Bayesian fit analysis to full distribution data of $\bar{B} \to D^{(*)} \ell \bar{\nu}$: Vcb determination and New Physics constraints

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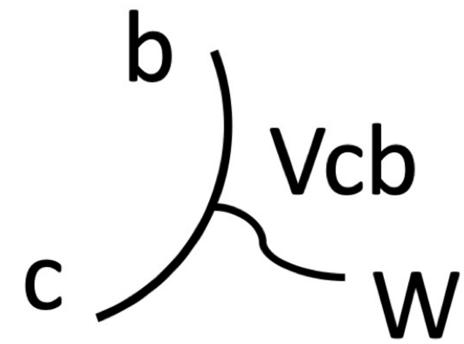
2004.10208 *JHEP* 08 (2020) 08, 006

We want to determine Vcb accurately

Q. What is Vcb?

A. One of a CKM matrix element



Q. Why we need to improve it?

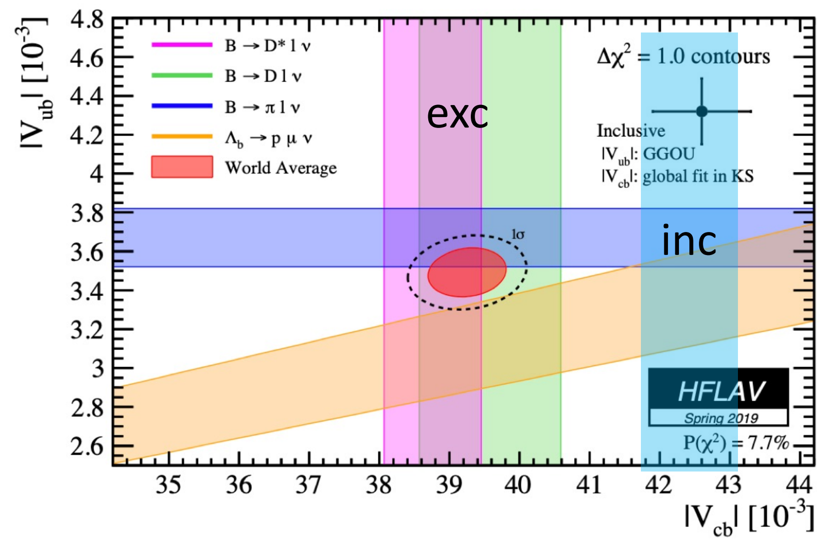
A. There is deviation between inclusive and exclusive Vcb

inclusive Vcb: determined from B->Xc lν mode

Xc: all hadronic state containing a charmed hadron.

2-3σ deviation?

exclusive Vcb: determined from B->D$^{(*)}$ l ν mode



Q. How to improve Vcb

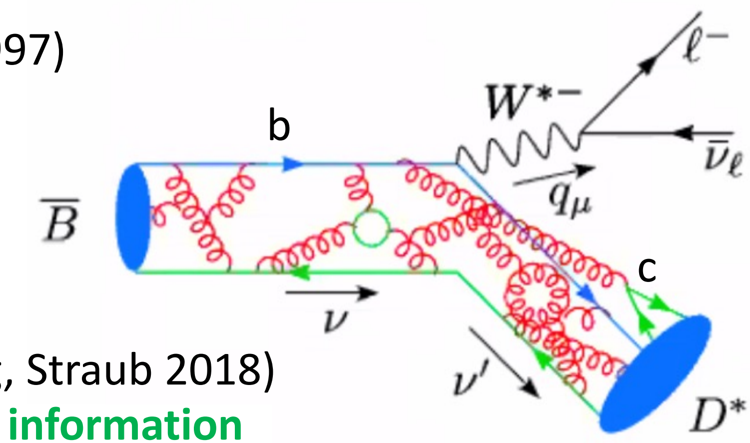
A. We will fit Vcb with more accurate Form Factors (FFs) for B->D$^{(*)}$

$\Gamma(B\text{->}D\ l\nu) \propto |Vcb \times FFs|^2$

Form Factors in B->D,D* transition

Conventional parametrization

- CNL parametrization (Caprini, Lellouch, Neubert 1997)
  -> too much simplified
- BGL parametrization (Boyd, Grinstein, Lebed 1997)
  -> too general to use for the NP analysis



Our approach

- General Heavy Quark Effective Theory(HQET) (Jung, Straub 2018)

QCD information

$$\langle D|\bar{c}\gamma^\mu b|B\rangle_{\mathrm{HQET}} = \sqrt{m_B m_D}\left[h_+(v+v')^\mu + h_-(v-v')^\mu\right],$$

SM

$$\langle D^*|\bar{c}\gamma^\mu\gamma^5 b|B\rangle_{\mathrm{HQET}} = \sqrt{m_B m_{D^*}}\left[h_{A_1}(w+1)\epsilon^{*\mu} - (\epsilon^*\cdot v)\left(h_{A_2}v^\mu + h_{A_3}v'^\mu\right)\right],$$

$$v^\mu = p_B^\mu/m_B,\ v'^\mu = p_{D^{(*)}}^\mu/m_{D^{(*)}},\ w = v\cdot v' = (m_B^2 + m_{D^{(*)}}^2 - q^2)/(2m_B m_{D^{(*)}}),$$

Main difference: h_+, h_-, h_{A1}... are described by common parameters

We want to determine h_X precisely.

L. Zoltan et al 2017

$$\hat{h}_X = \hat{h}_{X,0} + \frac{\alpha_s}{\pi}\delta\hat{h}_{X,\alpha_s} + \frac{\bar{\Lambda}}{2m_b}\delta\hat{h}_{X,m_b} + \frac{\bar{\Lambda}}{2m_c}\delta\hat{h}_{X,m_c} + \left(\frac{\bar{\Lambda}}{2m_c}\right)^2\delta\hat{h}_{X,m_c^2},$$

0.1 0.05 0.2 0.04

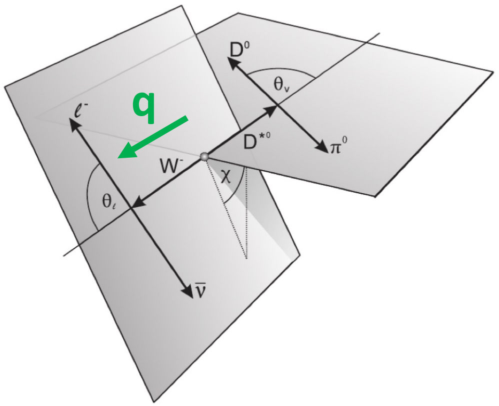
M. Bordone et al. EPJC 2020

z expansion

$$w = v \cdot v' = (m_B^2 + m_{D^{(*)}}^2 - q^2)/(2m_B m_{D^{(*)}})$$

$$w(z) = 2\left(\frac{1+z}{1-z}\right)^2 - 1$$

$H_x(w)$ -> $H_x(z)$



$0 < z < 0.05$ in B->D,D* transitions

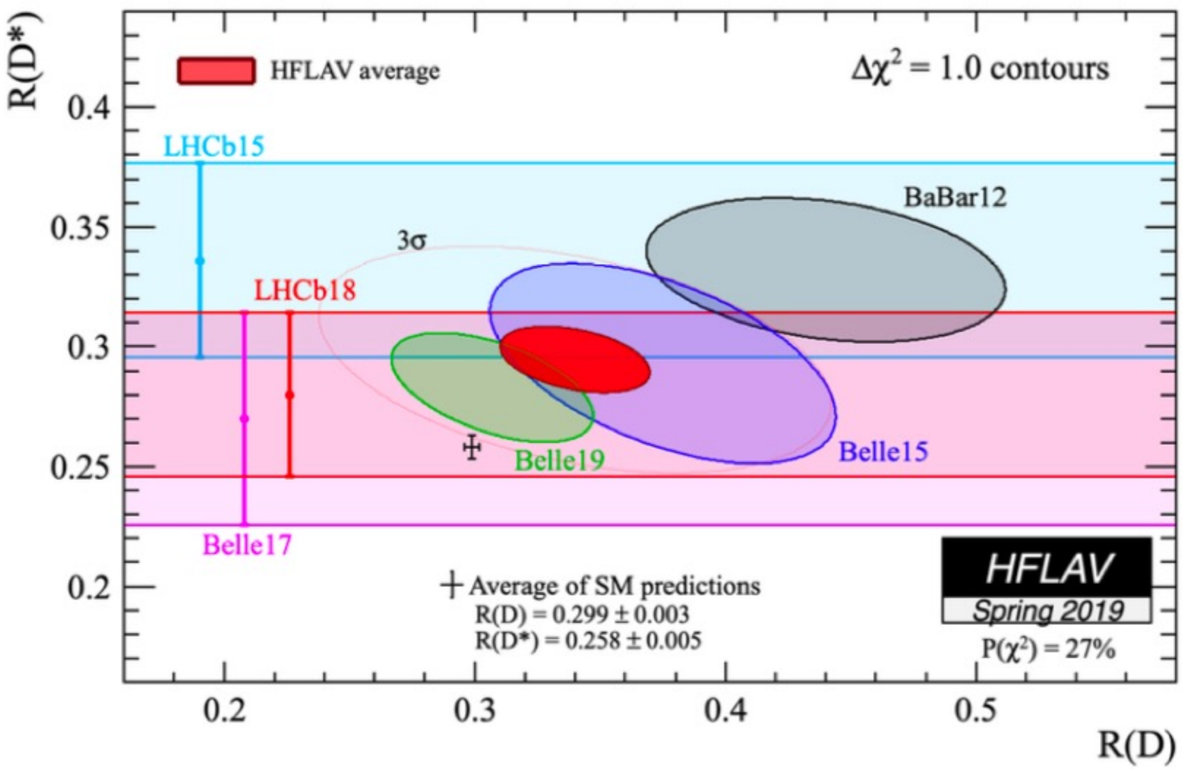
z is a good variable to expand around 0

Depending on to which order we expand form factors in z, we have different number of parameters to fit

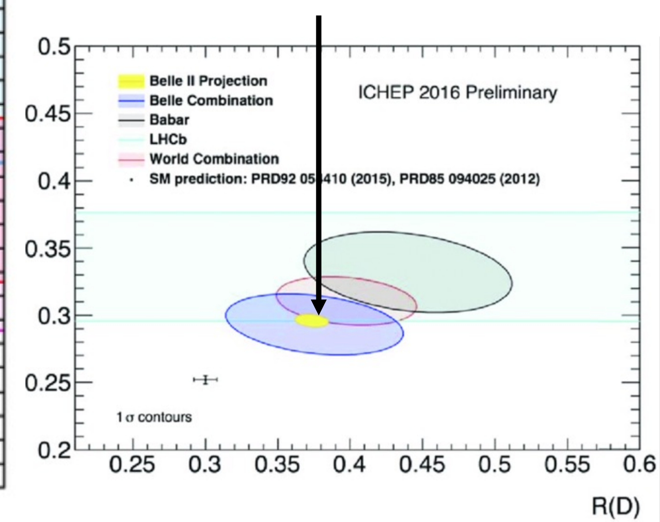
Anyway we have 10-20 parameters to fit

Another impact on $\mathrm{R}\left(\mathrm{D}^{(*)}\right)$ anomaly

$$\mathrm{R}\left(\mathrm{D}^{(*)}\right) = \frac{BR\left(B\to D^{(*)}\tau\nu\right)}{BR\left(B\to D^{(*)}l\nu\right)}, \quad l = \mu, \mathrm{e}$$



Belle II projection ～2027



We can also improve SM prediction for RD,RD*

Three kinds of constraints (input of the fit)

- Lattice (6)
  - prediction for large q^2
  - unstable particles (D*) are problematic

  -> hard to predict FF for B->D*

- Theory (45)

  e.g. QCDSR

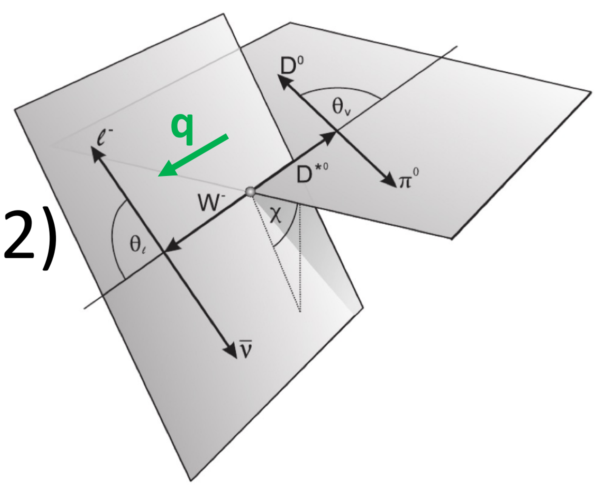
  LCSR

  Unitarity bound
  - prediction for small q^2

  we included constraints on higher derivative terms

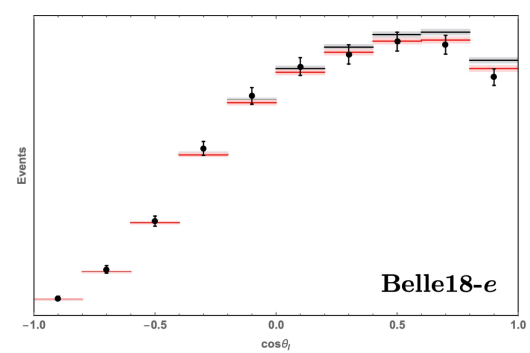
- Experiment (132)

  Belle 17,18



Experimental data from Belle

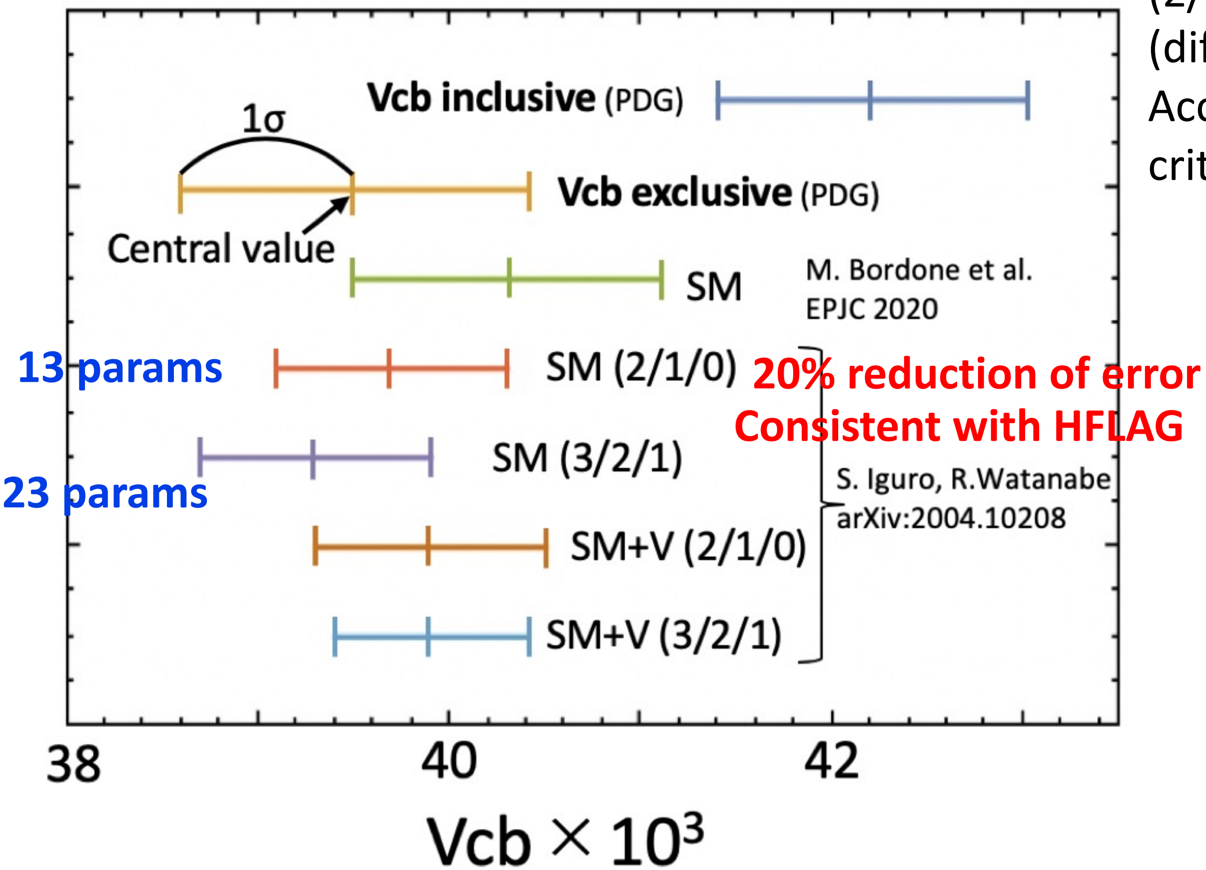
we also included data of Angular distribution in 1809.03290



full kinetic (q^2, θ_l, θ_V , χ) distributions of $B \to D^* l \nu$

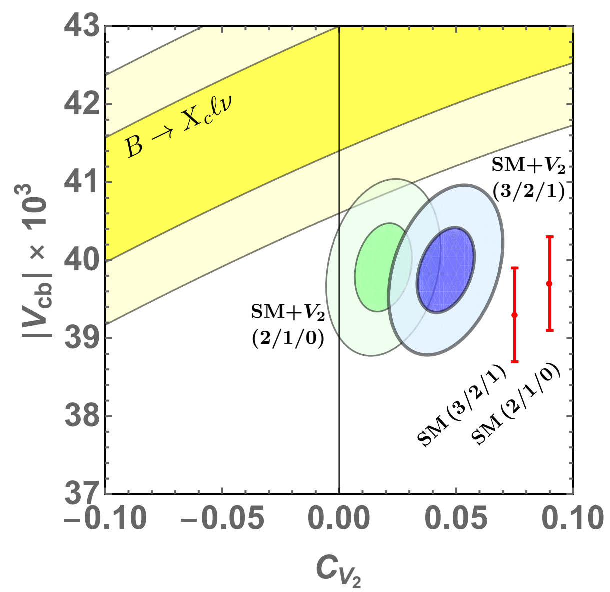
～180 constraints

Result 1 Vcb determination



(2/1/0), (3/2/1) is different model (different number of free parameters). According to AIC (Akaike Information criterion), (2/1/0) is more favored

Right handed vector int.

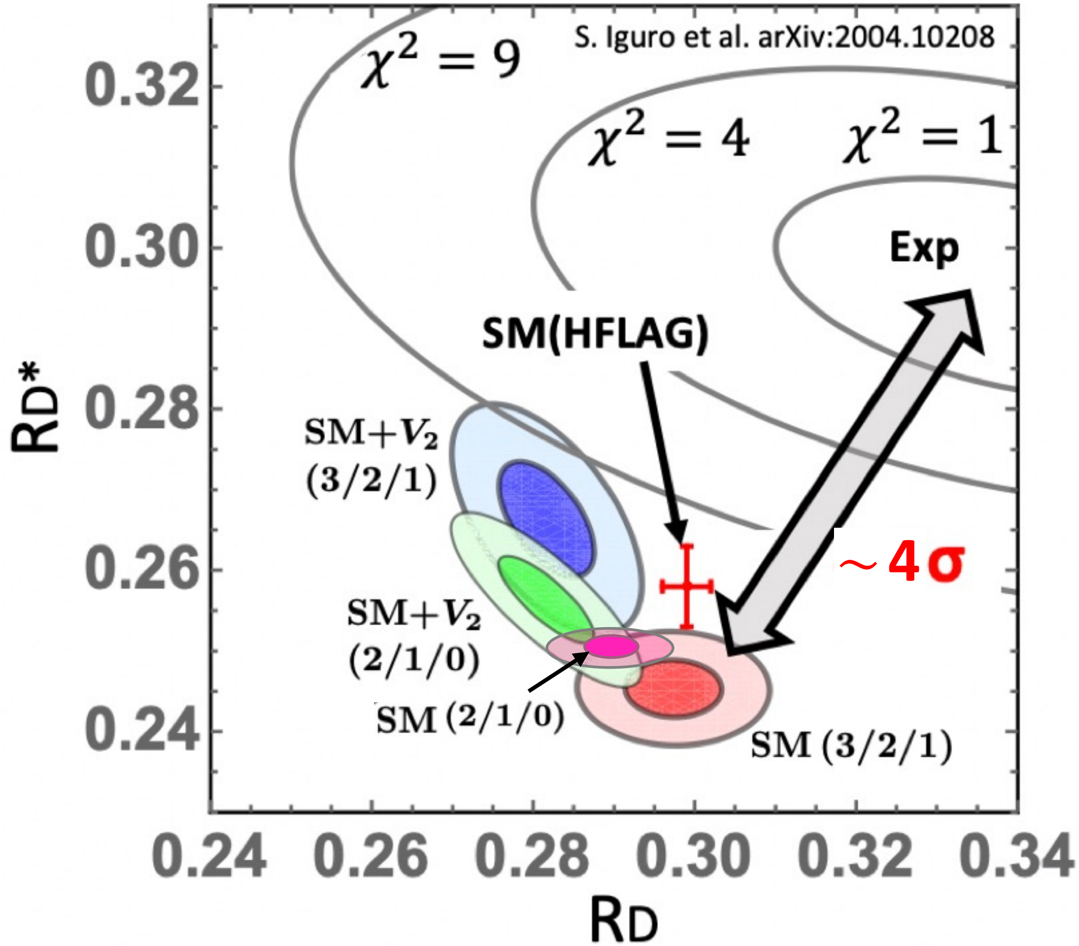


$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big[(\bar{c}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu_\ell) + C_{V_2} (\bar{c}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu P_L \nu_\ell) + C_T (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\ell}\sigma_{\mu\nu} P_L \nu_\ell) \Big]$$

New physics in b->c l v current does not solve the discrepancy

Result 2 RD,RD* prediction

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



We got the smaller RD* value. -> Now ~~3~~ 4σ discrepancy
Even if we have new physics in b->clν transition, the anomaly remains.

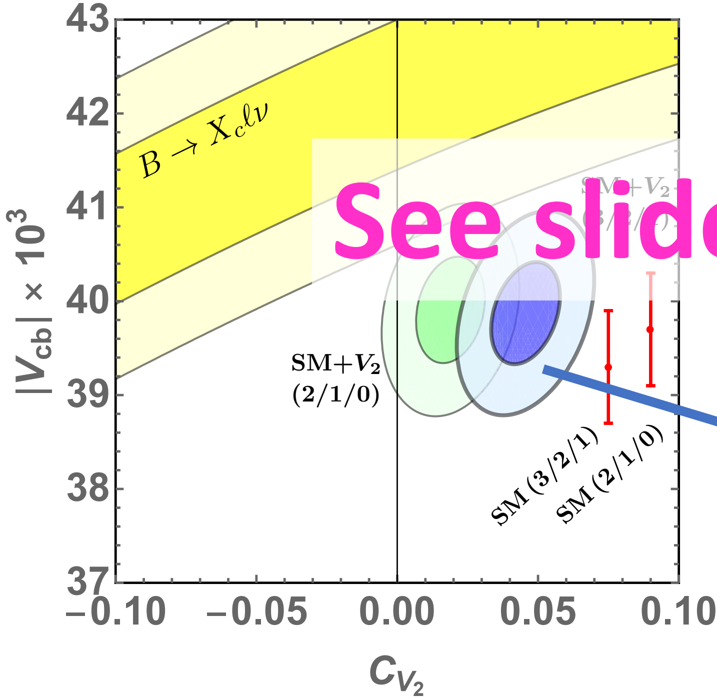
O(1)% non zero NP contribution (C_{V2} ,C_T) is still allowed

LQ (t-channel)

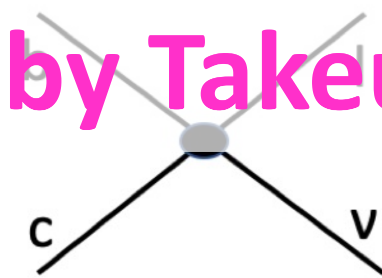
$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big[(\bar{c}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu_\ell) + C_{V_2} (\bar{c}\gamma^\mu P_R b)(\bar{\ell}\gamma_\mu P_L \nu_\ell) + C_T (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\ell}\sigma_{\mu\nu} P_L \nu_\ell) \Big]$$

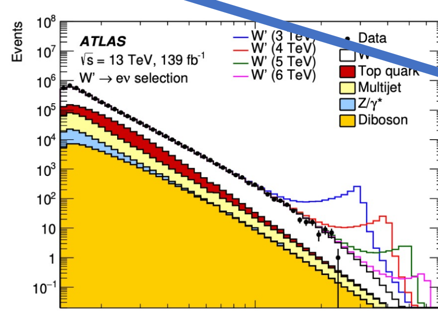
Can we test in LHC with high pT mono lepton search?

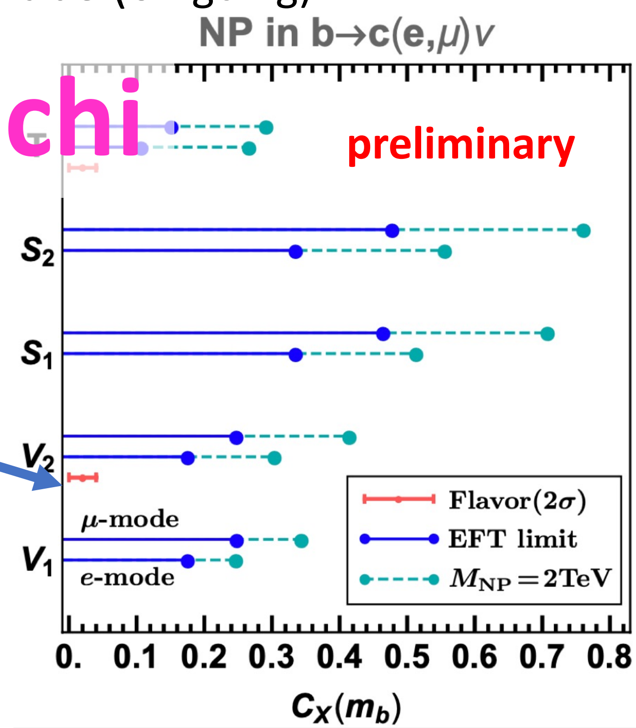
Iguro, Takeuchi, Watanabe (on going)



See slide by Takeuchi







Current LHC sensitivity is O(10)%, but would be O(1)% in HL-LHC.

Further improvement on S/B is on going

Conclusion

We determined FFs in B->D, D* transition more precisely

- Vcb puzzle does not disappear.

- New physics does not solve it

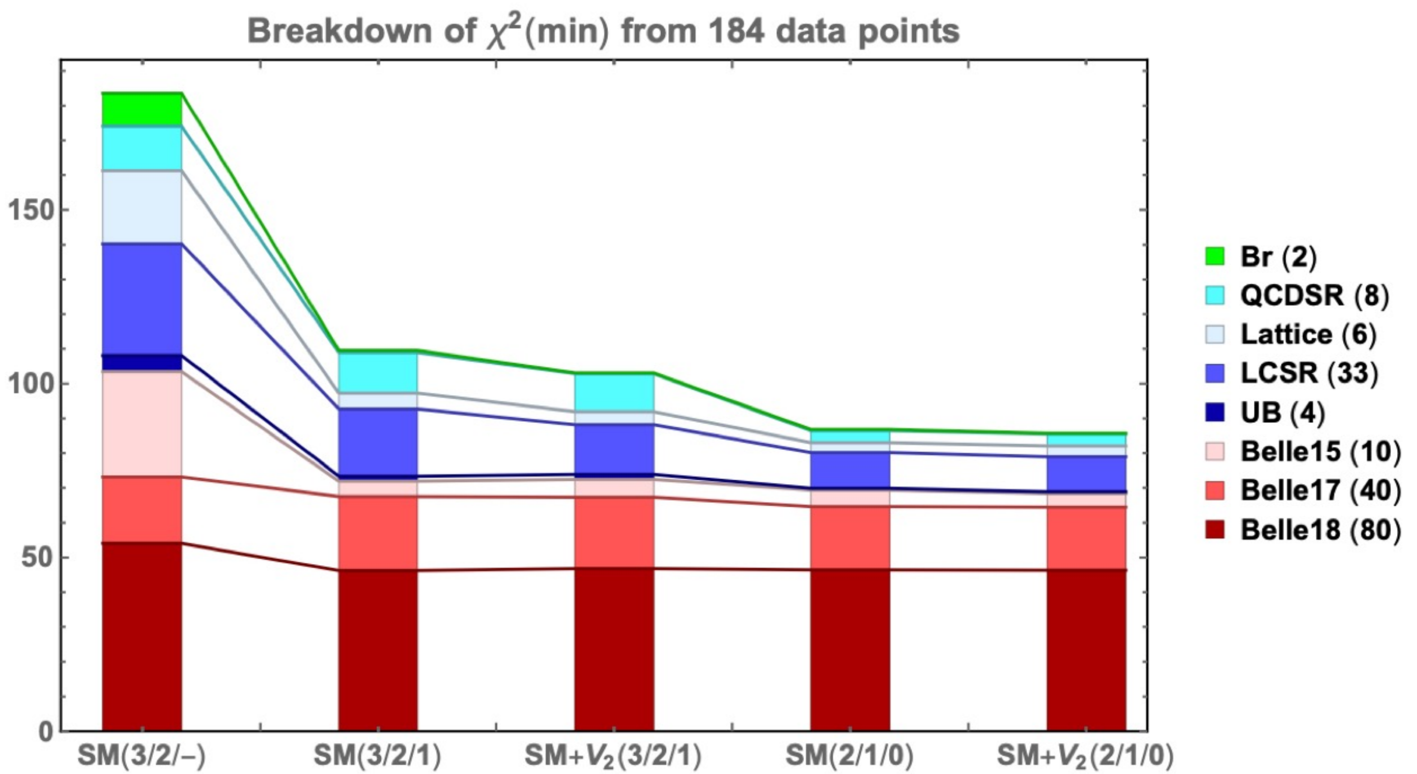
- We found the smaller RD*

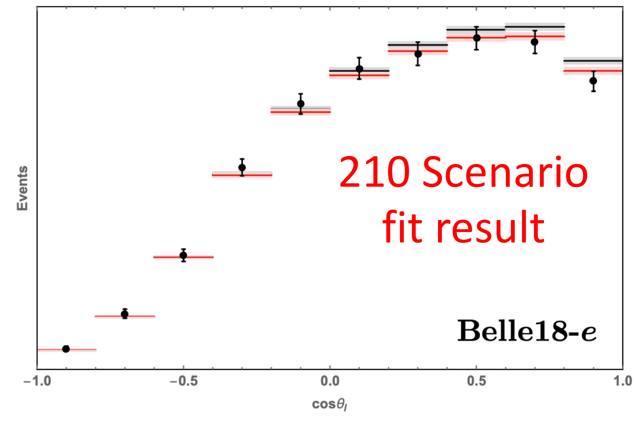
- The current discrepancy is about 4 σ

We need more experimental input from B-factory

Let's wait for it!

Fit result comparison





Scenario1: $(1+ax)^2 \sim 1 + 2ax$

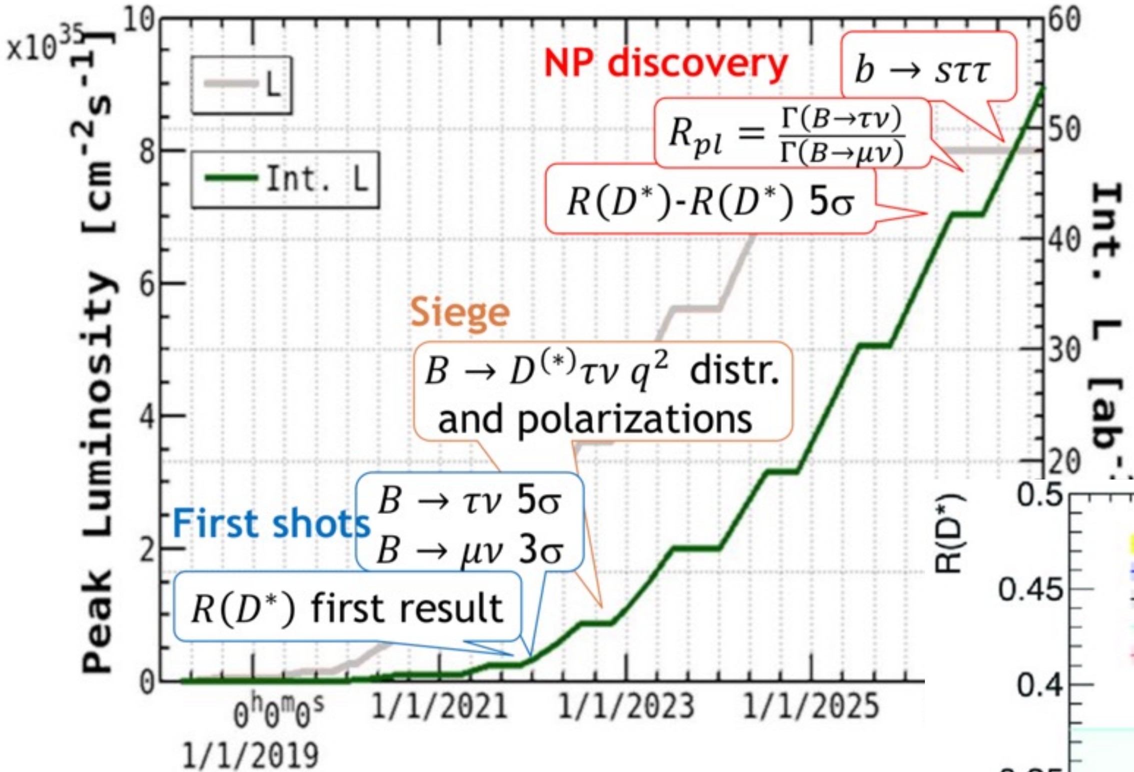
Scenario2: $(1+ax+bx^2)^2 \sim 1 + 2ax + (a^2+b^2)x^2$

Fit result comparison

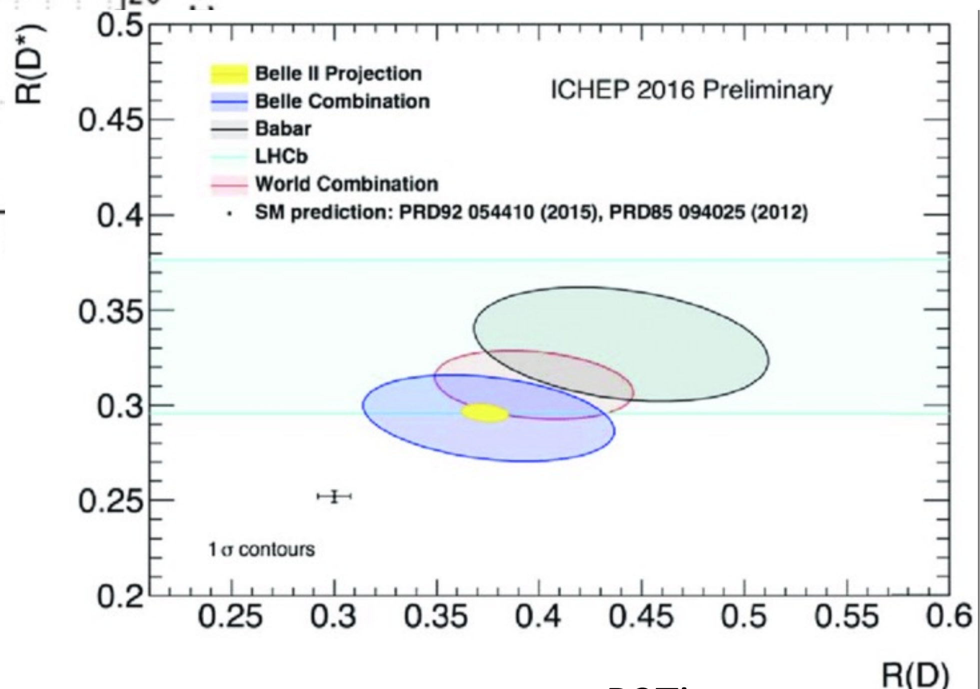
	R_D	R_{D^*}	P_τ^D	$P_\tau^{D^*}$	$F_L^{D^*}$
SM (2/1/0)	0.289 ± 0.004	0.248 ± 0.001	0.331 ± 0.004	-0.496 ± 0.007	0.464 ± 0.003
SM (3/2/1)	0.297 ± 0.006	0.245 ± 0.004	0.326 ± 0.003	-0.503 ± 0.020	0.460 ± 0.008
SM (HFLAV [40])	0.299 ± 0.003	0.258 ± 0.005	-	-	-
SM (Ref. [16])	0.297 ± 0.003	0.250 ± 0.003	0.321 ± 0.003	-0.496 ± 0.015	0.464 ± 0.010
$\mathrm{SM} + V_2$ (2/1/0)	0.282 ± 0.006	0.256 ± 0.005	0.332 ± 0.004	-0.499 ± 0.007	0.465 ± 0.003
$\mathrm{SM} + V_2$ (3/2/1)	0.282 ± 0.006	0.266 ± 0.007	0.329 ± 0.003	-0.506 ± 0.020	0.464 ± 0.008

Table 4: Predictions of the $\bar{B} \to D^{(*)}\tau\bar{\nu}$ observables.

Prospects



Slide by Kodai Matsuoka(KMI)



B2Tips

Akaike information criterion

The quantity to judge the model

$$\mathrm{AL}C = -2\, In\, L + 2k + 2k(k+1)/(n-k-1)$$

$\mathcal{L}$: maximum likelihood

k :number of model parameters, 14 for (2/1/0) and 24 for (3/2/1)

n :number of data points,184

The second term gives penalty for too many model parameters

The model with smaller AIC is favored

FF scenario	(3/2/1)		(2/1/0)			
Model	SM	SM+V_2	SM	SM+V_2	SM+T	SM+V_2 +T
$\|V_{cb}\| \times 10^3$	39.3 ± 0.6	39.9 ± 0.5	39.7 ± 0.6	39.9 ± 0.6	39.7 ± 0.6	39.9 ± 0.6
C_{NP}	-	0.05 ± 0.01	-	0.02 ± 0.01	$\|0.02 \pm 0.01\|$	$V_2 : 0.02 \pm 0.01$ $T : \|0.02 \pm 0.01\|$
$\xi^{(1)}$	-0.93 ± 0.10	-0.94 ± 0.09	-1.10 ± 0.04	-1.09 ± 0.04	-1.09 ± 0.04	-1.09 ± 0.04
$\xi^{(2)}$	$+1.35 \pm 0.26$	$+1.37 \pm 0.25$	$+1.57 \pm 0.10$	$+1.55 \pm 0.10$	$+1.56 \pm 0.10$	$+1.54 \pm 0.10$
$\xi^{(3)}$	-2.67 ± 0.75	-2.71 ± 0.73	-	-	-	-
$\hat{\chi}_2^{(0)}$	-0.05 ± 0.02	-0.05 ± 0.02	-0.06 ± 0.02	-0.06 ± 0.02	-0.06 ± 0.02	-0.06 ± 0.02
$\hat{\chi}_2^{(1)}$	$+0.01 \pm 0.02$	$+0.01 \pm 0.02$	$+0.01 \pm 0.02$	$+0.01 \pm 0.02$	$+0.01 \pm 0.02$	$+0.00 \pm 0.02$
$\hat{\chi}_2^{(2)}$	-0.01 ± 0.02	-0.02 ± 0.02	-	-	-	-
$\hat{\chi}_3^{(1)}$	-0.05 ± 0.02	-0.05 ± 0.02	-0.03 ± 0.01	-0.04 ± 0.01	-0.03 ± 0.01	-0.04 ± 0.01
$\hat{\chi}_3^{(2)}$	-0.03 ± 0.03	$+0.01 \pm 0.03$	-	-	-	-
$\eta^{(0)}$	$+0.74 \pm 0.11$	$+0.71 \pm 0.11$	$+0.38 \pm 0.06$	$+0.37 \pm 0.06$	$+0.40 \pm 0.06$	$+0.38 \pm 0.06$
$\eta^{(1)}$	$+0.05 \pm 0.03$	$+0.05 \pm 0.03$	$+0.08 \pm 0.03$	$+0.08 \pm 0.03$	$+0.08 \pm 0.03$	$+0.07 \pm 0.03$
$\eta^{(2)}$	-0.05 ± 0.05	-0.06 ± 0.05	-	-	-	-
$\hat{\ell}_1^{(0)}$	$+0.09 \pm 0.18$	$+0.19 \pm 0.18$	$+0.50 \pm 0.16$	$+0.48 \pm 0.16$	$+0.50 \pm 0.16$	$+0.49 \pm 0.16$
$\hat{\ell}_1^{(1)}$	$+1.20 \pm 2.09$	-0.70 ± 1.92	-	-	-	-
$\hat{\ell}_2^{(0)}$	-2.29 ± 0.33	-1.64 ± 0.36	-2.16 ± 0.29	-1.93 ± 0.32	-2.24 ± 0.29	-2.00 ± 0.33
$\hat{\ell}_2^{(1)}$	-3.66 ± 1.56	-2.92 ± 1.55	-	-	-	-
$\hat{\ell}_3^{(0)}$	-1.90 ± 12.4	-1.50 ± 12.6	-1.14 ± 2.34	-0.23 ± 2.39	-1.21 ± 2.29	-0.32 ± 2.41
$\hat{\ell}_3^{(1)}$	$+3.91 \pm 4.35$	$+4.29 \pm 4.31$	-	-	-	-
$\hat{\ell}_4^{(0)}$	-2.56 ± 0.94	-2.22 ± 0.94	$+0.82 \pm 0.47$	$+0.97 \pm 0.48$	$+0.76 \pm 0.47$	$+0.94 \pm 0.49$
$\hat{\ell}_4^{(1)}$	$+1.78 \pm 0.93$	$+1.82 \pm 0.91$	-	-	-	-
$\hat{\ell}_5^{(0)}$	$+3.96 \pm 1.17$	$+6.31 \pm 1.32$	$+1.39 \pm 0.43$	$+2.03 \pm 0.59$	$+1.32 \pm 0.43$	$+1.99 \pm 0.59$
$\hat{\ell}_5^{(1)}$	$+2.10 \pm 1.47$	$+2.29 \pm 1.51$	-	-	-	-
$\hat{\ell}_6^{(0)}$	$+4.96 \pm 5.76$	$+7.15 \pm 5.87$	$+0.17 \pm 1.15$	$+0.90 \pm 1.23$	$+0.06 \pm 1.15$	$+0.81 \pm 1.24$
$\hat{\ell}_6^{(1)}$	$+5.08 \pm 2.97$	$+5.52 \pm 3.04$	-	-	-	-
ΔIC	118.1	128.4	162.4	161.5	161.3	160.4

ΔAIC=AIC(3/2/0)- AIC

Larger ΔAIC model is favored

According to AIC SM(2/10) is better than SM(3/2/1)