What can $e^+e^- \to M_1 M_2$ tell us about power corrections in $B \to M_1 M_2$ decays?

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-based on work done with Murugesh Duraisamy, arXiv:0812.3162, and to appear

Outline

- Motivation
- Leading power vs. power corrections
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- VP final states
  - $e^+e^- \to VP$ at CLEO-c and at the $\Upsilon(4S)$
  - power corrections in $B \to K^*\pi$
- VV final states
  - $e^+e^- \to \rho^+\rho^-$ at the $\Upsilon(4S)$
  - the longitudinal polarizations in penguin dominated $B \to \phi K^*$, ρK^*
- Conclusion

Motivation

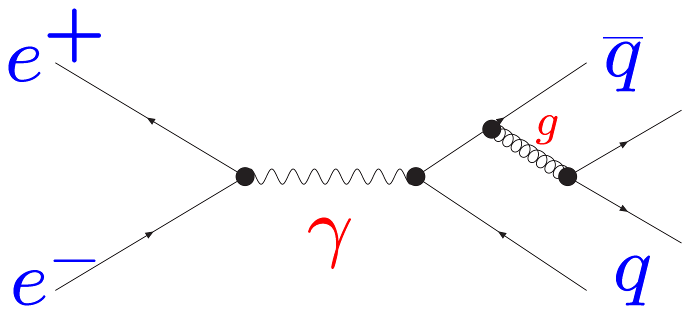
Many "puzzles" in charmless $B \to M_1 M_2$ at leading power in the $1/m_b$ expansion:

- in $B \to PP$:
  - $\mathrm{Br}(K^0\pi^0)$, $\mathrm{Br}(\pi^0\pi^0)$ 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
- in $B \to VP$:
  - $B \to \phi K$ and $B \to K^*\pi$ rates too small
- in $B \to VV$
  - $B \to \phi K^*$, $B \to K^*\rho$ longitudinal polarization fractions (≈ 1) much larger than observed ($\approx 50\%$)

Focus on possibility that

- certain power corrections (PC's) in $1/m_b$ are enhanced due to long-distance effects, e.g.,
  - in an outgoing meson, one valence quark is hard, the other soft
  - large "soft-overlap" between the fast and soft valence quarks is required
- can not estimate power correction magnitudes via comparison to leading power!!!
- CLEO-c and the B factories measure $e^+e^- \longrightarrow M_1 M_2$ cross sections at different $\sqrt{s}$. They are either PC dominated, or pure PC's in $1/\sqrt{s}$.
  - ideal for isolating PC's and checking for large soft-overlaps
- $\sqrt{s} \sim m_B \Rightarrow$ learn about the importance of soft-overlaps in $B \longrightarrow M_1 M_2$. Could they be $O(1)$?

Leading power vs. power corrections: $e^+e^- \to M_1 M_2$



$\propto \quad \langle M_1 M_2 | \bar{q}\, \gamma_\mu q | 0 \rangle$

parametrized in terms of dimensionless timelike form factors

- Each quark helicity flip requires transverse momentum, $k_\perp$

  $\Rightarrow O\left(\Lambda_{QCD}/\sqrt{s}\right)$ form factor suppression, for meson with energy $\sqrt{s}/2$

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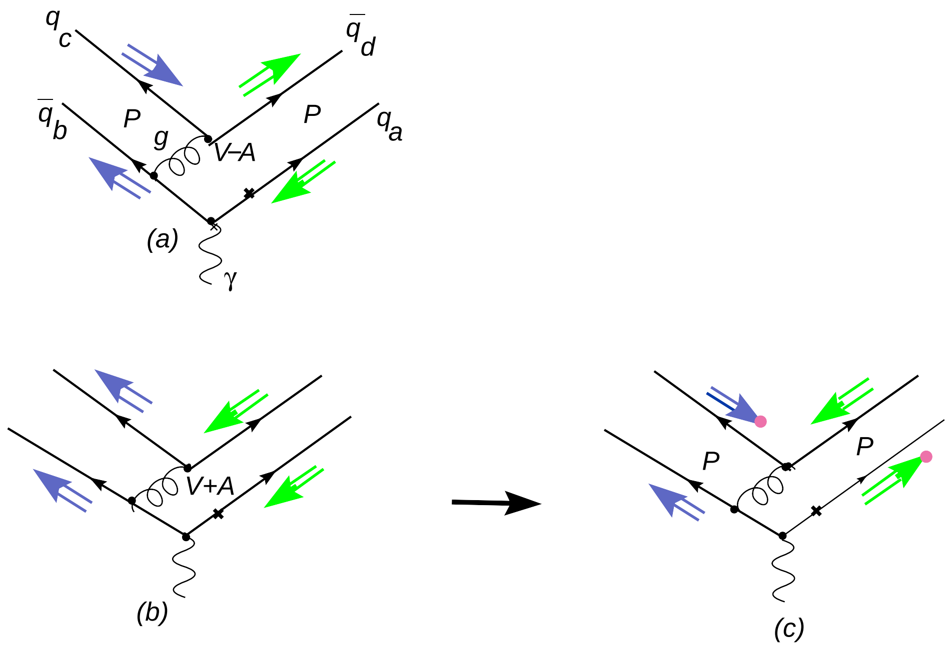
$e^+e^- \to \pi^+\pi^-$, K^+K^-: $\quad \langle P_1 P_2 | J^\mu_{\rm em} | 0 \rangle = F_P(s)(p_1 - p_2)^\mu$



(a) leading power: no helicity flip

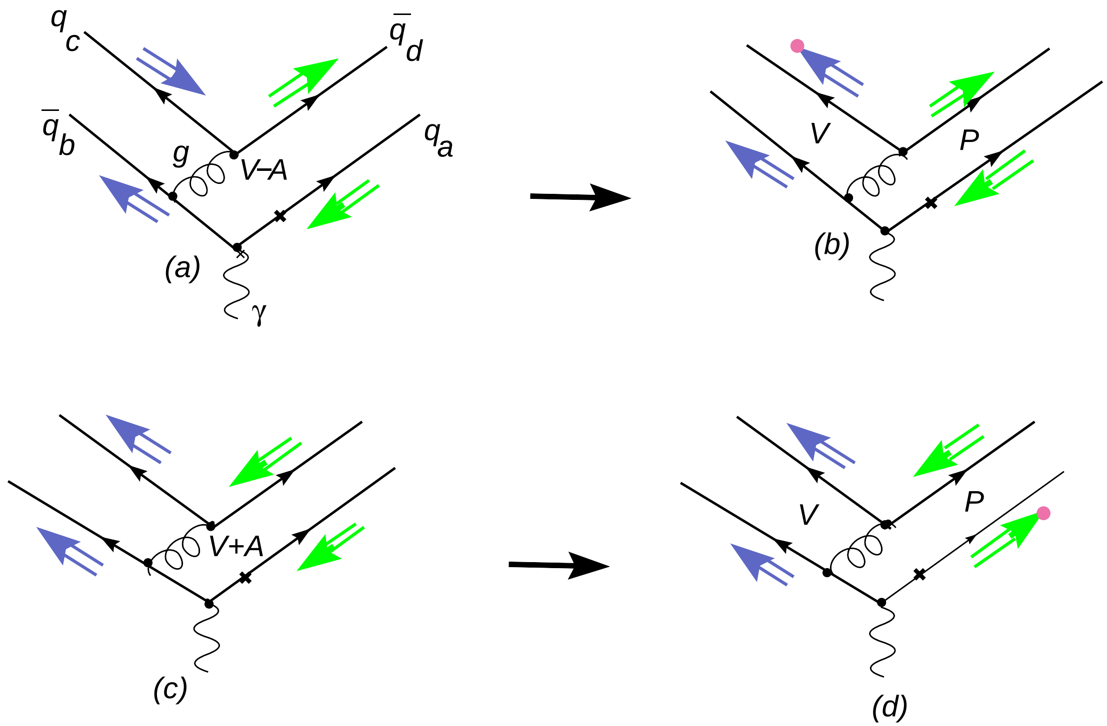
$$F_\pi^{\rm LP} \propto \frac{1}{s}, \quad \text{calculable in QCD Factorization}$$

(b), (c) power correction: two helicity flips

$$\delta F_\pi \propto \frac{1}{s^2}, \quad \text{infrared divergent, not calculable}$$

$e^+e^- \to VP$: $\quad \langle VP|J^\mu_{\rm em}|0\rangle = \frac{1}{m_P+m_V}\, 2\,i\,V_{VP}(s)\,\epsilon_{\mu\nu\rho\sigma}\epsilon^\nu p_V^\sigma p_P^\rho$

Parity + angular momentum conservation ⇒ V is transverse



always need one helicity flip ⇒ V_{VP} is a pure power correction

$$V_{VP} \propto \frac{1}{s^2}, \quad \text{infrared divergent , not calculable}$$

- $e^+e^- \to V_1 V_2$:

Three form factors: for LL, TL, and TT polarizations

$$T \equiv \text{transverse}, \quad L \equiv \text{longitudinal}$$

$$\langle V_1 V_2 \mid J^\mu_{em} \mid 0\rangle = \left[\frac{m_{V_1}(\epsilon_1^\star . p_2)}{2E^2}\right]\left[\frac{m_{V_2}(\epsilon_2^\star . p_1)}{2E^2}\right](p_1 - p_2)^\mu V_{LL}(s) + \left(\epsilon_{1\perp}^{\star\mu}\left[\frac{m_{V_2}(\epsilon_2^\star . p_1)}{2E^2}\right]\right.$$
$$\left. - \epsilon_{2\perp}^{\star\mu}\left[\frac{m_{V_1}(\epsilon_1^\star . p_2)}{2E^2}\right]\right) V_{LT}(s) + \left(\epsilon_{1\perp}^\star . \epsilon_{2\perp}^\star\right)(p_1 - p_2)^\mu V_{TT}(s)$$

- LL: no helicity flips $\Rightarrow$ leading power, $V_{LL}^{LP} \propto 1/s$

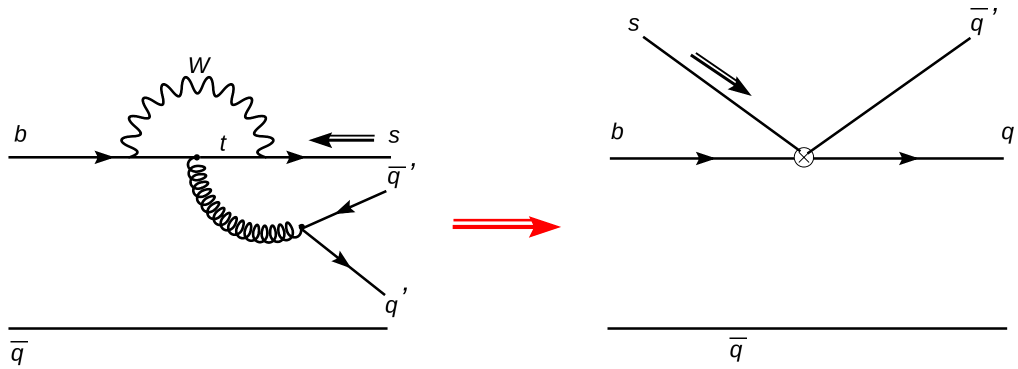
  two helicity flips $\Rightarrow$ power correction, $\delta V_{LL} \propto 1/s^2$
- LT: one helicity flip $\Rightarrow$ pure power correction, $V_{LT} \propto 1/s$
- TT: two helicity flips $\Rightarrow$ pure power correction, $O(\Lambda^2_{QCD}/s)$ suppression

The power corrections are infrared divergent, not calculable

Leading power vs. power corrections: $B \to M_1 M_2$

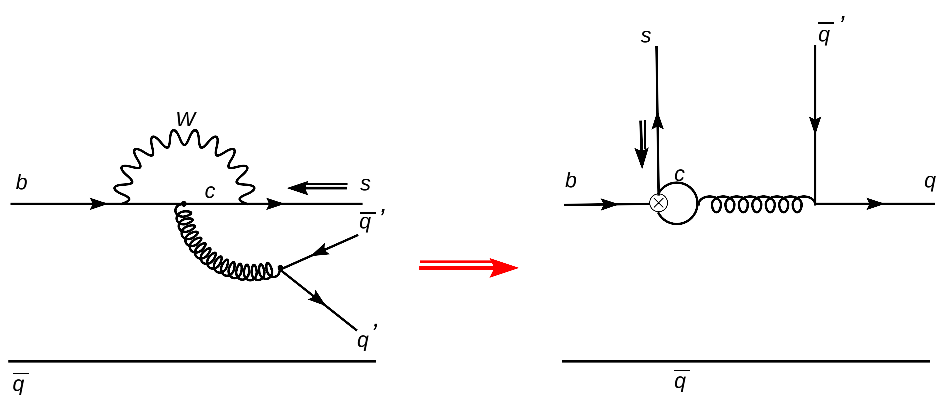
QCD penguin amplitude (P) at leading power:

- leading order in α_s (naive factorization), e.g.,



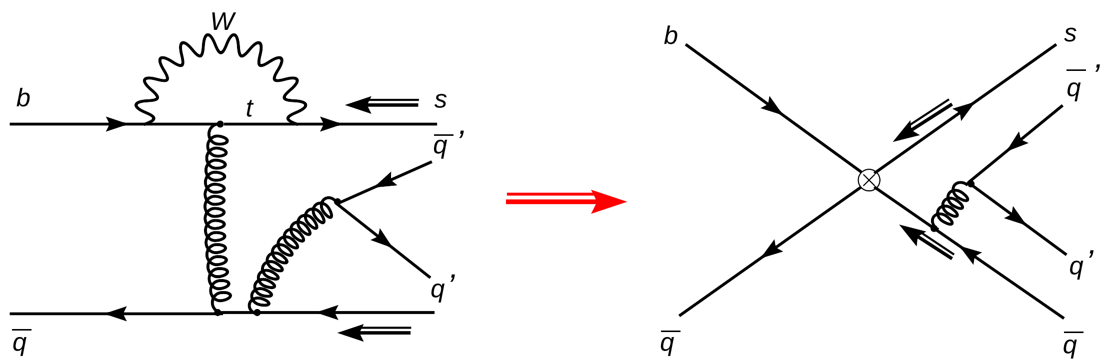
$$\mathcal{A} \quad \propto \langle M_2|\bar{s}\gamma^\mu(1\mp\gamma_5)q'|0\rangle\,\langle M_1|\bar{q}'\gamma_\mu(1-\gamma_5)b|\bar{B}\rangle$$
$$\propto \text{ decay constant} \times \text{form factor}, \text{ scales like } \mathrm{m_B^{1/2}}$$

- leading power but higher order in α_s, e.g., charm loops:



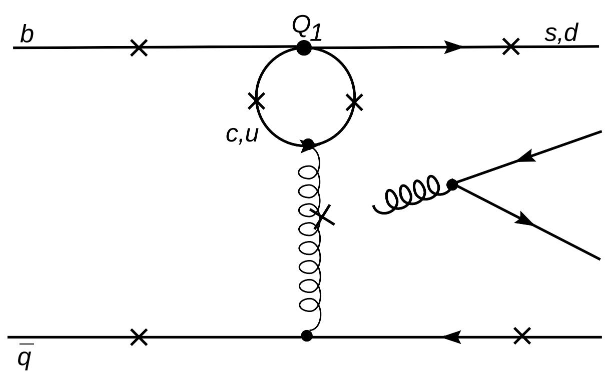
QCD penguin power corrections

- "Weak annihilation", e.g., (perturbative limit)



  - annihilation topology $\Rightarrow 1/m_b$ suppression ($\mathcal{A} \propto f_{M_1} f_{M_2} f_B$)
  - quark helicity flip in PP, VP, or VV final states $\Rightarrow 1/m_b$ suppression

- Charm loop power corrections, e.g., (perturbative limit)



  - charm loop PC's cancel weak annihilation (and hard spectator) leading $\log \mu_b$ renormalization scale dependence

Power correction amplitudes

- At subleading powers in $1/m_b$:

  short / long distance factorization breaks down

  $\Rightarrow$ amplitudes could be soft dominated

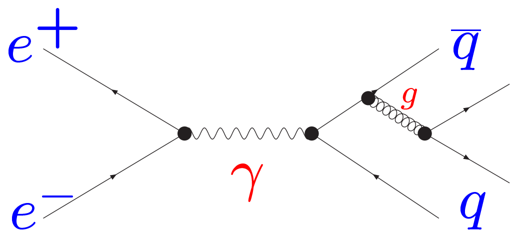
  - Signaled by infrared log divergences in the convolution integrals

    $\Rightarrow$ mesons produced in asymmetric configurations, e.g.,

    fast valence antiquark, soft valence quark

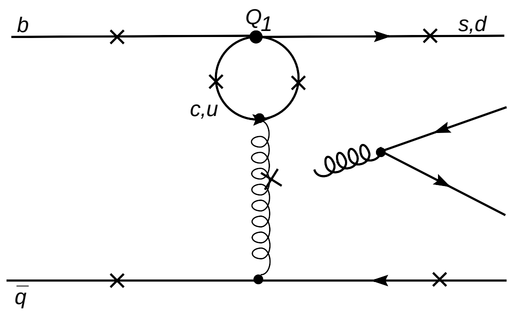
  - the light mesons would be produced via soft-overlaps, necessarily non-perturbative $\Rightarrow$ large strong phases are possible

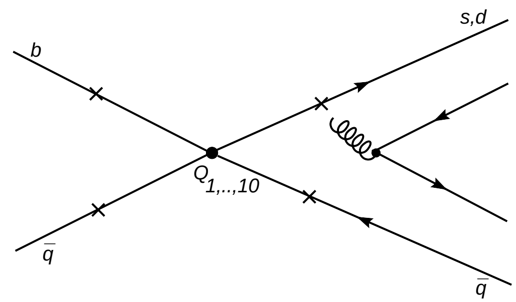
Compare timelike form factor PC's



$$F_{M_1 M_2} \propto \langle M_1 M_2 | \bar{q}\, \gamma_\mu q | 0 \rangle$$

to penguin PC's, e.g.,





in both cases

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- have hard outgoing quark and antiquark, $E \sim \sqrt{s}/2$ or $m_B/2$
- each hadronizes with soft quark or antiquark, i.e., both light mesons produced in asymmetric configurations via soft overlaps
- PC's for C (color suppressed amplitude): only one light meson produced via soft-overlap

Analysis Procedure

- Perturbative calculations of PC's on the light-cone contain infrared log-divergent terms

$$\sim \alpha_s(\mu_h) \left(\frac{1}{\sqrt{s}} \right)^n \left(\log \frac{\sqrt{s} \text{ or } m_B}{\Lambda} \right)^m ,$$

$\Lambda \sim \Lambda_{QCD}$ represents a physical IR cutoff

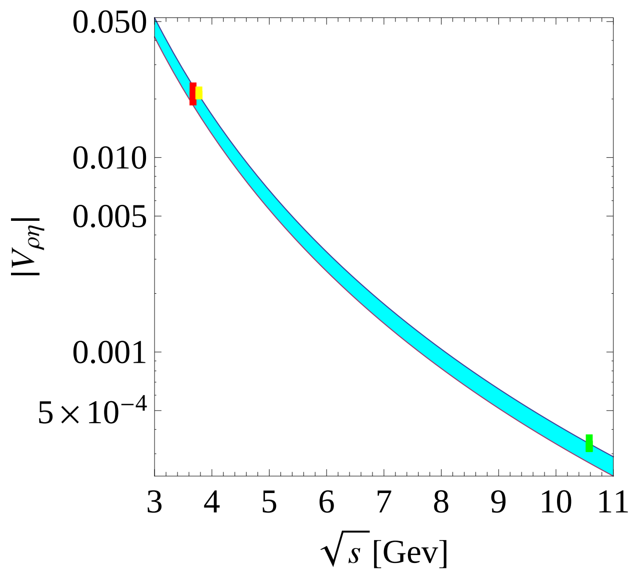
- Separate PC's into "perturbative" parts, and "non-perturbative" parts, e.g., for the pion form factor

$$\delta F_\pi = \delta F_\pi^{\text{pert.}} + \delta F_\pi^{\text{non-pert.}}$$

- perturbative parts correspond to $\Lambda \gtrsim \sqrt{1}$ GeV, $\quad 1 \text{ GeV} \lesssim \mu_h \lesssim \sqrt{s}$ or m_B
- comparison with $e^+e^- \to M_1 M_2$ data yields non-perturbative parts, e.g., $\delta F_\pi^{\text{non-pert.}} / \delta F_\pi^{\text{pert.}}$
- Asssume B decay "puzzles" due to PC's. Fit non-perturbative PC's to data.
- Compare ratios of non-perturbative to perturbative PC's in $e^+e^- \to M_1 M_2$ and $B \to M_1 M_2$.

Two ways to test power counting rules

- check $\sqrt{s}$ dependence of $e^+e^- \to M_1 M_2$ form factors, e.g., $V_{\rho\eta} \propto 1/s^2$ (CLEO-c, BELLE):



- compare power corrections in $e^+e^- \to PP$ (δF_π, δF_K) and in the QCD penguin amplitudes ($\delta P_{\pi\pi}$, $\delta P_{K\pi}$), and similarly for VP and VV final states
  - The "perturbative parts" of the power corrections are consistent with power counting rules $\Rightarrow$ ratios of non-perturbative to perturbative parts of PC's with similar kinematics should be consistent (order of magnitude), e.g.,

$$\delta F_\pi^{\mathrm{non-pert.}} / \delta F_\pi^{\mathrm{pert.}} \sim \delta P_{\pi\pi}^{\mathrm{non-pert.}} / \delta P_{\pi\pi}^{\mathrm{pert.}}$$

and similarly for VP, VV final states

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

- CLEO-c measures ($\langle P^+P^- | J^\mu_{\rm em} |0\rangle = F_P(s)\,(p^+ - p^-)^\mu$)

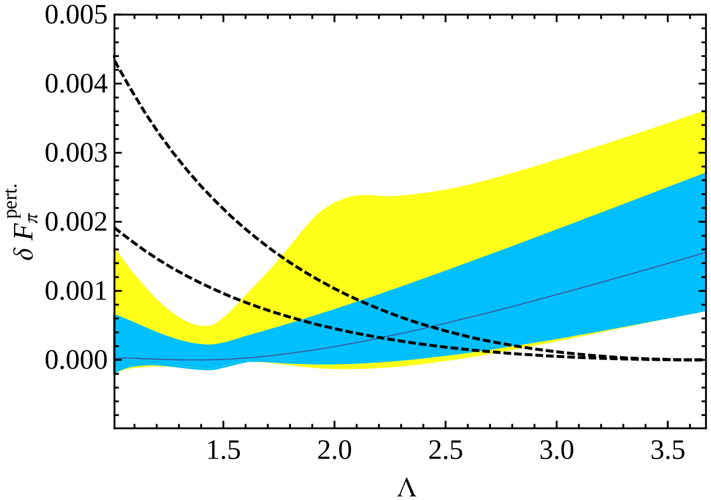
$$|F_\pi| = 0.075 \pm 0.009\,, \qquad |F_K| = 0.063 \pm 0.004$$

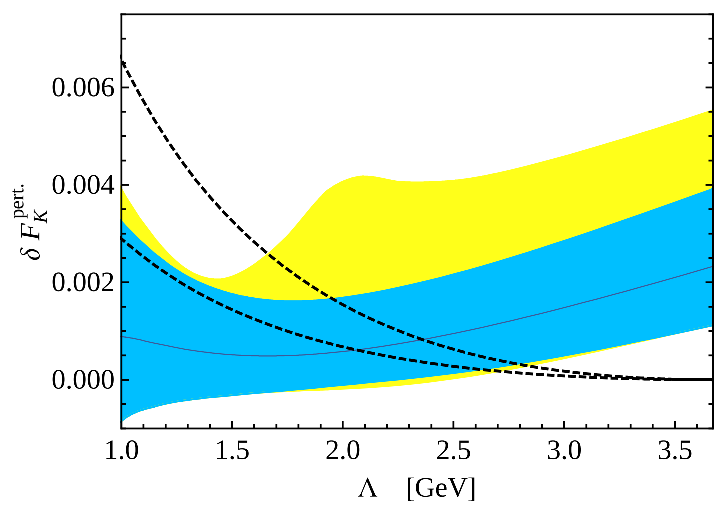
- calculable leading power contributions,

$$F_\pi^{\rm LP} = -0.01^{+0.002}_{-0.004}\,, \quad F_K^{\rm LP} = -0.014^{+0.002}_{-0.006}$$

$\Rightarrow$ F_π, F_K dominated by PC's entering at $O(1/s)$!

- perturbative PC's. blue bands: variation of inputs ($\mu_h = \Lambda$); yellow bands: add variation of μ_h; dashed lines: asymptotic light-cone distribution amplitudes





- CLEO-c data implies

$$\frac{\delta F_\pi^{\rm non-pert.}}{\delta F_\pi^{\rm pert.}} = O(10), \qquad \frac{\delta F_K^{\rm non-pert.}}{\delta F_K^{\rm pert.}} = O(10)$$

$\Rightarrow$ very large soft-overlaps !

  - similar soft enhancement would account for $F_\pi(m_{J/\Psi}) \approx 0.10$, obtained from J/Ψ decays

- Leading power form factors obey canonical $SU(3)_F$ flavor symmetry breaking

$$(F_\pi/F_K)_{\rm LP} \approx f_\pi^2/f_K^2 = 0.67$$

- $|F_\pi/F_K|_{\rm exp.} = 1.20 \pm 0.17 \Rightarrow$ PC's satisfy $|\delta F_\pi/\delta F_K| > 1$

  - apparently, soft-overlap larger for pions than kaons
  - source for large $SU(3)_F$ breaking

$B \to K\pi$, $\pi\pi$ power correction fit procedure

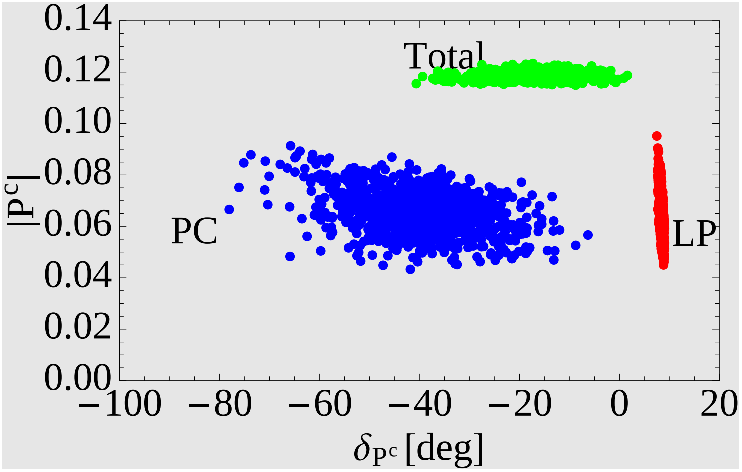
scan procedure:

- vary input parameters uniformly within errors, ($\gamma \in [50^\circ\ ,\ 80^\circ]$,....)
- require all Br's, direct CP asymmetries $A_{K^+\pi^-}$, $A_{K^0\pi^+}$, $A_{K^+\pi^0}$, $A_{\pi^+\pi^-}$, time-dep. CP asymmetry $S_{\pi^+\pi^-}$ lie within 1σ errors
- obtain predictions for $C_{K_s\pi^0} = -A_{K_s\pi^0}$, $S_{K_s\pi^0}$
- Goodness of $B \to K\pi$ fit:

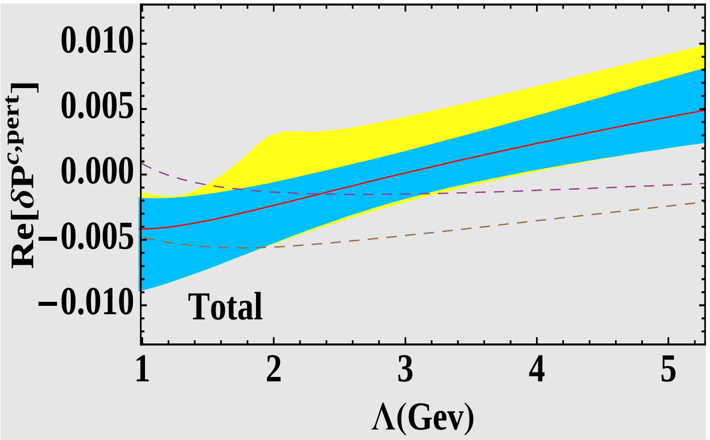
  $\chi^2_{\min}/d.\,o.\,f. \approx 3.5/2$ or only $\approx 1.4\sigma$ from Standard Model
- but are the power correction magnitudes in the fit natural?

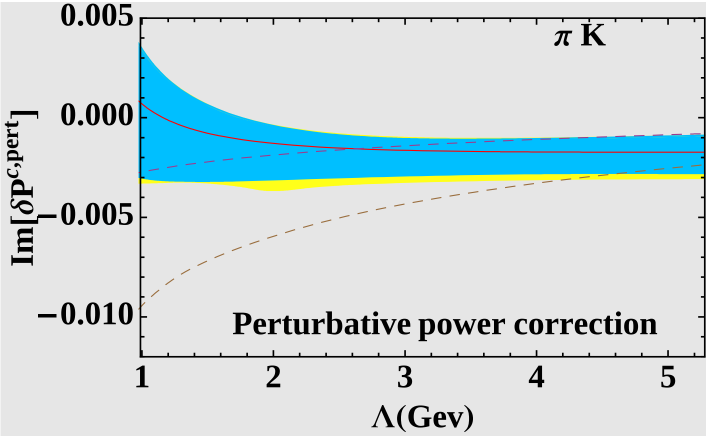
- $K\pi$ scatter plot for $|\delta P^c|$ vs. δ_{P^c} (strong phase relative to naive factorization):

  $A_{CP}(K^+\pi^-)$ favors $\delta P^c \approx P^c_{\rm LP}$ with significant strong phase



- Compare to $\delta P^{c\,,\mathrm{pert.}}$ for $K\pi$



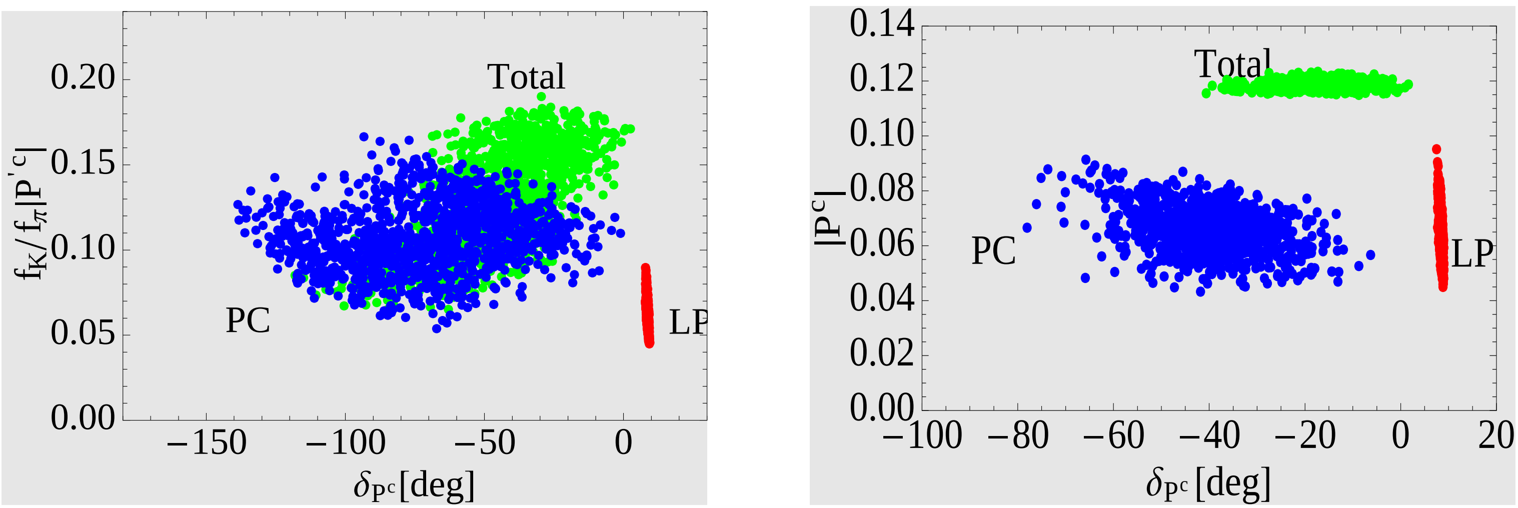


- Fits give:

$$K\pi: \quad \left|\frac{\delta P^{c\,,\mathrm{non-pert.}}}{\delta P^{c\,,\mathrm{pert.}}}\right| = O(10)\,, \qquad \pi\pi: \quad \left|\frac{\delta P'^{\,c\,,\mathrm{non-pert.}}}{\delta P'^{\,c\,,\mathrm{pert.}}}\right| = O(10)$$

similar to continuum $\delta F_{\pi,\,K}$ $\Rightarrow$ gives us confidence the fit is natural

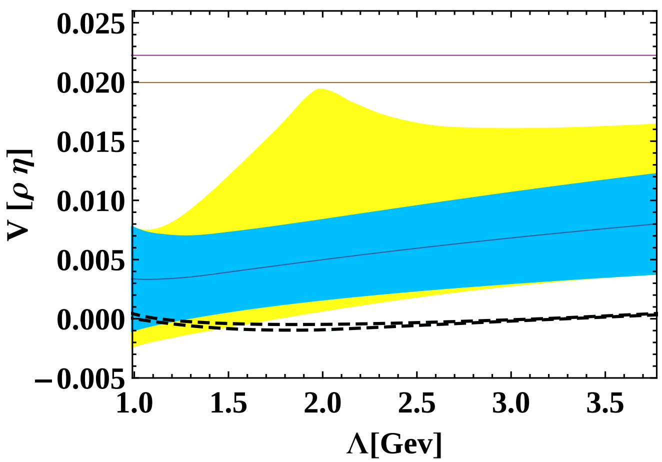
- LP penguins obey canonical $SU(3)_F$ breaking: $(f_K/f_\pi)P'^{\,c}_{\mathrm{LP}}(\pi\pi) \approx P^c_{\mathrm{LP}}(K\pi)$. Compare

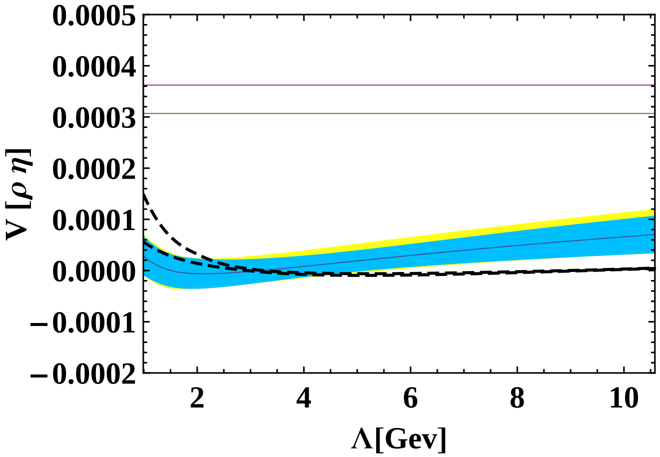


- appears $\delta P'^{\,c\,,\mathrm{non-pert.}}(\pi\pi) > \delta P^{c\,,\mathrm{non-pert.}}(K\pi)$, as in continuum $\delta F_\pi > \delta F_K$, i.e., again appears larger soft-overlap larger for pions than kaons!

$e^+e^- \to VP$ at $\sqrt{s} \approx 3.7$ GeV, 10.58 GeV

$V_{\rho\eta}$ at $\sqrt{s} = 3.77$ GeV (CLEO-c), and at the $\Upsilon(4S)$ (BELLE)

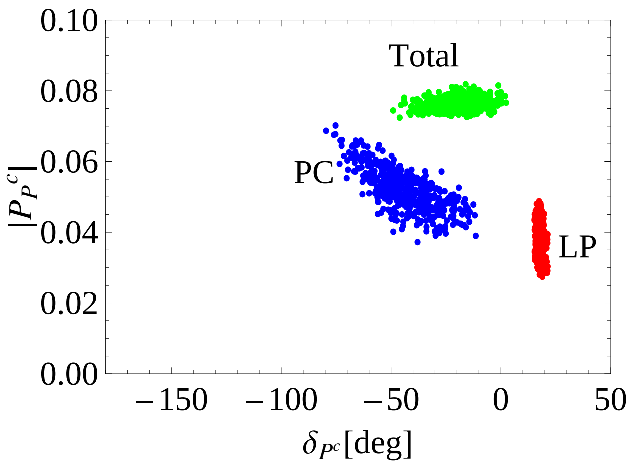




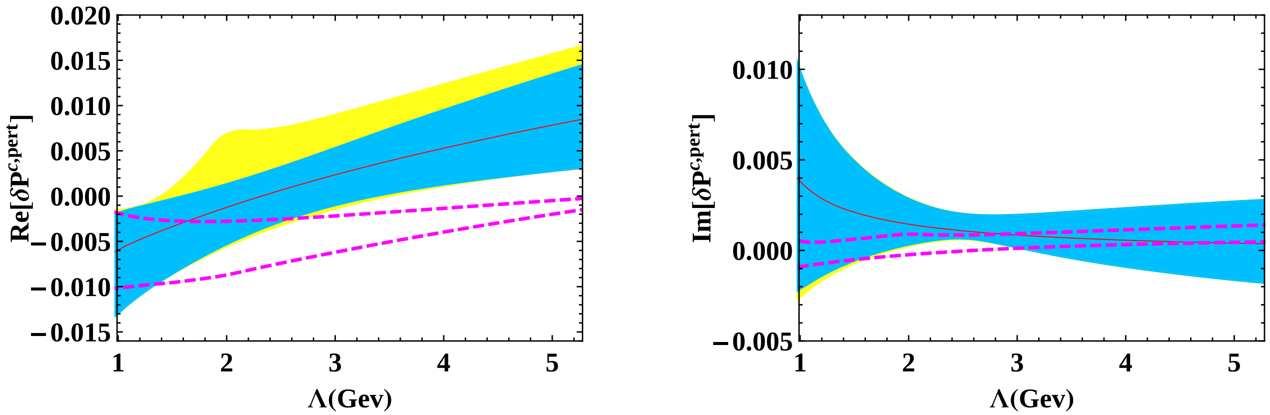
$$\frac{V_{VP}^{\rm non-pert.}}{V_{VP}^{\rm pert.}} \geq O(few), \text{ and appears } \frac{V_{VP}^{\rm non-pert.}}{V_{VP}^{\rm pert.}} < \frac{F_\pi^{\rm non-pert.}}{F_\pi^{\rm pert.}}$$

$B \to VP$ **penguin power corrections**

- $B \to K^*\pi$ PC fits: varied four Br's, four A_{CP}'s within 1σ errors



- $B \to K^*\pi$ "perturbative" QCD penguin PC's:



- For $B \to VP$, find $\left|\delta P^{c\,,\text{non-pert.}}/\delta P^{c\,,\text{pert.}}\right| \geq O(few)$, consistent with $e^+e^- \to VP$

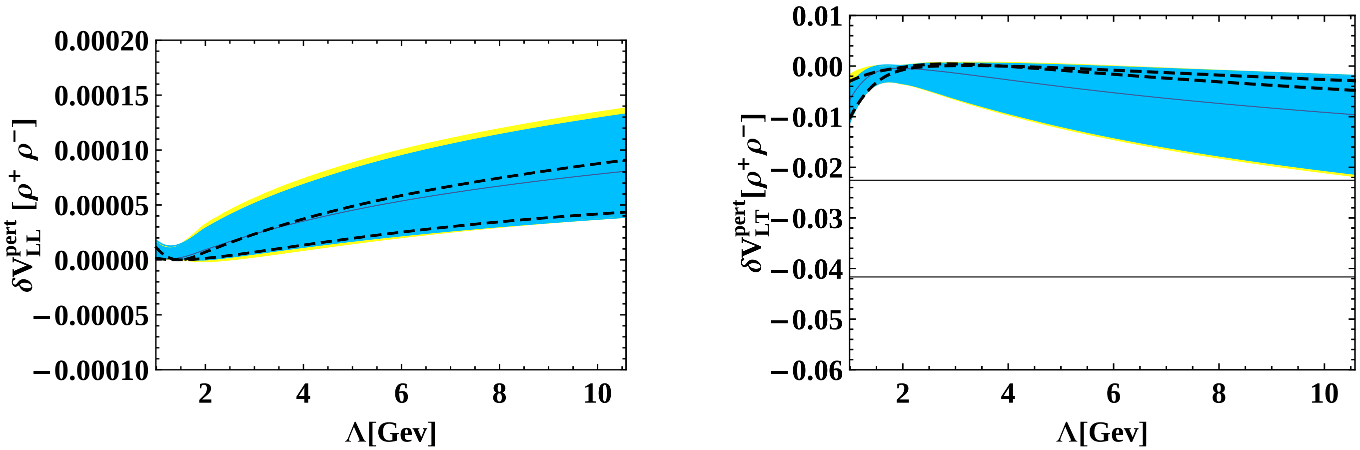
$e^+e^- \to \rho^+\rho^-$ at the $\Upsilon(4S)$ (BABAR)

$\sigma(e^+e^- \to \rho^+\rho^-) = 19.6 \pm 1.6 \pm 3.2$ fb + angular analysis

$$\Rightarrow |V_{LL}| = 0.0069 \pm 0.0017, \quad |V_{LT}| = 0.032 \pm 0.01$$

Angular analysis has large uncertainties, but contains useful information:

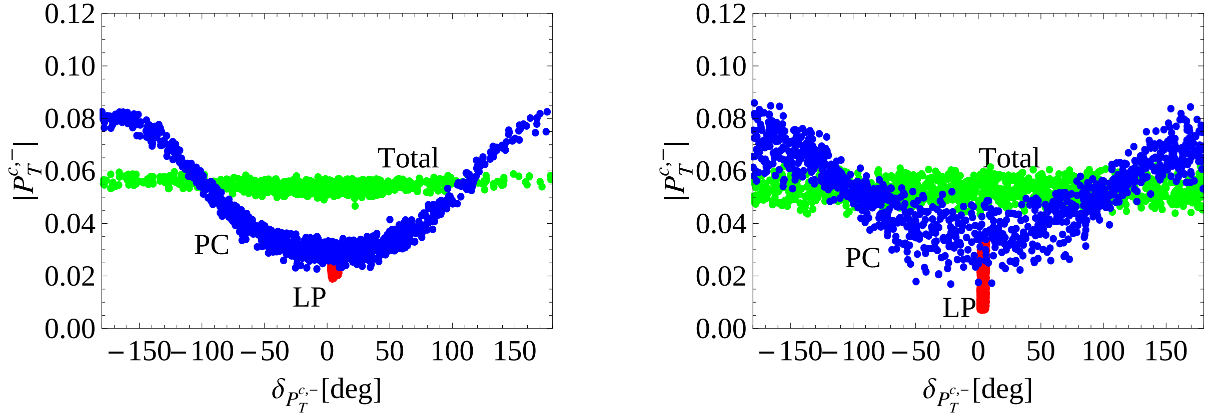
- V_{LL} has LP and PC contributions, V_{LT} is a pure PC
- Leading power contribution to V_{LL} is calculable in QCDF $\Rightarrow V_{LL}^{LP} = -0.002 \pm 0.0005$
- perturbative power corrections



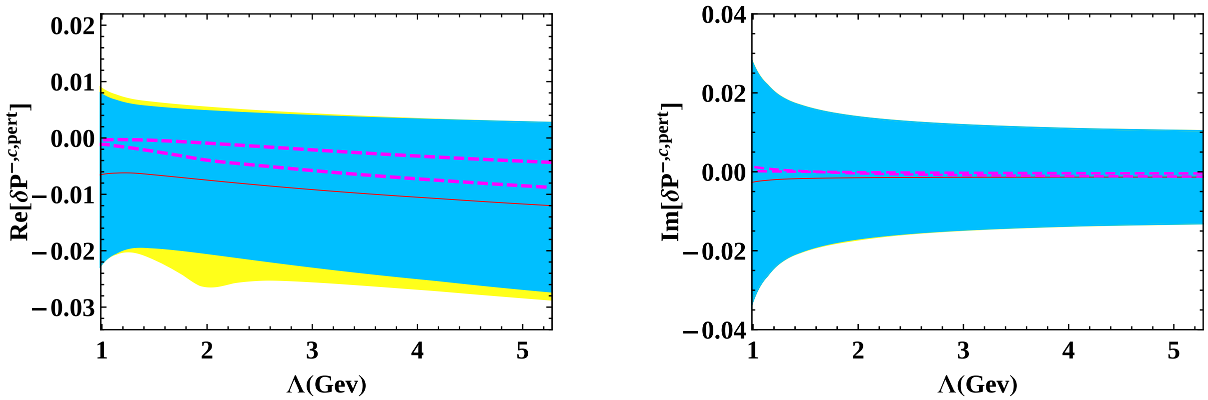
- V_{LL} should be dominated by the LP contribution
- $|\delta V_{LT}^{\text{non-pert.}}/\delta V_{LT}^{\text{pert.}}| = O(1 - \text{few})$, within large errors

QCD penguin PC's in $B \to \phi K^*$, $K^* \rho$

- PC fits: varied all available Br, CP asymmetry, transversity angular analysis measurements within 1σ errors
- The negative helicity $\overline{B} \to \phi K^{*0}$ and $B^- \to K^{*0}\rho^-$ QCD penguins



- $B \to \phi K^{*0}$ "perturbative" QCD penguin PC's:



Consistent with $\left|\delta P^{c\,,\mathrm{non-pert.}}/\delta P^{c\,,\mathrm{pert.}}\right| = O(1 - few)$,within large errors, and with $e^+e^- \to \rho^+\rho^-$

Conclusions

- puzzles in charmless $B \to M_1 M_2$ could be accounted for via power corrections if they have large soft-overlaps
  - PP, VP, VV penguin power corrections would be same order as leading power penguins
  - PP: $O(10)$ enhancement of PC's due to soft-overlaps
    VP, VV: consistent with more moderate $O(1)$ to $O(few)$ enhancement of PC's
- $e^+e^- \to PP, VP, VV$ provides a direct probe of non-perturbative power corrections
  - continuum CLEO-c and $\Upsilon(4S)$ data yields a similar pattern to what would be required in B decays:
  - $O(10)$ non-perturbative enhancement of power corrections in PP, and consistent with more moderate $O(1)$ to $O(few)$ enhancement in VP, VV
- Therefore, the e^+e^- data is telling us that the power correction orders of magnitude required in B decays are natural and not at all surprising

More measurements that would be helpful:

- strong phase difference between (LL) and (LT) helicity amplitudes in $e^+e^- \to \rho^+\rho^-$ at the $\Upsilon(4S)$, improve the precision of the $\rho^+\rho^-$ analysis
- BELLE should also do the $\rho^+\rho^-$ analysis
- we do not have a continuum $e^+e^- \to VV$ analysis at CLEO-c energies
- $V_{\omega\pi}$ at the $\Upsilon(4S)$. Can be combined with precise and clean CLEO-c measurement at 3.77 GeV, to further test power counting
- BABAR should also measure $V_{\rho\eta}$
- $V_{K^{*0}K^0}$ at the $\Upsilon(4S)$
- High luminosity flavor factories: use initial state radiation to measure F_π at $\sqrt{s} > 3.67$ GeV. Expect $\sigma(e^+e^- \to \pi^+\pi^-) \sim 0.5\, pb$ at $\sqrt{s} \approx m_B$