Measuring CP violation in $b \to c\tau^-\bar{\nu}_\tau$ using excited charm mesons

Daniel Aloni

LHCP 2019 – Puebla, Mexico

In collaboration with

Yuval Grossman (Cornell), Abner Soffer (TAU)

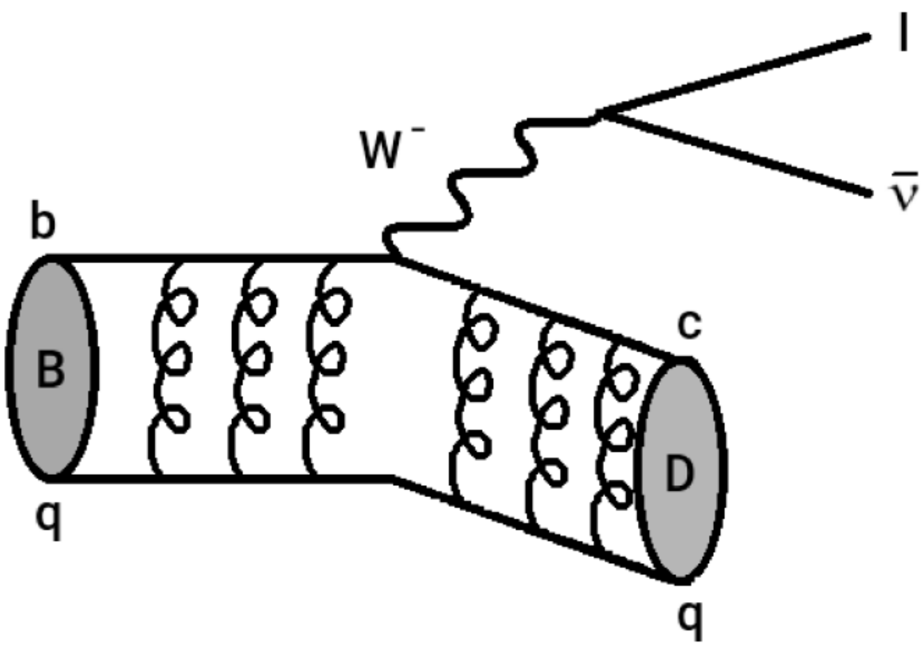
PRD 98 (2018) no.3, 035022, Arxiv: 1804.04146

WEIZMANN INSTITUTE OF SCIENCE

Why $b \to c\tau^- \bar{\nu}_\tau$?

Motivation

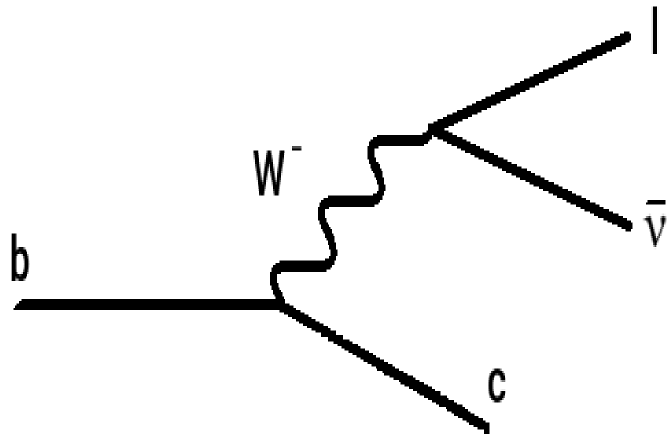
- $R(D^{(*)}) \equiv \frac{BR(B \to D^{(*)} \tau \bar{\nu})}{BR(B \to D^{(*)} \ell \bar{\nu})} \quad , \quad \ell = \mu, e$



Motivation

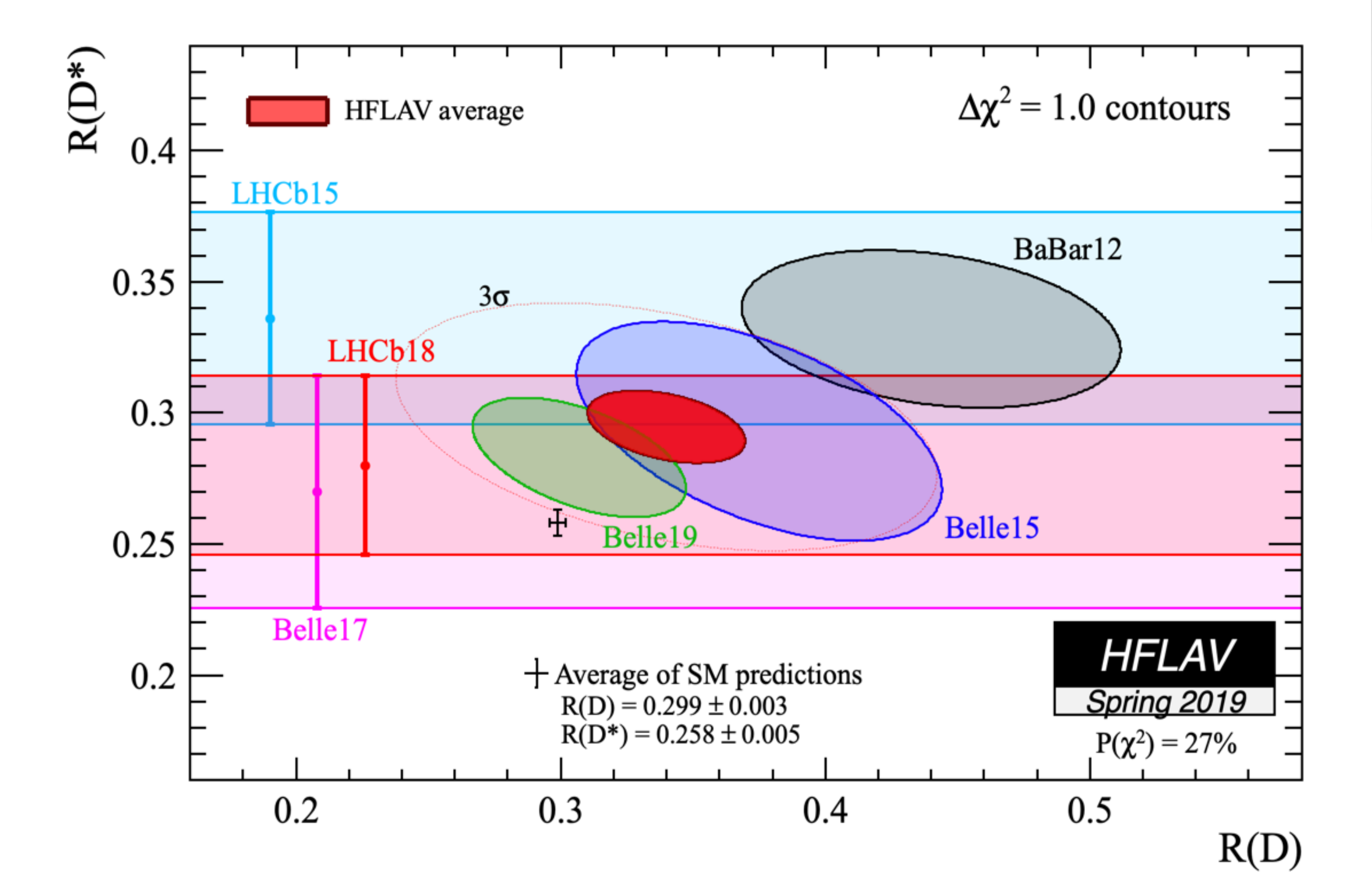
- $\mathrm{R(D^{(*)})} \equiv \frac{BR(B \to D^{(*)}\, \tau\, \bar{\nu})}{BR(B \to D^{(*)}\, \ell\, \bar{\nu})}$, $\ell = \mu, e$

- At the quark level: $b \to c\tau(\ell)\bar{\nu}$



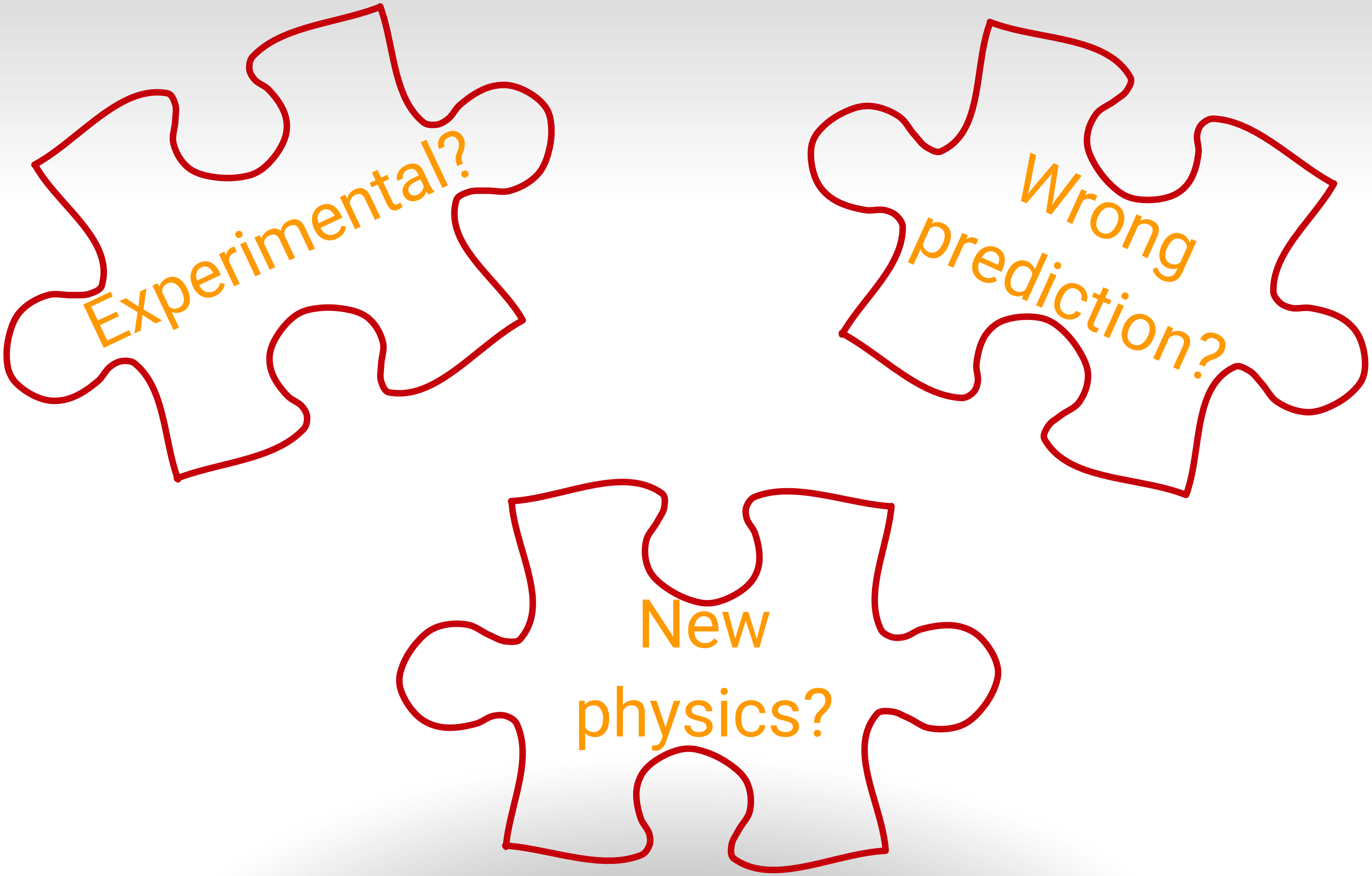
- SM: $b \to c\tau(\ell)\bar{\nu}$ transition is mediated by the W boson

Measurement: post-Moriond



- $\sim 3\sigma$ deviation from SM prediction

This is puzzling



If new physics

- Central values are enhanced by 30% compared to SM → NP amplitude ~15%-30% compared to SM
- New physics is non-universal and breaks lepton flavor symmetry
- New physics is probably heavy → Can work with an effective theory

EFT – complete basis

- Demand $G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$ invariance
- Assume no RH neutrinos, *i.e.* $B \to D\tau\bar{\nu}_L$
- A complete set for $b \to c\tau\bar{\nu}$ transitions contains only four operators
  - $(\bar{e}L)(\bar{u}Q)$
  - $(\bar{e}\sigma^{\mu\nu}L)(\bar{u}\sigma_{\mu\nu}Q)$
  - $(\bar{L}\gamma^{\mu}\tau_a L)(\bar{Q}\gamma^{\mu}\tau_a Q)$
  - $(\bar{Q}d)(\bar{e}L)$

EFT – complete basis

- Demand $G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$ invariance
- Assume no RH neutrinos, *i.e.* $B \to D\tau\bar{\nu}_L$
- A complete set for $b \to c\tau\bar{\nu}$ transitions contains only four operators
  - $(\bar{e}L)(\bar{u}Q)$
  - $(\bar{e}\sigma^{\mu\nu}L)(\bar{u}\sigma_{\mu\nu}Q)$
  - $(\bar{L}\gamma^{\mu}\tau_a L)(\bar{Q}\gamma^{\mu}\tau_a Q)$
  - $(\bar{Q}d)(\bar{e}L)$

Can we measure the phases?

Why is it interesting to have a phase?

- $R(D^{(*)})$ is puzzling!
- NP breaks LFU at O(1)! Why shouldn't it break CP at O(1)?
- CP violation = NP. No CPV within the SM

DA, Y. Grossman, A. Soffer, **arxiv: 1806.04146**

Checklist for CPV observables

- In order to observe CP in a decay
  - ➔ Two amplitudes – Interference
  - ➔ Weak phase – Changes sign under CP
  - ➔ Strong phase – Doesn't change sign under CP

- For example

$$\mathcal{A} = r_1 e^{i(\delta_1+\phi_1)} + r_2 e^{i(\delta_2+\phi_2)}$$
$$\bar{\mathcal{A}} = r_1 e^{i(\delta_1-\phi_1)} + r_2 e^{i(\delta_2-\phi_2)}$$

- gives

$$|\bar{\mathcal{A}}|^2 - |\mathcal{A}|^2 \propto r_1 r_2 \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2)$$

Can we measure CP asymmetry directly?

- The most naive observable

$$\mathcal{A}_{CP} \propto |A(\bar{B} \to \bar{D}^{(*)}\bar{\tau}\nu)|^2 - |A(B \to D^{(*)}\tau\bar{\nu})|^2$$

- Checklist:
  - ➔ Two amplitudes
  - ➔ Weak phase
  - ➔ Strong phase

Can we measure CP asymmetry directly?

- The most naive observable

$$\mathcal{A}_{CP} \propto |A(\bar{B} \to \bar{D}^{(*)}\bar{\tau}\nu)|^2 - |A(B \to D^{(*)}\tau\bar{\nu})|^2$$

- Checklist:
  - ➔ Two amplitudes ✓
  - ➔ Weak phase
  - ➔ Strong phase

Can we measure CP asymmetry directly?

- The most naive observable

$$\mathcal{A}_{CP} \propto |A(\bar{B} \to \bar{D}^{(*)}\bar{\tau}\nu)|^2 - |A(B \to D^{(*)}\tau\bar{\nu})|^2$$

- Checklist:
  - ➔ Two amplitudes ✓
  - ➔ Weak phase ✓
  - ➔ Strong phase

Can we measure CP asymmetry directly?

- The most naive observable

$$\mathcal{A}_{CP} \propto |A(\bar{B} \to \bar{D}^{(*)}\bar{\tau}\nu)|^2 - |A(B \to D^{(*)}\tau\bar{\nu})|^2$$

- Checklist:
  - ➔ Two amplitudes ✔
  - ➔ Weak phase ✔
  - ➔ Strong phase ✘

DA, Y. Grossman, A. Soffer, **arxiv: 1806.04146**

Can we measure CP asymmetry directly?

- The most naive observable

$$\mathcal{A}_{CP} \propto |A(\bar{B} \to \bar{D}^{(*)}\bar{\tau}\nu)|^2 - |A(B \to D^{(*)}\tau\bar{\nu})|^2$$

- Checklist:
  - ➔ Two amplitudes ✓
  - ➔ Weak phase ✓
  - ➔ Strong phase ✗

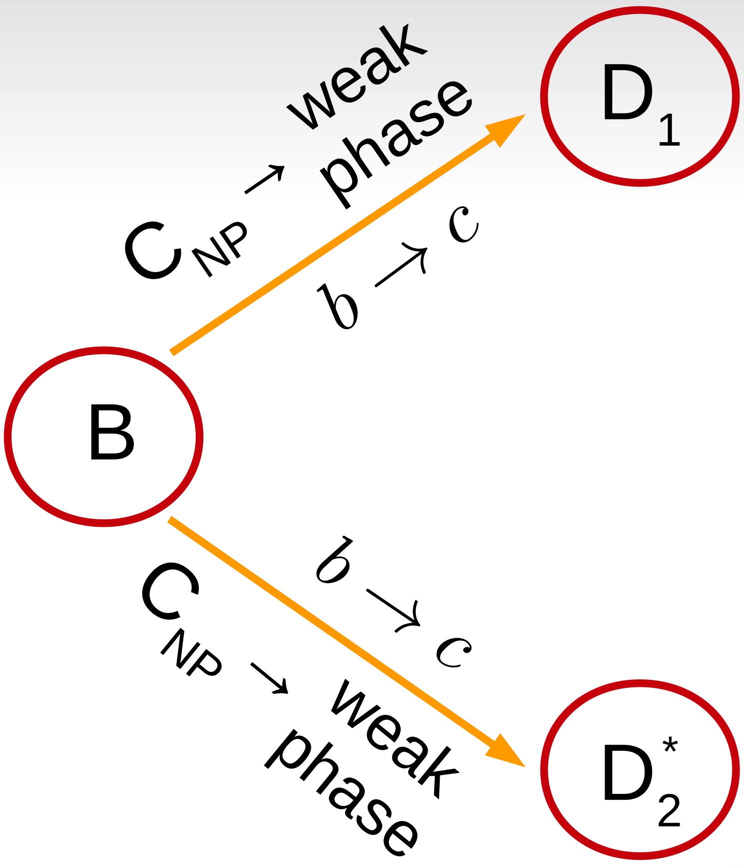
Triple product | **Our method**

DA, Y. Grossman, A. Soffer, **arxiv: 1806.04146**

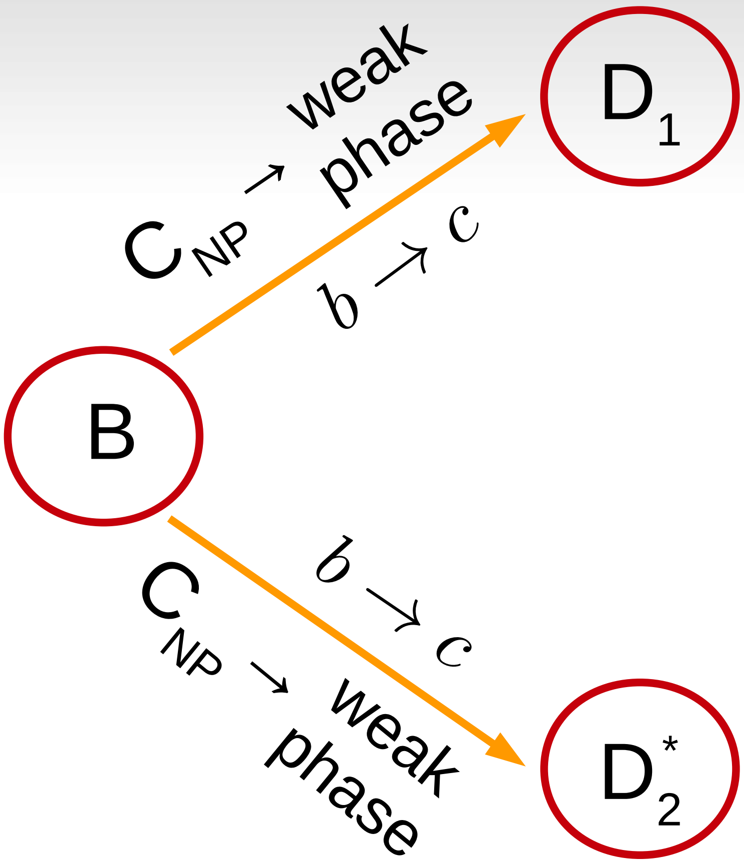
Our method – Interference of resonances

B

Our method – Interference of resonances



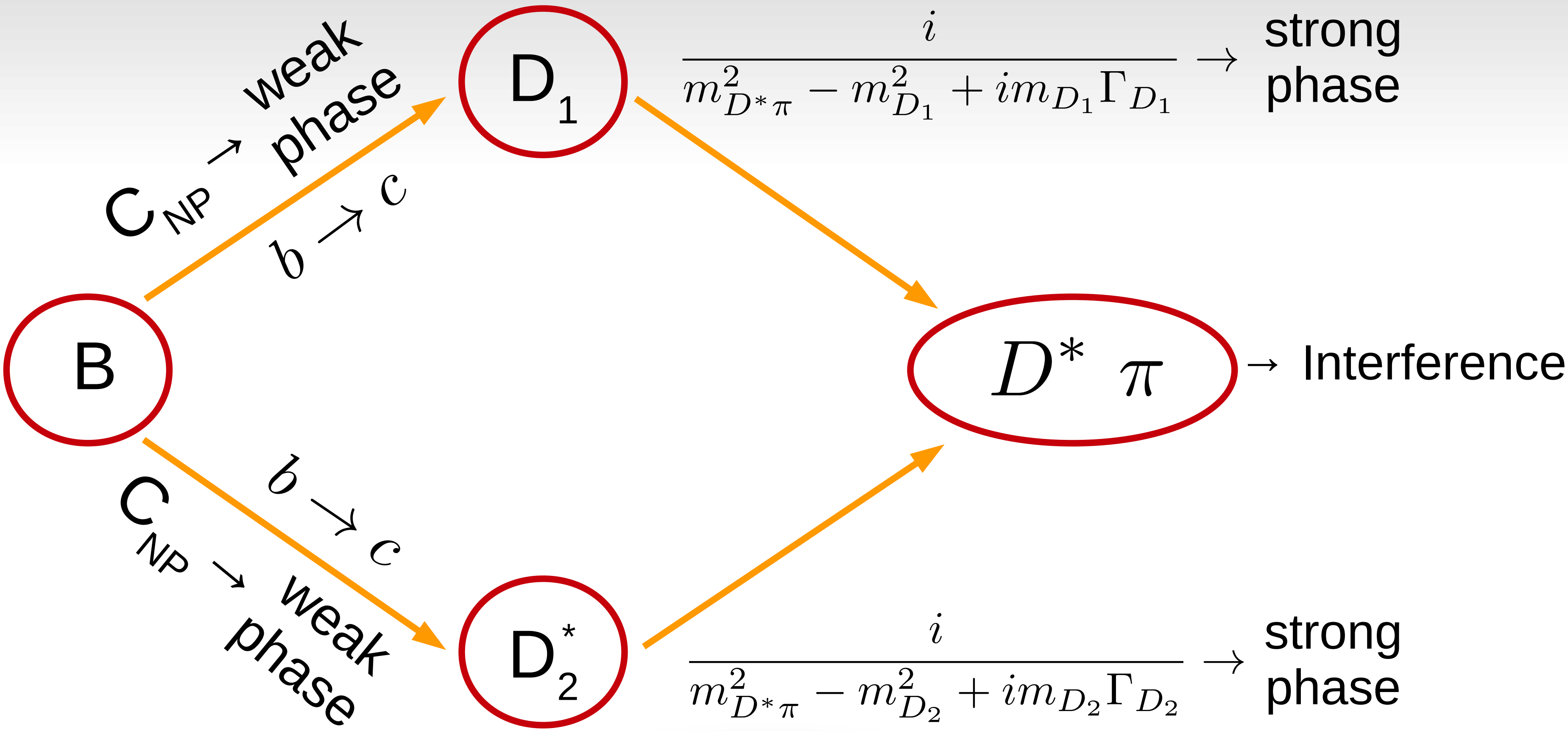
Our method – Interference of resonances



$$\frac{i}{m^2_{D^*\pi} - m^2_{D_1} + i m_{D_1}\Gamma_{D_1}} \rightarrow \text{strong phase}$$

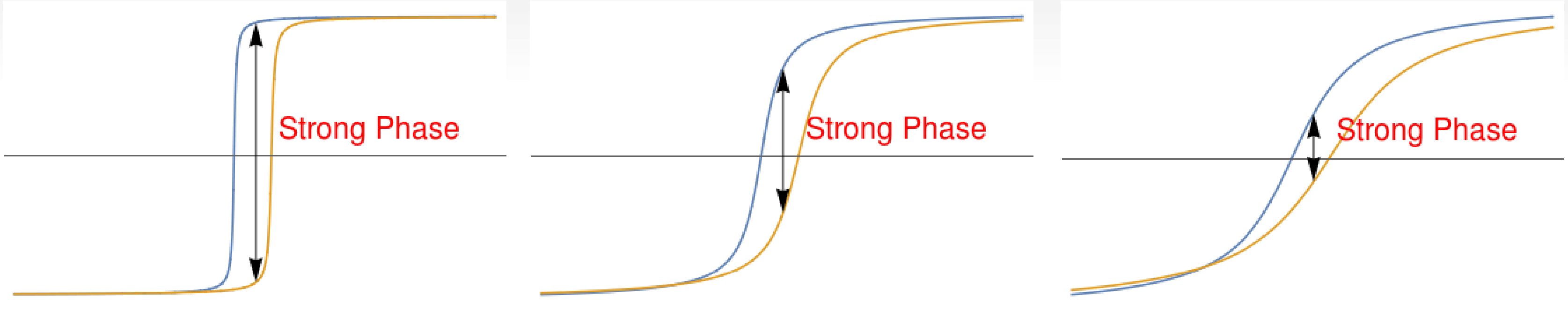
$$\frac{i}{m^2_{D^*\pi} - m^2_{D_2} + i m_{D_2}\Gamma_{D_2}} \rightarrow \text{strong phase}$$

Our method – Interference of resonances

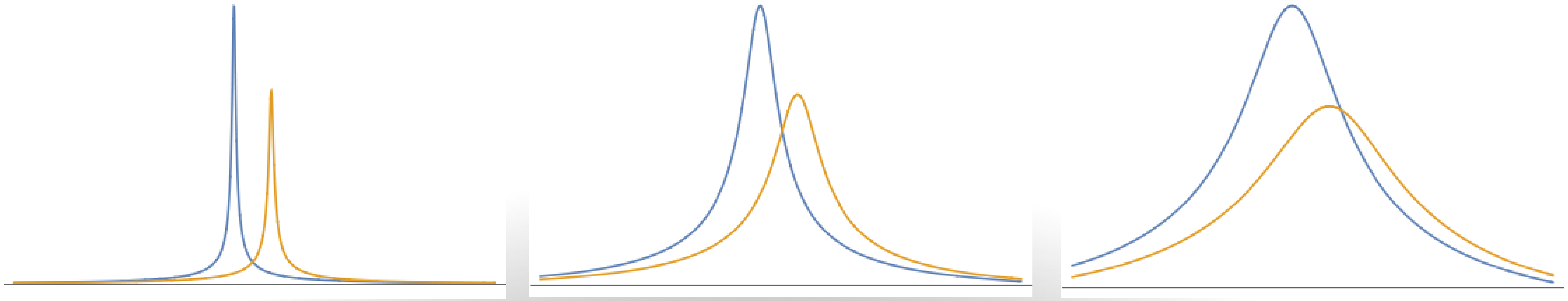


Our method – Interference of resonances

- Two resonances gives strong phase: $Arg\left(\frac{i}{p^2 - m^2 + im\Gamma}\right)$



- Need interference: $Abs\left(\frac{i}{p^2 - m^2 + im\Gamma}\right)$



Our method – use interference of D^{**} mesons

- What are D^{**} mesons?
  - ➔ The lowest energy charm mesons are D and D^*
  - ➔ D^{**} are excited charm mesons

Particle	J^P	$m\ (MeV)$	$\Gamma\ (MeV)$	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	$D^*\pi,\ D\pi$

- Out of four D^{**}, two are narrow and can decay to the same final state

- This two resonances, D_1 and D_2^*, have spin 1 and 2 respectively

Our method – use interference of D^{**} mesons

- What are D^{**} mesons?
  - ➔ The lowest energy charm mesons are D and D^{*}
  - ➔ D^{**} are excited charm mesons

Particle	J^P	$m\ (MeV)$	$\Gamma\ (MeV)$	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	$D^*\pi,\ D\pi$

- Out of four D^{**}, two are narrow and can decay to the same final state
- This two resonances, D_1 and D_2^{*}, have spin 1 and 2 respectively

DA, Y. Grossman, A. Soffer, **arxiv: 1806.04146**

Our method – use interference of D^{**} mesons

- What are D^{**} mesons?
  - ➔ The lowest energy charm mesons are D and D^*
  - ➔ D^{**} are excited charm mesons

Particle	J^P	$m\ (MeV)$	$\Gamma\ (MeV)$	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	$D^*\pi,\ D\pi$

- Out of four D^{**}, two are narrow and can decay to the same final state

- This two resonances, D_1 and D_2^*, have spin 1 and 2 respectively

DA, Y. Grossman, A. Soffer, **arxiv: 1806.04146**

Our method – use interference of D^{**} mesons

- What are D^{**} mesons?
  - ➔ The lowest energy charm mesons are D and D^*
  - ➔ D^{**} are excited charm mesons

Particle	J^P	$m\ (MeV)$	$\Gamma\ (MeV)$	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	$D^*\pi$, $D\pi$

- Out of four D^{**}, two are narrow and can decay to the same final state

- This two resonances, D_1 and D_2^*, have spin 1 and 2 respectively

DA, Y. Grossman, A. Soffer, **arxiv: 1806.04146**

Our method – use interference of D^{**} mesons

- What are D^{**} mesons?
  - ➔ The lowest energy charm mesons are D and D^*
  - ➔ D^{**} are excited charm mesons

Particle	J^P	$m\ (MeV)$	$\Gamma\ (MeV)$	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	$D^*\pi,\ D\pi$

- Out of four D^{**}, two are narrow and can decay to the same final state
- This two resonances, D_1 and D_2^*, have spin 1 and 2 respectively

Simplified model

- $B \to D^{**}$ transitions are calculated to LO in the heavy quark limit

- Introduce a single NP operator at a time:

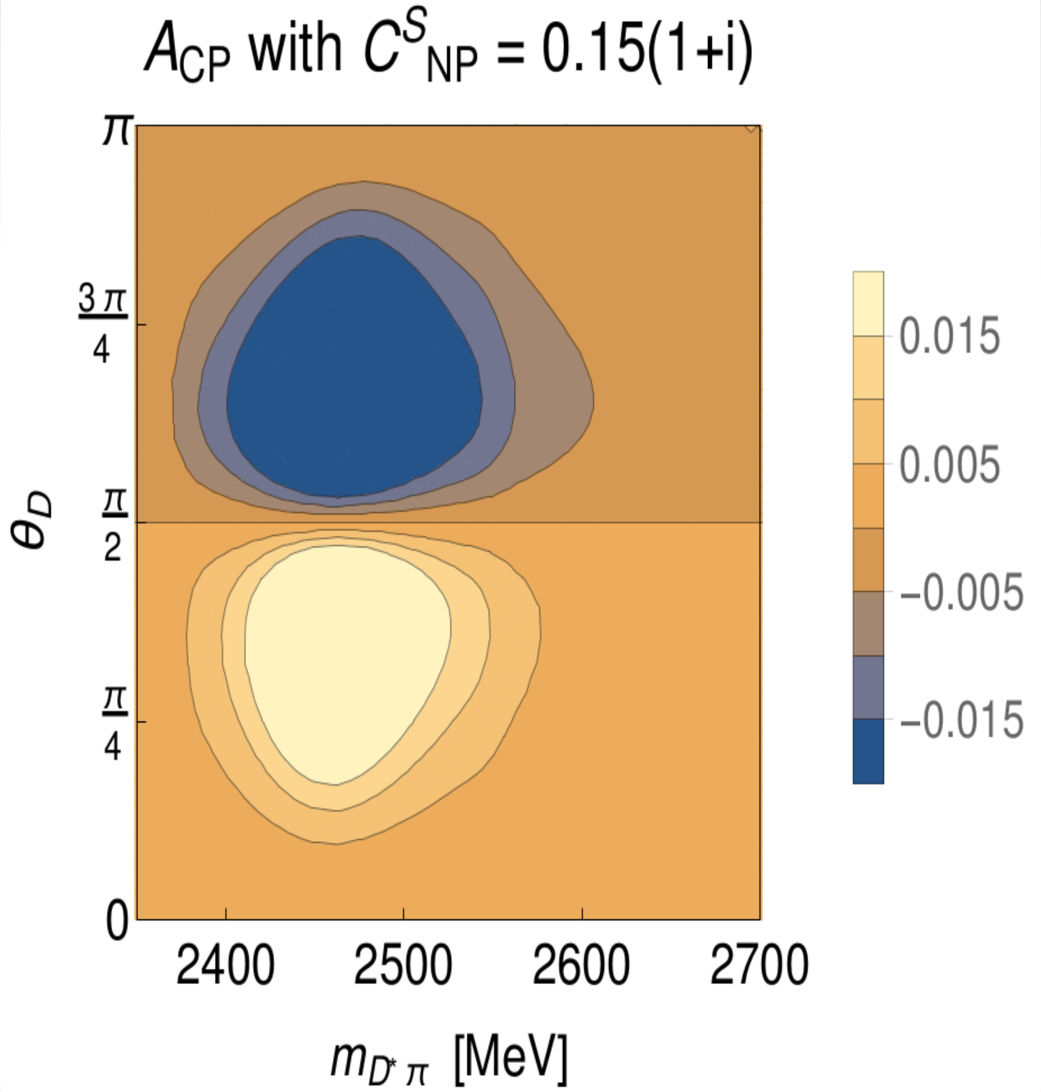
$$O_S = \bar{b}c,\ O_{PS} = \bar{b}\gamma^5 c,\ O_T = \bar{b}\sigma^{\mu\nu}c$$

- Integrate over leponic parameters $q^2,\ \theta_\ell,\ \phi$

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

DA, Y. Grossman, A. Soffer, **arxiv: 1806.04146**

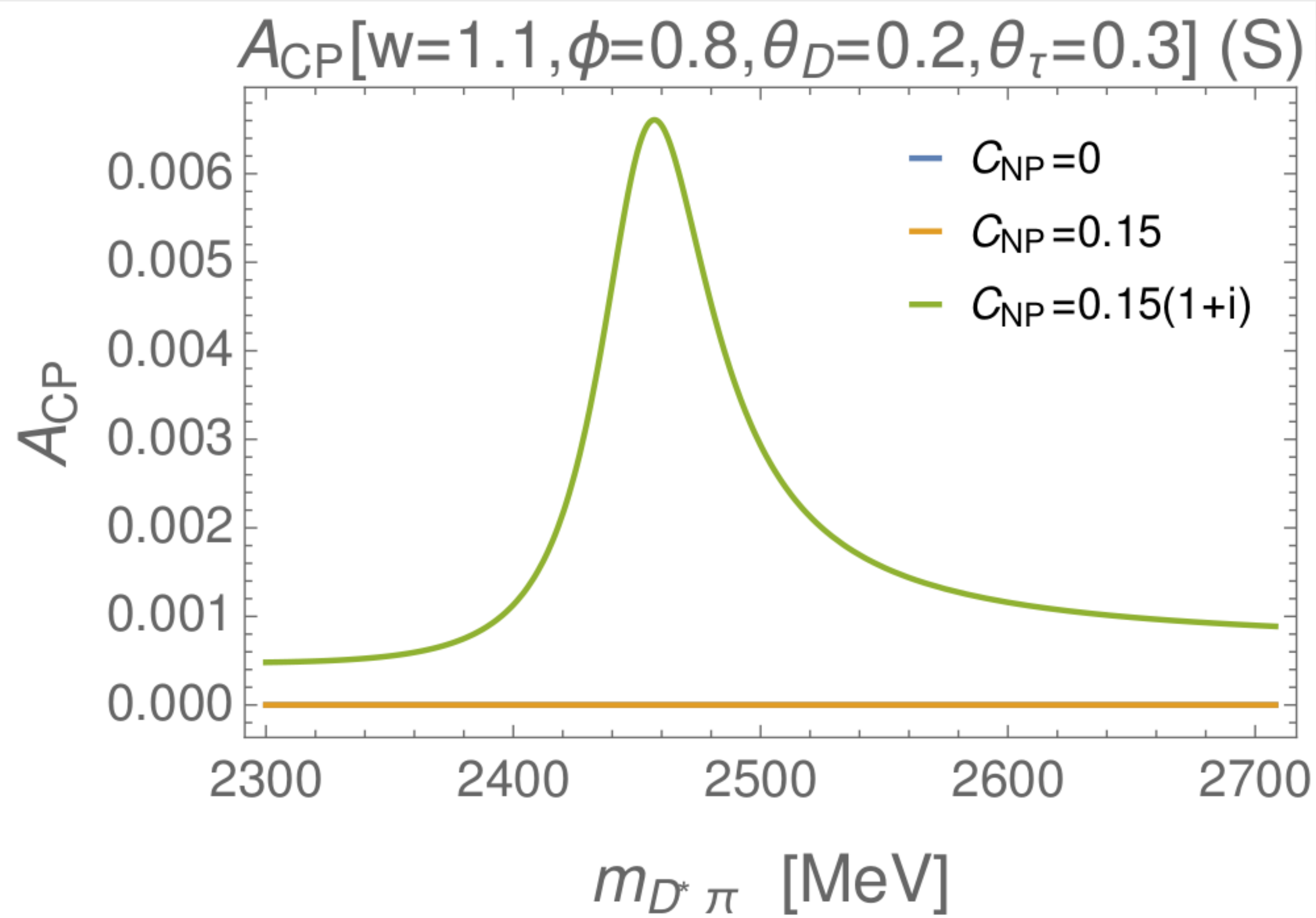
Results



DA, Y. Grossman, A. Soffer, **arxiv: 1806.04146**

Some cross checks

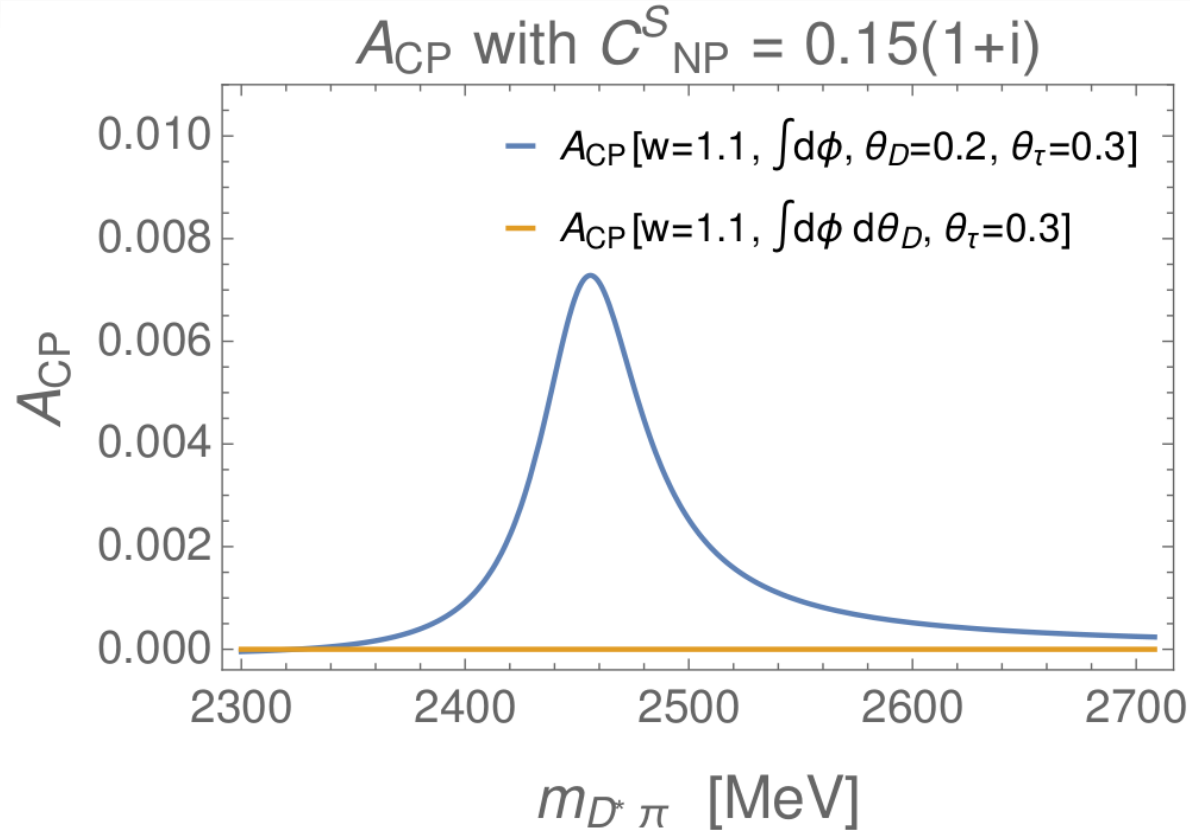
- No asymmetry without weak phase



DA, Y. Grossman, A. Soffer, **arxiv: 1806.04146**

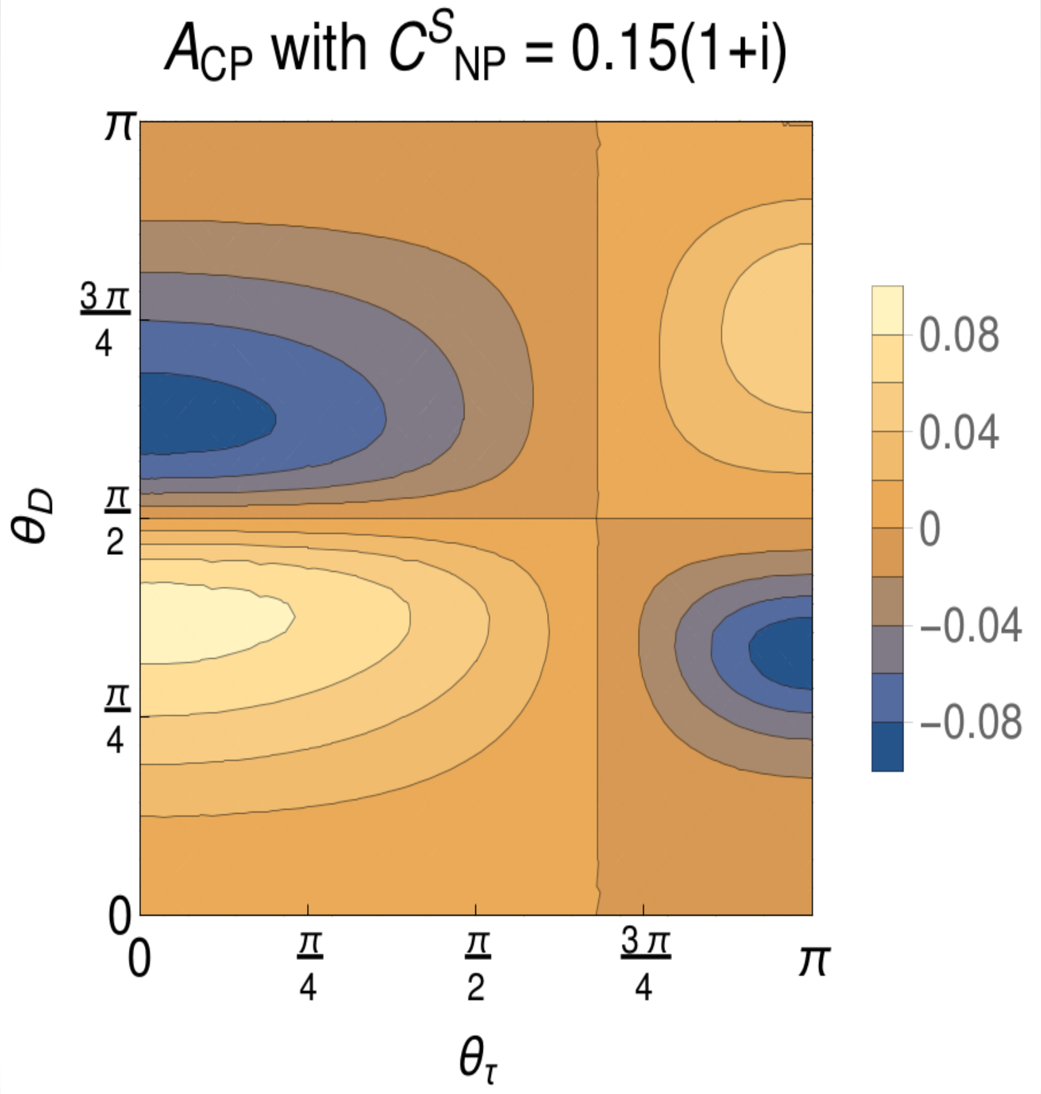
Some cross checks

- Integration over θ_D and ϕ kills the interference between D_1 and D_2^* (since $[\hat{P}, \hat{L}^2] \neq 0$ but $[\hat{P}^2, \hat{L}] = 0$)



DA, Y. Grossman, A. Soffer, **arxiv: 1806.04146**

Can we do better?



Summary

- New observable for CPV in $b \to c\tau\nu$ transitions

- A ~1-10% is found, depending on the observable, and on the strength and CPV phase of NP

- Can be measured at both Belle II and LHCb

Thank you!

Backup

The SM prediction

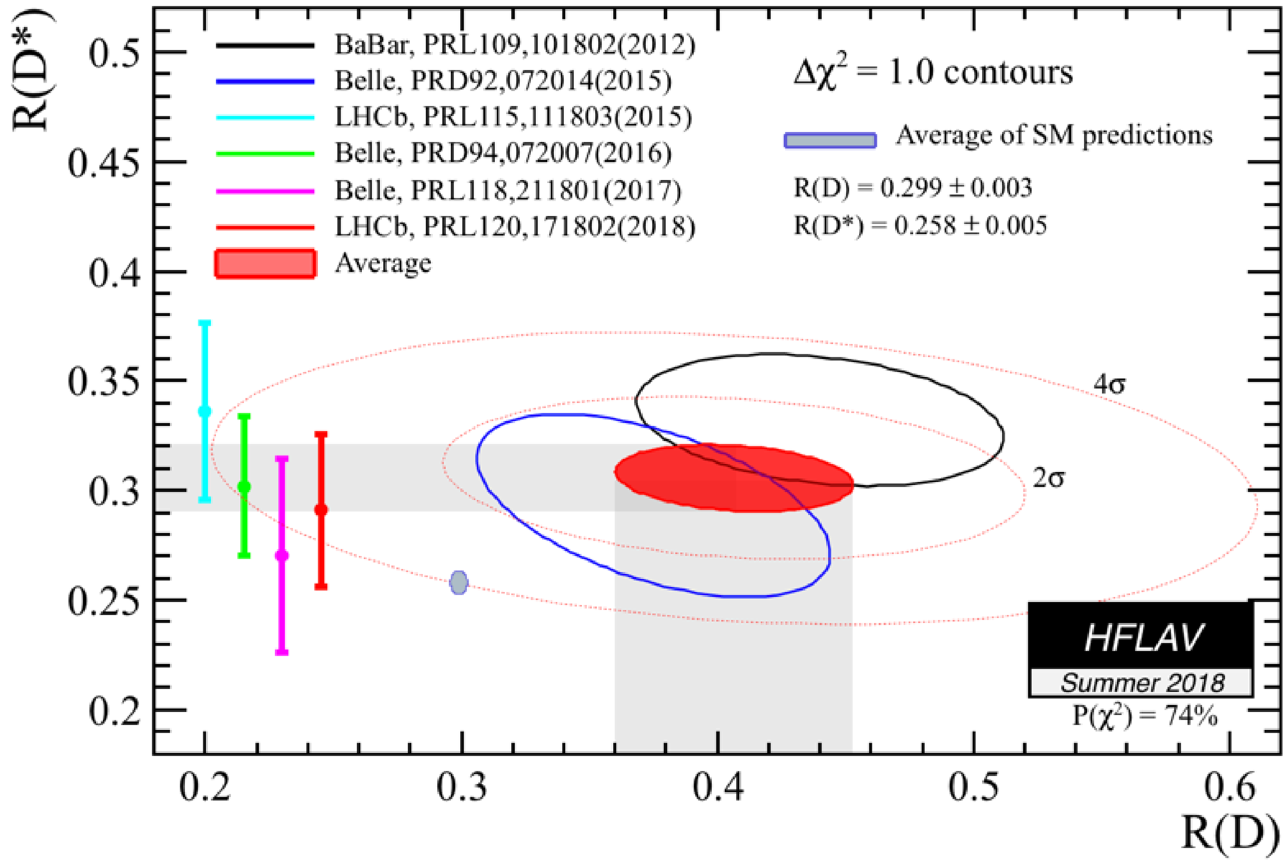
- $R^{SM}(D) = 0.299 \pm 0.003 \ , \ R^{SM}(D^*) = 0.258 \pm 0.005$ *

- How do we know that so well?
  - ➔ Semileptonic
  - ➔ Unknown parameters cancel in the ratio
  - ➔ In the heavy quark limit $m_b, m_c \to \infty$, we have only phase space suppression
  - ➔ In the degenerate lepton masses limit $m_\tau \to m_\ell$, R(D)=R(D*)=1

- We know to expand systematically around this small parameters

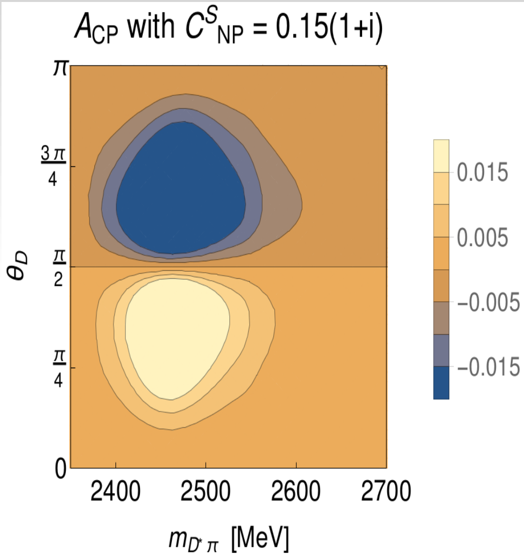
* HFLAV Average

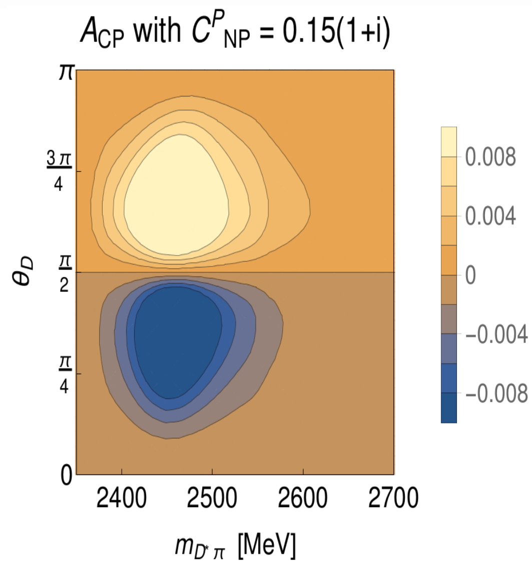
Measurement: pre-Moriond

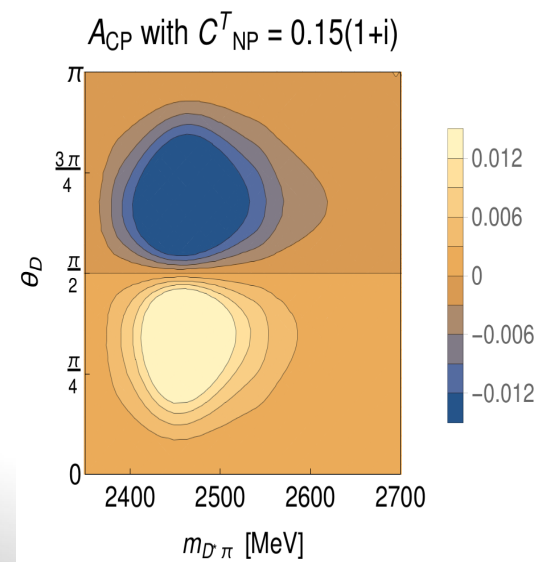


- $\sim 4\sigma$ deviation from SM prediction

Results



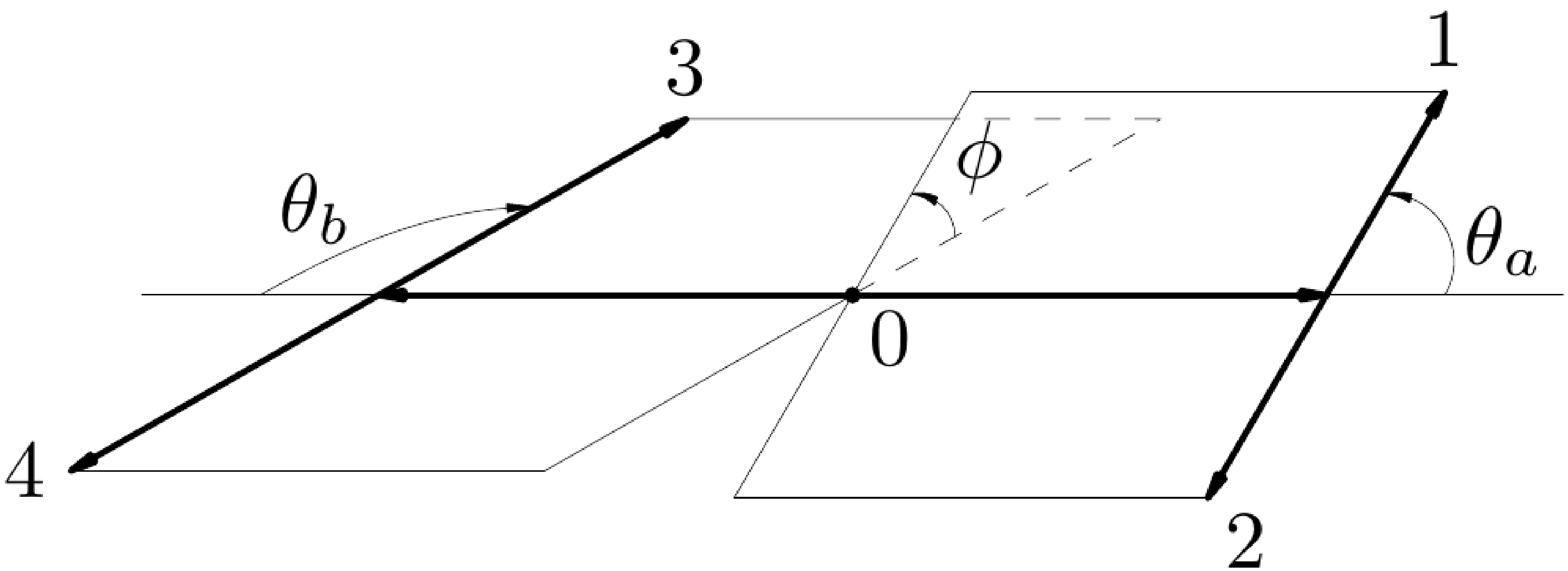




DA, Y. Grossman, A. Soffer, **arxiv: 1806.04146**

Triple product – Four body decay

- Four body decay depends on five kinematical variables
- Two invariant masses, three angles

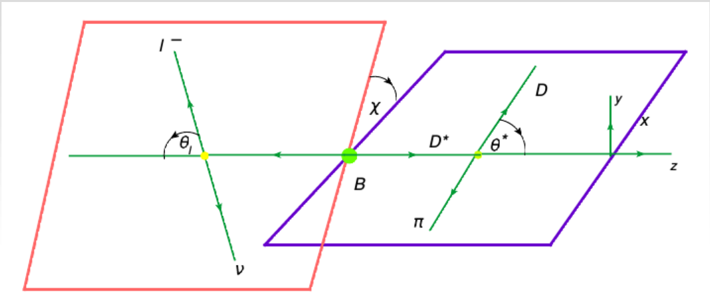


DA, Y. Grossman, A. Soffer, **arxiv: 1806.04146**

Previous ideas for measuring CPV

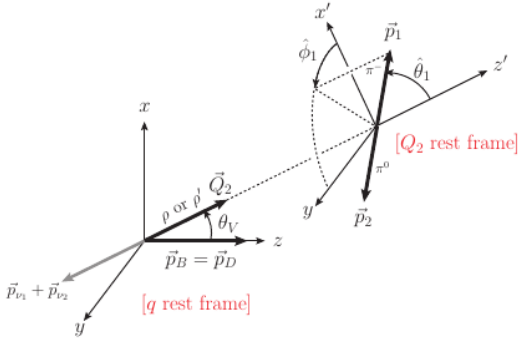
- Duraisamy and Datta (1302.7031)

$$D^*(\to D\pi)\ell^-\nu_\ell$$



- Hagiwara, Nojiri, Sakaki (1403.5892)

$$\overline{B}(p_B) \longrightarrow D(p_D)\tau^-(p_\tau)\overline{\nu_\tau}(p_{\nu_1})$$
$$\hookrightarrow V^-(Q_{2,3})\nu_\tau(p_{\nu_2})$$
$$\hookrightarrow \pi^-(p_1)\pi^0(p_2)$$
$$\pi^+(p_1)\pi^-(p_2)\pi^-(p_3)$$
$$\pi^-(p_1)\pi^0(p_2)\pi^0(p_3)$$



- Requires knowledge of τ angular distribution

- Requires τ hadronic decays

DA, Y. Grossman, A. Soffer, **arxiv: 1806.04146**