CP violation in $\bar{B} \to D^{**}\tau^-\bar{\nu}$

1806.04146

Abi Soffer

Tel Aviv University

with

Daniel Aloni

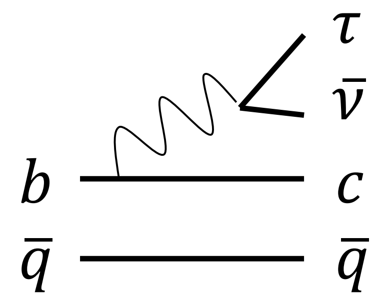
Weizmann Institute

Yuval Grossman

Cornell University

ICHEP 2018, Seoul, S. Korea

Motivation



- Currently, $R\left(D^{(*)}\right) \equiv \frac{Br\left(\bar{B}\to D^{(*)}\tau\bar{\nu}\right)}{Br\left(\bar{B}\to D^{(*)}\ell\bar{\nu}\right)}$ are higher than SM predictions by 3.8σ (https://hflav-eos.web.cern.ch/hflav-eos/semi/summer18/RDRDs.html)

- Even if this tension is reduced after new measurements, these $b \to c\tau\bar{\nu}$ processes are sensitive to new physics (NP) that couples more strongly to heavy fermions (e.g., charged Higgs)

- Processes that are sensitive to NP should be checked for potential CP violation.
  - Motivated by the baryon asymmetry of the universe
  - Many such studies done at BABAR, Belle, LHCb

CP asymmetry

- A simple CPV observable is the CP asymmetry

$$\mathcal{A}_{CP}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau) = \frac{BR(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau) - BR(B \to \bar{D}^{(*)}\tau^+\nu_\tau)}{BR(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau) + BR(B \to \bar{D}^{(*)}\tau^+\nu_\tau)}$$

- A CP asymmetry requires interference between 2 amplitudes with
  - A non-zero CP-violating ("weak") phase difference → SM & NP
  - A non-zero CP-conserving ("strong") phase difference
- One possibility is triple products [1302.7031, 1403.5892]. Requires:
  - Either knowing the τ momentum vector in the B rest frame – difficult due neutrinos
  - Or use of only hadronic τ decays – limits the analysis sensitivity

Using excited charm decays

- We study another possibility for generating the strong phase: interference between overlapping D^{**} resonances:

1606.09300

Particle	J^P	M (MeV)	Γ (MeV)	Decay modes
D_0^*	0^+	2330	270	$D\pi$
D_1^*	1^+	2427	384	$D^*\pi$
D_1	1^+	2421	34	$D^*\pi$
D_2^*	2^+	2462	48	$D^*\pi,\ D\pi$

- Focus on the narrow D_1 & $D_2^* \to D^*\pi$
  - These states overlap reasonably well
  - The broad states are experimentally harder to identify and have small overlap with the narrow states.
  - For this reason we also ignore the nonresonant $\bar{B} \to D^*\pi\tau^-\bar{\nu}$ process

Formalism 1

- The total amplitude is a sum over amplitudes with different intermediate D^{**} resonances:

$$\mathcal{A} \equiv \mathcal{A}(\bar{B} \to D^{(*)}\pi\tau^-\bar{\nu}_\tau) = \sum_i \mathcal{A}(\bar{B} \to D_i^{**}(\to D^{(*)}\pi)\tau^-\bar{\nu}_\tau)$$

- In the narrow-width approximation:

$$\mathcal{A}(\bar{B} \to D_i^{**}(\to D^{(*)}\pi)\tau^-\bar{\nu}_\tau) = \sum_\lambda \frac{i\mathcal{A}(\bar{B} \to D_i^{**}(\lambda)\tau^-\bar{\nu}_\tau)\mathcal{A}(D_i^{**}(\lambda) \to D^{(*)}\pi)}{m^2_{D^{(*)}\pi} - M^2_{D_i^{**}} + i\Gamma_{D_i^{**}} M_{D_i^{**}}}$$

D^{**} helicity

Mass of $D^*\pi$ system

Formalism 1

- The total amplitude is a sum over amplitudes with different intermediate D^{**} resonances:

$$\mathcal{A} \equiv \mathcal{A}(\bar{B} \to D^{(*)}\pi\tau^-\bar{\nu}_\tau) = \sum_i \mathcal{A}(\bar{B} \to D_i^{**}(\to D^{(*)}\pi)\tau^-\bar{\nu}_\tau)$$

- In the narrow-width approximation:

$$\mathcal{A}(\bar{B} \to D_i^{**}(\to D^{(*)}\pi)\tau^-\bar{\nu}_\tau) = \sum_\lambda \frac{i\mathcal{A}(\bar{B} \to D_i^{**}(\lambda)\tau^-\bar{\nu}_\tau)\mathcal{A}(D_i^{**}(\lambda) \to D^{(*)}\pi)}{m^2_{D^{(*)}\pi} - M^2_{D_i^{**}} + i\Gamma_{D_i^{**}}M_{D_i^{**}}}$$

D^{**} helicity

Mass of $D^*\pi$ system

- Assume:
  - No NP in the D^{**} decay
  - One NP weak phase φ^{NP}. Therefore (next page)

Formalism 2

SM CKM phase rephrased to 0

$$\mathcal{A}(\bar{B} \to D_i^{**}(\lambda)\tau^- \bar{\nu}_\tau) = r_i^{\rm SM}\, e^{i\delta_i^{\rm SM}} + r_i^{\rm NP}\, e^{i(\varphi^{\rm NP}+\delta_i^{\rm NP})}$$

Where the amplitudes and phases parameterize products of the Wilson coefficients and matrix elements:

$$\begin{aligned} r_i^{\rm SM} &= |C^{\rm SM}|\,|\langle D_i^{**\,+}\tau^-\bar{\nu}_\tau|\mathcal{O}^{\rm SM}|\bar{B}^0\rangle|\ , \\ r_i^{\rm NP} &= |C^{\rm NP}|\,|\langle D_i^{**\,+}\tau^-\bar{\nu}_\tau|\mathcal{O}^{\rm NP}|\bar{B}^0\rangle|\ , \\ \varphi^{\rm NP} &= \arg(C^{\rm NP}), \\ \delta_i^{\rm SM} &= \arg(\langle D_i^{**\,+}\tau^-\bar{\nu}_\tau|\mathcal{O}^{\rm SM}|\bar{B}^0\rangle), \\ \delta_i^{\rm NP} &= \arg(\langle D_i^{**\,+}\tau^-\bar{\nu}_\tau|\mathcal{O}^{\rm NP}|\bar{B}^0\rangle), \end{aligned}$$

Neglected
- Vanish to LO in HQET
- Can determine in experiment

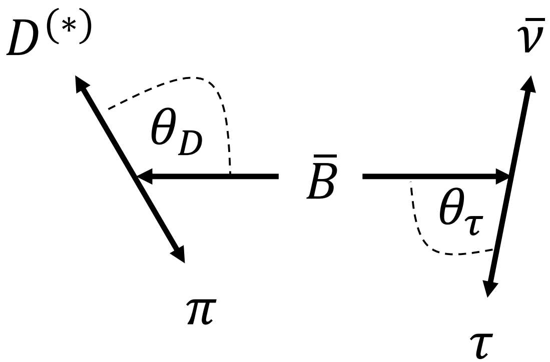
Conditions for a CP asymmetry

- We use the overlapping resonances to generate the strong phase difference between the interfering amplitudes
- So to have a CP asymmetry, there should also be a weak phase difference between the amplitudes involving different resonances
- This means

$$\frac{r_i^{\rm NP}}{r_i^{\rm SM}} \neq \frac{r_j^{\rm NP}}{r_j^{\rm SM}}$$

- This happens only if
  - The interfering resonances have different spins, and
  - The SM & NP operators have different Dirac structures: $\mathcal{O}_{NP} \neq \mathcal{O}_{SM}$
    - Note that if $\mathcal{O}_{NP} = \mathcal{O}_{SM}$, the triple-product methods have no CP asymmetry either

Observable CP asymmetry



- Phase-space variables:
  - q^2 = mass of $\tau\bar{\nu}$
  - $m_{D^{(*)}\pi}$ = mass of $D^{(*)}\pi$
  - θ_D = decay angle of D^{**}
  - θ_τ = "decay" angle of $\tau\bar{\nu}$
  - ϕ = angle between $D^{(*)}\pi$ and $\tau\bar{\nu}$ "decay" planes

- Experimentally easier to integrate the rates over some of PS
- But must not integrate over:
  - $m_{D^{(*)}\pi}$: gives Breit-Wigner phase
  - θ_D: due to orthogonality of $Y_{\ell m}$ for $\ell \neq \ell'$

$$\mathcal{A}_{\rm CP} = \frac{\int d\Phi \left(|\bar{\mathcal{A}}|^2 - |\mathcal{A}|^2 \right)}{\int d\Phi \left(|\bar{\mathcal{A}}|^2 + |\mathcal{A}|^2 \right)}$$

- The simplest asymmetry must be in terms of these variables
  - Both are easy to measure, since the D^{**} is fully reconstructed

Toy model

- Explore, in turn, the operators (arise in solutions to the $R(D^{(*)})$ puzzle)

$$\mathcal{O}_S = (\bar{\tau}_R \nu_{\tau_L})(\bar{c}b), \qquad \mathcal{O}_P = (\bar{\tau}_R \nu_{\tau_L})(\bar{c}\gamma^5 b), \qquad \mathcal{O}_T = (\bar{\tau}_R \sigma^{\mu\nu} \nu_{\tau_L})(\bar{c}\sigma_{\mu\nu} b)$$

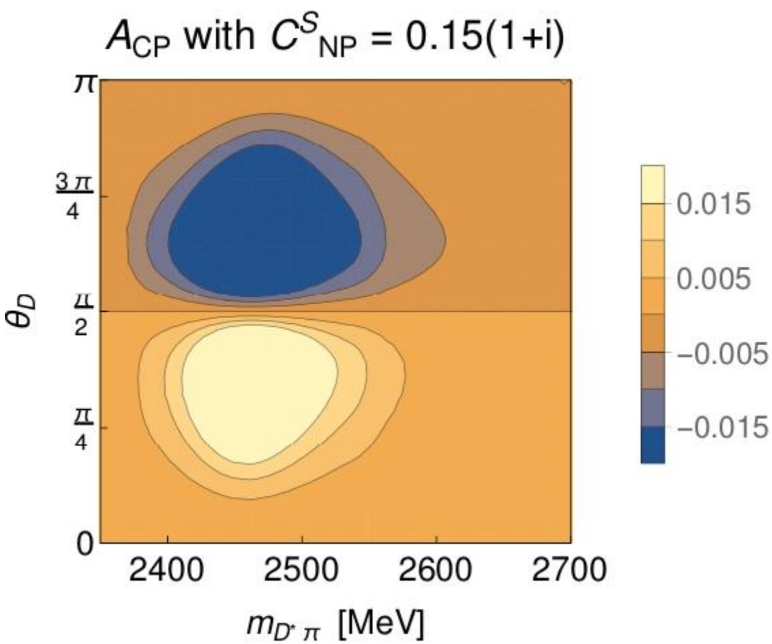
- Assume factorization of hadronic and leptonic currents:

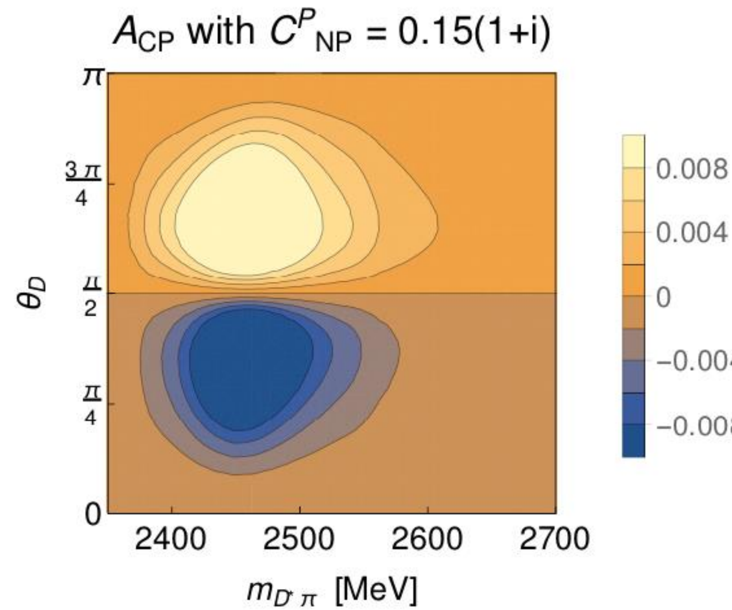
$$\langle D^{**+} \tau^- \bar{\nu}_\tau | \mathcal{O} | \bar{B}^0 \rangle \simeq \langle D^{**+} | \mathcal{O}_q | \bar{B}^0 \rangle \langle \tau^- \bar{\nu}_\tau | \mathcal{O}_\ell | 0 \rangle$$

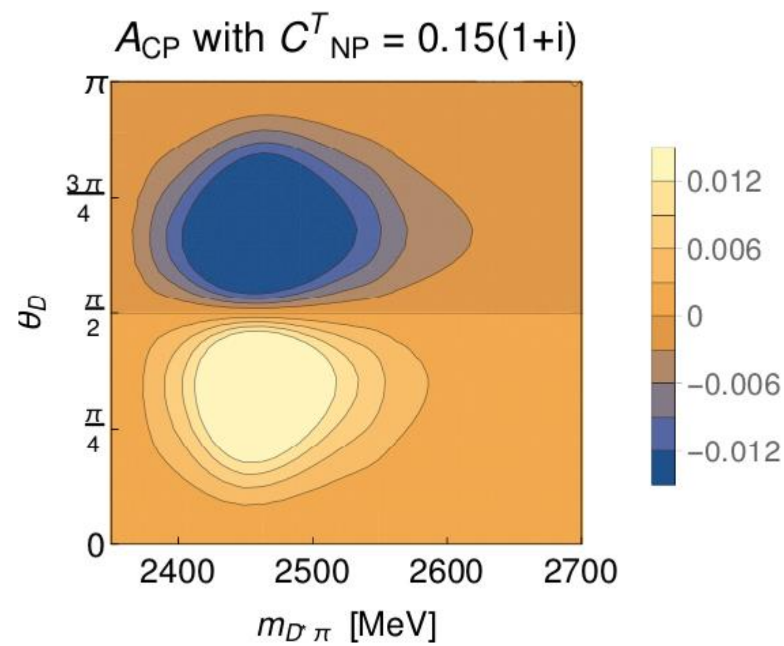
- Calculate leptonic currents in perturbation theory
- Calculate hadronic currents to LO in HQET
- For D^{**} decay, use model inspired by LO HQET [Phys. Rev. D45, 1553 (1992)]
  - These simplifications do not change the conclusions
  - Much detail in the paper, including extension to real-life experiment
- Inspired by $R(D^{(*)})$ ~30% excess and for maximal CP phase, take

$$C^{NP} = 0.15\, C^{SM}\,(1 + i)$$

$A_{CP}(m_{D^*\pi}, \theta_D)$

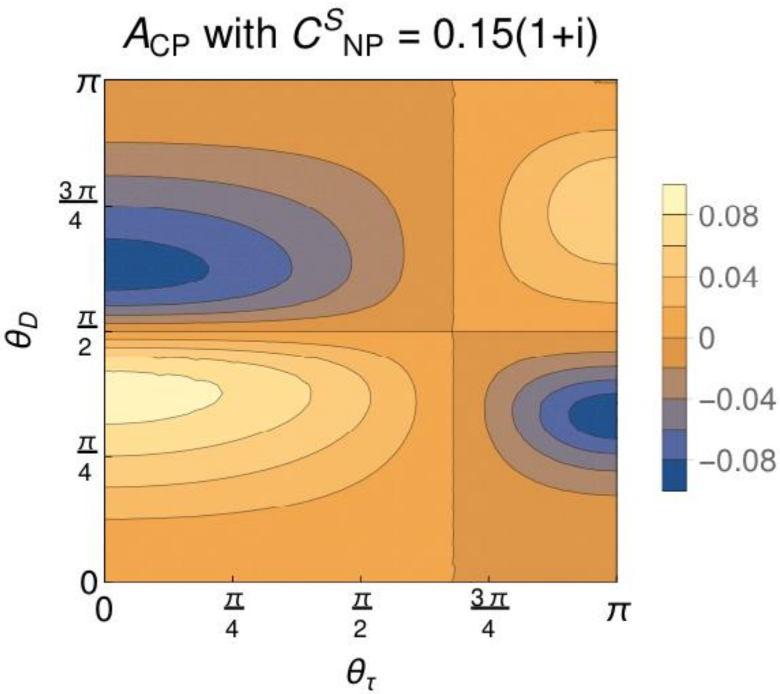




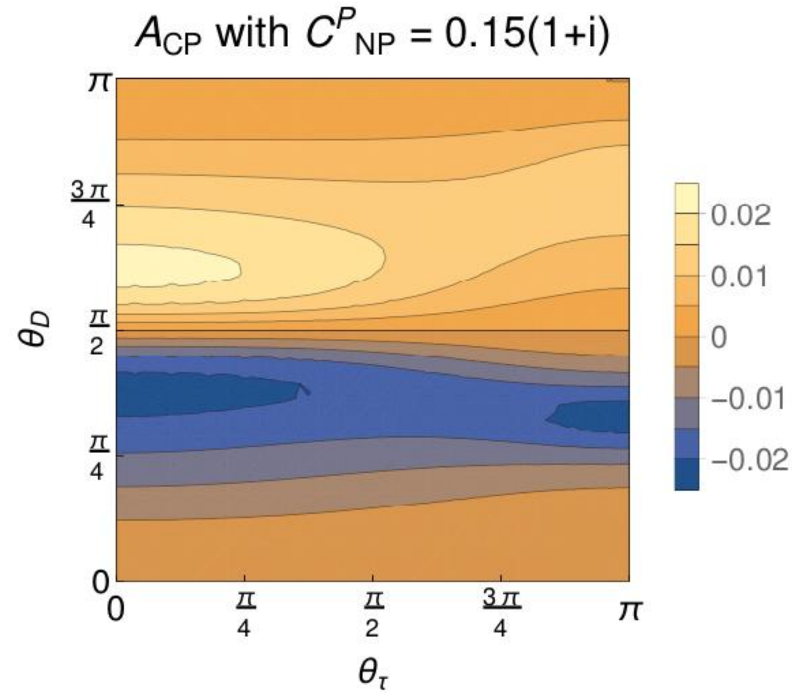


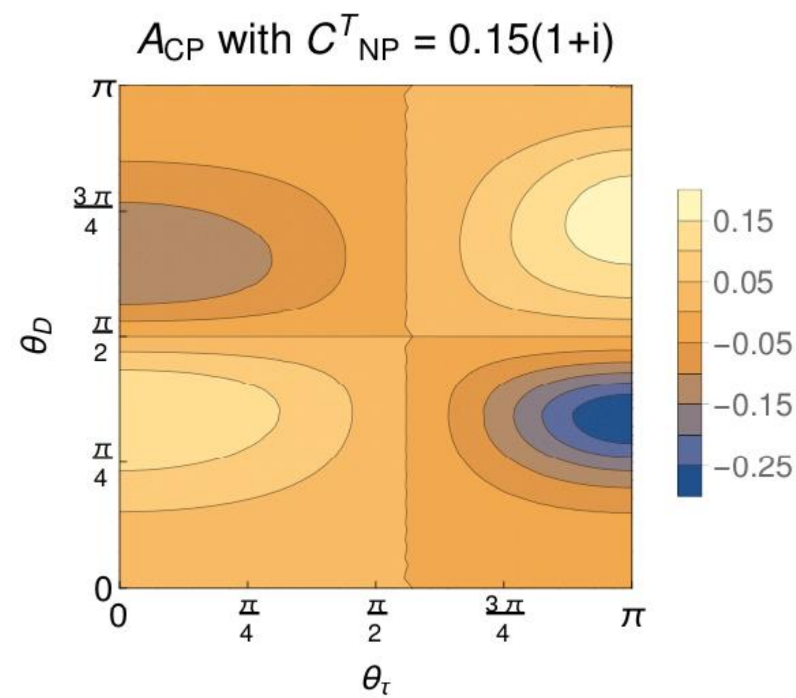
- $A_{CP}(m_{D^*\pi}, \theta_D)$ has the expected dependence
- But is at the ~1% level, due to
  - Resonance overlap
  - Cancellations in PS integration

$A_{CP}(\theta_D, \theta_\tau)$ for fixed $m_{D^*\pi}$



- In $e^+e^- \to B\bar{B}$, $\vec{q}$ is known well
- In $\vec{q}$ frame, θ_ℓ of the lepton from $\tau \to \ell\nu\bar{\nu}$ gives θ_τ to within about $\pi/4$.
- This is sufficient to avoid much of the cancellation due to integration over θ_τ
- LHCb probably has also sensitivity to θ_τ

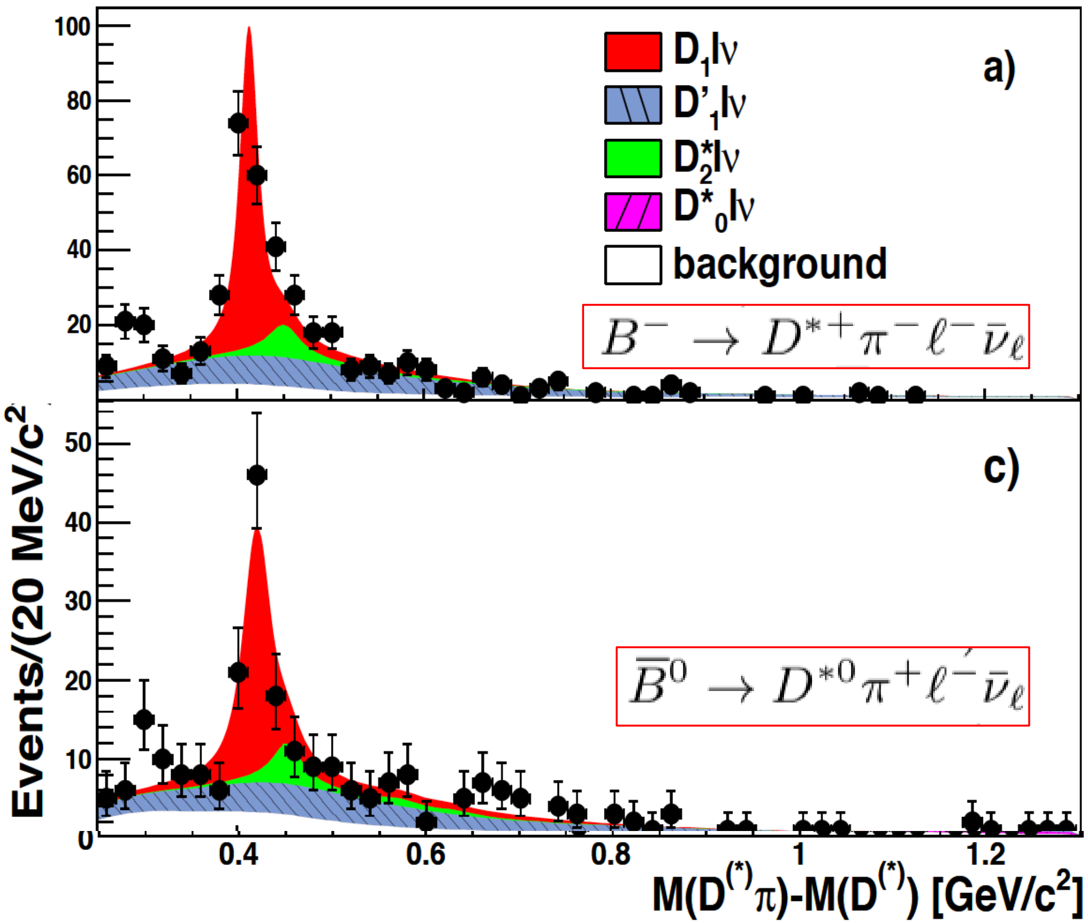




Rough sensitivity estimate

- Not enough information for accurate estimate, but…
- Belle II will have 100 times more integrated luminosity than BABAR
- $Br(\bar{B} \to D^{**}\tau^{-}\bar{\nu})$ is ~15 times smaller [1606.09300]
- → Belle II will have ~6 times more signal than in these plots.
- Also 100 times more background without further optimization
- With these assumptions, we obtain an estimate of 5% on the asymmetry under the D_1 peak

$\bar{B} \to D^{**}\ell^{-}\bar{\nu}$ at BABAR, 0808.0528



Summary

- $b \to c\tau\bar{\nu}$ processes sensitive to new physics, even without the current excess
- Therefore, interesting to search for a CP asymmetry
- Generating a strong phase is the trick
- We use interference between D^{**} resonances, and integrate the asymmetry over phase space as much as possible for a simpler experimental analysis
- A ~1-10% asymmetry is found, depending on the observable, and on the strength and CPV phase of the NP operator