$e^+e^- \to M_1 M_2$ and Power Corrections in B Decays

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based on work with Murugesh Duraisamy

Introduction

There are many puzzles in charmless $B \to M_1 M_2$ decays. Among the proposed explanations, I will focus on the possibility that

- power corrections, e.g., annihilation and hard-spectator interactions, are enhanced due to end-point meson production. A large soft-overlap between fast and soft valence quarks is required. This would correspond to large "infrared divergent" logs, e.g., $\ln^2(m_B/\Lambda)$, in the amplitudes and would imply a breakdown of short/long distance factorization. Because the soft-dominated dynamics could also lead to strong phases, all puzzles could in principle be explained

- It was recently claimed that (annihilation) power corrections factorize. Therefore no such logs, no enhanced end-point meson production, no large soft overlap, and no strong phases - zero-bin subtraction, unless an expansion in powers of $\alpha_s(\sqrt{\Lambda m_B})$ breaks down

- CLEO-c, and the B factories are measuring many $e^+e^- \to M_1 M_2$ cross sections at different $\sqrt{s}$. Because these processes are power correction dominated, or pure power corrections, this is the ideal laboratory in which to isolate power correction effects, and to address the question of whether or not end-point meson production is important.

- If we find that end-point meson production is important in $e^+e^- \to M_1 M_2$, then it is obviously important in B decays, and we can expect those large infrared "divergent" logs and strong phases to be present.

Outline

- Power Corrections in B Decays
  - Polarization in penguin-dominated $B \to VV$
  - Penguin-dominated $B \to VP$ rates
  - Rates and CP asymmetries in $B \to K\pi,\ \pi\pi$
- What can we learn from $e^+e^- \to M_1 M_2$
  - $e^+e^- \to \pi^+\pi^-,\ K^+K^-$
  - $e^+e^- \to VP$
  - $e^+e^- \to VV$
  - Are power corrections end-point enhanced? or can zero-bin subtraction be right?
- Conclusion

$$B \to M_1 M_2$$

Power Corrections in QCD factorization

- convolutions of short-distance hard-scattering amplitudes, H, with non-perturbative light-cone meson distribution amplitudes, $\phi(x)$

$$\mathcal{A} \propto \int_0^1 dx\, dy\, H(x,y)\, \phi_{M_1}(x)\, \phi_{M_2}(y)$$

x (y) = fraction of total light cone momentum of M_1 (M_2) carried by valence quark

- Leading power in $1/m_b$: amplitudes are calculable, factorize into

  short-distance parameters / long-distance universal non-perturbutive parameters

- At subleading powers in $1/m_b$:

  short / long distance factorization breaks down $\Rightarrow$ amplitudes soft dominated

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

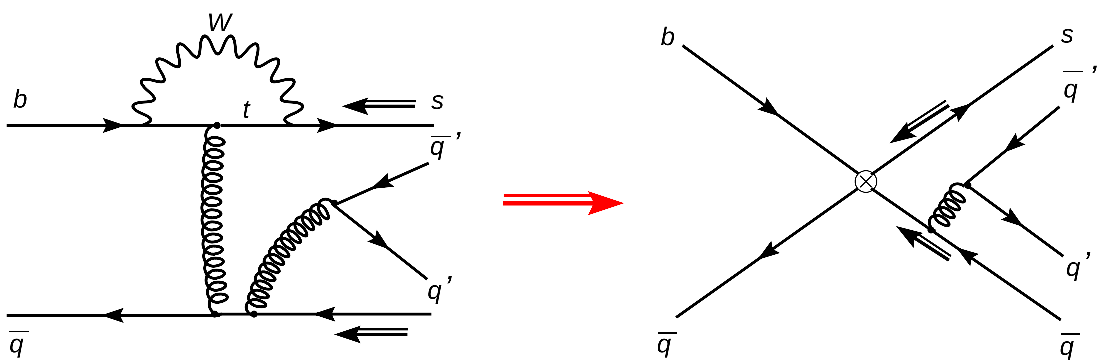
$$\int_0^1 dx/x \sim \ln \frac{m_b}{\Lambda}, \quad \text{physical IR cutoff } \Lambda \sim \Lambda_{QCD}$$

$$Amp \sim \left(\frac{1}{m_b}\right)^p \ln^q \frac{m_b}{\Lambda_h}$$

- Therefore mesons produced in "end-point" region $x \to 0$: fast valence antiquark, soft valence quark or *vice-versa*

penguin annihilation power corrections

- e.g., gluon emitted from final state quarks



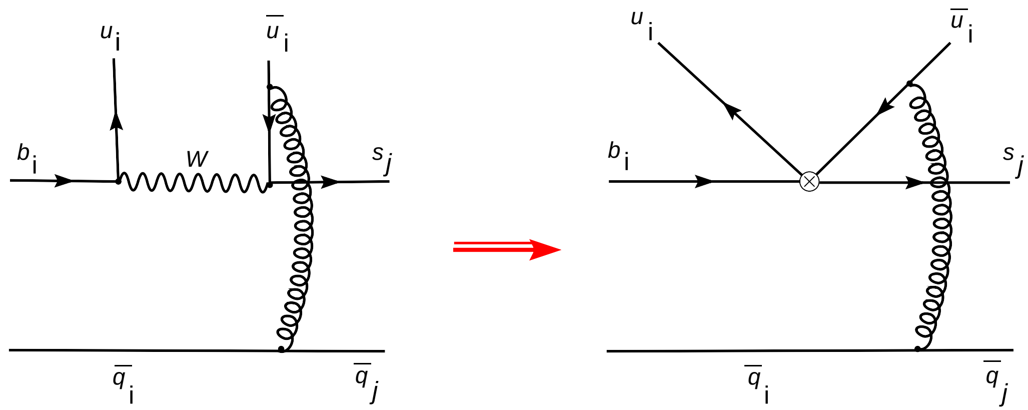
$$\mathcal{A} \quad \propto \langle M_1 M_2 | \bar{s}(1+\gamma_5) q | 0 \rangle \langle 0 | \bar{q}(1-\gamma_5) b | B \rangle$$

$$= O\left(\frac{g_s^2}{m_b^2} \ln^2 \frac{m_b}{\Lambda} \right)$$

  - $\ln^2$ from soft q', $\bar{q}'$ $\Rightarrow$ both M_1, M_2 produced in end-point region
- could be responsible for $A_{CP}(K^+\pi^-)$, $A_{CP}(\pi^+\pi^-)$, $f_L(\phi K^*)$, $Br(K^*\pi)$
- competitor of "non-perturbative charm loops"

Power corrections for color-suppressed amplitude C

- "hard-spectator" interaction:



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- leading-power part (short/long distance factorizable) can not explain large difference between $A_{CP}(K^+\pi^-)$, $A_{CP}(K^+\pi^0)$,...

  BBNS; beneke, jager (NNLO); bauer *et. al.*

- contains power correction

$$\mathcal{A} = O\left(\frac{g_s^2}{m_b} \ln \frac{m_b}{\Lambda}\right)$$

  - $\ln$ from soft spectator $\bar{q} \Rightarrow$ spectator meson M_1 produced in end-point region
  - could this be responsible for various features of $K\pi$ / $\pi\pi$ "puzzle"?

parametrization of end-point divergences

- use model of BBNS

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

  - Λ_h is a physical hadronic IR cut-off
  - Allow strong phase $\varphi \in [-\pi, \pi]$ from soft rescattering
  - find ranges for ρ, ϕ, or X's from experiment
  - large $X \Rightarrow$ large end-point enhancement of power corrections, large soft-overlap

- introduce
  - ρ_f , ϕ_f, or X_f for penguin annihilation with gluon emitted from final state quarks
  - ρ_h , ϕ_h or X_h for hard-spectator interactions (C color-suppressed tree)

$$\begin{aligned} \mathcal{A}(\text{peng ann}) &\propto \frac{g_s^2}{m_B^2}(A_f X_f^2 + B_f X_f + C_f) \\ \mathcal{A}(\text{hard spec}) &\propto \frac{g_s^2}{m_B}(A_h X_h + B_h) \end{aligned}$$

- g_s^2 presumably associated with soft gluon exchange, evaluate at low scale $\mu \approx 1$ GeV ($\alpha_s \approx .5$)

- conclusions qualitatively independent of model for end-point divergences

Polarization in charmless $B \to VV$

- 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 the SM $V - A$ structure of $b \to s(d)$ transitions imply a helicity amplitude hierarchy? In naive factorization
  - $\mathcal{A}^0$, $\mathcal{A}^-$, and $\mathcal{A}^+$ require none, one, and two final state quark helicity flips, respectively. Therefore they satisfy the approximate hierarchy

$$\mathcal{A}^0 : \mathcal{A}^- : \mathcal{A}^+ :: 1 : \frac{m_\phi}{m_B} : \frac{\Lambda_{QCD}}{m_b} \frac{m_\phi}{m_B}$$

(each quark helicity-flip requires a transverse momentum, $k_\perp$)

The measured longitudinal polarizations $f_L \equiv \Gamma_0/\Gamma_{\rm total}$

naive factorization power counting yields $f_L \approx 1$:

- penguin-dominated ($\Delta S = 1$):

$$f_L\,(\phi K^{*0}) = 0.49 \pm 0.04, \quad f_L\,(\phi K^{*\pm}) = 0.50 \pm 0.07$$

$$f_L\,(K^{*0}\rho^-) = 0.48{\pm}0.08, \;\; f_L\,(K^{*0}\rho^0)_{\rm BaBar} = 0.57{\pm}.12\,, \;\; f_L(K^{*-}\rho^0)_{\rm BaBar} = 0.96^{+0.06}_{-0.16}$$

contradicts naive factorization power counting

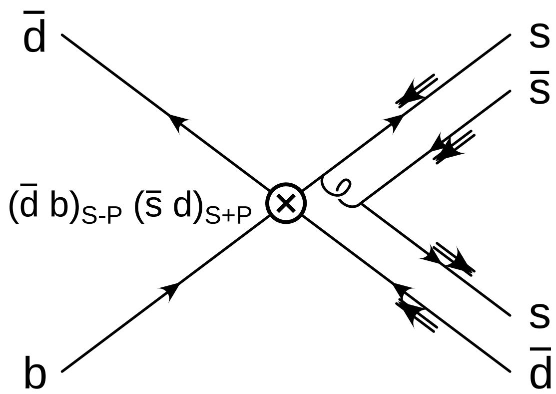
- CKM suppressed penguins ($\Delta S = 0$):

$$f_L(\rho^+\rho^0) = 0.91^{+0.04}_{-0.05}, \;\; f_L(\rho^+\rho^-) = 0.97 \pm 0.02, \;\; f_L(\rho^0\rho^0)_{\rm BaBar} = 0.86^{+0.12}_{-0.14}$$

consistent with naive factorization power counting

Penguin annihilation helicity ampltiudes

penguin annihilation: $< (\bar{d}b)_{S-P} \times (\bar{s}d)_{S+P} >$ (penguin operator Q_6)



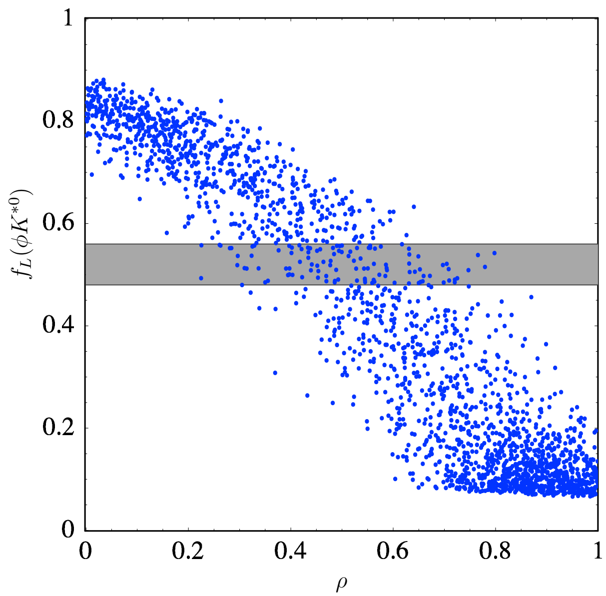
$\propto \langle \phi K^* | \bar{s}\, d | 0 \rangle$

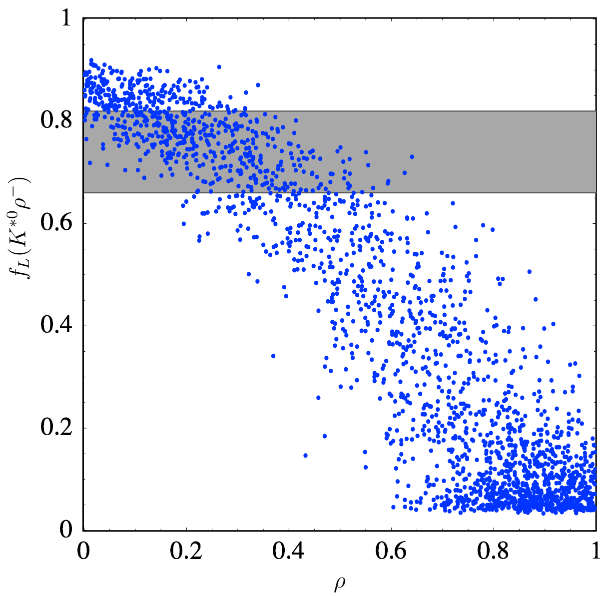
$$\mathcal{A}^0,\ \mathcal{A}^- = O\left(\frac{1}{m^2}\ln^2\frac{m}{\Lambda_h}\right), \qquad \mathcal{A}^+ = O(\frac{1}{m^4})$$

- $\mathcal{A}^0,\ \mathcal{A}^-$ of same order $\Rightarrow$ large penguin annihilation could explain low f_L in penguin-dominated decays

Scans for ϕK^{*0} and $K^{*0}\rho^+$

- require total BR's lie in exp 90% c.l. intervals
- simplified scans: set ρ_f's equal, $\phi_f = 0$ in $\mathcal{A}^0$, $\mathcal{A}^-$



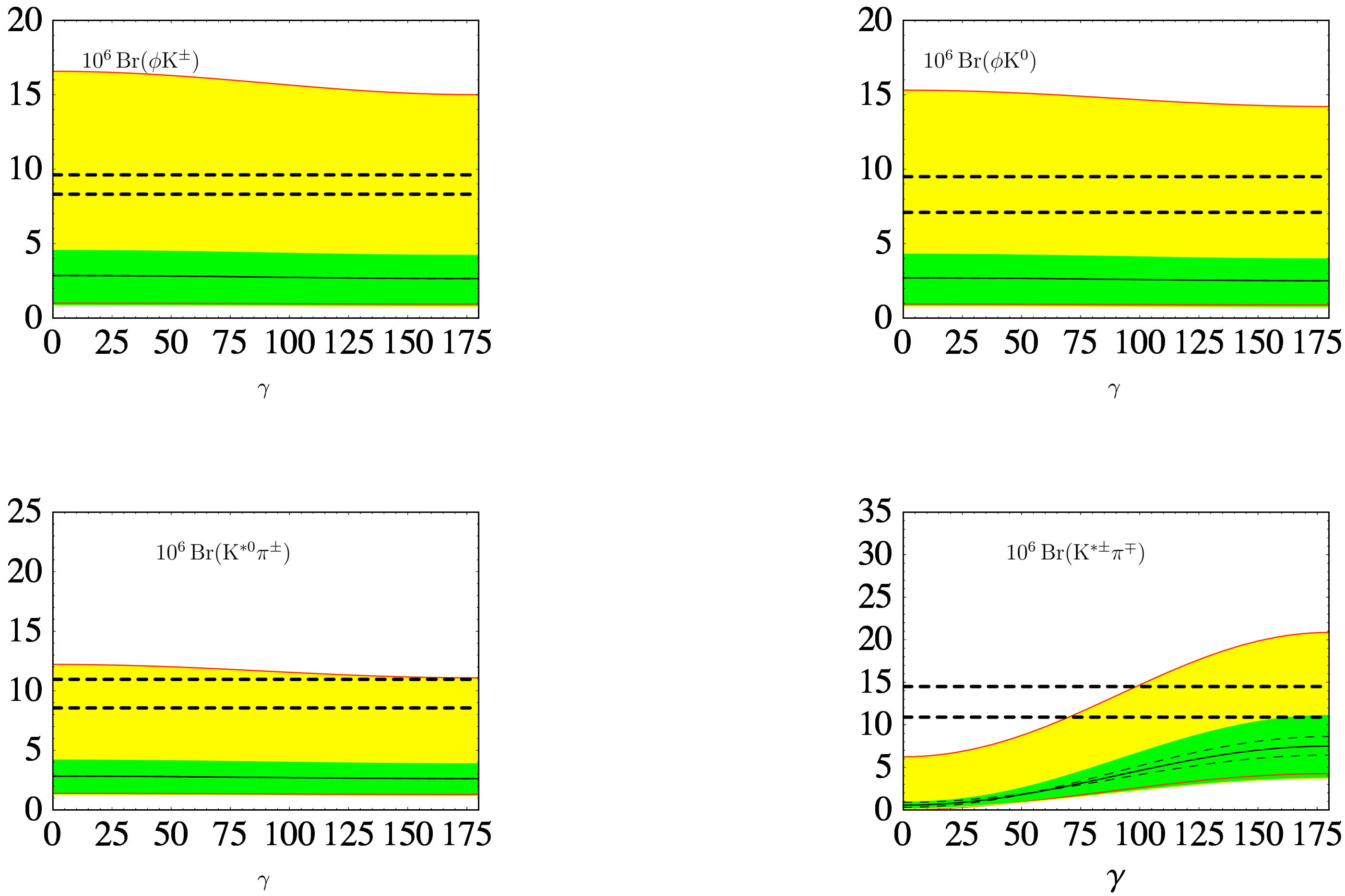


- data favors $\rho_f \sim 0.4 - 0.8$ (for asymptotic light-cone distribution amplitudes), or

$$X_f(VV) \approx \log\left(m_B/\Lambda_h\right)\,(1.4 - 1.8) \approx (3 - 4)$$

- penguin annihilation $\sim$ leading power penguin
- $f_L(\rho\rho)$ predictions consistent with experiment
  - $\rho^+\rho^0$: no penguin, penguin annihilation
  - $\rho^+\rho^-$, $\rho^0\rho^0$: CKM suppressed penguin, penguin annihilation

Power corrections and $\mathrm{Br}(\mathrm{B} \to \mathrm{VP})$



Green bands: uncertainty due to variation of input parameters. Yellow bands: include uncertainty from penguin annihilation power corrections, in quadrature, with $\rho_f \leq 0.8$

- data favors $\rho_f(K^*\pi) \sim 1.0$, $\rho_f(\phi K) < \rho_f(K^*\pi)$ (for asymptotic light-cone DAs), or

$$X_f(VP) \approx \log\left(m_B/\Lambda_h\right) 2 \approx 5$$

- penguin annihilation $\sim$ leading power penguin

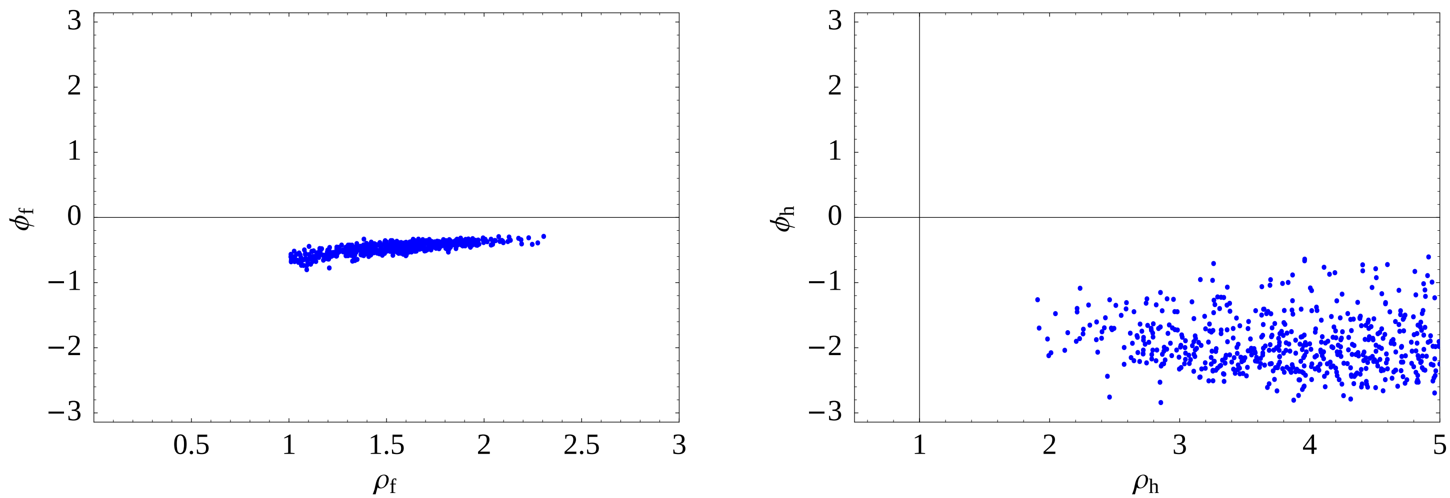
Power corrections and the $B \to K\pi$, $\pi\pi$ "puzzles"

- at leading-power in QCDF:
  - $\mathrm{Br}(K^0\pi^0)$, $\mathrm{Br}(\pi^0\pi^0)$ too small
  - $A_{CP}(\pi^+\pi^-)$ too small, $A_{CP}(K^+\pi^-)$ has wrong sign and magnitude too small
  - $A_{CP}(K^+\pi^-) \approx A_{CP}(K^+\pi^0)$ contrary to observation (also see bauer *et. al.*)

- large power-corrections could be responsible:
  - large penguin annihilation could explain $A_{CP}(\pi^+\pi^-)$, $A_{CP}(K^+\pi^-)$
  - large hard-spectator interaction could enhance C/T, explain remaining discrepancies.

Scans for $B \to K\pi$

- require all BR's, $A_{CP}(K^+\pi^-)$, $A_{CP}(K^+\pi^0)$ lie within observed 1σ ranges



- data favors $\rho_f \in [1.0, 2.3]$, $\rho_h \geq 2.0$ (for asymptotic DAs), or

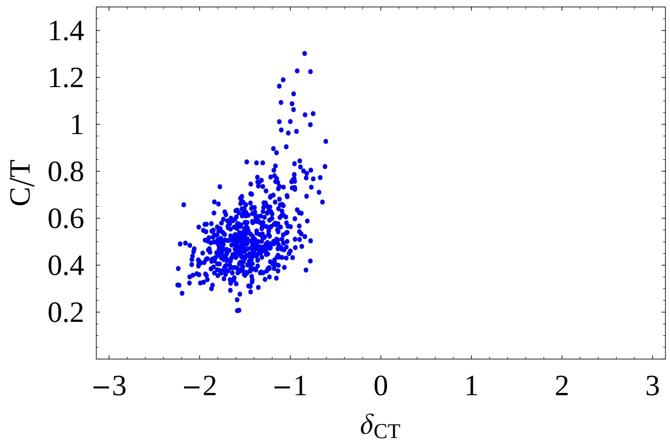
$$X_f(K\pi) \approx \log(\frac{m_B}{\Lambda_h})(2-3) \approx (5-8)$$

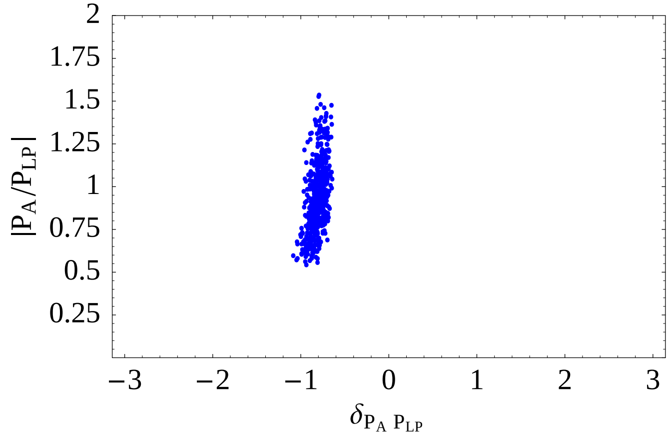
$$X_h(K\pi) \geq \log(\frac{m_B}{\Lambda_h})\,3 \geq 7$$

$\Rightarrow$ especially large end-point enhancement for PP

Scans for $B \to K\pi$ continued

- C vs. T, penguin annihilation (P_A) vs. leading power penguin (P_{LP}) amplitudes, relative strong phases:

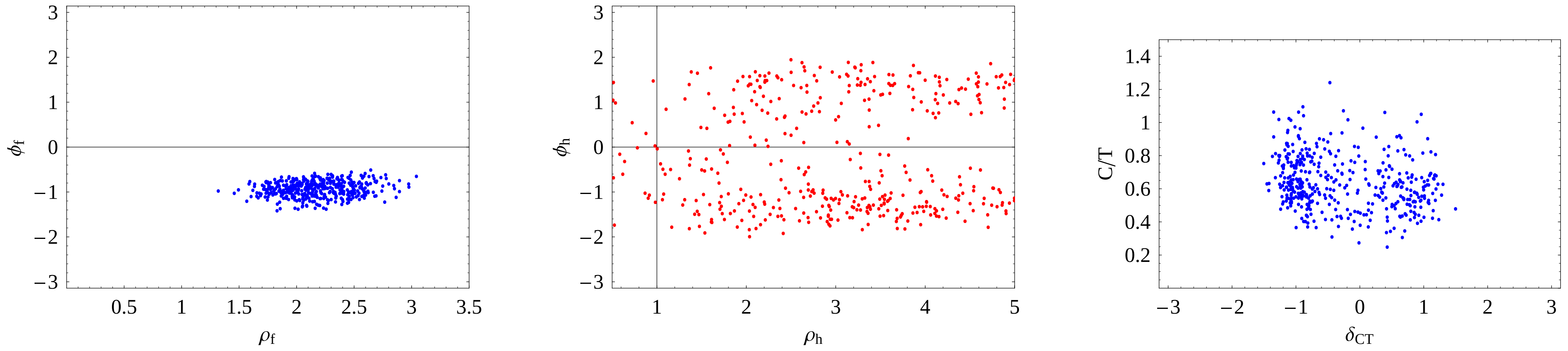




  - ranges of $|C/T|$, relative strong phase δ_{CT} compatible with recent $SU(3)_F$ fits e.g., Chiang, Zhou
  - penguin annihilation $\sim$ leading power penguin
  - relative strong phase $\delta_{P_A P_{LP}}$ fixed by $A_{CP}(K^+\pi^-)$

Scans for $B \to \pi\pi$

- require all BR's, $A_{CP}(\pi^+\pi^-)$, $S(\pi^+\pi^-)$ lie within observed 1σ ranges also see Kou and Pham



- data favors $\rho_f \in [1.5, 3.0]$, $\rho_h \gtrsim 1.0$ (for asymptotic DAs), or

$$X_f(\pi\pi) \approx \log(\frac{m_B}{\Lambda_h})(2.5 - 4.0) \approx (6 - 9)$$

$$X_h(\pi\pi) \geq \log(\frac{m_B}{\Lambda_h})(2) \geq 5$$

$\Rightarrow$ again, large end-point enhancement for PP

- C/T compatible with $SU(3)_F$ fits

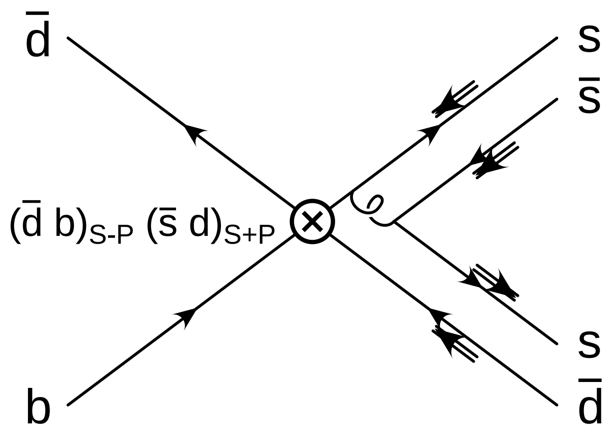
Power corrections in $B \to M_1 M_2$: Summary

- $f_L(VV)$, tranversity strong phases require $O(1)$ penguin annihilation with soft rescattering, $X_f(VV) \approx \log(m_B/\Lambda_h)(1.4 - 1.8)$
- $\Delta S = 1$ $B \to VP$ rates require $O(1)$ penguin annihilation, $X_f(K^*\pi) \approx \log(m_B/\Lambda_h)\,2$
- $B \to K\pi$, $\pi\pi$ rates, CP asymmetries require
  - $\mathcal{O}(1)$ penguin annihilation with soft-rescattering, $X_f(\pi\pi) \approx \log(\frac{m_B}{\Lambda_h})(2.5 - 4.0)$
  - large hard spectator interactions with soft-rescattering, $X_h(K\pi) \geq \log(\frac{m_B}{\Lambda_h})\,3$
- data requires large end-point enhancement in $B \to PP$, more moderate enhancement in $B \to VP\,, VV$
- need direct probe of power corrections to check if large would-be end-point enhancements in B decays arise elsewhere, at similar energies.

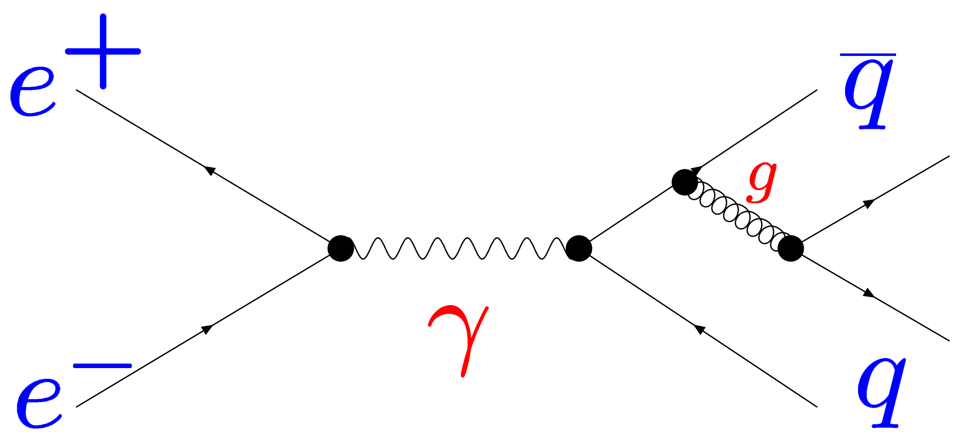
$$e^+e^- \longrightarrow M_1 M_2$$

probing power corrections directly in $e^+e^- \to M_1 M_2$

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

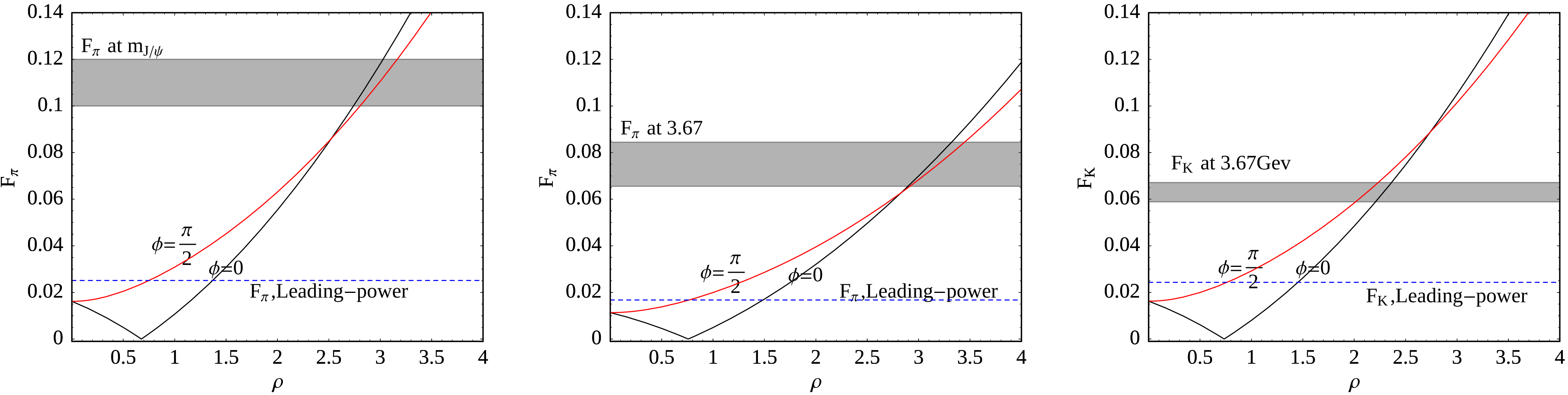
$$\langle VP|\bar{q}\,\gamma_\mu q|0\rangle = \frac{2iV^q}{m_P+m_V}\epsilon_{\mu\nu\rho\sigma}\epsilon^\nu p_V^\sigma p_P^\rho$$

$$\langle P_1P_2|\bar{q}\,\gamma^\mu q|0\rangle = F^q(p_1-p_2)^\mu$$

$\langle V_1V_2|\bar{q}\,\gamma^\mu q|0\rangle$ contains three form factors

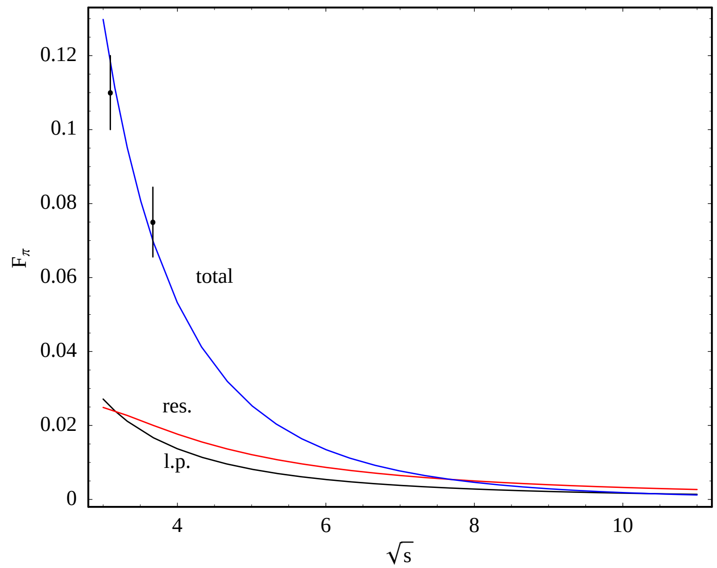
- use same parametrization for IR logs in form factor power corrections (X , ρ , ϕ)
  - $V^q \sim 1/s^2 ln^2(\sqrt{s}/\Lambda)$
  - F_π = leading-power pQCD $\sim 1/s$ (Brodsky, Lepage) +
    power correction $\sim 1/s^2 ln^2(\sqrt{s}/\Lambda)$
- Use continuum CLEO-c + BES data at $\sqrt{s} \approx 3.7$ GeV to determine ranges for ρ, X, or importance of end-point soft-overlap in F^q, V^q
- extrapolate to larger $\sqrt{s}$, e.g.,
  - $\sqrt{s} \sim m_B$ via initial state radiation (ISR)
  - $\sqrt{s} = m_{\Upsilon(4S)}$
    - compare with new Babar $e^+e^- \to \phi\eta$ cross-section

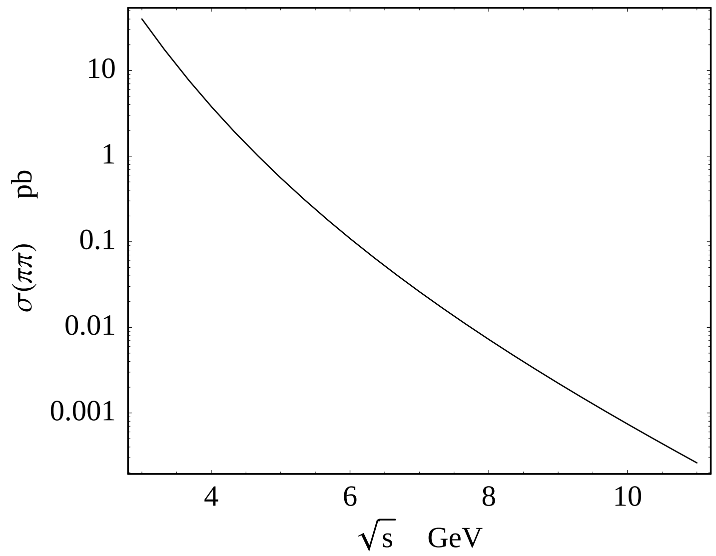
CLEO-c continuum $e^+e^- \to \pi^+\pi^-$, K^+K^- at $\sqrt{s} = 3.67$ GeV



- Mark III F_π determination from $J/\psi \to \pi^+\pi^-$: electromagnetic decay, but not as clean as continuum F_π measurement. assumes negligible J/Ψ bound state effects,...
- $O(1/s^2)$ power corrections dominate
- data favors $\rho \approx 2-3$ (for asymptotic DA's), or $X \approx \log(3.67/\Lambda_h)\,(3-4) \approx (6-8)$
  - large end-point enhancement similar to $B \to PP$ fit
- in $SU(3)_F$ limit, $F_\pi/F_K \to f_\pi^2/f_K^2 = 0.67$. Observed ratio $1.19 \pm 0.17 \Rightarrow$ significant $SU(3)_F$ breaking

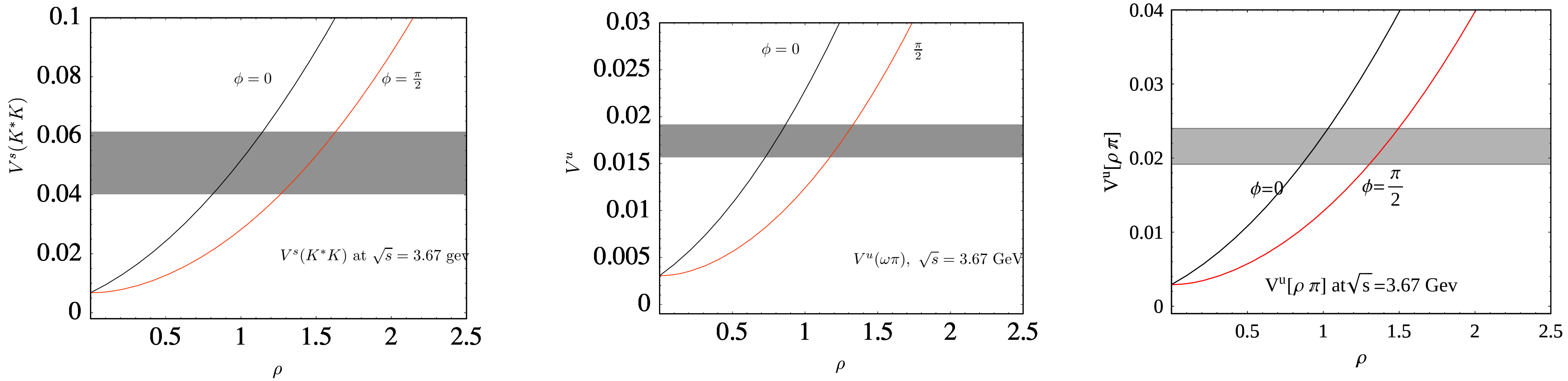
$e^+e^- \to \pi^+\pi^-$, K^+K^- continued





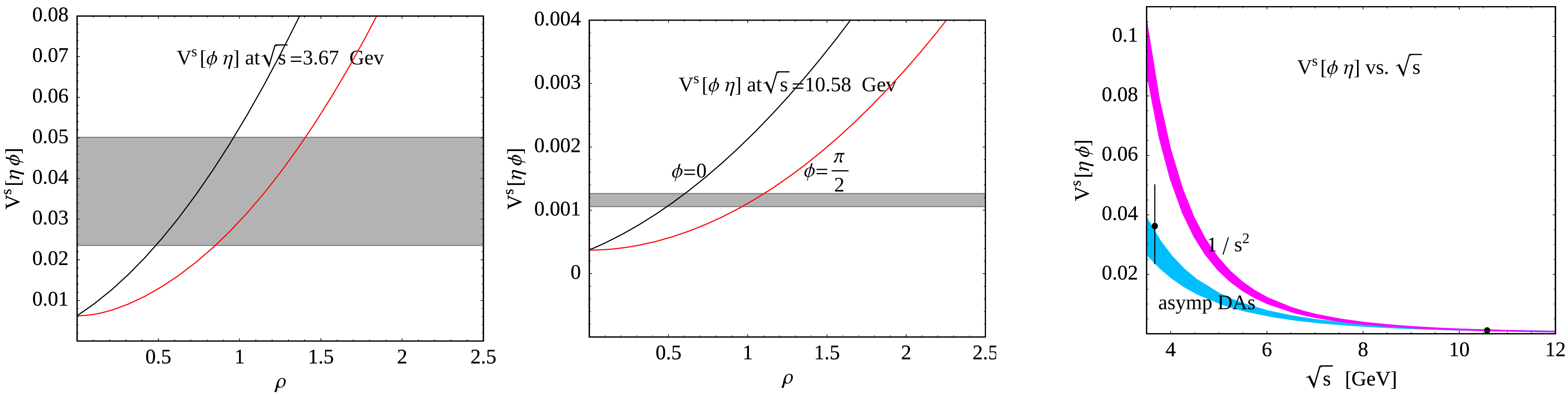
- Is $\sqrt{s} = 3.67$ GeV sufficiently beyond the resonance region to probe asymptotic power corrections, end-point meson production?
  - taking into account first 3 ρ resonances explicitly, dual resonance model for higher ρ excitations (Bruch, Khodjamirian, Kuhn) is consistent with leading-power F_π above 3 GeV
  - duality sets in sufficiently at 3.67 GeV to probe asymptotic effects
- $\sigma(\pi^+\pi^-) \sim 0.5$ pb at $\sqrt{s} \sim m_B$
  - effective luminosity at 1/ab from initial state radiation $\approx 50\ \mathrm{pb}^{-1}$ per 0.1 GeV for $\sqrt{s} \approx m_B$ (scaled up from BaBar 89.3 fb^{-1} Solodov ICHEP 04)
  - expect $\sim 25\ \pi^+\pi^-$ pairs per 0.1 GeV for $\sqrt{s} \approx m_B$ at 1/ab

CLEO-c continuum $e^+e^- \to VP$ at $\sqrt{s} = 3.67$ GeV



- data favors $\rho \sim 1$ (for asymptotic DA's), or $X \approx \log(3.67/\Lambda_h)\, 2 \approx 4$
  - end-point enhancement similar to $B \to VP$
- $\sigma(K^{*0}K^0) = 23.5 \pm 1.1 \pm 3.1$ pb, $\sigma(K^{*+}K^-) < 0.6$ pb $\Rightarrow$ large deviation from $SU(3)_F$ limit $\sigma(K^{*+}K^-)/\sigma(K^{*0}K^0) \to 1/4$
- $\sigma(K^{*0}K^0) \sim 3.0\,(0.04)$ pb at $\sqrt{s} \approx m_B\ (m_{\Upsilon(4S)})$
  - ISR with 1/ab: expect $\sim 150\ K^{*0}K^0$ pairs per 0.1 GeV at $\sqrt{s} \approx m_B$
  - at the $\Upsilon(4S)$ with 1/ab: $\sim 40K$ ($4K$) $K^{*0}K^0$ pairs on (off) peak

$e^+e^- \to \phi\eta$ at 3.67 GeV (CLEO-c) and at the $\Upsilon(4S)$ (Babar)



- Ranges of ρ at 3.67 GeV and at 10.58 GeV are consistent (a bit lower than for K^*K, $\omega\pi$, $\rho\pi$)
- extrapolation over a large range of $\sqrt{s}$ $\Rightarrow$ increased sensitivity to subleading s dependence, e.g., is there a $\log^2(\sqrt{s}/\Lambda)$ dependence? in the present model does ρ need to decrease with increasing s? is there an α_s factor which decreases with increasing s?....
- with the present CLEO-c experimental precision, the model s dependence

$$V^s(\phi\eta) \propto \frac{g_s^2}{s^2}(A\log^2(\sqrt{s}/\Lambda_h) + B\log\sqrt{s}/\Lambda_h + C)$$

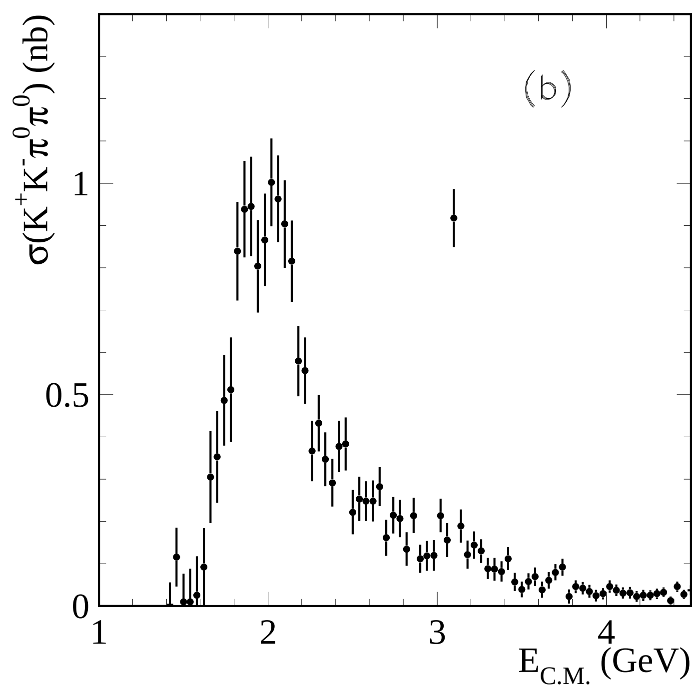
  where g_s, A, B, C are s-independent is consistent with the data
- at 1/ab more precise measurements of the $\sqrt{s}$ dependence for many modes will be possible

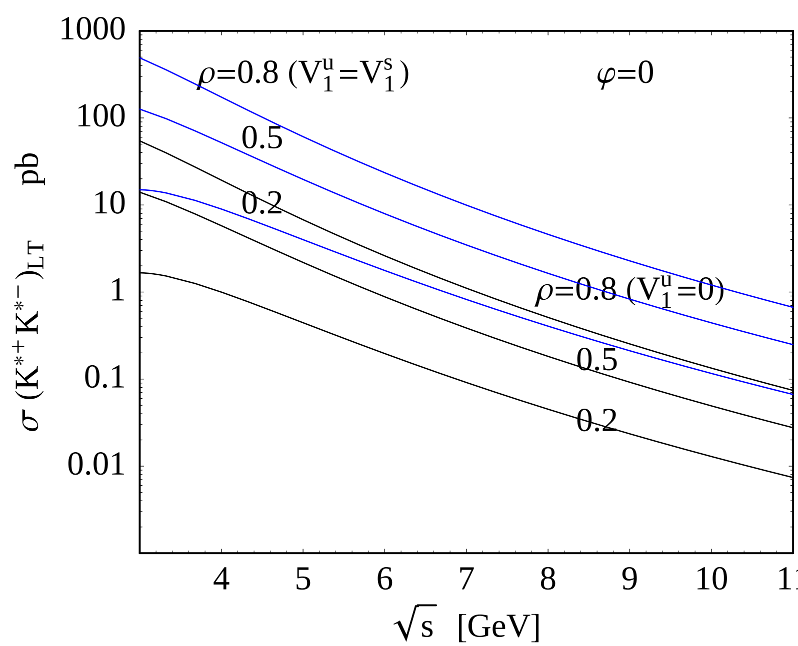
$e^+e^- \to VV$

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

Polarizations: $V_1^q \Rightarrow LT$ dominates, $\mathcal{A} \sim 1/Q^2\, \mathrm{Log}^2\, Q/\Lambda \qquad Q \equiv \sqrt{s}$

$V_3^q \Rightarrow LL$, $\mathcal{A} \sim$ (lead power $1/Q$)+($1/Q^3\, \mathrm{Log}^2\, Q/\Lambda$), $V_2^q \Rightarrow TT$, $\mathcal{A} \sim 1/Q^3\, \mathrm{Log}^2\, Q/\Lambda$





- BaBar $KK\pi\pi$ from ISR upper bound, hint for $\sigma(K^{*+}K^{*-}) = O(10-30)$ pb at $\sqrt{s} \approx 4$ GeV? (hep-ex/0610018, 232 fb^{-1})
  - would roughly correspond to $\rho \sim .2 - .8$ (depending on violation of $SU(3)_F$ relation $V_1^u = V_1^s$). comparable to end-point enhancement in $B \to VV$

Is there really a large end-point contribution?

- In all of the e^+e^- processes we have looked at, the X^2 terms dominate the cross-section fits, ranging from $X^2 \sim 16$ for VP (for $\rho \sim 1$ at 3.67 GeV) to $X^2 \sim 60$ for PP (for $\rho \sim 3$ at 3.67 GeV)
- If there are no large end-point contributions, e.g., if somehow the divergences are "tamed", then there are no large $\log$'s, and we can expect these terms to make negligible contributions. Our form factor predictions would typically be two orders of magnitude too small.
  - we have not included higher Fock-state amplitudes, and have restricted our discussion to asymptotic distribution amplitudes - but this could not possibly make up such a shortfall
- This is what happens in the "zero-bin subtraction" at leading order in α_s. manohar, stewart; arnesen, ligeti, rothstein, stewart. Applied to $e^+e^- \to M_1 M_2$, essentially trade

$$g_s^2 \ln^n(\sqrt{s}/\Lambda) \quad \text{for} \quad 4\pi\alpha_s(\mu) \ln^n(\sqrt{s}/\mu)\,,$$

  where $\mu \sim \sqrt{s}$ is a perturbative renormalization scale.
- It is difficult to imagine what could make up over an order of magnitude in the time-like form factors other than some non-perturbative dynamics, in which case we must have soft degrees of freedom in the outgoing mesons, i.e. large soft overlaps!

Summary

- puzzles in charmless $B \to M_1 M_2$ could, in principle, be accounted for via power corrections, with mesons produced in the end-point region
  - requires VV, VP, PP penguin annihilation amplitudes of same order as leading-power penguins, large PP hard-spectator C amplitudes $\Rightarrow$
    - large enhancement of end-point production (IR logs) in PP, more moderate enhancement in VV, VP
- $e^+e^- \to M_1 M_2$ provides a direct probe of power corrections, end-point meson production, $SU(3)_F$ violation in power corrections.
  - remarkably, continuum CLEO-c data + Babar yields same pattern required in B decays
    - large enhancement of end-point production in PP, moderate enhancement in VV, VP
- vital role to be played by continuum studies at the B factories. $\sqrt{s}$ dependence provides important check of power counting, possibly can probe subleading $\sqrt{s}$ dependence, e.g., due to large $\log$'s (soft overlap), α_s,..... At $1/ab$
  - VP and VV at $\sqrt{s} \sim m_B$ from ISR looks doable
  - VP and VV at the $\Upsilon(4S)$ looks doable. Look for helicity amplitude (LT vs. LL) strong phase difference in VV?
  - PP more challenging