Theory Summary

16th Conf. on Flavor Physics and CP violation-2018

Hyderabad, India

SPECIAL THANKS to
RUKMANI +
ANJAN !!

Amarjit Soni,

Los Angeles, CA 90077; USA

07/ 18 /2018

Thanks: Bhupal.

HIGLY subjective; OMISSIONS ARE Guranteed.
Apologies for both!

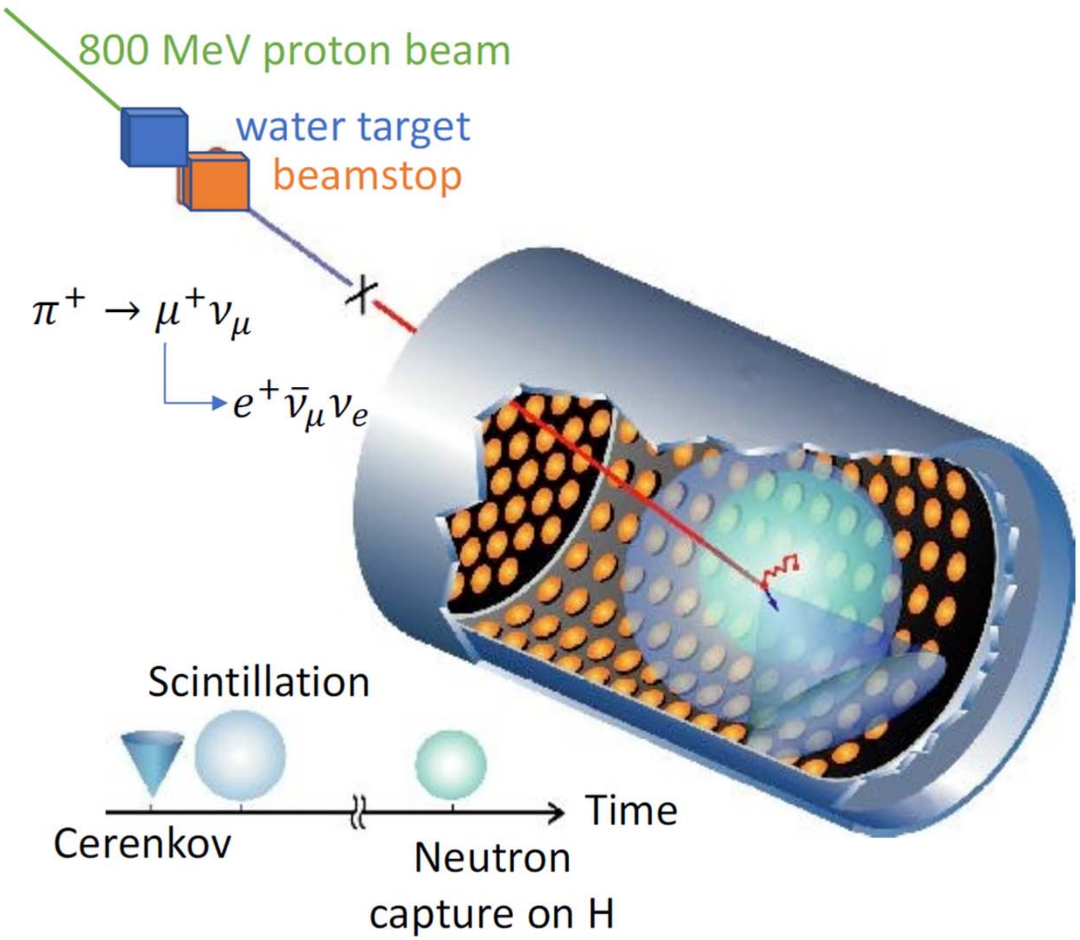
outline

- **ν highlights : very brief**
- **Gorilla and Godzilla & the quest for N P**
- **Summary & outlook**

NEUTRINOS IN BRIEF

1. MINIBOONE + LSND ANOMALY

LSND Anomaly



800 MeV proton beam

water target

beamstop

$\pi^+ \to \mu^+ \nu_\mu$

$\hookrightarrow e^+ \bar{\nu}_\mu \nu_e$

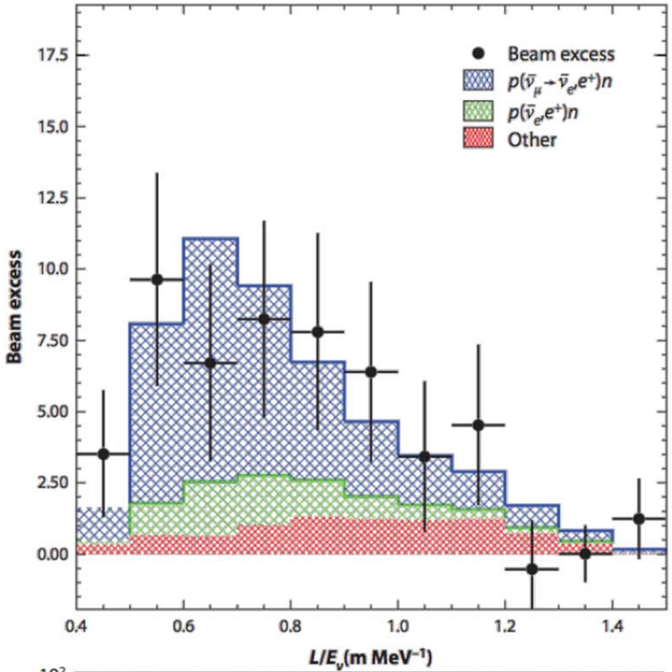
Scintillation

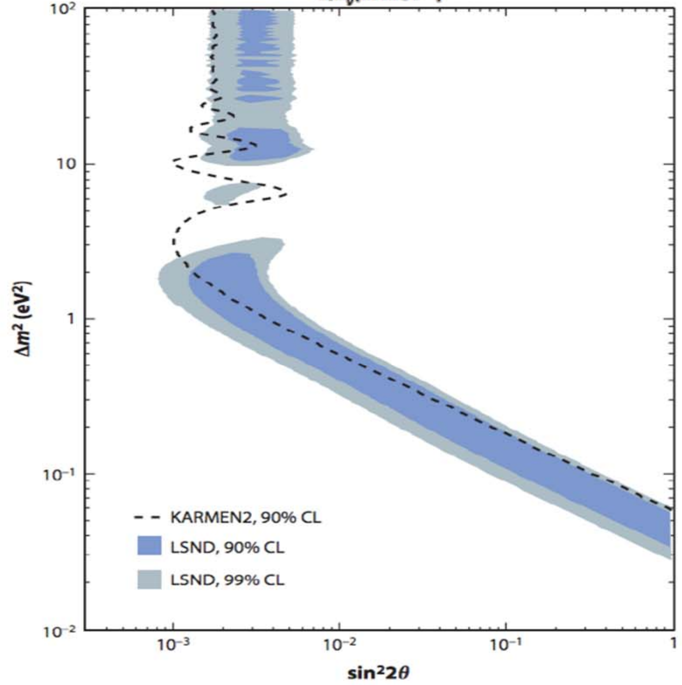
Cerenkov

Time

Neutron capture on H

LSND observed a 3.8σ excess

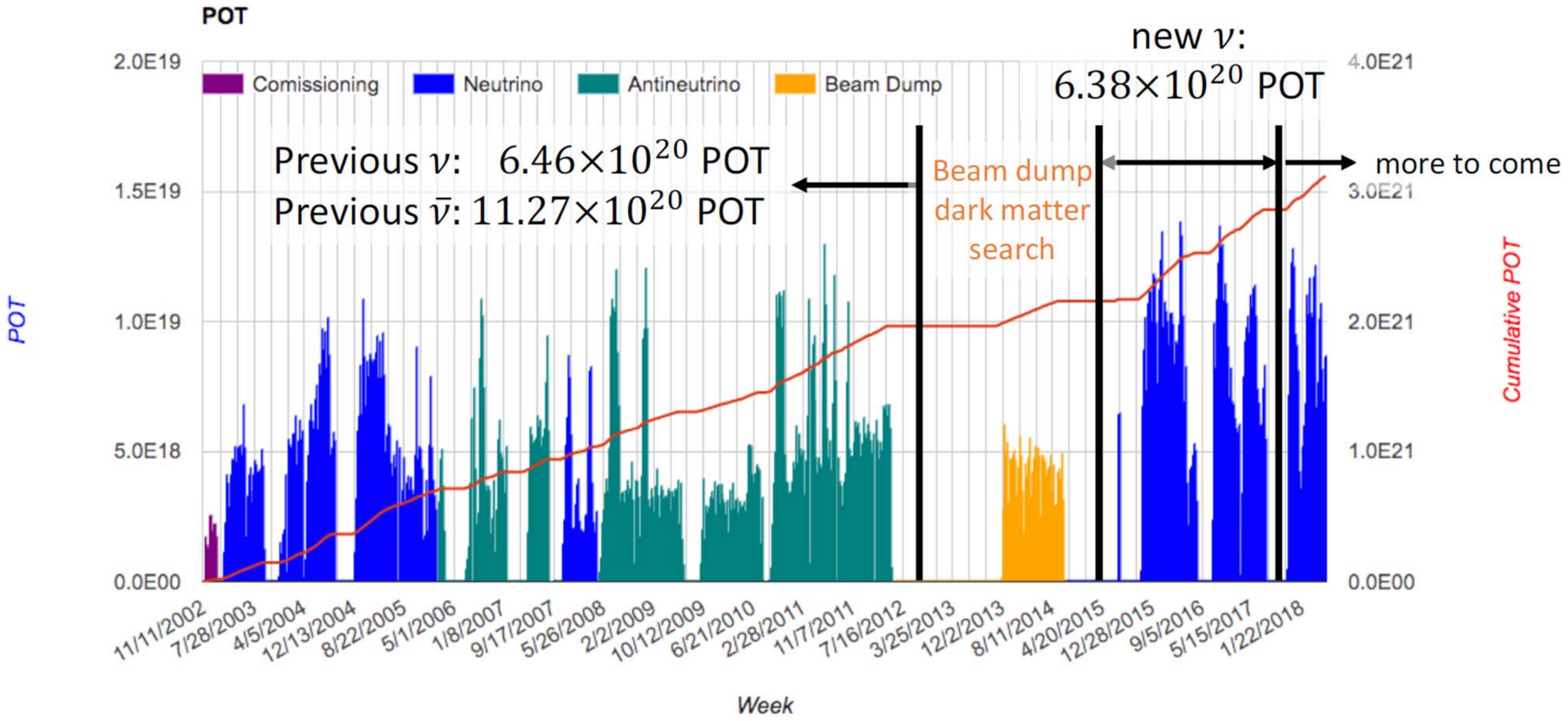




Annu. Rev. Nucl. Part. Sci., *63*(1), 45–67.

Data Set

- 15+ years of running in neutrino, antineutrino, and beam dump mode. More than 30×10^{20} POT to date.
- Result of a combined 12.84×10^{20} POT in ν mode + 11.27×10^{20} POT in $\bar{\nu}$ mode is presented in this talk



Previous ν: 6.46×10^{20} POT

Previous $\bar{\nu}$: 11.27×10^{20} POT

Beam dump dark matter search

new ν: 6.38×10^{20} POT

more to come

Excess

	$\boldsymbol{\nu}$ mode 12.84×10^{20} **POT**	**$\boldsymbol{\overline{\nu}}$ mode** $11.\mathbf{27}\times10^{20}$ **POT**	**Combined**
Data	1959	478	2437
Unconstrained Background	1590.5	398.2	1988.7
Constrained Background	1577.8	398.7	1976.5
Excess	381.2 ± 85.2 4.5σ	79.3 ± 28.6 2.8σ	460.5 ± 95.8 4.8σ
0.26% (LSND) $\nu_\mu \rightarrow \nu_e$	463.1	100.0	563.1

- Total excess for neutrino + antineutrino:

$$460.5 \pm 95.8(4.8\sigma)$$

- Combined with LSND (3.8σ), total significance is at 6.1σ

premature ∵ cf

Conclusion

- MiniBooNE confirms LSND excess at 4.8σ, with a combined significance at 6.1σ
- MiniBooNE continues data-taking, and analysis in the future will include time-of-flight information to better constrain backgrounds
- MicroBooNE will confirm whether excess is due to electrons or photons
- SBN will confirm whether the excess is due to neutrino oscillations
- Thanks to Fermilab for MiniBooNE operation (15 y) & for great beam delivery

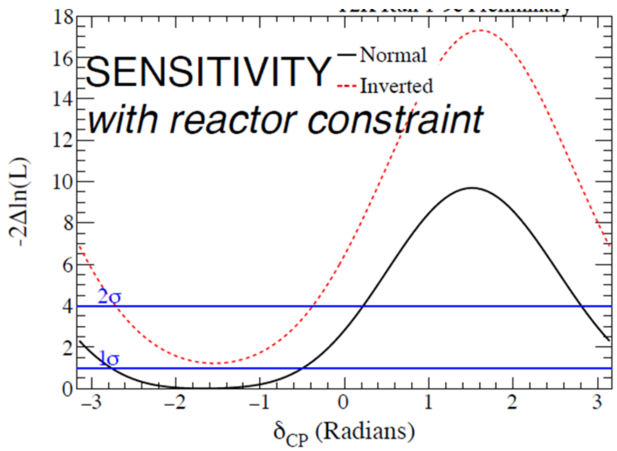
Conclusions

T2K

- T2K operated steadily at 485 kW beam power in 2017/18;
  - Collected total of 3.16×10^{21} POT, ~evenly split between FHC and RHC.

  ➡ **More than double the data set shown at Neutrino2016!**
- Analysed 1.49×10^{21} POT in FHC and 1.12×10^{21} POT in RHC:
  - **CP conserving values of δ_{CP} lie outside 2σ region.** !!!!
  - **Data show preference for Normal Hierarchy,**
    - Bayes factor for NH/IH is 7.9.
  - Analysis of full data set to be released late summer 2018.
- Upgrades to beam, near and far detectors progressing well:

CPV in neutrino sector is within reach! ←

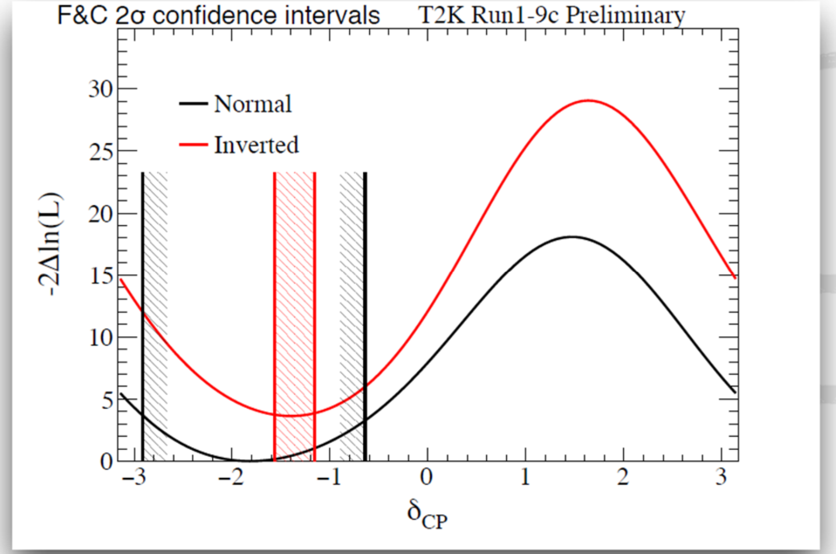


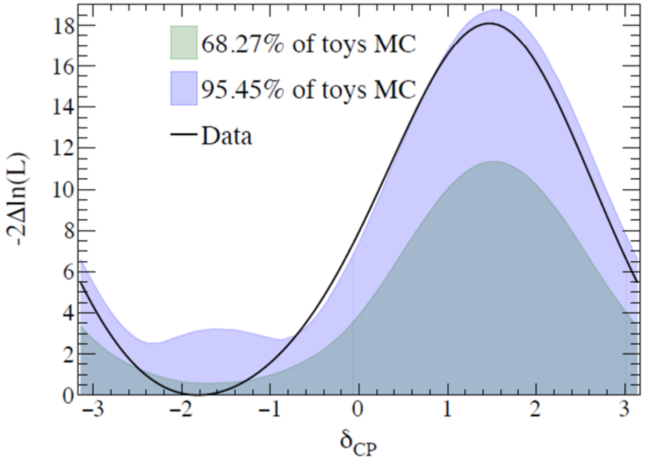
SENSITIVITY

with reactor constraint

- CP conserving values outside of 2σ reg
  for both hierarchies
- 19% of toys exclude CP conservation a
  2σ CL (both δ_{CP}=0 & δ_{CP}=π)

DATA FIT with reactor constraint





δ_{CP}	Hierarchy	90%	2σ
0	NH	0.421	0.288
π	NH	0.388	0.248
0	IH	0.768	0.660
π	IH	0.783	0.685

Imperial College
London
2018 / 06 / 04

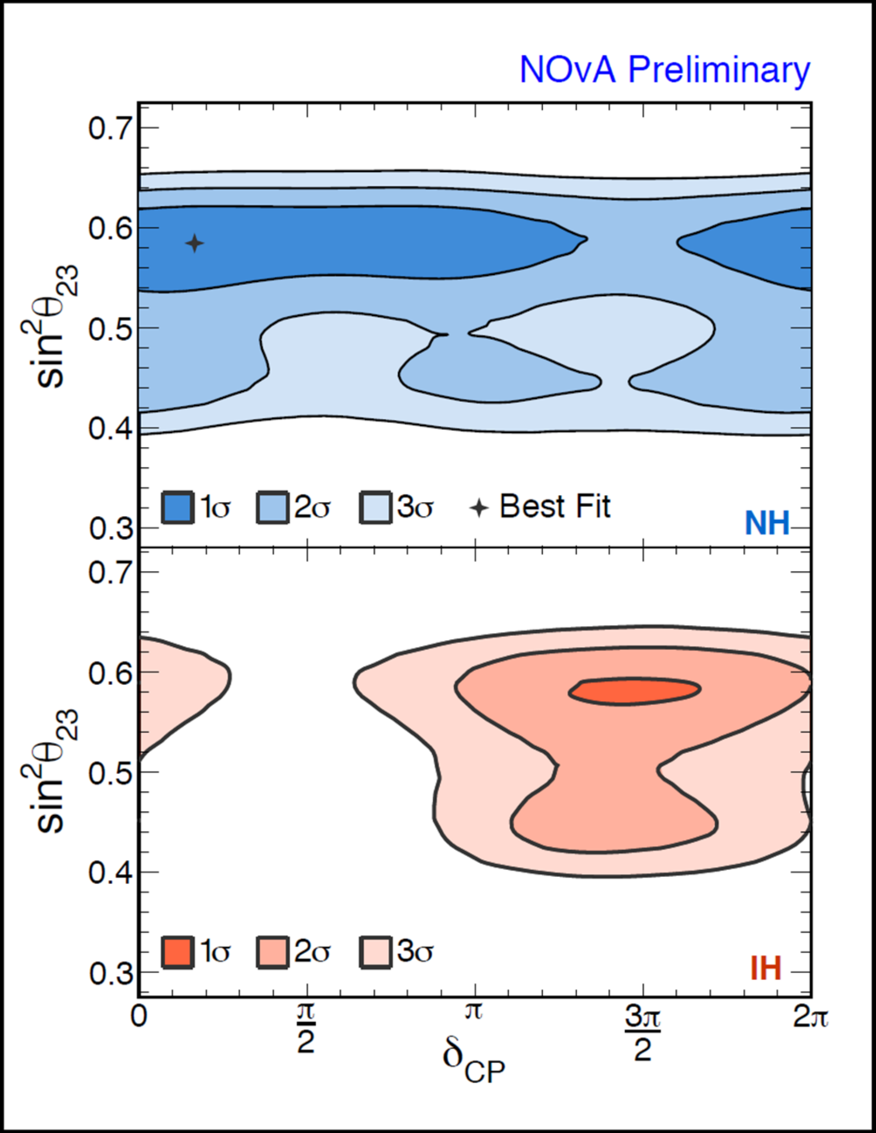
Neutrino 2018

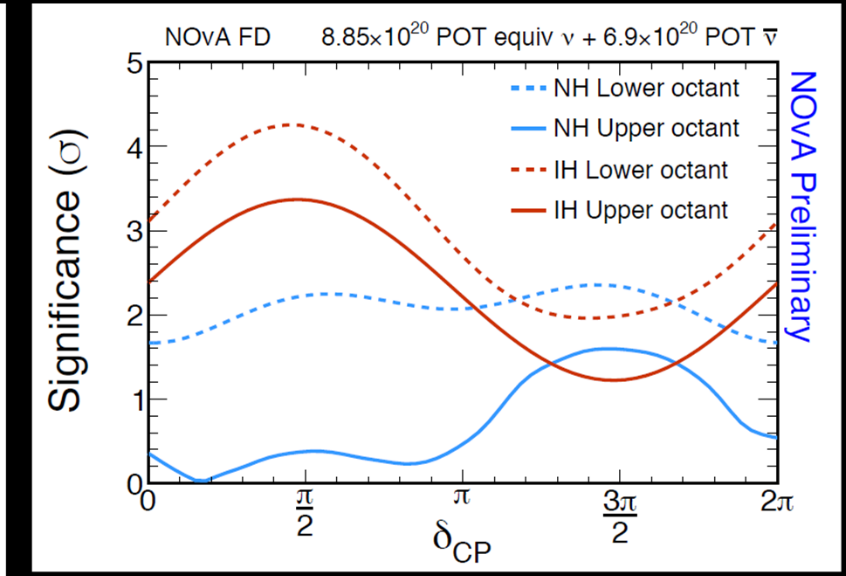
SUMMARY AND OUTLOOK

- First NOvA antineutrino data (6.9 $\cdot 10^{20}$ POT) has been analyzed together with 8.85 $\cdot 10^{20}$ POT of neutrino data.
  - Publication on analysis of 8.85 $\cdot 10^{20}$ POT of neutrino data on the arXiv today.
  - More antineutrino beam running up to the summer shutdown.
- We observe no evidence for mixing with sterile neutrinos or antineutrinos from the neutral current channel.
- We observe >4 σ evidence of electron antineutrino appearance.
- A joint appearance and disappearance analysis for these data:
  - Prefers Normal Hierarchy at 1.8 σ and excludes $\delta_{CP} = \pi/2$ at > 3 σ.
  - Rejects maximal mixing at 1.8 σ and the lower octant at a similar level.
- Future NOvA running can reach 3 σ sensitivity for the mass hierarchy by 2020 and covers significant CP range by 2024.

see poster #81

ALLOWED OSCILLATION PARAMETERS





- Best fit: Normal Hierarchy
  δ_{CP}= 0.17π
  $\sin^2\theta_{23}$ = 0.58±0.03 (UO)
  Δm^2_{32} = $(2.51^{+0.12}_{-0.08})\cdot10^{-3}$ eV^2

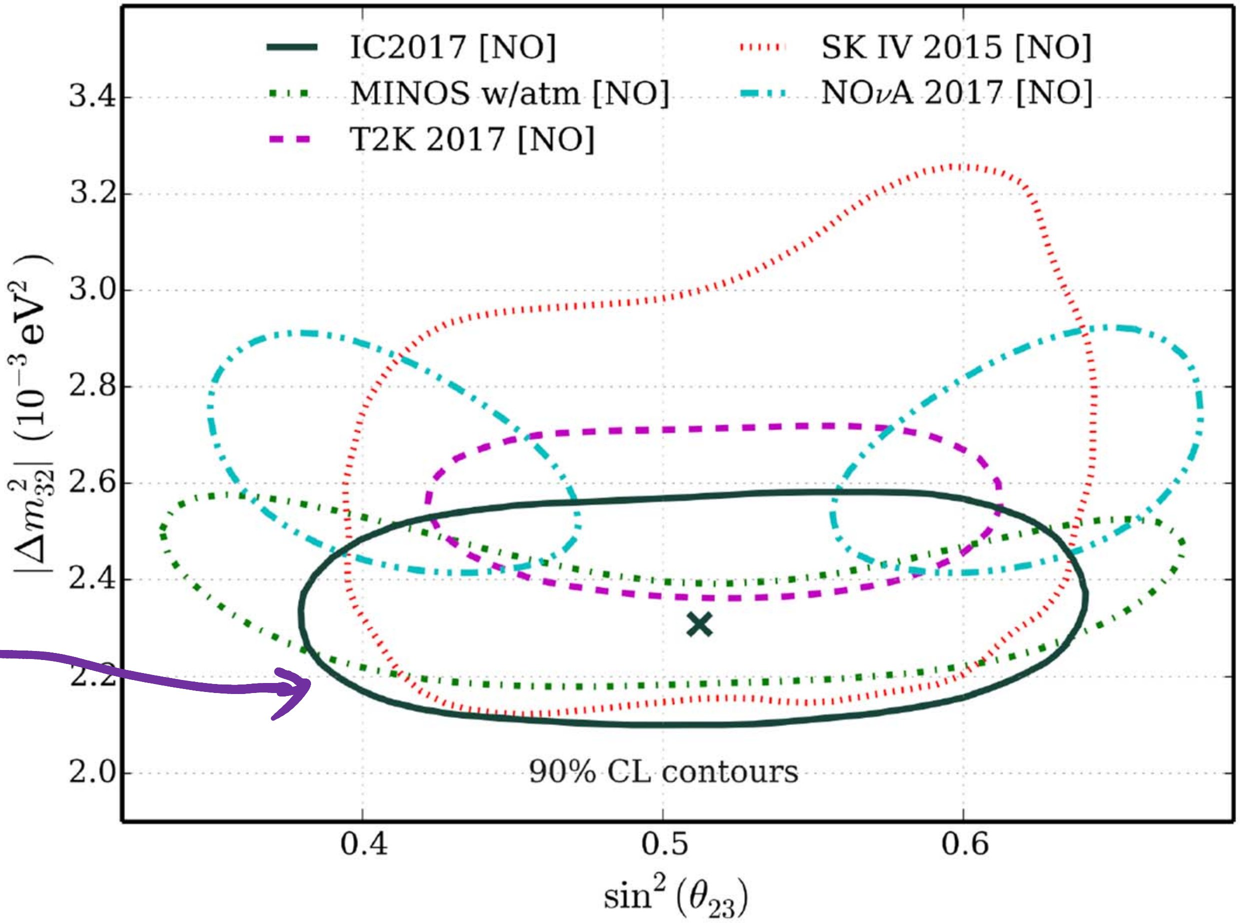
Prefer NH by 1.8σ
Exclude δ=π/2 in the IH at > 3σ

ν_μ disappearance probes oscillation parameters

O'Sullivan
FPCP2018

ICECUBE

Aartsen+ *Phys. Rev. Lett.* 120, 071801 (2018)



Many other interesting developments in neutrino sector

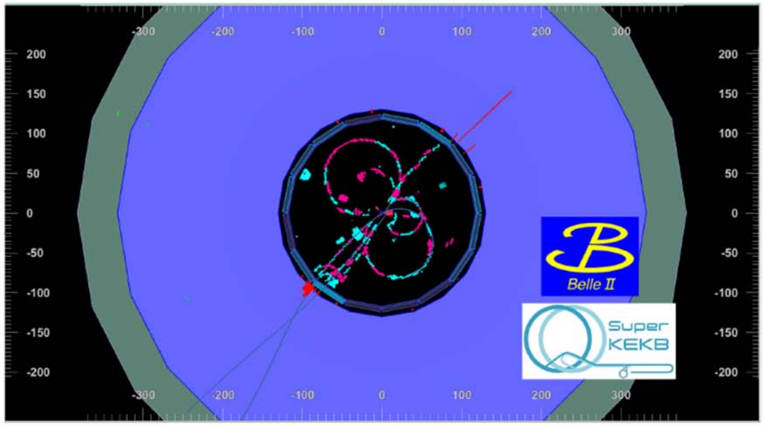
- **Icecube..detection of astrophysical neutrinos earmarks exciting entry into the arena of neutrino astronomy**
- **Werner Rodejohann cataloged many impressive developments especially noteworthy that neutrino mixing [PMNS] matrix is approaching precision ~CKM**
- **B. Dev : Leptogenesis is interesting with highly desirable features to address baryon asymmetry**
- **Indumathi: It is extremely frustrating that the true high caliber of the Indian scientific community with expertise in neutrinos is being thwarted for such a long period of time by an utterly ignorant elite…Hope Indumathi et al will soon find a way out of this mess**

GORRILA + GODZILLA

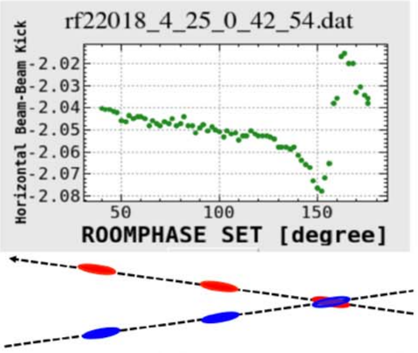
First collision

Apr. 26, 2018

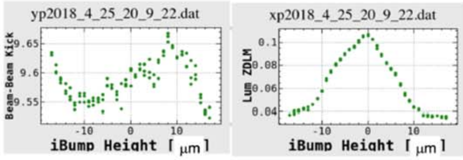
Belle II control room



First hadronic event observed by Belle II



Horizontal beam-beam kick



Vertical beam-beam kick

SuperKEKB control room

Toru Iijima @ SCGP May 31, 2018

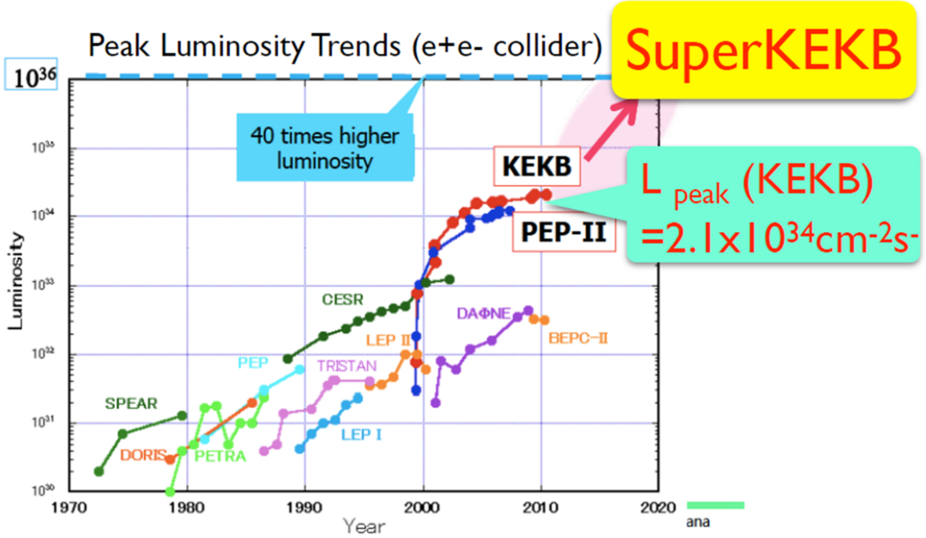
SuperKEKB/Belle II

New intensity frontier facility at KEK

- Target luminosity ; $L_{peak} = 8 \times 10^{35} cm^{-2}s^{-1}$

  $\Rightarrow \sim 10^{10}\ B\bar{B}, \tau^{+}\tau^{-}$ and charms per year !

  $L_{int} > 50\ ab^{-1}$


Peak Luminosity Trends (e+e- collider)

SuperKEKB

40 times higher luminosity

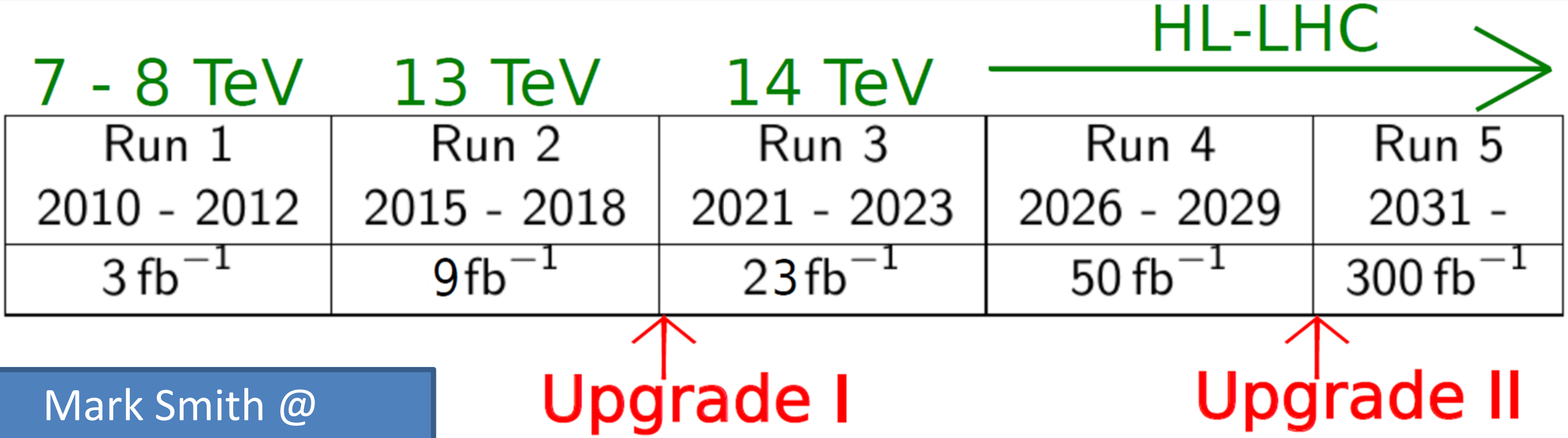
KEKB

PEP-II

L peak (KEKB) $=2.1\times10^{34} cm^{-2}s^{-}$

The first particle collider after the LHC !

Looking forward at LHCb



7 - 8 TeV | 13 TeV | 14 TeV | HL-LHC

Run 1	Run 2	Run 3	Run 4	Run 5
2010 - 2012	2015 - 2018	2021 - 2023	2026 - 2029	2031 -
3 fb^{-1}	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}

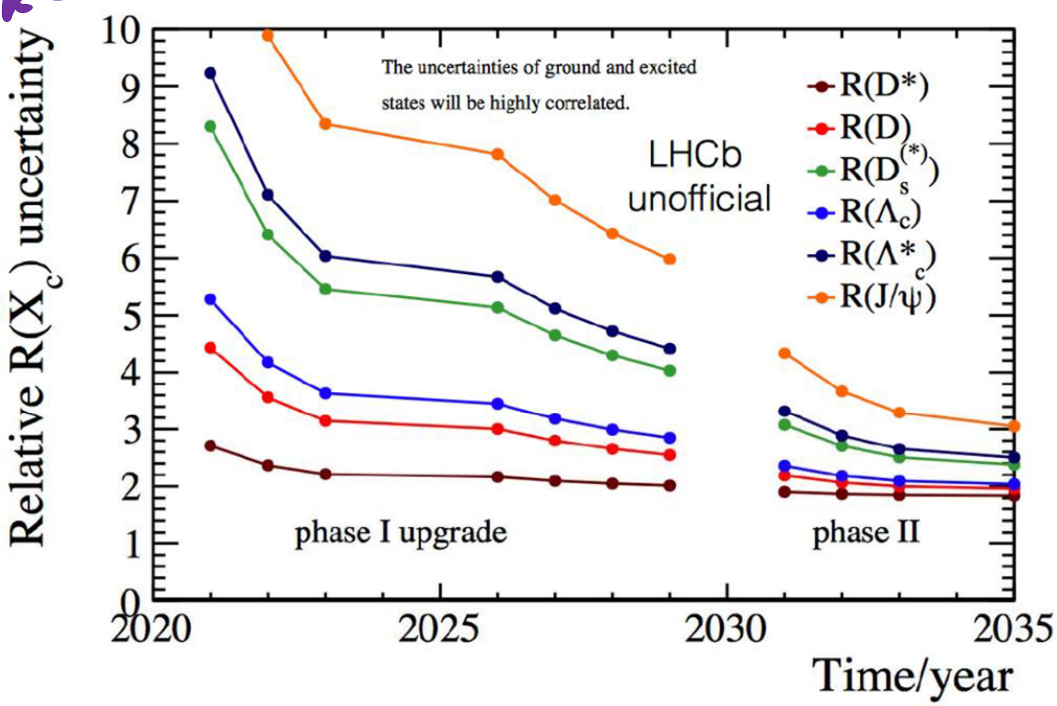
Upgrade I

Upgrade II

Mark Smith @ FPCP2018

C also T SZUMLAK@ FPCP 2018

Upgrade I:
CERN-LHCC-2012-007
Upgrade II:
CERN-LHCC-2017-003



Continued improvement reliant on:

- Simulation size
- Theory collaboration
- Experimental input

Gorrila + Godzilla

- These are two thousand pounds creatures sitting now right in front of us and it'd be stupid to ignore their presence

- THE POTENTIAL OF DISCOVERY OF NEW PHENOMENA BY THESE POWERFUL GADJETS IS NO LESS THAN WHEN WE MOVED FROM THE TEVATRON TO LHC!

So we have high expectations and I am excited to entertain the possibilties and so should you

Contrarian/Complementary view

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

- **[This is infact my rationale for going after eps’ for over 35 continuous years and the effort is sill continuing]**

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

- **In this context it is useful to stress**

- **We hold these truths to be self-evident…**

Importance of the "IF": score card

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

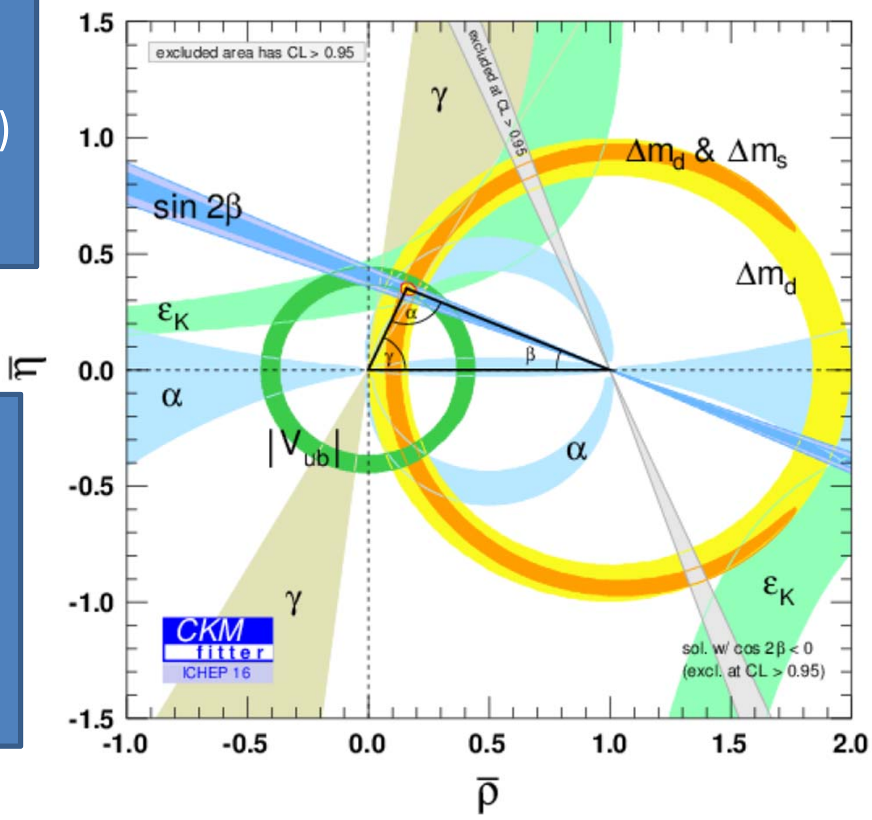
Main Goal of these powerful gadgets: find NP

- **At least 3 broad avenues in parallel**
- **1. Onwards march to precision of UT in search for inconsistencies via redundancy**
- **2. Anomalies: follow the clues**
- **3. null tests; illustrative examples: TDCP in radiative B's, (charm) DCP, tau- LFV test and scores more**

Overall consistency with the SM

http://ckmfitter.in2p3.fr
see also http://www.utfit.org

Looks great; but looks can be deceiving…
In fact at level of O(2σ) tension(s) exist



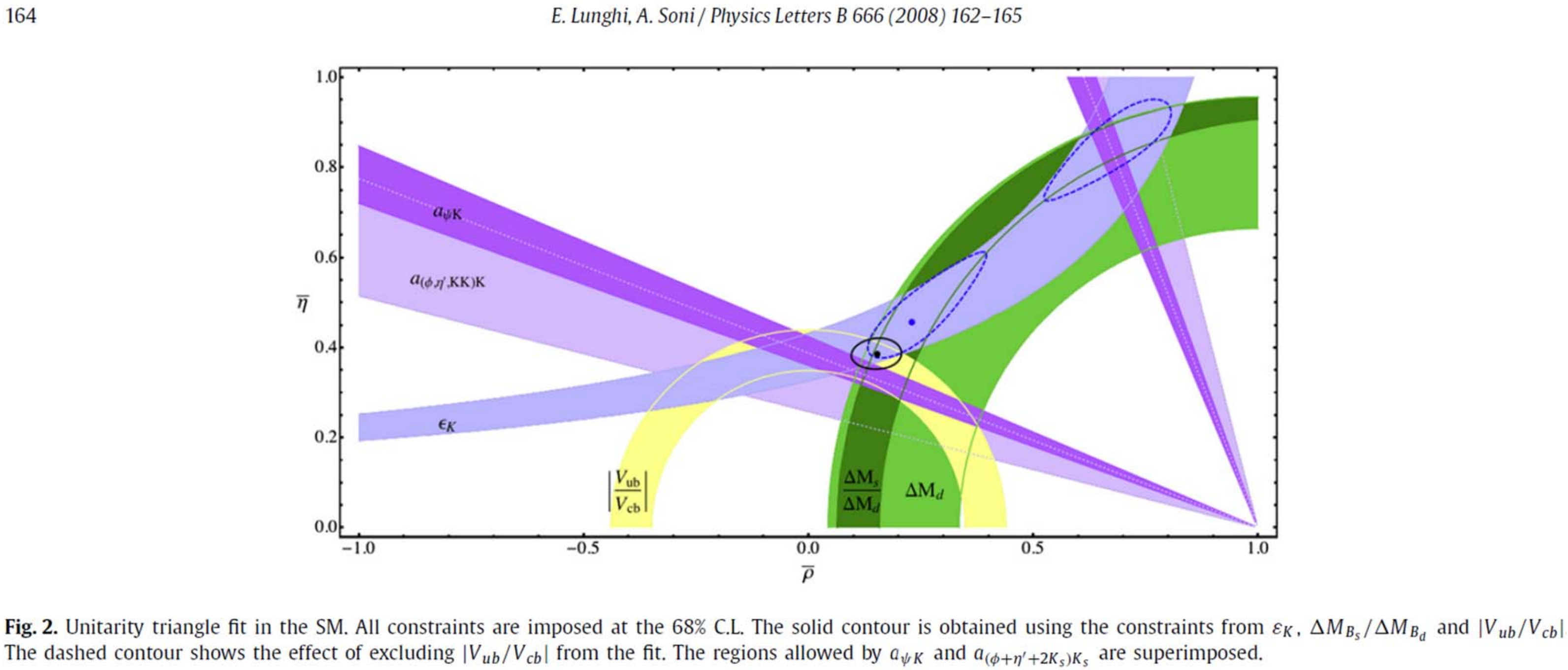
O(10-15%) new physics is possible and is HUGE!

Unitarity Triangle analysis in the SM:

M. Bona @fpcp2018

obtained excluding the given constraint from the fit

Observables	Measurement	Prediction	Pull (#σ)
sin2β	0.689 ± 0.018	0.738 ± 0.033	~ 1.2
γ	73.4 ± 4.4	65.8 ± 2.2	< 1
α	93.3 ± 5.6	90.1 ± 2.2	< 1
$\|V_{ub}\| \cdot 10^3$	3.72 ± 0.23	3.66 ± 0.11	< 1
$\|V_{ub}\| \cdot 10^3$ (incl)	4.50 ± 0.20	-	~ 3.8 ←
$\|V_{ub}\| \cdot 10^3$ (excl)	3.65 ± 0.14	-	< 1
$\|V_{cb}\| \cdot 10^3$	40.5 ± 1.1	42.4 ± 0.7	~ 1.4
$BR(B \rightarrow \tau\nu)[10^{-4}]$	1.09 ± 0.24	0.81 ± 0.05	~ 1.2
$A_{SL}^{d} \cdot 10^3$	-2.1 ± 1.7	-0.292 ± 0.026	~ 1
$A_{SL}^{s} \cdot 10^3$	-0.6 ± 2.8	0.013 ± 0.001	< 1



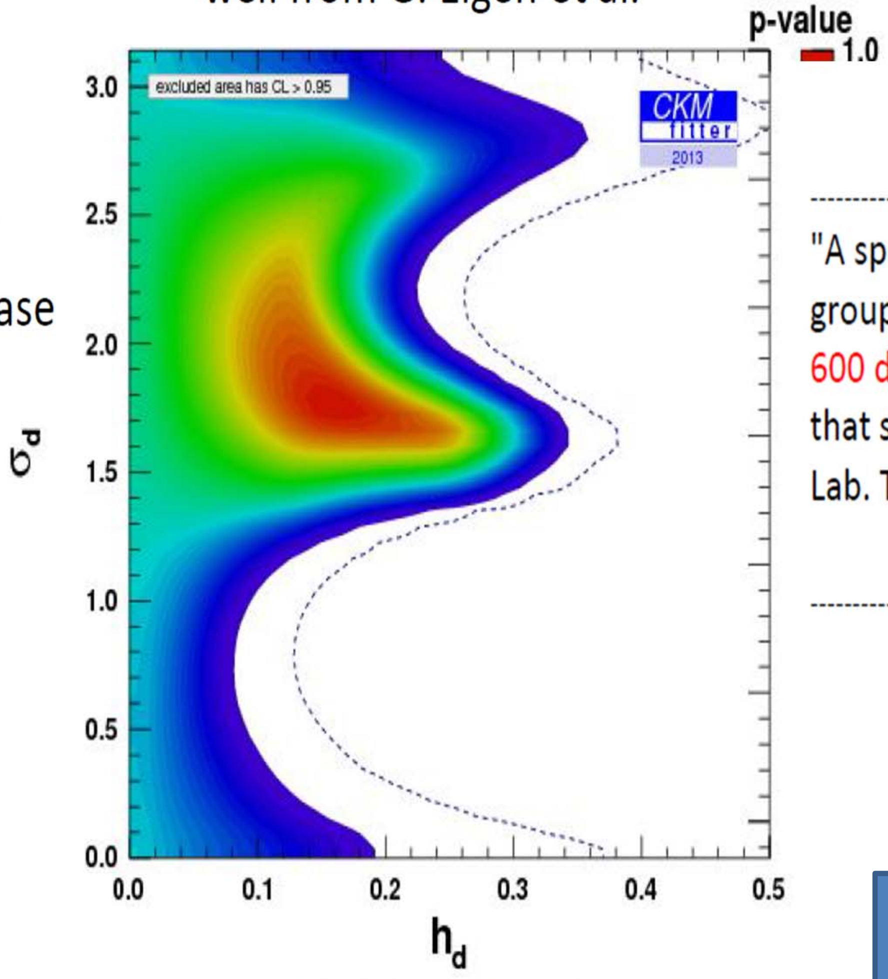
164 *E. Lunghi, A. Soni / Physics Letters B 666 (2008) 162–165*

Fig. 2. Unitarity triangle fit in the SM. All constraints are imposed at the 68% C.L. The solid contour is obtained using the constraints from ε_K, $\Delta M_{B_s}/\Delta M_{B_d}$ and $|V_{ub}/V_{cb}|$ The dashed contour shows the effect of excluding $|V_{ub}/V_{cb}|$ from the fit. The regions allowed by $a_{\psi K}$ and $a_{(\phi+\eta'+2K_s)K_s}$ are superimposed.

ICHEP2014: Similar results from UTFIT (D. Derkach) as well from G. Eigen et al.

Current O(few%) tests are far away from O(0.1%) asymmetry in KL=>pi pi

NP Phase



NP/SM amplitude ratio

A lesson from history (I)

"A special search at Dubna was carried out by E. Okonov and his group. They did not find a single $K_L \rightarrow \pi^+ \pi^-$ event among 600 decays into charged particles [12] (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the Lab. The group was unlucky."

-Lev Okun, "The Vacuum as Seen from Moscow"

1964: BF= 2 x 10^{-3}

A failure of imagination ? Lack of patience ?

Had KL=>pi pi been abandoned, history of Particle Physics would have been significantly different!

A great personal treat; thanks to

ADS: $B^{\pm} \to Dh^{\pm}, D \to \pi^+K^-$

$$\boxed{A^{\pi K}_{\mathrm{ADS}(K)} = -0.403 \quad \pm 0.056 \quad \pm 0.011}$$

8σ

Malcolm John@EW
MORIOND

Huge *direct CP* [tailor made] ~20 ago!
ADS PRL'97

⇒

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

DESIGNED for
MAXIMAL INTERFERENCE

DATA DRIVEN METHODS

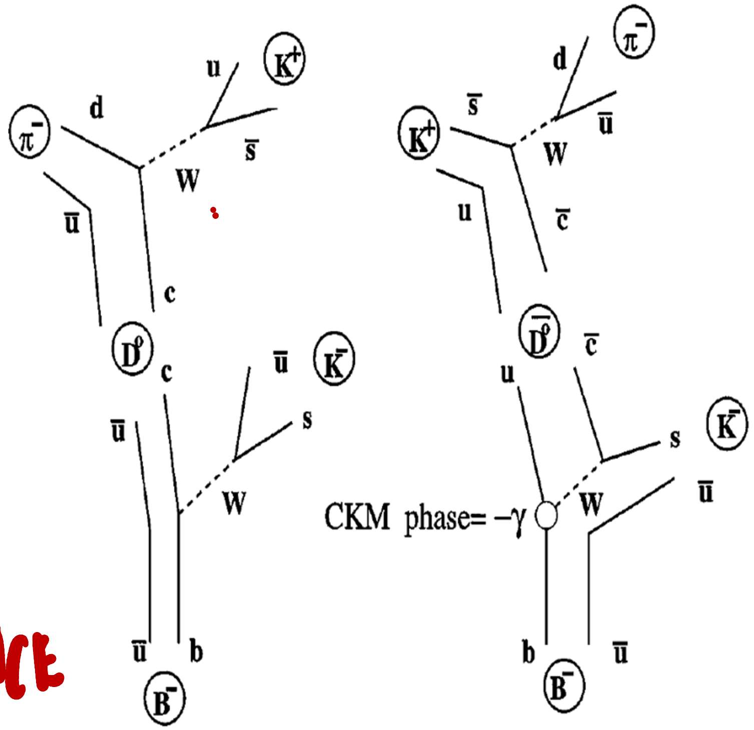


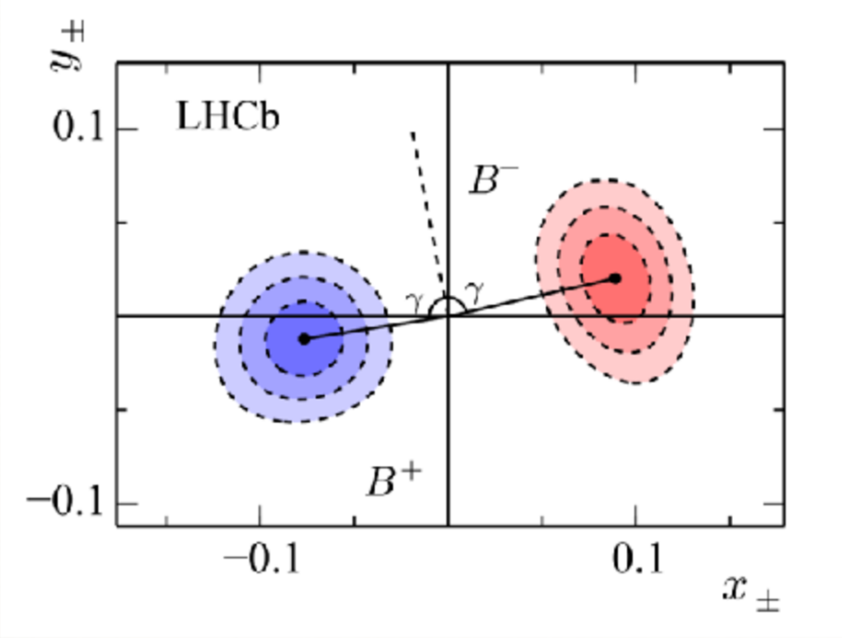
FIG. 1. Diagrams for the two interfering processes: $B^- \to K^-D^0$ (color-allowed) followed by $D^0 \longrightarrow K^+\pi^-$ (doubl Cabibbo suppressed) and $B^- \longrightarrow K^-\overline{D}^0$ (color-suppresse followed by $\overline{D}^0 \longrightarrow K^+\pi^-$ (Cabibbo allowed).

Recent LHCb GGSZ result

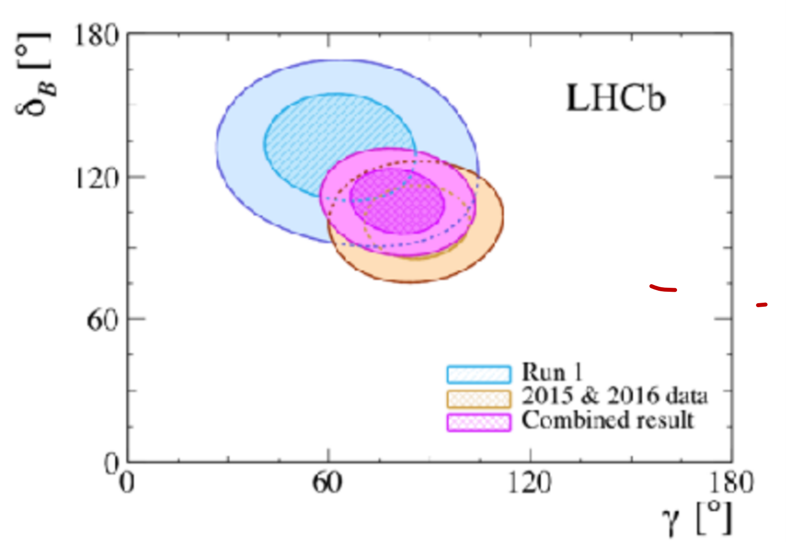
arxiv:1806.01202

GIRI et al hep-ph 0303187

This analysis is of 2015 and 2016 data.



Then combined with the Run 1 result



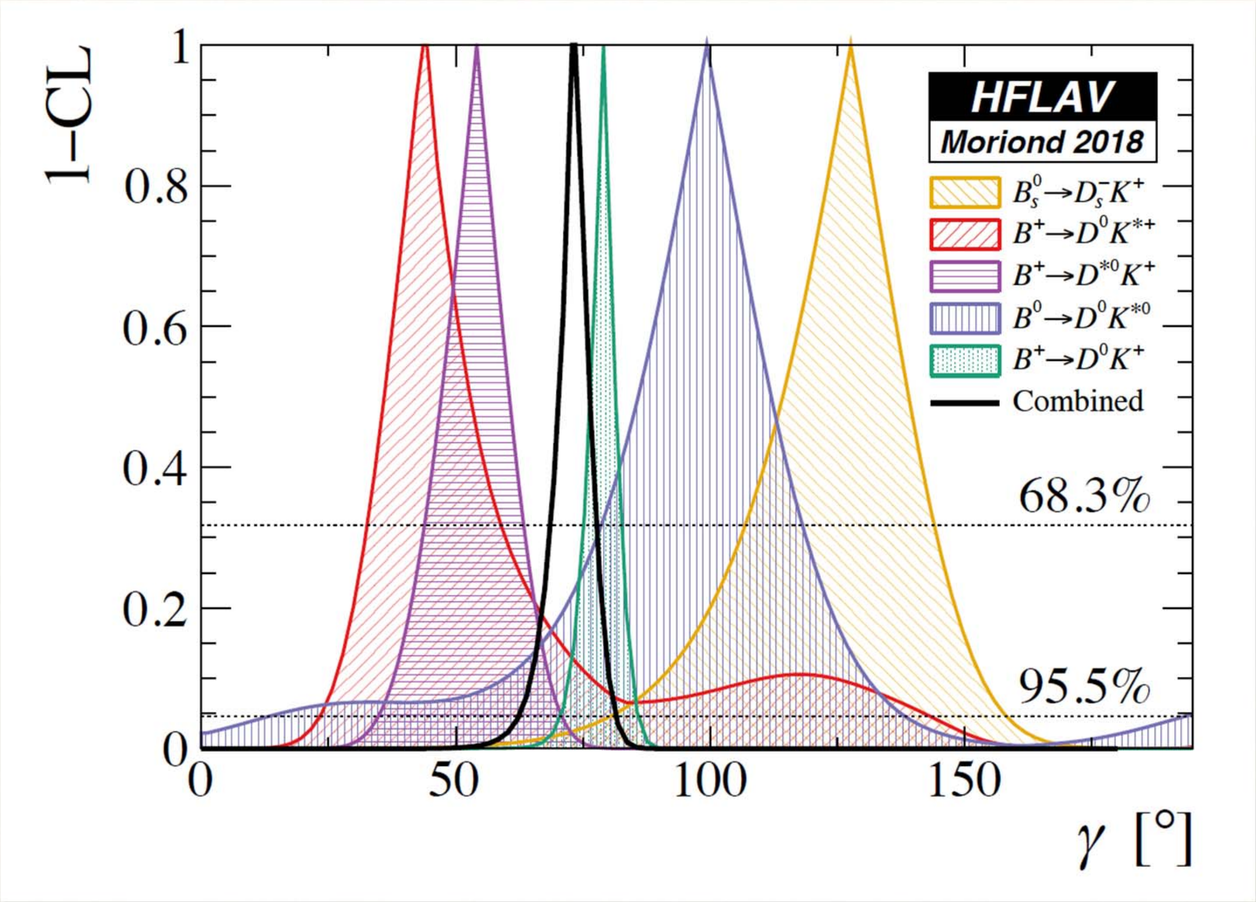
$$\gamma = 80^\circ\,{}^{+10^\circ}_{-9^\circ}\ \left({}^{+19^\circ}_{-18^\circ}\right),$$

$$r_B = 0.080\,{}^{+0.011}_{-0.011}\ \left({}^{+0.022}_{-0.023}\right),$$

$$\delta_B = 110^\circ\,{}^{+10^\circ}_{-10^\circ}\ \left({}^{+19^\circ}_{-20^\circ}\right).$$

World average (HFLAV)

UTFIT: 65.8+-2.2; M. Bona fpcp2018



$$\gamma = (73.5^{+4.2}_{-5.1})^\circ$$

Naive 1.6σ divergence from indirect predictio

$$\gamma_{\text{indirect}} = (65.3^{+1.0}_{-2.5})^\circ \quad \text{(CKMfitter)}$$

Relation bet.
ADS &
GGSZ

STILL Untapped
potential
in γ extraction
using DALITZ
Decays MODL Indep.

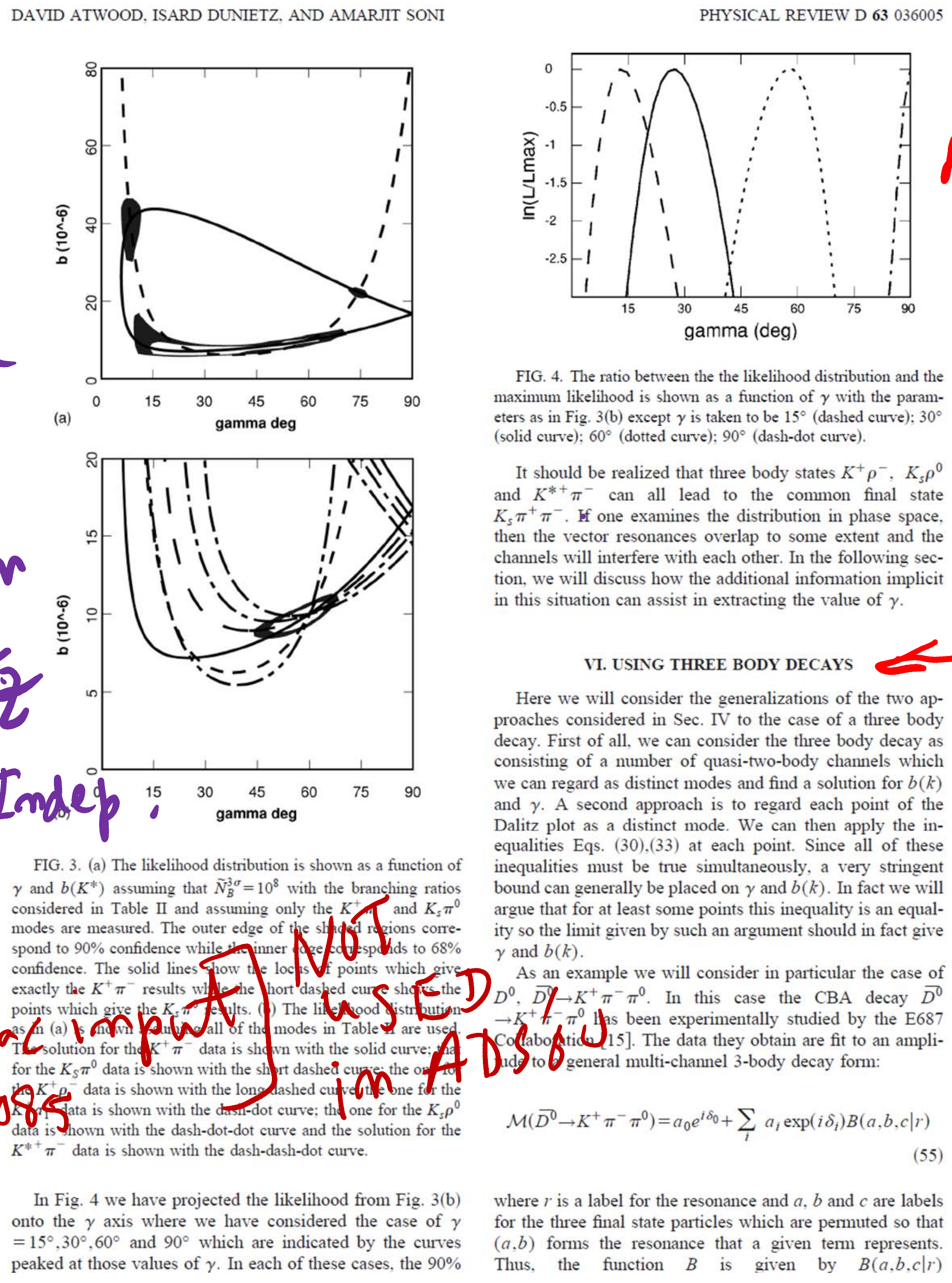


FIG. 3. (a) The likelihood distribution is shown as a function of γ and $b(K^*)$ assuming that $\tilde{N}_B^{3\sigma}=10^8$ with the branching ratios considered in Table II and assuming only the $K^+\pi^-$ and $K_s\pi^0$ modes are measured. The outer edge of the shaded regions correspond to 90% confidence while the inner edge corresponds to 68% confidence. The solid lines show the locus of points which give exactly the $K^+\pi^-$ results while the short dashed curve shows the points which give the $K_s\pi^0$ results. (b) The likelihood distribution as in (a) is shown assuming all of the modes in Table II are used. The solution for the $K^+\pi^-$ data is shown with the solid curve; that for the $K_S\pi^0$ data is shown with the short dashed curve; the one for the $K^+\rho^-$ data is shown with the long dashed curve; the one for the $K^+a_1^-$ data is shown with the dash-dot curve; the one for the $K_s\rho^0$ data is shown with the dash-dot-dot curve and the solution for the $K^{*+}\pi^-$ data is shown with the dash-dash-dot curve.

In Fig. 4 we have projected the likelihood from Fig. 3(b) onto the γ axis where we have considered the case of $\gamma=15°,30°,60°$ and $90°$ which are indicated by the curves peaked at those values of γ. In each of these cases, the 90%

FIG. 4. The ratio between the the likelihood distribution and the maximum likelihood is shown as a function of γ with the parameters as in Fig. 3(b) except γ is taken to be 15° (dashed curve); 30° (solid curve); 60° (dotted curve); 90° (dash-dot curve).

It should be realized that three body states $K^+\rho^-$, $K_s\rho^0$ and $K^{*+}\pi^-$ can all lead to the common final state $K_s\pi^+\pi^-$. If one examines the distribution in phase space, then the vector resonances overlap to some extent and the channels will interfere with each other. In the following section, we will discuss how the additional information implicit in this situation can assist in extracting the value of γ.

VI. USING THREE BODY DECAYS

Here we will consider the generalizations of the two approaches considered in Sec. IV to the case of a three body decay. First of all, we can consider the three body decay as consisting of a number of quasi-two-body channels which we can regard as distinct modes and find a solution for $b(k)$ and γ. A second approach is to regard each point of the Dalitz plot as a distinct mode. We can then apply the inequalities Eqs. (30),(33) at each point. Since all of these inequalities must be true simultaneously, a very stringent bound can generally be placed on γ and $b(k)$. In fact we will argue that for at least some points this inequality is an equality so the limit given by such an argument should in fact give γ and $b(k)$.

As an example we will consider in particular the case of D^0, $\overline{D^0}\rightarrow K^+\pi^-\pi^0$. In this case the CBA decay $\overline{D^0}\rightarrow K^+\pi^-\pi^0$ has been experimentally studied by the E687 Collaboration [15]. The data they obtain are fit to an amplitude to a general multi-channel 3-body decay form:

$$\mathcal{M}(\overline{D^0}\rightarrow K^+\pi^-\pi^0)=a_0e^{i\delta_0}+\sum_i a_i\exp(i\delta_i)B(a,b,c|r) \tag{55}$$

where r is a label for the resonance and a, b and c are labels for the three final state particles which are permuted so that (a,b) forms the resonance that a given term represents. Thus, the function B is given by $B(a,b,c|r)$

Role of charm fac input] NOT USED in ADS01

DA+AS 0304085

ADS
hep-ph/000809.

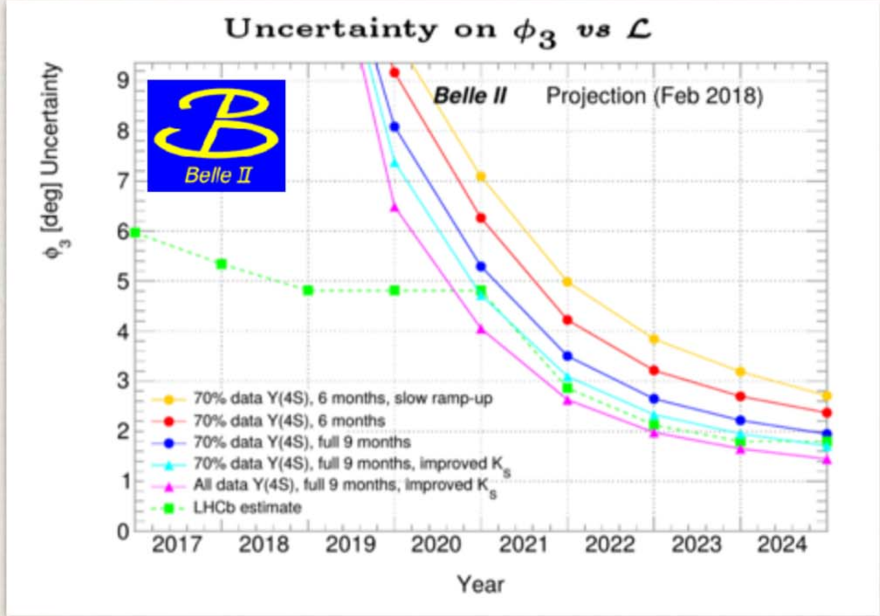
← $K_S\pi^+\pi^-$....

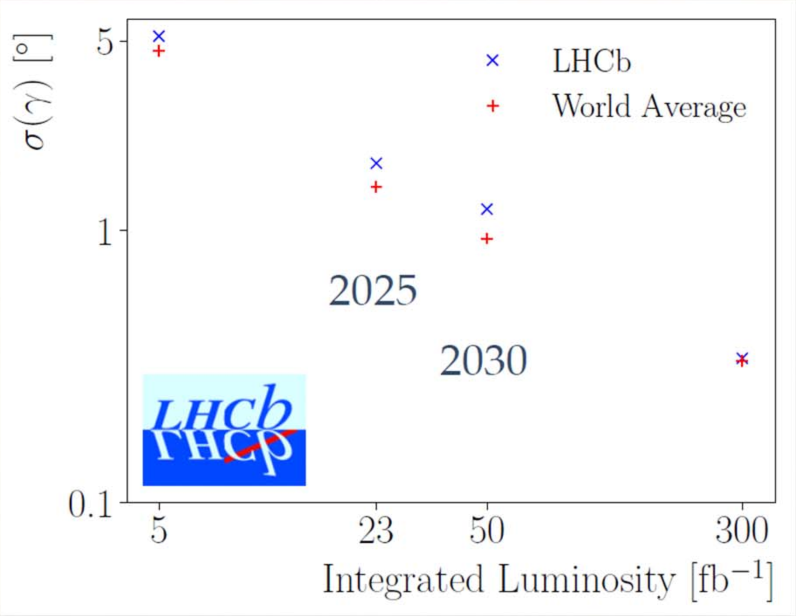
$D^0,\bar{D}^0\rightarrow K^+K^-\pi^0$
FNAL E687

Prospects

Expect Belle II and the LHCb upgrade to match each other's performance

- $\sigma(\gamma)$ ~2° each by 2025





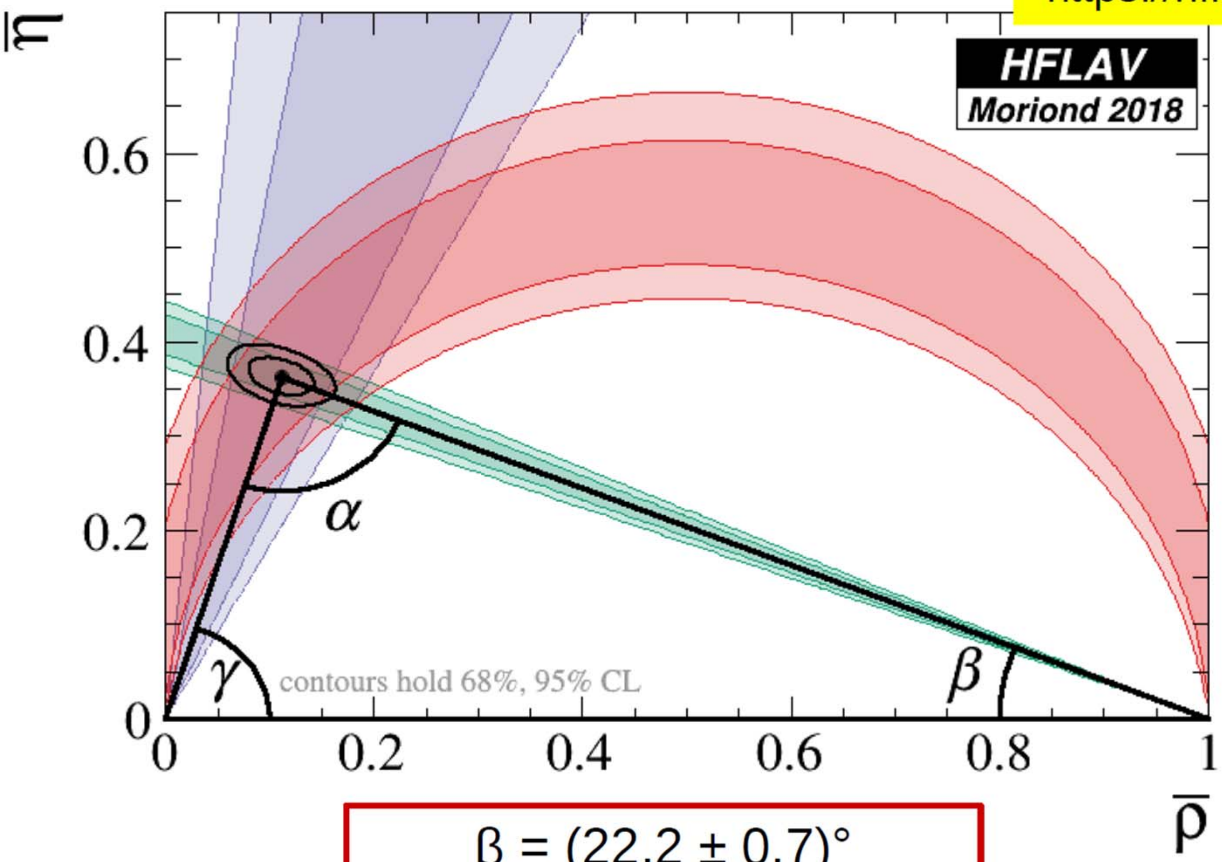
After 2025 Belle II stops but LHCb upgrade 1b and 2 aim for 300 fb^{-1} BROD + Zupan '14

- World average may have precision: $\sigma(\gamma)$ ~0.3° by 2035

STD. CANDLE $\frac{\delta\gamma}{\gamma} \sim 10^{-7}$

Latest$^{(*)}$ UT angles

https://hflav.web.cern.ch/



$\beta = (22.2 \pm 0.7)^\circ$

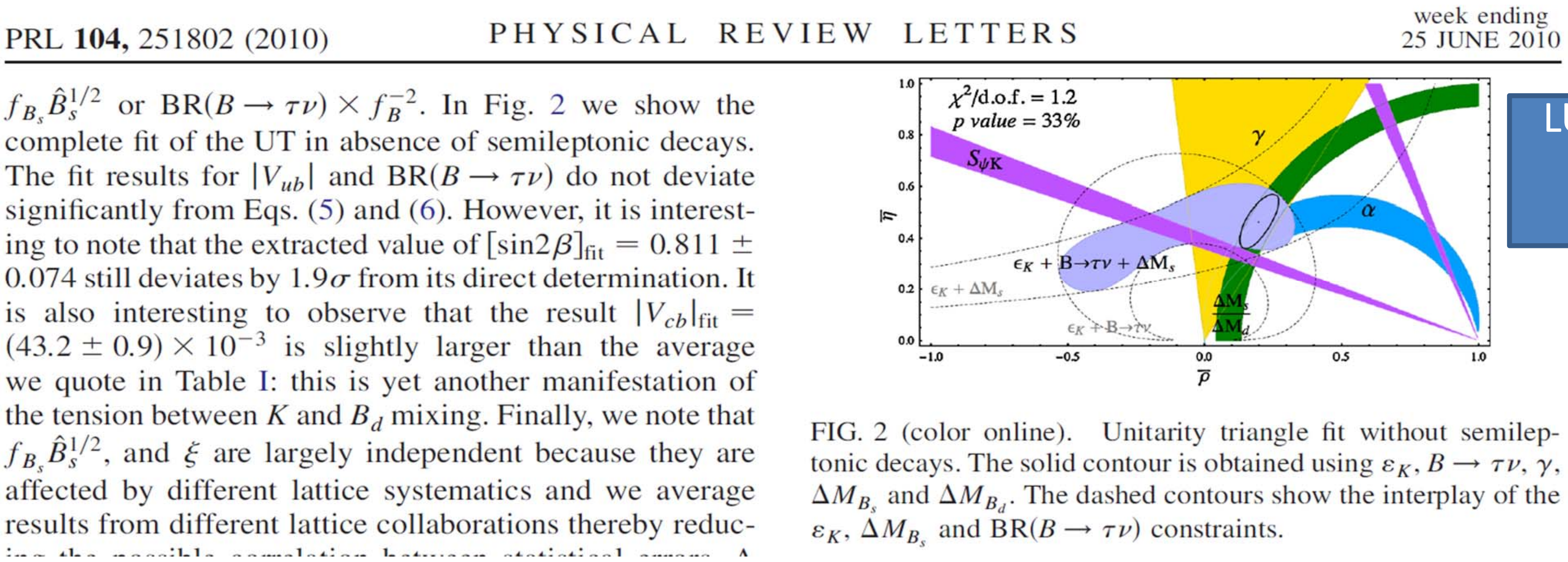
$\alpha = (84.9\,^{+5.1}_{-4.5})^\circ$

$\gamma = (73.5\,^{+4.2}_{-5.1})^\circ$

γ no longer least well measured of the angles

(*) not including some very recent new LHCb results on γ

More accurate determination of Br B=> tau nu is of crucial importance for many reasons



PRL **104,** 251802 (2010) PHYSICAL REVIEW LETTERS week ending 25 JUNE 2010

$f_{B_s}\hat{B}_s^{1/2}$ or $\mathrm{BR}(B \to \tau\nu) \times f_B^{-2}$. In Fig. 2 we show the complete fit of the UT in absence of semileptonic decays. The fit results for $|V_{ub}|$ and $\mathrm{BR}(B \to \tau\nu)$ do not deviate significantly from Eqs. (5) and (6). However, it is interesting to note that the extracted value of $[\sin 2\beta]_{\mathrm{fit}} = 0.811 \pm 0.074$ still deviates by 1.9σ from its direct determination. It is also interesting to observe that the result $|V_{cb}|_{\mathrm{fit}} = (43.2 \pm 0.9) \times 10^{-3}$ is slightly larger than the average we quote in Table I: this is yet another manifestation of the tension between K and B_d mixing. Finally, we note that $f_{B_s}\hat{B}_s^{1/2}$, and ξ are largely independent because they are affected by different lattice systematics and we average results from different lattice collaborations thereby reducing the possible correlation between statistical errors. A

FIG. 2 (color online). Unitarity triangle fit without semileptonic decays. The solid contour is obtained using ε_K, $B \to \tau\nu$, γ, ΔM_{B_s} and ΔM_{B_d}. The dashed contours show the interplay of the ε_K, ΔM_{B_s} and $\mathrm{BR}(B \to \tau\nu)$ constraints.

LUNGHI
+
SONI

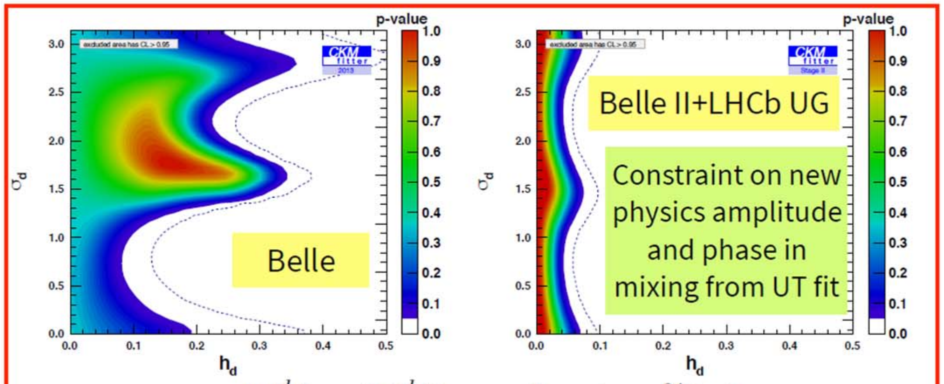
Higher luminosity of Belle-II would be extremely useful for a better determination of BrB=> tau nu as well as for better study of tau in many ways[see later]

V_{CKM} - Summary

URQUIJO @ ICHEP2018

- **$|V_{cb}|$ puzzle addressed by Belle**
  - **B→D$^{(*)}$ τ ν anomaly needs new B→D** l ν background studies**
- $|V_{ub}|/|V_{cb}|$ at LHCb has **better understood form factors!**
- $|V_{ub}|$ **inclusive-exclusive puzzle** - final B-factory results awaited.
- $|V_{cd}|$ & $|V_{cs}|$ direct constraints from BES III are world best. **Outstanding test of LQCD! No LFUV found.**

- **CPV for SM phase measurements (WA HFLAV)**
  - $\sin 2\Phi_1 = 0.70 \pm 0.02$
  - $\Phi_2 = (84.9^{+5.1}_{-4.5})°$
  - **$\Phi_3 = (73.5^{+4.2}_{-5.1})°$**
  - All measurements are statistics limited.
- **CPV for new physics searches:**
  - Large local asymmetries. Switching gear to amplitude analyses.
  - Baryon decays a new window to CPV (see backup)
  - $\Phi_s = -0.021 \pm 0.031$ WA HFLAV 2018 (see backup)



$$M_{12}^{d,s} = (M_{12}^{d,s})_{SM} \times \left(1 + h_{d,s} e^{2i\sigma_{d,s}}\right)$$

- **LHCb upgrade & Belle II will push 1 order of magnitude further on searches for CPV sources. 20-30% NP amplitude still allowed in CKM ΔB=2.**

!!

IMPROVED LATTICE INPUT

SET OF KEY ANOMALIES

Anomalies galore!

- RD(*) ~4σ(?)
- RK(*): 2.6σ(R_K);

- 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

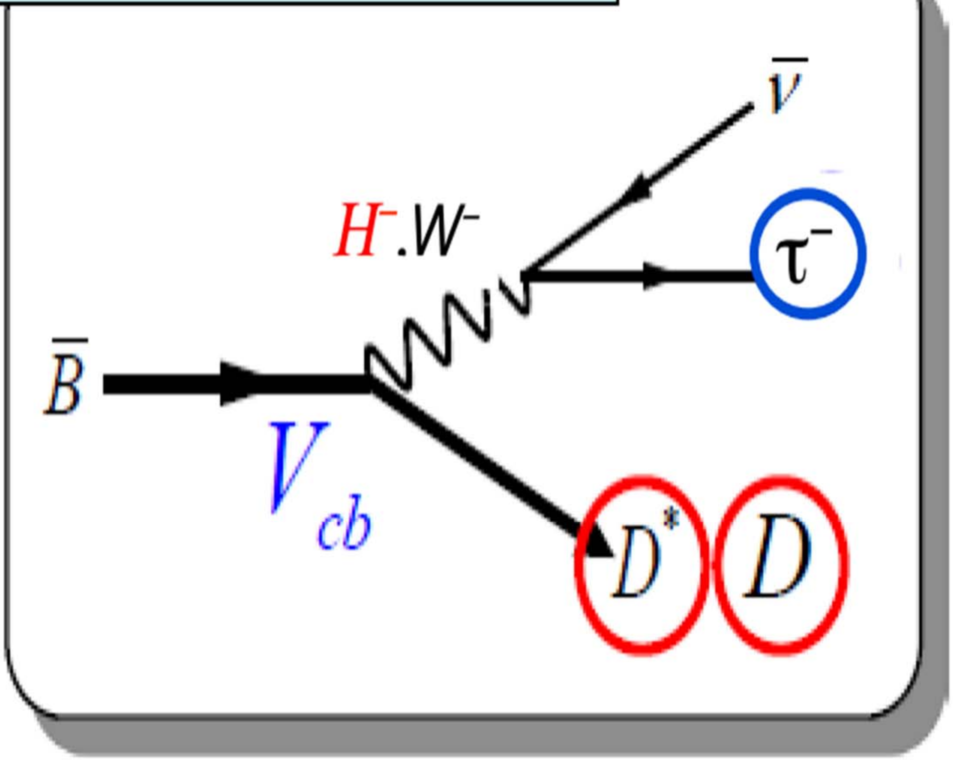
[2.1σ (2.9σ Buras; Nierste) => ??] …..few more months to new results

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

In decoding SM or not, lattice input is vital for each case!

RD(*)

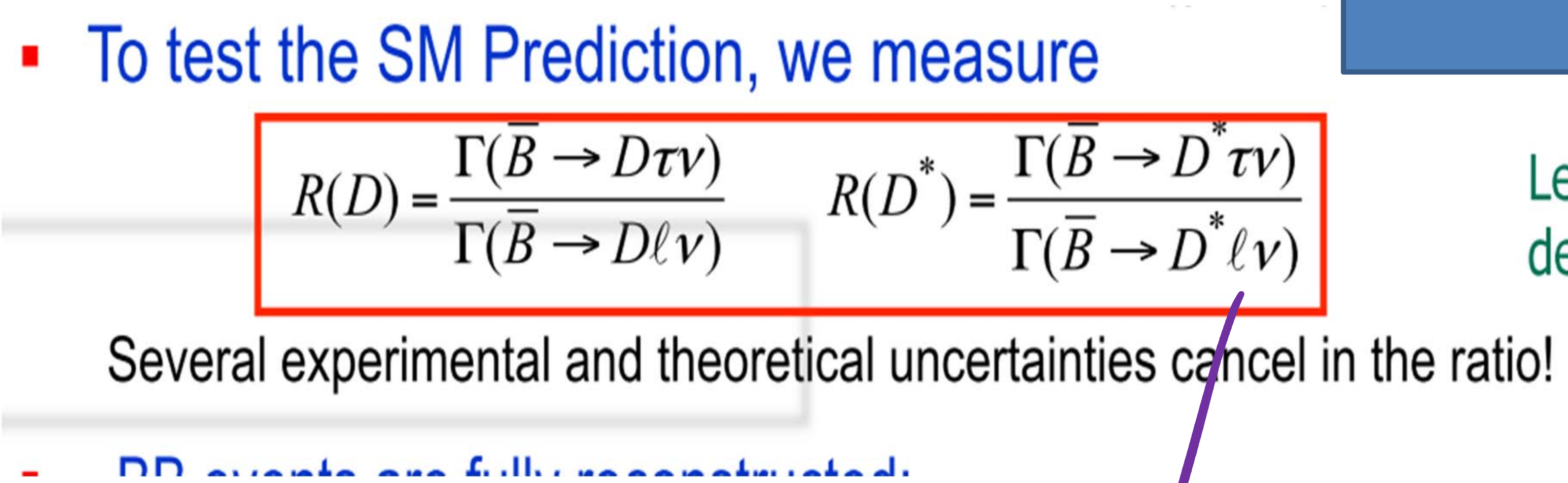
Exclusive $B \to D^{(*)}\tau\nu$



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

MANUEL FRANC
SEVILLA
PhD Thesis

Independent of Vcb!



- To test the SM Prediction, we measure

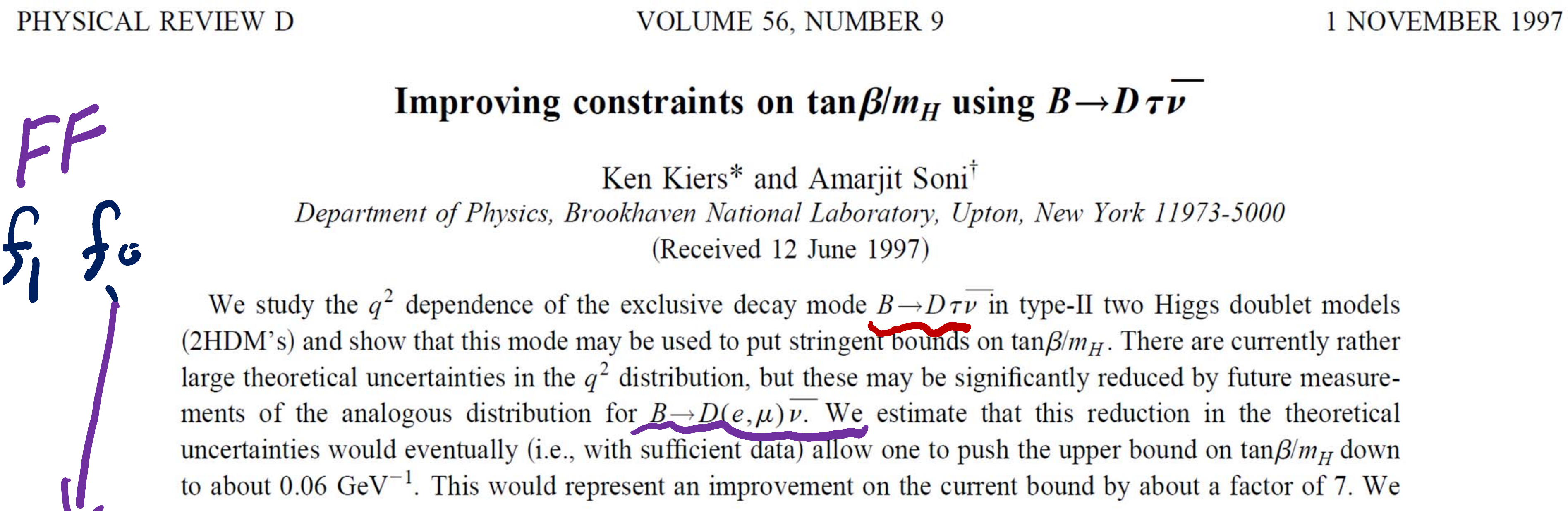
$$R(D)=\frac{\Gamma(\overline{B}\to D\tau\nu)}{\Gamma(\overline{B}\to D\ell\nu)}\qquad R(D^{*})=\frac{\Gamma(\overline{B}\to D^{*}\tau\nu)}{\Gamma(\overline{B}\to D^{*}\ell\nu)}$$

Several experimental and theoretical uncertainties cancel in the ratio!

- BB events are fully reconstructed:

Leptonic τ decays only

l=none



PHYSICAL REVIEW D VOLUME 56, NUMBER 9 1 NOVEMBER 1997

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

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

(Received 12 June 1997)

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

FF

f_1 f_0

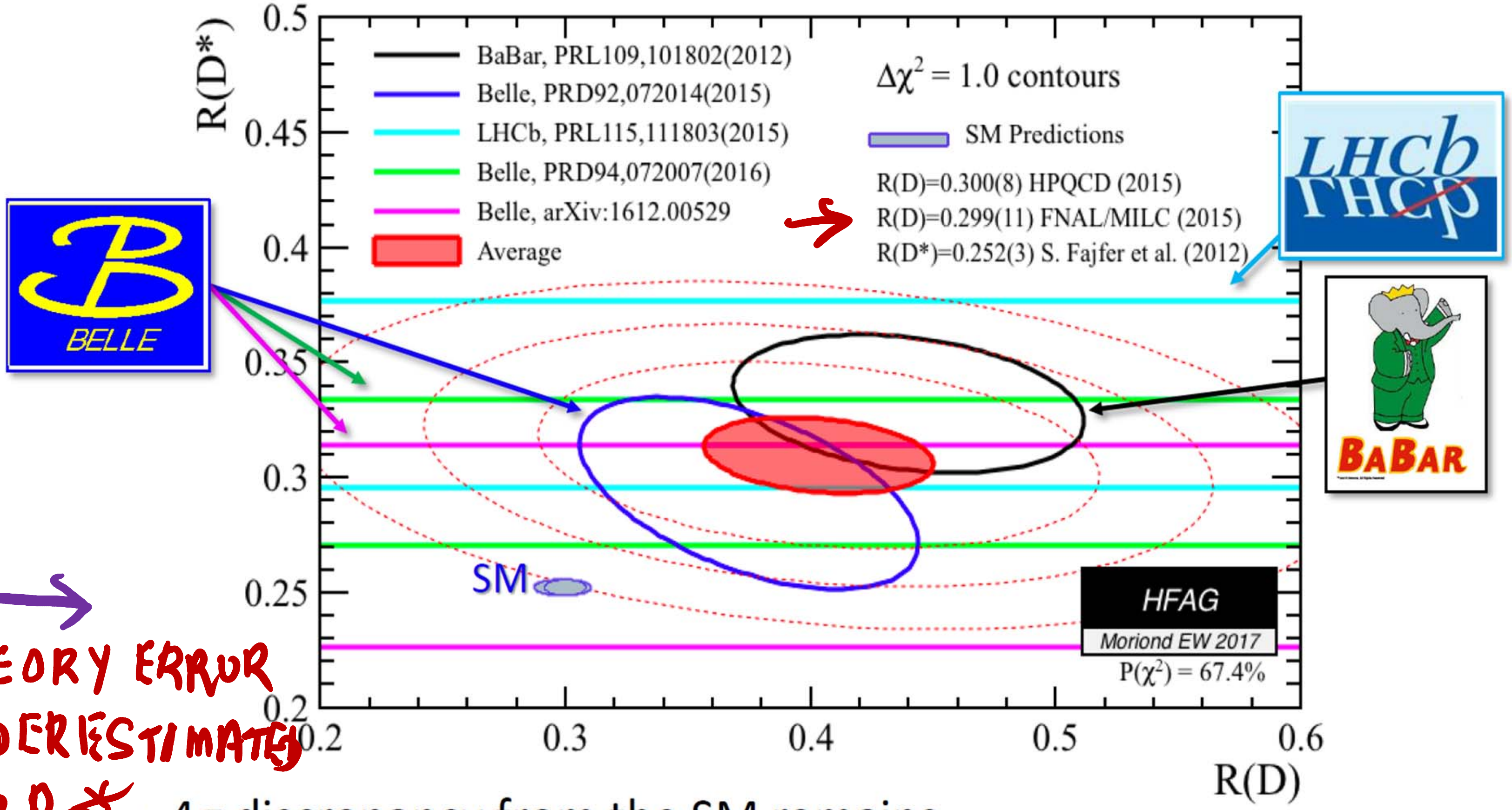
used HQS

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

■ $R(D^{(*)})$ by HFAG

Hirose [BELLE]@EW MORIOND Mar. 2017

11/15



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

Rencontres de Moriond EW 2017

Belle deviations quite mild

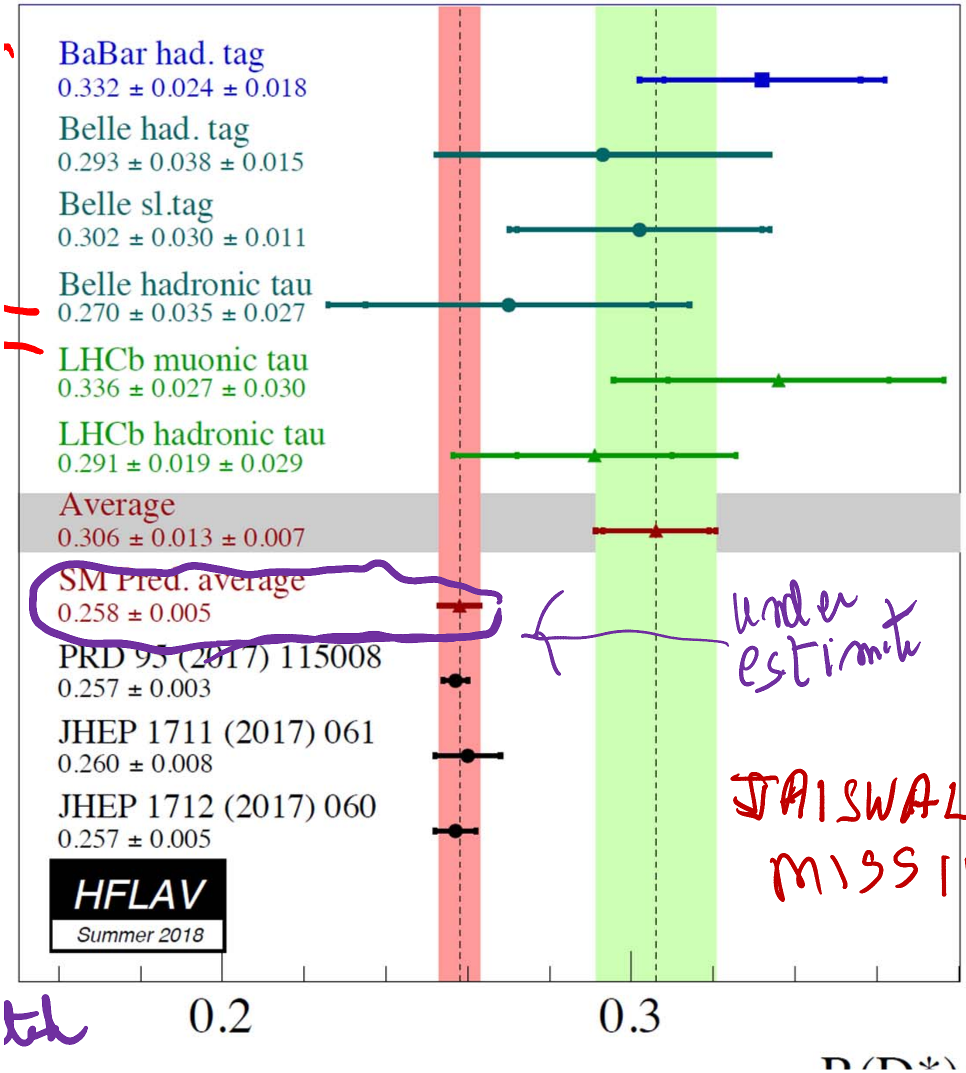
D) and R(D*)

DINGFELDER cf

URAUIJO

MORE/Better R_D EXTREMELY

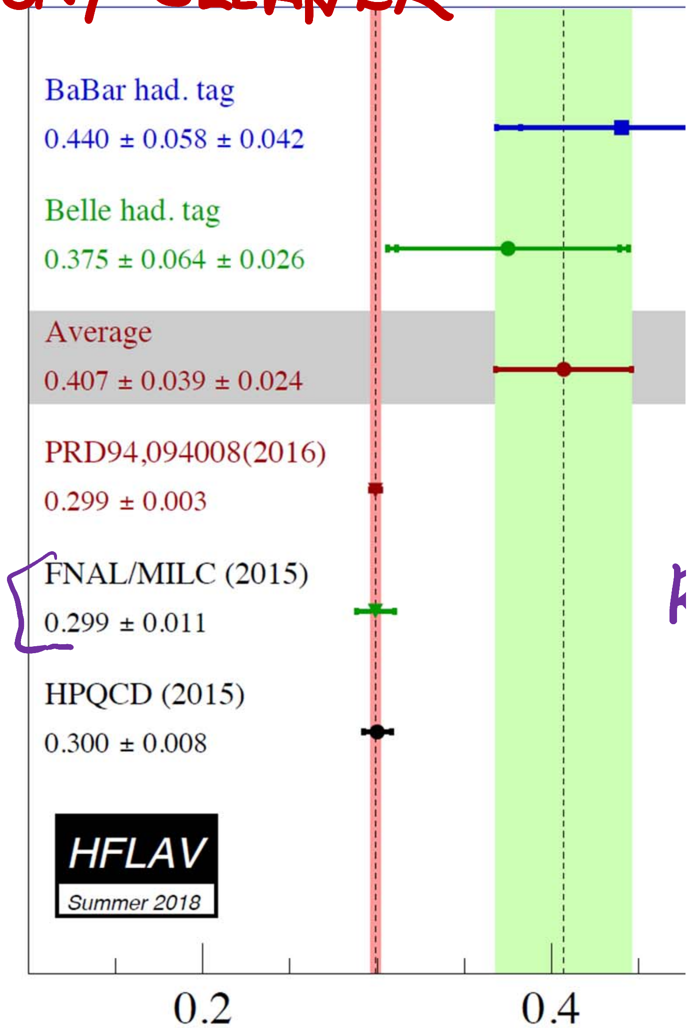
∵ THEORY CLEANER



under estimate

JAISWAL et al MISSING

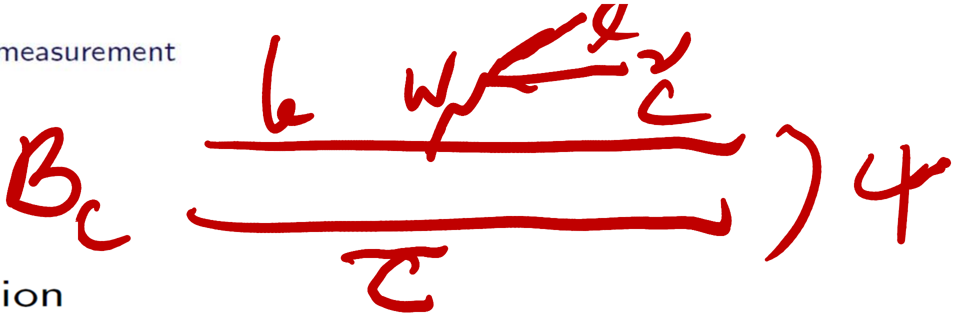
MOST REALISTIC ~4%



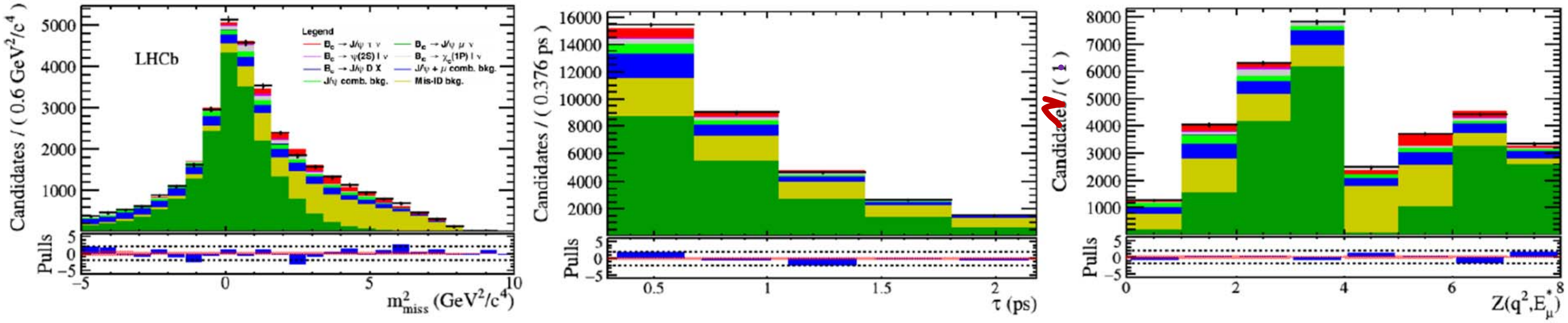
tah

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

2PM Jan 2018



Greg Ciezarek,
on behalf of the LHCb collaboration



c ALSO MARK SMITH @ FPCP 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

Lepton universality tests

LHCb introduced such v. well defined ratios

- In the SM, ratios

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

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

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

Lepton Flavour Universality

Arantza Oyanguren

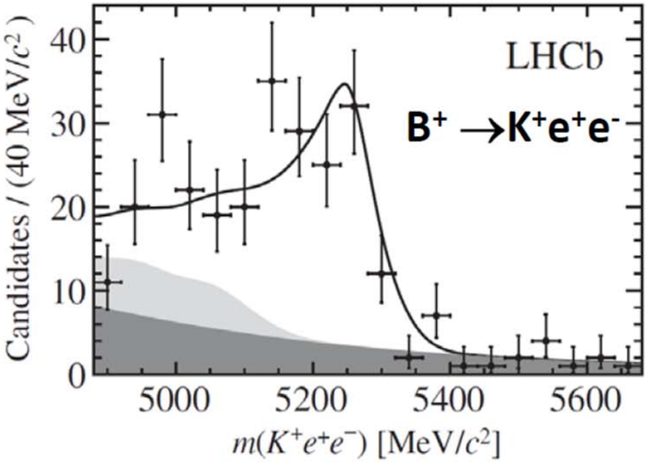
- In the SM all leptons are expected to behave in the sa

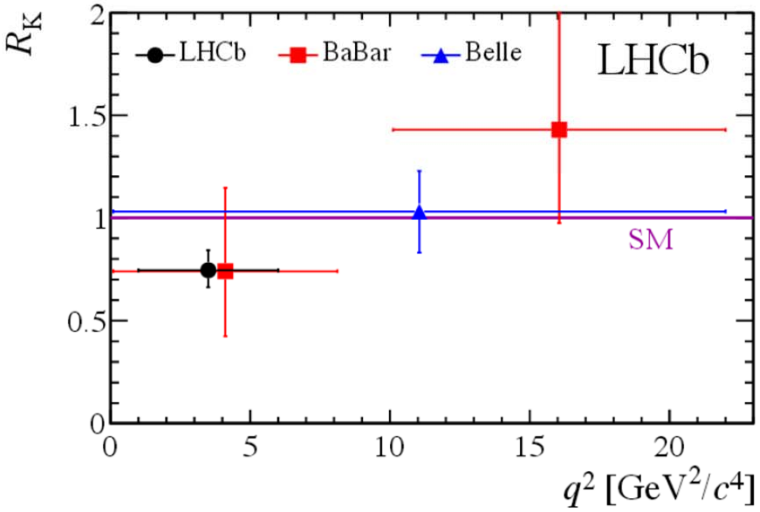
$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)}$$ = 1.000 + $O(m_\mu^2/m_b^2)$ (SM)

[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

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

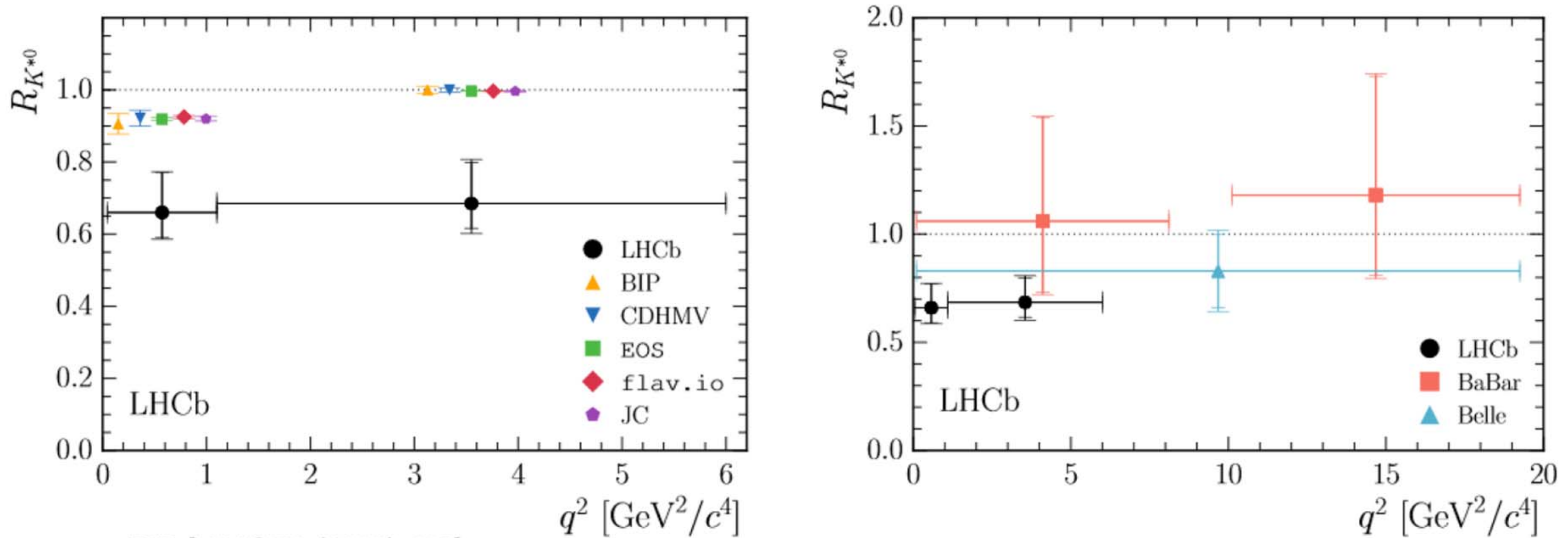
→ Consistent, but lower, than the SM at **2.6σ**

Arantza Oyanguren

Lepton Flavour Universality

- 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]

concern over low energy bin: G. Hou*

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

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

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

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

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

C: ISIDORI et al 2016 EPJC

Concerns on SM-theory

- **Good news is that lattice[FERMIL-MILC] study largely confirms pheno calculations for R_D [our RBC-UKQCD will present at Lattice 2018 & finalize very soon]**
- **For B=>D^* no complete lattice study so far; 4 rather than 2 FF, so , from the lattice perspective, anticipate appreciably larger errors than for B=>D**
- **Therefore, O(1%) errors in RD* (and in fact smaller than in RD) never made much sense.**
- **Recent phenomenological studies of** Bernlochner, Ligeti, Papucci and Robinson; Bigi, Gambino and Schacht and of Jaiswal, Nandi and Patra are very timely and greatly appreciated; errors O(3%) await lattice confirmation; **likely an underestimate for a variety of reasons.**
- Radiative corrections for sure on lattice corrections still need to be done; their errors ~5% [should be checked] need to be included on all latt determinations
- **Weighted average of theory errors should almost never be done**
- **Error estimates for RD(*) on SM given in our 2017 (ADS') paper are likely the most reliable.**

Comments on Theory

- For RD and RD*, non-lattice pheno efforts are on good, theo. grounds based on HQS….unlikely to be off by much but sym breaking are always questionable
- Need however precise lattice results esp for B=>D*
- For FCNC B=>K(*) ll, LUV tests theory is essentially irrelevant so long as m_ll>O(1 GeV)
- FCNC, B=>K(*) ll, absolute measured rates vs SM, theory is not reliable because of serious LD, non-perturbative contaminations
- THEREFORE extremely important for expts to provide

R_Bs(phi)

C also s. Descotes-Genon talk

Comments/Reservations pros & cons on Expts p1 of 2

- For RD(*), B=> D(*) τ ν; most experimental results are with τ => μ ν ν ….i.e 2 ν's …..so D** potential contamination is a serious problem, in my view, as I have been stressing for past few years
- These D** et al BGs cannot be reliably estimated by using GISW etc models. They should be measured
- It is important to note that both LHCb and Belle measurements of RD* with tau=>hadron + nu are essentially consistent with SM estimates.
- It'd be very useul if BABAR would also provide their RD(*) with tau=> hadron + nu
- The importance of more precise experimental numbers from both methods cannot be over-emphasized; results from LHCb Run-II and beyond and Belle(II) are eagerly awaited.

Reg. RK(*) mu/e UV

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

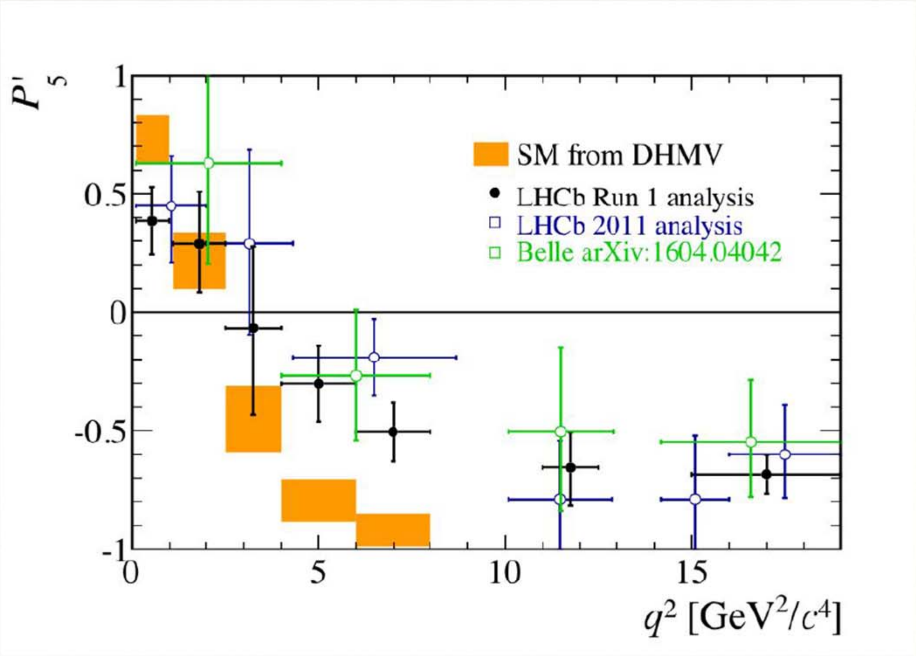
B-baryon decays should show it

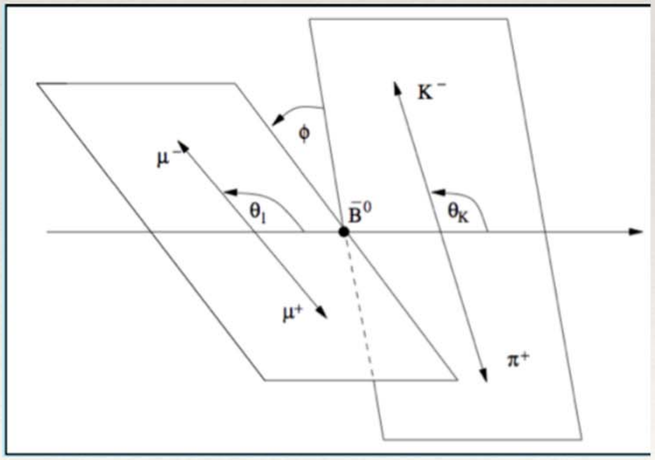
- **Current statistics is marginal; more final states are needed and even more important other experiments esp. BELLE (II) confirmation is essential**
- **This can take years as Br are O(10^{-6}) so not easy even for Belle-II**;
- **however, Belle-II will be able to do RXs…inclusive and that will likely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

B-flavor anomalies: P_5'

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]





Recent results from LHCb

PRL 118 (2017) 191801

- Updated analysis using combination of **Run2 data (1.4 /fb) & Run1 data (3/fb)**

→ new signal isolation

→ better rejection of di-hadron background due to better particle ID

→ Background rejection improved using new multivariate analysis (BDT)

- **Theoretical uncertainties (on V_{CKM}, f_{Bs}) well below statistical error**

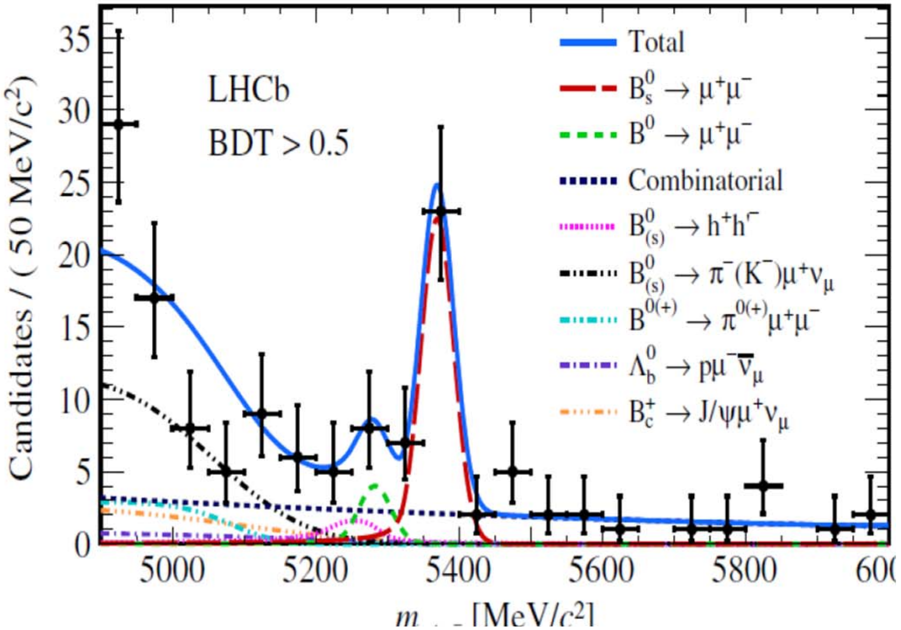
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

First observation by a single experiment with 7.8 σ significance

$$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$$

No evidence

Smaller compared to Run1 measurement



Role of lattice esp in FlavPh and in CP searches

- **Steve Gottlieb nice talk on lots of lattice results relevant for CKM physics….i regard Fermilab/Milc RD with error ~4% most reliable to date [but needs QED rad corr] ..our[RBC-UKQCD] will be completing soon Bs=>Ds and Bs=K semi-lep form factor…R-ratios to an excellent approx same as B=D, pi**

- **Xu Feng : rare K decays..New technique for handling matrix elements of non-local operators developed by RBC-UKQCD; see a bit more later**

RBC-UKQCD [WITZEL, JUTTNER, TSANG, FLYNN, LEHNER, IZUBUCHI + AS]
In final stages

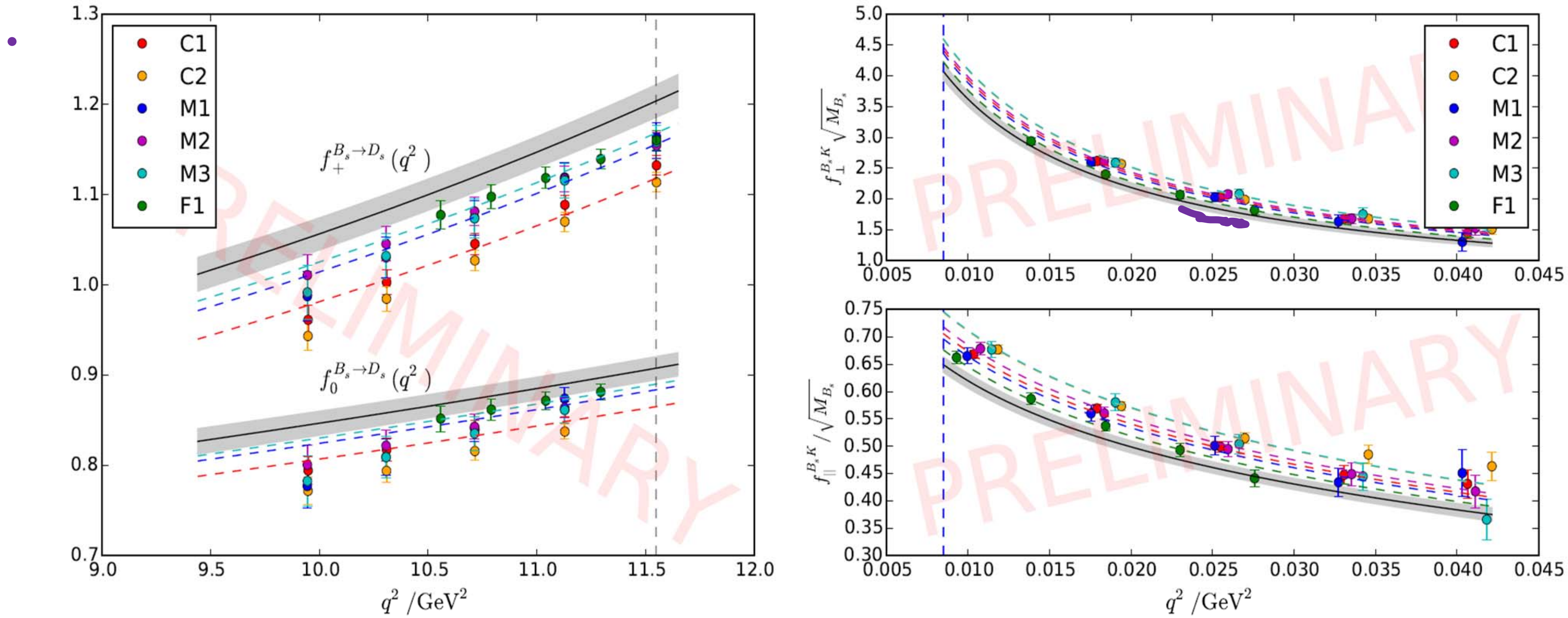


Figure 4. Chiral-continuum extrapolation for semi-leptonic form factors for $B_s \to D_s \ell\nu$ (left) and $B_s \to K\ell\nu$ (right). Performing a simple pole-ansatz for $B_s \to D_s$ we directly fit the phenomenological form factors f_+ and f_0. For $B_s \to K$ we use heavy meson chiral perturbation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

Form factors for $B_s \to D_s \ell\nu, K\ell\nu$

~ 2 months;

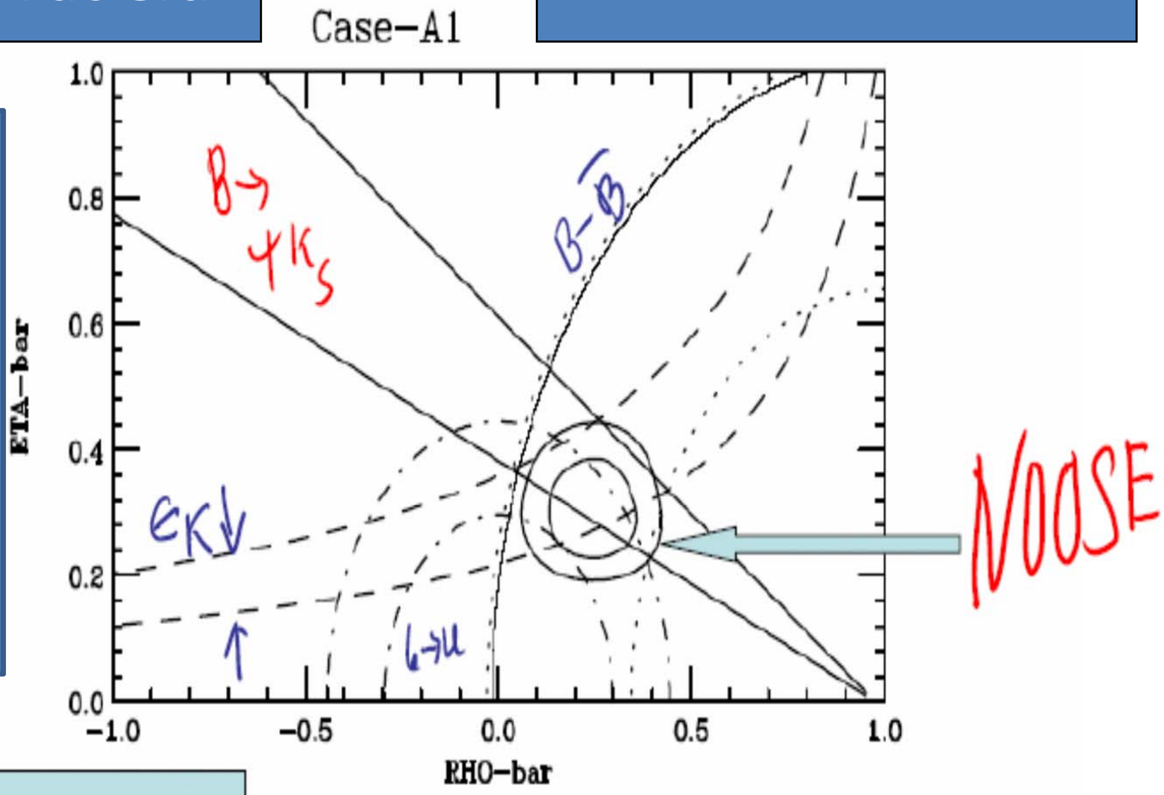
the “beginning” “Dawn “

the asymmetric B-Fac era

ood &AS, hepph/0103

Japan

1st Hint of confirmation of CKM CP description



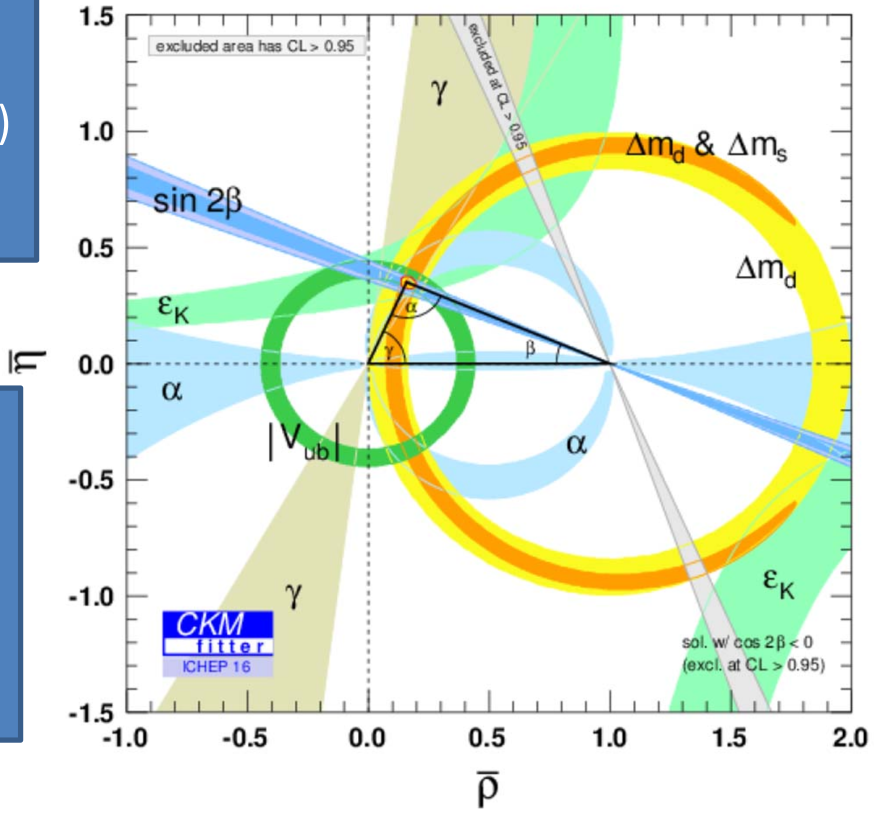
Most bands due
To theory errors

New physics will be a perturbation, impo
to use clean theory and lots of statisti .

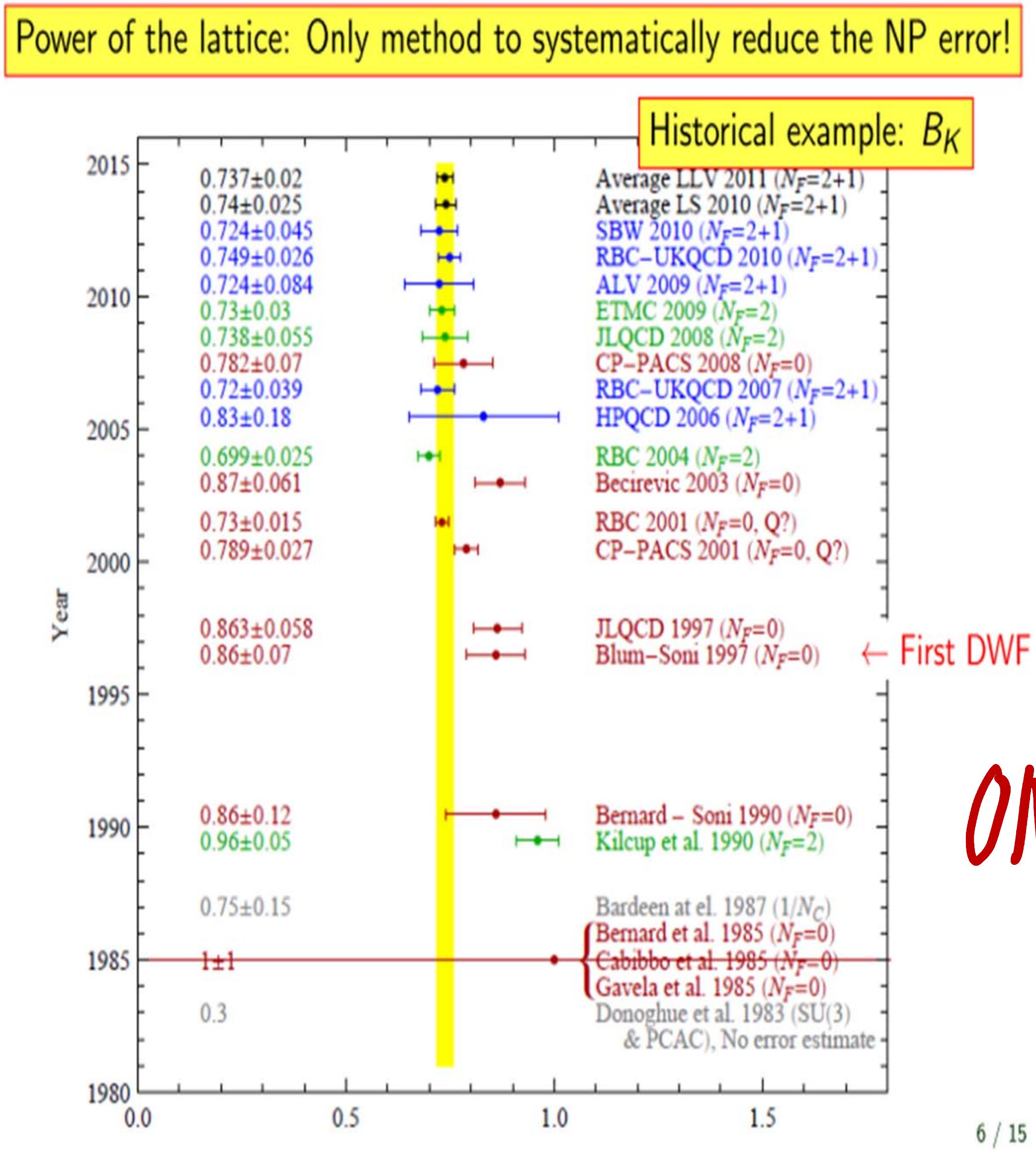
Overall consistency with the SM

http://ckmfitter.in2p3.fr
see also http://www.utfit.org

Looks great; but looks can be deceiving…
In fact at level of O(2σ) tension(s) exist



O(10-15%) new physics is possible and is HUGE!



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

Historical example: B_K

0.737±0.02	Average LLV 2011 (N_F=2+1)
0.74±0.025	Average LS 2010 (N_F=2+1)
0.724±0.045	SBW 2010 (N_F=2+1)
0.749±0.026	RBC–UKQCD 2010 (N_F=2+1)
0.724±0.084	ALV 2009 (N_F=2+1)
0.73±0.03	ETMC 2009 (N_F=2)
0.738±0.055	JLQCD 2008 (N_F=2)
0.782±0.07	CP–PACS 2008 (N_F=0)
0.72±0.039	RBC–UKQCD 2007 (N_F=2+1)
0.83±0.18	HPQCD 2006 (N_F=2+1)
0.699±0.025	RBC 2004 (N_F=2)
0.87±0.061	Becirevic 2003 (N_F=0)
0.73±0.015	RBC 2001 (N_F=0, Q?)
0.789±0.027	CP–PACS 2001 (N_F=0, Q?)
0.863±0.058	JLQCD 1997 (N_F=0)
0.86±0.07	Blum–Soni 1997 (N_F=0) ← First DWF
0.86±0.12	Bernard – Soni 1990 (N_F=0)
0.96±0.05	Kilcup et al. 1990 (N_F=2)
0.75±0.15	Bardeen at el. 1987 ($1/N_C$)
1±1	Bernard et al. 1985 (N_F=0) ~~Cabibbo et al. 1985 (N_F=0)~~ Gavela et al. 1985 (N_F=0)
0.3	Donoghue et al. 1983 (SU(3) & PCAC), No error estimate

AB-initio Calculat

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

ONE ILLUSTRATION

=>MILESTONE: FOR THE 1ST TIME CONFIRMATION OF THE SM-CKM-PARADIGM OF CPV

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

Lattice

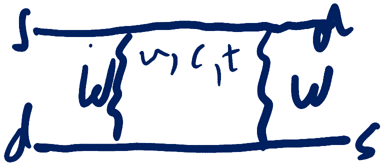
Bit more on lattice

- 1.Should be recognized that w/o input from the lattice its highly questionable if experimental measurement from B-factories alone could have achieved this goal
- That is of course the past
- 2. However, QCD is [will be] an integral part of SM [BSM]; there is no escape
- With the anticipated larger data samples from Belle-II and LHCb

[upgrades] + constant improvements in lattice calculations we can be sure that precise determination of numerous entities will continue so that more stringent tests of the SM and more powerful searches for BSM can be performed

Advances in lattice techniques

- Xu’s talk …~**6 years ago, RBC-UKQCD developed new methodology for calculating matrix elements of non-local operators**
- [Almost] Every Weak Interaction loop in SM has some non-local..non-perturbative contribution and it escapes usual OPE



- By now RBC-UKQCD has studied 3 examples : 1. Δ mK; 2. εK_LD ~5%

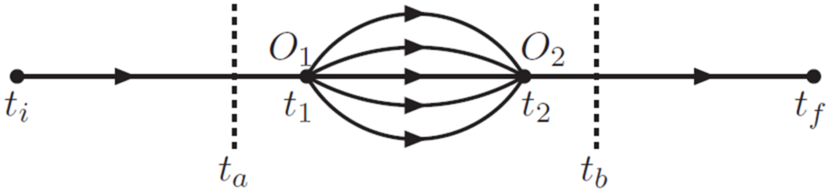
~50%

- 3. Rare K-decays ~5%
- =>in O(6 months) error on Δ mK will be reduced to 15-20% for the

1st time and thus we’ll have a new observable to test the SM

Bearing in mind Belle-II and LHCb [upgrades], slowly we are now making attempts to extent applications to charm and B-physics

LD processes and bilocal matrix elements from LQCD



Hadronic matrix element for the 2^{nd}-order weak interaction

$$\int_{-T}^{T} dt \, \langle f | T \left[O_1(t) O_2(0) \right] | i \rangle$$

$$= \sum_n \left\{ \frac{\langle f | O_1 | n \rangle \langle n | O_2 | i \rangle}{M_i - E_n} + \frac{\langle f | O_2 | n \rangle \langle n | O_1 | i \rangle}{M_i - E_n} \right\} \left(1 - e^{(M_i - E_n)T} \right)$$

- For $E_n > M_i$, the exponential terms exponentially vanish at large T
- For $E_n < M_i$, the exponentially growing terms must be removed

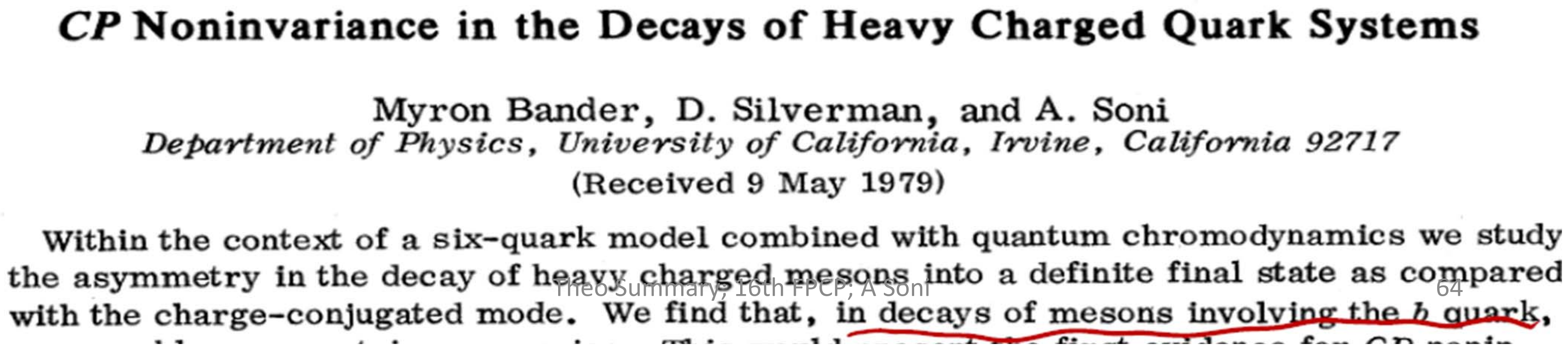
Euclidean time ⇒ exponentially growing contamination

DIRECT CP

Dedicated to the memory of
Myron Bander , who decades ago started
me off in the interesting and
important path of Direct CP

My 1st paper
on B - Physics

PRL

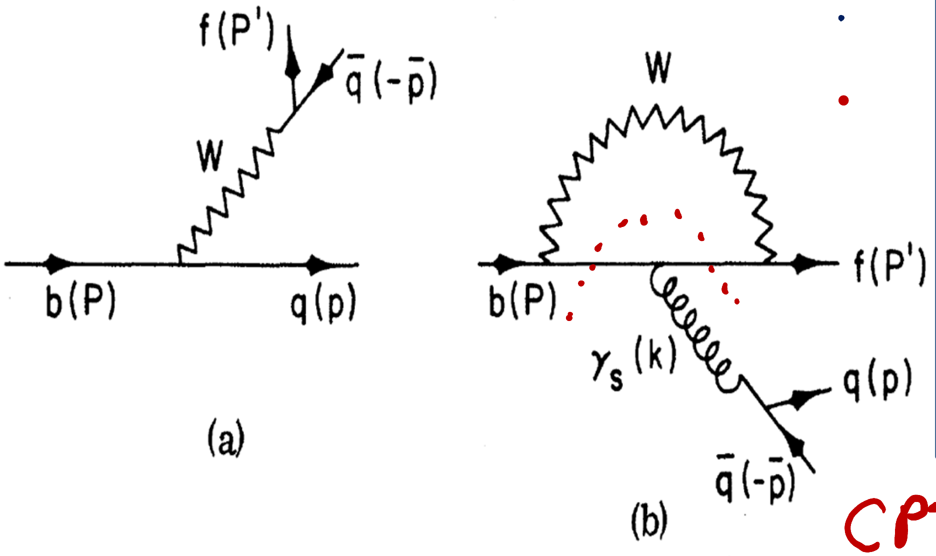


CP Noninvariance in the Decays of Heavy Charged Quark Systems

Myron Bander, D. Silverman, and A. Soni
Department of Physics, University of California, Irvine, California 92717
(Received 9 May 1979)

Within the context of a six-quark model combined with quantum chromodynamics we study the asymmetry in the decay of heavy charged mesons into a definite final state as compared with the charge-conjugated mode. We find that, in decays of mesons involving the b quark,

Simple ex. Of DCP in B-Physics: Tree-Penguin Int



Bander, Silverman and A. S. PRL '79

"measurable asymmetries may arise. This would present the first evidence for *CP* noninvariance in charged systems."

CPT: HOU+GERARD '86

Babar, Belle 1st obs ~2007

$$A = |A_1| \exp[i(\delta_1 + \phi_1)] + |A_2| \exp[i(\delta_2 + \phi_2)]$$

$$\bar{A} = |A_1| \exp[i(\delta_1 - \phi_1)] + |A_2| \exp[i(\delta_2 - \phi_2)] \, .$$

$$\alpha_{PRA} = \frac{\mathcal{B}(B \to f) - \mathcal{B}(\bar{B} \to \bar{f})}{\mathcal{B}(B \to f) + \mathcal{B}(\bar{B} \to \bar{f})}$$

$$= \frac{2|A_1|\,|A_2| \sin\delta \sin\phi}{|A_1|^2 + |A_2|^2 + 2|A_1|\,|A_2| \cos\delta \cos\phi} \, ,$$

$$A_{CP}(B^0 \to K^+\pi^-) = -0.082 \pm 0.006$$

5 orders of magnt ϵ'_K !!

REGRETTABLY still CANNOT BE USED TO RELIABLY TEST THE SM-CKM

$B^{\pm} \rightarrow K^{+}K^{-}\pi^{\pm}$

VIPIN GAUR @ FPCP 2018

$M_{K^+K^-}$ (GeV/c^2)	N_{sig}	Efficiency (%)	dBF/dM ($\times 10^{-7}$)	A_{CP}
0.8-1.1	59.8±11.4±2.6	19.7	14.0±2.7±0.8	-0.90±0.17±0.04
1.1-1.5	212.4±21.3±6.7	19.3	37.8±3.8±1.9	-0.16±0.10±0.01
1.5-2.5	113.5±26.7±18.6	15.6	10.0±2.3±1.7	-0.15±0.23±0.03
2.5-3.5	110.1±17.6±4.9	15.1	10.0±1.6±0.6	-0.09±0.16±0.01
3.5-5.3	172.6±25.7±7.4	16.3	8.1±1.2±0.5	-0.05±0.15±0.01

- ☐ Overall BF and A_{CP} from Belle

BSS PRL '79

ATWOOD + A.S. PRD '97

$$\text{BF}\,(B^{+} \rightarrow K^{+}K^{-}\pi^{+}) = (5.38 \pm 0.40 \pm 0.35) \times 10^{-6}$$

$$A_{CP} = -0.182 \pm 0.071 \pm 0.016$$

→ HUGE

PRD **96**, 031101 (2017)

LFUV WITH $B^0_s \to K^{*0} \mu^+\mu^-$

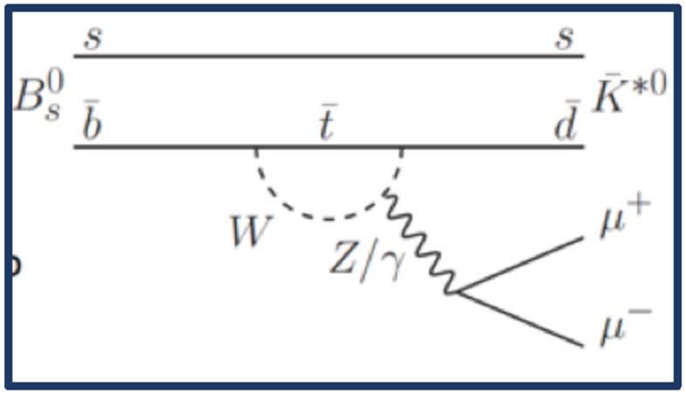
- Heavily suppressed b → dll transition in Standard Model
  - complementary to b → sll transitions in B^0_d decays

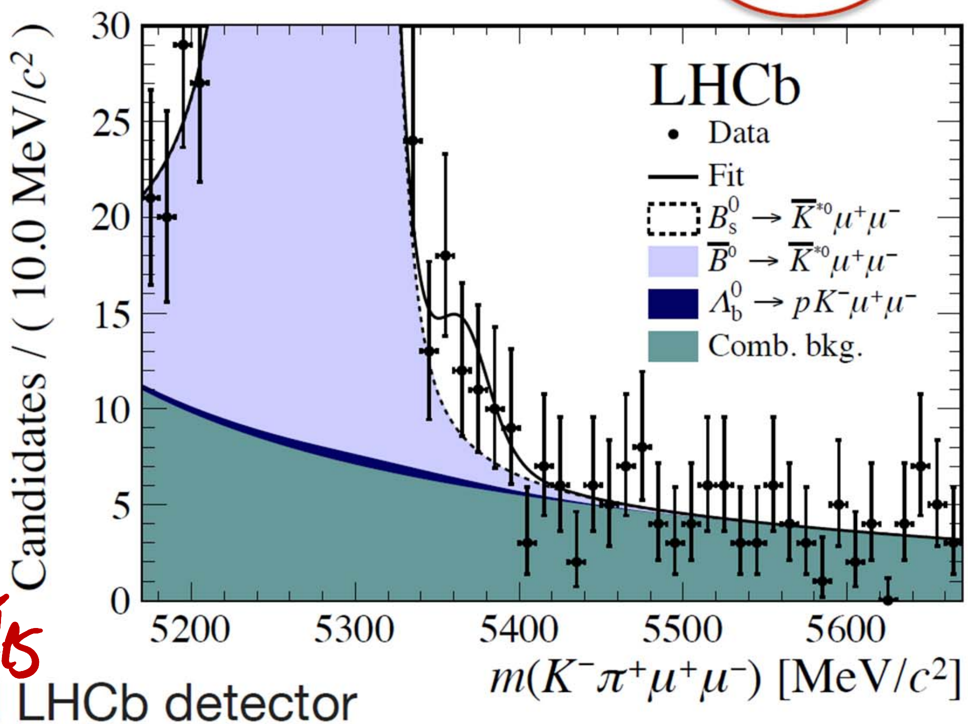
arXiv:1804.07167,
Run 1+2, 4.6 fb^{-1}

- Evidence of 3.4σ (38 ± 12 events) consistent with prediction

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

CONGRATS LHCb



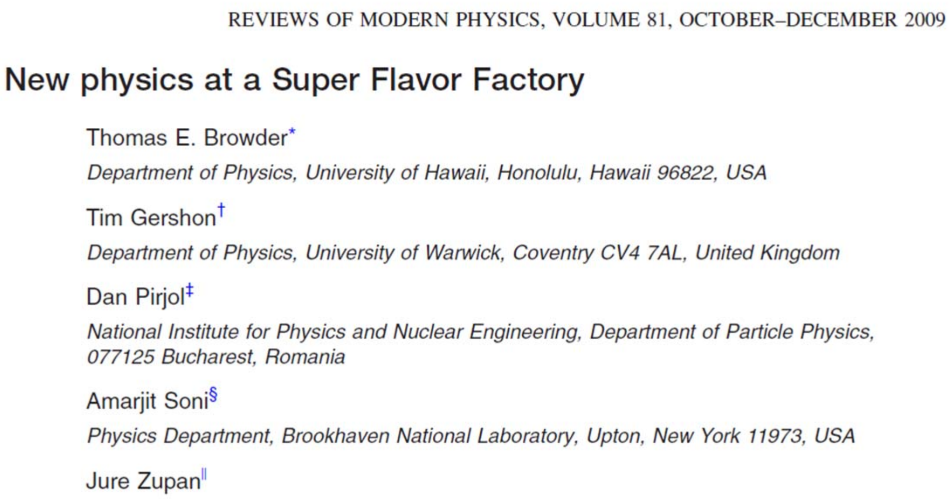


b → d!! CPT guarantees

- Angular analysis with upgraded LHCb detector
  - Sensitivity with Run3 possibly better than current B_d measurement

Large CP Asymmetries

SIGNIFIES IMPORTANCE of LHCb upGs



REVIEWS OF MODERN PHYSICS, VOLUME 81, OCTOBER–DECEMBER 2009

New physics at a Super Flavor Factory

Thomas E. Browder[*]
Department of Physics, University of Hawaii, Honolulu, Hawaii 96822, USA

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Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom

Dan Pirjol[‡]
National Institute for Physics and Nuclear Engineering, Department of Particle Physics, 077125 Bucharest, Romania

Amarjit Soni[§]
Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA

Jure Zupan[||]

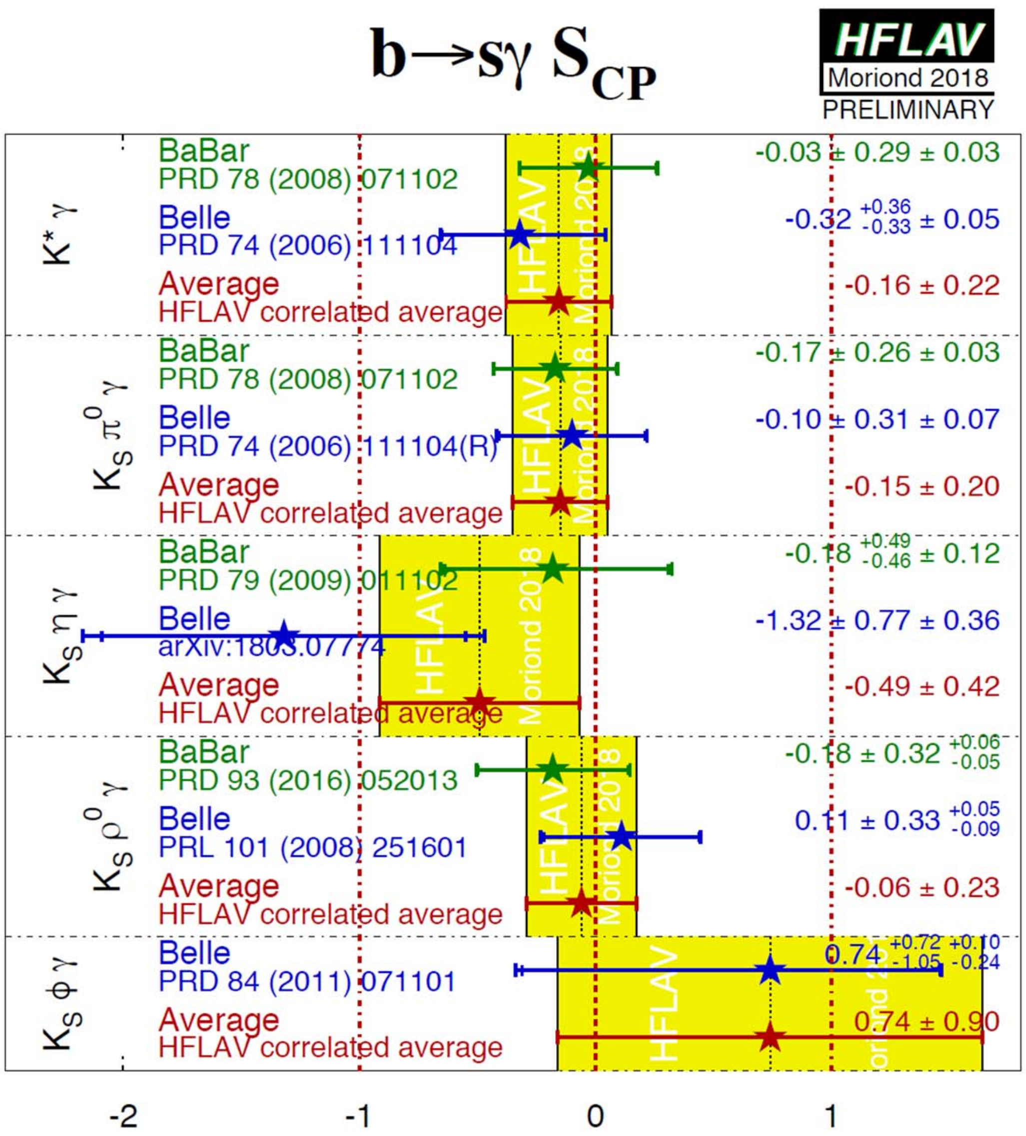
See also T. Gershon + AS,JPG'07

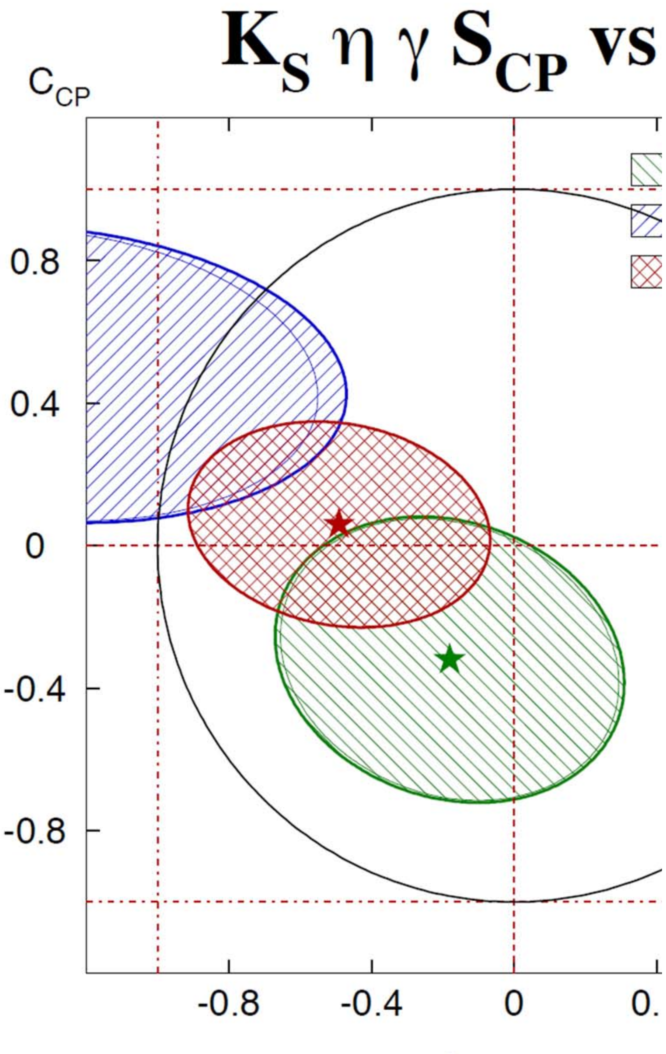
1. Jusak Tandean @ fpcp2018
2. Marco Gersabeck @fpcp2018

NULL TESTS…….FOR DETAILED DISCUSSIONS SEE ABOVE

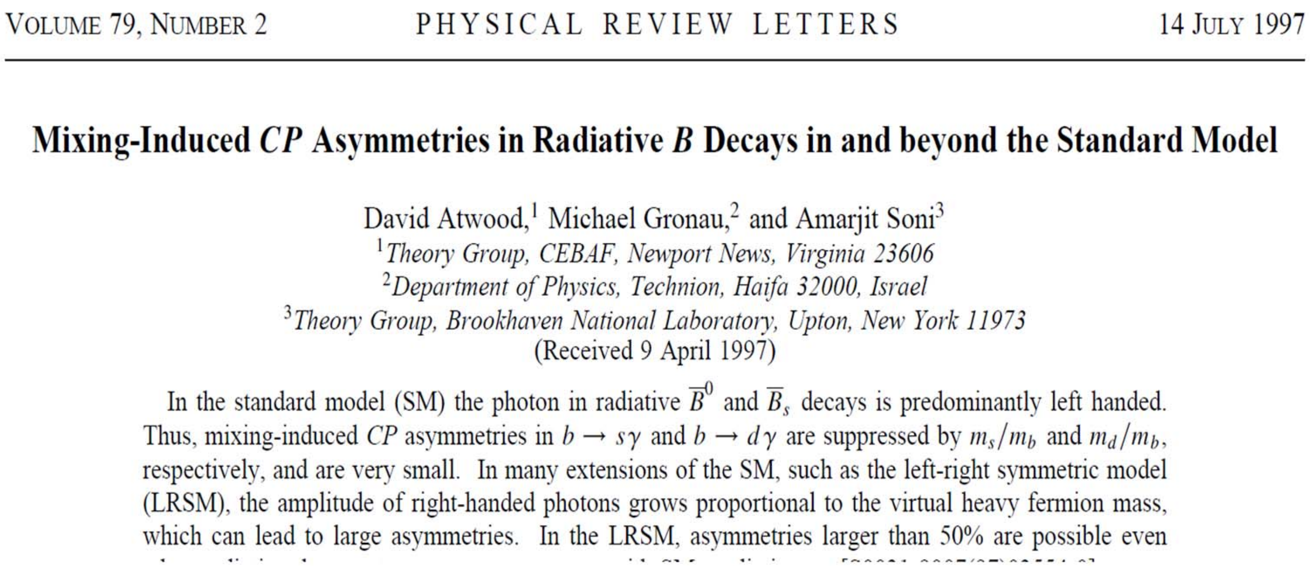
ILLUSTRATIVE EXAMPLES

Time dependent CP violation in b→s





Contours give $-2\Delta(\ln L) = \Delta\chi^2 = 1$, corresponding t



VOLUME 79, NUMBER 2 PHYSICAL REVIEW LETTERS 14 JULY 1997

Mixing-Induced *CP* Asymmetries in Radiative *B* Decays in and beyond the Standard Model

David Atwood,[1] Michael Gronau,[2] and Amarjit Soni[3]
[1]*Theory Group, CEBAF, Newport News, Virginia 23606*
[2]*Department of Physics, Technion, Haifa 32000, Israel*
[3]*Theory Group, Brookhaven National Laboratory, Upton, New York 11973*
(Received 9 April 1997)

In the standard model (SM) the photon in radiative $\overline{B}^0$ and $\overline{B}_s$ decays is predominantly left handed. Thus, mixing-induced *CP* asymmetries in $b \to s\gamma$ and $b \to d\gamma$ are suppressed by m_s/m_b and m_d/m_b, respectively, and are very small. In many extensions of the SM, such as the left-right symmetric model (LRSM), the amplitude of right-handed photons grows proportional to the virtual heavy fermion mass, which can lead to large asymmetries. In the LRSM, asymmetries larger than 50% are possible even

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PHYSICAL REVIEW D **71,** 076003 (2005)

Mixing-induced *CP* violation in $B \to P_1P_2\gamma$ in search of clean new physics signal

David Atwood
Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA

Tim Gershon and Masashi Hazumi
High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, Japan

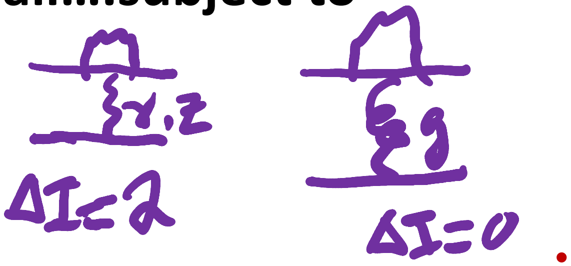
Amarjit Soni
Theory Group, Brookhaven National Laboratory, Upton, New York 11973, USA
(Received 17 December 2004; published 8 April 2005)

CPV in charm a powerful null test

- **All CP asymmetries in charm should be vanishingly small [how small? ..Devil is in ….] ΔACP[pipi – KK] a case in point. Some theorists 1st predicted any non-vanishing**

measurement would signal genuine NP. This is based on naïve thinking w/o understanding of non-perturbative effects. Consensus now is only if its >1% a compelling case for NP

- **D=>pi+ pi0 is another very interesting case.**
- **K+, D+, B+ => pi+ pi0 are all vanishingly small….subject to considerable non perurbative corrections**



But QED, EW, $m_u \neq m_d$
break Isospin

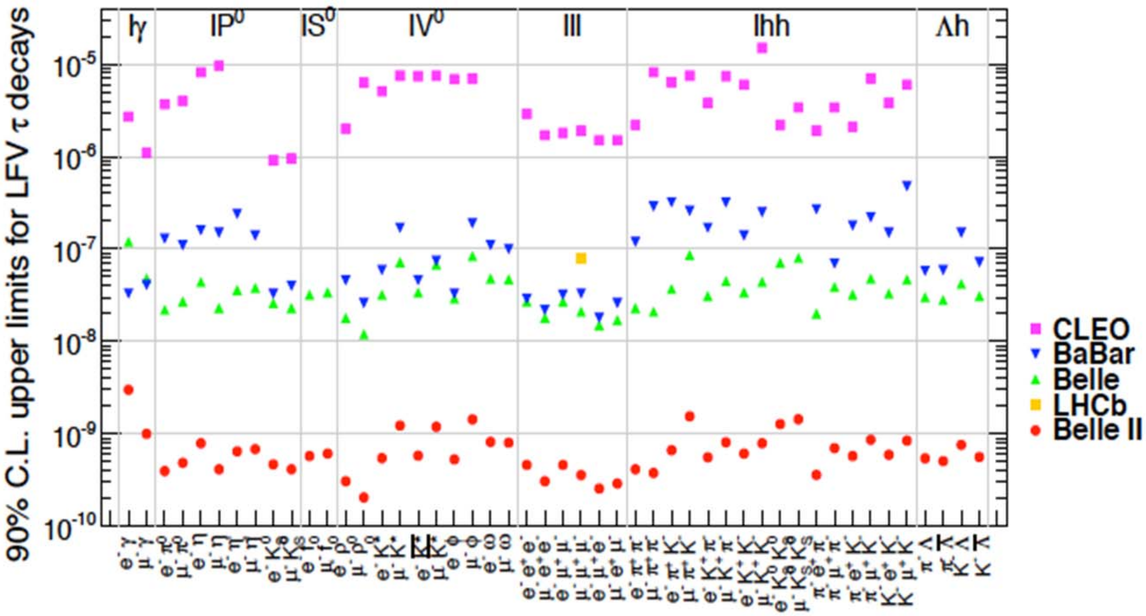
$A_{cp}(B^+) > A_{cp}(D^+) > A_{cp}(K^+)$ SM

SM expectations for DirCP: examples

- **ACP[b=>s]>ACP[c=>u] [l l]**
- **ACP[b=>d]>ACP[b=>s][l l]**
- **ACP[b=>d]>ACP[b=>s] [q q’]**

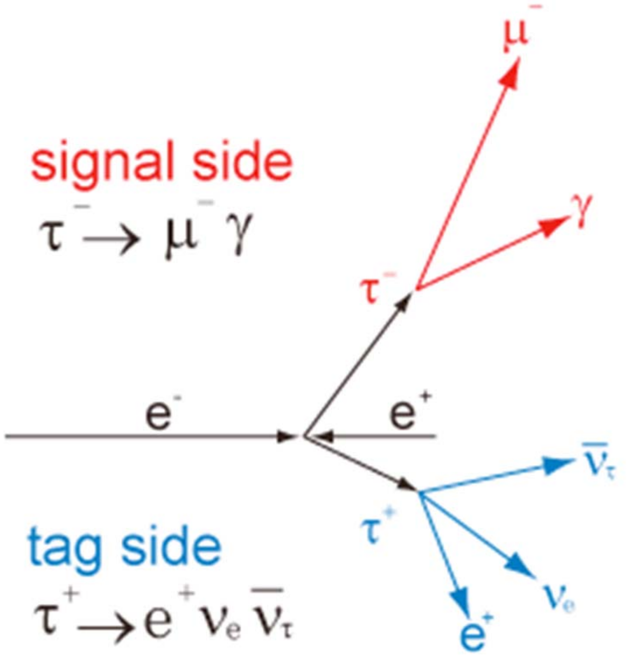
All follow from CPT

τ Lepton Flavor Violation



Note vertical log-scale (50 ab^{-1} assumed for Belle II; 3 fb^{-1} result for LHCb

Example of the decay topology



<u>Belle II will push many limits below 10^{-9}</u>;

LHCb, CMS and ATLAS have very *limited* capabilities.

LHC high pt: The modes τ→μγ and τ →μ h+ h- provide important constraints on H→μτ

SURVEY OF BSMS

Array of BSM approaches to address flavor anomalies

- **Model ind eff L**: Greljo; Camalich; Mandal; Mohanta
- **LQ**: Fajfer; Luzio; Neubert; Silva; Becirevic;
- **[Partial]Composite/warped**: Stangl; Ahmady;Barbieri;

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

- **SUSY-like**: Hiller; ADS'=> RPV3 **Natural flavor Non-Universality**
- **More BSMs**: Guadagnoli; Grinstein; Jung; Ricciardi;Fuentes-Martin; Neshatpour; Crivelin
- **New approaches**: Valli; Camalich;
- **C also s. Descotes-Genon talk**

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

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

Implications of Anomalies

- For Collider:From Isidori ; Kamenik; ADS’;
  Luzio; Hou;

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

ALTMANNSHOFER, Dev + AS
1704.06659 + Seq, WIP

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

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

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

Xsymm implications of anomalies for colliders

ADS'

$R_{D^{(*)}}$ ANOMALY: A POSSIBLE HINT FOR … PHYSICAL REVIEW D **96,** 095010 (2017)

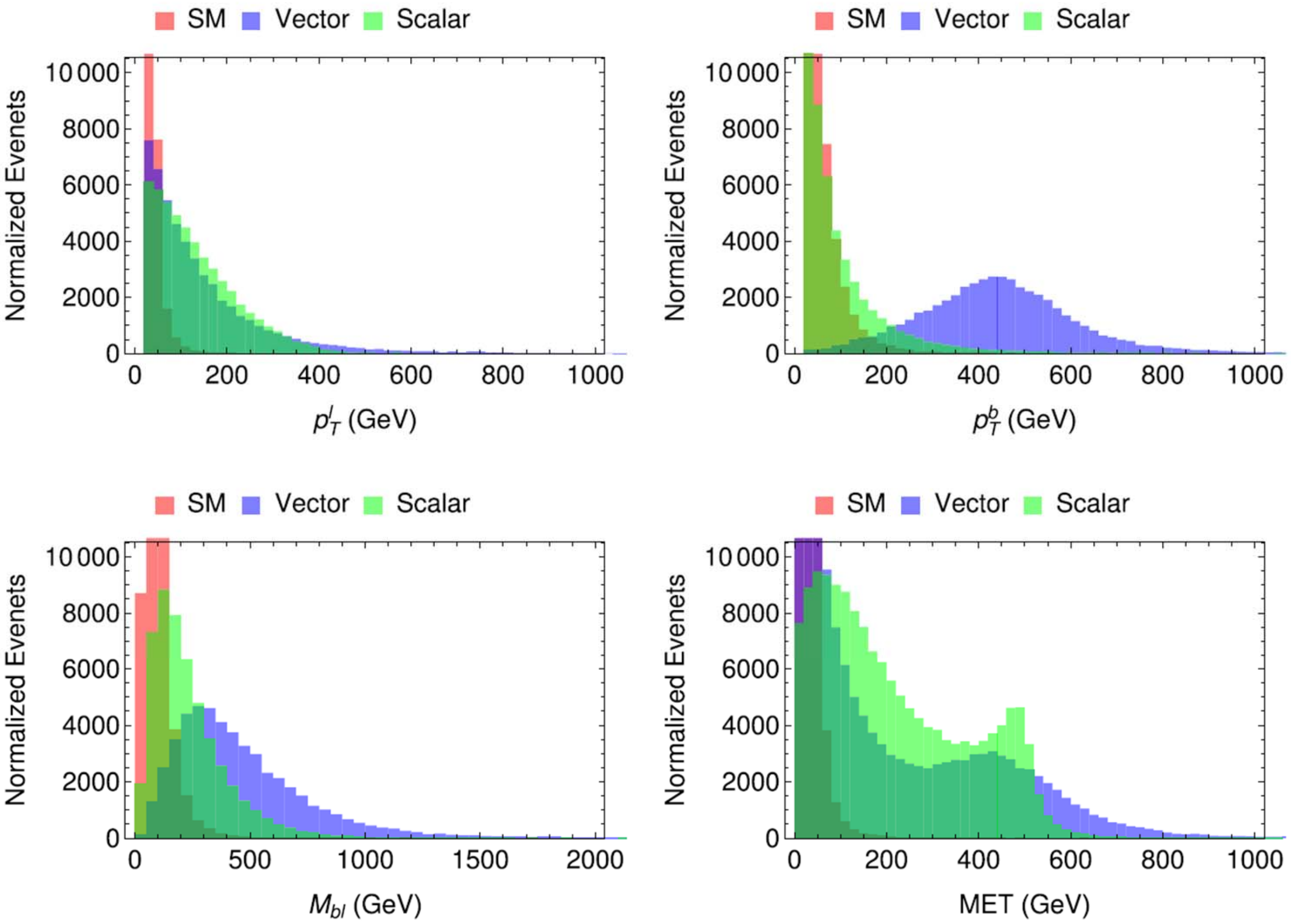


FIG. 1. Normalized kinematic distributions for the $pp \to b\tau\nu \to b\ell + \not{E}_T$ signal and background.

EXPECT DISTINCTIVE NP CONTRIBUTIONS IN COLLIDERS

ALTMANNSHOFER, Dev + AS
1704.06659 + Seq, WIP

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

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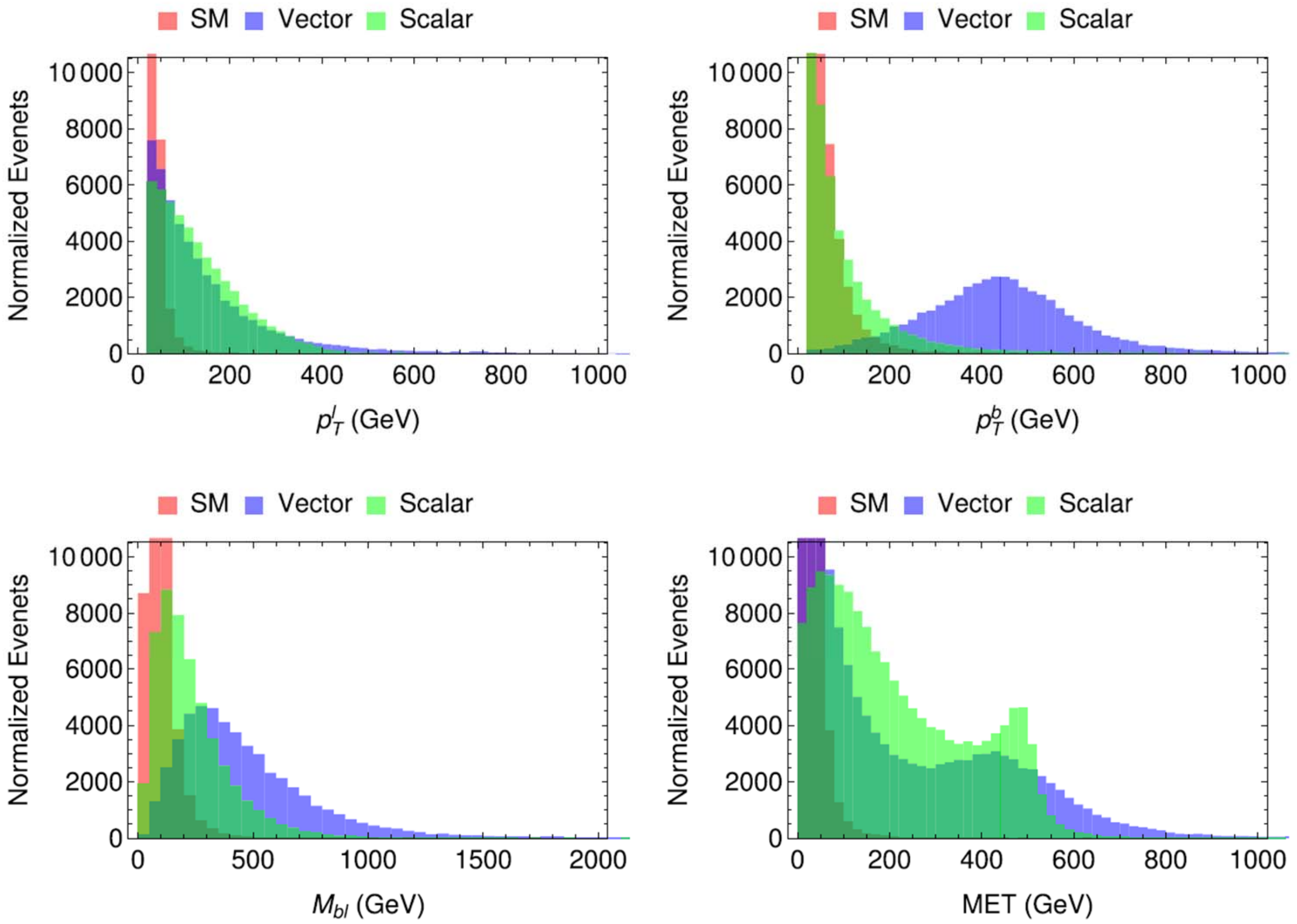


FIG. 1. Normalized kinematic distributions for the $pp \to b\tau\nu \to b\ell + \not{E}_T$ signal and background.

EXPECT DISTINCTIVE NP CONTRIBUTIONS IN COLLIDERS

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

- ASSUMING the anomaly is REAL & HERE TO STAY [BIG ASSUMPTION due to caveats mentioned]
- Anomaly involves simple tree-level semi-leptonic decays
- Also b => tau (3rd family)
- Speculate: May be related to Higgs naturalness
- Seek minimal solution: perhaps 3rd family super-partners(a lot) lighter than other 2 gens > proton decay concerns may not be relevant=> RPV ["natural" SUSY]
- RPV natural setting for LUV …can accommodate g-2 and eps' if needs be
- Collider signals tend to get a lot harder than (usual-RPC) SUSY
- RPV makes leptoquarks natural [and respectable]
- Moreover, RPV should be viewed as an umbrella i.e. under appropriate limits other models are incorporated

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

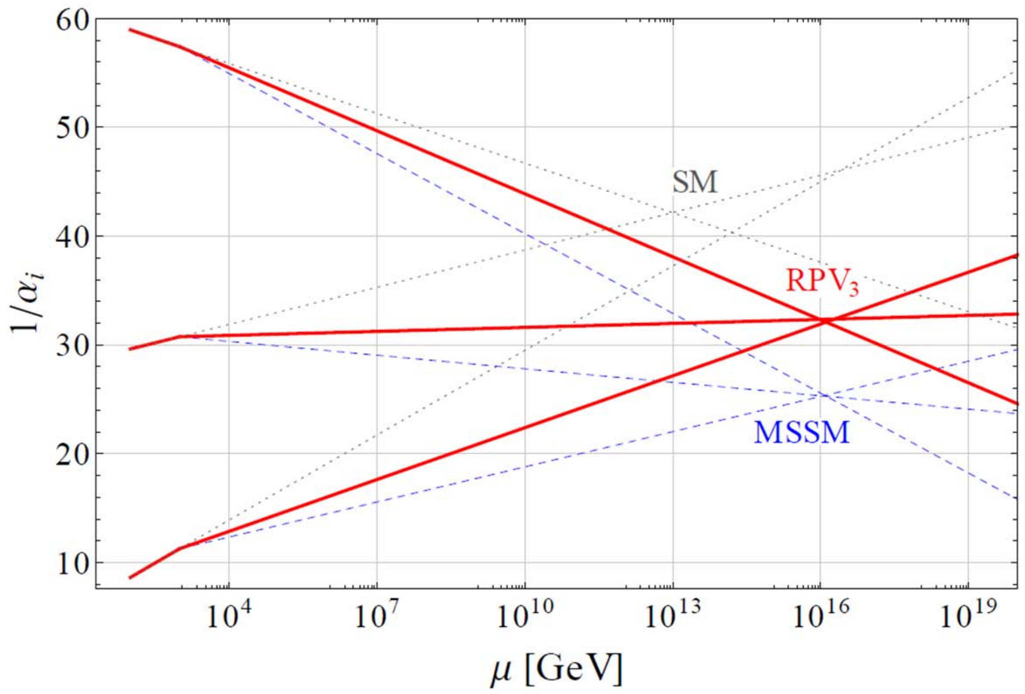


FIG. 2. RG evolution of the gauge couplings in the SM, MSSM and with partial supersymmetrization.

Unification scale ~ stays same, only value of couplings shifts

For pheno relevant terms:

ADS' PRD 2017

$$\left.\begin{aligned}\mathcal{L} &= \lambda'_{ijk}\big[\tilde{\nu}_{iL}\bar{d}_{kR}d_{jL} + \tilde{d}_{jL}\bar{d}_{kR}\nu_{iL} + \tilde{d}^*_{kR}\bar{\nu}^c_{iL}d_{jL} \\ &\quad -\tilde{e}_{iL}\bar{d}_{kR}u_{jL} - \tilde{u}_{jL}\bar{d}_{kR}e_{iL} - \tilde{d}^*_{kR}\bar{e}^c_{iL}u_{jL}\big] + \text{H.c.}\end{aligned}\right\} \text{RPV}_3 \text{ interaction}$$

Dim 6

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

For $R_{D(*)}$

NOTE:
ITS
SM-like!

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

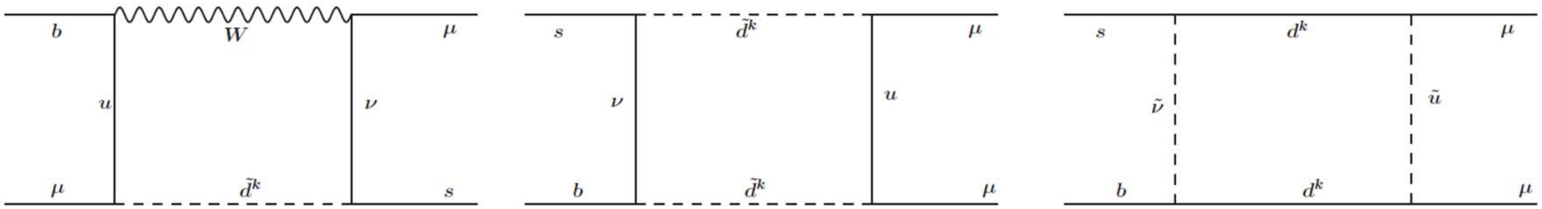


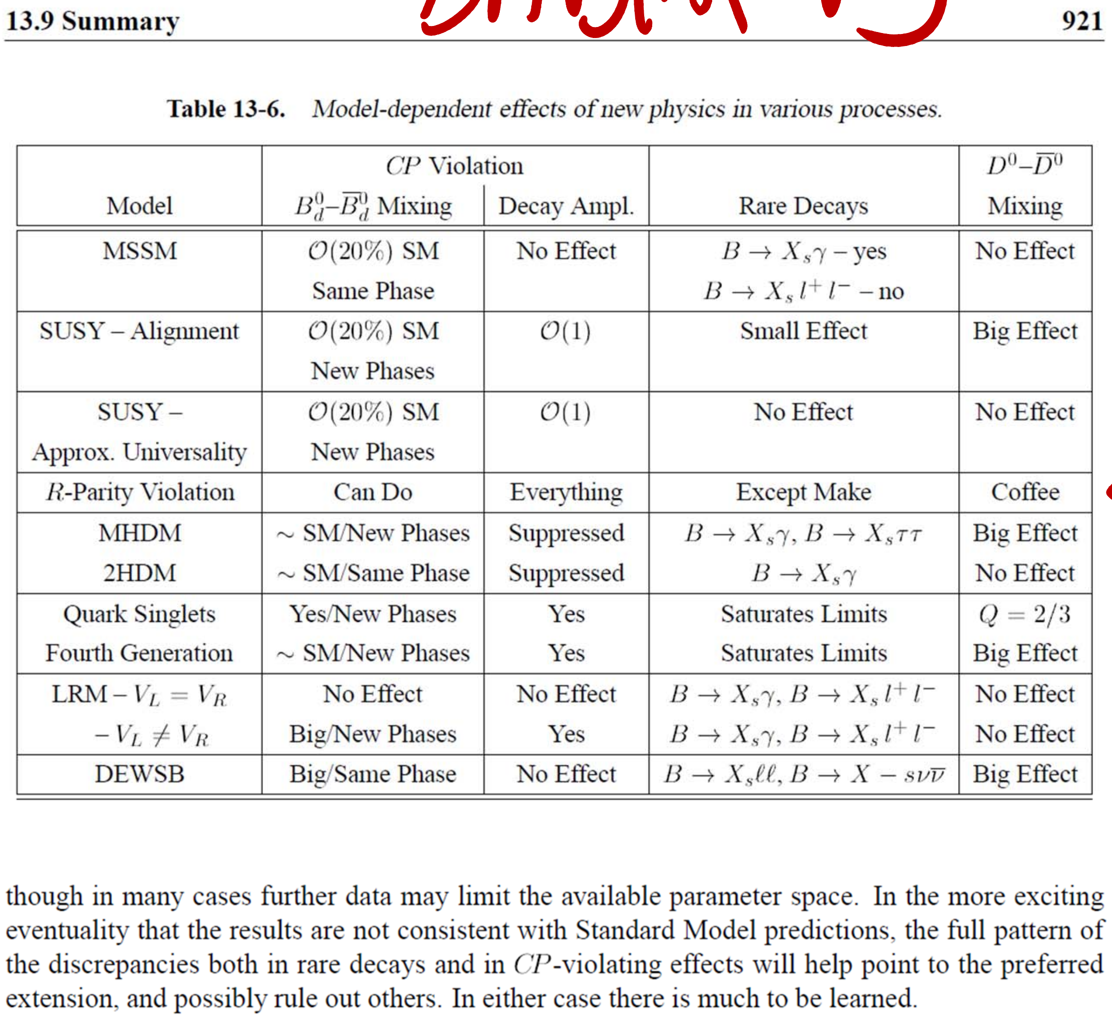
FIG. 1: Representative diagrams for $b \to s\mu^+\mu^-$ transition in R-parity violating interactions.

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

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

CONSTRAINTS: TIGHTENING EXPT'S NOOSE AGAINST SPECIFIC MODELS

BABAR Phy Book '97



13.9 Summary 921

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

Model	CP Violation B_d^0–$\overline{B}_d^0$ Mixing	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.

constraints

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

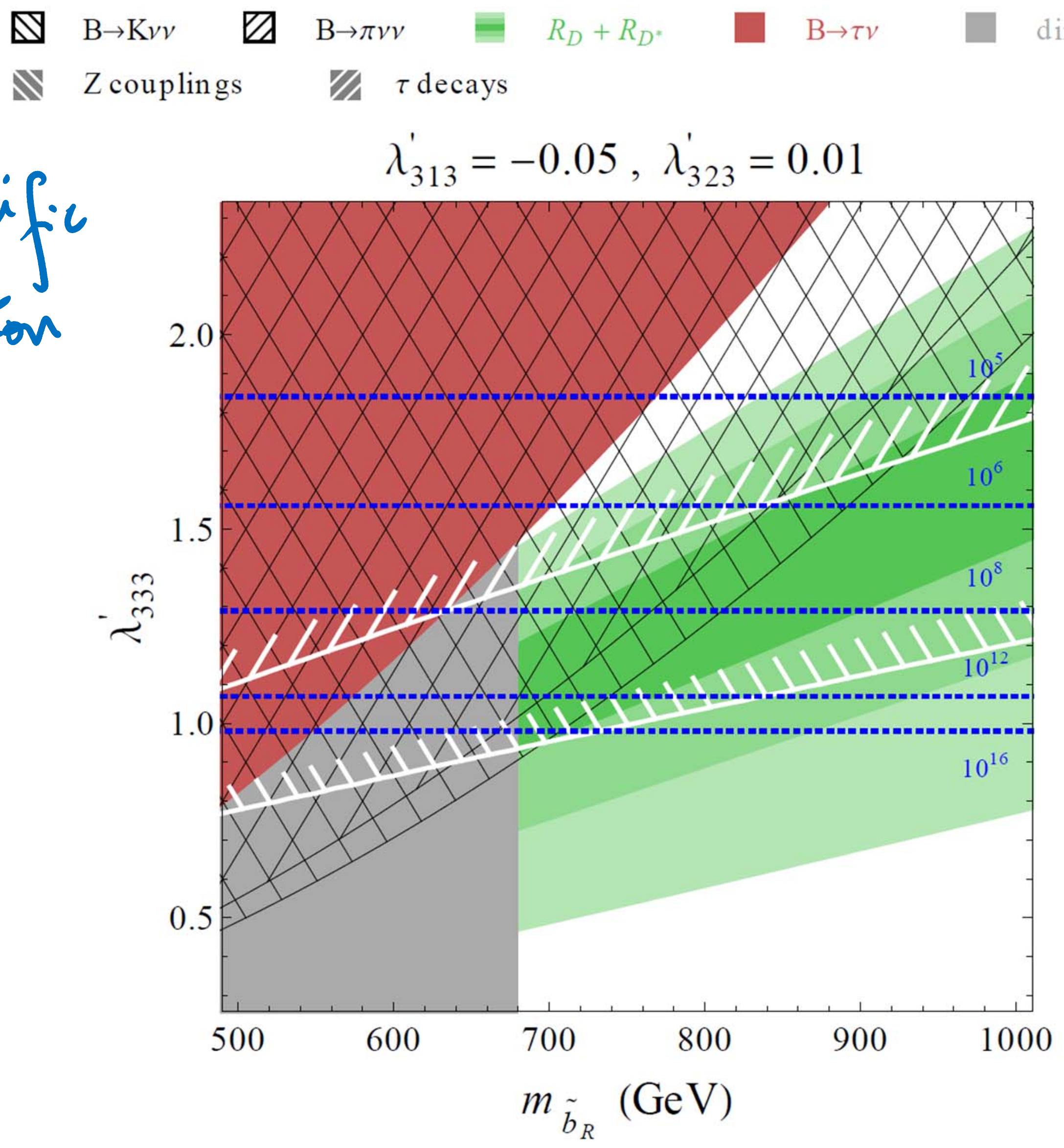
Indirect constraints considered due B=>τ ν; π τ ν; π(K) ν ν….
Also B_C =>τν….

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

⇒ TAKE HOME: This version of RPV is actually (surprisingly) well constrained

⇒ With improved measurements RD(*) in RPV3 may be difficult

As a specific illustration



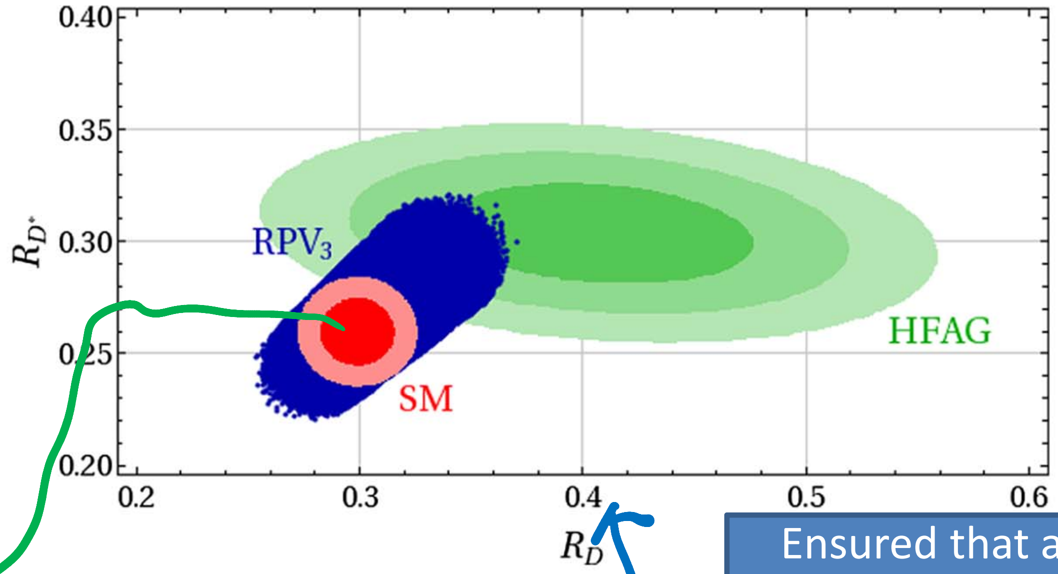
Constraints imposed

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

ALTMANNSHOFER, BHUPAL DEV, and SONI PRD 2017

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

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



More Realistic SM Blob

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

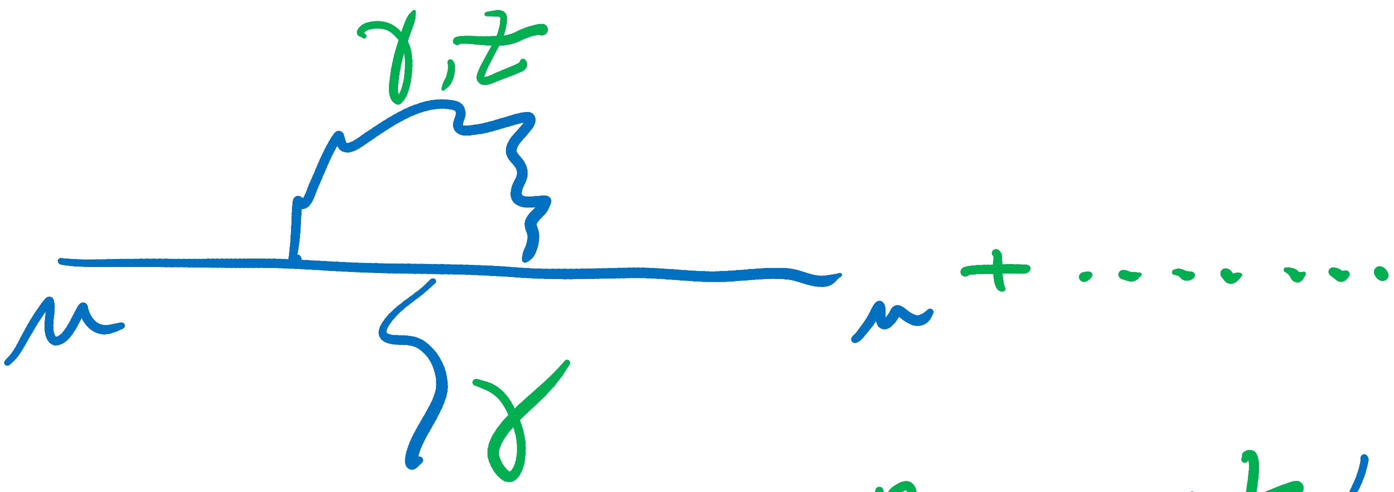
Ensured that all RPV3 couplings stay perturbative up to GUT

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

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

IN CLOSING

NOW FEW WORDS ON MUON G-2



BNL expt '06

~ 3.56 deviation

POSSIBLE CONNECTION OF G-2 TO OTHER FLAVOR ANOMALIES

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

PRD 2015

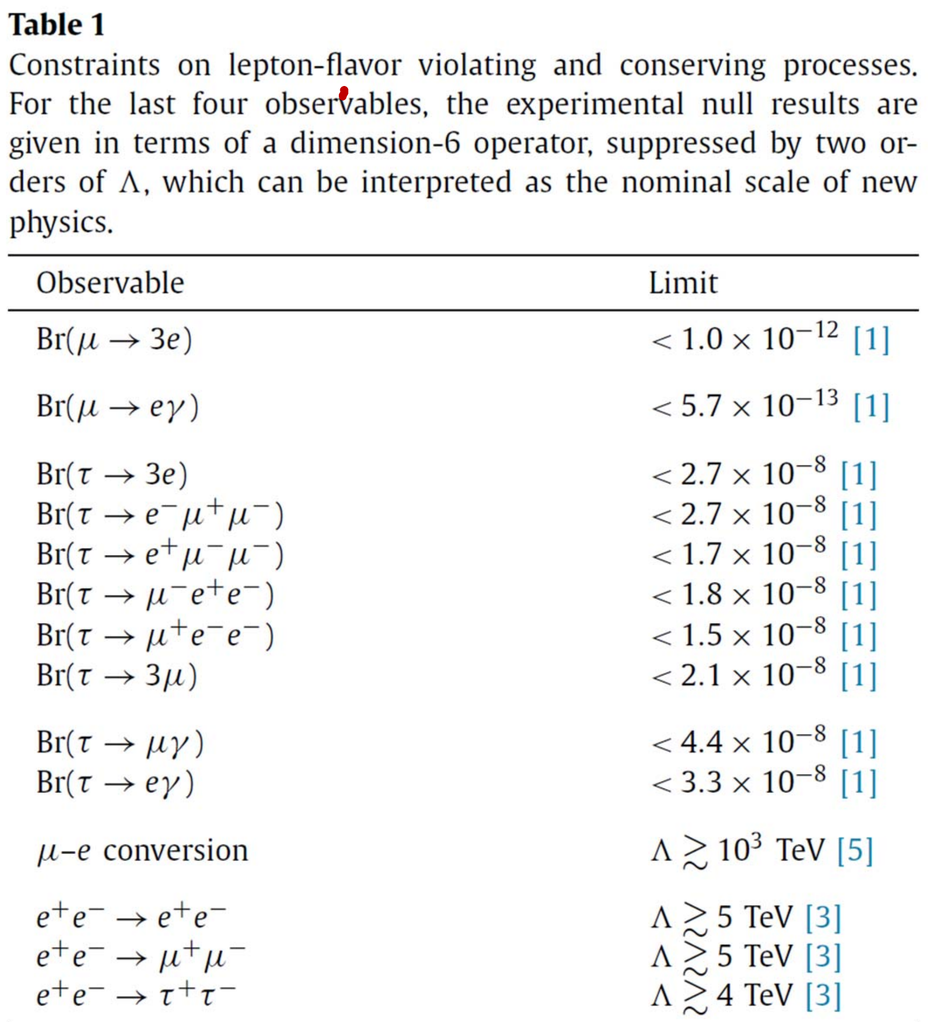


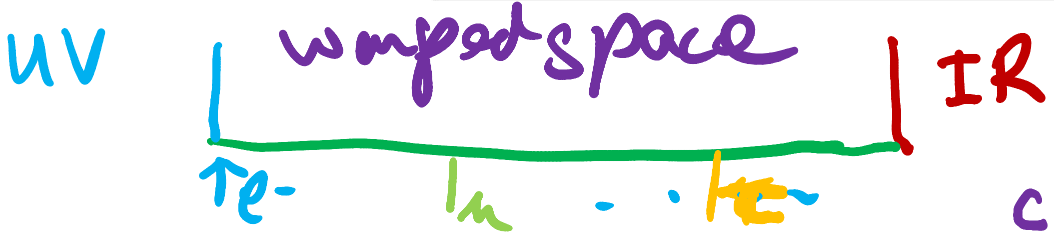
Table 1
Constraints on lepton-flavor violating and conserving processes. For the last four observables, the experimental null results are given in terms of a dimension-6 operator, suppressed by two orders of Λ, which can be interpreted as the nominal scale of new physics.

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

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

Kile, Kobach + AS PRD2015 ⇓ Speculation

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



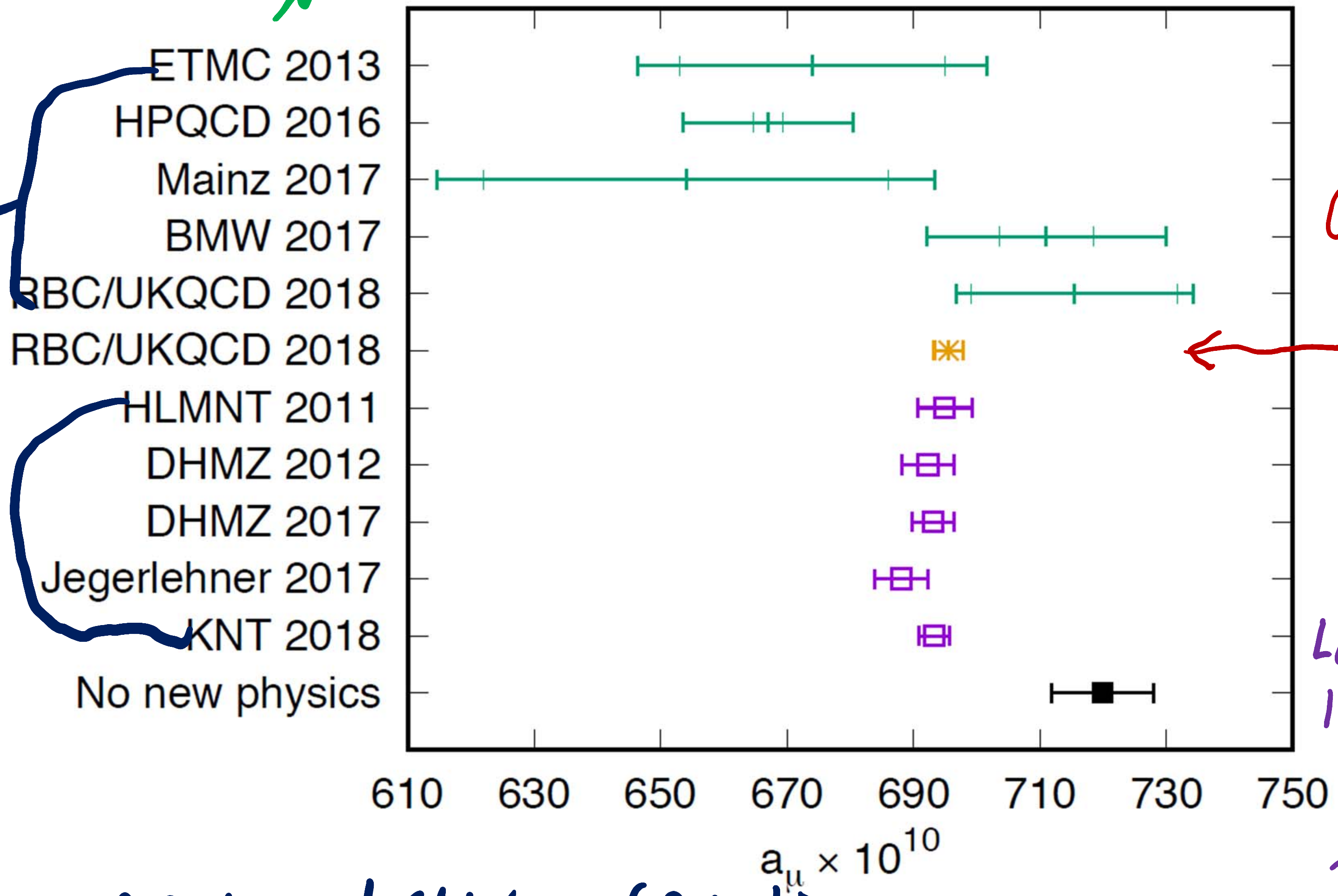
c ALSO A. IYER & LYON

QUICK UPDATE ON G-2

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

PURE Lattice

Pheno



C Lehner et al RBC-UKQCD HYBRID

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

SUMMARY: C. LEHNER (BNL)

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

Lunch Seminar 03/09/18

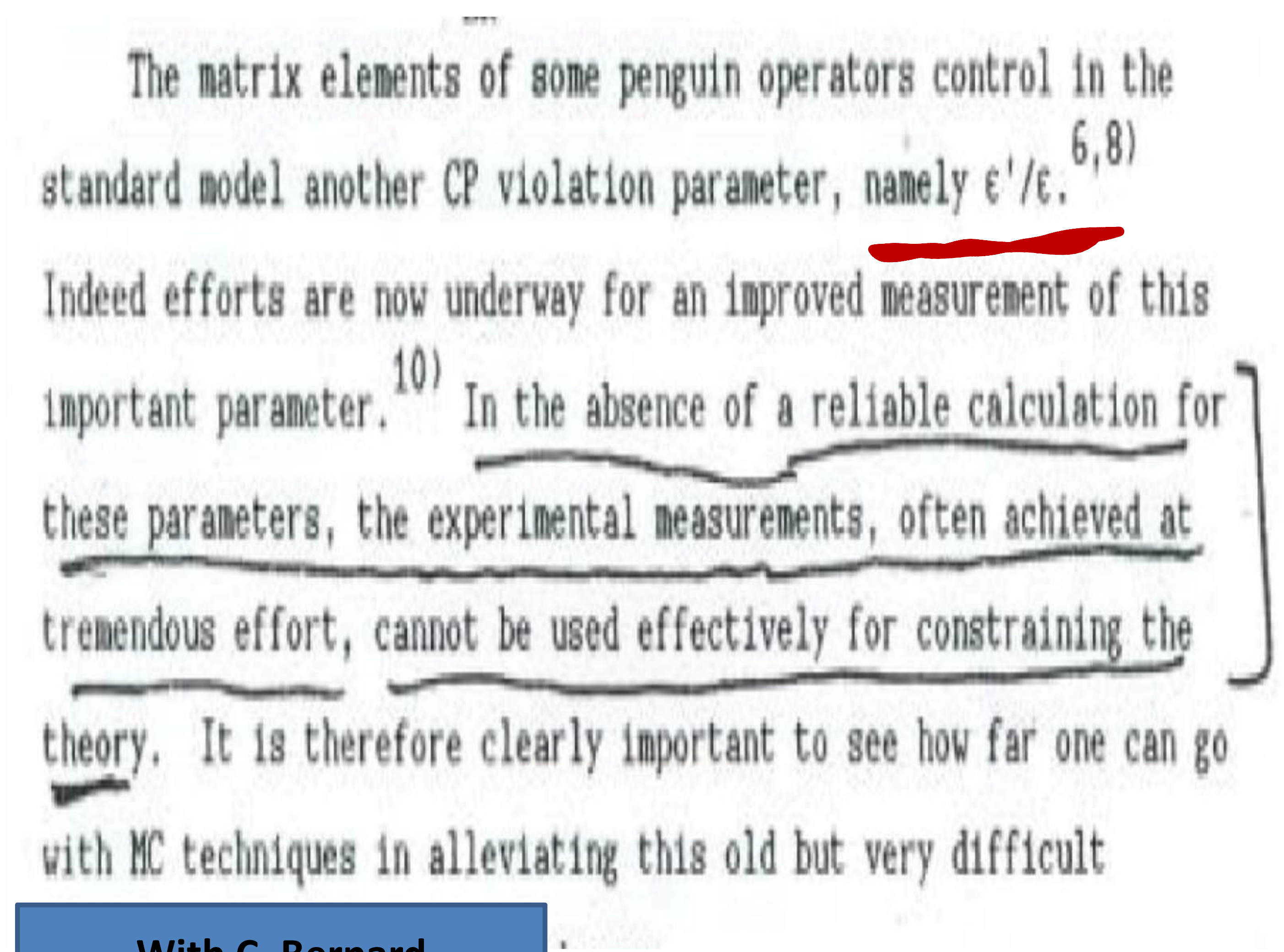
Personal take on g-2

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

Bottom line

- **NP or not depends critically not just on precise experiment but also reliable SM prediction from the lattice become mandatory**
- **Experiment + Lattice M.E. has the last word….[of course should be stressed that the lattice calculations often require sophisticated and demanding and essential input from perturbation theory]**
- **Experimental results often attained at huge cost can be used effectively, iff commensurate theory predictions are available…….mantra for past several decades**

A.S. in Proceedings of Lattice '85 (FSU)..1st Lattice meeting ever attended



The matrix elements of some penguin operators control in the standard model another CP violation parameter, namely ϵ'/ϵ.[6,8] Indeed efforts are now underway for an improved measurement of this important parameter.[10] In the absence of a reliable calculation for these parameters, the experimental measurements, often achieved at tremendous effort, cannot be used effectively for constraining the theory. It is therefore clearly important to see how far one can go with MC techniques in alleviating this old but very difficult

With C. Bernard [UCLA]

LATTICE QUEST FOR EPSILON’

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

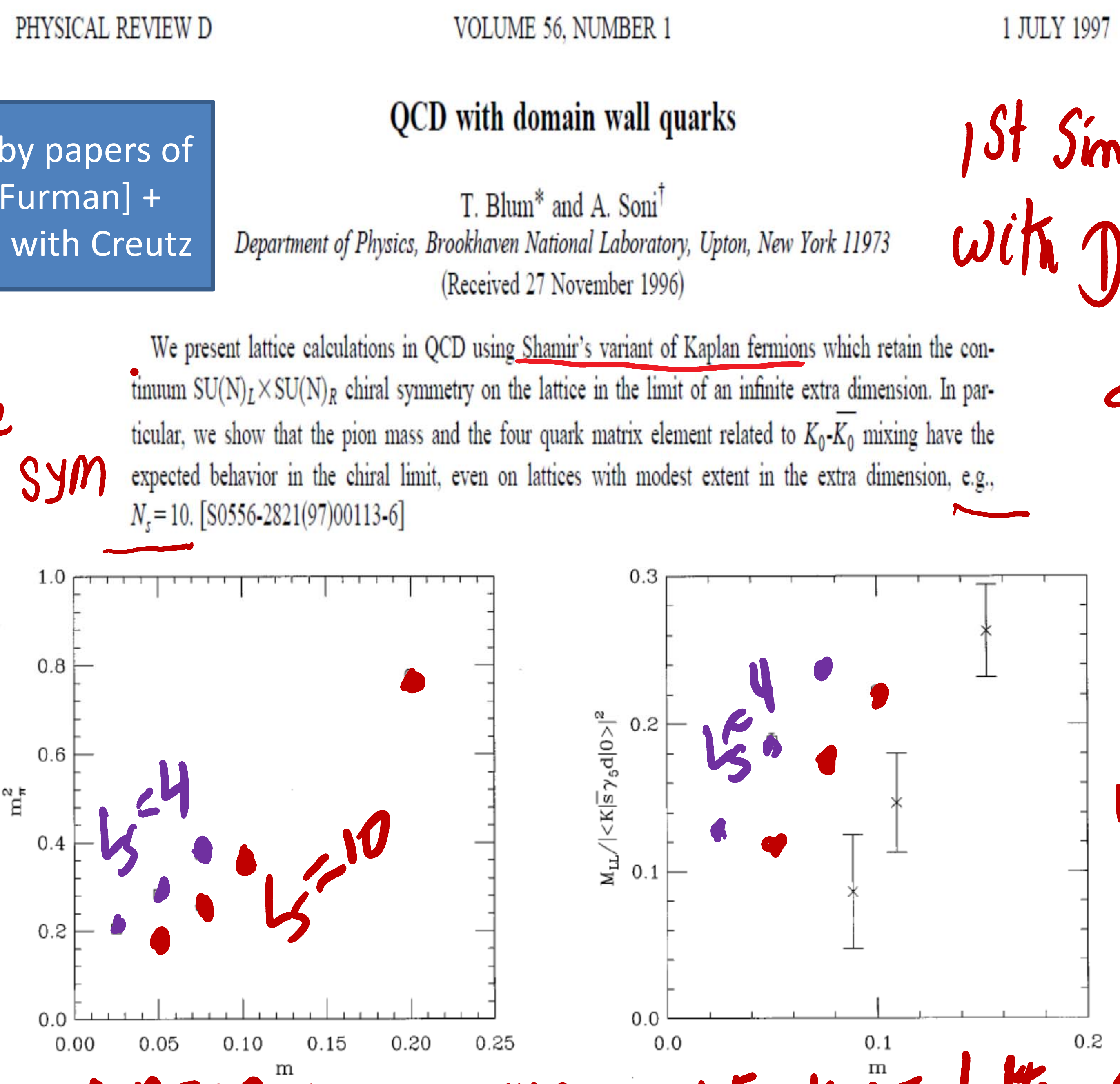
H. David Politzer and Mark B. Wise
Department of Physics, California Institute of Technology, Pasadena, California 91125

(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

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



PHYSICAL REVIEW D VOLUME 56, NUMBER 1 1 JULY 1997

QCD with domain wall quarks

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

(Received 27 November 1996)

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]

1St Simulation with DWQ

~'96-97

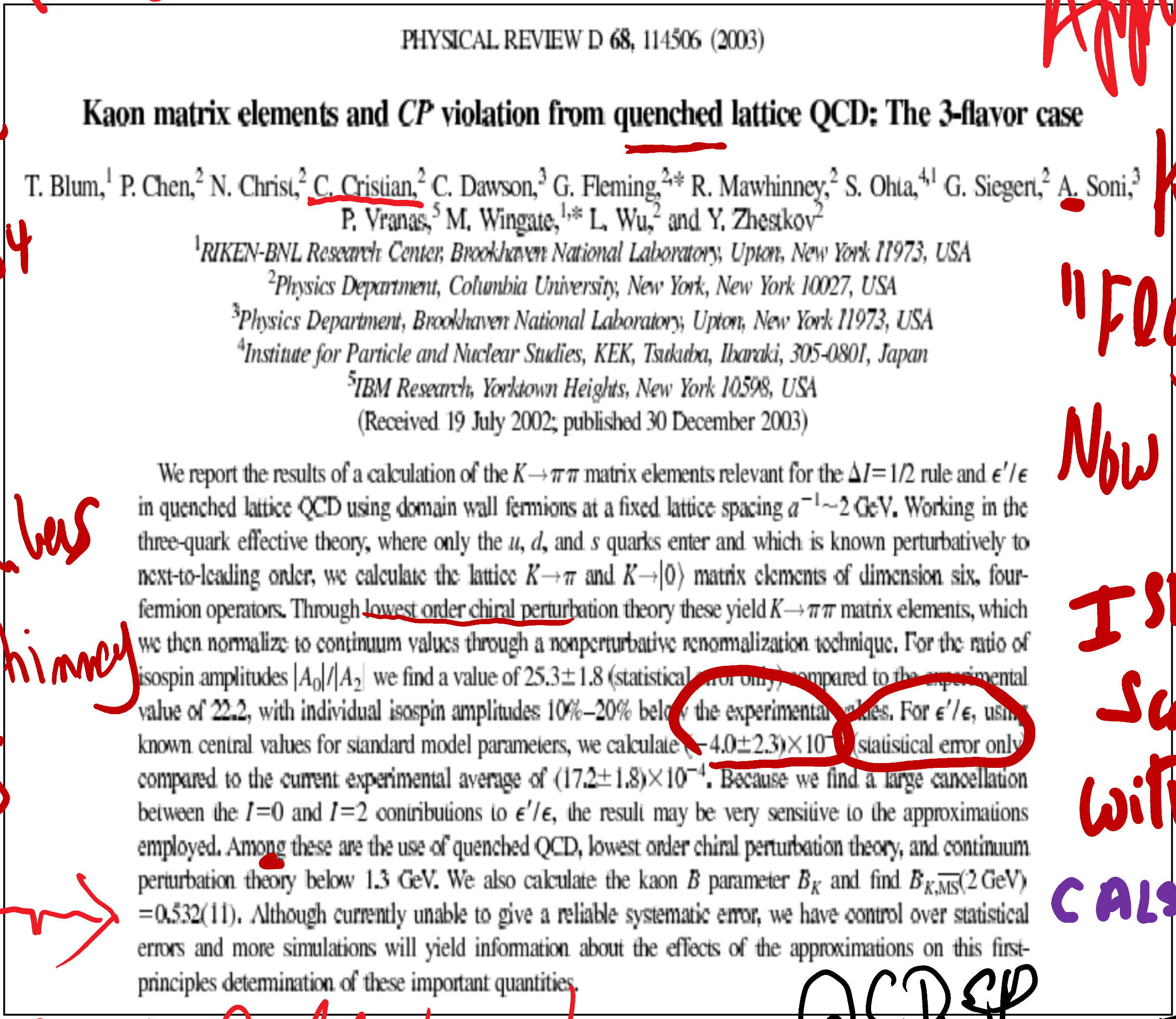
DWQ preserve CHIRAL SYM even at $a \neq 0$!!!

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

MAJOR BREAKTHROUGH For K→ππ Lattice Calculations

K→2π ChPT

With DWQ in Quench Approx



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]

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(Received 19 July 2002; published 30 December 2003)

We report the results of a calculation of the $K\to\pi\pi$ matrix elements relevant for the $\Delta I=1/2$ rule and ϵ'/ϵ in quenched lattice QCD using domain wall fermions at a fixed lattice spacing $a^{-1}\sim 2$ 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 $(-4.0\pm2.3)\times10^{-}$[illegible] (statistical error only) compared to the current experimental average of $(17.2\pm1.8)\times10^{-4}$. Because we find a large cancellation between the $I=0$ and $I=2$ contributions to ϵ'/ϵ, the result may be very sensitive to the approximations employed. Among these are the use of quenched QCD, lowest order chiral perturbation theory, and continuum perturbation theory below 1.3 GeV. We also calculate the kaon B parameter B_K and find $B_{K,\overline{\rm MS}}(2\text{ GeV})=0.532(11)$. 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.

1st application of BDSPW'84 with DWQ

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

K→2π & ε'/ε, "Flagship Project" Now ~20 yrs!

1st Large Scale Simulation with DWQ

(ALSO CP_PACS PRD'03

RBC Collaboration

QCDSP ~98→~'05 1TF

CMP/01.

a powerful new method

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

Boyle, Sachrajda et al

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

II Southampton}

* Allows to bypass Maini-Testa theorem

COMMON Interest: use of DWQ for simulations

Results for ε'

DIRECT K → ππ
[NO ChPT]

- Using Re(A_0) and Re(A_2) from experiment and our lattice values for Im(A_0) and Im(A_2) and the phase shifts,

→ EWP

→ QCDP

USING 216 independent measurements

RBC-UKQCD PRL'15
EDITOR'S CHOICE

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

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

LARGE CANCELLATION!!
(80-85%)

Full accounting of all errors

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

$$w = \frac{Re A_2}{Re A_0} \sim 0.045$$

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

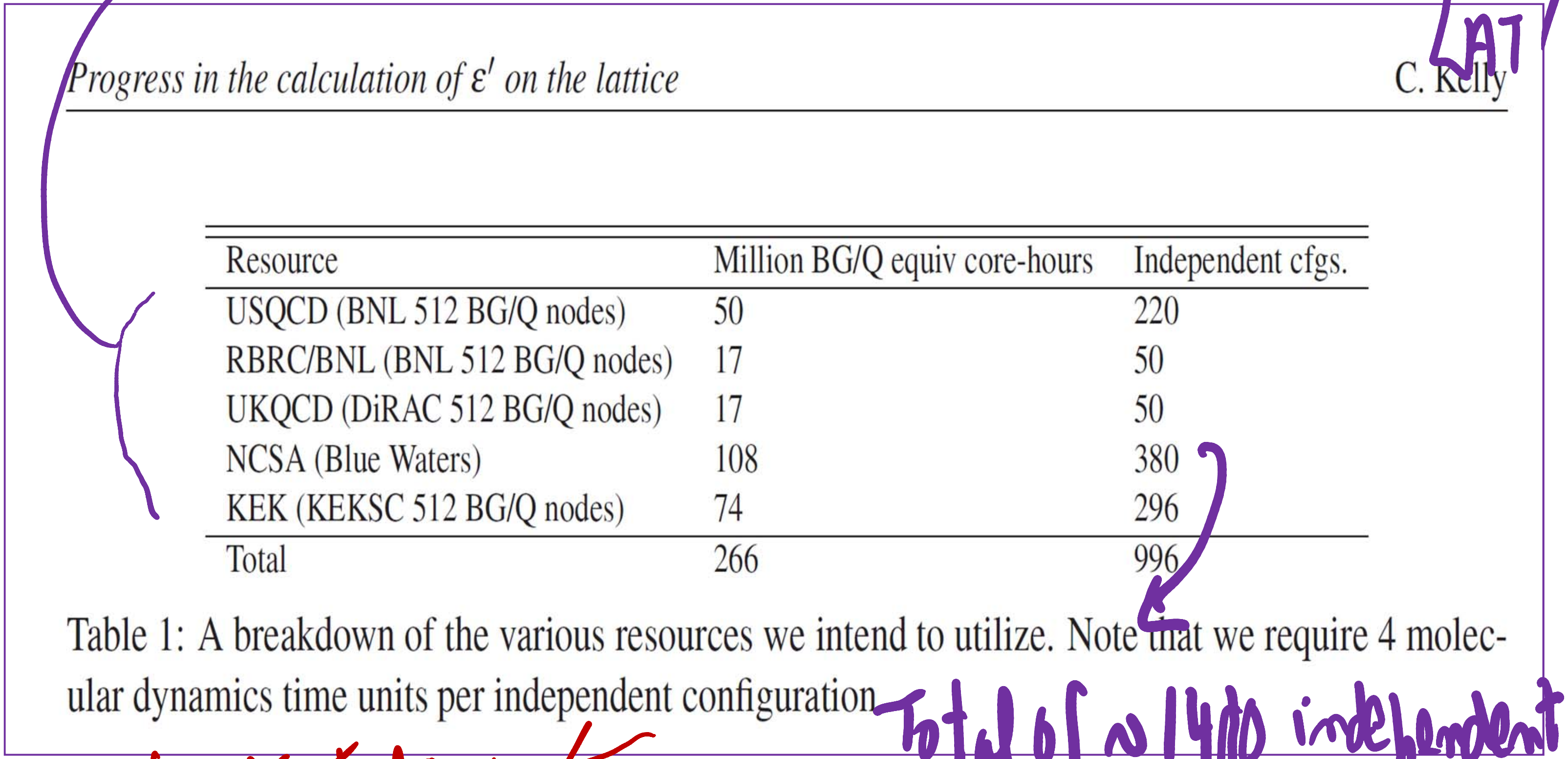
BURAS et al use own LME ⇒ effect is ~ 2.9σ
Nierste . . . ~ ''

Generation of New gauge configs

For past $\gtrsim 3$ 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.

Total of ~1400 independent configs

4 diff streams

MANY IMPLICATIONS, AS ONE EXAMPLE:K-UT

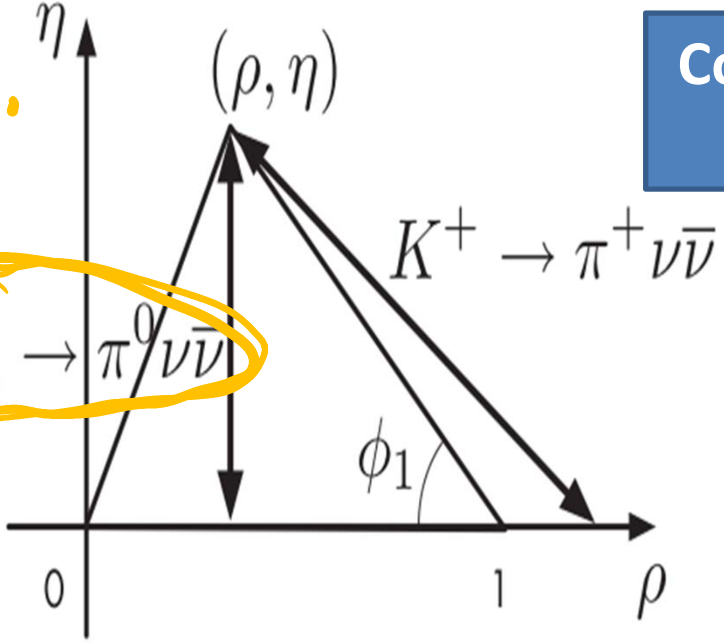
See Lehner, Lenghi + AS PLB '16

K-UT: A dream for some

Blucher, Winstein and Yamanaka '09; see also Buras

Construction of a Kaon UT

GOLD PLATED!!..



LITTENBERG PRD '89

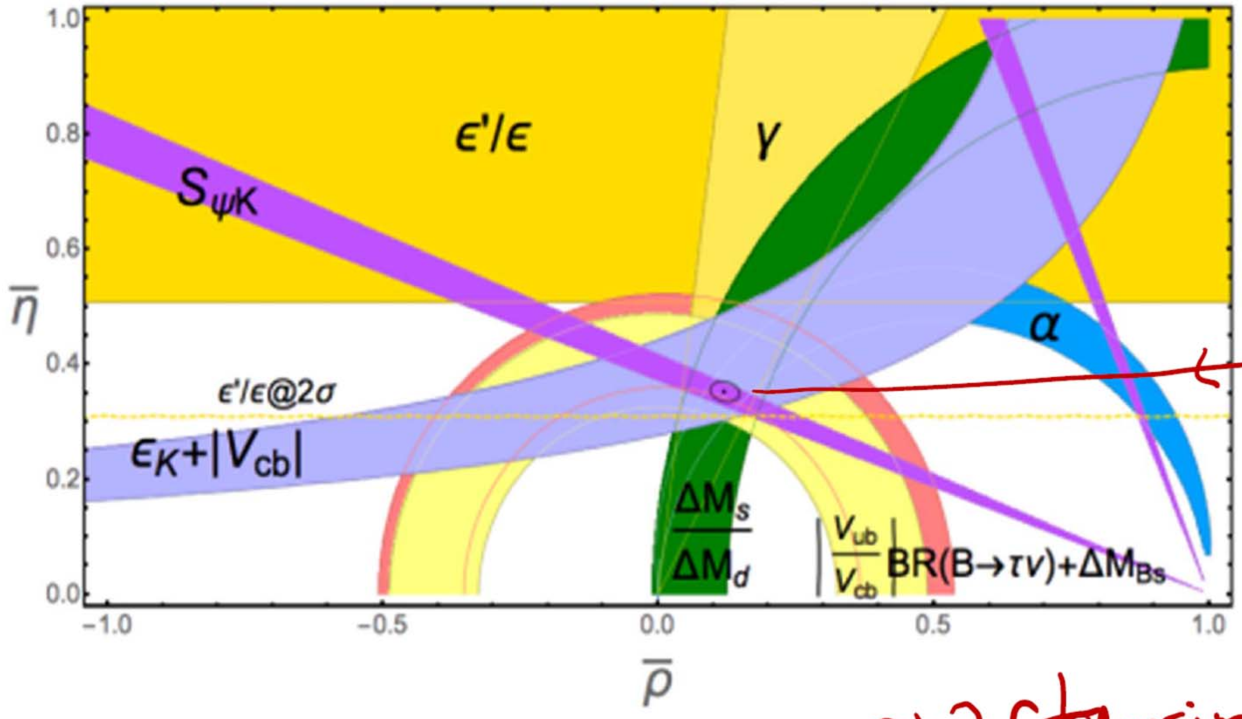
Lehner+Lunghi+AS PLB '2016

Fig. 14. Unitarity triangle.

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

Lattice ϵ'/ϵ & SUT: CIRCA ~ 2015

SUT ≡ Standard UT i.e. B-UT



solution to SUT

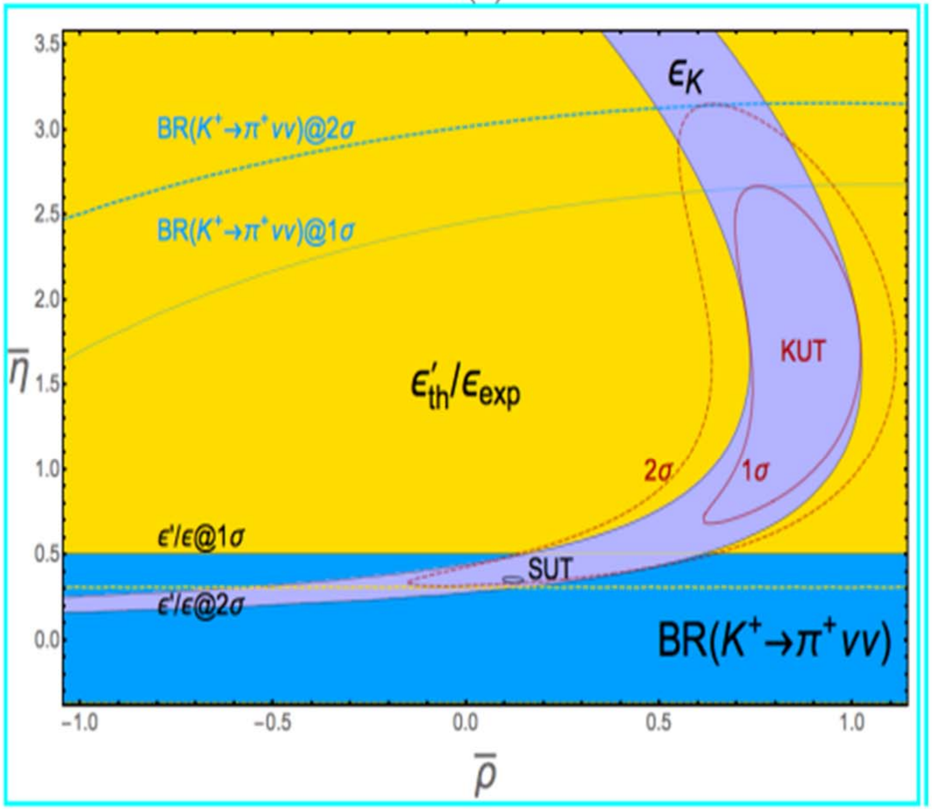
~2σ tension

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

I ϵ_K Indirect CP

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

(a)

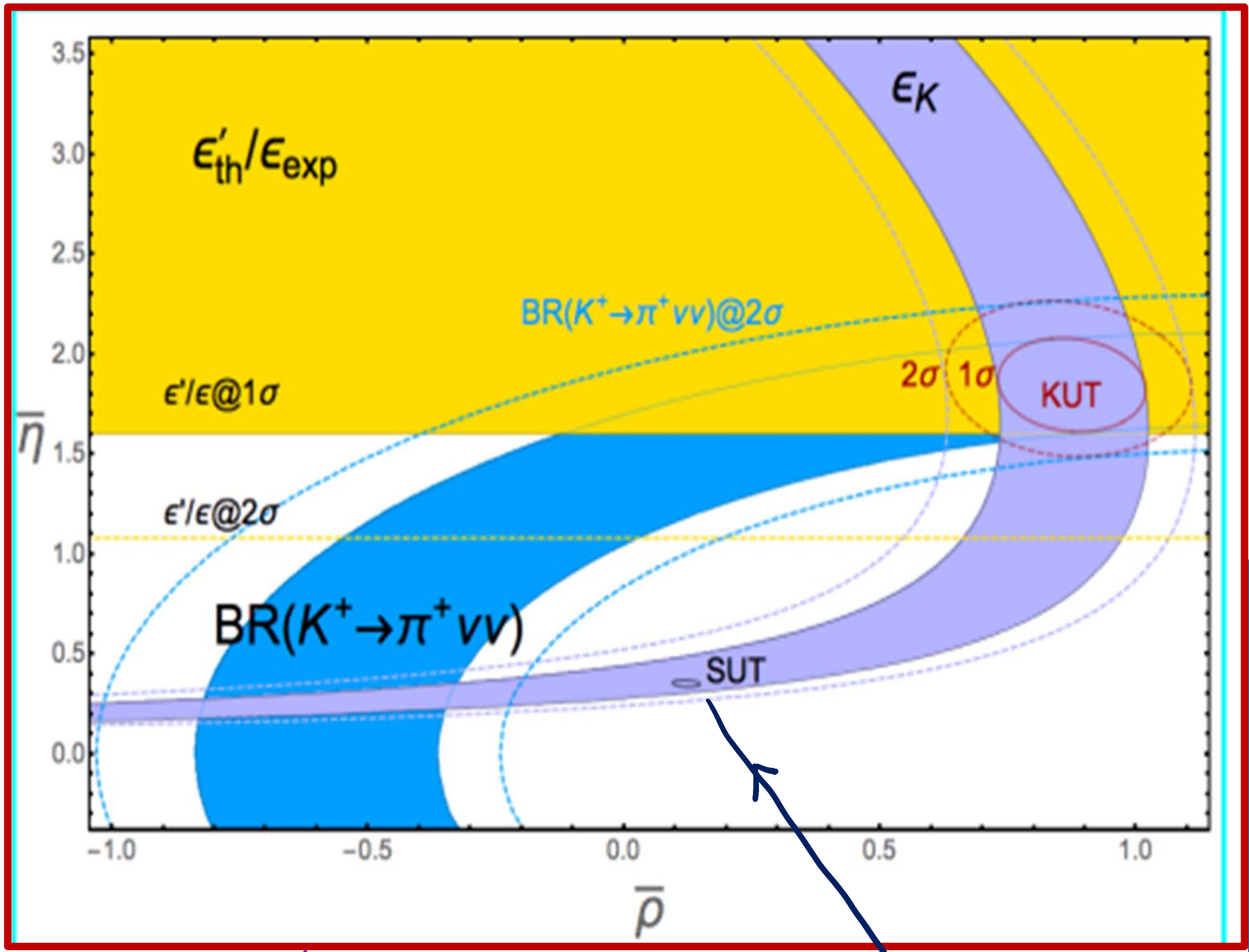


III $$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)_K = \begin{cases} (16.7 \pm 1.6) \times 10^{-4} \\ (1.36 \pm 5.21_{\text{stat}} \pm 4.49_{\text{syst}}) \times 10^{-4} \end{cases}$$

PDG 2015

RBC+UKQCD '15

POSSIBLE KUT CIRCA 2020: DUE NA62 + RBC-UKQCD



NO unique ρ, η

Assumed:
NA62, 100 events with ~7% error
RBC-UKQCD, δ(ImA0)~18%
[current ~60%]

"Standard" (B) UT

Lehner, Lunghi + AS PLB'16

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


REFRIGERATION & AIR CONDITIONI
SERVICE, TEL.
GMC

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

UNDERLYING REALIZATION

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

Contrarian/Complementary view

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

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

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

Its presumed importance:

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

IF YOU BUILD IT THEY WILL COME

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

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

FLAVOR AND DM

A model with a Z' portal

[Aristizabal Sierra, Staub, AV, 2015]

Vector-like = “joker”
for model builders

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_X$$

Exploit flavor-DM connection to
Account for flavor anomalies

Vector-like fermions

Link to SM fermions

$$Q = \left(\mathbf{3}, \mathbf{2}, \frac{1}{6}, 2\right) \qquad L = \left(\mathbf{1}, \mathbf{2}, -\frac{1}{2}, 2\right)$$

Scalars

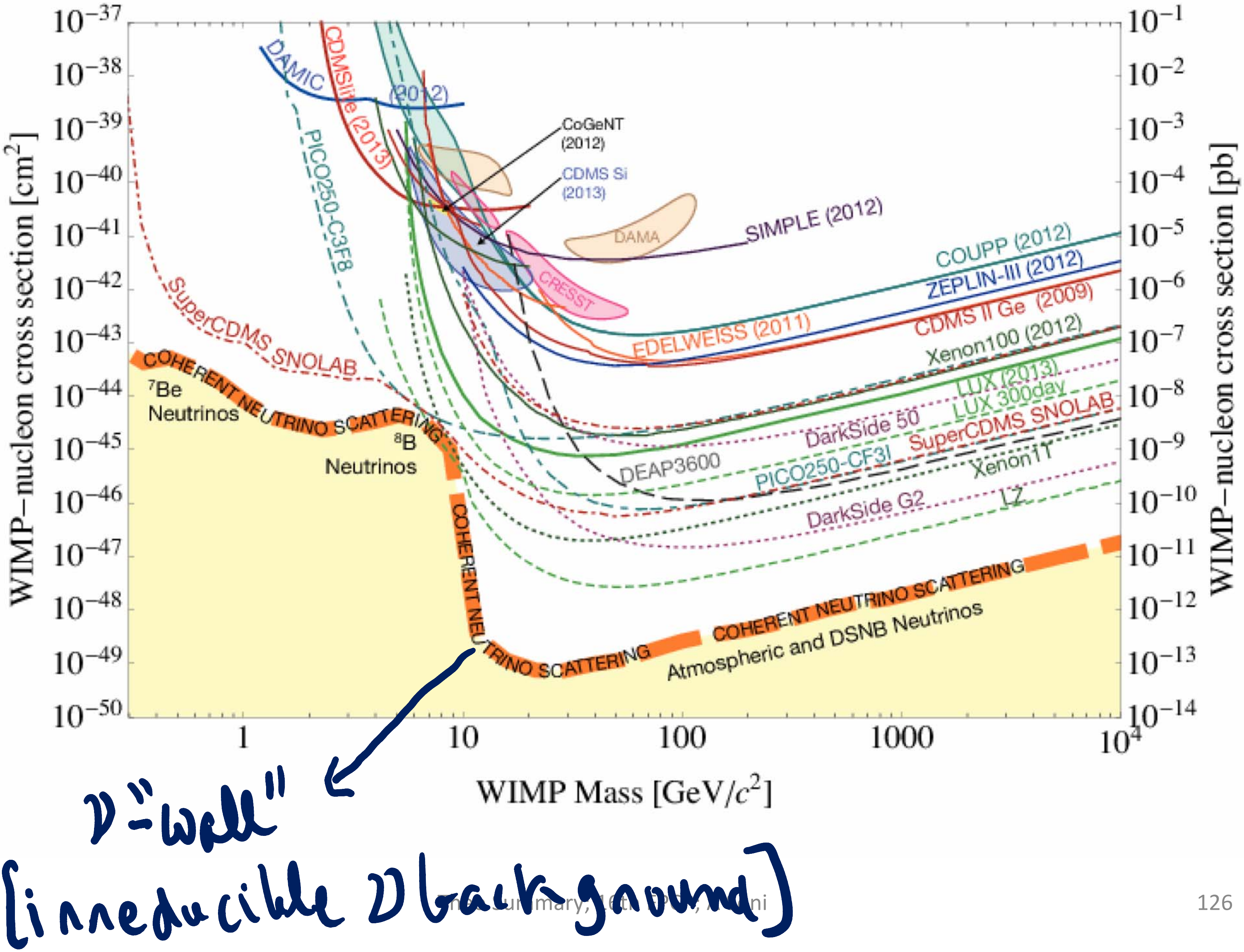
$$\phi = (\mathbf{1}, \mathbf{1}, 0, 2) \qquad \chi = (\mathbf{1}, \mathbf{1}, 0, -1)$$

$U(1)_X$ breaking

Dark matter candidate

Reg DM

- **Proven to be exceedingly difficult for direct detection ……………….=> fig**
- **Remarkably, the only compelling evidence of DM that so far we have is gravitational !**



ν "wall"

[irreducible ν background]

Lepton Flavored Dark Matter

J. Kile, A. Kobach and A. Soni (2015)

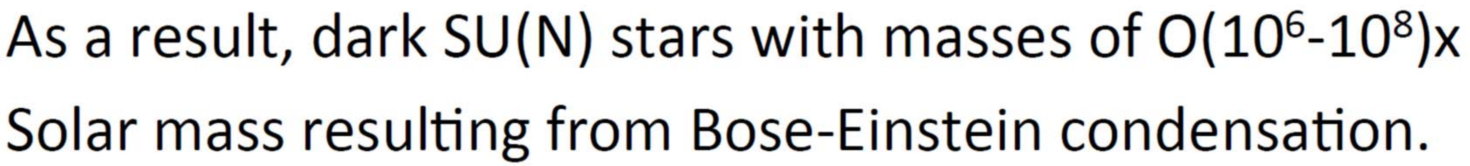
- Dark matter only interacts with normal : (detector) matter via loop effects which are suppressed. Makes direct detection of dark matter more difficult (explains negative findings.)

↑ naturally

Flavored Dark Matter in Direct Detection Experiments and at LHC
Jennifer Kile (Northwestern U.), Amarjit Soni (Brookhaven). 2011

DM: an unorthodox view

- Nature does NOT care whether we can detect
- It via direct detection or not. ***Nature really only cares about simplicity***
- **Only way we know to generate mass dynamically is via SU(N) ; fermions are an unnecessary complications so pure SU(N).**
- **That has lowest lying scalar and pseudo scalar glueballs..favored mass and N is m~0.1 to 10 KeV with N>>1 see Yue Zhang and AS 2016 + 2 more**



As a result, dark SU(N) stars with masses of O(10^6-10^8)x Solar mass resulting from Bose-Einstein condensation.

Such SUN-gluonia Dark stars only interact gravitationally naturally explaining
the grav. Observation and negative findings via other methods

Summary+Outlook [1 of 3]

- **Neutrinos: MiniBoone seems to suggest support for LSND and sterile neutrino(s) but it is not yet clear if their background is all under good control.**
- **T2K and Nova: both seem to prefer non-vanishing Delta_CP and normal hierarchy but significance of each measurement is somewhat marginal**
- **Icecube discovery of astrophysical neutrinos and the beginning of neutrino astronomy are extremely noteworthy developments**
- **Reactor Nu's + many other interesting topics…see Werner et al**
- **Belle-II's going on the air + much more data from LHCb [upgrades] are extremely significant for flavor physics and CP violation and their potential for discovery of new phenomena cannot be over-emphasized despite [or because of the] the null results from LHC.**
- **In particular there are several very interesting anomalies indicating possible violations of LU. Given how earth shattering such a discovery would be, we must exercise all the caution and care that we can muster. The current indications are NOT Compelling:**
- **There are some issues in theoretical predictions for R's indicating LUV in charge current semi-leptonic decays but these are currently dwarfed by experimental errors. A key issue for experiments is resolve any potential difference between tau=> hadron + nu vs tau=>mu/e nu nu'. Here BaBar's input for 1st method would be helpful. Also since B to D theory is more firm, more expt input on B to D tau/l nu would be very helpful**

p.2

- **FCNC : RK(*) are free of theory concerns so long as m_ll >1 GeV…But so far indications of mu-e UV are not compeling. Reservations are if its genuine LUV then it needs to be demonstrated in many related processes; e.g. Bs to phi, in baryonic B-decays etc. Moreover, confirmation from a different experiment [Belle-II] would be extremely desirable if not mandatory**

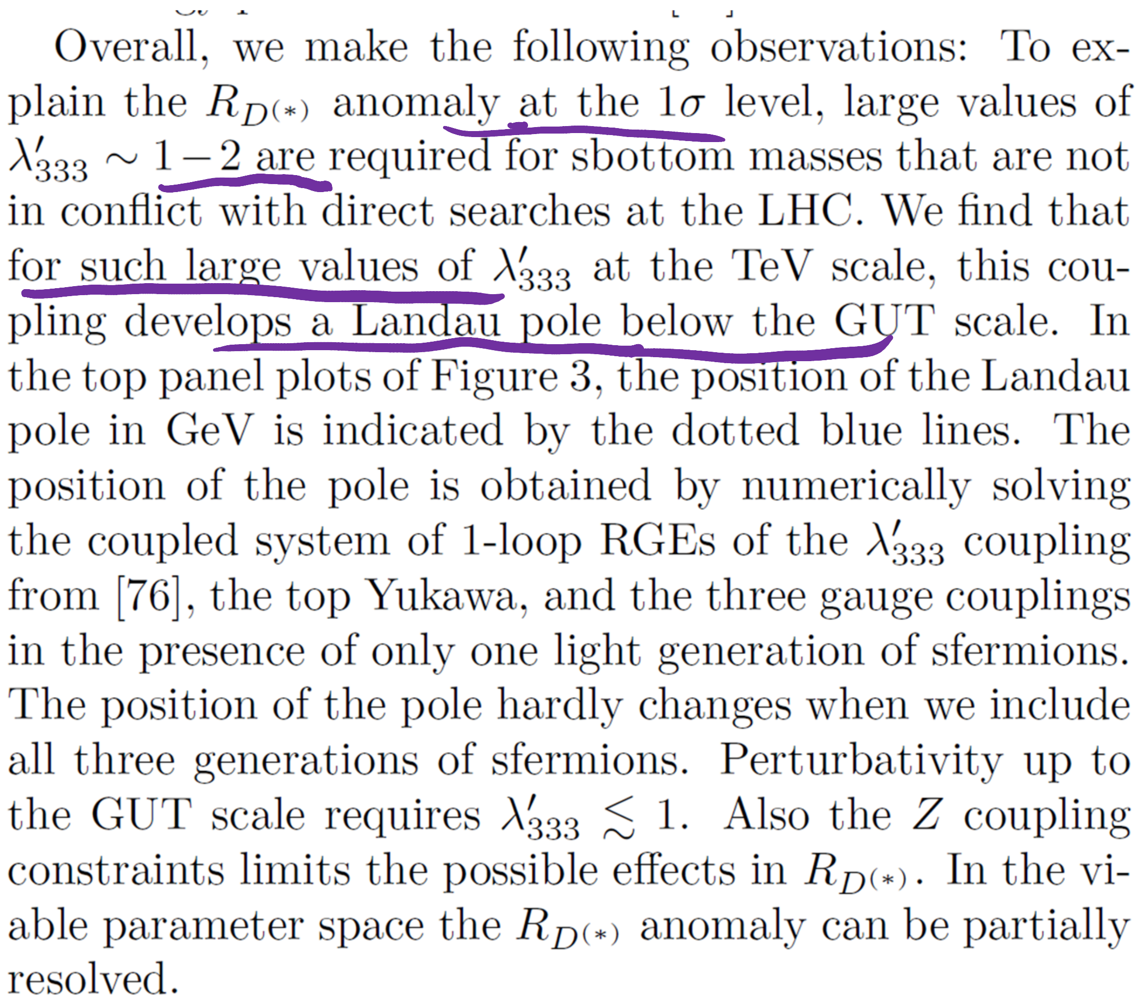
Summary and Outlook …p.3

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

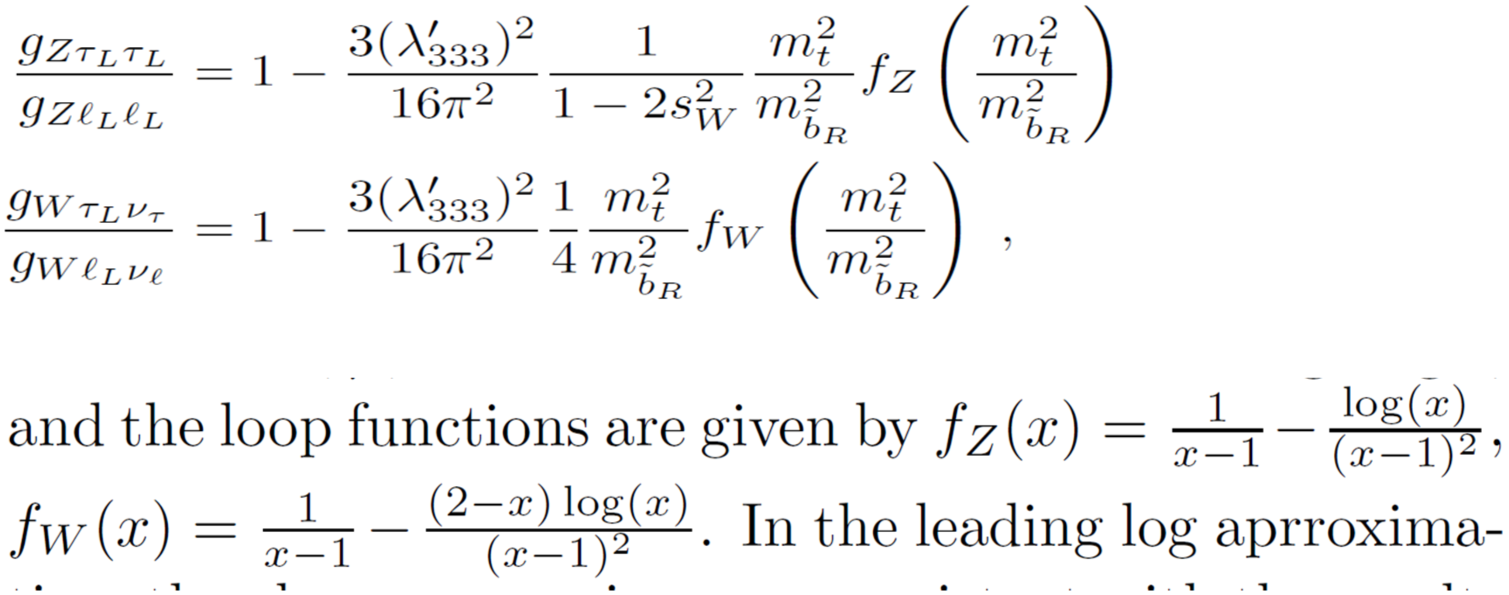
XTRAS

G – 2 table of #s

Lambda’ develop landau pole



Overall, we make the following observations: To explain the $R_{D^{(*)}}$ anomaly at the 1σ level, large values of $\lambda'_{333} \sim 1-2$ are required for sbottom masses that are not in conflict with direct searches at the LHC. We find that for such large values of λ'_{333} at the TeV scale, this coupling develops a Landau pole below the GUT scale. In the top panel plots of Figure 3, the position of the Landau pole in GeV is indicated by the dotted blue lines. The position of the pole is obtained by numerically solving the coupled system of 1-loop RGEs of the λ'_{333} coupling from [76], the top Yukawa, and the three gauge couplings in the presence of only one light generation of sfermions. The position of the pole hardly changes when we include all three generations of sfermions. Perturbativity up to the GUT scale requires $\lambda'_{333} \lesssim 1$. Also the Z coupling constraints limits the possible effects in $R_{D^{(*)}}$. In the viable parameter space the $R_{D^{(*)}}$ anomaly can be partially resolved.

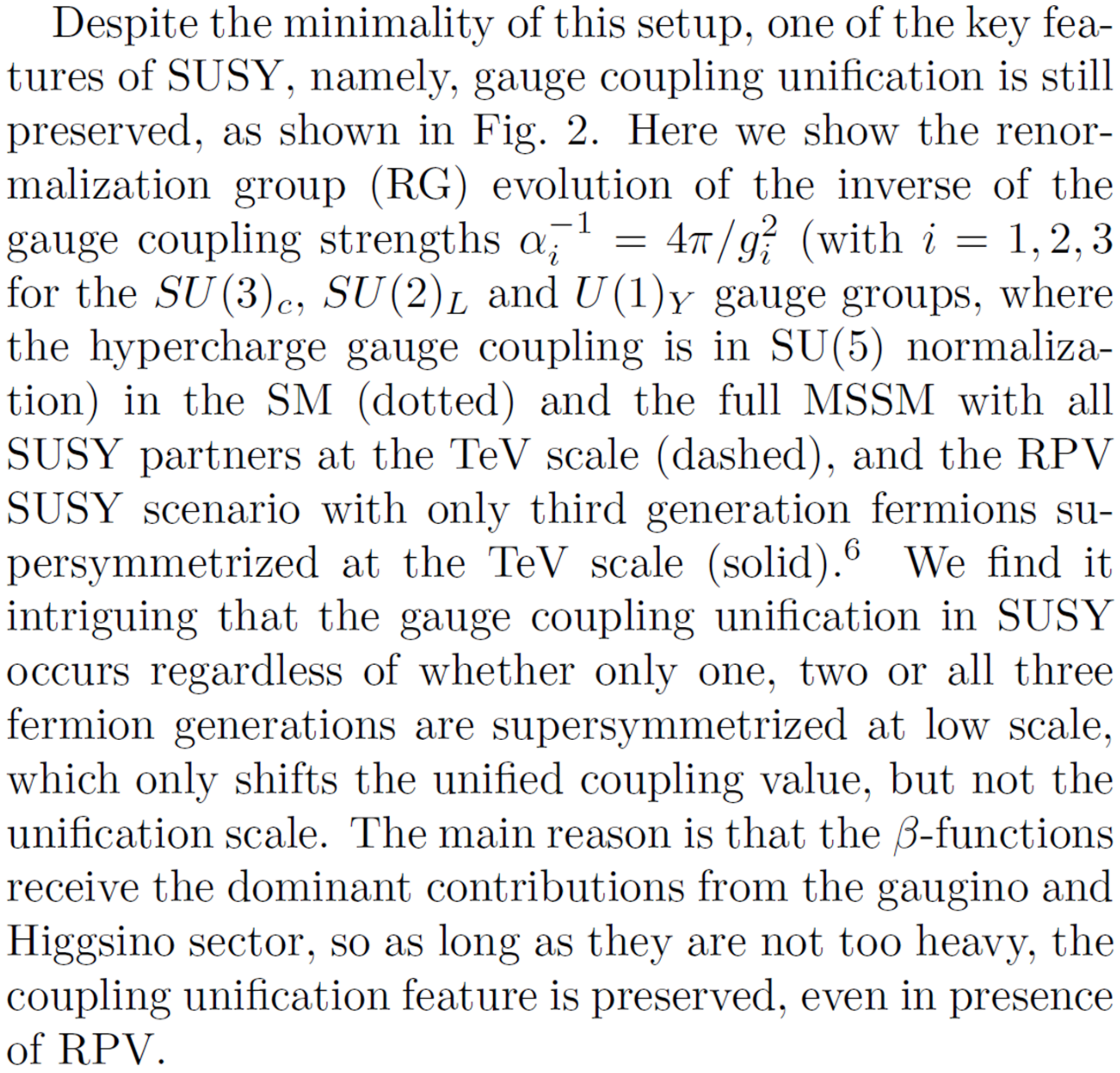


$$\frac{g_{Z\tau_L\tau_L}}{g_{Z\ell_L\ell_L}} = 1 - \frac{3(\lambda'_{333})^2}{16\pi^2}\frac{1}{1-2s_W^2}\frac{m_t^2}{m_{\tilde{b}_R}^2} f_Z\left(\frac{m_t^2}{m_{\tilde{b}_R}^2}\right)$$

$$\frac{g_{W\tau_L\nu_\tau}}{g_{W\ell_L\nu_\ell}} = 1 - \frac{3(\lambda'_{333})^2}{16\pi^2}\frac{1}{4}\frac{m_t^2}{m_{\tilde{b}_R}^2} f_W\left(\frac{m_t^2}{m_{\tilde{b}_R}^2}\right) \ ,$$

and the loop functions are given by $f_Z(x) = \frac{1}{x-1} - \frac{\log(x)}{(x-1)^2}$, $f_W(x) = \frac{1}{x-1} - \frac{(2-x)\log(x)}{(x-1)^2}$. In the leading log aprroxima-

Explicitly checked gauge coupling unification in RPV3



Despite the minimality of this setup, one of the key features of SUSY, namely, gauge coupling unification is still preserved, as shown in Fig. 2. Here we show the renormalization group (RG) evolution of the inverse of the gauge coupling strengths $\alpha_i^{-1} = 4\pi/g_i^2$ (with $i = 1,2,3$ for the $SU(3)_c$, $SU(2)_L$ and $U(1)_Y$ gauge groups, where the hypercharge gauge coupling is in SU(5) normalization) in the SM (dotted) and the full MSSM with all SUSY partners at the TeV scale (dashed), and the RPV SUSY scenario with only third generation fermions supersymmetrized at the TeV scale (solid).[6] We find it intriguing that the gauge coupling unification in SUSY occurs regardless of whether only one, two or all three fermion generations are supersymmetrized at low scale, which only shifts the unified coupling value, but not the unification scale. The main reason is that the β-functions receive the dominant contributions from the gaugino and Higgsino sector, so as long as they are not too heavy, the coupling unification feature is preserved, even in presence of RPV.

PHYSICAL REVIEW D VOLUME 43, NUMBER 7 1 APRIL 1991

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

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(Received 21 December 1990)

We present our results for the meson form factors of several semileptonic decays. They are computed from the corresponding matrix elements evaluated on the lattice as ratios of Green's functions. The renormalization of the local operators is calculated nonperturbatively. The dependence of the form factors on the four-momentum transfer q^2 is studied by injecting external three-momenta to the initial- and final-state mesons. We study the pseudoscalar decays $K \to \pi l \nu$, $D \to K l \nu$, $D \to \pi l \nu$, $D_s \to \eta l \nu$, and $D_s \to K l \nu$ on different lattices. We also analyze scaling, finite-size, and SU(3)-symmetry-breaking effects. The uncertainties in some lattice parameters, e.g., a^{-1}, as a source of systematic errors in this calculation are discussed.

PHYSICAL REVIEW D VOLUME 45, NUMBER 3 1 FEBRUARY 1992

Lattice study of semileptonic decays of charm mesons into vector mesons

data before publication. The computing for this project was done at the National Energy Research Supercomputer Center in part under the "Grand Challenge" program and at the San Diego Supercomputer Center.

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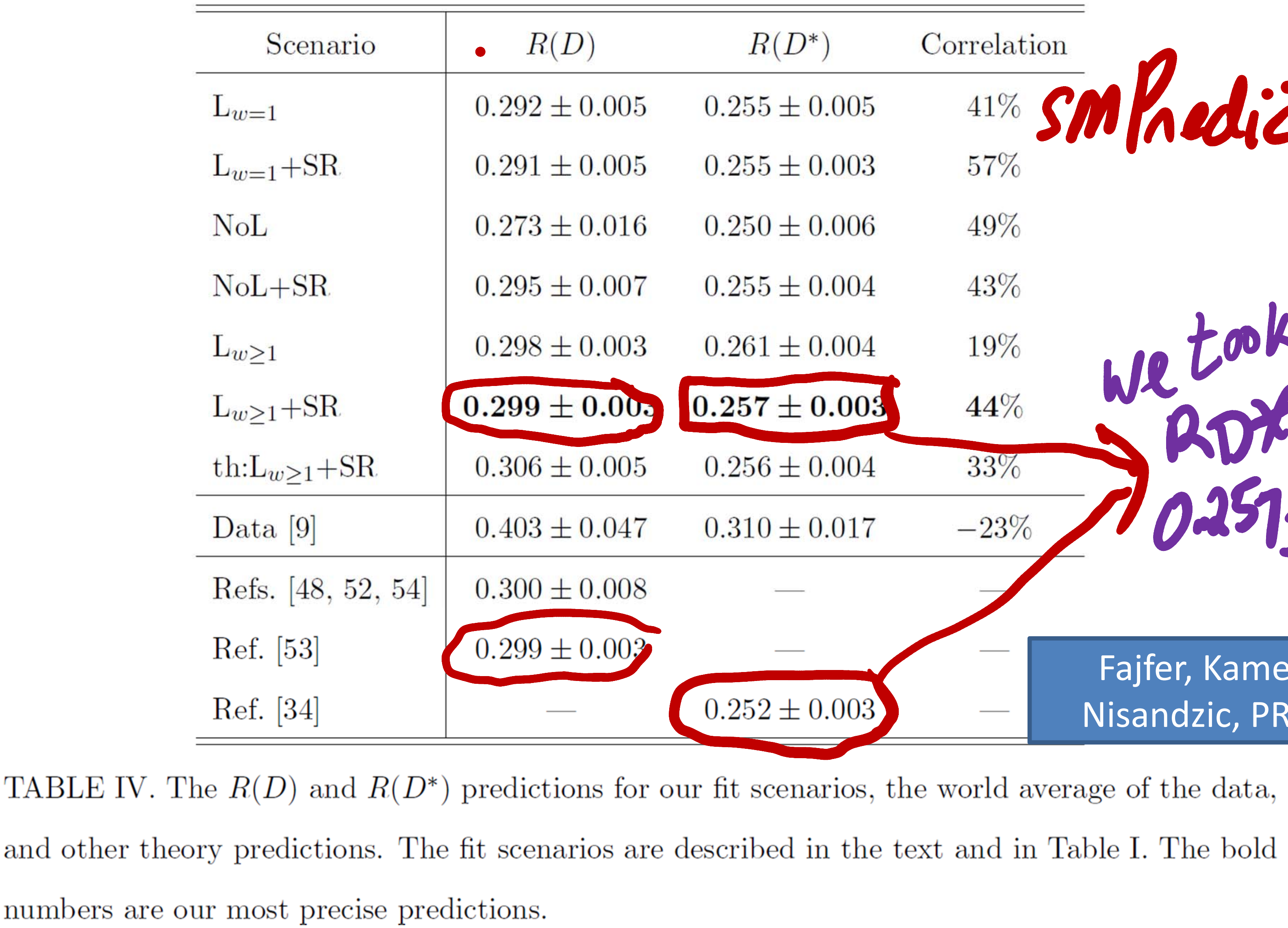
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973

(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.

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	—

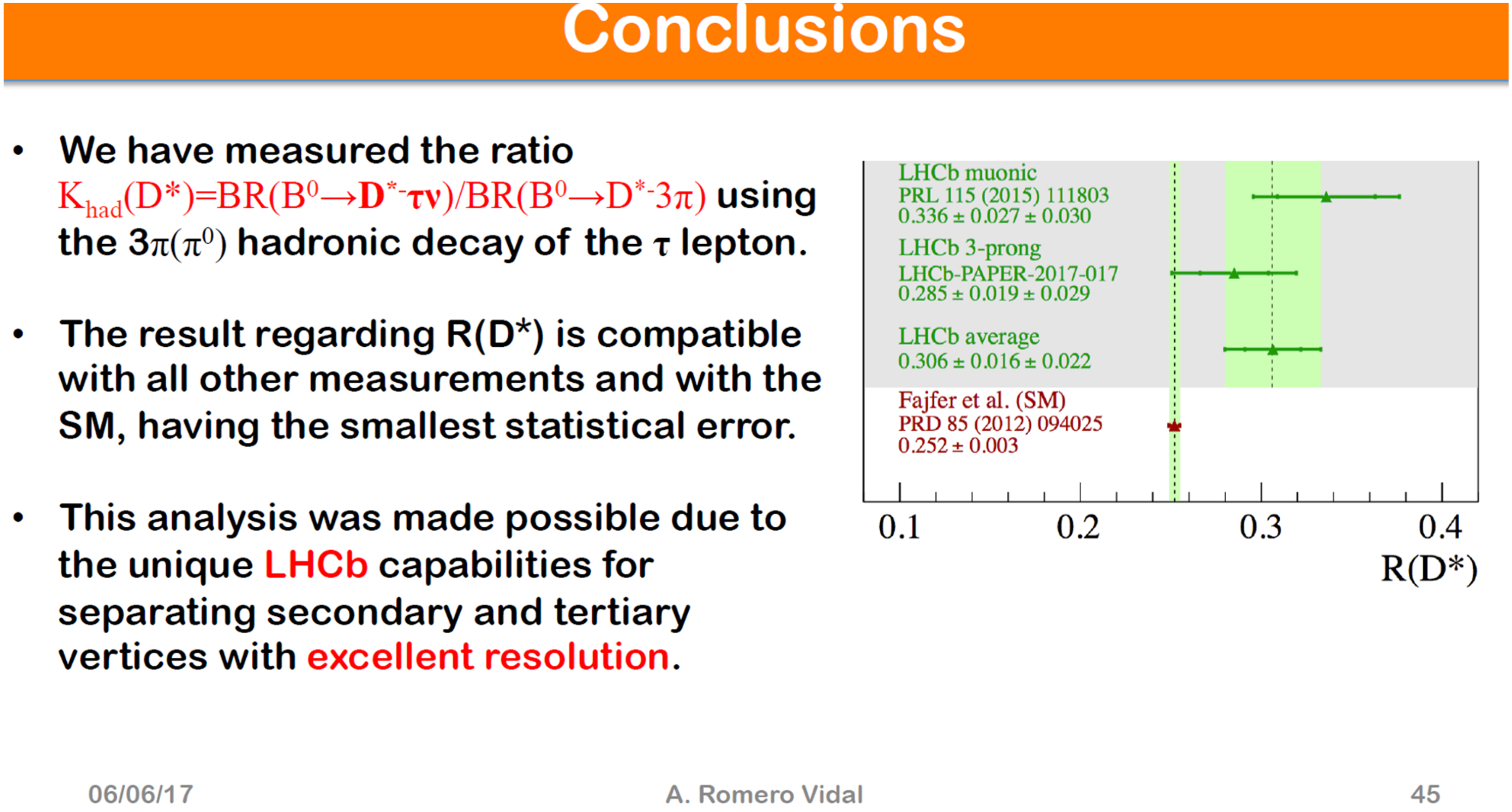
TABLE IV. The $R(D)$ and $R(D^*)$ predictions for our fit scenarios, the world average of the data, and other theory predictions. The fit scenarios are described in the text and in Table I. The bold numbers are our most precise predictions.

SM Prediction

we took $RD^* = 0.257 \pm .005$

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:

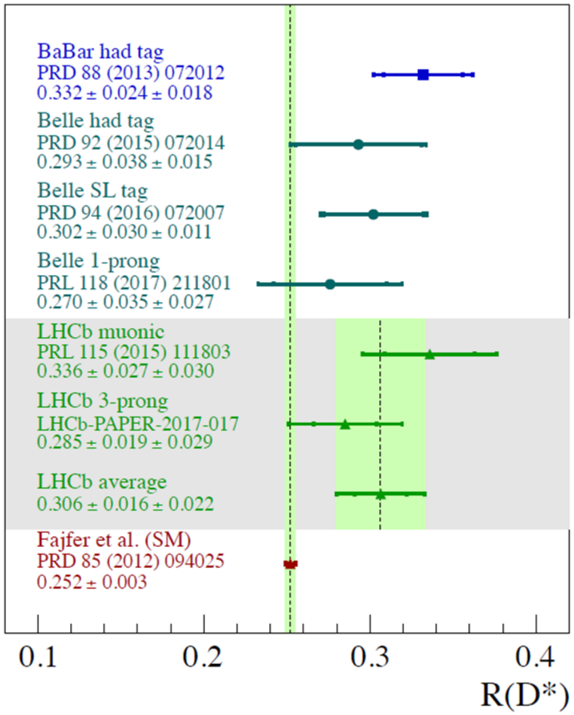
  - $R_{LHCb}(D^*)$ = 0.306 ± 0.016 ± 0.022
  - 2.1σ above the SM.

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

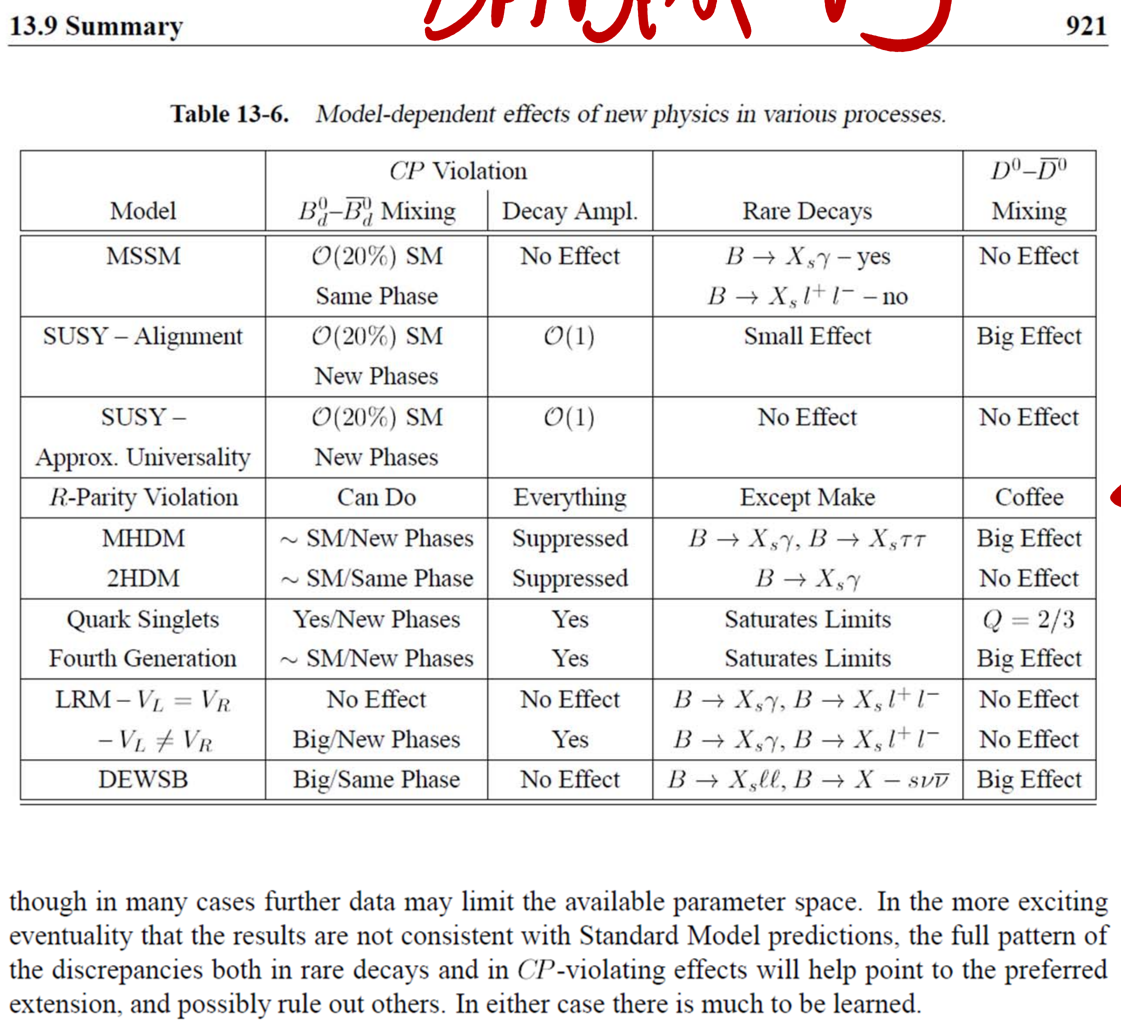
- Naïve R(D)/R(D*) combination at 4.1σ from SM.

Total of 6

LHCb-PAPER-2017-017



BABAR Phy Book '97

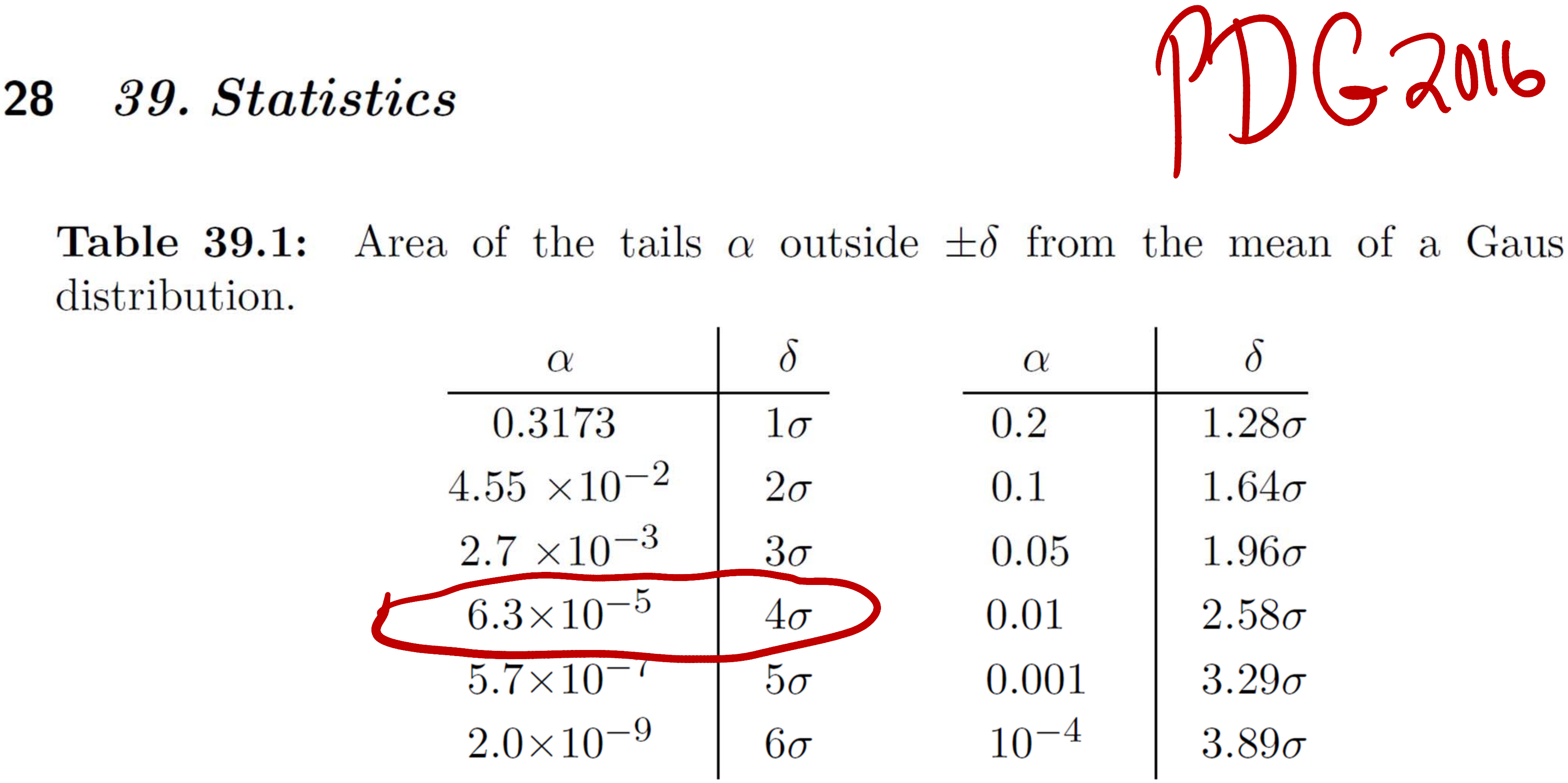


13.9 Summary 921

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

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

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



28 ***39. Statistics***

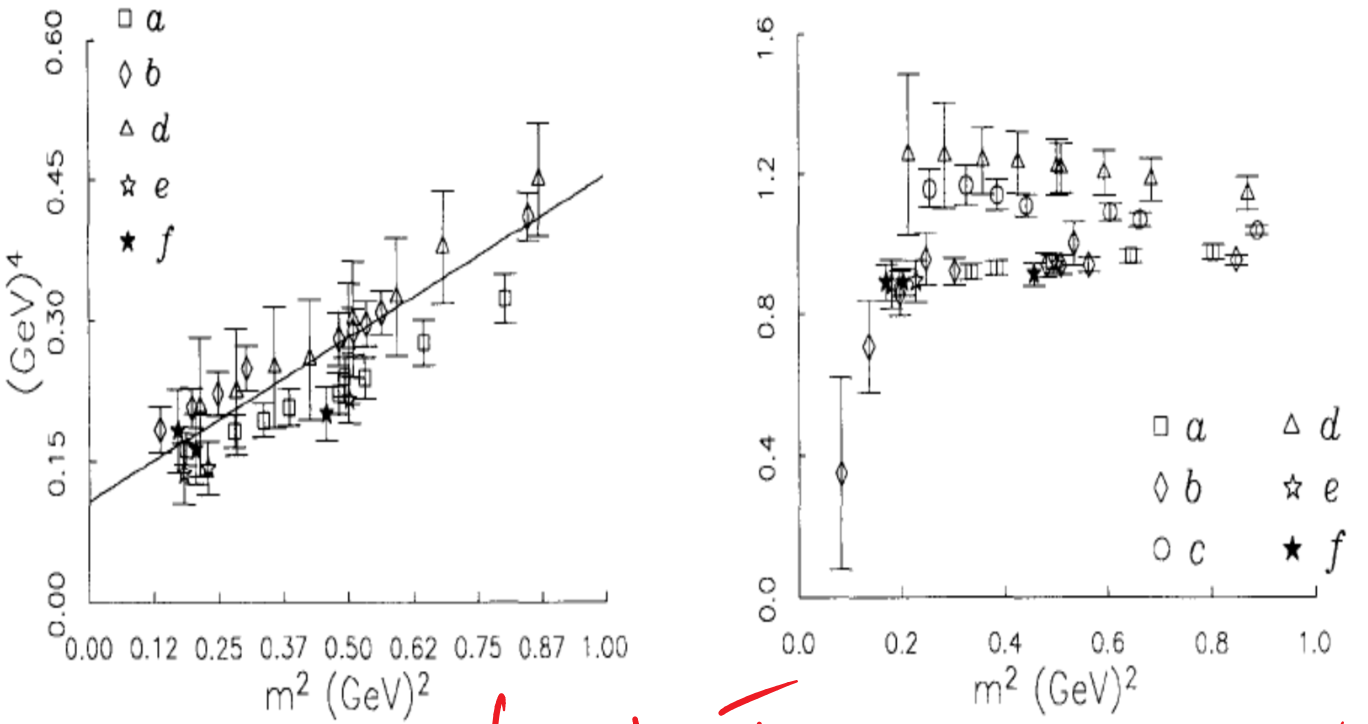
PDG2016

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

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

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



χS violation by K-K̄ ⇒ FINE TUNING PROBLEM

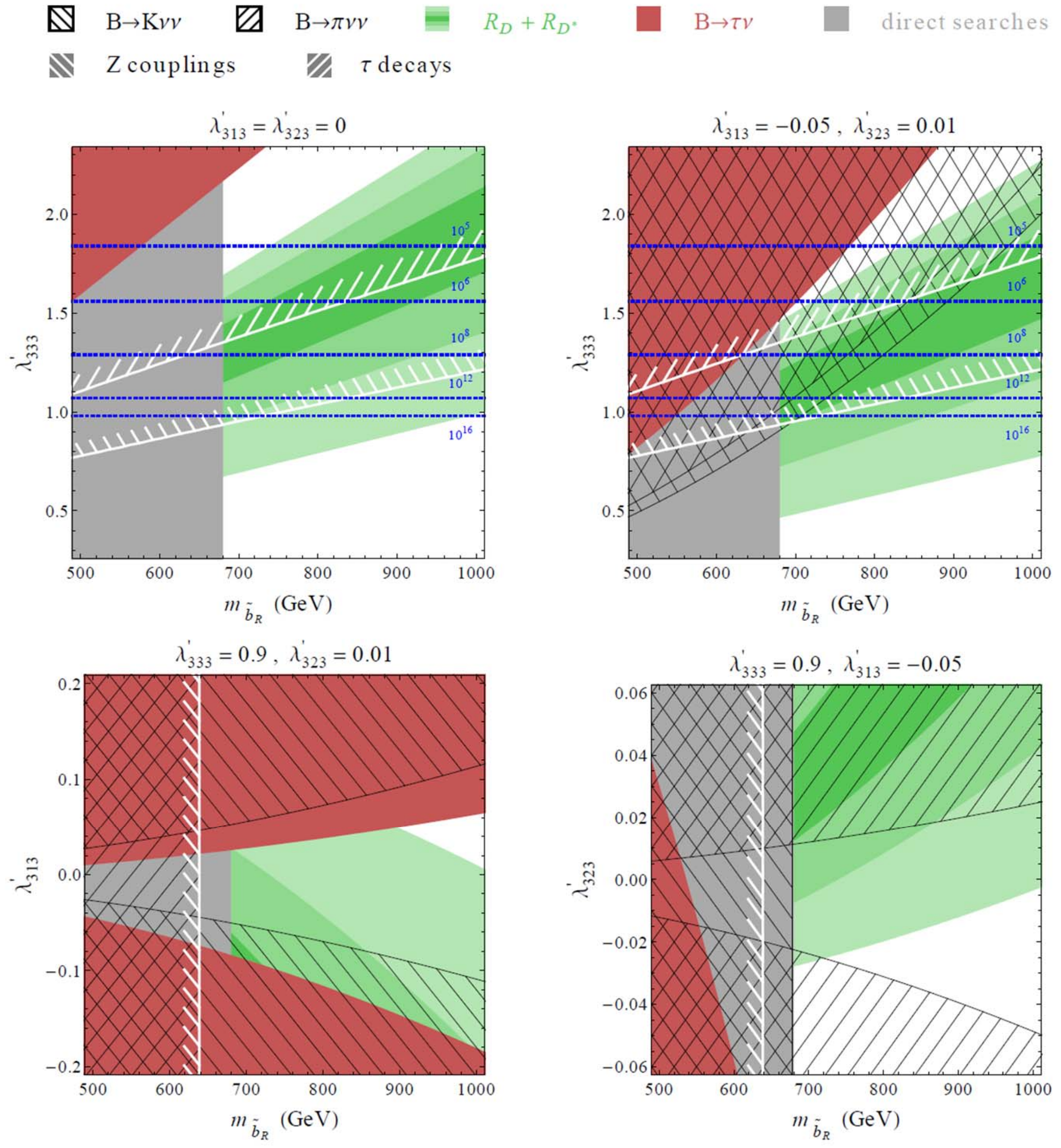


FIG. 3. RPV parameter space satisfying the $R_{D^{(*)}}$ anomaly and other relevant constraints.

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

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

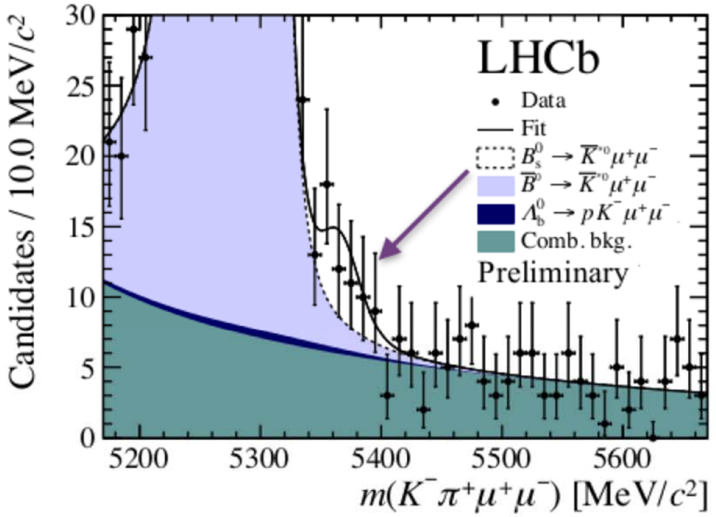
Run1 + part Run2 (2015 and 2016) data (4.6 fb^{-1})

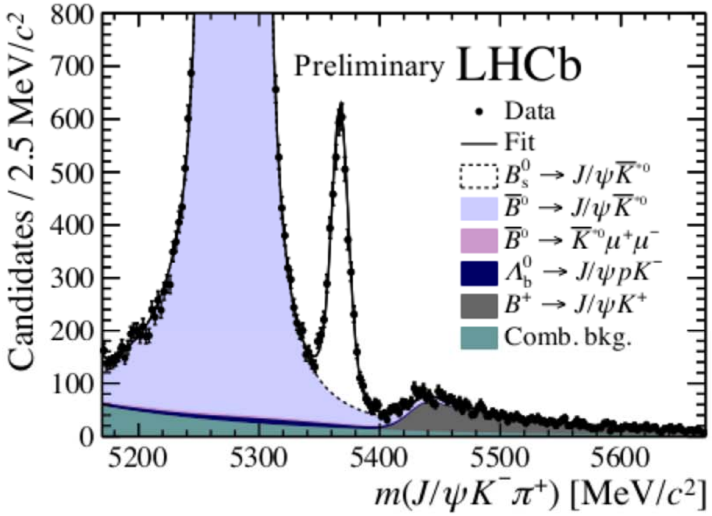
$N(B_s^0 \to \bar{K}^{*0}\mu^+\mu^-) = 38 \pm 12$, 3.4σ above bkg-only hypothesis

(first evidence)

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

(first measurement)





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

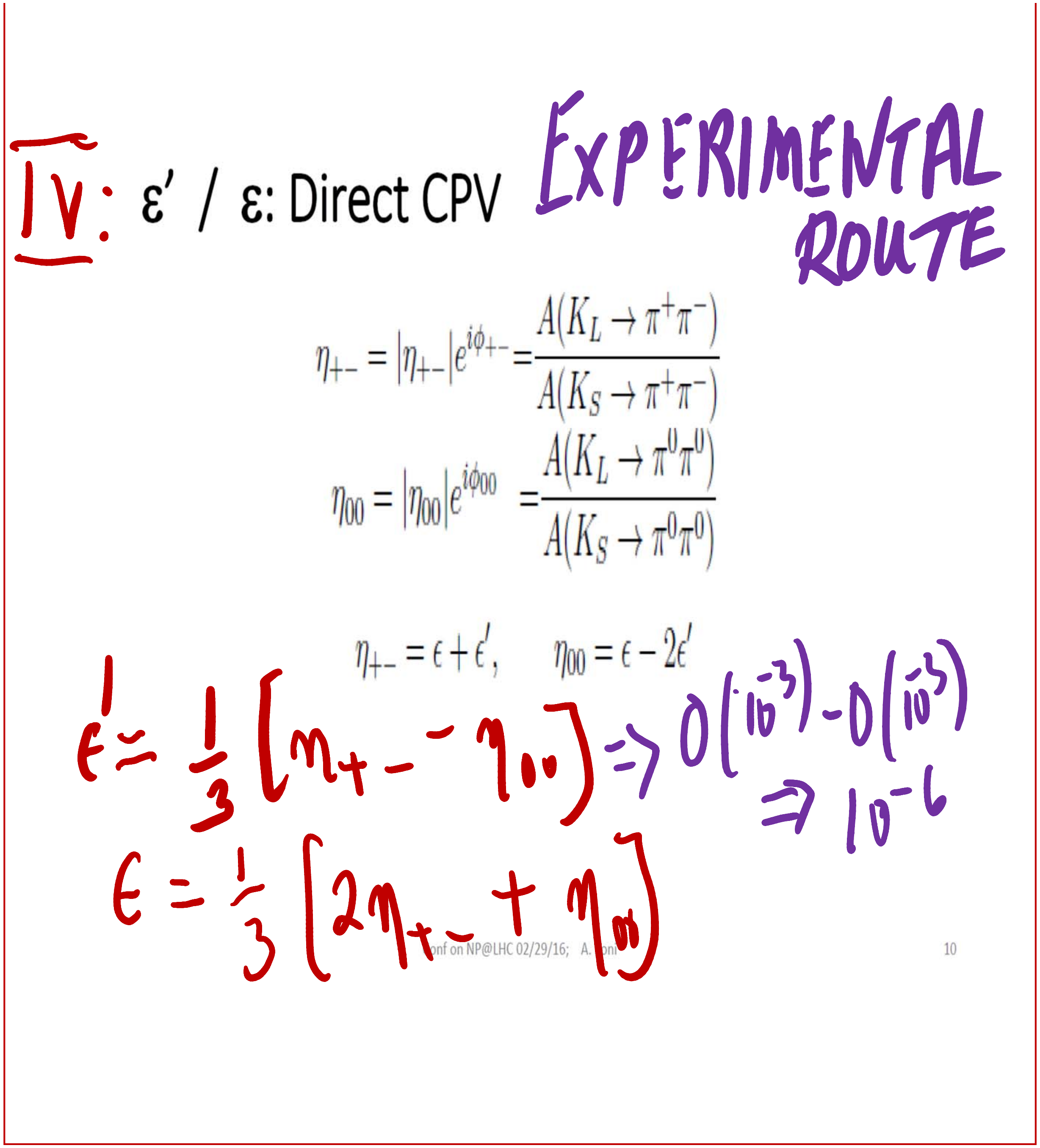
1% !! $\mathbf{0.299 \pm 0.003}$ D. Bigi et al 2017

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

$R_{D^*} \sim .254 \pm .020$ ⇐



IV: ε′ / ε: Direct CPV

EXPERIMENTAL ROUTE

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

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

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

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

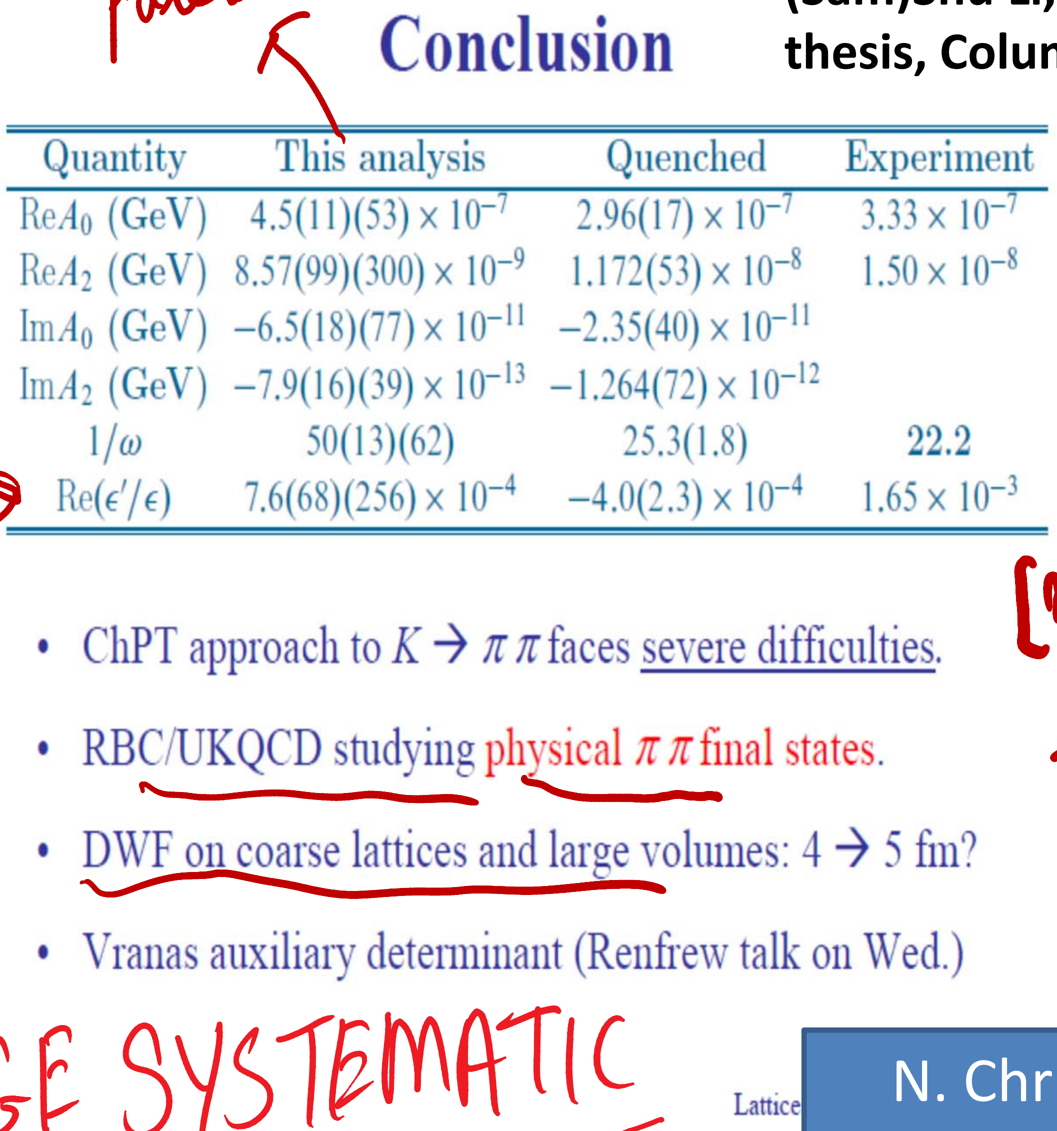
$$\epsilon = \frac{1}{3}\left[2\eta_{+-} + \eta_{00}\right]$$

onf on NP@LHC 02/29/16; A. oni

10

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

$\Rightarrow$

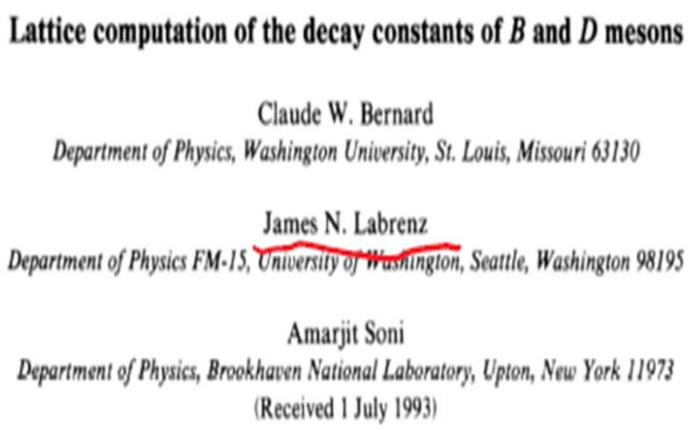
- ChPT approach to $K \rightarrow \pi\pi$ faces severe difficulties.
- RBC/UKQCD studying physical $\pi\pi$ final states.
- DWF on coarse lattices and large volumes: 4 → 5 fm?
- Vranas auxiliary determinant (Renfrew talk on Wed.)

Lattice

N. Christ @LAT08

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

LARGE SYSTEMATIC errors DUE ChPT



Lattice computation of the decay constants of B and D mesons

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Amarjit Soni
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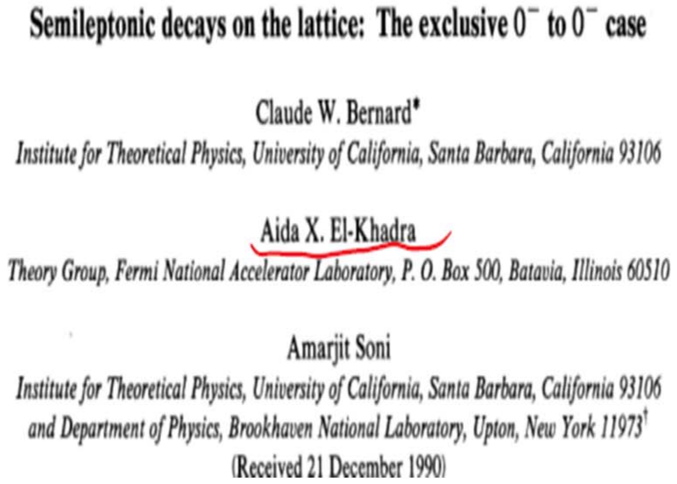
(Received 1 July 1993)



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

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Aida X. El-Khadra
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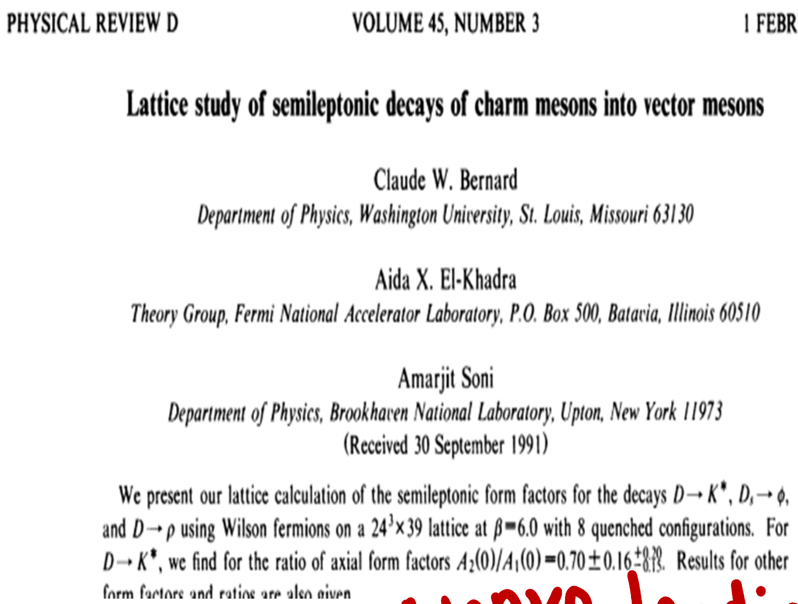
(Received 21 December 1990)



PHYSICAL REVIEW D VOLUME 45, NUMBER 3 1 FEBRUARY 1992

Lattice study of semileptonic decays of charm mesons into vector mesons

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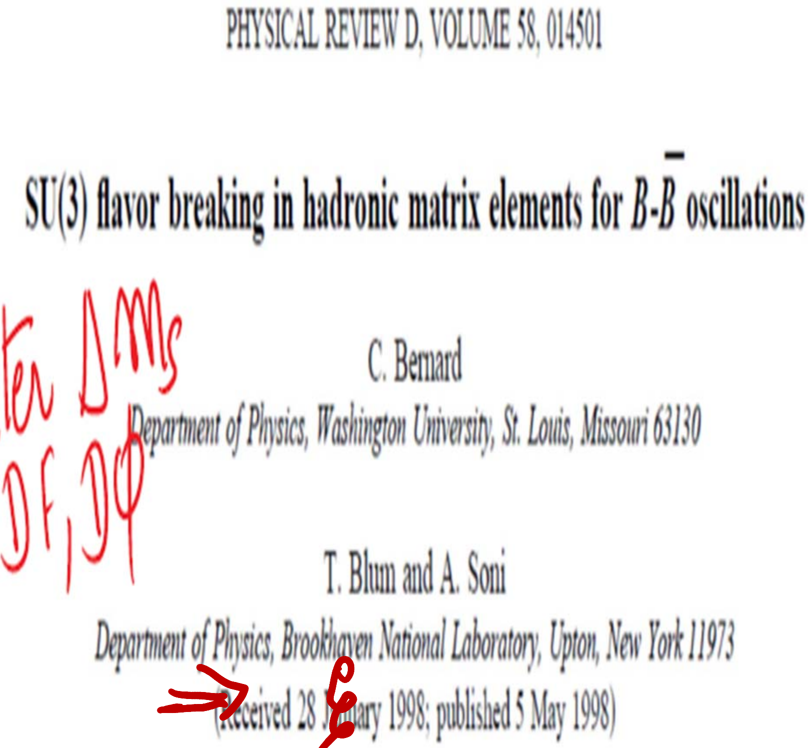
(Received 30 September 1991)

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 $A_2(0)/A_1(0) = 0.70 \pm 0.16^{+0.20}_{-0.13}$. 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

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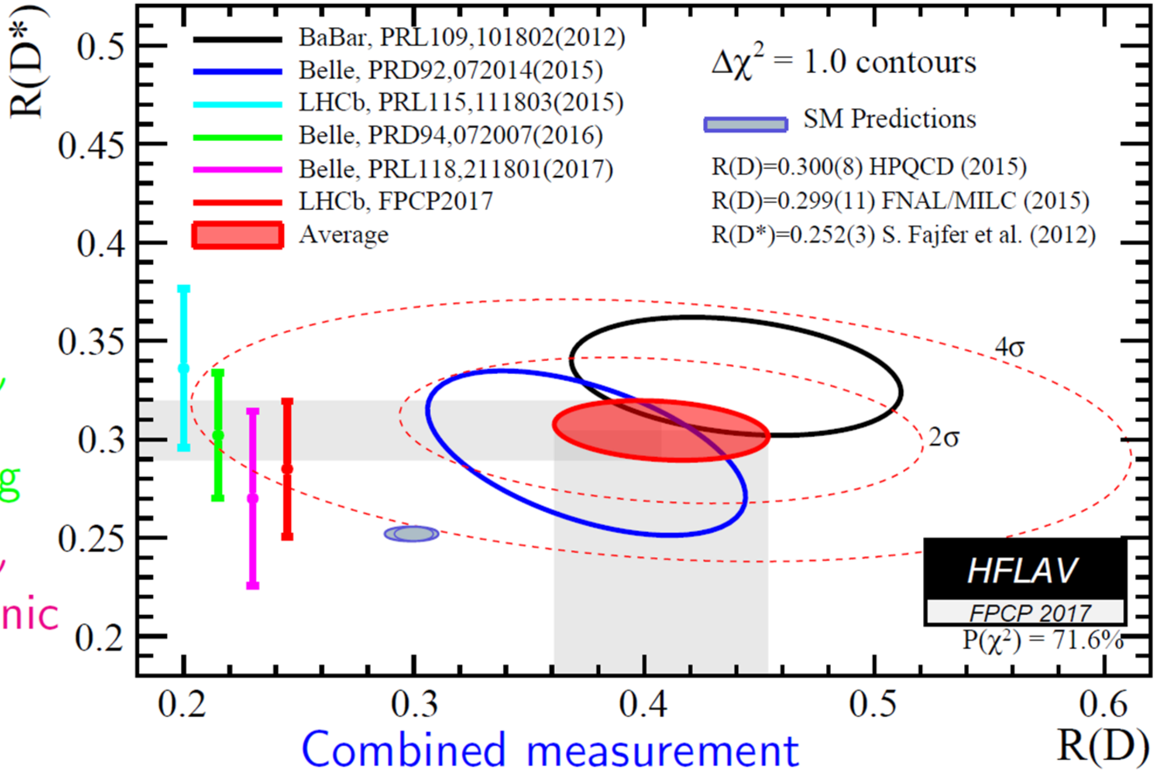
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973
(Received 28 January 1998; published 5 May 1998)

Later ΔM_s
CDF, D0

New status of $\mathcal{R}(D^*)$



$B \to D^*\tau\nu$
with semi-leptonic tag

$B \to D^*\tau\nu$
with hadronic
τ decays

Combined measurement
of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$

Thery
Blob
Needs
updating

Excess still 4σ: central value moved towards SM;

on $\mathcal{R}(D^*)$, discrepancy increased from 3.0σ to 3.4σ

The wealth and power of the experimental data

- Our version of RPV3 ability considerably clipped
- And potentially may face trouble

Implications of anomaly for colliders

At low energies, the effective 4-fermion Lagrangian for the quark-level transition $b \to c\tau\bar{\nu}$ in the SM is given by

$$-\mathcal{L}_{\mathrm{eff}} = \frac{4G_F V_{cb}}{\sqrt{2}} (\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau) + \mathrm{H.c.}\,, \qquad (4)$$

SM

BSM

DIM 6 OPS

"V" ←

"S" ←

$$\begin{aligned} \mathcal{O}_{V_{R,L}} &= (\bar{c}\gamma^\mu P_{R,L} b)(\bar{\tau}\gamma_\mu P_L \nu) && (5) \\ \mathcal{O}_{S_{R,L}} &= (\bar{c}P_{R,L} b)(\bar{\tau}P_L \nu)\,, && (6) \\ \mathcal{O}_T &= (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu)\,. && (7) \end{aligned}$$

SKIP 4 NOW

Rusa Mandal, PhD Thesis [IMSc Chennai]

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

LHCb

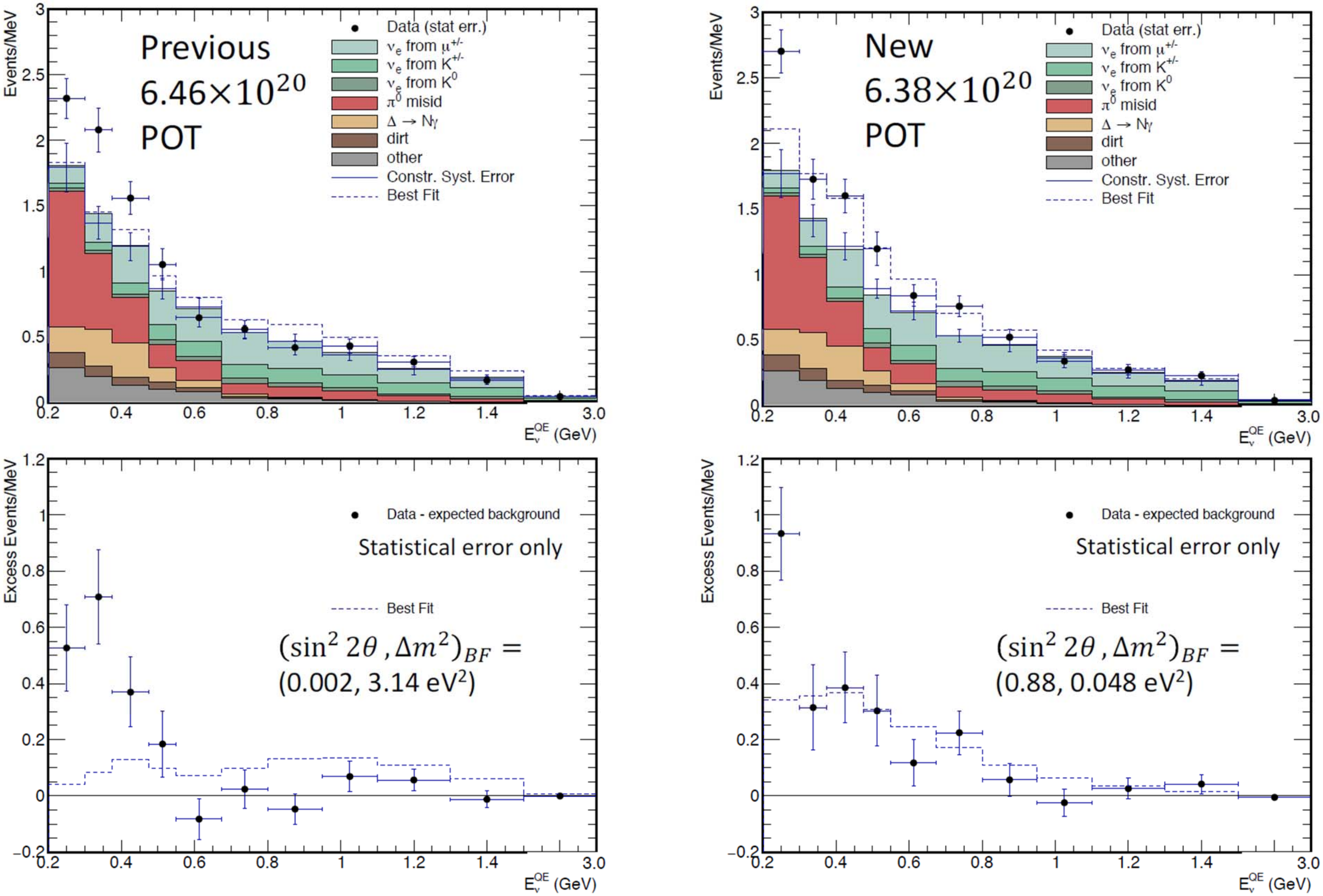
$$\Phi \equiv \frac{d}{dq^2}\mathrm{BR}(B_s \to \phi\mu\mu)\Big|_{q^2\in[1:6]\,\mathrm{GeV}^2} = \begin{cases} \left(2.58^{+0.33}_{-0.31} \pm 0.08 \pm 0.19\right) \times 10^{-8}\ \mathrm{GeV}^{-2} & \text{(exp.)} \\ (4.81 \pm 0.56) \times 10^{-8}\ \mathrm{GeV}^{-2} & \text{(SM)}\,. \end{cases} \tag{6.2.3}$$

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

M.Patel e LHCb: LHCb may be able to give R_ϕ.

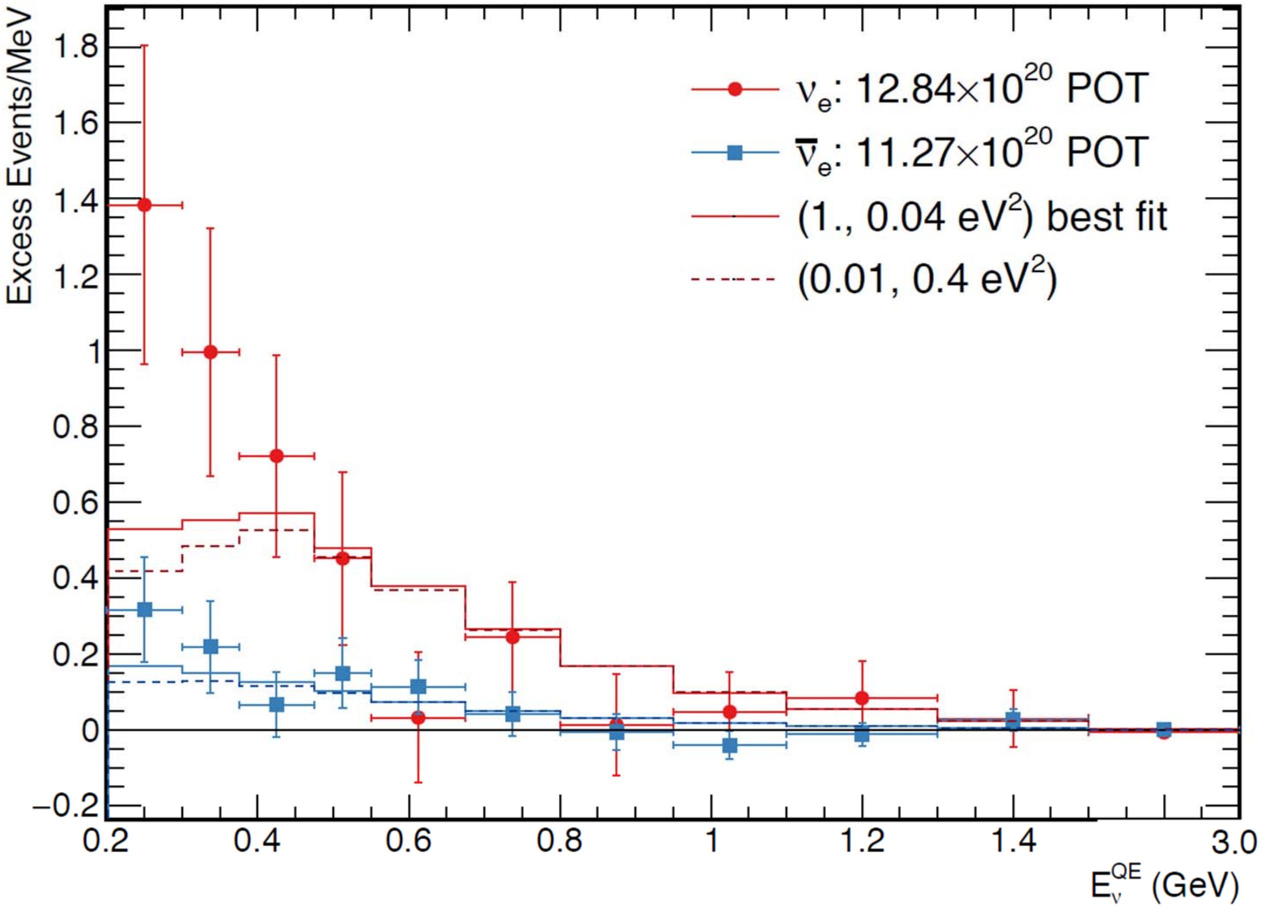
That would be great

Excess: Old vs New in $\boldsymbol{\nu}$ Mode



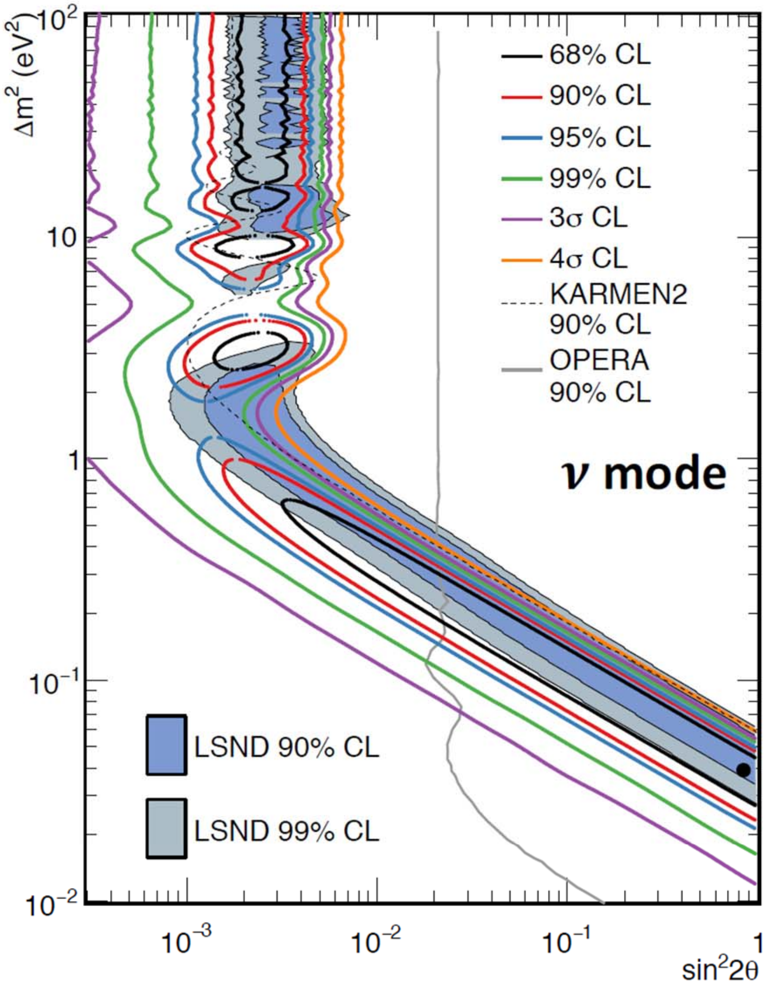
The observed ν_e spectra are statistically consistent between the new and previous data sets (KS prob =76%)

Excess: Neutrino vs Anti-neutrino

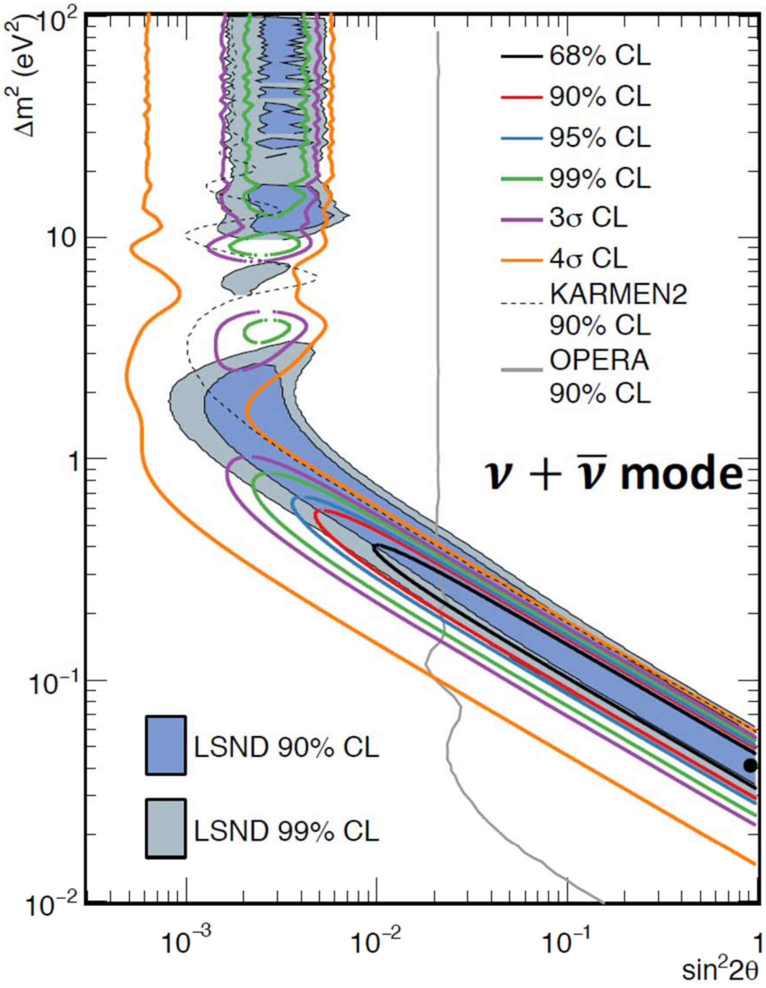


- Excess in neutrino and antineutrino mode is qualitatively consistent

Allowed Region

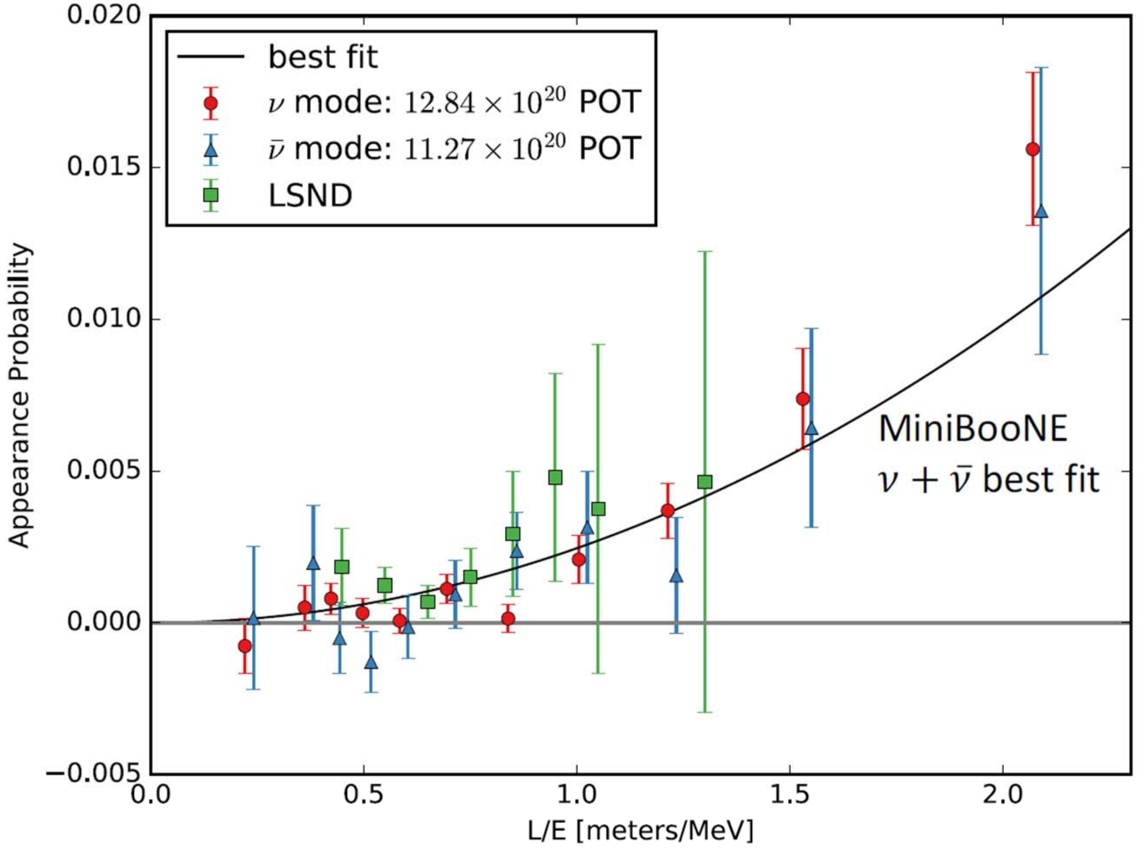


$(\Delta m^2, \sin^2 2\theta) = (0.037\ \mathrm{eV}^2, 0.958)$
$\chi^2/ndf = 10.0/6.6$ (prob = 15.4%)



$(\Delta m^2, \sin^2 2\theta) = (0.041\ \mathrm{eV}^2, 0.958)$
$\chi^2/ndf = 19.5/15.4$ (prob = 20.1%)

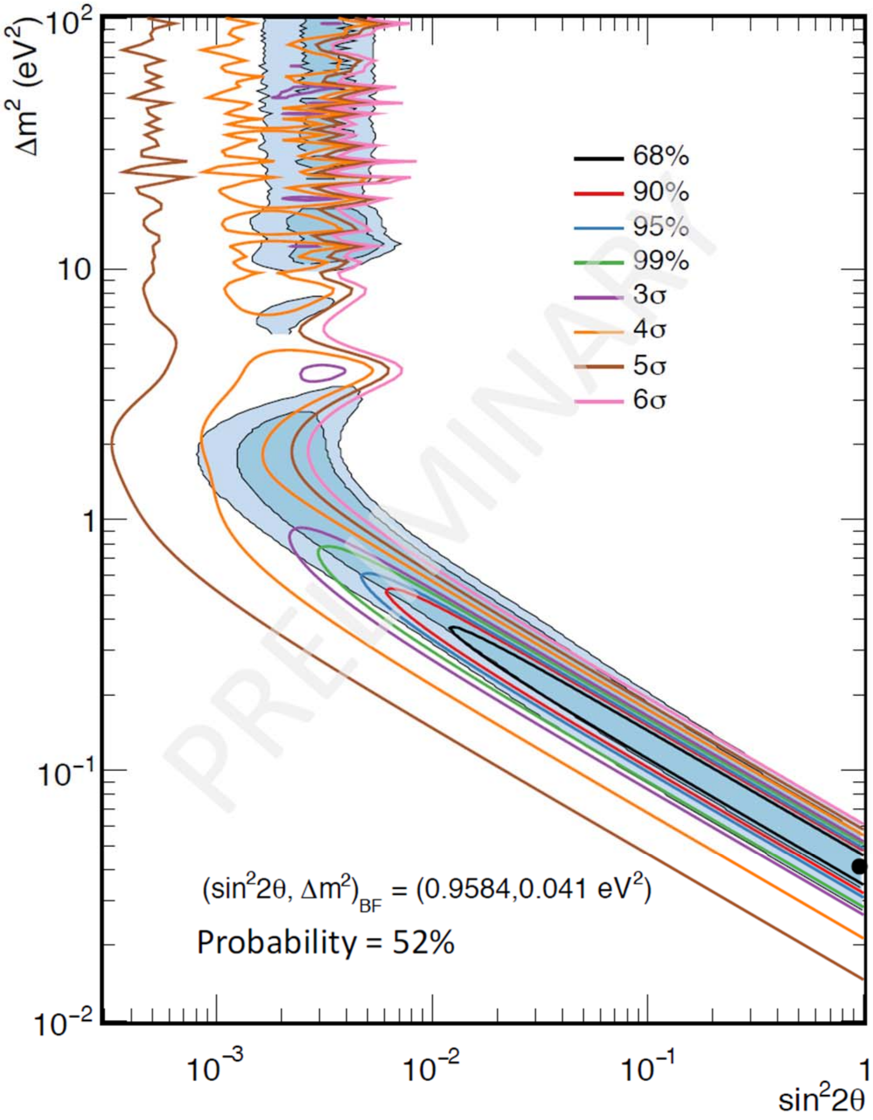
L/E



- Average E_{ν}^{QE} of each bin is used
- MiniBooNE neutrino, MiniBooNE antineutrino and LSND are **consistent** in appearance probability and L/E

Combined Fit with LSND

- Combined fit of MiniBooNE $\nu + \bar{\nu}$ mode and LSND is at 6σ level
- Assuming no correlation between MiniBooNE and LSND
- Best fit of MiniBooNE and LSND combined is **consistent** with our latest result
- Note: a large $\sin^2 2\theta$ is unphysical for a pure 3+1 model

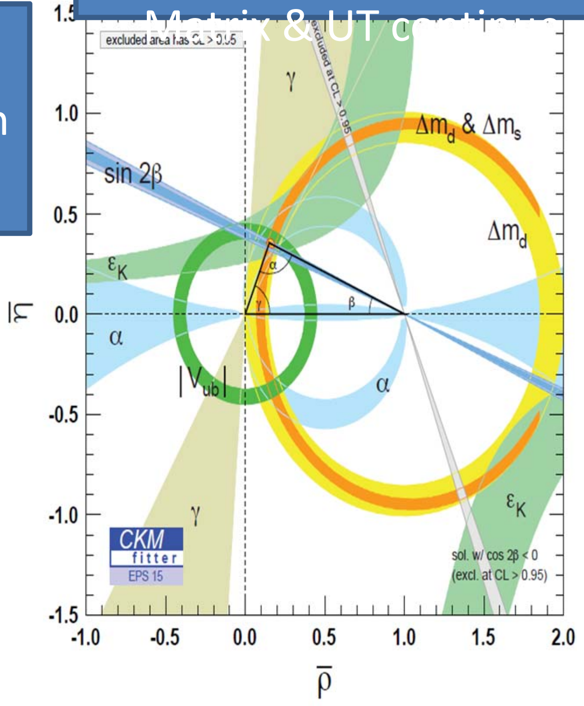


Luminosity performance summary

- Squeezing β_y^*
  - The β_y^* has been squeezed step by step.
  - Successfully squeezed down to $\beta_y^* = 2$ mm (world smallest value) for both rings. The optics performance is fine.
- Specific luminosity
  - After improved by increasing IP coupling knob scan region, reached the target value: $L_{spec} = 2 \times 10^{31}$ cm^{-2}s^{-1}.
- Peak luminosity
  - $L = 5.54 \times 10^{33}$ cm^{-2}s^{-1} has been achieved with 800 mA in LER and 780 mA in HER (N_b=1576).
  - At higher bunch current operation, $L = 2.29 \times 10^{33}$ cm^{-2}s^{-1} was achieved in 270 mA/225 mA ($N_b = 394$).
    - With four times bunches ($N_b = 1576$), ~ 9×10^{33} cm^{-2}s^{-1} is expected.
  - Phase 2 target ($L \sim O(1 \times 10^{34}$ cm^{-2}s^{-1})) is almost achieved.

Efforts to overconstrain the CKM Matrix & UT continue

Andreas Hoecker & Malcolm John EW Moriond '16



Key new results from LHCb

DATA DRIVEN Methods

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

ITE ~ 1% Mannel et al

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

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

which improved the previous LHCb-only conclusion by 2°

Brod Zupan'14 STD.

- Inline with B-factory conclusions from $B \to DK$,
  - BaBar: $\gamma = (70 \pm 18)^\circ$
  - Belle: $\gamma = (73^{+13}{}_{-15})^\circ$

Compatible with SM-CKM to ~15% accuracy

O(5-10%) new physics is possible and is HUGE

BELLE-II & LHCb(upgrade) ~ δγ ~1°, still long way to go before ultimate precision

A model with a Z' portal

[Aristizabal Sierra, Staub, AV, 2015]

$$\boxed{SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_X}$$

Vector-like = “joker”
for model builders

$$\mathcal{L}_m = m_Q \overline{Q} Q + m_L \overline{L} L$$

Vector-like (Dirac)
masses

$$\mathcal{L}_Y = \lambda_Q \overline{Q_R} \phi q_L + \lambda_L \overline{L_R} \phi \ell_L + \text{h.c.}$$

VL – SM mixing

FROM THEORY

K→2π

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

I=2 amp

I=0 amp

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

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

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

CERN+FNAL ~2004

Δ S=1 H_W

WC to NLO

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

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

CORE of the Calculation:

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

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

Tree

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

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

QCDP

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

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

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

I=0 ⇒

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

→ 0

$m_q \to 0$

EWP

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

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

I=2

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

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

→ const

$m \to 0$

EWP