$b \to c\tau\nu_\tau$ Decays : A Catalogue to Compare, Constrain, and Correlate New Physics

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Direct and Indirect Search

- New physics search can follow one of two tracks :
  - Direct detection of new particles at the collider
  - Indirect probes for new physics from precision measurements
- No direct evidence for physics beyond SM by LHC.
- Indirect hints for new physics (NP) in the flavour sector.
- NP can show up as a deviation of the experimental data from SM prediction.

$\mathcal{R}(D), \mathcal{R}(D^*)$: Experimental Status

- Observables with less theoretical uncertainty :

$$\mathcal{R}(D) = \frac{\mathcal{B}(\overline{B} \to D\tau\nu_\tau)}{\mathcal{B}(\overline{B} \to D\ell\nu_\ell)}$$

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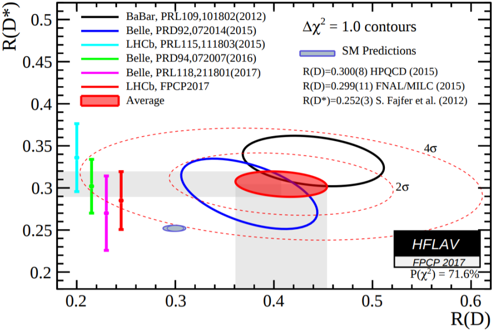
Stefania Vecchi's talk today morning



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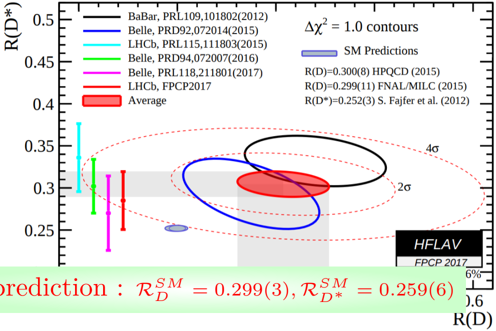

SM prediction : $\mathcal{R}_D^{SM} = 0.299(3), \mathcal{R}_{D^*}^{SM} = 0.259(6)$

S. Jaiswal, S. Nandi, and S. K. Patra, JHEP 12, 060(2017).

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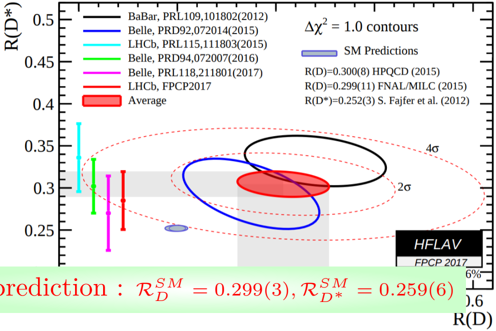

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- For both $\mathcal{R}(D)$, $\mathcal{R}(D^*)$: Deviations 4.1σ (Global) and 3.5σ ($\mathcal{R}(D^*)$).

More Observables...

- Present experimental status of these observables with their correlation:

	$\mathcal{R}_D$	$\mathcal{R}_{D^*}$	$\rightarrow$ Correlation	$P_\tau(D^*)$	$\mathcal{R}_{J/\Psi}$
BaBar	0.440(58)(42)	0.332(24)(18)	-0.27	-	-
Belle (2015)	0.375(64)(26)	0.293(38)(15)	-0.49	-	-
Belle (2016)	-	0.302(30)(11)	-	-	-
Belle (2016)	-	0.270(35)(37)	0.33	$-0.38(51)(26)$	-
LHCb (2015)	-	0.336(27)(30)	-	-	-
LHCb (2017)	-	0.286(19)(25)	-	-	-
LHCb (2017)	-	-	-	-	0.71(17)(18)

- $$P_\tau(D^{(*)}) = \frac{\Gamma^{(*)\lambda_\tau=1/2} - \Gamma^{(*)\lambda_\tau=-1/2}}{\Gamma^{(*)\lambda_\tau=1/2} + \Gamma^{(*)\lambda_\tau=-1/2}} \, ,$$

- $$\mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c \rightarrow J/\psi\tau\nu_\tau)}{\mathcal{B}(B \rightarrow J/\psi\ell\nu_\ell)}$$

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- $P_\tau(D^*)$: Large uncertainty, Consistent with SM

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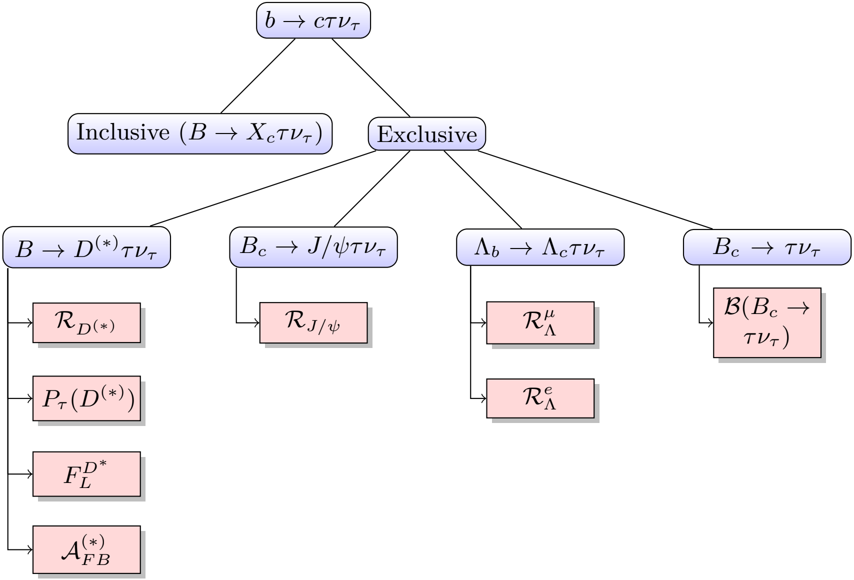
$\mathcal{R}_{J/\Psi}$: Large uncertainty, 2σ above SM prediction.

More Channels... More Observables...



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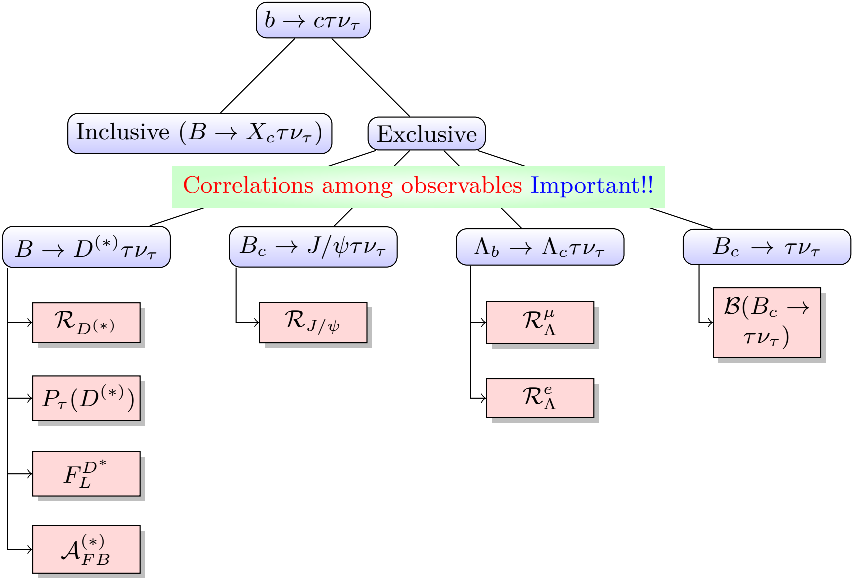

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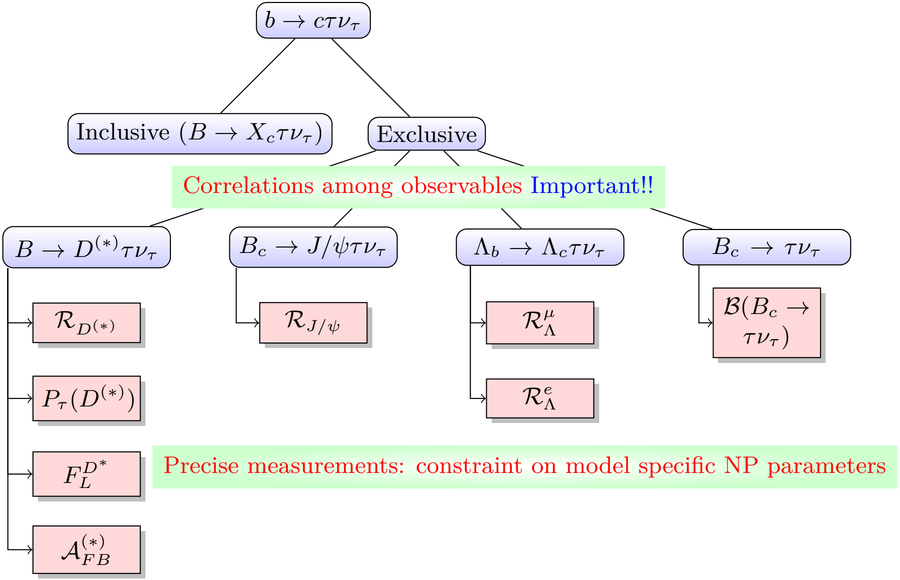

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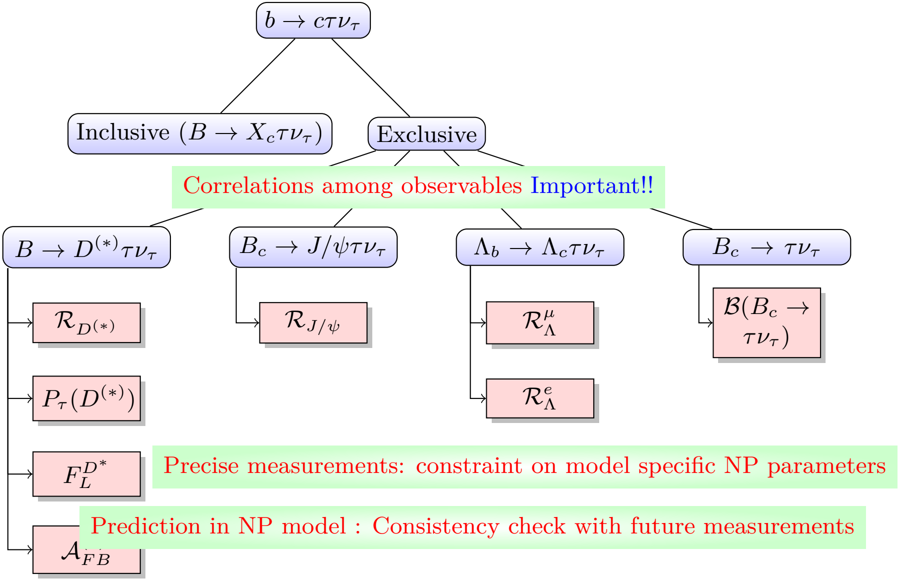

SM prediction (Exclusive)

- For SM calculation in $B \to D^{(*)}\tau\nu_\tau$: CLN parametrization is used. (Nucl. Phys. B530 (1998) 153–181)

- For SM calculation in $\Lambda_B \to \Lambda_c\tau\nu_\tau$: Lattice QCD in relativistice heavy quark limit. (Phys. Rev. D92 (2015), no. 3 034503)

- Unavailability of precise calculation of $B_c \to J/\psi$ form factors :
  - Option to choose different parametrization.
  - Two different parametrizations are considered
    - Light-front Covariant Quark Model (LFCQ) (Phys. Rev. D79 (2009) 054012)
    - Perturbative QCD (pQCD) (Chin. Phys. C37 (2013) 093102)
  - SM central value varying within range $0.25 - 0.29$

Inclusive SM prediction

- For Inclusive decay :

$$\mathcal{R}_{X_c} = \frac{\mathcal{B}\left(B \to X_c \tau \bar{\nu}_\tau\right)}{\mathcal{B}\left(B \to X_c \ell \bar{\nu}_\ell\right)},$$

- Upto NNLO corrections in α_s are considered (Phys. Lett. B346 (1995) 335–341, JHEP 02 (2010) 089).
- The contributions, both at the order $1/{m_b}^2$ and $1/{m_b}^3$ are considered separately. (Phys. Lett. B326 (1994) 145–153, Nucl. Phys. B921 (2017) 211–224)

SM prediction for $\mathcal{R}_{X_c}$

m_c in scheme:			
$\overline{MS}$ upto order		Kinetic up to order	
$\mathcal{O}(1/m_b^2)$	$\mathcal{O}(1/m_b^3)$	$\mathcal{O}(1/m_b^2)$	$\mathcal{O}(1/m_b^3)$
0.242(8)	0.218(8)	0.232(3)	0.209(4)

Phys. Rev. Lett. 114, 061802 (2015).

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$b-$quark mass: Kinetic scheme, $c-$quark mass: both Kinetic and $\bar{MS}$ scheme

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scheme dependence deviates the central value $\approx 4\%$ (consistent within error bar)

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"What we need is something new! Something fresh!

New Physics Analysis

- Varieties of NP models can contribute to $B \to D^{(*)}\tau\nu_\tau$
- An observable not equally sensitive to all types of NP.
- Useful to know :
  - Which type of new physics can best explain the present experimental data??
- Data- based Model Selection $\to$ a multi-scenario analysis on the experimentally available binned data, to obtain a data-based selection of a best NP scenario and ranking and weighting of the remaining models.

Model Independent Analysis

- Most general effective Hamiltonian describing the $b \to c\tau\nu_\tau$ [Y. Sakaki, M. Tanaka, A. Tayduganov and R. Watanabe,PRD **91**, no. 11, 114028 (2015)]

$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big[(1 + C_{V_1}) \mathcal{O}_{V_1} + C_{V_2} \mathcal{O}_{V_2} + C_{S_1} \mathcal{O}_{S_1} + C_{S_2} \mathcal{O}_{S_2} + C_T \mathcal{O}_T \Big],$$

Operator basis :

$$\begin{aligned} \mathcal{O}_{V_1} &= (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_{\tau L}), \ \mathcal{O}_{V_2} = (\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_L \gamma_\mu \nu_{\tau L}), \\ \mathcal{O}_{S_1} &= (\bar{c}_L b_R)(\bar{\tau}_R \nu_{\tau L}), \qquad \mathcal{O}_{S_2} = (\bar{c}_R b_L)(\bar{\tau}_R \nu_{\tau L}), \\ \mathcal{O}_T &= (\bar{c}_R \sigma^{\mu\nu} b_L)(\bar{\tau}_R \sigma_{\mu\nu} \nu_{\tau L}) \end{aligned}$$

- Neutrinos are assumed to be left handed.

Data- Based Model Selection

- Work Plan : Data-based selection of a 'best' case and ranking the remaining cases.

Data- Based Model Selection

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- Akaike Information criteria(Second Order) [N. Sugiura, Commun. Stat. Theor. Meth. A 7, 13 (1978).]

$$\text{AIC}_c = \chi^2_{min} + 2K + \frac{2K(K+1)}{n-K-1}$$

K = number of parameters ; n = sample size; $n/K < 40$.
- $\Delta_i^{AIC}(\text{AIC}_c^i - \text{AIC}_c^{min}) \Rightarrow$ Comparison and ranking of candidate models
- 'Best' model $\Rightarrow \Delta_i^{AIC} \equiv \Delta_{min}^{AIC} = 0$.

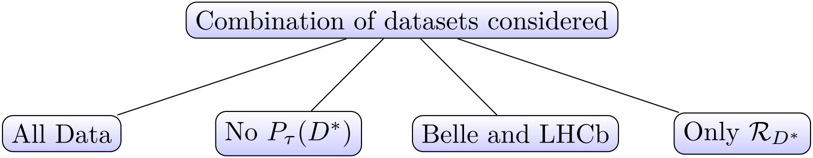
Δ_i^{AIC}	Level of Empirical Support for Model i
$0-2$	Substantial
$4-7$	Considerably Less
>10	Essentially None

- Akaike Weight : weight of evidence in favor of model i

$$w_i = \frac{e^{(-\Delta_i^{AIC}/2)}}{\sum_{r=1}^{R} e^{(-\Delta_r^{AIC}/2)}}$$

Model Selection

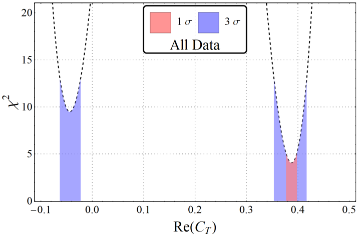
- Model Independent multi-scenario analysis with experimentally available results → data-based selection of a 'best' scenario.
- Four different combination of datasets :

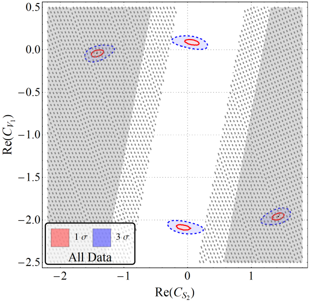


- 3 variations of similar combinations of datasets.
  - Without $\mathcal{R}_{J/\psi}$
  - With $\mathcal{R}_{J/\psi}$ in LFCQ
  - With $\mathcal{R}_{J/\psi}$ in pQCD
- Apparent tension among experimental and SM value ⇒ $\mathcal{R}_{J/\psi}$ treated separately.

Results

	Data Without $\mathcal{R}_{J/\Psi}$				
Index	χ^2_{min} / DoF	p-val (%)	Param.s	w^{AIC_c}	$B_c \to \tau\nu$
1	4.05/8	85.3	$\mathcal{R}e(C_T)$	35.85	✓
2	4.58/8	80.13	$\mathcal{R}e(C_{V_1})$	20.99	✓
3	4.64/8	79.54	$\mathcal{R}e(C_{S_2})$	19.82	×
4	3.54/7	83.07	$\mathcal{I}m(C_{S_2}),\mathcal{R}e(C_{S_2})$	1.92	×
5	3.54/7	83.07	$\mathcal{R}e(C_{S_1}),\mathcal{R}e(C_{S_2})$	1.92	×
6	3.56/7	82.9	$\mathcal{R}e(C_{S_2}),\mathcal{R}e(C_{V_1})$	1.89	✓!
7	3.56/7	82.9	$\mathcal{R}e(C_{S_2}),\mathcal{R}e(C_T)$	1.89	✓!
8	3.56/7	82.88	$\mathcal{R}e(C_{S_2}),\mathcal{R}e(C_{V_2})$	1.89	✓!
9	3.62/7	82.23	$\mathcal{R}e(C_T),\mathcal{R}e(C_{V_2})$	1.78	✓
10	3.69/7	81.45	$\mathcal{R}e(C_{S_1}),\mathcal{R}e(C_T)$	1.66	✓!
11	3.7/7	81.31	$\mathcal{R}e(C_{S_1}),\mathcal{R}e(C_{V_2})$	1.64	✓!
12	3.76/7	80.71	$\mathcal{R}e(C_{S_1}),\mathcal{R}e(C_{V_1})$	1.55	✓!
13	3.79/7	80.37	$\mathcal{R}e(C_{V_1}),\mathcal{R}e(C_{V_2})$	1.5	✓
14	3.79/7	80.37	$\mathcal{I}m(C_{V_2}),\mathcal{R}e(C_{V_2})$	1.5	✓
15	3.82/7	80.08	$\mathcal{R}e(C_T),\mathcal{R}e(C_{V_1})$	1.46	✓
16	3.87/7	79.49	$\mathcal{I}m(C_T),\mathcal{R}e(C_T)$	1.39	✓
17	4.58/7	71.09	$\mathcal{I}m(C_{V_1}),\mathcal{R}e(C_{V_1})$	0.68	✓





Results

Best One operator scenarios : $\mathcal{O}_T/\mathcal{O}_{V_1}$ with $\mathcal{R}e(C_W)$

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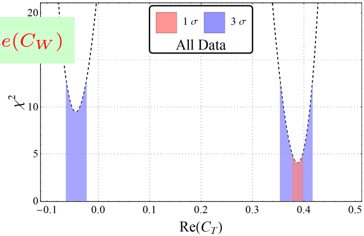

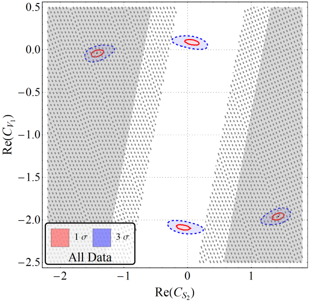

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$\mathcal{O}_{S_1}/\mathcal{O}_{S_2}$ disallowed by $\mathcal{B}(B_c \to \tau\nu_\tau) \leq 30\%$

Index	/ DoF	(%)			$\tau\nu$
1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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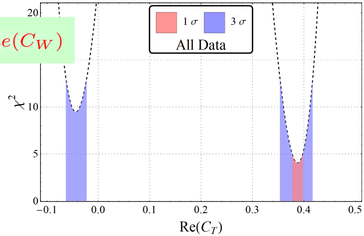
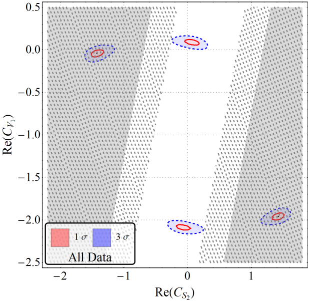
16	3.87/7	79.49	$\mathcal{I}m(C_T),\mathcal{R}e(C_T)$	1.39	✓
17	4.58/7	71.09	$\mathcal{I}m(C_{V_1}),\mathcal{R}e(C_{V_1})$	0.68	✓





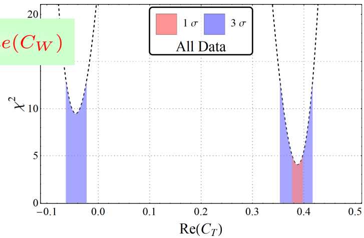
Results

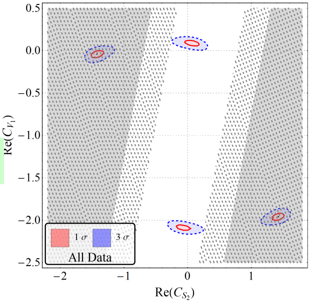
Best One operator scenarios : $\mathcal{O}_T/\mathcal{O}_{V_1}$ with $\mathcal{R}e(C_W)$

$\mathcal{O}_{S_1}/\mathcal{O}_{S_2}$ disallowed by $\mathcal{B}(B_c \to \tau\nu_\tau) \leq 30\%$

$\mathcal{O}_{V_2}$: Less favored, allowed with complex C_W

Index	/ DoF	(%)			$\tau\nu$
3	4.64/8	79.54	$\mathcal{R}e(C_{S_2})$	19.82	×
4	3.54/7	83.07	$\mathcal{I}m(C_{S_2}),\mathcal{R}e(C_{S_2})$	1.92	×
5	3.54/7	83.07	$\mathcal{R}e(C_{S_1}),\mathcal{R}e(C_{S_2})$	1.92	×
6	3.56/7	82.9	$\mathcal{R}e(C_{S_2}),\mathcal{R}e(C_{V_1})$	1.89	✓!
7	3.56/7	82.9	$\mathcal{R}e(C_{S_2}),\mathcal{R}e(C_T)$	1.89	✓!
8	3.56/7	82.88	$\mathcal{R}e(C_{S_2}),\mathcal{R}e(C_{V_2})$	1.89	✓!
9	3.62/7	82.23	$\mathcal{R}e(C_T),\mathcal{R}e(C_{V_2})$	1.78	✓
10	3.69/7	81.45	$\mathcal{R}e(C_{S_1}),\mathcal{R}e(C_T)$	1.66	✓!
11	3.7/7	81.31	$\mathcal{R}e(C_{S_1}),\mathcal{R}e(C_{V_2})$	1.64	✓!
14	3.79/7	80.37	$\mathcal{I}m(C_{V_2}),\mathcal{R}e(C_{V_2})$	1.5	✓
15	3.82/7	80.08	$\mathcal{R}e(C_T),\mathcal{R}e(C_{V_1})$	1.46	✓
16	3.87/7	79.49	$\mathcal{I}m(C_T),\mathcal{R}e(C_T)$	1.39	✓
17	4.58/7	71.09	$\mathcal{I}m(C_{V_1}),\mathcal{R}e(C_{V_1})$	0.68	✓



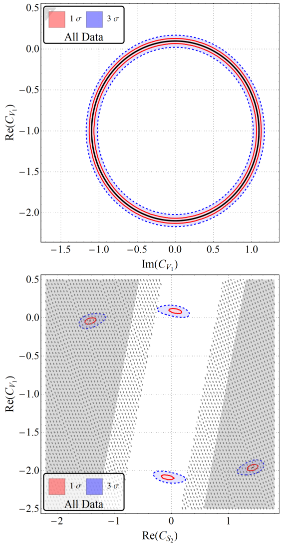


Results

- In absence of $P_\tau(D^*)$ the conclusions remain same.
- Without considering BABAR data : two more one-operator scenarios $\mathcal{R}e(C_{V_2})$ and $\mathcal{R}e(C_{S_1})$ are allowed.
- Considering only $\mathcal{R}_{D^*}$ data : All of $\mathcal{O}_{V_1}$, $\mathcal{O}_{V_2}$, $\mathcal{O}_{S_1}$, $\mathcal{O}_{S_2}$, $\mathcal{O}_T$ are allowed with $\mathcal{R}e(C_W)$. $\mathcal{B}(B_c \to \tau\nu_\tau)$ disfavors the scenarios with scaler operators.
- In all these analysis, conclusions remain unchanged in presence of $\mathcal{R}_{J/\psi}$ data.
- For all the scenarios allowed by ΔAIC_c as well as $\mathcal{B}(B_c \to \tau\nu_\tau)$ constraints the values of NP parameters with their uncertainties and correlations are estimated.

Results

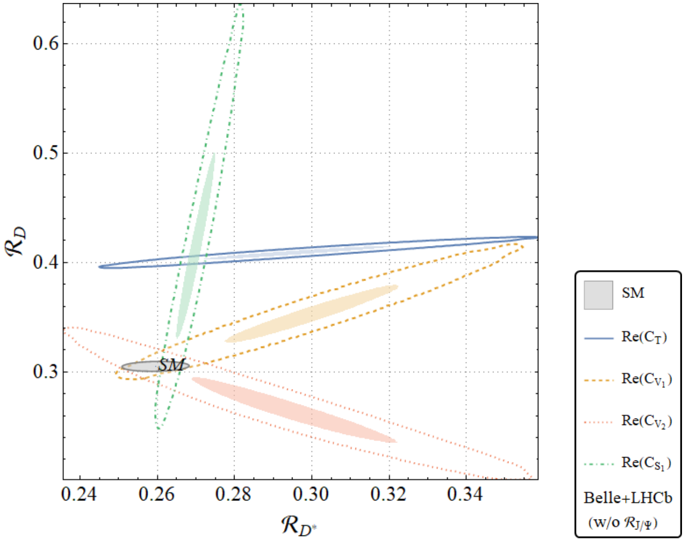
Data Without $\mathcal{R}_{J/\Psi}$			
Index	Param.s	Best-fit	Correlation
1	$\mathcal{R}e(C_T)$	0.387(11)	–
2	$\mathcal{R}e(C_{V_1})$	0.098(22)	–
6	$\mathcal{R}e(C_{S_2})$	0.073(79)	-0.409
	$\mathcal{R}e(C_{V_1})$	0.089(24)	
7	$\mathcal{R}e(C_{S_2})$	0.181(67)	0.075
	$\mathcal{R}e(C_T)$	-0.043(11)	
8	$\mathcal{R}e(C_{S_2})$	0.279(68)	-0.302
	$\mathcal{R}e(C_{V_2})$	-0.111(29)	
9	$\mathcal{R}e(C_T)$	-0.112(26)	-0.93
	$\mathcal{R}e(C_{V_2})$	0.196(74)	
10	$\mathcal{R}e(C_{S_1})$	0.179(66)	0.351
	$\mathcal{R}e(C_T)$	-0.033(12)	
11	$\mathcal{R}e(C_{S_1})$	0.245(60)	-0.01
	$\mathcal{R}e(C_{V_2})$	-0.075(28)	
12	$\mathcal{R}e(C_{S_1})$	0.086(90)	-0.684
	$\mathcal{R}e(C_{V_1})$	0.078(30)	
13	$\mathcal{R}e(C_{V_1})$	0.117(31)	0.709
	$\mathcal{R}e(C_{V_2})$	0.037(41)	
14	$\mathcal{I}m(C_{V_2})$	0.497(68)	0.716
	$\mathcal{R}e(C_{V_2})$	0.042(46)	
15	$\mathcal{R}e(C_T)$	0.030(34)	0.917
	$\mathcal{R}e(C_{V_1})$	0.142(54)	
16	$\mathcal{I}m(C_T)$	0.16(15)	-0.995
	$\mathcal{R}e(C_T)$	0.32(15)	
17		See Plot	



Results

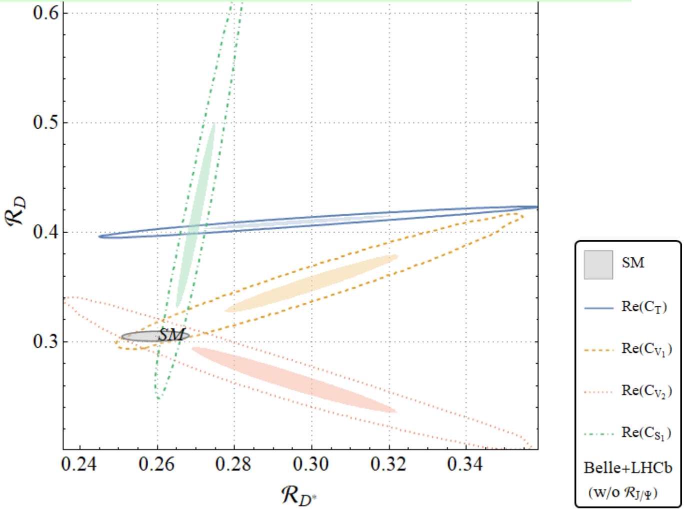
- Using these NP results, the values of all the observables are predicted.
- Trying to explain the deviation in $\mathcal{R}_{D^{(*)}}$ for a specific NP $\Rightarrow$ Information about the expected deviations in other associated observables.
- Any result, inconsistent with SM, but consistent with a future prediction of some observable $\Rightarrow$ indirect evidence in support for that specific scenario.
- The correlations between the observables will play an important role.

Correlation Plots



Correlation Plots

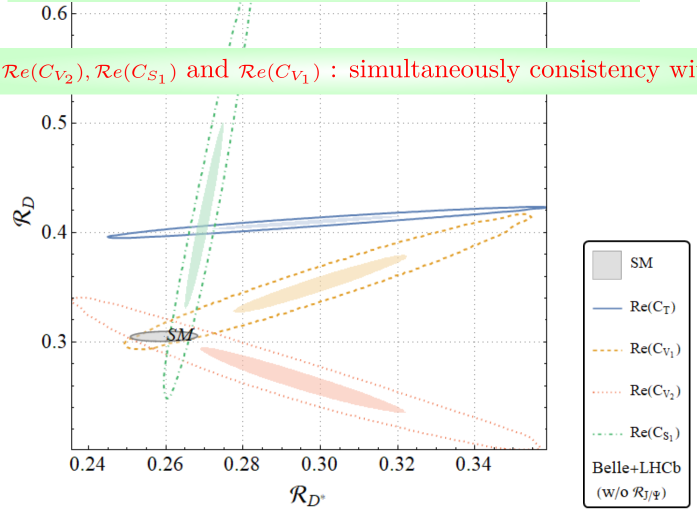
Only with $\mathcal{O}_{V_2}$ $\mathcal{R}_D$ and $\mathcal{R}_{D^*}$ are negatively correlated



Correlation Plots

Only with $\mathcal{O}_{V_2}$ $\mathcal{R}_D$ and $\mathcal{R}_{D^*}$ are negatively correlated

For $\mathcal{R}e(C_{V_2}), \mathcal{R}e(C_{S_1})$ and $\mathcal{R}e(C_{V_1})$: simultaneously consistency with SM

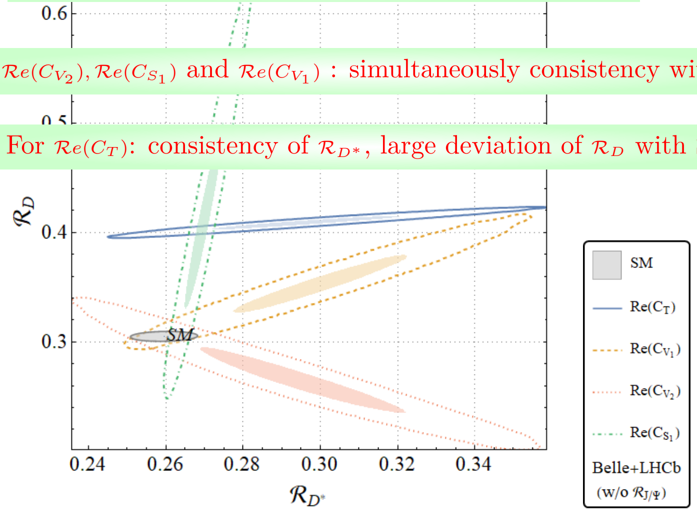


Correlation Plots

Only with $\mathcal{O}_{V_2}$ $\mathcal{R}_D$ and $\mathcal{R}_{D^*}$ are negatively correlated

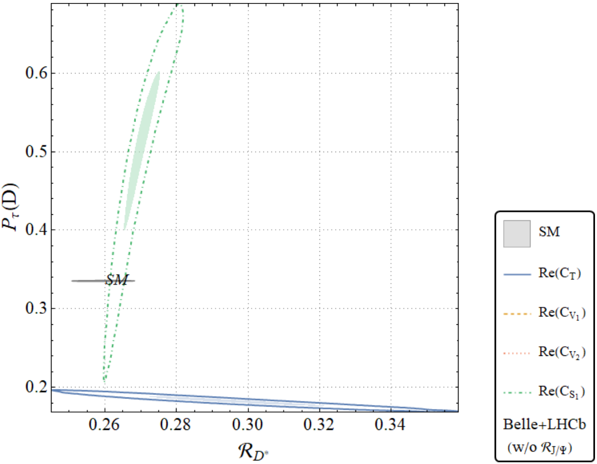
For $\mathcal{R}e(C_{V_2}), \mathcal{R}e(C_{S_1})$ and $\mathcal{R}e(C_{V_1})$: simultaneously consistency with SM

For $\mathcal{R}e(C_T)$: consistency of $\mathcal{R}_{D^*}$, large deviation of $\mathcal{R}_D$ with SM



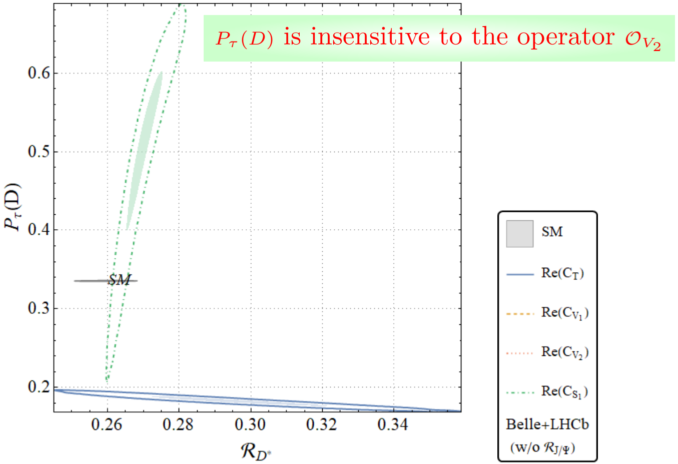
Correlation Plots

- asymmetric and angular observables : insensitive to $\mathcal{O}_{V_1}$ $\Rightarrow$ canceled in the ratios.



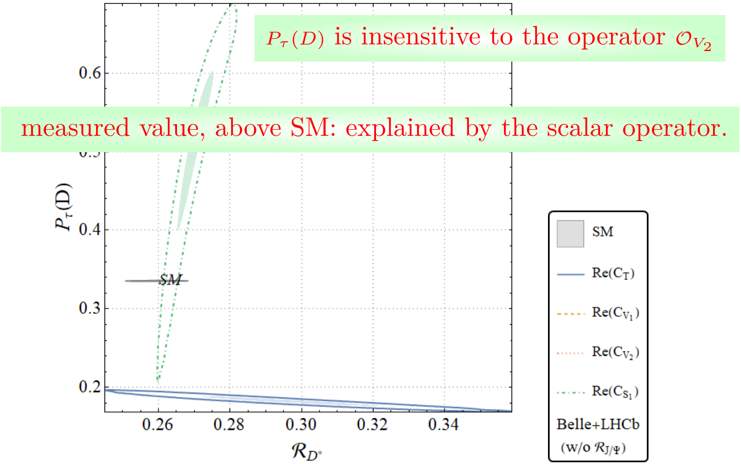
Correlation Plots

- asymmetric and angular observables : insensitive to $\mathcal{O}_{V_1}$ $\Rightarrow$ canceled in the ratios.



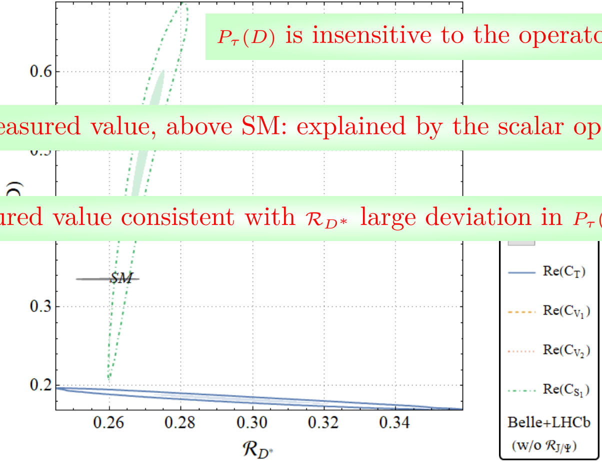
Correlation Plots

- asymmetric and angular observables : insensitive to $\mathcal{O}_{V_1}$ $\Rightarrow$ canceled in the ratios.



Correlation Plots

- asymmetric and angular observables : insensitive to $\mathcal{O}_{V_1}$ $\Rightarrow$ canceled in the ratios.

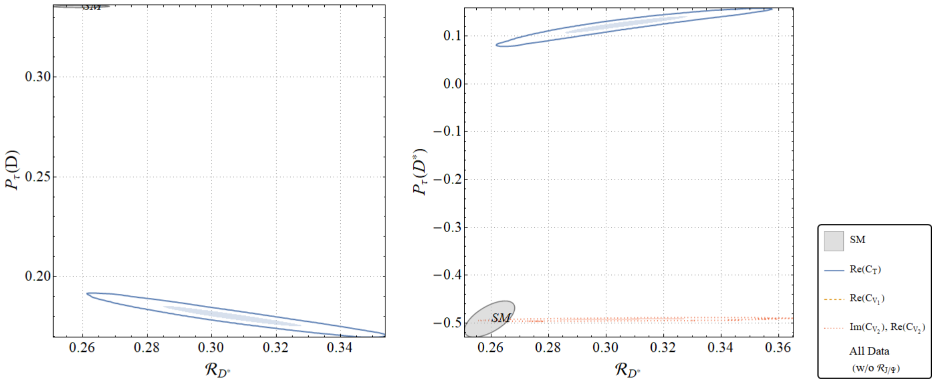


$P_\tau(D)$ is insensitive to the operator $\mathcal{O}_{V_2}$

measured value, above SM: explained by the scalar operator.

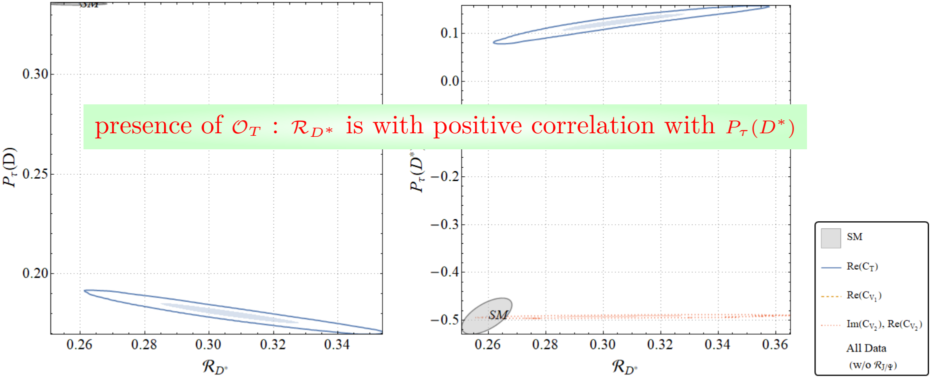
In future measured value consistent with $\mathcal{R}_{D^*}$ large deviation in $P_\tau(D)$: tensor NP

Correlation Plots



Correlation Plots

presence of $\mathcal{O}_T$: $\mathcal{R}_{D^*}$ is with negative correlation with $P_\tau(D)$

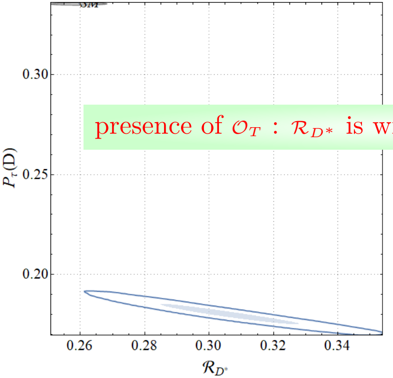


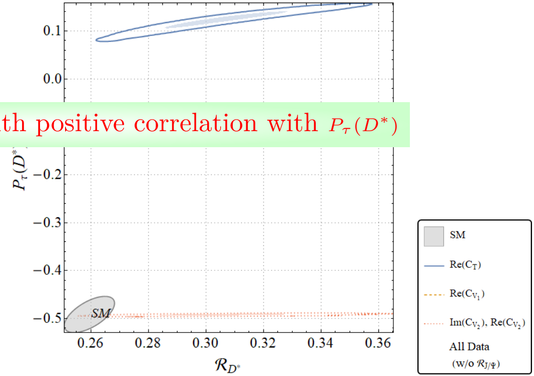
presence of $\mathcal{O}_T$: $\mathcal{R}_{D^*}$ is with positive correlation with $P_\tau(D^*)$

Correlation Plots

presence of $\mathcal{O}_T$: $\mathcal{R}_{D^*}$ is with negative correlation with $P_\tau(D)$

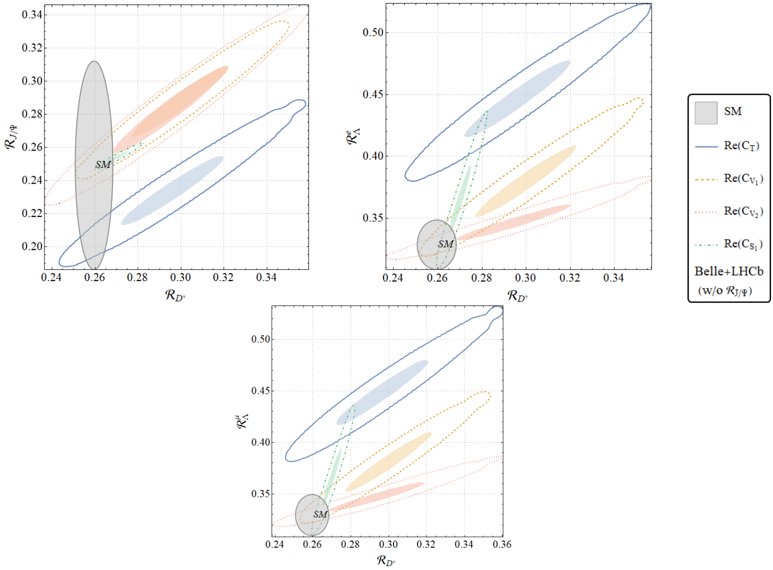
presence of $\mathcal{O}_T$: $\mathcal{R}_{D^*}$ is with positive correlation with $P_\tau(D^*)$



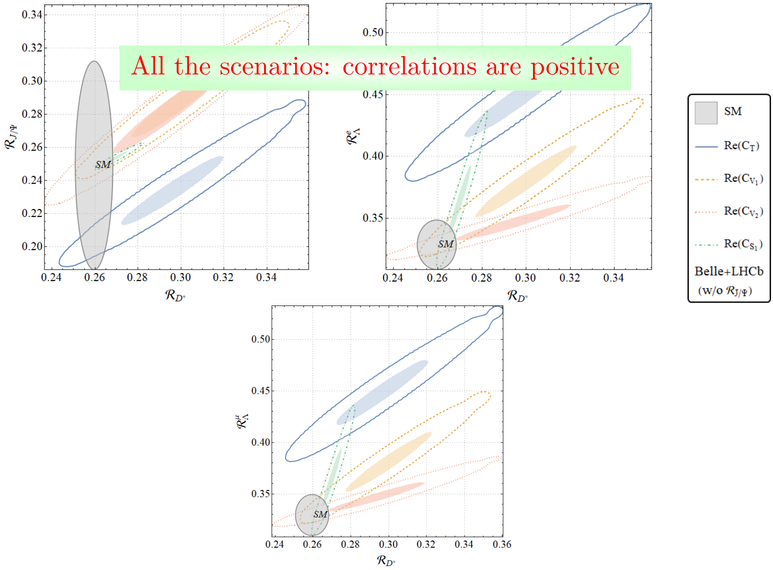


presence of $\mathcal{O}_T$: $P_\tau(D)$ and $P_\tau(D^*)$ below and above SM predictions

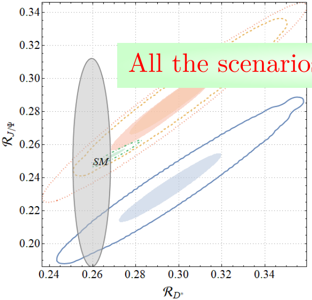
Correlation Plots

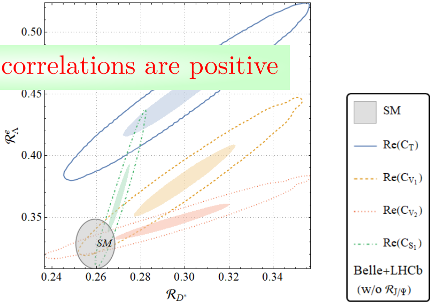


Correlation Plots

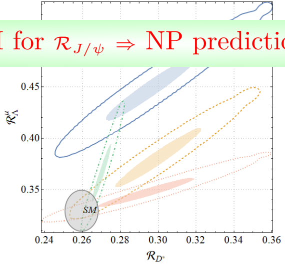


Correlation Plots



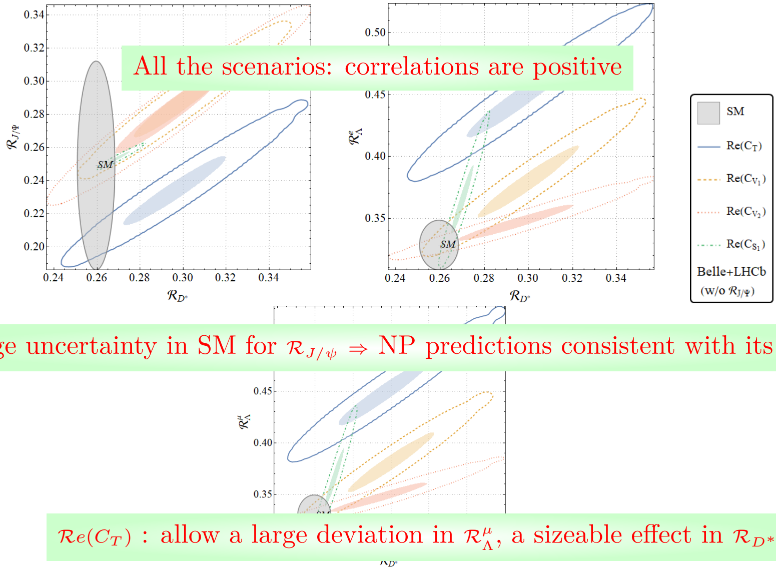


All the scenarios: correlations are positive



Large uncertainty in SM for $\mathcal{R}_{J/\psi}$ $\Rightarrow$ NP predictions consistent with its SM

Correlation Plots



All the scenarios: correlations are positive

Large uncertainty in SM for $\mathcal{R}_{J/\psi}$ $\Rightarrow$ NP predictions consistent with its SM

$\mathcal{R}e(C_T)$: allow a large deviation in $\mathcal{R}^\mu_\Lambda$, a sizeable effect in $\mathcal{R}_{D^*}$

Conclusion

- In the first part of analysis :
  - Following the result of up-to-date analysis on $B \to D^{(*)}\ell\nu_\ell \Rightarrow$ SM prediction of angular observables associated with $B \to D^{(*)}\tau\nu_\tau$
  - The SM prediction of inclusive semitaunic observable $\mathcal{R}_{X_c}$ is updated. These predictions are based on two different schemes of the charm quark mass ($\bar{M}S$ and Kinetic). These include the NNLO perturbative corrections, and power-corrections up to order $1/m_b^3$.
- In the next part :
  - we have analysed the semitaunic $b \to c\tau\nu_\tau$ decays in a model independent framework.
  - Among all the data sets the one operator scenario with real Wilson coefficient can best explain the available data.
  - Scalar operators are not allowed by the constraint $\mathcal{B}(B_c \to \tau\nu_\tau) \leq 30\%$
  - The most favoured scenarios are the ones with tensor ($\mathcal{O}_T$) or $(V - A)$ ($\mathcal{O}_{V_1}$) type of operators.
  - These one operator scenarios are easily distinguishable from each other by studying the correlations of $\mathcal{R}_{D^*}$ with $\mathcal{R}_D$ and all the other asymmetric and angular observables.

Thank You

SM prediction (Exclusive)

Observable	SM Prediction	Correlation						
$\mathcal{R}_{D^*}$	0.260(6)	1.	0.118	0.617	0.118	0.604	0.628	-0.118
$\mathcal{R}_D$	0.305(3)		1.	-0.023	1.	0.021	0.007	-1.
$P_\tau(D^*)$	-0.491(25)			1.	-0.023	0.803	0.895	0.023
$P_\tau(D)$	0.3355(4)				1.	0.021	0.007	-1.
$F_L^{D^*}$	0.457(10)					1.	0.921	-0.021
$\mathcal{A}_{FB}^*$	-0.058(14)						1.	-0.007
$\mathcal{A}_{FB}$	0.3586(3)							1.
$\mathcal{R}_{J/\Psi}$ (LFCQ)	0.249(42)							
$\mathcal{R}_{J/\Psi}$ (PQCD)	0.289(28)							
$\mathcal{R}_\Lambda^\mu$	0.329(13)							
$\mathcal{R}_\Lambda^e$	0.328(13)							
$\mathcal{B}(B_c \to \tau\nu)$	0.0208(18)							

Formalism

- q^2-distributions of the differential decay rates in $B \to D^{(*)}\tau\nu_\tau$ decays are given by

$$\begin{aligned}
\frac{d\Gamma(\overline{B} \to D\tau\overline{\nu}_\tau)}{dq^2} = & \frac{G_F^2|V_{cb}|^2}{192\pi^3 m_B^3} q^2 \sqrt{\lambda_D(q^2)} \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \times \{ \\
& |1 + C_{V_1} + C_{V_2}|^2 \left[\left(1 + \frac{m_\tau^2}{2q^2}\right) H_{V,0}^{s\,2} + \frac{3}{2}\frac{m_\tau^2}{q^2} H_{V,t}^{s\,2}\right] \\
& + \frac{3}{2}|C_{S_1} + C_{S_2}|^2 H_S^{s\,2} + 8|C_T|^2 \left(1 + \frac{2m_\tau^2}{q^2}\right) H_T^{s\,2} \\
& + 3Re[(1 + C_{V_1} + C_{V_2})(C_{S_1}{}^* + C_{S_2}{}^*)] \frac{m_\tau}{\sqrt{q^2}} H_S^s H_{V,t}^s \\
& - 12Re[(1 + C_{V_1} + C_{V_2}) C_T{}^*] \frac{m_\tau}{\sqrt{q^2}} H_T^s H_{V,0}^s \}
\end{aligned}$$

Formalism

$$\frac{d\Gamma(\overline{B} \to D^*\tau\overline{\nu}_\tau)}{dq^2} = \frac{G_F^2|V_{cb}|^2}{192\pi^3 m_B^3} q^2 \sqrt{\lambda_{D^*}(q^2)} \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \times \Bigg\{$$

$$(|1 + C_{V_1}|^2 + |C_{V_2}|^2) \left[\left(1 + \frac{m_\tau^2}{2q^2}\right)\left(H_{V,+}^2 + H_{V,-}^2 + H_{V,0}^2\right) + \frac{3}{2}\frac{m_\tau^2}{q^2} H_{V,t}^2\right]$$

$$- 2Re[(1 + C_{V_1})C_{V_2}{}^*] \left[\left(1 + \frac{m_\tau^2}{2q^2}\right)\left(H_{V,0}^2 + 2H_{V,+}H_{V,-}\right) + \frac{3}{2}\frac{m_\tau^2}{q^2} H_{V,t}^2\right]$$

$$+ \frac{3}{2}|C_{S_1} - C_{S_2}|^2 H_S^2 + 8|C_T|^2 \left(1 + \frac{2m_\tau^2}{q^2}\right)\left(H_{T,+}^2 + H_{T,-}^2 + H_{T,0}^2\right)$$

$$+ 3Re[(1 + C_{V_1} - C_{V_2})(C_{S_1}{}^* - C_{S_2}{}^*)] \frac{m_\tau}{\sqrt{q^2}} H_S H_{V,t}$$

$$- 12Re[(1 + C_{V_1})C_T{}^*] \frac{m_\tau}{\sqrt{q^2}} \left(H_{T,0}H_{V,0} + H_{T,+}H_{V,+} - H_{T,-}H_{V,-}\right)$$

$$+ 12Re[C_{V_2}C_T^*] \frac{m_\tau}{\sqrt{q^2}} \left(H_{T,0}H_{V,0} + H_{T,+}H_{V,-} - H_{T,-}H_{V,+}\right) \Bigg\}$$

Backup Slides

- A true model with true parameter values :

$$\chi^2 = d.o.f \text{ i.e. } \chi^2_{red} = 1 \text{ (no fit involved)}$$

- Not sufficient to assess convergence or compare different models ! (noise present in the data)

- For the true model, with a-priori known measurement errors:

  Distribution of normalized residuals (in our case, $\frac{R^{th}_{bin} - R^{exp}_{bin}}{\delta R_{bin}}$) is a Gaussian with mean $\mu = 0$ and variance $\sigma^2 = 1$.

- Test of significance of the fit $\rightarrow$ Fitting the distribution of residuals to the Gaussian.

- Validity of a hypothesis : p-value of the goodness of fit test $\geq 5\%$.

- p-value : probability that a random variable having a χ^2-distribution with $d.o.f \geq 1$ assumes a value which is larger than a given value of χ^2 (≥ 0)

Backup Sides

- To compare the latest *BABAR* and Belle binned data with a specific model, we devise a χ^2 defined as:

$$\chi^2_{NP} = \sum_{i,j=1}^{n_b} \left(R_i^{exp} - R_i^{th}\right) \left(V^{exp}\right)^{-1}_{ij} \left(R_j^{exp} - R_j^{th}\right) + \chi^2_{Nuisance}\,,$$

- $V_{ij}^{exp} = \delta_{ij}\ \delta R_i^{exp}\ \delta R_j^{exp}$, where δ_{ij} is the Kronecker delta. (Assumptions : correlations negligible)

- Total 10 unknown NP parameters and 26 observables for *BABAR* (14 bins for $B \to D\tau\nu$ and 12 bins for $B \to D^*\tau\nu$) and 17 observables for Belle.

- Minimize the χ^2_{NP} for different cases and different set of observables.

- Define reduced statistic $\chi^2_{red} = \chi^2_{min}/d.o.f$ where $d.o.f = N_{Obs} - N_{Params}$

- In information theory, the Kullback-Leibler (K-L) Information or measure $I(f, g) \Rightarrow$ information lost when g is used to approximate f. Here f is a notation for full reality or truth and g denotes an approximating model in terms of probability distribution.
- Akaike proposed the use of the K-L information as a fundamental basis for model selection.
- This is a rigorous way to estimate K-L information, based on the empirical log-likelihood function at its maximum point.
  'Akaike's information criterion'(AIC) with respect to our analysis can be defined as,

$$\mathrm{AIC} = \chi^2_{min} + 2K \tag{1}$$

  where K is the number of estimable parameters.
  AIC may perform poorly if there are too many parameters in relation to the size of the sample. second-order variant of AIC,

$$\mathrm{AIC}_c = \chi^2_{min} + 2K + \frac{2K(K+1)}{n-K-1} \tag{2}$$

  where n is the sample size. As a rule of thumb, Use of AIC_c is preferred in literature when $n/K < 40$.

5 C_W's $\rightarrow C_{V_1}, C_{V_2}, C_{S_1}, C_{S_2}, C_T$.
Each one complex $\rightarrow$ total 10 parameters.
We took a severl such combinations.
Which one fits the data best?
Standard method in Heavy Flavor physics: $\Delta\chi^2$ test (Likelihood-Ratio test):

- Can only be applied to nested models.
- $\Delta\chi^2 = \chi^2_{min,\ S} - \chi^2_{min,\ L}$.
- When model S (fewer parameters: null) is true (under certain conditions), **Wilks' Theorem** $\rightarrow \Delta\chi^2$ has a χ^2 distribution with the $d.of = p_L - p_S$.
- compute a p-value, compare it to a critical value $\rightarrow$ decide to reject the null in favor of the alternative.