BSM opportunities with CHARM and leptons

based on works with Stefan de Boer, arXiv:1510.00311 [hep-ph].

Gudrun Hiller, Dortmund

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Generational structure & mixing is a feature of the SM and many BSM particles. VIRTUES:

i) high sensitivity to BSM in flavor violation;
FCNCs $b \to s\ell\ell, \mu \to e\gamma, h \to \tau\mu, ...$
we may discover BSM in flavor physics (even first)

ii) flavorful processes are intrinsically linked to the ”flavor puzzle”:
masses, i.e., Y_{SM} do not appear to be random – from where?
with a BSM-signal, we may be able to progress here

iii) plenty of modes $s \to d$, $c \to u$, $b \to s, d$, $t \to c, u$, $\mu \to e$, $\tau \to \mu, e$
plus charged ones and $h \to f\bar{f}'$; ongoing & future experiments, too.
we may identify $\mathcal{L}_{BSM}$; complementary to direct searches

crosstalk theory(SM/BSM)/pheno/experiment

new bottom-up New Physics benchmark models

leptons $\leftrightarrow$ quarks

-SM precision: Higher order, hadronic matrix elements, lattice QCD

- multi-observable fits to couplings "Wilson coefficients" $C^{(\prime)}_{7,9,10}$ of standardized $|\Delta B| = |\Delta S| = 1$ effective hamiltonian; few groups, dedicated effort, exploit correlations, precision test of the SM

- design/use clean observables; related to (approximate) symmetries of the SM: lepton-nonuniversality, CP, helicity, LFV .. "null tests"

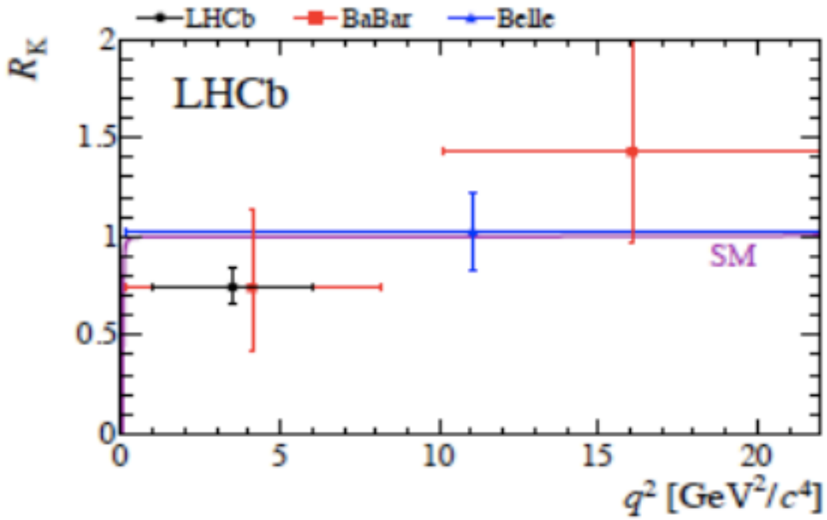
- bottom-up model-building/simplified models (Z', extra Higgses, leptoquarks..) "data-driven"

- Higgs physics: $hf\bar{f}$ and $hf\bar{f}'$ – are couplings SM-like?

- quarks together with leptons: recents hints of lepton-nonuniversality in B-decays R_K, R_{D^*}.

$$R_H = \frac{\mathcal{B}(\bar{B}\to\bar{H}\mu\mu)}{\mathcal{B}(\bar{B}\to\bar{H}ee)}, \quad H = K, K^*, X_s, ...$$

Lepton-universal models(SM): $R_H = 1+$tiny, GH, Kruger



LHCb 2014: $R_K = 0.745 \pm^{0.090}_{0.074} \pm 0.036 < 1$ at 2.6 σ

apriori too few muons, or too many electrons, or combination thereof.

Model-independent interpretations with V,A operators: Das et al

$$0.7 \lesssim \mathrm{Re}[X^e - X^\mu] \lesssim 1.5\,,$$
$$X^\ell = C_9^{\mathrm{NP}\ell} + C_9^{\prime\ell} - (C_{10}^{\mathrm{NP}\ell} + C_{10}^{\prime\ell})$$

Tensors and S,P muon operators are excluded as sole sources of R_K; S,P electronic operators allowed at 2 σ and require cancellations, testable with $\bar{B} \to \bar{K}ee$ angular distributions.

$X^e \simeq 0$ and $X^\mu \simeq C_9^{\mu NP} \simeq -1$ is consistent with global fit.

Why are muons different from electrons?

Splitting electrons from muons:

Z'- $U(1)_{\tau-\mu}$ (BSM in $b \to s\mu\mu$, not in $b \to see$).

Altmannshofer, Crivellin, Fuentes, Vicente, .. et al

Links with $h \to \tau\mu$ with extras Higgses Cvrivellin et al, Heeck et al

new particle exchanged at tree level, including leptoquarks, MSSM with R-Parity violation amended with Froggatt-Nielsen flavor symmetry (both $\mu\mu$ and/or ee possible) Schmaltz, Gripaios, Varzielas, .. et al

This naturally provides a link for LFV decays Guadagnoli, Kane, Varzielas which however is not strict , Alonso et al, Fuentes et al.

pl see original refs for complete list of contributions to this effort

Of course charm FCNCs are of interest by themselves, however, the recent anomalies in semileptonic B-decays add to the physics case of charm decays into leptons.

Improved (N)NLO calculation in SM: S de Boer et al, to appear, DO-TH 15-11

2-step matching:

$$\mathcal{L}_{\text{eff}}^{\text{weak}}|_{m_W \geq \mu > m_b} = \frac{4G_F}{\sqrt{2}} \sum_{q=d,s,b} V_{cq}^* V_{uq} \left(\tilde{C}_1(\mu) P_1^{(q)}(\mu) + \tilde{C}_2(\mu) P_2^{(q)}(\mu) \right) , \tag{1}$$

$$\mathcal{L}_{\text{eff}}^{\text{weak}}|_{m_b > \mu \geq m_c} = \frac{4G_F}{\sqrt{2}} \sum_{q=d,s} V_{cq}^* V_{uq} \left(\tilde{C}_1(\mu) P_1^{(q)}(\mu) + \tilde{C}_2(\mu) P_2^{(q)}(\mu) - \sum_{i=3}^{10} \tilde{C}_i(\mu) P_i(\mu) \right) . \tag{2}$$

$P_{1,2}^{(q)}$: tree-level W-induced. $P_{3..10}$: penguins

	$j=1$	$j=2$	$j=7$	$j=8$	$j=9$	$j=10$
$\tilde{C}_j^{(0)}$	-1.0275	1.0925	0	0	-0.0030	0
$(\alpha_s/(4\pi))\,\tilde{C}_j^{(1)}$	0.3214	-0.0549	0.0035	-0.0020	0.0004	0
$(\alpha_s/(4\pi))^2\,\tilde{C}_j^{(2)}$	0.0787	-0.0035	0.0002	-0.0001	-0.0048	0
$\tilde{C}_j$	-0.6274	1.0341	0.0037	-0.0021	-0.0074	0

Table 1: The ith order contributions $(\alpha_s/(4\pi))^i\,\tilde{C}_j^{(i)}$, $i=0,1,2$ to the SM Wilson coefficients, at $\mu = m_c$. The last row gives their sum, $\tilde{C}_j(m_c)$. For $j=3,4,5,6$ see 1510.00311.

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

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

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

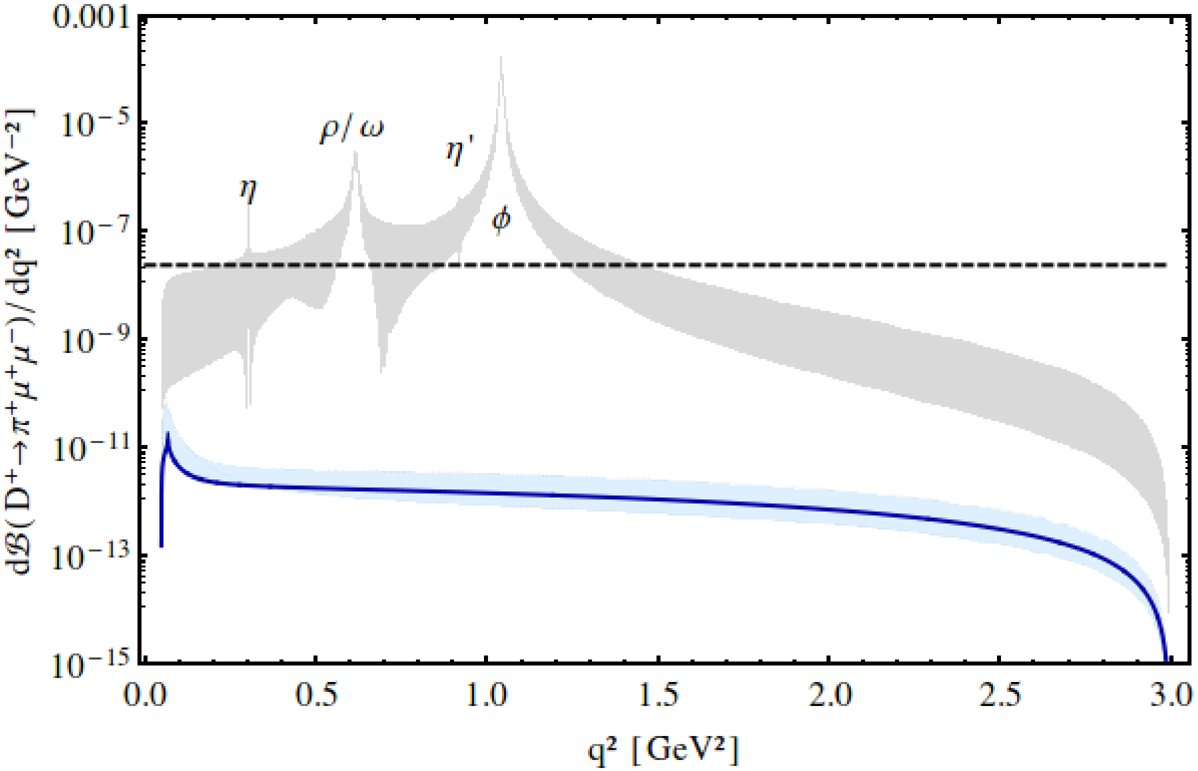
q^2-bin	$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)^{\mathrm{SM}}_{\mathrm{nr}}$	90% CL limit LHCb'13
full q^2:	$3.7 \cdot 10^{-12}\,(\pm1, \pm3, ^{+16}_{-15}, \pm1, ^{+4}_{-1}, ^{+158}_{-1}, ^{+16}_{-12})$	$7.3 \cdot 10^{-8}$
low q^2:	$7.4 \cdot 10^{-13}\,(\pm1, \pm4, ^{+23}_{-21}, ^{+10}_{-11}, ^{+11}_{-1}, ^{+238}_{-23}, ^{+6}_{-5})$	$2.0 \cdot 10^{-8}$
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, and are given in percent.

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

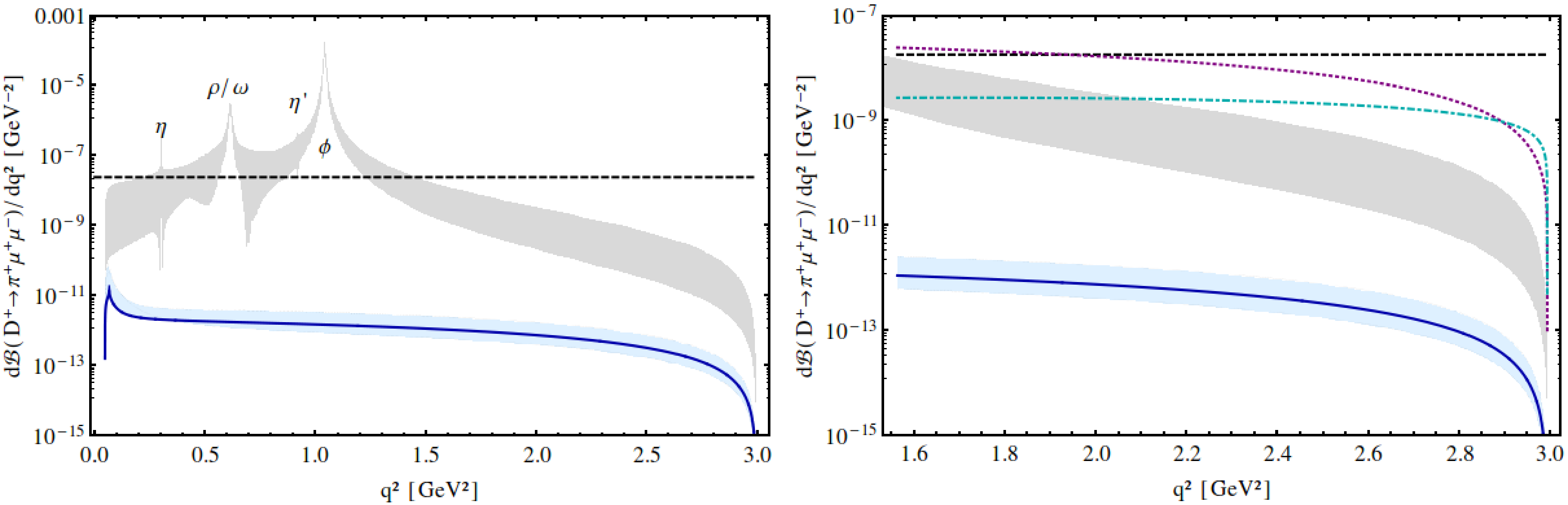
$D \to \pi M \to \pi l^+ l^-$, with $M = \eta^{(\prime)}, \rho, \omega, \Phi$

Model with Breit-Wigners, branching ratio data and relative phases:



solid blue: SM with μ_c-uncertainty, dashed 90% CL upper limit, gray: resonance contribution

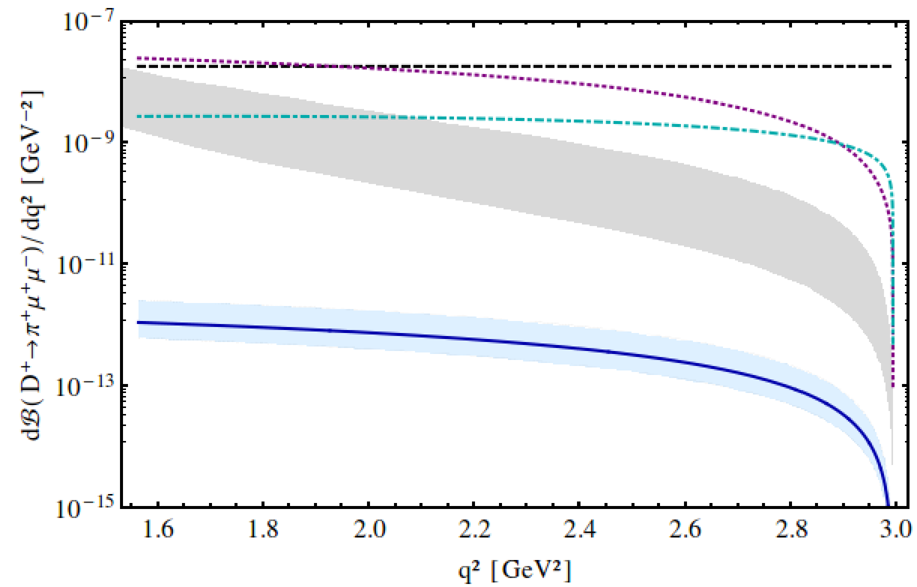
Resonance contributions vs BSM



BSM windows in $D \to \pi l^+ l^-$ branching ratios at high and very low $q2$ 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.)



$c \to u\mu\mu$: $|C^{(\prime)}_{V,A}| \lesssim 1$ (illustrated above), $|C_{T,T5}| \lesssim 1$, $|C^{(\prime)}_{S,P}| \lesssim 0.1$.

BSM weak loop $\Lambda_{NP} \gtrsim O(5)$ TeV, BSM tree level $\Lambda_{NP} \gtrsim$ weak scale.

$c \to uee$: constraints are weaker (data) by a (2-4) $\times$ muon bounds.

$c \to ue\mu$: weaker by (6-7) $\times$ muon bounds.

SM null tests

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).

Scalar or vector leptoquarks contribute to $c \to ull$, $l = e, \mu, \nu$ decays at tree level. Searches tell us $M \gtrsim 1$ TeV.

Models include $S_3(3, 3, -1/3)$ with $\mathcal{L} \sim \lambda Q^T L S_3^\dagger$ or $\tilde{V}_1(3, 1, -5/3)$ with $\mathcal{L} \sim \lambda \bar{U} E \tilde{V}_1^\dagger$.

If couplings are to doublet quarks constraints from rare kaon decays apply, e.g. for S_3, $|C_{V,A}^{(\prime)}| \lesssim 10^{-4}$.

If electrons AND muons are involved products of Wilson coefficients are severely constrained by $\mu \to e\gamma$ and $\mu \to e$-conversion, 10^{-7} and better.

$\to$ Size of LFV effects depends on flavor!

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

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

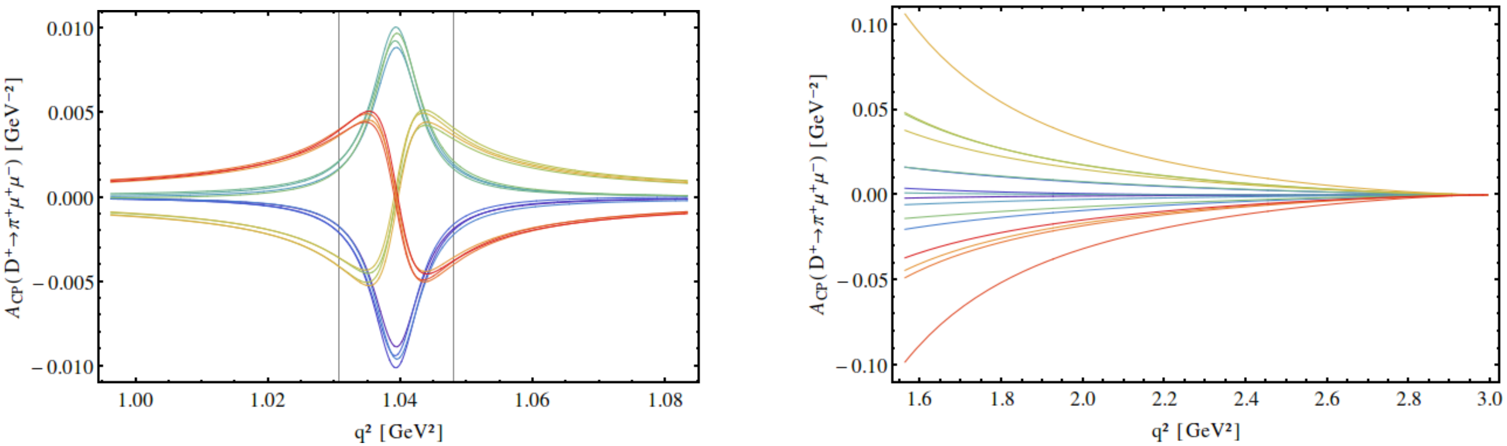
LQs make interesting link between quark (hierarchy) and lepton (anarchy? non-abelian discrete?) flavor 1503.01084.

	$\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-)$	$\mathcal{B}(D^0 \to \mu^+\mu^-)$	$\mathcal{B}(D^+ \to \pi^+e^\pm\mu^\mp)$	$\mathcal{B}(D^0 \to \mu^\pm e^\mp)$	$\mathcal{B}(D^+ \to \pi^+\nu\bar{\nu})$
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 3: 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 $\mathcal{B}(D^0 \to \mu\mu) \sim 10^{-13}$.

Probing even small couplings: A_{CP}

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 – which also allows for links between

CHARM and BEAUTY

– 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.

– Great prospects to test the SM and look for BSM physics in semileptonic rare decays.

– Whether new Physics can be seen depends on flavor, and vice versa; links between K, D, B-physics and LFV can provide new insights into flavor.

– Current anomalies in the flavor sector have triggered new types of bottom-up model-building (Z', leptoquarks, ..), that deserves attention in direct searches.