The phenomenology of rare and semileptonic B decays

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Outline

- Exclusive B decays can test the SM and probe for New Physics
- Theoretical methods:
  - HQET
  - Heavy Hadron χPT
  - Soft-collinear effective theory (SCET)
- Recent progress at small and large recoil
- Outlook

Disclaimer: no discussion of inclusive decays, see the talk by Z. Ligeti

Why are these decays interesting?

- Semileptonic $B \to M\ell\nu$ decays can be used to determine CKM matrix elements

$$\Gamma(B \to D^{(*)}e\nu) \sim |V_{cb}|^2 , \qquad \Gamma(B \to \pi/\rho e\nu) \sim |V_{ub}|^2$$

- Radiative decays give information about $|V_{td}|$

$$\frac{\mathcal{B}(B \to \rho\gamma)}{\mathcal{B}(B \to K^*\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 R(1+\varepsilon_A)$$

- The rare decays $B \to K^*\gamma$ and $B \to K^{(*)}\ell^+\ell^-$ are sensitive to New Physics effects through their total rate and differential distributions (e.g. forward-backward asymmetry)
- The leptonic radiative decay $B \to \gamma e\nu$ can give information about the hadronic structure of the B meson (light-cone wave function)

- Exclusive decay amplitudes depend on more hadronic details than the inclusive modes: normalization + shape
- In $b \to c$ transitions heavy quark symmetry gives the normalization of the form factor (+ Luke's theorem) Isgur, Wise (1990)
- No such luck for heavy-to-light decays $\longrightarrow$ need to think harder...

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Good news:

In certain regions of the phase space, a model-independent description becomes possible

Experimental status - semileptonic

$$\mathcal{B}(B^0 \to \rho^- e^+ \nu) = (3.39 \pm 0.44 \pm 0.52 \pm 0.60) \times 10^{-4}$$

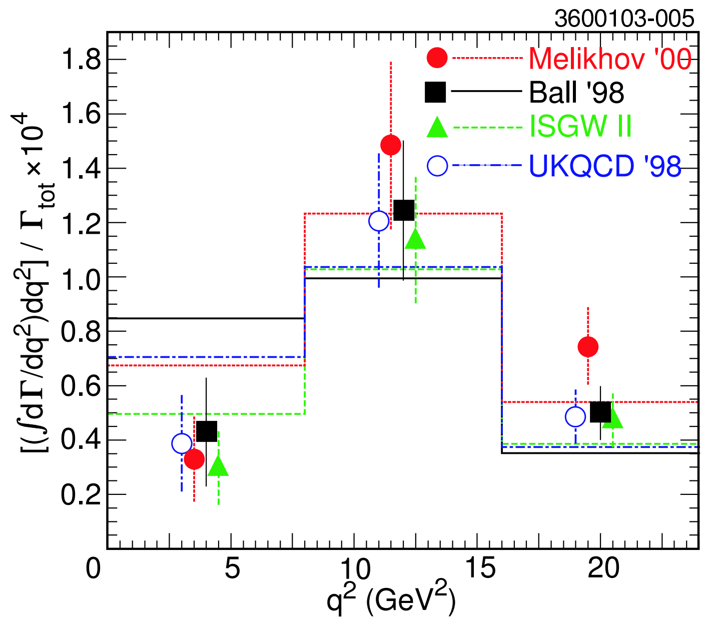
Babar, hep-ex/0207080

$$\begin{aligned}
\mathcal{B}(B^0 \to \pi^- \ell^+ \nu) &= (1.33 \pm 0.18 \pm 0.11 \pm 0.01 \pm 0.07) \times 10^{-4} \\
\mathcal{B}(B^0 \to \rho^- \ell^+ \nu) &= (2.17 \pm 0.34^{+0.47}_{-0.54} \pm 0.41 \pm 0.01) \times 10^{-4} \\
\mathcal{B}(B^+ \to \eta \ell^+ \nu) &= (0.84 \pm 0.31 \pm 0.16 \pm 0.09) \times 10^{-4}
\end{aligned}$$

CLEO, hep-ex/0304019

Decay distributions are also being probed $(B \to \rho e \nu)$

CLEO, hep-ex/0304019



Experimental status - radiative

1. Radiative decays

Experiment	Lumi (fb^{-1})	$\mathcal{B}(B^0 \to K^{*0}\gamma) \times 10^5$	$\mathcal{B}(B^{\pm} \to K^{*\pm}\gamma) \times 10^5$
CLEO	9	$4.55^{+0.72}_{-0.68} \pm 0.34$	$3.76^{+0.89}_{-0.83} \pm 0.28$
Belle	60	$3.91 \pm 0.23 \pm 0.25$	$4.21 \pm 0.35 \pm 0.31$
Babar	20.7	$4.23 \pm 0.40 \pm 0.22$	$3.83 \pm 0.62 \pm 0.22$

More precise data coming soon...

2. First observations of the rare radiative decays $B \to K^{(*)}\ell^+\ell^-$

$$\mathcal{B}(B \to K\ell^+\ell^-) = (0.78^{+0.24+0.11}_{-0.20-0.18}) \times 10^{-6}$$
$$\mathcal{B}(B \to K^*\ell^+\ell^-) = (1.68^{+0.68}_{-0.58} \pm 0.28) \times 10^{-6}$$

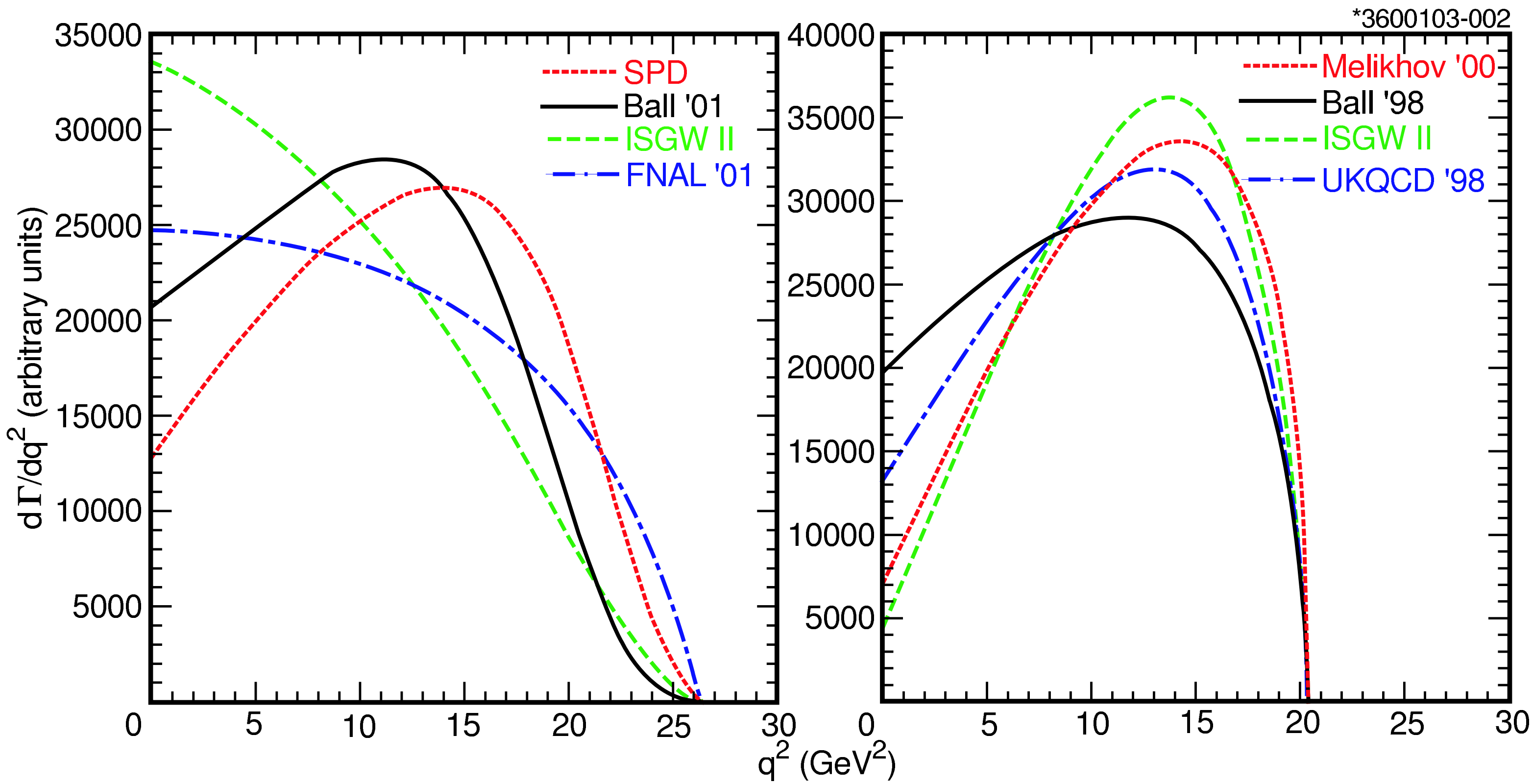
Babar, hep-ex/0207082

$$\mathcal{B}(B \to K\ell^+\ell^-) = (0.75^{+0.25}_{-0.21} \pm 0.09) \times 10^{-6}$$
$$\mathcal{B}(B \to K^*\ell^+\ell^-) < 1.4 \times 10^{-6}$$

Belle, hep-ex/0107072

Hadronic uncertainty

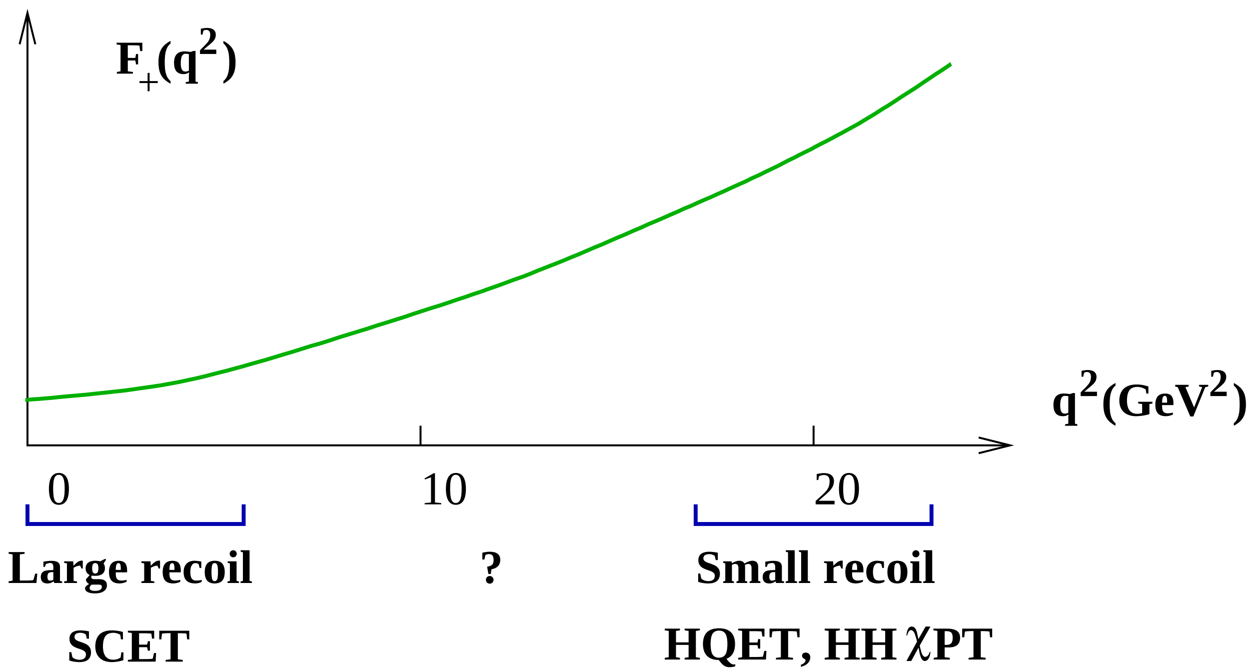
- The hadronic form factors describing $B \to M$ exclusive transitions are computed in models, QCD sum rules, lattice QCD, etc...
- Large spread of predictions $\to$ theoretical uncertainties



$B \to \pi e \nu$ $\qquad$ $B \to \rho e \nu$

In certain regions of phase space, a model-independent description becomes possible

Example: $B \to \pi \ell \nu$



Two regions where QCD simplifies $\to$ two effective theories:

$q^2 \sim q^2_{\rm max}$ - small recoil
QCD $\to$ HQET

$q^2 \sim 0$ - the large energy region
QCD $\to$ SCET

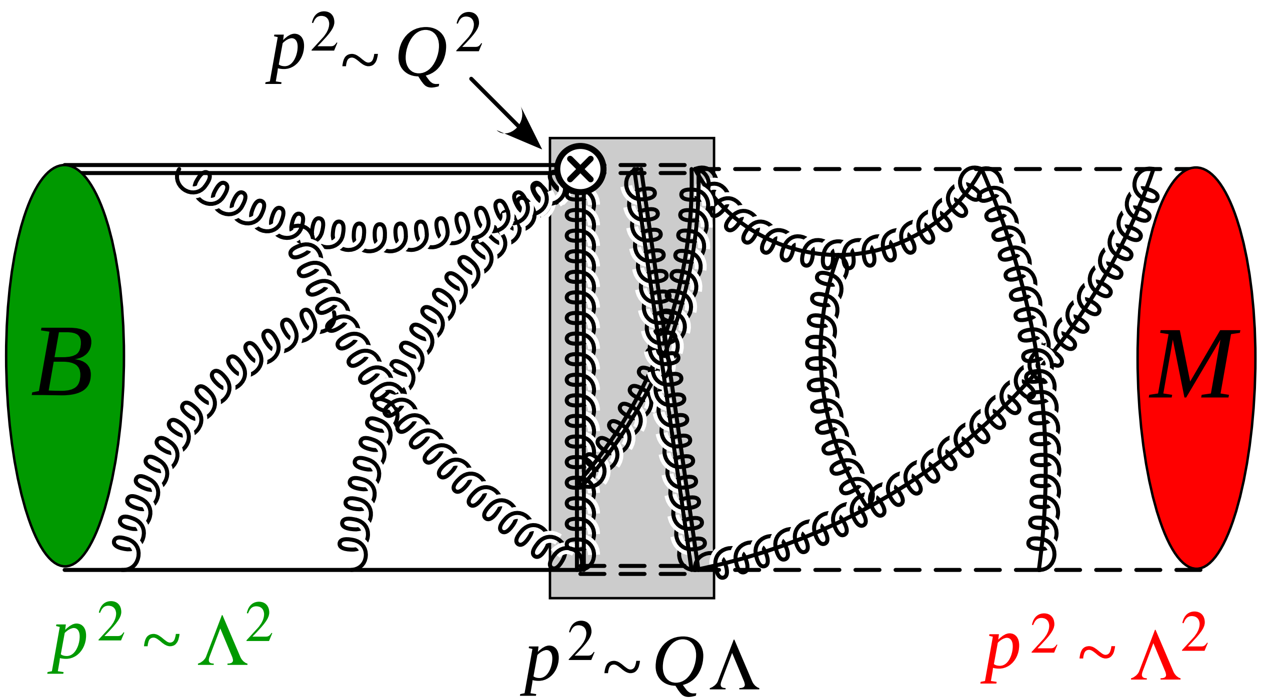
Bauer, Fleming, DP, Stewart, 2001 (see talk by S. Fleming)

Factorization

In the large energy region $E_\pi \gg \Lambda$, the heavy-light form factors satisfy a factorization theorem
Bauer, DP, Stewart

$$f_{B\to P}(q^2) \quad = \quad C(\mu)\zeta(E_\pi,\mu) + \int_0^1 dx dk_+ C_i(\mu,z) J_i(x,z,k_+,\mu)\phi_B^+(k_+)\phi_\pi(x)$$

"nonfactorizable" "factorizable"



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Ingredients: • Nonperturbative matrix elements (soft physics)

$\zeta(E_\pi,\mu)$ are matrix elements in the SCET

$\phi_B(k_+)$ and $\phi_\pi(x)$ are light-cone wave functions

• Perturbative quantities - calculable

Wilson coefficients $C_i(\mu) = 1 + O(\alpha_s(Q))$

Jet functions $J(x,z,k_+,\mu) = O(\alpha_s(\sqrt{\Lambda Q}))$

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Comments: • The Wilson coefficients $C(\mu)$ contain Sudakov logs: sometimes it is assumed that the nonfactorizable term is suppressed as $m_b \to \infty$

• In the absence of the factorizable term, there are many symmetry relations among form factors
Charles et al, 1999

• However, both terms are of the same order in Λ/Q

Model-independent approach

Measure as many independent form factors as possible, and extract the unknown nonperturbative matrix elements $\zeta(Q,\mu)$, $\phi_B(k_+)$, $\phi_\pi(x)$

E.g., at tree level in matching at the hard scale Q, the $B \to \pi/\rho$ form factors contain only 3 unknown matrix elements

$$\zeta_P(Q,\mu), \qquad \zeta_\perp(Q,\mu)\,, \qquad \langle k_+^{-1}\rangle_B = \int dk_+ \frac{\phi_B(k_+)}{k_+}$$

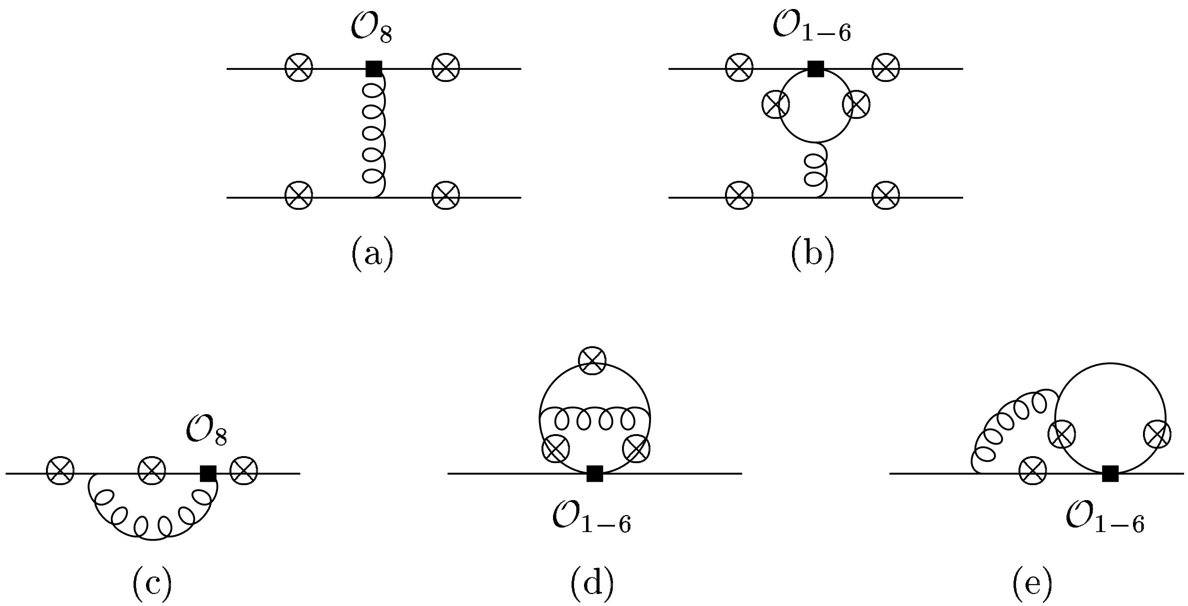
The B wave function moment can be also extracted from the shape of the photon spectrum in $B \to \gamma e \nu$ Korchemsky, DP, Yan, 1999

Working at tree level in $\alpha_s(Q)$ and $\alpha_s(\Lambda Q)$, there is one remaining symmetry relation for $B \to P$ Beneke, Chapovsky, Diehl, Feldmann

$$f_+(q^2) - f_0(q^2) = \frac{q^2}{m_B^2} f_T(q^2) + O(\Lambda/Q)$$

$B \to K^*\gamma$ **and** $B \to K^* e^+ e^-$

Additional contributions from matrix elements of 4-quark operators $\to$ have to be included in the factorization relation
Bosch, Buchalla; Beneke, Feldmann, Seidel; Ali, Parkhomenko



Accounting for these effects, the observed $\mathcal{B}(B \to K^*\gamma)$ gives

$T_1(0)|_{\mu=m_b} = 0.27 \pm 0.04$ [vs. 0.38 ± 0.06 (LC-QCDSR)] Ball, 1995

Close to new lattice QCD # $T_1(0) = 0.25(5)(2)$ S.P.QCD R. (2002)

Progress at zero recoil

- Normalization is not fixed from a symmetry
- Heavy quark symmetry determines the scaling of the form factors + symmetry relations among the tensor $T_{1,2}(q^2)$, vector $V(q^2)$ and axial $A(q^2)$ form factors Isgur, Wise; Burdman, Donoghue, 1991

$$T_1(q^2) - \frac{m_B^2 - m_V^2}{q^2} T_2(q^2) = \frac{2m_B}{m_B + m_V} V(q^2) + O(m_b^{-1/2})$$

$$T_1(q^2) + \frac{m_B^2 - m_V^2}{q^2} T_2(q^2) = -\frac{m_B^2 + m_V^2 - q^2}{m_B(m_B + m_V)} V(q^2) + \frac{m_B + m_V}{m_B} A_1(q^2) + O(m_b^{-\frac{3}{2}})$$

Extract $T_1(q^2)$ by combining them, which requires knowledge of the $O(m_b^{-1/2})$ correction in the first relation

Recently computed Grinstein, DP, 2002

$$T_1(q^2) = \frac{m_B - \bar{\Lambda}}{m_B + m_V} V(q^2) - \mathcal{D}(q^2) + O(m_b^{-3/2})$$

The correction depends only on the local matrix element of a dimension-4 operator

$$\langle V(p',\varepsilon)|\bar{q}iD_\mu b|B(v)\rangle = -2i\mathcal{D}(q^2)\epsilon_{\mu\nu\lambda\sigma}\varepsilon^*_\nu p_\lambda p'_\sigma$$

$\mathcal{D}(q^2)$ vanishes exactly in the quark model $\rightarrow$ likely to be small

Application:

- Predict the tensor form factor $T_1(q^2)$ (relevant for rare decays $D \rightarrow K^* e^+ e^-$) from the measured $D \rightarrow K^* e\nu$ form factors

$$T_1(1) = 0.74 \pm 0.06$$

using $V(1) = 1.35 \pm 0.11$ E791 Collaboration

Conclusions and outlook

- Significant recent progress in the theory of exclusive semileptonic and radiative B decays, with input from the soft-collinear effective theory (SCET)
- SCET separates the contributions of the physics on different scales, resulting into a factorization relation for the $B \to M$ form factor
- Clean separation into factorizable and nonfactorizable pieces
- Together with lattice QCD, the SCET provides a model-independent approach for the study of exclusive B decays

More work to do:

- Resum all Sudakov logs, potential large numerical impact
- Investigate the structure of the power corrections $\sim \Lambda/Q$