Understanding flavour anomalies

Sebastian Jäger

University of Sussex

UK HEP Forum: Anomalies & Deviations
Cosener's House, Abingdon, 06/11/2015

Contents

1
Flavour theory primer
(Express version)

Building blocks

(Ordered by elegance)

spin 1

electromagnetism U(1)

weak interactions SU(2)

strong interactions SU(3)

spin 1/2

$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{matrix} u_R \\ d_R \end{matrix}$	$\begin{pmatrix} c_L \\ s_L \end{pmatrix}$	$\begin{matrix} c_R \\ s_R \end{matrix}$	$\begin{pmatrix} t_L \\ b_L \end{pmatrix}$	$\begin{matrix} t_R \\ b_R \end{matrix}$	$\begin{matrix} Q = +2/3 \\ Q = -1/3 \end{matrix}$
$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	$\begin{matrix} - \\ e_R \end{matrix}$	$\begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$	$\begin{matrix} - \\ \mu_R \end{matrix}$	$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$	$\begin{matrix} - \\ \tau_R \end{matrix}$	$\begin{matrix} Q = 0 \\ Q = -1 \end{matrix}$

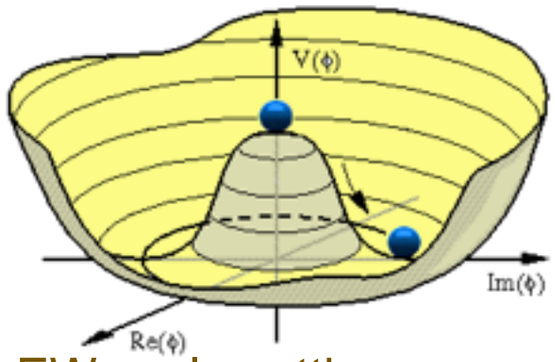
NEW **spin 0**

Higgs - sets mass scale of entire Standard Model depending on point of view:

- worst case LHC scenario (anonymous theorist)
- “the first SUSY particle” (attributed to S Heinemeyer)
- a new lab to look beyond the SM (yesterday’s talks)

Dynamics

The discovery of a Higgs scalar and apparent absence of other particles implies the following approximate Lagrangian at length scales between an attometre and a fermi



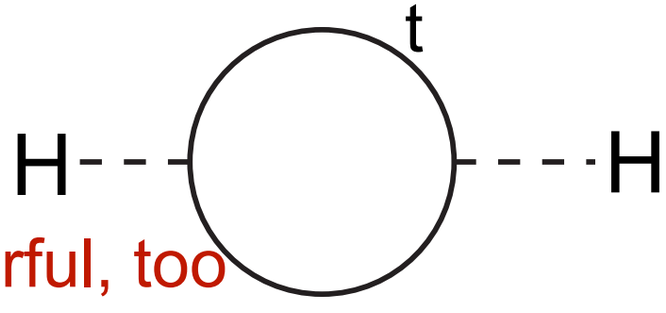
SU(3)^5 flavour symmetric kinetic/gauge terms

EW scale setting

$$\mathcal{L}_{\rm SM} \sum_f \bar{\psi}_f \gamma^\mu D_\mu \psi_f - \sum_{i,a} \frac{1}{4} g_i F^{ia}_{\mu\nu} F^{ia\mu\nu}$$
$$-\bar{u}_R Y_U \phi^{c\dagger} Q_L - \bar{d}_R Y_D \phi^\dagger D_L - \bar{e}_R Y_E \phi^\dagger E_L - \mu^2 \phi^\dagger \phi - \frac{\lambda}{2} (\phi^\dagger \phi)^2$$

flavour-breaking fermion masses and Higgs couplings

NB: naturalness problem is (mostly) caused by top Yukawa, a flavour-breaking term



Physics addressing naturalness should be flavourful, too

This happens in supersymmetry, extra dim/composite Higgs, ...

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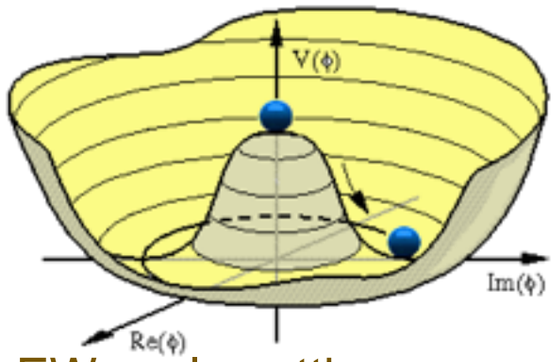

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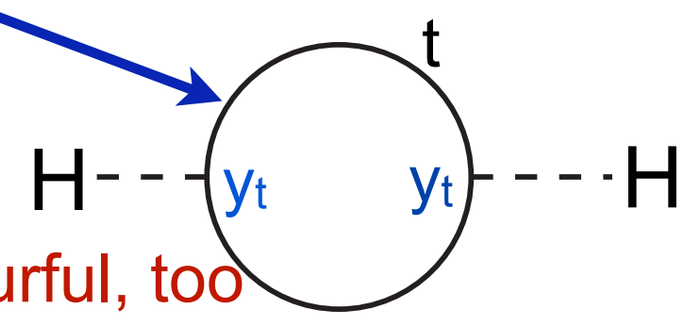

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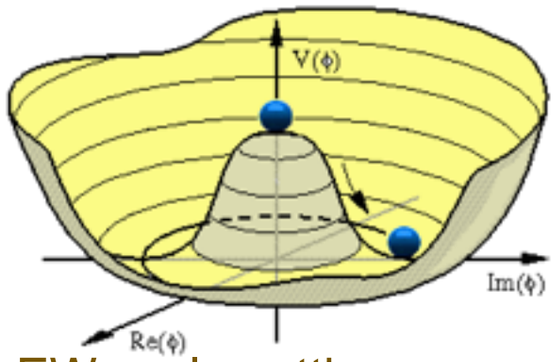

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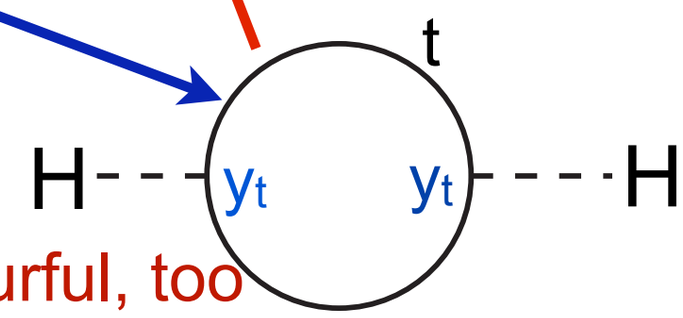
flavour-breaking fermion masses and Higgs couplings

$\propto y_t^2 M^2$



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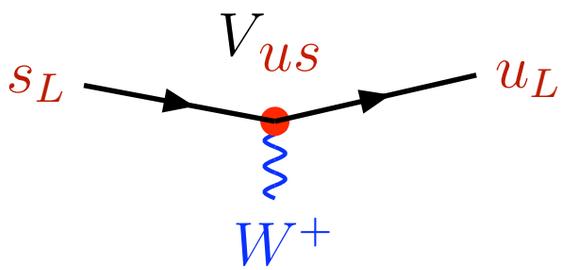
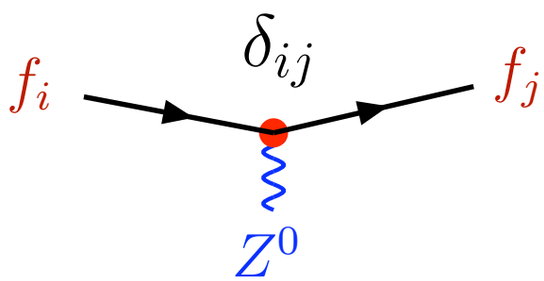
Flavour physics



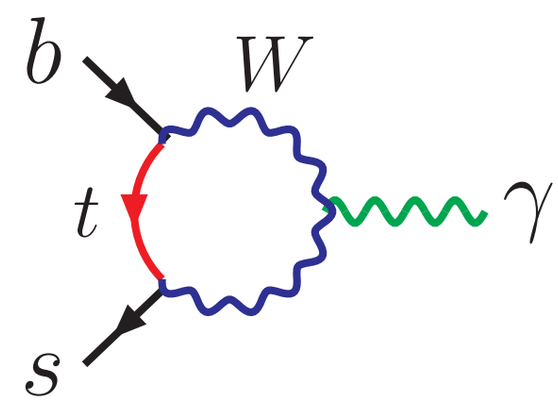
all flavour violation in charged weak current



(tree level) neutral current conserves flavor

strong & electromagnetic preserve flavour

Loop suppression of flavour-changing neutral current processes

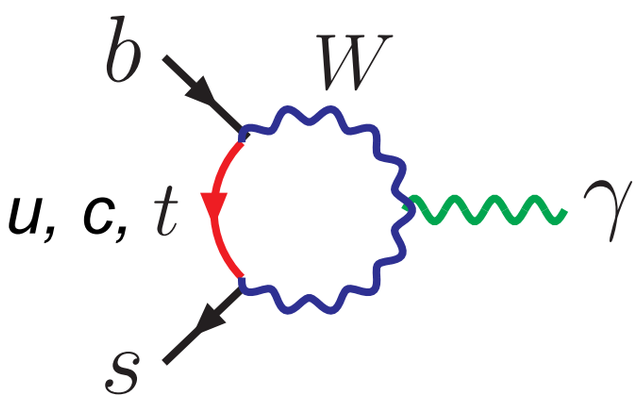


BSM flavour physics both motivated and may compete with SM

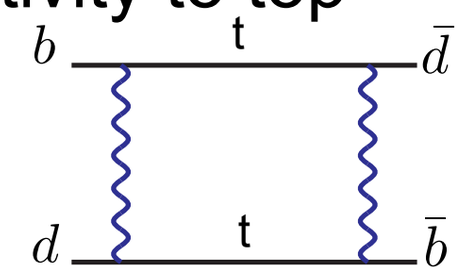
Rare decays

SM: Loop + CKM suppression of FCNC (GIM)

y_t main source of GIM breaking: enhanced sensitivity to top

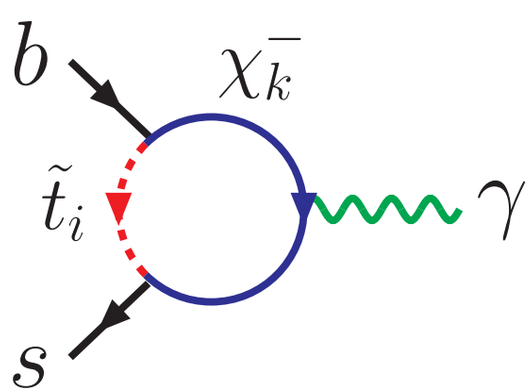


e.g. B-Bbar oscillations first indication of a heavy top (Argus 1987)



Charm contribution sometimes sizable/uncertain due to large logarithms and/or nonperturbative QCD effects. Often leading source of uncertainty

BSM: Can compete even in weakly coupled case (MSSM)



MSSM: sensitive to stops and their couplings
Stringent constraints on 1st-2nd generation mixing

In more general cases can have tree-level contributions (Z')

In strongly coupled models may lose loop suppression, flavour most stringent generic constraint absent flavour protection (RS)

What to look for?

Heavy physics with mass scale M described by local effective Lagrangian at energies below M (many incarnations)

Effective Lagrangian dimension-5,6 terms describes **all** BSM physics to $O(E^2/M^2)$ accuracy. **Systematic & simple**. E.g.

Buchmuller, Wyler 1986
Grzadkowski, Misiak, Iskrzynski, Rosiek 2010

Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu \tau^I q_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu \tau^I l_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$

operators (vertices) are catalogued for arbitrary (heavy) new physics

Only trace of BSM physics is in their (Wilson) coefficients

Much slower decoupling with M than in high-pT physics. Possibility to probe well beyond energy frontier.

B physics probes O(100) operators (more if lepton flavour violation)

2 Three beautiful anomalies

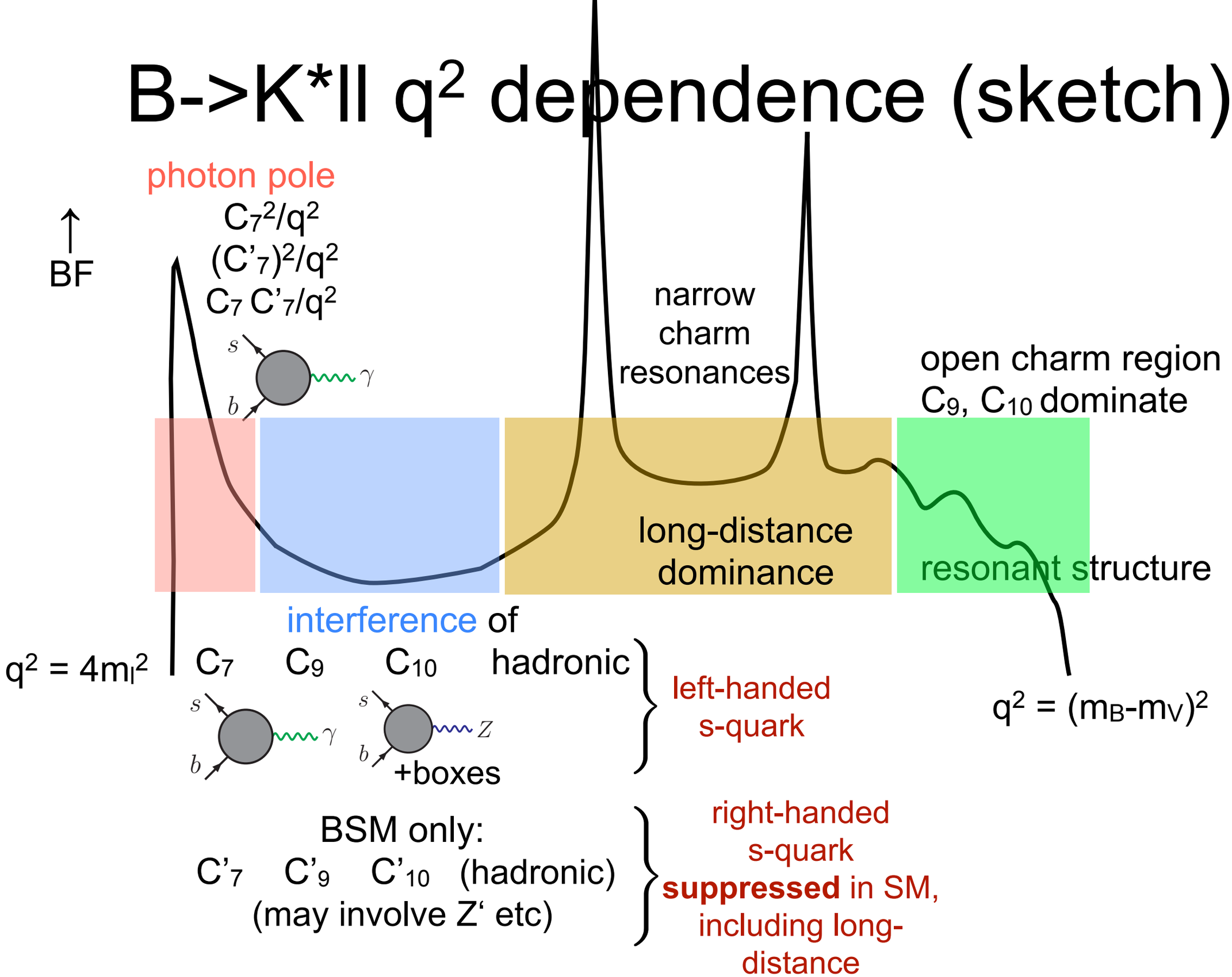
Focus on three anomalies in
rare semileptonic decay
b -> s l l (l = muon or electron)

当時三美人

Three beauties of the present day (Utamaro)

"at first glance their faces seem similar, but subtle differences in their features and expressions can be detected—" (Wikipedia)

B->K*ll q^2 dependence (sketch)



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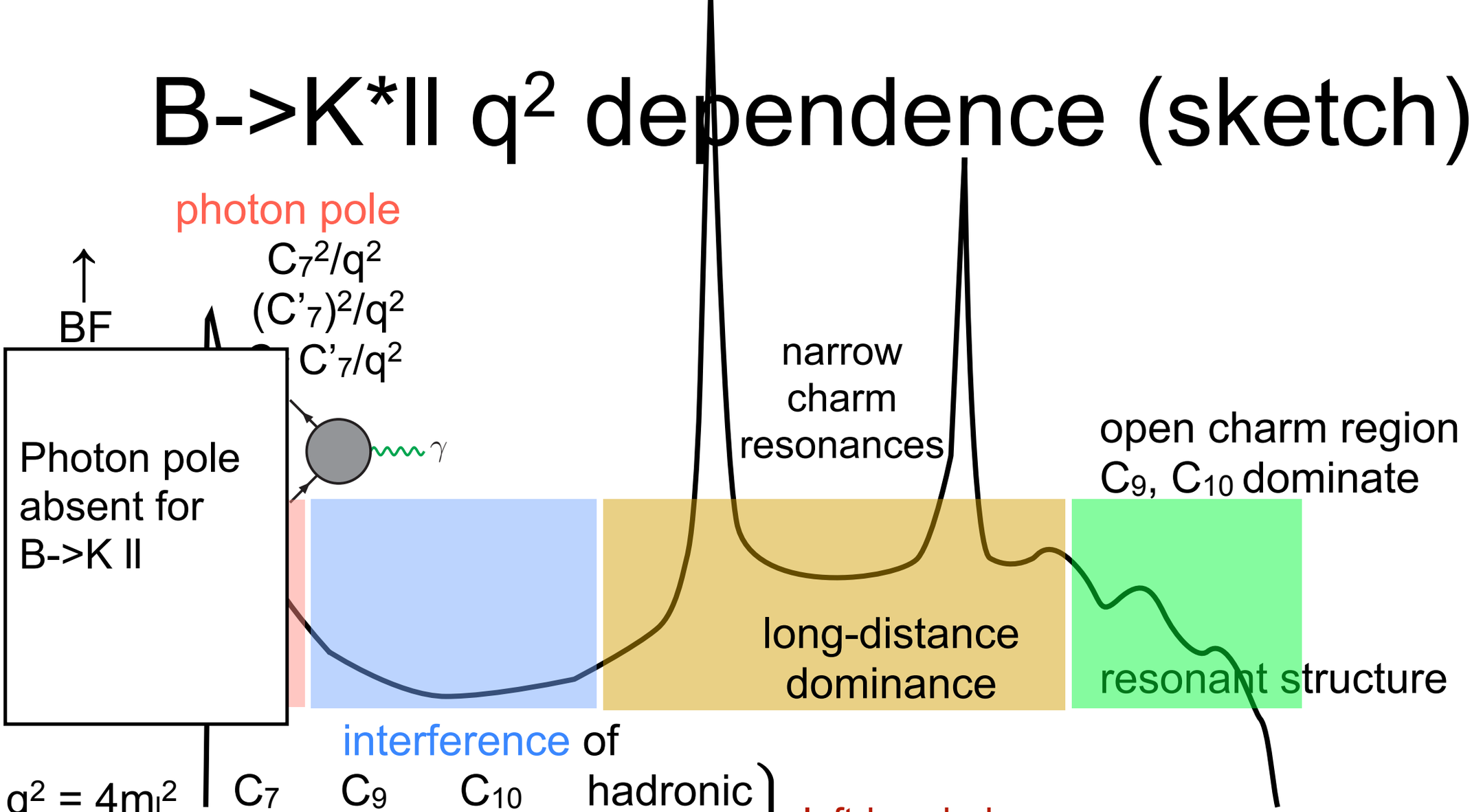


BSM only:
C'_7 C'_9 C'_{10} (hadronic)
(may involve Z' etc)

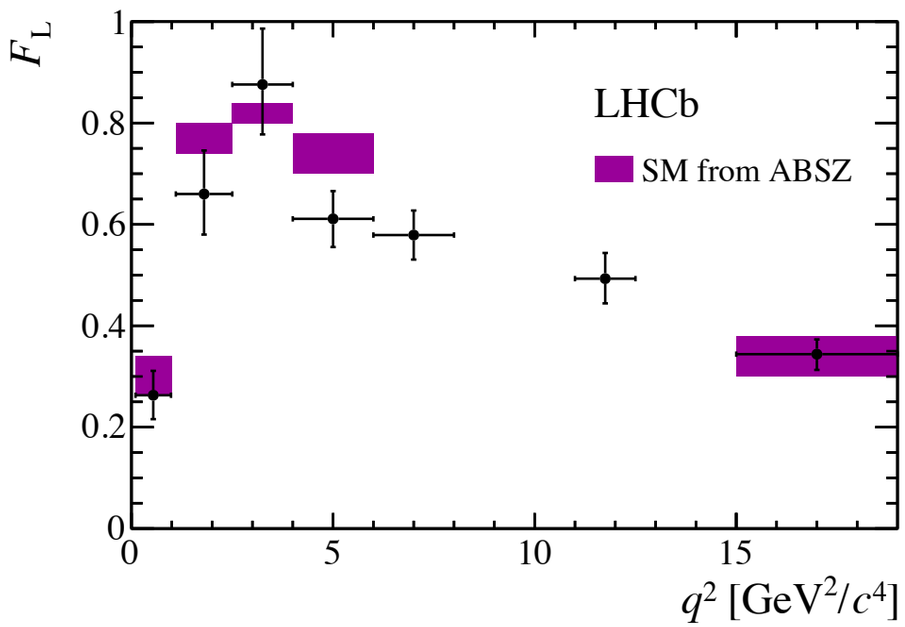
right-handed s-quark **suppressed** in SM, including long-distance

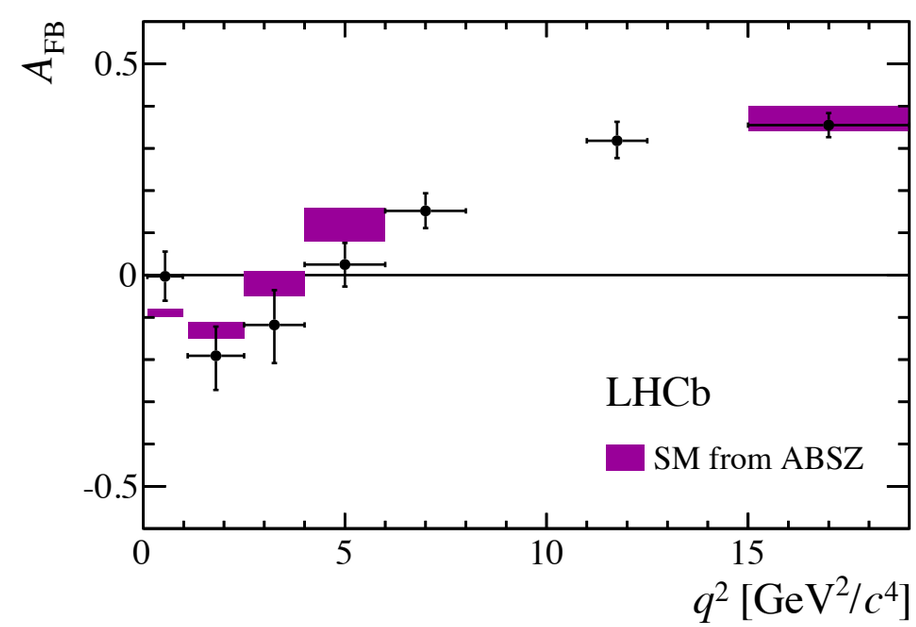
"low q^2 / large recoil"
will mostly talk about this

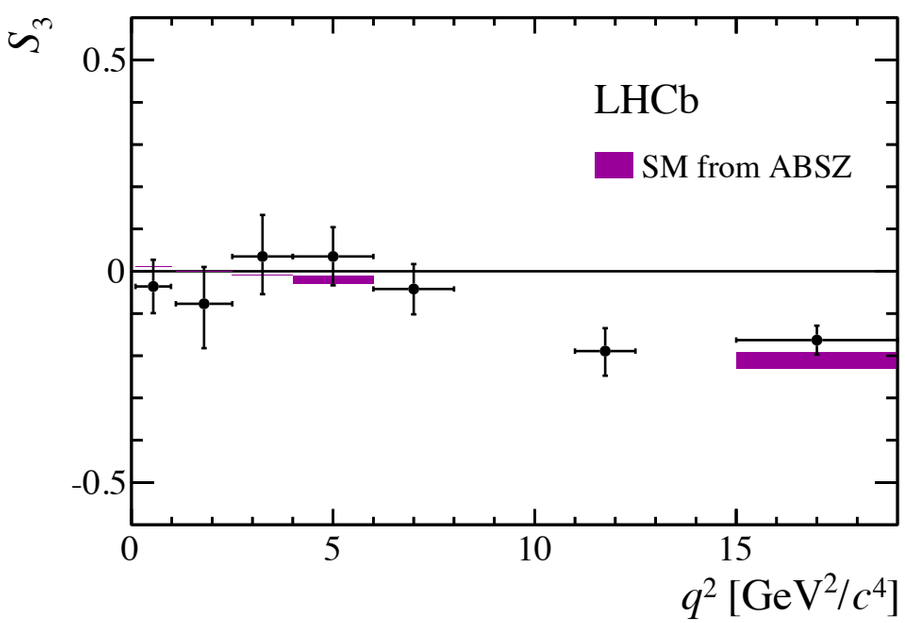
"high q^2 / low recoil"

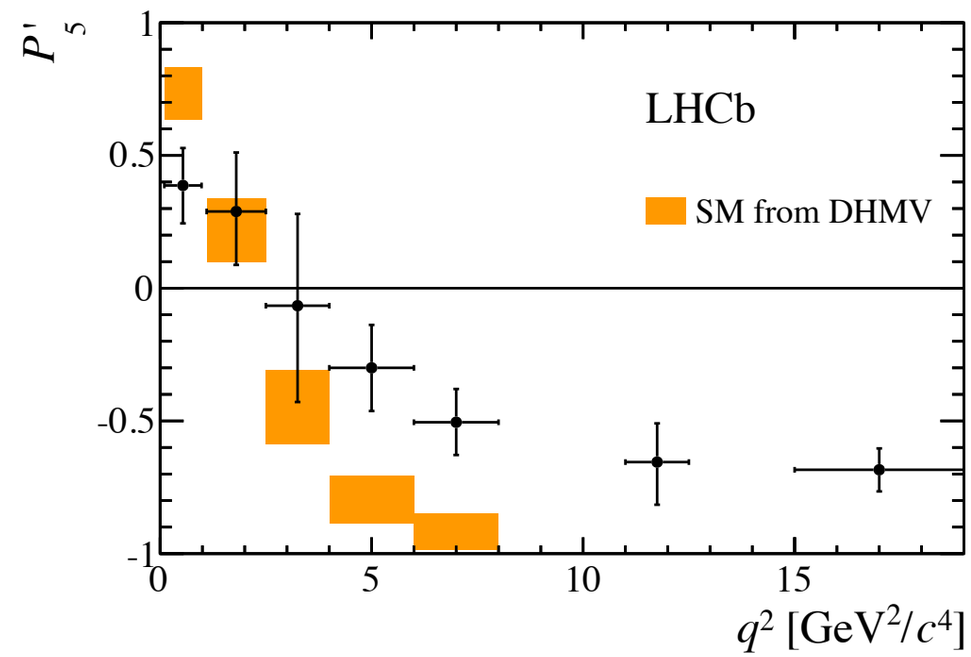
B->K*μ⁺μ⁻ angular distribution

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



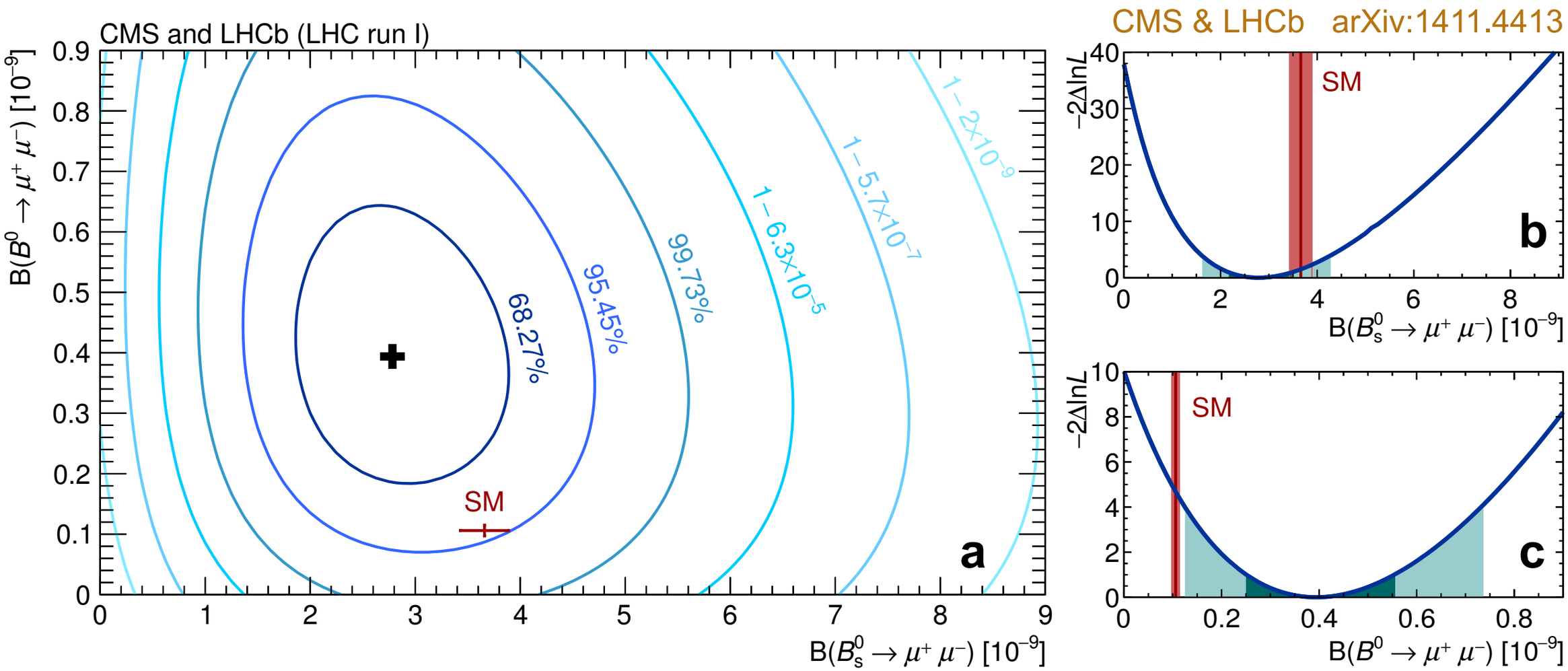






Deviations in lepton charge FB asymmetry (A_{FB})
and angular observable S_5 / P_5’

Rare leptonic B decays

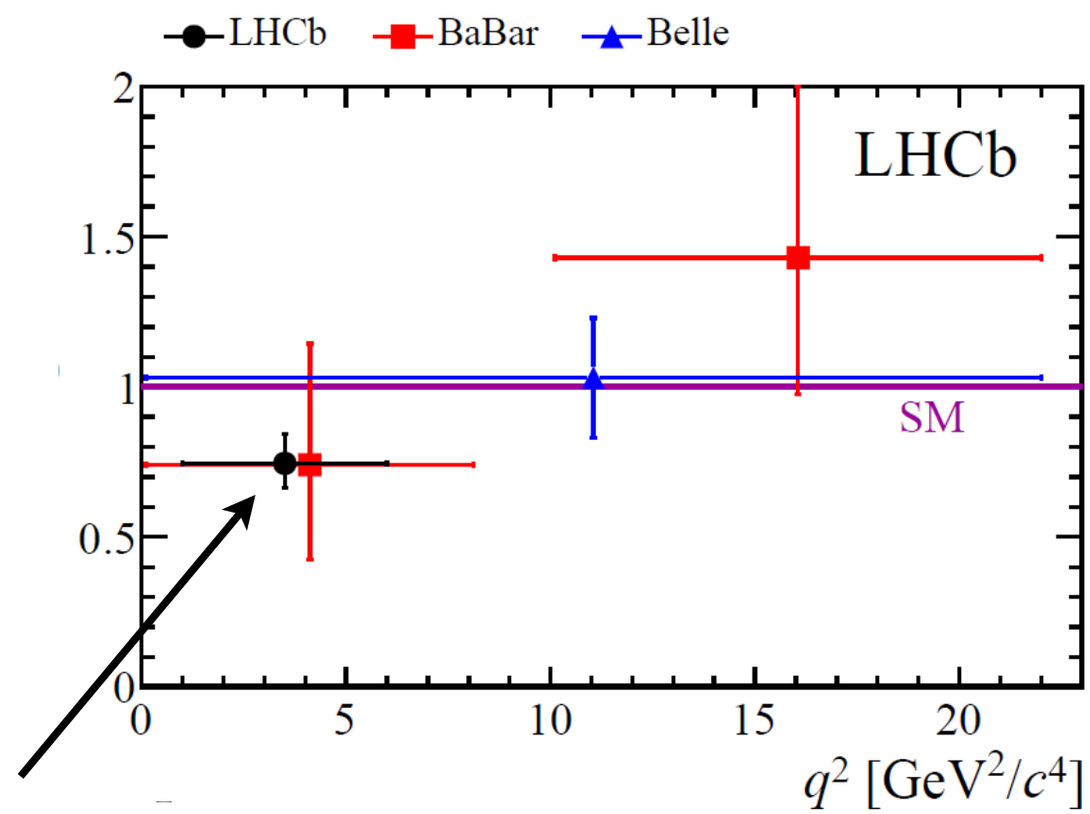


Central value quite far from SM - not significant however

good prospects from LHCb, (increasingly) CMS; eventually HL-LHC (completely dominated by experimental error)

Lepton universality violation

$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\Gamma[B^+ \to K^+\mu^+\mu^-]}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\Gamma[B^+ \to K^+e^+e^-]}{\mathrm{d}q^2}\mathrm{d}q^2}$$



$$0.745^{+0.090}_{-0.074}\,(\mathrm{stat})\ \pm 0.036\,(\mathrm{syst})$$

LHCb, PRL 113 (2014) 151601

naively =1 in SM if lepton masses negligible (as seems the case for 1 GeV^2 lower cutoff) Hiller, Krueger 2003

a large effect !

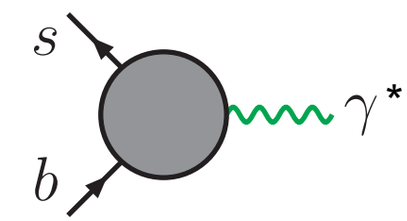
Main theory concern is role of soft photon radiation.
Informal consensus that the true theoretical uncertainty is at percent level at most. (Various unpublished studies / works in progress.)

Can it be BSM physics?

in SM

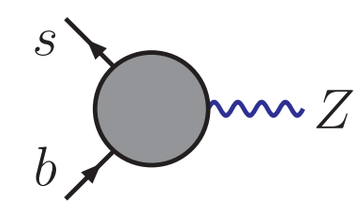
C_9 : coupling of a particular four-fermion operator

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



C_{10} : coupling of another four-fermion operator

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



- both can be obtained from Z' exchanges

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

- or leptoquarks

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

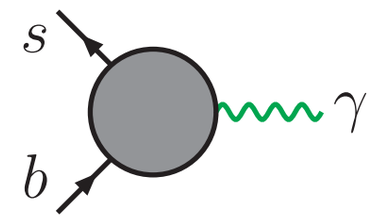
- for minimal lepton coupling to Z': C_9 favoured by low-energy precision constraints (model predicted $R_K \neq 1$, too)

Altmannshofer-Gori-Pospelov-Yavin

Possible problem: BSM effects in C_9 can be mimicked by a range of SM effects - how well are they controlled?

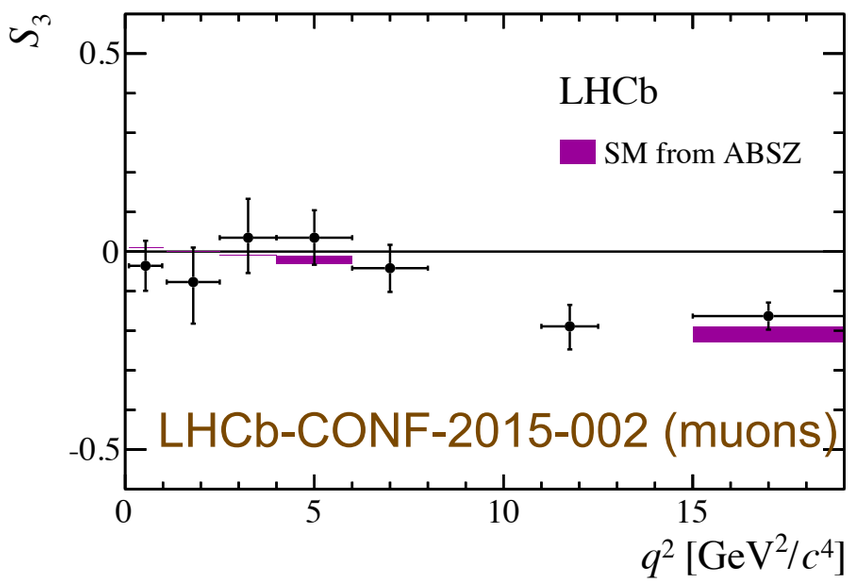
What it cannot be

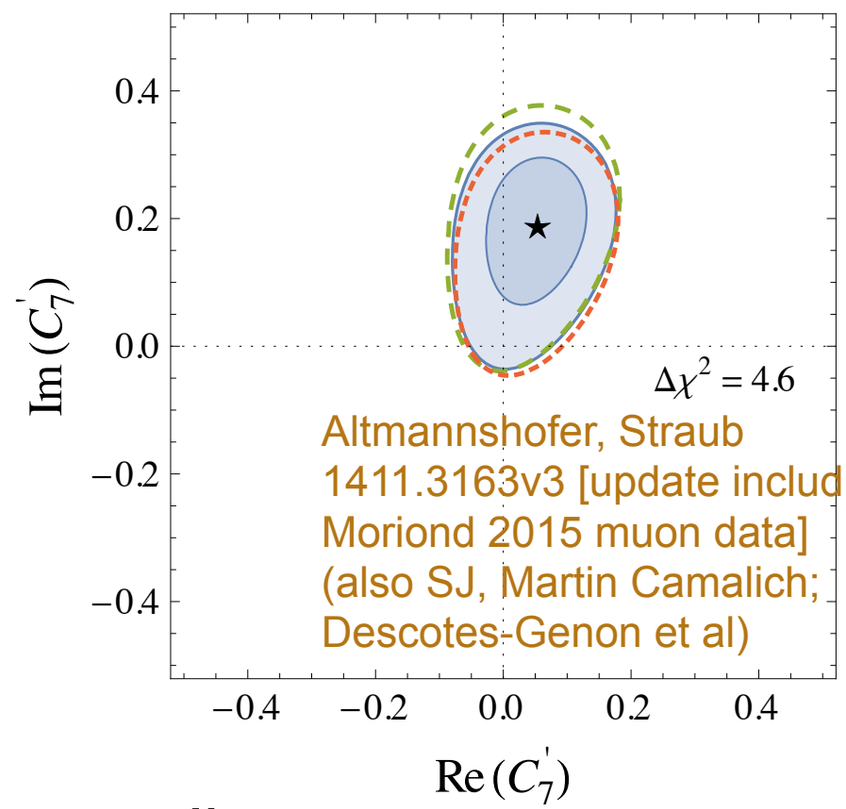
C_7 : electromagnetic dipole coupling
(strongly constrained by inclusive B->X_s gamma)



operators with right-handed strangequarks
(constrained by other angular observables)

SJ, Martin Camalich 2012, 2014;
various global fits 2014-2015





Altmannshofer, Straub
1411.3163v3 [update including
Moriond 2015 muon data]
(also SJ, Martin Camalich;
Descotes-Genon et al)

+ results on B->K* e^+e^-

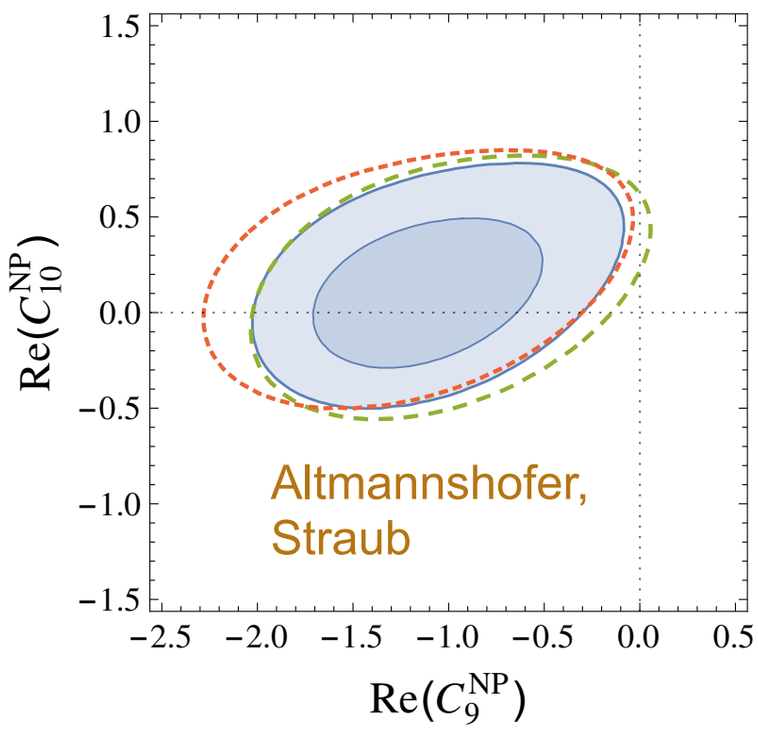
JHEP 1504 (2015) 064

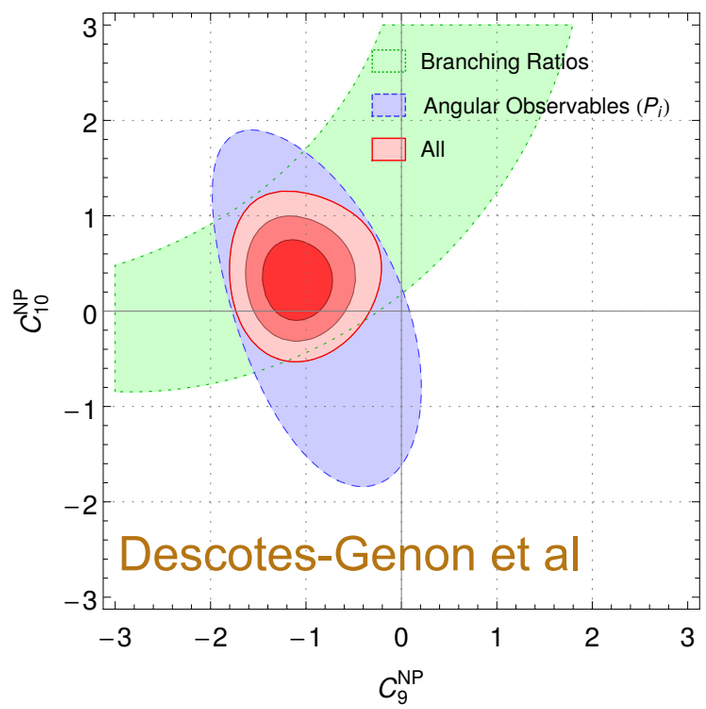
operators with scalar or pseudoscalar couplings
(gigantic effects in B_s -> mu mu due to SU(2)xU(1) symmetry)

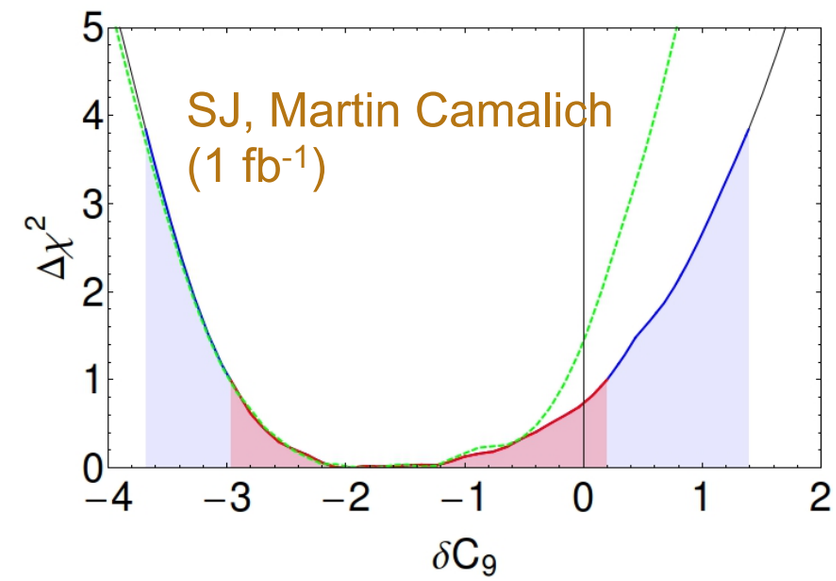
Grinstein, Martin Camalich 2014

Global fits

Fits of weak Hamiltonian to data on B->K(*)ll, Bs->mu mu, B->Xs gamma, B->phi ll, B->K*gamma prefer non-SM values.





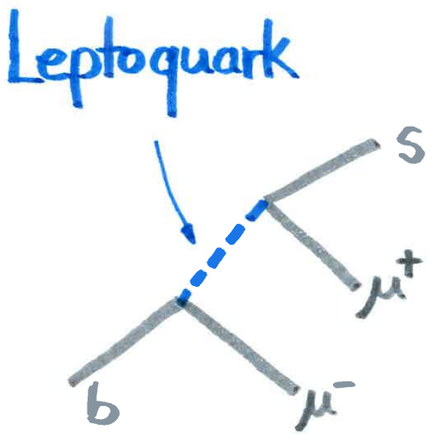


also: Bobeth et al; Hurth-Mahmoudi; Ciuchini et al (in prep); Ghosh et al,...

Most agree that best fit is for C_9^{NP} ~ -1..-2 but differ on significance

Some level of degeneracy C_9 / C_{10} (branching fractions - green band); angular observables prefer C_9

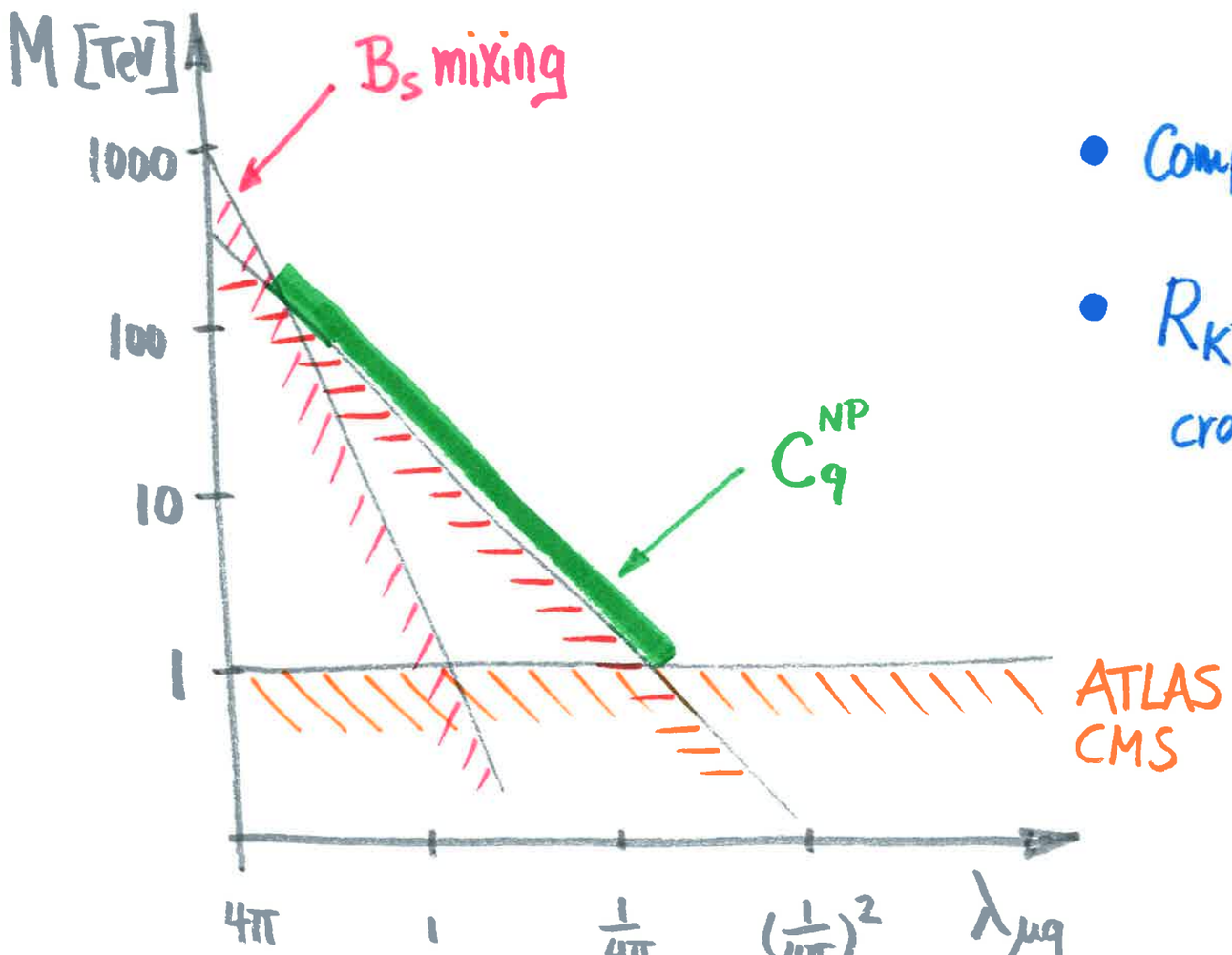
One leptoquark realisation



$$C_9^{NP\mu} = -C_{10}^{NP\mu} \sim \frac{\lambda^*_{\mu s}\lambda_{\mu b}}{M^2}$$

$$\text{fit}: \frac{1}{(25\,\text{TeV})^2}$$

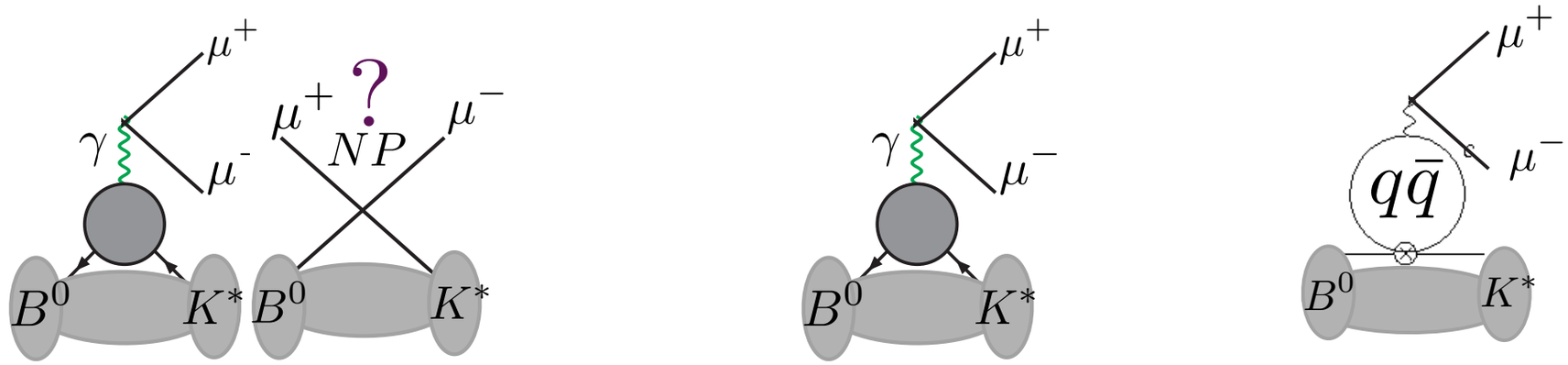
slides from
M Schmaltz
at LHCb Implications, 05/11/2015



- Complementarity
- $R_{K^*}, R_\phi \ldots$ cross-checks

Possible issues

λ=+1/0/-1 helicity of vector meson



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

no photon pole: vanishing relative contribution as q^2->0

photon pole at q^2=0

Only one form factor, drops out up to interference

photon pole at q^2=0

complicated nonlocal correction

λ=0 and λ=-1 amplitudes involve two nonperturbative form factors each, and nonlocal ("quark loop") contributions.
Implies degeneracies between C_9 and nonperturbative physics. (Eg, rescale V_- and C_9 by opposite amount.)

Can one explain apparent BSM C_9 by either form factor uncertainties or underestimated long-distance charm?

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

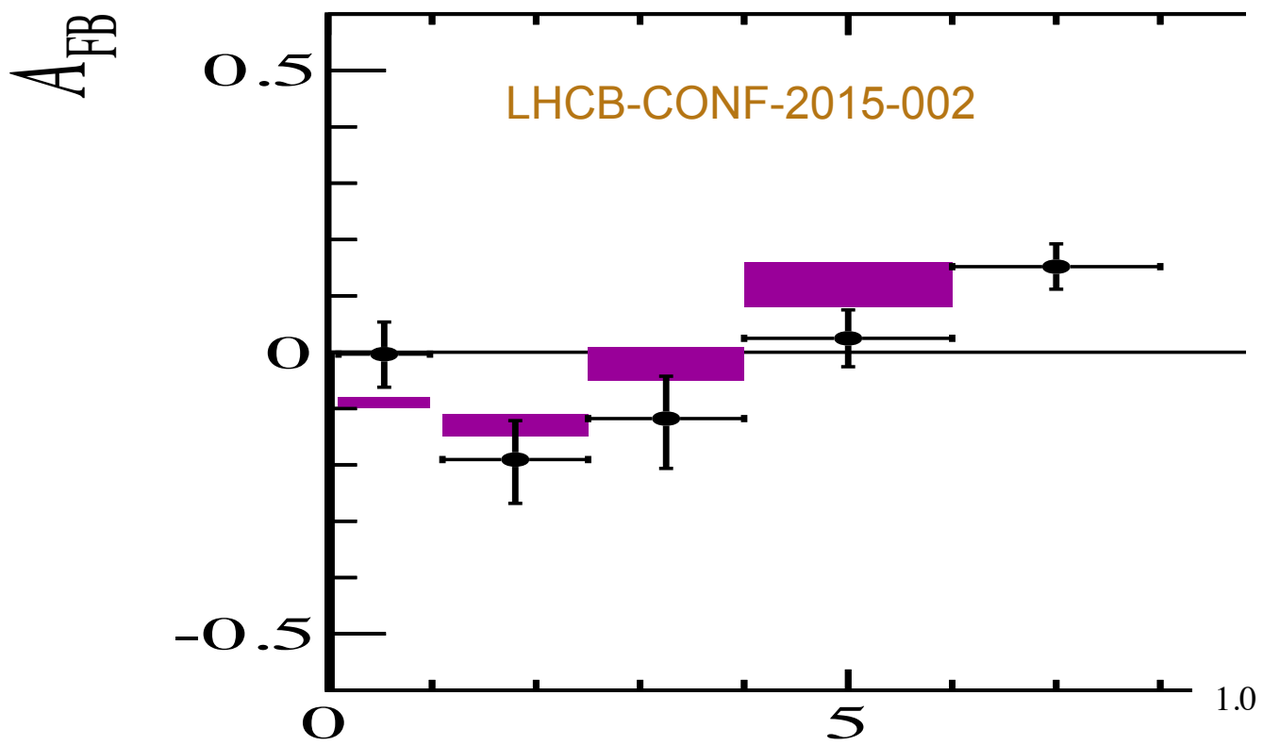
- Eliminates form factor dependence from some observables (eg P_2' and zero of A_{FB}) almost completely, up to Λ/m_b power corrections

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]
  LCSR computation with correlated parameter variations.
  Difference consistent with Λ/m_b power correction;
  remarkable 5% error

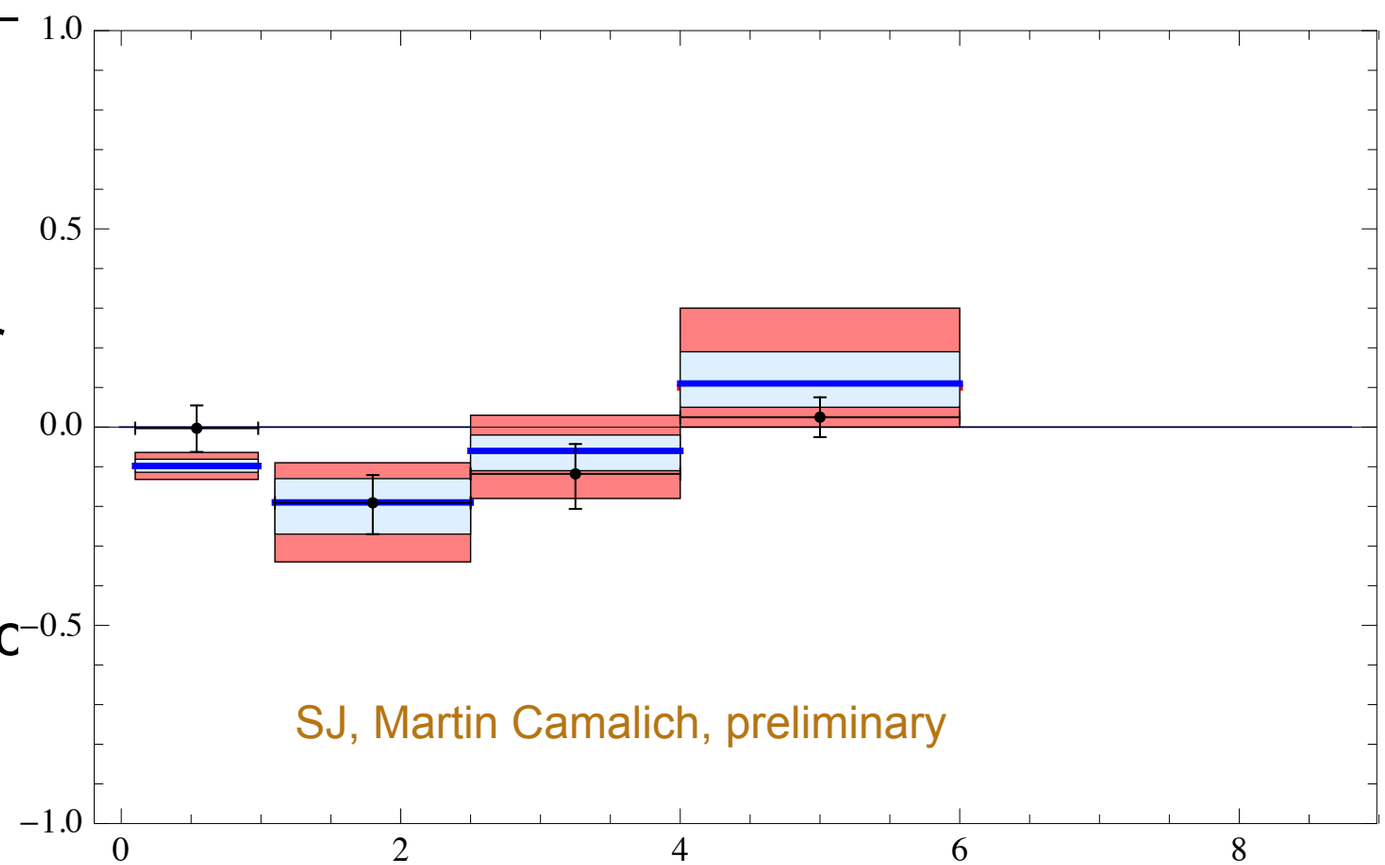
Forward-backward asymmetry



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)

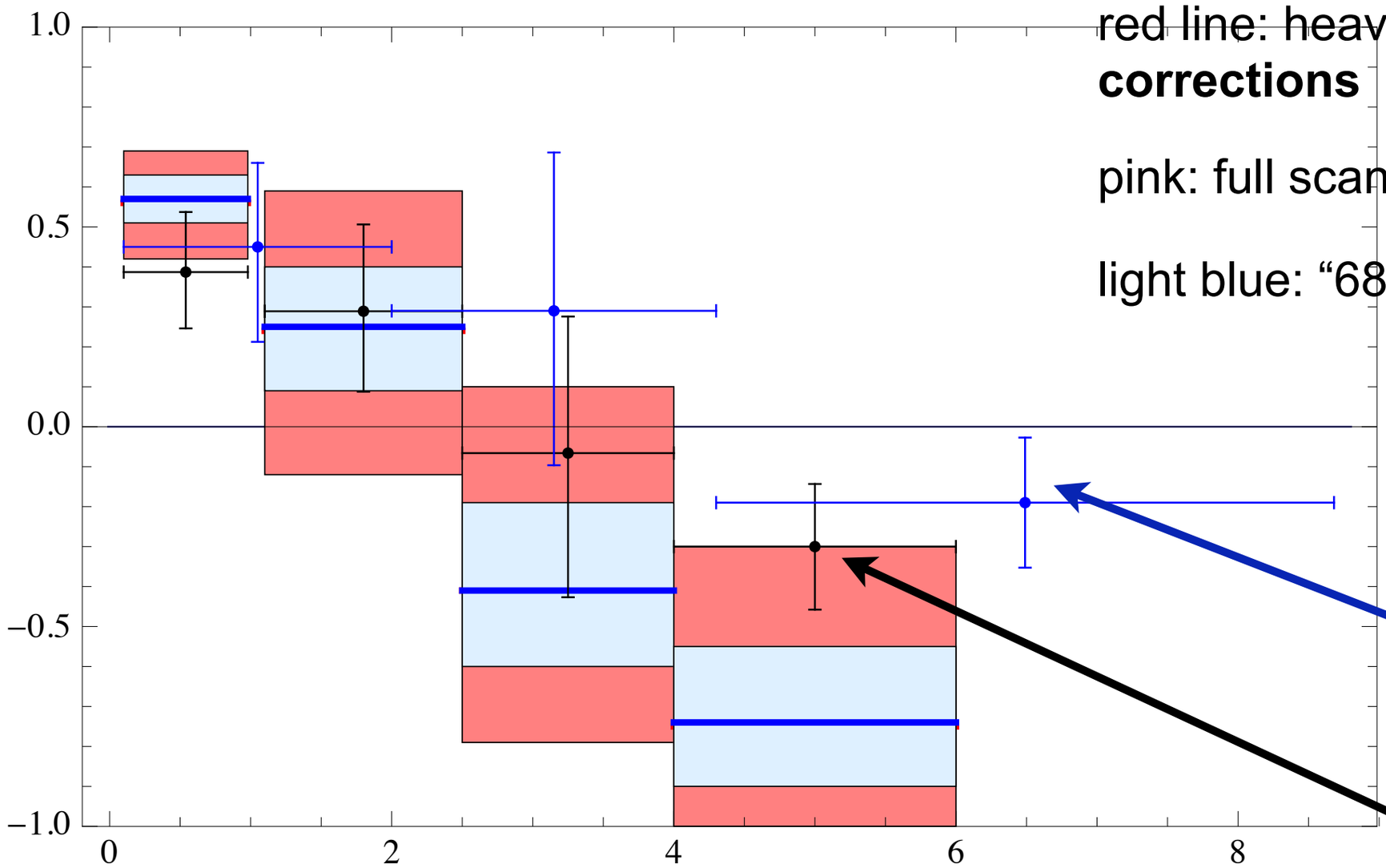
pink: full scan over all theory errors

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

“Clean” observables at present precision have noticeable form factor dependence

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

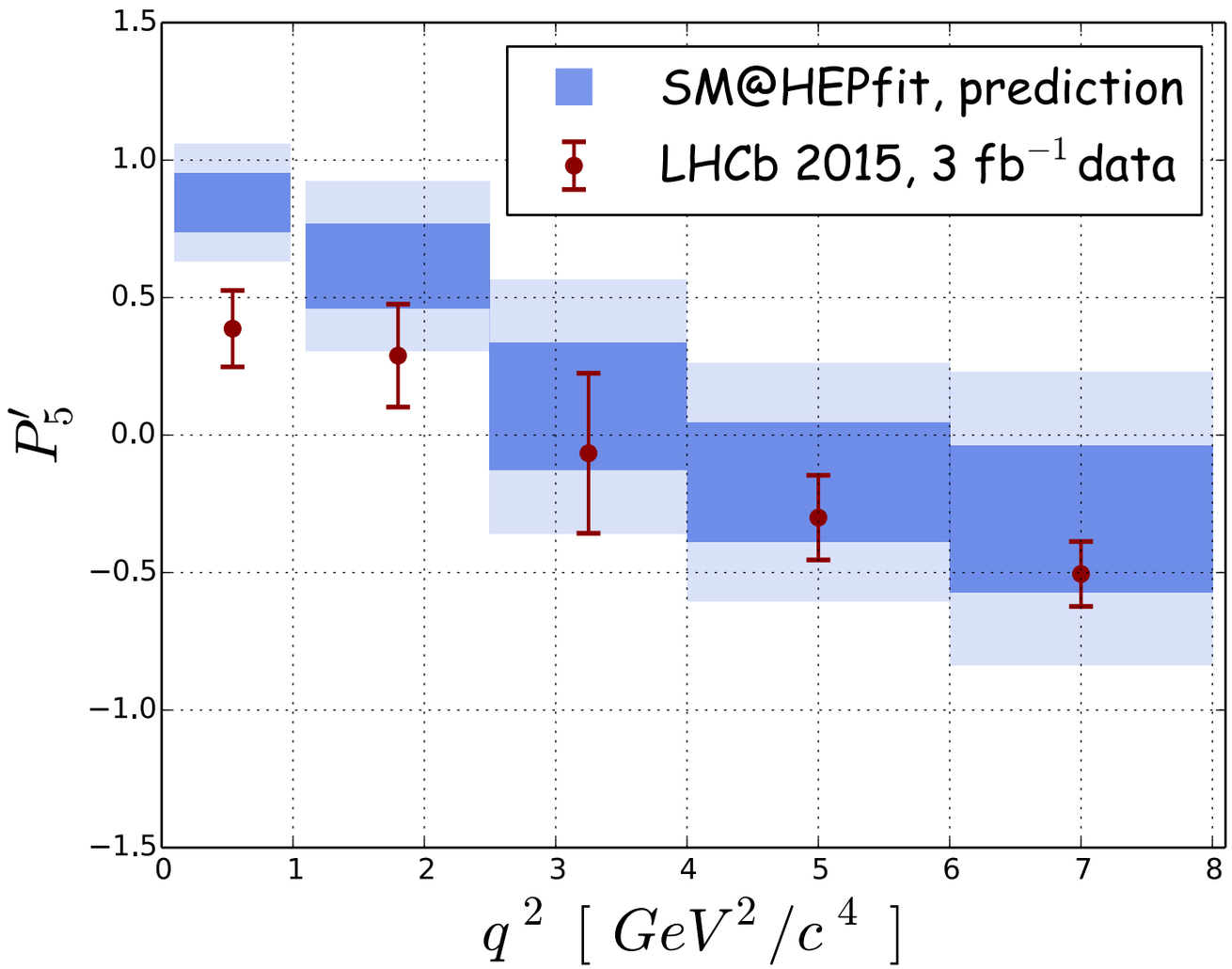
LHCb 2013 (1 fb^{-1})

LHCb Moriond 2015 (3 fb^{-1})

(Ignore 6..8 GeV bin, above perturbative charm threshold and very close to resonances.)

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

Charming penguin?



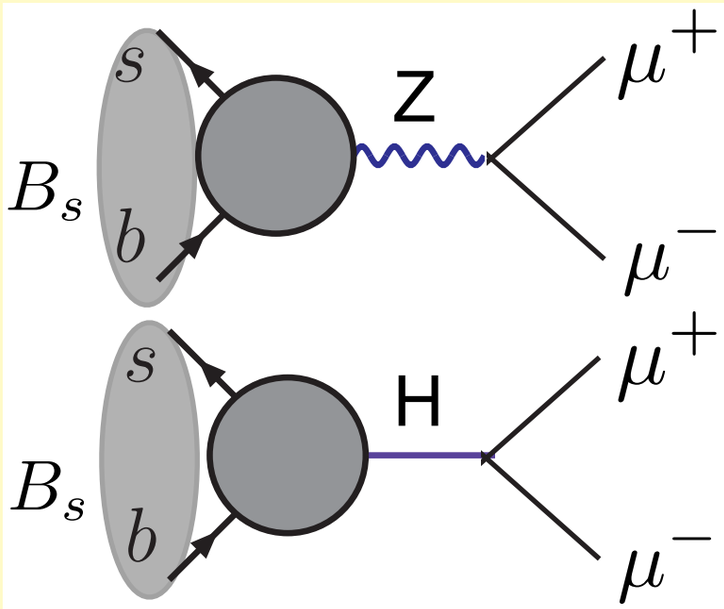
M Valli at LHCb Implications, 03/11/2015
preliminary

prediction involves Bayesian fit of charm loop to data

by design this can account for any effect depending on prior;
question is whether posterior is consistent with heavy-quark expansion

C_{10} and B_s -> mu mu

[slide based on talk by M Steinhauser, BEACH 2014



very NP sensitive (Z penguin C_{10}, heavy Higgses)

SM helicity suppression

- NLO QCD corrections [Buchalla,Buras'93'99; Misiak,Urban'99]
- leading-m_t NLO electroweak corrections [Buchalla,Buras'98]
- uncertainty (from higher orders): $\approx 7\%$

exp uncertainty will reach this during HL run

- NNLO QCD
- NLO EW

[Bobeth,Gorbahn,Hermann,Misiak,Stamou,Steinhauser'13]

missing $\mathcal{O}(\alpha_{em})$

- no enhancement factor (like $\frac{1}{\sin^2\theta_W}$, $\frac{m_t^2}{M_W^2}$ or $\ln^2\frac{M_W^2}{\mu_b^2}$)
- soft Bremsstrahlung: $B_s \to \mu^+\mu^- + (n\gamma)$ $(n = 0, 1, 2, \ldots)$
- Can QED corrections ($\alpha_{em}/\pi \approx 2 \times 10^{-3}$) remove helicity suppression factor ($m_\mu^2/M_{B_s}^2 \approx 10^{-4}$)?

helicity suppression remains

New prediction

$$\overline{\mathcal{B}}_{s\mu} = (3.65 \pm 0.06)\, R_{t\alpha}\, R_s \times 10^{-9} = 3.65 \pm 0.23 \times 10^{-9}$$

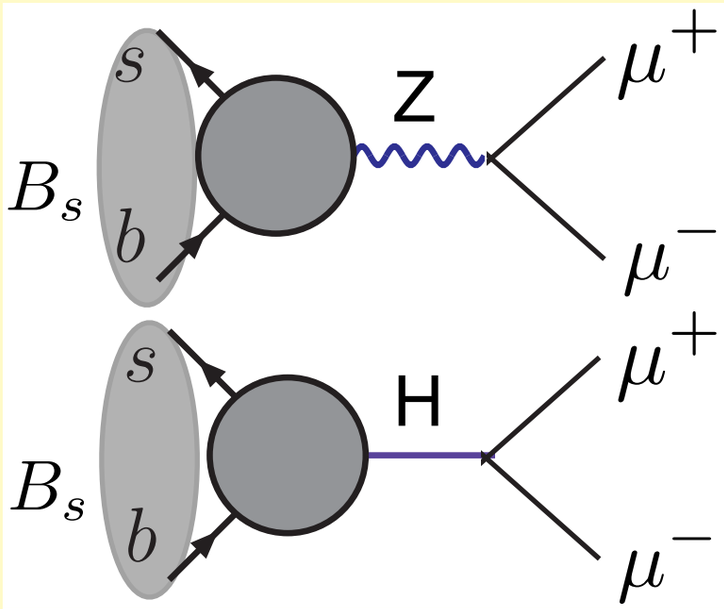
$$\overline{R}_{ql} = \frac{\overline{\mathcal{B}}_{ql}}{\ldots} = \frac{1 + \mathcal{A}_{\Delta\Gamma}^{\parallel} y_q}{\ldots} \left(|S|^2 + |P\right.$$

parametric uncertainties dominate

$$R_s = \left(\frac{f_{B_s}[\mathrm{MeV}]}{227.7}\right)^2 \left(\frac{|V_{cb}|}{0.0424}\right)^2 \left(\frac{|V_{tb}^\star V_{ts}/V_{cb}|}{0.980}\right)^2 \frac{\tau_H^s\,[\mathrm{ps}]}{1.615}$$

C_{10} and B_s -> mu mu

[slide based on talk by M Steinhauser, BEACH 2014



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parametric uncertainties dominate

$$R = \left(\frac{f_{B_s}[\mathrm{MeV}]}{\ldots}\right)^2 \left(\frac{|V_{cb}|}{\ldots}\right)^2 \left(|V_{tb}^\star V_{ts}/V_{cb}|\right)^2 \tau_H^s\,[\mathrm{ps}]$$

No contamination from long-distance charm. Precision ready for HL-LHC

Further LUV tests

SM predicts lepton universality to great accuracy. In particular, apart from lepton mass effects all helicity amplitudes coincide and hence, to our accuracy, the theory error on any LUV ratio or difference is zero. Altmannshofer, Straub; Hiller, Schmaltz; SJ, Martin Camalich

Two particular classes of observables:

(1)
$$R_{K^*_X} = \frac{\mathcal{B}(B \to K^*_X \mu^+ \mu^-)}{\mathcal{B}(B \to K^*_X e^+ e^-)}. \qquad X = L,\, T$$

$$R_i = \frac{\langle \Sigma_i^\mu \rangle}{\langle \Sigma_i^e \rangle} \qquad \Sigma_i = \frac{I_i + \bar{I}_i}{2}$$

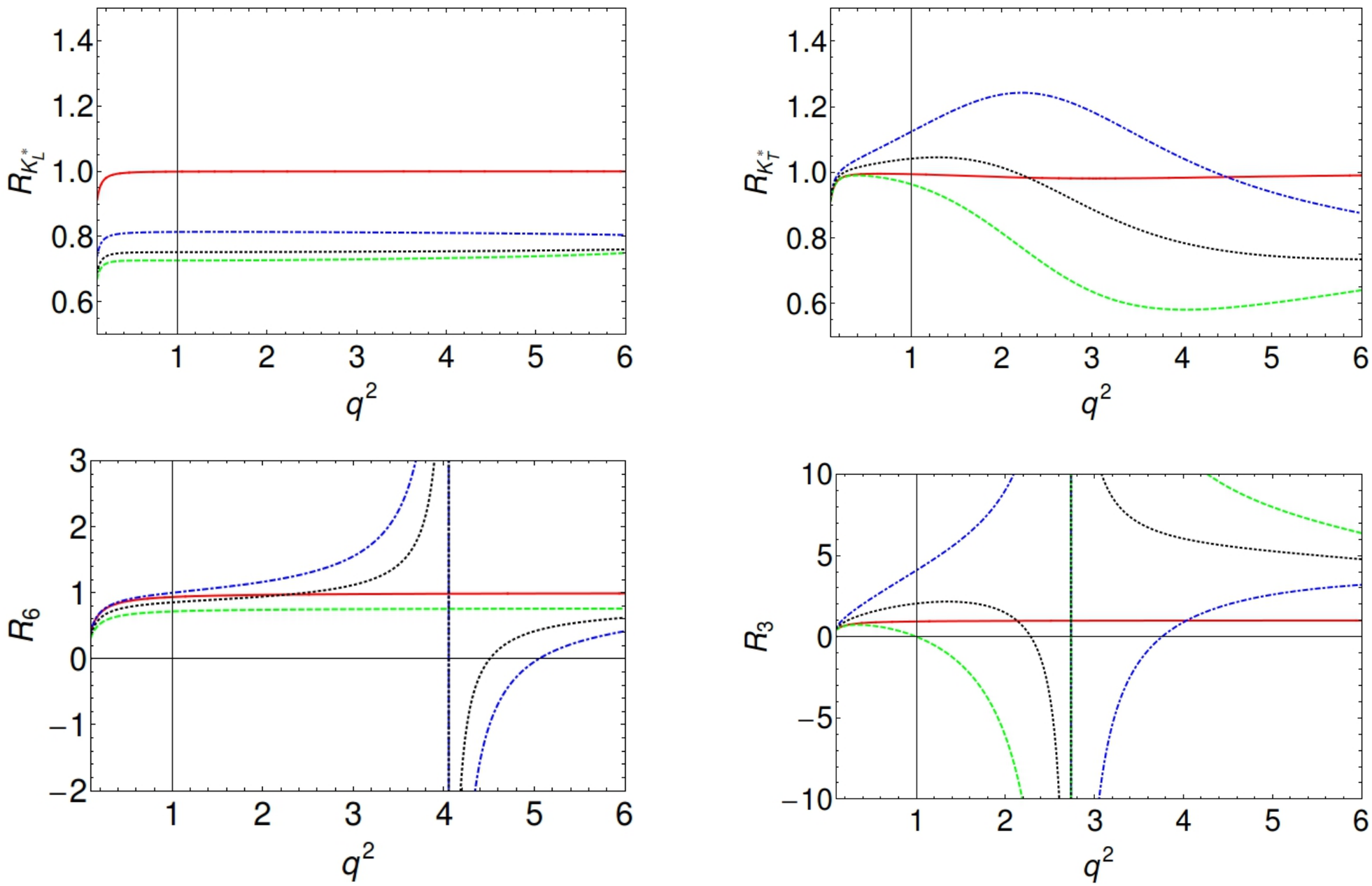
(2) lepton-flavour-dependence of position of zero-crossings

$$\Delta_0^i \equiv (q_0^2)_{I_i}^{(\mu)} - (q_0^2)_{I_i}^{(e)}$$

SJ, Martin Camalich 1412.3183

What would a signal look like?

SJ, Martin Camalich
1412.3183



Any observed deviation from one (R_i) or zero (Δ_0^i) would be a clear BSM signal

Different BSM explanations of R_K discriminated

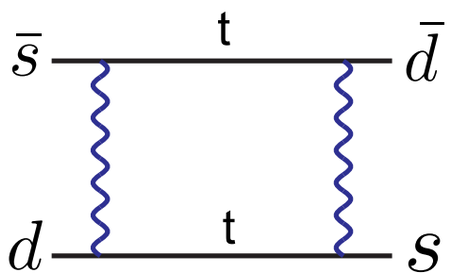
3
Kaons strike back

A few words on a new emerging precision observable

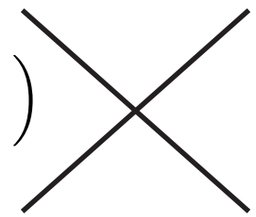
... due to fantastic progress in lattice QCD,
which can now compute all relevant long-distance effects that used to dominate the theoretical uncertainty

... and we discover a new anomaly

$K^0 - \bar{K}^0$ mixing: long-distance dominance

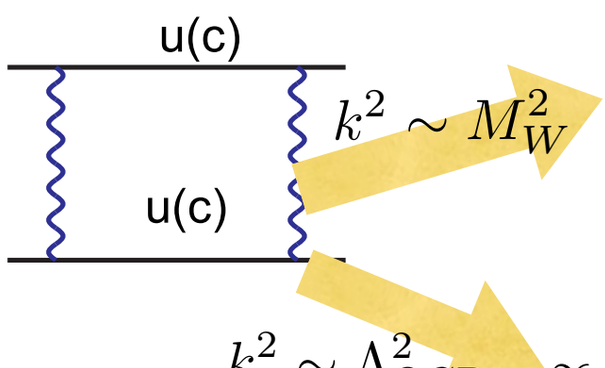


$$\propto (V_{ts}V_{td}^*)^2 \frac{1}{16\pi^2}\frac{1}{M_W^2}\left(\frac{m_t^2}{M_W^2}+\dots\right)$$

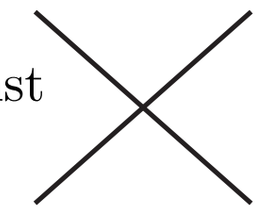


$$\sim \frac{10^{-6}}{M_W^2}$$

top quark loop
CKM-suppressed



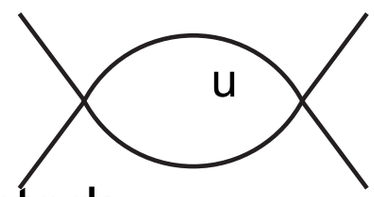
$$\propto (V_{us}V_{ud}^*)^2 \frac{1}{16\pi^2}\frac{1}{M_W^2} \times \text{const}$$



$$\sim \frac{10^{-4}}{M_W^2}$$

up/charm loop
CKM-enhanced

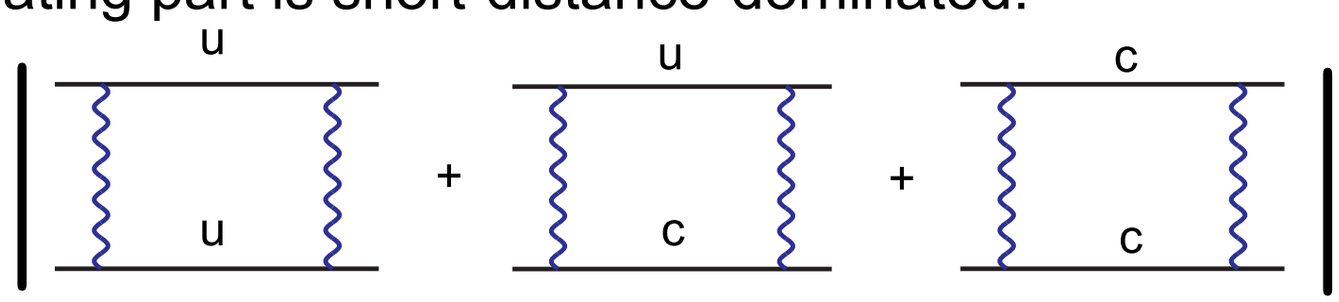
$$\propto (V_{us}V_{ud}^*)^2 \frac{1}{M_W^4}$$



$$\propto (V_{us}V_{ud}^*)^2 \frac{\Lambda_{\rm QCD}^2}{M_W^4}$$

long-distance
power-suppressed
but CKM-enhanced

CP violating part is short-distance-dominated:

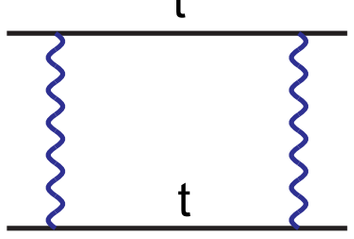


$$= \mathcal{O}(\Delta m_K^{\rm exp}) \quad \text{if} \quad m_c \lesssim \text{GeV}$$

$$(V_{us}V_{ud}^*)^2 + 2\,(V_{us}V_{ud}^*)(V_{cs}V_{cd}^*) + (V_{cs}V_{cd}^*)^2 = (V_{ts}V_{td}^*)^2$$

unitarity / GIM
cancellation

Im



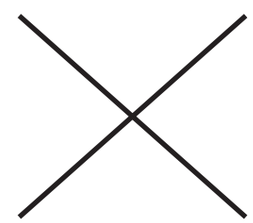
=> $\epsilon_K = \mathcal{O}(10^{-3})$ constraint on V_{td}

first direct (non-local) calculation of charm/up dominated K_L- K_S mass difference
by RBC-UKQCD 2015 - agrees with SM; still large error; no anomaly

CP violation in $K^0 - \bar{K}^0$ mixing

- CP-violating parameter (wrong-CP admixture)

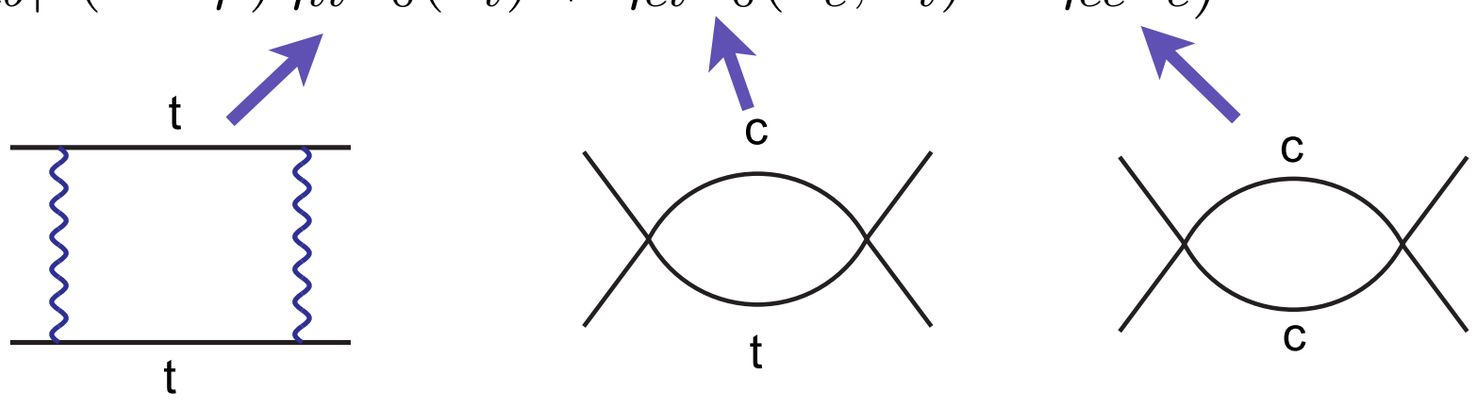
$$\epsilon_K = e^{i\phi_\epsilon} \sin\phi_\epsilon \left(\frac{\mathrm{Im}(M_{12}^K)}{\Delta M_K} + \xi \right)$$

$\hat{B}_K \propto \langle \bar{K} |$  $| K \rangle$

nonperturbative object

lattice calculation & continuum conversion

$$|\epsilon_K^{\mathrm{SM}}| = \kappa_\epsilon C_\epsilon \hat{B}_K |V_{cb}|^2 \lambda^2 \overline{\eta} \times$$
$$\left(|V_{cb}|^2 (1-\overline{\rho}) \eta_{tt} S_0(x_t) + \eta_{ct} S_0(x_c, x_t) - \eta_{cc} x_c \right)$$



$\kappa_\epsilon = 0.92 \pm 0.02$ Buras & Guadagnoli 08

No significant tension at present
(NNLO calculation of short distance)

Brod & Gorbahn 2012

Direct CP violation in K_L->pi pi

Precisely known from experiment for a decade (could potentially be measured even more precisely at NA62)

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

average of NA48 and KTeV

Theory calculation highly complex:

- weak, bottom, charm scale (at least) to NLO perturbation theory for comparable precision (many contributors)

- until recently, sizable parametric uncertainties (CKM, top mass, strange mass)

- until very recently, only crude estimates of nonperturbative hadronic matrix elements (scales m_K, Λ_{QCD}). Many conceptual issues for a lattice-QCD implementation

2015: Two pioneering results by RBC-UKQCD collaboration

RBC-UKQCD, PRD91 (2015) 7,074502
arXiv:1505.07863

ε' master fomula

Buras, Buchalla, ... 1990; Buras, Jamin 1993;1996; Bosch et al 1999;
Buras, Gorbahn, SJ, Jamin arXiv:1507.06345

$$\omega_+ = a\,\frac{\mathrm{Re}A_2}{\mathrm{Re}A_0} = (4.53 \pm 0.02) \times 10^{-2}$$

from experiment
Cirigliano et al 2003

leading isospin breaking
Cirigliano et al 2003

neglect small imaginary part (for simplicity; could easily be restored)

$$\frac{\varepsilon'}{\varepsilon} = -\frac{\omega_+}{\sqrt{2}|\varepsilon_K|}\left[\frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}(1-\Omega_{\mathrm{eff}}) - \frac{\mathrm{Im}A_2}{\mathrm{Re}A_2}\right]$$

from experiment

QCD isospin amplitudes
calculate in terms of weak Hamiltonian
perturbative NLO Wilson oefficients
& numerous nonperturbative hadronic matrix elements

minimize number of independent, relevant matrix elements
two matrix elements remain: $\langle Q_6\rangle_0$ (in Im A_0), $\langle Q_8\rangle_2$ (in Im A_2)

Buras et al 1990; Buras, Gorbahn, SJ, Jamin arXiv:1507.06345

Recent progress

2015: First full computation of physical hadronic matrix elements (10 for Im A_0 and 6 for Im A_2) by RBC-UKQCD

removes $\langle Q8 \rangle_2$ as relevant item of error budget (next slide)

RBC-UKQCD, PRD91 (2015) 7,074502 (I=2)

$\langle Q6 \rangle_0$: large uncertainty, but quantified error

RBC-UKQCD, arXiv:1505.07863 (I=0)

Moreover:

- substantial improvement in parametric uncertainties (CKM, m_t mainly) over last decade removes these once important sources of uncertainty

However:

- While Re A_0 and Re A_2 known from data, better use this only in V-A x V+A part of (Im A_I/Re A_I), as matrix element cancell-ations in V-AxV-A part of ratio (missed by RBC-UKQCD)

Buras et al 1990; Buras, Gorbahn, SJ, Jamin arXiv:1507.06345

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?
- note that the central values differ by an order of magnitude. Reducing the theory error could potentially increase the significance greatly.

Error budget

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
$\hat{\Omega}_{\rm eff}$	0.7	$B_8^{(1/2)}$	0.1
p_3	0.6	$\mathrm{Im}\lambda_t$	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		

- completely dominated by $\langle Q_6 \rangle_0$: **excellent lattice prospects!**
- next is NNLO: perturbation theory at the charm scale? Can reformulate theory for dynamical charm (including lattice)
- isospin breaking: current treatment relies on chiral perturbation theory and 1/N counting. More complete treatment seems possible on the lattice.

Did not talk about

V_{ub} inclusive/exclusive tension

V_{cb} inclusive/exclusive tension

B -> D(*) tau nu (another credible ~4 sigma anomaly)

hadronic B decays (eg penguin puzzle)

nor Higgs flavour physics (H -> tau mu)

charm physics

K_L -> pi^0 nu nu, K^+ -> pi^+ nu nu (experimental progress; also some relevant lattice progress)

Conclusions

After run I of LHCb, there is a manifold of “world’s first” results.

Discussed several interesting anomalies.

Consistent UV pictures exist. At the moment, the significance of some effects is still under debate.

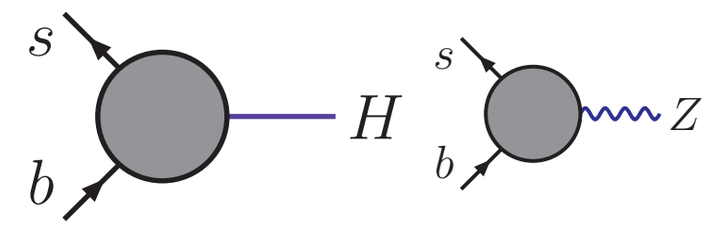
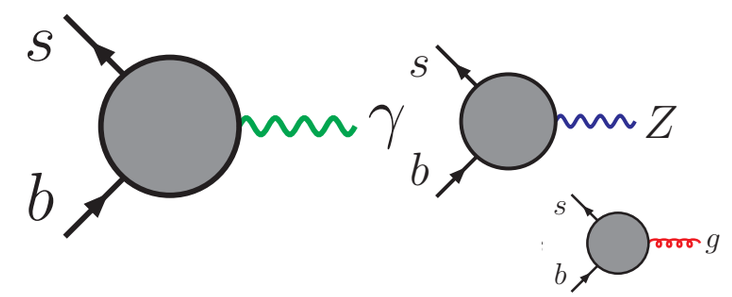
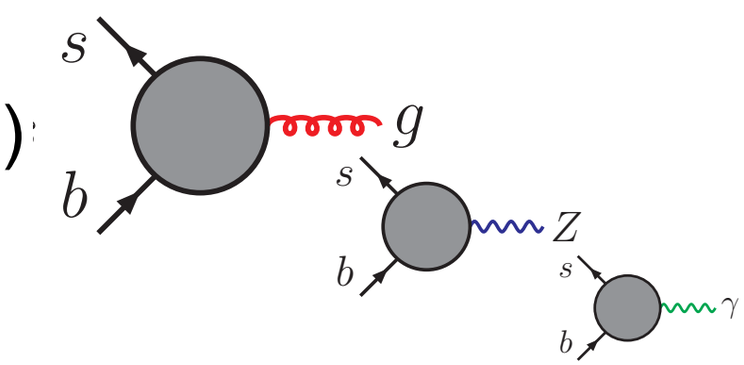
Prospect of lepton universality violation: R_K etc. Theoretically extremely clean.

Several new emerging precision Kaon observables, including direct CP violation in K_L -> pi pi decays: at present, ~3 sigma anomaly with excellent prospects

BACKUP

Rare decays at the LHC

experimental richness

final state	strong dynamics	#obs	NP enters through
Leptonic $B \to l^+ l^-$	decay constant $\langle 0 \vert j^\mu \vert B \rangle \propto f_B$	O(1)	
semileptonic, radiative $B \to K^* l^+ l^-$, $K^* \gamma$	mainly form factors $\langle \pi \vert j^\mu \vert B \rangle \propto f^{B\pi}(q^2)$	O(10)	
charmless hadronic $B \to \pi\pi$, πK, $\phi\phi$, ...	matrix element $\langle \pi\pi \vert Q_i \vert B \rangle$	O(100)	

Crucial theory input provided by lattice QCD.

Heavy-quark expansions/QCD factorisation, light-cone sum rules

Intense theory-experiment interaction in recent years

Rare decays at the LHC

experimental richness

theoretical complexity

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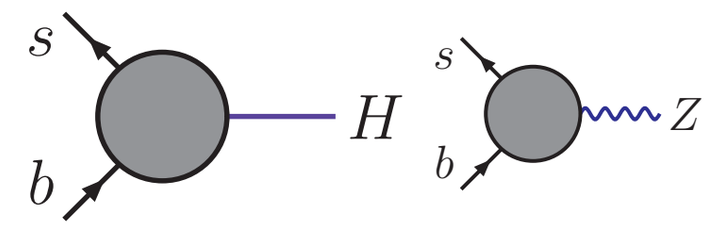
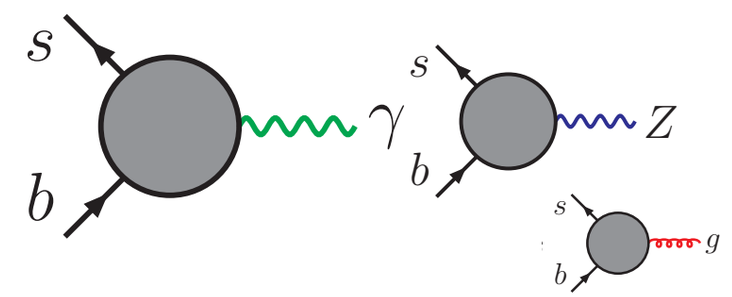
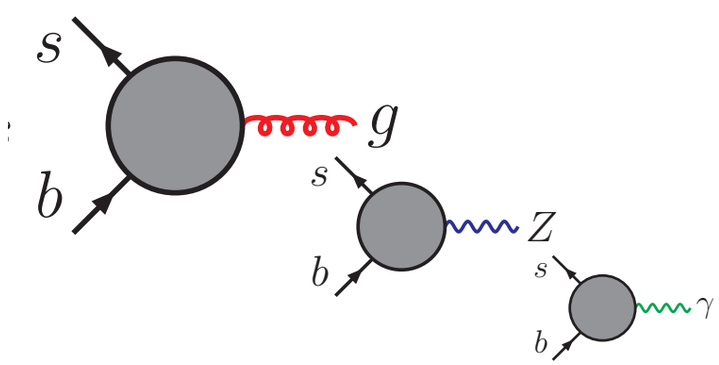
Leptonic $B \to l^+ l^-$	decay constant $\langle 0 \vert j^\mu \vert B \rangle \propto f_B$	O(1)	
semileptonic, radiative $B \to K^* l^+ l^-$, $K^* \gamma$	mainly form factors $\langle \pi \vert j^\mu \vert B \rangle \propto f^{B\pi}(q^2)$	O(10)	
charmless hadronic $B \to \pi\pi$, πK, $\phi\phi$, ...	matrix element $\langle \pi\pi \vert Q_i \vert B \rangle$	O(100)	

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