Sensitivity to New Physics in $B \to VV$ Polarization

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Extensions of Standard Model (SM) often include opposite chirality operators ($V - A \leftrightarrow V + A$), e.g.,

- QCD Penguin operators

$$\begin{array}{ll} \underline{\text{SM Chirality}} & \underline{\text{Opposite Chirality}} \\ Q_{3,5} = (\bar{s}b)_{V-A}\,(\bar{q}q)_{V\mp A} & \rightarrow \tilde{Q}_{3,5} = (\bar{s}b)_{V+A}\,(\bar{q}q)_{V\pm A} \\ Q_{4,6} = (\bar{s}_i b_j)_{V-A}\,(\bar{q}_j q_i)_{V\mp A} & \rightarrow \tilde{Q}_{4,6} = (\bar{s}_i b_j)_{V+A}\,(\bar{q}_j q_i)_{V\pm A} \end{array}$$

- Chromo/Electromagnetic Dipole Operators

$$Q_{7\gamma} = \frac{e}{8\pi^2} m_b \bar{s}_i \sigma^{\mu\nu}(1+\gamma_5) b_i F_{\mu\nu} \quad \rightarrow \tilde{Q}_{7\gamma} = \frac{e}{8\pi^2} m_b \bar{s}_i \sigma^{\mu\nu}(1-\gamma_5) b_i F_{\mu\nu}$$

$$Q_{8g} = \frac{g_s}{8\pi^2} m_b \bar{s} \sigma^{\mu\nu}(1+\gamma_5) t^a b G^a_{\mu\nu} \quad \rightarrow \tilde{Q}_{8g} = \bar{s} \sigma^{\mu\nu}(1-\gamma_5) t^a b G^a_{\mu\nu}$$

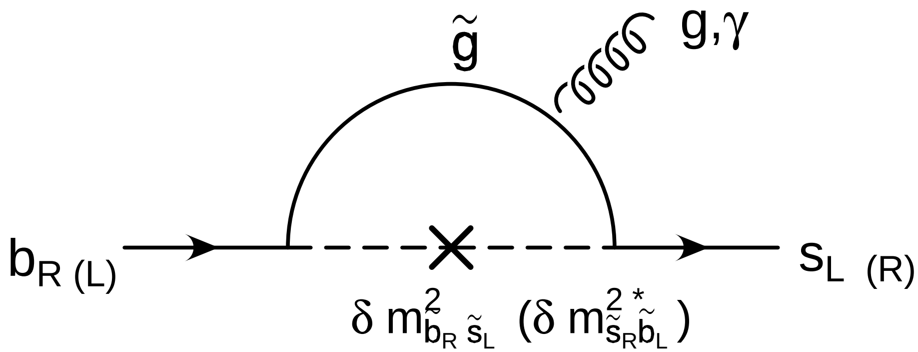
- Electroweak Penguin Operators

$$Q_{7,9} = \frac{3}{2}(\bar{s}b)_{\mathrm{V-A}}\, e_q\, (\bar{q}q)_{\mathrm{V\pm A}} \quad \rightarrow \tilde{Q}_{7,9} = \frac{3}{2}(\bar{s}b)_{\mathrm{V+A}}\, e_q\, (\bar{q}q)_{\mathrm{V\mp A}}$$

$$Q_{8,10} = \frac{3}{2}(\bar{s}_i b_j)_{\mathrm{V-A}}\, e_q\, (\bar{q}_j q_i)_{\mathrm{V\pm A}} \quad \rightarrow \tilde{Q}_{8,10} = \frac{3}{2}(\bar{s}_i b_j)_{\mathrm{V+A}}\, e_q\, (\bar{q}_j q_i)_{\mathrm{V\mp A}}$$

Examples of New Physics

- Loops: squark-gluino exchange



$$\delta m^2_{\tilde{b}_R \tilde{s}_L} \Rightarrow Q_{8g}, \qquad \delta m^2_{\tilde{b}_L \tilde{s}_R} \Rightarrow \tilde{Q}_{8g}$$

$$\delta m^2_{\tilde{b}_L \tilde{s}_L} \Rightarrow Q_{3,..,6}, \qquad \delta m^2_{\tilde{b}_R \tilde{s}_R} \Rightarrow \tilde{Q}_{3,..,6}$$

- Tree-level: Z or Z' exchange

$$Z^{(\prime)} s_L\, b_L \Rightarrow Q_{7,..,10}, \qquad Z^{(\prime)} s_R\, b_R \Rightarrow \tilde{Q}_{7,..,10}$$

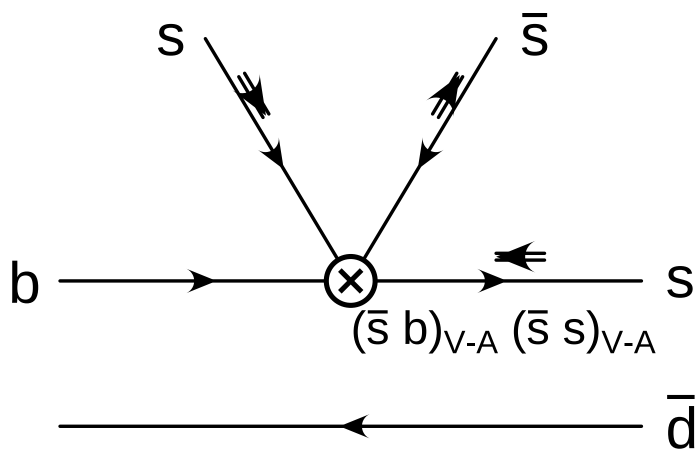
Helicity final states

- Three helicity amplitudes in $\bar{B} \to V_1 V_2$
  - $\mathcal{A}^0$: both vectors helicity h= 0 (longitudinaly polarized)
  - $\mathcal{A}^-$: both vectors helicity h=-1 (transversely polarized)
  - $\mathcal{A}^+$: both vectors helicity h=+1 (transversely polarized)

- Does $V - A$ structure of $b \to s(d)$ transitions in SM imply a helicity amplitude hierarchy, or polarization?

Naive Factorization (NF)

Leading order in α_s, $1/m_b$. Example: $\bar{B} \to \phi K^*$

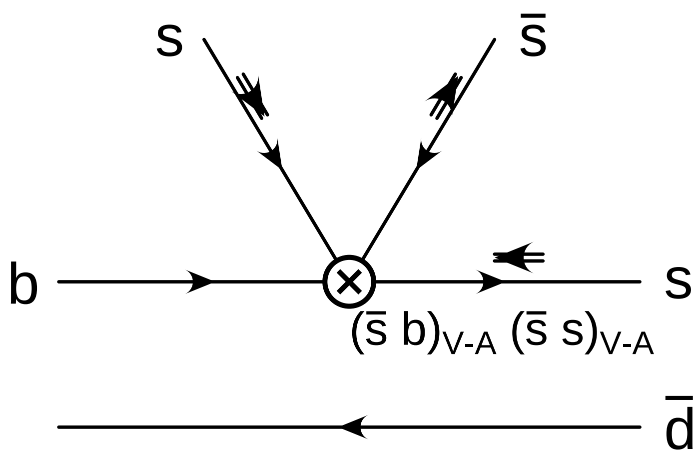


$$\mathcal{A}^h \quad \propto < \phi^h | \bar{s}\gamma^\mu s | 0 > < K^{*\,h} | \bar{s}\gamma_\mu\gamma_5 b | \bar{B} >, \quad h = 0, -, +$$

$$\propto \text{ decay constant} \times \text{form factor}$$

- Quark helicity-flip requires transverse momentum, $k_\perp$

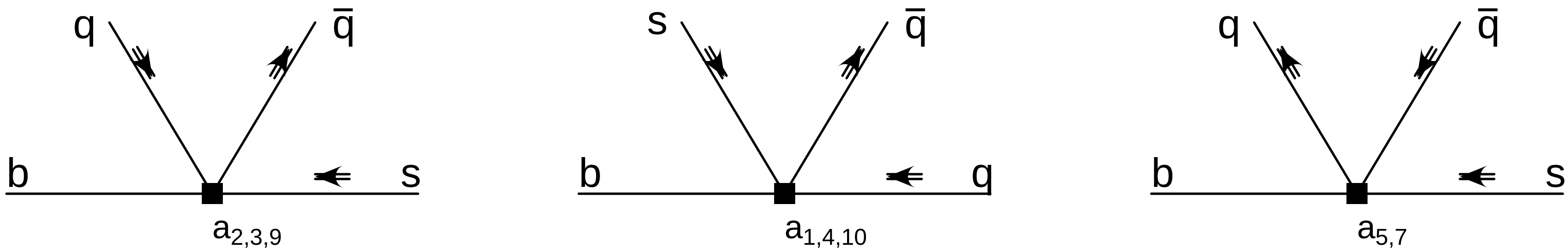
  $\Rightarrow \Lambda_{QCD}/m_b$ suppression



  - $\mathcal{A}^0 = O(1)$, $\mathcal{A}^- = O(1/m)$, $\mathcal{A}^+ = O(1/m^2)$
  - $\mathcal{A}^-/\mathcal{A}^0 = \mathcal{O}(m_\phi/m_B)$, helicity of $\bar{s}$ in ϕ flipped
  - $\mathcal{A}^+/\mathcal{A}^- = \mathcal{O}(\Lambda_{QCD}/m_b)$, helicity of s in K^* flipped

- power counting follows formally from large energy form factor relations of Charles et al

Summary: $\bar{B} \to V_1 V_2$ helicity amplitudes in NF



V_2: two upward lines, V_1: Form factor vector meson

- contributions to the helicity amplitudes, $\mathcal{A}^h(V_1 V_2)$:

$$\mathcal{A}^0(V_1V_2) \;\propto\; f_{V_2}\, m_B^2\, \zeta_{\parallel}^{V_1} = O(1)$$

$$\mathcal{A}^-(V_1V_2) \;\propto\; -2 f_{V_2}\, m_{V_2}\, m_B\, \zeta_{\perp}^{V_1} = O\left(\frac{1}{m}\right)$$

$$\mathcal{A}^+(V_1V_2) \;\propto\; -f_{V_2}\, m_{V_2}\, m_B \;\times O(\zeta_{\perp}^{V_1} \frac{\Lambda_{QCD}}{m_b}) = O\left(\frac{1}{m^2}\right)$$

- $\mathcal{A}^-$: quark helicity-flip costs $1/m$

- $\mathcal{A}^+$: additional helicity-flip $\Longrightarrow$ form factor suppression $1/m$

Transversity Basis

Transverse amplitudes in transversity basis:

$$A_{\perp,\parallel} \equiv (A^- \pm A^+)/\sqrt{2}$$

- In naive factorization, rates satisfy

$$\frac{\Gamma_\perp}{\Gamma_\parallel} = 1 + O\left(\frac{1}{m_b}\right)$$

- Total transverse rate, $\Gamma_T = \Gamma_\perp + \Gamma_\parallel$, satisfies

$$\frac{\Gamma_{\rm T}}{\Gamma_0} = O\left(\frac{1}{m_b^2}\right)$$

- Experimental situation $R_{0,\perp,\parallel} \equiv \Gamma_{0,\perp,\parallel}/\Gamma_{\rm total}$

$$R_0(B^0 \to \phi K^{*0})_{\rm Babar,\, Belle} = 0.58 \pm 0.10, \quad R_0(B^+ \to \phi K^{*+})_{\rm Babar} = 0.46 \pm 0.12$$

$$R_\perp(B^0 \to \phi K^{*0})_{\rm Belle} = 0.41 \pm 0.11, \quad R_\parallel(B^0 \to \phi K^{*0})_{\rm Belle} = .001 \pm 0.15$$

$$R_0(B^+ \to \rho^0 K^{*+})_{\rm Babar} = 0.96 \pm 0.16, \quad R_0(B^+ \to K^{*0}\rho^+) = ?$$

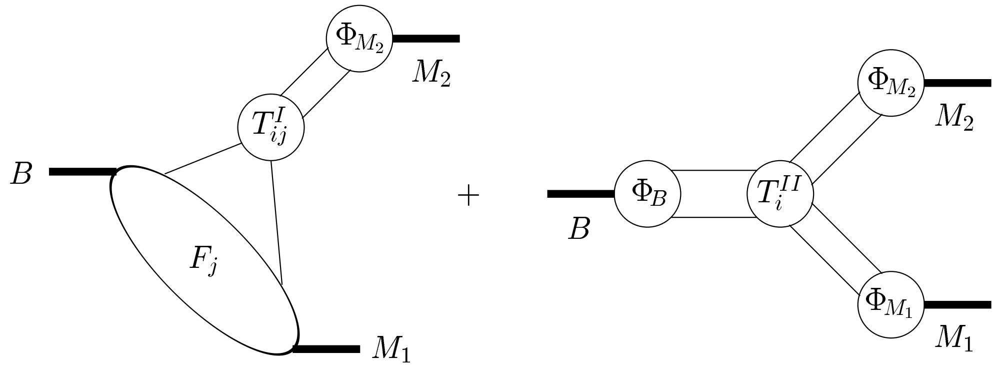
$$R_0(B^+ \to \rho^+\rho^0)_{\rm Babar,\, Belle} = 0.96 \pm 0.06, \quad R_0(B^0 \to \rho^+\rho^-)_{\rm Babar} = 0.99 \pm 0.08$$

- NF power counting $\Rightarrow$ New Physics in $R_0(B \to \phi K^*)$

- Is power counting preserved by non-factorizable graphs? (penguin contractions, vertex corrections, spectator interactions, annihilation graphs)

  Can address in QCD factorization

Non-factorizable amplitudes in QCD factorization (Beneke et al)



- convolutions of short-distance scattering amplitudes with long-distance meson light-cone distribution amplitudes
  - ‘Twist-expansion’ for distributions:

$$\text{Twist}-2 = O(1), \;\; \text{Twist}-3 = O\left(\frac{1}{m_b}\right), \;\; \text{Twist}-4 = O\left(\frac{1}{m_b^2}\right)$$

- Leading power in $1/m_b$, all orders in α_s: amplitudes factorize into calculable short-distance part /long-distance part given in terms of universal non-perturbative parameters

Formal proof in Soft Collinear Effective Theory is near

Subleading powers

- At subleading powers $\leq 1/m_b$

  short / long distance separation breaks down. Certain graphs soft dominated

  - Signaled by infrared log divergence in light cone quark momentum fraction x,

$$\int_0^1 \frac{dx}{x} \sim \ln \frac{m_b}{\Lambda_h}, \quad \text{physical IR cutoff } \Lambda_h \sim \Lambda_{QCD}$$

- Challenge: transverse amplitudes begin at $O(1/m)$

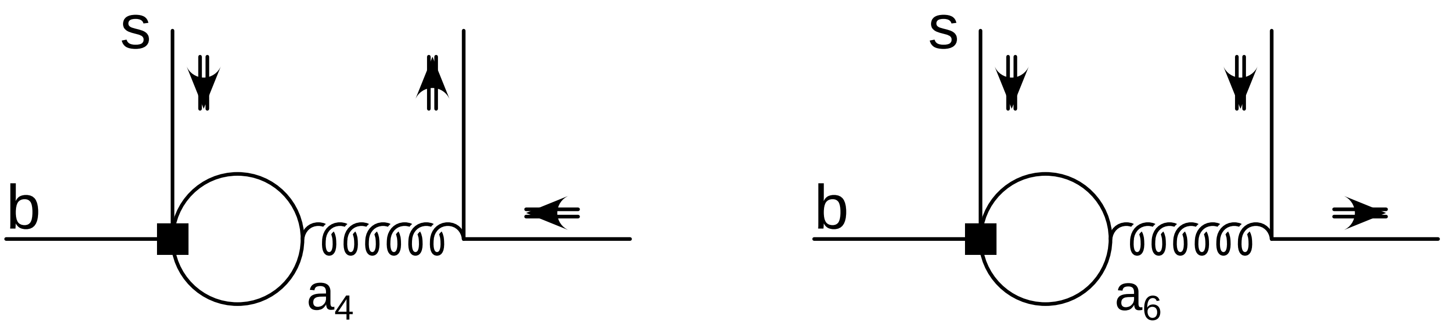
  Can we say anything about polarization? Strategy:

  - parametrize uncertainties for log divergences
  - hope observables not sensitive to them

Power counting for helicity amplitudes in QCD factorization

work to next-to-leading order in α_s

1) Penguin contractions: charm quark, up quark loops

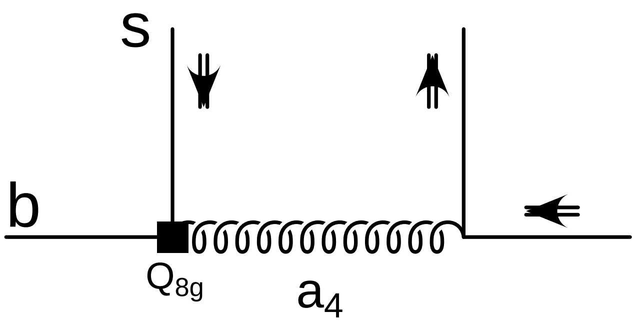


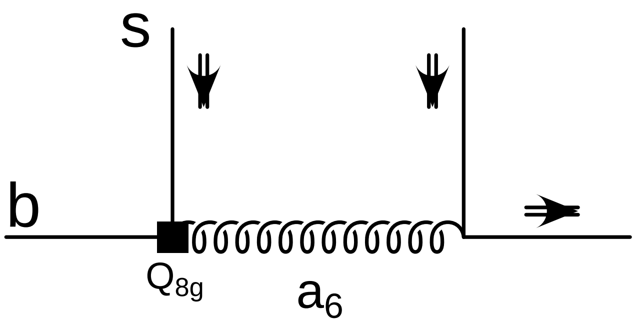
V_2: two upward lines, V_1: Form factor vector meson

	$\mathcal{A}^0$	$\mathcal{A}^-$	$\mathcal{A}^+$
a_4	$O(1)$	$O\left(\frac{1}{m_b}\right)$ twist-3^{V_2}	$O\left(\frac{1}{m_b^2}\right)$ twist-3$^{V_2}\times$ FF^{V_1}
a_6	$O\left(\frac{1}{m_b}\right)$ twist-3^{V_2}	—	—

Each helicity-flip costs $\frac{1}{m}$: one unit of twist or form factor (FF) suppression

2) Penguin contractions: chromomagnetic dipole operator Q_{8g}





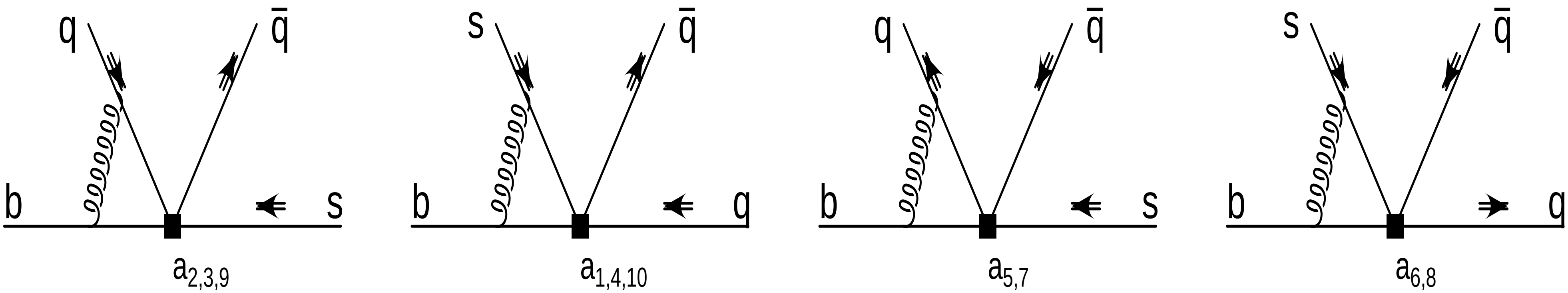
Contribution of a_4^0 to $\mathcal{A}^0$ is $O(1)$. All other contributions vanish!

- Physical reason? would require coupling to longitudinal component of gluon but:

  dipole operator tensor current only couples to transverse component

- Important implications for NEW PHYSICS
  - Anomalies in $S(\phi K_s)$, $S_0(\phi K^*)$, but NO anomaly in $S_{\perp,\parallel}(\phi K^*) \Rightarrow$ new physics in dipole operators.
  - Anomaly in $S_{\perp,\parallel}(\phi K^*) \Rightarrow$ new physics in four-quark operators

3) Vertex corrections:

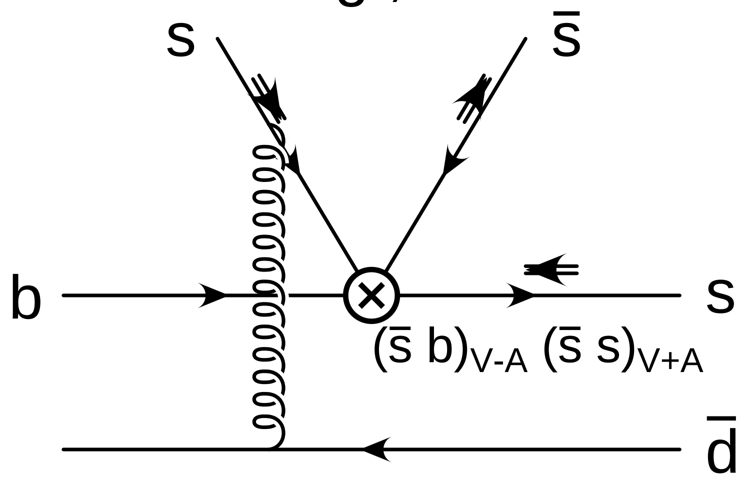


V_2: two upward lines, V_1: Form factor vector meson

	$\mathcal{A}^0$	$\mathcal{A}^-$	$\mathcal{A}^+$
$a_{1,..,4,9,10}$	$O(1)$	$O\left(\frac{1}{m_b}\right)$ twist-3^{V_2}	$O\left(\frac{1}{m_b^2}\right)$ twist-3^{V_2} $\times$ FF^{V_1}
$a_{1,..,4,9,10}$	$O(1)$	$O\left(\frac{1}{m_b}\right)$ twist-3^{V_2}	$O\left(\frac{1}{m_b^2}\right)$ twist-3^{V_2} $\times$ FF^{V_1}
$a_{6,8}$	$O\left(\frac{1}{m_b}\right)$ twist-3^{V_2}	$\leq O\left(\frac{1}{m_b^3}\right)$ twist-4^{V_2} $\times$ FF^{V_1}	$\leq O\left(\frac{1}{m_b^2}\right)$ twist-4^{V_2}

Each helicity-flip costs $\frac{1}{m}$: one unit of twist or FF suppression

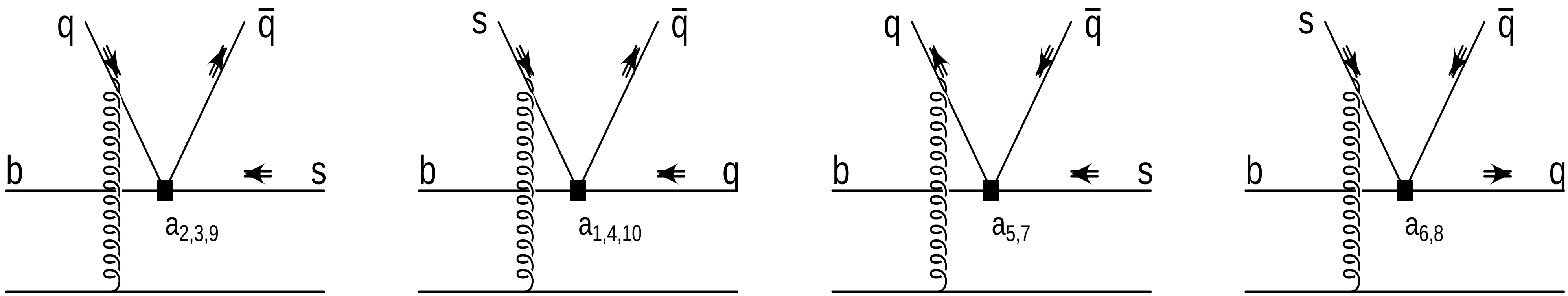
4) Spectator interactions: e.g.,



$$A^0 = O(1), \qquad A^- = O\left(\frac{1}{m}\ln\frac{m}{\Lambda_h}\right), \qquad A^+ = O\left(\frac{1}{m^2}\ln\frac{m}{\Lambda_h}\right)$$

- overall parametric suppression: $\frac{C_F}{N_c^2}\frac{f_B}{m_B\zeta} \approx .02$
- Soft spectator limit in $V_1 \Longrightarrow$ Log divergences

Spectator interaction summary:

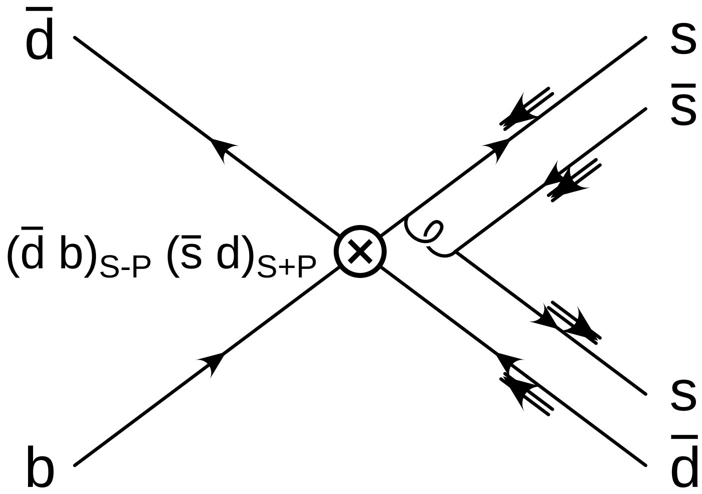


V_2: two upward lines, V_1: Form factor vector meson

	$\mathcal{A}^0$	$\mathcal{A}^-$	$\mathcal{A}^+$
$a_{1,..,4,9,10}$	$O(1)$	$O\left(\frac{1}{m}\ln\frac{m}{\Lambda_h}\right)$ twist-3^{V_2}	$O\left(\frac{1}{m^2}\ln\frac{m}{\Lambda_h}\right)$ twist-3^{V_1} $\times$ twist-3^{V_2}
$a_{5,7}$	$O(1)$	$O\left(\frac{1}{m}\ln\frac{m}{\Lambda_h}\right)$ twist-3^{V_2}	$O\left(\frac{1}{m^2}\ln\frac{m}{\Lambda_h}\right)$ twist-3^{V_1} $\times$ twist-3^{V_2}
$a_{6,8}$	—	$O\left(\frac{1}{m}\ln\frac{m}{\Lambda_h}\right)$ twist-3^{V_1}	$O\left(\frac{1}{m^2}\ln\frac{m}{\Lambda_h}\right)$ twist-4^{V_2}

- Each helicity-flip costs one unit of twist or $\frac{1}{m_b}$

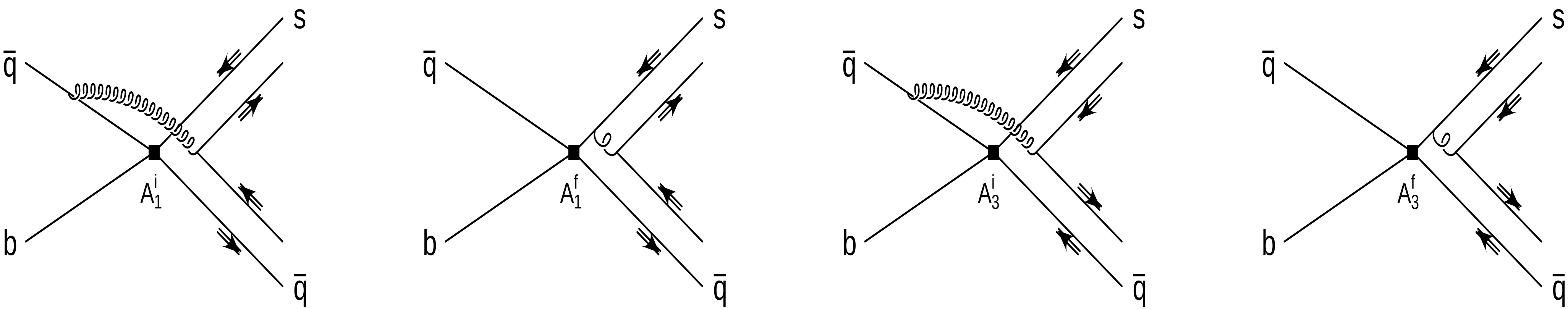
5) Annihilation graphs: e.g., $a_6 < (\bar{d}b)_{S-P} \times (\bar{s}d)_{S+P} >$



$$\mathcal{A}^0,\ \mathcal{A}^- = O\left(\frac{1}{m^2}\ln^2\frac{m}{\Lambda_h}\right), \qquad \mathcal{A}^+ = 0$$

- annihilation topology $\Longrightarrow$ overall $1/m$
- helicity-flips $\Longrightarrow$ rest of $1/m$ factors, or twists:
- overall parametric suppression: $\frac{C_F}{N_c^2}\frac{f_B}{m_B\zeta} \approx .02$

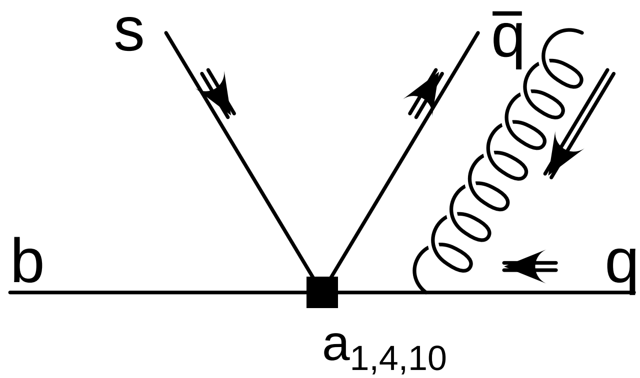
Annihilation summary:



	$\mathcal{A}^0$	$\mathcal{A}^-$	$\mathcal{A}^+$
$A_1^i,\ A_2^i$	$\frac{1}{m}\ln\frac{m}{\Lambda_h}$	$\frac{1}{m^3}$ (lin div) $\sim \frac{1}{m^2}$	$\frac{1}{m^3}\ln^2\frac{m}{\Lambda_h}$
$A_1^f,\ A_2^f$	—	$\frac{1}{m^3}\ln\frac{m}{\Lambda_h}$	$\frac{1}{m^3}\ln\frac{m}{\Lambda_h}$
$A_3^{i,f}$	$\frac{1}{m^2}\ln^2\frac{m}{\Lambda_h}$	$\frac{1}{m^2}\ln^2\frac{m}{\Lambda_h}$	$< \frac{1}{m^3}$
Totals	$\frac{1}{m}\ln\frac{m}{\Lambda_h}$	$\frac{1}{m^2}\ln^2\frac{m}{\Lambda_h}$	$\frac{1}{m^3}\ln\frac{m}{\Lambda_h}$

- NF power counting $(1, \frac{1}{m}, \frac{1}{m^2})$ preserved
- Each helicity-flip $\Longrightarrow$ one unit of twist, $\frac{1}{m}$

6) Higher Fock states with collinear gluons: e.g.,



V_2: two upward lines, V_1: Form factor vector meson

- $V_2(q\bar{q}g)$ has negative helicity but:

  $\phi(q\bar{q}g)$ distribution amplitudes are twist-3 $\Rightarrow \frac{1}{m}$

  $$\Longrightarrow \mathcal{A}^- \sim O(1/m)$$

- $\mathcal{A}^+$ could be obtained via, e.g.,

  $V_2(q\bar{q}g)$ + V_1 $(q\bar{q}g)$ $\Longrightarrow \mathcal{A}^+ \sim O(1/m^2)$

- $(q\bar{q}g)$ states preserve NF power counting

Power counting summary

- NF + $O(\alpha_s)$ corrections (penguin contractions, vertex corrections):

$$A^0 = O(1), \qquad A^- = O\left(\frac{1}{m}\right), \qquad A^+ = O\left(\frac{1}{m^2}\right)$$

- Spectator interactions:

$$A^0 = O(1), \qquad A^- = O\left(\frac{1}{m}\ln\frac{m}{\Lambda_h}\right), \qquad A^+ = O\left(\frac{1}{m^2}\ln\frac{m}{\Lambda_h}\right)$$

- Annihilation graphs:

$$A^0 = O\left(\frac{1}{m}\ln\frac{m}{\Lambda_h}\right), \quad A^- = O\left(\frac{1}{m^2}\ln^2\frac{m}{\Lambda_h}\right), \quad A^+ = O\left(\frac{1}{m^3}\ln\frac{m}{\Lambda_h}\right)$$

- Each quark helicity-flip costs $1/m$: via one unit of twist, or form factor suppression

Numerical study

- $B \to \rho^{\pm}\rho^{0}$
  - 'tree-level' (W-exchange) operator dominated
  - CKM suppressed electroweak penguin graphs
  - no QCD penguin, annihilation graphs

$$10^6\,\mathrm{Br} = \left[25.2^{+3.6}_{-2.1}(\text{ leading power}) \pm 1.5\left(\frac{1}{m}\right)\right] \times \left[\frac{|V_{ub}|}{.037}\,\frac{\zeta_{\parallel}^{B\to\rho}}{.37}\right]^2$$

$$R_0 = .97 \pm .02(\zeta_{\parallel,\perp}) \pm .01(\text{ leading power}) \pm .01\left(\frac{1}{m}\right)$$

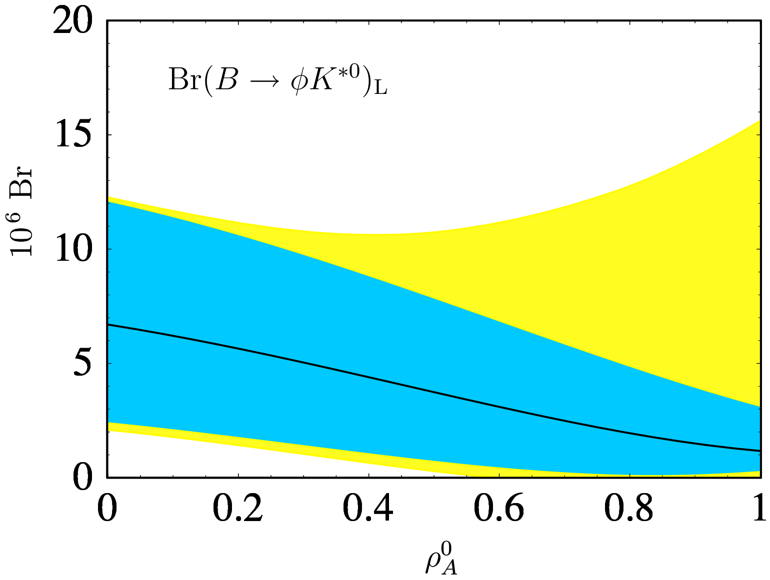
- $R_0^{\mathrm{exp}} = .96 \pm .06, \qquad 10^6\,\mathrm{Br}^{\mathrm{exp}} = 27.0 \pm 5.8$

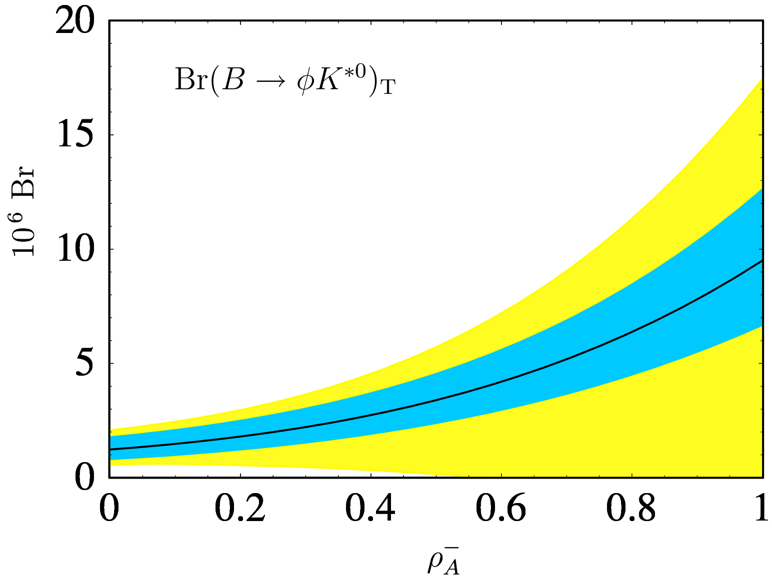
- $\bar{B}^0 \to \phi K^{*0}$
  - QCD penguin dominated
  - One penguin operator annihilation graph could be important
  - $O\left(\frac{1}{m_b^2}\ln^2\frac{m_b}{\Lambda_h}\right)$ but large Wilson coefficient, color factor
  - modeling log divergence uncertainties in annihilation Beneke et al:

$$\int_0^1 \frac{dx}{x} \to X_A = (1+\varrho_A e^{i\varphi_A})\ln\frac{m_B}{\Lambda_h}\,; \quad \varrho_A \lesssim 1\,, \quad \Lambda_h \approx 0.5\,\mathrm{GeV}$$

Arbitrary strong phases φ_A from soft rescattering

- Longitudinal BR vs. ρ_A^0, Transverse BR vs. ρ_A^-



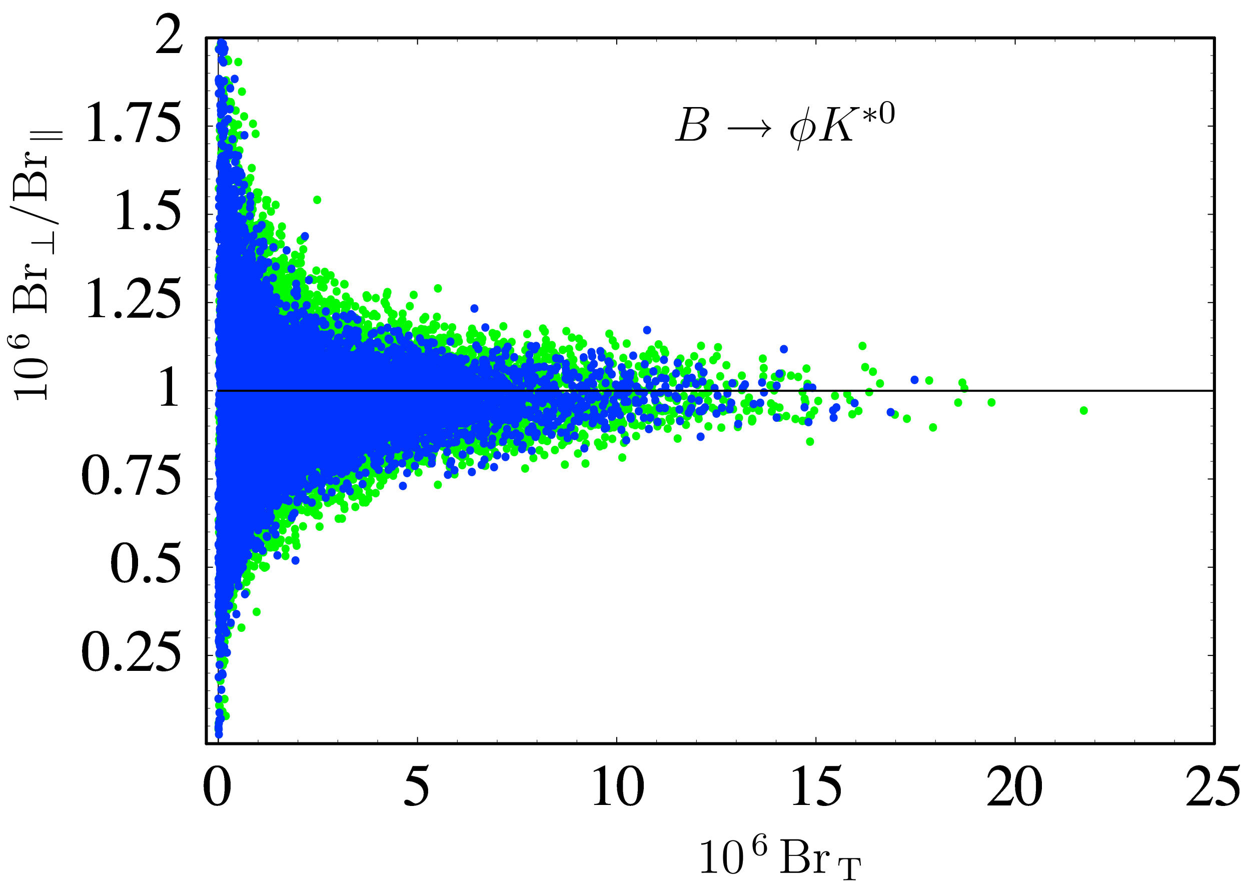


Blue bands: uncertainty due to variation of input parameters ($\phi_A^{0,-} = 0$). Yellow bands: include uncertainty from variation of $\phi_A^{0,-}$, variation of other annihilation and log divergent spectator interactions.

- Large sensitivity to annihilation / log divergences
- With annihilation can account for 'large' transverse rate:
  $10^6\,\mathrm{Br}_\mathrm{T}^\mathrm{exp} = 4.5 \pm 0.8$ (Babar+Belle)
- can account for $\Gamma_0 \approx \Gamma_T$, as observed

- Does NF prediction

$$\frac{\Gamma_\perp}{\Gamma_\parallel} = 1 + O\left(\frac{\Lambda_{QCD}}{m_b}\right) \quad \text{survive?}$$



Scatter plot for $\Gamma_\perp/\Gamma_\parallel$ vs. Br_T: varied all inputs, including for annihilation, hard spectator interactions, over full ranges. blue: $\zeta_\perp$ from $B \to K^*\gamma$ rate; green: $\zeta_\perp$ from QCD sum rules

- Full scan of theoretical input parameters.
  - SCET $\Rightarrow$ FF for $\mathcal{A}^+$ is $O\left(\zeta_\perp \frac{\Lambda_{QCD}}{m_b}\right)$.
    Take $[-0.2\,\zeta_\perp, +0.2\,\zeta_\perp]$. (QCD sum rules give $\approx .04\,\zeta_\perp$)
  - $\rho_{A_i} \leq 1$, $\phi_{A_i} = [0, 2\pi]$.
  - In the angular analysis, can measure strong phase differences between the transversity amplitudes.
    Reduce predicted range for $\Gamma_\perp/\Gamma_\parallel$.
- Obtain sensitive test of SM $V - A$ structure. Deviation implies new right-handed currents

Right-handed currents, or opposite chirality $\tilde{Q}_i$

- $\tilde{Q}_i$: inverted hierarchy, $A^+/A^- = \mathcal{O}(1/m)$. Recall

$$A_{\perp,\parallel} \equiv \frac{\mathcal{A}^+ \pm \mathcal{A}^-}{\sqrt{2}}$$

- dependence on SM, NP Wilson coefficients:

$$A_{0,\parallel} \propto C_i^{\rm SM} + C_i^{\rm NP} - \tilde{C}_i^{\rm NP}, \qquad A_\perp \propto C_i^{\rm SM} + C_i^{\rm NP} + \tilde{C}_i^{\rm NP}$$

- $\tilde{C}_i \neq 0$ could give constructive interference in $\mathcal{A}_\perp$, destructive in $\mathcal{A}_\parallel$

- Example: Opposite chiraliy QCD penguin operators with strenghth $\approx 0.2\times$ strenghth of SM operators $\Rightarrow \Gamma_\perp/\Gamma_\parallel \approx 2$

Summary

- Observed dominance of longitudinal polarization in $B \to \rho\rho$ modes well reproduced, with small theoretical errors

- Very large theoretical uncertainty in penguin dominated decays due to QCD penguin annihilation graph (Q_6)
  - can account for $\Gamma_\perp \approx \Gamma_0$ in $B \to \phi K^*$.
  - But $\Gamma_0 \gg \Gamma_\perp$ in $B \to K^{*0}\rho^\pm$ would imply new physics in $b \to s\bar{s}s$

- Predict

$$\frac{\Gamma_\perp}{\Gamma_\parallel} = 1 \pm 0.3$$

$\Rightarrow$ sensitive test for right-handed currents in $b \to s$ transitions

- Comparison of CP asymmetries in $0, \ \perp, \ \parallel$ transversities can further discriminate between different new physics operators