Theory of exclusive semileptonic and rare B decays

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Outline

- Exclusive B decays can test the SM and probe for New Physics
- Theoretical methods:
  - Heavy Quark Effective Theory (HQET)
  - Heavy Hadron Chiral Perturbation Theory (HHχPT)
  - Soft-collinear effective theory (SCET)
  - Lattice QCD
- Recent analytical progress for heavy-to-light decays in the large recoil region $(E_M \gg \Lambda)$
- How can the Super B factory help?
- Outlook

Why exclusive B decays?

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

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

while 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. photon helicity, forward-backward asymmetry)
- The $B \to M$ form factors are important ingredients entering the theoretical description of nonleptonic B decays $\to$ CP violation
- Experimentally, the detection efficiency is better in exclusive channels, at the expense of statistics $\to$ Super B factory

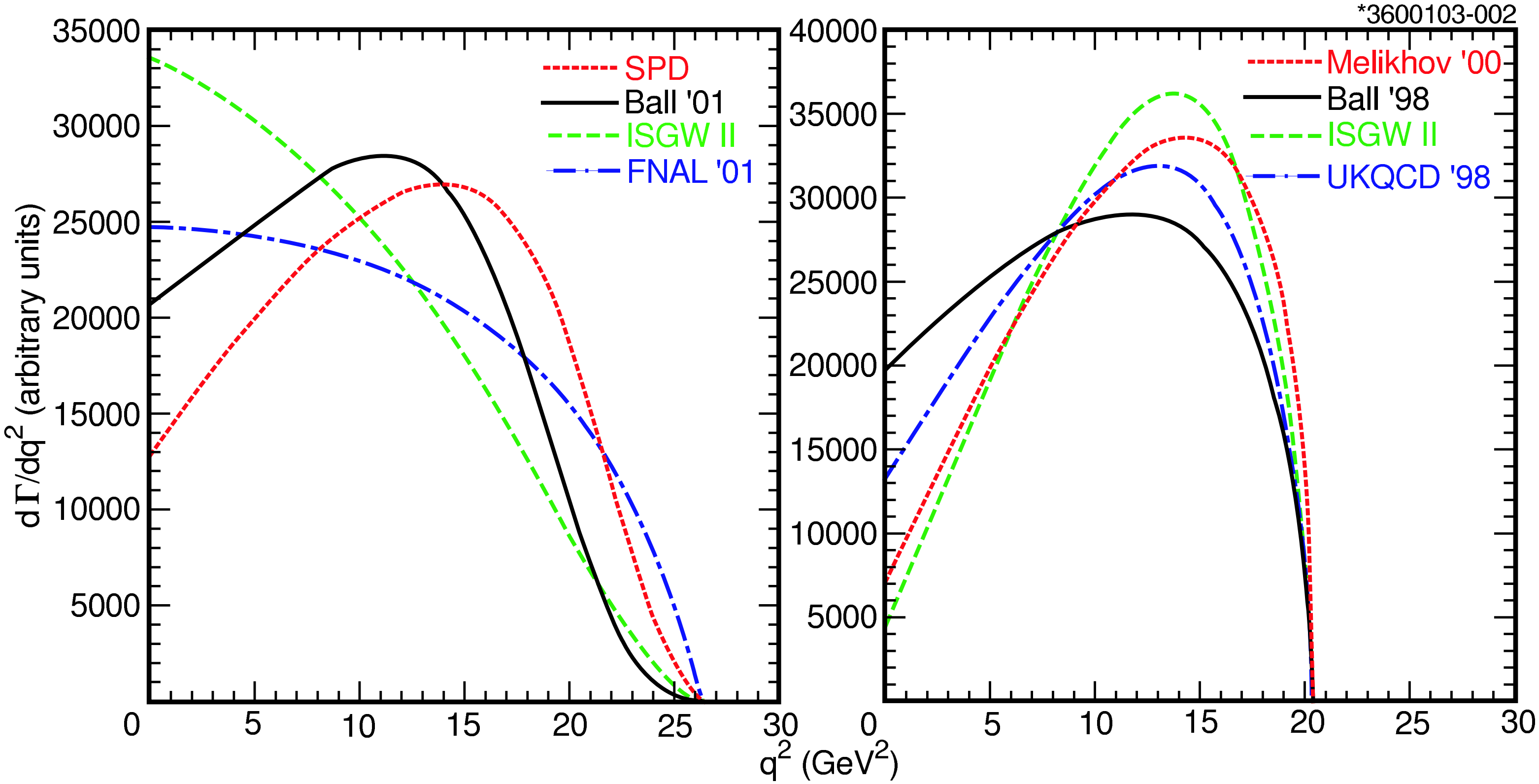
Theory issues

- Inclusive $B \to X_s\gamma$ and $B \to X_u e\bar{\nu}$ decays have a clean theoretical description: OPE + $1/m_b$ heavy quark expansion
- Exclusive decay amplitudes depend on more hadronic details than the inclusive modes
- In $b \to c$ transitions heavy quark symmetry is very predictive:
  - the shapes of $B \to D$ and $B \to D^*$ form factors are related
    Isgur, Wise (1990)
  - the normalization of these form factors is fixed at zero recoil
- No such information on normalization and shape is available in general for heavy-to-light decays $B \to M$

$\to$ need to think harder...

Hadronic uncertainty

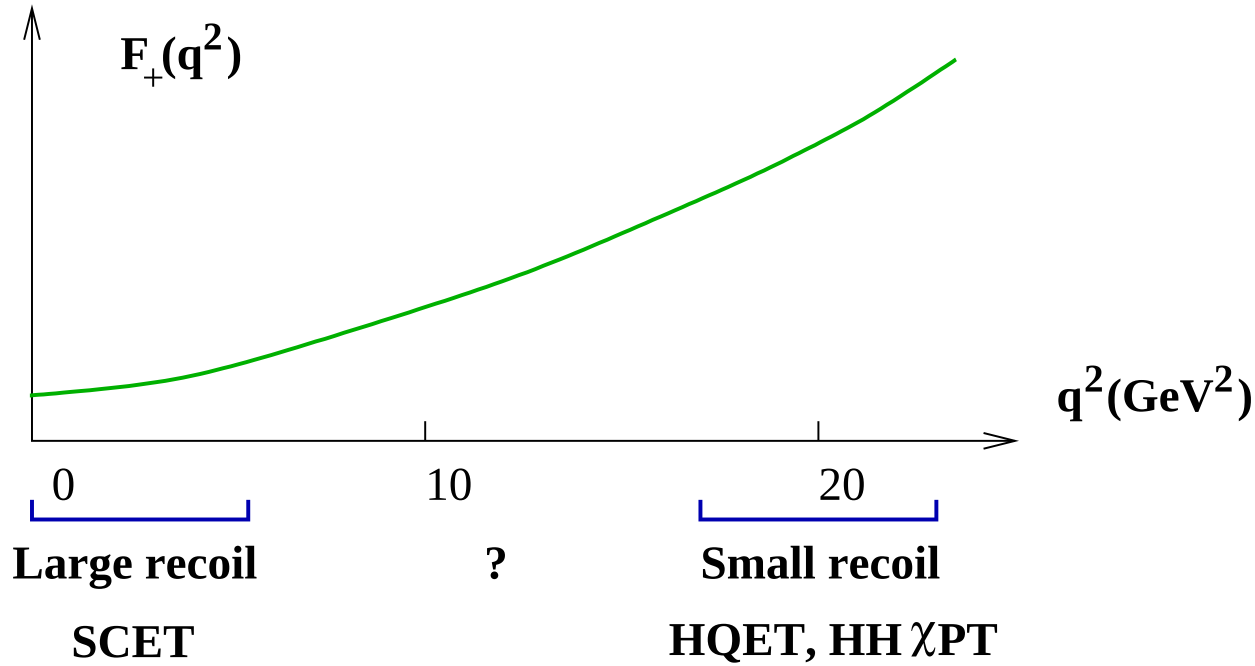
- The hadronic form factors describing $B \to M$ exclusive transitions are computed in models, QCD sum rules, lattice QCD, etc...
- Large spread of predictions $\to$ theoretical uncertainties



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

Good news: 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

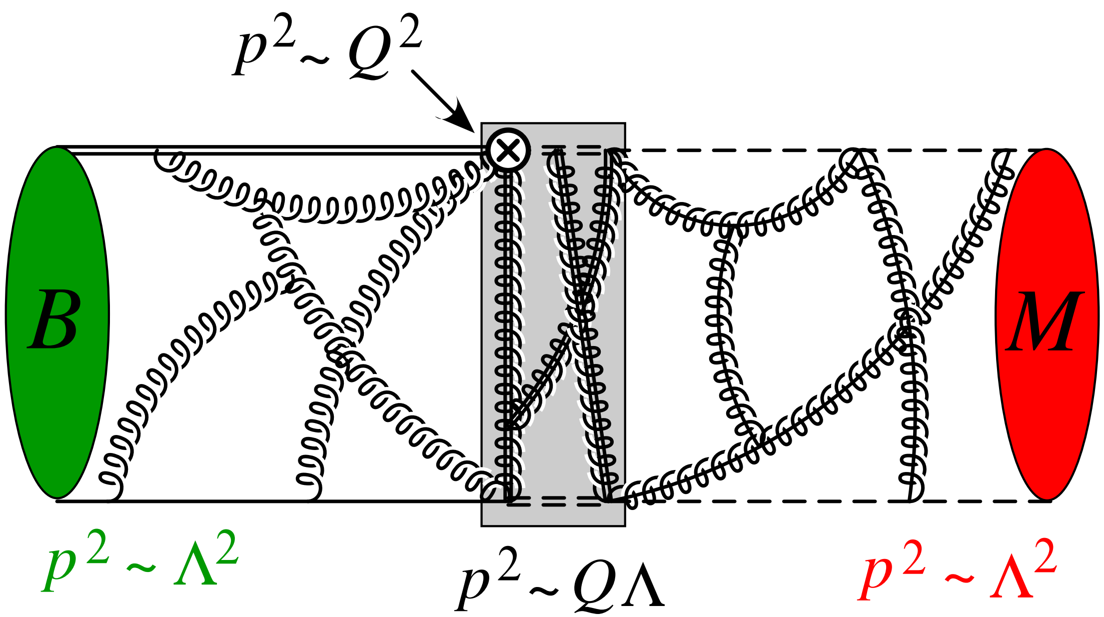
Factorization

In the large energy region $E_\pi \gg \Lambda$, the heavy-light form factors $B \to M$ satisfy a factorization theorem

{Beneke, Feldmann}, {Bauer, DP, Stewart}, {Lange, Neubert}

$$f_i(E) = C_i^{(0)}(E,\mu)\zeta(E,\mu) + \int_0^1 dx dk_+ C_i^{(1)}(E,\mu,z) J_i(x,z,k_+)\phi_B^+(k_+)\phi_M(x)$$

"nonfactorizable" "factorizable"



Factorization

$$f_i(E) = C_i^{(0)}(E,\mu)\zeta(E,\mu) + \int_0^1 dx dk_+ C_i^{(1)}(E,\mu,z) J_i(x,z,k_+)\phi_B(k_+)\phi_M(x)$$

<u>Ingredients</u>

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

Factorization

$$f_i(E) = C_i^{(0)}(E,\mu)\zeta(E,\mu) + \int_0^1 dx dk_+ C_i^{(1)}(E,z,\mu) J_i(x,z,k_+)\phi_B(k_+)\phi_\pi(x)$$

Comments

- Both terms are of same order in Λ/E, $f_i(E) \sim (\Lambda/Q)^{3/2}$
- Soft-collinear factorization of $\zeta(E, \sqrt{\Lambda E}, \mu)$, messenger modes
  Lange, Neubert
- Convergence of the x, k_+ convolutions Beneke, Feldmann
- The Wilson coefficients $C(E,\mu)$ contain Sudakov logs $\log^2(2E/\mu)$: $C^{(0)}(E,\mu) \sim E^{-\beta(E)}$, with $\beta(E) \sim 0.12 - 0.24$ (Sudakov suppression)
- Only power-like dependence on m_B/E is in $C^{(0,1)}(E,\mu)$

“Symmetry” relations

Reduction in the number of independent parameters:
Assuming that the jet function $J(x, k_+)$ is known, all $B \to M$ form factors are given in terms of a few reduced hadronic matrix elements

- $B \to P$ decays: $f_+(E), f_0(E), f_T(E)$ require $\zeta^P(E, \mu)$
- $B \to V$ decays: $V(E), A_{0,1,2}(E), T_{1,2}(E)$ require $\zeta_\perp^V(E), \zeta_\parallel^V(E)$

plus the leading twist meson light-cone wave functions $\phi_B^+(k_+)$ and $\phi^P(x), \phi_\parallel^V(x), \phi_\perp^V(x)$

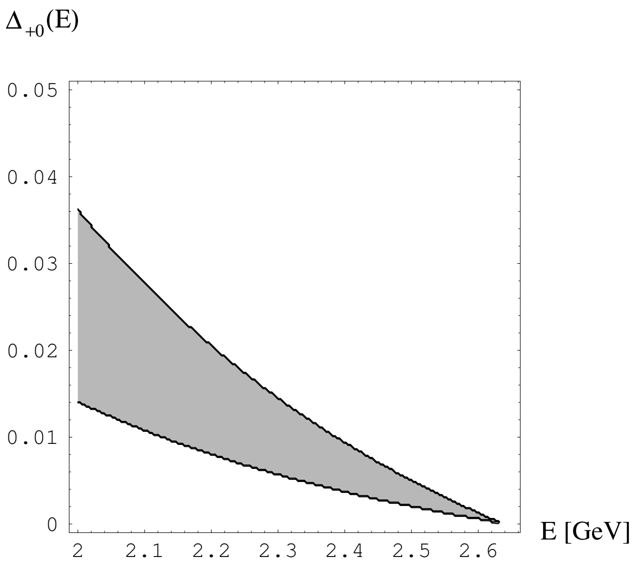
At tree level in the jet function $O(\alpha_s(Q\Lambda))$, only the inverse moments are required

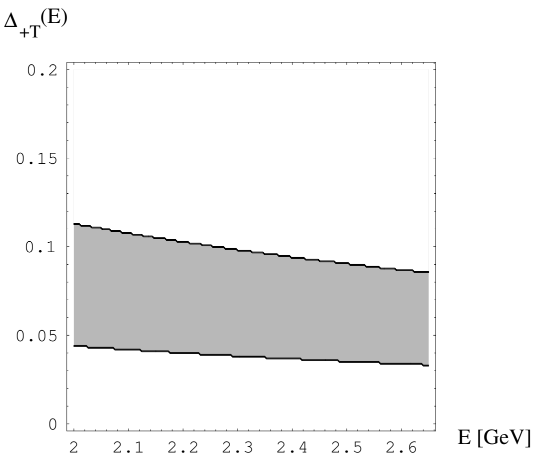
$$\langle k_+^{-1} \rangle_B = \int dk_+ \frac{\phi_B(k_+)}{k_+}, \quad \langle x^{-1} \rangle_{P,V\parallel,V\perp} = \int_0^1 dx \frac{\phi_{P,V\parallel,V\perp}(x)}{x}$$

Symmetry-breaking corrections

Define calculable combinations of form-factors.
E.g. for $B \to \pi$ Beneke, Feldmann

$$\Delta_{+0}(E) = f_+(E) - \frac{m_B}{2E} f_0(E)\,, \qquad \Delta_{+T}(E) = f_+(E) - \frac{m_B}{m_B + m_P} f_T(E)$$





<u>Problems:</u> Large hadronic uncertainties from $\phi_B^+(k_+)$
These predictions could have large corrections if $\alpha_s(E\Lambda) \sim O(1)$.
Need to include the jet function nonperturbatively!

Model-independent approach

Work to all orders in the jet function $\alpha_s^n(Q\Lambda)$ DP, I. Stewart

E.g. for the $B \to \pi$ form factors ($i = 0, +, T$)

$$f_i(E) = C_i^{(0)}(E)\zeta^P(E,\mu) + N\left(c_0^{(i)} + \frac{m_B}{E}c_1^{(i)} + \frac{m_B^2}{E^2}c_1^{(i)}\right)$$

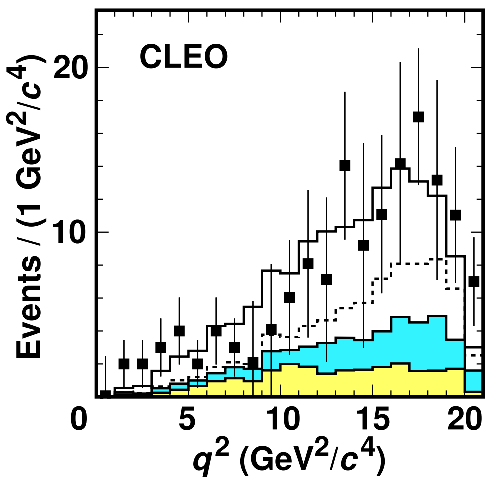
The expansion coefficients $c_{0,1,2}^{(i)}$ satisfy symmetry relations

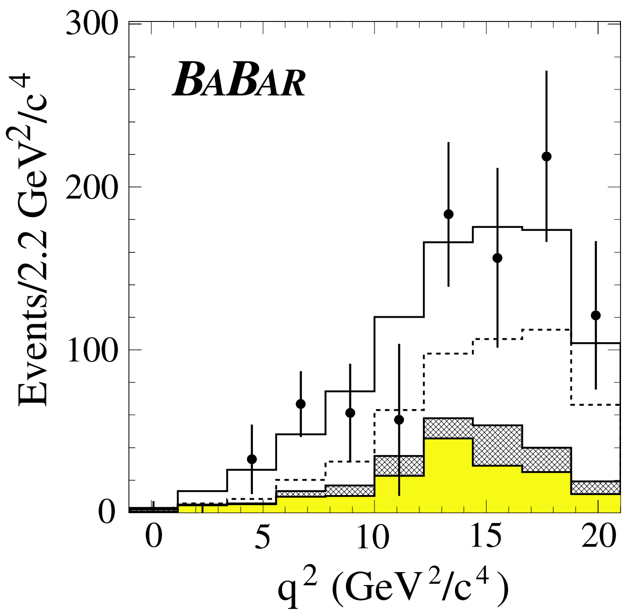
$$\frac{c_0^{(+)}}{c_0^{(0)}} = -2\,, \quad \frac{c_2^{(+)}}{c_2^{(0)}} = -1 + O(\alpha_s(E))\,, \quad \frac{c_2^{(+)}}{c_2^{(T)}} = 1 + O(\alpha_s(E))\,.$$

Determine the nonperturbative parameters from experiment

Input from experiment

Measure as many independent form factors as possible, and extract the hadronic parameters $\zeta^P, c_j^{(i)}$





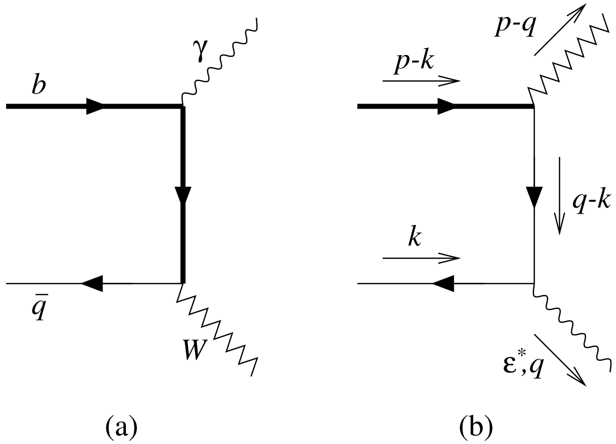
QCD based-approach (as opposed to pole fits).

Need more precise data $\longrightarrow$ Super B Factory

$B \to \gamma e \nu, B \to \gamma e^+ e^-$

Chirality suppression in leptonic decays $B \to \ell\nu$ can be avoided by adding one photon to the final state $\to$ enhanced branching ratios of $\sim 10^{-6}$

Burdman, Goldman, Wyler



Factorization theorem for $E_\gamma \gg \Lambda$

Sachrajda, de Gennon; Lunghi, DP, Wyler; Becher et al.

$$f_i(E_\gamma) = \frac{Q_q f_B m_B}{2E_\gamma} C_i(E_\gamma, \mu) \int dk_+ J(E_\gamma k_+, \mu) \frac{\phi_B(k_+)}{k_+}$$

Predictions

The jet function $J(E_\gamma k_+, \mu)$ has an expansion in $\alpha_s(\sqrt{\Lambda E_\gamma})$

- Predictions to all orders in the jet function: symmetry relations
  Lunghi, DP, Wyler; Sachrajda, de Gennon

$$f_V(E_\gamma) = f_A(E_\gamma)\,, \qquad \frac{f_T(E_\gamma)}{f_V(E_\gamma)} = 1 + O(\alpha_s(E_\gamma))$$

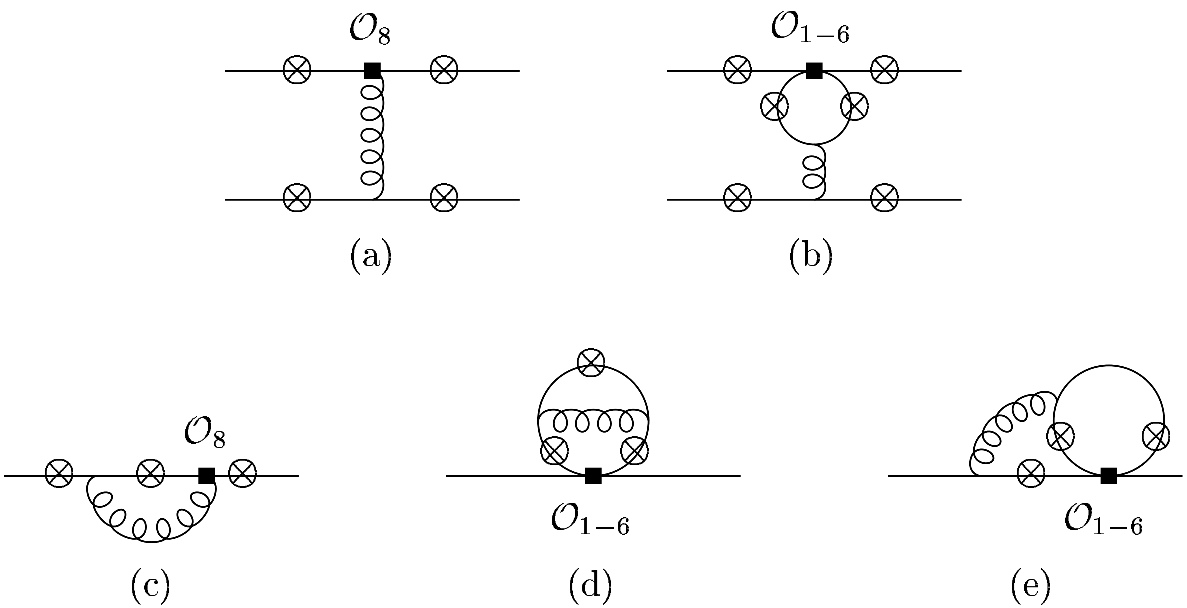
- Working at lowest order in the jet function, the decay amplitudes are given in terms of $\lambda_B = \langle k_+^{-1} \rangle_B$

Measuring the photon energy spectrum in $B \to \gamma e \nu$, one can extract information about the B light cone wave function.

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

Additional contributions from matrix elements of 4-quark operators in the weak Hamiltonian

$$\mathcal{H}_W = \frac{G_F}{\sqrt{2}} V_{cb}V_{cs}^*[C_1(\mu)(\bar{c}b)(\bar{s}c) + C_2(\mu)(\bar{s}b)(\bar{c}c)]$$



$\longrightarrow$ have to be included in the factorization relation

Bosch, Buchalla; Beneke, Feldmann, Seidel; Ali, Parkhomenko

Selected results

- The observed $\mathcal{B}(B \to K^*\gamma)$ gives Beneke, Feldmann, Seidel

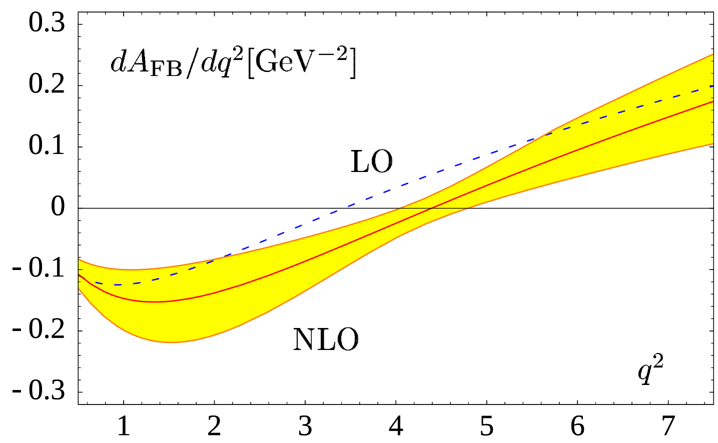
$T_1(0)|_{\mu=m_b} = 0.27 \pm 0.04$ [vs. 0.38 ± 0.06 (LC-QCDSR)] Ball, 1995

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

- Corrections to the forward-backward asymmetry in $B \to K^* e^+ e^-$

The position of the zero q_0^2 gives a relation between C_7 and C_9^{eff}, which are sensitive to the presence of New Physics Burdman, Ali et al.

Power corrections could be significant!



$$\text{Re}\left(\frac{C_7}{C_9^{\text{eff}}}\right) = -\frac{m_b}{q_0^2}\left[\frac{T_2(q_0^2)}{A_1(q_0^2)}(m_B - m_V) + \frac{T_1(q_0^2)}{V(q_0^2)}(m_B + m_V)\right]$$

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
- Model-independent approach for the study of exclusive heavy-light decays with energetic light mesons

Challenge to experimentalists:

- Measure q^2 spectra for semileptonic (e.g. $B \to \rho e \nu)$ and rare B decays (e.g. $B \to K^* \ell^+ \ell^-$)
- Measure the photon energy spectrum in the radiative leptonic decays $B \to \gamma e \nu$ (can give important information about the B light-cone wave function)

Further theory progress can come from:

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

Combined with information from lattice QCD, the SCET approach could give a complete theoretical description of the exclusive B decays