[GLIMPSES of]
↓

CP violation theory: SM & more

Amarjit Soni
HET-BNL

Heavy Quarks and Leptons

Virginia Tech, 05/26/16

[APPOLOGIES: HIGHLY SUBJECTIVE]

Outline

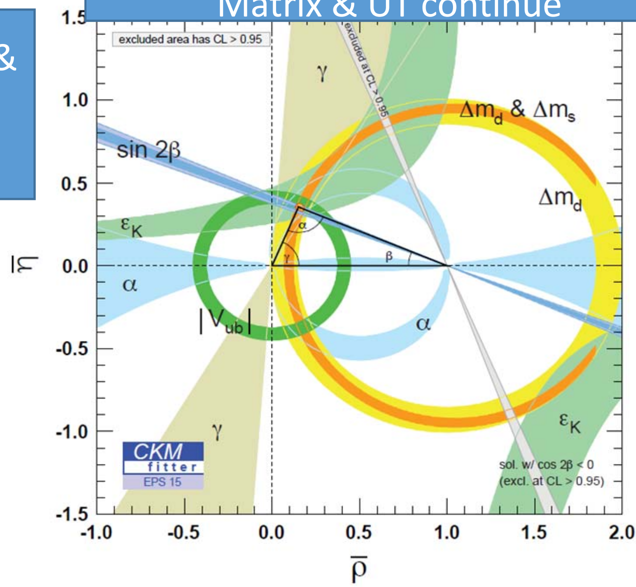
- **SM-CKM**
- **Recent update & near future expectations**

- **BSM**
- **Motivation …..theory**
- **Possible experimental hints…….[some critique]**
- **Strategies for the near future for BSM-CP searches**

- **Summary & Outlook**

Andreas Hoecker & Malcolm John
EW Moriond '16

Efforts to overconstrain the CKM Matrix & UT continue



Compatible with SM-CKM to ~15% accuracy

O(5-10%) new physics is possible and is HUGE

Key new results from LHCb

DATA DRIVEN Methods

Precision on sin(2β) approaches that of B-factories: 0.73 ± 0.04 ± 0.02

ITE ~ 1%
Mannel et al

- A world-leading measurement of γ is made from a combination of LHCb analysis, concluding with

$$\gamma = 70.9^{+7.1}_{-8.5}$$

ITE ~10^{-7} !!
Brod Zupan'14
STD. CANDLE

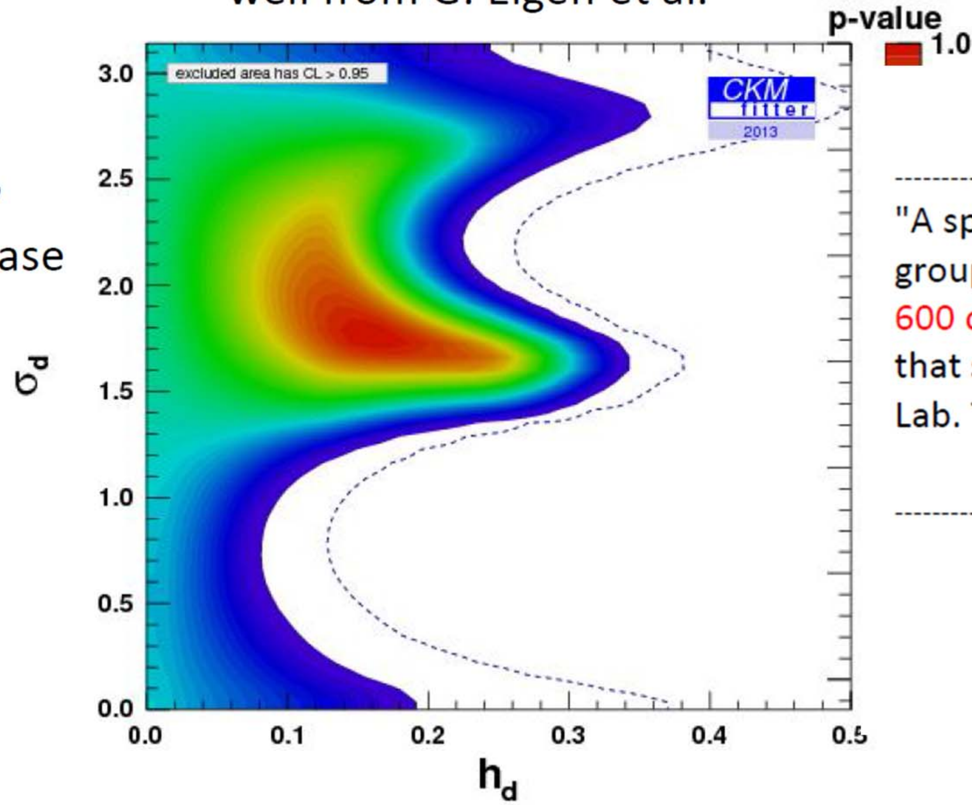
which improved the previous LHCb-only conclusion by 2°

- Inline with B-factory conclusions from $B \to DK$,
  - BaBar: $\gamma = (70 \pm 18)°$
  - Belle: $\gamma = (73^{+13}_{-15})°$

BELLE-II & LHCb(upgrade) ~ $\delta\gamma \sim 1°$, still long way to go before ultimate precision

ICHEP2014: Similar results from UTFIT (D. Derkach) as well from G. Eigen et al.

NP Phase



NP/SM amplitude ratio

A lesson from history (I)

"A special search at Dubna was carried out by E. Okonov and his group. They did not find a single $K_L \to \pi^+ \pi^-$ event among 600 decays into charged particles [12] (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the Lab. The group was unlucky."

-Lev Okun, "The Vacuum as Seen from Moscow"

1964: BF= 2 x 10^{-3}

A failure of imagination ? Lack of patience ?

A great personal treat; thanks to LHCb

ADS: $B^{\pm} \to Dh^{\pm}, D \to \pi^+ K^-$

$$A^{\pi K}_{\mathrm{ADS}(K)} = -0.403 \quad \pm 0.056 \quad \pm 0.011$$

8σ

Malcolm John@EW MORIOND

Huge *direct CP* [tailor made] ~20 year ago!
ADS PRL'97

[Recall ε' ~ 10^{-6} !]

DESIGNED for MAXIMAL INTERFERENCE

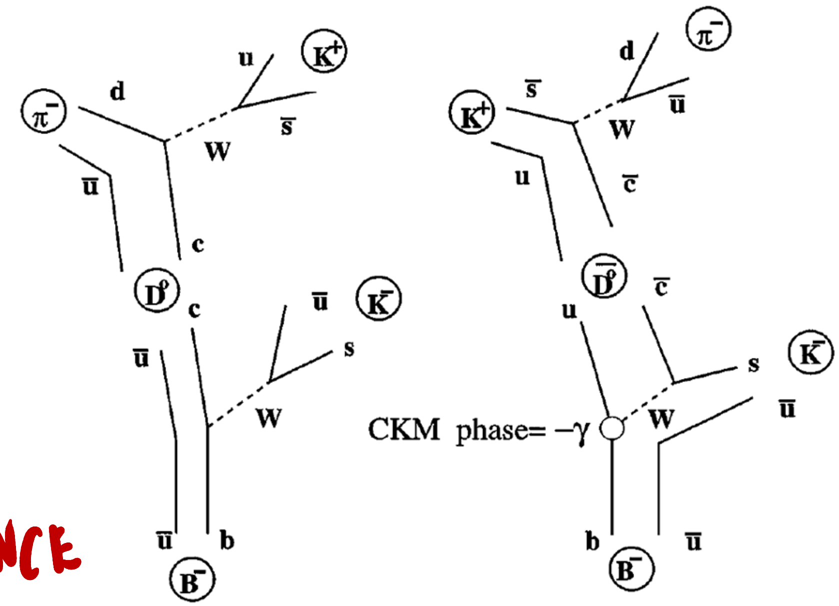
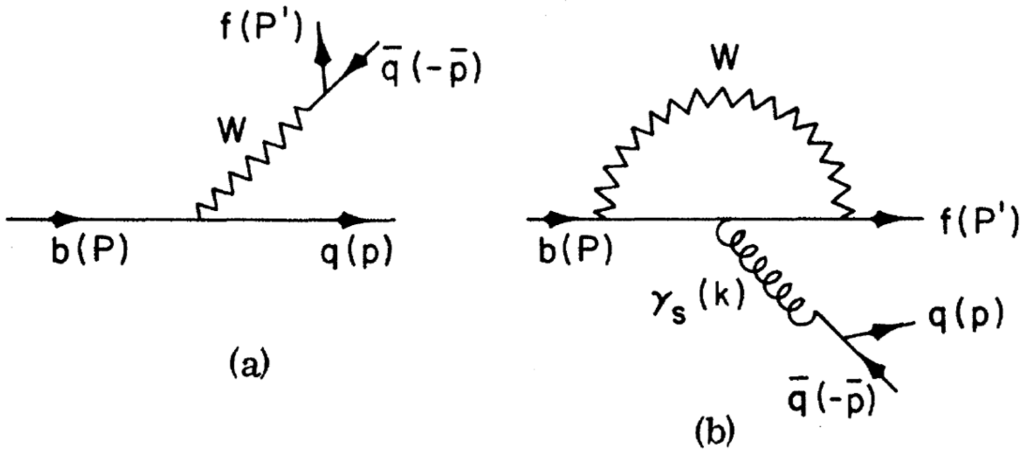


FIG. 1. Diagrams for the two interfering processes: $B^- \longrightarrow K^- D^0$ (color-allowed) followed by $D^0 \longrightarrow K^+\pi^-$ (doubl Cabibbo suppressed) and $B^- \longrightarrow K^- \overline{D}^0$ (color-suppressec followed by $\overline{D}^0 \longrightarrow K^+\pi^-$ (Cabibbo allowed).

DIRECT CP: Long-standing challenge for theorists

Simple example in B-Physics: Tree-Penguin Interference



Bander, Silverman and A. S. PRL '79

measurable asymmetries may arise. This would present the first evidence for *CP* noninvariance in charged systems.

$$A = |A_1| \exp[i(\delta_1 + \phi_1)] + |A_2| \exp[i(\delta_2 + \phi_2)]$$

$$\bar{A} = |A_1| \exp[i(\delta_1 - \phi_1)] + |A_2| \exp[i(\delta_2 - \phi_2)] .$$

$$\alpha_{PRA} = \frac{\mathcal{B}(B \to f) - \mathcal{B}(\bar{B} \to \bar{f})}{\mathcal{B}(B \to f) + \mathcal{B}(\bar{B} \to \bar{f})} = \frac{2|A_1|\,|A_2| \sin\delta \sin\phi}{|A_1|^2 + |A_2|^2 + 2|A_1|\,|A_2| \cos\delta \cos\phi} ,$$

$$A_{CP}(B^{\pm} \to \rho^0 K^{\pm}) = 0.37 \pm 0.10$$

$$A_{CP}(B^0 \to K^+\pi^-) = -0.082 \pm 0.006$$

$$A_{CP}(B_s \to \pi^+ K^-) = 0.28 \pm 0.04$$

REGRETTABLY CANNOT BE USED TO RELIABLY TEST THE SM-CKM

Update Direct CP in D^0 decays

- First measurement using $0.6\,\text{fb}^{-1}$ of D^{*+}-tagged D^0 decays [1]

LHCb PRL 2012

$$\Delta A_{CP} = (-0.82 \pm 0.21\,(\text{stat}) \pm 0.11\,(\text{syst}))\,\%$$

- New measurement using $3\,\text{fb}^{-1}$ of D^{*+}-tagged D^0 decays

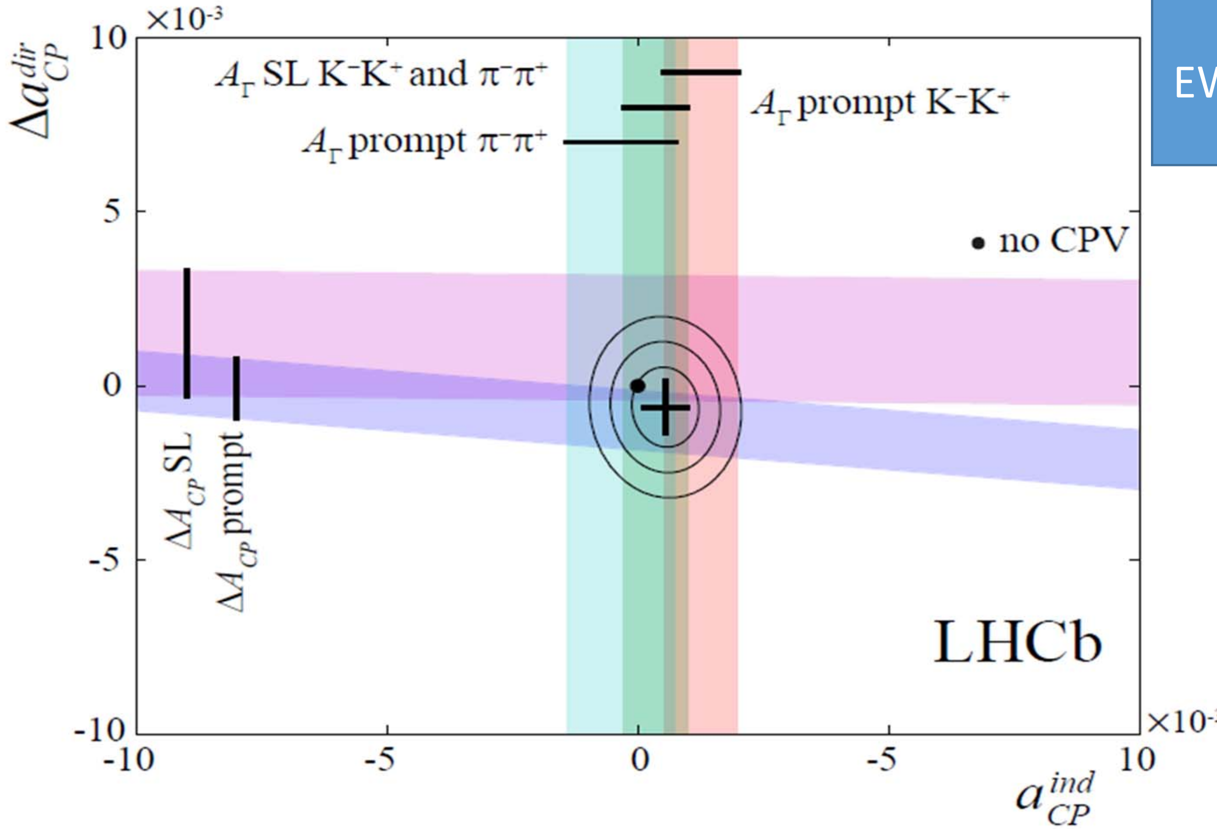
$$\Delta A_{CP} = (-0.10 \pm 0.08\,(\text{stat}) \pm 0.03\,(\text{syst}))\,\%$$

arXiv:1602.03160

M. Golden & B. Grinstein, PLB 222,501(1989)
Feldmann, Nandi and A.S., arXiV:1202.3795
Brod, Grossman, Kagan & Zupan, arXiv:1203.6659
Atwood & A. S.arXiv:1211.1026

Alex Pearce, LHCb
EW Moriond Mar. 2016

THEORY V MURKY
BSM only if $\Delta A_{CP} \gtrsim 1\%$



Alex Pearce, LHCb
EW Moriond Mar. 2016

Consistent with *CP* conservation hypothesis with $p = 0.32$

BSM-CP: Theoretical motivation

- **To the extent that SM is not a complete theory, BSM-CP phase(s) are highly likely to exist**
- **Adding fermions, scalars or gauge bosons entails new phase(s)**
- **Examples: 4G SM: + 2; LRS : at least + 1; 2HDM : neutral scalar sector**

as well as charged sector can have new phases; SUSY or WEXD : tens of new CP-odd phases in general may be there

- **SM cannot account of baryogenesis…..CKM CP not enough**
- **Due to all of the above (and some more), searching for BSM phases is just about the best way to look for NP**
- **Additional (new) motivation: hints of pretty serious anomalies**

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

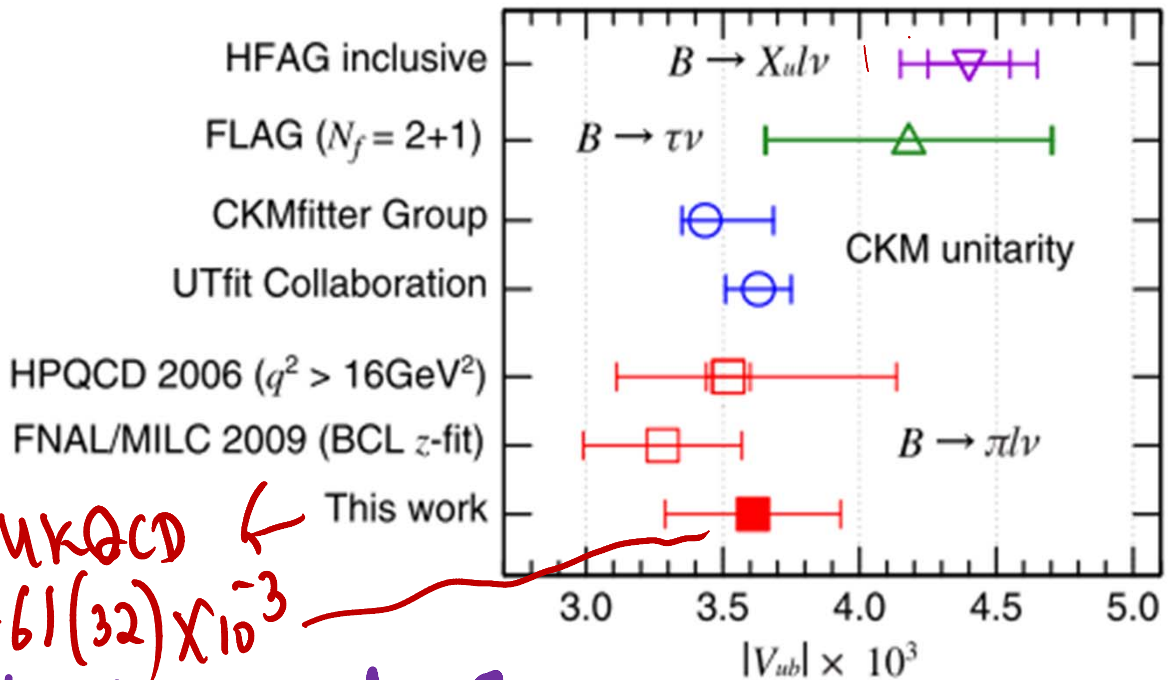
The long-standing saga of Vub

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]** $B \to X_u \ell \nu$ → No Charm
- **Absence of symmetry [unlike b => c l ν]**

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



RBC-UKQCD ←

$V_{ub} = 3.61(32) \times 10^{-3}$

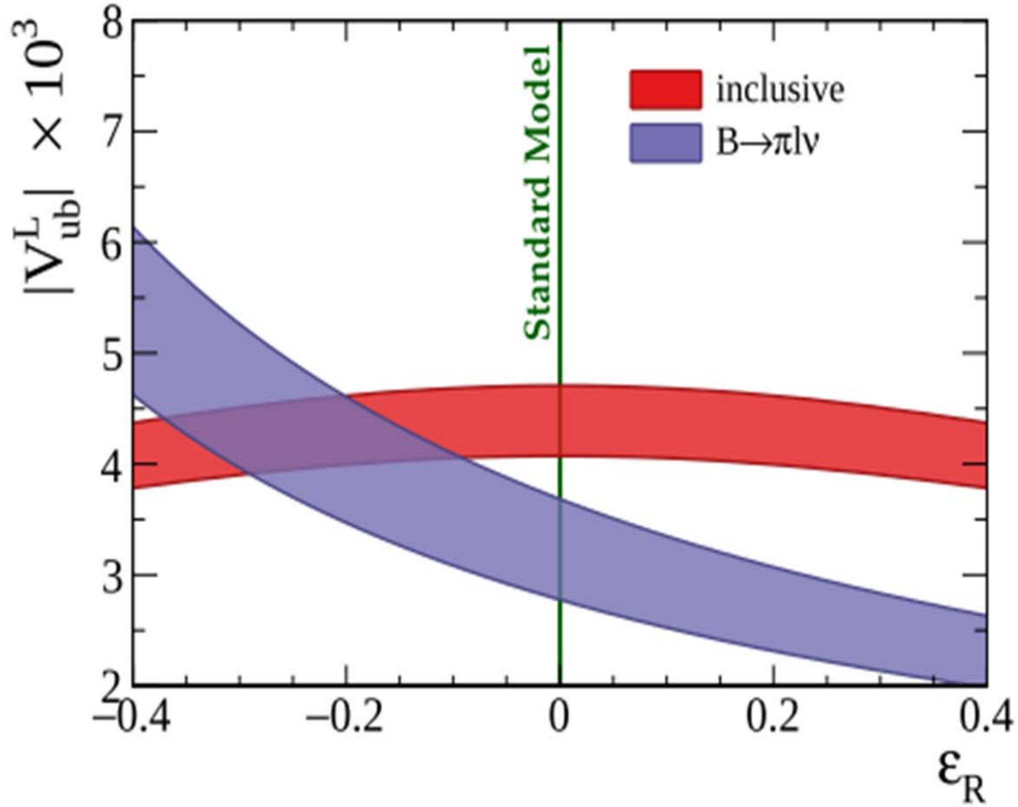
[USED in pheno analysis]

MILC 2015

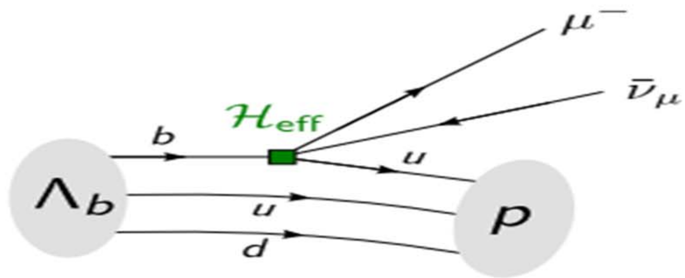
$3.72(16) \times 10^{-3}$

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



- 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)]

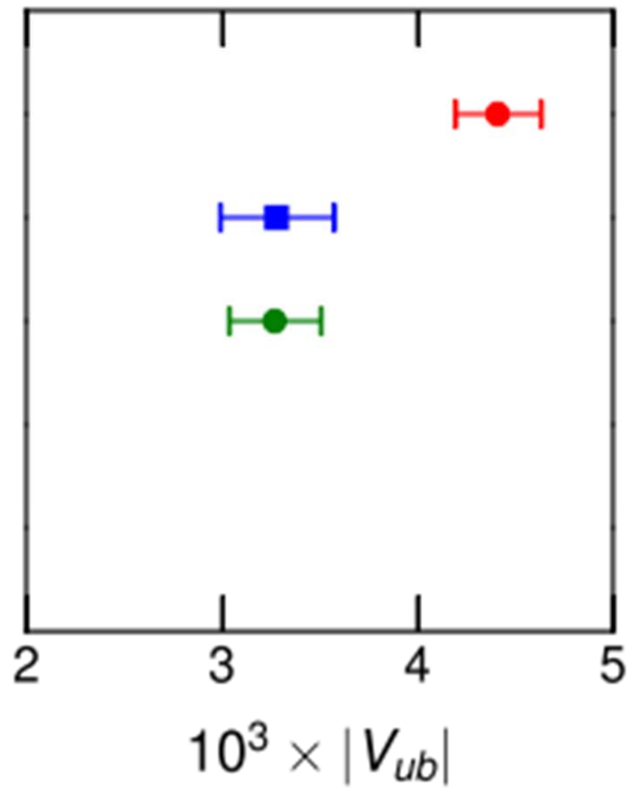
MIT HET-BNL → RBRC-BNL

LHCb + Lattice

$B \to X_u \ell \bar{\nu}_\ell$ (PDG 2014)

$B \to \pi \ell \bar{\nu}_\ell$ (PDG 2014)

$\Lambda_b \to p \ell \bar{\nu}_\ell$ (this work)



Striking consistency between completely independent exclusive determinatons

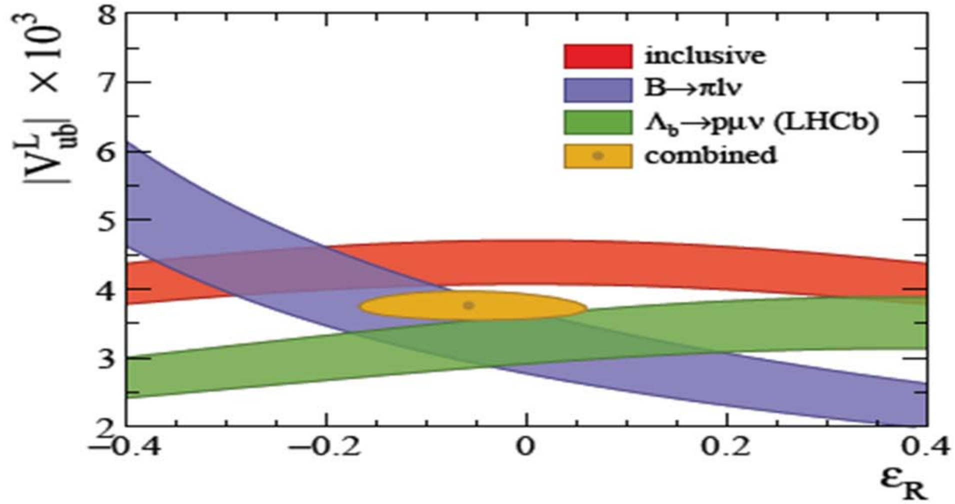


Figure 4: **Experimental constraints on the left-handed coupling, $|V_{ub}^{L}|$ and the fractional right-handed coupling, ϵ_R.** While the overlap of the 68% confidence level bands for the inclusive [14] and exclusive [7] world averages of past measurements suggested a right handed coupling of significant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

LHCb 1504.01586
Nature

RULES OUT RHC

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%**

R(D(*)): concerns

BABAR '12

Independent of Vcb!

- To test the SM Prediction, we measure

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

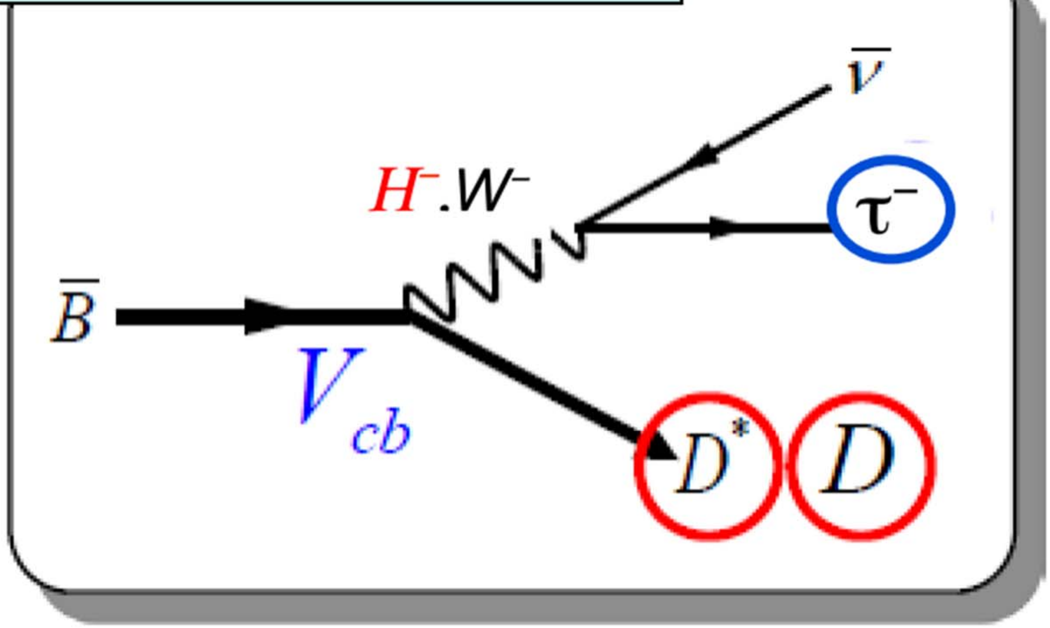
Leptonic τ decays only

Several experimental and theoretical uncertainties cancel in the ratio!

- BB events are fully reconstructed:

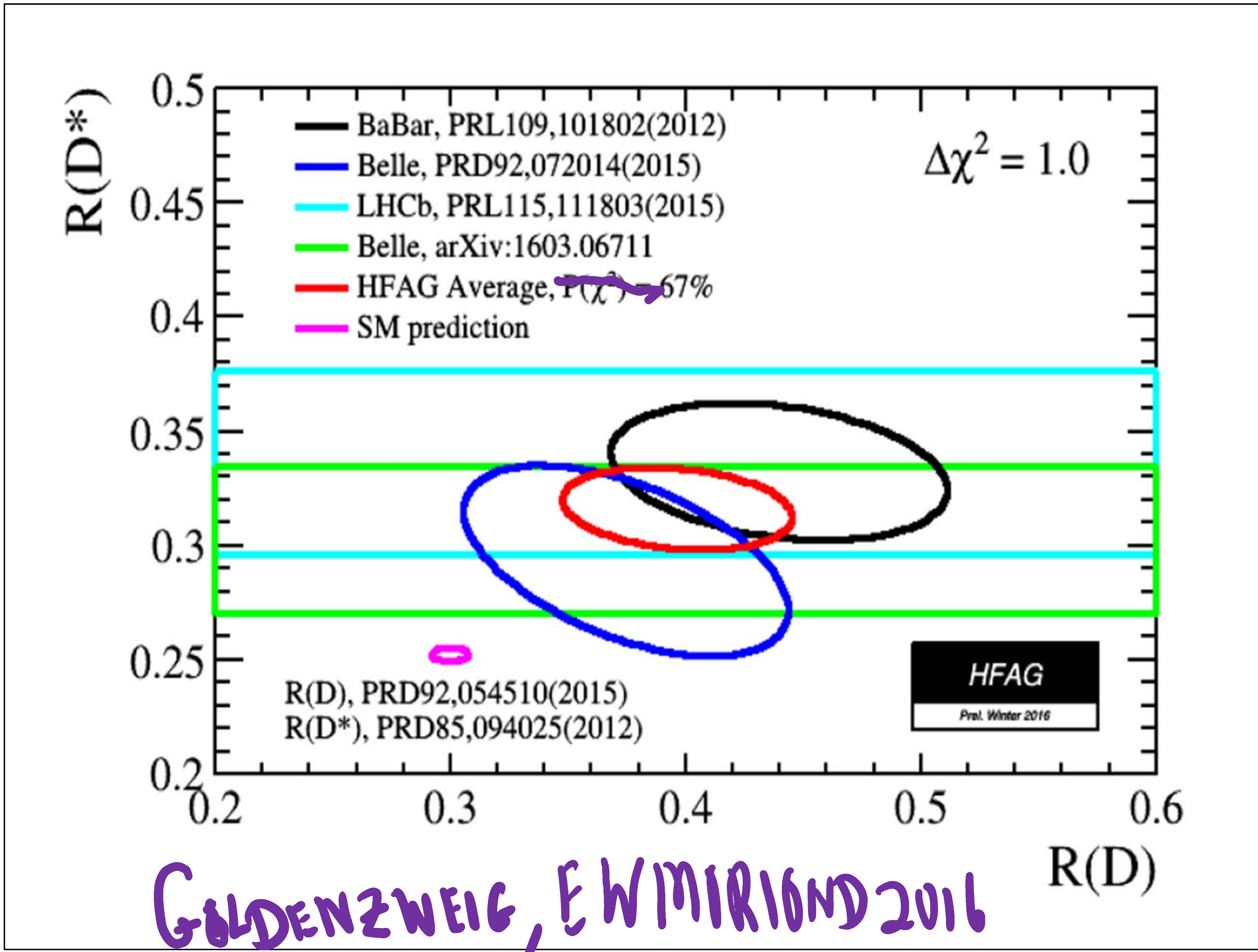
Suggested in theory papers for a long time
See e.g. Kiers & AS PRD'97; Kamenik et al PRD'08; Nierste et al PRD'08

Exclusive $B \to D^{(*)}\tau\nu$



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

MANUEL FRANCO
SEVILLA
PhD Thesis
SLAC



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

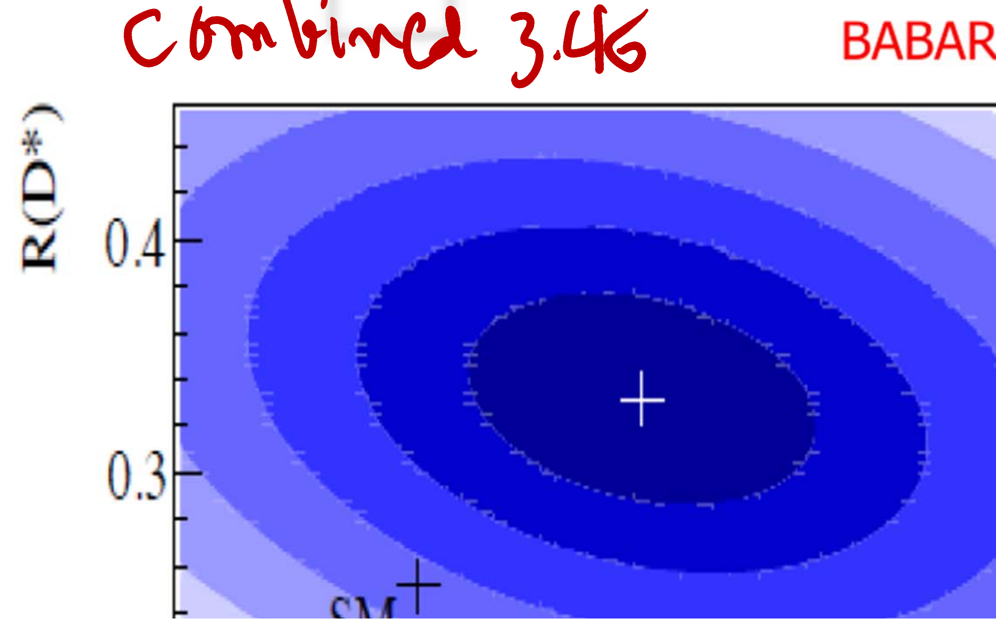
Decay	$N_{\rm sig}$	$N_{\rm norm}$	$R(D^{(*)})$	$\mathcal{B}(B \to D^{(*)}\tau\nu)$ (%)	$\Sigma_{\rm tot}(\sigma)$
$D^0\tau^-\overline{\nu}_\tau$	314 ± 60	1995 ± 55	$0.429 \pm 0.082 \pm 0.052$	$0.99 \pm 0.19 \pm 0.13$	4.7
$D^{*0}\tau^-\overline{\nu}_\tau$	639 ± 62	8766 ± 104	$0.322 \pm 0.032 \pm 0.022$	$1.71 \pm 0.17 \pm 0.13$	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

	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**

Combined 3.4σ



he combination of the two measurements (0.27 correlation) yields χ^2/NDF=14.6/2,

e. Prob. = 6.9 x10^{-4} !!

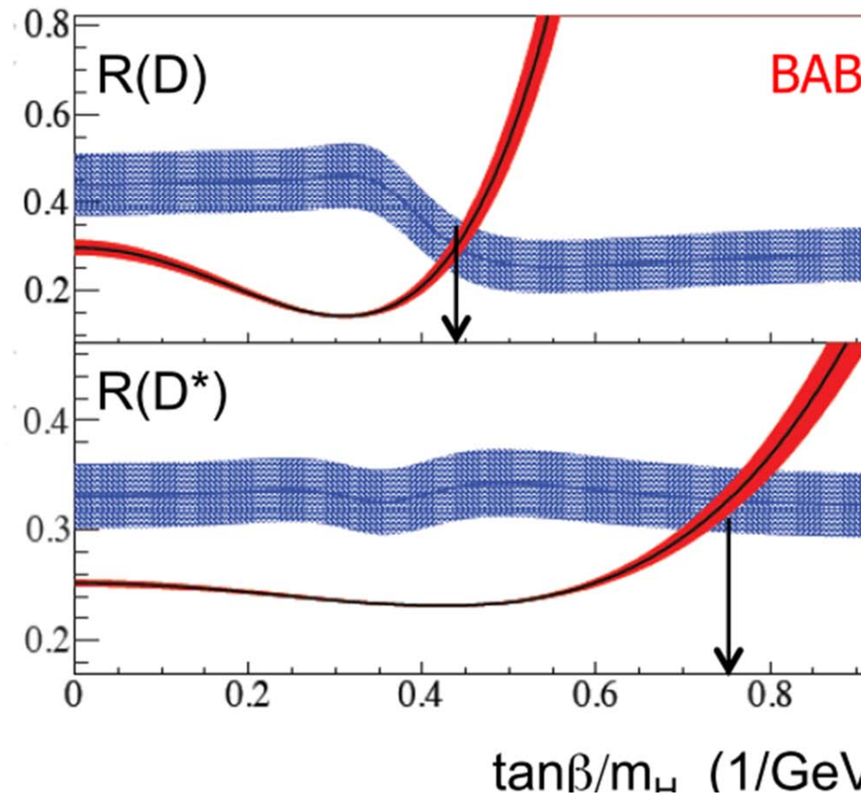
Combination to 3.4 sigma is too aggressive and worrysome

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

- 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

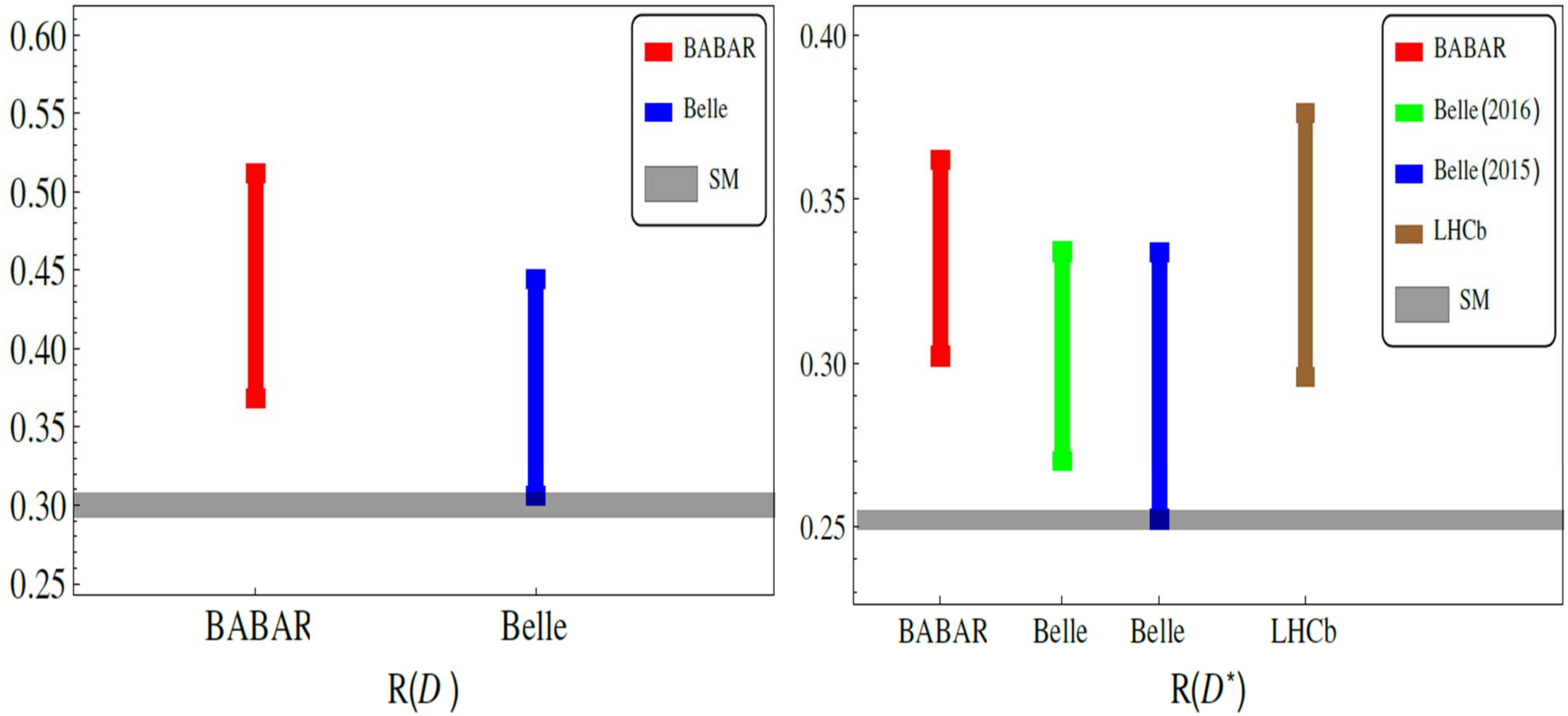
$\tan\beta/m_H = 0.44 \pm 0.02$ for R(D)

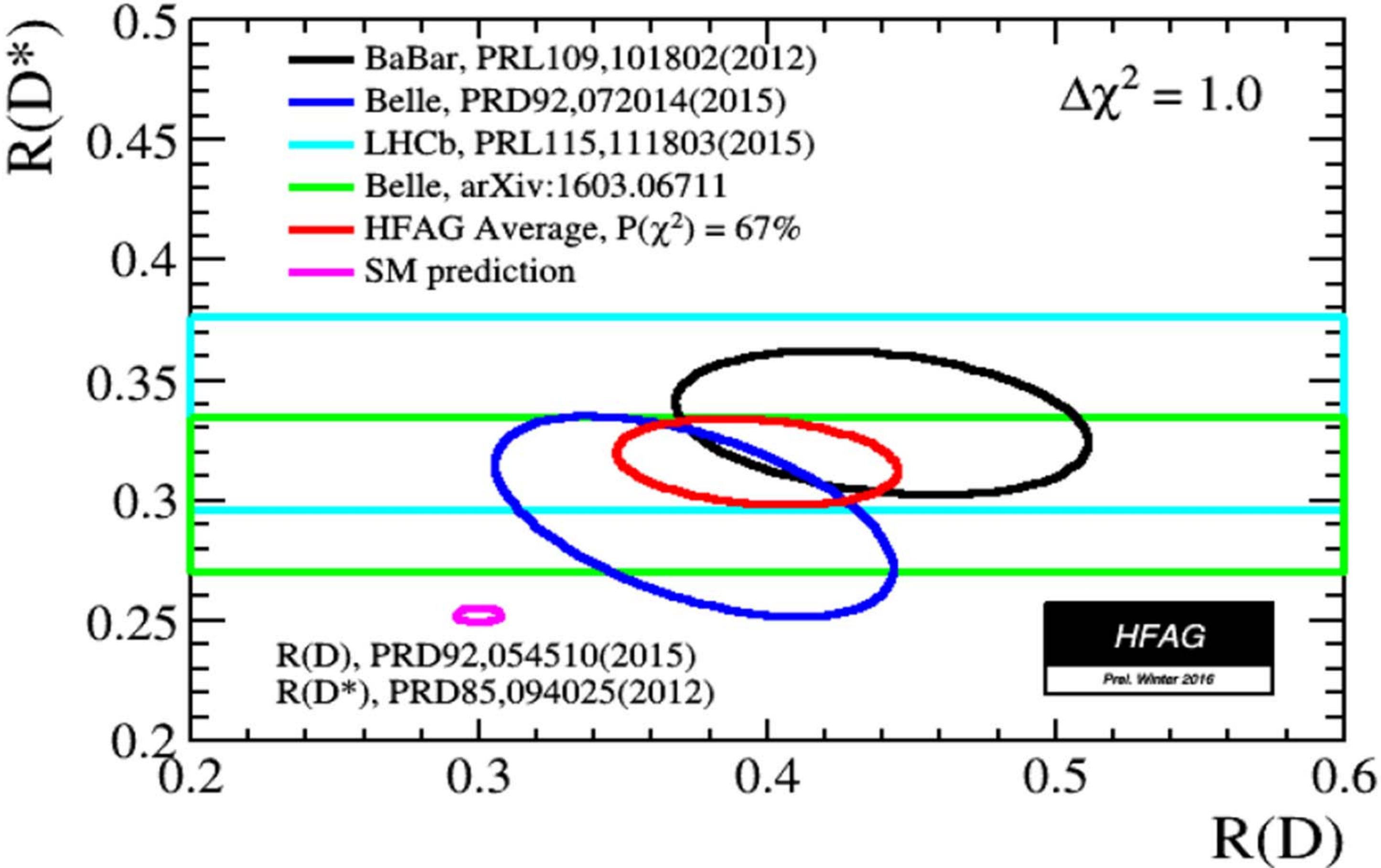
$\tan\beta/m_H = 0.75 \pm 0.04$ for R(D*)

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*

Recall the D-CP "discovery" through the D* trick

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

My (subjective) summary Part I

- **Theory is relatively clean; though 1 form factor does not get checked by light lepton as its contribution is mass suppressed…theory error**
- **A WEAK LINK: on D* theory error look anomalously small….reason NO LATTICE CALCULATION SO FAR**
- **It seems really impressive that all three experiments are lending support that this may be a problem…..but significance of each is quite low . [Remember DO-dir CP…]**
- **Tau's have always been extremely difficult historically…..many 1st results were problematic….this may share the same fate.**

A critique [SN+SP+AS → NPS
arxiv:1605.07191; WHEPP XIV,
IITK,India, Dec 2015]

My concerns

- **Esp for RD* theory errors look way too small**
- **Method of detecting tau is common to both RD AND RD***
- **So RD and RD* are not really independent observable**
- **Moreover, before RD(*), there in fact for about several years was a BR [B=>tau nu] anomaly originally seen in 2 ways in BABAR and also confirmed in both ways by BELLE**
- **However, around 07/04/12, BELLE made an important announcement**

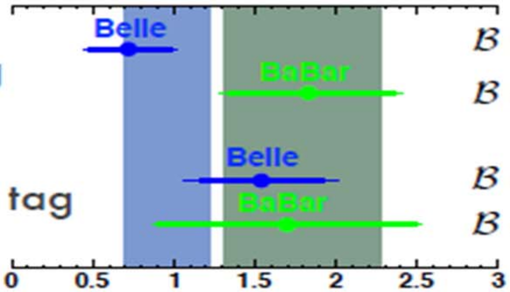
[Y KWON]

2012 Results

$B^+ \to \tau^+ \nu_\tau$ Belle/BaBar comparison

Hadronic tag

Semileptonic tag



$\mathcal{B} = [0.72^{+0.27}_{-0.25}(\text{stat}) \pm 0.11(\text{syst})] \times 10^{-4}$

$\mathcal{B} = [1.83^{+0.53}_{-0.49}(\text{stat}) \pm 0.24(\text{syst})] \times 10^{-4}$

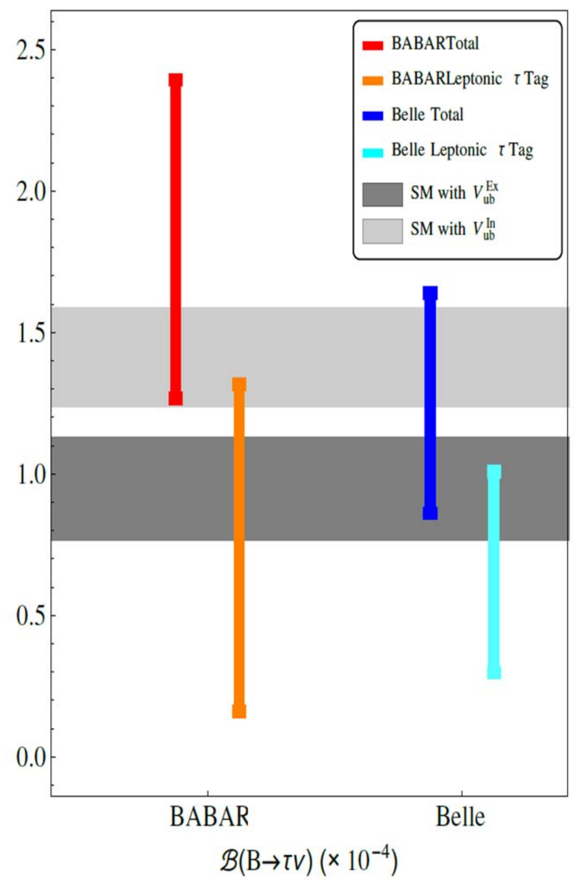
$\mathcal{B} = [1.54^{+0.38}_{-0.37}(\text{stat})^{+0.29}_{-0.31}(\text{syst})] \times 10^{-4}$

$\mathcal{B} = [1.7 \pm 0.8(\text{stat}) \pm 0.2(\text{syst})] \times 10^{-4}$

Belle combined: $\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = (0.96 \pm 0.26) \times 10^{-4}$
BaBar combined: $\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = (1.79 \pm 0.48) \times 10^{-4}$

- Belle vs. BaBar – consistent within $\sim 1.5\sigma$
- The results are consistent with $\mathcal{B}_{\text{SM}} = (1.10 \pm 0.30) \times 10^{-4}$, which is based on

  * $f_B = (190 \pm 13)$ MeV — from HPQCD, PRD 80, 014503 (2009)
  * $|V_{ub}| = (4.15 \pm 0.49) \times 10^{-3}$ — from PDG 2012 (via $B \to X_u \ell \nu$, incl.+excl.)



RECENT Belle UPDATE ON B=>τ ν

Within largish errors at this point pretty consistent with the SM and with each other

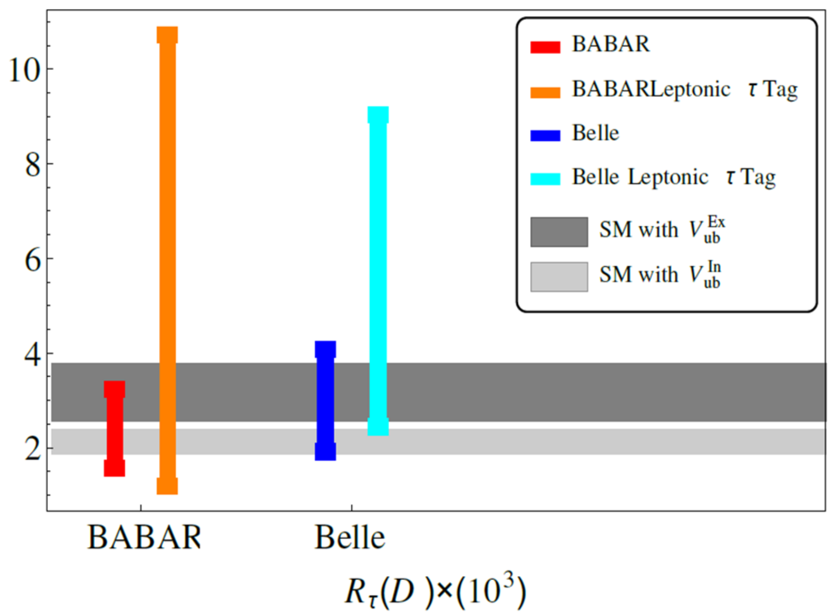
Bearing in mind all of the above, try a different route

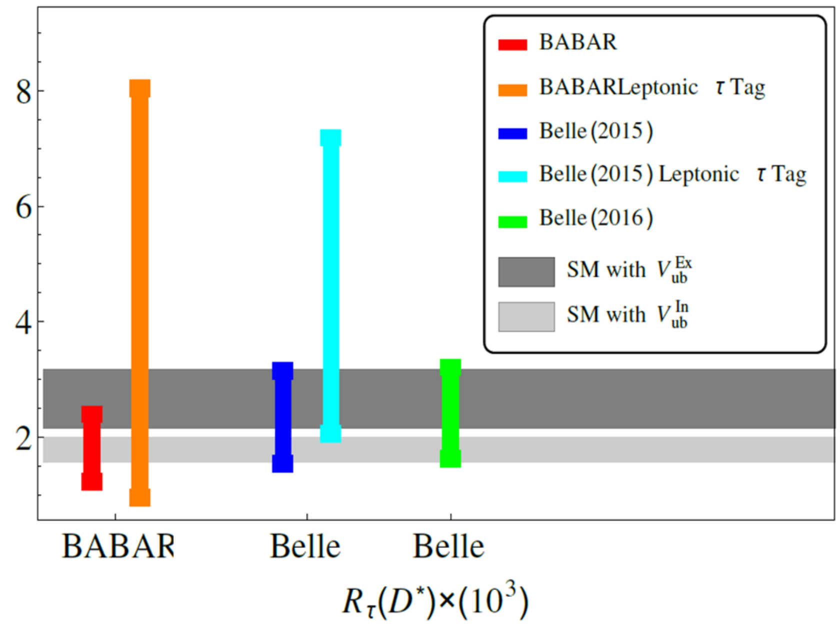
- **Introduce a new observable:**

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

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

SM, SP+AS [MIP]





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

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

Two conclusions

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

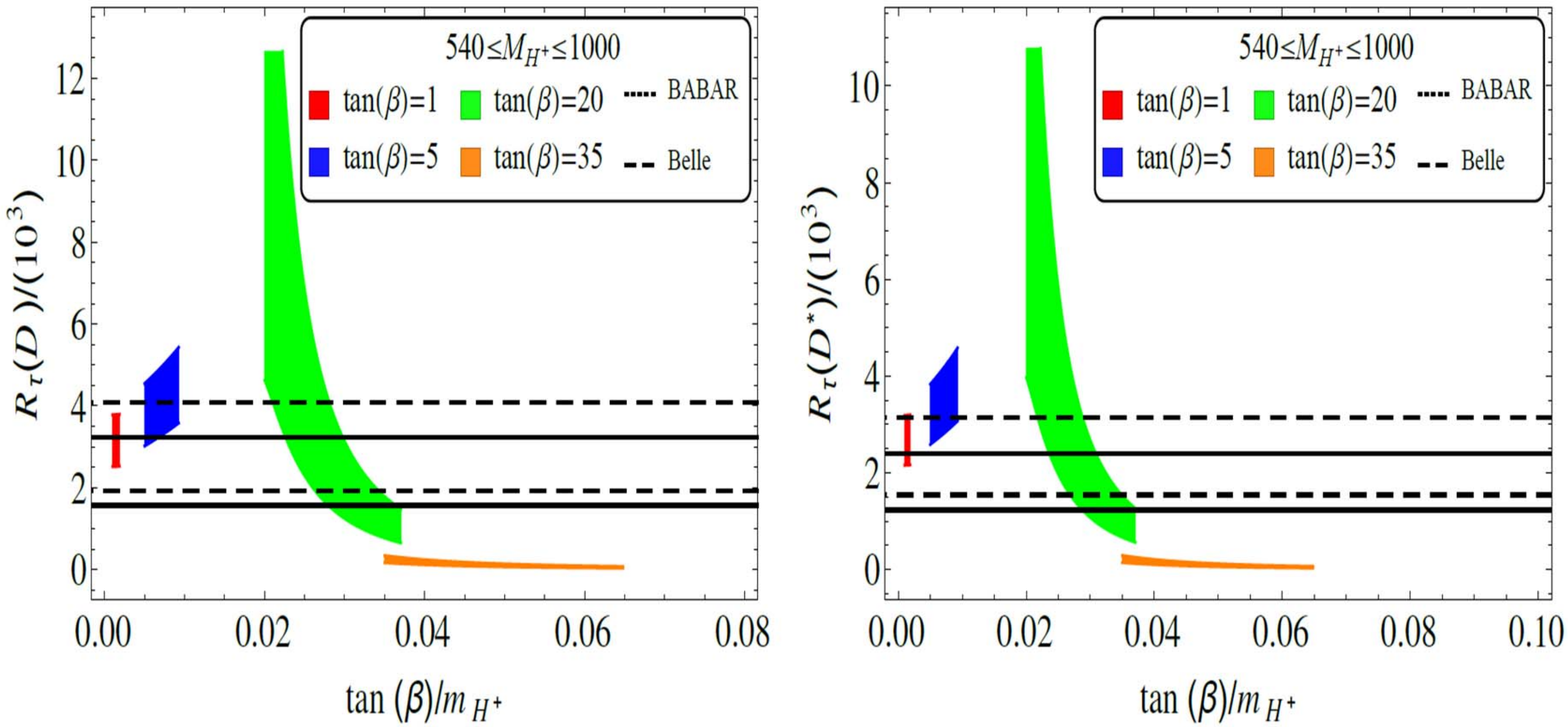


FIG. 7: Variations of $R_\tau(D)$ (left) and $R_\tau(D^*)$ (right) with the 2HDM-II parameter $r = \tan\beta/m_{H^+}$ for different values of $\tan\beta$. The 1σ experimental ranges are shown by the dotted (BABAR) and dashed (Belle) lines.

NPS

$\tan\beta \gtrsim 30$ Ruled out

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 3 years should also be extremely useful for this purpose.**
- **Improved determination of B=>tau nu also has important repercussion for UT …see Lunghi + AS, PRL' 10**

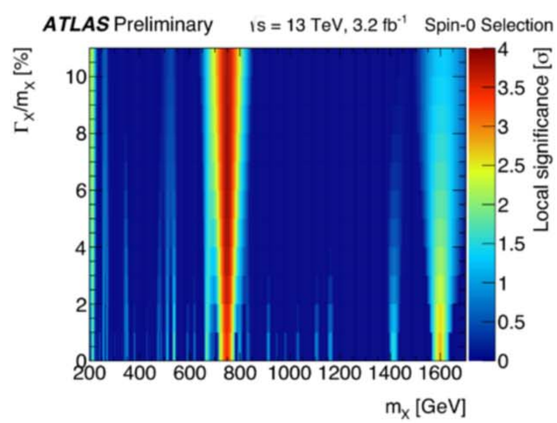
Possibly exciting news from the collider front

Diphoton anomaly @ 750 GeV

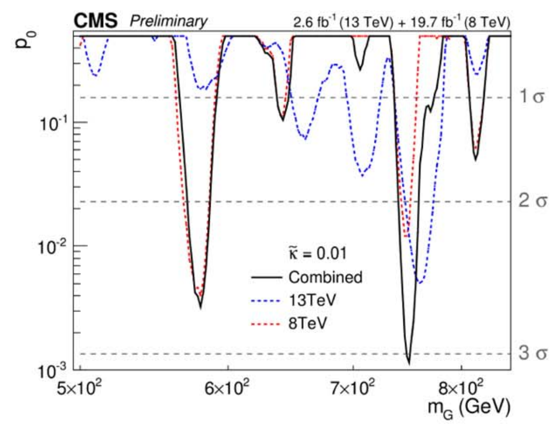
Ayana Arce @ ANL 04/21/16; c also Albert De Roeck @ BNL 04/08/16

local significance @ 750 GeV

ATLAS



CMS



Duke UNIVERSITY 29

Chances of sighting BSM seem high!

A highly plausible explanation of 750 GeV and or flavor anomalies is XHM----typeII-2HDM is a nice prototype =>FV & BSM-CP phase(s)

BSM-CPV: promising menu; few prime examples

- **In the SM CPA in t-decays are zilch due GIM**
- **BSM-CPV phase(s) in 2HDM….Neutral and or charged H exchanges**

- **t \bar t…..very sensitive to phase(s) from neutral higgs**
- **tth……. very sensitive to neutral higgs**

t=> b tau nu [also b=>c tau nu] …..;tau trans. Pol.very sensitive to charged higgs phase

- **TDCPV B => gamma K pi ….**
- **K : eps' ; KL=> pi0 nu nu; KUT**

Possibilities of large tree-level CP violation

- **$e^+ e^-$ => t \bar t h (Z)**
- **Simple example used 2HDM**
- **See Atwood et al PRD 96 ; PRD 98**
- **See also Gunion, Grzadkowski, He PRL96**

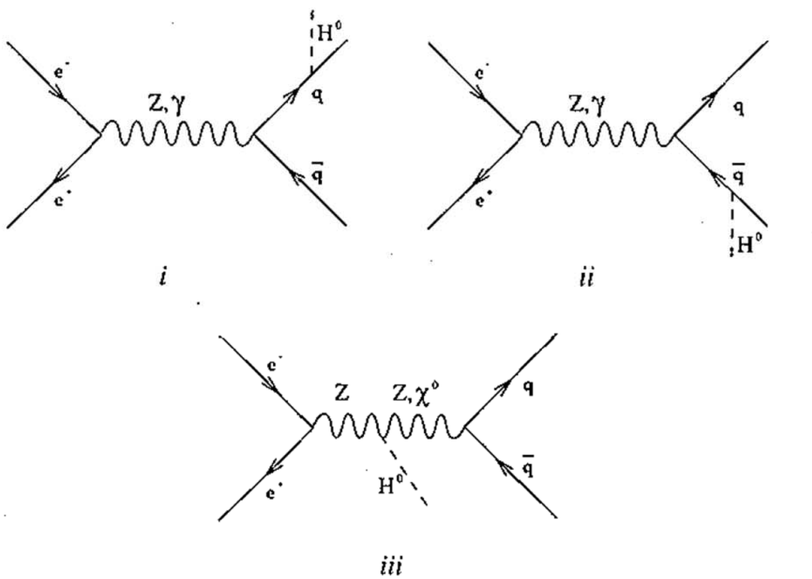


FIG. 1. Tree-level Feynman diagrams contributing to $e^+e^- \to t\bar{t}H^0$ within the two Higgs doublet model.

342 *S. Bar-Shalom et al. / Physics Letters B 419 (1998) 340–347*

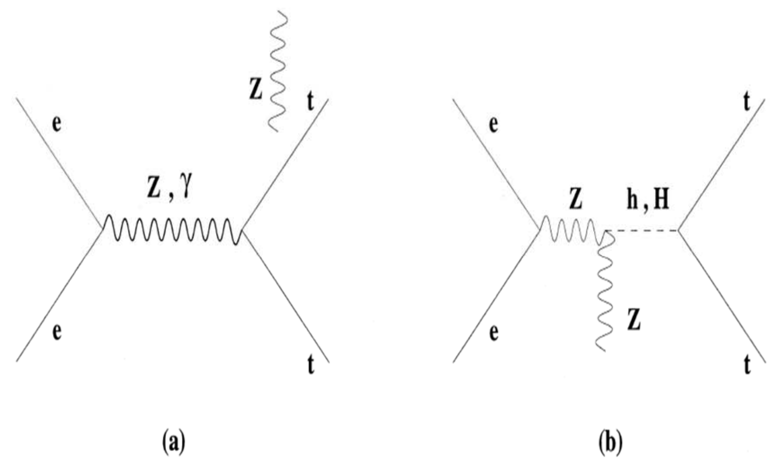


Fig. 1. Tree-level Feynman diagrams contributing to $e^+e^- \to t\bar{t}Z$ in a two Higgs doublet model. Diagram *a* represents 8 diagrams in which either Z or γ are exchanged in the s-channel and the outgoing Z is emitted from e^+, e^-, t or $\bar{t}$.

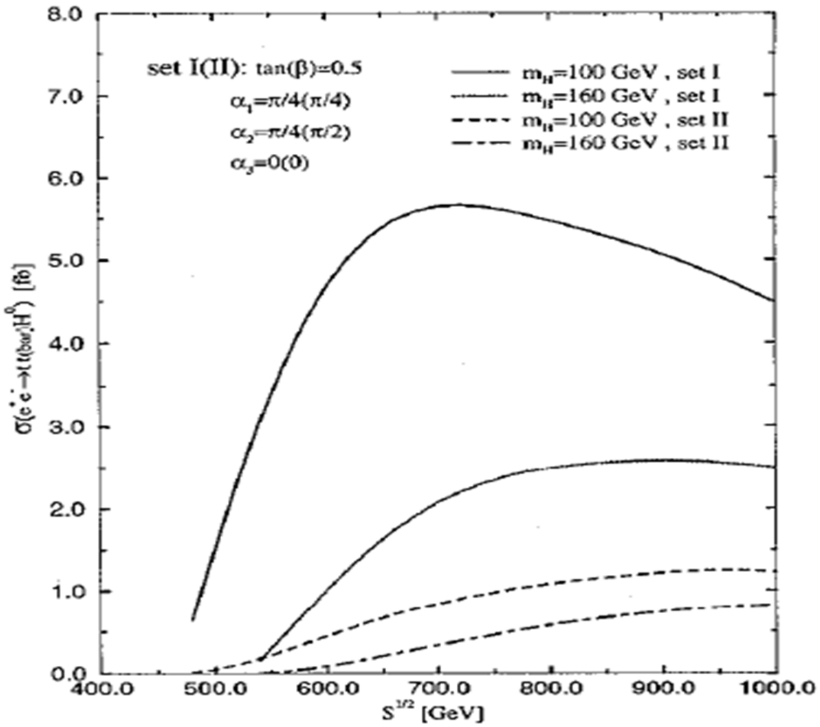


FIG. 2. The cross section (in [fb]) for the reaction $e^+e^- \to t\bar{t}H^0$, for sets I and II of the parameters a_t, b_t, and c and for $m_{H^0} = 100$ and 160 GeV assuming unpolarized electron and positron beams.

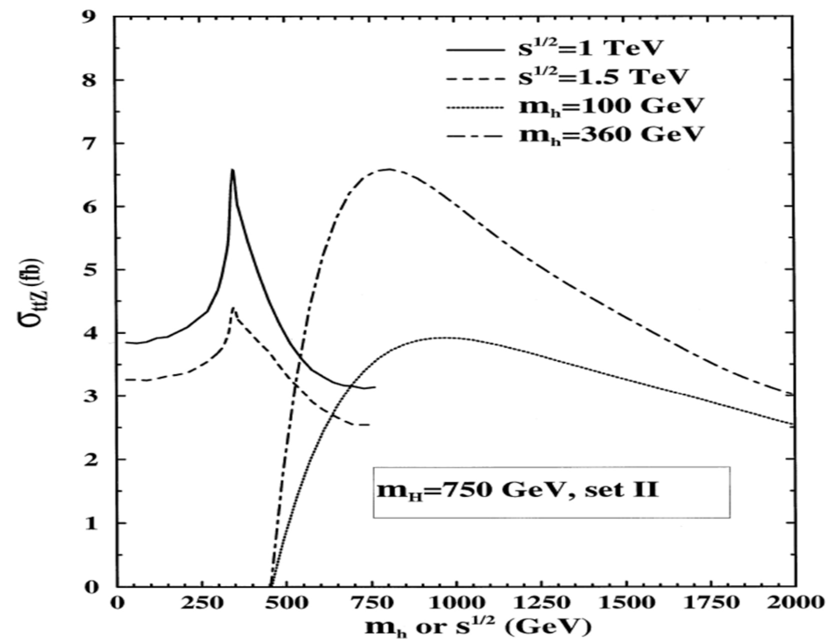


Fig. 2. The cross section (in [fb]) for the reaction $e^+e^- \to \bar{t}tZ$, assuming unpolarized electron and positron beams, for Model II with set II and as a function of m_h (solid and dashed lines) and $\sqrt{s}$ (dotted and dotted-dashed lines). Set II means $\{\tan\beta, \alpha_1, \alpha_2, \alpha_3\} \equiv \{0.3, \pi/2, \pi/4, 0\}$.

IV. *CP*-VIOLATING OBSERVABLES AND NUMERICAL RESULTS

Of course, at tree level there are no absorptive phases. Thus, the *CP*-violating term Σ^0_- can probe only *CP* asymmetries of the T_N-odd type. This leads us to consider the following *CP*-odd, T_N-odd, triple correlation product

$$O = \vec{p}_- \cdot (\vec{p}_t \times \vec{p}_{\bar{t}})/s^{3/2} \ . \tag{22}$$

top decays analyze its spin.

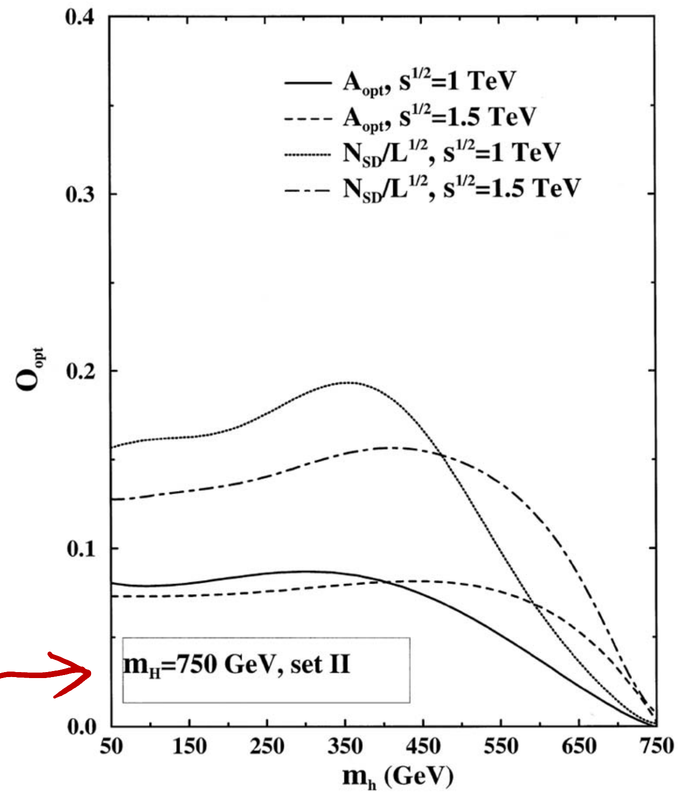


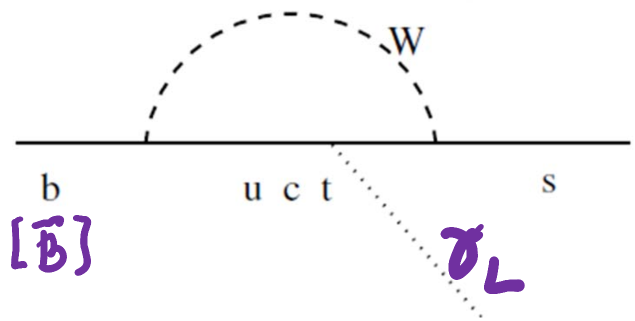
Fig. 3. The asymmetry, $A_{\rm opt}$, and scaled statistical significance, $N_{\rm SD}/\sqrt{L}$, for the optimal observable $O_{\rm opt}$ as a function of the light Higgs mass m_h, for $\sqrt{s}=1$ TeV and 1.5 TeV. See also caption to Fig. 2.

ASYMMETRY
O(10%)

Mixing induced (i.e. TD) CPV in radiative B-decays [Atwood, Gronau, AS, PRL'97]

$$H_{\rm eff} = -\sqrt{8}\, G_F \frac{e m_b}{16\pi^2} F_{\mu\nu}\left[\frac{1}{2} F_L^q \bar{q}\sigma^{\mu\nu}(1+\gamma_5)b + \frac{1}{2} F_R^q \bar{q}\sigma^{\mu\nu}(1-\gamma_5)b\right].$$

SM $F_R^q / F_L^q \sim m_q / m_b$



$b\,[B] \longrightarrow \gamma_R$

$\bar{B} \to \gamma_L$

$\bar{B} \to B \to \gamma_R$

No interference in SM

QCD Complications emphasized in:

B. Grinstein, Y. Grossman, Z. Ligeti, and D. Pirjol, Phys. Rev. D **71**, 011504 (2005).

Dalitz study of mixing induced CPV in B,Bs=> P1 P2 gamma; a data driven *clean* way to constrain NP [Atwood, Gershan, Hazumi &AS PRD'05]

- **Note P1, P2 are CP-eigenstates e.g Ks^{0}pi^0 γ ; pi$^+$ pi$^-$ γ.......**

TABLE I. Final states which can be used to probe $b \longrightarrow s\gamma$ and $b \longrightarrow d\gamma$ transitions in B_d and B_s decays. This list is not exhaustive; in particular, other neutral (pseudo-)scalar particles (η, η', f_0) may be used in the place of π^0.

	$K_S\pi^0\gamma$	$K_SK_S\gamma$	$\pi^+\pi^-\gamma$	$K^+K^-\gamma$	$K_SK_L\gamma$
$B_d/\overline{B}_d$	$b \longrightarrow s\gamma$	$b \longrightarrow d\gamma$	$b \longrightarrow d\gamma$	$b \longrightarrow d\gamma$	$b \longrightarrow d\gamma$
$B_s/\overline{B}_s$	$b \longrightarrow d\gamma$	$b \longrightarrow s\gamma$	$b \longrightarrow s\gamma$	$b \longrightarrow s\gamma$	$b \longrightarrow s\gamma$

LOOK FORWARD to BELLE-2 & possibly LHCb cashing in on these.

ε’: a possible gem in search of new phenomena

c also NORMAN CHRIST

ε' / ε: Direct CPV

$$\eta_{+-} = |\eta_{+-}| e^{i\phi_{+-}} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)}$$

$$\eta_{00} = |\eta_{00}| e^{i\phi_{00}} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)}$$

$$\eta_{+-} = \epsilon + \epsilon', \qquad \eta_{00} = \epsilon - 2\epsilon'$$

$$\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right) = \frac{\omega}{\sqrt{2}|\epsilon|}\left[\frac{\mathrm{Im}(A_2)}{\mathrm{Re}(A_2)} - \frac{\mathrm{Im}(A_0)}{\mathrm{Re}(A_0)}\right]; \quad \omega \simeq \frac{\mathrm{Re}\,A_2}{\mathrm{Re}\,A_0}.$$

Indirect CP

BNL '64
CRONIN + FITCH N.P.

$$|\epsilon| = 2.228(11) \times 10^{-3},$$

$$\mathrm{Re}(\epsilon'/\epsilon) = 1.65(26) \times 10^{-3}.$$

DIRECT CP

$\epsilon' \sim O(10^{-6})$!

Its presumed importance:

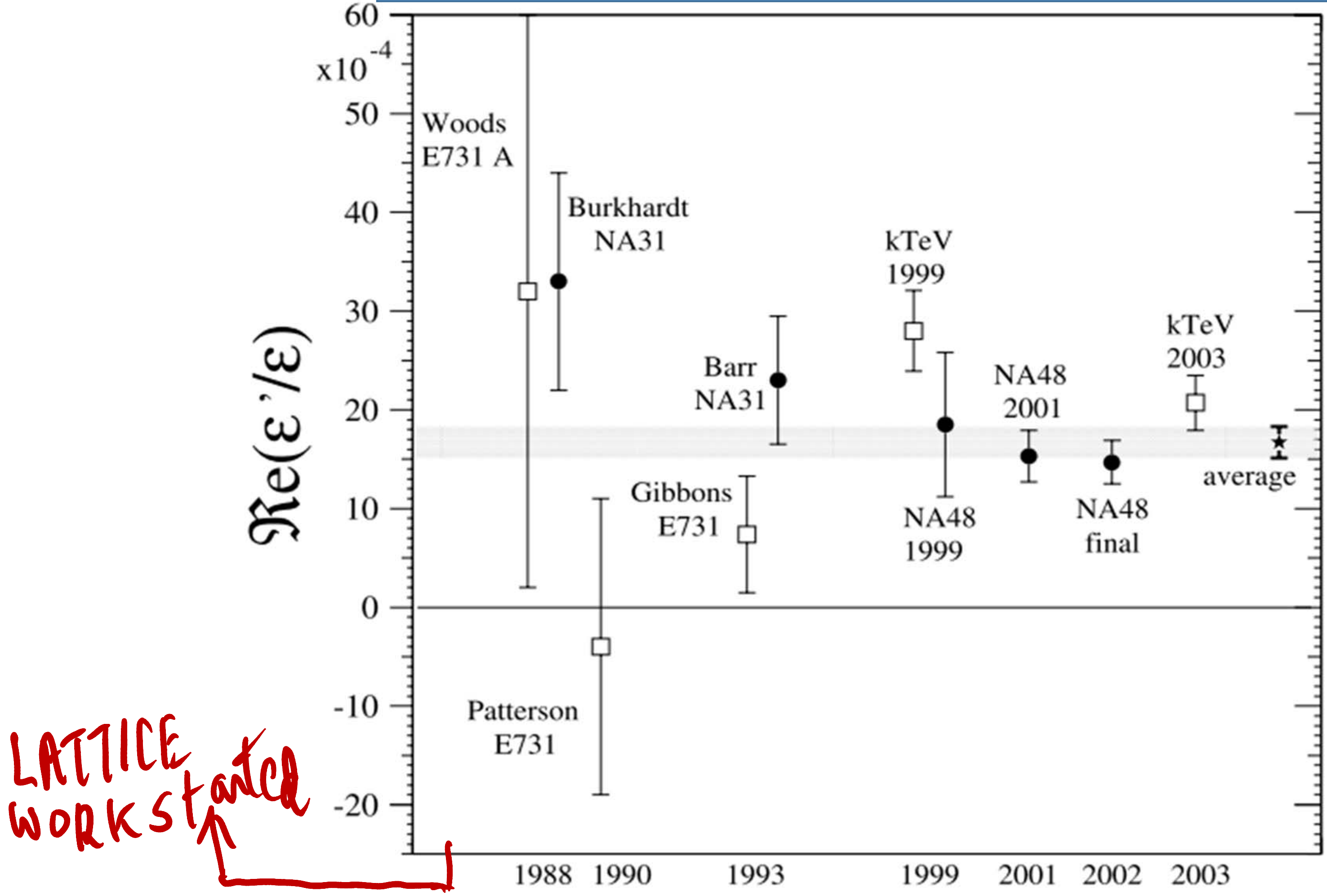
- **lies in its very small size => Perhaps new phenomena has a better chance of showing up**
- **Exceedingly important monitor of flavor –alignment**
- **Simple naturalness arguments strongly suggest eps' very sensitive to BSM – CP odd phases**
- **In many ways eps' is rather analogous to nedm…….both being very sensitive to BSM phases**
- **Understanding eps', nedm is extremely important for learning how naturalness really works in nature**

A.S. in Proceedings of Lattice '85 (FSU)..1st Lattice meeting ever attended

The matrix elements of some penguin operators control in the standard model another CP violation parameter, namely ϵ'/ϵ.[6,8) Indeed efforts are now underway for an improved measurement of this important parameter.[10)] In the absence of a reliable calculation for these parameters, the experimental measurements, often achieved at tremendous effort, cannot be used effectively for constraining the theory. It is therefore clearly important to see how far one can go with MC techniques in alleviating this old but very difficult

With C. Bernard [UCLA]

A monumental experimental achievement!



Konrad Kleinknecht "Uncovering CPV"

$16.6(2.3)\times10^{-4}$
PDG 2014

MOTHER of all (lattice) calculations to date: A Personal Perspective

- **As mentioned, calculation K=> pi pi & eps' were the reasons I went into lattice ~1/3 of a century ago**

- **9 PhD thesis: Terry Draper (UCLA), George Hockney(UCLA), Cristian Calin (Columbia=CU), Jack Laiho(Princeton), Sam Li(CU), Matthew Lightman(CU), Elaine Goode(Southampton), Qi Liu(CU), Daiqian Zhang(CU)**

I. Wilson Fermions with Bernard ~'82 See also Martinelli et al [WF] Giusti et al [WF] Sharpe et al [Stag F]	Lattice χ S is a pre-requisite for this physics Off-shoot B-physics important observables identified & studied=> evolved into UT		
II (a) DWF with Blum ~ '95 II(b) DWF with RBC[with Blum, Christ and Mawhinney became "flagship" project of RBC] ~'97.	LOχPT; Quenched approx.[QA] Same QA is disastrous for this physics [Golterman-Pallante] pathologies; NPR of full ΔS=1 accomplished for the 1st time used since then.	CRAY @ NERSC QCDSP ~ 1 TF	
III. DWF with full QCD RBC, ~ '02	Used LOχPT + full QCD Large chiral corrections	QCDSP ~ 1TF	
IV. DWF with full QCD RBC + UKQCD, ~ '06	**Direct K=>ππ, [Lellouch-Luscher method]** @ threshold	QCDOC ~ 10 TF	
V. DWF with full QCD, RBC + UKQCD ~ '11	Direct K=>ππ, [Lellouch-Luscher method] ; physical kinematics	BG/Q ~ 100TF@BNL; RBRC;ANL; Edinburgh	
Vi. Same ~now	Same	new hardware ~1.5PF;NERSC;ANL;UK	

HUGE # of OBSTACLES HAD to be overcome

~2006

Results for ε'

- Using Re(A_0) and Re(A_2) from experiment and our lattice values for Im(A_0) and Im(A_2) and the phase shifts,

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = \mathrm{Re}\left\{\frac{i\omega e^{i(\delta_2-\delta_0)}}{\sqrt{2}\varepsilon}\left[\frac{\mathrm{Im}A_2}{\mathrm{Re}A_2} - \frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}\right]\right\}$$

$$= 1.38(5.15)(4.43)\times 10^{-4}, \quad \text{(this work)}$$

$$16.6(2.3)\times 10^{-4} \quad \text{(experiment)}$$

RBC-UKQCD PRL'15
EDITOR'S CHOICE

Bearing in mind the largish errors in this first calculation, we interpret that our result are consistent with experiment at ~2σ level

EWP

QCDP

PARTIAL Cancellation

$\omega = \frac{\mathrm{Re}A_2}{\mathrm{Re}A_0} \sim 0.045$

Re A_0, A_2 from expt so we know ω.

Tree

$$Q_1 = (\bar{s}_\alpha d_\alpha)_L (\bar{u}_\beta u_\beta)_L,$$

$$Q_2 = (\bar{s}_\alpha d_\beta)_L (\bar{u}_\beta u_\alpha)_L,$$

QCDP

$$Q_3 = (\bar{s}_\alpha d_\alpha)_L \sum_{q=u,d,s} (\bar{q}_\beta q_\beta)_L,$$

$$Q_4 = (\bar{s}_\alpha d_\beta)_L \sum_{q=u,d,s} (\bar{q}_\beta q_\alpha)_L,$$

$$Q_5 = (\bar{s}_\alpha d_\alpha)_L \sum_{q=u,d,s} (\bar{q}_\beta q_\beta)_R,$$

$$Q_6 = (\bar{s}_\alpha d_\beta)_L \sum_{q=u,d,s} (\bar{q}_\beta q_\alpha)_R,$$

I=0 ⇒

→ 0

$m_q \to 0$

EWP

I=2

$$Q_7 = \frac{3}{2}(\bar{s}_\alpha d_\alpha)_L \sum_{q=u,d,s} e_q (\bar{q}_\beta q_\beta)_R,$$

$$Q_8 = \frac{3}{2}(\bar{s}_\alpha d_\beta)_L \sum_{q=u,d,s} e_q (\bar{q}_\beta q_\alpha)_R,$$

$$Q_9 = \frac{3}{2}(\bar{s}_\alpha d_\alpha)_L \sum_{q=u,d,s} e_q (\bar{q}_\beta q_\beta)_L,$$

$$Q_{10} = \frac{3}{2}(\bar{s}_\alpha d_\beta)_L \sum_{q=u,d,s} e_q (\bar{q}_\beta q_\alpha)_L,$$

→ const

$m \to 0$

QCDP

EWP

More demands on the calculation

- **~ The 1995 discovery of the huge top mass has accentuated the cancellation of I=0 and I=2 contributions to eps' significantly, putting additional demands on the calculation but also enhancing the potential for discovery of new physics**

$$c_8 \propto m_t^2/M_W^2$$

IF YOU BUILD IT THEY WILL COME

If there is new physics around below ~5 TeV, there is an excellent chance that eps' will find it!

[of course requires accurate theory calculation… RBC-UKQCD plans for X4 in stat and appreciable improvements in systematic in ~2 years]

Kaon Unitarity Traingle (KUT) Lehner,Lunghi +AS [LLS], arxiv:1508.01801

A dream for some

Blucher, Winstein and Yamanaka '09

LITTENBERG PRD '89

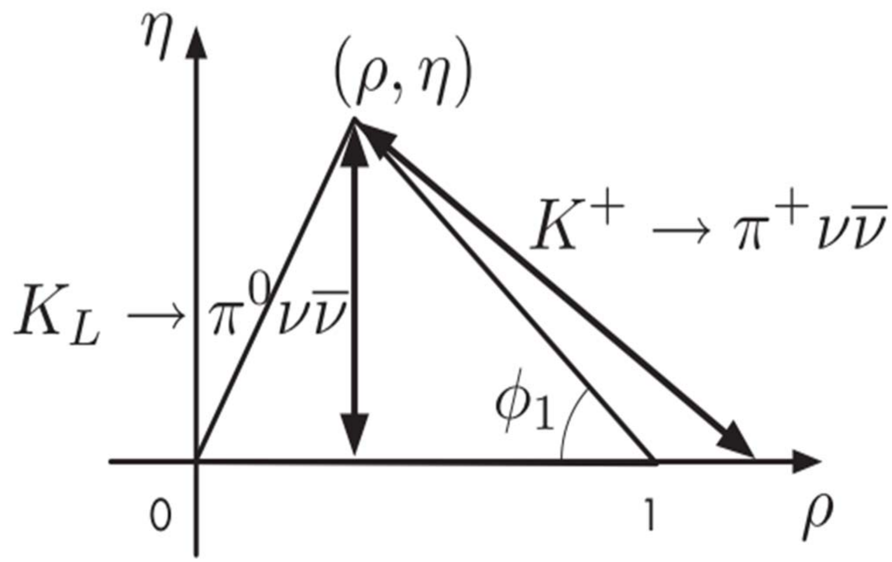
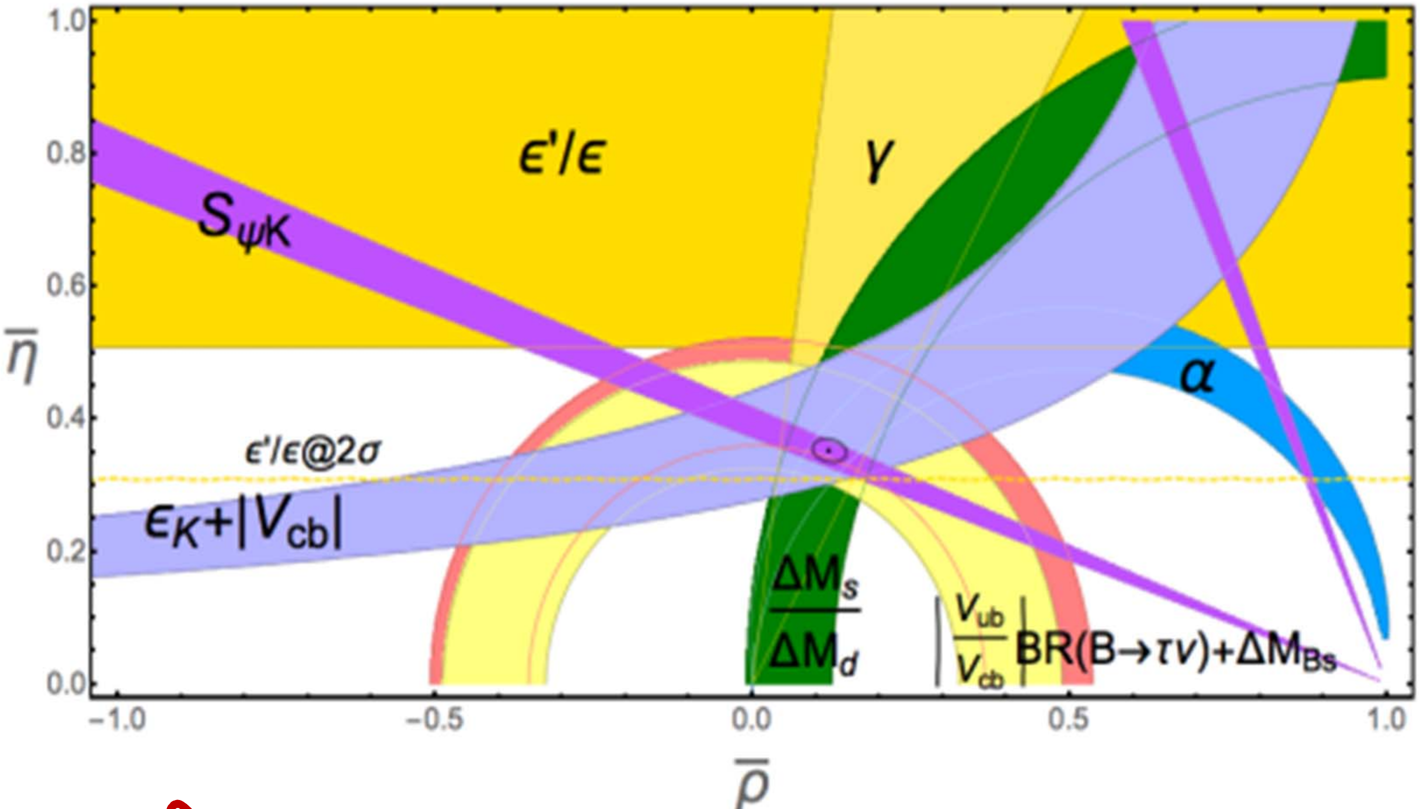


Fig. 14. Unitarity triangle.

A Faster way in the offing?

Lattice ϵ'/ϵ & SUT ≡ B-UT

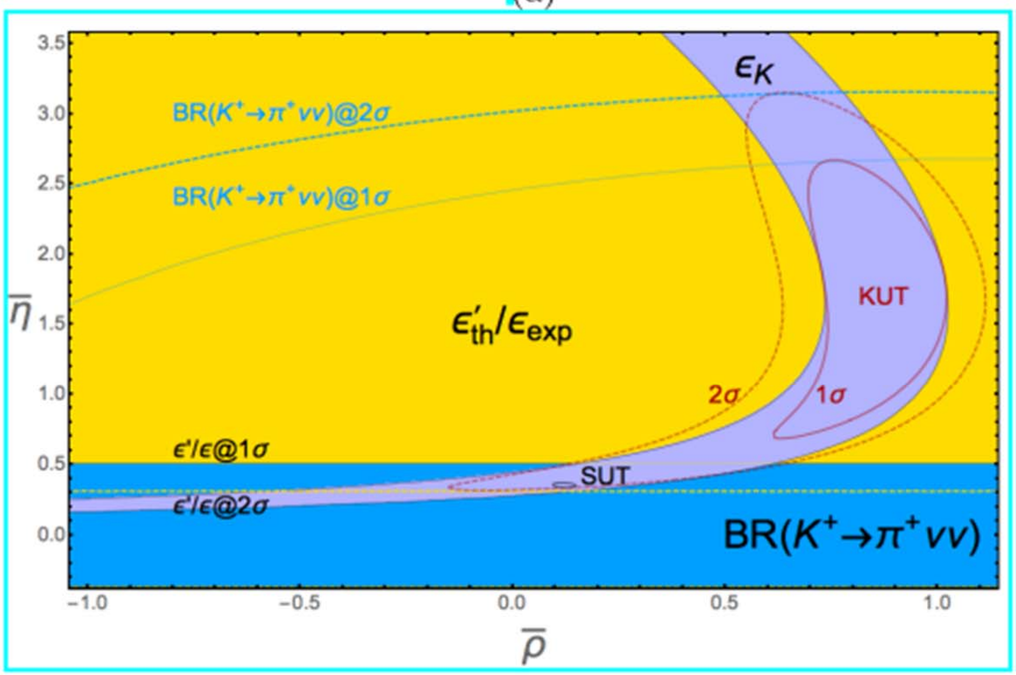


LLS

Sketch of an emerging K-UT

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \begin{cases} (8.64 \pm 0.60) \times 10^{-11} & \text{SM} \\ (17.3^{+11.5}_{-10.5}) \times 10^{-11} & \text{E949} \end{cases}$$ BNL

(a)



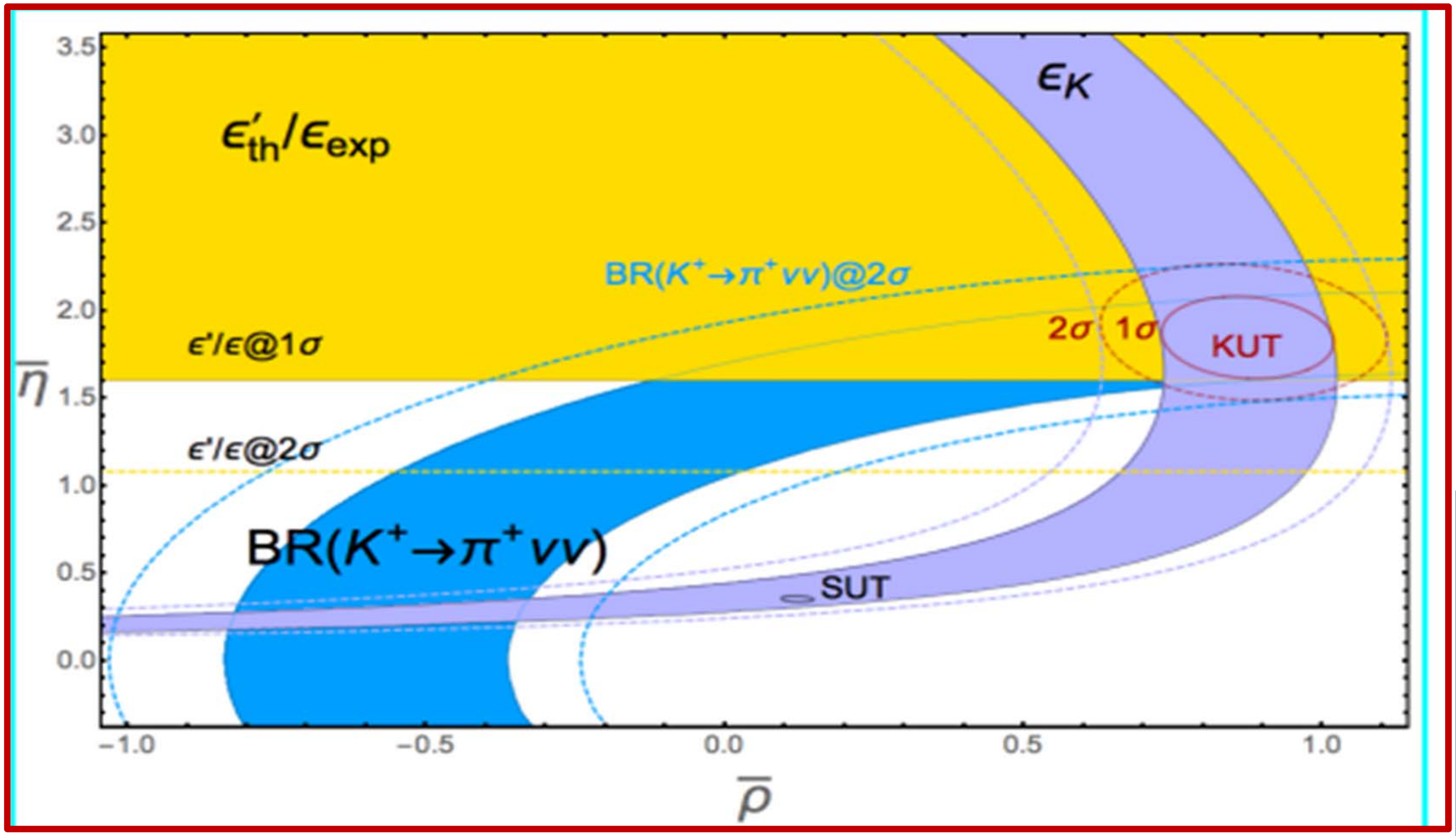
LLS '15

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)_K = \begin{cases} (16.7 \pm 1.6) \times 10^{-4} \\ (1.36 \pm 5.21_{\mathrm{stat}} \pm 4.49_{\mathrm{syst}}) \times 10^{-4} \end{cases}$$

PDG 2015

RBC+UKQCD '15

POSSIBLE KUT CIRCA 2020: DUE NA62 + RBC-UKQCD



NO unique ρ, η

Assumed: NA62, 100 events with ~7% error
RBC-UKQCD, δ(ImA0)~18% [current ~60%]

LLS

Summary & Outlook [p1 of 2]

- **SM-CKM works to ~15%=> we need to work harder to unearth new phases as it**

is extremely difficult to understand why they are not there…

- **Current hints of BSM in experiments clearly need scrutiny & clarification**
- **Vub diff bet exc and inc unlikely due NP**
- **R D(*) indications of NP are very interesting, careful understanding of experimental systematics of tau detection are essential.**
- **However, R D(*) anomaly is NOT different than NP in the simpler B=>tau nu; better measurement of Br of B=>tau nu is extremely important.**
- **Be that as it may it does not appear that type II, 2 HDM is ruled out….good news for SUSY**
- **Reg eps', if there is new physics around, then its very likely that eps' will find it.**

We believe we'll be able to reduce theory errors significantly in 3-5 years;

. ……Improvement in Expt may also be worth thinking.

Summary & Outlook [p.2]

- **LHC ~750 GeV diphoton signal is perhaps the strongest indication of new physics in a long long time**
- **If true very likely extended Higgs sector will be needed [possibly along with other things..]**
- **Strong renewed motivation for searches for BSM-CP phase(s) in: TDCPV in radiative B,Bs decays, B->M tau nu, eps’, KL=pi0nunu; in production of top pairs, tth; and in top decays are very worthwhile in near future experiments**
- **HIGH HOPES FOR RUN II, [upgraded] LHCb & Belle-II!**

EXTRAS

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:

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

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

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

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]:

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

Δ S=1 H_W

WC to NLO
Buchalla, Buras, Lautenbacher RMP '96; Ciuchini et al 95

$$H_W = \frac{G_F}{\sqrt{2}} V_{us}^* V_{ud} \sum_{i=1}^{10} [z_i(\mu) + \tau y_i(\mu)] Q_i(\mu).$$

$$\tau = -V_{ts}^* V_{td} / V_{us}^* V_{ud}.$$