Synergy between experiments and theorist's proposals in the quest for NP

(in $b \to c\tau\nu$ transitions)

Daniel Aloni

XIII Meeting on B Physics 03.10.2018

In collaboration with

Arxiv: 1702.07356: Aielet Efrati, Yuval Grossman, Yossi Nir

Arxiv: 1806.04146: Yuval Grossman, Abner Soffer

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Summary of B meson anomalies

Summary of B meson anomalies

$R(D)$

$B_s \to \mu\mu$

$R(K)$

V_{cb}

P_5'

$R(D^*)$

$\Lambda_b \to \Lambda\mu\mu$

$R(K^*)$

$B_s \to \phi\mu\mu$

$B \to K^*\mu\mu$

$R(J/\psi)$

$B \to K\mu\mu$

Summary of B meson anomalies

maybe σ

$R(D)$

$B_s \to \mu\mu$

$R(K)$

3.5σ

V_{cb}

4.1σ

P_5'

$R(D^*)$

$\Lambda_b \to \Lambda\mu\mu$

$(1-3)\sigma$

$R(K^*)$

no σ $B_s \to \phi\mu\mu$

$B \to K^*\mu\mu$

2σish

0.8σ

$R(J/\psi)$

$B \to K\mu\mu$

Summary of B meson anomalies

$R(D)$ maybe σ $B_s \to \mu\mu$ $R(K)$

$$R(D^{(*)})$$

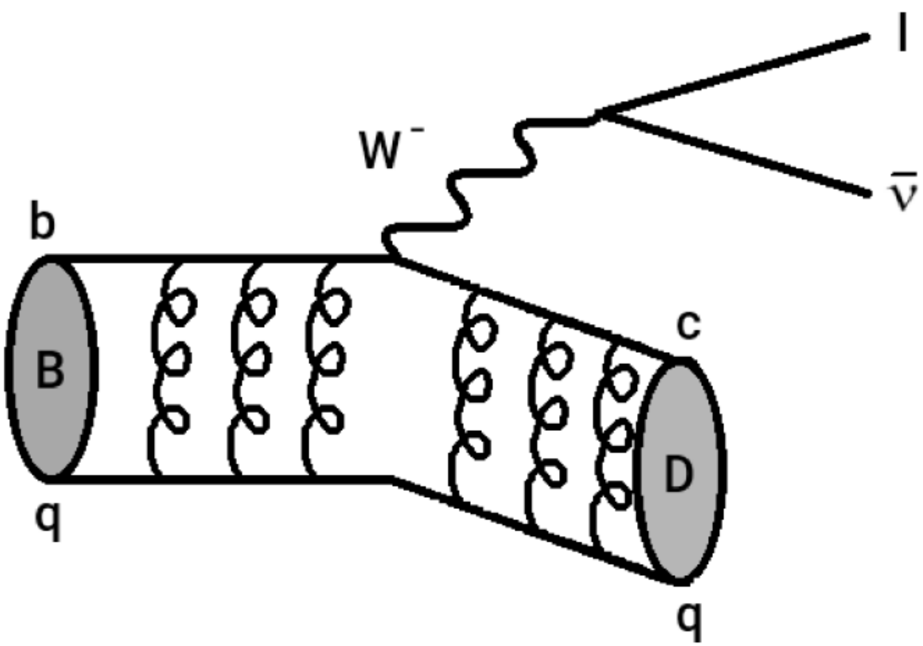
0.8σ

$B \to K\mu\mu$

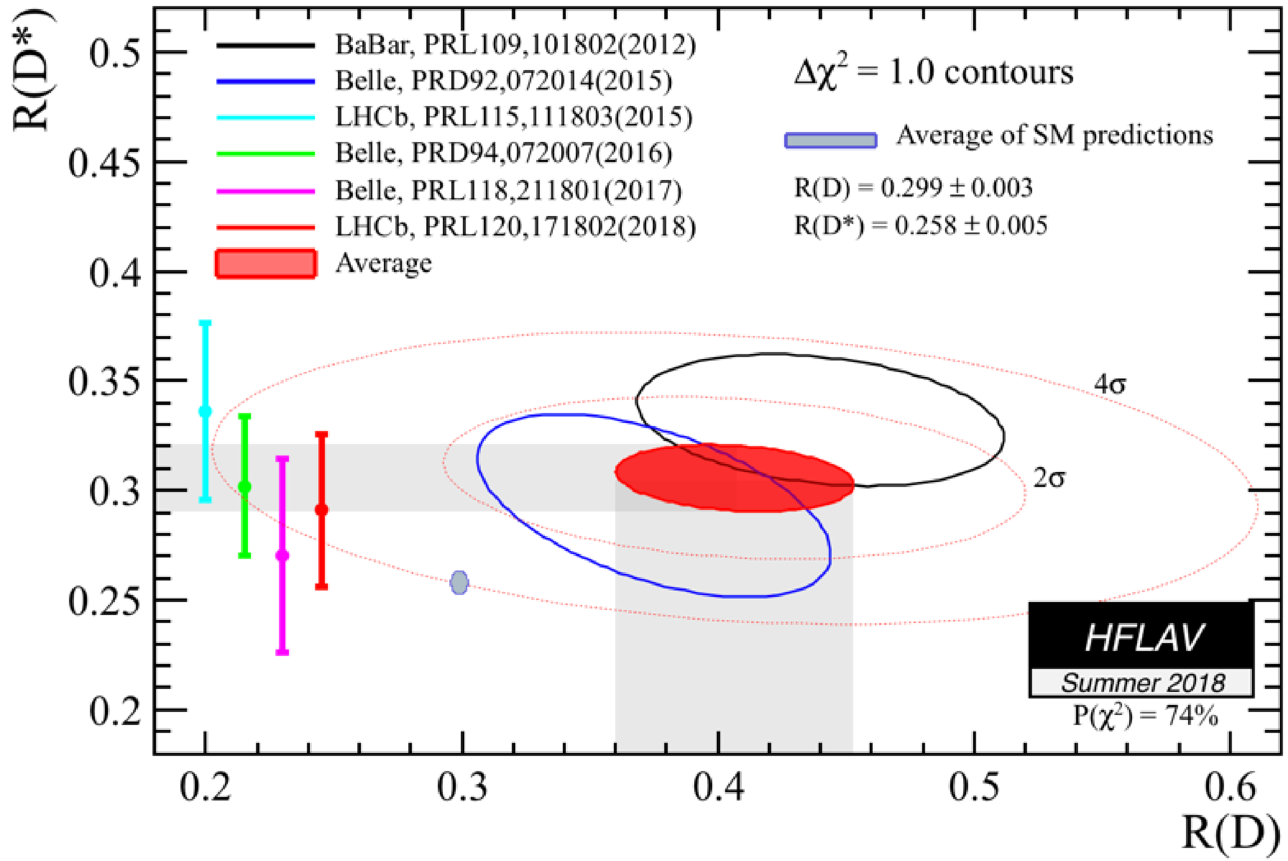
$R(J/\psi)$ 2σish

What is $R(D^{(*)})$?

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

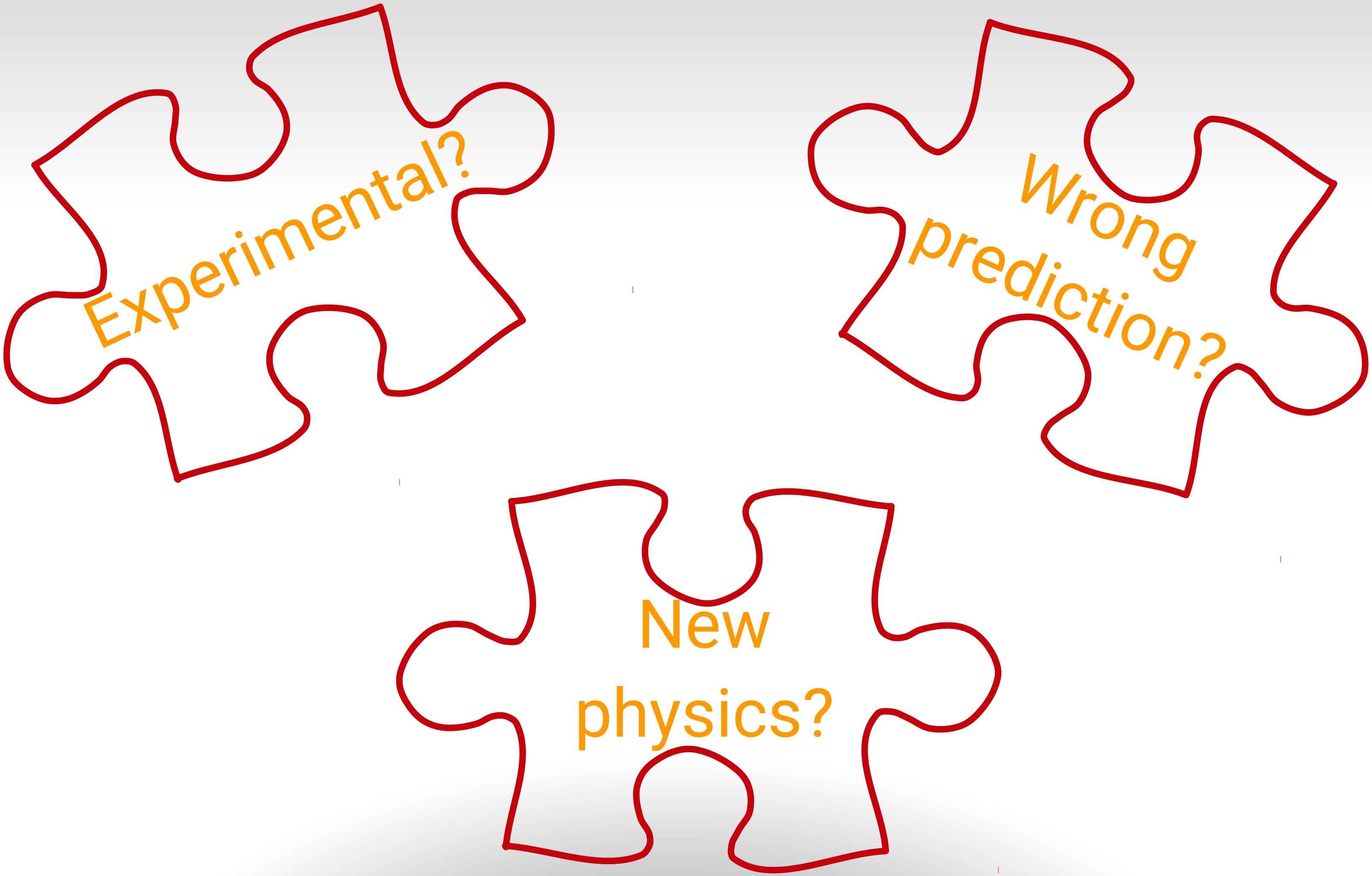


Measurement



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

This is puzzling



What can we do about it?

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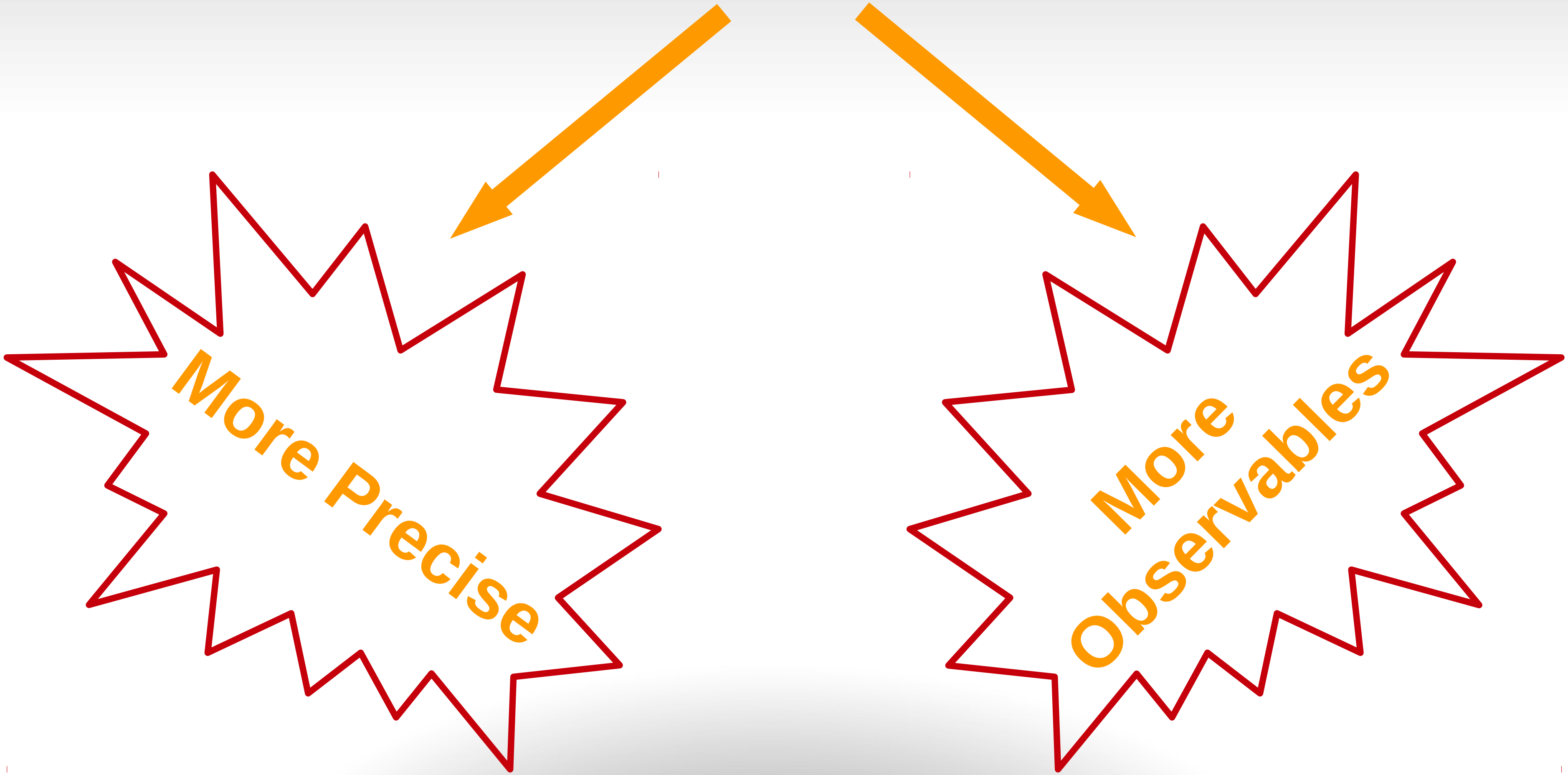

Great time for...

Great time for...

Synergy between
experimentalists and theorists

Outline

- Few words about $R(D^{(*)})$
- Υ and ψ decays as probes of solutions to the $R(D^{(*)})$ puzzle (1702.07356)
- Measuring the CP violation in $b \to c\tau\nu$ using excited charm mesons (1806.04146)

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
  - $(\bar{e}L)(\bar{u}Q)$
  - $(\bar{e}\sigma^{\mu\nu}L)(\bar{u}\sigma_{\mu\nu}Q)$
  - $(\bar{L}\gamma^{\mu}\tau_a L)(\bar{Q}\gamma^{\mu}\tau_a Q)$
  - $(\bar{Q}d)(\bar{e}L)$

Υ and ψ decays as probes of solutions to the $R(D^{(*)})$ puzzle

DA, Aielet Efrati (WIS), Yuval Grossman (Cornell), Yossi Nir (WIS)

JHEP 1706 (2017) 019, Arxiv: 1702.07356

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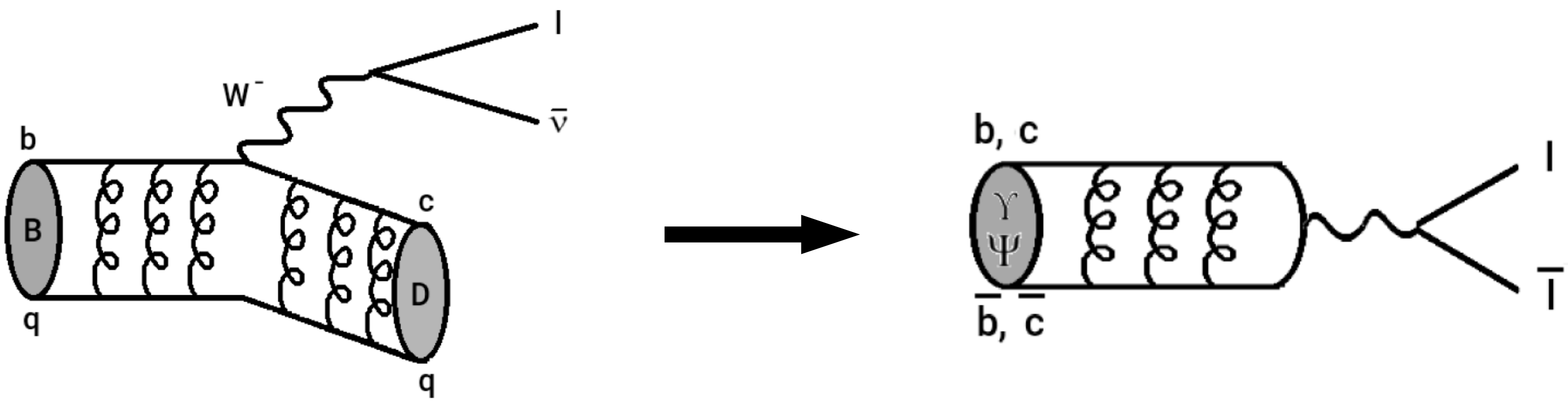

Charge current (CC) — Neutral current (NC)

ν is part of a doublet → if we have ν we have τ

DA, A. Efrati, Y. Grossman, Y. Nir, **arxiv: 1702.07356**

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DA, A. Efrati, Y. Grossman, Y. Nir, **arxiv: 1702.07356**

EFT – unavoidable NC

- All four operators contain also neutral currents (NC)
  - ➔ For instance

$$(\bar{e}L)(\bar{u}Q) = \overbrace{(\bar{e}_R \nu_L)(\bar{u}_R d_L)}^{CC} - \overbrace{(\bar{e}_R e_L)(\bar{u}_R u_L)}^{NC}$$

- We looked for observables sensitive to those NC

- Neutral currents unavoidably modify $b\bar{b}$ and/or $c\bar{c} \to \tau\bar{\tau}$

DA, A. Efrati, Y. Grossman, Y. Nir, **arxiv: 1702.07356**

EFT – NC observables

- *D. A. Faroughy, A. Greljo, J. F. Kamenik* * – High P_T distribution of $\tau\bar{\tau}$ signature at the LHC

- We looked on lepton non universality of Υ and ψ decays

$$R^V_{\tau/\ell} \equiv \frac{\Gamma(V \to \tau^+\tau^-)}{\Gamma(V \to \ell^+\ell^-)}, \quad (V = \Upsilon, \psi(2s);\ \ell = e, \mu)$$

  - $\Upsilon = b\bar{b}$ bound state
  - $\psi = c\bar{c}$ bound state

* *D. A. Fraoughy, A. Greljo, J. F. Kamenik,* ***Phys. Lett. B764 (2017) 126-134***

Vector meson decay - SM

- Within the SM

$$R^V_{\tau/\ell} \simeq \left[1 + \frac{2m_\tau^2}{m_V^2}\right]\left[1 - \frac{4m_\tau^2}{m_V^2}\right]^{1/2} = 1 - \mathcal{O}\left(\frac{m_\tau^4}{m_V^4}\right)$$

where $V = \Upsilon,\ \psi$

- Dominantly QED – 1 photon mediated

DA, A. Efrati, Y. Grossman, Y. Nir, **arxiv: 1702.07356**

$R^V_{\tau/\ell}$ - Prediction vs. measurement

$R^V_{\tau/\ell}$:

$V(nS)$	SM prediction	Exp. value $\pm\sigma_{\text{stat}} \pm \sigma_{\text{syst}}$
$\Upsilon(1S)$	$0.9924 \pm \mathcal{O}(10^{-5})$	$1.005 \pm 0.013 \pm 0.022$
$\Upsilon(2S)$	$0.9940 \pm \mathcal{O}(10^{-5})$	$1.04 \pm 0.04 \pm 0.05$
$\Upsilon(3S)$	$0.9948 \pm \mathcal{O}(10^{-5})$	$1.05 \pm 0.08 \pm 0.05$
$\psi(2S)$	$0.390 \pm \mathcal{O}(10^{-4})$	0.39 ± 0.05

DA, A. Efrati, Y. Grossman, Y. Nir, **arxiv: 1702.07356**

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$m_{\Upsilon(4S)} > 2m_B \quad \Rightarrow \Upsilon(1S),\ \Upsilon(2S),\ \Upsilon(3S)$

$m_{\psi(1S)} < 2m_\tau$

$m_{\psi(3S)} > 2m_D \quad \Rightarrow \psi(2S)$

DA, A. Efrati, Y. Grossman, Y. Nir, **arxiv: 1702.07356**

The need for assumptions

- There are four independent CC operators
- There are eight independent NC operators
- CC + Gauge invariance → NC

➔ Not enough measurements to fix the values of the Wilson coefficients of the four CC operators

➔ No information on the other four NC operators

DA, A. Efrati, Y. Grossman, Y. Nir, **arxiv: 1702.07356**

EFT from simplified models

- Recall that
  - Within the SM $b \to c\tau\bar{\nu}$ is a tree-level process
  - Central value is ~ 30% enhanced compared to prediction

- Huge enhancement of tree-level suggests new bosons which also modify $b \to c\tau\bar{\nu}$ at tree-level

- There are eight different possible mediators
  $W'_\mu \sim (1,3)_0, U_\mu \sim (3,1)_{2/3}, X_\mu \sim (3,3)_{2/3}, S \sim (3,1)_{-1/3},$
  $T \sim (3,3)_{-1/3}, \phi \sim (1,2)_{1,2}, D \sim (3,2)_{7/6}, V_\mu \sim (3,2)_{-5/6}$

- Each boson breaks LFU in Υ and/or ψ decays in a different way

Results

UV field content	$R_{\tau/\ell}^{\Upsilon(1S)}$	$R_{\tau/\ell}^{\psi(2S)}$	Predicted modification to $R_{\tau/\ell}^{\Upsilon(1S)}$
$W'_\mu \sim (1,3)_0$	0.989-0.991	0.390	Decrease by $0.2\% - 0.4\%$
$U_\mu \sim (3,1)_{+2/3}$	0.952-0.990	SM	Decrease by $0.3\% - 4.0\%$
$S \sim (3,1)_{-1/3}$	SM	0.389-0.390	–
$V_\mu \sim (3,2)_{-5/6}$	0.976-0.987	SM	Decrease by $0.5\% - 1.6\%$
SM	0.992	0.390	
Current measurement	1.005 ± 0.025	0.39 ± 0.05	
Achievable uncertainty (with current data)	± 0.01	± 0.02	
Projected uncertainty ($\mathcal{L}^{\Upsilon(3S)} = 1/\text{ab}$ in Belle II)	± 0.004	–	

- $R_{\tau/\ell}^{\Upsilon(1S)}$ is starting to probe relevant models

DA, A. Efrati, Y. Grossman, Y. Nir, **arxiv: 1702.07356**

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One thing to do

- Current error is $\sigma_{1S}^{BaBar} \sim 2\%$
- Running at $\Upsilon(3S)$ with $\mathcal{L} \sim 1/ab$ Belle II might reach $\sigma_{1S} \simeq 0.4\%$
- Cover most region of parameter space related to $R(D^{(*)})$
- LFU in Υ decays provide additional motivation to study $\Upsilon(3S)$ at Belle II
- Test the SM and Probe NP even if $R(D^{(*)})$ disappears

DA, A. Efrati, Y. Grossman, Y. Nir, **arxiv: 1702.07356**

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

DA, Yuval Grossman (Cornell), Abner Soffer (TAU)

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

EFT – complete basis

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- A complete set for $b \to c\tau\bar{\nu}$ transitions:
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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

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

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

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- Checklist:

➔ Two amplitudes ✓

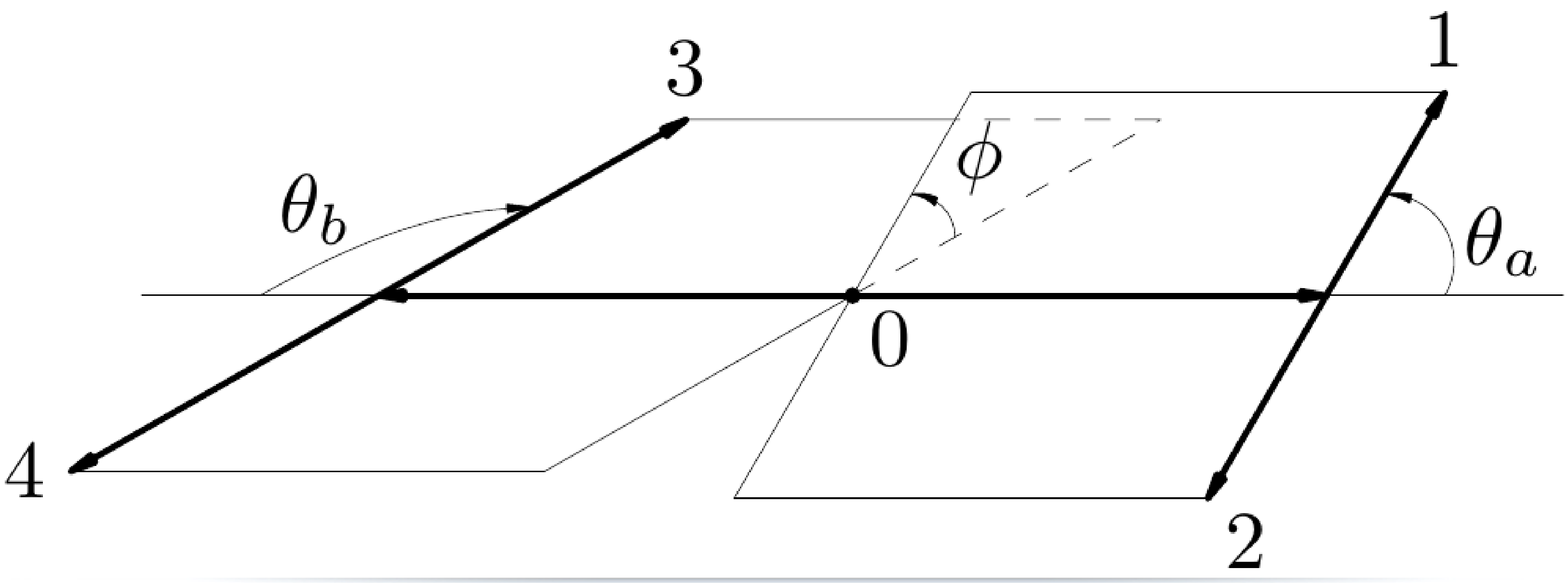
➔ Weak phase ✓

➔ Strong phase ✗

Triple product **Our method**

Triple product – Four body decay

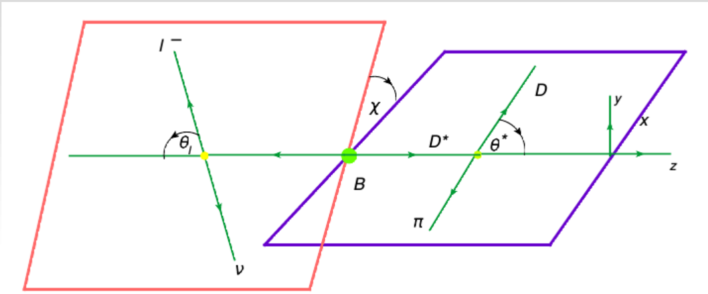
- Four body decay depends on five kinematical variables
- Two invariant masses, three angles



Previous ideas for measuring CPV

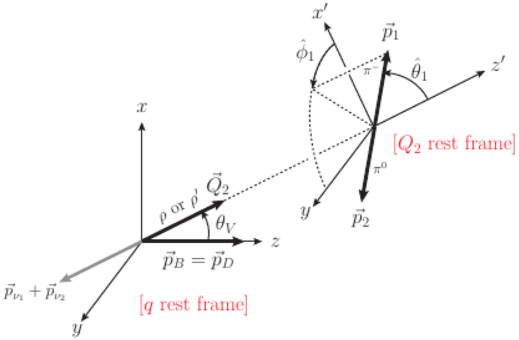
- Duraisamy and Datta (1302.7031)

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



- Hagiwara, Nojiri, Sakaki (1403.5892)

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

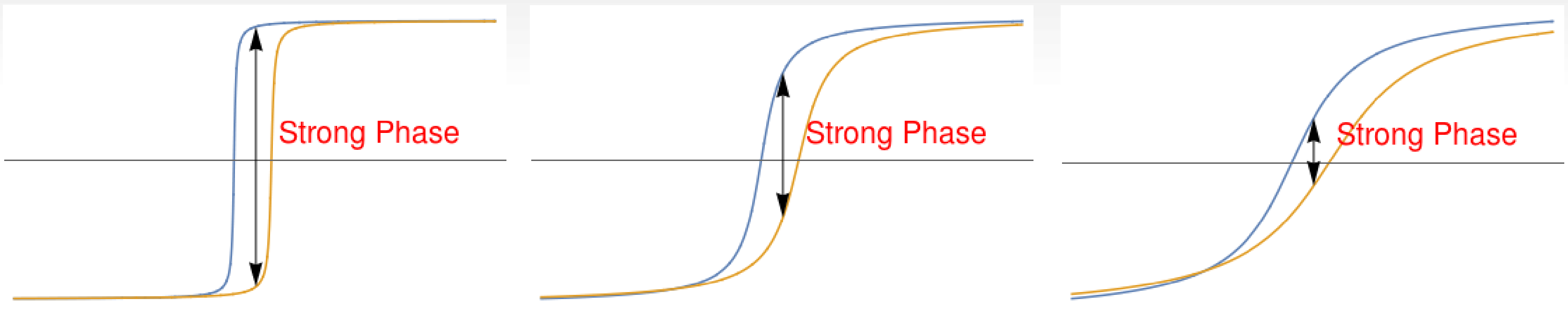


- Requires knowledge of τ angular distribution

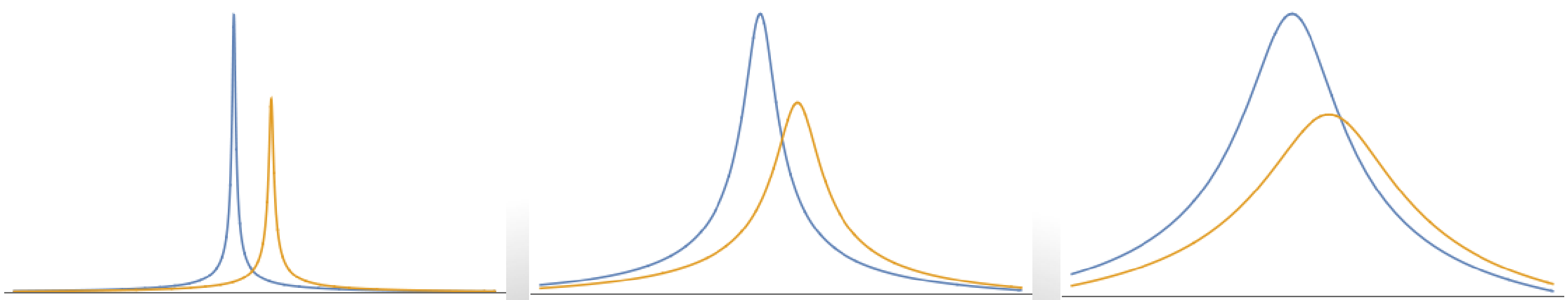
- Requires τ hadronic decays

Our method – Interference of resonances

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



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



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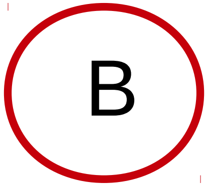

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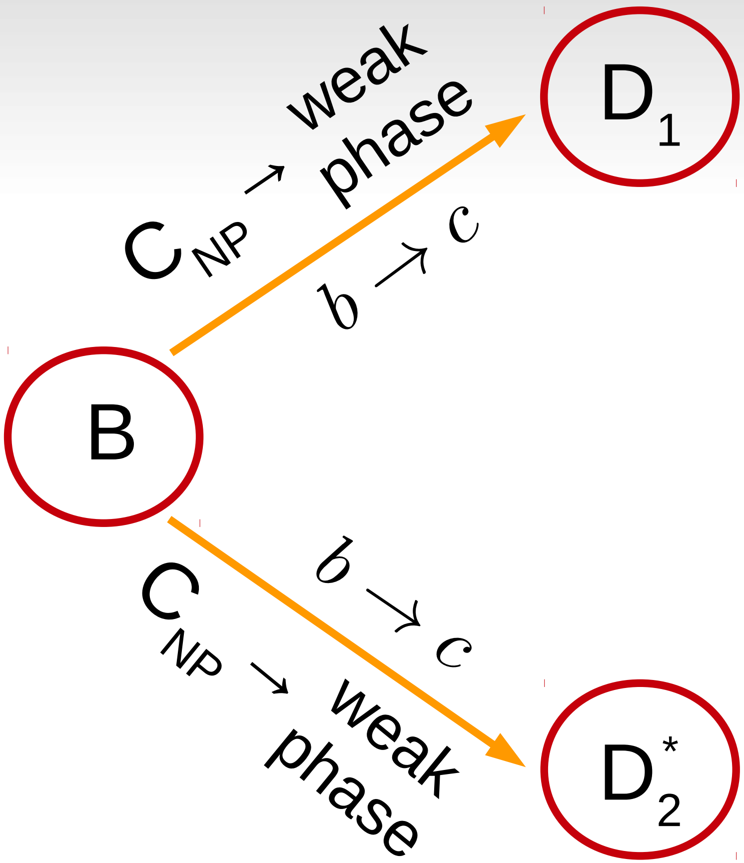

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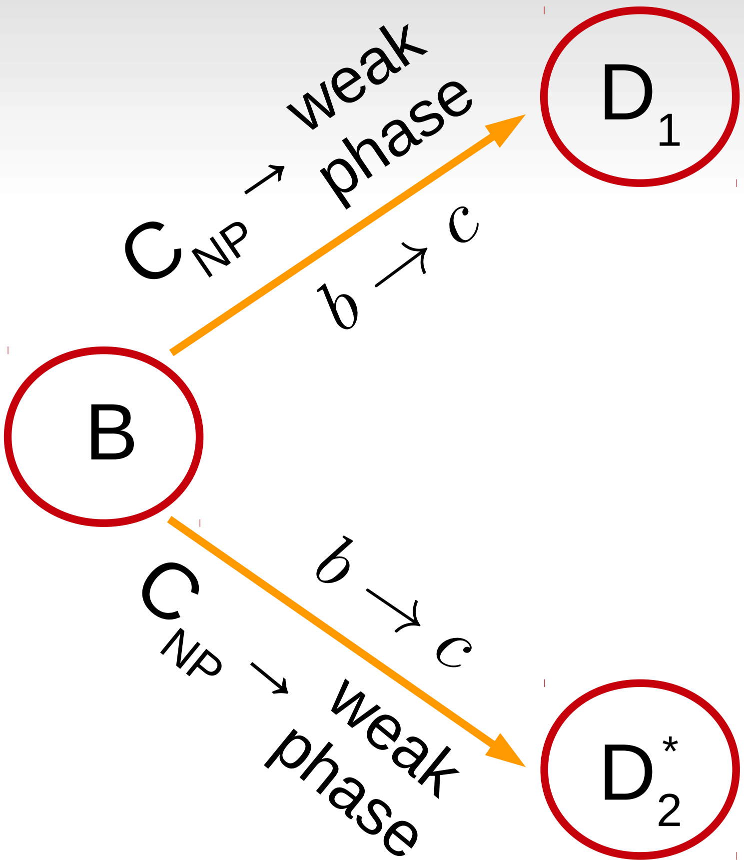

$$\frac{i}{m^2_{D^*\pi} - m^2_{D_1} + i m_{D_1}\Gamma_{D_1}} \rightarrow$$ strong phase

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

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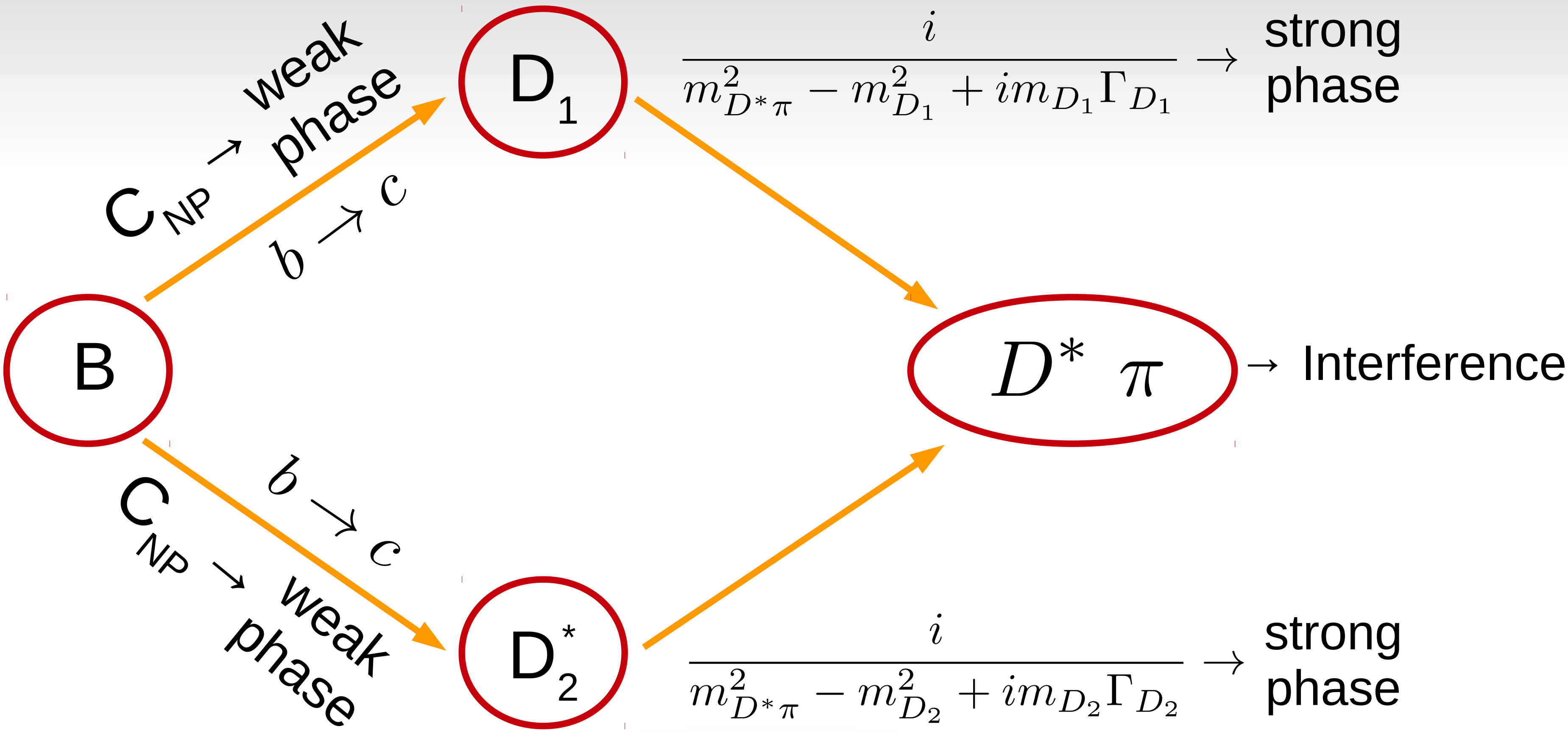

Our method – use interference of D^{**} mesons

- 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**

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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**

Simplified model

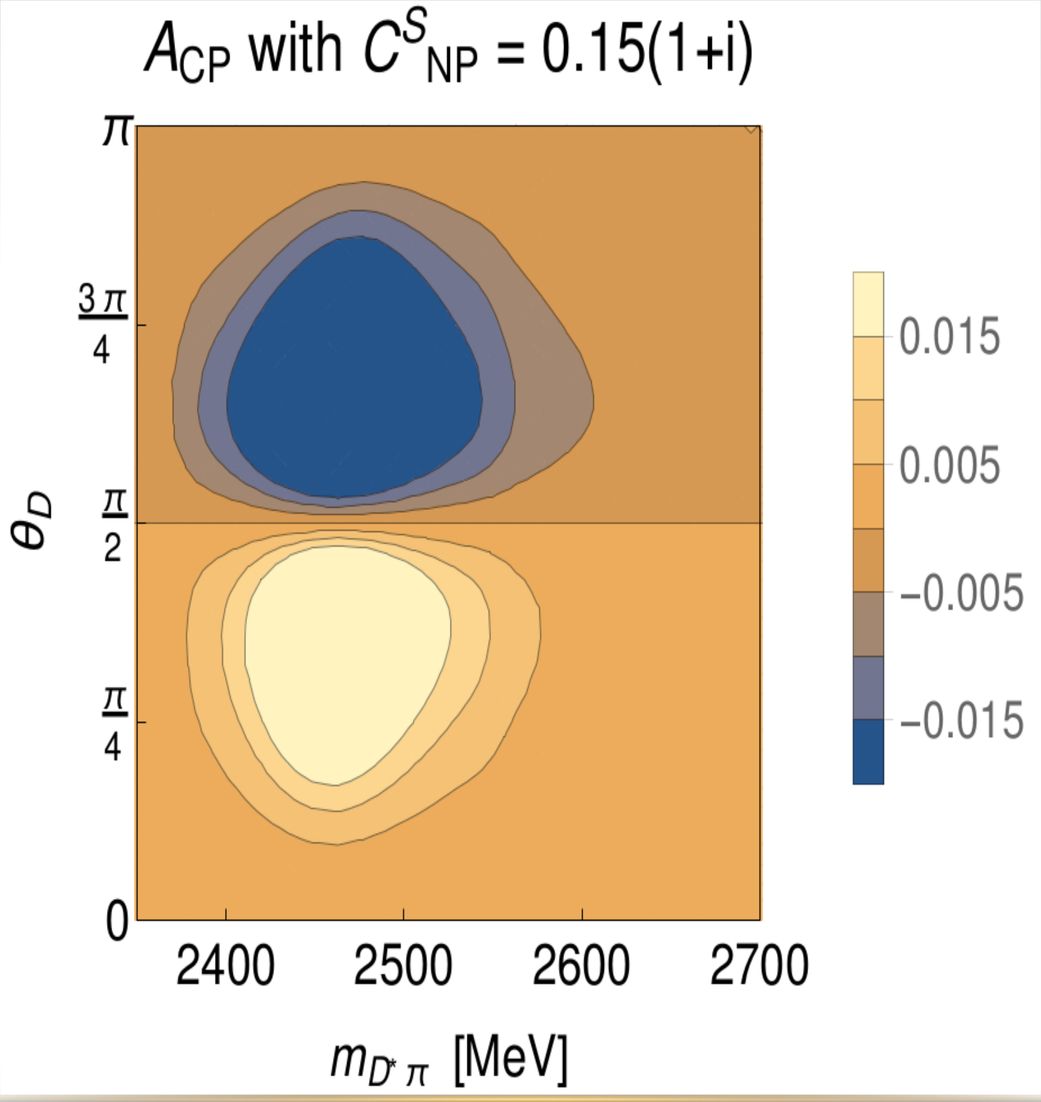
- $B \to D^{**}$ transitions are calculated to LO in the heavy quark limit

- Introduce a single NP operator at a time:

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

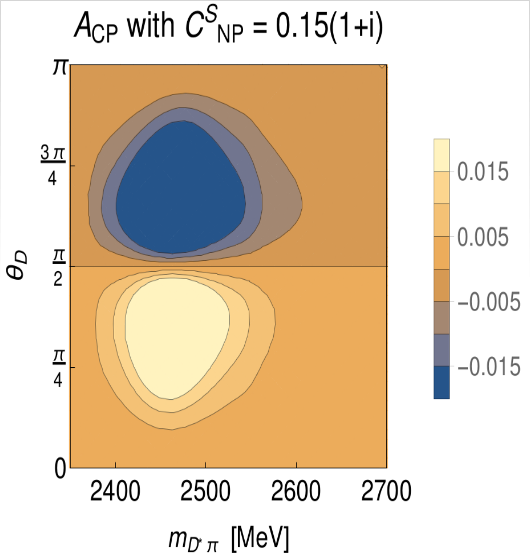
- Integrate over leponic parameters $q^2,\ \theta_\ell,\ \phi$

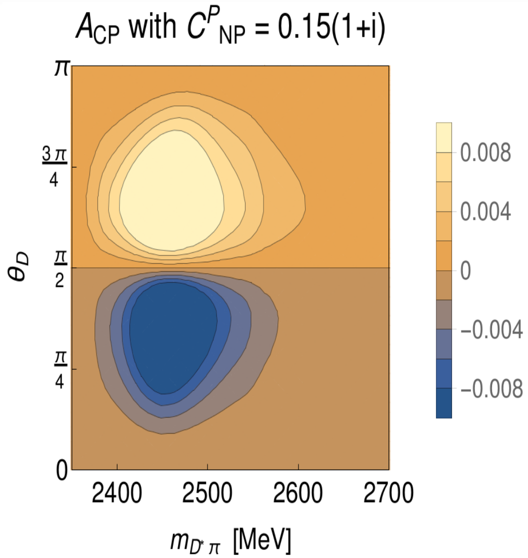
Results

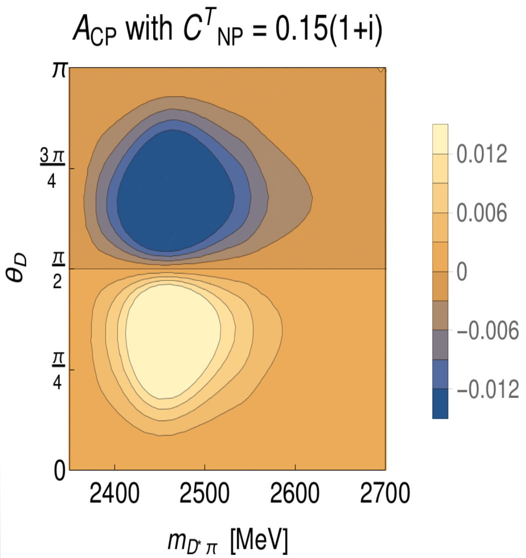


DA, Y. Grossman, A. Soffer, **arxiv: 1806.04146**

Results



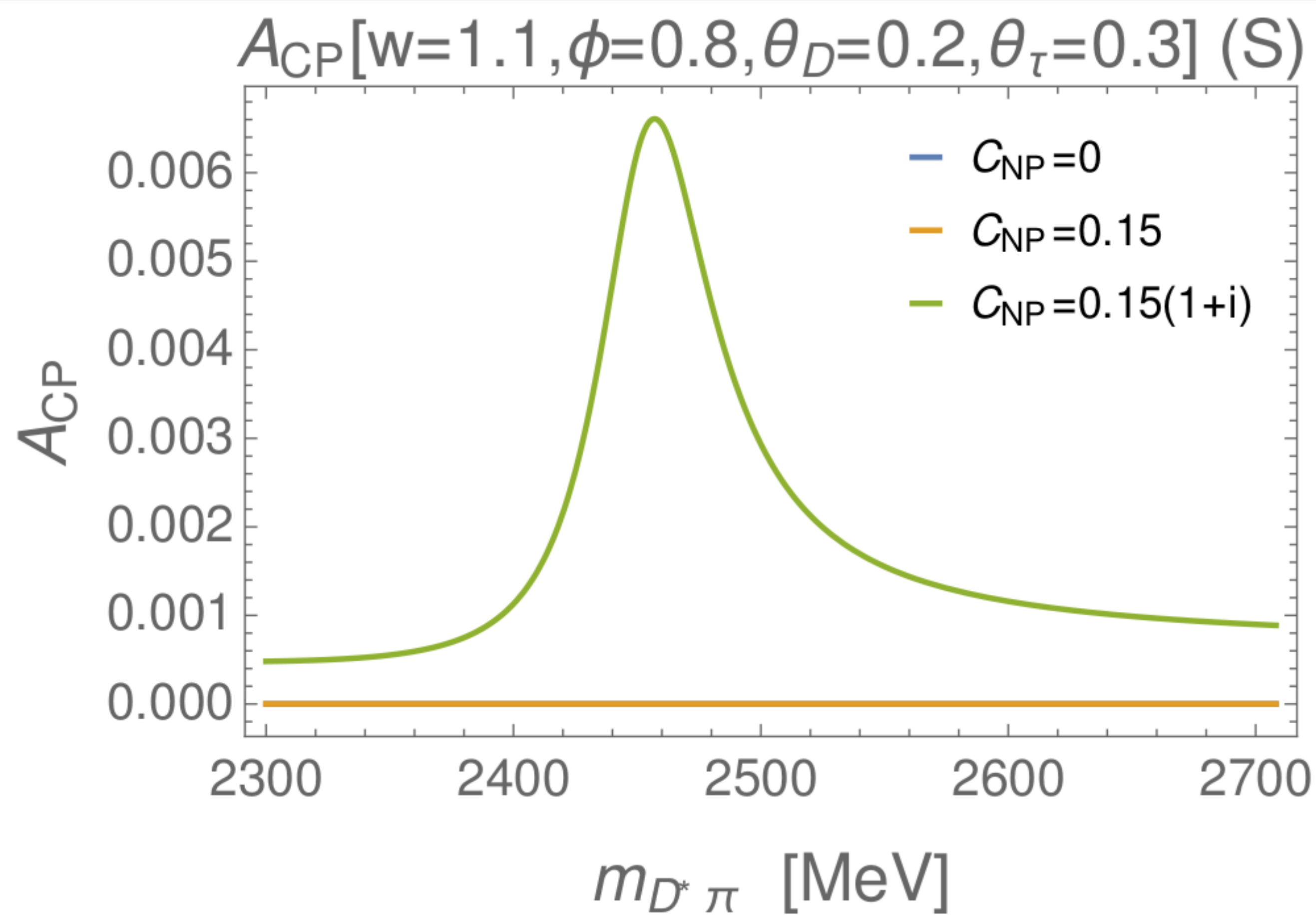




DA, Y. Grossman, A. Soffer, **arxiv: 1806.04146**

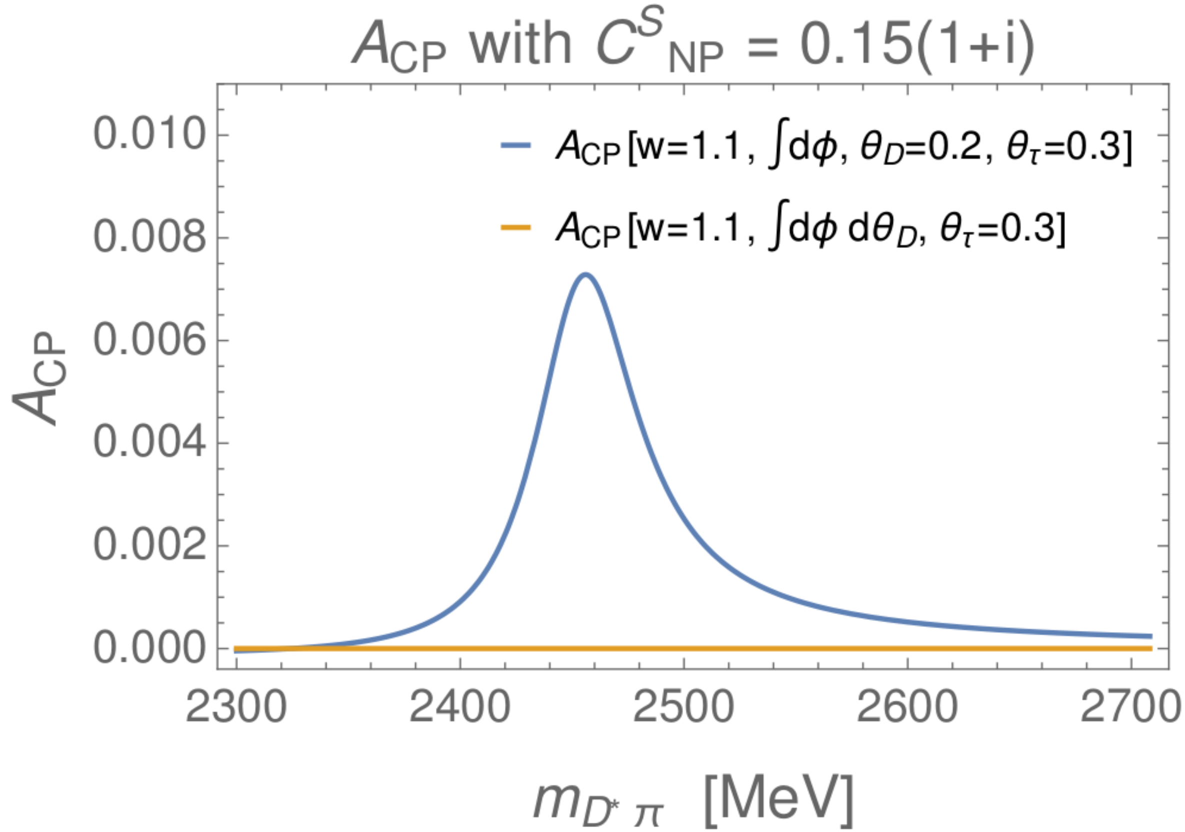
Some cross checks

- No asymmetry without weak phase



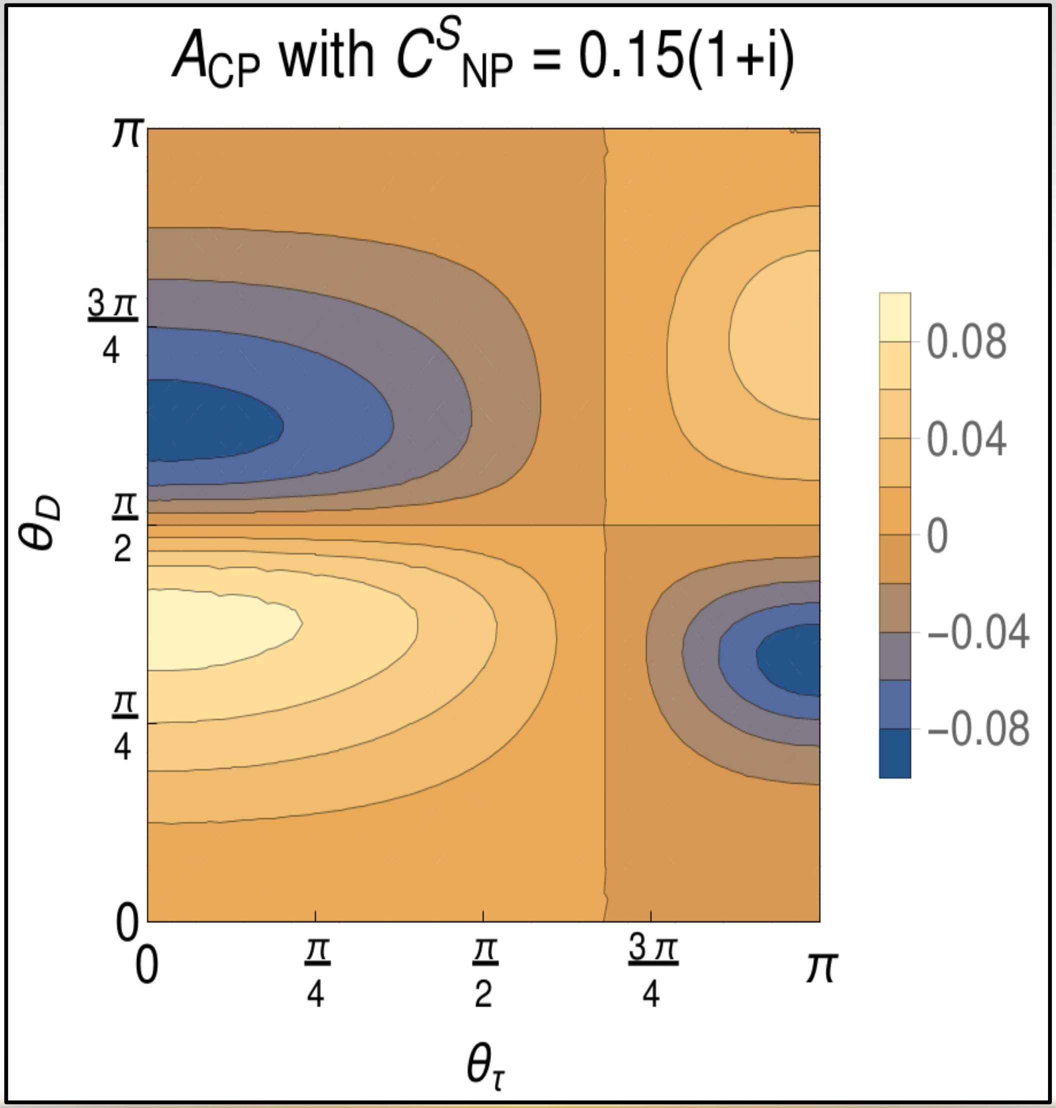
Some cross checks

- 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?



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

Summary of 1806.04146

- New observavble 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

Two things we can do

- $R(D^{(*)})$ is puzzling

- Belle2 and LHCb can tell us much more by measuring
  - ➔ LFU in Υ decays
  - ➔ CPV by using $B \to D^{**}\tau\bar{\nu}$

Thank you!