Flavour anomalies

Sebastian Jaeger
University of Sussex

XII Quark Confinement and the Hadron Spectrum
Thessaloniki, Greece, 29 August 2016

Outline

Motivation

Systematics of rare B decays

New precision tests with Kaons and a new anomaly

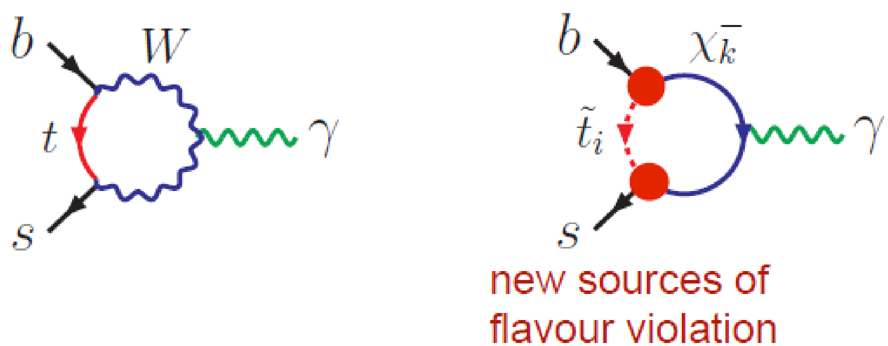
Summary

Why flavour physics?

After the Higgs discovery, the naturalness problem is a reality. But even natural new physics may lie beyond the LHC energy reach. ATLAS & CMS may point to that.

This places flavour (and precision Higgs) at the centre of the quest for physics beyond the Standard Model

Natural BSM models tend to be flavourful, eg SUSY:



$B \to K^* \gamma$, $K^* ll$
$B \to X_s \gamma$

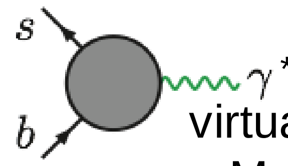
Unprecedented statistics & interesting results from LHCb, with Belle2 rapidly approaching. Meanwhile, Kaons are making a comeback (NA62, KOTO, theory).

Semileptonic ΔB=ΔS=1 Hamiltonian

in SM mainly

SM top loops and BSM effects give **Wilson coefficients** multiplying **effective local interactions (operators)**

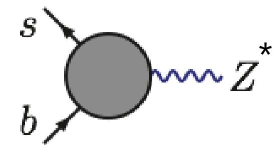
coefficient **C_9** : dilepton from vector current (L=1)



virtuality
$\sim M_W^2$

$$Q_{9V} = \frac{\alpha_{\rm em}}{4\pi}(\bar{s}\gamma_\mu b)(\bar{l}\gamma^\mu l)$$

C_{10} : dilepton from axial current (L=1 or 0)



$$Q_{10A} = \frac{\alpha_{\rm em}}{4\pi}(\bar{s}\gamma_\mu b)(\bar{l}\gamma^\mu\gamma^5 l)$$

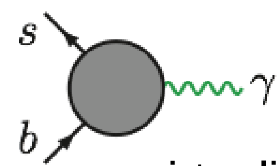
- both can be obtained from Z' exchanges
- or leptoquarks

Descotes-Genon et al; Altmannshofer et a
Crivellin et al; Gauld et al; ...

Alonso-Grinstein-Martin Camalich; Hiller-Schmaltz; Allanach et al; Gripajos et al; ...

C_7 : dilepton produced through photon (virtuality q^2, pole at q^2=0)

$$Q_{7\gamma} = \frac{e}{16\pi^2} m_b\,(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}$$



- strongly constrained from inclusive b->s decay

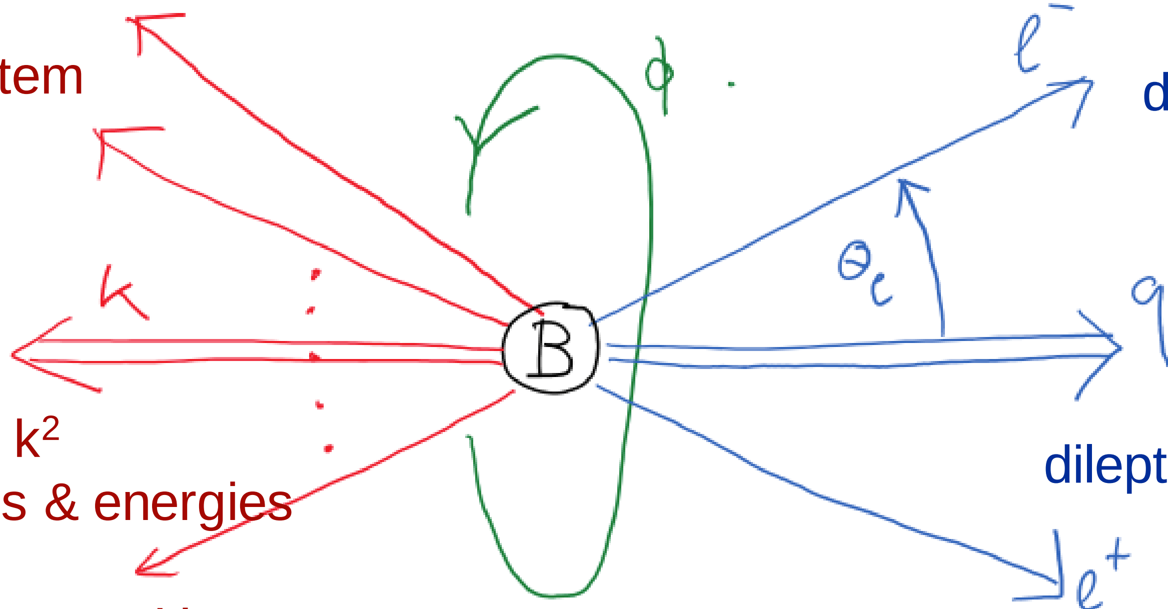
virtuality
<< M_W^2

BSM: also operators with opposite quark chiralities (C_9', C_{10}', C_7')
C_9, C_{10} can depend on the lepton flavour.
Universal BSM effects in C_9 mimicked by a range of SM effects

Semileptonic B decays

hadronic system

dilepton



hadronic mass k^2
hadronic angles & energies
equivalently:
angular momentum L'
helicity λ'
(+further angles if >2 hadrons)

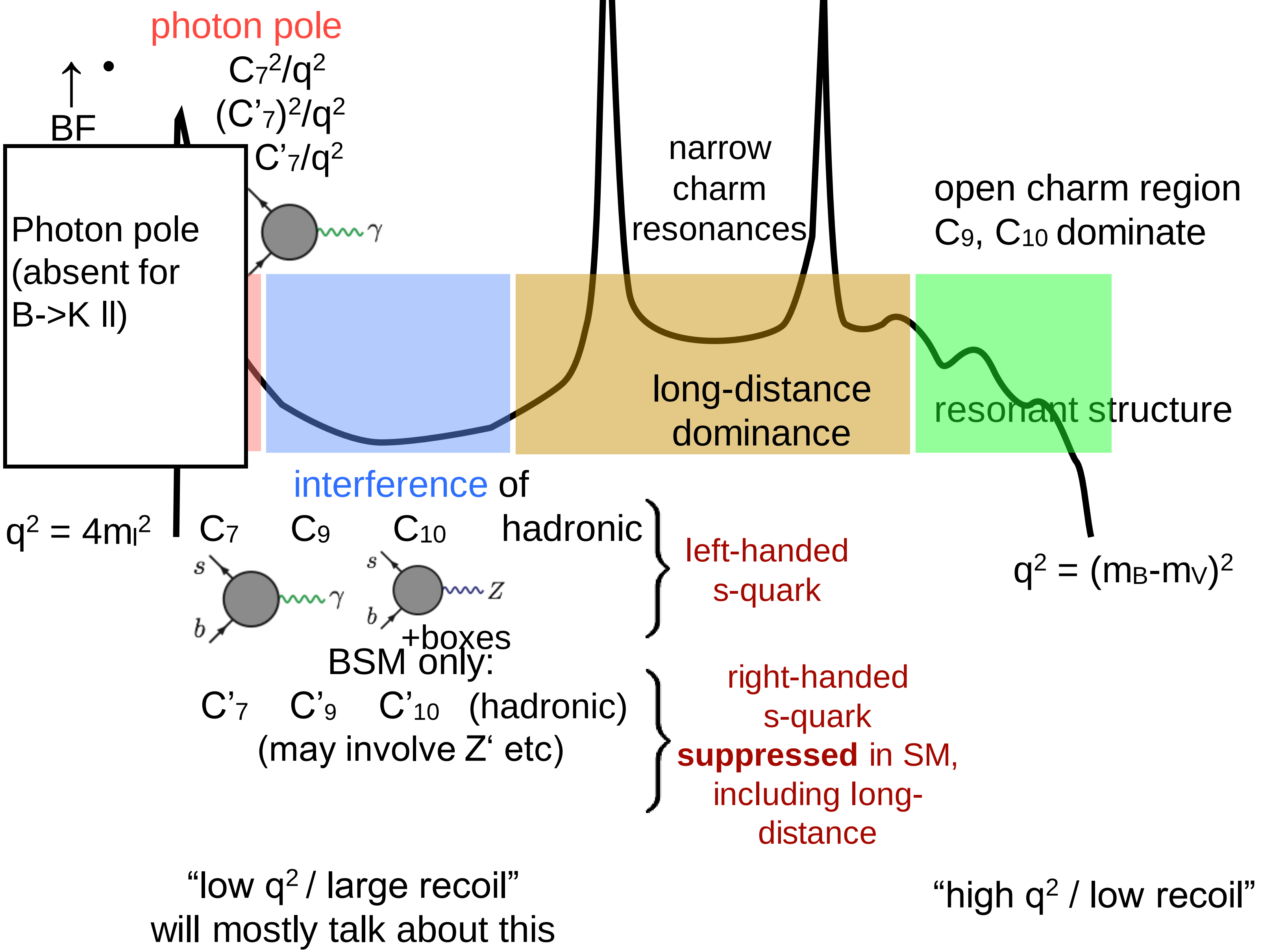
one hadronic/leptonic relative angle Φ
(requires >=2 hadrons)

dilepton mass q^2
leptonic angle
equivalently:
angular momentum
helicity λ

B has spin zero => hadronic and dilepton helicities agree: $\lambda = \lambda'$
For a spin-0 hadron (eg Kaon), $\lambda = \lambda' = 0$.
For spin-1 resonance (eg K*), $\lambda = \lambda' = 0, +/-1$

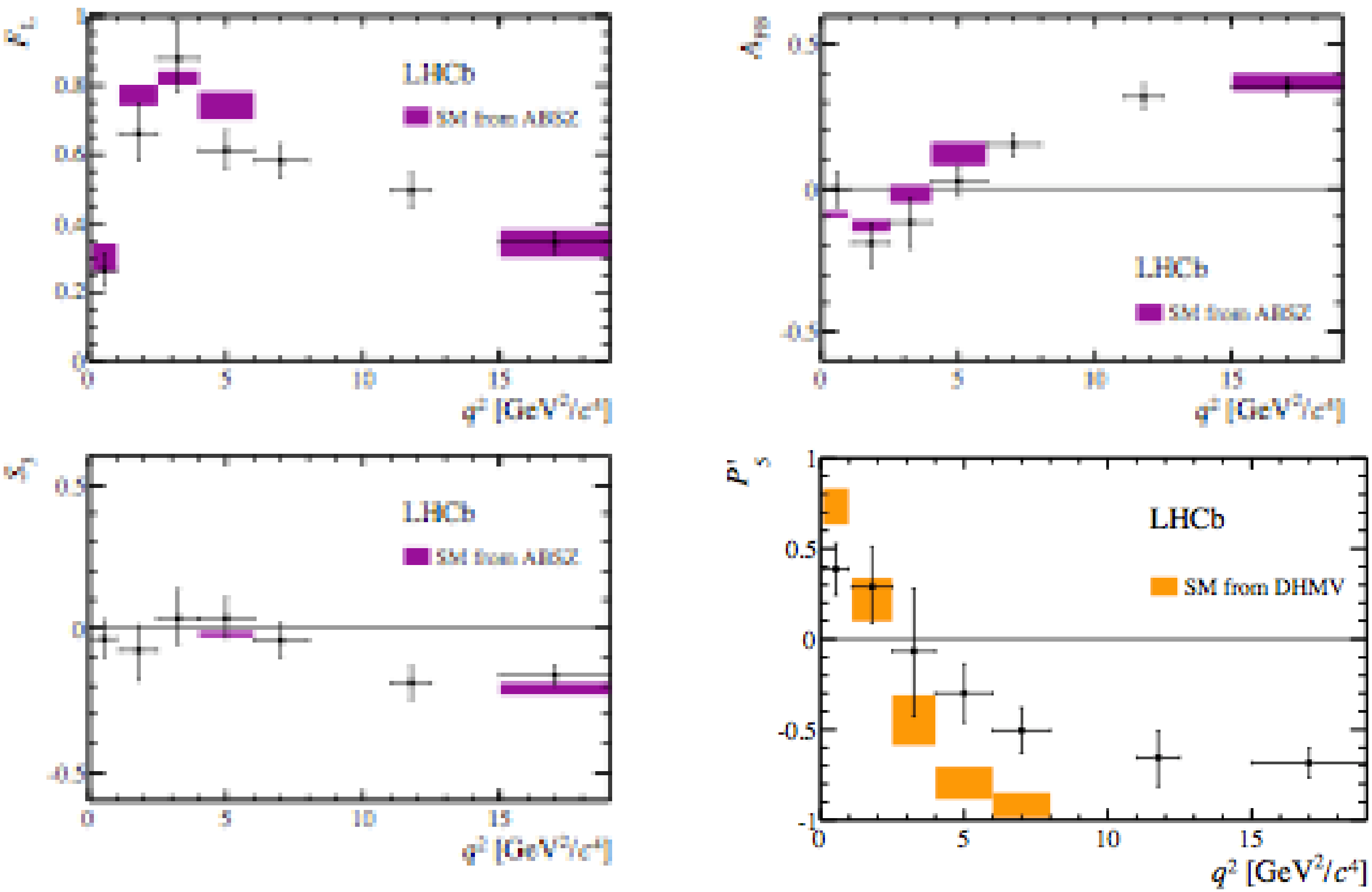
Observing Φ requires interference $A(\lambda_1)\, A(\lambda_2)^*$ $\exp(i\,(\lambda_1 - \lambda_2)\Phi)$. Good BSM probe.

B->K*ll : dilepton mass spectrum



B->K*$\mu^+\mu^-$ angular distribution

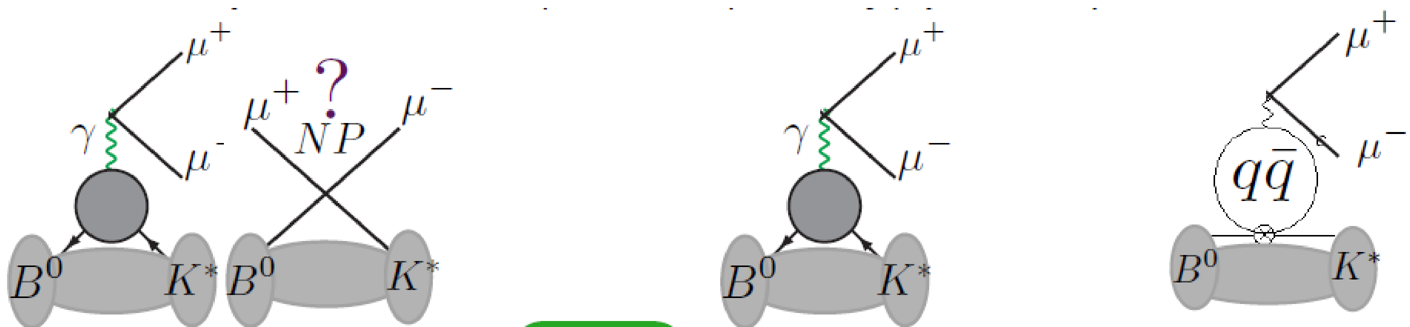
[S Cunliffe (LHCb), “LHCb Implications”, 03/05/15]



Deviations in lepton charge FB asymmetry (A_{FB})
and angular observable S_5 / P_5’

Rare B decays

The tension can (and has been) attributed to the vector helicity amplitudes (involving vector lepton current).



$$H_V(\lambda) \propto \tilde{V}_\lambda(q^2)C_9 - V_{-\lambda}(q^2)C_9' + \boxed{\frac{2\, m_b m_B}{q^2}}\left(\tilde{T}_\lambda(q^2)C_7 - \tilde{T}_{-\lambda}(q^2)C_7'\right) - \boxed{\frac{16\,\pi^2 m_B^2}{q^2}} h_\lambda(q^2)$$

photon pole at q^2=0

It could be attributed to

- form factors V_λ, T_λ
- semileptonic/radiative Wilson coefficients C9
- four-quark operators (“charm loop”) – SM uncertainty or BSM effect

Form factor relations

The heavy-quark limit is highly predictive both for form factor ratios and for virtual-charm effects, for instance:

Charles et al 1999
Beneke, Feldmann 2000
Beneke, Feldmann, Seidel 2001-4

$$\frac{T_-(q^2)}{V_-(q^2)} = 1 + \frac{\alpha_s}{4\pi} C_F \left[\ln \frac{m_b^2}{\mu^2} - L \right] + \frac{\alpha_s}{4\pi} C_F \frac{1}{2} \frac{\Delta F_\perp}{V_-} \quad \text{where} \quad L = -\frac{2E}{m_B - 2E} \ln \frac{2E}{m_B}$$

"vertex" correction:
parameter-free

"spectator scattering":
mainly dependent on B meson LCDA
but a_s suppressed

- Eliminates form factor dependence from some observables (eg P_2' and zero of A_{FB}) almost completely, up to Λ/m_b power corrections

Descotes-Genon, Hofer, Matias, Virto

- pure HQ limit: $T_-(0)/V_-(0) \sim 1.05 > 1$ Beneke,Feldmann 2000

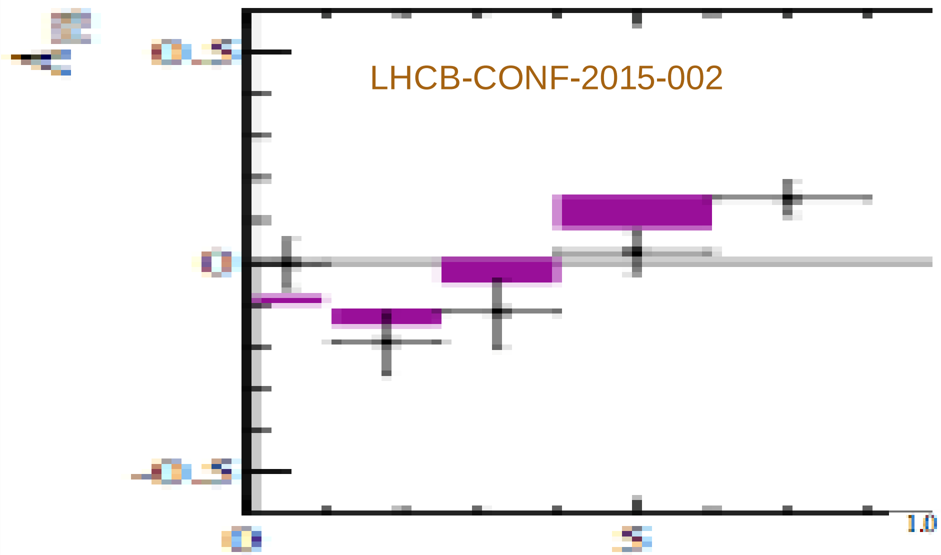
- compare to: $T_-(0)/V_-(0) = 0.94 +/- 0.04$ [D Straub, priv comm based on Bharucha, Straub, Zwicky 1503.05534]
light-cone sum rule computation with correlated parameter variations.
Difference consistent with Λ/m_b power correction;
remarkable 5% error

Forward-backward asymmetry

LHCb Moriond 2015 (3 fb^{-1})
downward shift of A_{FB} relative to LCSR-based prediction
(Bharucha, Straub, Zwicky 2015)

Such a shift is largely equivalent to a **rightward shift** of the zero crossing.

Zero crossing in LCSR has been significantly lower than heavy-quark limit for many years (as low as <3 GeV^2)

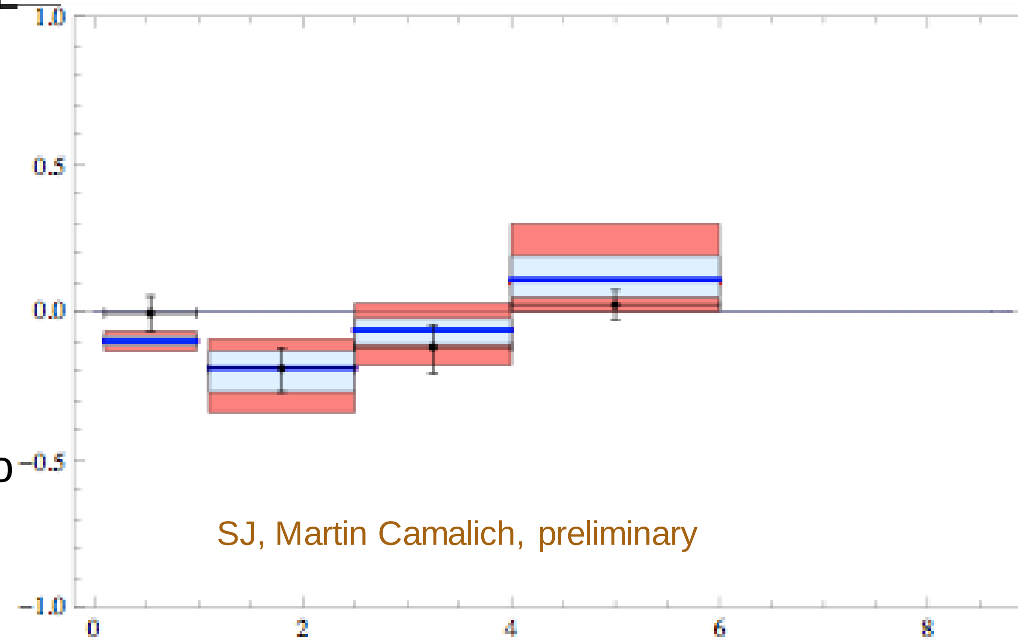


blue line: pure heavy-quark limit, **no power corrections**

light blue: “68% Gaussian” theory error (including power corrections)

pink: full scan over all theory errors

Surprising that pure HQ limit appears to agree reasonably well with data !



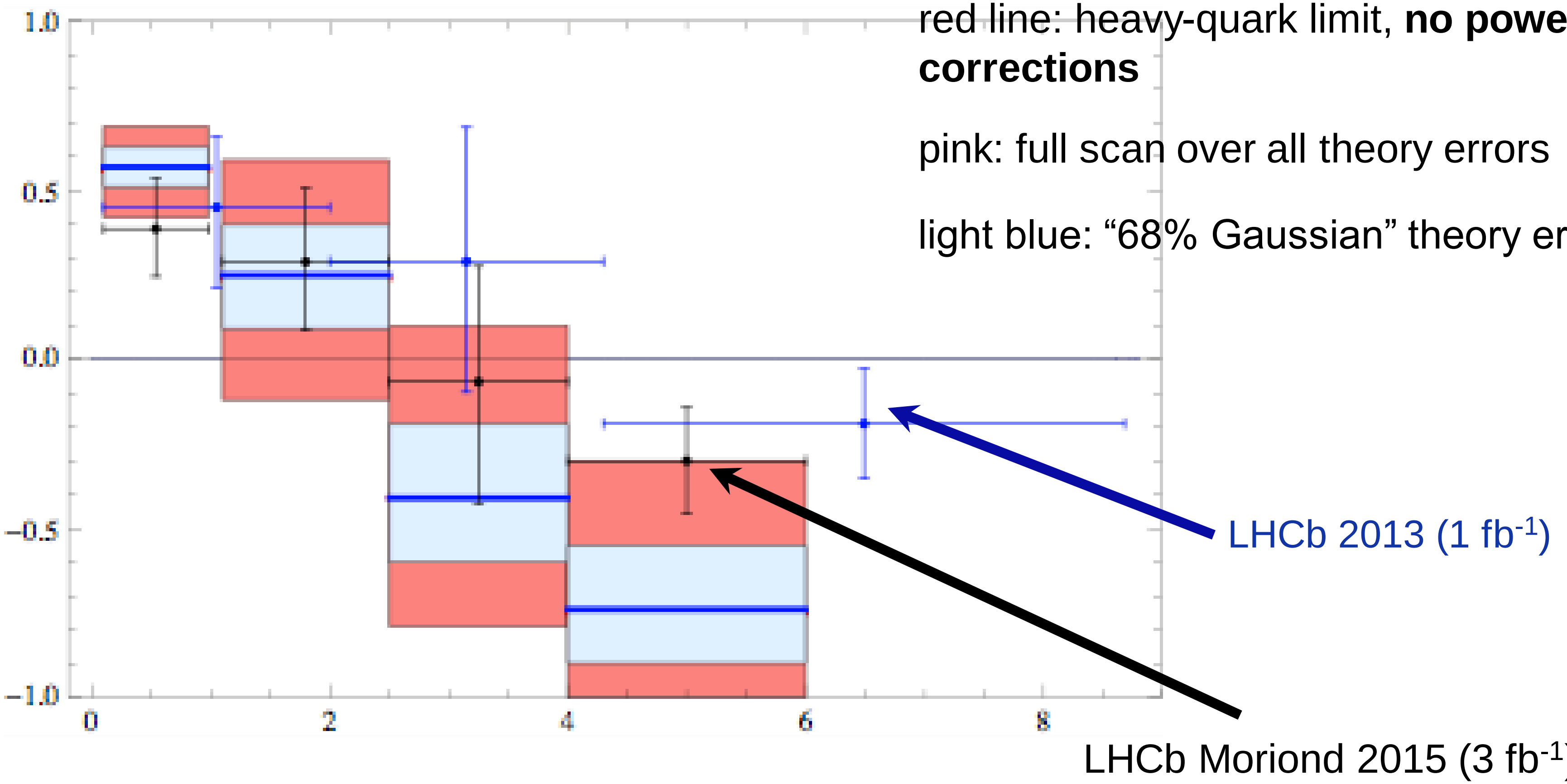
Experiment has reached a point where “clean” observables depend crucially on form factors

Angular observable P_5' SJ, Martin Camalich, preliminary

red line: heavy-quark limit, **no power corrections**

pink: full scan over all theory errors

light blue: “68% Gaussian” theory error

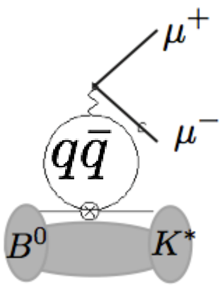


For Gaussian errors [corresponding to what most authors employ], there is a noticeable deviation in a single bin; but also here less drastic than with LCSR-based theory

NB – P5’ depends on a second, independent heavy-quark relation, with independent (and unknown) power corrections: inherently less clean than AFB zero (or P2’)

Nonlocal term / charm loop

$$H_V(\lambda) \propto \tilde{V}_\lambda(q^2)C_9 - V_{-\lambda}(q^2)C_9' + \frac{2\,m_b m_B}{q^2}\left(\tilde{T}_\lambda(q^2)C_7 - \tilde{T}_{-\lambda}(q^2)C_7'\right) \boxed{- \frac{16\,\pi^2 m_B^2}{q^2}\,h_\lambda(q^2)}$$



+ strong interactions!

more properly:

$$\frac{e^2}{q^2} L_V^\mu a_\mu^{\rm had} = -i\frac{e^2}{q^2}\int d^4x\, e^{-iq\cdot x}\langle \ell^+\ell^-|j_\mu^{\rm em,lept}(x)|0\rangle \boxed{\int d^4y\, e^{iq\cdot y}\langle M|j^{\rm em,had,\mu}(y)\mathcal{H}_{\rm eff}^{\rm had}(0)|\bar{B}\rangle}$$

$$h_\lambda \equiv \frac{i}{m_B^2}\epsilon^{\mu *}(\lambda)a_\mu^{\rm had}$$

nonlocal, nonperturbative, large normalisation ($V_{cb}^* V_{cs}$ C_2)

traditional•"ad hoc fix" : $C_9 \to C_9 + Y(q^2) = C_9^{\rm eff}(q^2)$, "taking into account the charm loop"
$C_7 \to C_7^{\rm eff}$

* for $C_7^{\rm eff}$ this seems ok at lowest order (pure UV effect; scheme independence)
* for $C_9^{\rm eff}$ amounts to factorisation of scales ~ m_b (, m_c ,q^2) and Λ (soft QCD)
* not justified in large-N limit (broken already at leading logarithmic order)
* what about QCD corrections?
* not a priori clear whether this even gets one closer to the true result!

only known justification is a heavy-quark expansion in Λ/m_b (just like inclusive decay is treated !)

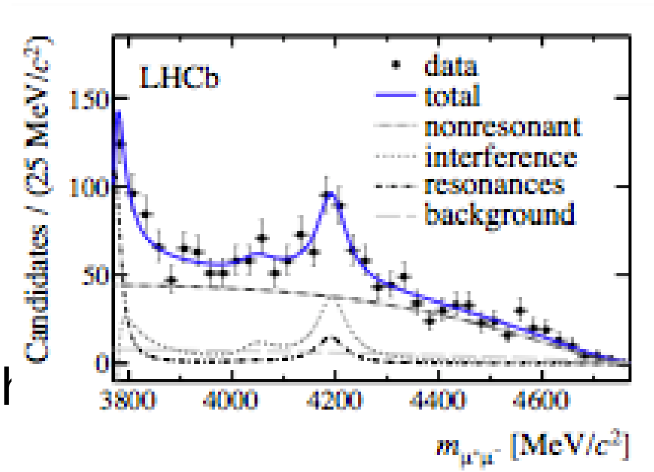
Beneke, Feldmann, Seidel 2001, 2004

High-q^2 region (sketch)

- - spectator scattering mechanism power-suppressed
- - above open-charm (and perturbative-charm) thresholds
- - however, for $q^2 >> 4m_c^2$, OPE at amplitude level

Grinstein, Pirjol 2004; Beylich, Buchalla, Feldmann 2011

- Duality violation (≡ error beyond OPE)
  - expected on general grounds
  for OPE above threshold
- - pronounced resonant
  structure observed (Chibisov et al; Shifman 1990's)
- - difficult to quantify uncertainty due to th



- - like in low-q^2, probably best to stay away from the charm
  threshold region in looking for new physics

Beylich, Buchalla, Feldmann 2011
(Chibisov et al; Shifman 1990's)
(Lyon, Zwicky 2013)

- - on the other hand, it has been suggested that the strong
  resonant features could point to BSM in b->c c s transition. Lyon, Zwicky 2013

BSM in charm?

A largely unexplored idea.

Operators with charm give correlated effects in mixing and rare decays. Schematically:

Both can be studied in heavy-quark expansion

(SJ, Kirk, Lenz, Leslie, w.i.p.)

Kaons strike back!

Kaons are where much of the SM structure was first discovered.

1956-57 parity violation

V-A structure of weak interactions

1964 CP violation

third generation (1973 Kobayashi-Maskawa)

1970 *charm quark to explain* K->mu mu non-observation

1974 *successful application of the naturalness argument (Gaillard&Lee: upper bound on charm quark mass from its contribution to* K-Kbar mixing*)*

Direct CP violation in $K_L \to \pi\pi$

There has been a precision measurement for a decade:

$$(\varepsilon'/\varepsilon)_{\rm exp} = (16.6 \pm 2.3) \times 10^{-4}$$

average of NA48 (CERN) and KTeV

$$\left|\frac{\eta_{00}}{\eta_{+-}}\right|^2 \simeq 1 - 6\,\mathrm{Re}(\frac{\varepsilon'}{\varepsilon})$$

$$\eta_{00} = \frac{A(K_{\rm L} \to \pi^0\pi^0)}{A(K_{\rm S} \to \pi^0\pi^0)}, \qquad \eta_{+-} = \frac{A(K_{\rm L} \to \pi^+\pi^-)}{A(K_{\rm S} \to \pi^+\pi^-)}$$

(magnitudes directly measurable from decay rates)

Even more precise measurement possible in principle at NA62/CERN

Theoretically very complicated multi-scale problem (weak scale, charm, QCD scale). Weak and charm scales to NLO in 1990s

QCD scale limiting theory accuracy to O(100%) until recently. Finally under quantitative control in 2015 (RBC-UKQCD)

Isospin limit

It is useful to formulate the problem in terms of isospin (as opposed to charge) final states.

Defining $A_I \equiv \langle (\pi\pi)_I | \mathcal{H}_{\rm eff} | K \rangle$

and

$$\langle Q_i \rangle_I \equiv \langle (\pi\pi)_I \, | Q_i | \, K \rangle \, , \qquad I = 0, 2$$

One has

$$\frac{\varepsilon'}{\varepsilon} = -\frac{\omega_+}{\sqrt{2}\,|\varepsilon_K|} \left[\frac{{\rm Im} A_0}{{\rm Re} A_0} (1 - \hat{\Omega}_{\rm eff}) - \frac{1}{a} \frac{{\rm Im} A_2}{{\rm Re} A_2} \right]$$

A small imaginary part on the l.h.s. has been neglected.
In the isospin limit, A_2 is pure electroweak penguin.

Moreover, the strong (rescattering) phases for a given isospin all coincide with the pi pi scattering phase shift (Watson's theorem).

Broken by QED and $m_u \neq m_d$: parameters $\Omega_{\rm eff}, a, \omega_+$

Lattice progress

The decay amplitudes depend on 20 hadronic matrix elements (10 operators, 2 isospins). (4 vanish.)

Traditionally estimated with chiral Lagrangians, with considerable model dependence.

First direct lattice evaluation of matrix elements in 2015

RBC-UKQCD collab 1502.00263 (I=2)

RBC-UKQCD, 1505.07863v4 (I=0)

Many conceptual obstacles needed to be overcome, such as
- computing strong phases in the Euclidean
- subtracting vacuum contribution (I=0 only)
- chiral symmetry properties essential

Direct evaluation of ε'/ε in isospin limit consistent with experiment at 2 sigma level. RBC-UKQCD, 1505.07863v4

A trick

An important simplification (in the 3-flavour theory, with the charm quark integrated out) is that Fierz identities and isospin imply for operators built from left-handed quarks, eg:

$$\langle Q_9 \rangle_2 = \langle Q_{10} \rangle_2 = \frac{3}{2} \langle Q_1 \rangle_2$$

The isospin-2 ratio depends essentially on a single ratio of hadronic matrix elements

$$\left(\frac{\mathrm{Im} A_2}{\mathrm{Re} A_2} \right)_{V-A} = \mathrm{Im}\tau \, \frac{3(y_9 + y_{10})}{2 z_+}$$

$$\left(\frac{\mathrm{Im} A_2}{\mathrm{Re} A_2} \right)_8 = - \frac{G_F}{\sqrt{2}} \, \mathrm{Im}\lambda_t \, y_8^{\mathrm{eff}} \, \frac{\langle Q_8 \rangle_2}{\mathrm{Re} A_2}$$

no nonperturbative input!

Can take Re A2 from CP-avg rates

Buras, Gorbahn, SJ, Jamin, arXiv:1507.06345

A similar argument shows that the isospin-0 ratio mainly depends on $\langle Q_6 \rangle_0$

Result

Combining all errors in quadrature,

$$(\varepsilon'/\varepsilon)_{\rm SM} = (1.9 \pm 4.5) \times 10^{-4}$$

Buras, Gorbahn, SJ, Jamin, arXiv:1507.06345

$$(\varepsilon'/\varepsilon)_{\rm exp} = (16.6 \pm 2.3) \times 10^{-4}$$

average of NA48 and KTeV

2.9 sigma discrepancy

New physics or underestimated error? (Cf B-anomalies)

The new theory result is quite consistent with old model estimates; the lattice corroborates these and gives for the first time a meaningful error estimates

Central values differ by order of magnitude, so a reduced theory error could potentially greatly enhance significance

Error budget and goals

Buras, Gorbahn, SJ, Jamin, arXiv:1507.06345

RBC-UKQCD 2015

quantity	error on ε'/ε	quantity	error on ε'/ε
$B_6^{(1/2)}$	4.1	$m_d(m_c)$	0.2
NNLO	1.6	q	0.2
$\hat{\Omega}_{\text{eff}}$	0.7	$B_8^{(1/2)}$	0.1
p_3	0.6	$\text{Im}\lambda_t$	0.1
$B_8^{(3/2)}$	0.5	p_{72}	0.1
p_5	0.4	p_{70}	0.1
$m_s(m_c)$	0.3	$\alpha_s(M_Z)$	0.1
$m_t(m_t)$	0.3		

(still) completely dominated by $\langle Q_6 \rangle_0 \propto B_6^{1/2}$

all in units of 10^-4

next steps:

improvement and independent confirmation of lattice (next few years)

NNLO bottom and charm thresholds

proper factorisation of QED (&QCD) between short and long distance

Cerda Sevilla, Gorbahn, SJ, Kokulu, wip

Look for BSM explanations

Buras, DeFazio; Goertz et al; Buras; Tanimoto, Yamamoto; Kitahara, Nierste, Tremper; Hisano et al; Endo et al; …

Summary

There are several anomalies in flavour physics, most of them in rare B decays.

I have focused on rare semileptonic decays. Attributing the anomalies to BSM effect requires knowledge of form-factor ratios to <10% accuracy in a range where they are not accessible from first principle. (In addition, there are uncertainties due to virtual charm.)

In Kaon physics, conceptual breakthroughs in lattice QCD put several observables on the verge of being precision SM tests.
One of them is the direct CP violation parameter ε'/ε showing a 2.9 sigma tension between SM and data.

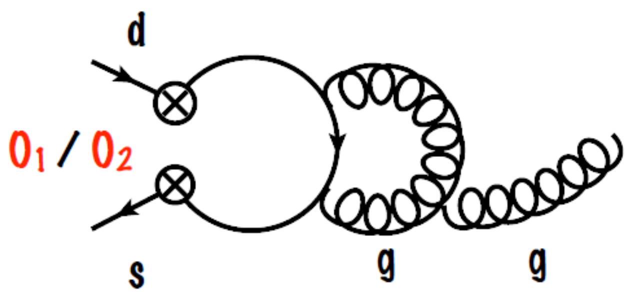
BACKUP

NNLO calculation

Cerda Sevilla, Gorbahn, SJ, Kokulu, w.i.p

NNLO weak Hamiltonian only known above b mass (from B->Xs gamma)

require bottom and charm threshold matching and (less importantly) NNLO mixing of QCD into EW penguins



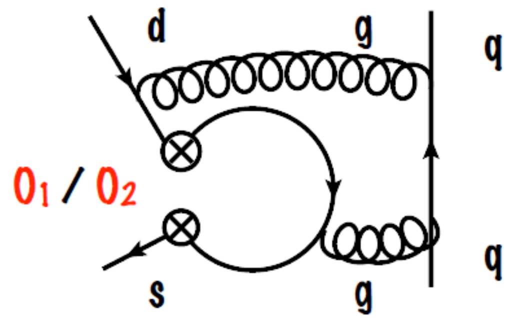


Fig. M Cerda Sevilla

extend the formalism (including operator relations, hadronic matrix element ratios, etc) to 4-flavour theory.
Will eventually obviate the need for perturbation theory at the charm scale.
P reliminary results show small perturbative corrections

Isospin breaking

complicated, particularly QED effects (IR subtractions, real emission, lattice matching, …)

- don’t respect the two-amplitude structure
- violate Watson’s theorem

Now conceptually understood on the lattice in QED perturbation theory. In practice need to

- define QED expansion of matrix element ratios
- carefully define&express observable at O(alpha).
- disentangle QED RG evolution from matrix element expansion, for matching short-distance and lattice

No more $\Omega_{\rm eff}$!

Cerda Sevilla, Gorbahn, SJ, Kokulu, w.i.p

Scheme issues

Wilson coefficients depends on renormalisation scale (and scheme)
Must be cancelled by a proper matrix element calculation.

Wilson coefficients calculated in dim. reg. – not on lattice!

Currently use of momentum-space schemes on lattice.
Conversion to MSbar more demanding than calculating the Wilson coefficient.
(The only existing NNLO calculation of this sort is for the light quark masses!)

Separating lattice and continuum parts of calculation is subtle in presence of operator mixing and QED corrections!

Cerda Sevilla, Gorbahn, SJ, Kokulu, w.i.p