Lepton-universality violation in *B* decays

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Frascati Seminar

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Outline

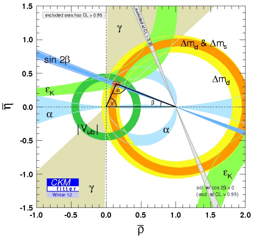
1. Flavor probes of new physics
2. The $b \to c\tau\nu$ transitions
   - Theoretical uncertainties
   - Angular analyses of the *observable* decay products
   - New physics
     - The bound of the lifetime of the B_c
3. LUV in $b \to s\ell\ell$ decays
   - $B_s \to \mu\mu$
   - R_K and R_{K^*}
   - Fits

Sources of flavor in the SM: Quark sector

Yukawa sector of the SM

$$-\mathcal{L}_Y = \bar{q}_L Y_d d_R H + \bar{q}_L Y_u u_R \tilde{H} + \bar{\ell}_L Y_e e_R H + h.c.$$

- Complex and Unitary matrix$\Rightarrow$ **3 angles** and **1 phase**



$$V_{CKM} \simeq \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$\lambda = 0.2253(7), \quad A = 0.808(22),$$
$$\bar{\rho} = 0.132(22), \quad \bar{\eta} = 0.341(13)$$

- **The structure of the CKM matrix is hierarchical!**

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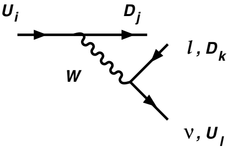
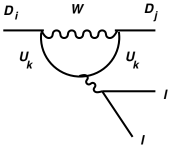
- **CC** $U_i \to D_j$: **Tree level**



- **FCNC** $D_i \to D_j$: **Loop**



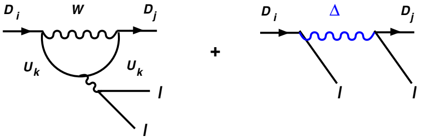
- $\mathcal{M} \sim G_F\, V_{ij} U^*_{kl}$,
  $V_{ij} U^*_{kl}$ can be $\mathcal{O}(1)$
- $\mathcal{M} \sim G_F \sum_k V_{ki} V^*_{kj} \frac{m_K^2}{m_W^2} \frac{\alpha}{4\pi}$,
  GIM and **loop** suppression
- In the SM, FCNCs are suppressed w.r.t. CC interactions: **"Rare" decays!**

Sources of flavor in the SM: Quark sector

Yukawa sector of the SM

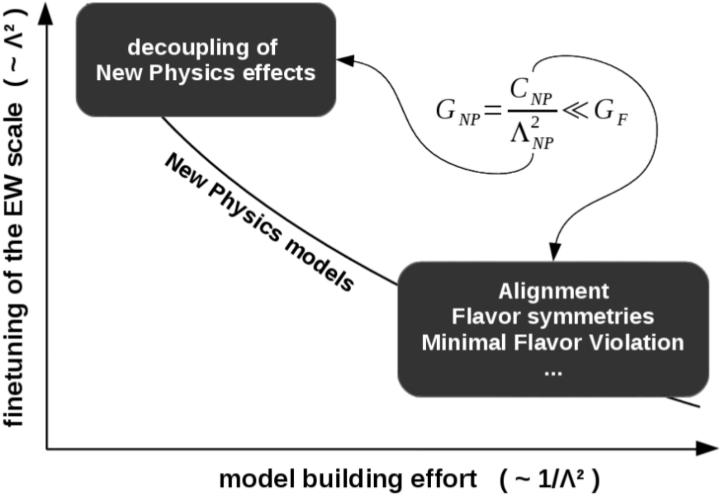
$$-\mathcal{L}_Y = \bar{q}_L Y_d d_R H + \bar{q}_L Y_u u_R \tilde{H} + \bar{\ell}_L Y_e e_R H + h.c.$$

- **FCNC** $b \to s$: Very sensitive to exchange of new particles



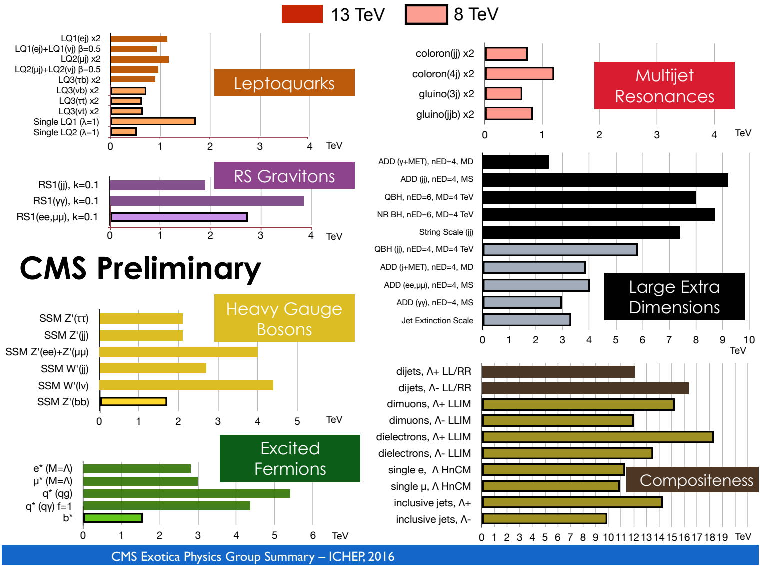
$$\mathcal{M} \sim G_F V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \Big(C^{\rm SM} + \overbrace{\frac{4\pi}{\alpha} \frac{1}{V_{tb} V_{ts}^*}}^{\sim 200^2} \frac{v^2}{M^2} g^2 \Big) \times \langle \bar{s} b \otimes \bar{\ell}\ell \rangle$$

Rare b decays sensitive to $M \sim 100$ TeV !!


decoupling of
New Physics effects
$G_{NP} = \frac{C_{NP}}{\Lambda^2_{NP}} \ll G_F$
New Physics models
Alignment
Flavor symmetries
Minimal Flavor Violation
...
finetuning of the EW scale (~ Λ²)
model building effort (~ 1/Λ²)

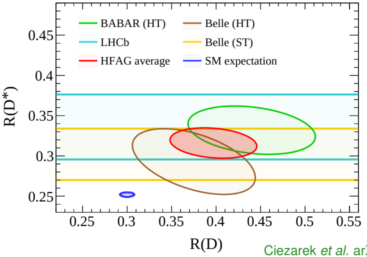
- No **New Physics** at colliders ...

https://twiki.cern.ch/twiki/bin/view/CMSPublic/ https://twiki.cern.ch/twiki/bin/view/AtlasPublic/



Lepton Univ. violating new-physics in B decays? $R_{D^{(*)}}$ anomalies

$$R_{D^{(*)}} = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu})}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu})} \quad \text{where} \quad \ell = e, \mu$$



Ciezarek *et al.* arXiv:1703.01766

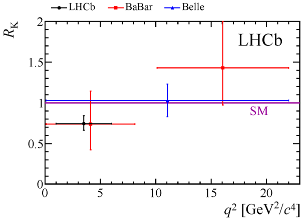
- ***Excesses*** reported by **3 different experiments** in **2 channels** at $\sim 4\sigma$
  - 15% enhancement of the tau SM amplitude:

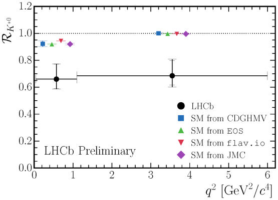
LUV in $b \to c\tau\nu$

$$\Lambda_{\mathrm{NP}} = \frac{v}{\sqrt{|V_{cb}| \times 0.15}} \sim 3\ \text{TeV}$$

Lepton Univ. violating new-physics in B decays? $R_{K^{(*)}}$ anomalies

$$R_{K^{(*)}} = \frac{\mathcal{B}(\bar{B} \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(\bar{B} \to K^{(*)}e^+e^-)}$$





- Skewed μ-to-e ratios reported by **LHCb** in **2 channels** at $\sim 4\sigma$
  - Anomalies in muonic **BRs** and **angular observables**: Muon-selective contribution?
  - 25% deficit (enhancement) of the SM muon (electron) amplitude:

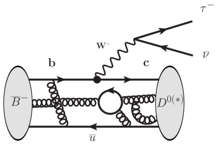
LUV in $b \to s\ell\ell$

$$\Lambda_{\rm NP} = \frac{v}{\sqrt{|V_{ts}||V_{tb}| \times \frac{\alpha_{\rm em}}{4\pi} \times 0.25}} \sim 50 \text{ TeV}$$

LUV in $b \to c\tau\nu$ decays

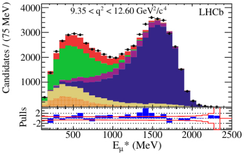
Issues that need to be understood

1. **Hadronic contributions**



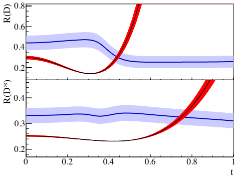
- We need form factors ...
- ... But hadronic interactions are lepton-universal!

2. **The τ is (experimentally) complicated**



- One does not *see directly* the τ
- Reconstruct events from τ decays with missing ν's (e.g. $\tau \to \ell\nu\bar{\nu}$)

3. **The structure of the putative New Physics effect**



- **Tree-level** exchange of new charged bosons (Higgses or leptoquarks)
- 2HDM of type II intepretations ruled out

Hadronic uncertainties (Form factors)

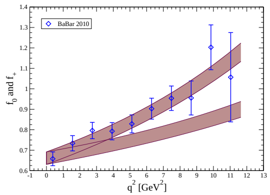
- Hadronic interactions are lepton universal⇒**Uncertainties largely cancel in R_{D^*}**
- **Fit** model-indep. parametrizations of FF to **experimental** $B \to D^{(*)}(\mu, e)\nu$ data

  Boyd, Grinstein & Lebed '96, Caprini, Lellouch & Neubert'98

- **Example:** $B \to D\tau\nu$ with LQCD

$$\langle D(k)|\bar{c}\gamma^\mu b|\bar{B}(p)\rangle = (p+k)^\mu f_+(q^2) + q^\mu \frac{m_B^2 - m_D^2}{q^2}\left(f_+(q^2) - f_0(q^2)\right)$$

  - Scalar $f_0(q^2)$ enters rate $\propto m_\ell^2$
  - **CVC** implies $f_0(0) = f_+(0)$



Na *et al.* PRD92(2015)no.5,054510 (see also Bailey *et al.* PRD92,034506)

- No non-zero recoil LQCD for $B \to D^*$: **HQET** (cont. from scalar FF is small)

  See: Bernlocher *et al.* arXiv: 1703.05330, Bigi *et al.* 1703.06124

Hadronic uncertainties (Form factors)

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Boyd, Grinstein & Lebed '96, Caprini, Lellouch & Neubert'98

SM predictions of $R_{D^{(*)}}$ seem to be well under control

- LQCD calculations for $B \to D^* \ell\nu$ will test **HQET**

Dealing with possible systematics in the reconstruction of the τ

- The τ's lifetime is $\sim 10^{-13}$ s (reconstruct signal from τ decays)
- **Experiment:**
  - Different τ decay modes $\Rightarrow$ Different backgrounds
  - Maximize the coverage of the τ's lifetime

Channel	$\tau \to \mu\nu\nu$	$\tau \to e\nu\nu$	$\tau \to \pi\nu$	$\tau \to \rho\nu$	$\tau \to 3\pi\nu$	TOTAL
$\mathcal{B}$	17.4%	17.8%	10.82%	25%	9%	$\sim$ 80%

- **Theory:**
  - Kinematic distributions of $B \to D\nu[\tau \to d\nu(\bar{\nu})]$ in terms of **visible** decay products

New observables to test systematics and the SM

- **Montecarlo:** Closer to experiment

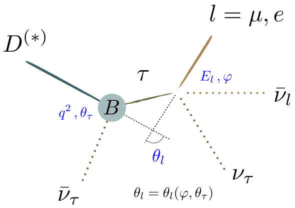
Hagiwara *et al.* PRD89, 094009 (2014), Bordone *et al.* EPJC76 (2016) no.7, 360, Ligeti *et al.* arXiv:1610.02045

- **Analytical:** More transparent

Nierste *et al.* PRD78,015006 '08, Alonso, Kobach & JMC, arXiv:1602.07671, Alonso, JMC & Westhoff

$B \to D^{(*)}\tau^-(\to \ell^- \bar{\nu}_\ell \nu_\tau)\bar{\nu}_\tau$

Alonso, Kobach, JMC, arXiv: 1602.07671



- **Integrate analytically the τ and ν's angular phase-space:**

$$\frac{d^3\Gamma_5}{dq^2\, dE_\ell\, d(\cos\theta_\ell)} = \mathcal{B}[\tau_\ell]\ \mathcal{N}\ \left[I_0(q^2, E_\ell) + I_1(q^2, E_\ell)\cos\theta_\ell + I_2(q^2, E_\ell)\cos\theta_\ell^2\right]$$

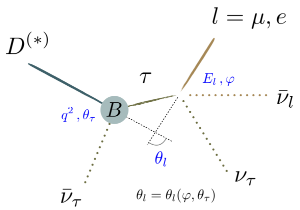
  - $I_{0,2}(q^2, E_\ell)$ accessed in $R_{D^{(*)}}$
  - $I_1(q^2, E_\ell)$ accessible only with a FB leptonic asymmetry!

$$\frac{d^2 A_{FB}(q^2, E_\ell)}{dq^2\, dE_\ell} = \left(\int_0^1 d(\cos\theta_\ell) - \int_{-1}^0 d(\cos\theta_\ell)\right) \frac{d^3\Gamma_5}{dq^2\, dE_\ell\, d(\cos\theta_\ell)}$$

$$R_{FB}^{(*)} = \frac{1}{\mathcal{B}[\tau_\ell]} \frac{1}{\Gamma_{\mathrm{norm.}}} A_{FB},$$

$B \to D^{(*)}\tau^-(\to \ell^-\bar{\nu}_\ell\nu_\tau)\bar{\nu}_\tau$

Alonso, Kobach, JMC, arXiv: 1602.07671



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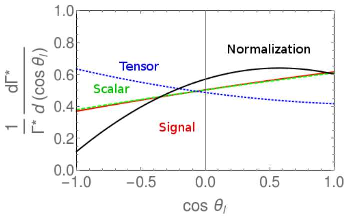
- Angular distribution help discriminate signal, **normalization**, NP



$\tau^- \to \pi^- \nu_\tau$ as a τ polarimeter: P_L

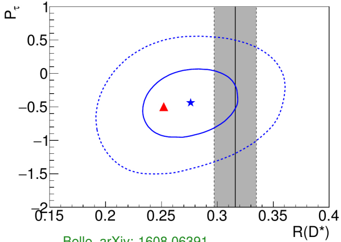
$$\frac{dP_L}{dq^2} = \frac{d\Gamma_{B,+}/dq^2 - d\Gamma_{B,-}/dq^2}{d\Gamma_B/dq^2}$$

Slope in E_π of $d\Gamma_4 \Rightarrow$ **Longitudinal Polarization**

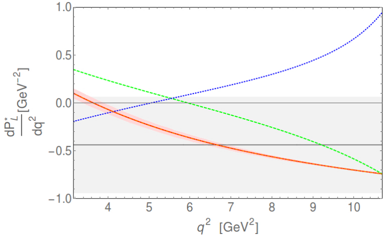
$$\frac{d^2\Gamma_4}{dq^2 dE_\pi} = \frac{\mathcal{B}[\tau_\pi]}{|\vec{p}_\tau|}\frac{d\Gamma_B}{dq^2}\left[1 + \xi(E_\pi, q^2)\frac{dP_L}{dq^2}\right], \quad \xi(E_\pi, q^2) = \frac{1}{\beta_\tau}\left(2\frac{E_\pi}{E_\tau} - 1\right)$$

M. Davier *et al.* PLB306, 411 (1993), Tanaka&Watanabe, PRD82, 034027 (2010)

- Applied to the BD^* channel by *Belle*



Belle, arXiv: 1608.06391



$\tau^- \to \pi^-\nu_\tau$ as a τ polarimeter: $P_\perp$ (and A_{FB}^τ!)

Alonso, JMC & Westhoff, arXiv:1702.02773

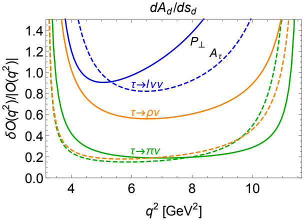
- $P_\perp$ probes **interference between τ polarization states**

$$d\Gamma\, dP_\perp = \frac{(2\pi)^4\, d\Phi_3}{2m_B} 2\mathrm{Re}\left[\mathcal{M}_{B+}\mathcal{M}_{B-}^\dagger\right]$$

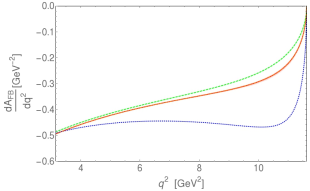
$$\frac{d^2 A_{FB}^d}{dq^2 dE_d} = \mathcal{B}[\tau_d]\left[f_{FB}^d(E_d,q^2)\frac{dA_\tau}{dq^2} + f_\perp^d(E_d,q^2)\frac{dP_\perp}{dq^2}\right]$$

$$f_{FB}^\pi = -\frac{\left(2E_\pi E_\tau - m_\tau^2\right)\left(E_\tau - |\vec{p}_\tau| - 2E_\pi\right)}{2|\vec{p}_\tau|^3 E_\pi} \qquad f_\perp^\pi = -\frac{4E_\pi^2 - 4E_\pi E_\tau + m_\tau^2}{\pi\, E_\pi |\vec{p}_\tau|^3 m_\tau}$$

- Prospects at Belle (II)



- Sensitivity to NP



New physics in $b \to c\tau\nu$: EFT

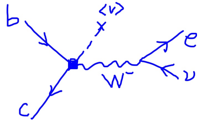
- Low-energy effective Lagrangian (no RH ν)

$$\mathcal{L}_{\rm eff}^{\ell} = -\frac{G_F V_{cb}}{\sqrt{2}}\Big[(1+\epsilon_L^{\ell})\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{c}\gamma^\mu(1-\gamma_5)b + \epsilon_R^{\ell}\, \bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell\ \bar{c}\gamma^\mu(1+\gamma_5)b$$
$$+\bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{c}[\epsilon_S^{\ell} - \epsilon_P^{\ell}\gamma_5]b + \epsilon_T^{\ell}\,\bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{c}\sigma^{\mu\nu}(1-\gamma_5)b\Big] + \mathrm{h.c.},$$

Wilson coefficients: ϵ_Γ decouple as $\sim v^2/\Lambda_{\rm NP}^2$

- Matching to high-energy Lagrangian – SMEFT
  - Symmetry relations for ϵ_Γ
    - In charged-currents ϵ_R^{ℓ}:

$$\mathcal{O}_{Hud} = \frac{i}{\Lambda_{\rm NP}^2}\left(\tilde{H}^\dagger D_\mu H\right)\left(\bar{u}_R\gamma^\mu d_R\right)$$

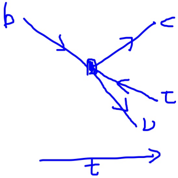


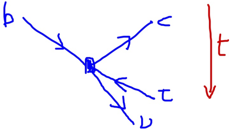
☛ RHC is lepton universal: $\epsilon_R^{\ell} \equiv \epsilon_R + \mathcal{O}(\frac{v^4}{\Lambda_{\rm NP}^4}) \Rightarrow$ **Cannot explain LUR $R_{D^{(*)}}$!**

Down to **4** operators to explain R_{D^*}: ϵ_L, ϵ_S, ϵ_P, ϵ_T

The constraint of the lifetime of the B_c meson

- $\mathcal{L}_{\rm eff}^{\tau}$ also contributes to $B_c \to \tau\nu$





- $B \to D^*\tau\nu$ receives a contribution from ϵ_P:

$$\epsilon_P \; \langle D^*(k,\epsilon)|\bar{c}\gamma_5 b|\bar{B}(p)\rangle = -\frac{2\epsilon_P \; m_{D^*}}{m_b+m_c} A_0(q^2)\epsilon^*\cdot q$$

- $B_c \to \tau\nu$ receives a **chirally enhanced** contribution from ϵ_P!

$$\mathrm{Br}(B_c^- \to \tau\bar{\nu}_\tau) = \tau_{B_c^-} \frac{m_{B_c} m_\tau^2 f_{B_c}^2 G_F^2 |V_{cb}|^2}{8\pi}\left(1-\frac{m_\tau^2}{m_{B_c}^2}\right)^2 \left|1+\epsilon_L+\frac{m_{B_c}^2}{m_\tau(m_b+m_c)}\epsilon_P\right|^2$$

Explain R_{D^*} with ϵ_P $\Rightarrow$ Br$(B_c \to \tau\nu)$ will receive a significant enhancement

The constraint of the lifetime of the B_c meson

- BRs of the B_c are experimentally almost unknown and $B_c \to \tau\nu$ challenging!
- **NEW STRATEGY:** Use the lifetime of B_c
  - Very high precision (1.5%): $\tau_{B_c} = 0.507(8)$ ps
  - **Rough app.:** $\Gamma(B_c) \approx \Gamma(B_c)_{\bar{c}\to\bar{s}} + \Gamma(B_c)_{b\to c} \approx \Gamma(D^0) + \Gamma(B_d) \Rightarrow \tau_{B_c} \approx 0.30$ ps
  - Overview of result using systematic approach (NR-OPE): Beneke&Buchalla, PRD53,4991

★ **QCD**: "Most of the B_c lifetime comes from $\bar{c} \to \bar{s}$ ($\sim$ 65%) and $b \to c$ ($\sim$ 30%) transitions"

Bigi PLB371 (1996) 105, Beneke *et al.* PRD53(1996)4991,...

$$\tau^{\rm OPE}_{B_c} = 0.52^{+0.18}_{-0.12}\ \text{ps}$$

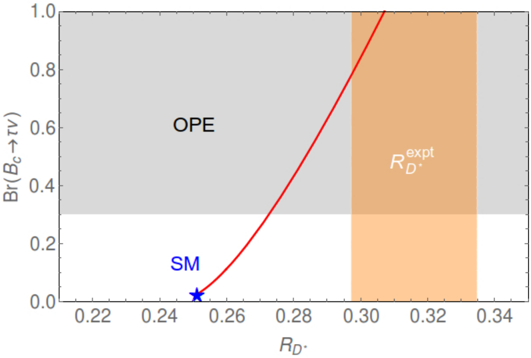
☛ **BR**($B_c \to \tau\nu$) $\leq$ 30% **(very conservative errors)**

Alonso, Grinstein&JMC,PRL118(2017)081802, Xin-Qiang Li *et al.*, JHEP 1608 (2016) 054

Mode	Partial rate (ps^{-1})
$\bar{b}\to\bar{c}u\bar{d}$	0.310
$\bar{b}\to\bar{c}c\bar{s}$	0.137
$\bar{b}\to\bar{c}e\nu$	0.075
$\bar{b}\to\bar{c}\tau\nu$	0.018
$\Sigma\bar{b}\to\bar{c}$	0.615
$c\to su\bar{d}$	0.905
$c\to se\nu$	0.162
$\Sigma c\to s$	1.229
WA:$\bar{b}c\to c\bar{s}$	0.138
WA:$\bar{b}c\to\tau\nu$	0.056
PI	−0.124
Total	1.914

The constraint of the lifetime of the B_c meson

- Parametric plot (Br($B_c \to \tau\nu$), R_{D^*}) as function of ϵ_P



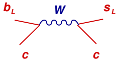
Alonso, Grinstein&JMC,PRL118(2017)081802

τ_{B_c} makes **highly implausible ANY** "scalar solution" (e.g. 2HDM and some leptoquarks) to the R_{D^*} anomaly!

LUV in $b \to s\ell\ell$ decays

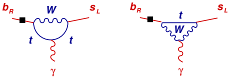
Effective field theory approach to $b \to s\ell\ell$ decays

- **CC** (Fermi theory):

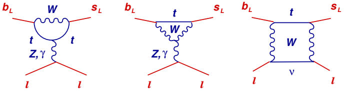


$$\Rightarrow \qquad G_F\, V_{cb}\, V_{cs}^*\, C_2\, \bar{c}_L\gamma^\mu b_L\, \bar{s}_L\gamma_\mu c_L$$

- **FCNC**:

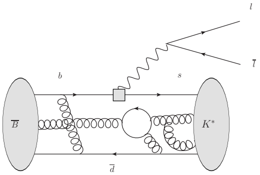


$$\Rightarrow \qquad \frac{e}{4\pi^2}\, G_F\, V_{tb}\, V_{ts}^*\, m_b\, C_7\, \bar{s}_L\sigma_{\mu\nu} b_R\, F^{\mu\nu}$$



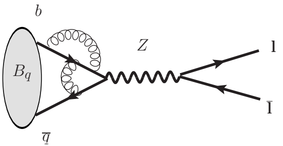
$$\Rightarrow \qquad G_F\, V_{tb}\, V_{ts}^*\, \frac{\alpha}{4\pi}\, C_{9(10)}\, \bar{s}_L\gamma^\mu b_L\, \bar{\ell}\gamma_\mu(\gamma_5)\ell$$

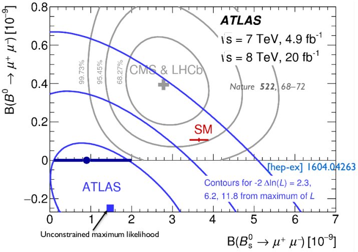
  - **New-Physics** also in C_i or e.g. $\mathcal{O}_i'$ obtained $P_L \to P_R$ in $\bar{s}_L b$



- Light fields active at long distances
  Nonperturbative QCD!
  - Factorization of scales m_b *vs.* $\Lambda_{\rm QCD}$
    HQEFT, QCDF, SCET,...

The beautiful example: $B_q^0 \to \ell\ell$





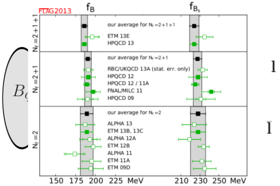
$$\mathcal{B}_{sl} \simeq \frac{G_F^2\alpha^2}{64\pi^3}\tau_{B_s} m_{B_s}^3 f_{B_s}^2 |V_{tb}V_{ts}^*|^2 \times \left\{ |C_S - C_S'|^2 + |C_P - C_P' + 2\frac{m_l}{m_{B_s}}(C_{10} - C_{10}')|^2 \right\}$$

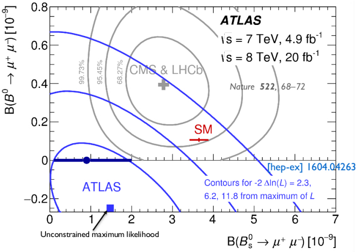
- Decay is chirally suppressed: Very sensitive to (pseudo)scalar operators!
- Semileptonic decay **constants** f_{B_q} can be calculated in LQCD FLAG averages
- Updated predictions:

Bobeth *et al.* PRL112(2014)101801

$$\overline{\mathcal{B}}_{s\mu}^{\rm SM} = 3.65(23) \times 10^{-9}$$
$$\overline{\mathcal{B}}_{s\mu}^{\rm expt} = 2.9(7) \times 10^{-9}$$

The beautiful example: $B_q^0 \to \ell\ell$





$$\mathcal{B}_{s l} \simeq \frac{G_F^2 \alpha^2}{64\pi^3} \tau_{B_s} m_{B_s}^3 f_{B_s}^2 |V_{tb} V_{ts}^*|^2 \times \left\{ |C_S - C_S'|^2 + |C_P - C_P' + 2\frac{m_l}{m_{B_s}}(C_{10} - C_{10}')|^2 \right\}$$

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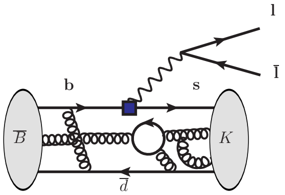
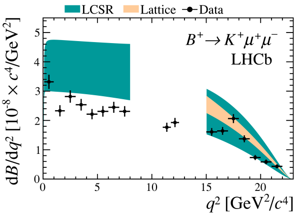
$$\overline{\mathcal{B}}_{s\mu}^{\rm expt} = 2.9(7) \times 10^{-9}$$

A complicated example: $\bar{B} \to \bar{K}^{(*)}\ell^+\ell^-$



LHCb JHEP06(2014)133, JHEP05(2014)082,...



$$\frac{d\Gamma_K}{dq^2} = \mathcal{N}_K |\vec{k}|^3 f_+(q^2)^2 \left(\left|C_{10}^{\ell} + C_{10}^{\prime\ell}\right|^2 + \left|C_9^{\ell} + C_9^{\prime\ell} + 2\frac{m_b}{m_B + m_K} C_7 \frac{f_T(q^2)}{f_+(q^2)} - 8\pi^2 h_K \right|^2 \right) + \mathcal{O}\left(\frac{m_\ell^4}{q^4}\right) + \dots$$

- Phenomenologically richer (3-body decay)
  - **1 angle**: Angular analysis sensitive only to scalar and tensor operators

    Bobeth *et al.*, JHEP 0712 (2007) 040
- **However:** Very complicated nonperturbative problem
  - **3** hadronic form factors (q^2-dependent functions)
  - "Non-factorizable" contribution of 4-quark operators+EM current

R_K

- **QCD interactions are lepton universal***

$$R_K \equiv \frac{\mathrm{Br}\left(B^+ \to K^+ \mu^+ \mu^-\right)}{\mathrm{Br}\left(B^+ \to K^+ e^+ e^-\right)} = 1 + \mathcal{O}(10^{-4})$$

  - * EM corrections are lepton-dependent but at $\sim$ % level Bordone *et al.* EPJC76(2016),8,440

The R_K anomaly LHCb, Phys.Rev.Lett.113(2014)151601

$$\langle R_K \rangle_{[1,6]} = 0.745^{+0.090}_{-0.074}(\mathrm{stat}) \pm 0.036(\mathrm{syst})$$

- 2.6σ discrepancy with the SM $\langle R_K \rangle_{[1,6]} = 1.0003(1)$
- $SU(2)_L \times U(1)_Y$:
  - **No tensors!**
  - **Scalar operators** constrained by $B_s \to \ell\ell$ alone:

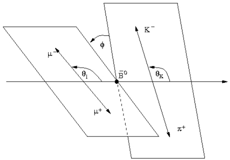
$$R_K \in [0.982, 1.007] \text{ at } 95\% \text{ CL}$$

The effect must come from $\mathcal{O}_{9,10}^{(\prime)}$

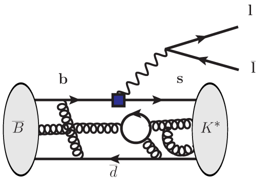
$$R_K \simeq 0.75 \text{ for } \delta C_9^{\mu(\prime)} = -1 \text{ or } \delta C_{10}^{\mu(\prime)} = +1$$

Alonso, Grinstein, JMC, PRL113(2014)241802 (see also Hiller&Schmaltz'14,...)

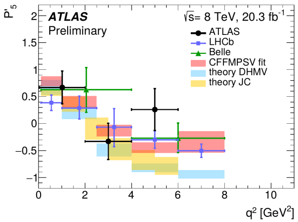
$$\frac{d^{(4)}\Gamma}{dq^2\, d(\cos\theta_l) d(\cos\theta_k) d\phi} = \frac{9}{32\pi}\Big(I_1^s \sin^2\theta_k + I_1^c \cos^2\theta_k$$
$$+ \quad (I_2^s \sin^2\theta_k + I_2^c \cos^2\theta_k)\cos 2\theta_l + I_3 \sin^2\theta_k \sin^2\theta_l \cos 2\phi$$
$$+ \quad I_4 \sin 2\theta_k \sin 2\theta_l \cos\phi + \mathbf{I_5} \sin 2\theta_k \sin\theta_l \cos\phi + I_6 \sin^2\theta_k \cos\theta_l$$
$$+ \quad I_7 \sin 2\theta_k \sin\theta_l \sin\phi + I_8 \sin 2\theta_k \sin 2\theta_l \sin\phi + I_9 \sin^2\theta_k \sin^2\theta_l \sin 2\phi\Big)$$



- Anomalies in the angular observables . . .



LHCb: JHEP 1602 (2016) 104

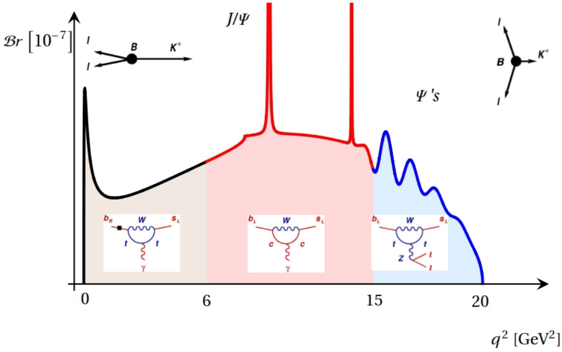


New physics?

$\delta C_9^{\mu} \simeq -1$

Descotes-Genon *et al.* PRD88,074002

- **Not-understood hadronic contributions?**



- **Large-recoil region** (low q^2)
  - **No LQCD** (Sum Rules, models ...) and **QCDf** and **SCET** (power-corrections)
  - Dominant effect of the photon pole
- **Charmonium region**
  - Dominated by long-distance (hadronic) effects
  - Starting at the perturbative $c\bar{c}$ threshold $q^2 \simeq 6 - 7$ GeV^2
- **Low-recoil region** (high q^2)
  - **LQCD**+**HQEFT** + **OPE** (duality violation)
  - Dominated by semileptonic operators

The lepton-universality ratios

Geng *et al.* arXiv: 1704.05446

(see also D'Amico *et al.* 1704.05438, Capdevila *et al.* 1704.05340, Altmannshofer *et al.* arXiv:1704.05435, Ciuchini *et al.* arXiv:1704.05447)

- Use the same trick as for $B \to K\ell\ell$ ...

$$\frac{d\Gamma_K}{dq^2} = \mathcal{N}_K |\vec{k}|^3 f_+(q^2)^2 \left(\left|C_{10}^\ell + C_{10}'^\ell\right|^2 + \left|C_9^\ell + C_9'^\ell + 2\frac{m_b}{m_B+m_K} C_7 \frac{f_T(q^2)}{f_+(q^2)} - 8\pi^2 h_K\right|^2 \right) + \mathcal{O}(\frac{m_\ell^4}{q^4}) + \ldots$$

- ... in $B \to K^*\ell\ell$

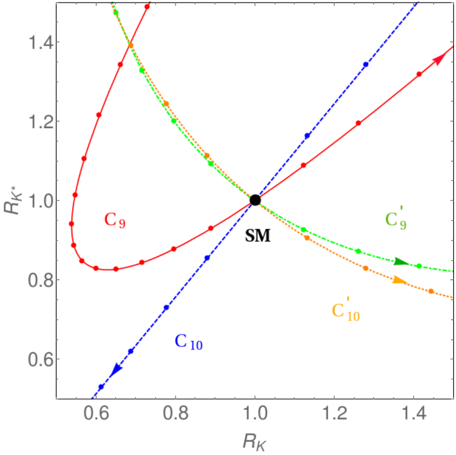
$$R_{K^*} \equiv \frac{\Gamma\left(B^0 \to K^{*0}\mu^+\mu^-\right)}{\Gamma\left(B^0 \to K^{0*}e^+e^-\right)}$$

$$\frac{d\Gamma_0}{dq^2} = \mathcal{N}_{K^*0} |\vec{k}|^3 V_0(q^2)^2 \left(\left|C_{10}^\ell - C_{10}'^\ell\right|^2 + \left|C_9^\ell - C_9'^\ell + \frac{2m_b}{m_B} C_7 \frac{T_0(q^2)}{V_0(q^2)} - 8\pi^2 h_{K^*0}\right|^2 \right) + \mathcal{O}\left(\frac{m_\ell^2}{q^2}\right)$$

$$\frac{d\Gamma_\perp}{dq^2} = \mathcal{N}_{K^*\perp} |\vec{k}| q^2 V_-(q^2)^2 \left(\left|C_{10}^\ell\right|^2 + \left|C_9'^\ell\right|^2 + \left|C_{10}'^\ell\right|^2 + \left|C_9^\ell + \frac{2m_b m_B}{q^2} C_7 \frac{T_-(q^2)}{V_-(q^2)} - 8\pi^2 h_{K^*\perp}\right|^2 \right) + \mathcal{O}\left(\frac{m_\ell^2}{q^2}\right)$$

Wilson coefficients in the SM

$$C_9^{\rm SM}(m_b) \simeq -C_{10}^{\rm SM} = +4.27 \qquad C_7^{\rm SM}(m_b) = -0.333$$



- Parametric dependence of R_K [1, 6] and R_{K^*} [1.1, 6] on the WCs
  - Nodes indicate steps of $\Delta C^\mu = +0.5$

Primed operators $C'_{9,10}$:
Monotonically decreasing dependence $R_{K^*}(R_K)$!

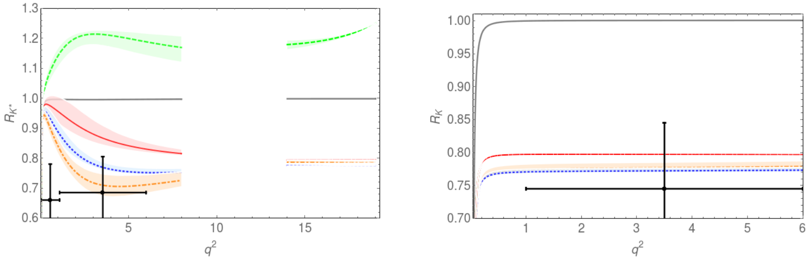


Figure: **SM**; $\delta C_9^\mu = -1$; $\delta C_{10}^\mu = 1$; $\delta C_9^{\prime\mu} = -1$; $\delta C_L^\mu = -0.5$

Obs.	Expt.	SM	$\delta C_L^\mu = -0.5$	$\delta C_9^\mu = -1$	$\delta C_{10}^\mu = 1$	$\delta C_9^{\prime\mu} = -1$
R_K $[1,\ 6]$ GeV^2	0.745 ± 0.090	$1.0004^{+0.0008}_{-0.0007}$	$0.773^{+0.003}_{-0.003}$	$0.797^{+0.002}_{-0.002}$	$0.778^{+0.007}_{-0.007}$	$0.796^{+0.002}_{-0.002}$
R_{K^*} $[0.045,\ 1.1]$ GeV^2	0.66 ± 0.12	$0.920^{+0.007}_{-0.006}$	$0.88^{+0.01}_{-0.02}$	$0.91^{+0.01}_{-0.02}$	$0.862^{+0.016}_{-0.011}$	$0.98^{+0.03}_{-0.03}$
R_{K^*} $[1.1,\ 6]$ GeV^2	0.685 ± 0.120	$0.996^{+0.002}_{-0.002}$	$0.78^{+0.02}_{-0.01}$	$0.87^{+0.04}_{-0.03}$	$0.73^{+0.03}_{-0.04}$	$1.20^{+0.02}_{-0.03}$
R_{K^*} $[15,\ 19]$ GeV^2	–	$0.998^{+0.001}_{-0.001}$	$0.776^{+0.002}_{-0.002}$	$0.793^{+0.001}_{-0.001}$	$0.787^{+0.004}_{-0.004}$	$1.204^{+0.007}_{-0.008}$

Very clean observables!

- Warning: Central Value at ultralow-q^2 is difficult to accommodate with UV physics

Fitting strategy

- We use the following χ^2

$$\tilde{\chi}^2(\vec{C},\ \vec{y}) = \chi^2_{\rm exp}(\vec{C},\ \vec{y}) + \chi^2_{\rm th}(\vec{y})$$

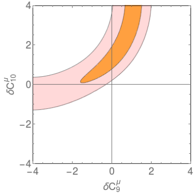
  - $\vec{C}$ vector of Wilson coefficients
  - $\vec{y}$ vector of **27** hadronic parameters
  - $\chi^2_{\rm th}$ depends on estimates of the values and errors of $\vec{y}$, $\chi^2_{\rm th}(\vec{y}) = \sum_i \left(\frac{y_i - \bar{y}_i}{\delta y_i}\right)^2$
- **Profile** over all hadronic uncertainties

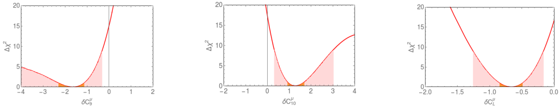
$$\chi^2(\vec{C}) = \min_{\vec{y}} \tilde{\chi}^2(\vec{C}, \vec{y})$$

- We perform **3 fits** to C_9^ℓ and C_{10}^ℓ or combinations thereof
  Do not consider $C_9^{\ell\prime}$ and $C_{10}^{\ell\prime}$
  - **Fit 1**: Only LURs, R_K and R_{K^*} in the two bins
  - **Fit 2** (μ-specific): R_K and R_{K^*} in the two bins and $B_s \to \mu\mu$
  - **Fit 3** (μ-specific): R_K and R_{K^*} in the two bins, $B_s \to \mu\mu$ and **61** measurements of angular observables of $B \to K^* \mu\mu$

Fit 1: Only LUR

- We chose μ-specific for reference (e-specific obtained by $\delta C_i^e \simeq \delta C_i^\mu$)



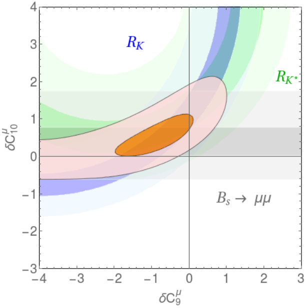


Coeff.	best fit	$\chi^2_{\rm min}$	p-value	SM exclusion $[\sigma]$	1σ range	3σ range
δC_9^μ	-1.64	4.52	0.104	3.87	[-2.31,-1.13]	[<-4, -0.31]
δC_{10}^μ	1.27	2.24	0.326	4.15	[0.91,1.70]	[0.31,3.04]
δC_L^μ	-0.66	2.93	0.231	4.07	[-0.85,-0.49]	[-1.26,-0.16]
Coeff.	best fit	$\chi^2_{\rm min}$	p-value	SM exclusion $[\sigma]$	parameter ranges	
$(\delta C_9^\mu, \delta C_{10}^\mu)$	(0.85, 2.69)	1.99	0.158	3.78	$C_9^\mu \in$ [-0.71, 1.38]	$C_{10}^\mu \in$ [0.61, >4]

- $\chi^2_{\rm SM,min} = 19.51$ (3 d.o.f) which corresponds to a p-value of 2×10^{-4} (3.7σ)
- **Requires C_{10}:** $\chi^2_{\rm min}/\text{d.o.f.} \simeq 1$
  Fit slighty tensed up by ultralow R_{K^*} bin

Fit 2: LUR+$B_s \to \mu\mu$

- **Need to assume NP is μ-specific**



Coeff.	best fit	$\chi^2_{\rm min}$	p-value	SM exclusion [σ]	1σ range	3σ range
δC_9^{μ}	-1.64	5.65	0.130	3.87	[-2.31, -1.12]	[<-4, -0.31]
δC_{10}^{μ}	0.91	4.98	0.173	3.96	[0.66, 1.18]	[0.20, 1.85]
δC_L^{μ}	-0.61	3.36	0.339	4.16	[-0.78, -0.46]	[-1.14, -0.16]
Coeff.	best fit	$\chi^2_{\rm min}$	p-value	SM exclusion [σ]	parameter ranges	
$(\delta C_9^{\mu}, \delta C_{10}^{\mu})$	(-0.76, 0.54)	3.31	0.191	3.76	$C_9^{\mu} \in$ [-1.50, -0.16]	$C_{10}^{\mu} \in$ [0.18, 0.92]

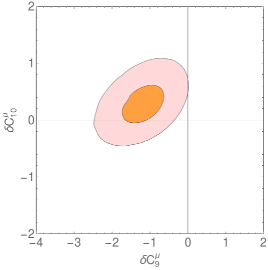
  - **Deviation of the SM**: p-value of 3.7×10^{-4} (3.6σ)
  - Best fit suggests a leptonic left-handed scenario δC_L^{μ}

Fit 3: Global fit

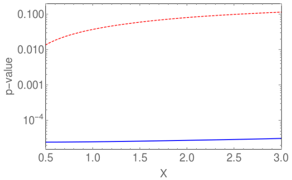
Coeff.	best fit	χ^2_{min}	p-value	SM exclusion [σ]	1σ range	3σ range
δC_9^μ	-1.37	61.98 [64 dof]	0.548	4.37	[-1.70, -1.03]	[-2.41, -0.41]
δC_{10}^μ	0.60	71.72 [64 dof]	0.237	3.06	[0.40, 0.82]	[-0.01, 1.28]
δC_L^μ	-0.59	63.62 [64 dof]	0.490	4.18	[-0.74, -0.44]	[-1.05, -0.16]
Coeff.	best fit	χ^2_{min}	p-value	SM exclusion [σ]	parameter ranges	
$(\delta C_9^\mu, \delta C_{10}^\mu)$	(-1.15, 0.28)	60.33 [63 dof]	0.572	4.17	$C_9^\mu \in$ [-1.54, -0.81]	$C_{10}^\mu \in$ [0.06, 0.50]

- The best fit is now driven by δC_9^μ!
- **However:** Remember that C_9 is subjet to severe hadronic uncertainties!

- Results in the $(\delta C_9^\mu,\ \delta C_{10}^\mu)$ plane



- *"Robustness"* studies (work in progress)



★ p-value of the SM in **Fit 1** and **Fit 3** as a function of x = *"factor by which I multiply all hadronic uncertainties"*

Precision probes of lepton nonuniversal $C^{\ell}_{9,10}$

- Go to the angular analysis of $B \to K^* \ell\ell$...

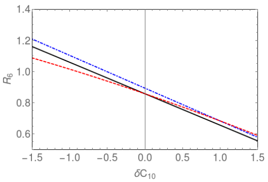
$$I_6^{(\ell)} = N C^{\ell}_{10} q^2 \beta_\ell^2(q^2)|\vec{k}| \left(\mathrm{Re}[H^{(\ell)}_{V-}(q^2)] V_-(q^2) + \mathrm{Re}[H^{(\ell)}_{V+}(q^2) \frac{H^{(\ell)}_{A+}(q^2)}{C^{\ell}_{10}}] \right)$$

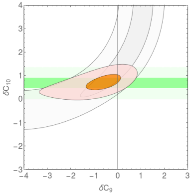
  - The $H_{V,A+}$ amplitudes are suppressed unles we have primed operators!

$$R_6[a,b] = \frac{\int_a^b \Sigma_6^\mu dq^2}{\int_a^b \Sigma_6^e dq^2} \approx \frac{C^\mu_{10}}{C^e_{10}} \times \frac{\int_a^b |\vec{k}| q^2 \beta_\mu^2 \, \mathrm{Re}[H^{(\mu)}_{V-}(q^2)] V_-(q^2)}{\int_a^b |\vec{k}| q^2 \, \mathrm{Re}[H^{(e)}_{V-}(q^2)] V_-(q^2)}$$

  - At low q^2 the red in R_6 is dominated by the photon pole and lepton universal!

R_6 is an optimal C_{10} LUV analyser!





- Combined sensitivity to C_9 and C_{10}
- Prospects with a 5% precision

Conclusions

"Extraordinary claims require Extraordinary evidence"

– C. Sagan

1. **"Evidence" for lepton universality violation in $b \to c\ell\nu$**
   - Different measurements by different experiments deviating at 4σ
   - Future: Angular analyses and new channels (τ and primary decay)
   - **New Physics interpretation**
     - ★ $R_{D^{(*)}}$, lifetime of B_c, P_L^* and theoretical considerations suggest:

$$\epsilon_L = 0.13$$

2. **"Evidence" for lepton universality violation in $b \to s\ell\ell$**
   - 3 single LUR measurements deviating at $2.0\sigma - 2.5\sigma$ each
   - Collectively point to a 4σ tension of the data with LUV (SM)
   - **Clean** observables prefer C_{10}^{ℓ}-type of scenario
   - **Global fits** pull the NP into C_9-type of scenario
     - ★ More LUV observables needed! (*viz* R_6)

Backup

Anatomy of the amplitude in a nutshell

Jäger and JMC, PRD93 (2016) no.1, 014028

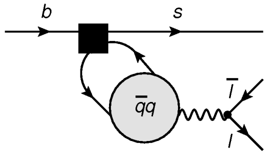
- Helicity amplitudes $\lambda = \pm 1, 0$

$$H_V(\lambda) = -iN\Big\{ \overbrace{\Big[C_9 \tilde{V}_{L\lambda} + \frac{m_B^2}{q^2} h_\lambda \Big]}^{C_9^{\rm eff}} - \frac{\hat{m}_b m_B}{q^2} C_7 \tilde{T}_{L\lambda} \Big\},$$

$$H_A(\lambda) = -iN C_{10} \tilde{V}_{L\lambda}, \qquad H_P = iN \frac{2\, m_l \hat{m}_b}{q^2} C_{10} \Big(\tilde{S}_L + \frac{m_s}{m_b} \tilde{S}_R \Big)$$

- Hadronic form factors: **7** independent q^2-dependent nonperturbative functions

"Charm" contribution



$$h_\lambda \propto \int d^4 y e^{iq\cdot y} \langle \bar{K}^* | T\{ j^{\rm em,had,\mu}(y), \mathcal{O}_{1,2}(0)\} | \bar{B} \rangle$$

- Charm and $\mathcal{O}_9$ are tied up by renormalization

Only $C_9^{\rm eff}$ is observable!