Factorization, B decays, and the Soft-Collinear Effective Theory

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Outline

- Motivation
- Soft-Collinear Effective Theory (SCET)
- Applications in B decays:

  i) Charm (test factorization):

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

  ii) Inclusive decays (Vub, shape functions):

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

  iii) ~~CP~~ : $B \to \pi\ell\bar{\nu}$ and $B \to \pi\pi$ $\quad |V_{ub}|$ & γ

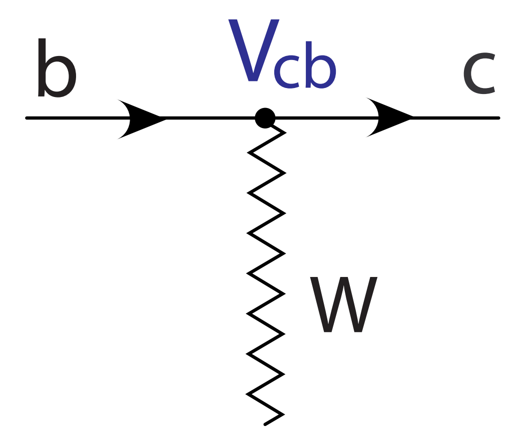
- Outlook

B decays - Motivation

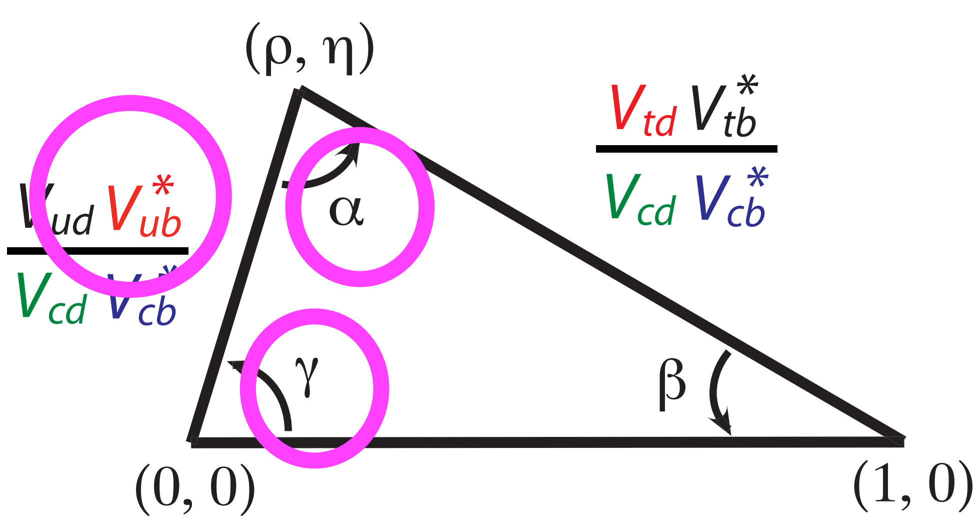
- Heavy Stable Hadrons $\longrightarrow$ lots of decays
- Probe the flavor sector of the SM

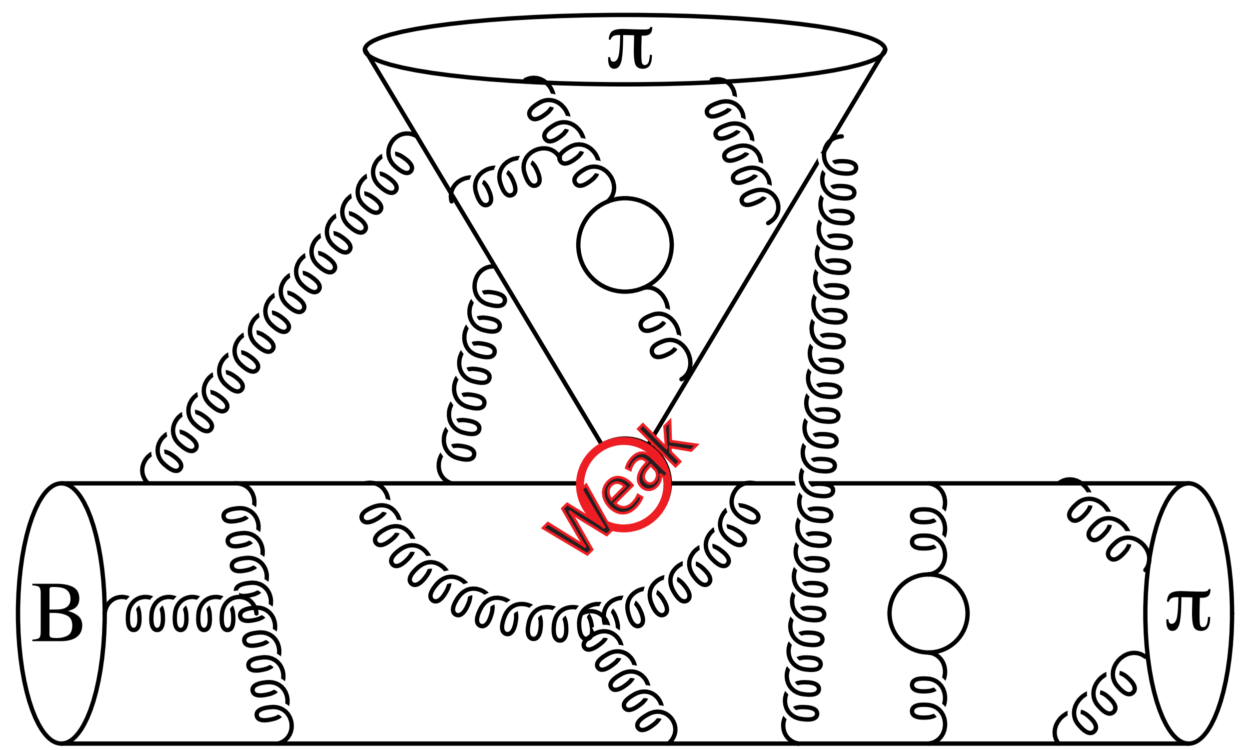
CKM matrix

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



$\cancel{CP}$:





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

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

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

$K^*(892)^0\pi^+\gamma$	$(2.0^{+0.7}_{-0.6})\times10^{-5}$		2562
$K^+\rho^0\gamma$	$<2.0\times10^{-5}$	CL=90%	2558
$K^+\pi^-\pi^+\gamma$ nonresonant	$<9.2\times10^{-6}$	CL=90%	2609
$K_1(1400)^+\gamma$	$<5.0\times10^{-5}$	CL=90%	2453
$K_2^*(1430)^+\gamma$	$<1.4\times10^{-3}$	CL=90%	2447
$K^*(1680)^+\gamma$	$<1.9\times10^{-3}$	CL=90%	2360
$K_3^*(1780)^+\gamma$	$<5.5\times10^{-3}$	CL=90%	2341
$K_4^*(2045)^+\gamma$	$<9.9\times10^{-3}$	CL=90%	2243

Light unflavored meson modes

$\rho^+\gamma$	$<2.1\times10^{-6}$	CL=90%	2583
$\pi^+\pi^0$	$(5.6^{+0.9}_{-1.1})\times10^{-6}$		2636
$\pi^+\pi^+\pi^-$	$(1.1\pm0.4)\times10^{-5}$		2630
$\rho^0\pi^+$	$(8.6\pm2.0)\times10^{-6}$		2581
$\pi^+f_0(980)$	$<1.4\times10^{-4}$	CL=90%	2547
$\pi^+f_2(1270)$	$<2.4\times10^{-4}$	CL=90%	2483
$\pi^+\pi^-\pi^+$ nonresonant	$<4.1\times10^{-5}$	CL=90%	2630
$\pi^+\pi^0\pi^0$	$<8.9\times10^{-4}$	CL=90%	2631
$\rho^+\pi^0$	$<4.3\times10^{-5}$	CL=90%	2581
$\pi^+\pi^-\pi^+\pi^0$	$<4.0\times10^{-3}$	CL=90%	2621
$\rho^+\rho^0$	$(2.6\pm0.6)\times10^{-5}$		2523
$a_1(1260)^+\pi^0$	$<1.7\times10^{-3}$	CL=90%	2494
$a_1(1260)^0\pi^+$	$<9.0\times10^{-4}$	CL=90%	2494
$\omega\pi^+$	$(6.4^{+1.8}_{-1.6})\times10^{-6}$	S=1.3	2580
$\omega\rho^+$	$<6.1\times10^{-5}$	CL=90%	2522
$\eta\pi^+$	$<5.7\times10^{-6}$	CL=90%	2609
$\eta'\pi^+$	$<7.0\times10^{-6}$	CL=90%	2551
$\eta'\rho^+$	$<3.3\times10^{-5}$	CL=90%	2492
$\eta\rho^+$	$<1.5\times10^{-5}$	CL=90%	2553
$\phi\pi^+$	$<4.1\times10^{-7}$	CL=90%	2539
$\phi\rho^+$	$<1.6\times10^{-5}$		2480
$\pi^+\pi^+\pi^+\pi^-\pi^-$	$<8.6\times10^{-4}$	CL=90%	2608
$\rho^0a_1(1260)^+$	$<6.2\times10^{-4}$	CL=90%	2433
$\rho^0a_2(1320)^+$	$<7.2\times10^{-4}$	CL=90%	2410
$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^0$	$<6.3\times10^{-3}$	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 $\pi^\pm$

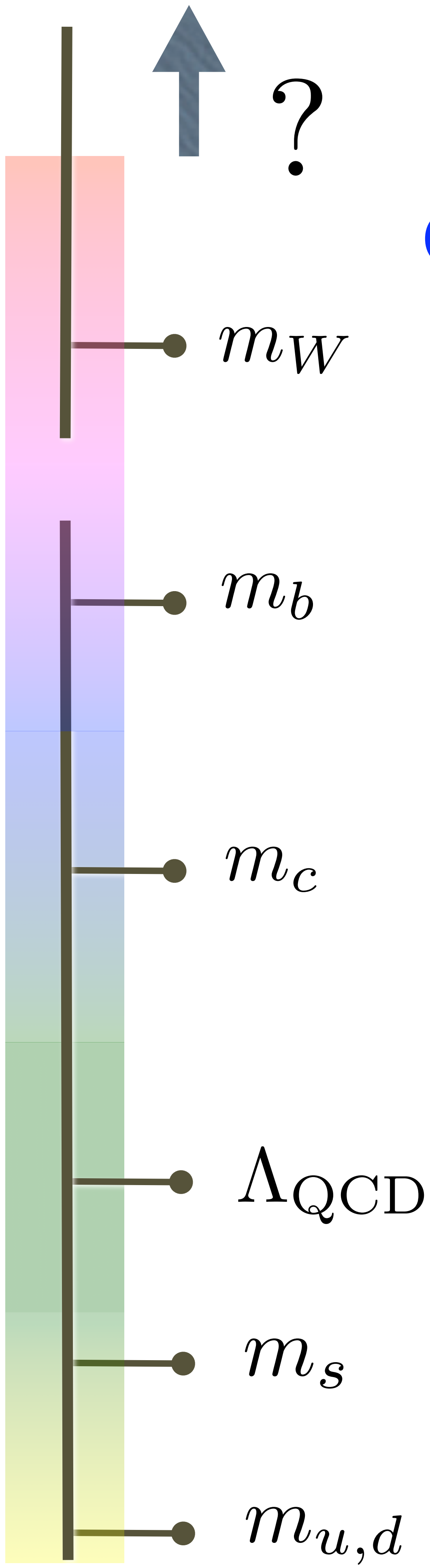
$h^+\pi^0$	$(1.6^{+0.7}_{-0.6})\times10^{-5}$		2636
ωh^+	$(1.38^{+0.27}_{-0.24})\times10^{-5}$		2580
h^+X^0 (Familon)	$<4.9\times10^{-5}$	CL=90%	–

Baryon modes

$p\overline{p}\pi^+$	$<3.7\times10^{-6}$	CL=90%	2439
$p\overline{p}\pi^+$ nonresonant	$<5.3\times10^{-5}$	CL=90%	2439
$p\overline{p}\pi^+\pi^+\pi^-$	$<5.2\times10^{-4}$	CL=90%	2369
$p\overline{p}K^+$	$(4.3^{+1.2}_{-1.0})\times10^{-6}$		2348
$p\overline{p}K^+$ nonresonant	$<8.9\times10^{-5}$	CL=90%	2348
$p\overline{\Lambda}$	$<1.5\times10^{-6}$	CL=90%	2430
$p\overline{\Lambda}\pi^+\pi^-$	$<2.0\times10^{-4}$	CL=90%	2367
$\overline{\Delta}^0p$	$<3.8\times10^{-4}$	CL=90%	2402
$\Delta^{++}\overline{p}$	$<1.5\times10^{-4}$	CL=90%	2402
$D^+p\overline{p}$	$<1.5\times10^{-5}$	CL=90%	1860
$D^*(2010)^+p\overline{p}$	$<1.5\times10^{-5}$	CL=90%	1786
$\overline{\Lambda}_c^-p\pi^+$	$(2.1\pm0.7)\times10^{-4}$		1981
$\overline{\Lambda}_c^-p\pi^+\pi^0$	$(1.8\pm0.6)\times10^{-3}$		1936
$\overline{\Lambda}_c^-p\pi^+\pi^+\pi^-$	$(2.3\pm0.7)\times10^{-3}$		1881
$\overline{\Lambda}_c^-p\pi^+\pi^+\pi^-\pi^0$	<1.34 %	CL=90%	1823
$\overline{\Sigma}_c(2455)^0p$	$<8\times10^{-5}$	CL=90%	1939
$\overline{\Sigma}_c(2520)^0p$	$<4.6\times10^{-5}$	CL=90%	1905
$\overline{\Sigma}_c(2455)^0p\pi^0$	$(4.4\pm1.8)\times10^{-4}$		1897
$\overline{\Sigma}_c(2455)^0p\pi^-\pi^+$	$(4.4\pm1.7)\times10^{-4}$		1845
$\overline{\Sigma}_c(2455)^{--}p\pi^+\pi^+$	$(2.8\pm1.2)\times10^{-4}$		1845
$\overline{\Lambda}_c(2593)^-/\overline{\Lambda}_c(2625)^-p\pi^+$	$<1.9\times10^{-4}$	CL=90%	–

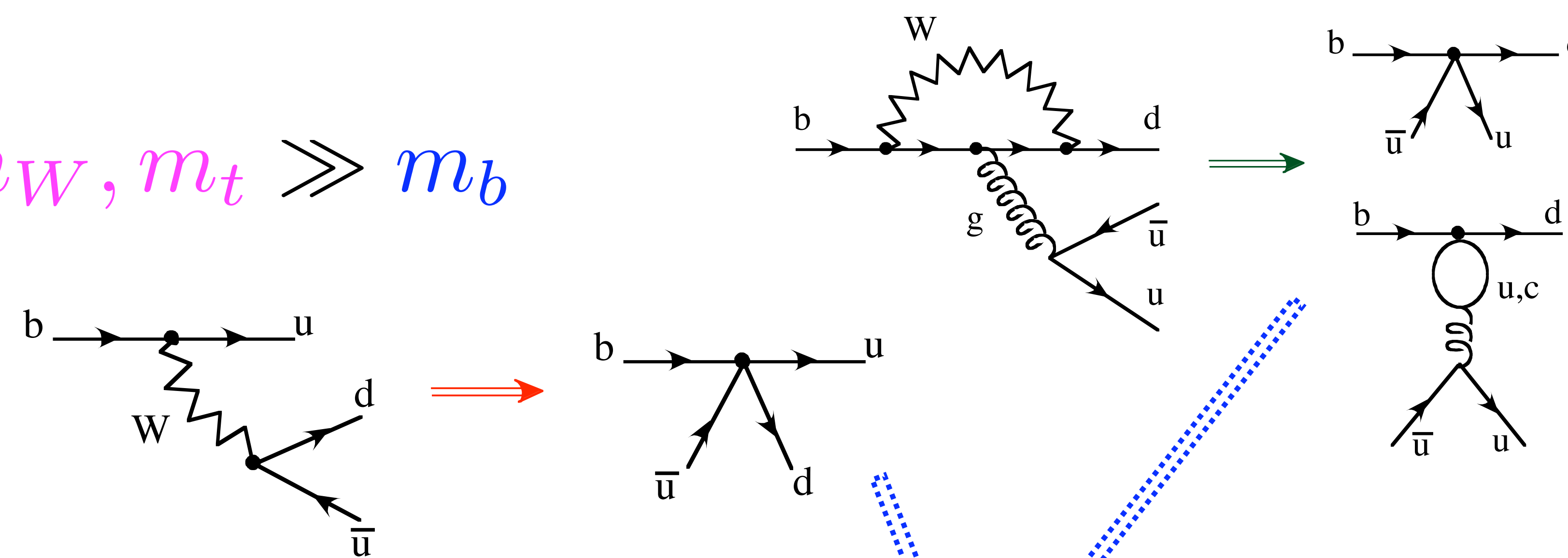
Lepton Family number (LF) or Lepton number (L) violating modes, or $\Delta B=1$ weak neutral current ($B1$) modes

$\pi^+e^+e^-$	*B1*		$<3.9\times10^{-3}$	CL=90%	2638
$\pi^+\mu^+\mu^-$	*B1*		$<9.1\times10^{-3}$	CL=90%	2633
$K^+e^+e^-$	*B1*		$(6.3^{+1.9}_{-1.7})\times10^{-7}$		2616
$K^+\mu^+\mu^-$	*B1*		$(4.5^{+1.4}_{-1.2})\times10^{-7}$		2612
$K^+\ell^+\ell^-$	*B1*	[a]	$(5.3\pm1.1)\times10^{-7}$		2616
$K^+\overline{\nu}\nu$	*B1*		$<2.4\times10^{-4}$	CL=90%	2616
$K^*(892)^+e^+e^-$	*B1*		$<4.6\times10^{-6}$	CL=90%	2564
$K^*(892)^+\mu^+\mu^-$	*B1*		$<2.2\times10^{-6}$	CL=90%	2560
$K^*(892)^+\ell^+\ell$	*B1*	[a]	$<2.2\times10^{-6}$	CL=90%	2564
$\pi^+e^+\mu^-$	*LF*		$<6.4\times10^{-3}$	CL=90%	2637
$\pi^+e^-\mu^+$	*LF*		$<6.4\times10^{-3}$	CL=90%	2637
$K^+e^+\mu^-$	*LF*		$<8\times10^{-7}$	CL=90%	2615
$K^+e^-\mu^+$	*LF*		$<6.4\times10^{-3}$	CL=90%	2615
$K^*(892)^+e^\pm\mu^\mp$	*LF*		$<7.9\times10^{-6}$	CL=90%	2563
$\pi^-e^+e^+$	*L*		$<1.6\times10^{-6}$	CL=90%	2638
$\pi^-\mu^+\mu^+$	*L*		$<1.4\times10^{-6}$	CL=90%	2633



Operator Product Expansion (I)

- $m_W, m_t \gg m_b$



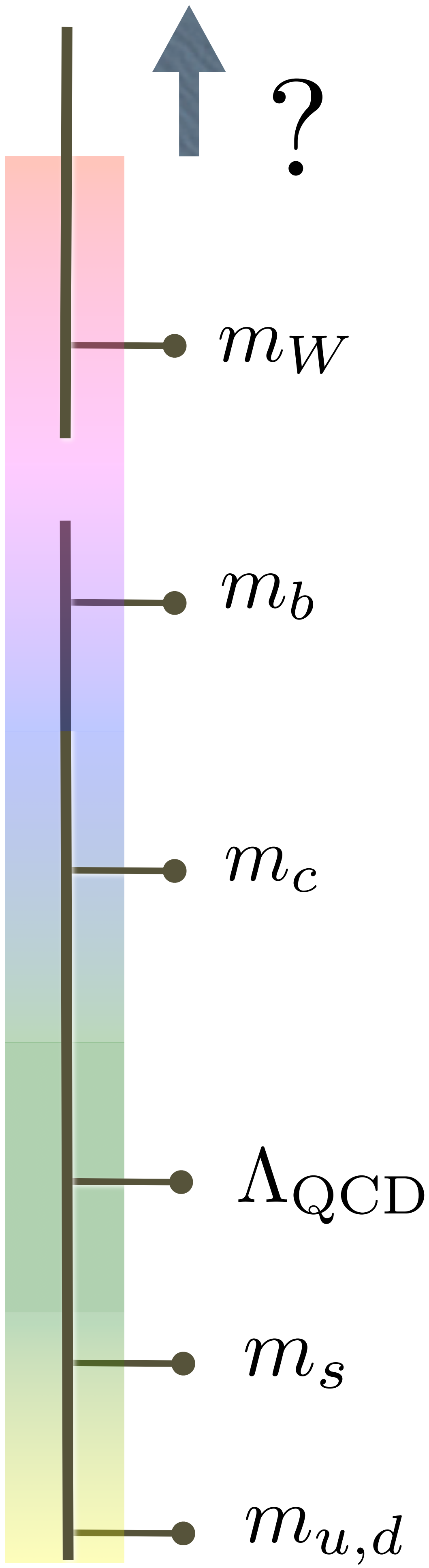
$$\boxed{H_{\text{weak}} = \frac{G_F}{\sqrt{2}} \sum_i \lambda^i C_i(\mu) O_i(\mu)}$$

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

perturbative QCD

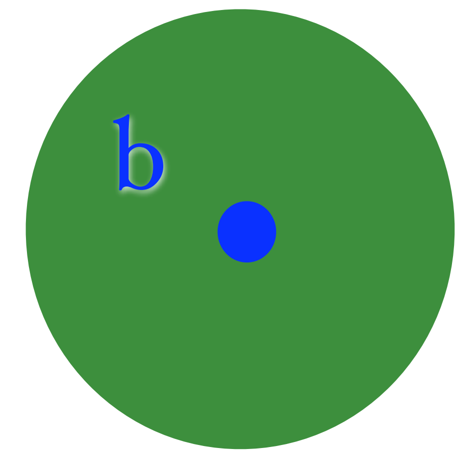
Decays like $B \to X_s\gamma$ & $B \to K\pi$
have contributions from ~ 12 operators

Operator Product Expansion (II)



- $m_b \gg \Lambda_{\mathrm{QCD}}$

B-meson



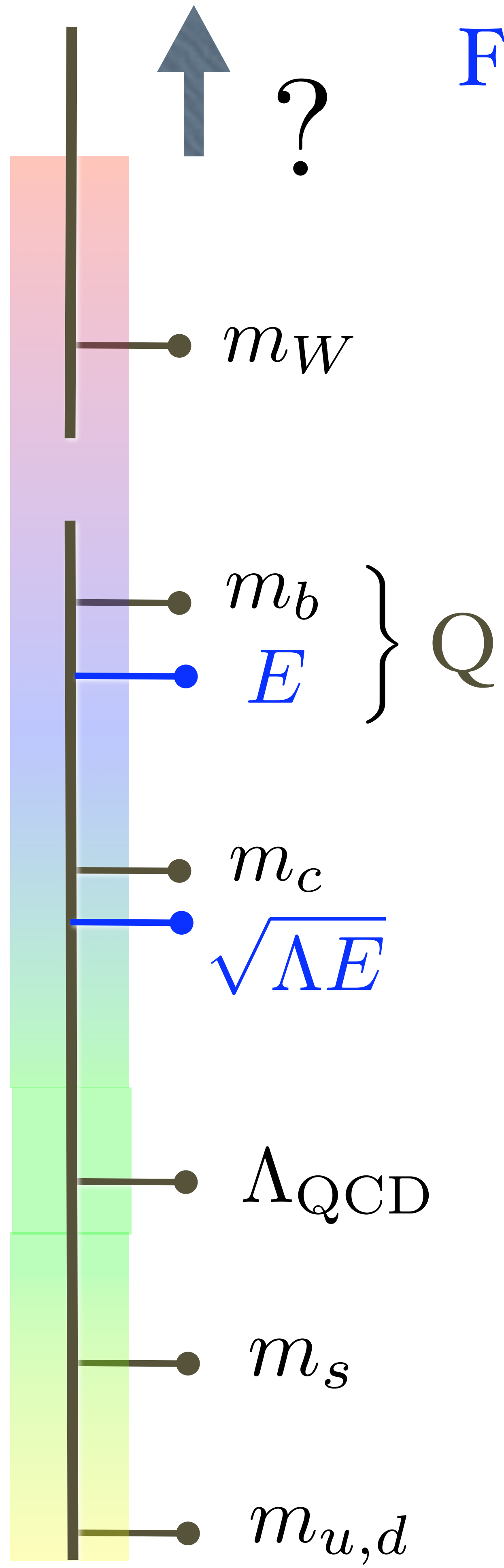
$$\Gamma = c^{(0)} f^{(0)} + \frac{1}{m_b} c^{(1)} f^{(1)} + \dots$$

Heavy Quark Effective Theory $\quad h_v, q$

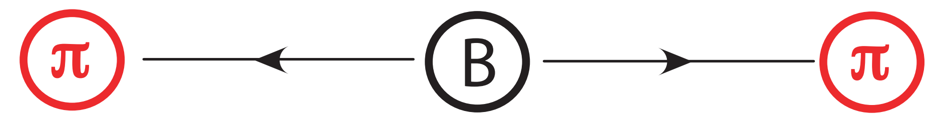
Local OPE for Inclusive Decays

- Justifies free quark decay as leading approximation $\quad b \to u e \bar{\nu}$

Factorization Theorems

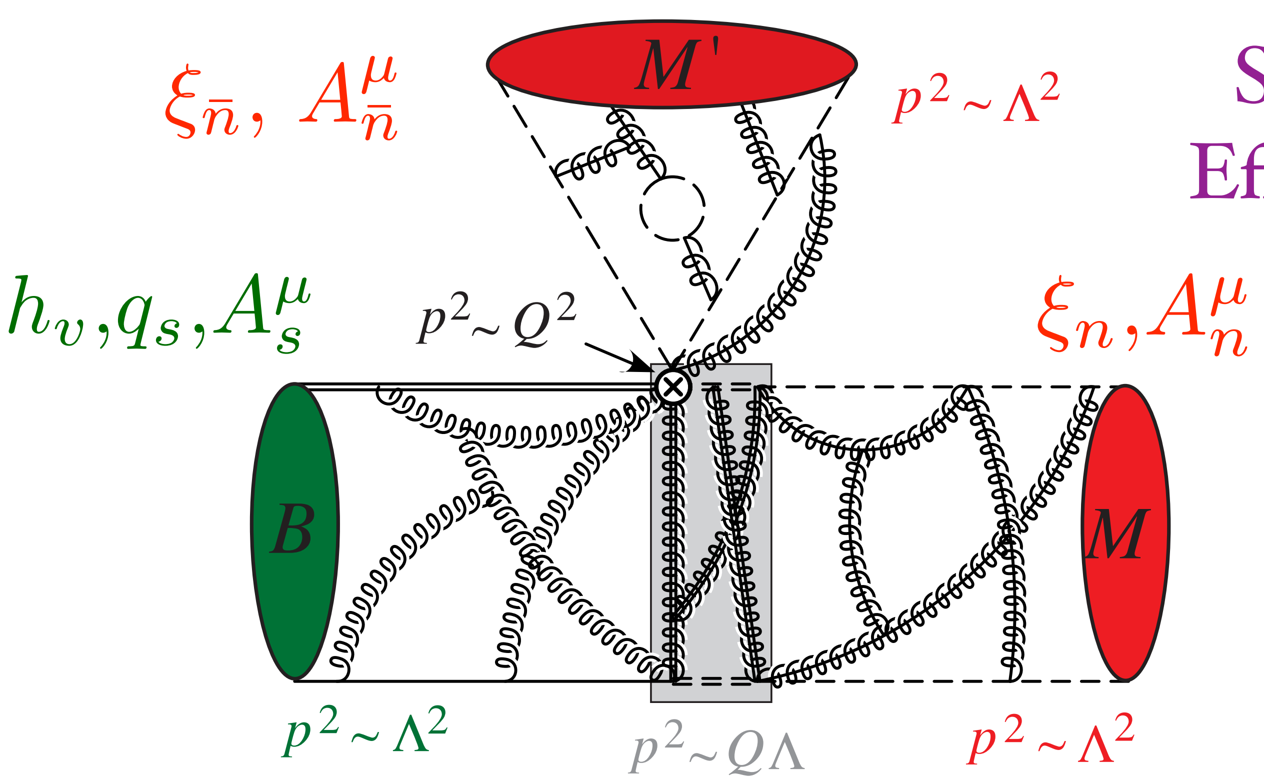


Energetic Hadrons



eg. $E_\pi \gg \Lambda_{\rm QCD}$

$$A = \int dz dx_i dk^+ \underbrace{T(z)}_{Q^2} \gg \underbrace{J(z, x_i, k^+)}_{E\Lambda} \gg \underbrace{\phi_1(x_1)\phi_2(x_2)\phi_B(k^+)}_{\Lambda^2} + \ldots$$



Soft-Collinear Effective Theory

Soft - Collinear Effective Theory

Bauer, Pirjol, Stewart
Fleming, Luke, ...

An effective field theory for energetic hadrons & jets

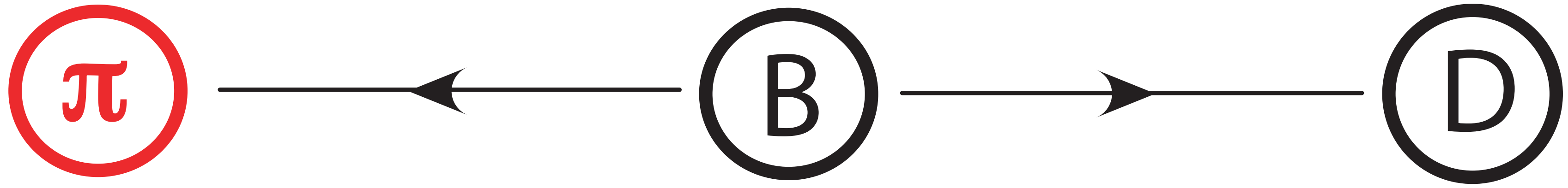
$$E \gg \Lambda_{\rm QCD}$$

Effective Field Theory

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

Soft Collinear Effective Theory

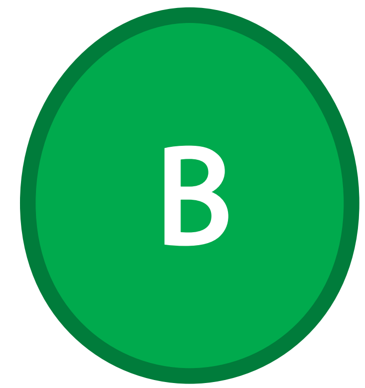
eg.



Pion has: $p_\pi^\mu \;=\; (2.3\,\mathrm{GeV})n^\mu = Q\,n^\mu$ $\qquad n^2 = \bar{n}^2 = 0, \;\; (\bar{n}\cdot p = p^-)$

Soft constituents:

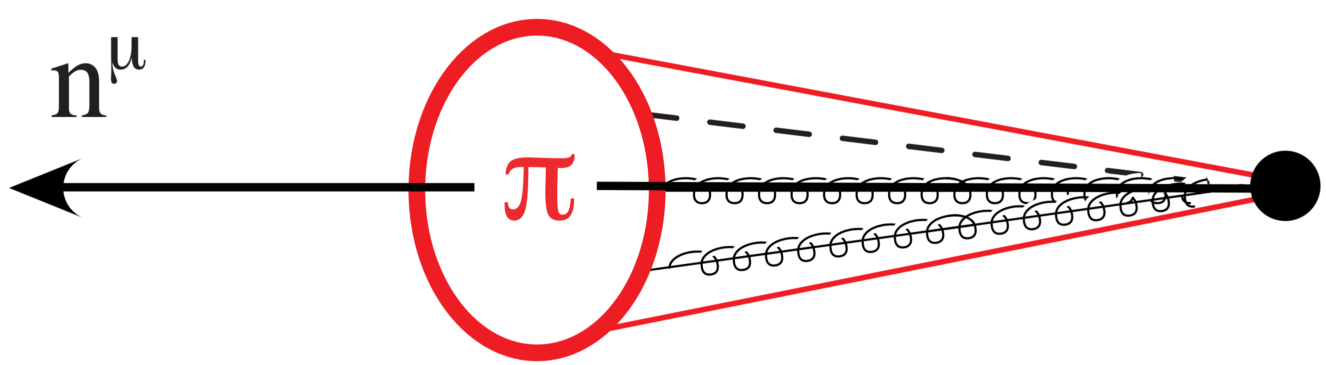
$$p_s^\mu = (p^+, p^-, p^\perp) \sim (\Lambda, \Lambda, \Lambda)$$



Collinear constituents:

$$p_c^\mu = (p^+, p^-, p^\perp) \sim \left(\frac{\Lambda^2}{Q}, Q, \Lambda\right) \sim Q(\lambda^2, 1, \lambda)$$

$$\lambda = \frac{\Lambda}{Q}$$



Degrees of freedom in SCET

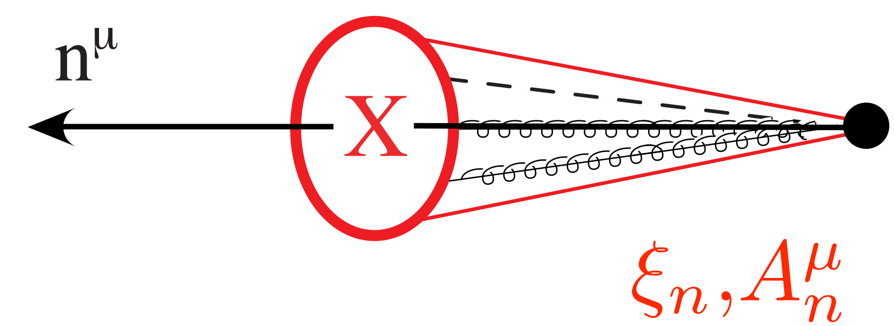
Introduce fields for infrared degrees of freedom (in operators)

modes	$p^\mu = (+, -, \perp)$	p^2	fields
collinear	$Q(\lambda^2, 1, \lambda)$	$Q^2\lambda^2$	$\xi_n,\ A_n^\mu$
soft	$Q(\lambda, \lambda, \lambda)$	$Q^2\lambda^2$	$q_s,\ A_s^\mu$
usoft	$Q(\lambda^2, \lambda^2, \lambda^2)$	$Q^2\lambda^4$	$q_{us},\ A_{us}^\mu$

$\mathrm{SCET_I}$ $\longrightarrow$ Energetic jets $\quad \Lambda^2 \ll Q\Lambda \ll Q^2$

usoft $\quad p^\mu \sim \Lambda$

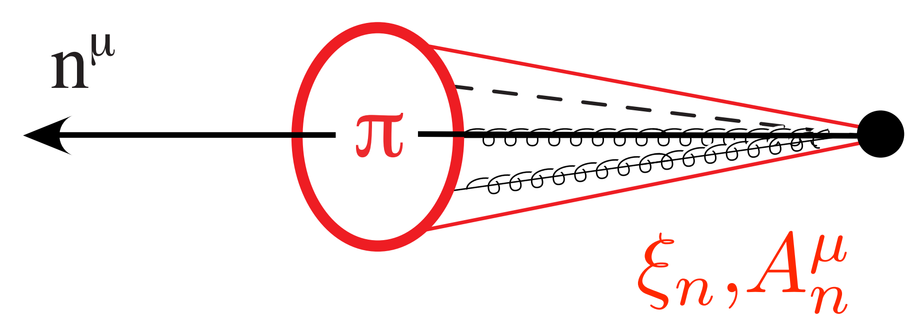
collinear $\quad p_c^2 \sim Q\Lambda, \quad \lambda = \sqrt{\Lambda/Q}$



$\mathrm{SCET_{II}}$ $\longrightarrow$ Energetic hadrons

soft $\quad p^\mu \sim \Lambda$

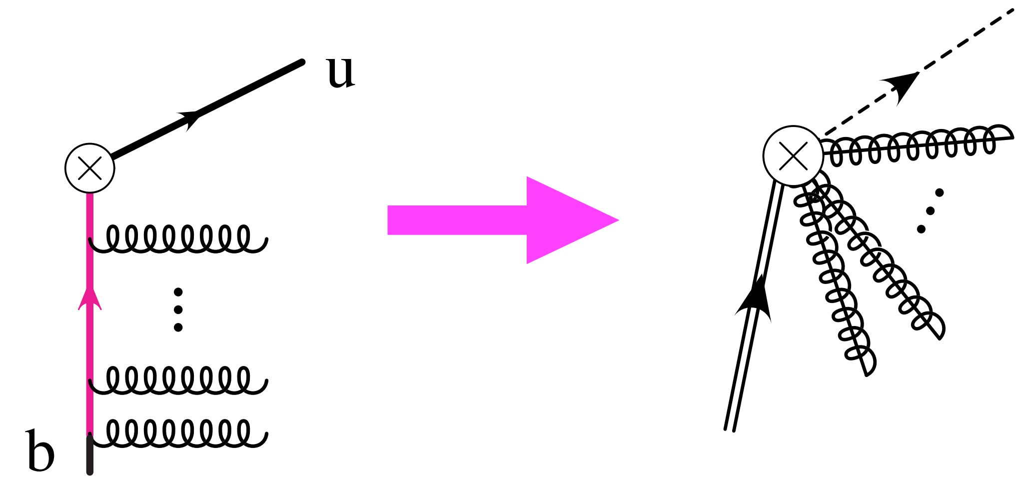
collinear $\quad p_c^2 \sim \Lambda^2, \quad \lambda = \Lambda/Q$



Factorization

Factorization

- Separation of scales
  and Decoupling



eg. $\bar{u}\,\Gamma\, b$

$\Rightarrow$ $\bar{\xi}_n W \;\Gamma\; h_v$ integrate out offshell quarks

$\Rightarrow$ $(\bar{\xi}_n W)\,\Gamma\,(Y^\dagger h_v)$ usoft-collinear factorization (field redefn.)

$\Rightarrow$ $\int d\omega\, C(\omega) (\bar{\xi}_n W)_\omega\, \Gamma\, (Y^\dagger h_v)$ hard-collinear factorization

$$\omega \sim p_c^- \sim Q$$

- operators are gauge invariant,
  so factorization is too

$$W = P \exp\left(ig \int_{-\infty}^{y} ds\; \bar{n}\cdot A_n(s\bar{n}^\mu)\right)$$

$$S = P \exp\left(ig \int_{-\infty}^{y} ds\; n\cdot A_s(s n^\mu)\right)$$

$$Y = P \exp\left(ig \int_{-\infty}^{y} ds\; n\cdot A_{us}(s n^\mu)\right)$$

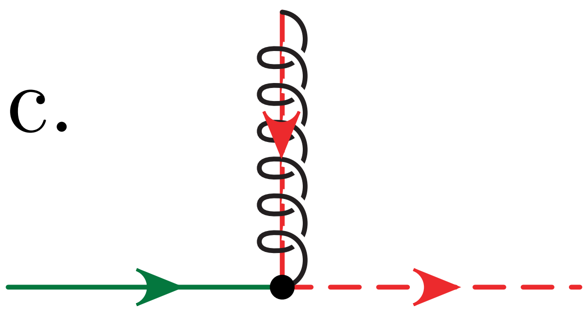
SCET$_\mathrm{I}$ Lagrangians

Expansion:

$$\mathcal{L}_c^{(0)} = \bar{\xi}_n \Big\{ n\cdot iD + i\not{D}_c^\perp W \frac{1}{\bar{\mathcal{P}}} W^\dagger i\not{D}_c^\perp \Big\} \frac{\not{\bar{n}}}{2} \xi_n$$

$$\mathcal{L}_{us,s}^{(0)} = \bar{q}\, i\not{D}\, q$$

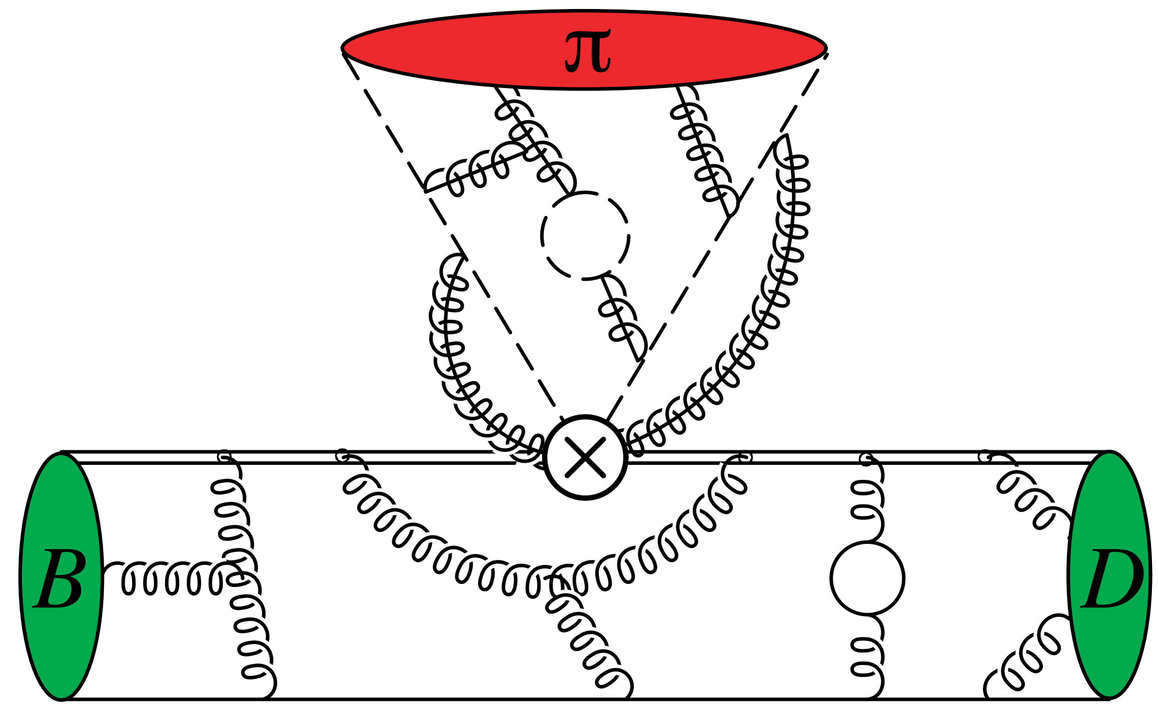
$$\mathcal{L}_{\xi q}^{(1)} = \bar{\xi}_n W \frac{1}{\bar{\mathcal{P}}} W^\dagger (ig\not{B}_c^\perp) W Y^\dagger q_{us} + \mathrm{h.c.}$$



$\mathcal{L}^{(2)}$ known

- Same (subleading!) Lagrangians for all processes
- Many processes require subleading Lagrangians or they vanish

Factorization



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

  B, D are soft, π collinear

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

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

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

Calculate T

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

Mantry, Pirjol, I.S.

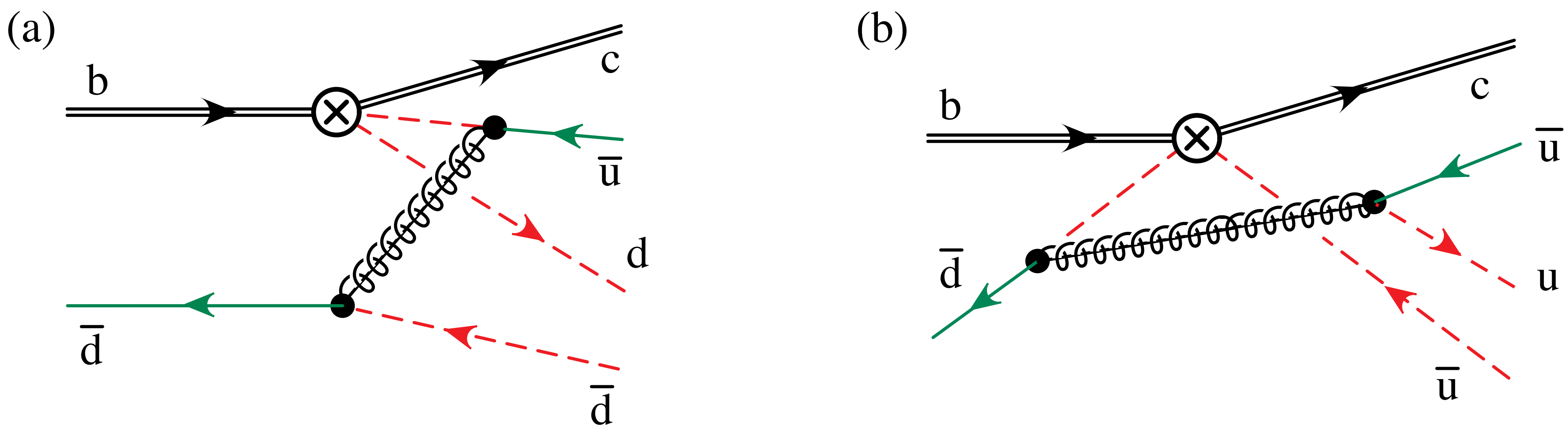
$$A_{00}^{D^{(*)}\pi} = N_0^{(*)}\int dx\,dz\,dk_1^+ dk_2^+\, T^{(i)}(z)\, J^{(i)}(z,x,k_1^+,k_2^+)\, S^{(i)}(k_1^+,k_2^+)\,\phi_\pi(x)$$
$$+A_{\rm long}^{D^{(*)}\pi}$$

$\frac{\Lambda}{E_M}$ & $\frac{1}{N_c}$ suppressed

Color Suppressed Decays

- Factorization with SCET

Single class of power suppressed SCET$_\mathrm{I}$ operators $T\{\mathcal{O}^{(0)}, \mathcal{L}^{(1)}_{\xi q}, \mathcal{L}^{(1)}_{\xi q}\}$



Order $\lambda^2 = \left(\sqrt{\Lambda/E}\right)^2 = \Lambda/E$

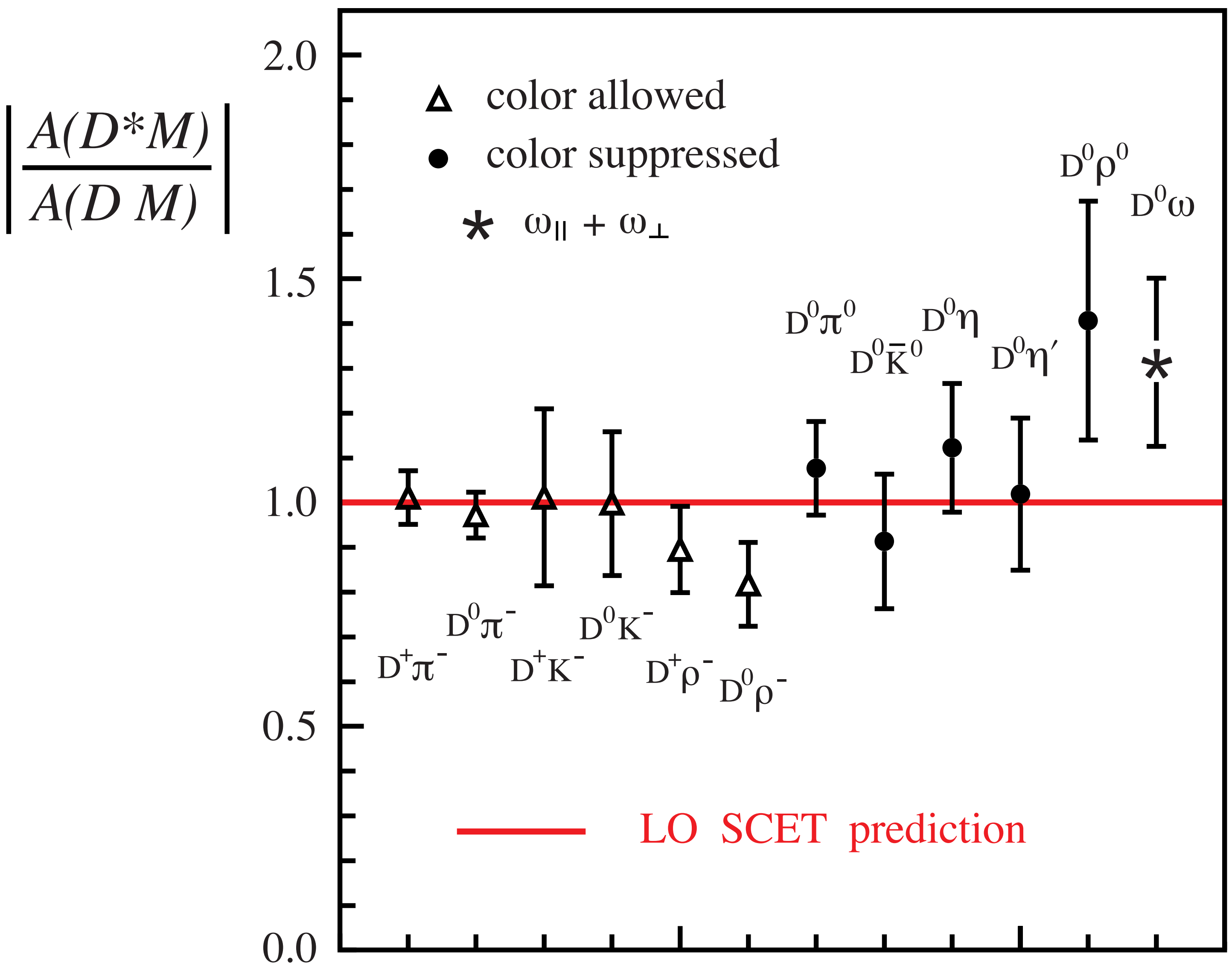
$$A_{00}^{D^{(*)}\pi} = N_0^{(*)} \int dx\, dz\, dk_1^+ dk_2^+\, T^{(i)}(z)\, J^{(i)}(z, x, k_1^+, k_2^+)\, S^{(i)}(k_1^+, k_2^+)\, \phi_\pi(x)$$
$$+A_{\text{long}}^{D^{(*)}\pi}$$

same for D, D* up to $\alpha_s(m_b)$

- with HQET for $\langle D^{(*)0}\pi|(\bar{c}\, b)(\bar{d}\, u)|\bar{B}^0\rangle$ get $\frac{p^\mu_\pi}{m_c} \to \frac{E_\pi}{m_c} = 1.5$

not a convergent expansion

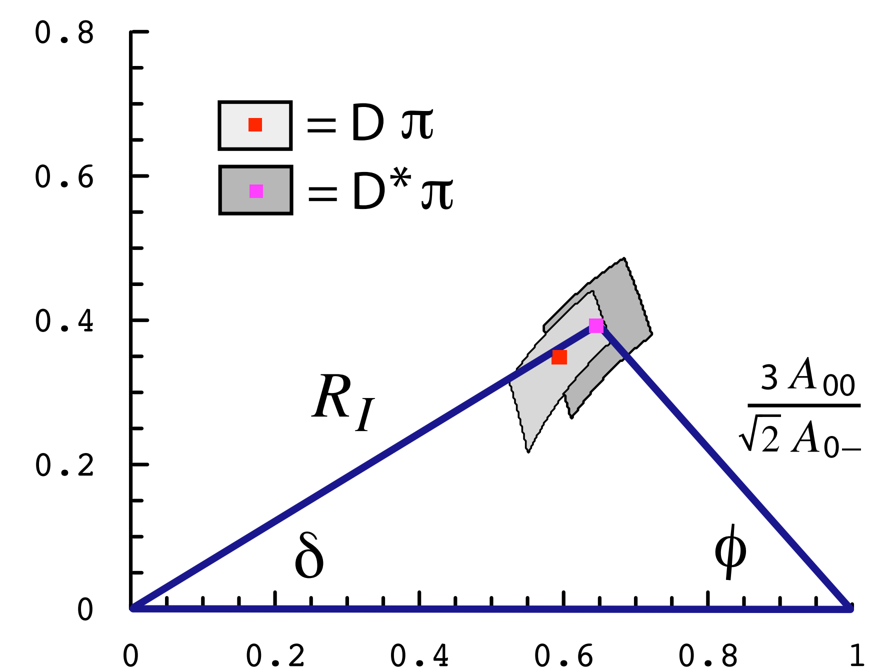
Expt Average (Cleo, Belle, Babar):



Extension to isosinglets:

Blechman, Mantry, I.S.

isospin triangle



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

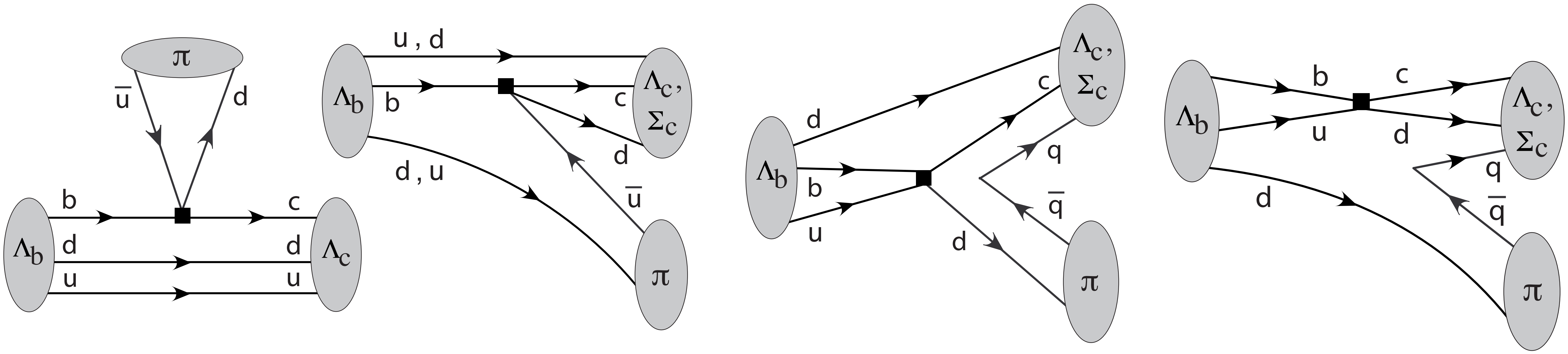
Not yet tested:

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

Baryon decays

$$\Lambda_b \to \Lambda_c\pi,\ \Lambda_c\rho,\ \Sigma_c^{(*)}\pi,\ \Sigma_c^{(*)}\rho$$

Leibovich et al.



T=tree

C= color commensurate

E= exchange

B = bow-tie

Predict In SCET: $T \gg C \sim E \gg B$ similar factorization theorems

$$\frac{\Gamma(\Lambda_b \to \Lambda_c\pi^-)}{\Gamma(\bar{B}^0 \to D^+\pi^-)} = \frac{8m_{\Lambda_b}^3(1-r_\Lambda^2)^3\, r_D}{m_B^3(1-r_D^2)^3(1+r_D)^2}\left(\frac{\zeta(w_{\max}^{\Lambda})}{\xi(w_{\max}^{D})}\right)^2$$

1.6

need semileptonic

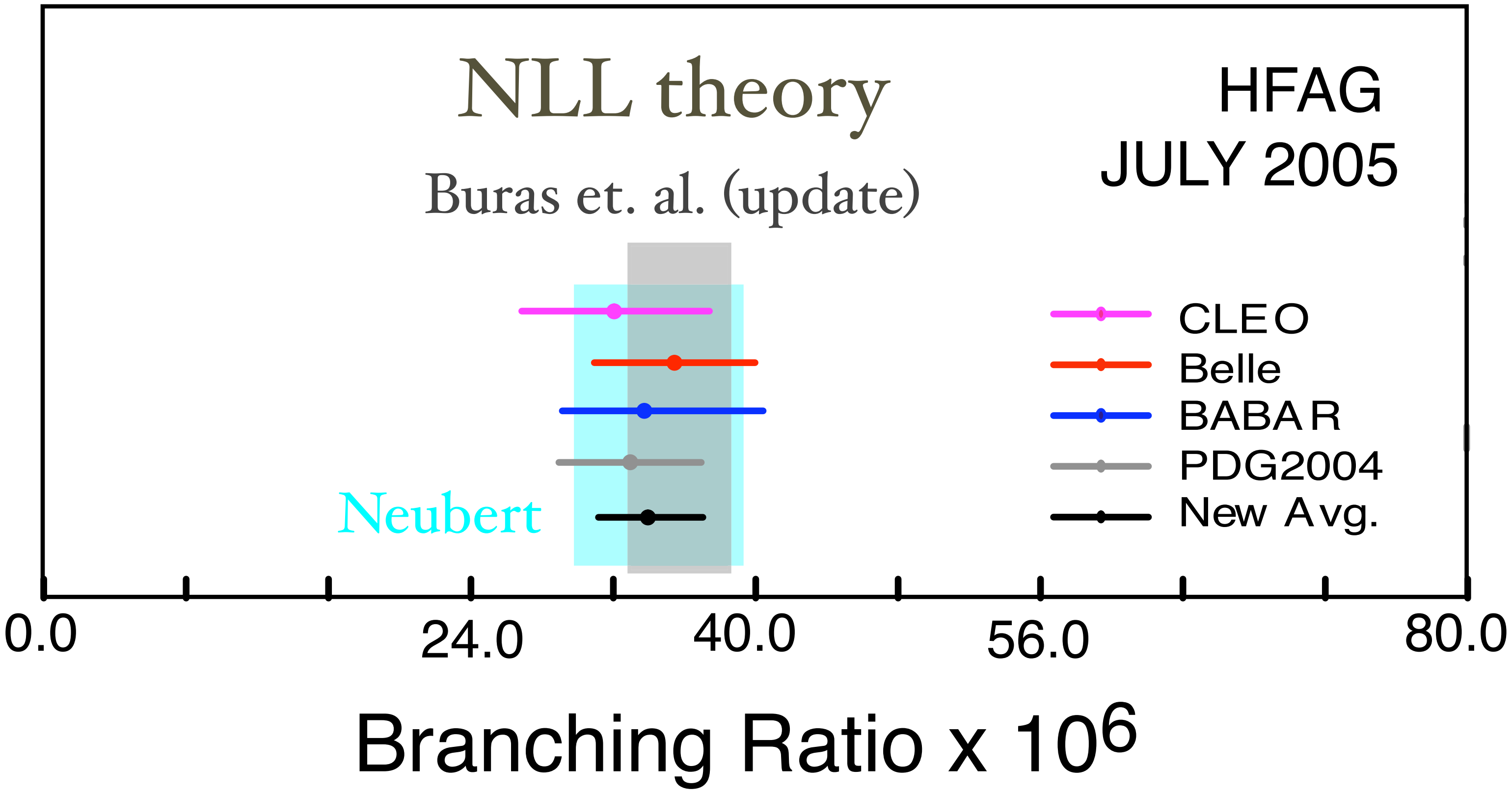
$$\frac{Br(\Lambda_b \to \Sigma_c^*\pi)}{Br(\Lambda_b \to \Sigma_c\pi)} = 2\,, \quad \frac{Br(\Lambda_b \to \Sigma_c^*\rho)}{Br(\Lambda_b \to \Sigma_c\rho)} = 2$$

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

Inclusive B-Decays

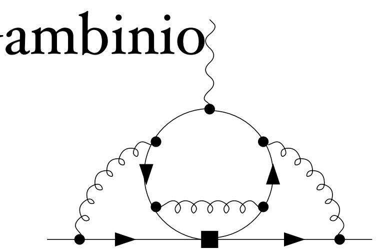
$\boxed{B \to X_s \gamma}$

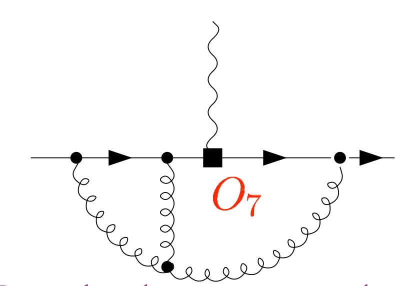
agrees with SM at current precision



NNLL theory OPE based calculations are progressing

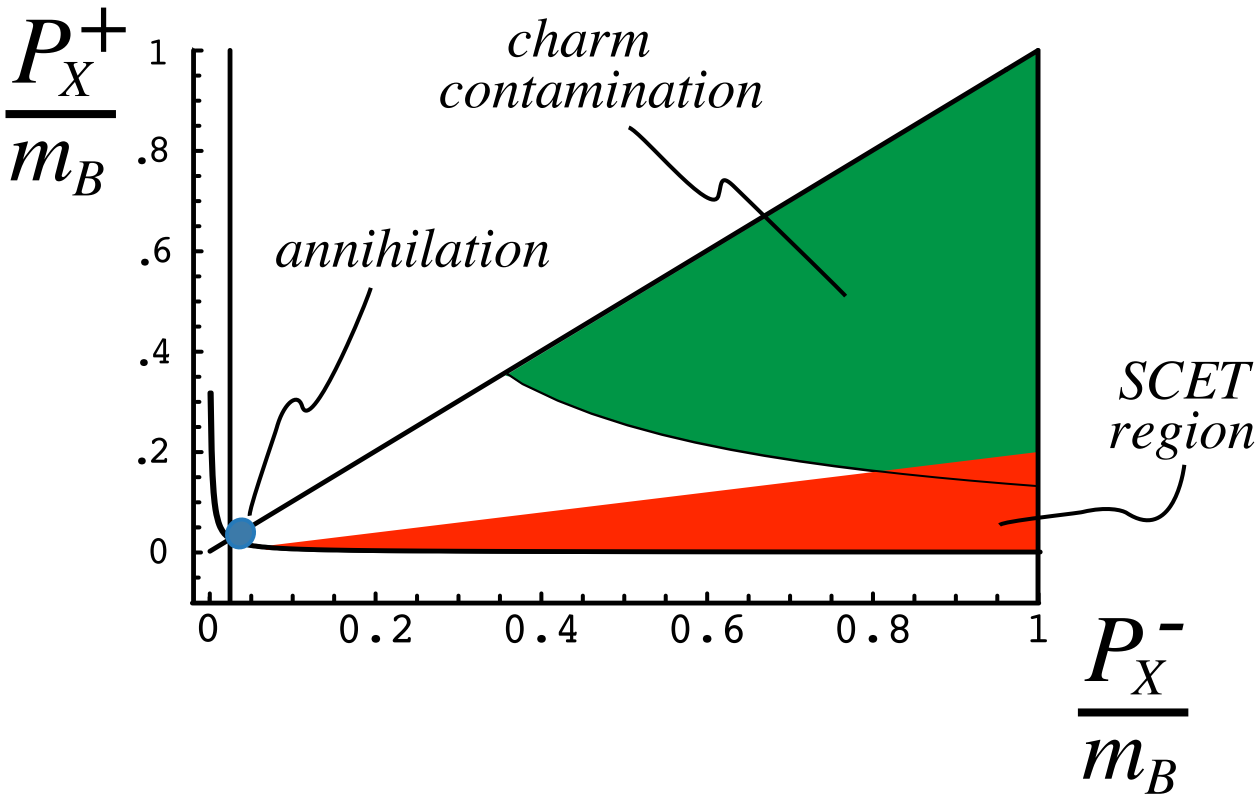
Matching	C_{1-6}	$2L$	Bobeth, Misiak, Urban
	$C_{7,8}$	$3L$	Misiak, Steinhauser
Running	$\hat{\gamma}$	$\begin{pmatrix} \text{3L} & \text{4L} \\ \text{2L} & \text{3L} \end{pmatrix}$	Haisch,Gorbahn,Gambinio Czakon et al.
M.Elts.	$\langle O_{1-6} \rangle$	$3L$	Bieri, Greub, Steinhauser
	$\langle O_{7,8} \rangle$	$2L$	Greub,Hurth,Asatrian Blockland et al., Melnikov, Mitov



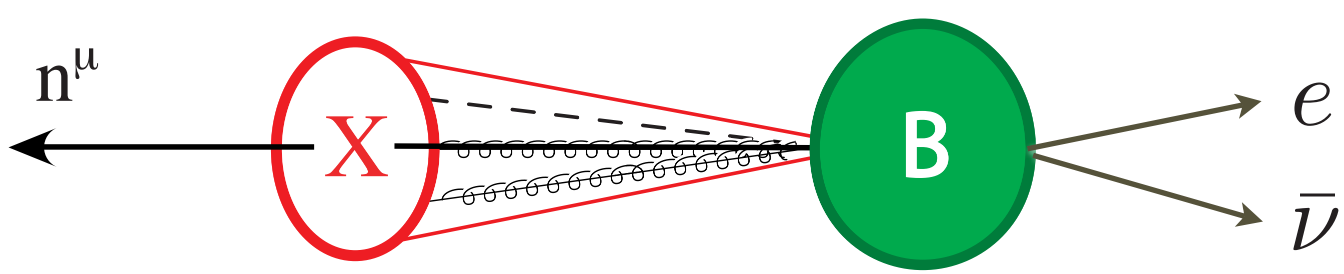


Gambina,Gorbahn,Haisch
Asatrian, Greub, Hurth
Misiak, Steinhauser

$\boxed{B \to X_u e \bar{\nu}}$ measure Vub



most cuts which avoid the charm background make X_u jet like



$$m_X^2 \sim m_b \Lambda$$

$$P_X^- \gg P_X^+$$

sensitive to "b" momentum

→ shape function

Shape function region

Neubert, Falk et al, Bigi et al
Korchemsky, Sterman

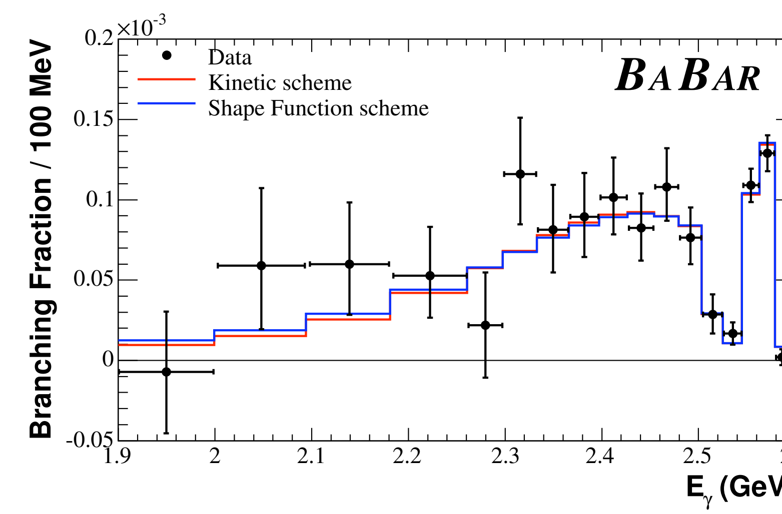
$$d\Gamma = \underbrace{H(m_b, p_X^-)}_{Q^2} \int dk^+ \, \underbrace{J(p_X^- k^+)}_{Q\Lambda} \, \underbrace{f(k^+ + \overline{\Lambda} - p_X^+)}_{\Lambda^2} \; + \mathcal{O}\Big(\frac{\Lambda}{m_b}\Big)$$

universal

measure in $B \to X_s \gamma$
use it in $B \to X_u \ell \bar{\nu}$

What's new from SCET:

$B \to X_s \gamma$

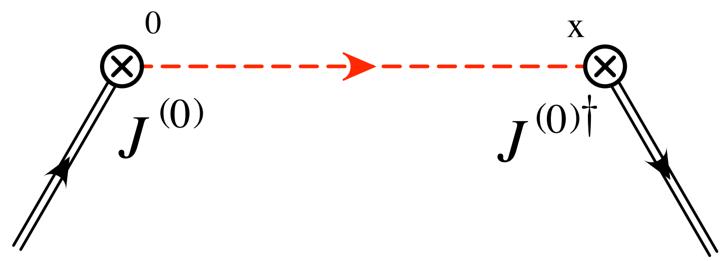


- $\mathcal{O}(\alpha_s)$ matching for H, J — Bauer et al.; Bauer, Manohar; Bosch et al
- moments of f require a cutoff
  (relation to $B \to X_c \ell \bar{\nu}$ parameters)

  now known at $\mathcal{O}(\alpha_s^2)$ — Becher, Neubert
- triple diff. rate for subleading terms, $\mathcal{O}\Big(\frac{\Lambda}{m_b}\Big)$
  Lee, I.S.; Bosch et al.; Beneke et al.
- $B \to X_s \ell^+ \ell^-$ in shape function region
  Lee, Ligeti, I.S. Tackmann

In SCET rate is given by simple graphs (not ∞ sets)

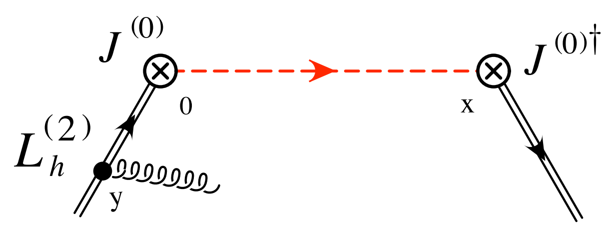
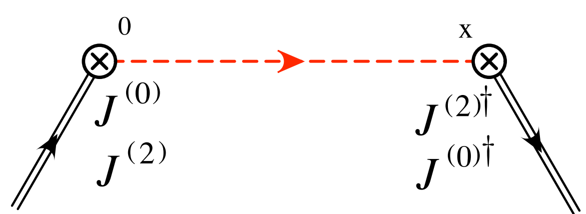
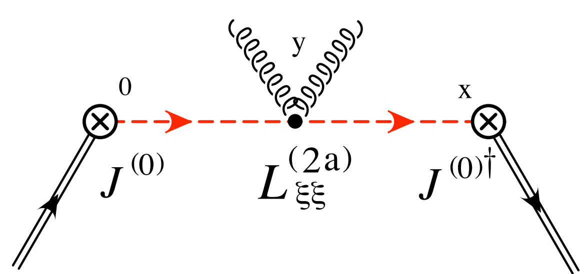
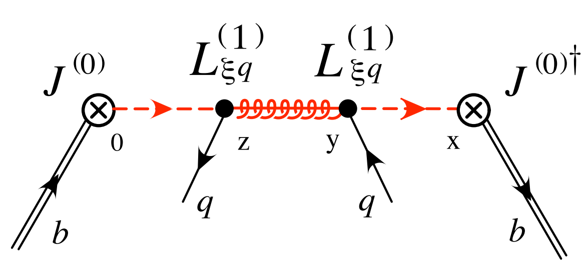
LO

T-product	Example Diagram
$T^{(0)}$	

$$J^{(0)} = \int d\omega\, C(\omega)(\bar{\xi}_n W)_\omega\, \Gamma\, (Y^\dagger h_v)$$

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

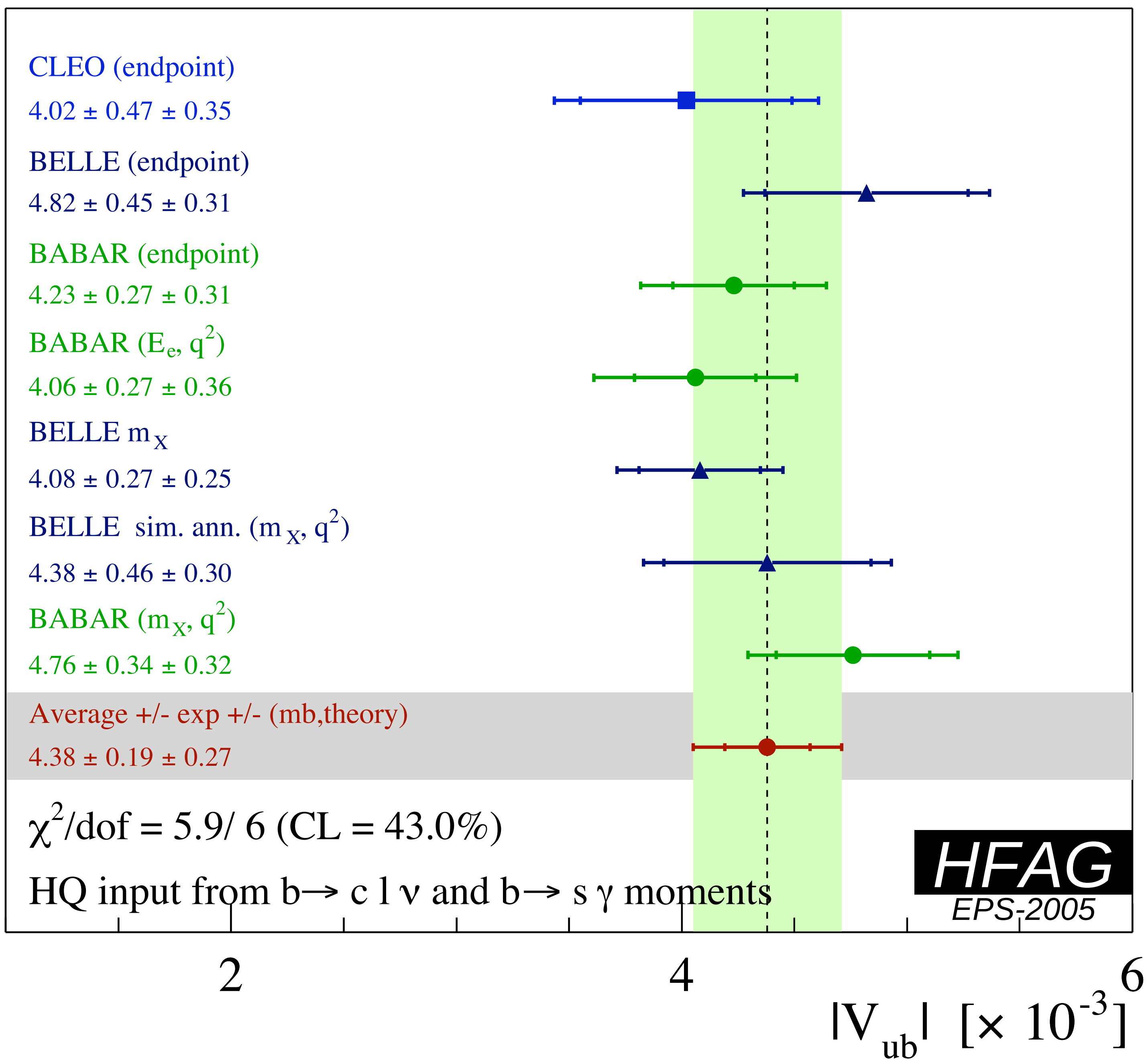
NLO

T-product	Example Diagram
$\hat{T}^{(2H)}$	
$\hat{T}^{(2a)}$	
$\hat{T}^{(2L)}$	
$\hat{T}^{(2q)}$	

$$d\Gamma^{\rm NLO} = \ldots$$

- Event generator for $b \to u$ Neubert, Lange, Paz

$$|V_{ub}|^{\text{incl}} = (4.38 \pm 0.33) \times 10^{-3}$$



M.Morri
Vxb workshop, Jan.06

- $|V_{ub}|$ determined to ±7.6%

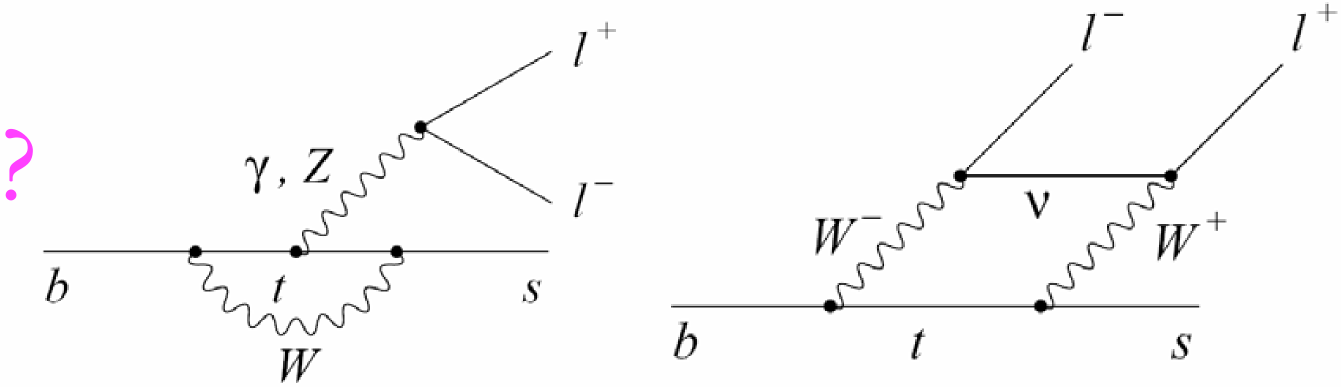
Statistical	±2.2%
Expt. syst.	±2.5%
$b \to c\ell v$ model	±1.9%
$b \to u\ell v$ model	±2.2%
SF params.	±4.7%
Theory	±4.0%

±4.4%

- The SF parameters can be improved with $b \to s\gamma$, $b \to c\ell v$ measurements
- What's the theory error?

$$\boxed{B \to X_s \ell^+ \ell^-}$$

new physics?



- rate depends mostly on

$$O_7 = m_b\, \bar{s}\sigma_{\mu\nu} e F^{\mu\nu} P_R b,$$

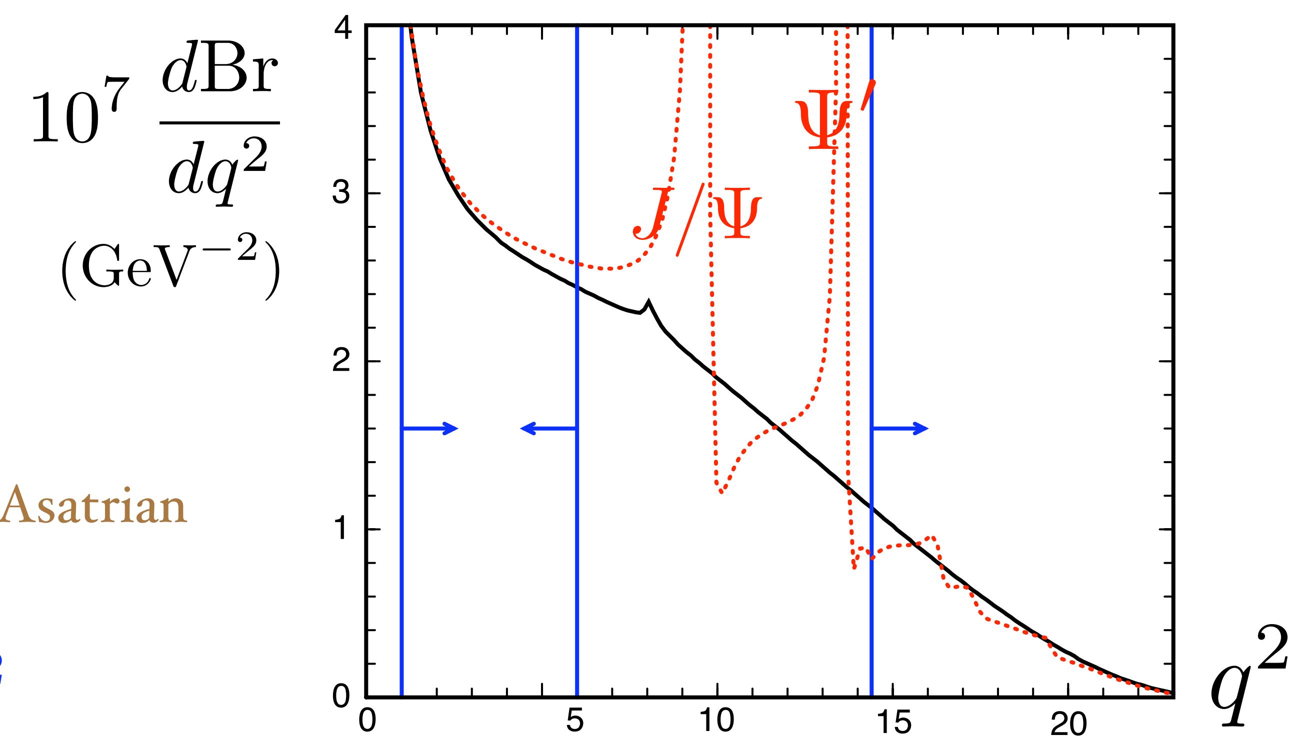
$$O_9 = e^2 (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell),$$

$$O_{10} = e^2 (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

- —— Calculations at NNLL order

Bobeth, Misiak, Urban, Gambino, Gorbahn, Haisch, Asatryan, Asatrian Greub, Walker, Ghinculov, Hurth, Isidori, Yao, ...

most precise for $1\,\mathrm{GeV}^2 \leq q^2 \leq 6\,\mathrm{GeV}^2$



Ghinculov, Hurth, Isidori, Yao

- But, we need additional cuts:

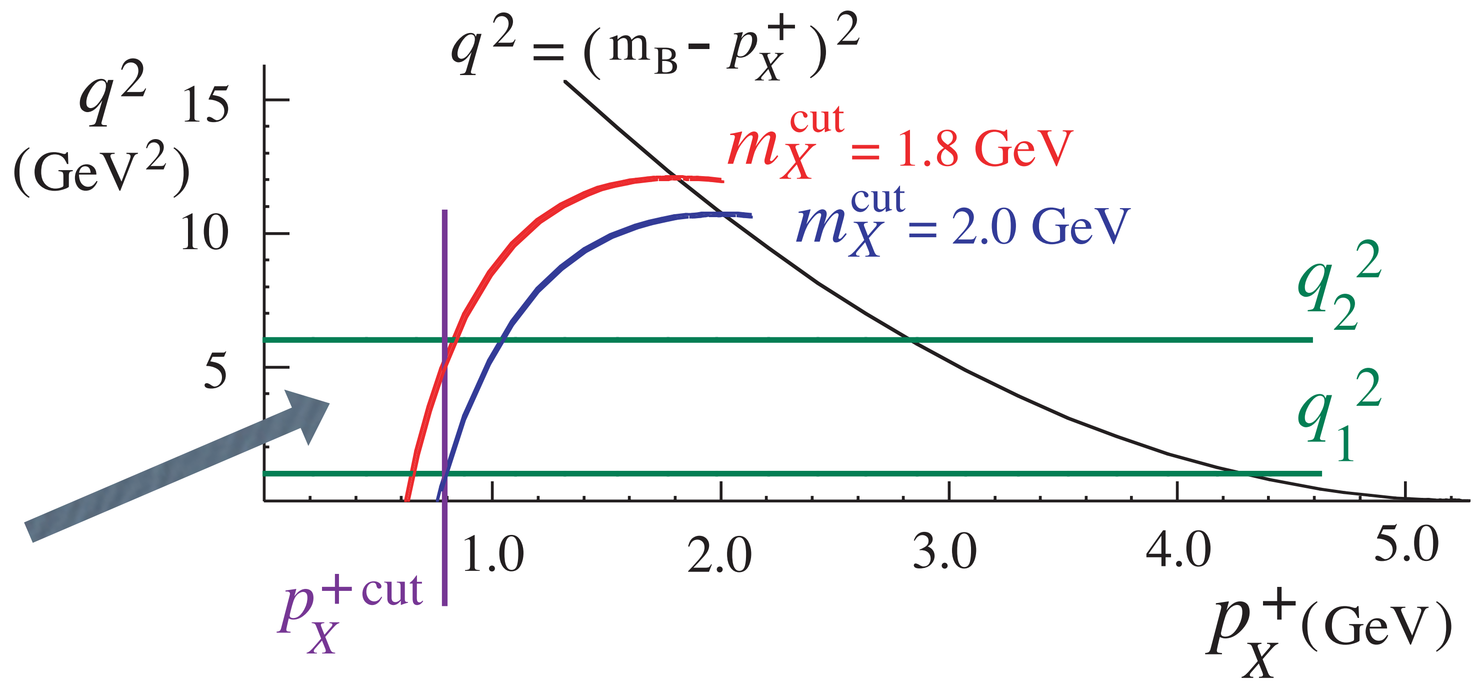
$m_{X_s} \leq 2\,\mathrm{GeV}$ [Belle], $m_{X_s} \leq 1.8\,\mathrm{GeV}$ [Babar]

to remove

$$b \to c(\to s e^+ \nu)\, e^- \bar{\nu} = b \to s e^+ e^- + \text{missing energy}$$

These cuts put us in the shape function region (with same J, f)*

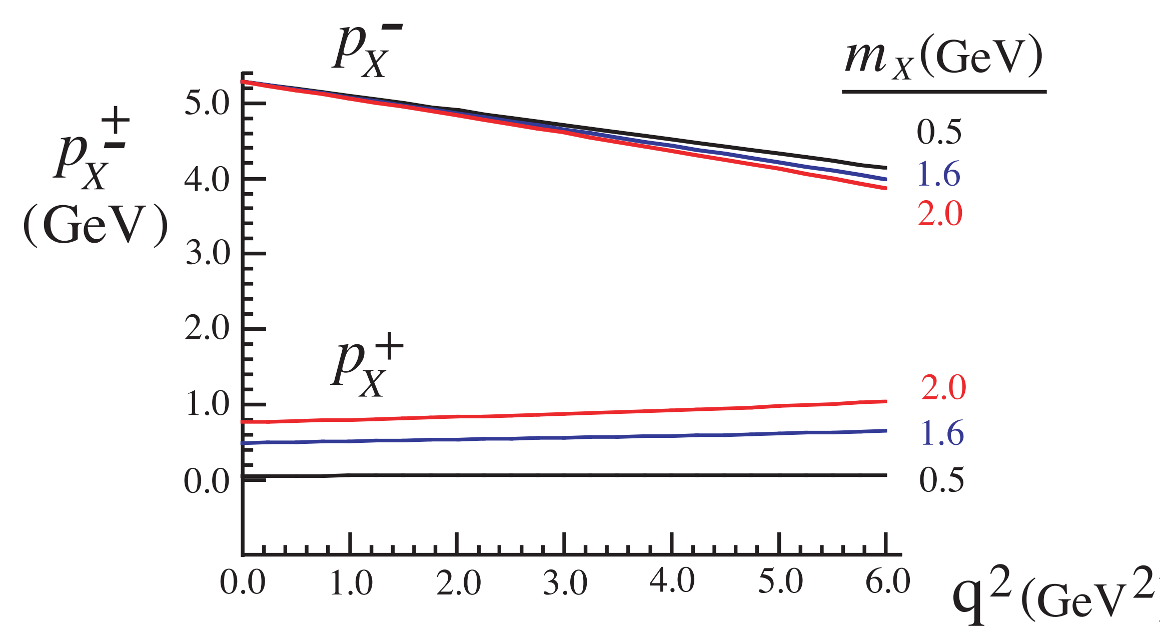
Kinematics



$$2m_B E_X = m_B^2 + m_X^2 - q^2$$

$$E_X^2 \gg m_X^2 \Rightarrow p_X \text{ near light-cone}$$

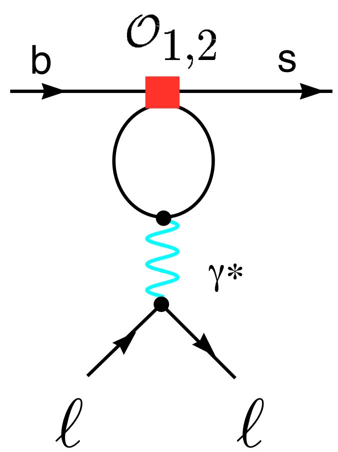
$$p_X^- \sim m_B \quad \gg \quad p_X^+ \sim \Lambda_{\rm QCD}$$



Perturbative Counting

- usual counting expands $\langle s\ell^+\ell^-|C_9 O_9 + C_{10} O_{10} + \ldots |b\rangle$

  in α_s with $\alpha_s \ln(m_W/m_b) = \mathcal{O}(1)$



$C_9 \sim 1/\alpha_s$

$C_{7,10} \sim 1$

but $|C_9(m_b)| \sim C_{10}$

- in shape function region only $\Gamma_{ij} \sim \mathrm{Im}\langle B|T\, O_i^\dagger(x) O_j(0)|B\rangle$
  makes sense

  BUT don't want $\langle B|O_9^\dagger O_9|B\rangle \sim 1/\alpha_s^2$, $\langle B|O_{10}^\dagger O_{10}|B\rangle \sim 1$

  Want $\Gamma_{ij} \sim 1$

Split Matching

Lee & I.S.

- Organize the rate as a product of μ–independent pieces:

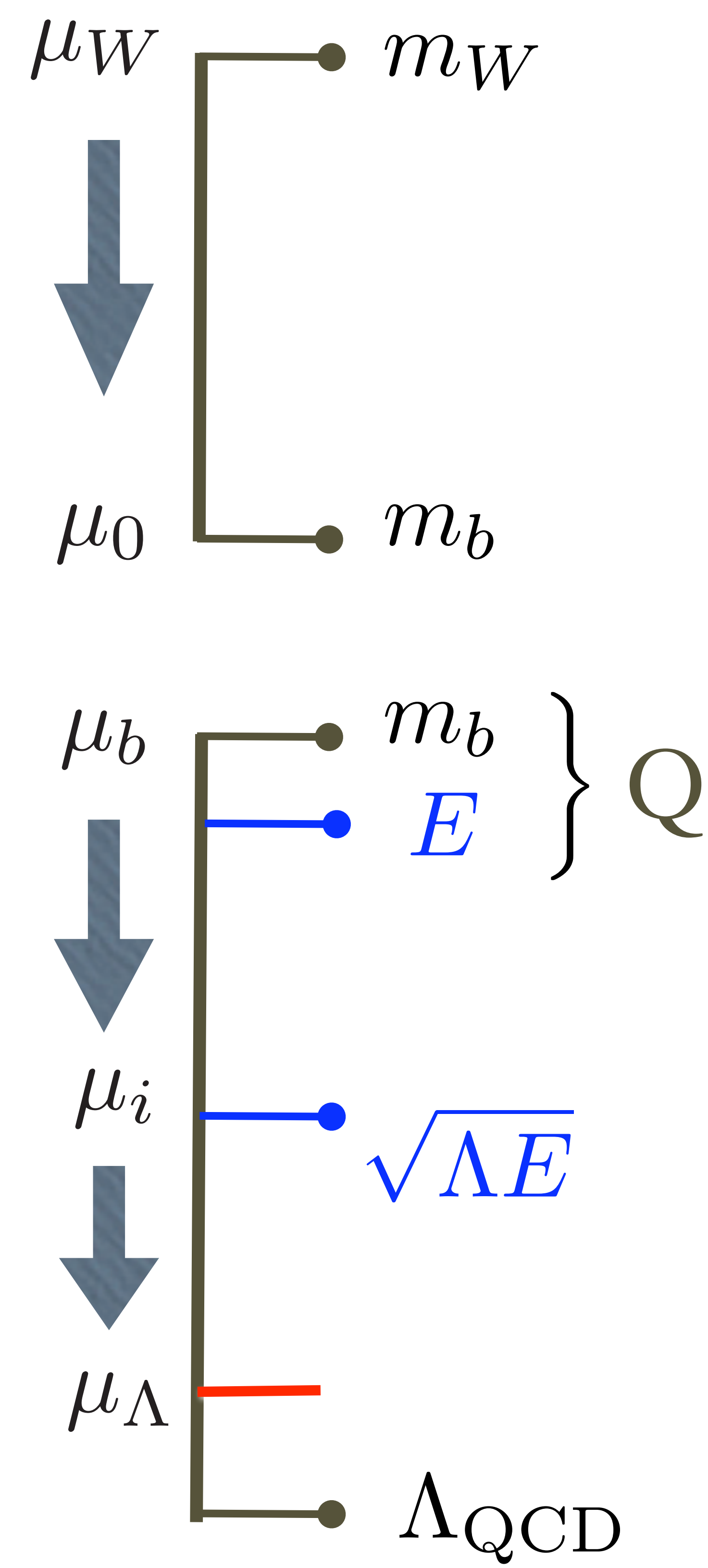
$$d\Gamma = \Big[A(\mu_W,\mu_0)\Big]\Big[B(\mu_b,\mu_i,\mu_\Lambda)\Big]$$

& organize perturbation theory differently for A, B

- * A strange fact about $B \to X_s \ell^+ \ell^-$:

as long as q^2 is not parametrically small in power counting, the factorization is the same as at $q^2 = 0$

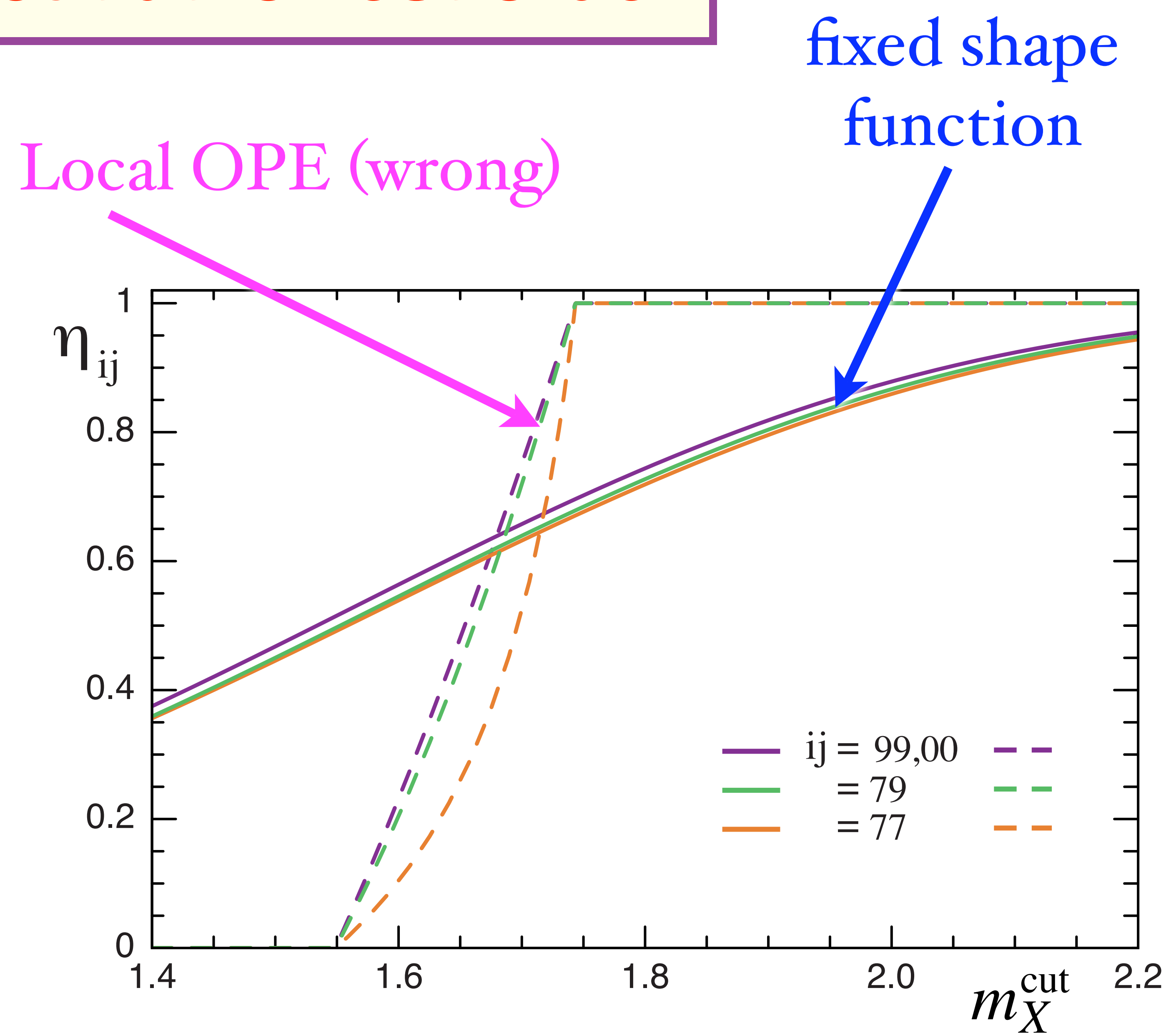
$$J^{(0)} = \int d\omega\, C(\omega)(\bar{\xi}_n W)_\omega \Gamma\, (Y^\dagger h_v)\;\; (\bar{\ell}\Gamma'\ell)$$



Effects of m_X cut at lowest order

Define

$$\eta_{ij} = \frac{\int_{1\,\mathrm{GeV}^2}^{6\,\mathrm{GeV}^2} dq^2 \int_0^{m_X^{\rm cut}} dm_X^2 \,\frac{d\Gamma_{ij}}{dq^2\, dm_X^2}}{\int_{1\,\mathrm{GeV}^2}^{6\,\mathrm{GeV}^2} dq^2 \,\frac{d\Gamma_{ij}}{dq^2}}$$



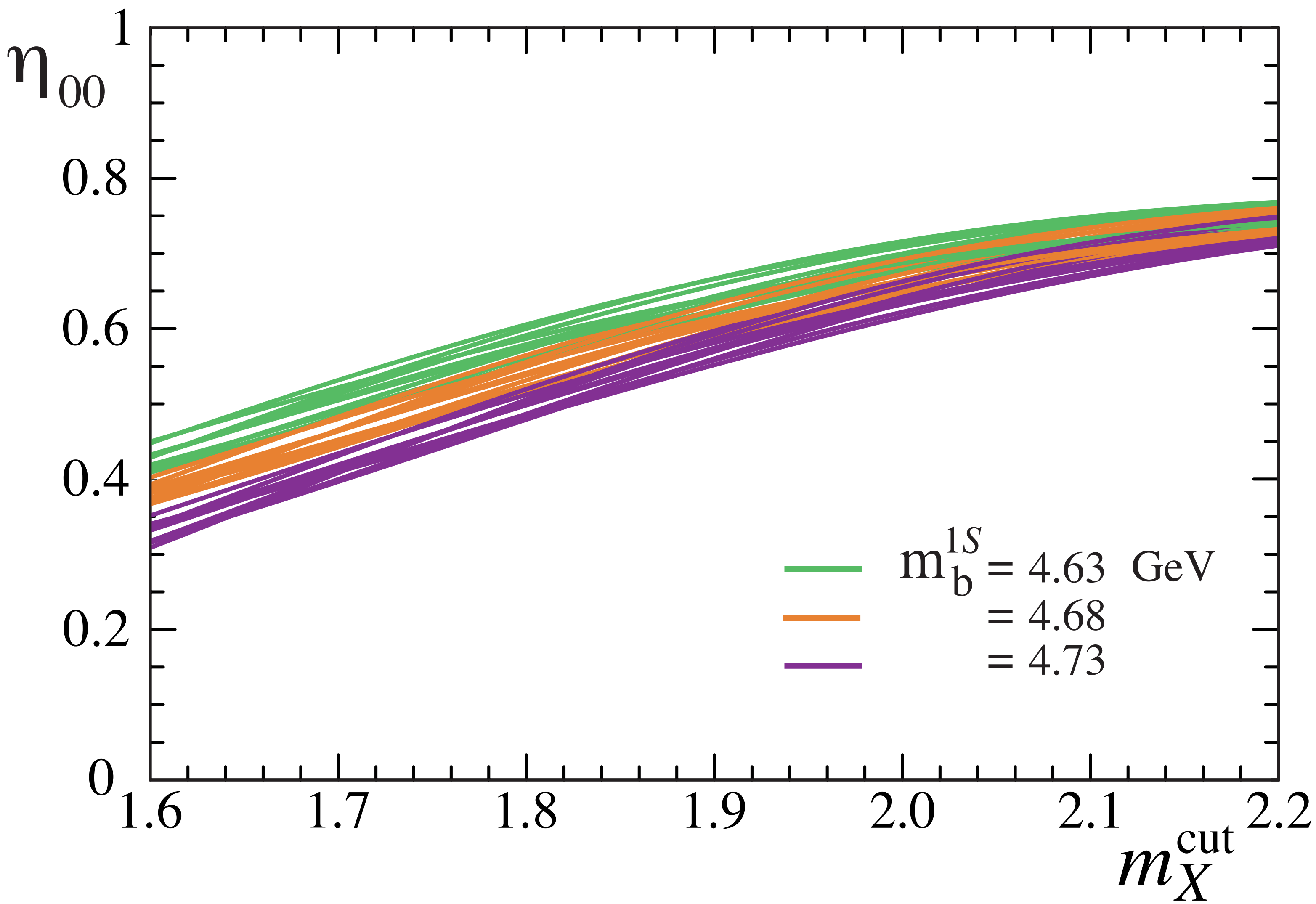
- **Strong** $m_X^{\rm cut}$ dependence

- **Universality**, $\eta_{ij} = \eta$

  since shape function varies rapidly, as p_X^+/Λ
  prefactors in $d\Gamma_{ij}$ vary slowly, as p_X^+/m_B

Including NLL corrections

- Universality maintained to 3%
- Estimate shape function uncertainties using $B \to X_s\gamma$:



10 models for each m_b^{1S}

at $m_X^{\rm cut} = 2.0\,{\rm GeV}$:

$3.5\,{\rm GeV} < \mu_b < 7.5\,{\rm GeV}$

$\eta_{00} \sim \pm 6\%$

$2\,{\rm GeV} < \mu_i < 3\,{\rm GeV}$

$\eta_{00} \sim \pm 5\%$

overall

$\simeq$ 10% uncertainty in η_{00}

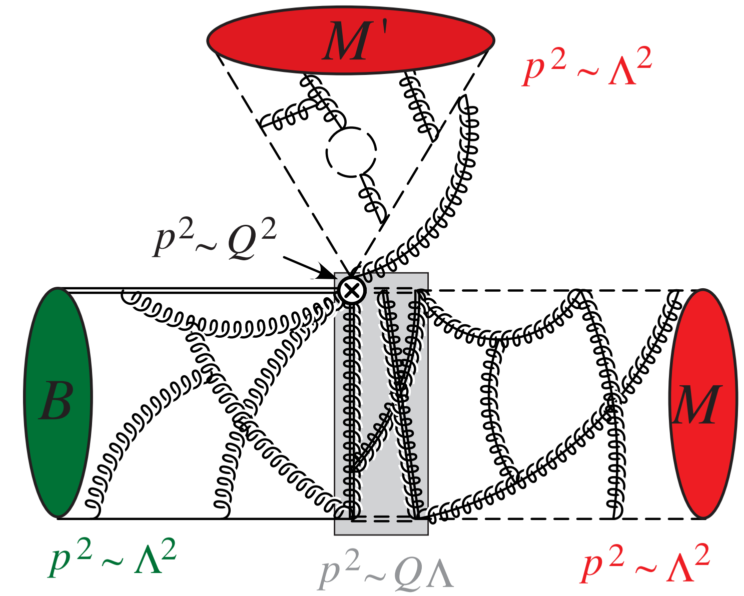
NNLL reduces μ-dependence, effect on q^2 spectrum small $\Rightarrow \eta^{(\rm NLL)} \approx \eta^{(\rm NNLL)}$

- Alternatively, could take $m_X^{\rm cut} < m_D$ and normalize with respect to $b \to u$ with same cuts

$$B \to \pi\pi\,,\;\; B \to \pi\ell\bar{\nu}$$

$$\&\quad |V_{ub}|$$

Factorization (with SCET)



Factorization at m_b

Bauer, Pirjol, Rothstein, I.S.
(BBNS; Chay,Kim)

Nonleptonic $B \to M_1 M_2$

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

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

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

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

universality at $E\Lambda$

Factorization at $\sqrt{E\Lambda}$

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

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

$\zeta^{BM} = ?$ (left as a form factor)

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

Use nonleptonic data: $B \to \pi\pi$

$$\boxed{|V_{ub}| f_+(0) = F(S_{\pi^+\pi^-}, C_{\pi^+\pi^-}, Br(\pi^+\pi^-), Br(\pi^0\pi^-), \beta, \gamma, V_{ud}) \;\; \Big[1 + \mathcal{O}\Big(\alpha_s(m_b)\,, \frac{\Lambda_{\rm QCD}}{E}\Big)\Big]}$$

- Uses data instead of hadronic parameters (remove complex penguin amplitude, and color suppressed amplitude)

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

$$|V_{ub}| f_+(0) = \left[\frac{64\pi}{m_B^3 f_\pi^2}\, \frac{\overline{B}r(B^- \to \pi^0\pi^-)}{\tau_{B^-} |V_{ud}|^2 G_F^2}\right]^{1/2} \times \left[\frac{(C_1+C_2)t_c - C_2}{C_1^2 - C_2^2}\right] \left[1 + \mathcal{O}\Big(\alpha_s(m_b), \frac{\Lambda_{\rm QCD}}{m_b}\Big)\right],$$

$$t_c = \frac{|T_{\pi\pi}|}{|T_{\pi\pi} + C_{\pi\pi}|}$$

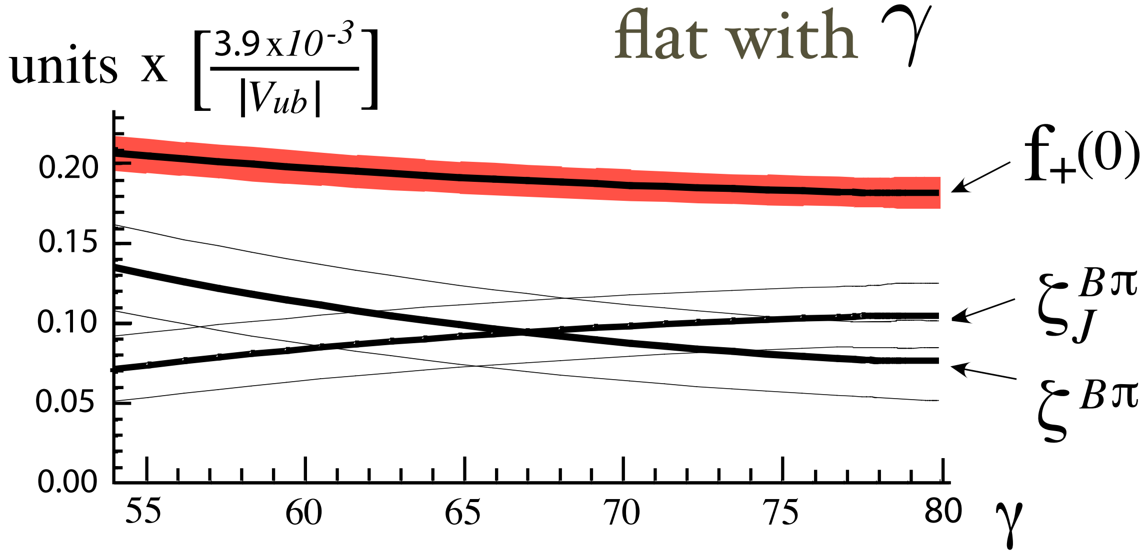
$$t_c = \sqrt{\overline{R}_c \,\frac{(1 + B_{\pi^+\pi^-} \cos 2\beta + S_{\pi^+\pi^-} \sin 2\beta)}{2\sin^2\gamma}}$$

$$\overline{R}_c = \frac{Br(B^0 \to \pi^+\pi^-)\tau_{B^-}}{2Br(B^- \to \pi^0\pi^-)\tau_{B^0}}$$

$$B_{\pi^+\pi^-} = \sqrt{1 - C^2_{\pi^+\pi^-} - S^2_{\pi^+\pi^-}}$$

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

flat with γ



Current Data

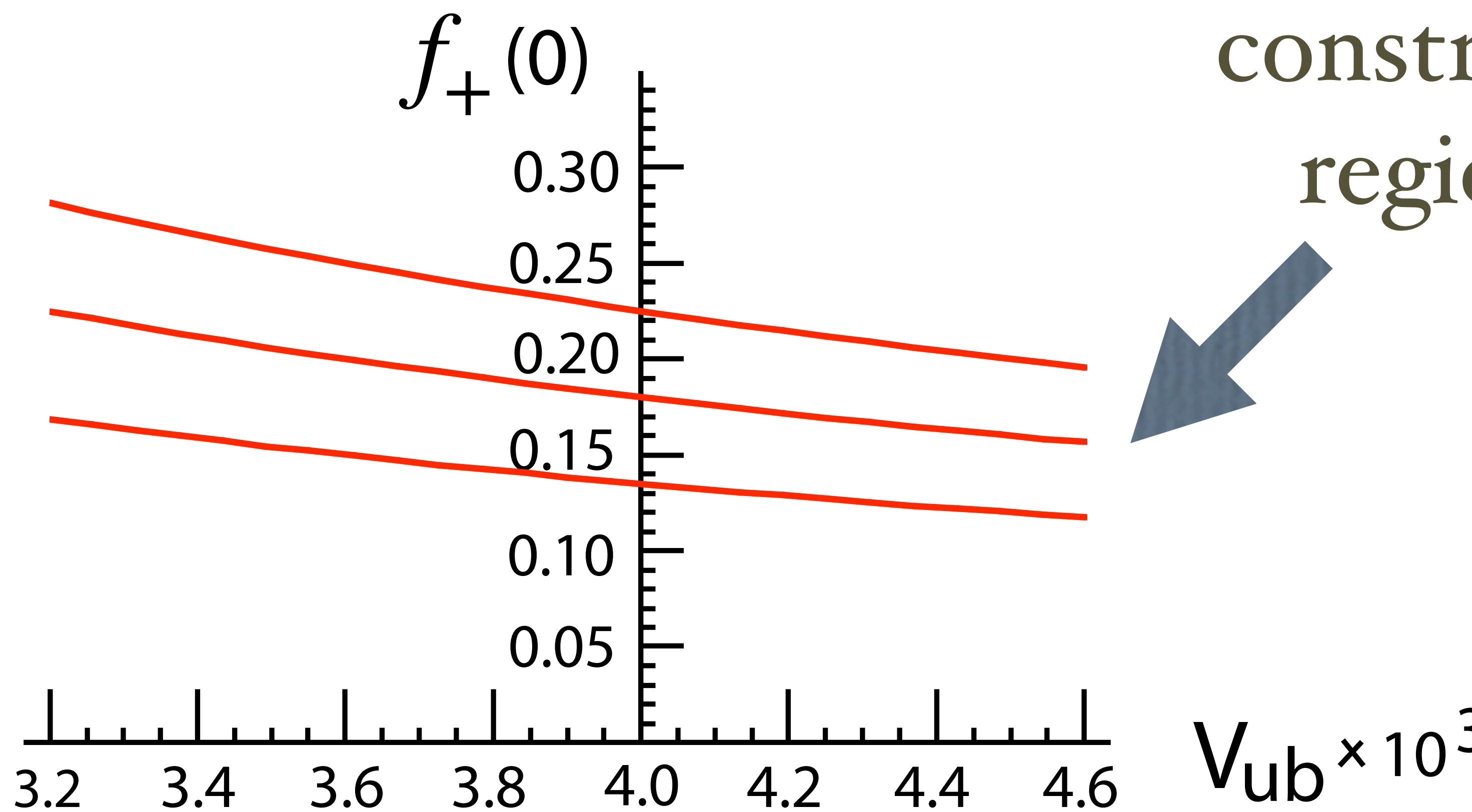
$$f_+(0) = (0.18 \pm 0.01 \pm 0.04)\left(\frac{3.9\times 10^{-3}}{|V_{ub}|}\right)$$

expt. theory

$$|V_{ub}|f_+(0) = (7.2 \pm 1.8)\times 10^{-4}$$

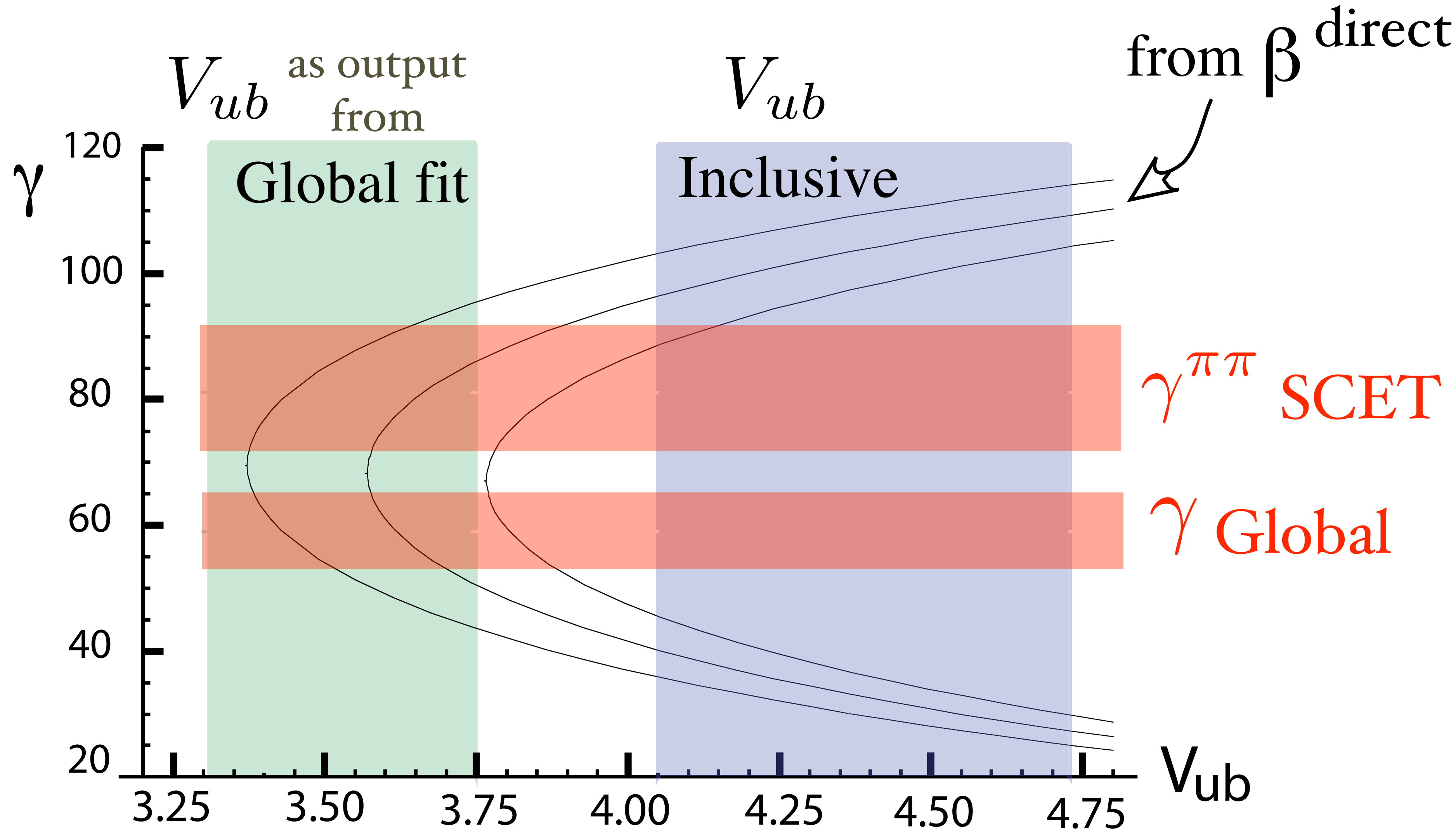
dominated by theory, estimate:
$\sim 25\%$ from perturbative
and power corrections

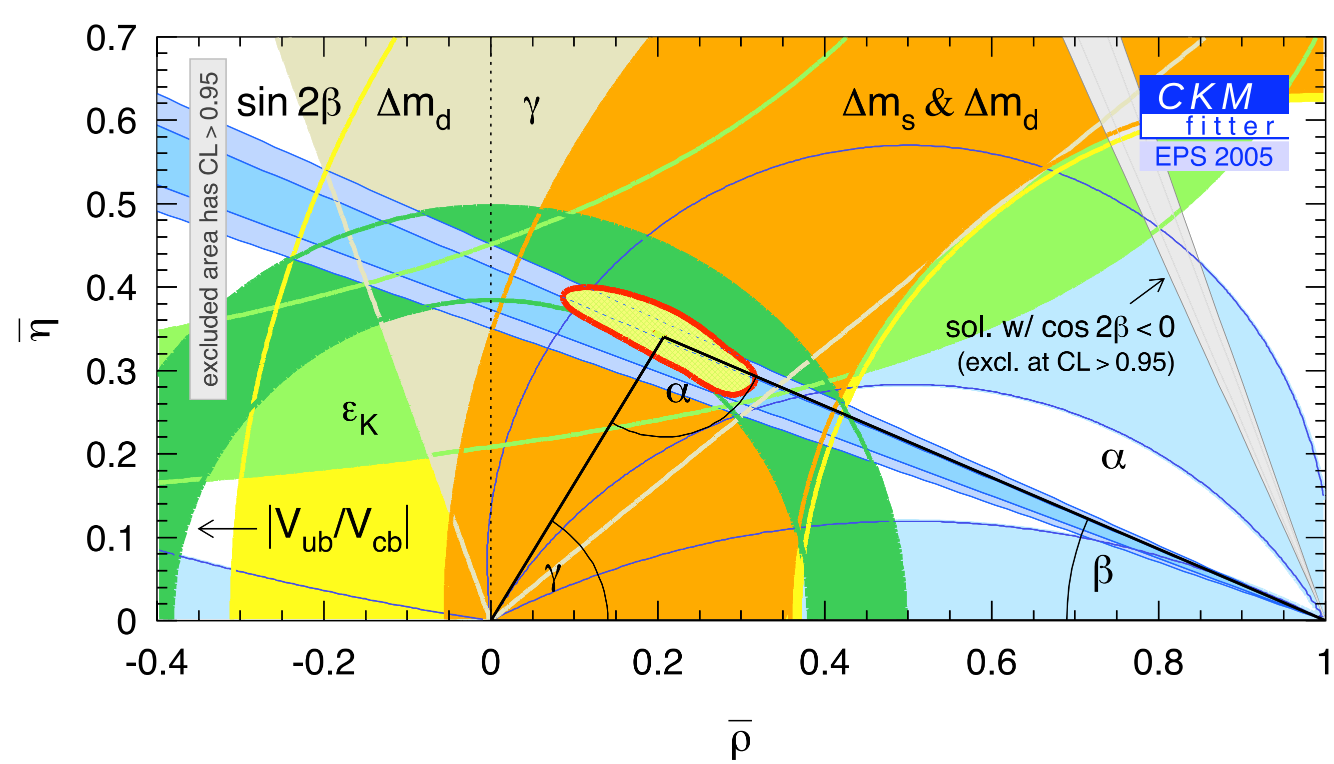
nonleptonic
constraint
region

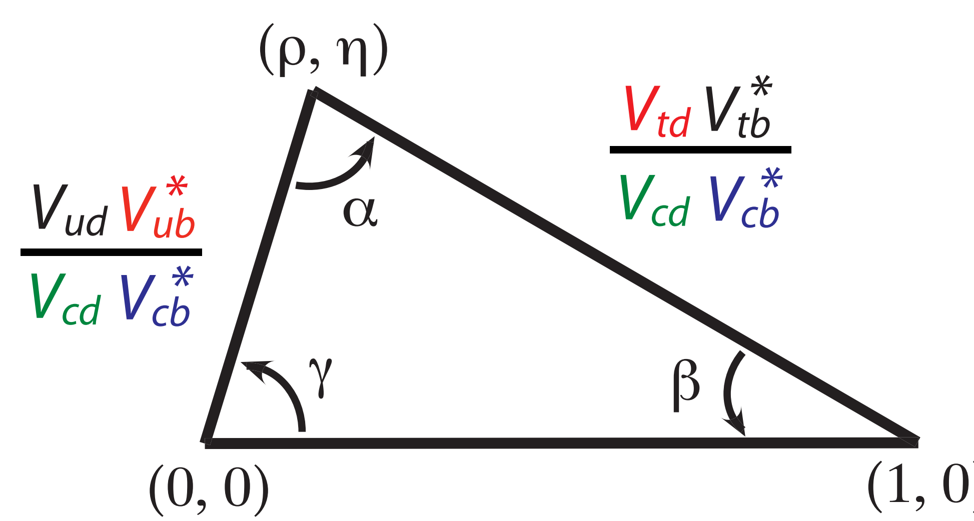


Which Vub?

Tension with $\sin(2\beta)$?

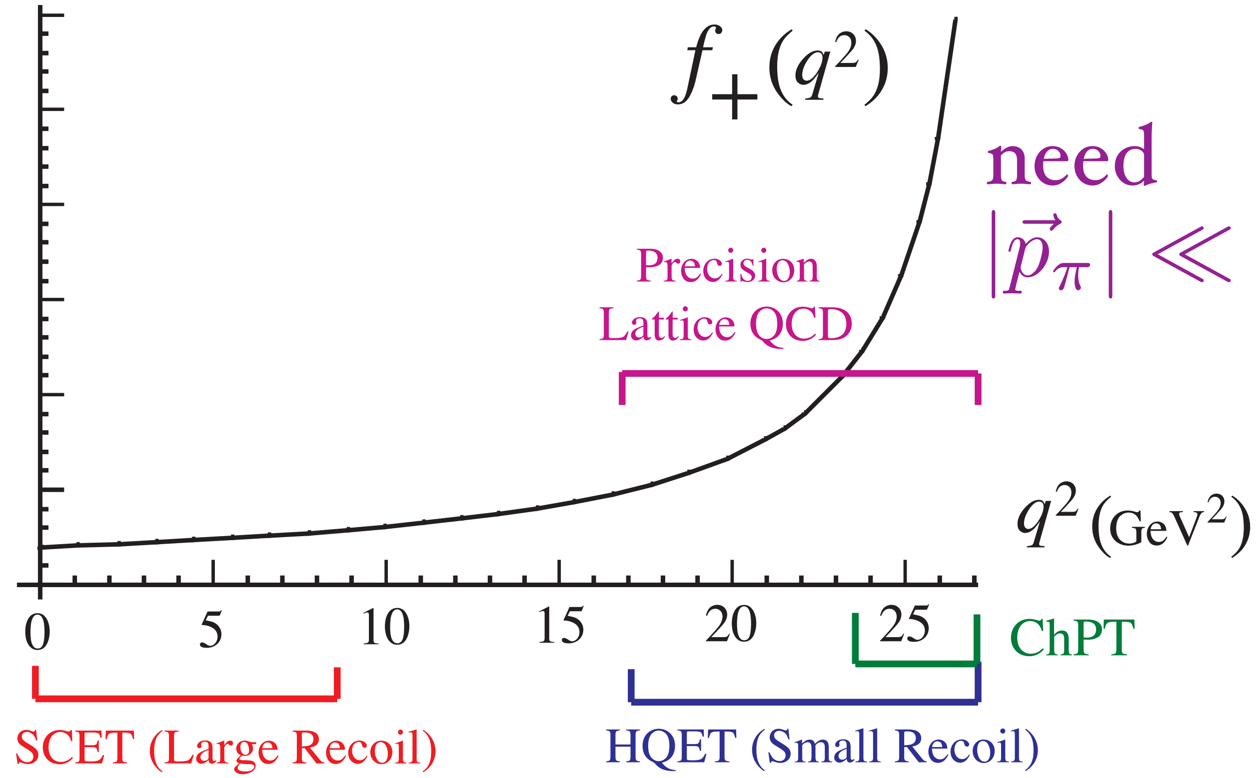




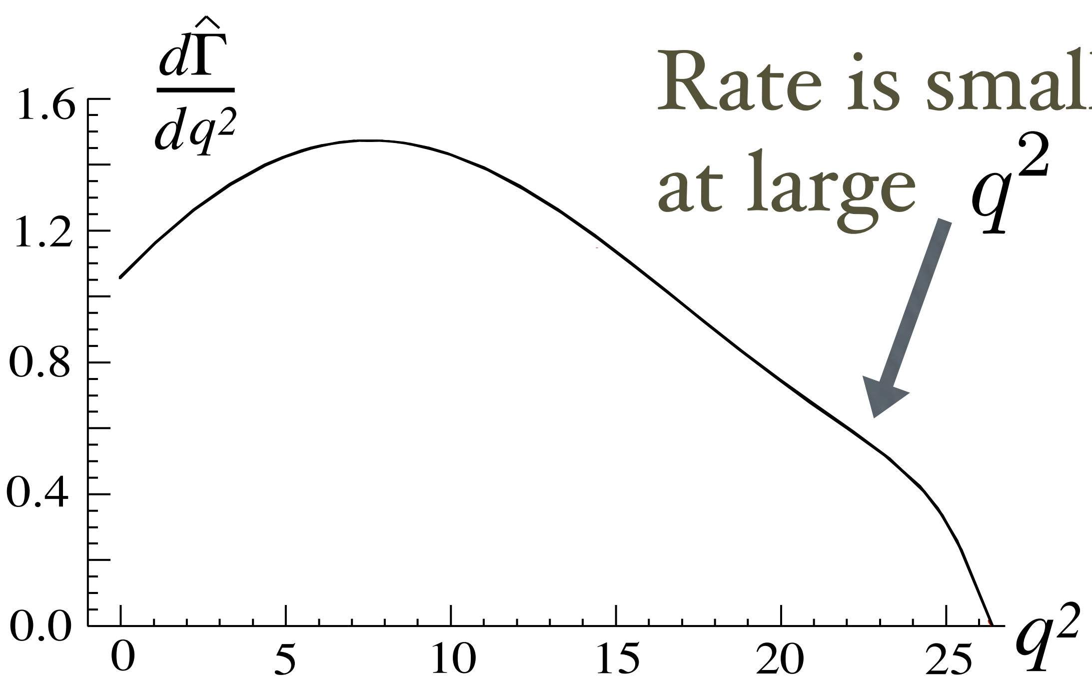


V_{ub}

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

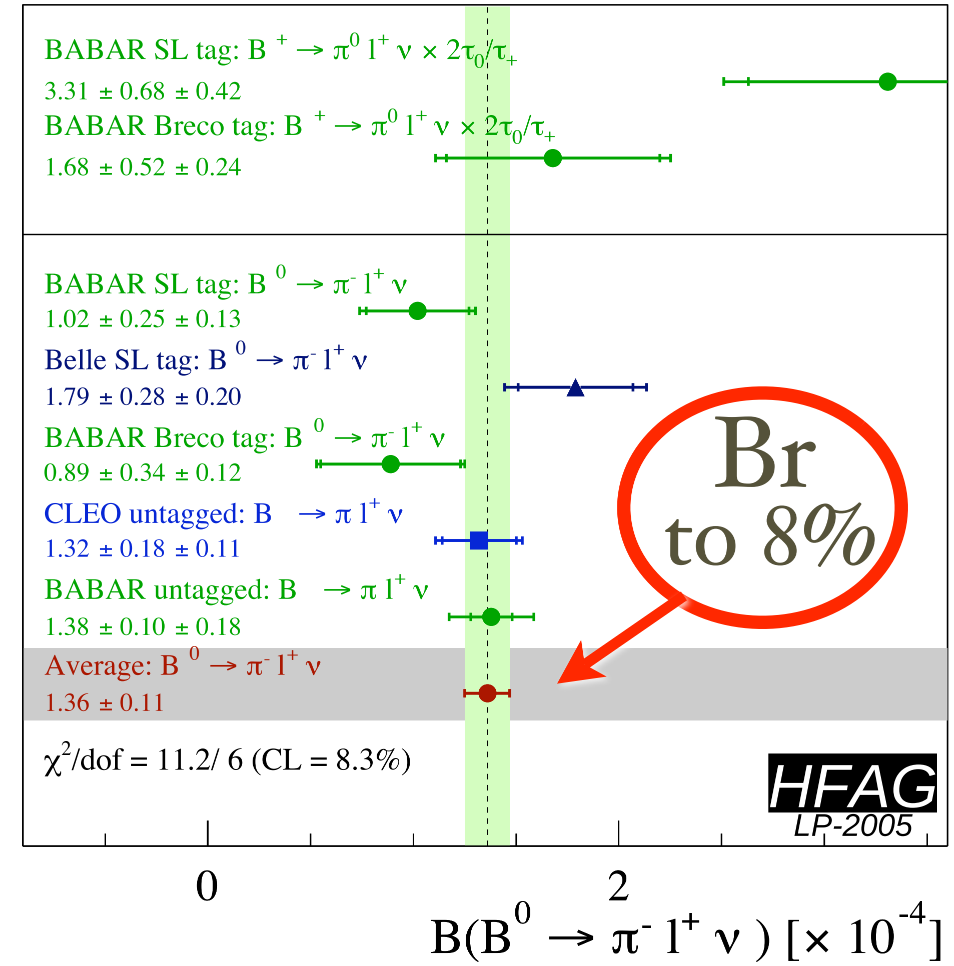


need $|\vec{p}_\pi| \ll 1/a$



Rate is smaller at large q^2

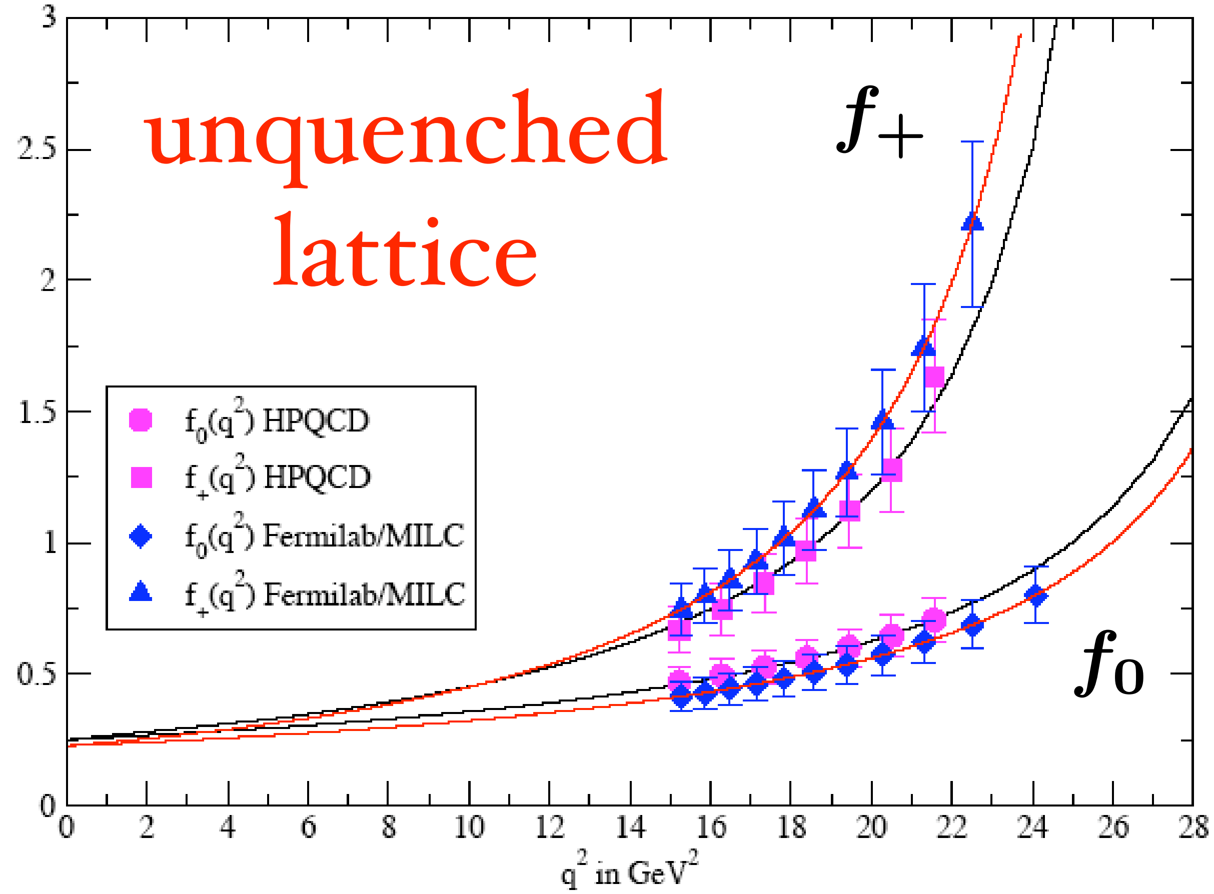
Average from Cleo, Belle, Babar:



$\Rightarrow$ $|V_{ub}|$ to 4% !?!

Uncertainty from theory dominates.

$$\frac{d\Gamma(\bar{B}^0 \to \pi^+ \ell \bar{\nu})}{dq^2} = \frac{G_F^2 |\vec{p}_\pi|^3}{24\pi^3} |V_{ub}|^2 \, |f_+(q^2)|^2$$



statistics
4-6%

Systematics	HPQCD errors
perturbative matching	9%
chiral extrapolation	4%
action discretization	2%
matching $a, 1/m_Q$	5%
Total	11%

$q^2 \geq 16\,\mathrm{GeV}^2$

statistics
$\sim 8\%$

Systematics	Fermilab/ MILC errors
matching	1%
chiral extrapolation	4%
q^2 interp.	4%
finite a	9%
Total	11%

HFAG expt. theory

$$10^3\times\,|V_{ub}| = 3.75 \pm 0.27^{+0.64}_{-0.42}$$ FNAL

$$10^3\times\,|V_{ub}| = 4.45 \pm 0.32^{+0.69}_{-0.47}$$ HPQCD

My LP'05 Average for this method:

$$10^3\times\,|V_{ub}| = 4.1 \pm 0.32^{+0.69}_{-0.47}$$

16%
total error

Lattice & QCD Dispersion Relations

Bourrely et al.,
Boyd, Grinstein, Lebed, Savage;
Lellouch; Fukunaga, Onogi;

Arnesen, Grinstein, Rothstein, I.S.

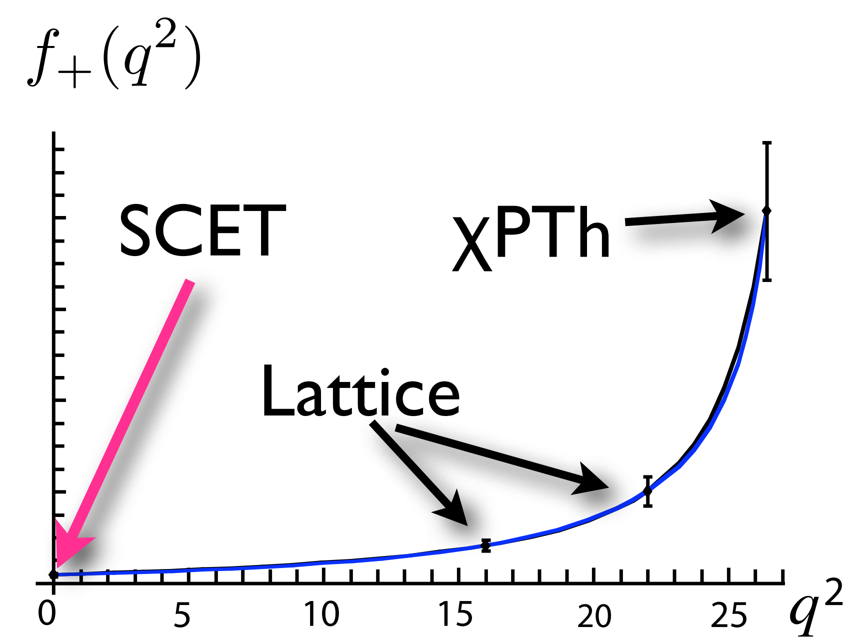
Focus on Vub determination, use:

i) Lattice qcd results at large q^2

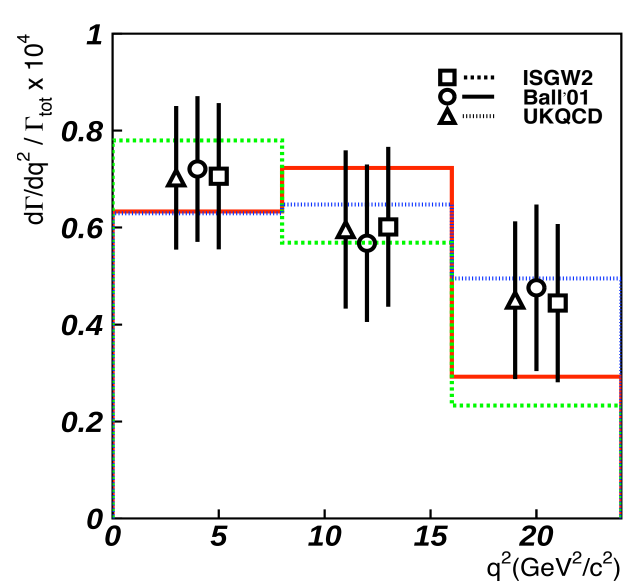
ii) chiral perturbation theory at $q^2_{\rm max}$

iii) expt. spectra for information at low q^2
& SCET constraint from $B \to \pi\pi$ at $q^2 = 0$

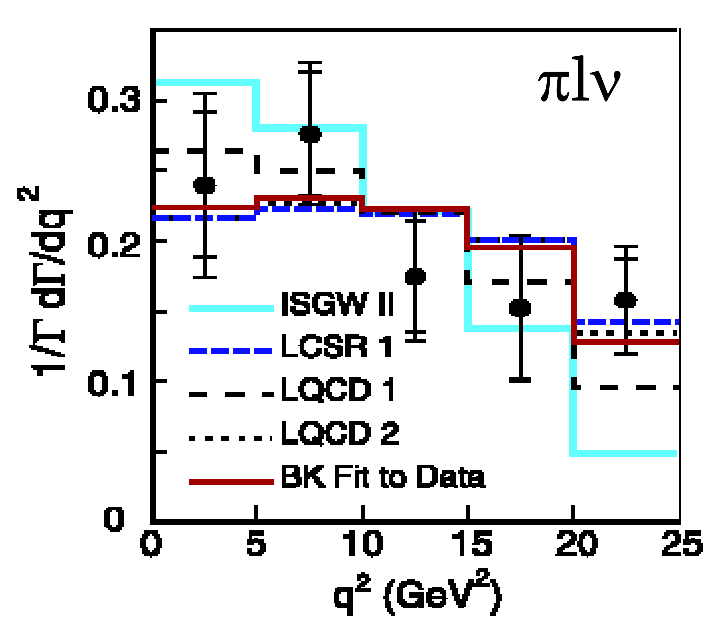
iv) QCD dispersion relations to constrain the form factors shape (model independent)



Belle



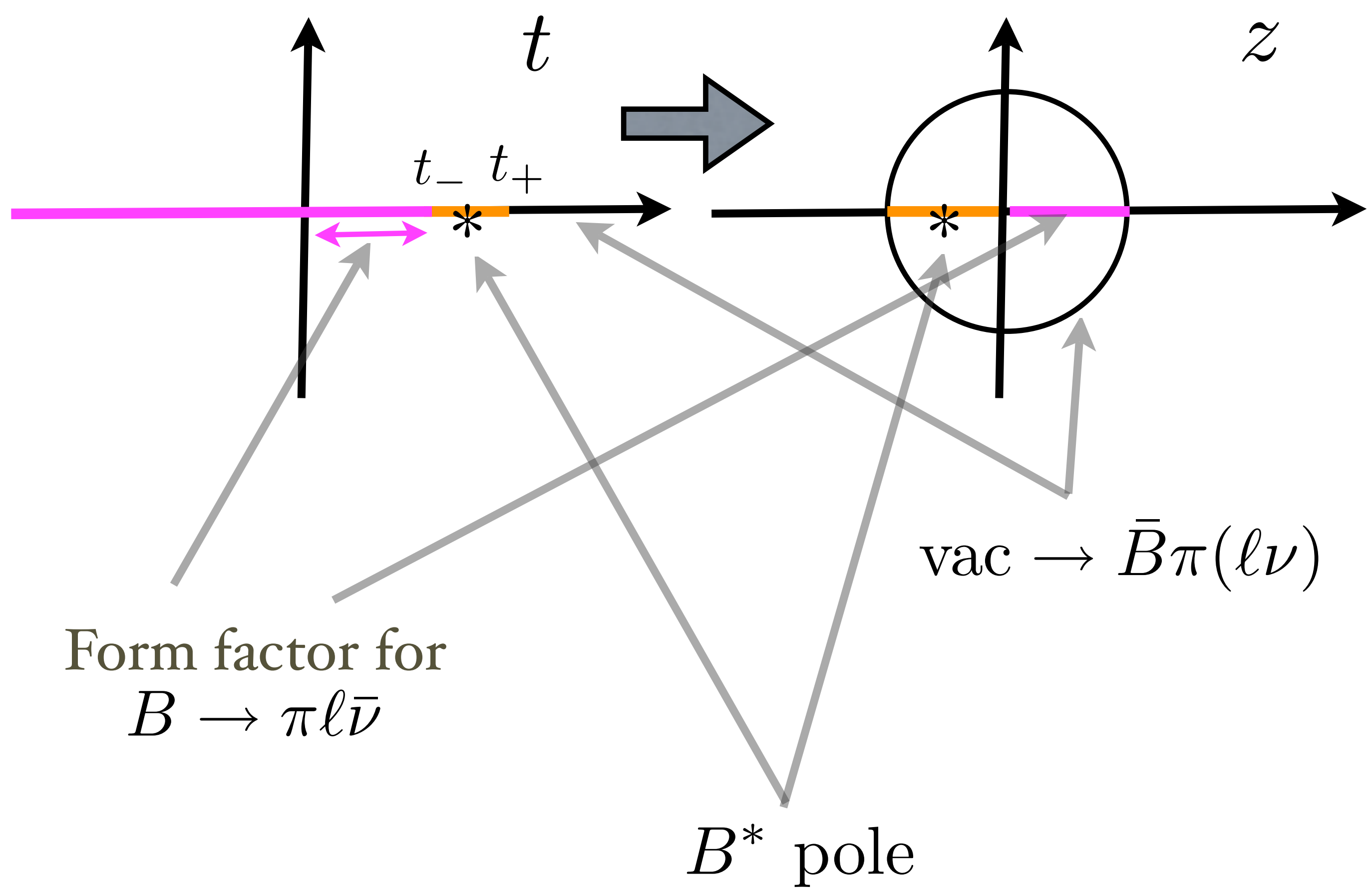
Babar



Complex Magic

$$z(t,t_0) = \frac{\sqrt{t_+ - t} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - t} + \sqrt{t_+ - t_0}}$$

$$t_\pm = (m_B \pm m_\pi)^2$$



$$P(t)\phi(t)f(t) = \sum_{n=0}^{\infty} a_n\, z^n$$

Blaschke Factor: remove pole at $t = m_{B^*}^2$

Outer function: phase space, Jacobian, $\chi^{(0)}$ in QCD

$t = q^2$

$$\boxed{f_+(t) = \frac{1}{P(t)\phi(t)} \sum_{n=0}^{\infty} a_n\, z^n}$$

$$\sum_n a_n^2 \leq 1$$

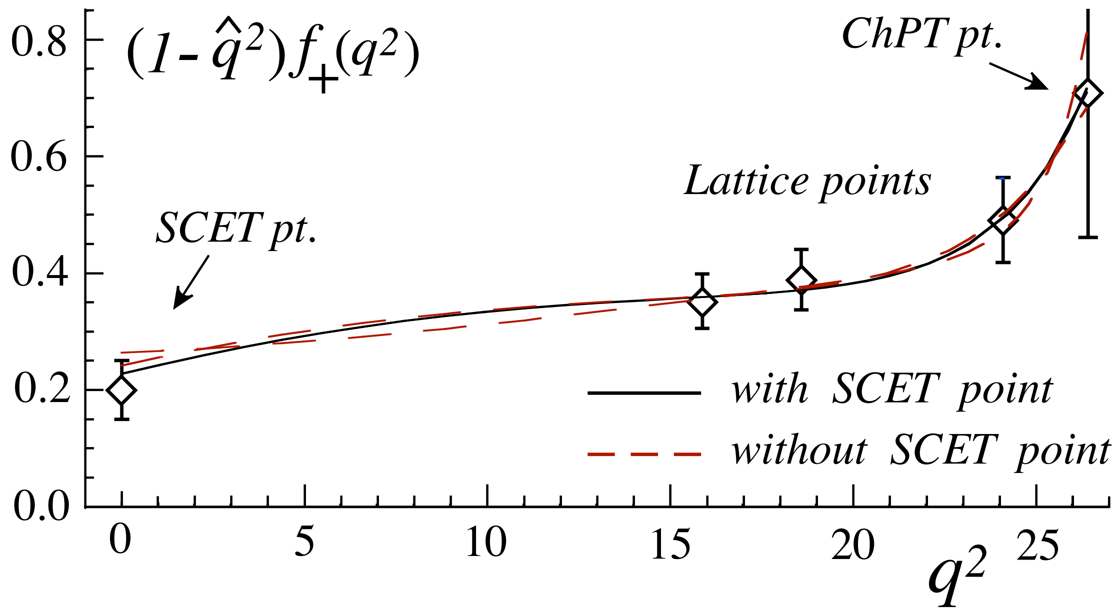
Pick $t_0 = 0.65\, t_-$ then

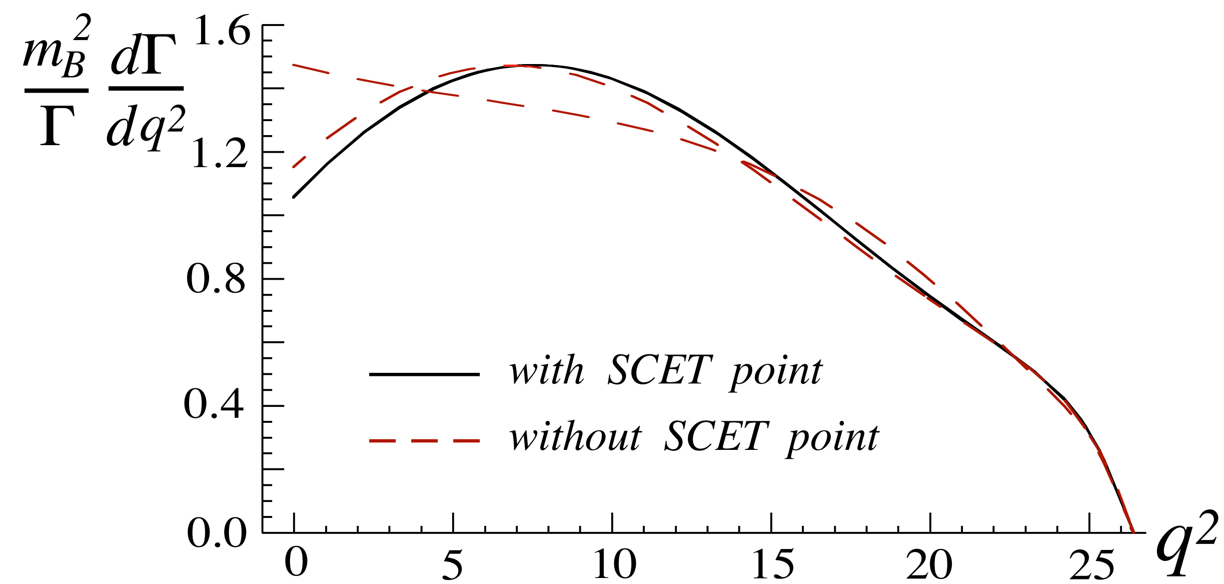
$$-0.34 \leq z \leq 0.22$$

from dispersion

Strategy: use input points to fix first few a's
vary all higher a's to determine uncertainty

Fit to expt. spectra & input points





- expt. spectrum prefers a larger form factor in $\sim$ 5–10 GeV^2 region
- Here the SCET point constrains the spectrum, but does not change the determination of Vub

Type of Error	Variation From	$\delta\lvert V_{ub}\rvert^{q^2}$
Input Points	1-σ correlated errors	$\pm 13\%$
Bounds	F_+ versus F_-	$< 1\%$
$m_b^{\rm pole}$	4.88 ± 0.40	$< 1\%$
OPE order	2 loop $\rightarrow$ 1 loop	$< 1\%$

Fit gives:

no SCET: $f_+(0) = 0.25 \pm 0.06$

similar to sum-rules

with SCET: $f_+(0) = 0.23 \pm 0.05$

χ^2 fits to data & input pts. with dispersion relations

Lepton Photon '05

(without SCET point)

$$\chi^2/(dof) \sim 1.0$$

expt. & theory

$$10^3 \times |V_{ub}| = 3.72 \pm 0.52 \quad \text{FNAL}$$

$$10^3 \times |V_{ub}| = 4.11 \pm 0.52 \quad \text{HPQCD}$$

My Average for this method:

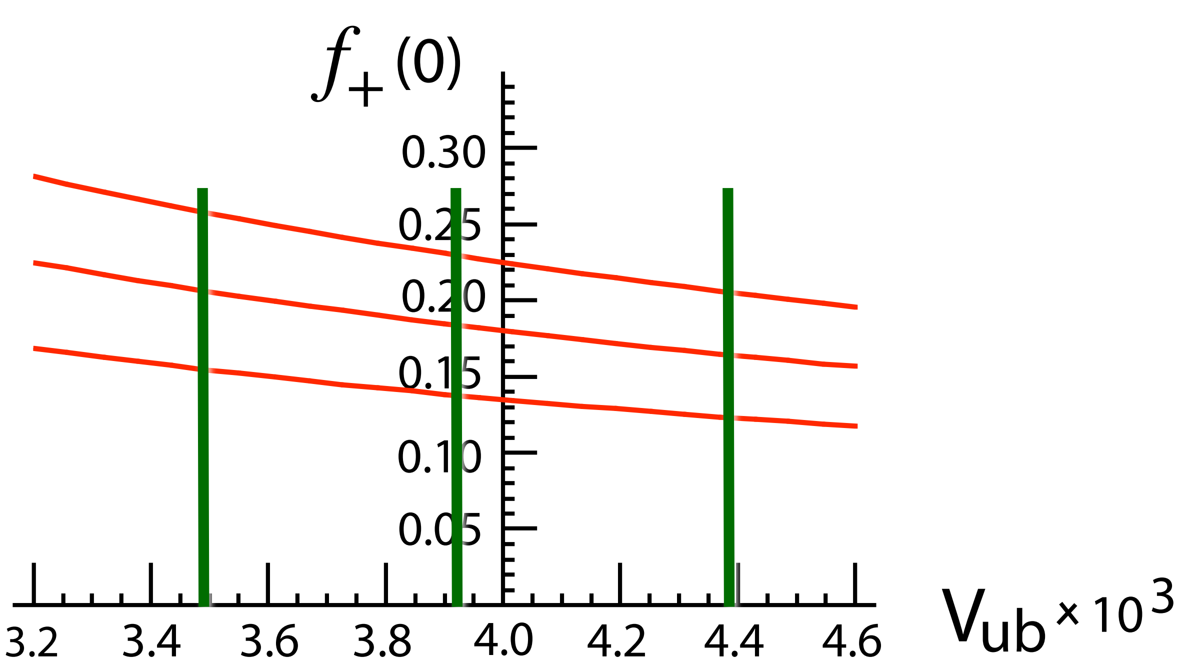
$$\boxed{10^3 \times |V_{ub}| = 3.92 \pm 0.52}$$

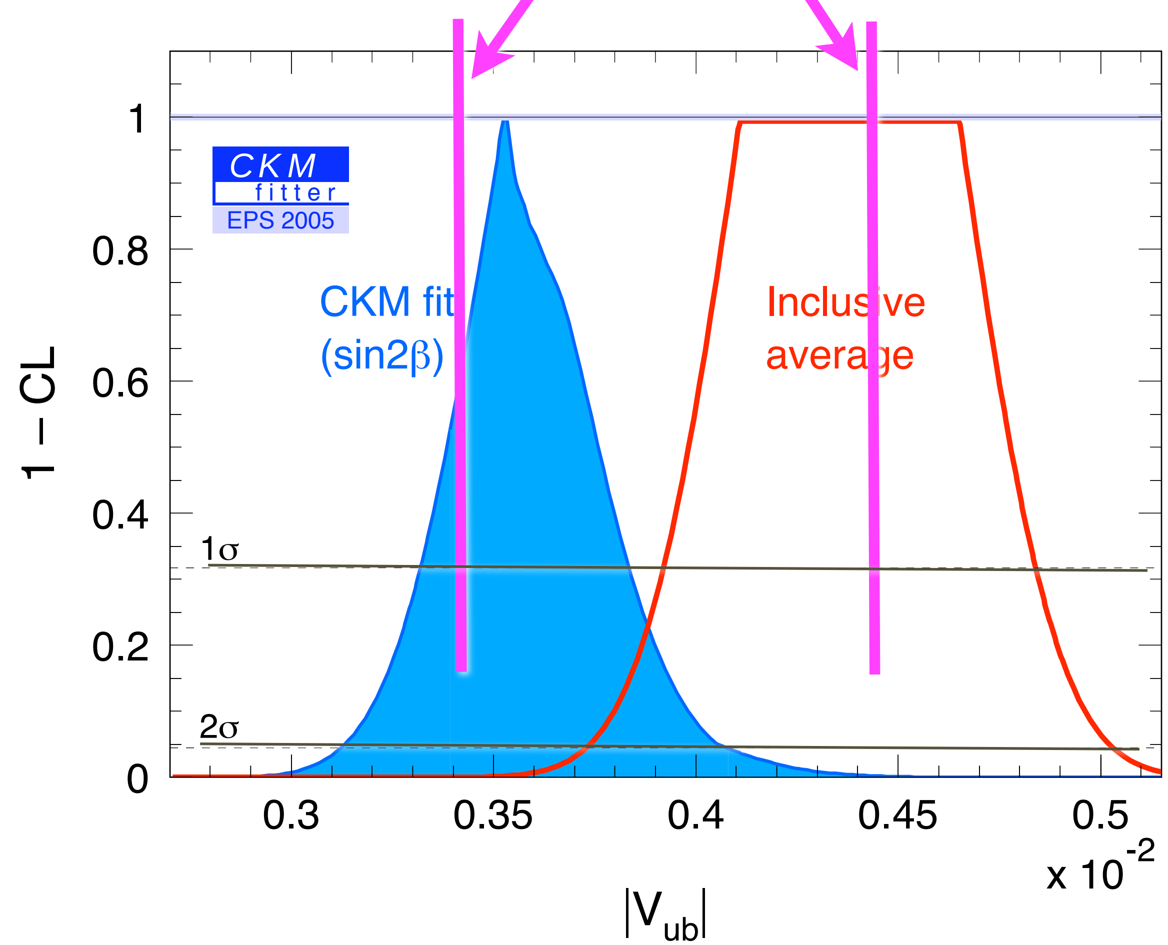
13% total error (4% expt.)

This includes the information in the pure lattice method

Compare Vub's

- $|V_{ub}|^{\rm incl} = (4.38 \pm 0.33) \times 10^{-3}$ (HFAG - EPS'05)
- $|V_{ub}|^{\text{treated as output}}_{\text{in global CKM}} = (3.53^{+0.22}_{-0.21}) \times 10^{-3}$ (CKMfitter)
- $|V_{ub}|^{\rm excl} = (3.92 \pm 0.52) \times 10^{-3}$ (Lattice + Disp. Analysis + Expt. spectrum)





In our analysis the errors near $q^2=0$ in $B \to \pi \ell \bar{\nu}$ are still much too big to determine $\zeta^{B\pi}$, $\zeta_J^{B\pi}$ and test factorization

More recently, Becher & Hill have imposed a stronger constraint on the form factor. Here the current $B \to \pi \ell \bar{\nu}$ data just starts to become interesting. Currently agrees with $B \to \pi\pi$ at the border of $1\!-\!\sigma$

Outlook

- There is an EFT for processes with energetic jets or hadrons
- We now have the tools to systematically study power corrections
  - ➡ color suppressed decays, inclusive decays
- Exclusive Vub from dispersion + Lattice + spectra
- Nonleptonics
  - ➡ predictions for the size of amplitudes
  - ➡ universal hadronic parameters, strong phases
  - ➡ γ (or α) from individual $B \to M_1 M_2$ channels
- 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 ...