Flavor Physics Theory

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July 7th, SUSY 2016, Melbourne

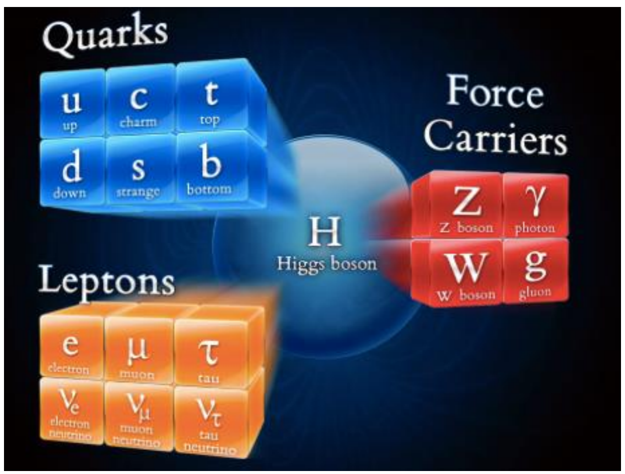
Standard Model and Flavor Physics

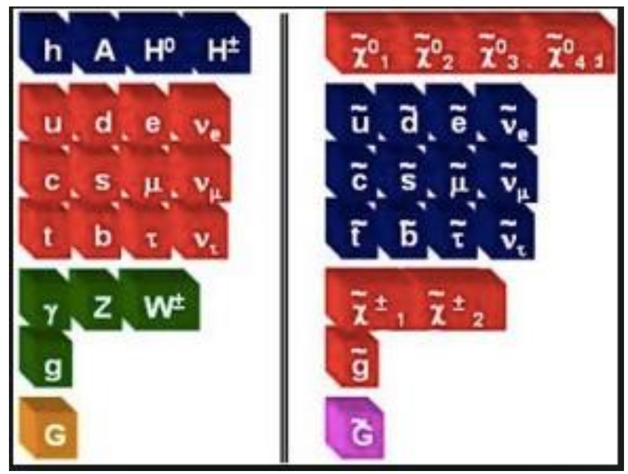
Wikpedia

Flavor (**flavour)** is the sensory impression of food or other substance, and is determined primarily by the chemical senses of taste and smell.

In particle physics, **flavor** refers to a species of an elementary particle. The Standard Model counts six flavors of quarks and six flavor of leptons.

Standard Model is based on $SU(3)_C xSU(2)_L xU(1)_Y$ gauge interaction.





SUSY flavor, Double the flavors. More interactions.

In SM mis-match of weak and mass eigen-bases, leads to flavor mixing and CP violation, part of the story of flavor physics.

Problem driven aspects!

A very exciting time for particle physics!

The last missing piece, Higgs, discovered in 2012 (announced here on 4th of July in Melbourne).

The SM is a complete story! But may be not all

Masses: All mass of order v_{ew} ~ 246 GeV??? No!

There exists a huge hierarchy among known particle mass… Also why electroweak scale is so much smaller than the Planck scale?

How different flavors mix with each other…

CP violation…

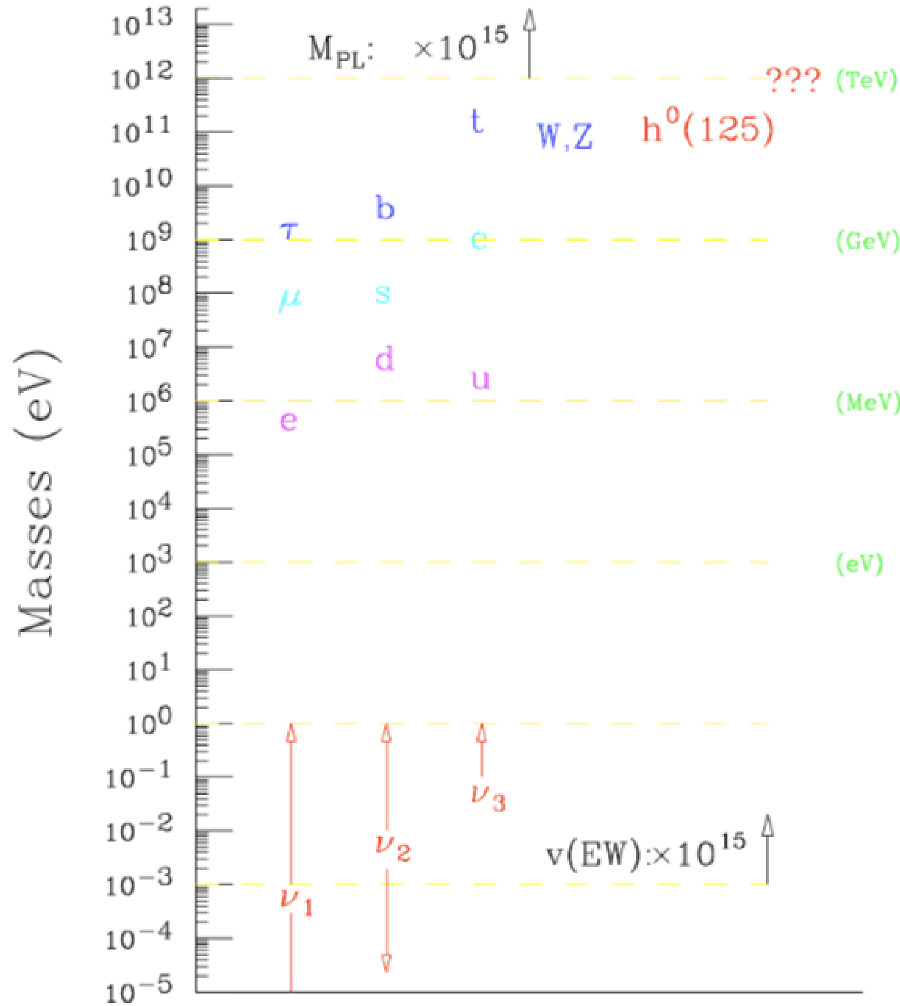
New particles or flavors?

SUSY expects a lot…, not insight

750 GeV resonance?

Light 17 MeV boson mediating a fifth force?

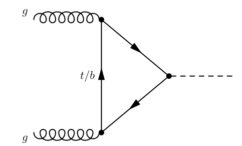
A lot to understand for flavor physics!



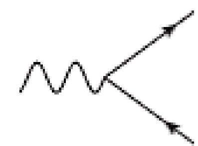
Number of SM generations

In the SM, only 3 generations of quarks and leptons are allowed.

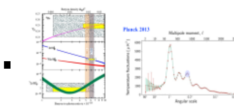
gg -> Higgs ~ (number of heavy quarks)^2, if fourth generation exist, their mass should be large, 9 times bigger production of Higgs. LHC data ruled out more than 3 generations of quarks.



LEP already ruled out more than 3 neutrinos with mass less than $m_Z/2$.

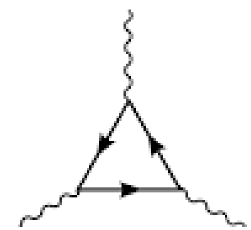


Cosmology and astrophysics, number of light neutrinos also less than 4.



SM, triangle anomaly cancellation: equal number of quarks and leptons!

There are only three generations of sequential quarks and leptons!



Why 3 generations? How do they mix with each other?

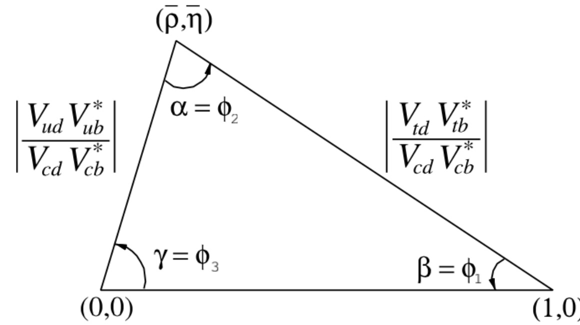
Beyond SM, conclusions may change, X-G He and G. Valencia, PPLB707 (2012)

Quark and Lepton mixing patterns

The mis-match of weak and mass eigen-state bases lead quark and lepton mix within generations.

Quark mixing the Cabibbo -Kobayashi-Maskawa (CKM) matrix $V_{\rm CKM}$,

lepton mixing the Pontecorvo -Maki-Nakawaga-Sakata (PMNS) matrix $U_{\rm PMNS}$



$$L = -\frac{g}{\sqrt{2}}\overline{U}_L\gamma^\mu V_{\rm CKM} D_L W_\mu^+ - \frac{g}{\sqrt{2}}\overline{E}_L\gamma^\mu U_{\rm PMNS} N_L W_\mu^- + H.C.\,,$$

$U_L = (u_L, c_L, t_L, ...)^T$, $D_L = (d_L, s_L, b_L, ...)^T$, $E_L = (e_L, \mu_L, \tau_L, ...)^T$, and $N_L = (\nu_1, \nu_2, \nu_3, ...)^T$

For n-generations, $V = V_{\rm CKM}$ or $U_{\rm PMNS}$ is an $n \times n$ unitary matrix.

A commonly used form of mixing matrix for three generations of fermions is given by

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix},$$

where $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$ are the mixing angles and δ is the CP violating phase.

If neutrinos are of Majorana type, for the PMNS matrix one should include an additional diagonal matrix with two Majorana phases $\mathrm{diag}(e^{i\alpha_1/2}, e^{i\alpha_2/2}, 1)$ multiplied to the matrix from right in the above.

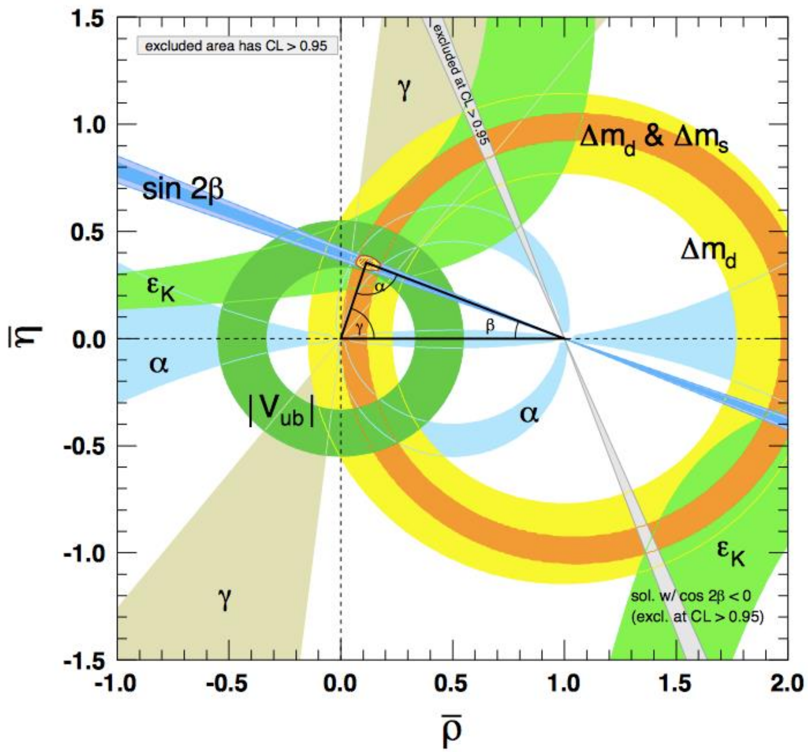
Status of Quark and Lepton

Quark Mixing

PDG

Neutrino Mixing

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

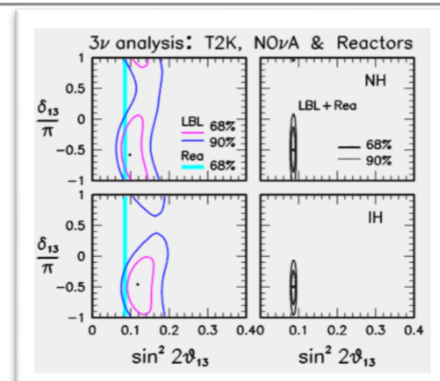


$$\lambda = 0.22537 \pm 0.00061\,, \qquad A = 0.814^{+0.023}_{-0.024}\,,$$

$$\bar\rho = 0.117 \pm 0.021\,, \qquad \bar\eta = 0.353 \pm 0.013\,.$$

$\Delta m^2 = \Delta m^2_{31} - \Delta m^2_{21}/2 > 0$, if $m_1 < m_2 < m_3$, and $\Delta m^2 = \Delta m^2_{32} + \Delta m^2_{21}/2 < 0$ for $m_3 < m_1 < m_2$.

Parameter	best-fit ($\pm 1\sigma$)	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	$7.54^{+0.26}_{-0.22}$	$6.99 - 8.18$
$\lvert\Delta m^2\rvert$ $[10^{-3}$ eV $^2]$	2.43 ± 0.06 (2.38 ± 0.06)	$2.23 - 2.61$ $(2.19 - 2.56)$
$\sin^2\theta_{12}$	0.308 ± 0.017	$0.259 - 0.359$
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	$0.437^{+0.033}_{-0.023}$	$0.374 - 0.628$
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	$0.455^{+0.039}_{-0.031}$,	$0.380 - 0.641$
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	$0.0234^{+0.0020}_{-0.0019}$	$0.0176 - 0.0295$
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	$0.0240^{+0.0019}_{-0.0022}$	$0.0178 - 0.0298$
δ/π (2σ range quoted)	$1.39^{+0.38}_{-0.27}$ $(1.31^{+0.29}_{-0.33})$	$(0.00 - 0.16) \oplus (0.86 - 2.00)$
		$((0.00 - 0.02) \oplus (0.70 - 2.00))$



Approximation:
$\delta = -\pi/2$ $\theta_{23} = \pi/4$

Palazzo, Phys. Lett. B757, 142(2015))

More data on neutrino this meeting: A. VillanuevaM. Martinez, B. Roskovec

Why they mix the pattern shown above? Some understanding.

Test SM predictions and Hints for new physics beyond

A consistent picture emerge for phenomena related to FCNC and CP violation. Predictions can be made and used to test SM.

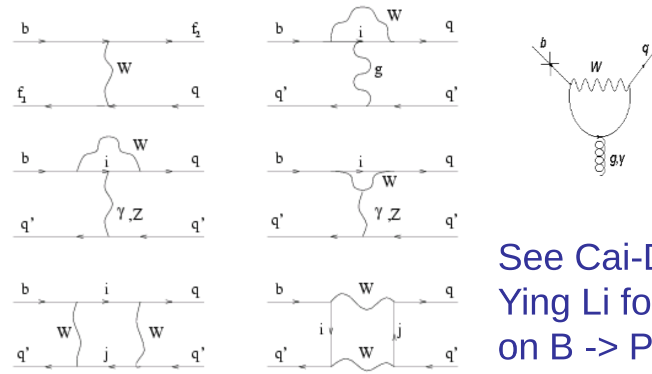
A global picture of B-> PP assisted with SU(3) flavor symmetry.

(Hsiao and He, PRD93,114002(2016))

A non-trivial example

(Deshpande&X-G He(1995), X-G He(1999), Gronau&Rosner (2000)

$$A(\bar B^0 \to K^-\pi^+) = V_{ub}V^*_{us}T + V_{tb}V^*_{ts}P\,, \quad A(B^0 \to K^+\pi^-) = V^*_{ub}V_{us}T + V^*_{tb}V_{ts}P$$
$$A(\bar B^0_s \to K^+\pi^-) = V_{ub}V^*_{ud}T + V_{tb}V^*_{td}P\,, \quad A(B^0_s \to K^-\pi^+) = V^*_{ub}V_{ud}T + V^*_{tb}V_{td}P$$



See Cai-Dian Lu. Ying Li for more on B -> PP, PV.

$$T = C^T_{\bar 3} + C^T_6 - A^T_{\overline{15}} + 3C^T_{\overline{15}}\,, \quad P = C^P_{\bar 3} + C^P_6 - A^P_{\overline{15}} + 3C^P_{\overline{15}}.$$
$$\Delta(B \to PP) = \Gamma(\bar B \to \bar P\,\bar P) - \Gamma(B \to P\,P)$$

$$Im(V_{ub}V^*_{ud}V^*_{tb}V_{td}) = -Im(V_{ub}V^*_{us}V^*_{tb}V_{ts}), \quad \Delta(B^0 \to K^+\pi^-) = -\Delta(B^0_s \to K^-\pi^+)$$

$$\frac{A_{CP}(B^0 \to K^+\pi^-)}{A_{CP}(B^0_s \to K^-\pi^+)} + \frac{Br(B^0_s \to K^-\pi^+)\tau_{B^0}}{Br(B^0 \to K^+\pi^-)\tau_{B^0_s}} = 0$$

Test for SU(3) flavor symmetry, and also SM with 3 generations!

Introduce $\mathcal{R}(\Delta^{B_d}_{\pi^+K^-}/\Delta^{B_s}_{K^+\pi^-})$ as a measure of the goodness of the relation

$$\frac{\mathcal{A}_{CP}(B_d \to \pi^+K^-)}{\mathcal{A}_{CP}(B_s \to K^+\pi^-)} + \mathcal{R}(\Delta^{B_d}_{\pi^+K^-}/\Delta^{B_s}_{K^+\pi^-})\frac{\mathcal{B}(B_s \to K^+\pi^-)/\tau_{B_s}}{\mathcal{B}(B_d \to \pi^+K^-)/\tau_{B_d}} = 0\,,$$

with $\mathcal{R}(\Delta^{B_d}_{\pi^+K^-}/\Delta^{B_s}_{K^+\pi^-}) = 1$ in SU(3) limit.

If annihilation amplitudes are neglected, there are additional relations, for example

$$\frac{\mathcal{A}_{CP}(B_d \to \pi^+K^-)}{\mathcal{A}_{CP}(B_d \to \pi^+\pi^-)} + \mathcal{R}'(\Delta^{B_d}_{\pi^+K^-}/\Delta^{B_d}_{\pi^+\pi^-})\frac{\mathcal{B}(B_d \to \pi^+\pi^-)}{\mathcal{B}(B_d \to \pi^+K^-)} \simeq 0\,,$$

with $\mathcal{R}'(\Delta^{B_d}_{\pi^+K^-}/\Delta^{B_d}_{\pi^+\pi^-}) \simeq 1$.

Several such relations exist. Further tests!

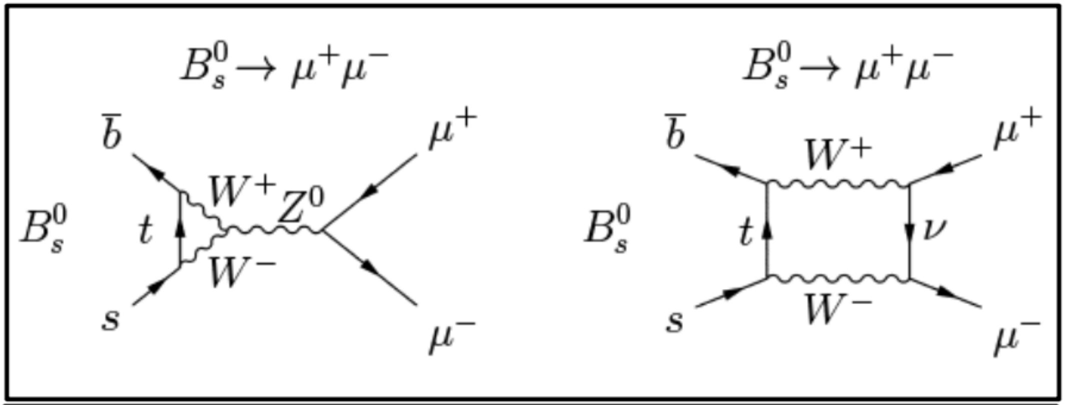
modes	$\mathcal{R}_{data}$	$\mathcal{R}^{(\prime)}_{fit}$
$\mathcal{R}(\Delta^{B_d}_{\pi^+K^-}/\Delta^{B_s}_{K^+\pi^-})$	1.12 ± 0.22	$(1.03 \pm 0.06, 1.06 \pm 0.08)$
$\mathcal{R}(\Delta^{B_s}_{K^+K^-}/\Delta^{B_d}_{\pi^+\pi^-})$	2.20 ± 1.77	$(0.98 \pm 0.06, 0.89 \pm 0.12)$
$\mathcal{R}(\Delta^{B_u}_{\pi^-\bar K^0}/\Delta^{B_u}_{K^-K^0})$	-3.52 ± 5.25	$(1.05 \pm 2.07, 1.02 \pm 3.48)$
$\mathcal{R}(\Delta^{B_d}_{\pi^0\bar K^0}/\Delta^{B_s}_{K^0\pi^0})$	—	$(1.06 \pm 0.06, 1.06 \pm 0.08)$
$\mathcal{R}(\Delta^{B_s}_{\pi^+\pi^-}/\Delta^{B_d}_{K^-K^+})$	—	$(—, 1.00 \pm 0.27)$
$\mathcal{R}(\Delta^{B_s}_{\pi^0\pi^0}/\Delta^{B_d}_{K^-K^+})$	—	$(—, 1.00 \pm 0.02)$
$\mathcal{R}'(\Delta^{B_d}_{\pi^+K^-}/\Delta^{B_d}_{\pi^+\pi^-})$	1.02 ± 0.19	$(0.99 \pm 0.06, 1.07 \pm 0.11)$
$\mathcal{R}'(\Delta^{B_d}_{\pi^0\bar K^0}/\Delta^{B_d}_{\pi^0\pi^0})$	0.00 ± 1.28	$(1.02 \pm 0.06, 0.70 \pm 0.05)$
$\mathcal{R}'(\Delta^{B_s}_{K^+K^-}/\Delta^{B_s}_{K^+\pi^-})$	2.42 ± 1.96	$(1.01 \pm 0.06, 0.88 \pm 0.10)$
$\mathcal{R}'(\Delta^{B_u}_{\pi^-\bar K^0}/\Delta^{B_d}_{\bar K^0K^0})$	-0.56 ± 0.83	$(1.14 \pm 2.28, 0.22 \pm 0.64)$

Globally, no call for new physics, there are rooms for NP.

Contents

1. Hints for New Physics Beyond SM

There are anomalies show in data hinting the need of new physics



higher-order FCNC allowed in SM

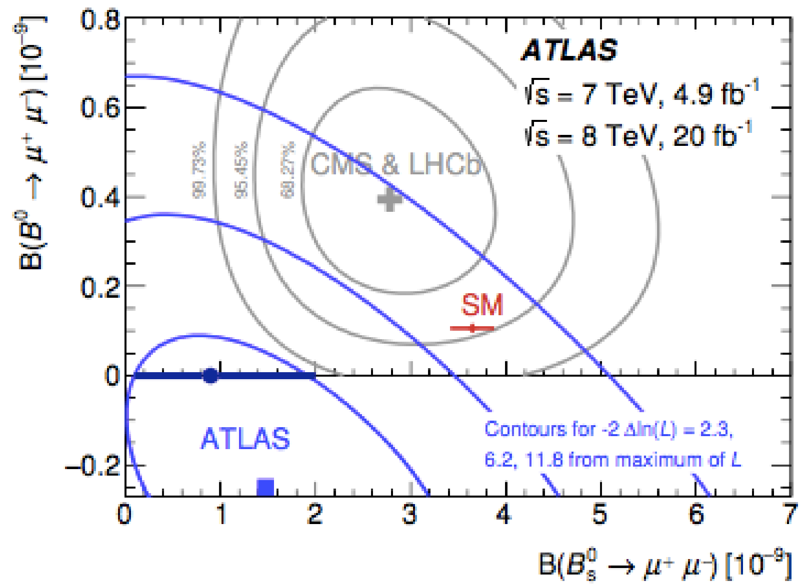
$B(B_s \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$

$B(B_d \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$

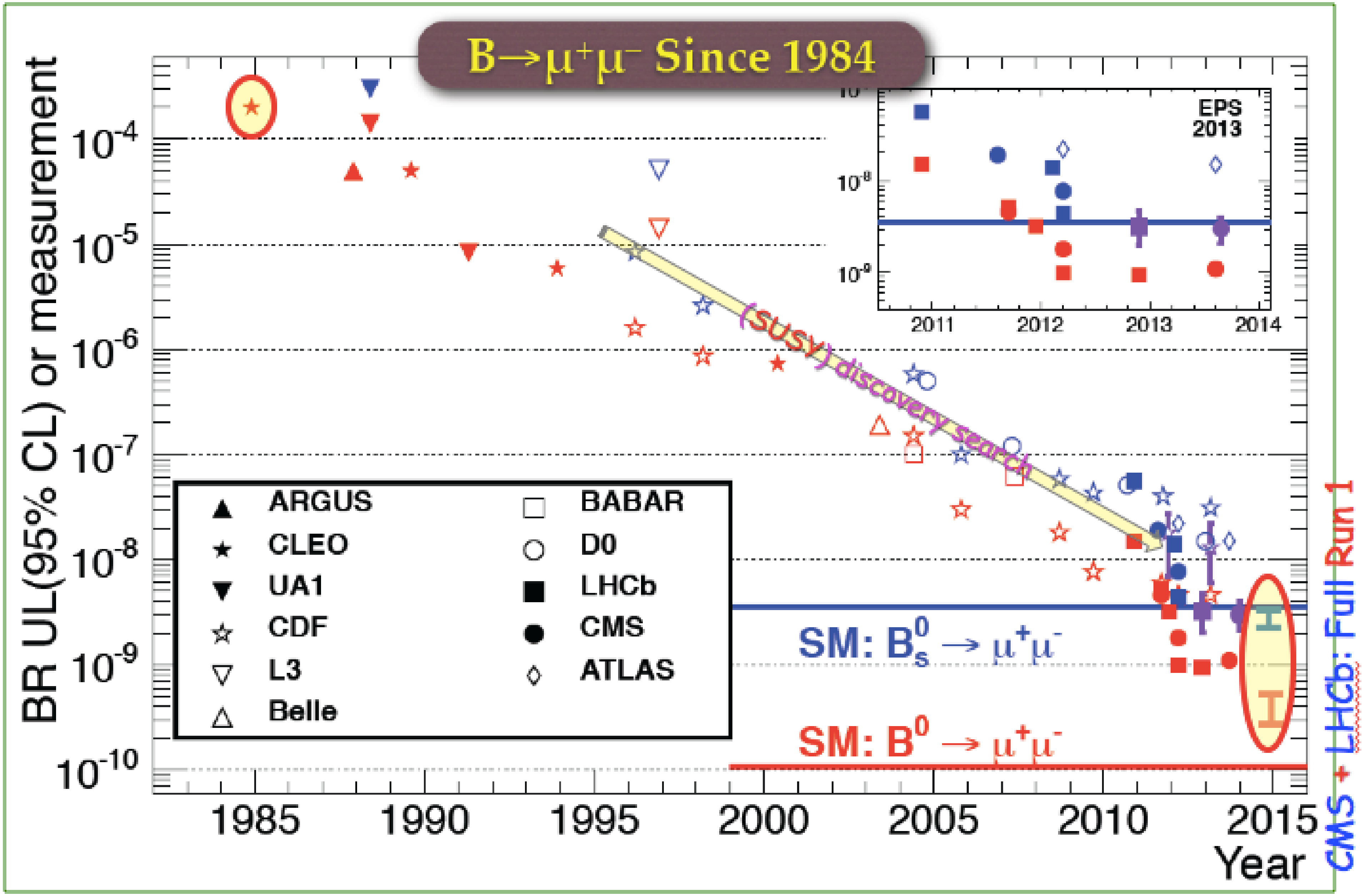
[Bobeth et al, PRL 112 (2014) 101801]

Exp. observations:

$$B(B_s \to \mu^+\mu^-)_{exp} \; \begin{array}{l} (3.2^{+1.4+0.5}_{-1.0-0.1}) \times 10^{-9} (LHCb), \\ (2.9^{+1.1+0.3}_{-1.0-0.1} \times 10^{-9})(CMS), \\ (3.0^{+0.9+0.6}_{-0.8-0.4}) \times 10^{-9} (ATLAS). \end{array}$$



$$B(B_d \to \mu^+\mu^-)_{exp} = (3.6^{+1.6}_{-1.4}) \times 10^{-10}$$


B→μ⁺μ⁻ Since 1984
BR UL(95% CL) or measurement
EPS 2013
ARGUS
CLEO
UA1
CDF
L3
Belle
BABAR
D0
LHCb
CMS
ATLAS
(SUSY) discovery search
SM: $B_s^0 \to \mu^+\mu^-$
SM: $B^0 \to \mu^+\mu^-$
CMS + LHCb: Full Run 1
Year

Some other deviations (anomalies)

Attracted a lot of attentions.

B -> $D^{(*)} \tau \nu$ $\sim 4\sigma$ anomaly

b -> s ll (B_s -> K^* ll, K(ee,$\mu\mu$) $\phi\mu\mu$, $\mu\mu$..) 2~3 σ

ε'/ε $\sim 3\sigma$

h -> $\mu\ \tau$ $\sim 2\sigma$

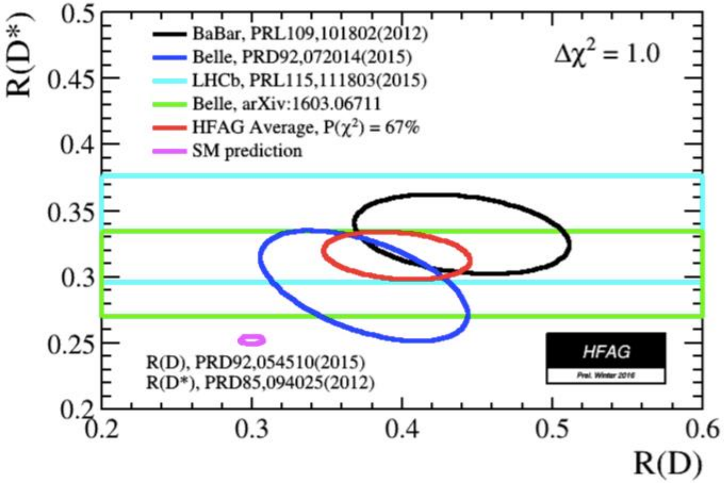
g – 2 of μ $\sim 3\sigma$

...

More data reports this meeting:
F. Wilson, O. Deschamps,
M Rozanska, M. Smizanska,
W-S. Hou, J. Schaarschmidt
G. Underwater

The B ->D$^{(*)}$ τ ν anomalies

$$R(D^{(*)}) = \frac{Br(B \to D^{(*)}\tau\bar{\nu}_\tau)}{Br(B \to D^{(*)}l\bar{\nu})}$$



BaBar

$R(D) = 0.440 \pm 0.058 \pm 0.042$
$R(D^*) = 0.332 \pm 0.024 \pm 0.018$

Belle

$R(D) = 0.375 \pm 0.064 \pm 0.026$
$R(D^*) = 0.293 \pm 0.038 \pm 0.015$

$R(D^*) = 0.302 \pm 0.030 \pm 0.011$

LHCb

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

average

$R(D) = 0.397 \pm 0.040 \pm 0.028$
$R(D^*) = 0.316 \pm 0.016 \pm 0.010$

difference with SM predictions is at **4.0σ** level

What needed ot solve the anomaly?

Exp: More precise measurements!

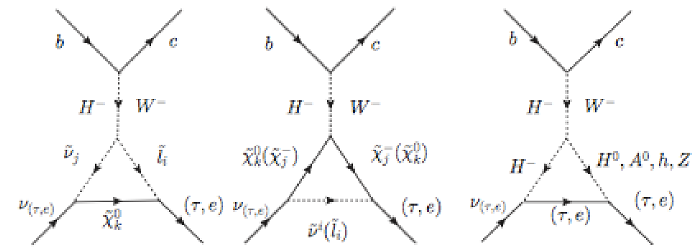
Thor: New Physics modify charged current interaction… in a way that

a) The first two and third generations interact differently;

b) Have P-parity conserving and violating ones differently!

THDM-II cannot explain both

MSSM OK, Boubaa et al, 1604.0341.



$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

X-G He, G. Valencia, PRD87, 014014(2013)

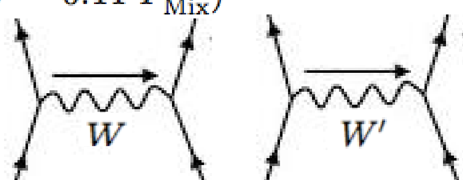
$$\Gamma(B \to D\tau\nu) = \Gamma(B \to D\tau\nu)_{SM}\,(F^q_{W'} + 2\,F^q_{\rm Mix})$$

$$\Gamma(B \to D^\star\tau\nu) = \frac{G_F^2\, m_B^5}{192\pi^3}\,|V_{qb}|^2\,(0.062\,F^q_{W'} - 0.11\,F^q_{\rm Mix})$$

$$F^q_{W'} = \left(1 + \left(\frac{g_R M_W}{g_L M_{W'}}\right)^4 \frac{|V^\ell_{R3\ell}|^2|V_{Rqb}|^2}{|V_{qb}|^2}\right)$$

$$F^q_{\rm Mix} = \xi_W \frac{g_R}{g_L}\frac{{\rm Re}\left(V^\star_{qb}V_{Rqb}\right)}{|V_{qb}|^2}\left(1 - \left(\frac{M_W}{M_{W'}}\right)^2\right)\left(1 + \left(\frac{g_R M_W}{g_L M_{W'}}\right)^2 |V^\ell_{R3\ell}|^2\right).$$

$$Q_L^{1,2} : (3,2,1)(1/3)\,, \quad U_R^{1,2} : (3,1,1)(4/3)\,, \quad D_R^{1,2} : (3,1,1)(-2/3)\,,$$
$$L_L^{1,2} : (1,2,1)(-1)\,, \quad E_R^{1,2} : (1,1,1)(-2)\,.$$



$$Q_L^3 : (3,2,1)(1/3)\,, \quad Q_R^3 : (3,1,2)(1/3)\,,$$
$$L_L^3 : (1,2,1)(-1)\,, \quad L_R^3 : (1,1,2)(-1)\,.$$

$$-\frac{g_L}{\sqrt{2}}\bar{U}_L\gamma^\mu V_{KM} D_L(\cos\xi_W W^+_\mu - \sin\xi_W W'^+_\mu)$$
$$-\frac{g_R}{\sqrt{2}}\bar{U}_R\gamma^\mu V_R D_R(\sin\xi_W W^+_\mu + \cos\xi_W W'^+_\mu) \;+\; \text{h. c.},$$

Third generation is different other genrtions, b and t properties are different.

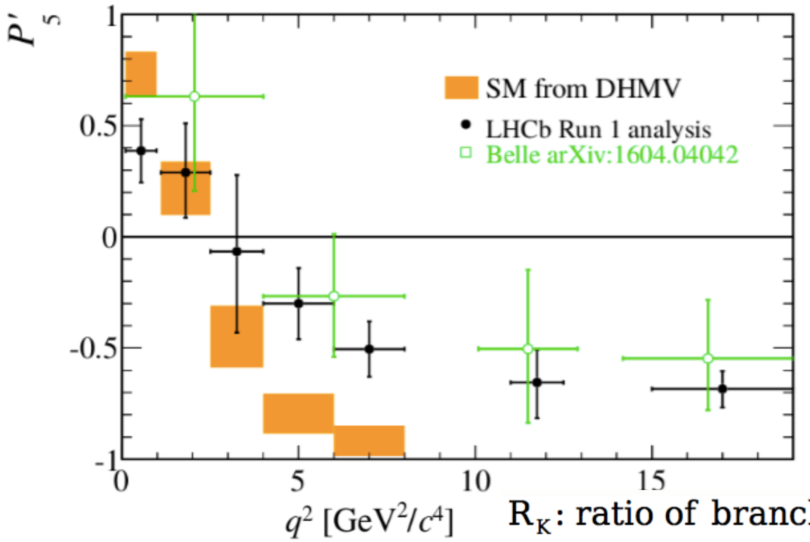
Other discussions on top FCNC, Chung Kao at this meeting

The b -> s l l anomalies

Angular analysis of $B_d^0 \to K^* \mu^+ \mu^-$ decays

[arXiv:1512.04442]

- no deviation for A_{FB} but…
- Form-factor independent observable $P'_5 = \dfrac{S_5}{\sqrt{F_L(1-F_L)}}$



$B^+ \to K^+\mu^+\mu^-$

$10^7 \times BR$	Theory (SM)	Experiment
[0.1, 0.98]	0.31 ± 0.09	0.29 ± 0.02
[1.1, 2]	0.32 ± 0.10	0.21 ± 0.02
[2, 3]	0.35 ± 0.11	0.28 ± 0.02
[3, 4]	0.35 ± 0.11	0.25 ± 0.02
[4, 5]	0.35 ± 0.11	0.22 ± 0.02
[5, 6]	0.34 ± 0.12	0.23 ± 0.02
[6, 7]	0.34 ± 0.12	0.25 ± 0.02
[7, 8]	0.34 ± 0.13	0.23 ± 0.02

$B^0 \to K^0\mu^+\mu^-$

$10^7 \times BR$	Theory (SM)	Experiment
[0.1, 2]	0.62 ± 0.19	0.23 ± 0.11
[2, 4]	0.65 ± 0.21	0.37 ± 0.11
[4, 6]	0.64 ± 0.22	0.35 ± 0.10
[6, 8]	0.63 ± 0.23	0.54 ± 0.12

$B_s \to \phi\mu^+\mu^-$

$10^7 \times BR$	Theory (SM)	Experiment
[0.1, 2.]	1.81 ± 0.36	1.11 ± 0.16
[2., 5.]	1.88 ± 0.32	0.77 ± 0.14
[5., 8.]	2.25 ± 0.41	0.96 ± 0.15
[15, 18.8]	2.20 ± 0.17	1.62 ± 0.20

Descotes-Genon, Matias, Virto arXiv:1510.04239

R_K: ratio of branching fractions for dilepton invariant mass squared range $1 < q^2 < 6\,\mathrm{GeV}^2/c^4$

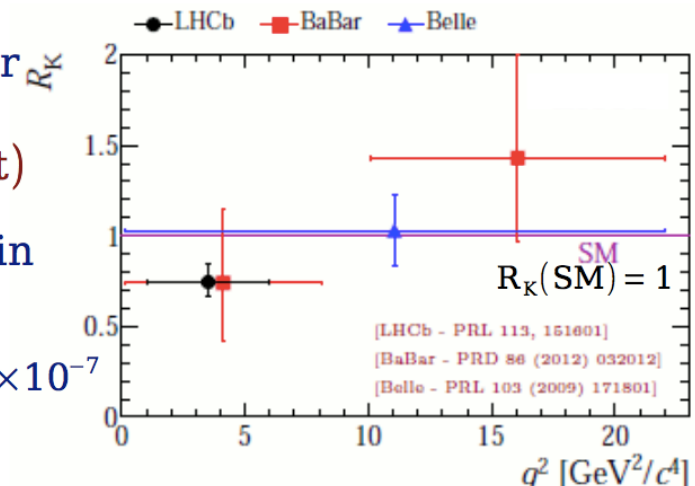
$$R_K = \frac{Br(B^+ \to K^+\mu^+\mu^-)}{Br(B^+ \to K^+e^+e^-)}$$

- The combination of the various trigger channels gives:

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

- Most precise measurement to date is in disagreement with SM at 2.6σ level

$\Rightarrow$ $B(B^+ \to e^+e^-K^+) = (1.56^{+0.19}_{-0.15}(\mathrm{stat})\,^{+0.06}_{-0.05}(\mathrm{syst})) \times 10^{-7}$ compatible with SM predictions

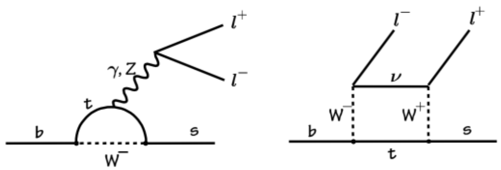


Lepton Flavor Non-Universality ? effect is in μμ, not ee

Theoretical modeling for b -> s ll anomalies

NP making a smaller b ->s μμ, not disturb b -> s e e too much or larger thn SM…

(Descotes-Genon Matias, Ramon, Virto, JHEP 1301 408(2013); arXiv:1605.06059)



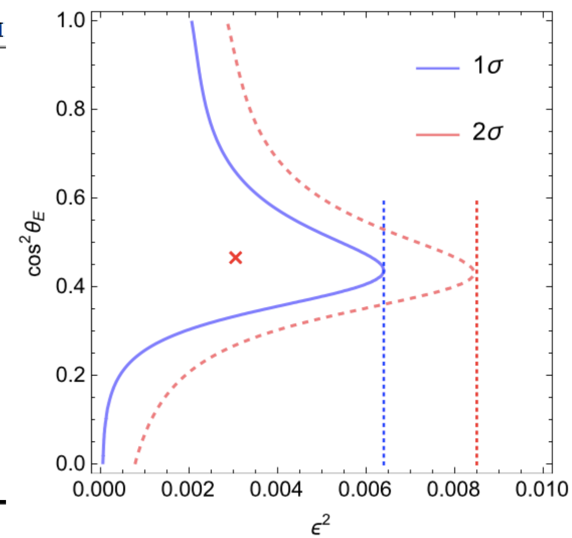
$C_9^{\rm SM} \approx 4.1, \qquad C_{10}^{\rm SM} \approx -4.1.$

$$\mathcal{O}_9^{(\prime)} = \frac{\alpha}{4\pi}[\bar{s}\gamma^\mu P_{L(R)} b][\bar{\mu}\gamma_\mu \mu],$$

$$\mathcal{O}_7^{(\prime)} = \frac{\alpha}{4\pi} m_b [\bar{s}\sigma_{\mu\nu} P_{R(L)} b] F^{\mu\nu},$$

$$\mathcal{O}_{10}^{(\prime)} = \frac{\alpha}{4\pi}[\bar{s}\gamma^\mu P_{L(R)} b][\bar{\mu}\gamma_\mu \gamma_5 \mu],$$

Coefficient	Best fit	1σ	3σ	$\mathrm{Pull}_{\mathrm{SM}}$
$\mathcal{C}_7^{\rm NP}$	−0.02	[−0.04, −0.00]	[−0.07, 0.03]	1.2
$\boldsymbol{\mathcal{C}_9^{\rm NP}}$	**−1.09**	[−1.29, −0.87]	[−1.67, −0.39]	**4.5**
$\mathcal{C}_{10}^{\rm NP}$	0.56	[0.32, 0.81]	[−0.12, 1.36]	2.5
$\mathcal{C}_{7'}^{\rm NP}$	0.02	[−0.01, 0.04]	[−0.06, 0.09]	0.6
$\mathcal{C}_{9'}^{\rm NP}$	0.46	[0.18, 0.74]	[−0.36, 1.31]	1.7
$\mathcal{C}_{10'}^{\rm NP}$	−0.25	[−0.44, −0.06]	[−0.82, 0.31]	1.3
$\mathcal{C}_9^{\rm NP} = \mathcal{C}_{10}^{\rm NP}$	−0.22	[−0.40, −0.02]	[−0.74, 0.50]	1.1
$\boldsymbol{\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{10}^{\rm NP}}$	**−0.68**	[−0.85, −0.50]	[−1.22, −0.18]	**4.2**
$\boldsymbol{\mathcal{C}_9^{\rm NP} = -\mathcal{C}_{9'}^{\rm NP}}$	**−1.06**	[−1.25, −0.85]	[−1.60, −0.40]	**4.8**



$$R_K = 0.745 \Rightarrow \sin^2\theta = 0.37\ ,$$

$$\frac{\mathcal{B}(B\to K\tau\bar{\tau})}{\mathcal{B}(B\to K\mu\bar{\mu})} = 1.36\ ,$$

$$\frac{\mathcal{B}(B\to K(e\bar{\tau},\tau\bar{e}))}{\mathcal{B}(B\to K\mu\bar{\mu})} = 0.037\ .$$

(C-W. Chiang, X-G He, G. Valencia,PRD93,074003)

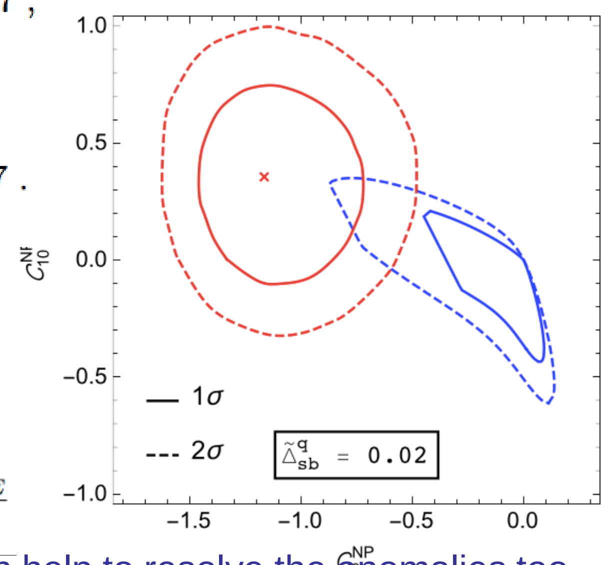
$$SU(3)\times SU(2)_l \times SU(2)_h \times U(1)_Y$$

$Q_L^{1,2}:(3,2,1,1/3)\ ,\ \ Q_L^3:(3,1,2,1/3)\ ,\ \ U_R^{1,2,3}:(3,1,1,4/3)\ ,\ \ D_R^{1,2,3}:(3,1,1,-2/3)\ ,$

$L_L^{1,2}:(1,2,1,-1)\ ,\ \ L_L^3:(1,1,2,-1)\ ,\ \ E_R^{1,2,3}:(1,1,1,-2)\ ,$

$$\mathcal{L} = \bar{\psi}\gamma_\mu\left[eA^\mu Q + \frac{g}{c_W} Z_L^\mu\left(T_3^l + T_3^h - Q s_W^2\right) + g Z_H^\mu\left(\frac{s_E}{c_E}T_3^l - \frac{c_E}{s_E}T_3^h\right)\right]\psi\ ,$$

$$Z_L = -\sin\xi Z_h + \cos\xi Z_l\ ,\quad Z_H = \cos\xi Z_h + \sin\xi Z_l\ ,\quad \xi \approx \frac{s_E c_E}{c_W}(s_\beta^2 - s_E^2)\epsilon^2\ ,\quad \frac{m_{Z_l}^2}{m_{Z_h'}^2} \approx \epsilon^2 \frac{s_E^2 c_E^2}{c_W^2}$$



Lμ- Lτ model (He, Joshi, Lew and Volkas, 1991; Foot, He, Lew and Volkas,1994) can help to resolve the anomalies too.

ε′/ε anomaly-a classic problem for flavor physics

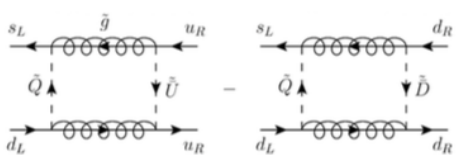
$$\frac{\epsilon'_K}{\epsilon_K} = \begin{cases} (16.6 \pm 2.3) \times 10^{-4} & \text{(PDG)} \\ (1.4 \pm 4.3 \pm 1.4 \pm 0.6) \times 10^{-4} & \text{(SM-NLO)} \end{cases}$$

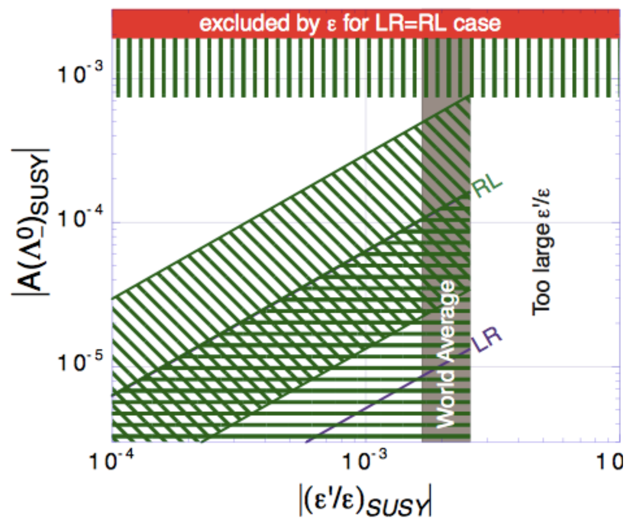
2.9σ effect

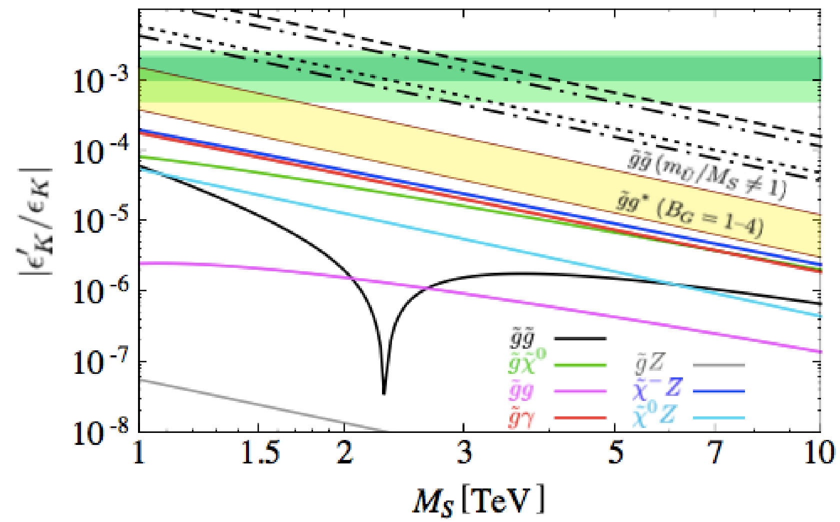
Change b to s in the diagrams for B -> PP in previous discussions

(Kithara, Nieste, Tremper, arXiv:1604.07400(2016))

New Physics beyond SM? SUSY a possibility.







Earlier calculations, can cover a large range (left)

(He, Murayama, Pakvasa, Valencia, PRD61,071701(2000))

New, can resolve the discrepancy at 1(2)σ level (right).

(Kithara, Nieste, Tremper, arXiv:1604.07400(2016))

Other Kao talk: K -> π νν(NA62: M. Zamkovsky

2. Minimal Flavor Violation

Too many model buildings, some more general analysis?

SM: FCNC and CP violation result from mis-match between weak and mass bases.

There are many ways beyond SM may go.

MFV provides a model independent way of organizing new contributions beyond SM.

Basic idea: FCNC and CP violation still reside in the tree level defined Yukawa couplings.

(D'Ambrosio, Giudice, Isidori, Strumia, Nucl. Phys. B645, 155(2002))

The renormalizable Lagrangian for flavor violation and CP violation in the SM

$$\mathcal{L}_{\rm k} = \bar{Q}_L\gamma^\mu D_\nu Q_L + \bar{U}_R\gamma^\mu D_\nu U_R + \bar{D}_R\gamma^\mu D_\nu D_R + \bar{L}_L\gamma^\mu D_\nu L_L + \bar{\nu}_R\gamma^\mu D_\nu \nu_R + \bar{E}_R\gamma^\mu D_\nu$$

$$\mathcal{L}_{\rm m} = -\bar{Q}_{i,L}(Y_u)_{ij}U_{j,R}\tilde{H} - \bar{Q}_{i,L}(Y_d)_{ij}D_{j,R}H - \bar{L}_{i,L}(Y_\nu)_{ij}\nu_{j,R}\tilde{H} - \bar{L}_{i,L}(Y_e)_{ij}E_{j,R}H - \frac{1}{2}\overline{\nu^c_{i,R}}(M_\nu)_{ij}\nu_{j,R} + \text{H.c.}\,,$$

In the basis where Y_d iand Y_e are already diagonalized,

$$Y_d = \frac{\sqrt{2}}{v}\hat{M}_d\,, Q_{i,L} = \begin{pmatrix} (V^\dagger_{\rm CKM})_{ij}U_{j,L} \\ D_{i,L}\end{pmatrix}, Y_u = \frac{\sqrt{2}}{v}V^\dagger_{\rm CKM}\hat{M}_u\,,$$

For Dirac neutrinos

$$Y_e = \frac{\sqrt{2}}{v}\hat{M}_e\,, L_{i,L} = \begin{pmatrix} (U_{\rm PMNS})_{ij}\nu_{j,L} \\ E_{i,L}\end{pmatrix}, Y_\nu = \frac{\sqrt{2}}{v}U_{\rm PMNS}\hat{m}_\nu\,,$$

If neutrinos are Majorana fermions, neutrino mass matrix

$$\mathsf{M} = \begin{pmatrix} 0 & M_{\rm D} \\ M_{\rm D}^{\rm T} & M_\nu \end{pmatrix},$$

$M_{\rm D} = vY_\nu/\sqrt{2}$ and $M_\nu = \text{diag}(M_1, M_2, M_3)$.

With $M_\nu \gg M_{\rm D}$, the light neutrinos' mass matrix m_ν is

$$m_\nu = -M_{\rm D}M_\nu^{-1}M_{\rm D}^{\rm T} = -\frac{v^2}{2}Y_\nu M_\nu^{-1}Y_\nu^{\rm T} = U_{\rm PMNS}\hat{m}_\nu U^{\rm T}_{\rm PMNS}\,.$$

This allows one to choose Y_ν to be

$$Y_\nu = \frac{i\sqrt{2}}{v}U_{\rm PMNS}\hat{m}_\nu^{1/2}OM_\nu^{1/2}\,, OO^{\rm T} = \mathbb{1}$$

Example: Muon g-2, and Higgs Decay Operators

Relevant operators for dipoles. Cirigiliano, Grinstein, Isidori, Wise, Nucl. Phys. B728, 121(2005); X-G He, etal., PRD89, 091901(2014); JHEP 1408, 019(2014); .

$$\begin{aligned} O_{RL}^{(u1)} &= g'\bar{U}_R Y_u^\dagger \Delta_{qu1}\sigma_{\mu\nu}\tilde{H}^\dagger Q_L B^{\mu\nu} , & O_{RL}^{(u2)} &= g\bar{U}_R Y_u^\dagger \Delta_{qu2}\sigma_{\mu\nu}\tilde{H}^\dagger \tau_a Q_L W_a^{\mu\nu} , \\ O_{RL}^{(d1)} &= g'\bar{D}_R Y_d^\dagger \Delta_{qd1}\sigma_{\mu\nu}H^\dagger Q_L B^{\mu\nu} , & O_{RL}^{(d2)} &= g\bar{D}_R Y_d^\dagger \Delta_{qd2}\sigma_{\mu\nu}H^\dagger \tau_a Q_L W_a^{\mu\nu} , \\ O_{RL}^{(e1)} &= g'\bar{E}_R Y_e^\dagger \Delta_{\ell 1}\sigma_{\mu\nu}H^\dagger L_L B^{\mu\nu} , & O_{RL}^{(e2)} &= g\bar{E}_R Y_e^\dagger \Delta_{\ell 2}\sigma_{\mu\nu}H^\dagger \tau_a L_L W_a^{\mu\nu} , \end{aligned}$$

W and B denote the usual $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$

One can express the effective Lagrangian containing these operators as

$$\mathcal{L}_{\rm eff} = \frac{1}{\Lambda^2}\left(O_{RL}^{(u1)} + O_{RL}^{(u2)} + O_{RL}^{(d1)} + O_{RL}^{(d2)} + O_{RL}^{(e1)} + O_{RL}^{(e2)}\right) \; + \; \mathrm{H.c.} \, ,$$

Relevant b->c l ν and b -> s ll operators

(C-J. Lee, J. Tandean, JHEP 1508, 123(2015))

$$\bar{Q}_L\gamma_\mu\Delta_{QQ}Q_L\bar{L}_L\gamma^\mu\Delta_{LL}L_L,$$
$$\bar{U}_R\Delta_{qu1}Q_L\bar{E}_r\Delta_{l2}L_L \;, \quad \bar{D}_R\Delta_{qd}Q_L\bar{L}_L\Delta_{l2}^\dagger E_R.$$

Relevant Higgs to mu tau decay operators

(Dery et al., JHEP1305, 039(2013); He, Tandean, Zheng, JHEP 1509, 093(2015))

$$\begin{aligned} O_{RL}^{(e1)} &= g'\bar{E}_R Y_e^\dagger \Delta_{RL}^{(1)}\sigma_{\rho\omega}H^\dagger L_L B^{\rho\omega} \\ O_{RL}^{(e2)} &= g\,\bar{E}_R Y_e^\dagger \Delta_{RL}^{(2)}\sigma_{\rho\omega}H^\dagger \tau_a L_L W_a^{\rho\omega} \\ O_{RL}^{(e3)} &= (\mathcal{D}^\rho H)^\dagger \bar{E}_R Y_e^\dagger \Delta_{RL}^{(3)} \mathcal{D}_\rho L_L \end{aligned}$$

$$\begin{aligned} O_{LL}^{(1)} &= \tfrac{i}{4}\left[H^\dagger(\mathcal{D}_\rho H) - (\mathcal{D}_\rho H)^\dagger H\right] \bar{L}_L\gamma^\rho\Delta_{LL}^{(1)}L_L \, , \\ O_{LL}^{(2)} &= \tfrac{i}{4}\left[H^\dagger\tau_a(\mathcal{D}_\rho H) - (\mathcal{D}_\rho H)^\dagger\tau_a H\right] \bar{L}_L\gamma^\rho\tau_a\Delta_{LL}^{(2)}L_L \end{aligned}$$

The MFV framework for quarks

L_K and L_m are formally invariant under a global group
$\mathrm{U}(3)_Q \times \mathrm{U}(3)_U \times \mathrm{U}(3)_D = G_q \times U(1)_Q \times U(1)_U \times U(1)_D$.
with $G_q = \mathrm{SU}(3)_Q \times \mathrm{SU}(3)_U \times \mathrm{SU}(3)_D$.
$Q_{i,L}$, $U_{i,R}$, and $D_{i,R}$ as fundamental representations of $SU(3)_{Q,U,D}$.
The Yukawa couplings $(Y_{u,d})_{ij}$ as spurions which transform as
$Q_L \to V_Q Q_L\ ,\quad U_R \to V_U U_R\ ,\quad D_R \to V_D D_R\ ,$
$Y_u \to V_Q Y_u V_U^\dagger\ ,\quad Y_d \to V_Q Y_d V_D^\dagger,\ V_{Q,U,D} \in \mathrm{SU}(3).$

MFV for the lepton sector

the global group is $\mathrm{U}(3)_L \times \mathrm{U}(3)_\nu \times \mathrm{U}(3)_E = G_\ell \times U(1)_L \times U(1)_\nu \times U(1)_E$
with $G_\ell = \mathrm{SU}(3)_L \times \mathrm{SU}(3)_\nu \times \mathrm{SU}(3)_E$.
$L_{i,L}$, $\nu_{i,R}$, and $E_{i,R}$ as fundamental representations of $SU(3)_{L,\nu,E}$.
Replacing $V_{\rm CKM}$ with $U^\dagger_{\rm PMNS}$
employing the leptonic building blocks $\mathsf{A} = Y_\nu Y_\nu^\dagger$ and $\mathsf{B} = Y_e Y_e^\dagger$
to form the corresponding Δ_ℓ, Δ_ν, and Δ_e
transforming under G_ℓ as $(8,1,1)$, $(3,\bar 3,1)$, and $(3,1,\bar 3)$, respectively.

For Dirac neutrinos: $Y_\nu \;=\; \frac{\sqrt2}{v} U_{\rm PMNS}\, \hat m_\nu$

For Majorana neutrinos: $Y_\nu \;=\; \frac{i\sqrt2}{v} U_{\rm PMNS}\, \hat m_\nu^{1/2} O M_\nu^{1/2}$,
O offers a potentially important new source of CP violation.

The operators are required to be invariant under the global G_q and G_l groups.

Using $A = Y_u Y_u^\dagger$ and $B = Y_d Y_D^\dagger$ for quarks. $A = Y_\nu Y_\nu^\dagger$ and $B = Y_e Y_e^\dagger$ for leptons.

$\Delta_f = \sum_{ijk\ldots} \xi_{ijk\ldots} A^i B^j A^k \ldots$ infinite!

Cayley-Hamilton indentyt tfor 3x3 matrix, $\quad X^3 - X^2 TrX + [(TrX)^2 - TrX^2]/2 - IDetX = 0$

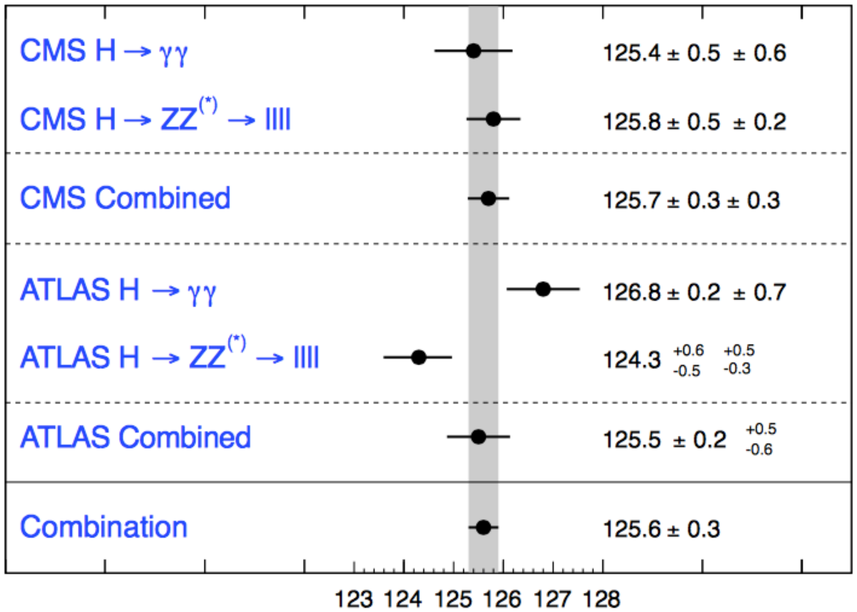
Colangelo, etal., Eur, Phys. J. C59, 75(2009); Mercolli et al., Nucl. Phys. B817, 1(2009)
X-G He, etal., PRD89, 091901(2014); JHEP 1408, 019(2014).

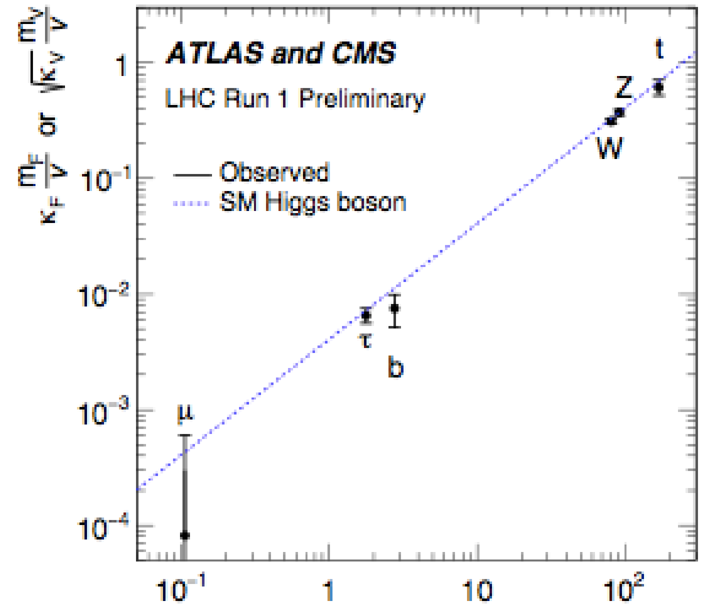
Resume into 17 terms

$$\Delta_f = \xi_1 I + \xi_2 A + \xi_3 B + \xi_4 A^2 + \xi_5 B^2 + \xi_6 AB + \xi_7 BA + \xi_8 ABA + \xi_9 BA^2 + \xi_{10} BAB$$
$$+\xi_{11} AB^2 + \xi_{12} ABA^2 + \xi_{13} A^2B^2 + \xi_{14} B^2A^2 + \xi_{15} B^2AB + \xi_{16} AB^2A^2 + \xi_{17} B^2A^2B$$

The anomalies discussed earlier can be carried out in this framework. (Jusak Tandean.)

3. Flavor Physics with Higgs and Leptons





Cepeda, Higgs Tasting,2016,Benasque,Spain

With the new CMS result

Channel	Coupling	95% CL Limit Pre-LHC	CMS	ATLAS
H→ μe	$\sqrt{\lvert Y_{\mu e}\rvert^2+\lvert Y_{e\mu}\rvert^2}$	$3.6\cdot10^{-6}$	$5.4\cdot10^{-4}$	-
H→ $\mu\tau$	$\sqrt{\lvert Y_{\mu\tau}\rvert^2+\lvert Y_{\tau\mu}\rvert^2}$	0.016	**0.00316**	0.0035
H→ $e\tau$	$\sqrt{\lvert Y_{e\tau}\rvert^2+\lvert Y_{\tau e}\rvert^2}$	0.014	0.0024	0.0029

The h -> $\mu\ \tau$ anomaly

(He, Tandean, Zheng, JHEP 1509, 093(2015))

Effective Lagrangian satisfying MFV criterion $\mathcal{L}_{\rm MFV} \supset \frac{\mathcal{O}_{RL}}{\Lambda^2} + \text{H.c.}$

$$\mathcal{O}_{RL} = (\mathcal{D}^\alpha H)^\dagger \overline{D}_R Y_d^\dagger \Delta_q \mathcal{D}_\alpha Q_L + (\mathcal{D}^\alpha H)^\dagger \overline{E}_R Y_e^\dagger \Delta_\ell \mathcal{D}_\alpha L_L$$

$$\Delta_q = \zeta_0 \mathbb{1} + \zeta_1 \mathsf{A}_q + \zeta_2 \mathsf{A}_q^2\,, \qquad \Delta_\ell = \xi_0 \mathbb{1} + \xi_1 \mathsf{A}_\ell + \xi_2 \mathsf{A}_\ell^2$$

$\zeta_{0,1,2}$ and $\xi_{0,1,2}$ are free parameters at most of $\mathcal{O}(1)$.

- Indirect limits from kaon & $B_{d,s}$-meson oscillation data

$$-5.9\times10^{-10} < \mathrm{Re}(\mathcal{Y}^2_{ds,sd}) < 5.6\times10^{-10}\,, \qquad |\mathrm{Re}(\mathcal{Y}^*_{ds}\mathcal{Y}_{sd})| < 5.6\times10^{-11}$$
$$-2.9\times10^{-12} < \mathrm{Im}(\mathcal{Y}^2_{ds,sd}) < 1.6\times10^{-12}\,, \qquad -1.4\times10^{-13} < \mathrm{Im}(\mathcal{Y}^*_{ds}\mathcal{Y}_{sd}) < 2.8\times10^{-13}$$
$$|\mathcal{Y}_{db,bd}|^2 < 2.3\times10^{-8}\,, \qquad |\mathcal{Y}_{db}\mathcal{Y}_{bd}| < 3.3\times10^{-9}$$
$$|\mathcal{Y}_{sb,bs}|^2 < 1.8\times10^{-6}\,, \qquad |\mathcal{Y}_{sb}\mathcal{Y}_{bs}| < 2.5\times10^{-7}$$

Harnik, Kopp, Zupan

- Indirect limit from new MEG data $\mathcal{B}(\mu\to e\gamma) < 4.2\times10^{-13}$

1605.05081

$$\sqrt{|(\mathcal{Y}_{\mu\mu}+r_\mu)\mathcal{Y}_{\mu e} + 9.19\,\mathcal{Y}_{\mu\tau}\mathcal{Y}_{\tau e}|^2 + |(\mathcal{Y}_{\mu\mu}+r_\mu)\mathcal{Y}_{e\mu} + 9.19\,\mathcal{Y}_{e\tau}\mathcal{Y}_{\tau\mu}|^2} < 4.4\times10^{-7}$$

$r_\mu = 0.29$

Goudelis, Lebedev, Park
Blankenburg, Ellis, Isidori
Harnik, Kopp, Zupan
Dery *et al.*

- From LHC data on $h\to bb,\ \mu^+\mu^-,\ \tau^+\tau^-$

$$0.4 < |\mathcal{Y}_{bb}/\mathcal{Y}^{\rm SM}_{bb}|^2 < 1.1\,, \qquad |\mathcal{Y}_{\mu\mu}/\mathcal{Y}^{\rm SM}_{\mu\mu}|^2 < 6.5\,, \qquad 0.9 < |\mathcal{Y}_{\tau\tau}/\mathcal{Y}^{\rm SM}_{\tau\tau}|^2 < 1.4$$

- CMS data on $h\to\mu\tau$

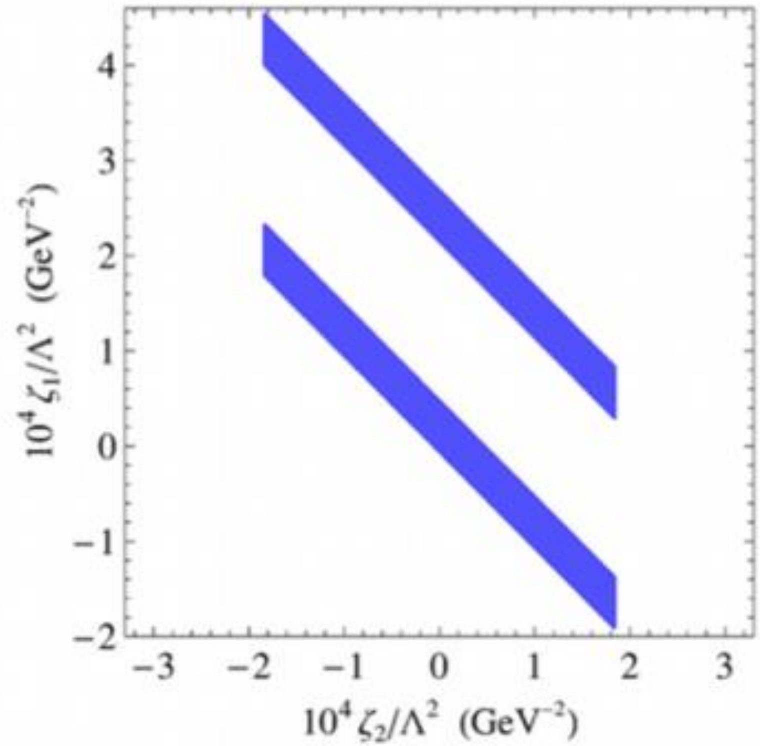
$$2.0\times10^{-3} < \sqrt{|\mathcal{Y}_{\tau\mu}|^2 + |\mathcal{Y}_{\mu\tau}|^2} < 3.3\times10^{-3}$$

1502.07400

- CMS data on $h\to e\tau$

$$\sqrt{|\mathcal{Y}_{e\mu}|^2 + |\mathcal{Y}_{\mu e}|^2} < 5.43\times10^{-4}\,, \qquad \sqrt{|\mathcal{Y}_{e\tau}|^2 + |\mathcal{Y}_{\tau e}|^2} < 2.41\times10^{-3}$$

CMS PAS HIG-14-040



Regions of ζ_1/Λ^2 and ζ_2/Λ^2 for $\zeta_4 = 0$ which fulfill the empirical constraints on the quark Yukawas.

The ζ_2/Λ^2 range is determined by the constraint $|\mathcal{Y}_{db}|^2 < 2.3\times10^{-8}$.

If $|\zeta_{1,2}| \sim 1$, these results imply a fairly weak lower-limit on the MFV scale, $\Lambda > 50$ GeV.

Gauged Lμ- Lτ model can provide solutions too, Altmannshofer, Carena and Crivellin, arxiv:1604.08221.

h -> μ τ and CP violation in h -> ττ

Models which provide source(s) inducing h -> μτ usually generate also correction to h -> ττ coupling (for example, MFL discussed earlier). If the corrections is CP violating, effects can show up in h -> ττ decay.

(Hayreter, He, Valencia, arXiv:1603.06326, arXiv:1606.00951)

$$L_Y = -\bar{L}_L[y\frac{v}{\sqrt{2}} + (y+\delta y)\frac{h}{\sqrt{2}}]E_R$$

Diagonalizing the mass term, $S_e^\dagger y T_e(v/\sqrt{2} = \hat{M}$,

the h interaction becomes $L_h = -\bar{l}_i(\frac{\hat{M}}{v} + \frac{1}{\sqrt{2}}S_e^\dagger \delta y T_e)l_j h$

If there is CP violation, the Higgs h coupling to tauon becomes

$$L_{h\tau\tau} = -\frac{h}{v}m_\tau\bar{\tau}(r_\tau + i\tilde{r}_\tau\gamma_5)\tau, \quad r_\tau = 1+\epsilon_\tau$$

For $\tau \to \pi^-\nu_\tau$, $\bar{\tau} \to \pi^+\bar{\nu}_\tau$,

one can construct T odd operator $O_\pi = \vec{p}_\tau \cdot (\vec{p}_\pi^{\,+} \times \vec{p}_\pi^{\,-})$,

One construct CP violating observable $A_\pi = \dfrac{N(\mathcal{O}_\pi > 0) - N(\mathcal{O}_\pi < 0)}{N(\mathcal{O}_\pi > 0) + N(\mathcal{O}_\pi < 0)} = \dfrac{\pi}{4}\beta_\tau\dfrac{(r_\tau\tilde{r}_\tau)}{\beta_\tau^2 r_\tau^2 + \tilde{r}_\tau^2}$,

Democratic and hierarchical Yukawa couplings Scenarios.

a) Democratice correction

$$(S_e^\dagger \delta y T_e)_{ij} \sim \lambda_{1,2}^e \sim \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}.$$

and the diagonal elements would satisfy

$$\frac{(\epsilon_i + i\tilde{r}_i)}{(\epsilon_j + i\tilde{r}_j)} \sim \frac{m_j}{m_i}.$$

b) Hierarchical correction

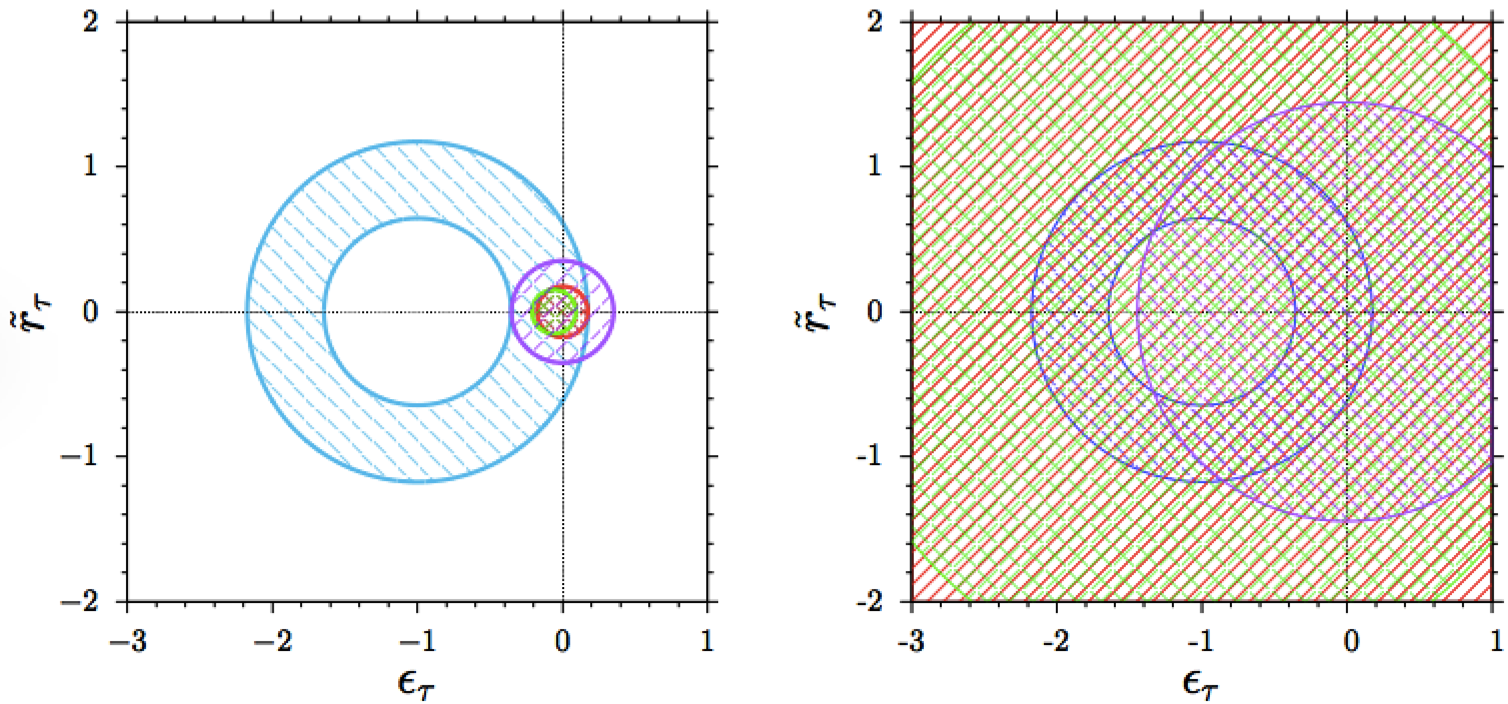
$$(S_e^\dagger \delta y T_e)_{ij} \sim \lambda_{1,2}^e \sim \begin{pmatrix} m_e & \sqrt{m_e m_\mu} & \sqrt{m_e m_\tau} \\ \sqrt{m_e m_\mu} & m_\mu & \sqrt{m_\mu m_\tau} \\ \sqrt{m_e m_\tau} & \sqrt{m_\mu m_\tau} & m_\tau \end{pmatrix}$$

and this time the diagonal elements would satisfy

$$\frac{(\epsilon_i + i\tilde{r}_i)}{(\epsilon_j + i\tilde{r}_j)} \sim 1.$$

(He, Ma, McKellar, Mod. Phys Lett. A9, 205(1994)Berge, Bereuther, Kirchner, PRD92,096012(2015))

Constraints on the allowed regions, left scenario a and right scenario b.Including all known h couplings to leptons



CP violation for case a) A_π can be as large as 15%

for case a) A_π can be as large as 50%

Experiments should look for such CPV violation.

g-2 and Lepton flavor violation

Muon g-2 anomaly is an outstanding problem. $\Delta a_\mu = a_\mu^{exp} - a_\mu^{the} = 288(80)10^{-11}$ 3σ effect.

In MFV, operator responsible for g-2 can be induced by dimension 6 operators.

They also induce lepton flavor violating processes.

$$O_{RL}^{(u1)} = g' \bar{U}_R Y_u^\dagger \Delta_{qu1} \sigma_{\mu\nu} \tilde{H}^\dagger Q_L B^{\mu\nu}, \qquad O_{RL}^{(u2)} = g \bar{U}_R Y_u^\dagger \Delta_{qu2} \sigma_{\mu\nu} \tilde{H}^\dagger \tau_a Q_L W_a^{\mu\nu},$$
$$O_{RL}^{(d1)} = g' \bar{D}_R Y_d^\dagger \Delta_{qd1} \sigma_{\mu\nu} H^\dagger Q_L B^{\mu\nu}, \qquad O_{RL}^{(d2)} = g \bar{D}_R Y_d^\dagger \Delta_{qd2} \sigma_{\mu\nu} H^\dagger \tau_a Q_L W_a^{\mu\nu},$$
$$O_{RL}^{(e1)} = g' \bar{E}_R Y_e^\dagger \Delta_{\ell 1} \sigma_{\mu\nu} H^\dagger L_L B^{\mu\nu}, \qquad O_{RL}^{(e2)} = g \bar{E}_R Y_e^\dagger \Delta_{\ell 2} \sigma_{\mu\nu} H^\dagger \tau_a L_L W_a^{\mu\nu},$$

$$a_\mu = \frac{4m_\mu^2}{\Lambda^2} \mathrm{Re}(\Delta_\ell)_{22} = \left(45\,\xi_1^\ell + 23\,\xi_2^\ell + 20\,\xi_4^\ell + 0.00085\,\xi_8^\ell + 0.00094\,\xi_{12}^\ell\right) \frac{\mathrm{GeV}^2}{10^3 \Lambda^2}$$

Numerical results

He, JT, Zheng, 1507.02673

	$\frac{\alpha_1}{\pi}$	$\frac{\alpha_2}{\pi}$	r_1	r_2	r_3	$10^5\xi_1/\Lambda^2$ (GeV^{-2})	$10^5\xi_2/\Lambda^2$ (GeV^{-2})	$10^5\xi_4/\Lambda^2$ (GeV^{-2})	$\frac{\mathcal{Y}_{ee}}{\mathcal{Y}_{ee}^{\mathrm{SM}}}$	$\frac{\mathcal{Y}_{\mu\mu}}{\mathcal{Y}_{\mu\mu}^{\mathrm{SM}}}$	$\frac{\mathcal{Y}_{\tau\tau}}{\mathcal{Y}_{\tau\tau}^{\mathrm{SM}}}$	$\frac{\lvert\mathcal{Y}_{e\mu}\rvert}{10^{-6}}$	$\frac{\lvert\mathcal{Y}_{e\tau}\rvert}{10^{-4}}$	$\frac{\lvert\mathcal{Y}_{\mu\tau}\rvert}{10^{-3}}$
NH	0	0	0.81	−1.6	−0.89	−7.5	6.4	5.8	1.6	1.3	0.95	1.0	0.1	3.2
	0	0	−0.90	1.8	−0.92	−8.4	6.0	7.1	1.7	1.3	0.97	1.4	0.4	3.5
	0	0.23	0.74	−0.80	−0.23	7.0	−5.3	−7.5	0.46	0.77	1.15	1.5	1.7	3.3
IH	0	0	0.04	0.63	−0.93	−7.9	8.8	3.0	1.5	1.2	1.08	2.3	2.9	3.3
	0	0	0.02	−0.75	1.1	−6.2	3.7	7.7	1.4	1.1	0.97	2.2	1.2	3.2
	0.79	1.3	−0.61	−0.79	1.4	−6.8	5.0	7.6	1.5	1.0	0.96	1.2	0.4	3.5

Leptonic Yukawa couplings for sample values of the Majorana phases $\alpha_{1,2}$, parameters $r_{1,2,3}$ of the complex O matrix, and coefficients $\xi_{1,2,4}$ in the MFV matrix Δ which can yield $|\mathcal{Y}_{\mu\tau}| \gtrsim 3\times10^{-3}$, corresponding to measured neutrino mixing parameters for the normal (NH) or inverted (IH) hierarchy of neutrino masses.

★ In these instances $\mathcal{B}(\mu\to e\gamma) = (1.8-4.3)\times10^{-13}$, $\mathcal{B}(\mu\mathrm{Al}\to e\mathrm{Al}) = (2.3-8.2)\times10^{-15}$

- $|\mathcal{Y}_{\mu\tau}|/|\mathcal{Y}_{e\tau}| \sim 10$ or more, consistent with CMS $h\to e\tau,\mu\tau$ results
- The $\mathcal{Y}_{\mu\mu}$ and $\mathcal{Y}_{\tau\tau}$ predictions are testable with future collider data
- MEG II may probe the $\mu\to e\gamma$ predictions

μ □ e conversion important probe for lepton flavor violation!

More on LFV at this meeting MEG final result: T. Iwamoto; LBCb, G. Onderwater

Theory: E.Schumacher, J. Rosiek, T. Rizzo, M. Schmidt… Top FCNC: Chung Kao…

Neutrino Sector, $\delta=-\pi/2$ and $\theta_{23}=\pi/4$

How to obtain such an mixing pattern?

$\mu-\tau$ conjugate symmetry

(Grimus, Lavoura, Phys. Lett. B579, 113(2004))

$$m_\nu = \begin{pmatrix} A & C & C^* \\ C & D^* & B \\ C^* & B & D \end{pmatrix} .$$

Assuming that the charged lepton mass matrix M_l is diagonalized from left by U_l ,

$$M_l = U_l \hat{m}_l U_r \ , \quad U_l = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega & \omega^2 \\ 1 & \omega^2 & \omega \end{pmatrix} ,$$

where $\omega = exp(i2\pi/3)$ and $\omega^2 = exp(i4\pi/3)$.

A_4 models usually have the above characteristic U_i.

U_r is a unitary matrix, but does not play a role in determining V_{PMNS}.

If neutrinos are Majorana particles, the most general mass matrix is

$$M_\nu = \begin{pmatrix} w_1 & x & y \\ x & w_2 & z \\ y & z & w_3 \end{pmatrix} ,$$

In the basis where charged lepton is diagonalized,

$m_\nu = U_l^\dagger M_\nu U_l$, If all w_i, x, y and z are all real

$$A = \frac{1}{3}(w_1 + w_2 + w_3 + 2(x + y + z)) ,$$
$$B = \frac{1}{3}(w_1 + w_2 + w_3 - x - y - z)) ,$$
$$C = \frac{1}{3}(w_1 + \omega^2 w_2 + \omega w_3 - \omega x - \omega^2 y - z)) ,$$
$$D = \frac{1}{3}(w_1 + \omega^2 w_2 + \omega w_3 + 2(\omega x + \omega^2 y + z)) .$$

Naturally give $\delta = \pm\pi/2$ and $\theta_{23} = \pi/4$.

A_4 models

(X-G He, Chin. J. Phys 53, 100101(2015);
X-G He and G-N Li, Phys. Lett. B750,620(2015);
E Ma, Phys. Rev. D92, 051301(2015))

4.Grand Unification, and 750GeV State and A 5th Force?

Anything grand unification can be of useful in flavor physics?

Of course, among many things,

quarks and leptons are related and may have interesting predictions.

Example, Minimal SO(10) grand unification.

SO(10) Yukawa couplings:

$$16_F(Y_{10}10_H + Y_{\overline{126}}\overline{126}_H + Y_{120}120_H)16_F$$

Minimal SO(10) Model without 120

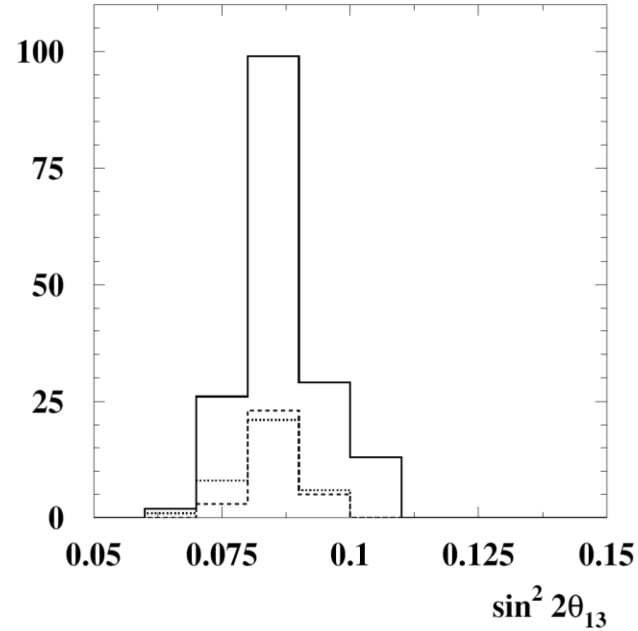
$$\mathcal{L}_{\text{Yukawa}} = Y_{10}\,\mathbf{16}\,\mathbf{16}\,\mathbf{10}_H + Y_{126}\,\mathbf{16}\,\mathbf{16}\,\overline{\mathbf{126}}_H$$

Two Yukawa matrices determine all fermion masses and mixings, including the neutrinos

$$M_u = \kappa_u Y_{10} + \kappa'_u Y_{126} \qquad M_{\nu R} = \langle\Delta_R\rangle Y_{126}$$
$$M_d = \kappa_d Y_{10} + \kappa'_d Y_{126} \qquad M_{\nu L} = \langle\Delta_L\rangle Y_{126}$$
$$M_\nu^D = \kappa_u Y_{10} - 3\kappa'_u Y_{126}$$
$$M_l = \kappa_d Y_{10} - 3\kappa'_d Y_{126}$$

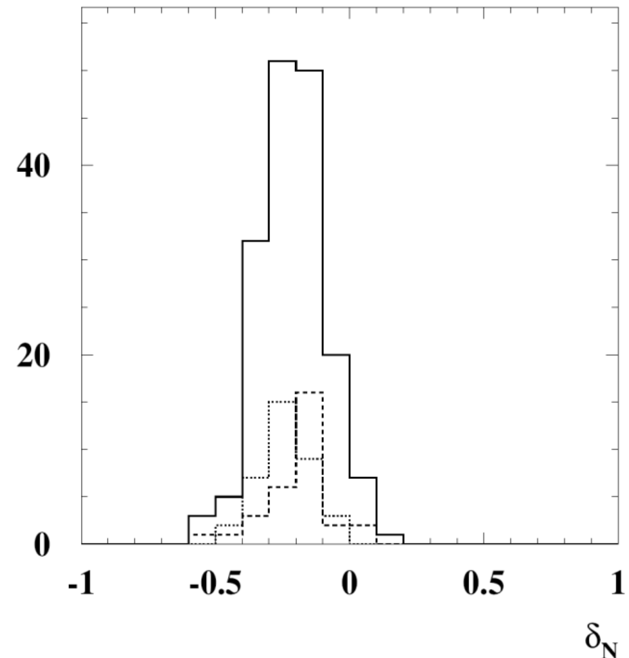
Model has only 11 real parameters plus 7 phases

Babu, Mohapatra (1993)
Fukuyama, Okada (2002)
Bajc, Melfo, Senjanovic, Vissani (2004)
Fukuyama, Ilakovac, Kikuchi, Meljanac, Okada (2004)
Aulakh et al (2004)
Bertolini, Frigerio, Malinsky (2004)
Babu, Macesanu (2005)
Bertolini, Malinsky, Schwetz (2006)
Dutta, Mimura, Mohapatra (2007)
Bajc, Dorsner, Nemevsek (2009)
Jushipura, Patel (2011)



Good prediction for θ_{13}

δ Away from $-\pi/2$!!! Tobe tested!!

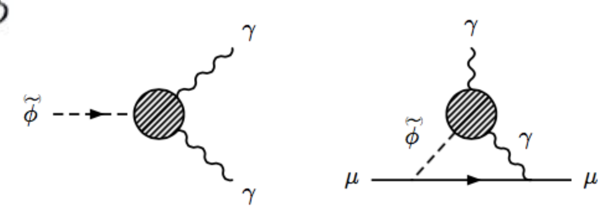


The 750 GeV resonance and muon g-2

B -> D(*) $\tau\nu$, This meeting: E. Schumacker

Hints for the existence of a 750 GeV resonance from LHC has attracted great attentions. Anything to do with flavor physics? "**flavor** refers to a species of an elementary particle." So, yes?! Anything it can do for the anomalies discussed before? Yes, $(g\text{-}2)_\mu$! (S. Baek, J-h Park, Phys. Lett. B 416(2016))

$\sigma(pp \to \tilde{\phi} \to \gamma\gamma) \sim 6fb$. If dominant production mechanism $gg \to \tilde{\phi}$



(a) (b)

$$\frac{\Gamma_{gg}\Gamma_{\gamma\gamma}}{\Gamma_{total}} \sim 1MeV\ , \quad 1.1\times 10^{-6} < \frac{\Gamma_{\gamma\gamma}}{m_{\tilde{\phi}}} < 2\times 10^{-3}\ .$$

CMS, narrow width, $\Gamma_{total} \sim 100$ MeV, ATLAS, broad width, $\Gamma_{total} \sim 45$ GeV

$$L = c_\gamma \frac{\alpha}{\pi v}\tilde{\phi}F_{\mu\nu}F^{\mu\nu}\ , \quad |c_\gamma| \approx 5.0\times\left(\frac{\Gamma_{\gamma\gamma}/m_{\tilde{\phi}}}{1.0\times 10{-}4}\right)^{1/2}\ .$$

$$\frac{\Delta a_\mu(f)}{c_\gamma^{H_2}(f)} \simeq -\frac{3\alpha s_\alpha m_\mu^2}{2\pi^3 v^2}\frac{\mathcal{F}_f(z_{fH_1})-\mathcal{F}_f(z_{fH_2})}{A_f(\tau_f)},$$
$$\frac{\Delta a_\mu(V)}{c_\gamma^{H_2}(V)} \simeq \frac{\alpha s_\alpha m_\mu^2}{7\pi^3 v^2}\frac{\mathcal{F}_v(z_{VH_1})-\mathcal{F}_v(z_{VH_2})}{A_v(\tau_V)},$$
$$\frac{\Delta a_\mu(S)}{c_\gamma^{H_2}(S)} \simeq -\frac{6\alpha s_\alpha m_\mu^2}{\pi^3 v^2}\frac{\mathcal{F}_s(z_{SH_1})-\mathcal{F}_s(z_{SH_2})}{A_s(\tau_S)}.$$

Generate c_γ by a particle with a mass m_X in the loop of Fig. (a), and generate Δa_μ through mixing of $\tilde{\phi}$ with SM h, $\lambda_{mix}\tilde{\phi}H^\dagger H$

$$h = c_\alpha H_1 + s_\alpha H_2\ , \tilde{\phi} = -s_\alpha H_1 + c_\alpha H_2\ .$$

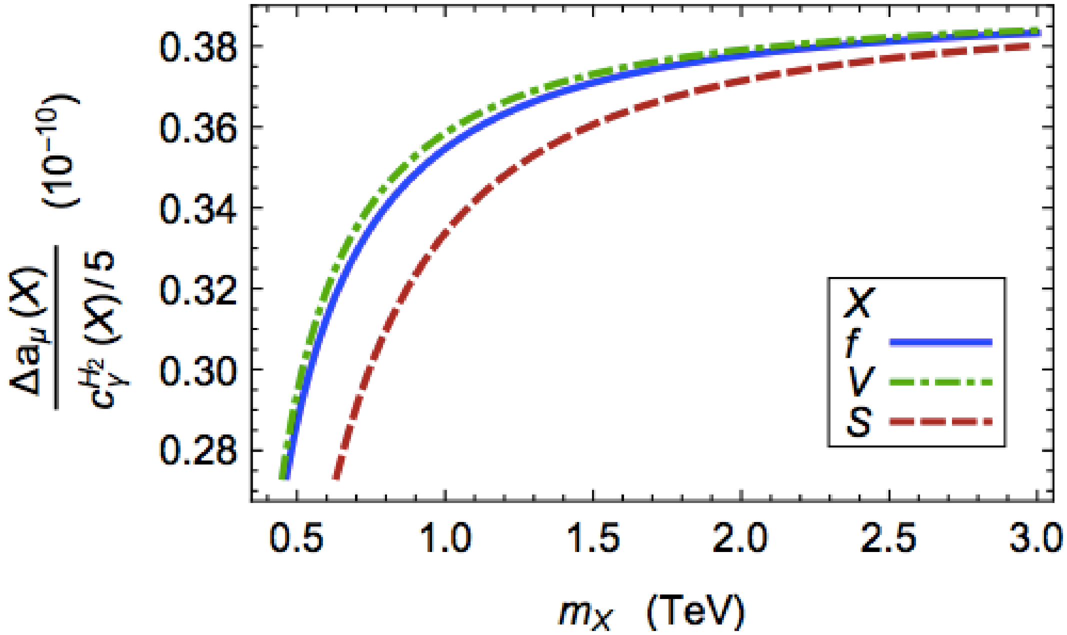


Figure draw with $s_\alpha = 0.1$. The Contributions to $\Delta a_\mu(x)$ are of order a Few times 10^{-11}.

Too smaller to play significant role in Resolving the muon g-2 anomaly.

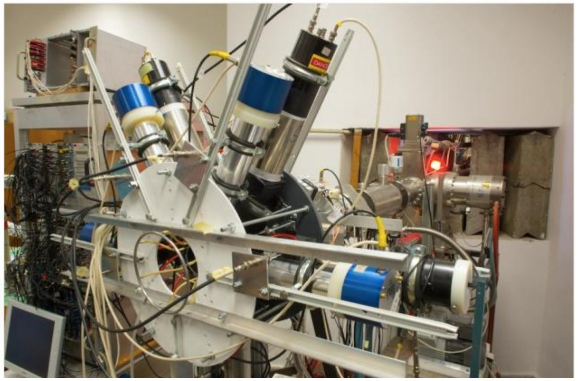
Enhancement can appear in 2HDW, for example, type II.

There are two Higgs doublets ϕ_1 and ϕ_2 producing two physical scalar Higgs H_1 and H_2 before mix with $\tilde{\phi}$.
Identify H_1 with the 125 GeV Higgs. The heavier H_2 coupling to μ is $\sim \tan\beta$.

H_2 has a component $s_\alpha \tilde{\phi}$. Ehancement factor $(c_\gamma^{H_2}/5)(s_\alpha/0.1)\tan\beta$.
Using $\Gamma_{\gamma\gamma}/m_{\tilde{\phi}} = 5 \times 10 \times 10^{-4}$, $s_\alpha = 0.3$ and $\tan\beta = 15$,
the enhancement factor is: 100.

$\tilde{\phi}$ contribution to Δa_μ can be as large as 300×10^{-11}!

The fifth force X boson and flavor physics



$^8Be^* \to {}^8Be e^+e^-$ is larger than expected e^+e^- opening angle at $140°$

The anomaly is at 6.9σ level. (Rev. Lett.116, 042501 (2016))

A. J. Krasznahorkay *et al.* found that the observed excess in shape and size are fit by a new boson with mass $m_X = 16.7 \pm 0.35(stat) \pm 0.5(sys)$ MeV.

J. Feng et al., constructed a protophobic model in which a X boson mediating a fifth force to explain the anomaly (arXiv:1604.07411 [hep-ph])

$$L = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}m_X^2 X_\mu X^\mu - X_\mu J_X^\mu\,, \quad J_X^\mu = \sum_{i=u,d,e,\nu_e\ldots} e\epsilon_i \bar{f}_i \gamma^\mu f_i$$

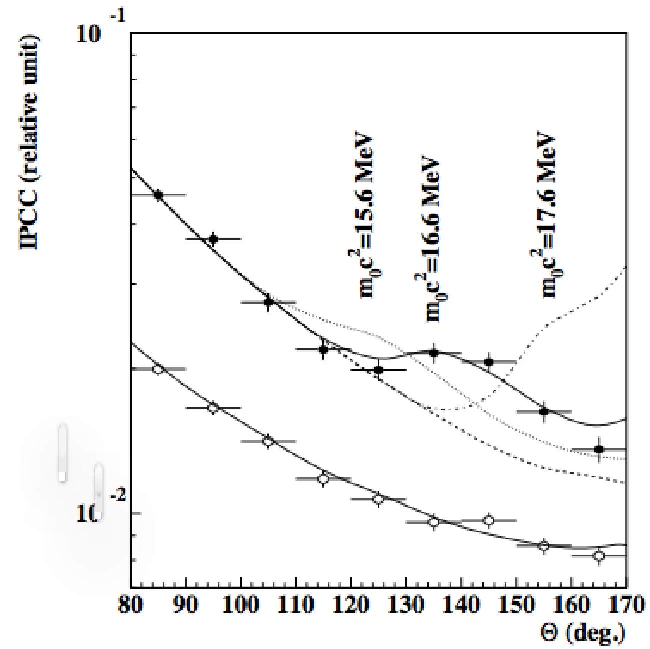
$$\epsilon_p = 2\epsilon_u + \epsilon_d \text{ and } \epsilon_n = \epsilon_u + 2\epsilon_d$$

Data can be explained by $^8Be^* \to {}^8B_e\, X$, then $X \to e^+e^-$ saturating X decay with $\epsilon_p + \epsilon_n \approx 0.011$.

Limit on $\pi^0 \to X\gamma$ constrain $-0.067 < \epsilon_p/\epsilon_n < 0.078$.

For $X \to e^+e^-$ is $Br(e^+e^-)$, $\epsilon_{u,d}$ should be scaled by a factor of $1/\sqrt{Br(e^+e^-)}$. Satisfying beam damp and $(g-2)_e$, and also $e - \nu_e$ scattering data, one obtains

$$\epsilon_u = \pm 3.7 \times 10^{-3}\,, \quad \epsilon_d = \mp 7.4 \times 10^{-3}\,,$$
$$2 \times 10^{-4} < |\epsilon_e| < 1.3 \times 10^{-3}\,, \quad |\epsilon_e \epsilon_{\nu_e}|^{1/2} < 7 \times 10^{-5}\,.$$



A realistic renormalizable model

(Pei-Hong Gu, Xiao-Gang He, 1605.05171)

$SU(3)_C \times SU(2)_L \times U(1)_Y \times U'_{Y'} \times U(1)_X$

Crucial to have X to have vector current to be $C^v_p = 2C^v_u + C^v_d = 0$, protophobic.
Dictates the choice of $U(1)_{Y'}$ charge.

$$
\begin{aligned}
&Q^1_L : (3,\ 2,\ 1/6)(-1,\ 0)\ , && u^1_R : (3,\ 1,\ 2/3)(5,0)\ , && d^1_R : (3,\ 1,\ -1/3)(-7,\ 0)\ ,\\
&L^1_L : (1,\ 2,\ -1/2)(\beta,\ 0)\ , && N^1_R : (1,\ 1,\ 0)(0,\ ,0)\ , && e^1_R : (1,\ 1,\ -1)(\beta,\ 0)\ ,\\
&Q^2_L : (3,\ 2,\ 1/6)(1\ ,0)\ , && u^2_R : (3,\ 1,\ 2/3)(-5\ ,0)\ , && d^2_R : (3,\ 1,\ -1/3)(7,\ 0)\ ,\\
&L^2_L : (1,\ 2,\ -1/2)(-\beta\ ,0)\ , && N^3_R : (1,\ 1;0)(0,\ ,0)\ , && e^2_R : (1,\ 1,\ -1)(-\beta\ ,0)\ ,
\end{aligned}
$$

Third generation does not transform with $U(1)_{Y'} \times U(1)_X$.
$U(1)$ kinetic mixing generates X coupling to SM particles: $L_{km} = -\frac{\epsilon}{2} Y'_{\mu\nu} X^{\mu\nu}$.
Add $S_{L,R} : (1,\ 1,\ 0)(\beta, \delta_{S_i})$, suppress $X - \nu_e$ coupling, through Yukawa couplings.

$$
J^\mu_X X_\mu = -\epsilon g_{Y'}[\bar u \gamma^\mu (4 + 6\gamma_5) u - \bar d \gamma^\mu (8 + 6\gamma_5) d + \beta \bar e \gamma^\mu e + \frac{\beta}{2} \frac{1 - \frac{g_X}{\epsilon g_{Y'}\beta} U_{S_1}}{1 + U_{S_1}} \bar\nu_e \gamma_\mu (1 - \gamma_5)\nu_e] X_\mu
$$

$$
\begin{aligned}
&e\epsilon^v_u = -4\epsilon g_{Y'}\ , && e\epsilon^v_d = 8\epsilon g_{Y'}\ ,\\
&e\epsilon^v_e = -\epsilon\beta g_{Y'}\ , && e\epsilon^v_{\nu_e} = -\frac{1}{2}\beta\epsilon g_{Y'} \frac{1 - g_X U_{S_1}/\epsilon g_{Y'}\beta}{1 + U_{S_1}}\ .
\end{aligned}
$$

$$
\begin{aligned}
&e\epsilon^a_u = -6\epsilon g_{Y'}\ , && e\epsilon^a_d = 6\epsilon g_{Y'}\ ,\\
&e\epsilon^a_e = 0\ , && e\epsilon^a_{\nu_e} = \frac{1}{2}\epsilon\beta g_{Y'} \frac{1 - g_X U_{S_1}/\epsilon g_{Y'}\beta}{1 + U_{S_1}}\ .
\end{aligned}
$$

Appearance of axial current, problem?

$^8Be^* \to {}^8BeX$: not affected,
isoscalar interaction $\epsilon^a_u + \epsilon^a_n = 3(\epsilon^a_u + \epsilon^a_d) = 0$.

Isovector axial current leading to $\pi^0 \to e^+e^-$?
No, $\bar e \gamma e$ vector coupling!

Contributions to $\Delta a_\mu = 152 \times 10^{-11}$.
Alleviate Δa_μ anomaly problem to be within 1.5σ.

Conclusions

Most of data can be accommodated by SM. For sure there are physics beyond minimal SM, <- neutrino masses and mixing.

There are a few anomalies in flavor physics (apart from neutrino masses and mixing). Models can be constructed to explain the anomalies. Too many models on the market, MFV provides a good framework for model independent analysis for flavor physics.

It is important to get experimental data confirmed. LHCb and BELLE II can provide data to further confirm anomalies in B decays. Experimental measurement of muon g-2, $\mu \to \varepsilon\, \gamma$, μ-e conversion, edm … can provide much needed information about flavor physics in lepton sector.

Higgs sector is also becoming an important arena for flavor physics.

Exciting time ahead for flavor physics.