Correlating new physics signals in flavor and possible impact for collider experiments

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BASED PRIMARILY ON NANDI, PATRA, AS [1605.07191] + WHEPP XIV, IIT KANPUR, INDIA DEC 2015

Outline

- **RD(*) and hints of NP; really?**
- **Important Correlation(s)**
- **If NP then a possible simple example**
- **Introduce other useful observables that could help clarify**
- **Summary & Outlook**

Season of anomalies….countless B-physics, K-physics, g-2, ATLAS-CMS diboson, sigma(tth); H=>mu tau ……

2 -3.5 sigma effects: while most [and may be all] will go away, not following can be a very serious mistake

R(D(*)): concerns

BaBar’s very nice idea

BABAR ’12

Independent of Vcb!

- To test the SM Prediction, we measure

$$R(D) = \frac{\Gamma(\overline{B} \to D\tau\nu)}{\Gamma(\overline{B} \to D\ell\nu)} \qquad R(D^*) = \frac{\Gamma(\overline{B} \to D^*\tau\nu)}{\Gamma(\overline{B} \to D^*\ell\nu)}$$

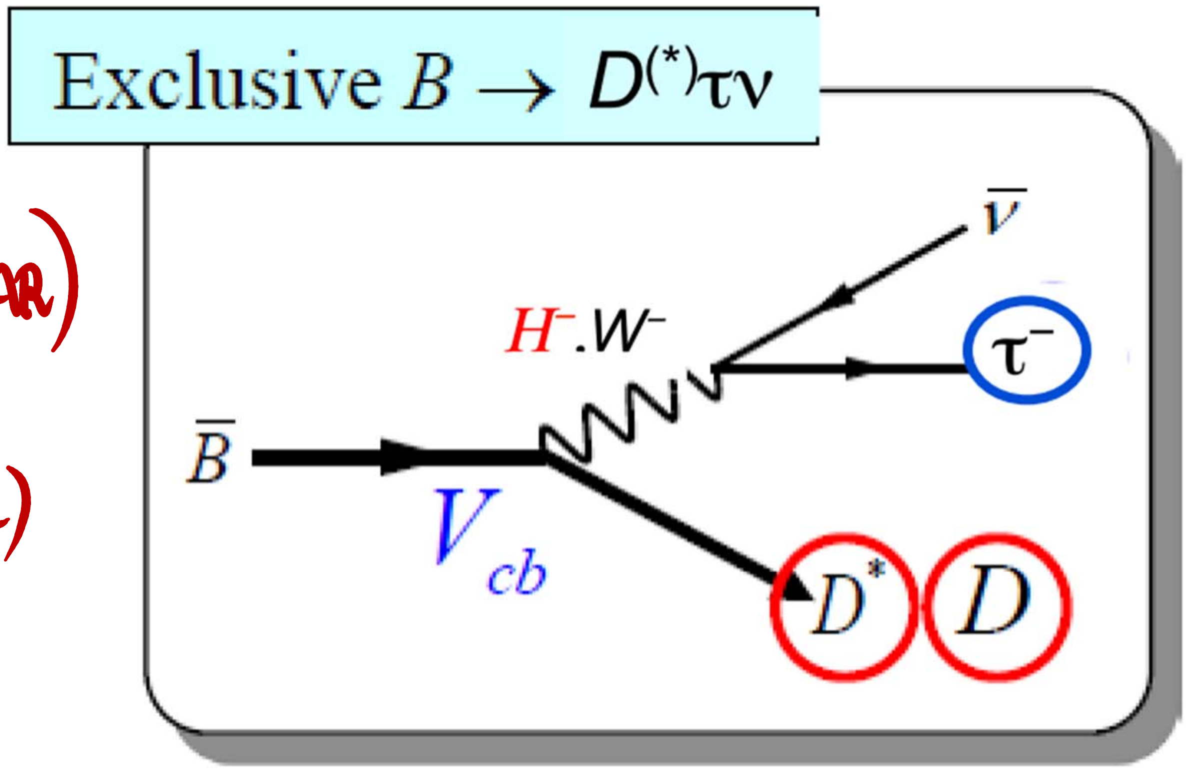
Leptonic τ decays only

Several experimental and theoretical uncertainties cancel in the ratio!

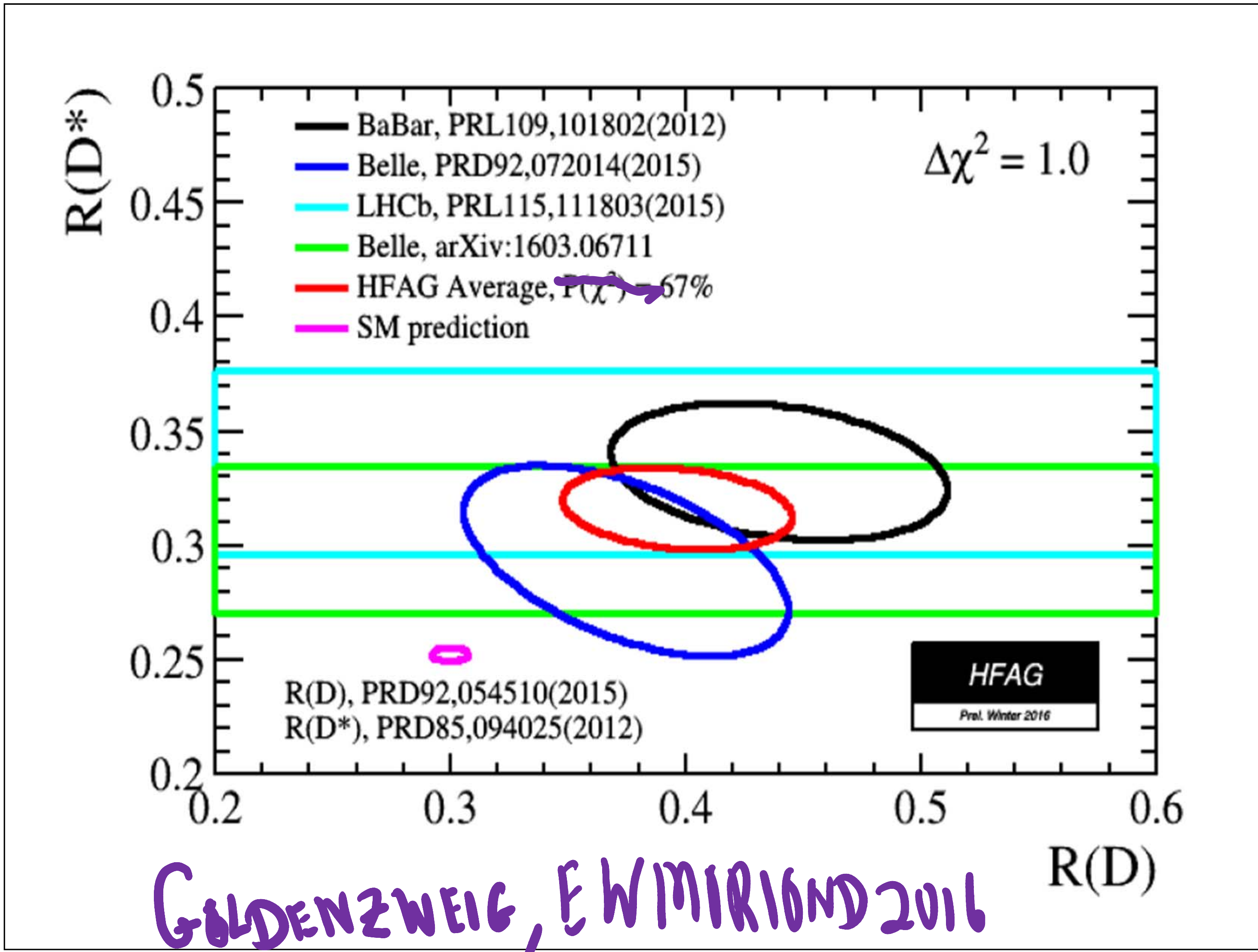
- BB events are fully reconstructed:

Suggested in theory papers for a long time
See e.g. Kiers & AS PRD’97; Kamenik et al PRD’08; Nierste et al PRD’08

RA LUTH (BABAR)
CP May 2012
(HEFEI, China)



MANUEL FRANCO
SEVILLA
PhD Thesis
SLAC



Lots of excitement for past ~ 3 years!
Claimed~3.9σ!
BUT.....

Decay	N_{sig}	N_{norm}	$R(D^{(*)})$	$\mathcal{B}(B \to D^{(*)}\tau\nu)$ (%)	$\Sigma_{tot}(\sigma)$
$D^0\tau^-\overline{\nu}_\tau$	314 ± 60	1995 ± 55	$0.429 \pm 0.082 \pm 0.052$	$0.99 \pm 0.19 \pm 0.13$	4.7
$D^{*0}\tau^-\overline{\nu}_\tau$	639 ± 62	8766 ± 104	$0.322 \pm 0.032 \pm 0.022$	$1.71 \pm 0.17 \pm 0.13$	9.4
$D^+\tau^-\overline{\nu}_\tau$	177 ± 31	986 ± 35	$0.469 \pm 0.084 \pm 0.053$	$1.01 \pm 0.18 \pm 0.12$	5.2
$D^{*+}\tau^-\overline{\nu}_\tau$	245 ± 27	3186 ± 61	$0.355 \pm 0.039 \pm 0.021$	$1.74 \pm 0.19 \pm 0.12$	10.4
$D\tau^-\overline{\nu}_\tau$	489 ± 63	2981 ± 65	$0.440 \pm 0.058 \pm 0.042$	$1.02 \pm 0.13 \pm 0.11$	6.8
$D^*\tau^-\overline{\nu}_\tau$	888 ± 63	11953 ± 122	$0.332 \pm 0.024 \pm 0.018$	$1.76 \pm 0.13 \pm 0.12$	13.2

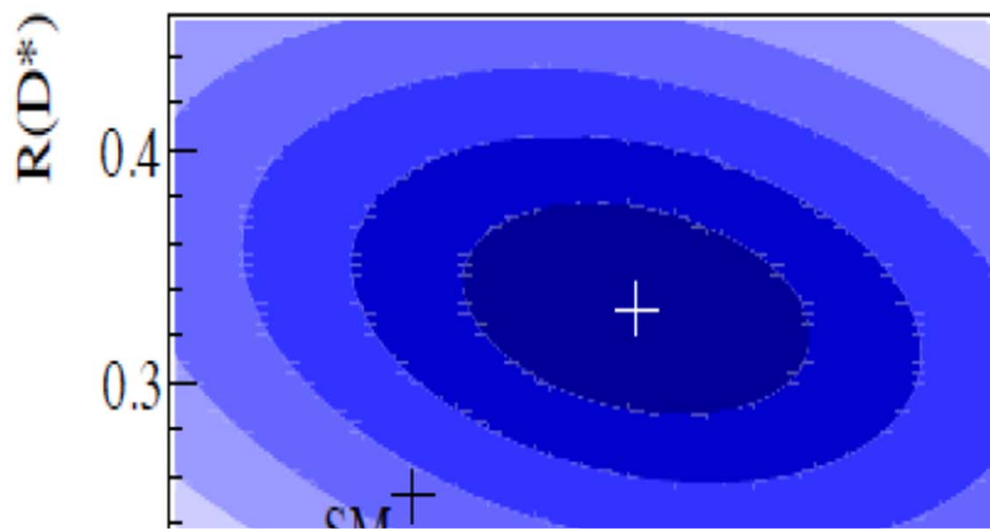
omparison with SM calculation:

LUTH

Combined 3.4σ

	R(D)	R(D*)
BABAR	0.440 ± 0.071	0.332 ± 0.029
SM	0.297 ± 0.017	0.252 ± 0.003
Difference	**2.0 σ**	**2.7 σ**

he combination of the two measurements
0.27 correlation) yields χ^2/NDF=14.6/2,
Prob = 6.9 x10^{-4} !!



Combination to 3.4 sigma is too aggressive and worrysome

$$H_t^{2\mathrm{HDM}} = H_t^{\mathrm{SM}} \times \left(1 \mp \frac{\tan^2\beta}{m_{H\pm}^2} \frac{q^2}{1 \mp m_c/m_b}\right)$$

- for $D\tau\nu$
+ for $D^*\tau\nu$

This could enhance or decrease the ratios R(D*) depending on $\tan\beta/m_H$

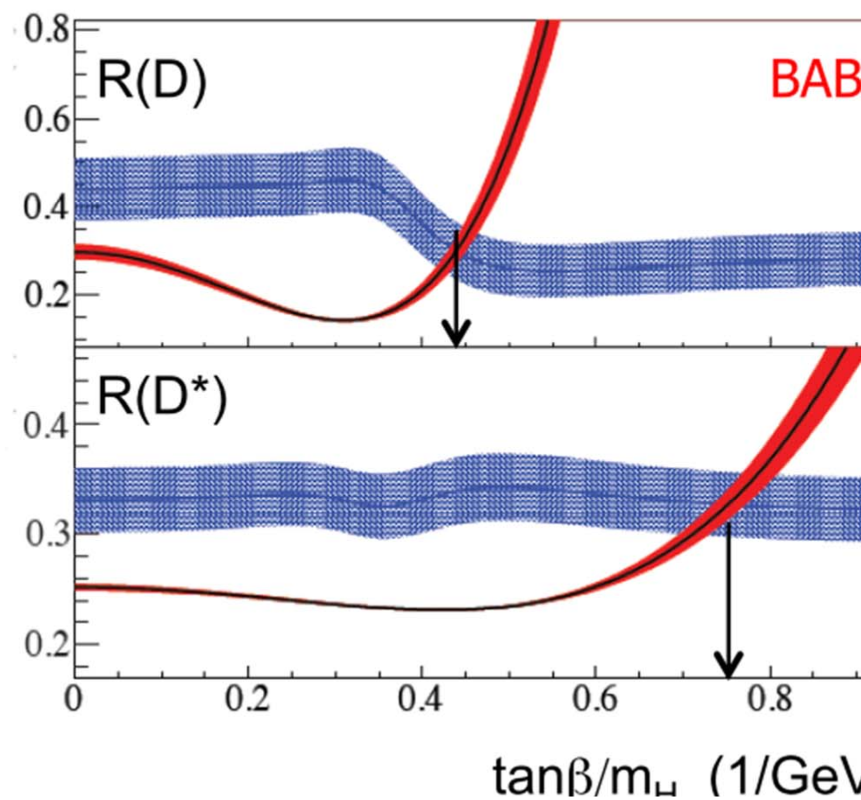
We estimate the effect of 2DHM, accounting for difference in efficiency, and its uncertainty

The data match 2DHM Type II at

$\tan\beta/m_H = 0.44 \pm 0.02$ for R(D)

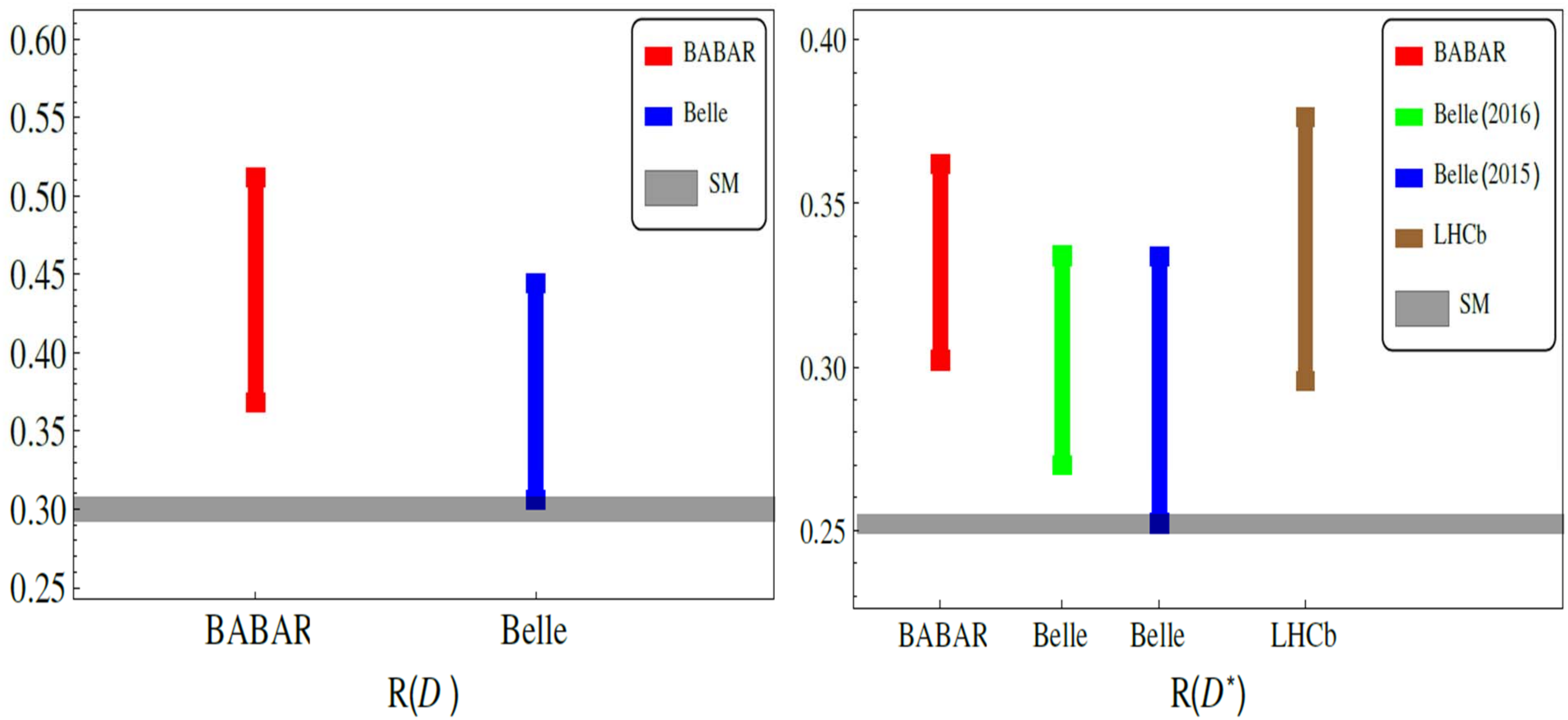
$\tan\beta/m_H = 0.75 \pm 0.04$ for R(D*)

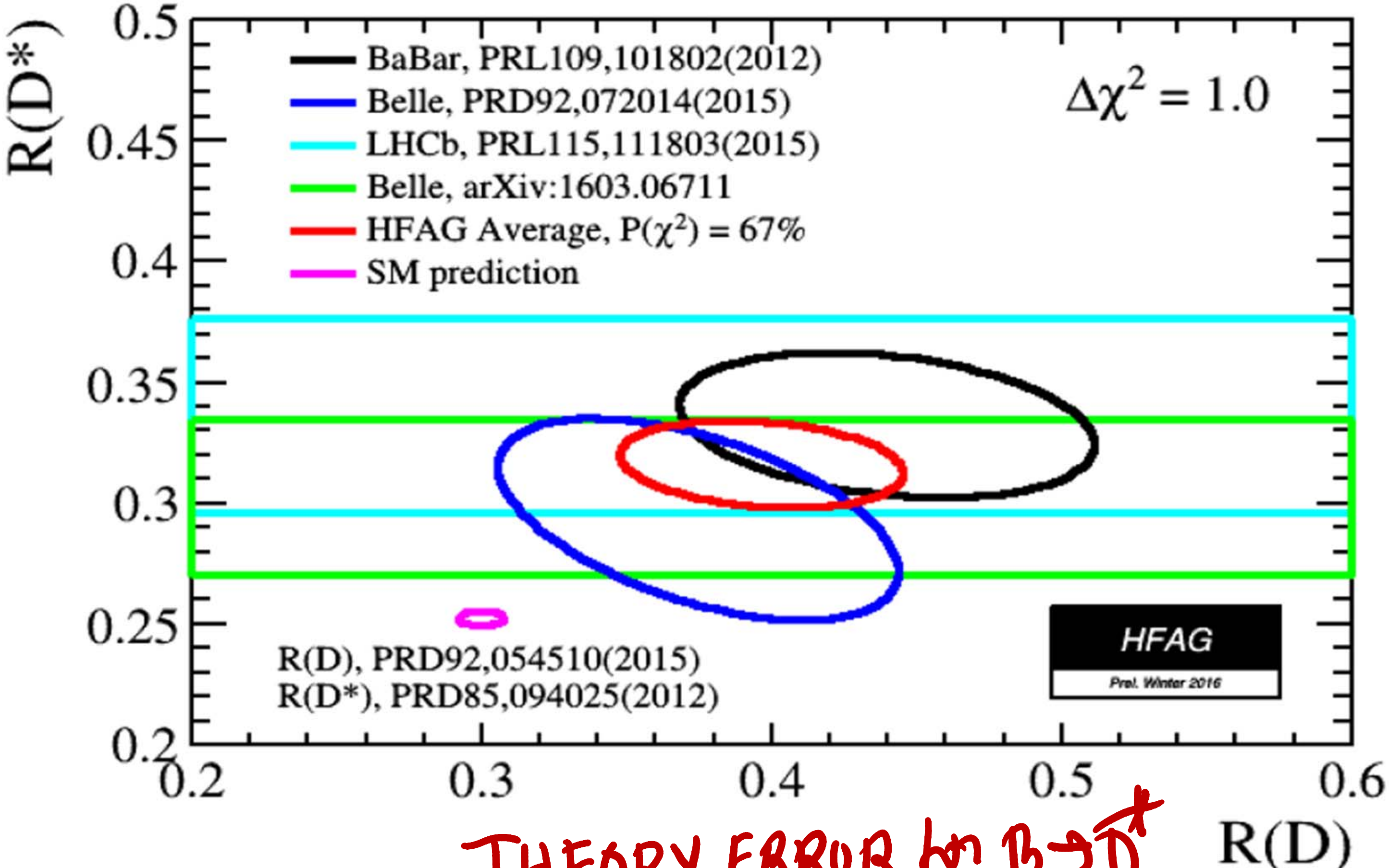
However, the combination of R(D) and R(D*) excludes the Type II 2HDM in the full $\tan\beta$-m_H parameter space with a probability of >99.8%, provided M_H>10GeV !



The conclusion that type II 2HDM is ruled out seems premature

Enter Belle & LHCb


0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
BABAR
Belle
SM
BABAR
Belle
R(D)
0.40
0.35
0.30
0.25
BABAR
Belle(2016)
Belle(2015)
LHCb
SM
BABAR
Belle
Belle
LHCb
R(D*)



LHCb can only do D*

THEORY ERROR for $B \to D^*$ APPEAR UNDERESTIMATED

$B \to D$ 2 FF
$B \to D^*$ 4 FF

Stated Theory errors on RD* a concern

Béranger Dumont,[1] Kenji Nishiwaki,[2,*] and Ryoutaro Watanabe[1,] 1603.05248

$$R(D)^{\text{exp.}} - R(D)^{\text{SM}} = 0.089 \pm 0.051\,,$$ ~ 1.86

$$R(D^*)^{\text{exp.}} - R(D^*)^{\text{SM}} = 0.070 \pm 0.022\,,$$ 3.26

⇓ > 0.051 ↓ 1.46

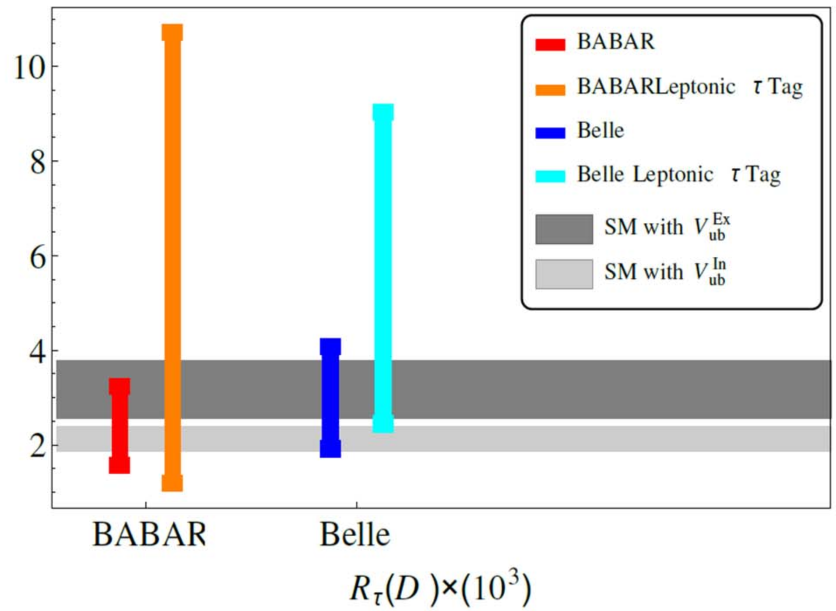
Bearing in mind all of the above, try a different route

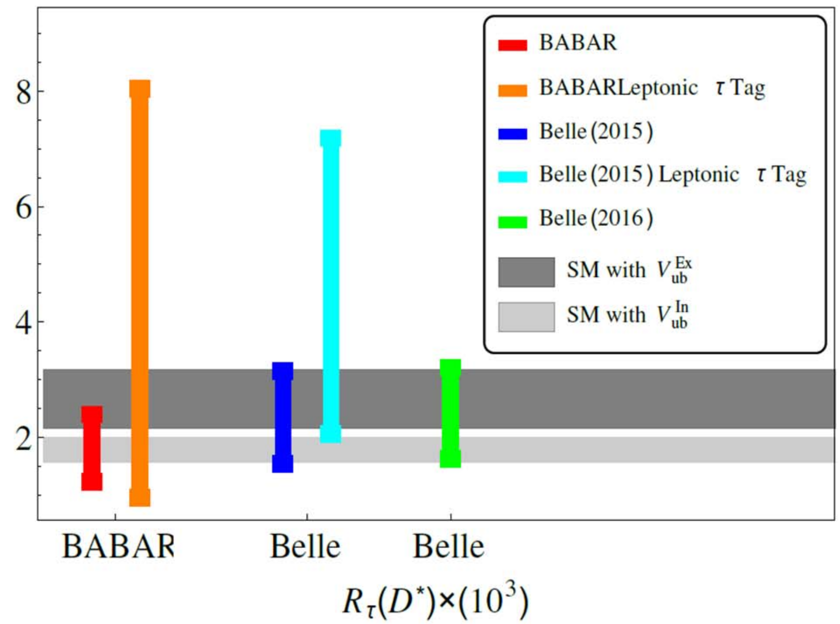
- **Introduce a new observable:**

$$R_\tau(D^{(*)}) = \frac{\mathcal{R}(D^{(*)})}{\mathcal{B}(B^+ \to \tau^+ \nu_\tau)}$$

- **This is designed to be less sensitive to possible systematics afflicting tau detection though this depends on Vub but…[excl Vub is essentially correct]**

See Nandi, Patra + AS, 1605.07191 [NPS]





REMARKABLY: NO deviation from the SM; all the few sigma problems are gone in here!

IN SHARP CONTRAST TO $R_{D(*)}$

Two conclusions
Experimental Systematics due tau detection cancel in this constructed ratio.

Hardly any indication of NP in here.
If there is any new physics then it seems largely cancelling away and an important consequence then is that Type II 2HDM may well be well and alive

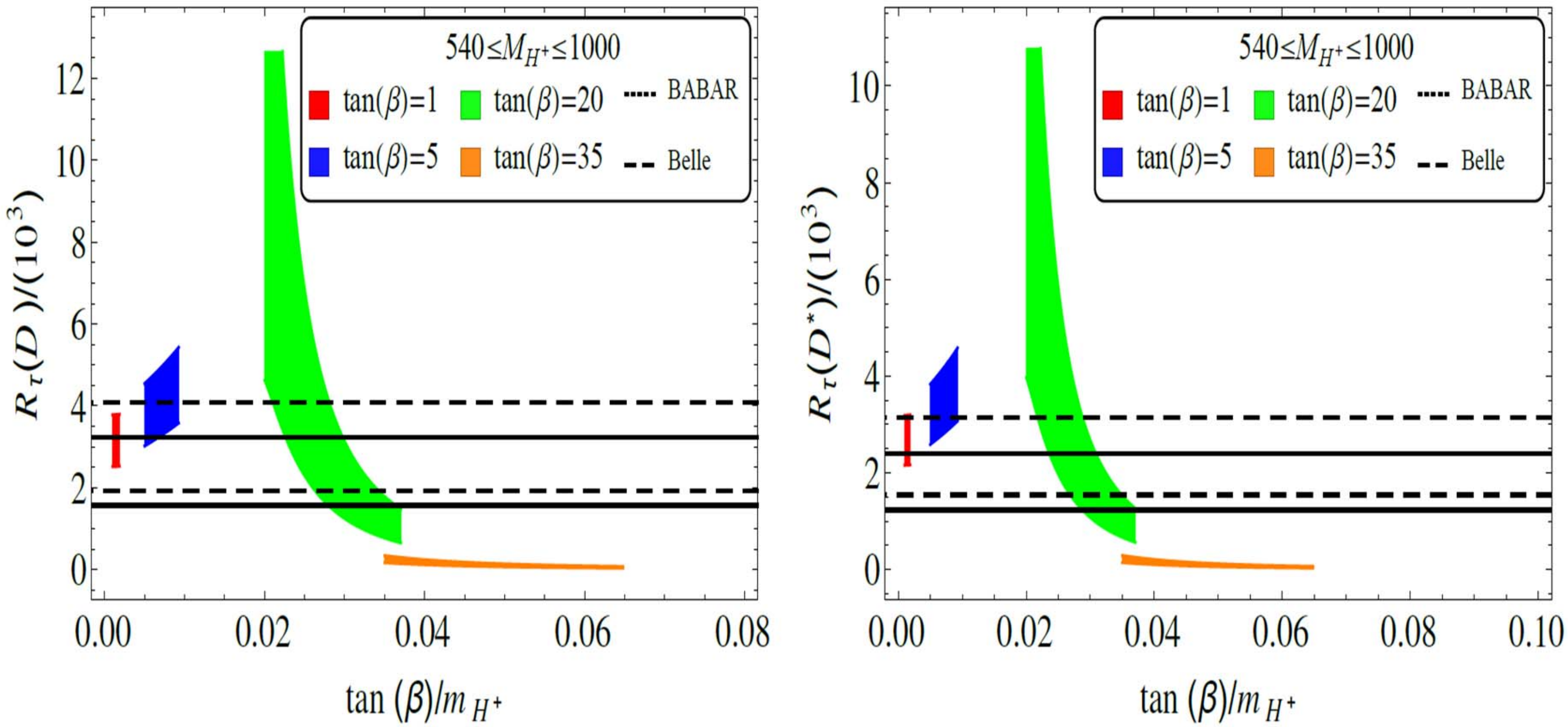


FIG. 7: Variations of $R_\tau(D)$ (left) and $R_\tau(D^*)$ (right) with the 2HDM-II parameter $r = \tan\beta/m_{H^+}$ for different values of $\tan\beta$. The 1σ experimental ranges are shown by the dotted (BABAR) and dashed (Belle) lines.

NPS   e.g. $\tan\beta \sim 20$ + $m_H \gtrsim 500$ GeV OK

$\tan\beta \gtrsim 30$ Ruled out

Extension to $\mathcal{R}(\pi)$ and $\mathcal{R}_{\tau}^{\pi}$

NPS

- Given that R(D(*)) are independent of Vcb, it is extremely important that semi-leptonic(tuonic) final states into pion be also considered, though the basic rates are rarer and higher luminosities are clearly needed but for a reliable understanding of underlying issues these extensions are well motivated.

For 1st lattice calculations see RBC-UKQCD, J. Flynn et al, PRD91, '15

See NPS

Introduce $\mathcal{R}(\pi)$ and $\mathcal{R}^{\pi}_{\tau}$

Both independent of Vub

$$\mathcal{R}(\pi) = \frac{\mathcal{B}(B \to \pi\tau\bar{\nu}_\tau)}{\mathcal{B}(B \to \pi\ell\bar{\nu}_\ell)}$$

New

$$\mathcal{R}^{\pi}_{\tau} = \frac{\mathcal{B}(B \to \pi\tau\bar{\nu}_\tau)}{\mathcal{B}(B \to \tau\nu_\tau)}$$

Insensitive to tau detection systematics

also for $B \to D(D^*)$

$$\frac{d\Gamma(B \to \pi\tau\bar{\nu}_\tau)}{dq^2} = \frac{8|\vec{p}_\pi|}{3}\frac{G_F^2|V_{ub}|^2q^2}{256\pi^3m_B^2}\left(1-\frac{m_\tau^2}{q^2}\right)^2 \left[H_0^2(q^2)\left(1+\frac{m_\tau^2}{2q^2}\right)+\frac{3m_\tau^2}{2q^2}H_t^2(q^2)\right]$$

Another useful observable

- **Asymmetry , e.g.   B(s)=>P l nu …..l+nu rest frame**

Flynn et al [RBC-UKQCD]PRD 91, ‘15; Meissner and Wang, 1311.5420

$$\mathcal{A}_{FB}^{B_{(s)}\to P\ell\nu}(q^2) \equiv \left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_\ell \frac{d^2\Gamma(\bar{B}_{(s)} \to P\ell\nu)}{dq^2 d\cos\theta_\ell}$$

- **For all these observables, RD(*),** $R_\tau(D^{(*)})$ $\mathcal{R}(\pi)$ $\mathcal{R}_\tau^\pi$

Lattice is highly relevant ……In drive for precision the corresponding ratios should also be systematically calculated on the lattice thereby reducing statistical fluctuations and also some systematics and with proper a/c of correlations

$$R(\pi)^{SM} = 0.598 \pm 0.024 \qquad \mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell) = (1.45 \pm 0.05) \times 10^{-4}$$

$$\mathcal{B}(B^0 \to \pi^- \tau^+ \nu_\tau) < 2.5 \times 10^{-4}$$

The current upper limit of $R(\pi) < 1.784$.

$$\mathcal{R}_\tau^{\pi,SM} = 0.733 \pm 0.144 \qquad \mathcal{B}(B^+ \to \tau \nu_\tau) = 1.25 \pm 0.08 \times 10^{-4}$$

The current upper limit for $\mathcal{R}_\tau^\pi < 2.62$

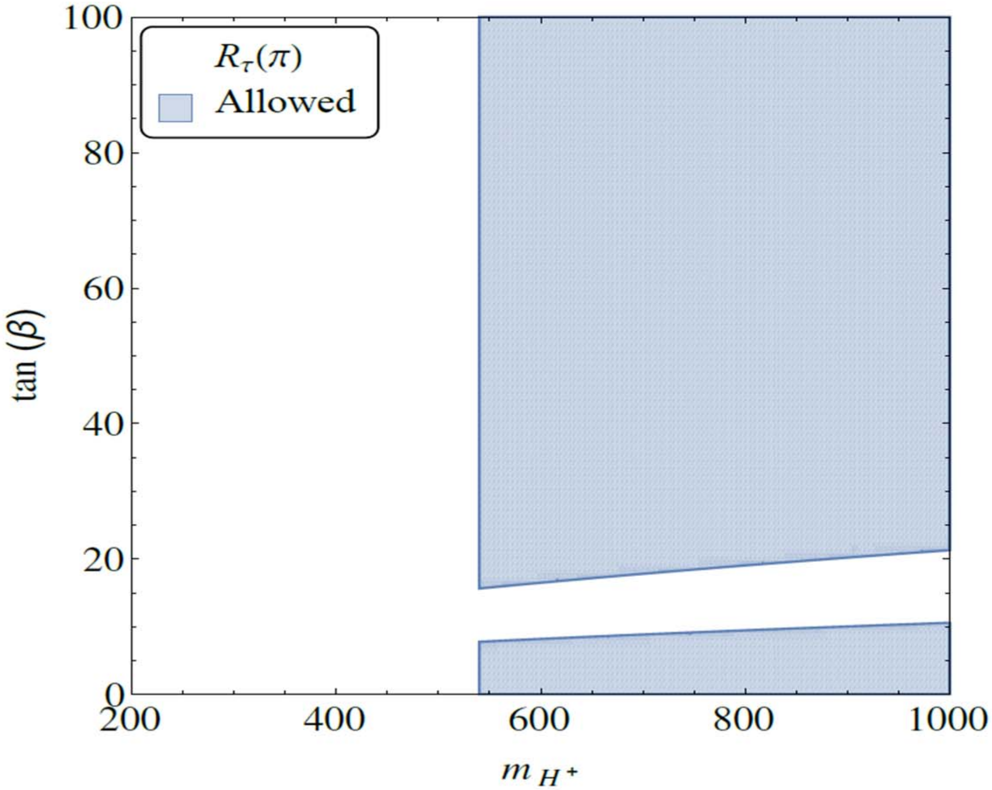


FIG. 13: Allowed parameter space for $\tan\beta$ and M_{H+} obtained from the analysis of $R_\tau(\pi)$ in 2HDM-II.

Since $B \to \pi \tau \nu_\tau$ not yet measured ample parameter space still allowed

Take home

- **The best test for NP is B=> tau nu [even though RD and RD* do also give impt info]**

- **Interpreted in terms of NP, type II-2HDM with tan beta less than about 30 is a viable candidate [good news for SUSY]**

- **Belle-II with 20-40 X stat should be able to decisively test the SM with B=>tau nu; improved lattice calculations in the next few years should also be extremely useful for this purpose.**
- **Improved determination of B=>tau nu also has important repercussion for UT[don't need use s.l. decays]   …see Lunghi + AS, PRL' 10**

Summary & Outlook [p1 of 2]

- **R D(*) indications of NP are very interesting, careful understanding of experimental systematics of tau detection are essential as they are the likely source.**
- **BaBar and LHCb each seem to see about ~ 2 σ deviation from SM in RD* and BaBar also in RD.**
- **Belle is consistent with SM at about 1.4 σ**
- **But stated theory error in RD* appear underestimated ; currently no lattice calculation on RD*….Given that B=>D* has 4 form factors and B=>D only two, it is difficult to see why theory errors should be so much smaller in B=>D* than in B=>D.**
- **Part of the explanation of these deviations is probably**

experimental tau systematics bearing in mind that historically tau has always been very difficult and also because normalized ratios appear consistent with SM for both Belle and BaBar. [At present this cannot be done for LHCb]

Summary & Outlook [p.2]

- **However, if R D(*) anomaly is due NP, then that NP is also in the simpler B=>tau nu; better measurement of Br of B=>tau nu for this and other reasons is exceedingly important.**
- **It does not appear that type II, 2HDM is ruled out....(good news for SUSY) . And indeed 2HDM II with mH+ > ~500 GeV and tan β< ~25 offers a plausible explanation**
- **Collider searches for H^+, e.g. in t b, Wh(Z) are very well motivated**
- **HIGH HOPES FOR RUN II, [upgraded] LHCb & Belle-II and better theory calculations for illuminating many of these puzzles in the next few years**

EXTRAS

For R=>pi l(tau) nu

$$|\vec{p}_\pi| = \sqrt{\left(\frac{m_B^2 + m_\pi^2 - q^2}{2m_B}\right)^2 - m_\pi^2}$$

and $H_{0/t}$ are helicity amplitudes defined as

$$H_0 = \frac{2m_B|\vec{p}_\pi|}{\sqrt{q^2}} f_+(q^2)$$

$$H_t = \frac{m_B^2 - m_\pi^2}{\sqrt{q^2}} f_0(q^2) \,.$$

II. TWO-HIGGS-DOUBLET MODEL WITH *CP* VIOLATION IN THE NEUTRAL HIGGS SECTOR

The model we use as the source for *CP* violation is a THDM [5,6] namely, a nonminimal SM with the two complex Higgs fields Φ_1 nd Φ_2, in which *CP* violation arises from exchanges of neutral Higgs particles. Flavor-changing neutral currents (FCNC's) at the tree level, will appear in the theory if the two vacuum expectation values (VEV's) contribute to the quark mass matrices. To avoid FCNC's one can impose the discrete symmetry D,

$$D : \Phi_2, u_{iR} \to -\Phi_2, -u_{iR} \ , \tag{1}$$

which gives the coupling scheme [10]

$$u_R \leftrightarrow \Phi_2, d_R, l_R \leftrightarrow \Phi_1 \ . \tag{2}$$

The invariant quark Yukawa interactions then read

$$\mathcal{L}_Y = -(\bar{u}_i, \bar{d}_i)_L \Gamma_u^{ij} \tilde{\Phi}_2 u_{jR} - (\bar{u}_i, \bar{d}_i)_L \Gamma_d^{ij} \Phi_1 d_{jR} + \text{H.c.} \ , \tag{3}$$

In general the Higgs potential can be written as:

$$V(\Phi_1, \Phi_2) = V_{\text{symm}}(\Phi_1, \Phi_2) + \delta V_{\text{soft}}(\Phi_1, \Phi_2) \ , \qquad (4)$$

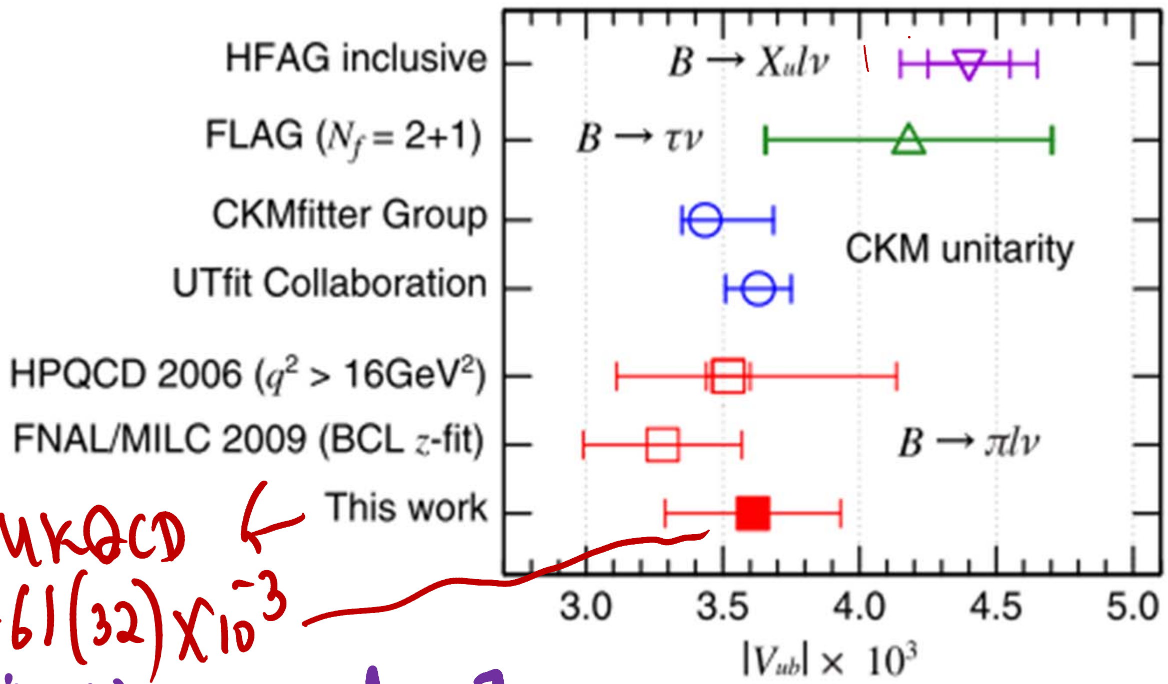
where $V_{\text{symm}}(\Phi_1, \Phi_2)$ is the part of the potential which is symmetric under D while δV_{soft} breaks this discrete symmetry and depends on the phases of Φ_1, Φ_2. In particular,

$$\delta V_{\text{soft}} = \mu \Phi_1 \Phi_2^+ + k(\Phi_1^+ \Phi_2)^2 + \text{H.c.} \qquad (5)$$

If $\text{Im}(k/\mu^2) \neq 0$, which is being assumed throughout this paper, then CP is no longer a symmetry of the Higgs potential. This will induce mixing between real and imaginary parts of the Higgs fields in the mass matrix of the Higgs boson, which means that the mass eigenstates do not have a definite CP property. Therefore, in the THDM CP violation may emanate from the neutral Higgs sector even when there is none in the charged Higgs sector. In general, the manifestation of such CP violation is that the neutral Higgs boson mass eigenstates couple to fermions with both scalar and pseudoscalar couplings.

For $e^+e^- \to t\bar{t}H^0$ the following interaction terms (which appear in a THDM) in $\mathcal{L}$ are required [5]:

$$\mathcal{L}_{H_j^0} = H_j^0 \bar{f}(a_{fj} + i b_{fj}\gamma_5) f + H_j^0 c_j g_{\mu\nu} Z^\mu Z^\nu + \frac{c_j}{2M_Z}[\chi^0(\partial_\mu H_j^0) - (\partial_\mu \chi^0) H_j^0] Z^\mu \ , \qquad (6)$$



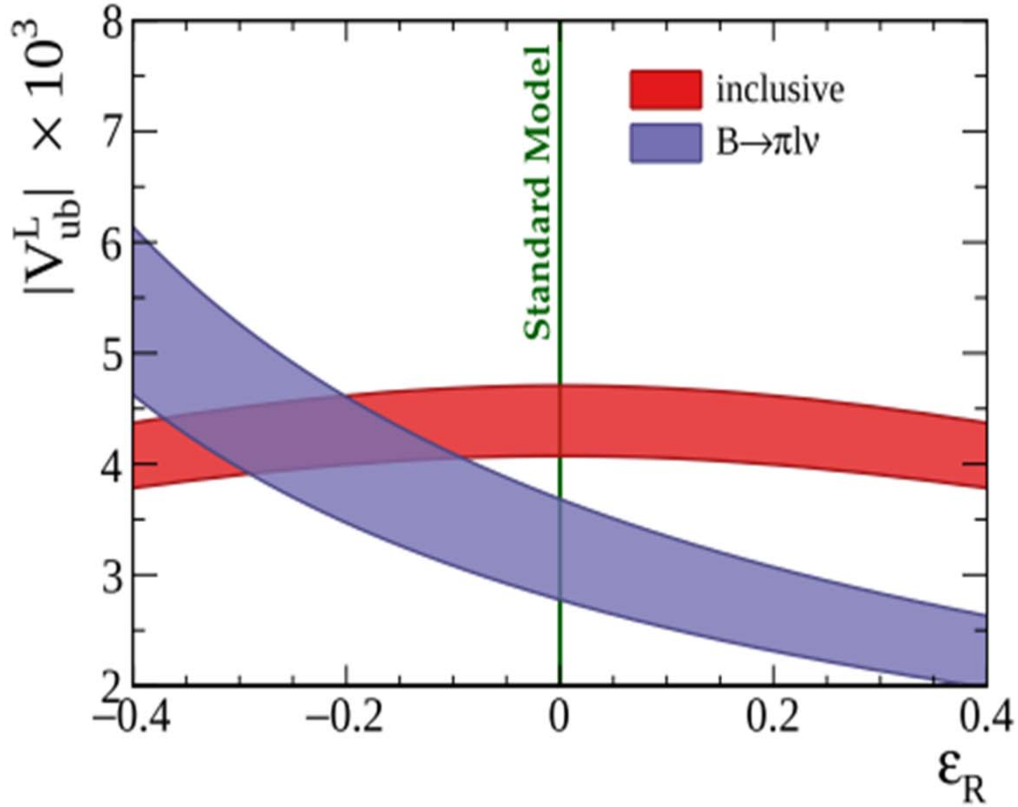
$(4.40 \pm 0.22) \times 10^{-3}$

MILC 2015
$3.72(16) \times 10^{-3}$

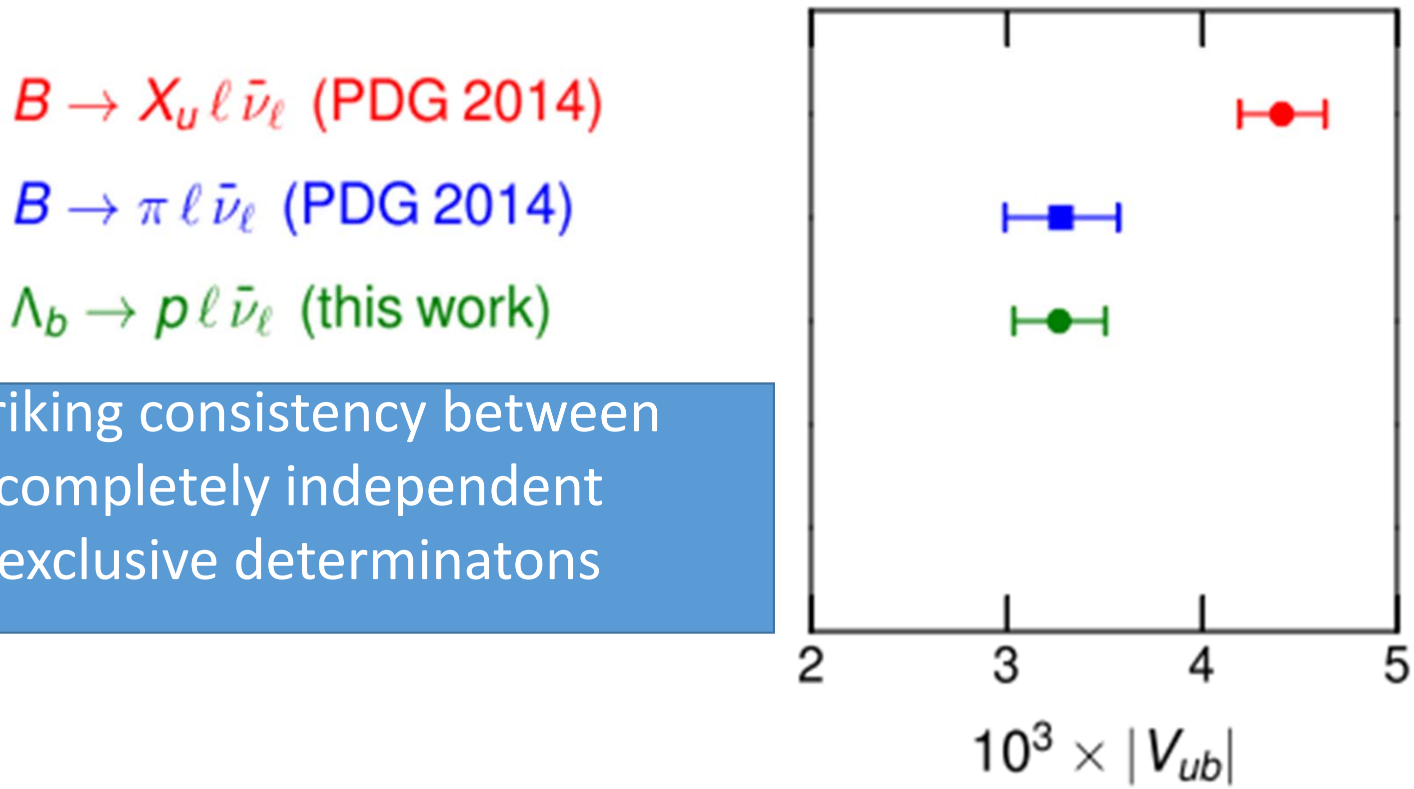
RBC-UKQCD
$V_{ub} = 3.61(32) \times 10^{-3}$
[USED in pheno analysis]

FIG. 22 (color online). Determinations of $|V_{ub}|$ from Table XIV. For points with double error bars, the inner error bars are experimental while the outer error bars show the total experimental plus theoretical uncertainty added in quadrature.

Fig from RBC-UKQCD PRD 2015



SOME introduce NP [RHC] to explain the diff



Striking consistency between completely independent exclusive determinatons

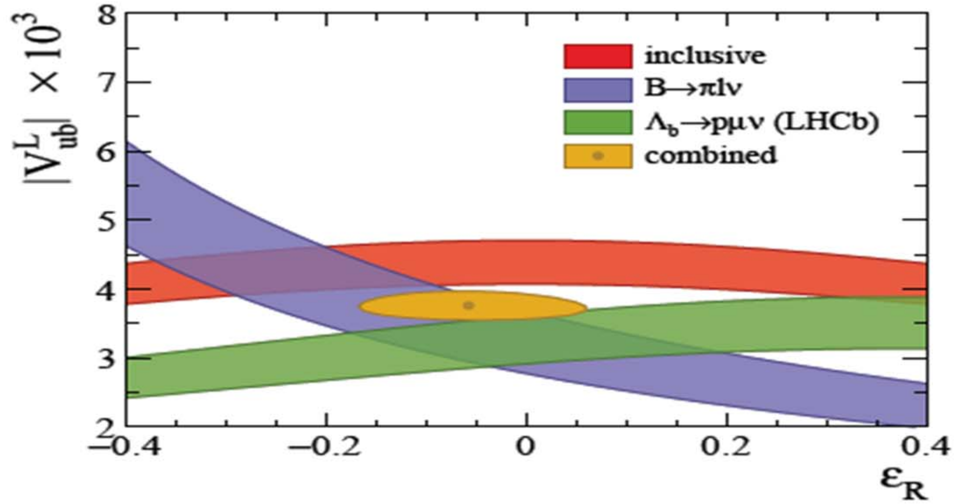
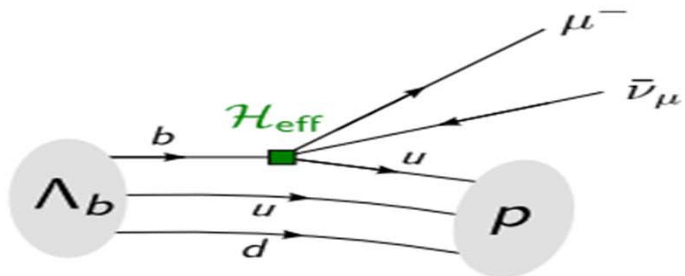


Figure 4: **Experimental constraints on the left-handed coupling, $|V_{ub}^{\mathbf{L}}|$ and the fractional right-handed coupling, ϵ_R.** While the overlap of the 68% confidence level bands for the inclusive [14] and exclusive [7] world averages of past measurements suggested a right handed coupling of significant magnitude, the inclusion of the LHCb $|V_{ub}|$ measurement does not support this.

LHCb 1504.01586
Nature

RULES OUT RHC



LHCb + Lattice

- At LHCb, $p\mu\bar{\nu}$ final state easier to identify than $\pi\mu\bar{\nu}$
- Complementary constraints on right-handed coupling

"$\Lambda_b \to p\,\ell^-\,\bar{\nu}_\ell$ and $\Lambda_b \to \Lambda_c\,\ell^-\,\bar{\nu}_\ell$ form factors from lattice QCD with relativistic heavy quarks"

[W. Detmold, C. Lehner, S. Meinel, arXiv:1503.01421 (~~to appear in~~ PRD)]

MIT   HET-BNL → RBRC-BNL

My (subjective) summary on V_{ub}

Bearing in mind the clean signal for experiment and also confirmation of exclusive meson versus baryonic extractions of V_{ub} and the simplicity of exclusive lattice studies

- **Most likely the resolution lies in some small underestimate of errors in both experiment and in theory in inclusive extraction rather than new physics**

Outlook for next 3-5 years

- **~40 times more data from BELLE II………**
- **Similarly…lot more data from LHCb anticipated**
- **Factor ~20 or even more computing power now for lattice**

- **Significant progress on this issue expected in ~3 years i.e. expect Vub errors from lattice studies to go down from ~7% now to around 3-4%**

Vub "anomaly" i.e inclusive ⇔exclusive tension

C also Grinstein

- **Exclusive….Experimentally as well as for theory is clean; esp since modes are accessible to the lattice=>B=> π l ν…..**
- **Inclusive…..experimental and theoretical difficulties**
- **Large background; need to discriminate from cascade charm decays…….[Recall Vub/Vcb ~0.08]**
- **Absence of symmetry [unlike b => c l ν]**

$B \to X_u l \nu$

↓ No Charm