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Closing talk: Flavor anomalies, model independent and new physics considerations

From flavor to new physics.

Lyon, France

Amarjit Soni, BNL-HET

04/20/2018

Clarification

- **Closing talk …..NOT A SUMMARY**
- **CLOSING TALK ~ LAST TALK of this very nice meeting in a really nice flavory town on flavor physics**

- **Of course, in the past several years, I have been giving considerable attention to these anomalies…..So will make some observations based on presentations here and elsewhere and come up with important take home messages from my perspective**
- **Bound to be subjective…..Sorry**

Outline

- several looming deviations from SM …i.e. “anomalies”
- For each case:
- briefly mention reservations for expt & for theory/comments
- Model independent collider implications → for ATLAS, CMS; also for IF
- Assuming NP is a source: array of BSMs
- An illustration,of one minimal, well motivated setup for a BSM origin
- Summary,Outlook & emphasize 4 taking home

SET OF KEY ANOMALIES

Anomalies galore!

- RD(*) ~ 46(?)
- RK(*): 2.66(R_K) ;

- g -2…BNL'06 =>FNAL expt. ~ 3.66 major lattice progress by RBC-UKQCD & others

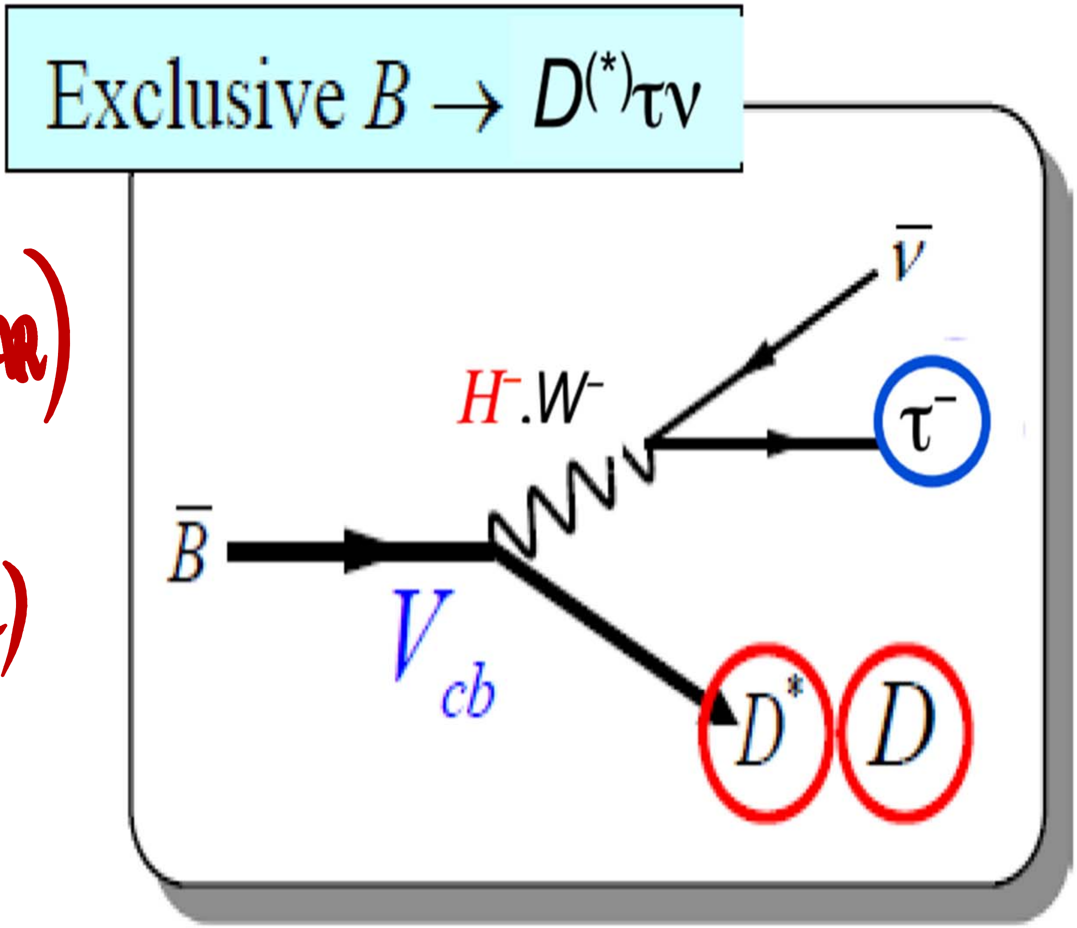
- Ɛ': a personal obsession….for a long^3 time=>'cause of the strong conviction that it is super-sensitive to NP EVER LOOMING

  216[PRL 2015] => ~1200 now => ~1400

[2.1σ (2.9σ Buras; Nierste) => ??] …..few more months to new results

In seeking BSM scenarios it is important to keep all these [INCLUDING ε'] + Higgs radiative stability in mind

RD(*)

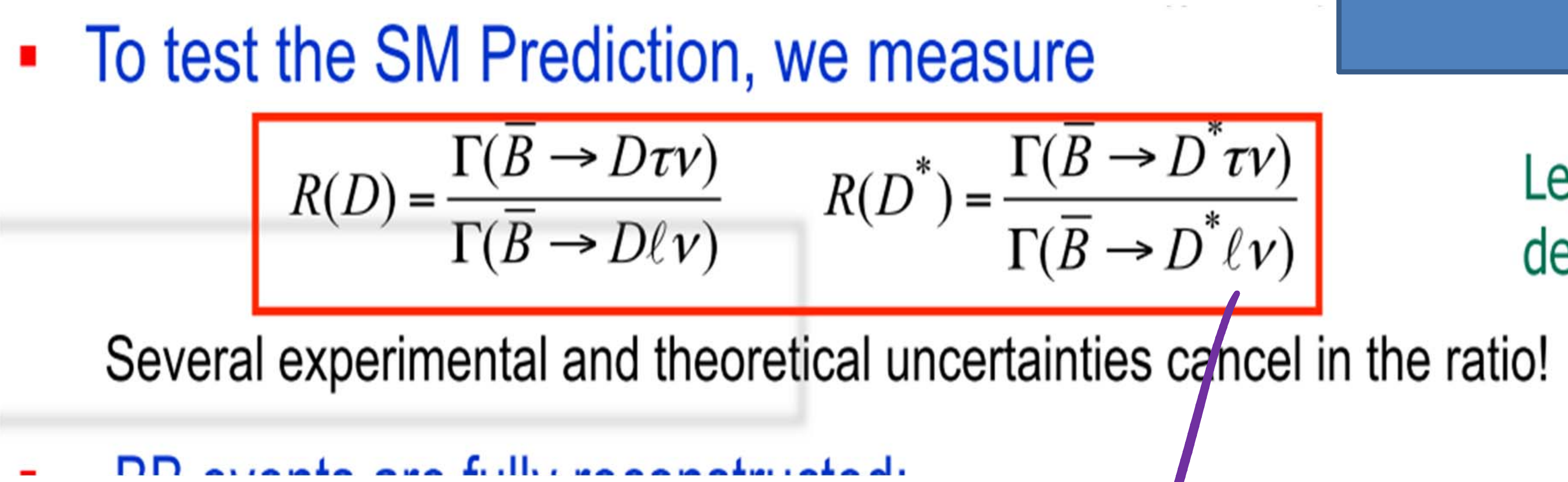


Exclusive $B \rightarrow D^{(*)}\tau\nu$

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

MANUEL FRANCO
SEVILLA
PhD Thesis

Independent of Vcb!



- To test the SM Prediction, we measure

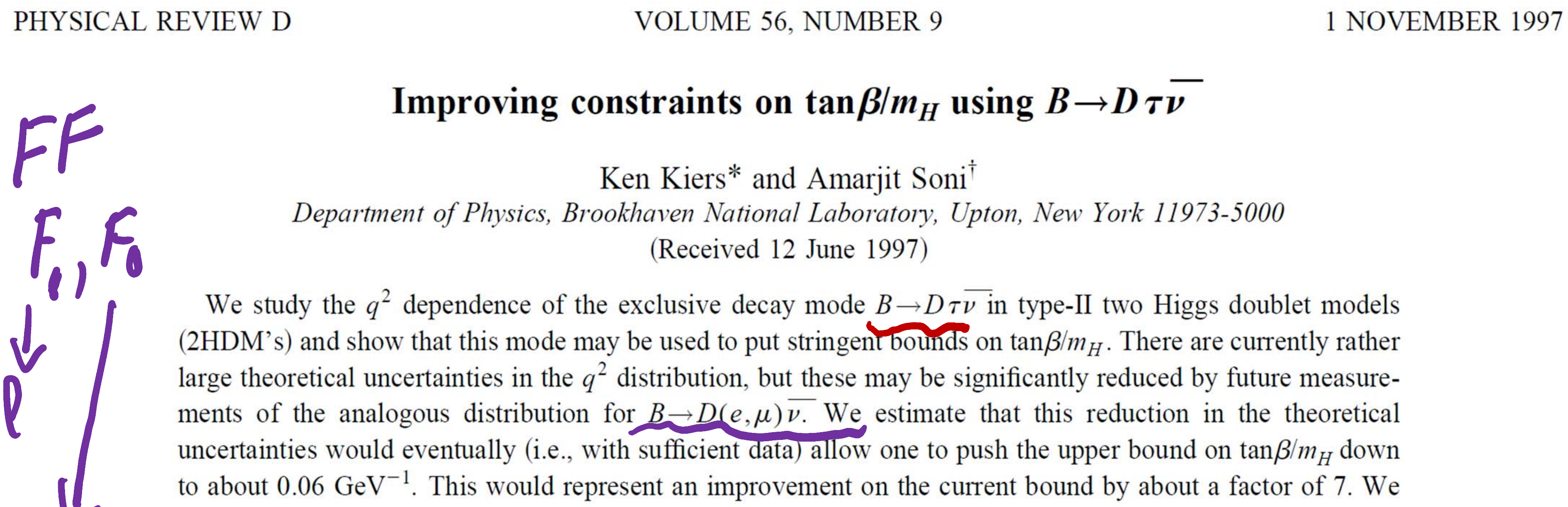
$$R(D)=\frac{\Gamma(\bar{B}\rightarrow D\tau\nu)}{\Gamma(\bar{B}\rightarrow D\ell\nu)}\qquad R(D^{*})=\frac{\Gamma(\bar{B}\rightarrow D^{*}\tau\nu)}{\Gamma(\bar{B}\rightarrow D^{*}\ell\nu)}$$

Several experimental and theoretical uncertainties cancel in the ratio!

- BB events are fully reconstructed:

Leptonic τ decays only

$\ell=\mu$ or e



PHYSICAL REVIEW D VOLUME 56, NUMBER 9 1 NOVEMBER 1997

Improving constraints on $\tan\beta/m_H$ using $B \rightarrow D\tau\overline{\nu}$

Ken Kiers* and Amarjit Soni†
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973-5000

(Received 12 June 1997)

We study the q^2 dependence of the exclusive decay mode $\underline{B \rightarrow D\tau\overline{\nu}}$ in type-II two Higgs doublet models (2HDM's) and show that this mode may be used to put stringent bounds on $\tan\beta/m_H$. There are currently rather large theoretical uncertainties in the q^2 distribution, but these may be significantly reduced by future measurements of the analogous distribution for $\underline{B \rightarrow D(e,\mu)\overline{\nu}}$. We estimate that this reduction in the theoretical uncertainties would eventually (i.e., with sufficient data) allow one to push the upper bound on $\tan\beta/m_H$ down to about 0.06 GeV^{-1}. This would represent an improvement on the current bound by about a factor of 7. We

FF

F_1, F_0

$\downarrow$

ℓ

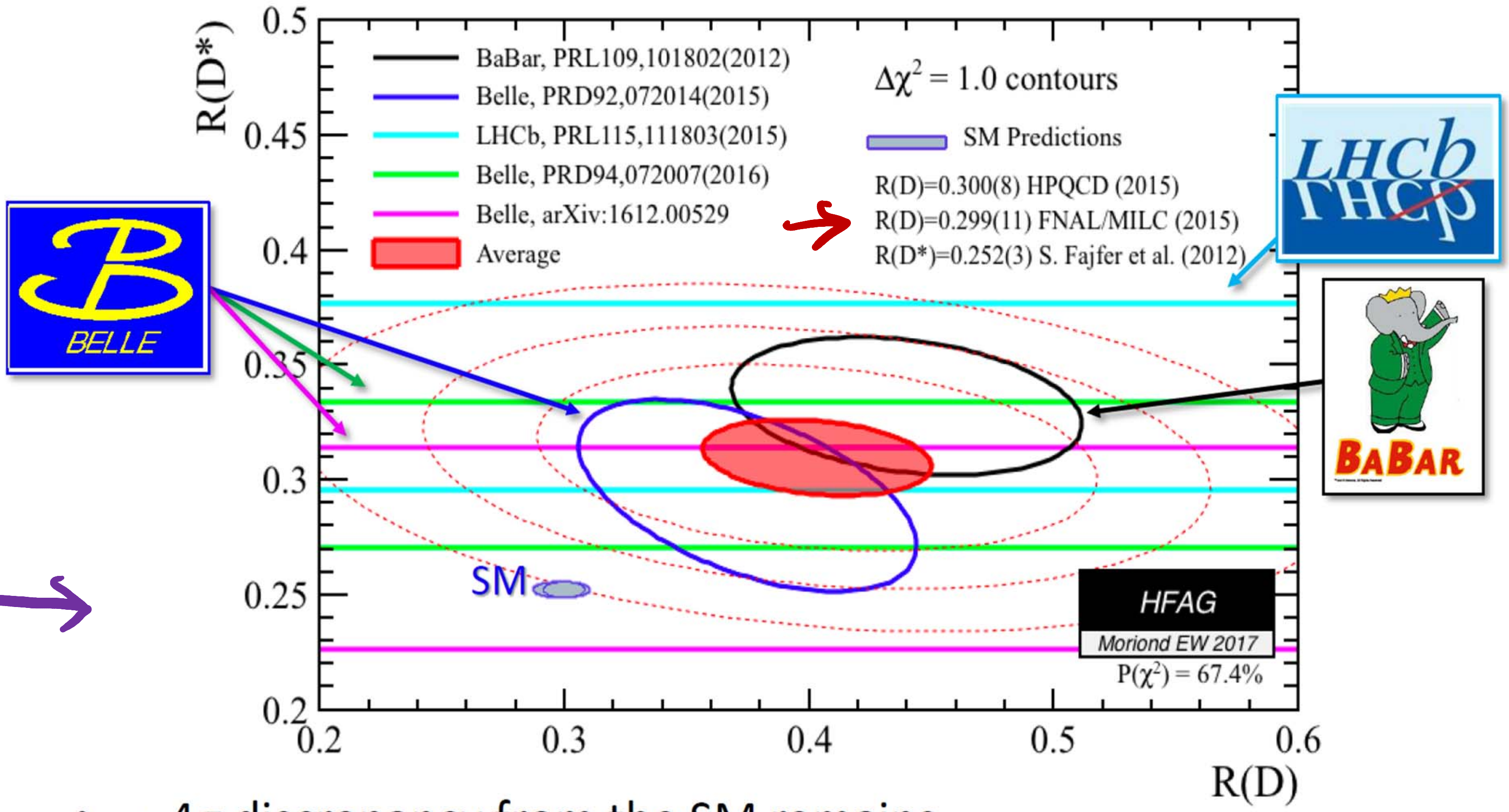
used HQS

⇒ Followed up by Nierste et al '08; Fajfer et al '12

■ $R\left(D^{(*)}\right)$ by HFAG

Hirose [BELLE]@EW
MORIOND Mar. 2017

11/15



- ~4σ discrepancy from the SM remains
  - All the experiments show the larger $R\left(D^{(*)}\right)$ than the SM
- More precise measurements at Belle II and LHCb are essential

Belle deviations quite mild

Lepton universality tests

LHCb introduced such v well defined ratios

- In the SM, ratios

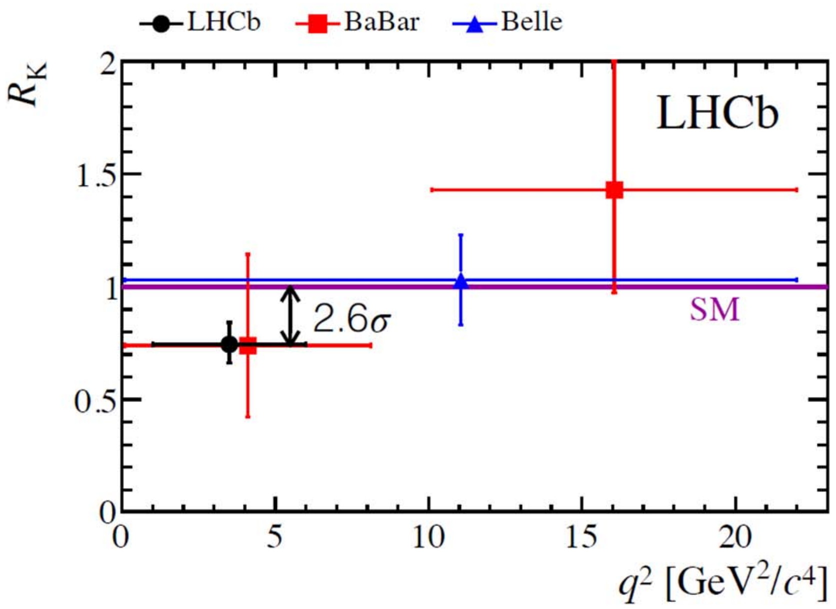
$$R_{\rm K} = \frac{\int {\rm d}\Gamma[B^+ \to K^+\mu^+\mu^-]/{\rm d}q^2 \cdot {\rm d}q^2}{\int {\rm d}\Gamma[B^+ \to K^+e^+e^-]/{\rm d}q^2 \cdot {\rm d}q^2}$$

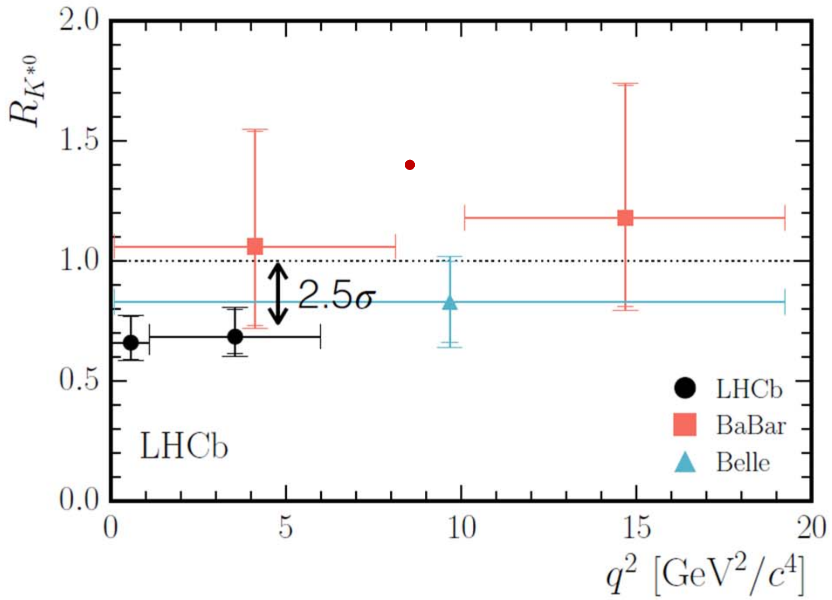
only differ from unity by phase space — the dominant SM processes couple equally to the different lepton flavours.

- Theoretically clean since hadronic uncertainties cancel in the ratio.
- Experimentally challenging due to differences in muon/electron reconstruction (in particular Bremsstrahlung from the electrons).
  - ➡ Take double ratios with $B \to J/\psi X$ decays to cancel possible sources of systematic uncertainty.
  - ➡ Correct for migration of events in q^2 due to FSR/Bremsstrahlung using MC (with PHOTOS).

Lepton universality tests

- We have interesting hints of non-universal lepton couplings in LHCb run 1 dataset:





[LHCb , PRL113 (2014) 151601]
[LHCb, LHCb-PAPER-2017-013]
[BaBar, PRD 86 (2012) 032012]
[Belle, PRL 103 (2009) 171801]

Radiative Correction See Isidori et al

NB $R_K \simeq 0.8$ is a prediction of one class of model explaining the $B^0 \to K^{*0}\mu^+\mu^-$ angular observables, see L_μ - L_τ models
W. Altmannshofer et al. [PRD 89 (2014) 095033]

RECENT UPDATES FROM EXPERIMENT AND FROM THEORY

R(D*) Status

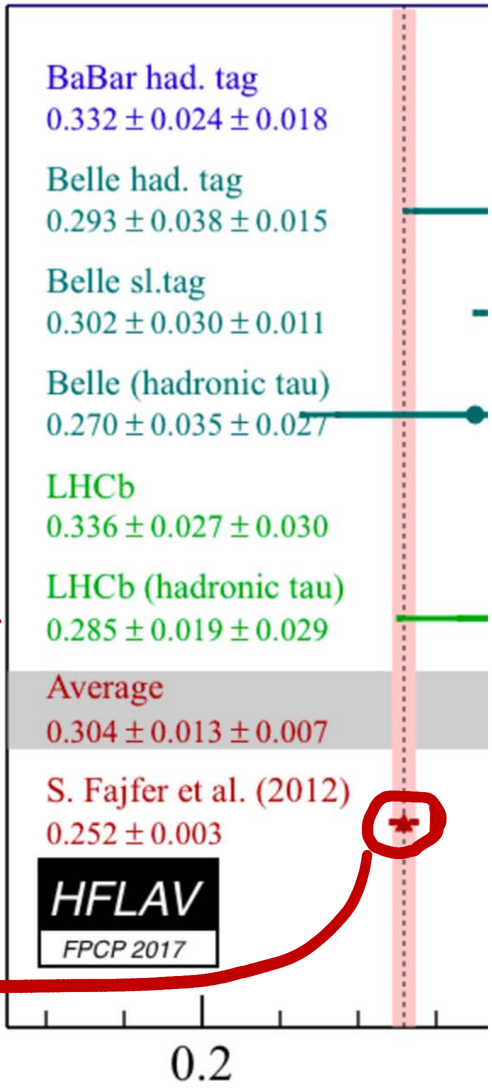
LHCb results have been incorporated on world average compilation.

Currently R(D*) shows a tension of 3.4σ with respect to SM prediction.

σR_{D^*}: 4 with 2-ν's; 2 with 1ν

MISLEADING

WORRY SOME

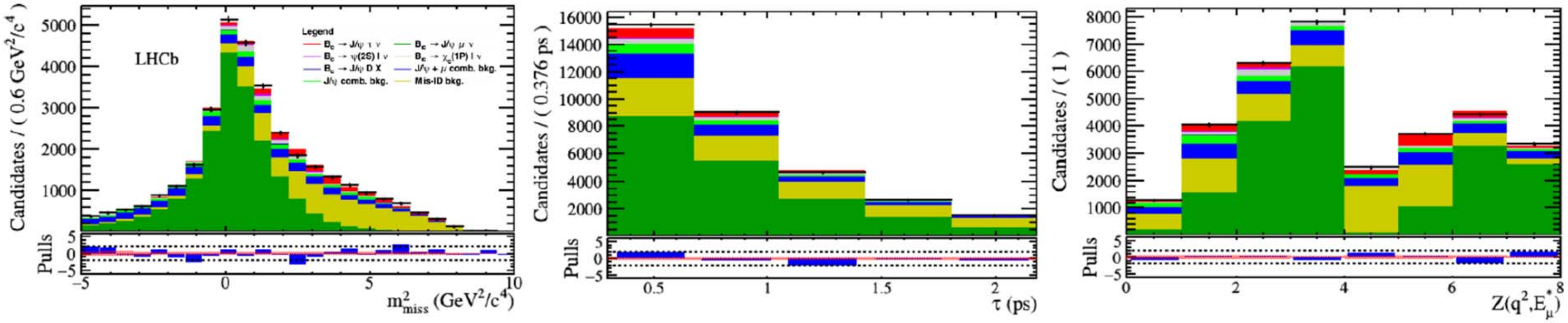


http://www.slac.stanford.edu/xorg/hflav/semi/fpcp17/RDRDs.html

$B_c \to J/\psi\, \tau \nu$

zPW Jan 2018

Greg Ciezarek,
on behalf of the LHCb collaboration



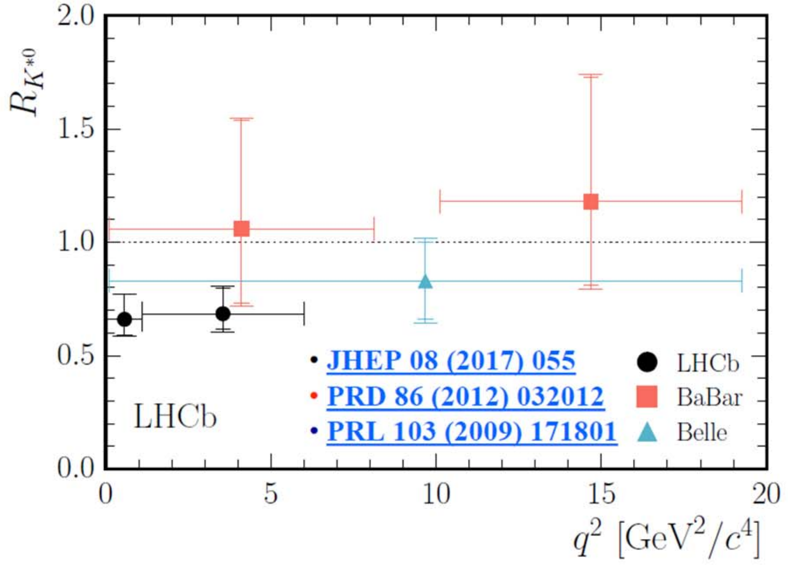
- $R_{J/\psi} \equiv B_c \to J/\psi\, \tau\nu / B_c \to J/\psi\, \mu\nu$
- Measured using very similar techniques to $\mathcal{R}(D^*)$, on run 1 data
- $R_{J/\psi} = 0.71 \pm 0.17 \pm 0.18$
  - $\sim 2\sigma$ from SM
  - But nearly as far from consistency with $\mathcal{R}(D^*)$
- LHCb-PAPER-2017-035(Run 1 data)

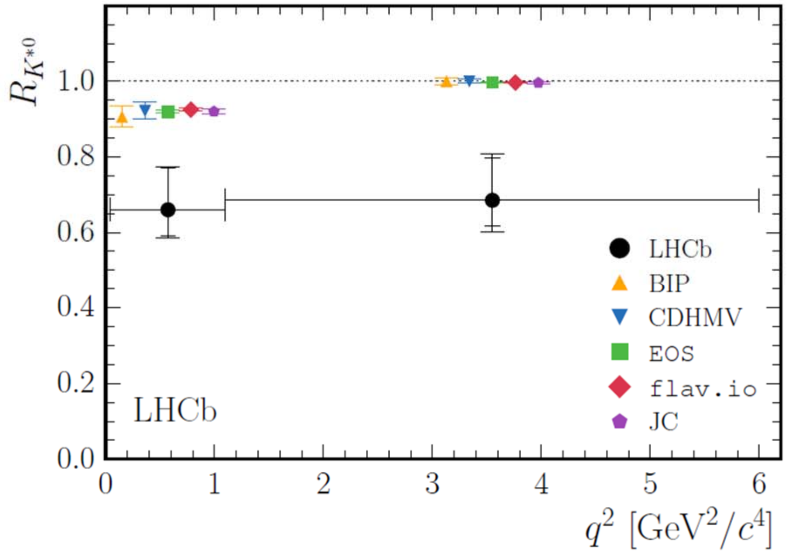
Theory here is trivial

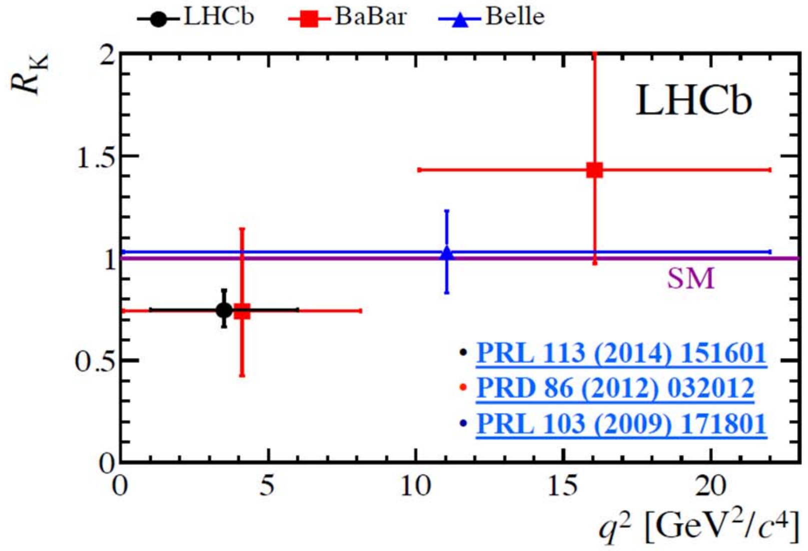
~ NR Bound State

Lepton Universality results

R_{K^*} shows similar results as R_K !







R_K: Central-q^2: 2.6σ from SM

R_{K^*}: Low-q^2: 2.1-2.3σ from SM

R_{K^*}: Central-q^2: 2.4-2.5σ from SM

Rusa Mandal, PhD Thesis [IMSc Chennai]

- Another hint of deviation (at a level of more than 3σ), for a particular neutral-current decay mode is evinced by $B_s \to \phi\mu\mu$ [8, 62, 63].

LHCb

$$\Phi \equiv \frac{d}{dq^2}\mathrm{BR}(B_s \to \phi\mu\mu)\Big|_{q^2\in[1:6]\,\mathrm{GeV}^2} = \begin{cases} \left(2.58^{+0.33}_{-0.31} \pm 0.08 \pm 0.19\right) \times 10^{-8}\ \mathrm{GeV}^{-2} & \text{(exp.)} \\ (4.81 \pm 0.56) \times 10^{-8}\ \mathrm{GeV}^{-2} & \text{(SM)}\,. \end{cases} \tag{6.2.3}$$

where $q^2 = m^2_{\mu\mu}$. Intriguingly, the q^2 region where this measurement has relatively low error (and data is quoted) is virtually the same as that for R_K and $R_{K^*}^{\mathrm{central}}$. This

M. Patel et al: LHCb may be able to give R_ϕ.

That would be great

Concerns on SM-theory

- **Good news is that lattice[FERMIL-MILC] study largely confirms pheno calculations for R_D [our RBC-UKQCD, Witzel et al needs bit more time]**
- **For B=>D^* no complete lattice study so far; 4 rather than 2 FF, so , from the lattice perspective, anticipate appreciably larger errors than for B=>D**
- **Therefore, O(1%) errors in RD* (and in fact smaller than in RD) are difficult to understand; lattice results should come in some months**
- **HFLAG should update the SM-theory with more realistic errors otherwise their fig is bit misleading**
- **Meantime recent phenomenological study of** Bernlochner, Ligeti, Papucci and Robinson, 1703.05330 [and even more recently…is/are very timely and greatly appreciated.

3%.

BIGI, Gambino, Schacht @ EPS

- **For now, for RD*, keeping these recent calculations and other reservations in mind best (conservative) guess is RD* ~ 0.258 +-0.020**

  [based on FERMIL-MILC error for RD]

~4%.

guess 8%.

→ 7

REMARKABLY: FOR RD* CENTRAL VALUE OF BEST THEORY ESTIMATEs APPEAR~~S~~ BIT HIGHER THAN ALL ~6 MEASUREMENTS! → of R_{D^*} + R_ψ

+2 for R_D

Comments on Theory

- For RD and RD*, non-lattice pheno efforts are on good, theo. grounds based on HQS….unlikely to be off by much
- Need however precise lattice results esp for B=>D*…see next p.
- For FCNC B=>K(*) ll, LUV tests theory is essentially irrelevant
- FCNC, B=>K(*) ll, absolute measured rates vs SM, theory is not reliable because of serious LD, non-perturbative contaminations

RBC-UKQCD [WITZEL, JUTTNER, TSANG, FLYNN, LEHNER, IZUBUCHI + AS]
work in progress

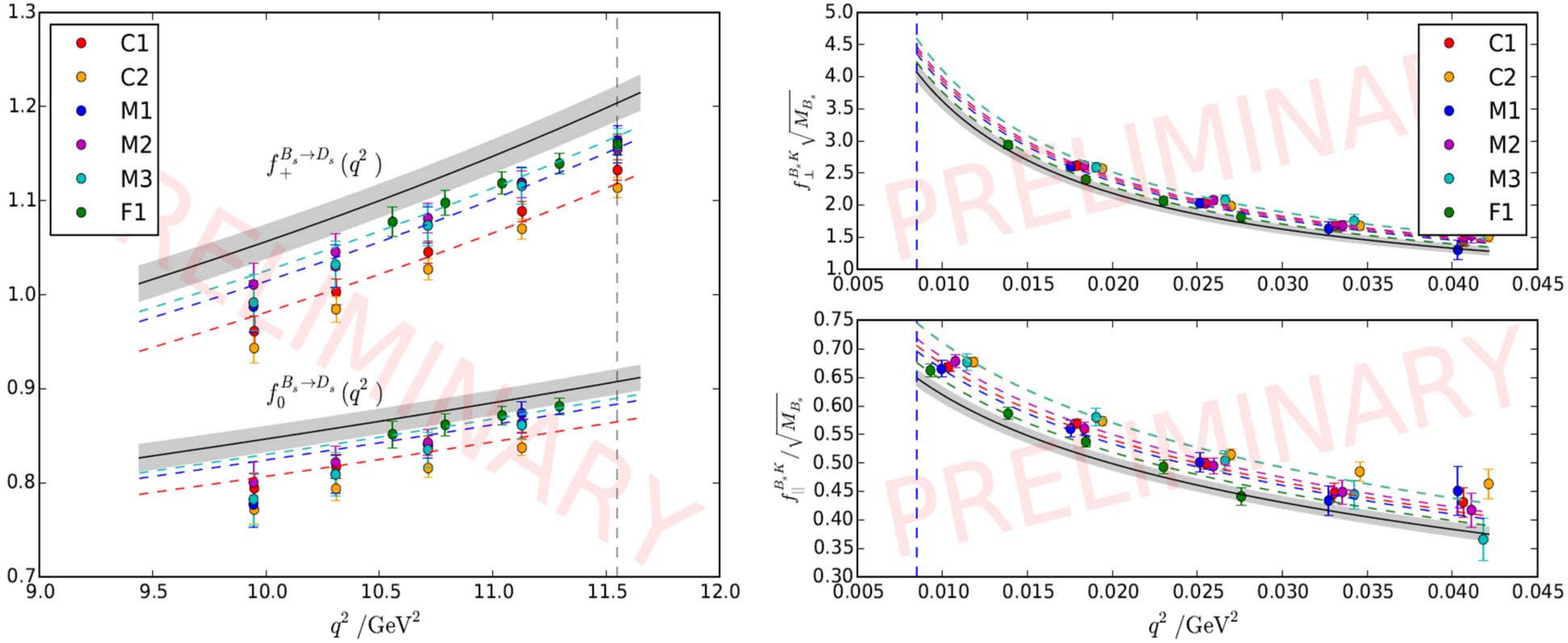


Figure 4. Chiral-continuum extrapolation for semi-leptonic form factors for $B_s \to D_s\ell\nu$ (left) and $B_s \to K\ell\nu$ (right). Performing a simple pole-ansatz for $B_s \to D_s$ we directly fit the phenomenological form factors f_+ and f_0. For $B_s \to K$ we use heavy meson chiral perturbation theory and show the fit to the "lattice" form factors $f_\parallel$ and $f_\perp$. The colored data points show results for our lattice calculations obtained at three values of the lattice spacing, whereas the black lines with the gray error band shows the chiral-continuum extrapolation. Only the statistical uncertainties are shown and no kinematical constraints are imposed.

∼ 6months

Comments/Reservations pros & cons on Expts p1 of 2

- For RD(*), B=> D(*) τ ν; most experimental results are with τ => μ ν ν ….i.e 2 ν's …..so D** potential contamination is a serious problem, in my view, as I have been stressing for past few years
- With that perspective in mind, it is worrysome that 2 new results, one from Belle and the other from LHCb with τ => hadrons + ν [i.e. 1 ν] is basically in agreement with SM though central value is mildly higher [i.e. roughly within ~ 1-σ]

Comments/Reservations pros & cons on Expts p2 of 2

- **HFLAV**: Its high time they update their SM theory blob. It is true that combining theoretical predictions is bit difficult but **it isnot good that they continue showing only predictions based on 2012 when recent ones with larger errors exist**. This can be esp. **misleading** since using these recent calculations [not my work] will for sure **reduce the tension with the SM**.

See, as an illustration how ADS' handles this a bit later.

Reg. RK(*) mu/e UV

- **Needless to say its of profound importance, if true**
- **If true not just B=>K, B=>K* but also Bs=> phi,**

B-baryon decays should show it

- **Current statistics is marginal; more final states are needed and even more important other experiments esp. BELLE (II) confirmation is essential**
- **This can take years as Br are O(10^{-6}) so not easy even for Belle-II;**
- **however, Belle-II will be able to do RXs…inclusive and that will likely have more sensitivity for them; See P Urquijo @ LIO**
- **OTOH, LHCB will have Bs and B-baryons; See M. Patel @ LIO**

SURVEY OF BSMS

Array of BSM approaches to address flavor anomalies

- **Model ind eff L**: Greljo; Camalich; Mandal;

LQ: Fajfer; Luzio; Neubert; Silva; Becirevic;

- **[Partial]Composite/warped**: Stangl; Ahmady;Barbieri;

Panico; Blanke ...**Natural set up for flavor Non-Universality**

- **SUSY-like**: Hiller; ADS'=> RPV3 **Natural flavor Non-Universality**
- **More BSMs**: Guadagnoli; Grinstein; Jung; Ricciardi;Fuentes-Martin; Neshatpour; Crivelin
- **New approaches**: Valli; Camalich;
- **Status + Outlook**: Matias....**Nice update ...some diff of opinion**

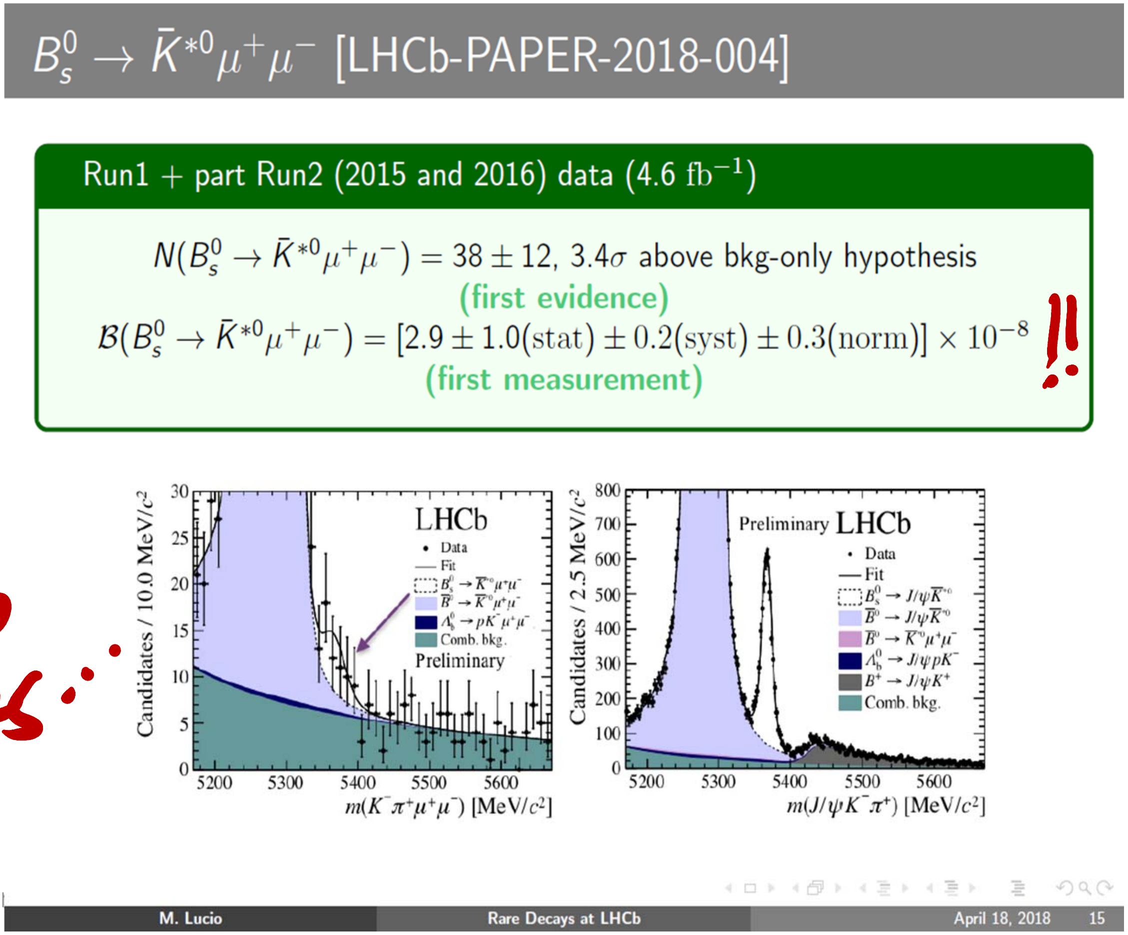
EXPT: Status + (near) future outlook

- **Martinez; Lima; Bertolini @LHCb**
- **Urquijo; Goi; @ Belle-II**
- **Patel @ LHCb-UG**

CONGRATS LHCb

FANTASTIC!!

XTREMELY IMPT TO Go for LHCb upgrades...



$B_s^0 \to \bar{K}^{*0}\mu^+\mu^-$ [LHCb-PAPER-2018-004]

Run1 + part Run2 (2015 and 2016) data (4.6 fb^{-1})

$N(B_s^0 \to \bar{K}^{*0}\mu^+\mu^-) = 38 \pm 12$, 3.4σ above bkg-only hypothesis

(first evidence)

$\mathcal{B}(B_s^0 \to \bar{K}^{*0}\mu^+\mu^-) = [2.9 \pm 1.0(\text{stat}) \pm 0.2(\text{syst}) \pm 0.3(\text{norm})] \times 10^{-8}$!!

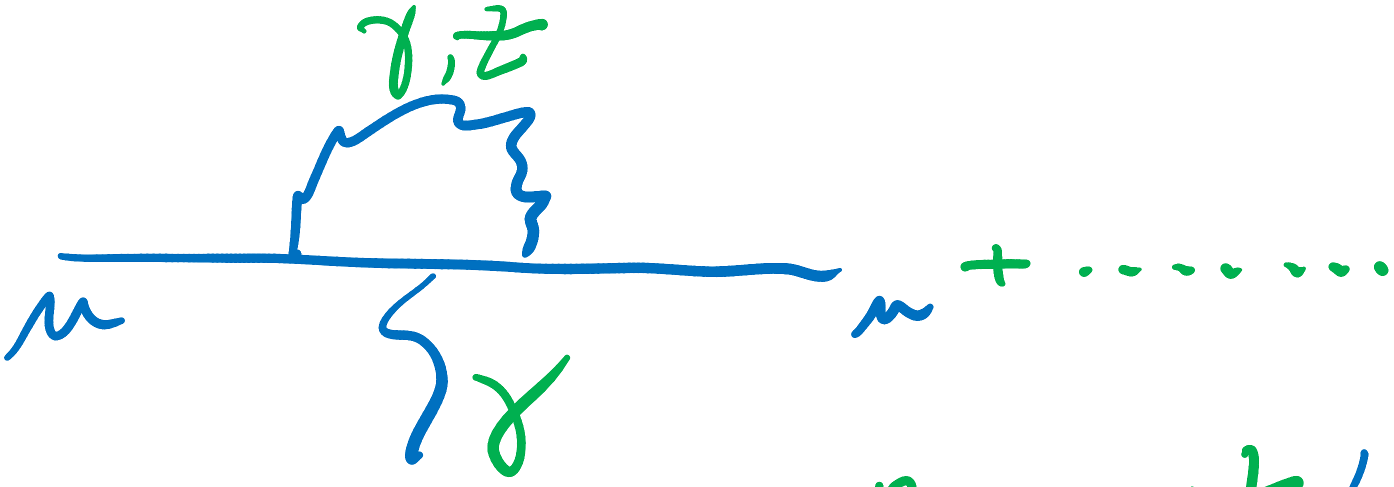
(first measurement)

Menu…more

- **SM/CKM….Hurth; Rusov**
- **Model independent tests@collider: Isidori; Kamenik;Hou; Nardecchia; ADS';**
- **Model Independent @ IF: Mandal; Fajfer; Neubert;**

- **Kaons [SM/NP]: Buras; D'Ambrosio; Pich**

NOW FEW WORDS ON MUON G-2



BNL expt '06

~ 3.5σ deviation

POSSIBLE CONNECTION OF G-2 TO OTHER FLAVOR ANOMALIES

MUON MAY NOT BE JUST A HEAVY ELECTRON: KILE, KOBACH AND AS

PRD 2015

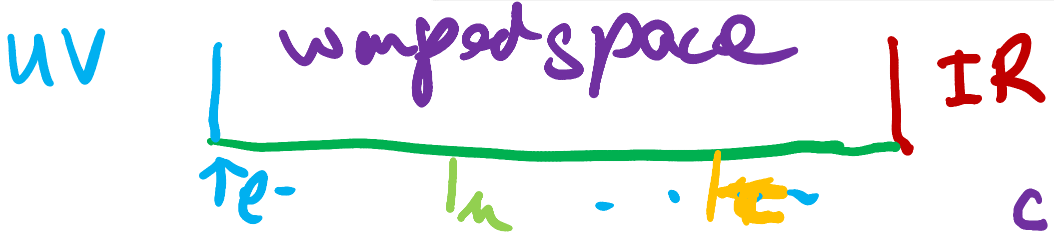
Table 1
Constraints on lepton-flavor violating and conserving processes. For the last four observables, the experimental null results are given in terms of a dimension-6 operator, suppressed by two orders of Λ, which can be interpreted as the nominal scale of new physics.

Observable	Limit
$\mathrm{Br}(\mu \to 3e)$	$< 1.0 \times 10^{-12}$ [1]
$\mathrm{Br}(\mu \to e\gamma)$	$< 5.7 \times 10^{-13}$ [1]
$\mathrm{Br}(\tau \to 3e)$	$< 2.7 \times 10^{-8}$ [1]
$\mathrm{Br}(\tau \to e^-\mu^+\mu^-)$	$< 2.7 \times 10^{-8}$ [1]
$\mathrm{Br}(\tau \to e^+\mu^-\mu^-)$	$< 1.7 \times 10^{-8}$ [1]
$\mathrm{Br}(\tau \to \mu^-e^+e^-)$	$< 1.8 \times 10^{-8}$ [1]
$\mathrm{Br}(\tau \to \mu^+e^-e^-)$	$< 1.5 \times 10^{-8}$ [1]
$\mathrm{Br}(\tau \to 3\mu)$	$< 2.1 \times 10^{-8}$ [1]
$\mathrm{Br}(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$ [1]
$\mathrm{Br}(\tau \to e\gamma)$	$< 3.3 \times 10^{-8}$ [1]
μ–e conversion	$\Lambda \gtrsim 10^3$ TeV [5]
$e^+e^- \to e^+e^-$	$\Lambda \gtrsim 5$ TeV [3]
$e^+e^- \to \mu^+\mu^-$	$\Lambda \gtrsim 5$ TeV [3]
$e^+e^- \to \tau^+\tau^-$	$\Lambda \gtrsim 4$ TeV [3]

Ist gen not sensitive to NP
+
$(g\text{-}2)_\mu$

Kile, Kobach +AS PRD2015
⇓
Speculation

May be 1st gen. is fundamental & its protection from NP

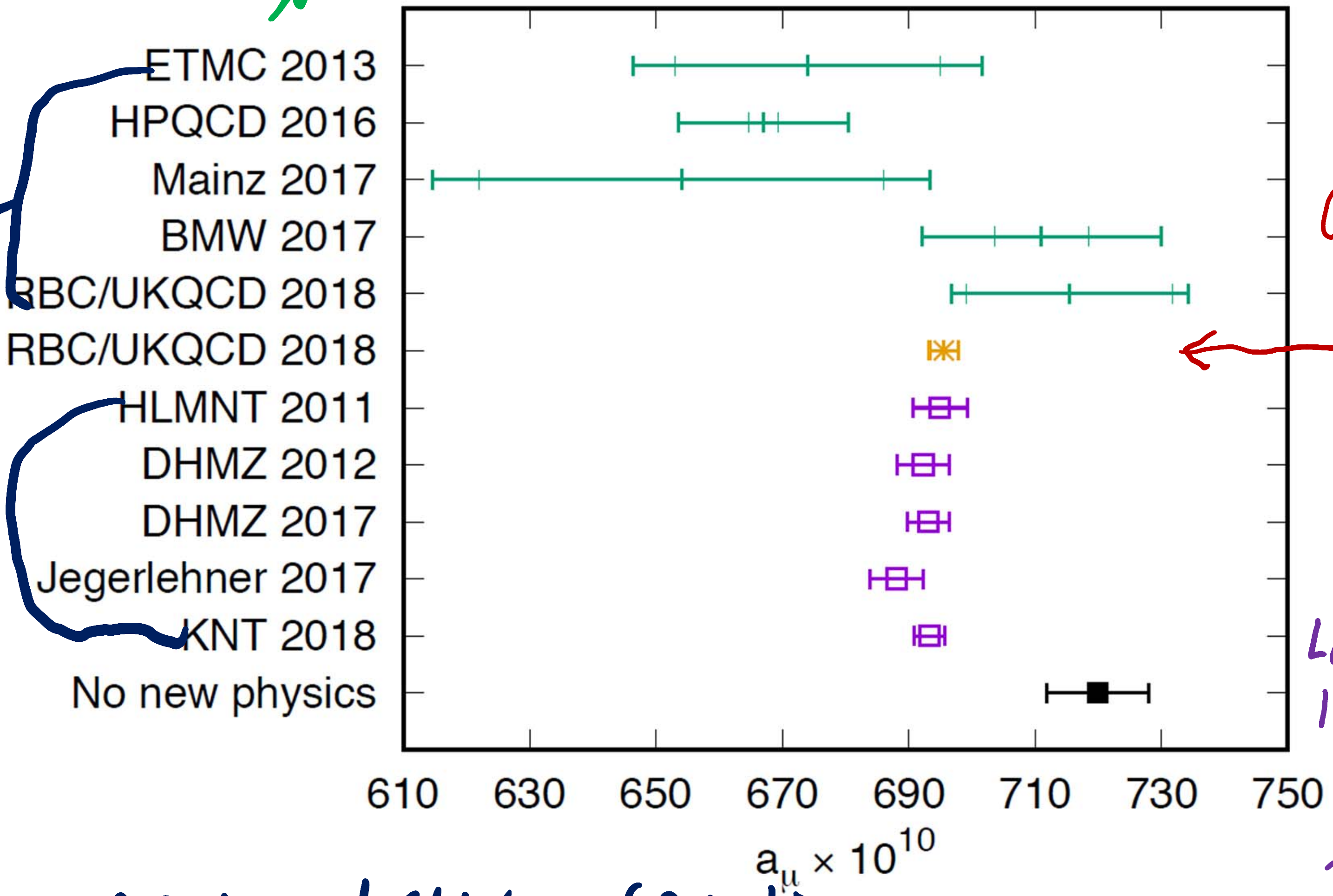


c ALSO A.IYER @ LYON

QUICK UPDATE ON G-2

$(g-2)_\mu$ on + off the Lattice

PURE Lattice



Pheno

C Lehner et al RBC-UKQCD HYBRID

Lattice use INITIATED BY T.BLUM ~2004 while@BNL

SUMMARY: C. LEHNER (BNL)

We need to improve the precision of our pure lattice result so that it can distinguish the "no new physics" results from the cluster of precise R-ratio results.

Lunch Seminar 03/09/18

Personal take on g-2

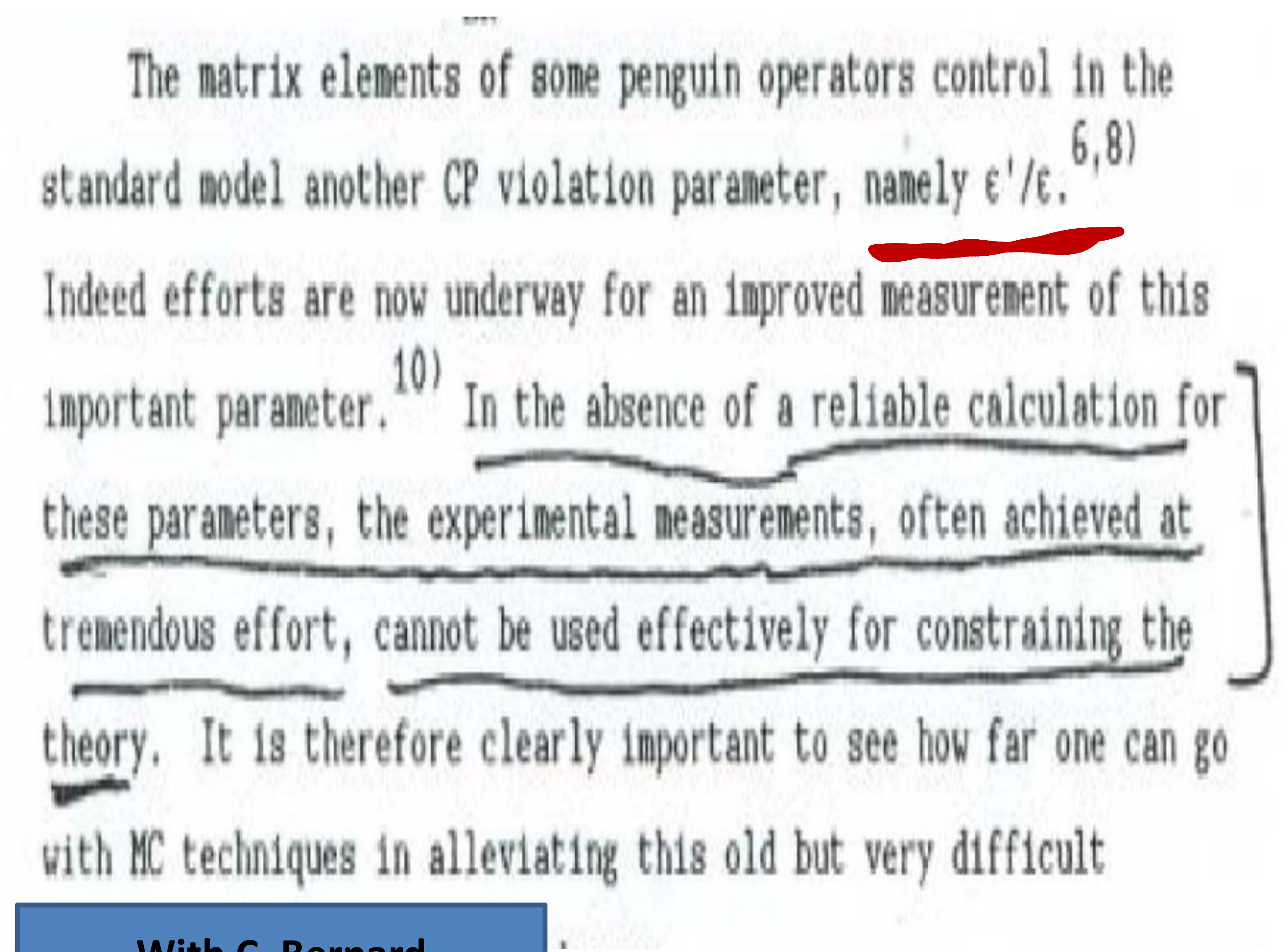
- **If you take pheno estimate of hadronic VP contributions via use of R-ratio method deviation for BNL-expt ~3.6 σ so likely culprit is under-estimate error on theory of around ½%; though recently RBC-UKQCD lattice hybrid method finds support for this pheno estimate**
- **Need to wait on pure lattice result after another factor of 4-5 reduction in error, may take another 2-3 years**
- **By that time improved experimental results should also become available**
- **Final verdict may need another 2-3 years**

Bottom line

- **NP or not depends critically not just on precise experiment but also reliable SM prediction from the lattice become mandatory**
- **Experiment + Lattice M.E. has the last word….[of course should be stressed that the lattice calculations often require sophisticated and demanding and essential input from perturbation theory]**

- **Experimental results often attained at huge cost can be used effectively, iff commensurate theory predictions are available…….mantra for past several decades**

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]

- **Already heard pheno perspective on K=> ππ and ε’ in nice talks from Buras and also from Pich**

- **So I skip exptal route for ε’ and such**

LATTICE QUEST FOR EPSILON’

FROM THEORY

K→2π

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

→ I=2 amp

→ I=0 amp

$\omega \approx \frac{ReA_2}{ReA_0}$.

$\frac{ReA_0}{ReA_2} \sim 25$ $\Delta I = 1/2$ Puzzle

INDIRECT CP
BNL '64
Cronin+Fitch
NP

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

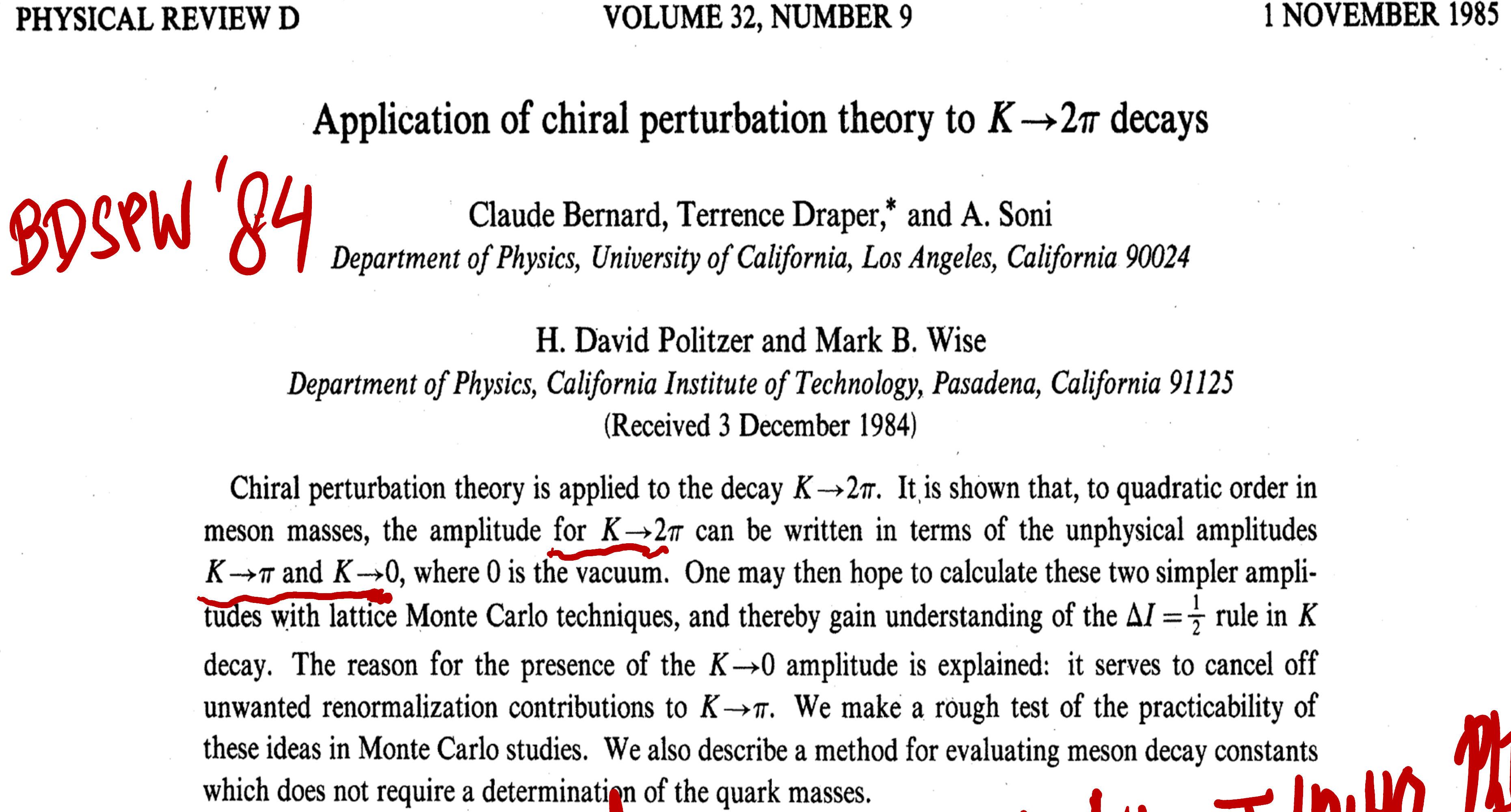
$$\mathrm{Re}(\epsilon'/\epsilon) = 1.65(26) \times 10^{-3}.$$

DIRECT CP ↗

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

CERN+FNAL ~2004

For simplicity: 1st Strategy via ChPT



PHYSICAL REVIEW D VOLUME 32, NUMBER 9 1 NOVEMBER 1985

Application of chiral perturbation theory to $K \to 2\pi$ decays

BDSPW '84

Claude Bernard, Terrence Draper,* and A. Soni
Department of Physics, University of California, Los Angeles, California 90024

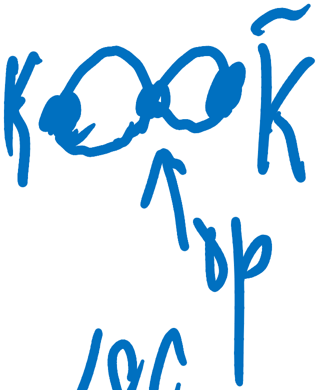
H. David Politzer and Mark B. Wise
Department of Physics, California Institute of Technology, Pasadena, California 91125

(Received 3 December 1984)

Chiral perturbation theory is applied to the decay $K \to 2\pi$. It is shown that, to quadratic order in meson masses, the amplitude for $\underline{K \to} 2\pi$ can be written in terms of the unphysical amplitudes $\underline{K \to \pi \text{ and } K \to}0$, where 0 is the vacuum. One may then hope to calculate these two simpler amplitudes with lattice Monte Carlo techniques, and thereby gain understanding of the $\Delta I = \frac{1}{2}$ rule in K decay. The reason for the presence of the $K \to 0$ amplitude is explained: it serves to cancel off unwanted renormalization contributions to $K \to \pi$. We make a rough test of the practicability of these ideas in Monte Carlo studies. We also describe a method for evaluating meson decay constants which does not require a determination of the quark masses.

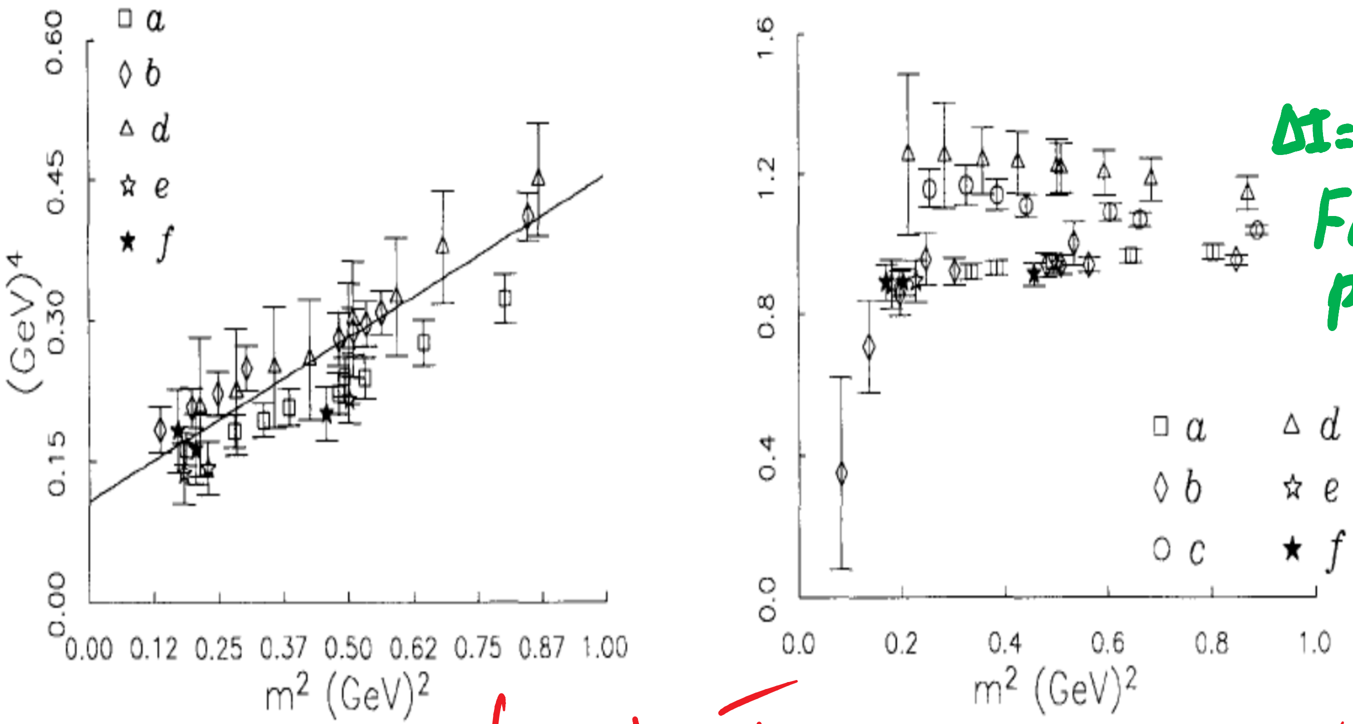
USED extensively on lattice for ~20 years ⇒ NLO J. LAIHO PhD Thesis ~'03

$\langle K|(\bar{s}\gamma_{\mu L} d)^2|\bar{K}\rangle$



'88

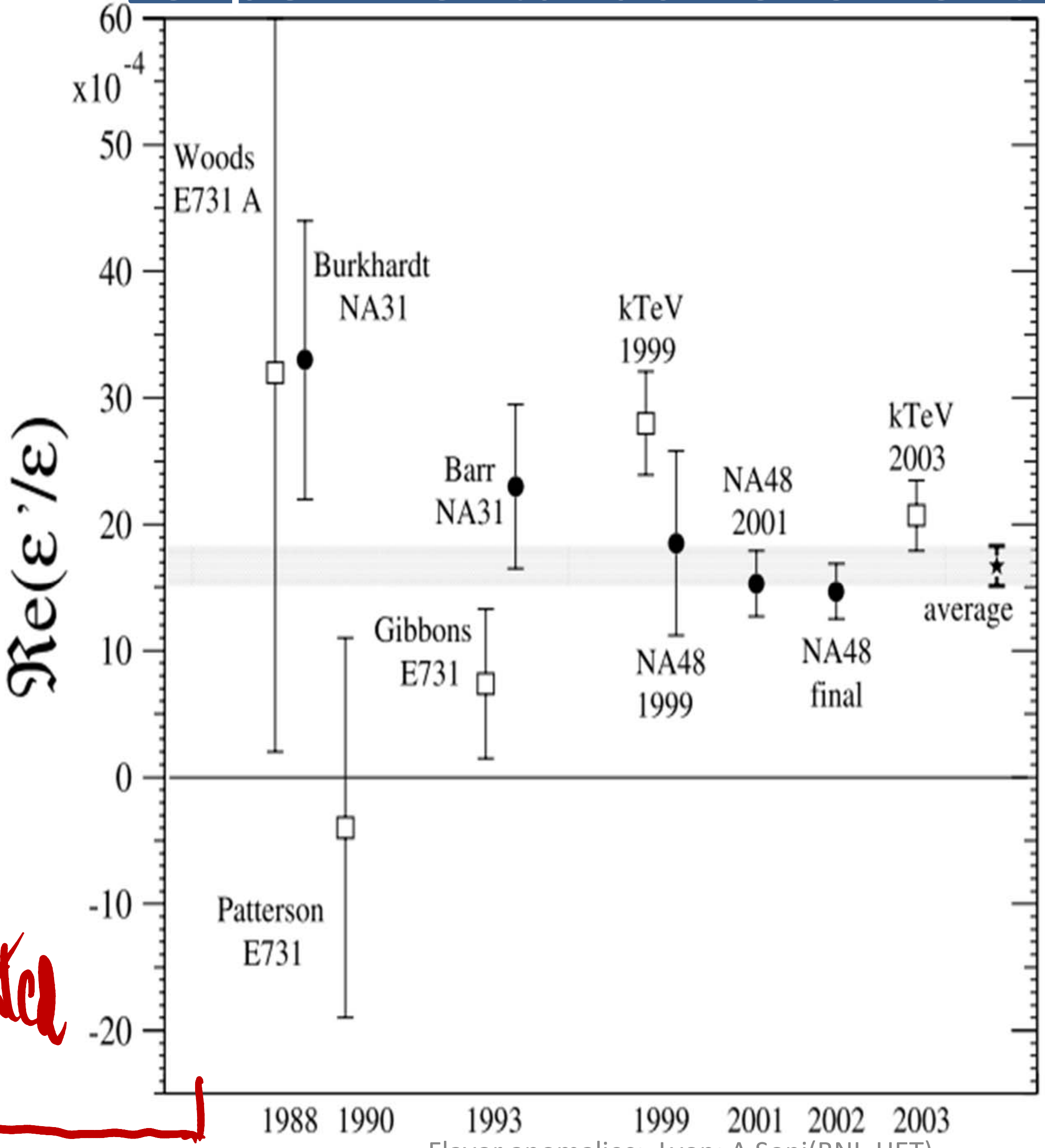
162 C. Bernard, A. Soni / Weak matrix elements on the lattice



ΔI=0 channel Far More PATHEOLOGICAL with Wilson Fermion 'cause of power div

χS violation by K-K̄ ⇒ FINE TUNING $\left[\frac{1}{a^n}\right]$ PROBLEM

A monumental experimental achievement!



Konrad Kleinknecht
"Uncovering CPV"

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

CB+AS

LATTICE WORK started

PHYSICAL REVIEW D VOLUME 56, NUMBER 1 1 JULY 1997

InspiredI.P. by papers of Shamir [+Furman] + discussions with Creutz

QCD with domain wall quarks

T. Blum* and A. Soni†
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973

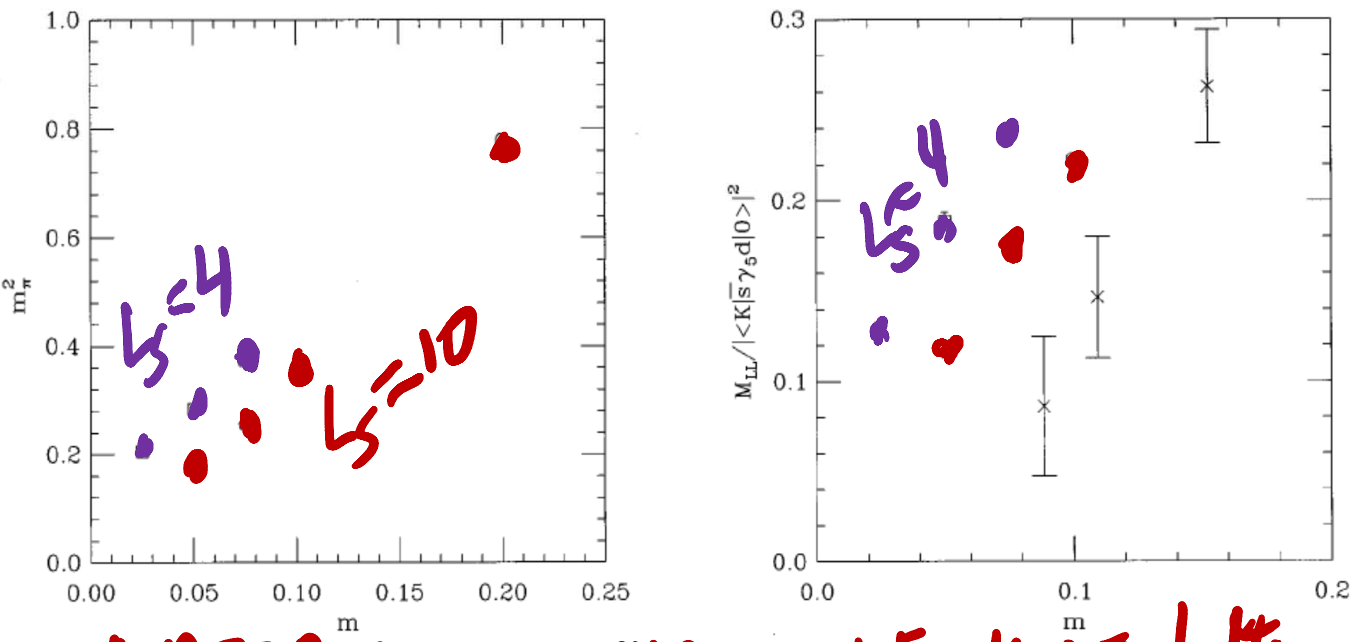
(Received 27 November 1996)

1st Simulation with DWQ

~ '96-97

We present lattice calculations in QCD using Shamir's variant of Kaplan fermions which retain the continuum $SU(N)_L \times SU(N)_R$ chiral symmetry on the lattice in the limit of an infinite extra dimension. In particular, we show that the pion mass and the four quark matrix element related to K_0-$\bar{K}_0$ mixing have the expected behavior in the chiral limit, even on lattices with modest extent in the extra dimension, e.g., $N_s=10$. [S0556-2821(97)00113-6]

DWQ preserve CHIRAL SYM even at a≠0!!!



excellent Chiral symmetry with ~10 sites in 5th dim.

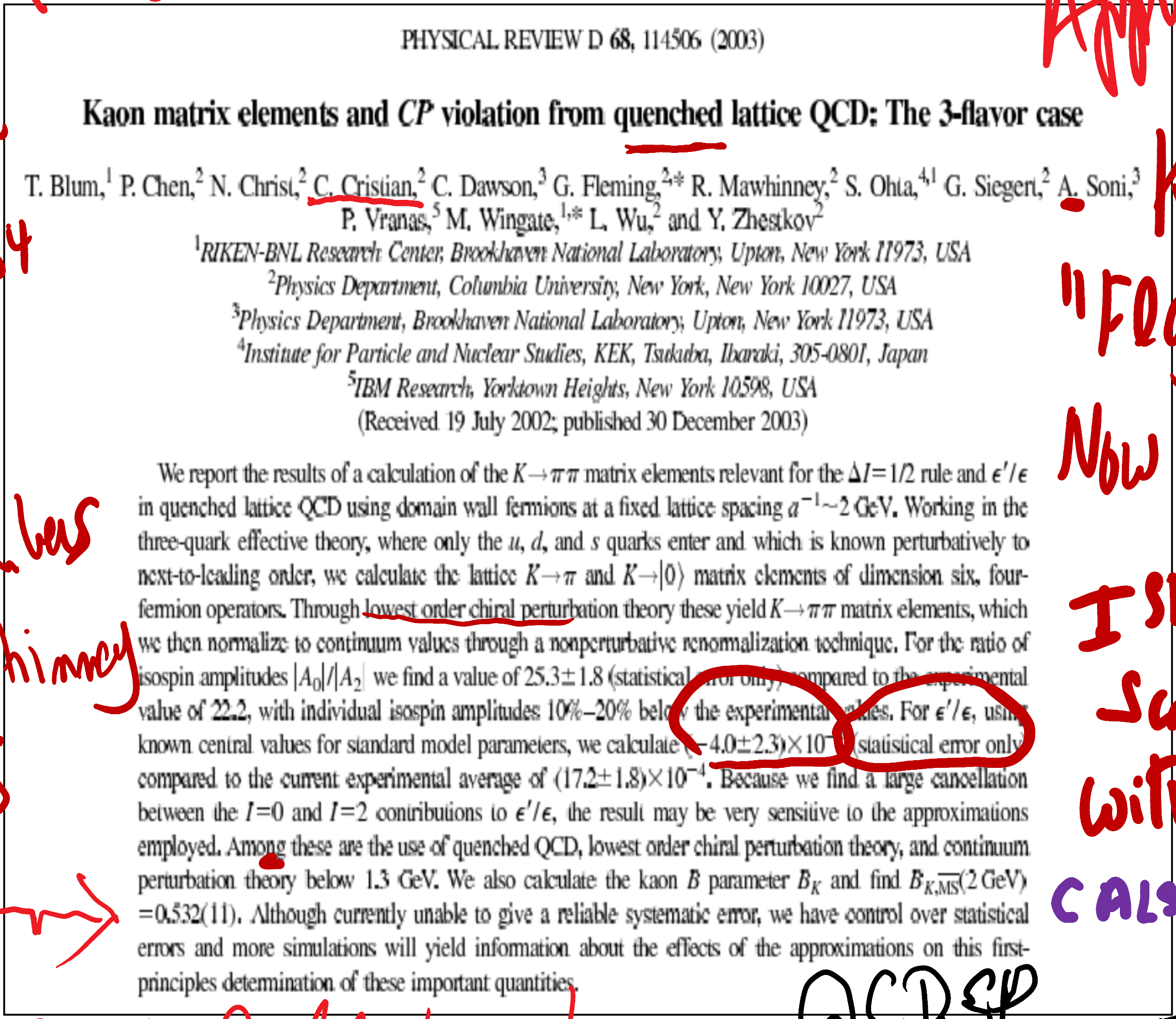
MAJOR BREAKTHROUGH FOR K→ππ Lattice Calculations

K→2π ChPT

With DWQ in Quench Approx

1st application of BDSPW'84 with DWQ

RBC: Founding members Christ, Mawhinney, Blum, AS ~'98



PHYSICAL REVIEW D **68**, 114506 (2003)

Kaon matrix elements and *CP* violation from quenched lattice QCD: The 3-flavor case

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(Received 19 July 2002; published 30 December 2003)

We report the results of a calculation of the $K\to\pi\pi$ matrix elements relevant for the $\Delta I=1/2$ rule and ϵ'/ϵ in quenched lattice QCD using domain wall fermions at a fixed lattice spacing $a^{-1}\sim2$ GeV. Working in the three-quark effective theory, where only the u, d, and s quarks enter and which is known perturbatively to next-to-leading order, we calculate the lattice $K\to\pi$ and $K\to|0\rangle$ matrix elements of dimension six, four-fermion operators. Through lowest order chiral perturbation theory these yield $K\to\pi\pi$ matrix elements, which we then normalize to continuum values through a nonperturbative renormalization technique. For the ratio of isospin amplitudes $|A_0|/|A_2|$ we find a value of 25.3 ± 1.8 (statistical error only) compared to the experimental value of 22.2, with individual isospin amplitudes 10%–20% below the experimental values. For ϵ'/ϵ, using known central values for standard model parameters, we calculate $(-4.0\pm2.3)\times10^{-4}$ (statistical error only) compared to the current experimental average of $(17.2\pm1.8)\times10^{-4}$. Because we find a large cancellation between the $I=0$ and $I=2$ contributions to ϵ'/ϵ, the result may be very sensitive to the approximations employed. Among these are the use of quenched QCD, lowest order chiral perturbation theory, and continuum perturbation theory below 1.3 GeV. We also calculate the kaon B parameter B_K and find $B_{K,\overline{MS}}(2\text{ GeV})=0.532(11)$. Although currently unable to give a reliable systematic error, we have control over statistical errors and more simulations will yield information about the effects of the approximations on this first-principles determination of these important quantities.

K→2π & ε'/ε, "Flagship Project"

Now ~20 yrs!

1st Large Scale Simulation with DWQ

(Also CP-PACS PRD'03

RBC Collaboration

QCDSP ~98→~'05 1TF

CMP/01.

a powerful new method

Direct K-> $\pi\pi$ (a la Lellouch-Luscher), using finite volume correlation* functions, [i.e. w/o ChPT] RBC initiates around 2005.

Boyle, Sachrajda et al

~ 2007 RBC-UKQCD {(mostly) Edinburgh — I

Southampton — II}

* Allows to bypass Maini-Testa theorem

Common Interest: use of DWQ for simulations

Δ S=1 H_W

WC to NLO

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

$$H_W = \frac{G_F}{\sqrt{2}} V_{us}^* V_{ud} \sum_{i=1}^{10} [\underbrace{z_i(\mu)}_{\text{Re } A_0} + \underbrace{\tau y_i(\mu)}_{\text{For Im } A_0}] Q_i(\mu).$$

CORE of the Calculation:

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

$M_i = \langle K | Q_i | \pi\pi \rangle$ Needed from the lattice

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

$\rightarrow 0$

$m_q \rightarrow 0$

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

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

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

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

EWP

I=2

$\rightarrow$ const

$m \rightarrow 0$

QCDP

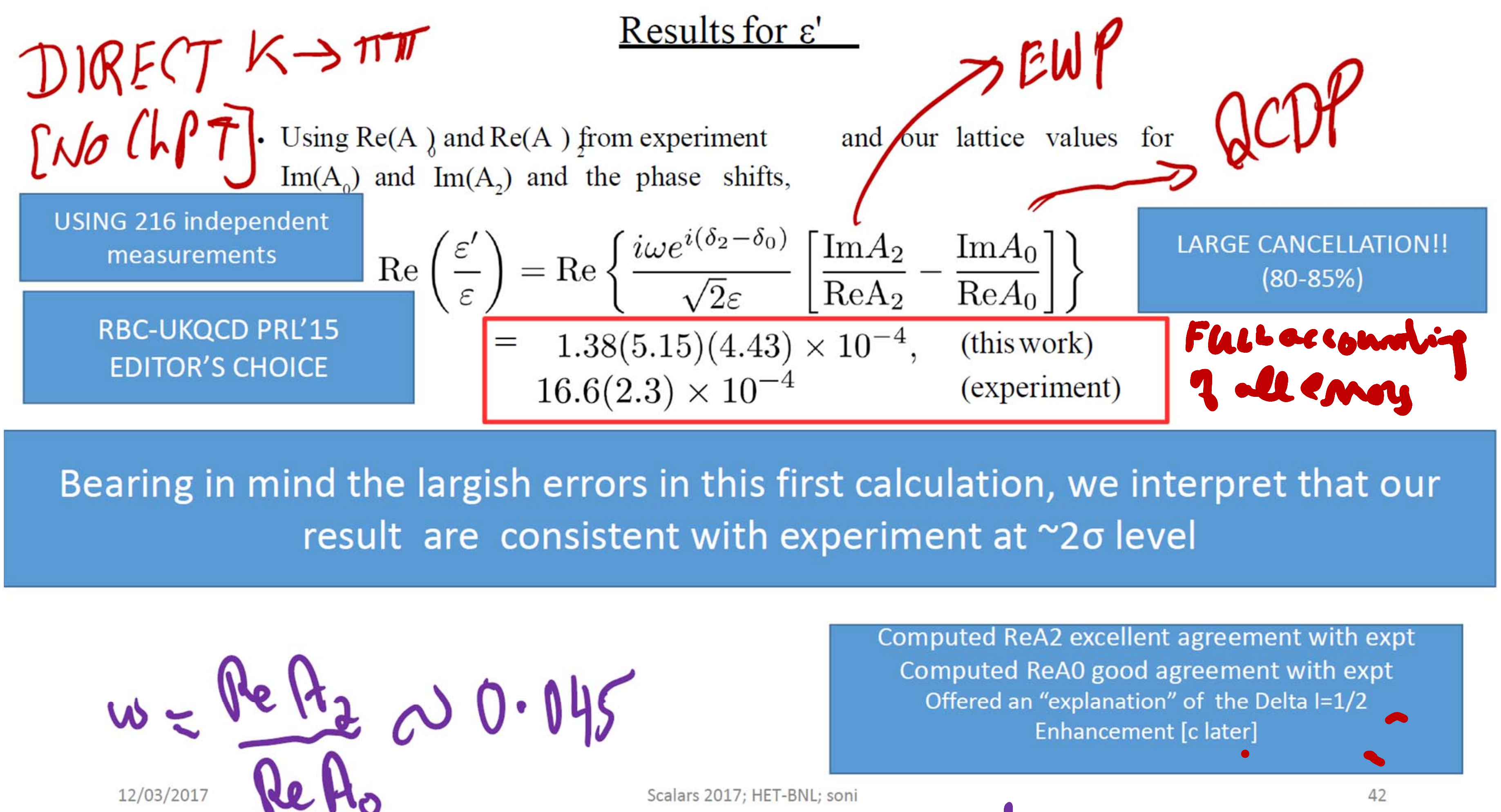
EWP

Acknowledge many significant contributions off & on the lattice

- **While focus is on lattice calculations of K=>ππ primarily by our RBC-UKQCD Collab**

- **Over the years many important contributors, in particular:**

- **(Mary K)Gaillard, (Ben) Lee; Altarelli, Maiani; Shifman, Vainshtein, Zhakrov; Gilman + Wise; Buras & Co; Martinelli & Co; (Claude) Bernard; de Rafael; Pich, Bijnens……**



Results for ε'

DIRECT K→ππ

[No ChPT]

- 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,

→ EWP

→ QCDP

USING 216 independent measurements

RBC-UKQCD PRL'15 EDITOR'S CHOICE

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

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

LARGE CANCELLATION!! (80-85%)

Full accounting of all errors

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

$$w = \frac{\mathrm{Re}\,A_2}{\mathrm{Re}\,A_0} \sim 0\cdot 045$$

Computed ReA2 excellent agreement with expt
Computed ReA0 good agreement with expt
Offered an "explanation" of the Delta I=1/2 Enhancement [c later]

12/03/2017 Scalars 2017; HET-BNL; soni 42

Buras et al use own LME ⇒ effect is ~2·9σ

Nierste · " " ~ "

RBC-UKQCD PRL 2015

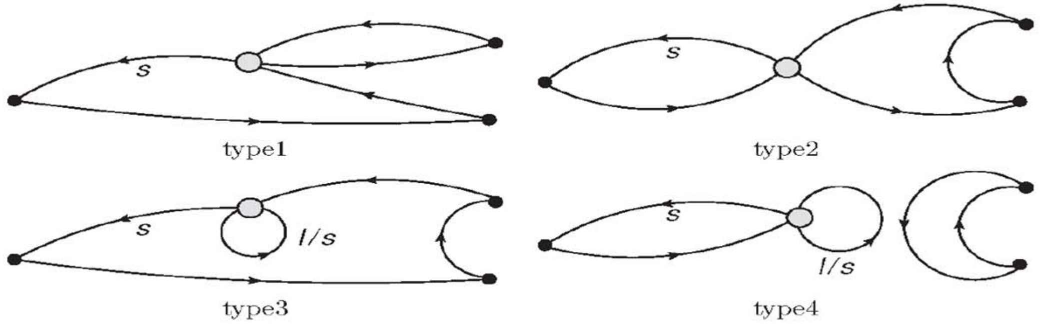
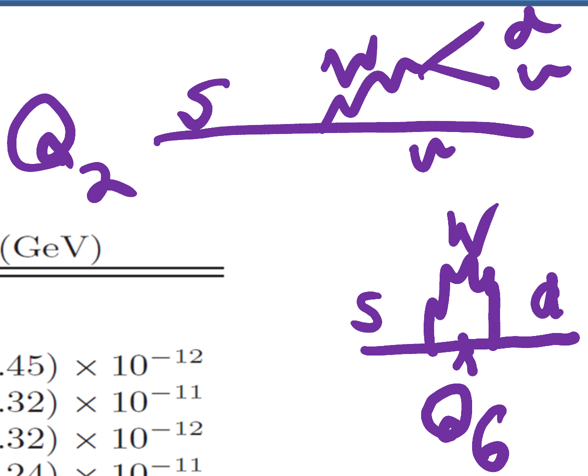


FIG. 1. Examples of the four types of diagram contributing to the $\Delta I = 1/2$, $K \to \pi\pi$ decay. Lines labeled ℓ or s represent light or strange quarks. Unlabeled lines are light quarks.



21%

77%

0.7%

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.

While ReA0 and ReA2 and δ2 agree well with expt a possible difficulty: δ0

- **The continuum and our lattice determinations of strong phase difference differs at the ~2σ level:**

not directly accessible to expt

-

$$\phi_{\varepsilon'} = \delta_2 - \delta_0 + \frac{\pi}{2} = \begin{cases} (42.3 \pm 1.5)^\circ \ \text{"PDG"} \ [2] \\ (54.6 \pm 5.8)^\circ \ \cancel{\text{RBC}} \ [47, 48] \end{cases} .$$

Colangelo et al

RBC-UKQCD

$\phi_\varepsilon \sim 43.5 \pm 0.5^\circ$

Fortunately, due to the central value of the combination $\delta_2 - \delta_0 + \pi/2 - \phi_\varepsilon$ and to the large uncertainties in the determination of the various matrix elements, these two choices yield almost identical results; fo~~r definiteness, we~~

Lehner, Lunghi + AS, 1508.01801

Sensitivity of ε’ to strong phase(s)

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

See also
Lehner, Lunghi + AS PLB'16

$$\cos\left(\underbrace{\delta_2-\delta_0+\pi/2}_{\phi_{\epsilon'}\,\sim\, 42.3\pm1.5^\circ} - \phi_\varepsilon\right)$$

$\phi_\varepsilon \to 43.5 \pm 0.5^\circ$ "PDG"

$\phi_{\epsilon'} \sim 42.3 \pm 1.5^\circ$ [Colangelo, Gasser, Leutwyler

$\Rightarrow \cos(\;) \Rightarrow 0.99978$;

$\phi_{\epsilon'} = 54.6 \pm 5.8^\circ$ RBC-UKQCD PRL'15

$\Rightarrow 0.981 \leftarrow$

Diff ~ 2% on ε'

phase diff ~ 26
BUT ε' totally insensitive!!

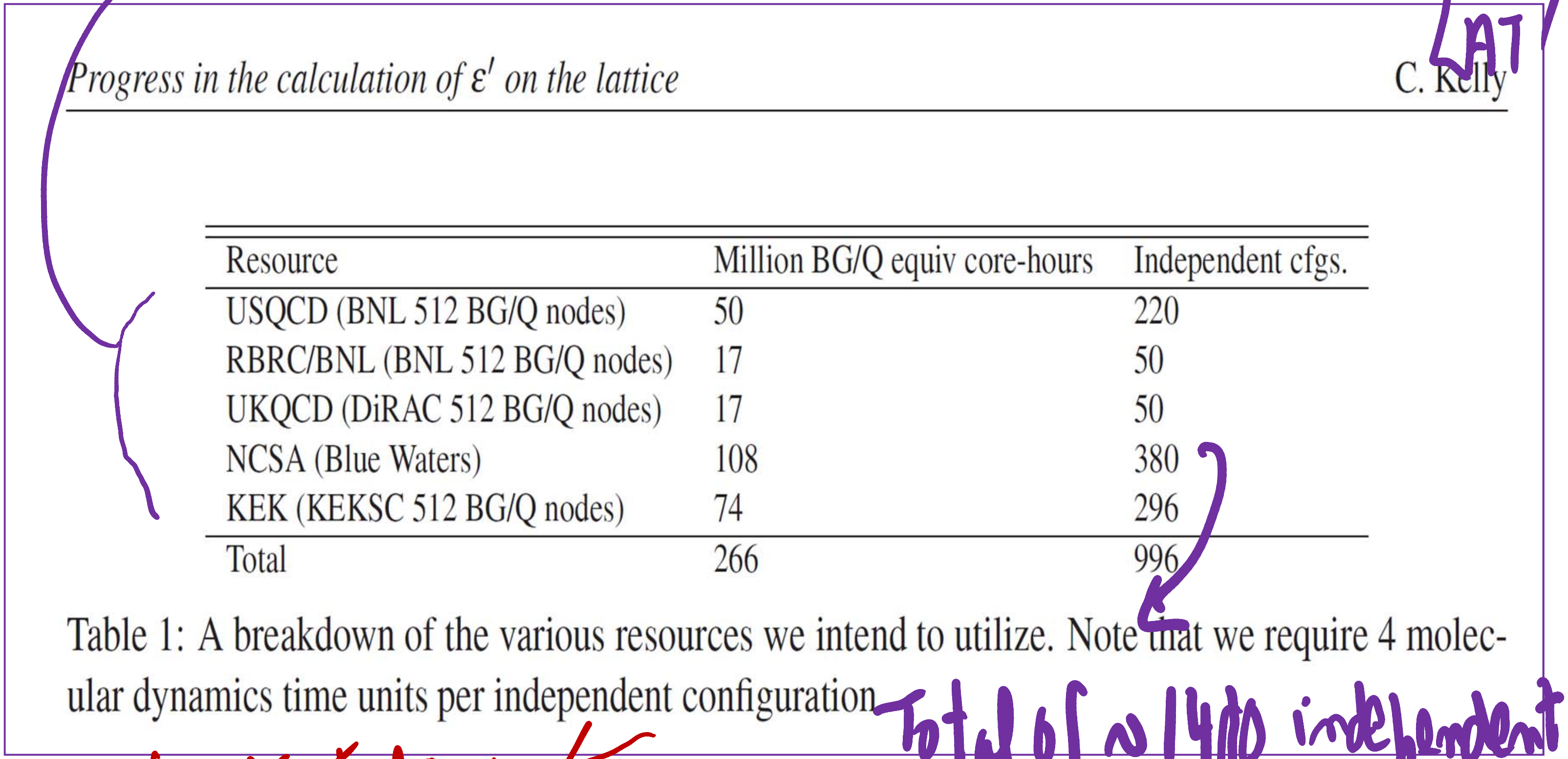
Significant effort is being put now to calculate and understand pi pi rescattering phases from diff pts of view

Generation of New gauge configs

For past ≳3 years

SUPERCOMPUTERS OVER 3 CONTINENTS!

LAT/17



Progress in the calculation of ε′ on the lattice C. Kelly

Resource	Million BG/Q equiv core-hours	Independent cfgs.
USQCD (BNL 512 BG/Q nodes)	50	220
RBRC/BNL (BNL 512 BG/Q nodes)	17	50
UKQCD (DiRAC 512 BG/Q nodes)	17	50
NCSA (Blue Waters)	108	380
KEK (KEKSC 512 BG/Q nodes)	74	296
Total	266	996

Table 1: A breakdown of the various resources we intend to utilize. Note that we require 4 molecular dynamics time units per independent configuration.

4 diff streams

Total of ~1400 independent configs

By now ~ ~~1200~~ 1300 measurements done

Guess estimate of reduction of errors

- δ (Im A0) from 65% => 20-25%
- δ(ReA0) from 35% => 15-20% [don't use for ε' for now] → with 216 measurements
- Uncorrelated fits (due to lack of stat) =>

Very good chance we'll be able to correlated fits now with > 1200

Possible Bonus: reduction in errors [2014]

- Systematic error from ~ 27% => ~ 20%
- Effect on ε' unclear : 'cause of hefty cancellations

$$\mathrm{Re}\left[\frac{\epsilon'}{\epsilon}\right] \propto \left[\frac{\boxed{\mathrm{Im}A_2}}{\mathrm{Re}A_2} - \frac{\boxed{\mathrm{Im}A_0}}{\mathrm{Re}A_0}\right]$$

$\mathrm{Im}A_2 \rightarrow \delta \sim 15\%$

$\mathrm{Im}A_0 \rightarrow \delta \sim 60\%$

Additional Improvements/checks in lattice Ɛ' determination underway for past ~2 years

- EM+ isospin… Under extensive study

Pheno estimate ~15±8%.
Cirigliano, Neufeld, Ecker+Pich '03

UConn PhD Student Dan Hoying

- Completely diff method(s)
- I) excited pipi state → CU PhD '16 Dan Murphy ChPT works!!
- II) Revisit ChPT well for physical π, K masses @ NLO!

→ Reexamine BDSPW'84, Laiho+AS'04 for ε'

underlying method is systematically improvable =>multitude of successful demonstrations by now

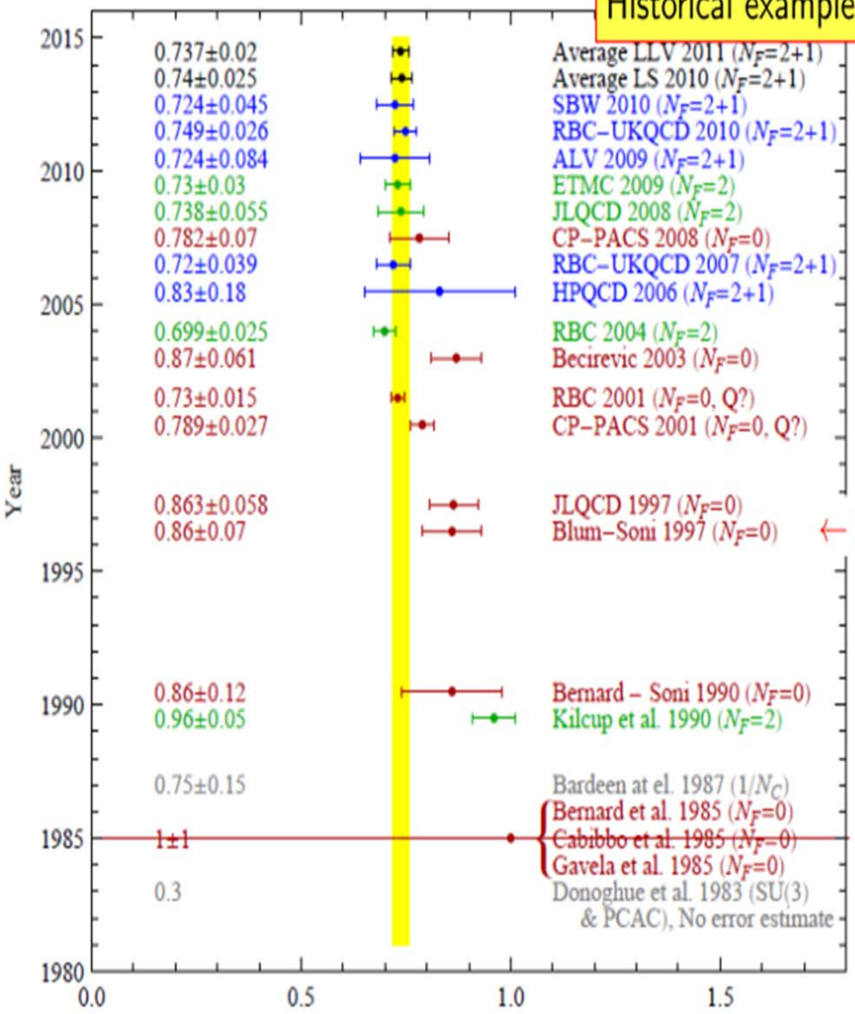
- **BK in full QCD with DWF '07 RBC-UKQCD error O(7%)**
- **Since ~2012 many discretizations , WA error O(1-2%)**
- **Re A2 from ~25% around 2012 to now ~10% (now no longer due to lattice but only only due to perturbation theory error upto NLO!)**
- **Kl3, A2, fB's , BB's……..**
- **Quark masses; in particular ms no longer anywhere around ~150 MeV [used to be PDG value] but now ~100 MeV.**
- ***No doubt that A0 and ε' will also go that way for quite***

sometime to come………to ~10% total in another ~ 3-5years!.

After that EM& isospin effects need to be ascertained quantitatively; WIP

Power of the lattice: Only method to systematically reduce the NP error!

Historical example: B_K



← First DWF

6 / 15

AB-initio Calculat

$$B_K = \frac{\langle K|(\bar{s}d)^2|\bar{K}\rangle}{8/3 f_K^2 m_K^2}$$

ONE ILLUSTRATION

MANY IMPLICATIONS, AS ONE EXAMPLE:K-UT

See Lehner, Lunghi + AS PLB'16

K-UT: A dream for some

AS

Blucher, Winstein and Yamanaka '09; see also Buras

Construction of a Kaon UT

LITTENBERG PRD'89

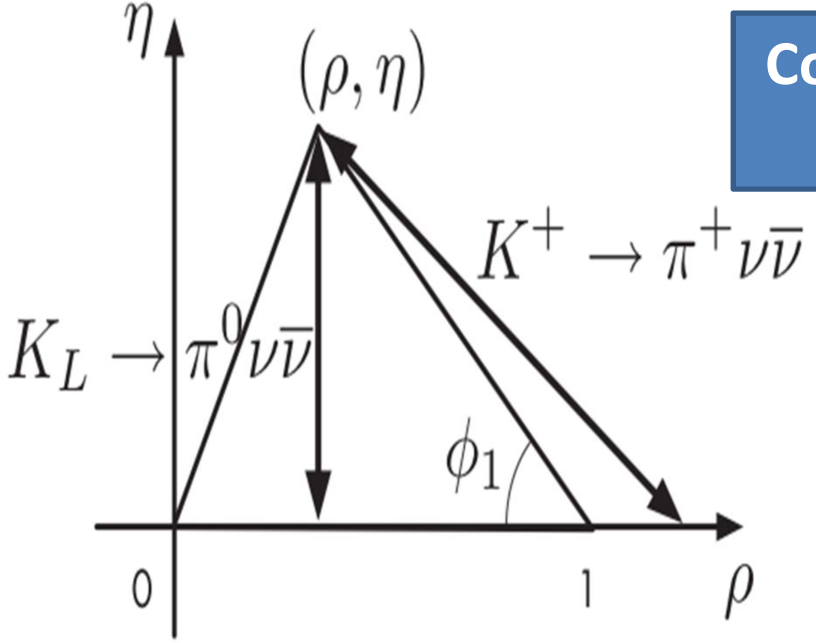
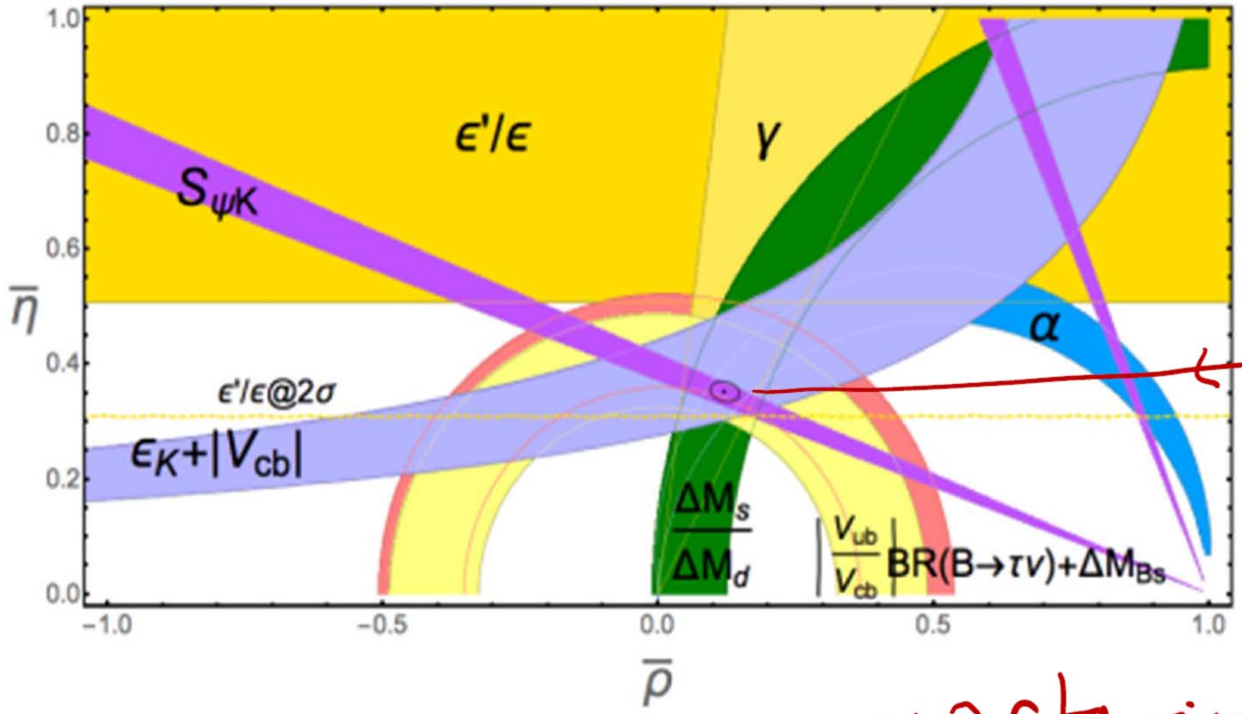


Fig. 14. Unitarity triangle.

Lehner+Lunghi+AS PLB'2016

Instead of [or in addition to] $K_L \to \pi^0 \nu\bar{\nu}$ can now plan on using ϵ'/ϵ

Lattice ε'/ε & SUT : CIRCA ~ 2015



SUT ≡ Standard UT i.e. B-UT

solution to SUT

~2σ tension

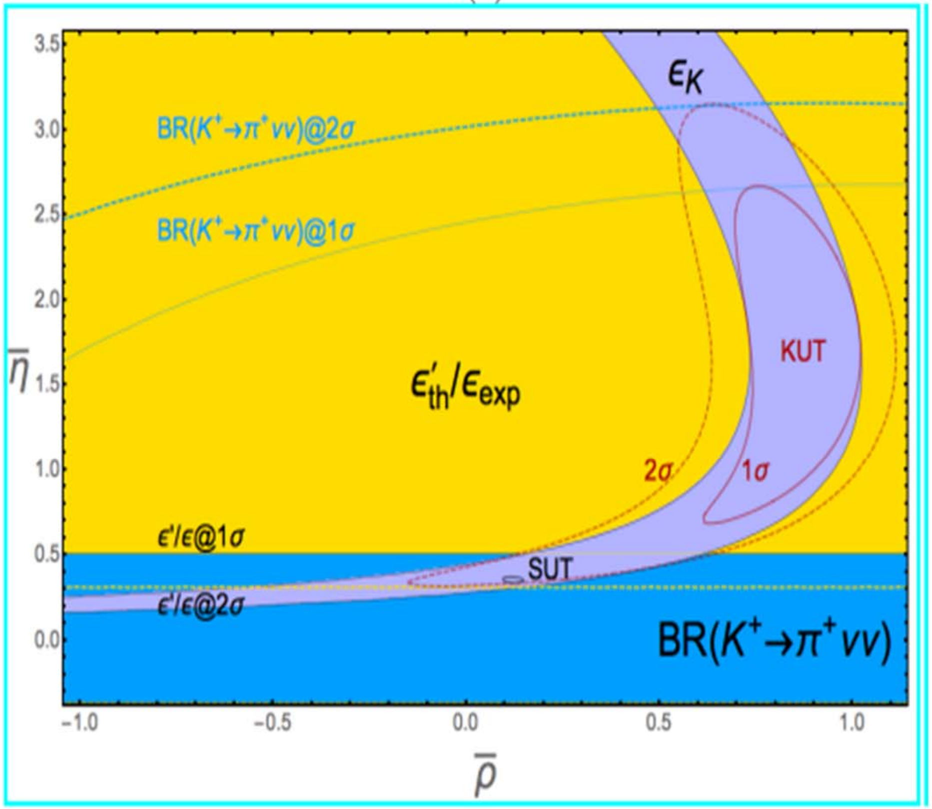
Sketch of an emerging K-UT: 3 key Kaonic inputs:

I ϵ_K Indirect CP

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

BNL

(a)

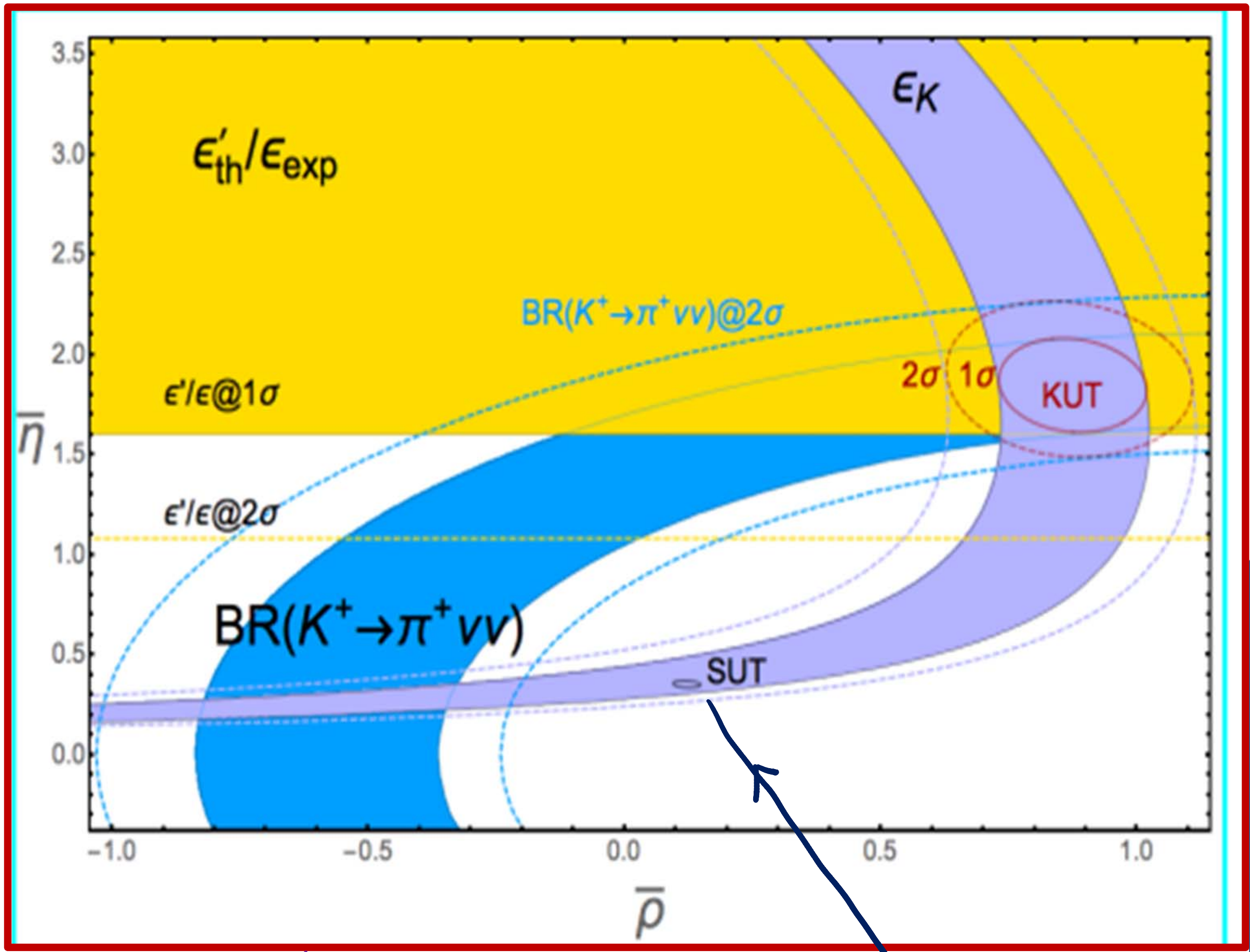


III
$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)_K = \begin{cases} (16.7 \pm 1.6) \times 10^{-4} \\ (1.36 \pm 5.21_{\mathrm{stat}} \pm 4.49_{\mathrm{syst}}) \times 10^{-4} \end{cases}$$

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%]

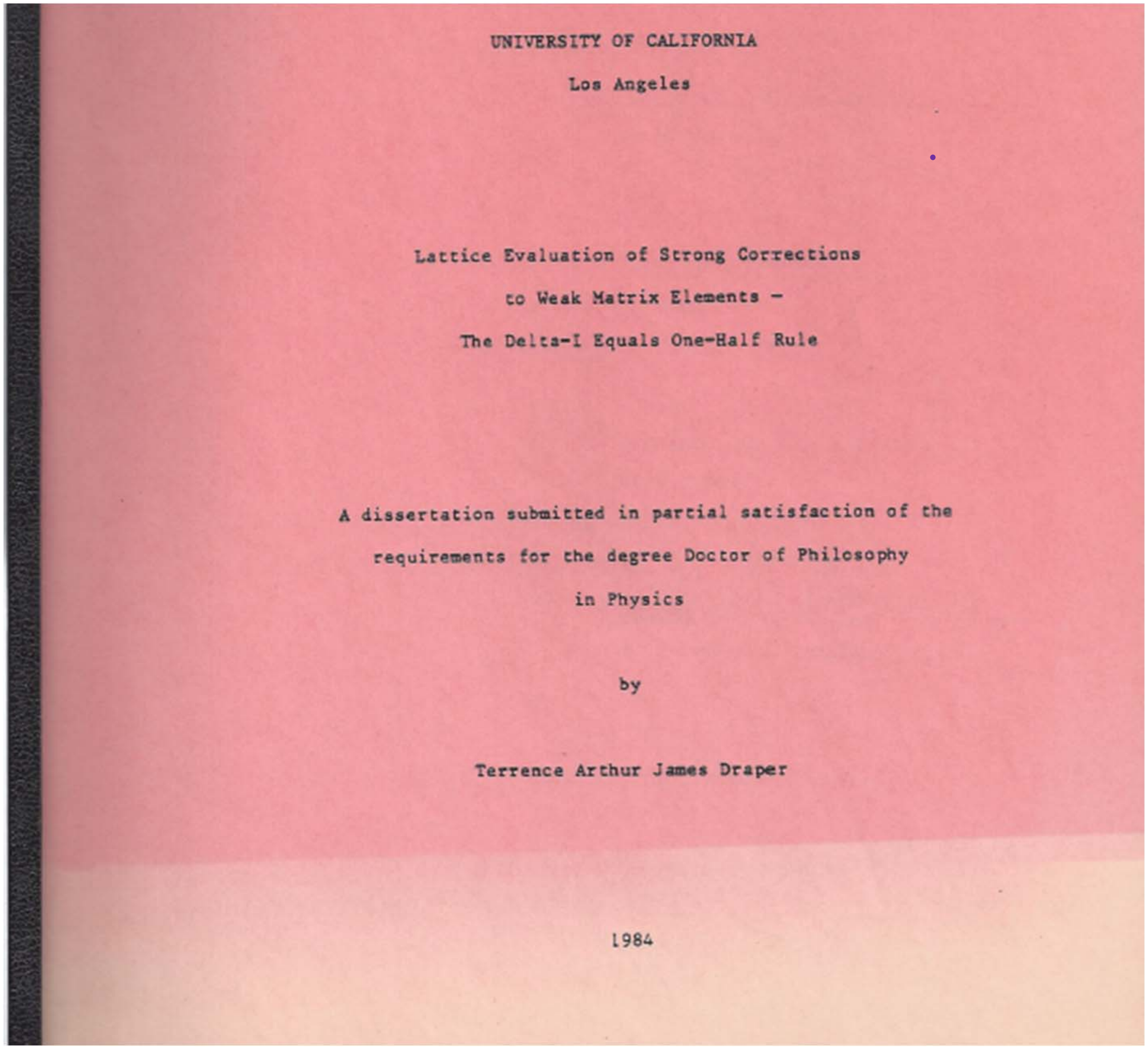
"Standard" (B) UT

Lehner, Lunghi+AS PLB'16

ITS MY ~36TH YEAR ON K=>ΠΠ & Ɛ'…..WHY?


REFRIGERATION & AIR CONDITIONI
SERVICE, TEL.
GMC

The 1st
PhD
Thesis



UNIVERSITY OF CALIFORNIA

Los Angeles

Lattice Evaluation of Strong Corrections
to Weak Matrix Elements –
The Delta-I Equals One-Half Rule

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy
in Physics

by

Terrence Arthur James Draper

1984

Grew from
end of year
Beer Party
~June 20, 1982!!
[UCLA]

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

- **Calculation K=> ππ & ε' were the reasons I went into lattice over 1/3 of a century ago!**
- ***9 + (3 new) PhD thesis*: Terry Draper (UCLA'84), George Hockney(UCLA'86), Cristian Calin (Columbia=CU'01), Jack Laiho(Princeton'04), Sam Li(CU'06), Matthew Lightman(CU'09), Elaine Goode(Southampton'10), Qi Liu(CU'12), Daiqian Zhang(CU'15)+ [new ones starting from CU, U Conn and Southampton] + many PD's & junior facs.. obstacles & challenges (and of course "mistakes"!) ad infinitum…..**

WHY FOCUS with SUCH intense DETERMINATION
All these many many years?

UNDERLYING REALIZATION

Ɛ': MOST LIKELY A GEM IN SEARCH OF NEW PHENOMENA

Contrarian/Complementary view

- **flavor physics is actually hanging by perhaps the weakest link i.e. a single CP-phase endowed by the 3g –SM.**

- **In many ways this is a contrarian (or complementary) point of view, in sharp contrast to the overwhelming majority following the naturalness lamp post via Higgs radiative stability.**

- **Ɛ' due to its miniscule value, esp because it results from unnatural large cancellations seemed clearly highly vulnerable…The mantra being followed for a very very long time**

Its presumed importance:

- lies in its very small size => Perhaps new phenomena has a better chance of showing up
- Smallness also renders it exceedingly sensitive monitor of flavor –alignment
- Simple naturalness arguments strongly suggest ε’ very sensitive to BSM – CP odd phases
- In many ways, (superficially) ε’ is rather analogous to nedm…….both being very sensitive to BSM-CP phases; however, key diff for (now) nedm expt is the key, theory has marginal role, in sharp contrast to ε’
- Understanding ε’, nedm are extremely important for uncovering new physics and/or learning how naturalness really works in nature

IF YOU BUILD IT THEY WILL COME

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

[of course requires accurate theory calculation… RBC-UKQCD plans for X5 in stat and appreciable improvements in systematic in ~2 years]

Soni's ε’ Rule

- If ε’ ends up being due SM then:

- I. Other anomalies, RD(*), RK(*), g-2 will ALL go away
- 2. ~~It~~ If so, that will give us a vitally important new info on naturalness

MODEL INDEPENDENT IMPLICATIONS OF RD(*) ANOMALIES FOR [LHC] COLLIDER EXPERIMENTS: SAMPLE ILLUSTRATIONS

Implications of Anomalies

- **For Collider:From Isidori ; Kamenik; ADS';**

  Luzio; Hou;

- **FOR IF: Guadagnoli; Fajfer; Neubert; Mandal; Fuentes-Martin**

Conclusions

FUENTES-MARTIN

It is possible to find **well-motivated** combined explanations of the B anomalies, compatible with current data in both low- and high-energies C ALSO Mandal

The model I presented, a **Pati-Salam flavor deconstruction**, predicts several characteristic smoking-gun signatures that differentiate it from other solutions

- $\Delta R_{D^*}/\Delta R_D \simeq 0.45$
- NP in $b \to s\tau\tau \sim b \to s\mu\mu$ and $b \to s\tau\mu \sim \mathcal{O}(5) \times b \to s\mu\mu$ ⟸ !!
- Possibility of a deficit in $\Delta B = 2$ & CP violation involving the 3rd quark family
- Possible large enhancements in $B \to \tau\nu$ ⟸ C ALSO NPS '16

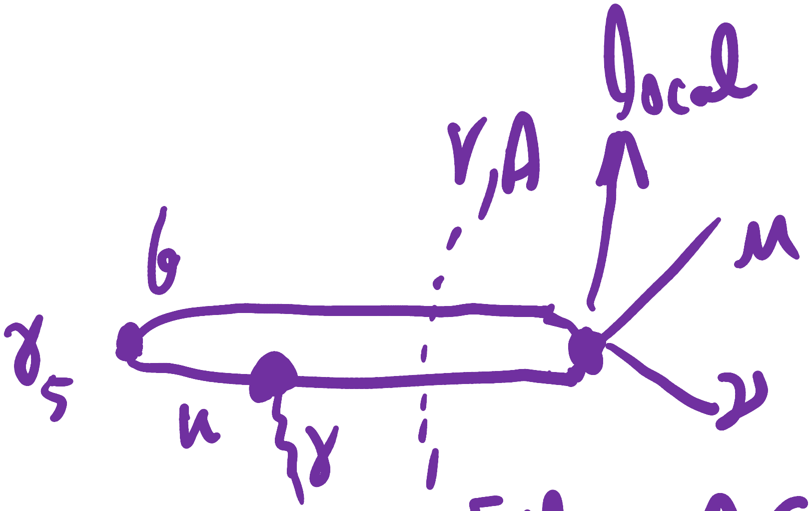
If the anomalies are really pointing to NP, **new experimental indications** (both in high-p_T and at low energies) will show up soon in several observables

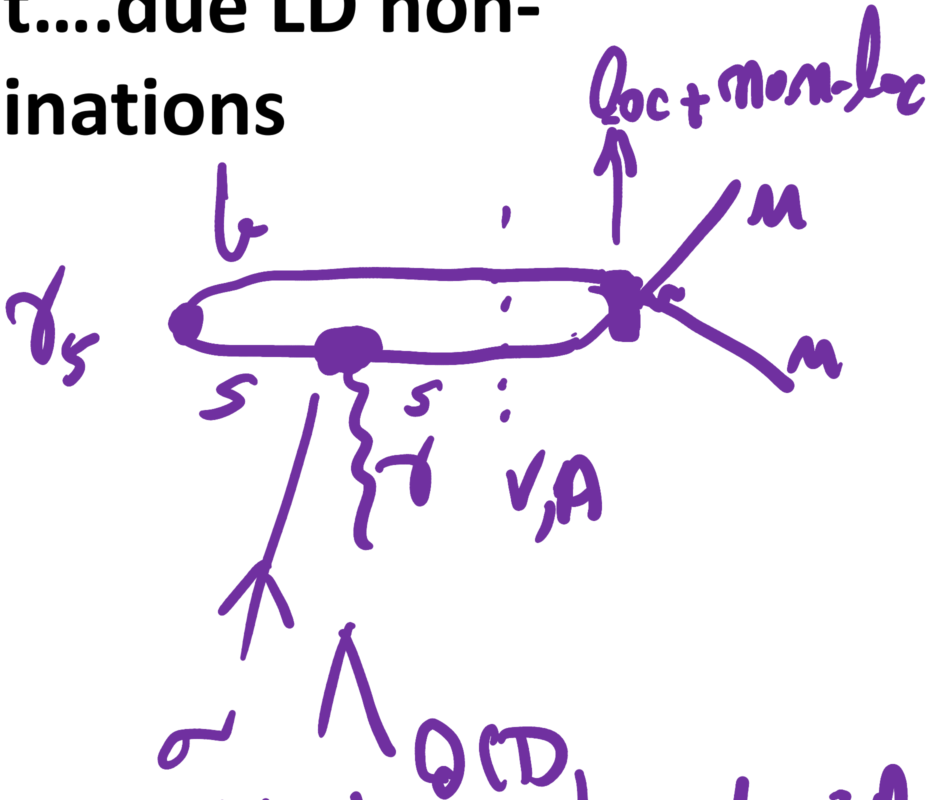
Exciting times ahead of us. Let's have fun

Guadagnoli B(s)=>mu mu gamma

- **Nice idea but difficult….due LD non-perturbative contaminations**

LATTICE INPUT Seems essential





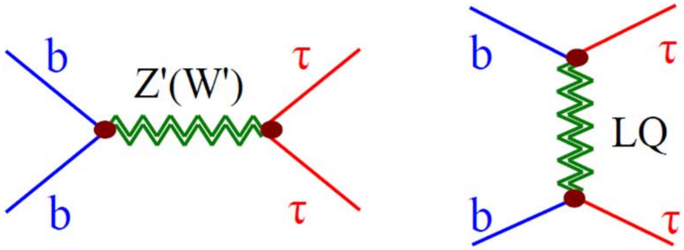
photon is hard ∴ b spin flip

See Atwood, Eilam, AS J1009ns/2

EFT-type considerations [The main problems]

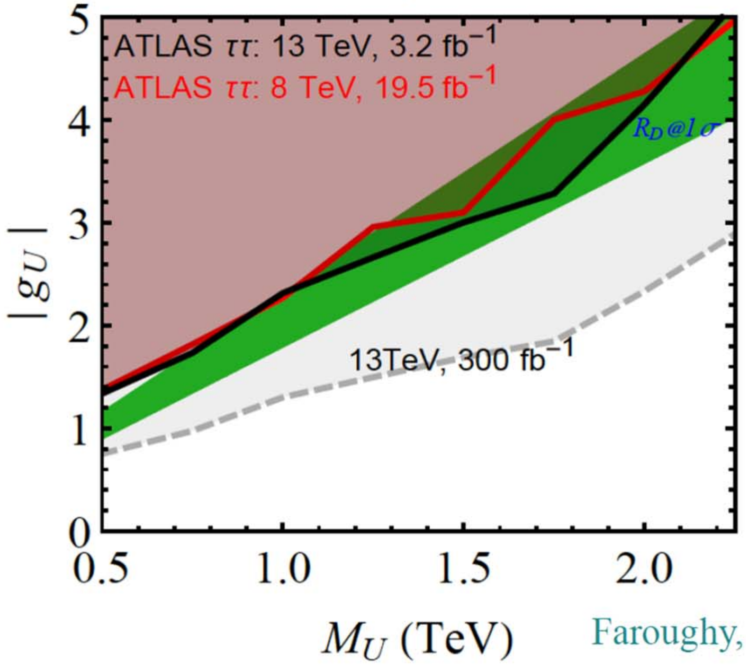
Three main problems identified in the recent literature (*driven mainly by R_D...*):

I. *high-p_T constraints*

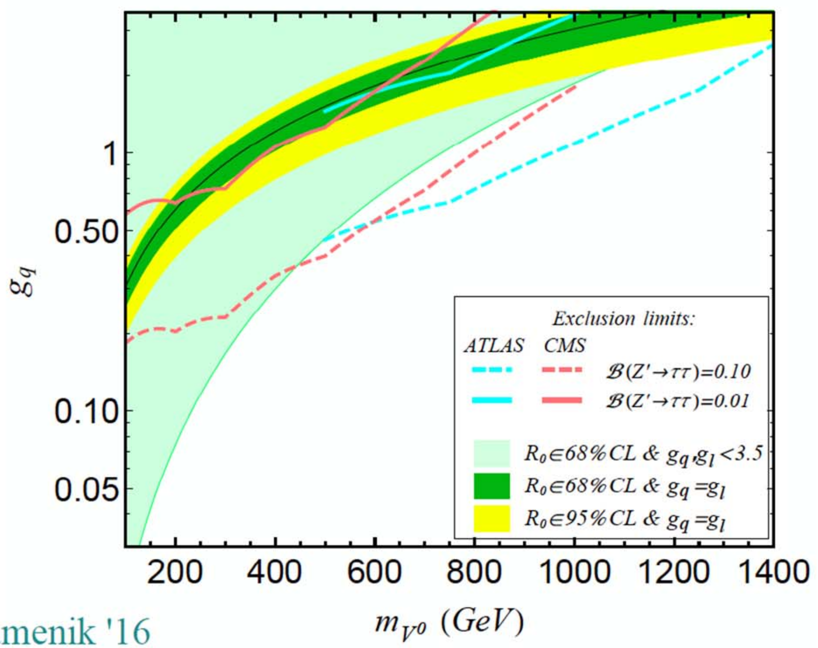


Naïve EFT scale
[*from R_D - setting g, λ → 1*]: $\Lambda \sim 700$ GeV

Vector LQ exclusion



Z' exclusion

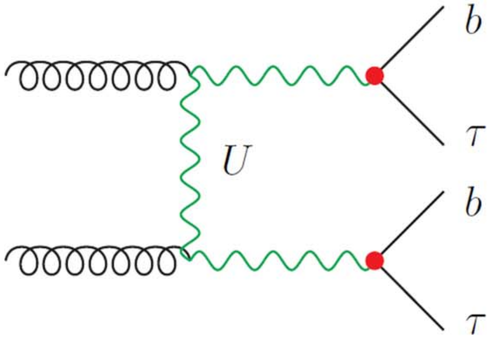


Faroughy, Greljo, Kamenik '16

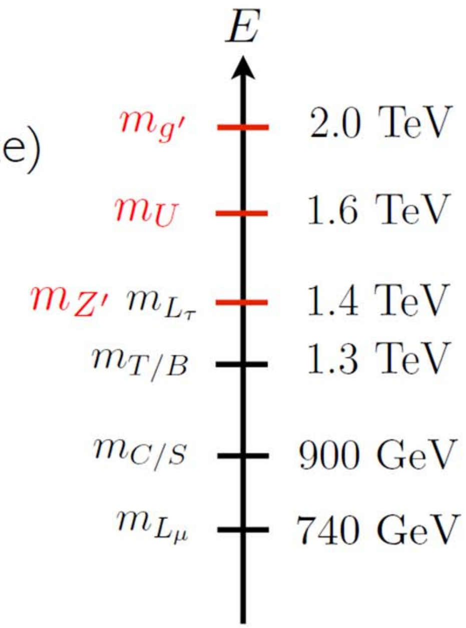
High-p_T searches

- LQ pair production via QCD

  - 3rd generation final states (fixed by anomaly and $SU(2)_L$ invariance)



$$\begin{cases} U \to b\tau^+, & \text{BR} = 50\ \% \\ U \to t\overline{\nu}, & \text{BR} = 50\ \% \end{cases}$$



[CMS search for spin-0, 1703.03995
recast for spin-1 1706.01868 (see also 1706.05033) + Moriond EW update]

$m_U \gtrsim 1.5$ TeV → LQ mass sets the overall scale: $M_{g'} \simeq \sqrt{2}\, M_U \quad M_{Z'} \simeq \frac{1}{\sqrt{2}} M_U$

ALTMANNSHOFER, DEV + AS
1704.06659 + Seq, WIP

MODEL INDEPENDENT IMPLICATIONS OF RD(*) ANOMALIES FOR [LHC] COLLIDER EXPERIMENTS

- **In a nut-shell B-experiments seem to find anomalous behavior in the underlying b=>c tau nu**
- **This necessarily [by XSym] implies there should be analogous anomaly in   g + c => b tau nu…=>pp => b tau nu**

- ***Thus it immediately leads to inescapable search channels for possible NP at the high energy frontier for ATLAS & CMS and these are urgently urged***

Xsymm implications of anomalies for colliders

ADS'

$R_{D^{(*)}}$ ANOMALY: A POSSIBLE HINT FOR …

PHYSICAL REVIEW D **96,** 095010 (2017)

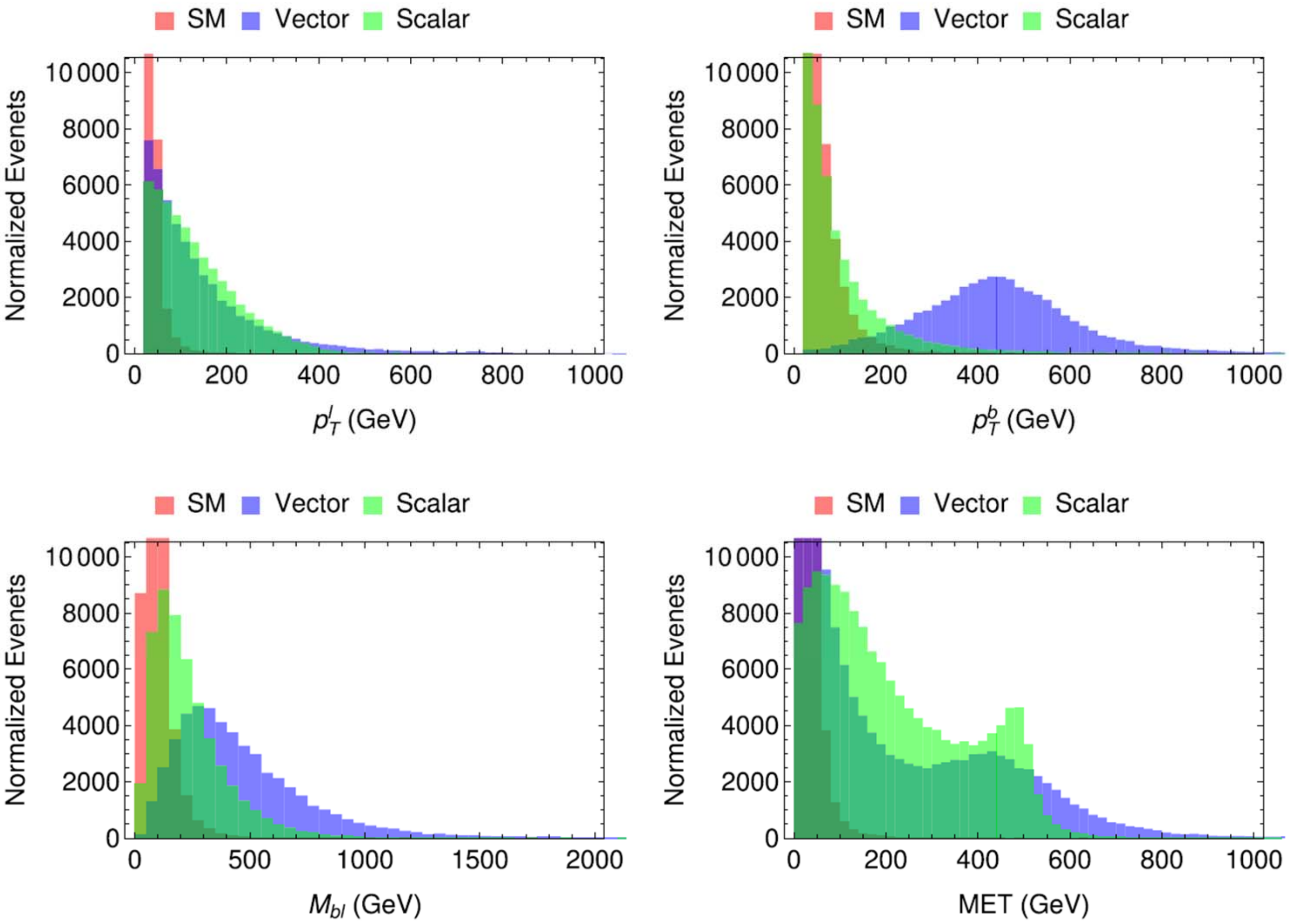


FIG. 1. Normalized kinematic distributions for the $pp \to b\tau\nu \to b\ell + \not{E}_T$ signal and background.

EXPECT DISTINCTIVE NP CONTRIBUTIONS IN COLLIDERS

ANOMALY: POSSIBLY A HINT FOR (NATURAL) SUSY-WITH RPV

- **ASSUMING the anomaly is REAL & HERE TO STAY [BIG ASSUMPTION due to caveats mentioned]**
- **Anomaly involves simple tree-level semi-leptonic decays**
- **Also b => tau (3rd family)**
- **Speculate: May be related to Higgs naturalness**
- **Seek minimal solution: perhaps 3rd family super-partners(a lot) lighter than other 2 gens > proton decay concerns may not be relevant=> RPV [“natural” SUSY]**
- **RPV natural setting for LUV …can accommodate g-2 and eps’ if needs be**
- **Collider signals tend to get a lot harder than (usual-RPC) SUSY**

RPV$_3$ preserves gauge coupling unification irrespective of # of effective gens. 1, 2 or 3.

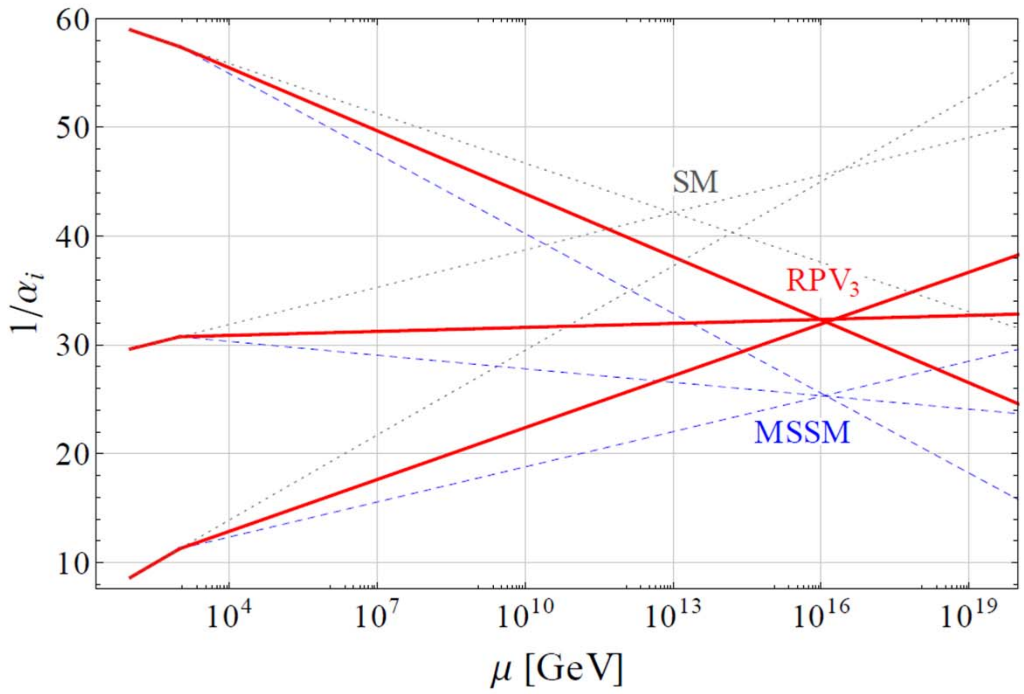


FIG. 2. RG evolution of the gauge couplings in the SM, MSSM and with partial supersymmetrization.

Unification scale ~ stays same, only value of couplings shifts

For pheno relevant terms:

ADS' PRD 2017

$$\begin{aligned}\mathcal{L} = \lambda'_{ijk}\big[&\tilde{\nu}_{iL}\bar{d}_{kR}d_{jL} + \tilde{d}_{jL}\bar{d}_{kR}\nu_{iL} + \tilde{d}^*_{kR}\bar{\nu}^c_{iL}d_{jL}\\ &-\tilde{e}_{iL}\bar{d}_{kR}u_{jL} - \tilde{u}_{jL}\bar{d}_{kR}e_{iL} - \tilde{d}^*_{kR}\bar{e}^c_{iL}u_{jL}\big] + \mathrm{H.c.}\end{aligned}$$

} RPV$_3$ interaction

Dim 6

$$\boxed{\begin{aligned}\mathcal{L}_{\mathrm{eff}} \supset \frac{\lambda'_{ijk}\lambda'^*_{mnk}}{2m^2_{\tilde{d}_{kR}}}\Big[&\bar{\nu}_{mL}\gamma^\mu\nu_{iL}\bar{d}_{nL}\gamma_\mu d_{jL}\\ &-\underline{\nu_{mL}\gamma^\mu e_{iL}\bar{d}_{nL}\gamma_\mu\left(V^\dagger_{\mathrm{CKM}}u_L\right)}_j + \mathrm{h.c.}\Big]\\ &-\frac{\lambda'_{ijk}\lambda'^*_{mjn}}{2m^2_{\tilde{u}_{jL}}}\bar{e}_{mL}\gamma^\mu e_{iL}\bar{d}_{kR}\gamma_\mu d_{nR}\,,\end{aligned}}$$

→ For $R_{D(*)}$

NOTE:
ITS
SM-like!

For addressing RK(*) in RPV, see e.g. Das et al , 1705.09188

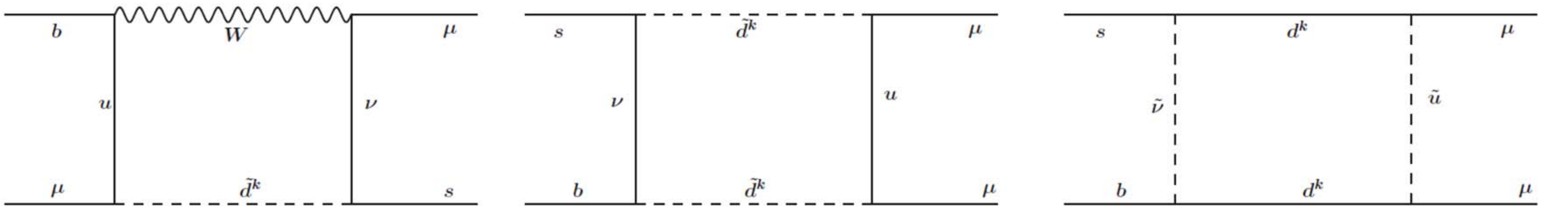


FIG. 1: Representative diagrams for $b \to s\mu^+\mu^-$ transition in R-parity violating interactions.

g-2 with RPV has a long history, see, e.g.Kim, Kyae and Lee, PLB 2001

We [ALTMANNSHOFER+DEV+AS] are examining+update in light of current flavor anomalies

WORK IN Progress

CONSTRAINTS: TIGHTENING EXPT’S NOOSE AGAINST SPECIFIC MODELS

BABAR Phy Book '97

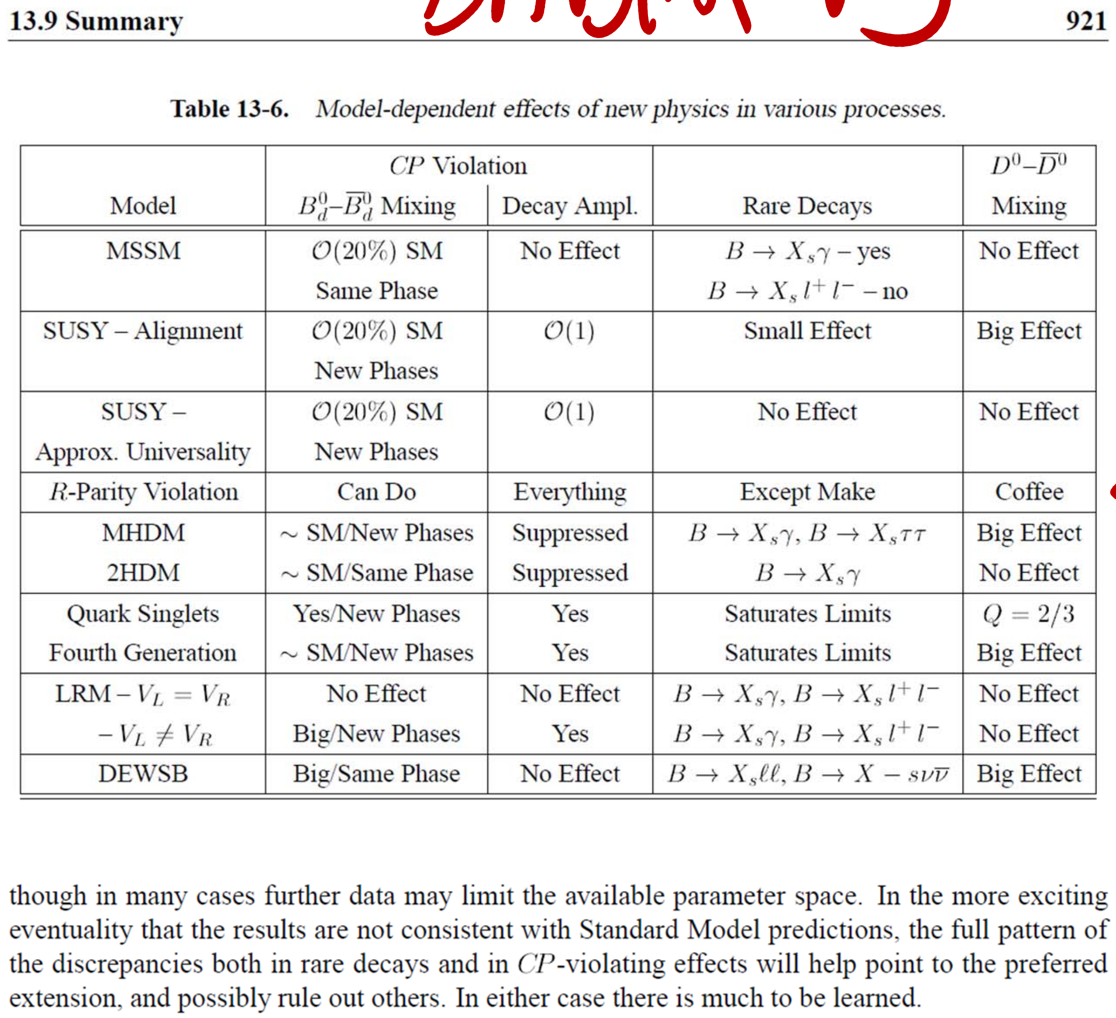


Table 13-6. *Model-dependent effects of new physics in various processes.*

Model	CP Violation		Rare Decays	D^0–$\overline{D}^0$
	B_d^0–$\overline{B}_d^0$ Mixing	Decay Ampl.		Mixing
MSSM	$\mathcal{O}(20\%)$ SM Same Phase	No Effect	$B \to X_s\gamma$ – yes $B \to X_s l^+ l^-$ – no	No Effect
SUSY – Alignment	$\mathcal{O}(20\%)$ SM New Phases	$\mathcal{O}(1)$	Small Effect	Big Effect
SUSY – Approx. Universality	$\mathcal{O}(20\%)$ SM New Phases	$\mathcal{O}(1)$	No Effect	No Effect
R-Parity Violation	Can Do	Everything	Except Make	Coffee
MHDM 2HDM	~ SM/New Phases ~ SM/Same Phase	Suppressed Suppressed	$B \to X_s\gamma$, $B \to X_s\tau\tau$ $B \to X_s\gamma$	Big Effect No Effect
Quark Singlets Fourth Generation	Yes/New Phases ~ SM/New Phases	Yes Yes	Saturates Limits Saturates Limits	$Q = 2/3$ Big Effect
LRM – $V_L = V_R$ – $V_L \neq V_R$	No Effect Big/New Phases	No Effect Yes	$B \to X_s\gamma$, $B \to X_s l^+ l^-$ $B \to X_s\gamma$, $B \to X_s l^+ l^-$	No Effect No Effect
DEWSB	Big/Same Phase	No Effect	$B \to X_s\ell\ell$, $B \to X - s\nu\overline{\nu}$	Big Effect

though in many cases further data may limit the available parameter space. In the more exciting eventuality that the results are not consistent with Standard Model predictions, the full pattern of the discrepancies both in rare decays and in CP-violating effects will help point to the preferred extension, and possibly rule out others. In either case there is much to be learned.

constraints

- Direct searches via $pp \rightarrow \tilde{b}\tilde{b} \rightarrow \tau^+\tau^- t\bar{t}$

Indirect constraints considered due B=>τ ν; π τ ν; π(K) ν ν….

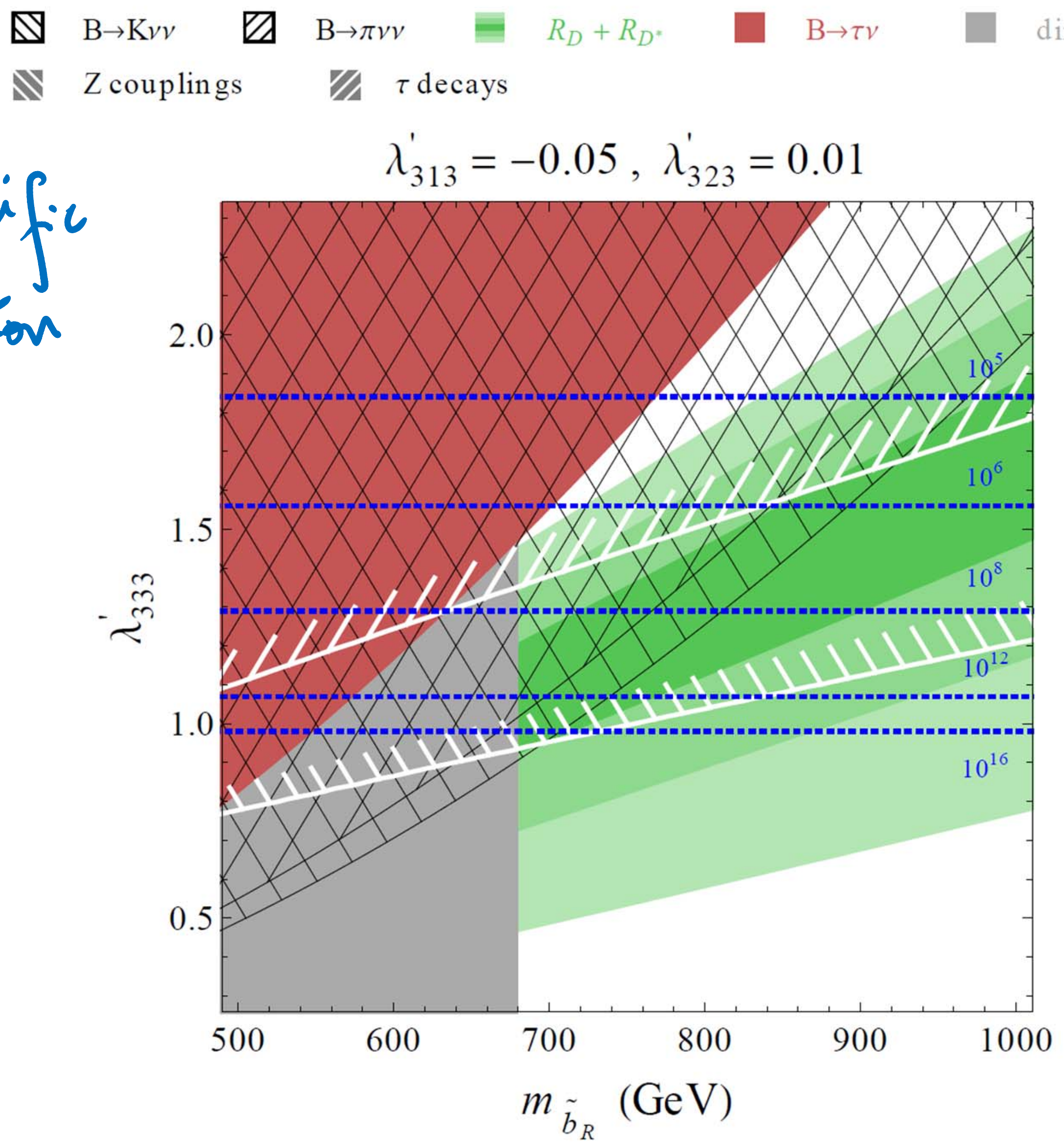
Also B_C =>τν….

To a/c (within 1σ) of expt for RD(*) needs largish λ’333 ~1 – 2 range with quite heavy sbottoms but such large couplings develop landau pole below GUT scale.We require couplings stay perturbative below GUT so with λ’333 < ~1 ,

$\Rightarrow$ TAKE HOME: This version of RPV is actually (surprisingly) well constrained

$\Rightarrow$ With improved measurements RD(*) in RPV3 may be difficult

As a specific illustration



))

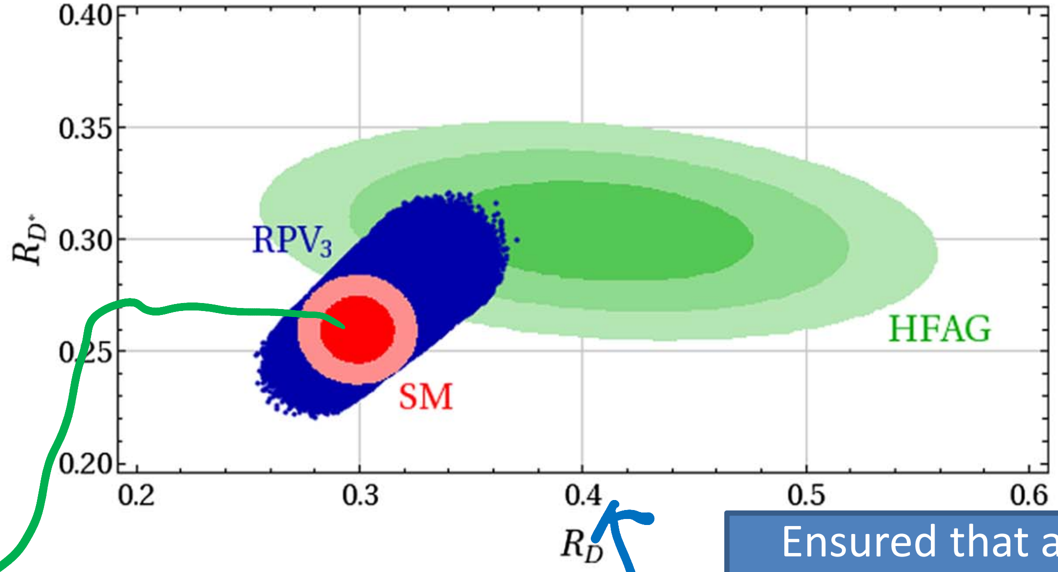
Constraints imposed

FIG. 3. RPV parameter space satisfying the $R_{D(*)}$ anomaly and other relevant constraints.

RPV3 allows
RD=(.254-.371)
RD*=(.220-.320)
Contrast Fuentes-Martin:

$\frac{\Delta R_D^*}{\Delta R_D} \simeq 0.45$

ALTMANNSHOFER, BHUPAL DEV, and SONI PRD 2017



HFAG dec2016
RD=.403+-.040+-.024
RD*=.310+-.015+-.008
LHCb 06/06/17
RD* 0.305

Ensured that all RPV3 couplings stay perturbative up to GUT

FIG. 4. The SM predictions (red), experimental world average (green), and accessible values in our RPV-SUSY scenario (blue) in the R_D vs. R_{D^*} plane. For the SM, bearing in mind recent works [17,20,22] we are taking $(R_D^{SM}, R_{D^*}^{SM}) = (0.299 \pm 0.011, 0.260 \pm 0.010)$.

More Realistic SM Blob

all constraints……RPV(blue) region obtained by scanning with sbottom mass 680-1000Gev, 0<λ333<2;|λ323|<0.1;|λ313|<0.3 ….

IN CLOSING

Contrarian/Complementary view

- **flavor physics is actually hanging by perhaps the weakest link i.e. a single CP-phase endowed by the 3g –SM.**
- **In many ways this is a contrarian (or complementary) point of view, in sharp contrast to the overwhelming majority following the naturalness lamp post via Higgs radiative stability.**
- **In this context it is useful to stress**

Importance of the “IF”: score card

- Beta decay => Gf => W….
- Huge suppression of KL => mu mu; miniscule ΔmK=> charm
- KL =>2 pi but very rarely; mostly to 3pi =>CP violation => 3 families
- Largish Bd –mixing => large top mass
- etc…….
- => extremely unwise to put all eggs in HEF
- Complementary info from IF can be a crucial guide

  for pointing to new thresholds as well as provide important clues to the nature of the signals there from

Summary and Outlook..[p1 of 2]

- **Hints of LUV [from 3 B experiments] in sl B decays are interesting though not yet compelling despite the claimed 4.1 sigma; FCNC mu/e LUV indications in B=K (and K*) l l are also extremely interesting and may well be related to LUV in sl B….If so similar mu/e LUV should be seen in FCNC channels [e.g] in baryonic B decays as well as a multitude of other channels.**
- **Though not yet compelling; OTOH no good reason that experimental hints are wrong. While we are accustomed to respecting LU the sensitivities of the current experiments are better than the past.**
- **This is not a violation of SR or GR, but only of accepted dogma; experimental results on LUV therefore deserve serious attention.**
- **That is my interest, try get to the bottom of it all AFAP using on & off the lattice tools**
- **Accurate SM predictions are usually very challenging and demanding but are extremely important; BSM scenarios are easy to cook up but 1/N^N' of being correct with N, N' >1000**
- **However, in the context of BSM note also the truly impressive constraints on models that past decade or so studies have resulted [as illustrated by RPV3].**
- **More data from LHCb from Run 2 < 1 year should help and further ~2 years down Belle II should start to help more….On the theory side, of critical importance is FF for B=>D*…should start to get results in ~ 6 months to 1 year RBC/UKQCD as well as others**
- **FCNC mu/e LUV so far only LHCb data shows the effect…confirmation from other experiments would be extremely helpful.**

Summary and Outlook …p.2

- **It may well be that BNL's observed g-2 signals of possible NP were just a precursor to these observations in B decays.**
- **Lattice progress in g-2 by RBC-UKQCD as well as global efforts are impressive …But needs to reduce errors further by ~X4…Expect next reduction X2 in a year or so**
- **ε': RBC-UKQCD should be able to appreciably improve their 2015 result of ~2.1 sigma tension, in <6 months**
- **Personally, this is the ~36th year of trying to tame this really wild beast; so it'd be welcome indeed.**
- **There is now an exciting and may be even a revolutionary possibility that one or more of these avenues will show significant departure from SM in ~ 1-2 years**

XTRAS

Lattice computation of the decay constants of B and D mesons

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(Received 1 July 1993)

Semileptonic decays on the lattice: The exclusive 0^- to 0^- case

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(Received 21 December 1990)

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Lattice study of semileptonic decays of charm mesons into vector mesons

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(Received 30 September 1991)

We present our lattice calculation of the semileptonic form factors for the decays $D\rightarrow K^*$, $D_s\rightarrow\phi$, and $D\rightarrow\rho$ using Wilson fermions on a $24^3\times39$ lattice at $\beta=6.0$ with 8 quenched configurations. For $D\rightarrow K^*$, we find for the ratio of axial form factors $A_2(0)/A_1(0)=0.70\pm0.16^{+0.20}_{-0.15}$. Results for other form factors and ratios are also given.

PIONEERING WORKS Leading to modern Day UT ?

PHYSICAL REVIEW D, VOLUME 58, 014501

SU(3) flavor breaking in hadronic matrix elements for B-$\bar{B}$ oscillations

Later ΔM_s
CDF, D0

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⇒ (Received 28 February 1998; published 5 May 1998)

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  - Greg McGlynn
  - David Murphy
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