Polarization in $B \rightarrow VV$, or

e^+e^- \rightarrow M_1M_2$ and $\mathcal{O}(1)$ Annihilation in $B$ Decays

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Outline

- Polarization in $B \rightarrow VV$
- New Physics in $B \rightarrow \phi K^*$?
- Annihilation: BBNS parametrization vs. PQCD

- Power corrections in $e^+ e^- \rightarrow M_1 M_2$ with Murugesh Duraisamy
- What can we already learn about $B$ decays from CLEO-C, BES
- What can we learn at the $B$ factories from radiative return (Initial State Radiation), and continuum at the $\Upsilon(4S)$?
Helicity-flip suppression: Naive Factorization

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

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

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

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

- $\mathcal{A}^-/\mathcal{A}^0 = O(m_\phi/m_B)$, 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 \( f_{L,\perp,\parallel} \equiv \frac{\Gamma_{0,\perp,\parallel}}{\Gamma_{\text{total}}} \)

\[ f_L(\phi K^{*0})_{\text{Babar, Belle}} = 0.52 \pm 0.04, \quad f_L(\phi K^{*\pm})_{\text{Babar, Belle}} = 0.47 \pm 0.09 \]

\[ f_{\perp}(\phi K^{*0})_{\text{Babar, Belle}} = 0.25 \pm 0.044, \quad f_{\perp}(\phi K^{*\pm})_{\text{Belle}} = 0.12^{+0.07}_{-0.03} \pm 0.03 \]

\[ f_L(\rho^0 K^{*+})_{\text{Babar}} = 0.96 \pm 0.16, \quad f_L(K^{*0} \rho^+)_{\text{Babar, Belle}} = 0.74 \pm 0.08 \]

\[ f_L(\rho^+ \rho^0)_{\text{Babar, Belle}} = 0.962^{+0.049}_{-0.065}, \quad f_L(\rho^+ \rho^-)_{\text{Babar}} = 0.99 \pm 0.03^{+0.04}_{-0.03} \]

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

But \( \phi K^{*0} \) data consistent with \( \Gamma_{\perp}/\Gamma_{\parallel} \approx 1 \)
**New Physics: Tensor operators**

C.S. Kim, Y.D. Yang; P.K. Das, K.C. Yang; A.K.

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

\[ \begin{align*}
A^0 &= O(1/m), & A^- &= O(1), & A^+ &= O(1/m^3)
\end{align*} \]

- \( \kappa \sim C_4^{SM}/16 \Rightarrow \Gamma_T \sim \Gamma_0^{SM} \)
- \( A^+/A^- = O(\Lambda_{QCD}/m_b) \Rightarrow \Gamma_\perp/\Gamma_\parallel \approx 1 \) maintained
- \( f_L(\phi K^*) \) very sensitive to tensor operators, but exotic
Standard Model beyond naive factorization

- penguin contractions, vertex corrections, spectator interactions, annihilation graphs,...

examine in QCD factorization
Subleading powers

At subleading powers in $1/m_b$:

- short / long distance separation breakdown

  ⇒ amplitudes soft dominated

- signaled by IR soft, collinear log divergences in quark light-cone momentum fraction $x$ (end-point singularities)

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

$$
Amp \sim \left( \frac{\Lambda_h}{m_b} \right)^p \ln^q \frac{m_b}{\Lambda_h}
$$

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

  Can we say anything about polarization?
Example of power corrections

Annihilation graphs: QCD penguin operator

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

\begin{align*}
\mathcal{A}^0, \quad \mathcal{A}^- &= O \left( \frac{1}{m^2} \ln^2 \frac{m}{\Lambda_h} \right), \\
\mathcal{A}^+ &= O \left( \frac{1}{m^4} \right)
\end{align*}

- annihilation topology \( \rightarrow \) overall \( 1/m \)
- helicity-flips \( \rightarrow \) rest of \( 1/m \) factors, or twists
Parametrizing the divergences \( \text{BBNS} \)

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

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

- BBNS take \( \alpha_s(\sqrt{\Lambda_h m_B}) \) for all power corrections; \( \alpha_s \approx 1 \) more appropriate for divergent 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’ \((W\text{-exchange})\) dominated
  - CKM suppressed electroweak penguin graphs
  - no QCD penguin, annihilation graphs
  
  \[
  f_L = 0.98 \pm 0.02 \text{ (FF' s)} \pm 0.01 \text{ (hadronic parameters, } \mu) \pm 0.01 \left( \frac{1}{m} \right)
  \]
  - Good agreement with experiment, power counting

- \( B \rightarrow \rho^+ \rho^- \)
  - ‘tree-level’ \((W\text{-exchange})\) dominated
  - CKM suppressed EW, QCD penguins, annihilation graphs
  
  \[
  f_L = 0.96^{+0.03}_{-0.04} \text{ (FF' s)} ^+_{-0.01} \text{ (hadronic parameters, } \mu) \pm 0.01 \left( \frac{1}{m} \right)
  \]
  - good agreement with experiment, power counting
$\bar{B} \to \phi K^{*0, -}, K^{*0} \rho^-$

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 $\Rightarrow$ can be $O(1)$

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 BR’s lie in exp 90% c.l. intervals
- set $\rho$’s equal, $\phi = 0$
- 20% uncertainty on $SU(3)$ Violn in QCD sum rule form factor ratios

bands are $1\sigma$ averages of BaBar and Belle

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

- next, 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
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.,

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

$\Psi^\phi$, $\Psi^{K^*}$ 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: contains threshold resummation, parametrized as $(x(1 - x))^c$
Assume for all meson twist-2, twist-3 DA's

\[ \Psi(u, b, |\vec{p}|, \mu) = e^{-S(|\vec{p}|, b)} e^{-G(\mu, b)} \phi(u, \mu = 1/b). \]

holds 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
- \( G \) evolves DA from \( 1/b \) to renormalization scale \( \mu \)
Annihilation in PQCD: results for neg. helicity amplitude

\begin{align*}
\langle \phi K^*|\bar{s}d\rangle_{S+P}|0\rangle &\quad \text{vs. } b^{max}, \text{ with } b^{max} \leq 1/\Lambda_{QCD}.
\end{align*}

\begin{itemize}
  \item Comparison with QCDF for $\rho \sim .5 - .8$ suggests annihilation in PQCD could accommodate $BR_T(\phi K^*)$, $(BR_T(K^{*0}\rho^+))$
  \item Li, Mishima concluded PQCD annihilation not sufficiently large for $f_L(\phi K^*)$. Suggest that $A^0_{B\rightarrow K^*}$ could be lower, e.g., .32 vs. .4
  \item Is $b^{max}$ dependence consistent, i.e., perturbative? (Descotes-Genon, Sachrajda)
\end{itemize}
Is annihilation calculable in PQCD?

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

![Graphs showing contributions vs. b_max](image)

Comparison of contributions to $\langle \phi K^* 0 |(\bar{s}d)_{S+P}|0 \rangle$ vs. $b_{\text{max}}$ 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)

- almost entire imaginary part generated in end-point region, with large contribution from non-perturbative transverse separation. persists for larger $\sqrt{s} \approx 10$ GeV.

- Real part saturates at non-perturbative transverse separation! 50% contribution from end-point region

- Conclusion: Sudakov suppression not large enough. Time-like form factors dominated by soft-overlap region, strong phases not calculable, $\mathcal{O}(1)$ uncertainty for real part
Power corrections and $e^+e^- \to M_1M_2$

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

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

- $A_{CP}(K^+\pi^-)$ can be accounted for with $\rho = O(1) + \text{large strong phase}$ in QCD penguin 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 $\rho \sim 1$ in BBNS parametrization, $O(1)$ power corrections? can we test for large strong phases?
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

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

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

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

- use QCDF + usual parametrization for logs in form factor power corrections
  - \( V^q \sim 1/s^2 \ln^2(\sqrt{s}/\Lambda) \)
  - \( F_{\pi\pi} \): 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 \( |V^q| \), determine range for \( \rho \) parameter

extrapolate to larger \( \sqrt{s} \approx m_B \), compare with effective luminosity at \( m_B \) due to initial state radiation (ISR)

no continuum data for \( PP \) at \( \sqrt{s} \geq 3 \) GeV
Considered three values of $\alpha_s = 1, \frac{5}{3}, \alpha_s(\sqrt{\Lambda_h})$; three values of strong phase $\phi_A = 0, \pm \pi/2, \pi$. Measurements $\Rightarrow \rho_A \sim 1$.
\[ e^+e^- \rightarrow K^{*0}K^0 \text{ in PQCD} \]

Comparison of contributions to \( V_s \) vs. \( b^{\text{max}} \) for full range of longitudinal momentum fractions \( u, v \in [0, 1] \) (black), and for 250 MeV end-point regions cut out \( 1 - u, v \in [.14, 1] \) (blue)
$SU(3)$ violation in $K^* \bar{K}$

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

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

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 $\sigma(K^{*-} K^-) / \sigma(K^{*0} K^0) = 0.03^{+0.06}_{-0.01}, 3.66\sigma$ 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 $\sqrt{s} \approx m_B$
Extrapolating to higher energies

Fix range of $\sigma(VP)$ 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. $\sqrt{s}$
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 already see signal for $K^{*0} \bar{K}^0$ with 200 fb$^{-1}$?

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. $K^- \pi^+ \bar{K}^0$

would strengthen case for strong phases from QCD annihilation in $B$ decays
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:

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

  \Rightarrow \text{O (10000) events for 200 fb}^{-1} \text{ 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

\[ F_{\pi\pi} \text{ vs. } \rho \text{ at } \psi(2s) \text{ left; at } J/\psi \text{ right} \]

- at $\psi(2s)$ $F_{\pi\pi} \sim 0.45 \pm 0.17$ Wang, Mo, Yuan; at $J/\psi$ $F_{\pi\pi} \sim 0.11 \pm 0.01$

- 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 $F_{\pi\pi} \approx 0.045$
\(e^+e^- \rightarrow VV\)

\[
\langle K^*K^*|\bar{q}\gamma_\mu q|0\rangle = V_1^q (\epsilon^*_\mu \eta^* \mathbf{p}_1 - \eta^*_\mu \epsilon^* \mathbf{p}_2) + V_2^q (\epsilon^* \eta^*) q_\mu + V_3^q \frac{\epsilon^* \cdot \mathbf{p}_2 \eta^* \cdot \mathbf{p}_1}{Q^2} q_\mu
\]

Polarizations:

\(V_1^q \Rightarrow LT, \quad Amp \sim 1/Q^3 \log^2 Q/\Lambda_h \quad Q \equiv \sqrt{s}\)

\(V_3^q \Rightarrow LL, \quad Amp \sim 1/Q^4 \log^2 Q/\Lambda_h, \quad V_2^q \Rightarrow LL, \quad Amp \sim m_q/Q^4 \log^2 Q/\Lambda_h\)

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

\[
\frac{\sigma_{LT}(K^*0\bar{K}^*0)}{\sigma_{LT}(K^+K^-)} = \frac{|V_1^s - V_1^d|^2}{|V_1^s + 2V_1^d|^2}
\]
Summary

- observed longitudinal polarizations in $B \to \phi K^*, \ K^* \rho$ easily accomodated via $O(1)_{0, \perp, \parallel}$ QCD penguin annihilation amplitudes

- observed $B \to \phi K, \ K^* \pi$ branching ratios, $A_{CP}(K^+ \pi^-)$ reproduced with $O(1$ QCD penguin annihilation

- PQCD annihilation calculations support soft dominance

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

- Continuum $e^+ e^- \to M_1 M_2$ 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

- checks for large strong phases from annihilation dynamics in $KK\pi$ Dalitz plot, $VV$ angular analysis?

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

- search for $e^+ e^- \to K^* K^*, \ K^+ K^-, \ \pi^+ \pi^-$