.

LU…anomalies, naturalness, new physics & more

Pheno 2018

Univ of Pittsburgh

Amarjit Soni

BNL-HET

05/08/18

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
- Assuming NP is a source: An interesting, minimal setup for a BSM origin
- Summary & Outlook

ALTMANNSHOFER + DEV + AS
1704.06659

Anomalies galore!

- RD(*) ~ 4σ(?)
- RK(*): 2.6σ(RK);

- g -2…BNL'06 =>FNAL expt ~ 3.6σ   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

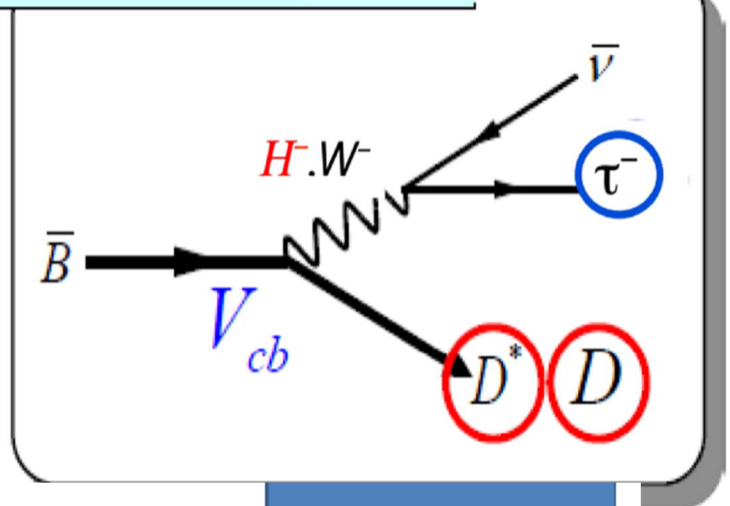
[2.1σ (2.9σ Buras; Nierste) => ??] …..few more months to new results

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

$R_{D(*)}$

VERA LUTH (BABAR)
FPCP May 2012
(HEFEI, China)

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



MANUEL FRANCO SEVILLA PhD Thesis

Independent of Vcb!

- To test the SM Prediction, we measure

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

Leptonic τ decays only

Several experimental and theoretical uncertainties cancel in the ratio!

$\ell = \mu$ or e

PHYSICAL REVIEW D VOLUME 56, NUMBER 9 1 NOVEMBER 1997

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

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 $B \to D\tau\overline{\nu}$ 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 $B \to D(e,\mu)\overline{\nu}$. 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

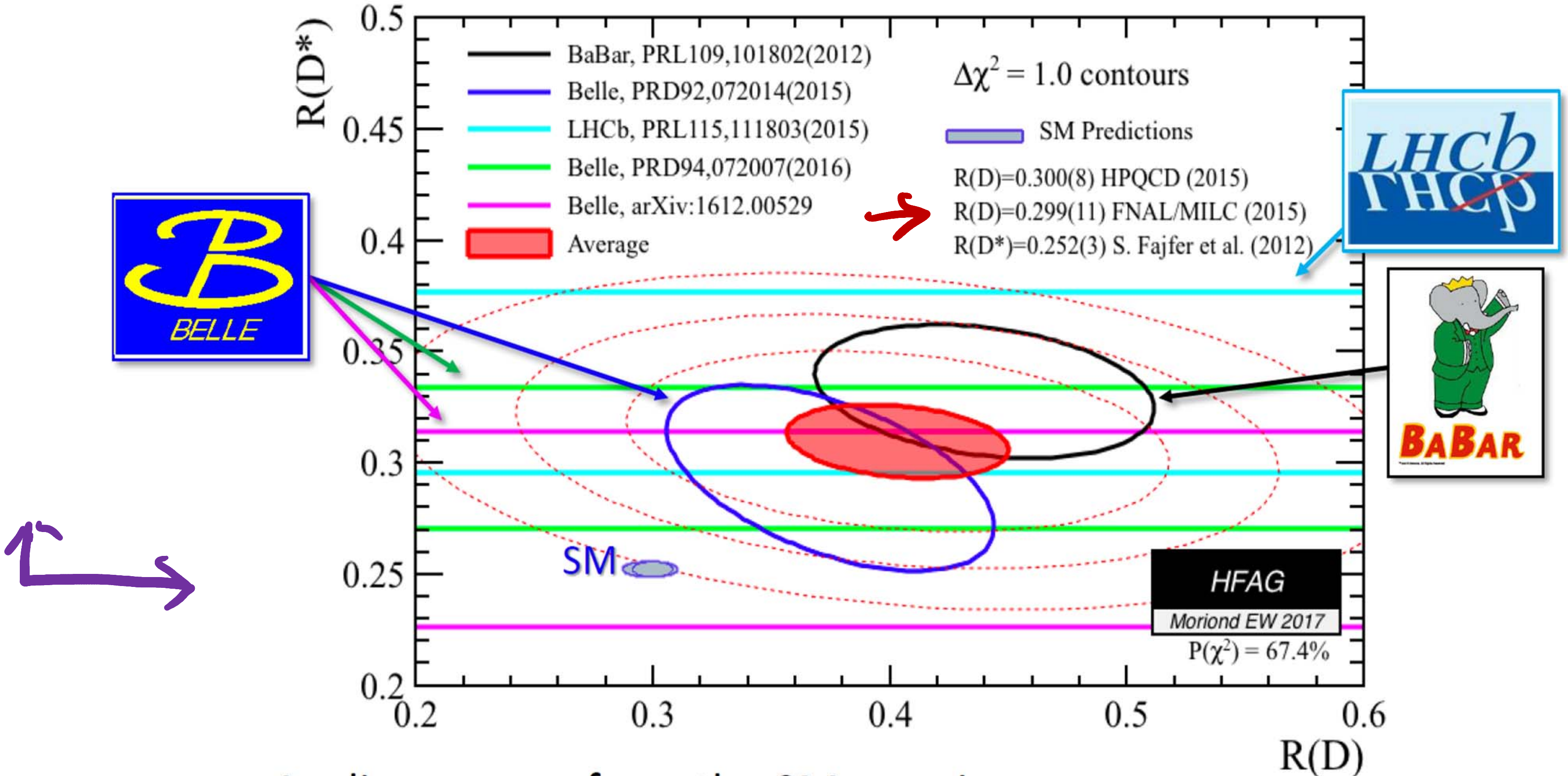
ρ

used HQS

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

■ $R(D^{(*)})$ by HFAG

Hirose [BELLE]@EW MORIOND Mar. 2017



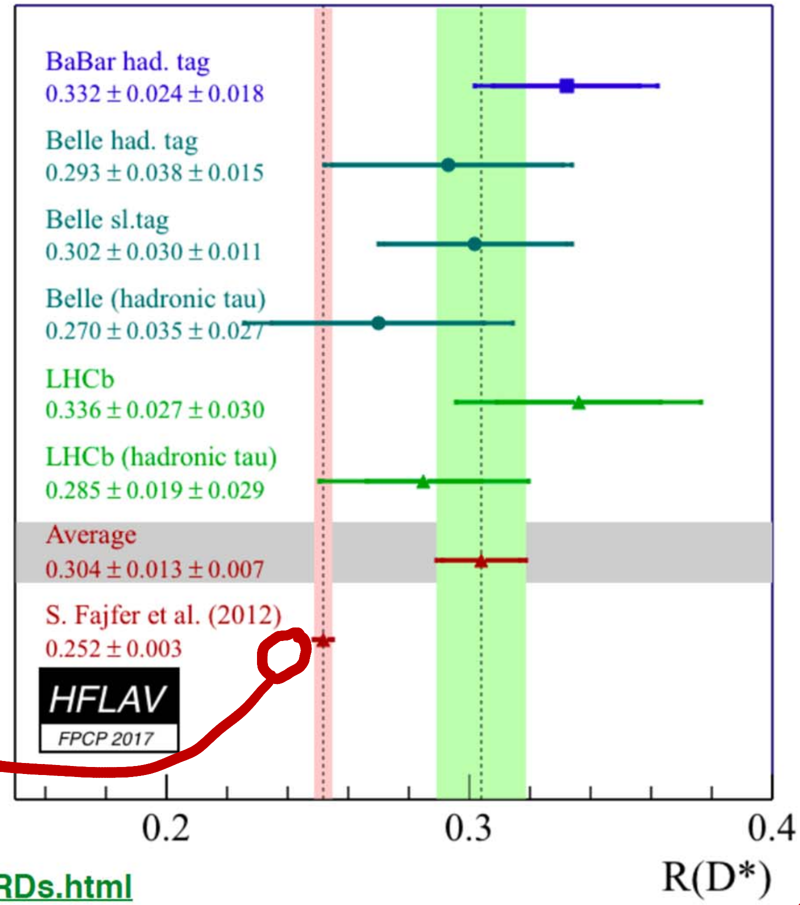
- ~4σ discrepancy from the SM remains
  - All the experiments show the larger $R(D^{(*)})$ than the SM
- More precise measurements at Belle II and LHCb are essential

Belle deviations quite mild

R(D*) Status UPDATE

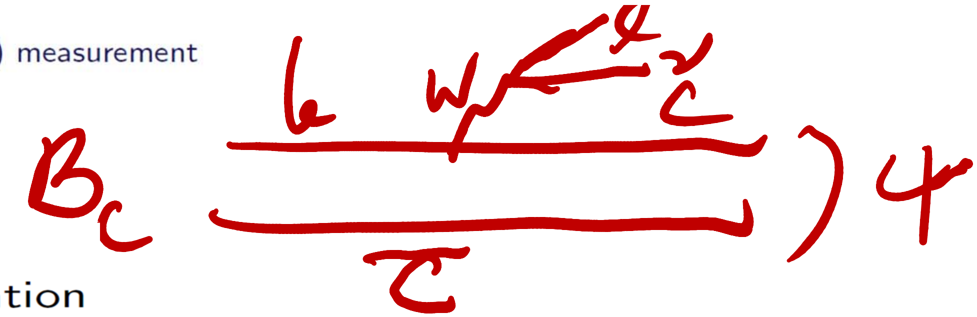
LHCb results have been incorporated on world average compilation.

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



MISLEADING

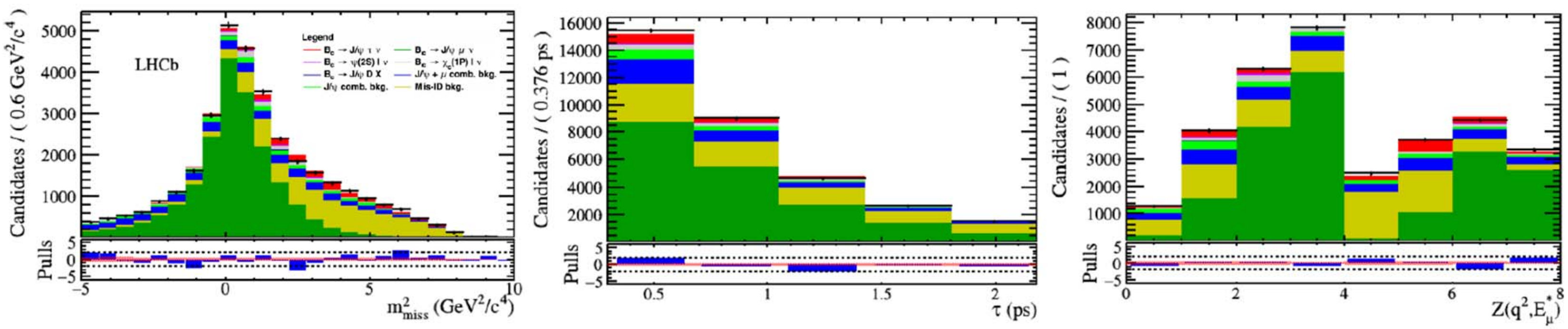
http://www.slac.stanford.edu/xorg/hflav/semi/fpcp17/RDRDs.html



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

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

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 some more time]**

- **For B=>D* no complete lattice study so far; 4 rather than 2 FF, so , from the lattice perspective, anticipate larger errors than for B=>D…Another ~6 months to complete**

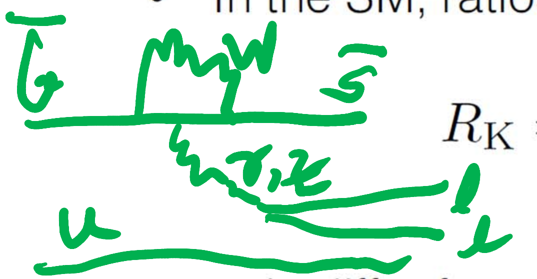
- **Therefore, O(1%) errors in RD* (and in fact smaller than in RD) are difficult to understand; lattice results should come in some months**
- **HFAG should update the SM-theory with more realistic errors otherwise their fig is bit misleading** → $R_{D*} = 0.257 \pm .005$ 2%
- **Meantime recent phenomenological study of** Bernlochner, Ligeti, Papucci and Robinson, 1703.05330 [and even more recently…is/are very timely and greatly appreciated.

BIGI, Gambino + Schacht: $.259 \pm .009$ 4%

JAISWAL + NANDI + PATRA

Lepton universality tests

LHCb introduced such v. well defined ratios



- In the SM, ratios

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

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.

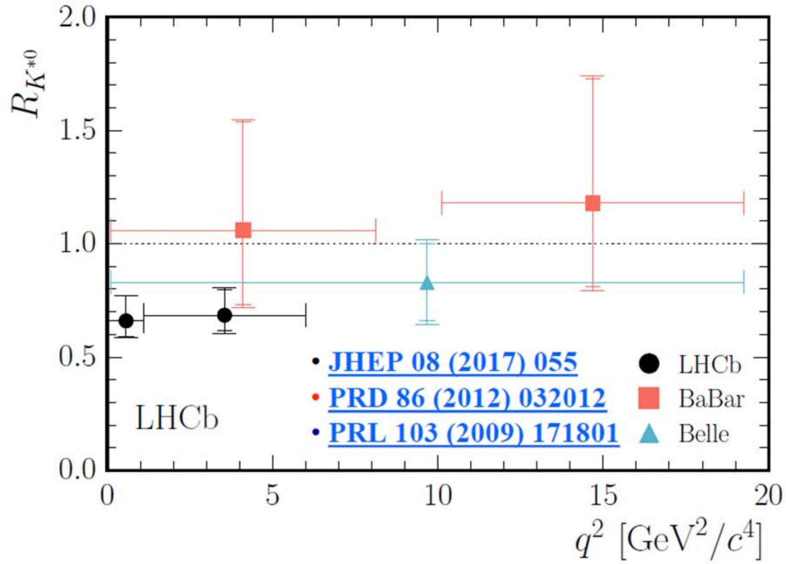
- Experimentally challenging due to differences in muon/electron reconstruction (in particular Bremsstrahlung from the electrons).

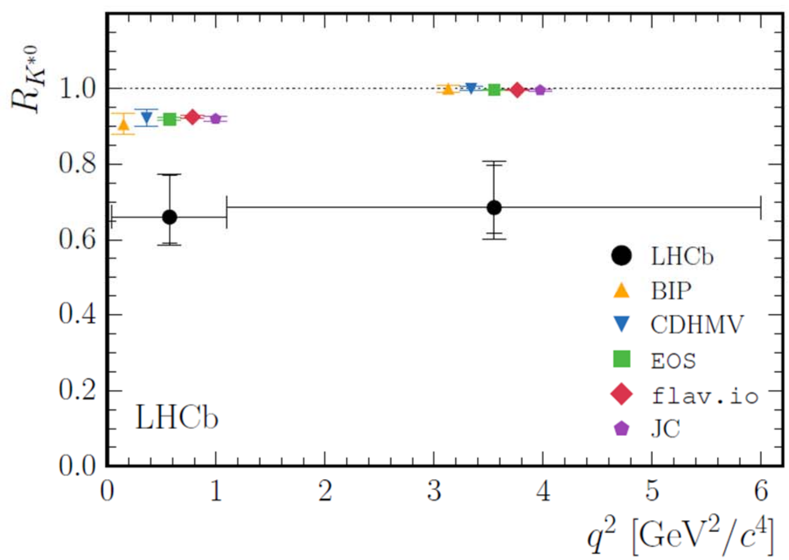
  ➡ Take double ratios with $B \to J/\psi X$ decays to cancel possible sources of systematic uncertainty.

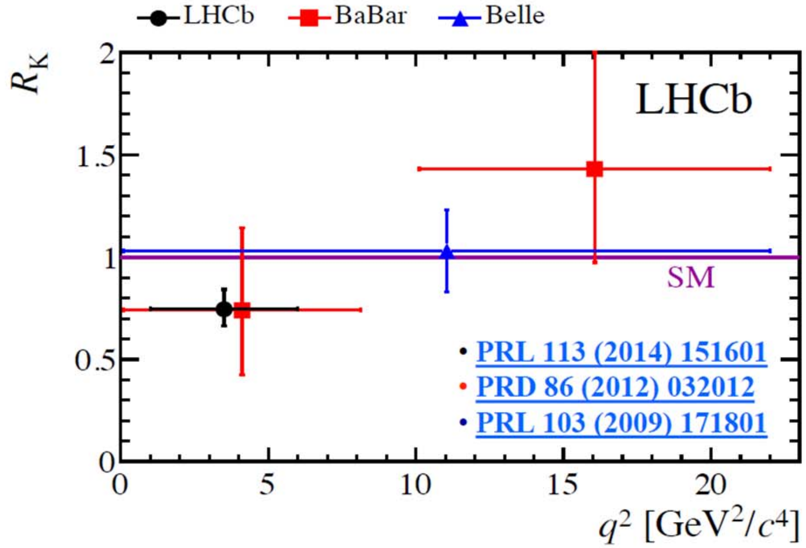
  ➡ Correct for migration of events in q^2 due to FSR/Bremsstrahlung using MC (with PHOTOS).

Lepton Universality results

Rk* shows similar results as Rk!



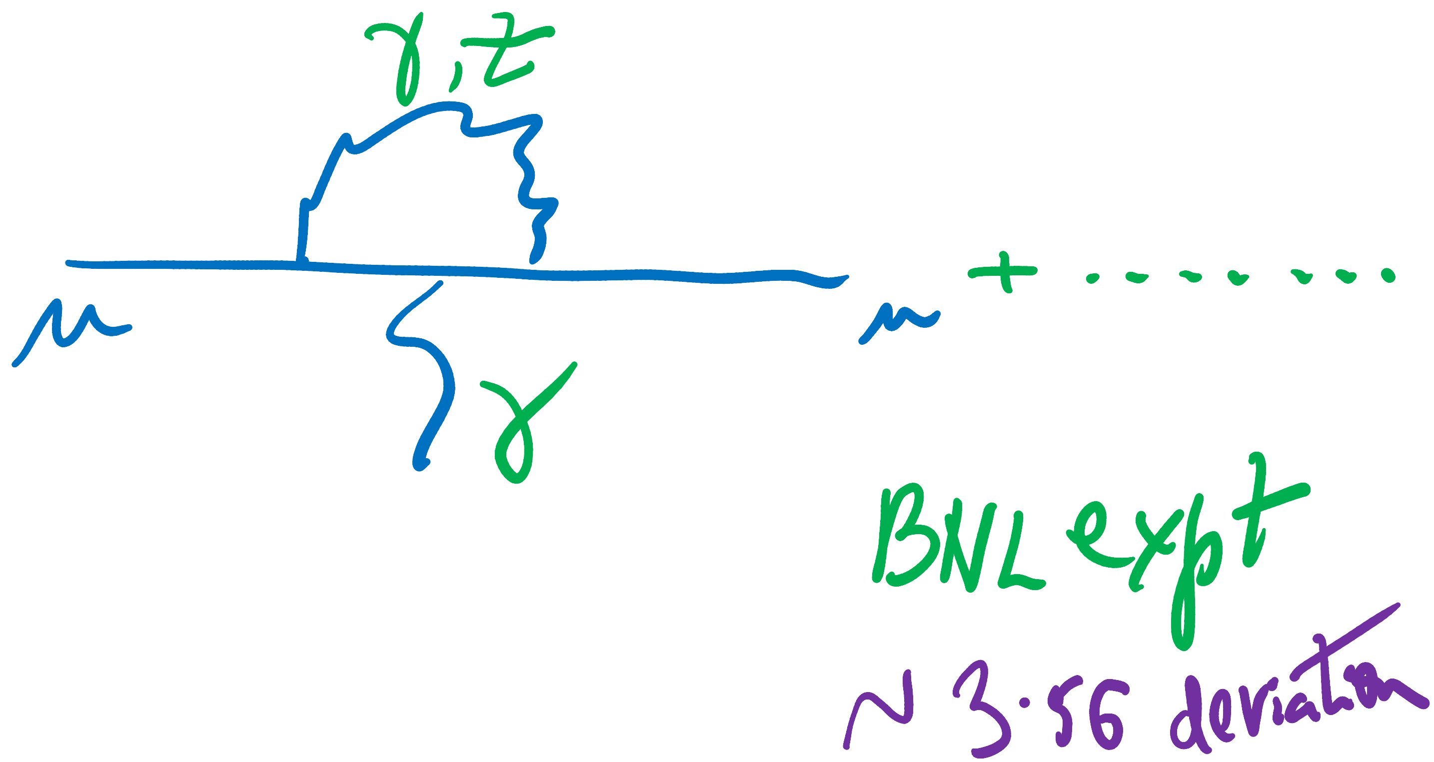




R_K: Central-q^2: 2.6σ from SM

R_{K^*}: Low-q^2: 2.1-2.3σ from SM

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



POSSIBLE CONNECTION TO G-2

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

PRD 2015

Table 1

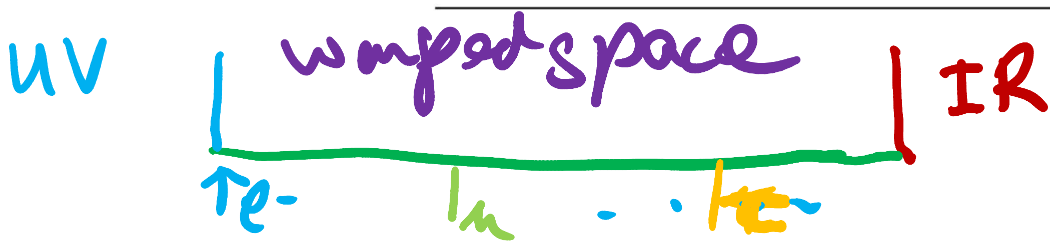
Constraints on lepton-flavor violating and conserving processes. For the last four observables, the experimental null results are given in terms of a dimension-6 operator, suppressed by two orders of Λ, which can be interpreted as the nominal scale of new physics.

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]

1st gen not sensitive to NP + $(g-2)_\mu$

Kile, Kobach + AS PRD 2015 ⇓ Speculation

Maybe 1st gen. is fundamental & its protection from NP

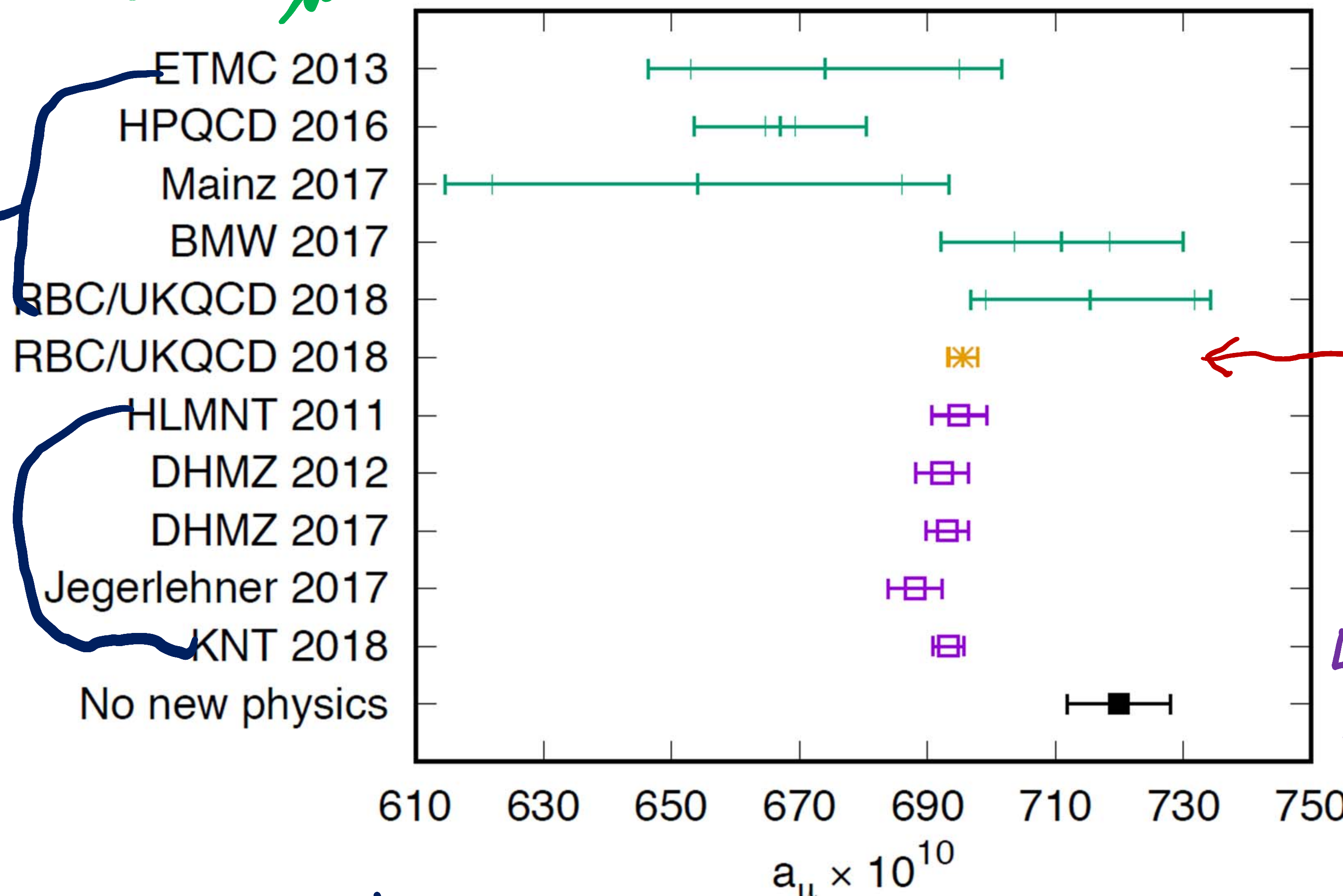


QUICK UPDATE ON G-2

$(g-2)_\mu$ 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

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 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]

IV: ε′ / ε: Direct CPV

EXPERIMENTAL ROUTE

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

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

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

$$\epsilon' \simeq \frac{1}{3}\left[\eta_{+-} - \eta_{00}\right] \Rightarrow O(10^{-3}) \cdot O(10^{-3}) \Rightarrow 10^{-6}$$

$$\epsilon = \frac{1}{3}\left[2\eta_{+-} + \eta_{00}\right]$$

After decades of exptal effort @ CERN and FNAL ~ 2000

$$\mathrm{Re}\, \epsilon'/\epsilon = 16.6 \pm 2.3 \times 10^{-4}$$

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 $K \to 2\pi$ can be written in terms of the unphysical amplitudes $K \to \pi$ 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

PHYSICAL REVIEW D VOLUME 56, NUMBER 1 1 JULY 1997

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

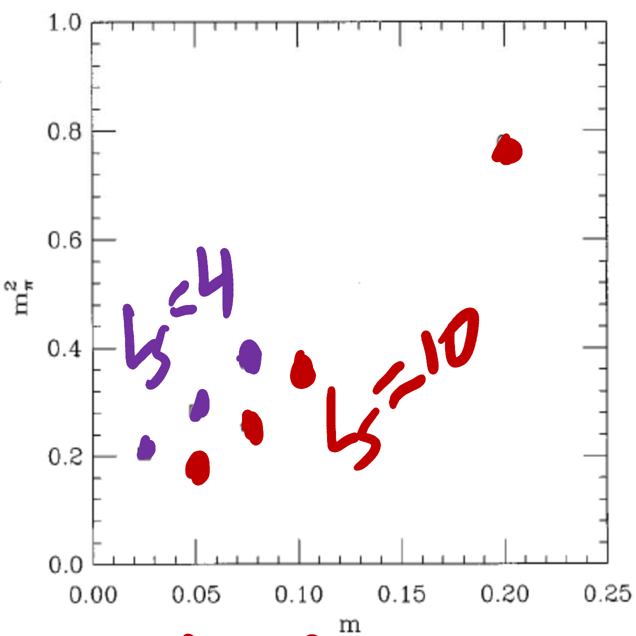
QCD with domain wall quarks

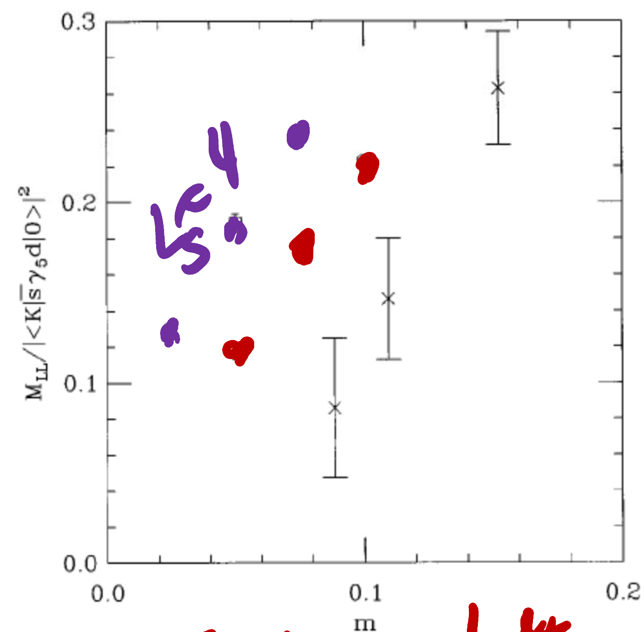
T. Blum* and A. Soni†
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973

(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-$\overline{K_0}$ 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]





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

MAJOR BREAKTHROUGH FOR K→ππ Lattice Calculations

$K \to 2\pi$ 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

T. Blum,[1] P. Chen,[2] N. Christ,[2] C. Cristian,[2] C. Dawson,[3] G. Fleming,[2,*] R. Mawhinney,[2] S. Ohta,[4,1] G. Siegert,[2] A. Soni,[3] P. Vranas,[5] M. Wingate,[1,*] L. Wu,[2] and Y. Zhestkov[2]

[1]*RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973, USA*

[2]*Physics Department, Columbia University, New York, New York 10027, USA*

[3]*Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA*

[4]*Institute for Particle and Nuclear Studies, KEK, Tsukuba, Ibaraki, 305-0801, Japan*

[5]*IBM Research, Yorktown Heights, New York 10598, USA*

(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 $a^{-1} \sim 2$ 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 $(-4.0 \pm 2.3) \times 10^{-4}$ (statistical error only) compared to the current experimental average of $(17.2 \pm 1.8) \times 10^{-4}$. 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 $B_{K,\overline{\rm MS}}(2\text{ GeV}) = 0.532(11)$. 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.

$K \to 2\pi$ & ϵ'/ϵ, "Flagship Project" Now ~20 yrs!

1st Large Scale Simulation with DWQ

(ALSO CP-PACS PRD'03

RBC Collaboration

QCDSP ~98 → ~'05 1TF

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

* Allows to bypass Maini-Testa theorem

DIRECT $K \to \pi\pi$ [NO ChPT]

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,

→ EWP

→ QCDP

USING 216 independent measurements

RBC-UKQCD PRL'15 EDITOR'S CHOICE

LARGE CANCELLATION!! (80-85%)

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

$$= 1.38(5.15)(4.43)\times 10^{-4}, \quad \text{(this work)}$$
$$16.6(2.3)\times 10^{-4} \quad \text{(experiment)}$$

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

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

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

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

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

ε': 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**

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]

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***

ADS'

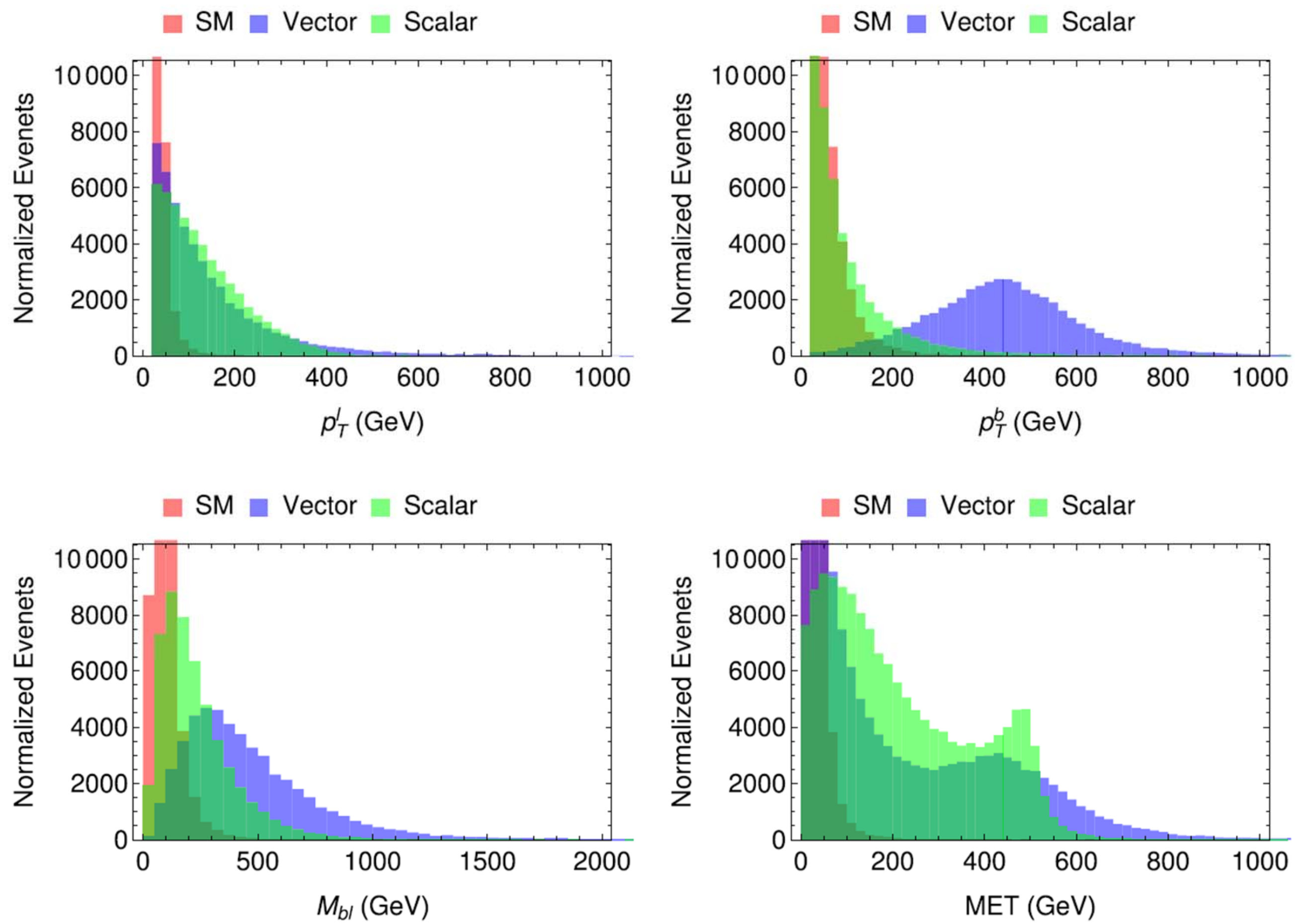


FIG. 1. Normalized kinematic distributions for the $pp \to b\tau\nu \to b\ell + \not{E}_T$ signal and background.

EXPECT DISTINCTIVE NP CONTRIBUTIONS IN COLLIDERS

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

See Altmannshofer, Dev +AS, arXiv:1704.06659 + WIP

- 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.

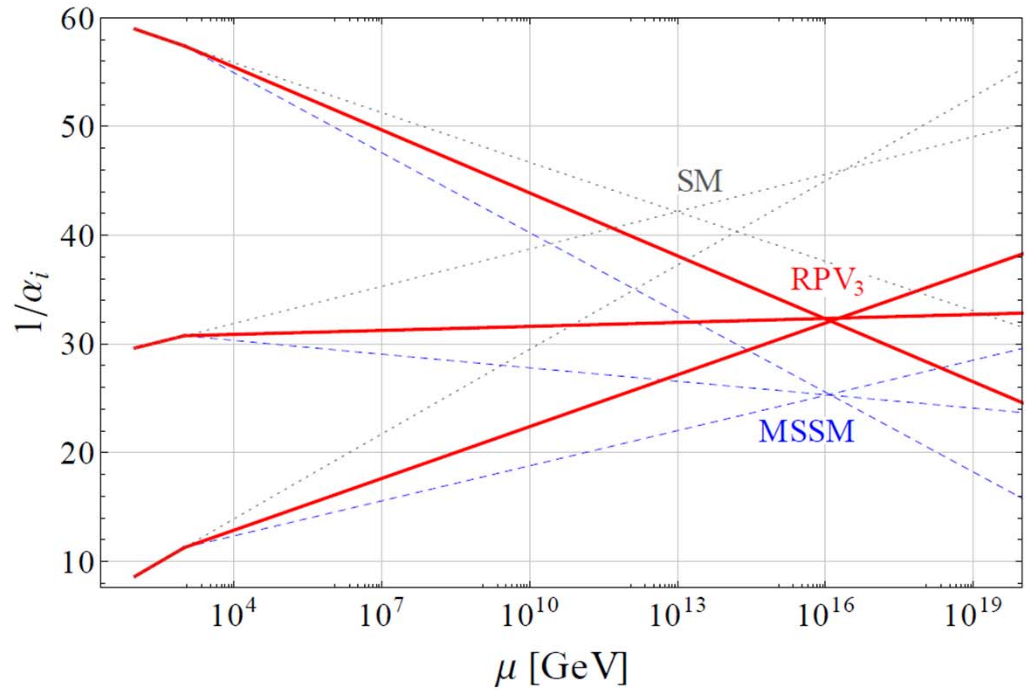


FIG. 2. RG evolution of the gauge couplings in the SM, MSSM and with partial supersymmetrization.

Unification scale ~ stays same, only value of couplings shifts

For pheno relevant terms:

ADS' PRD 2017

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

} RPV$_3$ interaction

Dim 6

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

For $R_{D(*)}$

NOTE: ITS SM-like!

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

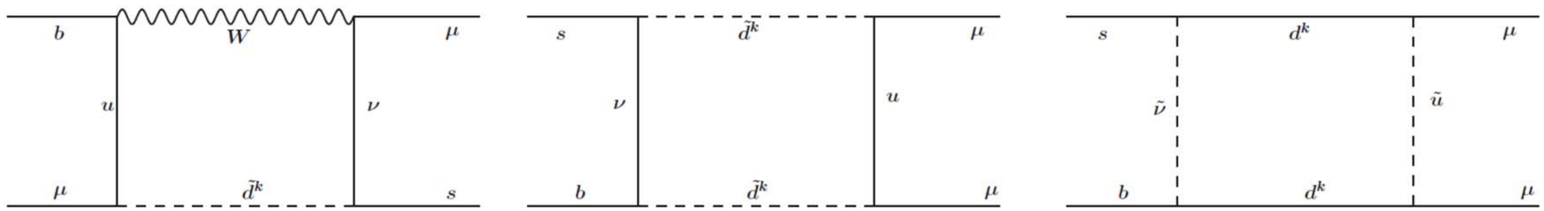


FIG. 1: Representative diagrams for $b \to s\mu^+\mu^-$ transition in R-parity violating interactions.

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

MULTITUDE OF CONSTRAINTS ON OUR RPV3 [AND ALSO OTHER PROPOSED IDEAS]

As a specific illustration

Constraints imposed

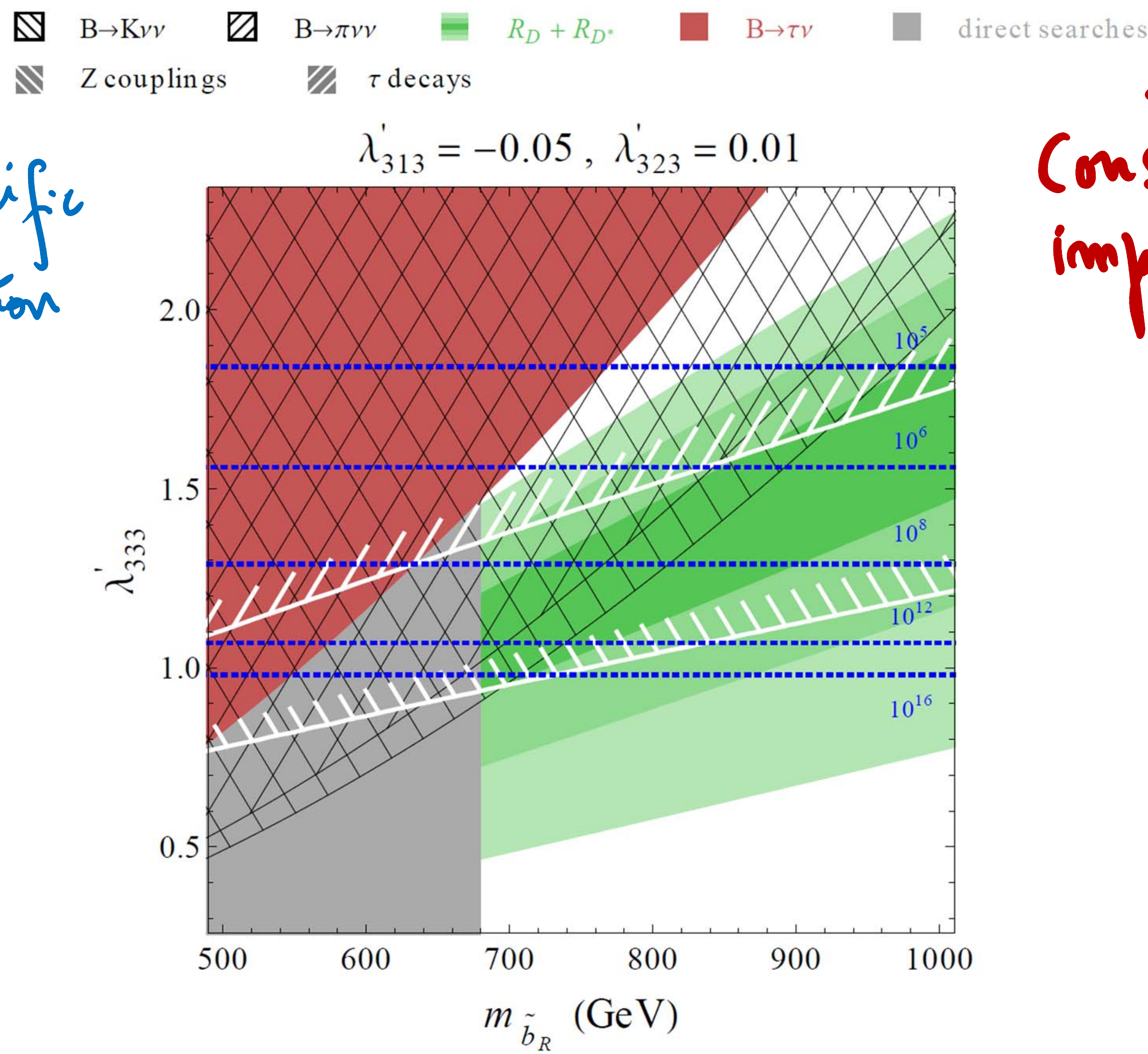
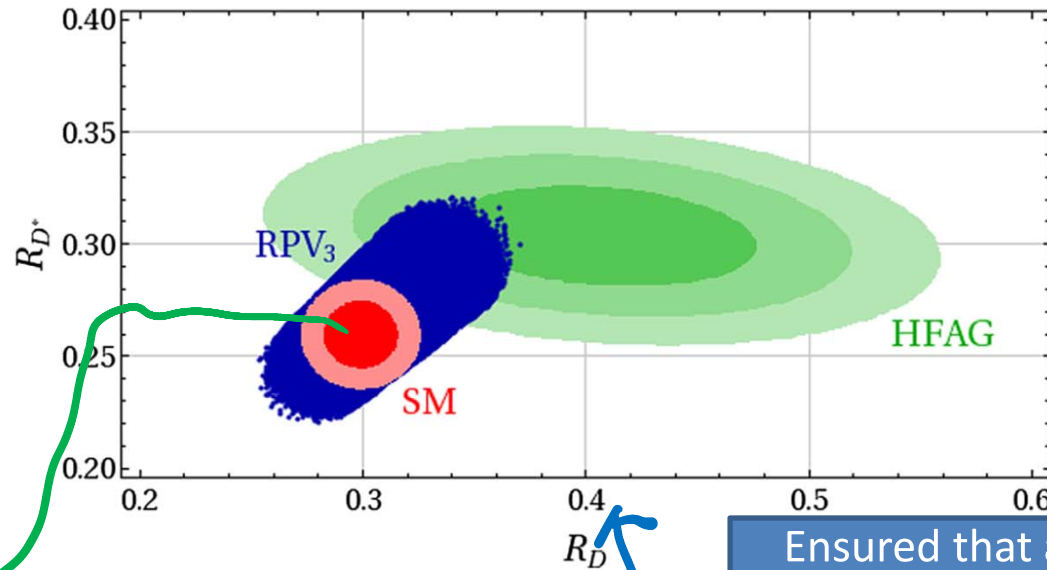


FIG. 3. RPV parameter space satisfying the $R_{D(*)}$ anomaly and other relevant constraints.

ALTMANNSHOFER, BHUPAL DEV, and SONI PRD2017

RPV3 allows
RD=(.254-.371)
RD*=(.220-.320)



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

More Realistic SM Blob

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 $(R_D^{SM}, R_{D^*}^{SM}) = (0.299 \pm 0.011, 0.260 \pm 0.010)$.

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

Summary and Outlook..[p1 of 2]

- **Hints of LUV [from 3 B experiments] in sl B decays claimed to be around 4 sigma and also of FCNC ~ 2.5 sigma in B=K(*) ll are interesting but not yet compelling.**
- **For RD(*) an important experimental concern is that systematics in tau =>l nu nu may not be in good control; this concern is accentuated as both Belle and LHCb measurements of RD* with tau => hadron + nu appear consistent with SM within ~ 1 sigma.**
- **From lattice B=>D* semi lep form factors and RD* are urgently needed; likely ~6 months.**
- **For RK(*) [theory is irrelevant] need confirmation from another expt…Even for Belle II this will take time because of the small Br ~O(10^-6). LHCb needs to study R_{ϕ} through Bs=>ϕ μμ AND Bs=>phi e e; also via B-baryons**
- **More data from LHCb from Run 2 < 1 year should help and further ~2 years down Belle II should start to help more….**
- **Belle II with X50 Belle lumi and LHCb upgrade have a lot of potential for searches related to these & many others and likely to be a game changer in search of new phenomena.**
- **It may well be that BNL's observed g-2 signals of possible NP were just a precursor to these observations of LUV 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**
- **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 the next few years**

XTRAS

Bernlochner, Ligeti, Papucci and Robinson, 1703.05330

Scenario	$R(D)$	$R(D^*)$	Correlation
$\mathrm{L}_{w=1}$	0.292 ± 0.005	0.255 ± 0.005	41%
$\mathrm{L}_{w=1}$+SR	0.291 ± 0.005	0.255 ± 0.003	57%
NoL	0.273 ± 0.016	0.250 ± 0.006	49%
NoL+SR	0.295 ± 0.007	0.255 ± 0.004	43%
$\mathrm{L}_{w\geq1}$	0.298 ± 0.003	0.261 ± 0.004	19%
$\mathrm{L}_{w\geq1}$+SR	$\mathbf{0.299 \pm 0.003}$	$\mathbf{0.257 \pm 0.003}$	**44%**
th:$\mathrm{L}_{w\geq1}$+SR	0.306 ± 0.005	0.256 ± 0.004	33%
Data [9]	0.403 ± 0.047	0.310 ± 0.017	−23%
Refs. [48, 52, 54]	0.300 ± 0.008	—	—
Ref. [53]	0.299 ± 0.003	—	—
Ref. [34]	—	0.252 ± 0.003	—

TABLE IV. The $R(D)$ and $R(D^*)$ predictions for our fit scenarios, the world average of the data, and other theory predictions. The fit scenarios are described in the text and in Table I. The bold numbers are our most precise predictions.

SM Prediction

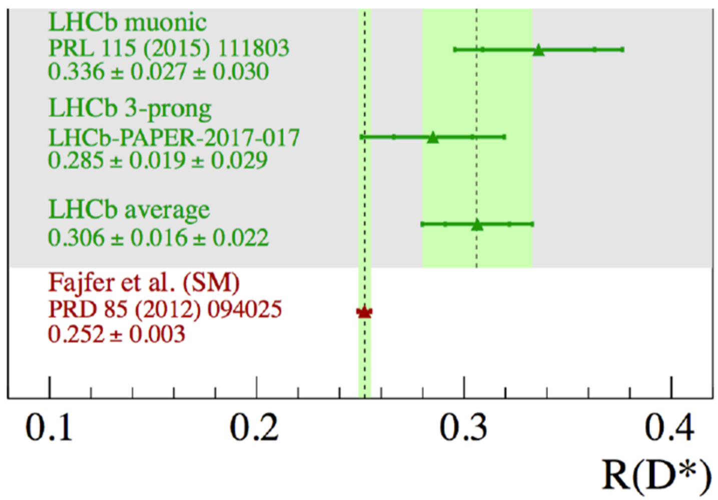
we took RD* = 0.257 ± .005

Fajfer, Kamenik, Nisandzic, PRD'12

Very timely & useful phenomenological study by BLPR 2017

Conclusions

- We have measured the ratio $K_{had}(D^*)=BR(B^0\to \mathbf{D^{*-}\tau\nu})/BR(B^0\to D^{*-}3\pi)$ using the $3\pi(\pi^0)$ hadronic decay of the τ lepton.
- The result regarding R(D*) is compatible with all other measurements and with the SM, having the smallest statistical error.
- This analysis was made possible due to the unique LHCb capabilities for separating secondary and tertiary vertices with excellent resolution.



06/06/17 A. Romero Vidal 45

LHCb Seminar CERN 6/6/'17

World average

- Using BR($B^0 \to D^* \mu\nu$) = (4.93 ± 0.11)% [PDG-2016] we measure:

  R(D*) = 0.285 ± 0.019(stat) ± 0.025(syst) ± 0.014(ext)

- In combination with the muonic LHCb measurement:

  R(D*) = 0.336 ± 0.027 ± 0.030,

  the LHCb average is:

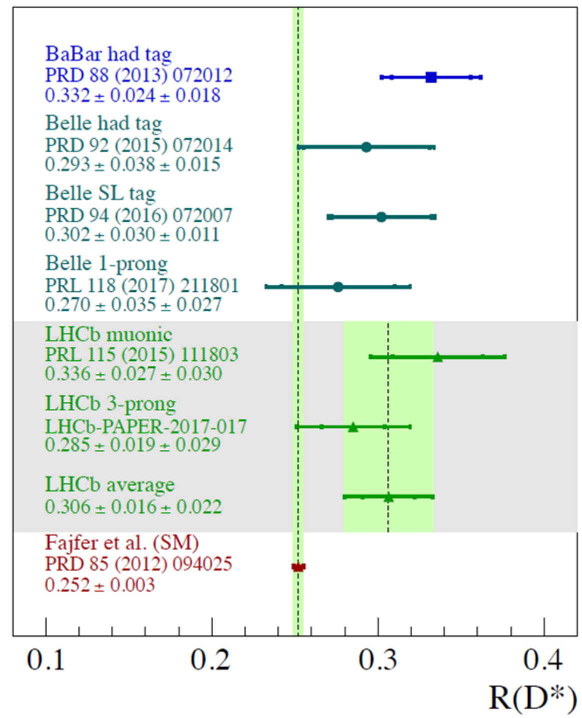
  - $R_{LHCb}(D^*)$ = 0.306 ± 0.016 ± 0.022
  - 2.1σ above the SM.

- Naïve new WA:
  - R(D*) = 0.305 ± 0.015
  - 3.4σ above the SM.

- Naïve R(D)/R(D*) combination at 4.1σ from SM.

Total of 6

LHCb-PAPER-2017-017



06/06/17 A. Romero Vidal 43

BABAR Phy Book '97

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

Model	*CP* Violation: B_d^0–$\overline{B}_d^0$ Mixing	*CP* Violation: Decay Ampl.	Rare Decays	D^0–$\overline{D}^0$ 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	$\sim$ SM/New Phases	Suppressed	$B \to X_s\gamma$, $B \to X_s\tau\tau$	Big Effect
2HDM	$\sim$ SM/Same Phase	Suppressed	$B \to X_s\gamma$	No Effect
Quark Singlets	Yes/New Phases	Yes	Saturates Limits	$Q = 2/3$
Fourth Generation	$\sim$ SM/New Phases	Yes	Saturates Limits	Big Effect
LRM – $V_L = V_R$	No Effect	No Effect	$B \to X_s\gamma$, $B \to X_s l^+ l^-$	No Effect
– $V_L \neq V_R$	Big/New Phases	Yes	$B \to X_s\gamma$, $B \to X_s l^+ l^-$	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.

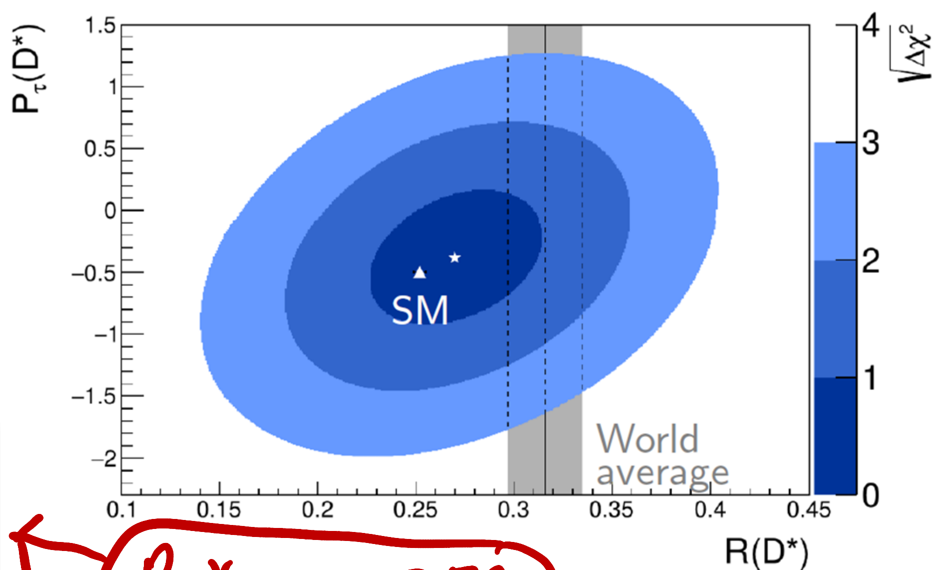
Results

BELLE@EPS July 2017

- $\mathcal{R}(D^*)$ can be calculated as before from extracted yields
- Polarisation from forward/backward asymmetry

$\tau \to had + \nu$

$$\frac{\epsilon_{norm}}{\epsilon_{sig}} = 0.97 \pm 0.02 \; (B^{\pm}, \tau \to \pi\nu)$$
$$= 1.21 \pm 0.03 \; (B^{0}, \tau \to \rho\nu)$$
$$= 3.42 \pm 0.07 \; (B^{\pm}, \tau \to \rho\nu)$$
$$= 3.83 \pm 0.12 \; (B^{0}, \tau \to \rho\nu)$$



Result

$$\mathcal{R}(D^*) = 0.270 \pm 0.035^{+0.028}_{-0.025}$$
$$P_\tau(D^*) = -0.38 \pm 0.51^{+0.21}_{-0.16}$$

$R_{D^*}SM \sim .258$

- Consistent with SM and previous measurements!
- Error can be reduced in Belle II

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.....**
- **Started with CBernard (Wilson F); for this physics Chiral symm on the lattice is a pre-requisite [off-shoot B-physics] => on to DWF (with T Blum)=> RBC with ChPT + quenched => huge quench pathlogies=full QCD is mandatory for this physics; full QCD + ChPT=> large chiral corrections => RBC-UKQCD direct K=> 2 π a la Lellouch- Luscher @ threshold=> @physical kinematics……**

Anomalies galore!

- RD(*)
- RK(*)
- ....
- g -2
- ....
- epsilon’: The meaning of life

216[PRL 2015] => ~720 now => ~1200

[2.1σ (2.9σ?) => ????] …..some months

few months

LATTICE is vital for all!

LFV , tree level sl BSM are natural in RPV
eps' and higgs stability are bonus
For Delta M_Bs NNLO EW corr may be appricaible?

- Semi-leptonic B-decays r claimed to indicate ~4.1 sigma deviation from SM
- ATLAS, CMS ought to vigorously search for BSM in : b τ ν and in t τ
- Expt BG from higher D** etc resonances a concern and should b measured; tau detection via hadronic modes should be given very high priority as its much

  less susceptible to D** contaminations
- More independent theory effort on and off lattice for determination of SM value for RD* are urgently needed
- More info from expts on R(D), R(D*), R(π), R(ρ), analogous Bs, B-baryon, B=>τ ν are all urgently needed
- Also RD from LHCb as well as Belle would be helpful [since in this case theory is very solid]; BELLE-II and LHCb-upgrades would of course help a lot
- RPV-SUSY effectively involving 3^{rd} gen is economical, minimal and natural and may be an interesting origin of the anomaly [if it persists!]
- => classic large missing energy hunt for SUSY not relevant for that scenario
- => many RPV signatures tend to become rather challenging
- **=> our version gives new interesting avenues in b τ ν; t τ .....final states**
- **More studies in progress (inc e,g. RK(*), Bs=>μ μ and much more): see ADS' II**

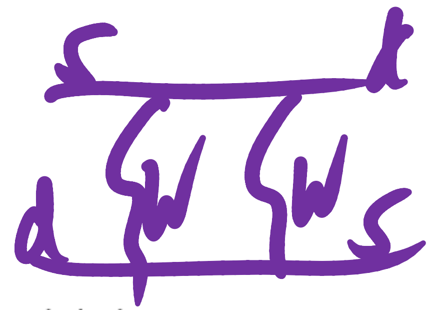
28 *39. Statistics*

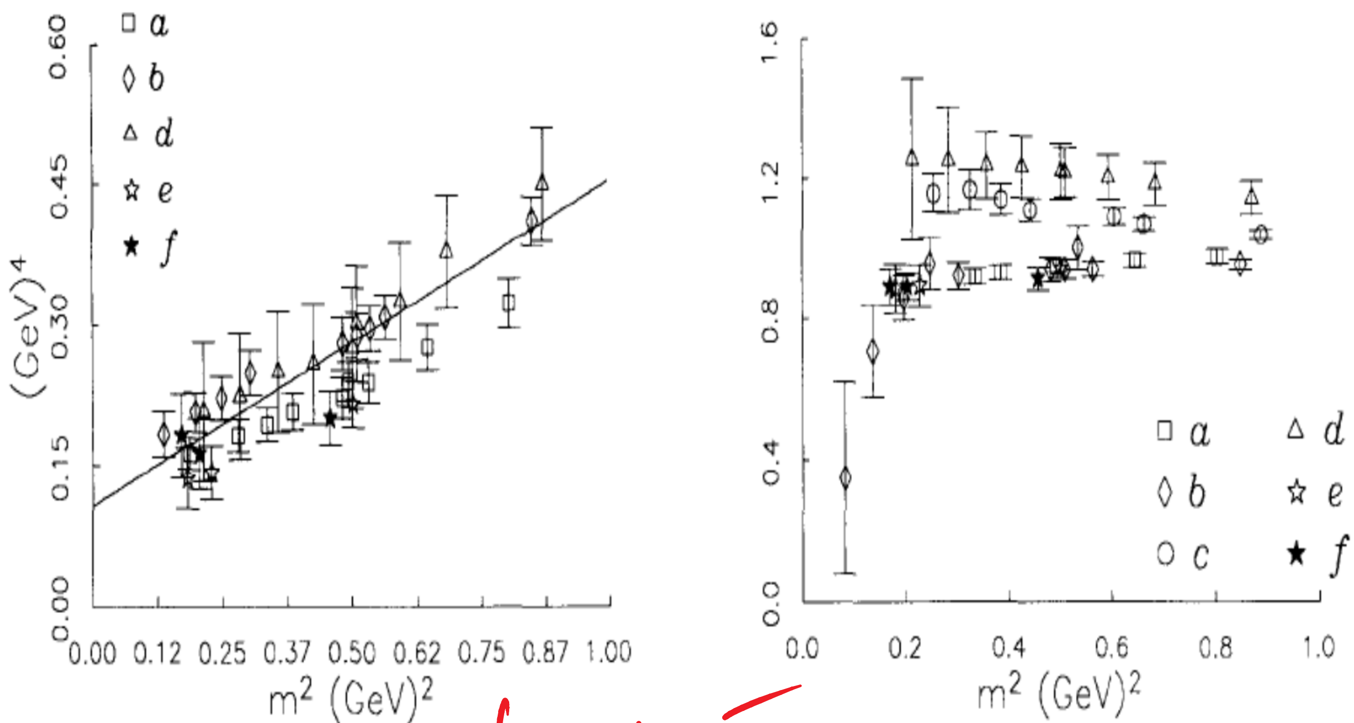
PDG 2016

Table 39.1: Area of the tails α outside $\pm\delta$ from the mean of a Gaus distribution.

α	δ	α	δ
0.3173	1σ	0.2	1.28σ
4.55×10^{-2}	2σ	0.1	1.64σ
2.7×10^{-3}	3σ	0.05	1.96σ
6.3×10^{-5}	4σ	0.01	2.58σ
5.7×10^{-7}	5σ	0.001	3.29σ
2.0×10^{-9}	6σ	10^{-4}	3.89σ

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





χS violation by K-K̄ ⇒ FINE TUNING PROBLEM

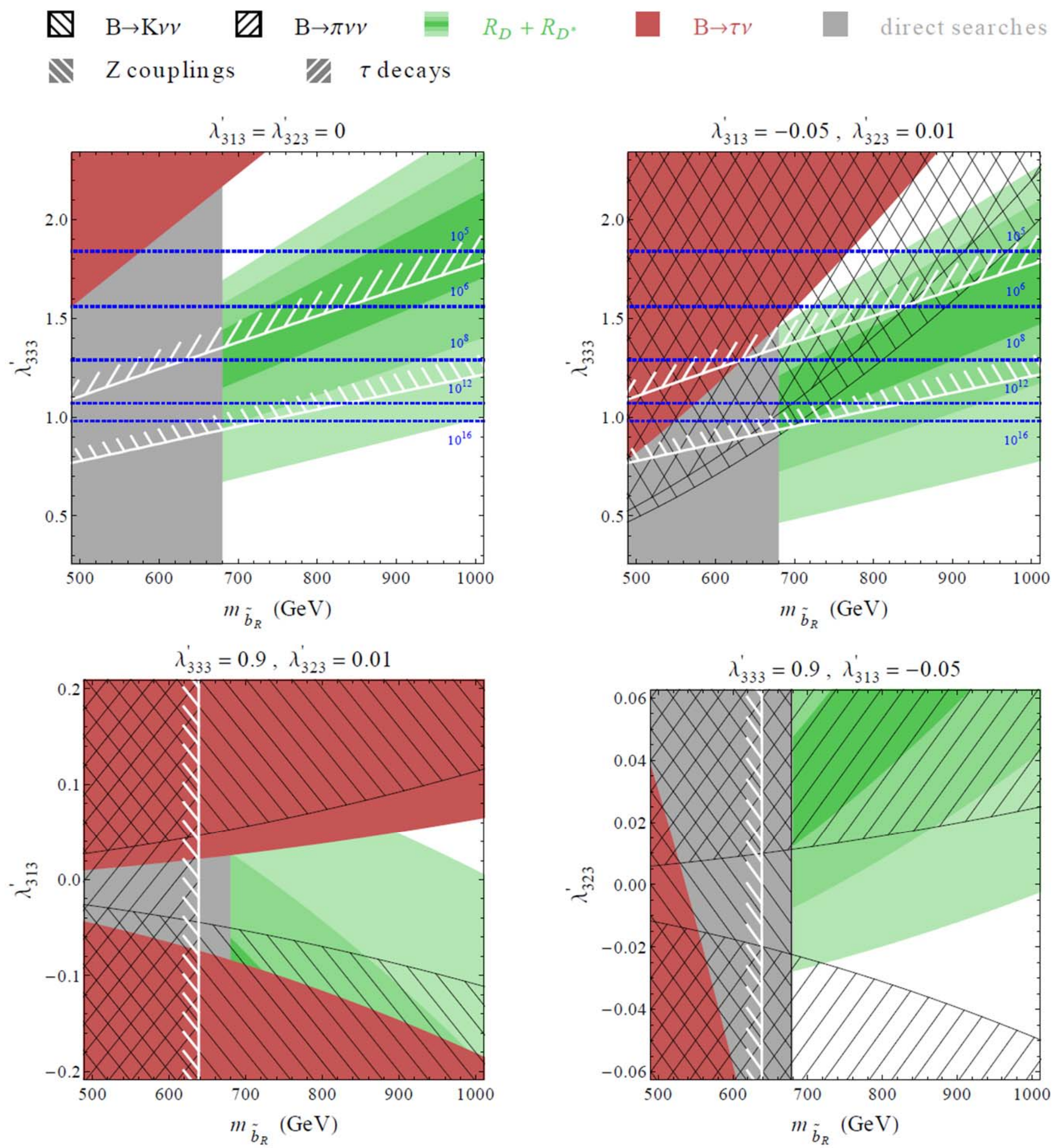


FIG. 3. RPV parameter space satisfying the $R_{D^{(*)}}$ anomaly and other relevant constraints.

Concern on Experiments

- Leptonic decays: $\tau \Rightarrow \mu\nu\nu$…total 3 ν's in event
- Higher D** etc resonances….use of theo models for subtraction of these backgrounds is fraught with danger…..Backgrounds should be measured experimentally for reliable estimate of errors
- Bearing that in mind, it is striking that LHCb new result june 2017: $B \Rightarrow D^* \tau \nu$; $\tau \Rightarrow 3\pi+\nu$ is

consistent with the SM at ~1-σ=> heightens anxiety about D**….contaminations in $\tau \Rightarrow \mu\nu\nu$

- Furthermore, new Belle result with hadronic tau decay also consistent with SM well within 1 sigma!
- Claimed ~"4 sigma" probably not that solid

Near future outlook

- LHCb has so far only used Run 1 data
- Plenty more data from Run 2 available but needs to be analyzed…may be will get bit of news on this from EWM in < 1 month
- Lattice calculations for slff for B=>D* in <6 months
- Lattice g-2 improved results will continually come perhaps once/[6 months] for next several years….global effort including a lot from our RBC-UKQCD
- Improved lattice results for eps’ from our RBC-UKQCD in a few (O(6))months

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

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

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

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

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

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

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

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

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

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

Summary of Theo Calculations

R(D)=0.300(8) HPQCD (2015)

4% ← R(D)=0.299(11) FNAL/MILC (2015) * ← my Take 4 Now

1% !! 0.299 ± 0.003 Bernlochner et al 2017

1% !! $\mathbf{0.299 \pm 0.003}$ D. Bigi et al 2017

1% !! R(D*)=0.252(3) S. Fajfer et al. (2012)

1% $\mathbf{0.257 \pm 0.003}$ Bernlochner et al

4% $$R(D^*) = 0.258^{+9}_{-8}$$ Bigi et al EPS July

$R_{D^*} \sim .258 \pm .020$

FROM THEORY

$K \to 2\pi$

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

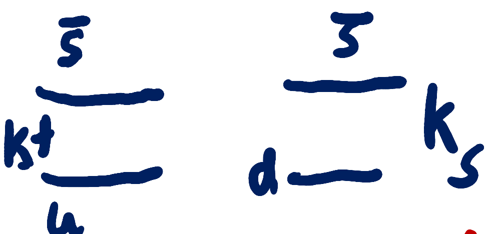
→ I=2 amp

→ I=0 amp

$\omega \approx \frac{\mathrm{Re}A_2}{\mathrm{Re}A_0}$

$\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2} \sim 25$ $\Delta I = 1/2$ 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

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

CERN+FNAL ~2004

Lattice computation of the decay constants of B and D mesons

Claude W. Bernard
Department of Physics, Washington University, St. Louis, Missouri 63130

James N. Labrenz
Department of Physics FM-15, University of Washington, Seattle, Washington 98195

Amarjit Soni
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973
(Received 1 July 1993)

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

Claude W. Bernard*
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106

Aida X. El-Khadra
Theory Group, Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, Illinois 60510

Amarjit Soni
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
and Department of Physics, Brookhaven National Laboratory, Upton, New York 11973†
(Received 21 December 1990)

PHYSICAL REVIEW D VOLUME 45, NUMBER 3 1 FEBRUARY 1992

Lattice study of semileptonic decays of charm mesons into vector mesons

Claude W. Bernard
Department of Physics, Washington University, St. Louis, Missouri 63130

Aida X. El-Khadra
Theory Group, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510

Amarjit Soni
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973
(Received 30 September 1991)

We present our lattice calculation of the semileptonic form factors for the decays $D \to K^*$, $D_s \to \phi$, and $D \to \rho$ using Wilson fermions on a $24^3 \times 39$ lattice at $\beta = 6.0$ with 8 quenched configurations. For $D \to K^*$, we find for the ratio of axial form factors $A_2(0)/A_1(0) = 0.70 \pm 0.16^{+0.20}_{-0.15}$. 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

C. Bernard
Department of Physics, Washington University, St. Louis, Missouri 63130

T. Blum and A. Soni
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973
(Received 28 February 1998; published 5 May 1998)

Full QCD But ChPT a la BDSPW

(Sam)Shu Li, PhD thesis, Columbia '08

Conclusion

Quantity	This analysis	Quenched	Experiment
$\mathrm{Re}A_0$ (GeV)	$4.5(11)(53)\times10^{-7}$	$2.96(17)\times10^{-7}$	3.33×10^{-7}
$\mathrm{Re}A_2$ (GeV)	$8.57(99)(300)\times10^{-9}$	$1.172(53)\times10^{-8}$	1.50×10^{-8}
$\mathrm{Im}A_0$ (GeV)	$-6.5(18)(77)\times10^{-11}$	$-2.35(40)\times10^{-11}$	
$\mathrm{Im}A_2$ (GeV)	$-7.9(16)(39)\times10^{-13}$	$-1.264(72)\times10^{-12}$	
$1/\omega$	50(13)(62)	25.3(1.8)	22.2
$\mathrm{Re}(\epsilon'/\epsilon)$	$7.6(68)(256)\times10^{-4}$	$-4.0(2.3)\times10^{-4}$	1.65×10^{-3}

- ChPT approach to $K\rightarrow\pi\pi$ faces severe difficulties.
- RBC/UKQCD studying physical $\pi\pi$ final states.
- DWF on coarse lattices and large volumes: $4\rightarrow5$ fm?
- Vranas auxiliary determinant (Renfrew talk on Wed.)

[m_M too large for ChPT.... HINDSIGHT]

LARGE SYSTEMATIC errors DUE ChPT

Lattice

N. Christ @LAT08

RBC Collaboration

Since ~ '98 ←

- 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 → PKU
  - Norman Christ
  - Luchang Jin
  - Robert Mawhinney
  - Greg McGlynn
  - David Murphy
  - **Daiqian Zhang**
- Connecticut
  - **Tom Blum**

FOUNDING Members of RBC Collab: Blum, Christ, Mawhinney + AS

UKQCD Collaboration

Since ~'07

- 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

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

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

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; for 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

$$\cos\left(\delta_2 - \delta_0 + \pi/2 - \phi_\varepsilon\right)$$

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

$\Rightarrow 0.981$

phase diff ~ 26 BUT ε' totally insensitive!!

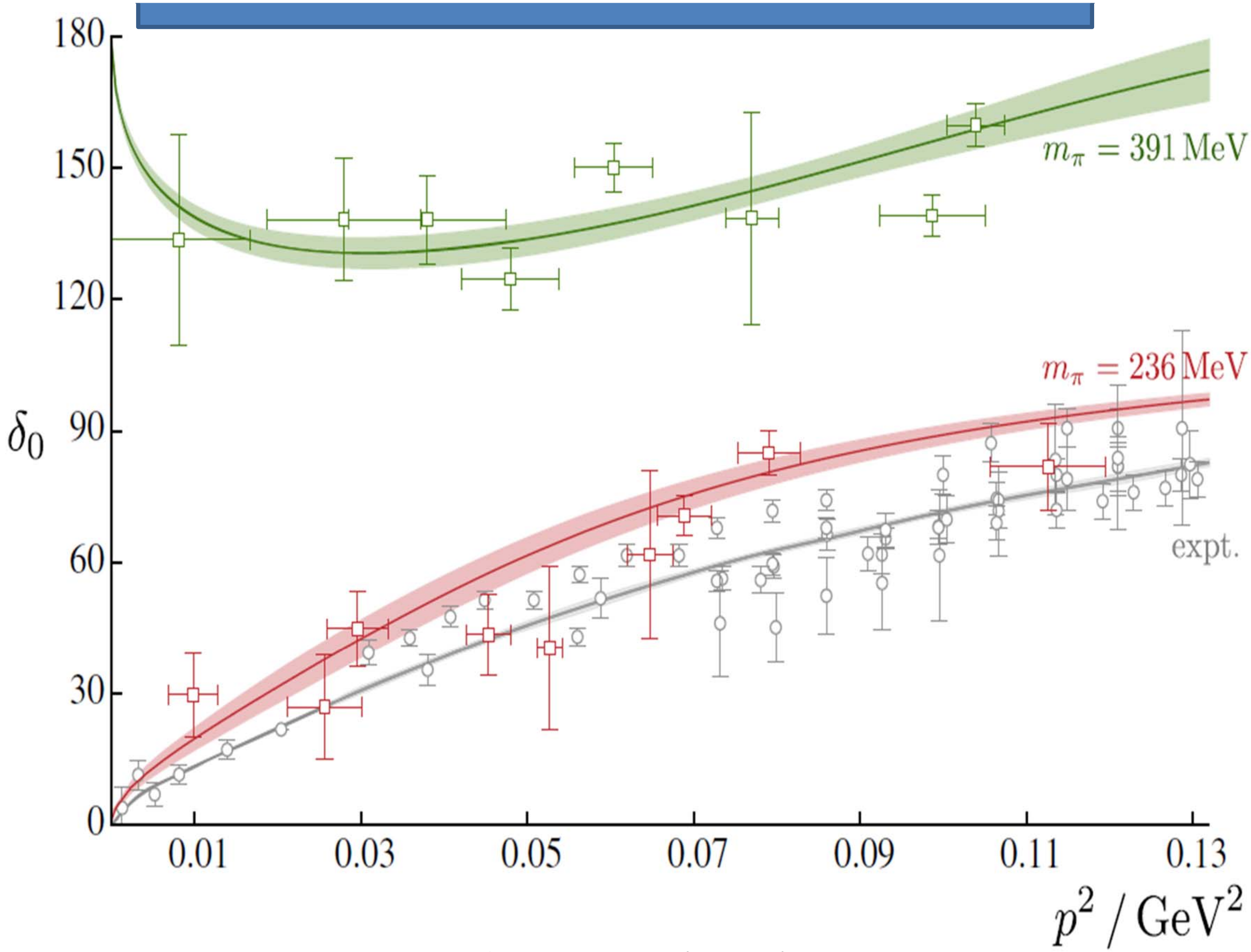
Diff ~ 2% on ε'

PRL 118, 022002 (2017) PHYSICAL REVIEW LETTERS week ending 13 JANUARY 2017

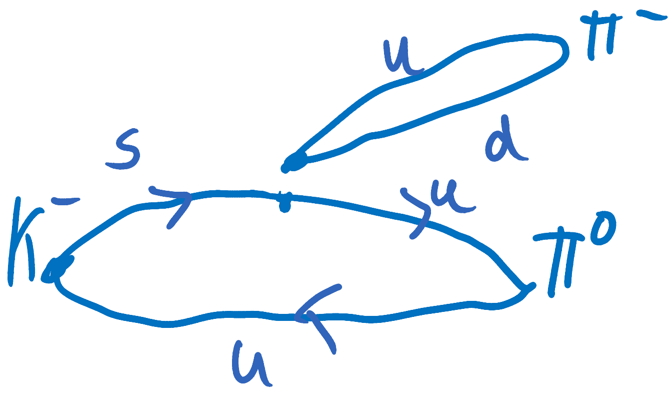
Isoscalar $\pi\pi$ Scattering and the σ Meson Resonance from QCD

Raul A. Briceño,[1,*] Jozef J. Dudek,[1,2,†] Robert G. Edwards,[1,‡] and David J. Wilson[3,§]
(for the Hadron Spectrum Collaboration)

PRL'17



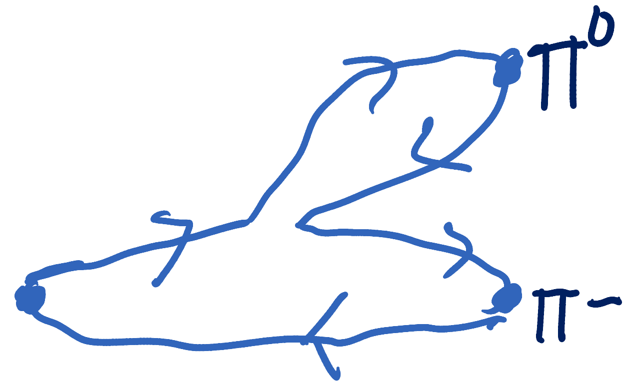
Dissecting (the much easier) ΔI=3/2 [I=2 ππ] Amp on the lattice: 2 contributing topologies only



Tr X Tr

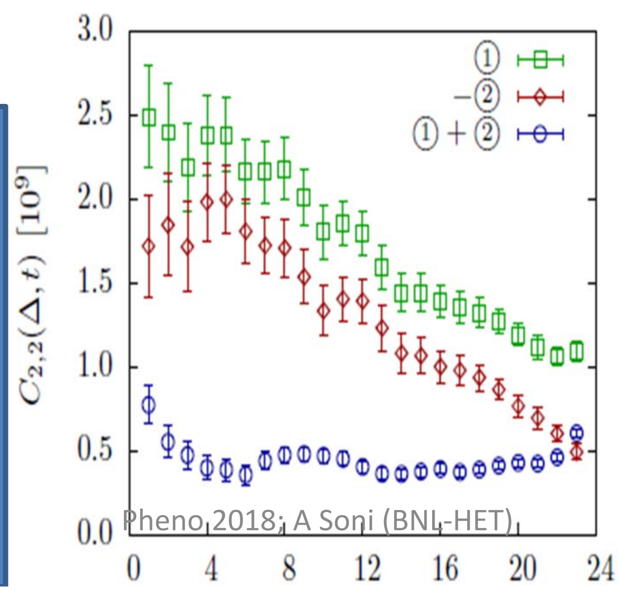
(N²)

+

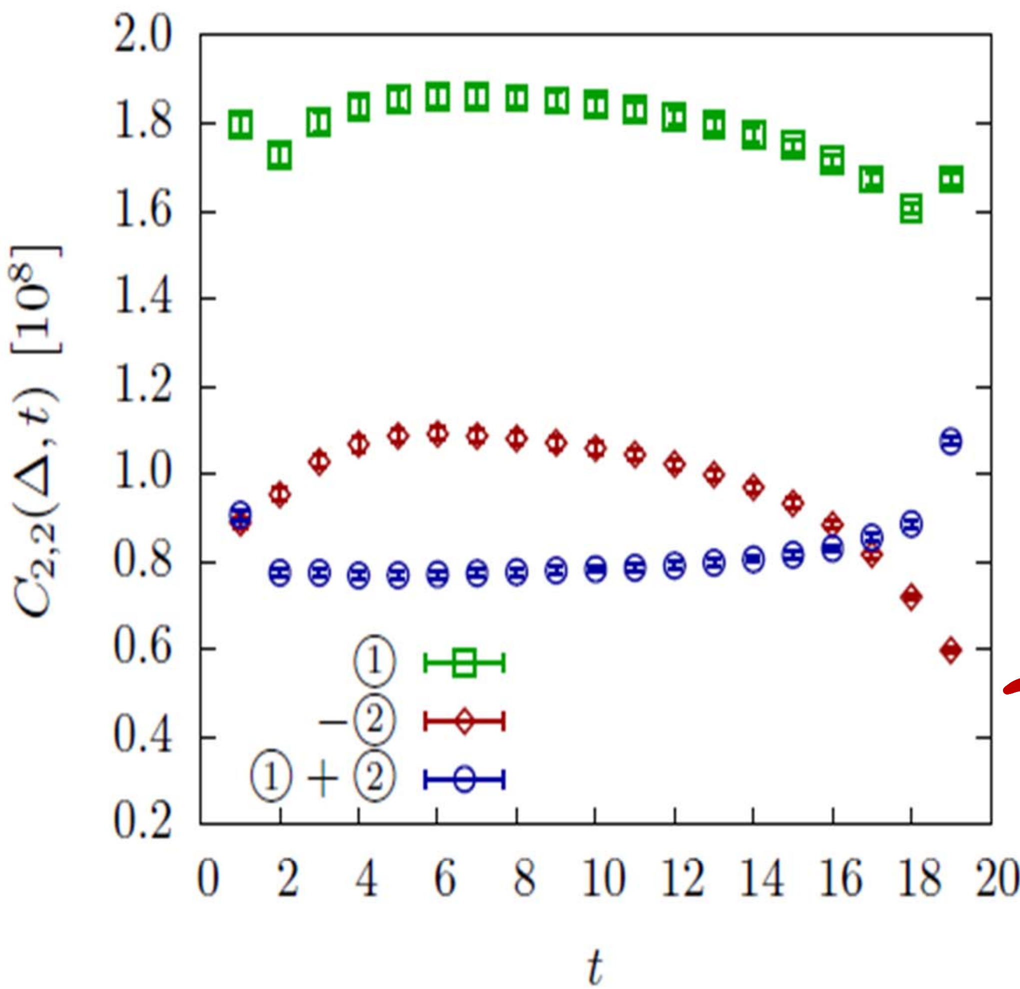


Tr (N)

Simplest basic step is Significantly different from phenomenological Expectations!



DRAMATIC CANCELLATION! ($m_\pi \sim 140$ MeV)



For heavier π,
$m_\pi \sim 330$ MeV
less cancellation
bet. N^2 & N
Large N begins
to improve!

FIG. 3: Contractions ①, -② and ① + ② as functions of t from the simulation at threshold with $m_\pi \simeq 330\,\mathrm{MeV}$ and $\Delta = 20$.

Mass depends of ReA2, A0

PRL 2013

	a^{-1} [GeV]	m_π [MeV]	m_K [MeV]	$\mathrm{Re}A_2$ [10^{-8} GeV]	$\mathrm{Re}A_0$ [10^{-8} GeV]	$\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2}$	notes
16^3 Iwasaki	1.73(3)	422(7)	878(15)	4.911(31)	45(10)	9.1(2.1)	threshold calculation
24^3 Iwasaki	1.73(3)	329(6)	662(11)	2.668(14)	32.1(4.6)	12.0(1.7)	threshold calculation
IDSDR	1.36(1)	142.9(1.1)	511.3(3.9)	1.38(5)(26)	-	-	physical kinematics
Experiment	–	135 - 140	494 - 498	1.479(4)	33.2(2)	22.45(6)	

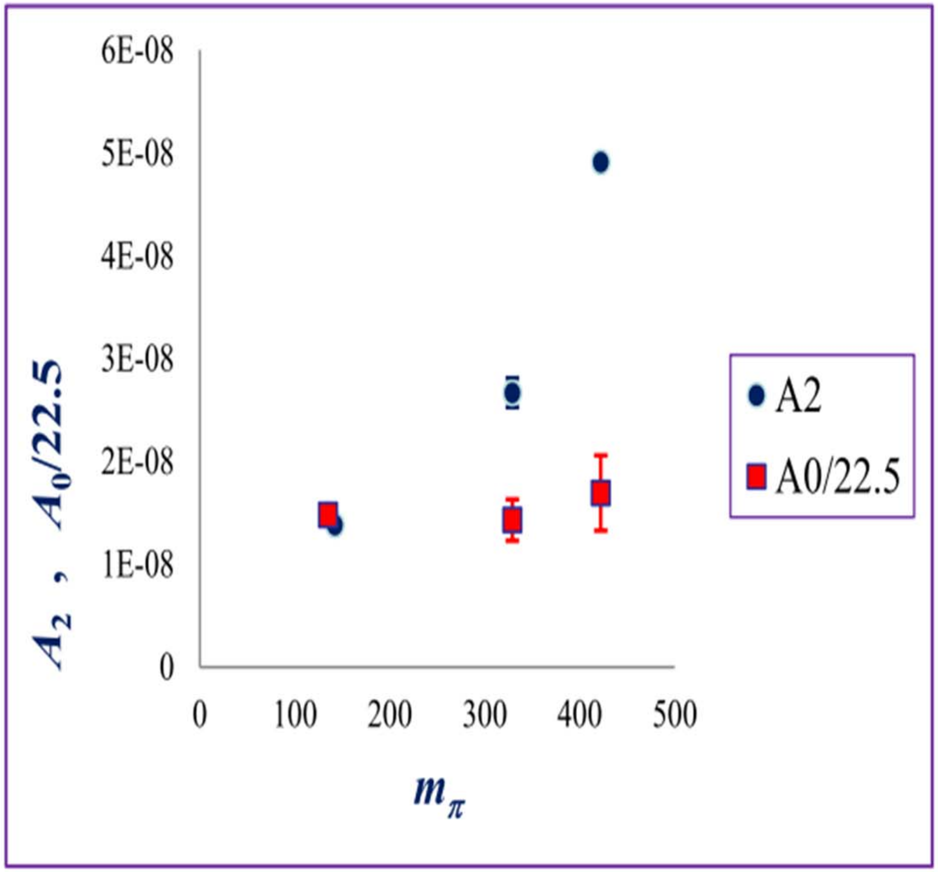
TABLE I: Summary of simulation parameters and results obtained on three DWF ensembles.

Due to the cancellation, 3/2 amplitude decreases significantly as the pion mass is lowered towards its physical value

Because of mass dependent cancellation ReA_2 changes with m_π dramatically.

For ReA_0 mass dependence is rather mild

Compare A_2 and $A_0/22.5$



NHCC KITP Aug '15

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

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

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

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

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

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

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

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

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

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

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

- EM+ isospin…
- Completely diff method(s)
- I) excited pipi state
- II) Revisit ChPT

Under extensive study

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

U Conn PhD Student Dan Hoying

CU PhD '16 Dan Murphy

ChPT works!! well for physical π, K masses @ NLO!

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

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]
- Uncorrelated fits (due to lack of stat) =>

Very good chance we'll be able to correlated fits

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

$$\left[\frac{\mathrm{Im}A_2}{\mathrm{Re}A_2} - \frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}\right]$$

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