The shape of (new) physics in the *B* decay anomalies

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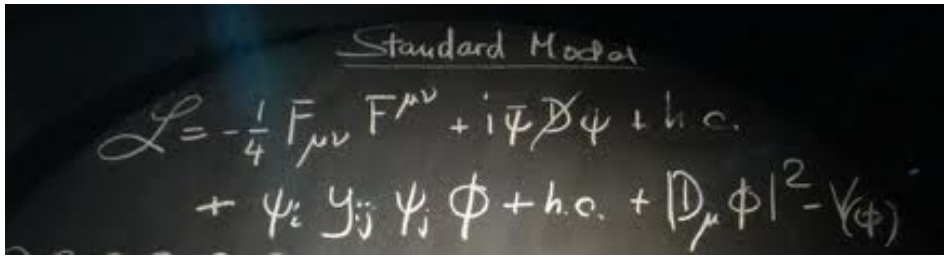
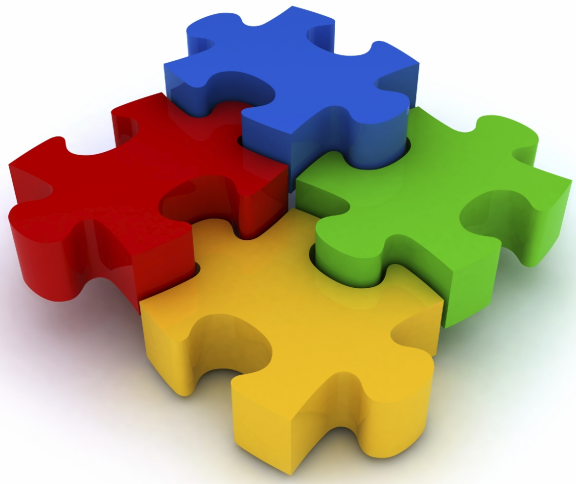
CERN

13th of January 2017



The **Standard Model** **very sucessfully** describes particle physics experiments



However there are **theoretical puzzles** . . .

- Origin of EW scale and hierarchy problem
- Not enough $\not{CP}$ (strong CP problem)
- Dark matter
- Hierarchies in flavor
- . . .

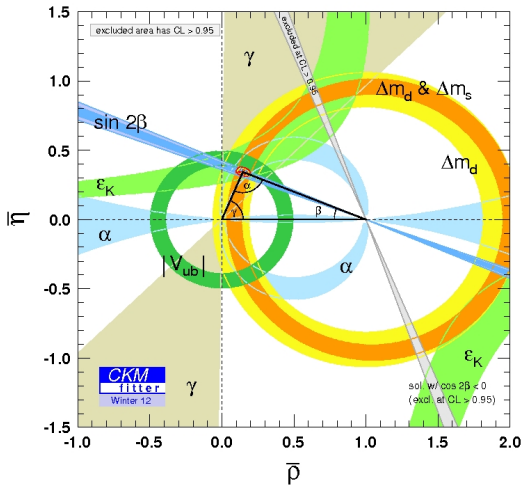
Answering these questions require physics beyond the SM

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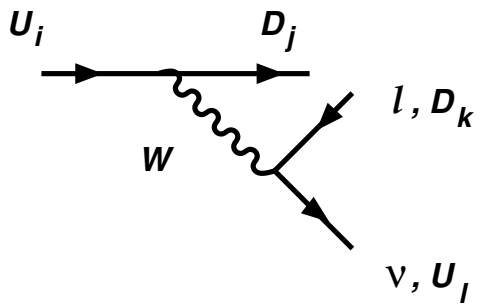
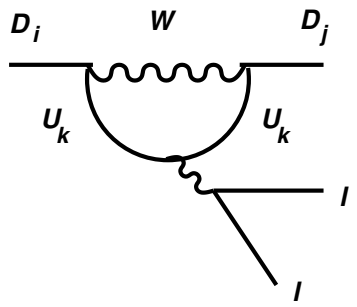
- **CC $U_i \to D_j$: Tree level**



- $\mathcal{M} \sim G_F\, V_{ij} U_{kl}^*$,
  $V_{ij} U_{kl}^*$ can be $\mathcal{O}(1)$

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



- $\mathcal{M} \sim G_F \sum_k V_{ki} V_{kj}^* \frac{m_K^2}{m_W^2} \frac{\alpha}{4\pi}$,
  GIM and **loop** suppression

- In the SM, FCNCs are suppressed w.r.t. CC interactions: **"Rare" decays!**

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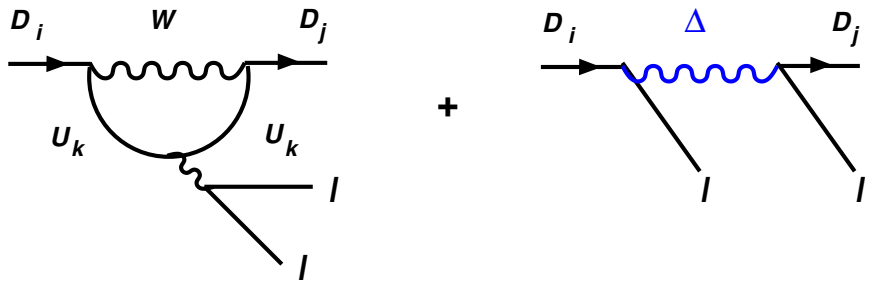
$$-\mathcal{L}_Y = \bar{q}_L Y_d d_R H + \bar{q}_L Y_u u_R \tilde{H} + \bar{\ell}_L Y_e e_R H + h.c.$$

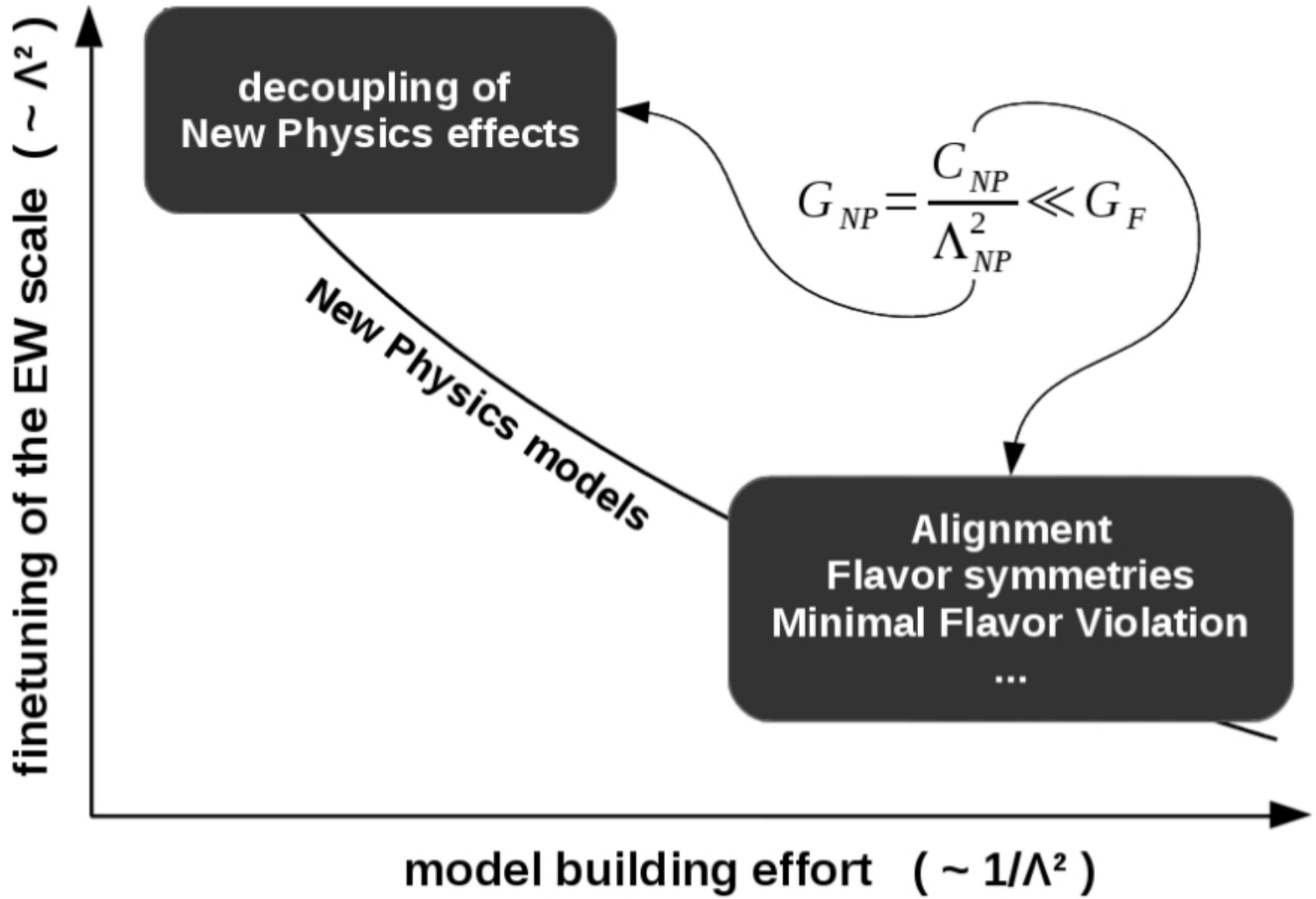
- **FCNC** $b \to s$: Very sensitive to exchange of new particles



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

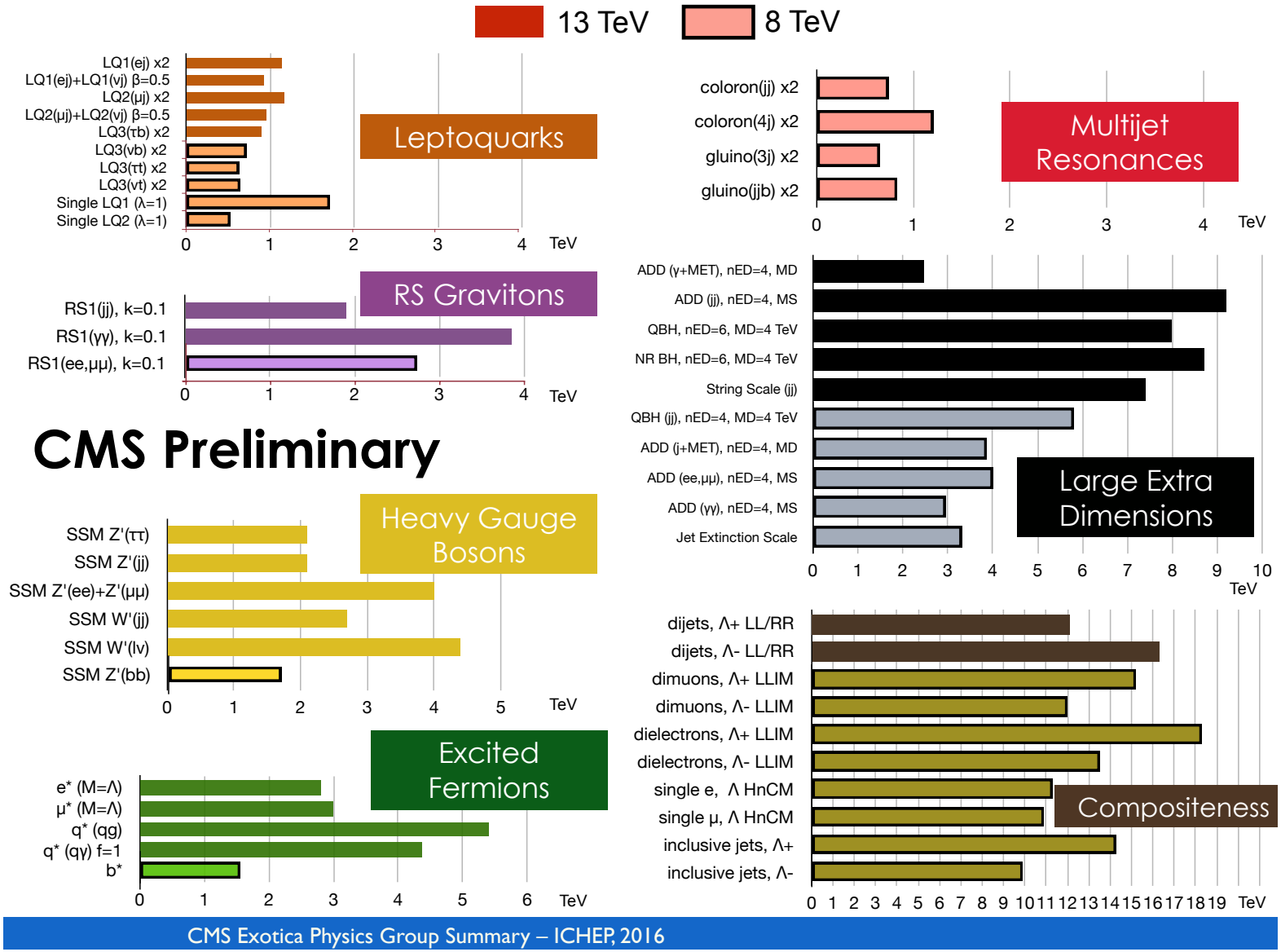
Rare b decays sensitive to $M \sim 100$ TeV !!

Approaches to the New Physics Flavor Puzzle



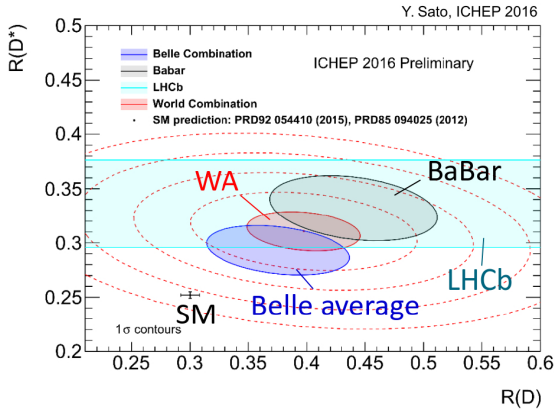
- No **New Physics** at colliders ...

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



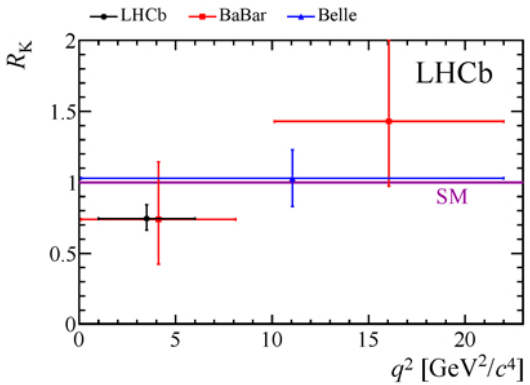
(Lepton universality violating) New-Physics in B decays?

- **"$R_{D^{(*)}}$ anomaly"** in $B \to D^{(*)}\ell\nu$!



- **"R_K anomaly"** in $B \to K\ell\ell$ (**FCNC**)!

LHCb PRL113(2014)151601



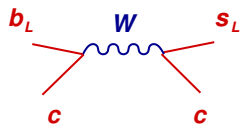
- ***Excesses*** observed at $\sim 4\sigma$
- Other "anomalies" in $b \to (u, c)\ell\nu$
  - Inclusive *vs.* Exclusive V_{ub} and V_{cb}
- $\Lambda_{\rm NP} \sim 2$ TeV

- Tension with **SM** $\sim 2.6\sigma$
- Other anomalies in $b \to s\mu\mu$
  - Branching fractions
  - Angular analysis $B \to K^*\mu\mu$
- Up to 4σ in global fits
- $\Lambda_{\rm NP} \sim 10$ TeV

- **Anomalies addressed in many models of NP**

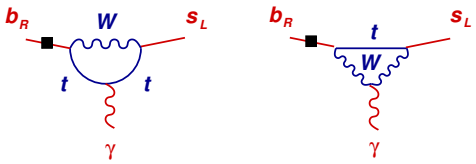
Effective field theory approach to $b \to s\ell\ell$ decays

- **CC** (Fermi theory):

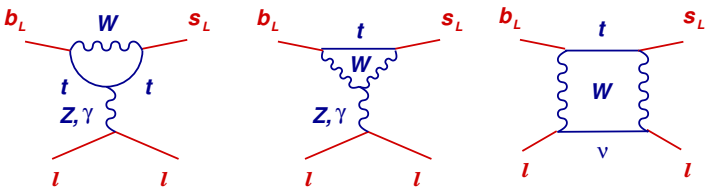


$$\Rightarrow \qquad G_F\, V_{cb}\, V_{cs}^*\, C_2\, \bar{c}_L \gamma^\mu b_L\, \bar{s}_L \gamma_\mu c_L$$

- **FCNC**:

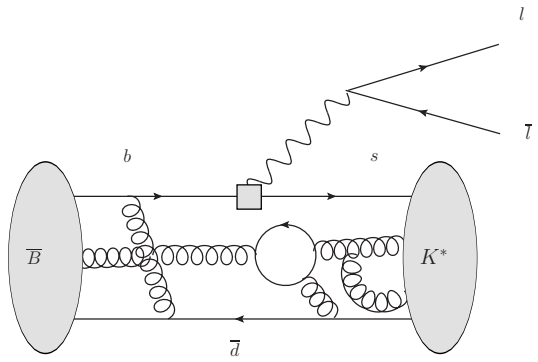


$$\Rightarrow \qquad \frac{e}{4\pi^2}\, G_F\, V_{tb}\, V_{ts}^*\, m_b\, C_7\, \bar{s}_L \sigma_{\mu\nu} b_R\, F^{\mu\nu}$$



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

- Wilson coefficients $C_k(\mu)$ calculated in P.T. at $\mu = m_W$ and rescaled to $\mu = m_b$



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

Effective field theories: Bottom-up approach to new physics

Guiding principle

Construct the most general effective operators $\mathcal{O}_k$ made of $\phi \in u, d, s, c, b, l, \nu, F_{\mu\nu}$ and subject to the strictures of $SU(3)_c \times U(1)_{em}$

- New physics manifest at the operator level through. . .
  - Different values of the Wilson coefficients $C_i^{\text{expt.}} = C_i^{\text{SM}} + \delta C_i$
  - New operators absent or very suppressed in the SM
    - ★ New chirally-flipped operators

$$\mathcal{O}_7' = \frac{4G_F}{\sqrt{2}} \frac{e}{4\pi^2} \hat{m}_b \, \bar{s}\sigma_{\mu\nu} P_L F^{\mu\nu} b; \qquad \mathcal{O}_{9(10)}' = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} \, \bar{s}\gamma^\mu P_R b \, \bar{\ell}\gamma_\mu(\gamma_5)\ell$$

    - ★ **4** new scalar and pseudoscalar operators

$$\mathcal{O}_S^{(\prime)} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} \, (\bar{s}P_{R,L} b) \, (\bar{\ell}\,\ell); \qquad \mathcal{O}_P^{(\prime)} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} \, (\bar{s}P_{R,L} b) \, (\bar{\ell}\,\gamma_5\,\ell)$$

    - ★ **2** new tensor operators

$$\mathcal{O}_{T(5)} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} \, (\bar{s}\sigma^{\mu\nu} b) \, (\bar{\ell}\,\sigma_{\mu\nu}(\gamma_5)\ell).$$

  - The Wilson coefficients can be complex and introduce new sources of $\not{CP}$

- But hold on...
  - No evidence of new-particles *on-shell* at colliders up to $E \simeq 1$ TeV...
    ...except a scalar at $s \simeq 125$ GeV that very much resembles to the SM Higgs

Guiding principle *(rewritten)*

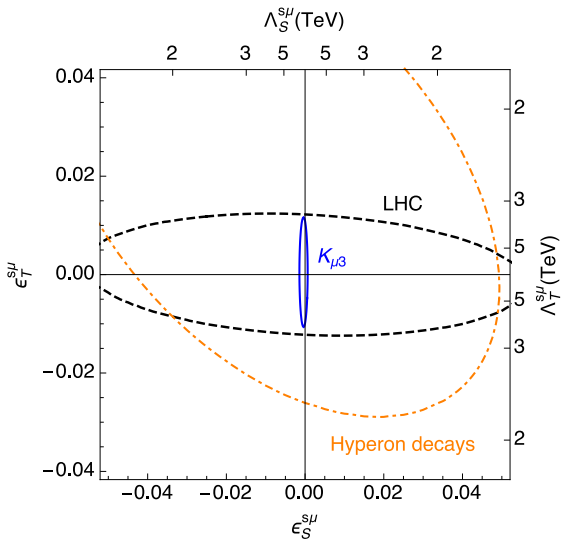
Construct the most general effective operators $\mathcal{O}_k$ built with ***all*** the SM fields and subject to the strictures of $SU(3)_c \times SU(2)_L \times U(1)_Y$

Buchmuller *et al.*'86,Grzadkowski *et al.*'10

- **Example:** Application to searches of NP in $s \to u\ell\nu$ charged-current decays

Cirigliano *et al.*'09'10,

$$\mathcal{L}_{\rm c.c.} \supset -\frac{G_F V_{us}}{\sqrt{2}} \Big[\epsilon_S (\bar{u}\, s)\, (\bar{e}(1-\gamma_5)\nu_e) + \epsilon_T (\bar{u}\sigma^{\mu\nu} s)\, (\bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_e) \Big]$$



- Complementary between hyperon rates and LHC
- Bounds set of NP at $\Lambda_{\rm NP} \sim$ **4-10 TeV**

Chang, Gonzalez-Alonso and JMC, PRL114(2015)161802

Gonzalez-Alonso and JMC, arXiv 1605.07114

Relations in FCNCs with dimension-6 operators

Fields	q_L	ℓ_L	u_R	d_R	e_R
Y	1/6	-1/2	2/3	-1/3	-1

- For **scalar** and **tensor** operators $\Gamma = \mathbb{I}, \sigma_{\mu\nu}$ we only have:

$$\frac{1}{\Lambda^2}(\bar{q}_L^a \Gamma d_R)(\bar{e}_R \Gamma \ell_L^a) \qquad \frac{1}{\Lambda^2}\varepsilon^{ab}(\bar{q}_L^a \Gamma u_R)(\bar{\ell}_L^b \Gamma e_R)$$

- Furthermore:

$$(\bar{d}_j \sigma_{\mu\nu} P_R d_i)(\bar{\ell}\sigma^{\mu\nu} P_L \ell) = 0$$

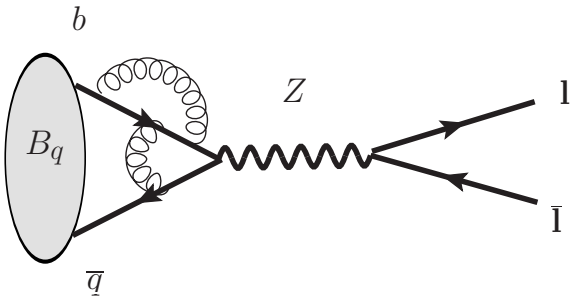
Constraints in $b \to s\ell\ell$ up to $\mathcal{O}(v^2/\Lambda^2)$

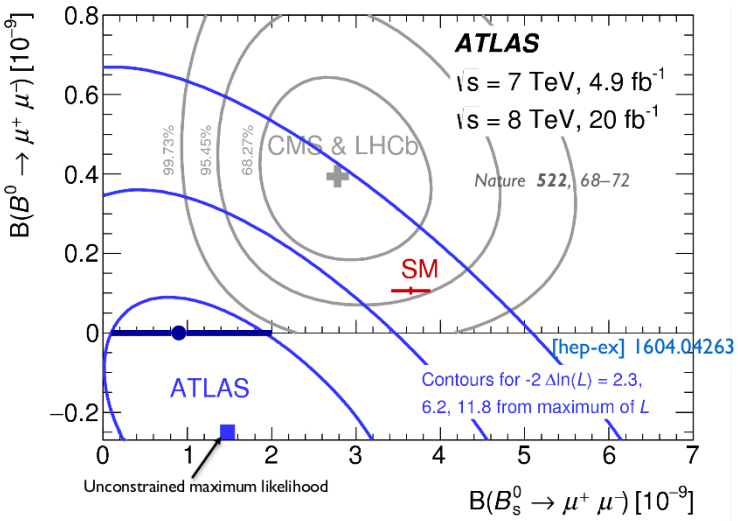
- From **4** scalar operators to only **2**!
- From **2** tensor operators to **none**!

Alonso, Grinstein, JMC, PRL113(2014)241802

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

$B_q^0 \to \ell\ell$





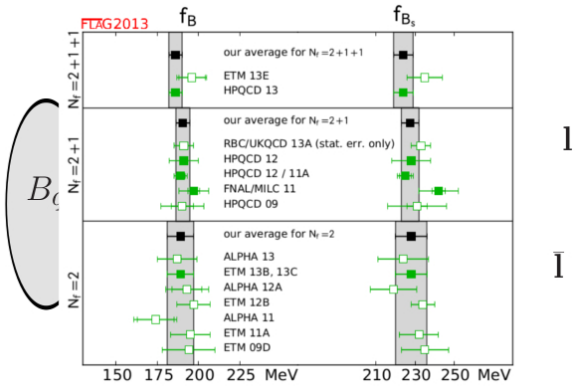
$$\mathcal{B}_{sl} \simeq \frac{G_F^2\alpha^2}{64\pi^3}\tau_{B_s} m_{B_s}^3 f_{B_s}^2 |V_{tb}V_{ts}^*|^2 \times \left\{ |C_S - C_S'|^2 + |C_P - C_P' + 2\frac{m_l}{m_{B_s}}(C_{10} - C_{10}')|^2 \right\}$$

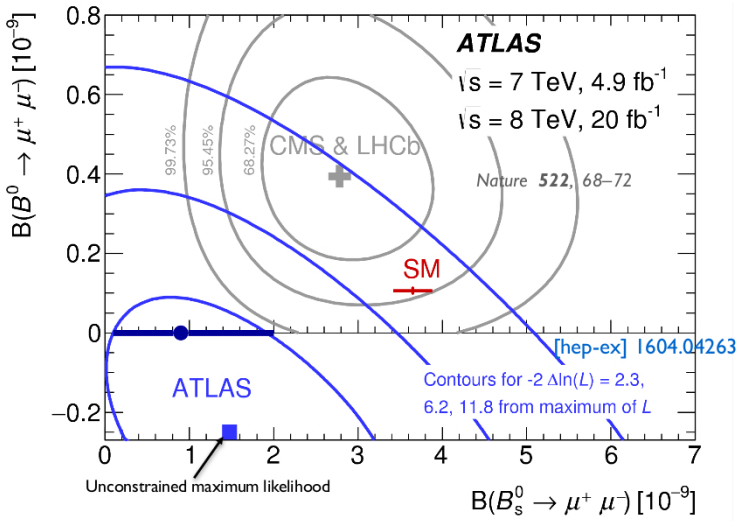
- Decay is chirally suppressed: Very sensitive to (pseudo)scalar operators!
- Semileptonic decay **constants** f_{B_q} can be calculated in LQCD FLAG averages
- Updated predictions:

Bobeth *et al.* PRL112(2014)101801

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

$B_q^0 \to \ell\ell$





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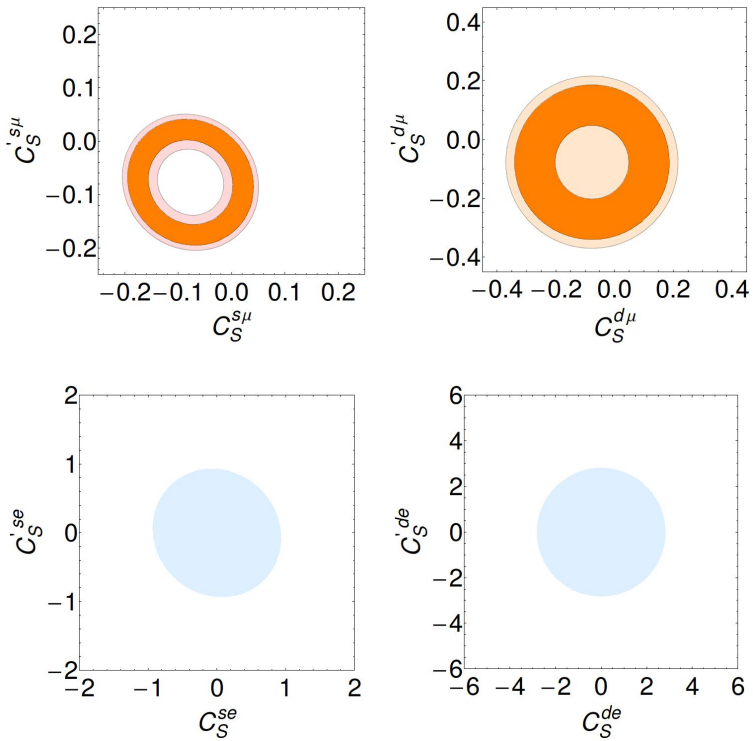
Phenomenological consequences of $SU(2) \times U(1)$ in $B_q \to \ell\ell$

$$\overline{R}_{ql} = \frac{\overline{\mathcal{B}}_{ql}}{\left(\overline{\mathcal{B}}_{ql}\right)_{\rm SM}} \simeq \left(|S|^2 + |P|^2\right),$$

$$S = \frac{m_{B_q}}{2m_l}\frac{m_{B_q}}{m_b + m_q}\frac{C_S - C'_S}{C_{10}^{\rm SM}}, \qquad P = \frac{C_{10} - C'_{10}}{C_{10}^{\rm SM}} - \frac{m_{B_q}}{2m_l}\frac{m_{B_q}}{m_b + m_q}\frac{C_S + C'_S}{C_{10}^{\rm SM}}$$



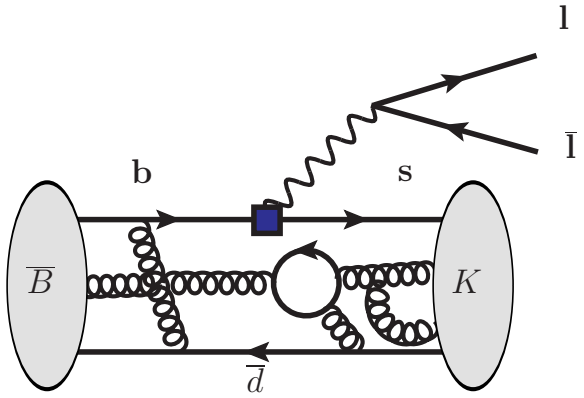
- $\Lambda_{\rm NP}$ (95%C.L.) RGE of QCD+EW+Yukawas

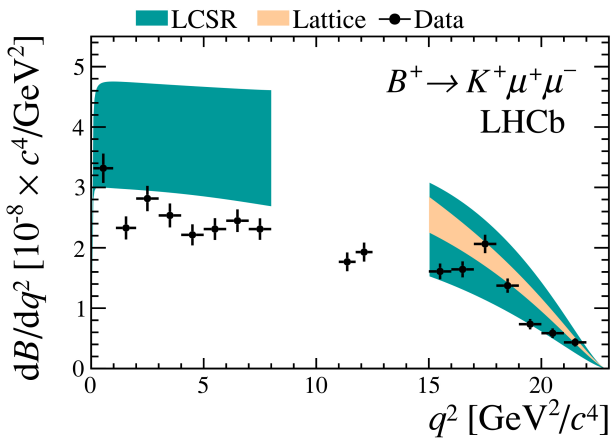
Channels	$s\mu$	$d\mu$	se	de
$C_S^{(\prime)}(m_W)$	0.1	0.15	0.6	1.5
Λ [TeV]	79	130	36	49

Alonso, Grinstein, JMC, PRL113(2014)241802

$B \to K\ell\ell$

LHCb JHEP06(2014)133, JHEP05(2014)082,PRL111 (2013)112003,...





$$\frac{d\Gamma}{dq^2} = \frac{G_F^2\,\alpha^2\,|V_{tb}V_{ts}^*|^2}{1536\pi^5}\, f_+^2 \left(\left| C_9 + C_9' + 2\frac{\mathcal{T}_K}{f_+} \right|^2 + \left| C_{10} + C_{10}' \right|^2 \right) + \mathcal{O}\left(\frac{m_\ell^4}{q^4}\right)$$

- Phenomenologically richer (3-body decay)
  - Decay rate is a function of dilepton invariant mass $q^2 \in [4m_\ell^2, (m_B - m_K)^2]$
  - **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 in $SU(2) \times U(1)$

- Then in the SM for $q^2 \gtrsim 1$ GeV^2

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

The R_K anomaly

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

LHCb, Phys.Rev.Lett.113(2014)151601

- 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:

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

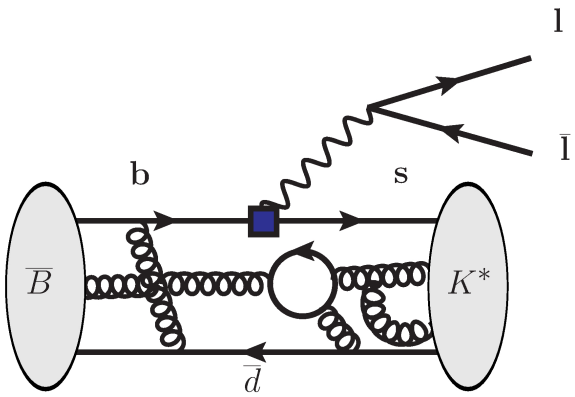
The effect must come from $\mathcal{O}^{(\prime)}_{9,10}$

$$R_K \simeq 0.75 \text{ for } \delta C_9^\mu = -1$$

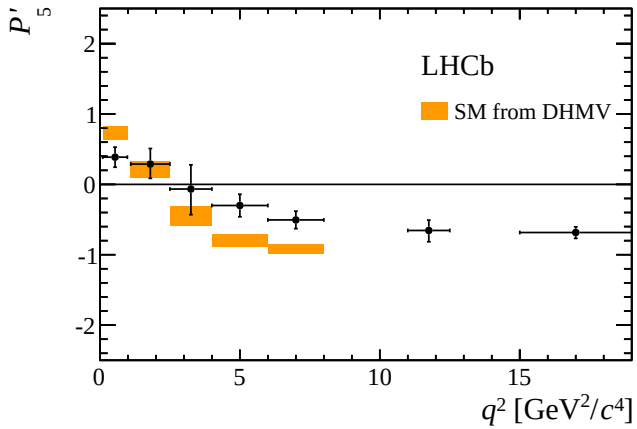
Alonso, Grinstein, JMC, PRL113(2014)241802 (see also Hiller&Schmaltz'14,...)

$\bar{B} \to \bar{K}^* \ell^+ \ell^-$

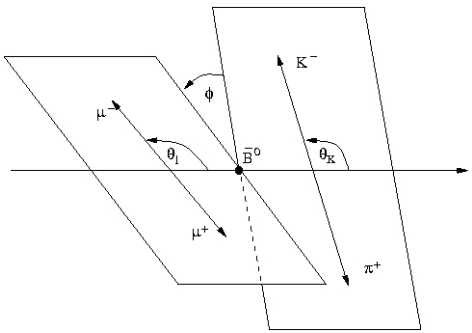
LHCb, JHEP 1602 (2016) 104, (see also Belle, arXiv:1604.04042)



Descotes-Genon *et al.* JHEP 1412 (2014) 125



- **4-body decay**



$$\frac{d^{(4)}\Gamma}{dq^2\, d(\cos\theta_l) d(\cos\theta_k) d\phi} = \frac{9}{32\pi} \left(I_1^s \sin^2\theta_k + I_1^c \cos^2\theta_k \right.$$

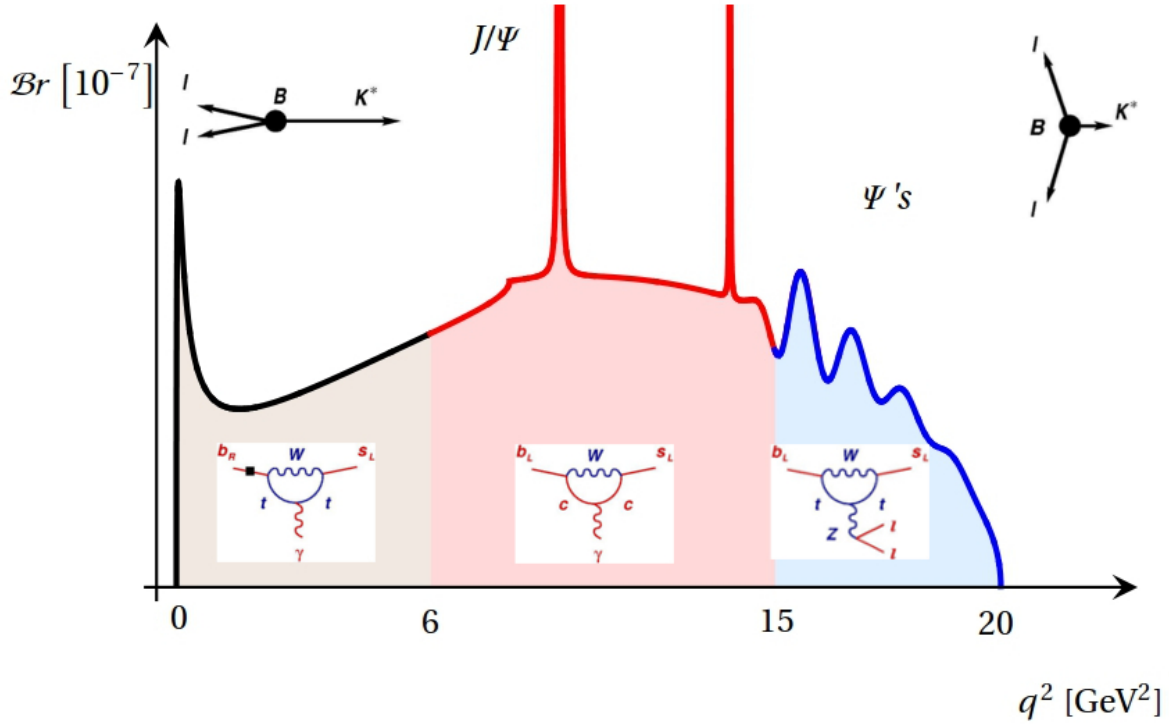
$$+ \quad (I_2^s \sin^2\theta_k + I_2^c \cos^2\theta_k) \cos 2\theta_l + I_3 \sin^2\theta_k \sin^2\theta_l \cos 2\phi$$

$$+ \quad I_4 \sin 2\theta_k \sin 2\theta_l \cos\phi + \mathbf{I_5} \sin 2\theta_k \sin\theta_l \cos\phi + I_6 \sin^2\theta_k \cos\theta_l$$

$$\left. + \quad I_7 \sin 2\theta_k \sin\theta_l \sin\phi + I_8 \sin 2\theta_k \sin 2\theta_l \sin\phi + I_9 \sin^2\theta_k \sin^2\theta_l \sin 2\phi \right)$$

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

Descotes-Genon *et al.* PRD88,074002



- **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

Connecting theory to experiment: The helicity amplitudes

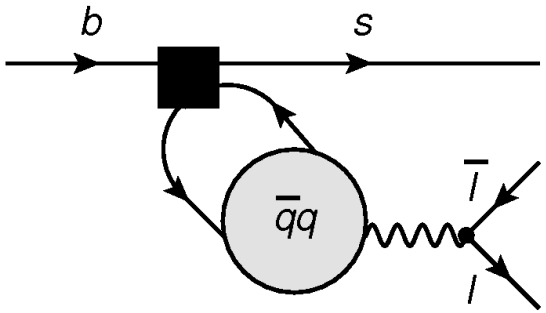
- Helicity amplitudes $\lambda = \pm 1, 0$

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

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

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

"Charm" contribution



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

- Charm and $\mathcal{O}_9$ are tied up by renormalization
  Only $C_9^{\rm eff}$ is observable!

Description at low q^2 using QCD factorization

- **Heavy-quark** and **large-recoil** (K^*) limit only **2** independent "soft form factors"

$$T_+ = V_+ = 0, \qquad T_- = V_- = \frac{2E}{m_B}\xi_\perp, \qquad T_0 = V_0 = S = \xi_\parallel$$

Dugan *et al.* PLB255(1991)583, Charles *et al.* PRD60(1999)014001

- The observable P_5' Matias *et al.*'12

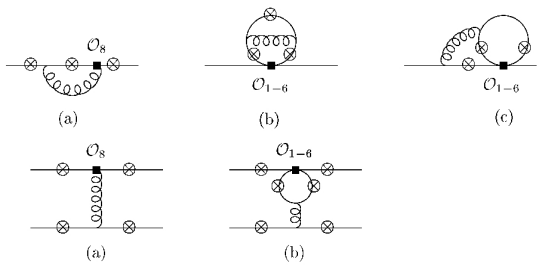
$$P_5'|_\infty = \frac{I_5}{2\sqrt{-I_{2s}I_{2c}}} \simeq \frac{C_{10}\left(C_{9,\perp}+C_{9,\parallel}\right)}{\sqrt{(C_{9,\parallel}^2+C_{10}^2)(C_{9,\perp}^2+C_{10}^2)}},$$

$$\begin{cases} C_{9,\perp} = C_9^{\rm eff}(q^2) + \dfrac{2\,m_b\,m_B}{q^2}\,C_7^{\rm eff} \\ C_{9,\parallel} = C_9^{\rm eff}(q^2) + \dfrac{2\,m_b\,E}{q^2}\,C_7^{\rm eff} \end{cases}$$

- For the charm Beneke, Feldmann&Seidel, NPB612(2001)25

$$\langle \ell^+\ell^- \bar{K}_a^* | \mathcal{H}_{\rm w} | \bar{B}\rangle = C_a\xi_a + \Phi_B \otimes T_a \otimes \Phi_{K^*} + \mathcal{O}(\Lambda_{\rm QCD}/m_b)$$

Below $c\bar{c}$ threshold! $q^2 \leq 6$ GeV^2



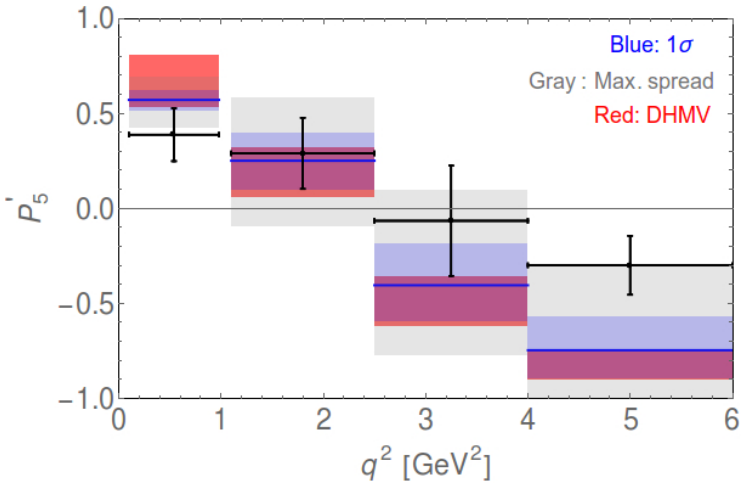
No model-independent treatment for Λ/m_b corrections

$$P_5' = P_5'|_\infty \left(1 + \frac{a_{V_-} - a_{T_-}}{\xi_\perp} \frac{m_B}{|\vec{k}|} \frac{m_B^2}{q^2} C_7^{\text{eff}} \frac{C_{9,\perp} C_{9,\parallel} - C_{10}^2}{(C_{9,\perp}^2 + C_{10}^2)(C_{9,\perp} + C_{9,\parallel})} + \frac{a_{V_0} - a_{T_0}}{\xi_\parallel} 2\, C_7^{\text{eff}} \frac{C_{9,\perp} C_{9,\parallel} - C_{10}^2}{(C_{9,\parallel}^2 + C_{10}^2)(C_{9,\perp} + C_{9,\parallel})} \right.$$

$$\left. + 8\pi^2 \frac{\tilde{h}_-}{\xi_\perp} \frac{m_B}{|\vec{k}|} \frac{m_B^2}{q^2} \frac{C_{9,\perp} C_{9,\parallel} - C_{10}^2}{C_{9,\perp} + C_{9,\parallel}} + \ldots \right) + \mathcal{O}(\Lambda^2/m_B^2)$$

Jäger and JMC, PRD93(2016)no.1,014028

- **Predictions** for $P_i^{(\prime)}$ observables strongly depend on theoretical assumptions

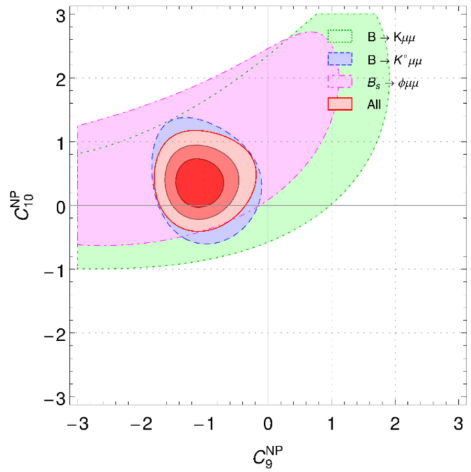


Better understanding of had. uncert. desirable!

- **Use models of QCD, sum rules, etc ...?**
- **Charm under control?** Lyon&Zwicky arXiv:1406.0566, Ciuchini *et al.* arXiv:1512.07157

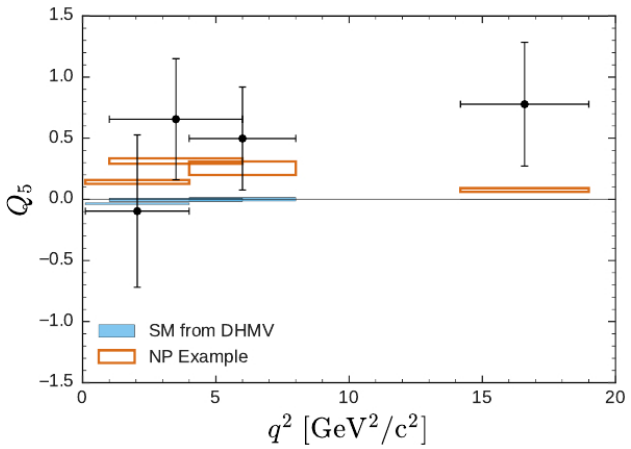
Global fits and future prospects on LUV

- **Global fits:** Data to be at odds with the SM at 4σ (modulo **th. assumptions!**)
  - Consistent tension from different decays
  - Different QCD uncertainties!
  - Compeling reason for NP?



Descotes-Genon *et al.* JHEP06,092 (also Hurth *et al.* NPB909,737)

- Signals of **LUV** would be clearly NP!
  - Long-awaited analysis of R_{K*}
  - Analysis of R_ϕ (less statistics)
  - Re-analysis of R_K
  - Angular analysis μ vs. e



Belle arXiv:1612.05014

The shape of the (new) physics

Let's assume R_K and P_5' are NP

$$\delta C_9^\mu = -\delta C_{10}^\mu = -0.5$$
$$\delta C_9^e = \delta C_{10}^e = 0$$

- Only 2 dim-6 $SU(2)_L \times U(1)_Y$-invariant operators

$$Q_{\ell q}^{(1)} = \frac{1}{\Lambda^2}(\bar{q}_L \gamma^\mu q_L)(\bar{\ell}_L \gamma_\mu \ell_L) \qquad Q_{\ell q}^{(3)} = \frac{1}{\Lambda^2}(\bar{q}_L \gamma^\mu \vec{\tau} q_L) \cdot (\bar{\ell}_L \gamma_\mu \vec{\tau} \ell_L)$$

1. **Lepton Universality Violation $\Rightarrow$ Lepton flavor Violation**?
2. **Operators with $SU(2)_L$ quark doublets**
   - FCNC with neutrinos and/or up quarks
   - $V - A$ Contributions CC ($b \to c\ell\bar{\nu}$, $t \to b\bar{\ell}\nu \ldots$)

Lepton flavor symmetries in the SM

$$SU(3)_\ell \times SU(3)_e \times U(1)_L \times U(1)_{e-\ell}\,, \qquad \ell_L \sim (3,1)_{1,-1}\,, \qquad e_R \sim (1,3)_{1,1}$$

Broken **only** by the Yukawas in the SM

$$-\mathcal{L}_Y \supset \epsilon_e\, \bar{\ell}_L \hat{Y}_e e_R H + h.c., \qquad (Y_e = \epsilon_e\, \hat{Y}_e,\ \ \mathrm{tr}(\hat{Y}_e\, \hat{Y}_e^\dagger) = 1)$$

$U(1)_\tau \times U(1)_\mu \times U(1)_e$ survives

- **However:** Any new source of flavor violation will lead to LF violation...

  Glashow *et al.* PRL114(2015)091801, Bhattacharya *et al.* arXiv:1505.04692, Lee *et al.* arXiv:1505.04692

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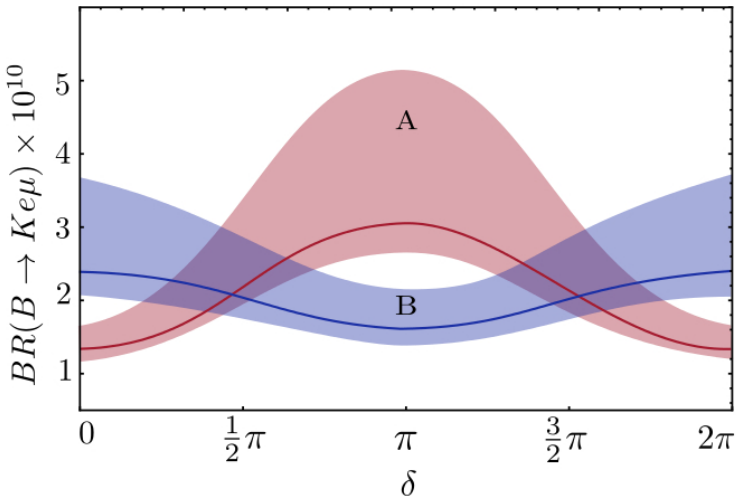
LFV in $b \to s\ell\ell'$!!

$$\begin{aligned}
\mathrm{BR}(B \to K e^\pm \mu^\mp) &\in [1.2, 1.7] \times 10^{-10} \\
\mathrm{BR}(B \to K e^\pm \tau^\mp) &\in [1.9, 5.8] \times 10^{-10} \\
\mathrm{BR}(B \to K \mu^\pm \tau^\mp) &\in [3.4, 7.2] \times 10^{-9}\,.
\end{aligned}$$



Boucenna *et al.* arXiv:1503.07099

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  Glashow *et al.* PRL114(2015)091801, Bhattacharya *et al.* arXiv:1505.04692, Lee *et al.* arXiv:1505.04692

- ...unless it is "aligned" with the Yukawas (e.g. Crivellin *et al.* PRL114(2015)151801, Celis *et al.* arXiv:1505.03079)

Minimal flavor violation

The only source of lepton flavor structure in the new physics *are* the Yukawas

Chivukula *et al*'87s, D'Ambrosio *et al*'02, Cirigliano *et al*'05

Introduce spurions $\hat{Y}_e \sim (3, \bar{3})$ and $\epsilon_e \sim (-1, 1)$

Alonso, Grinstein and JMC JHEP 1510 (2015) 184

$$\mathcal{L}^{\rm NP} = \frac{1}{\Lambda^2}\left[(\bar{q}'_L\, C_q^{(1)}\gamma^\mu q'_L)(\bar{\ell}'_L\, \hat{Y}_e\, \hat{Y}_e^\dagger \gamma_\mu \ell'_L) + (\bar{q}'_L\, C_q^{(3)}\gamma^\mu \vec{\tau} q'_L)\cdot(\bar{\ell}'_L\, \hat{Y}_e\, \hat{Y}_e^\dagger \gamma_\mu \vec{\tau} \ell'_L)\right]$$

Hierarchic leptonic couplings (no LFV)

Interactions $\sim \delta_{\alpha\beta} m_\alpha^2 / m_\tau^2$

1. **Boost of 10^3 in $b \to s\tau\tau$!**

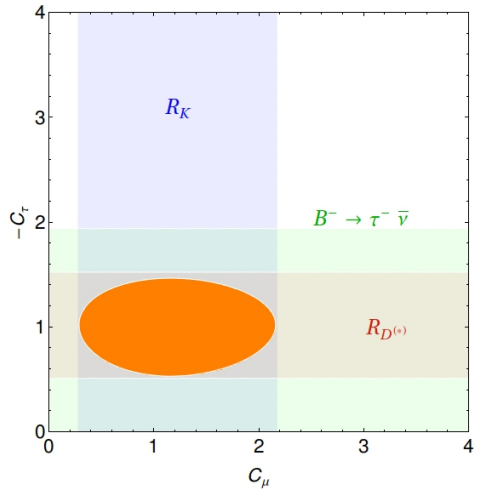
$$\mathcal{B}(B \to K\tau^-\tau^+) \simeq 2\times 10^{-4}, \qquad \mathcal{B}(B^+ \to K^+\tau\tau)^{\rm expt} < 3.3\times 10^{-3}$$

2. **Very strong constraint from $b \to s\nu_\tau\nu_\tau$**
3. **Sizable effects in CC tauonic B decays!**

$$R_{D^{(*)}} = \frac{\mathcal{B}(\bar{B}\to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(\bar{B}\to D^{(*)}\ell\bar{\nu}_\ell)}$$

	SM	Expt.
R_D	0.297(17)	0.421(58)
R_{D^*}	0.252(3)	0.337(25)

- **Can be realized with a class of vector leptoquarks $M_{LQ} \simeq 3$ TeV**



Alonso, Grinstein, JMC JHEP 1510 (2015)

The $b \to c\tau\nu$ anomalies

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

- Define lepton-universality ratios:

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

- Low-energy effective Lagrangian (no RH ν)

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

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

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

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

      - ☛ **RHC is lepton universal:** $\epsilon_R^{\ell} \equiv \epsilon_R + \mathcal{O}(\frac{v^4}{\Lambda_{\text{NP}}^4})$

RHC cannot explain **LUR** $R_{D^{(*)}}$!

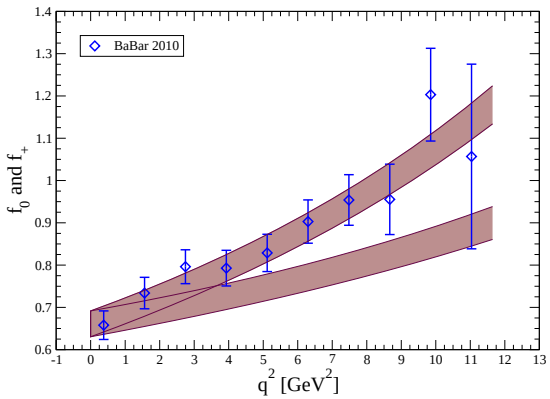
QCD uncertainties: Form factors

- Form factors are fitted to **experimental** $B \to D^{(*)}\ell\nu$ spectrum and **LQCD!**

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

- **Example:** $B \to D$

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



  - 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)

- In $B \to D^*$ (pseudo)scalar form factor $A_0(q^2)$ much less important

	R_D	R_{D^*} HFAG (CLN)
SM	0.310(19)	0.252(4)
Expt.	0.391(41)(28)	0.322(18)(12)

SM predictions of $R_{D^{(*)}}$ well under control!

Systematics and new observables to test the SM

- **However** the τ's lifetime is $\sim 10^{-13}$ s
  - It is not *observed* but *reconstructed* from decay products with **missing neutrinos**!

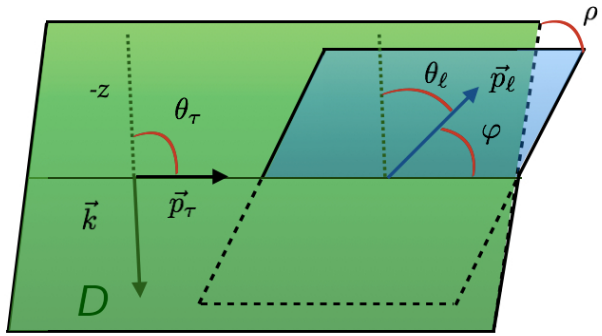
1. Looking for LUR in **new decay modes**
   - Semileptonic $B_c \to J/\Psi \ell\nu$ decays (**Coming soon from LHCb!**)
   - $\Lambda_b \to \Lambda_c^{(*)} \ell\nu$ S. Meinel @ HC2NP–Tenerife
   - $B_s \to D_s^{(*)} \ell\nu$ A. Bhol, EPL106(2014)31001
2. **Kinematic distributions** of the **observable** τ decay products
   - 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%

   - **Different τ decay modes are subject to very different backgrounds!**
   - Two different strategies in the literature
     - ⋆ **Montecarlo:** Closer to experiment and more useful for expt's
     - ⋆ **Analytical:** More transparent and independent analytical check of expt's Montecarlos

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

Alonso, Kobach, JMC, arXiv: 1602.07671



- **Integrate analytically τ angular phase-space:** (nontrivial)

$$\frac{d^3\Gamma_5}{dq^2\,dE_\ell\,d(\cos\theta_\ell)} = \mathcal{B}[\tau_\ell]\,\frac{G_F^2\,|V_{cb}|^2\,\eta_{\rm EW}^2}{32\pi^3}\,\frac{|\vec{k}|}{m_B^2}\left(1-\frac{m_\tau^2}{q^2}\right)^2\frac{E_\ell^2}{m_\tau^3}\times\left[I_0(q^2,E_\ell)+I_1(q^2,E_\ell)\cos\theta_\ell+I_2(q^2,E_\ell)\cos\theta_\ell^2\right]$$

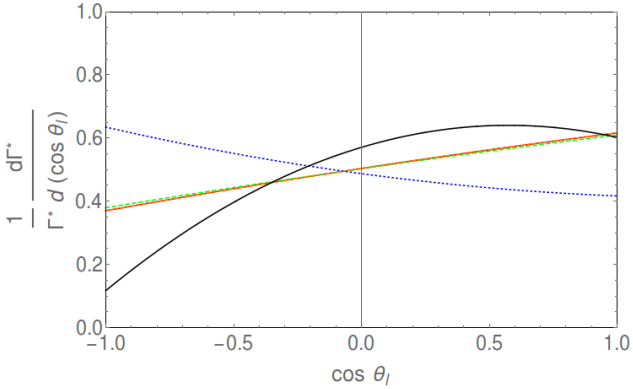
  - $\cos\theta_\ell$ defined as for the normalization mode (w.r.t recoiling $D^{(*)}$ in the q rest frame)
  - $I_{0,2}(q^2, E_\ell)$ accessed in $R_{D^{(*)}}$
  - $I_1(q^2, E_\ell)$ accessible only with a FB leptonic asymmetry!

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

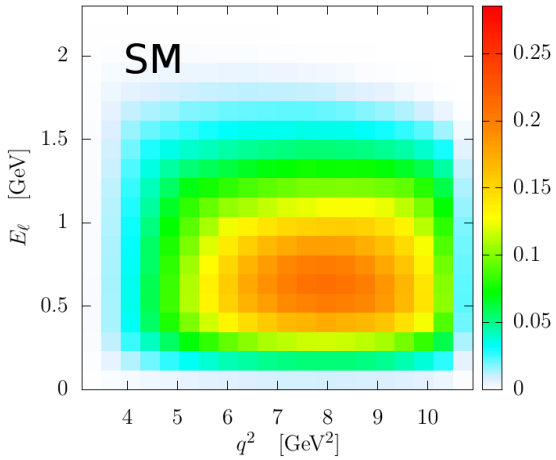
$$R_{FB}^{(*)} = \frac{1}{\mathcal{B}[\tau_\ell]}\,\frac{1}{\Gamma_{\rm norm.}}\,A_{FB},$$

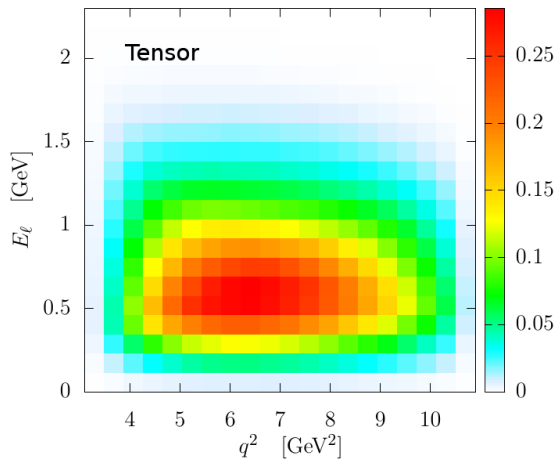
- Angular distributions can help to discriminate signal *vs.* normalization

	R_{D*}	R^*_{FB}
SM	0.252(4)	0.0310(7)
Current	0.333	0.0410
Scalar	0.315	0.0363
Tensor	0.346	−0.0377
Expt.	0.322(18)(12)	–



- E_ℓ and double (E_ℓ, q^2) spectra can also be studied





Ligeti *et al.* arXiv:1610.02045

$B \to D^{(*)}\tau^-(\to \pi^-\nu_\tau)\bar{\nu}_\tau$: $\tau^- \to \pi^-\nu_\tau$ as a τ polarimeter

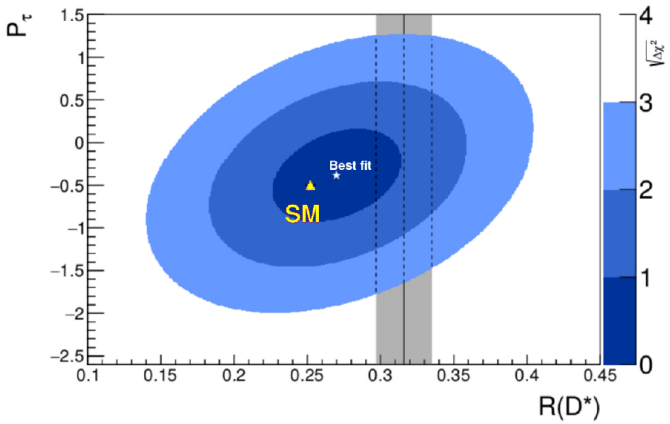
$$\frac{d^2\Gamma_4}{dq^2 dE_\pi} = \frac{\mathcal{B}[\tau_\pi]\, m_\tau^2}{|\vec{p}_\tau|(m_\tau^2 - m_\pi^2)} \frac{d\Gamma_B}{dq^2}\left[1 + \xi(E_\pi, q^2)\frac{dP_L}{dq^2}\right], \quad \xi(E_\pi, q^2) = \frac{1}{\beta_\tau}\left(2\frac{E_\pi}{E_\tau} - 1\right)$$

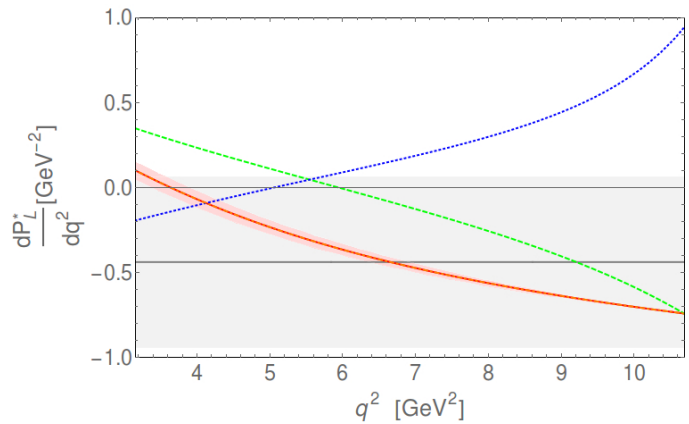
Tanaka&Watanabe, PRD82, 034027 (2010)

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

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

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





Belle, arXiv: 1608.06391

The lifetime of the B_c meson and new physics

- **4** Wilson coefficients can explain R_{D^*} anomalies: ϵ_L, ϵ_S, ϵ_P, ϵ_T
  - **2HDM** with discrete symmetries:

$$\epsilon_S \simeq \epsilon_P \simeq \xi^b \xi^\ell \frac{m_b\, m_\ell}{m^2_{H^\pm}}$$

- BD^* depends on ϵ_P
- $B_c \to \tau\nu$ **also** receives a **chiral enhanced** contribution from ϵ_P!

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

The constraint from the B_c lifetime

- **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, Kiselev *et al.* NPB585 (2000) 353

  ☛ **BR($B_c \to \tau\nu$) $\leq 30\%$ (accounting conservatively for errors)**

  Alonso, Grinstein&JMC, arXiv: 1611.06676 (see also Xin-Qiang Li *et al.*, JHEP 1608 (2016) 054)

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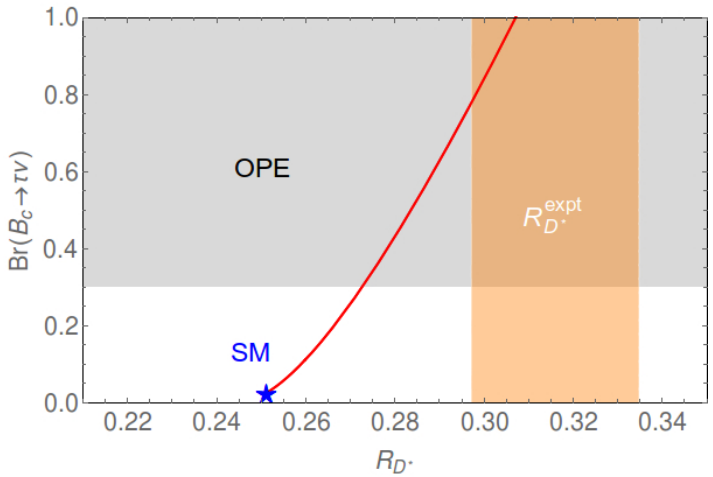
$$\epsilon_S \simeq \epsilon_P \simeq \xi^b \xi^\ell \frac{m_b\, m_\ell}{m^2_{H^\pm}}$$

- BD^* depends on ϵ_P
- $B_c \to \tau\nu$ **also** receives a **chiral enhanced** contribution from ϵ_P!

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



Alonso, Grinstein&JMC, arXiv: 1611.06676

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

The lifetime of the B_c meson and new physics

- **4** Wilson coefficients can explain R_{D^*} anomalies: ϵ_L, ϵ_S, ϵ_P, ϵ_T
  - **2HDM** with discrete symmetries:

$$\epsilon_S \simeq \epsilon_P \simeq \xi^b \xi^\ell \frac{m_b\, m_\ell}{m^2_{H^\pm}}$$

- BD^* depends on ϵ_P
- $B_c \to \tau\nu$ **also** receives a **chiral enhanced** contribution from ϵ_P!

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What type of New Physics remain?

1. Enhanced $V_{cb}^\tau = V_{cb}(1 + \epsilon_L^\tau)$
   - Best fit to data
   - Do not manifest in normalized observables (e.g. P_L)
2. **Simultaneous** presence of chirally-flipped operators ϵ_S^τ and ϵ_T^τ
   - **Contrived?** Leptoquarks can make the job (Fierzing)
   - Should show themselves in normalized observables

Conclusions

"Extraordinary claims require Extraordinary evidence"
– C. Sagan

1. We find new particles at the LHC
   - Modelling their flavor structure should explain anomalies+new predictions!
2. We do not find new particles but we confirm LUV
   - Reading the shape with more sophisticated (angular) observables
     - ★ Take LUV ratios between angular observables in $B \to K^* \ell\ell$
   - Look also at $B_s \to \mu\mu$!
   - **Bottom-up model-building:** Path for discovery at LHC or beyond!
3. No new particles+No LUV
   - More data needed to confirm or rule out q^2-dependence of the effect
   - Tackling theoretical errors **systematically** will require a **theoretical breakthrough**
   - **New ideas:** e.g. $B_s^* \to \ell\ell$ (Grinstein&JMC, Phys.Rev.Lett. 116 (2016) no.14, 141801)