$B \to M\ell\ell$: Quick Theory Overview

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Theoretishe Physik 1

UNIVERSITÄT SIEGEN

DFG FOR 1873

Aim

- To avoid repetition of trivial things in (theory) talks

- I will say the trivial things here once for all in this workshop (hopefully)

- Success of this overview talk:

$$S = 1 - \frac{\text{Minutes of introduction in theory talks}}{\text{Total minutes of theory talks}}$$

- Likewise I hope to see the LHCb detector picture only once in exp. talks...

First trivialities

- New Physics is up there (or even down here...)

  The SM is not complete... etc. etc. etc.

- Rare B decays are an excellent tool to look for it
- Also interesting for QCD issues

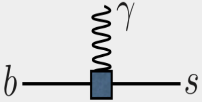
  (Can we do both things at the same time?)

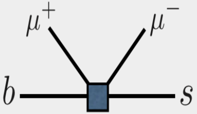
So we know why this workshop is interesting

EFT at $\mu = m_b$ and $b \to s$ transitions

Radiative and Dileptonic $b \to s$ Operators

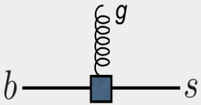
$$\mathcal{O}_{7(')} = [\bar{s}\sigma^{\mu\nu} P_{R(L)} b] F_{\mu\nu}$$
$$\mathcal{O}_{9(')} = [\bar{s}\gamma^{\mu} P_{L(R)} b][\bar{\ell}\gamma_{\mu}\ell]$$
$$\mathcal{O}_{10(')} = [\bar{s}\gamma^{\mu} P_{L(R)} b][\bar{\ell}\gamma_{\mu}\gamma_5\ell]$$
$$\mathcal{O}_{S(')}, \mathcal{O}_{P(')}, \mathcal{O}_{T,T5}$$

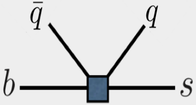




Hadronic $b \to s$ Operators

$$\mathcal{O}_1 = [\bar{s}\gamma^{\mu} P_L c][\bar{c}\gamma_{\mu} P_L b]$$
$$\mathcal{O}_{3(5)} = [\bar{s}\gamma^{\mu} P_L b] \textstyle\sum_q [\bar{q}\gamma_{\mu} P_{L(R)} q]$$
$$\mathcal{O}_{8g} = [\bar{s}\sigma^{\mu\nu} P_{R(L)} T^a b] G^a_{\mu\nu}$$





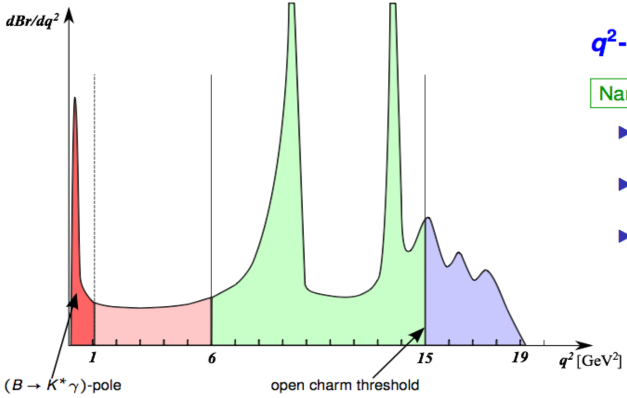
($\mathcal{O}_{2,4,6} \sim \mathcal{O}_{1,3,5}$ with mixed color indices)

Effective Hamiltonian

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \Bigg[\sum_{7,7',9,9',10,10'} \mathcal{C}_i \mathcal{O}_i + \sum_{1,\ldots,6,8g} \mathcal{C}_i \mathcal{O}_i \Bigg]$$

$\mathcal{C}_{7\rm eff}^{\rm SM} = -0.3,\ \mathcal{C}_9^{\rm SM} = 4.1,\ \mathcal{C}_{10}^{\rm SM} = -4.3,\ \mathcal{C}_1^{\rm SM} = 1.1,\ \mathcal{C}_2^{\rm SM} = -0.4,\ \mathcal{C}_{\rm rest}^{\rm SM} \lesssim 10^{-2}$

$m_{\ell\ell}^2$ spectrum



q^2-Regions in $B \to K^* \bar{\ell}\ell$

Narrow resonances

- dominated by charged-cur. (tree-level) op's
- not sensitive to new physics in $b \to s\bar{\ell}\ell$
- nonperturbative predictions via: dispersion relations + $B \to K^*(\bar{c}c)$ data

Large Recoil (low-q^2)

- very low-q^2 ($\lesssim 1$ GeV^2) dominated by $\mathcal{O}_7$
- low-q^2 ($[1, 6]$ GeV^2) dominated by $\mathcal{O}_{9,10}$
- 1) QCD factorization or SCET
  2) LCSR
  3) non-local OPE of $\bar{c}c$-tails

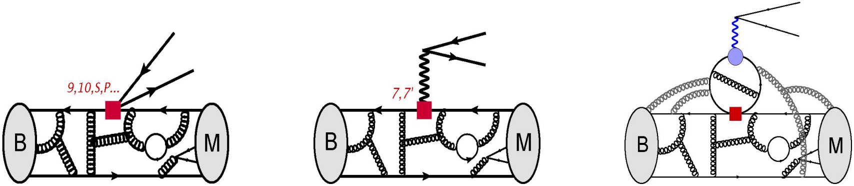
Low Recoil (high-q^2)

- dominated by $\mathcal{O}_{9,10}$
- local OPE (+ HQET) $\Rightarrow$ theory only for sufficiently large q^2-integrated obs's

(slide from C. Bobeth)

EFT Amplitudes

$$\mathcal{L} = \mathcal{L}_{QED+QCD} - \mathcal{C}_7\,[\bar{s}\sigma^{\mu\nu}P_R b]\,F_{\mu\nu} - \mathcal{C}_2\,[\bar{s}\gamma^{\nu}P_L c]\,[\bar{c}\gamma^{\mu}P_L b] + \cdots$$



$\mathcal{C}_9$ **contribution:** $\mathcal{A}_9 = \mathcal{C}_9\,\langle M_\lambda|\bar{s}\gamma_\mu P_L b|B\rangle L^\mu = \mathcal{C}_9\,F_\lambda(q^2)$

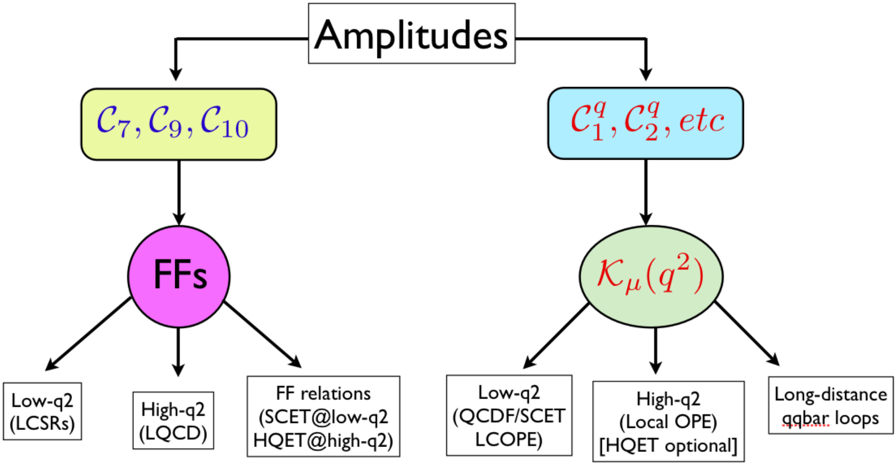
$\mathcal{C}_7$ **contribution:** $\mathcal{A}_7 = \mathcal{C}_7\,\langle M_\lambda|\bar{s}\sigma_{\mu\nu} P_R b|B\rangle \frac{eq^\mu}{q^2} L^\nu = \mathcal{C}_7\,T_\lambda(q^2)$

$\mathcal{C}_2$ **contribution:** $\mathcal{A}_2 = \mathcal{C}_2 \cdot \frac{e^2}{q^2} L^\mu \int dx^4 e^{iq\cdot x} \langle M_\lambda|\,T\{\mathcal{J}^{em}_\mu(x)\mathcal{O}_2(0)\}|B\rangle$

2 main problems:

1. Determination of Form Factors (LCSRs, LQCD, . . .)
2. Computation of the hadronic contribution (SCET/QCDF, OPE, . . .)

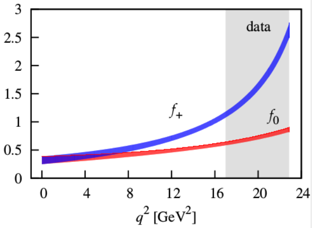
Outline-chart of theory amplitudes

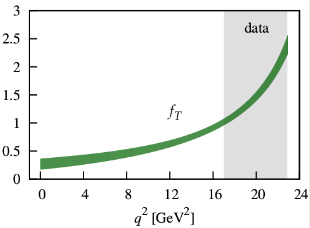


$$\left(\text{where} \quad \mathcal{K}_\mu(q^2) = -\frac{8\pi}{q^2} \int d^4x e^{iq\cdot x} T\{\mathcal{J}_\mu^{\text{em}}(x)\mathcal{H}(0)\}\right)$$

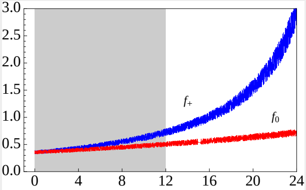
$B \to K\ell\bar{\ell}$: Form Factors

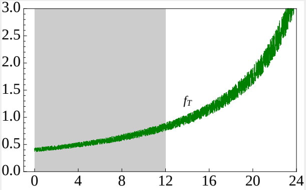
Unquenched LQCD Bouchard, Lepage, Monahan, Na, Shigemitsu '2013





LCSRs Khodjamirian, Mannel, Pivovarov, Wang '2010

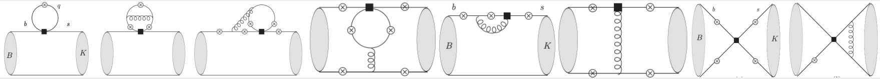




$B \to K$ form factors are well known in the full kinematical regime, but still constitute a dominant source of uncertainty in some regions.

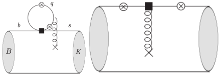
$B \to K\ell\bar{\ell}$: Hadronic Contributions – Low-q^2

"Hard" contributions: QCDF Beneke,Feldmann,Seidel'2001, Asatrian, et al'2001



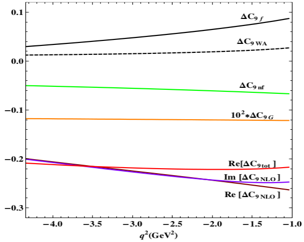
up to unknown Power Corrections

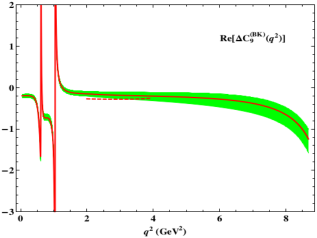
"Soft" contributions: LC-OPE at $q^2 < 0$ Khodjamirian, Mannel, Wang'2012

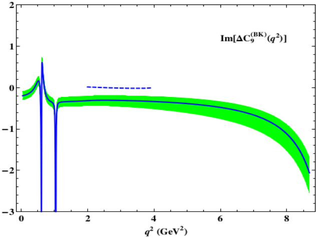


$$\mathcal{K}_{BK}(q^2) \sim \log\left(4m_c^2 - q^2\right) + \sum_{n=1,2,\ldots} \frac{\Lambda_{\rm QCD}^{2n}}{(4m_c^2 - q^2)^n}$$

Contain Power Corrections and reproduce QCDF for hard contributions

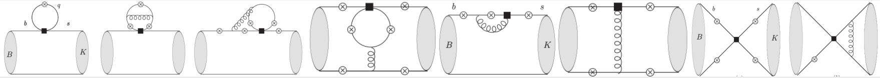






$B \to K\ell\bar{\ell}$: Hadronic Contributions – Low-q^2

"Hard" contributions: QCDF Beneke,Feldmann,Seidel'2001, Asatrian, et al'2001



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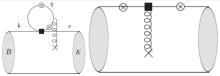
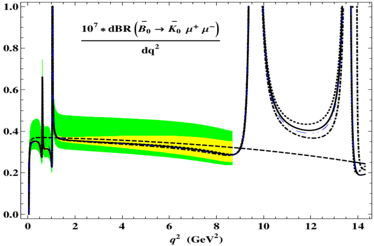
"Soft" contributions: LC-OPE at $q^2 < 0$ Khodjamirian, Mannel, Wang'2012



$$\mathcal{K}_{BK}(q^2) \sim \log(4m_c^2 - q^2) + \sum_{n=1,2,\dots} \frac{\Lambda_{\rm QCD}^{2n}}{(4m_c^2 - q^2)^n}$$

Contain Power Corrections and reproduce QCDF for hard contributions



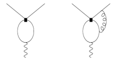
- Soft contributions reduce the BR by a few %.
- FFs are the dominant source of uncertainty below ~ 6 GeV^2.
- Model-dependence is small in $[1, 8]$ GeV^2.

$B \to K\ell\bar{\ell}$: Hadronic Contributions – High-q^2

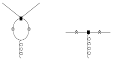
Local OPE for $q^2 \sim m_b$: Beylich, Buchalla, Feldman'2011, Grinstein, Pirjol'2004

$$\mathcal{K}^\mu(q^2) \sim \int dx^4 e^{iq.x}\, T\{j^\mu_{c\bar{c}}(x)\mathcal{H}^c(0)\} \xrightarrow{q^2\sim m_b^2} \sum_{n,d} C_{d,n}(q)\mathcal{O}^\mu_{d,n}$$

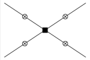
$$= \quad \mathcal{K}^\mu_3(q^2) \quad + \quad \mathcal{K}^\mu_5(q^2) \quad + \quad \mathcal{K}^\mu_6(q^2) \quad + \quad \mathcal{O}[(\Lambda/m_b)^3]$$



Usual FFs
NLO $\sim$ 10-15%



$\lesssim 1\%$



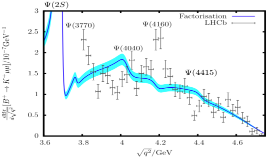
$\lesssim 1‰$

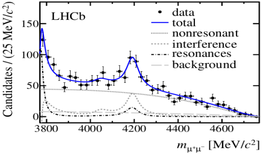
Duality violations: Beylich, Buchalla, Feldman'2011

From a model fitted to BES data: $\pm 2\%$ for *integrated BR over high-q^2 region.*

Non-fact. corrections:
Seem to be large

figures from Lyon,Zwicky'2014
and LHCb-1307.7595

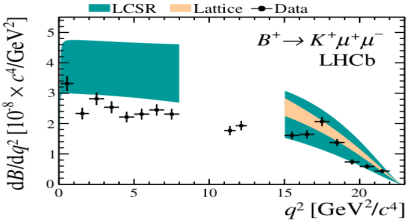




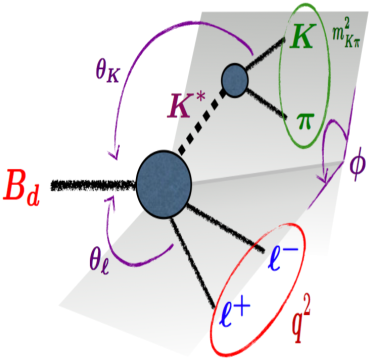
$B \to K\ell\bar{\ell}$: Summary

- **Form Factors** are well known but still a dominant source or uncertainty.
- **Perturbative NLO corrections** to charm-loop are important since they lift color suppression:
  - $\sim -5\%$ in the space-like region.
  - $\sim -10\%$ at low-q^2.
  - ~ -10-15% at high-q^2.
- **Soft contributions** reduce the BR by a few percent.
- At **high-q^2** wide resonances are difficult to assess theoretically, but the OPE should give an accurate determination for the integrated BR in a large high-q^2 bin (DV contributions $\lesssim \pm 2\%$??).
- There is **some tension** between SM and data, at least at **low-q^2** [remember $BR \sim (\mathcal{C}_9 + \mathcal{C}_{9'})$, so it goes in the direction of decreasing $\mathcal{C}_9$]. But theory correlations are O(1)!!

Plot from LHCb-1403.8044



$B \to K^*(\to K\pi)\ell^+\ell^-$: Angular Distribution



$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi} \times$$

$$\Big[\mathbf{J}_{1s}\sin^2\theta_K + \mathbf{J}_{1c}\cos^2\theta_K + \mathbf{J}_{2s}\sin^2\theta_K\cos 2\theta_l$$

$$+\mathbf{J}_{2c}\cos^2\theta_K\cos 2\theta_l + \mathbf{J}_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$

$$+\mathbf{J}_4\sin 2\theta_K\sin 2\theta_l\cos\phi + \mathbf{J}_5\sin 2\theta_K\sin\theta_l\cos\phi$$

$$+\mathbf{J}_{6s}\sin^2\theta_K\cos\theta_l + \mathbf{J}_{6c}\cos^2\theta_K\cos\theta_l$$

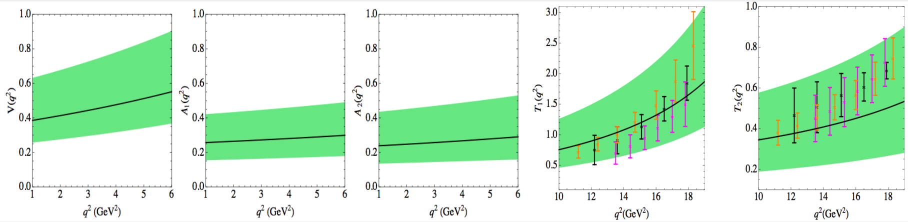
$$+\mathbf{J}_7\sin 2\theta_K\sin\theta_l\sin\phi + \mathbf{J}_8\sin 2\theta_K\sin 2\theta_l\sin\phi$$

$$+\mathbf{J}_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

- ⋆ Which observables do we want to have? ($P_i^{(\prime)}$ vs. S_i, etc.)
- ⋆ CP violation?
- ⋆ Time dependence? (not for this mode)
- ⋆ Polarization?? Taus?? ...

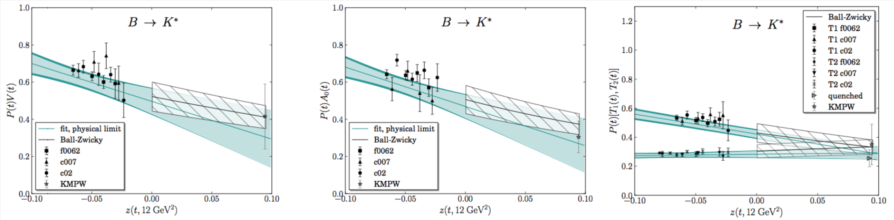
$B \to K^* \ell\bar{\ell}$: Form Factors

LCSRs-low-q^2 Khodjamirian et.al'2010 extrapolated vs. LQCD Becirevic et.al'2007



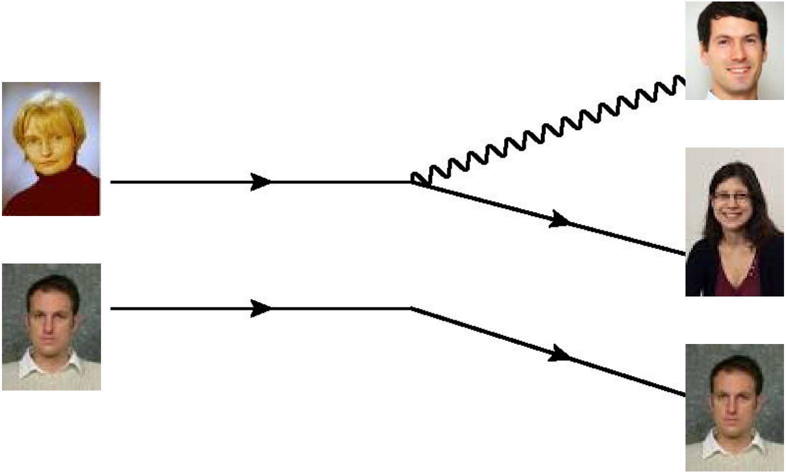
also in fair agreement with Ball, Zwicky'2004 (figs from Descotes-Genon, Hurth, Matias, JV'2013)

Recent "full QCD" LQCD results Horgan et.al'2013

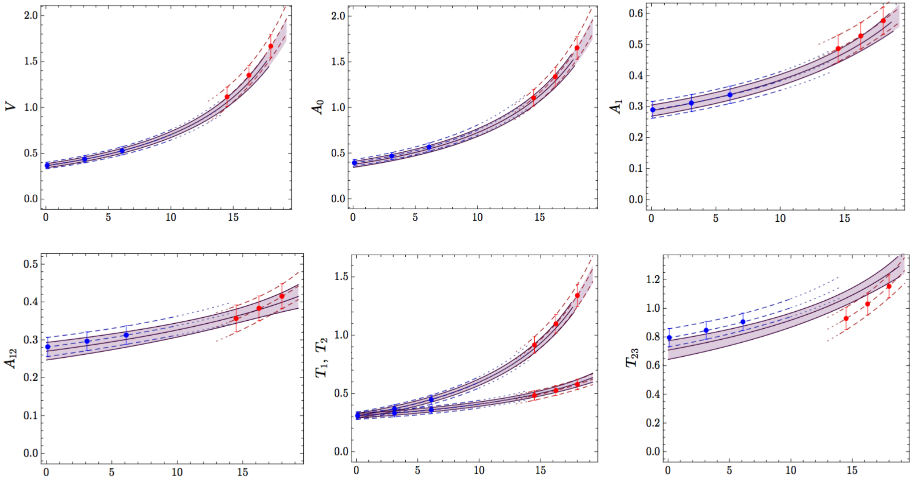


$B \to K^*\ell\bar{\ell}$: Form Factors

From BZ to BSZ: Very rare decay



$B \to K^*\ell\bar{\ell}$: Form Factors



Bharucha, Straub, Zwicky'2015

$B \to K^*\ell\bar{\ell}$: Form Factors

Low q^2 ::

- Altmannshofer, Bharucha, Straub, Zwicky:

  LCSRs with K^* DAs + Correlations + EOM constraint

  q^2 dependence given by simplified z-expansion

- Descotes-Genon et al:

  LCSRs with B DAs (uncorrelated) + SCET relations + Power corrections

  q^2 dependence given by simplified z-expansion

- Jäger + Camalich:

  Try to rely only on HQ/LE expansion, both for $q^2 = 0$ and q^2-dependence

  Input: LCSRs, DSE, $B \to K^*\gamma$, + power corrections

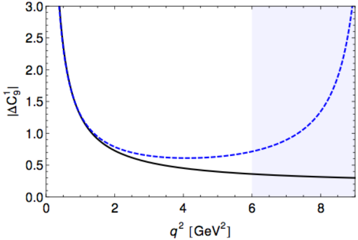
Large q^2 ::

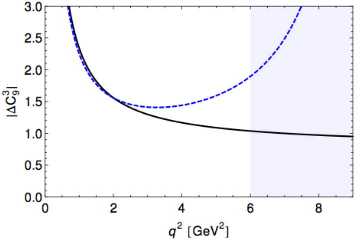
- Horgan et al: Lattice QCD

$B \to K^*\ell\bar{\ell}$: Hadronic Contributions

Similar to $B \to K\ell\ell$ with some differences.

Jäger,Camalich'2014

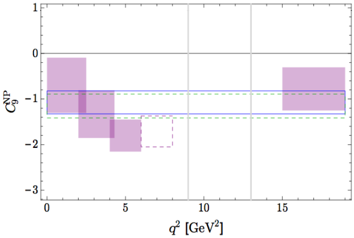




It mimics a $\mathcal{C}_9$ but...

- The effect is q^2-depedent
- The effect is different for each helicity/transversity amplitude
- Phases: Weak vs. Strong

Altmannshofer,Straub'2015



Would be nice to see this clearly from the data.

LHCb $b \to s$ Anomalies

1. Angular observables in $B \to K^* \mu\mu$. $\mathcal{C}_9^\mu < 0$ ✓

   Descotes-Genon et al'2013, Altmannshofer,Straub'2013, Horgan et al'2013, Bobeth et al'2013, ... + others + updates

2. Branching ratios: $B \to K\mu\mu$, $B \to K^*\mu\mu$, $B \to \phi\mu\mu$. $\mathcal{C}_9^\mu < 0$ ✓

   Roman: "it is *not* a factor of 2 in the normalisation of *my* form factors!!"

3. $R_K \equiv BR(B \to K\mu\mu)/BR(B \to Kee)$ at low-q^2. $\mathcal{C}_9^\mu < 0$ ✓

   Hiller,Schmaltz'2014, Gosh et al'2014, Hurth et al'2014, Altmannshofer,Straub'2014, ... + others + updates

Note: Anomalies live mostly in the low-q^2,
would be nice to have them also at high-q^2...

LHCb $b \to s$ Anomalies

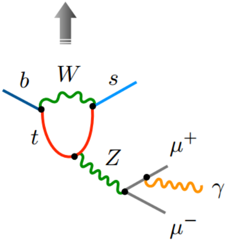
	branching ratios	angular observables	LFU ratios
parametric uncertainties?	✓	✗	✗
hadronic effects?	✓	✓	✗
New Physics?	✓	✓	✓

(slide from W. Altmannshofer)

LHCb $b \to s$ Anomalies

R_K: null test in SM?

$$R_K^{SM} = 1 + \mathcal{O}\left(\frac{m_\mu^2}{m_b^2}\right) + \mathcal{O}\left(\alpha \ln \frac{m_\mu^2}{m_b^2}\right) = 1 + \mathcal{O}(0.01)$$



(slide from U. Haisch '2014)

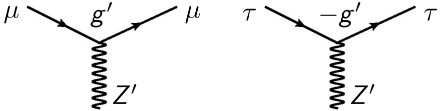
A prediction could be that the effect is *opposite* in the large-q^2

Huber, Hurth, Lunghi 2015 But it seems waaay too large anyway

New Physics?

- "Obvious" possibility: Z'-models

  Buras et al, Descotes-Genon et al, Haisch et al, Altmannshofer et al, Crivellin et al, Aristizabal et al, ... (mostly everyone)



$L_\mu - L_\tau$ model
Altmannshofer et al'2013
Lepton-non-universal
Causality violation
("Cristal Ball" effect)

- (Scalar) Leptoquaks Hiller+Schmaltz, Shoo+Mohanta, Nardecchia et al, Hiller+Ivo,...
  - Attractive for a number of reasons
- Please fill in
- Lepton Flavor violation??

  Glashow et al, Bhattacharya et al, Crivellin et al, Aristizabal et al, Hiller+Ivo, Crivellin et al ... (almost everyone)

  - Glashow, Guadagnoli, Lane: "**LFNU** "necessarily associated" with **LFV** "
  - Grinstein: " Bullshit!" (More precisely: "I have a family of counterexamples")
  - If you pay attention you'll see they do not really disagree
  - But most proposed models for R_K do have that feature
  - Important to establish what to expect on general grounds (benchmarks, etc.)

Conclusions

No Conclusions. Let's begin!!