Is the muon just a heavy electron?
11/08/19
Paul Mackenzie Symposium, FermiL

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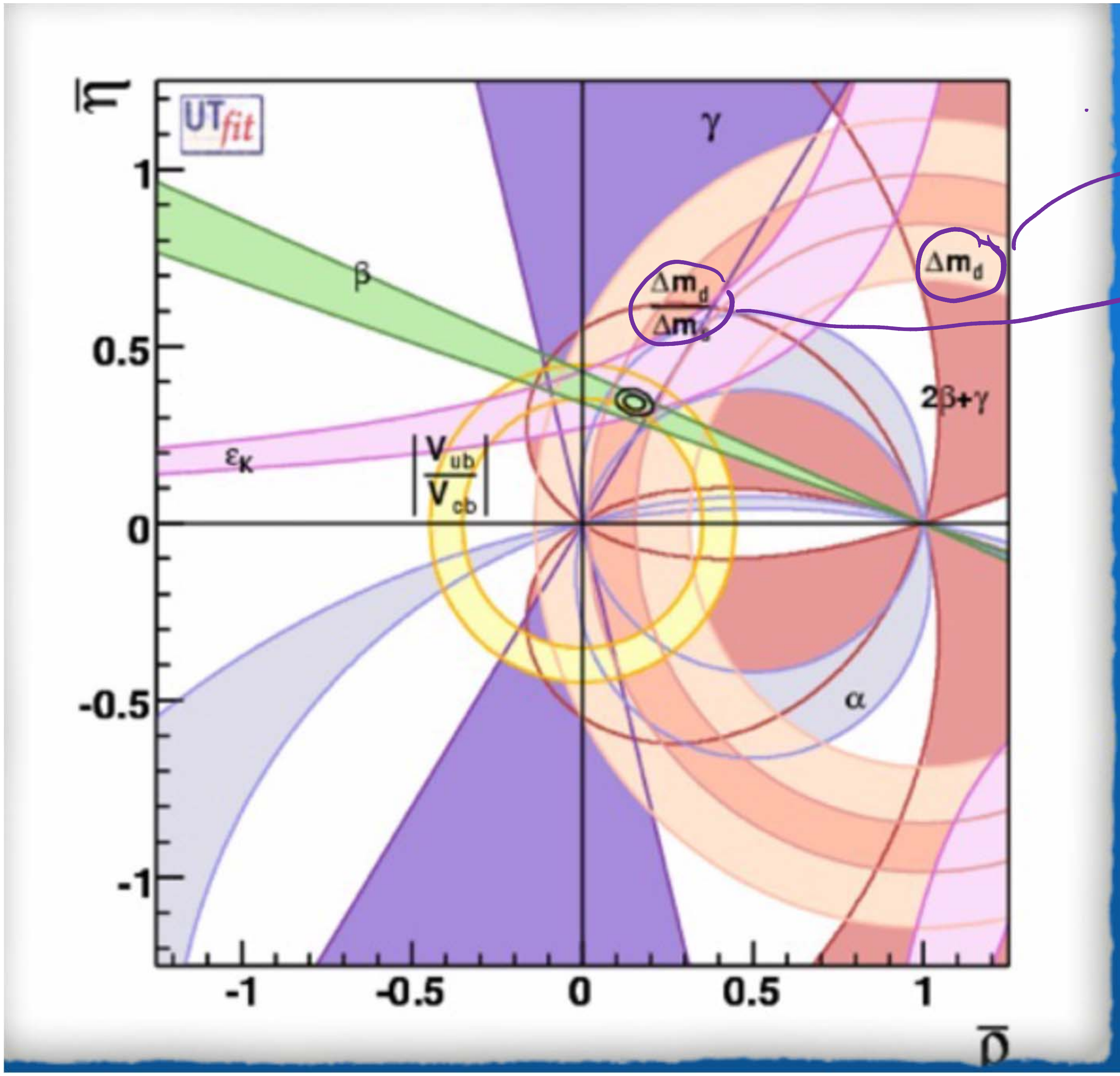
outline

- **Core my talk will be on LFUV with some extras ……….**

ODE TO LGT!



$\to f_B, B_B$

ξ SU(3) breaking

$B \to \ell \nu \pi$

$\to \ell \nu D$

MILESTONE in our understanding of CPV: SM-CKM

Courtesy: Tom Browder

Critical Role of the B factories in the verification of the KM hypothesis was recognized and cited by the Nobel Foundation

A single irreducible phase in the weak interaction matrix accounts for most of the CPV observed in kaons and B's.

CP violating effects in the B sector are O(1) rather than O(10^{-3}) as in the kaon system.

Seminal paper providing basis for dealing with HQs on the Lattice

PHYSICAL REVIEW D VOLUME 55, NUMBER 7 1 APRIL 1997

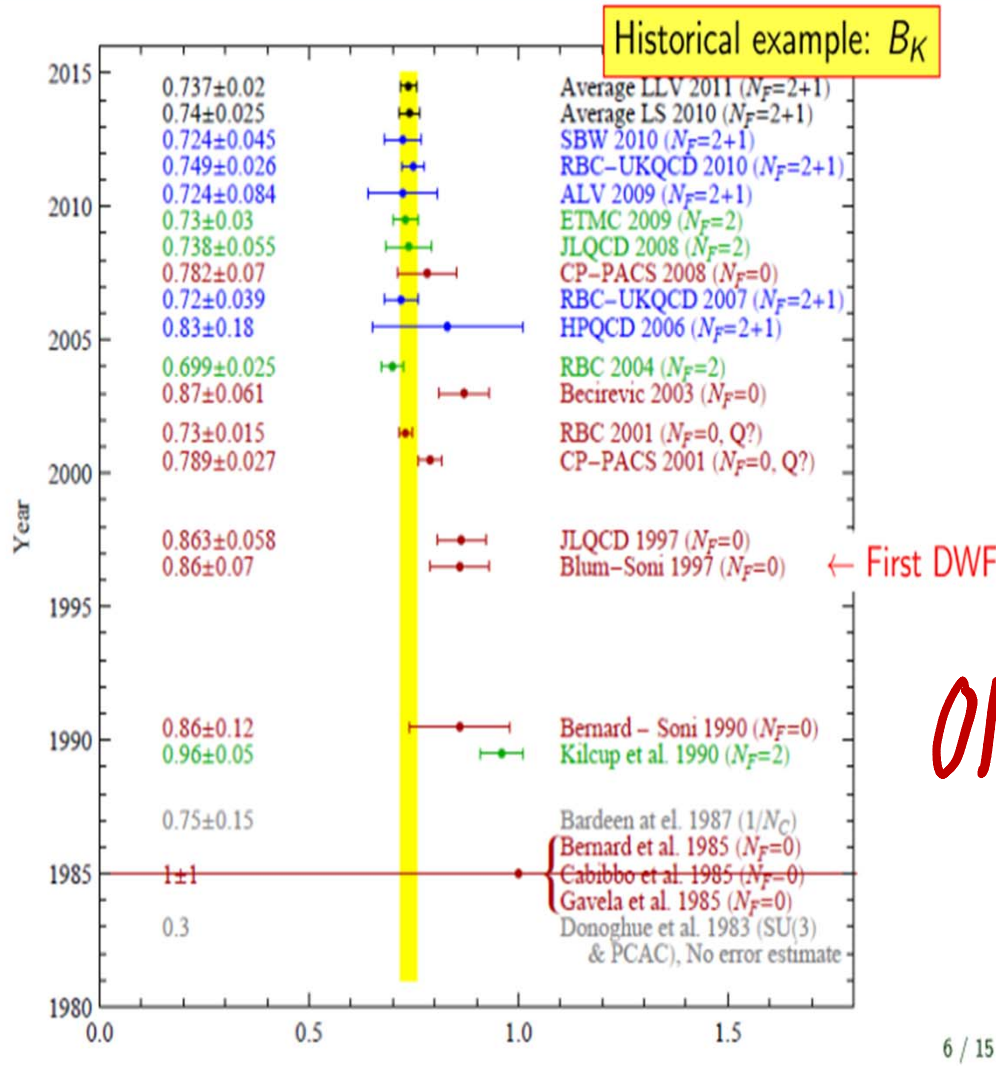
Massive fermions in lattice gauge theory

Aida X. El-Khadra
Department of Physics, University of Illinois, 1110 W. Green Street, Urbana, Illinois 61801

Andreas S. Kronfeld and Paul B. Mackenzie
Theoretical Physics Group, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510
(Received 4 April 1996)

This paper presents a formulation of lattice fermions applicable to all quark masses, large and small. We incorporate interactions from previous light-fermion and heavy-fermion methods, and thus ensure a smooth connection to these limiting cases. The couplings in improved actions are obtained for arbitrary fermion mass m_q, without expansions around small- or large-mass limits. We treat both the action and external currents. By interpreting on-shell improvement criteria through the lattice theory's Hamiltonian, one finds that cutoff artifacts factorize into the form $b_n(m_q a)[\mathbf{p}a]^{s_n}$ where $\mathbf{p}$ is a momentum characteristic of the system under study, s_n is related to the dimension of the nth interaction, and $b_n(m_q a)$ is a bounded function, numerically always of order 1 or less. In heavy-quark systems $\mathbf{p}$ is typically rather smaller than the fermion mass m_q. Therefore, artifacts of order $(m_q a)^s$ do not arise, even when $m_q a \gtrsim 1$. An important by-product of our analysis is an interpretation of the Wilson and Sheikholeslami-Wohlert actions applied to nonrelativistic fermions. [S0556-2821(97)03607-2]

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



AB-initio Calculation

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

ONE ILLUSTRATION

Flag 2019: sample [Nf=2 +1]

- BK^hat = 0.7625(97) ….1.5%
- fB= 192.0 (4.3) MeV…….2.2 %
- \xi = 1.206 (17)………..1.5%
- B=>D, δ[sl FF (q^2)] ~ 5-10%
- RD ~ 4%

Need lot more work esp due expts on the horizon

Couplings between CWB+ AS & PBM et al

- With Claude, we identified rather early on important observables in K, B…weak decays for lattice studies

- George Hockney, UCLA ~85=> FermiL
- Aida E-K, UCLA/BNL ~’91 => FermiL

- Jim S, UCLA/BNL/Edinburgh ~’94=> FermiL

- Jack L, Princeton/BNL ~’04 => FermiL

- Ruth VdW FermiL=>BNL => FermiL

And of course also in Physics

- For long CWB + AS used suggestions of Lepage and Mackenzie in renormalization of operators via “boosted coupling”, see L&M, PRD’93.
- And in heavy quark treatments we dealt with large am difficulties as suggested originally by Kronfeld and Mackenzie [inspired Jim Labrenz PhD work]. All that eventually evolved into a systematic treatment as in El-K, K & M, PRD’97.

Anomalies galore!

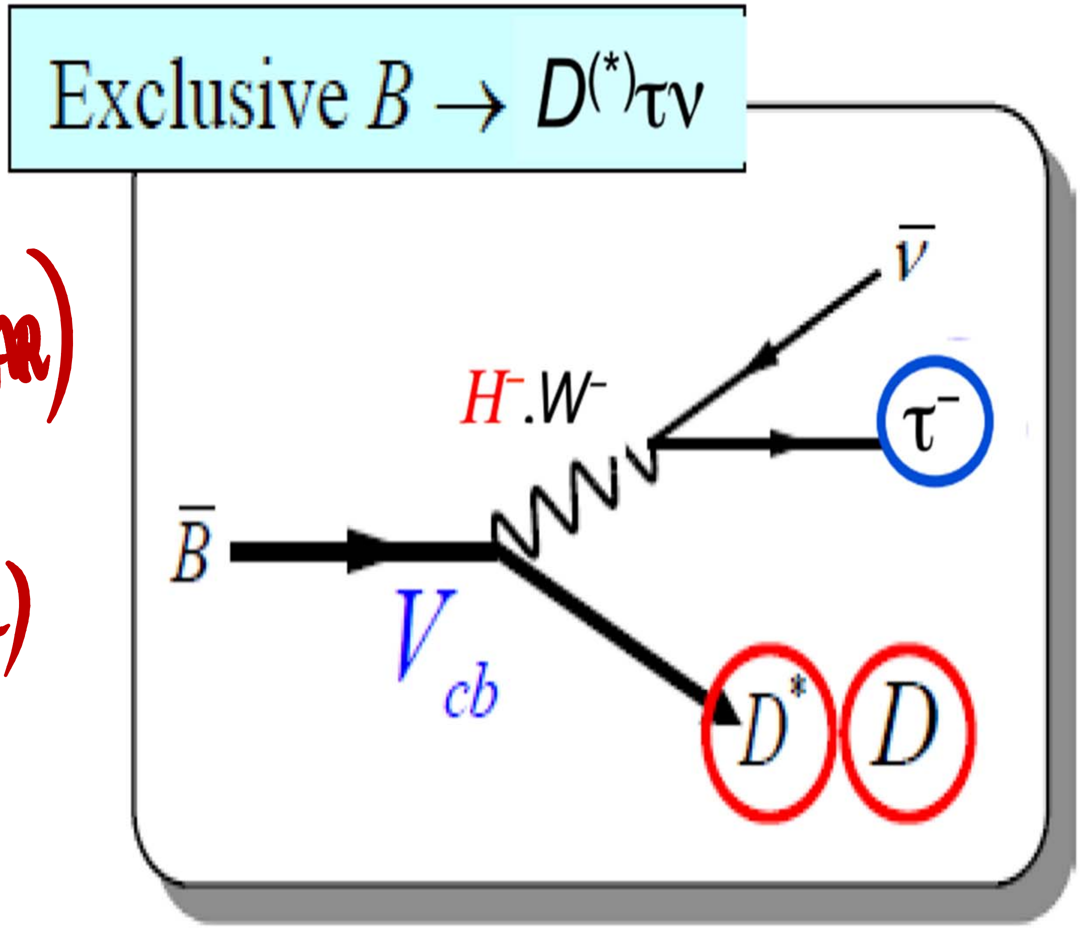
- RD(*) ~ 4σ(?) ; ALSO Rψ ~ 2σ LHCb
- RK(*): 2.6σ(RK) ; 2.2 & 2.5 σ RK*
- g -2…BNL =>FNAL expt... ~ 3.6σ major lattice progress
- Ɛ': a personal obsession….for a long^3 time=>'cause of the strong belief that it is super-sensitive to NP

216[PRL 2015] => ~1400 of which ~740 g c analyzed } See NHC talk

[2.1σ => ??] …..few more months to new results

- **Notice in each case, because of the omnipresence of non-perturbative effects, lattice methods provide crucial info for experiments to be able to use the data in the most economical manner**

BEST CHANCE IN A VERY LONG TIME OF POSSIBLE SIGHTINGS OF BSM



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

MANUEL FRANCO
SEVILLA
PhD Thesis

Independent of Vcb!

- To test the SM Prediction, we measure

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

Leptonic τ decays only

Several experimental and theoretical uncertainties cancel in the ratio!

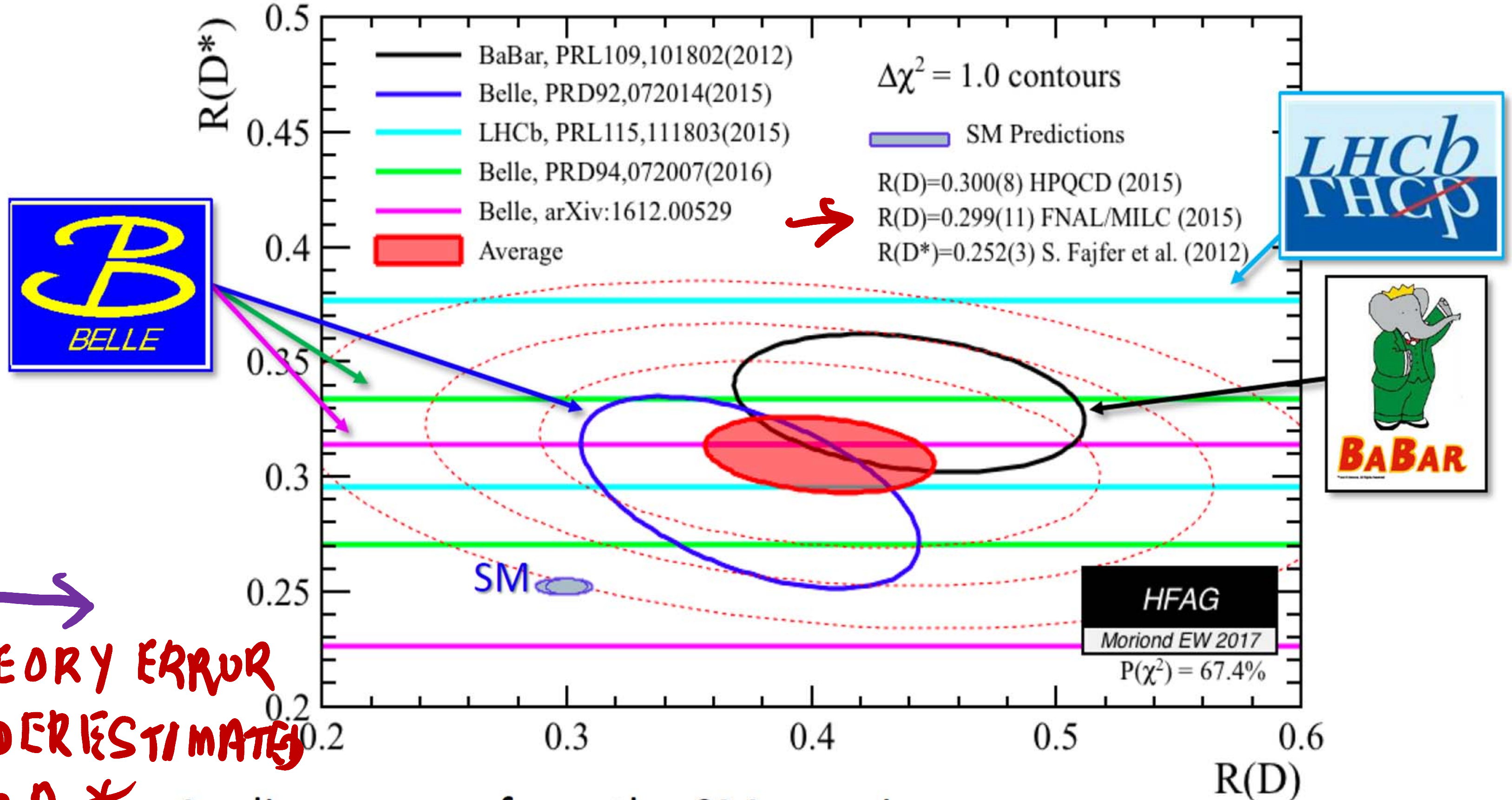
- BB events are fully reconstructed:

Some exptal & also some Theory errors tend to cancel

$\ell = \mu$ or e

■ $R(D^{(*)})$ by HFAG

Hirose [BELLE]@EW MORIOND Mar. 2017



THEORY ERROR UNDERESTIMATED ESP R D*

- ~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

Semileptonic B decays

BaBar measured an excess of $B^0 \to D^{(*)}\tau^- \nu_\tau$ (**3σ away from SM!**) [PRD 88 (2013) 072012] [Nature 546 (2017) 227]

LHCb:

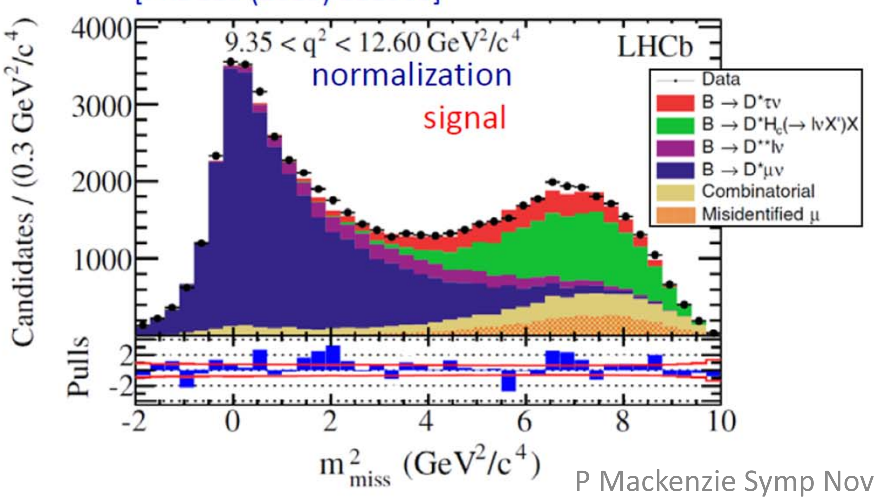
R(D*)
- $\overline{B}^0 \to D^{*+} \tau^- \overline{\nu}_\tau$, with $\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$ [PRL 115 (2015) 111803]
- $B^0 \to D^{*-} \tau^+ \nu$, with $\tau^+ \to \pi^+ \pi^- \pi^+ (\pi^0) \overline{\nu}_\tau$ [PRL 120 (2018) 171802]

R(J/ψ)
- $B^+_c \to J/\psi\ ^-\tau^+ \nu$, with with $\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$ [PRL 120 (2018) 121801]

■ Using $\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$

Information from the missing mass squared $m_{miss}^2 = (P_B - P_{D*} - P_\mu)^2$ and muon energy

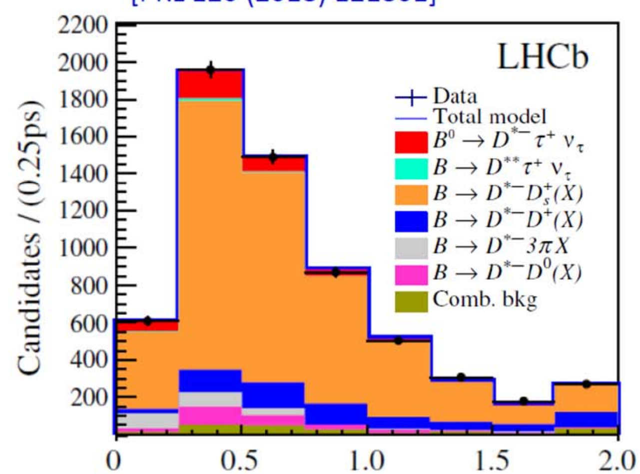
[PRL 115 (2015) 111803]



■ Using $\tau^+ \to \pi^+ \pi^- \pi^+ \overline{\nu}_\tau$

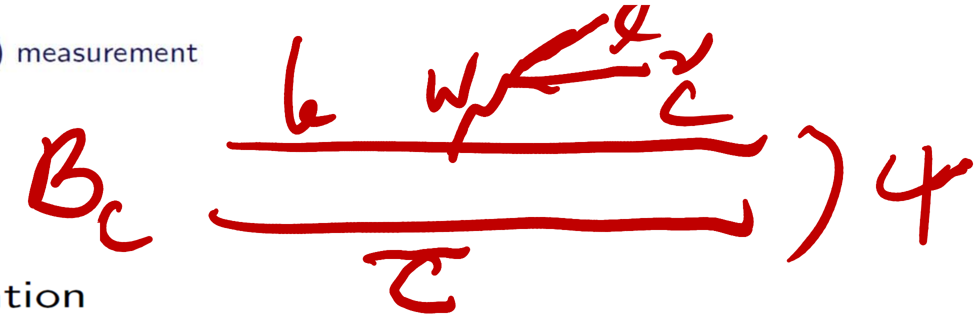
Information from the position of the pions. Normalized to $B^0 \to D^{*-} \pi^+ \pi^- \pi^+$

[PRL 120 (2018) 121801]

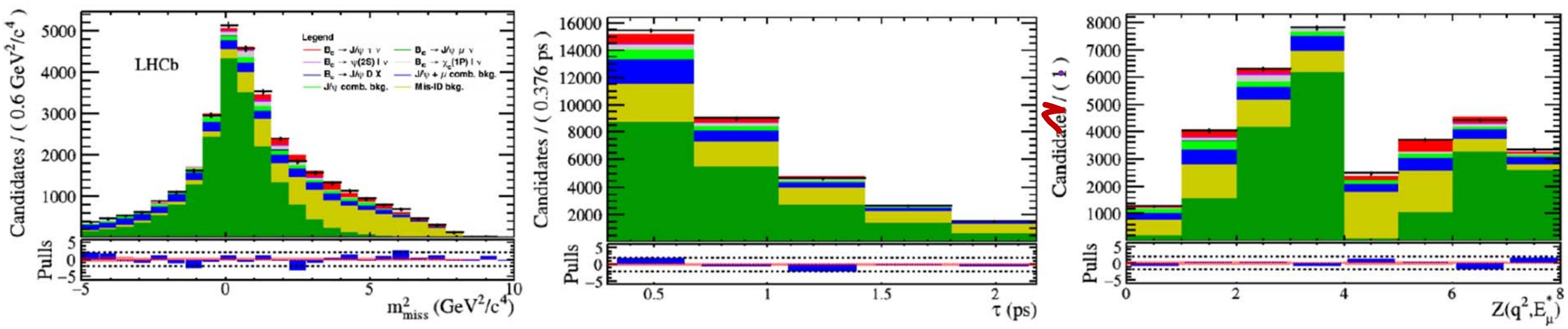


$B_c \to J/\psi \tau \nu$

2PM Jan 2018



Greg Ciezarek,
on behalf of the LHCb collaboration



C ALSO MARK SMITH eFPP 2018

- $R_{J/\psi} \equiv B_c \to J/\psi \tau \nu / B_c \to J/\psi \mu \nu$
- 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)

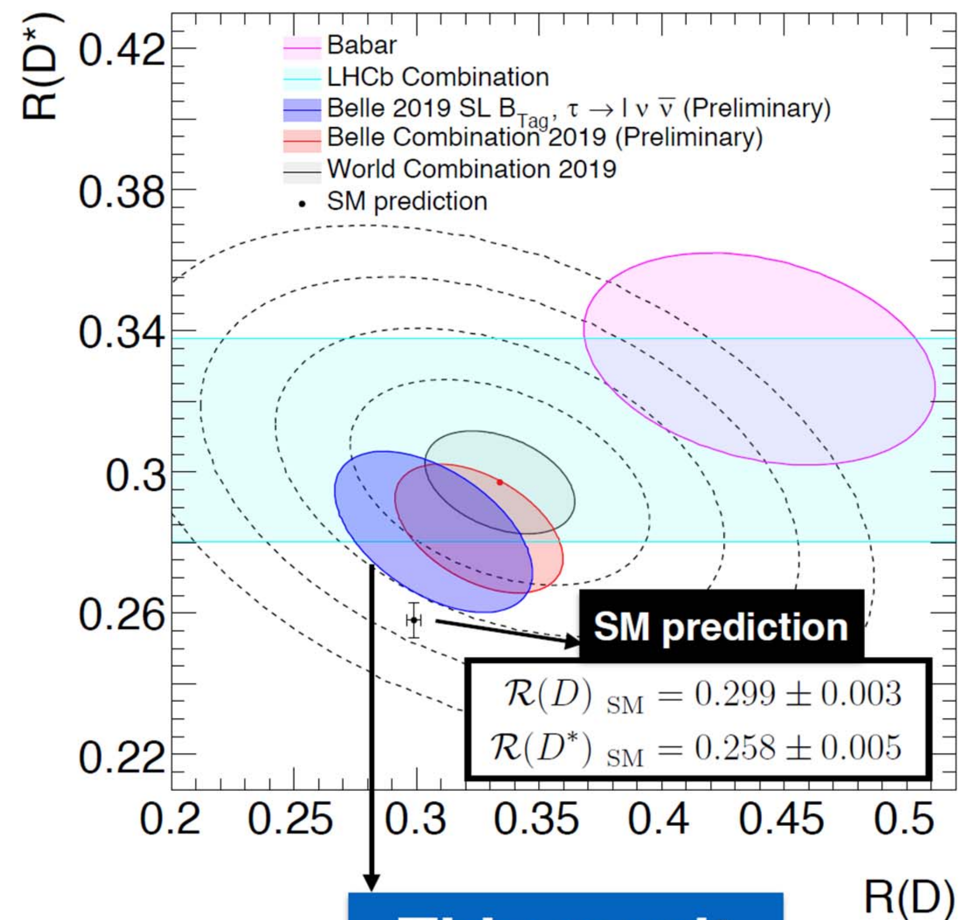
REMAINING ISSUES PRIMARILY EXPTAL
1. Stat 2. D^{**} 3. $\tau \to$ had $+ 2\nu$

SM $R_\psi \sim .265 \pm .015$

QUITE ROBUST! ESSENTIALLY A NR Bound State

Conclusion / Preliminary $R(D^{(*)})$ averages

- **Most precise measurement** of R(D) and R(D*) to date
- First **R(D)** measurement performed with a **semileptonic tag**
- Results **compatible with SM** expectation within **1.2σ**
- **R(D) - R(D*) Belle average** is now within **2σ** of the SM prediction
- **R(D) - R(D*) exp. world average** tension with SM expectation **decreases from 3.8σ to 3.1σ**



This result

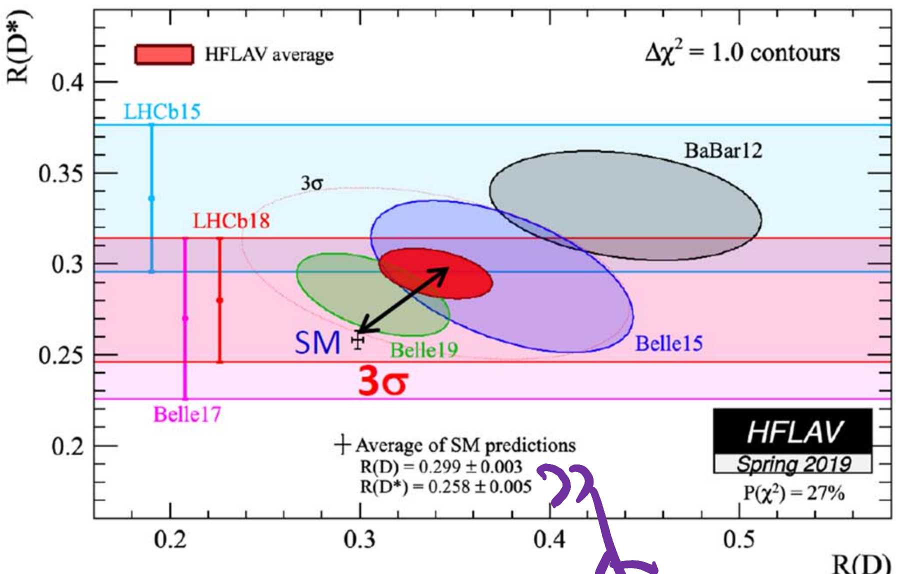
$$\mathcal{R}(D) = 0.307 \pm 0.037 \pm 0.016$$
$$\mathcal{R}(D^*) = 0.283 \pm 0.018 \pm 0.014$$

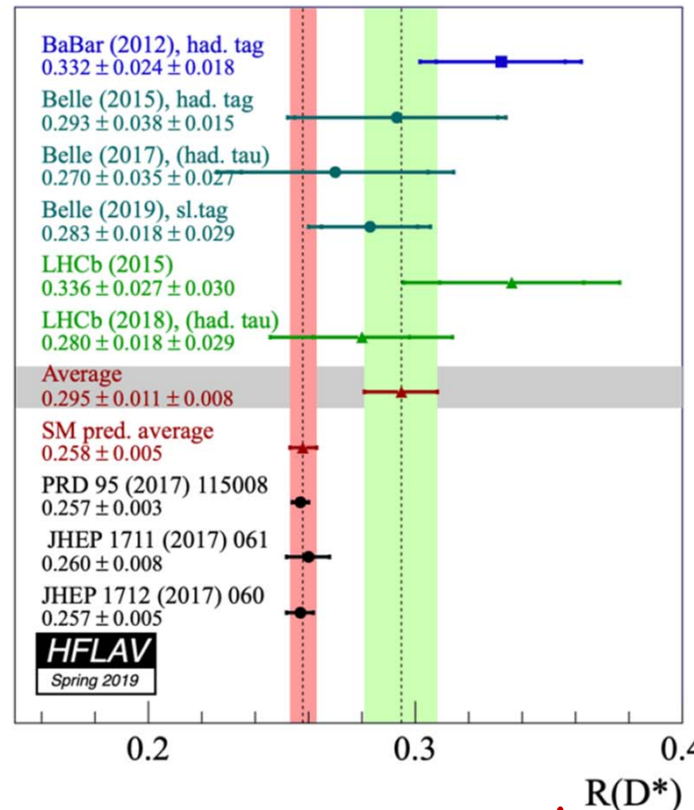
Semileptonic B decays

6 R_{D^*} measurements

New results (Moriond 2019) from Belle:

- Global picture of R_D and R_{D^*}





→ New results from Belle: 4σ →3σ deviation from SM

R_D: 3 Babar, + Belle

B→D* Form factors from Lattice still cooking

FACT OR FARCE?

11 exptal results [not all independent]; ALL central values above Theory

4

experiment	tag method	τ decay mode	R_D	$R_D^\star$	R_ψ
Babar (2012)[1]	hadronic	l $\nu\nu$	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.0.018$	
Belle (2015)[2]	hadronic	l $\nu\nu$	$0.375 \pm 0.064 \pm 0.026$	$0.293 \pm 0.038 \pm 0.015$	
LHCb (2015)[5]	hadronic	l $\nu\nu$	-	$0.336 \pm 0.027 \pm 0.030$	
Belle (2016)[2]	semileptonic	l $\nu\nu$	-	$0.302 \pm 0.030 \pm 0.011$	
Belle (2017)[4]	hadronic	$\pi(\rho)\nu$	-	$0.270 \pm 0.035 \pm 0.027$	
LHCb (2017)[6]	hadronic	$3\pi\nu$	-	$0.291 \pm 0.019 \pm 0.029$	
Belle (2019)[7]	semileptonic	l $\nu\nu$	$0.307 \pm 0.037 \pm 0.016$	$0.283 \pm 0.018 \pm 0.014$	
LHCb(2016) [9]	hadronic	l $\nu\nu$	-	-	$0.71 \pm 0.17 \pm 0.18$
SM	-	-	0.299 ± 0.011	0.260 ± 0.008	0.26 ± 0.02

TABLE I: All experimental results announced to date on R_D, R_{D^*} and on R_ψ versus the predictions of those for the SM

ALTMANNSHOFER, DEV+AS, Yicong Sui (in prep)

excellent g.s

RECAP

- 3 different major B-experiments
- 3 with B => D
- 7 with B=> D*
- 1 with Bc => ψ
- 9 with tau => l (l=μ or e) nu nu'
- 2 with tau => hadron + nu

- Each and everyone of the 11 experimental results seem to imply tau is NOT just a heavy muon(electron) as dictated by SM.

Imp. Historical ~~Aside~~ CAUTION

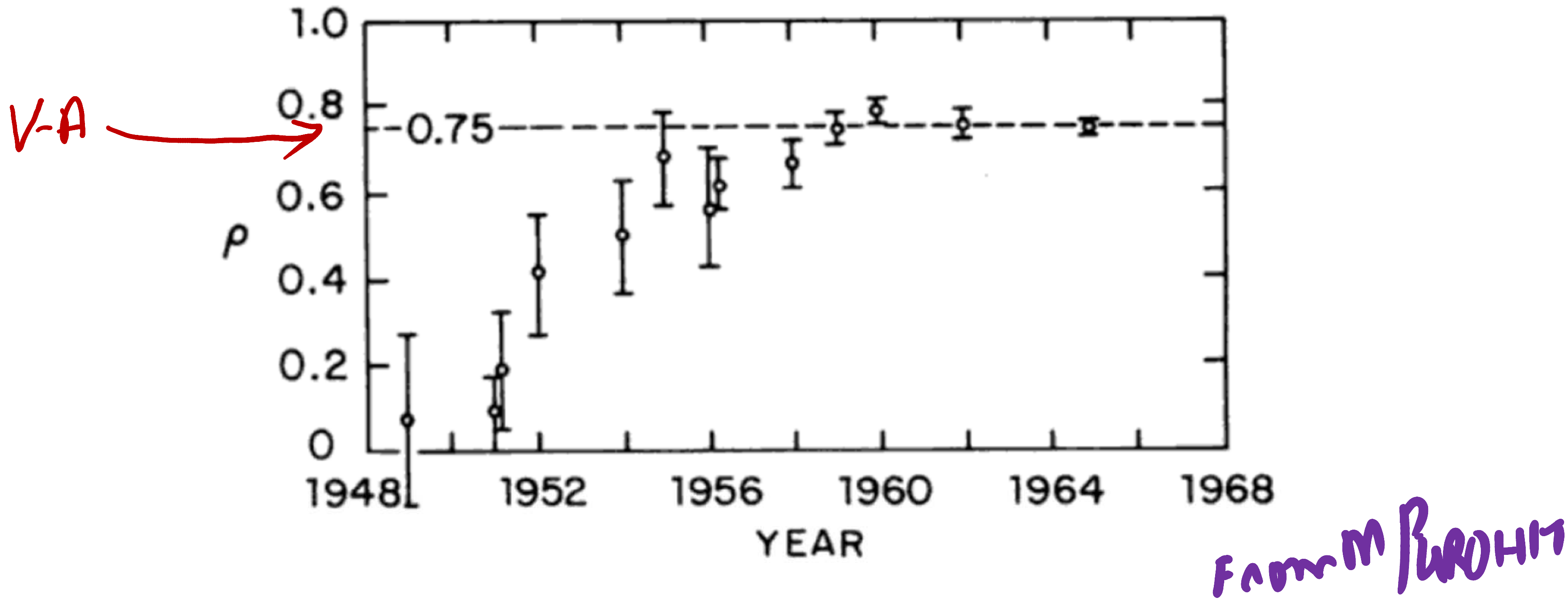


Figure 16. The change of the Michel parameter ρ from year to year.

From T. D. Lee's text

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).

LHCb

Lepton Flavour Universality

Arantza Oyanguren

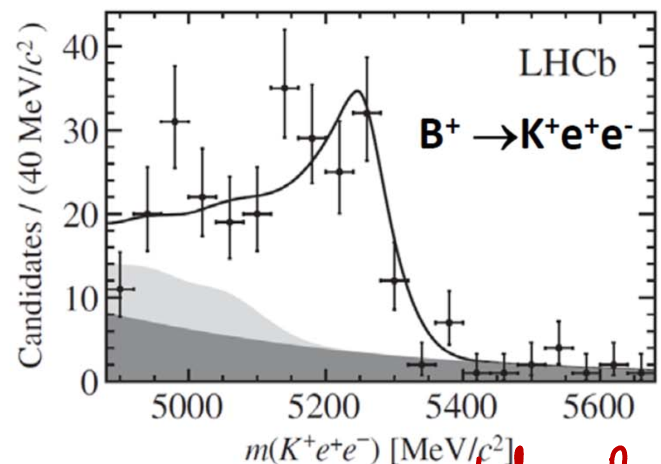
- In the SM all leptons are expected to behave in the sa

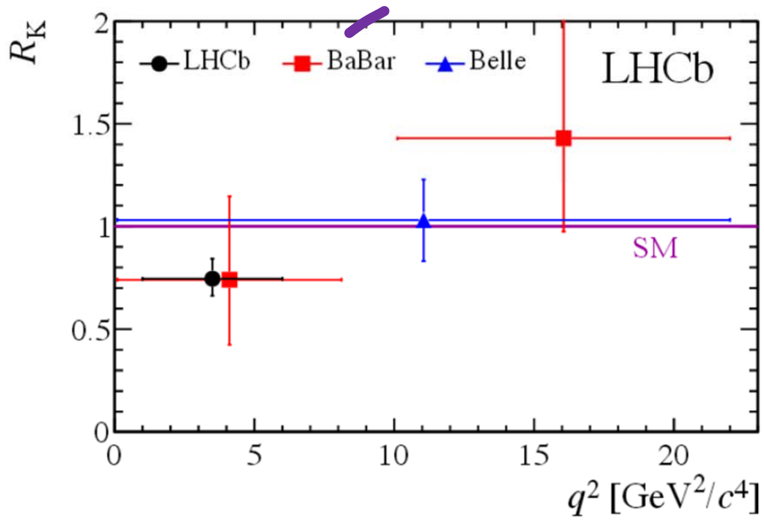
$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)}$$ $= 1.000 + O(m_\mu^2/m_b^2)$ (SM)

[PRL 113 (2014) 151601]

- Experimentally, use the $B^+ \to K^+ J/\psi(\to e^+e^-)$ and $B^+ \to K^+ J/\psi(\to \mu^+\mu^-)$ to perform a double ratio

- Precise theory prediction due to cancellation of hadronic form factor uncertainties





1 GeV < q^2 < 6 GeV ← should be safe from Rad Corr

$$R_K = 0.745^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})$$

→ Consistent, but lower, than the SM at **2.6σ**

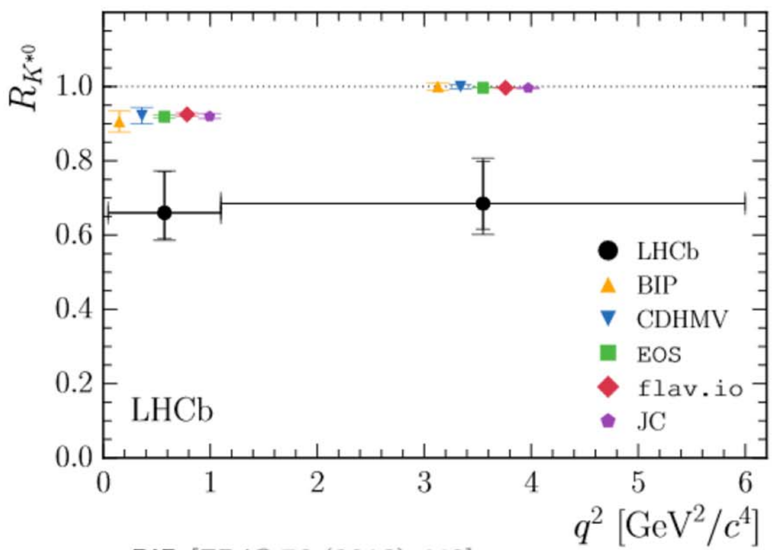
Arantza Oyanguren

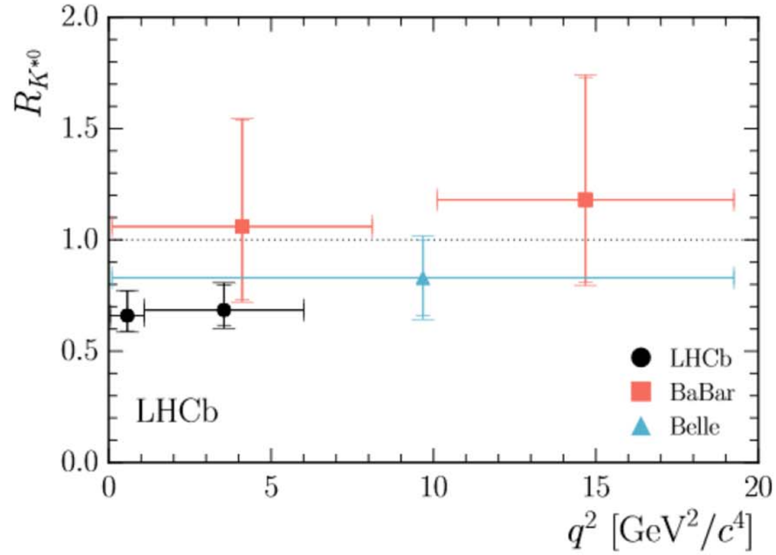
Lepton Flavour Universality

LHCb

- Results:

LHCb, JHEP08(2017)055





▲ BIP [EPJC 76 (2016) 440]
▼ CDHMV [JHEP 04 (2017) 016]
■ EOS [PRD 95 (2017) 035029]
◆ flav.io [EPJC 77 (2017) 377]
⬟ JC [PRD 93 (2016) 014028]

● LHCb [PRL 113 (2014) 151601]
▲ Belle [PRL 103 (2009) 171801]
■ BaBar [PRD 86 (2012) 032012]

$\lesssim 3.4\sigma$

Low q^2 [0.045-1.1 GeV^2]: SM$_▼$ = 0.922(22)

$$R_{K^{*0}} = 0.66\ ^{+\ 0.11}_{-\ 0.07}\,(\text{stat}) \pm 0.03\,(\text{syst})$$

Central q^2: [1.1-6 GeV^2]: SM$_▼$ = 1.000(6)

$$R_{K^{*0}} = 0.69\ ^{+\ 0.11}_{-\ 0.07}\,(\text{stat}) \pm 0.05\,(\text{syst})$$

→ Consistent, but lower than the SM at **2.1-2.3σ** (low q^2) and **2.4-2.5σ** (central q^2)

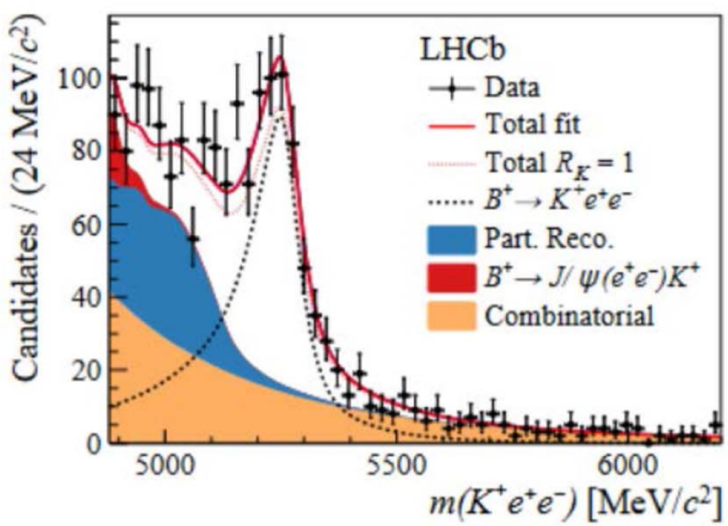
Rare B decays: R_K

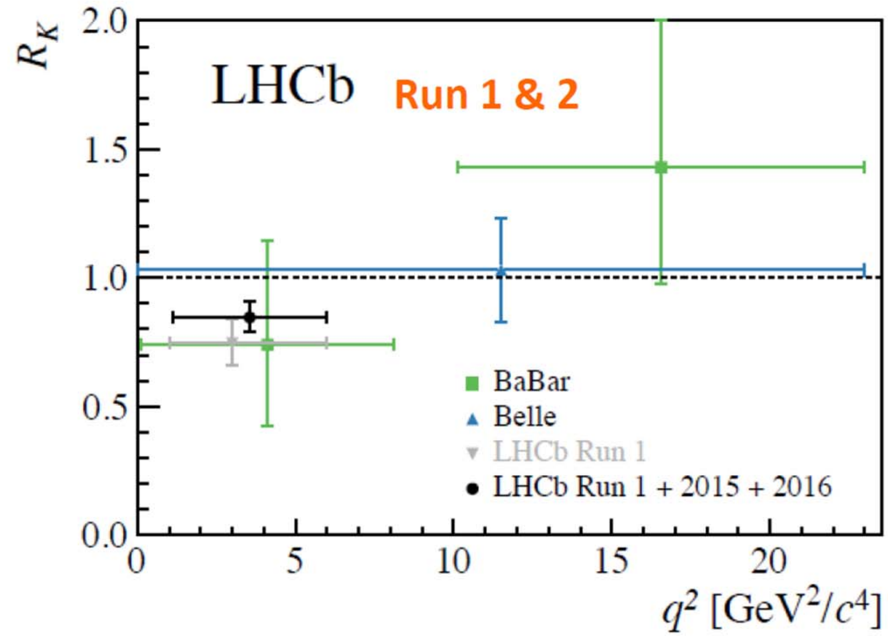
New results (Moriond 2019):

Including partial sample of Run2 ($2fb^{-1}$)

[LHCb, *PRL* 122 (2019) 191801]

With improved reconstruction and re-optimized analysed strategy





1.1 GeV < q^2 < 6 GeV

$$R_K = 0.846 \,^{+0.060}_{-0.054}\,(\text{stat.})\,^{+0.016}_{-0.014}\,(\text{syst.})$$

→ Still consistent, lower, than the SM at **2.5σ**

Not confirmed, not ruled out…

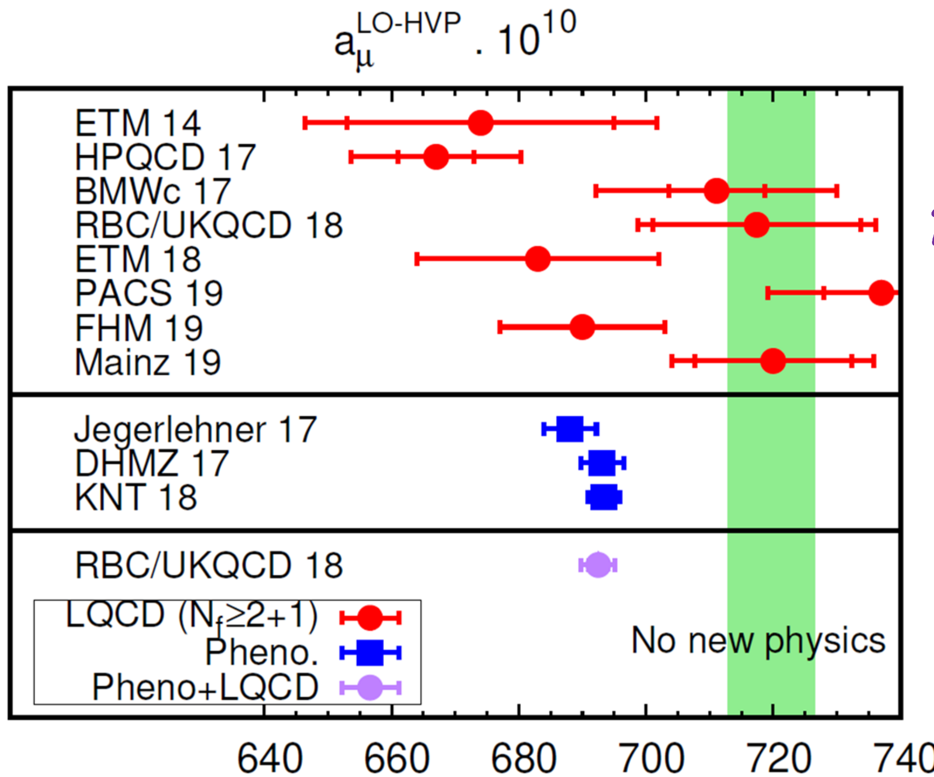
A. El-Khadra's talk at Seattle INT workshop.

Sept 2019

$(g-2)_\mu$

[prepared by K. Miura for WP]

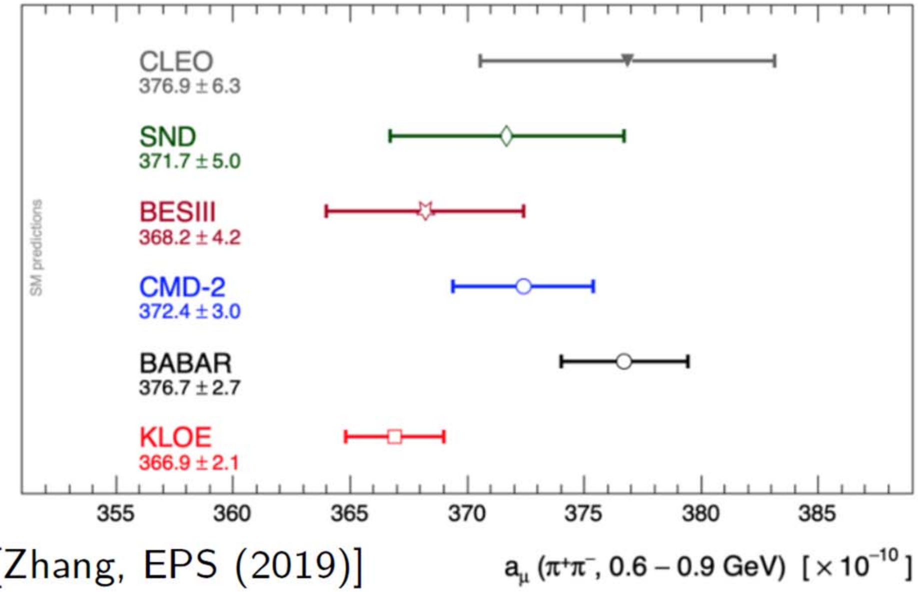
[V.



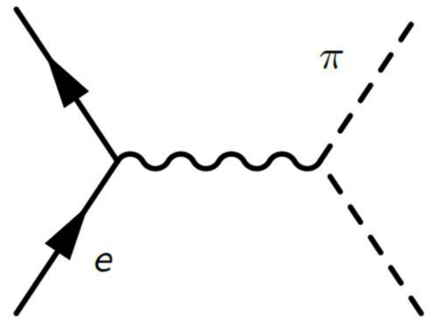
x 1/3 reduction in errors very soon

Lattice work started by Tom Blum @ BNL ~'04

Tensions in Experiment



[Zhang, EPS (2019)]



R-ratio data for $ee \to \pi\pi$ exclusive channel, $\sqrt{s} = 0.6 - 0.9\ \mathrm{GeV}$ region
Tension between most precise measurements (BABAR/KLOE)
R-ratio a_μ^{HVP} uncertainty $<$ difference in this channel

Avoid tension by computing precise lattice-only estimate of a_μ^{HVP}
Use lattice QCD to inform experiment, resolve discrepancy

Kile, Kobach +AS PRD2015

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
+
$(g-2)_\mu$
+
$R_{K(*)}$
+
$R_{D(*)}$

Possibly interesting inter-related story reg. LUV evolving over the past ~15 years

- **muon (g-2)…….BNL ~2004; FermiL ~2017=>?**
- **RD(*)………… BaBar, Belle, LHCb ….~2012-----→**
- **RK(*) …………..LHCb ~2014--------→**
- **Intriguing rather long tell- tale signs of LUV or few sigma flukes?**
- **Fortunately, wont have to wait too long < ~ 2 years due to FermiL, LHCb & Belle-II AND LATTICE**

IF

exptal hints stay then

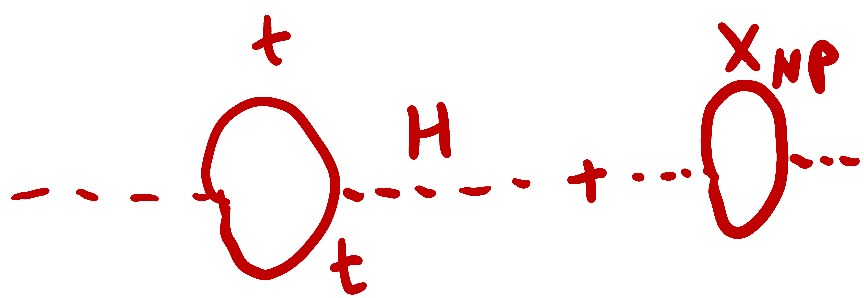
Altmannshofer, Dev, A.S. 2017
+ WIP

ANOMALIES: POSSIBLY A HINT FOR (NATURAL) SUSY-WITH RPV3

then RPV - SUSY extremely well motivated

- 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, RK(*) if needs be
- Collider signals tend to get a lot harder than (usual-RPC) SUSY
- RPV makes leptoquarks natural [and respectable]
- Moreover, RPV should be viewed as an umbrella i.e. under appropriate limits other models are incorporated

$m_H \lesssim 126$ GeV



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

ADS - PRD '17

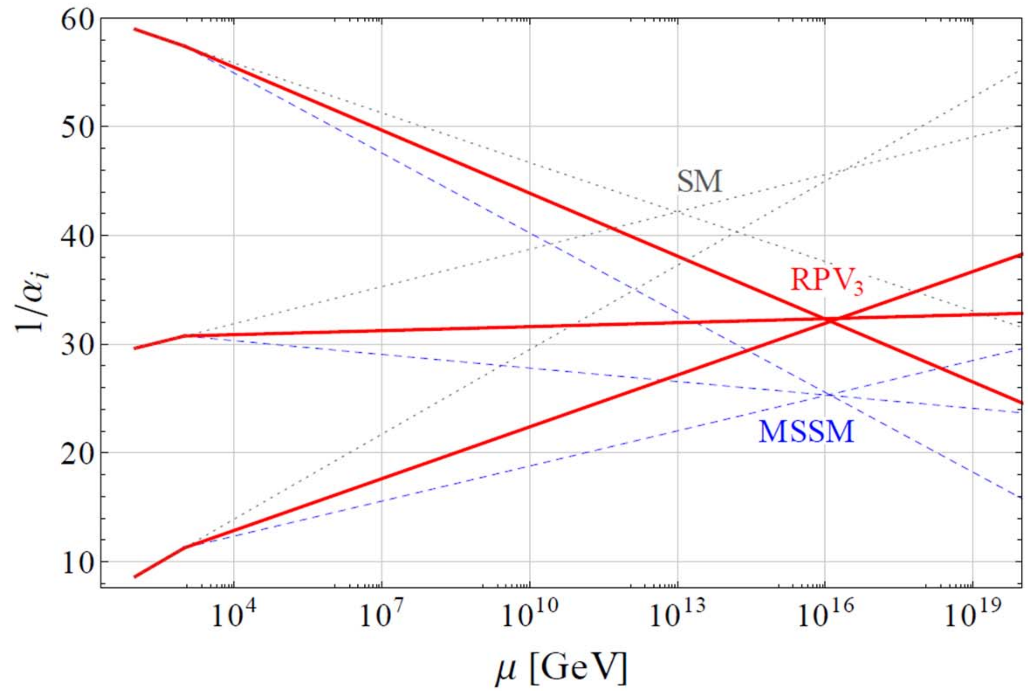


FIG. 2. RG evolution of the gauge couplings in the SM, MSSM and with partial supersymmetrization.

Unification scale stays same, only value of couplings shifts

For pheno relevant terms:

ADS' PRD 2017

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

} RPV$_3$ interaction

Analogue of $\frac{G_F}{\sqrt{2}}$

Dim 6

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

→ For $R_{D(*)}$

NOTE: ITS SM-like!

$C_{V_L} \neq 0 \Rightarrow$ corresponds to our RPV3

MURGUI et al
1904.09311
MARTIN J. ....

2 Theoretical framework

2.1 Effective Hamiltonian

We adopt the most general $SU(3)_C \otimes U(1)_Q$-invariant effective Hamiltonian describing $b \to c\ell\bar{\nu}_\ell$ transitions at the bottom quark scale, not considering the possibility of light right-handed neutrinos:

$$\mathcal{H}_{\rm eff}^{b\to c\ell\nu} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[(1 + C_{V_L}) \mathcal{O}_{V_L} + C_{V_R}\mathcal{O}_{V_R} + C_{S_R}\mathcal{O}_{S_R} + C_{S_L}\mathcal{O}_{S_L} + C_T\mathcal{O}_T \right] + \text{h.c.}. \quad (2.1)$$

The above fermionic operators are given by[4]

$$\mathcal{O}_{V_{L,R}} = (\bar{c}\gamma^\mu b_{L,R})(\bar{\ell}_L\gamma_\mu\nu_{\ell L}), \quad \mathcal{O}_{S_{L,R}} = (\bar{c}\, b_{L,R})(\bar{\ell}_R\nu_{\ell L}), \quad \mathcal{O}_T = (\bar{c}\,\sigma^{\mu\nu} b_L)(\bar{\ell}_R\sigma_{\mu\nu}\nu_{\ell L}), \quad (2.2)$$

Very useful work includes constraints from $R_{D(*)}$, q^2 distribution, D^* pol & $B_c \to \tau\nu$

not only

Murgui et al

- On the other hand, considering scenarios with only a single Wilson coefficient present, there *is* a clear preference for C_{V_L}: removing the other three Wilson coefficients increases χ^2 only by 1.4, corresponding to 0.14σ. Hence, Min 1 is well compatible with a global modification of the SM, that is, C_{V_L} being the only non-zero coefficient.

Incl. Belle EWM & ni and

central values do change. Again all individual coefficients are roughly compatible with zero at 1σ. C_{V_L} alone also still provides an excellent fit to all the data, now with a smaller central value of ~ 0.08. Interestingly, the fit with only C_T is improved by the new results, which,

A striking endorsement for RPV3 ∴ IF NP is needed!

But CVL only solution also has a bad news

[esp small non-vanishing CVL]

- **It may just be SM + (expt + theory) errors**

- **Assuming NP is needed then RPV3 is a very good candidate**

Sequel to our work on RPV3

Addressing B-anomalies, muon $g-2$ and ANITA anomaly in a Minimal R-parity violating supersymmetric framework

Wolfgang Altmannshofer[1], P. S. Bhupal Dev[2], Amarjit Soni[3], Yicong Sui[2]

Excellent grad student @ WUSTL

$(g-2)_\mu \oplus R_{D^{(*)}} \oplus R_{K^{(*)}}$ + ANITA anomalies

10 + ALL known expt'al constraints

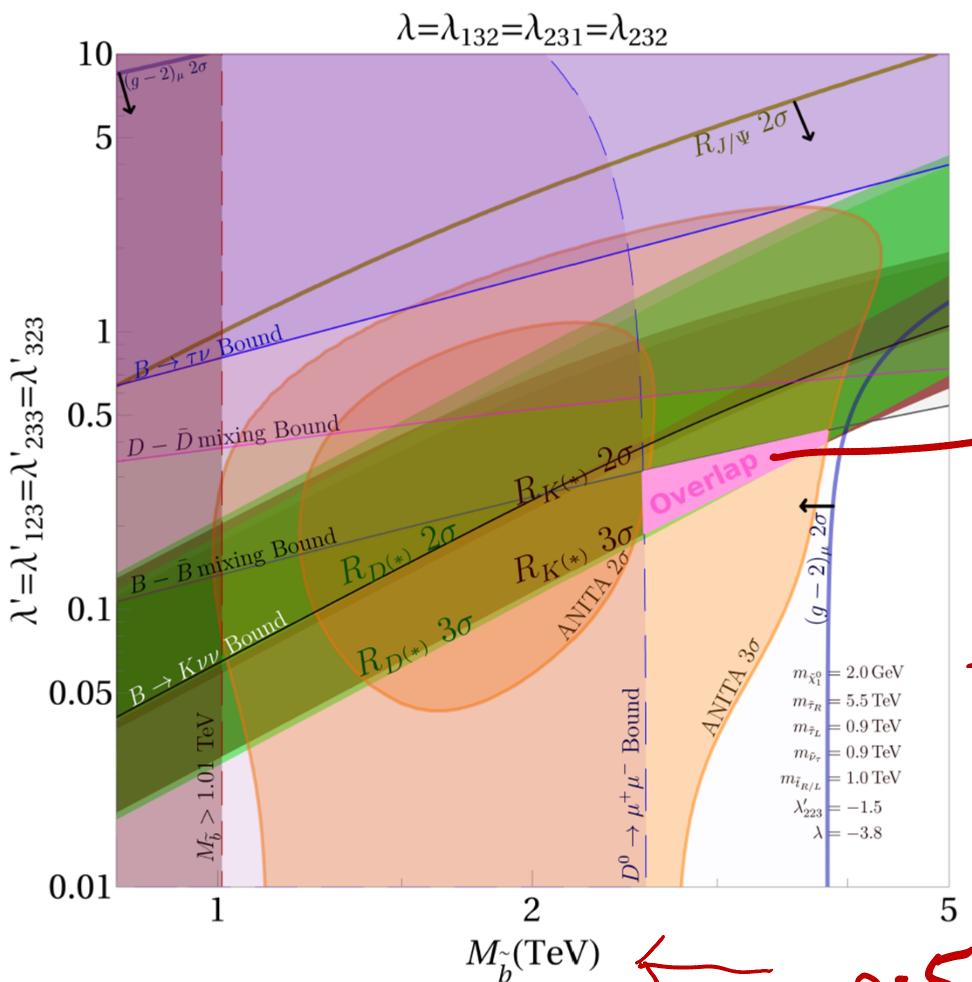


FIG. 4: Benchmark scenario with overlapping $R_D^{(*)}$, $R_{J/\Psi}$, $R_K^{(*)}$, $(g-2)_\mu$ and ANITA regions. The total overlap is shown as pink area. $R_D^{(*)}$ 2, 3 σ flavored regions are denoted as green regions; $R_K^{(*)}$ 2, 3 σ flavored regions are shown in red regions; $(g-2)_\mu$ and $R_{J/\Psi}$ 2 σ flavored region is marked by thick blue and dark yellow edges, respectively, with arrows pointing inwards to the allowed regions; ANITA anomaly 2, 3 σ flavored regions are shown in orange regions. $B \to K\nu\nu$ bound is shown as dark gray curve with forbidden region indicated as dark gray region while $B-\bar{B}$ mixing bound shown as gray curve with forbidden region in gray; $D \to \mu\mu$ is shown as dashed light purple curve with forbidden region in light purple. $D-\bar{D}$ mixing bound is shown as the pink curve with forbidden region in light pink.

IN CLOSING: A REMINDER

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.......

History may repeat yet again!

- => extremely unwise to put all eggs in HEF
- info from IF complementary to HEF can be a crucial guide for pointing to new thresholds as well as to provide important clues to the nature of the signals there from

Summary + Outlook + . . . –

- **Hints of LUV are extremely interesting, intriguing and important.** ***There is nothing we know of that tells us that these hints cannot be true.***

- **While these indications are rather serious, they are not yet compelling. They ask for too radical a departure from conventional understanding so we must exercise extreme caution and care before accepting them. Moreover, in each of the 3 cases there are features that cause concern.**

- **Fortunately significant experimental/theoretical progress should occur in < ~2 years and is eagerly awaited.**

- **Given all the above hints, may be just may be with some luck the IF will lead us to the gem of NP and once again, as many times in the past, guide collider physics et al**

Thank you, Paul

- **For many contributions to physics via leading the FermiLab lattice group for long. In much of the topics I touched on, Paul + FermiLab Lattice group indeed played the central role.**
- **And also for the major impact on USQCD via his leadership in its Executive Committee.**
- **We all wish you the very best in your retirement years!**

LQ EFT SBS + JW et al

LHCb also finds deficit in observed $B_s \to \phi\mu\mu$ compared to "SM"

$\sim 2.5\,\sigma$

Less reliable due to LD contamination

URGENTLY Needed! FROM LHCb $\Rightarrow$ $R_\phi = \dfrac{B_s \to \phi\mu\mu}{B_s \to \phi ee}$

Revisiting R-parity violating interactions as an explanation of the B-physics anomalies

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"S-T" sym

introduces a nice formal sym arguement to implement our RPV3 [3rd gen is lightest]

Abstract

In the last few years, the ratios $R_{D^{(*)}}$ and of $R_{K^{(*)}}$ have reportedly exhibited significant deviations from the relevant Standard Model predictions, hinting towards a possible violation of Lepton Flavor Universality and a window to New Physics. We investigate to what extent the inclusion of R-parity violating couplings in the Minimal Supersymemtric Standard Model can provide a better fit to the anomalies simultaneously. We perform this analysis employing an approximate, non-abelian $\mathcal{G}_f = U(2)_q \times U(2)_\ell$ flavour symmetry, which features a natural explanation of the appropriate hierarchy of the R-parity violating couplings. We show that, under the requirement of a supersymmetric spectrum with much heavier left-handed doublet superpartners, our assumption favors a considerable enhancement in the tree-level charged-current $B \to D^{(*)}\tau\overline{\nu}$, while the the anomalies induced by $b \to s\ell^+\ell^-$ receive up to an approximate 30% improvement. The consistency with all relevant low-energy constraints is assessed.

Implementing S-T sym simplifies things considerably by reducing # of parameters.

BUT cannot a/c for $(g-2)_\mu$

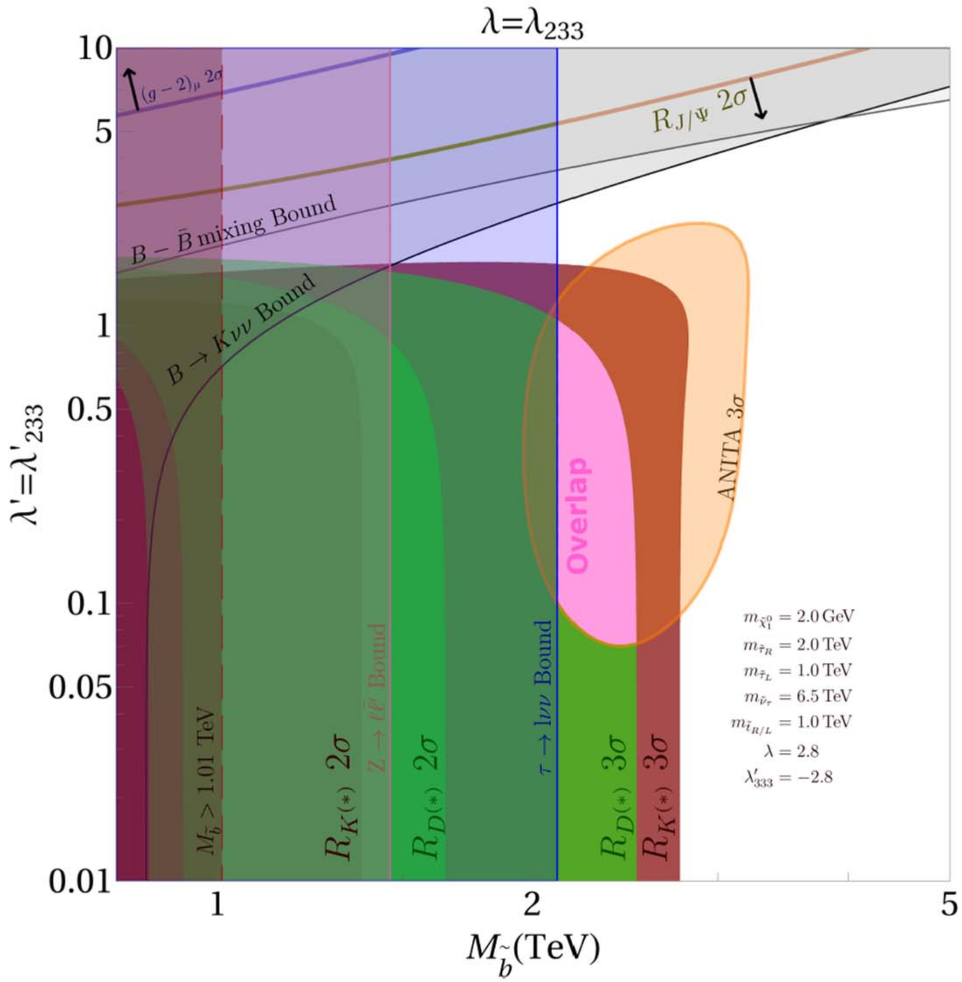


FIG. 5: Benchmark scenario for ST symmetry with overlapping $R_D^{(*)}$, $R_{J/\Psi}$, $R_K^{(*)}$ and ANITA regions. The total overlap is shown as pink area. $R_D^{(*)}$ 2, 3σ flavored regions are denoted as green regions; $R_K^{(*)}$ 2, 3σ flavored regions are shown in red regions; $(g-2)_\mu$ and $R_{J/\Psi}$ 2σ flavored region is marked by thick blue and dark yellow edges, respectively, with arrows pointing inwards to the allowed regions; ANITA anomaly 3σ flavored region is shown in orange regions. $B \to K\nu\nu$ bound is shown as black curve with forbidden region indicated as dark gray region while $B-\bar{B}$ mixing bound shown as gray curve with forbidden region in gray; $Z \to \ell\bar{\ell}'$ bound is shown as pink vertical line with forbidden region in light pink;$\tau \to \ell\nu\nu$ bound is shown as blue vertical line with forbidden region in light blue.

BACK TO LOW PT: NOTABLE LFV DECAYS OF TAU AND B [IN RPV3]

LFV of τ & of B's

→ 3-g centric RPV_3 : altmannshofer, Dev, AS, YS # in prep

Mode	Model dependent BR	Current bound
$\tau \to \mu\phi$	2×10^{-10}	8×10^{-8}
$\tau \to \mu K K$	3×10^{-11}	4×10^{-8}
$\tau \to \mu K_s^0$	6×10^{-11}	2×10^{-8}
$\tau \to 3\mu$	1.5×10^{-10}	2×10^{-8}
$\tau \to \mu\gamma$	1.1×10^{-11}	4×10^{-8}
$\tau \to \mu l^+ l^-$	6×10^{-12}	2×10^{-8}
$b \to s\mu\tau$	7×10^{-7}	4.5×10^{-5}
$B_s \to \tau\mu$	1.3×10^{-8}	N/A

TABLE I: Few examples of lepton flavor violating decay modes of τ and of $B - mesons$. Shown are also loop decays $\tau \to \mu\gamma$ and $\tau \to \mu l^+ l^-$; see text

$Br[B \to K\mu\tau \sim 10^{-7}]$! ⇐ Recall $B \to X_c \ell \nu \propto V_{cb} \sim \lambda^2$

& $B \to K\tau\tau$ also deserves attention

In passing, a side remark, please

- QCD and therefore non-perturbative dynamics critically effects SM and or BSM
- In almost all of these "IF" experiments, quantitative understanding of non-perturbative [non-P] effects is of crucial importance to make most economical use of experimental data, often obtained at huge cost. The non-P methods do not just need humungous computing hardware, (wo)man power needs are also very large. Given their vital use, they deserve greater support from the (experimental) community.

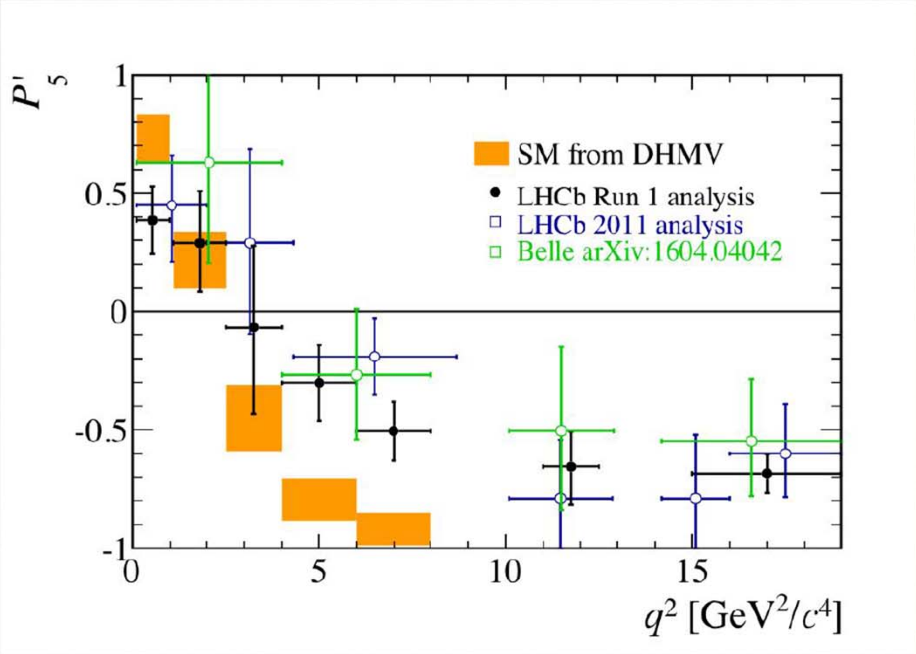
B-flavor anomalies: P_5'

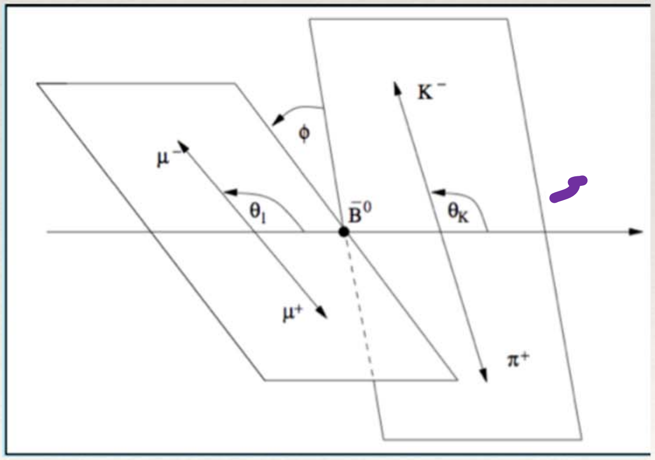
B→Kμμ

much LESS clean esp in low q^2

REMAIN CONCERNED ABOUT NON-local contributions

- Several angular observables measured as functions of q^2
- Some, like P_5', are optimized to be insensitive to hadronic uncertainties: [Descotes-Genon, Matias, Ramon, Virto: 1207.2753]





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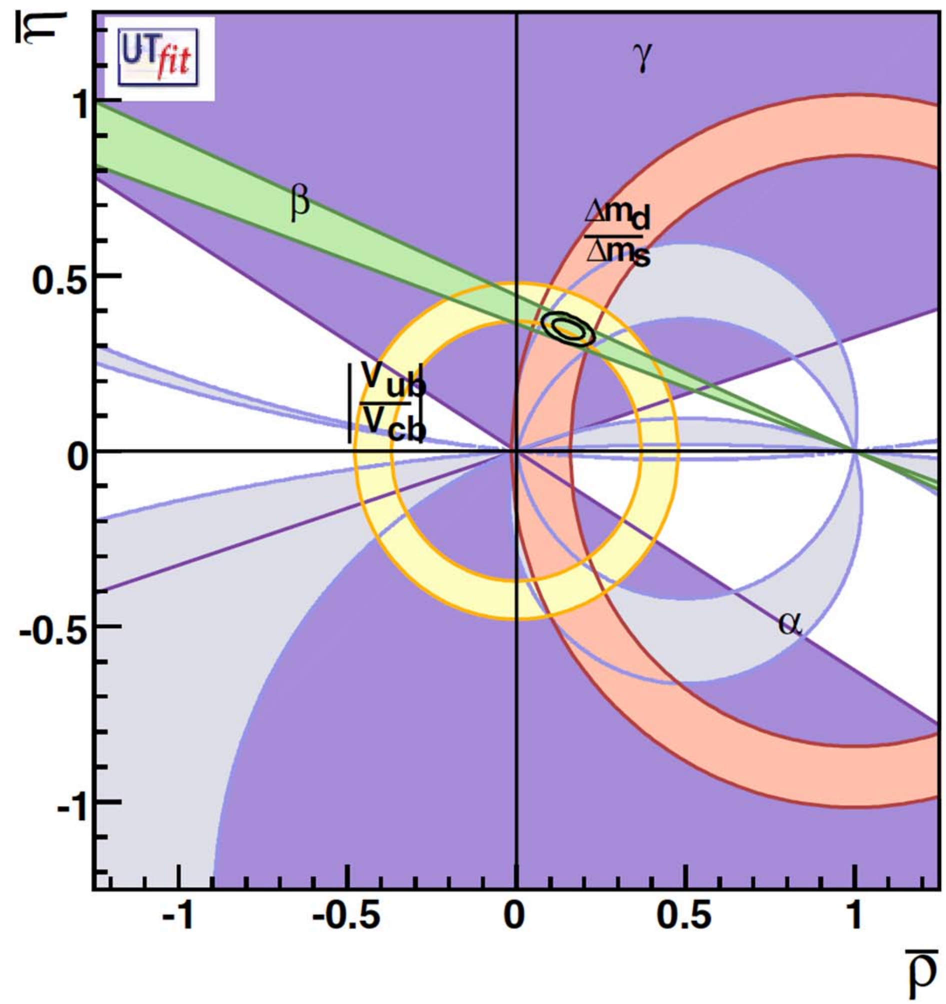

MARCELLA BONA ~2007

COUPLINGS BETWEEN CWB+ AS & PBM ET AL

PHYSICAL REVIEW D VOLUME 56, NUMBER 9 1 NOVEMBER 1997

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

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(Received 12 June 1997)

FF

f_1 f_0

We study the q^2 dependence of the exclusive decay mode $B\to D\tau\bar{\nu}$ 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 $B\to D(e,\mu)\bar{\nu}$. 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

used HQS

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

ALL 11 EXPERIMENTAL CENTRAL VALUES ARE ABOVE THEORY!