Heavy-to-Light B and Bs Decays

Lattice Meets Continuum :

QCD Calculations in Flavor Physics

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Heavy-to-Light Transitions

These processes provide many opportunities for testing consistency of the Standard Model (SM) and for searching for New Physics (NP).

- **CKM/Unitarity Triangle Physics**

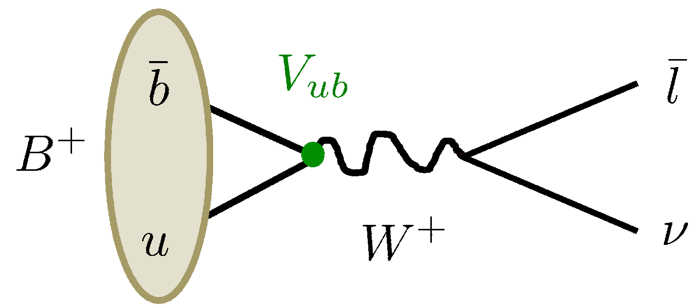
  wealth of consistency checks

- **Rare Decays**

  suppressed in SM, hence sensitive to NP

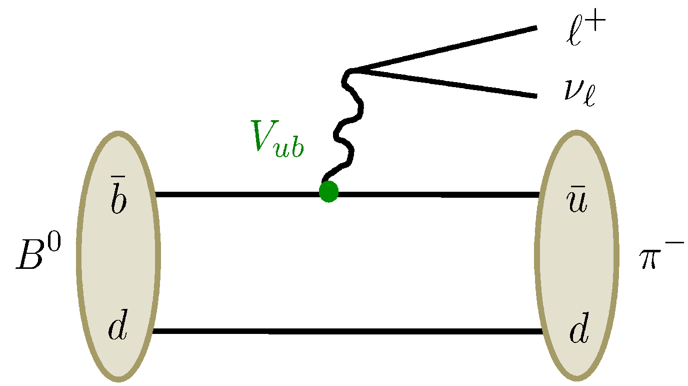
Heavy Meson Leptonic Decays

$B \to \tau\nu_\tau \qquad \propto |V_{ub}|^2 f_B^2$



Heavy Meson Semileptonic Decays

$B \to \pi l\nu, \quad B_s \to Kl\nu$,
$B \to D^{(*)}l\nu, \quad B_s \to D_s^{(*)}l\nu$
$\Longrightarrow |V_{ub}|^2 \left[\text{or } |V_{cb}|^2\right] \left(f_+(q^2)\right)^2$
or $\left(f_0(q^2)\right)^2$



Many consistency checks possible :

—- compare $|V_{xy}|$ from leptonic and semileptonic

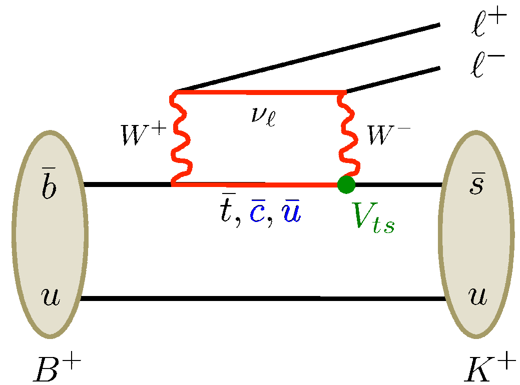
—- sides and angles of Unitarity Triangle

Heavy Meson Rare Decays

$B \to K l^+ l^-$

$B \to \pi l^+ l^-$

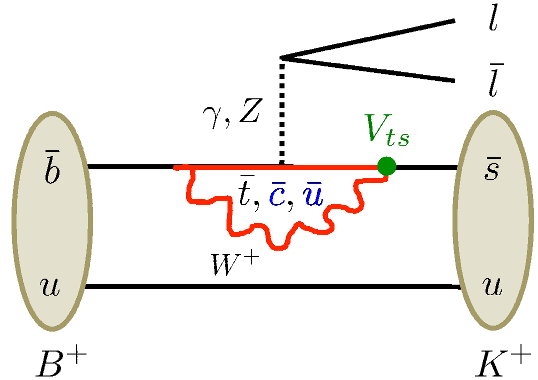
form factors f_+, f_0, f_T, angular distributions, constraints on Wilson Coeff.



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

$B_s \to \Phi l^+ l^-$

need many more form factors, ang. distr.



$B_{s,d} \to \mu^+ \mu^-$ requires f_{B_s}, f_B

These are all FCNC processes which occur via loops and are highly suppressed in the SM. Sensitive to New Physics.

More on $B_{s,d} \to \mu^+\mu^-$

Experiment (LHCb and CMS; F.Archilli CKM2014)

$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

$$\overline{\mathcal{B}}(B_d \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

SM Prediction (Bobeth et al. PRL 112:101801 (2014))

$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)|_{SM} = (3.65 \pm 0.23) \times 10^{-9}$$

$$\overline{\mathcal{B}}(B_d \to \mu^+\mu^-)|_{SM} = (1.06 \pm 0.09) \times 10^{-10}$$

Uses new results on NLO EW and NNLO QCD matching corrections which reduced "non-parametric" uncertainties to ~ 1.5%

Dominant errors from : CKM ($|V_{cb}|^2$, $|V_{ts}V_{td}/V_{cb}|^2$)
$f^2_{B_s}$ (4%) or f^2_B (4.5%)

So, the first task for the lattice in heavy-to-light decays is to get,

Decay constants : f_B, f_{B_s}, f_{B_s}/f_B

Form factors : $f_+(q^2)$, $f_0(q^2)$, $f_T(q^2)$

as accurately and in as many ways as possible.

Also important to coordinate with experimentalists (e.g. choices for q^2 bins, correlated error matrices, etc.) and with continuum theorists (e.g. how are lattice inputs used, uncertainty in Wilson Coeff., what order in α_s^n or $1/M_H^n$ are things known ..... etc.)

$B_{(s)}$ Meson Decay Constants

Huge progress in recent years

— statistics (increases in computing power)

— discretization (better, more highly improved actions)

— simulations close to or at physical point

— more sophisticated fitting methods

— starting to estimate isospin breaking/e&m effects

Remarkable spread in different heavy and light actions employed

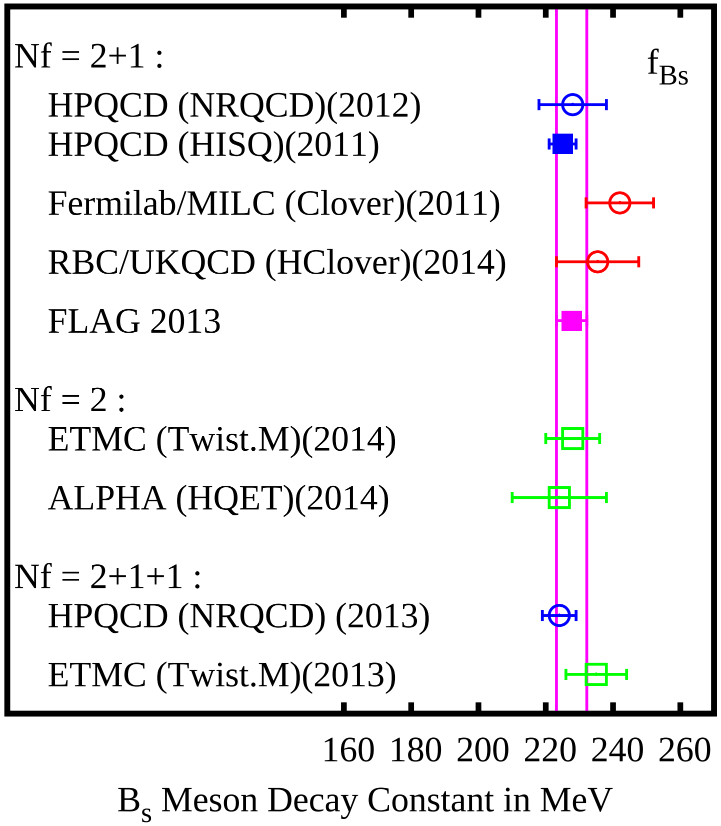
— Fermilab-Clover/AsqTad, NRQCD/AsqTad, NRQCD/HISQ Heavy-HISQ on Staggered Sea

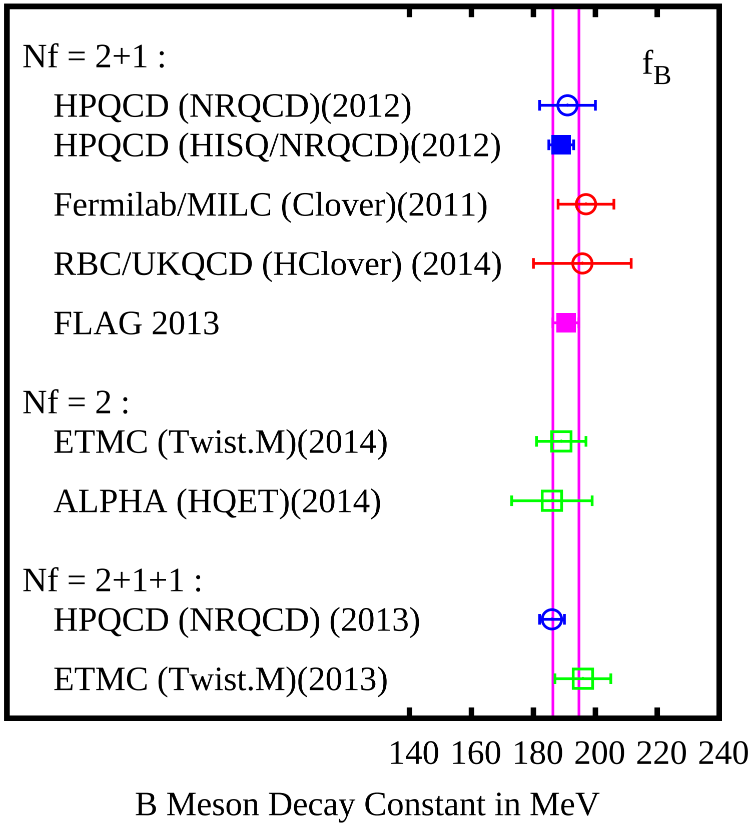
— HQET (including 1/M)/Clover on Clover Sea

— Columbia-Clover/Domain-wall on Domain-wall Sea

— Heavy Twisted Mass plus Static on Twisted Mass Sea

Results for Decay Constants





f_B **can be combined with** $\mathcal{B}(B \to \tau\nu_\tau)$ **to extract** $|V_{ub}|$**.**

f_{B_s} **important for** $\mathcal{B}(B_s \to \mu^+\mu^-)$**.**

$|V_{ub}|$ from B Leptonic Decays

Following FLAG 2013 I will use the Belle and BaBar quoted averages of hadronic and semileptonic tagging modes and the $N_f = 2 + 1$ FLAG average for f_B.

Belle :

$\mathcal{B}(B \to \tau\nu_\tau) = (0.96 \pm 0.26) \times 10^{-4} \Longrightarrow |V_{ub}| = 3.87(9)(52) \times 10^{-3}$

BaBar :

$\mathcal{B}(B \to \tau\nu_\tau) = (1.79 \pm 0.48) \times 10^{-4} \Longrightarrow |V_{ub}| = 5.28(12)(71) \times 10^{-3}$

Belle + BaBar

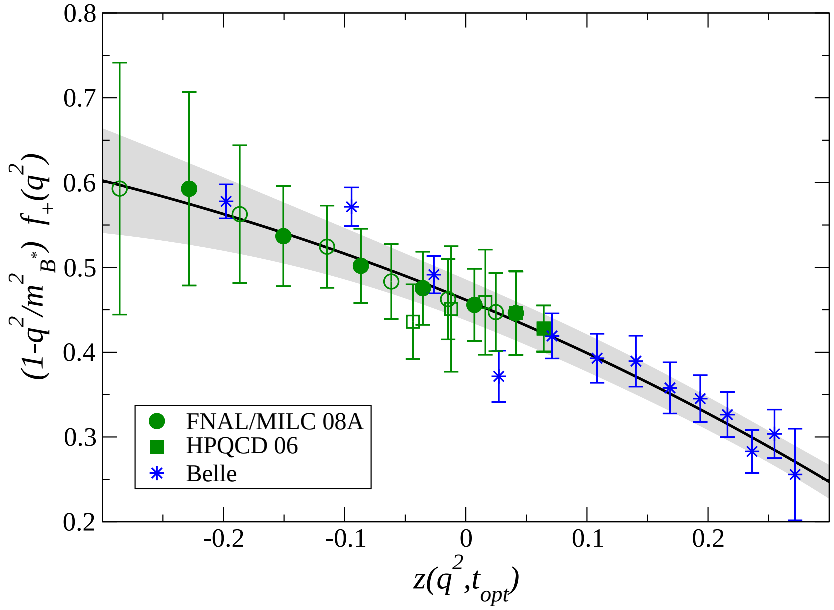
$\mathcal{B}(B \to \tau\nu_\tau) = (1.12 \pm 0.28) \times 10^{-4} \Longrightarrow |V_{ub}| = 4.18(9)(52) \times 10^{-3}$

At the moment experimental (2^{nd}) errors dominate.

$|V_{ub}|$ from $B \to \pi l \nu$ Semileptonic Decays

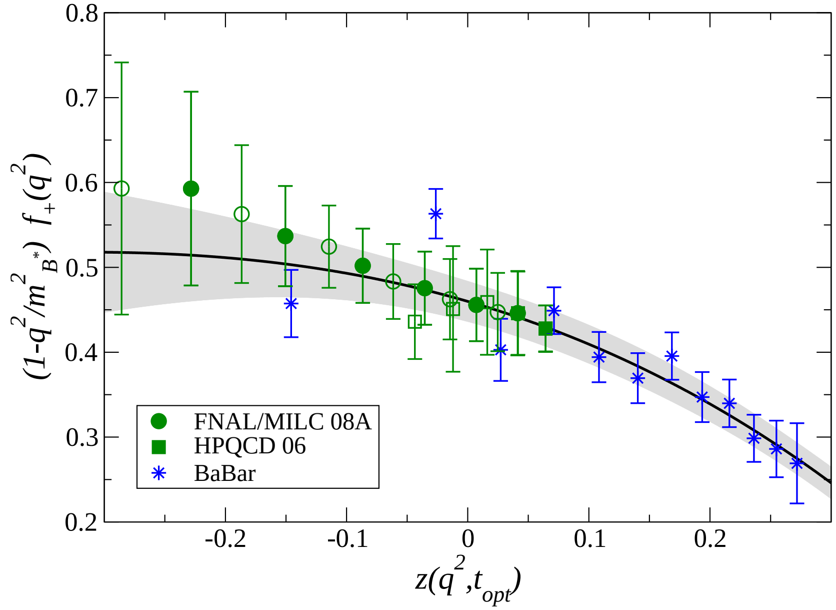
(FLAG 2013)

Lattice + Belle



$|V_{ub}| = 3.47(22) \times 10^{-3}$

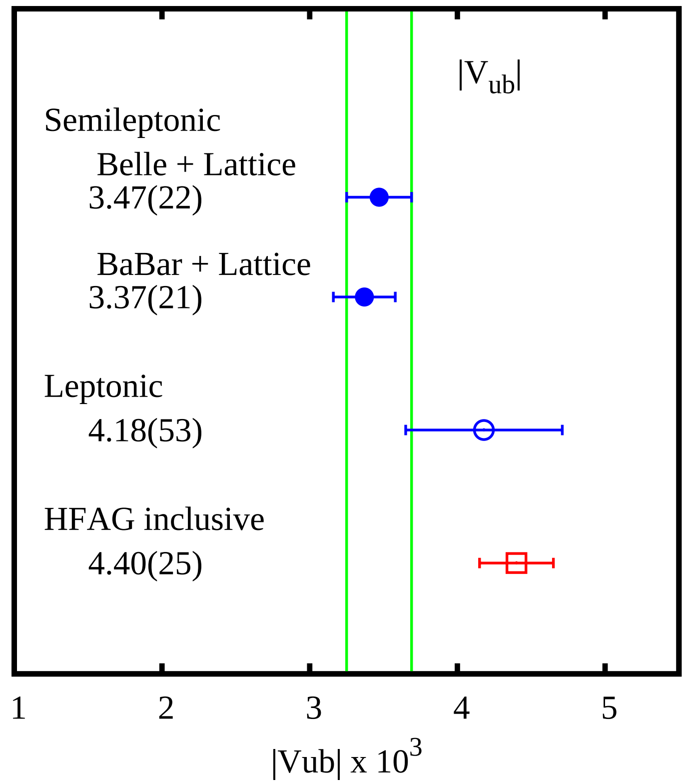
Lattice + BaBar



$|V_{ub}| = 3.37(21) \times 10^{-3}$

Simultaneous fit of Lattice and Experimental data to a BCL "z-expansion" ansatz for $[1 - q^2/M^2_{B^*}]f_+(q^2)$. Experiment divided by $|V_{ub}|$ whose value is fitted for.

Summary: $|V_{ub}|$ from Semileptonic and Leptonic B Decays



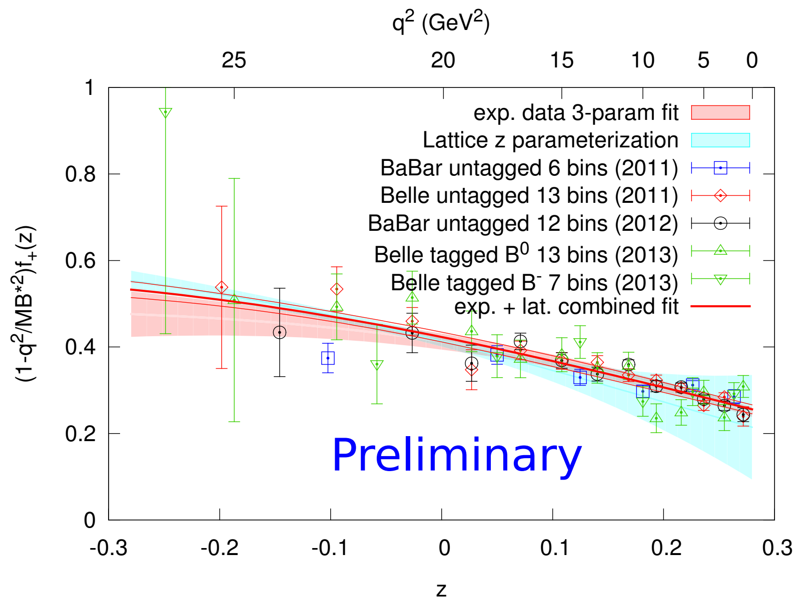
Obviously need improvements in lattice results for $B \to \pi l \nu$ and experimental determinations of $\mathcal{B}(B \to \tau \nu_\tau)$.

Several new, significantly improved $B \to \pi l \nu$ studies in progress by Fermilab/MILC, HPQCD, ALPHA and RBC/UKQCD.

Soon to appear New $B \to \pi l \nu$ Semileptonic Results

C.Bouchard: Review talk at CKM2014

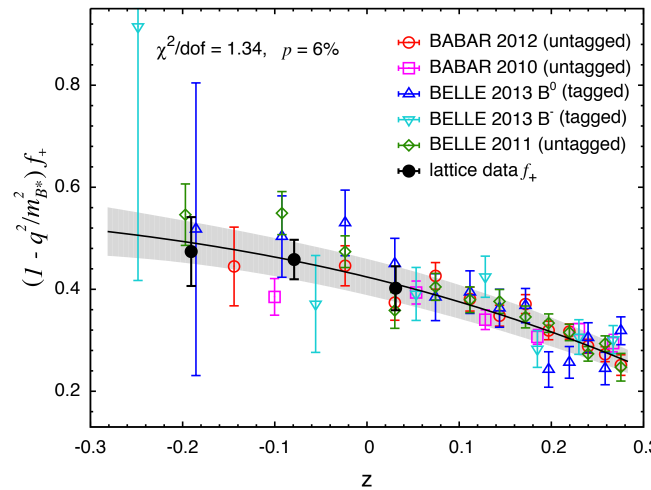
FNAL/MILC



$|V_{ub}| = 3.70(14) \times 10^{-3}$

PRELIMINARY

RBC-UKQCD



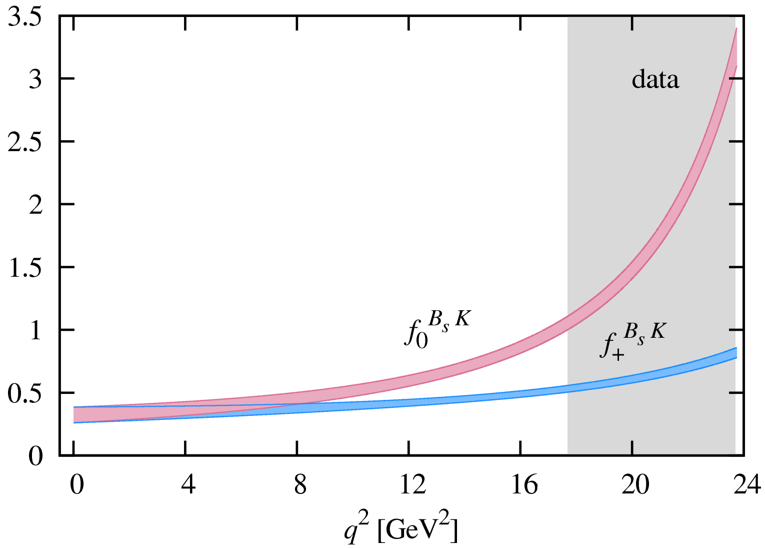
$|V_{ub}| = 3.59(32) \times 10^{-3}$

PRELIMINARY

$B_s \to K l \nu$ Semileptonic Decays

(another approach to $|V_{ub}|$)

The first unquenched lattice studies of form factors for $B_s \to K l \nu$ semileptonic decays were completed recently (C. Bouchard et al., arXiv:1406.2279 [hep-lat]).



Form factors extrapolated outside region of simulation data using the Bourrely-Caprini-Lellouch (BCL) z-expansion ansatz.

Experimental measurements planned by LHCb, Belle II.

The BLC z-Expansion

Form factors are often written as functions of $q^2 = (p_\mu^{Bs} - p_\mu^K)^2$ or of E_K. A third alternative is to use the kinematic variable,

$$z(q^2, t_0) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}.$$

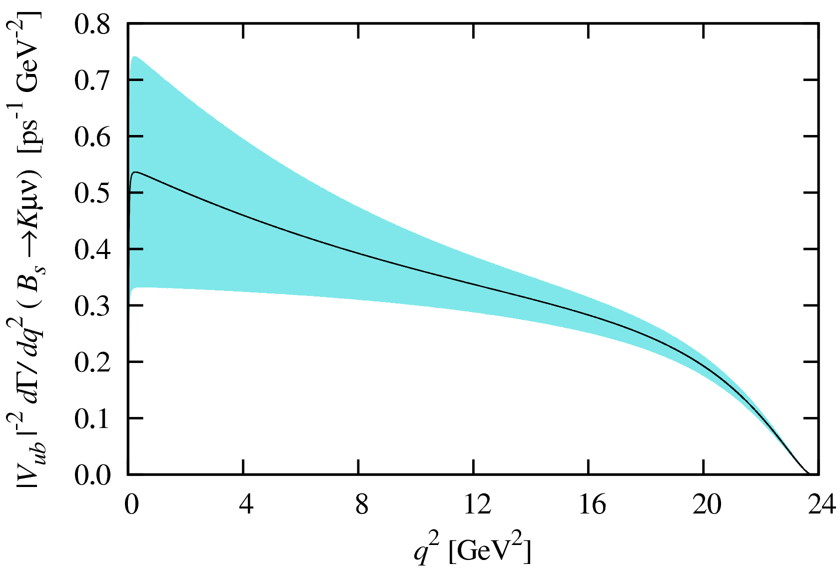
$t_+ = (M_{B_s} + M_K)^2$ and t_0 is an arbitrary parameter chosen usually to minimize values of z corresponding to physical range of q^2. e.g. for sensible choices of t_0 one has $|z| \leq 0.15$ $\Longrightarrow$ z **is an excellent expansion variable.**

$$f_+(q^2) = \frac{1}{P(q^2)} \sum_k a_k z(q^2)^k$$

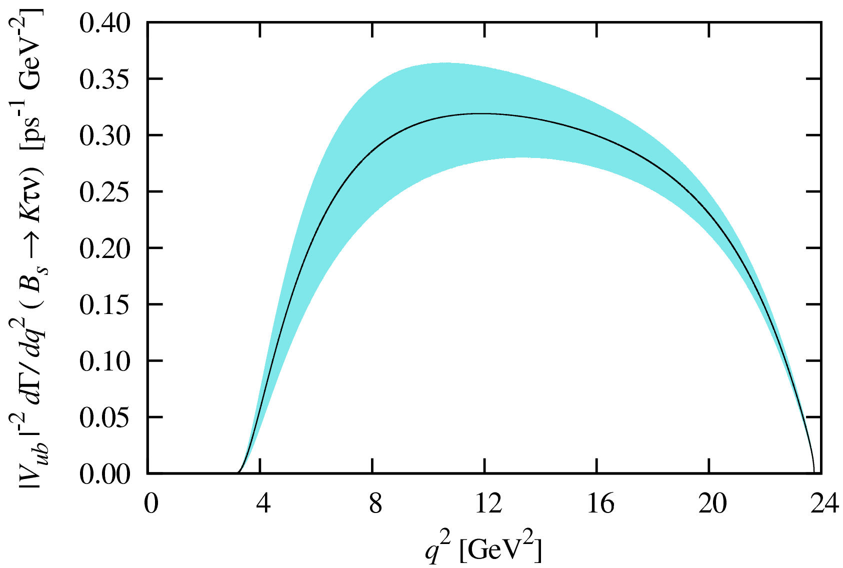
The Blaschke factor $P(q^2)$ accounts for any poles in the form factors below the $B_s + K$ threshold. The expansion coefficients are obtained through fits to lattice data extrapolated to the physical limit. This gives us the form factors for the entire q^2 range.

Differential Branching Fractions divided by $|V_{ub}|^2$

$B_s \to K\mu(e)\nu$



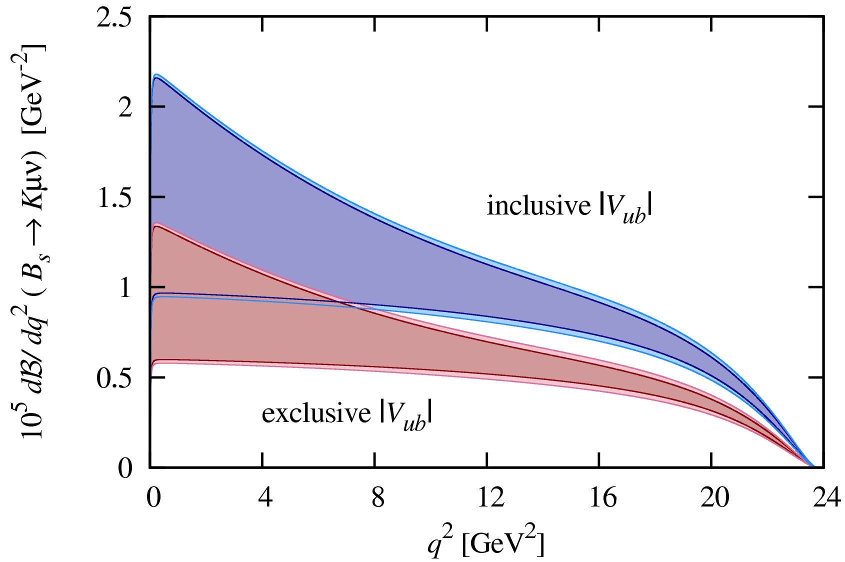
$B_s \to K\tau\nu$



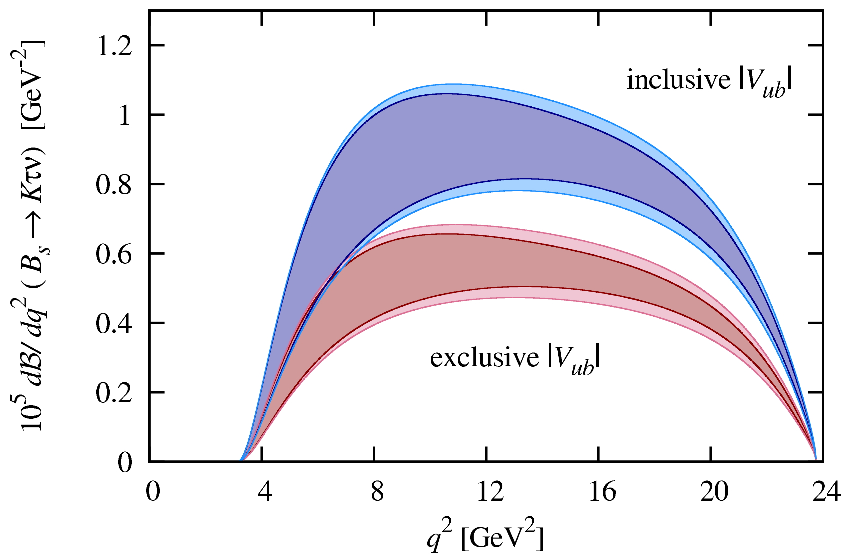
$$\frac{1}{|V_{ub}|^2}\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3 M_{B_s}^2}\left(1-\frac{m_l^2}{q^2}\right)^2 |\vec{p}_K|$$
$$\left[\left(1+\frac{m_l^2}{2q^2}\right) M_{B_s}^2 \vec{p}_K^{\,2} |f_+|^2 + \frac{3m_l^2}{8q^2}(M_{B_s}^2 - M_K^2)^2 |f_0|^2\right]$$

Differential Branching Fraction with Exclusive or Inclusive $|V_{ub}|$

$B_s \to K\mu(e)\nu$



$B_s \to K\tau\nu$

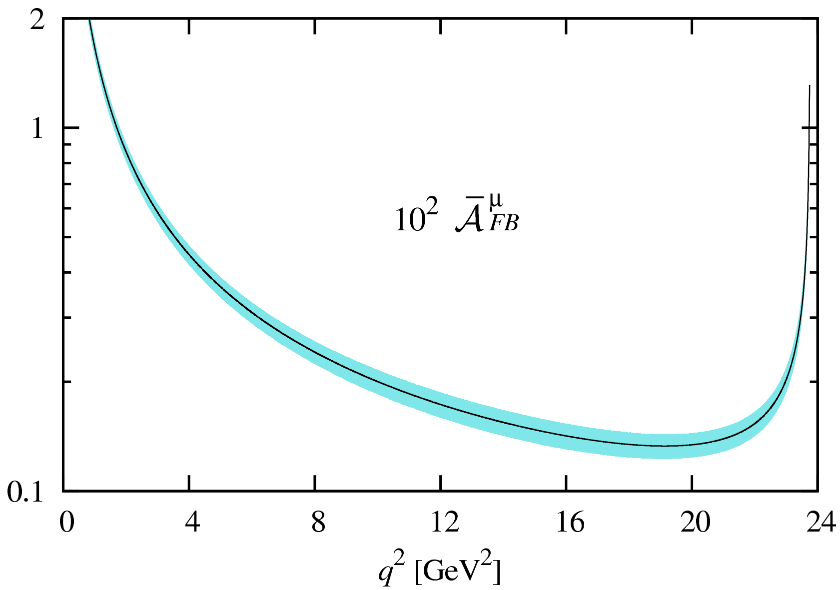


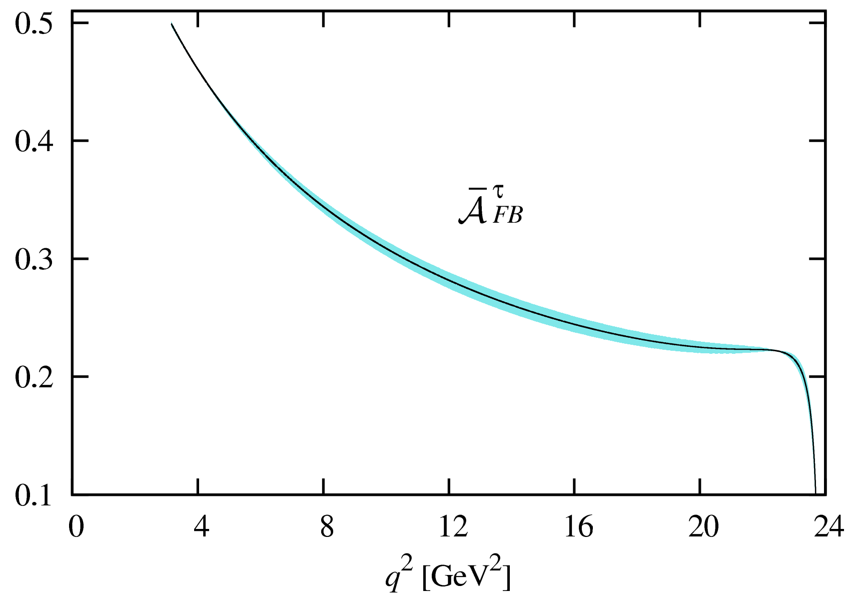
$$R_\mu^\tau = \frac{\int_{m_\mu^2}^{q^2_{max}} dq^2\, dB/dq^2(B_s \to K\tau\nu)}{\int_{m_\mu^2}^{q^2_{max}} dq^2\, dB/dq^2(B_s \to K\mu\nu)} = 0.695(50)$$

This ratio should be sensitive to new physics.

Forward - Backward Asymmetry

$B_s \to K\mu(e)\nu$ $\qquad$ $B_s \to K\tau\nu$





$$A^l_{FB} = \left[\int_0^1 - \int_{-1}^0\right] dcos\Theta_l \frac{d^2\Gamma}{dq^2 dcos\Theta_l}$$

Θ_l **is the angle between the lepton and the** B_s **in** q^2 **rest frame.**

$B_{(s)}$ Meson Rare Decays

2013 witnessed the first unquenched results from the lattice.

$B \to K l^+ l^-$

arXiv:1306.0434 (Bouchard et al., PRL 111 (2013) 162002)

Comparisons with Belle, BaBar, CDF and LHCb differential branching fractions in several q^2 bins, for $l = e, \mu$. Predictions for $B \to K \tau^+ \tau^-$.

arXiv:1306.2384 (Bouchard et al., PRD 88 (2013) 054509)

Lattice results for $f_0(q^2)$, $f_+(q^2)$ and $f_T(q^2)$ with info on how readers can reconstruct them for their use.
Angular observable, F_H (Flat Term) (Bobeth et al.)

Rare Decays (cont'd)

$B \to K^*\mu^+\mu^-$, $B_s \to \phi\mu^+\mu^-$

arXiv:1310.3887 (Horgan et al., PRL 112 (2014) 212003)

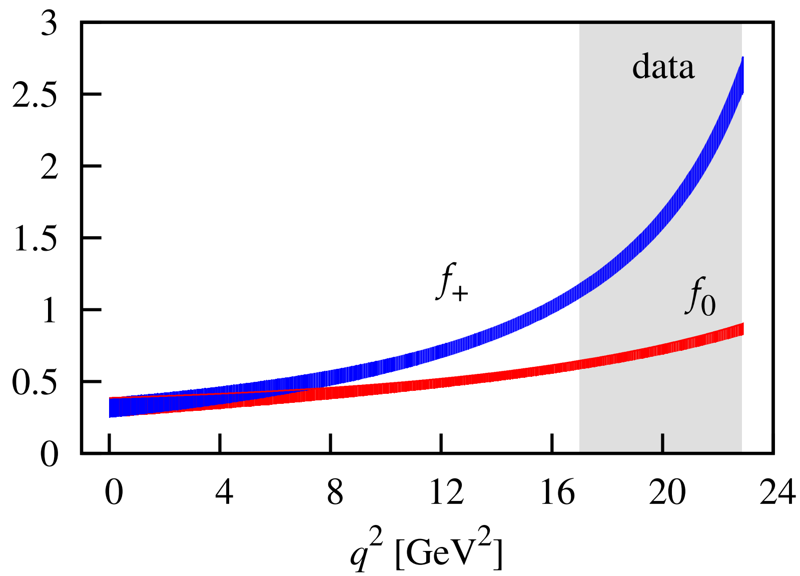
Comparisons with CDF, LHCb, ATLAS and CMS of differential branching fractions and several angular observables. F_L, S_3, S_4, S_5, P_4', P_5', A_{FB}... (Altmannshofer, Straub et al.).

arXiv:1310.3722 (Horgan et al., PRD 89 (2014) 094501)

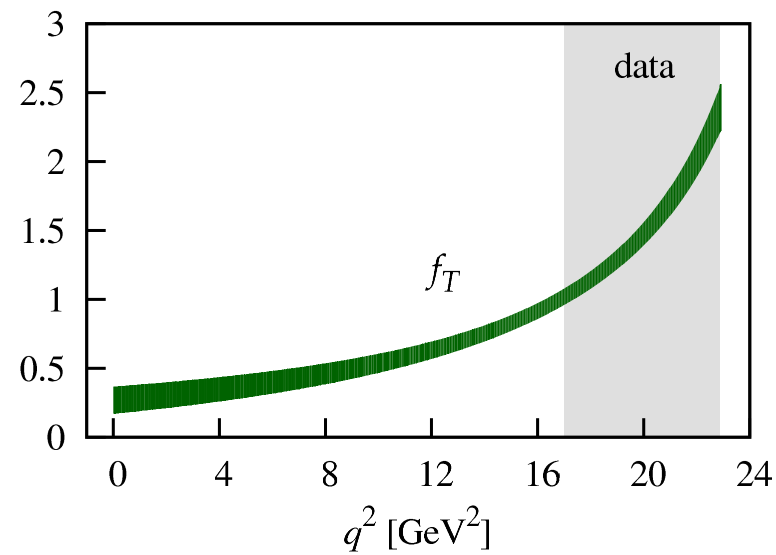
Lattice results for relevant form factors (also for $B_s \to K^* l\nu$ semileptonic).

$B \to K l^+ l^-$ Form Factors

$f_+(q^2)$ **and** $f_0(q^2)$



$f_T(q^2)$



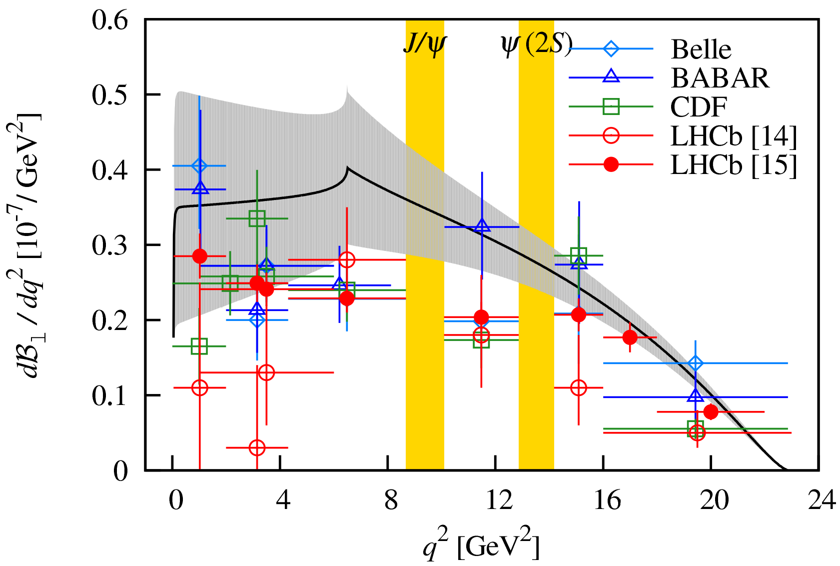
Again,Form factors extrapolated outside region of simulation data using the BCL z-expansion ansatz.

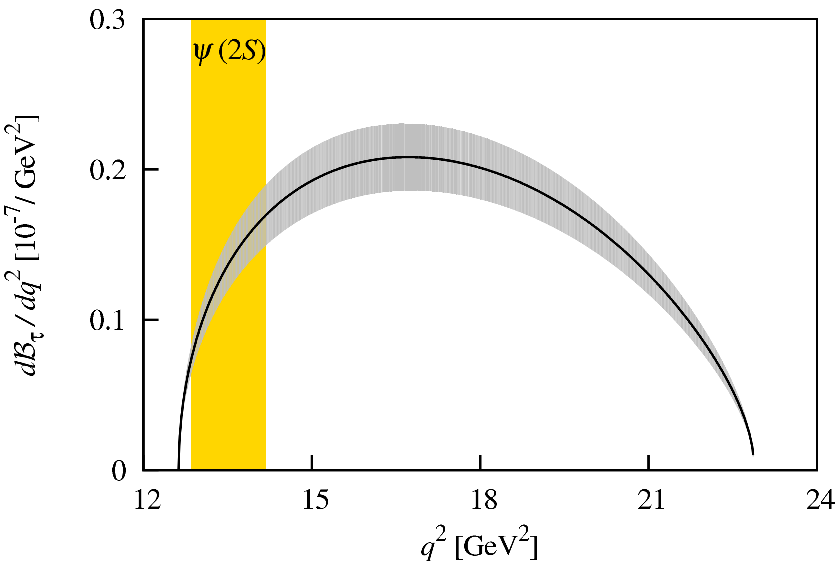
Differential Branching Fractions: Comparisons with Experiment

In SM $\frac{d\Gamma_l}{dq^2} = 2a_l + \frac{2}{3}c_l$, $\quad l = e, \mu, \tau$.

a_l, c_l : functions of form factors, Wilson coeff. masses etc.

$B \to K l^+ l^-$ $\qquad$ $B \to K \tau^+ \tau^-$



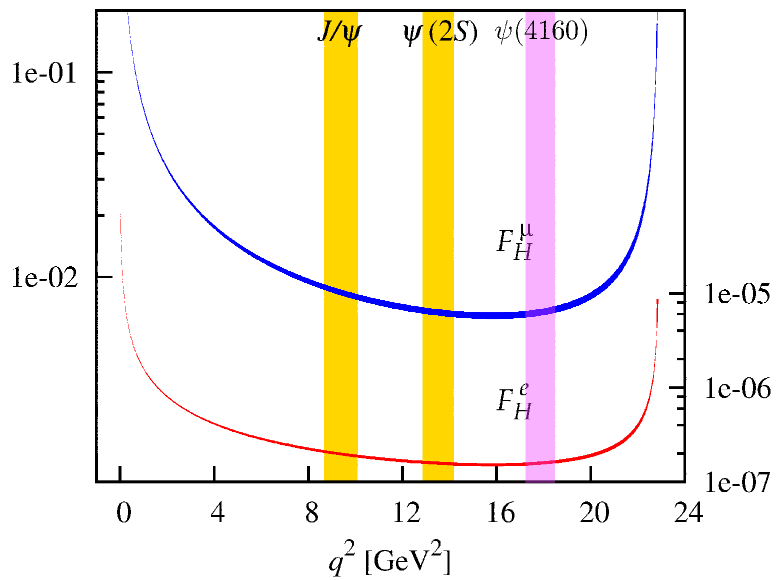


Note: $c\bar{c}$ effects/resonances treated in very naive way

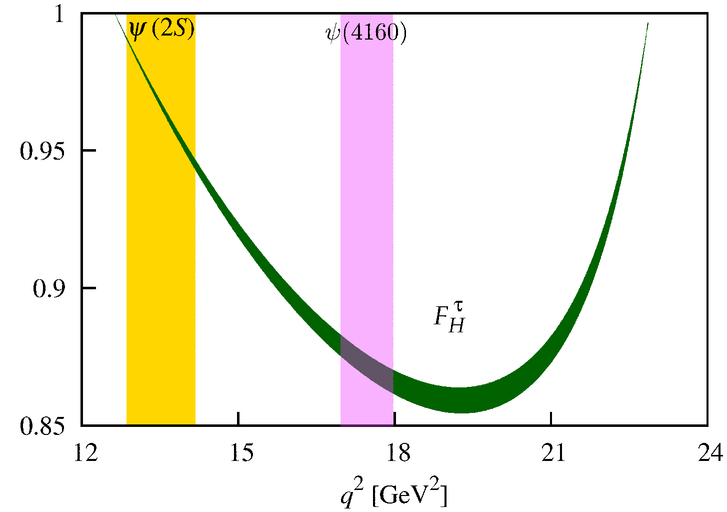
“Flat Term” in the Angular Distribution

Use definition given by Bobeth et al. $F_H^l(q^2) = \frac{a_l + c_l}{a_l + \frac{1}{3}c_l}$

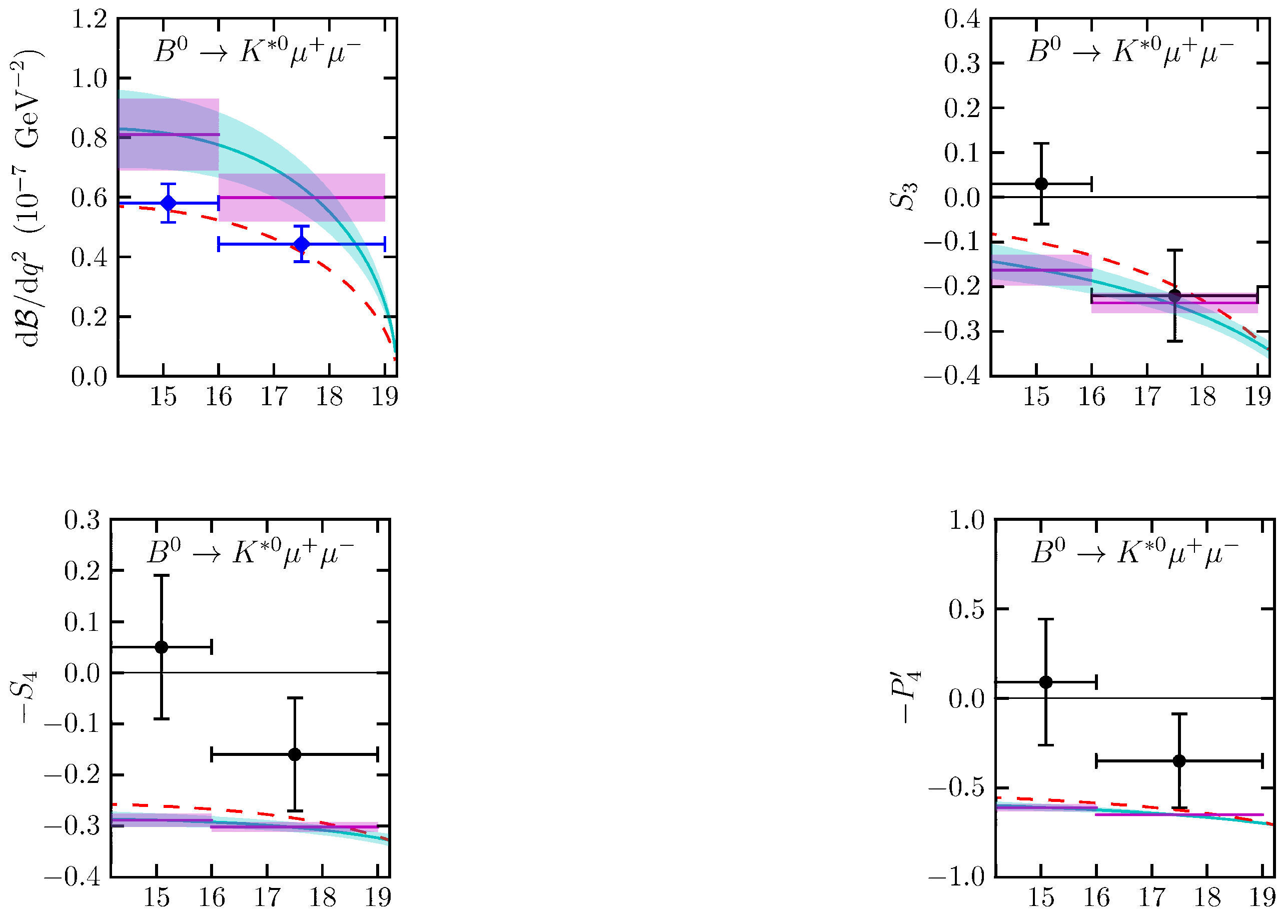
$B \to K l^+ l^-$



$B \to K \tau^+ \tau^-$

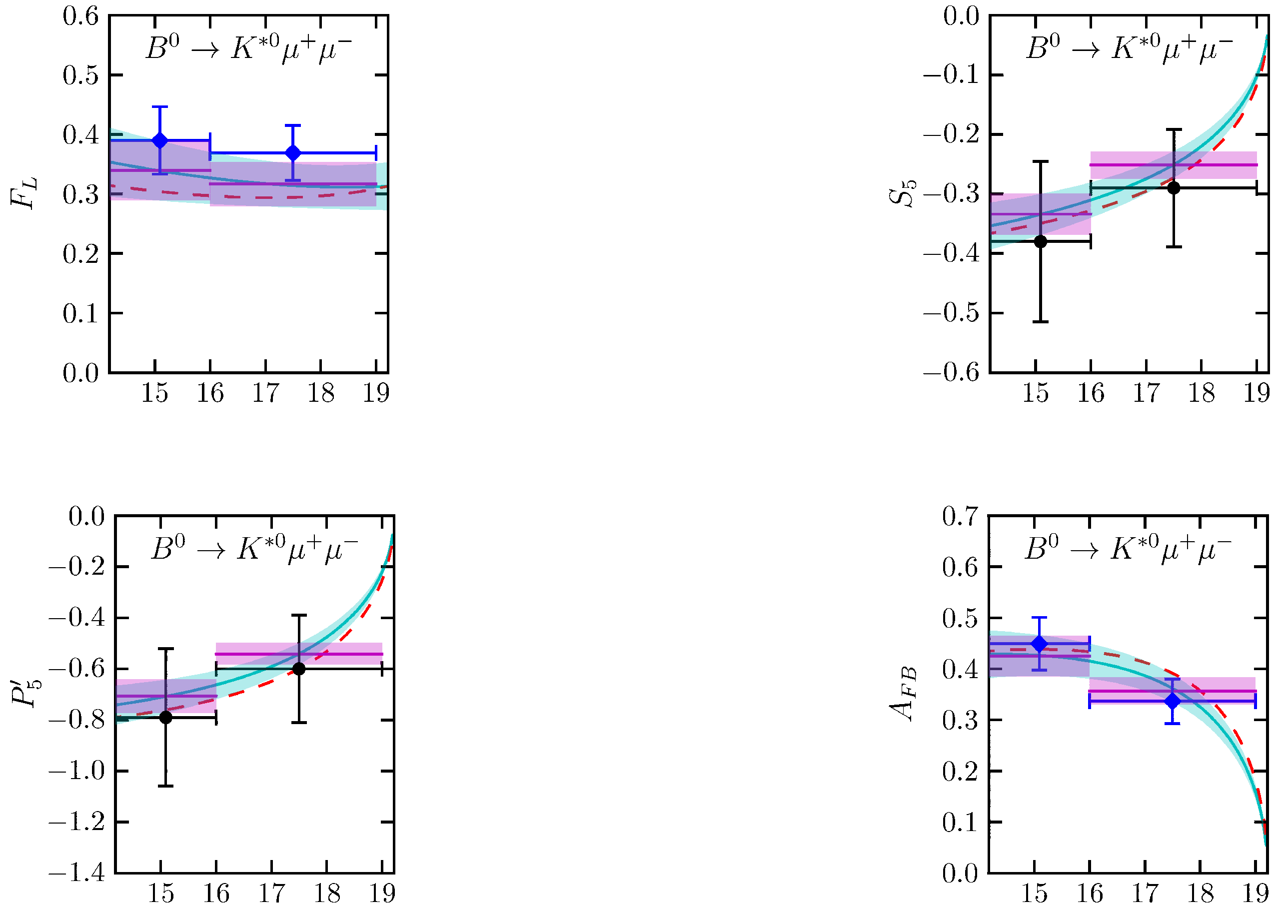


$B \to K^* l^+ l^-$: Comparisons between Experiment and Theory



– – – $C_9^{NP} = -1.1$, $C_9' = 1.1$ **Bands = SM ($C_9^{NP} = C_9' = 0$)**

$B \to K^* l^+ l^-$: Comparisons (cont'd)



– – – $C_9^{NP} = -1.1$, $C'_9 = 1.1$ **Bands = SM ($C_9^{NP} = C'_9 = 0$)**

Future Prospects for Decay Constants

— Currently the most accurate B(s) meson decay constants have errors of $\sim$2%

e.g. Heavy HISQ (heavy relativistic) results have dominant errors:

statistics ... 1.3%
$M_{Hs} \to M_{Bs}$ extrap ... 0.81%
r_1 (scale) ... 0.74%
a^2 extrapolation ... 0.63%

All these errors can be improved upon.
Would be great to have 0.03 fm lattices.

— Important that calculations with other lattice actions also achieve $\sim$2% or less errors

Future Prospects for Form Factors

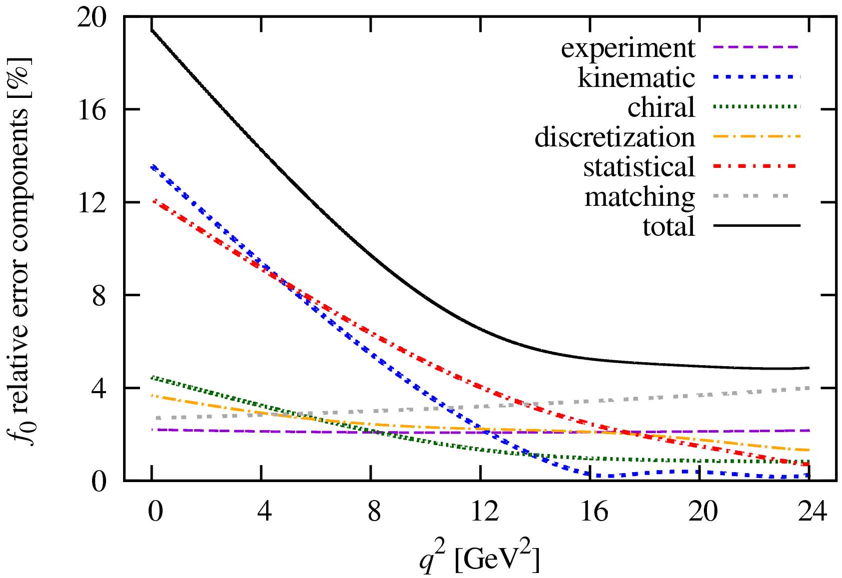
Dominant sources of error change with q^2. So, the best strategy for reducing the total error depends on which q^2 range one is interested in. e.g.

extracting $|V_{ub}|$: not crucial to go to very small q^2. Need sufficient overlap with experiment.

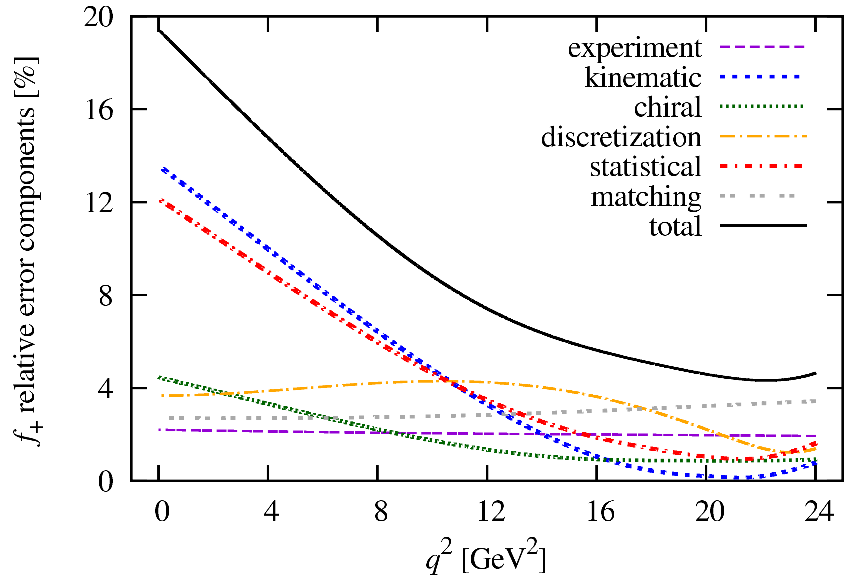
Rare decays : lattice results in entire q^2 range of interest.

Breakdown of Errors for $B_s \to K l \nu$ and Their q^2 Dependence

Form factor f_0



Form factor f_+



Need to focus on strategies to simulate at lower q^2 and to reduce matching uncertainties.

Note that the importance of matching errors depends on lattice actions used.

Strategies for going to lower q^2

All $B_{(s)}$ meson semileptonic and rare decay studies on the lattice have the limitation that form factors are not directly calculable for the entire physicsl q^2 range, i.e. $q^2 \geq q^2_{min} \approx 16$Gev^2. Challenges to going to smaller q^2_{min} include,

1. **statistical errors increase with daughter meson momentum**

2. **discretization effects increase with momentum**

3. **traditional methods, such as ChPT, for chiral extrapolations break down with large momenta**

Strategies for going to lower q^2 (cont'd)

1. statistical errors increase with daughter meson momentum $\Longrightarrow$ vastly increase statistics

2. discretization effects increase with momentum $\Longrightarrow$ work with improved actions; and/or go to smaller lattice spacings

3. traditional methods, such as ChPT, for chiral extrapolations break down with large momenta $\Longrightarrow$ not an issue if simulating with physical pions; can use "Hard Pion ChPT" inspired z-expansion for chiral extrapolations

Studies underway to try to go below $q^2 \approx 16\text{GeV}^2$ using HISQ pions and kaons.

Getting Around Perturbative Matching Errors

Exploit Ratios

e.g. the most accurate f_{B_s} to date came from absolutely normalized HISQ-HISQ heavy-light pseudoscalar density (via PCAC relation).

then,

the most accurate f_B can be obtained from

$$\left[\frac{f_B}{f_{B_s}}\right]_{NRQCD} \times \left[f_{B_s}\right]_{HISQ} \equiv f_B$$

Of course, eventually one wants to calculate f_B directly with relativisitic HISQ b-quarks. Will require physical light HISQ quarks on very fine lattices.

Getting Around Perturbative Matching Errors (cont'd)

For vector currents in semileptonic decays, HISQ-HISQ heavy-light currents will obey the PCVC relation,

$$q^{\mu}\langle V_{\mu}\rangle = (m_H - m_l)\langle S\rangle$$

e.g. for $B_s \to \eta_s l\nu$, one has

$$(M_{B_s} - E_{\eta_s})\langle V_0^L\rangle Z_t + \vec{p}_{\eta_s}\cdot\langle\vec{V}^L\rangle Z_s = (m_b - m_s)\langle S^L\rangle$$

The RHS is a RG invariant quantity $\Longrightarrow$ completely non-perturbative determination of Z_t and Z_s.

Again combine HISQ-b and NRQCD-b matrix elements,

$$\left[\frac{f_{\|,\perp}^{B_s\to K}(q^2)}{f_{\|,\perp}^{B_s\to\eta_s}(Q_0^2)}\right]_{NRQCD} \times \left[f_{\|,\perp}^{B_s\to\eta_s}(Q_0^2)\right]_{HISQ} = \left[f_{\|,\perp}^{B_s\to K}(q^2)\right]_{renorm}$$

HISQ calculation needed at only two fixed well chosen Q_0^2.

Longer Term Prospects

In the long term, Heavy Flavor physics is likely to be studied on the lattice with physical light quarks and the same relativistic action for heavy and light quarks.

No need for chiral extrapolations nor for explicit 1/M expansions. Fully nonperturbative matching possible.

This is already starting to happen for $m_c < m_H < m_b$ with HISQ, Twisted Mass heavy quarks.

In the future :

Highly Improved Twisted Mass
Highly Improved Domain Wall
Highly Improved Overlap
Highly Improved XXX.

Summary

- Lattice studies of heavy-to-light heavy meson decays are steadily improving. Better improved lattice actions, new strategies for reducing errors, more sophisticated data analyses and fitting methods, many different lattice actions .....

- Urgent need to further reduce errors
  —– $f_{B(s)}$ source of a dominant error in $\mathcal{B}(B_q \to \mu^+\mu^-)$
  —– tensions in $|V_{ub}|$ between inclusive and exclusive semileptonic determinations
  —– tensions with SM for several "angular variables" in B rare decays
  —– tensions with SM in ratios $\mathcal{B}(B \to P(V)\tau\nu)/\mathcal{B}(B \to P(V)\mu(e)\nu)$

- Need good communications with continuum theorists and with experimentalists

PLEASE GIVE US A FURTHER SHOPPING LIST