Flavor Physics With Higgs and Leptons

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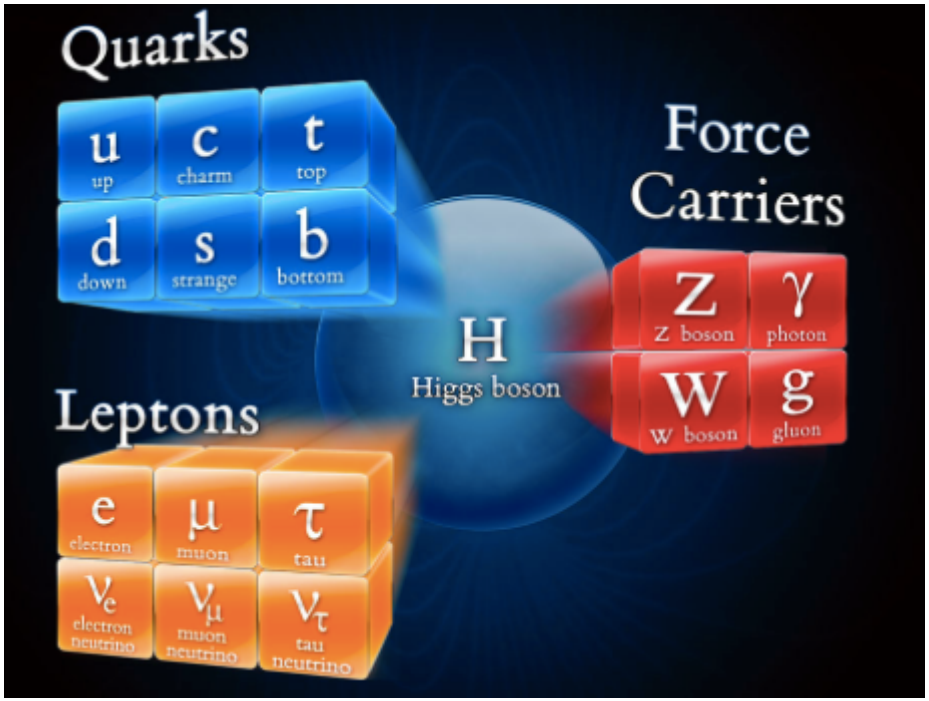
Standard Model and Flavor Physics

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

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

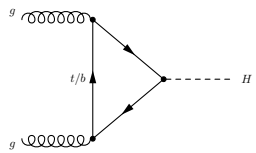
When going beyond SM, more possibilities!



Number of SM generations

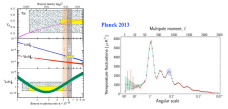
In the SM, only 3 generations of quarks and leptons are allowed.

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.

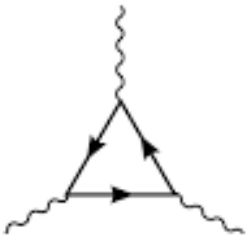


LEP already ruled out more than 3 neutrinos with mass less than $m_Z/2$.

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?

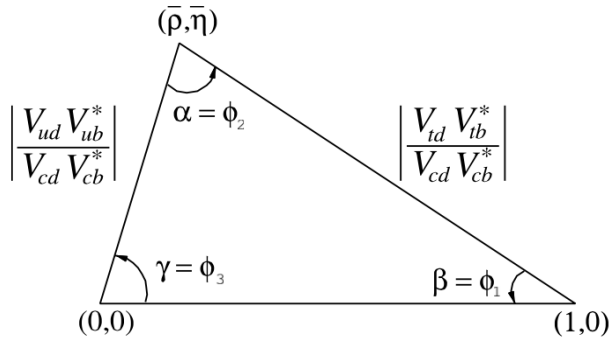
Beyond SM, conclusions may change, X-G He and G. Valencia, PPLB707 (2012)

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.

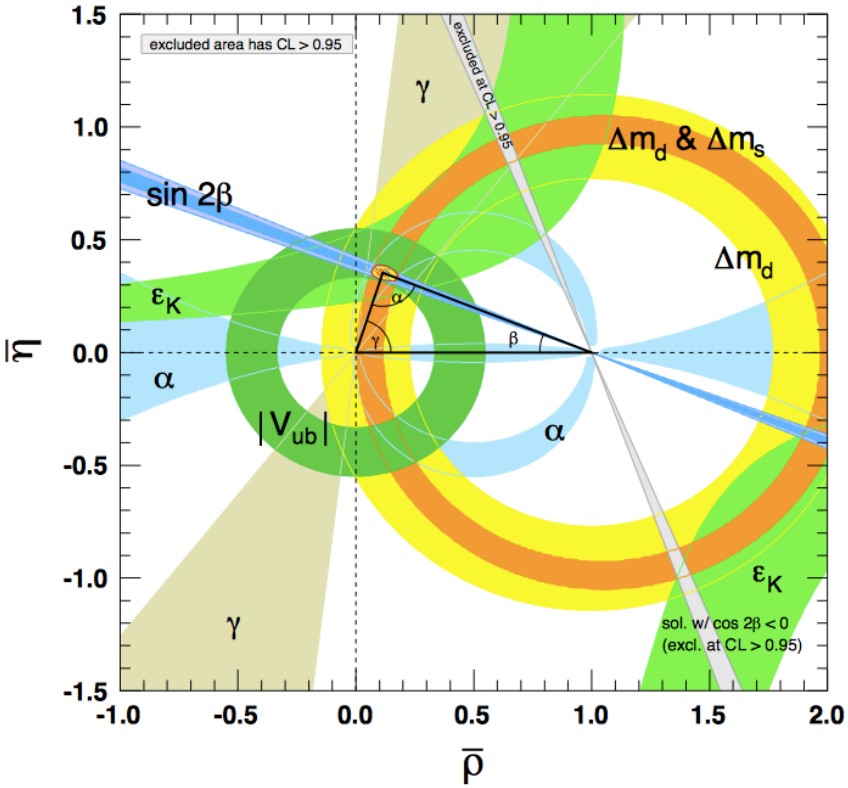
If neutrinos are of Majorana type, for the PMNS matrix one should include an additional diagonal matrix with two Majorana phases $\mathrm{diag}(e^{i\alpha_1/2}, e^{i\alpha_2/2}, 1)$ multiplied to the matrix from right in the above.

Status of Quark and Lepton

Quark Mixing

PDG

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

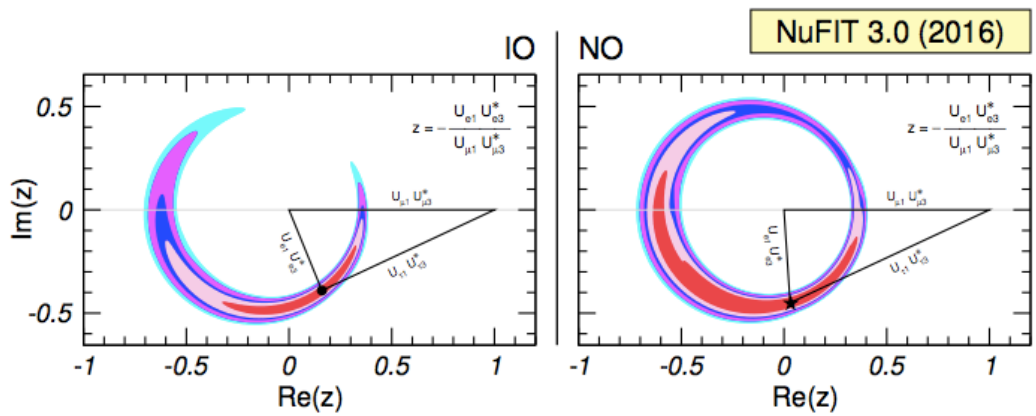


$$\lambda = 0.22537 \pm 0.00061\,, \qquad A = 0.814^{+0.023}_{-0.024}\,,$$
$$\bar{\rho} = 0.117 \pm 0.021\,, \qquad \bar{\eta} = 0.353 \pm 0.013\,.$$

Neutrino Mixing

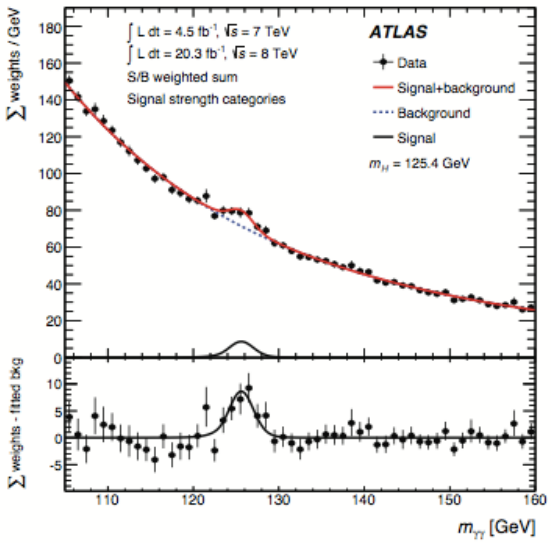
$\Delta m^2 = m_3^2 - (m_2^2 + m_1^2)/2$. Thus, $\Delta m^2 = \Delta m_{31}^2 - \Delta m_{21}^2/2 > 0$, if $m_1 < m_2 < m_3$ and $\Delta m^2 = \Delta m_{32}^2 + \Delta m_{21}^2/2 < 0$ for $m_3 < m_1 < m_2$.

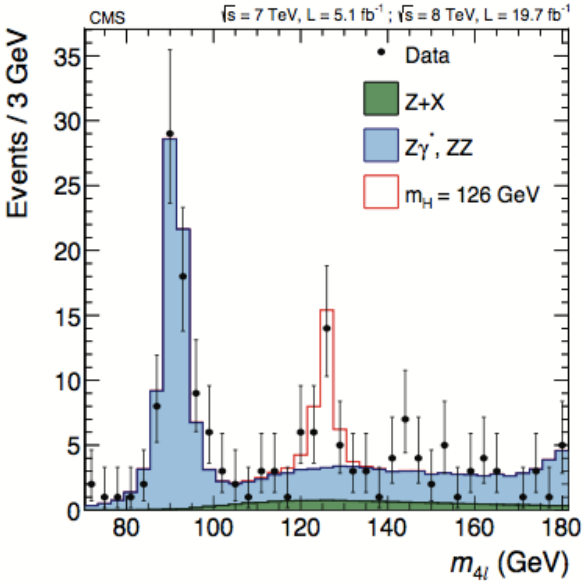
Parameter	best-fit	3σ
Δm_{21}^2 $[10^{-5}$ eV $^2]$	7.37	$6.93 - 7.97$
$\lvert\Delta m^2\rvert$ $[10^{-3}$ eV $^2]$	2.50 (2.46)	$2.37 - 2.63$ $(2.33 - 2.60)$
$\sin^2\theta_{12}$	0.297	$0.250 - 0.354$
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	0.437	$0.379 - 0.616$
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	0.569	$0.383 - 0.637$
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	0.0214	$0.0185 - 0.0246$
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	0.0218	$0.0186 - 0.0248$
δ/π	1.35 (1.32)	$(0.92 - 1.99)$
		$((0.83 - 1.99))$

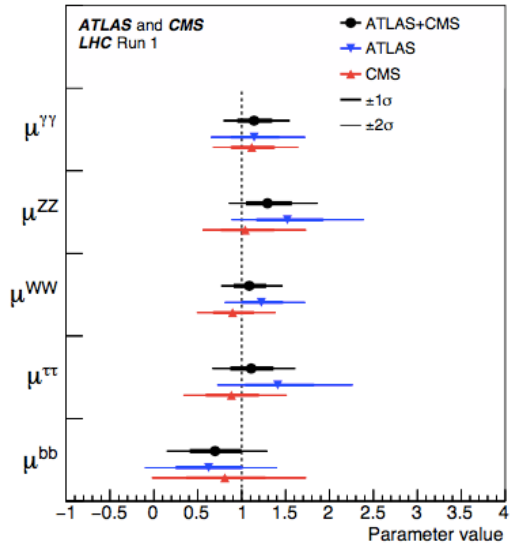


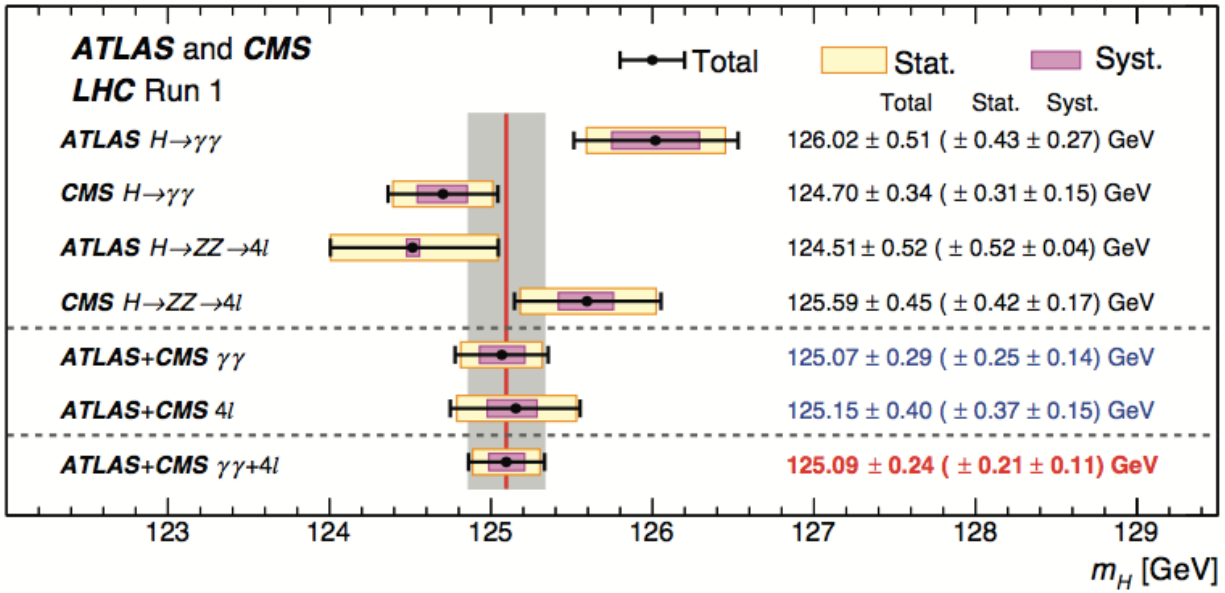
Why they mix the pattern shown above? Some understanding.

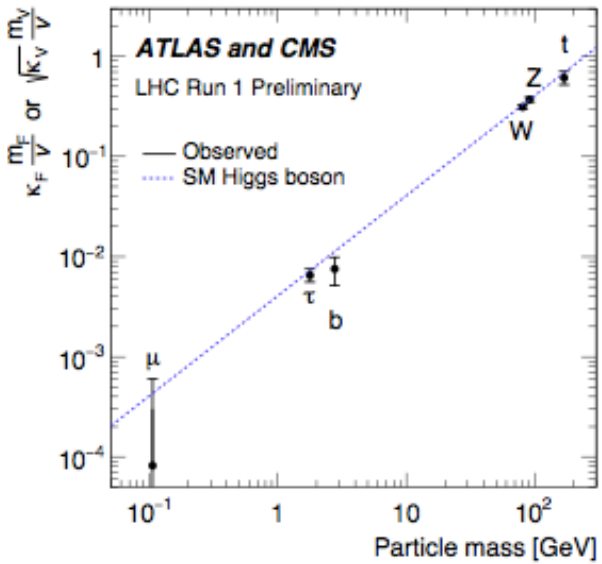
The 125 GeV Higgs is consistent with SM one!











1. Flavor Physics with Leptons

(g-2)μ, B and lepton anomalies, $^8Be^*$ -> ^8Be e e and a 17 MeV X-boson

2. Flavor Physics with Higgs

General Yukawa coupling, precision test from B_s -> $\mu\ \mu$, CP violation in h -> $\tau\ \tau$

3. Flavor Physics with Neutrino Mixing

Model for δ_{CP}= -π/2 and θ_{23}= π/4? Grand Unification prediction?

1. Flavor Physics with Leptons

The longstanding problem of $(g\text{-}2)_\mu$

$$a_\mu^{\rm exp} = 11659209.1(5.4)(3.3) \times 10^{-10}\,,$$
$$a_\mu^{\rm SM} = 11659180.3(0.1)(4.2)(2.6) \times 10^{-10}\,.$$

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 288(63)(49) \times 10^{-11}$$

PDG

arXiv:1705.00263

Muon $g-2$ Theory: the Hadronic Part

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Abstract
I present a status report of the hadronic vacuum polarization effects for the muon $g-2$, to be considered as an update of [1]. The update concerns recent new inclusive R measurements from KEDR in the energy range 1.84 to 3.72 GeV. For the leading order contributions I find $a_\mu^{\rm had(1)} = (688.07 \pm 4.14)[688.77 \pm 3.38] \times 10^{-10}$ based on e^+e^-data [incl. τ data], $a_\mu^{\rm had(2)} = (-9.93 \pm 0.07) \times 10^{-10}$ (NLO) and $a_\mu^{\rm had(3)} = (1.22 \pm 0.01) \times 10^{-10}$ (NNLO). Collecting recent progress in the hadronic light-by-light scattering I adopt π^0, η, η' [95 ± 12] + axial–vector [8 ± 3] + scalar [−6 ± 1] + π, K loops [−20 ± 5] + quark loops [22 ± 4] + tensor [1 ± 0] + NLO [3 ± 2] which yields $a_\mu^{(6)}$(lbl, had) = $(103 \pm 29) \times 10^{-11}$. With these updates I find $a_\mu^{\rm exp} - a_\mu^{\rm the} = (31.3 \pm 7.7) \times 10^{-10}$ a 4.1 σ deviation. Recent lattice QCD results and future prospects to improve hadronic contributions are discussed.

B and lepton physics anomalies

The R_{K*} Anomaly

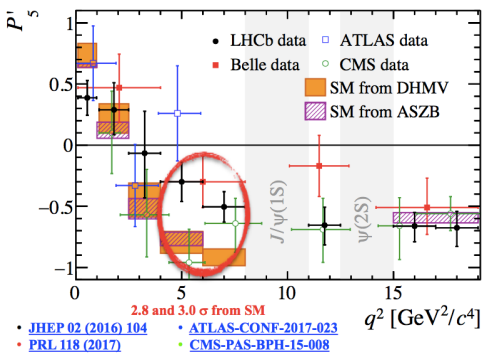
S. Bifani, CERN Seminar, 18th April, 2017

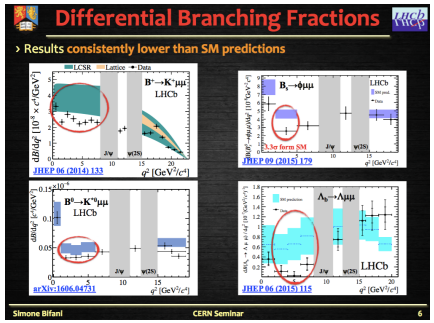
› R_{K*0} determined as double ratio to reduce systematic effects

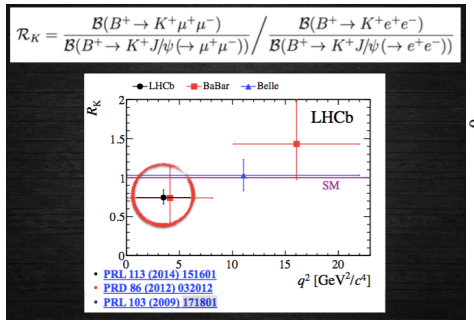
$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

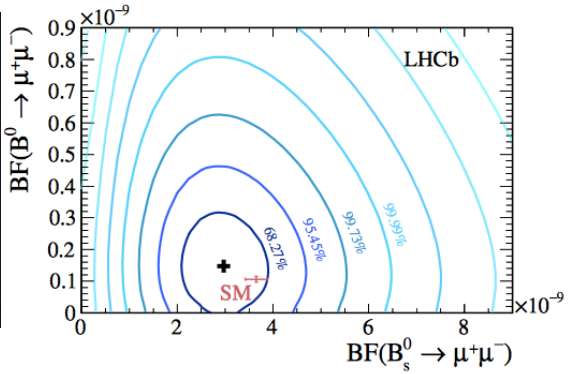
LHCb Preliminary	low-q^2	central-q^2
$\mathcal{R}_{K^{*0}}$	$0.660 \pm^{0.110}_{0.070} \pm 0.024$	$0.685 \pm^{0.113}_{0.069} \pm 0.047$
95% CL	[0.517–0.891]	[0.530–0.935]
99.7% CL	[0.454–1.042]	[0.462–1.100]

LHCb arXiv: 1705.05802









All these processes are induced by b -> s ll interaction. Consistently lower than SM predictions.

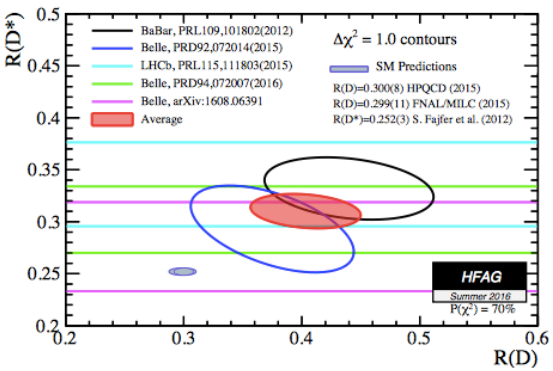
Combined effects are now about 4σ !

The $R_{D(*)}$ anomalies

	$R(D)$	$R(D^*)$
World average	0.403 ± 0.047	0.310 ± 0.017
SM expectation [15]	0.299 ± 0.005	0.257 ± 0.005
Belle II, 50/ab	± 0.010	± 0.005

$R_{D(*)} = B(B \to D^{(*)}\tau\nu)/B(B \to D^{(*)}l\nu)$

Again, a 4σ effects!



Models for $R(D^{(*)})$ and $b \to s\mu^+\mu^-$ anomalies

A lot of model building activities trying to provide solutions to $R(D^{(*)})$ and $b \to s\ \mu^+\mu^-$ induced anomalies.

Making $b \to s\ \mu^+\mu^-$ smaller or $b \to s\ e^+e^-$ larger than SM predictions.

Z' and W' models, Multi-Higgs models, leptoquark models,

Susy, R-parity violating models, …

Hundreds of papers written on related subjects!

Since the new LHCb R_{K^*} data, just to the end of April 17 papers:

arXiv: 1703.09189, 1703.09627, 1704.05340, 1704.05435, 1704.05438, 1704.05444, 1704.05446, 1704.05447, 1704.05672, 1704.05835, 1704.06005, 1704.06188, 1704.06200, 1704.06240, 1704.07347, 1704.07397, 1704.08168, …

Model independent analysis for flavor physics

Too many ways to build theoretical models. Effective operator analysis provides a model independent method.

Operator analysis, more complicated than our collider friends, they usually just take flavor conserving interactions.

For flavor physics, this is obviously not enough! The flavor changing interaction is at the core of the study. More complicated.

Some guideline to parameterize flavour changing interactions needed!

Minimal Flavor violation provides a very economic and efficient way for guide flavor physics when using effective operators:

All flavor and CP violations have their origin in the known structure of Yukawa couplings.

The MFV framework for quarks

D'Ambrosio, Giudice, Isidori, Strumia, arXiv: 0207036

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

$$Q_L \to V_Q Q_L\,, \quad U_R \to V_U U_R\,, \quad D_R \to V_D D_R\,,$$

$$Y_u \to V_Q Y_u V_U^\dagger\,, \quad Y_d \to V_Q Y_d V_D^\dagger,\ V_{Q,U,D} \in \mathrm{SU}(3).$$

$$Y_u \sim (3,\bar{3},1) \ \text{ and } \ Y_d \sim (3,1,\bar{3})$$

$$-(Y_u)_{jk}\,\overline{Q_j} P_R U_k \tilde{H} - (Y_d)_{jk}\,\overline{Q_j} P_R D_k H$$

$$-(Y_e)_{jk}\,\overline{L_j} P_R E_k H - (Y_\nu)_{jk}\,\overline{L_j} P_R N_k \tilde{H}$$

$$-\tfrac{1}{2}(M_N)_{jk}\,\overline{(N_j)^c} P_R N_k$$

$$Y_d = \frac{\sqrt{2}}{v}\,\mathrm{diag}(m_d, m_s, m_b)\,,$$

$$Y_u = \frac{\sqrt{2}}{v}\,V_{\mathrm{CKM}}^\dagger\,\mathrm{diag}(m_u, m_c, m_t)$$

$$Y_e = \frac{\sqrt{2}}{v}\,\mathrm{diag}(m_e, m_\mu, m_\tau)$$

For Dirac neutrinos: $Y_\nu = \frac{\sqrt{2}}{v} U_{\mathrm{PMNS}}\,\hat{m}_\nu$

For Majorana neutrinos: $Y_\nu = \frac{i\sqrt{2}}{v} U_{\mathrm{PMNS}}\,\hat{m}_\nu^{1/2} O M_\nu^{1/2}$,

O offers a potentially important new source of CP violation.

Construct $\Delta_{q,l}$ so that $O^6_{1,2}$ are invariant of the flavor global groups. Building blocks:

$$O_1^6 = \overline{Q}\gamma_\eta \Delta_q P_L Q\, \overline{L}\gamma^\eta \Delta_\ell P_L L\,,$$

$$O_2^6 = \overline{Q}\gamma_\eta \tilde{\Delta}_q P_L \tau_a Q\, \overline{L}\gamma^\eta \tilde{\Delta}_\ell P_L \tau_a L\,,$$

$$\mathsf{A}_q = Y_u Y_u^\dagger\,, \qquad \mathsf{B}_q = Y_d Y_d^\dagger\,,$$

$$\mathsf{A}_\ell = Y_\nu Y_\nu^\dagger\,, \qquad \mathsf{B}_\ell = Y_e Y_e^\dagger\,.$$

MFV for the lepton sector

Cirigliano, Grinstein, Isidori, arXiv:0507001

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_{CKM} with $U_{\mathrm{PMNS}}^\dagger$ $\qquad Y_\nu \sim (3,\bar{3},1)$ and $Y_e \sim (3,1,\bar{3})$

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.

Similarly for quarks

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).

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

Cayley-Hamilton indentyt tfor 3x3 matrix,

$$X^3 - X^2 TrX + [(TrX)^2 - TrX^2]/2 - IDetX = 0$$

Resume into 17 terms

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

Practically for B anomalies, the first two terms are sufficient.

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

The anomalies discussed earlier can be carried out in this framework.
(Lee, Tandean, arXiv:1505.04692)

More restrictive way of generating O_i, by Z'

$$\mathcal{L}_{Z'} = -\left(\overline{Q}\gamma^\eta \Delta_q P_L Q + \overline{L}\gamma^\eta \Delta_\ell P_L L\right) Z'_\eta ,$$

Able to solve b -> s μμ anomalies?

$$\mathcal{L}_{\rm MFV} = \frac{-1}{m_{Z'}^2}\left(\mathcal{O}^{4q} + \mathcal{O}^{4\ell} + \mathcal{O}^{2q2\ell}\right) ,$$
$$\mathcal{O}^{4q} = \tfrac{1}{2}\overline{Q}\gamma_\eta \Delta_q P_L Q\, \overline{Q}\gamma^\eta \Delta_q P_L Q ,$$
$$\mathcal{O}^{4\ell} = \tfrac{1}{2}\overline{L}\gamma_\eta \Delta_\ell P_L L\, \overline{L}\gamma^\eta \Delta_\ell P_L L ,$$
$$\mathcal{O}^{2q2\ell} = O_1^6 = \overline{Q}\gamma_\eta \Delta_q P_L Q\, \overline{L}\gamma^\eta \Delta_\ell P_L L ,$$

C-W. Cheng, He, Tandean, Yuan, aXrXiv: 1706.02696

$$\mathcal{L}_{\rm eff} \supset \frac{\sqrt{2}\,\alpha_{\rm e}\,\lambda_{sb}\,G_{\rm F}}{\pi}\,C_{\ell\ell'}\,\bar{s}\,\gamma^\eta P_L b\,\bar{\ell}\gamma_\eta P_L \ell'\,,$$

$$\begin{aligned}
\mathsf{c}_{\ell_j\ell_k} &= \frac{-\pi}{\sqrt{2}\,\alpha_{\rm e} G_{\rm F}\, m_{Z'}^2}\left(\zeta_1 y_t^2 + \zeta_2 y_t^4\right)(\Delta_\ell)_{jk} \\
&\simeq -25.3\,{\rm TeV}^2\,\frac{\left(\zeta_1 y_t^2 + \zeta_2 y_t^4\right)(\Delta_\ell)_{jk}}{m_{Z'}^2}\,,
\end{aligned}$$

$$\lambda_{sb} = V_{ts}^* V_{tb}\,, \qquad C_{\ell\ell'} = \delta_{\ell\ell'}\,C_9^{\rm SM} + \mathsf{c}_{\ell\ell'}\,, \qquad \frac{\left|\zeta_1 y_t^2 + \zeta_2 y_t^4\right|}{m_{Z'}} \leq \frac{0.13}{\rm TeV}\,.$$

$$\mathsf{c}_{ee} = 0\,, \qquad -1.00 \leq \mathsf{c}_{\mu\mu} \leq -0.32$$

$$0.60 \leq \frac{\Delta M_d^{\rm exp}}{\Delta M_d^{\rm SM}} \leq 1.16\,, \qquad 0.71 \leq \frac{\Delta M_s^{\rm exp}}{\Delta M_s^{\rm SM}} \leq 1.19$$

Constraints on Δ_l

$$\mathsf{A}_\ell = \frac{2}{v^2}\mathcal{M}\, U_{\rm PMNS}\, \hat{m}_\nu^{1/2} O O^\dagger \hat{m}_\nu^{1/2} U_{\rm PMNS}^\dagger\,, \qquad OO^\dagger = e^{2i\mathsf{R}}\,, \qquad \mathsf{R} = \begin{pmatrix} 0 & r_1 & r_2 \\ -r_1 & 0 & r_3 \\ -r_2 & -r_3 & 0 \end{pmatrix}$$

Real O disfavored. Complex O can do the job!

Parameter	NH	IH
$\sin^2\theta_{12}$	0.306 ± 0.012	0.306 ± 0.012
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.587^{+0.020}_{-0.024}$
$\sin^2\theta_{13}$	0.02166 ± 0.00075	0.02179 ± 0.00076
$\delta/^\circ$	261^{+51}_{-59}	277^{+40}_{-46}
$\Delta m^2_{21} = m_2^2 - m_1^2$	$(7.50^{+0.19}_{-0.17}) \times 10^{-5}$ eV^2	$(7.50^{+0.19}_{-0.17}) \times 10^{-5}$ eV^2
$\Delta m^2_{3\ell}$	$m_3^2 - m_1^2 = (2.524^{+0.039}_{-0.040}) \times 10^{-3}$ eV^2	$m_3^2 - m_2^2 = (-2.514^{+0.038}_{-0.041}) \times 10^{-3}$ eV^2

$$a_{\ell_j}^{Z'} = \frac{-m_{\ell_j}^2}{12\pi^2\, m_{Z'}^2} \sum_k \left|(\Delta_\ell)_{jk}\right|^2 .$$

Wrong sign to solve a_μ anomaly

$$\frac{\mathcal{B}(\tau \to e\nu\nu')_{\rm exp}}{\mathcal{B}(\tau \to e\nu\nu')_{\rm SM}} = 1.002 \pm 0.006\,,$$

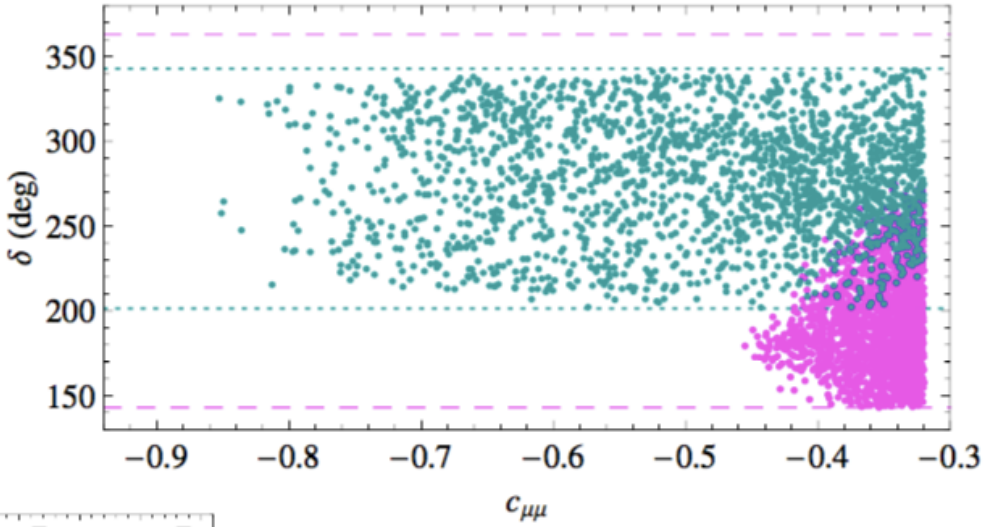
$$\frac{\mathcal{B}(\tau \to \mu\nu\nu')_{\rm exp}}{\mathcal{B}(\tau \to \mu\nu\nu')_{\rm SM}} = 1.006 \pm 0.006$$

$$\mathcal{B}(\tau \to ee\bar{\mu})_{\rm exp} < 1.5 \times 10^{-8}\,, \qquad \mathcal{B}(\tau \to \mu\mu\bar{e})_{\rm exp} < 1.7 \times 10^{-8}\,,$$

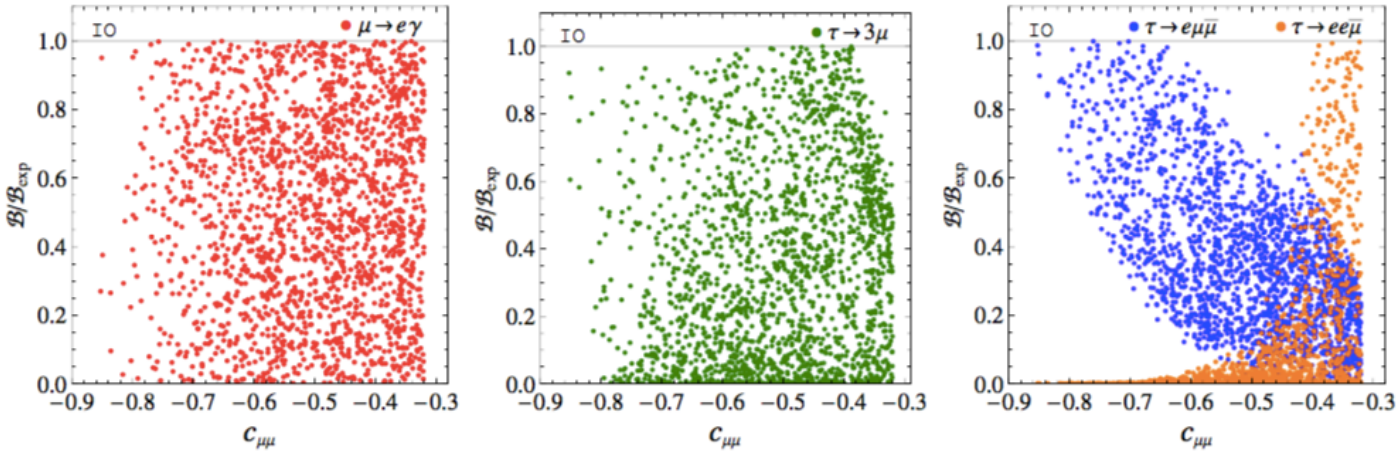
$$\mathcal{B}(\tau \to e\mu\bar{\mu})_{\rm exp} < 2.7 \times 10^{-8}\,, \qquad \mathcal{B}(\tau \to 3\mu)_{\rm exp} < 2.1 \times 10^{-8}\,,$$

$$\mathcal{B}(\tau \to \mu e\bar{e})_{\rm exp} < 1.8 \times 10^{-8}\,, \qquad \mathcal{B}(\mu \to e\gamma)_{\rm exp} < 4.2 \times 10^{-13}\,,$$

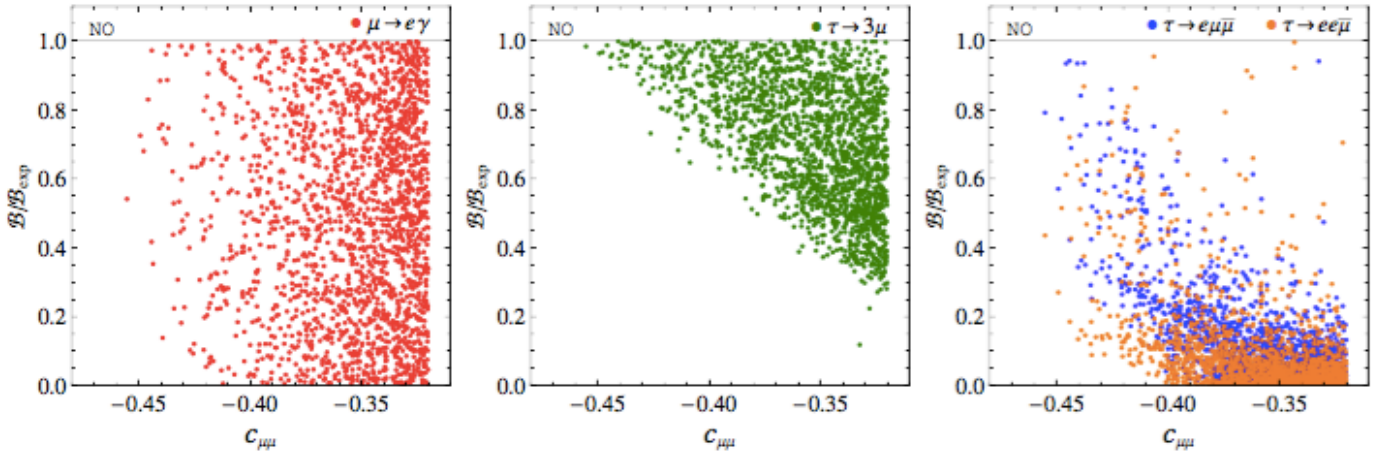
$$\mathcal{B}(\tau \to e\gamma)_{\rm exp} < 3.3 \times 10^{-8}\,, \qquad \mathcal{B}(\tau \to \mu\gamma)_{\rm exp} < 4.4 \times 10^{-8}\,,$$



Complex O



IO



NO

Decay mode	Branching fractions		
	Measured upper limit at 90% CL [39, 56]	Prediction ranges	
		NO	IO
$B \to K e^{\pm}\mu^{\mp}$	3.8×10^{-8}	$[0.0002, 2.9] \times 10^{-9}$	$[\sim 0, 3.2] \times 10^{-9}$
$B \to K^{*} e^{\pm}\mu^{\mp}$	5.1×10^{-7}	$[0.001, 7.2] \times 10^{-9}$	$[\sim 0, 8.2] \times 10^{-9}$
$B_s \to e^{\pm}\mu^{\mp}$	1.1×10^{-8}	$[0.001, 8.6] \times 10^{-12}$	$[\sim 0, 9.5] \times 10^{-12}$
$B \to \pi e^{\pm}\mu^{\mp}$	9.2×10^{-8}	$[0.0001, 1.2] \times 10^{-10}$	$[\sim 0, 1.3] \times 10^{-10}$
$B \to \rho e^{\pm}\mu^{\mp}$	3.2×10^{-6}	$[0.0003, 3.1] \times 10^{-10}$	$[\sim 0, 3.4] \times 10^{-10}$
$B^0 \to e^{\pm}\mu^{\mp}$	2.8×10^{-9}	$[0.0002, 3.0] \times 10^{-13}$	$[\sim 0, 2.9] \times 10^{-13}$
$B^{+} \to K^{+} e^{\pm}\tau^{\mp}$	3.0×10^{-5}	$[0.02, 8.1] \times 10^{-9}$	$[0.05, 6.9] \times 10^{-9}$
$B^{+} \to K^{*+} e^{\pm}\tau^{\mp}$	–	$[0.003, 1.4] \times 10^{-8}$	$[0.01, 1.3] \times 10^{-8}$
$B_s \to e^{\pm}\tau^{\mp}$	–	$[0.02, 7.2] \times 10^{-9}$	$[0.01, 1.3] \times 10^{-8}$
$B^{+} \to \pi^{+} e^{-}\tau^{+}$	2.0×10^{-5}	$[0.004, 1.8] \times 10^{-10}$	$[0.02, 3.3] \times 10^{-10}$
$B^{+} \to \rho^{+} e^{\pm}\tau^{\mp}$	–	$[0.01, 6.5] \times 10^{-10}$	$[0.02, 3.3] \times 10^{-10}$
$B^0 \to e^{\pm}\tau^{\mp}$	2.8×10^{-5}	$[0.005, 2.2] \times 10^{-10}$	$[0.01, 2.0] \times 10^{-10}$
$B^{+} \to K^{+} \mu^{\pm}\tau^{\mp}$	4.8×10^{-5}	$[1, 3] \times 10^{-9}$	$[\sim 0, 2.6] \times 10^{-9}$
$B^{+} \to K^{*+} \mu^{\pm}\tau^{\mp}$	4.8×10^{-5}	$[2, 6] \times 10^{-9}$	$[\sim 0, 2.6] \times 10^{-9}$
$B_s \to \mu^{\pm}\tau^{\mp}$	–	$[1, 3] \times 10^{-9}$	$[\sim 0, 2.6] \times 10^{-9}$
$B^{+} \to \pi^{+} \mu^{\pm}\tau^{\mp}$	7.2×10^{-5}	$[0.5, 1.4] \times 10^{-10}$	$[\sim 0, 1.2] \times 10^{-10}$
$B^{+} \to \rho^{+} \mu^{\pm}\tau^{\mp}$	7.2×10^{-5}	$[0.9, 2.6] \times 10^{-10}$	$[\sim 0, 1.2] \times 10^{-10}$
$B^0 \to \mu^{\pm}\tau^{\mp}$	2.2×10^{-5}	$[3, 9] \times 10^{-11}$	$[\sim 0, 7.6] \times 10^{-11}$
$K_L \to e^{\pm}\mu^{\mp}$	4.7×10^{-12}	$[\sim 0, 1.4] \times 10^{-12}$	$[\sim 0, 1.5] \times 10^{-12}$

Decay mode	Branching fractions				
	Measured upper limit at 95% CL [39]	Predicted ranges			
		NO		IO	
		0.6 TeV	1 TeV	0.6 TeV	1 TeV
$Z \to e^{\pm}\mu^{\mp}$	7.5×10^{-7}	$[\sim 0, 8.3] \times 10^{-10}$	$[\sim 0, 1.8] \times 10^{-11}$	$[\sim 0, 8.3] \times 10^{-10}$	$[\sim 0, 1.8] \times 10^{-11}$
$Z \to e^{\pm}\tau^{\mp}$	9.8×10^{-6}	$[\sim 0, 3.2] \times 10^{-6}$	$[\sim 0, 7.0] \times 10^{-8}$	$[\sim 0, 4.7] \times 10^{-7}$	$[\sim 0, 1.0] \times 10^{-8}$
$Z \to \mu^{\pm}\tau^{\mp}$	1.2×10^{-5}	$[0.8, 8.5] \times 10^{-7}$	$[0.2, 1.9] \times 10^{-8}$	$[\sim 0, 8.8] \times 10^{-7}$	$[\sim 0, 1.9] \times 10^{-8}$

In the Z' MFV framework, not possible to solve $R_{K(*)}$ and $R_{D(*)}$ simultaneously!

Bring R($D^{(*)}$) and b -> s μμ anomalies together

A role of a leptoquark scalar

Bauer&Neubert, arXiv: 1511.01900, N. Deshpande&X-G He, arXiv:1608.04817, D. Becirevic et al., Y. Cai et al, arXiv: 1704.05849.

$$L_{int} = \frac{1}{2m_\phi^2}[x_{ij}x_{i'j'}\bar{\nu}_L^{i'}\gamma^\mu\nu_L^i\bar{d}_L^{j'}\gamma_\mu d_L^j + z_{ij}z_{i'j'}\bar{e}_L^{i'}\gamma^\mu e_L^i\bar{u}_L^{j'}\gamma_\mu u_L^j]$$

K-> π νν, B-> $K^{(*)}$ νν D->μμ, πμμ

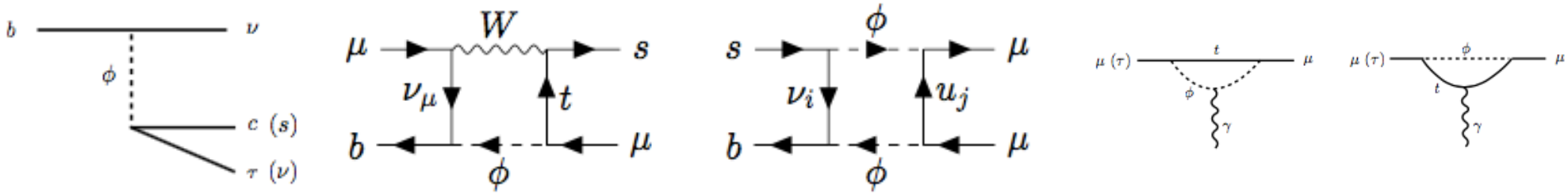
$$-\frac{1}{2m_\phi^2}[x_{ij}z_{i'j'}\bar{\nu}_L^{i'}\gamma^\mu e_L^i\bar{d}_L^{j'}\gamma_\mu u_L^j - x_{ij}z_{i'j'}\bar{e}_L^{i'}\gamma^\mu\nu_L^i\bar{u}_L^{j'}\gamma_\mu d_L^j]$$

R($D^{(*)}$), B->$D^{(*)}$ (ρ,π) lν, B_c -> τ ν

$$+\frac{1}{2m_\phi^2}[y_{ij}y_{i'j'}\bar{e}_R^{i'}\gamma^\mu e_R^i\bar{u}_R^{j'}\gamma_\mu u_R^j + x_{ij}y_{i'j'}(\bar{e}_R^{i'}\nu_L^i\bar{u}_R^{j'}\gamma_\mu d_L^j - \frac{1}{2}\bar{e}_R^i\sigma_{\mu\nu}\nu_L^{i'}\bar{u}_R^{j'}\sigma_{\mu\nu}d_L^j)]$$

D->μμ, π μμ R($D^{(*)}$), B->$D^{(*)}$ (ρ,π) lν, B_c -> τ ν

One loop contributions for b -> s μμ



Significant contribution needed from $\bar{e}_R Y U_R^c \phi$ coupling! Can also solve (g-2)μ anomaly!

The protophobic fifth force by a 17 MeV X boson

$^8Be^* \to {}^8Bee^+e^-$ 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., PRL117,071803; PRD95, 035017

The X boson is likely a vector boson of mass 16.7 MeV,

$$L = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}m_X^2 X_\mu X^\mu - X_\mu J_X^\mu \,, \quad J_\mu = \sum_{f=u,d,e,\nu_e,\ldots} e\varepsilon_f^v \bar{f}\gamma_\mu f \,.$$

In geenral there are also axial current coupling: $\sum_{f=u,d,e,\nu_e,\ldots} e\varepsilon_f^a \bar{f}\gamma_\mu\gamma_5 f$.

Assuming $^8Be^* \to {}^8B_e\, X$ followed by $X \to e^+e^-$ saturating X decay

Using the fact that the interaction matrix element of X with ^8Be and $^8Be^*$ is iso-scalar and proportional to $\varepsilon_p^v + \varepsilon_n^v$: $\varepsilon_p^v = 2\varepsilon_u^v + \varepsilon_d^v$ and $\varepsilon_n^v = \varepsilon_u^v + 2\varepsilon_d^v$.

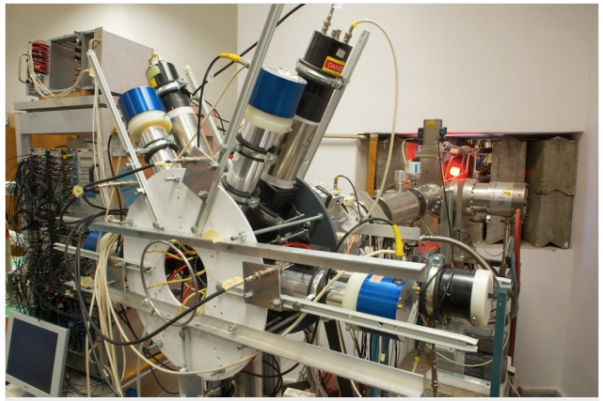
Data can be explained with: $\varepsilon_p^v + \varepsilon_n^v \approx 0.011$.

Constraint: $B(\pi^0 \to X\gamma) < 8 \times 10^{-4}$ leads to: $-0.067 < \varepsilon_p^v/\varepsilon_n^v < 0.078$.

A protophobic interaction: $\varepsilon_p^v = 0$, is consistent!

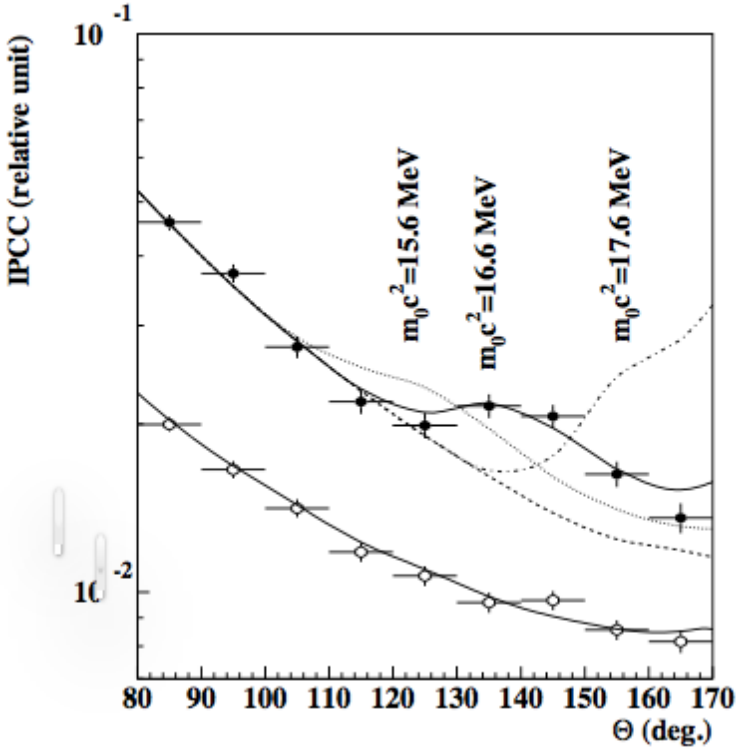
Satisfying beam damp and $(g-2)_\mu$ and also $e-\nu$ scattering data,

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



MTA-Atomki

Physicists at the Institute for Nuclear Research in Debrecen, Hungary, say this apparatus — an electron-



For $B(X \to e^+e^-)$ not equal to 1, the couplings are scaled by $1/\sqrt{B(X \to e^+e^-)}$.

A realistic renormalizable model

(Pei-Hong Gu, Xiao-Gang He, Nucl. Phys. B919, 209 [arXiv: 1605.05171]

A protophobic gauge model $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{Y'}$

$$
\begin{array}{lll}
Q_L^1 : (3,\ 2,\ 1/6)(-1)\ , & u_R^1 : (3,\ 1,\ 2/3)(5)\ , & d_R^1 : (3,\ 1,\ -1/3)(-7)\ , \\
L_L^1 : (1,\ 2,\ -1/2)(\beta)\ , & e_R^1 : (1,\ 1,\ -1)(\beta)\ , & \\
Q_L^2 : (3,\ 2,\ 1/6)(1)\ , & u_R^2 : (3,\ 1,\ 2/3)(-5)\ , & d_R^2 : (3,\ 1,\ -1/3)(7)\ , \\
L_L^2 : (1,\ 2,\ -1/2)(-\beta)\ , & e_R^2 : (1,\ 1,\ -1)(-\beta)\ , &
\end{array}
$$

and the third generation does not have any $U(1)_{Y'}$ charges.

Can change the 2nd generation to 3rd generation.

Y' boson as the desired X boson yet!

The Higgs scalars have non-trivial $U(1)_Y$ and $U(1)_{Y'}$ numbers.

The VEV should be much smaller than electroweak scale.

The couplings of neutrinos to Y' are too large to satisfy the constraints.

Introduce an additional $U(1)_X$ which do not couple to SM fermions.
But has a kinetic mixing of $U(1)_{Y'}$ and $U(1)_X$ gauge fields, $-(\epsilon/2)Y'_{\mu\nu}X^{\mu\nu}$,
The X boson to the $J^{\mu}_{Y'}$ current as, $\epsilon X_{\mu} J^{\mu}_{Y'}$.

$$\begin{aligned}\epsilon J^{\mu}_{Y'} &= \epsilon g_{Y'}\left[\bar{u}\gamma^{\mu}(4+6\gamma_5)u - \bar{d}\gamma^{\mu}(8+6\gamma_5)d + \beta\bar{e}\gamma^{\mu}e + \frac{\beta}{2}\bar{\nu}_e\gamma^{\mu}(1-\gamma_5)\nu_e\right] , \\ &- \epsilon g_{Y'}\left[\bar{c}\gamma^{\mu}(4+6\gamma_5)c - \bar{s}\gamma^{\mu}(8+6\gamma_5)s + \beta\bar{\mu}\gamma^{\mu}\mu + \frac{\beta}{2}\bar{\nu}_{\mu}\gamma^{\mu}(1-\gamma_5)\nu_{\mu}\right] ,\end{aligned}$$

$g_{Y'}$ being the $U(1)_{Y'}$ gauge coupling.
The full gauge group is: $SM \times U(1)_{Y'} \times U(1)_X$.

Neutrino couplings still too large.

Make ν_e mixes with a vector-like fermion $S = S_L + S_R$ with $U(1)_X$ charge x_S

With three iso-doublet Higgs scalars $\phi_e(0,0)$, $\phi_{\nu_e}(\beta,0)$, and $\eta(\beta,-x_S)$,

$$L = -y_e \bar{L}_L^1 \tilde{\phi}_e e_R - y_N \bar{L}_L^1 \phi_{\nu_e} N_R - \frac{1}{2} M_N \bar{N}_R^c N_R - f_S \bar{L}_L^1 \eta S_R - m_S \bar{S}_L S_R$$

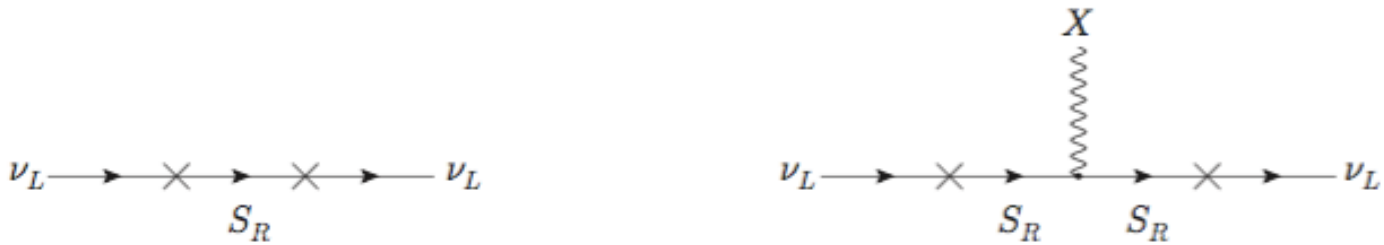


FIG. 1: The effects of the $\nu_L - S$ mixing, generation of the U_s matrix (left) and modification of the interaction of the X boson with the left-handed neutrinos (right).

One finds the effective coupling ν_e to the X boson should be

$$\frac{\epsilon g_{Y'} \beta}{2} \bar{\nu}_e \gamma_\mu (1-\gamma_5) \nu_e X^\mu \to \frac{\epsilon g_{Y'} \beta}{2} \frac{1 - \frac{g_X x_S}{\epsilon g_{Y'} \beta} U_S}{1 + U_S} \bar{\nu}_e \gamma_\mu (1-\gamma_5) \nu_e X^\mu \,.$$

The parameters ε_f^v in the effective theory are given by

$$\varepsilon_u^v = -\frac{4\epsilon g_{Y'}}{e}\,, \quad \varepsilon_d^v = \frac{8\epsilon g_{Y'}}{e}\,, \quad \varepsilon_e^v = -\frac{\epsilon\beta g_{Y'}}{e}\,, \quad \varepsilon_{\nu_e}^v = \frac{\epsilon g_{Y'}\beta}{2e}\frac{1 - g_X U_S/(\epsilon g_{Y'}\beta)}{1 + U_S}\,.$$

and also non-zero ε_f^a

$$\varepsilon_u^a = -\frac{6\epsilon g_{Y'}}{e}\,, \quad \varepsilon_d^a = \frac{6\epsilon g_{Y'}}{e}\,, \quad \varepsilon_e^a = 0\,, \quad \varepsilon_{\nu_e}^a = -\frac{\epsilon g_{Y'}\beta}{2e}\frac{1 - g_X U_S/(\epsilon g_{Y'}\beta)}{1 + U_S}\,.$$

Enough freedom to fit requird ε_f^v. Vector like interaction is protophobic! However, the model above also contains axial-vector current interactions Needs to check if OK!

$^8Be^* \to {}^8BeX$ is induced by iso-scalar,

in our model proportional to $[(\varepsilon_u^a + \varepsilon_d^a)/2](\bar{u}\gamma^\mu\gamma_5 u + \bar{d}\gamma^\mu\gamma_5 d)$.

It is dentically equal to Zero! Do not affect previous discussions!

No $\pi^0 \to e^+e^-$ decay, because X coupling to $\bar{e}\gamma_\mu e$.

Parity violatione-quark scattering. $L_{PV} = (G_F/\sqrt{2})C_{2f}\bar{e}\gamma^\mu e\bar{f}\gamma_\mu\gamma_5 f$.

Data: $2C_{2u} - C_{2d} = -0.145 \pm 0.086$, $2C_{2u} - C_{2d} = -0.095\left(1 - 1.7\frac{\varepsilon_e^v}{10^{-3}}\frac{\varepsilon_n^v}{10^{-2}}\right)$

To produce the experimental central value for $2C_{2u} - C_{2d}$,

$\varepsilon_e^v\varepsilon_n^v$ needs to be -0.3×10^{-5}.

If one keeps as large a ε_n^v close to its upper bound,

ϵ_e^v needs to be 0.21×10^{-3}.

But can be as large as 1.4×10^{-3}, contributes $\Delta a_\mu = 152 \times 10^{-11}$.

A viable model for $^8B_e^* \to^8 Be\, e^+e^-$ anomaly!.

2. Flavor Physics with Higgs

In the SM, there is just one Higgs doublet $H : (1,2)(-12) \to (0,(v+h)/\sqrt{v})^T$

$$L_4 = -\bar{f}_L Y_f^{SM} H f_R + H.C. \;\to\; -\bar{f}(M_f + Y_f^{SM}\frac{h}{\sqrt{2}})f \;,$$

$$M_f = \mathrm{diag}(m_f^1, m_f^2, m_f^3) \;,\;\; Y_f^{SM} = \frac{M_f}{v/\sqrt{2}} \;.$$

Going beyond SM, Yukawa couplings will in general be modified.

Example

$$L_6 = -\frac{1}{\Lambda^2}(H^\dagger H)\bar{f}_L g_f H f_R \;, \to L_6 = -\frac{v^2}{2\sqrt{2}\Lambda^2}\bar{f}_L g_f v(1+3\frac{h}{v})f_R \;, \qquad Y_l = \begin{pmatrix} Y_{ee} & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & Y_{\mu\mu} & Y_{\mu\tau} \\ Y_{\tau e} & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix}$$

$$L = -\bar{f}(M_f + (Y_f + i\gamma_5\bar{Y}_f)\frac{h}{\sqrt{2}})f \;,\;\; M_f = S_f^\dagger \frac{v}{\sqrt{2}}(Y_f^{SM} + \frac{v^2}{2\Lambda^2}g_f)T_f \;,$$

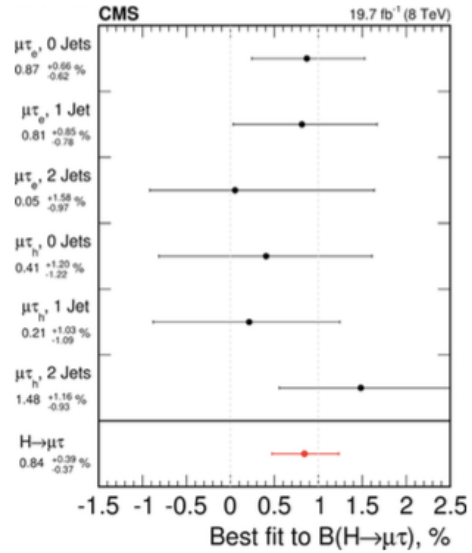
$$Y_f = \sqrt{2}\frac{M_f}{v} + (\delta Y_f + \delta Y_f^\dagger) \;,\;\; \bar{Y}_f = -i(\delta Y_f - \delta Y_f^\dagger) \;,\;\; \delta Y = \frac{v^2}{2\Lambda^2}S_f^\dagger g_f T_f \qquad \bar{Y}_l = \begin{pmatrix} \bar{Y}_{ee} & \bar{Y}_{e\mu} & \bar{Y}_{e\tau} \\ \bar{Y}_{\mu e} & \bar{Y}_{\mu\mu} & \bar{Y}_{\mu\tau} \\ \bar{Y}_{\tau e} & \bar{Y}_{\tau\mu} & \bar{Y}_{\tau\tau} \end{pmatrix}$$

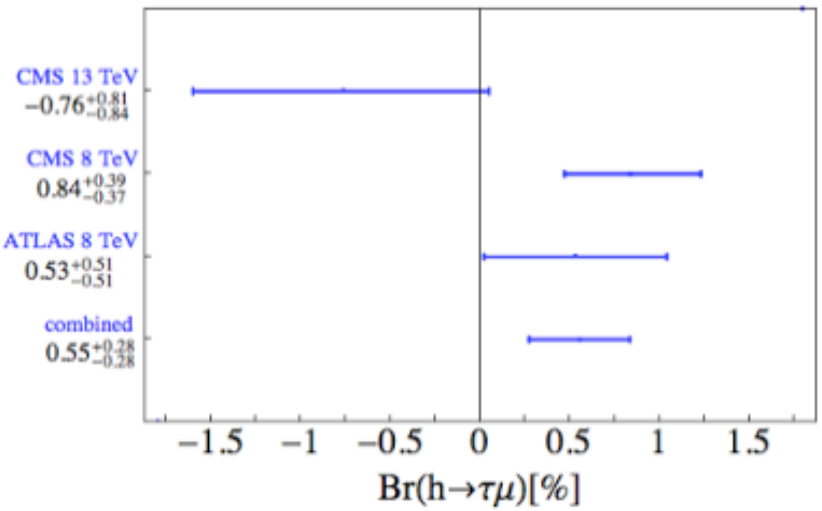
Flavor Physics with Higgs is largely related to the Yukawa couplings.

Higgs to μ τ anomaly is going away!

CMS: Run I Best Fit

- Small deviations per category (at most ~1sigma)
- Hemu and Heτ fits compatible with 0





2016 CMS result: Br(h -> tua mu) = (-0.76+-0.81)% in May

Cepeda, Higgs Tasting,2016,Benasque,Spain

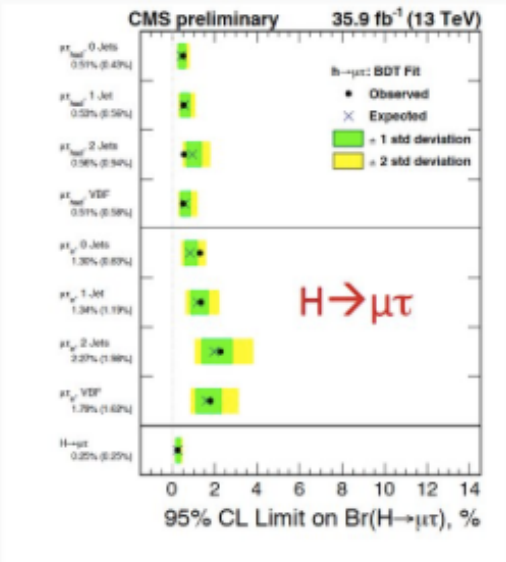
With the new CMS result

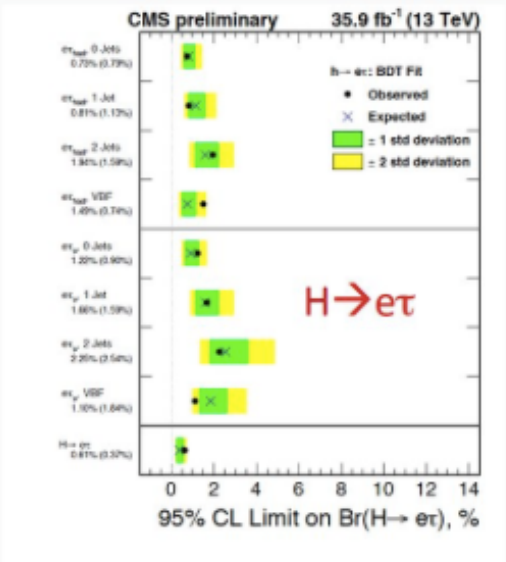
Channel	Coupling	95% CL Limit		
		Pre-LHC	CMS	ATLAS
H→ μe	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$3.6 \cdot 10^{-6}$	$5.4 \cdot 10^{-4}$	-
H→ $\mu\tau$	$\sqrt{\lvert Y_{\mu\tau}\rvert^2 + \lvert Y_{\tau\mu}\rvert^2}$	0.016	**0.00316**	0.0035
H→ $e\tau$	$\sqrt{\lvert Y_{e\tau}\rvert^2 + \lvert Y_{\tau e}\rvert^2}$	0.014	0.0024	0.0029

Going back to the normal

H->mutau 2.6 sigma is ruled out by the 35.9 fb^-1 @CMSexperiment #LHCP2017

Results of H→μτ and H→eτ searches





- No excess of data
- Best fit branching fraction: 0.00 ± 0.12%
- B(H→μτ) < 0.25% at 95% CL

- Slight excess of data (1.6 σ)
- Best-fit branching fraction: 0.30 ± 0.18%
- B(H→eτ) < 0.61% at 95% CL

9

$$BR(H \to e\tau) < 0.61\% \ (0.37\% \ expected)$$
$$BR(H \to \mu\tau) < 0.25\% \ (0.25\% \ expected)$$

$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.43 \times 10^{-3}$$

$$\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 2.26 \times 10^{-3}$$

$B_s \to \mu^+\mu^-$ as a precision test for Higgs Yukawa couplings

Chiang, He, Ye and Yuan, arXiv: 1703.06289

See Xingbo Yuan's talk Friday

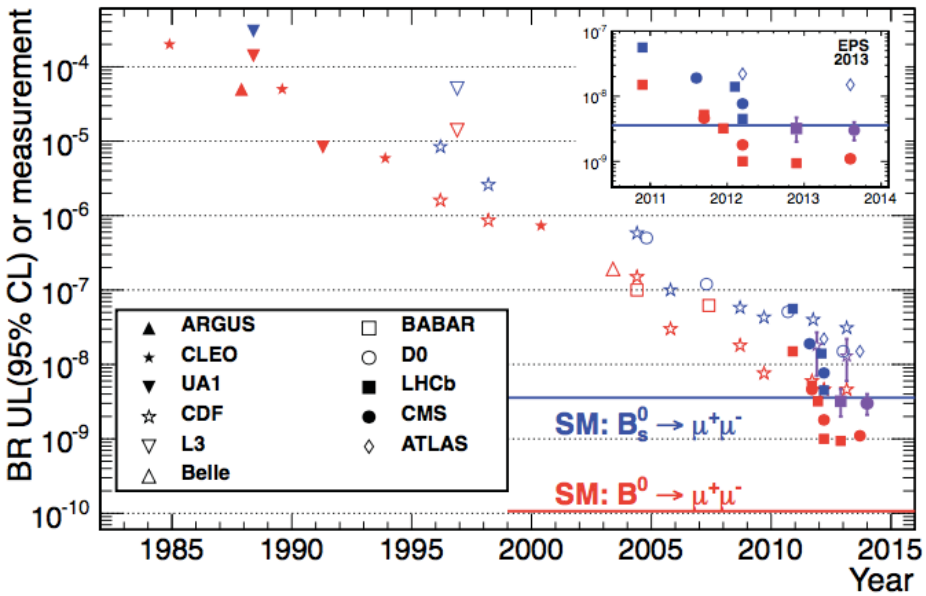
$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)_{\rm LHCb} = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}\,,$$

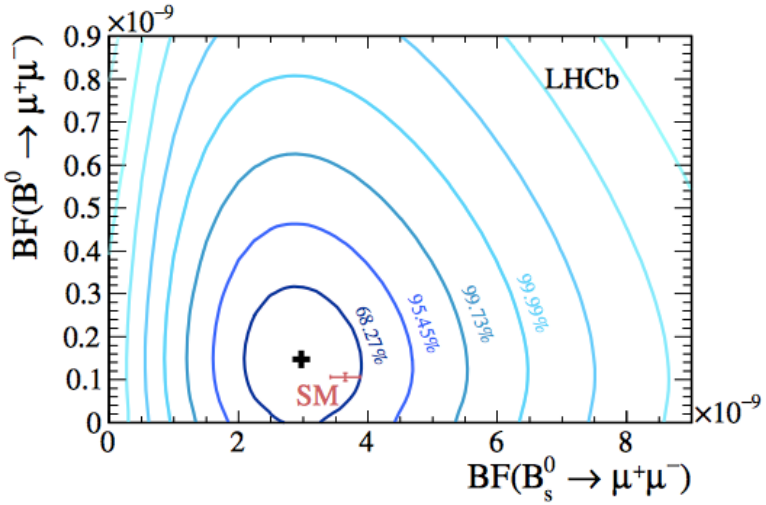
$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)_{\rm CMS} = (3.0^{+1.0}_{-0.9} \times 10^{-9}\,,$$

$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)_{\rm avrage} = (3.0 \pm 0.5) \times 10^{-9}\,,$$

$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)_{\rm SM} = (3.44 \pm 0.19) \times 10^{-9}\,.$$

$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)_{\rm avg}/\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)_{\rm SM} \approx 0.87.$$



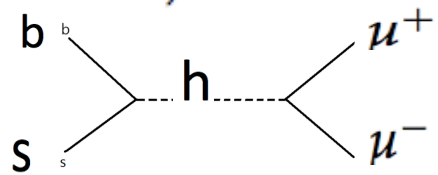


LHCb arXiv:1705.03274

Constraints and Implications on Higgs FCNC Couplings from Precision Measurement of $B_s \to \mu^+\mu^-$ Decay

$$\mathcal{L}_{h\bar{f}f} \equiv -\frac{1}{\sqrt{2}}\bar{f}(Y^f + i\gamma_5\bar{Y}^f)fh$$

$$Y^f = \sqrt{2}\hat{M}^f/v + (\delta Y^f + \delta Y^{f\dagger}) \text{ and } \bar{Y}^f = -i(\delta Y^f - \delta Y^{f\dagger})$$



CP violation in h -> ττ

Models beyond SM usually generate correction to h -> ττ coupling. If the corrections is CP violating, effects can show up in h -> ττ decay.

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

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

Data still allow A to be as large as π/8

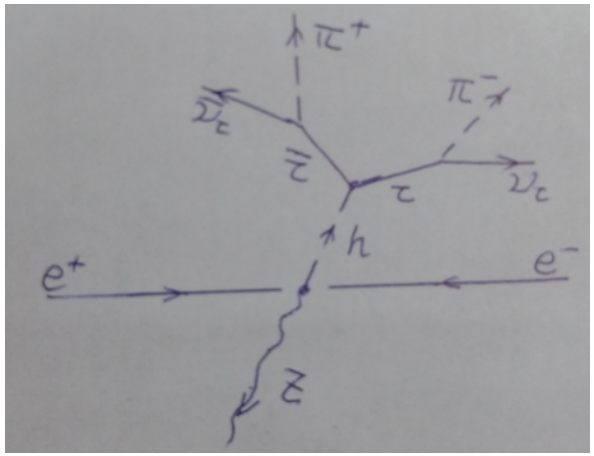
Experiments should look such CPV.

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

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



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

one can construct T odd operator $O_\pi = \vec{p}_\tau \cdot (\vec{p}_\pi^+ \times \vec{p}_\pi^-)$, Br(h ->ττ) ~ 5x10^{-2} , Br(τ –> π ν) ~ 0.1

One construct CP violating observable

$$A_\pi = \frac{N(\mathcal{O}_\pi > 0) - N(\mathcal{O}_\pi < 0)}{N(\mathcal{O}_\pi > 0) + N(\mathcal{O}_\pi < 0)} = \frac{\pi}{4}\beta_\tau\frac{(r_\tau\tilde{r}_\tau)}{\beta_\tau^2 r_\tau^2 + \tilde{r}_\tau^2},$$

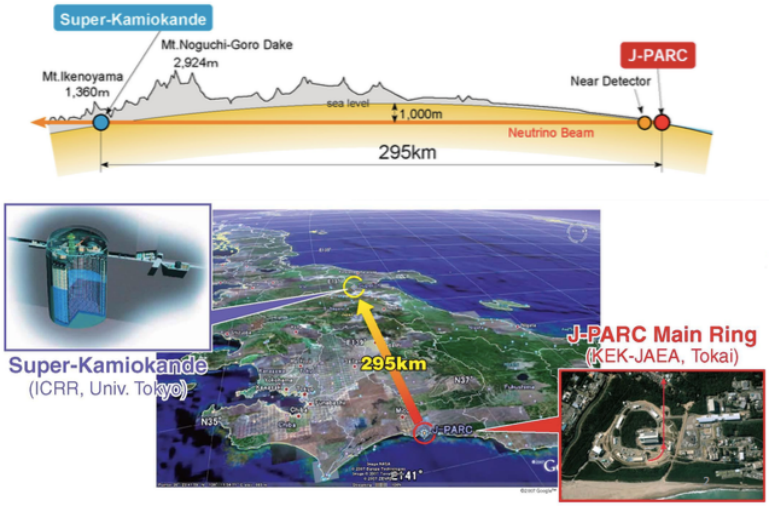
10^6 Higgs bosons, sensitivity to A_π can be 10% at CEPC.

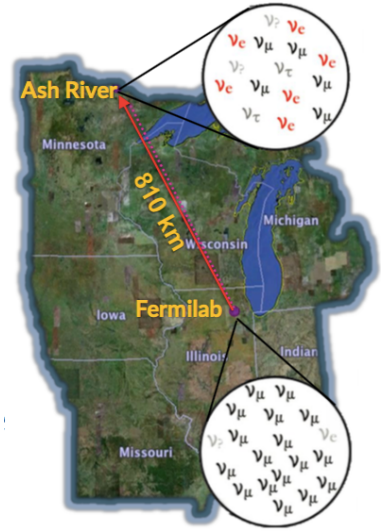
(He, Ma, McKellar, Mod. Phys Lett. A9, 205(1994); Berge, Bereuther, Kirchner, PRD92,096012(2015))

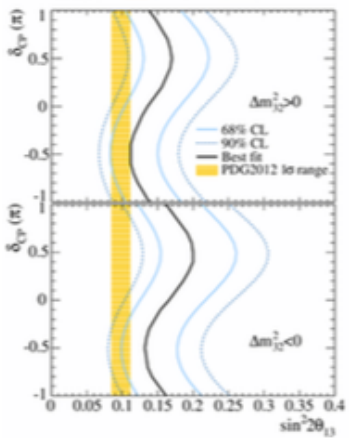
3. Flavor Physics with Neutrino Mixing

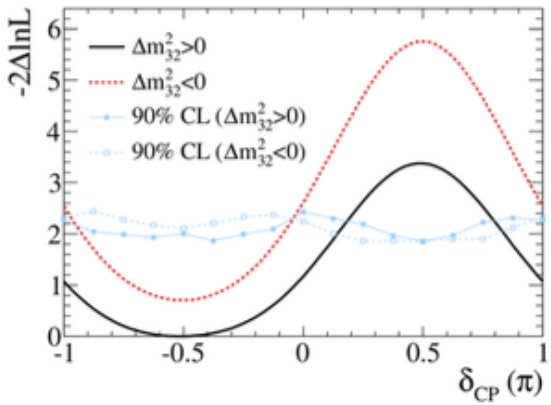
Model for δ_{CP}= -π/2 and θ_{23}= π/4? Grand Unification prediction?

T2K Experiment



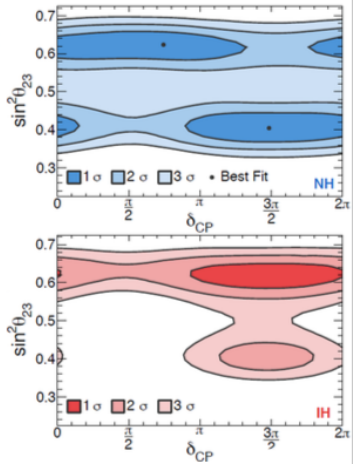






ν_e appearance results

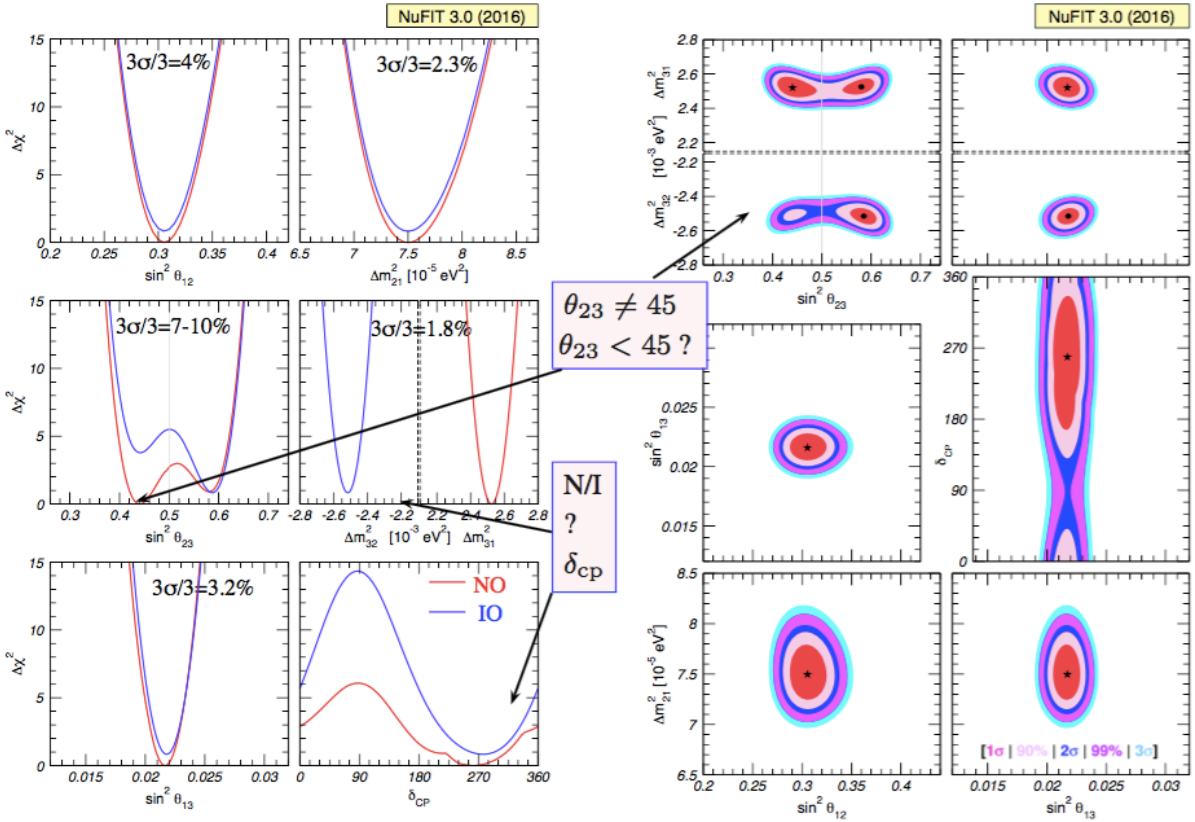
- 2 degenerate best fit points:
  - NH, δ_{CP} = 1.48π
    $\sin^2\theta_{23}$ = 0.404
  - NH, δ_{CP} = 0.74π
    $\sin^2\theta_{23}$ = 0.623
- Inverted hierarchy slightly disfavored - $\Delta\chi^2$ = 0.47
- Lower octant in the IH is disfavored at 93% CL
- arXiv:1703.03328



	Expected number of events (MC, Normal Hierarchy)				Observed data
	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$	T2K
ν_e	28.7	24.2	19.6	24.2	32
$\bar{\nu}_e$	6.0	6.9	7.7	6.8	4

Global 6-parameter fit http://www.nu-fit.org

Esteban, Maltoni, Martinez-Soler, Schwetz, MCG-G ArXiv:1611:01514



Neutrino mixing ata summary

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

Parameter	best-fit	3σ
Δm_{21}^2 $[10^{-5}$ eV $^2]$	7.37	$6.93 - 7.97$
$\lvert\Delta m^2\rvert$ $[10^{-3}$ eV $^2]$	2.50 (2.46)	$2.37 - 2.63$ $(2.33 - 2.60)$
$\sin^2\theta_{12}$	0.297	$0.250 - 0.354$
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	0.437	$0.379 - 0.616$
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	0.569	$0.383 - 0.637$
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	0.0214	$0.0185 - 0.0246$
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	0.0218	$0.0186 - 0.0248$
δ/π	1.35 (1.32)	$(0.92 - 1.99)$
		$((0.83 - 1.99))$

Leading approximation: $\delta_{CP} = -\pi/2$ and $\theta_{23} = \pi/4$. Models???

SO(10) Predictions

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

Minimal SO(10) Model without 120

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

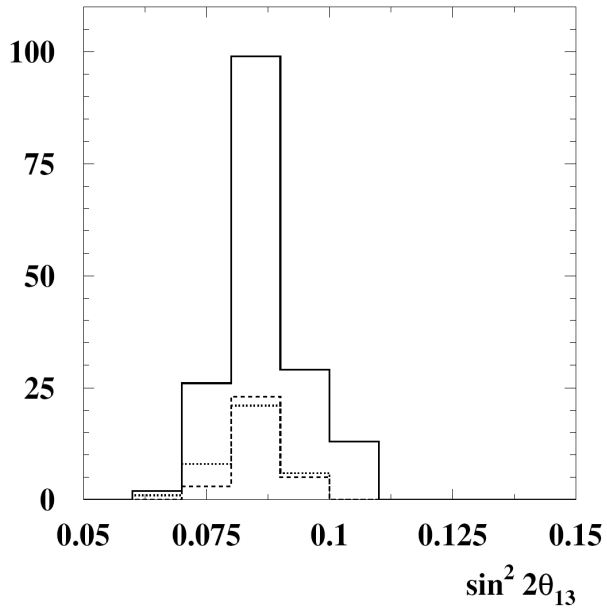
Two Yukawa matrices determine all fermion masses and mixings, including the neutrinos

$$\begin{aligned} M_u &= \kappa_u Y_{10} + \kappa'_u Y_{126} \\ M_d &= \kappa_d Y_{10} + \kappa'_d Y_{126} \\ M_\nu^D &= \kappa_u Y_{10} - 3\kappa'_u Y_{126} \\ M_l &= \kappa_d Y_{10} - 3\kappa'_d Y_{126} \end{aligned}$$

$$\begin{aligned} M_{\nu R} &= \langle \Delta_R \rangle\, Y_{126} \\ M_{\nu L} &= \langle \Delta_L \rangle\, Y_{126} \end{aligned}$$

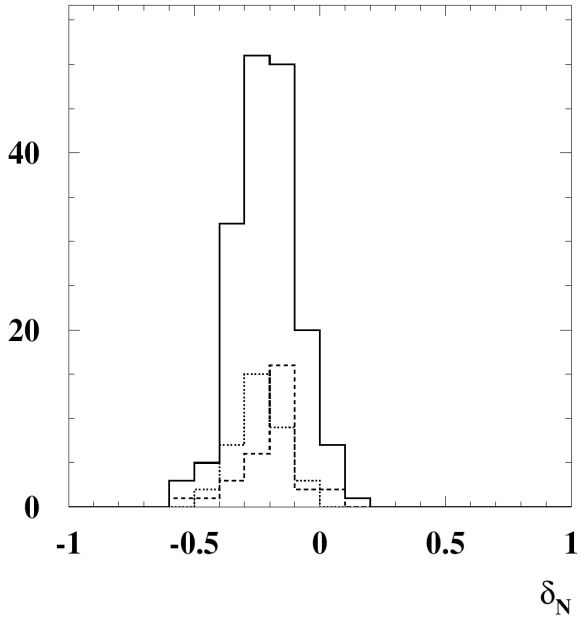
Model has only 11 real parameters plus 7 phases

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!!



Neutrino models for $\delta_{CP}=-\pi/2$ and $\theta_{23}=\pi/4$

How to obtain such an mixing pattern?

$\mu-\tau$ conjugate symmetry

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

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

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 $\theta_{23} = \pi/4$.

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

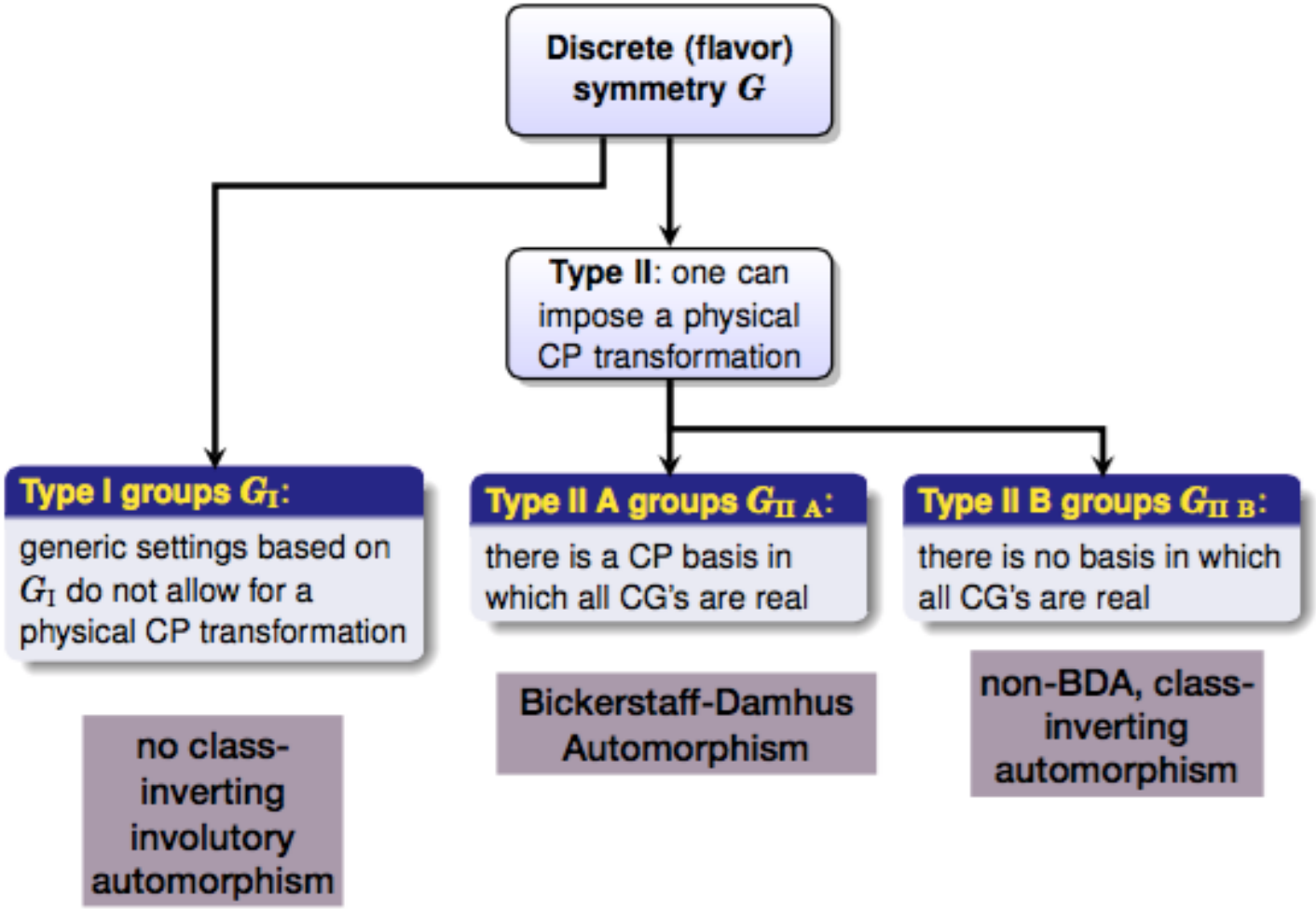
$$M_\nu = \begin{pmatrix} w_1 & x & y \\ x & w_2 & z \\ y & z & w_3 \end{pmatrix} ,$$

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))

Three Types of Discrete Groups

M.-C.C, M. Fallbacher, K.T. Mahanthappa, M. Ratz, A. Trautner, NPB (2014)



Examples

M.-C.C., M. Fallbacher, K.T. Mahanthappa, M. Ratz, A. Trautner (2014)

- Type I: all odd order non-Abelian groups

group	$\mathbb{Z}_5 \rtimes \mathbb{Z}_4$	T_7	$\Delta(27)$	$\mathbb{Z}_9 \rtimes \mathbb{Z}_3$
SG	(20,3)	(21,1)	(27,3)	(27,4)

- Type IIA: dihedral and all Abelian groups

group	S_3	Q_8	A_4	$\mathbb{Z}_3 \rtimes \mathbb{Z}_8$	T′	S_4	A_5
SG	(6,1)	(8,4)	(12,3)	(24,1)	(24,3)	(24,12)	(60,5)

- Type IIB

group	$\Sigma(72)$	$((\mathbb{Z}_3 \times \mathbb{Z}_3) \rtimes \mathbb{Z}_4) \rtimes \mathbb{Z}_4$
SG	(72,41)	(144,120)

A model with Type II seesaw

Particle contents and their transformation properties under standard $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge and A_4 family symmetry properties

$$l_L : (1,2,-1)(3)\ ,\quad l_R : (1,1,-2)(1+1''+1')\ ,$$
$$\phi : (1,2,-1)(1)\ ,\quad \Phi : (1,2,-1)(3)\ ,$$
$$\Delta^{0,',''} : (1,3,-2)(1+1'+1'')\ ,\quad \chi : (1,3,-2)(3)\ .$$

The Lagrangian responsible for the lepton mass matrix is

$$L = y_e \bar{l}_L \tilde{\Phi} l_R^1 + y_\mu \bar{l}_L \tilde{\Phi} l_R^2 + y_\tau \bar{l}_L \tilde{\Phi} l_R^3$$
$$+ Y_\nu^0 \bar{l}_L \Delta^0 l_L^c + Y_\nu^{'} \bar{l}_L \Delta^{'} l_L^c + Y_\nu^{''} \bar{l}_L \Delta^{''} l_L^c + y_\nu \bar{l}_L \chi l_L^c + H.C.$$

If the structure of the vacuum expectation value (vev) is of the form $< \Phi_{1,2,3} >= v^{\Phi}_{1,2,3} = v^{\Phi}$, $< \chi_i >= v^{\chi}_i$, $< \phi >= v_{\phi}$, and $< \Delta^{0,',''} >= v^{0,',''}_{\Delta}$,

$$M_l = U_l \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix} \ , \quad M_\nu = \begin{pmatrix} w_1 & x & y \\ x & w_2 & z \\ y & z & w_3 \end{pmatrix} \ ,$$

In general $w_i,\ x,\ y,\ z$ are complex!
where $m_{e,\mu,\tau} = \sqrt{3} y_{e,\mu,\tau} v^{\Phi}$ and

$$\begin{aligned} w_1 &= Y^0_\nu v^0_\Delta + Y^{'}_\nu v^{'}_\Delta + Y^{''}_\nu v^{''}_\Delta \ , \\ w_2 &= Y^0_\nu v^0_\Delta + \omega^2 Y^{'}_\nu v^{'}_\Delta + \omega Y^{''}_\nu v^{''}_\Delta \ , \\ w_3 &= Y^0_\nu v^0_\Delta + \omega Y^{'}_\nu v^{'}_\Delta + \omega^2 Y^{''}_\nu v^{''}_\Delta \ , \\ x &= y_\nu v^\chi_3 \ , \quad y = y_\nu v^\chi_2 \ , \quad z = y_\nu v^\chi_1 \ . \end{aligned}$$

In general $w_i,\ x,\ y,\ z$ are complex!

If w_i, x, y and z are real $\delta_{CP} = -\pi/2$ and $\theta_{23} = \pi/4$!

Complex ones, a natural way to be away from the real limit value.

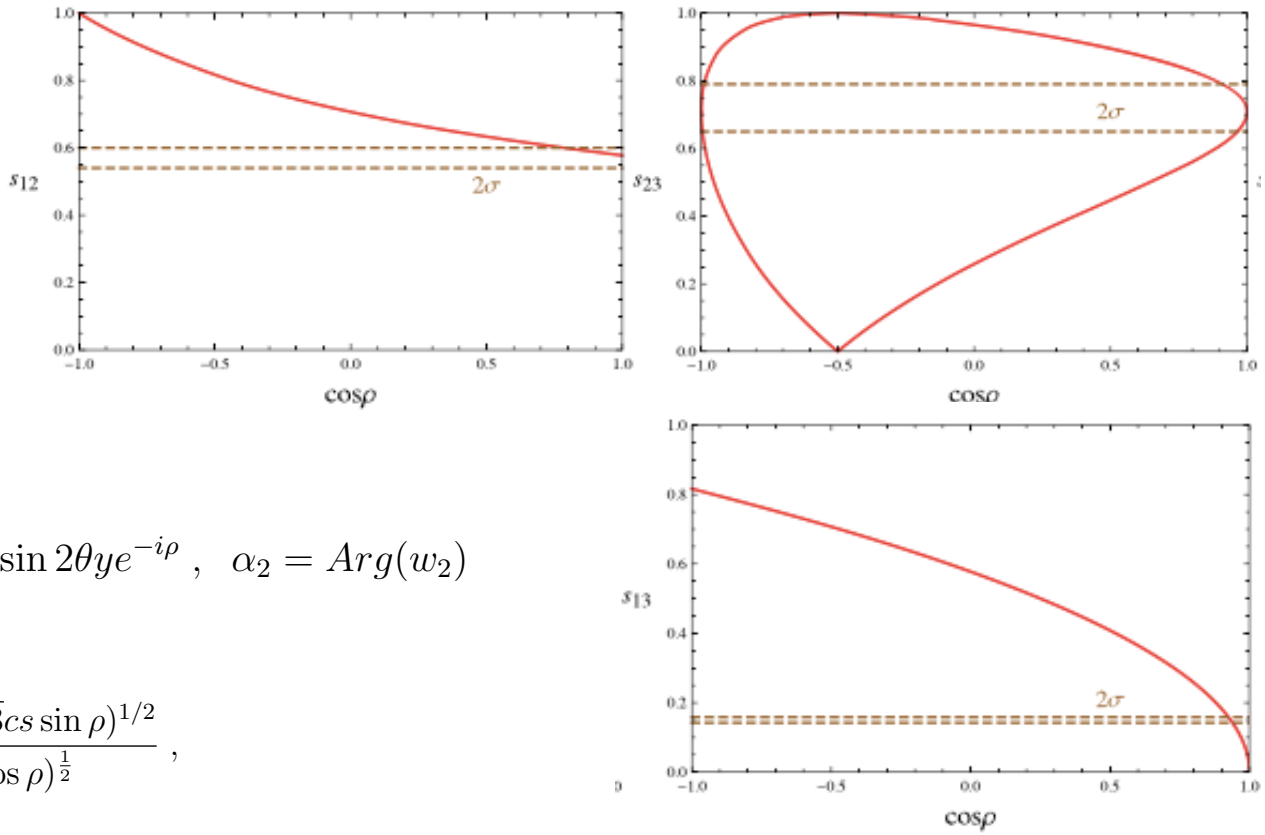
Diagonalizing the mass matrices, we have

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

$$V_{PMNS} = \frac{1}{\sqrt{3}} \begin{pmatrix} c + se^{i\rho} & 1 & ce^{i\rho} - s \\ c + \omega se^{i\rho} & \omega^2 & \omega ce^{i\rho} - s \\ c + \omega^2 se^{i\rho} & \omega & \omega^2 ce^{i\rho} - s \end{pmatrix}$$

$\tan\rho = Im(yw_1^* + y^* w_3)/Re(yw_1^* + y^* w_3)$,
$s = \sin\theta$ and $c = \cos\theta$,

$$\tan 2\theta = \frac{2|yw_1^* + w_3 y^*|}{|w_1|^2 - |w_3|^2} \ .$$



Majorana phases α_i of m_i

$$\alpha_{1,3} = Arg(w_i(1 \pm \cos 2\theta) + w_2 e^{-i2\rho}(1 \mp \cos 2\theta) \pm 2\sin 2\theta y e^{-i\rho} \ , \quad \alpha_2 = Arg(w_2)$$

Translate into standard parameterization

$$s_{12} = \frac{1}{\sqrt{2}(1 + cs\cos\rho)^{1/2}} \ , \ s_{23} = \frac{(1 + cs\cos\rho + \sqrt{3}cs\sin\rho)^{1/2}}{\sqrt{2}(1 + cs\cos\rho)^{\frac{1}{2}}} \ ,$$
$$s_{13} = \frac{(1 - 2cs\cos\rho)^{1/2}}{\sqrt{3}} \ .$$

and

$$\sin\delta = (1 + \frac{4c^2 s^2 \sin^2\rho}{(c^2 - s^2)^2})^{-1/2}(1 - \frac{3c^2 s^2 \sin^2\rho}{(1 + cs\cos\rho)^2})^{-1/2} \times \begin{cases} -1 \ , & \text{if } c^2 > s^2 \ , \\ +1 \ , & \text{if } s^2 > c^2 \ . \end{cases}$$

It is clearly that if $\sin\rho$ is not zero,
$|\delta|$ and θ_{23} deviate from $\pi/2$ and $\pi/4$, respectively.
In the limit ρ goes to zero, that real parameter set P
$\delta = \pm\pi/2$ and $\theta_{23} = \pi/4$.

Predictions: $|V_{i2}| = 1/\sqrt{3}$

$J = Im(V_{11}V^*_{12}V^*_{21}V_{22}) = (s^2 - c^2)/6\sqrt{3}$
independent of ρ

4. Conclusions

There are a few anomalies in B and lepton flavor physics. 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.

Protophobic model explaining anomaly in 8Be* to 8Be e e can be realized.

Flavor physics with Higgs is now becoming a precision test for SM. Consistent with SM Higgs sector. But there are rooms for new 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, μ –> e γ, μ-e conversion, edm … can provide much needed information about flavor physics in lepton sector.

Most of data can be accommodated by SM. For sure there are physics beyond minimal SM from neutrino mixing data.

Mixing pattern is emerging with δ_{CP} =-π/2 and θ_{23}=π/4. Theoretical models have been constructed to realize such mixing pattern.

A lot can be lernt from flavor physics with leptons and Higgs.