QCD effects in B-decays: Lecture 2

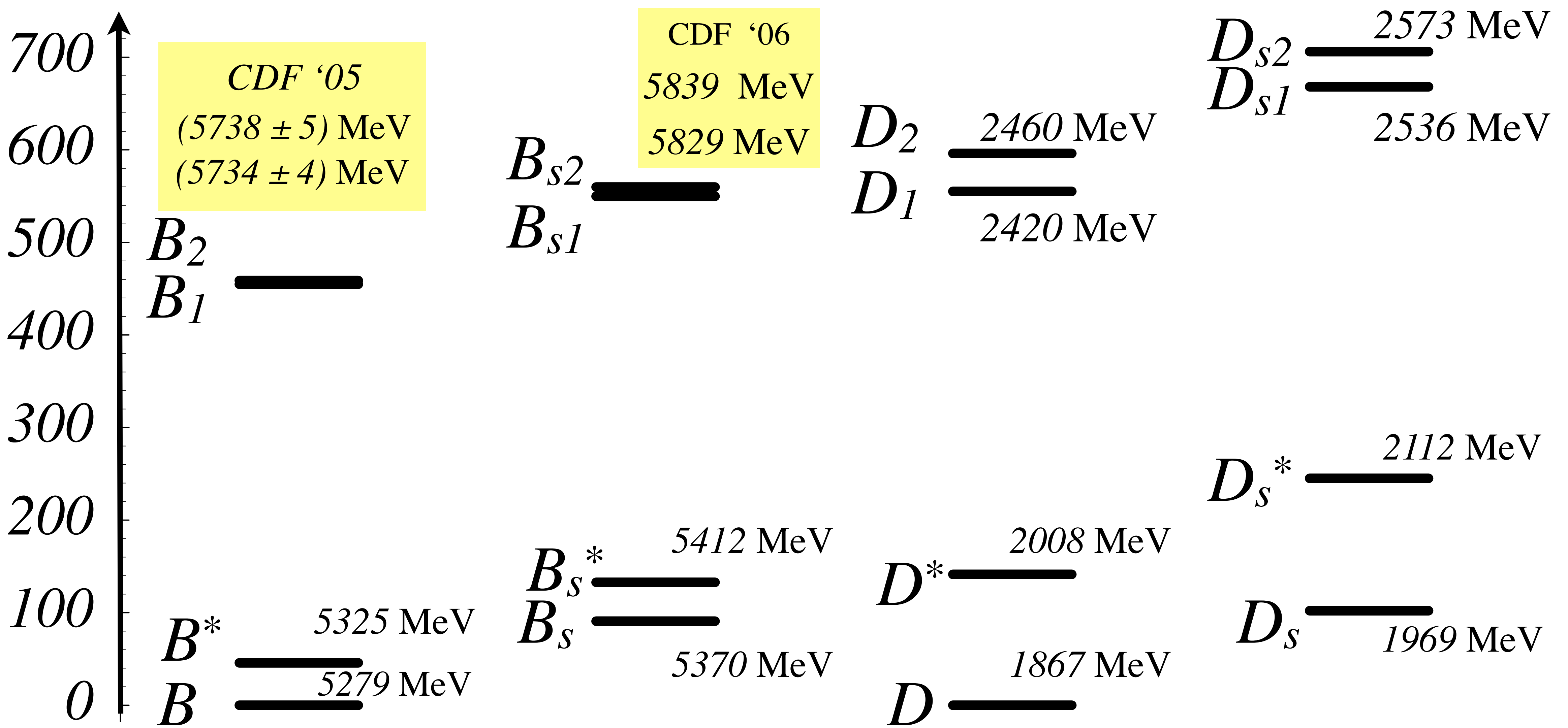
Thomas Becher

Academic lectures on Flavor Physics, Fermilab, Feb. 20, 2007

Outline of these lectures

1. Heavy quark physics
   - Heavy-quark spin and flavor symmetry
     - Spectroscopic implications
   - Heavy Quark Effective Theory
     - V_{cb} from exclusive semileptonic decay
2. Inclusive B-decays
   - Operator Product Expansion
   - Determination of V_{ub}, V_{cb} from semileptonic decays
   - Radiative decays: test of FCNC interactions
   - Heavy hadron lifetimes
3. Exclusive radiative and hadronic B-decays
   - Factorization, Soft Collinear Effective Theory

Heavy-light meson spectrum

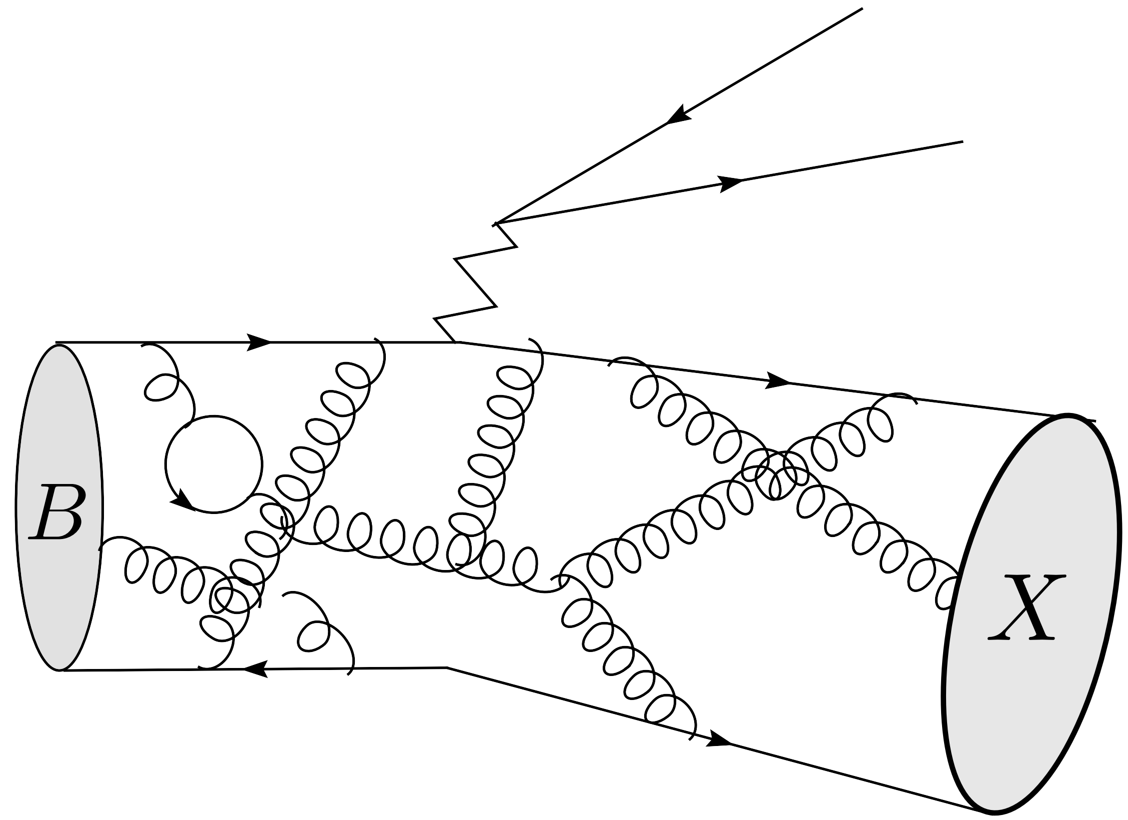


- To leading power, bottom and charm spectra are simply shifted by constant amount m_b-m_c=3.4GeV.
  - M_{B1}-M_B = (455±4) MeV, M_{D1}-M_D = (555±1)MeV
- "Spin doublets" almost degenerate:
  - e.g. M_{B^*} - M_B = 46 MeV

Operator Product Expansion and Inclusive Weak Decays

Inclusive decays

$$\Gamma = \sum_X \Bigg|$$



$$\Bigg|^2$$

- Inclusive decays rates are much less sensitive to hadronization effects than exclusive decays.
- Scale hierarchy

$$1/m_b \qquad \ll \qquad 1/\Lambda_{QCD}$$

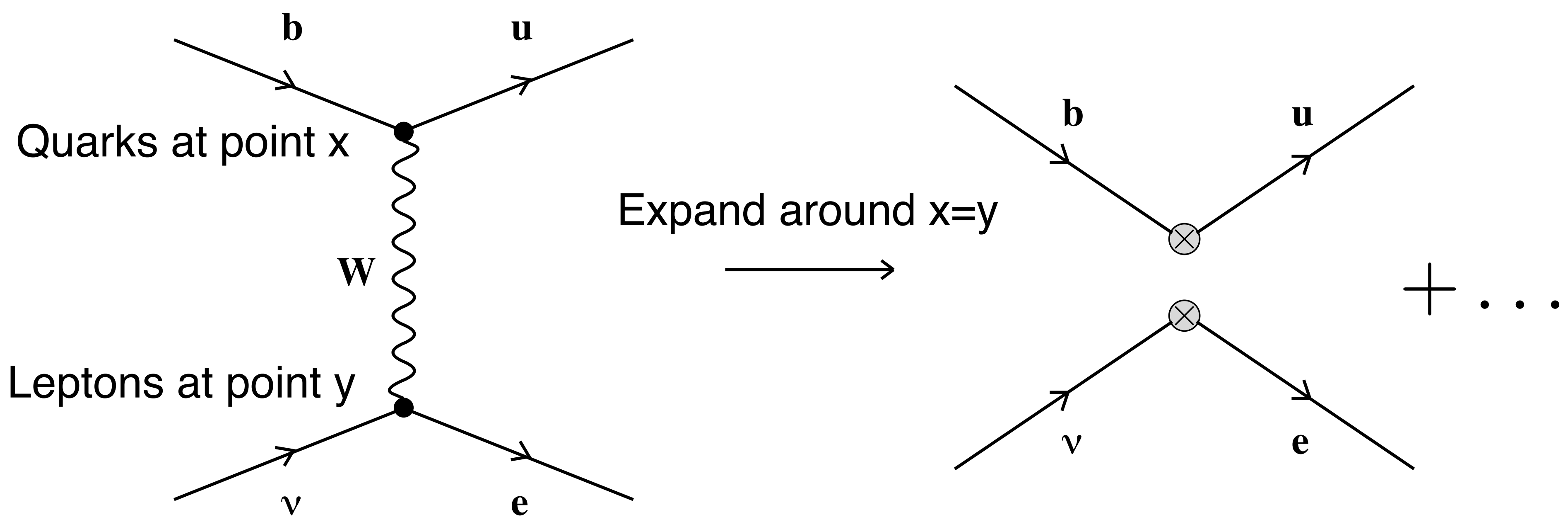
b-quark decay — hadronic effects

Inclusive *b*-decays

- Important class of decays, since rate can be calculated perturbatively $m_Q \to \infty$
  - Semileptonic decay $B \to X_c\, l\, \nu$
    - Most precise determination of $|V_{\mathrm{cb}}|$, m_{b} and m_{c}.
  - Semileptonic decay $B \to X_u\, l\, \nu$
    - Most precise determination of $|V_{\mathrm{ub}}|$
  - Radiative decays $B \to X_s\, \gamma$, $B \to X_s\, l^+ l^-$
    - Sensitive probe of FCNC interactions
  - Lifetime: $B \to X$

Operator Product Expansion

- Used this tool before, when integrating out heavy particles in the construction of the effective weak Hamiltonian.



- At low energies W is highly virtual. Propagates only very short distance. Expand around x=y.
- In momentum space this translates into expansion of W-propagator

$$\frac{1}{p^2 - m_W^2} = \frac{1}{-m_W^2} + \ldots$$

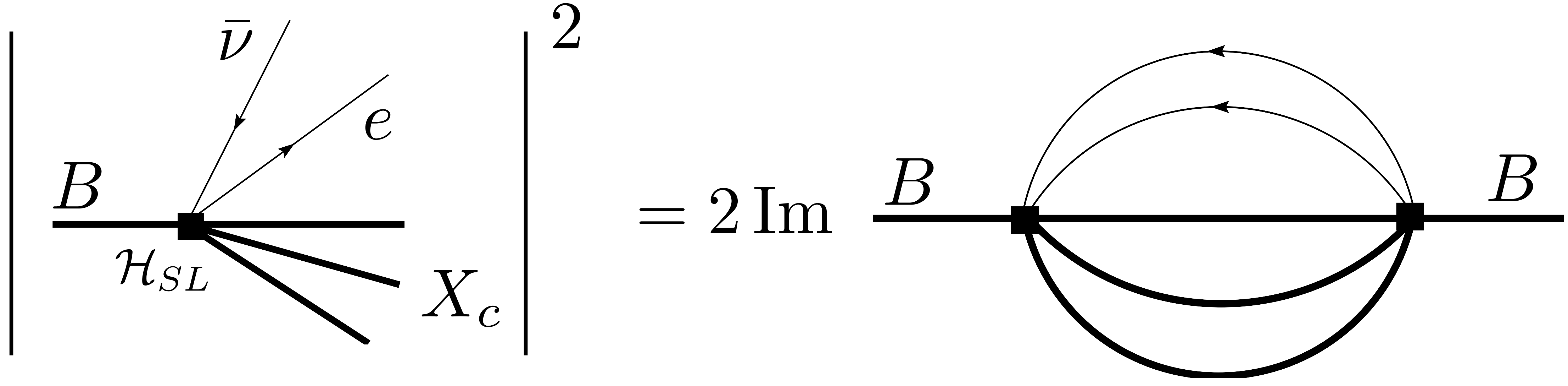
Optical theorem

- To apply the same technique to the inclusive B-decay, first use the optical theorem

$$\Gamma(B \to X_c e\bar{\nu}) = \frac{1}{2M_B}\sum_X (2\pi)^4\delta^4(p_B - p_{X_c} - p_e - p_\nu)\,|\langle X_c e\bar{\nu}|\mathcal{H}_{\rm SL}|B\rangle|^2$$

$$= \frac{1}{2M_B}\,2\,{\rm Im}\,\langle B|\, i\int d^4x\; T\left\{\mathcal{H}^\dagger_{\rm SL}(x), \mathcal{H}_{\rm SL}(0)\right\}\,|B\rangle$$

forward-scattering amplitude



Operator product expansion

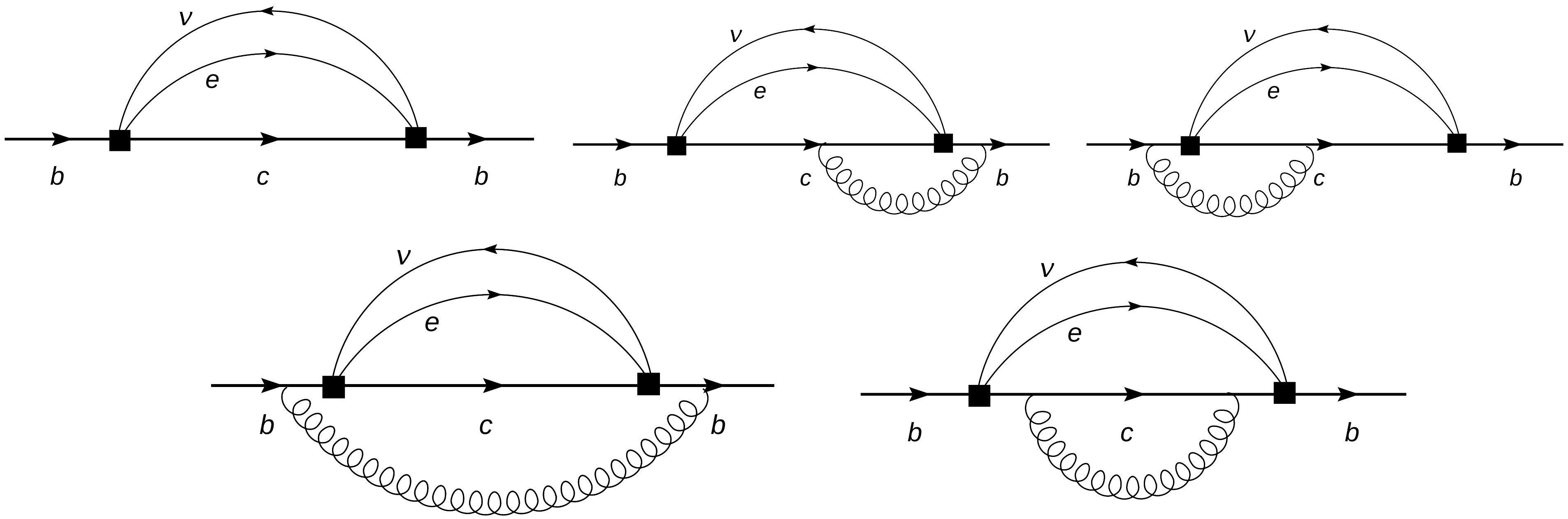
- Expand the product of operators into local ones

$$i\int d^4x\, T\left\{\mathcal{H}_{\rm SL}^\dagger(x), \mathcal{H}_{\rm SL}(0)\right\} = C_3\, \bar{b}\, b + \frac{C_5}{m_b^2}\, \bar{b}\, \sigma_{\mu\nu} G^{\mu\nu}\, b + \ldots$$

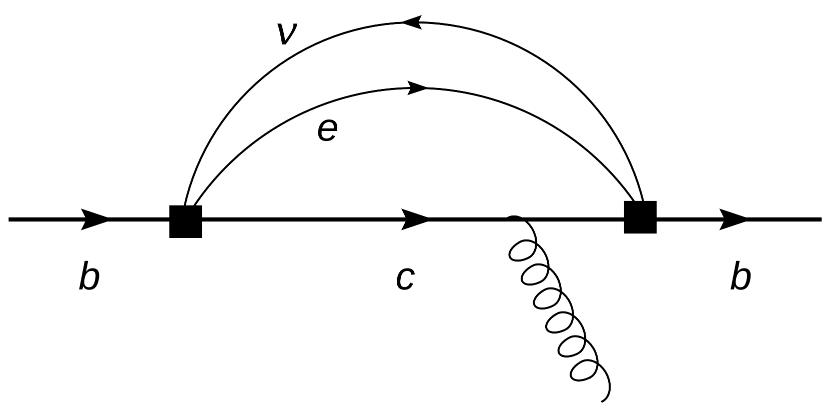
No dim. 4 operators: $\bar{b}\, i\not{D}\, b = m_b\, \bar{b}\, b$

- To evaluate the coefficients C_3 and C_5, we can use arbitrary external states
  - Use quark and gluon states and calculate the coefficients in perturbation theory!
- Then use HQET to evaluate the B-meson matrix elements of the operators $\bar{b}\, b$ and $\bar{b}\, \sigma_{\mu\nu} G^{\mu\nu}\, b$
  - Will be given by HQET parameters λ_1, λ_2, etc.
- Q: Is the expansion well behaved? Are the higher order terms really suppressed by $1/m_b^2$?

Feynman Diagrams



$$C_3\,\bar{b}\,b$$



$$C_5\,\bar{b}\,\sigma_{\mu\nu}G^{\mu\nu}b$$

Matrix elements

- To calculate the matrix elements, we use HQET.

$$\frac{1}{2M_B}\langle B|\,\bar{b}b\,|B\rangle = 1 + \frac{\lambda_1 + 3\lambda_2}{2m_b^2} + \ldots$$

No $1/m_b$ corrections!

$$\frac{1}{m_b^2}\frac{1}{2M_B}\langle B|\,\bar{b}\,\sigma_{\mu\nu}G^{\mu\nu}\,b\,|B\rangle = \frac{6\lambda_2}{m_b^2} + \ldots$$

$$\lambda_2 = \frac{1}{4}\left(M_{B^*}^2 - M_B^2\right) = 0.12\mathrm{GeV}^2$$

Result for the rate

$$\Gamma(B \to X_c e\bar{\nu}) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{\rm cb}|^2 \left\{ \left(1 + \frac{\lambda_1 + 3\lambda_2}{2m_b^2}\right) \left[f(\rho) + \frac{\alpha_s}{\pi} g(\rho) \right] - \frac{6\lambda_2}{m_b^2}(1-\rho)^4 + \dots \right\}$$

$$f(\rho) = 1 - 8\rho - 12\rho^2 \log\rho + 8\rho^3 - \rho^4 \,, \qquad \rho = \frac{m_c^2}{m_b^2}$$

$$g(\rho) = \text{"lengthy, known expression"}$$

- Leading term in limit $m_Q \to \infty$ is the free b-quark decay ("naive parton model")!
- Hadronization effects are suppressed as $1/m_{\rm b}^2$. Reduce the rate by ≈4%
- Values of $m_{\rm b}$, $m_{\rm c}$ and λ_1?
- Strictly speaking expansion is $1/(m_{\rm b}-m_{\rm c}) \approx 1/m_{\rm b}$

Side remark: *b*-quark mass

- We calculated in terms of the b-quark pole mass, i.e. the location of the pole in the heavy quark propagator.
  - Well defined in perturbation theory, but
  - does not make sense non-perturbatively because of confinement.
- The lack of a non-perturbative definition shows up via large higher-order perturbative corrections.
  - Upon relating the pole to the $\overline{\text{MS}}$ quark mass, one finds a badly divergent PT series.
  - Can resum this series, but prescription is not unique ("renormalon ambiguity").

b-quark mass definition

- Bad perturbative behavior also shows up in the decay rate, if it is expressed in the pole mass.
- Eliminate pole mass in favor quark mass! Many mass schemes in the literature:
  - $\overline{\text{MS}}$ mass (not suited for HQET)
  - Kinetic mass (Uraltsev)
  - Υ(1S) mass (Hoang, Ligeti, Manohar)
  - Potential subtracted (Beneke)
  - Shape-function (Bosch, Lange, Neubert, Paz)
- Also, better definition for λ_1, λ_2 are available in the kinetic and shape-function scheme.
  - The corresponding parameters are denoted by μ_π^2 ($\equiv -\lambda_1$) and μ_G^2 ($\equiv \lambda_2$)

Moments

- Calculate moments of the decay spectrum (with exp. cuts).
  - Leptonic moments

$$L_n = \frac{1}{\Gamma}\int dE_e (E_e)^n \frac{d\Gamma}{dE_e}$$

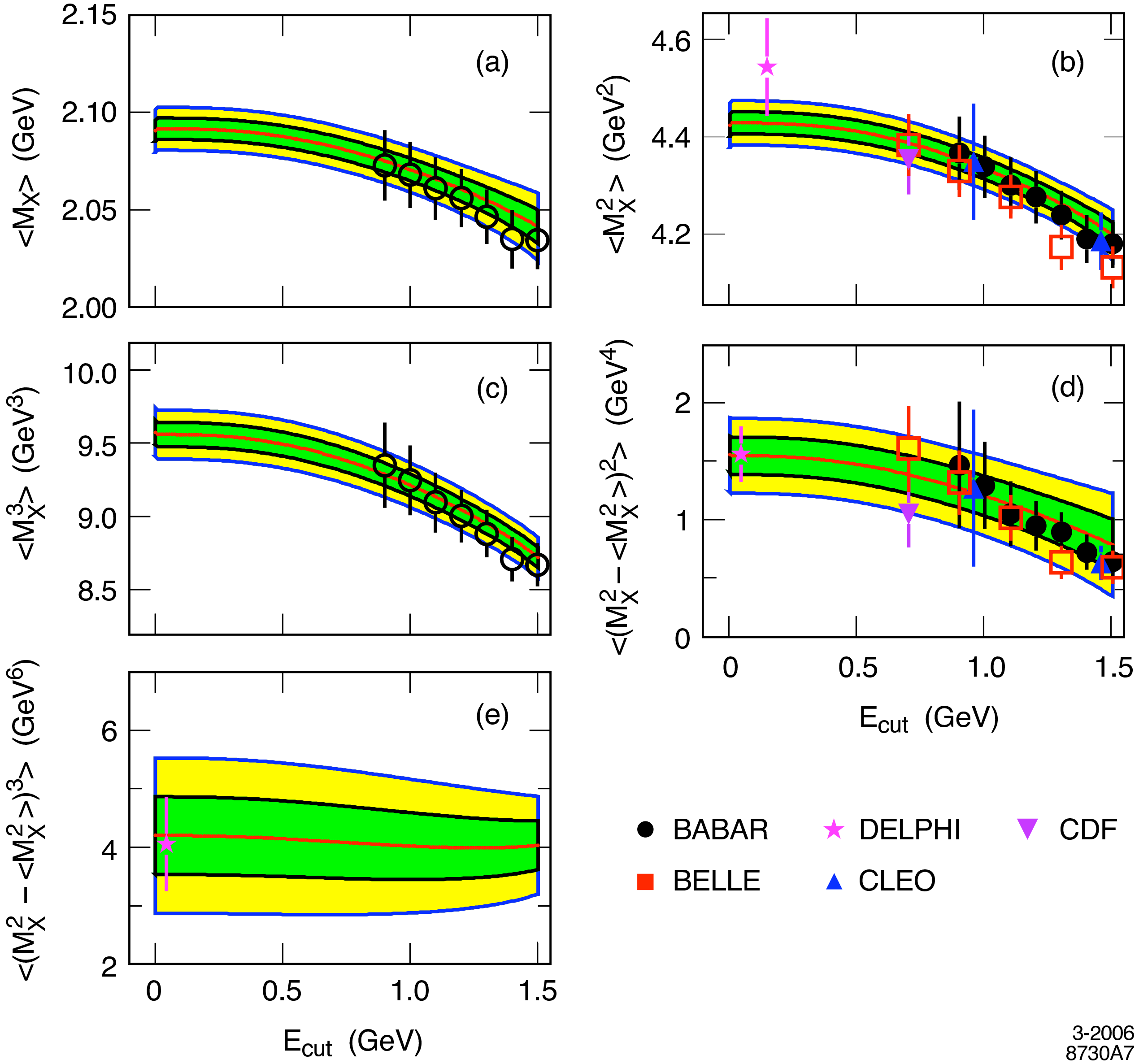
  - Hadronic moments

$$H_{ij} = \frac{1}{\Gamma}\int dM_X^2\, dE_X\, (M_X^2)^i\, (E_X)^j\, \frac{d\Gamma}{dM_X^2 dE_X}$$

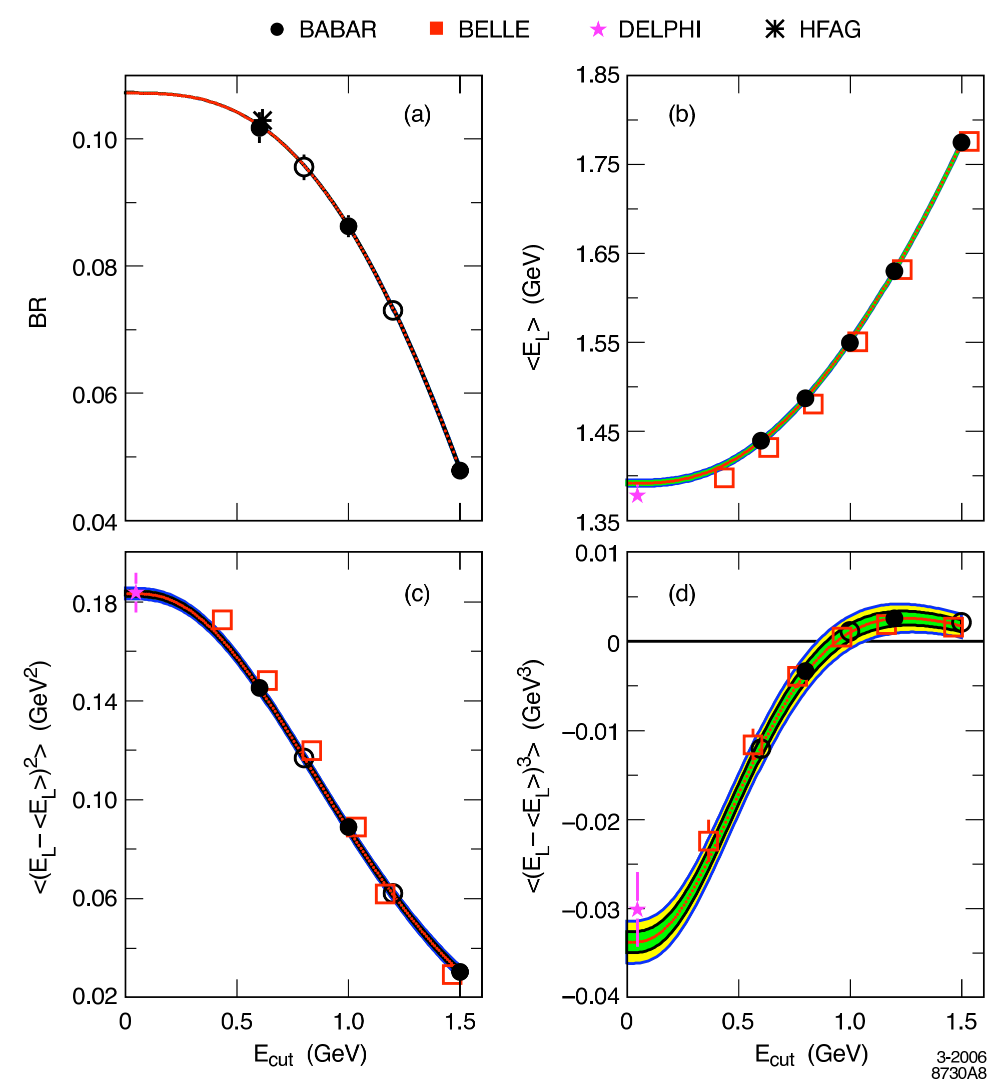
- Measurement of the moments and the rate determines V_{cb} m_{b}, m_{c} and λ_1.

Moment measurements and global fit

hadronic mass moments



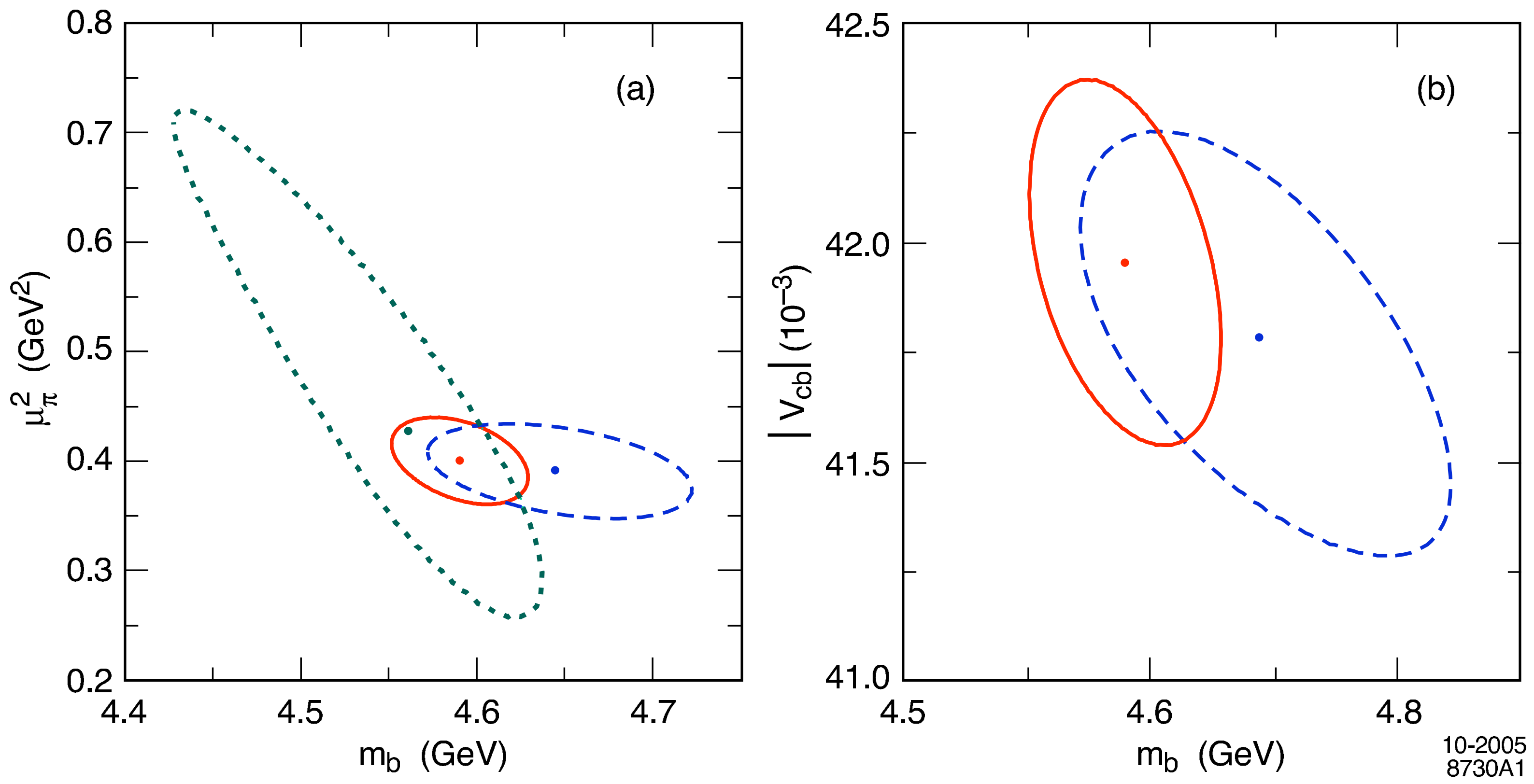
lepton energy moments



- Red line: fit result. Green band: exp. uncertainty. Yellow band: exp. + th. uncertainty

Buchmüller and Flächer, hep-ph/0507253

Fit results



Moments included:

Solid red: all

Dashed blue: $B \to X_c\, e\, \nu$

Dotted green: $B \to X_s\, \gamma$

kinetic scheme

$$
\begin{aligned}
|V_{cb}| &= (41.96 \pm 0.23_{\rm exp} \pm 0.35_{\rm HQE} \pm 0.59_{\Gamma_{\rm SL}}) \times 10^{-3} \\
m_b &= 4.590 \pm 0.025_{\rm exp} \pm 0.030_{\rm HQE}\,\mathrm{GeV} \\
m_c &= 1.142 \pm 0.037_{\rm exp} \pm 0.045_{\rm HQE}\,\mathrm{GeV} \\
\mu_\pi^2 &= 0.401 \pm 0.019_{\rm exp} \pm 0.035_{\rm HQE}\,\mathrm{GeV}^2
\end{aligned}
$$

results of hep-ph/0507253, see also hep-ph/0408002

Most precise determination of 3 SM parameters in a single process!

News flash

- The "most precise determination" statement was true until last Tuesday:

arXiv.org > hep-ph

Search for (Help | Advanced search)

All papers Go!

High Energy Physics - Phenomenology

hep-ph new abstracts, Tue, 13 Feb 07 01:00:10 GMT
0702103 -- 0702123 received

hep-ph/0702103 [abs, ps, pdf, other] :

Title: **Heavy Quark Masses from Sum Rules in Four-Loop Approximation**
Authors: Johann H. Kuehn, Matthias Steinhauser, Christian Sturm
Comments: 29 pages

New data for the total cross section $\sigma(e^+e^-\to{hadrons})$ in the charm and bottom threshold region are combined with an improved theoretical analysis, which includes recent four-loop calculations, to determine the short distance $\bar{\rm MS}$ charm and bottom quark masses. A detailed discussion of the theoretical and experimental uncertainties is presented. The final result for the $\bar{\rm MS}$-masses, $m_c(3 {GeV})=0.986(13)$ GeV and $m_b(10 {GeV})=3.609(25)$ GeV, can be translated into $m_c(m_c)=1.286(13)$ GeV and $m_b(m_b)=4.164(25)$ GeV. This analysis is consistent with but significantly more precise than a similar previous study.

Future improvements of the moment analysis

- To go to next higher level in theoretical precision, we'll need
  - Tree-level OPE to $1/m_b^3$. Already included.
    - Has recently even been calculated up to $1/m_b^4$, hep-ph/0611168.
  - Perturbative corrections to the leading power corrections, terms

$$\alpha_s(m_b)\frac{\mu_\pi^2}{2m_b} \qquad \alpha_s(m_b)\frac{\mu_G^2}{2m_b}$$

    - doable, but nontrivial 1-loop calculation
  - Two-loop corrections to the leading power rate
    - Possible with new numerical techniques. Muon decay has been calculated, hep-ph/0505069 (same kinematics, but QED instead of QCD corrections)

Quark hadron duality

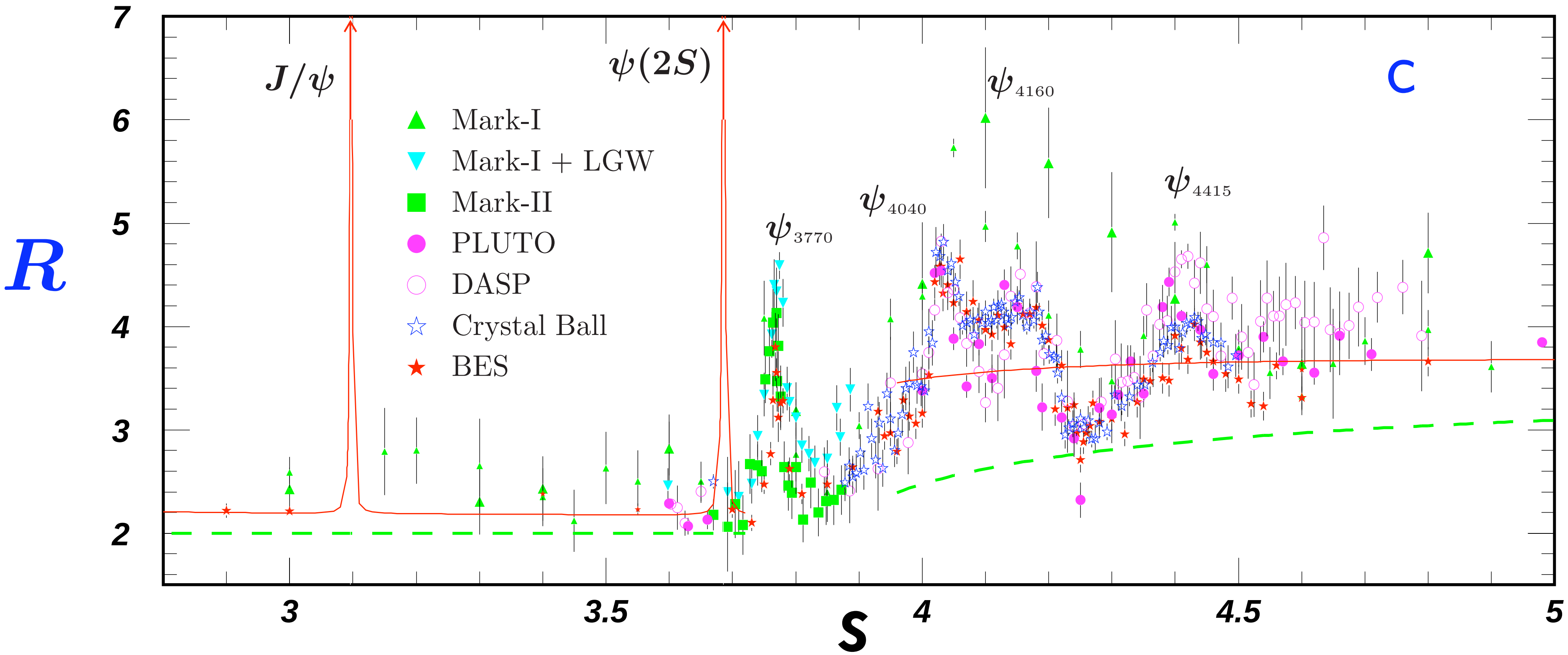
- Are there pieces that we are missing when calculating the rate using the OPE?
- It is often stated that the OPE calculation "assumes quark hadron duality", since we calculated the coefficients C_3 and C_5 with quarks instead of hadrons.
- More precisely, we have expanded in the rate $1/m_b$, $\alpha_s(m_b)$ and $1/m_W^2$. Upon expanding, we loose non-analytic terms, such as

pert. expansion	OPE integrating out W	OPE for incl. B-decay
e^{-1/α_s} ,	e^{-a^2/m_W^2} ,	$\frac{1}{m_b^n}\sin(\frac{m_b}{b})$
	W cannot go on-shell (Euclidean OPE)	quark, gluons can be on shell (Minkowskian OPE)

- Models give n=8 suppression compared to leading order in SL decay, see hep-ph/0009131. Hopefully, these effects are tiny.

"duality violation"

Example of oscillatory behavior



$$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons}, s)}{\sigma(e^+e^- \to \mu^+\mu^-, s)}$$

- Oscillatory behavior is not captured by OPE calculation.
- In inclusive quantities, the oscillations average out.

Heavy hadron lifetimes

and the Λ_b (ex-)puzzle

Heavy hadron lifetimes

- Same OPE technique can also be used to calculate the hadron lifetimes $\tau=1/\Gamma$

$$\begin{aligned}\Gamma(H_b) = \Gamma(H_b \to X) &= \frac{1}{2M_B}\sum_X (2\pi)^4\delta^4(p_B - p_X)\,|\langle X|\mathcal{H}_{\Delta B=1}|B\rangle|^2 \\ &= \frac{1}{2M_B}\,2\,\mathrm{Im}\,\langle B|\,i\int d^4x\;T\left\{\mathcal{H}_{\Delta B=1}(x),\mathcal{H}_{\Delta B=1}(0)\right\}\,|B\rangle\end{aligned}$$

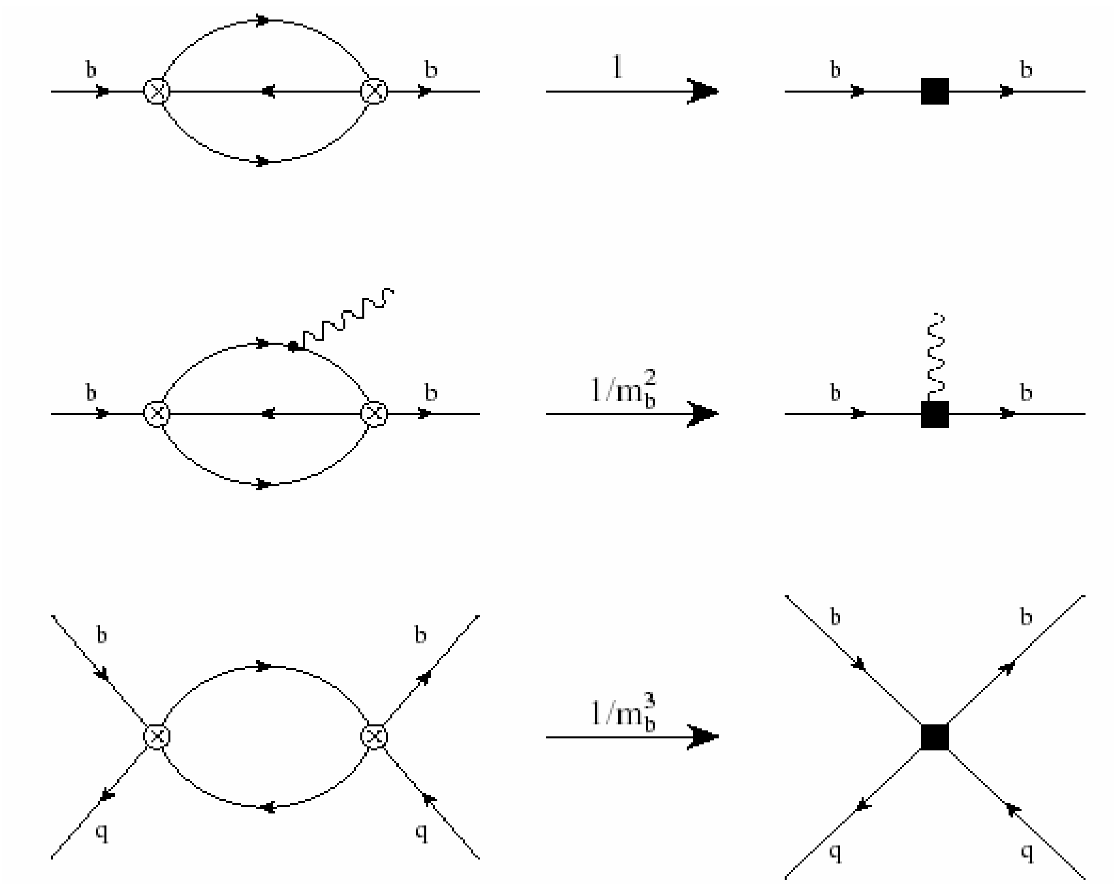
- Complete ΔB=1 eff. Hamiltonian:

$$\begin{aligned}\mathcal{H}_{\Delta B=1} = \frac{4G_F}{\sqrt{2}}V_{cb}\Big\{ & c_1(m_b)\left[\bar{d}'_L\gamma_\mu u_L\,\bar{c}_L\gamma^\mu b_L + \bar{s}'_L\gamma_\mu c_L\,\bar{c}_L\gamma^\mu b_L\right] \\ & + c_2(m_b)\left[\bar{c}_L\gamma_\mu u_L\,\bar{d}'_L\gamma^\mu b_L + \bar{c}_L\gamma_\mu c_L\,\bar{s}'_L\gamma^\mu b_L\right] \\ & + \sum_{\ell=e,\mu,\tau}\bar{\ell}_L\gamma_\mu\nu_\ell\,\bar{c}_L\gamma^\mu b_L\Big\} + \mathrm{h.c.}\,,\end{aligned}$$

hadronic decays

semileptonic decays

OPE



$$\bar{b}\, b$$

$$\bar{b}\, \sigma_{\mu\nu} G^{\mu\nu}\, b$$

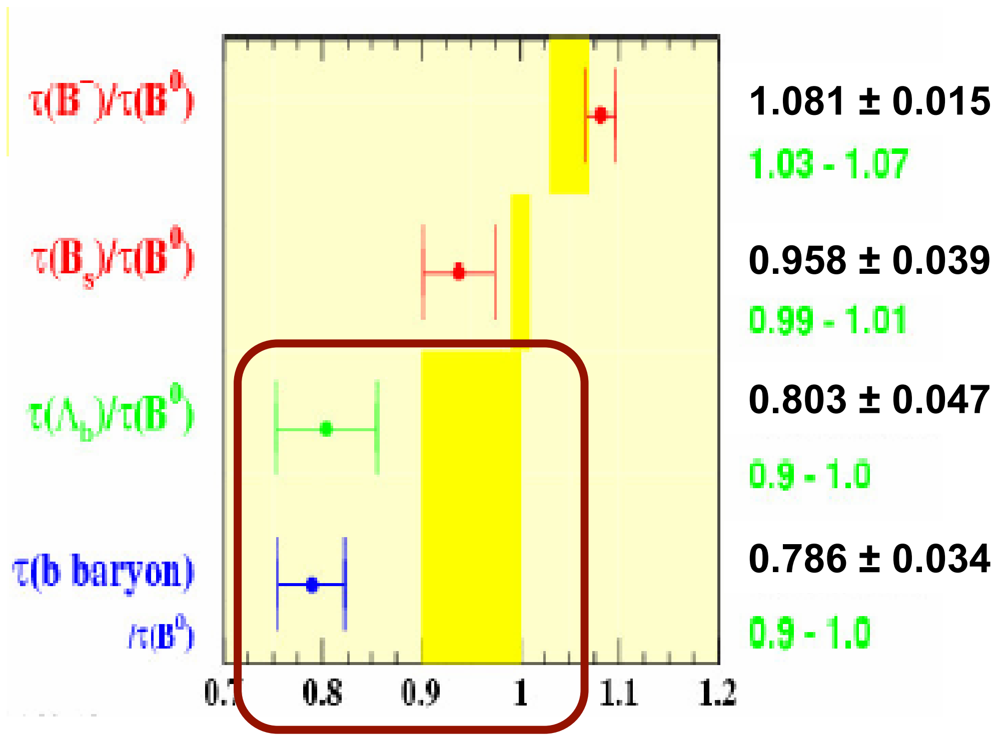
$$\bar{b}\, \Gamma_i\, q\ \ \bar{q}\, \Gamma_i\, b$$

Dependence on light quarks! Induces lifetime differences. Evaluate matrix elements with LQCD.

- Result for the rate has the same structure as we had before.
  - Only small lifetime differences ~1-2% to O(Λ^2/m_b^2). Arise because λ_1, λ_2 are slightly different for different hadrons.
  - Dominant contribution to lifetime *differences* from the four-quark operators suppressed by $(\Lambda/m_b)^3$. Enhanced by a large numerical prefactor $4\pi^2$, they are are O(5-10%).

The Λ_b ex-puzzle

Situation a few years ago



Before HFAG 2004

Latest numbers:

Theory, hep-ph/0612176

$$\left[\frac{\tau(B^+)}{\tau(B_d^0)}\right]_{\rm NLO} = 1.063 \pm 0.027$$

$$\frac{\tau(B_s)}{\tau(B_d)} = 1.00 \pm 0.01$$

hep-ph/9906031

$$\frac{\tau(\Lambda_b)}{\tau(B_d)} = \begin{cases} 0.91(1) & \text{for } am_\pi = 0.74(4) \\ 0.93(1) & \text{for } am_\pi = 0.52(3) \end{cases}$$

a^{-1}=1.1GeV

Experiment

$$\left[\frac{\tau(B^+)}{\tau(B_d^0)}\right] = 1.071 \pm 0.009$$

$$\frac{\tau(B_s)}{\tau(B_d)} = 0.957 \pm 0.027$$

- New CDF result, hep-ex/0609021

$$\frac{\tau(\Lambda_b^0)}{\tau(B^0)} = 1.041 \pm 0.057 \ (\text{stat.} + \text{syst.}).$$

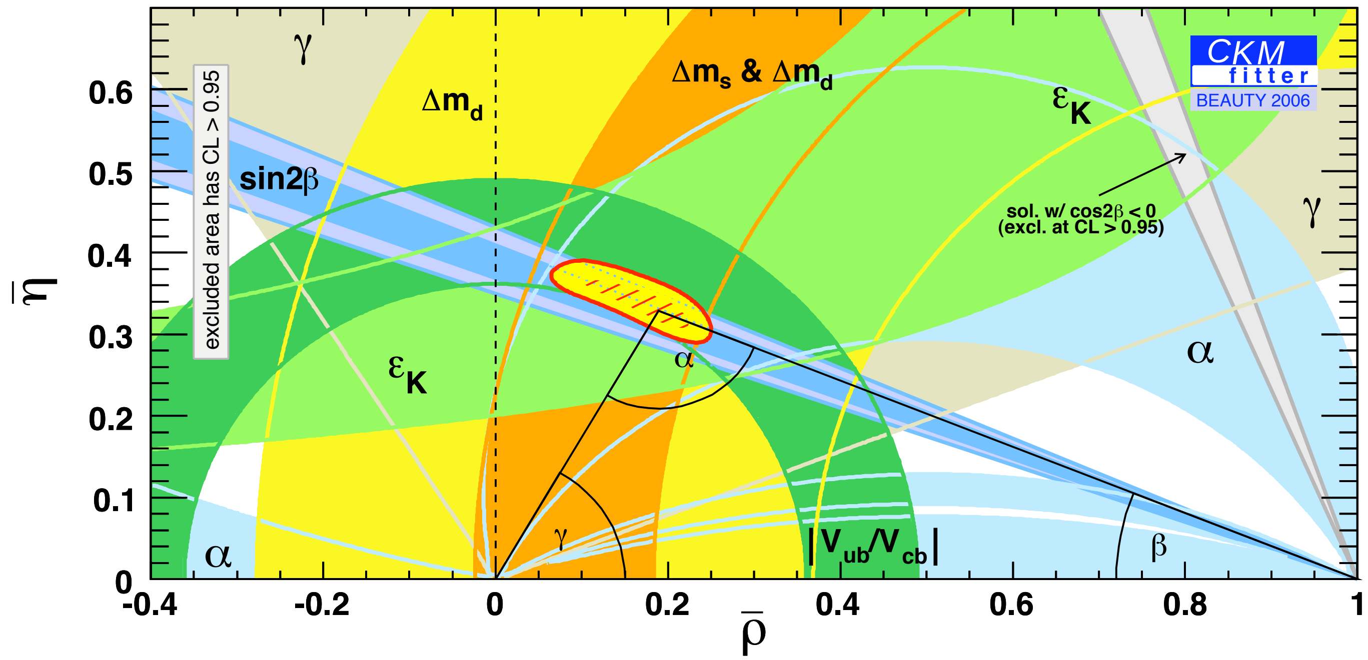
DZero: $$\frac{\tau(\Lambda_b^0)}{\tau(B^0)} = 0.87^{+0.17}_{-0.14} \ (\text{stat}) \pm 0.03 \ (\text{syst}),$$

3.2σ higher than world average, with comparable precision!

$B \longrightarrow X_u e\nu$

Experimental cuts, shape function and the extraction of V_{ub}

$|V_{ub}|$



- Interesting tension between $|V_{ub}|$ and sin(2β) measurements
  - sin(2β): loop process in SM
    - sensitive to new physics
  - $|V_{ub}|$: tree level weak decay
    - insensitive to new physics,
    - but extraction is sensitive to QCD effects!

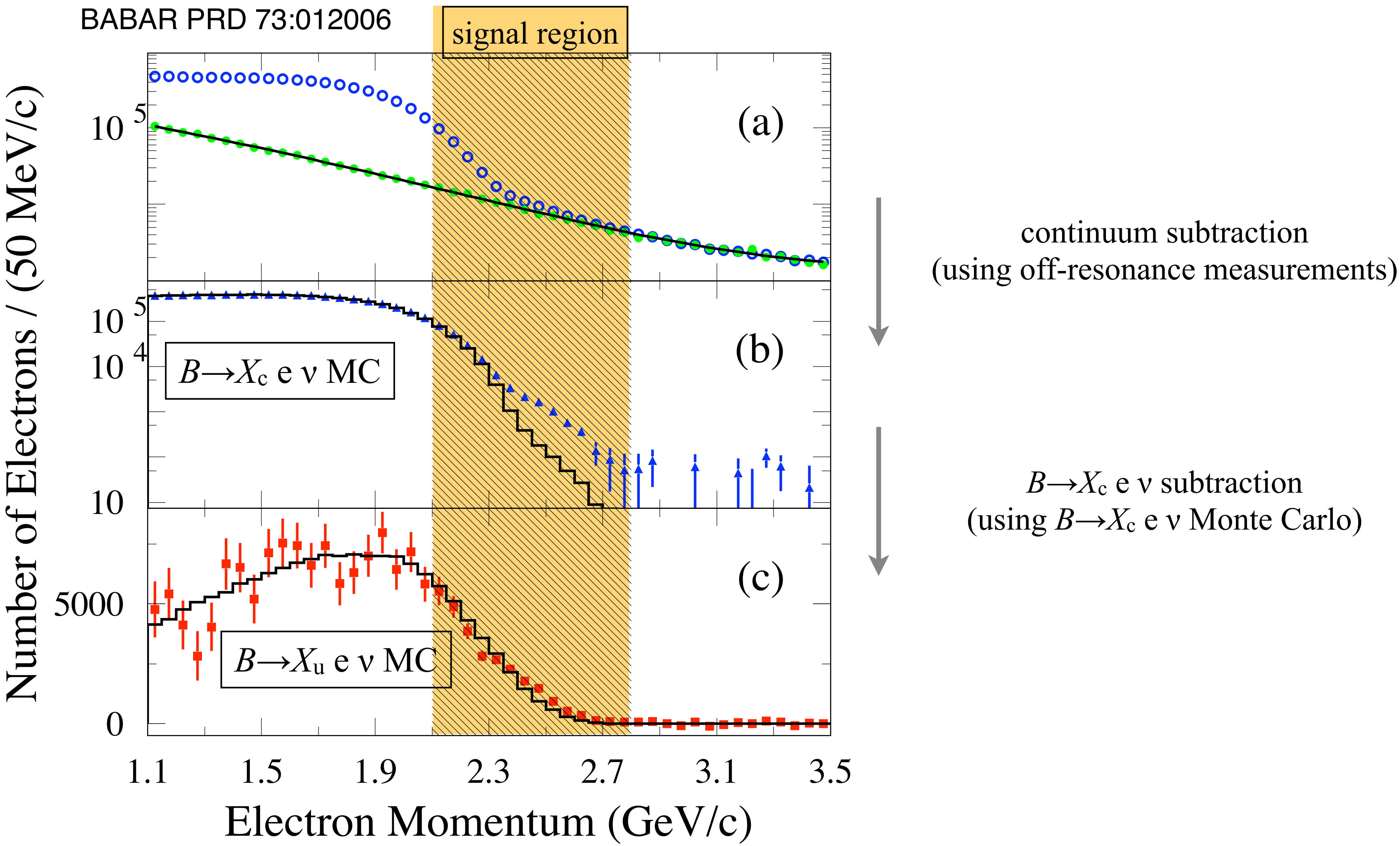
$|V_{ub}|$

- It is trivial to obtain the $B \to X_u \, e \, \nu$ rate from our expression for $B \to X_c \, e \, \nu$
  - Set $m_c = 0$, replace $V_{cb} \to V_{ub}$
- However, experimentally, it is impossible to measure the total $B \to X_u \, e \, \nu$ rate.
  - $B \to X_c \, e \, \nu$ signal is much larger

$$\left|\frac{V_{ub}}{V_{cb}}\right| \approx 0.1 \qquad \frac{\Gamma_c}{\Gamma_u} = \left|\frac{V_{cb}}{V_{ub}}\right|^2 \left(1 - 8\rho - \rho^4 - 12\rho^2 \ln\rho + 8\rho^3\right) \approx 50$$

  - Need kinematical cuts to eliminate $B \to X_c \, e \, \nu$
    - *e.g.* $M_X < M_D \quad \text{or} \quad E_e > \dfrac{M_B^2 - M_D^2}{2M_B}$

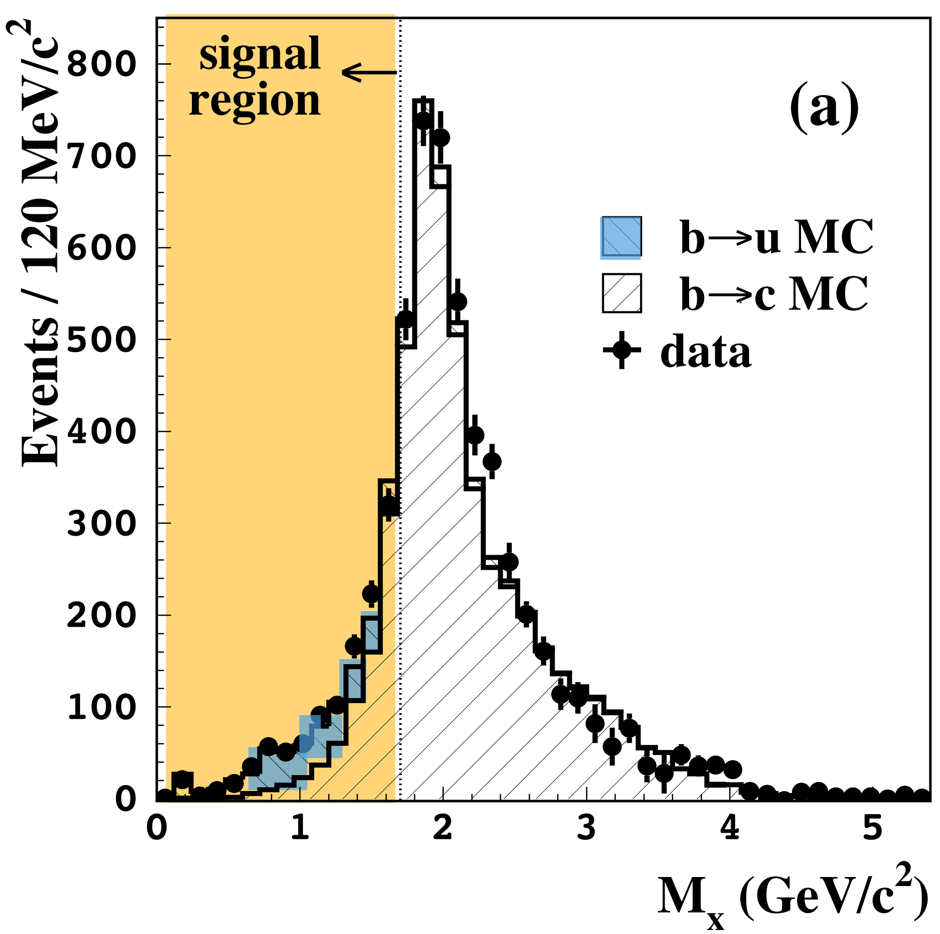
E_e spectrum



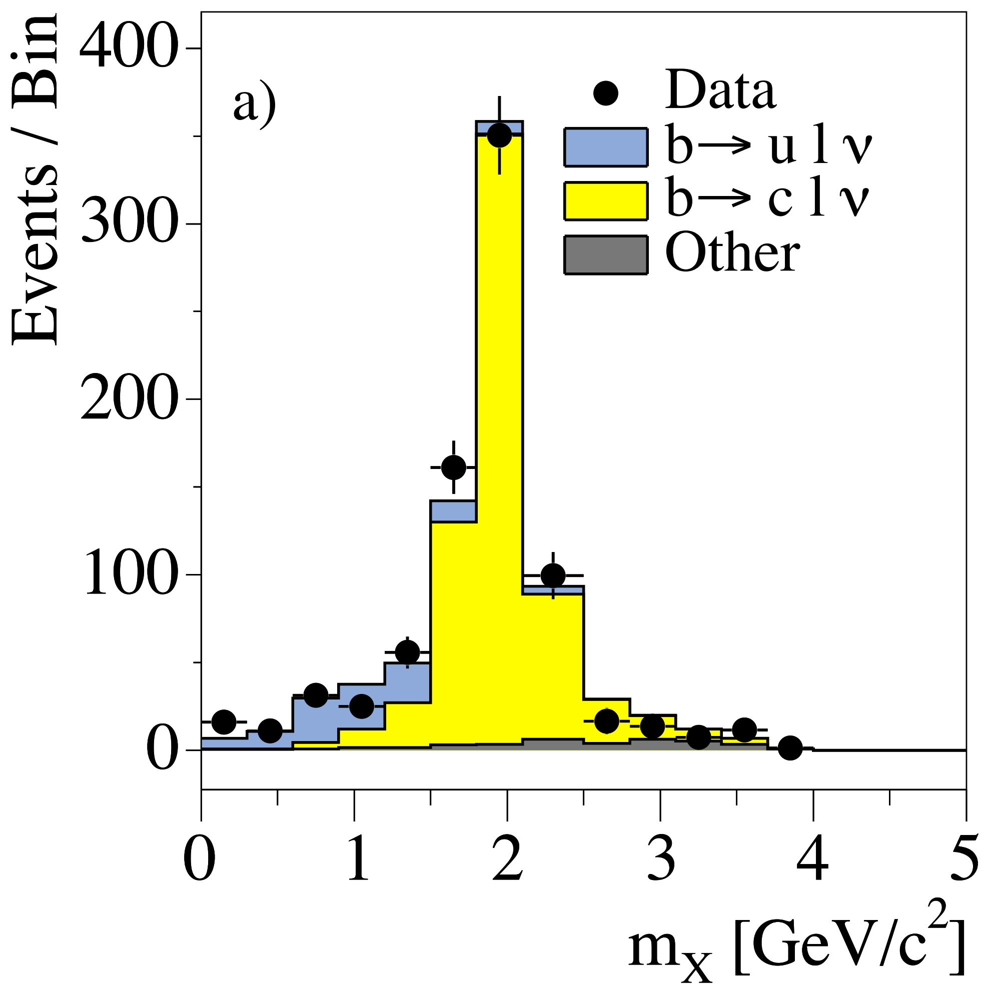
- S/B ~ 1/15 for E_e>2GeV. Background subtraction challenging!

M_X spectrum

Belle

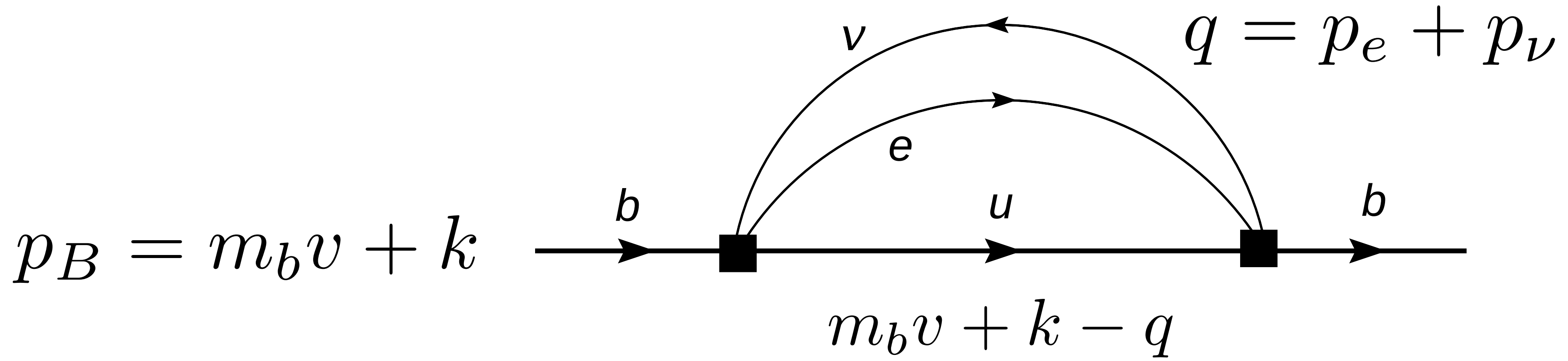


Babar



- The cuts reduce the small $b \to u$ signal even farther!
- Are a theoretical challenge
  - Reduce available phase space enforce small M_X.
  - OPE breaks down! Terms $\frac{\Lambda_{QCD} E_X}{M_X^2}$ in OPE are no longer suppressed.

OPE with cut



- u-quark propagator denominator

$$\frac{1}{(m_b v + k - q)^2} = \frac{1}{(m_b v - q)^2 - 2(m_b v - q)k + k^2}$$

- Total rate: ($p_X = m_b\, v - q$)

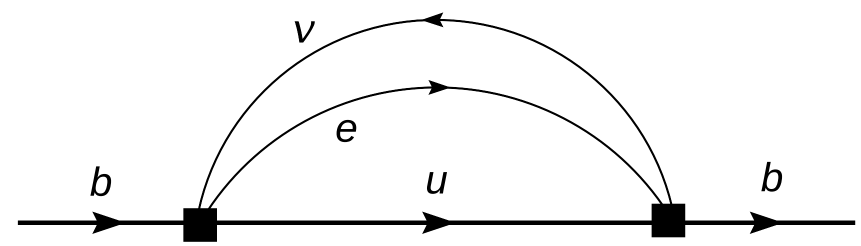
$$p_X^2 \sim m_b^2\,, \qquad p_X \cdot k \sim m_b \Lambda_{\rm QCD}\,, \qquad k^2 \sim \Lambda_{\rm QCD}^2$$

- After cut to eliminate $B \to X_c\, e\, \nu$

$$p_X^2 \sim m_b \Lambda_{\rm QCD}\,, \qquad p_X \cdot k \sim m_b \Lambda_{\rm QCD}\,, \qquad k^2 \sim \Lambda_{\rm QCD}^2$$

Shape function

$$p_B = m_b v + k$$



$$q = p_e + p_\nu$$

$$m_b v + k - q$$

- Without cut (or modest cuts)

$$\frac{1}{(p_X + k)^2} = \frac{1}{p_X^2}\left[1 + \frac{2\,p_X \cdot k}{p_X^2} + \ldots\right]$$

  - Hadronic part: local operators with derivatives

$$h_v(k)\;h_v(k) \to h_v(x)\,h_v(x)\,,$$

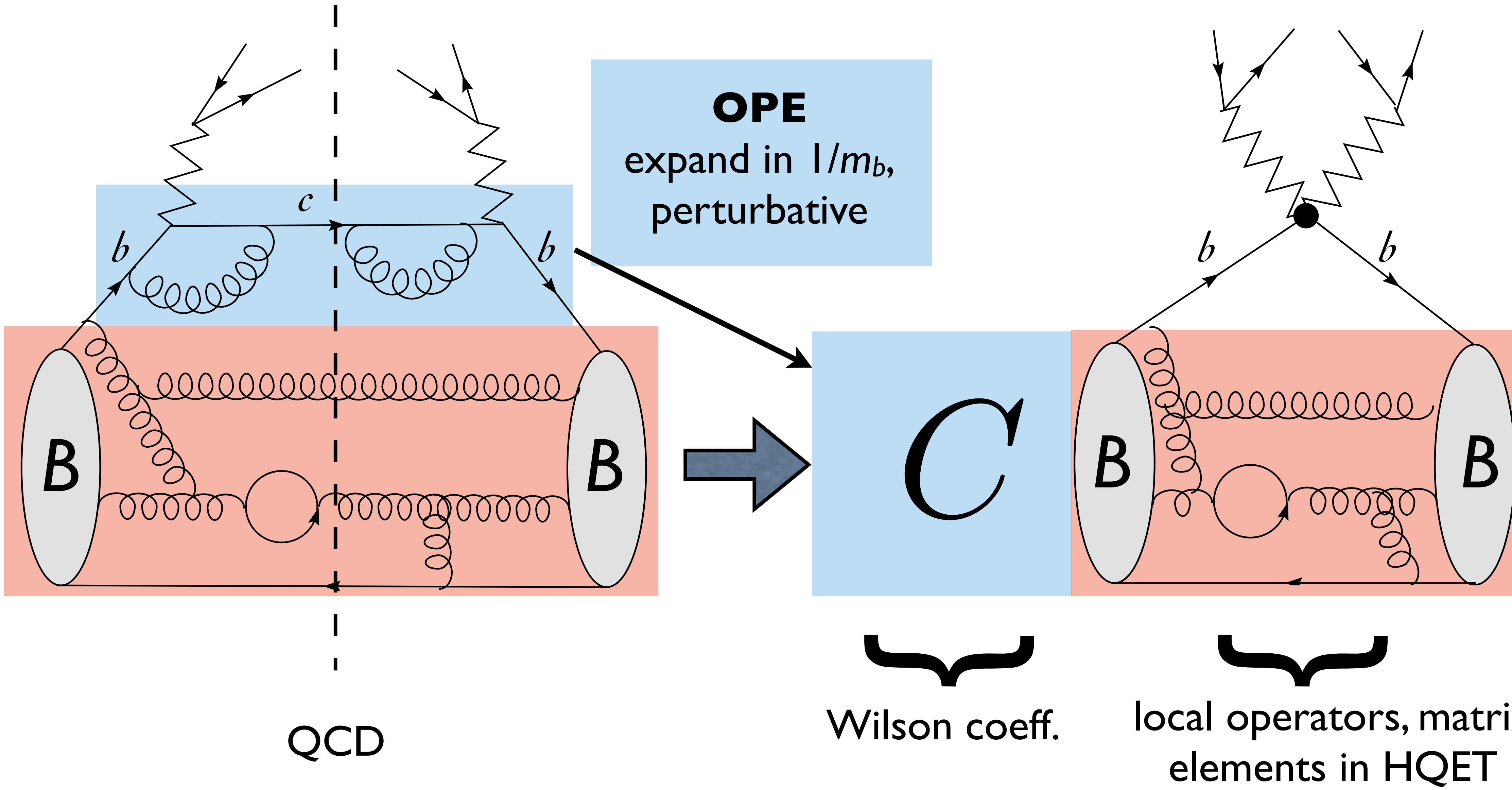
$$h_v(k)\,k_\mu\,h_v(k) \to h_v(x)\,iD_\mu\,h_v(x)\ \text{etc.}$$

- With cut to eliminate $B \to X_c\, e\, \nu$

$$\frac{1}{(m_b v + k - q)^2} = \frac{1}{p_X \cdot (p_X - k)}\left[1 + \frac{k^2}{p_X \cdot (p_X - k)} + \ldots\right]$$

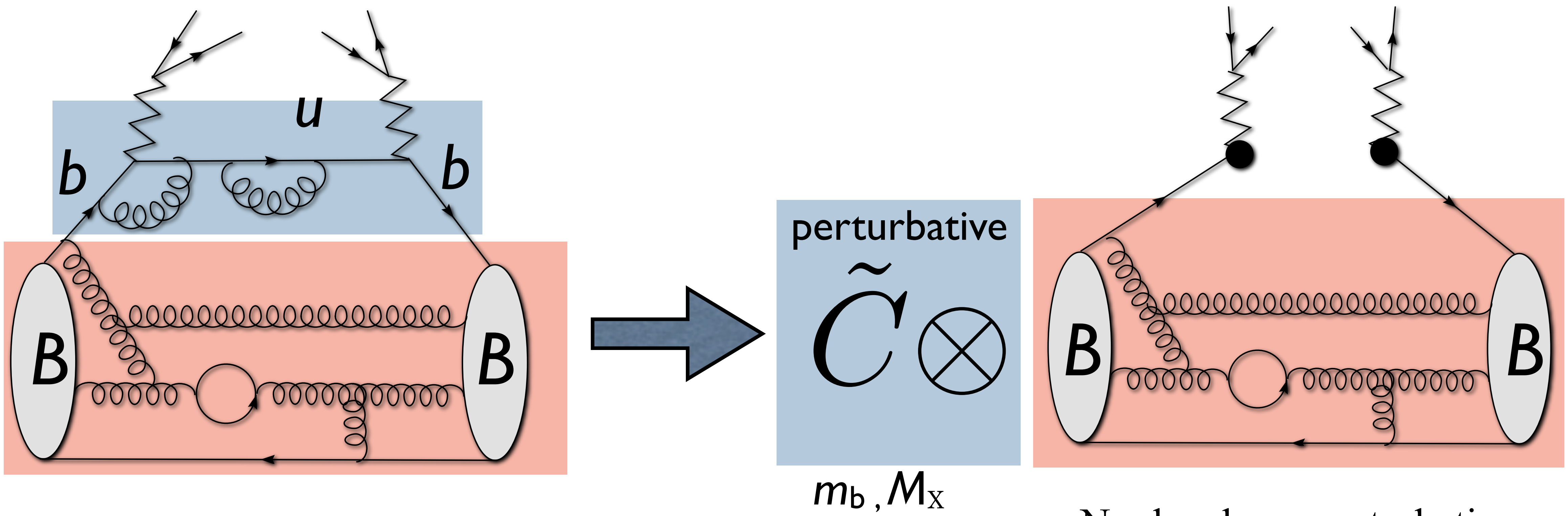
Function of $p_X \cdot k$! Nonlocal object in position space. Matrix element is “Shape function”

Total rate (or mild cuts)



Two relevant scales: $m_b \gg \Lambda_{QCD}$

Small M_X: “shape function region”

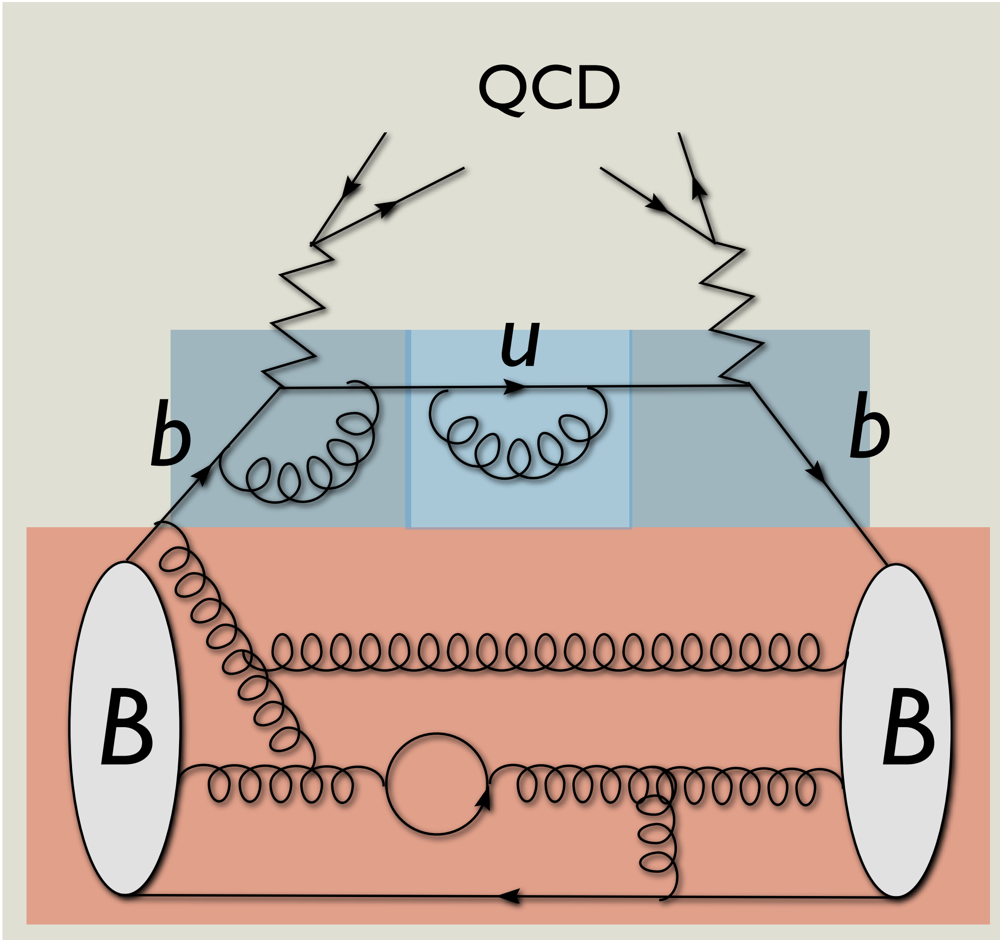


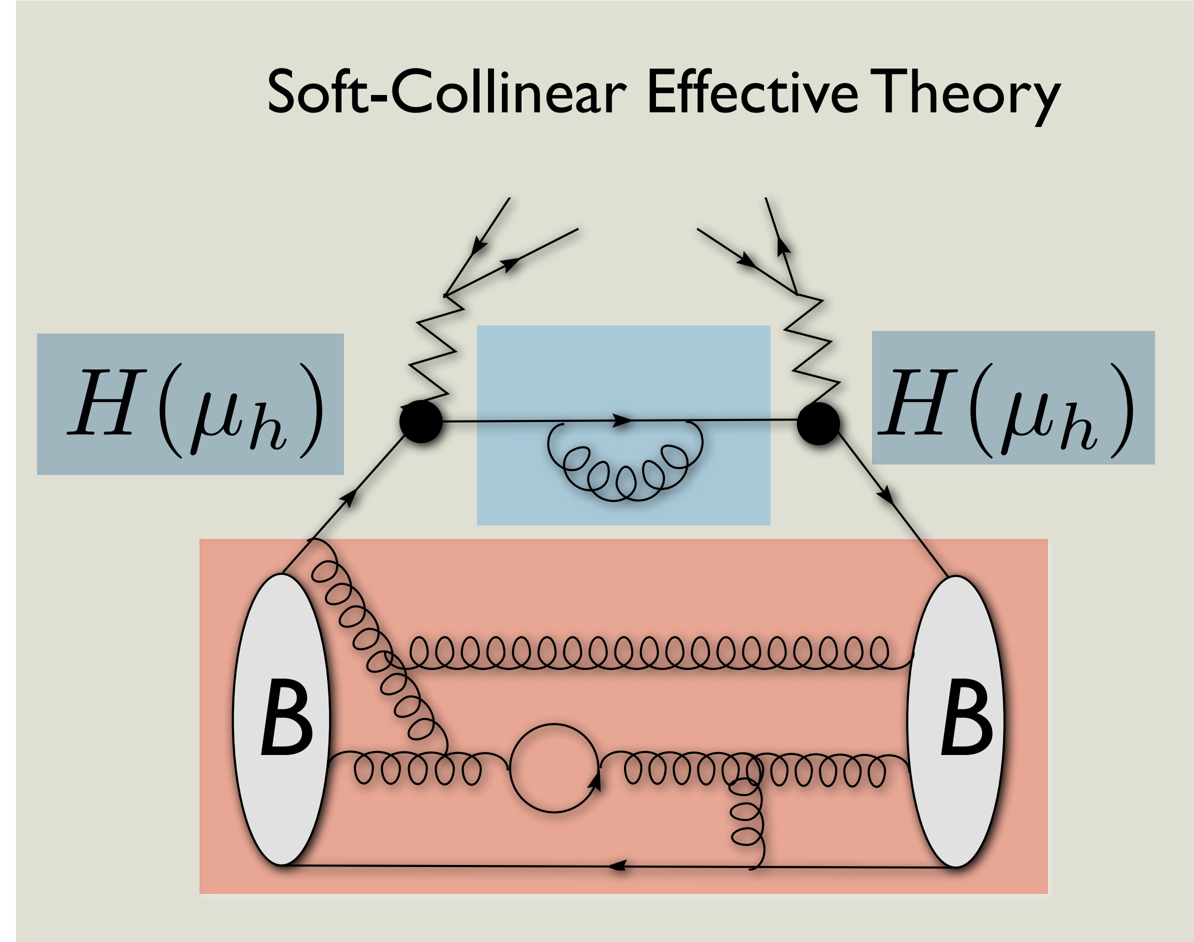
Nonlocal, nonperturbative matrix element “Shape function”

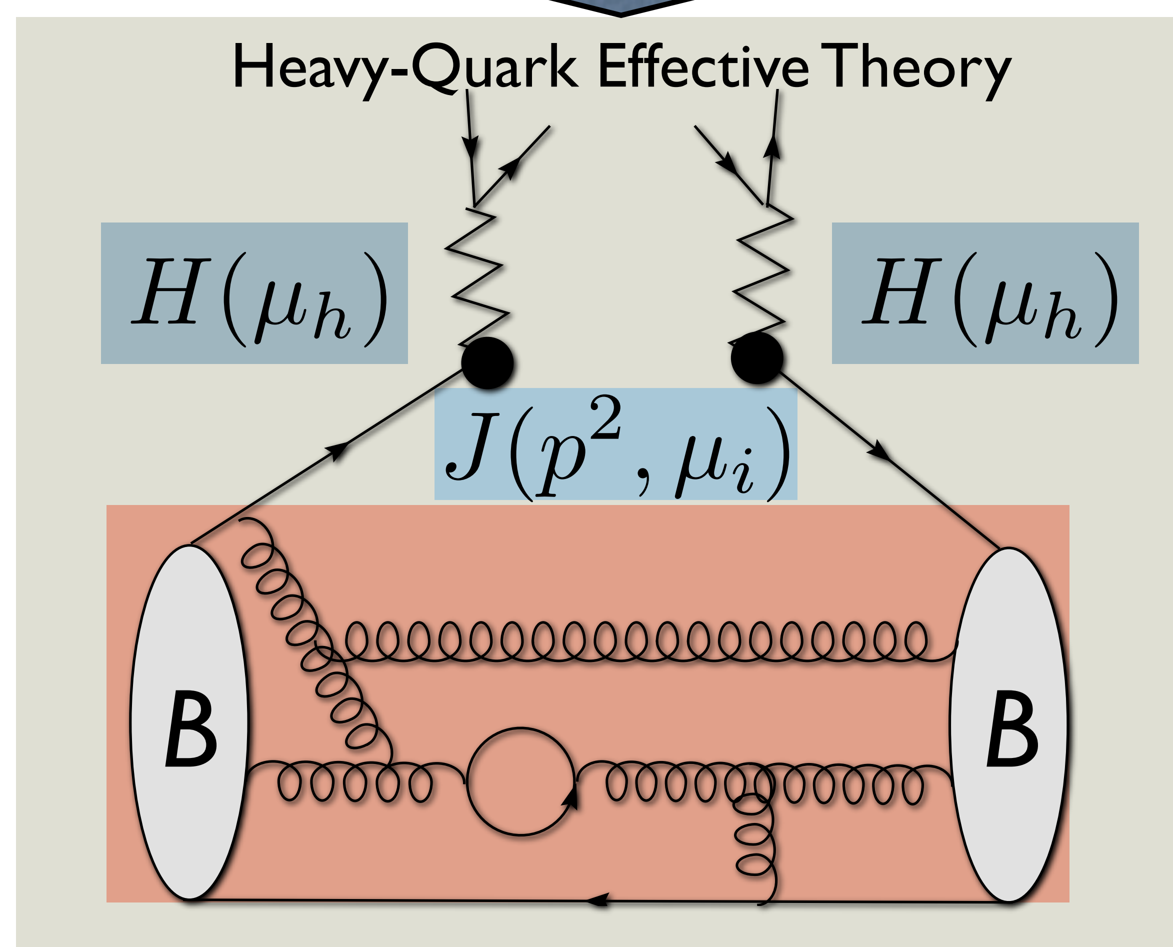
Three different scales: $m_b \gg M_X \gg \Lambda_{QCD}$

Double expansion: M_X/m_b and Λ_{QCD}/M_X

Can use soft-collinear effective theory (SCET) to perform expansion in a systematic way







Factorization theorem

$$\Gamma \sim H^2 J \otimes S$$

hard jet soft

shape function

Korchemsky, Sterman '94

Shape function S(ω)

- At this point things look bleak: Even in the limit $m_b \to \infty$, we need a nonperturbative shape *function* S(ω) as input!
  - Similar to hadron collider physics, where we need non-perturbative parton distributions to make predictions.
- Know a few properties: once we integrate over the spectrum, we obtain usual OPE expression.
  - Moments are given in terms of HQET parameters, such as m_b, λ_1.

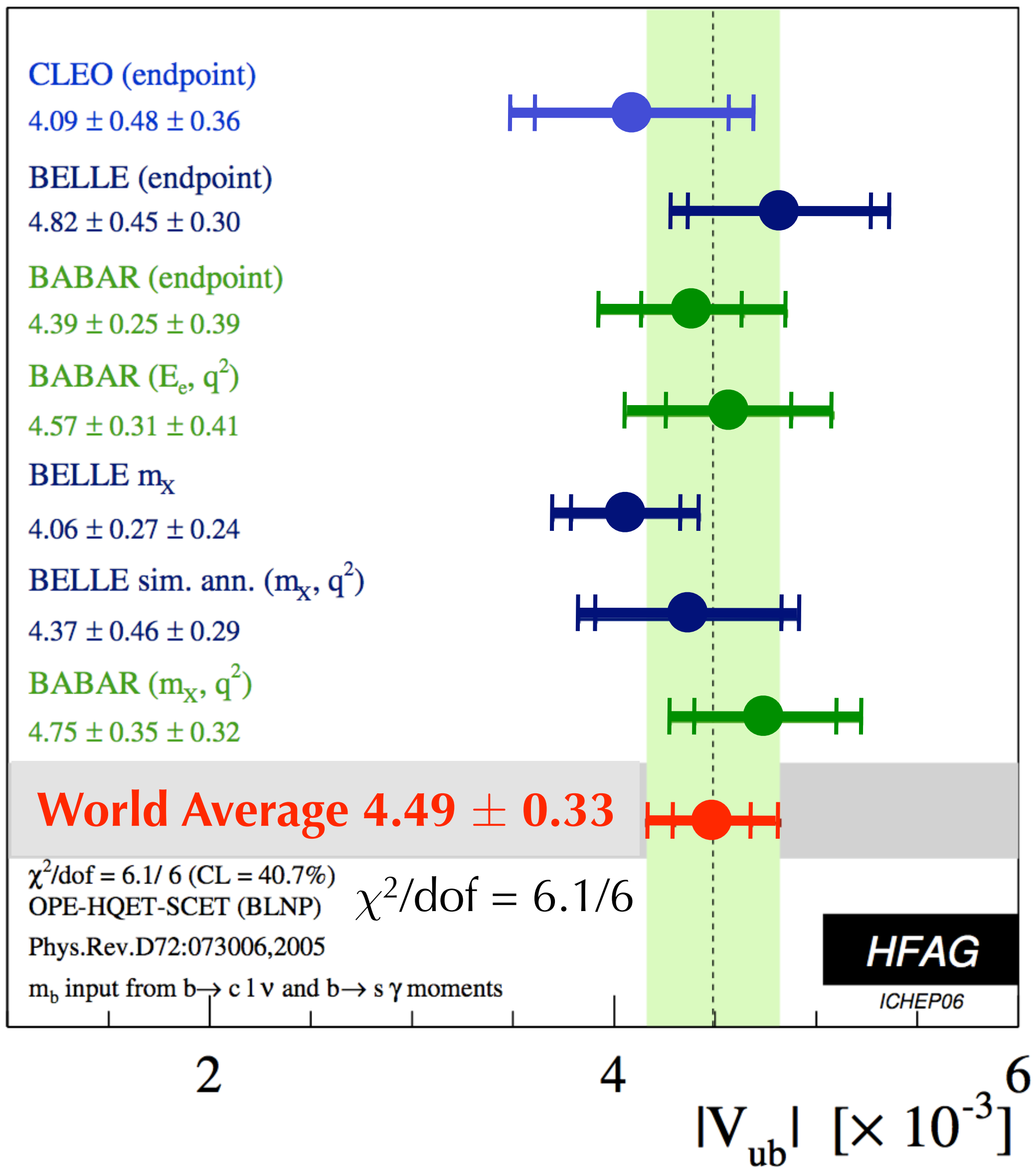
$B \to X_s \gamma$ to the rescue

- Fortunately, the *same* shape function S(ω) appears in the calculation of the $B \to X_s \gamma$ photon energy spectrum.

$$\frac{d\Gamma}{dE_\gamma} = H_\gamma \, J \otimes S$$

  - Only hard function differs from $B \to X_u l \nu$.
- Two strategies to extract $|V_{ub}|$:
  - Make ansatz for S(ω), depending on a number of parameters. Constrain with $B \to X_s \gamma$ spectrum and $B \to X_c l \nu$ moments.
  - Use relations between the $B \to X_s \gamma$ and $B \to X_u l \nu$ spectra in which shape function drops out.

V_{ub} using shape function



- $|V_{ub}|$ determined to ±7.3%

Statistical	±2.2%
Expt. syst.	±2.8%
$b \to c\ell\nu$ model	±1.9%
$b \to u\ell\nu$ model	±1.6%
SF params.	±4.2%
Theory	±4.2%

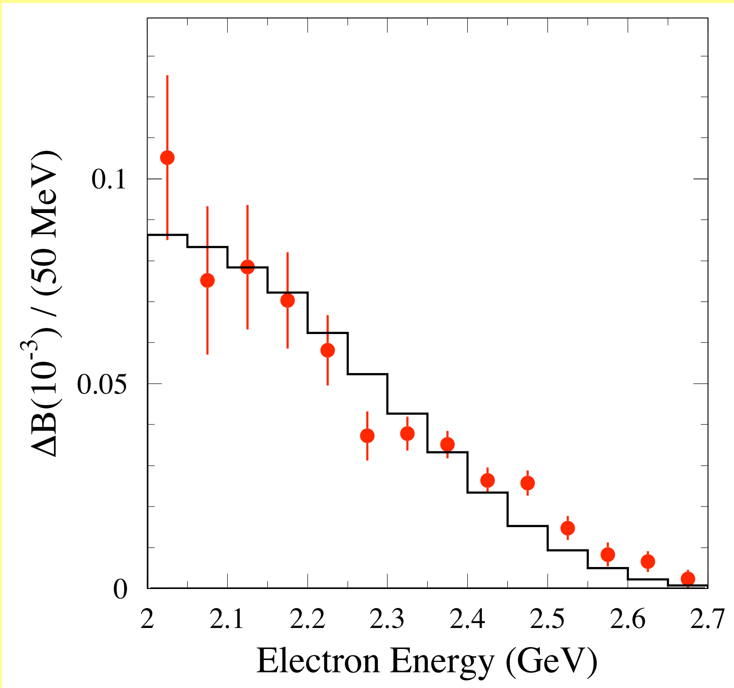
subleading SF, PT, WA

HFAG number is based on Lange, Neubert and Paz Phys.Rev.D72:073006,2005

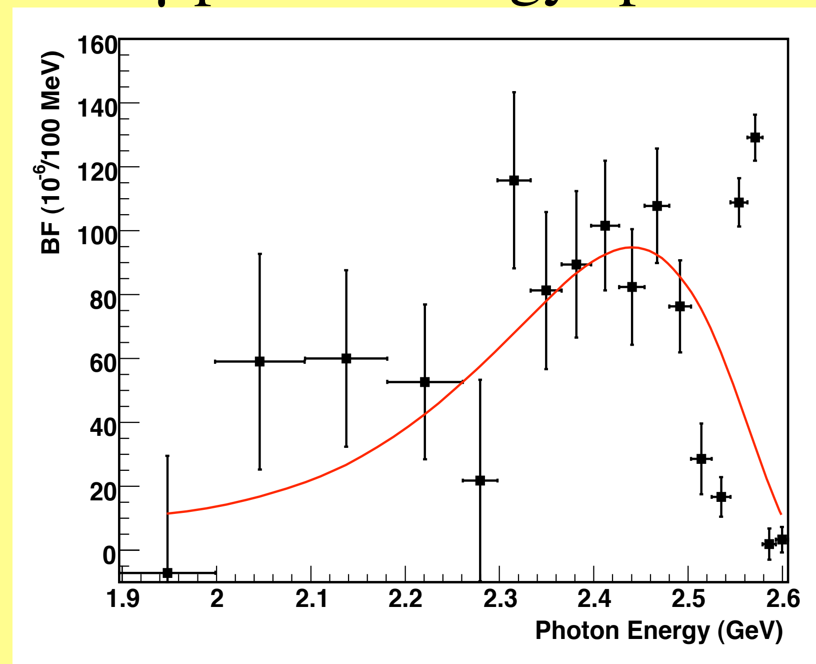
- Analysis also includes subleading shape functions.
- Uses $B \to X_s \gamma$ and $B \to X_c\, l\, \nu$ to constrain shape functions.
- Uses different parameterizations to estimate dependence on functional form.

V_{ub} without shape function

$B \to X_u\, e\, \nu$ electron energy spectrum



$B \to X_s\, \gamma$ photon energy spectrum



- Babar $|V_{ub}|$ values from weighted integrals over the two spectra appeared very recently in hep-ph/0702072.
- They use 3 different theoretical evaluations of the weight function.

Method	$\lvert V_{ub}\rvert \cdot 10^3$
LLR [3, 4]	$4.28 \pm 0.29 \pm 0.29 \pm 0.26 \pm 0.28$
Neubert [6]	$4.01 \pm 0.27 \pm 0.29 \pm 0.32 \pm 0.27$
BLNP [7, 8]	$4.40 \pm 0.30 \pm 0.41 \pm 0.23$

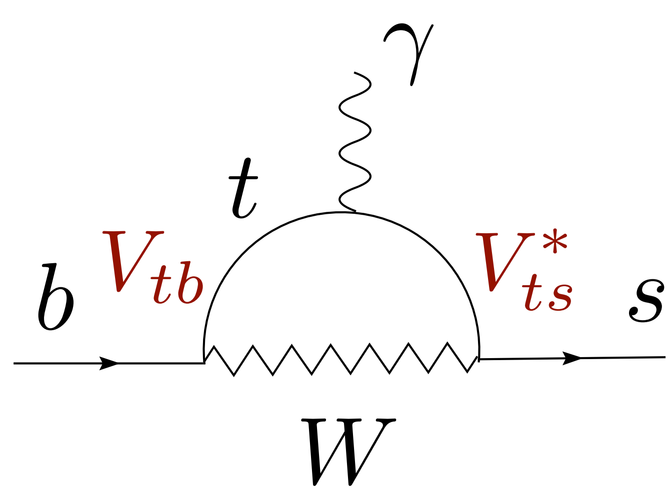
Uncertainties: $b \to u$, $b \to s$, theory, V_{ts}

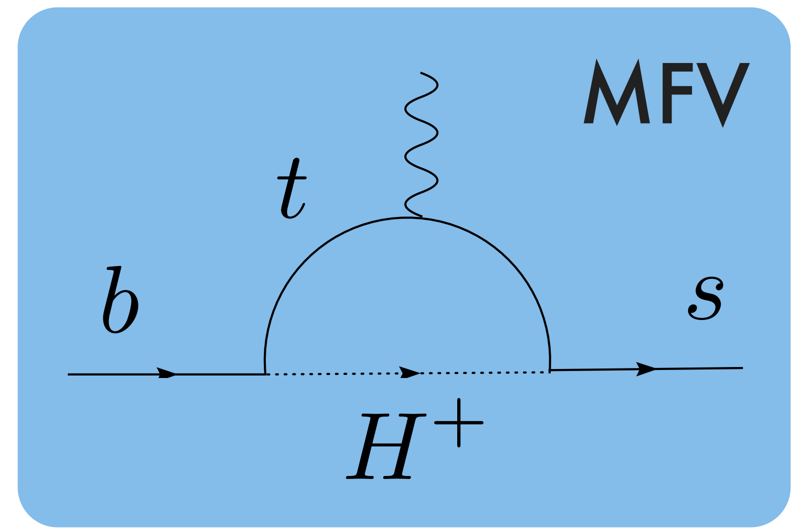
$B \to X_s \gamma$

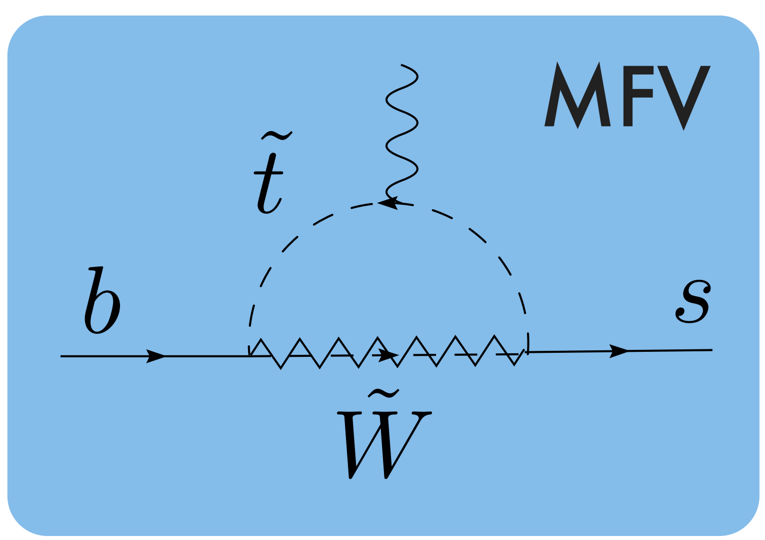
Chasing New Physics with 4-loops

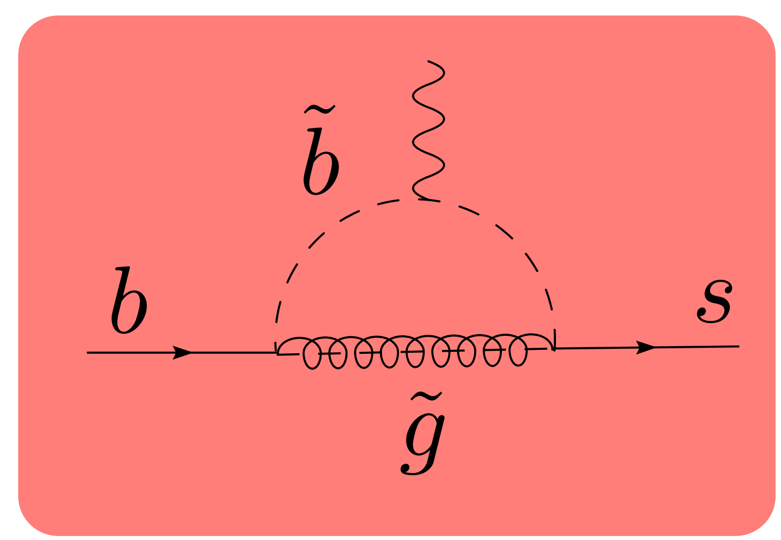
A sensitive probe of New Physics

- FCNC process. Loop suppressed in the SM
- e.g. strong constraint on the MSSM









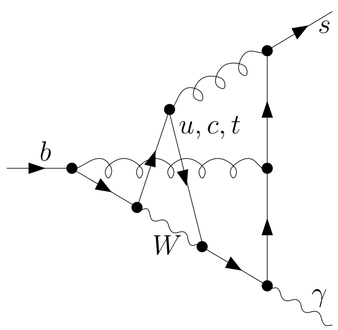
Elements of the NNLO calculation

- After large theory effort over the last years we have obtained the rate at NNLO level.
  - $O(20)$ papers with necessary calculations.
- Needs all of the following at NNLO:

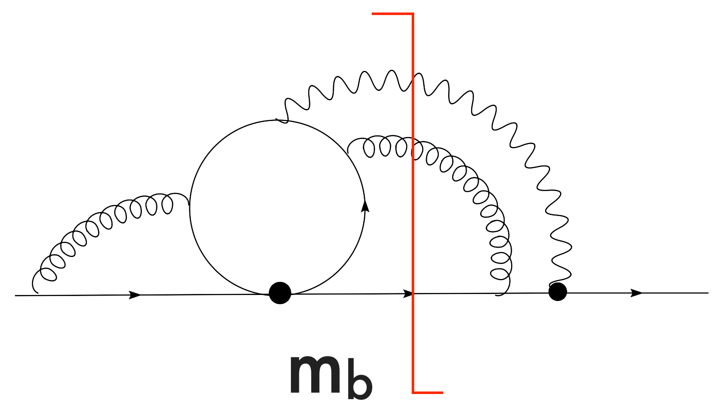
1. Effective weak Hamiltonian
   a. Matching at high scale (2- and 3-loop)
   b. RG evolution to low scale (3- and 4-loop)
2. Calculation of rate at NNLO
   a. OPE for total rate ($\leftarrow$ so far only estimate)
   b. Effect of the photon energy cut $E_\gamma > E_0 \approx 1.9\text{GeV}$

Match and run, match and run...

- Many energy scales. Use different effective theories to treat each of them in turn.
- $O(10^5)$ diagrams along the way...

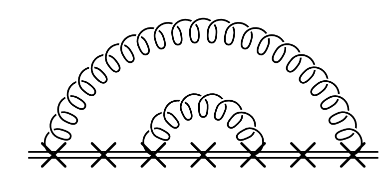


M_W, m_t, ...



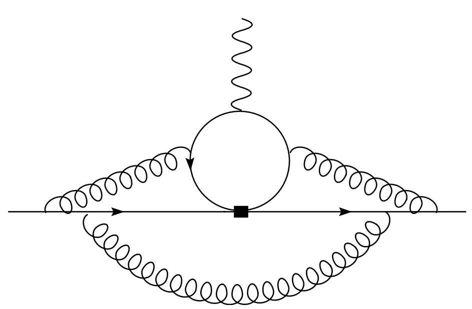
m_b

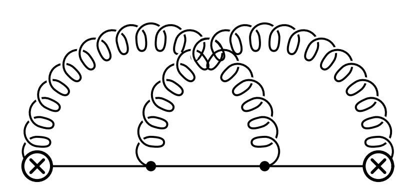
M_X



after photon energy cut

SM → Fermi Theory → SCET → HQET





NNLO result

- Experimental average (HFAG)

$$\mathrm{Br}(\bar{B} \to X_s \gamma) = (3.55 \pm 0.24\,^{+0.09}_{-0.10} \pm 0.03) \cdot 10^{-4}$$

  - for cut $E_\gamma > E_0 = 1.6\,\mathrm{GeV}$
  - stat.+syst., extrapolation to low E_0, $b \to \gamma d$ subtr.

- Theory @ NNLO (hep-ph/0610067 with hep-ph/0609232)

$$\mathrm{Br}(\bar{B} \to X_s \gamma) = (2.98 \pm 0.26) \cdot 10^{-4}$$

  - $^{+4}_{-6}\,\%$ perturbative, 4% parametric, 5% power corrections, 3% interpolation in m_c.
  - 1.4σ below exp. value. 1-2σ below NLO value. (Gambino Misiak '01 found BR=$(3.6\pm0.3)\times10^{-4}$ at NLO.)