Polarization in $B \to VV$

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Outline

- Polarization in $B \rightarrow VV$
  - QCD penguin annihilation in $\Delta S = 1$ decays
    - BBNS parametrization
    - PQCD

- Power corrections in $e^+e^- \rightarrow M_1M_2$ with Murugesh Duraisamy
  - What can we already learn about annihilation from CLEO-C, BES?
  - What can we learn at the $B$ factories?
Helicity-flip suppression: Naive Factorization

- \( A^h, h = 0, -, +: \) amplitudes for longitudinal, negative, positive helicity vectors

- Quark helicity-flip requires transverse momentum, \( k_\perp \)
  \[ \Rightarrow \Lambda_{QCD}/m_b \text{ suppression} \]

\[
\begin{align*}
\mathcal{A}^0 &= O(1), \\
\mathcal{A}^- &= O(1/m), \\
\mathcal{A}^+ &= O(1/m^2)
\end{align*}
\]

- \( \mathcal{A}^- / \mathcal{A}^0 = O(m_\phi / m_B), \) helicity of \( \bar{s} \) in \( \phi \) flipped

- \( \mathcal{A}^+ / \mathcal{A}^- = O(\Lambda_{QCD}/m_b), \) helicity of \( s \) in \( K^* \) flipped
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

\[ \frac{\Gamma_T}{\Gamma_0} = O\left( \frac{1}{m_b^2} \right) \]
Experimental situation \( f_{L,\perp,\parallel} \equiv \frac{\Gamma_{0,\perp,\parallel}}{\Gamma_{\text{total}}} \)

\[
f_L(\phi K^{*0})_{\text{Babar, Belle}} = 0.48 \pm 0.04, \quad f_L(\phi K^{*\pm})_{\text{Babar, Belle}} = 0.50 \pm 0.07
\]

\[
f_\perp(\phi K^{*0})_{\text{Babar, Belle}} = 0.26 \pm 0.04, \quad f_\perp(\phi K^{*\pm})_{\text{Belle}} = 0.19 \pm 0.08
\]

\[
f_L(\rho^{0} K^{*+})_{\text{Babar}} = 0.96^{+0.06}_{-0.15}, \quad f_L(K^{*0} \rho^{+})_{\text{Babar, Belle}} = 0.66 \pm 0.17
\]

\[
f_L(\rho^{+} \rho^{0})_{\text{Babar, Belle}} = 0.97^{+0.05}_{-0.07}, \quad f_L(\rho^{+} \rho^{-})_{\text{Babar}} = 0.99^{+0.05}_{-0.04}
\]

NF power counting would \( \Rightarrow \) New Physics in \( f_L(B \rightarrow \phi K^*) \)

But \( \phi K^{*0} \) data consistent with \( \Gamma_\perp / \Gamma_\parallel \approx 1 \)
Beyond naive factorization: power corrections

Example: annihilation graphs due to QCD penguin operator

\[ Q_6 \Rightarrow < (\bar{d}b)_{S-P} \times (\bar{s}d)_{S+P} > \quad \text{(part of } P) \]

\[ (\bar{d} b)_{S-P} (\bar{s} d)_{S+P} \]

\[ \propto \langle \phi K^* | (\bar{s} d)_{S+P} | 0 \rangle \]

\[ \mathcal{A}^0, \mathcal{A}^- = O \left( \frac{1}{m^2} \ln^2 \frac{m}{\Lambda_h} \right), \quad \mathcal{A}^+ = O \left( \frac{1}{m^4} \right) \]

- annihilation topology \( \rightarrow \) overall \( 1/m \)

- helicity-flips \( \rightarrow \) rest of \( 1/m \) factors, or twists
Parametrizing log divergences in quark light-cone momentum fraction \( x \) BBNS

\[
\int_0^1 \frac{dx}{x} \rightarrow X = (1 + \varrho e^{i\varphi}) \ln \frac{m_B}{\Lambda_h}; \quad \varrho \lesssim 1, \quad \Lambda_h \approx 0.5 \text{ GeV}
\]

Allow for strong phase \( \varphi \) from soft rescattering

BBNS take \( \alpha_s(\sqrt{\Lambda_h m_B}) \) for all power corrections

for example, \( \langle \phi K^* | (\bar{s} d)_{S+P} | 0 \rangle \propto (2X - 3)(1 - X) \)
Numerical study

- $B \rightarrow \rho^\pm \rho^0$
  - ‘tree-level’ ($W$-exchange) dominated
  - CKM suppressed electroweak penguin graphs
  - no QCD penguin, annihilation graphs
  
  \[
  f_L = .98 \pm .02 \text{(FF's)} \pm .01 \text{(hadronic parameters, } \mu) \pm .01 \left( \frac{1}{m} \right)
  \]
  - Good agreement with experiment, power counting

- $B \rightarrow \rho^+ \rho^-$
  - ‘tree-level’ ($W$-exchange) dominated
  - CKM suppressed EW, QCD penguins, annihilation graphs
  
  \[
  f_L = .96^{+0.03}_{-0.04} \text{(FF's)}^{+0.01}_{-0.02} \text{(hadronic parameters, } \mu) \pm .01 \left( \frac{1}{m} \right)
  \]
  - good agreement with experiment, power counting
$\bar{B} \rightarrow \phi K^{*0,-}, K^{*0} \rho^-$

- QCD penguin dominated - ‘pure-penguin’

- $(S + P)(S - P)$ QCD penguin annihilation important

- $O \left( \frac{1}{m_b^2} \ln^2 \frac{m_b}{\Lambda_h} \right)$, large Wilson coefficient, color factor

- destructive interference in $A^0$, constructive in $A^-$

- $\rho \in [0, 1] \Rightarrow$ order of magnitude amplitude variation
Scans for $\phi K^{*0}$ and $K^{*0} \rho^+$

- require total $\phi K^{*0}$, $K^{*0} \rho^\pm$ rates lie in exp 90% c.l. intervals
- set $\rho$'s equal, $\phi = 0$
- use light-cone QCD sum-rule form factors Ball et. al,...

bands are $1\sigma$ exp averages

data favors $\rho \sim .5$ (for $\phi = 0$)

without annihilation, predict $10^6 \text{Br}_T(\phi K^{*0}) = 0.6^{+0.6}_{-0.4}$ (inputs) $^{+0.4}_{-0.3} \left( \frac{1}{m} \right)$, versus

$10^6 \text{Br}_{T}^{\text{exp}} = 5.43 \pm 0.88$ (Babar+Belle)
\( f_L(\phi K^*) \) vs. \( f_L(K^{*0}\rho^-) \): both easily accommodated

\[ f_L(K^{*0}\rho^-) \]

\[ f_L(\phi K^*) \]

next, will include QCD annihilation strong phases. Require reproduce observed strong phase differences \( \phi_\parallel, \phi_\perp \)

introduce additional \( SU(3) \) violating effects, due to non-asymptotic DA’s. can be amplified due to inverse moments. (s\(\bar{s}\) vs. \(u\bar{u}\), \(d\bar{d}\) popping) Mantay, Pirjol, Stewart
\( f_\perp / f_\parallel (\phi K^{*0}) \) vs. \( Br_T \):

- **Naive BaBar + Belle avg:** \( (f_\perp / f_\parallel)^{\text{exp}} = 0.9 \pm 0.3 \)

- **Sensitive test of \( V - A \) structure:**
  - \( f_\perp / f_\parallel \approx 1 \) \( \Rightarrow \) no indication for RH currents from 4-quark ops
introduce valence quark transverse momenta $\vec{k}_\perp$

resummation of large logs into Sudakov form factors should regulate end-point singularities sufficiently to allow consistent perturbative amplitude calculation, e.g.,

$$\langle \phi K^*0 | (\bar{s}d)_{S+P} | 0 \rangle = \int_0^1 du \int_0^1 dv \int d^2 \vec{b}_\phi \int d^2 \vec{b}_K^* \Psi^\phi (u, \vec{b}_\phi) H(u, v, \vec{b}_\phi, \vec{b}_K^*, c) \Psi^{K^*}(v, \vec{b}_K^*)$$

$u, v$ are quark light-cone momentum fractions

$\Psi^\phi, \Psi^{K^*}$ DA’s contain resummed Sudakov effects

$\vec{b}_\phi, \vec{b}_K^*$ are transverse separations of valence quarks, conjugate to transverse momenta

$H$ is Fourier transform of transverse momenta dependent hard-scattering kernel
Assume for all meson twist-2, twist-3 DA's

$$\Psi(u, b, |\vec{p}|) = e^{-S(|\vec{p}|, b)} \phi(u).$$

known to hold for twist-2 pseudoscalar DA's in light-cone gauge, up to unknown $O(\alpha_s(1/b))$ corrections Botts, Sterman

- $S$ is Sudakov factor, suppresses large transverse separations $b$
- $\phi$ is light-cone DA
Annihilation in PQCD: results for neg. helicity amplitude

\[ \langle \phi K^* | (\bar{s}d)_{S+P} | 0 \rangle \] vs. \( b^{max} \), with \( b^{max} \leq 1/\Lambda_{QCD} \).

- Comparison with QCDF for \( \rho \sim 0.5 \sim 0.8 \) implies magnitude of annihilation in PQCD in right ballpark to accomodate \( \text{BR}_T(\phi K^*) \), also see Chun, Keum, Li; Li, Mishima

- Is \( b^{max} \) dependence perturbative? (Descotes-Genon, Sachrajda \( B \rightarrow \pi \) FF discussion)
Is annihilation calculable (perturbative) in PQCD?

PQCD philosophy: Sudakov suppression sufficiently strong to cut out non-perturbative contributions from end-point regions of the DA’s (Feynman mechanism). Lets check:

Comparison of contributions to $\langle \phi K^*|\bar{s}d|S_P|0 \rangle$ vs. $b^{max}$ for full range of longitudinal momentum fractions $u, v \in [0, 1]$ (black), and for 250 MeV end-point regions cut out $1 - u, v \in [.1, 1]$ (blue)
Contributions to \( \text{Im} \langle \phi K^* | \bar{s}s_{S+P} | 0 \rangle \), \( \text{Re} \langle \phi K^* | \bar{s}s_{S+P} | 0 \rangle \) in end-point regions of quark light-cone momentum fractions \( x_\phi \), \( 1 - x_{K^*} \).

- almost entire imaginary part generated in end-point region, with large contribution from non-perturbative transverse separation \( b \)
- Real part saturates at non-perturbative transverse separation; large end-point region dependence
- Conclusion: Sudakov suppression not large enough to eliminate large contributions from end-point and small \( \vec{k}_\perp \) regions \( \Rightarrow \) large non-perturbative effects
Power corrections and $e^+e^- \rightarrow M_1M_2$

- $f_L$ can be accommodated with $O(1)$ QCD annihilation amplitude - formally $O(ln^2/m^2) \Rightarrow \rho = O(1)$

- large $\Delta S = 1$ $B \rightarrow \phi K$, $K^*\pi$ rates can be accounted for with $O(1)$ QCD annihilation amplitudes $\Rightarrow \rho = O(1)$.

- $A_{CP}(K^+\pi^-)$ can be accounted for with $\rho = O(1) +$ large strong phase in QCD annihilation

- In principle all of the above could also be accounted for with ‘charming penguins’: Leading power? Bauer et al, Subleading power? Ciuchini et al, FSI models Cheng et al, Colangelo et al

Can annihilation dynamics be probed directly: can we test for $O(1)$ power corrections, or $\rho \sim 1$ in BBNS parametrization?
Compare

\[ \propto \langle M_1 M_2 | \bar{s} d | 0 \rangle \]

\[ \propto \langle M_1 M_2 | \bar{q} \gamma_\mu q | 0 \rangle \]
Vector-current annihilation form factors

\[ \langle VP|\bar{q} \gamma_\mu q|0\rangle = \frac{2iV^q}{m_P + m_V} \epsilon_{\mu\nu\rho\sigma} \epsilon^\nu p_\sigma p_\rho \]

\[ \langle P_1 P_2|\bar{q} \gamma^m u q|0\rangle = F^q (p_1 - p_2)^\mu \]

\[ \langle V_1 V_2|\bar{q} \gamma^\mu q|0\rangle \text{ contains three form factors} \]

- \( V^q \sim 1/s^2 \ln^2(\sqrt{s}/\Lambda) \)
- \( F^q \): finite \( 1/s \) contribution Brodsky, Lepage + \( 1/s^2 \ln^2(\sqrt{s}/\Lambda) \) correction
- Use continuum CLEO-c (20.46 pb\(^{-1}\))+ BES \( VP \) data at \( \sqrt{s} \approx 3.7 \) GeV, near \( \psi(2s) \), to extract \( |V^q| \). Compare with BBNS parametrization, PQCD
- Extrapolate to larger \( \sqrt{s} \approx m_B \), compare with reach of luminosity at \( m_B \) from initial state radiation (ISR)
\[ e^+e^- \rightarrow VP \text{ in BBNS parametrization} \]

considered three values of \( \alpha_s = 1, .5, \alpha_s(\sqrt{s\Lambda_h}) \); three values of strong phase \( \phi_A = 0, \pm \pi/2, \pi \). Measurements \( \Rightarrow \rho_A \sim 1 \) or \((m/\sqrt{s})"\text{Log } \sqrt{s}/\Lambda" \sim 1 \)
$e^+e^- \rightarrow K^{*0}K^0$ in PQCD

\[ |V_s| \text{ vs. } b^{\text{max}}, \sqrt{s} = 3.67 \text{ GeV} \]

- PQCD annihilation in right ballpark, but
- again dominated by end-point region, with large contributions from non-perturbative transverse separations $\Rightarrow$ large non-perturbative contributions
**SU(3) violation in $K^*\bar K$**

Let $r e^{i\delta} \equiv V^u/V^s$

$$k \equiv \frac{\sigma(K^{*+}K^-)}{\sigma(K^0\bar K^0)} = \frac{|V^s - 2 V^u|^2}{|V^s + V^u|^2} = \frac{1 - 4r \cos \delta + 4r^2}{1 + 2r \cos \delta + r^2}$$

gives allowed region in $(r = |V^u/V^s|, \delta)$ plane

- $V^u/V^s = 1$ in $SU(3)$ limit $\Rightarrow k = 1/4$  Haber, Perrier

- CLEO-c measures $\sigma(K^{*+}K^-)/\sigma(K^0\bar K^0) = 0.03^{+0.06}_{-0.01}, 3.7\sigma$ away. Allowed region:
Implication for $B$ decays?

- probe of $SU(3)$ violation due to $s\bar{s}$ vs. $u\bar{u}$ popping (form factors, decay constants have small impact in ratio)

- large $SU(3)$ violation in annihilation + $O(1)$ QCD penguin annihilation amplitudes would imply large $SU(3)$ violation in the total penguin amplitudes, $P$

- can play similar game with $K^*(0)\bar{K}^*(0)$ (vanish in $SU(3)$ limit) vs. $K^*(0) + K^*(0)$

- would be nice to have measurements at $\sqrt{s} \approx m_B$
Effective luminosity vs. $\sqrt{s}$ from ISR

from BaBar, E. Solodov ICHEP04 with 89.3 pb$^{-1}$
corrected for ISR photon acceptance
Scale to 1 ab$^{-1}$ $\Rightarrow$ approximately

$$780 \ K^*0 K^0 ; \ 260 \ \rho \pi ; \ 450 \ \omega \pi ; \ 45 \ \pi^+ \pi^-$$

events for $5.0 < \sqrt{s} < 5.3$ GeV, i.e., $\sqrt{s} \sim m_B$.

Can we already see signal for $K^*0 \bar{K}^0$?

With large statistics could do Dalitz plot analysis for $e^+ e^- \rightarrow K^- \pi^+ \bar{K}^0$? Check for strong phase difference in production of $K^*0 \bar{K}^0$ vs. non res $K^- \pi^+ \bar{K}^0$?

Would strengthen case for strong phases from QCD annihilation in $B$ decays
Summary

- observed longitudinal polarizations in $B \rightarrow \phi K^*$, $K^* \rho$ can be accommodated via $O(1)$ QCD penguin annihilation amplitudes

- $\left(\frac{f_\perp}{f_\parallel}\right)^{\text{exp}}(\phi K^{*0}) \approx 1 \Rightarrow$ no large right-handed currents from four-quark operators

- PQCD annihilation in right ballpark, but large contribution from non-perturbative region

- irony: PQCD may be a useful model for estimating soft form factors

- Continuum $e^+e^- \rightarrow M_1 M_2$ studies at $\sqrt{s} \approx 3.7$ GeV favor $O(1)$ QCD annihilation amplitudes in $B$ decays $\Rightarrow$ should include power corrections in $B$ decay fits

- using ISR can test prediction for $\sqrt{s}$ dependence of form factors: $K^{*0}\bar{K}^0$ may be possible at $\sqrt{s} \approx m_B$ with current data sample

- high statistics at $\Upsilon(4S)$ allow further test of $\sqrt{s}$ dependence

- important probe of $SU(3)$ violation in annihilation due to $s\bar{s}$ vs. $u\bar{u}$, $d\bar{d}$ popping

- search for $e^+e^- \rightarrow K^+K^-, \pi^+\pi^-, K^{*+}K^{*-}$, at CLEO-c, $B$ factories
Extrapolating to higher energies

Fix range of $\sigma(V P)$ to CLEO-c measurement at $\sqrt{s} = 3.67$, e.g.,

left: $\sigma(K^{*0} K^0)$ vs. $\sqrt{s}$; right: $V^u(\omega \pi)$ vs. $\sqrt{s}$
Continuum at the $\Upsilon(4S)$

- alternative: measure $e^+e^- \rightarrow M_1M_2$ at $\Upsilon(4S)$

- $M_1M_2$ final state must be due to continuum

- huge luminosity:

  $$\sigma(e^+e^- \rightarrow K^*0\bar{K}^0) \approx 0.05 \text{ pb at } 10.58 \text{ GeV}$$

$\Rightarrow$ O (10000) events for $200 \text{ fb}^{-1}$ if scale using BBNS parametrization or PQCD
What do we know about $\pi^+\pi^-$?

based on unpublished BES $\psi(2s) \rightarrow \pi^+\pi^-$ BR, Mark III $J/\Psi \rightarrow \pi^+\pi^-$ BR: although electromagnetic decays, not as theoretically clean as continuum form factor determinations

![Graph showing $F_{\pi\pi}$ vs. $\rho$ at $\psi(2s)$ (left) and $J/\Psi$ (right).]

- at $\psi(2s)$ $F_{\pi\pi} \sim 0.045 \pm 0.017$ Wang, Mo, Yuan; at $J/\Psi$ $F_{\pi\pi} \approx 0.11 \pm 0.01$

- suggests $\rho > 1$ for $\pi^+\pi^-$

- at $\psi(2s)$, $F_{\pi\pi} \approx 0.01$ at twist-2 or $O(1/s)$. Implies $1/s^2$ power correction dominates. Extrapolation to larger energies implies this should persist at $\sqrt{s} \approx m_B$

- CLEO-c should search for $e^+e^- \rightarrow \pi^+\pi^-, K^+K^-, K^0\bar{K}^0$ at $\sqrt{s} = 3.67$ GeV to get more reliable $PP$ form factor measurements: $\approx 75$ events for $F_{\pi\pi} \approx 0.045$
\[ e^+ e^- \rightarrow VV \]

\[ \langle K^* K^* | \bar{q} \gamma_\mu q | 0 \rangle = V_1^q (\epsilon^*_\mu \eta^* \cdot p_1 - \eta^*_\mu \epsilon^* \cdot p_2) + V_2^q (\epsilon^* \cdot \eta^*) q_\mu + V_3^q \frac{\epsilon^* \cdot p_2 \eta^* \cdot p_1}{Q^2} q_\mu \]

Polarizations:

\[ V_1^q \Rightarrow LT, \quad Amp \sim 1/Q^3 \log^2 Q/\Lambda_h \quad Q = \sqrt{s} \]

\[ V_2^q \Rightarrow LL, \quad Amp \sim m_q/Q^4 \log^2 Q/\Lambda_h \]

\[ V_3^q \Rightarrow TT, \quad Amp \sim 1/Q^4 \log^2 Q/\Lambda_h \]

\[ \sqrt{s} = 3.67 \text{ GeV}, \phi = 0, \text{ left: } V_1^s (K^{*+} \bar{K}^{*-}) \text{ vs. } \rho; \quad \text{right: } \sigma_{LT} (K^{*+} \bar{K}^{*-}) [\text{pb}] \text{ vs. } \rho \text{ for } V_1^u = V_1^d = 0 \text{ (lower), } SU(3) \text{ limit } V_1^s = V_1^{d,u} \text{ (upper).} \]

\[ \frac{\sigma_{LT} (K^{*0} \bar{K}^{*0})}{\sigma_{LT} (K^{*+} \bar{K}^{*-})} = \frac{|V_1^s - V_1^d|^2}{|V_1^s + 2 V_1^d|^2} \]
New Physics: Tensor operators

Example: \( \frac{G_F}{\sqrt{2}} \lambda_t \kappa \bar{s} \sigma_{\mu\nu} (1 + \gamma_5) b \bar{q} \sigma^{\mu\nu} (1 + \gamma_5) q \)

\[
\begin{align*}
\kappa \sim C_4^{\text{SM}} / 8 \quad &\implies \Gamma_T \sim \Gamma_0^{\text{SM}} \\
\mathcal{A}^+ / \mathcal{A}^- = O(\Lambda_{\text{QCD}} / m_b) \quad &\implies \Gamma_\perp / \Gamma_\parallel \approx 1 \text{ maintained} \\
f_L(\phi K^*) \text{ very sensitive to tensor operators, but exotic}
\end{align*}
\]