Rare decays: Theory Perspective

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High Luminosity LHC Workshop
CERN, 11-13 May 2015

Why and what BSM physics?

The discovery of a Higgs scalar has, in my view, **strengthened** the naturalness argument: If there is a physical scale M above M_Z, as suggested by near-unification of gauge couplings, baryon asymmetry, neutrino masses, gravity, then the weak scale is unstable to quantum corrections unless $M \sim M_Z$

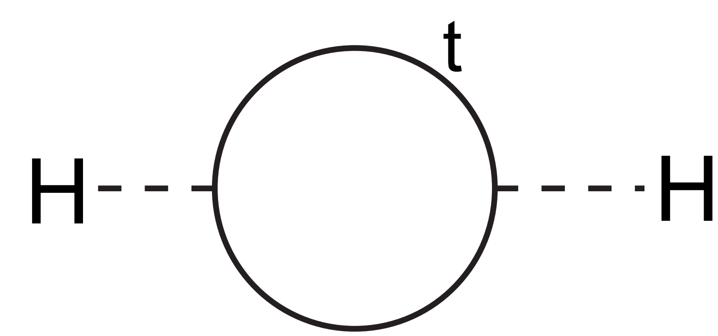
$SU(3)^5$ flavour symmetric kinetic/gauge terms

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

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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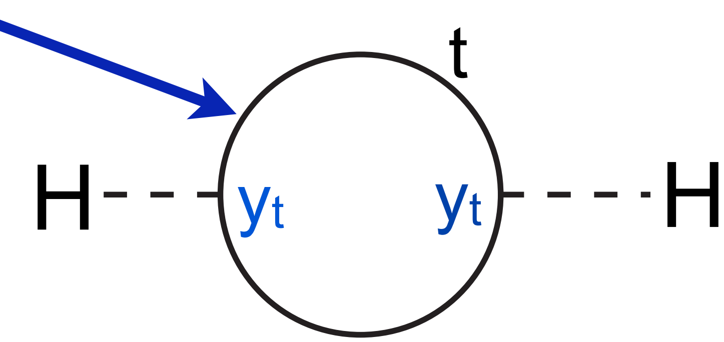

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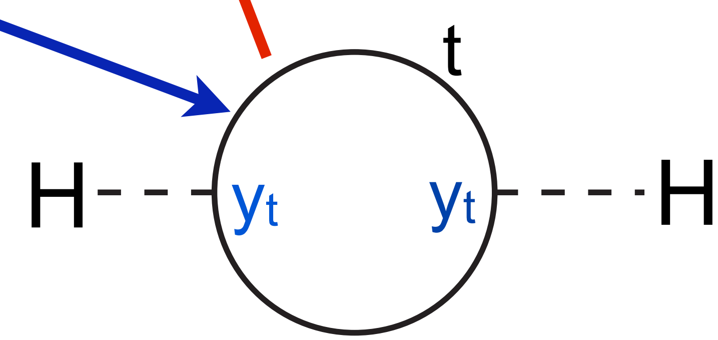
flavour-breaking fermion masses and Higgs couplings

$\propto y_t^2 M^2$



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What BSM effects?

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}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
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operators (vertices) are catalogued for arbitrary (heavy) new physics

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

Higgs physics (production & decay) probes about 20 operators

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

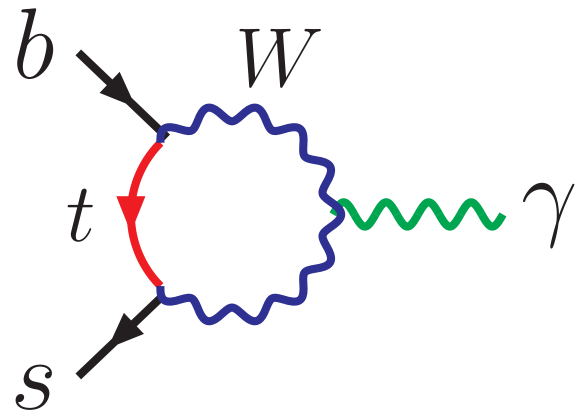
LFV lepton decays O(100)

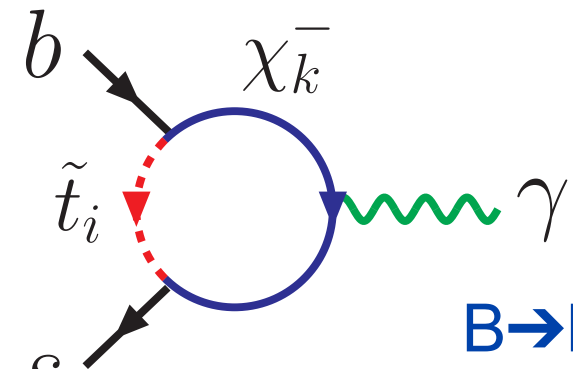
eg Crivellin, Najjari, Rosiek 2013

Top physics in principle many more, most of them 4-quark operators mediating 3-body hadronic decays.

BSM flavour

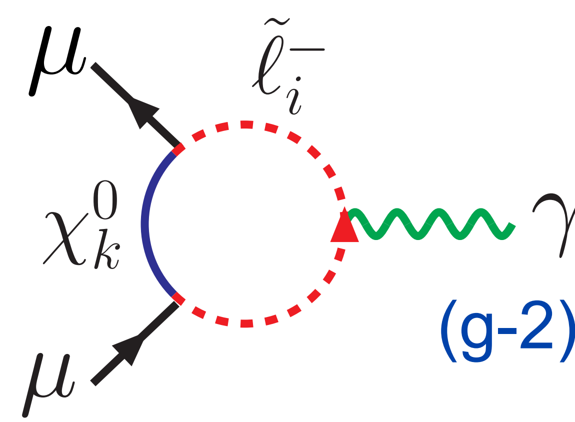
New particles addressing naturalness will at least have CKM-like flavour violations (minimal flavour violation), so will always affect rare decays. E.g.,





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

Of course BSM particles will mediate flavour-*conserving* processes, too. (Correlations.)



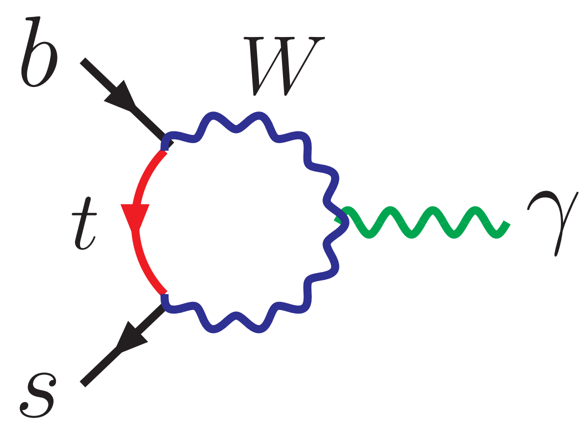
$(g-2)_{muon}$

The absence of BSM particle discoveries so far challenges theoretical paradigms (eg CMSSM) and strengthens the importance of indirect, precision probes. They may provide the leading avenue to physics beyond the Standard Model.

Rare decays

SM: Loop + CKM suppression of FCNC (GIM)

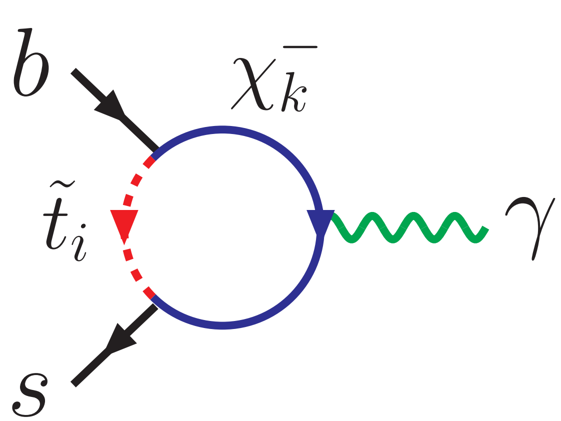
y_t main source of GIM breaking: enhanced sensitivity to top



B-Bbar oscillations were first indication of a heavy top (Argus 1990)

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
Beyond MFV stringent constraints on 1-2 mixing

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

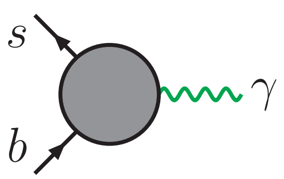
In strongly coupled models may lose loop suppression, flavour most stringent generic constraint absent flavour protection (RS)

weak ΔB=ΔS=1 Hamiltonian

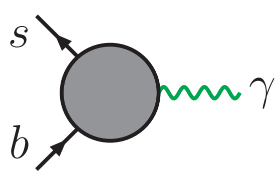
= EFT for ΔB=ΔS=1 transitions (up to dimension six)

$$\mathcal{H}_{\rm eff}^{\rm had} = \frac{4G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \left[C_1 Q_1^p + C_2 Q_2^p + \sum_{i=3\ldots 6} C_i P_i + C_{8g} Q_{8g} \right] \qquad C_i \sim g_{\rm NP} \frac{m_W^2}{M_{\rm NP}^2}$$

$$\mathcal{H}_{\rm eff}^{\rm sl} = -\frac{4G_F}{\sqrt{2}} \lambda_t \Big[C_7 Q_{7\gamma} + C_7' Q_{7\gamma}' + C_9 Q_{9V} + C_9' Q_{9V}' + C_{10} Q_{10A} + C_{10}' Q_{10A}'$$
$$+ C_S Q_S + C_S' Q_S' + C_P Q_P + C_P' Q_P' + C_T Q_T + C_T' Q_T' \Big].$$

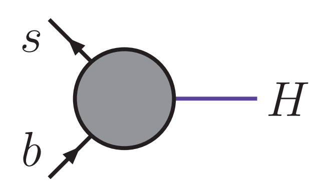


$$\mathcal{O}_7 = \frac{e}{16\pi^2} \hat{m}_b \, \bar{s} \sigma_{\mu\nu} P_R F^{\mu\nu} b \,,$$



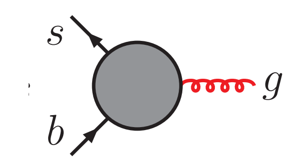
$$\mathcal{O}_V = \frac{\alpha_{\rm em}}{4\pi} (\bar{s} \gamma_\mu P_L b)(\bar{l} \gamma^\mu l) \,,$$

$$\mathcal{O}_S = \frac{\alpha_{\rm em}}{4\pi} \hat{m}_b (\bar{s} P_R b)(\bar{l} l) \,,$$

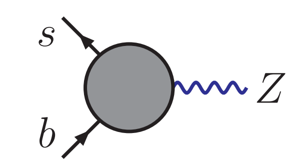


$$\mathcal{O}_T = \frac{\alpha_{\rm em}}{4\pi} \hat{m}_b (\bar{s} \sigma_{\mu\nu} P_R b)(\bar{l} \sigma^{\mu\nu} P_R s) \,,$$

$$\mathcal{O}_8 = \frac{g_s}{16\pi^2} \hat{m}_b \, \bar{s} \sigma_{\mu\nu} P_R G^{\mu\nu} b \,,$$



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

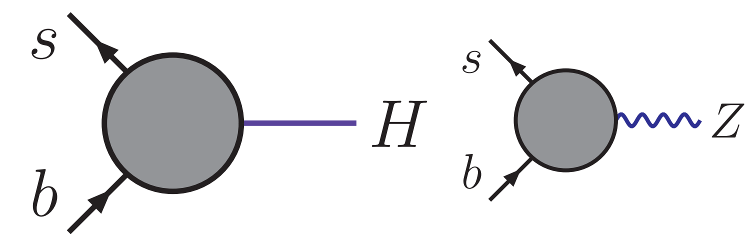
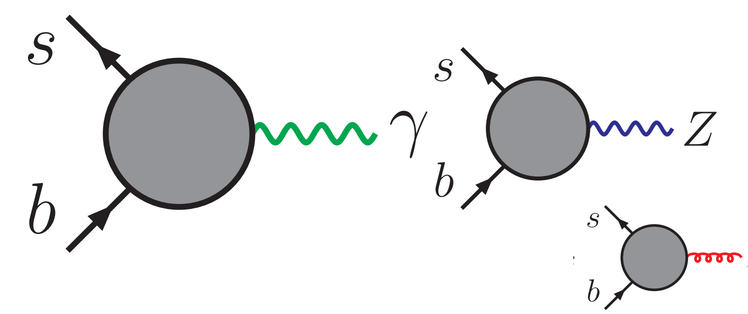


$$\mathcal{O}_P = \frac{\alpha_{\rm em}}{4\pi} \hat{m}_b (\bar{s} P_R b)(\bar{l} \gamma^5 l) \,,$$

Primed operators: P_L <-> P_R, very suppressed in SM

look for observables sensitive to C_i's, specifically those suppressed in the SM

Rare B decays at the LHC

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)	

(also rare charmless hadronic: see Z Ligeti's talk)

Crucial theory input provided by lattice QCD.

Heavy quark expansions/QCD factorisation (OPE in inclusive decay), light-cone sum rules

Tensions in rare decay data

A number of rare decay observables deviate from SM expectations.

Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	$10^7\ \frac{dBR}{dq^2}$	$[2, 4.3]$	0.44 ± 0.07	0.29 ± 0.05	LHCb	$+1.8$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	$10^7\ \frac{dBR}{dq^2}$	$[16, 19.25]$	0.47 ± 0.06	0.31 ± 0.07	CDF	$+1.8$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.81 ± 0.02	0.26 ± 0.19	ATLAS	$+2.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[4, 6]$	0.74 ± 0.04	0.61 ± 0.06	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[4, 6]$	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	-2.2
$B^- \to K^{*-}\mu^+\mu^-$	$10^7\ \frac{dBR}{dq^2}$	$[4, 6]$	0.54 ± 0.08	0.26 ± 0.10	LHCb	$+2.1$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8\ \frac{dBR}{dq^2}$	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8\ \frac{dBR}{dq^2}$	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF	$+2.2$
$B_s \to \phi\mu^+\mu^-$	$10^7\ \frac{dBR}{dq^2}$	$[1, 6]$	0.48 ± 0.06	0.23 ± 0.05	LHCb	$+3.1$
$B \to X_s e^+e^-$	10^6 BR	$[14.2, 25]$	0.21 ± 0.07	0.57 ± 0.19	BaBar	-1.8

Table 1: Observables where a single measurement deviates from the SM by 1.8σ or more. The full list of observables is given in appendix B.

From Altmannshofer, Straub 1411.3161v3

Several global fits find significances up to 4 sigma.

Descotes-Genon et al
Altmannshofer, Straub
Hurth, Mahmoudi
SJ, Martin Camlich

Significances depend on treatment of several nonperturbative effects

- Prospects with HL upgrade?

- Cross checks? Both for experiment and theory.

- Consistent BSM interpretations?

Experimental prospects

- Some modes are no longer particularly “rare”, we have large samples of some decays already in run I.
- Extrapolating to the future:

	channel	1fb^{-1}	3fb^{-1}	run II	upgrade	
	$B^0 \to K^{*0}\mu^+\mu^-$	883	2,400	10,500	85,000	
	$B^+ \to \pi^+\mu^+\mu^-$	25	80	360	2500	
	$B^0_s \to \mu^+\mu^-$	–	15	65	520	
	$B^0 \to K^{*0}\gamma$	5,300	17,000	76,000	500,000	challenge to retain trigger efficiency in run II
[low q^2]	$B^0 \to K^{*0}e^+e^-$	–	150	650	5,200	

scaling naively by luminosity, assuming $\sigma_{b\bar{b}}$ scales linearly with $\sqrt{s}$

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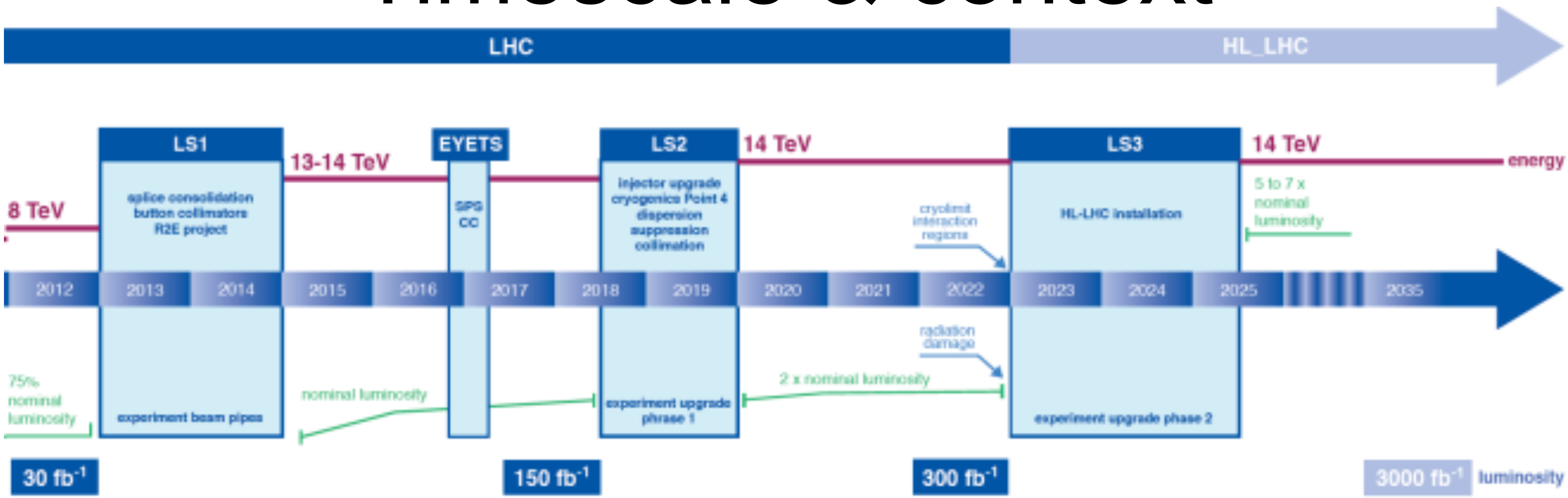
[Tom Blake, Rare B decay workshop, Edinburgh, 12/05/15]

Huge improvements in precision
NP mass reach scales like delta$^{1/2}$ ...
... as long as theory accuracy matches experiment

Timescale & context



Belle 2 (e+e-) will report results from about 2018 and coexist with the HL-LHC

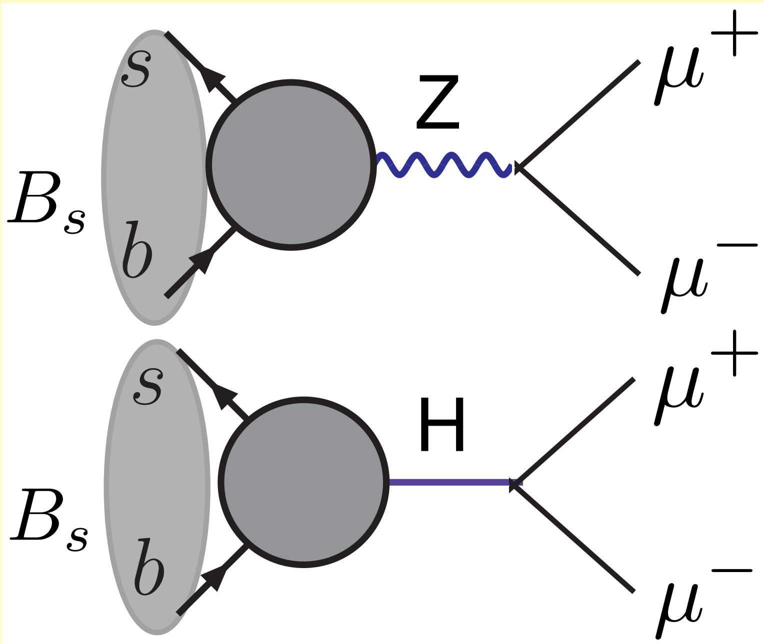
- possibility of inclusive measurements (B->X_s gamma,...)
- much better acceptance & energy resolution for electrons

However, LHC will retain the statistics edge for accessible modes

- complementarity (obvious)
- interplay (eg modes for normalising B_s->mu mu at LHCb ?)

interplay with developments in hight pT

Rare leptonic B decays



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

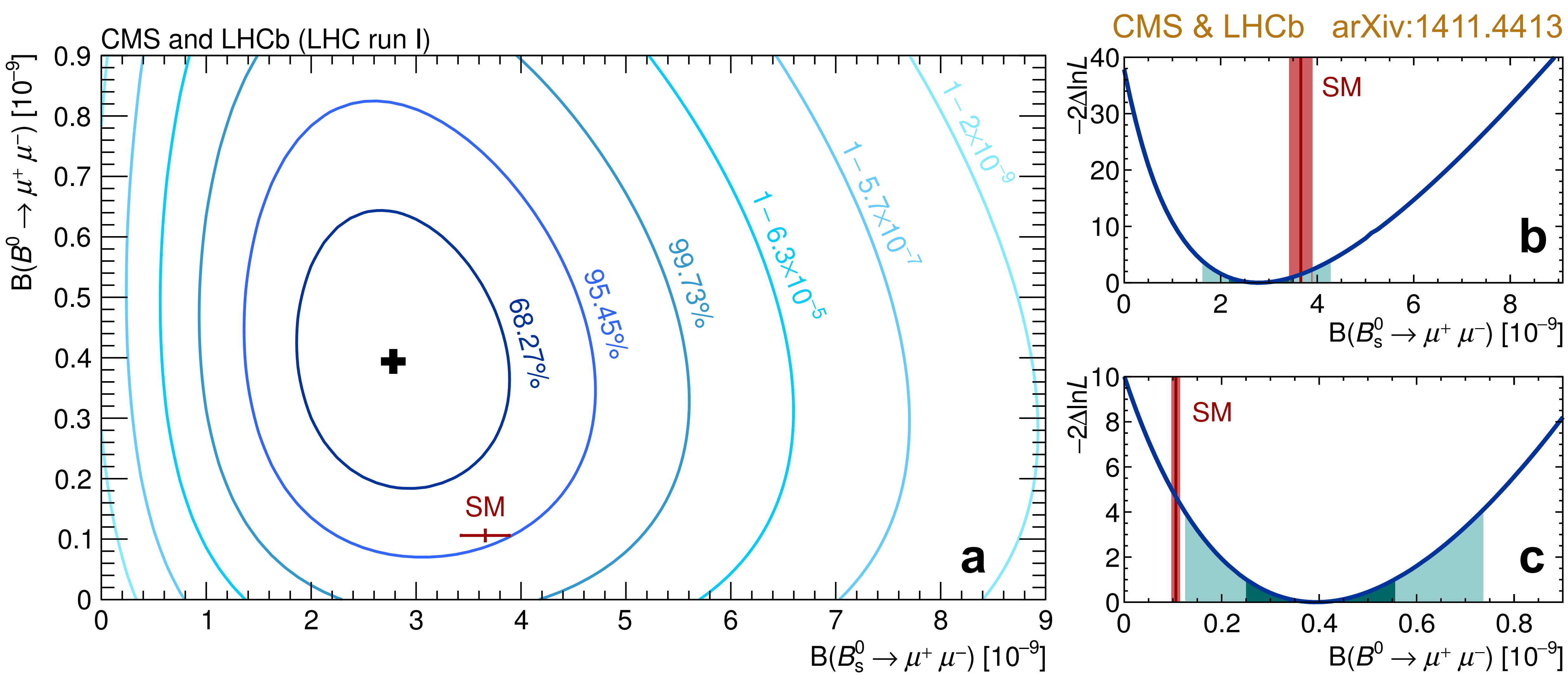
SM helicity suppression

SM: Pure Z penguin decay (no single-photon mediated contribution)

"power-like GIM" (no $\log(m_c/m_W)$)

Helicity suppression; this could be lifted eg by heavy MSSM Higgses (proportional $\tan(\beta)^6$) ...

... or by emission of a soft, undetected photon



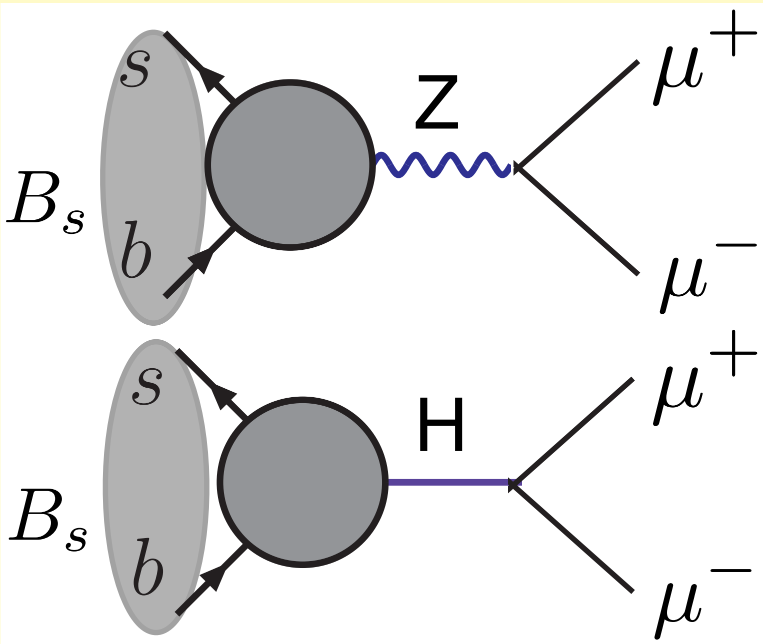
Central value quite far from SM - not significant however

Prospective uncertainty of order 5% (LHCb-PUB-2014-040) by end of HL-LHC

Theory will match this provided parametric uncertainties reduce (f_{Bs}, V_{cb}, V_{ts}, lifetime) (next slide)

Rare leptonic B decays

[slide based on talk by M Steinhauser, BEACH 2014]



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- 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

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

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

parametric uncertainties dominate

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

Rare leptonic B decays

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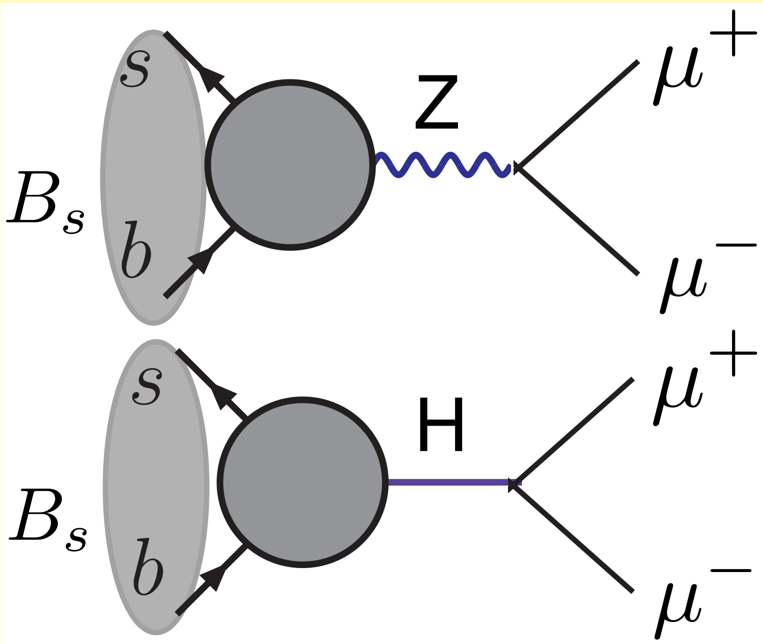

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Leptonic decay theory is fully ready for HL-LHC

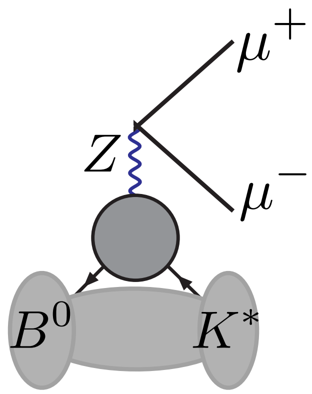
B->Vll decay amplitudes

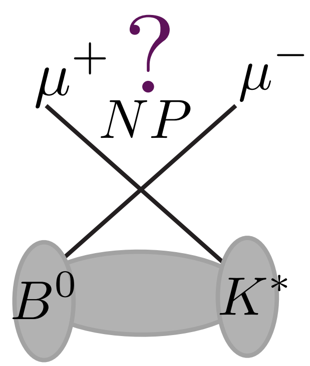
Two mechanisms to produce dilepton in & beyond SM

B->Vll decay amplitudes

Two mechanisms to produce dilepton in & beyond SM

- via axial lepton current (in SM: Z, boxes)





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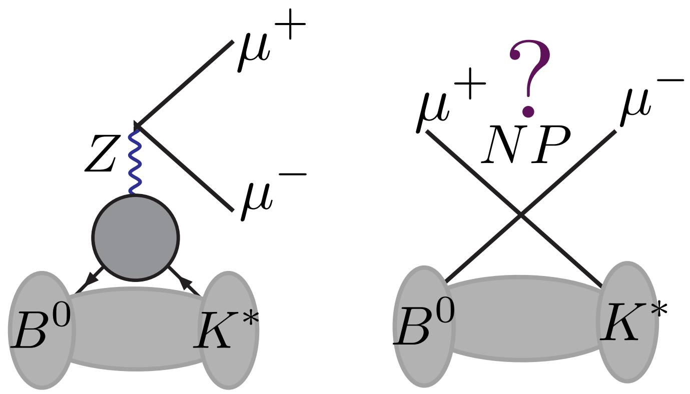

$$H_A(\lambda) \propto \tilde{V}_\lambda(q^2) C_{10} - V_{-\lambda}(q^2) C'_{10}$$

B->Vll decay amplitudes

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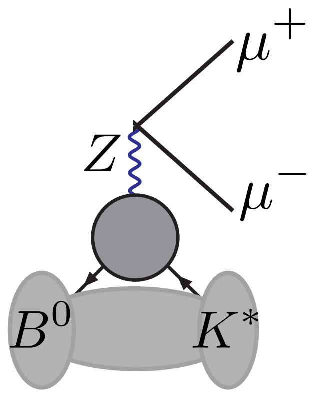

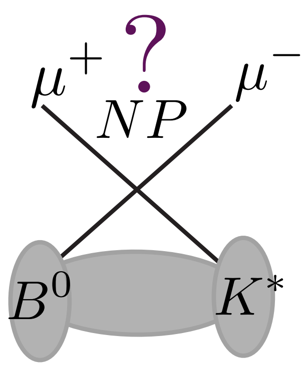

K* helicity

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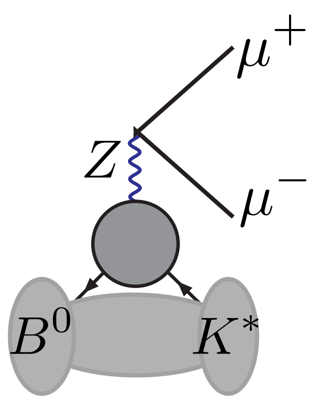

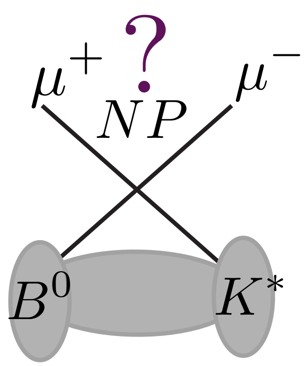

K* helicity

$$H_A(\lambda) \propto \boxed{\tilde{V}_\lambda(q^2)} C_{10} - V_{-\lambda}(q^2) C'_{10}$$

one form factor (nonperturbative) per helicity

amplitudes factorize naively

[nb - one more amplitude if not neglecting lepton mass]

B->Vll decay amplitudes

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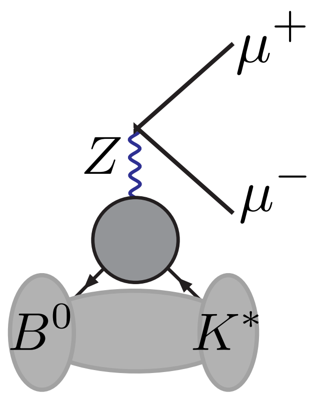

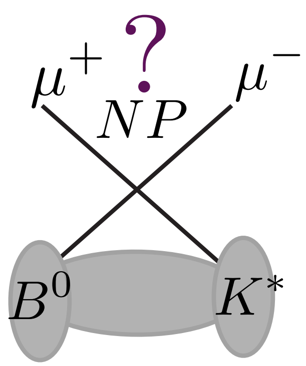

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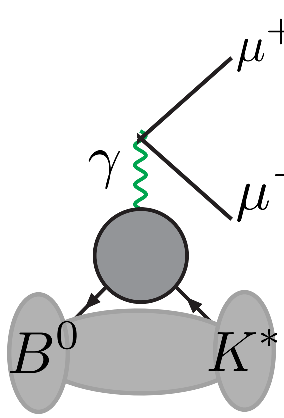

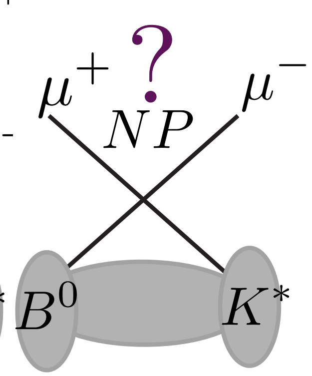

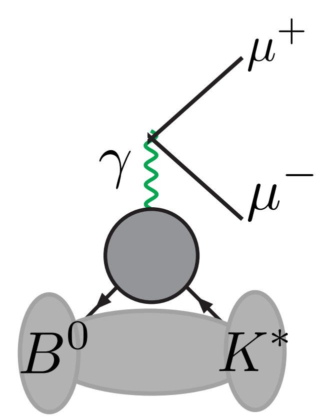

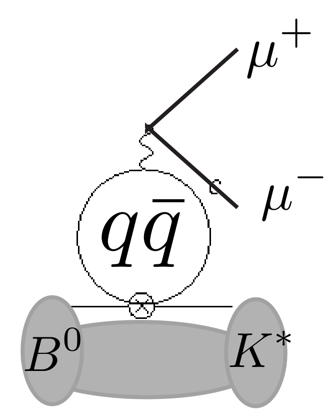

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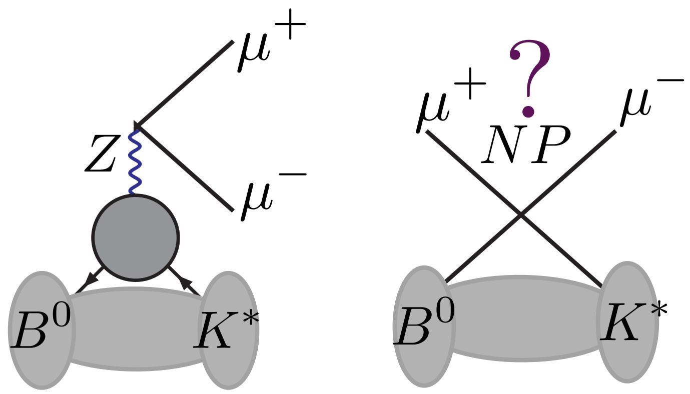

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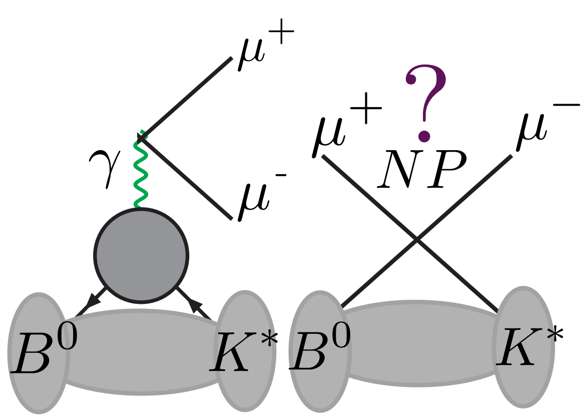

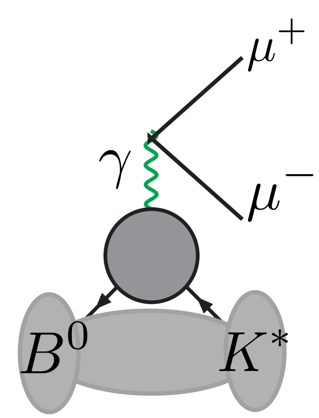

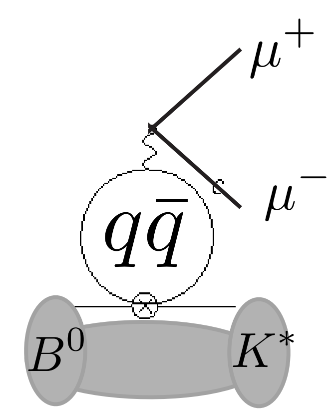

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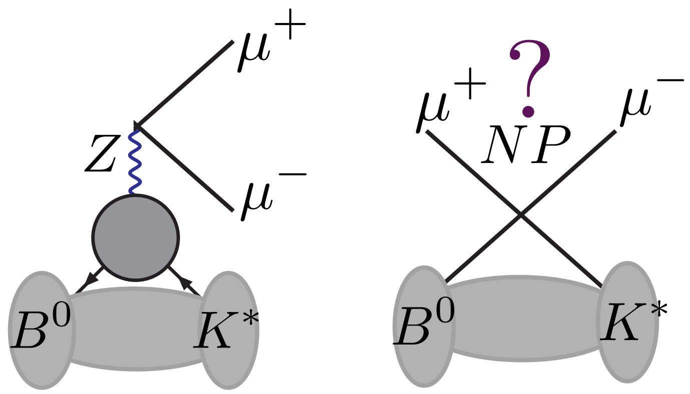

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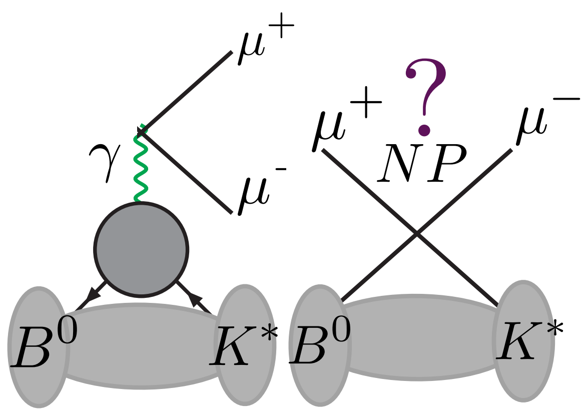

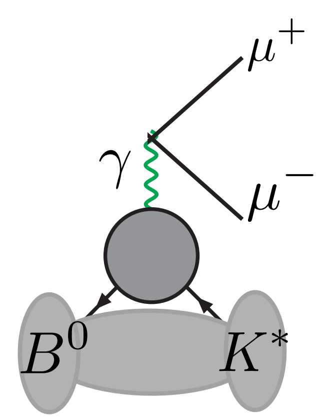

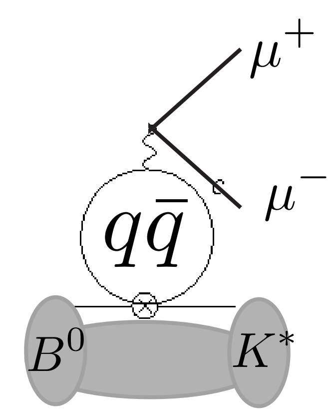

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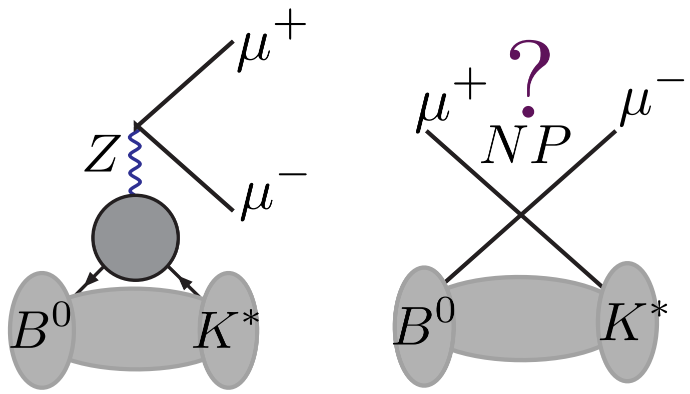

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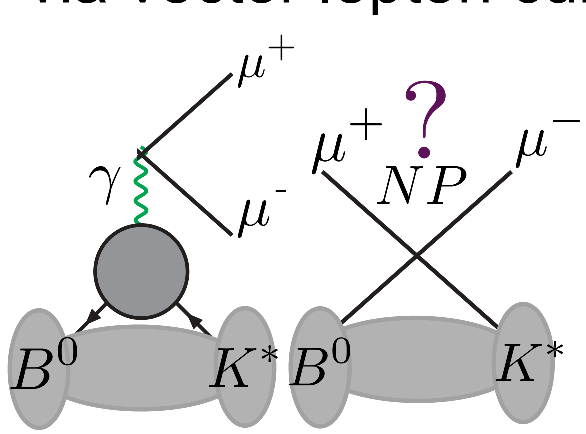

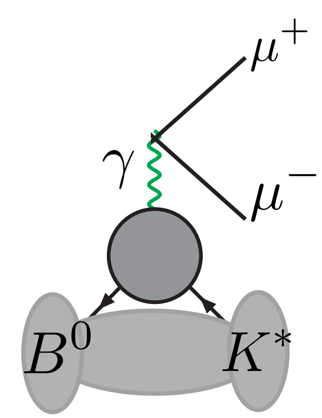

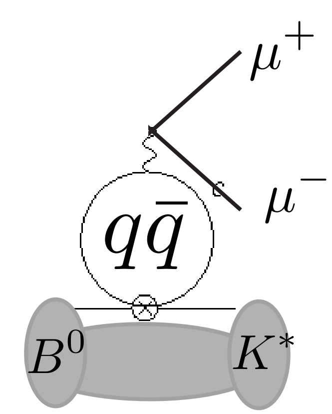

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do **not** factorize naively

two form factors interfere for each helicity

natural and transparent discussion in terms of 6 (7 if m_l != 0) helicity amplitudes

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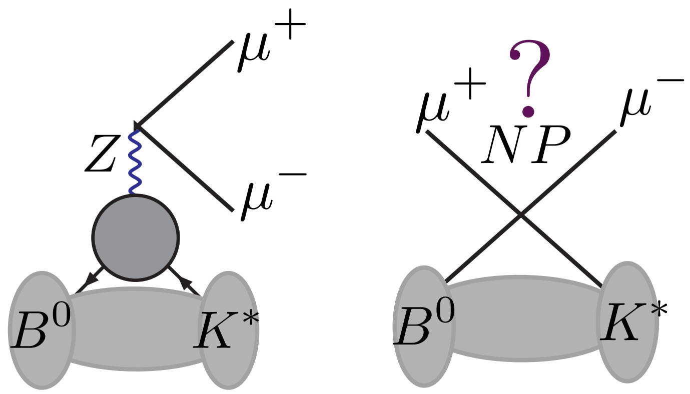

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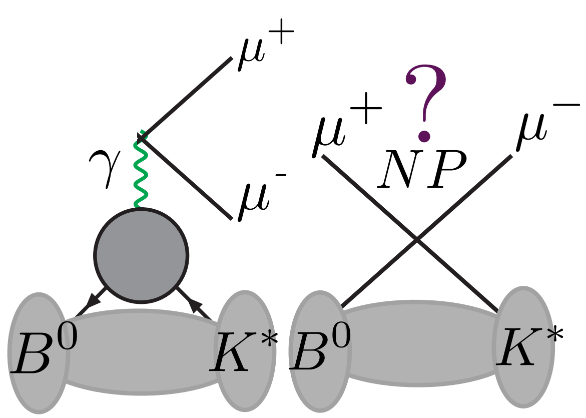

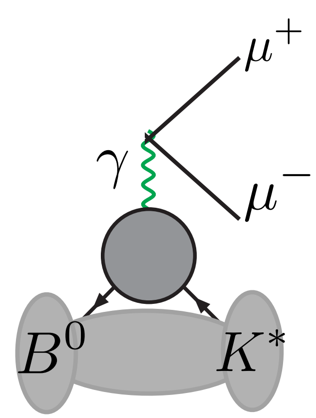

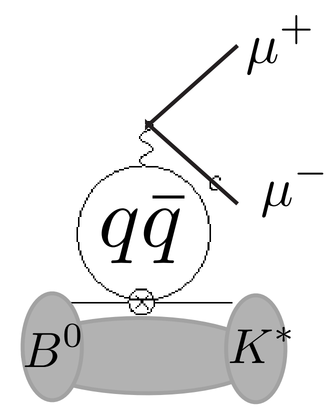

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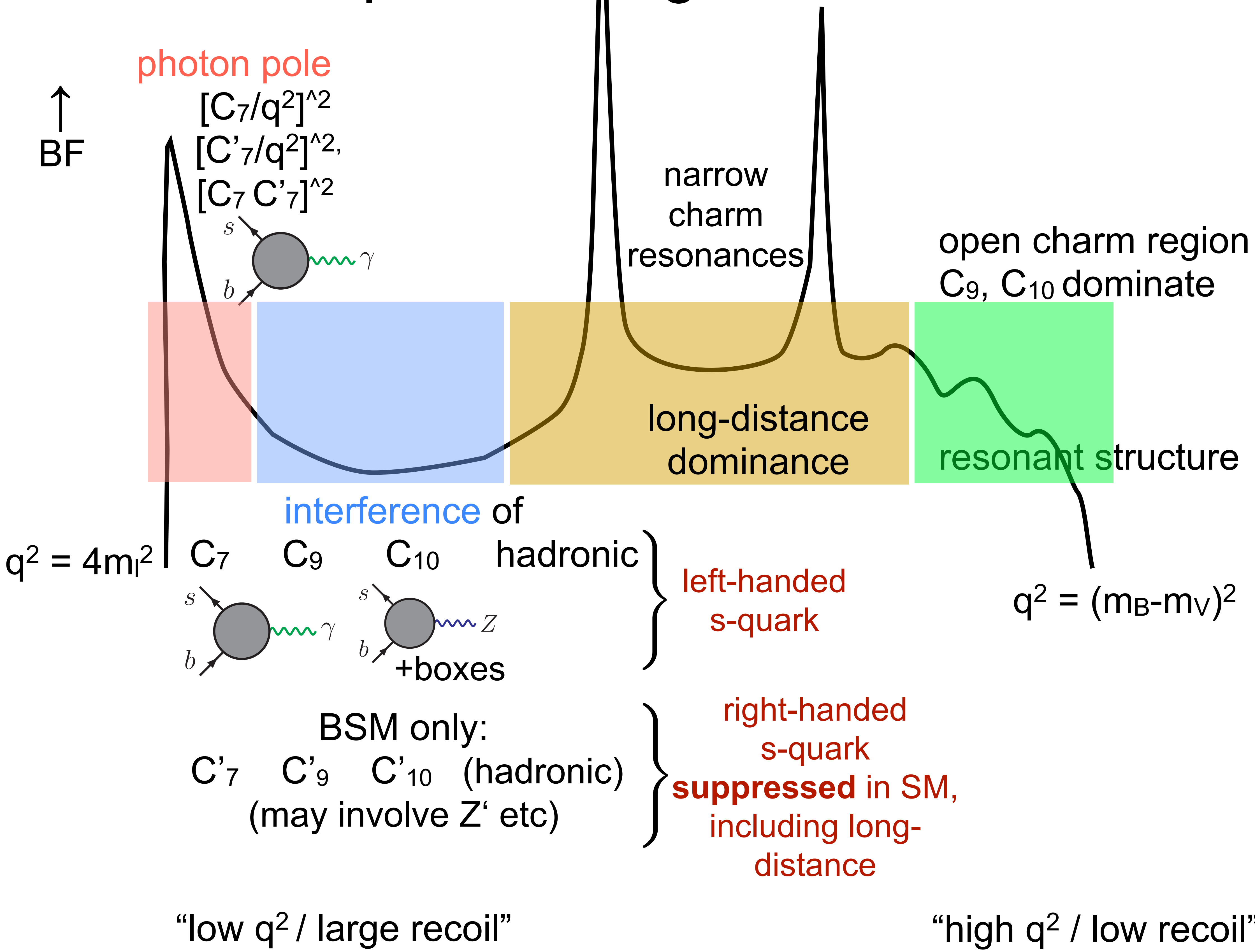
natu

Form factors important source of errors; FF ratios affect eg zero crossing of FB asymmetry (sensitive to C_9/C_7)

Photon pole and right-handed currents



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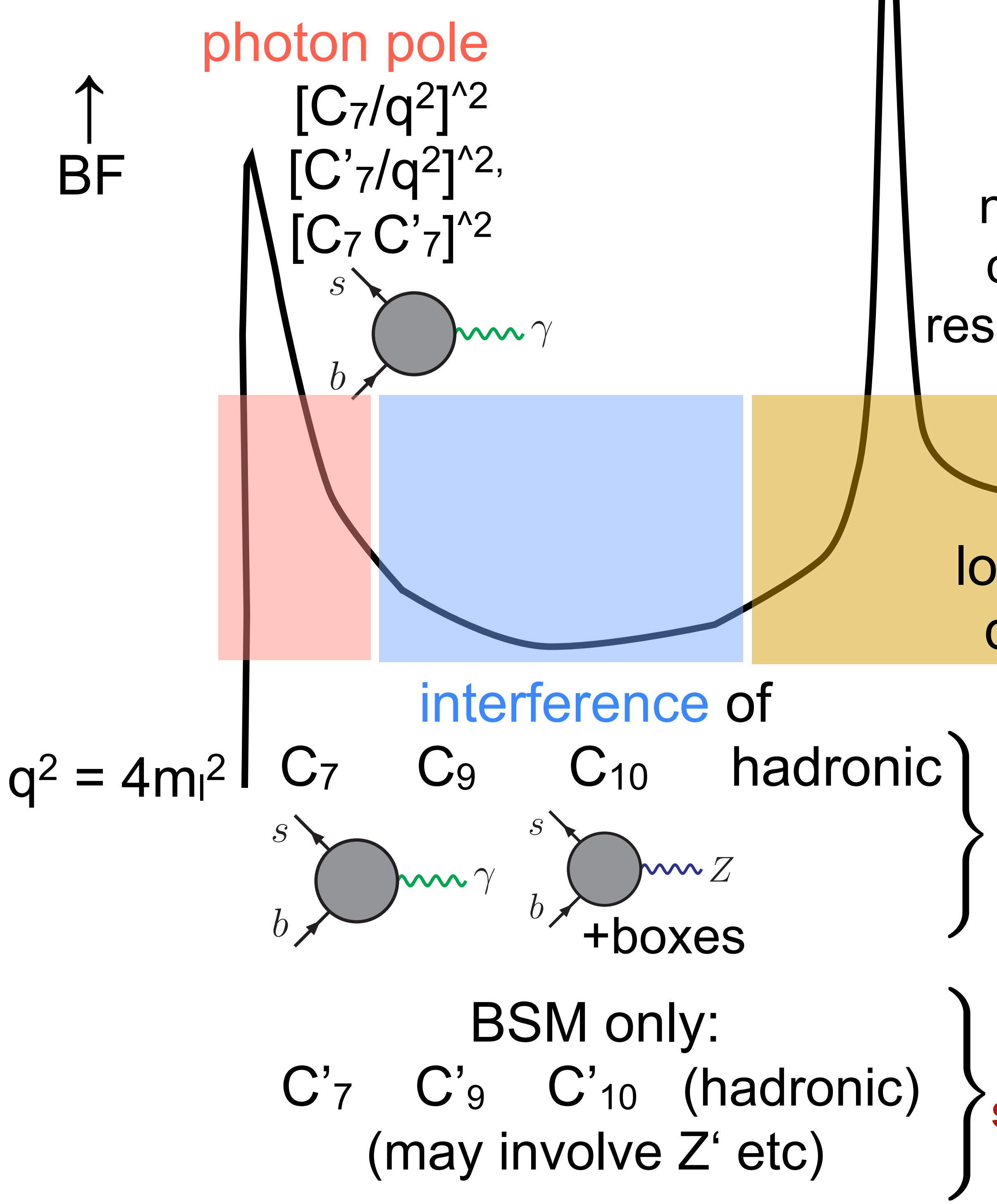

At very low q^2 photon pole dominates
axial vector amplitudes small perturbation

Specific sensitivity to C_7 (constrained from b->s gamma) and C_7' (well-motivated BSM effect)

Related to B->K*γ (completely model-independently)

Unlike other observables, form factor ratios play almost not role.

Main issue is to rule out (or control) sizable effects from the nonleptonic hamiltonian (charm loops etc). Good complementarity of heavy quark expansions & LCSR

"low q^2 / large recoil" "high q^2 / low recoil"

Optimised angular observables

=functions of the angular coefficients for which form factors drop out in the heavy quark limit if perturbative QCD corrections neglected.

E.g.

neglecting strong phase differences
[tiny; take into account in numerics]

Krueger,Matias 2005; Egede et al 2008
Becirevic, Schneider 2011
Matias, Mescia, Ramon, Virto 2012
Descotes-Genon et al 2012

$$P_1 \equiv \frac{I_3 + \bar{I}_3}{2(I_{2s} + \bar{I}_{2s})} = \frac{-2\,\mathrm{Re}(H_V^+ H_V^{-*} + H_A^+ H_A^{-*})}{|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2} = 0$$

$$P_3^{CP} \equiv -\frac{I_9 - \bar{I}_9}{4(I_{2s} + \bar{I}_{2s})} = -\frac{\mathrm{Im}(H_V^+ H_V^{-*} + H_A^+ H_A^{-*})}{|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2} = 0$$

(Melikhov 1998)
Krueger, Matias 2002
Lunghi, Matias 2006
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$$P_5' = \frac{\mathrm{Re}[(H_V^- - H_V^+) H_A^{0*} + (H_A^- - H_A^+) H_V^{0*}]}{\sqrt{(|H_V^0|^2 + |H_A^0|^2)(|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2)}} = \frac{C_{10}\left(C_{9,\perp} + C_{9,\parallel}\right)}{\sqrt{(C_{9,\parallel}^2 + C_{10}^2)(C_{9,\perp}^2 + C_{10}^2)}}$$

in SM, neglecting power corrections and pert. QCD corrections

where

$$C_{9,\perp} = C_9^{\mathrm{eff}}(q^2) + \frac{2\,m_b\,m_B}{q^2}\,C_7^{\mathrm{eff}}$$

$$C_{9,\parallel} = C_9^{\mathrm{eff}}(q^2) + \frac{2\,m_b\,E}{q^2}\,C_7^{\mathrm{eff}}$$

C_7 and C_9 opposite sign
destructive interference enhances vulnerability to anything that violates the large-energy form factor relations (or more generally underestimated errors on form facors

much less of an issue in than to P_1 or P_3^{CP} than eg in P_5' (and others)

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Two approximate null tests of the SM

What are the leading corrections?

where

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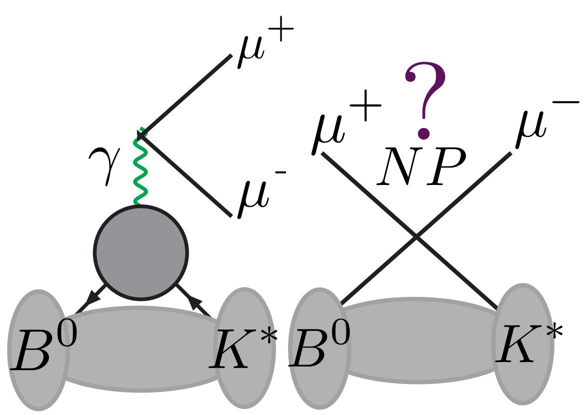
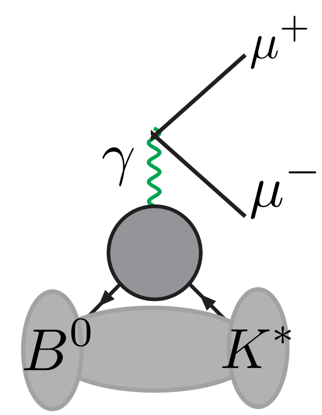
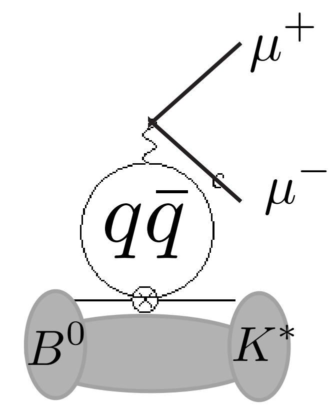
B->Vll vector amplitudes

Only helicity +1 and -1 contribute to P_1 and P_3^{CP}







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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

Helicity +1 power suppressed in the heavy-quark limit

Burdman, Hiller 2000

form factor T_+ doubly suppressed (further q^2/m_B^2 factor)

nonlocal term known to be singly suppressed (Λ/m_b)

Beneke, Feldmann, Seidel 2001

could be the dominant uncertainty for null tests

Grinstein et al 2004

Khodjamirian et al 2010

(Ball, Jones, Zwicky 2006)

however, extra suppression ~ Λ/m_b

SJ, Martin Camalich 2012

Predictions at very low q^2

SJ, Martin Camalich
1412.3183

Bin [GeV^2]	Br [10^{-8}]	P_1	P_2	P_3^{CP} [10^{-4}]
[0.1, 0.98]	$9.5^{+5.2}_{-3.5}$	$0.024^{+0.053}_{-0.055}$	$-0.16^{+0.05}_{-0.04}$	$0.1^{+0.7}_{-0.8}$
Electron	26^{+12}_{-9}	$0.030^{+0.047}_{-0.044}$	$-0.073^{+0.020}_{-0.016}$	$0.1^{+0.6}_{-0.6}$

[0.0004,1.12+/-0.06]

- only use HQ limit + general parameterisation of power corrections. Very clean, very insensitive to form factor input!
- Boost in BR: nearly 3x more electrons, most of the extra ones in the relevant q^2 region -> partly offsets lower efficiency in LHCb. Will be important Belle2 observable

	Result	QCDF	Fact. p.c.'s	Non-fact. p.c.'s
P_1	$0.030^{+0.047}_{-0.044}$	$^{+0.008}_{-0.003}$	± 0.012	$^{+0.028}_{-0.026}$
P_3^{CP} [10^{-4}]	$0.1^{+0.7}_{-0.6}$	± 0.3	± 0.2	± 0.3

$$A_{\rm T}^{(2)} = -0.23 \pm 0.23 \pm 0.05$$

LHCb, 1501.03028, JHEP 1504 (2015) 064

$$A_{\rm T}^{\rm Im} = +0.14 \pm 0.22 \pm 0.05$$
$$A_{\rm T}^{\rm Re} = +0.10 \pm 0.18 \pm 0.05$$

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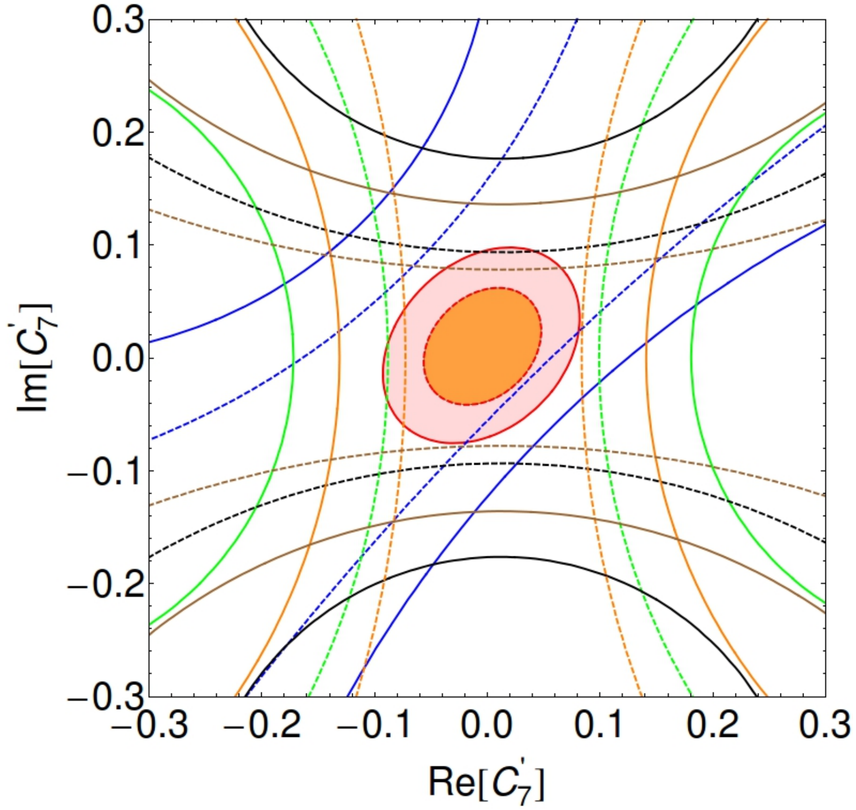
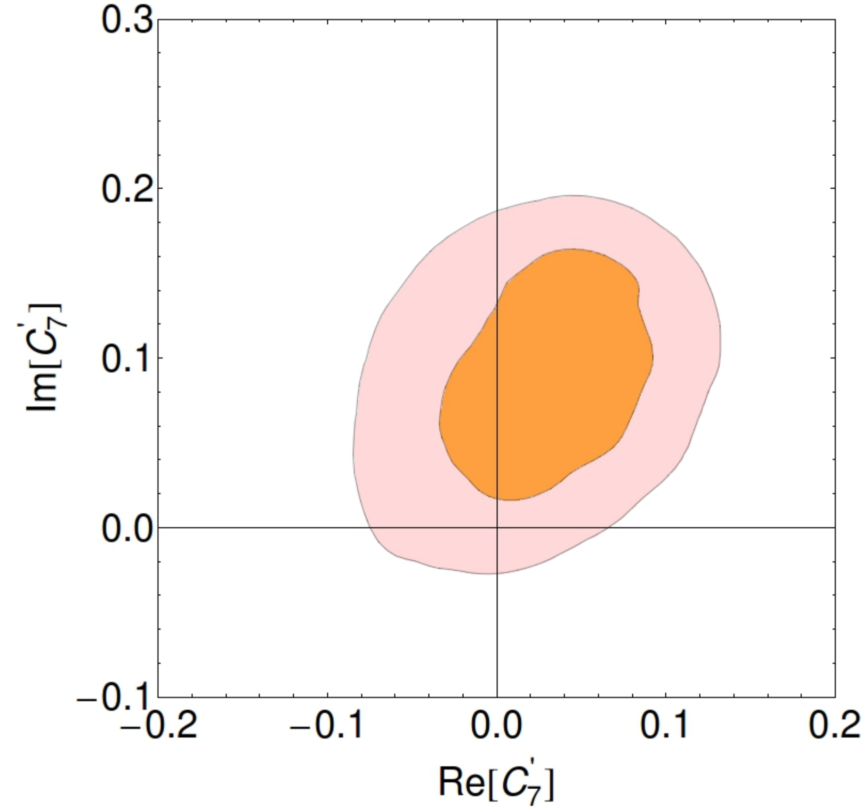
LHCb, 1501.03028, JHEP 1504 (2015) 064

Status/prospects





SJ, Martin Camalich
1412.2183

awaiting update with 2015 LHCb electron and muon data!

$$\boxed{S \simeq \frac{2\mathrm{Im}(e^{-2i\beta} C_7 C_7')}{|C_7|^2 + |C_7'|^2},} \quad \boxed{P_1 \simeq \frac{2\mathrm{Re}(C_7 C_7')}{|C_7|^2 + |C_7'|^2},} \quad \boxed{P_3^{\mathrm{CP}} \simeq \frac{2\mathrm{Im}(C_7 C_7')}{|C_7|^2 + |C_7'|^2}}$$

- Left: schematic of situation pre-2015 LHCb data (neglect theory error)
- Right: Profile likelihood for 2014 data (1sigma and 95% CL)
- Sensitivity to C_7' scales with that to P_1 (S_3) and P_3^{CP} (A_9). LHCb will reach theoretical limit by end of HL-LHC for P_1 but not for P_3^{CP} (CP violating but does not require strong phase)

LHCb anomaly

The full angular distribution as measured by LHCb contains many observables (8 angular coefficients in several bins each)

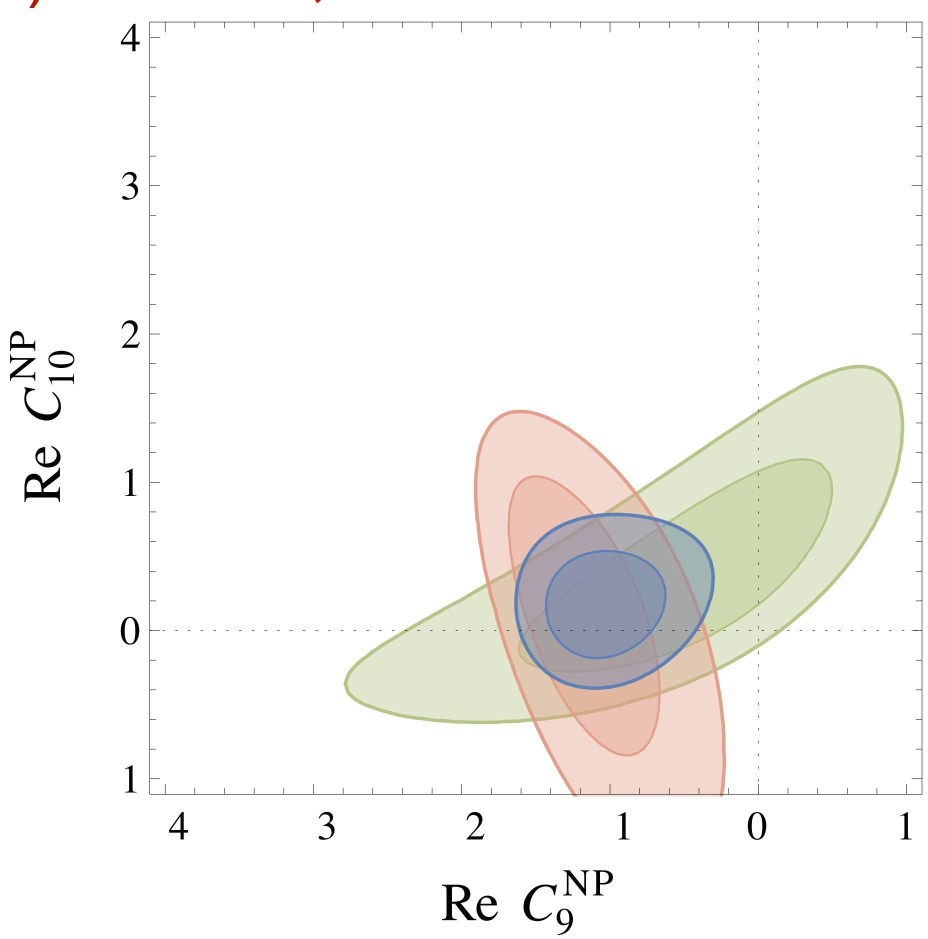
Their treatment depends on form factor ratios; most treatments are (very) reliant on light-cone sum rule calculations.

Independent corroboration (or refutation) needed; should come from lattice QCD in HL-LHC timescales

In the following, assume the effect is real.

Can fit to Wilson coefficients (independent of BSM model).

Best fits obtained with a negative shift to C_9. Too large to be a loop effect (as it would be in MSSM).



Altmannshofer, Straub 1411.3161v3

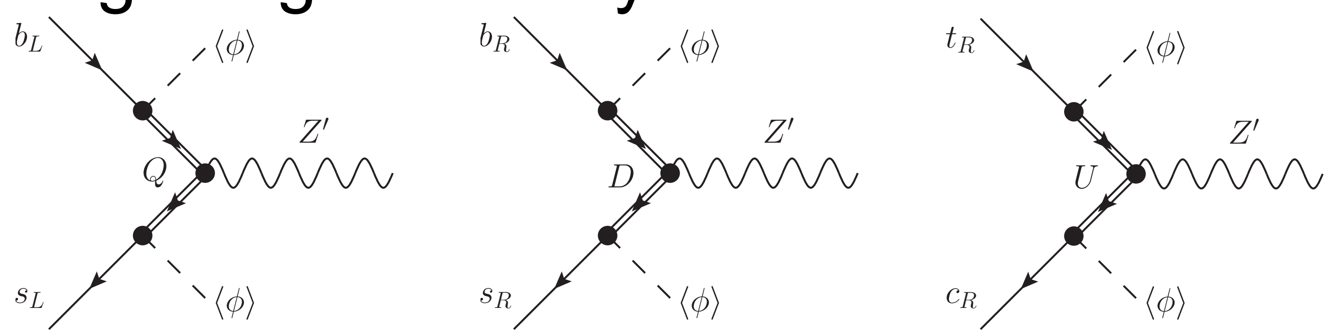
Models

Interpretations have been given in terms of Z' models, leptoquark models (elementary and composite)... several dozen studies of particular models in response to LHCb papers (apologies for not giving a long list of references)

One interesting case: "Dressing L_{mu}-L_{tau} in color"

Altmannshofer, Gori, Pospelov, Yavin
1403.1269

Integrating out heavy vector-like matter



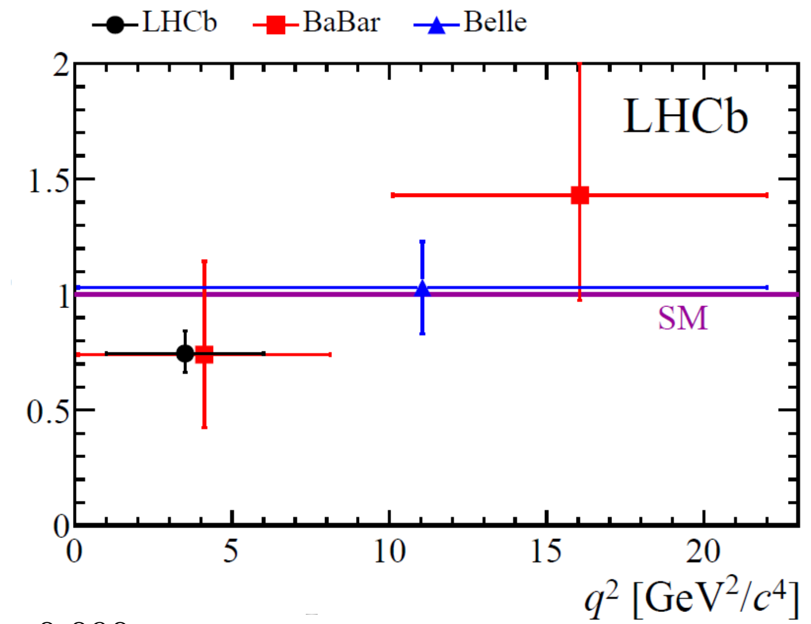
gives a realisation of the "effective Z' " of Fox et al (dim-6 coupling)

The Z' couples minimally to the anomaly-free L_{mu}-L_{tau}

This gives a shift to C_9 but **predicts** a lepton flavour non-universality (no coupling to electrons). Later observed!

Lepton universality tests

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



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

A Shires, workshop Paris, June 2014
LHCb arXiv:1406.6482

* naively =1 in SM if lepton masses negligible (as seems the case for 1 GeV^2 lower cutoff)).
Hiller, Krueger 2003
Only QED radation corrects this; estimated to be tiny (but important experimental issue)

* a large effect !

* can be ascribed to a negative C_9^{NP} , for muons only (Altmannshofer et al, prev. slide)
* scalar operators ruled out by B_s -> mu mu data Alonso, Grinstein, Martin Camalich 2014
Hiller, Schmaltz; Ghosh, Nardecchia, Renner; ...

* could be explained in terms of Z' or leptoquark models
Altmannshofer et al; Hiller and Schmaltz; Gripaios et al; ...

Other rare decays and issues

Not discussed in this talk, for lack of time, not lack of interest, or because there are much more competent audience members

Kaons

LHC is a K factory, first bound on K_S->mu mu
probes Z penguin in s->d transition! Prospects for K->pi mu mu etc?

Pronounced charm resonance structure in B->K mu mu
larger than estimated in a toy model of OPE duality violation; interesting from a strong interaction point of view Lyon, Zwicky 2014

Can we make use of the date to extract long-distance charm loop effects in a model-independent way (dispersive analysis)?

Presence of resonant structure does not (in my judgment) cause concern on theory status below the charm resonances

Lepton flavour violation

Essentially free from theory uncertainties. Interesting correlations with b->s anomalies (work of Crivellin and collaborators; others)

Theory needs

Form factors: very reliant on light-cone sum rules. Need independent corroboration.

- expect significant progress in lattice QCD (conceptual and numerical)

- flavour has been a driving force behind the European, and world wide, lattice programme for many years

- model-independent constraints from heavy quark expansion (Beneke-Feldmann); but limited accuracy so P_5' anomaly significance lost. More data needed.

New observables - to test lepton universality violation, but also to constrain hadronic inputs better from data eg Hambrock/Hiller/Zwicky 1308.4379

Systematic exploitation of LHC-Belle2 complementarity

Better (correct?) models of BSM, if anomalies accumulate

Conclusions

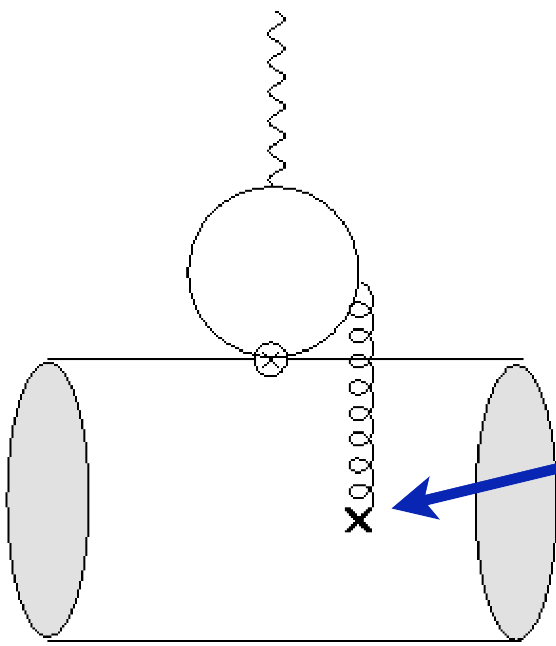
In my view rare B (and K) decays remain one of the most promising windows to & beyond the TeV scale.

Various anomalies require better statistics and further measurements: potential for multiple 5-sigma effects. The LHC upgrade will be necessary and able to deliver these measurements, with important interplay/complementarity with Belle2

Numerous models explaining and correlating (and in one case predicting) anomalies exist. Perhaps we are already holding clues to flavour dynamics at relatively low scale?

Conversely if nothing is found the upgrade will significantly push up the effective scale of flavour violation (via Bs->mu mu, right-handed current probes, and other observables as theory control improves)

Charm loop long-distance estimate



$$h_\lambda|_{c\bar{c}} \;=\; \frac{1}{m_B^2}\frac{2}{3}\epsilon^{\mu*}(\lambda)\int d^4y\, e^{iq\cdot y}\langle M|\boxed{T[(\bar{c}\gamma^\mu c)(y)(C_1^c Q_1^c + C_2^c Q_2^c)(0)]}|\bar{B}\rangle$$

consider soft gluon (in B rest frame)

From collinear factorisation viewpoint this represents the endpoint region, which is known to give a power-suppressed contribution

perform a “light-cone OPE”
(This is equivalent to expanding the charm loop, treating $\Lambda^2/(4\, m_c^2) \sim \Lambda/m_b$) Khodjamirian et al 2010

obtain

$$h_\lambda|_{c\bar{c},\mathrm{LD}} = \epsilon^{\mu*}(\lambda)\langle M(k,\lambda)|\tilde{\mathcal{O}}_\mu|\bar{B}\rangle$$

$$\tilde{\mathcal{O}}_\mu = \int d\omega I_{\mu\rho\alpha\beta}(q,\omega)\bar{s}_L\gamma^\rho\delta\Big(\omega - \frac{in_+\cdot D}{2}\Big)\tilde{G}^{\alpha\beta}b_L$$

(a nonlocal, light-cone operator)

need estimate of $\langle M(k,\lambda)|\tilde{\mathcal{O}}_\mu|\bar{B}\rangle$ (which goes into H_V^λ)

light-cone SR based on Khodjamirian et al 2010 for K* helicity amplitudes SJ, Martin Camalich 2012
outcome: helicity hierarchy remains for the endpoint region
same conclusion for (anyway CKM-suppressed) light-quark LD effects at low q^2 (estimated via VMD)

Relation to B->K*γ

$$\mathcal{A}(\bar{B}\to V(\lambda)\gamma(\lambda)) = \lim_{q^2\to 0}\frac{q^2}{e}H_V(q^2=0;\lambda)$$ exact (LSZ)

$$= \frac{iNm_B^2}{e}\left[\frac{2\hat{m}_b}{m_B}(C_7\tilde{T}_\lambda(0) - C_7'\tilde{T}_{-\lambda})(0) - 16\pi^2 h_\lambda(q^2=0)\right]$$

(only λ=+/- 1)

same amplitudes as in B->Kll incuding all long-distance details

$$S_{K^*\gamma} = 2\,\frac{\mathrm{Im}(e^{-i\phi_d}H_V^+(0)H_V^{-*}(0))}{|H_V^+(0)|^2+|H_V^-(0)|^2} \approx 2\,\frac{\mathrm{Im}(e^{-i\phi_d}C_7C_7'^*)}{|C_7|^2+|C_7'|^2}$$

Power corrections: analytical

SJ, Martin Camalich 1412.3183

Compare

$$P_5' = P_5'|_\infty \Bigg(1 + \frac{a_{V_-} - a_{T_-}}{\xi_\perp} \frac{m_B}{|\vec{k}|} \frac{m_B^2}{q^2} C_7^{\rm eff} \frac{C_{9,\perp} C_{9,\parallel} - C_{10}^2}{(C_{9,\perp}^2 + C_{10}^2)(C_{9,\perp} + C_{9,\parallel})}$$
$$+ \frac{a_{V_0} - a_{T_0}}{\xi_\parallel} \, 2\, C_7^{\rm eff} \frac{C_{9,\perp} C_{9,\parallel} - C_{10}^2}{(C_{9,\parallel}^2 + C_{10}^2)(C_{9,\perp} + C_{9,\parallel})}$$
$$+ 8\pi^2 \frac{\tilde{h}_-}{\xi_\perp} \frac{m_B}{|\vec{k}|} \frac{m_B^2}{q^2} \frac{C_{9,\perp} C_{9,\parallel} - C_{10}^2}{C_{9,\perp} + C_{9,\parallel}} + \text{further terms} \Bigg) + \mathcal{O}(\Lambda^2/m_B^2)$$

(truncated after 3 out of 11 independent power-correction terms!)
also, dependence on soft form factors reappears at PC level

and

$$P \;= \frac{1}{C_{\,,\perp} + C} \frac{m_B}{|\vec{k}|} \Bigg(- \frac{a_{T_+}}{\xi_\perp} \frac{2\, m_B}{q} C^{\;\rm ff} C_{\;,\perp} - \frac{a_{V_+}}{\xi_\perp} (C_{\;,\perp} C^{\;\rm ff} + C \quad) - \frac{b_{T_+}}{\xi_\perp} 2C^{\;\rm ff} C_{\;,\perp}$$
$$- \frac{b_{V_+}}{\xi_\perp} \frac{q}{m_B} (C_{\;,\perp} C^{\;\rm ff} + C \quad) + 16\pi \frac{h}{\xi_\perp} \frac{m_B}{q} C_{\;,\perp} \Bigg) + \mathcal{O}(\Lambda \;/m_B).$$

(complete expression)

Further notice that a_{T+} vanishes as q^2->0, h_+ helicity suppressed, and the other three terms lacks the photon pole.

Hence P_1 **much** cleaner than P_5', especially at very low q^2

Form factor relations

Once one accepts the heavy-quark limit as necessary evil (?) for dealing with the nonleptonic Hamiltonian ("charm loops" etc) one takes note that it also predicts simple relations between the (helicity) form factors, for instance:

Charles et al 1999
Beneke, Feldmann 2000
...

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

where

$$L = -\frac{2E}{m_B - 2E} \ln \frac{2E}{m_B}$$

"vertex" correction: no new parameter

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

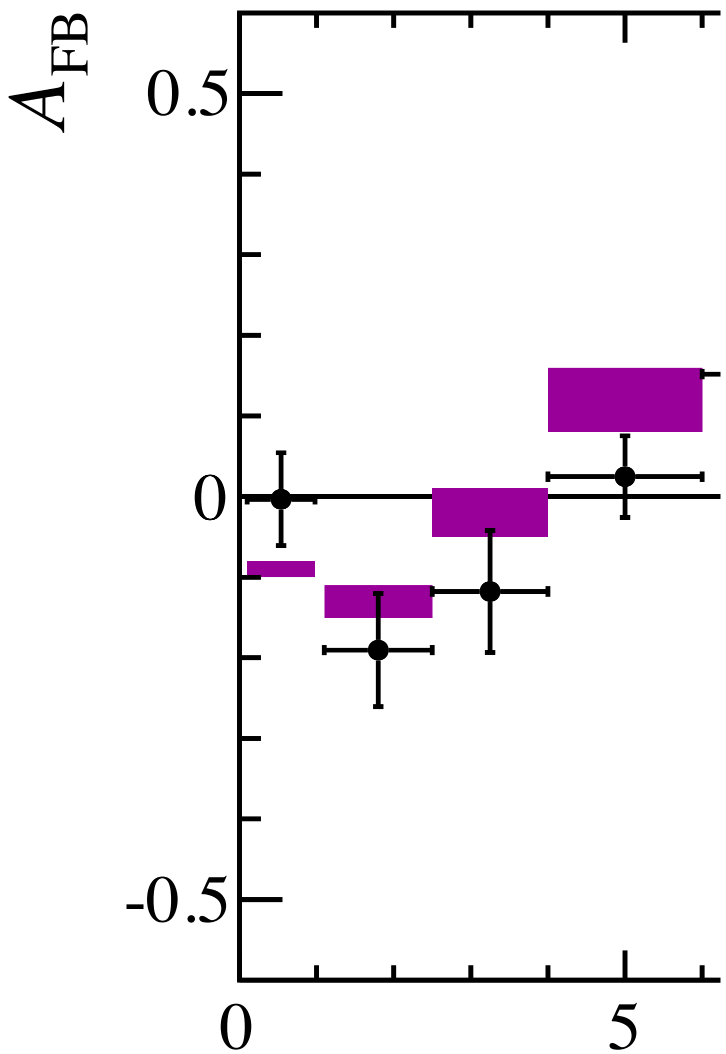
Eliminates form factor dependence from some observables (eg P_2') almost completely, up to power corrections

Descotes-Genon, Hofer, Matias, Virto

(earlier: Egede et al; Becirevic and Schneider; Bobeth et al, ...)

Numerically favours values >1 where light-cone sum rules give values >1, with very small error estimate

Forward-backward asymmetry



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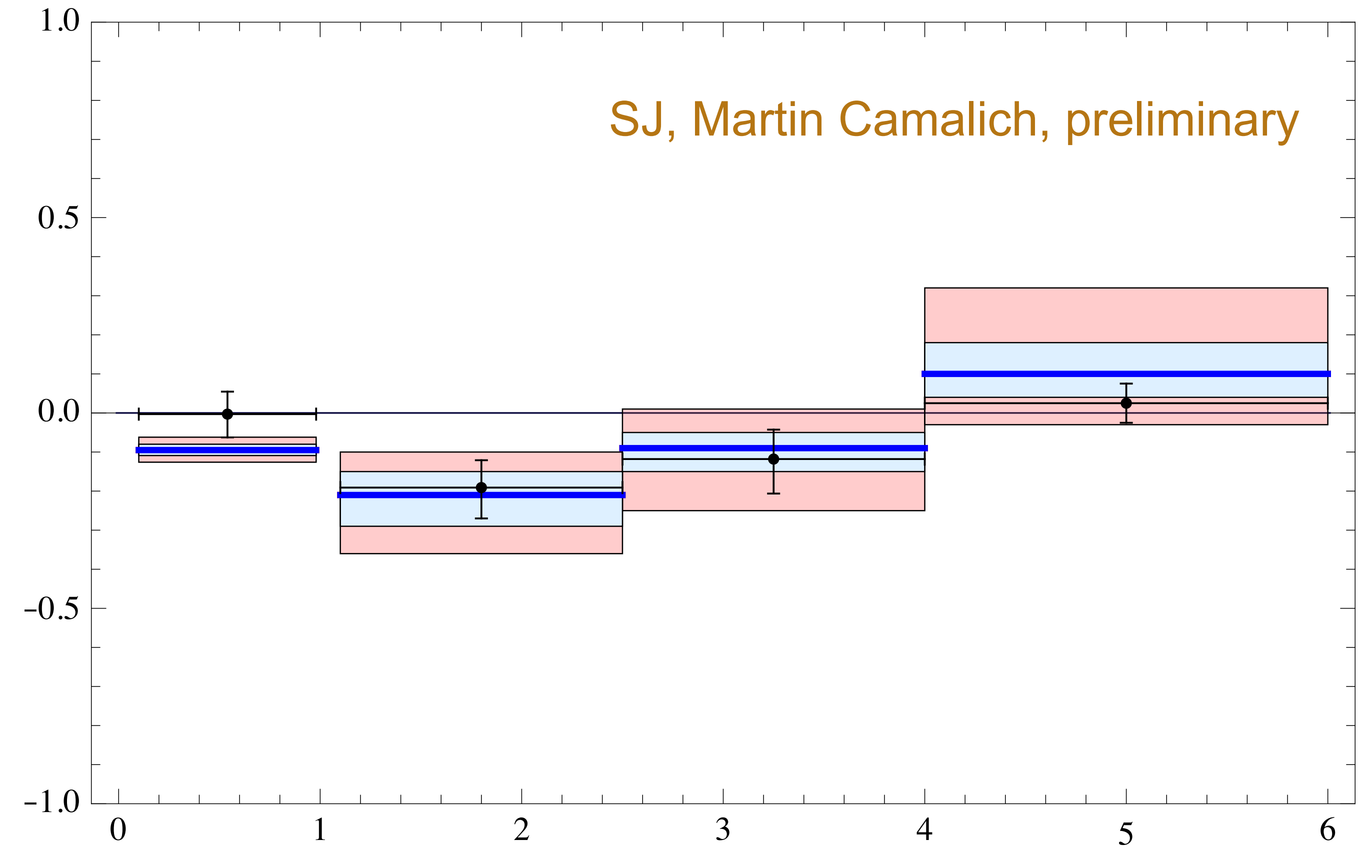

blue line: heavy-quark limit, **no power corrections**

light blue: 68% Gaussian prior theory error

pink: full scan over all theory errors

Pure heavy-quark limit (!) matches data. Even at central values nothing of significance.

Tension arises when using LCSR form factors Bharucha/Straub/Zwicky

The discrepancy is of a size consistent with a power correction. The comparison does show that form factor dependence is strong with the current precision.