Rare B Decays at the Tevatron

Gustavo Burdman

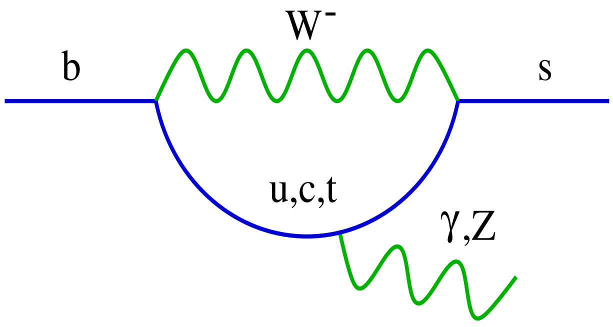
University of Wisconsin, Madison

Outline

- Intro: The resolving power of loop-induced B decays.
- Exclusive vs. Inclusive. Two examples:
  ($b \to s\gamma$ vs. $B \to K^*\gamma$) and
  ($b \to s\ell^+\ell^-$ vs. $B \to K^*\ell^+\ell^-$).
  Discussion of Tevatron potential.
- New Physics: Examples. Clean observables sensitive to SM extensions. Correlations with K physics and CP violation in Bs.
- Other: B_s, B_c, Heavy Baryons; ...

FCNCs Induced at One Loop

- In the SM, Flavor Changing Neutral Currents (FCNCs) are forbidden at tree level. For instance, $b \to s$ transitions can only occur starting at one loop:



- These transitions are sensitive to heavy physics in the loop. For instance, in the SM $b \to s$ is dominated by the top-W loop. $=>$ Test of the SM.

- Physics beyond the SM contributing to the loop could give large deviations. E.g.: In SUSY, contributions from charged scalars, gauginos and squarks could lead to deviations of $\mathcal{O}(1)$.

Exclusive vs. Inclusive Decays

- Inclusive Modes: $B \to X_s \gamma$, $B \to X_s \ell^+ \ell^-$, ...
  - Theoretically cleaner. They have small theoretical uncertainties mostly from perturbative QCD and other controlled approximations such as the HQET and the OPE.
  - Experimentally more challenging. Need clean detector environment for precise measurements.
- Exclusive Modes: $B \to K^* \gamma$, $B \to K^* \mu^+ \mu^-$, ...
  - Large theoretical uncertainties from hadronic form-factors. The stuff of Lattice calculations. Symmetries and related tricks may help in *some* cases.
  - Cleaner experimental signals, especially at hadron colliders.

Factorization of Short Distance Physics in $b \to s$ Transitions

Effective Hamiltonian at low energies:

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}^* V_{ts} \sum_{i=1}^{10} C_i(\mu)\, \mathcal{O}_i(\mu)$$

Results from integrating out heavy particles.

- C_i: Wilson coefficients. Reflect the content of the short distance physics, e.g. the stuff inside the loop.
- $\mathcal{O}_i$: Operator basis. All possible (Lorentz invariant, etc.) giving rise to $b \to s$. Their matrix elements contains the long distance physics.

New Physics will affect the matching conditions on the C_i at $\mu = M$.
E.g. in the SM $M \simeq M_W$.

$B \to X_s\gamma$

- Short distance determined by $C_7(\mu)$ corresponding to

$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b \bar{s}_L \sigma_{\mu\nu} b_R \, F^{\mu\nu}$$

So that the branching ratio is

$$Br(B \to X_s\gamma) = \ldots |C_7^{eff}(m_b)|^2$$

- The theoretical prediction is
$Br(B \to X_s\gamma)_{\rm th} = (3.30 \pm 0.15 \pm 0.26) \times 10^{-4}$

- Experimentally:
$Br(B \to X_s\gamma)_{\rm CLEO} = (3.15 \pm 0.35 \pm 0.41) \times 10^{-4}$
$Br(B \to X_s\gamma)_{\rm ALEPH} = (3.11 \pm 0.80 \pm 0.72) \times 10^{-4}$

$B \to K^*\gamma$

- In the exclusive mode, the branching ratio involves hadronic uncertainties from the transition form-factor

$$Br(B \to K^*\gamma) = ...|C_7^{eff}(m_b)|^2 \; |T_1(0)|^2$$

with $T_1(q^2)$ a form-factor from

$$\langle K^*|\mathcal{O}_7|B\rangle$$

- Theoretical uncertainties large from predictions for T_1:
  - Lattice calculations: $q^2 = 0 \Rightarrow$ large K^* momentum. Difficult, but lots of progress.
  - Symmetries: Heavy Quark Symmetries relate T_1 to semileptonic form-factors.

$B \to X_s \ell^+ \ell^-$

- More complexity: γ-penguin + Z-penguin + box diagrams. Short distance is now determined by C_7 plus C_9 and C_{10}, where

$$\mathcal{O}_9 = \frac{e^2}{16\pi^2}(\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$$

$$\mathcal{O}_{10} = \frac{e^2}{16\pi^2}(\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

- Additional observables. Dilepton mass distribution, angular distributions (e.g. forward-backward asymmetry for leptons). More handles to disentangle new physics. For instance: sgn(C_7) not known from $B \to X_s\gamma$.

- Theoretically clean. Similar sources of uncertainty as from $B \to X_s\gamma$ (renormalization scale and scheme dependence, initial state Fermi motion, ...).

- Theoretical prediction:
  $Br^{\text{th.}}(B \to X_s \ell^+ \ell^-) \simeq (6-8) \times 10^{-6}$.
  Experimental bounds:
  $Br^{\text{exp.}}(B \to X_s \ell^+ \ell^-) < 5.7 \times 10^{-5}$.

$B \to K^* \ell^+ \ell^-$

- Hadronic uncertainties large from various form-factors. Almost all observables affected but these large theoretical errors.

- Hope:
  - Lattice calculations of weak transition matrix elements => predictions for form-factors.
  - Heavy Quark Spin Symmetry: relates the $B \to K^* \ell^+ \ell^-$ form-factors to the semileptonic form-factors in $B \to \rho \ell \nu$.
  - Forward-backward asymmetry zero: $A_{FB}(m_{\ell\ell})$ has a zero in the SM. The value of $m_{\ell\ell}$ for which $A_{FB}(m_{\ell\ell}) = 0$ (seems to be) free of hadronic uncertainties.

- May be best rare B mode at Tevatron: Clean signal and largest branching ratio. $Br^{\mathrm{th.}}(B \to K^* \ell^+ \ell^-) \simeq (1-5) \times 10^{-6}$

- Current limits: $Br^{\mathrm{exp.}}(B \to K^* \ell^+ \ell^-) < 10^{-5}$ from CLEO, CDF.

Test of the SM in $B \to K^* \ell^+ \ell^-$

$\ast$ Amplitude in terms of form-factors:

- "Semileptonic" type (from $\mathcal{O}_9, \mathcal{O}_{10}$):

$$\langle K^*(\mathbf{k},\epsilon)|\bar{s}_L \gamma_\mu b_L|B(\mathbf{p})\rangle => \begin{cases} V(q^2), A_1(q^2) \\ A_2(q^2), A_0(q^2) \end{cases}$$

- "Photonic" type (from $\mathcal{O}_7$):

$$\langle K^*(\mathbf{k},\epsilon)|\bar{s}_L \sigma_{\mu\nu} b_R|B(\mathbf{p})\rangle => \{T_1(q^2), T_2(q^2), T_3(q^2)$$

$\ast$ Using Heavy Quark Spin Symmetry (HQSS) we can write the T_i in terms of the semileptonic form-factors. Measurement of $B \to \rho\ell\nu$ => prediction for $B \to K^* \ell^+ \ell^-$ (assuming $SU(3)$).

$\ast$ But extracting V, A_1, A_2 from $B \to \rho\ell\nu$ is difficult. => Uncertainties still present in Br, $d\Gamma/dm_{\ell\ell}$ and $A_{FB}(m_{\ell\ell})$.

But, A_{FB} zero seems to be model-independent !!

$*$ The numerator of $A_{FB}(m_{\ell\ell})$ is

$$A_{FB}(s) \sim 4m_B k C_{10} \left\{ \frac{m_b}{s} \bar{C}_7 \left[(m_b + m_{K^*}) A_1 T_1 + (m_b - m_{K^*}) V T_2 \right] - \bar{C}_9 V A_1 \right\}$$

$*$ $A_{FB}(m_{\ell\ell}) = 0 =>$

$$\frac{\bar{C}_9}{\bar{C}_7} = \frac{m_b}{s_0} \left((m_B + m_{K^*}) \frac{T_1}{V} + (m_B - m_{K^*}) \frac{T_2}{A_1} \right)$$

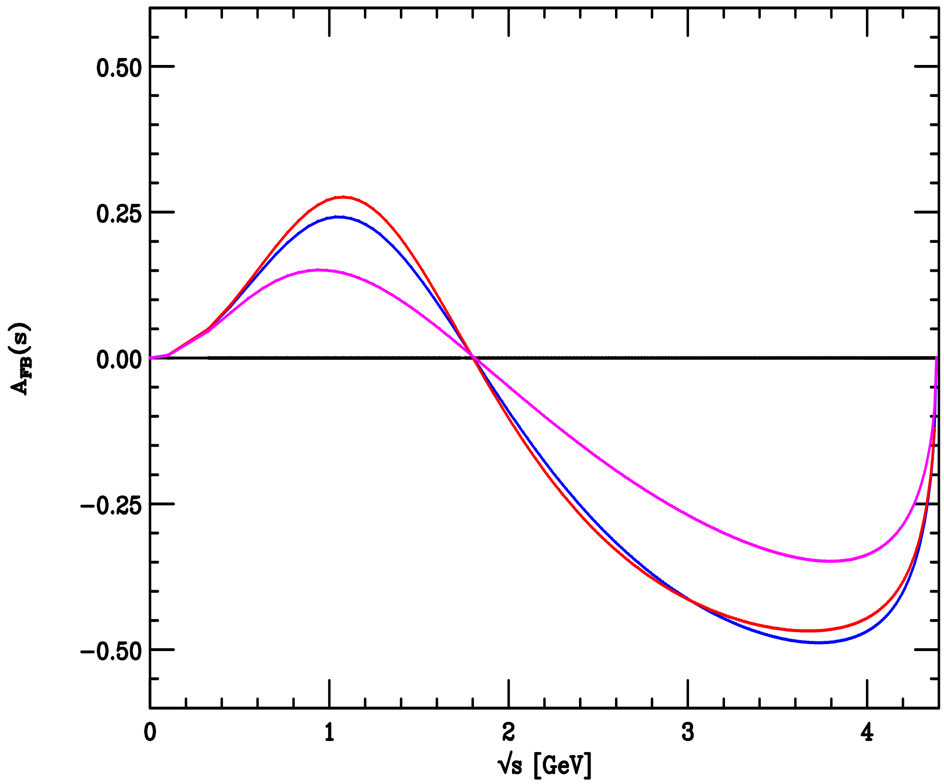
where s_0 is the dilepton mass where the asymmetry vanishes.

$*$ Using HQSS, we solve for T_1, T_2 in terms of V, A_1

$$\frac{\bar{C}_9}{\bar{C}_7} = \frac{mb}{s_0} \left\{ \frac{4m_B k^2}{(m_B + m_{K^*})^2} R_V + \frac{(m_B + m_{K^*})^2}{m_B R_V} + 4(m_B - E_{K^*}) \right\}$$

with $R_V \equiv V/A_1$ evaluated at s_0.

∗ The ratio R_V is very stable across models!



⟶ BSW*: Bauer, Stech and Wirbel, Z. Phys. C29, 637 (1985); Stech, Phys. Lett. B354, 447 (1995).

⟶ LCSR: Ball and Braun, Phys. Rev. D55, 5561 (1997).

⟶ MNS: Melikhov, Nikitin and Simula, Phys. Lett. B410, 210 (1997).

∗ R_V model-independent => Determination of s_0 ($A_{FB}(s_0) = 0$) is a clean test of the SM.
The position of the asymmetry zero is largely free from hadronic uncertainties and sensitive to new physics.

∗ But why is R_V insensitive to details of model calculations ?

- In constituent quark models (CQM), the "wave-function overlaps" for V and A_1 are the same and cancel in the ratio.
  E.g. BSW as well as other relativistic CQM.

- There is even a controlled approximation that gives this result: Large Energy Effective Theory (LEET).
  The limit $E_h \gg m_h$ (together with HQET) leads to m_h/E_h expansion and reduction of independent form-factors via LEET relations.

$*$LEET: (*Dugan and Grinstein '91, Charles et al. '99.*)

- For instance, for V and A_1 it predicts:

$$V = (1 + \frac{m_B}{m_{K^*}})\xi_T$$
$$A_1 = \frac{2E_{K^*}}{m_B + m_{K^*}}\xi_T$$

where ξ_T is the "transverse" form-factor and cancels in the ratio.

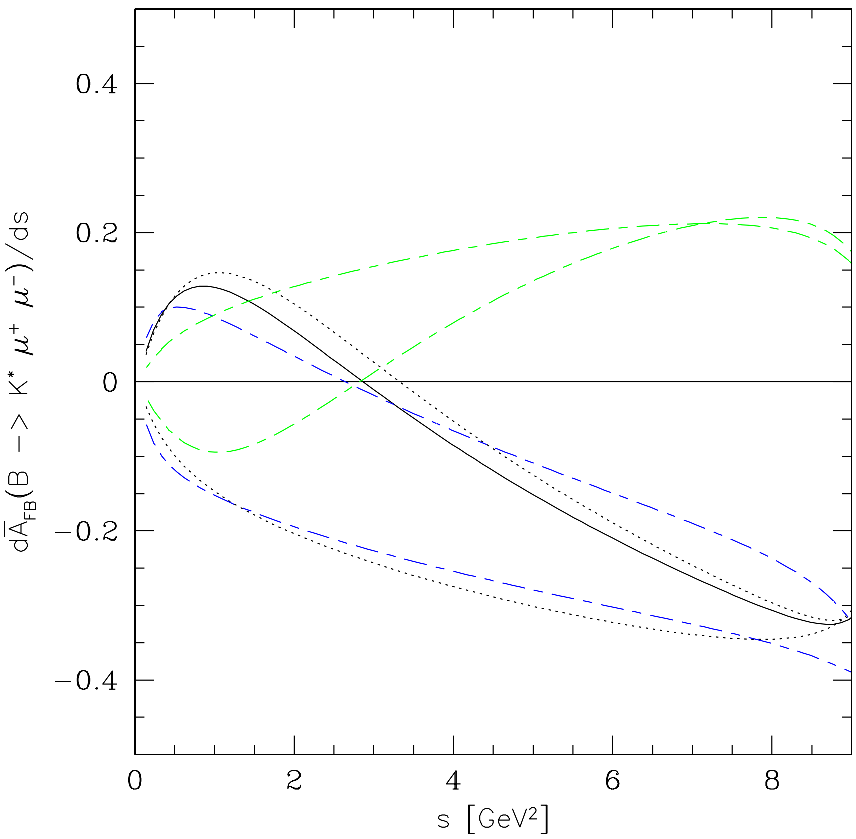
- This leads to $R_V \simeq (m_B + m_{K^*})^2/2m_b E_{K^*}$, which agrees with many CQM predictions (*e.g. Stech '95, Soares '95*);

- With this R_V we obtain: $\frac{\bar{C}_9}{\bar{C}_7} \simeq -\frac{2m_b}{s_0}(m_B - E_{K^*} - k)$ which in the SM gives $s_0 \simeq 3.3 \text{ GeV}^2$, or $m^0_{\ell\ell} \simeq 1.8 \text{ GeV}^2$.

New Physics

- SUSY : One loop contributions from superpartners as well as from the charged Higgs. A_{FB} is sensitive to the differences in the SUSY models and their choice of parameters.

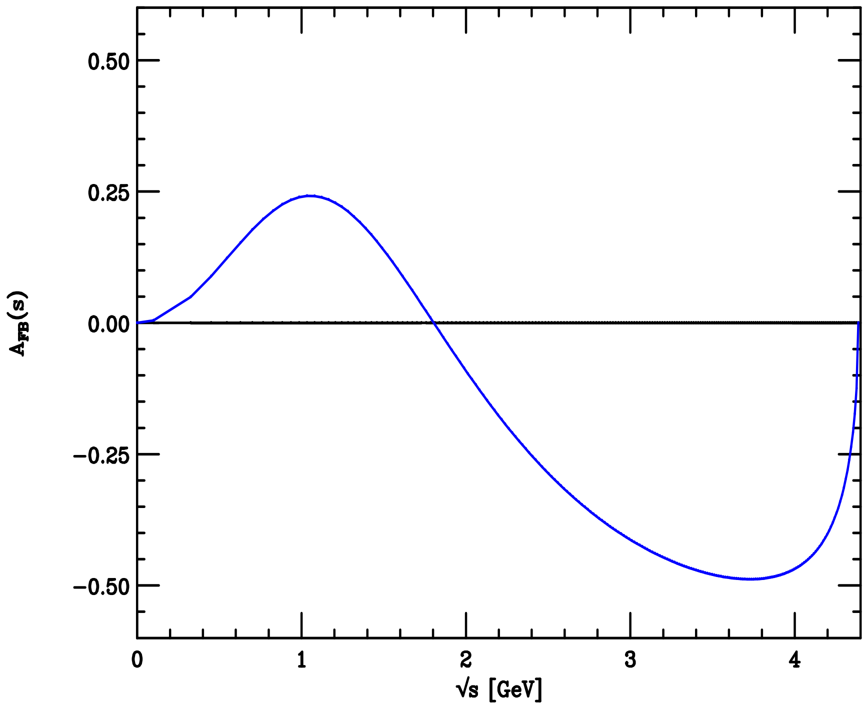
G. Hiller et al.



$\rightarrow$ SM, $\cdots >$ SUGRA with $\pm C_7$, $\rightarrow$ MIA with suppressed Br, $\rightarrow$ MIA with enhanced Br.

- Anomalous TGCs : Largest effects in B decays come from $\Delta\kappa_\gamma$ and Δg_1^Z (*G.B. '99*).
  - $\Delta\kappa_\gamma$: Affects C_7 and C_9
    => changes in A_{FB} zero.
  - Δg_1^Z: Affects only C_{10}
    => No effect on A_{FB} zero, although large effect on Br is possible.

Comment on the measurement of the A_{FB} zero:



Other modes:

- $B_s \to \phi \ell^+ \ell^-$: Very similar to $B \to K^* \ell^+ \ell^-$.
- $B_{d,s} \to \ell^+ \ell^-$: In general, Brs are small. With the exception of $Br(B_s \to \tau^+ \tau^-) \simeq 10^{-6}$. This is particularly sensitive to GIM violating extensions of the SM: e.g. a 2 TeV Topcolor Z' can give a factor of 4 enhancement.
- $\Lambda_b \to \Lambda \gamma$, $\Lambda_b \to \Lambda \ell^+ \ell^-$: Although theoretically more complicated than mesons, we should think what can we learn from them.