SCET and Model Independent predictions For Exclusive B Decays

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Can the SM Fit that data?

- w/o some theory input enough free parameters to fit the data.

- To test the SM we need some theory input to reduce number of degrees of freedom in the fit.

$$SU(2): \frac{m_q}{\Lambda} \sim \%2$$

$$SU(3): \frac{m_s}{\Lambda} \sim \%30$$

$$EFT: \frac{\Lambda}{m_b} \sim \%20$$

Parameter Counting

<table>
<tr><th></th><th>no expn.</th><th>SU(2)</th><th>SU(3)</th><th>SCET +SU(2)</th><th>SCET +SU(3)</th></tr>
<tr><td>$B \to \pi\pi$</td><td>11</td><td>7/5</td><td rowspan="2">15/13</td><td>4</td><td rowspan="2">4</td></tr>
<tr><td>$B \to K\pi$</td><td>15</td><td>11</td><td>+5(6)</td></tr>
<tr><td>$B \to K\bar{K}$</td><td>11</td><td>11</td><td>+4/0</td><td>+3(4)</td><td>+0</td></tr>
</table>

SCET imposes strong constraints on the SM, but how confident are we that a violation of the resulting predictions implies the existence of new physics?

SCET and Factorization

- Factorization implies the disentangling of fields with differing kinematics. i.e. B is soft, pions are collinear, in different directions.

- This is accomplished by showing that the various types of fields do not couple at the level of the LAGRANGIAN.

$$L_0 = L_n + L_{\bar{n}} + L_s$$

- Couplings between fields are various types do couple but only perturbatively in Λ/m_b

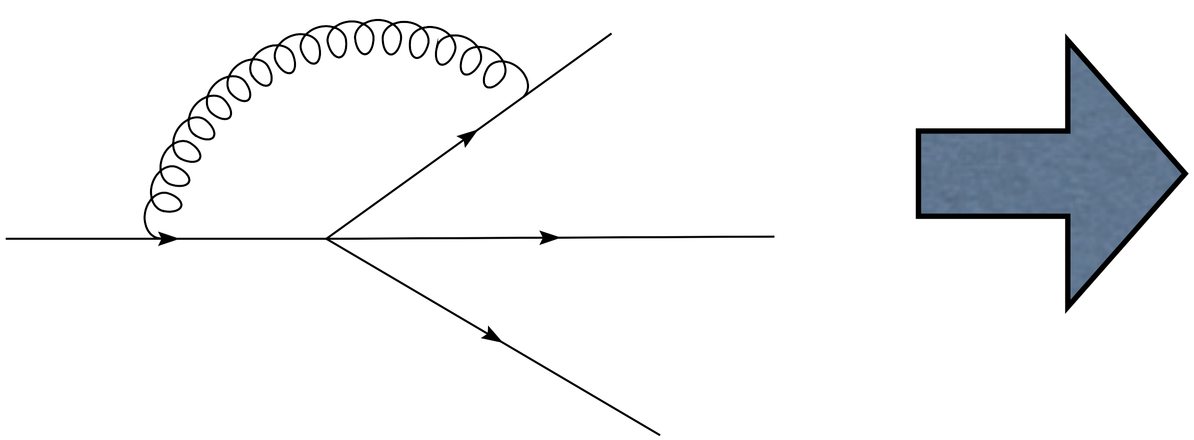
Two relevant hard scales

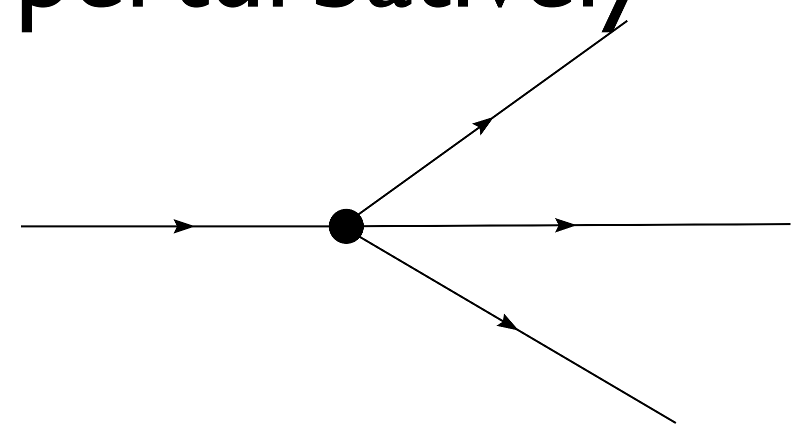
$$m_b > \sqrt{\Lambda m_b} > \Lambda$$

Step one: Integrate out hard modes in two steps:

m_b : All matching coefficients ~ $\alpha_s(m_b)$

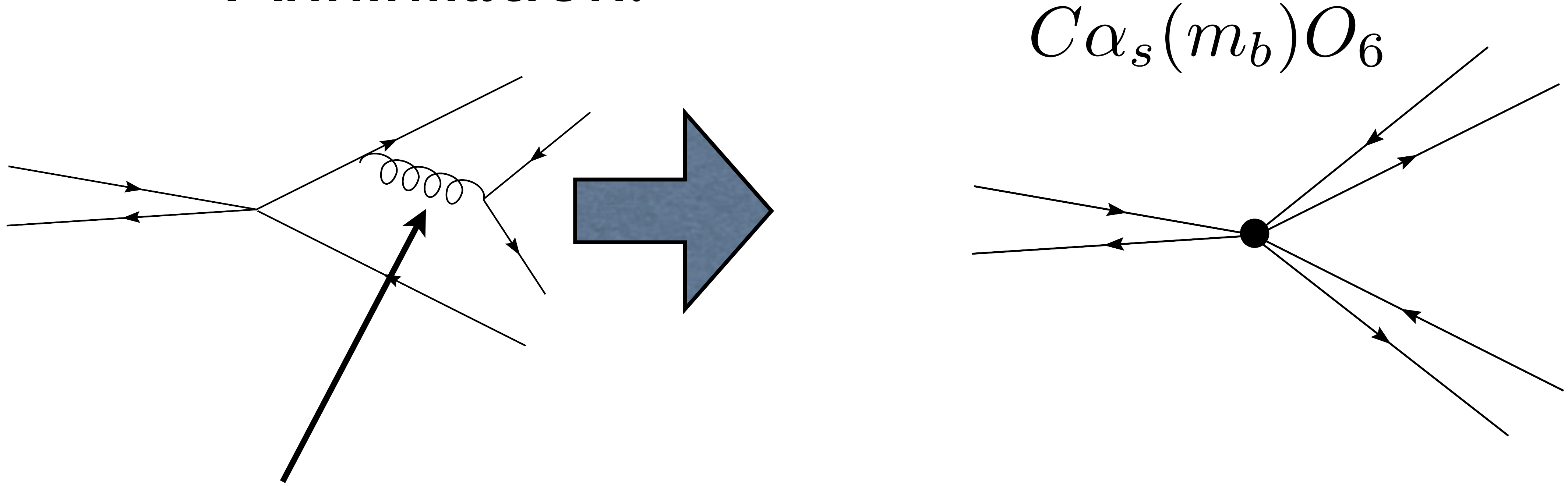
Can generate strong phases perturbatively





$$(1 + C\alpha_s(m_b))\ O_4$$

Annihilation:



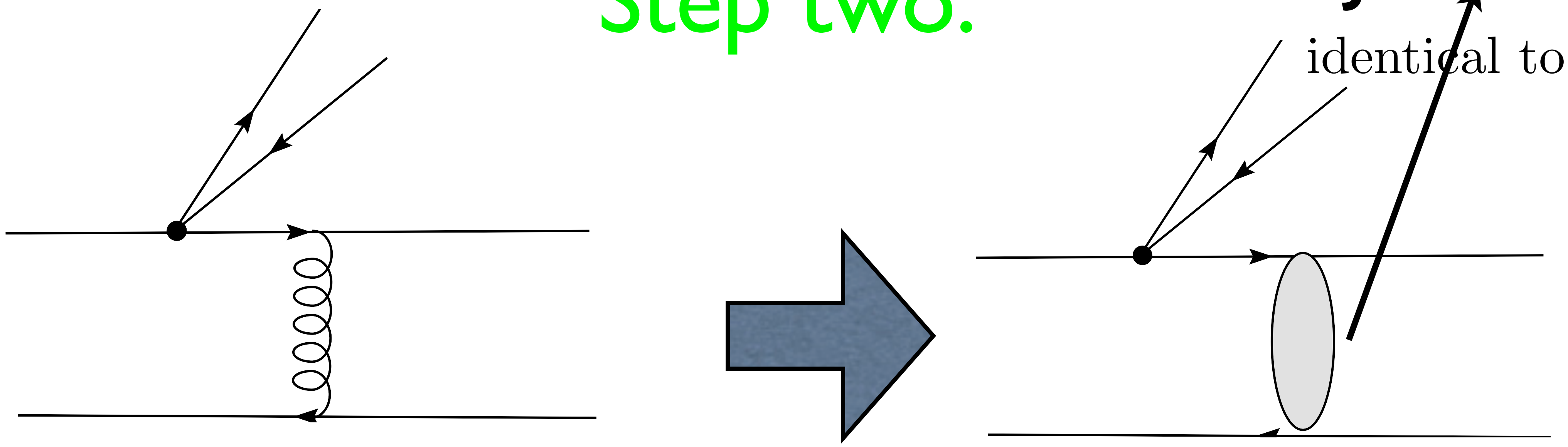
Off-shell by ~mb

C is real at leading order, complex at higher orders in $\alpha_s(m_b)$

Step two:

“Jet function”

identical to form factor



$q^2 \sim \Lambda m_b$

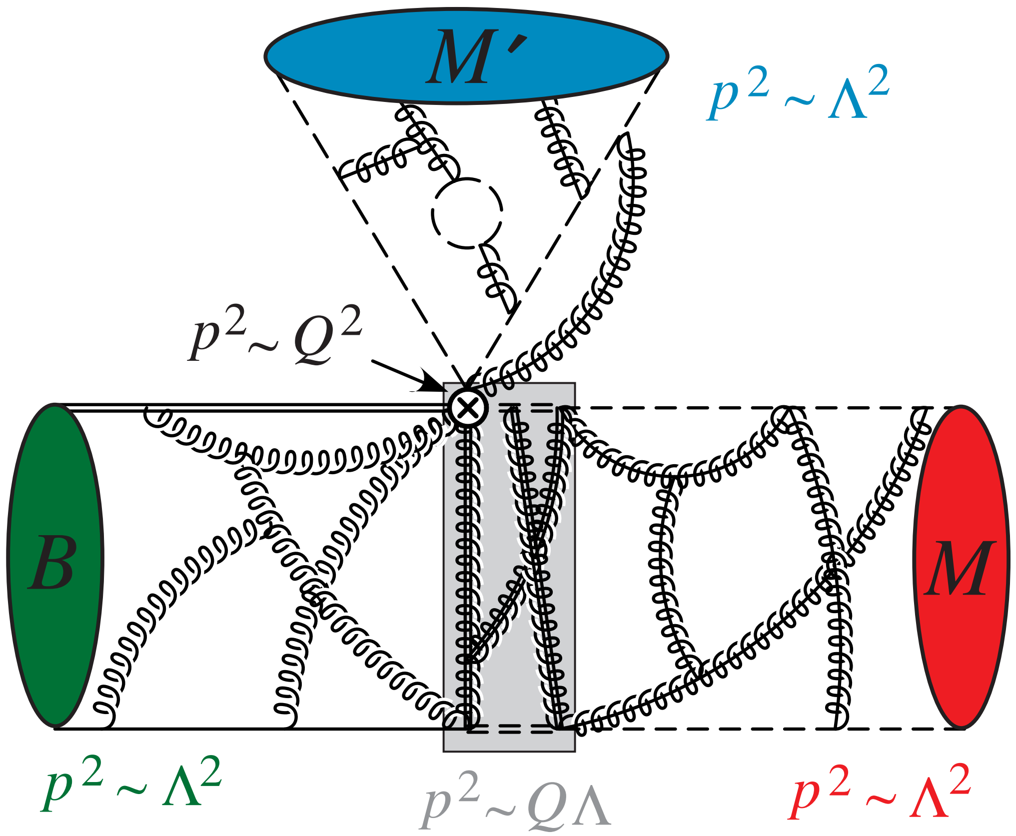
Jet function is real

$C(\alpha_s(m_b))$

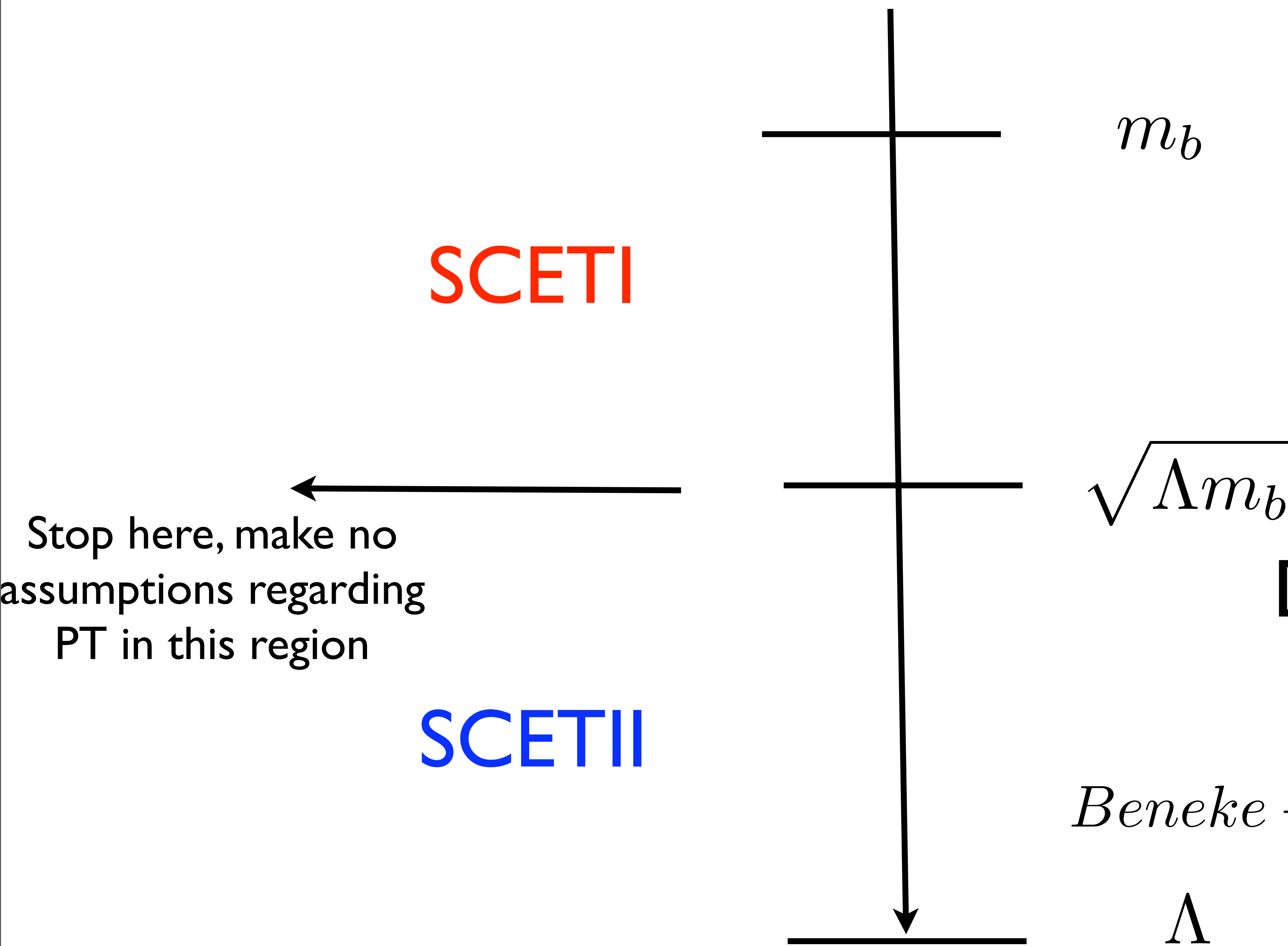
$$A = \frac{G_F m_B^2}{\sqrt{2}}\Big[\Big\{ f_{M_1}\int_0^1 du\, dz\, T_{1J}(u,z)\zeta_J^{BM_2}(z)\phi^{M_1}(u) + f_{M_1}\zeta^{BM_2}\int_0^1 du\, T_{1\zeta}(u)\phi^{M_1}(u)\Big\} + \Big\{1 \leftrightarrow 2\Big\}$$

Leading order (in Λ/m_b) Factorization formula

Schematically



In SCET Factorization is manifest at the level of the ACTION, allows one to systematically include power corrections



Does P.T. work here?

$$\sqrt{\Lambda m_B} \sim 2m_c$$

$$Beneke + Jager \quad \%40\ corrections$$

Working in this Lagrangian approach allows us to get a handle on scale to evaluate α_s (in most cases, ahhilation?)

- Note that in SCET power counting there is no reason to expect C<<T. Both start at $\alpha_s(\sqrt{m_b\Lambda})$

$$\zeta_J \sim \zeta$$

- ζ_J piece is proportional to

$$C_2 + (1 + \frac{1}{\bar{u}})C_1/N_c$$

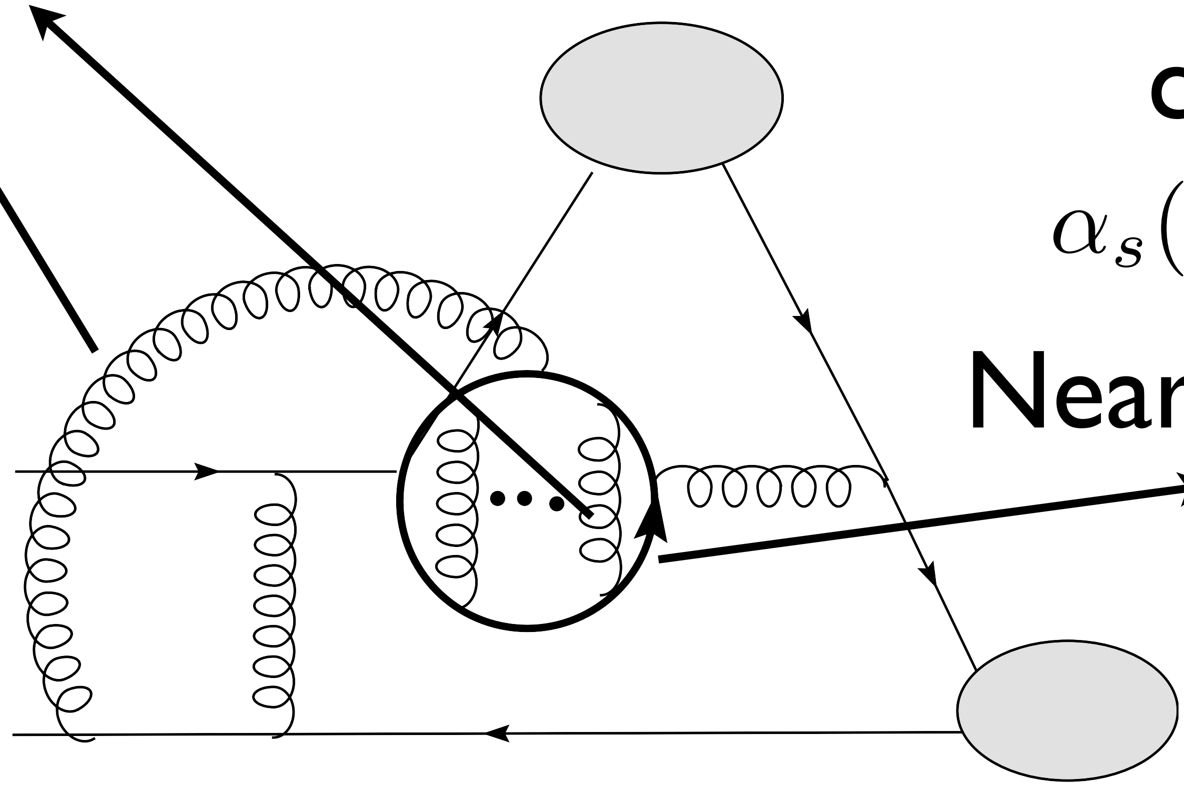
So where are the strong phases hiding? Charming Penguins

Soft Gluons

NRQCD power counting ~ v~.5

$\alpha_s(m_c)F((2m_c/m_b))v$

Nearly on shell charm quarks



In general would expect this to have a phase at leading order

Also, for VV not necessarily Transveresly polarized.

9 uknown parameters in

$$(\zeta_{B\pi} + \zeta^J_{B\pi}, \beta_\pi \zeta^J_{B\pi}, A^{\pi\pi}_{cc})$$

$$(\zeta_{B\pi} + \zeta^J_{B\pi}, \beta_K \zeta^J_{B\pi}, \zeta_{BK} + \zeta^J_{BK}, \beta_\pi \zeta^J_{BK}, A^{\pi\pi}_{cc})$$

If we assume SU(3)

$$(\zeta_{B\pi} = \zeta_{BK}, \beta_K = \beta_\pi, A^{\pi\pi}_{cc} = A^{\pi K}_{cc})$$

4 UKNOWN PARAMETERS IN PI-K SYSTEM (LO)

(Will not use)

Drastic increase in prediction power but are we confident in our power counting?

Hints it may be "working"

- $$f_{+}^{HPQCD}(0) = 0.22 \pm 0.03$$ Lattice+Data +dispersion relations

$$\zeta_{B\pi} + \zeta_{B\pi}^{J} = (0.19 \pm 0.01 \mid_{exp} \pm 0.05 \mid_{th}) \left(\frac{3.8 \times 10^{-3}}{\mid V_{ub} \mid} \right)$$ SCET

- SCET predicts $\delta(D\pi) = \delta(D^{\star}\pi)$ $[\delta = Arg(A_{3/2}A_{1/2}^{\star})]$

$$B \to D\pi, B \to D^{\star}\pi$$

$$\delta(D\pi) = 30.4 \pm 4.8$$

$$\delta(D^{\star}\pi) = 31.0 \pm 5.0$$

(NOT an HQET prediction due to soft gluons connecting heavy to light quarks)

$mantry + Stewart$

- In pi-pi system exract γ

$$\gamma^{\pi\pi} = 73.9^{+7.5}_{-10.3}\,|_{exp}\ {}^{+1.0}_{-2.5}\,|_{thy} \qquad \gamma_2^{\pi\pi} = 27.7^{+9.9}_{-7.3}\,|_{exp}\ {}^{+10}_{-4.5}\,|_{thy}$$

Disfavored theoretically

$\zeta < 0$

- In rho-rho system

$$\gamma^{\rho\rho} = 77.5^{7.4}_{28}\,|_{exp}\ {}^{1.0}_{-5.2}\,|_{thy} \qquad \gamma_2^{\rho\rho} = 57.3\ {}^{+2.8}_{-4.5}\,|_{exp}\ {}^{+6.7}_{-4.1}\,|_{thy}$$

$$\gamma^{\pi\pi}_{CKMfit} = 67.6^{+2.8}_{-4.5} \qquad \gamma^{\pi\pi}_{UTfit} = 66.7 \pm 6.4$$

K-Pi is where things get interesting

$$
\begin{aligned}
A(B^- \to \pi^- \bar{K}^0) &= \lambda_u^{(s)} A_{K\pi} + \lambda_c^{(s)} P_{K\pi} \qquad (1)\\
\sqrt{2}A(B^- \to \pi^0 K^-) &= -\lambda_u^{(s)} (C_{K\pi} + T_{K\pi} + A_{K\pi}) \\
&\quad -\lambda_c^{(s)} (P_{K\pi} + EW^T_{K\pi}) \\
A(\bar{B}^0 \to \pi^+ K^-) &= -\lambda_u^{(s)} T_{K\pi} \\
&\quad -\lambda_c^{(s)} (P_{K\pi} + EW^C_{K\pi}) \\
\sqrt{2}A(\bar{B}^0 \to \pi^0 \bar{K}^0) &= -\lambda_u^{(s)} C_{K\pi} \\
&\quad +\lambda_c^{(s)} (P_{K\pi} - EW^T_{K\pi} + EW^C_{K\pi})
\end{aligned}
$$

Most General SU(3) decomposition

At LO in SCET all real except P, which we treat to all orders in Λ/m_b

K-pi asymmetries seem to pose a problem

$$
\begin{aligned}
&A(B^- \to \pi^- \bar{K}^0) \\
&\qquad = \lambda_c^{(s)} P_{K\pi}\Big[1 - \frac{1}{2}\epsilon_A e^{-i\gamma} e^{i\phi_A}\Big], \\
&A(\bar{B}^0 \to \pi^+ K^-) \\
&\qquad = -\lambda_c^{(s)} P_{K\pi}\Big[1 + \frac{1}{2}\big(\epsilon_C^{ew} e^{i\phi_C^{ew}} - \epsilon_T e^{i\phi_T - i\gamma}\big)\Big], \\
&\sqrt{2}A(B^- \to \pi^0 K^-) \\
&\qquad = -\lambda_c^{(s)} P_{K\pi}\Big[1 + \frac{1}{2}\big(\epsilon_T^{ew} e^{i\phi_T^{ew}} - \epsilon e^{i\phi - i\gamma}\big)\Big], \\
&\sqrt{2}A(\bar{B}^0 \to \pi^0 \bar{K}^0) \\
&\qquad = \lambda_c^{(s)} P_{K\pi}\Big[1 - \frac{1}{2}\big(\epsilon_{ew} e^{i\phi_{ew}} - \epsilon_C e^{i\phi_C - i\gamma}\big)\Big],
\end{aligned} \tag{1}
$$

In SCET all relative phases are equal δ

$$
\begin{aligned}
A(\bar{B}^0 \to \pi^- \bar{K}^0) &= \lambda_c^{(s)} P_{K\pi}, \\
A(\bar{B}^0 \to \pi^+ K^-) &= -\lambda_c^{(s)} P_{K\pi}\Big[1 + \frac{e^{i\delta}}{2}\big(\epsilon_C^{ew} - \epsilon_T e^{-i\gamma}\big)\Big], \\
\sqrt{2}A(B^- \to \pi^0 K^-) &= -\lambda_c^{(s)} P_{K\pi}\Big[1 + \frac{e^{i\delta}}{2}\big(\epsilon_T^{ew} - \epsilon e^{-i\gamma}\big)\Big], \\
\sqrt{2}A(\bar{B}^0 \to \pi^0 \bar{K}^0) &= \lambda_c^{(s)} P_{K\pi}\Big[1 - \frac{e^{i\delta}}{2}\big(\epsilon^{ew} - \epsilon_C e^{-i\gamma}\big)\Big],
\end{aligned} \tag{1}
$$

$$\Delta_1 = (1 + R_1) A_{CP}(\pi^0 K^-)$$
$$\Delta_2 = (1 + R_2) A_{CP}(\pi^- K^+)$$

SCET

$$\Delta_1 = -\epsilon \sin\gamma \sin\phi + O(\epsilon^2)$$
$$\Delta_2 = -\epsilon_T \sin\gamma \sin\phi_T + O(\epsilon^2)$$

$$\Delta_1 = -\epsilon \sin(\delta) \sin(\gamma)$$
$$\Delta_2 = -\epsilon_T \sin(\delta) \sin(\gamma)$$

$$\epsilon = \epsilon_T + \epsilon_C$$

$$\epsilon_T = 1.4(\zeta_{B\pi} + \zeta^J_{B\pi}) + 0.35 \beta_K \zeta^J_{B\pi}$$

$$\epsilon_C = .12(\zeta_{BK} + \zeta^J_{BK}) + 1.27 \beta_\pi \zeta^J_{BK}$$

Δ_1, Δ_2 have same sign

Belle $$A_{K^+\pi^-} = -0.094 \pm 0.018 \pm 0.008$$

$$A_{K^+\pi^0} = +0.07 \pm 0.03 \pm 0.01$$

Using the charged asymmetry to as input we may extract a prediction (NO SU(3) ERRORS)

$$A_{K^+\pi^0} = -0.18 \pm 0.08$$

This error does not reflect the new data, will come down once new analysis is performed

- What are we to conclude from this?

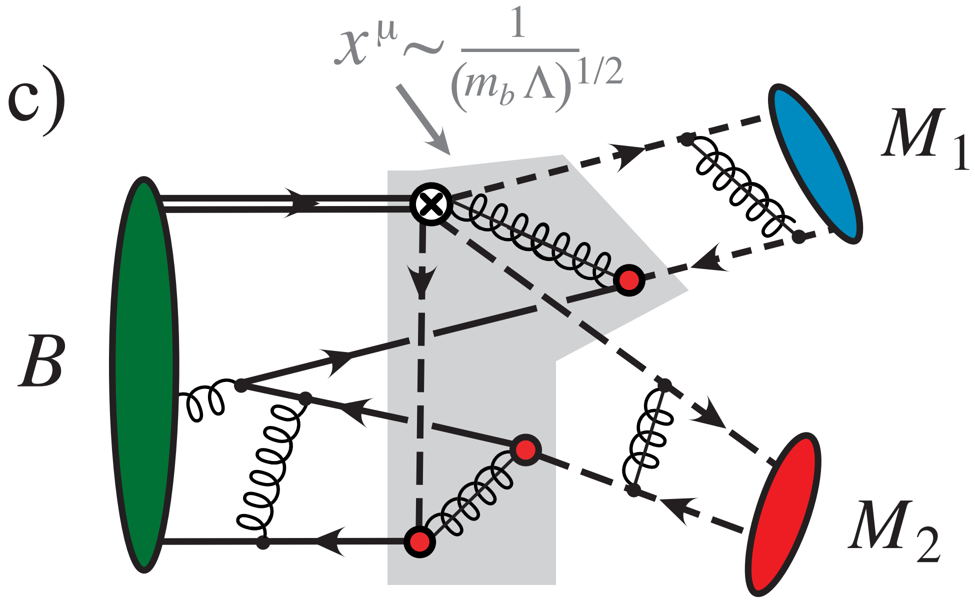
Certainly something very interesting is going on

What are the possibilities?

- Large complex power corrections

Annihilation

Due to "soft functions"



$O(\alpha_s^2(\sqrt{\Lambda m_b})$

Complex in SCET as opposed to "local annihilation"

The problem is that these (dominantly) contribute to both modes identically, so will NOT explain the difference.

Arenesen et al

Chirally Enhanced Terms

Certain power corrections are numerically (not parametrically) enhanced $\Lambda_\chi/\Lambda \sim 3-4$

$\mu/m_b \sim 2$

For Penguins contribute identically to both modes

1

M_1M_2	R_1	R_2	R_1^χ	R_2^χ
$\pi^-\pi^+$, $\rho^-\pi^+$	$c^\chi_{1(qfq)}+c^\chi_{2(qfq)}$	0	$b^\chi_{1(qfq)}+b^\chi_{1(ufu)}$	0
$\pi^-\rho^+$	$-c^\chi_{1(qfq)}-c^\chi_{2(qfq)}$	0	$b^\chi_{1(qfq)}+b^\chi_{1(ufu)}$	0
$\pi^-\pi^0$	$\frac{1}{\sqrt2}\left[c^\chi_{1(qfq)}+c^\chi_{2(qfq)}\right]$	$\frac{-1}{\sqrt2}\left[c^\chi_{1(qfq)}-\frac12 c^\chi_{2(qfq)}\right]$	$\frac{1}{\sqrt2}\left[b^\chi_{1(ufu)}+b^\chi_{1(qfq)}\right]$	$\frac{1}{\sqrt2}\left[b^\chi_{1(fuu)}-b^\chi_{2(fuu)}-b^\chi_{1(qfq)}\right]$
$\rho^-\pi^0$	$\frac{1}{\sqrt2}\left[c^\chi_{1(qfq)}+c^\chi_{2(qfq)}\right]$	$\frac{1}{\sqrt2}\left[c^\chi_{1(qfq)}-\frac12 c^\chi_{2(qfq)}\right]$	$\frac{1}{\sqrt2}\left[b^\chi_{1(ufu)}+b^\chi_{1(qfq)}\right]$	$\frac{1}{\sqrt2}\left[b^\chi_{1(fuu)}-b^\chi_{2(fuu)}-b^\chi_{1(qfq)}\right]$
$\pi^-\rho^0$	$\frac{-1}{\sqrt2}\left[c^\chi_{1(qfq)}+c^\chi_{2(qfq)}\right]$	$\frac{-1}{\sqrt2}\left[c^\chi_{1(qfq)}-\frac12 c^\chi_{2(qfq)}\right]$	$\frac{1}{\sqrt2}\left[b^\chi_{1(ufu)}+b^\chi_{1(qfq)}\right]$	$\frac{1}{\sqrt2}\left[b^\chi_{1(fuu)}+b^\chi_{2(fuu)}-b^\chi_{1(qfq)}\right]$
$\pi^0\pi^0$	$-\frac12 c^\chi_{1(qfq)}+\frac14 c^\chi_{2(qfq)}$	$\frac{-1}{2}c^\chi_{1(qfq)}+\frac14 c^\chi_{2(qfq)}$	$\frac12\left[b^\chi_{1(fuu)}-b^\chi_{2(fuu)}-b^\chi_{1(qfq)}\right]$	$\frac12\left[b^\chi_{1(fuu)}-b^\chi_{2(fuu)}-b^\chi_{1(qfq)}\right]$
$\rho^0\pi^0$	$\frac{-1}{2}c^\chi_{1(qfq)}+\frac14 c^\chi_{2(qfq)}$	$\frac12 c^\chi_{1(qfq)}-\frac14 c^\chi_{2(qfq)}$	$\frac12\left[b^\chi_{1(fuu)}+b^\chi_{2(fuu)}-b^\chi_{1(qfq)}\right]$	$\frac12\left[b^\chi_{1(fuu)}-b^\chi_{2(fuu)}-b^\chi_{1(qfq)}\right]$
$K^{(*)0}K^-$, $K^{(*)0}\bar K^0$	$-c^\chi_{1(qfq)}+\frac12 c^\chi_{2(qfq)}$	0	$-b^\chi_{1(qfq)}$	0
K^0K^{*-}, $K^0\bar K^{*0}$	$c^\chi_{1(qfq)}-\frac12 c^\chi_{2(qfq)}$	0	$-b^\chi_{1(qfq)}$	0
$K^{(*)-}K^{(*)+}$	—	—	—	—
$\pi^+K^{(*)-}$	0	$c^\chi_{1(qfq)}+c^\chi_{2(qfq)}$	0	$b^\chi_{1(ufu)}+b^\chi_{1(qfq)}$
ρ^+K^-	0	$-c^\chi_{1(qfq)}-c^\chi_{2(qfq)}$	0	$b^\chi_{1(ufu)}+b^\chi_{1(qfq)}$
$\pi^0K^{(*)-}$	0	$\frac{1}{\sqrt2}\left[c^\chi_{1(qfq)}+c^\chi_{2(qfq)}\right]$	$\frac{1}{\sqrt2}\left[b^\chi_{1(fuu)}-b^\chi_{2(fuu)}\right]$	$\frac{1}{\sqrt2}\left[b^\chi_{1(ufu)}+b^\chi_{1(qfq)}\right]$
ρ^0K^-	0	$\frac{-1}{\sqrt2}\left[c^\chi_{1(qfq)}+c^\chi_{2(qfq)}\right]$	$\frac{1}{\sqrt2}\left[b^\chi_{1(fuu)}+b^\chi_{2(fuu)}\right]$	$\frac{1}{\sqrt2}\left[b^\chi_{1(ufu)}+b^\chi_{1(qfq)}\right]$
$\pi^-\bar K^{(*)0}$	0	$-c^\chi_{1(qfq)}+\frac12 c^\chi_{2(qfq)}$	0	$-b^\chi_{1(qfq)}$
$\rho^-\bar K^0$	0	$c^\chi_{1(qfq)}-\frac12 c^\chi_{2(qfq)}$	0	$-b^\chi_{1(qfq)}$
$\pi^0\bar K^{(*)0}$	0	$\frac{-1}{\sqrt2}\left[c^\chi_{1(qfq)}-\frac12 c^\chi_{2(qfq)}\right]$	$\frac{1}{\sqrt2}\left[b^\chi_{1(fuu)}-b^\chi_{2(fuu)}\right]$	$-\frac{1}{\sqrt2}b^\chi_{1(qfq)}$
$\rho^0\bar K^0$	0	$\frac{1}{\sqrt2}\left[c^\chi_{1(qfq)}-\frac12 c^\chi_{2(qfq)}\right]$	$\frac{1}{\sqrt2}\left[b^\chi_{1(fuu)}+b^\chi_{2(fuu)}\right]$	$-\frac{1}{\sqrt2}b^\chi_{1(qfq)}$

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- There could be (Color Suppressed) complex power corrections which could induce a split (have not been categorized). However, if this were truly the explaination, then this constitutes a breakdown of the power counting, and begs the question "why does the power counting work so well elsewhere?" Perhaps an alternative power counting?

- There exists new physics (Electro-weak Penguins?)
- Wont be confident that its new physics until we see a coherent pattern of deviations from the SM all consistent with the power counting that has been assumed to hold.
- More work needs to be done to better understand non-local power corrections.