SAS1

Precision tau physics: Challenge for Theory, on & off the lattice

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BNL-HET

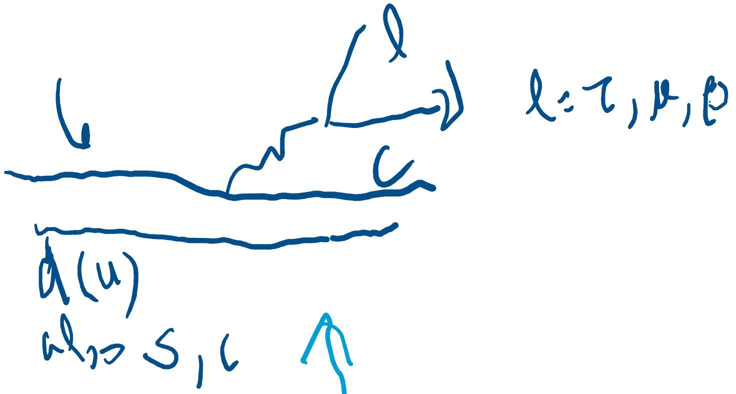
tau 2021 [virtual]
University of Indiana
9/27/21

Slide 1

SAS1 Soni, Amarjit S, 9/24/2021

Points to make

- **tau is playing an important role in flavor anomalies, Circa 2021**
- **3 of the key anomalies are over 3-sigma each; just the 2 updates of 2021, added in quad are over 5 sigma=> chances for LUV (non-universal) BSM are consequently high**
- **If so, then naturalness arguments strongly suggest BSM-CP-odd phase(s)**
- **tau decays are self-analyzers of its spin; also possibility of multibody FSs make tau a powerful probe for CP-odd effects**
- **Moreover, most new physics models invoked to account for LUV involve LFV in decays of tau**
- **Therefore very relevant to all this is upcoming Belle-II (also LHC expts) with significant increase in available tau's to study in unprecedented details, its decays including its polarization**
- **tau mass offers a great opportunity for lattice methods to provide precise tests (say) for rates for production and decay and thereby test SM and BSMs**



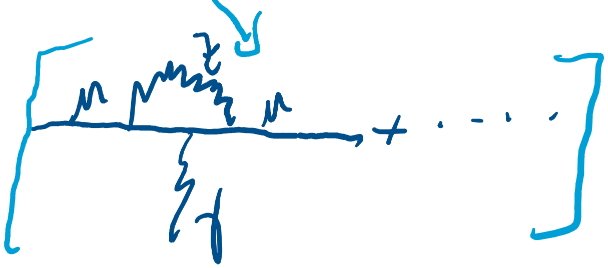
ADDRESSING $R_{D(*)}$, $R_{K(*)}$, MUON $G-2$ AND … PHYS. REV. D **102,** 015031 (2020)

As of 2020

TABLE I. Summary of the anomalies in the observables $R_{D^{(*)}}$, $R_{J/\psi}$, $R_{K^{(*)}}$, and $(g-2)_\mu$. Listed are the pulls of various subsets of observables. The pulls are combined assuming the observables are independent from each other. The values in parentheses exclude the *BABAR* results for $R_{D^{(*)}}$.

Observable	$R_{D^{(*)}}, R_{J/\psi}$	$R_{K^{(*)}}$	$(g-2)_\mu$	All but $(g-2)_\mu$	All
Pull	3.3σ (2.2σ)	3.4σ	3.3σ	4.5σ (3.7σ)	5.3σ (4.6σ)

See ALTMANNSHOFER, DEV, SUI + AS
2020



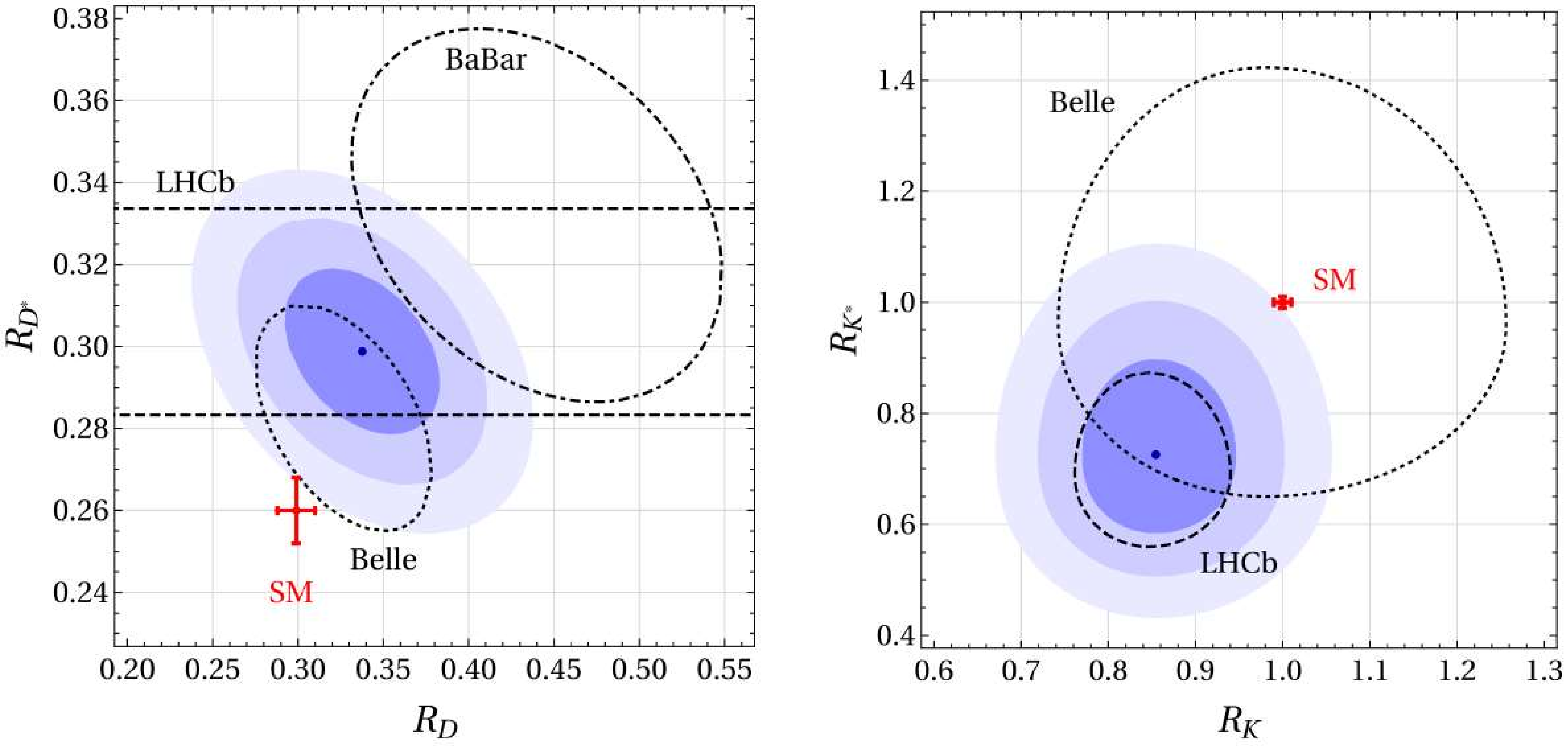


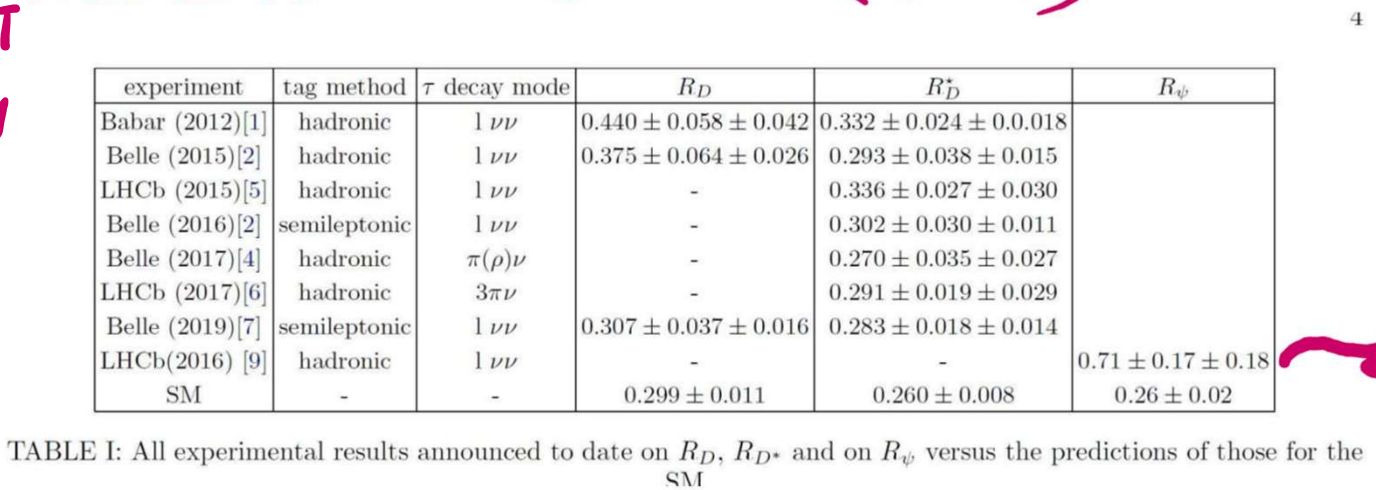
FIG. 1. Experimental averages (shown by the blue dot for the best-fit and darker-to-lighter shaded regions for $1\sigma, 2\sigma, 3\sigma$) and SM predictions (shown by red error bars) for the LFUV observables R_D and R_{D^*} (left), as well as R_K and R_{K^*} (right). The values for $R_{K^{(*)}}$ correspond to a dilepton invariant mass squared of $1.1\ \mathrm{GeV}^2 < q^2 < 6\ \mathrm{GeV}^2$. Individual 1σ regions from Belle, LHCb, and *BABAR* are also shown by the dotted, dashed, and dash-dotted contours, respectively.

FACT OR FARCE? [Charge Current only]

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

~ O(6) are independent

IMPORTANT CAUTION



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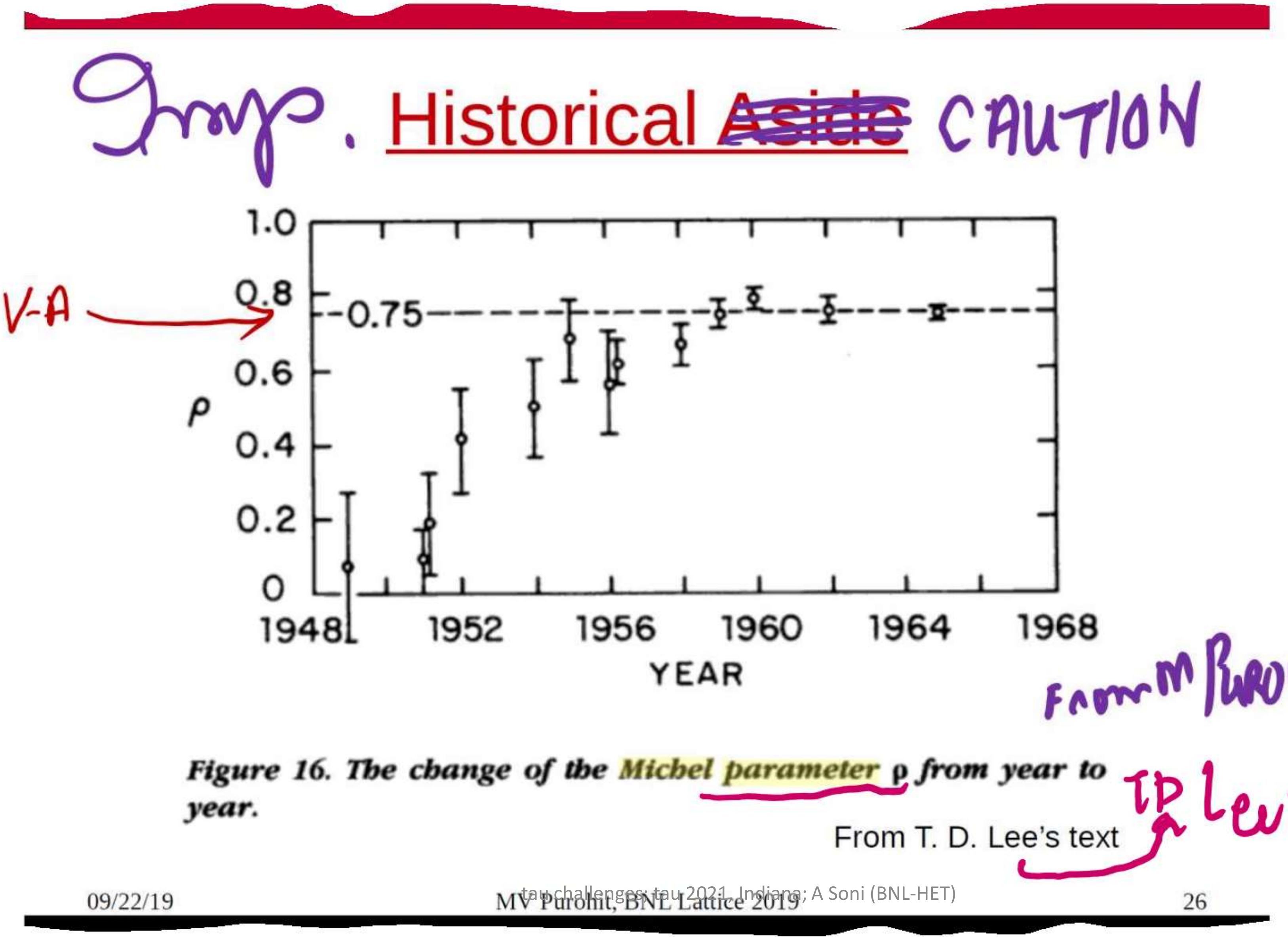
experiment	tag method	τ decay mode	R_D	R^*_D	R_ψ
Babar (2012)[1]	hadronic	$l\,\nu\nu$	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.0.018$	
Belle (2015)[2]	hadronic	$l\,\nu\nu$	$0.375 \pm 0.064 \pm 0.026$	$0.293 \pm 0.038 \pm 0.015$	
LHCb (2015)[5]	hadronic	$l\,\nu\nu$	-	$0.336 \pm 0.027 \pm 0.030$	
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; see 2002.12910



Imp. Historical ~~Aside~~ CAUTION

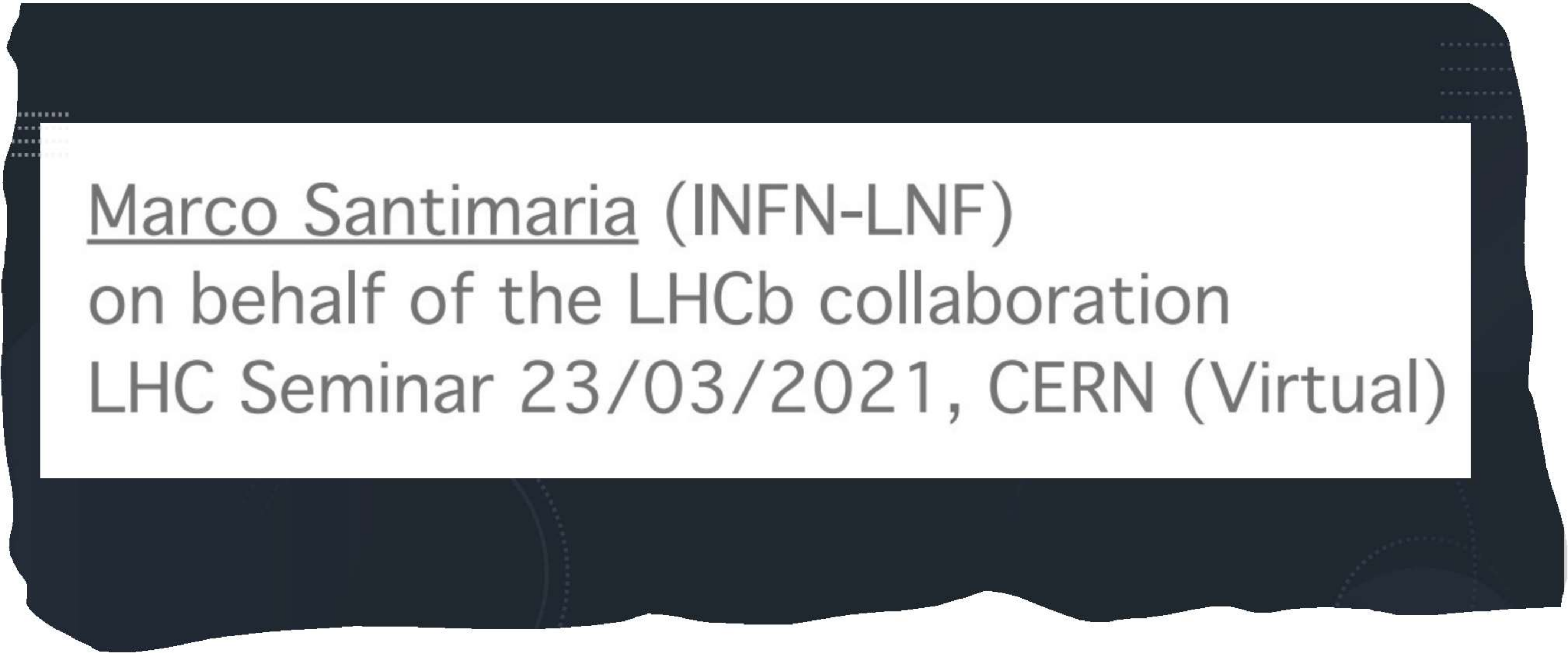
From M Purohit

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

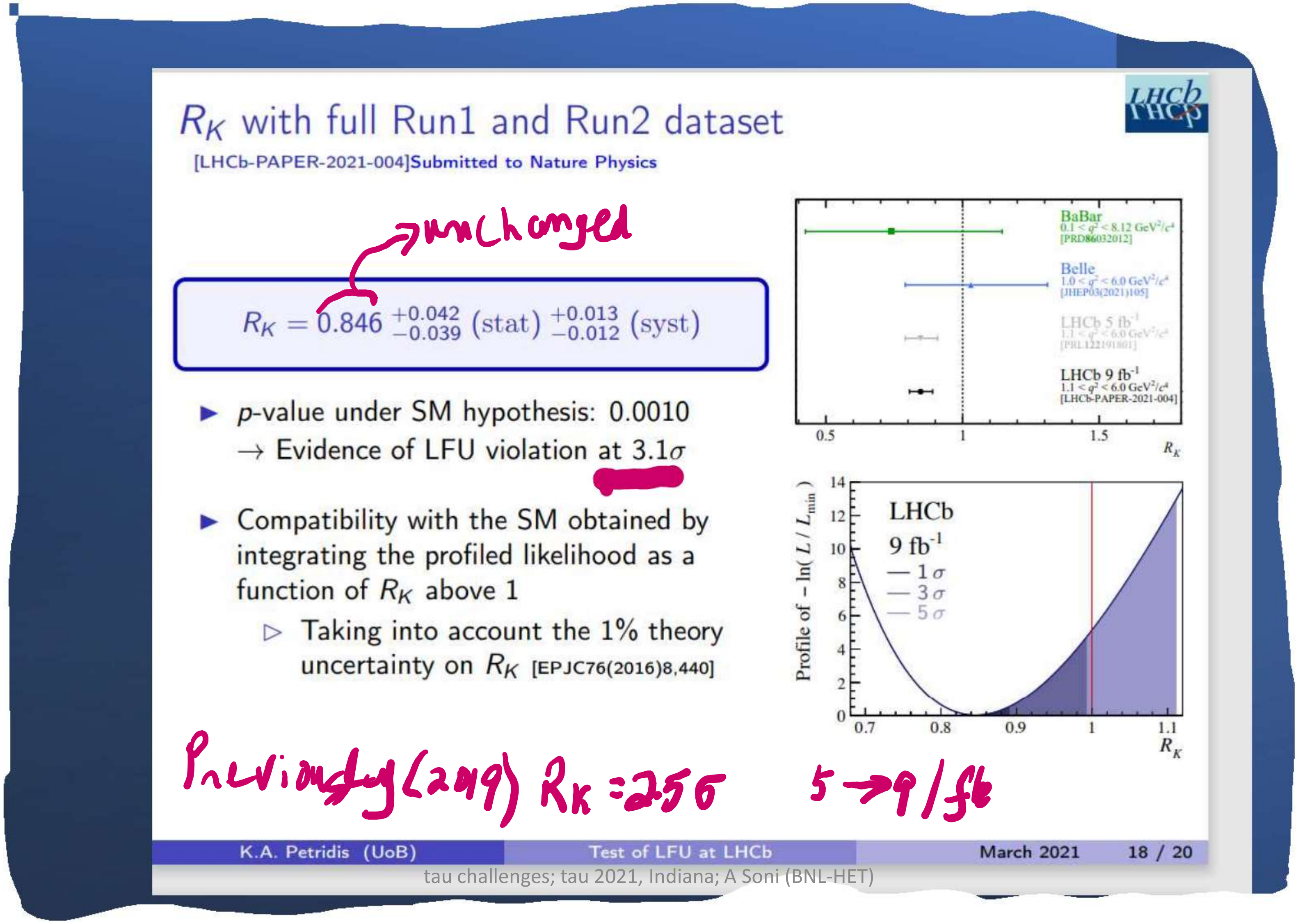
From T. D. Lee's text

TD Lee + CS Wu

09/22/19 MV Purohit, BNL Lattice 2019 26



Marco Santimaria (INFN-LNF)
on behalf of the LHCb collaboration
LHC Seminar 23/03/2021, CERN (Virtual)



R_K with full Run1 and Run2 dataset

[LHCb-PAPER-2021-004]**Submitted to Nature Physics**

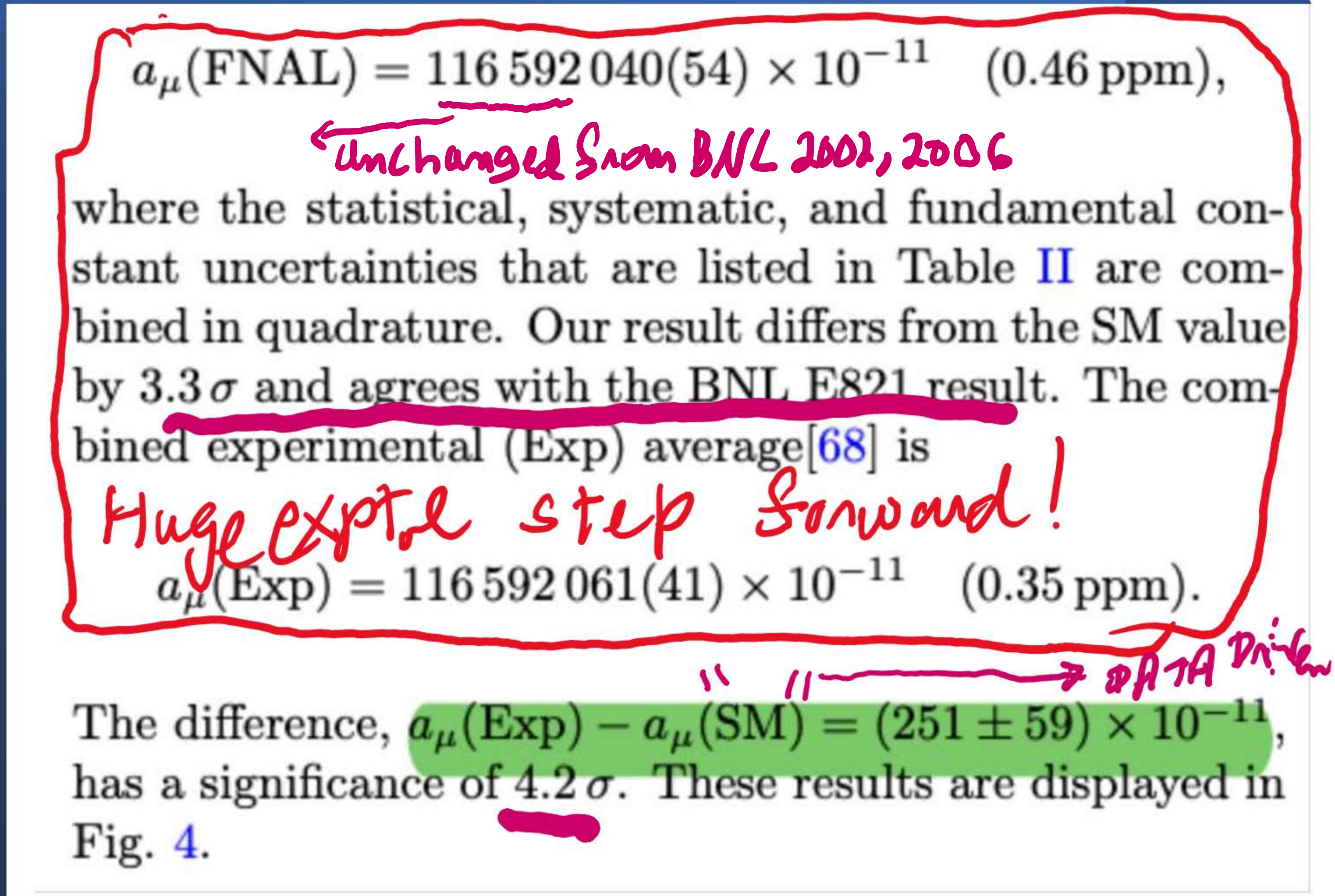
→unchanged

$$R_K = 0.846\,^{+0.042}_{-0.039}\,(\text{stat})\,^{+0.013}_{-0.012}\,(\text{syst})$$

- *p*-value under SM hypothesis: 0.0010
  → Evidence of LFU violation at 3.1σ
- Compatibility with the SM obtained by integrating the profiled likelihood as a function of R_K above 1
  - Taking into account the 1% theory uncertainty on R_K [EPJC76(2016)8,440]

Previously (2019) R_K = 2.5σ 5 → 9/fb

K.A. Petridis (UoB) Test of LFU at LHCb March 2021 18 / 20



$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm}),$$

← Unchanged from BNL 2002, 2006

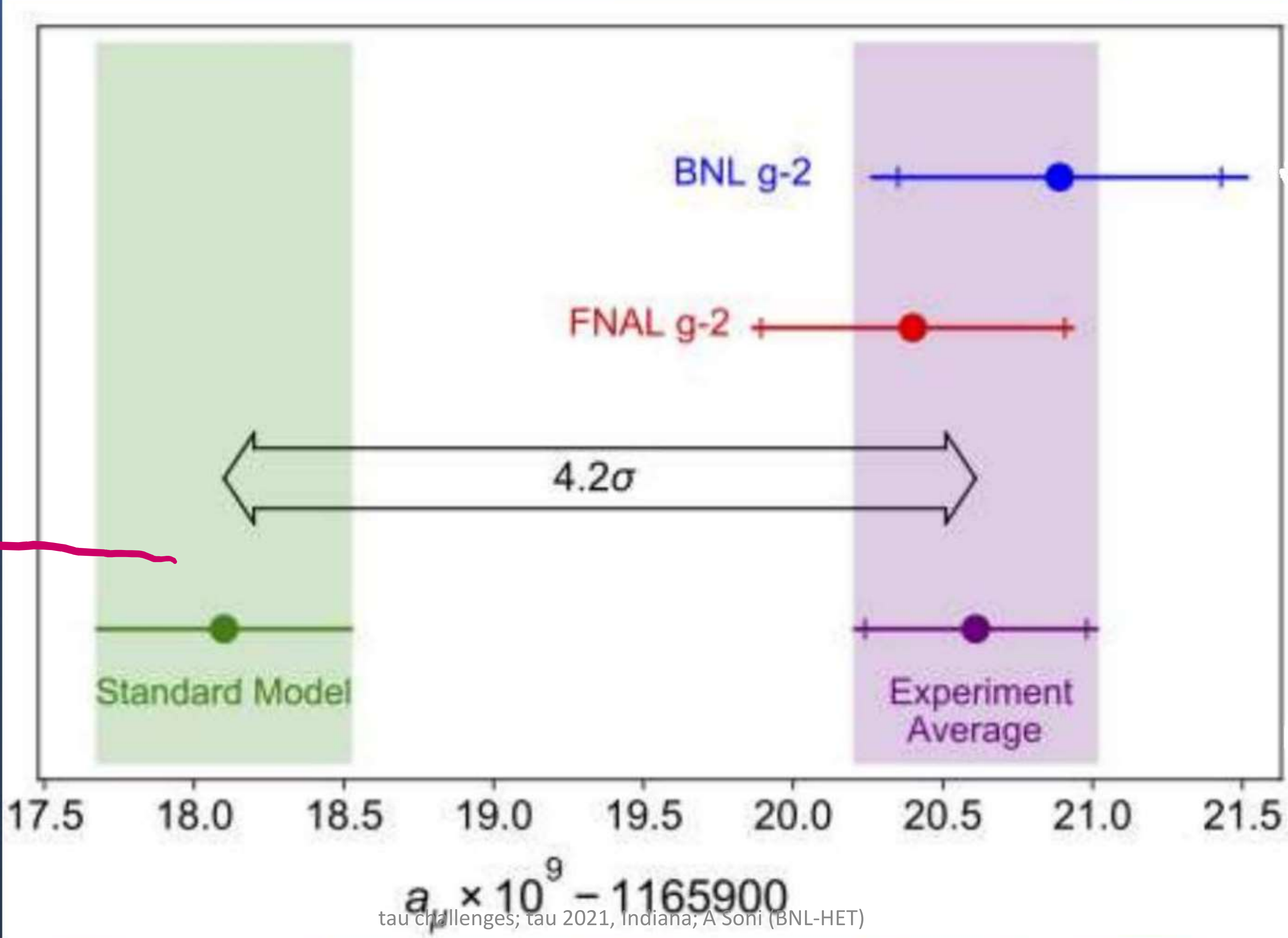
where the statistical, systematic, and fundamental constant uncertainties that are listed in Table II are combined in quadrature. Our result differs from the SM value by $3.3\,\sigma$ and agrees with the BNL E821 result. The combined experimental (Exp) average[68] is

Huge exptal step forward!

$$a_\mu(\mathrm{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35\,\mathrm{ppm}).$$

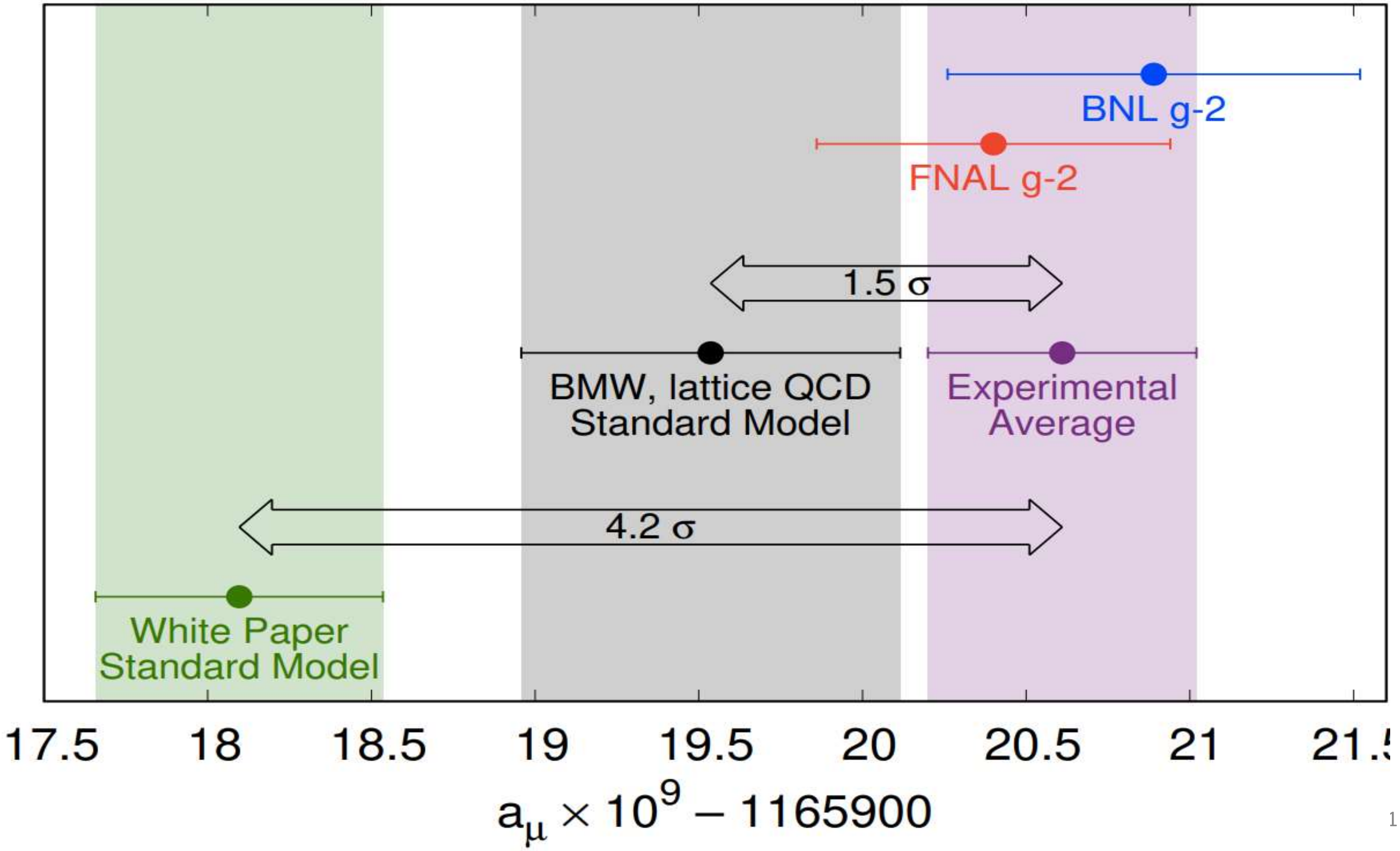
" " → DATA Driven

The difference, $a_\mu(\mathrm{Exp}) - a_\mu(\mathrm{SM}) = (251 \pm 59) \times 10^{-11}$, has a significance of $4.2\,\sigma$. These results are displayed in Fig. 4.



DATA
DRIVEN
[illegible]
See White
Paper

KALMAN SZABO (BMW) Talk @ "BNL"



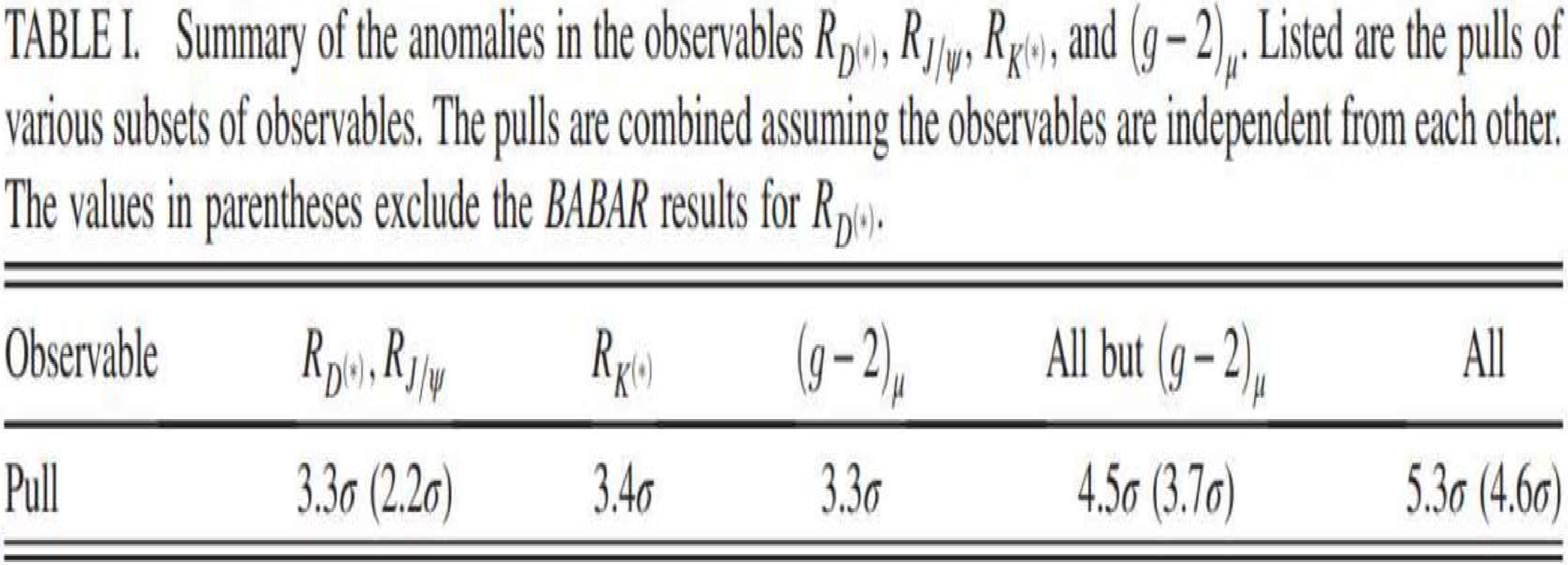


TABLE I. Summary of the anomalies in the observables $R_{D^{(*)}}$, $R_{J/\psi}$, $R_{K^{(*)}}$, and $(g-2)_\mu$. Listed are the pulls of various subsets of observables. The pulls are combined assuming the observables are independent from each other. The values in parentheses exclude the *BABAR* results for $R_{D^{(*)}}$.

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Pull	3.3σ (2.2σ)	3.4σ	3.3σ	4.5σ (3.7σ)	5.3σ (4.6σ)

2020

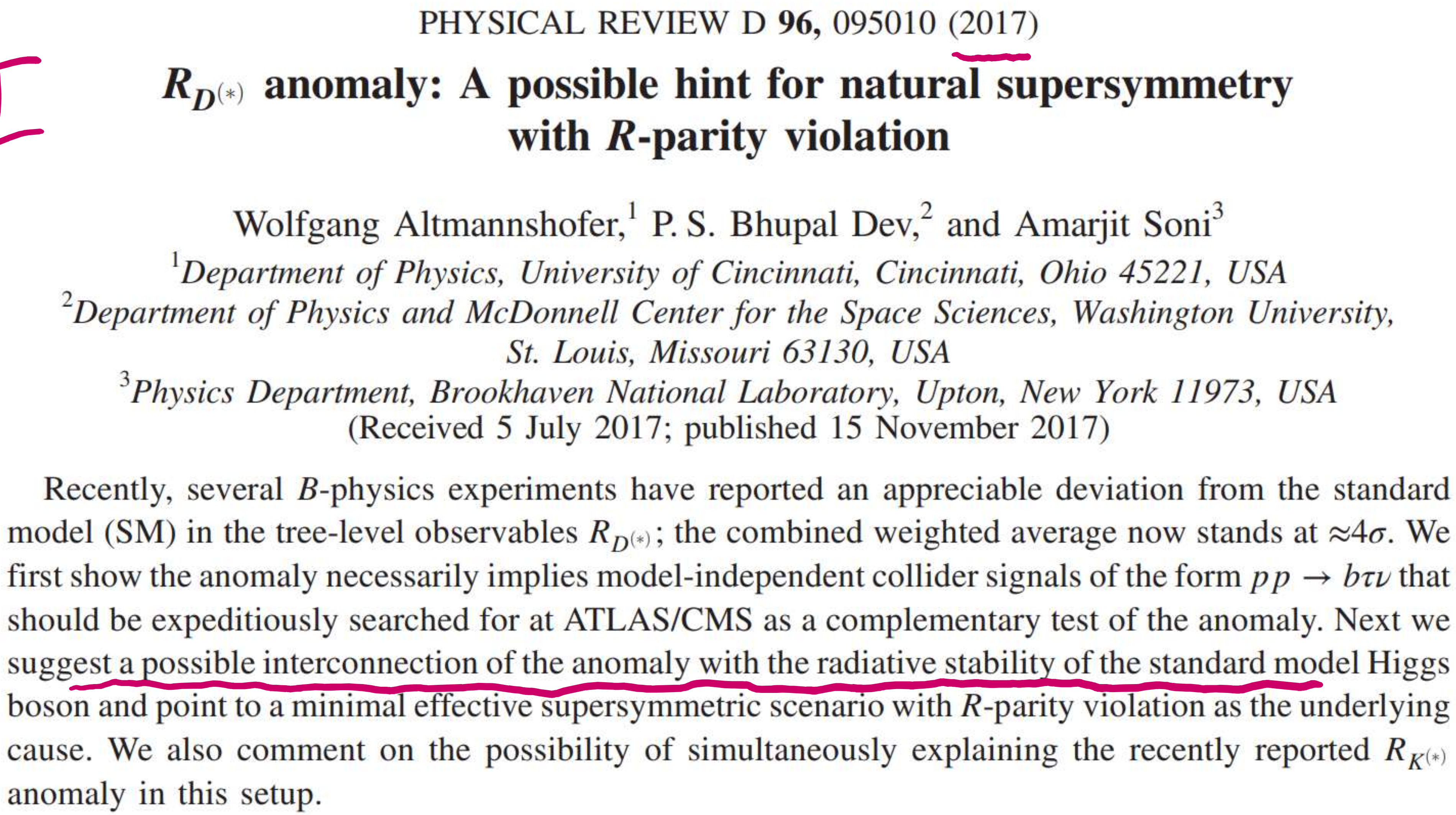
2021

R_K 3.1σ 4.2σ

↳ in quad $> 5\sigma$

Taking at Face value

I



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

$R_{D^{(*)}}$ anomaly: A possible hint for natural supersymmetry with R-parity violation

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[2] *Department of Physics and McDonnell Center for the Space Sciences, Washington University, St. Louis, Missouri 63130, USA*
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(Received 5 July 2017; published 15 November 2017)

Recently, several B-physics experiments have reported an appreciable deviation from the standard model (SM) in the tree-level observables $R_{D^{(*)}}$; the combined weighted average now stands at $\approx 4\sigma$. We first show the anomaly necessarily implies model-independent collider signals of the form $pp \to b\tau\nu$ that should be expeditiously searched for at ATLAS/CMS as a complementary test of the anomaly. Next we suggest a possible interconnection of the anomaly with the radiative stability of the standard model Higgs boson and point to a minimal effective supersymmetric scenario with R-parity violation as the underlying cause. We also comment on the possibility of simultaneously explaining the recently reported $R_{K^{(*)}}$ anomaly in this setup.

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

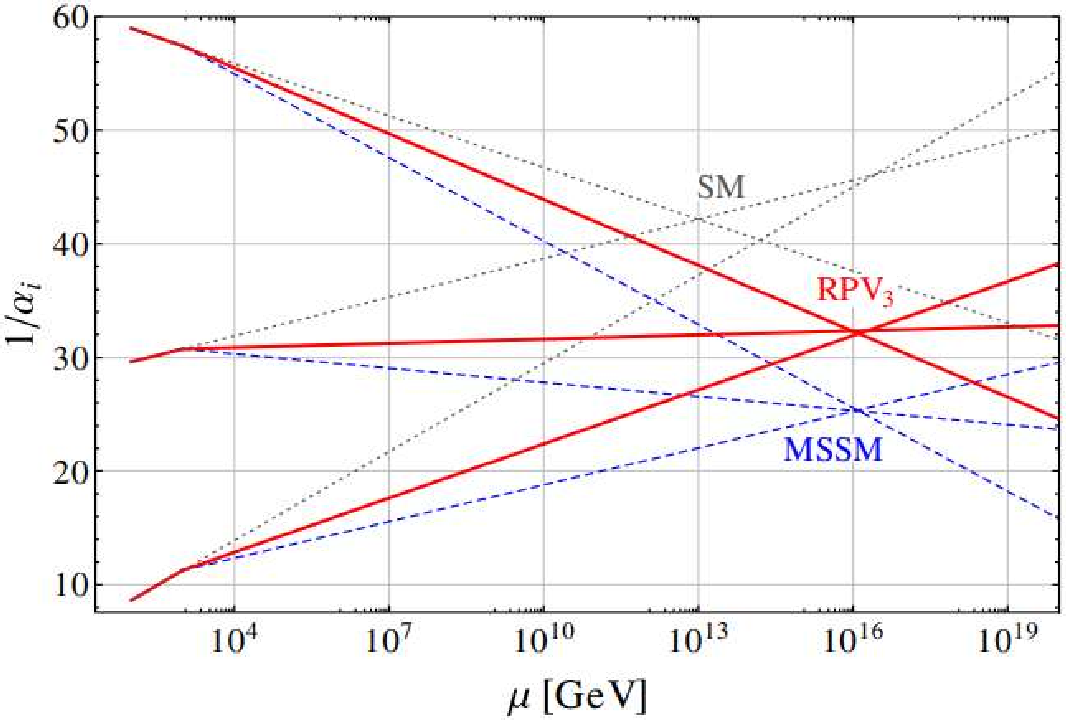


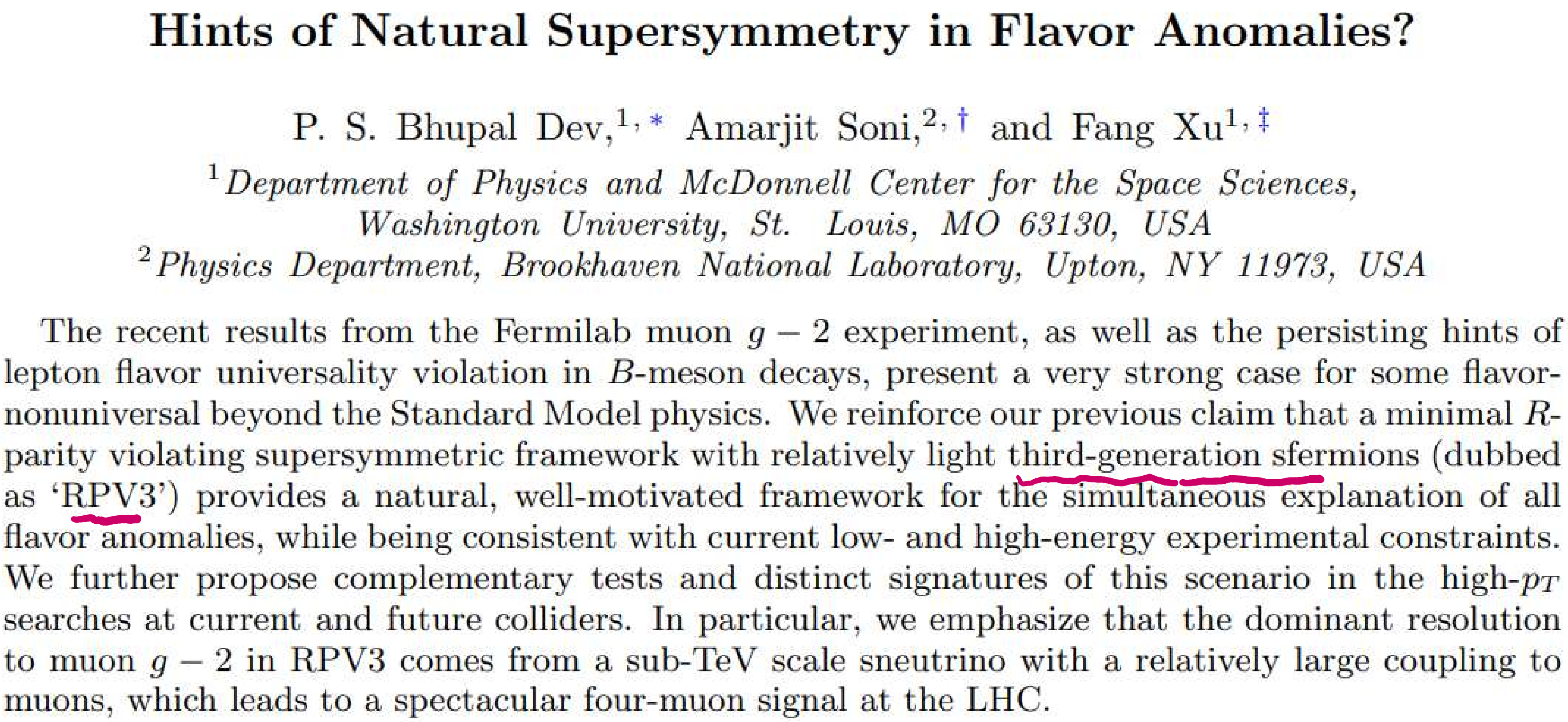
FIG. 2. RG evolution of the gauge couplings in the SM, MSSM and in our natural RPV SUSY scenario.

RPV$_3$

3rd gen superpartners are lightest

III

arXiv: 2106.15647



Hints of Natural Supersymmetry in Flavor Anomalies?

P. S. Bhupal Dev,[1,*] Amarjit Soni,[2,†] and Fang Xu[1,‡]

[1] *Department of Physics and McDonnell Center for the Space Sciences,*
Washington University, St. Louis, MO 63130, USA
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The recent results from the Fermilab muon $g-2$ experiment, as well as the persisting hints of lepton flavor universality violation in B-meson decays, present a very strong case for some flavor-nonuniversal beyond the Standard Model physics. We reinforce our previous claim that a minimal R-parity violating supersymmetric framework with relatively light third-generation sfermions (dubbed as 'RPV3') provides a natural, well-motivated framework for the simultaneous explanation of all flavor anomalies, while being consistent with current low- and high-energy experimental constraints. We further propose complementary tests and distinct signatures of this scenario in the high-p_T searches at current and future colliders. In particular, we emphasize that the dominant resolution to muon $g-2$ in RPV3 comes from a sub-TeV scale sneutrino with a relatively large coupling to muons, which leads to a spectacular four-muon signal at the LHC.

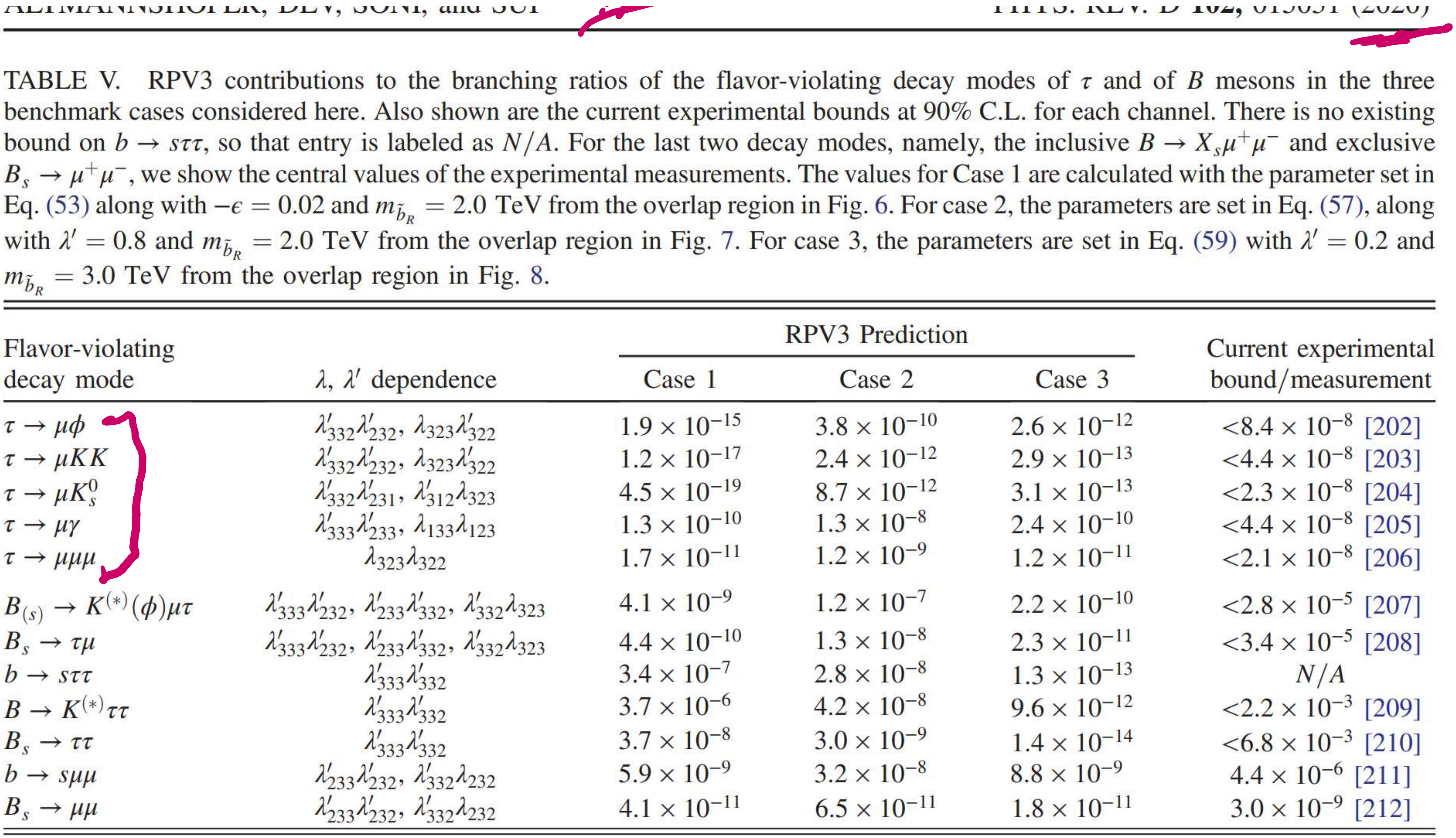
If current hints of LUV survive the test of time

- **Under such a watershed departure from the past, we believe, it is very likely that nature is also trying to address some long-standing, persistent issue(s) with the SM. One such basic concern with the SM is the fact that it is exceedingly fine-tuned, i.e. unnatural due to radiative instability of the Higgs which primarily originates from the heaviness of the top quark, a member of the third generation.**

Generalization of YM=> RPV LUV arise rather naturally

- Note also that, as a necessary **generalization of the Yang-Mills theory [42], all the interactions allowed by the enlarged internal [Bose-Fermi] symmetry readily remove the accidental flavor symmetry of the SM and lead naturally to LFUV**.

LFV of tau are a general consequence of these BSMs, Specifically for RPV3:



ALTMANNSHOFER, DEV, SONI, and SUI PHYS. REV. D 102, 015031 (2020)

TABLE V. RPV3 contributions to the branching ratios of the flavor-violating decay modes of τ and of B mesons in the three benchmark cases considered here. Also shown are the current experimental bounds at 90% C.L. for each channel. There is no existing bound on $b \to s\tau\tau$, so that entry is labeled as N/A. For the last two decay modes, namely, the inclusive $B \to X_s\mu^+\mu^-$ and exclusive $B_s \to \mu^+\mu^-$, we show the central values of the experimental measurements. The values for Case 1 are calculated with the parameter set in Eq. (53) along with $-\epsilon = 0.02$ and $m_{\tilde{b}_R} = 2.0$ TeV from the overlap region in Fig. 6. For case 2, the parameters are set in Eq. (57), along with $\lambda' = 0.8$ and $m_{\tilde{b}_R} = 2.0$ TeV from the overlap region in Fig. 7. For case 3, the parameters are set in Eq. (59) with $\lambda' = 0.2$ and $m_{\tilde{b}_R} = 3.0$ TeV from the overlap region in Fig. 8.

Flavor-violating decay mode	λ, λ' dependence	RPV3 Prediction Case 1	RPV3 Prediction Case 2	RPV3 Prediction Case 3	Current experimental bound/measurement
$\tau \to \mu\phi$	$\lambda'_{332}\lambda'_{232}$, $\lambda_{323}\lambda'_{322}$	1.9×10^{-15}	3.8×10^{-10}	2.6×10^{-12}	$<8.4 \times 10^{-8}$ [202]
$\tau \to \mu KK$	$\lambda'_{332}\lambda'_{232}$, $\lambda_{323}\lambda'_{322}$	1.2×10^{-17}	2.4×10^{-12}	2.9×10^{-13}	$<4.4 \times 10^{-8}$ [203]
$\tau \to \mu K^0_s$	$\lambda'_{332}\lambda'_{231}$, $\lambda'_{312}\lambda_{323}$	4.5×10^{-19}	8.7×10^{-12}	3.1×10^{-13}	$<2.3 \times 10^{-8}$ [204]
$\tau \to \mu\gamma$	$\lambda'_{333}\lambda'_{233}$, $\lambda_{133}\lambda_{123}$	1.3×10^{-10}	1.3×10^{-8}	2.4×10^{-10}	$<4.4 \times 10^{-8}$ [205]
$\tau \to \mu\mu\mu$	$\lambda_{323}\lambda_{322}$	1.7×10^{-11}	1.2×10^{-9}	1.2×10^{-11}	$<2.1 \times 10^{-8}$ [206]
$B_{(s)} \to K^{(*)}(\phi)\mu\tau$	$\lambda'_{333}\lambda'_{232}$, $\lambda'_{233}\lambda'_{332}$, $\lambda'_{332}\lambda_{323}$	4.1×10^{-9}	1.2×10^{-7}	2.2×10^{-10}	$<2.8 \times 10^{-5}$ [207]
$B_s \to \tau\mu$	$\lambda'_{333}\lambda'_{232}$, $\lambda'_{233}\lambda'_{332}$, $\lambda'_{332}\lambda_{323}$	4.4×10^{-10}	1.3×10^{-8}	2.3×10^{-11}	$<3.4 \times 10^{-5}$ [208]
$b \to s\tau\tau$	$\lambda'_{333}\lambda'_{332}$	3.4×10^{-7}	2.8×10^{-8}	1.3×10^{-13}	N/A
$B \to K^{(*)}\tau\tau$	$\lambda'_{333}\lambda'_{332}$	3.7×10^{-6}	4.2×10^{-8}	9.6×10^{-12}	$<2.2 \times 10^{-3}$ [209]
$B_s \to \tau\tau$	$\lambda'_{333}\lambda'_{332}$	3.7×10^{-8}	3.0×10^{-9}	1.4×10^{-14}	$<6.8 \times 10^{-3}$ [210]
$b \to s\mu\mu$	$\lambda'_{233}\lambda'_{232}$, $\lambda'_{332}\lambda_{232}$	5.9×10^{-9}	3.2×10^{-8}	8.8×10^{-9}	4.4×10^{-6} [211]
$B_s \to \mu\mu$	$\lambda'_{233}\lambda'_{232}$, $\lambda'_{332}\lambda_{232}$	4.1×10^{-11}	6.5×10^{-11}	1.8×10^{-11}	3.0×10^{-9} [212]

If current hints survive and do require new physics

- **BNL 1964 Fitch-Cronin expt demonstrated CP is NOT a symmetry of nature**
- **Therefore, it follows that, naturalness arguments strongly suggest BSMs should entail new CP-odd phase(s)**
- **Spin analyzing capability and possibility of multibody FSs in tau decays makes it extremely powerful probe for searching new BSM-phase(s)**

A very popular class of BSMs to address these anomalies involve lepto-quark interactions

- **LQ interactions for tau –edm may well involve top-quark resulting in enhanced tau-edm**

- **Also in RPV3 lepton edms have potential for appreciable enhancements; see, e.g. R. Godbole, 2007.**

Interesting decay modes for CP studies $\tau \rightarrow [K_S \pi^-, K^{*0} \pi^-, \rho^0 K^-] \nu$

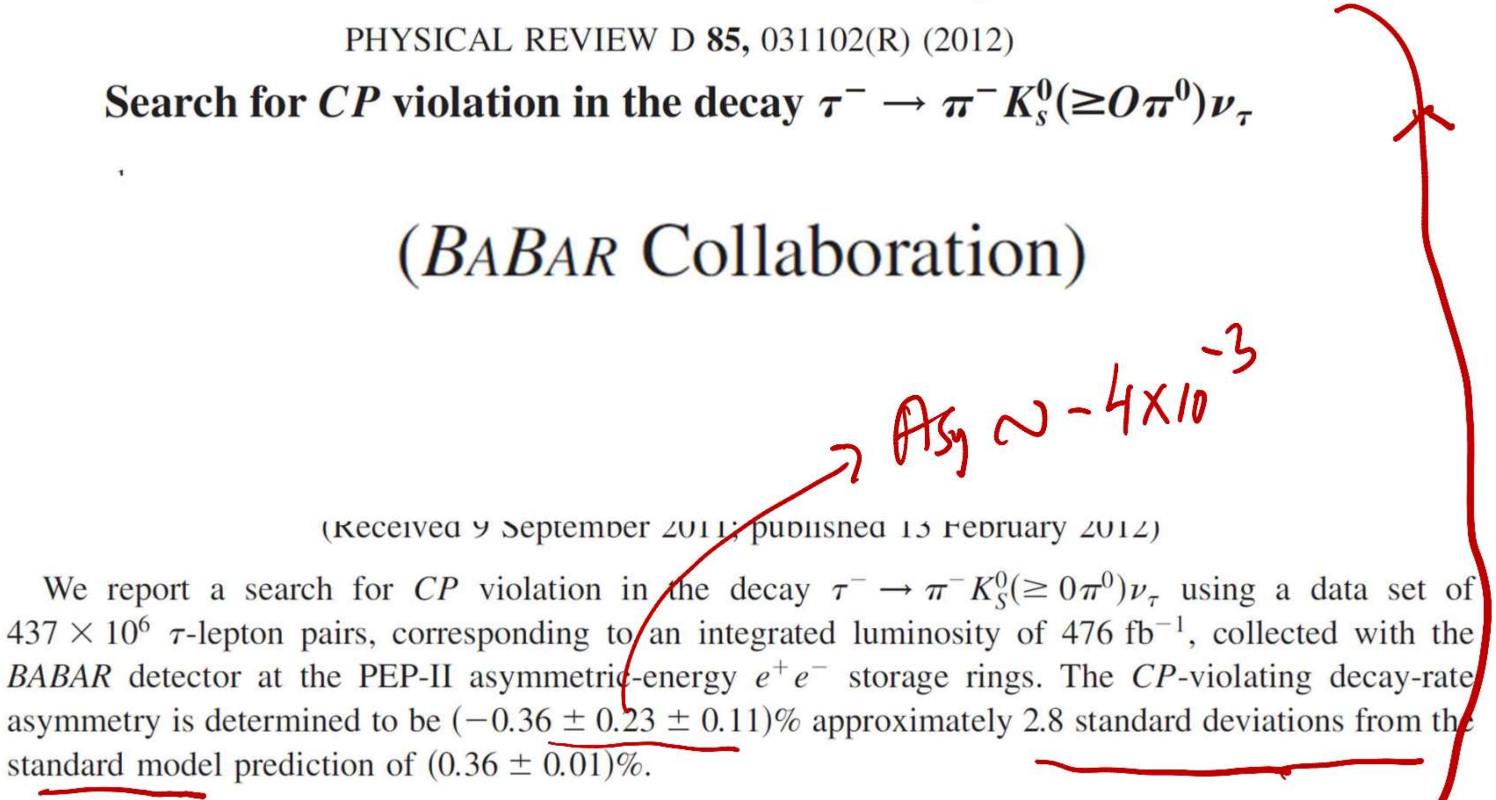
4 body FS

CP-odd T_N even
RATE or Energy asy

T_N-odd
Triple Corrl

Atwood, Ban-Shalom, Eilam + AS
Phys. Report 2001

Great for BELLE-II & STCF



PHYSICAL REVIEW D **85,** 031102(R) (2012)

Search for *CP* violation in the decay $\tau^- \to \pi^- K_s^0 (\geq 0\pi^0)\nu_\tau$

(*BABAR* Collaboration)

(Received 9 September 2011; published 13 February 2012)

We report a search for *CP* violation in the decay $\tau^- \to \pi^- K_S^0(\geq 0\pi^0)\nu_\tau$ using a data set of 437×10^6 τ-lepton pairs, corresponding to an integrated luminosity of 476 fb^{-1}, collected with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- storage rings. The *CP*-violating decay-rate asymmetry is determined to be $(-0.36 \pm 0.23 \pm 0.11)\%$ approximately 2.8 standard deviations from the standard model prediction of $(0.36 \pm 0.01)\%$.

$A_{sy} \sim -4 \times 10^{-3}$

NOTE

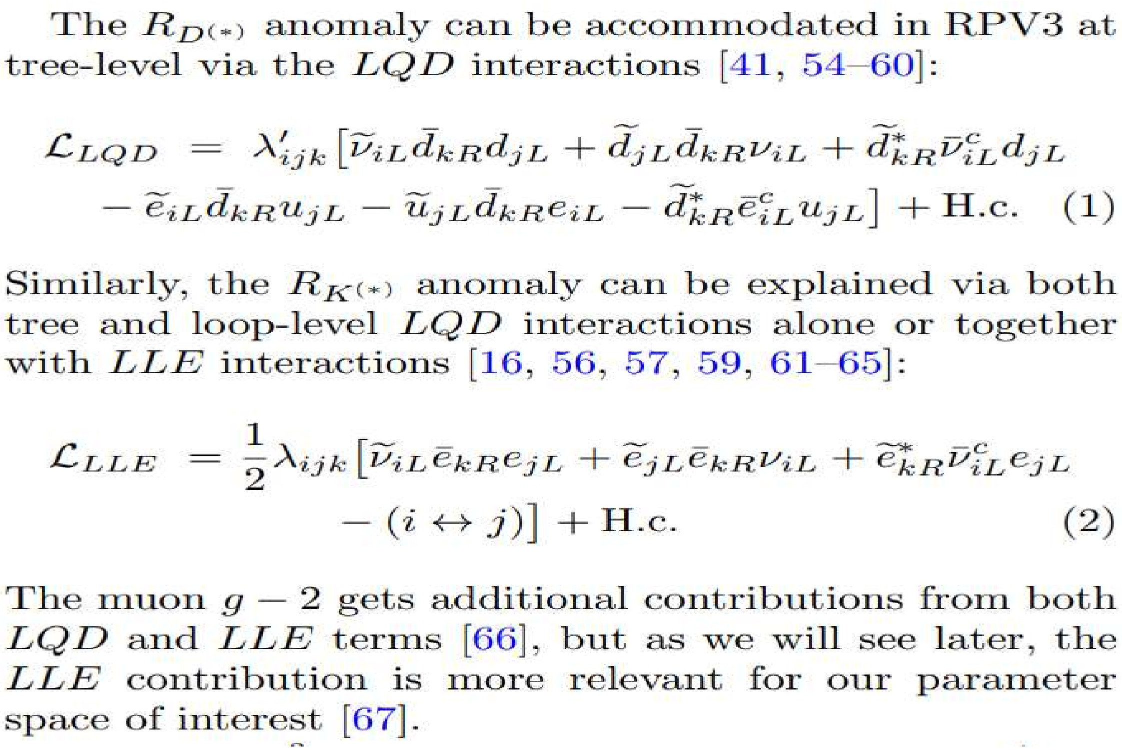
$B_r[\tau \to \nu \pi^- \bar{K}^0] = (8.40 \pm .14) \times 10^{-3}$

$\sim 2\%$

$N_{\tau\tau} \sim 10^9$ needed

Facilitating precision lattice studies: tau mass ~1.8 GeV is not that large [contrast with B mesons]

⇒ even with chiral sym Lattice simulations are already doable



The $R_{D^{(*)}}$ anomaly can be accommodated in RPV3 at tree-level via the LQD interactions [41, 54–60]:

$$\mathcal{L}_{LQD} = \lambda'_{ijk}\left[\widetilde{\nu}_{iL}\bar{d}_{kR}d_{jL} + \widetilde{d}_{jL}\bar{d}_{kR}\nu_{iL} + \widetilde{d}^*_{kR}\bar{\nu}^c_{iL}d_{jL} - \widetilde{e}_{iL}\bar{d}_{kR}u_{jL} - \widetilde{u}_{jL}\bar{d}_{kR}e_{iL} - \widetilde{d}^*_{kR}\bar{e}^c_{iL}u_{jL}\right] + \text{H.c.} \quad (1)$$

Similarly, the $R_{K^{(*)}}$ anomaly can be explained via both tree and loop-level LQD interactions alone or together with LLE interactions [16, 56, 57, 59, 61–65]:

$$\mathcal{L}_{LLE} = \frac{1}{2}\lambda_{ijk}\left[\widetilde{\nu}_{iL}\bar{e}_{kR}e_{jL} + \widetilde{e}_{jL}\bar{e}_{kR}\nu_{iL} + \widetilde{e}^*_{kR}\bar{\nu}^c_{iL}e_{jL} - (i \leftrightarrow j)\right] + \text{H.c.} \quad (2)$$

The muon $g-2$ gets additional contributions from both LQD and LLE terms [66], but as we will see later, the LLE contribution is more relevant for our parameter space of interest [67].

QCD is still an integral part whether Short Dist in SU(2)xU(1) SM or some BSM

Lattice methods can be used for precise predictions for tau

- **Some possible examples:**
- **g-2**

- **edm**

- **Decay amplitudes**
- **Dir CP asymmetries [if needs be scattering phases may be used from Chpt though lattice methods at least for some cases have become doable; see e.g. RBC-UKQCD 2103.15131, pi pi (I=0 & 2) at physical masses]**

Power of tau spin for searching BSM phase

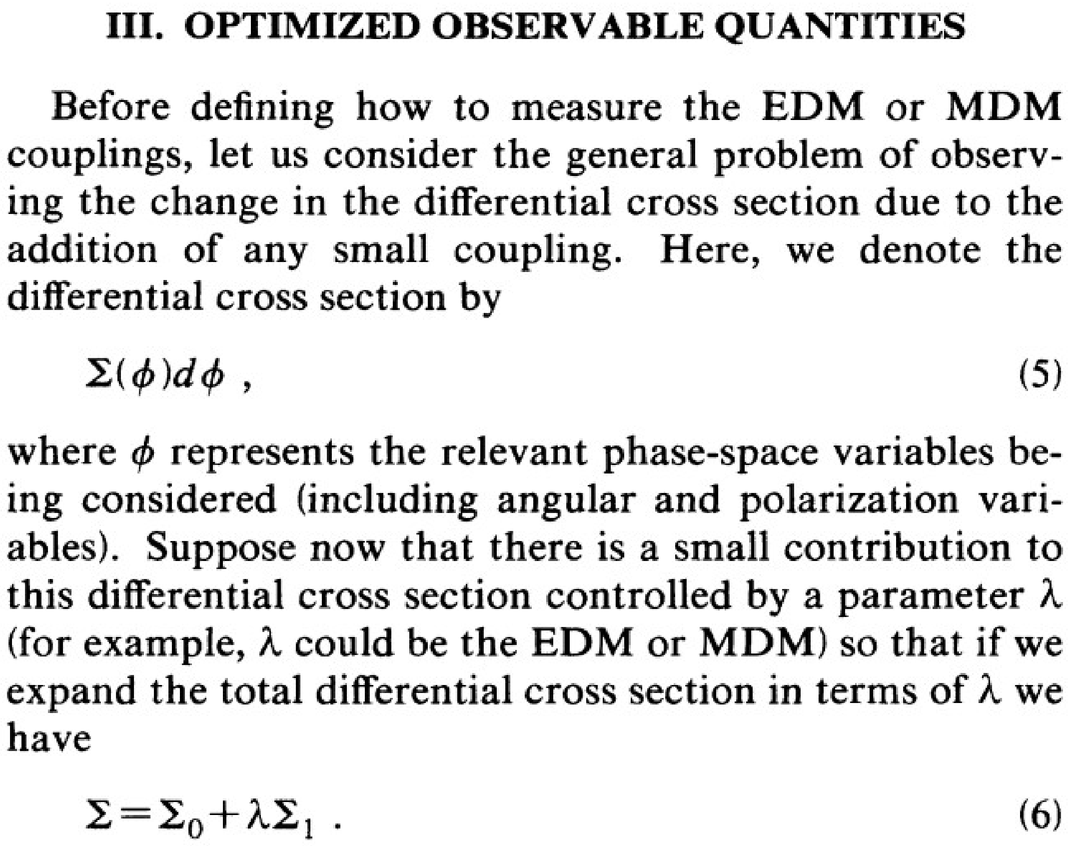
- **See, Atwood + AS PRD, 1992**
- **Actually the analysis there is for top quark production and decay**
- **But applies equally well to tau with appropriate (obvious) changes**
- **The main point is many observables to monitor magnetic and electric dipole moments can be constructed from the final states**
- **In fact the paper proves a simple theorem [see section III] for constructing "optimal" observable among those**
- **Nowadays, the construction in that paper is commonly used for "machine learning"; See e.g. Ref 27 in J. Brehmer et al, arXiv: 1907.10621 [More in backup]**

Summary

- Current hints from muon g-2 and from B-anomalies indicate non-universal flavor BSM physics
- If these hints survive the test of time some type of LQ interactions or RPV may well be the underlying BSM
- tau-physics likely to be extremely informative about the underlying BSM
- Increased luminosities at Belle-II and LHC-experiments should be very valuable for tau studies
- tau mass of ~1.8 GeV means precision studies with lattice fermions that are very much continuum-like (so Chpt is continuum like as well)=>extrapolations are a lot cleaner [as no unphysical dof are entailed]

XTRA’S

ATWOOD + AS
PRD 92



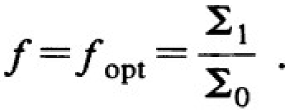
III. OPTIMIZED OBSERVABLE QUANTITIES

Before defining how to measure the EDM or MDM couplings, let us consider the general problem of observing the change in the differential cross section due to the addition of any small coupling. Here, we denote the differential cross section by

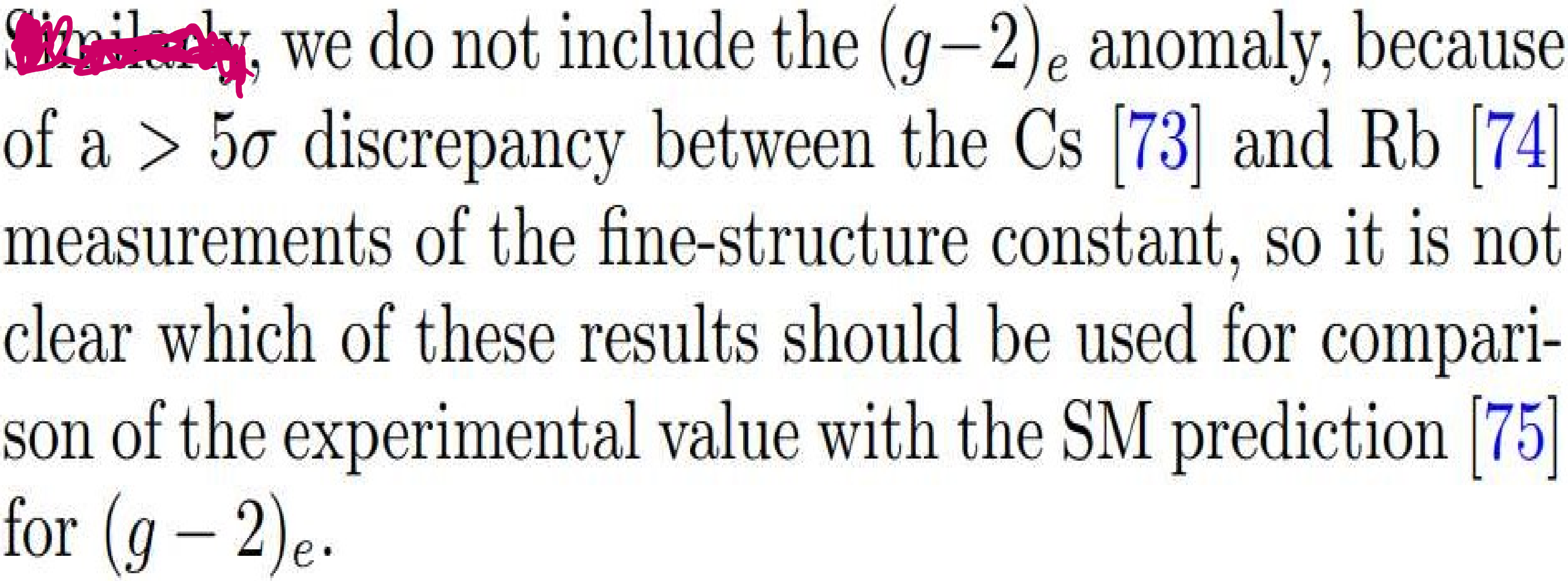
$$\Sigma(\phi)d\phi\ , \tag{5}$$

where ϕ represents the relevant phase-space variables being considered (including angular and polarization variables). Suppose now that there is a small contribution to this differential cross section controlled by a parameter λ (for example, λ could be the EDM or MDM) so that if we expand the total differential cross section in terms of λ we have

$$\Sigma=\Sigma_0+\lambda\Sigma_1\ . \tag{6}$$



$$f=f_{\rm opt}=\frac{\Sigma_1}{\Sigma_0}\ .$$



[redacted], we do not include the $(g-2)_e$ anomaly, because of a $> 5\sigma$ discrepancy between the Cs [73] and Rb [74] measurements of the fine-structure constant, so it is not clear which of these results should be used for comparison of the experimental value with the SM prediction [75] for $(g-2)_e$.