Δa_{CP} as BSM

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Based on [1903.10490] with M. Chala, A. Lenz and A.V. Rusov

Plan?

1. Definitions and Measurements
2. Is it BSM?
3. If it is, what kind of BSM?
4. Conclusions?

Definitions

Because (some) theorists love commuting diagrams

$$A_{CP}(f,t) = \frac{\Gamma(D^0(t) \to f) - \Gamma(\overline{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\overline{D}^0(t) \to f)}$$

$$A_{CP}(f,t) = a_{CP}^{\text{dir}}(f) + \frac{t}{\tau(D^0)} a_{CP}^{\text{ind}}$$

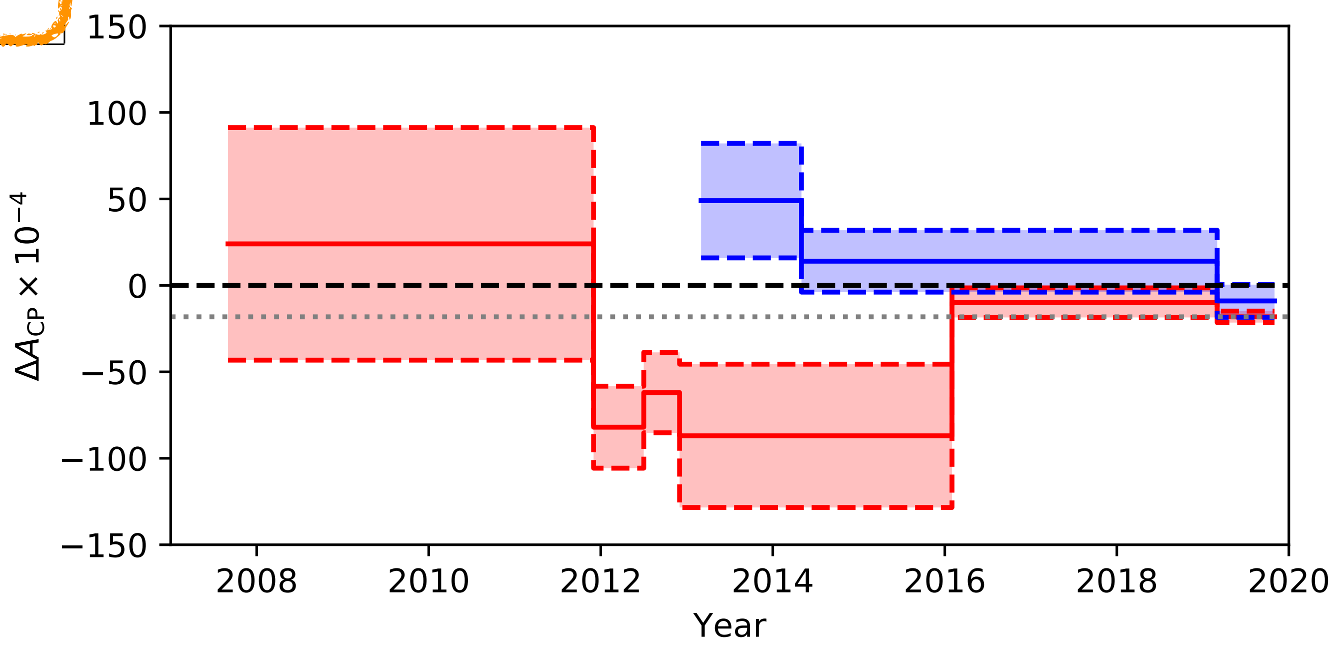
$$\Delta A_{CP} = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

$$\Delta a_{CP} = a_{CP}^{\text{dir}}(K^-K^+) - a_{CP}^{\text{dir}}(\pi^-\pi^+)$$

CPV in time

Experiment	$\Delta A_{CP} \times 10^4$	Tag	arXiv	Reference
BaBar	$+24 \pm 62 \pm 26$	pion	0709.2715	[22]
LHCb	$-82 \pm 21 \pm 11$	pion	1112.0938	[1]
CDF	$-62 \pm 21 \pm 10$	pion	1207.2158	[2]
Belle	$-87 \pm 41 \pm 6$	pion	1212.1975	[3]
LHCb	$+49 \pm 30 \pm 14$	muon	1303.2614	[4]
LHCb	$+14 \pm 16 \pm 8$	muon	1405.2797	[5]
LHCb	$-10 \pm 8 \pm 3$	pion	1602.03160	[6]
LHCb	$-18.2 \pm 3.2 \pm 0.9$	pion	1903.08726	[21]
LHCb	$-9 \pm 8 \pm 5$	muon	1903.08726	[21]

$$\Delta a_{\rm CP} = (-15.7 \pm 2.9) \times 10^{-4}$$



Naive Estimate in SM

$$A \;=\; \frac{G_F}{\sqrt{2}}\left[\lambda_d \sum_{i=1,2} C_i \langle Q_i^d\rangle^{T+P+E+R} + \lambda_s \sum_{i=1,2} C_i \langle Q_i^s\rangle^{P+R} + \lambda_b \sum_{i>3} C_i \langle Q_i^b\rangle^{T}\right]$$

$$\lambda_q = V_{cq}^* V_{uq}$$

$$A \equiv \frac{G_F}{\sqrt{2}}\lambda_d \, T\left[1 + \frac{\lambda_b}{\lambda_d}\frac{P}{T}\right]$$

$$\begin{aligned} T &= \sum_{i=1,2} C_i \langle Q_i^d\rangle^{T+P+E+R} - \sum_{i=1,2} C_i \langle Q_i^s\rangle^{P+R} \\ P &= \sum_{i>3} C_i \langle Q_i^b\rangle^{T} - \sum_{i=1,2} C_i \langle Q_i^s\rangle^{P+R}. \end{aligned}$$

$$\begin{aligned} \mathrm{Br} &\propto \frac{G_F^2}{2}|\lambda_d|^2|T|^2\left|1 + \frac{\lambda_b}{\lambda_d}\frac{P}{T}\right|^2, \\ a_{CP}^{\mathrm{dir}} &= \frac{-2\left|\frac{\lambda_b}{\lambda_d}\right|\sin\gamma\left|\frac{P}{T}\right|\sin\phi}{1 - 2\left|\frac{\lambda_b}{\lambda_d}\right|\cos\gamma\left|\frac{P}{T}\right|\cos\phi + \left|\frac{\lambda_b}{\lambda_d}\right|^2\left|\frac{P}{T}\right|^2} \end{aligned}$$

$\longrightarrow$

$$\mathrm{Br} \sim \frac{G_{\mathrm{F}}^2}{2}|\lambda_d|^2|T|^2$$

$$a_{CP}^{\mathrm{dir}} \sim -2\left|\frac{\lambda_b}{\lambda_d}\right|\sin\gamma\left|\frac{P}{T}\right|\sin\phi$$

What do we want?

$$a_{CP}^{\mathrm{dir}} \sim -2 \left|\frac{\lambda_b}{\lambda_d}\right| \sin\gamma \left|\frac{P}{T}\right| \sin\phi = -13 \times 10^{-4} \left|\frac{P}{T}\right| \sin\phi = (-15.7 \pm 2.9) \times 10^{-4}$$

If P/T=1 and the strong phase is maximal, then SM can explain this CP violation

$$\left|\frac{P}{T}\right| \sin\phi \sim 1$$

We are looking at BSM

OR

Resonant Enhancement

What do we get?

Lattice QCD is not quite there yet.

Right now, it is very time consuming calculation to compute |T| and it will be done. Meanwhile (we can fit |T| from data), but we can compute/estimate |P|

NDA gives us: $\left|\frac{P}{T}\right| \sim 0.1$

The LCSR gives: $\left|\frac{P}{T}\right|_{\pi^+\pi^-} = 0.093 \pm 0.056 \qquad \left|\frac{P}{T}\right|_{K^+K^-} = 0.075 \pm 0.048$

Khodjamirian et al.: [hep-ph/0304179, hep-ph/0012271,1706.07780]

Do we have reasons to expect O(10) non-perturbative enhancements?

Is Λ/m_q small enough?

Consider the <u>fully inclusive</u> decays

In the B sector

$\Lambda/m_b = 0.1$

- Determination of V_{ub}, V_{cb} from inclusive decays
- B_s/B_d lifetime works at 0.4%
- B^+/B_d lifetime works at 2%
- Λ_b/B_d lifetimes works at 5%
- $\Delta\Gamma_s$ works at 15-20%

Thanks to a lot of progress in both Experiment and Theory

In the D sector

$\Lambda/m_c = 0.3$

- D^+/D lifetime works well:

$$\left.\frac{\tau(D^+)}{\tau(D^0)}\right|_{\text{HQE.}} = 2.70^{+0.74}_{-0.82} = \left[1 + 16\pi^2(0.25)^3(1-0.34)\right]^{+0.74}_{-0.82}$$

$$\left.\frac{\tau(D^+)}{\tau(D^0)}\right|_{\text{Exp.}} = \frac{(1040 \pm 7)\,\text{fs}}{(410.1 \pm 1.5)\,\text{fs}} = 2.536 \pm 0.019$$

- D-mixing suffers from extreme GIM cancellations overshadowing the determination of y - GIM might be less pronounced at higher orders in the HQE. So, the answer is to calculate more, not to give up.

Is this ΔI=1/2 rule?

Experiment

$$\frac{\Re\left(A_0\right)}{\Re\left(A_2\right)} := \frac{\Re\left[A(K\to\pi\pi)_{I=0}\right]}{\Re\left[A(K\to\pi\pi)_{I=2}\right]} = 22.5$$

Theory

$$\frac{\Re\left(A_0\right)}{\Re\left(A_2\right)} = \begin{cases} 1 & \text{Naive} \\ 2 & \text{pert. QCD} \end{cases}$$

The emerging explanation of the $\Delta I = 1/2$ rule is a combination of the perturbative running to scales of $O(2\,\mathrm{GeV})$, a relative suppression of $\mathrm{Re}A_2$ through the cancellation of the two dominant contributions and the corresponding enhancement of $\mathrm{Re}A_0$. QCD and EWP penguin operators make only very small contributions at such scales.

RBC and UKQCD [1212.1474]

There is no such thing as magical enhancement of penguins… that we know about.

The BSM Menu

SU(3) charged states

1. Flavour changing heavy gluon (8)
2. Diquark (6)
3. Leptoquark (3)
4. Scalar octet (8)

SU(3) singlets

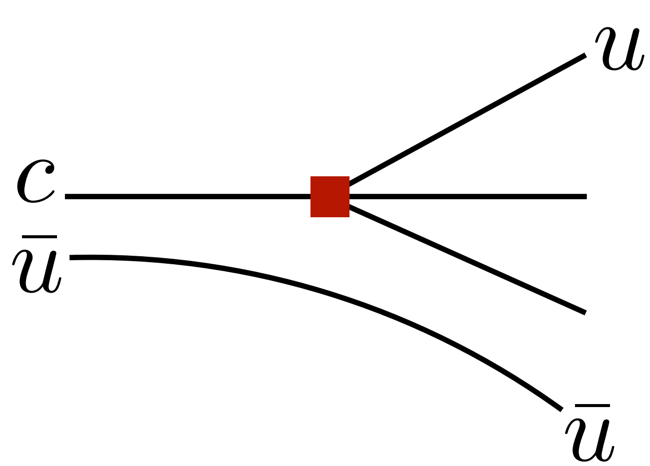
1. Flavour changing Z (vector-like quarks)
2. Z’
3. 2HDM

Many of these were discussed in extensively in [1202.2866] and also in [hep-ph/0609178]

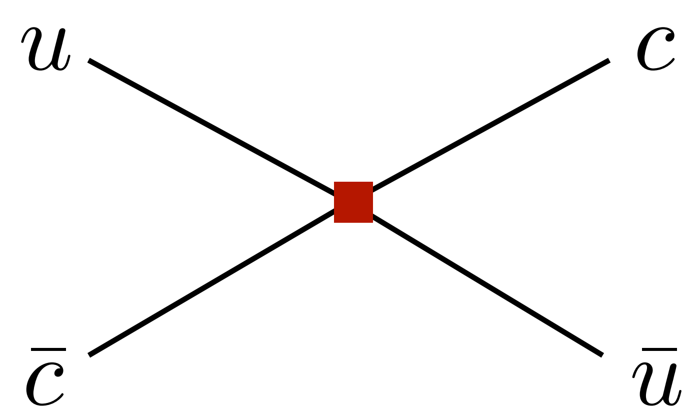
Note 1:

D^0-$\bar{D}^0$ mixing vs Δa_{CP}

- Both are dim-6 operators, i.e. suppressed by $(M_{NP})^2$
- But Δa_{CP} goes like (g_{uc}), while mixing goes as $(g_{uc})^2$.
- The mixing constraints are always weaker for lower mass BSM (as is well known in B physics).



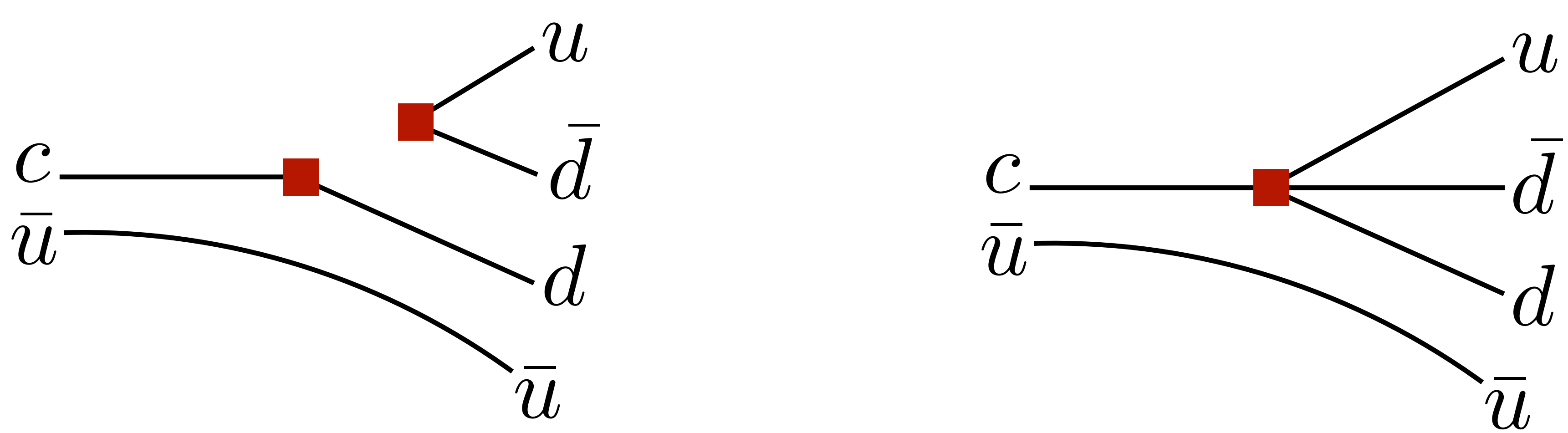
$$\mathcal{A} \propto \frac{g_{uc} g_{qq'}}{M_{NP}^2}$$



$$\mathcal{A} \propto \frac{g_{uc}^2}{M_{NP}^2}$$

Note 2:

W’ just doesn’t cut it…



- W’ generates operators that have the same hadronic matrix elements as W. (Mesons are equal combinations of L and R quarks)
- Hence the strong phase is the same as the SM. There is no CPV generated at tree level.
- You can generate CPV with W’ penguins that interfere with tree level SM, but since $M_{W'} > M_W$ this is impossible.

Note 3:
SU(3) charged states

Since 2011 (last time we had a ΔA_{CP} theory rush) the constraints on SU(3) charged states have become much tighter (your colleagues have been busy):

- CMS: [1412.7706], stops excluded 200-400GeV (20ifb, 8TeV)
- ATLAS: [1710.07171], stops excluded 100-500GeV (36ifb, 13TeV)
- CMS: [1710.00159], no resonance decaying into pairs of jets in 50-300 GeV (36ifb, 13TeV)

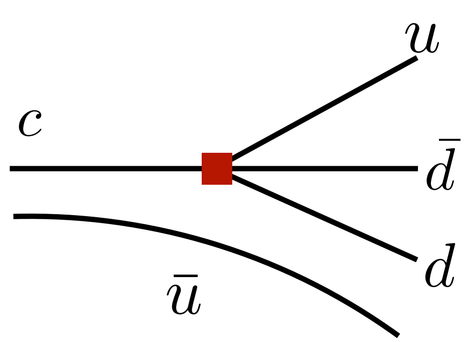
(Keep in mind that stop is a 3, so the pair-production constraints are worse for 6s and 8s).

If coloured states cause tree level CPV,
they are probably below 100 GeV.*

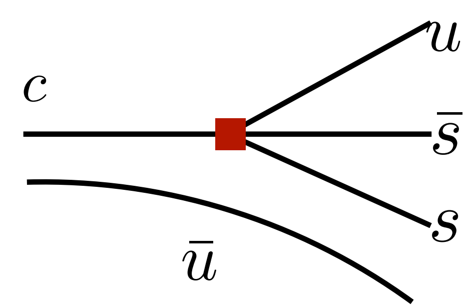
An example: Z’

[1202.2866, 1903.10490]

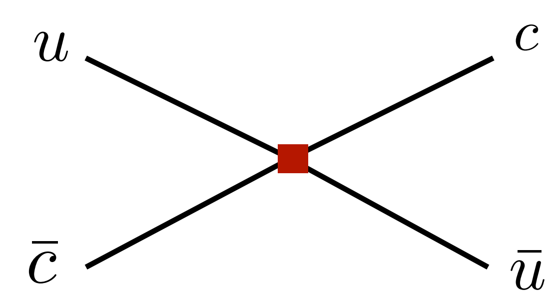
$$\mathcal{L}_{BSM} = \frac{m_{Z'}^2}{2} Z'^{\mu} Z'_{\mu} + Z'_{\mu} \left[g_{dd} \bar{d}_R \gamma^{\mu} d_R + g_{ss} \bar{s}_R \gamma^{\mu} s_R + g_{cu} \bar{u}_R \gamma^{\mu} c_R \right]$$



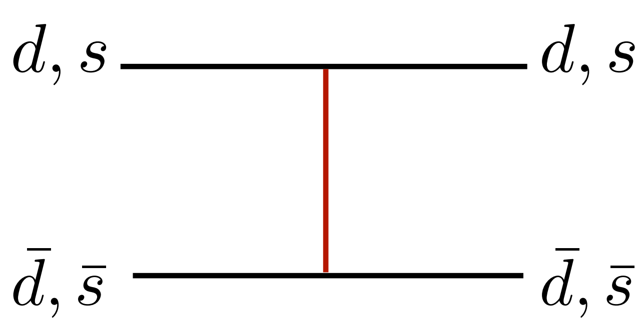
$$D \to \pi^- \pi^+ \propto \frac{g_{dd} g_{cu}}{M_{Z'}^2}$$



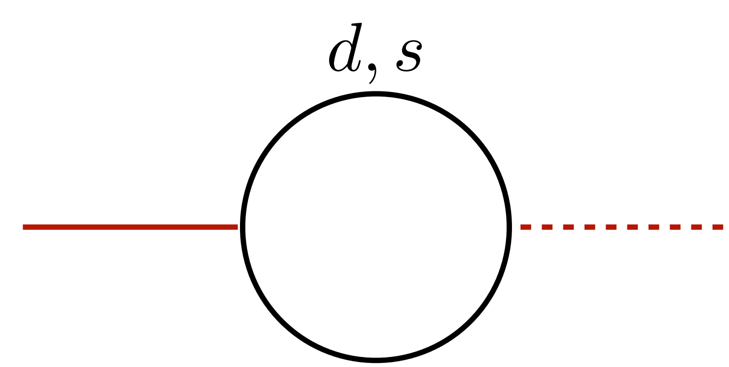
$$D \to K^- K^+ \propto \frac{g_{ss} g_{cu}}{M_{Z'}^2}$$



$$D \leftrightarrow \bar{D} \propto \frac{g_{cu}^2}{M_{Z'}^2}$$

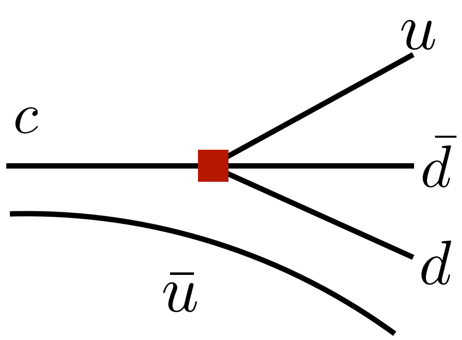


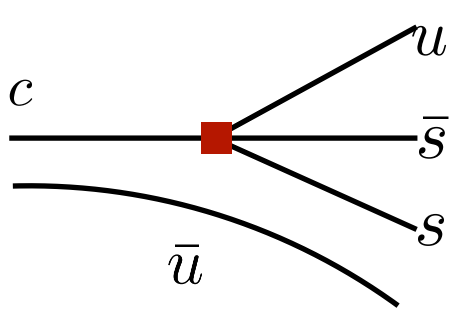
$$pp \to jj \propto \frac{g_{qq} g_{q'q'}}{\hat{s} - M_{Z'}^2} + (s \leftrightarrow t)$$



$$Z \leftrightarrow Z' \propto \frac{g_{qq}^2}{16\pi^2}$$

ΔA_{CP} with Z'





$$A = \frac{G_F}{\sqrt{2}}(\lambda_s T + \lambda_b P) + \frac{1}{4}\frac{g_{cu}g_{ss}}{m_{Z'}^2} A^s_{BSM} = \frac{G_F}{\sqrt{2}}\lambda_s T\left[1 + \frac{\lambda_b}{\lambda_s}\frac{P}{T} + \tilde{g}_s^2 \tilde{A}^s_{BSM}\right]$$

$$\tilde{g}_s^2 \equiv \frac{\sqrt{2} g_{cu} g_{ss}}{4 G_F \lambda_s m_{Z'}^2}, \quad \tilde{A}^s_{BSM} \equiv \frac{A^s_{BSM}}{T} = \frac{\langle K^+K^-|\bar{u}\gamma^\mu(1-\gamma_5)c\ \bar{s}\gamma^\mu(1-\gamma_5)s|D^0\rangle}{\langle K^+K^-|\bar{u}\gamma^\mu(1-\gamma_5)s\ \bar{s}\gamma^\mu(1-\gamma_5)c|D^0\rangle} \approx 1/N_c$$

Here we don't use the data to determine T

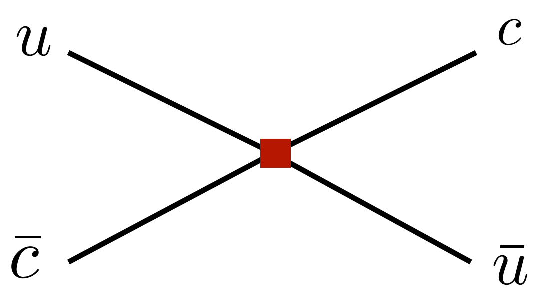
We merrily neglect the SM penguin and only consider the interference between SM Tree and BSM Tree

↓

$$\Delta_{NP} = 2\,|\tilde{g}_s|^2 \left|\tilde{A}^s_{BSM}\right| \sin\delta^s_{BSM} \sin\phi^s_{BSM}$$

$$\tilde{O}_3 = (\bar{u}c)_{V+A}(\bar{q}q)_{V+A}$$

D^0-$\bar{D}^0$ mixing with Z'



Our ΔF=1 operators generate ΔF=2 operator:

$$\tilde{O}_2^{(2)D} = (\bar{u}_\alpha P_R c_\alpha)(\bar{u}_\beta P_R c_\beta)$$

With

$$\tilde{C}_1^{(2),D} = \frac{(g_{cu}^*)^2}{2M_{Z'}^2} < 4 \times 10^{-8} \frac{G_F}{\sqrt{2}}$$

We are driven towards small FCNC … (not a surprise)

$$|g_{cu}| \lesssim 10^{-4} \frac{M_{Z'}}{100\text{GeV}}$$

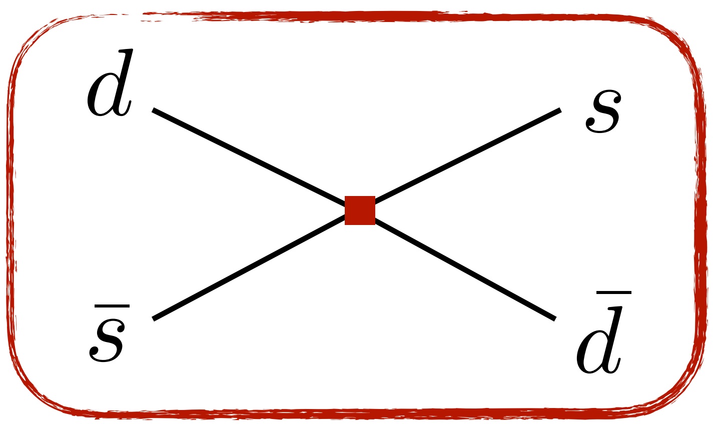
[The phase in mixing is twice the phase in ΔAcp and so it is possible to minimise CPV in mixing while maximise CPV in decays]

K^0-$\bar{K}^0$ mixing with Z'

$$\mathcal{L} = Z'_\mu \bar{u}_L \gamma^\mu c_L$$

↓

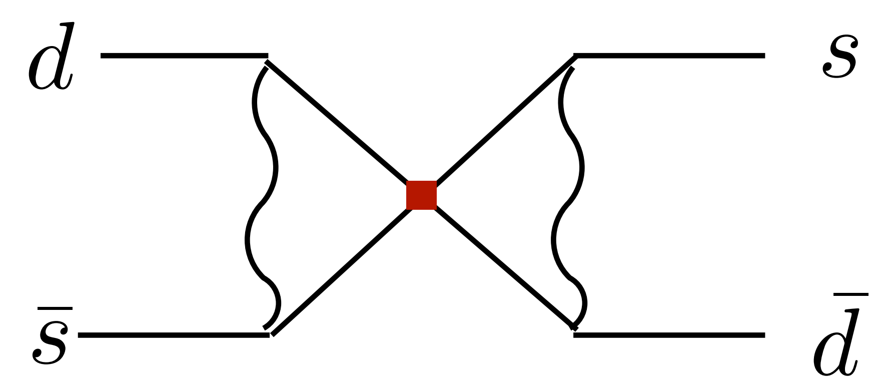
$$\mathcal{L} = Z'_\mu \bar{d}_L \gamma^\mu s_L$$



ϵ'/ϵ

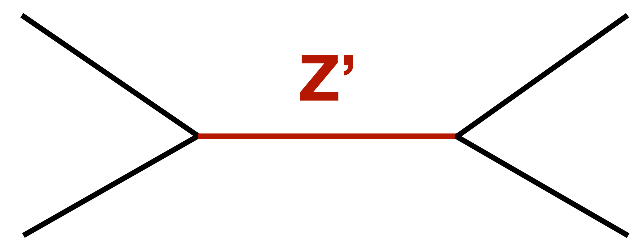
$$\mathcal{L} = Z'_\mu \bar{u}_R \gamma^\mu c_R$$

Safe... from Kaon mixing (at tree level)

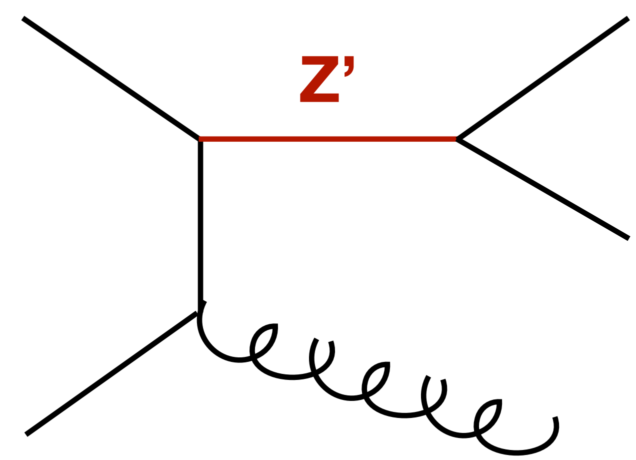


Collider Bounds

- We can look for dijet resonances…



- We can look for resonances inside on of the dijets [1710.00159], goes all the way down to 50GeV.

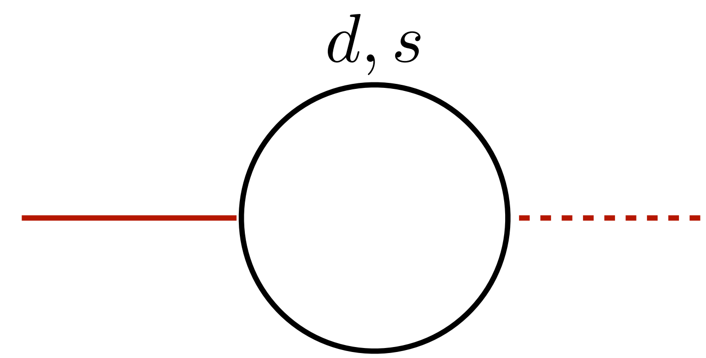


- Z and Z’ mix [1107.2666]:

$$\frac{\Delta\Gamma_Z}{\Gamma_Z} = \frac{g_{ss} c_Z s_w c_w V_d}{3g(1 - M_{Z'}^2/M_Z^2)(2V_u^2 + 3V_d^2 + 5/16)}$$

But the mixing runs:

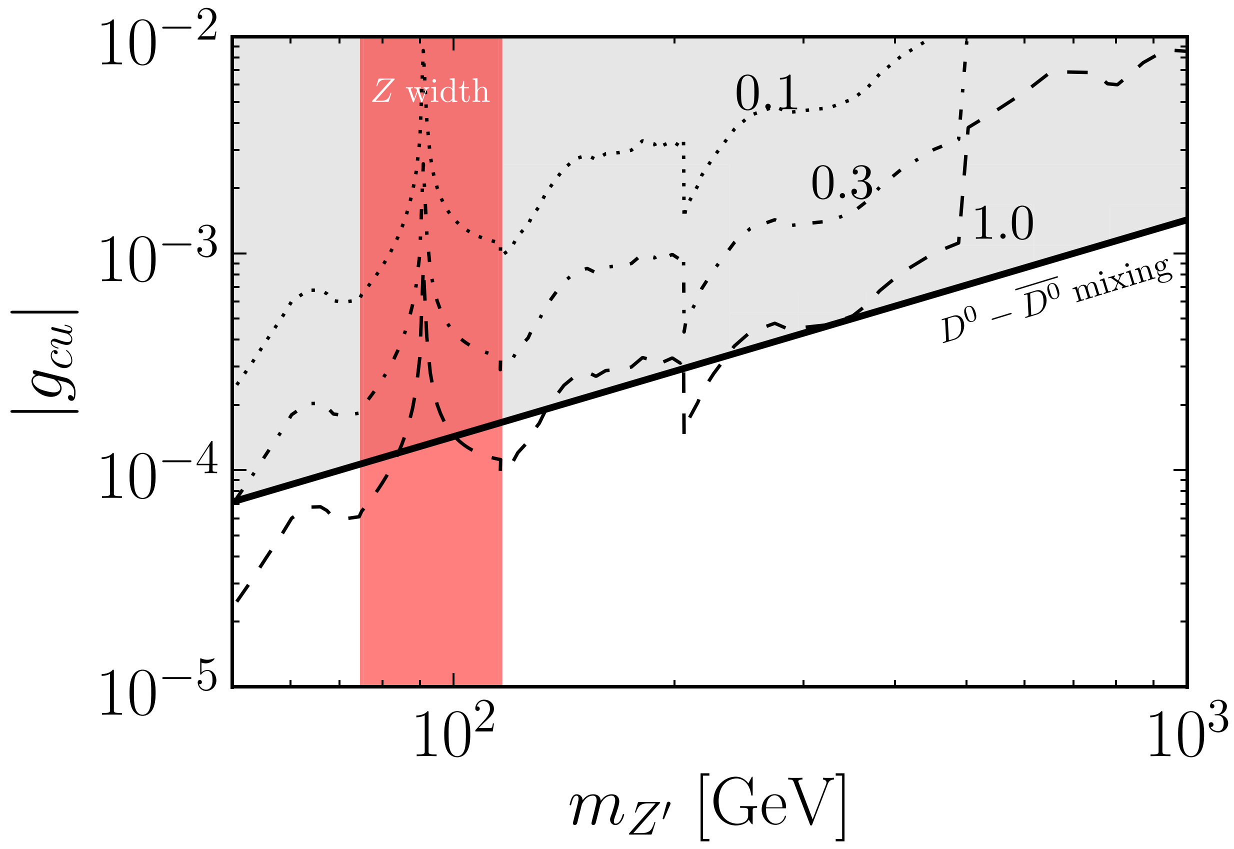
$$\mu \frac{dc_Z}{d\mu} = -\frac{g_{ss} e}{32\pi^2 s_w^2 c_w}\left[3 - 4s_w^2\right]$$



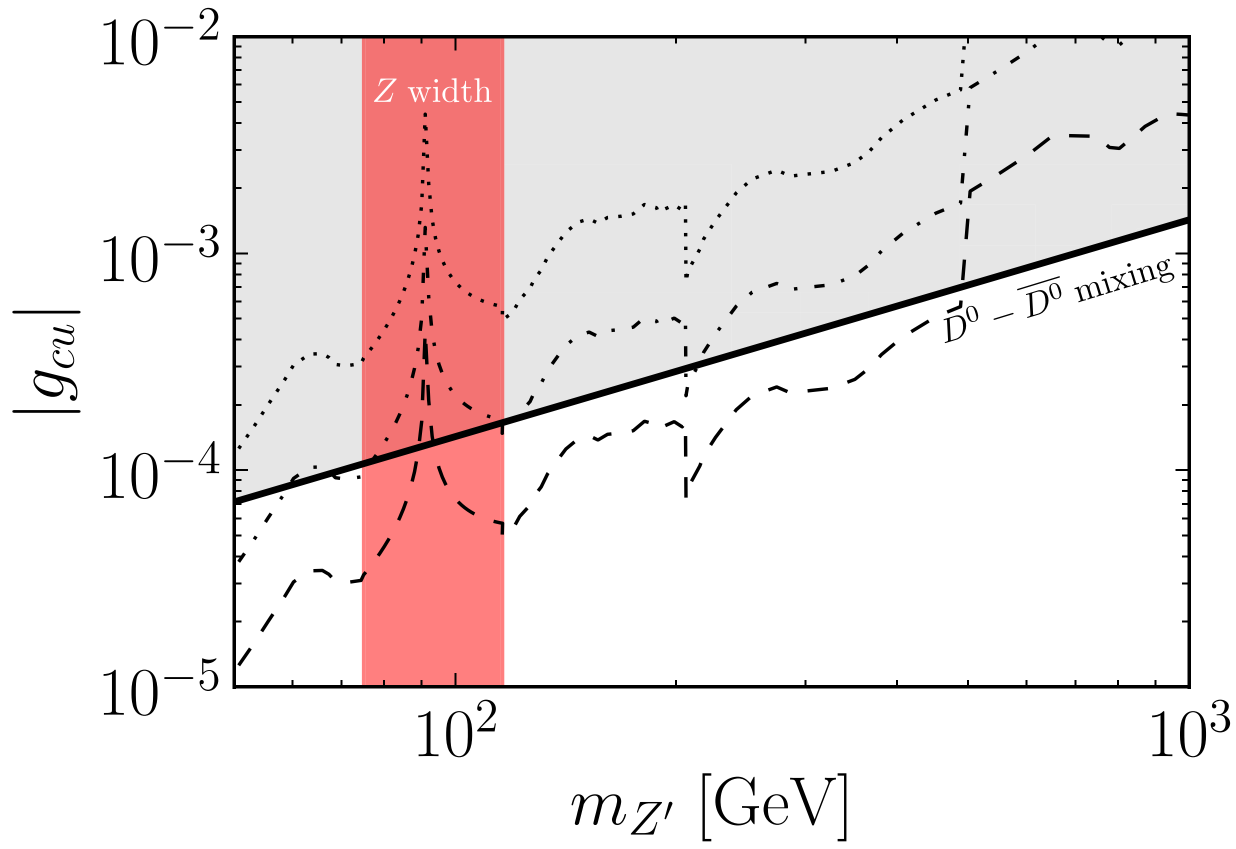
Z', Plots

- We set $g_{dd} = 0$, and g_{ss} to fit the ΔA_{CP} with new physics.
- The dashed curves correspond to different assumptions for A_{BSM}.
- The red region is ruled out due to Z-Z'

$\Delta A_{CP,BSM} = \Delta A_{CP}$



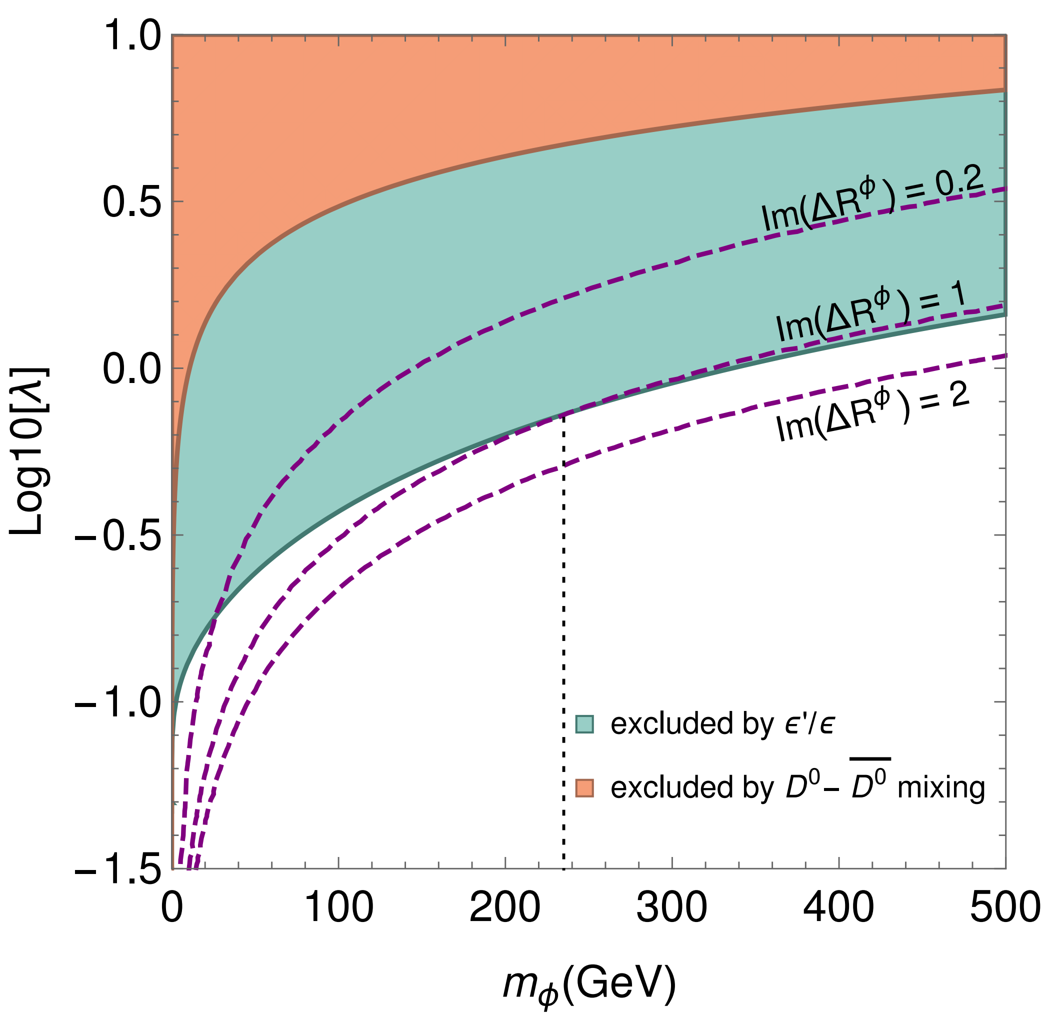
$\Delta A_{CP,BSM} = 0.6\ \Delta A_{CP}$



Other Options

Paraphrasing Dery & Nir [1909.11242]

2HDM



MSSM

- If we adopt MFV or FN, then it can't work
- More relaxed flavour structures can do the job.

Vector-like Quarks

- If we adopt MFV or FN, then it can't work
- More relaxed flavour structures can do the job.

Conclusion

- The direct CPV in charm sector is real and 5σ! (but as always, can still go away)
- It is possible, this is a sign of new physics, but we are some distance away from being able to say it is definitely new physics.
- But this means that we should push on the theory, calculate more terms in HQE, push lattice and any other method we know. (We should all agree that giving up at this point is silly)
- If it is new physics, we are driven towards light physics by the DDbar mixing.
- Some of the SU(3) charged candidates are very likely dead this time round.
- Z', vector-like quarks, 2HDM and even MSSM can still do the job.
- It maybe possible to connect this to ε'/ε