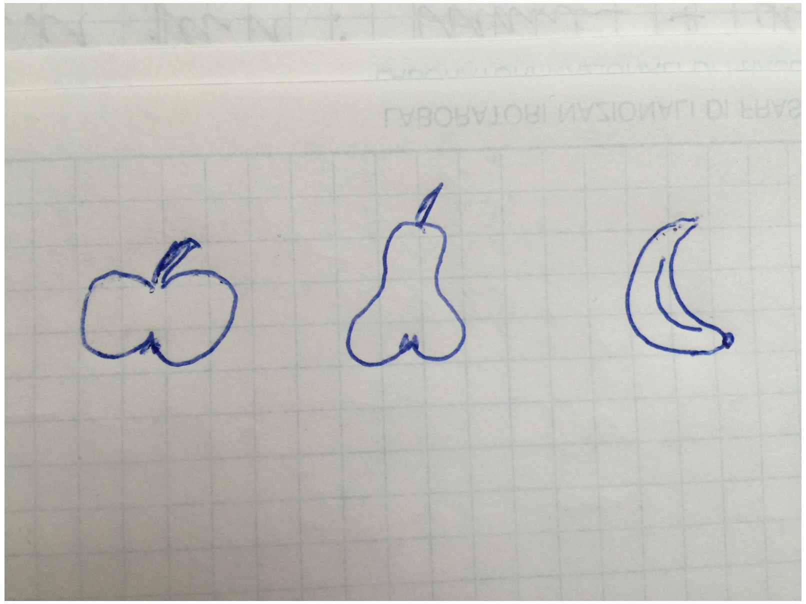
Theory prospects for LNU starting from semileptonic B decays

thanks to collaboration with Christoph Bobeth, Stefan de Boer, Frank Krüger, Dennis Loose, Ivan Nisandzic, Martin Schmaltz, Kay Schönwald and Ivo de Medeiros Varzielas hep-ph/0310219, 0709.4174, 1408.1627, 1411.4773, 1503.01084, 1510.00311, 1609.08895, 1704.05444

Gudrun Hiller, TU Dortmund



The same yet not the same

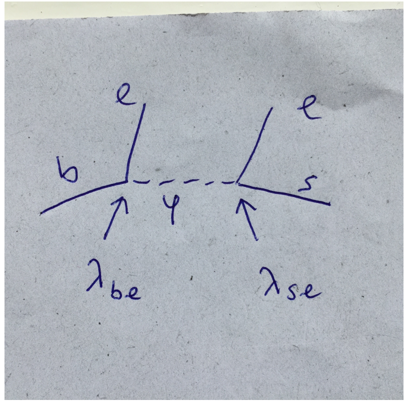
Iff $R_K, R_{K^*} \neq 1$ it would not only be a (loud) breakdown of the SM, it tells us something about flavor $\rightarrow$ hope to learn something about flavor

R_K, R_{K^*} today: Face-value interpretations (popular)

$C_9^\mu = -C_{10}^\mu \simeq -0.6$ vs $C_9^{SM} \simeq -C_{10}^{SM} \simeq 4$

about 20 % BSM contribution to $O_{LL} = \bar{s}\gamma_\mu L b \ell \gamma^\mu L \ell$.

this is actually exactly according to the program behind testing the SM with FCNCs. They are suppressed (GIM,CKM,loop) in SM and BSM physics can show up without big competition.



Tree level explanations:

$\frac{\lambda^2}{M^2} \sim \frac{1}{5}\frac{g^4}{m_W^2}\frac{1}{16\pi^2}V_{tb}V_{ts}^* \sim \frac{1}{(30\mathrm{TeV})^2}$

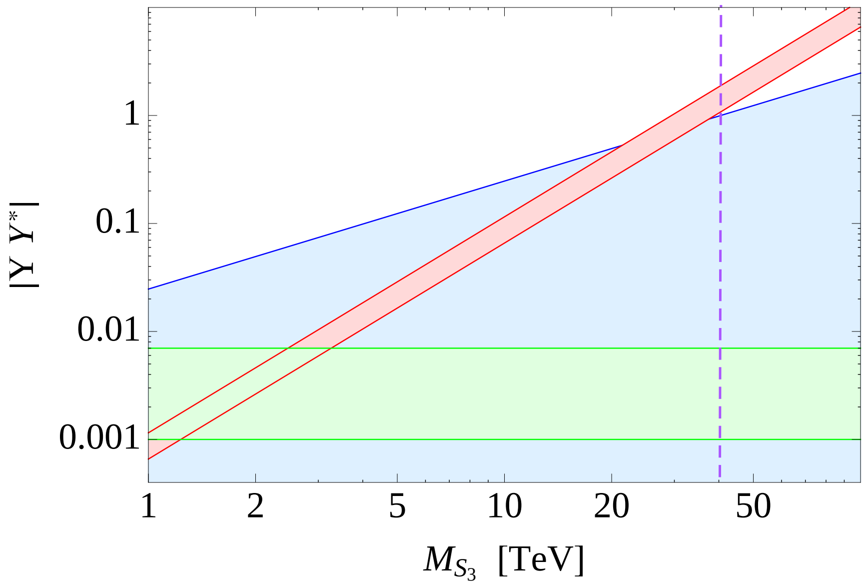
with order one couplings this points to a collider-mass scale.

with (minimal) flavor $\frac{\lambda^2}{M^2} \sim \frac{1}{5}\frac{g^4}{m_W^2}\frac{1}{16\pi^2} \sim \frac{1}{(6\mathrm{TeV})^2}$

this is within reach of the LHC

Flavor models that explain quark, lepton masses, CKM, PMNS the BSM couplings can be furthers suppressed $\rightarrow$ lower BSM mass.

R_{K,K^*}: $\frac{Y_{b\mu}Y^*_{s\mu} - Y_{be}Y^*_{se}}{M^2} \simeq \frac{1.1}{(35\,\text{TeV})^2}$, (S_3) scalar triplet GH, Nisandzic, 1704.05444



red: explains R_K, R_{K^*}, blue: allowed by B_s mixing, green: flavor model prediction

$Y_{q_3\ell} \sim c_l\,, \quad Y_{q_2\ell} \sim c_l\lambda^2\,, \quad q_3 = b,t, \;\; q_2 = s,c, \;\; \lambda, c_l \lesssim 0.2$ points to low mass!

Model-independent upper limit by B_s-mixing $\propto \lambda^4/M^2$ at 40 TeV.

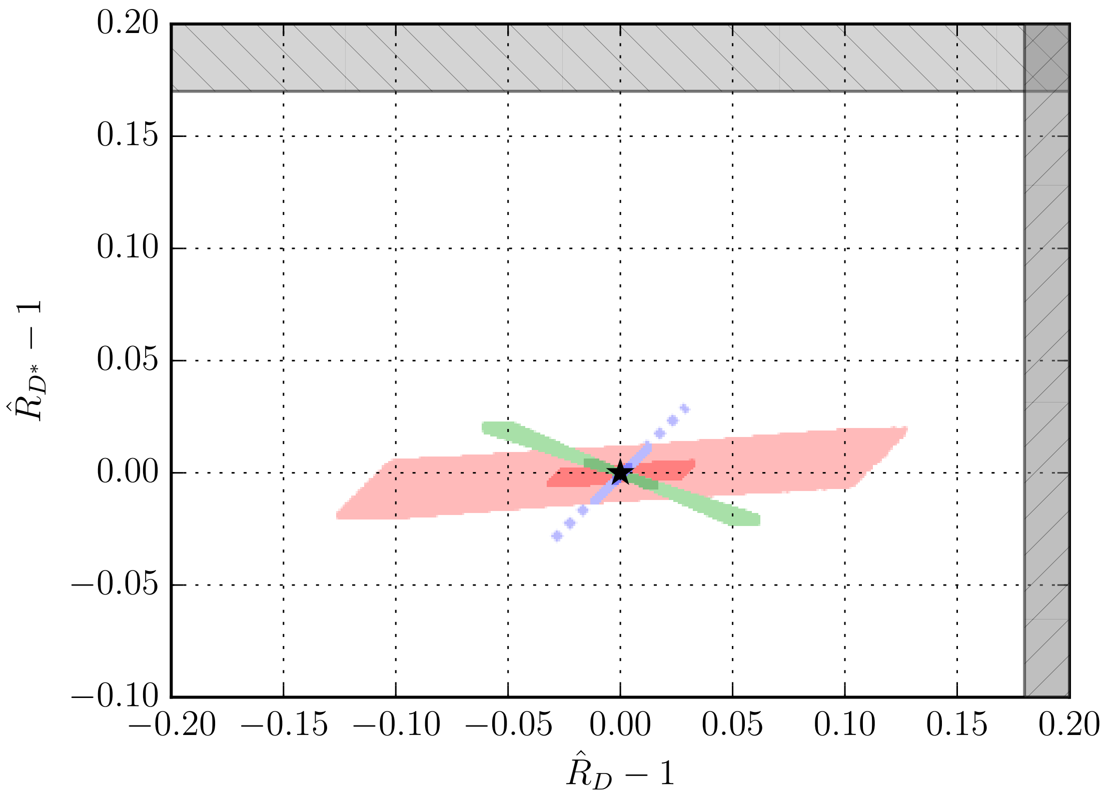
The expected mass scale depends on flavor.

The size of the effect – current hints for SM deviation – in $R_K(*)$ is ”natural”, in the center of parameter space. How about $R_D(*)$? tree-level in SM, similar order of anomalous data as $R_K(*)$ implies large couplings and very low BSM: see talk by Y.Soreq and G.Isidori,A.Crivellin

	gen	minimal	PMNS/CKM
$R_K(*)$ tree	30 TeV	6 TeV	few TeV
$R_K(*)$ loop	few TeV	0.5 TeV	expected similar to $R_D(*)$
$R_D(*)$ tree	$\sim$ a TeV	0.3 TeV	not viable 1609.08895

Linking the anonalies is intruiging however not straigthforward, lower deviation in $R_D(*)$, in particular R_D* would be more ”natural”.

$R_D^{(*)}$ from leptoquarks with flavor?



$\hat{R}_{D(*)} = R_{D(*)}/R^{\rm SM}_{D(*)}$; star: SM, grey: exp 1σ band (too far away from SM to fit the plot); red:V_1,blue V_3, green S_2 LQs with flavor patterns, constraints: rare K decays, $\mu - e$ conversion, $B \to K\nu\nu$, perturbativity

$R_{K^{(*)}}$

- triggered different type of model-building Z', leptoquarks
- its plausible
- its an opportunity
- how to consolidate? rule out?
- if this really stays, decipher

1. Study more ratios and more precisely including in high q^2 bins see talks by M.Schune,M.Patel

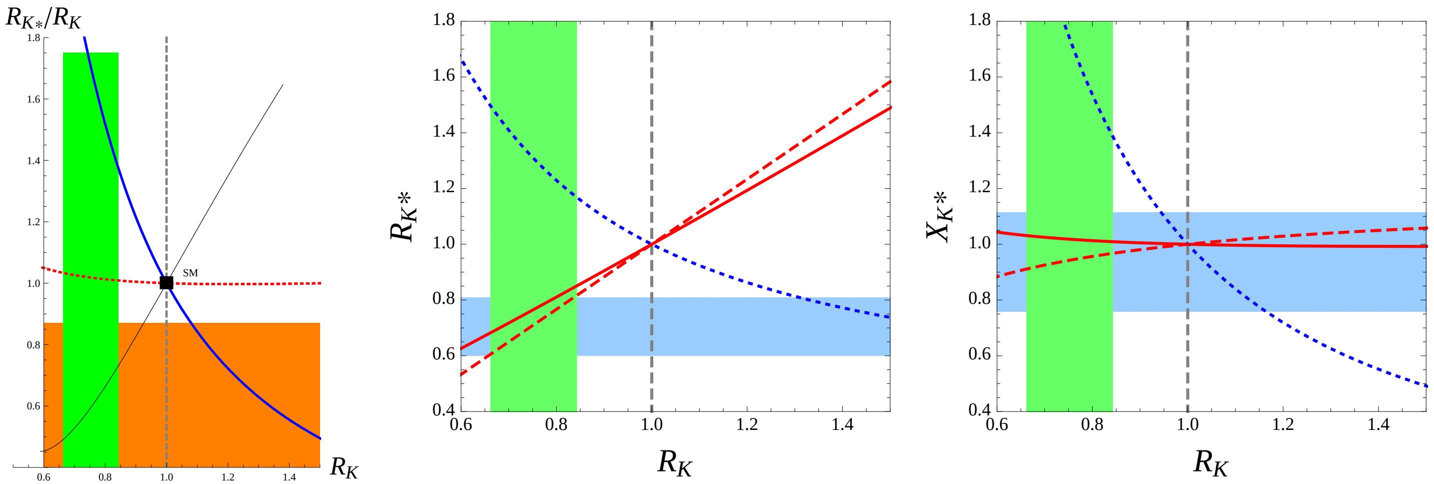
$$R_H = \frac{\mathcal{B}(\bar{B}\to\bar{H}\mu\mu)}{\mathcal{B}(\bar{B}\to\bar{H}ee)}, \quad H = K, K^*, X_s, \ldots$$ GH, Krüger '03

At linear approximation it suffices to measure 2 different (by spin parity of final hadron) R_H ratios and then all others serve as consistency checks 1411.4773.

$$\begin{aligned} C + C' : &\quad K, K^*_\perp, \ldots \\ C - C' : &\quad K_0(1430), K^*_{0,\parallel}, \ldots \end{aligned}$$

and at both high and low q^2 windows $K^*_\perp$ subleading, predictions: $R_K \simeq R_\eta$, $R_{K^*} \simeq R_\Phi \simeq R_{K_0(1430)}$ and all R_H equal if no V+A currents.

The measurement of R_K and R_{K^*} does this diagnozing job. SM-like chirality operators are the dominant source behind the anomalies. Prediction: $R_{X_s} \simeq 0.73 \pm 0.07$ inclusive decays, Belle II



Green band: R_K 1 σ LHCb, blue band R_{K^*} 1 σ LHCb. Different BSM scenarios are red dashed: pure C_{LL} (LQ triplet). Black solid: $C_{LL} = -2C_{RL}$. Blue: C_{RL} (LQ dublet)/disfavoured as doninant source.

$R_H < 1$: too few muons, or too many electrons, or combination thereof.

2. To disentangle this lepton specific modes are required.

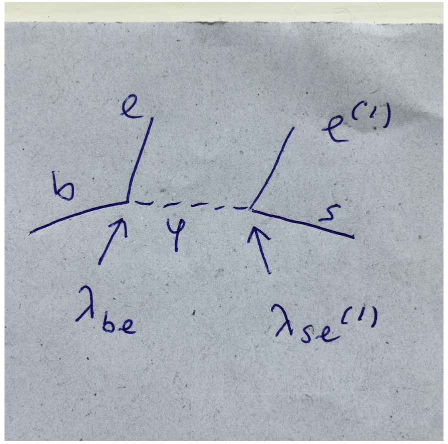
$B \to Hee$ and $B \to H\mu\mu$ studies; global fits see talks by K.Petridis,N.Mahmoudi,J.Virto,s.Jäger

It is interesting that also $B \to K, K^* \mu\mu$ has presently an anomaly, that even can point to the same direction as R_{K,K^*}.

LNU in explicit models can be arranged by gauging lepton flavor (Z'); LQs can be charged under flavor group. see talks by D.Straub,J.Fuentes,F.Bishara, M.Quiros, G.Panico

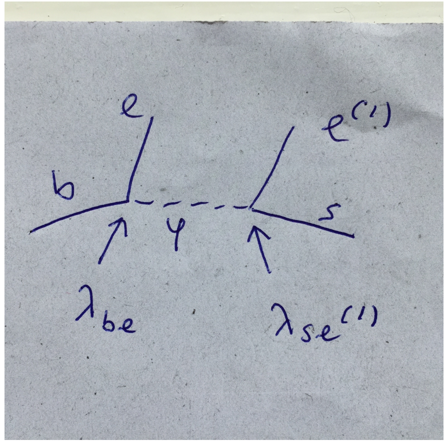
From a flavor perspective, LNU quite generically implies LFV

Guadagnoli, Kane



3. Search for LFV

in B-decays, in charm decays, and with charged leptons (μ -e conversion, rare decays) see ttalks by Crivellin, Paradisi



Leptoquark coupling matrix: $\lambda_{ql} \equiv \begin{pmatrix} \lambda_{q_1 e} & \lambda_{q_1 \mu} & \lambda_{q_1 \tau} \\ \lambda_{q_2 e} & \lambda_{q_2 \mu} & \lambda_{q_2 \tau} \\ \lambda_{q_3 e} & \lambda_{q_3 \mu} & \lambda_{q_3 \tau} \end{pmatrix}$

columns$=$leptons

rows$=$quarks

structures not present in standard model!

columns=leptons, discrete non-abelian flavor symmteries (sub-groups of $SU(3)$), e.g.. A_4) ”zeros and ones”

Rows=quarks, hierarchical, $U(1)$-Froggatt-Nielsen-Symmetry
$1 \gg \rho \gg \rho_d$

We can use these symmetries to explain quark and lepton properties. Then predict the leptoquark coupling, e.g.,

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

second matrix can explain R_K – leptoquark couples to muons only.

Very general ansatz 1503.01084

LQ coupling matrix: $\lambda_{ql} \equiv \begin{pmatrix} \lambda_{q_1 e} & \lambda_{q_1 \mu} & \lambda_{q_1 \tau} \\ \lambda_{q_2 e} & \lambda_{q_2 \mu} & \lambda_{q_2 \tau} \\ \lambda_{q_3 e} & \lambda_{q_3 \mu} & \lambda_{q_3 \tau} \end{pmatrix} \sim \begin{pmatrix} \rho_d \kappa & \rho_d & \rho_d \\ \rho \kappa & \rho & \rho \\ \kappa & 1 & 1 \end{pmatrix}$

rows $=$quarks, columns$=$ leptons

data:

$$\rho_d \lesssim 0.02\,, \quad \kappa \lesssim 0.5\,, \quad 10^{-4} \lesssim \rho \lesssim 1\,, \quad \kappa/\rho \lesssim 0.5\,, \quad \rho_d/\rho \lesssim 1.6\,.$$

Froggatt-Nielsen:

$\rho \sim \epsilon^2$, $\rho_d \sim \epsilon^3$ or ϵ^4 , (Q_L) $\qquad$ $\rho \sim \epsilon$, $\rho_d \sim \epsilon$ or ϵ^2 , (D_R) with $\epsilon \sim 0.2$.

observable	current 90 % CL limit	constraint	future sens.
$\mathcal{B}(\mu \to e\gamma)$	$5.7 \cdot 10^{-13}$ MEG	$\lvert\lambda_{qe}\lambda^*_{q\mu}\rvert \lesssim \frac{M^2}{(34\mathrm{TeV})^2}$	$6 \cdot 10^{-14}$ MEG
$\mathcal{B}(\tau \to e\gamma)$	$1.2 \cdot 10^{-8}$ Belle	$\lvert\lambda_{qe}\lambda^*_{q\tau}\rvert \lesssim \frac{M^2}{(1\mathrm{TeV})^2}$	
$\mathcal{B}(\tau \to \mu\gamma)$	$4.4 \cdot 10^{-8}$ Babar	$\lvert\lambda_{q\mu}\lambda^*_{q\tau}\rvert \lesssim \frac{M^2}{(0.7\,\mathrm{TeV})^2}$	$5 \cdot 10^{-9}$ $[B2]$
$\mathcal{B}(\tau \to \mu\eta)$	$6.5 \cdot 10^{-8}$ Belle	$\lvert\lambda_{s\mu}\lambda^*_{s\tau}\rvert \lesssim \frac{M^2}{(3.7\,\mathrm{TeV})^2}$	$2 \cdot 10^{-9}$ $[B2]$
$\mathcal{B}(B \to K\mu^\pm e^\mp)$	$3.8 \cdot 10^{-8}$ BaBar	$\sqrt{\lvert\lambda_{s\mu}\lambda^*_{be}\rvert^2 + \lvert\lambda_{b\mu}\lambda^*_{se}\rvert^2} \lesssim \frac{M^2}{(19.4\,\mathrm{TeV})^2}$	
$\mathcal{B}(B \to K\tau^\pm e^\mp)$	$3.0 \cdot 10^{-5}$ PDG	$\sqrt{\lvert\lambda_{s\tau}\lambda^*_{be}\rvert^2 + \lvert\lambda_{b\tau}\lambda^*_{se}\rvert^2} \lesssim \frac{M^2}{(3.3\,\mathrm{TeV})^2}$	
$\mathcal{B}(B \to K\mu^\pm \tau^\mp)$	$4.8 \cdot 10^{-5}$ PDG	$\sqrt{\lvert\lambda_{s\mu}\lambda^*_{b\tau}\rvert^2 + \lvert\lambda_{b\mu}\lambda^*_{s\tau}\rvert^2} \lesssim \frac{M^2}{(2.9\,\mathrm{TeV})^2}$	$\lesssim 10^{-6}$ K.Petridis
$\mathcal{B}(B \to \pi\mu^\pm e^\mp)$	$9.2 \cdot 10^{-8}$ BaBar	$\sqrt{\lvert\lambda_{d\mu}\lambda^*_{be}\rvert^2 + \lvert\lambda_{b\mu}\lambda^*_{de}\rvert^2} \lesssim \frac{M^2}{(15.6\,\mathrm{TeV})^2}$	

Table 1: Selected LFV data, constraints and future sensitivities. Here, $q = d, s, b$. The Belle II projections $[B2]$ are for $50\,ab^{-1}$. For the constraint from $\mathcal{B}(\tau \to \mu\eta)$ we ignored the possibility of cancellations with $\lambda_{d\mu}\lambda^*_{d\tau}$, see *e.g.*, [**?**]. We ignore tuning between leading order diagrams in the $\ell \to \ell'\gamma$ amplitudes. R_K: $0.7 \lesssim \mathrm{Re}[\lambda_{se}\lambda^*_{be} - \lambda_{s\mu}\lambda^*_{b\mu}]\frac{(24\mathrm{TeV})^2}{M^2} \lesssim 1.5$, K-decays $\lvert\lambda_{d\mu}\lambda^*_{s\mu}\rvert \lesssim \frac{M^2}{(183\mathrm{TeV})^2}$

predictions:

$$\mathcal{B}(B \to K\mu^{\pm}e^{\mp}) \simeq 3 \cdot 10^{-8}\, \kappa^2 \left(\frac{1 - R_K}{0.23}\right)^2 , \tag{1}$$

$$\mathcal{B}(B \to Ke^{\pm}\tau^{\mp}) \simeq 2 \cdot 10^{-8}\, \kappa^2 \left(\frac{1 - R_K}{0.23}\right)^2 , \tag{2}$$

$$\mathcal{B}(B \to K\mu^{\pm}\tau^{\mp}) \simeq 2 \cdot 10^{-8} \left(\frac{1 - R_K}{0.23}\right)^2 , \tag{3}$$

and

$$\mathcal{B}(\mu \to e\gamma) \simeq 2 \cdot 10^{-12} \, \frac{\kappa^2}{\rho^2} \left(\frac{1 - R_K}{0.23} \right)^2 , \tag{4}$$

$$\mathcal{B}(\tau \to e\gamma) \simeq 4 \cdot 10^{-14} \, \frac{\kappa^2}{\rho^2} \left(\frac{1 - R_K}{0.23} \right)^2 , \tag{5}$$

$$\mathcal{B}(\tau \to \mu\gamma) \simeq 3 \cdot 10^{-14} \, \frac{1}{\rho^2} \left(\frac{1 - R_K}{0.23} \right)^2 , \tag{6}$$

$$\mathcal{B}(\tau \to \mu\eta) \simeq 4 \cdot 10^{-11} \, \rho^2 \left(\frac{1 - R_K}{0.23} \right)^2 . \tag{7}$$

asymmetric branching ratios:

$$\frac{\mathcal{B}(B_s \to \ell^+\ell'^-)}{\mathcal{B}(B_s \to \ell^-\ell'^+)} \simeq \frac{m_\ell^2}{m_{\ell'}^2}\,. \quad \text{Left-handed leptons only} \tag{8}$$

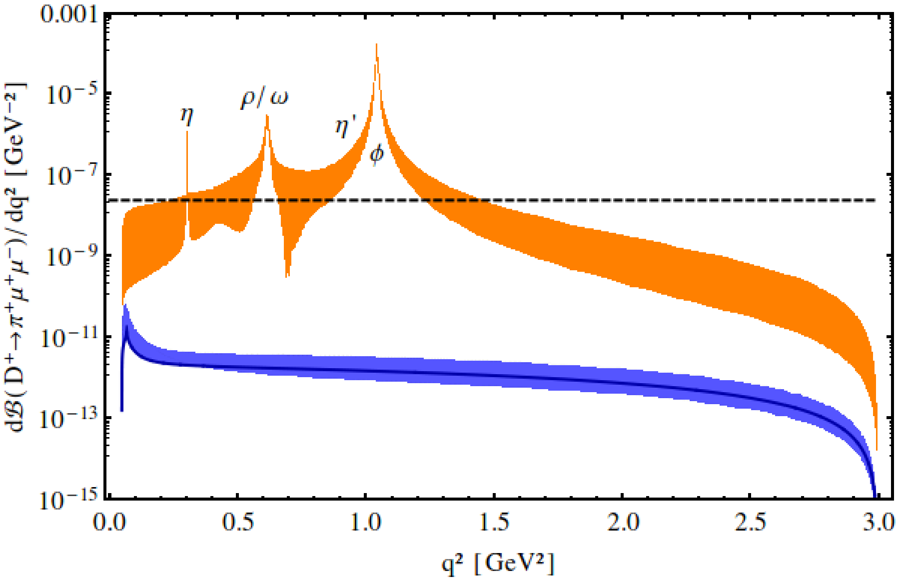
$$\frac{\mathcal{B}(B_s \to \mu^+e^-)}{\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm SM}} \simeq 0.01\,\kappa^2 \cdot \left(\frac{1-R_K}{0.23}\right)^2\,, \tag{9}$$

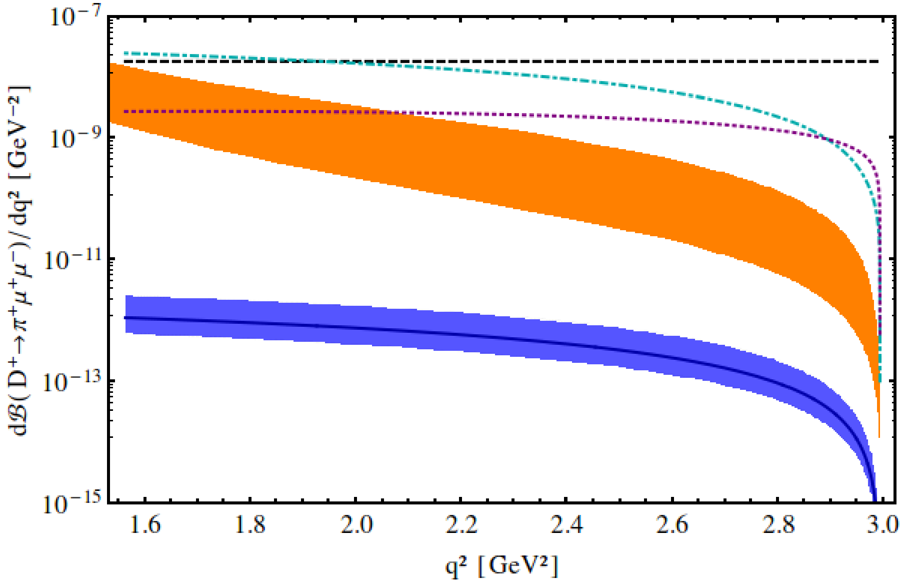
$$\frac{\mathcal{B}(B_s \to \tau^+e^-)}{\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm SM}} \simeq 4\,\kappa^2 \cdot \left(\frac{1-R_K}{0.23}\right)^2\,, \tag{10}$$

$$\frac{\mathcal{B}(B_s \to \tau^+\mu^-)}{\mathcal{B}(B_s \to \mu^+\mu^-)_{\rm SM}} \simeq 4 \cdot \left(\frac{1-R_K}{0.23}\right)^2\,, \tag{11}$$

Impact on $c \to u\ell\ell$?

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.

$|C_9^R(q^2 = 1.5\,\text{GeV}^2)| \simeq 0.8$ versus $|C_9^{nr\,\text{SM}}(q^2 \gtrsim 1\,\text{GeV}^2)| \lesssim 5 \cdot 10^{-4}$.

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.)

Sample flavor patterns of leptoquark coupling matrix λ (rows=quark flavor, columns=lepton flavor) that follow from $U(1) \times A_4$

$$\lambda_{i)} \sim \begin{pmatrix} \rho_d \kappa & \rho_d & \rho_d \\ \rho \kappa & \rho & \rho \\ \kappa & 1 & 1 \end{pmatrix}, \quad \lambda_{ii)} \sim \begin{pmatrix} 0 & * & 0 \\ 0 & * & 0 \\ 0 & * & 0 \end{pmatrix}, \quad \lambda_{iii)} \sim \begin{pmatrix} * & 0 & 0 \\ 0 & * & 0 \\ 0 & * & 0 \end{pmatrix},$$

	$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)$	$\mathcal{B}(D^0 \to \mu^+\mu^-)$	$\mathcal{B}(D^+ \to \pi^+e^\pm\mu^\mp)$	$\mathcal{B}(D^0 \to \mu^\pm e^\mp)$	$\mathcal{B}(D^+ \to \pi^+\nu\bar{\nu})$
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 2: 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 $Q = (c, s)$

A leptoquark -triplet model

Scalar LQ $S_3(3,3,-1/3)$, $C_9^{\mathrm{NP}\mu} = -C_{10}^{\mathrm{NP}\mu}$ and $M < 40$ TeV and lower with flavor considerations (similar for vector Lqs V_1 with $M < 45$ TeV and , V_3 with $M < 20$ TeV)

Decay modes of LQ-triplet (assuming R_{K,K^*} from muons)

$$\begin{aligned}
\varphi^{2/3} &\rightarrow (t,c)\nu \\
\varphi^{-1/3} &\rightarrow (b,s)\,\nu\,,\;(t,c)\,\mu^- \\
\varphi^{-4/3} &\rightarrow (b,s)\,\mu^-
\end{aligned}$$

other leptons (e,τ) equally interesting to probe flavor

4. Pursue dedicated collider searches (LQs: pair-productions, single LQ production) see talk by G.Isidori

more leptoquarks and R_K Fajfer, Kosnik Nisandzic, Gripaios, Nardeccia, Crivellin, Neubert, Renner, et al ..

Summary

- Current anomalies $R_K, R_{K^*}, R_D, R_{D^*}$ in semileptonic B-meson decays hint at violation of lepton-universality – and therefore breakdown of standard model.
- The recent release of R_{K^*} by LHCb has strengthened the hints and allows to pin down the Dirac structure: predominantly $V - A$-type.
- Possible explanations naturally connect to the flavor puzzle; important to clarify the anomalies as they can give new insights towards the origin of flavor and generational structure by probing models of flavor.
- Future data – LNU updates and other observables R_Φ, R_{Xs}...– from LHCb and in the nearer future from Belle II (KEK, Japan) are eagerly awaited.
- New BSM model-buildung (UV-completion ...) has been triggered that deserves attention in direct searches at ALTAS and CMS.