Flavor physics [& CPV] in the LHC era

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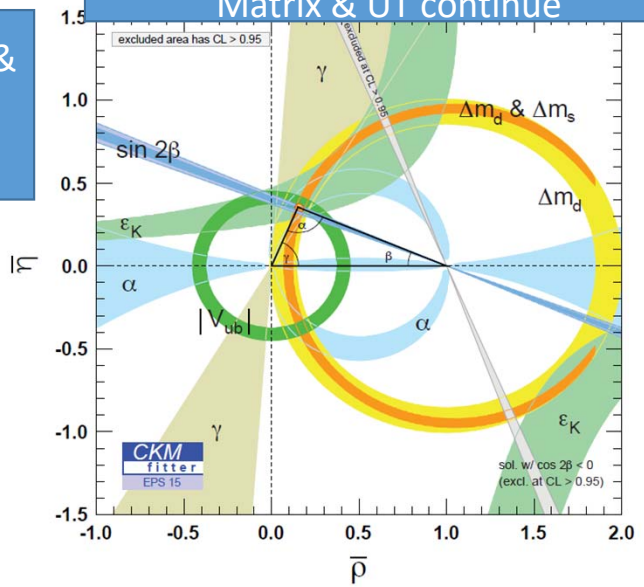
Univ of Pittsburgh, 05/09/16

Outline

- **Quick update on CKM-UT**
- **Flavor anomalies …….a critical analysis**
- **Outlook for tightening these**
- **eps'….Direct CP in K-decays**
- **LHC diphoton …….possible sighting of BSM**
- **Collider FV**
- **BSM – CP: Promising avenues in collider physics**
- **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

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

ITEN 1%.

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

ITES 10^{-7}!!
Brod+Zupan '14

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

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: $\gamma = (73^{+13}_{-15})°$

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* just as predicted ~20 years ago!
ADS PRL'97

[Recall $\epsilon' \sim 10^{-6}$!]

DESIGNED FOR MAXIMAL Interference

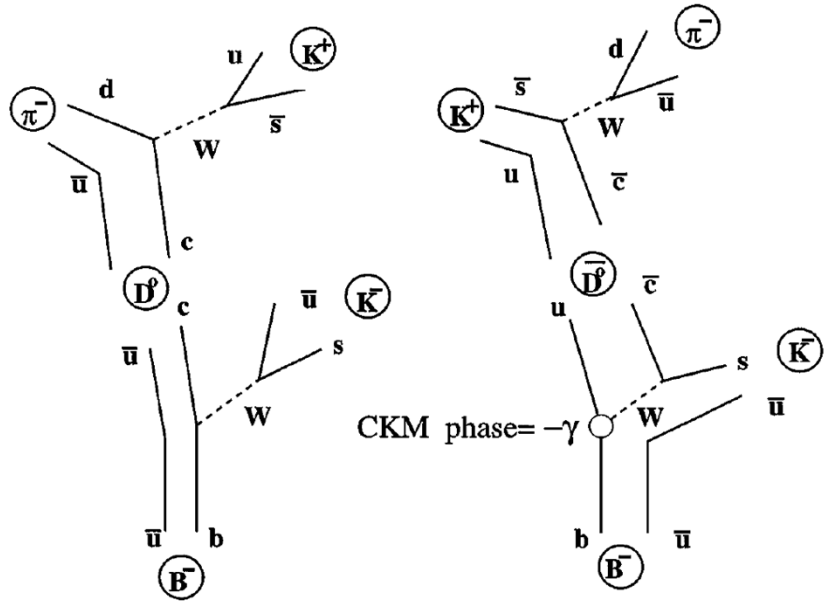


FIG. 1. Diagrams for the two interfering processes: $B^- \to K^- D^0$ (color-allowed) followed by $D^0 \to K^+ \pi^-$ (doubly Cabibbo suppressed) and $B^- \to K^- \overline{D}^0$ (color-suppressed) followed by $\overline{D}^0 \to K^+ \pi^-$ (Cabibbo allowed).

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

2 -3.5 sigma effects

Why take them seriously?

Don’t mean every anomaly is real & will survive: On the contrary

- Most will disappear but once in a while, one will survive and if simply discount them all then you can get badly burned

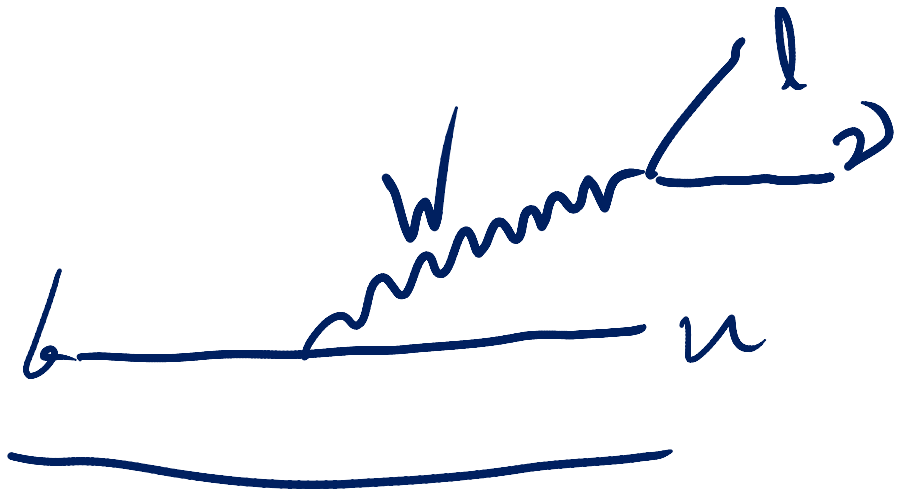
- It is important to follow experimental developments and see if one can **select & focus on what is likely genuine**

The long-standing saga of Vub

Vub “anomaly” i.e inclusive ⇔exclusive tension

- **Exclusive….some 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]**



Inclusive

$B \to X_u l \nu$

What is X_u?

Exclusive

$B^- \to \pi^0 l \nu, \rho^0 l \nu, \eta l \nu \ldots$

$B^0 \to \pi^- l \nu, \rho^- l \nu \ldots$

$B_s \to K^- l \nu, K^{*-} l \nu \ldots$

$\Lambda_b \to p l \nu \ldots$

$\left[\frac{V_{ub}}{V_{cb}} \sim 0.08 \right]$

Semi-leptonic (exclusive) form factors from the lattice:Basics lattice studies since '89.....matured

$$H_{int} = \frac{G_F}{\sqrt{2}} \left[J_\mu^{had} + J^\mu_{lep} \right] V_{if}^{CKM}$$

$$J^\mu + A^\mu \equiv \bar{u}\gamma_\mu b + \bar{u}\gamma_\mu\gamma_5 b$$

$$\langle \pi(p_f) | J_\mu^h | B(p_i) \rangle = (p_i + p_f) f_+(q^2) + (p_i - p_f) f_-(q^2)$$

$$= f_+(q^2) \left[(p_i + p_f)^\mu + \frac{m_f^2 - m_i^2}{q^2} (p_i - p_f)^\mu \right] +$$

$$f_0(q^2) \frac{m_B^2 - m_A^2}{q^2} (p_f - p_i)^\mu ; \quad q \equiv p_f - p_i$$

RBC-UKQCD

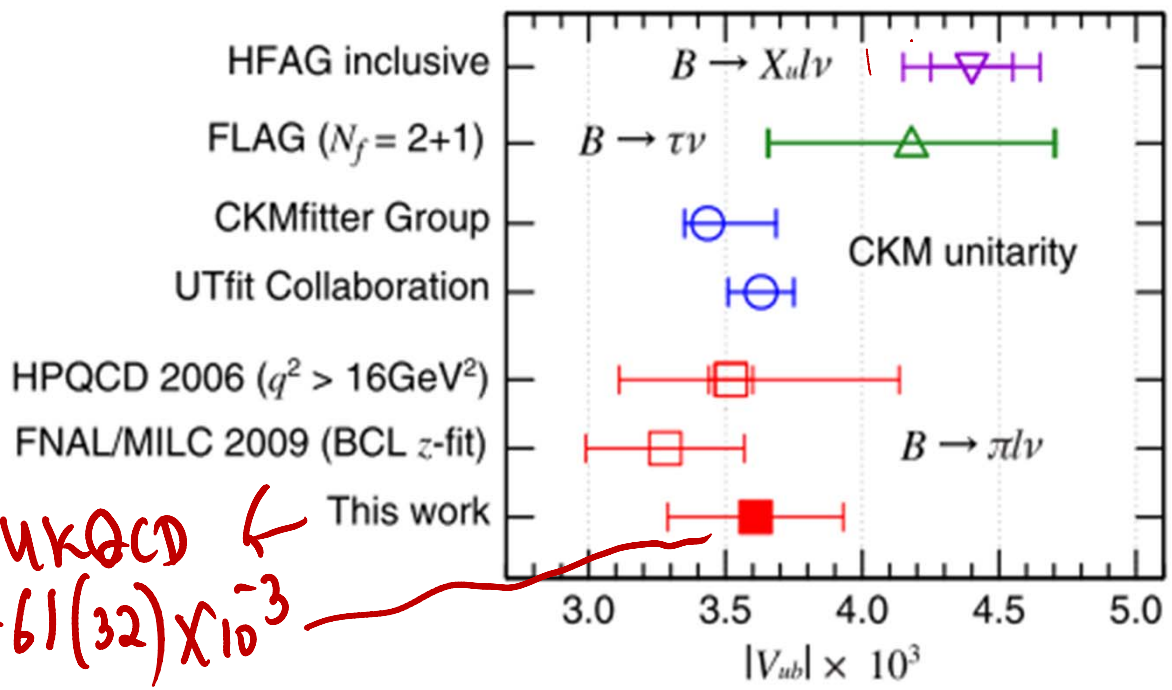
TABLE VI. Error budgets for the $B \to \pi \ell \nu$ and $B_s \to K \ell \nu$ form factors at three representative q^2 values in the range of simulated lattice momenta. For convenience, we also show the corresponding pion or kaon energy, E_P. Errors are given in %. The total error is obtained by adding the individual errors in quadrature.

	$f_+^{B\pi}$			$f_0^{B\pi}$			$f_+^{B_sK}$			$f_0^{B_sK}$		
E_P [GeV]	0.85	0.50	0.27	0.85	0.50	0.27	1.07	0.77	0.53	1.07	0.77	0.53
q^2 [GeV^2]	19.0	22.6	25.1	19.0	22.6	25.1	17.6	20.8	23.4	17.6	20.8	23.4
$f(q^2)$	1.21	2.27	4.11	0.46	0.68	0.92	0.99	1.64	2.77	0.48	0.63	0.81
Statistics	7.9	5.9	12.4	7.3	4.6	3.3	4.1	3.4	3.2	3.4	2.7	2.6
Chiral-continuum extrapolation	6.3	5.0	6.2	10.9	7.6	5.8	3.2	2.8	2.5	5.0	4.9	5.1
Light-quark mass m_{ud}	0.3	0.2	0.2	0.4	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Strange-quark mass m_s	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.0
Lattice-scale uncertainty	2.0	2.0	2.0	2.2	2.2	2.2	2.0	2.0	2.0	2.2	2.2	2.2
RHQ parameter tuning	0.9	0.9	0.8	1.0	1.0	1.0	0.9	0.9	0.9	1.0	1.0	1.0
Renormalization factor	0.8	0.8	0.7	1.6	1.6	1.7	0.9	0.8	0.8	1.6	1.6	1.7
Finite volume	0.5	0.4	0.3	0.7	0.5	0.4	0.2	0.2	0.2	0.2	0.1	0.1
Heavy-quark discretization errors	1.8	1.8	1.8	1.7	1.7	1.7	1.8	1.8	1.8	1.7	1.7	1.7
Light-quark and gluon discretization errors	1.1	1.1	1.1	1.1	1.1	1.1	1.3	1.3	1.3	1.3	1.3	1.3
Isospin breaking	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Total (%)	10.6	8.4	14.3	13.6	9.6	7.6	6.2	5.5	5.3	7.1	6.7	6.8

$a^{-1} = 1.729 \pm 2.28$ GeV; $289 < m_\pi < 422$ MeV

Unfortunately

- **Lack of (wo)man power [rather than computing power] is causing significant delay in moving to the physical point**



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

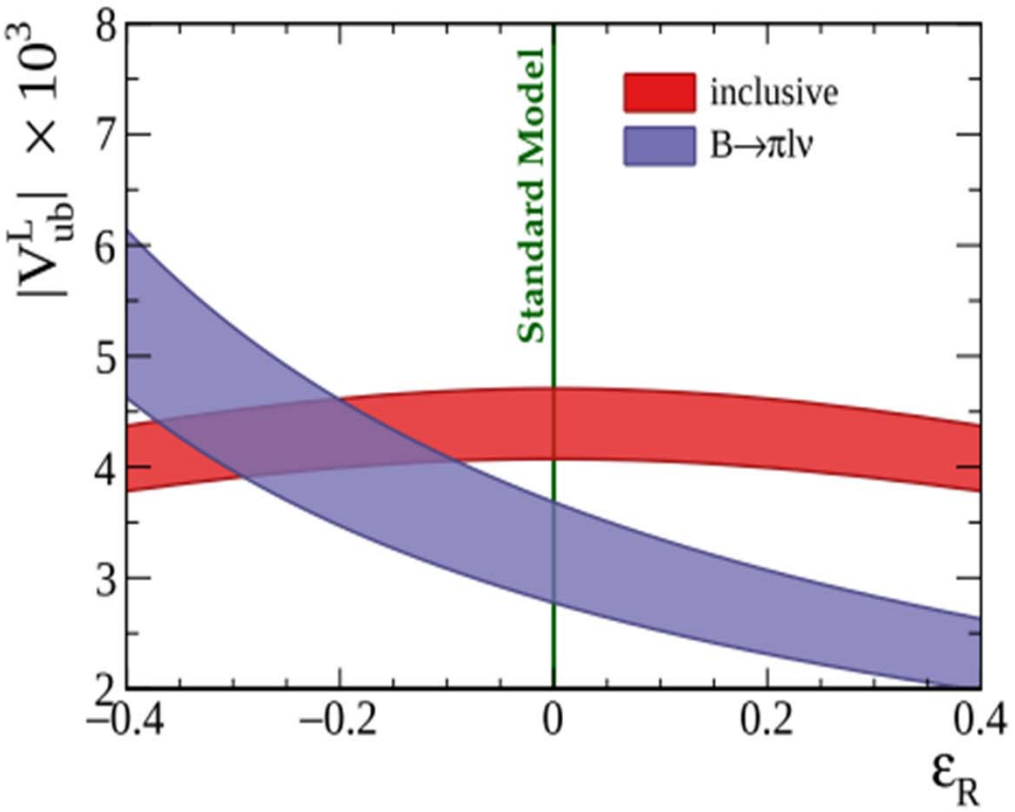
$\Rightarrow$

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

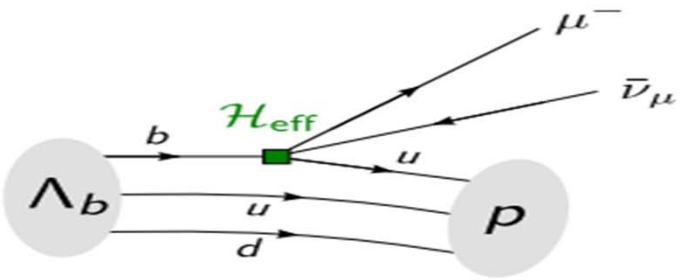
RBC-UKQCD $\leftarrow$
$V_{ub} = 3.61(32) \times 10^{-3}$

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



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)]

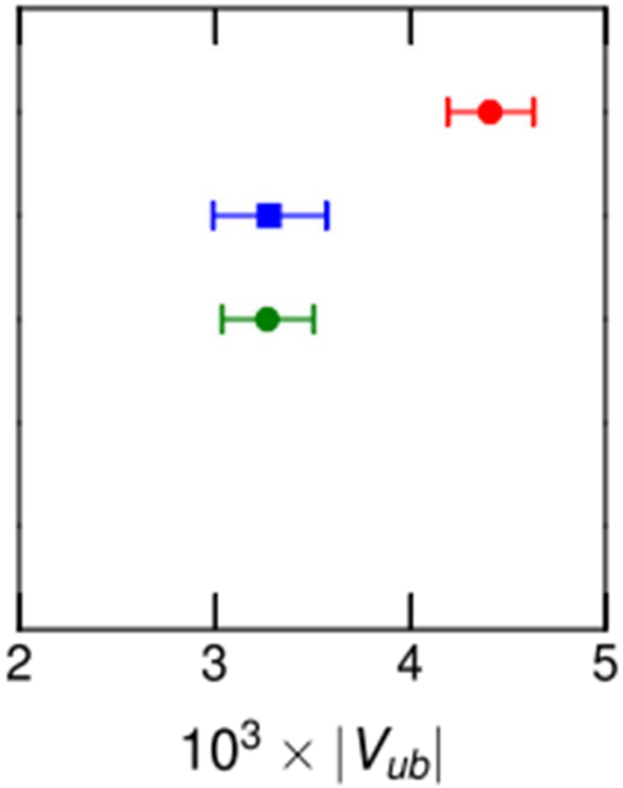
MIT HET-BNL → RBRC-BNL

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



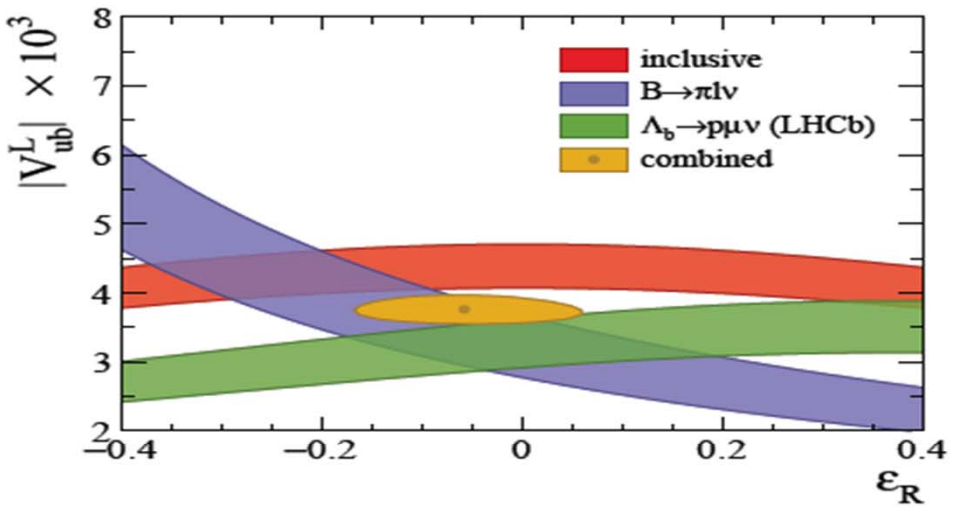
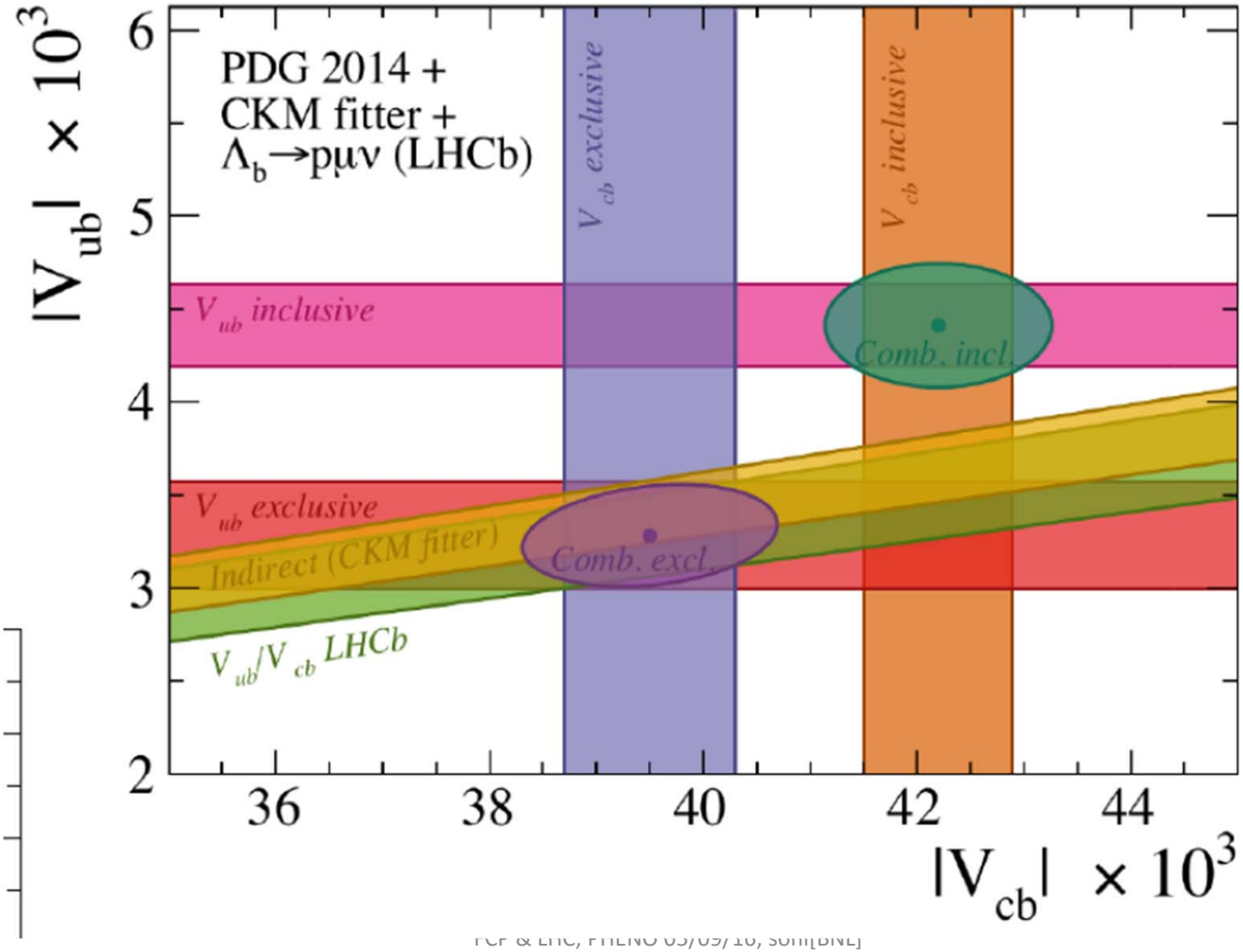


Figure 4: **Experimental constraints on the left-handed coupling, $|V_{ub}^{\mathrm{L}}|$ and the fractional right-handed coupling, ϵ_R.** While the overlap of the 68% confidence level bands for the inclusive [14] and exclusive [7] world averages of past measurements suggested a right handed coupling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

LHCb 1504.01586 Nature

RULES OUT RHC


PDG 2014 +
CKM fitter +
Λb→pμν (LHCb)
V cb exclusive
V cb inclusive
V ub inclusive
Comb. incl.
V ub exclusive
Indirect (CKM fitter)
Comb. excl.
V ub/V cb LHCb
|V ub| × 10^3
|V cb| × 10^3
2
3
4
5
6
36
38
40
42
44

ISIDORI

My (subjective summary)

- **Exclusive (lattice) determination of Vub from B=>pi l nu by now a matured subject has received strong support from exclusive (lattice) baryonic extraction thanks to LHCb …Exclusive Vub appears very robust now.**
- **The precision of Vub from inclusive determination appears difficult to justify rigorously at least from my simplistic understanding of things**
- **Experimentally also the inclusive final state is difficult to implement**
- **Most likely the resolution lies in some small underestimate of errors 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(*))

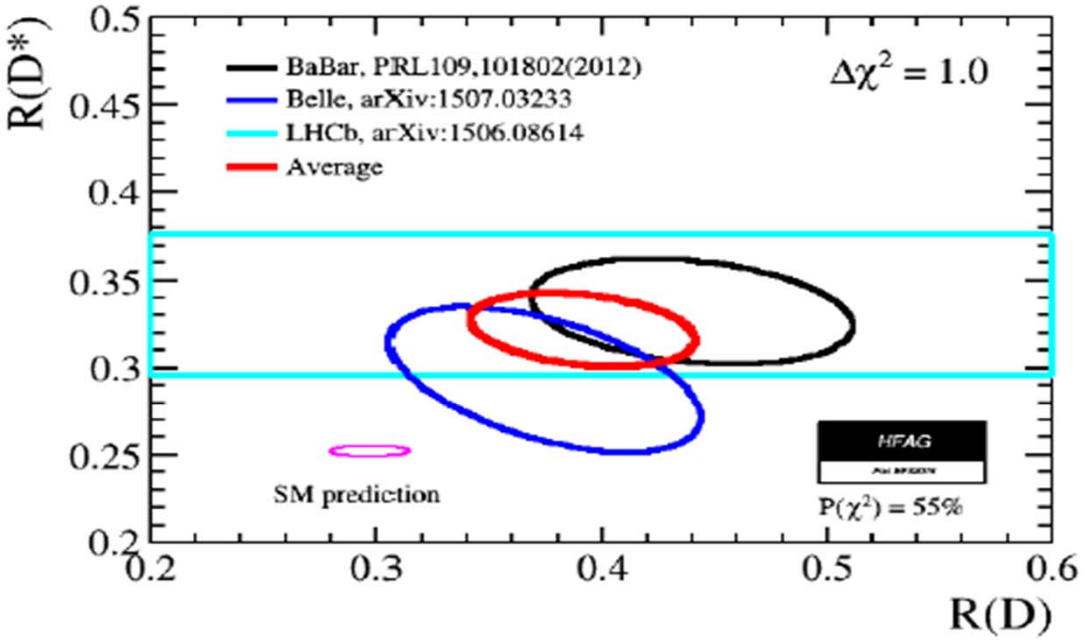


FIG. 1: Current experimental status in the measurements of $R(D)$ and $R(D^*)$.

Lots of excitement for past ~ 3 years! ~3.5σ! BUT…..

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

- S.L. decays involving a $\tau^{\pm}$ have an additional helicity amplitude (for D*

$$\frac{d\Gamma_\tau}{dq^2} = \frac{G_F^2 |V_{cb}|^2 |\mathbf{p}| q^2}{96\pi^3 m_B^2} \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \left[\left(|H_{++}|^2 + |H_{--}|^2 + |H_{00}|^2\right) \left(1 + \frac{m_\tau^2}{2q^2}\right) + \frac{3}{2} \frac{m_\tau^2}{q^2} |H_t \right.$$

For $D\tau\nu$, only H_{00} and H_t contribute!

- To test the SM Prediction, we measure

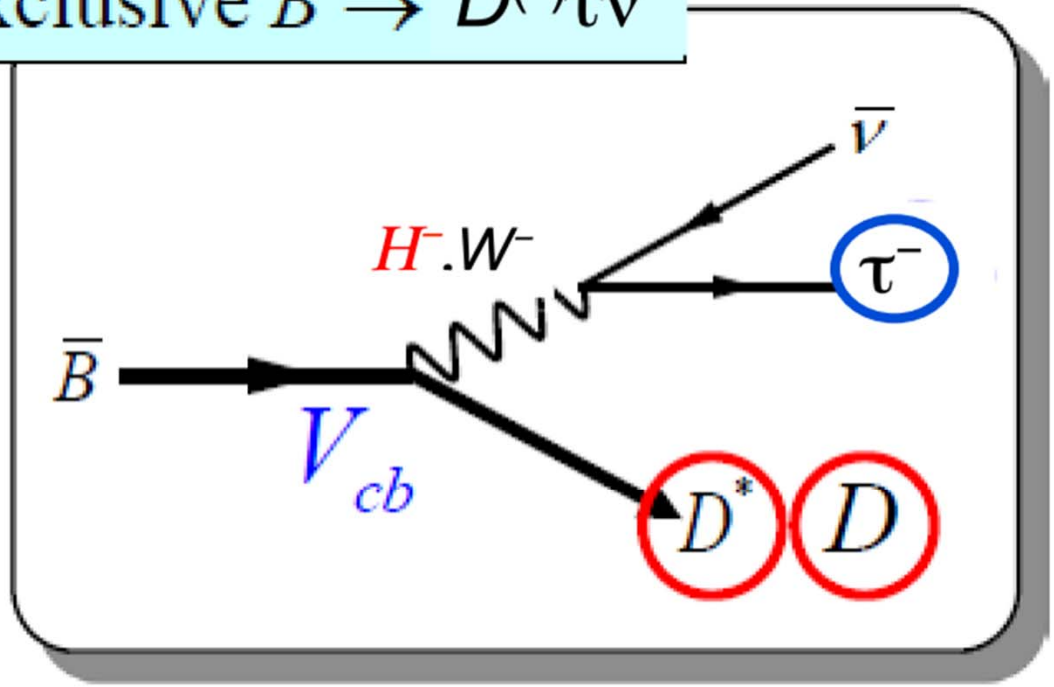
$$R(D) = \frac{\Gamma(\overline{B} \to D\tau\nu)}{\Gamma(\overline{B} \to D\ell\nu)} \qquad R(D^*) = \frac{\Gamma(\overline{B} \to D^*\tau\nu)}{\Gamma(\overline{B} \to D^*\ell\nu)}$$

Leptonic τ decays only

Several experimental and theoretical uncertainties cancel in the ratio!

- BB events are fully reconstructed:
  - full reconstruction of hadronic B decay: Btag (tag efficiency improved)
  - reconstruction of $D^{(*)}$ and $e^{\pm}$ or $\mu^{\pm}$ (extend to lower momenta)
  - no additional charged particles
  - kinematic selections: $q^2 > 4$ GeV^2

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



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

MANUEL FRANCO
SEVILLA
PhD Thesis
SLAC

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:

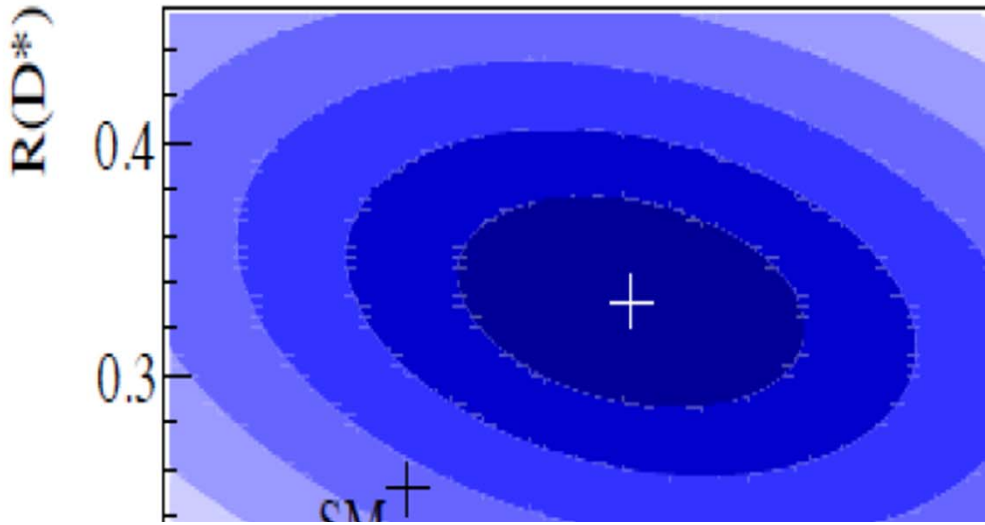
LUTH

	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**

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

Combined 3.4σ

BABAR



Combination to 3.4 sigma is too aggressive and most likely inaccurate!

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

- for Dτν
+ for D*τν

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

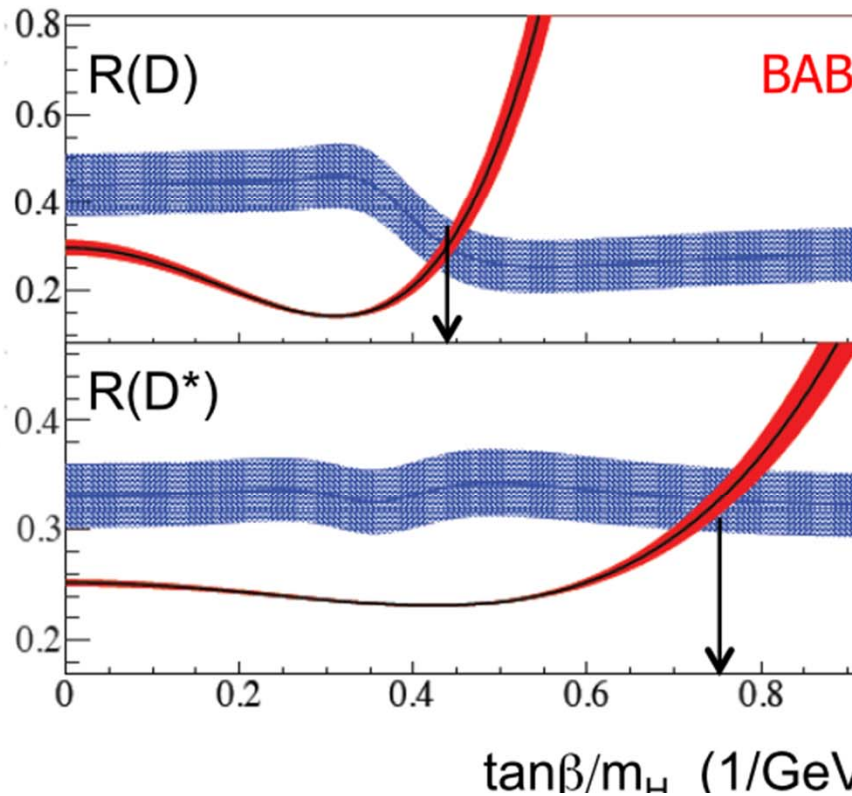
We estimate the effect of 2DHM, accounting for difference in efficiency, and its uncertainty

The data match 2DHM Type II at

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

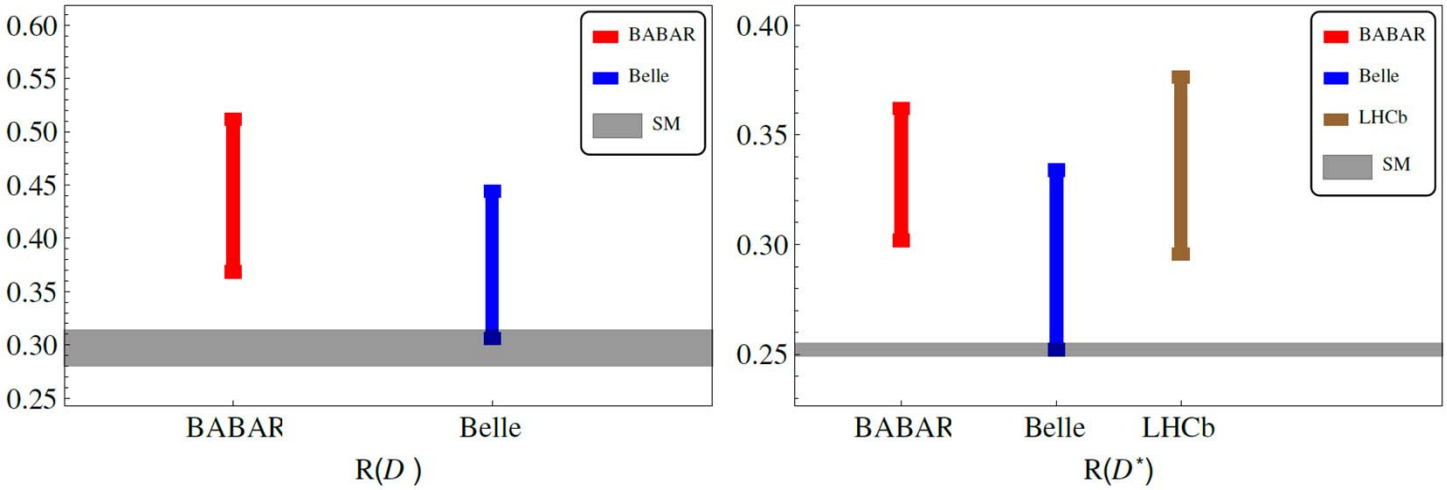
$\tan\beta/m_H = 0.75 \pm 0.04$ for R(D*)

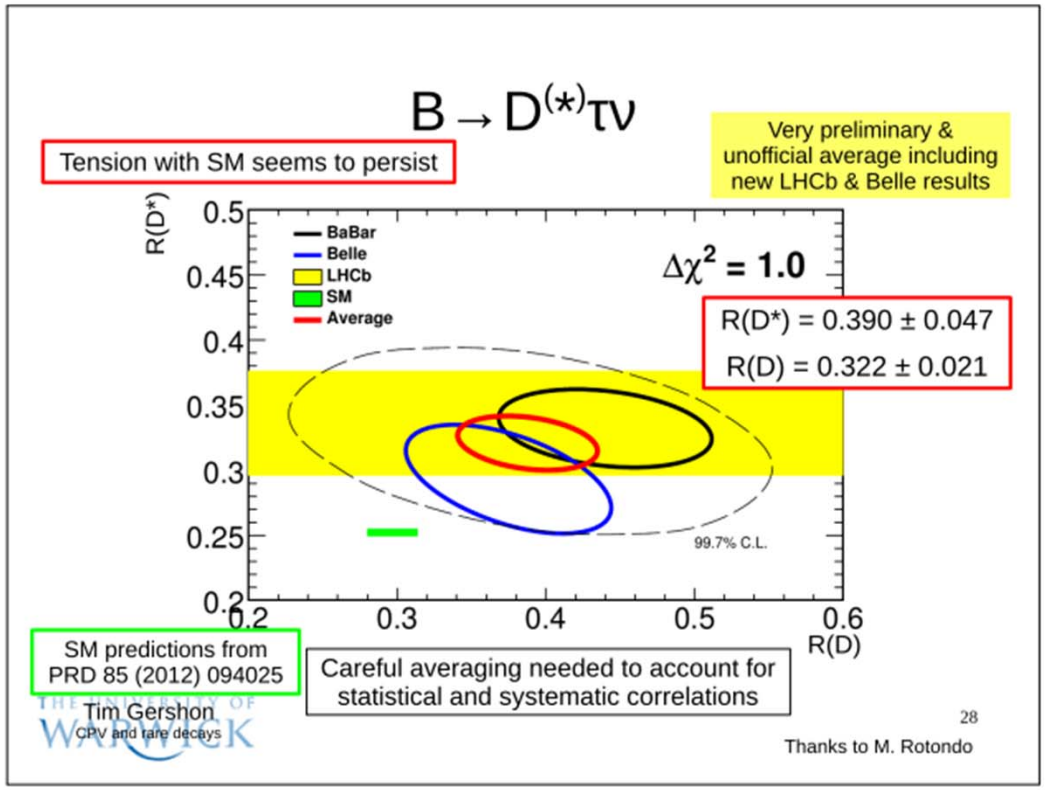
However, the combination of R(D) and R(D*) excludes the Type II 2HDM in the full $\tan\beta$-m_H parameter space with a probability of >99.8%, provided M_H>10GeV !



The conclusion that type II 2HDM is ruled out is highly unreliable!

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
LHCb
SM
BABAR
Belle
LHCb
R(D*)



[T. Gershon, Talk at MIAPP, 2015/06/24]

LHCb can only do D*

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

My (subjective) summary Part I

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

A critique [SN+SP+AS in prep; WHEPP XIV, IITK,India, Dec 2015]

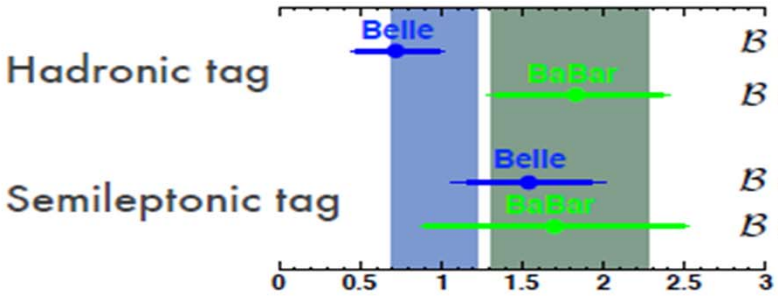
My concerns

- **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



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

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

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

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

NEEDS BELLE ATTENTION

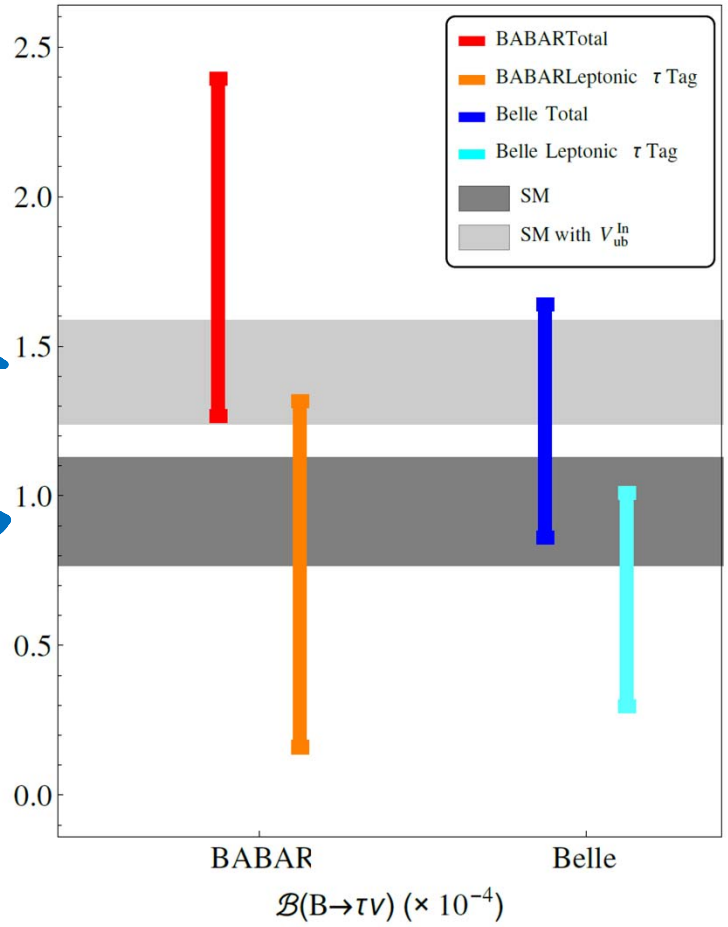
Belle combined: $\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = (0.96 \pm 0.26) \times 10^{-4}$

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

STEP BACK?

- 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.)

SUPER KEK B



SM ← Vub inc
SM ← Vub exc

NPs in play.

RECENT Belle UPDATE ON
B=>τ ν

Within largish errors 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 depends on Vub**

SM, SP+AS [MIP]

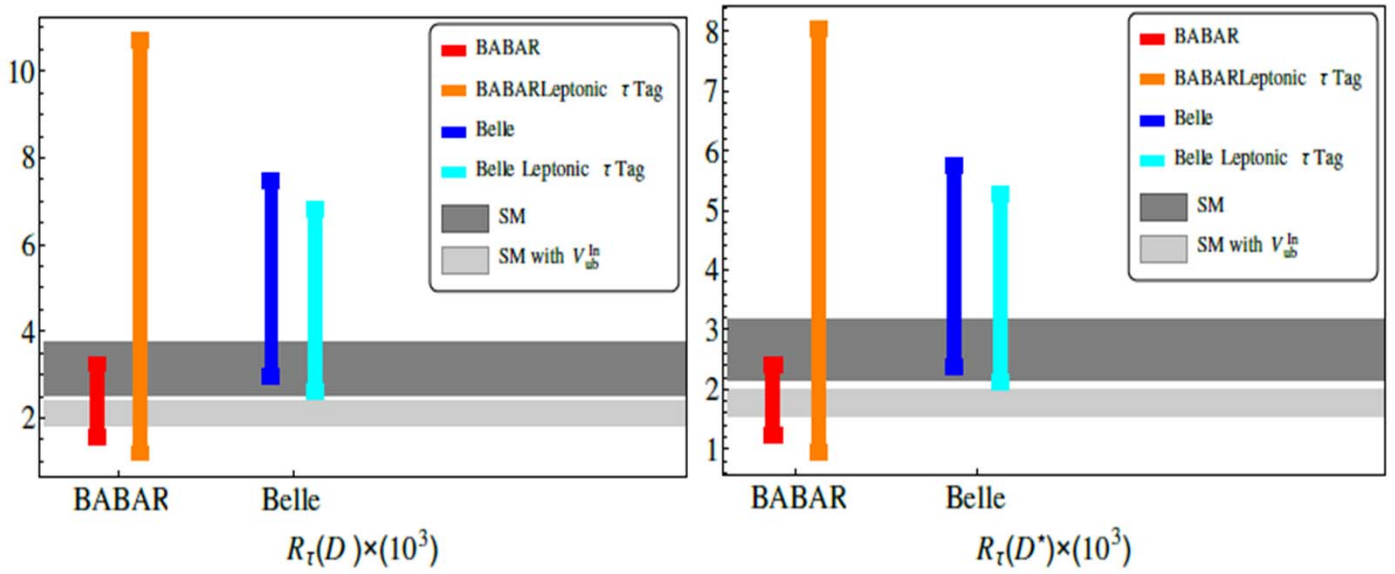


FIG. 4: $R_\tau(D^{(*)})$: SM vs. Exp.

REMARKABLY: NO deviation from the SM; all the 2 or 2.7 sigma problems are gone in here!

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

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

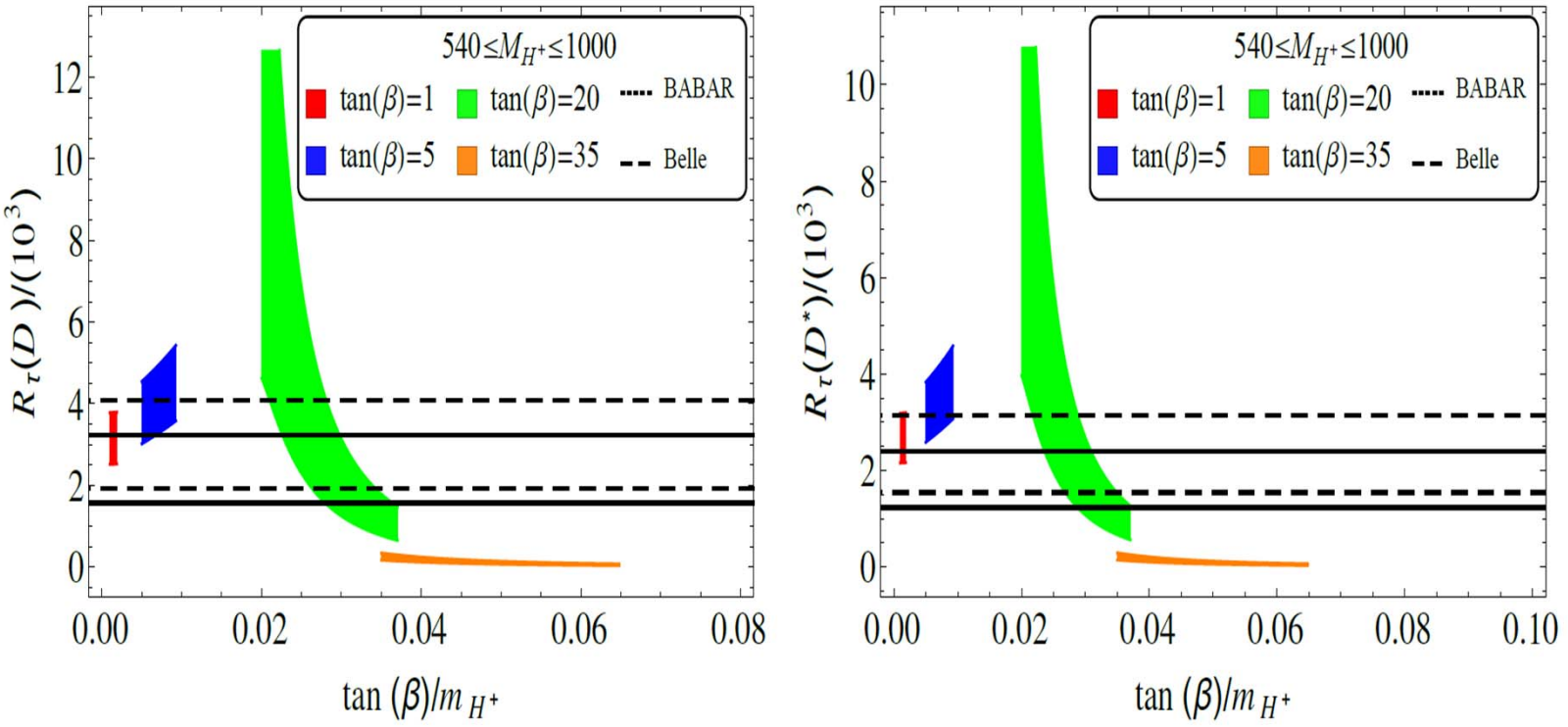


FIG. 7: Variations of $R_\tau(D)$ (left) and $R_\tau(D^*)$ (right) with the 2HDM-II parameter $r = \tan\beta/m_{H^+}$ for different values of $\tan\beta$. The 1σ experimental ranges are shown by the dotted (*BABAR*) and dashed (Belle) lines.

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**

LUV?

Test of lepton universality using $B^+ \to K^+ l^+ l^-$ decays

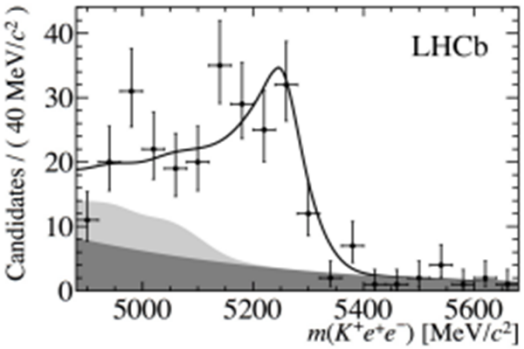
LHCb-PAPER-2014-024

$$R_K = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma[B^+ \to K^+ \mu^+ \mu^-]}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma[B^+ \to K^+ e^+ e^-]}{dq^2} dq^2}$$

expected to be $R_K^{SM} = 1 + O(\frac{m_\mu^2}{m_b^2})$ in the SM with low theoretical uncertainty

➜ Use double ratio to reduce systematics

$$R_K = (\frac{N_{K^+\mu^+\mu^-}}{N_{K^+e^+e^-}})(\frac{N_{J/\psi(e^+e^-)K^+}}{N_{J/\psi(\mu^+\mu^-)K^+}})(\frac{\epsilon_{K^+e^+e^-}}{\epsilon_{K^+\mu^+\mu^-}})(\frac{\epsilon_{J/\psi(\mu^+\mu^-)K^+}}{\epsilon_{J/\psi(e^+e^-)K^+}})$$



e triggered

0, 1 and 2 photons combined

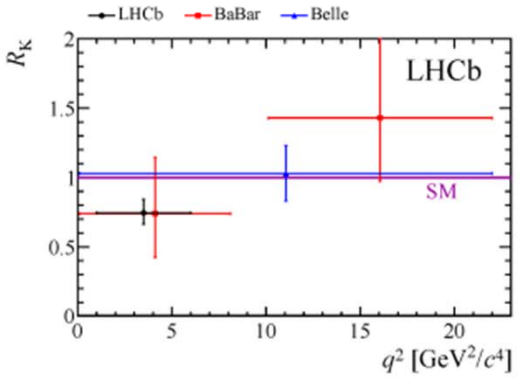
➜ Challenging measurement in $B^+ \to K^+e^+e^-$ channel
→ proof of principle for future electron analyses

➜ Separate PDF according to:

1) Particle firing the hardware trigger
2) Number of bremsstrahlung photons

R_K: Results

- $R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$ in the range $1 < q^2 < 6\ \text{GeV}^2$, using $3.0\,\text{fb}^{-1}$
- Compatible with SM expectation at 2.6σ



- Could point to additional Higgs bosons or Z'
- Try to improve analysis technique and add R_{K^*}, $R_{(K\pi)^*}$, R_{Λ^*}, R_ϕ and more...
- Can extend analysis to other q^2 bins with addition of Run 2 data

comments

- **Thanks to lhcb for coining a simple and powerful observable for probing LUV**
- **For cleaner e+ e- environment, especially very powerful; lot of data available but not analyzed in this careful manner…what a shame!**
- **My Concern…Radiative corrections can be very important; brings in detector dependence**
- **q^2 dependence is of crucial importance [Need of lot of statistics]**
- **Genuine LUV should be "independent" of whether M is K, K*, pi, rho; Data not available yet**

A peek @ pdg

Many possible few sigmas [naïve] indications that deserve careful experimental examination

PDG(2015) NAIVE RATIOS $R_{K(*)}$ Belle II

$K^+ e^+ e^-$	B1	$(5.5 \pm 0.7) \times 10^{-7}$	0.8 ± 0.1	0.025
$K^+ \mu^+ \mu^-$	B1	$(4.43 \pm 0.24) \times 10^{-7}$		
$K^*(892)^+ e^+ e^-$	B1	$(1.55 \pm^{0.40}_{0.31}) \times 10^{-6}$	0.6 ± 0.07	0.015
$K^*(892)^+ \mu^+ \mu^-$	B1	$(9.6 \pm 1.0) \times 10^{-7}$		

PDG 2015

$K^0 e^+ e^-$	B1	$(1.6 \pm^{1.0}_{0.8}) \times 10^{-7}$
$K^0 \mu^+ \mu^-$	B1	$(3.39 \pm 0.34) \times 10^{-7}$

$\sim 2.1 \pm 1.3 \rightarrow 0.25$

$K^*(892)^0 e^+ e^-$	B1	$(1.03 \pm^{0.19}_{0.17}) \times 10^{-6}$
$K^*(892)^0 \mu^+ \mu^-$	B1	$(1.05 \pm 0.10) \times 10^{-6}$

$\sim 1 \pm 0.25 \rightarrow 0.05$

PDG 2015

se^+e^-	B1	$(6.7 \pm 1.7) \times 10^{-6}$
$s\mu^+\mu^-$	B1	$(4.3 \pm 1.0) \times 10^{-6}$

0.65 ± 0.22

$\searrow$ 0.04

It is quite ironic that so many of the existing PDG results indicate possibly weak hints of LUV!
Demands attention!

Take home messages for LUV from rare B's

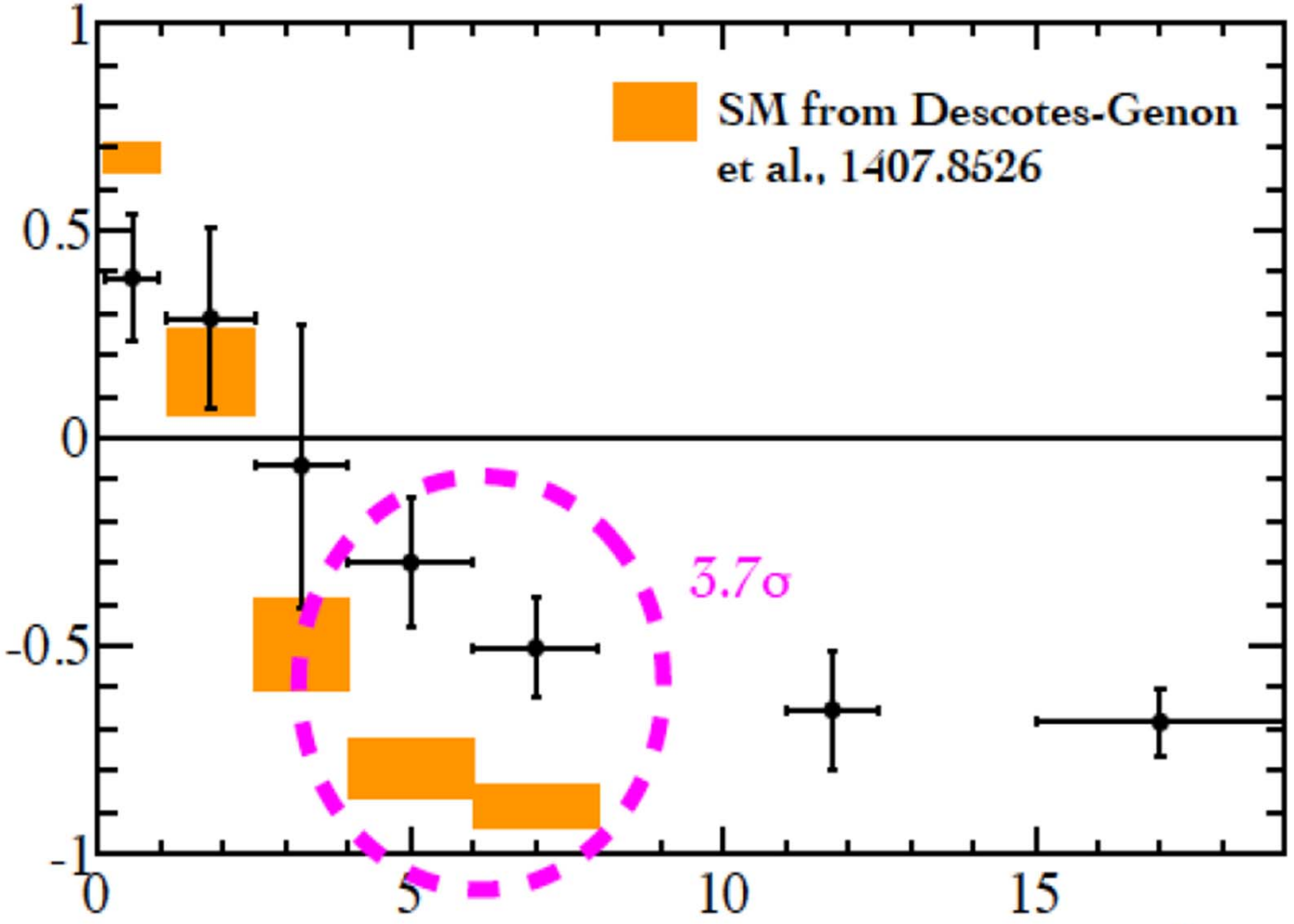
- **Several existing measurements even in PDG possibly indicate few sigma deviations**
- **Expect BELLE II and more data from LHCb to provide much more stringent and decisive tests**

- **Also, BABAR, BELLE, BELLEII should easily be able to provide direct comparisons to LHCb in a given q^2 range that can be compared to LHCb**
- **Radiative corrections need to be carefully included….serious concern**

Moreover, if its genuine e->mu UV then we should see irrespective of final meson(s), i.e.
B(s) => M mu mu vs M e e, for all M and similarly for inclusive final states

B =>K* l l

[LHCb-CONF-2015-002]



SM should be "SM"

yesterday's talks]

My take on

$\Lambda_{QCD}/m_c \sim 25\%$

Coeff $\sim 2\text{-}4 \ldots$

- **The so-called SM numbers are not reliable**.
- There are large uncertainties in these calculations because **charm mass is uncomfortably small.**
- So, the usual dim-6 effective Hamiltonian coming from OPE ignores all these

LD effects. You can think of them (for example) by a tower of higher dimensional operators that fall off with mc^2. You need to know the coefficients of these operators and their matrix elements through some non-perturbative method to provide you a reliable error on the truncation

of the OPE that you have done in giving your simple "SM" values.

- Related to this also is the fact that the region is rich with **charmonia resonances**. Proper estimate of their effects is difficult as resonances can have long tails

Related analysis of Karan et al

arXiv:1603.04355

Signal of right-handed currents using $B \to K^* \ell^+ \ell^-$ observables at the kinematic endpoint.

as a binned function of q^2, the dilepton invariant mass squared. We show that LHCb data implies a 5σ overall signal for new physics and provides unambiguous evidence for right-handed currents, which are absent in the SM. These conclusions are derived in the maximum q^2 limit and are free from hadronic corrections. Our approach differs from other approaches that probe new physics at

BUT Need Reliable Estimate of Symmetry Breaking

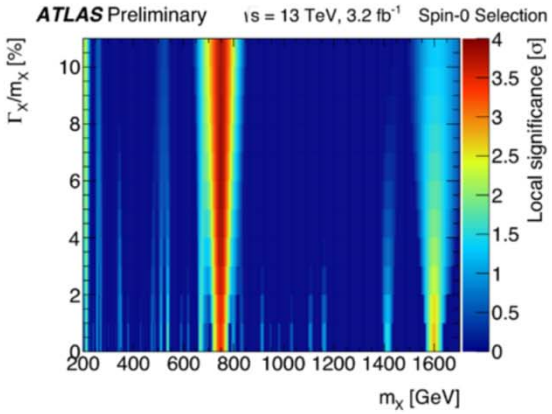
ALSO LD Charm as before

Diphoton anomaly @ 750 GeV

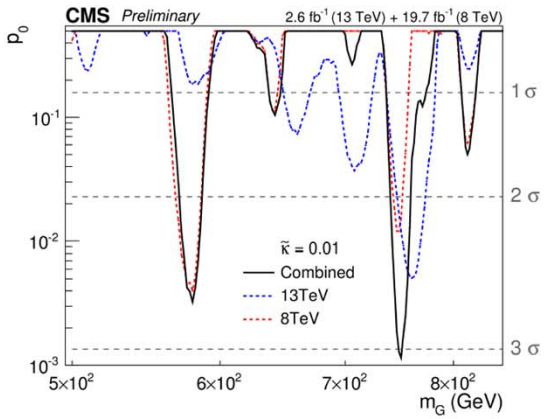
Ayana Arce @ ANL 04/21/16; c also Albert De Roeck @ BNL 04/08/16

local significance @ 750 GeV

ATLAS



CMS



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)

In BSM Large Flavor violation in t-decays are possible (likely)

Recall in SM, e.g. t=>cZ (h) is exceedingly small…see

Eilam, Hewett and A. S PRD '91

$\sim 10^{-13} - 10^{-14}$

Mele, Petrarca, Soddu
PLB '98

Need to keep an eye also on

$\frac{m_\tau m_u}{m_t m_c} \sim 10^{-3}$

H → τμ:

ATLAS:

BR = 0.53 ± 0.51% < 1.43% (95% CL)

CMS:

BR = $0.84^{+0.39}_{-0.37}$ % < 1.51% (95% CL)

Andreas Hoecker: Expt Summary EW Moriond

In BSM top FV can be significantly enhanced

- **In RS t=> cZ, ch Br can reach ~10^-7 for mKK ~10TeV**

[Agashe, Perez AS, PRD'07] Enhanced tc is hallmark of RS theory of flavor

e^+ e^- => t c gives a great signal @ CME < 2mt

…Atwood, Reina, AS , PRD'96

pp => t c h can provide powerful constraint …see Atwood, Gupta, AS JHEP 2014; Chen, Hou, Kao & Kohda PLB 2013

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] …..very sensitive to charged**
- **TDCPV B => gamma K pi**
- **K : eps' ; KL=> pi0 nu nu**

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**

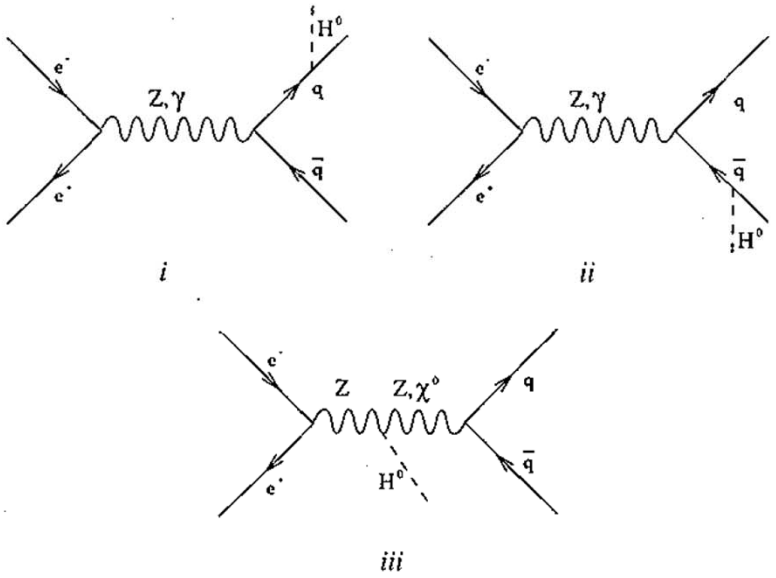


FIG. 1. Tree-level Feynman diagrams contributing to $e^+e^- \to t\bar{t}H^0$ within the two Higgs doublet model.

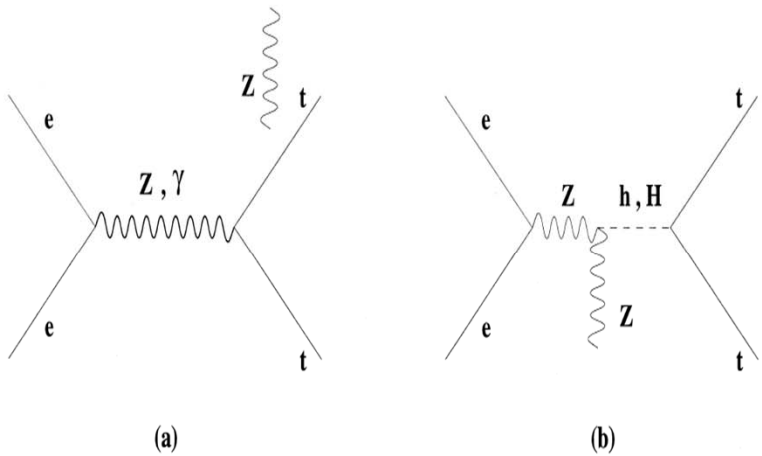


Fig. 1. Tree-level Feynman diagrams contributing to $e^+e^- \to t\bar{t}Z$ in a two Higgs doublet model. Diagram *a* represents 8 diagrams in which either Z or γ are exchanged in the s-channel and the outgoing Z is emitted from e^+, e^-, t or $\bar{t}$.

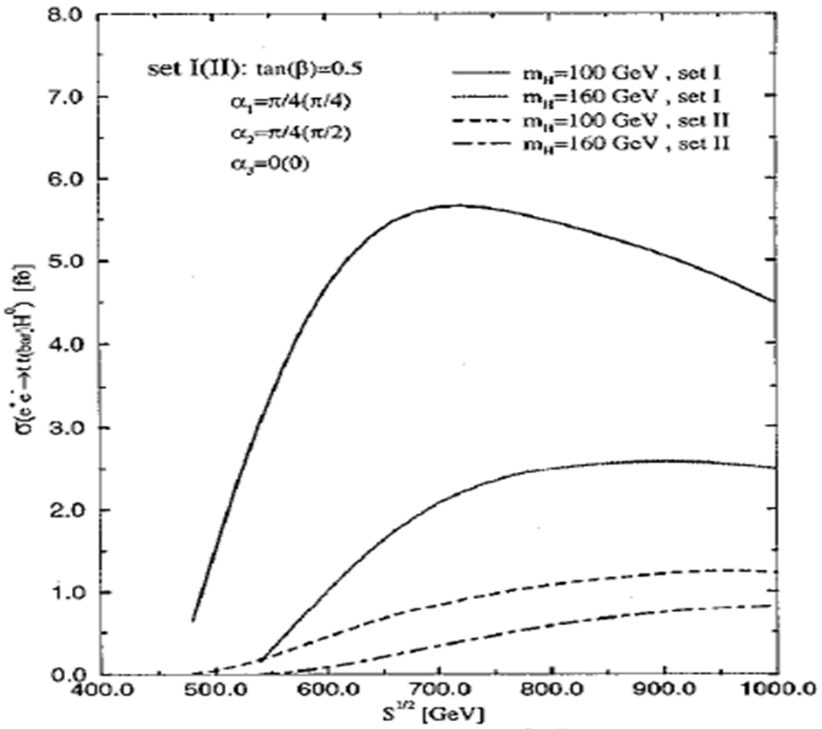


FIG. 2. The cross section (in [fb]) for the reaction $e^+e^- \to t\bar{t}H^0$, for sets I and II of the parameters a_t, b_t, and c and for $m_{H^0} = 100$ and 160 GeV assuming unpolarized electron and positron beams.

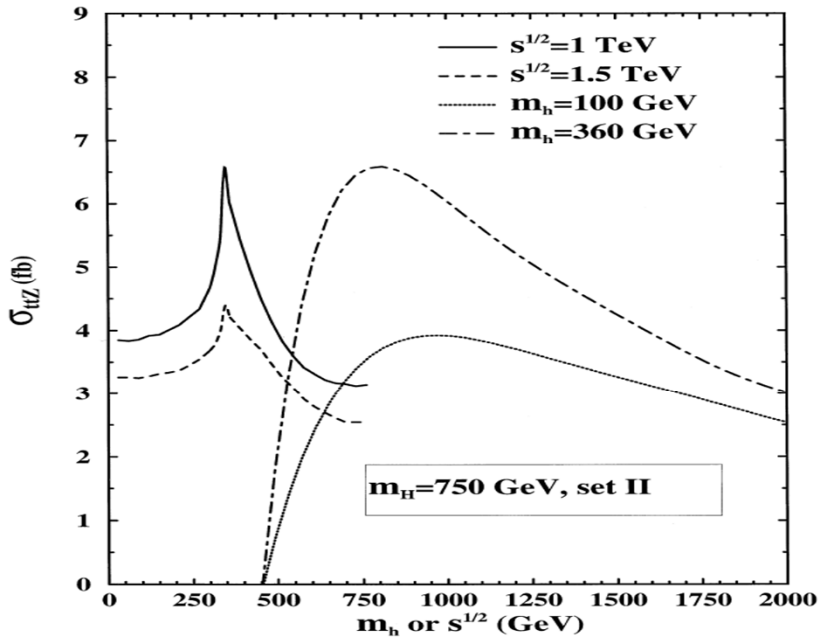


Fig. 2. The cross section (in [fb]) for the reaction $e^+e^- \to \tilde{t}\tilde{t}Z$, assuming unpolarized electron and positron beams, for Model II with set II and as a function of m_h (solid and dashed lines) and $\sqrt{s}$ (dotted and dotted-dashed lines). Set II means $\{\tan\beta, \alpha_1, \alpha_2,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

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

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

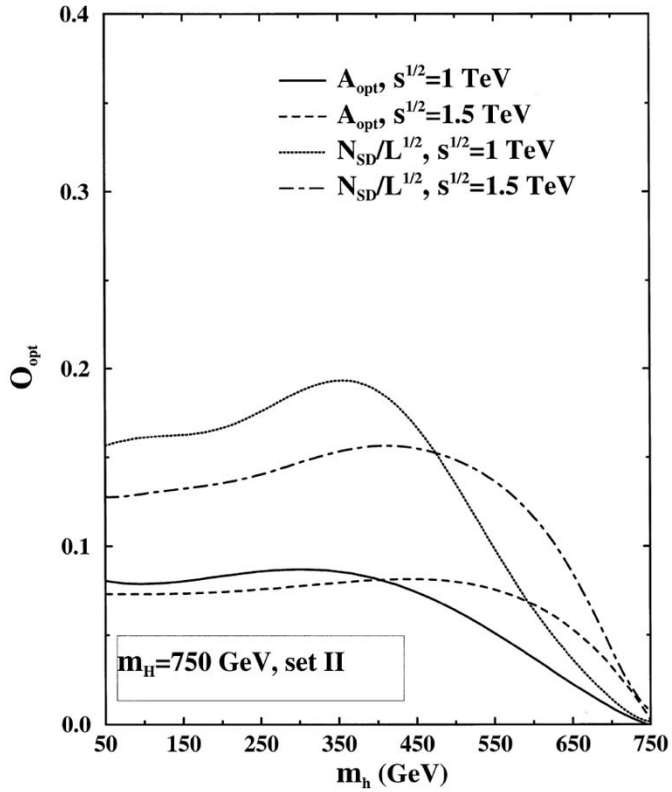


Fig. 3. The asymmetry, $A_{\rm opt}$, and scaled statistical significance, $N_{\rm SD}/\sqrt{L}$, for the optimal observable $O_{\rm opt}$ as a function of the light Higgs mass m_h, for $\sqrt{s}=1$ TeV and 1.5 TeV. See also caption to Fig. 2.

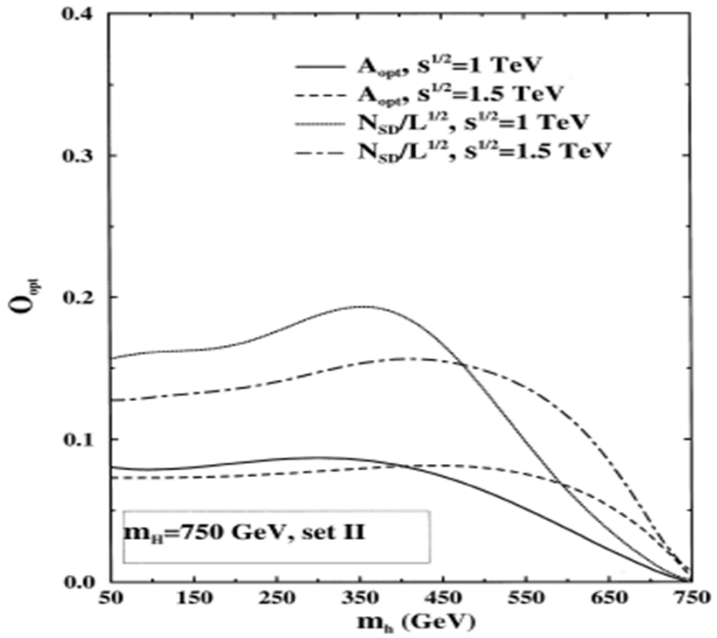


Fig. 3. The asymmetry, A_{opt}, and scaled statistical significance, $N_{SD}/\sqrt{L}$, for the optimal observable O_{opt} as a function of the light Higgs mass m_h, for $\sqrt{s}=1$ TeV and 1.5 TeV. See also caption to Fig. 2.

ε'

ε’ / ε: Direct CPV

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

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

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

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

BNL '64
CRONIN + FITCH N.P.

→ Indirect CP

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

DIRECT CP

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

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

Its presumed importance:

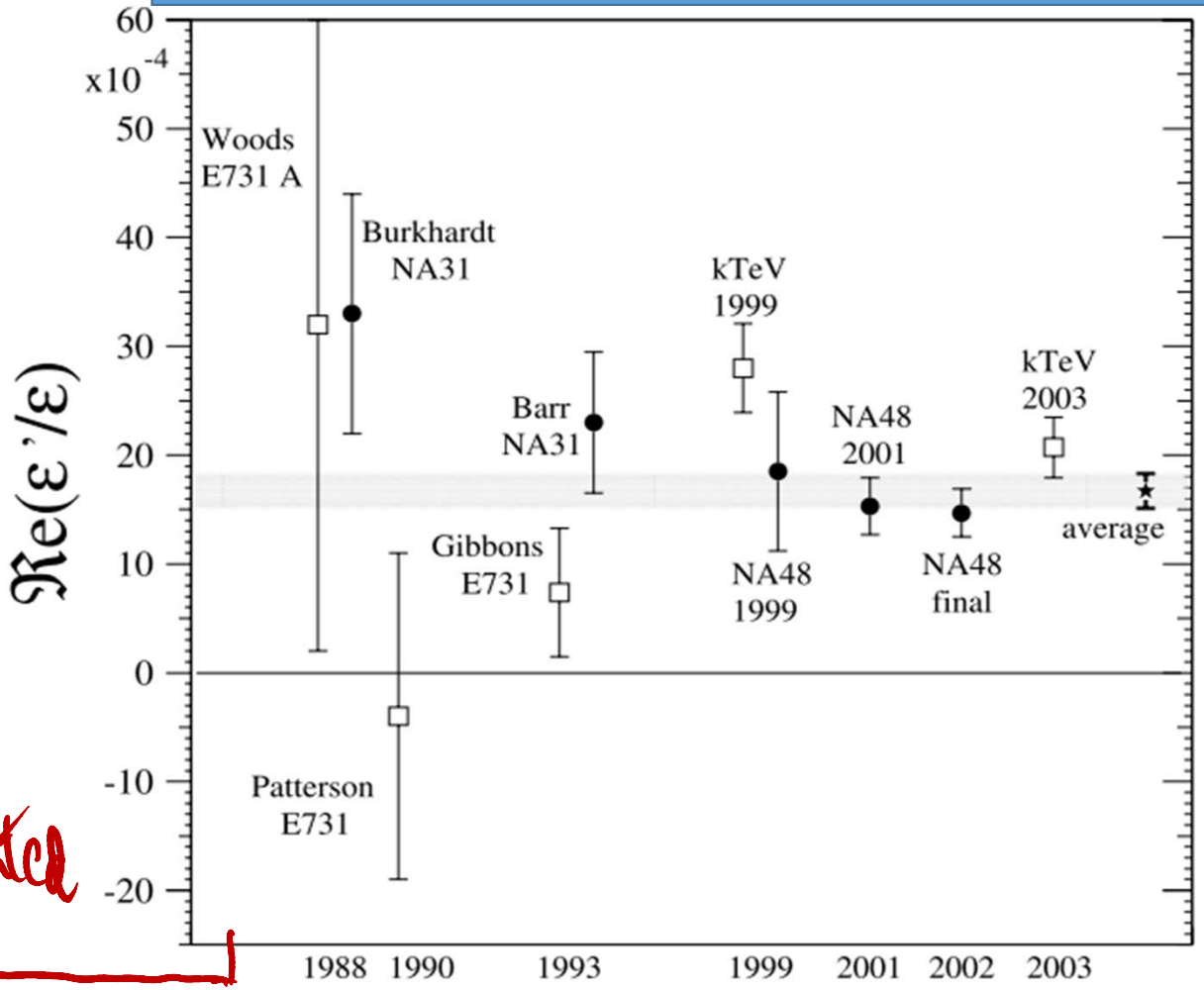
- **lies in its very small size => Perhaps new phenomena has a better chance of showing up**
- **Exceedingly important monitor of flavor –alignment**
- **Simple naturalness arguments strongly suggest eps' very sensitive to BSM – CP odd phases**
- **In many ways eps' is rather analogous to nedm…….both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



LATTICE workstarted

Konrad Kleinknecht "Uncovering CPV"

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

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)**

- **Post-docs & such: Tom Blum (U Conn), Chris Dawson(google), Chris Kelly (RBRC); Christoph Lehner (HET; BNL); Taku Izubuchi (HET/RBRC); Chulwoo Jung(SCIDAC/BNL)**

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	

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,

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

$$= \begin{array}{ll} 1.38(5.15)(4.43) \times 10^{-4}, & \text{(this work)} \\ 16.6(2.3) \times 10^{-4} & \text{(experiment)} \end{array}$$

EWP

QCDP

PARTIAL Cancellation

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

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

$\mathrm{Re}A_0, A_2$ from expt for now.

RBC Collaboration

Since ~ '97

- BNL
  - Chulwoo Jung
  - Taku Izubuchi (RBRC)
  - Christoph Lehner
  - Meifeng Lin
  - Amarjit Soni
- RBRC
  - **Chris Kelly**
  - Tomomi Ishikawa
  - Taichi Kawanai
  - Shigemi Ohta (KEK)
  - Sergey Syritsyn
- Columbia
  - Ziyuan Bai
  - Xu Feng
  - Norman Christ
  - Luchang Jin
  - Robert Mawhinney
  - Greg McGlynn
  - David Murphy
  - **Daiqian Zhang**
- Connecticut
  - **Tom Blum**

RBC–

UKQCD Collaboration

Since ~2006

- Edinburgh
  - Peter Boyle
  - Luigi Del Debbio
  - Julien Frison
  - Jamie Hudspith
  - Richard Kenway
  - Ava Khamseh
  - Brian Pendleton
  - Karthee Sivalingam
  - Oliver Witzel
  - Azusa Yamaguchi
- Plymouth
  - Nicolas Garron
- York (Toronto)
  - Renwick Hudspith
- Southampton
  - Jonathan Flynn
  - Tadeusz Janowski
  - Andreas Juttner
  - Andrew Lawson
  - Edwin Lizarazo
  - Antonin Portelli
  - Chris Sachrajda
  - Francesco Sanfilippo
  - Matthew Spraggs
  - Tobias Tsang
- CERN
  - Marina Marinkovic

mc KITP

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

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

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

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

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

$\to 0$ as $m_q \to 0$

EWP

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

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

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

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

$\to$ const as $m \to 0$

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**

i	Re(A_0)(GeV)	Im(A_0)(GeV)
1	$1.02(0.20)(0.07) \times 10^{-7}$	0
2	$3.63(0.91)(0.28) \times 10^{-7}$	0
3	$-1.19(1.58)(1.12) \times 10^{-10}$	$1.54(2.04)(1.45) \times 10^{-12}$
4	$-1.86(0.63)(0.33) \times 10^{-9}$	$1.82(0.62)(0.32) \times 10^{-11}$
5	$-8.72(2.17)(1.80) \times 10^{-10}$	$1.57(0.39)(0.32) \times 10^{-12}$
6	$3.33(0.85)(0.22) \times 10^{-9}$	$-3.57(0.91)(0.24) \times 10^{-11}$
7	$2.40(0.41)(0.00) \times 10^{-11}$	$8.55(1.45)(0.00) \times 10^{-14}$
8	$-1.33(0.04)(0.00) \times 10^{-10}$	$-1.71(0.05)(0.00) \times 10^{-12}$
9	$-7.12(1.90)(0.46) \times 10^{-12}$	$-2.43(0.65)(0.16) \times 10^{-12}$
10	$7.57(2.72)(0.71) \times 10^{-12}$	$-4.74(1.70)(0.44) \times 10^{-13}$
Tot	$4.66(0.96)(0.27) \times 10^{-7}$	$-1.90(1.19)(0.32) \times 10^{-11}$

TABLE I. Contributions to A_0 from the ten continuum, $\overline{\text{MS}}$ operators $Q_i(\mu)$, for $\mu = 1.53$ GeV. Two statistical errors are shown: one from the lattice matrix element (left) and one from the lattice to $\overline{\text{MS}}$ conversion (right). See the Supplemental Material at [*URL to be inserted*] for tables of the separate matrix elements in the lattice, RI/SMOM and $\overline{\text{MS}}$ schemes as well as the renormalization matrices which relate them.

IF YOU BUILD IT THEY WILL COME

If there is new physics around below ~5 TeV, it is essentially guranteed that eps' will find it!

[of course requires accurate theory calculation]

plan

- **1. generate new ~215 configs so that we can directly verify the result of the previous calculation……longer version of the PRL, possibly 6-9 months**

- **2. Quadruple statistics …possibly before summer 2017 ….thanks to new hardware**

Summary & Outlook [p1 of 2]

- **There are long-standing differences between the values of Vub and of Vcb between exclusive and inclusive methods. These probably result from some underestimate of errors. With more data from experiments (esp Belle II) on B=> pi l nu, B=> Xu l nu, B=>D(*) l nu, B=>Xc l nu and corresponding baryonic modes from LHCb and forthcoming improvements in lattice calculations should lead to resolution.**

- **Systematic tests of mu, e universality in FCNC B, Bs decays are of obvious compelling importance. in face of LHCb results in one channel; careful reanalysis of BABAR, BELLE existing data should be given a high priority in as many relevant channels as possible. Radiative corrections need to be carefully incorporated.**
- **Belle II and also more data and analysis of other related channels at LHC is extremely important.**
- **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.**

It is extremely important to improve our calculation of eps' to see if the current~2 sigma deviation becomes more significant or not

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..]**
- **Should be a strong motivation for FV searches in Higgs and in top decays and in production**
- **Also searches for BSM-CP phase(s) in top pair, tth, top decays are very worthwhile ……**
- **HIGH HOPES FOR RUN 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]:

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

$\Delta S=1$ H_W

WC to NLO

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

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

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