Theory Aspects of Charm Physics

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Hystory:

Predicted by Glashow, Iliopoulos, Miani (1070)

Discovered by Richter (SLAC1974) and Thing (1974)
(Nobel prize in 1976)

Properties:

Mass 1.29 GeV
Decays into s quark (~95%)
and d quark (~5%)

Electric charge 2/3 e
Spin ½
color: 3
weak isospin: left-handed ½. Right-handed 0
weak hypercharge: left-handed +1/3, Right-handed +4/3
($Q=I_3+Y/2$)

Charm

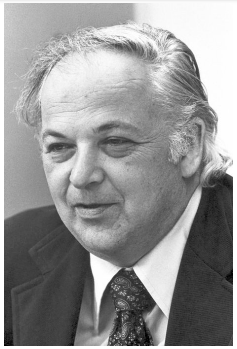
In 1964, Sheldon L. Glashow had written an article with James Bjorken suggesting a possible fourth quark. "We called our construct the 'charmed quark,'" recalled Glashow, "for we were fascinated and pleased by the symmetry it brought to the subnuclear world." Later in 1974 Glashow was pushing scientists to find the charm. In doing so, he stated at a conference that there were three possibilities: "One, charm is not found, and I eat my hat. Two, charm is found by spectroscopists, and we celebrate. Three, charm is found by 'outlanders' (other kinds of physicists who did neutrino scattering or measured electron-positron collisions in storage rings), and you eat your hats."
In 1976, charm was found by "outlanders", and a year later Glashow gave a rabble-rousing talk titled "Charm Is Not Enough." Then they all had a big laugh as the spectroscopists present finally ate their hats – Mexican candy hats were supplied by the organizers.

On Sunday, November 10, 1974, after searching for the charm quark around 3 GeV, Richter's group found a peak at 3.105 GeV. Richter called one of his friends, James Bjorken, just as he had sat down to dinner and gave him the startling news. "I couldn't believe such a crazy thing was so low in mass, was so narrow, and had such a high peak cross-section," Bjorken recalled. "It was sensational." He returned to the table a few minutes later, seemingly in a daze. His wife and children then watched open-mouthed as he unthinkingly heaped a large tablespoon of horseradish onto his baked potato and quietly began munching away, staring absentmindedly off into space. "BJ," his wife finally counseled, "I think you'd better go down to the lab now."

J/Ψ particle

The J/Ψ particle is a combination of two names. J was the name given to the particle by Samuel Ting's group from MIT and Brookhaven. Ψ was the name given to the particle by Burton Richter's group at SLAC. Each group had found the particle independently and almost simultaneously. As the story goes. . .

Nobel Prize in Physics 1976



Do not forget Nicola Cabibbo (1963)!

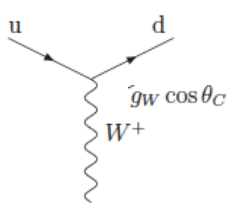
$$BR(K^- \to \mu^- \bar{\nu}_\mu) = 63.5\% \qquad BR(\pi^- \to \mu^- \bar{\nu}_\mu) = 99.9\%$$

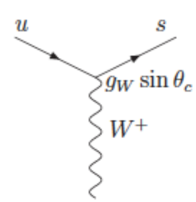
$\theta_C = 13.04°$

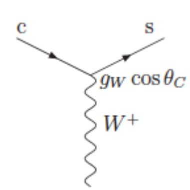
$$\begin{pmatrix} u \\ d' \end{pmatrix} = \begin{pmatrix} u \\ d\cos\theta_c + s\sin\theta_c \end{pmatrix} \qquad \begin{pmatrix} c \\ s' \end{pmatrix} = \begin{pmatrix} c \\ s\cos\theta_c - d\sin\theta_c \end{pmatrix}$$

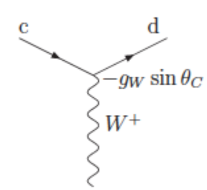
$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

$$\frac{BR(K^0 \to \mu^+\mu^-)}{BR(K^+ \to \mu^+\nu_\mu)} = \frac{7\times 10^{-9}}{0.64} \approx 10^{-8}$$









Mass of c quark predicted from Δm_K!

Outline

Charm in SM

Charm and New Physics

Charm in QCD

Charm in electroweak interactions

- Leptonic/semileptonic decays
- CP violation
- $\mathbf{D^0 - \bar{D}^0}$ oscillations
- FCNC processes
- Rare decays

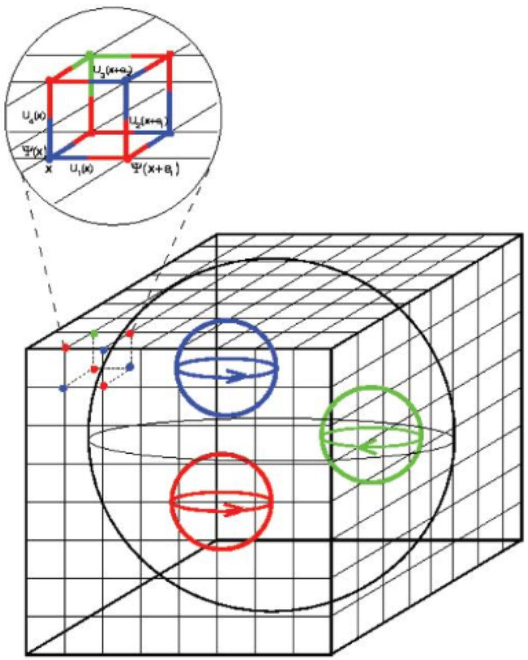
Charm at LHC

Theory goals

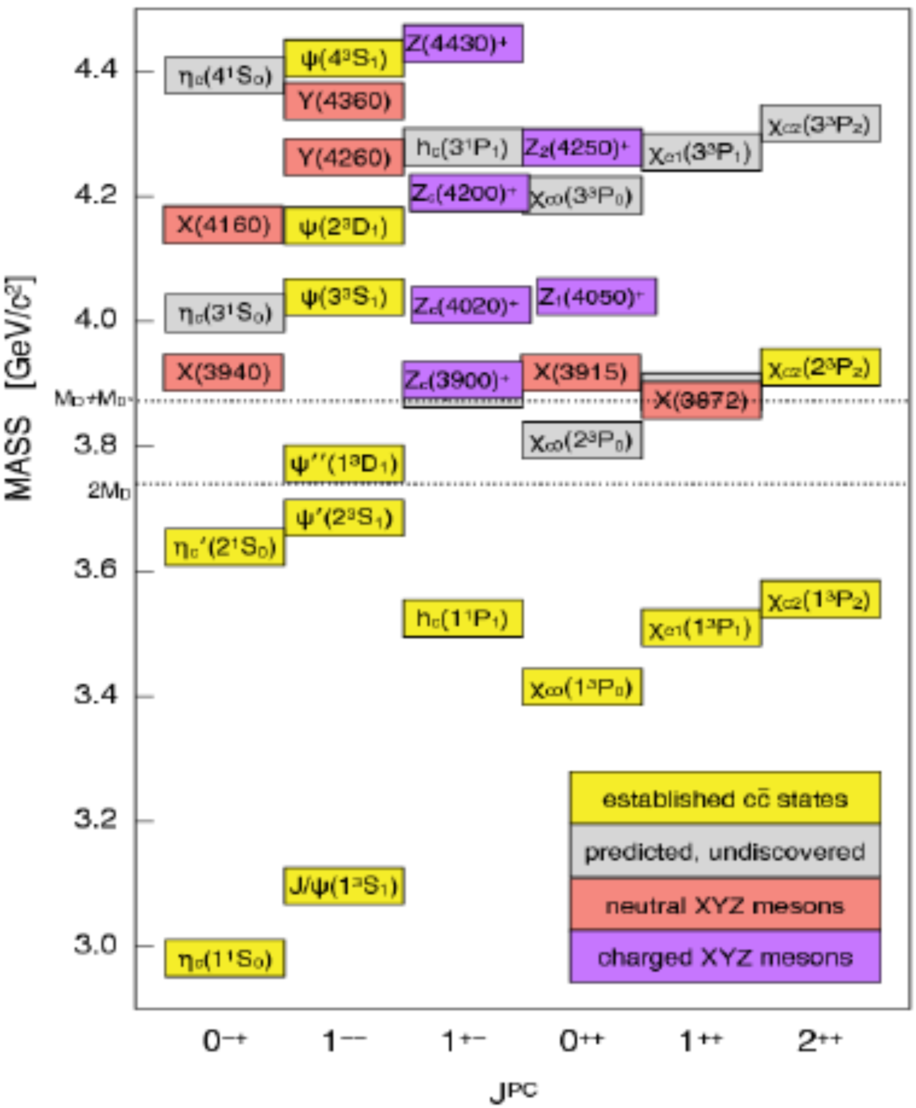
Deepening our knowledge of SM ⟶ QCD

Charm spectroscopy- tetraquark states
decay constants, form-factors, mixing parameters…

QCD (lattice) in action!



QCD in action:
Charmonium and Exotic Spectroscopy with Charm Quarks in Lattice QCD



- Plethora of unexpected charmonium-like (X , Y , Z) states discovered experimentally
- Masses and widths of some D_s states significantly lower than those expected from quark model.
- Tetraquarks? Molecules? Cusps? Hybrids?
- First principles calculations using lattice QCD to understand these states.

Search for New Physics

B meson puzzles → Solution by New Physics

B meson puzzles → Tests of Lepton flavour universality

$(g\text{-}2)_\mu$ discrepancy SM prediction and experimental result

How about charm?

- Unique tests of CP violation in the up sector;
- Charm offers tests of possible NP in up sector at low-energies;
- If NP couples to weak doublets of quarks, CKM connects it with charm sector.
- Can one see NP in charm decays not being present in B meson ?

New Physics in charm processes

Two possibilities

- Effective Lagrangian approach
- Model of NP (hopefully UV complete)

NP in charm

- Constraints from K, B physics
- Constraints from EW physics, oblique corrections, $Z \to b\bar{b}$
- Constraints from LHC

Up quark in weak doublet "talks" to down quark via CKM!

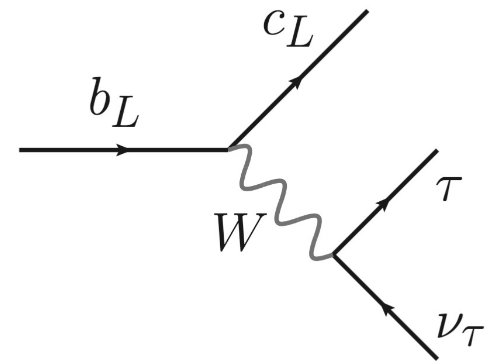
Effects of NP in charm suppressed by $V_{cb}^{*} V_{ub}$.

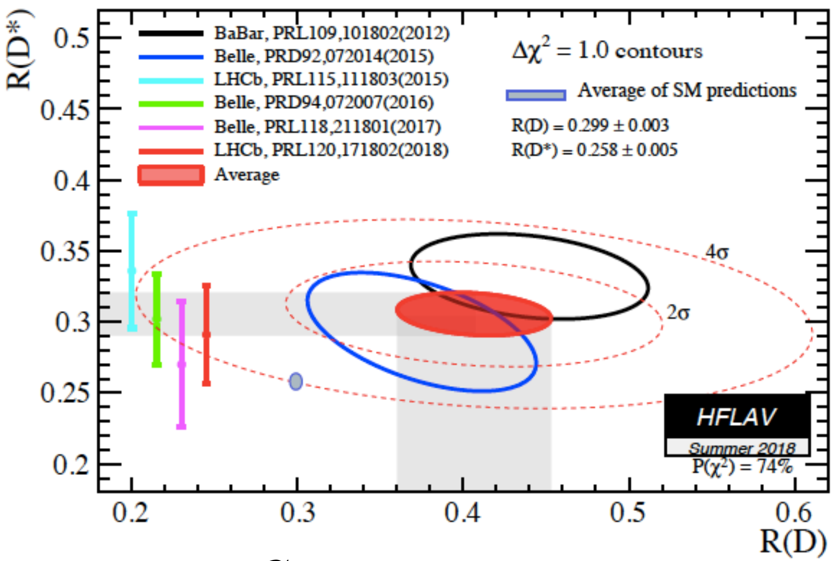
$$Q_{iL} = \begin{bmatrix} V^*_{il} u_J \\ d_i \end{bmatrix}_L$$

B physics anomalies: experimental results ≠ SM predictions!

charged current (SM tree level)

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)} \tau \nu_\tau)}{BR(B \to D^{(*)} \mu \nu_\mu)}$$ 3.8σ



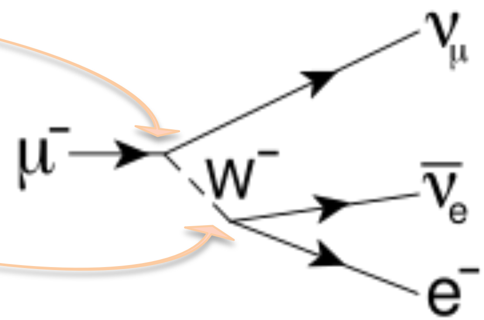


Freytsis, et al., 1506.08896, S.F. et al., 1206.1872;
Di Luzio & Nardecchia, 1706.01868,
Bernlochner et al., 1703.05330,
F. Feruglio et al., 1806.10155,
1606.00524.

$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{cb}[(1+g_{V_L})(\bar{c}_L\gamma_\mu b_L)(\bar{l}_L\gamma^\mu\nu_L) + g_{V_R}(\bar{c}_R\gamma_\mu b_R)(\bar{l}_L\gamma^\mu\nu_L)$$
$$+ g_{S_R}(\bar{c}_L b_R)(\bar{l}_R\nu_L) + g_{T_R}(\bar{c}_L\sigma_{\mu\nu} b_R)(\bar{l}_R\sigma^{\mu\nu}\nu_L)]$$

Lepton Flavour Universality (LFU)

the same coupling of lepton
and its neutrino with
W for all three lepton generations!



$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \quad '(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau) = \Gamma(\tau^- \to e^- \bar{\nu}_e \nu_\tau)$$

valid for quarks too!

Basic property of the SM: universal g

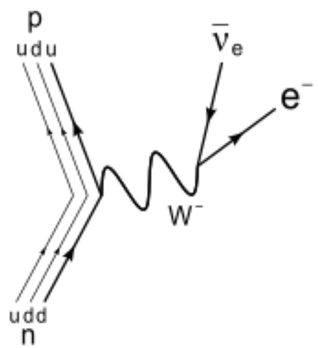
$$\mathcal{L}_f = \bar{f} i D_\mu \gamma^\mu f \quad f = l_L^i,\ q_L^i,\ i = 1, 2, 3$$

for each of three generations in weak interactions

$$D_\mu = \partial_\mu + ig\frac{1}{2}\vec{\tau} \cdot \vec{W}_\mu + ig'\frac{1}{2}Y_W B_\mu$$

the same for all SM fermions

At low energies



$$\frac{1}{q^2 - m_W^2} \simeq \frac{1}{m_W^2}(1 + \frac{q^2}{m_W^2} + ...)$$

$$\frac{g^2}{8m_W^2} = \frac{G_F}{\sqrt{2}}$$

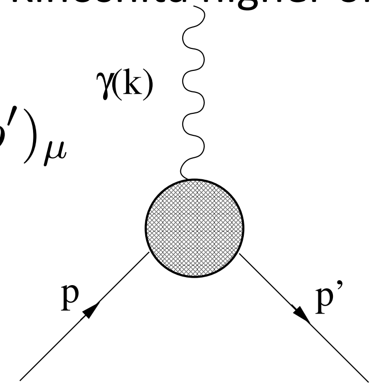
Fermi, 1933

$$\mathcal{L}_{eff} = -\frac{G_F}{\sqrt{2}} J_\mu^\dagger J^\mu$$

Muon anomalous magnetic moment

(Schwinger α/π,
Kinoshita higher orders in α)

$$ie\bar{u}_\ell(p')\left[\gamma^\mu - \frac{a_\ell}{2m_\ell} i\sigma^{\mu\nu} q_\nu\right] u_\ell(p)\epsilon^*_\mu, \qquad q_\mu = (p-p')_\mu$$



Dirac equation predicts g=2 $\quad a = (g-2)/2$

$$a_\mu^{th} - a_\mu^{exp} = -(3.06 \pm 0.76) \times 10^{-8}$$

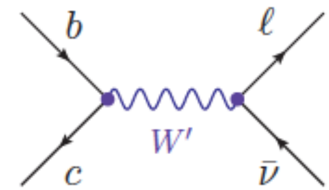
4 σ

Theory: uncertainty in hadronic contributions to the muon g − 2, (Jägerlehner, 1809.07413). Lattice QCD great progress vacuum polarization and light-by-light study (RBC & UKQCD, 1801.07224, Wittig 1807.09370).

Fermilab and J-Park experiments are expected to clarify existing discrepancy!

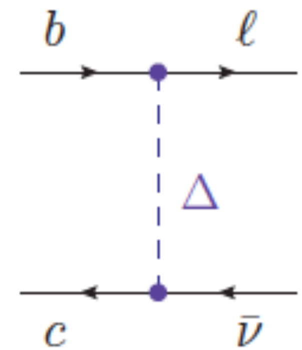
Assuming NP at scale Λ_{NP} (Di Luzio, Nardecchia, 1706.0!868)

$$\frac{4G_F}{\sqrt{2}} V_{cb}\, g_V \to \frac{2}{\Lambda_{NP}^2}$$



What is the scale of New Physics?

$$\Lambda_{NP} \simeq 3\,\mathrm{TeV}$$



Perturbativity of NP

$$\mathcal{L}_{NP} \supset \frac{C_D}{\Lambda_{NP}^2} (\bar{c}_L \Gamma_\mu b_L)(\tau_L \gamma^\mu \nu_L)$$

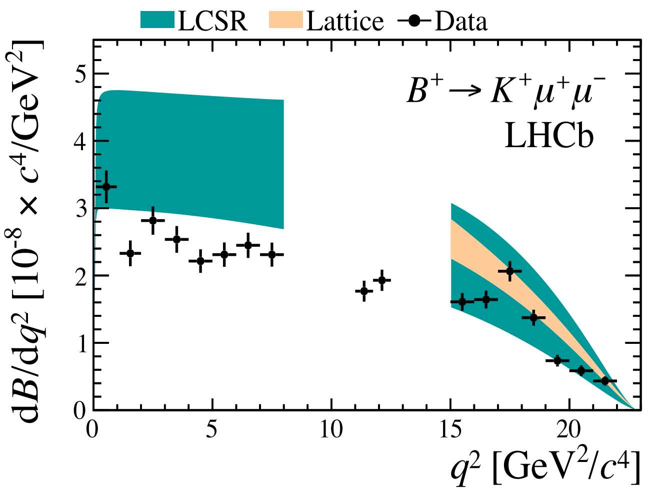
V-A form of NP

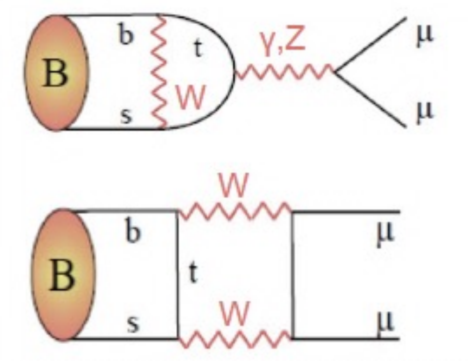
(current)(current) operators
are invariant under QCD running

$\Lambda_{NP} > 3\,\mathrm{TeV}$ C_D becomes non-perturbative!

Hiller et al., 1609.08895 $R_{D(*)}$

FCNC - SM loop process





$$R_K = \frac{\mathcal{B}(B \to K\mu\mu)_{q^2\in[1,6]\mathrm{GeV}^2}}{\mathcal{B}(B \to Kee)_{q^2\in[1,6]\mathrm{GeV}^2}} = 0.745 \pm^{0.090}_{0.074} \pm 0.036$$

2.4σ

$$R_{K^*}^{\mathrm{central}} = \frac{\mathcal{B}(B \to K\mu\mu)_{q^2\in[1.1,6]\mathrm{GeV}^2}}{\mathcal{B}(B \to Kee)_{q^2\in[1.1,6]\mathrm{GeV}^2}} = 0.685 \pm^{0.113}_{0.069} \pm 0.047\,,$$

Capdevila et al.,1704.05340, Altmannshofer et al., 1704.05435, D'Amico et al., 1704.05438.

What is the scale of New Physics?

$$\mathcal{L}_{NP} = \frac{1}{\Lambda_{NP}^2}\bar{s}_L\gamma^\alpha b_L\bar{\mu}_L\gamma_\alpha\mu_L$$

$$\Lambda_{NP} \simeq 30\,\mathrm{TeV}$$

NP explaining both B anomalies

$$R_{D^{(*)}}^{exp} > R_{D^{(*)}}^{SM}$$

$$\mathcal{L}_{NP} = \frac{1}{(\Lambda^D)^2} 2\, \bar{c}_L \gamma_\mu b_L \bar{\tau} \gamma^\mu \nu_L$$

$$\Lambda^D \simeq 3\,\mathrm{TeV}$$

$$R_{K^{(*)}}^{exp} < R_{K^{(*)}}^{SM}$$

$$\mathcal{L}_{NP} = \frac{1}{(\Lambda^K)^2} \bar{s}_L \gamma_\mu b_L \bar{\mu}_L \gamma^\mu \mu_L$$

$$\Lambda^K \simeq 30\,\mathrm{TeV}$$

$$\Lambda^D \simeq \Lambda^K \equiv \Lambda$$

NP in FCNC $B \to K^{(*)} \mu^+ \mu^-$ has to be suppressed

$$\frac{1}{(\Lambda^K)^2} = \frac{C_K}{\Lambda^2} \qquad C_K \simeq 0.01$$

suppression factor

Charged current charm meson decays and New Physics

$$\mathcal{L}_{SM} = \frac{4G_F}{\sqrt{2}} V_{cs} \bar{s}_L \gamma^\mu c_L \, \bar{\nu}_l \gamma_\mu l$$

$$\mathcal{L}_{NP} = \frac{2}{\Lambda_c^2} \bar{s}_L \gamma^\mu c_L \, \bar{\nu}_l \gamma_\mu l$$

electro-magnetic correction 1-3%

1 % error in

$$\Gamma(D_s^+ \to l^+ \nu_l)$$

$$\Lambda_c \sim 2.5 \ \ \mathrm{TeV}$$

Message:
Even if there is NP at 3 TeV scale
the effect on charm leptonic decay
can be ~ 1%!

Charm weak decays and CKM

(Semi)leptonic charm inputs to the CKM fit

$\mathcal{B}(B^- \to \tau^- \overline{\nu}_\tau)$	$(1.08 \pm 0.21) \times 10^{-4}$
$\mathcal{B}(D_s^- \to \mu^- \overline{\nu}_\mu)$	$(5.57 \pm 0.24) \times 10^{-3}$
$\mathcal{B}(D_s^- \to \tau^- \overline{\nu}_\tau)$	$(5.55 \pm 0.24) \times 10^{-2}$
$\mathcal{B}(D^- \to \mu^- \overline{\nu}_\mu)$	$(3.74 \pm 0.17) \times 10^{-4}$
$\mathcal{B}(K^- \to e^- \overline{\nu}_e)$	$(1.581 \pm 0.008) \times 10^{-5}$
$\mathcal{B}(K^- \to \mu^- \overline{\nu}_\mu)$	0.6355 ± 0.0011
$\mathcal{B}(\tau^- \to K^- \overline{\nu}_\tau)$	$(0.6955 \pm 0.0096) \times 10^{-2}$
$\mathcal{B}(K^- \to \mu^- \overline{\nu}_\mu)/\mathcal{B}(\pi^- \to \mu^- \overline{\nu}_\mu)$	1.3365 ± 0.0032
$\mathcal{B}(\tau^- \to K^- \overline{\nu}_\tau)/\mathcal{B}(\tau^- \to \pi^- \overline{\nu}_\tau)$	$(6.43 \pm 0.09) \times 10^{-2}$
$\mathcal{B}(B_s \to \mu\mu)$	$(2.8^{+0.7}_{-0.6}) \times 10^{-9}$
$\lvert V_{cd}\rvert f_+^{D\to\pi}(0)$	0.148 ± 0.004
$\lvert V_{cs}\rvert f_+^{D\to K}(0)$	0.712 ± 0.007

CKMFitter (using unitarity)

$$|V_{cd}| = 0.22529^{+0.00041}_{-0.00032}$$

$$|V_{cs}| = 0.973394^{+0.000074}_{-0.000096}$$

Direct extraction using lattice (HFAG+FLAG)

Leptonic

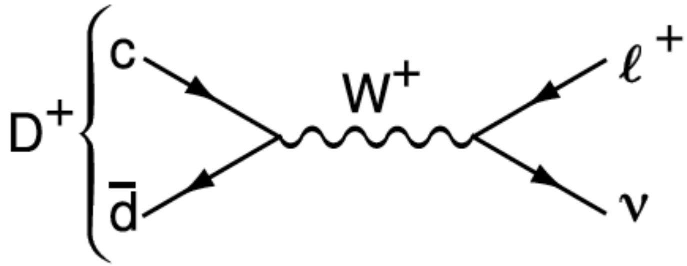
$$|V_{cd}| = 0.2164(63)$$

$$|V_{cs}| = 1.008(21)$$

Semileptonic

$$|V_{cd}| = 0.214(12)$$

$$|V_{cs}| = 0.975(32)$$



$$\langle 0|\bar{q}_1\gamma_\mu\gamma_5 q_2|P(p)\rangle = ip_\mu f_P$$

$$f_\pi \approx 130 \text{ MeV}$$

$$\Gamma(P\to \ell\nu) = \frac{G_F^2}{8\pi} f_P^2\, m_\ell^2 M_P \left(1-\frac{m_\ell^2}{M_P^2}\right)^2 |V_{q_1q_2}|^2$$

electromagnetic correction

$$\Gamma(P\to\ell\nu) = \Gamma^{(0)}\left[1+\frac{\alpha}{\pi}C_P\right]$$

$$\delta_P \equiv (\alpha/\pi)C_P$$

Lattice QCD

$$f_{D^+} = 211.9(1.1)\ \text{MeV}$$

$$f_{D_s} = 249.0(1.2)\ \text{MeV}$$

$$\frac{f_{D_s}}{f_{D^+}} = 1.173(3)\,.$$

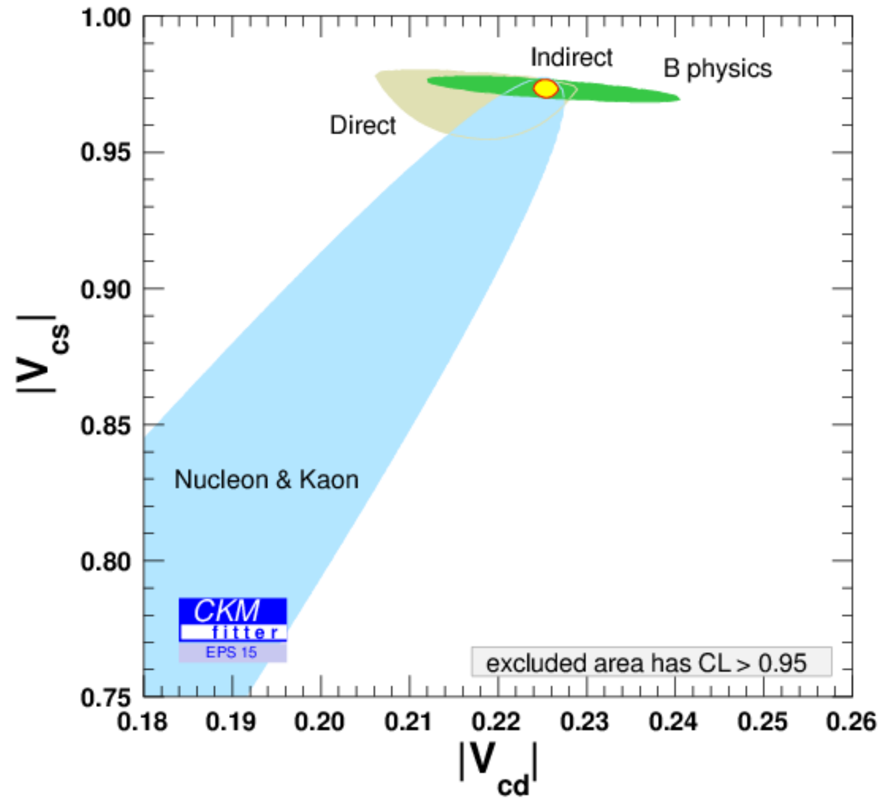
$$\delta_\pi = 0.0176(21)$$

$$\delta_K = 0.0107(21)$$

- Great advance in lattice determination of decay constants and form factors enables progress in testing consistency of the SM

- Assuming unitarity of V_{CKM}, the values of V_{cs} and V_{cd} are dominated by V_{cb} measurement and nuclear & kaon data;

- V_{cs} and V_{cd} values are largely driven by indirect constraints;



Search for NP in charged current transitions (charm mesons)

- Effective Lagrangian approach describing NP in $c \to s l \nu_l$ transition;

  - Pseudoscalar operator
  - Scalar operator

  } Wilson coefficients

- NP in branching ratios, forward-backward asymmetry transversal muon polarization;

1502.07488, S.F., I. Nišandžić, U. Rojec
1404.0454, J. Barranco et al.,

Questions for theory:

- Can current precision on charm meson decay constants/form factors enables to search for New Physics in charm?

- What are the most appropriate observables?

Approach:

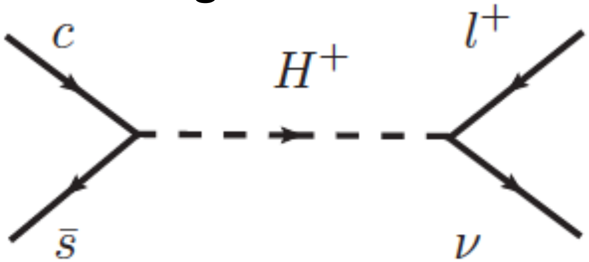
Effective Lagrangian to describe NP in $c \to s l \nu_l$ transition

$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{cs} \sum_{\ell=e,\mu,\tau} \sum_i c_i^{(\ell)} \mathcal{O}_i^{(\ell)} + \mathrm{H.c.}$$

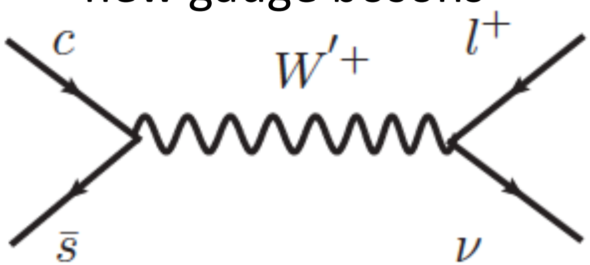
$$\mathcal{O}_{SM}^{(\ell)} = (\bar{s}\gamma_\mu P_L c)(\bar{\nu}_\ell \gamma^\mu P_L \ell) \qquad c_{SM}^{(\ell)} = 1$$

NP proposals in $c \to s l \nu_l$

charged scalar

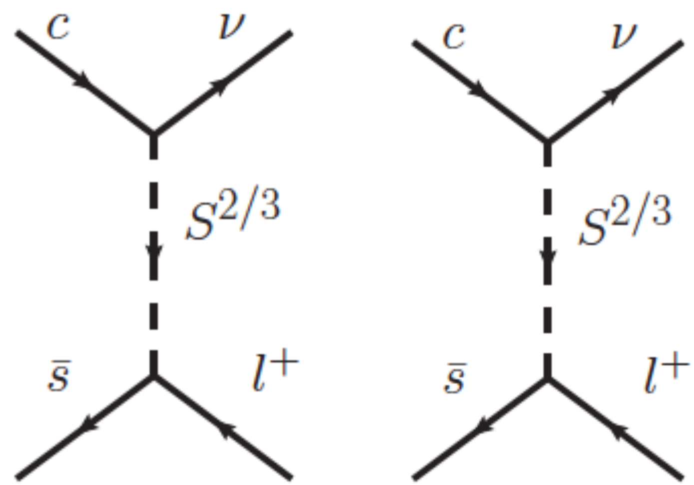


new gauge bosons



J. Barranco et al. 1303.3896;
Akeyrod and Chen, hep-ph/0701078

leptoquarks



e.g.I.Dorsner, S.F.J.F. Kamenik,
N. Kosnik, 0906.5585

$\not{R}$ SUSY A.G. Akeroyd, S. Recksiegel,
hep-ph/0210376.

Simplest proposal for NP - scalar/pseudoscalar operators:

$$\begin{cases} \mathcal{O}^{(\ell)}_{L(R)} = \left(\bar{s} P_{L(R)} c\right)\left(\bar{\nu}_\ell P_R \ell\right) \\ \mathcal{O}^{(\ell)}_{V,R} = \left(\bar{s}\gamma_\mu P_R c\right)\left(\bar{\nu}_\ell \gamma^\mu P_L \ell\right) \end{cases}$$

Examples:

Two Higgs Doublet Models

New physics might modify branching ratios

$$\mathcal{B}(D_s \to \ell\nu_\ell) = \tau_{Ds}\frac{m_{Ds}}{8\pi} f_{Ds}^2 \left(1 - \frac{m_\ell^2}{m_{Ds}^2}\right)^2 G_F^2 \, |V_{cs}|^2 m_\ell^2 \left|1 - c_P^{(\ell)} \frac{m_{Ds}^2}{(m_c + m_s) m_\ell}\right|^2$$

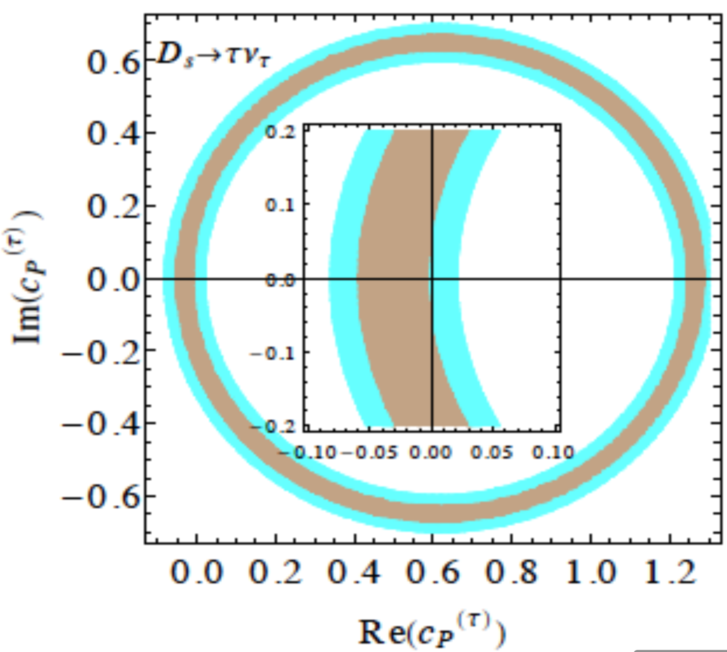
$$c_P^{(\ell)} \equiv c_R^{(\ell)} - c_L^{(\ell)}$$

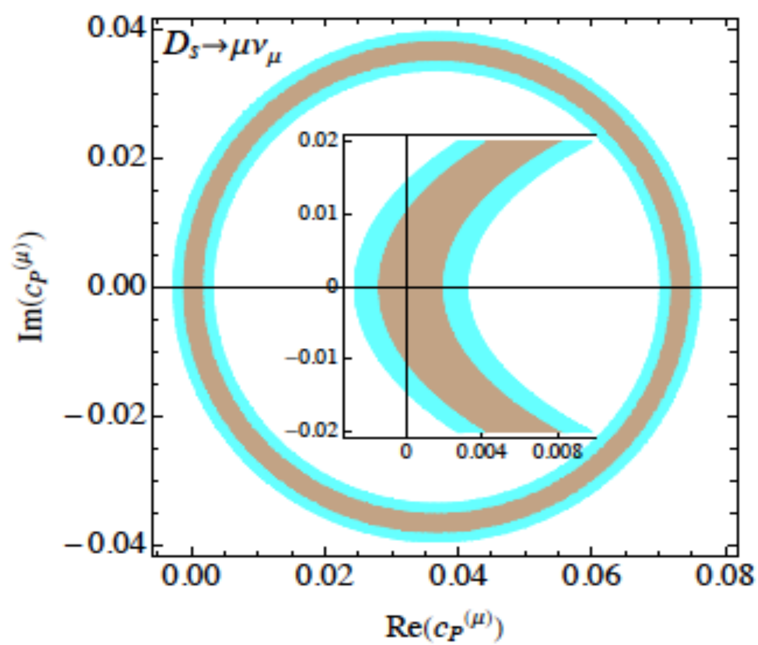
$$\mathcal{B}(D_s \to \ell\nu_\ell) = \begin{cases} (5.7 \pm 0.21^{+0.31}_{-0.3})\%, & D_s \to \tau\nu_\tau, \\ (0.531 \pm 0.028 \pm 0.020)\%, & D_s \to \mu\nu_\mu, \\ < 1.0 \cdot 10^{-4}\,,\ 95\%\,\text{C.L.}, & D_s \to e\nu_e. \end{cases}$$

For $f_{D_s} = 249.0(0.3)(^{+1.1}_{-1.5})\,\text{MeV}$ (lattice, Fermilab & MILC)

and $V_{cs} = 0.97317^{+0.00053}_{-0.00059}$ obtained from global CKM unitarity fit,

allowed parameter space of new physics coupling:





$$|c_P^{(e)}| < 0.005$$

$D \to K^* l \nu_l$

$c_P^{(l)}$ can contribute to $D \to K^* l \nu_l$ (four form-factors necessary!)

Using helicity formalism: $D \to K^*$"W"

polarization of W

$$H_\pm(q^2) = \mp \frac{\sqrt{\lambda(m_P^2, m_V^2, q^2)}}{m_P + m_V} V(q^2) + (m_P + m_V) A_1(q^2)$$

$$H_0(q^2) = \frac{1}{2 m_V \sqrt{q^2}} \left[(m_P + m_V)(m_P^2 - m_V^2 - q^2) A_1(q^2) - \frac{\lambda(m_P^2, m_V^2, q^2)}{m_P + m_V} A_2(q^2) \right]$$

$$H_t(q^2) = \left[1 - c_P^{(\ell)} \frac{q^2}{m_\ell (m_q + m_{\bar{q}})} \right] \frac{\sqrt{\lambda(m_P^2, m_V^2, q^2)}}{\sqrt{q^2}} A_0(q^2).$$

$c_P^{(l)}$ modifies H_t $\quad H_t \to \left(1 - c_P^{(\ell)} \frac{q^2}{m_\ell (m_c + m_s)} \right) H_t$

Rather weak knowledge of form-factors.
FOCUS performed non-parametric measurements of helicity amplitudes (errors too big), hep-ph /0509027;
BaBar (1012.1810) single pole parameterization used in our fit: $\mathrm{R}_{\mathrm{L/T}} = \frac{\Gamma_{\mathrm{L}}}{\Gamma_{\mathrm{T}}}$

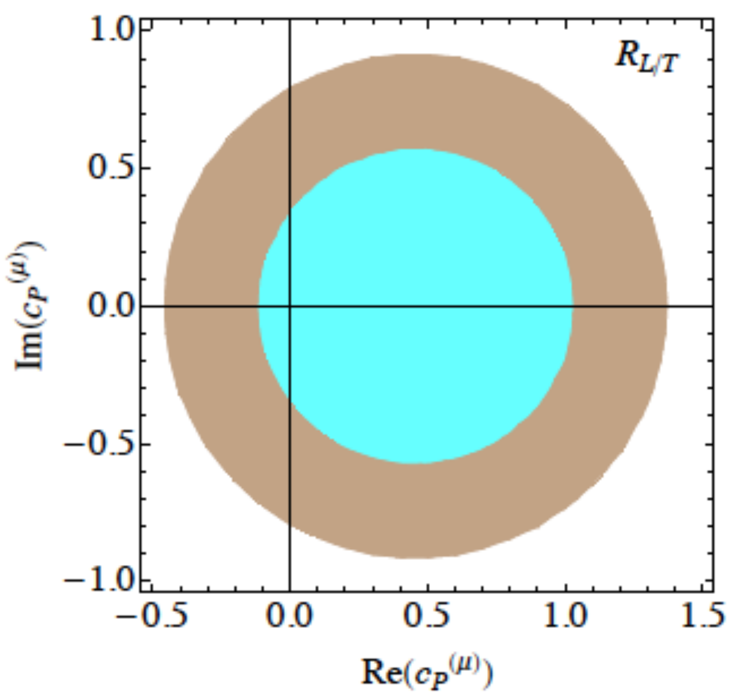
$$V(0)/A_1(0) = 1.463 \pm 0.035$$
$$A_2(0)/A_1(0) = 0.801 \pm 0.03$$
$$A_1(0) = 0.6200 \pm 0.0057$$

PDG:
$R_{L/T}$ =1.13±0.08

$$\frac{d\Gamma_L}{dq^2} = \mathcal{N}(q^2)\left(1-\frac{m_\ell^2}{q^2}\right)^2\left[(1+\frac{m_\ell^2}{2q^2})|H_0|^2 + \frac{3m_\ell^2}{2q^2}|H_t|^2\right] \quad \frac{d\Gamma_T}{dq^2} = \mathcal{N}(q^2)\left(1-\frac{m_\ell^2}{q^2}\right)^2\left[(1+\frac{m_\ell^2}{2q^2})(|H_+|^2+|H_-|^2)\right]$$

$$\mathcal{N}(q^2) = G_F^2|V_{cs}|^2 q^2 |\mathbf{q}|/(96\pi^3 m_D^2)$$

Not competitive with the constraints coming from pure leptonic decay!



The Wilson coefficient of the scalar operator

NP in $D \to K l \nu_l$

$$\langle K(k')|\bar{s}\gamma_\mu c|D(k)\rangle = f_+(q^2)\left((k+k')_\mu - \frac{m_D^2 - m_K^2}{q^2}q_\mu\right) + f_0(q^2)\frac{m_D^2 - m_K^2}{q^2}q_\mu$$

$$f_+(0) = f_0(0)$$

Helicity amplitudes

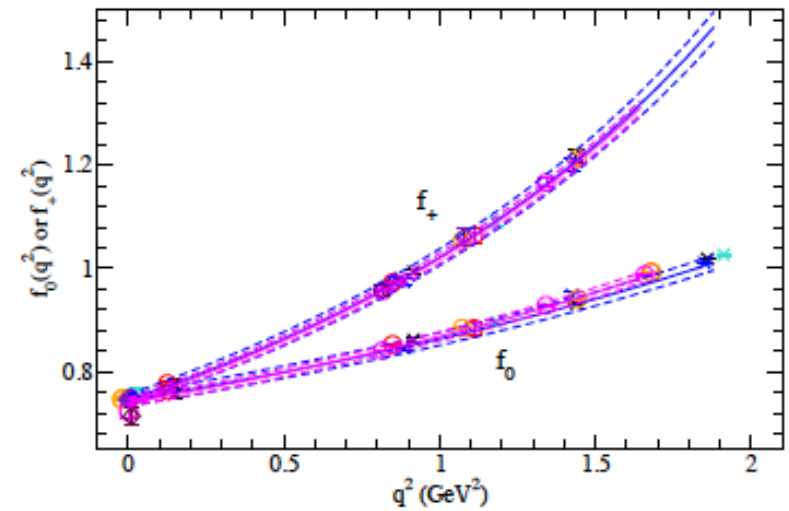
$$h_0(q^2) = \frac{\sqrt{\lambda(m_D^2, m_K^2, q^2)}}{\sqrt{q^2}} f_+(q^2)$$

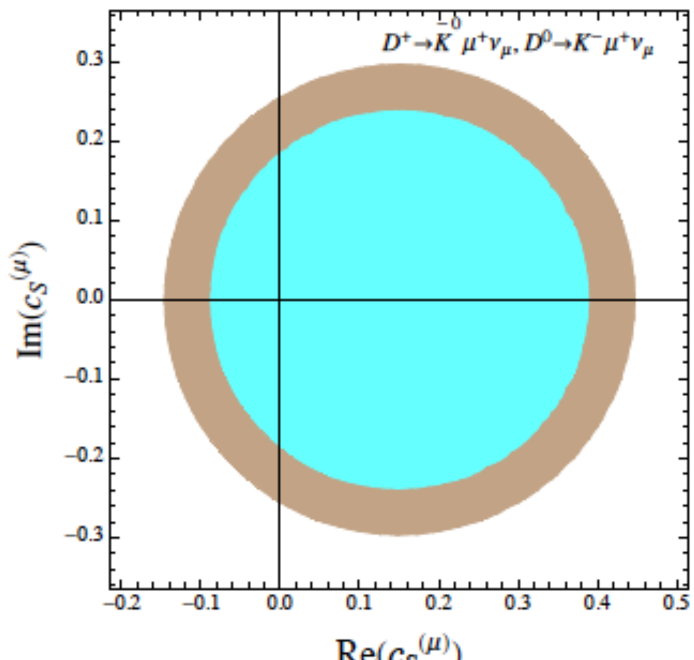
$$h_t(q^2) = \left(1 + c_S^{(l)} \frac{q^2}{m_\ell(m_s - m_c)}\right)\frac{m_D^2 - m_K^2}{\sqrt{q^2}} f_0(q^2)$$

$$\frac{d\Gamma^{(\ell)}}{dq^2} = \frac{G_F^2 |V_{cs}|^2 |\mathbf{q}| q^2}{96\pi^3 m_D^2}\left(1 - \frac{m_\ell^2}{q^2}\right)^2 \left[|h_0(q^2)|^2\left(1 + \frac{m_\ell^2}{2q^2}\right) + \frac{3m_\ell^2}{2q^2}|h_t(q^2)|^2\right]$$

$$\mathcal{B}(D \to K\ell\nu_\ell) = \begin{cases} (8.83 \pm 0.22)\%, & D^+ \to \bar{K}^0 e^+ \nu_e, \\ (9.2 \pm 0.6)\%, & D^+ \to \bar{K}^0 \mu^+ \nu_\mu, \\ (3.55 \pm 0.04)\%, & D^0 \to K^- e^+ \nu_e, \\ (3.30 \pm 0.13)\%, & D^0 \to K^- \mu^+ \nu_\mu. \end{cases}$$

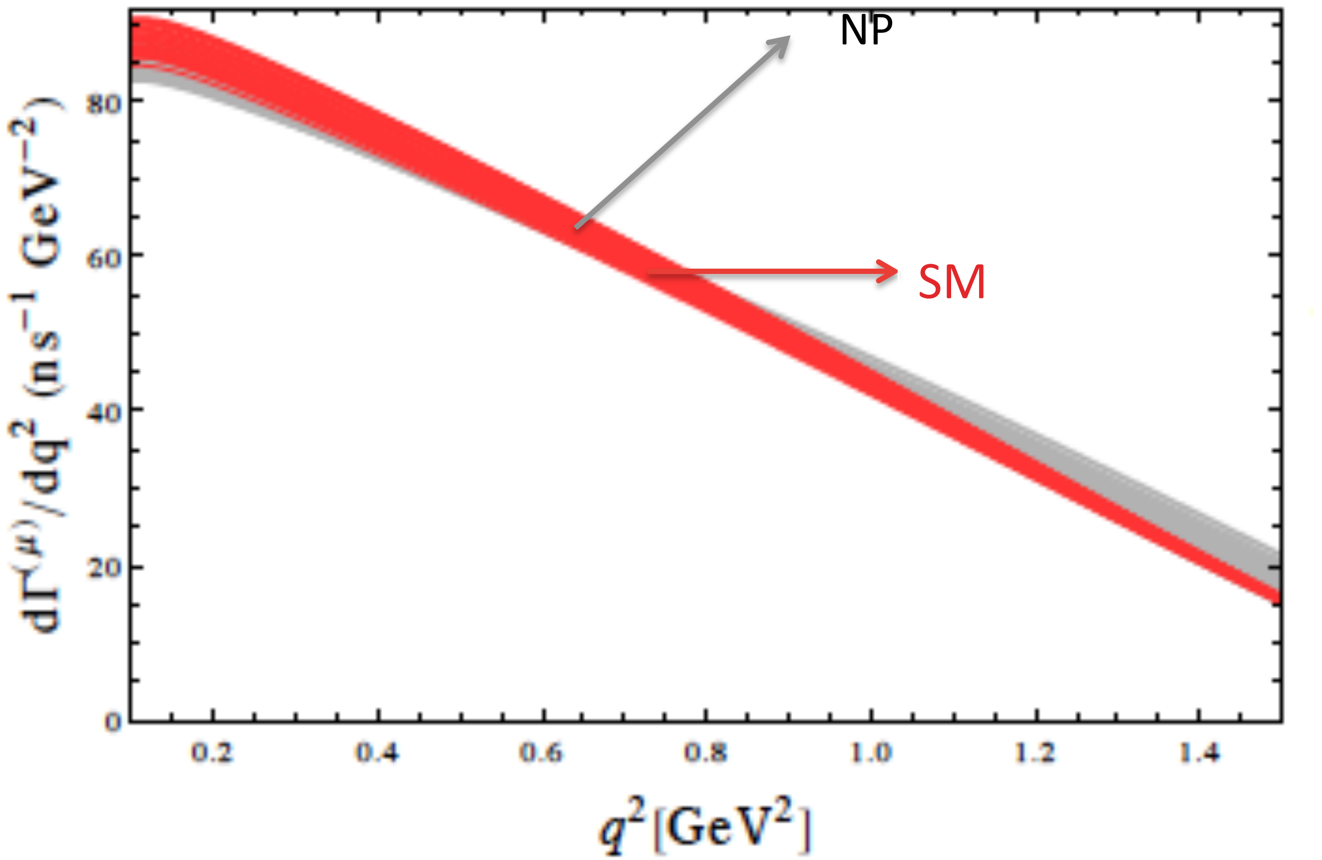
Form-factors calculated by lattice collaboration HPQCD (1305.1462)
crosses $\mathrm{D} \to \mathrm{K}$
circles $\mathrm{D_s} \to \eta$





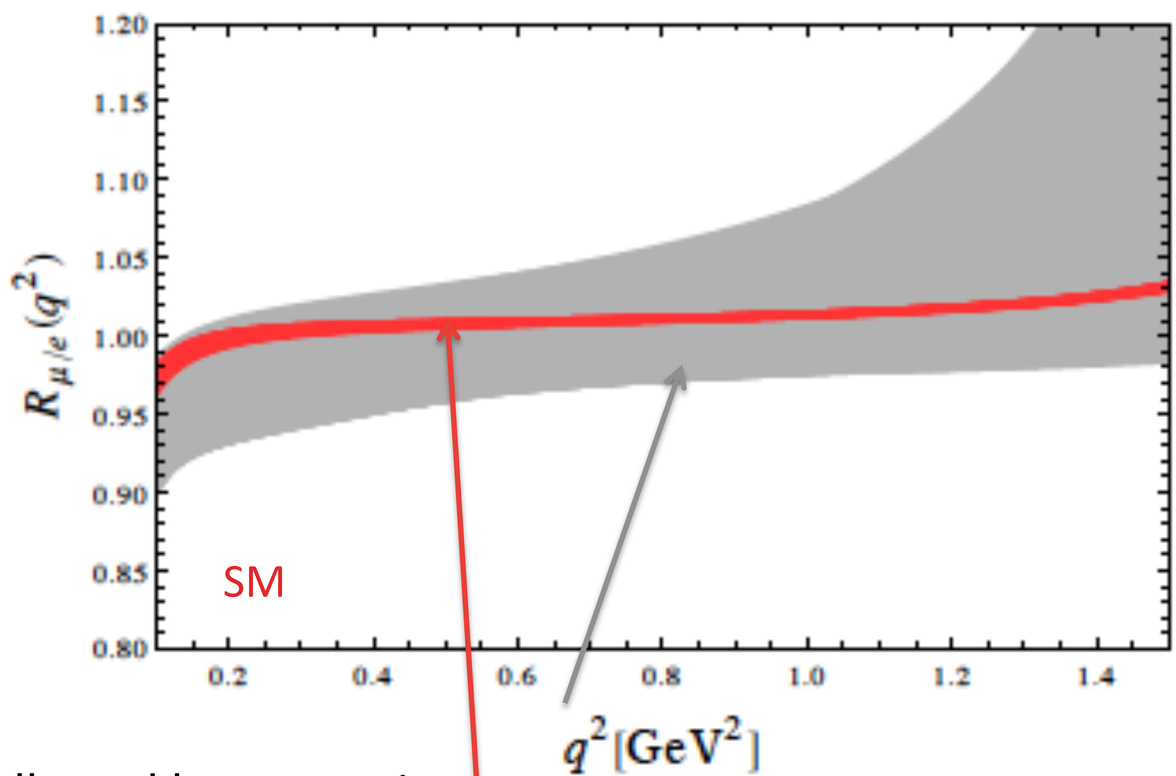
Allowed region for c_s from
$BR(D \to K l \nu_l)$

NP in differential width distribution



NP, allowed by constraint from the fit of c_S from the branching ratio

Check of lepton universality



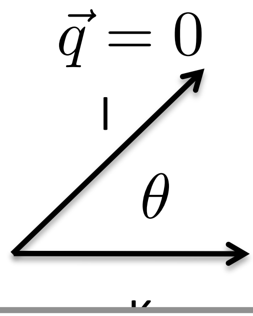
NP, allowed by constraint from the fit to the branching ratio which gives constraint on c_S, assuming $c_S^{(e)} = 0$

$$R_{\mu/e}(q^2) \equiv \frac{d\Gamma^{(\mu)}}{dq^2} \Big/ \frac{d\Gamma^{(e)}}{dq^2}$$

$$R_{\mu/e} = 0.978 \pm 0.007_{\text{stat.}} \pm 0.012_{\text{syst.}}$$

BESSIII (PRL 118 (2017) 111801)

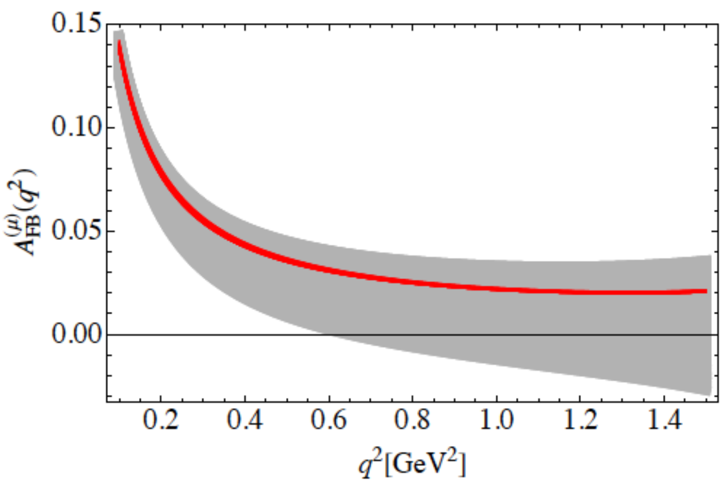
Forward-backward asymmetry in $D \to K l \nu_l$



$$\frac{d^2\Gamma^{(\ell)}}{dq^2 d\cos\theta_\ell} = a_\ell(q^2) + b_\ell(q^2)\cos\theta_\ell + c_\ell(q^2)\cos^2\theta_\ell.$$

$$b_\ell(q^2) = -\frac{G_F^2 |V_{cs}|^2 |\mathbf{q}| q^2}{128\pi^3 m_D^2}\left(1 - \frac{m_\ell^2}{q^2}\right)^2 \frac{m_\ell^2}{q^2} 2Re(h_0 h_t^*)$$

$$A_{FB}^{(\ell)}(q^2) \equiv \frac{\int_{-1}^{0} \frac{d^2\Gamma^{(\ell)}(q^2)}{dq^2 d\cos\theta_\ell} d\cos\theta_\ell - \int_{0}^{1} \frac{d^2\Gamma^{(\ell)}(q^2)}{dq^2 d\cos\theta_\ell} d\cos\theta_\ell}{d\Gamma^{(\ell)}/dq^2(q^2)} = -\frac{b_\ell(q^2)}{d\Gamma^{(\ell)}(q^2)/dq^2}$$



Sensitive on the real part of c_s!

SM value: $\langle A_{FB}^{(\mu)} \rangle = 0.055(2)$

Forward-backward asymmetry would not show deviation from SM!

THDM with more general flavor structure might lead to different c_S and c_P and A_{FB} can differ from SM.

LQ in charm charged current: Test of Lepton Flvour Universality

Triplet LQ S_3 in charm leptonic decays decay

$$\mathcal{L}_{\bar{u}^i d^j \bar{\ell} \nu_k} = -\frac{4G_F}{\sqrt{2}} \left[(V_{ij} U_{\ell k} + g^L_{ij;\ell k})(\bar{u}^i_L \gamma^\mu d^j_L)(\bar{\ell}_L \gamma_\mu \nu^k_L) \right]$$

C_V modifies CKM

Test of lepton flavour universality (LFU)

$$R^c_{\tau,\mu} = \frac{\Gamma(D_s \to \tau\nu)}{\Gamma(D_s \to \mu\nu)}$$

$$\frac{R^c_{\tau,\mu,LQ}}{R^c_{\tau,\mu,SM}} = [1 - \frac{v^2}{2M^2_{S3}} \mathrm{Re}((Vy*)_{c\tau} y_{s\tau} - (Vy*)_{c\mu} y_{s\mu})]$$

Comes from the fit of $R_{K(*)}$ with S_3

m_{S3} [TeV]	$1 - R^c_{\tau,\mu,LQ}/R^c_{\tau,\mu,SM}$
1.0	3.2%
1.2	2.4%
1.5	1.5%

Doršner, SF, Greljo, Kamenik Košnik, 1603.04993;

NP in transversal muon polarization

The relative complex phase between nonstandard scalar Wilson coefficient and V_{cs} is a possible new source of the CP violation.

The measurement of the T-odd transverse polarization of charge lepton might give information on that effect. In SM it is vanishing effect.

$$P_\perp^{(\mu)} = \frac{|\mathcal{A}(\vec{s})|^2 - |\mathcal{A}(-\vec{s})|^2}{|\mathcal{A}(\vec{s})|^2 + |\mathcal{A}(-\vec{s})|^2}$$

$\mathcal{A}(\pm\vec{s})$ amplitude for spin projection along $\vec{s}$

$$\vec{s} \equiv (\vec{p}_K \times \vec{p}_\ell)/|\vec{p}_K \times \vec{p}_\ell|$$

$$P_\perp^{(\mu)}(q^2, E_\mu) = \left(\frac{d\Gamma}{dq^2 dE_\mu}\right)^{-1} \kappa(q^2, E_\mu)\, \mathrm{Im}\left(h_0(q^2) h_t^*(q^2)\right)$$

For allowed value of $c_S^{(\mu)} \simeq \pm 0.1\, i$

$$\langle P_\perp^{(\mu)} \rangle \simeq \pm 0.2$$

CP violation in charm

i) CP violation in the $\Delta C = 1$ decay amplitudes,

δ_i strong phases
ϕ_i weak phases

$$A_f = |A_1| e^{i\delta 1} e^{i\phi 1} + |A_2| e^{i\delta 2} e^{i\phi 2} \qquad A_{\bar{f}} = |A_1| e^{i\delta 1} e^{-i\phi 1} + |A_2| e^{i\delta 2} e^{-i\phi 2}$$

ii) CP violation in $D^0 - \bar{D}^0$, $\Delta C = 2$ $\quad \left[M - i\frac{\Gamma}{2}\right]_{ij} = \begin{pmatrix} A & p^2 \\ q^2 & A \end{pmatrix}$

iii) CP violation in the interference of decays with and without mixing.
The same final states to which both D^0 and $\bar{D}^0$ can decay

- CPV in D - $\bar{D}$ mixing suppressed due to $\mathcal{O}(V_{cb}V_{ub}^*/V_{cs}V_{us}^*) \sim 10^{-3}$
- direct CPV suppressed due to $\mathcal{O}([V_{cb}V_{ub}^*/V_{cs}V_{us}^*]\alpha_s/\pi) \sim 10^{-4}$

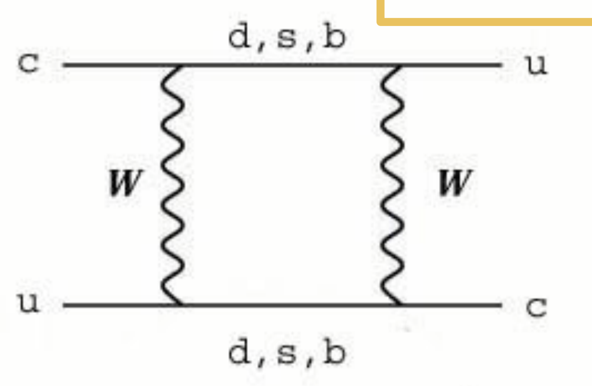
Mixing and indirect CP violation

$$|D_{L,S}\rangle = p\,|D^0\rangle \pm q\,|\overline{D}^0\rangle \qquad |p|^2 + |q|^2 = 1$$

If $p = q$, then CP eigenstates $CP|D_\pm\rangle = \pm|D_\pm\rangle$

$$\Delta M \equiv m_{D_+} - m_{D_-}$$

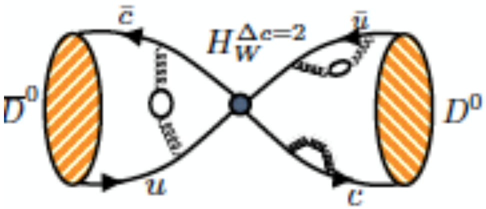
$$\Delta\Gamma \equiv \Gamma_{D_+} - \Gamma_{D_-}$$

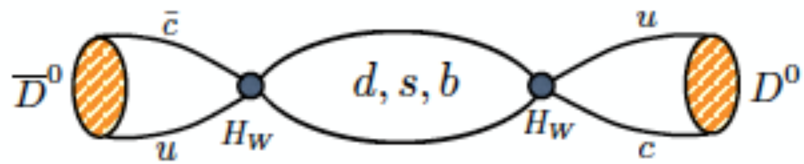


- intermediate down-type quarks;
- due to CKM contribution of b – quark negligible;
- in the SU(3) limit 0;
- Dominated by non-perturbative dynamics!
- m_d, $m_{\leq} \leq \Lambda_{QCD}$

m_c not large enough for $1/m_c$ expansion as in B physics

$$M_{12} - \frac{i}{2}\Gamma_{12} \propto \langle D^0 | H_W^{\Delta c=2} | \overline{D}^0 \rangle + \sum_n \frac{\langle D^0 | H_W^{\Delta c=1} | n \rangle \langle n | H_W^{\Delta c=1} | \overline{D}^0 \rangle}{M_D - E_n + i\epsilon}$$





Short distance
Lattice QCD helps !

Long distance
difficult to determine

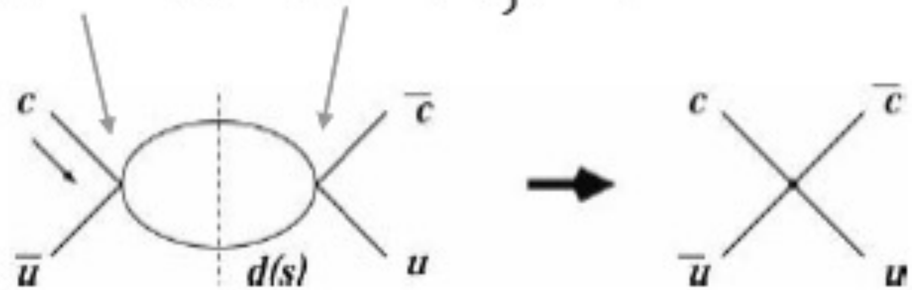
$$y_D = \frac{1}{2M_D\Gamma_D} \mathrm{Im}\, \langle \overline{D^0} | \, i \int \mathrm{d}^4x\, T \Big\{ \mathcal{H}_w^{|\Delta C|=1}(x)\, \mathcal{H}_w^{|\Delta C|=1}(0) \Big\} | D^0 \rangle$$

$$x_D = \frac{1}{2M_D\Gamma_D} \mathrm{Re} \Big[2 \langle \overline{D^0} | H^{|\Delta C|=2} | D^0 \rangle + \langle \overline{D^0} | \, i \int \mathrm{d}^4x\, T \Big\{ \mathcal{H}_w^{|\Delta C|=1}(x)\, \mathcal{H}_w^{|\Delta C|=1}(0) \Big\} | D^0 \rangle \Big]$$

How to approach to long distance contributions?

- operator product expansion

$$y_D = \frac{1}{2M_D\Gamma_D}\,\mathrm{Im}\,\langle\overline{D^0}|\,i\int d^4x\,T\left\{\mathcal{H}_w^{|\Delta C|=1}(x)\,\mathcal{H}_w^{|\Delta C|=1}(0)\right\}|D^0\rangle$$



(D meson is not heavy enough) use of duality

Lattice determined

$$\langle\mathcal{O}_i\rangle \equiv \langle D^0|\mathcal{O}_i|\overline{D}^0\rangle(\mu) = e_i M_D^2 f_D^2 B_D^{(i)}(\mu)$$

One assumes that D transitions are dominated by a small number of exclusive processes, which are examined explicitly.

Falk et al, hep-ph/0110317

$$y = \sum_n \eta_{\rm CKM}(n)\, \eta_{CP}(n)\, \cos\delta_n \sqrt{\mathcal{B}(D^0 \to n)\, \mathcal{B}(\overline{D}^0 \to n)}$$

Strong phase

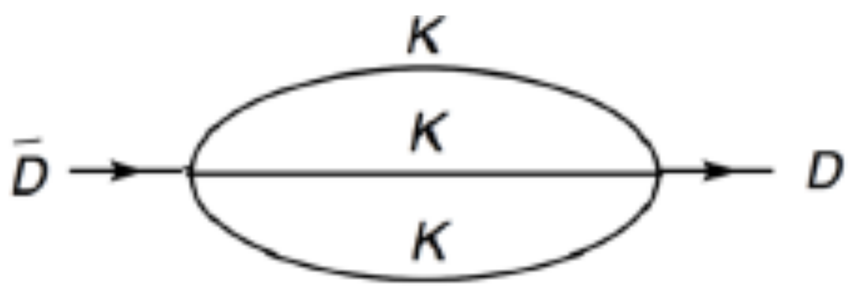
$$\eta_{\rm CKM} = (-1)^{n_s}$$

Number of s and bar s in the final state

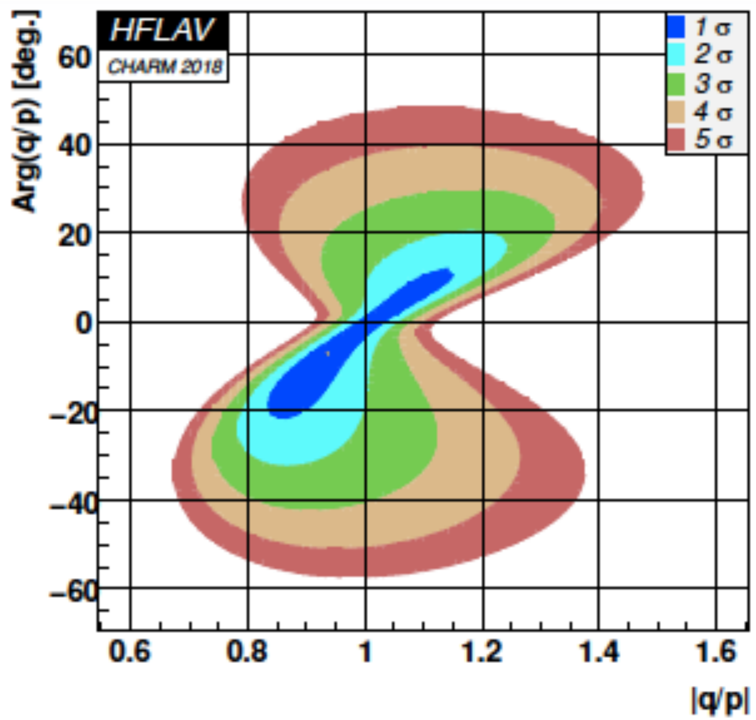
$$\eta_{CP} = \pm 1$$

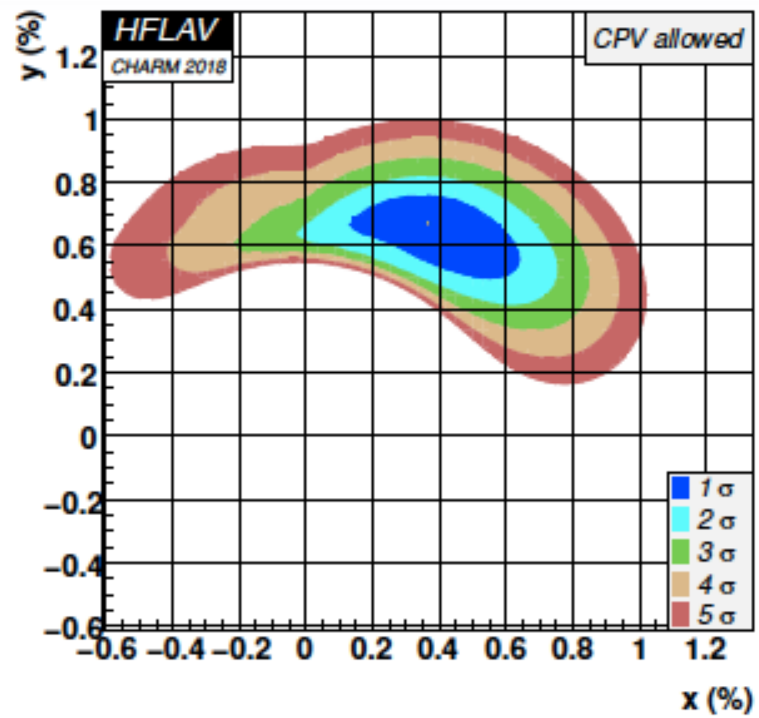
$$\eta_{\rm CKM}(K^+K^-) = +1 \quad \eta_{\rm CKM}(K^+\pi^-) = -1$$

$$CP|f> = \eta_{CP}|\bar{f}>$$



- |q/p≠|1 would indicate CPV in mixing.
- Arg(q/p) ≠ 0 would indicate CPV from interference mixing/decay.
- Mixing parameters x =Δm/Γ and y = ΔΓ/(2Γ).





if CP-violation is neglected…

$$x = 0.50^{+0.13}_{-0.14}\%$$
$$y = 0.63 \pm 0.08\%$$

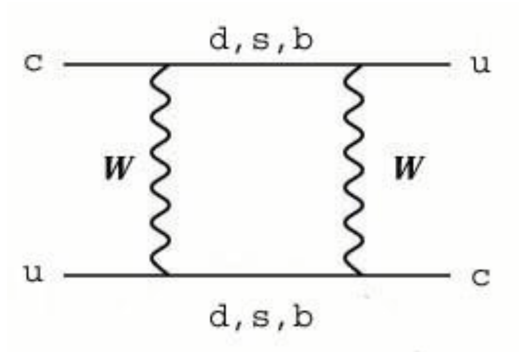
if CP-violation is allowed

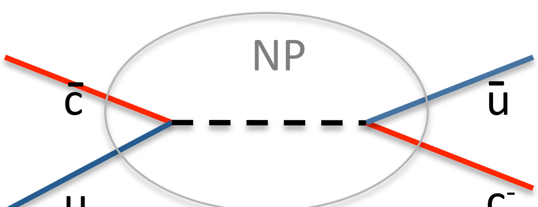
$$x = 0.36^{+0.21}_{-0.16}\%$$
$$y = 0.67^{+0.06}_{-0.13}\%$$

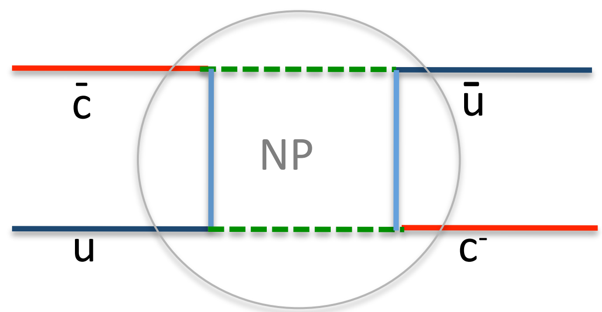
New physics in charm FCNC processes

$$D^0 - \bar{D}^0$$

SM box contribution







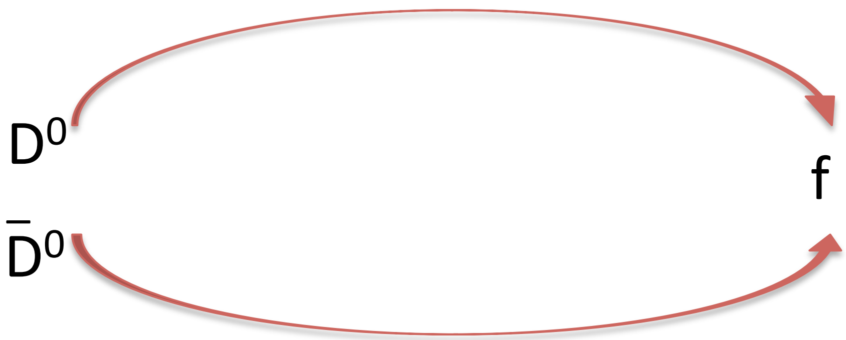
$$D^0 - \bar{D}^0$$

NP at tree level

NP at loop level (box)

$$A \equiv A(D^0 \to f)$$

indirect CP violation



CP eigenstate

Result of CP violation in D mixing

CP violation ⟶ the interference between mixing and decay amplitude

$$\bar{A} \equiv A(\bar{D}^0 \to f)$$

$$A_{CP}(D^0 \to h^- h^+) \equiv \frac{\Gamma(D^0 \to h^- h^+) - \Gamma(\overline{D}^0 \to h^- h^+)}{\Gamma(D^0 \to h^- h^+) + \Gamma(\overline{D}^0 \to h^- h^+)}$$

$$\Delta A_{CP} = A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+),$$

$$\Delta A_{CP} = (-0.10 \pm 0.08 \pm 0.03)\%$$

LHCb, 1602.03160

direct CP violation

Nierste, Schaht 1508.00074

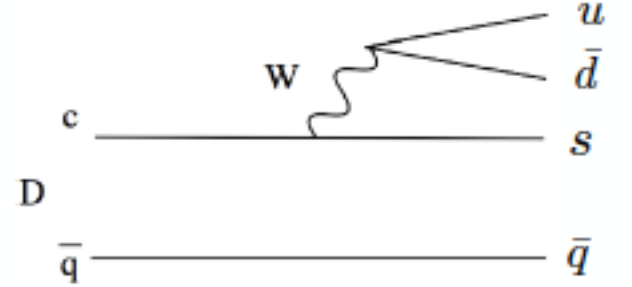
$$a_{CP}^{\text{dir}} \equiv \frac{|A|^2 - |\overline{A}|^2}{|A|^2 + |\overline{A}|^2}$$

$|a_{CP}^{\text{dir}}(D^0 \to K_S K_S)| \leq 1.1\%$ @95% CL

Cabibbo-favored (CF) decay

- $c \rightarrow s\ ud$
- examples: $D^0 \rightarrow K^- \pi^+$

$V_{cs}V_{ud}^*$

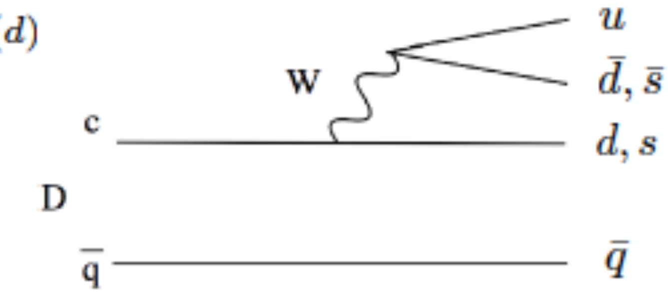


Singly Cabibbo-suppressed (SCS) decay

$c \rightarrow q\ uq$

- examples: $D^0 \rightarrow \pi\pi$ and
- $D^0 \rightarrow KK$

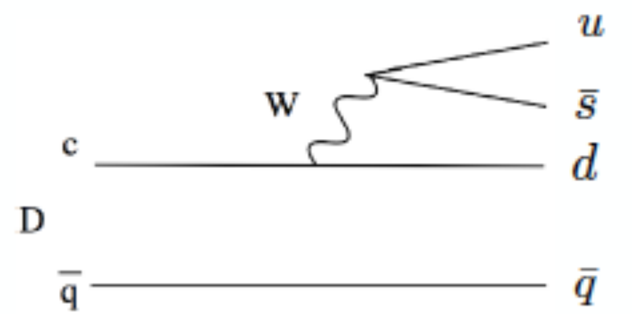
$V_{cs(d)}V_{us(d)}^*$



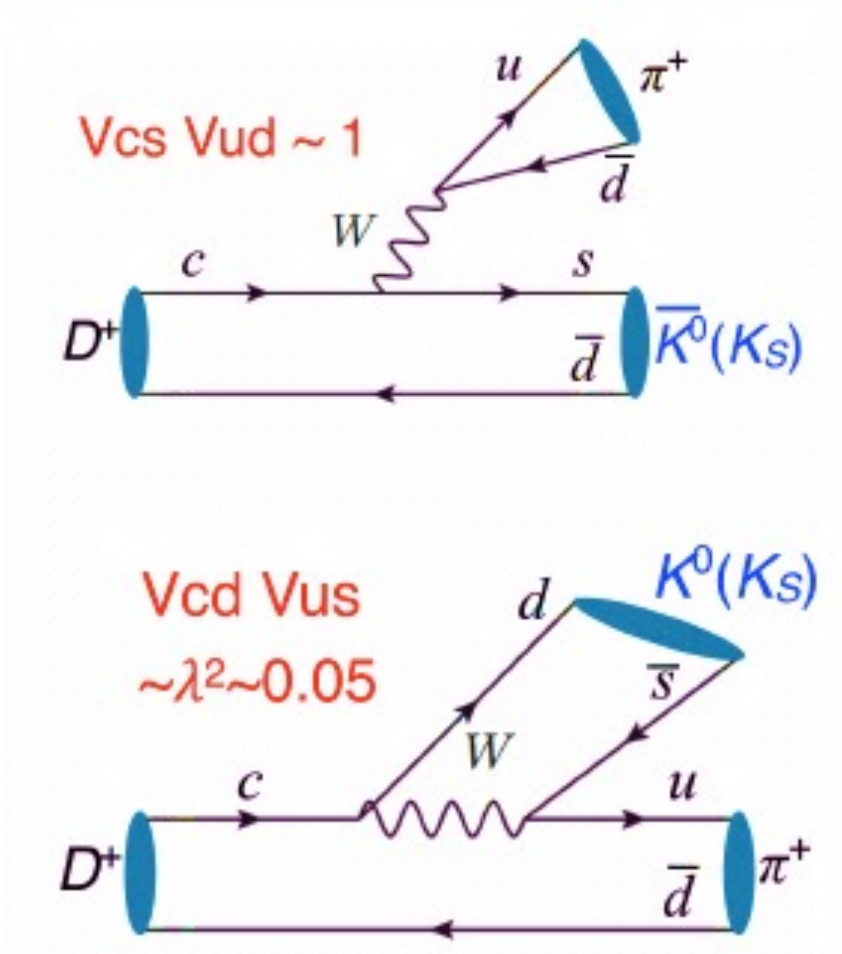
Doubly Cabibbo-suppressed (DCS) decay

- $c \rightarrow d\ us$
- Example $D^0 \rightarrow K^+ \pi^-$

$V_{cd}V_{us}^*$



A measurement of D^0-D^0 mixing and CP violation can be obtained by comparing the ratio of $D^0 \rightarrow K^- \pi^+$ and $D^0 \rightarrow K^+ \pi^-$ decay rates, as a function of the D^0 decay time,



the interference CF and the DCS amplitudes with the K mixing, effect of the order 10^{-3}.

NP and CP violation in charm decays

$$a_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}$$

sensitive to both indirect and direct

$$\Delta A_{CP} = A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+),$$

$$\mathcal{H}^{\rm eff}_{|\Delta c|=1} = \lambda_d \, \mathcal{H}^d_{|\Delta c|=1} + \lambda_s \, \mathcal{H}^s_{|\Delta c|=1} + \lambda_b \, \mathcal{H}^{\rm peng}_{|\Delta c|=1}$$

$$\lambda_q = V^*_{cq} V_{uq},$$

$$\mathcal{H}^q_{|\Delta c|=1} = \frac{G_F}{\sqrt{2}} \sum_{i=1,2} C^q_i Q^s_i + {\rm H.c.}\,, \qquad q = s, d,$$

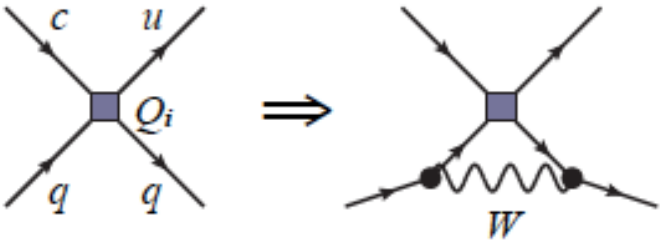
$$Q^q_1 = (\bar{u}q)_{V-A} \, (\bar{q}c)_{V-A}\,,$$
$$Q^q_2 = (\bar{u}_\alpha q_\beta)_{V-A} \, (\bar{q}_\beta c_\alpha)_{V-A}\,,$$

SM

NP effective operators

$$\mathcal{H}^{\rm eff-NP}_{|\Delta c|=1} = \frac{G_F}{\sqrt{2}} \sum_{i=1,2,5,6} \sum_q (C^q_i Q^q_i + C'^q_i Q'^q_i) + \frac{G_F}{\sqrt{2}} \sum_{i=7,8} (C_i Q_i + C'_i Q'_i) + {\rm H.c.}\,,$$

$$Q^q_5 = (\bar{u}c)_{V-A} \, (\bar{q}q)_{V+A}\,,$$
$$Q^q_6 = (\bar{u}_\alpha c_\beta)_{V-A} \, (\bar{q}_\beta q_\alpha)_{V+A}\,,$$
$$Q_7 = -\frac{e}{8\pi^2} \, m_c \, \bar{u}\sigma_{\mu\nu}(1+\gamma_5) F^{\mu\nu} \, c\,,$$
$$Q_8 = -\frac{g_s}{8\pi^2} \, m_c \, \bar{u}\sigma_{\mu\nu}(1+\gamma_5) T^a G^{\mu\nu}_a c\,,$$



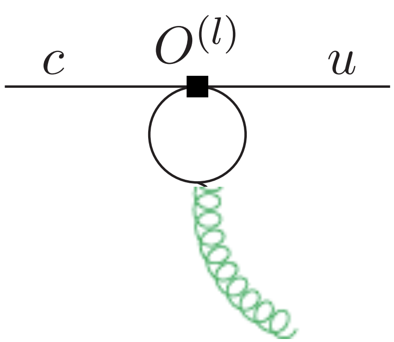
by integrating out heavy degrees of freedom
These operators contribute to D- mixing

$$\mathcal{H}^{\rm eff}_{|\Delta c|=2} = \frac{G_F}{\sqrt{2}}\left(\sum_{i=1}^{5} C_i^{cu} Q_i^{cu} + \sum_{i=1}^{3} C_i^{cu\prime} Q_i^{cu\prime}\right)$$

$$\langle \bar{D}^0 | \mathcal{H}^{\rm eff}_{|\Delta c|=2} | D^0 \rangle \sim C_i^{cu}(\mu) \langle \bar{D}^0 | Q_r^{cu} | D^0 \rangle$$

$$\begin{aligned}
Q_1^{cu} &= (\bar{u}c)_{V-A}\,(\bar{u}c)_{V-A}\,,\\
Q_2^{cu} &= (\bar{u}c)_{S-P}\,(\bar{u}c)_{S-P}\,,\\
Q_3^{cu} &= (\bar{u}_\alpha c_\beta)_{S-P}\,(\bar{u}_\beta c_\alpha)_{S-P}\,,\\
Q_4^{cu} &= (\bar{u}c)_{S-P}\,(\bar{u}c)_{S+P}\,,\\
Q_5^{cu} &= (\bar{u}_\alpha c_\beta)_{S-P}\,(\bar{u}_\beta c_\alpha)_{S+P}\,,
\end{aligned}$$

$$\begin{aligned}
|C_1^{cu}| &\lesssim 5.7\times10^{-8}\,, & \mathrm{Im}(C_1^{cu}) &\lesssim 1.6\times10^{-8}\,,\\
|C_2^{cu}| &\lesssim 1.6\times10^{-8}\,, & \mathrm{Im}(C_2^{cu}) &\lesssim 4.3\times10^{-9}\,,\\
|C_3^{cu}| &\lesssim 5.8\times10^{-8}\,, & \mathrm{Im}(C_3^{cu}) &\lesssim 1.6\times10^{-8}\,,\\
|C_4^{cu}| &\lesssim 5.6\times10^{-9}\,, & \mathrm{Im}(C_4^{cu}) &\lesssim 1.6\times10^{-9}\,,\\
|C_5^{cu}| &\lesssim 1.6\times10^{-8}\,, & \mathrm{Im}(C_5^{cu}) &\lesssim 4.5\times10^{-9}\,.
\end{aligned}$$



RGE running for C_i

$$\left|\frac{\epsilon'}{\epsilon}\right|$$

Correlation to NP in kaon sector

CHARM quark electric (chromo-electric) dipole moment

$$\mathcal{L}_{\rm eff} = d_q \frac{1}{2}(\bar{q}\sigma_{\mu\nu} i\gamma_5 q)F^{\mu\nu} + \tilde{d}_q \frac{1}{2}(\bar{q}\sigma_{\mu\nu} T^a i\gamma_5 q) g_s G_a^{\mu\nu} + w\,\frac{1}{6} f^{abc}\epsilon^{\mu\nu\lambda\rho} G^a_{\mu\sigma} G^{b\,\sigma}_{\nu} G^c_{\lambda\rho}$$

quark EDM

quark CEDM

Weingerg operator

mixing under RGE

$$w = \frac{g_s^3}{32\pi^2}\frac{\tilde{d}_q}{m_q};$$

CEDM threshold correction to w

Sala, 1312.2589

Considered charm quark EDM and CEDM

$|\tilde{d}_c| \lesssim 1.0 \times 10^{-22}\text{cm}$ from neutron EDM

$|d_c| \lesssim 4.4 \times 10^{-17} e\,\text{cm}$ from $B \to X_s\gamma$

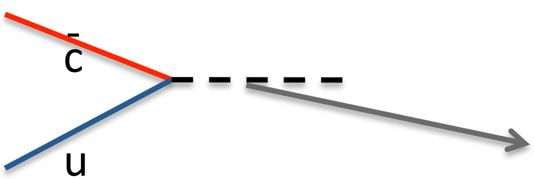
In 1809.09114, Dekens et al, NP from B anomalies creates c-quark EDM, which can be related to neutron (lattice computation of c –bar c content of neutron~ 2%) or Hg EDM!

More studies of charm quark EDM(CEDM) – new source of CP violation!

Properties of FCNC in charm physics

- conspiracy: d,s, b quarks are in the loops;
- very strong GIM suppression;
- $m_{s,d} \ll \Lambda_{QCD}$

long distance contribution dominant!



a weak singlet, doublet or triplet

$$Q_{iL} = \begin{bmatrix} V^*_{iJ}\, u_J \\ d_i \end{bmatrix}_L$$

up quark weak doublet “talks” to down quark via CKM!

SM effective Hamiltonian for rare charm decays -FCNC

$$\mathcal{H}_{\rm eff} = \lambda_d \mathcal{H}^d + \lambda_s \mathcal{H}^s - \frac{4G_F\lambda_b}{\sqrt{2}} \sum_{i=3,\ldots,10,S,P,\ldots} C_i \mathcal{O}_i$$

$$\lambda_q = V_{uq} V_{cq}^* \qquad \bar{u}\gamma_\mu 1/2(1-\gamma_5) q\, \bar{q}\gamma_\mu 1/2(1-\gamma_5) c$$

Tree-level 4-quark operators (Short-distance) penguin operators

1) At scale m_W all penguin contributions vanish due to GIM;

2) SM contributions to $C_{7\ldots10}$ at scale m_c entirely due to mixing of tree-level operators into penguin ones under QCD

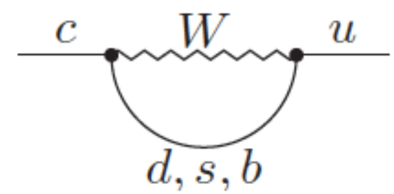
3) SM values at

$$C_7 = 0.12, \qquad C_9 = -0.41$$

(recent results: de Boer, Hiller, 1510.00311, 1701.06392, De Boer et al, 1606.05521) 1707.00988)

SM in $c \to u\gamma$ and $c \to ul^+l^-$

Rare charm decays much rarer than rare B decays.
For same statistics much less events.



$$Q_7 = \frac{e}{8\pi^2} m_c F_{\mu\nu} \bar{u} \sigma^{\mu\nu} (1 + \gamma_5) c,$$

$$Q_9 = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \ell,$$

$$Q_{10} = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \gamma_5 \ell,$$

Q_7 contributes to $c \to u\gamma$ and $c \to ul^+l^-$

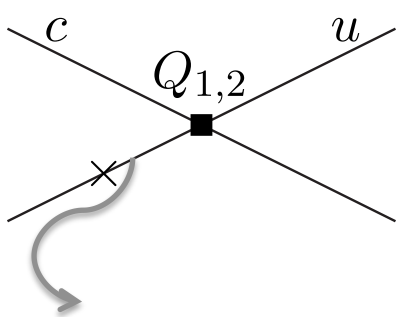
all three operators contribute to

$c \to ul^+l^-$

GIM suppression

C. Greub et al., PLB 382 (1996) 415; $BR(D \to X_u \gamma) \sim 10^{-8}$

branching ratio	$D^0 \to \rho^0\gamma$	$D^0 \to \omega\gamma$	$D^0 \to \phi\gamma$	$D^0 \to \bar{K}^{*0}\gamma$
Belle [24]†	$(1.77 \pm 0.31) \times 10^{-5}$	–	$(2.76 \pm 0.21) \times 10^{-5}$	$(4.66 \pm 0.30) \times 10^{-4}$
BaBar [33]$^{\dagger\, a}$	–	–	$(2.81 \pm 0.41) \times 10^{-5}$	$(3.31 \pm 0.34) \times 10^{-4}$
CLEO [34]	–	$< 2.4 \times 10^{-4}$	–	–



photon emission

Hiller & De Boer 1701.06392

Note: all SM th. predictions for
BR($D^0 \to \rho^0\gamma$) smaller than exp. rate!

previuos works:
SF& Singer, hep-ph/9705327, SF, Prelovsek &hep-ph/9801279
S. F. P. Singer and J. Zupan, EPJC 27(2003) 201 Burdman et al. hep-ph/9502329,
Khodjamirian et al, hep-ph/9506242

CP asymmetry in charm radiative decays

$$A_{CP}(D \to V\gamma) = \frac{\Gamma(D \to V\gamma) - \Gamma(\bar{D} \to \bar{V}\gamma)}{\Gamma(D \to V\gamma) + \Gamma(\bar{D} \to \bar{V}\gamma)}$$

$$|A_{CP}^{\mathsf{SM}}| < 2 \cdot 10^{-3}$$

Hiller& de Boer 1701. 06392

LQs give as large

contributions as SM

Belle, 1603.03257

$$A_{CP}(D^0 \to \rho^0\gamma) = 0.056 \pm 0.152 \pm 0.006\,,$$

$$A_{CP}(D^0 \to \phi\gamma) = -0.094 \pm 0.066 \pm 0.001$$

$$A_{CP}(D^0 \to \bar{K}^{*0}\gamma) = -0.003 \pm 0.020 \pm 0.000$$

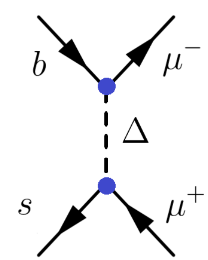
Models of NP explaining B anomalies

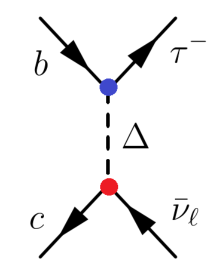
Spin	Color singlet	Color tripet
0	2HDM	Scalar LQ $\not{R}$ parity - sbottom
1	W' ,Z'	Vector LQ
		Dark matter?

2HDMII cannot explain $R_{D(*)}$

New gauge bosons, W', Z'- difficult to construct UV complete theory

Leptoquarks?

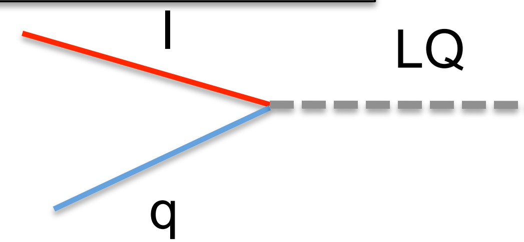




Nature of anomaly requires NP in quark and lepton sector!
It seems that LQs are ideal candidates to explain all B anomalies at tree level!

- Is charm physics sensitive on NP explaining B puzzles ?
- Can some NP be present in charm and not in beauty mesons?

Popular scenario: Leptoquarks as a resolution of B anomalies:



LQ=$(SU(3)_c, SU(2)_L)_Y$

$Q=I_3+Y$

or LQ=$(SU(3)_c, SU(2)_L, Y)$

no proton decay at tree level

Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$	
$S_1 = (\bar{3}, 1)_{1/3}$	✓	✗	✗	Spin 0
$R_2 = (3, 2)_{7/6}$	✓	✗*	✗	
$S_3 = (\bar{3}, 3)_{1/3}$	✗	✓	✗	
$U_1 = (3, 1)_{2/3}$	✓	✓	✓	Spin 1
$V_2 = (3, 1)_{2/3}$	✗	✗	✗	
$\widetilde{V}_2 = (\bar{3}, 2)_{-1/6}$	✗	✗	✗	
$U_3 = (3, 3)_{2/3}$	✗	✓	✗	

No single scalar LQ to solve simultaneously both anomalies!

Doršner, SF, Greljo, Kamenik , Košnik, 1603.04993

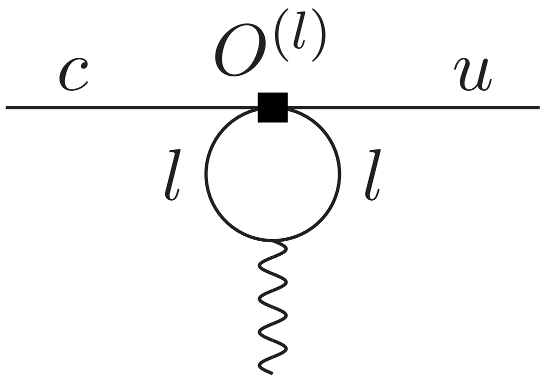
Scalar LQ → simpler UV completion;

Only R_2 and S_1 might explain $(g\text{-}2)_\mu$ (both chiralities are required with the enhancement factor m_t/m_μ) Muller 1801.0338.

New Physics in FCNC charm decays

Leptoquarks in $c \to u\gamma$

Hiller& de Boer 1701. 06392
SF and Košnik, 1510.00965



Constraints from

$$\tau^- \to \pi^- \nu_\tau$$

$$\tau^- \to K^- \nu_\tau$$

$$\Delta m_D$$

$$D^+ \to \tau^+ \nu_\tau$$

$$D_s^+ \to \tau^+ \nu_\tau$$

$$K^+ \to \pi^+ \nu \bar{\nu}$$

Even for τ in the loop too small contribution!

Masses of $m_{LQ} \approx 1$ TeV.

Within LQ models the $c \to u\gamma$ branching ratios are SM-like with CP asymmetries at O(0.01) for $S_{1,2}$ and $\tilde{V}_2$ and SM-like for S_3.

Vector LQ $\tilde{V}_1$ A_{CP} ~ O(10%). The largest effects arise from τ-loops.

S_3 can explain $R_{K(*)}$!

NP in $c \to u l^+ l^-$

Most general dimension 6 effective Lagrangian for $c \to u l^+ l^-$

$$\mathcal{O}_7 = \frac{e m_c}{(4\pi)^2} (\bar{u}\sigma_{\mu\nu} P_R c) F^{\mu\nu} , \qquad \mathcal{O}_S = \frac{e^2}{(4\pi)^2} (\bar{u} P_R c)(\bar{\ell}\ell) ,$$

$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2} (\bar{u}\gamma^\mu P_L c)(\bar{\ell}\gamma_\mu \ell) , \qquad \mathcal{O}_P = \frac{e^2}{(4\pi)^2} (\bar{u} P_R c)(\bar{\ell}\gamma_5 \ell) ,$$

$$\mathcal{O}_{10} = \frac{e^2}{(4\pi)^2} (\bar{u}\gamma^\mu P_L c)(\bar{\ell}\gamma_\mu \gamma_5 \ell) , \qquad \mathcal{O}_T = \frac{e^2}{(4\pi)^2} (\bar{u}\sigma_{\mu\nu} c)(\bar{\ell}\sigma^{\mu\nu} \ell) ,$$

$$\mathcal{O}_{T5} = \frac{e^2}{(4\pi)^2} (\bar{u}\sigma_{\mu\nu} c)(\bar{\ell}\sigma^{\mu\nu} \gamma_5 \ell)$$

$$D^0 \to \mu^+ \mu^-$$

SF, N. Kosnik, 1510.00965

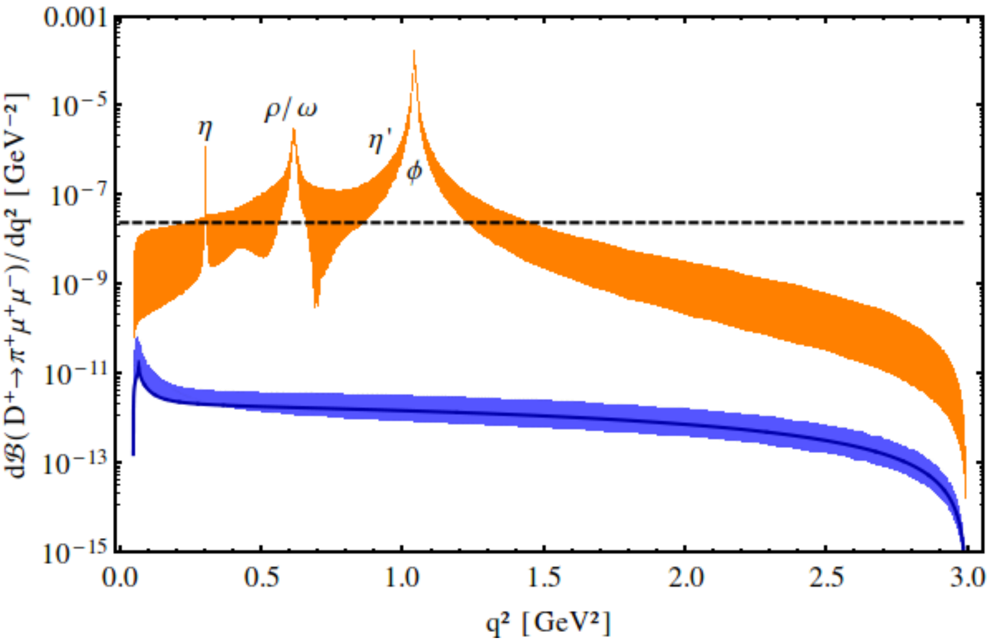
LHCb bound, 1305.5059

$$\mathcal{B}(D^0 \to \mu^+ \mu^-) < 6.2 \cdot 10^{-9} \text{ at CL=90\%}$$

Helicity suppressed decay!

$$|C_S - C_S'|^2 + |C_P - C_P' + 0.1(C_{10} - C_{10}')|^2 \lesssim 0.007$$

$D \to \pi l^+ l^-$

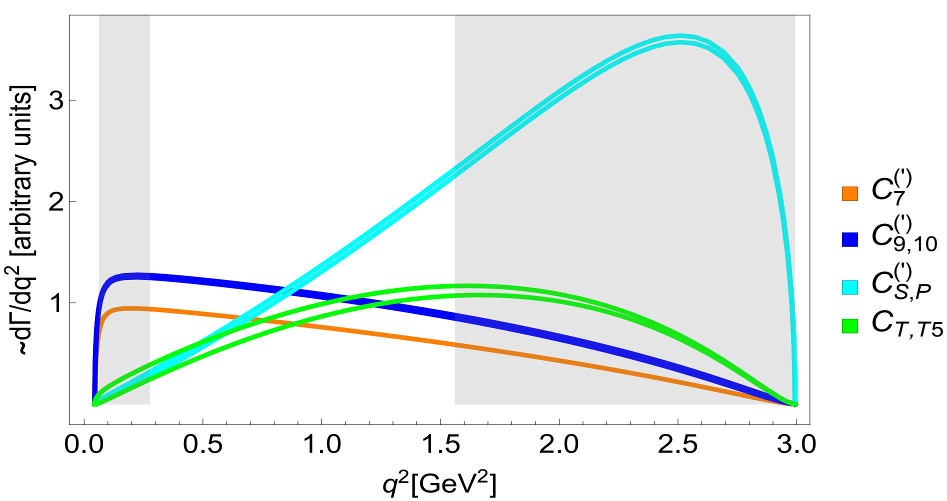


SM prediction: Long distance contributions most important!

$D \to \pi V \to \pi l^+ l^-$

peaks at ρ,ω,φ and η resonances

de Boer, Hiller, 1510.00311,
SF and Kosnik, 1510.00965

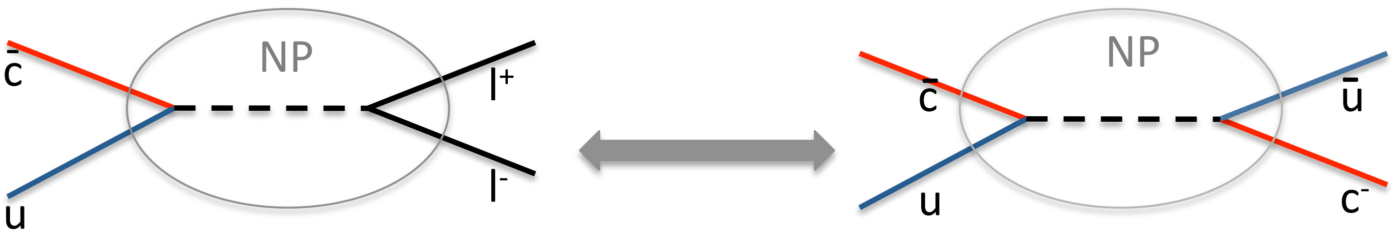


Maximally allowed values of the Wilson coefficients in the low and high energy bins, according to LHCb 1304.6365 :

LHCb 1304.6365

NP in $c \to u l^+ l^-$

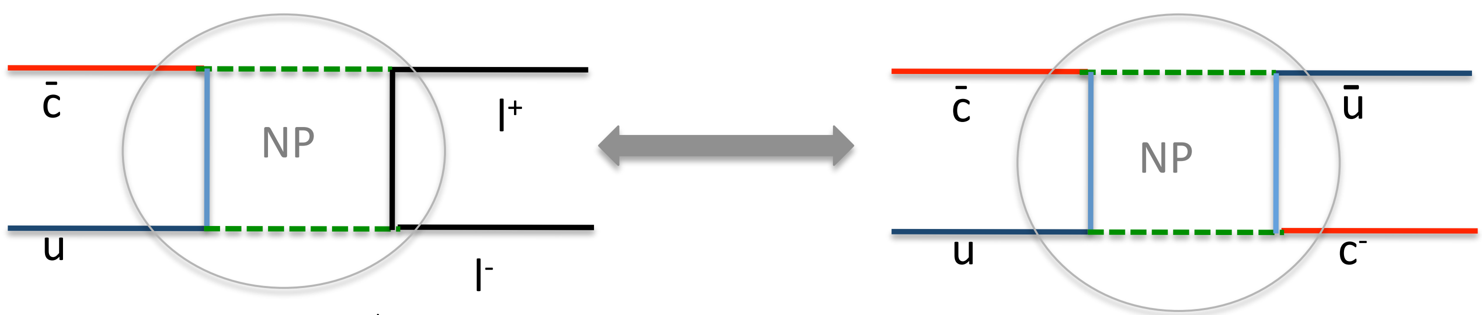
Tree level FCNC



The same couplings immediately create contributions to $D^0 - \bar{D}^0$

Loop level

(e.g.)



$c \to u l^+ l^-$ $\qquad$ $D^0 - \bar{D}^0$

	$\lvert\tilde{C}_i\rvert_{\max}$		
	$BR(\pi\mu\mu)_{I}$	$BR(\pi\mu\mu)_{II}$	$BR(D^0 \to \mu\mu)$
$\tilde{C}_7$	2.4	1.6	-
$\tilde{C}_9$	2.1	1.3	-
$\tilde{C}_{10}$	1.4	0.92	0.56
$\tilde{C}_S$	4.5	0.38	0.043
$\tilde{C}_P$	3.6	0.37	0.043
$\tilde{C}_T$	4.1	0.76	-
$\tilde{C}_{T5}$	4.4	0.74	
$\tilde{C}_9 = \pm\tilde{C}_{10}$	1.3	0.81	0.56

Best bounds from

$$D^0 \to \mu^+\mu^-$$

$$|\tilde{C}_i| = |V_{ub}V_{cb}^* C_i|$$

0.043

region I

$$q^2 \in [0.0625, 0.276]\, GeV^2$$

region II

$$q^2 \in [1.56, 4.00]\, GeV^2$$

$$BR(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$$

Test of lepton flavour universality violation in charm FCNC decays

$$R_\pi^{\mathrm{I}} = \frac{\mathrm{BR}(D^+ \to \pi^+\mu^+\mu^-)_{q^2\in[0.25^2,0.525^2]\mathrm{GeV}^2}}{\mathrm{BR}(D^+ \to \pi^+e^+e^-)_{q^2\in[0.25^2,0.525^2]\mathrm{GeV}^2}} \quad R_\pi^{\mathrm{II}} = \frac{\mathrm{BR}(D^+ \to \pi^+\mu^+\mu^-)_{q^2\in[1.25^2,1.73^2]\mathrm{GeV}^2}}{\mathrm{BR}(D^+ \to \pi^+e^+e^-)_{q^2\in[1.25^2,1.73^2]\mathrm{GeV}^2}}$$

$$R_\pi^{I,SM} = 0.87 \pm 0.09$$

	$\lvert\tilde{C}_i\rvert_{\max}$	R_π^{II}
SM	-	0.999 ± 0.001
$\tilde{C}_7$	1.6	$\sim$ 6–100
$\tilde{C}_9$	1.3	$\sim$ 6–120
$\tilde{C}_{10}$	0.63	$\sim$ 3–30
$\tilde{C}_S$	0.05	$\sim$ 1–2
$\tilde{C}_P$	0.05	$\sim$ 1–2
$\tilde{C}_T$	0.76	$\sim$ 6–70
$\tilde{C}_{T5}$	0.74	$\sim$ 6–60
$\tilde{C}_9 = \pm\tilde{C}_{10}$	0.63	$\sim$ 3–60
$\tilde{C}'_9 = -\tilde{C}'_{10}\rvert_{\mathrm{LQ}(3,2,7/6)}$	0.34	$\sim$ 1–20

Assumptions:

- e^+e^- modes are SM-like;
- NP enters in $\mu^+\mu^-$ mode only;
- listed Wilson coefficients are maximally allowed by current LHCb data.

Angular distributions in $D \to P_1 P_2\, l^+ l^-$

LHCb, 1707.08377

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-)|_{[0.565-0.950]\,\mathrm{GeV}} = (40.6 \pm 5.7) \times 10^{-8}\,,$$
$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-)|_{[0.950-1.100]\,\mathrm{GeV}} = (45.4 \pm 5.9) \times 10^{-8}\,,$$
$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-)|_{[>0.565]\,\mathrm{GeV}} = (12.0 \pm 2.7) \times 10^{-8}\,,$$

- study of angular distributions SM – null tests
- simpler then in B decays due to dominance of long distance physics (resonances)
- NP induced integrated CP asymmetries can reach few percent
- sensitive on $C_{10}^{(')}$

$$A_{\mathrm{FB}}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (3.3 \pm 3.7 \pm 0.6)\%,$$
$$A_{2\phi}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (-0.6 \pm 3.7 \pm 0.6)\%,$$
$$A_{CP}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (4.9 \pm 3.8 \pm 0.7)\%,$$
$$A_{\mathrm{FB}}(D^0 \to K^+K^-\mu^+\mu^-) = (0 \pm 11 \pm 2)\%,$$
$$A_{2\phi}(D^0 \to K^+K^-\mu^+\mu^-) = (9 \pm 11 \pm 1)\%,$$
$$A_{CP}(D^0 \to K^+K^-\mu^+\mu^-) = (0 \pm 11 \pm 2)\%,$$

De Beor and Hiller, 1805.08516

Modes sensitive to NP

$$D^0 \to \pi^+\pi^- l^+ l^-\,, \quad D^0 \to K^+K^- l^+ l^-\,,$$
$$D^+ \to K^+ \bar{K}^0 l^+ l^-\,,$$
$$D_s \to K^+\pi^0 l^+ l^-\,, \quad D_s \to K^0\pi^+ l^+ l^-\,,$$

$$R_{\pi\pi}^{D\,\mathrm{SM}} = 1.00 \pm \mathcal{O}(\%)$$

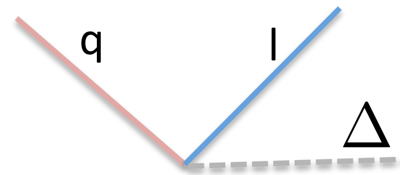
$$R_{KK}^{D\,\mathrm{SM}} = 1.00 \pm \mathcal{O}(\%)$$

Tests of LFU

$$R^D_{P_1P_2} = \frac{\int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} d\mathcal{B}/dq^2(D \to P_1P_2\mu^+\mu^-)}{\int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} d\mathcal{B}/dq^2(D \to P_1P_2 e^+e^-)}$$

LHCb , 1806.10793
consistent with SM

Scalar LQ in charm FCNC processes



(3,3,-1/3)

$$\mathcal{L}_{\bar{c}u\bar{\ell}\ell} = -\frac{4G_F}{\sqrt{2}}\left[c_{cu}^{LL}(\bar{c}_L\gamma^\mu u_L)(\bar{\ell}_L\gamma_\mu\ell_L)\right] + \text{h.c.},$$

$$C_{cu}^{LL} = -\frac{v^2}{2m_{S_3}^2}(V_{cs}^* g_{s\mu} + V_{cb}^* b_{b\mu})(V_{us} g_{s\mu} + V_{ub} b_{b\mu})$$

C_{cu}^{LL} 100 times smaller than current LHCb bound!

(3,1,-1/3)

(3,1,-1/3) introduced by Bauer and Neubert in 1511.01900 to explain both B anomalies. In 1608.07583, Becirevic et al., showed that model cannot survive flavor constraints:

$K \to \mu\nu,\ B \to \tau\nu,\ \tau \to \mu\gamma$

$D_s \to \tau\nu,\ D \to \mu^+\mu^-$

Scalar LQ (3,2,7/6)

In the case of Δ C= 2 in $D^0 - \bar{D}^0$ oscillation there is also a LQ contribution

$$\mathcal{H} = C_6(\bar{u}_R\gamma^\mu c_R)(\bar{u}_R\gamma_\mu c_R)$$

Bound from ΔC =2 slightly stronger,
but comparable to the bound coming from

$$D^0 \to \mu^+\mu^-$$

R_2 (3,2,7/6) can explain $R_{D(*)}$
(Becirevic, Dorsner, SF,Faroughy, Kosnik, Sumensari, 1806.05689
and can generate c quark EDM)

Vector LQ(3,1,5/3)

$$\mathcal{L} = Y_{ij}\,(\bar{\ell}_i\gamma_\mu P_R u_j)\,V^{(5/3)\mu} + \mathrm{h.c.}\,.$$

not present in B physics at tree level!

$$D^0 - \bar{D}^0$$

(for loop effects in B
Camargo-Molina, Celis, Faroughy
1805.04917)

Model	Effect	Size of the effect
Scalar leptoquark (3,2,7/6)	$C_S, C_P, C_S', C_P', C_T, C_{T5}, C_9, C_{!0}, C_9', C_{10}'$	$V_{cb}V_{ub}\|C_{9,}\ C_{10}\| < 0.34$
Vector leptoquark (3,1,5/3)	$C_9' = C_{10}'$	$V_{cb}V_{ub}\|C_9'_{,}\ C_{10}'\| < 0.24$
Two Higgs doublet Model type III	C_S, C_P, C_S', C_P'	$V_{cb}V_{ub}\|C_S - C_S'\| < 0.005$ $V_{cb}V_{ub}\|C_P - C_P'\| < 0.005$
Z' model	C_9', C_{10}'	$V_{cb}V_{ub}\|C_9'_{,}\| < 0.001$ $V_{cb}V_{ub}\|C_{10}'\| < 0.014$

Lepton flavor violation

$$c \to u\mu^{\pm}e^{\mp}$$

1510.00311 (de Beor and Hiller)
1705.02251 (Sahoo and Mohanta)

$$\mathcal{L}_{\rm eff}^{\rm weak}(\mu \sim m_c) = \frac{4G_F}{\sqrt{2}}\frac{\alpha_e}{4\pi}\sum_i \left(K_i^{(e)}O_i^{(e)} + K_i^{(\mu)}O_i^{(\mu)}\right)$$

$$O_9^{(e)} = (\bar{u}\gamma_\mu P_L c)\,(\bar{e}\gamma^\mu \mu)$$

$$O_9^{(\mu)} = (\bar{u}\gamma_\mu P_L c)\,(\overline{\mu}\gamma^\mu e)$$

LHCb bound, 1512.00322

$$BR(D^0 \to e^+\mu^- + e^-\mu^+) < 2.6 \times 10^{-7}$$

$$BR(D^+ \to \pi^+ e^+\mu^-) < 2.9 \times 10^{-6}$$

$$BR(D^+ \to \pi^+ e^-\mu^+) < 3.6 \times 10^{-6}$$

$$\left|K_{S,P}^{(l)} - K_{S,P}^{(l)\prime}\right| \lesssim 0.4\,,$$

$$\left|K_{9,10}^{(l)} - K_{9,10}^{(l)\prime}\right| \lesssim 6\,, \quad \left|K_{T,T5}^{(l)}\right| \lesssim 7\,,$$

$$l = e, \mu$$

$$BR(D^0 \to e^{\pm}\tau^{\mp}) < 7 \times 10^{-15}$$

Dark Matter in charm decays

Belle collaboration 1611.09455
BR($D^0 \rightarrow$ invisible) $< 9.4 \times 10^{-5}$

SM: BR($D^0 \rightarrow \nu\nu$) = 1.1×10^{-30}

Badin & Petrov 1005.1277 suggested to search for processes with missing energy $\not{E}$ in

$$D^0 \rightarrow \gamma \not{E}$$ could be SM neutrinos or DM!

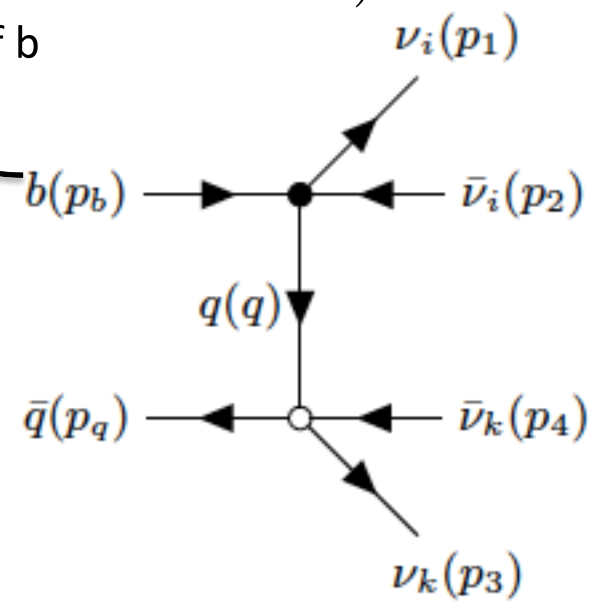
Bhattacharya, Grant and Petrov 1809.04606

$$\mathcal{B}(D \rightarrow invisibles) = \mathcal{B}(D \rightarrow \nu\bar{\nu}) + \mathcal{B}(D \rightarrow \nu\bar{\nu} + \nu\bar{\nu}) + \ldots$$

c instead of b

The SM contributions to invisible widths of heavy mesons $\Gamma(D^0 \rightarrow$ missing energy) are completely dominated by the four-neutrino transitions $D^0 \rightarrow \nu\bar{\nu}\nu\bar{\nu}$.

$$\mathcal{B}(D^0 \rightarrow \nu\bar{\nu}\nu\bar{\nu}) = (2.96 \pm 0.39) \times 10^{-27}$$



$U(1)_X$ dark sector

F. C. Correia, SF, 1609.0860,
Batell et al.1103.0721
F. C. Correia, SF, in preparation

Gauge group SU(3) x SU(2) X $U(1)_Y$ X $U(1)_X$

- Request anomalies cancelled:

$$U(1)^3_X,\ U(1)^2_X U(1)_Y,\ U(1)_X U(1)^2_Y \text{ and } SU(3)^2 U(1)_X$$

- Higgs sector: 2 doublets, one singlet

$$\phi_0 = \begin{pmatrix} \varphi_0^+ \\ \frac{v_0+H_0+i\chi_0}{\sqrt{2}} \end{pmatrix}; \qquad \phi_X = \begin{pmatrix} \varphi_X^+ \\ \frac{v_X+H_X+i\chi_X}{\sqrt{2}} \end{pmatrix}; \qquad s = \frac{v_s + H_s + i\chi_s}{\sqrt{2}}$$

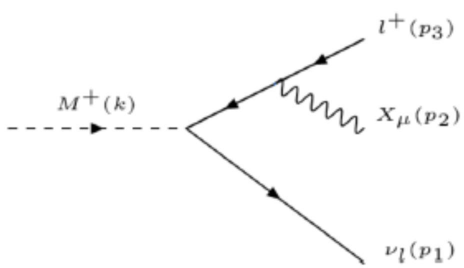
$$v^2 \equiv (v_0^2 + v_X^2), \qquad \bar{v}^2 \equiv (v_s^2 + v_X^2), \qquad c_\beta^2 = \frac{v_X^2}{v^2}$$

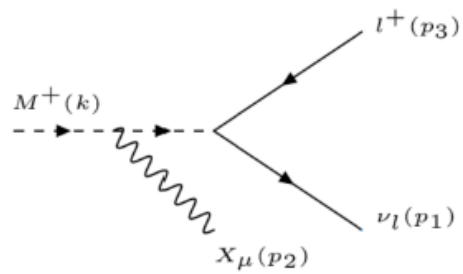
- invisible fermions necessary for anomaly cancellation

$$\mathcal{L} \longrightarrow -Y_s\, \overline{\chi_L}\chi_R s - Y_s^*\, \overline{\chi_R}\chi_L s^*$$

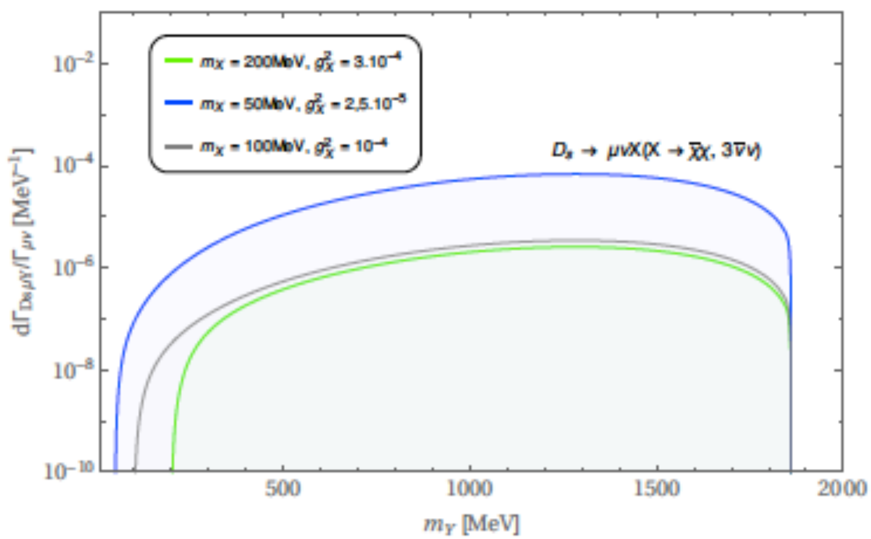
A_μ and X_μ mix via κ

$$M^+ \to \mu^+ \not{E}$$





Radiative - not γ but X



Is it possible to search for decay

D → μ X

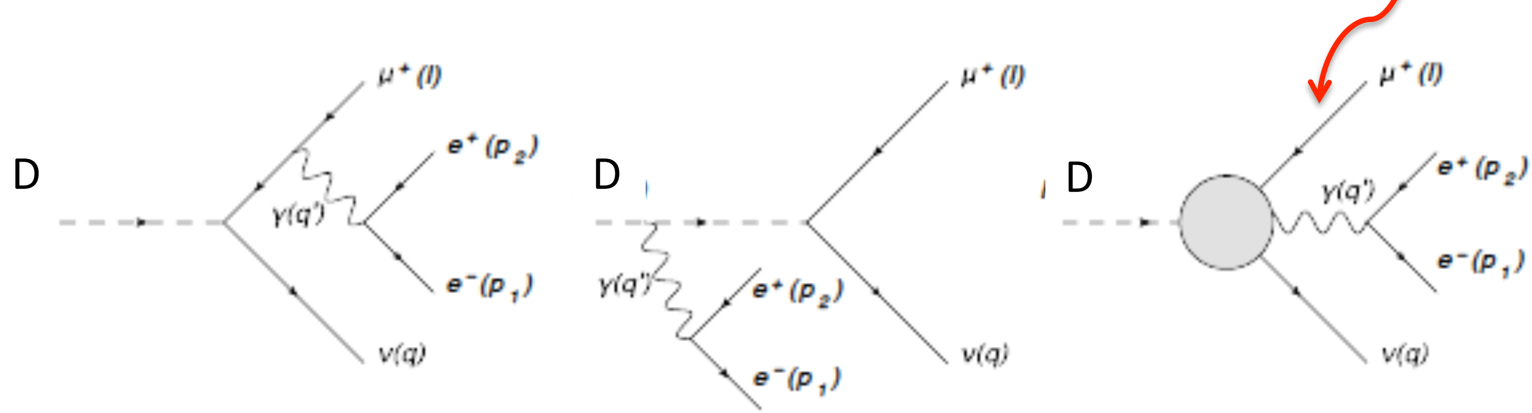
X is SM ν_μ + DM gauge boson → invisible fermions

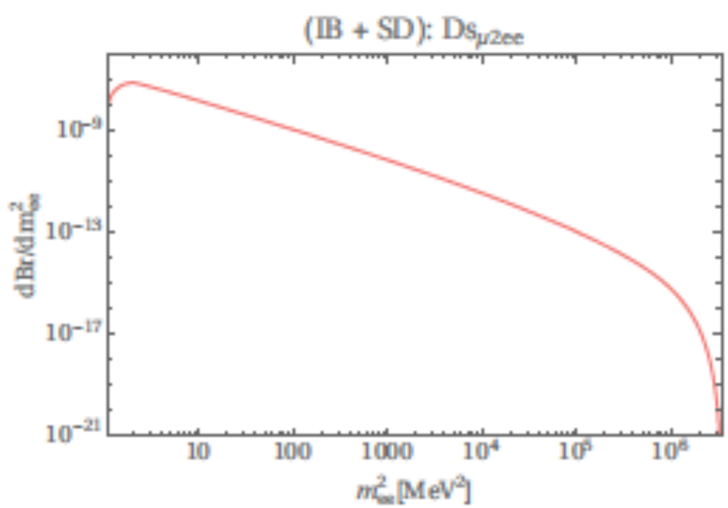
Exp: $D \to \tau \bar{\nu}_\tau \to \mu \bar{\nu}_\mu \nu_\tau \bar{\nu}_\tau$

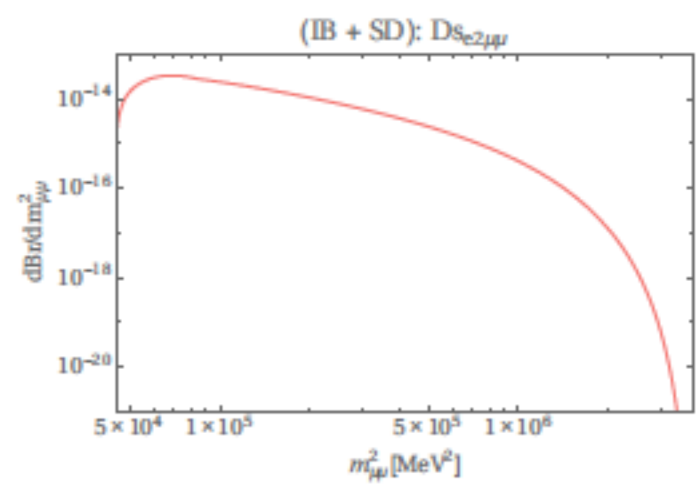
Difficult to differentiate

- There is a possibility that X → e^+e^-
- Can one see it in the decays P→μ νX → μυ e^+e
- First one should calculate SM values

Thanks D. Melikhov for providing us with $<\gamma^* | J_\mu | D_s>$

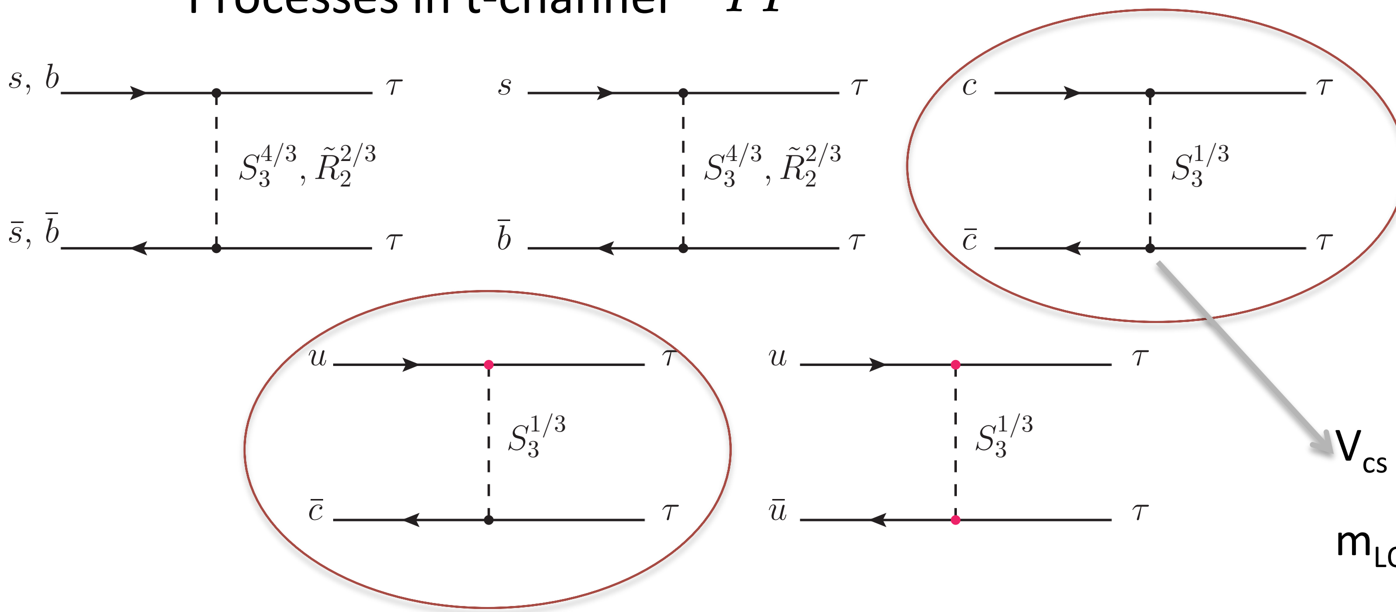






LHC constraints in high-mass ττ production

Processes in t-channel $pp \to \tau^+\tau^-$



$V_{cs}{}^* y_{s\tau} + V_{bs}{}^* y_{b\tau}$

$m_{LQ} \approx 1$ TeV

Flavour anomalies generate s τ , bτ and cτ relatively large couplings.

s quark pdf function for protons are ~ 3 times lagrer contribution then for b quark.

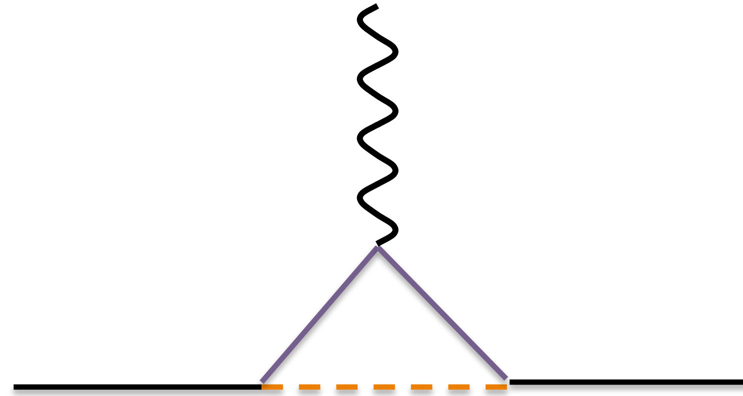
1706.07779, Doršner,SF,Faroughy, Košnik
1812.06851, Kowalska et al.

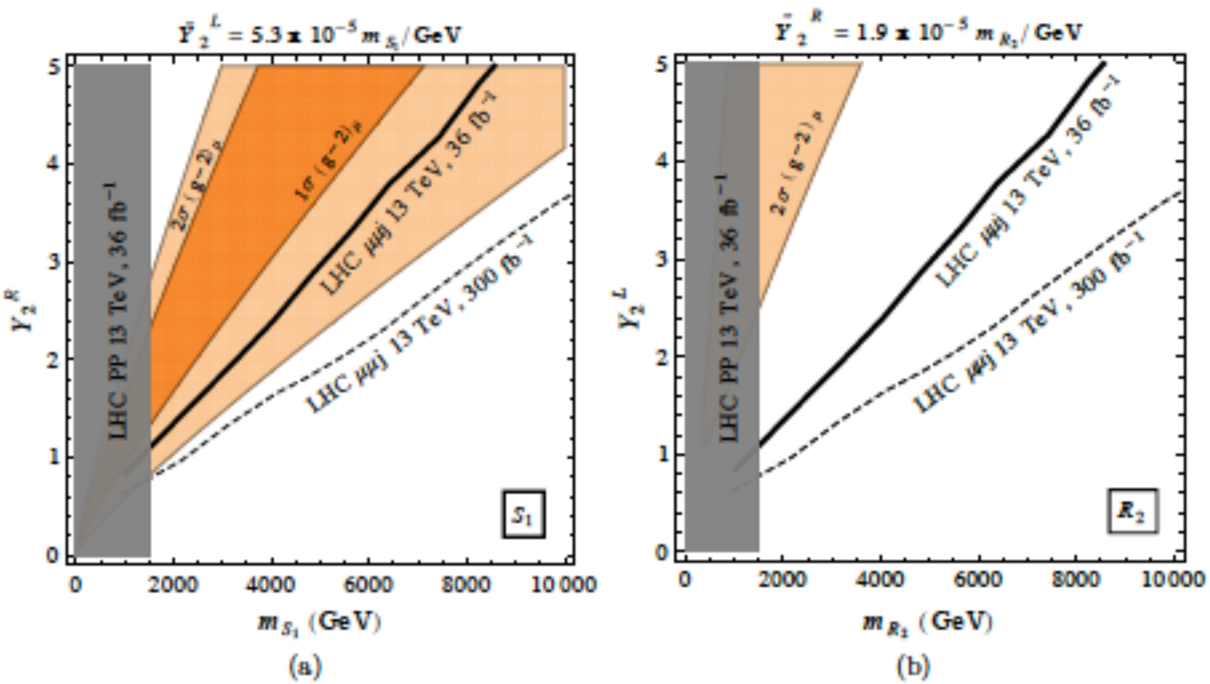
$$\sigma_{s\bar{s}}(y_{s\tau}) = 12.042\, y_{st}^4 + 5.126\, y_{st}^2\,,$$
$$\sigma_{s\bar{b}}(y_{s\tau}, y_{b\tau}) = 12.568\, y_{s\tau}^2 y_{b\tau}^2\,,$$
$$\sigma_{b\bar{b}}(y_{b\tau}) = 3.199\, y_{b\tau}^4 + 1.385\, y_{b\tau}^2\,,$$
$$\sigma_{c\bar{c},u\bar{u},u\bar{c}}(y_{s\tau}) = 3.987\, y_{s\tau}^4 - 5.189\, y_{s\tau}^2\,.$$

1812.06851, Kowalska et al.

Charm quark in $(g\text{-}2)_\mu$ and S_1 or R_2

and BR($D \longrightarrow \mu\mu$)< 7.6 10^{-9}





Summary and outlook

- QCD (lattice) a lot of open issues in Charm spectroscopy!
  Improvement on decay constants and form-factors!
- CP-violation in up sector (NP search) more studies on direct CP violation and (C)EDM of c-quark ;
- New physics explaining B anomalies, leads to rather small effects in charge current transitions ;
- FCNC transition small contribution of Leptoquarks in charm decays observables;
- To perform all possible test of LFU;
- Few proposals to test DM in charm physics;
- Search for NP in charm physics requires high precision theoretical and experimental studies!!