The Theory of B-Decays

Iain Stewart
MIT

Aspen Winter Conference
February, 2005

Outline

- Why B decay's ?
- Scales and Expansions
  (e-weak H, HQET, SCET, ...)
- Precision Measurements
- Recent Results (V_{ub}, γ)
- Outlook

Motivation

- Heavy Stable Hadrons $\longrightarrow$ lots of decays

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 χ_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
  χ_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:

- Λ_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
$c\tau = 501$ μm

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 ψ 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 (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Semileptonic and leptonic modes			
$\ell^+ \nu_\ell$ anything	[a] (10.2 ± 0.9) %		–
$\overline{D}^0 \ell^+ \nu_\ell$	[a] (2.15 ± 0.22) %		2310
$\overline{D}^*(2007)^0 \ell^+ \nu_\ell$	[a] (6.5 ± 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 ± 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 ± 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

$\overline{D}^*(2007)^0 \pi^+ \pi^+ \pi^-$	$(9.4 \pm 2.6) \times 10^{-3}$		2236
$\overline{D}^*(2007)^0 a_1(1260)^+$	(1.9 ± 0.5) %		2062
$\overline{D}^*(2007)^0 \pi^- \pi^+ \pi^+ \pi^0$	(1.8 ± 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 ± 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 ± 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 ± 0.5) %		1737
$\overline{D}^*(2007)^0 D_s^{*+}$	(2.7 ± 1.0) %		1651
$D_s^{(*)+} \overline{D}^{**0}$	(2.7 ± 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 ± 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

$D_s^+ \rho^0$	$< 4 \times 10^{-4}$	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

ηK^+	$< 6.9 \times 10^{-6}$	CL=90%	2588
$\eta K^*(892)^+$	$(2.6 {}^{+1.0}_{-0.9}) \times 10^{-5}$		2534
ωK^+	$(9.2 {}^{+2.8}_{-2.5}) \times 10^{-6}$		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

$K^*(892)^0\pi^+\gamma$	$(2.0\ ^{+0.7}_{-0.6})$	$\times 10^{-5}$		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
ωh^+	$(1.38\,^{+0.27}_{-0.24})$	$\times 10^{-5}$		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

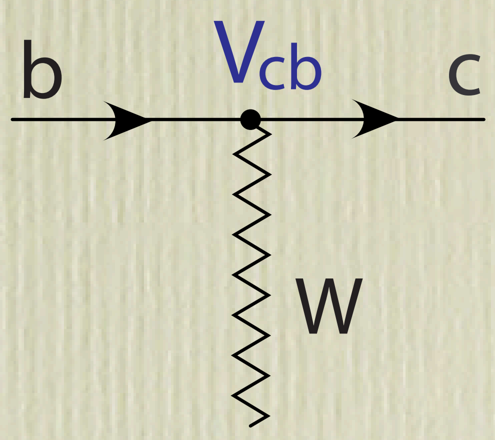
$\pi^+e^+e^-$	$B1$		< 3.9	$\times 10^{-3}$	CL=90%	2638
$\pi^+\mu^+\mu^-$	$B1$		< 9.1	$\times 10^{-3}$	CL=90%	2633
$K^+e^+e^-$	$B1$		$(6.3\ ^{+1.9}_{-1.7})$	$\times 10^{-7}$		2616
$K^+\mu^+\mu^-$	$B1$		$(4.5\ ^{+1.4}_{-1.2})$	$\times 10^{-7}$		2612
$K^+\ell^+\ell^-$	$B1$	[a]	$(5.3\ \pm 1.1)$	$\times 10^{-7}$		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

Motivation

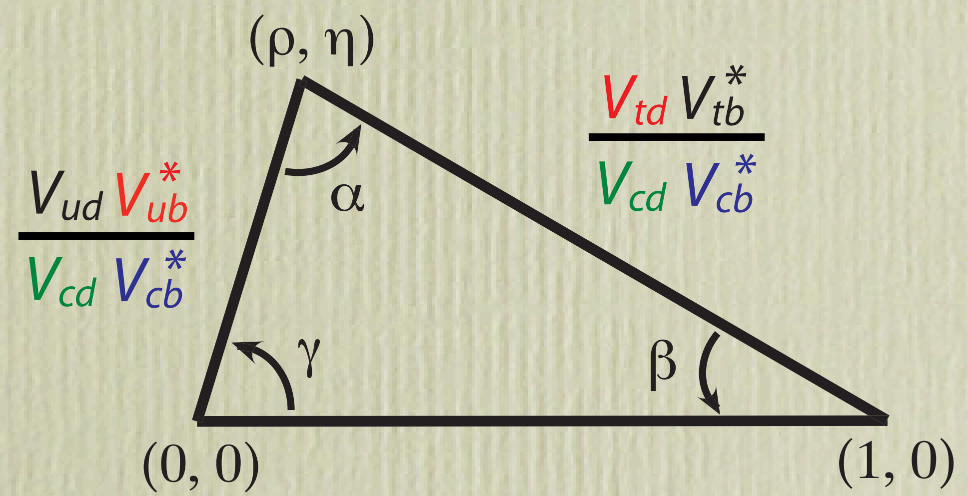
- Heavy Stable Hadrons → lots of decays
- Probe the flavor sector of the SM

CKM matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



$\cancel{CP}$:

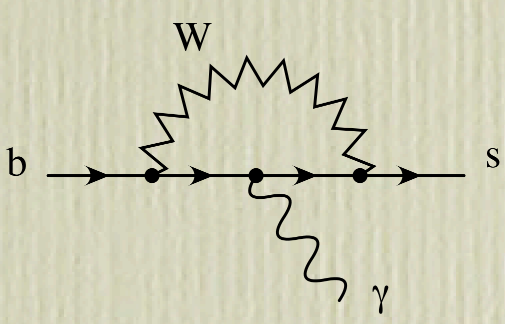


Motivation

- Heavy Stable Hadrons → lots of decays
- Probe the flavor sector of the SM; CKM matrix
- Look for new physics: ~~CP~~

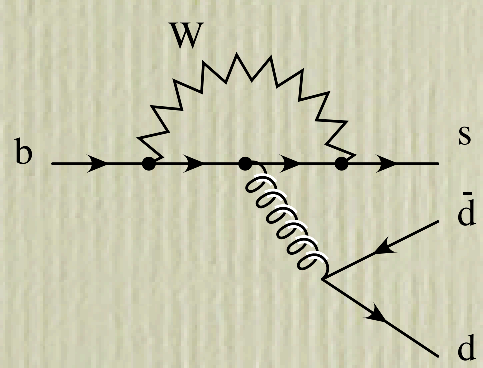
  redundant measurements,

  precision measurements,



$B \to X_s\gamma$

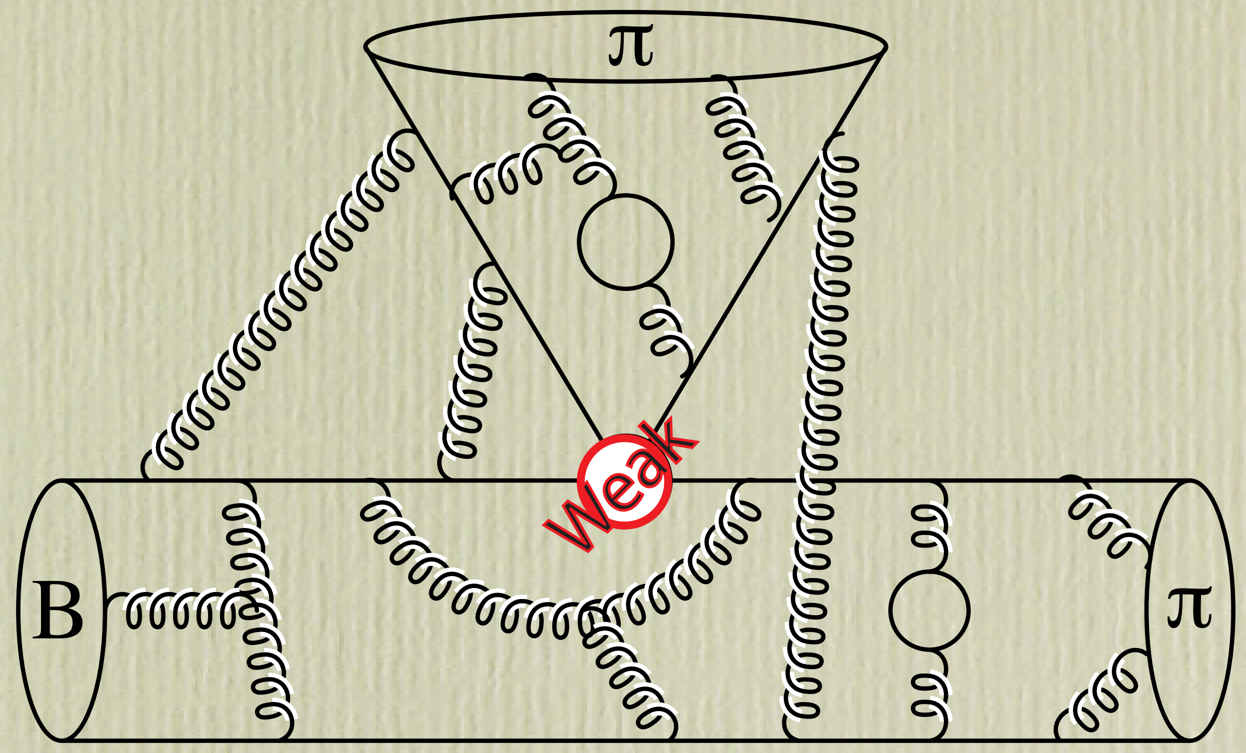
  rare decays



$B \to K\pi$

(forbidden decays)

- Measure fundamental hadronic parameters & improve our understanding of QCD



π
Weak
B
π

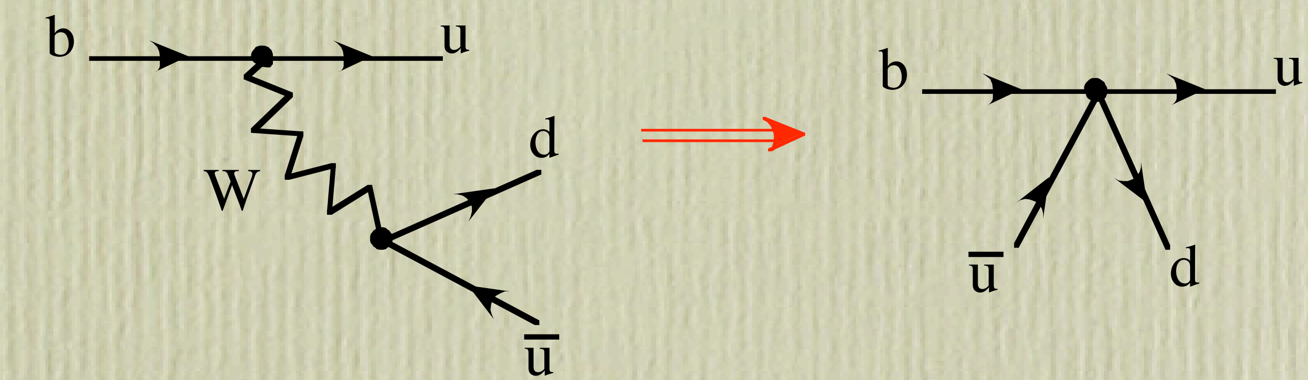
Electroweak Hamiltonian

$m_W, m_t \gg m_b$

λ^i = CKM factors

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

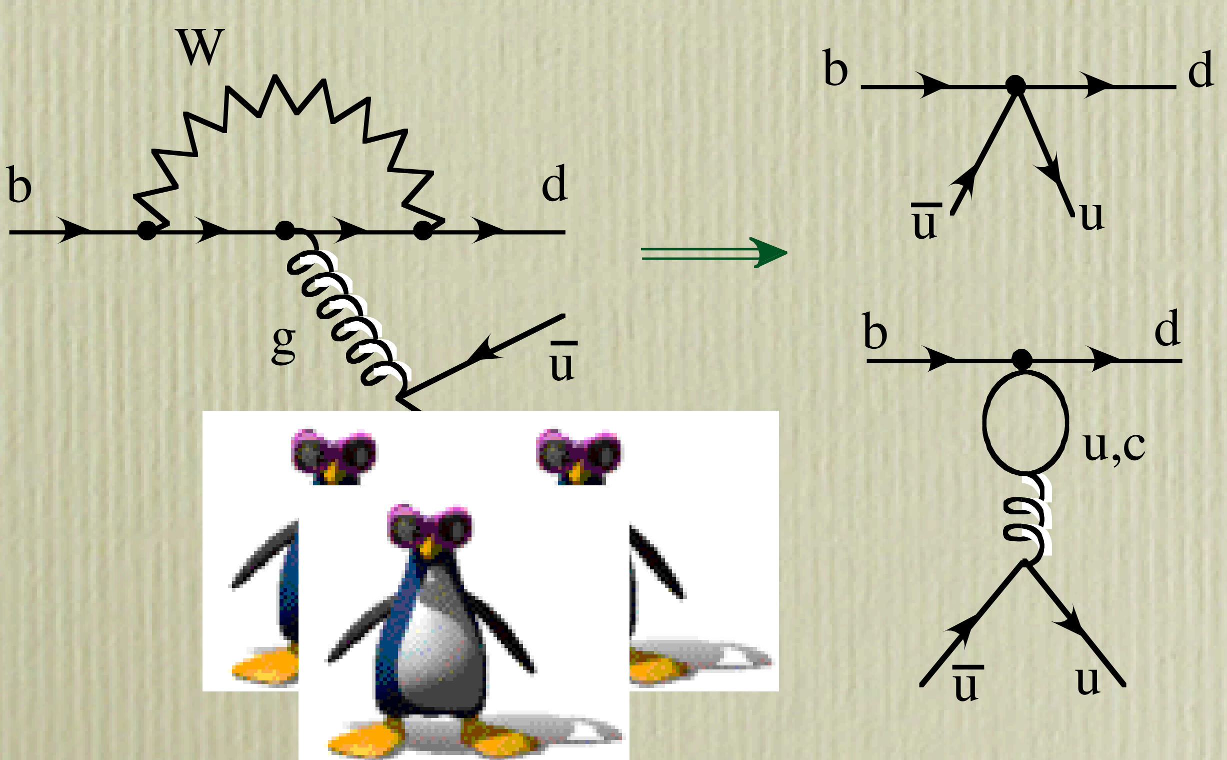
$\lambda^1 = V_{ub} V_{ud}^*$ $\quad \lambda^3 = V_{tb} V_{td}^*$



trees

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

$$O_2 = (\bar{u}_i b_j)_{V-A}(\bar{d}_j u_i)_{V-A}$$



penguins

$$O_3 = (\bar{d}b)_{V-A} \sum_q (\bar{q}q)_{V-A}$$

$$O_{4,5,6} = \ldots$$

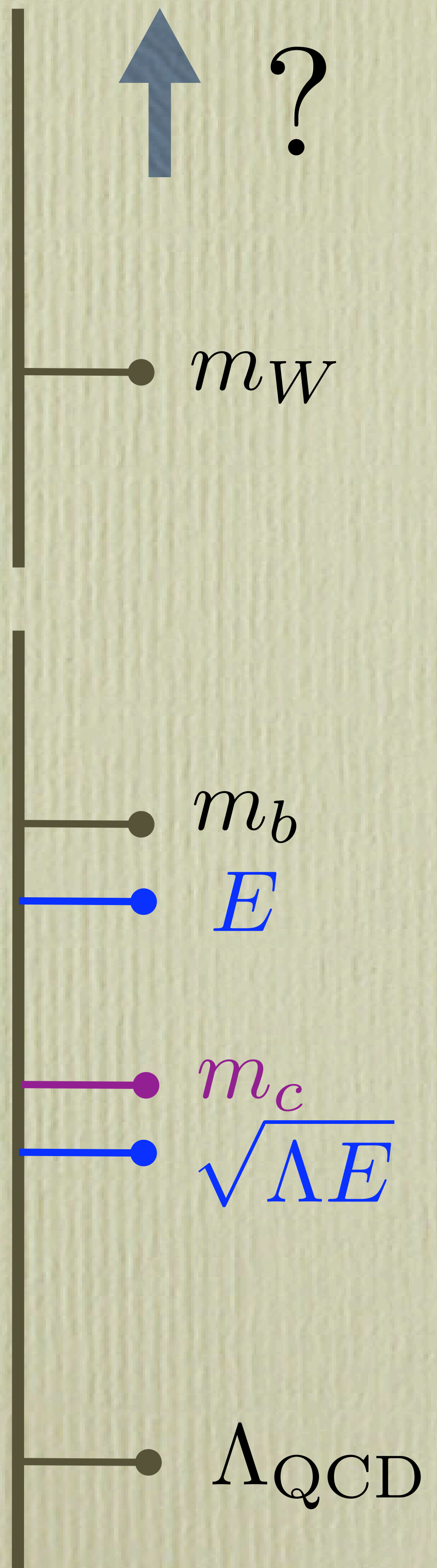
$$O_{7\gamma,8G} = \ldots$$

$$O^{ew}_{7,\ldots,10} = \ldots$$

Effective Field Theory

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

egs. H_W, HQET, ChPT



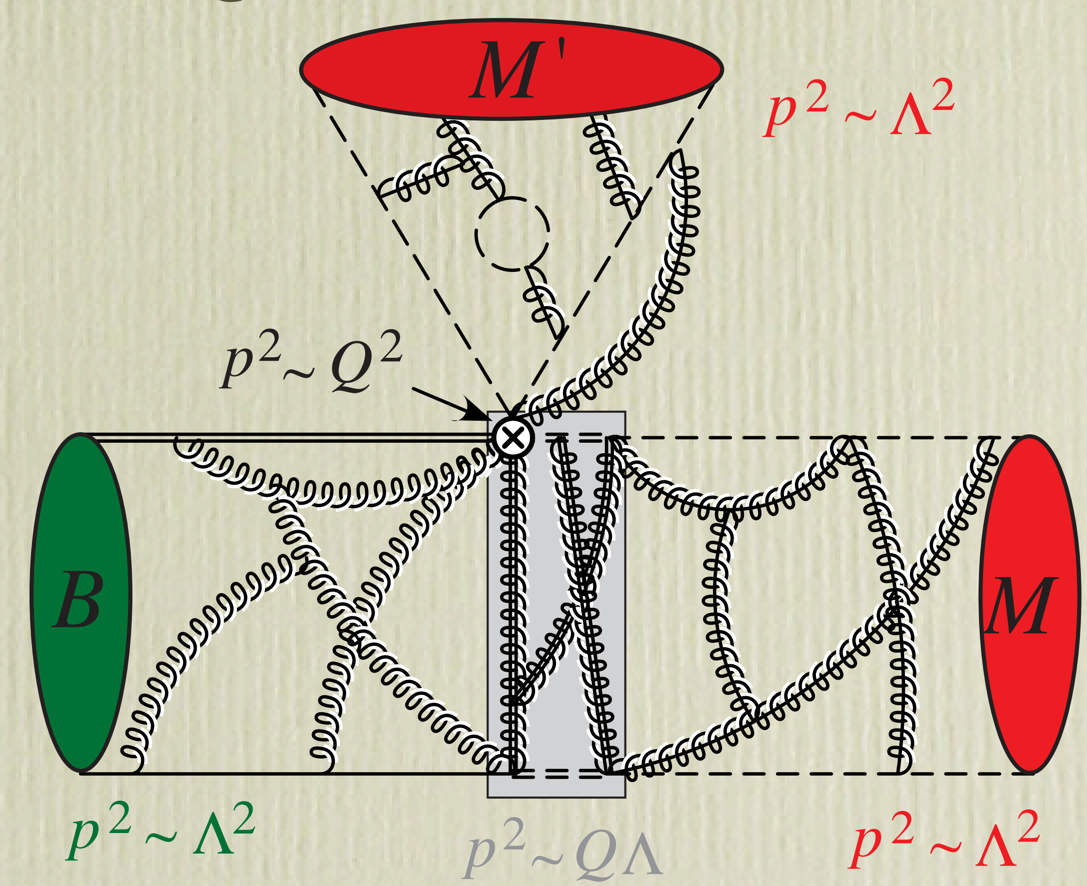
B-meson

Heavy Quark
Effective Theory

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

Energetic Hadrons

Soft-Collinear
Effective Theory



Need expansion parameters to make model independent predictions

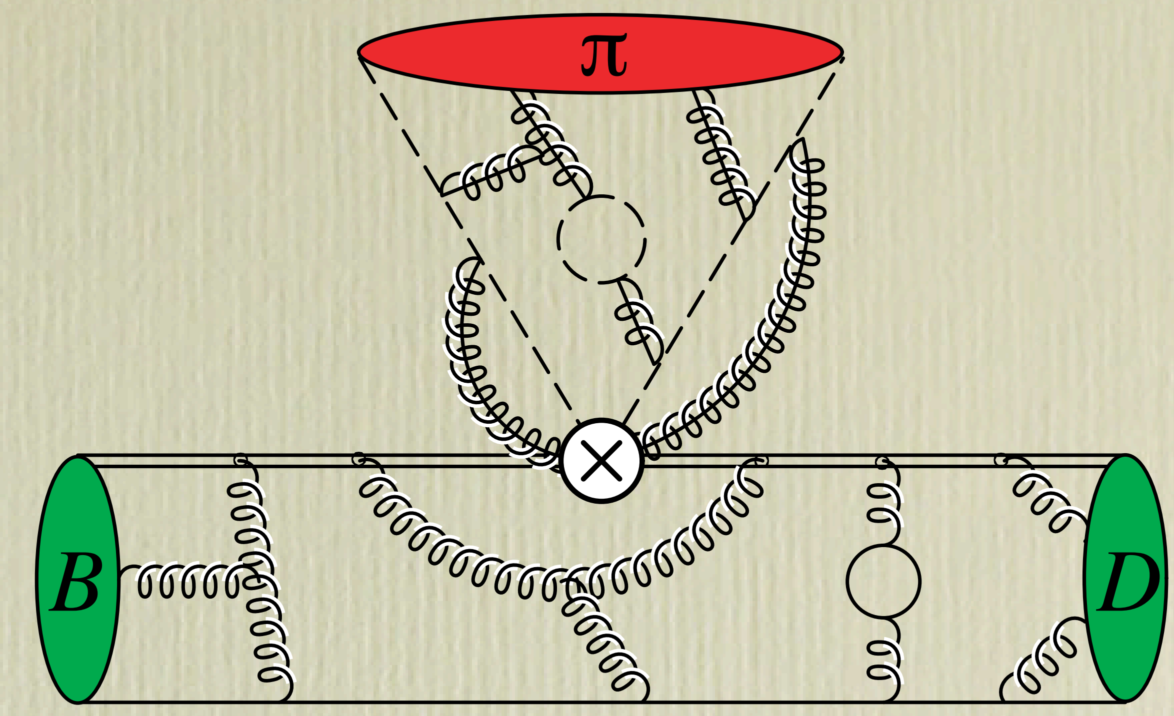
$$\boxed{\alpha_s(m_b) \simeq 0.2 \qquad \frac{\Lambda}{m_b} \simeq 0.1 \qquad \frac{\Lambda}{E_M} \simeq 0.2} \qquad \frac{m_s}{\Lambda} \simeq 0.3$$

QCD is a predictive theory

- For a given systematic expansion the terms in the series are unique and model independent
- Model dependence arises from assumptions about nonperturbative parameters

Proof of Factorization means Known to be Model Independent once hadronic parameters are determined

Factorization Example



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

  B, D are soft, π collinear

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

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

  Bauer, Pirjol, I.S.

  Calculate T

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

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

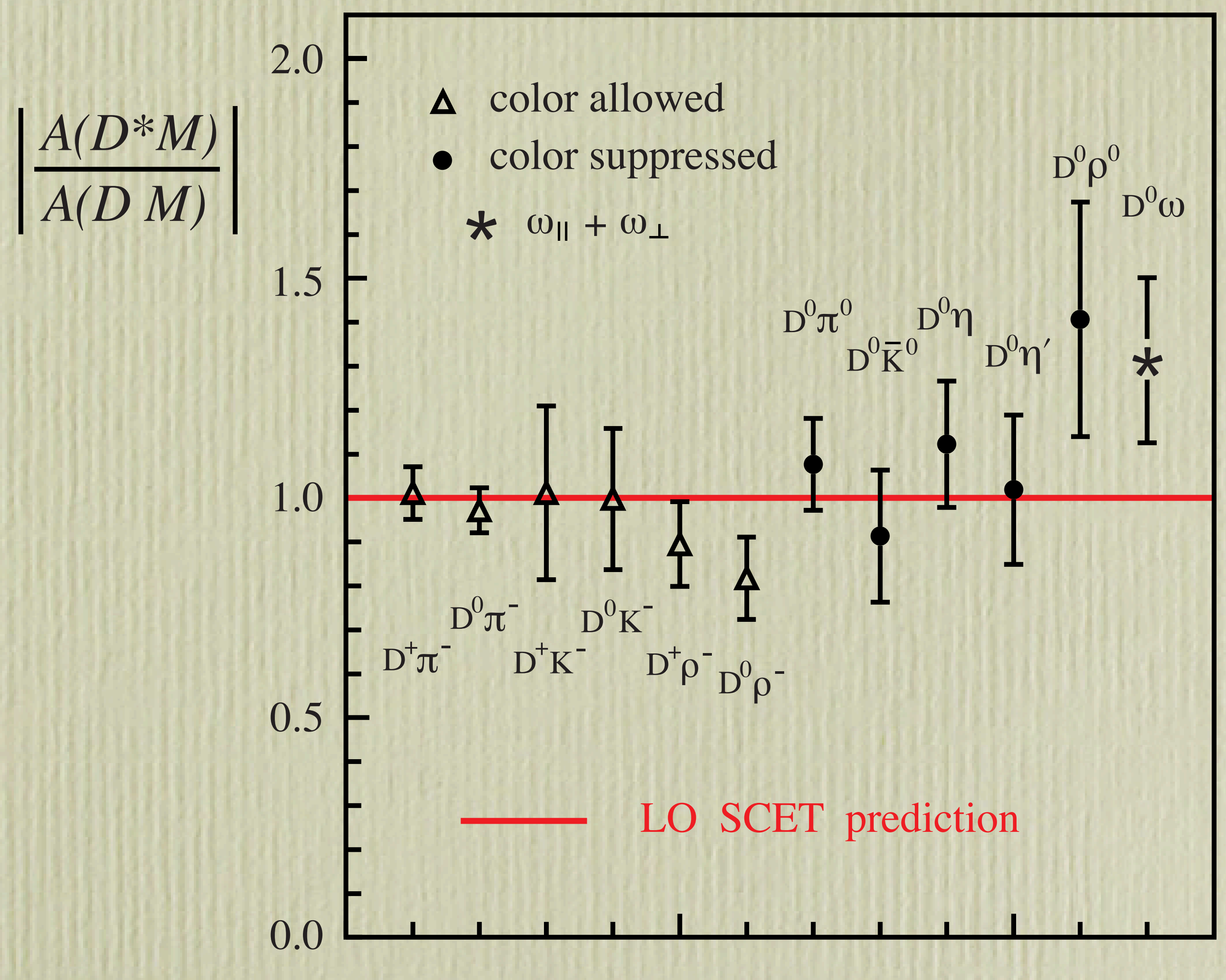
  Mantry, Pirjol, I.S.

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

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

$$Q^2 \gg Q\Lambda \gg \Lambda^2$$

Expt Average (Cleo, Belle, Babar):



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

- can predict other ratios of amplitudes, some not yet tested by data
- can relate different channels eg. π to ρ

FKS mixing angle

Extension to isosinglets:

Blechman, Mantry, I.S.

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

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

Precision Measurements

Some decays are clean

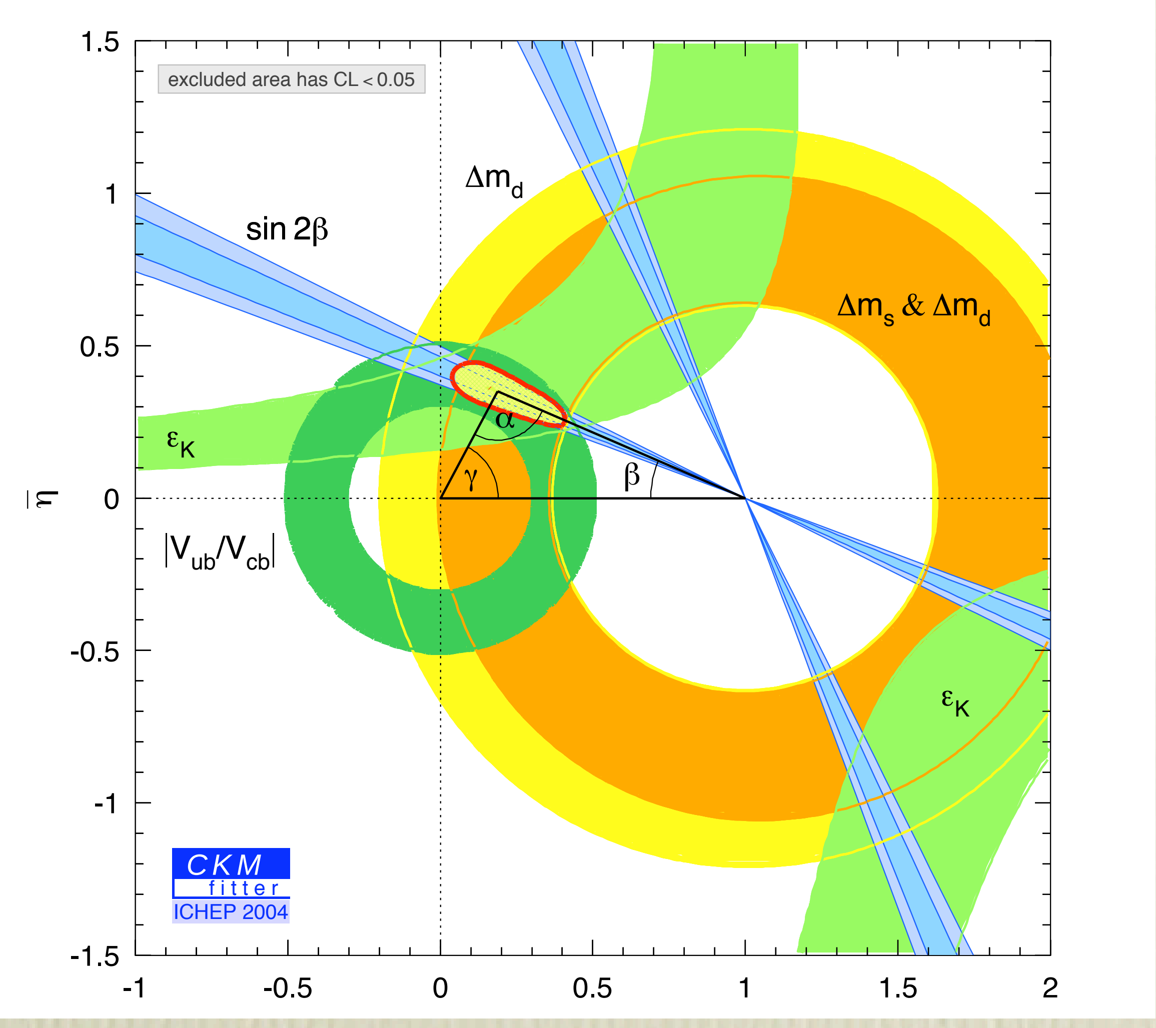
$$b \longrightarrow c\bar{c}s \qquad (B^0, \bar{B}^0 \to J/\Psi K_s, \Psi' K_s, J/\Psi K_L, \ldots)$$

A dominant weak phase $\quad (V_{cb}V_{cs}^* \sim \lambda^2 \ , \ V_{ub}V_{us}^* \sim \lambda^4 \,)$

Strong effects cancel in $A^{\overline{\mathrm{CP}}}/A$

$a_{CP}(t) \propto sin(2\beta)$ [we now know β at ~5% level]

Note: do not need to untangle scales $\leq m_b$



QCD effects: precision measurements are still possible

Inclusive: $B \to X_c \ell \bar{\nu}_\ell$

Operator Product Expansion in $\frac{\Lambda_{\rm QCD}}{m_b} \simeq 0.1$

- $m_b \to \infty$ is free quark decay, $\alpha_s(m_b)$ computable
- No $\frac{\Lambda_{\rm QCD}}{m_b}$ corrections $\longrightarrow$ uses HQET
- At $\frac{\Lambda^2_{\rm QCD}}{m_b^2}$ two hadronic parameters λ_1, λ_2

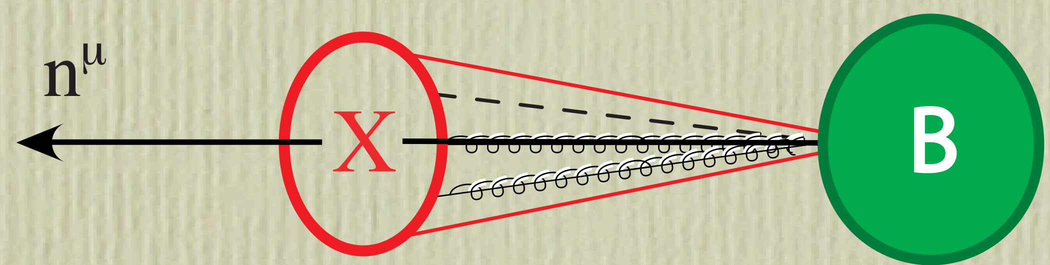
[gives $|V_{cb}|$ at ~3% level]

Recent Results

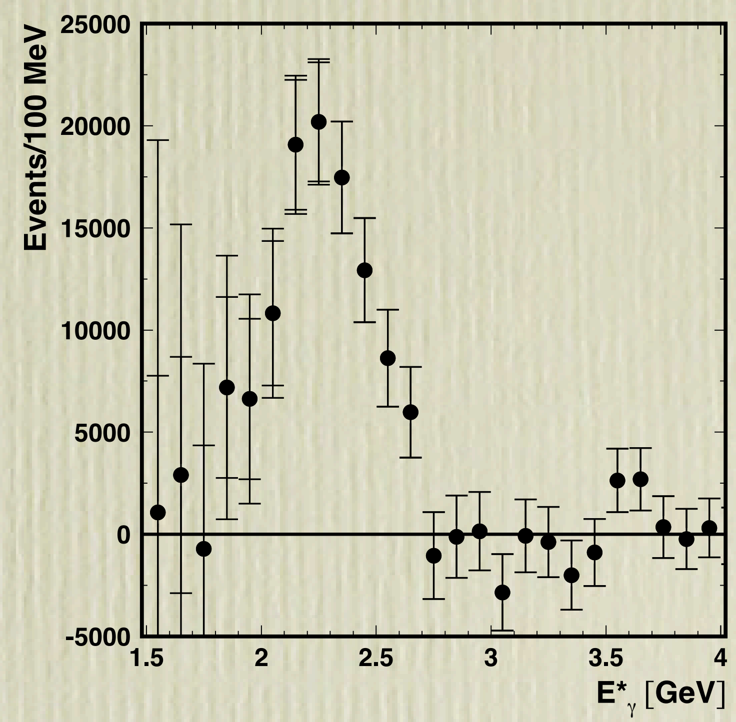
Inclusive Decays

$B \to X_u \ell \bar{\nu}$ $\qquad$ $B \to X_s \gamma$

- With enough phase space can use local OPE, known to $\dfrac{1}{m_b^3}$
- But some cuts put us in endpoint region:



$$m_X^2 \sim m_b \Lambda$$
$$P_X^- \gg P_X^+$$

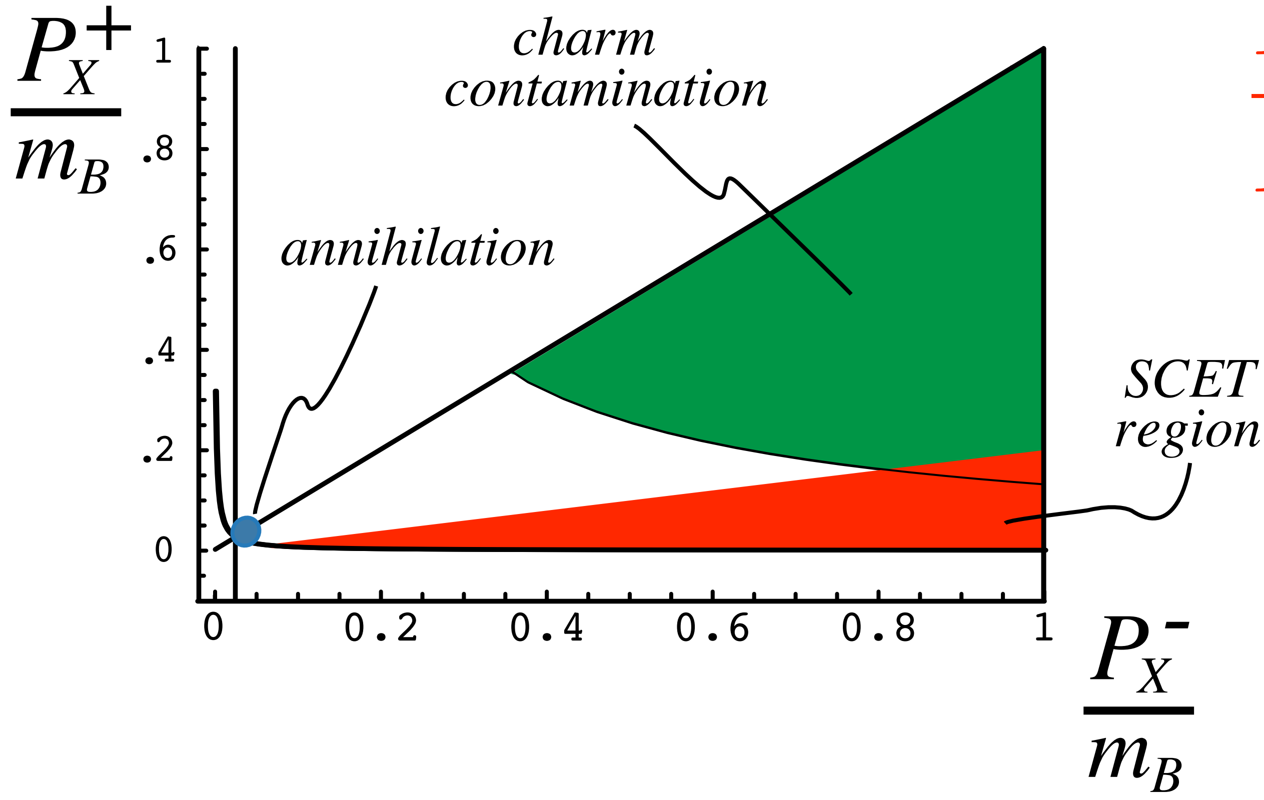


$$d\Gamma = H(m_b, p_X^-) \int dk^+ \, J(p_X^- k^+) \, f(k^+ + \overline{\Lambda} - p_X^+)$$

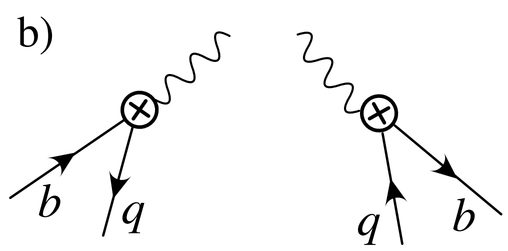
SCET gives systematic expansion in this region

$$\lambda^2 = \frac{\Lambda}{m_b}$$

shape function for $B \to X_s \gamma$, f



$$\frac{P_X^+}{P_X^-} \le 0.2$$



LO endpoint factorization

- triple differential known
- summation of double logs known
- full α_s now known

Bauer, Manohar

Bosch, Lange, Neubert, Paz

NLO endpoint

- some $1/m_b$ terms known
- annihilation effects

Bauer, Luke, Mannel

Leibovich, Ligeti, Wise

Bigi, Uraltsev; Voloshin

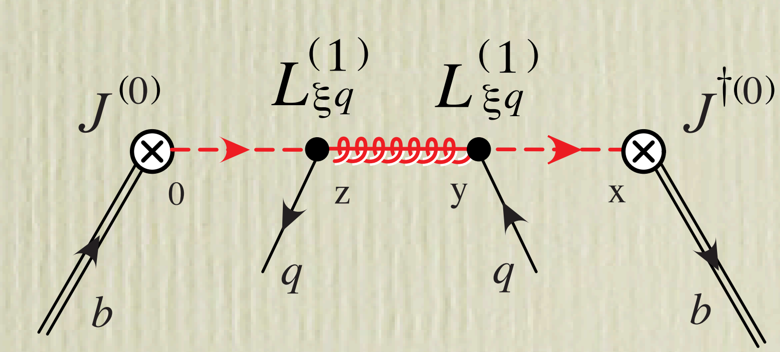
Factorization at NLO

K. Lee, I.S. hep-ph/0409045
Bosch et al. hep-ph/0409115
Beneke et al. hep-ph/0411395

- derive factorization theorems at subleading order
- complete categorization of all terms at $\dfrac{\Lambda}{m_b}$ (all orders in α_s)
- at $\dfrac{\alpha_s}{\pi}\dfrac{\Lambda}{m_b}$ many new shape functions , keep $4\pi\alpha_s\dfrac{\Lambda}{m_b}$

$$
\begin{aligned}
&\frac{h_i^{0f}(\bar{n}\cdot p)}{2m_b}\int_0^{p_X^+} dk^+\,\mathcal{J}^{(0)}(\bar{n}\cdot p\,k^+,\mu)\,f_0^{(2)}(k^+ + r^+,\mu)\\
&+\sum_{r=1}^{2}\frac{h_i^{rf}(\bar{n}\cdot p)}{m_b}\int_0^{p_X^+} dk^+\,\mathcal{J}^{(0)}(\bar{n}\cdot p\,k^+,\mu)\,f_r^{(2)}(k^+ + r^+,\mu)\\
&+\sum_{r=3}^{4}\frac{h_i^{rf}(\bar{n}\cdot p)}{m_b}\int dk_1^+\,dk_2^+\,\mathcal{J}_{1\pm 2}^{(-2)}(\bar{n}\cdot p\,k_j^+,\mu)\,f_r^{(4)}(k_j^+ + r^+,\mu)\\
&+\sum_{r=5}^{6}\frac{h_i^{rf}(\bar{n}\cdot p)}{\bar{n}\cdot p}\int dk_1^+ dk_2^+ dk_3^+\,\mathcal{J}_1^{(-4)}(\bar{n}\cdot p\,k_{j'}^+,\mu)\,f_r^{(6)}(k_{j'}^+ + r^+,\mu)
\end{aligned}
$$

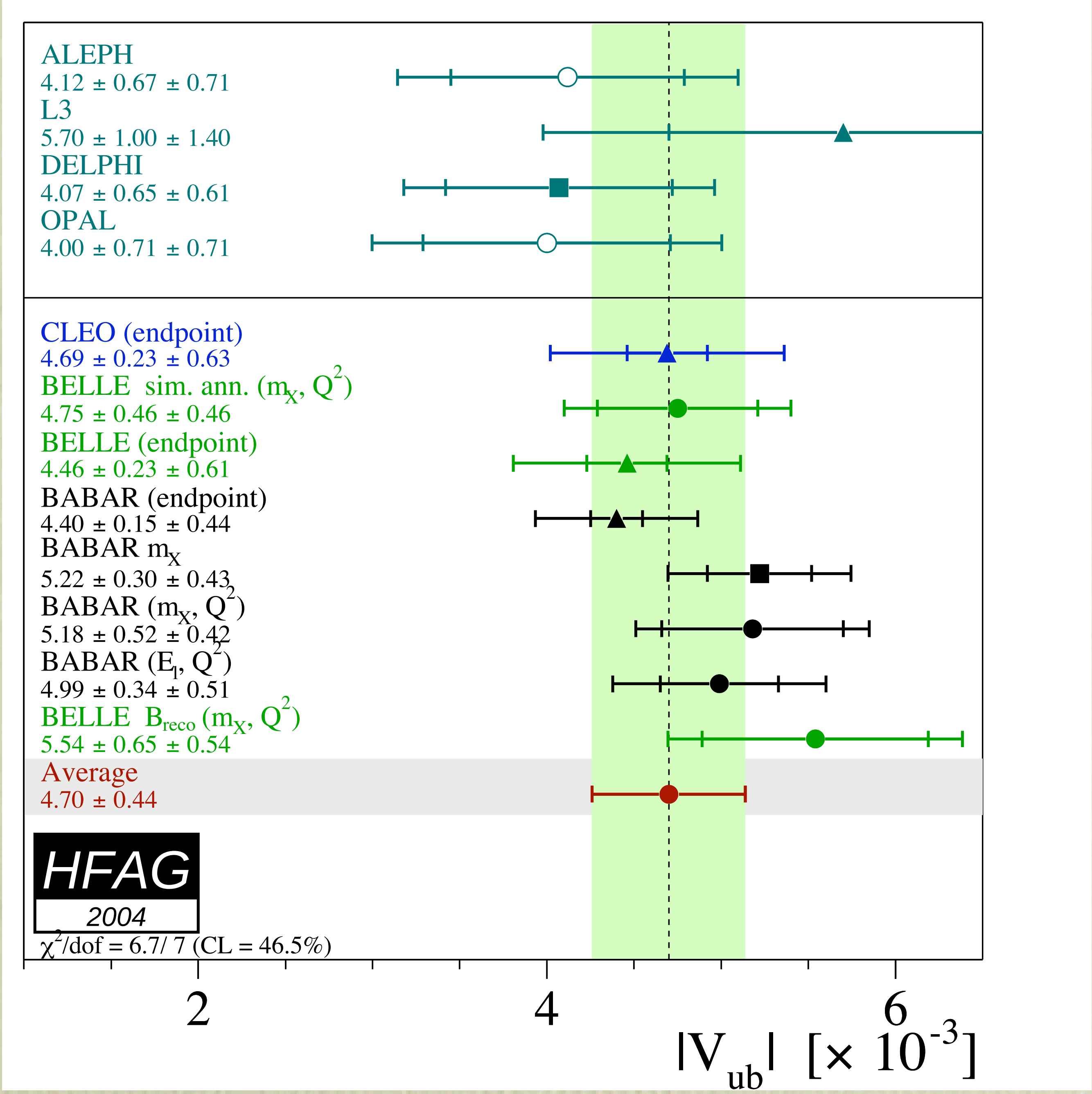
+ phase space & kinematic corrections



(dim 6 = $\dfrac{\Lambda^3}{m_b^3}$)

4-quark operators enhanced by $\dfrac{m_b^2}{\Lambda^2}$

Inclusive



ALEPH
4.12 ± 0.67 ± 0.71
L3
5.70 ± 1.00 ± 1.40
DELPHI
4.07 ± 0.65 ± 0.61
OPAL
4.00 ± 0.71 ± 0.71
CLEO (endpoint)
4.69 ± 0.23 ± 0.63
BELLE sim. ann. (m_X, Q^2)
4.75 ± 0.46 ± 0.46
BELLE (endpoint)
4.46 ± 0.23 ± 0.61
BABAR (endpoint)
4.40 ± 0.15 ± 0.44
BABAR m_X
5.22 ± 0.30 ± 0.43
BABAR (m_X, Q^2)
5.18 ± 0.52 ± 0.42
BABAR (E_l, Q^2)
4.99 ± 0.34 ± 0.51
BELLE B_{reco} (m_X, Q^2)
5.54 ± 0.65 ± 0.54
Average
4.70 ± 0.44
HFAG
2004
χ^2/dof = 6.7/ 7 (CL = 46.5%)
2
4
6
$|V_{ub}|$ [× 10^{-3}]

$B \to X_s\gamma$

- Ongoing NNLO calculations in local OPE will reduce pert. uncertainty to ~ 5%

  Bobeth, Misiak, Urban, Steinhauser, Haisch, Gorban, Gambino, Schroeder, Czakon, Bieri, Greub, Hurth, Asatrian, ...

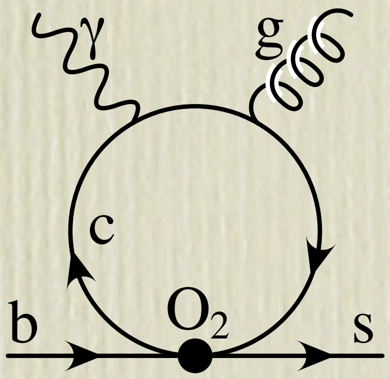
- Photon cut dependence, $1.0\,\text{GeV} \leq E_0 \leq 1.9\,\text{GeV}$, is significant

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

  Neubert

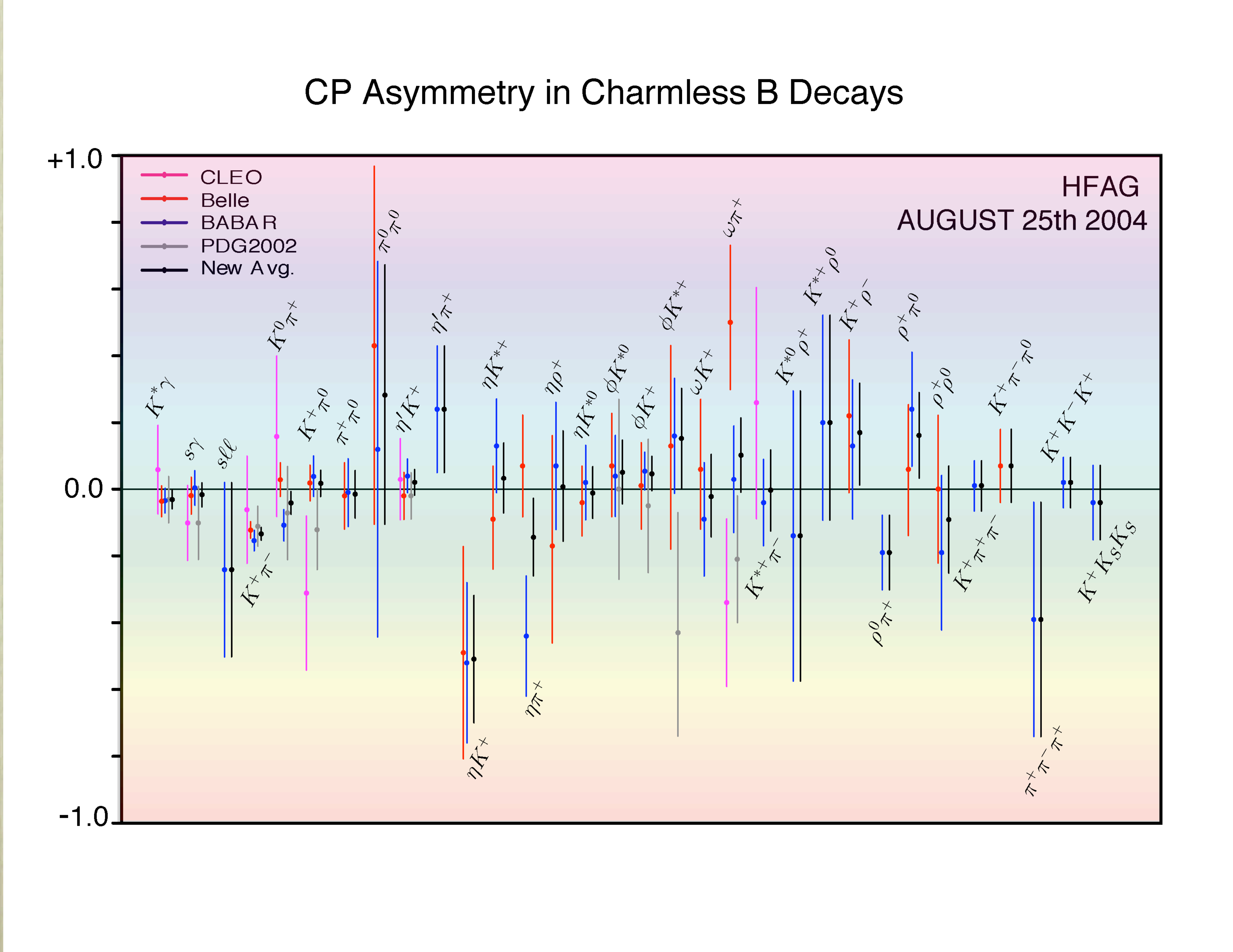
- Right-handed photon polarization may be larger than expected

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



Grinstein, Grossman, Ligeti, Pirjol

$B \to M_1 M_2$ "The Landscape"

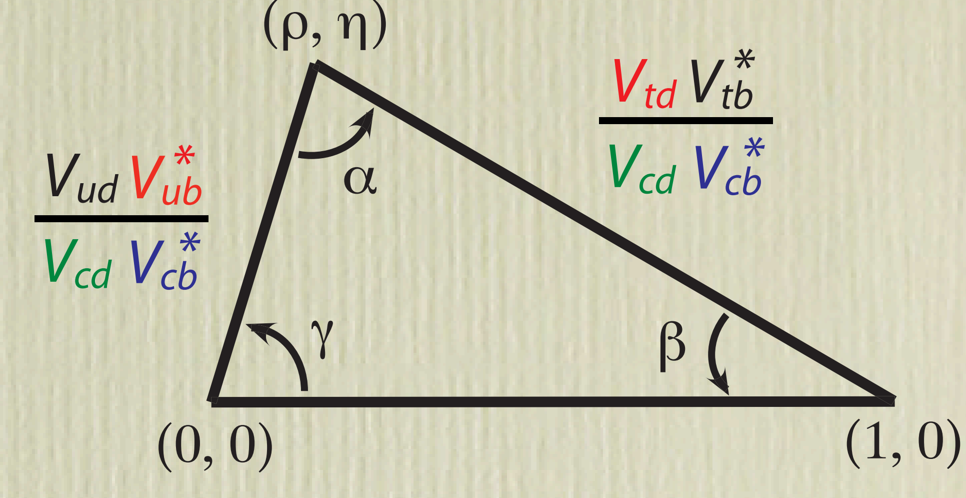


Phenomenology for $B \to \pi\pi$

CP Asymmetries

Test
CP violation

$$\mathcal{A}_{\mathrm{CP}}(t) = -S_{\pi\pi}\sin(\Delta m_B t) + C_{\pi\pi} cos(\Delta m_B t)$$



World Averages (BABAR, BELLE)

	$\overline{\mathrm{Br}} \times 10^6$	$C_{\pi\pi}$	$S_{\pi\pi}$
$\pi^+\pi^-$	4.6 ± 0.4	-0.37 ± 0.11	-0.61 ± 0.13
$\pi^0\pi^0$	1.51 ± 0.28	-0.28 ± 0.39	
$\pi^+\pi^0$	5.61 ± 0.63		

Warning: The BaBar and Belle asymmetries do not agree.

	$C_{\pi^+\pi^-}$	$S_{\pi^+\pi^-}$
Babar	-0.09 ± 0.15	-0.30 ± 0.17
Belle	-0.58 ± 0.17	-1.00 ± 0.22

Pure Isospin Analysis

Gronau, London

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

Data: $S_{\pi^+\pi^-}, C_{\pi^+\pi^-} \Rightarrow p_c, p_s$

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

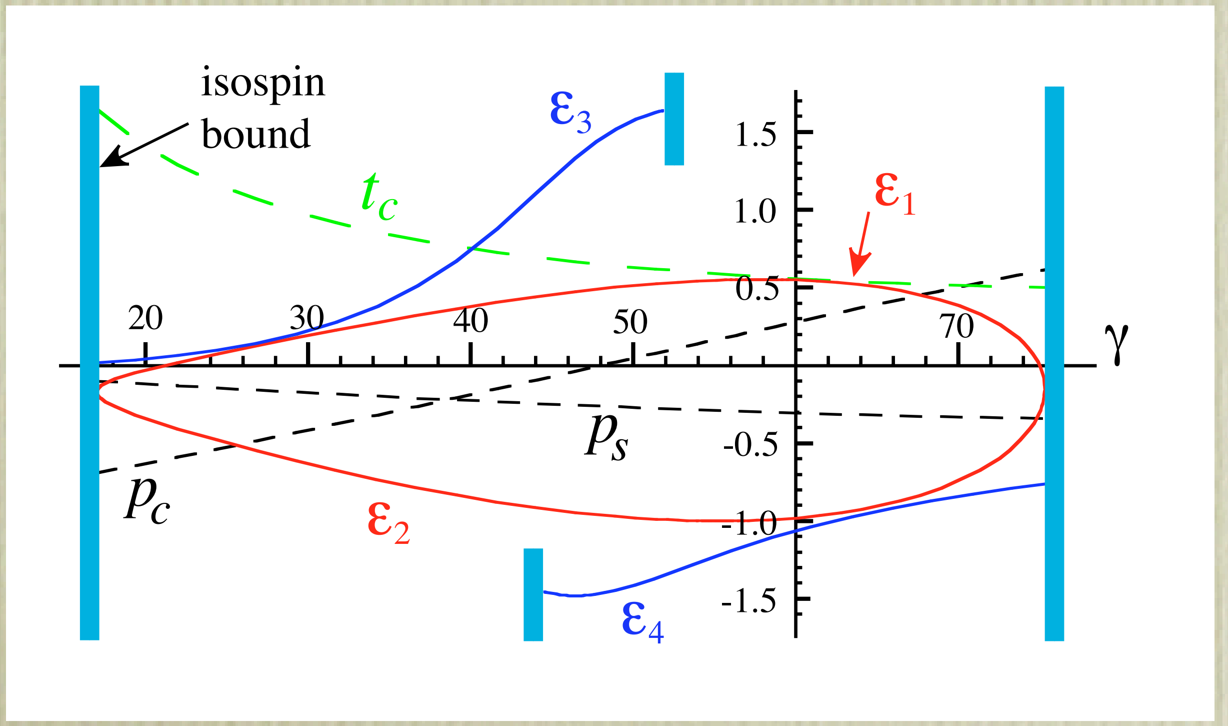
$$C_{\pi^0\pi^0} \Rightarrow \epsilon_{3,4}$$

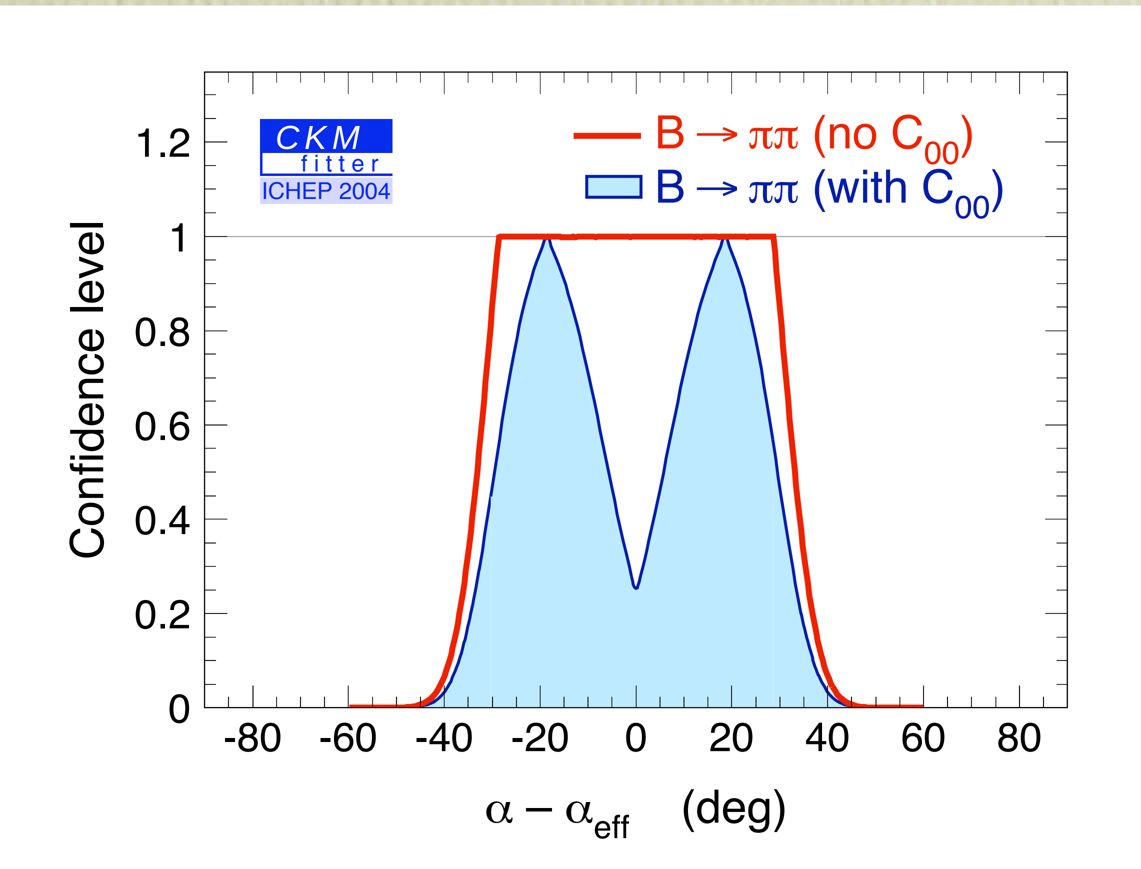
Parameters: γ +4 from isospin

β known

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

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



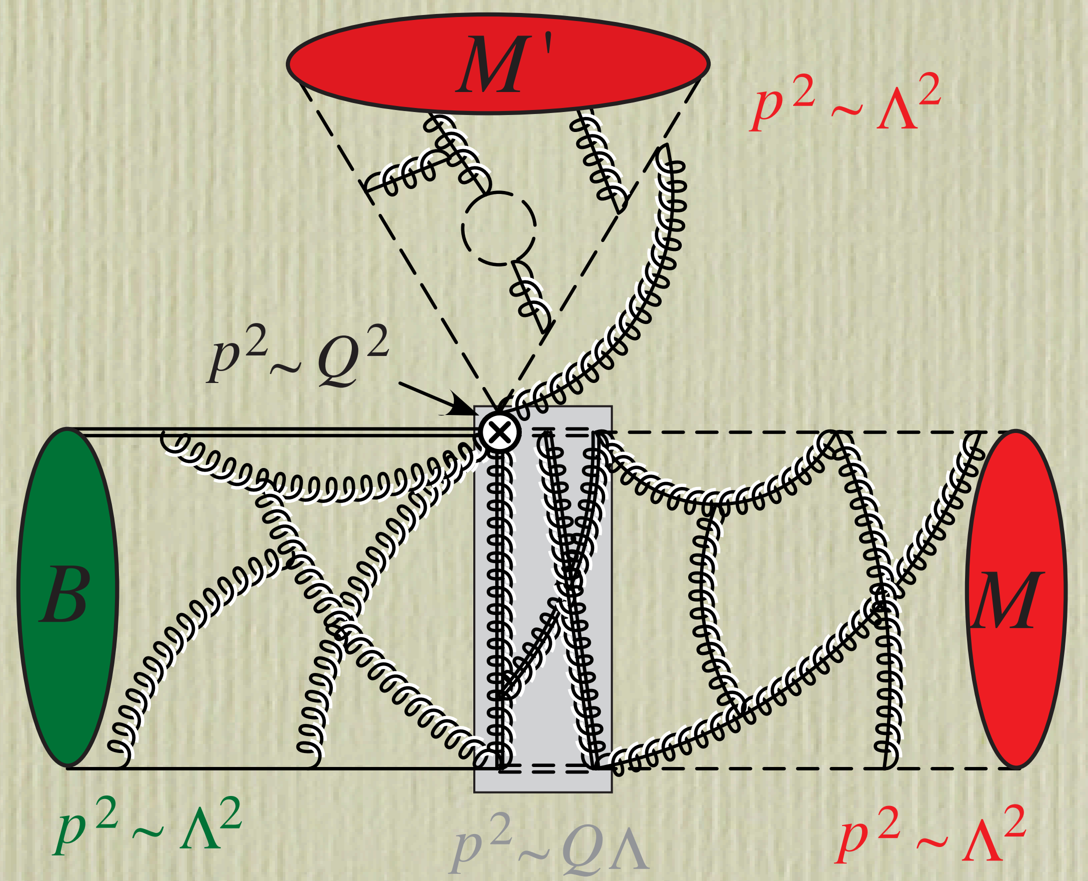


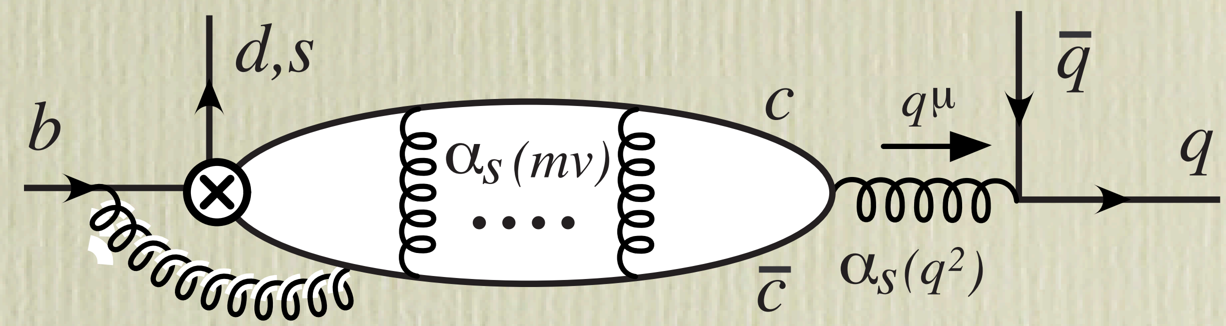
Problem is that $C_{\pi^0\pi^0}$ will remain uncertain for quite some time

$B \to M_1 M_2$ Factorization in SCET

Chay, Kim

Bauer, Pirjol, Rothstein, I.S.
(earlier work by Beneke et al.)





Ciuchini et al,
Colangelo et al

- hard spectator & form factor terms ⟶ same
- possible long distance charming penguin amplitude

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

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

Nonperturbative Result in $\alpha_s(\sqrt{E\Lambda})$:

$$A(B \to M_1 M_2) = A^{c\bar{c}} + N\Big\{ f_{M_2}\,\zeta^{BM_1} \int_0^1 du\, T_{2\zeta}(u)\phi^{M_2}(u) + f_{M_1}\zeta^{BM_2} \int_0^1 du\, T_{1\zeta}(u)\phi^{M_1}(u)$$
$$+ f_{M_2} \int_0^1 du \int_0^1 dz\, T_{2J}(u,z)\zeta_J^{BM_1}(z)\phi^{M_2}(u) + f_{M_1} \int_0^1 du \int_0^1 dz\, T_{1J}(u,z)\zeta_J^{BM_2}(z)\phi^{M_1}(u) \Big\}$$

where $\zeta^{BM} \sim \zeta_J^{BM}(z) \sim (\Lambda/Q)^{3/2}$ and appear in $B \to M$

Hard Coefficients

M_1M_2	$T_{1\zeta}(u)$	$T_{2\zeta}(u)$	M_1M_2	$T_{1\zeta}(u)$	$T_{2\zeta}(u)$
$\pi^-\pi^+$, $\rho^-\pi^+$, $\pi^-\rho^+$, $\rho_\parallel^-\rho_\parallel^+$	$c_1^{(d)}+c_4^{(d)}$	0	$\pi^+K^{(*)-}$, ρ^+K^-, $\rho_\parallel^+K_\parallel^{*-}$	0	$c_1^{(s)}+c_4^{(s)}$
$\pi^-\pi^0$, $\rho^-\pi^0$	$\frac{1}{\sqrt{2}}(c_1^{(d)}+c_4^{(d)})$	$\frac{1}{\sqrt{2}}(c_2^{(d)}-c_3^{(d)}-c_4^{(d)})$	$\pi^0K^{(*)-}$	$\frac{1}{\sqrt{2}}(c_2^{(s)}-c_3^{(s)})$	$\frac{1}{\sqrt{2}}(c_1^{(s)}+c_4^{(s)})$
$\pi^-\rho^0$, $\rho_\parallel^-\rho_\parallel^0$	$\frac{1}{\sqrt{2}}(c_1^{(d)}+c_4^{(d)})$	$\frac{1}{\sqrt{2}}(c_2^{(d)}+c_3^{(d)}-c_4^{(d)})$	ρ^0K^-, $\rho_\parallel^0K_\parallel^{*-}$	$\frac{1}{\sqrt{2}}(c_2^{(s)}+c_3^{(s)})$	$\frac{1}{\sqrt{2}}(c_1^{(s)}+c_4^{(s)})$
$\pi^0\pi^0$	$\frac{1}{2}(c_2^{(d)}-c_3^{(d)}-c_4^{(d)})$	$\frac{1}{2}(c_2^{(d)}-c_3^{(d)}-c_4^{(d)})$	$\pi^-\bar{K}^{(*)0}$, $\rho^-\bar{K}^0$, $\rho_\parallel^-\bar{K}_\parallel^{*0}$	0	$-c_4^{(s)}$
$\rho^0\pi^0$	$\frac{1}{2}(c_2^{(d)}+c_3^{(d)}-c_4^{(d)})$	$\frac{1}{2}(c_2^{(d)}-c_3^{(d)}-c_4^{(d)})$	$\pi^0\bar{K}^{(*)0}$	$\frac{1}{\sqrt{2}}(c_2^{(s)}-c_3^{(s)})$	$-\frac{1}{\sqrt{2}}c_4^{(s)}$
$\rho_\parallel^0\rho_\parallel^0$	$\frac{1}{2}(c_2^{(d)}+c_3^{(d)}-c_4^{(d)})$	$\frac{1}{2}(c_2^{(d)}+c_3^{(d)}-c_4^{(d)})$	$\rho^0\bar{K}^0$, $\rho_\parallel^0\bar{K}_\parallel^{*0}$	$\frac{1}{\sqrt{2}}(c_2^{(s)}+c_3^{(s)})$	$-\frac{1}{\sqrt{2}}c_4^{(s)}$
$K^{(*)0}K^{(*)-}$, $K^{(*)0}\bar{K}^{(*)0}$	$-c_4^{(d)}$	0	$K^{(*)-}K^{(*)+}$	0	0

similar for T_J's in terms of $b_i^{(f)}$'s

Note: have not used isospin yet

Matching

$$c_1^{(f)} = \lambda_u^{(f)}\Big(C_1+\frac{C_2}{N_c}\Big) - \lambda_t^{(f)}\frac{3}{2}\Big(C_{10}+\frac{C_9}{N_c}\Big) + \Delta c_1^{(f)}\,,$$

$$b_1^{(f)} = \lambda_u^{(f)}\Big[C_1 + \Big(1-\frac{m_b}{\omega_3}\Big)\frac{C_2}{N_c}\Big] - \lambda_t^{(f)}\Big[\frac{3}{2}C_{10} + \Big(1-\frac{m_b}{\omega_3}\Big)\frac{3C_9}{2N_c}\Big] + \Delta b_1^{(f)}\,,$$

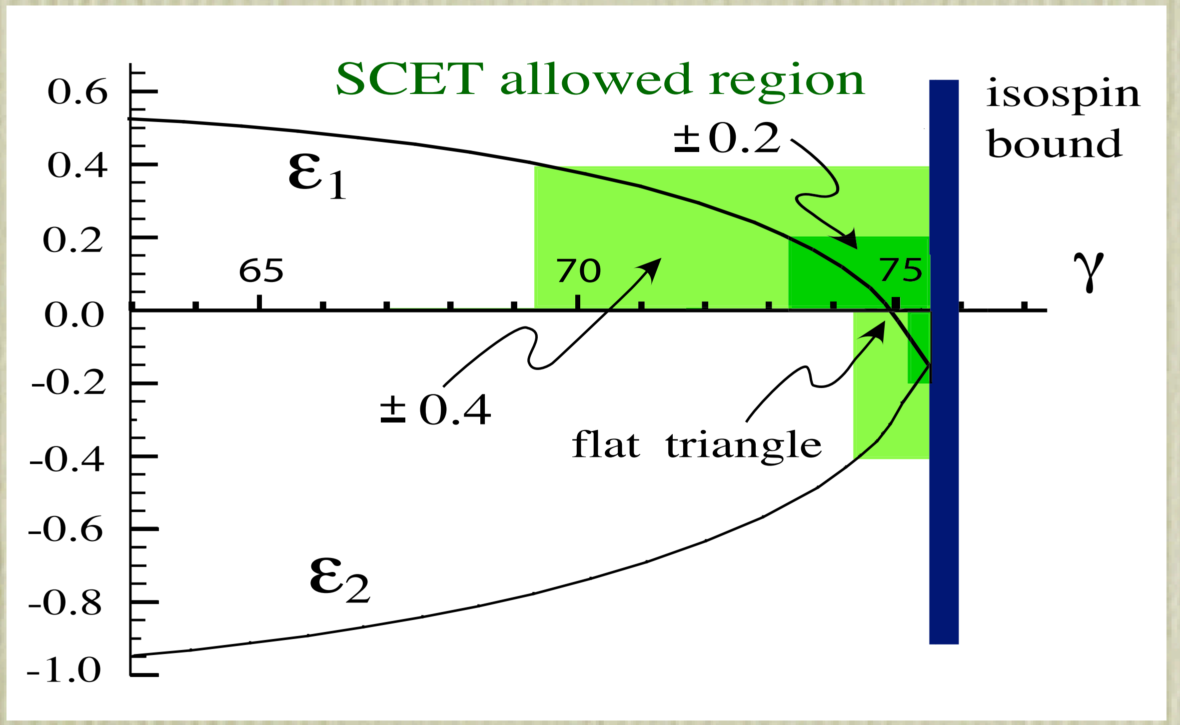
A New Method for Determining γ

Bauer, Rothstein, I.S.

Isospin + bare minimum from Λ/m_b expansion

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

This gives



2nd solution $\gamma = 21.5^{\circ}{}^{+8.7^{\circ}}_{-4.4^{\circ}}{}^{+11.1^{\circ}}_{-7.9^{\circ}}$

global fits give

$\gamma \simeq 62^{\circ} \pm 12^{\circ}$

$$\gamma = 74.9^{\circ} \pm 2^{\circ}{}^{+9.4^{\circ}}_{-13.3^{\circ}}\,.$$

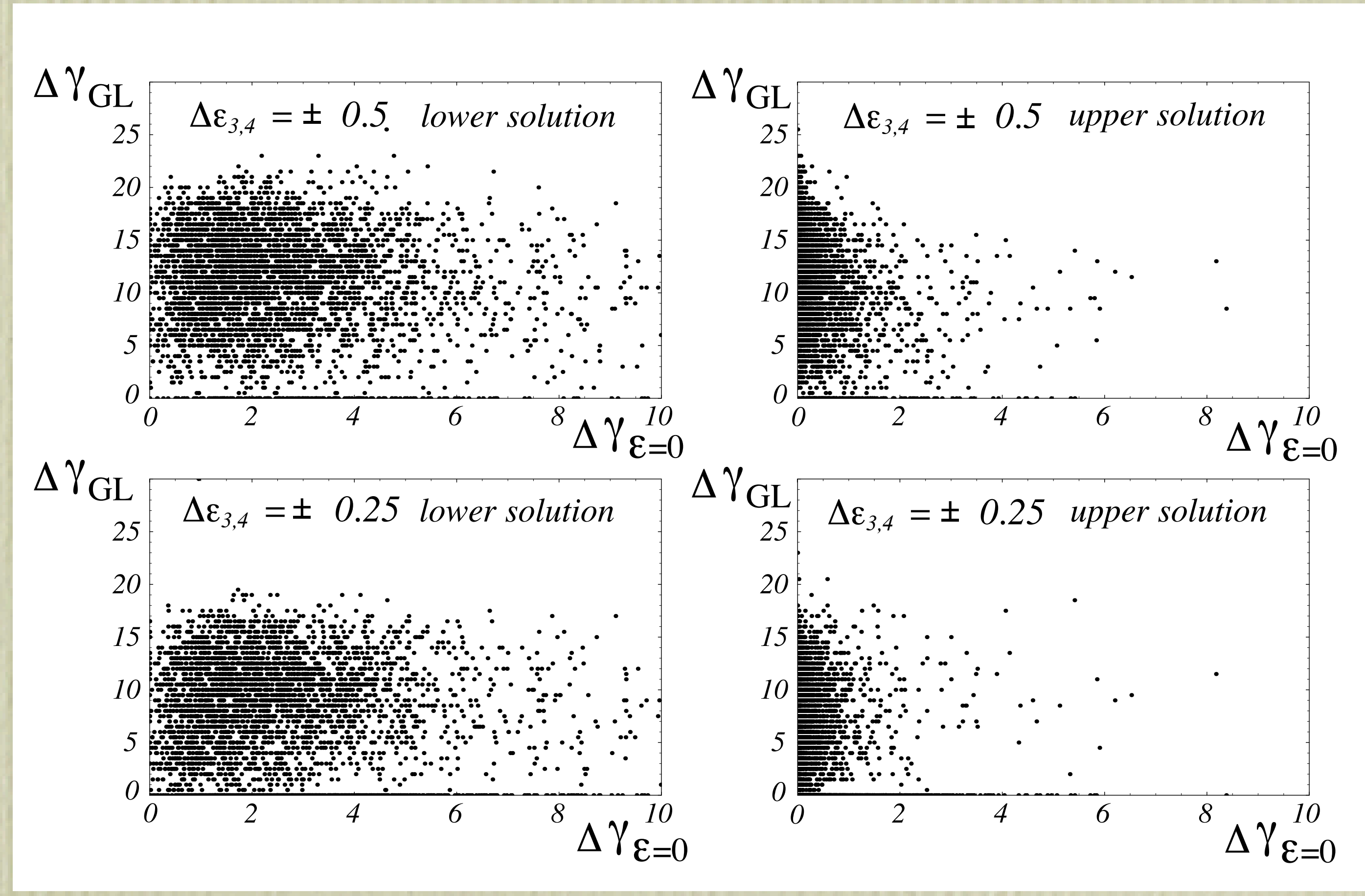
$$(\mathrm{or}{}^{+2^{\circ}}_{-5.2^{\circ}})$$

Theory uncertainty is small since curves are steep near $\epsilon = 0$

Future?

Sample data for central values (4000 pts shown)

Assume $C_{\pi^0\pi^0}$ error dominates GL analysis



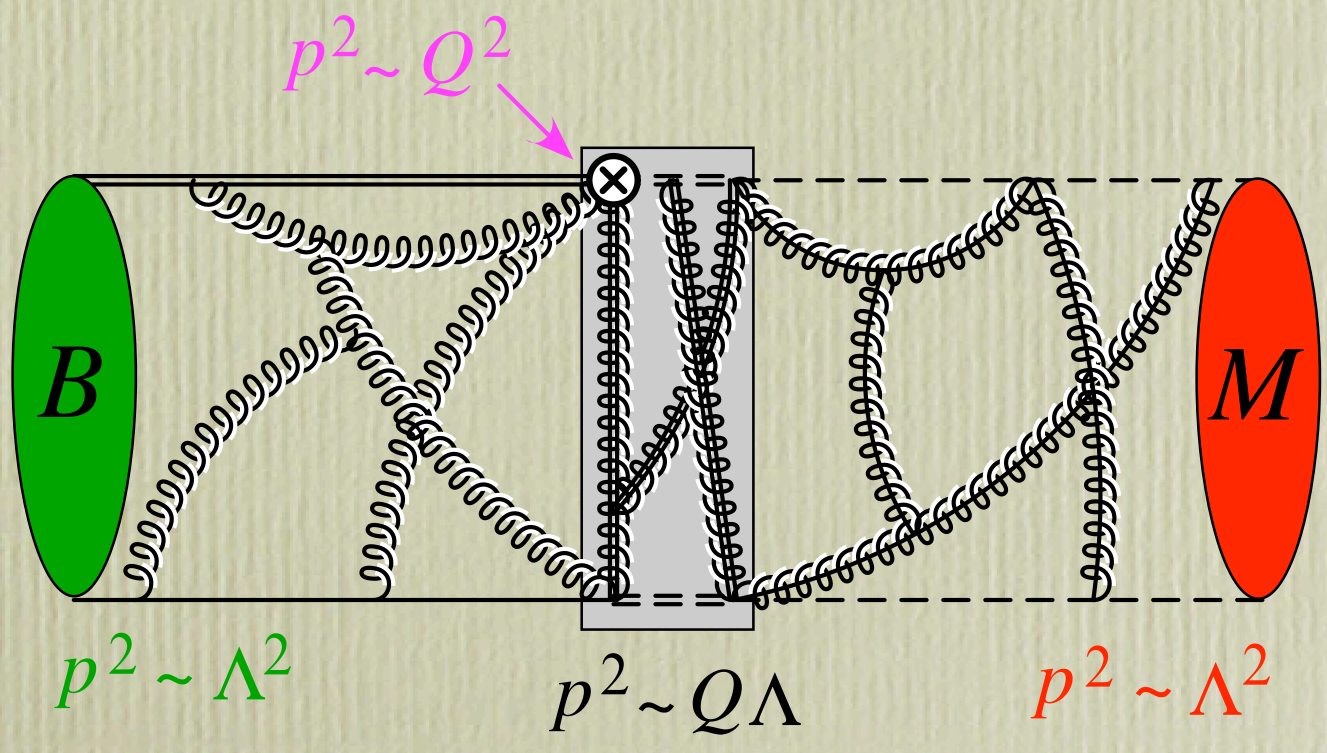
Relation to Form Factors in SCET

$B \to$ pseudoscalar: f_+, f_0, f_T

$B \to$ vector: V, A_0, A_1, A_2, T_1, T_2, T_3

$$f(E) = \int_0^1 dz\, T(z,E,m_b)\, \zeta_J^{BM}(z,E) \quad \Big\} \text{ “hard spectator”, “factorizable”}$$

$$+ \; C(E,m_b)\, \zeta^{BM}(Q\Lambda,\Lambda^2) \quad \Big\} \text{ “soft form factor”, “non-factorizable”}$$



result at LO in λ, all orders in α_s, where $Q = \{m_b, E_M\}$

$\Lambda/Q \ll 1$

power corrections are $\sim 20\%$

Which of ζ^{BM}, ζ_J^{BM} is bigger?

Relation to Form Factors in SCET

$B \to$ pseudoscalar: $f_+,\ f_0,\ f_T$

$B \to$ vector: $V,\ A_0,\ A_1,\ A_2,\ T_1,\ T_2,\ T_3$

$$f(E) \quad = \quad \frac{f_B f_M m_B}{4E^2} \int_0^1 dz \int_0^1 dx \int_0^\infty dr_+\, T(z,E,m_b) \times J(z,x,r_+,E)\,\phi_M(x)\,\phi_B^+(r_+)$$

$$+ \quad C(E,m_b)\,\zeta^{BM}(Q\Lambda,\Lambda^2)$$

One Loop Matching Known:

$C_k(E,m_b)$ Bauer, Fleming, Pirjol, I.S.

$T_i(z,E,m_b)$ Beneke, Kiyo, Yang

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

Lange, Neubert

Log Resummation:

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

→ small for physical b-quark mass

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

$$\zeta^{B\pi}\big|_{\gamma=75^\circ} = (0.052 \pm 0.023)\Big(\frac{4.7\times 10^{-3}}{|V_{ub}|}\Big)$$

$$\zeta_J^{B\pi}\big|_{\gamma=75^\circ} = (0.095 \pm 0.017)\Big(\frac{4.7\times 10^{-3}}{|V_{ub}|}\Big)$$

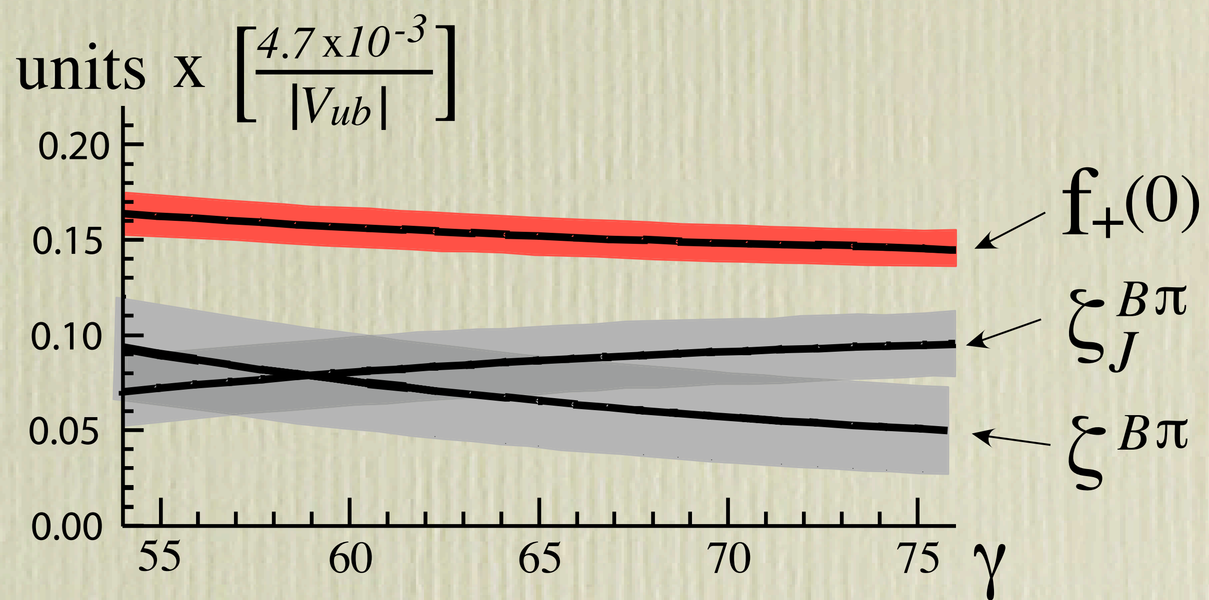
$$\int dx \frac{\phi_\pi(x)}{x} = 3$$

hard scattering bigger than soft form factor

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

$$f_+(0) = (0.15 \pm 0.01 \pm 0.04)\Big(\frac{4.7\times 10^{-3}}{|V_{ub}|}\Big)$$

expt. theory estimate



$$\int dx \frac{\phi_\pi(x)}{x} = 2.25 \qquad \zeta^{B\pi}\big|_{\gamma=75^\circ} = 0.02 \qquad \zeta_J^{B\pi}\big|_{\gamma=75^\circ} = 0.13$$

$$\int dx \frac{\phi_\pi(x)}{x} = 3.75 \qquad \zeta^{B\pi}\big|_{\gamma=75^\circ} = 0.07 \qquad \zeta_J^{B\pi}\big|_{\gamma=75^\circ} = 0.08$$

Possible explanations for small value of $f^+(0)$:

- its correct
- current $B \to \pi\pi$ WA should not be trusted
- there are large corrections to the above analysis

Note: a smaller $f^+(0)$ would increase exclusive Vub determinations, bringing them closer to the inclusive result

Outlook

- The theory of B decays is challenging, but progress is begin made

SCET

- Allows power corrections to be addressed in a model independent way
- Lots of theory left to work out: new factorization theorems, one-loop Wilson coefficient calculations
- Lots of data to study, phenomenology to do

We have only seen
the tip of the iceberg