# A few comments on $b \to c\tau\nu$ decays

Martin Jung

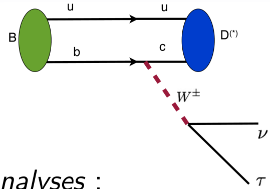
Deutsche Forschungsgemeinschaft

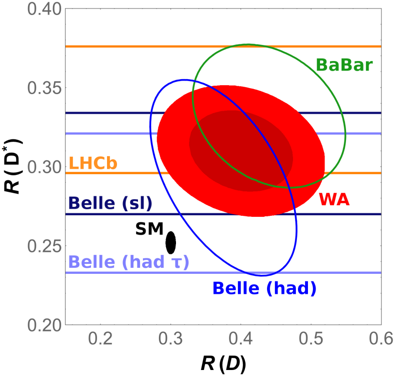
MIAPP programme
"Flavour physics with high-luminosity experiments"
11th November 2016, Munich

# Experimental Situation for $b \to c\tau\nu$ 2016

Importance of semi-leptonic decays:

- SM: Determination of $|V_{ij}|$ (7/9)
  - ➥ Minimal hadronic input, improvable!
- NP: Relative to tree, $\tau$ least constrained




contours: 68% CL
filled: 95(68)% CL

4 recent $R(D^{(*)})$*analyses* :

- $R(D^*)$ from LHCb [1506.08614]
- Belle update + new measurement (had./sl tag) [1507.03233,1603.06711] , $\tau$-polarization + $R(D^*)(\tau \to \text{had})$ [1608.06391]

➥ $4.0\sigma$ tension [HFAG]

Further $b \to c\tau\nu$ inputs:

- Differential rates from Belle, BaBar
- $b \to X_c\tau\nu$ by LEP
- Total width of $B_c$

# SM predictions

Strategy for SM predictions: $V_{cb}$ cancels, for FF's combine data and theoretical input from LQCD/HQET

$B \to D$: 2 form factors $f_{+,0}$

- Data from $B \to D\ell\nu$ determines shape of $f_+(q^2)$
- LQCD input required for $f_0$: fit HPQCD + FNAL/MILC + use relation $f_+(0) = f_0(0)$ [Bigi/Gambino'16]

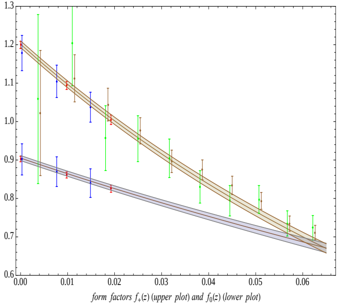
➥ $R(D) = 0.301 \pm 0.003$

$B \to D^*$: 4 form factors $V, A_{0,1,2}$

- Data from $B \to D^*\ell\nu$ determines 3/4 (with HQET input → CLN)
- HQET relation used for $A_0$ [Falk/Neubert'92] plus enhanced uncertainty [Fajfer/Kamenik]

➥ $R(D^*) = 0.252 \pm 0.003$

- LQCD for non-maximal recoil underway



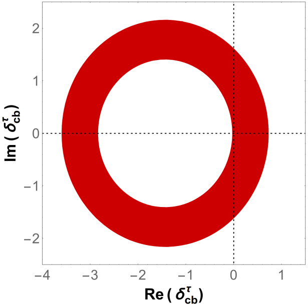

(Very) good control, effect too large to be in CLN relations

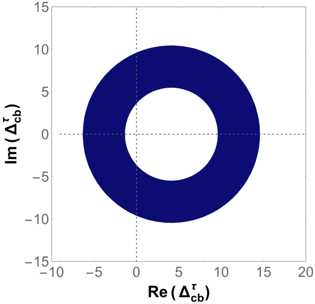
# Charged scalars in $b \to c\tau\nu$

A charged scalar generally results in ($g_{L,R}^{q_u q_d l}$ complex)

$$\mathcal{L}_H^{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{q_u q_d} \left[\bar{q}_u \left(g_L^{q_u q_d l}\mathcal{P}_L + g_R^{q_u q_d l}\mathcal{P}_R\right) q_d\right] [l \mathcal{P}_L \nu_l]$$

- Model-independent subclass as long as $g_{L,R}^{q_u q_d l}$ general

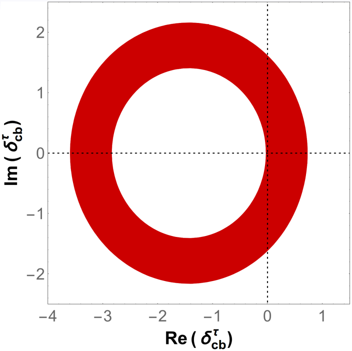


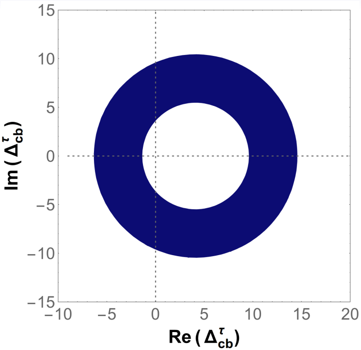




$$\delta^{cbl} \equiv \frac{(g_L^{cbl}+g_R^{cbl})(m_B-m_D)^2}{m_l(\bar{m}_b-\bar{m}_c)} \qquad \Delta^{cbl} \equiv \frac{(g_L^{cbl}-g_R^{cbl})m_B^2}{m_l(\bar{m}_b+\bar{m}_c)}$$

Can trivially explain $R(D^{(*)})$! Exclusion possible with specific flavour structure or more $b \to c\tau\nu$ observables!

# $b \to c\tau\nu$ data and scalar NP

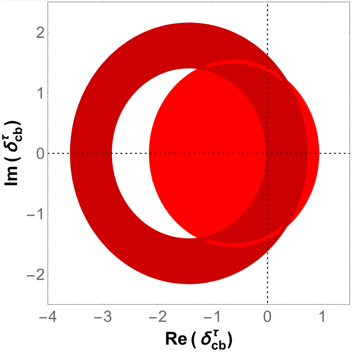


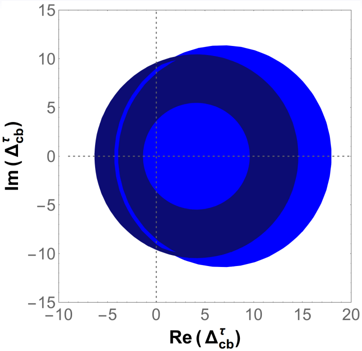




$R(D), R(D^*)$:

- $R(D)$ compatible with SM at $\sim 2\sigma$
- Preferred scalar couplings from $R(D^*)$ huge

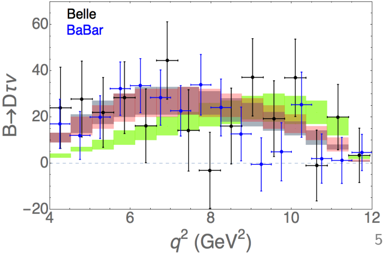
# $b \to c\tau\nu$ data and scalar NP



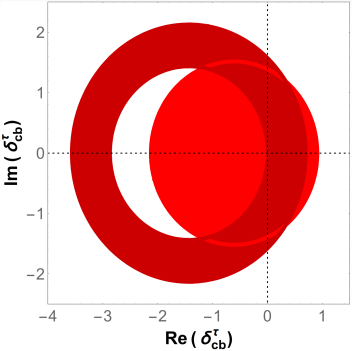



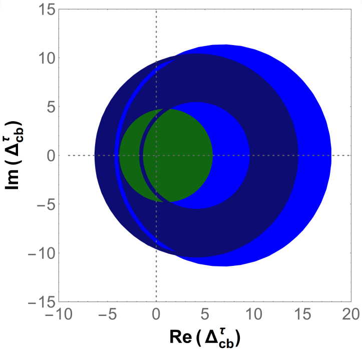

Differential rates:

- compatible with SM and NP
- already now constraining, especially in $B \to D\tau\nu$
- exclude 2nd real solution in $\delta^{\tau}_{cb}$



# $b \to c\tau\nu$ data and scalar NP

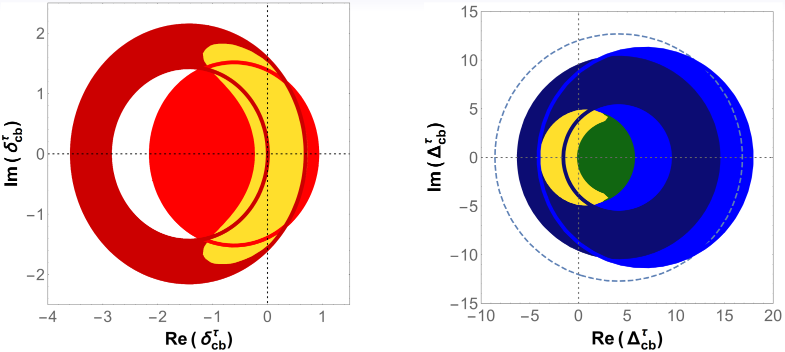



Total width of $B_c$:

- $B_c \to \tau\nu$ is an obvious $b \to c\tau\nu$ transition
  - not measurerable in foreseeable future
  - can oversaturate total width of $B_c$! [X.Li+'16]
- Excludes second real solution in $\Delta_{cb}^{\tau}$ plane

# $b \to c\tau\nu$ data and scalar NP



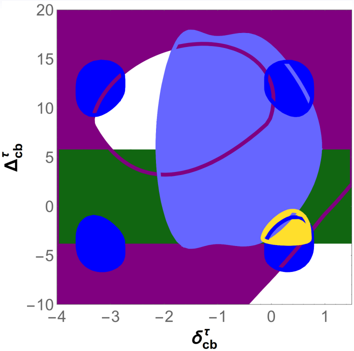

$\tau$ polarization:

- So far not constraining (shown: $\Delta\chi^2 = 1$)
- Differentiate NP models: with scalar NP [Celis/MJ/Li/Pich'13]

$$X_2^{D^{(*)}}(q^2) \equiv R_{D^{(*)}}(q^2) \left[A_\lambda^{D^{(*)}}(q^2) + 1\right] = X_{2,SM}^{D^{(*)}}(q^2)$$

Consistent explanation in 2HDMs possible, flavour structure?

# $b \to c\tau\nu$ data and scalar NP




Consistent explanation in 2HDMs possible, flavour structure?

# Generic features and issues in 2HDMs

Charged Higgs possible as explanation of $b \to c\tau\nu$ data...
However, generically $\Delta R(D^*) < \Delta R(D)$

Generic feature: Relative influence larger in leptonic decays!

- No problem in $b \to c\tau\nu$ since $B_c \to \tau\nu$ won't be measured
- Large charm coupling required for $R(D^*)$
- ➥ Embedding $b \to c\tau\nu$ into a viable model complicated!
- ➥ $D_{d,s} \to \tau, \mu\nu$ kill typical flavour structures with $g \sim m$
- ➥ Only fine-tuned models survive all (semi-)leptonic constraints

$b \to s\ell\ell$ very complicated to explain with scalar NP
➥ 2HDM alone tends to predict $b \to s\ell\ell$ to be QCD-related

$b\bar{b} \to (H, A) \to \tau^+\tau^-$ poses a severe constraint [Faroughy+'16]

2HDMs strongly prefer a smaller value for $R(D^*)$!

# Other models and model-independent observations

Semi-model-independent approaches: put $S_{L,R}$ or $V_{L,R}$:

EFT above the EW scale $\rightarrow$ $V_R$ coupling lepton-flavour universal!

[Cirigliano+'09,Catà/MJ'15,Camalich-Martin+'15]

Exception: EW symmetry non-linearly realized [Catà/MJ'15]

Large $R(D^*)$ possible with NP in $V_L$ ($\hat{R}(X) = R(X)/R(X)_{SM}$):

- trivial prediction: $\hat{R}(D) = \hat{R}(D^*) = R(\Lambda_c) = \ldots$
  $\hat{R}(D) \overset{exp}{=} 1.33 \pm 0.16$, $\hat{R}(D^*) \overset{exp}{=} 1.23 \pm 0.07$
- can be related to anomaly in $B \to K^{(*)}\ell^+\ell^-$ modes
- Suppression of light-lepton couplings less generic
- $\hat{R}(X_c) = 0.99 \pm 0.10$ measured by LEP
  ➥ Generally $R(D^*)$ vs. $R(X_c)$: no space for $B \to D^{**}\tau\nu$ [Ligeti+'15]
- Models with $(\bar{Q}\gamma^\mu t^A Q)(\bar{L}\gamma^\mu t^A L)$ create $\tau \to \mu\bar{\nu}\nu$ on 1-loop!

➥ violates generically $\Gamma(\tau \to \mu\bar{\nu}\nu)/\Gamma(\mu \to e\bar{\nu}\nu)$-bound! [Feruglio+'16]

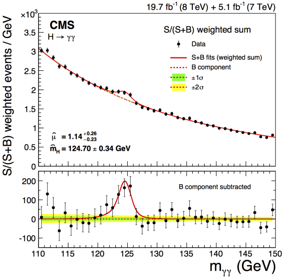
➥ Issue for LQ models, models with a $W'$ [e.g. Isidori+'15]

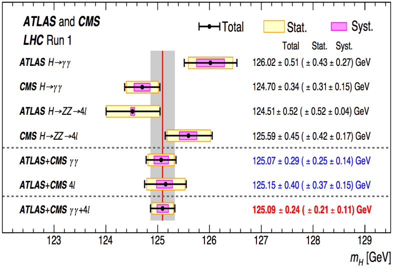
- Again $b\bar{b} \to X \to \tau^+\tau^-$ poses a severe constraint [Faroughy+'16]

# Back-up slides

# A hierarchy of scales

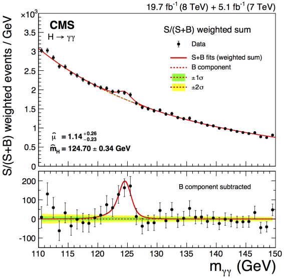
## A long-sought new particle. . .

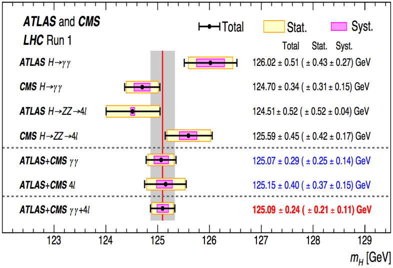


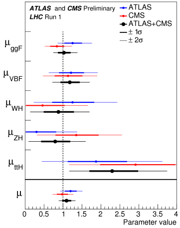
# A hierarchy of scales

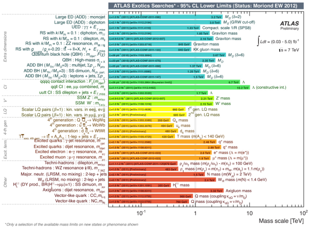
A long-sought new particle. . .

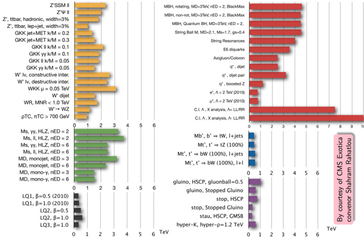



. . . but again everything looks like the Standard Model!



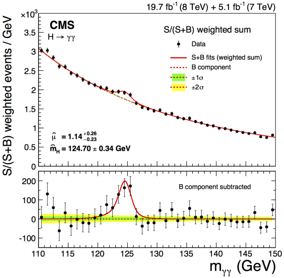



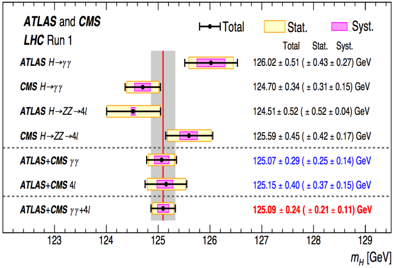




➡ Apparently hierarchy between the electroweak and NP scales!

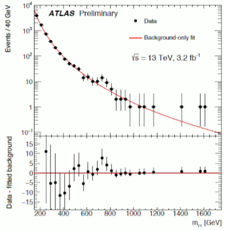
# A hierarchy of scales

A long-sought new particle. . .




. . . but again everything looks like the Standard Model! (almost)

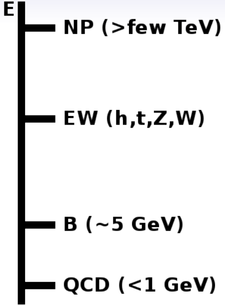



➥ Apparently hierarchy between the electroweak and NP scales!

# Higgs EFT(s)

EFT approach at the electroweak scale:

- ✓ SM particle content
- ✓ SM gauge group
- ? Embedding of $h$
- ? Power-counting
- ➥ Formulate NLO




Linear embedding of $h$:

- $h$ part of doublet $H$
- Appropriate for weakly-coupled NP
- Power-counting: dimensions
  ➥ Finite powers of fields

Non-linear embedding of $h$:

- $h$ singlet, $U$ Goldstones
- Appropriate for strongly-coupled NP
- Power-counting: loops ($\sim\chi$PT)
  ➥ Arbitrary powers of $h/v, \phi$

Non-linear EFT generalizes linear EFT, LO $\kappa$ framework

# Flavour EFTs for semi-leptonic decays

At scales $\mu \ll v, M_W$:
Construct EFT from $\psi_f, F_{\mu\nu}, G_{\mu\nu}$,
gauge group $SU(3)_C \times U(1)_{\rm em}$

Generically:

1. All coefficients independent
2. Coefficients for other processes unrelated (e.g. $\tau \leftrightarrow e, \mu$)

Implications of HEFT for the flavour-EFTs? [Cata/MJ'15]
Differences between linear and non-linear realization?
➥ Separate operators specific for non-linear HEFT

Previous work (linear EFT) e.g. [D'Ambrosio+'02,Cirigliano+'09,Alsonso+'14]

A word of caution: flavour hierarchies have to be considered!
➥ Mostly relevant when SM is highly suppressed, *e.g.* for EDMs

# Implications of the Higgs EFT for flavour [Cata/MJ'15]

$\mathbf{q \to q'\ell\ell}$ :

- Tensor operators absent in linear EFT for $d \to d'\ell\ell$ [Alonso+'14]
  - ➥ Present in general! (already in linear EFT for $u \to u'\ell\ell$)
- Scalar operators: linear EFT $C_S^{(d)} = -C_P^{(d)}$, $C_S'^{(d)} = C_P'^{(d)}$ [Alonso+'14]
  - ➥ Analogous for $u \to u'\ell\ell$, but no relations in general!

$\mathbf{q \to q'\ell\nu}$ :

- All operators are independently present already in the linear EFT
- However: Relations between different transitions:
  $C_{V_R}$ is lepton-flavour universal [see also Cirigliano+'09]
  Relations between charged- and neutral-current processes, *e.g.*
  $\sum_{U=u,c,t} \lambda_{Us} C_{S_R}^{(U)} = -\frac{e^2}{8\pi^2} \lambda_{ts} C_S^{(d)}$ [see also Cirigliano+'12,Alonso+'15]
- These relations are again absent in the non-linear EFT

Flavour physics sensitive to Higgs embedding!
➥ Surprising, since no Higgs is involved
➥ Difficult differently [e.g. Barr+, Azatov+'15]

# Implications of the Higgs EFT for Flavour: $q \to q'\ell\ell$

$$\mathcal{L}_{\text{eff}}^{b\to s\ell\ell} = \frac{4G_F}{\sqrt{2}}\lambda_{ts}\frac{e^2}{(4\pi)^2}\sum_i^{12} C_i^{(d)}\mathcal{O}_i^{(d)}\,, \quad \lambda_{ts} = V_{tb}V_{ts}^*, \quad \text{with}$$

$$\mathcal{O}_7^{(\prime)} = \frac{m_b}{e}(\bar{s}\sigma^{\mu\nu}P_{R(L)}b)F_{\mu\nu}\,,$$

$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}b)\,\bar{l}\gamma^\mu l\,, \qquad \mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}b)\,\bar{l}\gamma^\mu\gamma_5 l\,,$$

$$\mathcal{O}_S^{(\prime)} = (\bar{s}P_{R(L)}b)\,\bar{l}l\,, \qquad \mathcal{O}_P^{(\prime)} = (\bar{s}P_{R(L)}b)\,\bar{l}\gamma_5 l\,,$$

$$\mathcal{O}_T = (\bar{s}\sigma_{\mu\nu}b)\,\bar{l}\sigma^{\mu\nu}l\,, \qquad \mathcal{O}_{T5} = (\bar{s}\sigma_{\mu\nu}b)\,\bar{l}\sigma^{\mu\nu}\gamma_5 l\,.$$

Generalized matching from HEFT yields:

- No changes for photon penguin, insensitive to EWSB
- Additional contributions in $C_{9,10}^{(\prime)}$ (but linear EFT already general)
- Tensor operators absent in linear EFT for $d \to d'\ell\ell$ [Alonso+'14]
  ➥ Present in general! (already in linear EFT for $u \to u'\ell\ell$)
- Scalar operators: linear EFT $C_S^{(d)} = -C_P^{(d)}$, $C_S^{\prime(d)} = C_P^{\prime(d)}$ [Alonso+'14]
  ➥ Analogous for $u \to u'\ell\ell$, but no relations in general!

# Implications of the Higgs EFT for Flavour: $q \to q'\ell\nu$

$b \to c\tau\nu$ transitions (SM: $C_{V_L} = 1, C_{i\neq V_L} = 0$):

$$\mathcal{L}_{\rm eff}^{b\to c\tau\nu} = -\frac{4G_F}{\sqrt{2}} V_{cb} \sum_j^5 C_j \mathcal{O}_j\,, \qquad \text{with}$$

$$\mathcal{O}_{V_{L,R}} = (\bar{c}\gamma^\mu P_{L,R} b)\bar{\tau}\gamma_\mu \nu\,, \qquad \mathcal{O}_{S_{L,R}} = (\bar{c}P_{L,R}b)\bar{\tau}\nu\,,$$

$$\mathcal{O}_T = (\bar{c}\sigma^{\mu\nu}P_L b)\bar{\tau}\sigma_{\mu\nu}\nu\,.$$

- All operators are independently present already in the linear EFT
- However: Relations between different transitions:
  $C_{V_R}$ is lepton-flavour universal [see also Cirigliano+'09]
  Relations between charged- and neutral-current processes, *e.g.*
  $\sum_{U=u,c,t} \lambda_{Us} C_{S_R}^{(U)} = -\frac{e^2}{8\pi^2}\lambda_{ts} C_S^{(d)}$ [see also Cirigliano+'12,Alonso+'15]
- These relations are again absent in the non-linear EFT

# Interpretation

Lessons:

- When assuming a linear EFT:
  Simplifications of model-indepent analyses
- However: Relations do *not* hold model-independently
  ➥ $SU(2)_L \times U(1)_Y$ together with linear embedding

Flavour physics can help to distinguish between embeddings!
➥ Surprising, since no Higgs is involved
➥ Difficult differently [e.g. Barr+, Azatov+'15]

- Key operators $\mathcal{O}_{Y_i}$: 4f-operators with Goldstone fields
  ➥ Hypercharges of fermions alone do not sum to 0
  ➥ Appear in linear EFT at dimension 8

# Operator basis

$\hat{\tau}_3 = U\tau_3 U^\dagger$, $\hat{\tau}_\pm = U\frac{1}{2}(\tau_1 \pm i\tau_2)U^\dagger$, $L_\mu \equiv iUD_\mu U^\dagger$.

$$\mathcal{O}_{X1,2} = g'\bar{q}\sigma^{\mu\nu}UP_\pm rB_{\mu\nu}, \quad \mathcal{O}_{X3,4} = g\bar{q}\sigma^{\mu\nu}UP_\pm r\langle\hat{\tau}_3 W_{\mu\nu}\rangle,$$

$$\mathcal{O}'_{X1,2} = g'\bar{r}P_\pm U^\dagger\sigma^{\mu\nu}qB_{\mu\nu}, \quad \mathcal{O}'_{X3,4} = g\bar{r}P_\pm U^\dagger\sigma^{\mu\nu}q\langle\hat{\tau}_3 W_{\mu\nu}\rangle,$$

$$\mathcal{O}_{V1} = \bar{q}\gamma^\mu q\langle\hat{\tau}_3 L_\mu\rangle\,, \qquad \mathcal{O}_{V2} = \bar{q}\gamma^\mu\hat{\tau}_3 q\langle\hat{\tau}_3 L_\mu\rangle\,,$$

$$\mathcal{O}_{V3} = \bar{u}\gamma^\mu u\langle\hat{\tau}_3 L_\mu\rangle\,, \qquad \mathcal{O}_{V4} = \bar{d}\gamma^\mu d\langle\hat{\tau}_3 L_\mu\rangle\,,$$

$$\mathcal{O}_{V5} = \bar{q}\gamma^\mu\hat{\tau}_+ q\langle\hat{\tau}_- L_\mu\rangle\,, \qquad \mathcal{O}_{V6} = \bar{u}\gamma^\mu d\langle\hat{\tau}_- L_\mu\rangle\,,$$

$$\mathcal{O}_{V7} = \bar{l}\gamma^\mu\hat{\tau}_- l\langle\hat{\tau}_+ L_\mu\rangle\,,$$

$$\mathcal{O}_{LL1} = \bar{q}\gamma^\mu q\ \bar{l}\gamma_\mu l\,, \qquad \mathcal{O}_{LL2} = \bar{q}\gamma^\mu\tau^j q\ \bar{l}\gamma_\mu\tau^j l\,,$$

$$\hat{\mathcal{O}}_{LL3} = \bar{q}\gamma^\mu\hat{\tau}_3 q\ \bar{l}\gamma_\mu l\,, \qquad \hat{\mathcal{O}}_{LL4} = \bar{q}\gamma^\mu q\ \bar{l}\gamma_\mu\hat{\tau}_3 l\,,$$

$$\hat{\mathcal{O}}_{LL5} = \bar{q}\gamma^\mu\hat{\tau}_3 q\ \bar{l}\gamma_\mu\hat{\tau}_3 l\,, \qquad \hat{\mathcal{O}}_{LL6} = \bar{q}\gamma^\mu\hat{\tau}_3 l\ \bar{l}\gamma_\mu\hat{\tau}_3 q\,,$$

$$\hat{\mathcal{O}}_{LL7} = \bar{q}\gamma^\mu\hat{\tau}_3 l\ \bar{l}\gamma_\mu q\,,$$

# Operator basis II

$$\mathcal{O}_{LR1} = \bar{q}\gamma^{\mu} q \; \bar{e}\gamma_{\mu} e\,, \qquad \mathcal{O}_{LR2} = \bar{u}\gamma^{\mu} u \; \bar{l}\gamma_{\mu} l\,,$$
$$\mathcal{O}_{LR3} = \bar{d}\gamma^{\mu} d \; \bar{l}\gamma_{\mu} l\,, \qquad \hat{\mathcal{O}}_{LR5} = \bar{q}\gamma^{\mu}\hat{\tau}_3 q \; \bar{e}\gamma_{\mu} e\,,$$
$$\hat{\mathcal{O}}_{LR6} = \bar{u}\gamma^{\mu} u \; \bar{l}\gamma_{\mu}\hat{\tau}_3 l\,, \qquad \hat{\mathcal{O}}_{LR7} = \bar{d}\gamma^{\mu} d \; \bar{l}\gamma_{\mu}\hat{\tau}_3 l\,,$$

$$\mathcal{O}_{RR1} = \bar{u}\gamma^{\mu} u \bar{e}\gamma_{\mu} e\,, \qquad \mathcal{O}_{RR2} = \bar{d}\gamma^{\mu} d \; \bar{e}\gamma_{\mu} e\,.$$

$$\mathcal{O}_{LR4} = \bar{q}\gamma^{\mu} l \; \bar{e}\gamma_{\mu} d\,, \qquad \hat{\mathcal{O}}_{LR8} = \bar{q}\gamma^{\mu}\hat{\tau}_3 l \; \bar{e}\gamma_{\mu} d\,,$$

$$\mathcal{O}_{S1} = \epsilon_{ij}\bar{l}^i e \bar{q}^j u\,, \qquad \mathcal{O}_{S2} = \epsilon_{ij}\bar{l}^i \sigma^{\mu\nu} e \bar{q}^j \sigma_{\mu\nu} u\,,$$
$$\hat{\mathcal{O}}_{S3} = \bar{q} U P_+ r \bar{l} U P_- \eta\,, \qquad \hat{\mathcal{O}}_{S4} = \bar{q}\sigma_{\mu\nu} U P_+ r \bar{l}\sigma^{\mu\nu} U P_- \eta\,,$$
$$\hat{\mathcal{O}}_{S5} = \bar{q}\hat{\tau}_- U r \bar{l}\hat{\tau}_+ U \eta\,, \qquad \hat{\mathcal{O}}_{S6} = \bar{q}\sigma_{\mu\nu}\hat{\tau}_- U r \bar{l}\sigma^{\mu\nu}\hat{\tau}_+ U \eta\,,$$

$$\hat{\mathcal{O}}_{Y1} = \bar{q} U P_- r \bar{l} U P_- \eta\,, \qquad \hat{\mathcal{O}}_{Y2} = \bar{q}\sigma_{\mu\nu} U P_- r \bar{l}\sigma^{\mu\nu} U P_- \eta\,,$$
$$\hat{\mathcal{O}}_{Y3} = \bar{l} U P_- \eta \bar{r} P_+ U^{\dagger} q\,, \qquad \hat{\mathcal{O}}_{Y4} = \bar{l} U P_- r \bar{r} P_+ U^{\dagger} l\,.$$

Flavor family indices have been omitted.

# Matching for $b \to s\ell\ell$ transitions

$\mathcal{N}_{\rm NC}^{(d)} = \frac{4\pi^2}{e^2\lambda_{ts}}\frac{v^2}{\Lambda^2}$

$$\delta C_{7(d)}^{(\prime)} = \frac{8\pi^2}{m_b\lambda_{ts}}\frac{v^2}{\Lambda^2}\left[c_{X2}^{(\prime)} + c_{X4}^{(\prime)}\right] ,$$

$$\delta C_{7(u)}^{(\prime)} = \frac{8\pi^2}{m_c\lambda_{bu}}\frac{v^2}{\Lambda^2}\left[c_{X1}^{(\prime)} + c_{X3}^{(\prime)}\right] ,$$

$$\delta C_{9,10}^{(q)} = \mathcal{N}_{\rm NC}^{(q)}\left[(C_{LR}^{(q)} \pm C_{LL}^{(q)}) \pm 4g_{V,A}\frac{\Lambda^2}{v^2}C_{VL}^{(q)}\right] ,$$

$$C_{9,10}^{\prime(q)} = \mathcal{N}_{\rm NC}^{(q)}\left[(C_{RR}^{(q)} \pm C_{RL}^{(q)}) \pm 4g_{V,A}\frac{\Lambda^2}{v^2}C_{VR}^{(q)}\right] .$$

$$C_{LL}^{(d)} = c_{LL1} + c_{LL2} - \hat{c}_{LL3} - \hat{c}_{LL4} + \hat{c}_{LL5} + \hat{c}_{LL6} - \hat{c}_{LL7} ,$$

$$C_{RR}^{(d)} = c_{RR2} ,\ C_{LR}^{(d)} = c_{LR1} - \hat{c}_{LR5} ,\ C_{RL}^{(d)} = c_{LR3} - \hat{c}_{LR7} ,$$

$$C_{VL}^{(d)} = c_{V1} - c_{V2} ,\ C_{VR}^{(d)} = c_{V4} .$$

# $b \to s\ell\ell$ matching continued

$$C_{S,P}^{(d)} = \mathcal{N}_{\rm NC}^{(d)} \left[ \pm c_S^{(d)} + \hat{c}_{Y1} \right] , \quad C_{S,P}^{\prime(d)} = \mathcal{N}_{\rm NC}^{(d)} \left[ c_S^{\prime(d)} \pm \hat{c}_{Y1}^{\prime} \right] ,$$

$$C_T^{(d)} = \mathcal{N}_{\rm NC}^{(d)} \left[ \hat{c}_{Y2} + \hat{c}_{Y2}^{\prime} \right] , \quad C_{T5}^{(d)} = \mathcal{N}_{\rm NC}^{(d)} \left[ \hat{c}_{Y2} - \hat{c}_{Y2}^{\prime} \right] ,$$

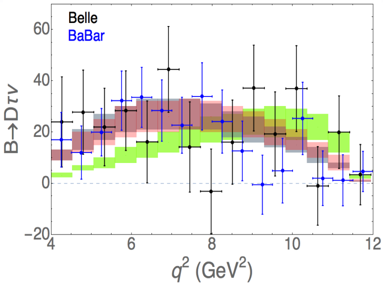
where $c_S^{(\prime)(d)} = 2(\hat{c}_{LR8}^{(\prime)} - c_{LR4}^{(\prime)})$.

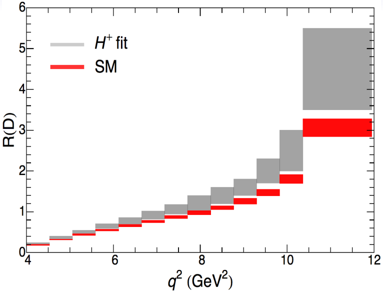
# Matching for $b \to c\ell\nu$ transitions

$$
\begin{aligned}
C_{V_L} &= -\mathcal{N}_{\rm CC}\left[C_L + \frac{2}{v^2}c_{V5} + \frac{2V_{cb}}{v^2}c_{V7}\right],\\
C_{V_R} &= -\mathcal{N}_{\rm CC}\left[\hat{C}_R + \frac{2}{v^2}c_{V6}\right],\\
C_{S_L} &= -\mathcal{N}_{\rm CC}\left(c'_{S1} + \hat{c}'_{S5}\right),\\
C_{S_R} &= 2\,\mathcal{N}_{\rm CC}\left(c_{LR4} + \hat{c}_{LR8}\right),\\
C_T &= -\mathcal{N}_{\rm CC}\left(c'_{S2} + \hat{c}'_{S6}\right),
\end{aligned}
$$

where $\mathcal{N}_{\rm CC} = \frac{1}{2V_{cb}}\frac{v^2}{\Lambda^2}$, $C_L = 2c_{LL2} - \hat{c}_{LL6} + \hat{c}_{LL7}$ and $\hat{C}_R = -\frac{1}{2}\hat{c}_{Y4}$.

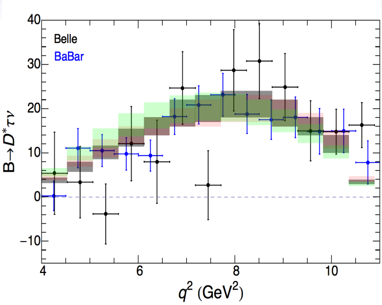
# The differential distributions $d\Gamma(B \to D^{(*)}\tau\nu)/dq^2$

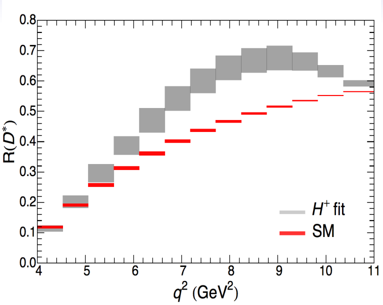



- Data stat. uncertainties only, BaBar rescaled
- Bands 68% CL (bins highly correlated):
  Grey: NP fit including $R(D)$
  Red: SM fit (distributions only)
  Green: Allowed by $R(D)$, excluded by distribution
- Need better experimental precision, ideally $dR(D)/dq^2$
- Parts of NP parameter space clearly excluded

# The differential distributions $d\Gamma(B \to D^{(*)}\tau\nu)/dq^2$




- Data stat. uncertainties only, BaBar rescaled
- Bands 68% CL (bins highly correlated):
  Grey: NP fit including $R(D^*)$
  Red: SM fit (distributions only)
  Green: Allowed by $R(D^*)$, excluded by distribution
- Need better experimental precision, ideally $dR(D^*)/dq^2$
- Not very restrictive at the moment

# BR measurements and isospin violation

Isospin asymmetries test NP with $\Delta I = 1, 3/2$ (e.g. $b \to s\bar{u}u$)
Again: relevant due to high precision and small NP

Branching ratio measurements require normalization...

- $B$ factories: depends on $\Upsilon \to B^+B^-$ vs. $B^0\bar{B}^0$
- LHCb: normalization mode, usually obtained from $B$ factories

Assumptions entering this normalization:

- PDG: assumes $r_{+0} \equiv \Gamma(\Upsilon \to B^+B^-)/\Gamma(\Upsilon \to B^0\bar{B}^0) \equiv 1$
- LHCb: assumes $f_u \equiv f_d$, uses $r_{+0}^{\rm HFAG} = 1.058 \pm 0.024$

Both approaches problematic: [MJ'16 [1510.03423]]

- Potential large isospin violation in $\Upsilon \to BB$ [Atwood/Marciano'90]
- Measurements in $r_{+0}^{\rm HFAG}$ assume isospin in exclusive decays
  - ➥ This is one thing we want to test!
- ➥ Avoiding this assumption yields $r_{+0} = 1.027 \pm 0.037$
- ➥ Isospin asymmetry $B \to J/\psi K$: $A_I = -0.009 \pm 0.024$

Improvement necessary for high-precision BRs
➥ $B \to J/\Psi K$ can be used to determine $f_u/f_d$!

# Other models and model-independent observations

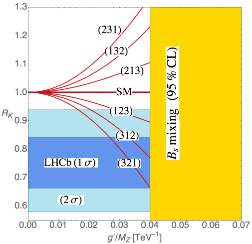
LFV possibly related to LFNU $\Rightarrow$ NP typically *not* in mass basis

➥ Rotation to mass basis induces LFV [Glashow+,Bhattacharya+'14,...]

- LFV $B$ decays additionally motivated!
- Strong constraints from LFV processes

However...

- "typically" does not mean "necessarily"
  ➥ diagnonal mass matrix possible
- Examples: [Altmannshofer+'14,Celis+'15⇒]




LQ models ok as templates, but UV-embedding complicated ($p \to X$)

➥ light LQ very complicated with simple groups [e.g. Doršner+'16]

➥ more complicated groups can work, but many more d.o.f.!

Models with $(\bar{Q}\gamma^\mu t^A Q)(\bar{L}\gamma^\mu t^A L)$ create $\tau \to \mu\bar{\nu}\nu$ on 1-loop!

➥ violates generically $\Gamma(\tau \to \mu\bar{\nu}\nu)/\Gamma(\mu \to e\bar{\nu}\nu)$-bound! [Feruglio+'16]

➥ Issue for LQ models, models with a $W'$ [e.g. Isidori+'15]