# Taming Hadronic Uncertainties with SCET

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# Outline

- The Soft-Collinear Effective Theory (SCET)
- Topics:

power expansion of QCD

i) charm (test factorization):

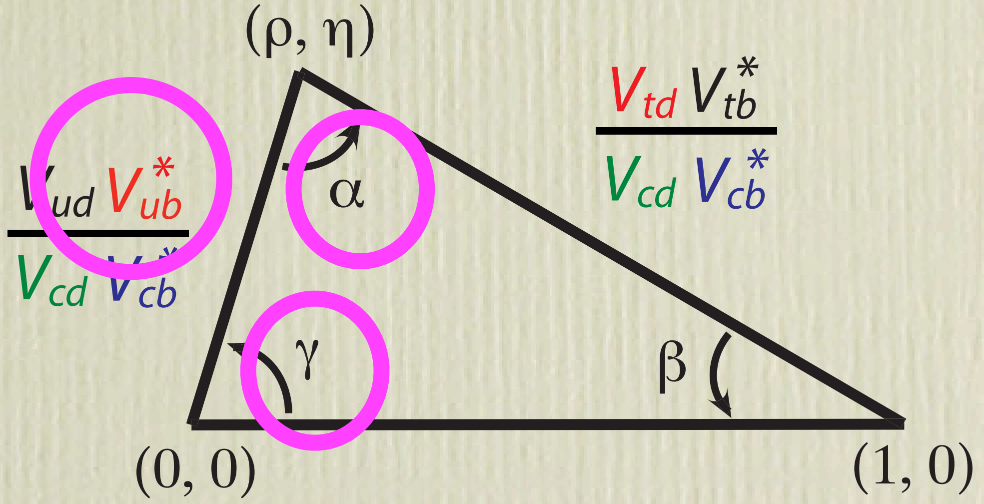
$$B \to D\pi \qquad B \to D\rho \qquad \Lambda_b \to \Sigma_c^{(*)}\pi$$

ii) ~~CP~~ : $B \to \pi\pi \qquad B \to \rho\rho \qquad B \to K\pi$

iii) $|V_{ub}|$ to 10% from $B \to \pi\ell\bar{\nu}$

iv) Other Highlights

- Summary



# BOTTOM MESONS ($B = \pm 1$)

$B^+ = u\overline{b}$, $B^0 = d\overline{b}$, $\overline{B}^0 = \overline{d}\,b$, $B^- = \overline{u}\,b$, similarly for $B^*$'s

## $B$-particle organization

Many measurements of $B$ decays involve admixtures of $B$ hadrons. Previously we arbitrarily included such admixtures in the $B^\pm$ section, but because of their importance we have created two new sections: "$B^\pm/B^0$ Admixture" for $\Upsilon(4S)$ results and "$B^\pm/B^0/B^0_s/b$-baryon Admixture" for results at higher energies. Most inclusive decay branching fractions and $\chi_b$ at high energy are found in the Admixture sections. $B^0$-$\overline{B}^0$ mixing data are found in the $B^0$ section, while $B^0_s$-$\overline{B}^0_s$ mixing data and $B$-$\overline{B}$ mixing data for a $B^0/B^0_s$ admixture are found in the $B^0_s$ section. $CP$-violation data are found in the $B^\pm$, $B^0$, and $B^\pm$ $B^0$ Admixture sections. $b$-baryons are found near the end of the Baryon section.

The organization of the $B$ sections is now as follows, where bullets indicate particle sections and brackets indicate reviews.

- $B^\pm$
  mass, mean life, branching fractions $CP$ violation
- $B^0$
  mass, mean life, branching fractions
  polarization in $B^0$ decay, $B^0$-$\overline{B}^0$ mixing, $CP$ violation
- $B^\pm$ $B^0$ Admixtures
  branching fractions, $CP$ violation
- $B^\pm/B^0/B^0_s/b$-baryon Admixtures
  mean life, production fractions, branching fractions
  $\chi_b$ at high energy, $V_{cb}$ measurements
  - $B^*$
    mass
  - $B^0_s$
    mass, mean life, branching fractions
    polarization in $B^0_s$ decay, $B^0_s$-$\overline{B}^0_s$ mixing
  - $B^\pm_c$
    mass, mean life, branching fractions

At end of Baryon Listings:

- $\Lambda_b$
  mass, mean life, branching fractions
- $b$-baryon Admixture
  mean life, branching fractions





## $B^\pm$

$I(J^P) = \frac{1}{2}(0^-)$

$I$, $J$, $P$ need confirmation. Quantum numbers shown are quark-model predictions.

Mass $m_{B^\pm} = 5279.0 \pm 0.5$ MeV
Mean life $\tau_{B^\pm} = (1.671 \pm 0.018) \times 10^{-12}$ s
$c\tau = 501$ $\mu$m

### $CP$ violation

$A_{CP}(B^+ \to J/\psi(1S) K^+) = -0.007 \pm 0.019$
$A_{CP}(B^+ \to J/\psi(1S) \pi^+) = -0.01 \pm 0.13$
$A_{CP}(B^+ \to \psi(2S) K^+) = -0.037 \pm 0.025$
$A_{CP}(B^+ \to \overline{D}^0 K^+) = 0.04 \pm 0.07$
$A_{CP}(B^+ \to D_{CP(+1)} K^+) = 0.06 \pm 0.19$
$A_{CP}(B^+ \to D_{CP(-1)} K^+) = -0.19 \pm 0.18$
$A_{CP}(B^+ \to \pi^+ \pi^0) = 0.05 \pm 0.15$
$A_{CP}(B^+ \to K^+ \pi^0) = -0.10 \pm 0.08$
$A_{CP}(B^+ \to K^0_S \pi^+) = 0.03 \pm 0.08$ (S = 1.1)
$A_{CP}(B^+ \to \pi^+ \pi^- \pi^+) = -0.39 \pm 0.35$
$A_{CP}(B^+ \to \rho^+ \rho^0) = -0.09 \pm 0.16$
$A_{CP}(B^+ \to K^+ \pi^- \pi^+) = 0.01 \pm 0.08$
$A_{CP}(B^+ \to K^+ K^- K^+) = 0.02 \pm 0.08$
$A_{CP}(B^+ \to K^+ \eta') = 0.009 \pm 0.035$
$A_{CP}(B^+ \to \omega \pi^+) = -0.21 \pm 0.19$
$A_{CP}(B^+ \to \omega K^+) = -0.21 \pm 0.28$
$A_{CP}(B^+ \to \phi K^+) = 0.03 \pm 0.07$
$A_{CP}(B^+ \to \phi K^*(892)^+) = 0.09 \pm 0.15$
$A_{CP}(B^+ \to \rho^0 K^*(892)^+) = 0.20 \pm 0.31$

$B^-$ modes are charge conjugates of the modes below. Modes which do not identify the charge state of the $B$ are listed in the $B^\pm/B^0$ ADMIXTURE section.

The branching fractions listed below assume 50% $B^0\overline{B}^0$ and 50% $B^+B^-$ production at the $\Upsilon(4S)$. We have attempted to bring older measurements up to date by rescaling their assumed $\Upsilon(4S)$ production ratio to 50:50 and their assumed $D$, $D_s$, $D^*$, and $\psi$ branching ratios to current values whenever this would affect our averages and best limits significantly.

Indentation is used to indicate a subchannel of a previous reaction. All resonant subchannels have been corrected for resonance branching fractions to the final state so the sum of the subchannel branching fractions can exceed that of the final state.

For inclusive branching fractions, *e.g.*, $B \to D^{\pm}$ anything, the values usually are multiplicities, not branching fractions. They can be greater than one.

| $B^+$ DECAY MODES | Fraction ($\Gamma_i/\Gamma$) | Scale factor/ Confidence level | $p$ (MeV/c) |
|---|---|---|---|
| **Semileptonic and leptonic modes** | | | |
| $\ell^+ \nu_\ell$ anything | [a] $(10.2 \pm 0.9)$ % | | – |
| $\overline{D}^0 \ell^+ \nu_\ell$ | [a] $(2.15 \pm 0.22)$ % | | 2310 |
| $\overline{D}^*(2007)^0 \ell^+ \nu_\ell$ | [a] $(6.5 \pm 0.5)$ % | | 2258 |
| $\overline{D}_1(2420)^0 \ell^+ \nu_\ell$ | $(5.6 \pm 1.6) \times 10^{-3}$ | | 2084 |
| $\overline{D}{}^*_2(2460)^0 \ell^+ \nu_\ell$ | $< 8 \times 10^{-3}$ | CL=90% | 2067 |
| $\pi^0 e^+ \nu_e$ | $(9.0 \pm 2.8) \times 10^{-5}$ | | 2638 |
| $\eta \ell^+ \nu_\ell$ | $(8 \pm 4) \times 10^{-5}$ | | 2611 |
| $\omega \ell^+ \nu_\ell$ | [a] $< 2.1 \times 10^{-4}$ | CL=90% | 2582 |
| $\rho^0 \ell^+ \nu_\ell$ | [a] $(1.34^{+0.32}_{-0.35}) \times 10^{-4}$ | | 2583 |
| $p \overline{p} e^+ \nu_e$ | $< 5.2 \times 10^{-3}$ | CL=90% | 2467 |
| $e^+ \nu_e$ | $< 1.5 \times 10^{-5}$ | CL=90% | 2640 |
| $\mu^+ \nu_\mu$ | $< 2.1 \times 10^{-5}$ | CL=90% | 2638 |
| $\tau^+ \nu_\tau$ | $< 5.7 \times 10^{-4}$ | CL=90% | 2340 |
| $e^+ \nu_e \gamma$ | $< 2.0 \times 10^{-4}$ | CL=90% | 2640 |
| $\mu^+ \nu_\mu \gamma$ | $< 5.2 \times 10^{-5}$ | CL=90% | 2638 |
| ***D*, *D**, or $D_s$ modes** | | | |
| $\overline{D}^0 \pi^+$ | $(4.98 \pm 0.29) \times 10^{-3}$ | | 2308 |
| $\overline{D}^0 \rho^+$ | $(1.34 \pm 0.18)$ % | | 2236 |
| $\overline{D}^0 K^+$ | $(3.7 \pm 0.6) \times 10^{-4}$ | S=1.1 | 2280 |
| $\overline{D}^0 K^*(892)^+$ | $(6.1 \pm 2.3) \times 10^{-4}$ | | 2213 |
| $\overline{D}^0 K^+ \overline{K}^0$ | $(5.5 \pm 1.6) \times 10^{-4}$ | | 2189 |
| $\overline{D}^0 K^+ \overline{K}^*(892)^0$ | $(7.5 \pm 1.7) \times 10^{-4}$ | | 2071 |
| $\overline{D}^0 \pi^+ \pi^+ \pi^-$ | $(1.1 \pm 0.4)$ % | | 2289 |
| $\overline{D}^0 \pi^+ \pi^+ \pi^-$ nonresonant | $(5 \pm 4) \times 10^{-3}$ | | 2289 |
| $\overline{D}^0 \pi^+ \rho^0$ | $(4.2 \pm 3.0) \times 10^{-3}$ | | 2207 |
| $\overline{D}^0 a_1(1260)^+$ | $(5 \pm 4) \times 10^{-3}$ | | 2123 |
| $\overline{D}^0 \omega \pi^+$ | $(4.1 \pm 0.9) \times 10^{-3}$ | | 2206 |
| $D^*(2010)^- \pi^+ \pi^+$ | $(2.1 \pm 0.6) \times 10^{-3}$ | | 2247 |
| $D^- \pi^+ \pi^+$ | $< 1.4 \times 10^{-3}$ | CL=90% | 2299 |
| $\overline{D}^*(2007)^0 \pi^+$ | $(4.6 \pm 0.4) \times 10^{-3}$ | | 2256 |
| $\overline{D}^*(2007)^0 \omega \pi^+$ | $(4.5 \pm 1.2) \times 10^{-3}$ | | 2149 |
| $\overline{D}^*(2007)^0 \rho^+$ | $(9.8 \pm 1.7) \times 10^{-3}$ | | 2181 |
| $\overline{D}^*(2007)^0 K^+$ | $(3.6 \pm 1.0) \times 10^{-4}$ | | 2227 |
| $\overline{D}^*(2007)^0 K^*(892)^+$ | $(7.2 \pm 3.4) \times 10^{-4}$ | | 2156 |
| $\overline{D}^*(2007)^0 K^+ \overline{K}^0$ | $< 1.06 \times 10^{-3}$ | CL=90% | 2132 |
| $\overline{D}^*(2007)^0 K^+ K^*(892)^0$ | $(1.5 \pm 0.4) \times 10^{-3}$ | | 2008 |





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|---|---|---|---|
| $\overline{D}^*(2007)^0 \pi^+ \pi^+ \pi^-$ | $(9.4 \pm 2.6) \times 10^{-3}$ | | 2236 |
| $\overline{D}^*(2007)^0 a_1(1260)^+$ | $(1.9 \pm 0.5)$ % | | 2062 |
| $\overline{D}^*(2007)^0 \pi^- \pi^+ \pi^+ \pi^0$ | $(1.8 \pm 0.4)$ % | | 2219 |
| $D^*(2010)^+ \pi^0$ | $< 1.7 \times 10^{-4}$ | CL=90% | 2255 |
| $\overline{D}^*(2010)^+ K^0$ | $< 9.5 \times 10^{-5}$ | CL=90% | 2225 |
| $D^*(2010)^- \pi^+ \pi^+ \pi^0$ | $(1.5 \pm 0.7)$ % | | 2235 |
| $D^*(2010)^- \pi^+ \pi^+ \pi^+ \pi^-$ | $< 1$ % | CL=90% | 2217 |
| $\overline{D}{}^*_1(2420)^0 \pi^+$ | $(1.5 \pm 0.6) \times 10^{-3}$ | S=1.3 | 2081 |
| $\overline{D}{}^*_1(2420)^0 \rho^+$ | $< 1.4 \times 10^{-3}$ | CL=90% | 1995 |
| $\overline{D}{}^*_2(2460)^0 \pi^+$ | $< 1.3 \times 10^{-3}$ | CL=90% | 2064 |
| $\overline{D}{}^*_2(2460)^0 \rho^+$ | $< 4.7 \times 10^{-3}$ | CL=90% | 1977 |
| $\overline{D}^0 D_s^+$ | $(1.3 \pm 0.4)$ % | | 1815 |
| $\overline{D}^0 D_{sJ}(2317)^+$ | seen | | 1605 |
| $\overline{D}^0 D_{sJ}(2457)^+$ | seen | | – |
| $\overline{D}^0 D_{sJ}(2536)^+$ | not seen | | 1447 |
| $\overline{D}^*(2007)^0 D_{sJ}(2536)^+$ | not seen | | 1338 |
| $\overline{D}^0 D_{sJ}(2573)^+$ | not seen | | 1417 |
| $\overline{D}^*(2007)^0 D_{sJ}(2573)^+$ | not seen | | 1306 |
| $\overline{D}^0 D_s^{*+}$ | $(9 \pm 4) \times 10^{-3}$ | | 1734 |
| $\overline{D}^*(2007)^0 D_s^+$ | $(1.2 \pm 0.5)$ % | | 1737 |
| $\overline{D}^*(2007)^0 D_s^{*+}$ | $(2.7 \pm 1.0)$ % | | 1651 |
| $D_s^{(*)+} \overline{D}^{**0}$ | $(2.7 \pm 1.2)$ % | | – |
| $\overline{D}^*(2007)^0 D^*(2010)^+$ | $< 1.1$ % | CL=90% | 1713 |
| $\overline{D}^0 D^*(2010)^+ + \overline{D}^*(2007)^0 D^+$ | $< 1.3$ % | CL=90% | 1792 |
| $\overline{D}^0 D^+$ | $< 6.7 \times 10^{-3}$ | CL=90% | 1866 |
| $\overline{D}^0 D^+ K^0$ | $< 2.8 \times 10^{-3}$ | CL=90% | 1571 |
| $\overline{D}^*(2007)^0 D^+ K^0$ | $< 6.1 \times 10^{-3}$ | CL=90% | 1475 |
| $\overline{D}^0 \overline{D}^*(2010)^+ K^0$ | $(5.2 \pm 1.2) \times 10^{-3}$ | | 1476 |
| $\overline{D}^*(2007)^0 D^*(2010)^+ K^0$ | $(7.8 \pm 2.6) \times 10^{-3}$ | | 1362 |
| $\overline{D}^0 D^0 K^+$ | $(1.9 \pm 0.4) \times 10^{-3}$ | | 1577 |
| $\overline{D}^*(2010)^0 D^0 K^+$ | $< 3.8 \times 10^{-3}$ | CL=90% | – |
| $\overline{D}^0 D^*(2007)^0 K^+$ | $(4.7 \pm 1.0) \times 10^{-3}$ | | 1481 |
| $\overline{D}^*(2007)^0 D^*(2007)^0 K^+$ | $(5.3 \pm 1.6) \times 10^{-3}$ | | 1368 |
| $D^- D^+ K^+$ | $< 4 \times 10^{-4}$ | CL=90% | 1571 |
| $D^- D^*(2010)^+ K^+$ | $< 7 \times 10^{-4}$ | CL=90% | 1475 |
| $D^*(2010)^- D^+ K^+$ | $(1.5 \pm 0.4) \times 10^{-3}$ | | 1475 |
| $D^*(2010)^- D^*(2010)^+ K^+$ | $< 1.8 \times 10^{-3}$ | CL=90% | 1363 |
| $(\overline{D} + \overline{D}^*)(D + D^*) K$ | $(3.5 \pm 0.6)$ % | | – |
| $D_s^+ \pi^0$ | $< 2.0 \times 10^{-4}$ | CL=90% | 2270 |
| $D_s^{*+} \pi^0$ | $< 3.3 \times 10^{-4}$ | CL=90% | 2215 |
| $D_s^+ \eta$ | $< 5 \times 10^{-4}$ | CL=90% | 2235 |
| $D_s^{*+} \eta$ | $< 8 \times 10^{-4}$ | CL=90% | 2178 |

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|---|---|---|---|
| $D_s^+ \rho^0$ | $< 4 \times 10^{-4}$ | CL=90% | 2197 |
| $D_s^{*+} \rho^0$ | $< 5 \times 10^{-4}$ | CL=90% | 2138 |
| $D_s^+ \omega$ | $< 5 \times 10^{-4}$ | CL=90% | 2195 |
| $D_s^{*+} \omega$ | $< 7 \times 10^{-4}$ | CL=90% | 2136 |
| $D_s^+ a_1(1260)^0$ | $< 2.2 \times 10^{-3}$ | CL=90% | 2079 |
| $D_s^{*+} a_1(1260)^0$ | $< 1.6 \times 10^{-3}$ | CL=90% | 2014 |
| $D_s^+ \phi$ | $< 3.2 \times 10^{-4}$ | CL=90% | 2141 |
| $D_s^{*+} \phi$ | $< 4 \times 10^{-4}$ | CL=90% | 2079 |
| $D_s^+ \overline{K}^0$ | $< 1.1 \times 10^{-3}$ | CL=90% | 2241 |
| $D_s^{*+} \overline{K}^0$ | $< 1.1 \times 10^{-3}$ | CL=90% | 2184 |
| $D_s^+ \overline{K}^*(892)^0$ | $< 5 \times 10^{-4}$ | CL=90% | 2172 |
| $D_s^{*+} \overline{K}^*(892)^0$ | $< 4 \times 10^{-4}$ | CL=90% | 2112 |
| $D_s^- \pi^+ K^+$ | $< 8 \times 10^{-4}$ | CL=90% | 2222 |
| $D_s^{*-} \pi^+ K^+$ | $< 1.2 \times 10^{-3}$ | CL=90% | 2164 |
| $D_s^- \pi^+ K^*(892)^+$ | $< 6 \times 10^{-3}$ | CL=90% | 2138 |
| $D_s^{*-} \pi^+ K^*(892)^+$ | $< 8 \times 10^{-3}$ | CL=90% | 2076 |
| **Charmonium modes** | | | |
| $\eta_c K^+$ | $(9.0 \pm 2.7) \times 10^{-4}$ | | 1754 |
| $J/\psi(1S) K^+$ | $(1.00 \pm 0.04) \times 10^{-3}$ | | 1683 |
| $J/\psi(1S) K^+ \pi^+ \pi^-$ | $(7.7 \pm 2.0) \times 10^{-4}$ | | 1612 |
| $X(3872) K^+$ | seen | | – |
| $J/\psi(1S) K^*(892)^+$ | $(1.35 \pm 0.10) \times 10^{-3}$ | | 1571 |
| $J/\psi(1S) K(1270)^+$ | $(1.8 \pm 0.5) \times 10^{-3}$ | | 1390 |
| $J/\psi(1S) K(1400)^+$ | $< 5 \times 10^{-4}$ | CL=90% | 1308 |
| $J/\psi(1S) \phi K^+$ | $(5.2 \pm 1.7) \times 10^{-5}$ | S=1.2 | 1227 |
| $J/\psi(1S) \pi^+$ | $(4.0 \pm 0.5) \times 10^{-5}$ | | 1727 |
| $J/\psi(1S) \rho^+$ | $< 7.7 \times 10^{-4}$ | CL=90% | 1611 |
| $J/\psi(1S) a_1(1260)^+$ | $< 1.2 \times 10^{-3}$ | CL=90% | 1414 |
| $J/\psi(1S) p \overline{\Lambda}$ | $(1.2 ^{+0.9}_{-0.6}) \times 10^{-5}$ | | 567 |
| $\psi(2S) K^+$ | $(6.8 \pm 0.4) \times 10^{-4}$ | | 1284 |
| $\psi(2S) K^*(892)^+$ | $(9.2 \pm 2.2) \times 10^{-4}$ | | 1115 |
| $\psi(2S) K^+ \pi^+ \pi^-$ | $(1.9 \pm 1.2) \times 10^{-3}$ | | 1178 |
| $\chi_{c0}(1P) K^+$ | $(6.0 ^{+2.4}_{-2.1}) \times 10^{-4}$ | | 1478 |
| $\chi_{c1}(1P) K^+$ | $(6.8 \pm 1.2) \times 10^{-4}$ | | 1411 |
| $\chi_{c1}(1P) K^*(892)^+$ | $< 2.1 \times 10^{-3}$ | CL=90% | 1265 |
| ***K* or *K** modes** | | | |
| $K^0 \pi^+$ | $(1.88 \pm 0.21) \times 10^{-5}$ | | 2614 |
| $K^+ \pi^0$ | $(1.29 \pm 0.12) \times 10^{-5}$ | | 2615 |
| $\eta' K^+$ | $(7.8 \pm 0.5) \times 10^{-5}$ | | 2528 |
| $\eta' K^*(892)^+$ | $< 3.5 \times 10^{-5}$ | CL=90% | 2472 |





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|---|---|---|---|
| $\eta K^+$ | $< 6.9 \times 10^{-6}$ | CL=90% | 2588 |
| $\eta K^*(892)^+$ | $(2.6 ^{+1.0}_{-0.9}) \times 10^{-5}$ | | 2534 |
| $\omega K^+$ | $(9.2 ^{+2.8}_{-2.5}) \times 10^{-6}$ | | 2557 |
| $\omega K^*(892)^+$ | $< 8.7 \times 10^{-5}$ | CL=90% | 2503 |
| $K^*(892)^0 \pi^+$ | $(1.9 ^{+0.6}_{-0.8}) \times 10^{-5}$ | | 2562 |
| $K^*(892)^+ \pi^0$ | $< 3.1 \times 10^{-5}$ | CL=90% | 2562 |
| $K^+ \pi^- \pi^+$ | $(5.7 \pm 0.4) \times 10^{-5}$ | | 2609 |
| $K^+ \pi^- \pi^+$ nonresonant | $< 2.8 \times 10^{-5}$ | CL=90% | 2609 |
| $K^+ \rho^0$ | $< 1.2 \times 10^{-5}$ | CL=90% | 2558 |
| $K_2^*(1430)^0 \pi^+$ | $< 6.8 \times 10^{-4}$ | CL=90% | 2445 |
| $K^- \pi^+ \pi^+$ | $< 1.8 \times 10^{-6}$ | CL=90% | 2609 |
| $K^- \pi^+ \pi^+$ nonresonant | $< 5.6 \times 10^{-5}$ | CL=90% | 2609 |
| $K_1(1400)^0 \pi^+$ | $< 2.6 \times 10^{-3}$ | CL=90% | 2451 |
| $K^0 \pi^+ \pi^0$ | $< 6.6 \times 10^{-5}$ | CL=90% | 2609 |
| $K^0 \rho^+$ | $< 4.8 \times 10^{-5}$ | CL=90% | 2558 |
| $K^*(892)^+ \pi^+ \pi^-$ | $< 1.1 \times 10^{-3}$ | CL=90% | 2556 |
| $K^*(892)^+ \rho^0$ | $(1.1 \pm 0.4) \times 10^{-5}$ | | 2504 |
| $K^*(892)^+ K^*(892)^0$ | $< 7.1 \times 10^{-5}$ | CL=90% | 2484 |
| $K_1(1400)^+ \rho^0$ | $< 7.8 \times 10^{-4}$ | CL=90% | 2387 |
| $K_2^*(1430)^+ \rho^0$ | $< 1.5 \times 10^{-3}$ | CL=90% | 2381 |
| $K^+ \overline{K}^0$ | $< 2.0 \times 10^{-6}$ | CL=90% | 2593 |
| $\overline{K}^0 K^+ \pi^0$ | $< 2.4 \times 10^{-5}$ | CL=90% | 2578 |
| $K^+ K_S^0 K_S^0$ | $(1.34 \pm 0.24) \times 10^{-5}$ | | 2521 |
| $K_S^0 K_S^0 \pi^+$ | $< 3.2 \times 10^{-6}$ | CL=90% | 2577 |
| $K^+ K^- \pi^+$ | $< 6.3 \times 10^{-6}$ | CL=90% | 2578 |
| $K^+ K^- \pi^+$ nonresonant | $< 7.5 \times 10^{-5}$ | CL=90% | 2578 |
| $K^+ K^+ \pi^-$ | $< 1.3 \times 10^{-6}$ | CL=90% | 2578 |
| $K^+ K^+ \pi^-$ nonresonant | $< 8.79 \times 10^{-5}$ | CL=90% | 2578 |
| $K^+ K^*(892)^0$ | $< 5.3 \times 10^{-6}$ | CL=90% | 2540 |
| $K^+ K^- K^+$ | $(3.08 \pm 0.21) \times 10^{-5}$ | | 2522 |
| $K^+ \phi$ | $(9.3 \pm 1.0) \times 10^{-6}$ | S=1.3 | 2516 |
| $K^+ K^- K^+$ nonresonant | $< 3.8 \times 10^{-5}$ | CL=90% | 2522 |
| $K^*(892)^+ K^+ K^-$ | $< 1.6 \times 10^{-3}$ | CL=90% | 2466 |
| $K^*(892)^+ \phi$ | $(9.6 \pm 3.0) \times 10^{-6}$ | S=1.9 | 2460 |
| $K_1(1400)^+ \phi$ | $< 1.1 \times 10^{-3}$ | CL=90% | 2339 |
| $K_2^*(1430)^+ \phi$ | $< 3.4 \times 10^{-3}$ | CL=90% | 2332 |
| $K^+ \phi \phi$ | $(2.6 ^{+1.1}_{-0.9}) \times 10^{-6}$ | | 2306 |
| $K^*(892)^+ \gamma$ | $(3.8 \pm 0.5) \times 10^{-5}$ | | 2564 |
| $K_1(1270)^+ \gamma$ | $< 9.9 \times 10^{-5}$ | CL=90% | 2486 |
| $\phi K^+ \gamma$ | $(3.4 \pm 1.0) \times 10^{-6}$ | | 2516 |
| $K^+ \pi^- \pi^+ \gamma$ | $(2.4 ^{+0.6}_{-0.5}) \times 10^{-5}$ | | 2609 |

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|---|---|---|---|
| $K^*(892)^0 \pi^+ \gamma$ | $(2.0\ ^{+0.7}_{-0.6}) \times 10^{-5}$ | | 2562 |
| $K^+ \rho^0 \gamma$ | $< 2.0 \times 10^{-5}$ | CL=90% | 2558 |
| $K^+ \pi^- \pi^+ \gamma$ nonresonant | $< 9.2 \times 10^{-6}$ | CL=90% | 2609 |
| $K_1(1400)^+ \gamma$ | $< 5.0 \times 10^{-5}$ | CL=90% | 2453 |
| $K_2^*(1430)^+ \gamma$ | $< 1.4 \times 10^{-3}$ | CL=90% | 2447 |
| $K^*(1680)^+ \gamma$ | $< 1.9 \times 10^{-3}$ | CL=90% | 2360 |
| $K_3^*(1780)^+ \gamma$ | $< 5.5 \times 10^{-3}$ | CL=90% | 2341 |
| $K_4^*(2045)^+ \gamma$ | $< 9.9 \times 10^{-3}$ | CL=90% | 2243 |

**Light unflavored meson modes**

| | | | |
|---|---|---|---|
| $\rho^+ \gamma$ | $< 2.1 \times 10^{-6}$ | CL=90% | 2583 |
| $\pi^+ \pi^0$ | $(5.6\ ^{+0.9}_{-1.1}) \times 10^{-6}$ | | 2636 |
| $\pi^+ \pi^+ \pi^-$ | $(1.1 \pm 0.4) \times 10^{-5}$ | | 2630 |
| $\rho^0 \pi^+$ | $(8.6 \pm 2.0) \times 10^{-6}$ | | 2581 |
| $\pi^+ f_0(980)$ | $< 1.4 \times 10^{-4}$ | CL=90% | 2547 |
| $\pi^+ f_2(1270)$ | $< 2.4 \times 10^{-4}$ | CL=90% | 2483 |
| $\pi^+ \pi^- \pi^+$ nonresonant | $< 4.1 \times 10^{-5}$ | CL=90% | 2630 |
| $\pi^+ \pi^0 \pi^0$ | $< 8.9 \times 10^{-4}$ | CL=90% | 2631 |
| $\rho^+ \pi^0$ | $< 4.3 \times 10^{-5}$ | CL=90% | 2581 |
| $\pi^+ \pi^- \pi^+ \pi^0$ | $< 4.0 \times 10^{-3}$ | CL=90% | 2621 |
| $\rho^+ \rho^0$ | $(2.6 \pm 0.6) \times 10^{-5}$ | | 2523 |
| $a_1(1260)^+ \pi^0$ | $< 1.7 \times 10^{-3}$ | CL=90% | 2494 |
| $a_1(1260)^0 \pi^+$ | $< 9.0 \times 10^{-4}$ | CL=90% | 2494 |
| $\omega \pi^+$ | $(6.4\ ^{+1.8}_{-1.6}) \times 10^{-6}$ | S=1.3 | 2580 |
| $\omega \rho^+$ | $< 6.1 \times 10^{-5}$ | CL=90% | 2522 |
| $\eta \pi^+$ | $< 5.7 \times 10^{-6}$ | CL=90% | 2609 |
| $\eta' \pi^+$ | $< 7.0 \times 10^{-6}$ | CL=90% | 2551 |
| $\eta' \rho^+$ | $< 3.3 \times 10^{-5}$ | CL=90% | 2492 |
| $\eta \rho^+$ | $< 1.5 \times 10^{-5}$ | CL=90% | 2553 |
| $\phi \pi^+$ | $< 4.1 \times 10^{-7}$ | CL=90% | 2539 |
| $\phi \rho^+$ | $< 1.6 \times 10^{-5}$ | | 2480 |
| $\pi^+ \pi^+ \pi^+ \pi^- \pi^-$ | $< 8.6 \times 10^{-4}$ | CL=90% | 2608 |
| $\rho^0 a_1(1260)^+$ | $< 6.2 \times 10^{-4}$ | CL=90% | 2433 |
| $\rho^0 a_2(1320)^+$ | $< 7.2 \times 10^{-4}$ | CL=90% | 2410 |
| $\pi^+ \pi^+ \pi^+ \pi^- \pi^- \pi^0$ | $< 6.3 \times 10^{-3}$ | CL=90% | 2592 |
| $a_1(1260)^+ a_1(1260)^0$ | $< 1.3$ % | CL=90% | 2335 |

**Charged particle ($h^\pm$) modes**

$h^\pm = K^\pm$ or $\pi^\pm$

| | | | |
|---|---|---|---|
| $h^+ \pi^0$ | $(1.6\ ^{+0.7}_{-0.6}) \times 10^{-5}$ | | 2636 |
| $\omega h^+$ | $(1.38\ ^{+0.27}_{-0.24}) \times 10^{-5}$ | | 2580 |
| $h^+ X^0$ (Familon) | $< 4.9 \times 10^{-5}$ | CL=90% | – |



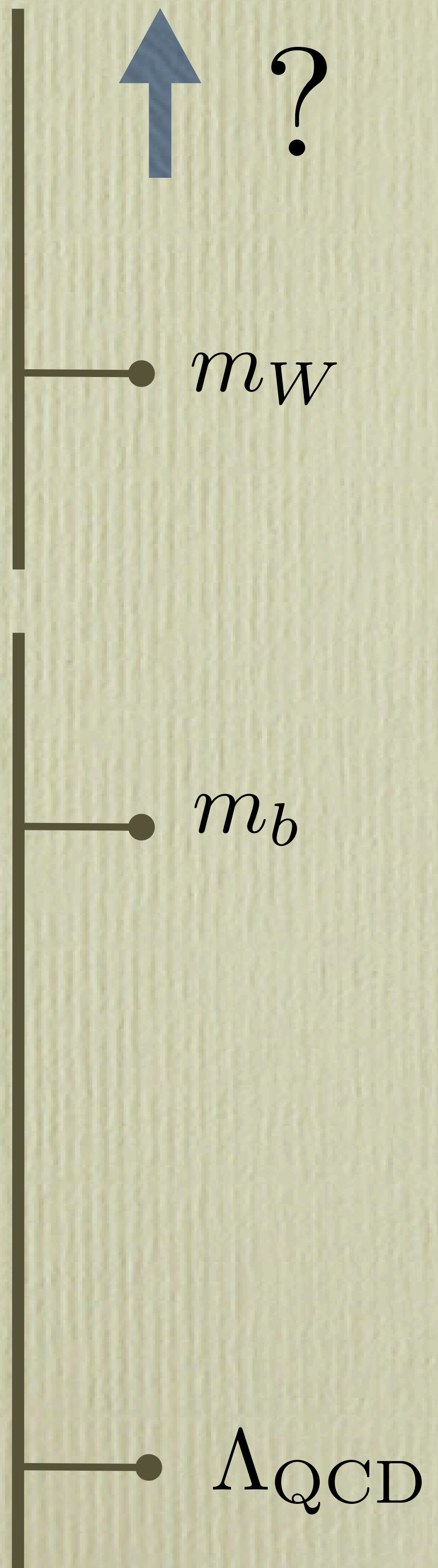


**Baryon modes**

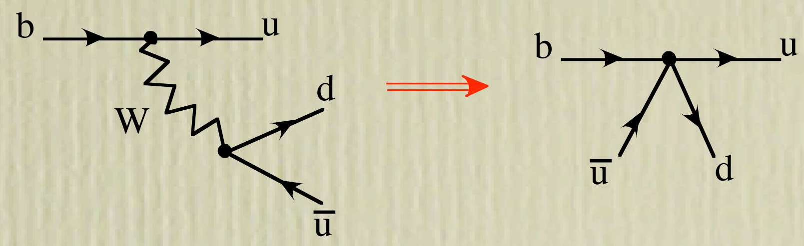
| | | | |
|---|---|---|---|
| $p \overline{p} \pi^+$ | $< 3.7 \times 10^{-6}$ | CL=90% | 2439 |
| $p \overline{p} \pi^+$ nonresonant | $< 5.3 \times 10^{-5}$ | CL=90% | 2439 |
| $p \overline{p} \pi^+ \pi^+ \pi^-$ | $< 5.2 \times 10^{-4}$ | CL=90% | 2369 |
| $p \overline{p} K^+$ | $(4.3\ ^{+1.2}_{-1.0}) \times 10^{-6}$ | | 2348 |
| $p \overline{p} K^+$ nonresonant | $< 8.9 \times 10^{-5}$ | CL=90% | 2348 |
| $p \overline{\Lambda}$ | $< 1.5 \times 10^{-6}$ | CL=90% | 2430 |
| $p \overline{\Lambda} \pi^+ \pi^-$ | $< 2.0 \times 10^{-4}$ | CL=90% | 2367 |
| $\overline{\Delta}^0 p$ | $< 3.8 \times 10^{-4}$ | CL=90% | 2402 |
| $\Delta^{++} \overline{p}$ | $< 1.5 \times 10^{-4}$ | CL=90% | 2402 |
| $D^+ p \overline{p}$ | $< 1.5 \times 10^{-5}$ | CL=90% | 1860 |
| $D^*(2010)^+ p \overline{p}$ | $< 1.5 \times 10^{-5}$ | CL=90% | 1786 |
| $\overline{\Lambda}_c^- p \pi^+$ | $(2.1 \pm 0.7) \times 10^{-4}$ | | 1981 |
| $\overline{\Lambda}_c^- p \pi^+ \pi^0$ | $(1.8 \pm 0.6) \times 10^{-3}$ | | 1936 |
| $\overline{\Lambda}_c^- p \pi^+ \pi^+ \pi^-$ | $(2.3 \pm 0.7) \times 10^{-3}$ | | 1881 |
| $\overline{\Lambda}_c^- p \pi^+ \pi^+ \pi^- \pi^0$ | $< 1.34$ % | CL=90% | 1823 |
| $\overline{\Sigma}_c(2455)^0 p$ | $< 8 \times 10^{-5}$ | CL=90% | 1939 |
| $\overline{\Sigma}_c(2520)^0 p$ | $< 4.6 \times 10^{-5}$ | CL=90% | 1905 |
| $\overline{\Sigma}_c(2455)^0 p \pi^0$ | $(4.4 \pm 1.8) \times 10^{-4}$ | | 1897 |
| $\overline{\Sigma}_c(2455)^0 p \pi^- \pi^+$ | $(4.4 \pm 1.7) \times 10^{-4}$ | | 1845 |
| $\overline{\Sigma}_c(2455)^{--} p \pi^+ \pi^+$ | $(2.8 \pm 1.2) \times 10^{-4}$ | | 1845 |
| $\overline{\Lambda}_c(2593)^- / \overline{\Lambda}_c(2625)^- p \pi^+$ | $< 1.9 \times 10^{-4}$ | CL=90% | – |

**Lepton Family number (*LF*) or Lepton number (*L*) violating modes, or $\Delta B = 1$ weak neutral current (*B1*) modes**

| | | | | | |
|---|---|---|---|---|---|
| $\pi^+ e^+ e^-$ | *B1* | | $< 3.9 \times 10^{-3}$ | CL=90% | 2638 |
| $\pi^+ \mu^+ \mu^-$ | *B1* | | $< 9.1 \times 10^{-3}$ | CL=90% | 2633 |
| $K^+ e^+ e^-$ | *B1* | | $(6.3\ ^{+1.9}_{-1.7}) \times 10^{-7}$ | | 2616 |
| $K^+ \mu^+ \mu^-$ | *B1* | | $(4.5\ ^{+1.4}_{-1.2}) \times 10^{-7}$ | | 2612 |
| $K^+ \ell^+ \ell^-$ | *B1* | [a] | $(5.3 \pm 1.1) \times 10^{-7}$ | | 2616 |
| $K^+ \overline{\nu} \nu$ | *B1* | | $< 2.4 \times 10^{-4}$ | CL=90% | 2616 |
| $K^*(892)^+ e^+ e^-$ | *B1* | | $< 4.6 \times 10^{-6}$ | CL=90% | 2564 |
| $K^*(892)^+ \mu^+ \mu^-$ | *B1* | | $< 2.2 \times 10^{-6}$ | CL=90% | 2560 |
| $K^*(892)^+ \ell^+ \ell$ | *B1* | [a] | $< 2.2 \times 10^{-6}$ | CL=90% | 2564 |
| $\pi^+ e^+ \mu^-$ | *LF* | | $< 6.4 \times 10^{-3}$ | CL=90% | 2637 |
| $\pi^+ e^- \mu^+$ | *LF* | | $< 6.4 \times 10^{-3}$ | CL=90% | 2637 |
| $K^+ e^+ \mu^-$ | *LF* | | $< 8 \times 10^{-7}$ | CL=90% | 2615 |
| $K^+ e^- \mu^+$ | *LF* | | $< 6.4 \times 10^{-3}$ | CL=90% | 2615 |
| $K^*(892)^+ e^\pm \mu^\mp$ | *LF* | | $< 7.9 \times 10^{-6}$ | CL=90% | 2563 |
| $\pi^- e^+ e^+$ | *L* | | $< 1.6 \times 10^{-6}$ | CL=90% | 2638 |
| $\pi^- \mu^+ \mu^+$ | *L* | | $< 1.4 \times 10^{-6}$ | CL=90% | 2633 |




$$m_W, m_t \gg m_b$$

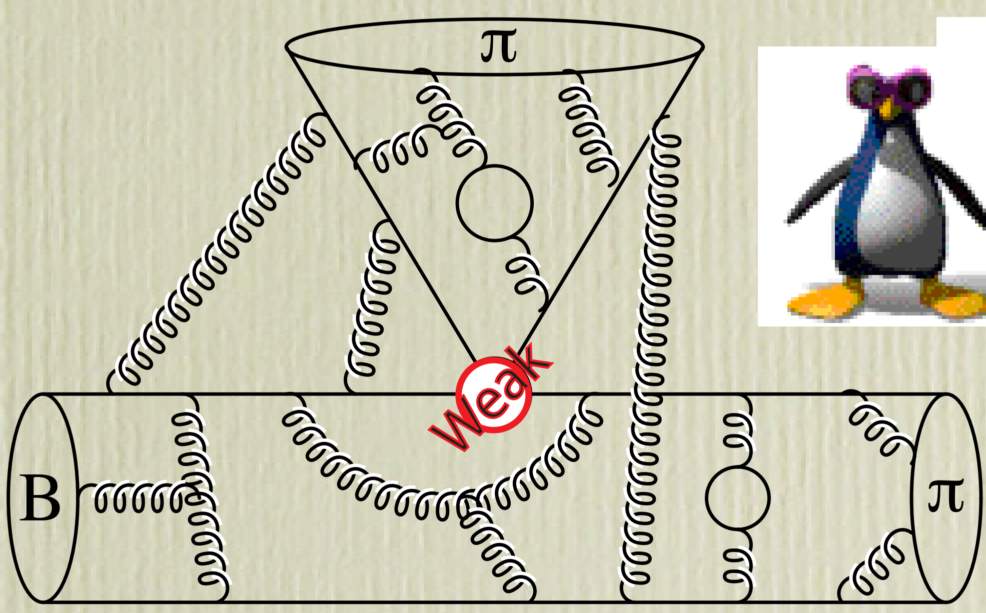


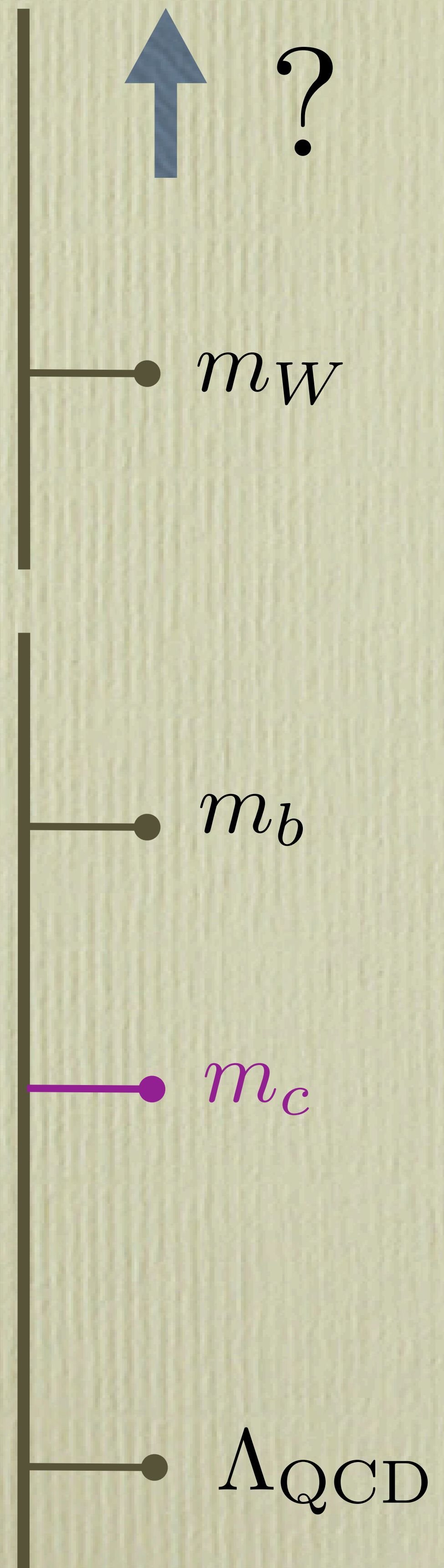

$$H_{\rm weak} = \frac{G_F}{\sqrt{2}} \sum_i \lambda^i C_i(\mu) O_i(\mu)$$

- $\lambda^i = \text{CKM},\ \lambda^1 = V_{ub}V_{ud}^*$

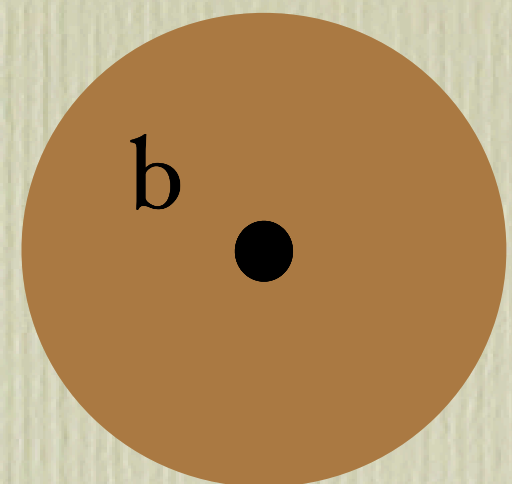
  $C_1 > C_2, C_{7\gamma}, C_{8g} \gg C_{4,6} > C_{3,5,9,10} > C_{7,8}$

- $O_1 = (\bar{u}b)_{V-A}(\bar{d}u)_{V-A}$ , ...




B-meson

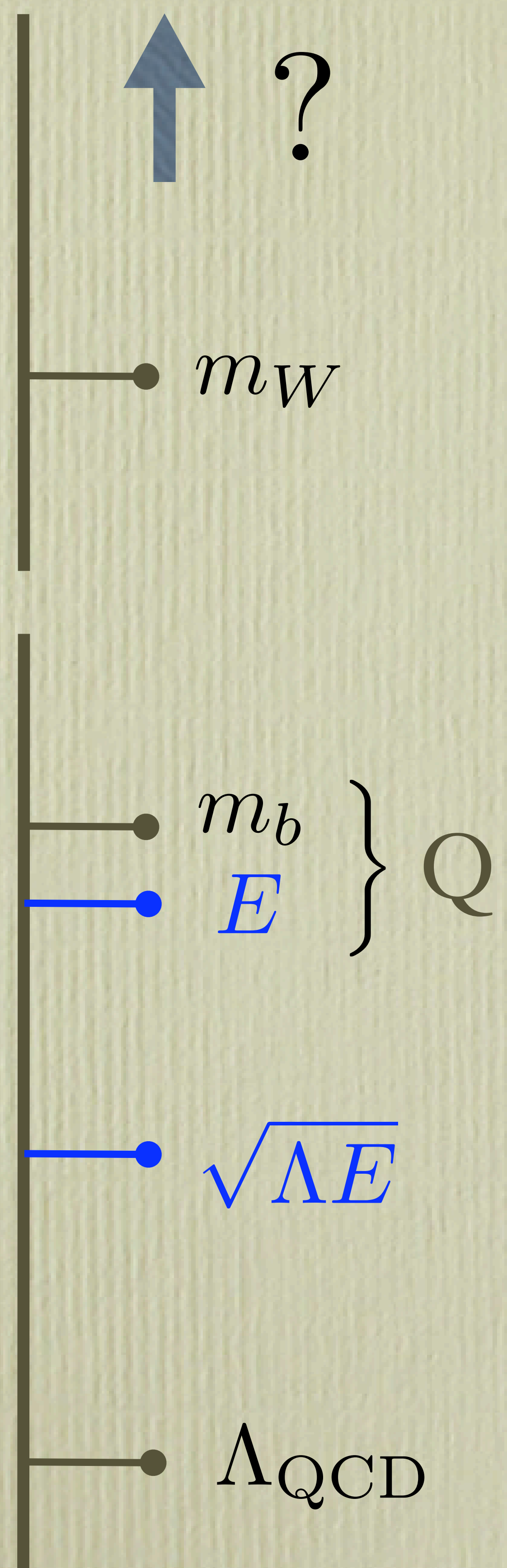



$\Lambda_{\mathrm{QCD}} \ll m_b$

Heavy Quark Effective Theory

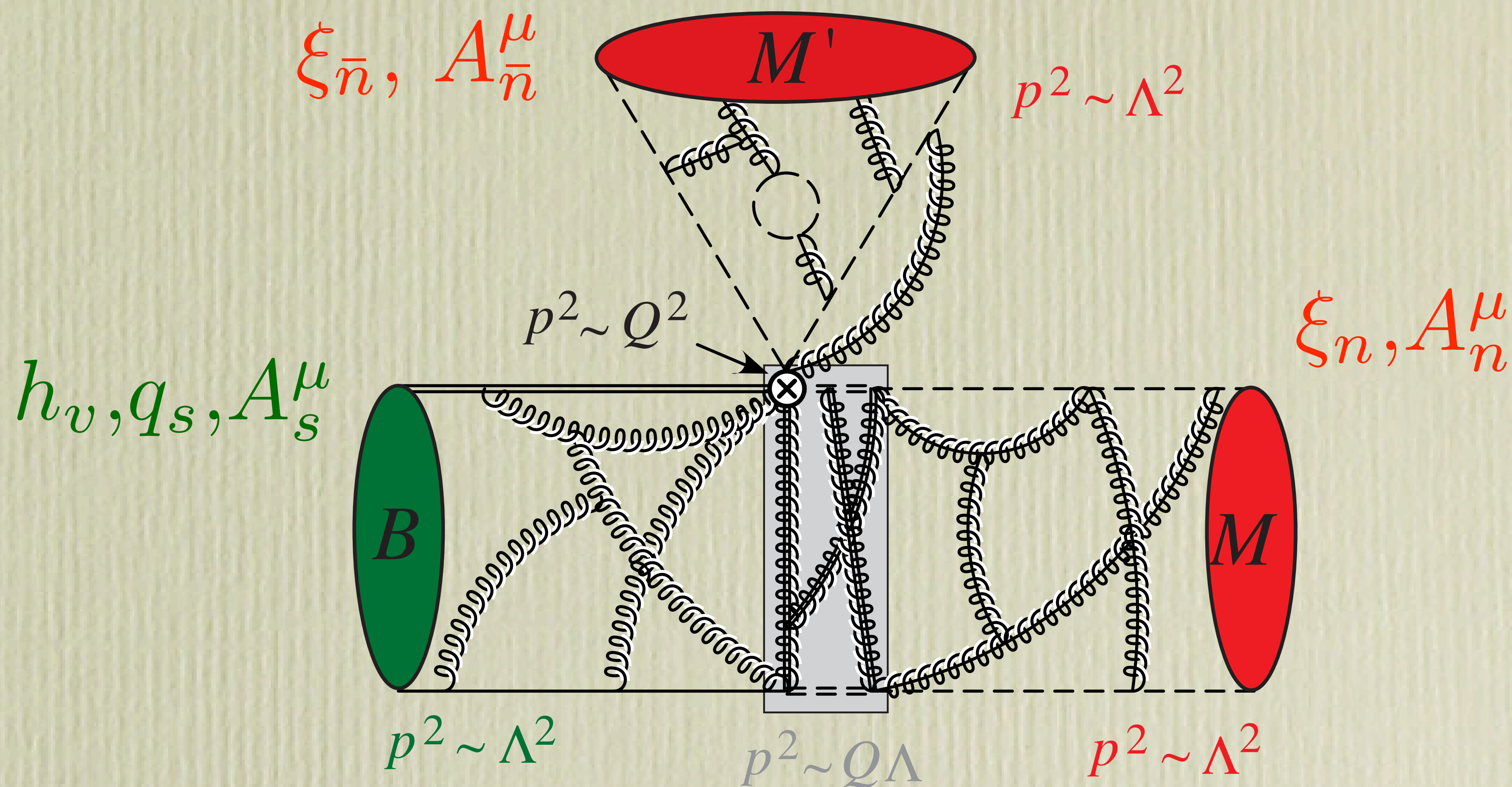
$h_v, q, A^\mu$

$B \to \pi\pi$ , ...




# Energetic Hadrons

Soft-Collinear Effective Theory




- Separate physics at different momentum scales
- Model independent, systematically improvable
- Power expansion, can estimate uncertainty
- Exploit symmetries, sum Sudakov logarithms

# A short History of SCET

LEET, NRQCD C.S.S. QCDF

Brodsky/Lepage

Formalism:

hep-ph/0005275, Bauer, Fleming, Luke

hep-ph/0011336, Bauer, Fleming, Pirjol, I.S.

hep-ph/0107001, Bauer, I.S.

hep-ph/0109045, Bauer, Pirjol, I.S.

More work:

hep-ph/0201197, Chay, Kim

hep-ph/0202088, Bauer, Fleming, Pirjol, Rothstein, I.S.

hep-ph/0204229, Pirjol, Manohar, Mehen, I.S.

hep-ph/0206152, Beneke, Chapovsky, Diehl, Feldmann

hep-ph/0211018, Hill, Neubert

...

# QCD Expansion Parameters

| | | |
|---|---|---|
| 1) Isospin | $\frac{m_{u,d}}{\Lambda} \simeq 0.02$ | |
| 2) Heavy b-quark | $\frac{\Lambda}{m_b} \simeq 0.1, \quad \alpha_s(m_b) \simeq 0.2$ | |
| 3) Energetic Hadron | $\frac{\Lambda}{E_M} \simeq 0.2$ | SCET |
| 4) Jet Scale expansion | $\alpha_s(\sqrt{E\Lambda}) \simeq 0.3$ | SCET |
| 5) Heavy c-quark | $\frac{\Lambda}{m_c} \simeq 0.3$ | |
| 6) SU(3) | $\frac{m_s}{\Lambda} \simeq 0.3$ | |

Terms in the series expansion are unique

nonperturbative parameters

$$\mathrm{Obs} = \sum_i f_i^{(0)} + \epsilon \sum_i f_i^{(1)} + \epsilon^2 \sum_i f_i^{(2)} + \dots$$

Predictions are model independent only if $f_i^{(n)}$ are fit to data

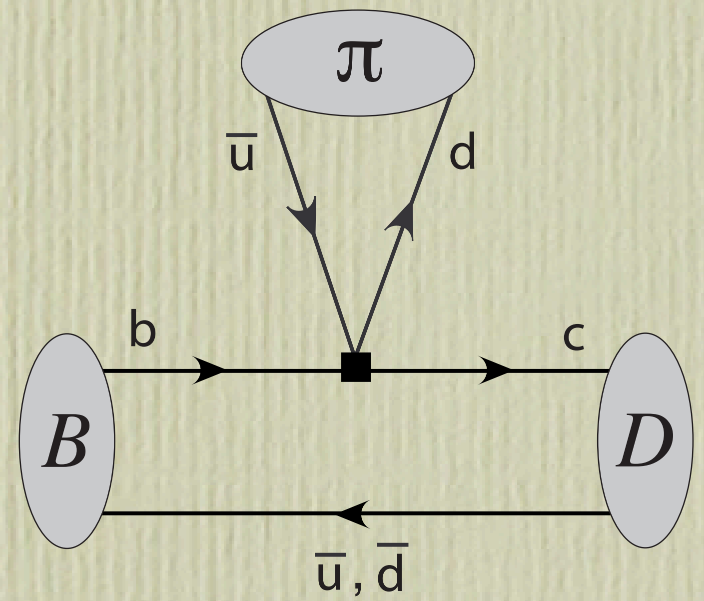
More expansions (more uncertainty) $\longleftrightarrow$ More universality (less parameters)

Test the expansions, then exploit them!

# “$B \to D\pi$” Decays in SCET

Bauer, Pirjol, I.S.
Mantry, Pirjol, I.S.

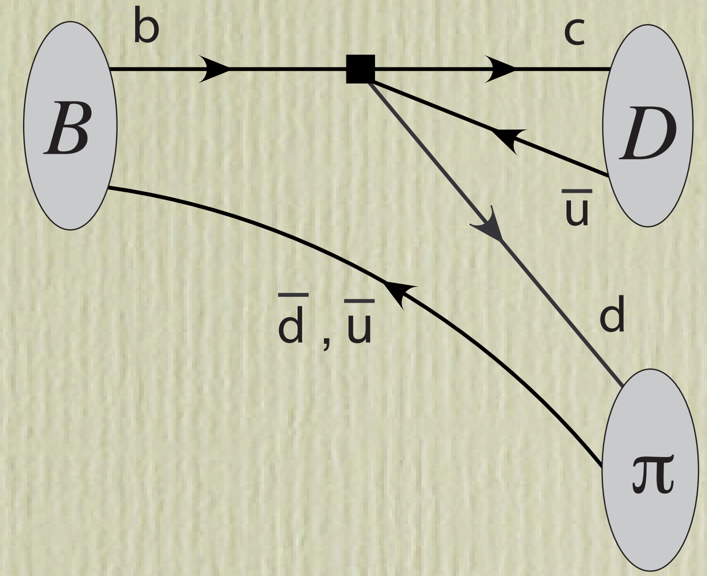
"Tree"




$$\bar{B}^0 \to D^+\pi^-$$
$$B^- \to D^0\pi^-$$

$$\mathcal{O}(1)$$

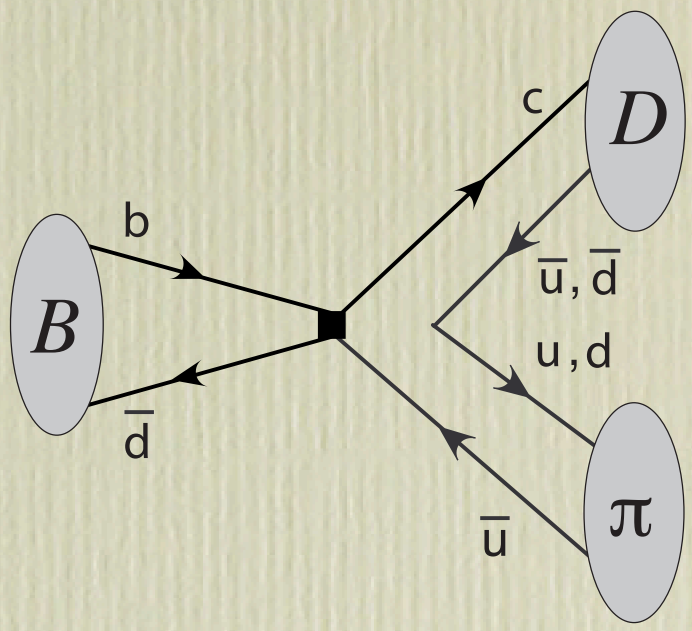
"Color suppressed"




$$B^- \to D^0\pi^-$$
$$\bar{B}^0 \to D^0\pi^0$$

$$\mathcal{O}\left(\frac{\Lambda}{E}\right)$$

"Exchange"




$$\bar{B}^0 \to D^+\pi^-$$
$$\bar{B}^0 \to D^0\pi^0$$

$$\mathcal{O}\left(\frac{\Lambda}{E}\right)$$

Naive Factorization - too small & disagrees with SCET/QCD(!)

$$A(\bar{B}^0 \to D^0\pi^0) \sim a_2 \langle \pi^0 | (\bar{d}b) | \bar{B}^0 \rangle \langle D^0 | (\bar{c}u) | 0 \rangle$$

# Factorization

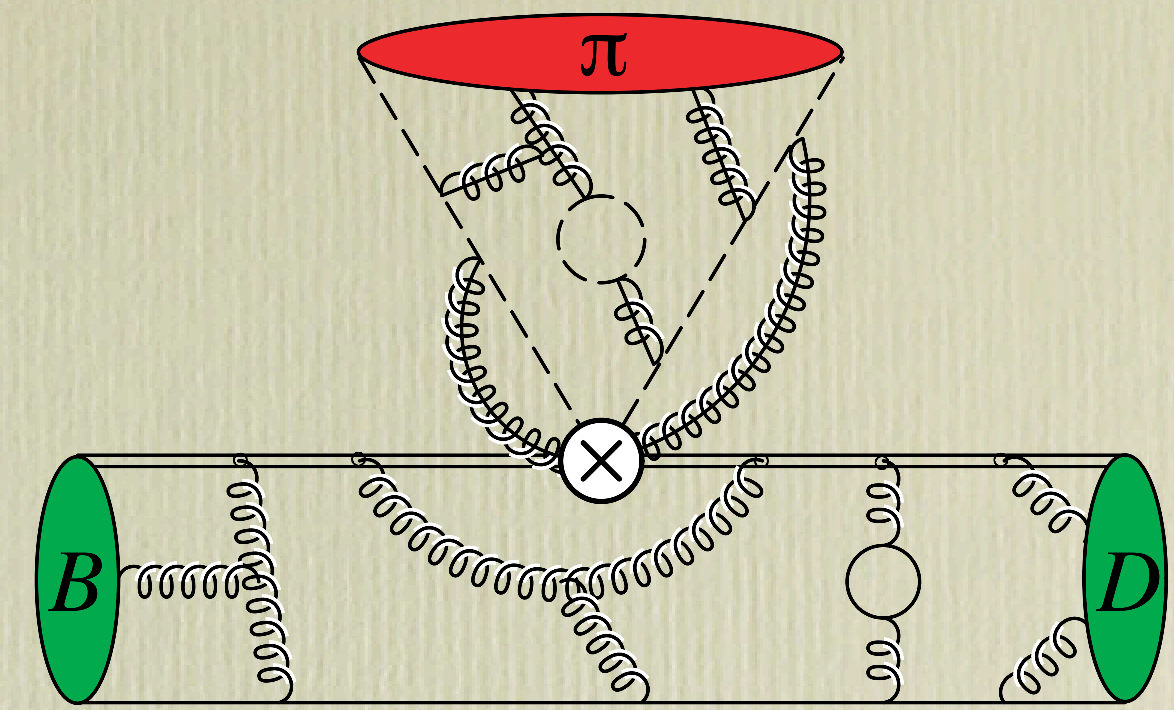
- $\bar{B}^0 \to D^+\pi^- \;\;, \;\; B^- \to D^0\pi^-$

  $B, D$ are soft, $\pi$ collinear

  $$\mathcal{L}_{\rm SCET} = \mathcal{L}_s^{(0)} + \mathcal{L}_c^{(0)}$$

  Factorization if $\mathcal{O} = O_c \times O_s$

  $$\langle D\pi|(\bar{c}b)(\bar{u}d)|B\rangle = N\,\xi(v\cdot v')\int_0^1 dx\, T(x,\mu)\,\phi_\pi(x,\mu)$$




Calculate T

- $\bar{B}^0 \to D^{(*)0}\pi^0$ (power suppressed)

$$A_{00}^{D^{(*)}\pi} = N_0^{(*)}\int dx\,dz\,dk_1^+dk_2^+\,\underbrace{T^{(i)}(z)}_{Q^2}\;\gg\;\underbrace{J^{(i)}(z,x,k_1^+,k_2^+)}_{Q\Lambda}\;\gg\;\underbrace{S^{(i)}(k_1^+,k_2^+)}_{\Lambda^2}\,\phi_\pi(x)$$

$$+A_{\rm long}^{D^{(*)}\pi}$$

1) Test $\Lambda/E$ expansion (no expansion for jet, J)

$$\langle D^{(*)0}|O_s^{(0,8)}|\bar{B}^0\rangle \to S^{(0,8)}(k_1^+, k_2^+)$$

same for $D$ and $D^*$

complex (universal nonperturbative phases)

with HQET $\langle D^{(*)0}\pi|(\bar{c}\,b)(\bar{d}\,u)|\bar{B}^0\rangle$ gives $\frac{p_\pi^\mu}{m_c} \to \frac{E_\pi}{m_c} = 1.5$

not a convergent expansion

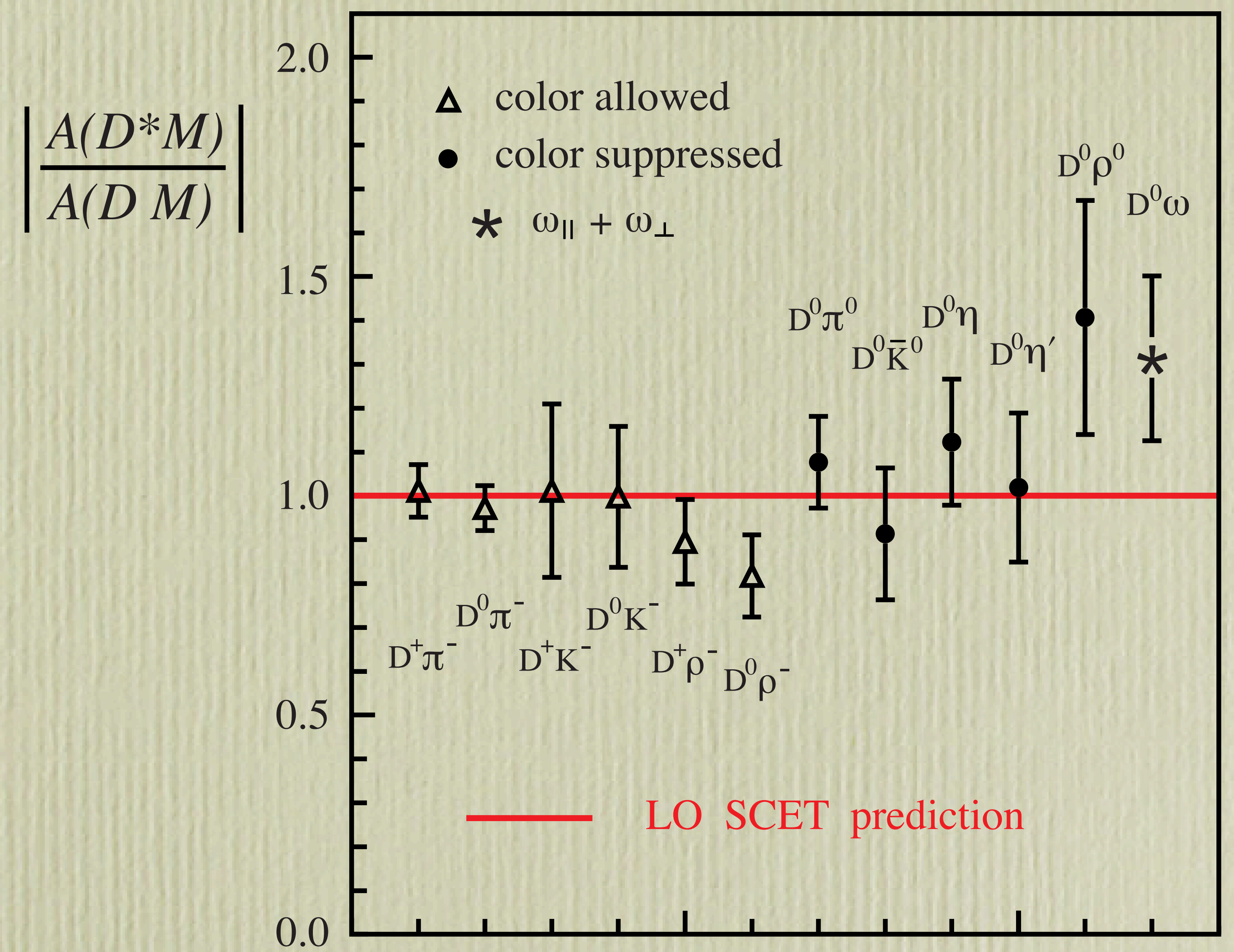
Predict

equal strong phases $\delta^D = \delta^{D^*}$

equal amplitudes $A_{00}^D = A_{00}^{D*}$

corrections to this are $\alpha_s(m_b)$, $\Lambda/Q$

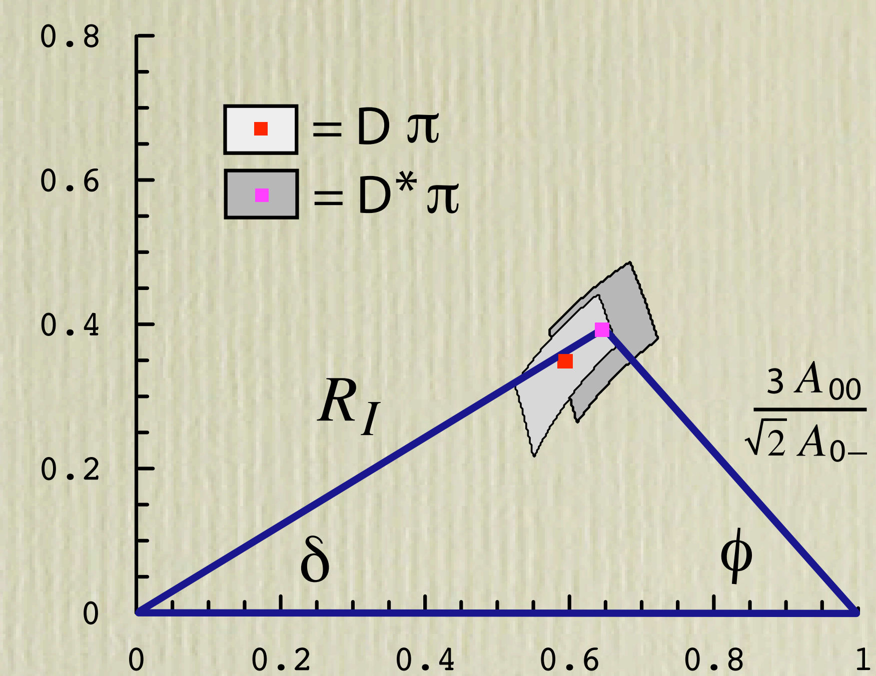
# Expt Average (Cleo, Belle, Babar):




Extension to isosinglets:

Blechman, Mantry, I.S.

isospin triangle




$$\delta(D\pi) = 30.4 \pm 4.8^\circ$$
$$\delta(D^*\pi) = 31.0 \pm 5.0^\circ$$

Not yet tested:

- $Br(D^*\rho^0_\parallel) \gg Br(D^*\rho^0_\perp)$ , $Br(D^{*0}K^{*0}_\parallel) \sim Br(D^{*0}K^{*0}_\perp)$
- equal ratios $D^{(*)}K^*$, $D_s^{(*)}K$, $D_s^{(*)}K^*$; triangles for $D^{(*)}\rho$, $D^{(*)}K$

Not yet tested:

- Excited D's

Mantry

$$\frac{Br(B \to D_2^* \pi)}{Br(B \to D_1 \pi)} = 1 \qquad \phi_{D_2^* \pi} = \phi_{D_1 \pi}$$

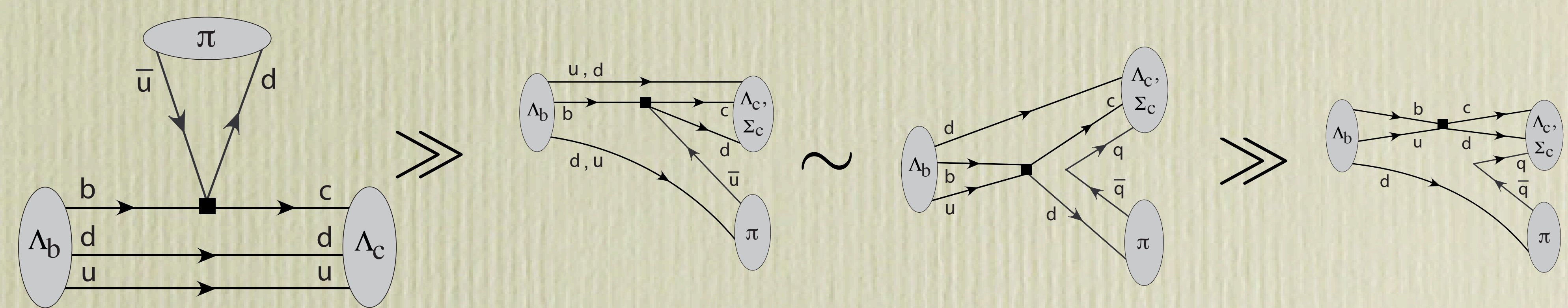
Belle:

$$\frac{Br(B^- \to D_2^{*0} \pi^-)}{Br(B^- \to D_1^0 \pi^-)} = 0.77 \pm 0.15$$

- Baryons

Leibovich, Ligeti, I.S., Wise

topologies:




$$\frac{Br(\Lambda_b \to \Sigma_c^* \pi)}{Br(\Lambda_b \to \Sigma_c \pi)} = 2\,, \quad \frac{Br(\Lambda_b \to \Sigma_c^* \rho)}{Br(\Lambda_b \to \Sigma_c \rho)} = 2 \qquad \frac{Br(\Lambda_b \to \Xi_c^* K)}{Br(\Lambda_b \to \Xi_c' K)} = 2\,, \quad \frac{Br(\Lambda_b \to \Xi_c^* K_\parallel^*)}{Br(\Lambda_b \to \Xi_c' K_\parallel^*)} = 2$$

# 2) Test $\alpha_s(E\Lambda)$ expansion (expansion for J)

## Relate $\pi$ and $\rho$

- Recall data gives

$$|r^{D\pi}| \;=\; \frac{|A(\bar{B}^0 \to D^+\pi^-)|}{|A(B^- \to D^0\pi^-)|} = 0.77 \pm 0.05\,, \qquad |r^{D\rho}| = 0.80 \pm 0.09$$

SCET predicts weak dependence on $M$ through $\langle x^{-1}\rangle_\pi \simeq \langle x^{-1}\rangle_\rho$ :

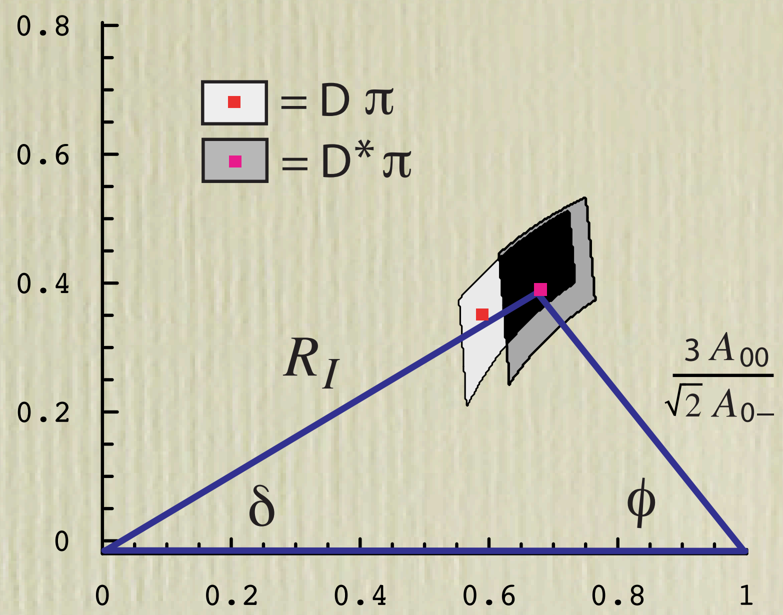
$$r^{DM} = 1 - \frac{16\pi\alpha_s m_D}{9(m_B+m_D)}\,\frac{\langle x^{-1}\rangle_M}{\xi(w_{max})}\,\frac{s_{\rm eff}}{E_M}$$

no $f_\rho = 1.6\, f_\pi$

natural parameters fit data, $s_{\rm eff} \simeq (430\,\text{MeV})e^{i\,44^\circ}$

## 2) Test $\alpha_s(E\Lambda)$ expansion (expansion for J)

### Relate $\pi$ and $\rho$




- predict that $\phi^{D\rho} = \phi^{D\pi}$, not yet tested

if $\langle x^{-1}\rangle_\pi \simeq \langle x^{-1}\rangle_\rho$ then this implies $\delta^{D\pi} \simeq \delta^{D\rho}$

### Relate $\eta$ and $\eta'$

FKS mixing angle

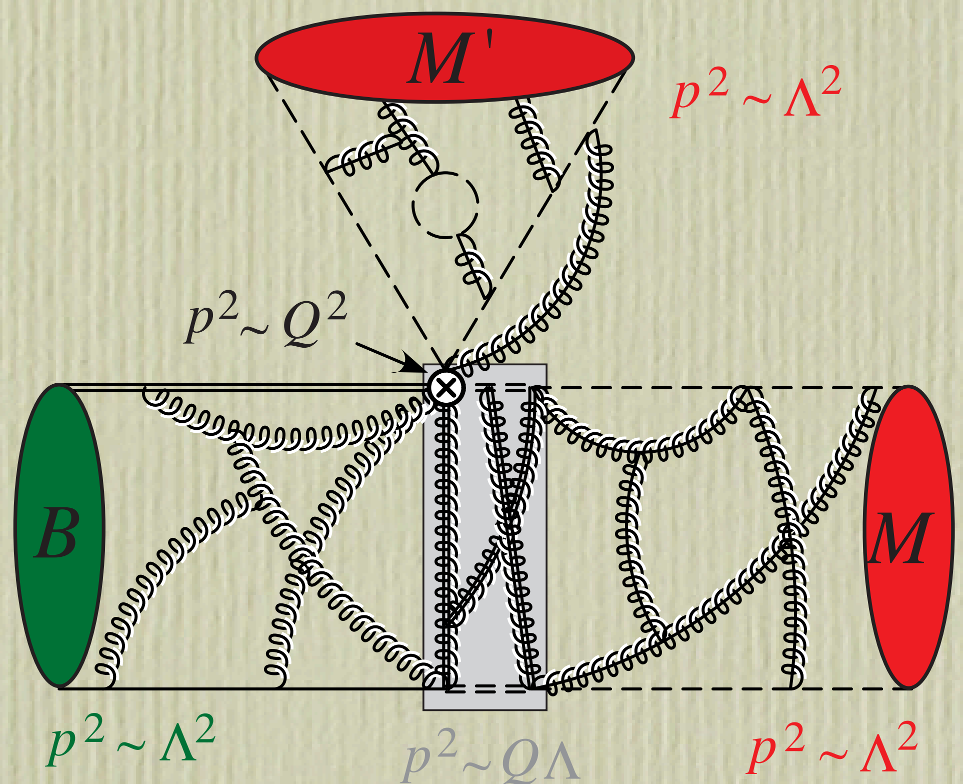
- $$\frac{Br(\bar{B} \to D^{(*)}\eta')}{Br(\bar{B} \to D^{(*)}\eta)} = \tan^2(\theta) = 0.67 \quad +\mathcal{O}(\alpha_s(\sqrt{E\Lambda}))$$

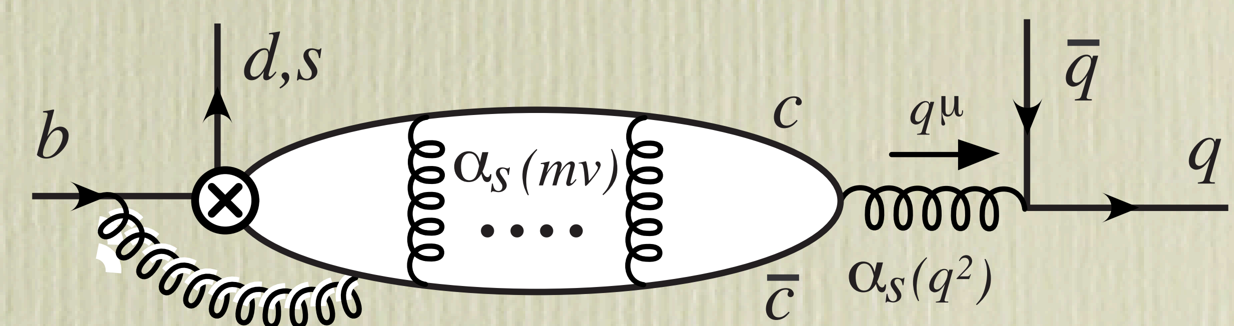
$$\text{data} = 0.61 \pm 0.12(D), \quad 0.51 \pm 0.18(D^*)$$

# $B \to M_1 M_2$ Factorization in SCET

$\Lambda^2 \ll E\Lambda \ll E^2, m_b^2$

Bauer, Pirjol, Rothstein, I.S.
Chay, Kim
(earlier work by B.B.N.S.)




Ciuchini et al,
Colangelo et al

- hard spectator & form factor terms → same, universality at $E\Lambda$

  → Same Jet function as $B \to M$ form factors

- long distance charm penguin $= A_{c\bar{c}} \sim \alpha_s(2m_c)v$ not $\frac{\Lambda}{m_b}$

  → treat $c\bar{c}$ Penguin as a complex parameter (use isospin)

## Factorization at $m_b$

expansion in $\frac{\Lambda}{Q}$, $\alpha_s(m_b)$,

corrections $\sim 20\%$

**Nonleptonic** $B \to M_1 M_2$

$$A(B \to M_1 M_2) = A^{c\bar{c}} + N\Big\{ f_{M_2}\zeta^{BM_1} \int du\, T_{2\zeta}(u)\phi^{M_2}(u) + f_{M_2} \int du dz\, T_{2J}(u,z)\zeta_J^{BM_1}(z)\phi^{M_2}(u) + (1 \leftrightarrow 2)\Big\}$$

**Form Factors**

$B \to$ pseudoscalar: $f_+$, $f_0$, $f_T$
$B \to$ vector: $V$, $A_0$, $A_1$, $A_2$, $T_1$, $T_2$, $T_3$

$$f(E) = \int dz\, T(z,E)\, \zeta_J^{BM}(z,E) \quad \Big\} \quad \text{“hard spectator”, “factorizable”}$$

$$+\, C(E)\, \zeta^{BM}(E) \quad \Big\} \quad \text{“soft form factor”, “non-factorizable”}$$

## Factorization at $\sqrt{E\Lambda}$

expansion in $\alpha_s(\sqrt{E\Lambda})$

$$\zeta_J^{BM}(z) = f_M f_B \int_0^1 dx \int_0^\infty dk^+ J(z,x,k^+,E)\phi_M(x)\phi_B(k^+)$$

$$\zeta^{BM} = ?$$

Beneke, Feldmann
Bauer, Pirjol, I.S.
Becher, Hill, Lange, Neubert

One Loop Matching: $C_k(E, m_b)$ $T_f(z, E)$ Bauer, Fleming, Pirjol, I.S.; Beneke, Kiyo, Yang

$T_{2\zeta}(u)$ BBNS

$T_{2J}(u)$ MISSING!

$J(z, x, r_+, E)$ Becher, Hill, Lee, Lange, Neubert

Log Resummation:

Sudakov suppression of "soft" relative to "hard" form factors

→ small for physical b-quark mass

## Model Independent Predictions:

- small phases between non-penguin amplitudes → $\gamma$
- relations between semi & non - leptonics → $V_{ub}$
- power suppressed annihilation

I will not use model dependent input parameters (pQCD,QCDF)

→ see parallel talks

# Phenomenology for $B \to \pi\pi$

Test
CP violation

Averages ('05) (BABAR, BELLE)

| | $\overline{\text{Br}} \times 10^6$ | $C_{\pi\pi}$ | $S_{\pi\pi}$ |
|---|---|---|---|
| $\pi^+\pi^-$ | $4.6 \pm 0.4$ | $-0.37 \pm 0.10$ | $-0.50 \pm 0.12$ |
| $\pi^0\pi^0$ | $1.51 \pm 0.28$ | $-0.28 \pm 0.39$ | |
| $\pi^+\pi^0$ | $5.61 \pm 0.63$ | | |

| | $C_{\pi\pi}$ | $S_{\pi\pi}$ |
|---|---|---|
| Babar | $-0.09 \pm 0.15$ | $-0.30 \pm 0.17$ |
| Belle | $-0.56 \pm 0.13$ | $-0.67 \pm 0.17$ |

## Pure Isospin Analysis

ala Gronau, London

$$A(\bar{B}^0 \to \pi^+\pi^-) = e^{-i\gamma}\,|\lambda_u|\,T - |\lambda_c|\,P$$
$$A(\bar{B}^0 \to \pi^0\pi^0) = e^{-i\gamma}\,|\lambda_u|\,C + |\lambda_c|P$$
$$\sqrt{2}A(B^- \to \pi^0\pi^-) = e^{-i\gamma}\,|\lambda_u|\,(T + C)$$

extract weak phase &
hadronic parameters

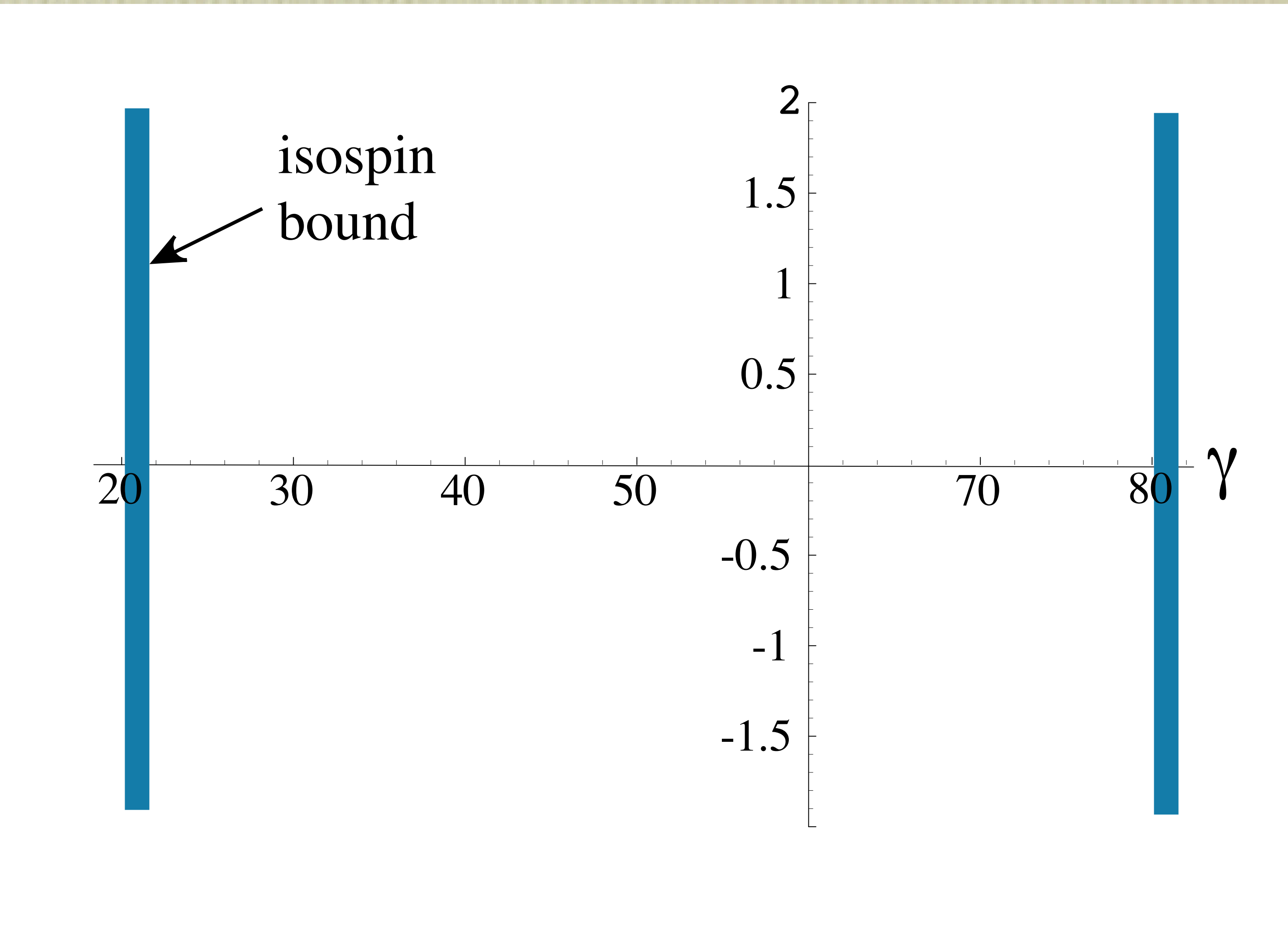
$|\lambda_{c,u}| = \text{CKM factors}$ , $\beta$ known

## Parameters:

$\gamma$ +5 hadronic

one, say T, just sets Br scale

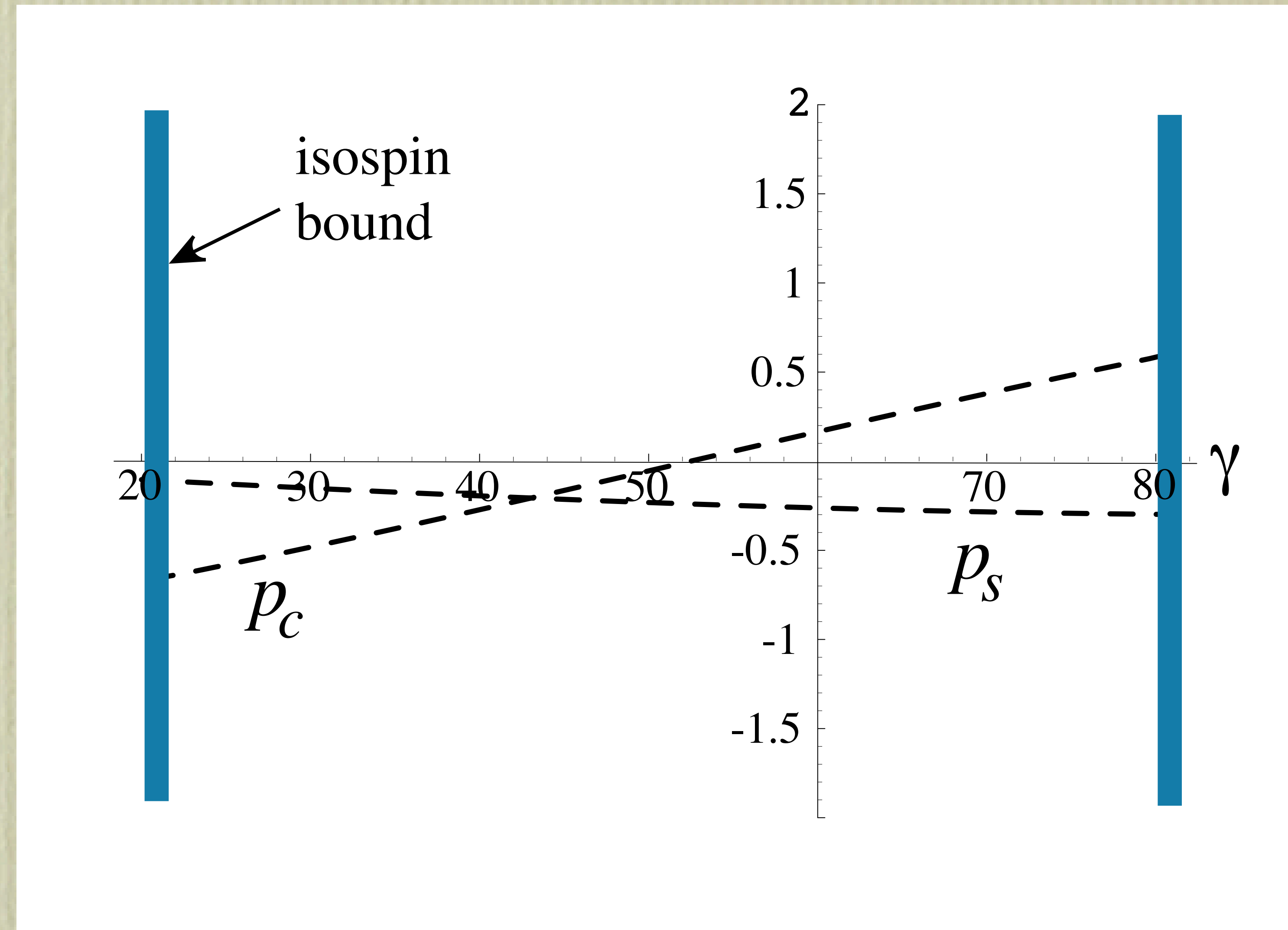
$$p_c \equiv -\frac{|\lambda_c|}{|\lambda_u|}\,\mathrm{Re}\Big(\frac{P}{T}\Big), \quad p_s \equiv -\frac{|\lambda_c|}{|\lambda_u|}\,\mathrm{Im}\Big(\frac{P}{T}\Big),$$
$$t_c \equiv \frac{|T|}{|T+C|}, \qquad \epsilon \equiv \mathrm{Im}\Big(\frac{C}{T}\Big).$$




Grossman, Quinn
Charles
Gronau, London, Sinha^2

$$p_c \equiv -\frac{|\lambda_c|}{|\lambda_u|}\,\mathrm{Re}\left(\frac{P}{T}\right), \quad p_s \equiv -\frac{|\lambda_c|}{|\lambda_u|}\,\mathrm{Im}\left(\frac{P}{T}\right),$$

$$t_c \equiv \frac{|T|}{|T+C|}, \qquad \epsilon \equiv \mathrm{Im}\left(\frac{C}{T}\right).$$




Data:

$$S_{\pi^+\pi^-}, C_{\pi^+\pi^-} \Rightarrow p_c, p_s \;\; (\gamma)$$

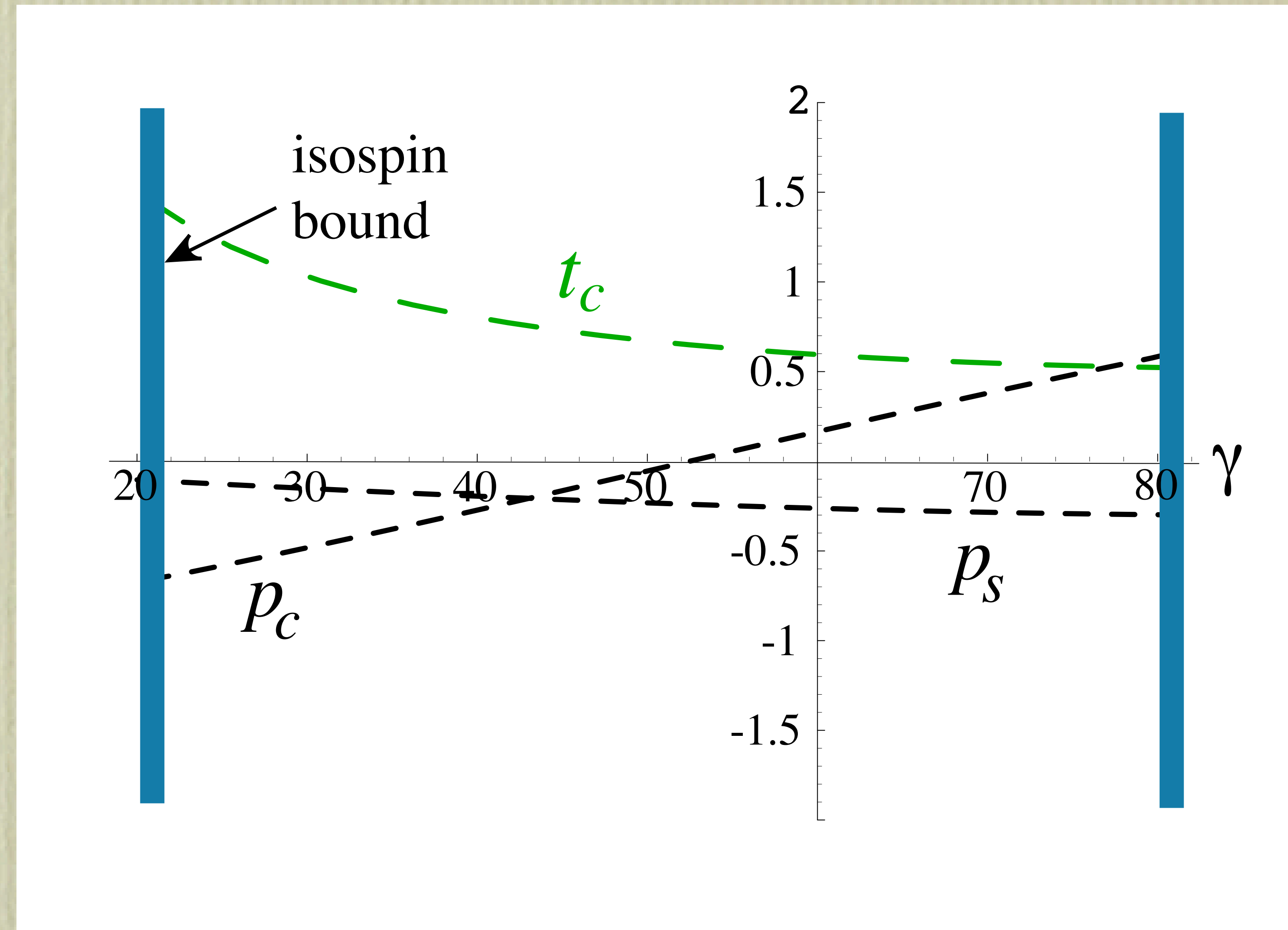
large Im(penguin)

SCET:

- size of penguin consistent with $A_{c\bar{c}} \sim v\, \alpha_s(2m_c)$

$$p_c \equiv -\frac{|\lambda_c|}{|\lambda_u|}\,\mathrm{Re}\Big(\frac{P}{T}\Big)\,, \quad p_s \equiv -\frac{|\lambda_c|}{|\lambda_u|}\,\mathrm{Im}\Big(\frac{P}{T}\Big)\,,$$

$$t_c \equiv \frac{|T|}{|T+C|}\,, \qquad \epsilon \equiv \mathrm{Im}\Big(\frac{C}{T}\Big)\,.$$




$$\frac{Br(\pi^+\pi^-)}{Br(\pi^0\pi^-)} \Rightarrow t_c(\gamma)$$

large C amplitude

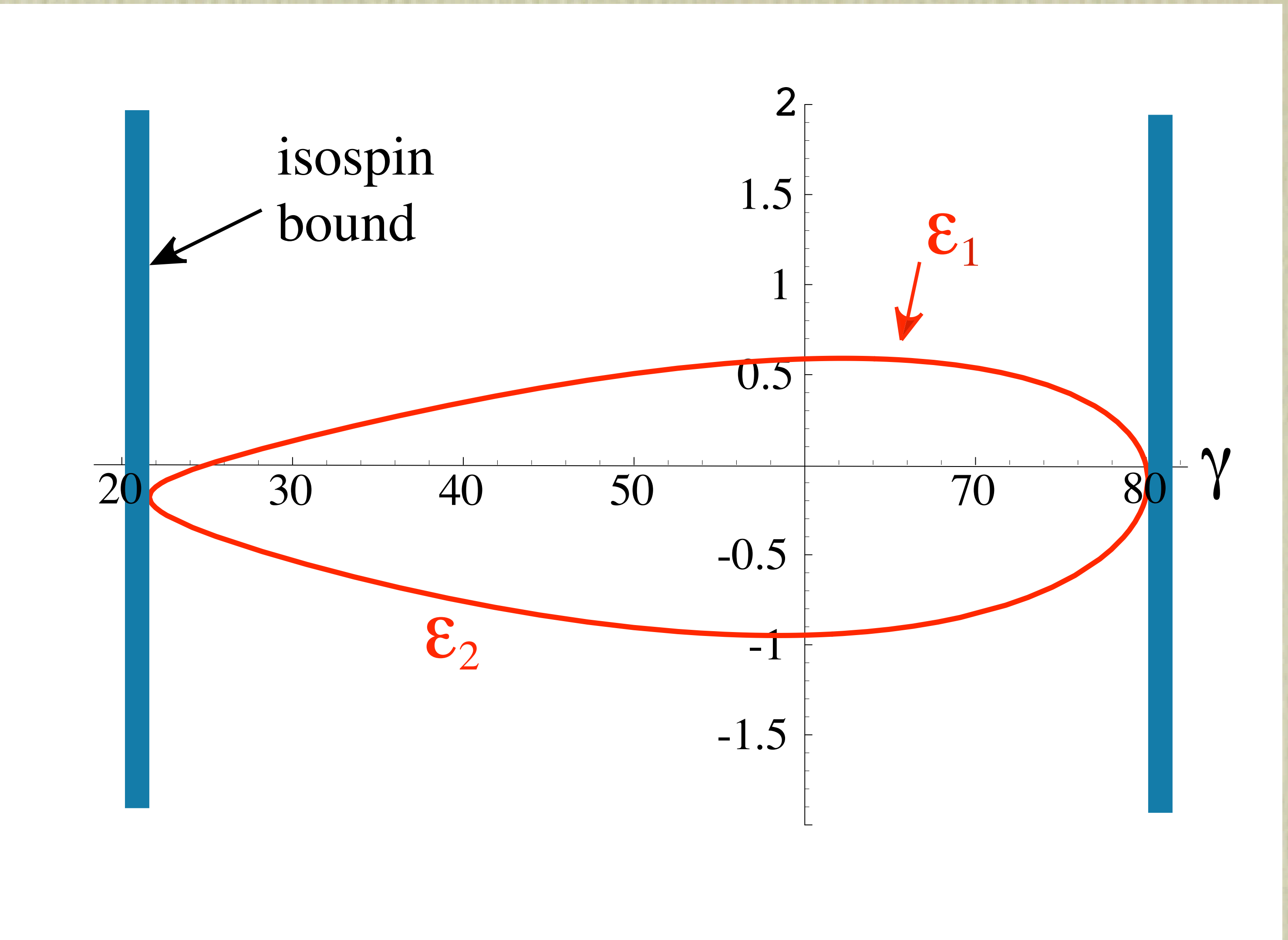
SCET:

$\simeq 3$

- an extra term $\frac{C_1}{N_c}\langle \bar{u}^{-1}\rangle_\pi\, \zeta_J^{B\pi}$ ruins color suppression

$$p_c \equiv -\frac{|\lambda_c|}{|\lambda_u|}\,\mathrm{Re}\Big(\frac{P}{T}\Big), \quad p_s \equiv -\frac{|\lambda_c|}{|\lambda_u|}\,\mathrm{Im}\Big(\frac{P}{T}\Big),$$

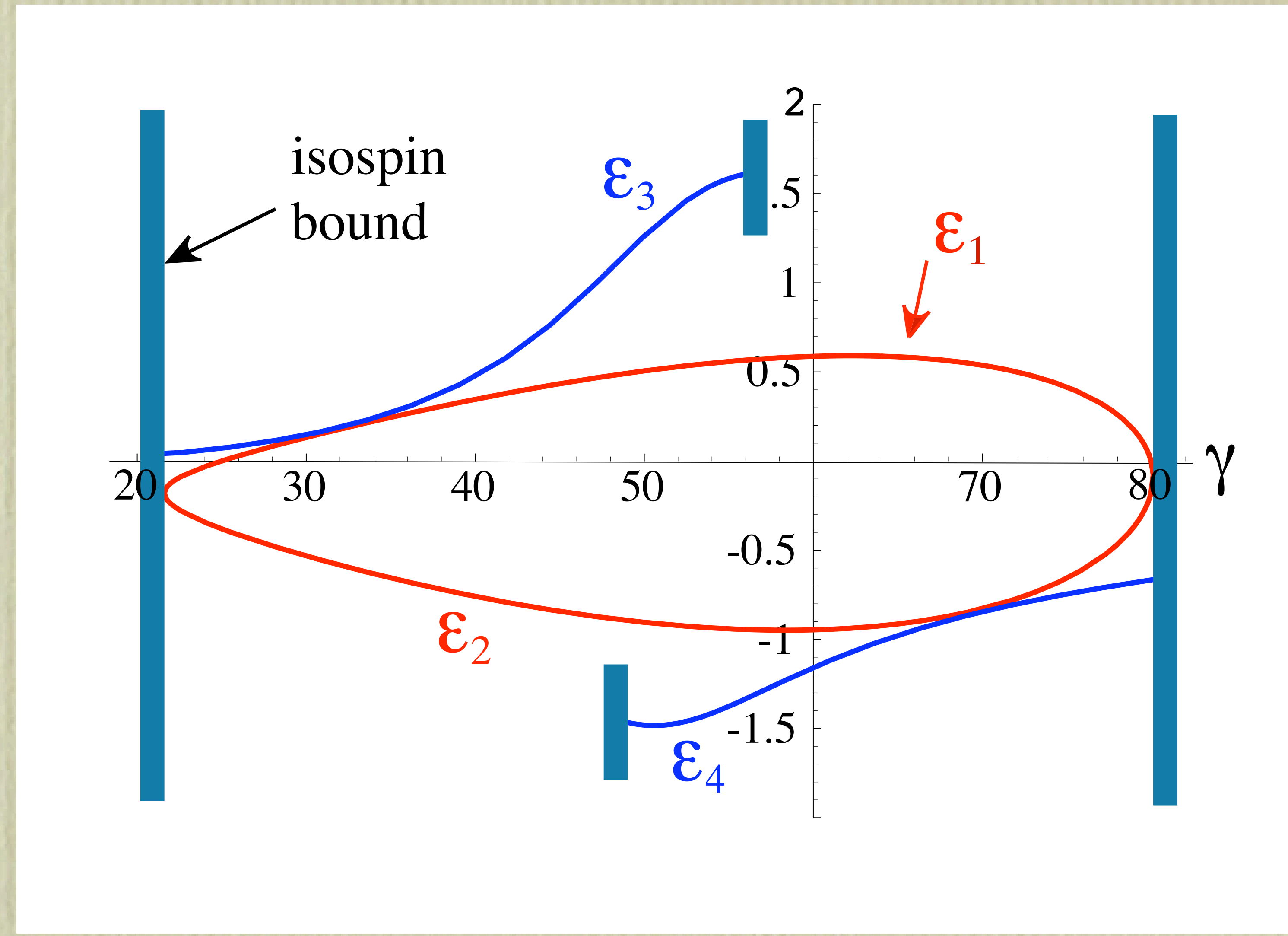
$$t_c \equiv \frac{|T|}{|T+C|}, \qquad \epsilon \equiv \mathrm{Im}\Big(\frac{C}{T}\Big).$$




$$\frac{Br(\pi^0\pi^0)}{Br(\pi^0\pi^-)} \Rightarrow \epsilon_{1,2}\,(\gamma)$$

$$p_c \equiv -\frac{|\lambda_c|}{|\lambda_u|}\,\mathrm{Re}\left(\frac{P}{T}\right), \quad p_s \equiv -\frac{|\lambda_c|}{|\lambda_u|}\,\mathrm{Im}\left(\frac{P}{T}\right),$$

$$t_c \equiv \frac{|T|}{|T+C|}, \qquad \epsilon \equiv \mathrm{Im}\left(\frac{C}{T}\right).$$

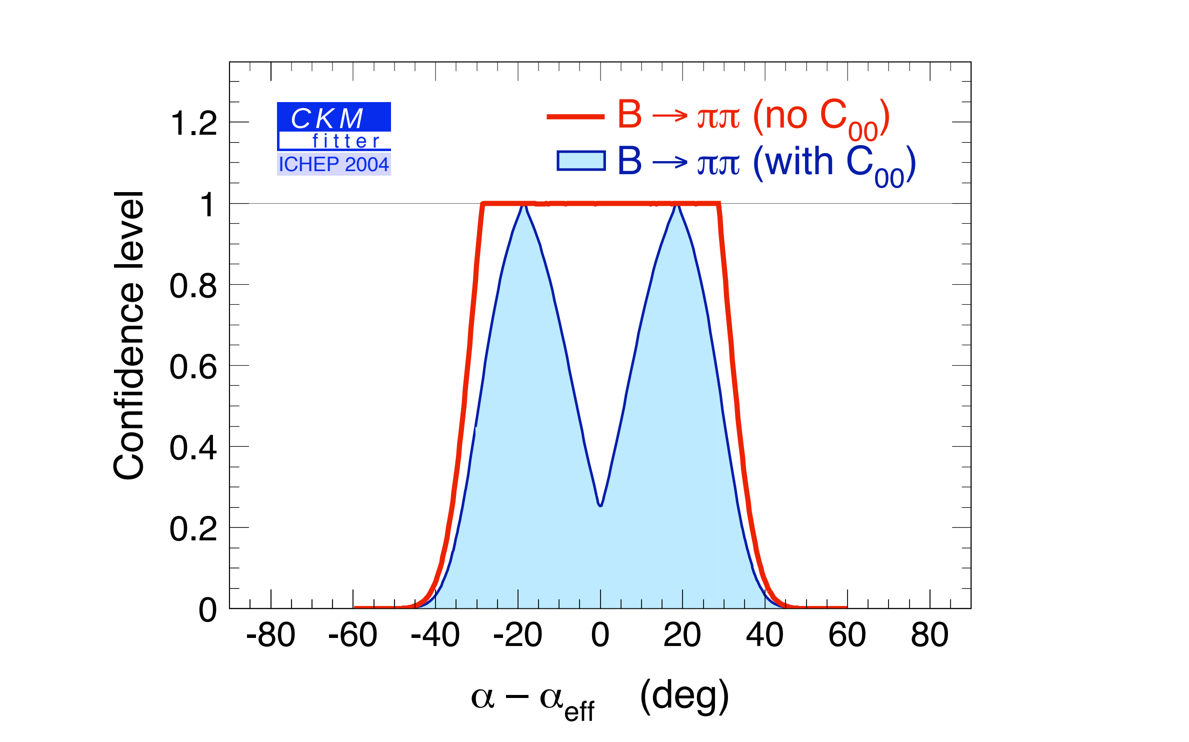



$$\frac{Br(\pi^0\pi^0)}{Br(\pi^0\pi^-)} \Rightarrow \epsilon_{1,2}(\gamma)$$

$$C_{\pi^0\pi^0} \Rightarrow \epsilon_{3,4}(\gamma)$$

solutions should agree

isospin:



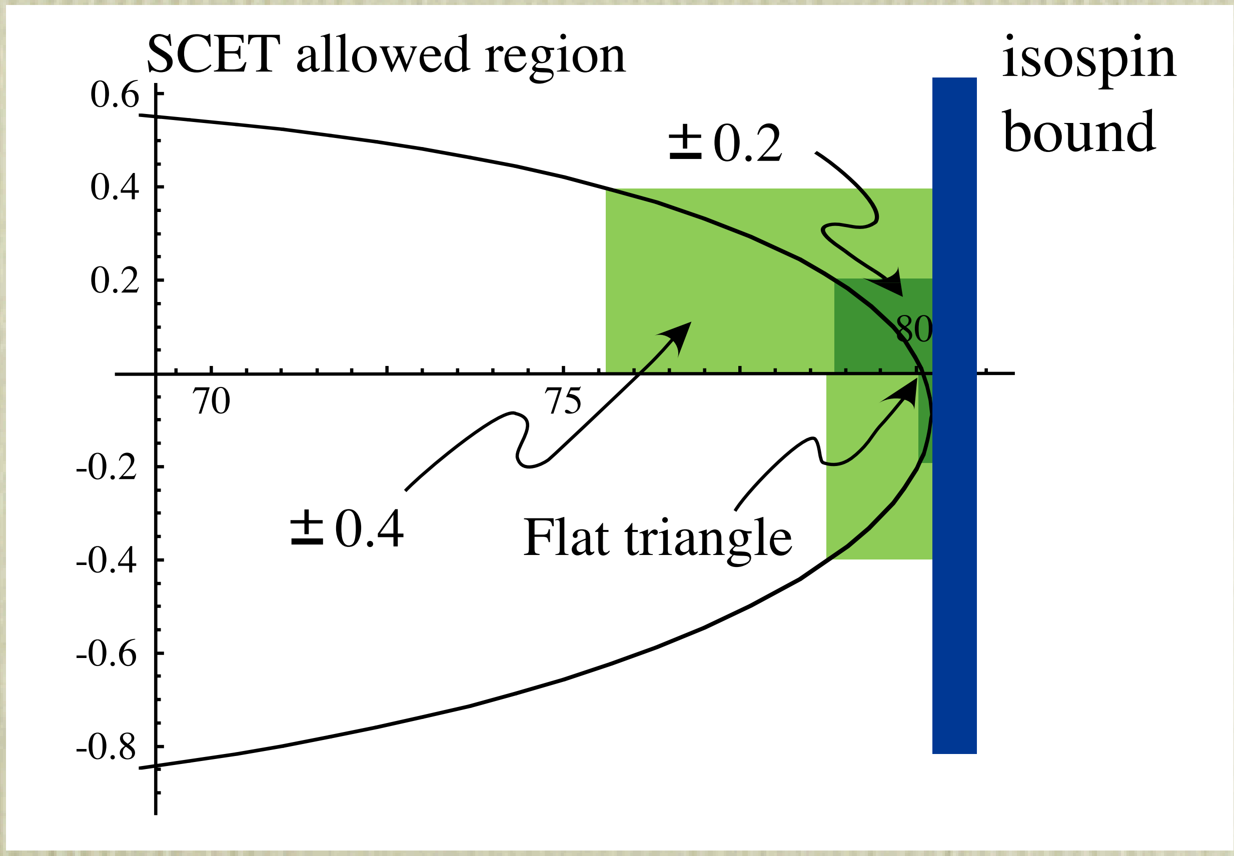

Problem is $C_{\pi^0\pi^0}$ uncertainty

# A New Method for Determining $\gamma$

Bauer, Rothstein, I.S.

Isospin + bare minimum from $\Lambda/m_b$ expansion

Factorization from SCET: $\epsilon \sim \mathcal{O}\Big(\frac{\Lambda_{\rm QCD}}{m_b}, \alpha_s(m_b)\Big)$. This gives




Theory uncertainty is small

$$\gamma = 80.1^\circ \pm 2.5^\circ{}^{+7.2^\circ}_{-9.1^\circ}$$
$$(\text{or}{}^{+2^\circ}_{-4^\circ})$$

near the isospin bound

older ICHEP'04:

$$\gamma = 74.9^\circ \pm 2^\circ{}^{+9.4^\circ}_{-13.3^\circ}\,.$$
$$(\text{or}{}^{+2^\circ}_{-5.2^\circ})$$

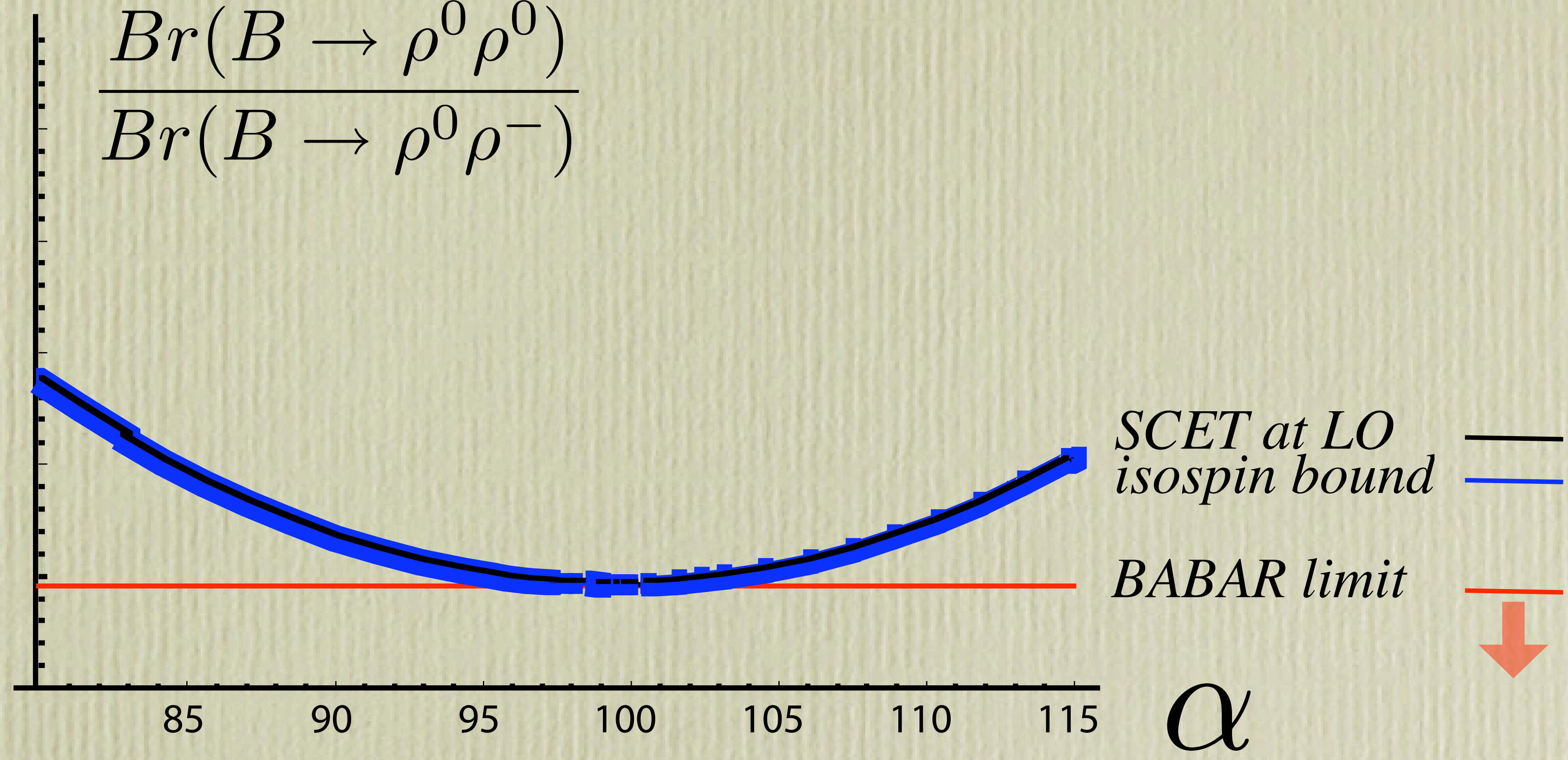
(J.Smith, here)

$$\gamma = 180^\circ - \beta - \alpha$$

isospin $(\pi\pi)$ $\quad \gamma = 70^\circ{}^{+15^\circ}_{-19^\circ}$

$(\pi\pi, \rho\pi, \rho\rho)$ $\quad \gamma = 56^\circ{}^{+9^\circ}_{-16^\circ}$

# Consistency check: $B \to \rho\rho$



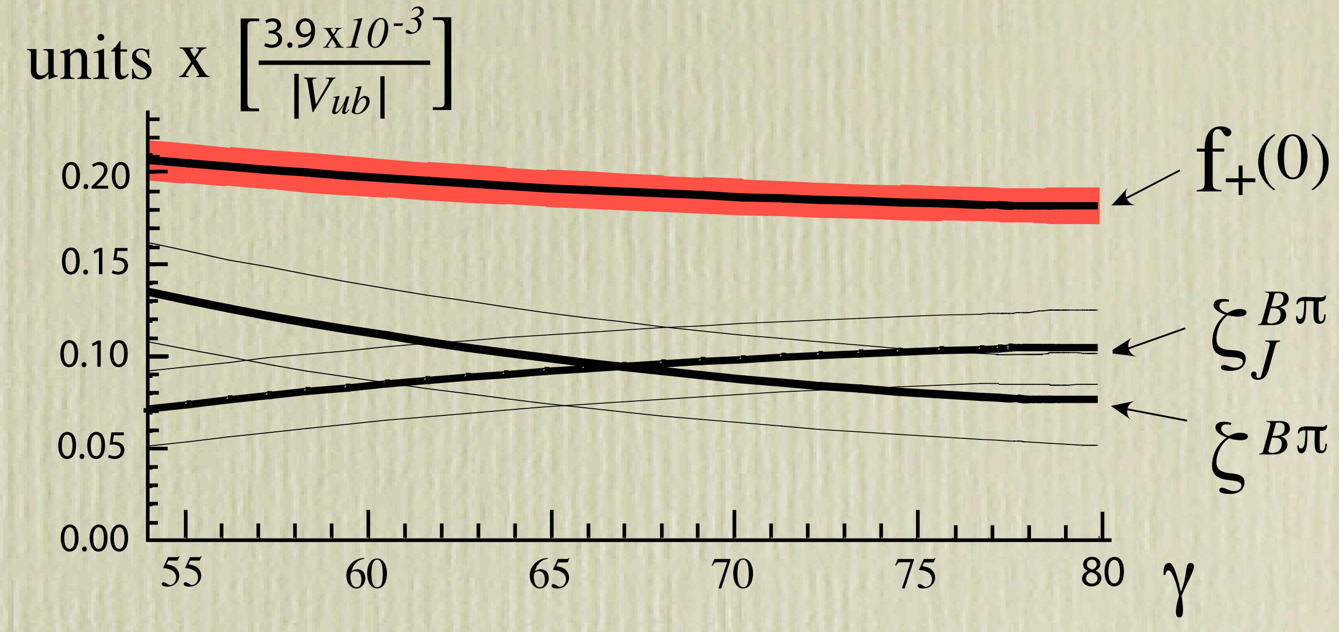

$Br(\rho^0\rho^0)$ consistent with small $C/T$ phase in this channel

Use nonleptonic data: $B \to \pi\pi$ determines the parameters

$$\zeta^{B\pi}\big|_{\gamma=80^\circ} = (0.076 \pm 0.024)\left(\frac{3.9\times10^{-3}}{|V_{ub}|}\right)$$

$$\zeta_J^{B\pi}\big|_{\gamma=80^\circ} = (0.106 \pm 0.019)\left(\frac{3.9\times10^{-3}}{|V_{ub}|}\right)$$

hard scattering $\sim$ soft form factor




$$f_+(0) = \zeta^{B\pi} + \zeta_J^{B\pi}$$

$$f_+(0) = (0.18 \pm 0.01 \pm 0.04)\left(\frac{3.9\times10^{-3}}{|V_{ub}|}\right)$$

expt. theory estimate

$\sim 25\%$ from perturbative and power corrections

smaller than models

$$f_+(0) \sim 0.25$$

independent of :

$$\int dx\, \frac{\phi_\pi(x)}{x} \quad , \quad C_{\pi^+\pi^-}$$

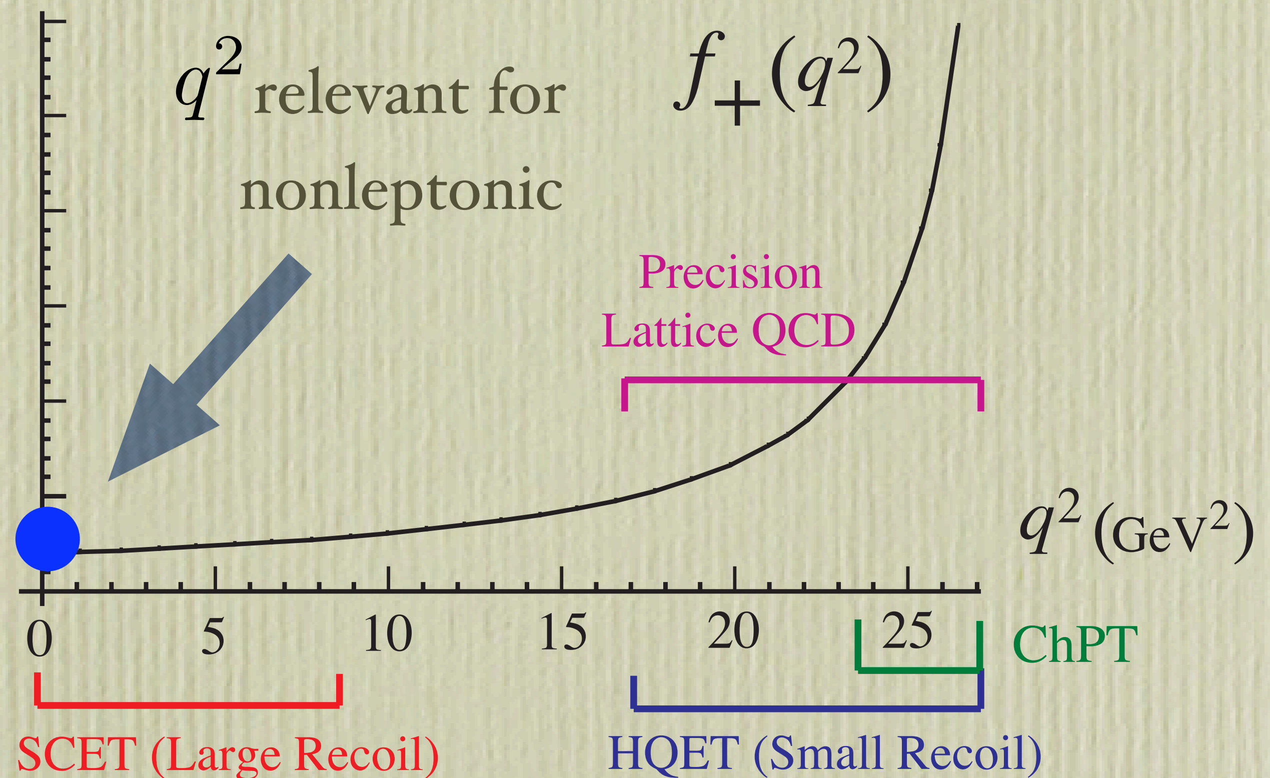
Factorization & $B \to \pi\pi$ determines $|V_{ub}| f_+(0)$

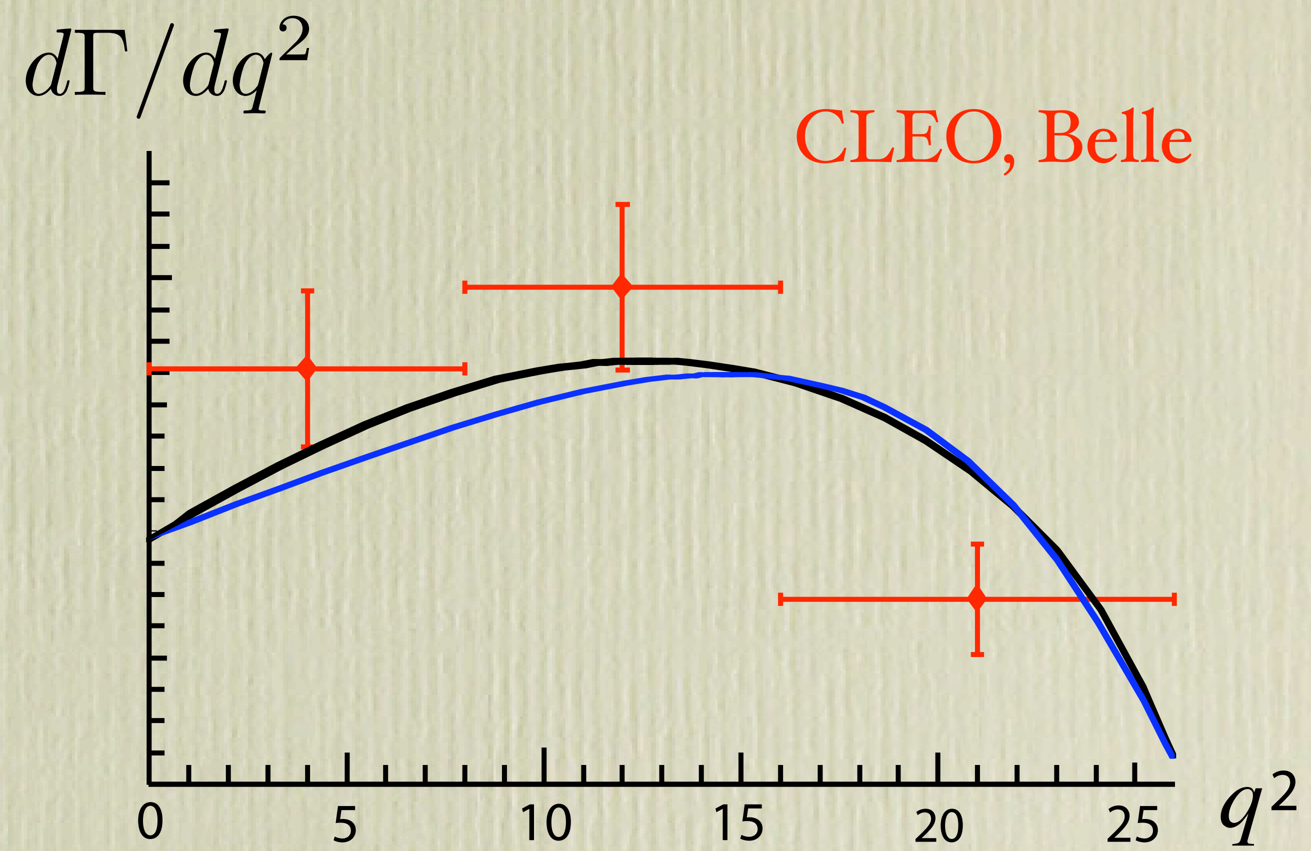
# A precision model independent Exclusive Vub:

unquenched Lattice (FNAL, HPQCD) + SCET

Arnesen, Grinstein, Rothstein, I.S. (to appear)

$B \to \pi \ell \bar{\nu}$ form factor



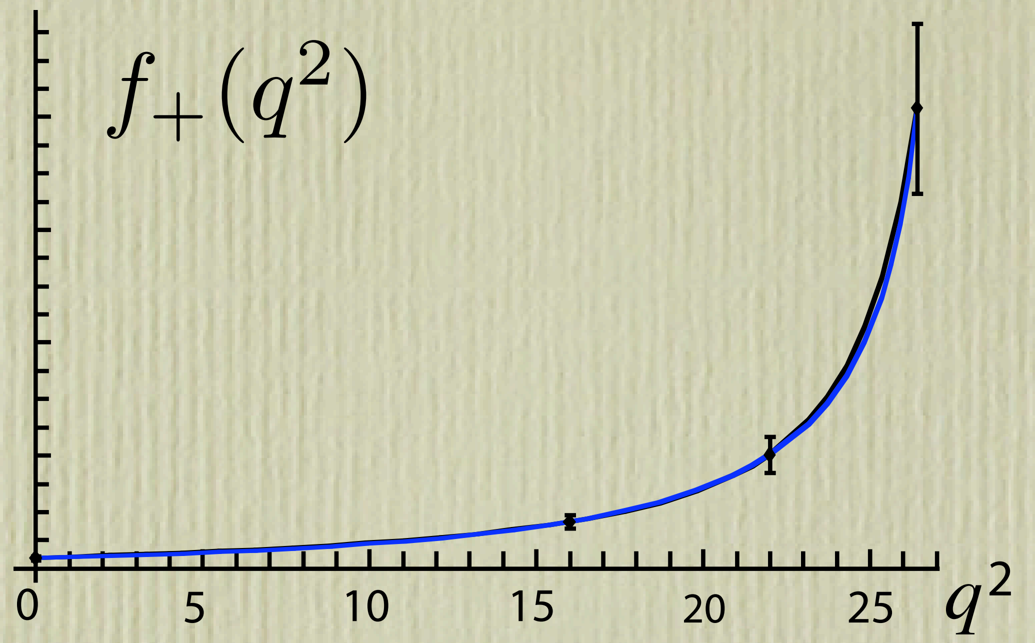



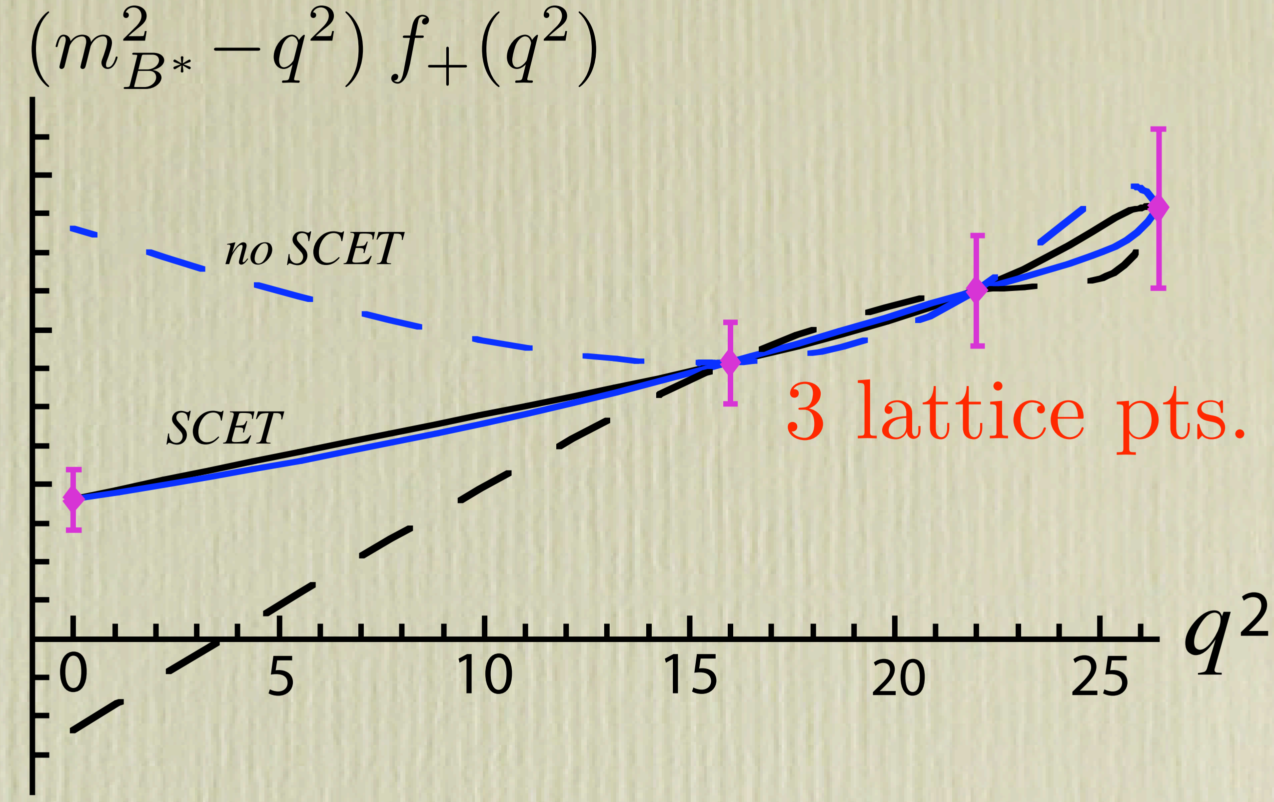

Dispersion relations bound the shape of the form factor

(Boyd, Grinstein, Lebed; ...)

$$\chi^{(n)} \geq \frac{3}{2\pi} \int_{(m_B+m_\pi)^2}^{\infty} dt\; t^{-n-3} k(t)\, |F(t)|^2$$

(these bounds are also used for excl. Vcb)




Data (avg. Belle, Babar, Cleo):

J.Dingfelder (WGII)

$Br(B \to \pi\ell\bar{\nu}) = (1.39 \pm 0.12) \times 10^{-4}$

theory error dominated by input point uncertainty

- $B \to \pi\ell\bar{\nu}$ $\quad |V_{ub}| = 4.08 \pm 0.22 \pm 0.40$

  (Lattice + SCET+ dispersion)

Preliminary

- $B \to X_u\ell\bar{\nu}$ $\quad |V_{ub}| = 4.70 \pm 0.44$

  (OPE, shape function analysis, HFAG '04 avg.)

$|V_{ub}|_{(q^2 \geq 16)} = (3.87 \pm 0.70 \pm 0.22^{+0.62}_{-0.48}) \times 10^{-3}$(Belle, FNAL)

# Highlights

(parallel talks)

# $B \to X_s\gamma$

- Photon cut dependence, $1.0\,\mathrm{GeV} \leq E_0 \leq 1.9\,\mathrm{GeV}$ , is significant

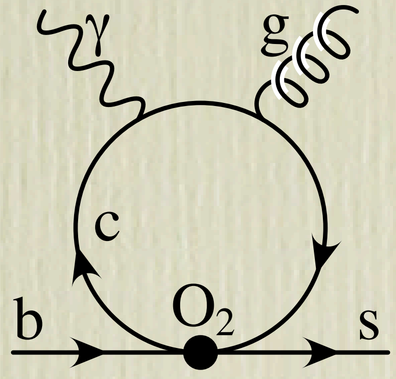
  unknown $\alpha_s^2(m_b - 2E_0)$ terms can be ~ 10%

  Neubert

- Right-handed photon polarization may be larger than expected

$$\frac{A(\bar{B} \to X_s\gamma_R)}{A(\bar{B} \to X_s\gamma_L)} \sim 0.1$$

Grinstein, Grossman, Ligeti, Pirjol



## $B \to X_u \ell \bar{\nu}$ in endpoint region

- LO factorization: full $\alpha_s$ known , triple differential known
  $p_X^+$ spectrum
  Bauer, Manohar
  Bosch, Lange, Neubert, Paz

- NLO factorization:
  progress on subl. shape functions ,
  triple differential known, factorization thm.
  K. Lee, I.S.
  Bosch et al.
  Beneke et al.

## $B \to M_1 M_2$

- start to examine subleading operators
  Feldmann, Hurth

- polarization in VV: $A^0_{LO} = \{A_{c\bar{c}}, \zeta^{BV}, \zeta^{BV}_J\}$
  $A^T_{LO} = A_{c\bar{c}}$ or $0$
  see Kagan, WGIV

with apologies for things left out ....

# Outlook

- There is a theory for B-decays with energetic hadrons
  - ➡ predictions for the size of amplitudes
  - ➡ universal hadronic parameters, strong phases
  - ➡ $\gamma$ (or $\alpha$) from individual $B \to M_1 M_2$ channels
  - ➡ exclusive Vub
- We now have the tools to systematically study power corrections
  - ➡ color suppressed decays, inclusive decays
- The SCET can be applied to:

  Nonleptonic decays, Other $B$ decays
  Jet physics, Exclusive form factors
  Charmonium, Upsilon physics
  ... others ?
- A lot of theory and phenomenology left to study ...