Anomalies in Flavor Physics
Theoretical Overview

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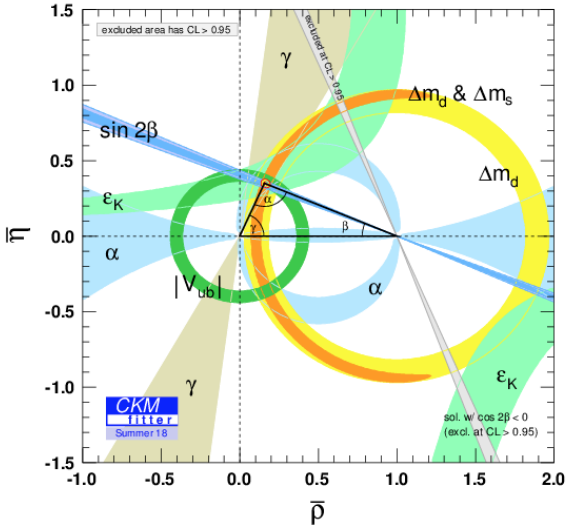
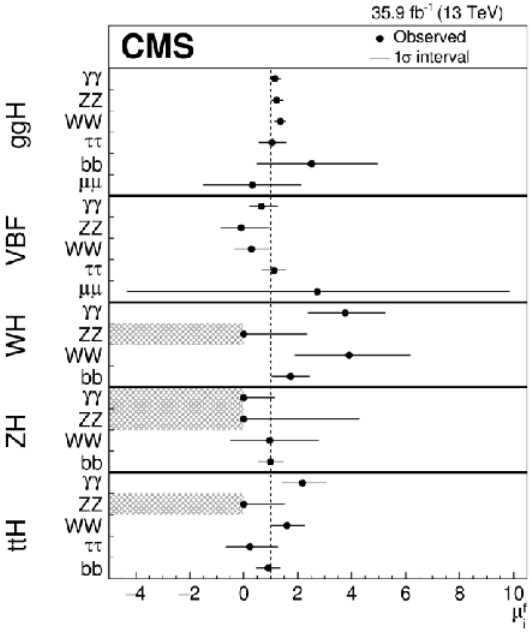
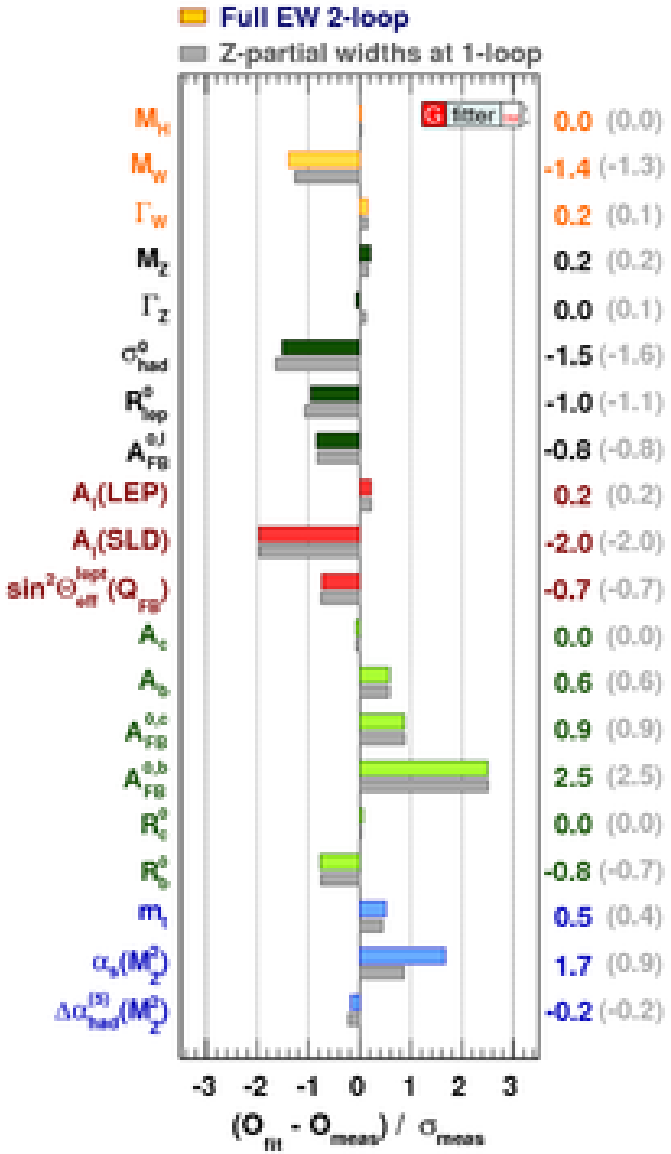
Introduction

The SM works!



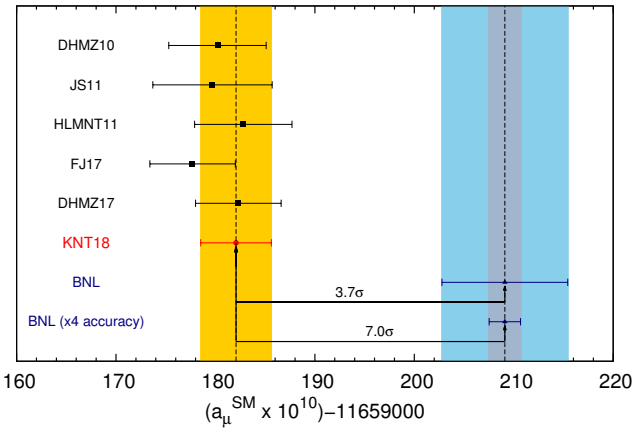




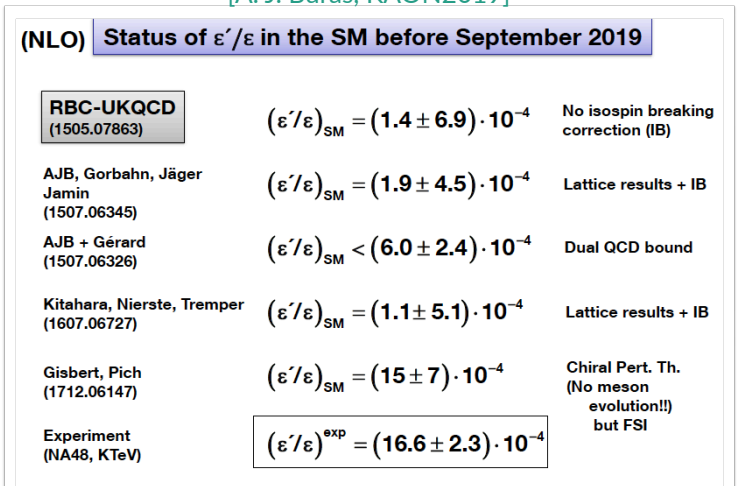
Introduction

But there are hiccups

[T. Teubner, HC2NP 2019]



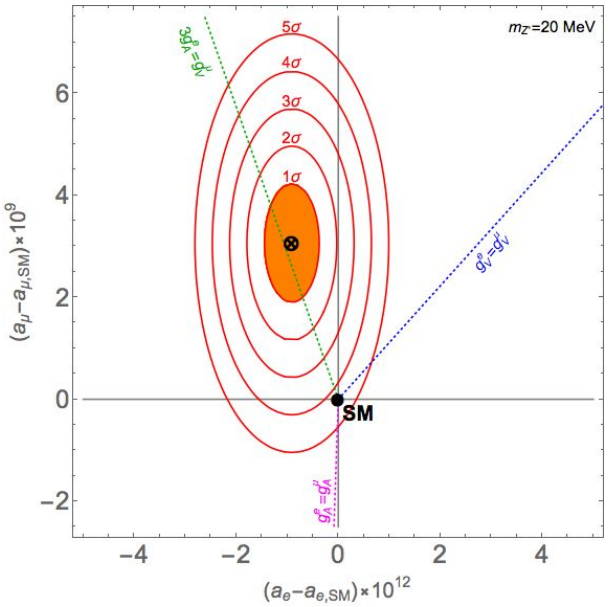
[A. J. Buras, KAON2019]



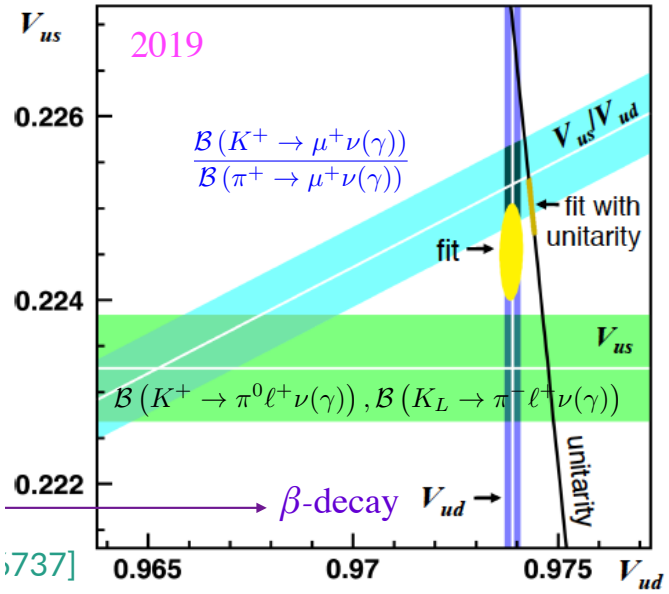
(NLO) **Status of ε′/ε in the SM before September 2019**

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)	$(\varepsilon'/\varepsilon)^{exp} = (16.6 \pm 2.3) \cdot 10^{-4}$	

[Z. Pagel, HC2NP 2019]



[E. Passemar, KAON2019]



737]

$\Gamma(W \to \tau)/\Gamma(W \to \mu)$: $g_\tau / g_\mu = 1.034(13)$

[A. Pich, 1310.7922]

Lepton Universality Anomalies

Why we love LUV

This talk is about hints of deviations from lepton universality (a.k.a. "anomalies") in decays of heavy hadrons to leptons.

- Is this ambulance chasing?
  LHC has seen no BSM particles. We are in a phase of "leave no stone unturned". This has been used to secure funding for searches for long lived particles, axion-like particles, light DM, etc. It seems to me its **mandatory** *that we investigate hints of deviations, and in fact they seem (to me) a better bet.*
- Why these rather than those in the previous slide?
  There is no common thread to those in the previous page, no unifying theme other than the possibility of NP at short distances.
  And there is limited time for the talk and session.
- Some of us find compelling:
  - Several observables pointing the same way
  - LUV observables are largely free from hadronic uncertainties ("clean")
  - Several experiments, same direction
  - Simple/coherent explanation (1 or 2 EFT wilson coefficients)
  - Additional (dirty) observables fit well with the *same* explanation
  - Collection of results is more constraining: not everything works
    contrast a_μ (no offense)

Outline

- $b \to s\ell\ell$, results, EFT, fits
- $b \to c\ell\nu$, results, EFT, fits
- Microscopic models
  - $b \to c\ell\nu$
  - $b \to s\ell\ell$
- Conclusion
  - yada yada
  - Postscript: Towards a theory of Flavor

- Left out much, eg, new observables
- No recent updates
- See, eg, Diego Guadagnoli talk Snowmass last week
  LUV / LFV in meson and baryon decays – TH overview

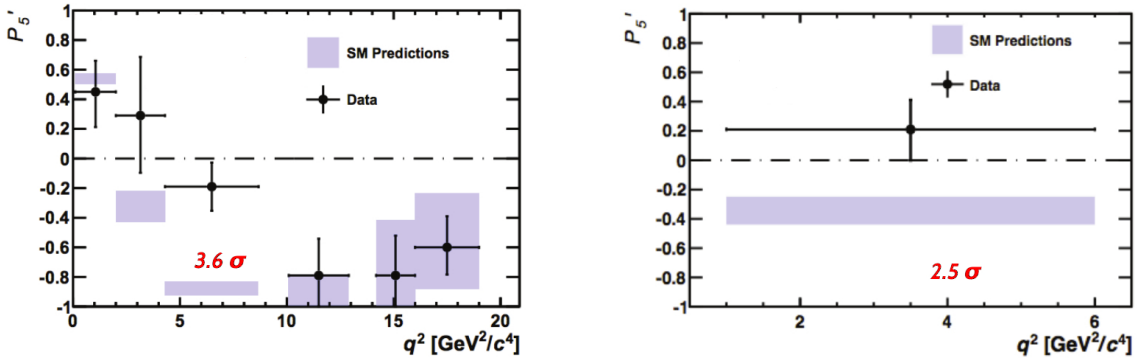
Anomalies in B decays?

First hints: The P_5' anomaly at low q^2 (1 fb^{-1})

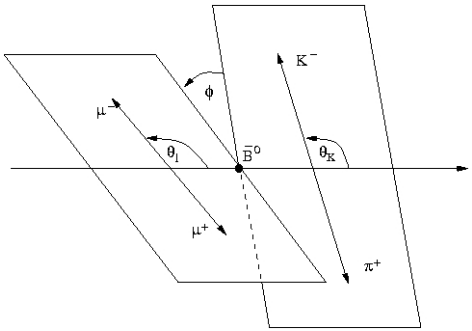
PRL 111, 191801 (2013) PHYSICAL REVIEW LETTERS week ending 8 NOVEMBER 2013

Measurement of Form-Factor-Independent Observables in the Decay $B^0 \to K^{*0}\mu^+\mu^-$

R. Aaij *et al.**
(LHCb Collaboration)
(Received 9 August 2013; published 4 November 2013)



- **4-body decay**



$$\frac{d^{(4)}\Gamma}{dq^2\, d(\cos\theta_l)d(\cos\theta_k)d\phi} = \frac{9}{32\pi}\,(I_1^s \sin^2\theta_k + I_1^c \cos^2\theta_k$$

$$+(I_2^s \sin^2\theta_k + I_2^c \cos^2\theta_k)\cos 2\theta_l + I_3 \sin^2\theta_k \sin^2\theta_l \cos 2\phi$$

$$+I_4 \sin 2\theta_k \sin 2\theta_l \cos\phi + I_5 \sin 2\theta_k \sin\theta_l \cos\phi + I_6 \sin^2\theta_k \cos\theta_l$$

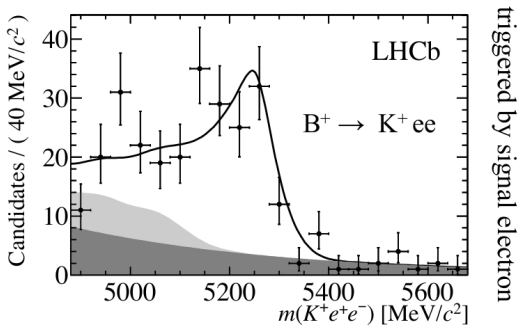
$$+I_7 \sin 2\theta_k \sin\theta_l \sin\phi + I_8 \sin 2\theta_k \sin 2\theta_l \sin\phi + I_9 \sin^2\theta_k \sin^2\theta_l \sin 2\phi)$$

Anomalies in B decays?

$b \to sll$

- **"R_K anomaly"** (**FCNC!**) $R_K = \frac{\mathrm{Br}(B \to K\mu\mu)}{\mathrm{Br}(B \to Kee)}\Big|_{[1.1,6]}$ **LHCb CERN-EP-2019-043**

  where "[,]" means $m^2_{\mu^+\mu^-} \in [1.1, 6.0]$ GeV^2



Old fig from LHCb, PRL113(2014)151601

- $R_K = 0.846^{+0.060}_{-0.054}(\mathrm{stat})^{+0.016}_{-0.014}(\mathrm{syst})$
- Tension with **SM** $\sim 2.5\sigma$

  (Here and below using:

  Aebischer, *et al*, 19030434
  Kumar, Kowalska, Sessolo, 1906.08596)

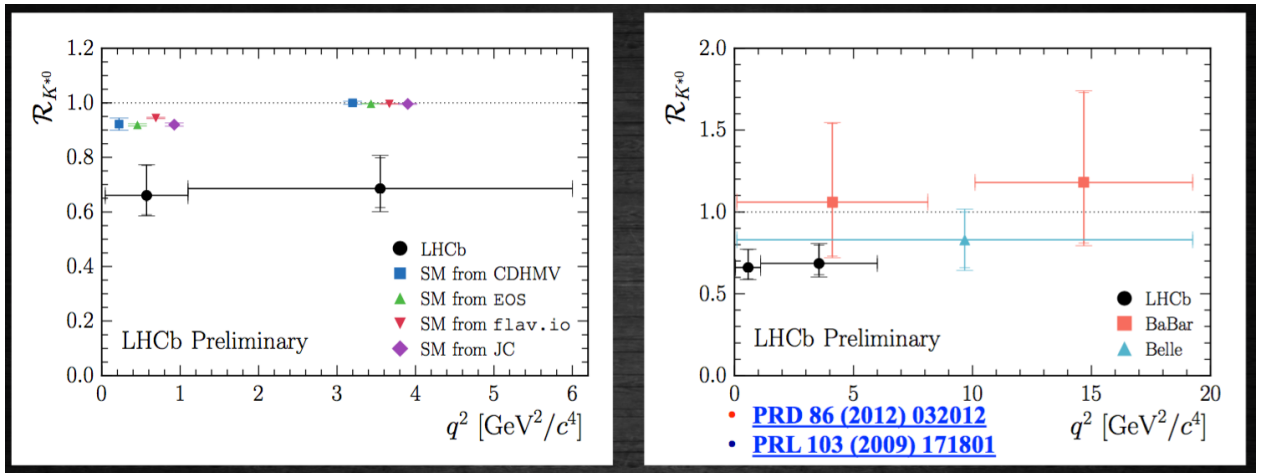
- Other anomalies in $b \to s\mu\mu$
  - Branching fractions $B \to K\mu\mu$, $B_s \to \phi\mu\mu$
  - Angular analysis $B \to K^*\mu\mu$
  - Up to 4σ in pre-2017 global fits **Altmannshofer and Straub '14**
  - "Dirty"

Anomalies in B decays?

$b \to sll$

- **"$R_{K^*} = \mathbf{Br}(B \to K^* \mu\mu)/\mathbf{Br}(B \to K^* ee)$ anomaly"** (**FCNC**)!

  LHCb, JHEP 1708 (2017) 055



LHCb Preliminary	low-q^2	central-q^2
$\mathcal{R}_{K^{*0}}$	$0.660 \,^{+\,0.110}_{-\,0.070} \pm 0.024$	$0.685 \,^{+\,0.113}_{-\,0.069} \pm 0.047$
95% CL	[0.517–0.891]	[0.530–0.935]
99.7% CL	[0.454–1.042]	[0.462–1.100]

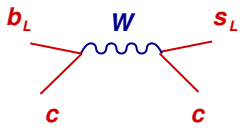
- Compatibility with **SM** 2.1-2.3σ (low-q^2) 2.4-2.5σ (central-q^2)
- Morerecently – large uncertainties **and** other regions Belle 1904.02440

  $R_{K*}[1.1, 6] = 0.96^{+0.45}_{-0.29} \pm 0.11$ $\quad R_{K*}[0.1, 8] = 0.90^{+0.27}_{-0.21} \pm 0.10$

  $R_{K*}[15, 19] = 1.18^{+0.52}_{-0.32} \pm 0.10$

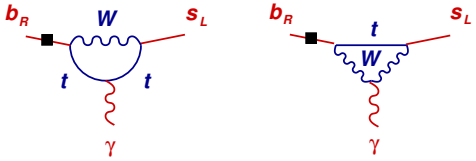
Effective field theory approach to $b \to s\ell\ell$ decays

- **CC** (Fermi theory):

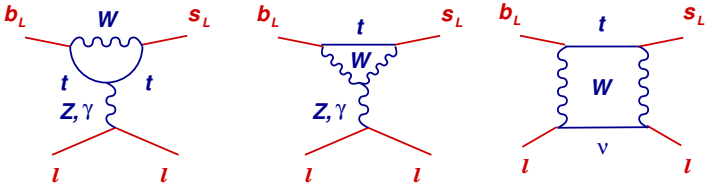


$$\Rightarrow \qquad G_F\, V_{cb}\, V_{cs}^*\, C_2\, \bar{c}_L \gamma^\mu b_L\, \bar{s}_L \gamma_\mu c_L$$

- **FCNC**:



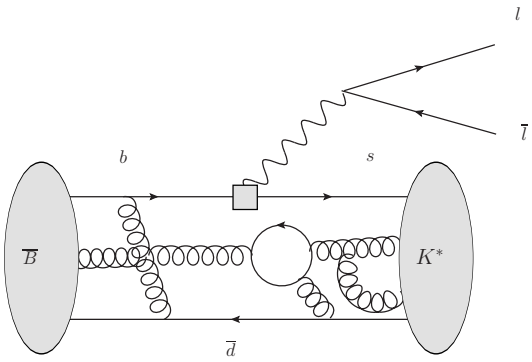
$$\Rightarrow \qquad \frac{e}{4\pi^2}\, G_F\, V_{tb}\, V_{ts}^*\, m_b\, C_7\, \bar{s}_L \sigma_{\mu\nu} b_R\, F^{\mu\nu}$$



$$\Rightarrow \qquad G_F\, V_{tb}\, V_{ts}^*\, \frac{\alpha}{4\pi}\, C_{9(10)}\, \bar{s}_L \gamma^\mu b_L\, \bar{\ell} \gamma_\mu (\gamma_5) \ell$$

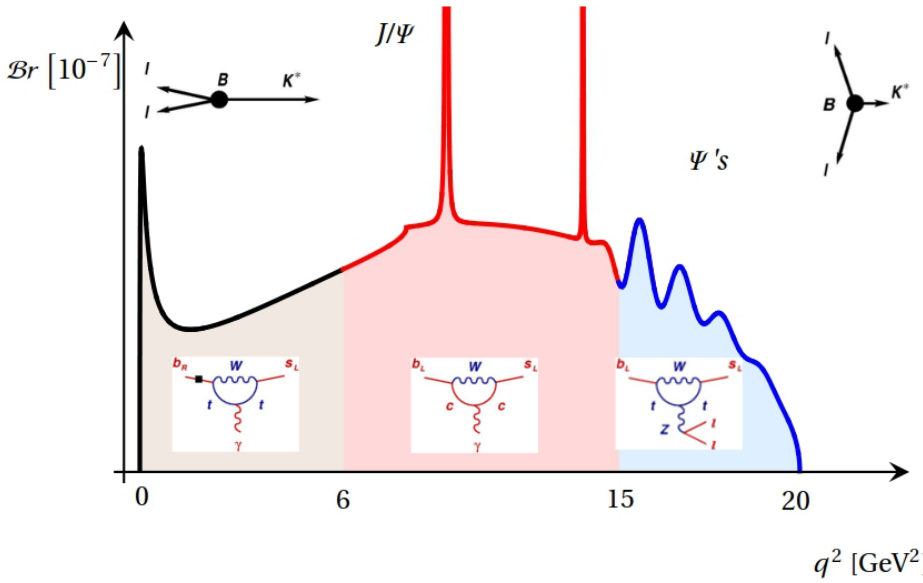
- Wilson coefficients $C_k(\mu)$ calculated in P.T. at $\mu = m_W$ and rescaled to $\mu = m_b$

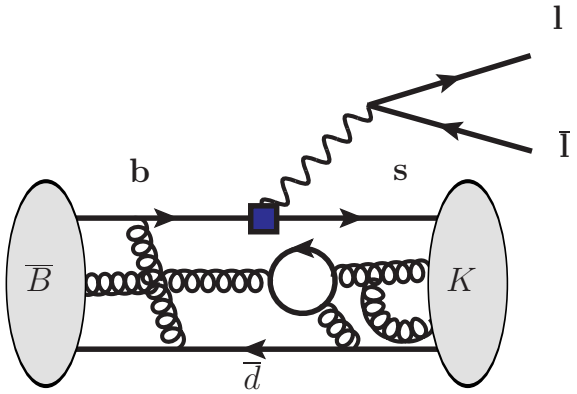
BG, Savage & Wise, NPB319 (1989) 271-290



- Light fields active at long distances
  Nonperturbative QCD! $\Rightarrow$ LQCD (sometimes)
- Factorization of scales m_b *vs.* $\Lambda_{\rm QCD}$
  HQEFT, QCDF, SCET,...

$b \to s\ell\ell$ theory: Hadronic complications

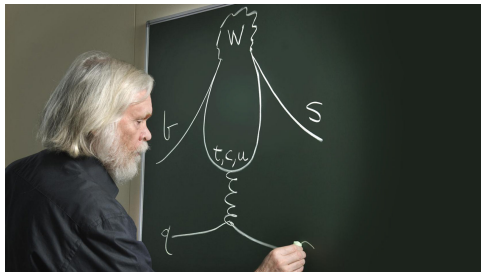




$$\frac{d\Gamma}{dq^2} = \frac{G_F^2\,\alpha^2|V_{tb}V_{ts}^*|^2}{1536\pi^5}\, f_+^2 \left(|C_9 + C_9' + 2\frac{\mathcal{T}_K}{f_+}|^2 + |C_{10} + C_{10}'|^2 \right) + \mathcal{O}(\frac{m_\ell^4}{q^4})$$

- NP: (pseudo)scalar contributions, $C_{S,P}^{(\prime)}$, have been suppressed:
  - SM-EFT $\Rightarrow C_P = -C_S, C_P' = C_S'$
  - (Pseudo)scalars chirally enhanced in $\Gamma(B_s \to \mu^+\mu^-)$

  $\Rightarrow$ $C_S^{(\prime)} \lesssim 0.2$
- $\mathcal{T}_K$ = long distance contribution, from charm penguin

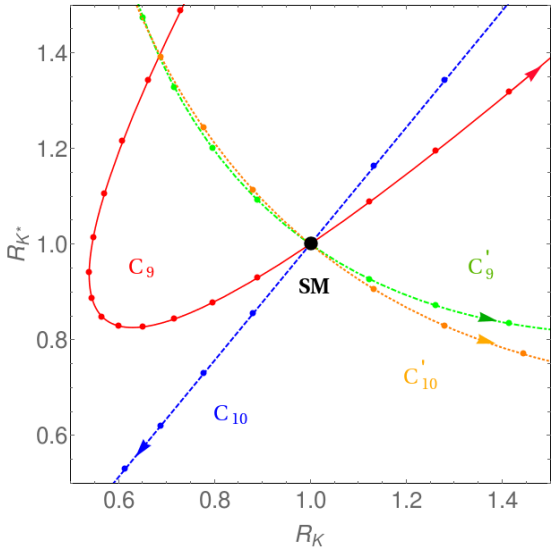


$B \to K^* \ell\ell$: R_{K^*}

G. D'Amico, et al, JHEP 1709 (2017) 010

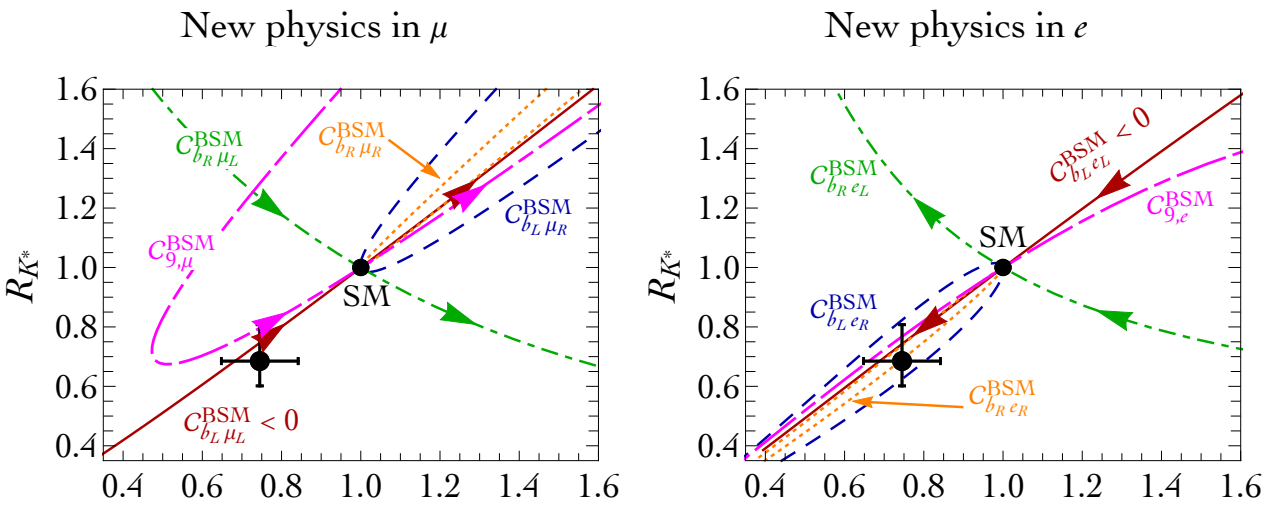
Li-Sheng Geng, et al, PRD96 (2017) 093006

Theoretical interpretation in pictures



- Recall $C_9^{SM} \approx -C_{10}^{SM} \approx 4.5$
- Figure shows $\delta C_i = C_i^{NP}$
- Arrows: increasing δC_i
- Dots: intervals of $\Delta(\delta C_i) = 0.5$
- Central Value (R_K, R_{K^*}) on blue line
- Not C_9', C_{10}' (ie, not $V + A$)

μ vs e



Anomalies in B decays?

$b \to sll$

Aebischer, *et al*, 19030434
One example, but many more like this

- Caveat: like most fits, assumes LCSRs for non-local $\mathcal{T}_{K(*)}$

Coeff.	best fit	1σ	2σ	pull
$C_9^{bs\mu\mu}$	-0.95	$[-1.10, -0.79]$	$[-1.26, -0.63]$	5.8σ
$C_9^{\prime bs\mu\mu}$	$+0.09$	$[-0.07, +0.24]$	$[-0.23, +0.39]$	0.5σ
$C_{10}^{bs\mu\mu}$	$+0.73$	$[+0.59, +0.87]$	$[+0.46, +1.01]$	5.6σ
$C_{10}^{\prime bs\mu\mu}$	-0.19	$[-0.30, -0.07]$	$[-0.41, +0.04]$	1.6σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$+0.20$	$[+0.05, +0.35]$	$[-0.09, +0.51]$	1.4σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	-0.53	$[-0.62, -0.45]$	$[-0.70, -0.36]$	6.5σ
C_9^{bsee}	$+0.88$	$[+0.62, +1.15]$	$[+0.36, +1.44]$	3.4σ
$C_9^{\prime bsee}$	$+0.32$	$[+0.09, +0.61]$	$[-0.16, +0.91]$	1.3σ
C_{10}^{bsee}	-0.82	$[-1.06, -0.59]$	$[-1.31, -0.37]$	3.7σ
$C_{10}^{\prime bsee}$	-0.27	$[-0.52, -0.05]$	$[-0.78, +0.17]$	1.2σ
$C_9^{bsee} = C_{10}^{bsee}$	-1.65	$[-1.93, -1.36]$	$[-2.19, -1.02]$	4.0σ
$C_9^{bsee} = -C_{10}^{bsee}$	$+0.45$	$[+0.31, +0.59]$	$[+0.19, +0.74]$	3.6σ
$(C_S^{bs\mu\mu} = -C_P^{bs\mu\mu}) \times \mathrm{GeV}$	-0.005	$[-0.008, -0.003]$	$[-0.013, -0.001]$	2.6σ
$(C_S^{\prime bs\mu\mu} = C_P^{\prime bs\mu\mu}) \times \mathrm{GeV}$	-0.005	$[-0.008, -0.003]$	$[-0.013, -0.001]$	2.6σ

Anomalies in B decays?

$b \to sll$

M. Beneke, et al, NPB 612(2001)25 (hep-ph/0106067)
A. Khodjamirian,et al, JHEP1009(2010)089 (1006.4945)
T. Blake,et al, Eur. Phys. J. C 78 (2018) no.6, 453 (1709.03921)
M. Ciuchini, et al, PoS BEAUTY2018 (2018), 044 (1809.03789)

More on the caveat

- For small q^2 the non-local ("non-factorizable") $\mathcal{T}_K$ is formally suppressed.
- How small is it?
  - Dominant in resonant region
  - Fits used LCSR; suppressed strong phases
  - Models of sum of Breit-Wigner resonances:
    - ★ small strong phases: agree with LCSR
    - ★ large phases: quite different from LCSR
  - Parametrized ignorance approach: expand in powers of q^2
    - ★ Fit to data
    - ★ Order of magnitude as expected
    - ★ "The constraining power of $B \to K^* \mu\mu$ on New Physics (NP) is lost, as some coefficients of the $\mathcal{T}_K$ expansion are indistinguishable from NP contributions"

Anomalies in B decays?

Decays to τ

- **"$R_{D^{(*)}}$ anomaly"** (CC)

$$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)}\tau\nu)}{\mathrm{Br}(B \to D^{(*)}\ell\nu)}$$

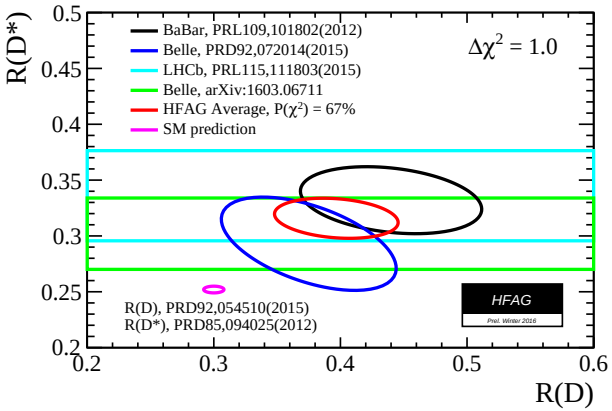
- **"$R_{J/\psi}$ anomaly"**

$$R_{J/\psi} = \frac{\mathrm{Br}(B_c \to \psi\tau\nu)}{\mathrm{Br}(B_c \to \psi\mu\nu)}$$

- **Polarizations**

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

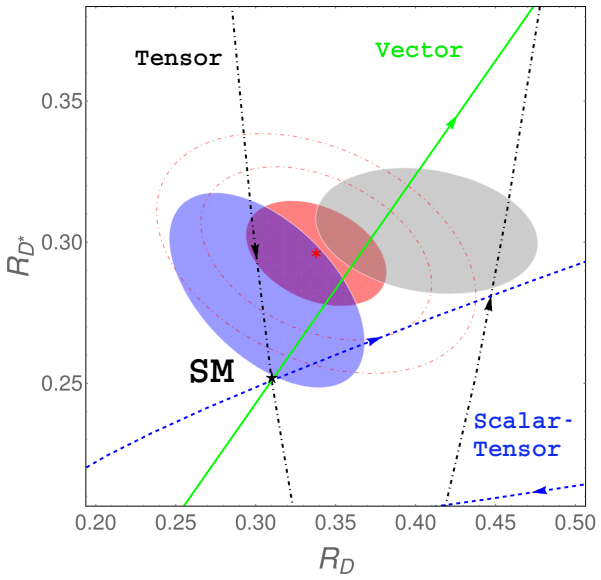
- ***Excesses*** observed at more than 4σ



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)

Anomalies in B decays?

Decays to τ



- SM: charged current, tree level
- $m_\tau \neq 0$
- Null hypothesis SM: p-value 5.56×10^{-3} (or 2.7σ, down from 3.0σ(2018)).
- Low energy EFT:

$$\mathcal{L}_{\rm eff}^{\rm LE} \supset -\frac{4G_F V_{cb}}{\sqrt{2}}[(1+\epsilon_L^\tau)(\bar\tau\gamma_\mu P_L\nu_\tau)(\bar c\gamma^\mu P_L b) + \epsilon_R^\tau(\bar\tau\gamma_\mu P_L\nu_\tau)(\bar c\gamma^\mu P_R b)$$

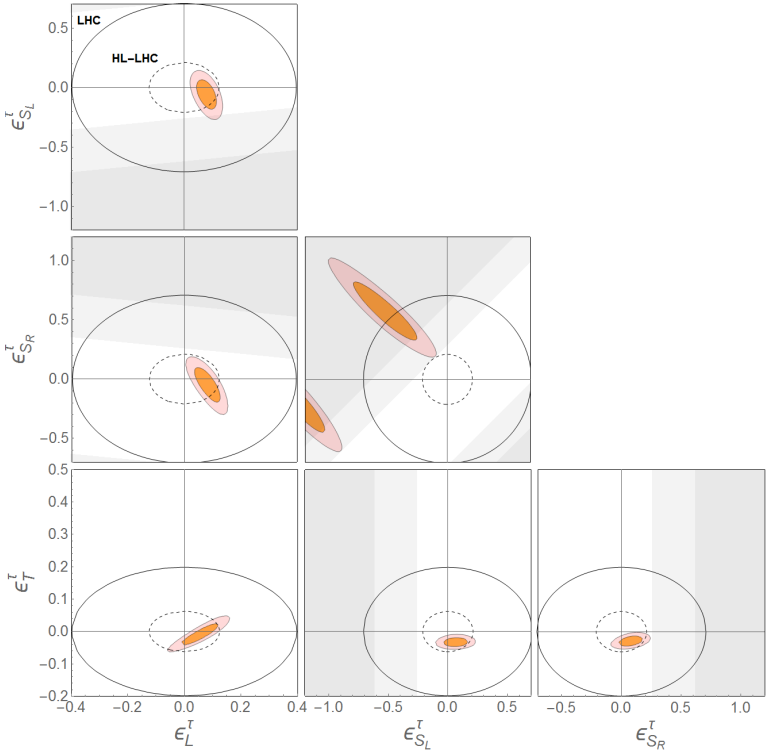
$$+\epsilon_{S_L}^\tau(\bar\tau P_L\nu_\tau)(\bar c P_L b) + \epsilon_{S_R}^\tau(\bar\tau P_L\nu_\tau)(\bar c P_R b) + \epsilon_T^\tau(\bar\tau\sigma_{\mu\nu}P_L\nu_\tau)(\bar c\sigma^{\mu\nu}P_L b)] + \text{H.c.},$$

- Linearly realized EWSB $\Rightarrow \epsilon_R^\tau = \epsilon_R^{e,\mu}$
- Add also $\epsilon P_L\nu_\tau \to \tilde\epsilon P_R\nu_\tau$.
  - No interference with SM $\Rightarrow \delta\Gamma \propto |\tilde\epsilon|^2 \Rightarrow$ Large $\tilde\epsilon$ needed (as single WC) $\Rightarrow$ tension with B_c-lifetime and large p_T data on mono-τ
- $\epsilon_{S_L}^\tau(\Lambda_{\rm NP}) = -4\epsilon_T^\tau(\Lambda_{\rm NP})$ "scalar-tensor"; natural in *e.g.*, some leptoquark models
  - Large $\epsilon_{S_L}^\tau$-ϵ_T^τ mixing in running Gonzlez-Alonso, Martin Camalich, Mimouni, PLB772(2017)777

Anomalies in B decays?

Decays to τ

	Best fit	$\chi^2_{\rm min}$	p-value	Pull$_{\rm SM}$	1σ range
ϵ_L^τ	0.07	14.56	0.20	3.46	$(0.05, 0.09)$
ϵ_T^τ	-0.03	15.70	0.15	3.29	$(-0.04, -0.02)$
$\epsilon_{S_L}^\tau$	0.08	25.23	8.44×10^{-3}	1.14	$(0.01, 0.14)$
$\epsilon_{S_R}^\tau$	0.14	21.24	3.10×10^{-2}	2.30	$(0.08, 0.20)$
$(\epsilon_{S_L}^\tau, \epsilon_T^\tau)$	$(0.07, -0.03)$	13.75	0.18	3.14	$\epsilon_{S_L}^\tau \in (0.00, 0.13)$ $\epsilon_T^\tau \in (-0.04, -0.02)$
$(\epsilon_{S_L}^\tau, \epsilon_{S_R}^\tau)$	$(-0.51, 0.56)$	12.14	0.28	3.37	$\epsilon_{S_L}^\tau \in (-0.69, -0.34)$ $\epsilon_{S_R}^\tau \in (0.41, 0.73)$
$(\epsilon_{S_R}^\tau, \epsilon_T^\tau)$	$(0.08, -0.03)$	14.38	0.16	3.05	$\epsilon_{S_R}^\tau \in (0.01, 0.14)$ $\epsilon_T^\tau \in (-0.04, 0.2)$
$\epsilon_L^\tau, \epsilon_T^\tau)$	$(0.05, -0.01)$	14.32	0.16	3.06	$\epsilon_L^\tau \in (0.01, 0.10)$ $\epsilon_T^\tau \in (-0.03, 0.01)$
$\epsilon_L^\tau, \epsilon_{S_L}^\tau)$	$(0.08, -0.06)$	14.09	0.17	3.09	$\epsilon_L^\tau \in (0.06, 0.10)$ $\epsilon_{S_L}^\tau \in (-0.14, 0.03)$
$\epsilon_L^\tau, \epsilon_{S_R}^\tau)$	$(0.08, -0.05)$	14.33	0.16	3.06	$\epsilon_L^\tau \in (0.05, 0.11)$ $\epsilon_{S_R}^\tau \in (-0.14, 0.05)$



- **Light (Dark) gray: Constraints from B_c-lifetime, assuming Br$(B_c \to \tau\nu) < 10\%(30\%)$**
- **Black continuous (dashed) lines: Constraints from LHC (projected HL-LHC) high p_T mono-τ data**

Microscopic Models

- $o(10^2)$ papers on models; here, general observations Refs: apologies!

$b \to c\tau\nu$: Tree level, $\lesssim$ few TeV mediators; loop mediated only if $M \lesssim v_{EW}$ **and** no CKM-like suppression (not flavor models)

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	**1**	**2**	+1/2	✗	✗	✓	✓	✗
W_L'	1	**1**	**3**	0	✓	✗	✗	✗	✗
W_R'	1	**1**	**1**	+1	✗	✓	✗	✗	✗
S_1	0	$\bar{\mathbf{3}}$	**1**	+1/3	✓	✓	✗	✓	✓
S_3	0	$\bar{\mathbf{3}}$	**3**	+1/3	✓	✓	✗	✗	✗
R_2	0	**3**	**2**	+7/6	✓	✓	✗	✓	✓
U_1	1	**3**	**1**	+2/3	✓	✓	✓	✗	✗
U_3	1	**3**	**3**	+2/3	✓	✓	✗	✗	✗
V_2	1	$\bar{\mathbf{3}}$	**2**	+5/6	✗	✗	✓	✗	✗

- W_L' comes with Z', troubled by FCNC's ($X^0\bar{X}^0$ mixing) or $\bar{\tau}\tau$ @LHC, or both
- W_R' requires RH-neutrinos ($\tilde{\epsilon}_R$) eg, He et al 1711.09525, Babu et al 1811.04496, Greljo et al 1804.04642, ...
- LQs: ... Asadi et al 1804.04135
  - No dim-4 proton decay: Only R_2, U_1 & U_3
  - No dim-5 proton decay: Only R_2 Assad et al, 1708.06350

Microscopic Models

$b \to sll$ anomalies

Refs: more apologies!

- Approaches:
  - Short distance: decoupling particles, heavier than EW, weak coupling (tree level)
    - Z'
      - LUV: couple (typically) to $L_\mu - L_\tau$, strength $g_{\mu\mu}$
      - FCNC: non-diag coupling to $\bar{s}b$, strength g_{bs}; B_s-mixing $\Rightarrow$ $g_{bs}/M_{Z'} < 5 \times 10^{-3}$ TeV^{-1}
      - B-anomalies: $g_{\mu\mu}/M_{Z'} > 1/(3.7 \text{ TeV})$, or $M_{Z'} < 13$ TeV for $g_{\mu\mu} < \sqrt{4\pi}$
      - Need to address LFV (eg, $\mu \to e\gamma$) and other quark FCNC
    - Leptoquarks: only S_3, U_1, U_3 give $C_9 = -C_{10}$
      - Only U_1 gives $C_\nu = 0$
      - U_1 has no tree level proton decay
      - U_1 arises naturally in Pati-Salam
  - Non-decoupling, EW scale
    - **SM-EFT analysis does not necessarily apply**
    - Loop mediators Arnan et al, 1608.07832; Gripaios et al, JHEP1606(2016)083; Kamenik et al, 1704.06005
      - LE Frogatt-Nielsen models?
    - Composites, partial composites eg Gripaios et al, JHEP1505(2015)006
  - Long distance, lighter than EW Sala & Straub, 1704.06188, Bishara et al, 1705.03465, ...

Outlook, Conclusions, Wishful thinking

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

SM does not explain, it parametrizes

Yet what we do after precise measurements and calculations, in light of hints of NP:

- Fit to EFT
- Map to simplified mediators
- Invent UV completion that parametrizes flavor — much like SM $\Rightarrow$ *no progress!*

What would a theory of flavor do?

One of these:

- Differentiate among generations by their very short distance interactions, eg, different representations of gauge group (or charges under Froggatt-Nielsen?)
- Explain generations as excitations of composites (meaning: made of more fundamental stuff, surely tightly bound, rather than the modern meaning made of mixed fields)
- ??

Consider, eg, the U_1 LQ (vector in $(3,1)_{2/3}$

UV Completion:

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

Fermions in SU(4): $\begin{bmatrix} Q_L^{\alpha} \\ Q_L^{\beta} \\ Q_L^{\gamma} \\ L_L \end{bmatrix} \quad \begin{bmatrix} Q_R^{\alpha} \\ Q_R^{\beta} \\ Q_R^{\gamma} \\ L_R \end{bmatrix}$

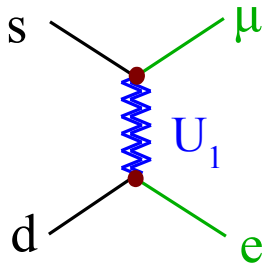
Main Pati-Salam idea:
Lepton number as "the 4th color"

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

Three generations of fermions (identical gauge group reps) added. Masses and mixings much like in the SM

Plain vanilla PS model: 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]

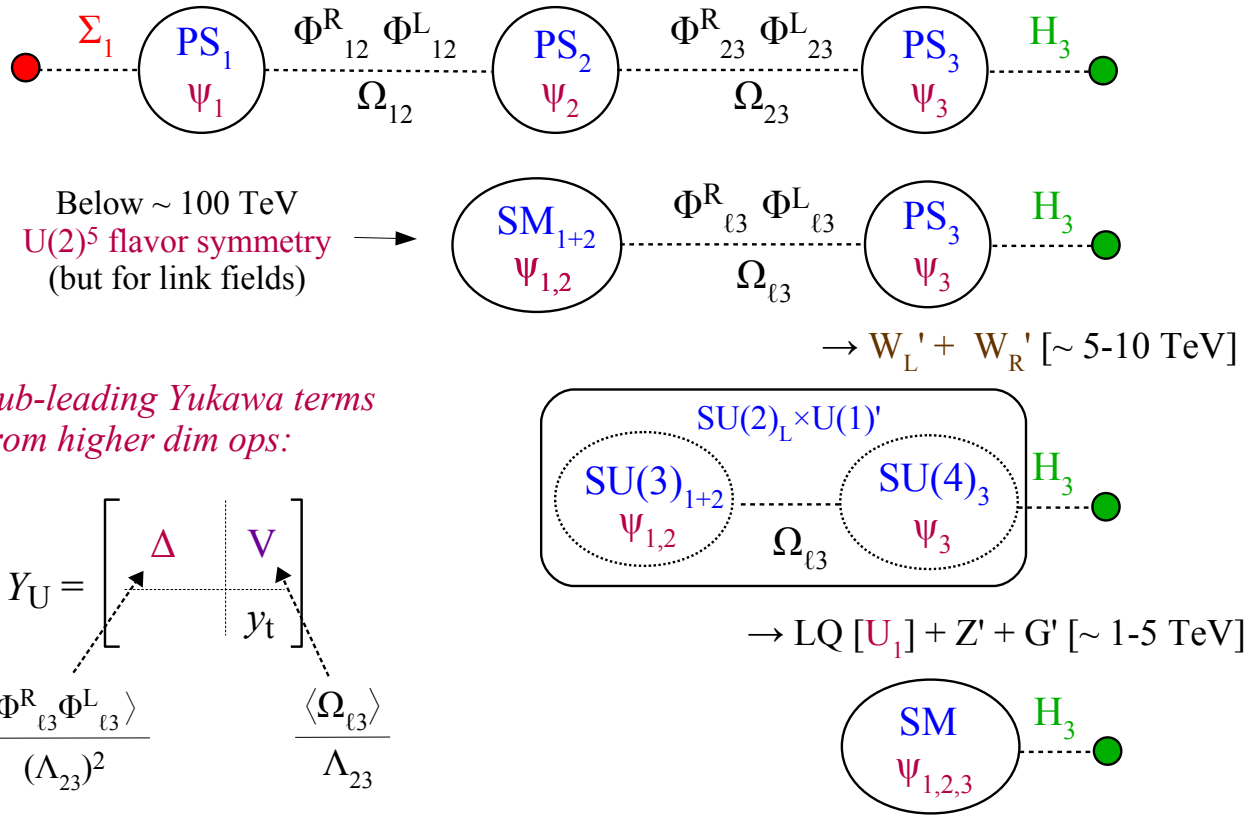
Still not a theory of flavor!

But there is hope: some models are being proposed, eg, PS^3 model

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

G. Isidori – New prospects for BSM physics *HC2NP 2019, Tenerife*

- *The* PS^3 *model*



More hope: For loop mediators, a Froggatt-Nielsen-like model has been proposed

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

And this is why we love LUV

The End