Clean* observables in rare decays

– Motivation

– Lessons

– LNU 2018 +

– Uncharted territory: mapping out $|\Delta c| = |\Delta u| = 1$

* clean $=$ clean enough

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We'd like to understand 1. the borders of the SM (test the SM and look for BSM physics) and 2. "flavor" (Pattern of fermion masses and mixings).

To do so, we invoke model-independent analyses (fits to Wilson coefficients C_i), study (and design) null test observables and aim at leaving no stone unturned (diverse searches, synergy with collider and dark matter searches).

top 10 observables beyond $\mathcal{B}(b \to s\gamma)$

1. CP asymmetry $a_{CP}(b \to s\gamma)$; in SM direct CP violation in $b \to s$ is small: $a_{CP} = \frac{|A|^2-|\bar{A}|^2}{|A|^2+|\bar{A}|^2} \propto \alpha_s(m_b) Im \frac{V_{ub}V_{us}^*}{V_{tb}V_{ts}^*} \sim \alpha_s(m_b)\lambda^2 \lesssim \mathcal{O}(1\%)$ $a_{CP} = (-0.079 \pm 0.108 \pm 0.022)(1 \pm 0.03)$ CLEO hep-ex/0010075
2. search for wrong helicity $\bar{s}_R \sigma_{\mu\nu} b_L$ in $b \to s\gamma$; in SM small $C_7' = m_s/m_b C_7$ e.g. with polarization studies in $\Lambda_b \to \Lambda\gamma$ at Tevatron, LHC, GigaZ hep-ph/0108074
3. $|\sin 2\beta_{(J/\Psi K)} - \sin 2\beta_{(\Phi K)}|$ is $\lesssim \mathcal{O}(\lambda^2)$ in SM; direct CPX in $b \to s\bar{s}s$ $\mathcal{B}(B \to \Phi K_0)_{ave} = 8.8^{+2.7}_{-2.3} \cdot 10^{-6}$ Belle, Babar preliminary $\sigma_{\Phi K_s}(stat) = 0.56, 0.18$ with $0.1, 1ab^{-1}$ hep-ph/0112312
4. precision study in inclusive $b \to s\ell^+\ell^-$ branching ratio at NNLO for low dilepton inv mass below $c\bar{c}$ threshold hep-ph/0112300

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top 10 observables beyond $\mathcal{B}(b \to s\gamma)$

5. For-Back-asymmetry $A_{FB}(B \to (X_s, K^*)\ell^+\ell^-)$ sign/shape
6. if it exists, what is the position of the A_{FB} zero in low q^2
7. Forward-Back-CP asymmetry $A_{FB}^{CP} \equiv \frac{A_{FB}+\bar{A}_{FB}}{A_{FB}-\bar{A}_{FB}} \sim \frac{Im(C_{10})}{Re(C_{10})}$ probes non-SM CP phase in sZb vertex; in SM $A_{FB}^{CP} < 10^{-3}$ hep-ph/0006136
8. $B_s - \bar{B}_s$ mixing, Z-penguins
9. $\mathcal{B}(B_{d,s} \to \mu^+\mu^-)$, sensitive to neutral higgs exchange
10. nEDMs, strong CP problem $\bar{\Theta} < 10^{-10}, \delta_{CKM} \sim O(1)$? sensitive to flavor blind CP violation if PQ-axion solution, if spontaneously broken CP tight constraints on flavor structure hep-ph/0201251

top 100: $b \to s\nu\bar{\nu}$, $K \to \pi\nu\bar{\nu}$, $D_0 - \bar{D}_0$, leptons, neutrinos

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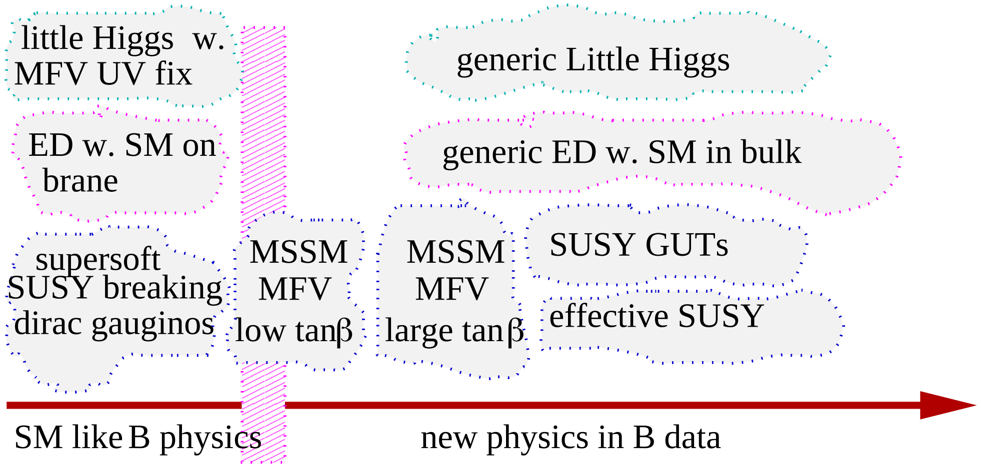
Key topics 2002: CP, observation of rare B-decays, start of angular analysis, C_7, C_7', C_{10}, C_P ... and K, D physics

Key themes now: precision, CP, lepton nonuniversality ... and K, D

plot from hep-ph/0207121



2002: top-down models

2018: $U(1)$-extensions, leptoquarks,...

Lepton nonuniverslity (LNU)

We are seeing $\sim 2.6\sigma$ hints of new physics in $b \to sll$, LNU between e's and μ's in both observables R_K and R_{K^*} LHCb '14, '17,

$$R_H = \frac{\mathcal{B}(\bar{B}\to\bar{H}\mu\mu)}{\mathcal{B}(\bar{B}\to\bar{H}ee)}, \text{ same cuts e and mu, } \quad H = K, K^*, X_s, \ldots$$

Lepton-universal models (incl. SM): $R_H = 1+$tiny GH, Krüger, hep-ph/0310219

This needs to be consolidated/ deciphered/understood

1. Correlations among R_H **Predictions:** 1411.4773

$$R_K \simeq R_\eta \simeq R_{K_1(1270,1400)}, \qquad R_{K^*} \simeq R_\Phi \simeq R_{K_0(1430)}$$

All R_H equal if no V+A currents present.

$R_{X_s} \simeq 0.73 \pm 0.07$ inclusive decays 1704.05444 Belle II

2. BSM in electrons, or muons, or in both? Lepton-specific measurements $B \to K^* ee$ angular distribution

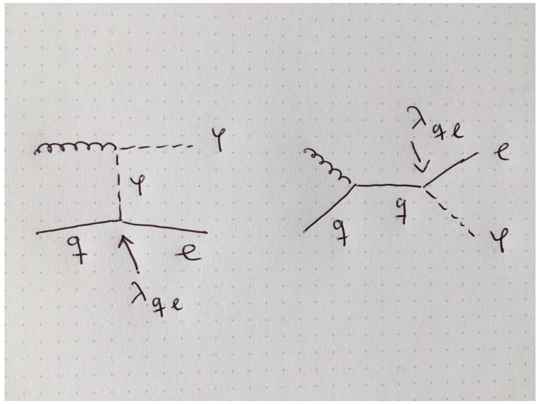
3. Side effects from flavor: LFV, τ's, by $SU(2)$ ν's 1411.0565 ,1412.7164,1503.01084

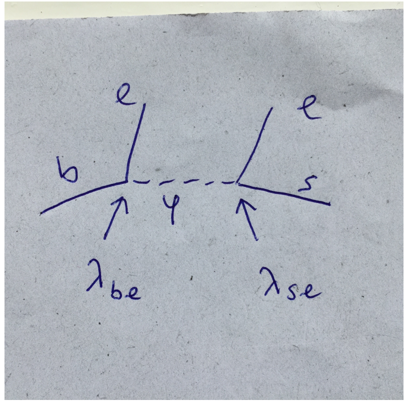
LQ coupling patterns rows: quarks, columns: leptons red: K, D-physics

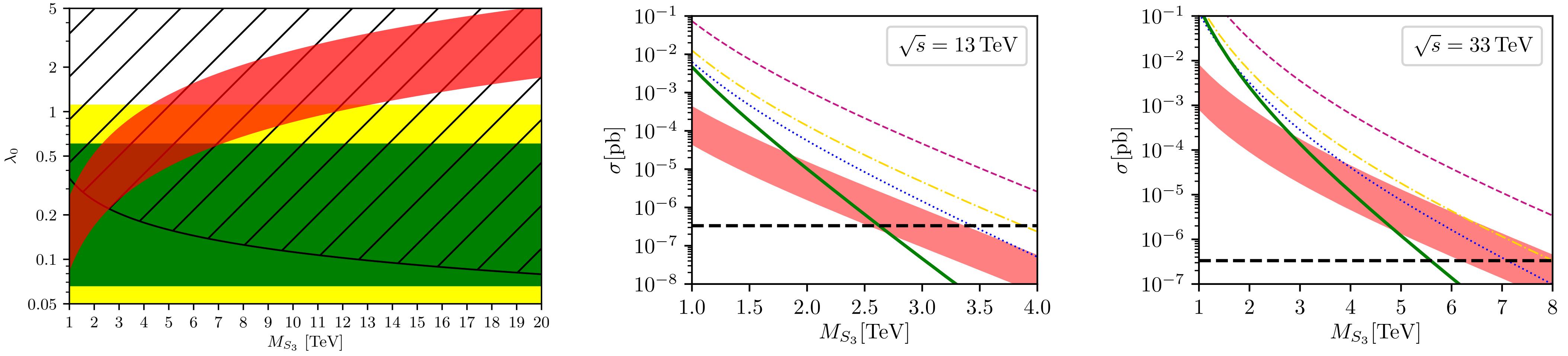
$$\lambda_{q\ell} = \begin{pmatrix} \lambda_{q_1 e} & \lambda_{q_1 \mu} & \lambda_{q_1 \tau} \\ \lambda_{q_2 e} & \lambda_{q_2 \mu} & \lambda_{q_2 \tau} \\ \lambda_{q_3 e} & \lambda_{q_3 \mu} & \lambda_{q_3 \tau} \end{pmatrix}, \begin{pmatrix} * & * & * \\ \lambda_{q2e} & \lambda_{q2\mu} & * \\ \lambda_{q3e} & \lambda_{q3\mu} & * \end{pmatrix} + \text{Occam's razor}: \begin{pmatrix} * & * & * \\ * & \lambda_{q2\mu} & * \\ * & \lambda_{q3\mu} & * \end{pmatrix}.$$

4. Collider implications (leptoquarks!) $\frac{\lambda_{b\mu}\lambda^*_{s\mu} - \lambda_{be}\lambda^*_{se}}{M^2} \simeq \frac{1.1}{(35\,\mathrm{TeV})^2}$

Single leptoquark production from b-anomalies 1801.09399 in association with a lepton $\sigma(pp \to \varphi\ell) \propto |\lambda_{q\ell}|^2 \alpha_s$ depends on flavor







red: R_{K,K^*} with flavor $M/11.6$ TeV $\lesssim \lambda_{b\ell} \lesssim M/3.9$ TeV

left plot: green: flavor model prediciton points to multi-TeV mass

other plots: magenta, yellow, blue: $\lambda_{d\mu} = 1, \lambda_{s\mu} = 1, \lambda_{b\mu} = 1$, black: no-loss reach with 3 ab^{-1}

green curve: pair production (LO Madgraph) 1801.09399

– Beauty wins over PDF if λ_{ql} follow quark mass hierarchies. Inverted hierarchies $\lambda_{sl} > \lambda_{bl}$ would be surprising from a symmetry-based flavor perspective and suggests means beyond.

LNU anomalies in B-decays will be sorted out.

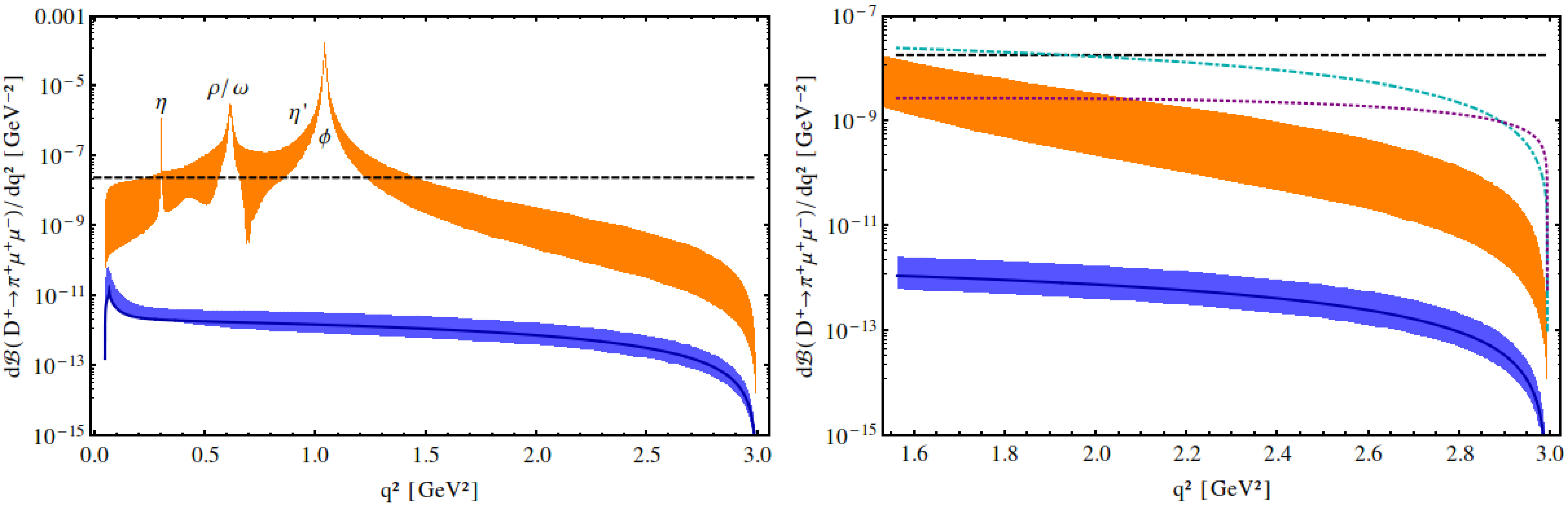
Irrespective of this, it is a truly flavor-type question whether BSM in $b \to s$-FCNC decays has implications for $c \to u$ decays.

What do we know about $|\Delta c| = |\Delta u| = 1$ couplings anyway? – genuine probe of flavor in the up-quark sector. Consider therefore

rare charm decays

works by Bigi, Fajfer, Kosnic, Zwicky, de Boer, GH 1510.00311 on $D \to \pi ll$, 1701.06392 on Br and A_{CP} in radiative D-decays, 1802.02769 on photon polarization from TDA or up-down asymmetry; measure SM BGD

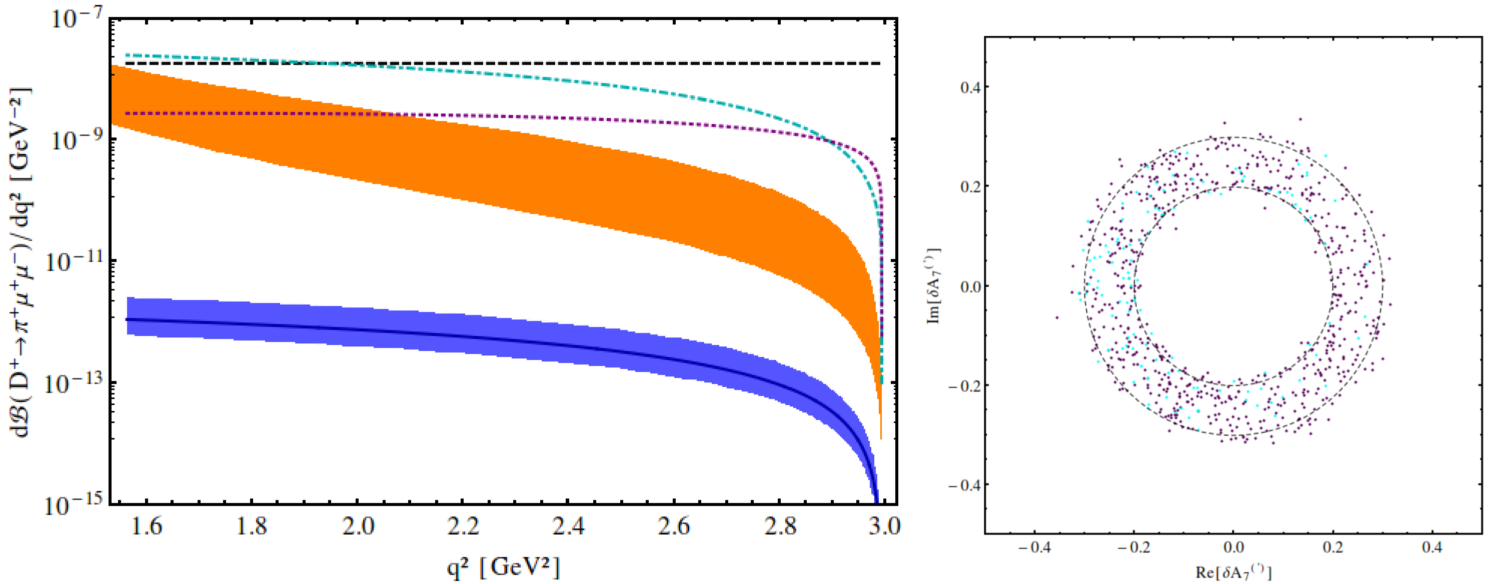
Resonance contributions vs BSM



BSM windows in $D \to \pi l^+ l^-$ branching ratios at high and very low q^2 only; BSM Wilson coefficients need to be very large, ~ 1.

To observe BSM in rare charm either i) BSM is very large (plot to the right) or ii) contributes to SM null tests (LFV, LNU, CP, angular distr.)

Model-independent constraints on BSM



$c \to u\mu\mu, \gamma$: $|C_{9,10}^{(\prime)}| \lesssim 1$, $|C_7^{(\prime)}| \lesssim 0.3$, $|C_{T,T5}| \lesssim 1$, $|C_{S,P}^{(\prime)}| \lesssim 0.1$.

vs

$C_7^{\rm SM} \simeq 0.004\,, C_9^{\rm SM} \simeq -0.01\,, \quad C_{10}^{\rm SM} = 0\,,$ (GIM !) $\quad C^{\prime \rm SM}, C_{S,P,T,T5}^{\rm SM} = 0$

$c \to uee$: constraints are (2-4) $\times$ weaker (data) than $u\mu\mu$ constraints.

$c \to ue\mu$: (6-7) $\times$ weaker than $u\mu\mu$ constraints.

	$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)$	$\mathcal{B}(D^0 \to \mu^+\mu^-)$	$\mathcal{B}(D^+ \to \pi^+e^\pm\mu^\mp)$	$\mathcal{B}(D^0 \to \mu^\pm e^\mp)$	$\mathcal{B}(D^+ \to \pi^+\nu\bar{\nu})$
i)	SM-like	SM-like	$\lesssim 2 \cdot 10^{-13}$	$\lesssim 7 \cdot 10^{-15}$	$\lesssim 3 \cdot 10^{-13}$
ii.1)	$\lesssim 7 \cdot 10^{-8}$ $(2 \cdot 10^{-8})$	$\lesssim 3 \cdot 10^{-9}$	0	0	$\lesssim 8 \cdot 10^{-8}$
ii.2)	SM-like	$\lesssim 4 \cdot 10^{-13}$	0	0	$\lesssim 4 \cdot 10^{-12}$
iii.1)	SM-like	SM-like	$\lesssim 2 \cdot 10^{-6}$	$\lesssim 4 \cdot 10^{-8}$	$\lesssim 2 \cdot 10^{-6}$
iii.2)	SM-like	SM-like	$\lesssim 8 \cdot 10^{-15}$	$\lesssim 2 \cdot 10^{-16}$	$\lesssim 9 \cdot 10^{-15}$

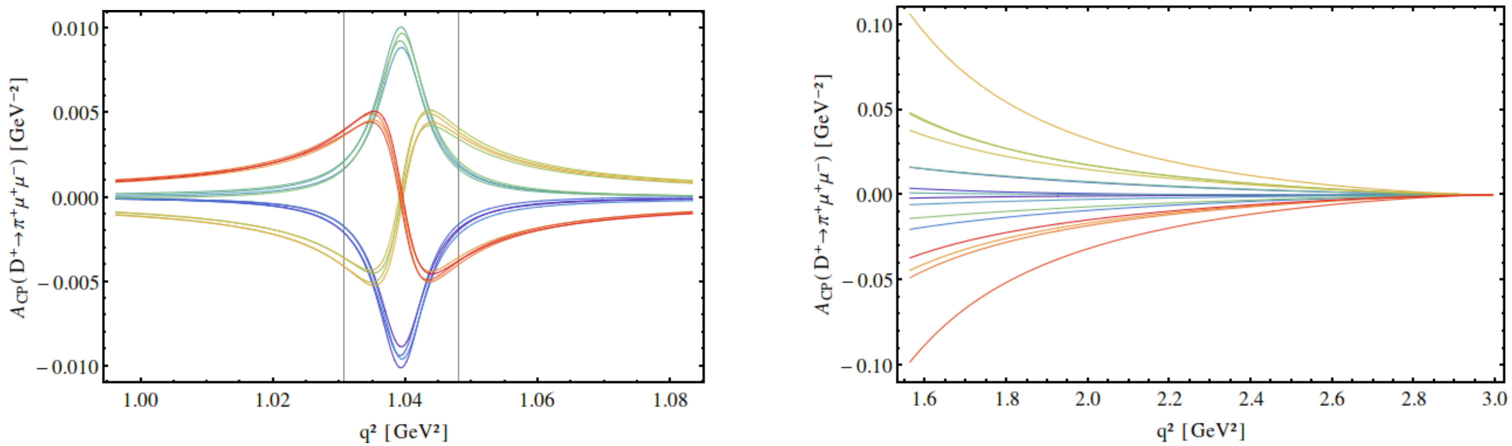
Table 1: Branching fractions for the full q^2-region (high q^2-region) for different classes of leptoquark couplings. Summation of neutrino flavors is understood. "SM-like" denotes a branching ratio which is dominated by resonances or is of similar size as the resonance-induced one. All $c \to ue^+e^-$ branching ratios are "SM-like" in the models considered. Note that in the SM $\mathcal{B}(D^0 \to \mu\mu) \sim 10^{-13}$.

LHCb: arXiv:1512.00322 [hep-ex] $\mathcal{B}(D^0 \to e^\pm\mu^\mp) < 1.3 \cdot 10^{-8}$ at 90 % CL

i): hierarchy, ii) muons only iii) skewed, 1) no kaon bounds 2) kaon bounds apply for $SU(2)_L$-dublets $Q = (c, s)$ 1510.00311

Probing even small couplings: $A_{CP}(D \to \pi ll)$

GIM-suppression can be eased by the resonances, which are less $SU(3)_F$-symmetric than the nr- contributions. also "resonance-catalyzed CP", Fajfer et al '13



Large uncertainties, however, large BSM signals possible ($|A_{CP}^{\rm SM}| \lesssim few 10^{-3}$) even independent of strong phases around Φ.

Opportunity to probe SM-like lorentz-structure $C_{V,A}$ even in presence of $SU(2)$-link to K-physics – links between charm and b-physics

Time-dependent analysis $D^0, \bar{D}^0 \to V\gamma$, $V = \rho^0, \Phi, \bar{K}^{*0}$ (decays to CP eigenstate with CP eigenvalue ξ) 1210.6546 ,1802.02769

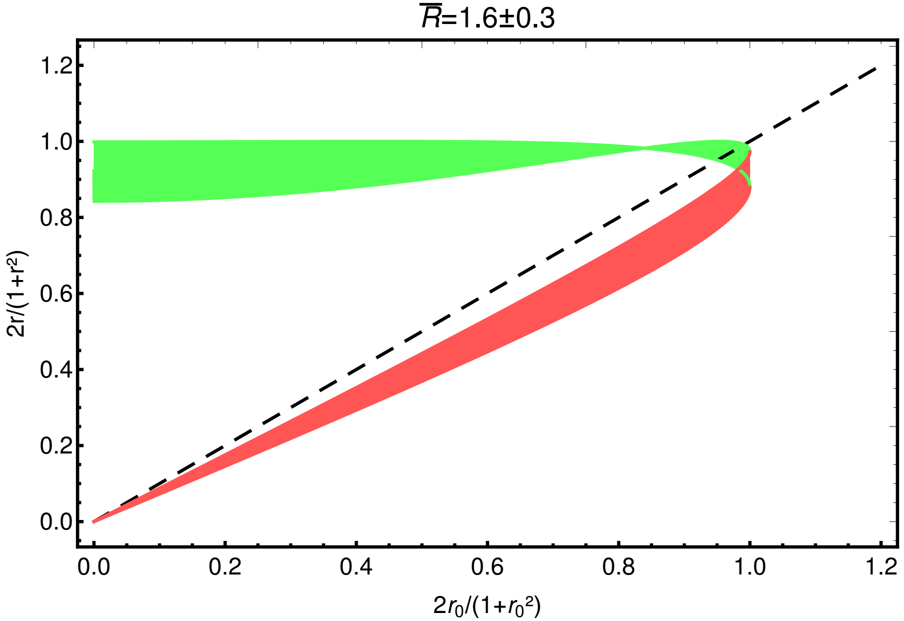
$\Gamma(t) = \mathcal{N} e^{-\Gamma t} \left(\cosh[\Delta\Gamma t/2] + A^{\Delta} \sinh[\Delta\Gamma t/2] + \zeta C \cos[\Delta m t] - \zeta S \sin[\Delta m t]\right)$

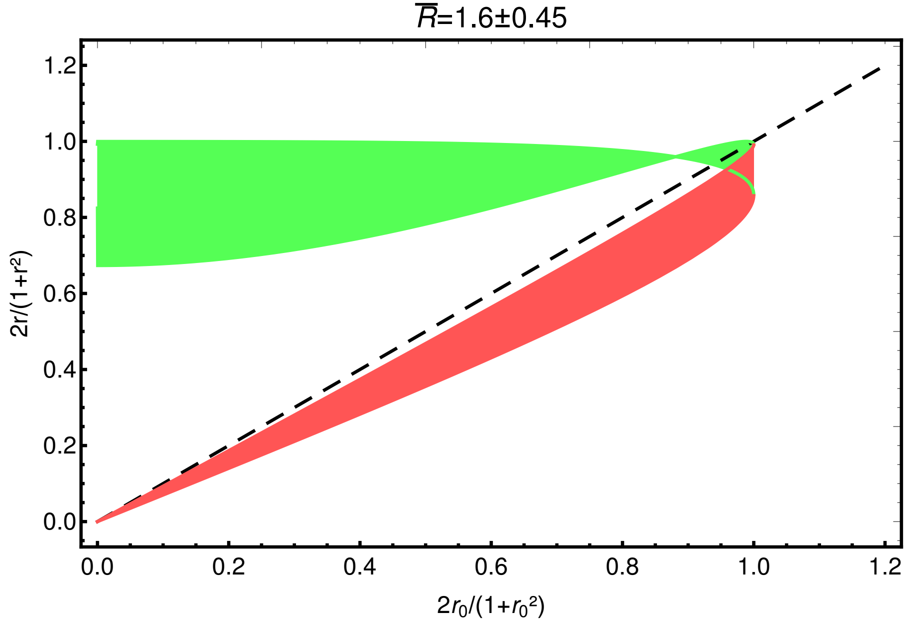
$A^{\Delta}(D^0 \to \bar{K}^{*0}\gamma) \simeq \frac{4\,\xi_{\bar{K}^{*0}} \left|\frac{q}{p}\right| \cos\varphi}{\left(1+\left|\frac{q}{p}\right|^2\right)} \frac{r_0}{1+r_0^2}$ Here, r_0 is ratio of wrong-chirality (RH) to LH-photons in SM-like process $D^0 \to \bar{K}^{*0}\gamma$.

Up to $SU(3)$-breaking: $r(D^0 \to \Phi\gamma) = r_0$, $r(D^0 \to \rho\gamma) = r_0$; perturbative $r = C_7'/C_7$, in SUSY, r unconstrained.

Br's	$D^0 \to \rho^0\gamma$	$D^0 \to \omega\gamma$	$D^0 \to \Phi\gamma$	$D^0 \to \bar{K}^{*0}\gamma$
Belle 2016	$(1.77 \pm 0.31) \times 10^{-5}$	–	$(2.76 \pm 0.21) \times 10^{-5}$	$(4.66 \pm 0.30) \times 10^{-4}$
BaBar 2008	–	–	$(2.81 \pm 0.41) \times 10^{-5}$	$(3.31 \pm 0.34) \times 10^{-4}$
CLEO 1998	–	$< 2.4 \times 10^{-4}$	–	–

Photon polarization in $c \to u\gamma$ from TDA





$2r/(1+r^2)$ as a function of $2r_0/(1+r_0^2)$ (plots to the right), in the cases a) (SM case) $C_7, C_7' \simeq 0$ (black, dashed curve), c) $C_7 \simeq 0$ (green, upper band) and d) $C_7' \simeq 0$ (red, lower band). The upper (lower) plots correspond to $\bar{R}_{ave} = 1.6 \pm 0.3$ ($\bar{R} = 1.6 \pm 0.45$ from 50% inflated uncertainty).

$\bar{R} = 1/f^2 \frac{|V_{cs}|^2}{|V_{cd}|^2} \frac{\mathcal{B}(D^0 \to \rho\gamma)}{\mathcal{B}(D^0 \to \bar{K}^{*0}\gamma)}$ with leading U-spin breaking removed $f = m_\rho f_\rho / (m_{K^{*0}} f_{K^{*0}})$

Photon polarization from up-down asymmetry

Method 2: probe the photon polarization with an up-down asymmetry in $D^0 \to \bar{K}_1(\to \bar{K}\pi\pi)\gamma$ (a la $B \to K_1\gamma$ (Gronau, Pirjpl, Grossman, Kou)

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}s_{13}\,\mathrm{d}s_{23}\,\mathrm{d}\cos\vartheta} \propto |\boldsymbol{J}|^2(1+\cos^2\vartheta) + \lambda_\gamma 2\,\mathrm{Im}[\boldsymbol{n}\cdot(\boldsymbol{J}\times\boldsymbol{J}^*)]\cos\vartheta\,,\ \lambda_\gamma = -\frac{1-r_0^2(\bar{K}_1)}{1+r_0^2(\bar{K}_1)}$$

The corresponding BSM-sensitive mode is $D_s \to \bar{K}_1(\to \bar{K}\pi\pi)\gamma$.

Method requires D-tagging but unlike TDA, does not depend on strong phases between LH and RH amplitude.

$K_1(1270)$ dominant in charm as $K(1400)$ family phase space suppressed by about factor of 2.

Constraints on up-sector FCNCs are at the level of b-physics in the last millenium. $c \to u\mu\mu, \gamma$: $|C_{9,10}^{(\prime)}| \lesssim 1$, $|C_7^{(\prime)}| \lesssim 0.3$, $|C_{T,T5}| \lesssim 1$, $|C_{S,P}^{(\prime)}| \lesssim 0.1$.

versus $C_7^{\rm SM} \simeq 0.004\,, C_9^{\rm SM} \simeq -0.01\,, \quad C_{10}^{\rm SM} = 0\,,$ (GIM !) $\quad C'^{\rm SM}, C_{S,P,T,T5}^{\rm SM} = 0$

Charm decays into leptons are plagued by resonance contributions; BSM physics can be seen in rates only if very large (still possible!), or in SM null tests, several of which we discussed. SM BGD in $c \to u$ photon polarization can be measured using U-spin. – Great prospects to test the SM and look for BSM physics in semileptonic and radiative rare D decays, complementary to K, B-decays.

Opportunities for BESIII, Belle II and LHCb

Unique information on flavor in the up-sector

Summary

- Current anomalies $R_{K^{(*)}}, R_{D^{(*)}}$ in semileptonic B-meson decays hint at violation of lepton-universality – and breakdown of SM. The April 2017 release of R_{K^*} by LHCb has strengthened the hints and allowed to pin down the Dirac structure: predominantly $V-A$-type.

- Future data – LNU updates and other observables $R_\Phi, R_{X\,s}..., B \to K^* ee$ – from LHCb and in the nearer future from Belle II are eagerly awaited.

- What makes these LNU-anomalies – iff true– so important? Because they are theoretically clean and intimately linked to "flavor": Look for imprints in other sectors: D, K physics, LFV. see talks

- In addition, new BSM model-buildung has been triggered that deserves attention in direct searches at ATLAS and CMS and future colliders.
  Leptoquarks are flavorful and can be in reach of the LHC, where they can provide complementary information to rare decays: $\lambda_{s\ell}, \lambda_{b\ell}, M$ vs $\lambda_{b\ell}\lambda^*_{s\ell}/M^2 \simeq 1/(35\,\text{TeV})^2$
  Model-independent upper limit by B_s-mixing $\propto (\lambda_{b\ell}\lambda_{s\ell})^2/M^2$ at ~ 40 TeV.
  bulk of parameter space outside of LHC.

BACK-UP

$c \to u$ amplitudes are strongly GIM-suppressed:

$\mathcal{A}_{c\to u} \simeq \sin\Theta_C[f(m_s^2/m_W^2) - f(m_d^2/m_W^2)] + O(\sin^5\Theta_C)$

Resulting (non-resonant) SM branching ratios are $10^{-12} - 10^{-13}$:

q^2-bin	$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)^{\rm SM}_{\rm nr}$	90% CL limit LHCb'13
full q^2:	$3.7 \cdot 10^{-12}\,(\pm1, \pm3, ^{+16}_{-15}, \pm1, ^{+4}_{-1}, ^{+158}_{-1}, ^{+16}_{-12})$	$7.3 \cdot 10^{-8}$
low q^2:	$7.4 \cdot 10^{-13}\,(\pm1, \pm4, ^{+23}_{-21}, ^{+10}_{-11}, ^{+11}_{-1}, ^{+238}_{-23}, ^{+6}_{-5})$	$2.0 \cdot 10^{-8}$
high q^2:	$7.5 \cdot 10^{-13}\,(\pm1, \pm6, ^{+15}_{-14}, \pm6, ^{+2}_{-1}, ^{+136}_{-45}, ^{+27}_{-20})$	$2.6 \cdot 10^{-8}$

Table 2: Non-negligible uncertainties correspond to (normalization, m_c, m_s, μ_W, μ_b, μ_c, f_+), respectively, given in percent arXiv:1510.00311, see PhD thesisof S de Boer (2017) for 2-loop effects

Largest uncertainty: μ_c-scale dependence $m_c/\sqrt{2} < \mu_c \leq \sqrt{2}m_c$.

Θ: angle between negatively charged lepton and D in dilepton cms

$$\frac{d\Gamma(D \to \pi l^+ l^-)}{d\cos\Theta} = \frac{3}{4}(1 - F_H)(1 - \cos^2\Theta) + A_{FB}\cos\Theta + F_H/2$$ Bobeth et al '07

SM: $A_{FB}, F_H \simeq 0$ by lorentz-structure and small lepton masses. Both require S,P- and or tensor operators.

Model-independently, striking BSM signals possible (high q^2):

$|A_{\rm FB}(D^+ \to \pi^+\mu^+\mu^-)| \lesssim 0.6$, $|A_{\rm FB}(D^+ \to \pi^+e^+e^-)| \lesssim 0.8$ and $F_H(D^+ \to \pi^+l^+l^-) \lesssim 2$ for $l = e, \mu$.

LFV-rates and dineutrino modes which vanish in SM can be just around the corner (model-independently).

Flavor patterns of leptoquark coupling matrix λ (rows=quark flavor, columns=lepton flavor):

$$\lambda_{ql} \sim \begin{pmatrix} \rho_d\kappa & \rho_d & \rho_d \\ \rho\kappa & \rho & \rho \\ \kappa & 1 & 1 \end{pmatrix}, \quad \begin{pmatrix} 0 & * & 0 \\ 0 & * & 0 \\ 0 & * & 0 \end{pmatrix}, \quad \begin{pmatrix} * & 0 & 0 \\ 0 & * & 0 \\ 0 & * & 0 \end{pmatrix}, \ldots$$

LQs make interesting link between quark (hierarchy) and lepton (anarchy? non-abelian discrete?) flavor 1503.01084.