A PATH TO FALVOR

Benjamin Grinstein
(UC San Diego)

Implications of LHCb measurements and future prospects
the 2019 edition of a series of workshops between the LHCb collaboration and the theory community

CERN
16-18 October 2019

PHYSICS BRIEFING BOOK

INPUT FOR THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS UPDATE 2020

- Just came out 2 weeks ago
- LHCb is often mentioned
- We learn that
    - *The LHCb Upgrade II, combined with the enhanced B-physics capabilities of ATLAS and CMS Phase II upgrades, will enable a wide range of flavour observables to be determined at HL- LHC with unprecedented precision, complementing and extending the reach of Belle II, and of the high transverse-momentum physics programme.*
- And yet
    - *In the mid-term planning in Europe, much can be gained from the Upgrade II of the LHCb experiment for the HL-LHC, that is still pending approval, in addition to the hope that the pending question of lepton number universality will be fully resolved.*
- Pending approval; resolve LUV. uh?
- I am not sure who writes this stuff, but it is priceless:
    - *The* ***search for flavour*** *and CP violation in the quark and lepton sectors at different energy frontiers has a great potential to lead to new physics at moderate cost and therefore flavour physics should remain at the forefront of the European Strategy.*

IMPLICATIONS OF LHCB MEASUREMENTS AND FUTURE PROSPECTS

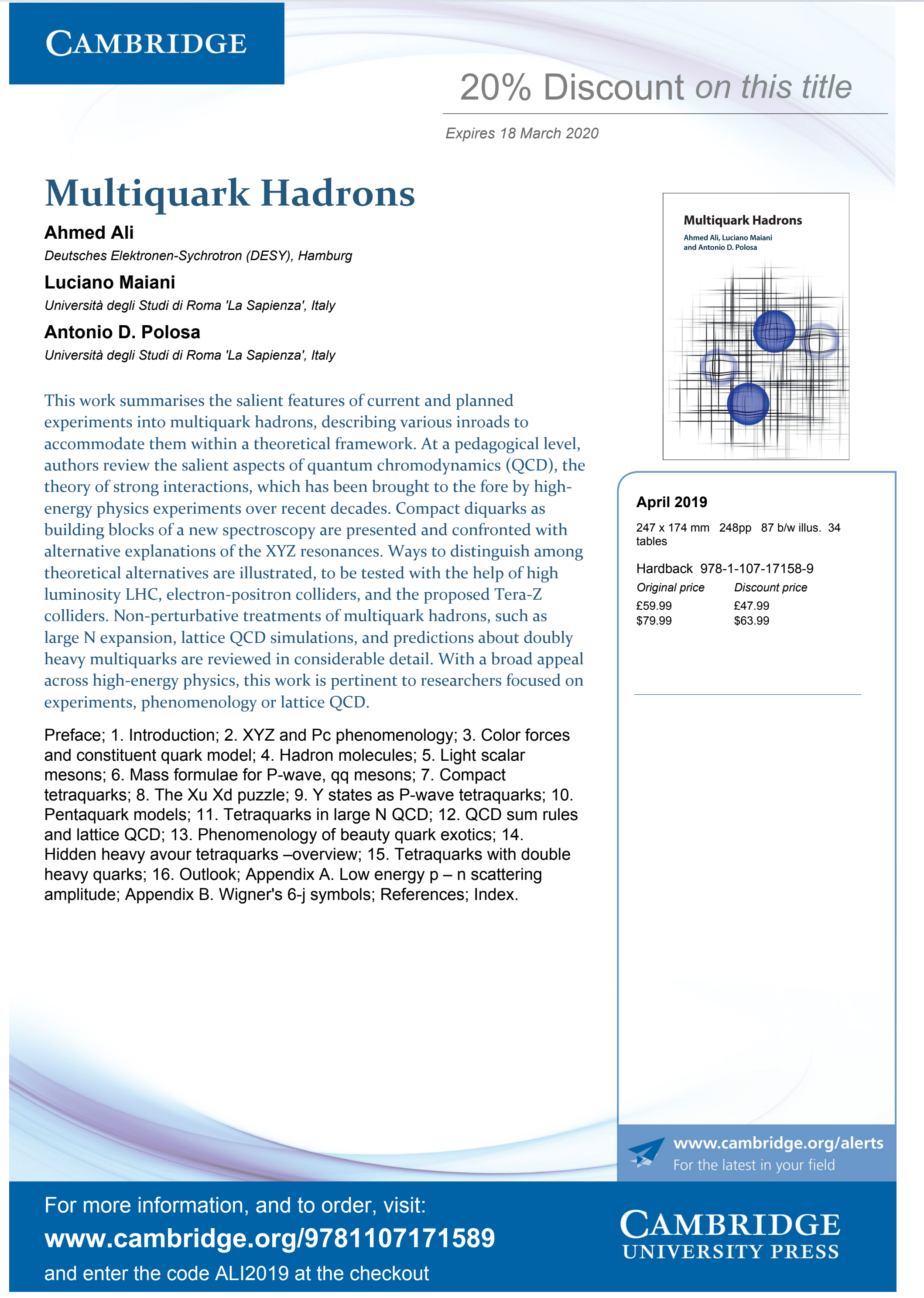
- 4 Streams:
  - Mixing and CP violation in Beauty and Charm
  - Semileptonic decays, rare decays, and tests of lepton flavour universality
  - Electroweak physics, heavy flavour production, implications for (n)PDFs, heavy ions, and exotica searches
  - QCD spectroscopy and exotic hadrons

- Physics Briefing Book
  - EW chapter : no mention of LHCb
  - QCD chapter:
    - Heavy ion program (several times)
    - PDFs (once)
    - X(3842) (once, in lattice QCD context)

You will excuse me for going along with tha-book, I will concentrate on flavor
(only a couple of slides on XYZ)

A mature field now

A mature field now



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Expires 18 March 2020

Multiquark Hadrons

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This work summarises the salient features of current and planned experiments into multiquark hadrons, describing various inroads to accommodate them within a theoretical framework. At a pedagogical level, authors review the salient aspects of quantum chromodynamics (QCD), the theory of strong interactions, which has been brought to the fore by high-energy physics experiments over recent decades. Compact diquarks as building blocks of a new spectroscopy are presented and confronted with alternative explanations of the XYZ resonances. Ways to distinguish among theoretical alternatives are illustrated, to be tested with the help of high luminosity LHC, electron-positron colliders, and the proposed Tera-Z colliders. Non-perturbative treatments of multiquark hadrons, such as large N expansion, lattice QCD simulations, and predictions about doubly heavy multiquarks are reviewed in considerable detail. With a broad appeal across high-energy physics, this work is pertinent to researchers focused on experiments, phenomenology or lattice QCD.

Preface; 1. Introduction; 2. XYZ and Pc phenomenology; 3. Color forces and constituent quark model; 4. Hadron molecules; 5. Light scalar mesons; 6. Mass formulae for P-wave, qq mesons; 7. Compact tetraquarks; 8. The Xu Xd puzzle; 9. Y states as P-wave tetraquarks; 10. Pentaquark models; 11. Tetraquarks in large N QCD; 12. QCD sum rules and lattice QCD; 13. Phenomenology of beauty quark exotics; 14. Hidden heavy flavour tetraquarks –overview; 15. Tetraquarks with double heavy quarks; 16. Outlook; Appendix A. Low energy p – n scattering amplitude; Appendix B. Wigner's 6-j symbols; References; Index.

April 2019

247 x 174 mm 248pp 87 b/w illus. 34 tables

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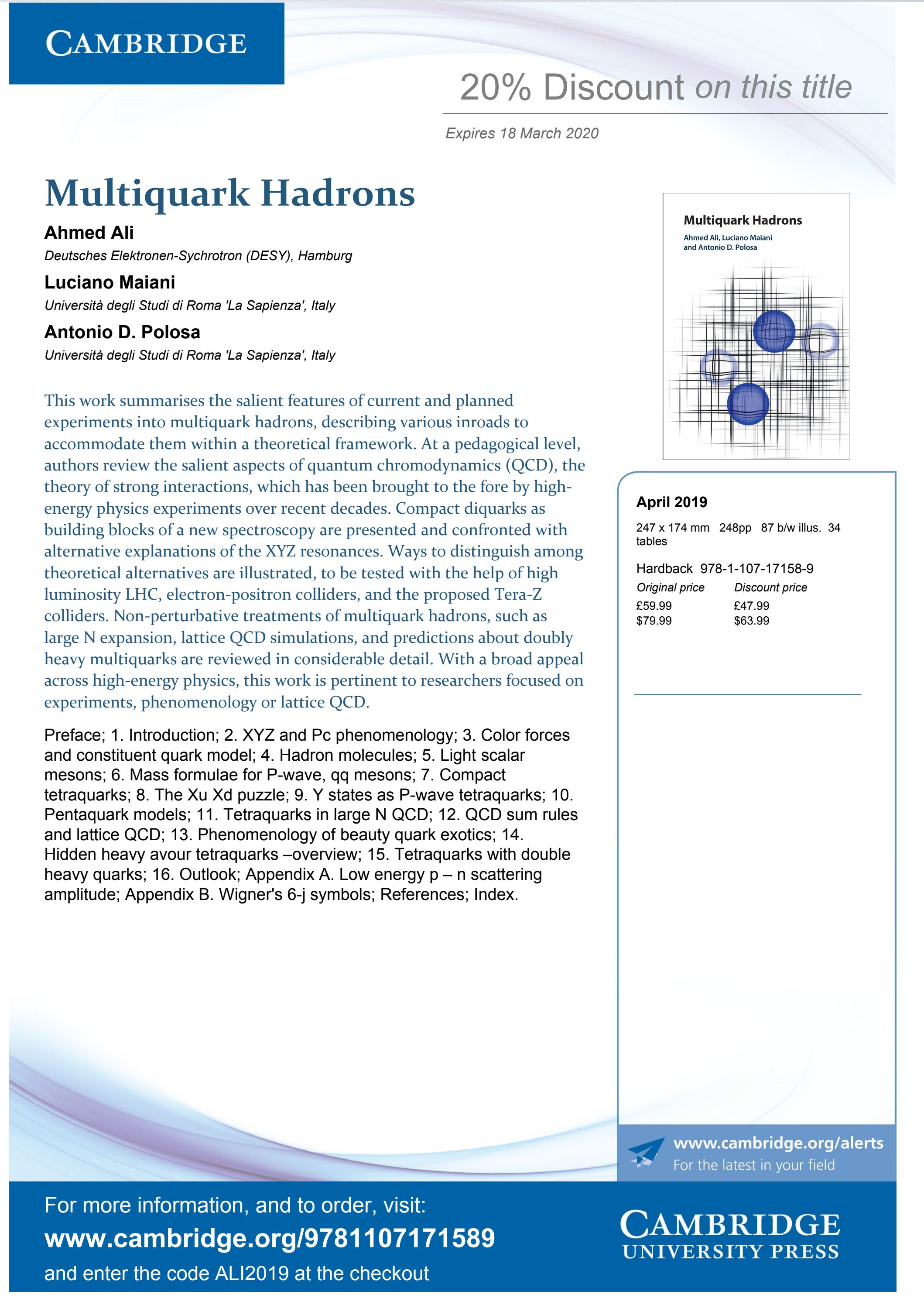
A mature field now

LHCb is killing it!



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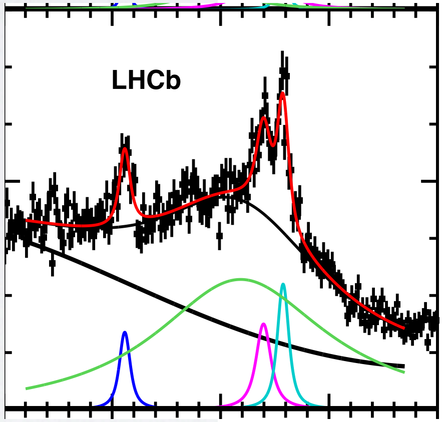
incredibble precision, eg

2015:

[Tomasz Skwarnicki, Exotic Hadrons, Shnaghai 2019]

$P_c(4450)^+$ $M = 4450 \pm 2 \pm 3\ MeV$
$\Gamma = 39 \pm 5 \pm 19\ MeV$
$F.F. = 4.1 \pm 0.5 \pm 1.1\ \%$

$P_c(4380)^+$ $M = 4380 \pm 8 \pm 29\ MeV$
$\Gamma = 205 \pm 18 \pm 86\ MeV$
$F.F. = 8.4 \pm 0.7 \pm 4.2\ \%$



2019: [LHCb, Phys.Rev.Lett. 122 (2019) no.22, 222001]

State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

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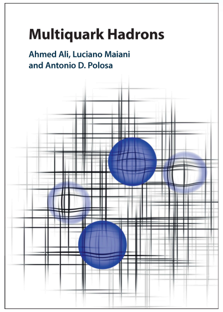

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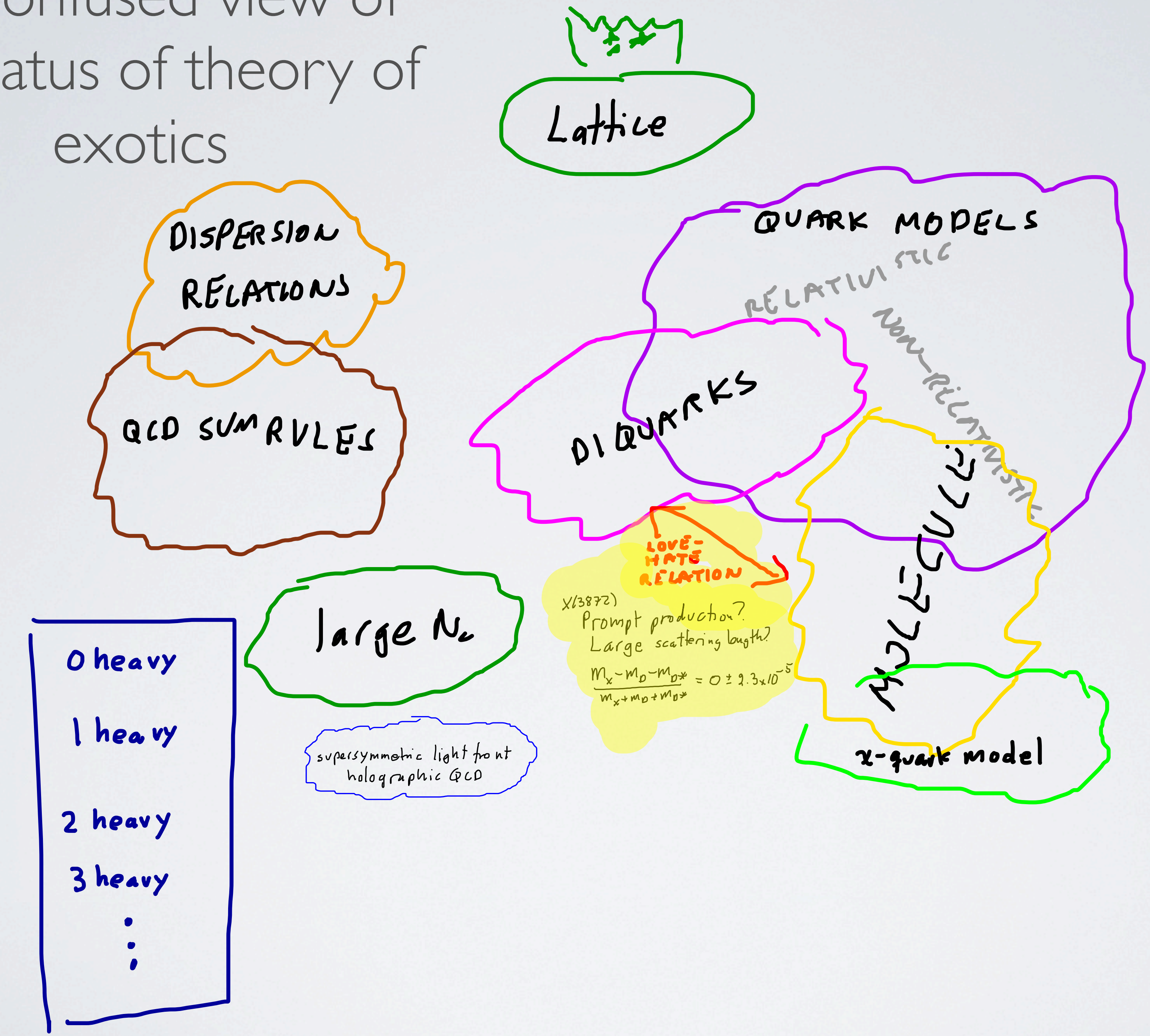
My confused view of the status of theory of exotics



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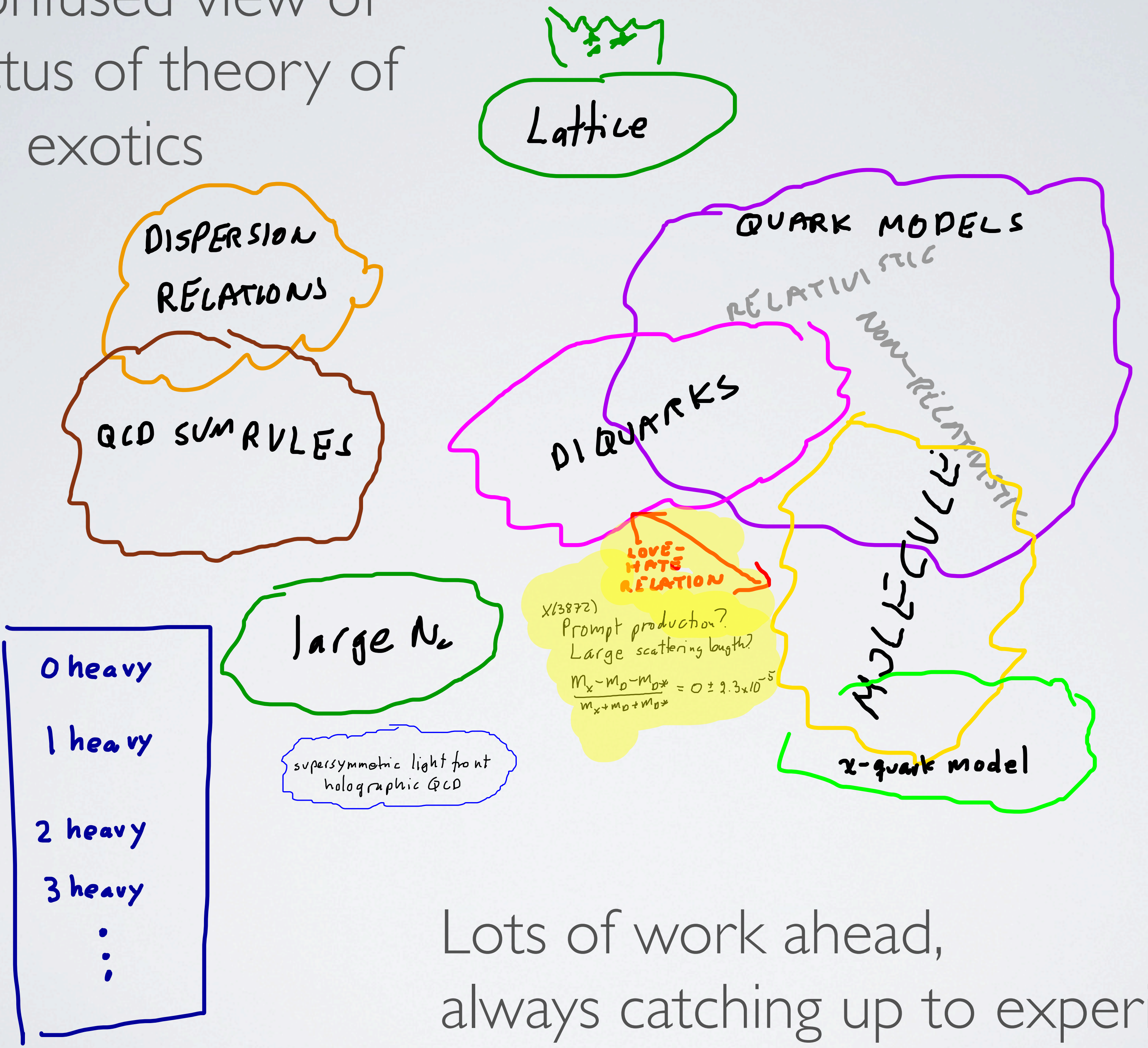


Lots of work ahead,
always catching up to experiment

A PATH TO UNDERSTANDING FLAVOR?

THE MANTRA

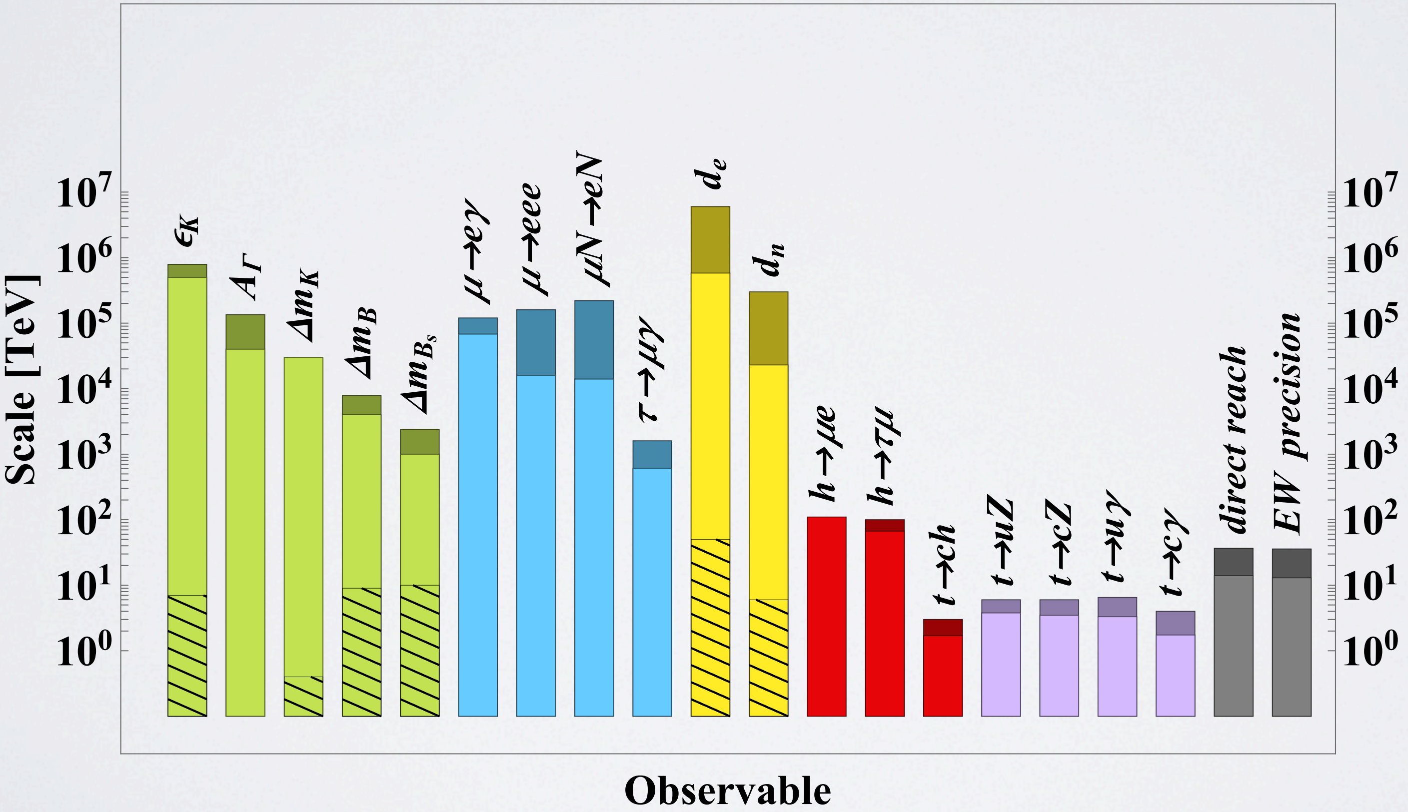
- Generic flavor speaker motivation slide (or flavor paper introduction)
  - Explain origin of matter (ugh)
  - Why are there 3 generations
  - Why hierarchies of masses
  - Why texture of mixing matrices

OUR (MODEST) ANSWERS

- Flavor probes very short distance scales

OUR (MODEST) ANSWERS

- Flavor probes very short distance scales



REACH IN NEW PHYSICS SCALE OF PRESENT AND FUTURE FACILITIES, FROM GENERIC DIMENSION SIX OPERATORS
LIGHT (DARK) COLORS CORRESPOND TO PRESENT DATA (MID-TERM PROSPECTS)

OUR (MODEST) ANSWERS

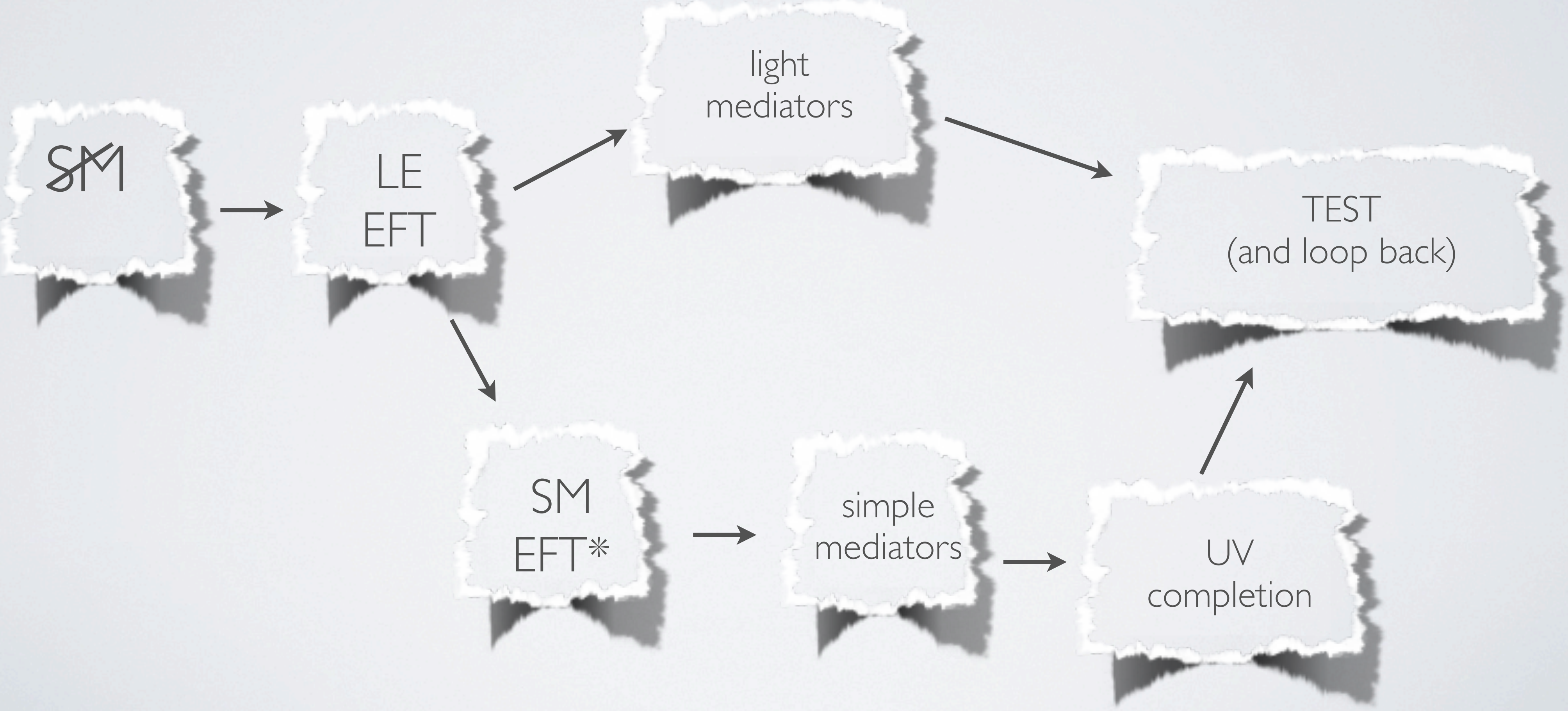
- Flavor probes very short distance scales
- Therefore masses of resonances/states of associated flavor dynamics is very high
- Therefore we do not expect to see any direct evidence of new flavor dynamics
- Best we can do: measure flavor in SM very precisely

WAIT!

WHAT?

OF COURSE NOT

- Measure flavor very precisely ⇒ hope to see deviations from SM
- Establish a deviation from SM ⇒ New Physics required
- A path to understanding flavor



~~SM~~

LE
EFT

light
mediators

SM
EFT*

simple
mediators

UV
completion

TEST
(and loop back)

*Modulo strong EWSB - but there is a higgs!

But:

Is this really what we mean by understanding flavor?

In principle this works, of course.

But does it lead to undertsanding of flavor if the models we test parametrize flavor-much like the SM does, by taking

- N = 3
- Masses as free parameters
- CKM/PMNS as free parameters

?

We should see flavor anomalies
as short distance probes that differentiate flavors

plagiarized from Gino Isidori

120 years ago:

They appeared identical except for mass:
“Same” charge, both pointlike

Only microscope available: long wavelength
-unable to “see” structure

Shorter wavelength microscopes revealed the source of the difference.

Today:

Identical, save for mass (“lepton universality”)

But perhaps not

Perhaps they are different
they feel different forces
ie, they transform differently under the underlying
(UV) gauge group

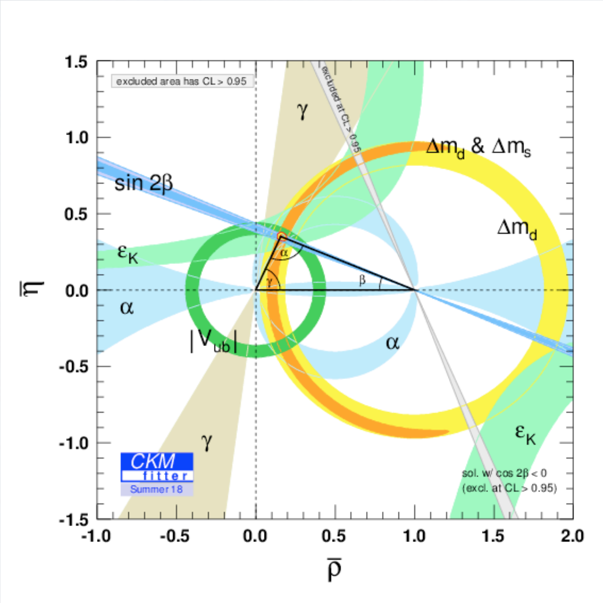
They appear the same because of accidental symmetries

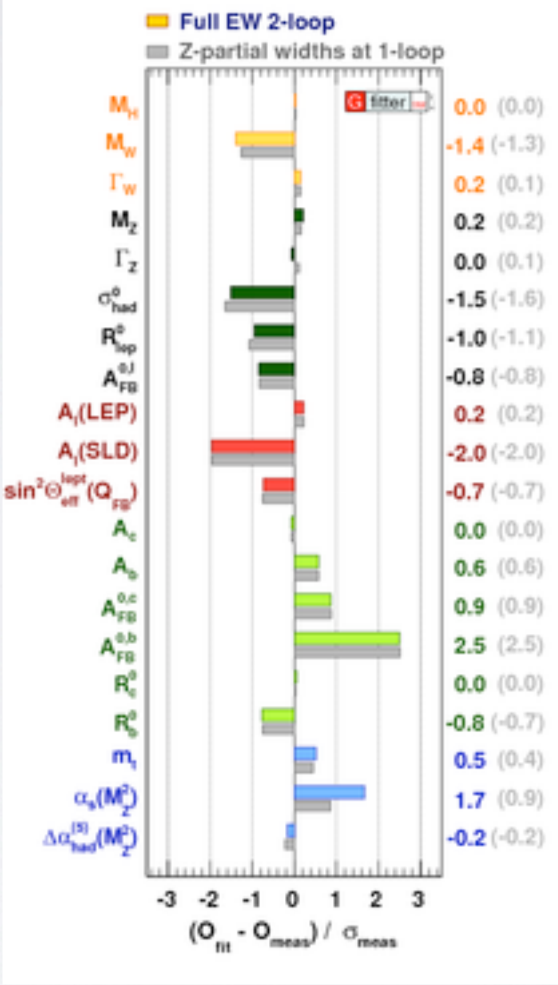
We just need a bigger microscope

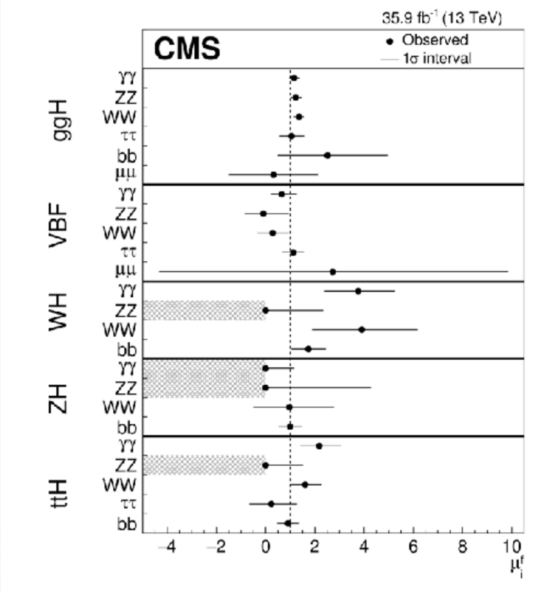
Now, THAT would be an answer to the question(s) of FLAVOR

So, where are we with the program?

1. Measuring the SM with precision

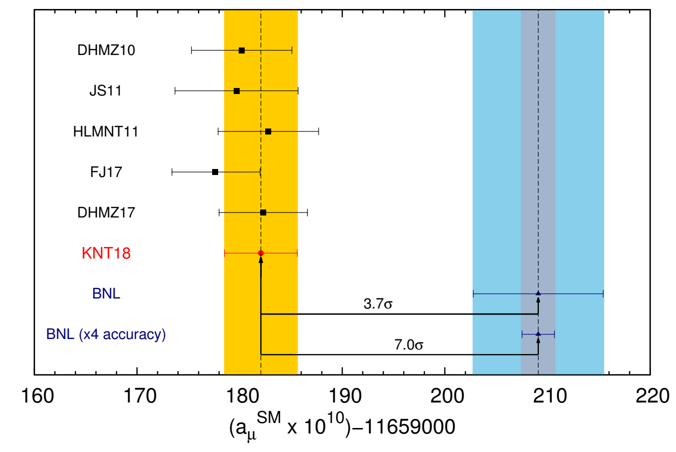


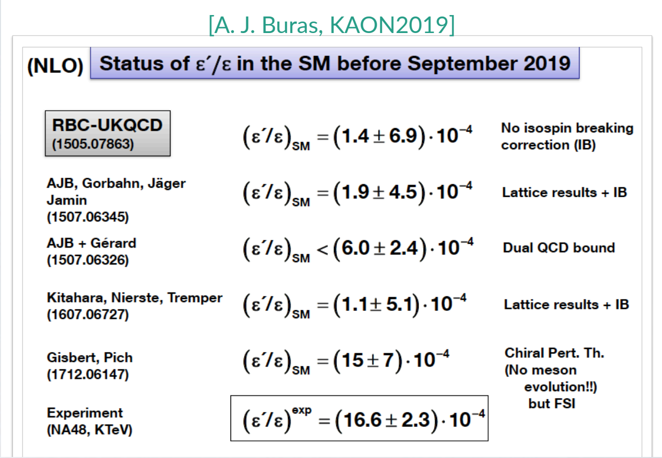




2. Deviations (aka, "anomalies")

[T. Teubner, HC2NP 2019]



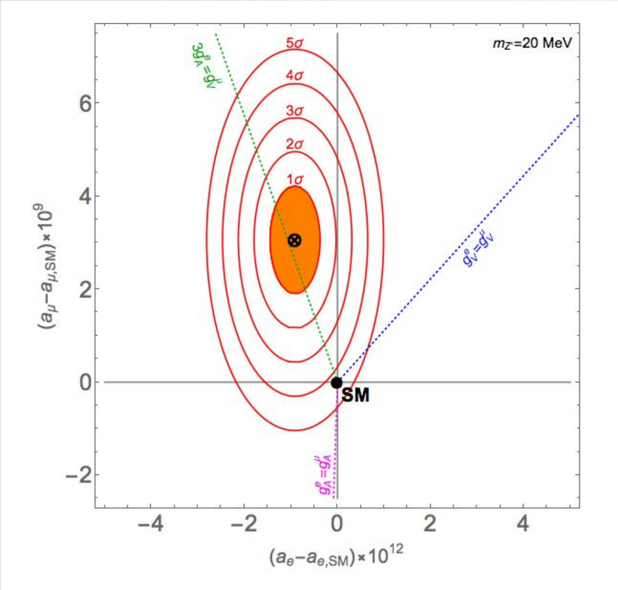


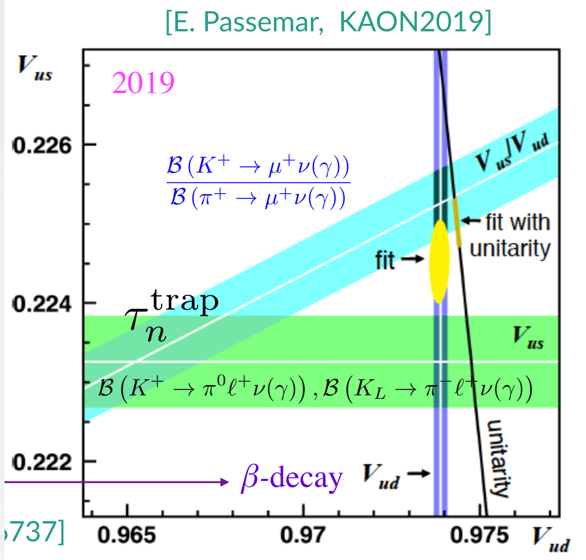
[A. J. Buras, KAON2019]

(NLO) Status of ε′/ε in the SM before September 2019

RBC-UKQCD (1505.07863)	$(\varepsilon'/\varepsilon)_{SM} = (1.4 \pm 6.9) \cdot 10^{-4}$	No isospin breaking correction (IB)
AJB, Gorbahn, Jäger Jamin (1507.06345)	$(\varepsilon'/\varepsilon)_{SM} = (1.9 \pm 4.5) \cdot 10^{-4}$	Lattice results + IB
AJB + Gérard (1507.06326)	$(\varepsilon'/\varepsilon)_{SM} < (6.0 \pm 2.4) \cdot 10^{-4}$	Dual QCD bound
Kitahara, Nierste, Tremper (1607.06727)	$(\varepsilon'/\varepsilon)_{SM} = (1.1 \pm 5.1) \cdot 10^{-4}$	Lattice results + IB
Gisbert, Pich (1712.06147)	$(\varepsilon'/\varepsilon)_{SM} = (15 \pm 7) \cdot 10^{-4}$	Chiral Pert. Th. (No meson evolution!!) but FSI
Experiment (NA48, KTeV)	$\boxed{(\varepsilon'/\varepsilon)^{exp} = (16.6 \pm 2.3) \cdot 10^{-4}}$	

[Z. Pagel, HC2NP 2019]





[E. Passemar, KAON2019]

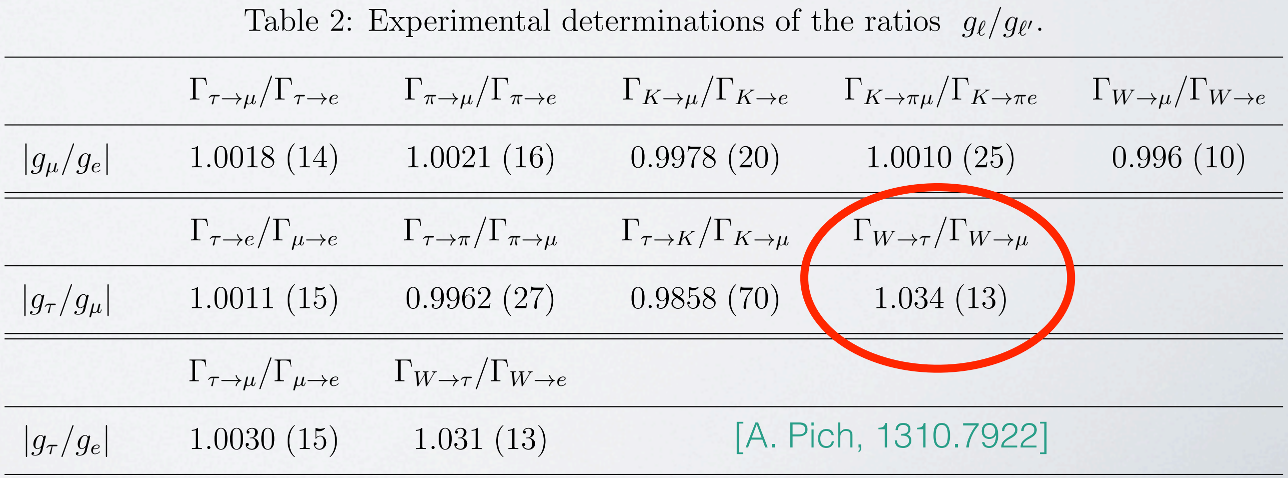


Table 2: Experimental determinations of the ratios $g_\ell/g_{\ell'}$.

	$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$	$\Gamma_{\pi\to\mu}/\Gamma_{\pi\to e}$	$\Gamma_{K\to\mu}/\Gamma_{K\to e}$	$\Gamma_{K\to\pi\mu}/\Gamma_{K\to\pi e}$	$\Gamma_{W\to\mu}/\Gamma_{W\to e}$
$\lvert g_\mu/g_e\rvert$	1.0018 (14)	1.0021 (16)	0.9978 (20)	1.0010 (25)	0.996 (10)
	$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$	$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	$\Gamma_{W\to\tau}/\Gamma_{W\to\mu}$	
$\lvert g_\tau/g_\mu\rvert$	1.0011 (15)	0.9962 (27)	0.9858 (70)	1.034 (13)	
	$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$	$\Gamma_{W\to\tau}/\Gamma_{W\to e}$			
$\lvert g_\tau/g_e\rvert$	1.0030 (15)	1.031 (13)			

[A. Pich, 1310.7922]

More to the point: LUV anomalies

Some of us find compelling:

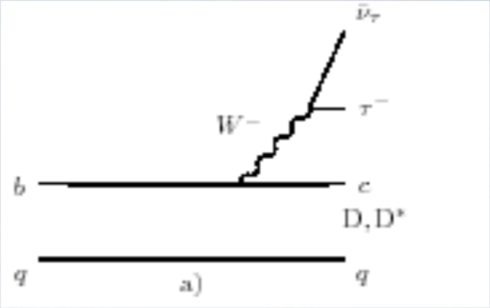
- Several observables pointing the same way
- Several experiments, same direction
- Simple/coherent explanation
  (1 or 2 EFT wilson coefficients)

Let's focus on them:

- Theory more directed: not everything works
- LUV: address flavor!

Charged currents

Tree level in SM!



$$R_{D^{(*)}} = \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)} \qquad (\text{with } \ell = e \text{ or } \mu), \qquad R_{J/\psi} = \frac{\mathrm{BR}(B_c^+ \to J/\psi\tau^+\nu_\tau)}{\mathrm{BR}(B_c^+ \to J/\psi\mu^+\nu_\mu)},$$

$$P_\tau^{D^*} = \frac{\Gamma(\lambda_\tau = \frac{1}{2}) - \Gamma(\lambda_\tau = -\frac{1}{2})}{\Gamma(\lambda_\tau = \frac{1}{2}) + \Gamma(\lambda_\tau = -\frac{1}{2})}, \qquad F_L^{D^*} = \frac{\Gamma(\lambda_{D^*} = 0)}{\Gamma(\lambda_{D^*} = 1) + \Gamma(\lambda_{D^*} = 0) + \Gamma(\lambda_{D^*} = -1)},$$

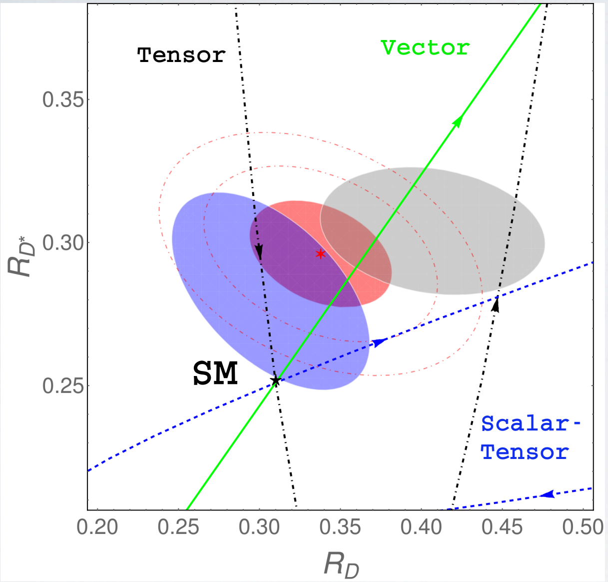
[R-X Shi etal, 1905.08498]

Observables	Data (averages)				SM
	HFLAV 2018		HFLAV 2019		
R_D	0.407(39)(24)	corr = −0.20	0.340(27)(13)	corr = −0.38	0.312(19)
R_{D^*}	0.306(13)(7)		0.295(11)(8)		0.253(4)
$R_{J/\psi}$	0.71(17)(18)				0.248(3)
$P_\tau^{D^*}$	−0.38(51)(19)				−0.505(23)
$F_L^{D^*}$	0.60(8)(4)				0.455(9)

3. Jump to LE-EFT and SM-EFT

R-X Shi et al 1905.08498
A. Kumar Alok et al , 1903.10486
Bardan & Ghosh, 1904.10432
Kumbhakar et al, 1909.02840

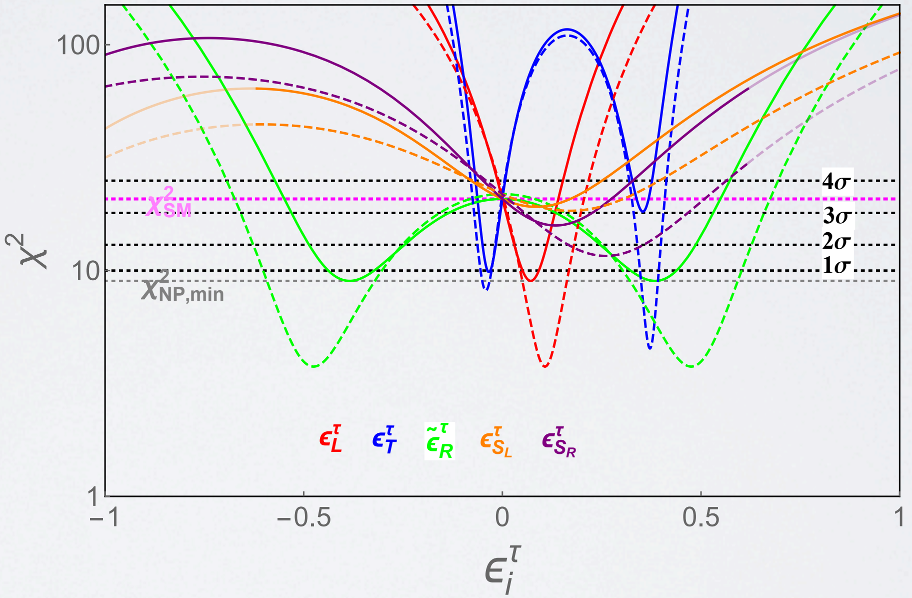
$$\mathcal{L}_{\text{eff}}^{\text{LE}} \supset -\frac{4G_F V_{cb}}{\sqrt{2}}[(1+\epsilon_L^\tau)(\bar{\tau}\gamma_\mu P_L \nu_\tau)(\bar{c}\gamma^\mu P_L b) + \epsilon_R^\tau(\bar{\tau}\gamma_\mu P_L \nu_\tau)(\bar{c}\gamma^\mu P_R b)$$
$$+\epsilon_{S_L}^\tau(\bar{\tau}P_L\nu_\tau)(\bar{c}P_L b) + \epsilon_{S_R}^\tau(\bar{\tau}P_L\nu_\tau)(\bar{c}P_R b) + \epsilon_T^\tau(\bar{\tau}\sigma_{\mu\nu}P_L\nu_\tau)(\bar{c}\sigma^{\mu\nu}P_L b)] + \text{H.c.},$$



Grey/Red: HFLAV pre-post Moriond19
Blue: Belle 19 semilep-tag

$$\mathcal{L}_{\text{eff}}^{\text{LE}} \supset -\frac{4G_F V_{cb}}{\sqrt{2}}(\tilde{\epsilon}_R^\tau \bar{\tau}\gamma_\mu N_R)(\bar{c}\gamma^\mu P_R b) + \text{H.c.},$$

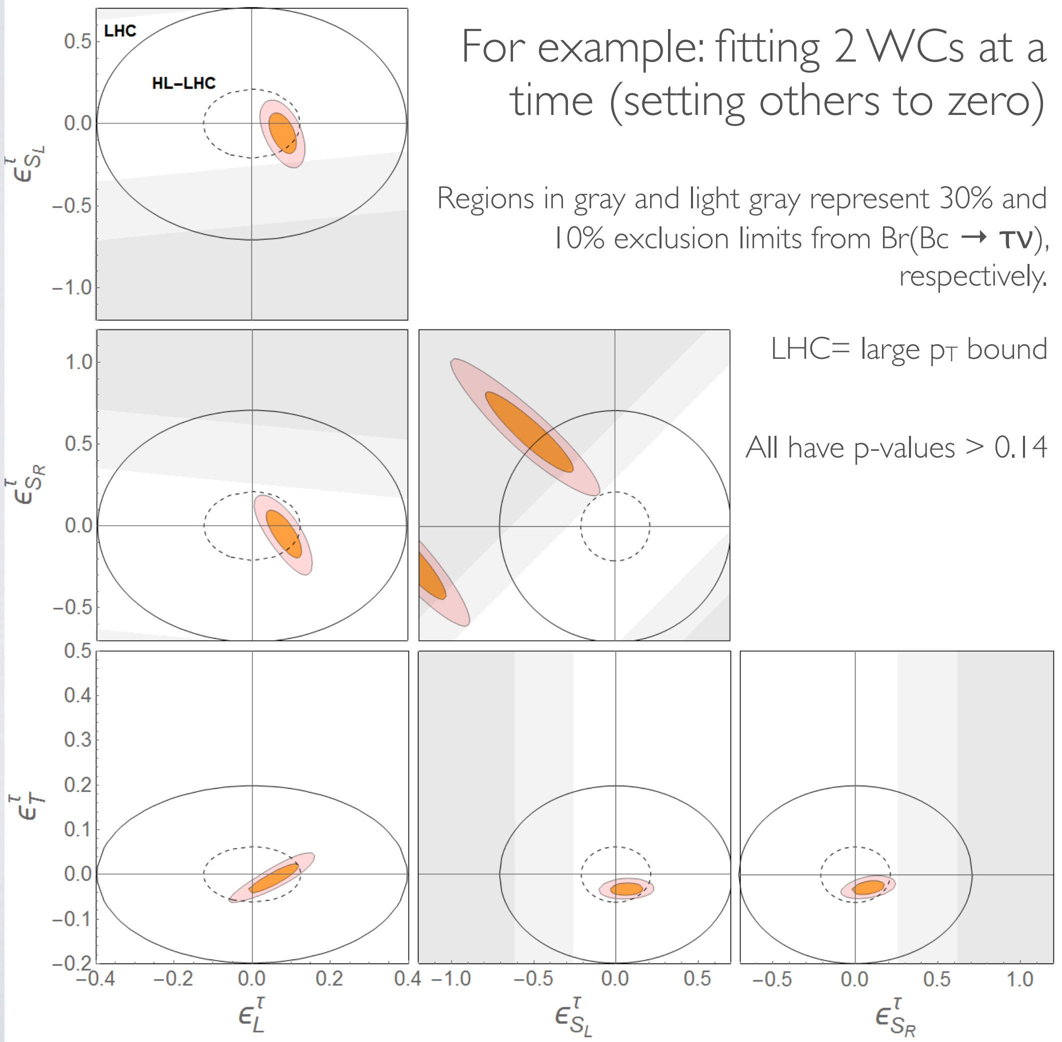
allowing for R-handed neutrino, sample term



dotted: pre-Moriond2019

- Magnitude of WCs lower; same significance
- Smaller WCs: some possibilities (like scalars) re-opened
- Constraints from Bc lifetime (Br(Bc→τν)) and large p_T single τ

pre/post Moriond19:
-little change in R(D*)
-reduced R(D)
⇒new combinations of WCs allowed



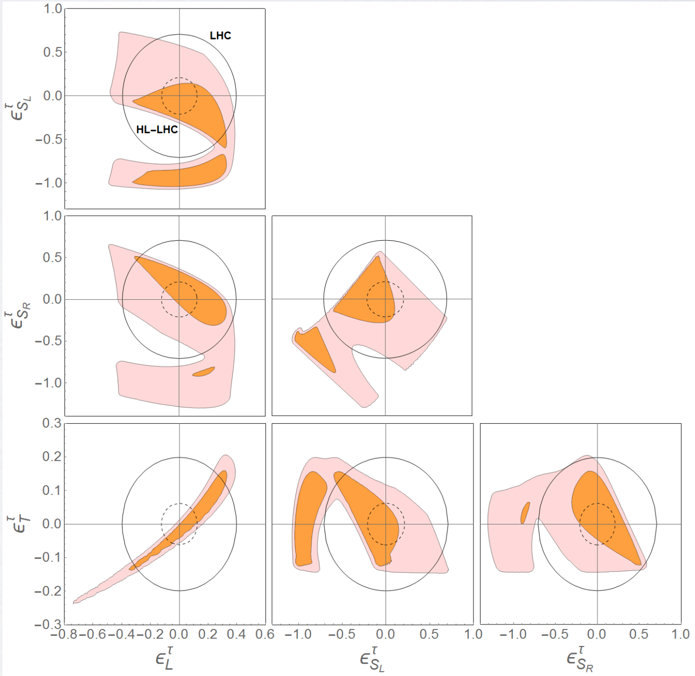
For example: fitting 2 WCs at a time (setting others to zero)

Regions in gray and light gray represent 30% and 10% exclusion limits from Br($B_c \to \tau\nu$), respectively.

LHC= large p_T bound

All have p-values > 0.14

More useful for "understanding" flavor than profiling over rest of WCs, which however can be done: :



4. Jump to simple mediators

Mediator	Spin	$SU(3)$	$SU(2)$	$U(1)$	ϵ_L^τ	$\tilde{\epsilon}_R^\tau$	$\epsilon_{S_R}^\tau$	$\epsilon_{S_L}^\tau$	ϵ_T^τ	
H	0	$\mathbf{1}$	$\mathbf{2}$	$+1/2$	✗	✗	✓	✓	✗	Babar: does not work (q2-dependence, efficiency)
W'_L	1	$\mathbf{1}$	$\mathbf{3}$	0	✓	✗	✗	✗	✗	Disfavored by Z' FCNC, di-tau
W'_R	1	$\mathbf{1}$	$\mathbf{1}$	$+1$	✗	✓	✗	✗	✗	Disfavored by B$_c$ lifetime/Br(B$_c$ $\to \tau \nu$)
S_1	0	$\bar{\mathbf{3}}$	$\mathbf{1}$	$+1/3$	✓	✓	✗	✓	✓	
S_3	0	$\bar{\mathbf{3}}$	$\mathbf{3}$	$+1/3$	✓	✓	✗	✗	✗	
R_2	0	$\mathbf{3}$	$\mathbf{2}$	$+7/6$	✓	✓	✗	✓	✓	With smaller R(D) (2019), no longer disfavored
U_1	1	$\mathbf{3}$	$\mathbf{1}$	$+2/3$	✓	✓	✓	✗	✗	
U_3	1	$\mathbf{3}$	$\mathbf{3}$	$+2/3$	✓	✓	✗	✗	✗	
V_2	1	$\bar{\mathbf{3}}$	$\mathbf{2}$	$+5/6$	✗	✗	✓	✗	✗	Disfavored by B$_c$ lifetime/Br(B$_c$ $\to \tau \nu$)

Leptoquarks?

5. UV Completion

say, for vector leptoquark U_1 – $(3,1)_{2/3}$

Pati-Salam group: $SU(4)\times SU(2)_L\times SU(2)_R$

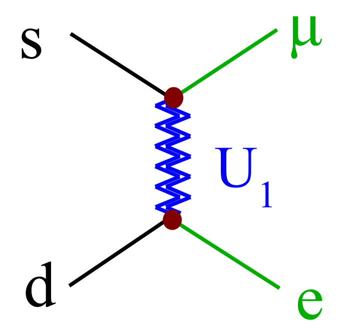
Fermions in SU(4):

$$\begin{bmatrix} Q_L^{\alpha} \\ Q_L^{\beta} \\ Q_L^{\gamma} \\ L_L \end{bmatrix} \quad \begin{bmatrix} Q_R^{\alpha} \\ Q_R^{\beta} \\ Q_R^{\gamma} \\ L_R \end{bmatrix}$$

Main Pati-Salam idea:
Lepton number as “the 4th color”

The massive LQ [U_1] arise from the breaking $SU(4) \rightarrow SU(3)_C\times U(1)_{B-L}$

The problem of the plain vanilla PS model is: bounds on the LQ couplings to light generations require M > 200 TeV



Possible to solve this problem adding extra fermions and/or modifying the gauge group

[Calibbi, Crivellin, Li, '17; Di Luzio, Greljo, Nardecchia, '17; Fornal, Gadam, BG, '18]

Rare radiative decays: b → sll

Aebischer et al, 1903.10434
A Kumar Alok et al, 1903.09617
...

Tests of Lepton Universality

$$R_K = \frac{\mathrm{BR}(B \to K\mu\mu)}{\mathrm{BR}(B \to Kee)} \qquad R_{K^*} = \frac{\mathrm{BR}(B \to K^*\mu\mu)}{\mathrm{BR}(B \to K^*ee)}$$

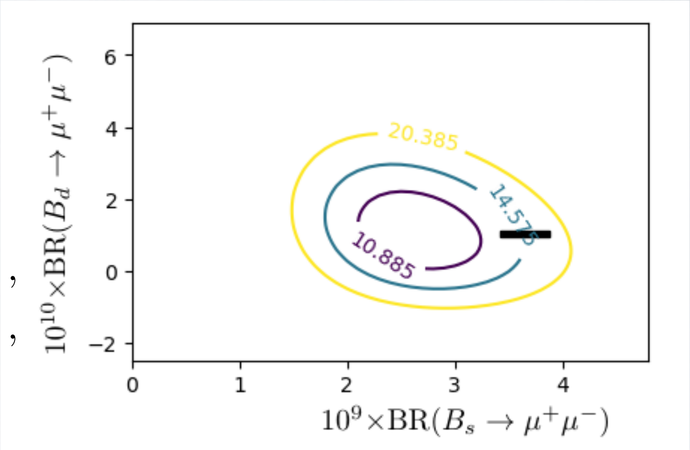
$$R_{K_{\mathrm{LHCb}}}^{[1.1,6]} = 0.846^{+0.060}_{-0.054}{}^{+0.016}_{-0.014}\,,$$
$$R_{K_{\mathrm{Belle}}}^{[1,6]} = 0.98^{+0.27}_{-0.23} \pm 0.06\,,$$

Belle LHCb

$$R_{K^*}^{[0.045,1.1]} = 0.52^{+0.36}_{-0.26} \pm 0.05\,,\ 0.66^{+0.11}_{-0.07} \pm 0.03\,,$$
$$R_{K^*}^{[1.1,6]} = 0.96^{+0.45}_{-0.29} \pm 0.11\,,\ 0.69^{+0.11}_{-0.07} \pm 0.05\,,$$

(not same bins)

Imprtant associated observables, eg



Cut to the chase

$$\mathcal{H}_{\text{eff, NP}}^{bs\ell\ell} = -\mathcal{N}\left(C_7^{bs}O_7^{bs} + C_7^{\prime bs}O_7^{\prime bs} + \sum_{\ell=e,\mu}\sum_{i=9,10,S,P}\left(C_i^{bs\ell\ell}O_i^{bs\ell\ell} + C_i^{\prime bs\ell\ell}O_i^{\prime bs\ell\ell}\right)\right) \qquad \mathcal{N} = \frac{4G_F}{\sqrt{2}}V_{tb}V_{ts}^*\frac{e^2}{16\pi^2}\,.$$

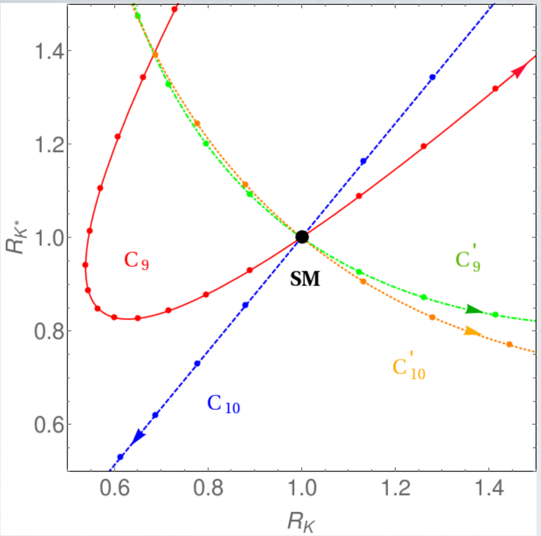
$$O_7^{bs} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}\,, \qquad O_7^{\prime bs} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_L b)F^{\mu\nu}\,,$$

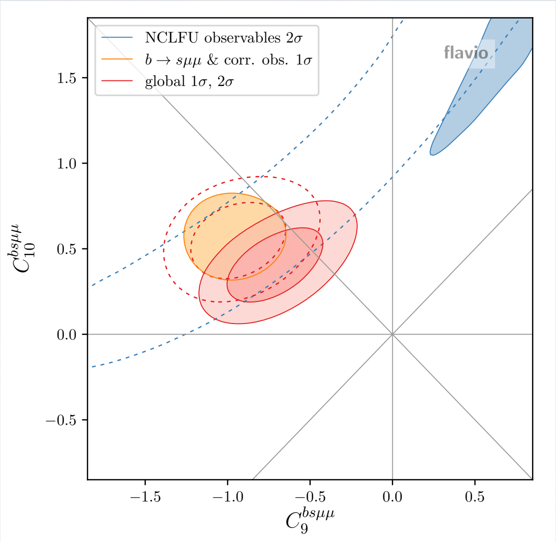
$$O_9^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\ell)\,, \qquad O_9^{\prime bs\ell\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu\ell)\,,$$

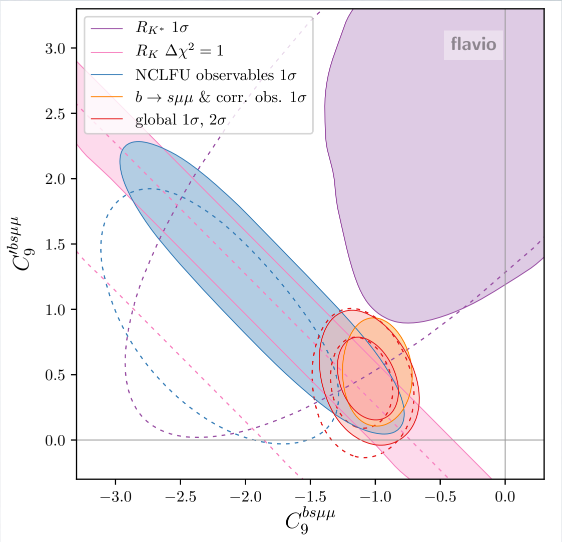
$$O_{10}^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5\ell)\,, \qquad O_{10}^{\prime bs\ell\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu\gamma_5\ell)\,,$$

$$O_S^{bs\ell\ell} = m_b(\bar{s}P_R b)(\bar{\ell}\ell)\,, \qquad O_S^{\prime bs\ell\ell} = m_b(\bar{s}P_L b)(\bar{\ell}\ell)\,,$$

$$O_P^{bs\ell\ell} = m_b(\bar{s}P_R b)(\bar{\ell}\gamma_5\ell)\,, \qquad O_P^{\prime bs\ell\ell} = m_b(\bar{s}P_L b)(\bar{\ell}\gamma_5\ell)\,.$$







and a gazillion other plots like these

Coeff.	best fit	1σ	2σ	pull
$C_9^{bs\mu\mu}$	-0.97	$[-1.12, -0.81]$	$[-1.27, -0.65]$	5.9σ
$C_9'^{bs\mu\mu}$	$+0.14$	$[-0.03, +0.32]$	$[-0.20, +0.51]$	0.8σ
$C_{10}^{bs\mu\mu}$	$+0.75$	$[+0.62, +0.89]$	$[+0.48, +1.03]$	5.7σ
$C_{10}'^{bs\mu\mu}$	-0.24	$[-0.36, -0.12]$	$[-0.49, +0.00]$	2.0σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$+0.20$	$[+0.06, +0.36]$	$[-0.09, +0.52]$	1.4σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	-0.53	$[-0.61, -0.45]$	$[-0.69, -0.37]$	6.6σ
C_9^{bsee}	$+0.93$	$[+0.66, +1.17]$	$[+0.40, +1.42]$	3.5σ
$C_9'^{bsee}$	$+0.39$	$[+0.05, +0.65]$	$[-0.27, +0.95]$	1.2σ
C_{10}^{bsee}	-0.83	$[-1.05, -0.60]$	$[-1.28, -0.37]$	3.6σ
$C_{10}'^{bsee}$	-0.27	$[-0.57, -0.02]$	$[-0.84, +0.26]$	1.1σ
$C_9^{bsee} = C_{10}^{bsee}$	-1.49	$[-1.79, -1.18]$	$[-2.05, -0.79]$	3.2σ
$C_9^{bsee} = -C_{10}^{bsee}$	$+0.47$	$[+0.33, +0.59]$	$[+0.20, +0.73]$	3.5σ
$\left(C_S^{bs\mu\mu} = -C_P^{bs\mu\mu}\right) \times \text{GeV}$	-0.006	$[-0.009, -0.003]$	$[-0.014, -0.001]$	2.8σ
$\left(C_S'^{bs\mu\mu} = C_P'^{bs\mu\mu}\right) \times \text{GeV}$	-0.006	$[-0.009, -0.003]$	$[-0.014, -0.001]$	2.8σ

And again, simplified models.

And again, leptoquarks fare well. Eg U_1

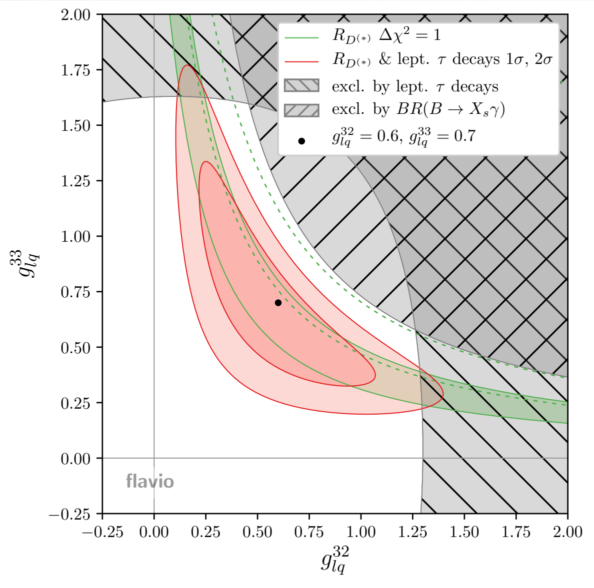
With

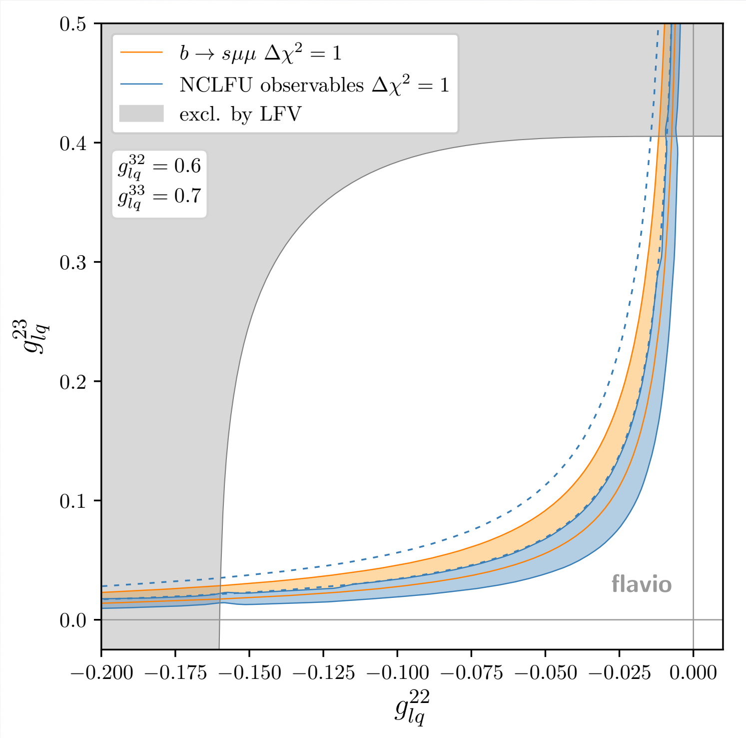
$$\mathcal{L}_{U_1} \supset g_{lq}^{ji}\left(\bar{q}^i\gamma^\mu l^j\right)U_\mu + \text{h.c.}$$

a single leptoquark can account for R(D) and R(K), with

with R(D) depending only on g_{lq}^{32} and g_{lq}^{33},

and R(K) depending only on g_{lq}^{22} and g_{lq}^{23}





Conclusions, so far

- Several deviations from the SM
- Can fit with LE-EFT
- Can fit with SM-EFT
- Can provide simplified models for this
- Moreover, there are UV completions to the simplified models (eg, Patti-Salam for vector LQs)

But, can we address the main question?

THEORIES OF FLAVOR

- Theories of flavor do exist, eg
  - Froggart-Nielsen: quark masses and CKM
  - Gauged flavor: N=3, inverse hierarchy, $M_{med} \sim 1/m_\psi$
  - Discrete G: neutrinos and PMNS
  - ...
- Based on our "setp 1": precise knowledge of SM
  - Assume no anomalies
  - Very high scale of bew physics

- Flip it around! Use what nature is telling us (anomalies) to craft a theory:
  - Modest: Adapt/modify known models
  - Bold: Large departure from existing proposals

FEW EXAMPLES

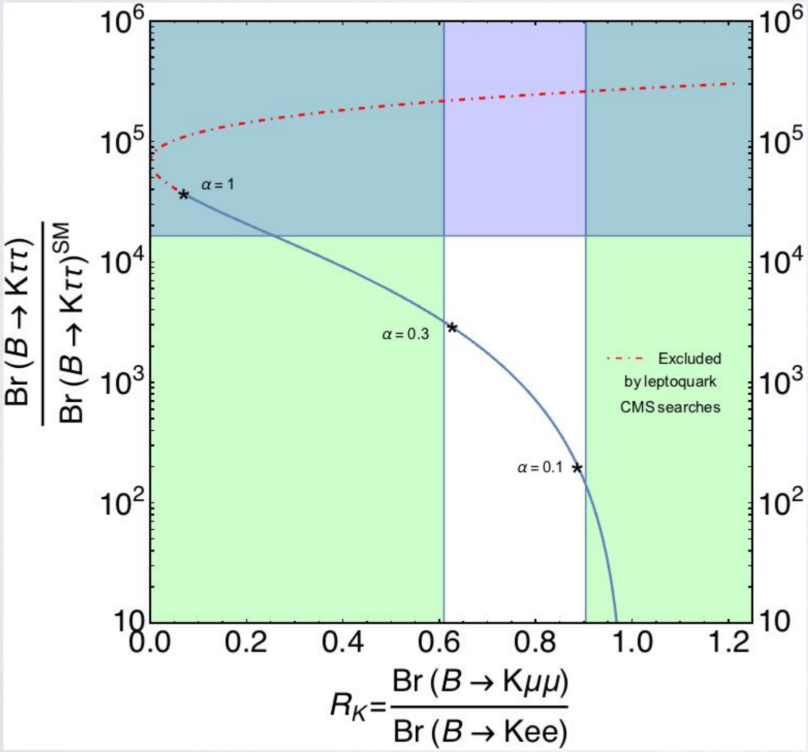
(actually, few exist)

R. Alonso et al, JHEP 1510 (2015) 184
M. Bordonne et al, 1910.02641

MFV EFT
FROGGATT-NIELSEN EFT

M(L)FV: flavor-symmetry broken by minimal set of spurions

➧ large(r) effects in the 3rd family



Natural expectation, large

$$R_{K^{(*)}\nu} = \frac{\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})}{\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})^{\mathrm{SM}}},$$

with exp. bound (90%CL)

$$R_{K\nu} < 4.3, \qquad R_{K^*\nu} < 4.4,$$

- Some operators avoid this
- Running (may) produce it

Feruglio et al, PRL118(2017)011801

- Automatic cancellations in some UV completions, eg, Patti-Salam LQs

Assad et al, PLB777 (2018) 324

FN: entries in mass matrix break $U(1)$, breaking by small spurion of unit charge

$$(Y_U)_{ij} \sim \lambda^{|b^i_Q - b^j_U|}\,, \qquad (Y_D)_{ij} \sim \lambda^{|b^i_Q - b^j_U|}\,, \qquad (Y_E)_{\alpha\beta} \sim \lambda^{|b^\alpha_L - b^\beta_E|}\,.$$

Carry over to WCs in SM-EFT

May also carry over to couplings of simplified mediators e.g., U_1 – the vector, $(3,1)_{2/3}$ leptoquark

$$\mathcal{L} = \Delta^{i\alpha}_{QL}\left(\bar{Q}^i \gamma_\mu L^\alpha\right) U_1^\mu + \Delta^{i\alpha}_{DE}\left(\bar{d}^i \gamma_\mu e^\alpha\right) U_1^\mu + \text{h.c.}\,.$$

with

$$\Delta^{i\alpha}_{QL} = c^{i\alpha}_{QL}\lambda^{|b^i_Q - b^\alpha_L|}\,,$$
$$\Delta^{i\alpha}_{DE} = c^{i\alpha}_{DE}\lambda^{|b^i_D - b^\alpha_E|}\,.$$

Steps in the right direction, or flavor inspired constrained paramterization of generic physics?

TeV scale FN

- What we (I?) really want is:

  that which is responsible for flavor (flavor-dynamics) be also directly responsible for anomalies

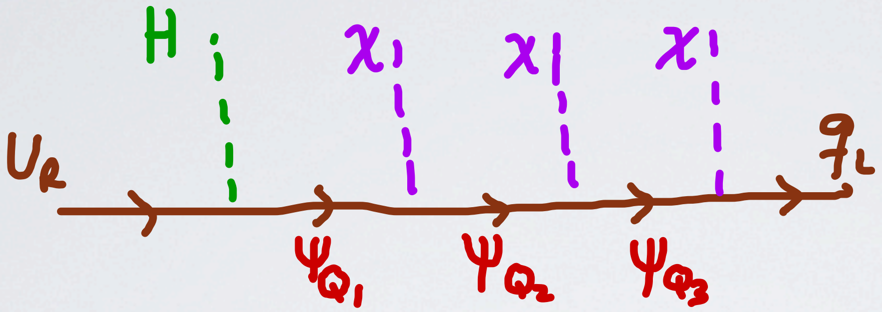
➡ Can the new scalars and spinors that are introduced in FN (possibly adding some more) account for the anomalies?

- Neccesarily this is TeV scale physics (in contrast to standard FN)

BG, Pokorski, Ross, JHEP 1812 (2018) 079

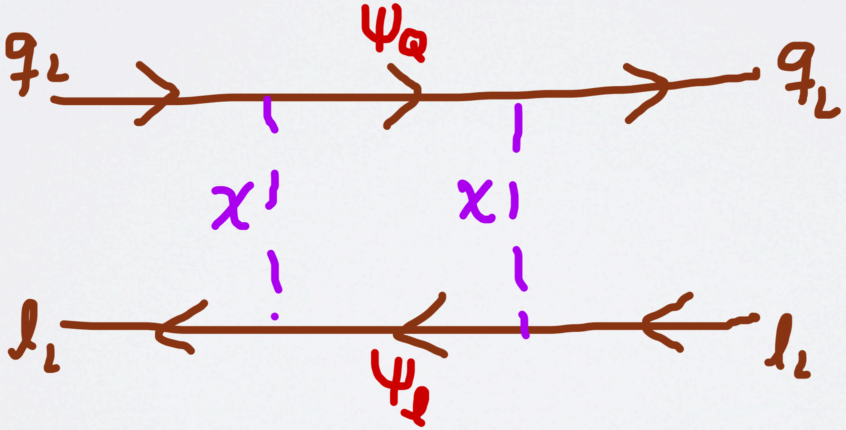
FN-like model

One-line review of FN:



$$\sim H\bar{q}_L u_R \left(\frac{\chi}{M}\right)^3$$

Question: If FN scale is sufficiently low, can one generate C_9, C_{10}? After all.



Not quite; need to add some vector-like fermion doublets $\mathbf{\Psi_Q}$, $\mathbf{\Psi_\ell}$ and a scalar $\mathbf{\Phi}$

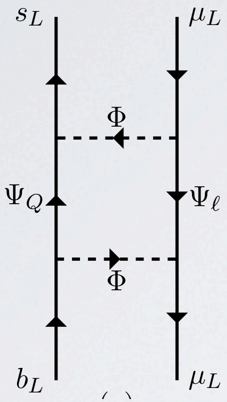
	Q_2	q_2	Q_3	q_3	L_2	l_2	L_3	l_3	$\Psi_{Q,(L,R)}$	$\Psi_{\ell,(L,R)}$	Φ	H	χ
Q_F	2	0	0	0	2	1	-2	-2	2	4	-2	0	1

$$\mathcal{L}_{\text{int}} = \Gamma_b \bar{Q}_3 P_R \Psi_Q \Phi + \Gamma_\mu \bar{L}_2 P_R \Psi_\ell \Phi + \text{h.c.}$$

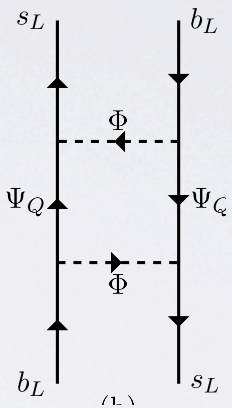
$\Rightarrow \Gamma_i^m \sim V_{3i}\Gamma_b$ in mass basis

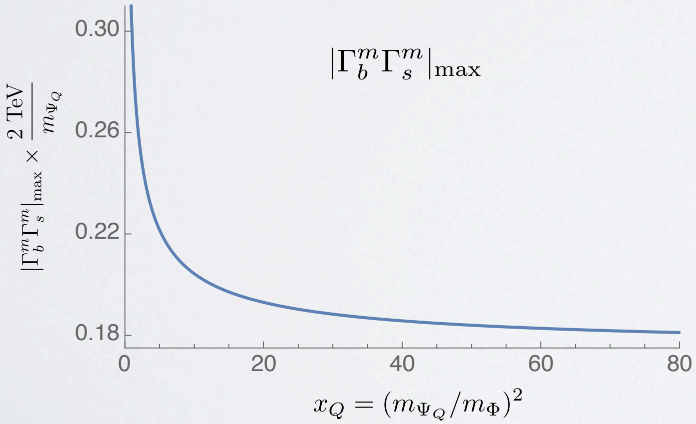
Much like for Z’ models:

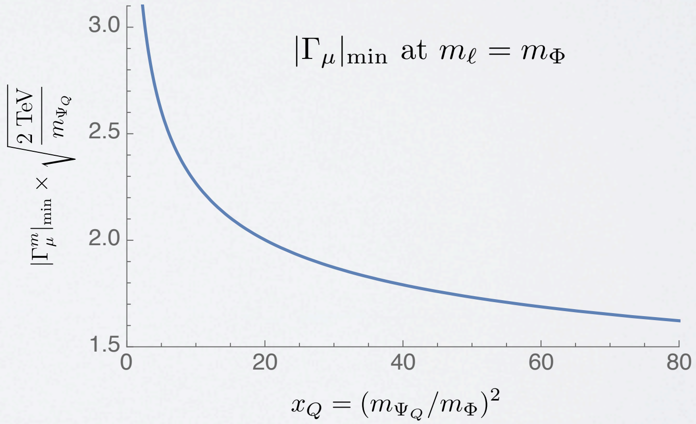
if you have this



you also get this





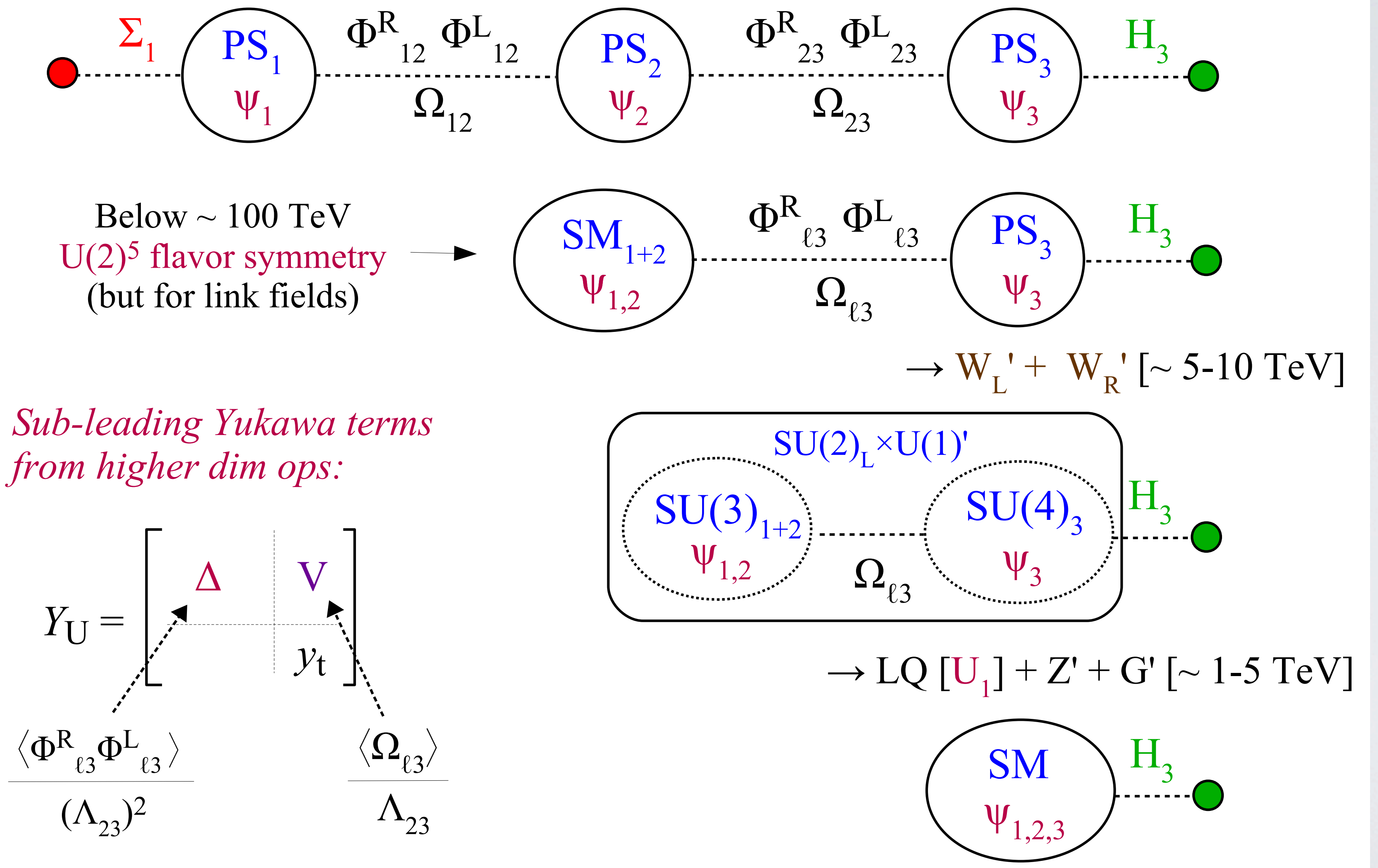


Works but tense. Tension relieved (somewhat) with additional scalar. No chance *of* $R(D^{(*)})$
(Because of flavor; one can do everything in an ad hoc nHDM Marzo, Marzola, Raidal, 1901.08290)

Bordone et al, Phys.Lett. B779 (2018) 317-323

PS^3: The 3-site Pati-Salam

- ***The PS^3 model***



Below ~ 100 TeV
U(2)^5 flavor symmetry
(but for link fields) →

→ $W_L' + W_R'$ [~ 5-10 TeV]

→ LQ [U_1] + Z' + G' [~ 1-5 TeV]

Sub-leading Yukawa terms from higher dim ops:

$$Y_U = \begin{bmatrix} \Delta & V \\ & y_t \end{bmatrix}$$

$$\Delta \leftarrow \frac{\langle \Phi^R_{\ell 3} \Phi^L_{\ell 3} \rangle}{(\Lambda_{23})^2} \qquad V \leftarrow \frac{\langle \Omega_{\ell 3} \rangle}{\Lambda_{23}}$$

Key pheno difference: lots of new states!

BRIEF SUMMARY-CONCLUSIONS

- XYZ&Pc is a mature field. But continues to suprise. Theory lags experiment by wide margin
- Hints for departure from Lepton Universality demonstrate the discovery potential of high lumi, “low” energy searches.
- They form a very consistent set of “hints”: they can be described by remarkably few Wilson Coefficients in an Effective Theory. They point to enhanced coupling of NP to 3rd generation.
- In UV completions, often easy to account for other one-off anomalies (eg, $g_\mu - 2$), and even DM.
- They have forced both theory and experiment to rethink program, discard prejudices.
- If “hints” turn to “observation”, a path of discovery islaid, but lots of work (and fun!!) ahead.

FIN