Topical lectures on flavor physics & CP-violation

Amarjit Soni

Los Angeles, CA 90077; USA

The 2018 Weihai High-Energy Physics School (WHEPS)

08/23/18

II. Flavor anomalies and possible indications of new physics

THIS LECTURE FOCUSSES ON SEVERAL DIFFERENT EXPERIMENTAL INDICATIONS FROM FLAVOR PHYSICS OF POSSIBLE BREAKDOWN OF ONE ASPECT OF SM

Anomalies galore!

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

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

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

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

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

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

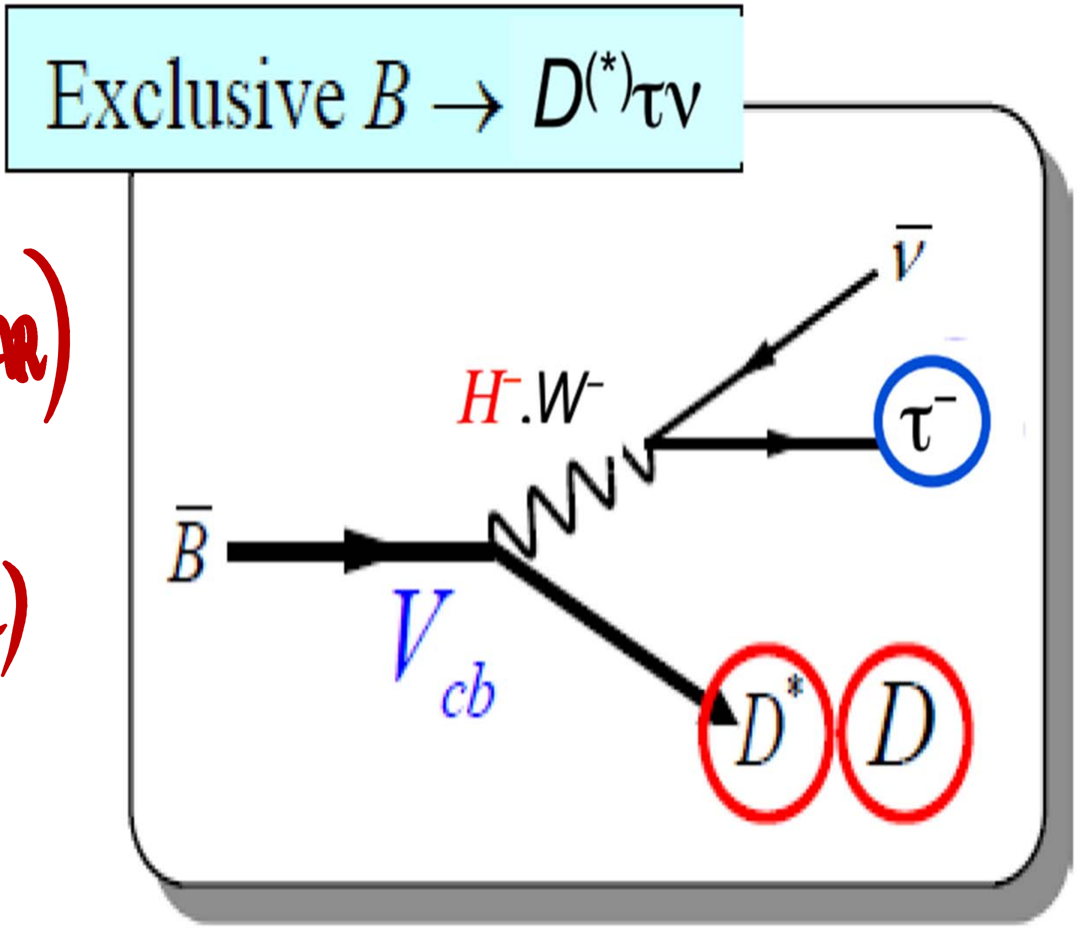
In decoding SM or not, lattice input is vital for each case!

RD(*)

RA LUTH (BABAR)

CP May 2012

(HEFEI, China)



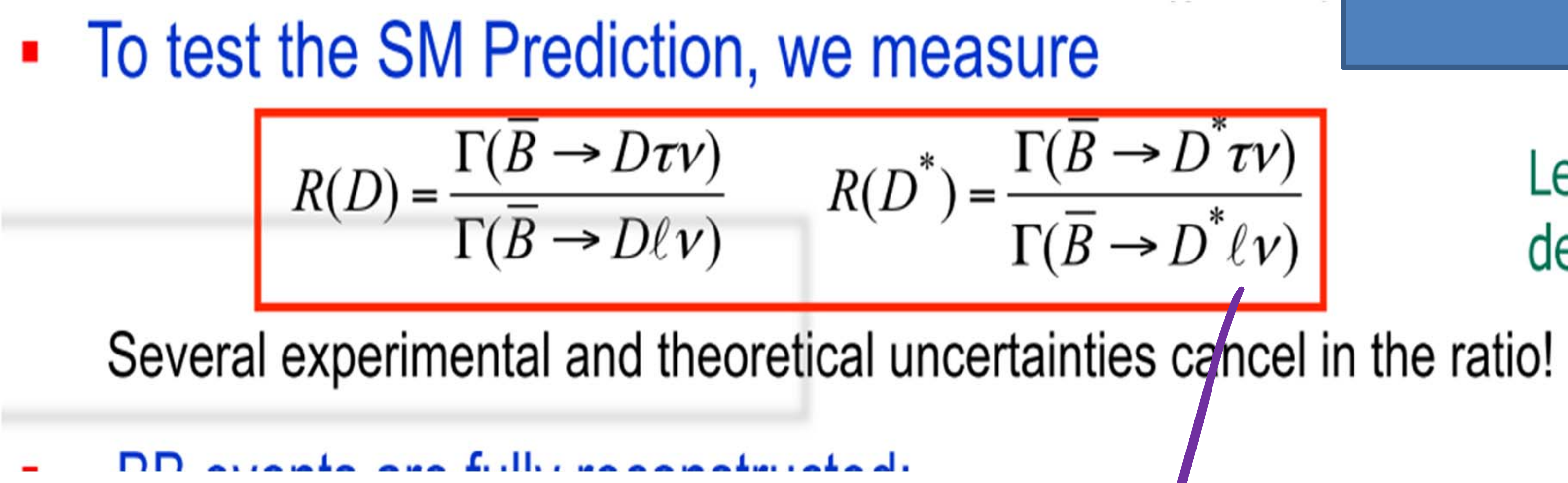
MANUEL FRANCO

SEVILLA

PhD Thesis

BABAR 2012

Independent of Vcb!



- To test the SM Prediction, we measure

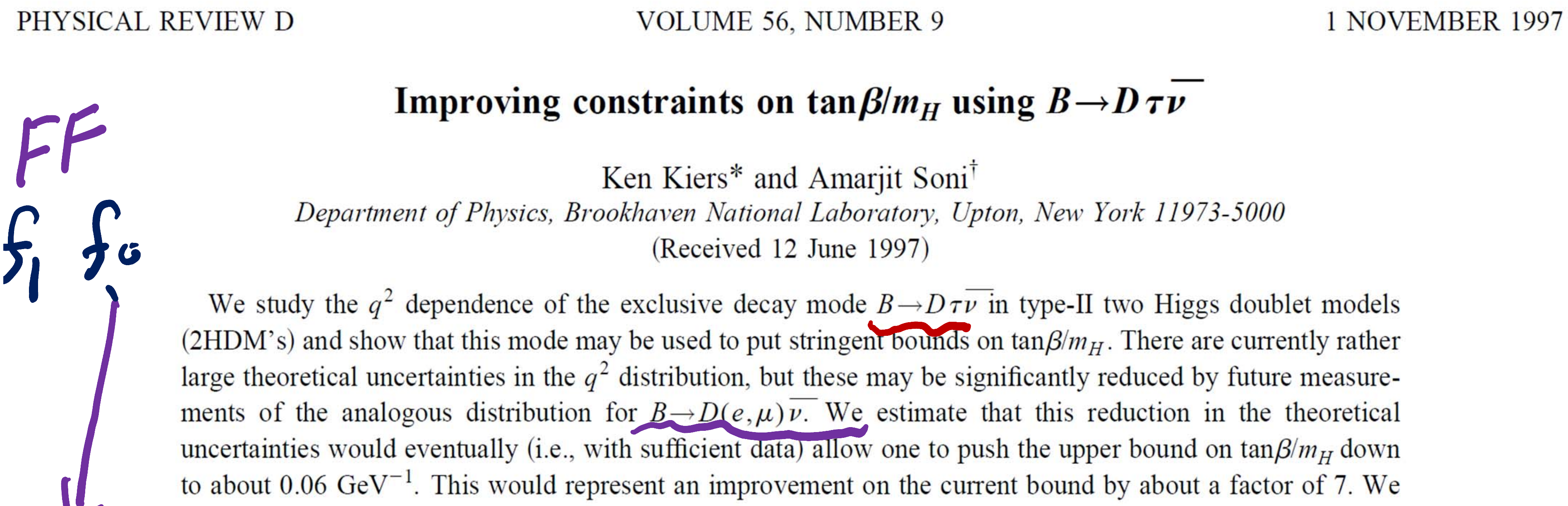
$$R(D) = \frac{\Gamma(\overline{B} \to D\tau\nu)}{\Gamma(\overline{B} \to D\ell\nu)} \qquad R(D^*) = \frac{\Gamma(\overline{B} \to D^*\tau\nu)}{\Gamma(\overline{B} \to D^*\ell\nu)}$$

Several experimental and theoretical uncertainties cancel in the ratio!

- BB events are fully reconstructed:

Leptonic τ decays only

$\ell = \mu$ or e



PHYSICAL REVIEW D VOLUME 56, NUMBER 9 1 NOVEMBER 1997

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

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

(Received 12 June 1997)

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

Form factors: B=>D vs B=>D*

- **For B to D [0- to 0-] due to Parity,**

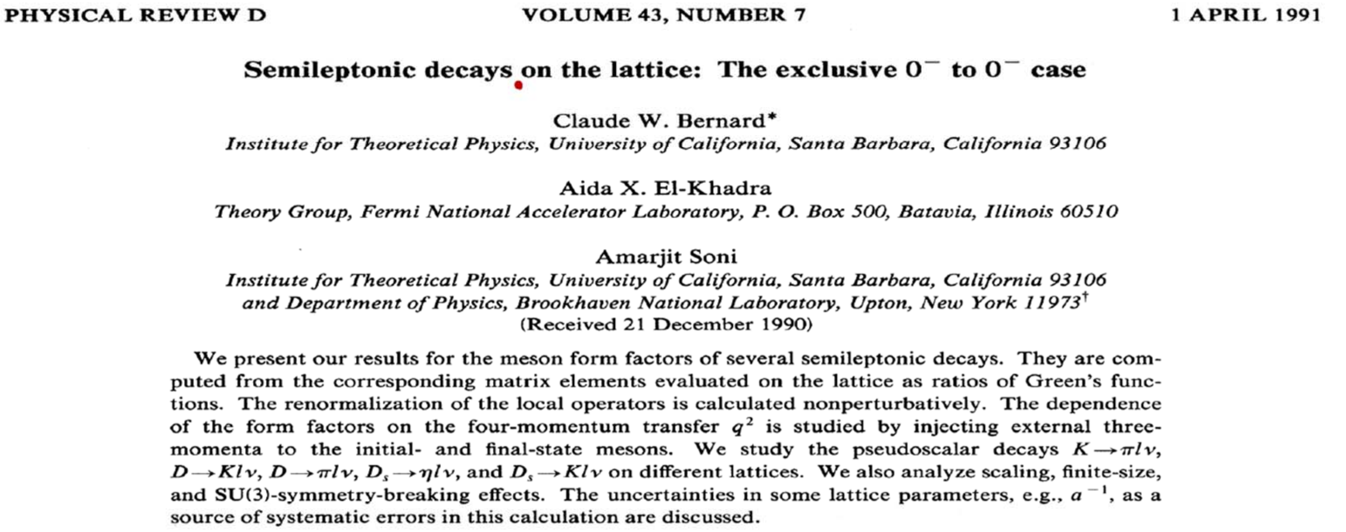
Only vector current contributes: 2 form factor of which, contribution of one is prop. to lepton mass

For B to D* both vector and axial vector conribute;

Now 4 FF, again contribution of one FF is

prop. to lepton mass

AIDA X E-K THESIS: 1ST PHD THESIS (~'89) INITIATING THE USE OF LATTICE METHODS FOR DEDUCING SL FF'S



PHYSICAL REVIEW D VOLUME 43, NUMBER 7 1 APRIL 1991

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

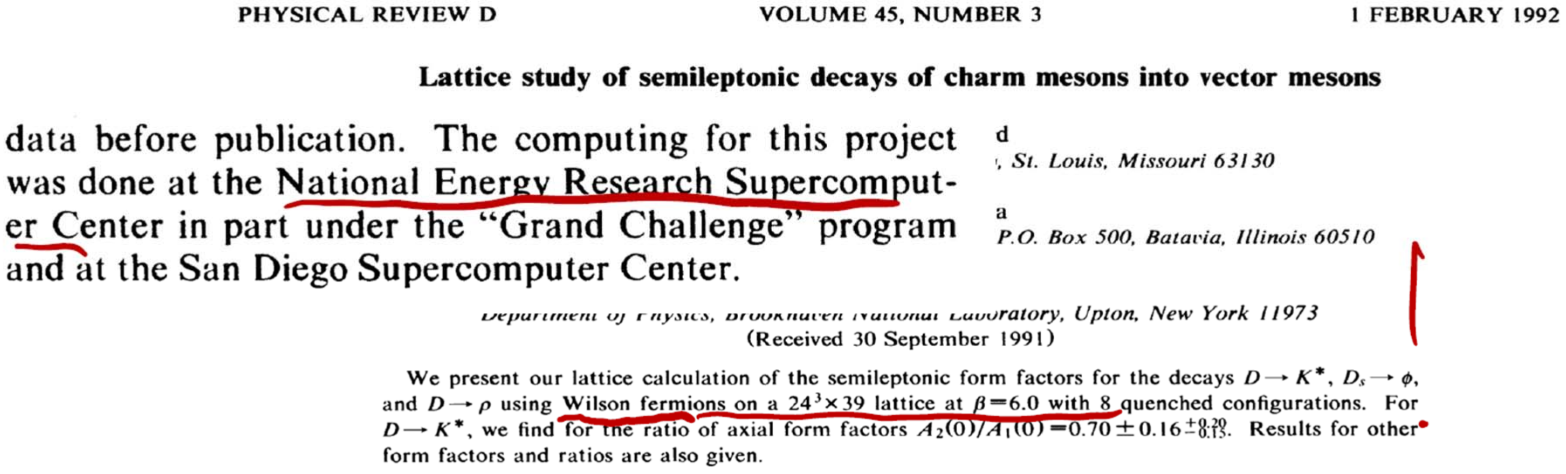
Claude W. Bernard*
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106

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

Amarjit Soni
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
and Department of Physics, Brookhaven National Laboratory, Upton, New York 11973[†]

(Received 21 December 1990)

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.

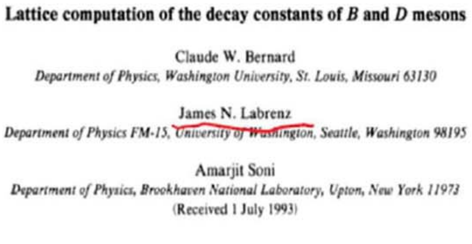
d
, St. Louis, Missouri 63130

a
P.O. Box 500, Batavia, Illinois 60510

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.



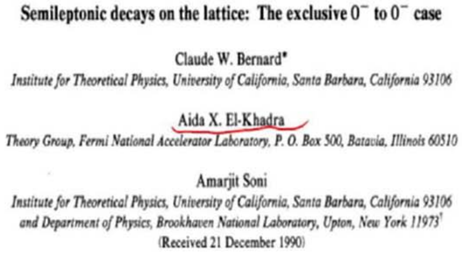
Lattice computation of the decay constants of B and D mesons

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

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

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

(Received 1 July 1993)



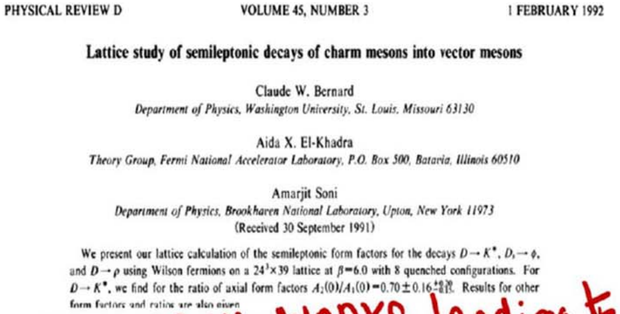
Semileptonic decays on the lattice: The exclusive 0^- to 0^- case

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

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

Amarjit Soni
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
and Department of Physics, Brookhaven National Laboratory, Upton, New York 11973†

(Received 21 December 1990)



PHYSICAL REVIEW D VOLUME 45, NUMBER 3 1 FEBRUARY 1992

Lattice study of semileptonic decays of charm mesons into vector mesons

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

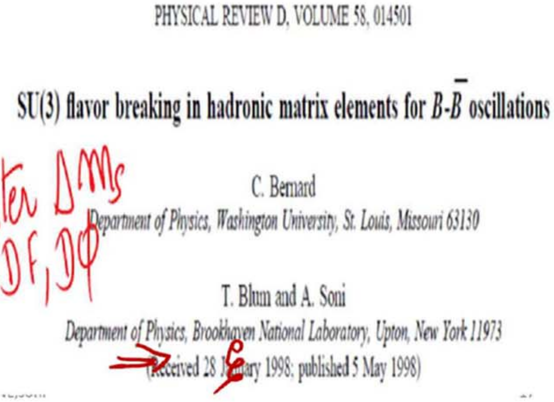
Aida X. El-Khadra
Theory Group, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510

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

(Received 30 September 1991)

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

PIONEERING WORKS Leading to
Modern Day UT ?



PHYSICAL REVIEW D, VOLUME 58, 014501

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

Later ΔM_s
CDF, DΦ

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

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

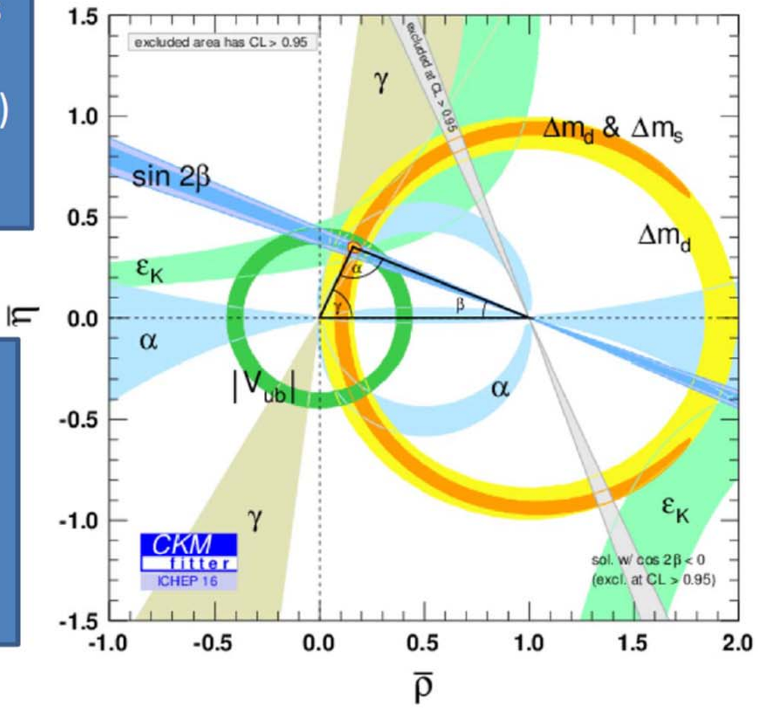
(Received 28 January 1998; published 5 May 1998)

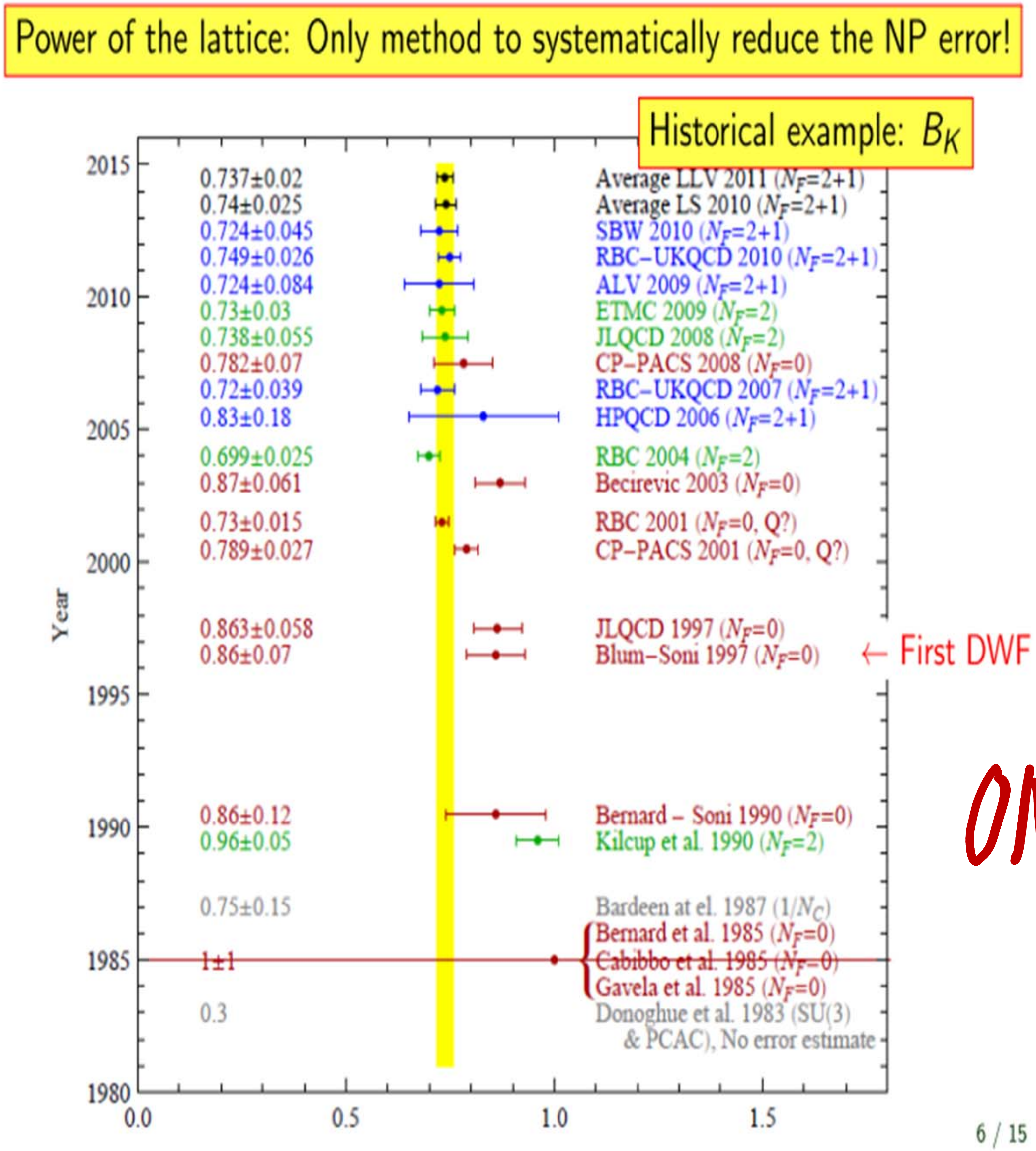
Overall consistency with the SM

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

← First DWF

6 / 15

AB-initio Calculat

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

ONE ILLUSTRATION

Semi-leptonic (exclusive) form factors:Basics

$$\mathcal{T} = \langle A l \nu | H_{\text{eff}} | B \rangle \qquad H_{\text{eff}} = \frac{G_F}{\sqrt{2}} J^{\mu}_{\text{hadron}} J^{\dagger}_{\text{lepton},\mu}$$

$$\mathcal{T} = \frac{G_F}{\sqrt{2}} V_{ab} H^{\mu} L^{\dagger}_{\mu} \ ,$$

$$L_{\mu} = \bar{v}(l^{+}) \gamma_{\mu} (1 - \gamma^{5}) u(\nu) \ ,$$

$$H^{\mu} = \langle A | \bar{a} \gamma^{\mu} (1 - \gamma^{5}) b | B \rangle \ .$$

$$\begin{tikzcd} B \arrow[r] \arrow[dr, bend right] & A \arrow[d] & l\nu \\ & 0^- & \end{tikzcd}$$

e.g. $B \to D(\pi)\, \ell \nu$

Bernard, El-Khadra, A.S. PRD'90

$V_{ab} \Rightarrow V_{cb}\ (V_{ub})$

There are two conventional parametrizations:

$$H^{\mu} = f_{+}(q^2)(p_B + p_A)^{\mu} + f_{-}(q^2)(p_B - p_A)^{\mu} \xrightarrow{\quad} m_\ell \qquad (4)$$

and

$$H^{\mu} = f_{+}(q^2)\left[(p_B + p_A)^{\mu} - \frac{m_B^2 - m_A^2}{q^2}(p_B - p_A)^{\mu} \right] \xrightarrow{\quad} m_\ell$$

$$+ f_0(q^2) \frac{m_B^2 - m_A^2}{q^2} (p_B - p_A)^{\mu} \xrightarrow{\quad} m_\ell \ ,$$

$$(m_B^2 - m_A^2) f_0(q^2) = (m_B^2 - m_A^2) f_{+}(q^2) + q^2 f_{-}(q^2) \ , \qquad (5)$$

$$f_0(0) = f_{+}(0) \ .$$

- S.L. decays involving a $\tau^\pm$ have an additional helicity amplitude (for D

$$\frac{d\Gamma_\tau}{dq^2} = \frac{G_F^2|V_{cb}|^2|\mathrm{p}|q^2}{96\pi^3 m_B^2}\left(1-\frac{m_\tau^2}{q^2}\right)^2\left[\left(|H_{++}|^2+|H_{--}|^2+|H_{00}|^2\right)\left(1+\frac{m_\tau^2}{2q^2}\right)+\frac{3}{2}\frac{m_\tau^2}{q^2}|H_t$$

For $D\tau\nu$, only H_{00} and H_t contribute!

- To test the SM Prediction, we measure

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

Leptonic τ decays only

Several experimental and theoretical uncertainties cancel in the ratio!

- BB events are fully reconstructed:
  - full reconstruction of hadronic B decay: Btag (tag efficiency improved)
  - reconstruction of $D^{(*)}$ and $e^\pm$ or $\mu^\pm$ (extend to lower momenta)
  - no additional charged particles
  - kinematic selections: $q^2 > 4$ GeV^2

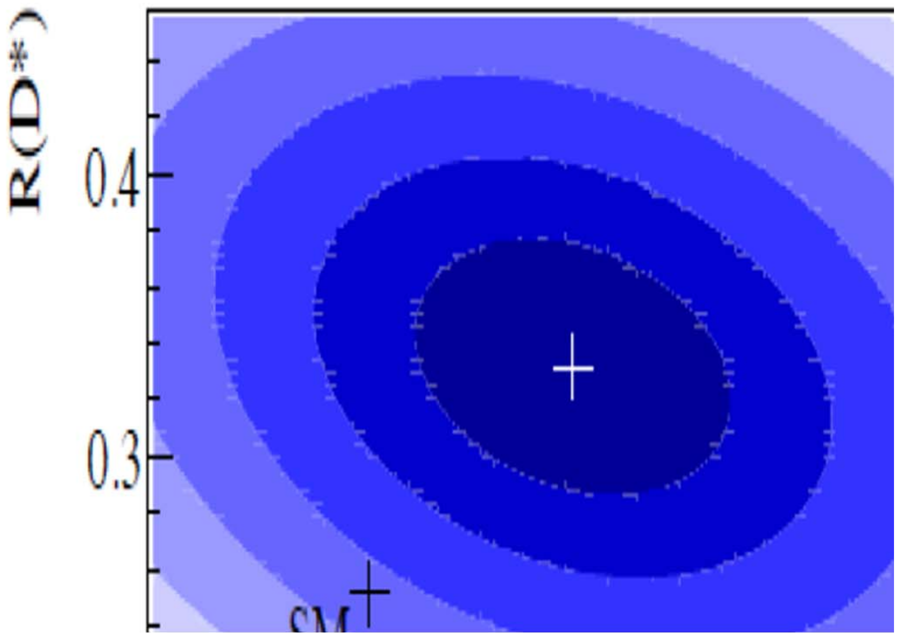
Decay	N_{sig}	N_{norm}	$R(D^{(*)})$	$\mathcal{B}(B \to D^{(*)}\tau\nu)$ (%)	$\Sigma_{\mathrm{tot}}(\sigma$
$D^0\tau^-\overline{\nu}_\tau$	314 ± 60	1995 ± 55	0.429 ± 0.082 ± 0.052	0.99 ± 0.19 ± 0.13	4.
$D^{*0}\tau^-\overline{\nu}_\tau$	639 ± 62	8766 ± 104	0.322 ± 0.032 ± 0.022	1.71 ± 0.17 ± 0.13	9.
$D^+\tau^-\overline{\nu}_\tau$	177 ± 31	986 ± 35	0.469 ± 0.084 ± 0.053	1.01 ± 0.18 ± 0.12	5.
$D^{*+}\tau^-\overline{\nu}_\tau$	245 ± 27	3186 ± 61	0.355 ± 0.039 ± 0.021	1.74 ± 0.19 ± 0.12	10.
$D\tau^-\overline{\nu}_\tau$	489 ± 63	2981 ± 65	0.440 ± 0.058 ± 0.042	1.02 ± 0.13 ± 0.11	6.
$D^*\tau^-\overline{\nu}_\tau$	888 ± 63	11953 ± 122	0.332 ± 0.024 ± 0.018	1.76 ± 0.13 ± 0.12	13.

omparison with SM calculation:

4UTH

Combined 3.4σ

	R(D)	R(D*)
BABAR	0.440 ± 0.071	0.332 ± 0.029
SM	0.297 ± 0.017	0.252 ± 0.003
Difference	**2.0 σ**	**2.7 σ**



ne combination of the two measurements

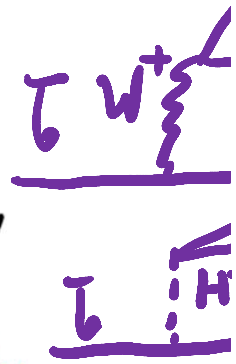
).27 correlation) yields χ^2/NDF=14.6/2,

Prob = 6.9 $\times 10^{-4}$!!

A charged Higgs (2HDM type II) of spin 0 couples to the τ and will only affect H_t

$$H_t^{2\mathrm{HDM}} = H_t^{\mathrm{SM}} \times \left(1 - \frac{\tan^2\beta}{m^2_{H\pm}} \frac{q^2}{1 \mp m_c/m_b}\right)$$

- for Dτν
+ for D*τν



This could enhance or decrease the ratios R(D*) depending on tanβ/m_H

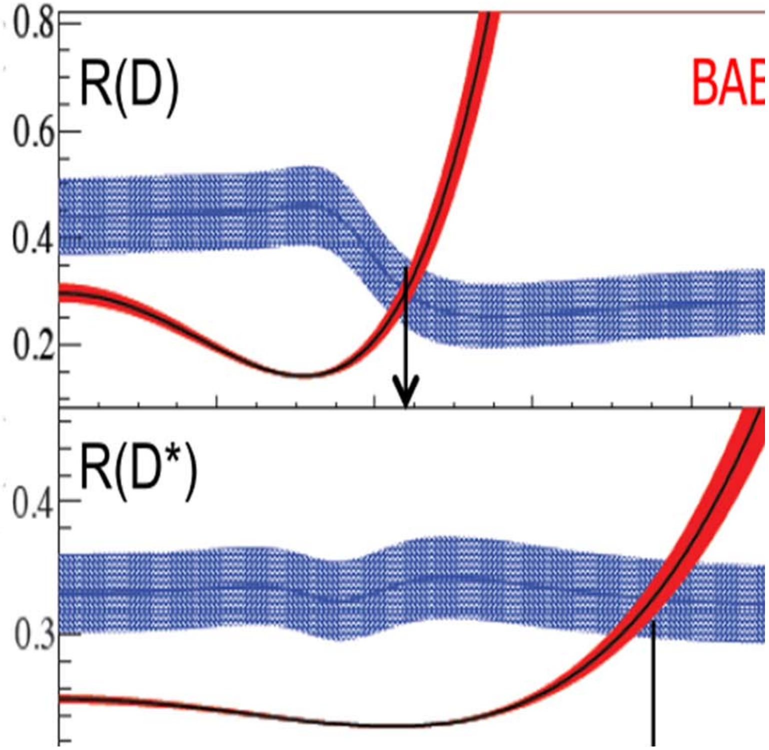
We estimate the effect of 2DHM, accounting for difference in efficiency, and its uncertainty

The data match 2DHM Type II at

tanβ/m_H= 0.44 ± 0.02 for R(D)

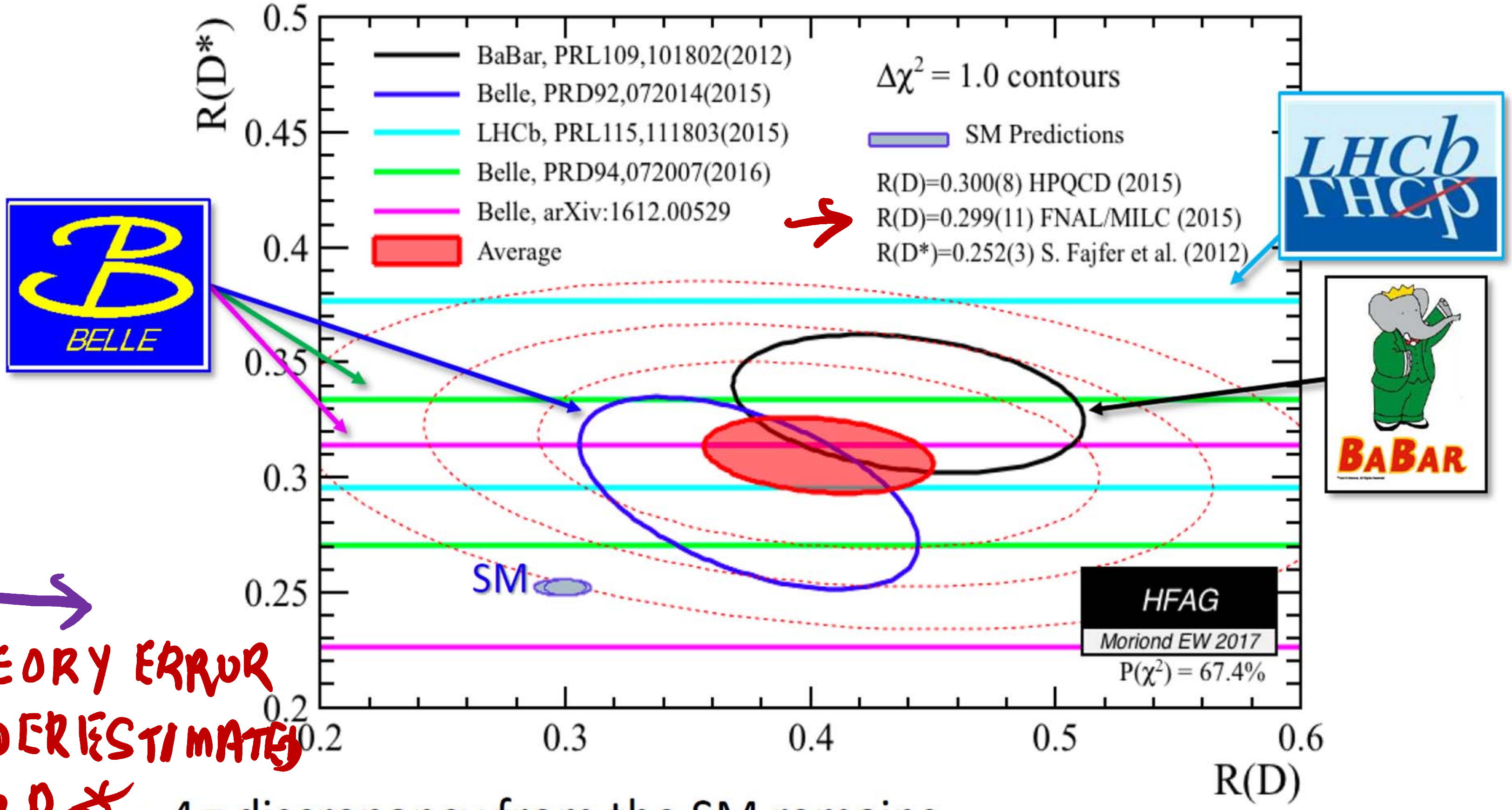
tanβ/m_H= 0.75 ± 0.04 for R(D*)

However, the combination of R(D) and R(D*) excludes the Type II 2HDM in the full tanβ-m_H parameter space with a probability



$R\left(D^{(*)}\right)$ by HFAG

Hirose [BELLE]@EW MORIOND Mar. 2017

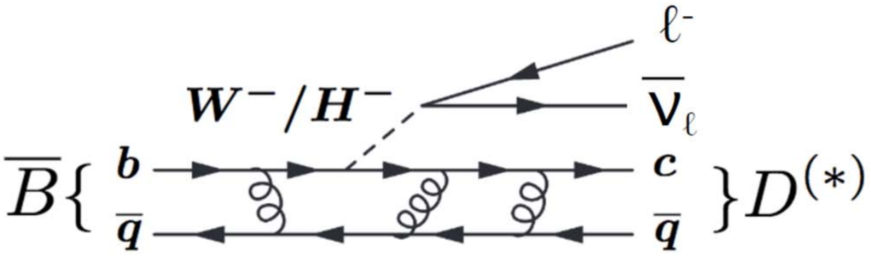


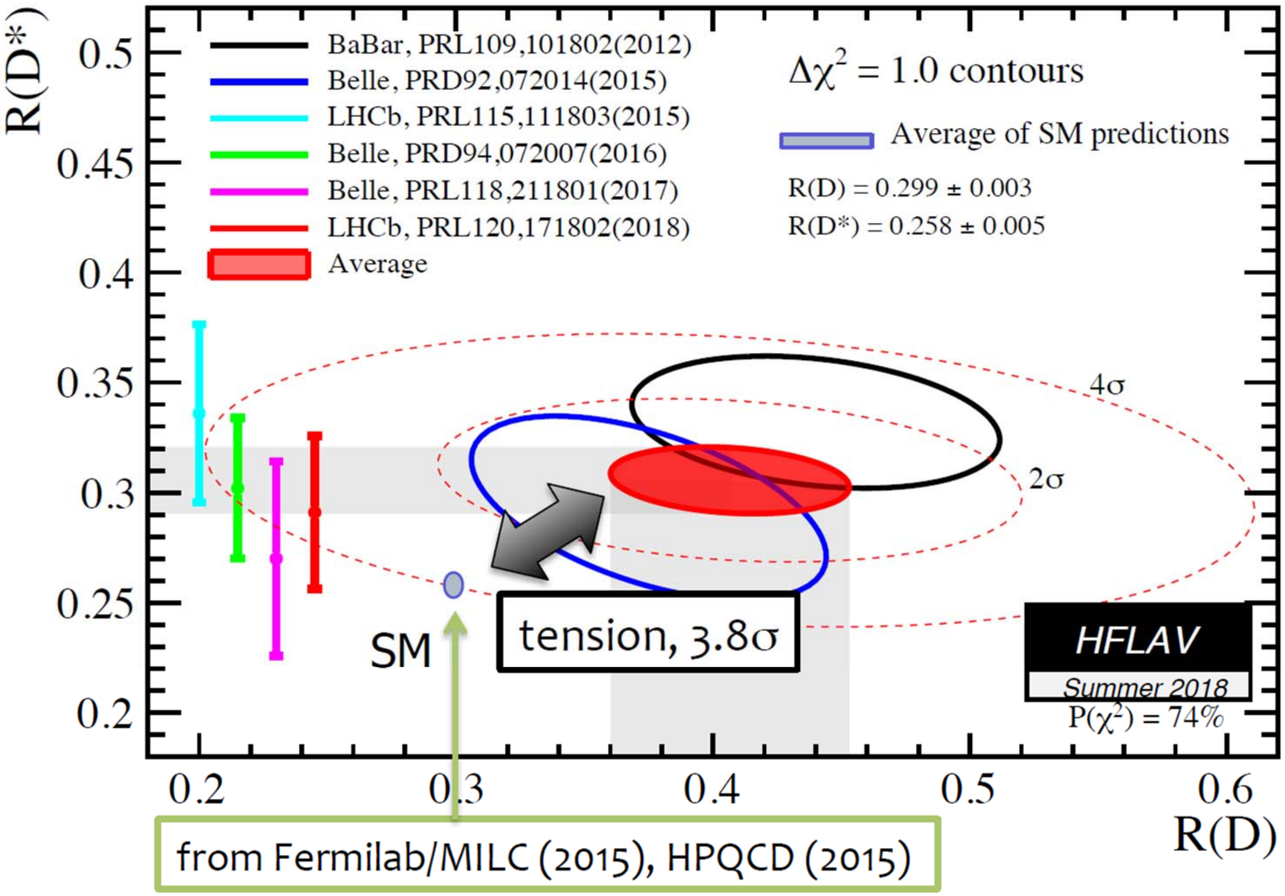
THEORY ERROR
UNDERESTIMATED
ESP R_{D^*}

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

Belle deviations quite mild

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





SM

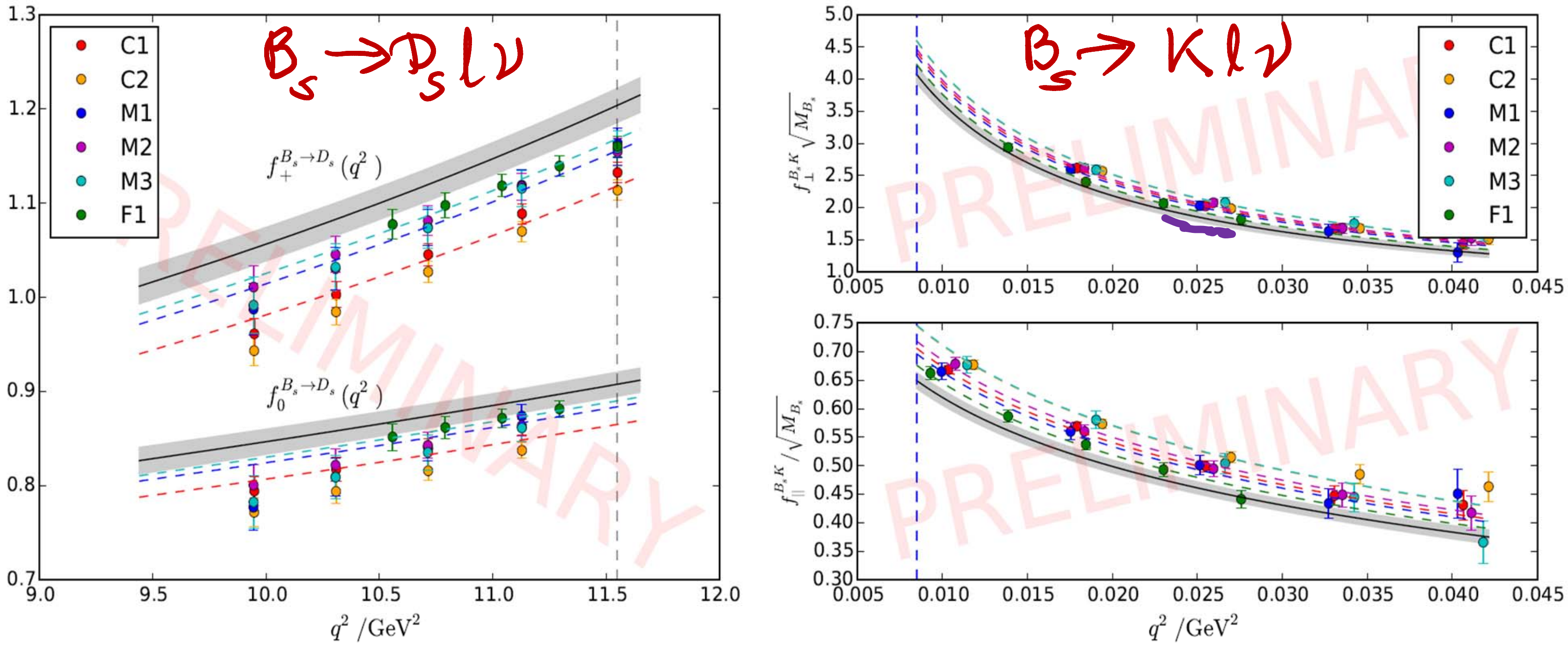
tension, 3.8σ

from Fermilab/MILC (2015), HPQCD (2015)

R_D

Lattice inputs used for form factors (together with exp data)

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



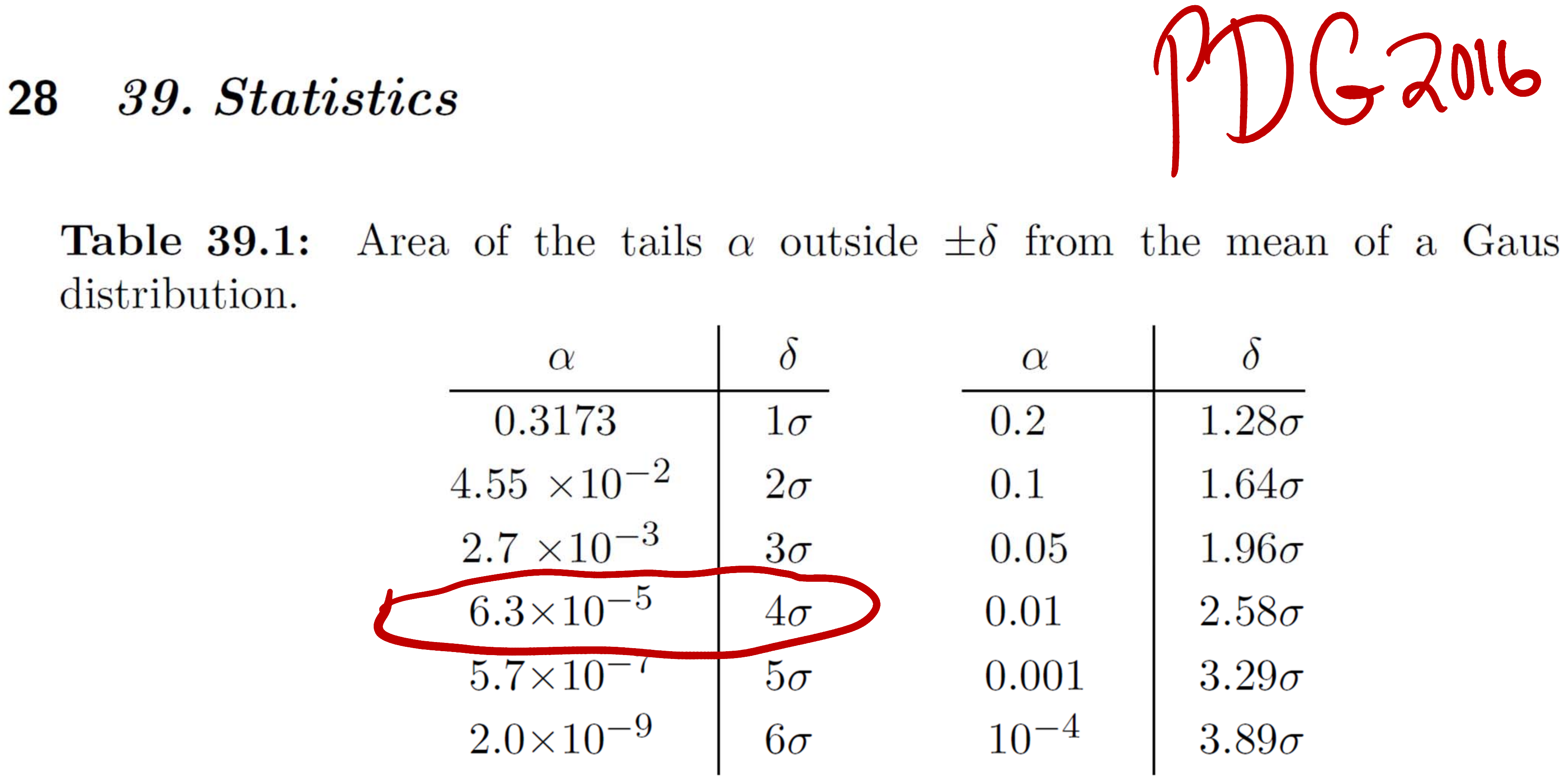
$B_s \to D_s l \nu$

$B_s \to K l \nu$

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 $B_s \to D_s \, l\nu, K l\nu$

$\sim$ 2 months.



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

Status of R(D$^{(*)}$) results

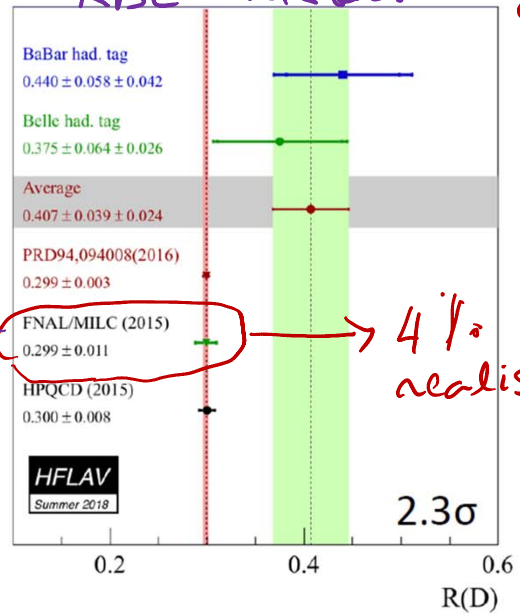
A

R_D Theory much cleaner but QED radiative corr needed.

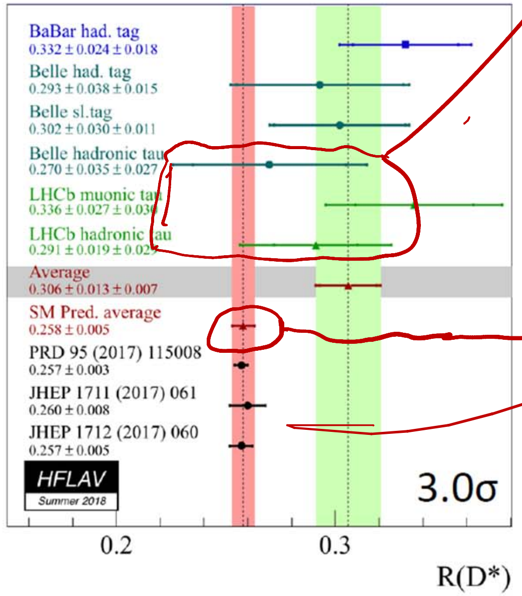
More expt effort on R_D needed

POTENTIALLY VERY SERIOUS EXPTAL PROBLEM

also WITZEL et al RBC – UKQCD

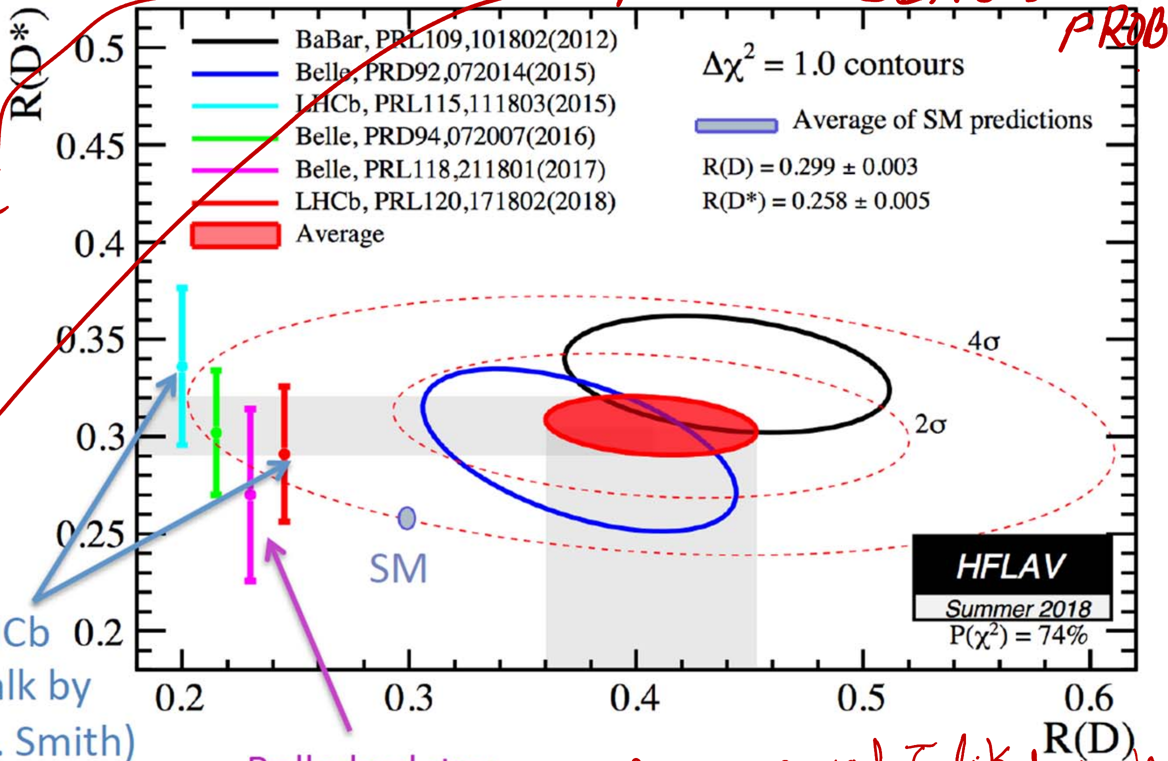


4% realistic



Serious

Likely also affects V_{cb}



LHCb (talk by M. Smith)

Belle had. tag (τ polarization)

also on recoil τ likely problem

note ↑ Theory errors Because D^* has spin B

Deviation from SM prediction: 3.9 σ

v Likely OVERESTIMATE

Concerns on SM-theory

- Good news is that lattice[FERMIL-MILC] study largely confirms pheno calculations for RD but with somewhat larger [~4%] errors; our RBC-UKQCD finalize very soon.

- 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

- 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.

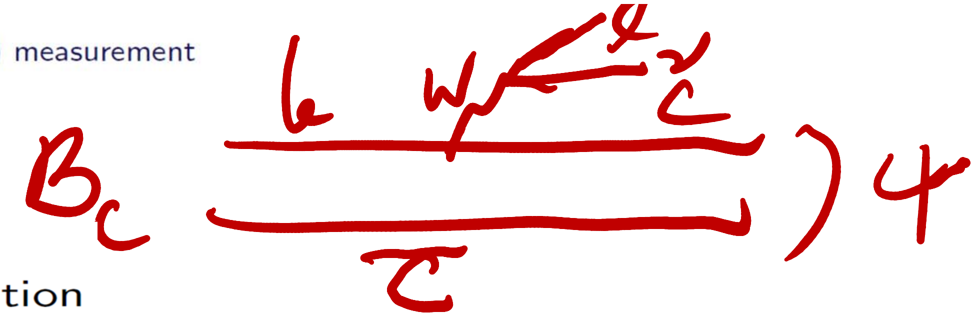
small

- These theory errors on RD* are likely to be too aggressive as D* is spin-one and proper quantum –mechanical [coherent] treatment requires production and decay vertices cannot be factorized

Comments/Reservations pros & cons on Expts p1 of 2

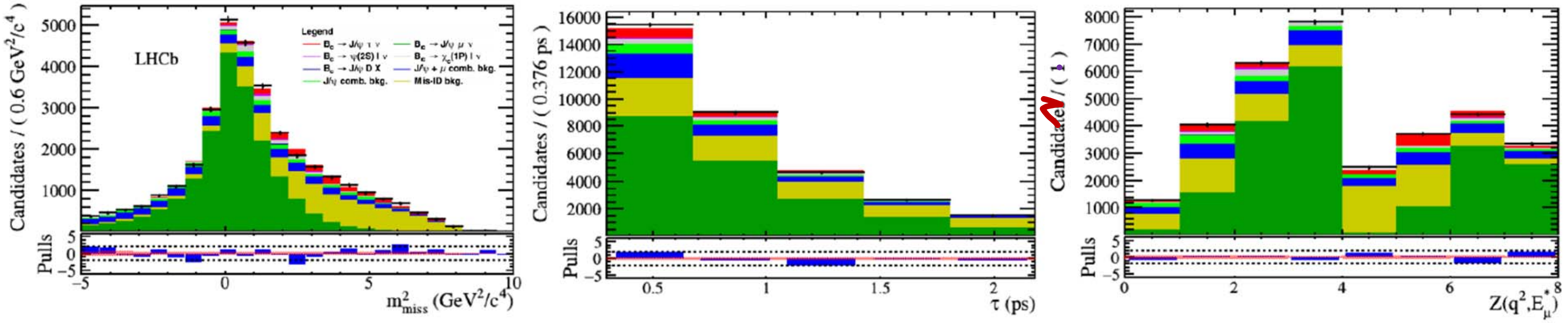
- For RD(*), B=> D(*) τ ν; most experimental results are with τ => μ ν ν ….i.e 2 ν's …..so D** potential contamination is a serious problem, in my view, as I have been stressing for past few years
- These D** et al BGs cannot be reliably estimated by using GISW etc models. They should be measured
- It 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.

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



zPW Jan 2018

Greg Ciezarek,
on behalf of the LHCb collaboration



c ALSO MARK SMITH eFPP 2018

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

REMAINL ISSues
PRIMARILY EXPTAL
1.Stat 2.D^{**} 3.$\tau \to$ hcd $+ 2\nu$

SM $R_\psi \sim$ .265+.015
QUITE ROBUST! ESSENTIALLY A NR Bound State

Lepton universality tests

LHCb introduced such v well defined ratios

- In the SM, ratios

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

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

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

Lepton Flavour Universality

Arantza Oyanguren

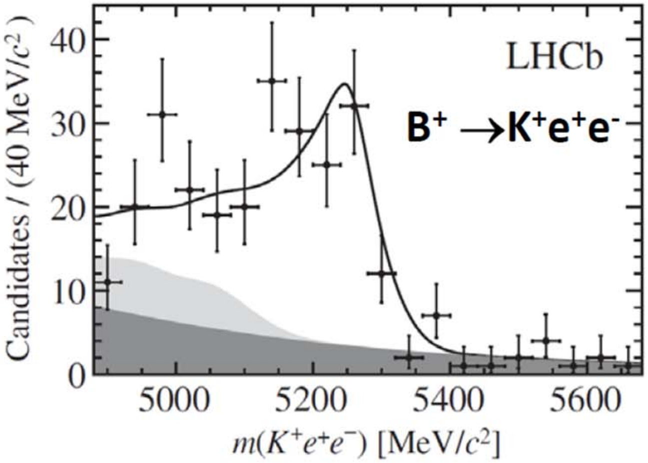
- In the SM all leptons are expected to behave in the sa

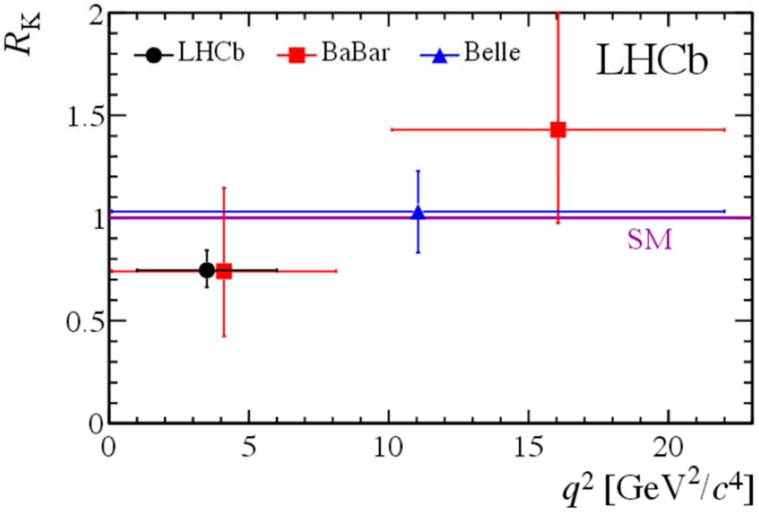
$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} = 1.000 + O(m_\mu^2/m_b^2) \ \text{(SM)}$$

[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

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

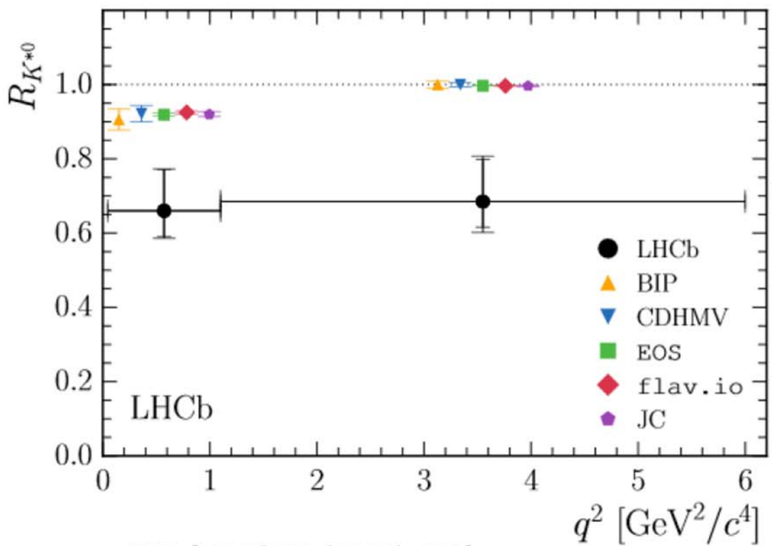
→ Consistent, but lower, than the SM at **2.6σ**

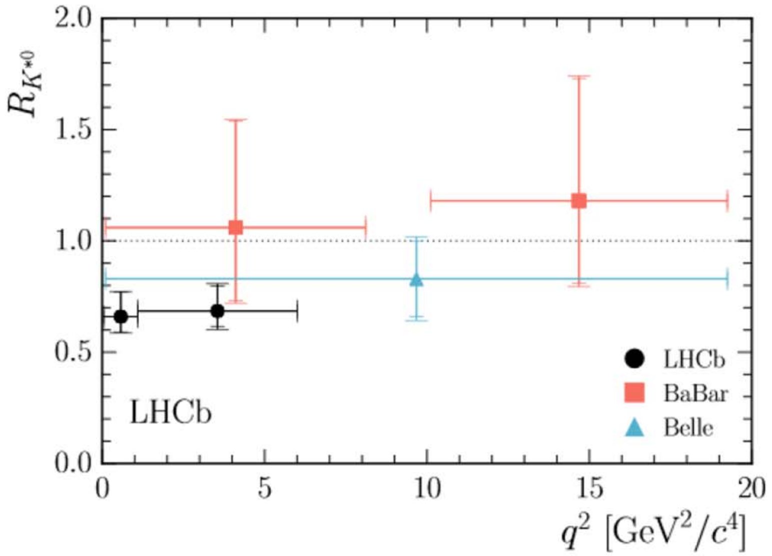
Arantza Oyanguren

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]

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

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

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

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

concern over low energy bin: G. Hou*

→ 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

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,**

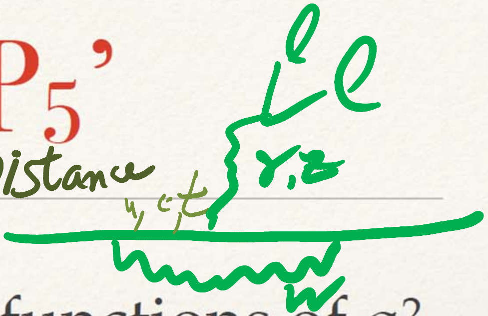
B-baryon decays should show it

- **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 maylikely have more sensitivity for them**
- **OTOH, LHCB will have Bs and B-baryons with more data**

B-flavor anomalies: P5’

REMAIN CONCERNED ABOUT NON-local contributions

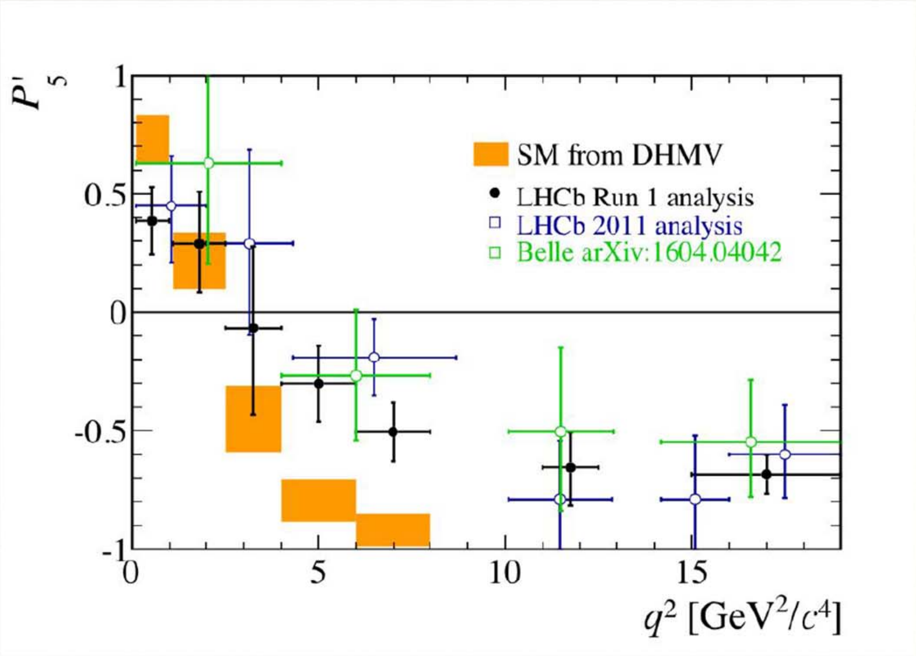
DOMINANT LONG Distance Contamination due to charm

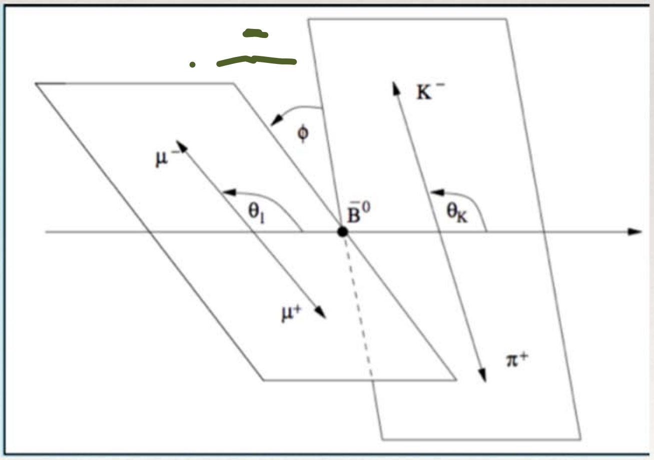


- Several angular observables measured as functions of q^2

Lattice Efforts are underway to attack this LD issues But will take time (Later

- Some, like P_5', are optimized to be insensitive to hadronic uncertainties: [Descotes-Genon, Matias, Ramon, Virto: 1207.2753]





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

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

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 $R^{\text{central}}_{K^*}$. This

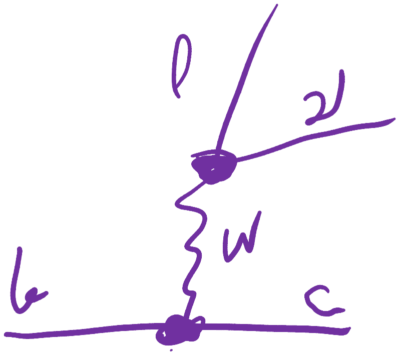
R_ϕ from LHCb would be very useful

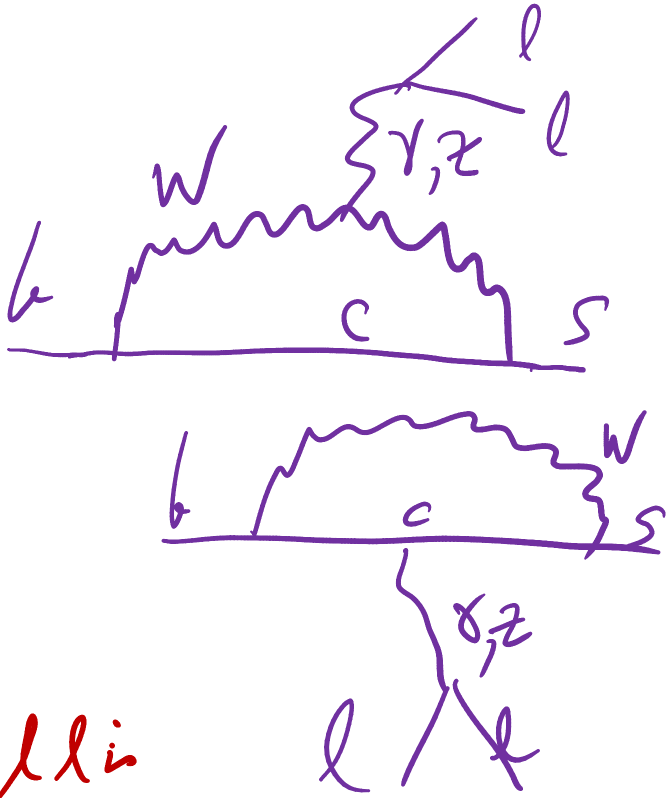
Comments on Theory

- For RD and RD*, non-lattice pheno efforts are on good, theo. grounds based on HQS but sym breaking is always difficult to reliably ascertain.
- This is why precise lattice results esp for B=>D* are needed.
- 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) as well as R's for baryonic modes.

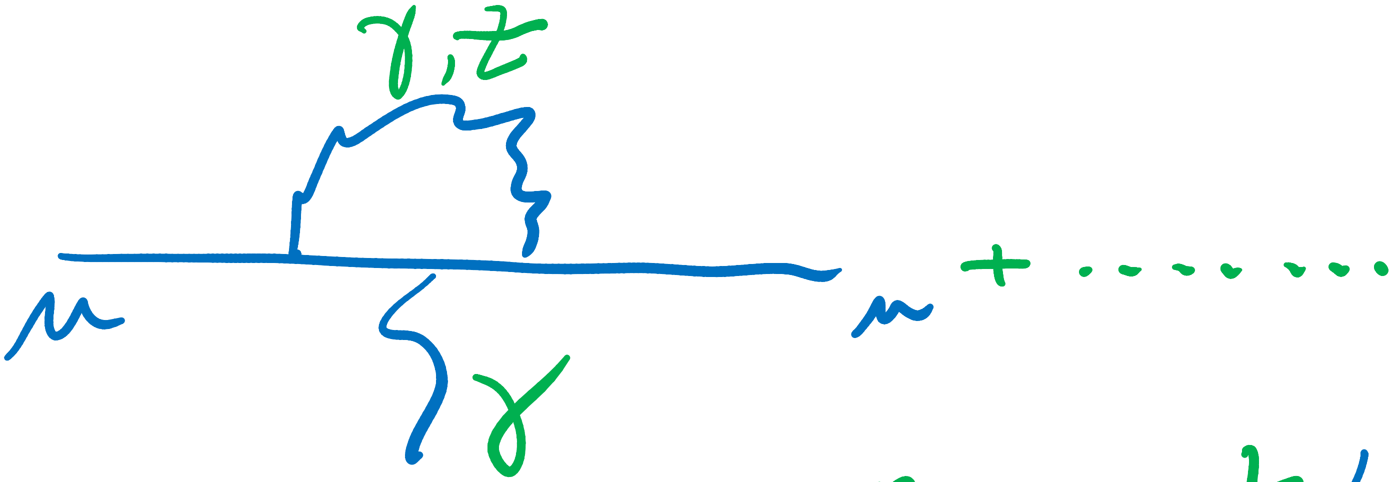
RD(*) => RK(*)





If LUV in charge current is due $W l \nu$ vertex then its highly plausible that $Z l l$ is also affected.

NOW FEW WORDS ON MUON G-2

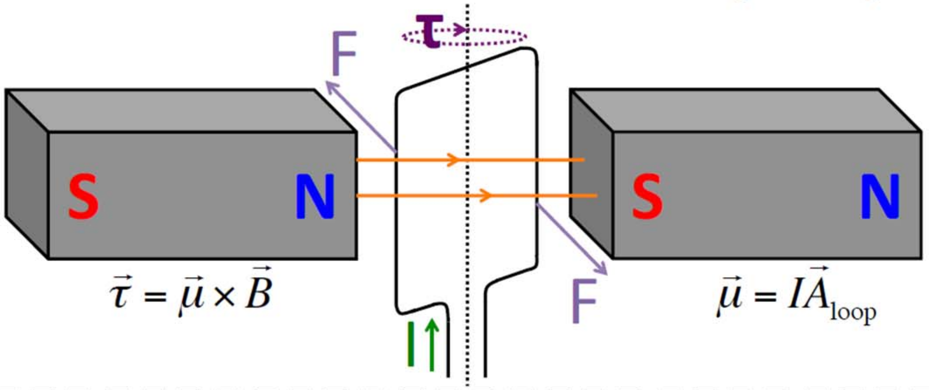


BNL expt '06

$\sim 3.5\sigma$ deviation

Magnetic dipole moments lead to spin precession.

Classical Picture



$\vec{\tau} = \vec{\mu} \times \vec{B}$

$\vec{\mu} = I\vec{A}_{\text{loop}}$

Quantum Picture

g-factor:

$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s}$$

Dirac Equation for EM potential:

$$\left[i\gamma^{\mu}\left(\partial_{\mu} + ieA_{\mu}\right) - m\right]\psi = 0$$

- **Spin-1/2 point particles**
- **Leads to Pauli Theory**
- **Predicts g = 2**

Larmor Precession (particle rest frame):

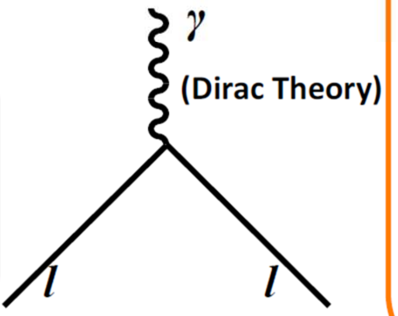
$$\frac{d\vec{s}}{dt} = \vec{\tau} = g\left(\frac{q}{2m}\right)\vec{s} \times \vec{B}$$

Quantum Field Theory Picture

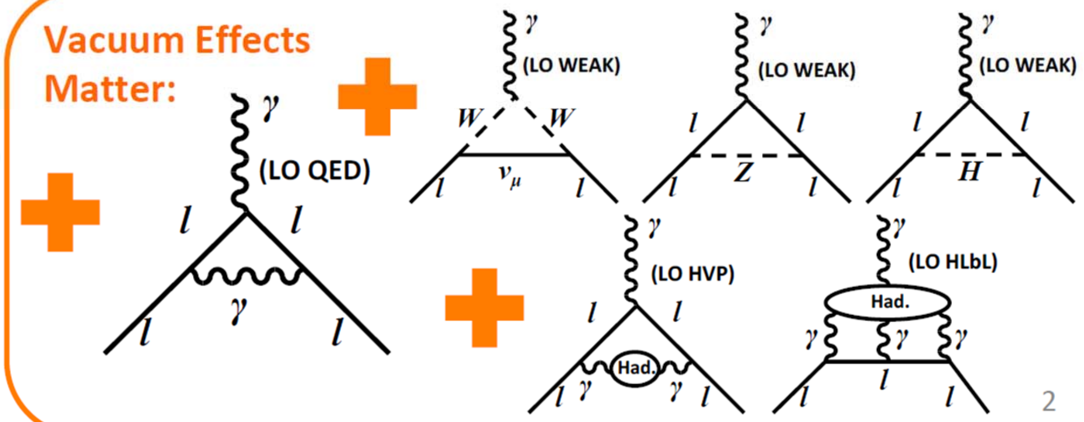
Anomaly:

$$a \equiv \frac{g-2}{2}$$

- **Predicts g ≠ 2**



Vacuum Effects Matter:



Non-perturbative QCD dominates SM muon g-2 uncertainty.

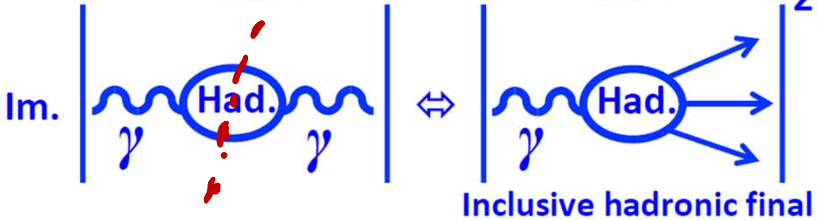
[1]

Contribution	a_μ [$\times 10^{-11}$]	δa_μ [$\times 10^{-11}$]
QED incl. 4-loops + 5-loops	116 584 718.86	0.03
hadronic LO VP	6 894.6	32.5
hadronic LbL	103.4	28.8
Hadronic HO VP	-87.0	0.6
Weak to 2-loops	153.6	1.1
Theory	116 591 783	43
Experiment	116 592 091	63
The. – Exp. (4.0σ difference)	-306	76

Largest source of SM error

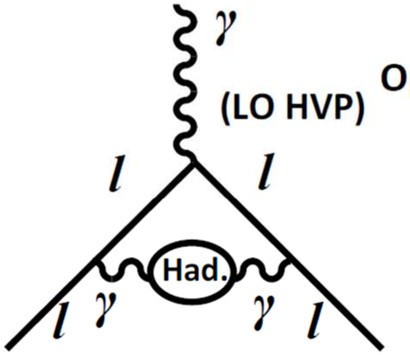
Optical Theorem

$\mathrm{Im}\,\Pi_{\mathrm{had}}(q^2)$ ~ $\sigma_{\mathrm{had}}(q^2)$



Inclusive hadronic final state cross section

$$a_\mu^{\text{had. LO VP}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} R(s)\hat{K}(s)$$



Analyticity
&
Optical Theorem

⇔

Can obtain from data for low energies

$$R(s) = \frac{\sigma\left(e^+e^- \to \text{hadrons}\right)}{\left(4\pi\alpha^2/3s\right)}$$

$\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ at tree level

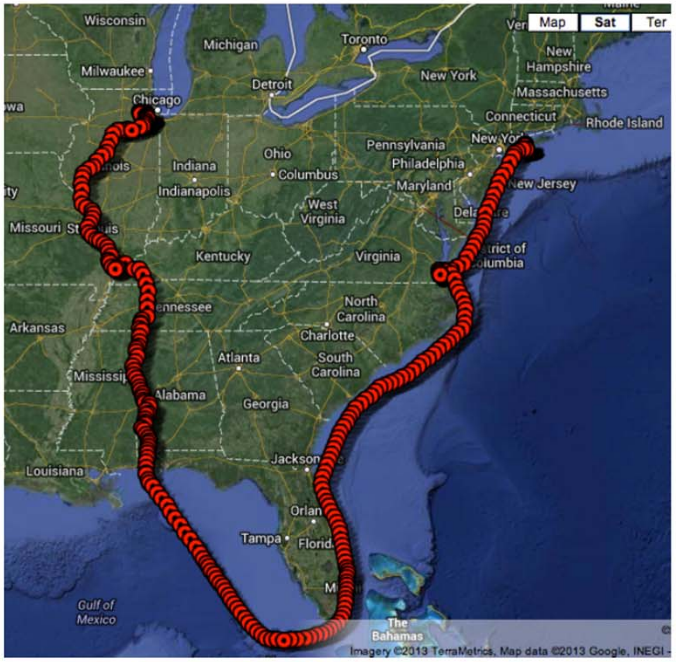
$$\hat{K}(s) = \frac{3s}{m_\mu^2}\int_0^1 dx \frac{x^2(1-x)}{x^2 + \left(s/m_\mu^2\right)(1-x)}$$

Amplifies low energy $\sigma(e^+e^- \rightarrow \text{hadrons})$

[1] F. Jegerlehner, arXiv:1804.07409 [hep-ph].

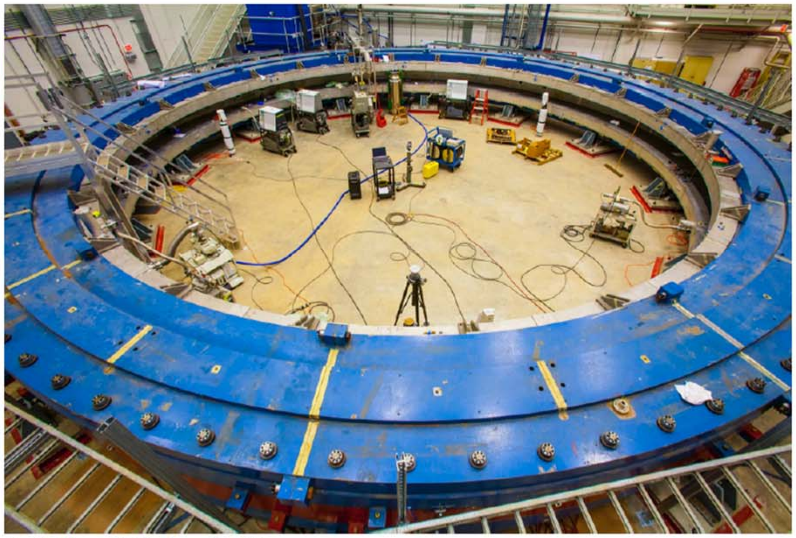
BNL muon storage ring was moved to Fermilab.

[1]



[2]

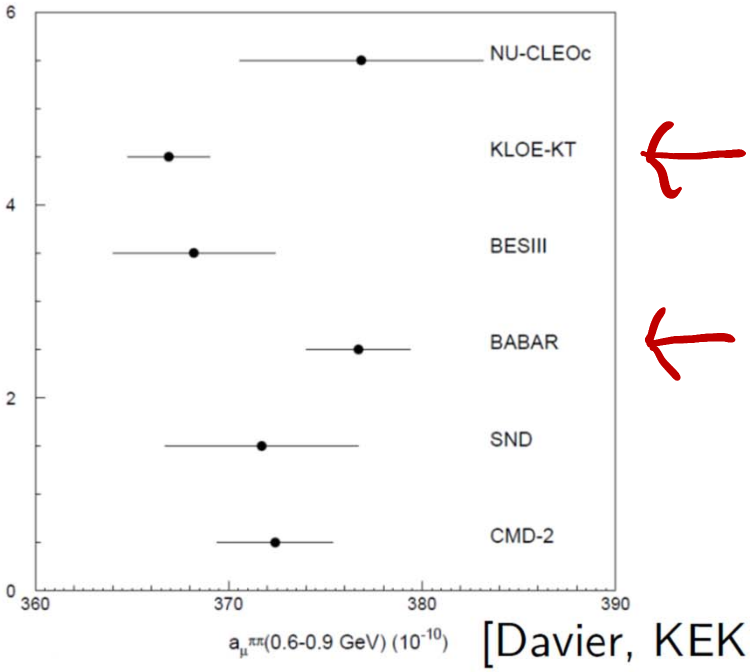
[2]



[2]

[1] C. Polly, GM2-doc-4096
[2] C. Polly and E. Swanson, GM2-doc-4284

Tensions in Experiment



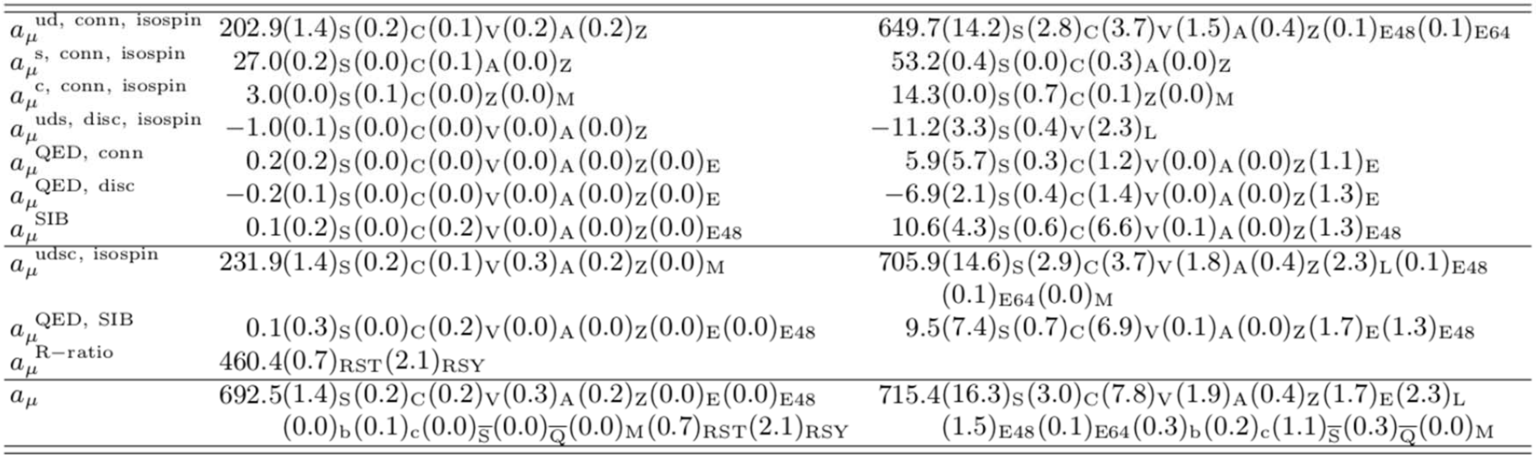
[Davier, KEK (2018)]

R-ratio data for $ee \to \pi\pi$ exclusive channel, $\sqrt{s} = 0.6 - 0.9\ \mathrm{GeV}$ region
Significant tension between KLOE and BABAR
Other experiments not precise enough to favor either

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

Error Budget

RBC-UKQCD, PRL 2018



$a_\mu^{\mathrm{ud,\ conn,\ isospin}}$	$202.9(1.4)_\mathrm{S}(0.2)_\mathrm{C}(0.1)_\mathrm{V}(0.2)_\mathrm{A}(0.2)_\mathrm{Z}$	$649.7(14.2)_\mathrm{S}(2.8)_\mathrm{C}(3.7)_\mathrm{V}(1.5)_\mathrm{A}(0.4)_\mathrm{Z}(0.1)_\mathrm{E48}(0.1)_\mathrm{E64}$
$a_\mu^{\mathrm{s,\ conn,\ isospin}}$	$27.0(0.2)_\mathrm{S}(0.0)_\mathrm{C}(0.1)_\mathrm{A}(0.0)_\mathrm{Z}$	$53.2(0.4)_\mathrm{S}(0.0)_\mathrm{C}(0.3)_\mathrm{A}(0.0)_\mathrm{Z}$
$a_\mu^{\mathrm{c,\ conn,\ isospin}}$	$3.0(0.0)_\mathrm{S}(0.1)_\mathrm{C}(0.0)_\mathrm{Z}(0.0)_\mathrm{M}$	$14.3(0.0)_\mathrm{S}(0.7)_\mathrm{C}(0.1)_\mathrm{Z}(0.0)_\mathrm{M}$
$a_\mu^{\mathrm{uds,\ disc,\ isospin}}$	$-1.0(0.1)_\mathrm{S}(0.0)_\mathrm{C}(0.0)_\mathrm{V}(0.0)_\mathrm{A}(0.0)_\mathrm{Z}$	$-11.2(3.3)_\mathrm{S}(0.4)_\mathrm{V}(2.3)_\mathrm{L}$
$a_\mu^{\mathrm{QED,\ conn}}$	$0.2(0.2)_\mathrm{S}(0.0)_\mathrm{C}(0.0)_\mathrm{V}(0.0)_\mathrm{A}(0.0)_\mathrm{Z}(0.0)_\mathrm{E}$	$5.9(5.7)_\mathrm{S}(0.3)_\mathrm{C}(1.2)_\mathrm{V}(0.0)_\mathrm{A}(0.0)_\mathrm{Z}(1.1)_\mathrm{E}$
$a_\mu^{\mathrm{QED,\ disc}}$	$-0.2(0.1)_\mathrm{S}(0.0)_\mathrm{C}(0.0)_\mathrm{V}(0.0)_\mathrm{A}(0.0)_\mathrm{Z}(0.0)_\mathrm{E}$	$-6.9(2.1)_\mathrm{S}(0.4)_\mathrm{C}(1.4)_\mathrm{V}(0.0)_\mathrm{A}(0.0)_\mathrm{Z}(1.3)_\mathrm{E}$
a_μ^{SIB}	$0.1(0.2)_\mathrm{S}(0.0)_\mathrm{C}(0.2)_\mathrm{V}(0.0)_\mathrm{A}(0.0)_\mathrm{Z}(0.0)_\mathrm{E48}$	$10.6(4.3)_\mathrm{S}(0.6)_\mathrm{C}(6.6)_\mathrm{V}(0.1)_\mathrm{A}(0.0)_\mathrm{Z}(1.3)_\mathrm{E48}$
$a_\mu^{\mathrm{udsc,\ isospin}}$	$231.9(1.4)_\mathrm{S}(0.2)_\mathrm{C}(0.1)_\mathrm{V}(0.3)_\mathrm{A}(0.2)_\mathrm{Z}(0.0)_\mathrm{M}$	$705.9(14.6)_\mathrm{S}(2.9)_\mathrm{C}(3.7)_\mathrm{V}(1.8)_\mathrm{A}(0.4)_\mathrm{Z}(2.3)_\mathrm{L}(0.1)_\mathrm{E48}$ $(0.1)_\mathrm{E64}(0.0)_\mathrm{M}$
$a_\mu^{\mathrm{QED,\ SIB}}$	$0.1(0.3)_\mathrm{S}(0.0)_\mathrm{C}(0.2)_\mathrm{V}(0.0)_\mathrm{A}(0.0)_\mathrm{Z}(0.0)_\mathrm{E}(0.0)_\mathrm{E48}$	$9.5(7.4)_\mathrm{S}(0.7)_\mathrm{C}(6.9)_\mathrm{V}(0.1)_\mathrm{A}(0.0)_\mathrm{Z}(1.7)_\mathrm{E}(1.3)_\mathrm{E48}$
$a_\mu^{\mathrm{R-ratio}}$	$460.4(0.7)_\mathrm{RST}(2.1)_\mathrm{RSY}$	
a_μ	$692.5(1.4)_\mathrm{S}(0.2)_\mathrm{C}(0.2)_\mathrm{V}(0.3)_\mathrm{A}(0.2)_\mathrm{Z}(0.0)_\mathrm{E}(0.0)_\mathrm{E48}$ $(0.0)_\mathrm{b}(0.1)_\mathrm{c}(0.0)_{\overline{\mathrm{S}}}(0.0)_{\overline{\mathrm{Q}}}(0.0)_\mathrm{M}(0.7)_\mathrm{RST}(2.1)_\mathrm{RSY}$	$715.4(16.3)_\mathrm{S}(3.0)_\mathrm{C}(7.8)_\mathrm{V}(1.9)_\mathrm{A}(0.4)_\mathrm{Z}(1.7)_\mathrm{E}(2.3)_\mathrm{L}$ $(1.5)_\mathrm{E48}(0.1)_\mathrm{E64}(0.3)_\mathrm{b}(0.2)_\mathrm{c}(1.1)_{\overline{\mathrm{S}}}(0.3)_{\overline{\mathrm{Q}}}(0.0)_\mathrm{M}$

TABLE I. Individual and summed contributions to a_μ multiplied by 10^{10}. The left column lists results for the window method with $t_0 = 0.4$ fm and $t_1 = 1$ fm. The right column shows results for the pure first-principles lattice calculation. The respective uncertainties are defined in the main text.

[Blum *et al.*, (2018)]

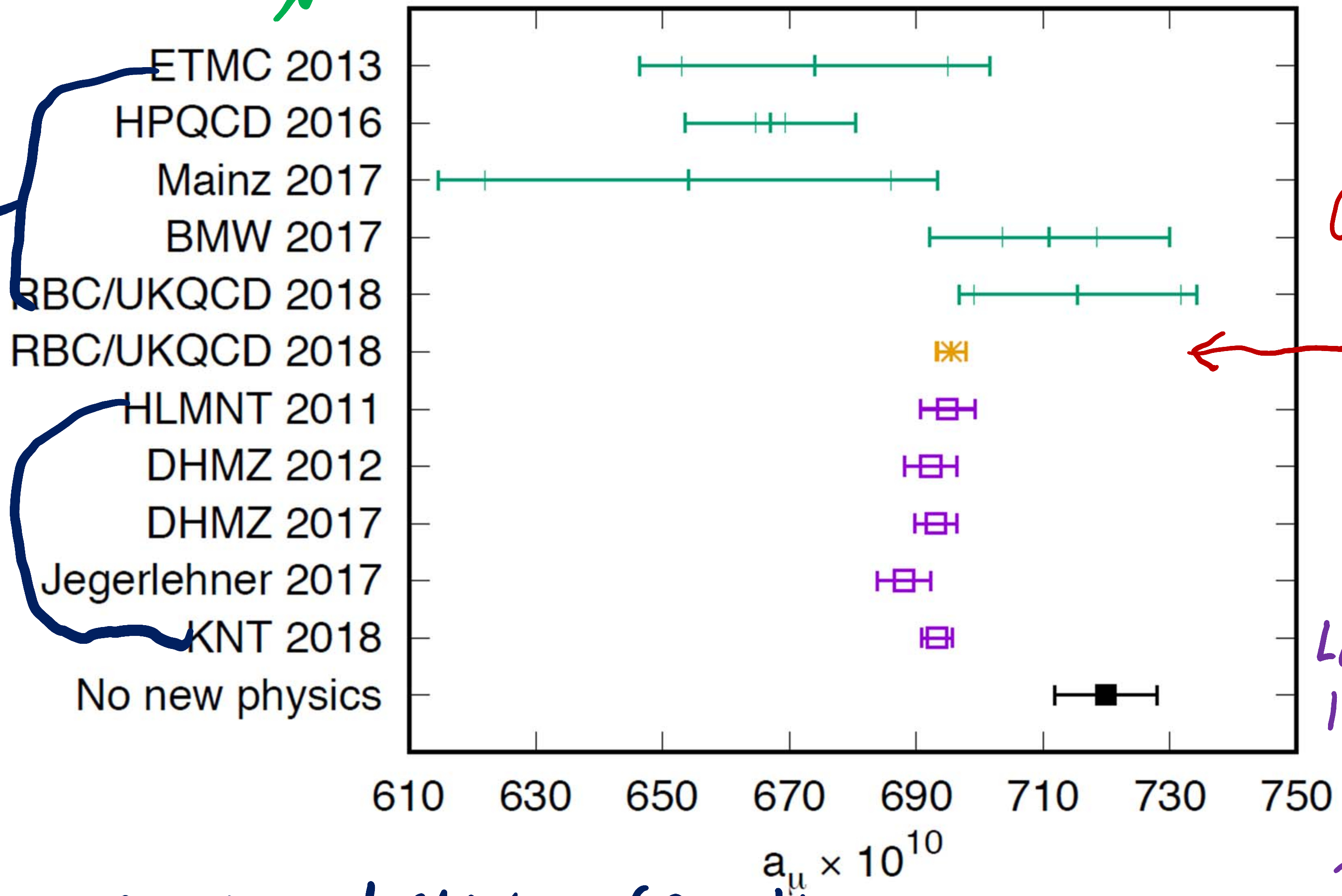
Full program of computations to improve total uncertainties:

- Reduce statistical uncertainties on light connected contribution
- Compute QED contributions
- Improve lattice spacing determination
- Finite volume and continuum extrapolation study

$(g-2)_\mu$ 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.

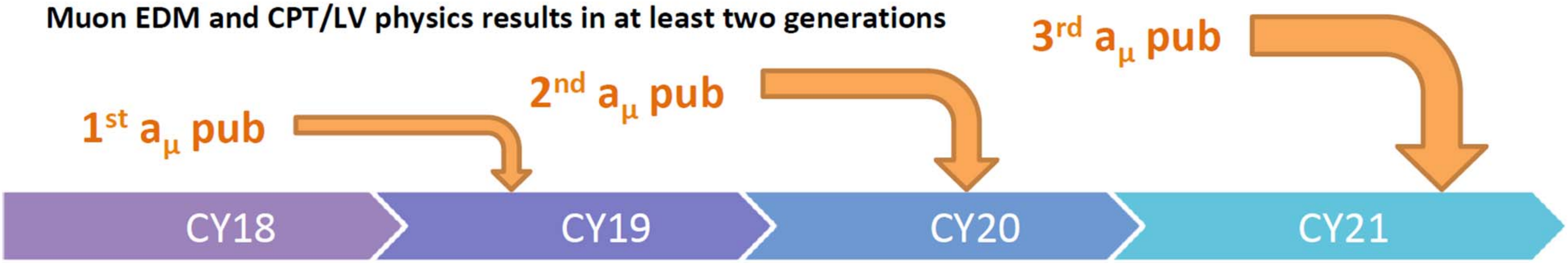
Lunch Seminar 03/09/18

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**

Fermilab Muon g-2 Experiment publication plan:

- 3 generations of a_μ publications
  - ~2 × BNL data (~400 ppb) collected in FY18 with 2019 publication goal
  - 5-10 × BNL data (~200 ppb) collected over FY18+FY19 with 2020 publication goal … caveat that we now enter unknown regime
  - 20+ × BNL data (~140 ppb) collected by end of FY20 with 2021 final publications goal
- Muon EDM and CPT/LV physics results in at least two generations



1st a_μ pub

2nd a_μ pub

3rd a_μ pub

CY18

CY19

CY20

CY21

2 caveats to publications plan:

- BNL publications lagged 2-3 years behind acquiring data
  - Understanding systematics and fixing for next run take priority
  - However, we benefit from BNL experience and analysis tools much more advanced
- Likely 2020 running will be required to complete μ^+ statistics

Fermilab Accelerator Experiments' Run Schedule

		FY 2017	FY 2018	FY 2019	FY 2020	
NuMI	MI	MINERvA	MINERvA	MINERvA ?	OPEN	ν
		NOvA	NOvA	NOvA	NOvA	
BNB	B	MicroBooNE	MicroBooNE ?	SBN: MicroBooNE	SBN: MicroBooNE	
		SBN: ICARUS	SBN: ICARUS	SBN: ICARUS SBN:ICARUS	SBN: ICARUS	
		SBN: SBND	SBN: SBND	SBN: SBND	SBN: SBND	
Muon Campus		g-2	g-2	g-2	OPEN	μ
		Mu2e	Mu2e	Mu2e	Mu2e	
SY 120	MT	FTBF - MTEST	FTBF - MTEST	FTBF - MTEST	FTBF - MTEST	p
	MC	OPEN LArIAT	FTBF - MC	FTBF - MC	FTBF - MC	
	NM4	SeaQuest	OPEN	OPEN	OPEN	

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

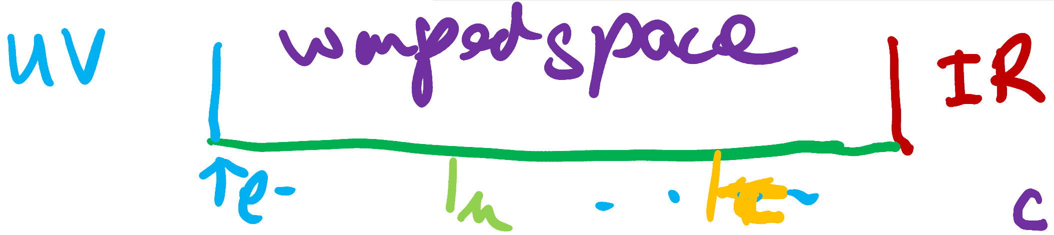
Constraints on lepton-flavor violating and conserving processes. For the last four observables, the experimental null results are given in terms of a dimension-6 operator, suppressed by two orders of Λ, which can be interpreted as the nominal scale of new physics.

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]

Kile, Kobach +AS
PRD2015
$\Downarrow$
Speculation

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

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



c ALSO A. IYER & LYON

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***

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

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

SM

BSM

DIM 6 OPS

"V" ←

"S" ←

$$\mathcal{O}_{V_{R,L}} = (\bar{c}\gamma^\mu P_{R,L} b)(\bar{\tau}\gamma_\mu P_L \nu) \qquad (5)$$

$$\mathcal{O}_{S_{R,L}} = (\bar{c} P_{R,L} b)(\bar{\tau} P_L \nu)\,, \qquad (6)$$

$$\mathcal{O}_T = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu)\,. \qquad (7)$$

SKIP 4 NOW

Backgrounds and such

- **Anomaly implies BSM signals in pp=> b tau nu..with tau => l + nu's….FOR ATLAS, CMS!**
- **There is SM contribution too[though suppressed by Vcb~0.04] but in addition there is potentially a huge background from W+j with about ~1% misidentification of light jets as b's…At 13TeV, SM+BG (with cuts)XS=1.5pb**
- **signal XS for Vector (scalar) case for Λ/[1TeV]~ gNP~1 is about 1.1(1.8)pb @13TeV …With 300/fb may b probe to ~ 4TeV …Moreover, distinctive kinematic distributions can b exploited with say ptb >100 GeV, Mbl>200 GeV to enhance searched for higher mediator masses.** ~ 5TeV

Xsymm implications of anomalies for colliders

ADS'

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

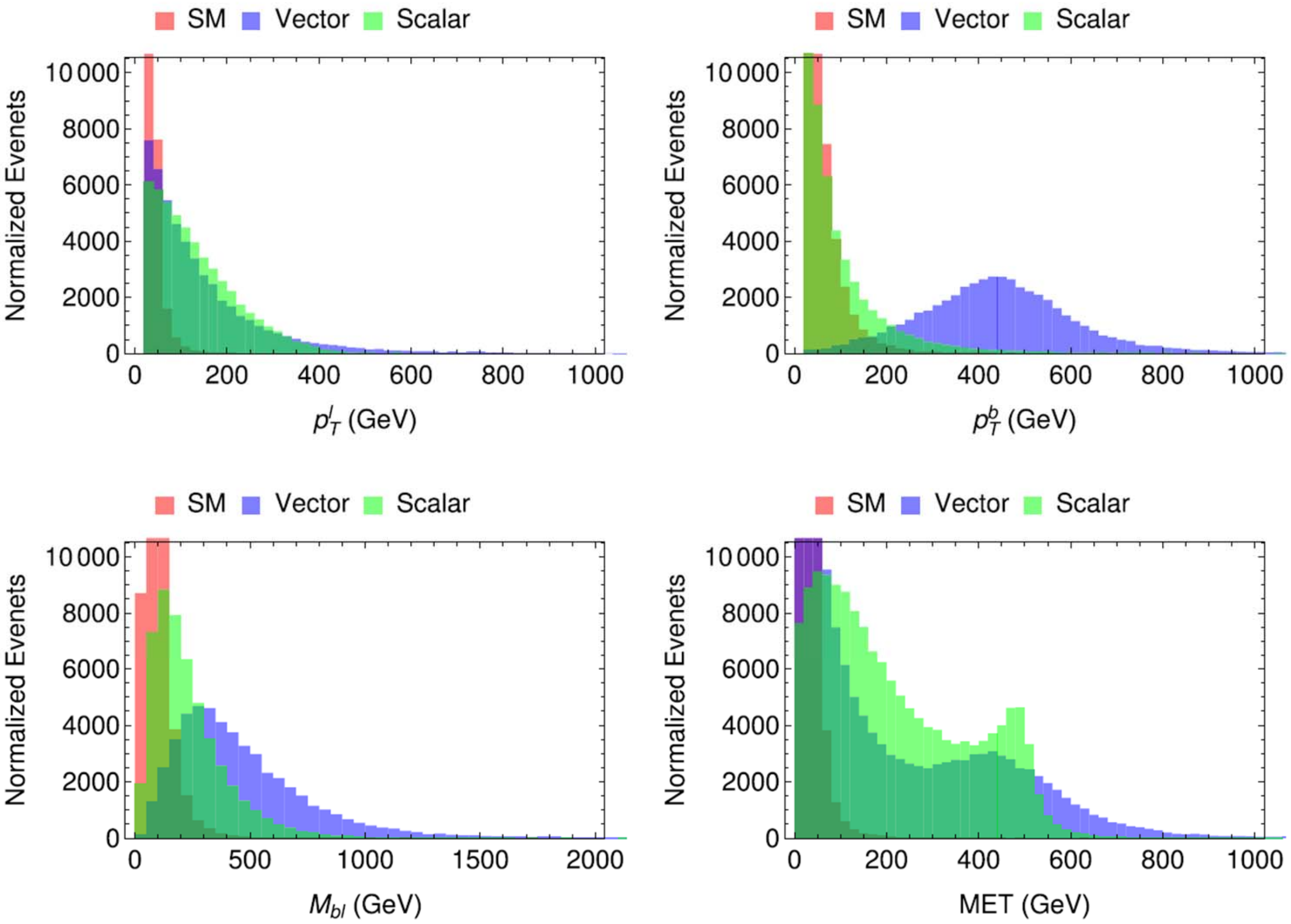


FIG. 1. Normalized kinematic distributions for the $pp \to b\tau\nu \to b\ell + \not{E}_T$ signal and background.

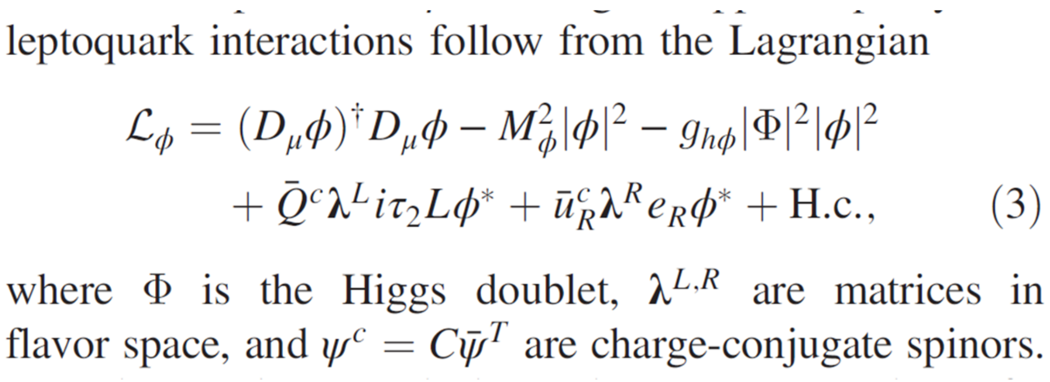
EXPECT DISTINCTIVE NP CONTRIBUTIONS IN COLLIDERS

ILLUSTRATIVE EXAMPLES OF BSMS

Minimal Leptoquark Explanation for the $R_{D^{(*)}}$, R_K, and $(g-2)_\mu$ Anomalies

Martin Bauer[1] and Matthias Neubert[2,3]

We show that by adding a single new scalar particle to the standard model, a TeV-scale leptoquark with the quantum numbers of a right-handed down quark, one can explain in a natural way three of the most striking anomalies of particle physics: the violation of lepton universality in $\bar{B} \to \bar{K}\ell^+\ell^-$ decays, the enhanced $\bar{B} \to D^{(*)}\tau\bar{\nu}$ decay rates, and the anomalous magnetic moment of the muon. Constraints from other precision measurements in the flavor sector can be satisfied without fine-tuning. Our model predicts enhanced $\bar{B} \to \bar{K}^{(*)}\nu\bar{\nu}$ decay rates and a new-physics contribution to $B_s - \bar{B}_s$ mixing close to the current central fit value.



leptoquark interactions follow from the Lagrangian

$$\mathcal{L}_\phi = (D_\mu\phi)^\dagger D_\mu\phi - M_\phi^2|\phi|^2 - g_{h\phi}|\Phi|^2|\phi|^2 + \bar{Q}^c\boldsymbol{\lambda}^L i\tau_2 L\phi^* + \bar{u}_R^c\boldsymbol{\lambda}^R e_R\phi^* + \text{H.c.}, \quad (3)$$

where Φ is the Higgs doublet, $\boldsymbol{\lambda}^{L,R}$ are matrices in flavor space, and $\psi^c = C\bar{\psi}^T$ are charge-conjugate spinors.

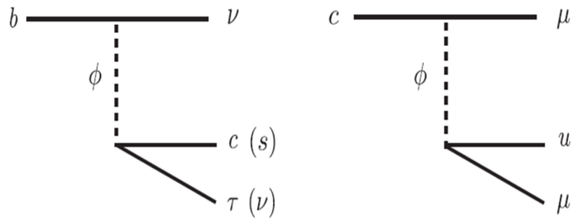


FIG. 1. Tree-level diagrams contributing to weak decays.

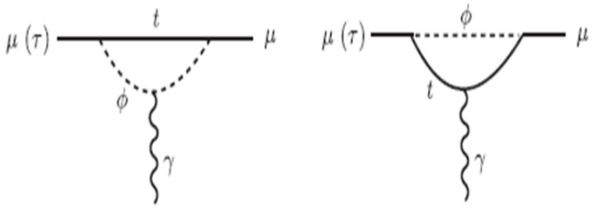
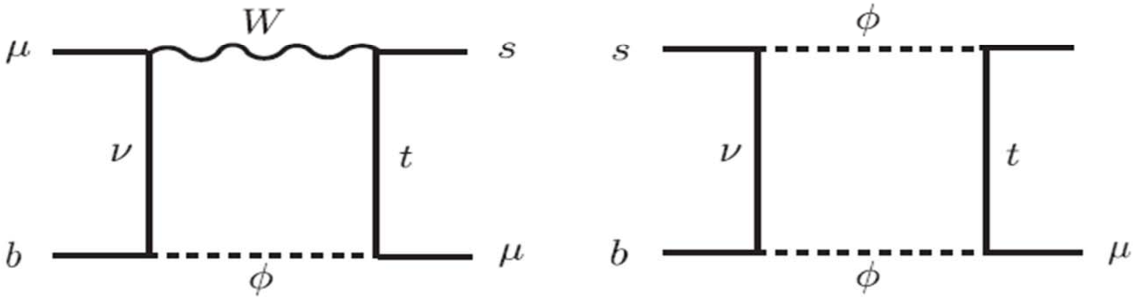


FIG. 3. Loop diagrams contributing to $(g-2)_\mu$ and $\tau \rightarrow$



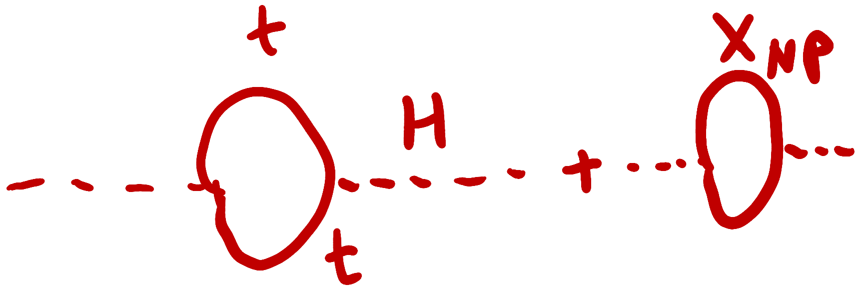
G. 2. Loop graphs contributing to $b \rightarrow s\mu^+\mu^-$ transitions.

Altmannshofer, Dev, A.S. 2017
+WIP

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**

$m_H \lesssim 126\,\text{GeV}$



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

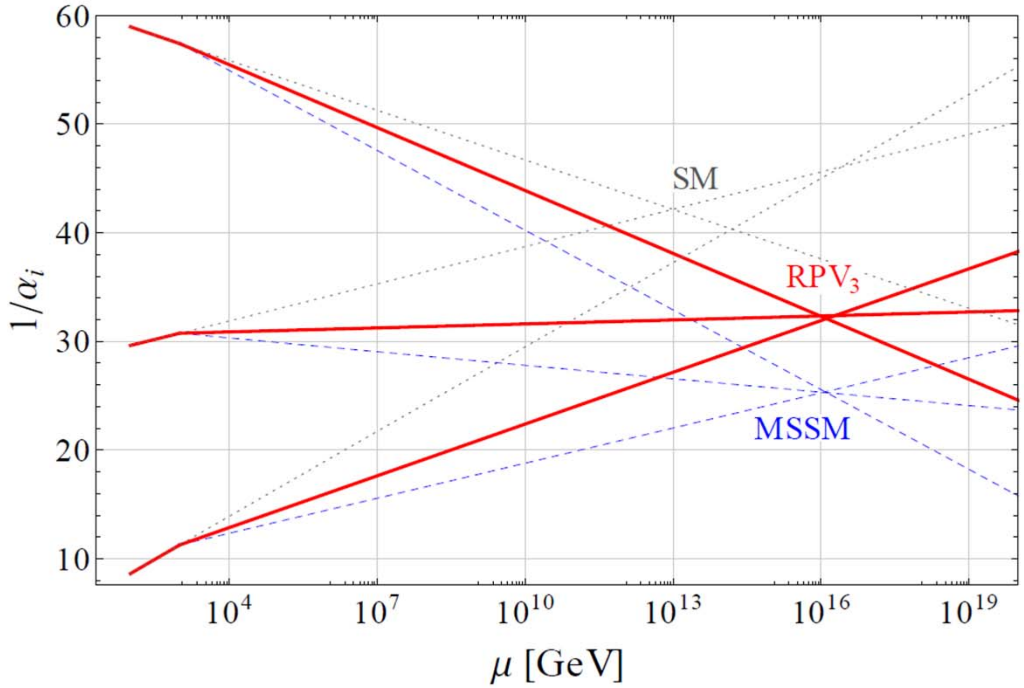


FIG. 2. RG evolution of the gauge couplings in the SM, MSSM and with partial supersymmetrization.

Unification scale ~ stays same, only value of couplings shifts

For pheno relevant terms:

ADS' PRD 2017

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

} RPV_3 interaction

Dim 6

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

For $R_{D(*)}$

NOTE:
ITS
SM-like!

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

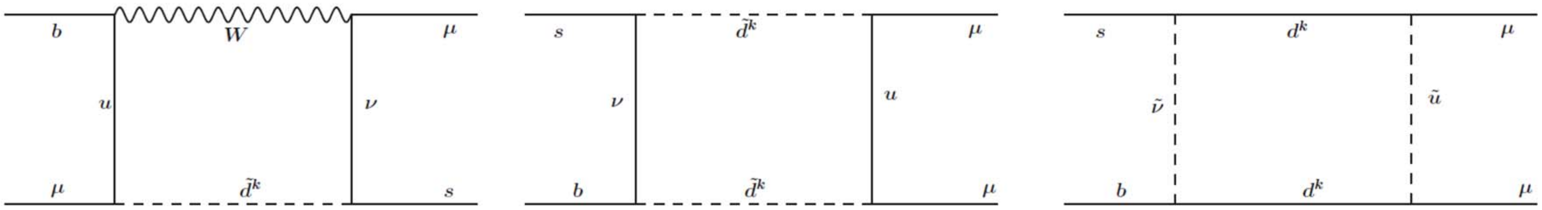


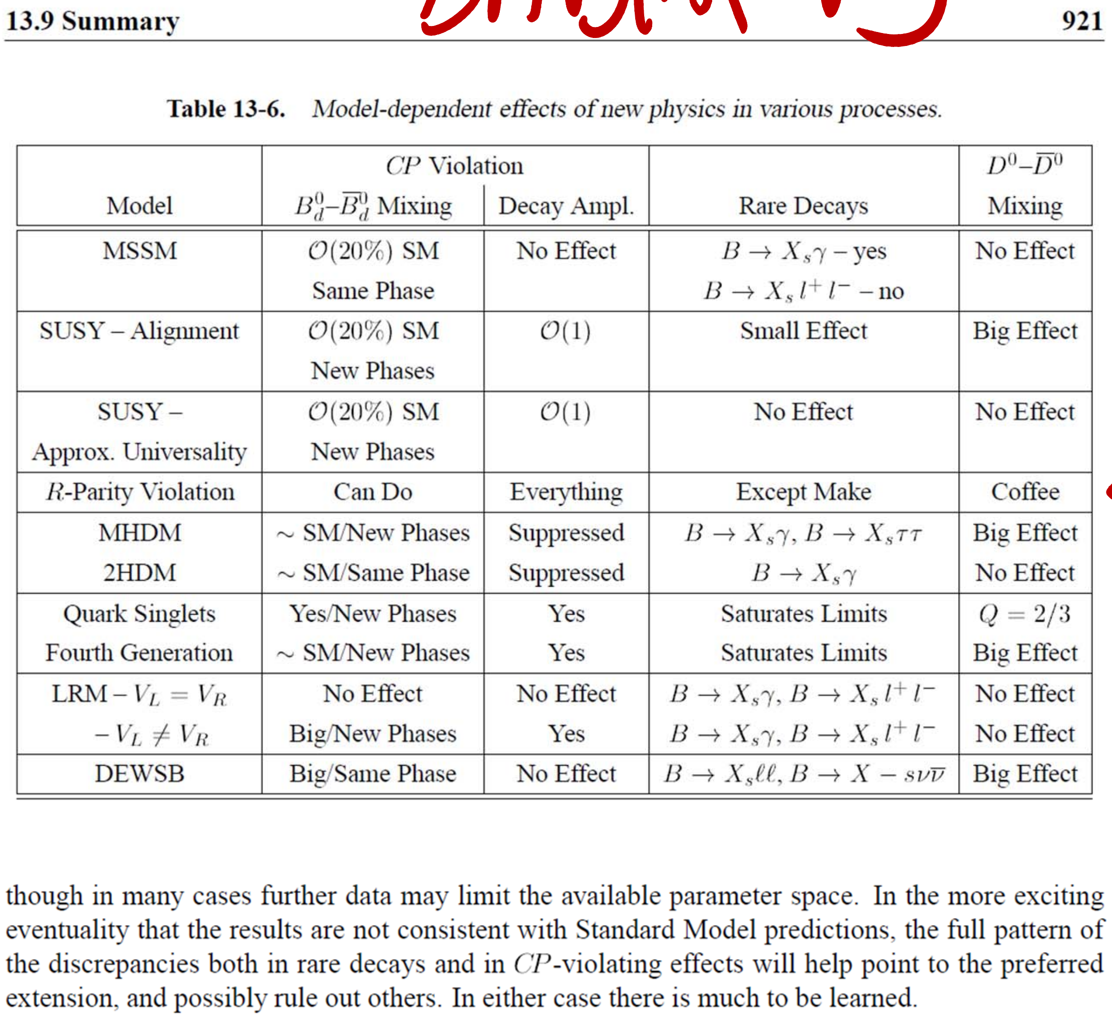
FIG. 1: Representative diagrams for $b \to s\mu^+\mu^-$ transition in R-parity violating interactions.

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

BABAR Phy Book '97



13.9 Summary 921

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

	CP Violation			D^0–$\overline{D}^0$
Model	B_d^0–$\overline{B}_d^0$ Mixing	Decay Ampl.	Rare Decays	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	~ SM/New Phases	Suppressed	$B \to X_s\gamma$, $B \to X_s\tau\tau$	Big Effect
2HDM	~ SM/Same Phase	Suppressed	$B \to X_s\gamma$	No Effect
Quark Singlets	Yes/New Phases	Yes	Saturates Limits	$Q = 2/3$
Fourth Generation	~ 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: TIGHTENING EXPT’S NOOSE AGAINST SPECIFIC MODELS

The wealth and power of the experimental data

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

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

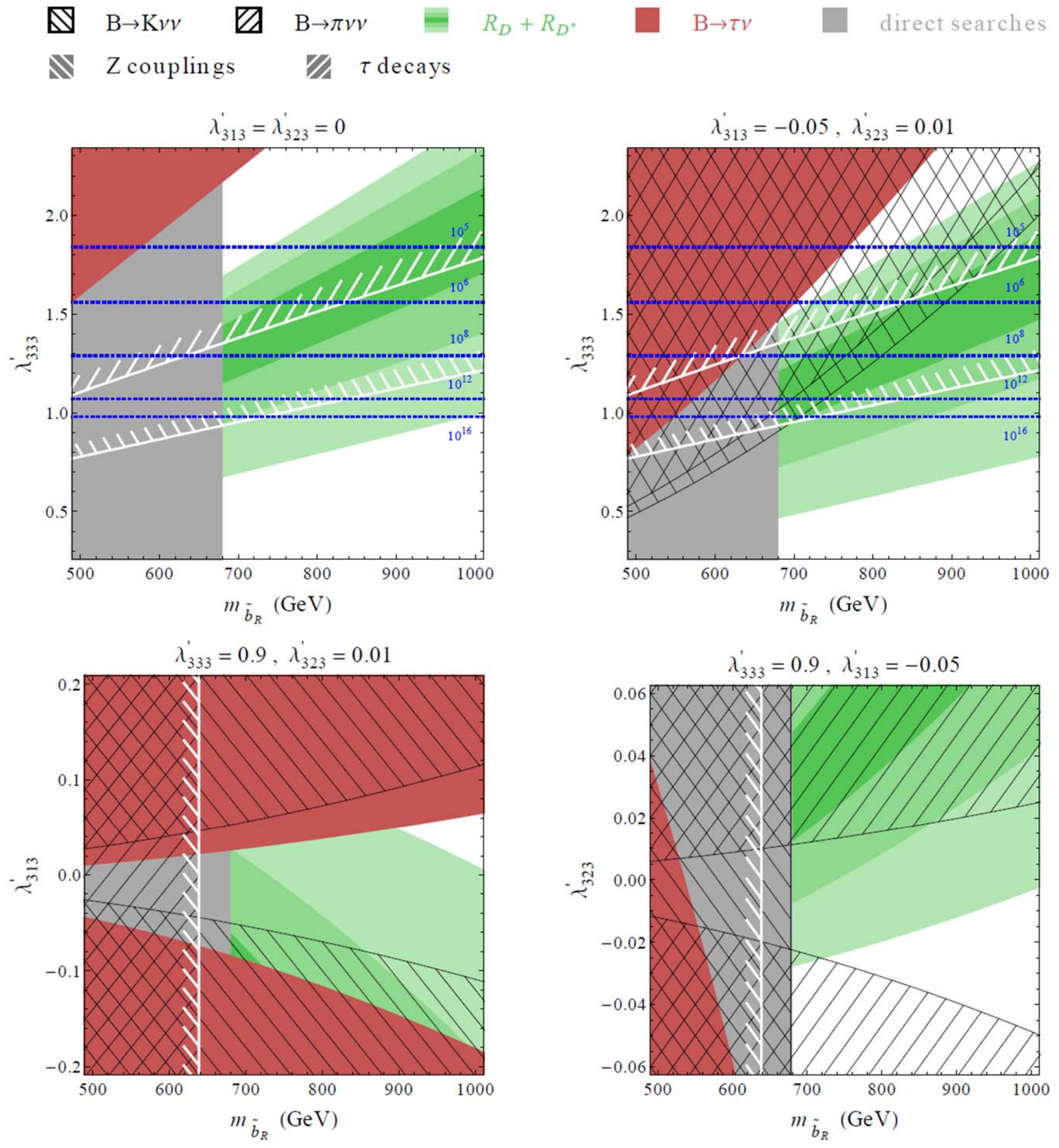
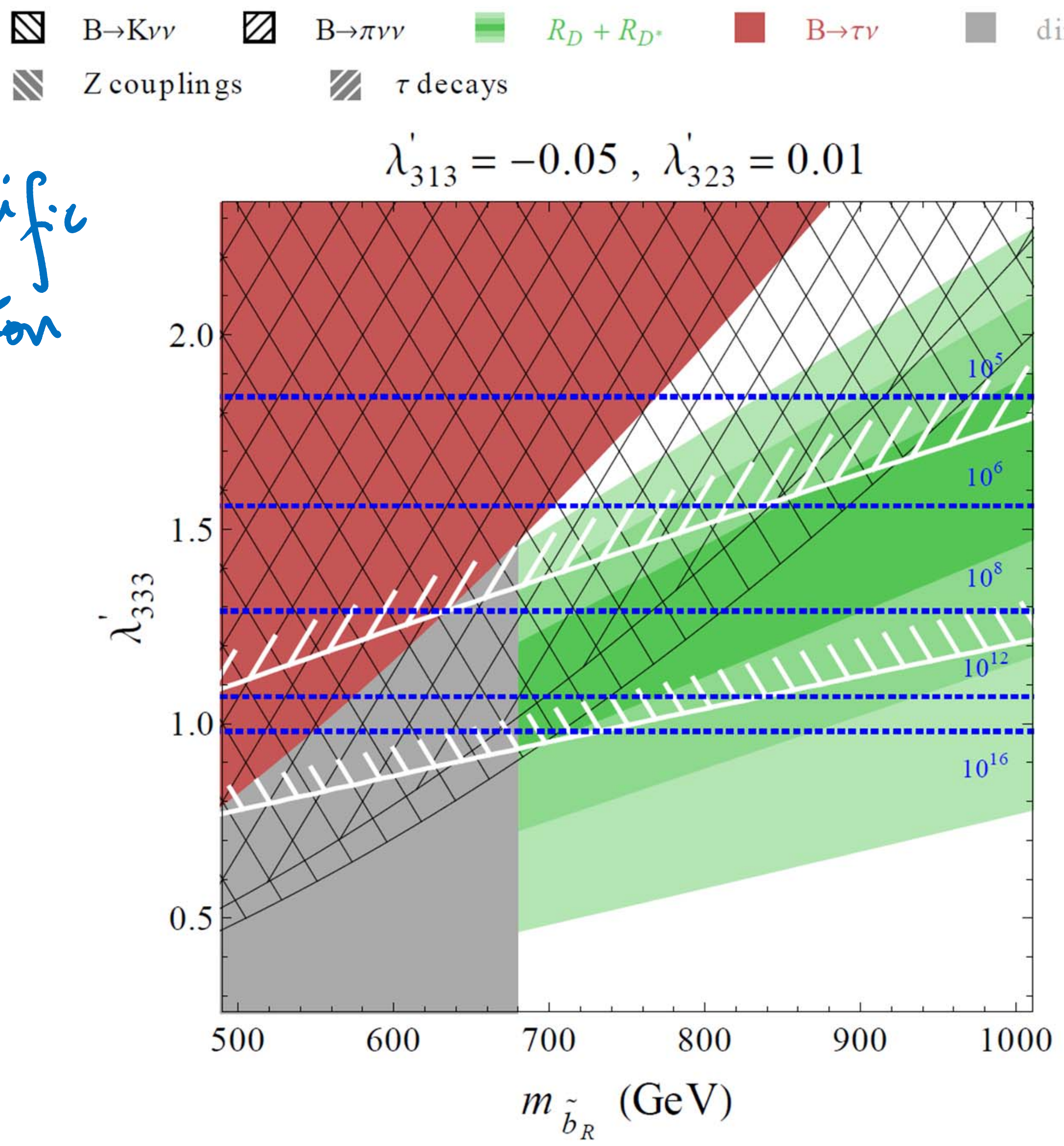


FIG. 3. RPV parameter space satisfying the $R_{D^{(*)}}$ anomaly and other relevant constraints.

As a specific illustration



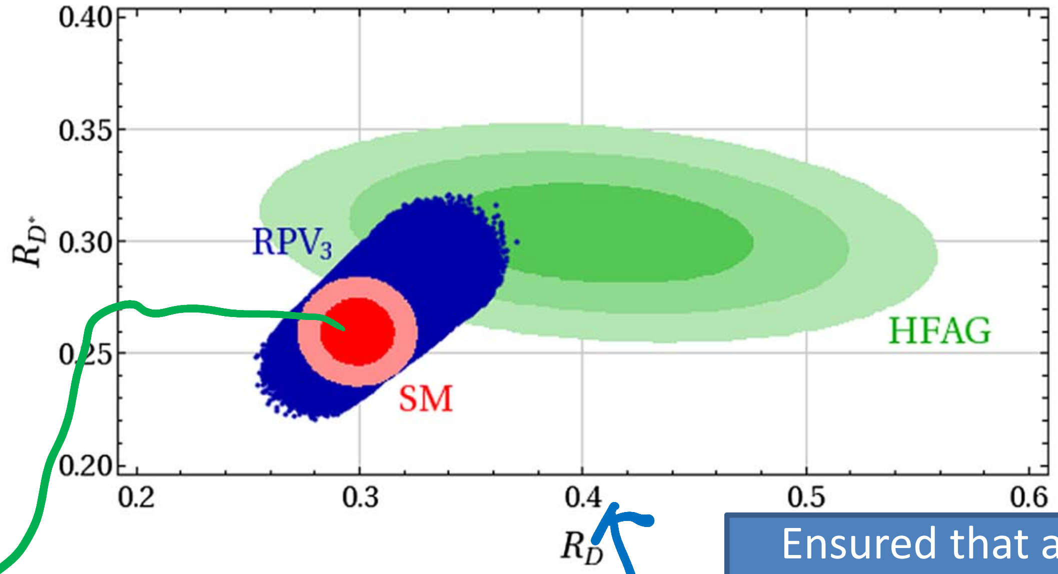
Constraints imposed

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:

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



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

Ensured that all RPV3 couplings stay perturbative up to GUT

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

More Realistic SM Blob

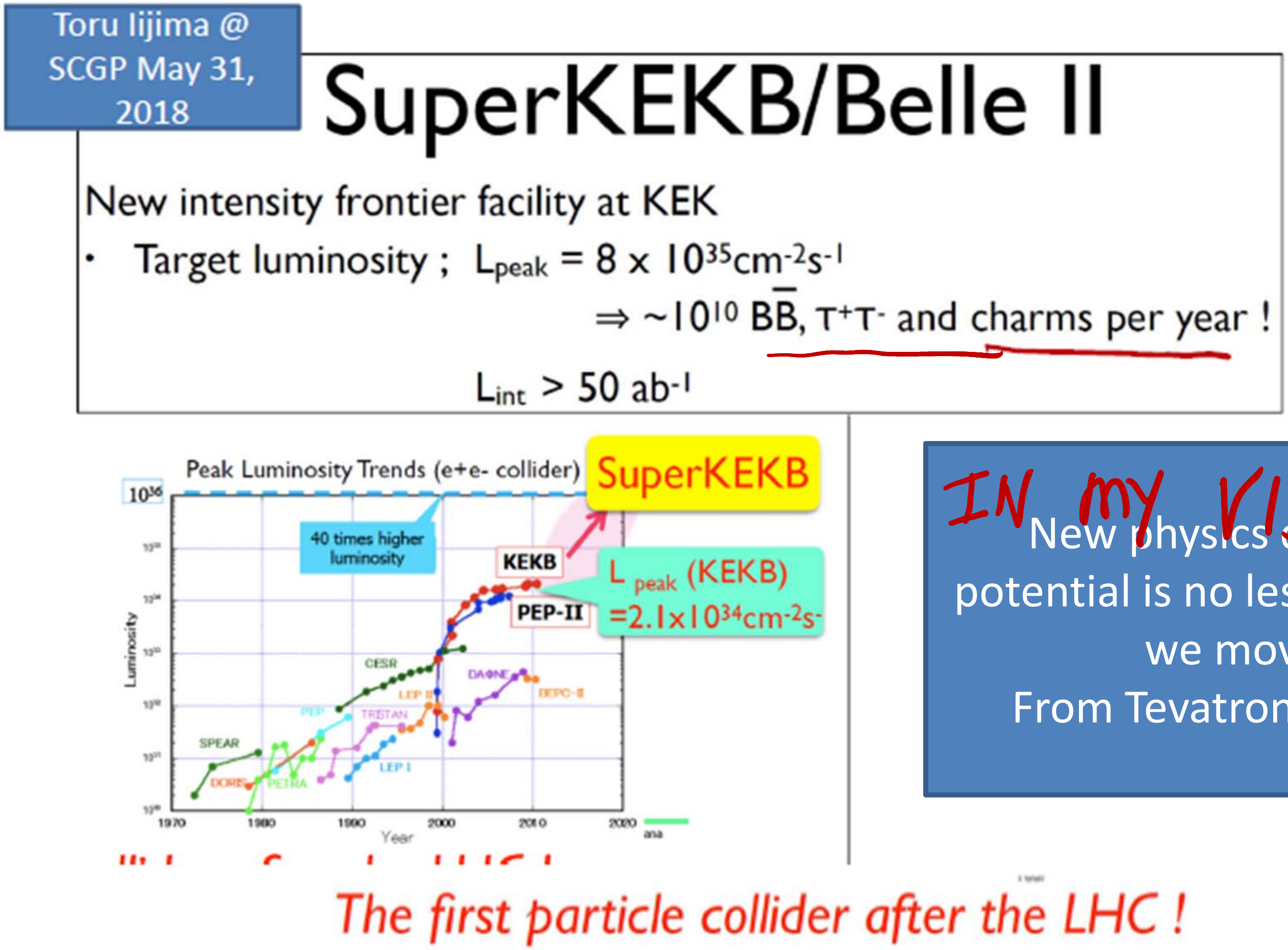
all constraints……RPV(blue) region obtained by scanning with sbottom mass 680-1000Gev, 0<λ333<2;|λ323|<0.1;|λ313|<0.3 ….

A NEW WAY TO TEST LUV IN THE BELLE-II ERA [LHCB?]

Testing LUV in the era of Belle-II

- I. **A new thousand pound gorilla is in our midst:**

Calho
Shoji



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 !

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

The first particle collider after the LHC !

IN MY VIEW

New physics discovery potential is no less than when we moved
From Tevatron to LHC!!!

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

Role of lattice esp in FlavPh and in CP searches

- **For RD Fermilab/Milc 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**

- **Delta mK, epsilon_K[LD], rare K decays..concrete examples where new technique for handling matrix elements of non-local operators suitable for calulating LD contributions developed by RBC-UKQCD. How to extend this to havier heavy-light systems.**

- **This talk illustrates with a simple example that becomes relevant in the high luminosity days of Belle-II and possibly for LHCb**

Bit more on lattice

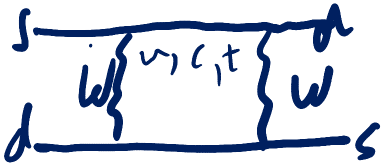
- **Should be recognized that w/o input from the lattice its highly questionable if experimental measurement from B-factories alone could have achieved the current precsion of the Unitarity test for the KM mecanism of CP violation.**
- **That is of course the past**
- **Clearly QCD is [will be] an integral 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

$K^+ \to \pi^+ \nu \bar\nu$



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

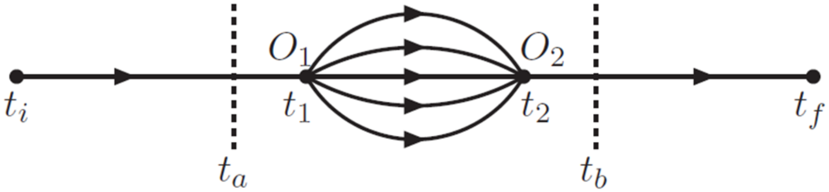
~50%

- 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

Testing LUV in the era of Belle-II

- II. **On the lattice technical front, RBC-UKQCD collab** $B, D_s \Rightarrow \ell \nu \gamma$

has developed the methodology over the past ~6 years for calculating from 1st principles contributions from non-local operators

- **Here we illustrate this use in the simplest example that can have important phenomenological impact in light of larger data samples that will become available in the era of Belle-II**
- **The simplest illustrative reaction to display developments in the exptal and in the lattice front that we choose is M_hl =>** $\tau/\ell \, \nu \gamma$
- **Lets start with a very simple observation that LUV is very difficult to test with respectable accuracy via the simplest reaction**
- **Br** $B \to \tau\nu/\mu\nu$ **because the denominator suffers from severe helicity suppression. Indeed,**
- **Br[B+ =>mu+ nu] ~ 2 X 10^-7**
- **Note, however that naïve models seem to suggest** ⇒ Atwood, Eilam, AS hep-ph/9411367
- **Br [B => mu nu gamma]/Br[B=> mu nu] ~16**

$[B \Rightarrow e\nu\gamma]/[B \to e\nu] \sim 5 \times 10^5$!!

Testing LUV in the era of Belle-II

- II. **On the lattice technical front, RBC-UKQCD collab**

has developed the methodology over the past ~6 years for calculating from 1^{st} principles contributions from non-local operators

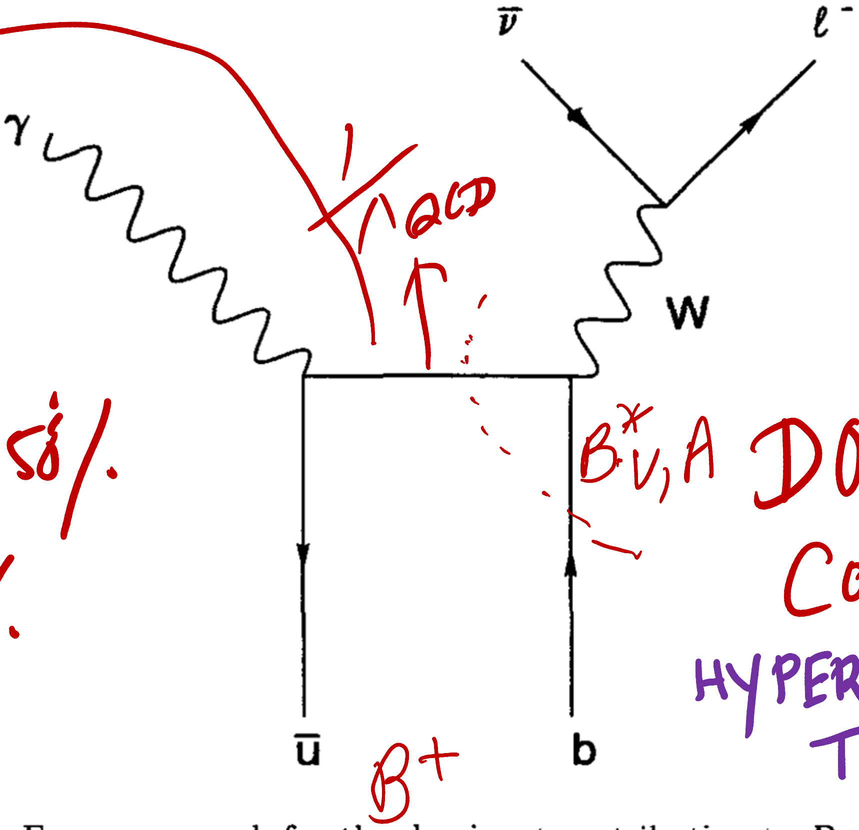
- **Here we illustrate this use in the simplest example that can have important phenomenological impact in light of larger data samples that will become available in the era of Belle-II**
- **The simplest illustrative reaction to display developments in the exptal and in the lattice front that we choose is M_hl =>** $\tau/\ell\, \nu\, \gamma$
- **Lets start with a very simple observation that LUV is very difficult to test with respectable accuracy via the simplest reaction**
- **Br** $B \to \tau\nu/\mu\nu$ **because the denominator suffers from severe helicity suppression. Indeed,**
- **Br[B+ =>mu+ nu] ~ 2 X 10^-7**
- **Note, however that naïve models seem to suggest**
- **Br [B => mu nu gamma]/Br[B=> mu nu] ~16**

→ Atwood, Eilam, AS
hep-ph/9411367

$[B \Rightarrow e\nu\gamma]/[B \to e\nu] \sim 5 \times 10^5$!!

Radiative leptonic decays of heavy-light mesons

Non-local
[RBC-UKQCD]
$\Delta m_K \to$ Bigeng $\sim 5\%$
$\epsilon_K^{LD} \sim 5-10\%$
$K^+ \to \pi^+ \nu\bar{\nu}$ X_u
$\sim 5-10\%$



$+ \ldots$

DOMINANT Contribution

HYPERFINE Transition

Fig. 1. Feynman graph for the dominant contribution to $B \to \ell\nu\gamma$.

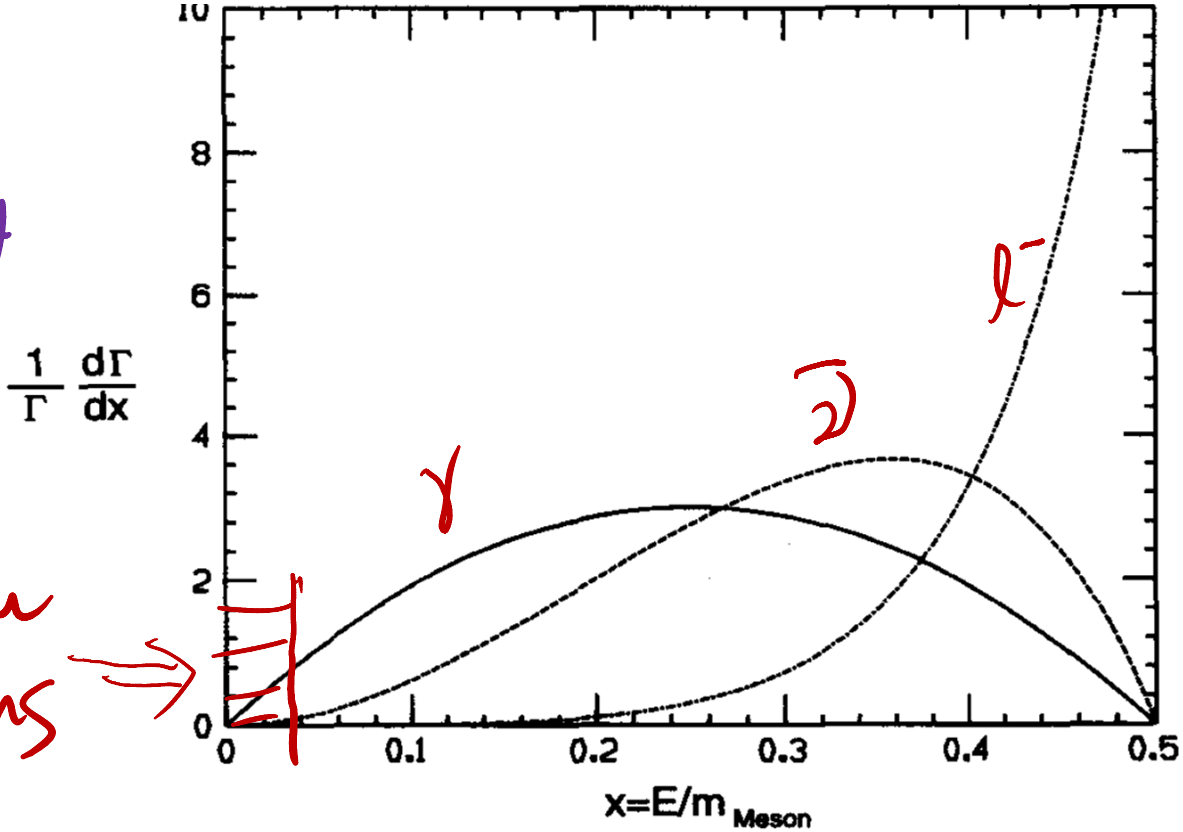
c. also, AOKI + X_u F + S.H ... $\pi^0 \to 2\gamma$ PRL 2012

Radiative leptonic decays of heavy-light mesons

- These are distinctly 3-body final state not to be confused with soft photons that necessarily accompany physical processes and their treatment is strictly linked to detector resolution….also typically these are brehmms with steeply falling spectrum
- In contrast, the 3-body final state such as Ds, B+ => l nu gamma are important corrections to pure leptonic decays l + nu have whose importance has been stressed due to their ability to overcome helicity suppression via hyperfine transitions
- To get a clear intutive understanding it may help to think in terms of the naïve quark model [though from the outset one recognizes its limitation in accuracy esp for a heavy-light system]
- In that naïve picture, one can resort to the Weisskopf-Van Royen text book approx and clearly identify the underlying physical processes:

AES'94

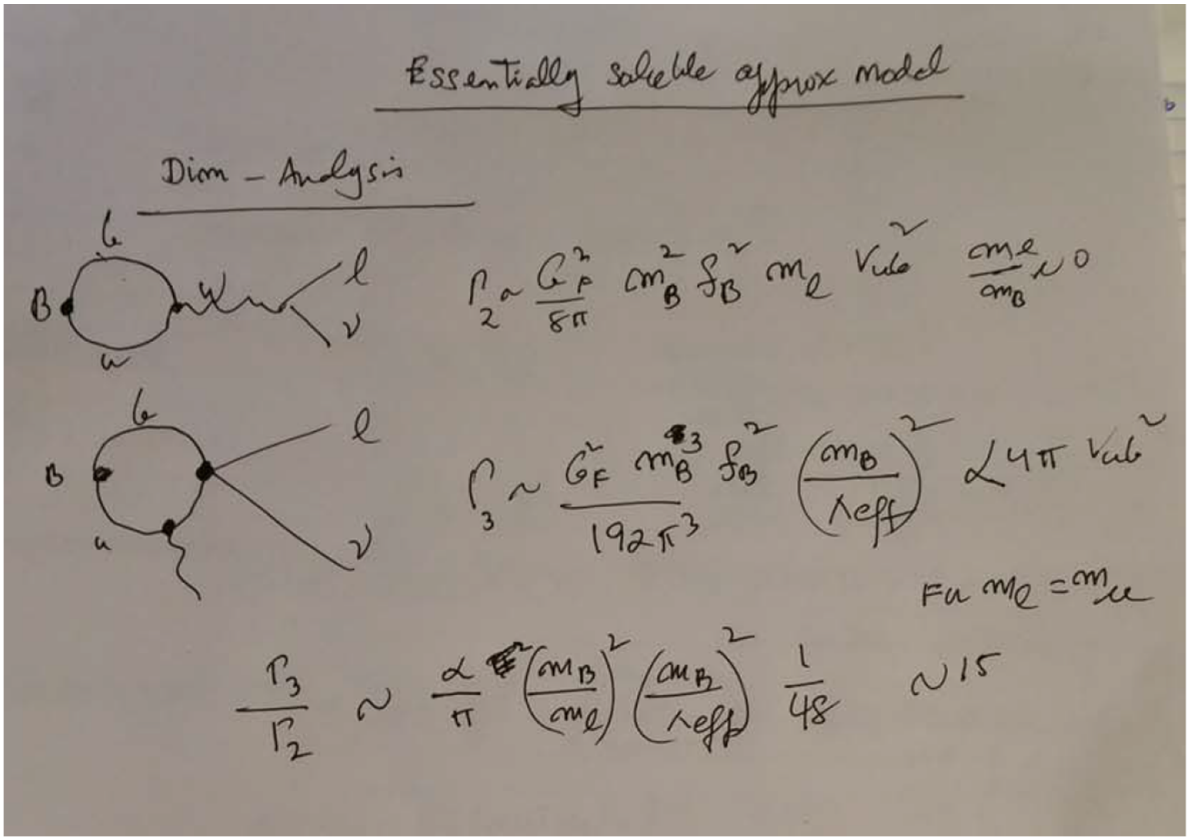
B^-



Stay away from soft photons

Fig. 2. $B \to \ell^- \bar{\nu}\gamma$ normalized energy spectra are shown. Solid line is for the photon energy, the dashed is for the neutrino energy (which is directly related to invariant mass of the electron-photon combination) and the dash-dot for the electron energy. For the case of $D_s \to \ell^+\nu\gamma$ the dashed curve represents the neutrino energy spectrum while the dash-dot curve represents the lepton energy since in this case the roles of the lepton and neutrino are reversed.

D_s^+



Essentially solvable approx model

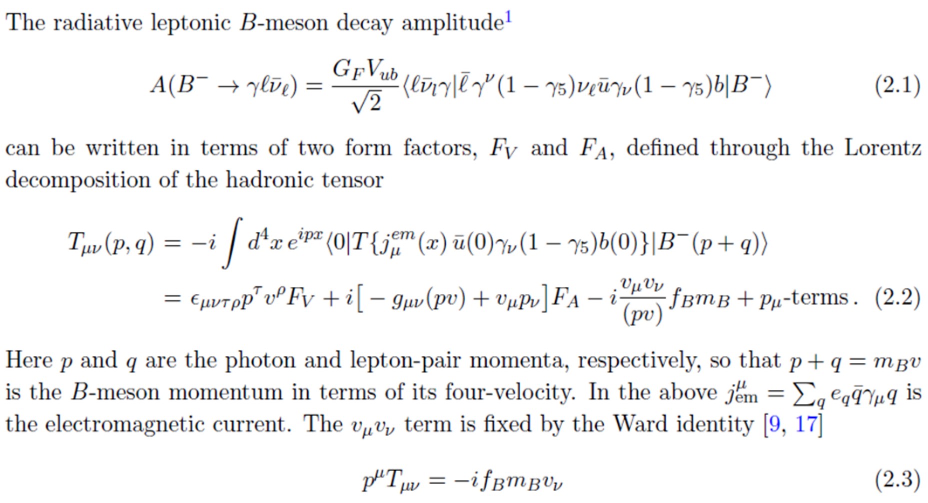
Dim – Analysis

$$\Gamma_2 \sim \frac{G_F^2}{8\pi} m_B^2 f_B^2 m_\ell V_{ub}^2 \qquad \frac{m_\ell}{m_B} \sim 0$$

$$\Gamma_3 \sim \frac{G_F^2 m_B^3 f_B^2}{192\pi^3} \left(\frac{m_B}{\Lambda_{eff}}\right)^2 \alpha 4\pi V_{ub}^2$$

For $m_\ell = m_\mu$

$$\frac{\Gamma_3}{\Gamma_2} \sim \frac{\alpha}{\pi} \left(\frac{m_B}{m_\ell}\right)^2 \left(\frac{m_B}{\Lambda_{eff}}\right)^2 \frac{1}{48} \quad \sim 15$$



The radiative leptonic B-meson decay amplitude[1]

$$A(B^- \to \gamma \ell \bar\nu_\ell) = \frac{G_F V_{ub}}{\sqrt{2}} \langle \ell \bar\nu_l \gamma | \bar\ell \gamma^\nu (1-\gamma_5)\nu_\ell \bar u \gamma_\nu (1-\gamma_5) b | B^-\rangle \tag{2.1}$$

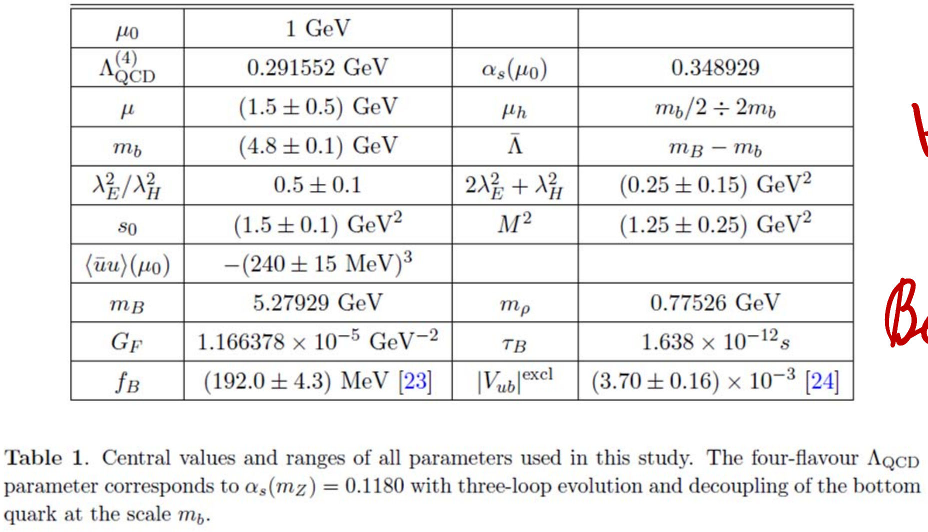
can be written in terms of two form factors, F_V and F_A, defined through the Lorentz decomposition of the hadronic tensor

$$\begin{aligned} T_{\mu\nu}(p,q) &= -i \int d^4x\, e^{ipx} \langle 0| T\{ j_\mu^{em}(x)\, \bar u(0)\gamma_\nu(1-\gamma_5) b(0)\} | B^-(p+q)\rangle \\ &= \epsilon_{\mu\nu\tau\rho} p^\tau v^\rho F_V + i\big[-g_{\mu\nu}(pv) + v_\mu p_\nu\big] F_A - i\frac{v_\mu v_\nu}{(pv)} f_B m_B + p_\mu\text{-terms}\,. \end{aligned} \tag{2.2}$$

Here p and q are the photon and lepton-pair momenta, respectively, so that $p + q = m_B v$ is the B-meson momentum in terms of its four-velocity. In the above $j^\mu_{\text{em}} = \sum_q e_q \bar q \gamma_\mu q$ is the electromagnetic current. The $v_\mu v_\nu$ term is fixed by the Ward identity [9, 17]

$$p^\mu T_{\mu\nu} = -i f_B m_B v_\nu \tag{2.3}$$

Beneke etal
1804.04962
(also DESCOTES-GENON + CTS '03



μ_0	1 GeV		
$\Lambda^{(4)}_{\text{QCD}}$	0.291552 GeV	$\alpha_s(\mu_0)$	0.348929
μ	(1.5 ± 0.5) GeV	μ_h	$m_b/2 \div 2m_b$
m_b	(4.8 ± 0.1) GeV	$\bar\Lambda$	$m_B - m_b$
λ_E^2/λ_H^2	0.5 ± 0.1	$2\lambda_E^2 + \lambda_H^2$	(0.25 ± 0.15) GeV^2
s_0	(1.5 ± 0.1) GeV^2	M^2	(1.25 ± 0.25) GeV^2
$\langle \bar u u\rangle(\mu_0)$	$-(240 \pm 15$ MeV$)^3$		
m_B	5.27929 GeV	m_ρ	0.77526 GeV
G_F	1.166378×10^{-5} GeV^{-2}	τ_B	$1.638 \times 10^{-12} s$
f_B	(192.0 ± 4.3) MeV [23]	$\lvert V_{ub}\rvert^{\text{excl}}$	$(3.70 \pm 0.16) \times 10^{-3}$ [24]

Table 1. Central values and ranges of all parameters used in this study. The four-flavour Λ_{QCD} parameter corresponds to $\alpha_s(m_Z) = 0.1180$ with three-loop evolution and decoupling of the bottom quark at the scale m_b.

9 non-pert params!!
HUGE Buffalo!

Beneke etal
'2018

On the lattice

- **On the lattice this calculation of B^+ [Ds^-]=>l ν γ is rather similar to π^0 => 2 γ [see Xu Feng et al, PRL] and to RBC-UKQCD recent attempts at LBL contribution to muon g-2 via the π^0 exch.** *
- **Except now 1 photon gets replaced by the V, A**

[heavy –light states] which dominate the transition to the final l + nu [w/o helicity suppression]

- **The dominant graph is when the light quark emits the photon, though of course [QED] gauge invariance requires emission from all charged legs.**
- **The emission of photon off the charged lepton will be helicity suppressed so it will also be an important contributor when emitted from tau**
- **The details of Minkowski-Euclidean connection closely follow pi^0 => 2 gamma with appropriate changes**

* c also X d Ji + C w Jung PRL '01

$$M^{\rm mink}_{\mu\nu}(p_1,p_2) = i\int d^4x e^{ip_1x}\langle 0|T\{j_\mu(x)j_\nu(0)\}|\pi^0(q)\rangle \longrightarrow EMC \tag{1}$$

$$= \varepsilon_{\mu\nu\alpha\beta}p_1^\alpha p_2^\beta \mathcal{F}_{\pi\gamma\gamma}(m_\pi^2, p_1^2, p_2^2) \tag{2}$$

CL NOTES

$p_2 = [E_{\pi,\vec q} - \omega, \vec q - \vec p_1]$

$p_1 = (\omega, \vec p_1)$

$q = [E_{\pi,\vec q}, \vec q]$; $E_\pi^2 = m_\pi^2 + \vec q^{\,2}$

$$\begin{aligned}
M^{\rm mink}_{\mu\nu}(p_1,p_2) = i\int d^3x e^{-i\tilde p_1 \tilde x}\Bigg[\sum_n \int_{-\infty}^0 dt e^{i(\omega+\tilde E_n - i\varepsilon)t}\langle 0|j_\nu(0)|n\rangle\langle n|j_\mu(\tilde x)|\pi^0(q)\rangle \\
+\sum_n \int_0^\infty dt e^{i(\omega - E_n + i\varepsilon)t}\langle 0|j_\mu(\tilde x)|n\rangle\langle n|j_\nu(0)|\pi^0(q)\rangle\Bigg]
\end{aligned} \tag{7}$$

$$\begin{aligned}
= \sum_n \frac{1}{\tilde E_n + \omega}\langle 0|j_\nu(0)|n\rangle\langle n|j_\mu(-\tilde p_1)|\pi^0(q)\rangle \quad \longleftarrow \\
+\sum_n \frac{1}{E_n - \omega}\langle 0|j_\mu(-\tilde p_1)|n\rangle\langle n|j_\nu(0)|\pi^0(q)\rangle\,. \quad \longleftarrow
\end{aligned} \tag{8}$$

with $j_\mu(t,\tilde x) = e^{iHt}j_\mu(\tilde x)e^{-iHt}$, $\tilde E_n = E_n - E_{\pi,\tilde q}$, $H|n\rangle = E_n|n\rangle$, and

$$j_\mu(\tilde p) \equiv \int d^3x e^{i\tilde p\tilde x}j_\mu(\tilde x)\,. \tag{9}$$

$$M^{\mathrm{eucl}}_{\mu\nu}(p_1, p_2) = \int d^3x e^{-i\tilde{p}_1\tilde{x}} \int dt e^{\omega t} \langle 0|T\{j_\mu(\tilde{x}, t) j_\nu(0)\}|\pi^0(q)\rangle \tag{10}$$

$$\begin{aligned} &= \sum_n \int_{-\infty}^{0} dt e^{(\omega+\tilde{E}_n)t} \langle 0|j_\nu(0)|n\rangle\langle n|j_\mu(-\tilde{p}_1)|\pi^0(q)\rangle \\ &\quad + \sum_n \int_{0}^{\infty} dt e^{(\omega-E_n)t} \langle 0|j_\mu(-\tilde{p}_1)|n\rangle\langle n|j_\nu(0)|\pi^0(q)\rangle \end{aligned} \tag{11}$$

$$\begin{aligned} &= \sum_n \frac{1}{\tilde{E}_n + \omega} \langle 0|j_\nu(0)|n\rangle\langle n|j_\mu(-\tilde{p}_1)|\pi^0(q)\rangle \\ &\quad + \sum_n \frac{1}{E_n - \omega} \langle 0|j_\mu(-\tilde{p}_1)|n\rangle\langle n|j_\nu(0)|\pi^0(q)\rangle , \end{aligned} \tag{12}$$

with Euclidean $j_\mu(t, \tilde{x}) = e^{Ht} j_\mu(\tilde{x}) e^{-Ht}$ and where both integrals converge as long as $-\tilde{E}_n < \omega < E_n$. With this restriction of domain of ω, we can therefore relate Minkowski and Euclidean space

$$M^{\mathrm{mink}} = M^{\mathrm{eucl}} . \tag{13}$$

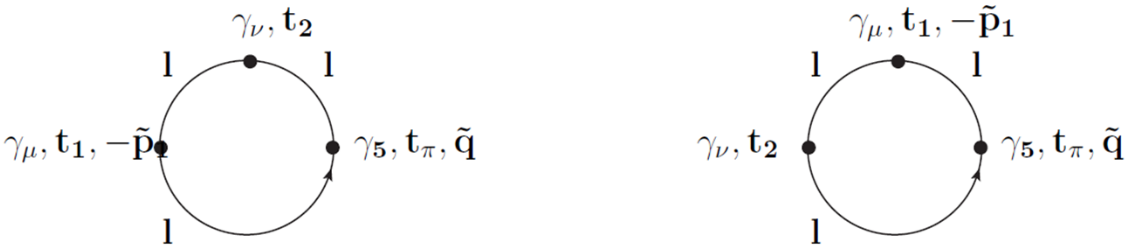


Figure 1: $\pi^0 \to \gamma\gamma$ diagram A (left) and B (right). There are additional disconnected diagrams not yet drawn here.

EM

Weak V, A

$$T_{\mu\nu} = -i \int d^4x e^{iPx} \langle 0|T\{j_\mu(x) j_\nu^W(0)\}|B^-(P+Q)\rangle \tag{19}$$

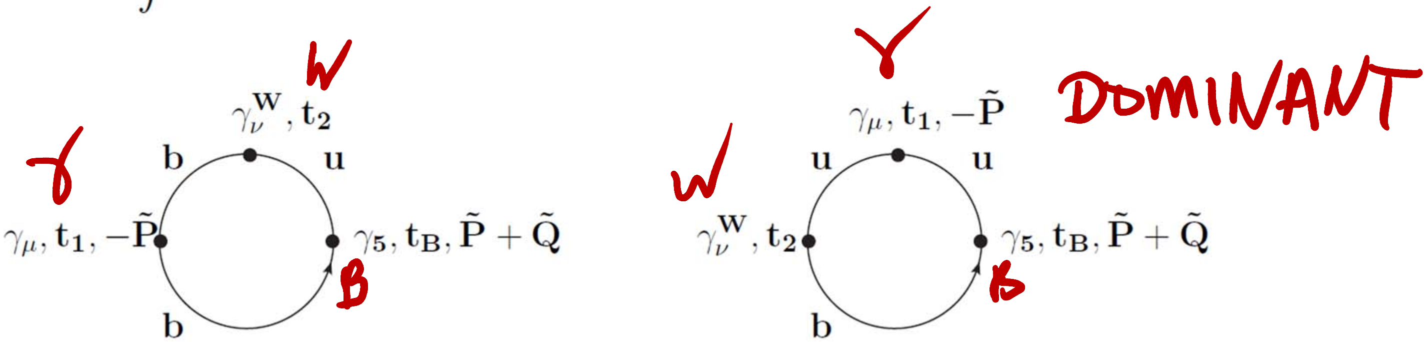


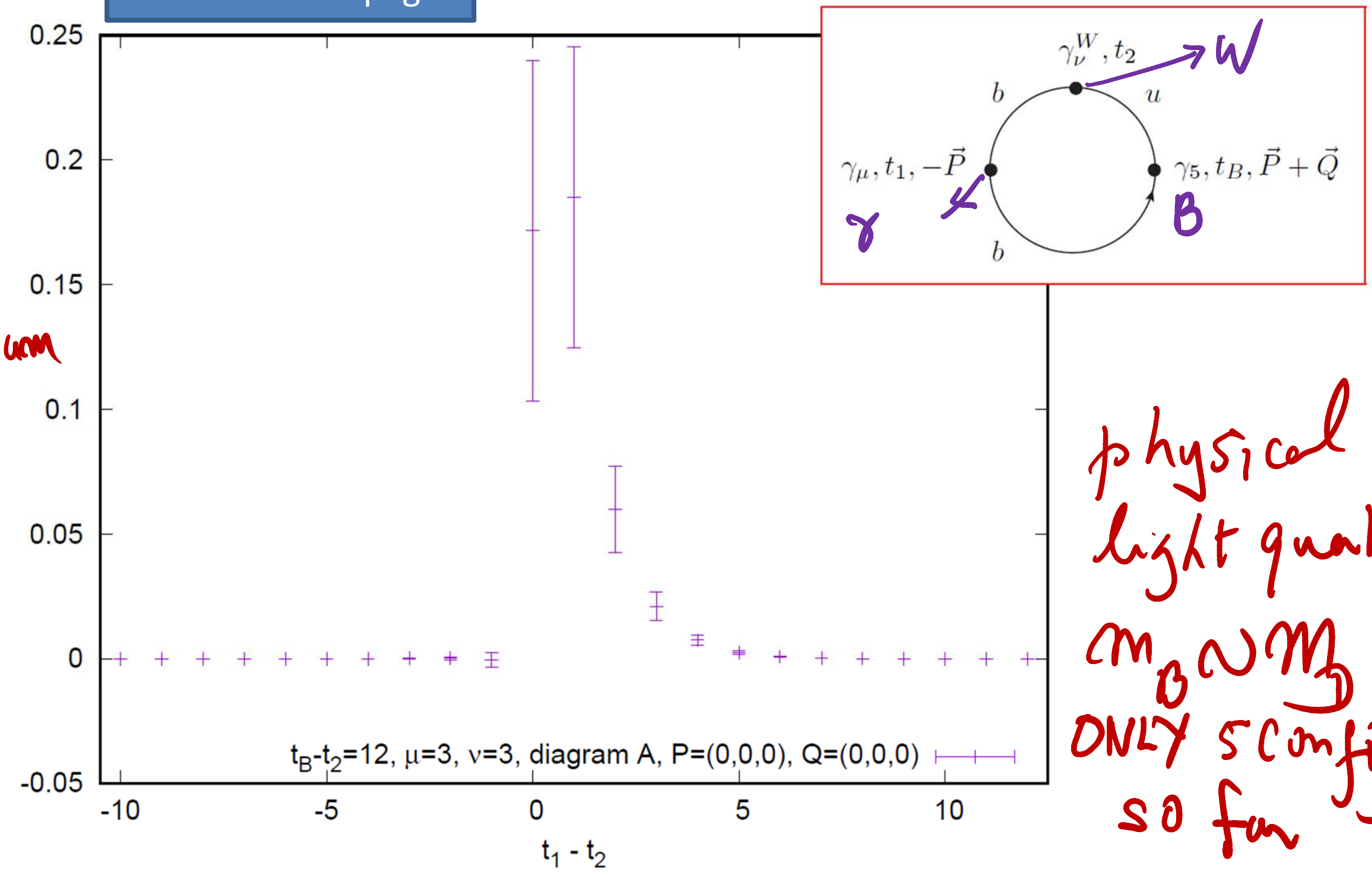
Figure 3: Radiative leptonic B decay diagram A (left) and B (right). There are additional disconnected diagrams not yet drawn here.

C some lattice
Details in back pages

0 momentum

diagram A

b quark emits γ



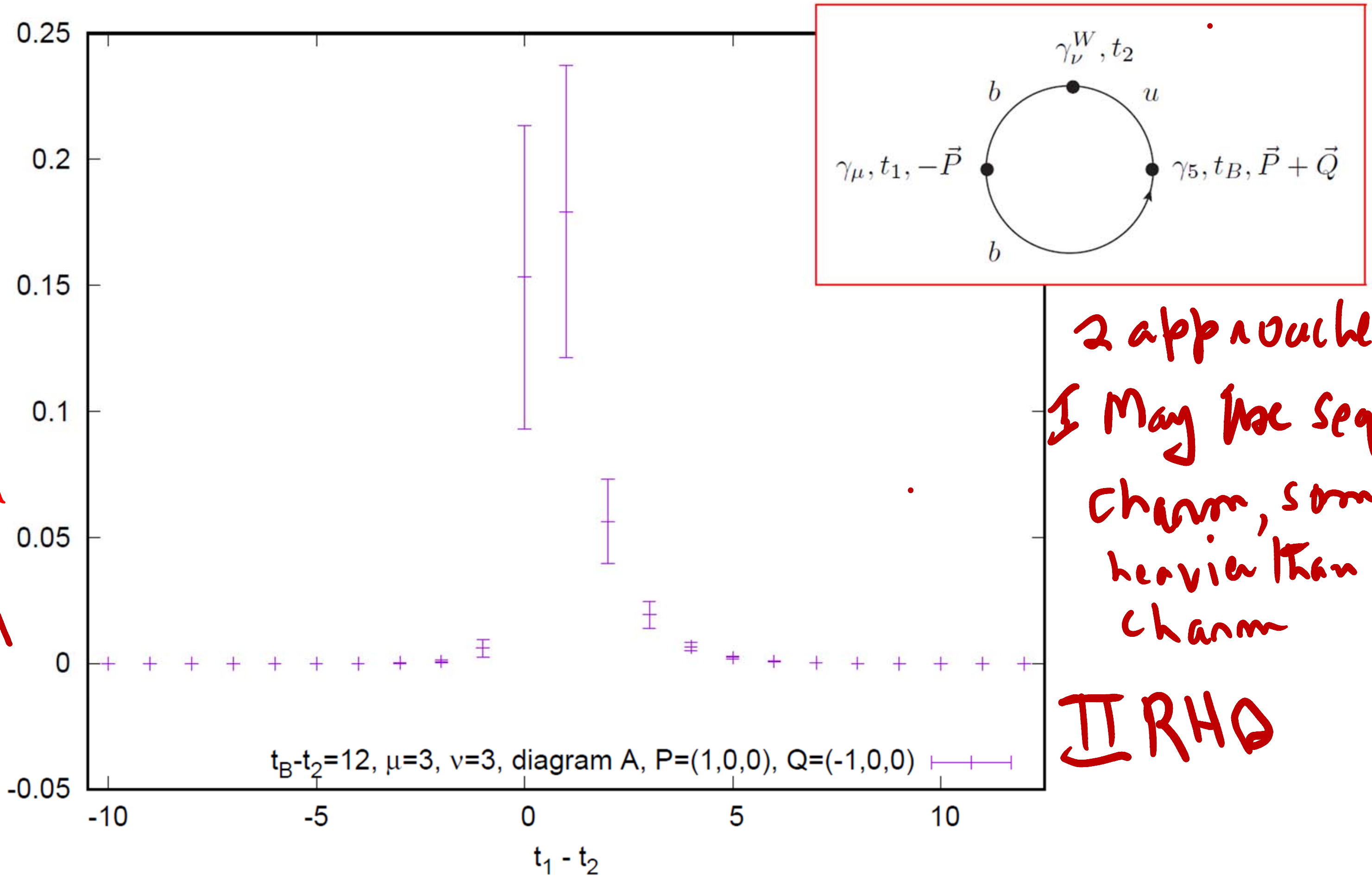
physical light quarks

$m_B \sim m_D$;

ONLY 5 configs so far

Show $\sum_{\vec{x}} e^{-i\vec{p}_1\vec{x}} \langle 0| T\{j_\mu(\vec{x}, t_1) j_\nu^W(\vec{0}, t_2)\}|B^-(P+Q)\rangle$ for $m_\pi = 139$ MeV, $m_B \approx m_D$, $a^{-1} = 1.73$ GeV; MDWF, $m_5=1.4$, $b=.75$, $c=0.25$

$48^3 \times 96$



1 unit of momentum ~210 MeV

diagram A

2 approaches

I May use seq of charm, some heavier than phys charm

II RHQ

Show $\sum_{\vec{x}} e^{-i\vec{p}_1\vec{x}}\langle 0|\, T\{j_\mu(\vec{x}, t_1) j_\nu^W(\vec{0}, t_2)\}|B^-(P+Q)\rangle$ for $m_\pi = 139$ MeV, $m_B \approx m_D$, $a^{-1} = 1.73$ GeV u quark emits γ

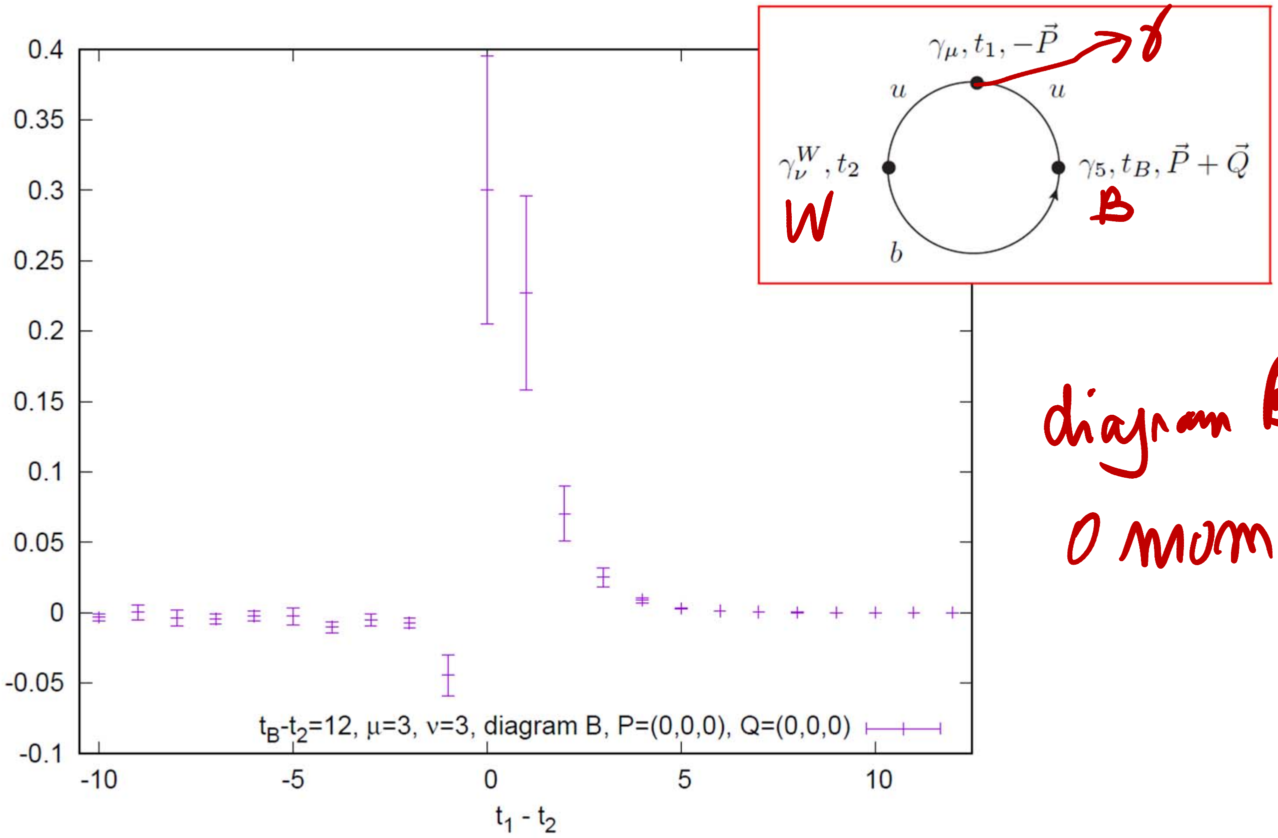


diagram B

0 momentum

Show $\sum_{\vec{x}} e^{-i\vec{p}_1\vec{x}}\langle 0|T\{j_\mu(\vec{x},t_1)j_\nu^W(\vec{0},t_2)\}|B^-(P+Q)\rangle$ for $m_\pi = 139$ MeV, $m_B \approx m_D$, $a^{-1} = 1.73$ GeV

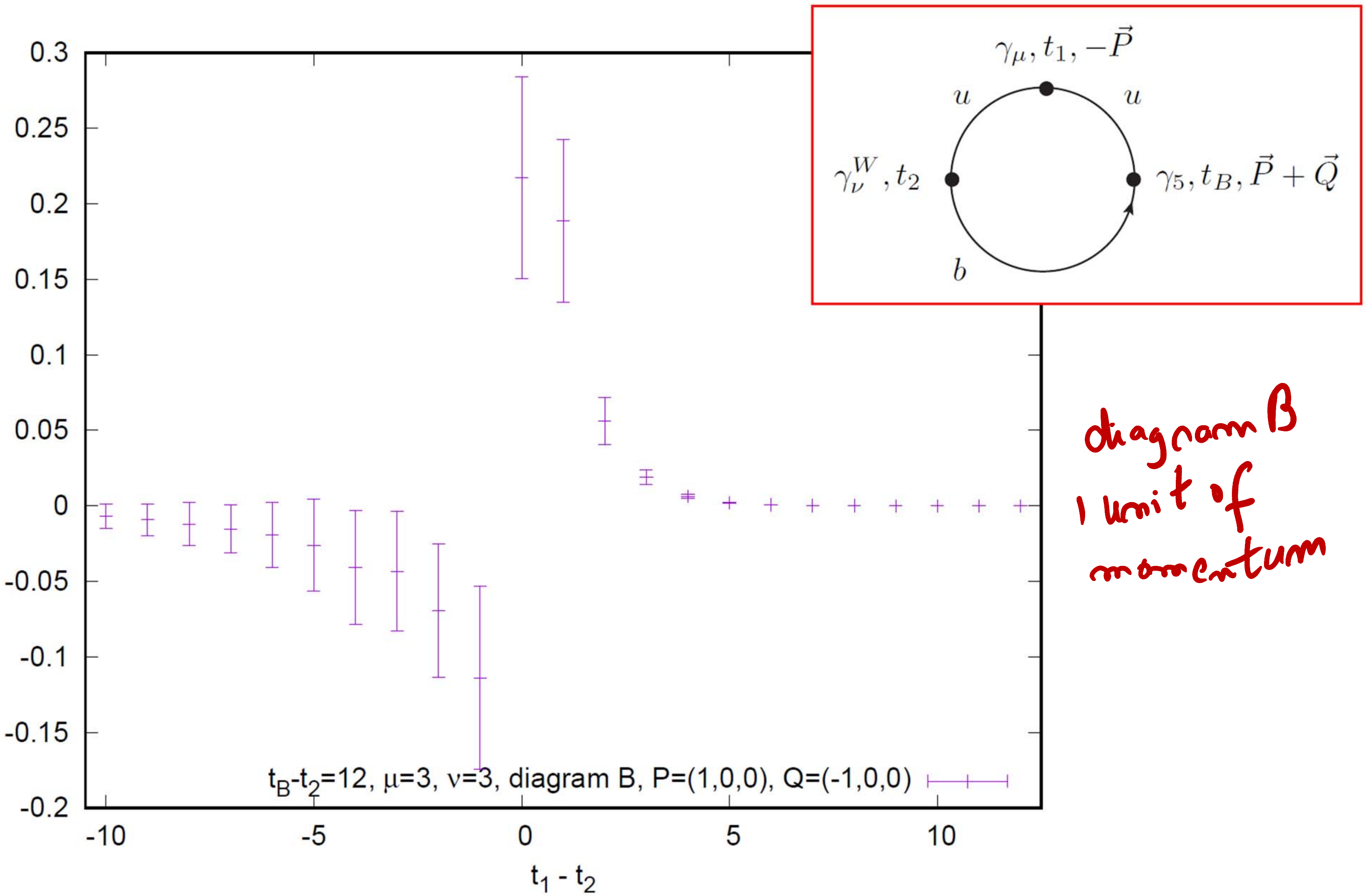
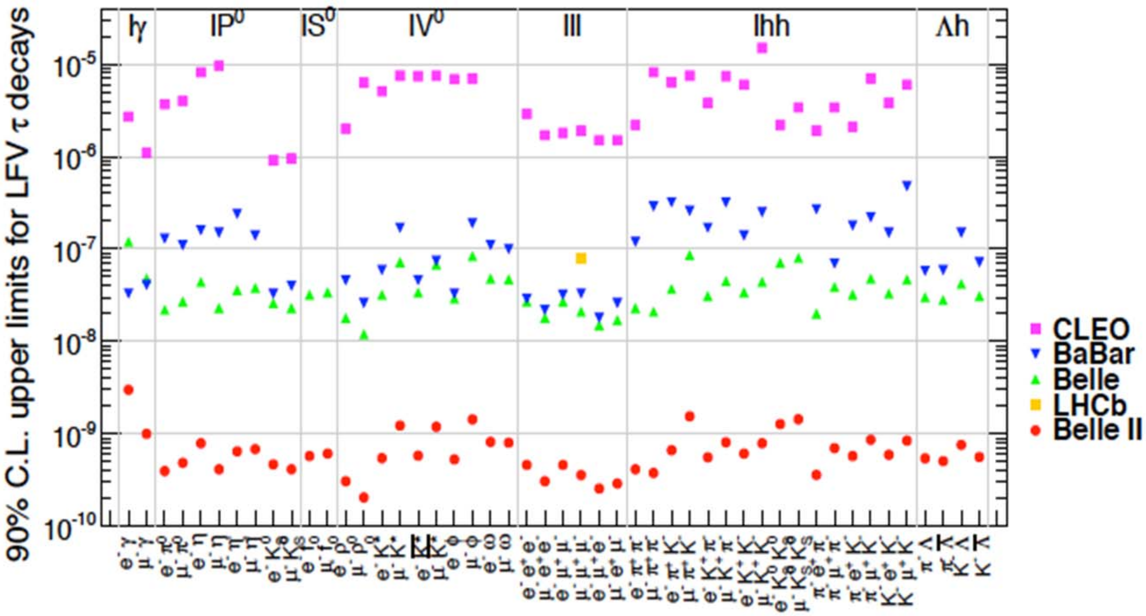


diagram B
1 unit of
momentum

Show $\sum_{\vec{x}} e^{-i\vec{p}_1\vec{x}}\langle 0|T\{j_\mu(\vec{x},t_1)j_\nu^W(\vec{0},t_2)\}|B^-(P+Q)\rangle$ for $m_\pi = 139$ MeV, $m_B \approx m_D$, $a^{-1} = 1.73$ GeV

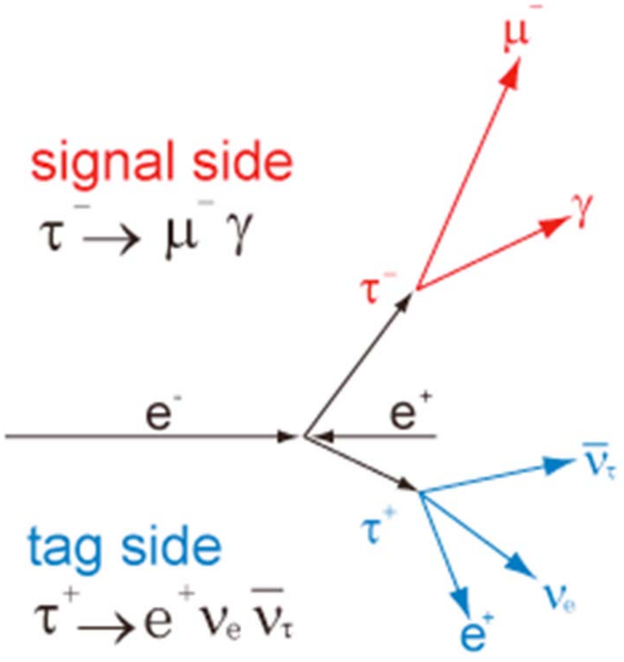
ANOTHER CLASS OF IMPORTANT TESTS IN THE ERA OF BELLE-II

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



Belle II will push many limits below 10^{-9} ;

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

GORRILLA + GODZILLA

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

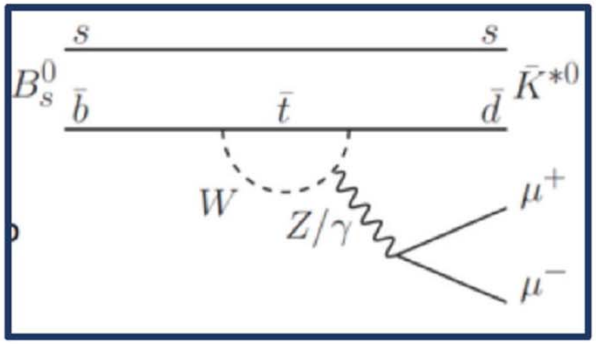
- Heavily suppressed b → dll transition in Standard Model
  - complementary to b → sll transitions in B^0_d decays

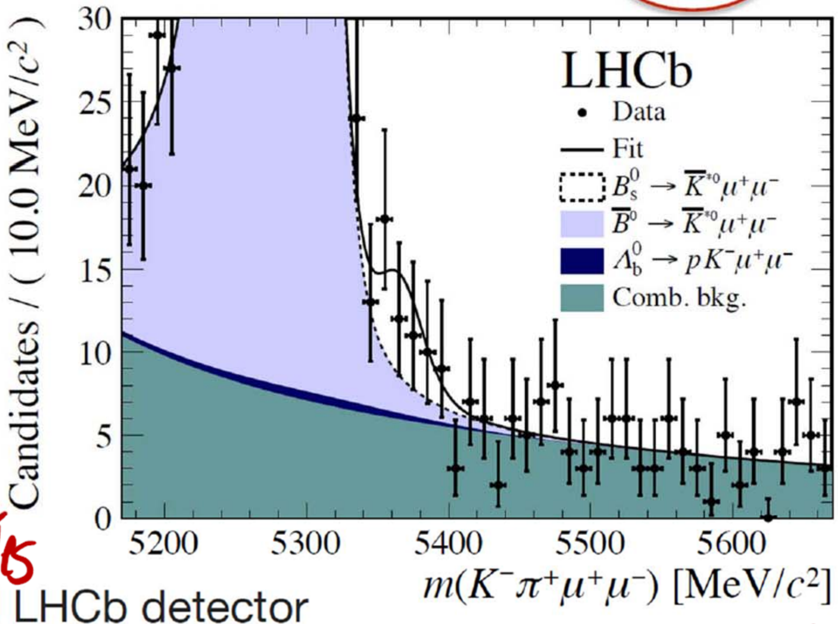
arXiv:1804.07167,
Run 1+2, 4.6 fb^{-1}

- 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 4 LHCb upgs

Near future outlook

- LHCb has so far only used Run 1 data
- Plenty more data from Run 2 available but needs to be analyzed
- Belle-II with large amount of data and some new important channels starting about a year from now
- Expect better experimental results on RD(*), RK(*) including additional channels relevant for LUV in the coming 1-3 years.
- Improved theory calculations for RD(*), off and on the lattice anticipated in < 1 year
- 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
- Fermilab g-2 new results in ~ < 1 year and then more in the foll 2-3 years.
- Improved lattice results for eps’ from our RBC-UKQCD in a few (O(6))months

Summary

- Although over 3 sigma anomalies in each class of sl cc, fcnc and in g-2 ; DO NOT THINK as yet THESE PROVIDE COMPELLING EVIDENCE FOR LUV
- In each case have reservations….A plausible resolution may well be few exptal results suffer from few sigma fluctuations and also possibly underestimated theory errors….
- Need improvements in theory and even more so in expt. For example for RD(*) possibility of appreciable systematic difference between tau => l nu nu and tau => hadrons + nu must be removed..This requires more data
- Belle-II, Lhcb-Run II [upgrade] and new Fermilab g-2 expt[X2BNL already!] are all very timely
- Esp. Belle-II, huge new gorilla for searching NP
- Therefore should think of lattice calculations to facilitate `old/new tests

in addition to improving accuracy of traditional FF calculations in sl cc and FCNC

- As a simple example suggest Ds, B^+ => tau/l nu gamma a distinct and powerful avenue to test LUV (and CP) for tau/mu/e many ways
- Direct CP null tests,K, D, B =>pi+ pi0; SM prediction needed from lattice
- D, B => pi[K] l l diff rate[high m_ll] and dir-CP; again SM prediction needed from lattice; experimental measurements will be useful to motivate theory

Δ S=1 H_W

WC to NLO

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

$$H_W = \frac{G_F}{\sqrt{2}} V_{us}^* V_{ud} \sum_{i=1}^{10} [\overbrace{z_i(\mu) + \tau y_i(\mu)}] Q_i(\mu).$$

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

$M_i = \langle K | Q_i | \pi\pi \rangle$ Needed

Tree

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

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

QCDP

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

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

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

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

I=0 ⟹

→ 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

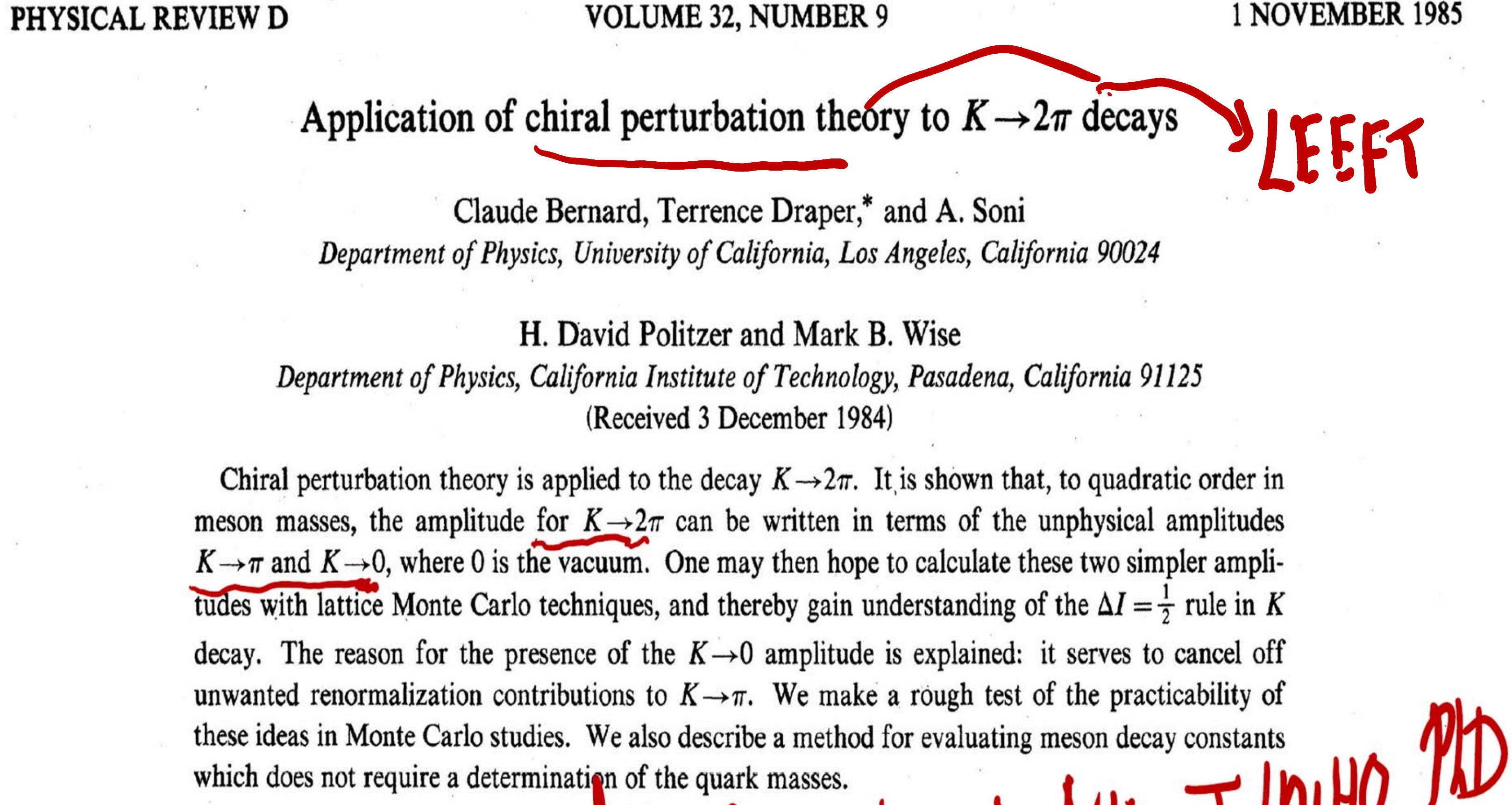
$$Q_9 = \frac{3}{2}(\bar{s}_\alpha d_\alpha)_L \sum_{q=u,d,s} e_q (\bar{q}_\beta q_\beta)_L,$$

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

→ const

$m \to 0$

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

LEEFT

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

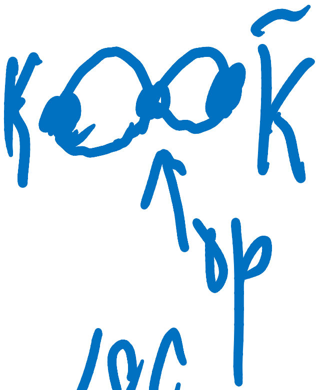
H. David Politzer and Mark B. Wise
Department of Physics, California Institute of Technology, Pasadena, California 91125

(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.

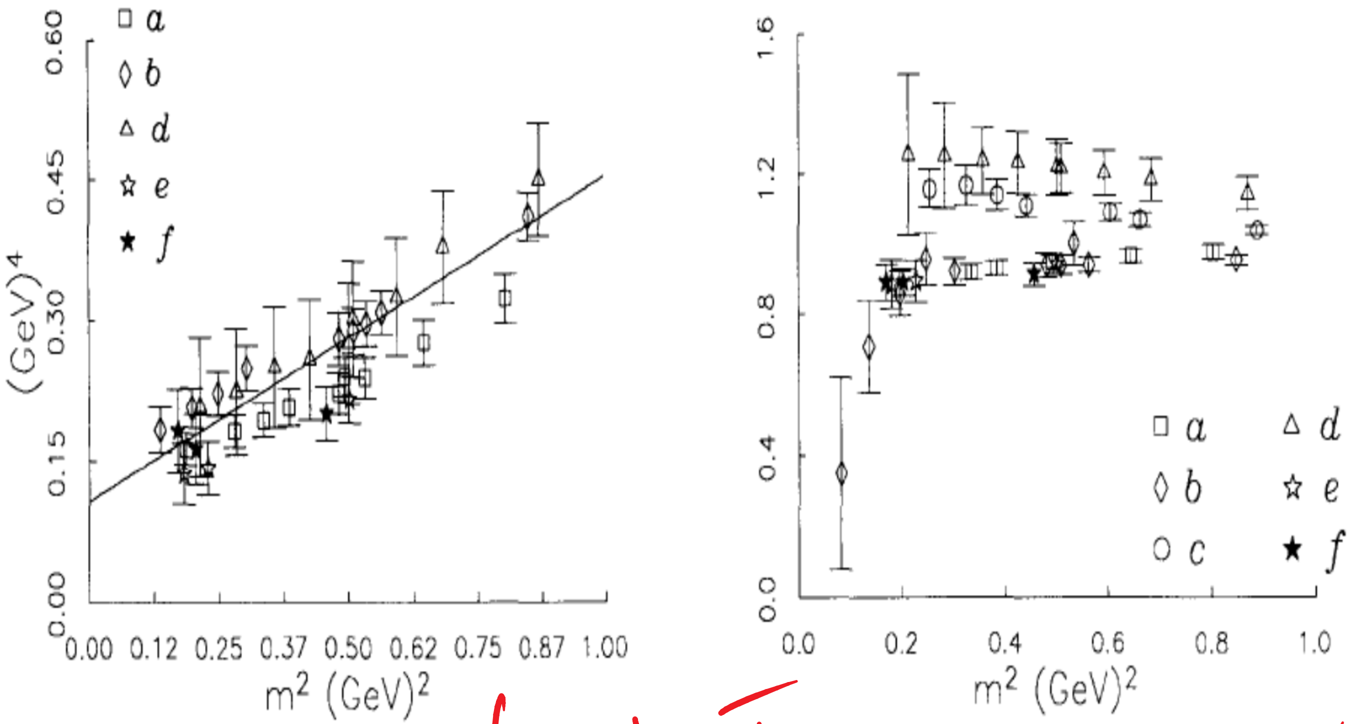
USED extensively on lattice for ~ 20 years ⇒ NLO J. LAIHO PhD Thesis ~ '03

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



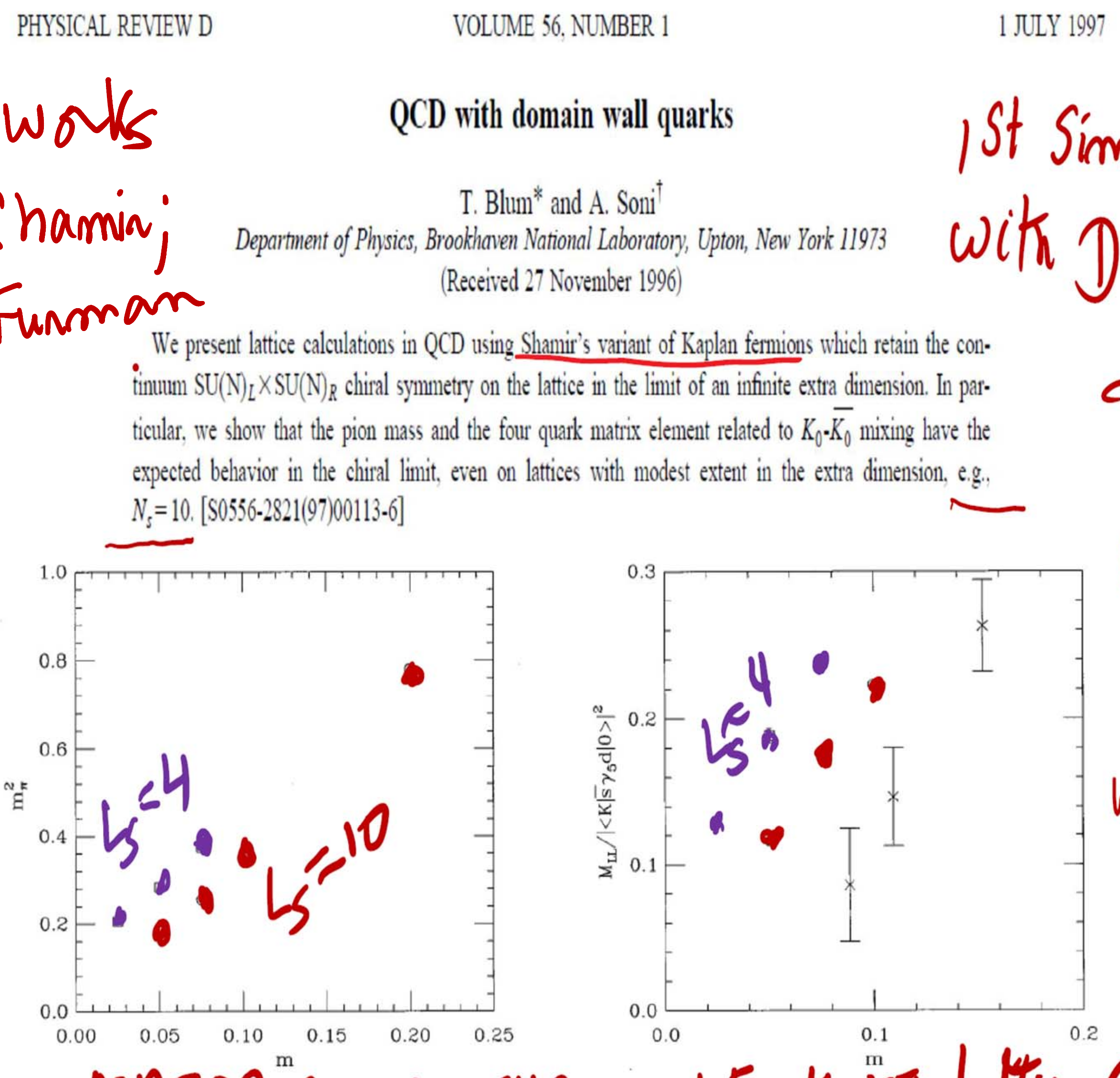
'88

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



χS violation by K-$\bar{K}$ ⇒ FINE TUNING PROBLEM

Motivated by works of Yigal Shamir; of Shamir + Furman



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 ~'97

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

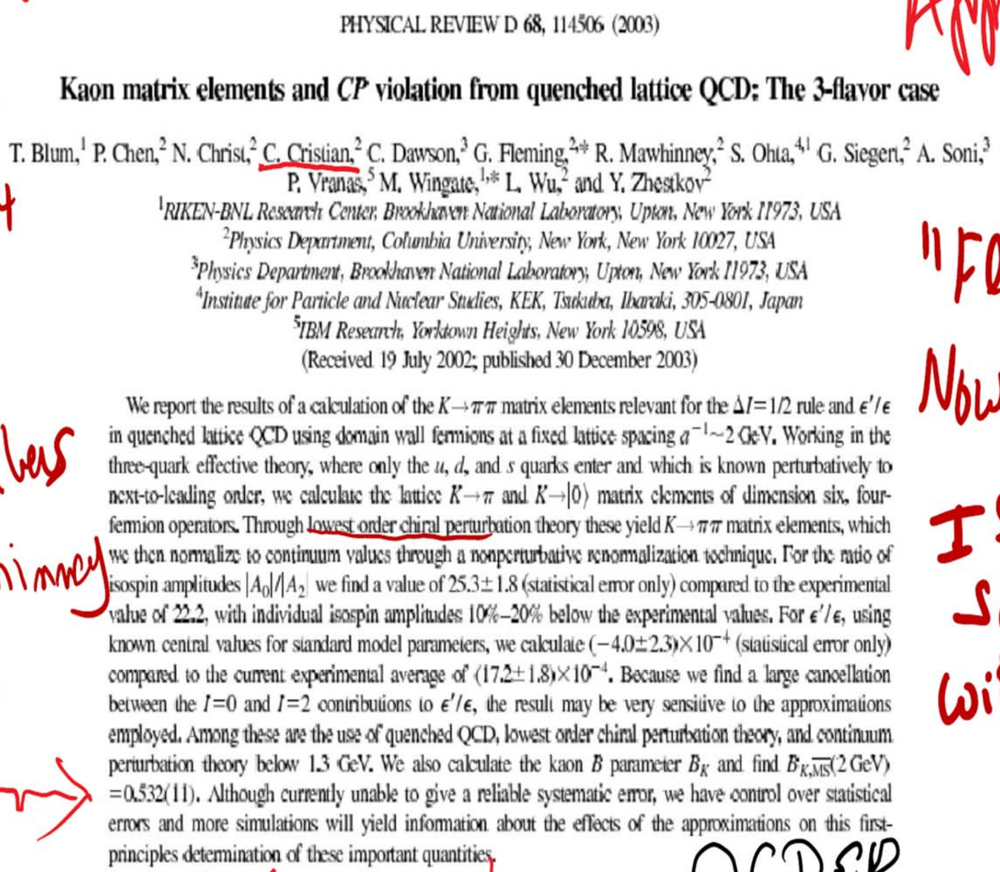
MAJOR BREAKTHROUGH For K→ππ Lattice Calculations

K→2π ChPT

With DWQ in Quench Approx

1st application of BDSPW'84 with DWQ

Founding members Christ, Mawhinney, Blum, AS ~'98 →



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

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

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

[1]*RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973, USA*
[2]*Physics Department, Columbia University, New York, New York 10027, USA*
[3]*Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA*
[4]*Institute for Particle and Nuclear Studies, KEK, Tsukuba, Ibaraki, 305-0801, Japan*
[5]*IBM Research, Yorktown Heights, New York 10598, USA*

(Received 19 July 2002; published 30 December 2003)

We report the results of a calculation of the $K \to \pi\pi$ matrix elements relevant for the $\Delta I = 1/2$ rule and ϵ'/ϵ in quenched lattice QCD using domain wall fermions at a fixed lattice spacing $a^{-1} \sim 2$ GeV. Working in the three-quark effective theory, where only the u, d, and s quarks enter and which is known perturbatively to next-to-leading order, we calculate the lattice $K \to \pi$ and $K \to |0\rangle$ matrix elements of dimension six, four-fermion operators. Through lowest order chiral perturbation theory these yield $K \to \pi\pi$ matrix elements, which we then normalize to continuum values through a nonperturbative renormalization technique. For the ratio of isospin amplitudes $|A_0|/|A_2|$ we find a value of 25.3 ± 1.8 (statistical error only) compared to the experimental value of 22.2, with individual isospin amplitudes 10%–20% below the experimental values. For ϵ'/ϵ, using known central values for standard model parameters, we calculate $(-4.0 \pm 2.3) \times 10^{-4}$ (statistical error only) compared to the current experimental average of $(17.2 \pm 1.8) \times 10^{-4}$. Because we find a large cancellation between the $I=0$ and $I=2$ contributions to ϵ'/ϵ, the result may be very sensitive to the approximations employed. Among these are the use of quenched QCD, lowest order chiral perturbation theory, and continuum perturbation theory below 1.3 GeV. We also calculate the kaon B parameter B_K and find $B_{K,\overline{\mathrm{MS}}}(2\,\mathrm{GeV}) = 0.532(11)$. Although currently unable to give a reliable systematic error, we have control over statistical errors and more simulations will yield information about the effects of the approximations on this first-principles determination of these important quantities.

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

1st Large Scale Simulation with DWQ

RBC Collaboration

QCDSP ~98→~'05 1TF

RBC Collab'98

QA ; ChPT

PRD ~ 02

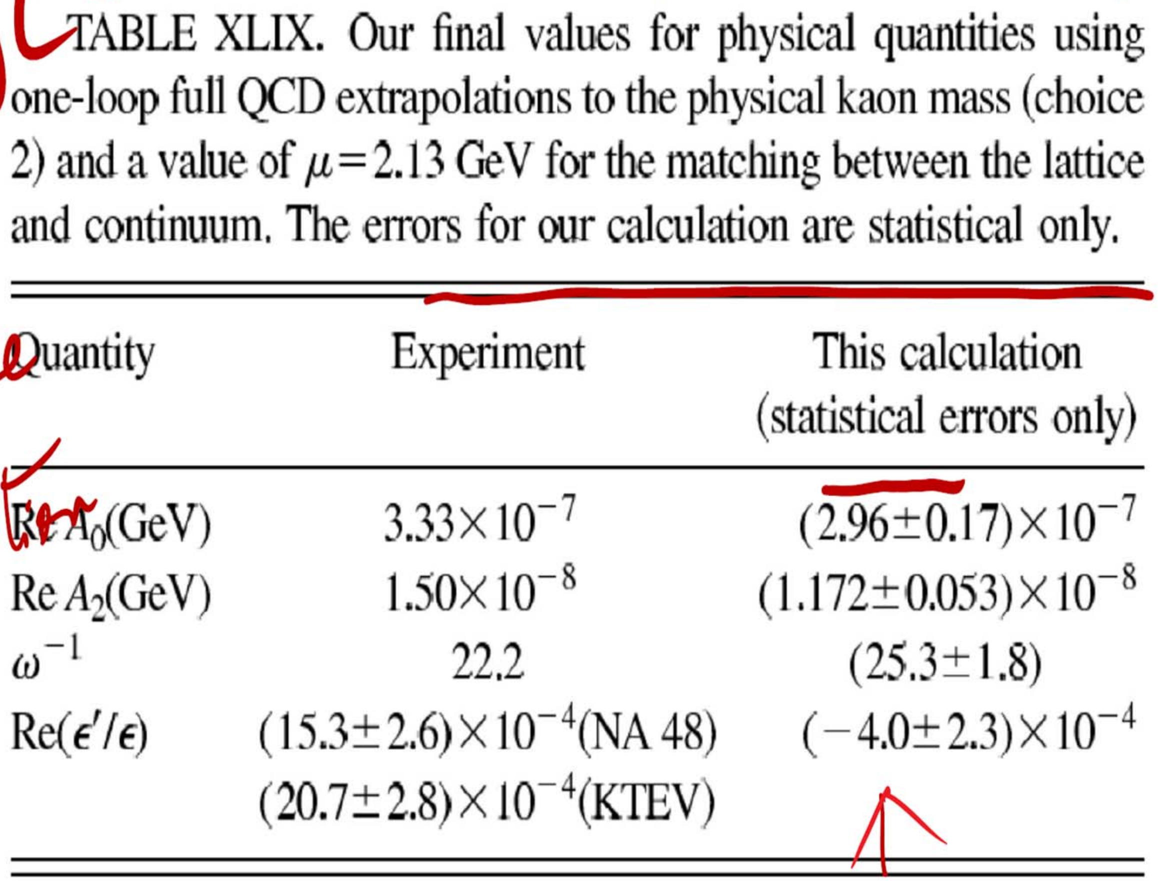


TABLE XLIX. Our final values for physical quantities using one-loop full QCD extrapolations to the physical kaon mass (choice 2) and a value of $\mu = 2.13$ GeV for the matching between the lattice and continuum. The errors for our calculation are statistical only. ←

DWQ
1st Large
Scale
simulation

Quantity	Experiment	This calculation (statistical errors only)
Re A_0(GeV)	3.33×10^{-7}	$(2.96 \pm 0.17) \times 10^{-7}$
Re A_2(GeV)	1.50×10^{-8}	$(1.172 \pm 0.053) \times 10^{-8}$
ω^{-1}	22.2	(25.3 ± 1.8)
Re(ϵ'/ϵ)	$(15.3 \pm 2.6) \times 10^{-4}$(NA 48) $(20.7 \pm 2.8) \times 10^{-4}$(KTEV)	$(-4.0 \pm 2.3) \times 10^{-4}$ ↑

RBC = RBRC + BNL + C[illegible]

CMP /01.

a new method

another key development for light meson physics from lattice

Direct K-> $\pi\pi$ (a la Lellouch-Luscher), using finite volume correlation* functions, [i.e. w/o ChPT] RBC initiates around 2006

CONTINUED BY RBC-UKQCD {(mostly) Edinburgh-Southampton}

* Allows to bypass Maini-Testa theorem

COMMON interest : use of DWQ for simulations

;

?

Results for ε'

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

EWP

QCDP

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

$$\boxed{= 1.38(5.15)(4.43) \times 10^{-4}, \quad 16.6(2.3) \times 10^{-4}}$$

LARGE CANCELLATION!!

RBC-UKQCD PRL'15
EDITOR'S CHOICE

(t

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

or

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

with expt
Computed ReA0 good agreement with expt
Offered an "explanation" of the Delta I=1/2 enhancement

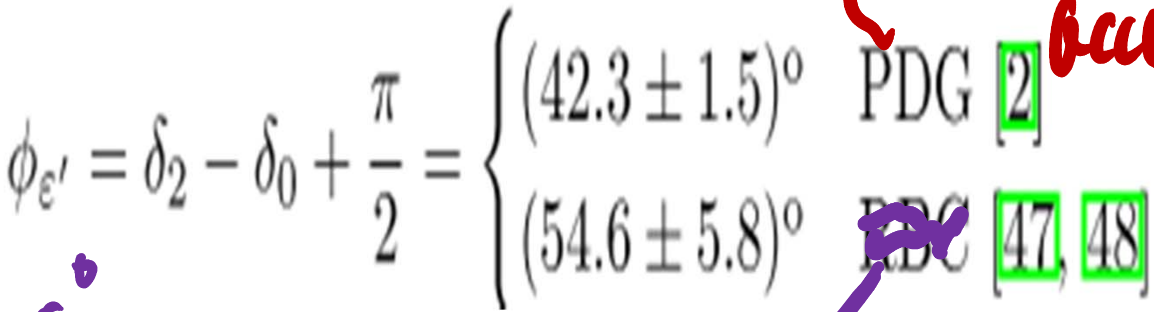
p
er
:

A possible difficulty: strong phases

- The continuum and our lattice determinations of strong phas

Not directly accessible to expt

diffe

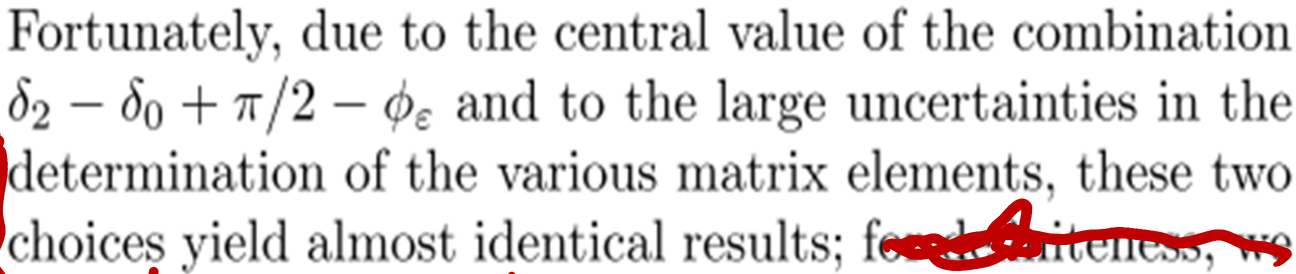


$$\phi_{\varepsilon'} = \delta_2 - \delta_0 + \frac{\pi}{2} = \begin{cases} (42.3 \pm 1.5)^{\circ} & \text{PDG [2]} \\ (54.6 \pm 5.8)^{\circ} & \text{RBC [47, 48]} \end{cases}.$$

RBC-UKQCD

-

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



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

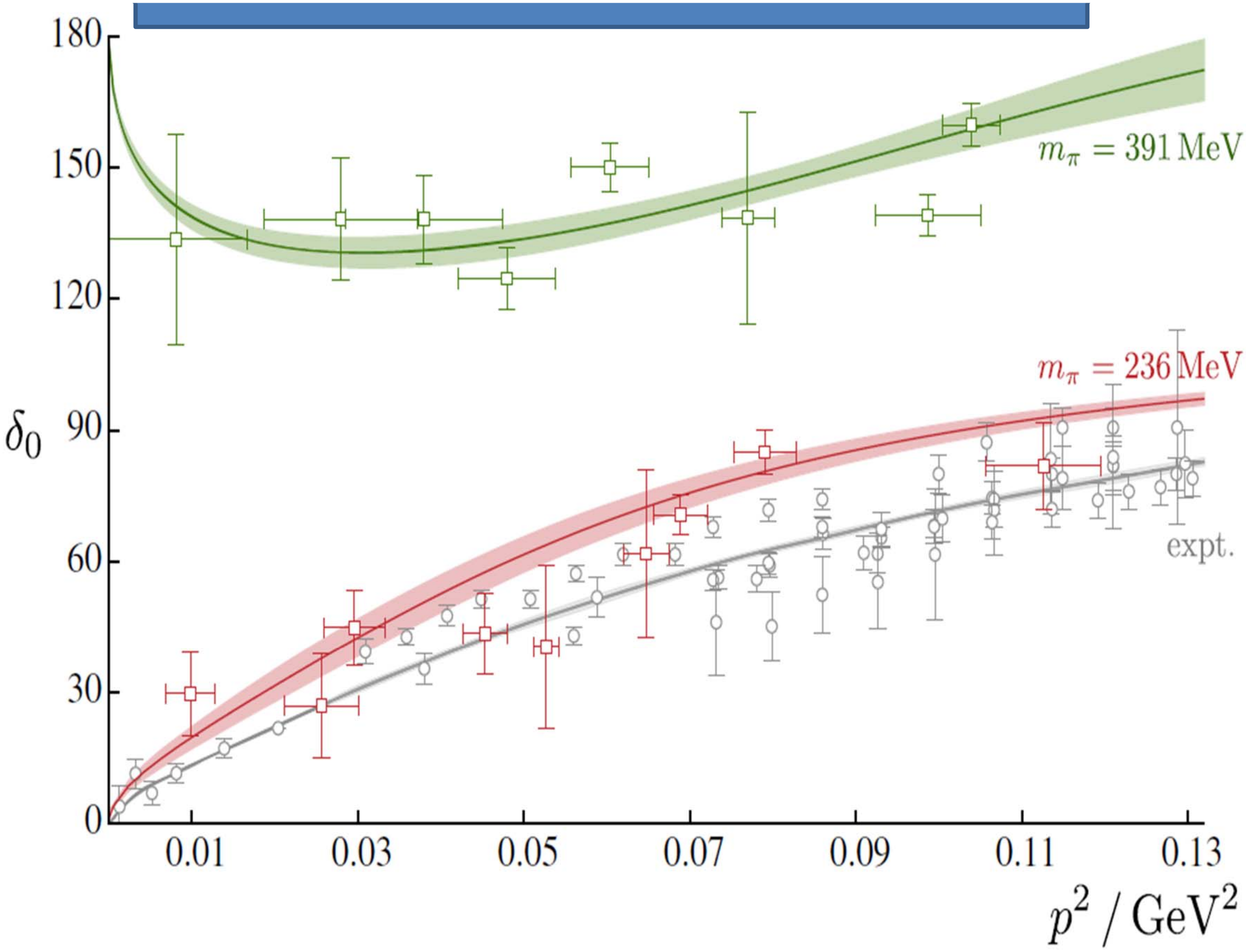
Lehner, Lunghi + AS, 1508.01801

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

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

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

PRL'17



RBC-UKQCD PRL 2015

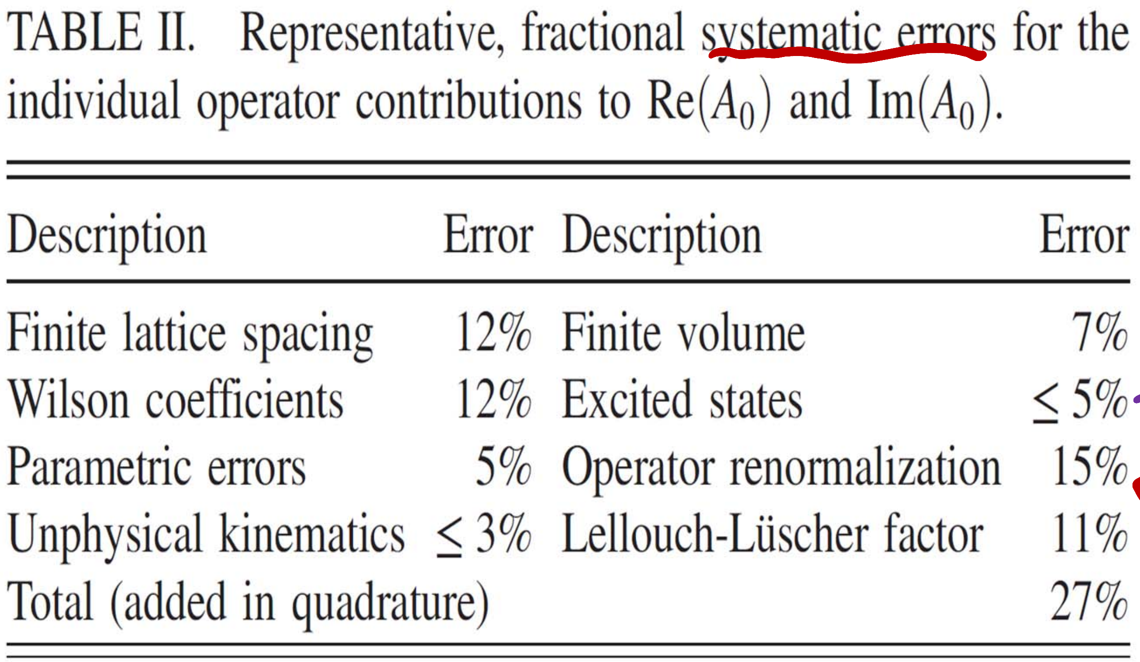


TABLE II. Representative, fractional systematic errors for the individual operator contributions to Re(A_0) and Im(A_0).

Description	Error	Description	Error
Finite lattice spacing	12%	Finite volume	7%
Wilson coefficients	12%	Excited states	$\leq 5\%$
Parametric errors	5%	Operator renormalization	15%
Unphysical kinematics	$\leq 3\%$	Lellouch-Lüscher factor	11%
Total (added in quadrature)			27%

Lattice *

* 2018

Re phases see talks by Tianle Wang & Chris Kelly Lattice 2018

75%

15%

$Q_2 =$


large cancellation

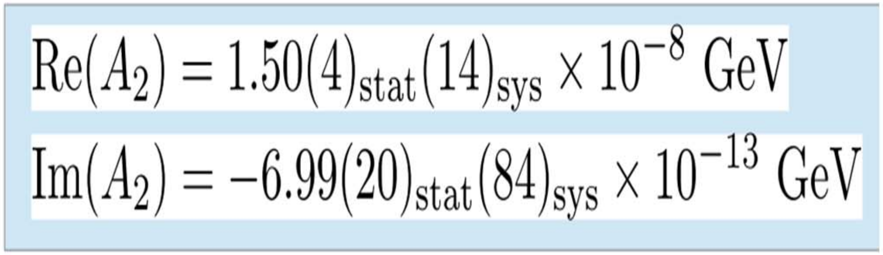
→ dominant

<1%

i	$\mathrm{Re}(A_0)(\mathrm{GeV})$	$\mathrm{Im}(A_0)(\mathrm{GeV})$
1	$1.02(0.20)(0.07) \times 10^{-7}$	0
2	$3.63(0.91)(0.28) \times 10^{-7}$	0
3	$-1.19(1.58)(1.12) \times 10^{-10}$	$1.54(2.04)(1.45) \times 10^{-12}$
4	$-1.86(0.63)(0.33) \times 10^{-9}$	$1.82(0.62)(0.32) \times 10^{-11}$
5	$-8.72(2.17)(1.80) \times 10^{-10}$	$1.57(0.39)(0.32) \times 10^{-12}$
6	$3.33(0.85)(0.22) \times 10^{-9}$	$-3.57(0.91)(0.24) \times 10^{-11}$
7	$2.40(0.41)(0.00) \times 10^{-11}$	$8.55(1.45)(0.00) \times 10^{-14}$
8	$-1.33(0.04)(0.00) \times 10^{-10}$	$-1.71(0.05)(0.00) \times 10^{-12}$
9	$-7.12(1.90)(0.46) \times 10^{-12}$	$-2.43(0.65)(0.16) \times 10^{-12}$
10	$7.57(2.72)(0.71) \times 10^{-12}$	$-4.74(1.70)(0.44) \times 10^{-13}$
Tot	$4.66(0.96)(0.27) \times 10^{-7}$	$-1.90(1.19)(0.32) \times 10^{-11}$

TABLE I. Contributions to A_0 from the ten continuum, $\overline{\mathrm{MS}}$ operators $Q_i(\mu)$, for $\mu = 1.53$ GeV. Two statistical errors are shown: one from the lattice matrix element (left) and one from the lattice to $\overline{\mathrm{MS}}$ conversion (right).

continuum limit #s → Expt 1.48×10^{-8} GeV

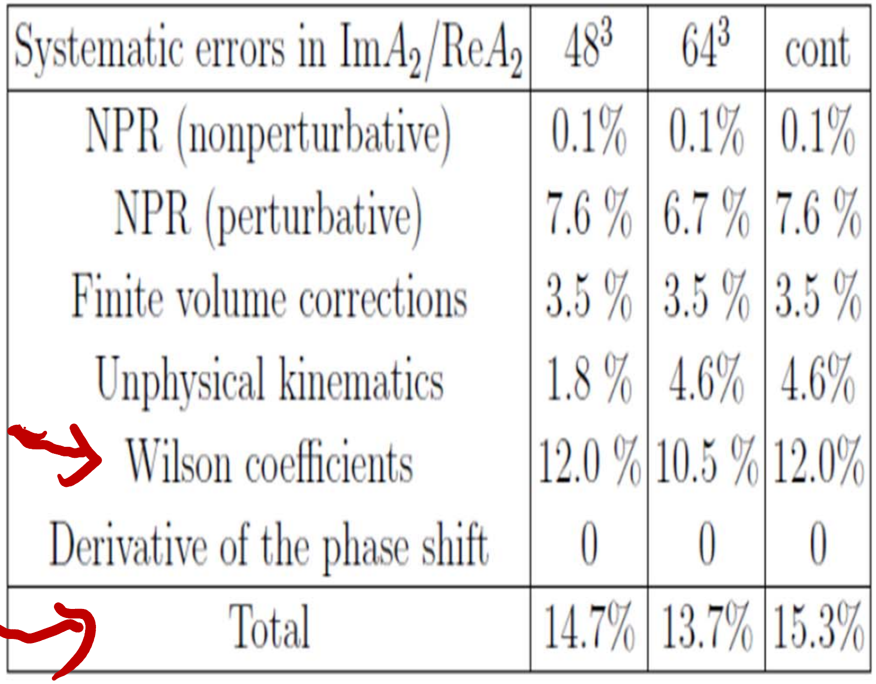


$$\mathrm{Re}(A_2) = 1.50(4)_{\rm stat}(14)_{\rm sys} \times 10^{-8}\ \mathrm{GeV}$$

$$\mathrm{Im}(A_2) = -6.99(20)_{\rm stat}(84)_{\rm sys} \times 10^{-13}\ \mathrm{GeV}$$

10%, 12% total errors on Re, Im!

- Systematic error completely dominated by perturbative error on NPR and Wilson coefficients! !!
- Future considerations:
  - Higher order PT calculation of NPR and Wilson coeffs.
  - Step-scaling NPR to higher energy scale.



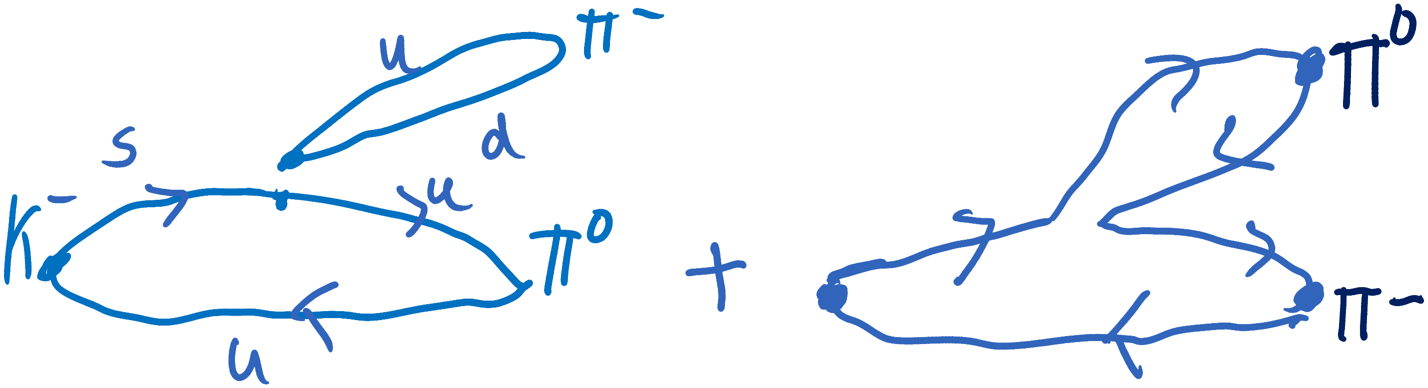
Systematic errors in $\mathrm{Im}A_2/\mathrm{Re}A_2$	48^3	64^3	cont
NPR (nonperturbative)	0.1%	0.1%	0.1%
NPR (perturbative)	7.6 %	6.7 %	7.6 %
Finite volume corrections	3.5 %	3.5 %	3.5 %
Unphysical kinematics	1.8 %	4.6%	4.6%
→ Wilson coefficients	12.0 %	10.5 %	12.0%
Derivative of the phase shift	0	0	0
→ Total	14.7%	13.7%	15.3%

TABLE XIII: Systematic error breakdown for $\mathrm{Im}A_2/\mathrm{Re}A_2$.

WILSON Coeff to NLO are the limiting error NOT LATTICE

Need NNLO W.C.

Dissecting 3/2 Amp on the lattice

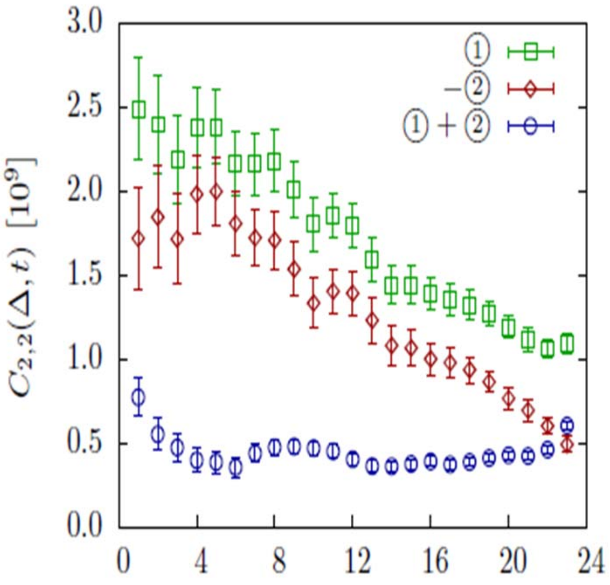


$\mathrm{Tr} \times \mathrm{Tr}$

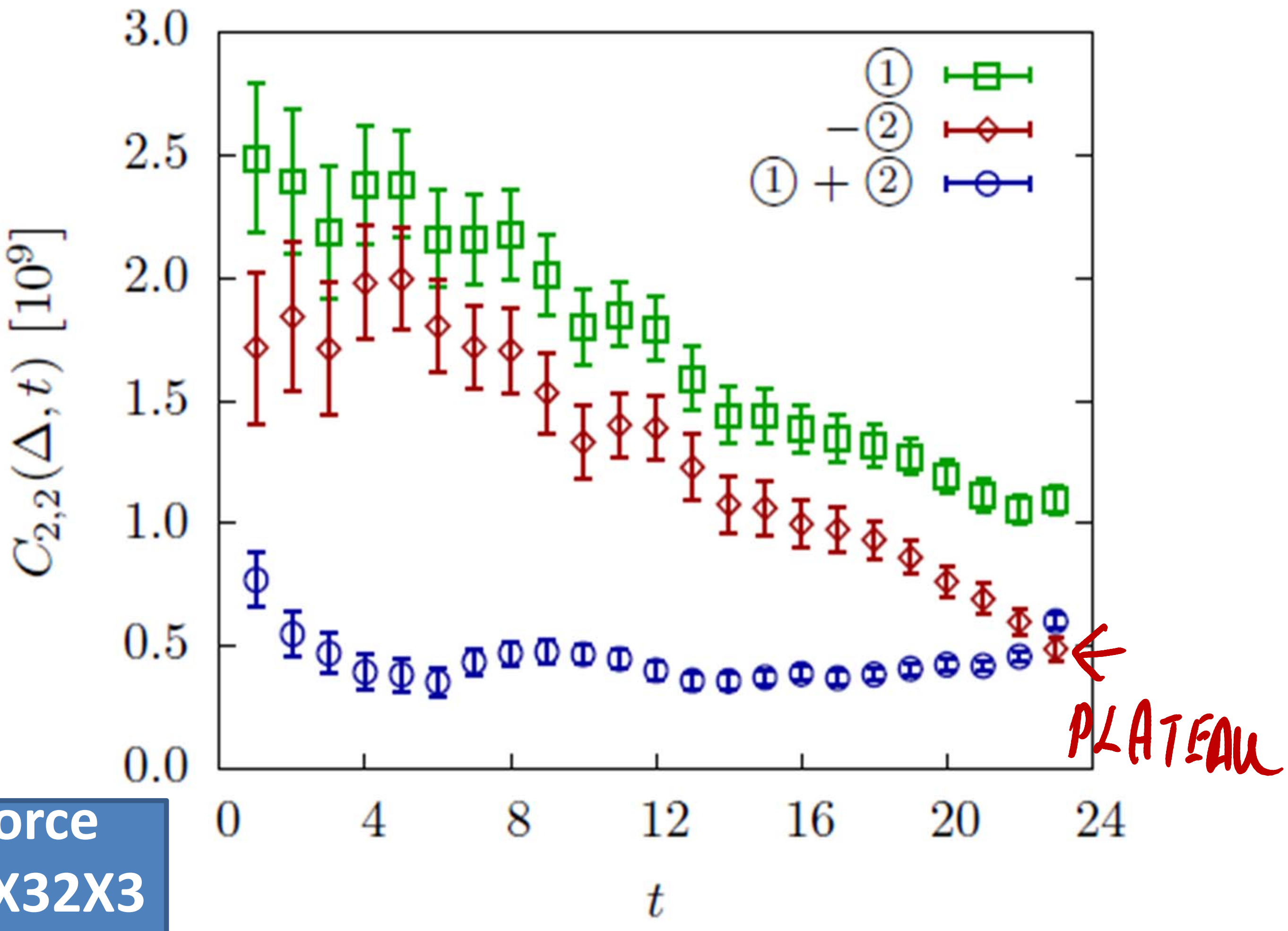
(N^2)

$\mathrm{Tr}\,(N)$

Simplest basic step is Significantly different from phenomenological expectations



DRAMATIC CANCELLATION!



force
32X32X3
2X
64X

FIG. 2: Contractions ①, -② and ① + ② as functions of t from the simulation at physical kinematics and with $\Delta = 24$.

QCDOC 10 Tf

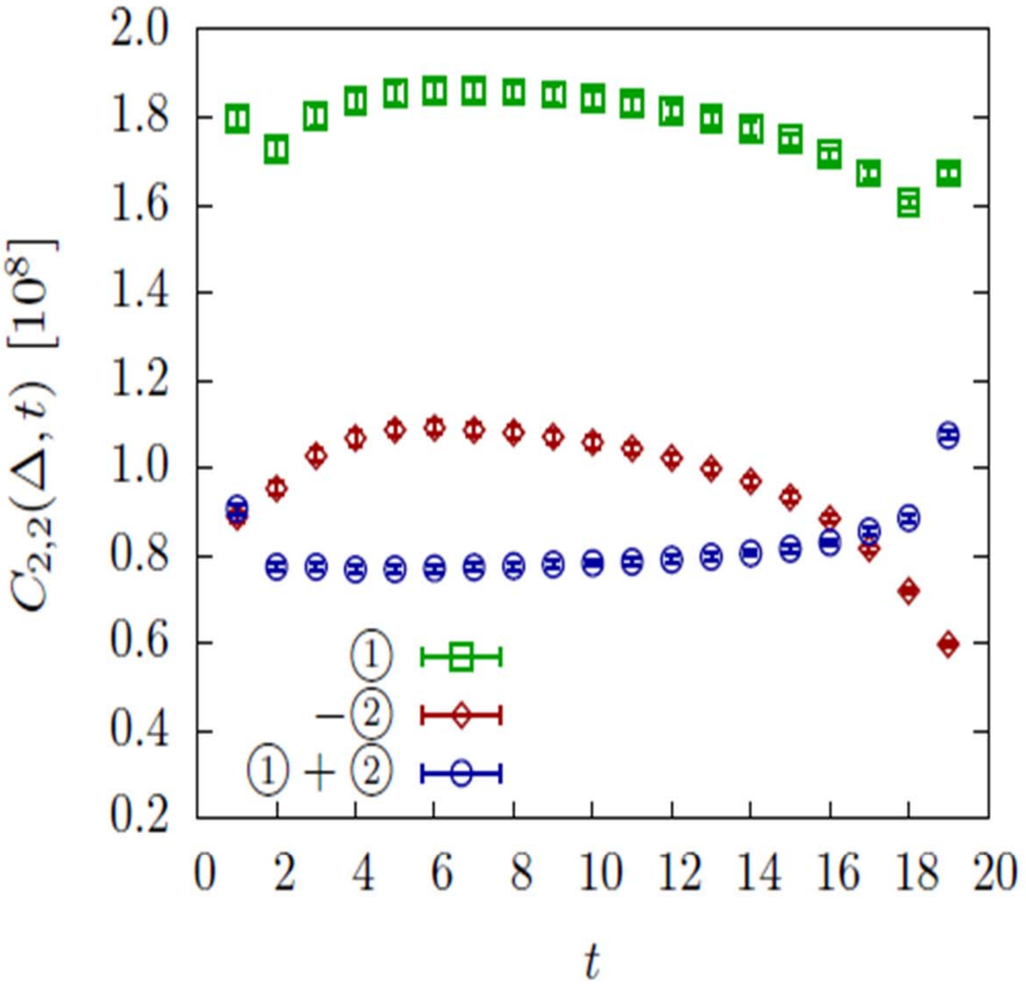
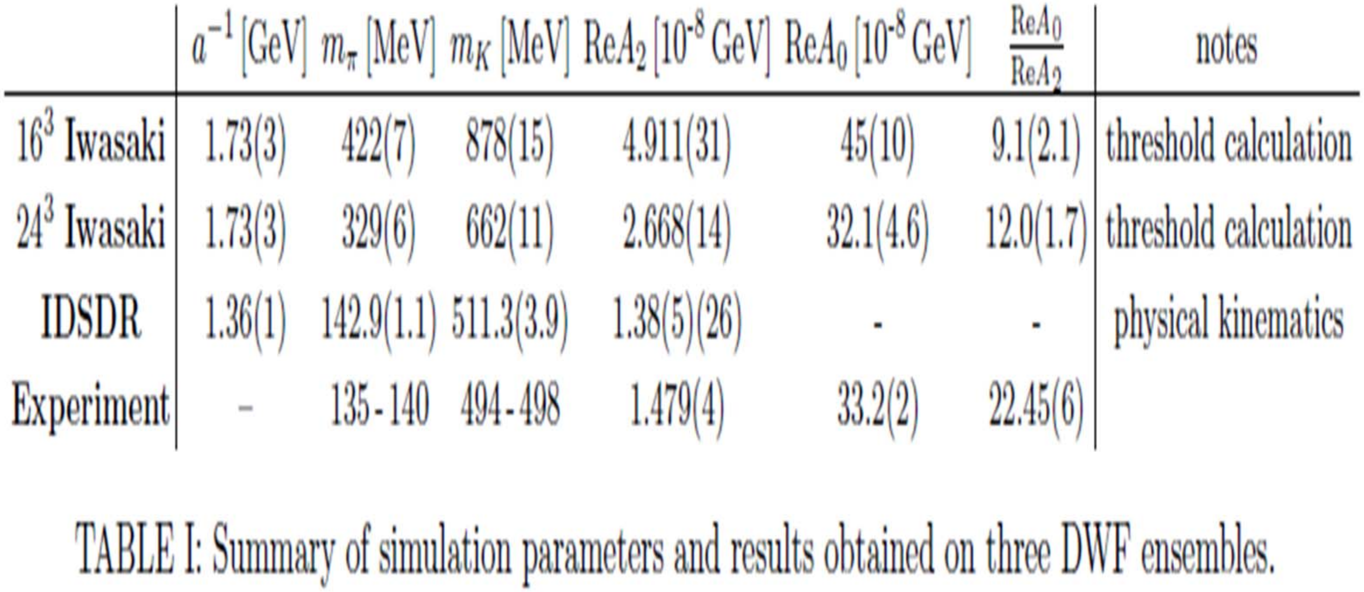


FIG. 3: Contractions ①, -② and ① + ② as functions of t from the simulation at threshold with $m_\pi \simeq 330\,\mathrm{MeV}$ and $\Delta = 20$.

Mass depends of ReA2, A0

PRL
2013

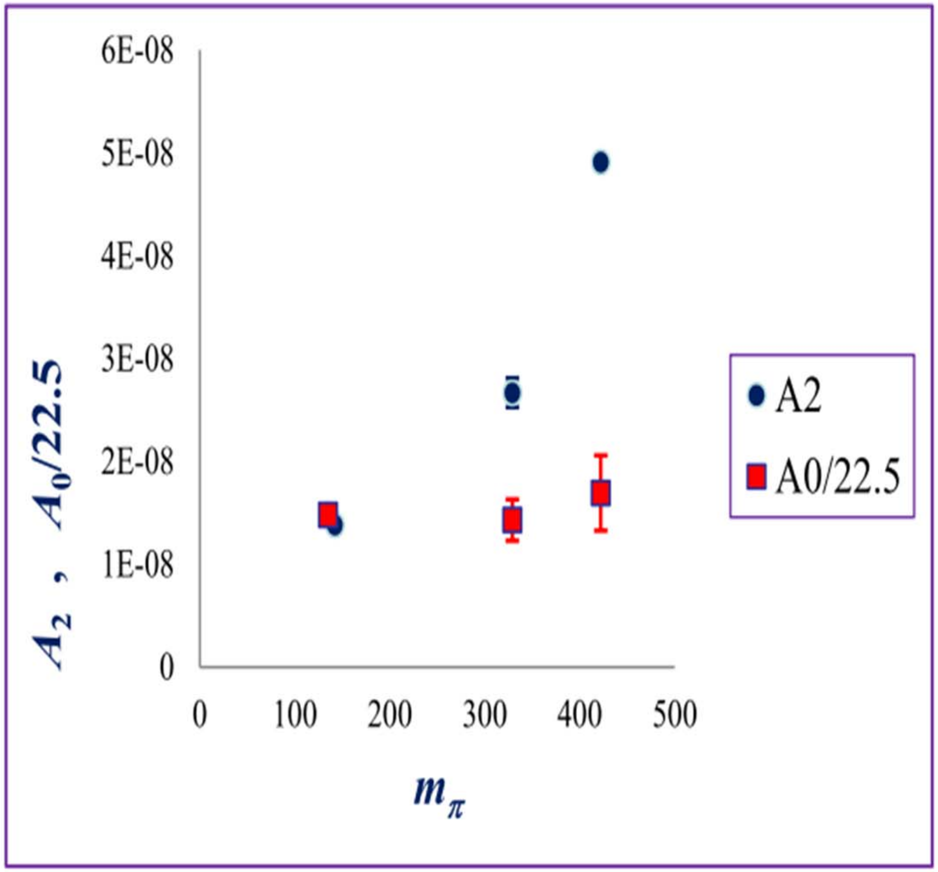


	a^{-1} [GeV]	m_π [MeV]	m_K [MeV]	$\mathrm{Re}A_2$ [10^{-8} GeV]	$\mathrm{Re}A_0$ [10^{-8} GeV]	$\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2}$	notes
16^3 Iwasaki	1.73(3)	422(7)	878(15)	4.911(31)	45(10)	9.1(2.1)	threshold calculation
24^3 Iwasaki	1.73(3)	329(6)	662(11)	2.668(14)	32.1(4.6)	12.0(1.7)	threshold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

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

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

Compare A_2 and $A_0/22.5$



NHCl
KITP,
Aug '15

Improvements in lattice Ɛ' determination underway for past ~3 years

[Previous result uses 215 configs]

- Statistics X [> ~ 5] now aiming for
- Systematics…..some already done..

EMI

- EM+ isospin….

$\delta[\mathrm{Im}\,A_0] \sim (15 \pm 8)\%$

Cirigliano et al '04

- Completely diff method(s)

TB student

- A) excited pipi state
- B) Revisit ChPT

→ BDSPW '84; LAIHO + AS ~'04

$LO\chi PT$ NLO

RBC-UKQCD D Murphy et al [1511.01950]

D. HOYING

Best guesses

EXPECTATIONS FOR IMPROVED DETERMINATION OF IMA0 IN ANOTHER ~3 YEARS……Δ[IMA0] ~10%(ST);15%(SY)=> 18% (TOTAL)

2015 60% 27%

THANK YOU ALL!

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**

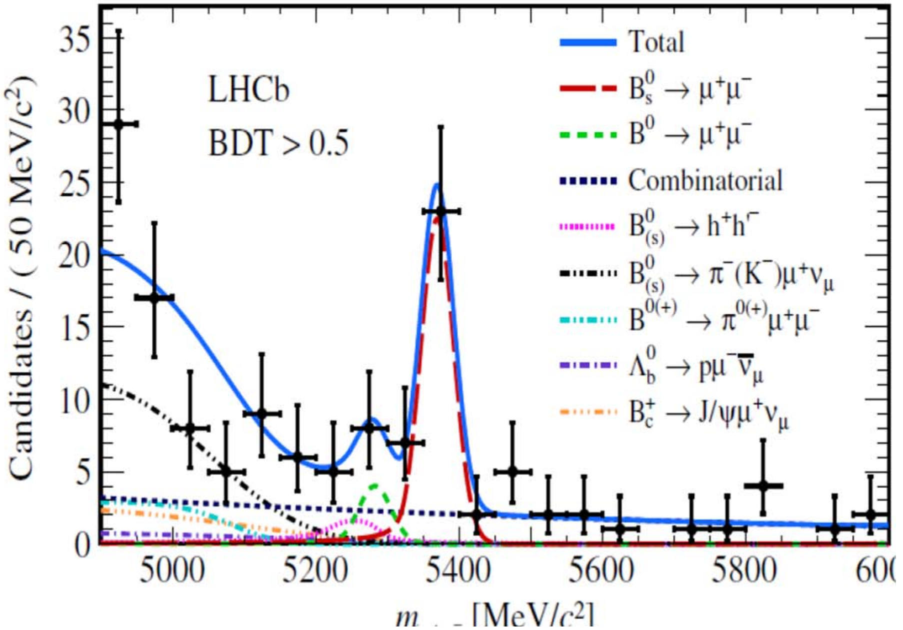
$$\boxed{\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}}$$

First observation by a single experiment with 7.8 σ significance

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

No evidence

Smaller compared to Run1 measurement



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

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**

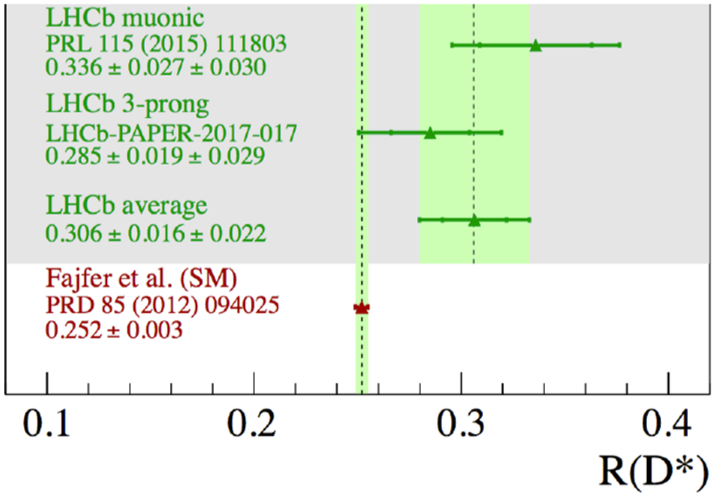
Summary and Outlook …p.3

- **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

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.



LHCb Seminar CERN
6/6/'17

World average

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

  $R(D^*) = 0.285 \pm 0.019(\text{stat}) \pm 0.025(\text{syst}) \pm 0.014(\text{ext})$

- In combination with the muonic LHCb measurement:

  $R(D^*) = 0.336 \pm 0.027 \pm 0.030$,

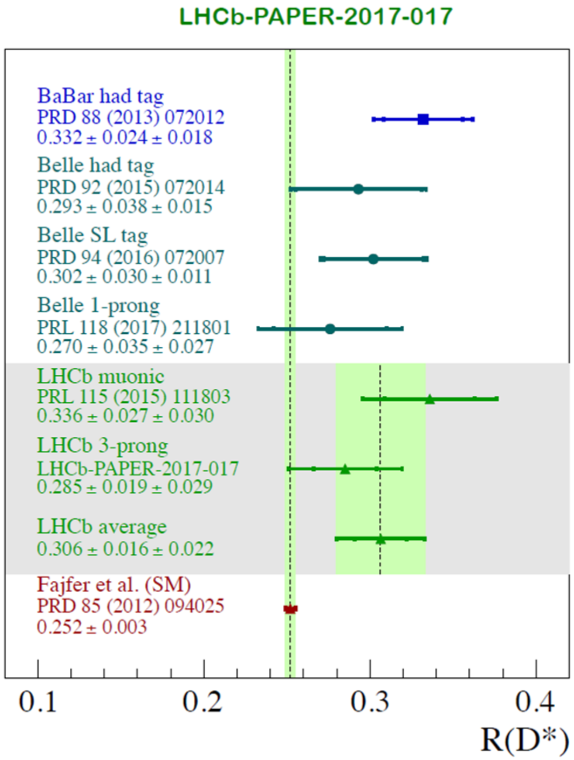
  the LHCb average is:

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

- Naïve new WA:
  - $R(D^*) = 0.305 \pm 0.015$
  - 3.4σ above the SM.

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

Total of 6



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

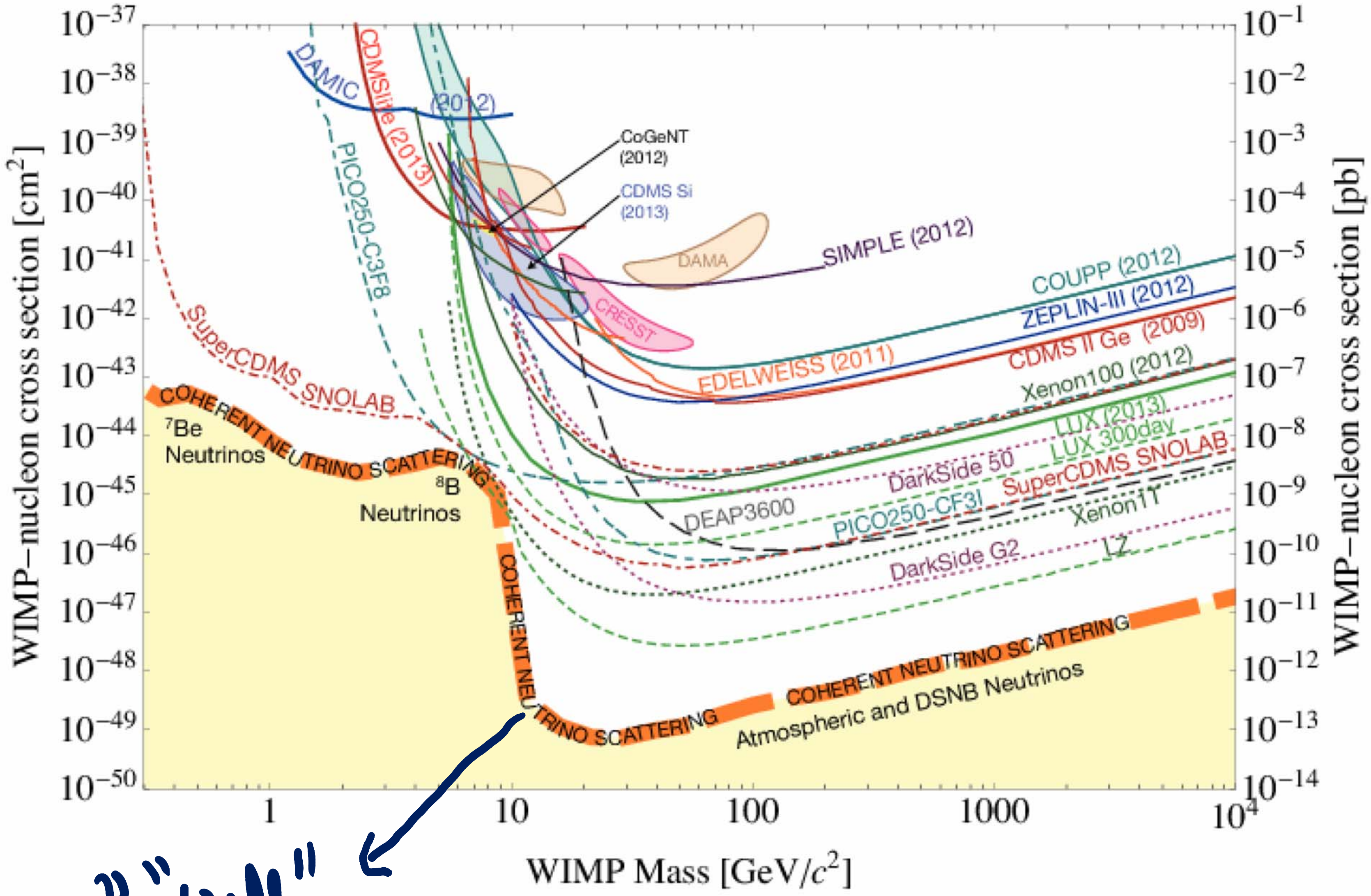
4% $R(D^*) = 0.258^{+9}_{-8}$ Bigi et al EPS July

$R_{D^*} \sim .254 \pm .020$

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)

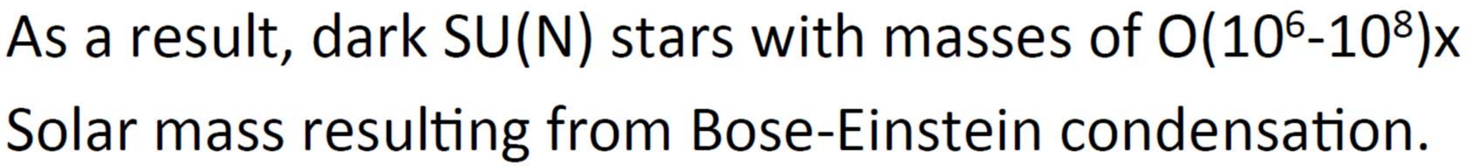
- Dark matter only interacts with normal: (detector) matter via loop effects which are suppressed. Makes direct detection of dark matter more difficult (explains negative findings.)

↑ 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**

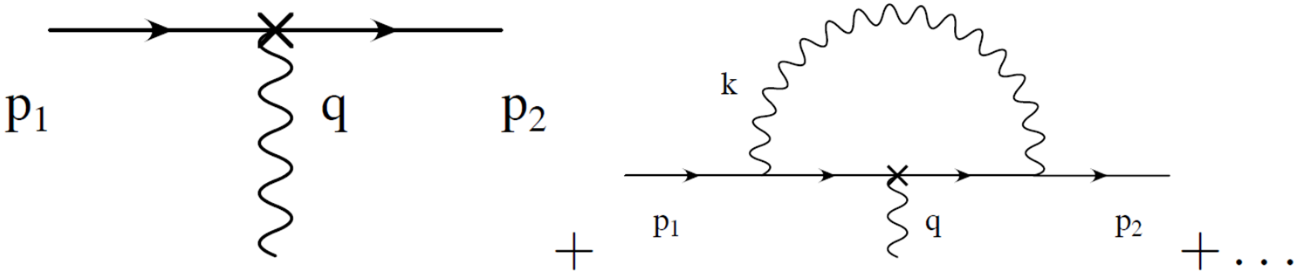


As a result, dark SU(N) stars with masses of O(10^6-10^8)x Solar mass resulting from Bose-Einstein condensation.

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

The magnetic moment of the muon

In interacting quantum (field) theory g gets corrections



$$\gamma^\mu \quad \rightarrow \quad \Gamma^\mu(q) = \left(\gamma^\mu F_1(q^2) + \frac{i\,\sigma^{\mu\nu}\, q_\nu}{2m} F_2(q^2) \right)$$

which results from Lorentz and gauge invariance when the muon is on-mass-shell.

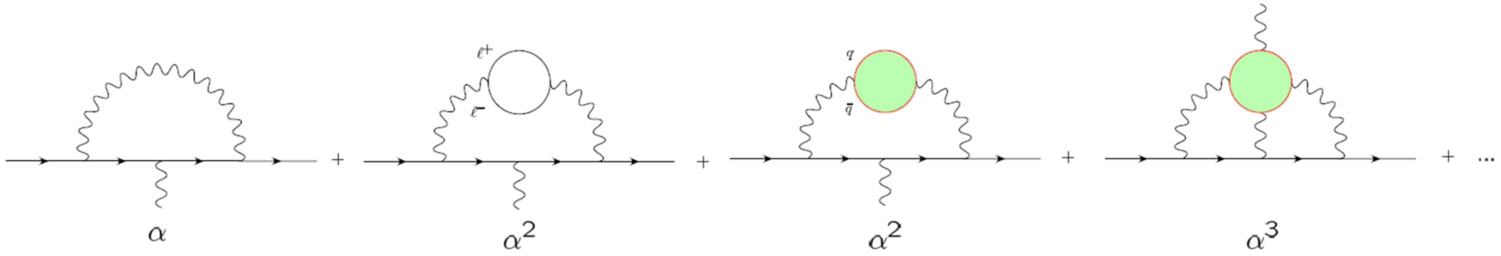
$$F_2(0) \quad = \quad \frac{g-2}{2} \equiv a_\mu \qquad\qquad (F_1(0) = 1)$$

(the anomalous magnetic moment, or anomaly)

The magnetic moment of the muon

Compute these corrections order-by-order in perturbation theory by expanding $\Gamma^\mu(q^2)$ in QED coupling constant

$$\alpha = \frac{e^2}{4\pi} = \frac{1}{137} + \ldots$$



Corrections begin at $\mathcal{O}(\alpha)$; Schwinger term $= \frac{\alpha}{2\pi} = 0.0011614\ldots$

<u>hadronic contributions</u> $\sim 6 \times 10^{-5}$ times smaller (leading error).

New experiments + new theory = (?) new physics

muon anomaly a_μ provides important test of the SM

- BNL E821: $a_\mu^{\rm exp}$ accuracy is 0.54 ppm
- Fermilab E989, start is ∼ 3 years away, goal is 0.14 ppm
- J-PARC E34
- $a_\mu(\text{Expt})$-$a_\mu(\text{SM}) = 287(63)(51)$ ($\times 10^{-11}$), or $\sim 3.6\sigma$
- If both central values stay the same,
  - E989 (∼ 4× smaller error) $\rightarrow\sim 5\sigma$
  - E989+new HLBL theory (models+lattice, 10%) $\rightarrow\sim 6\sigma$
  - E989+new HLBL +new HVP (50% reduction) $\rightarrow\sim 8\sigma$
- Big discrepancy! (New Physics ∼ 2× Electroweak)
- Lattice calculations crucial

Pieces of Muon $g-2$ Theory Prediction

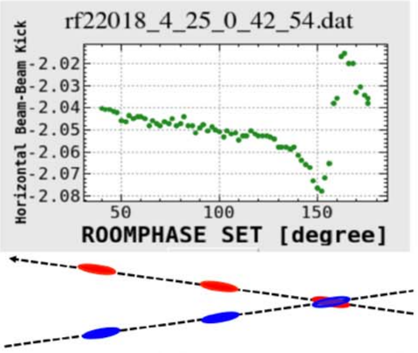
Contribution	Value $\times 10^{10}$	Uncertainty $\times 10^{10}$
QED	11 658 471.895	0.008
EW	15.4	0.1
HVP LO	692.5	2.7
HVP NLO	-9.84	0.06
HVP NNLO	1.24	0.01
Hadronic light-by-light	10.5	2.6
Total SM prediction	11 659 181.7	3.8
BNL E821 result	11 659 209.1	6.3
Fermilab E989 target		≈ 1.6

Experiment-Theory difference is 27.4(7.3) $\Longrightarrow$ 3.7σ tension!

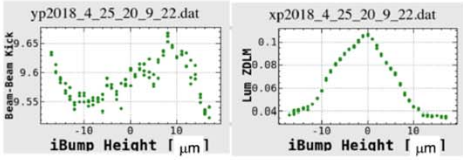
First collision

Apr. 26, 2018

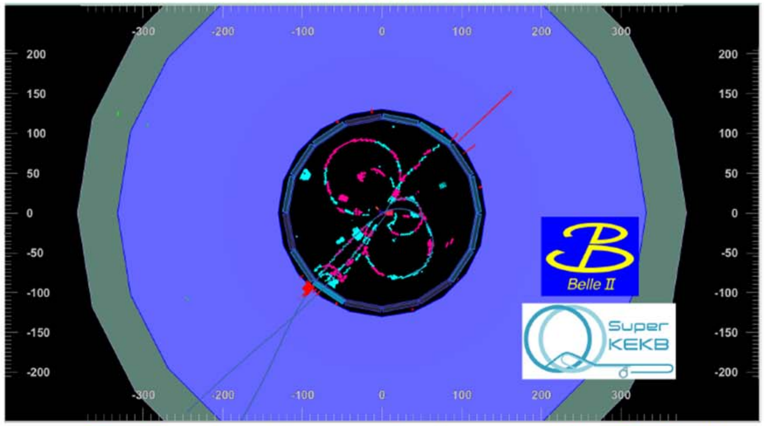
Belle II control room



Horizontal beam-beam kick



Vertical beam-beam kick



First hadronic event observed by Belle II

SuperKEKB control room

K. Akai, SuperKEKB/Belle II status, ICHEP2018, July 9, 2018

Toru Iijima @ SCGP May 31, 2018

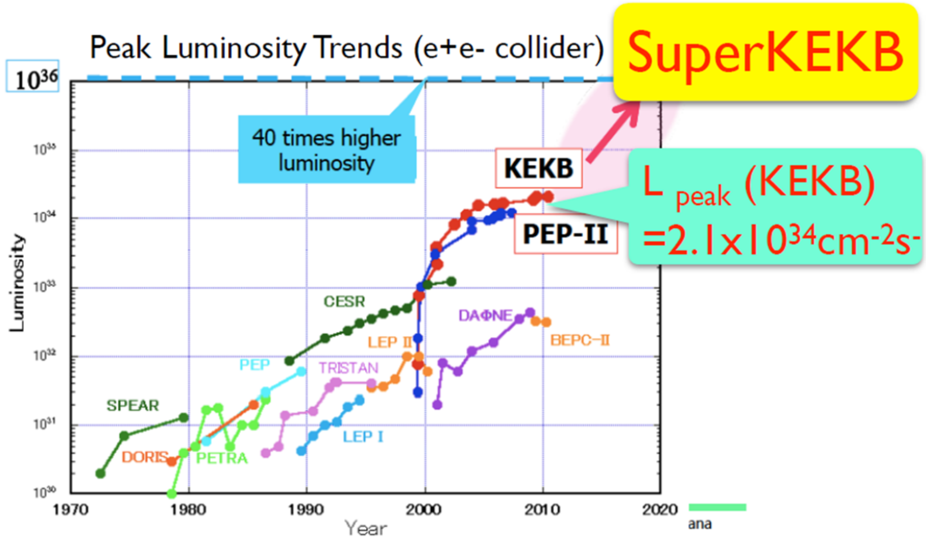
SuperKEKB/Belle II

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 !

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



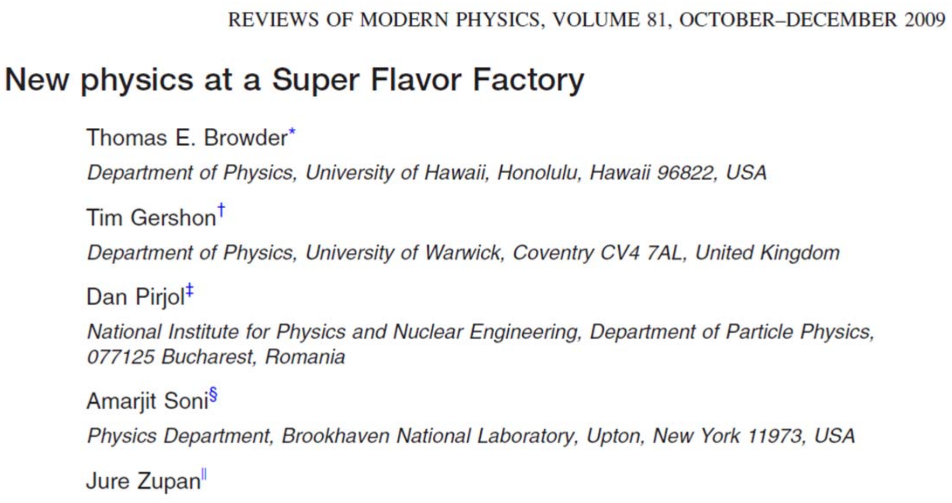
Peak Luminosity Trends (e+e- collider)

SuperKEKB

40 times higher luminosity

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

The first particle collider after the LHC !



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

Tim Gershon[†]
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

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	—

SM Prediction

we took RD* = 0.257 ± .005

Fajfer, Kamenik, Nisandzic, PRD'12

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.

Very timely & useful phenomenological study by BLPR 2017