B Germany meeting 2020

Exploiting CP–asymmetries in rare charm decays

Marcel Golz

September 14th, **2020**
based on

R. Bause, H. Gisbert, MG, **G. Hiller**
2004.01206

R. Bause, MG, **G. Hiller, A. Tayduganov**
1909.11108

Outline

- Trouble and opportunities with charm predictions
- CP–violation in charm
- Anomaly-free Z' models
- Patterns in hadronic decays aka. „What experiment can do“
- Summary

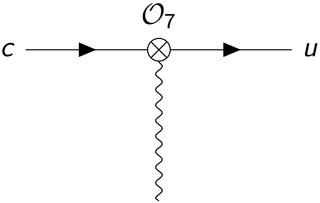
Semileptonic decays $c \to u\ell\ell$

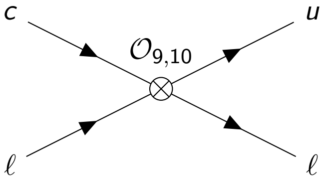
$D \to \pi\ell\ell$

$D_s \to K\ell\ell$

$\Lambda_c \to p\ell\ell$

$\dots$



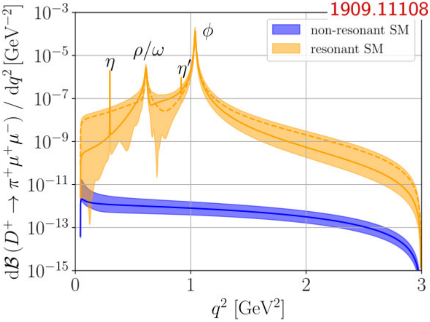


EFT at the charm scale de Boer, (2017), PhD thesis, TU Dortmund

What is the difference between $b \to s$ and $c \to u$ penguins?

- Light quark masses need to be set to zero at μ_W
- Effective GIM-mechanism kills $C_{7,9,10}$ at μ_W
- $C_{7,9}$ are induced by RG running to μ_c
- $C_{10}(\mu_c) = 0$

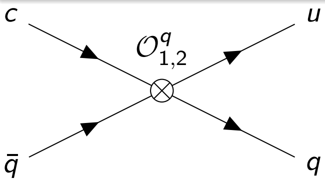
Trouble and opportunities with charm predictions



- $C_9^{\mathrm{SM}} = C_9^{\mathrm{eff}} + C_9^{\mathrm{resonant}} \simeq C_9^{\mathrm{resonant}}$ with resonant contributions from $D \to \pi M$ and $M \to \ell\ell$ ($M = \eta, \rho, \omega, \phi, \eta'$)
- $C_{10}^{\mathrm{SM}} = 0$ → unique feature in charm physics! (angular analysis)

Trouble and opportunities with charm predictions

SM effects are induced by four-quark operators, that also dominate pure hadronic decays $c \to u$ such as $D \to \pi\pi$, $D \to KK$



$$\frac{\Lambda_{\mathrm{QCD}}}{m_c} \begin{cases} \approx 1 \\ \ll 1 \\ < 1 \end{cases} \quad ?$$

- Tree and loop contributions exist.
- Long range QCD effects exist/dominate.
- The charm quark is neither really heavy nor light.
- Naive factorization not trustworthy.

Quick example:

Naive estimation of $\Delta A_{CP} = A_{\mathrm{CP}}(D^0 \to K^+K^-) - A_{\mathrm{CP}}(D^0 \to \pi^+\pi^-)$ yields

$$\Delta A_{CP} \sim 2\,\frac{|V_{cb}V_{ub}^*|}{|V_{cd}V_{ud}^*|}\left|\frac{P}{T}\right| \sim 2 \cdot 7 \cdot 10^{-4} \cdot 0.1 \sim 1.4 \cdot 10^{-4}$$

One order away from the experimental value.

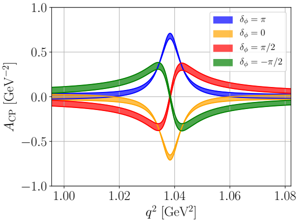
Discussed in the literature:

1111.4987, 1203.6659, 1706.07780, 1903.10490, 1903.10952, 1909.11242

CP–violation in charm

CP–assymmetry in $c \to u\ell\ell$ given by $A_{\mathrm{CP}}(q^2) = \frac{1}{\Gamma+\bar{\Gamma}}\left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} - \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2}\right)$ with $\Gamma = \int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} \frac{\mathrm{d}\Gamma}{\mathrm{d}q^2}\mathrm{d}q^2$

- Strong phase from resonances needed → measurement around the ϕ resonance, or in the high q^2 region.
- NP weak phase needed. → benchmark $C_9 = 0.1\exp(i\pi/4)$.
- Binning necessary.
  See also : Fajfer, Kosnik 1208.0759, 1510.00965; de Boer, Hiller 1510.00311



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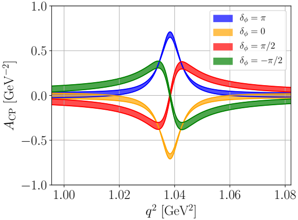

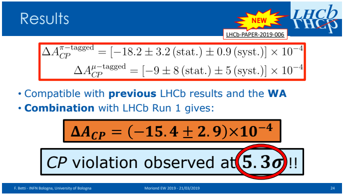
Results

NEW

LHCb-PAPER-2019-006

$$\Delta A_{CP}^{\pi-\text{tagged}} = [-18.2 \pm 3.2\,(\text{stat.}) \pm 0.9\,(\text{syst.})] \times 10^{-4}$$
$$\Delta A_{CP}^{\mu-\text{tagged}} = [-9 \pm 8\,(\text{stat.}) \pm 5\,(\text{syst.})] \times 10^{-4}$$

- Compatible with **previous** LHCb results and the **WA**
- **Combination** with LHCb Run 1 gives:

$$\boldsymbol{\Delta A_{CP} = (-15.4 \pm 2.9)\times 10^{-4}}$$

CP violation observed at **5.3σ**!!

F. Betti - INFN Bologna, University of Bologna   Moriond EW 2019 - 21/03/2019   24

Moriond 2019 offered interesting results including the discovery of charm CP violation by the LHCb coll.!
Talk by Frederico Betti, **Phys.Rev.Lett. 122 (2019) no.21, 211803**
$\Delta A_{\mathrm{CP}} = A_{\mathrm{CP}}(D^0 \to K^+K^-) - A_{\mathrm{CP}}(D^0 \to \pi^+\pi^-) = (-15.4 \pm 2.9) \times 10^{-4}$

CP–violation in charm

CP–assymmetry in $c \to u\ell\ell$ given by $A_{\rm CP}(q^2) = \frac{1}{\Gamma + \bar{\Gamma}}\left(\frac{d\Gamma}{dq^2} - \frac{d\bar{\Gamma}}{dq^2}\right)$ with $\Gamma = \int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\Gamma}{dq^2} dq^2$

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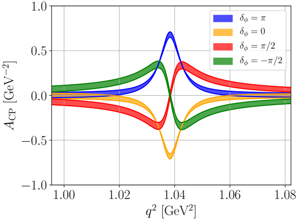

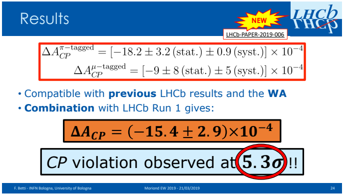
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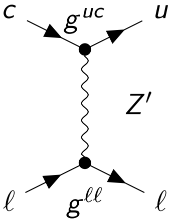
Any links??

Z' models



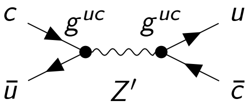
$$\begin{aligned}\mathcal{L}_{Z'} \supset \big(& g_L^{uc}\,\bar{u}_L\gamma^\mu c_L Z'_\mu + g_R^{uc}\,\bar{u}_R\gamma^\mu c_R Z'_\mu + \text{h.c.}\big)\\ &+\; g_L^d\,\bar{d}_L\gamma^\mu d_L Z'_\mu + g_R^d\,\bar{d}_R\gamma^\mu d_R Z'_\mu\\ &+\; g_L^s\,\bar{s}_L\gamma^\mu s_L Z'_\mu + g_R^s\,\bar{s}_R\gamma^\mu s_R Z'_\mu\\ &+\; g_L^{\ell\ell}\bar{\ell}_L\gamma^\mu \ell_L Z'_\mu + g_R^{\ell\ell}\bar{\ell}_R\gamma^\mu \ell_R Z'_\mu\,,\end{aligned}$$

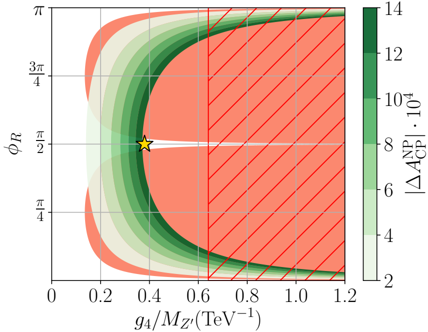
with $\ell = e,\ \mu,\ \tau$ and $g^{d,s}_{L,R}$ and $g^{\ell\ell}_{L,R}$ given by $U(1)'$–gauge coupling g_4 times the associated charge F_ψ.

$$\begin{aligned} g_R^{\ell\ell} &= g_4\,F_{e_i}\,,\\ g_L^{uc} &\approx g_4\,\lambda_{\text{CKM}}\,\Delta F_L\,,\\ g_R^{uc} &= g_4 \sin\theta_u \cos\theta_u\, e^{\mathrm{i}\phi_R}\Delta F_R\,,\end{aligned}$$

$\Delta F_L = F_{Q_2} - F_{Q_1}$, $\Delta F_R = F_{u_2} - F_{u_1}$ and $\Delta\tilde{F}_R = \Delta F_R \sin\theta_u\cos\theta_u$

$D - \bar{D}$ mixing in Z' models

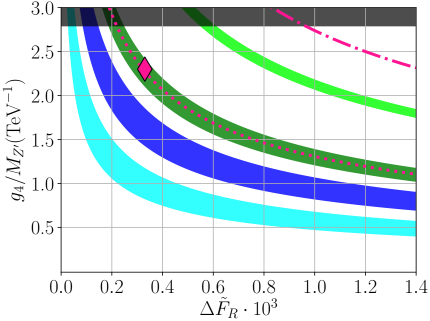


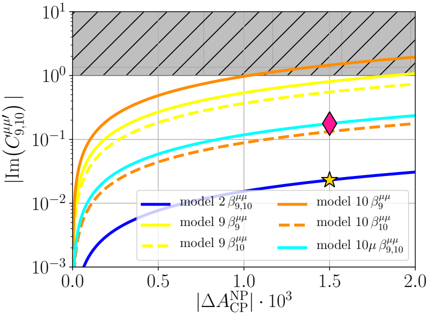


$$\left|(g_L^{uc})^2 + (g_R^{uc})^2 - X\, g_L^{uc}\, g_R^{uc}\right| \lesssim 6 \cdot 10^{-7} \left(\frac{M_{Z'}}{\mathrm{TeV}}\right)^2 ,$$

with $X \sim 20$ for $M_{Z'}$ in the TeV range (1909.11108)

Patterns in hadronic decays

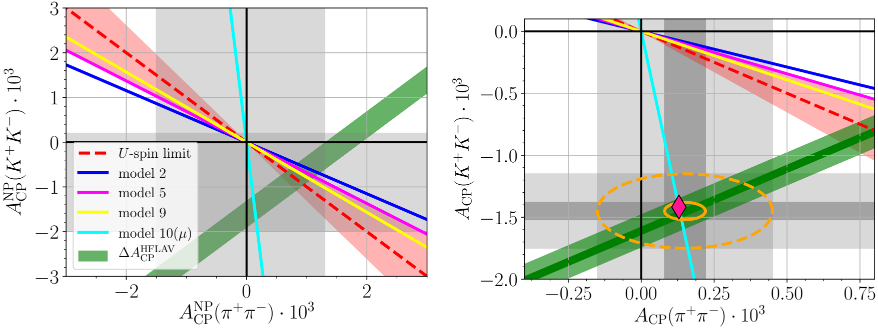




If ΔA_{CP} is NP, a huge effect is necessary.
Strong correlation between CP–asymmetries in $c \to u\ell\ell$ and ΔA_{CP}.

$$\text{NP in } c \to u\ell\ell \quad \Leftrightarrow \quad \text{NP in } \Delta A_{\mathrm{CP}}$$

Patterns in hadronic decays



U-spin breaking beyond 30% possible and clear NP signal.
Z' models explicitly break U–spin.

model	F_{Q_i}			F_{u_i}			F_{d_i}			F_{L_i}			F_{e_i}			F_{ν_i}		
10	0	0	0	-13	6	7	-1	-14	15	-15	15	0	-14	18	-4	0	0	0

Patterns in hadronic decays

$\times 10^{-4}$	Data	σ_{LHCb}	$\sigma_{\text{Belle II}}$
ΔA_{CP}	$-15.4 \pm 2.9^{\text{LHCb}}$	1.3 (0.3)	–
$\Delta A_{\text{CP}}^{\text{HFLAV}}$	$-16.4 \pm 2.8^{\text{HFLAV}}$	1.3 (0.3)	–
$A_{\text{CP}}(D^0 \to K^+K^-)$	$-9 \pm 11^{\text{HFLAV}}$	3 (0.7)	3
$A_{\text{CP}}(D^0 \to \pi^+\pi^-)$	$-1 \pm 14^{\text{HFLAV}}$	3 (0.7)	5
$A_{\text{CP}}(D^0 \to \pi^0\pi^0)$	$-3 \pm 64^{\text{HFLAV}}$	–	9
$A_{\text{CP}}(D^+ \to \pi^+\pi^0)$	$+290 \pm 290 \pm 30^{\text{CLEO}}$	–	17

Belle II sensitivities with $50\,\text{ab}^{-1}$.

$$Z'\text{possibilities} \Rightarrow \left\{ \begin{array}{ll} A_{\text{CP}}^{\text{NP}}(\pi^+\pi^0) & \sim (1-2)\cdot \Delta A_{\text{CP}}^{\text{NP}}\,, \\ A_{\text{CP}}^{\text{NP}}(\pi^0\pi^0) & \lesssim 2 \cdot \Delta A_{\text{CP}}^{\text{NP}}\,, \\ \frac{A_{\text{CP}}^{\text{NP}}(\pi^0\pi^0)}{A_{\text{CP}}^{\text{NP}}(\pi^+\pi^0)} & \sim 1.08 \pm 0.10\,, \end{array} \right\} \quad \Rightarrow \quad \text{Isospin tests}$$

$A_{\text{CP}}(\pi^+\pi^0)$ is a good null tests! 1204.3557

Summary

- Charm unique up-type candidate to do flavor physics
- Belle II can help to disentangle NP nature of ΔA_{CP} measurement
- CP tests in charm
  - Null tests provide clean playground to find NP
  - Correlations are helpful
- Z' models suitable minimal candidate to explore ΔA_{CP} vs. CP–asymmetries in $c \to u\ell\ell$

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Take home message:
Hadronic uncertainties can also be overcome with null tests, correlations and data!

BACKUP

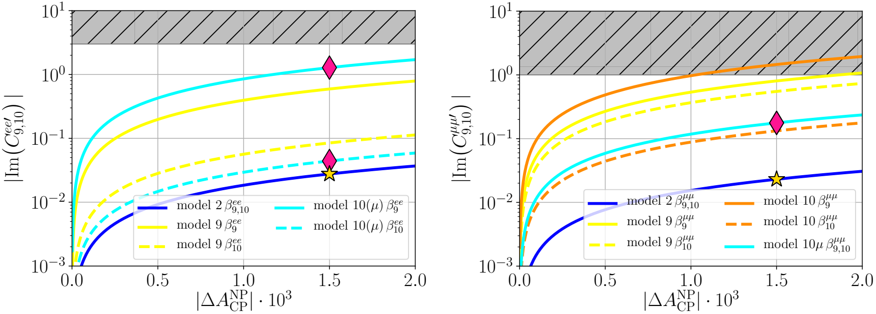
$$\mathcal{H}_{\text{eff}} \supset -\frac{4G_F}{\sqrt{2}}\frac{\alpha_e}{4\pi}\left[\sum_{i=7,9,10,S,P}\left(C_i O_i + C_i' O_i'\right) + \sum_{i=T,T5} C_i O_i\right],$$

$$\begin{aligned}
O_7 &= \frac{m_c}{e}(\overline{u}_L \sigma_{\mu\nu} c_R) F^{\mu\nu}\,, \\
O_9 &= (\overline{u}_L \gamma_\mu c_L)(\overline{\ell}\gamma^\mu \ell)\,, \\
O_{10} &= (\overline{u}_L \gamma_\mu c_L)(\overline{\ell}\gamma^\mu \gamma_5 \ell)\,, \\
O_S &= (\overline{u}_L c_R)(\overline{\ell}\ell)\,, \\
O_P &= (\overline{u}_L c_R)(\overline{\ell}\gamma_5 \ell)\,, \\
O_T &= \frac{1}{2}(\overline{u}\sigma_{\mu\nu} c)(\overline{\ell}\sigma^{\mu\nu}\ell)\,, \\
O_{T5} &= \frac{1}{2}(\overline{u}\sigma_{\mu\nu} c)(\overline{\ell}\sigma^{\mu\nu}\gamma_5 \ell)\,.
\end{aligned}$$

- Extend the SM gauge group by an additional $U(1)'$
- Choose non-universal charges using restrictions from anomaly cancellation conditions
- Assume the $U(1)$ symmetry to be (spontaneously) broken at a high NP scale ⇒ massive Z'
- Rotations from gauge to mass basis along with non-universal charges give rise to off-diagonal quark couplings.

Constraints from

- $D - \bar{D}$ mixing
- Kaons ⇒ avoid FCNC's in down-type sector
- Direct searches


10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
$|\mathrm{Im}(C_{9,10}^{ee\prime})|$
0.0
0.5
1.0
1.5
2.0
$|\Delta A_{\mathrm{CP}}^{\mathrm{NP}}| \cdot 10^{3}$
model 2 $\beta_{9,10}^{ee}$
model 9 β_{9}^{ee}
model 9 β_{10}^{ee}
model 10(μ) β_{9}^{ee}
model 10(μ) β_{10}^{ee}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
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0.0
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model 2 $\beta_{9,10}^{\mu\mu}$
model 9 $\beta_{9}^{\mu\mu}$
model 9 $\beta_{10}^{\mu\mu}$
model 10 $\beta_{9}^{\mu\mu}$
model 10 $\beta_{10}^{\mu\mu}$
model 10μ $\beta_{9,10}^{\mu\mu}$

LFU tests

$$R_P^D = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\mathcal{B}(D \to P\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{\mathrm{d}\mathcal{B}(D \to Pe^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2}$$

Same cuts for electrons and muons necessary.

R_π^D	SM	$\lvert C_9\rvert = 0.5$	$\lvert C_{10}\rvert = 0.5$	$\lvert C_9\rvert = \pm\lvert C_{10}\rvert = 0.5$
full q^2	$1.00 \pm \mathcal{O}(\%)$	SM-like	SM-like	SM-like
low q^2	$0.95 \pm \mathcal{O}(\%)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$	$\mathcal{O}(100)$
high q^2	$1.00 \pm \mathcal{O}(\%)$	$0.2 \ldots 11$	$3 \ldots 7$	$2 \ldots 17$

$R_K^{D_s}$	SM	$\lvert C_9\rvert = 0.5$	$\lvert C_{10}\rvert = 0.5$	$\lvert C_9\rvert = \pm\lvert C_{10}\rvert = 0.5$
full q^2	$1.00 \pm \mathcal{O}(\%)$	SM-like	SM-like	SM-like
low q^2	$0.94 \pm \mathcal{O}(\%)$	$0.1 \ldots 3.0$	$1.3 \ldots 1.5$	$0.5 \ldots 3.6$
high q^2	$1.00 \pm \mathcal{O}(\%)$	$0.2 \ldots 16$	$3 \ldots 11$	$2 \ldots 26$

model	F_{Q_i}			F_{u_i}			F_{d_i}			F_{L_i}			F_{e_i}			F_{ν_i}		
2	3	3	-6	-8	4	4	-10	10	0	-6	5	1	0	0	0	0	0	0
4	-1	-1	2	-1	2	-1	0	0	0	-1	1	0	-2	2	0	-2	-1	3
5	-1	-1	2	-1	2	-1	2	-1	-1	-1	1	0	-1	1	0	0	0	0
9	0	0	0	-11	-2	13	7	7	-14	-8	3	5	-6	16	-10	0	0	0
10	0	0	0	-13	6	7	-1	-14	15	-15	15	0	-14	18	-4	0	0	0
10μ	0	0	0	-13	6	7	-1	-14	15	-15	0	15	-14	-4	18	0	0	0