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Direct CPV in Charm

On the theory interpretation of existing and future results

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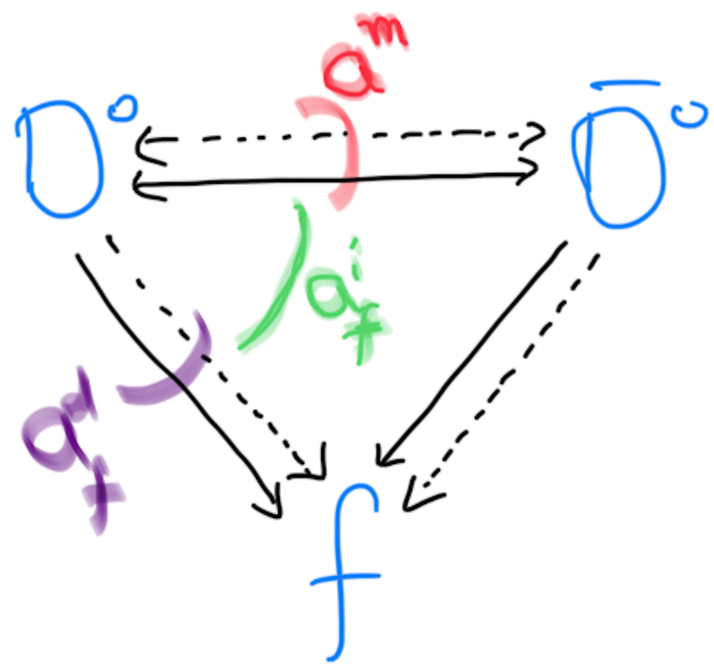
$$\Delta A_{CP} \equiv A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$$
$$= -(1.54 \pm 0.29) \times 10^{-3}$$

First discovery of CPV in Charm

We are beginning to probe previously unexplored phenomena!

ΔA_{CP} is dominated by CPV *in decay*

$$A^f_{CP} \equiv \frac{A(D^0 \to f) - A(\overline{D}^0 \to \bar{f})}{A(D^0 \to f) + A(\overline{D}^0 \to \bar{f})} = a^d_f + a^m + a^i_f$$



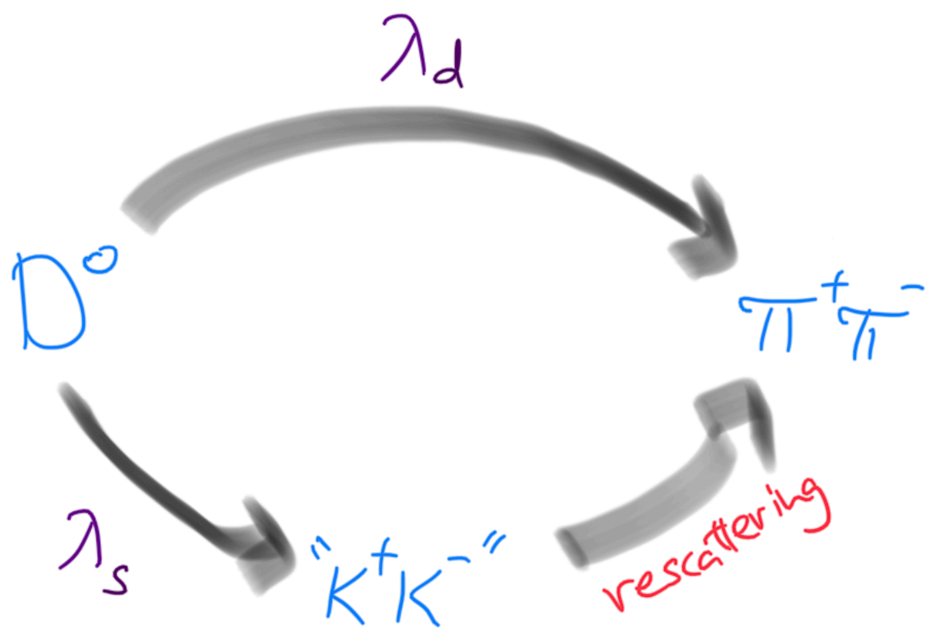
a^m is UNIVERSAL.

a^i_f is small and UNIVERSAL TO LEADING ORDER

=> cancel in the difference $\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$

What interferes? Tree <=> rescattering

(Penguins are **irrelevant** for D decays due to strong GIM suppression)



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

$$\lambda_d = -\lambda_s + \mathcal{O}(\lambda^4)$$

$$A_{\pi^+\pi^-} = \lambda_d\, A_{d\bar{d}} + \lambda_s\, A_{s\bar{s}} \quad = \quad \underbrace{\frac{(\lambda_d - \lambda_s)}{2}}(A_{d\bar{d}} - A_{s\bar{s}}) + \underbrace{\frac{(\lambda_d + \lambda_s)}{2}}(A_{d\bar{d}} + A_{s\bar{s}})$$

$$= \quad \lambda_d \cdot A_{\Delta U=1} \quad + \quad \frac{1}{2}\lambda_b \cdot A_{\Delta U=0}$$

weak phases

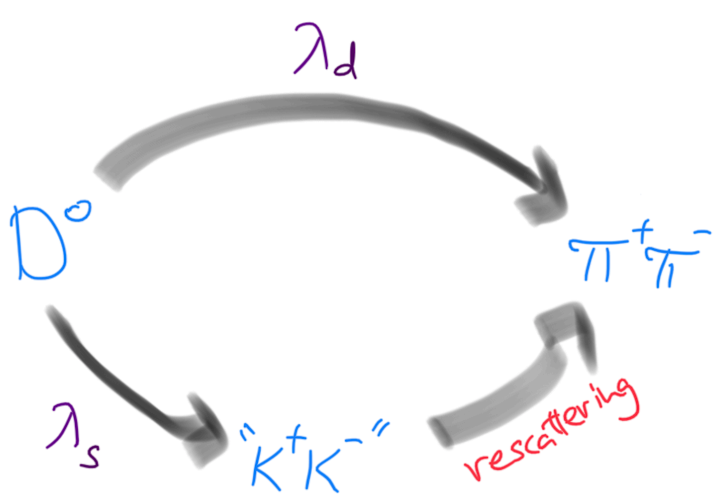
goes to zero in the limit of Unitary 2x2 CKM

What interferes? Tree <=> rescattering

$$A_{\pi^+\pi^-} = \lambda_d\, A_{d\bar d} + \lambda_s\, A_{s\bar s} \quad = \quad \underbrace{\frac{(\lambda_d - \lambda_s)}{2}}(A_{d\bar d} - A_{s\bar s}) + \underbrace{\frac{(\lambda_d + \lambda_s)}{2}}(A_{d\bar d} + A_{s\bar s})$$

$$= \quad \lambda_d \cdot A_{\Delta U=1} \qquad + \quad \frac{1}{2}\lambda_b \cdot A_{\Delta U=0}$$

$$a^d_{\pi^+\pi^-} = 2\, r \sin\phi \sin\delta = \underbrace{\mathrm{Im}\left(\frac{\lambda_b}{\lambda_d}\right)}_{\epsilon_{\mathrm{NU}} \;\sim\; 10^{-3}} \underbrace{\mathrm{Im}\left(\frac{A_{\Delta U=0}}{A_{\Delta U=1}}\right)}_{r_{\mathrm{QCD}} \sin\delta \;\sim ?}$$



$$\frac{A_{\Delta U=0}}{A_{\Delta U=1}} = 1 + r_{\mathrm{QCD}} e^{i\delta}$$

How large are rescattering effects? $(r_{\mathrm{QCD}} \sin\delta)$

1. Light-cone-sum-rules : $r_{\mathrm{QCD}} \sim \frac{\alpha_S}{\pi} \sim 0.1$ => NP needed!

   [Chala Lenz Rusov Scholtz 1903.10490]

   [Petrov Khodjamirian 1706.07780]

2. Non-pertubative low-energy QCD : $r_{\mathrm{QCD}} \sim 1$ => consistent with SM

   [Grossman Schacht 1903.10952]

   [Brod Grossman Kagan Zupan 1203.6659]

   $\sin\delta \sim 1,$
   on-shell intermediate states

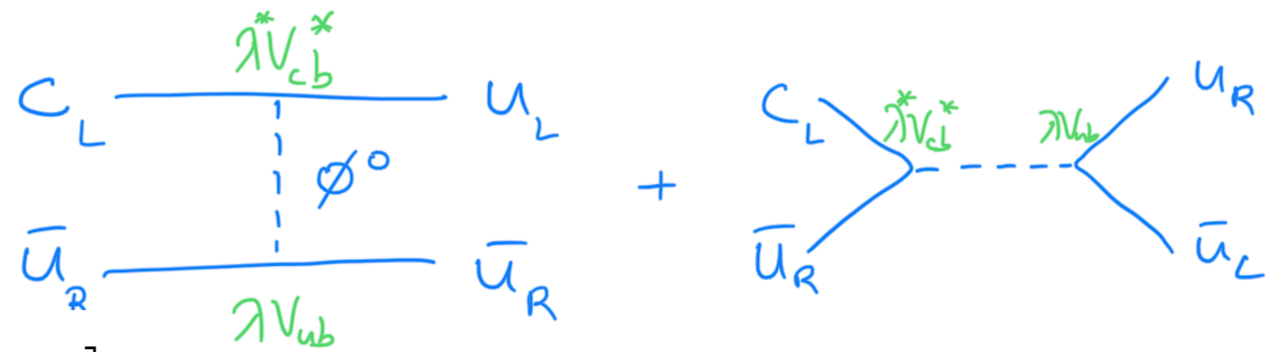
[See also topological amplitude approach in talk by Hai-Yang Cheng]

NP or SM?

(1) NP interpretation ($r_{\text{QCD}} \sim 0.1$)

Which NP models could play a role? [AD Nir 1909.11242]

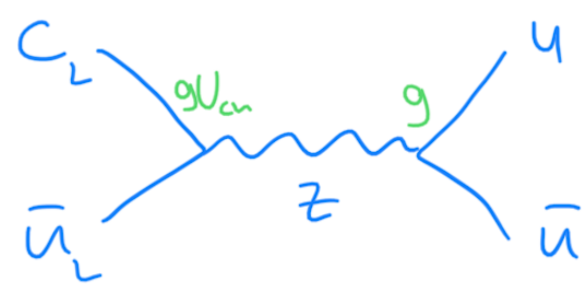
- 2HDM, $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$



$$\mathcal{L}_\Phi = -V(\Phi) + 2\lambda \left[\phi^0 \overline{U_{Li}} V_{ib} u_R + \phi^- \overline{b_L} u_R + \text{h.c.} \right]$$

- Flavor-changing Z (vector-like quarks)

$$-\mathcal{L}_Z = \frac{g U^u_{ij}}{2\cos\theta_W} \overline{u_L}_i \gamma_\mu u_{Lj} Z^\mu + \text{h.c.}$$



Non-generic but simple models can do the job.

(2) SM Interpretation ($r_{\text{QCD}} \sim 1$)

Comparison to the $\Delta I = 1/2$ rule

$K \to \pi\pi$

$$\left|\frac{A^K_{\Delta I=1/2}}{A^K_{\Delta I=3/2}}\right| \approx 22$$

perturbative calc. : $\sqrt{2}$

$D \to \pi\pi$

$$\left|\frac{A^D_{\Delta I=1/2}}{A^D_{\Delta I=3/2}}\right| \approx 2.5$$

perturbative calc. : $\sqrt{2}$

$B \to \pi\pi$

$$\left|\frac{A^B_{\Delta I=1/2}}{A^B_{\Delta I=3/2}}\right| \approx 1.5$$

perturbative calc. : $\sqrt{2}$

$$\frac{A_{\Delta U=0}}{A_{\Delta U=1}} = 1 + r_{\text{QCD}} e^{i\delta}$$

Could there be an analogous $\Delta U = 0$ rule, $r_{\text{QCD}} \sim 1$?

The ΔA_{CP} result is consistent
with the SM with **$\mathcal{O}(1)$ rescattering effects.**

Testing the $\Delta U = 0$ rule with future data

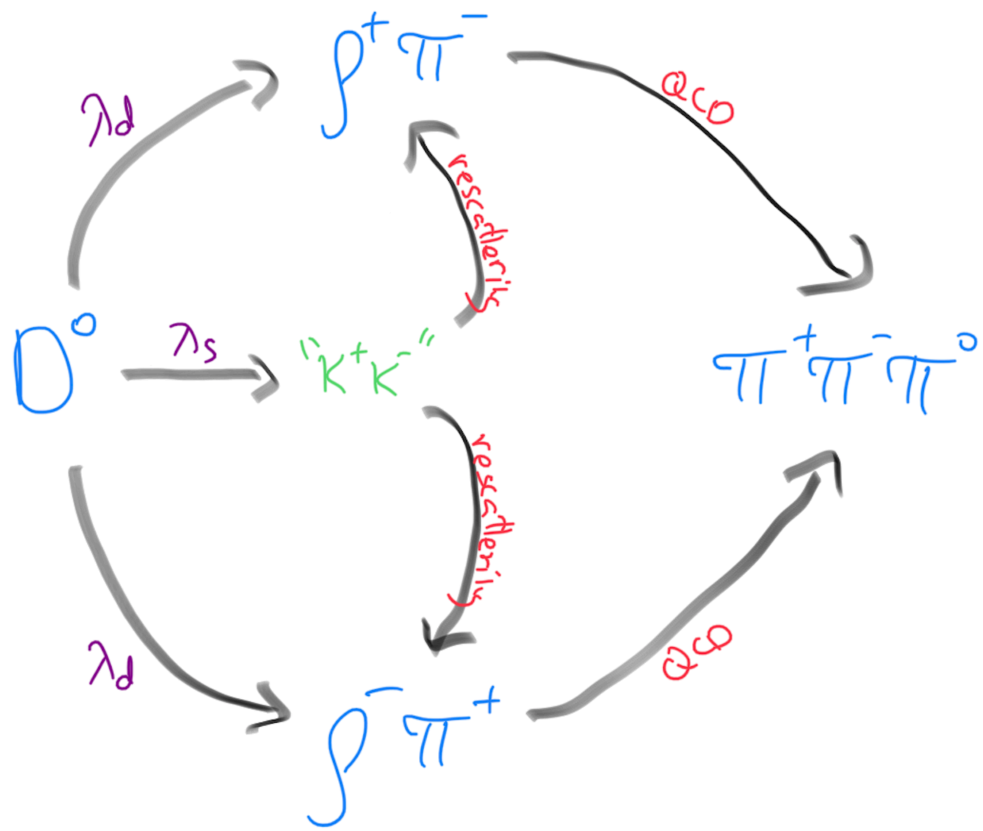
- Measurements of the strong phases, $\delta_{KK}, \delta_{\pi\pi}$ from time-dependent rates
- Measurement of a_f^d in additional modes -
  a testing ground for the $\Delta U = 0$ rule

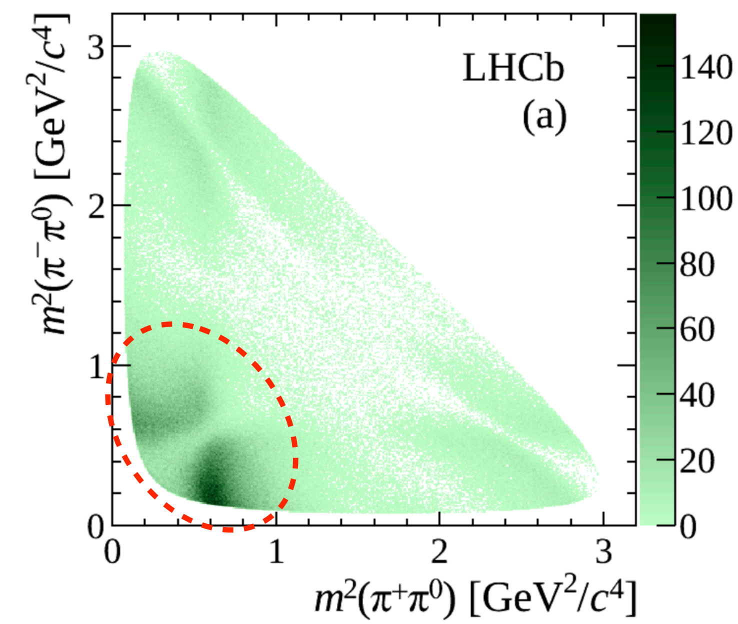
One interesting possibility - measure $\mathrm{Im}(A_{\Delta U=0}/A_{\Delta U=1})$ in

$$D^0 \to V^{\pm}P^{\mp} \to P^{\pm}P^0P^{\mp}$$

Testing the $\Delta U = 0$ in 3-body charm decays

[AD Grossman Schacht Soffer, 2101.02560]





[LHCb 1410.4170]

- Interference between 2 resonances enables extraction of r_{QCD} AND $sin\delta$, separately, from the time-integrated measurement.
- Kinematic dependence in Dalitz plot replaces time-dependence

Testing the $\Delta U = 0$ in 3-body charm decays

All parameters can be extracted from the time-integrated Dalitz:

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

$$A_{\pi^+\pi^-} = \lambda_{sd} \cdot A_{\Delta U=1} + \lambda_b \cdot A_{\Delta U=0}$$

$$|A_{\Delta U=1}|, |A_{\Delta U=0}|, \arg(A_{\Delta U=0}/A_{\Delta U=1})$$

3 physical parameters

$$D \to \rho^\pm\pi^\mp \to \pi^+\pi^-\pi^0$$

$$\begin{cases} A_{\rho^+\pi^-} = \lambda_{sd} \cdot A^{\rho\pi}_{\Delta U=1} + \lambda_b \cdot A^{\rho\pi}_{\Delta U=0} \\ A_{\rho^-\pi^+} = \lambda_{sd} \cdot A^{\pi\rho}_{\Delta U=1} + \lambda_b \cdot A^{\pi\rho}_{\Delta U=0} \end{cases}$$

$$|A^{\rho\pi}_{\Delta U=1}|, |A^{\rho\pi}_{\Delta U=0}|, \arg(A^{\rho\pi}_{\Delta U=0}/A^{\rho\pi}_{\Delta U=1})$$

$$|A^{\pi\rho}_{\Delta U=1}|, |A^{\pi\rho}_{\Delta U=0}|, \arg(A^{\pi\rho}_{\Delta U=0}/A^{\pi\rho}_{\Delta U=1})$$

$$\arg(A^{\rho\pi}_{\Delta U=1}/A^{\pi\rho}_{\Delta U=1})$$

7 physical parameters

Testing the $\Delta U = 0$ in 3-body charm decays

All parameters can be extracted from the time-integrated Dalitz:

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

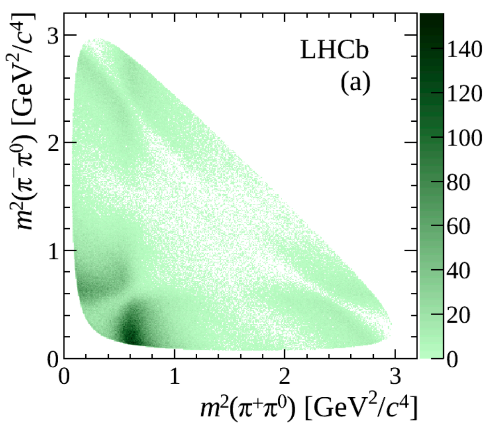
$$\mathcal{B}(D \to \pi^+\pi^-) = \frac{\mathcal{B}(D^0 \to \pi^+\pi^-) + \mathcal{B}(\overline{D}^0 \to \pi^+\pi^-)}{2}$$

$$A_{CP}(\pi^+\pi^-) = \frac{|A(D^0 \to \pi^+\pi^-)|^2 - |A(\overline{D}^0 \to \pi^+\pi^-)|^2}{|A(D^0 \to \pi^+\pi^-)|^2 + |A(\overline{D}^0 \to \pi^+\pi^-)|^2}$$

2 time-integrated measurements

3 physical parameters

$$D \to \rho^\pm\pi^\mp \to \pi^+\pi^-\pi^0$$



7 points on the Dalitz plot naively suffice

7 physical parameters

Additional advantage of Dalitz analyses

- Production/detection asymmetries are constant across the Dalitz plot, to leading order => can be eliminated

$$A_{\rm CP}^{\delta} = \frac{|A|^2 - (1-\delta)|\bar{A}|^2}{|A|^2 + (1-\delta)|\bar{A}|^2}$$

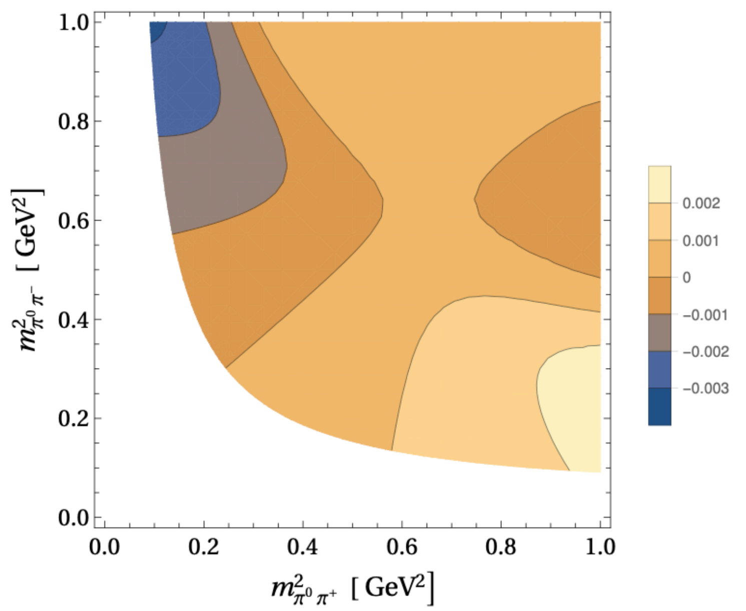
$$A_{\rm CP}^{\delta}(D^0 \to \pi^+\pi^-) = A_{\rm CP}(D^0 \to \pi^+\pi^-) + \frac{\delta}{2}\Big(1 + \mathcal{O}\left(\varepsilon_{NU}\right)\Big) \qquad \varepsilon_{NU} = \left|\frac{\lambda_d + \lambda_s}{\lambda_d - \lambda_s}\right| \sim 10^{-3}$$

$$A_{\rm CP}^{\delta}(D^0 \to \rho^\pm\pi^\mp)(s,t) = A_{\rm CP}(D^0 \to \rho^\pm\pi^\mp)(s,t) + \underbrace{\frac{\delta}{2}\Big(1}\, + \mathcal{O}\left(\varepsilon_{NU}\right)(s,t)\Big)$$

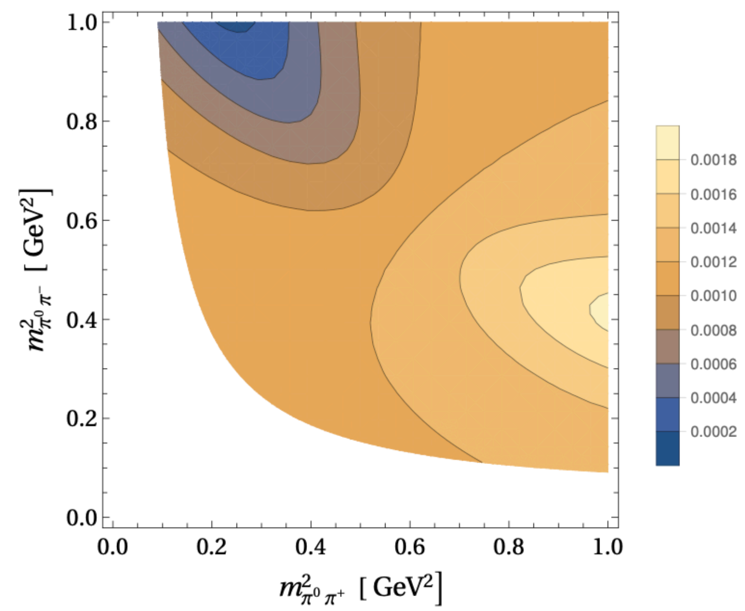
Caveats of the proposed method

- The 2 narrow resonances picture is simplistic.
- It should suffice for probing $\mathcal{O}(1)$ rescattering effects.
- With improved experimental precision in the future, more sophisticated methods will be needed, using a multiple resonance model.

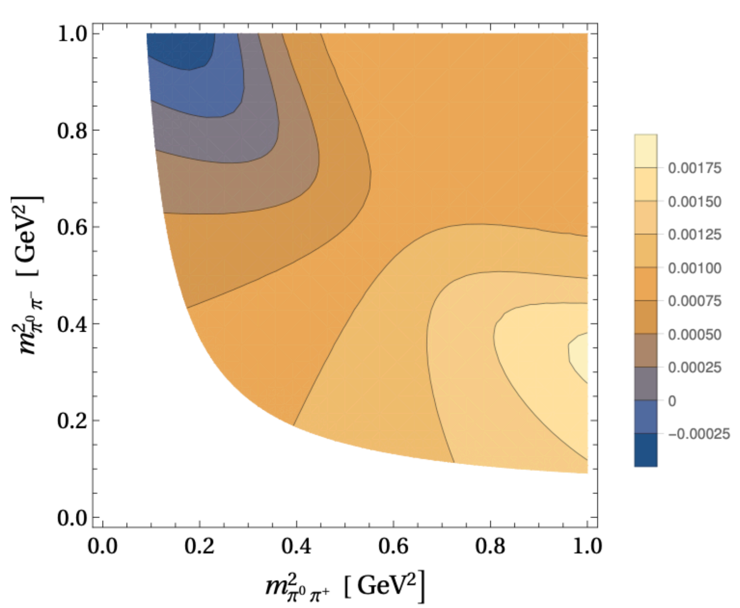
Local CP asymmetry in $D^0 \to \pi^+\pi^-\pi^0$ for different values of r_{QCD} and $\sin\delta$



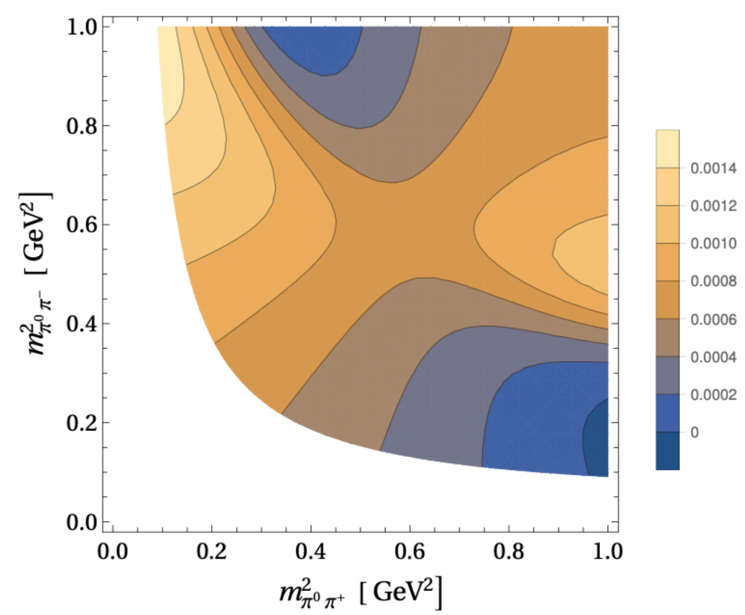
(a) $\widetilde{R}^{P_1V_2} = \exp(i3\pi/2)$, $\widetilde{R}^{P_2V_1} = \exp(i\pi/3)$



(b) $\widetilde{R}^{P_1V_2} = \exp(i\pi/2)$, $\widetilde{R}^{P_2V_1} = \exp(i\pi/3)$



(c) $\widetilde{R}^{P_1V_2} = \frac{1}{2}\exp(i\pi/2)$, $\widetilde{R}^{P_2V_1} = \exp(i\pi/3)$



(d) $\widetilde{R}^{P_1V_2} = \exp(i\pi/2)$, $\widetilde{R}^{P_2V_1} = \frac{1}{4}\exp(i\pi/3)$

U-spin relation to $K^+K^-\pi^0$

Is it possible to construct an analogous observable to $\Delta A_{\rm CP}$?

$$\begin{pmatrix}\pi^- \\ K^-\end{pmatrix}, \qquad \begin{pmatrix}K^+ \\ \pi^+\end{pmatrix}$$

$$\Delta A_{\rm CP}^{P^+P^-} \equiv A_{\rm CP}(D^0 \to K^+K^-) - A_{\rm CP}(D^0 \to \pi^+\pi^-)$$

$$\begin{pmatrix}\rho^- \\ K^{*-}\end{pmatrix}, \qquad \begin{pmatrix}K^{*+} \\ \rho^+\end{pmatrix}$$

$$D^0 \to K^{*\pm}\pi^{\mp} \to K^+K^-\pi^0 \qquad \leftrightarrow \qquad D^0 \to \rho^{\pm}\pi^{\mp} \to \pi^+\pi^-\pi^0$$

$$\Delta A_{\rm CP}^{V^\pm P^\mp}(s,t) \equiv \frac{|A(D^0 \to K^+K^-\pi^0)|^2 - |A(\overline{D}^0 \to K^+K^-\pi^0)|^2}{|A(K^* \to K\pi)|^2} - \frac{|A(D^0 \to \pi^+\pi^-\pi^0)|^2 - |A(\overline{D}^0 \to \pi^+\pi^-\pi^0)|^2}{|A(\rho \to \pi\pi)|^2}$$

U-spin relation to $K^+K^-\pi^0$

Is it possible to construct an analogous observable to ΔA_{CP} ?

$$D^0 \to K^{*\pm}\pi^\mp \to K^+K^-\pi^0 \qquad \leftrightarrow \qquad D^0 \to \rho^\pm\pi^\mp \to \pi^+\pi^-\pi^0$$

$$\Delta A_{CP}^{V^\pm P^\mp}(s,t) \equiv \frac{|A(D^0 \to K^+K^-\pi^0)|^2 - |A(\overline{D}^0 \to K^+K^-\pi^0)|^2}{|A(K^* \to K\pi)|^2} - \frac{|A(D^0 \to \pi^+\pi^-\pi^0)|^2 - |A(\overline{D}^0 \to \pi^+\pi^-\pi^0)|^2}{|A(\rho \to \pi\pi)|^2}$$

Limitations of this approach:

- Pseudo two-body decays have exact U-spin correspondence, however, the 3-body final states are not related by a full interchange of $d \leftrightarrow s$.
- Additional source of $\mathrm{SU}(3)$-breaking from the different masses and widths of the intermediate resonances, ρ, K^*.
- Fundamental problem - no meaningful way to associate two points on different Dalitz plots.

Conclusion and Outlook

Exciting times ahead!

- The discovery of CPV in charm opens up a new arena
- Future results will inevitably either strengthen the NP hypothesis, or will teach us about low-energy QCD
- In particular, we will test the prediction that arises from ΔA_{CP}, the $\Delta U = 0$ rule.
- Compared to 2-body decays, 3-body Dalitz analyses have advantages:
  - The entire system of parameters can be extracted without requiring time-dependent measurements. In particular, can separate between r and $\sin\delta$.
  - Production and detection asymmetries can be eliminated within a single mode.