
- end-point singularities appear in exclusive QCD processes
  $m^2_{1,2} \ll Q^2$, light-cone coordinate $p_1 = (\frac{Q}{\sqrt{2}}, 0, 0_{\mathrm{T}})$, $p_2 = (0, \frac{Q}{\sqrt{2}}, 0_{\mathrm{T}})$,
  (anti-)valence quarks: $k_1 = x_1 p_1, \bar{k}_1 = \bar{x}_1 p_1$



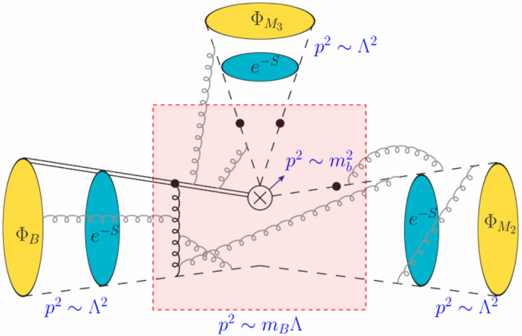
$\phi \propto u(1-u), \quad m_0^{\pi} \phi^{P,\sigma} \propto 1$

$\propto \sum_t \int du_1\, du_2\, \kappa_t(u_i) \frac{\alpha_s(\mu)\phi_1^t(u_1)\phi_2^t(u_2)}{(u_1 u_2 Q^2)(u_2 Q^2)}$

- pick up k_T in the internal propagators
  $\mathcal{M} \propto \sum_{t=2,3,4} \int du_1\, du_2\, dk_{1\,T} dk_{2\,T} K_t(u_i) \frac{\alpha_s(\mu)\phi_1^t(u_1)\phi_2^t(u_2)}{[u_1 u_2 Q^2 - (\Delta k_T)^2][u_2 Q^2 - k^2_{2\,T}]}$
- end-point singularity at leading and subleading powers
  $\mathcal{H} \propto \frac{\alpha_s(\mu)}{u_1 u_2 Q^2 - k_T^2} \sim \frac{\alpha_s(\mu)}{u_1 u_2 Q^2} - \frac{\alpha_s(\mu) k_T^2}{(u_1 u_2 Q^2)^2} + \cdots$
- k_T Factorization Soft+colinear divergence appears double logarithmic term $\alpha_s ln^2(Q/k_T)$



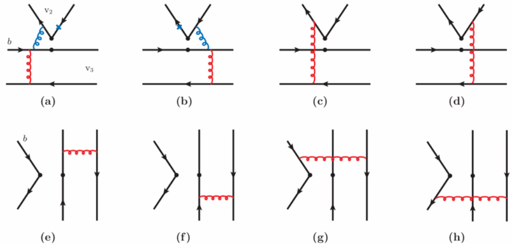
two-body hadronic B decay amplituide



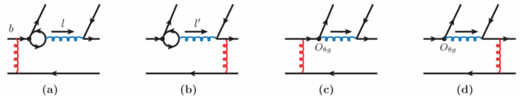
$$\mathcal{M}(B \to M_2 M_3) = H_r(M_W, t_f) \otimes H(t_f, \mu) \otimes \phi(u, P, b, \mu)$$

$$= \sum_{i=1}^{10} \sum_{t=2}^{3} \prod_{j=1,2,3} C_i(M_W, t_f) \otimes H_i(t_f, b) \otimes \phi_j^t(u, b) \cdot S_{t,j}(u) e^{-s_j(P,b) - \int_{1/b_j}^{t_f} \frac{d\overline{\mu}}{\overline{\mu}} \gamma_\phi(\alpha_s(\overline{\mu}))}.$$

Progresses towards to NLO



Feynman diagrams contributing to $B_{(s)} \to M_2 M_3$ decays at LO and NLO from vertex corrections.



Quark-loop and Chromomagnetic penguin contributions to $B \to M_2 M_3$ decays.

power corrections

‡ 1 spectator-light-quark momentum fraction u_1

‡ 2 the heavy-quark expansion parameter $r_b = m_b/m_B$

Outline

Decay amplitudes for $B \to VV$ can be decomposed into (A_0), $(A_\perp)$ and $(A_\parallel)$ components:

$$\mathcal{M} = \sum_{\lambda=0,\perp,\parallel} \mathcal{M}_\lambda = iA_0 + i\,(\epsilon^*_{2\mathrm{T}} \cdot \epsilon^*_{3\mathrm{T}})\,\frac{A_\parallel}{\sqrt{2}} + \left(\varepsilon_{\mu\nu\rho\sigma}\, n_1^\mu n_2^\nu \epsilon^{*\rho}_{2\mathrm{T}} \epsilon^{*\sigma}_{3\mathrm{T}}\right)\frac{A_\perp}{\sqrt{2}}.$$

Branching fractions:

$$\mathcal{B}_\lambda = \frac{|\vec{p}|}{16\pi m_{B_{(s)}}} \tau_{B_{(s)}} \left[|\mathcal{M}_\lambda(\bar{B}_{(s)} \to f)|^2 + |\mathcal{M}_\lambda(B_{(s)} \to \bar{f})|^2\right],$$

Helicity $(\lambda = 0, \perp, \parallel)$ polarization fractions:

$$f_\lambda = \frac{|\bar{A}_\lambda|^2 + |A_\lambda|^2}{\sum_\lambda \left(|\bar{A}_\lambda|^2 + |A_\lambda|^2\right)}, \qquad f_\lambda^+ = \frac{|A_\lambda|^2}{\sum_\lambda |A_\lambda|^2}, \quad f_\lambda^- = \frac{|\bar{A}_\lambda|^2}{\sum_\lambda |A_\lambda|^2}.$$

Helicity-dependent CP asymmetry of squared magnitudes and phase that takes the difference:

$$\mathcal{A}^\lambda_{\mathrm{CP}} = \frac{|\bar{A}_\lambda|^2 - |A_\lambda|^2}{|A_\lambda|^2 + |\bar{A}_\lambda|^2}, \quad \mathcal{A}_{\mathrm{CP}} = \frac{\sum_\lambda \left(|\bar{A}_\lambda|^2 - |A_\lambda|^2\right)}{\sum_\lambda \left(|A_\lambda|^2 + |\bar{A}_\lambda|^2\right)}, \quad \triangle\mathcal{A}^\lambda_{\mathrm{CP}} = \mathrm{Arg}(\bar{A}_\lambda) - \mathrm{Arg}(A_\lambda).$$

Branching fractions of $B_{(s)} \to \rho\rho, \rho K^*$ and $K^* K^*$ decays. (10^{-6})

Modes	$\mathcal{B}_0$	$\mathcal{B}_\parallel$	$\mathcal{B}_\perp$	$\mathcal{B}$	Data[PDG]
$B^+ \to K^{*+}\bar{K}^{*0}$	0.89	0.10	0.08	$0.66^{+0.15}_{-0.12}$	0.91 ± 0.29
$B^+ \to \rho^0\rho^+$	42.5	0.66	0.68	$14.0^{+4.1}_{-3.1}$	24.0 ± 1.9
$B^+ \to \rho^+ K^{*0}$	11.2	1.91	1.52	$9.40^{+1.70}_{-1.64}$	9.2 ± 1.5
$B^+ \to \rho^0 K^{*+}$	15.6	2.32	1.67	$6.25^{+1.27}_{-1.00}$	4.6 ± 1.1
$B^0 \to K^{*0}\bar{K}^{*0}$	0.44	0.11	0.09	$0.38^{+0.09}_{-0.06}$	0.83 ± 0.24
LHCb [PRD113,092002]					0.47 ± 0.05
$B^0 \to K^{*+}K^{*-}$	0.29	0.0	0.0	$0.17^{+0.05}_{-0.04}$	< 2.0
$B^0 \to \rho^+\rho^-$	36.0	1.26	1.12	$22.7^{+6.3}_{-4.8}$	27.7 ± 1.9
Belle-II [PRD111,092001]					$28.9^{+0.37}_{-0.35}$
$B^0 \to \rho^0\rho^0$	1.48	0.19	0.16	$0.54^{+0.16}_{-0.12}$	0.96 ± 0.15
$B^0 \to \rho^- K^{*+}$	10.3	1.81	1.51	$8.72^{+1.60}_{-1.30}$	10.3 ± 2.6
$B^0 \to \rho^0 K^{*0}$	7.50	1.69	1.37	$3.37^{+0.57}_{-0.49}$	3.9 ± 1.3
$B_s^0 \to K^{*0}\bar{K}^{*0}$	6.46	2.31	1.92	6.17	11.1 ± 2.7
LHCb [PRD113,092002]					9.38 ± 0.48
$B_s^0 \to K^{*+}K^{*-}$	9.59	1.84	1.63	7.55	$---$
$B_s^0 \to \rho^+\rho^-$	2.54	0.0	0.0	1.46	$---$
$B_s^0 \to \rho^0\rho^0$	2.49	0.0	0.0	0.72	< 320
$B_s^0 \to K^{*-}\rho^+$	24.0	0.76	0.69	14.7	$---$
$B_s^0 \to \bar{K}^{*0}\rho^0$	2.15	0.15	0.13	0.71	< 767

Preliminary

Branching fractions of $B_{(s)} \to \rho\rho, \rho K^*$ and $K^* K^*$ decays.

- 1 Longitudinal helicity amplitude provides the dominant contribution across nearly all the decay modes
- 2 Penguin-dominated modes, namely $B \to \rho K^*$ and $B^0_{(s)} \to K^{*0}\bar{K}^{*0}, K^{*+}K^{*-}$,
  Longitudinal component is not expected to be overwhelmingly dominant.
  Perpendicular and parallel polarizations both contribute sizable to the total decay width.
- 3 isospin symmetry

Modes	$\mathcal{B}_0$	$\mathcal{B}_\parallel$	$\mathcal{B}_\perp$	$\mathcal{B}$	Data[PDG]
$B^+ \to \rho^0\rho^+$	42.5	0.66	0.68	$14.0^{+4.1}_{-3.1}$	24.0 ± 1.9
$B^0 \to \rho^+\rho^-$	36.0	1.26	1.12	$22.7^{+6.3}_{-4.8}$	27.7 ± 1.9
Belle-II [PRD111,092001]					$28.9^{+0.37}_{-0.35}$

Preliminary

- 4 long-standing $\pi\pi$ puzzle

$$B^0 \to \pi^0\pi^0 = 0.23^{+0.07+0.01}_{-0.05-0.01}(1.59 \pm 0.26)$$

$$B^0 \to \rho^0\rho^0 = 0.54^{+0.16+0.04}_{-0.11-0.04}(0.96 \pm 0.15)$$

Polarization fractions (10^{-2}) from each helicity amplitude.

Preliminary

Modes	f_0^+	f_0^-	f_0	$f_\parallel^+$	$f_\parallel^-$	$f_\parallel$	$f_\perp^+$	$f_\perp^-$	$f_\perp$
$B^+ \to \rho^0 K^{*+}$	66.3	79.6	$80.0^{+1.5}_{-1.5}$	19.5	7.7	11.83	14.1	5.5	8.51
LHCb [PRL136, 021803]	49.1 ± 8.7	79.4 ± 2.6	72.0 ± 2.9						
HFLAV [PRD113,012008]			78 ± 12						
$B^0 \to K^{*0} \bar{K}^{*0}$	69.0	68.4	$68.8^{+5.3}_{-5.3}$	17.0	17.7	17.25	14.0	14.0	14.0
LHCb [PRD113,092002]			60.0 ± 2.8						
HFLAV [PRD113,012008]			73 ± 5						
$B^0 \to \rho^+ \rho^-$	96.6	90.9	$93.8^{+0.1}_{-0.1}$	1.81	4.79	3.27	1.57	4.30	2.90
Belle-II [PRD111,092001]			92.1 ± 2.9						
$B_s^0 \to K^{*0} \bar{K}^{*0}$	60.3	60.5	60.4	21.6	21.5	21.6	18.0	18.0	18.0
LHCb [PRD113,092002]			15.9 ± 1.2						

The decays $B \to K^{*0} \bar{K}^{*0}$ and $B_s \to K^{*0} \bar{K}^{*0}$ share nearly identical penguin-dominated topological structures. Their primary difference arises from the corresponding CKM matrix elements($d \to s$).

Polarization fractions (10^{-2}) from each helicity amplitude.

Comparison of theoretical predictions with recent LHCb measurements of the longitudinal polarization fraction in $B_s \to K^{*0}\bar{K}^{*0}$ decay and the associated U-spin symmetry ratio relative to the $B \to K^{*0}\bar{K}^{*0}$ channel.

Observables	pQCD	QCDF NPB774,64-101	SCET PRD96,073004	FAT EPJC77,5,333	LHCb PRD9,092001
$f_0 \times 10^2$	$60.4 \pm ...$	63^{+42}_{-29}	44.9 ± 18.3	34.3 ± 12.6	15.9 ± 1.2
$\mathcal{U}$	$1.14 \pm ...$	$1.10 \pm ...$	$1.11 \pm ...$	$1.70 \pm ...$	3.77 ± 0.42

Preliminary

To mitigate common systematic uncertainties, we focus on the U-spin ratio of the longitudinal polarization fractions:

$$\mathcal{U} = \frac{f_0(B^0 \to K^{*0}\bar{K}^{*0})}{f_0(B_s^0 \to K^{*0}\bar{K}^{*0})},$$

- With modest U-spin breaking of order $\mathcal{O}(m_s/\Lambda_{\rm QCD})$, $\mathcal{U}$ is expected to be close to unity.
- In stark contrast, the recent LHCb deviates from unity by more than six standard deviations.

If confirmed by independent measurements, this discrepancy would signal either large non-factorizable spectator contributions, or otherwise point to new physics beyond the Standard Model.

Anatomy of the CP asymmetries (in unit of 10^{-2}) from each helicity amplitude.

Preliminary

Modes	$\mathcal{A}_0^{\mathrm{CP}}$	$\Delta\mathcal{A}_0^{CP}$	$\mathcal{A}_\parallel^{\mathrm{CP}}$	$\Delta\mathcal{A}_\parallel^{CP}$	$\mathcal{A}_\perp^{\mathrm{CP}}$	$\Delta\mathcal{A}_\perp^{CP}$	$\mathcal{A}^{\mathrm{CP}}$
$B^+ \to \rho^0 K^{*+}$	42.23	0.44	−14.57	0.12	−15.11	0.20	$30.6^{+0.5+0.1}_{-0.7-0.2}$
LHCb [PRL136, 021803]	66.4 ± 8.4	0.72 ± 0.18	-6.3 ± 14.0	0.48 ± 0.20	28.4 ± 14.9	0.41 ± 0.22	50.7 ± 6.4
$B^0 \to \rho^+ \rho^-$	−4.89	−2.28	43.67	−2.19	45.10	−2.23	$C = -1.85^{+0.20}_{-0.11}$ $S = -12.7^{+0.4}_{-0.3}$
Belle-II PRD111,092001							$C = -2.00 \pm 13.0$ $S = -26.0 \pm 20.0$

- 1 $B^+ \to \rho^0 K^{*+}$ decay, the pQCD calculation confirms the longitudinally dominated mechanism and reproduces the relatively large CP asymmetries, although a discrepancy of 3σ to 4σ remains.
- 2 In particular, the predicted transverse CP asymmetry for the squared magnitude has the opposite sign to the data.
- 3 The direct and mixing-induced CP asymmetries in $B^0 \to \rho^+\rho^-$ decays are in good agreement with the Belle-II measurements within experimental errors.

Outline

Conclusion

- Performed comprehensive pQCD analysis of $B_{(s)} \to \rho\rho, \rho K^*, K^* K^*$ with all known NLO corrections + HQET power corrections (u_1, r_b)

- **Branching fractions**: broadly consistent with LHCb data
  - $B^0 \to K^{*0} \bar{K}^{*0}$: pQCD 0.38 vs LHCb 0.47 ± 0.05 ✓
  - $B_s^0 \to K^{*0} \bar{K}^{*0}$: pQCD 6.17 vs LHCb 9.38 ± 0.48 ✓

- **Polarization fractions**: two key discrepancies
  - $B_s^0 \to K^{*0} \bar{K}^{*0}$: $f_0 = 60.4\%$ vs LHCb $15.9\% \to \mathcal{U} = 1.14$ vs 3.77 ± 0.42
  - All theories predict $U \approx 1.1$; $> 6\sigma$ tension → "polarization puzzle"

- **CP asymmetries**: pQCD captures qualitative features but underestimates
  - $B^+ \to \rho^0 K^{*+}$: $A_{CP} = 30.6\%$ vs data 50.7%, $A_{CP}^{\perp}$ sign wrong

- These tensions point to non-factorizable dynamics beyond current pQCD, motivating further theoretical and experimental investigation

Thank you for your patience...