Flavor Physics With Higgs Boson and Leptons

Xiao-Gang He

SJTU/NTU

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Collaborators
Jin-Jun Zhang, Min He, and Xing-Bo Yuan

1. Standard Model and Flavor Physics

2. Beyond SM Higgs Couplings to Fermions

3. Flavor Violating Higgs Interaction without MFV

4. Flavor Violating Higgs Interaction with MFV

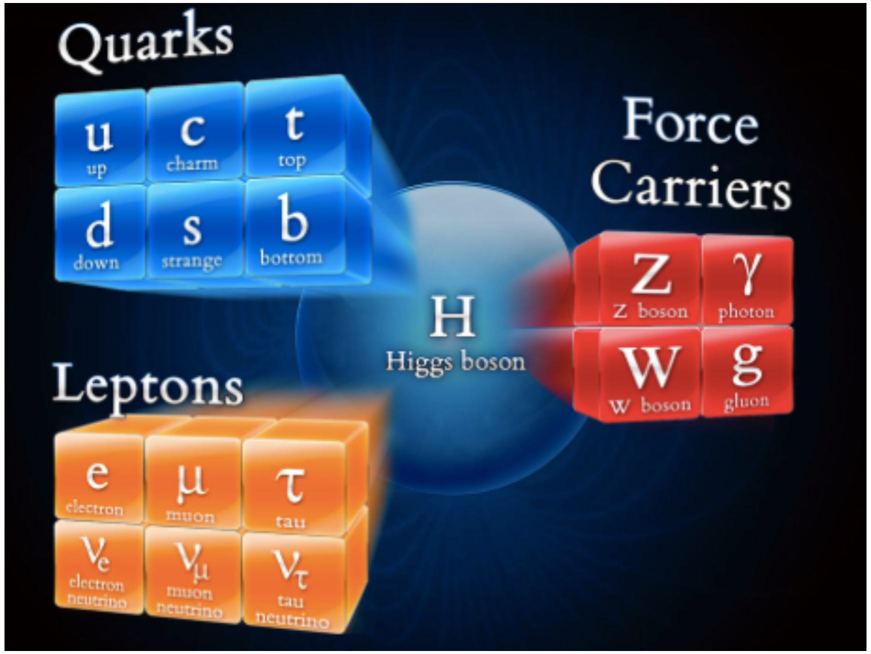
5. Conclusions

1. 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.

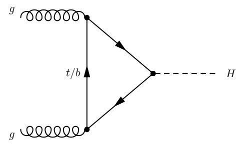
When going beyond SM, more possibilities!



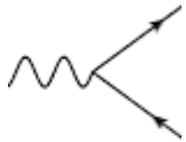
Number of SM generations

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

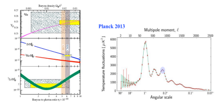
gg -> Higgs ~ (number of heavy quarks)^2, if fourth generation exist, their mass should be large, 9 times bigger production of Higgs. LHC data ruled out more than 3 generations of quarks.



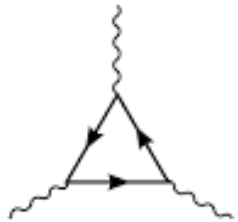
LEP already ruled out more than 3 neutrinos with mass less than $m_Z/2$.



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?

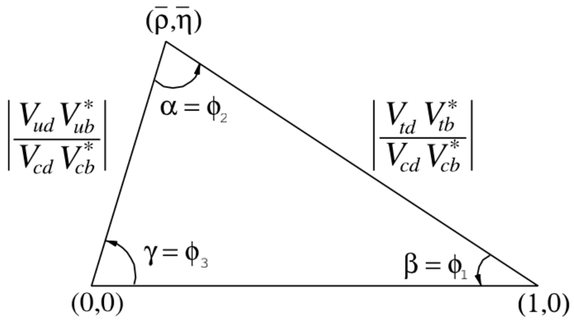
Beyond SM, conclusions may change, X-G He and G. Valencia, PPLB707 (2012)

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.

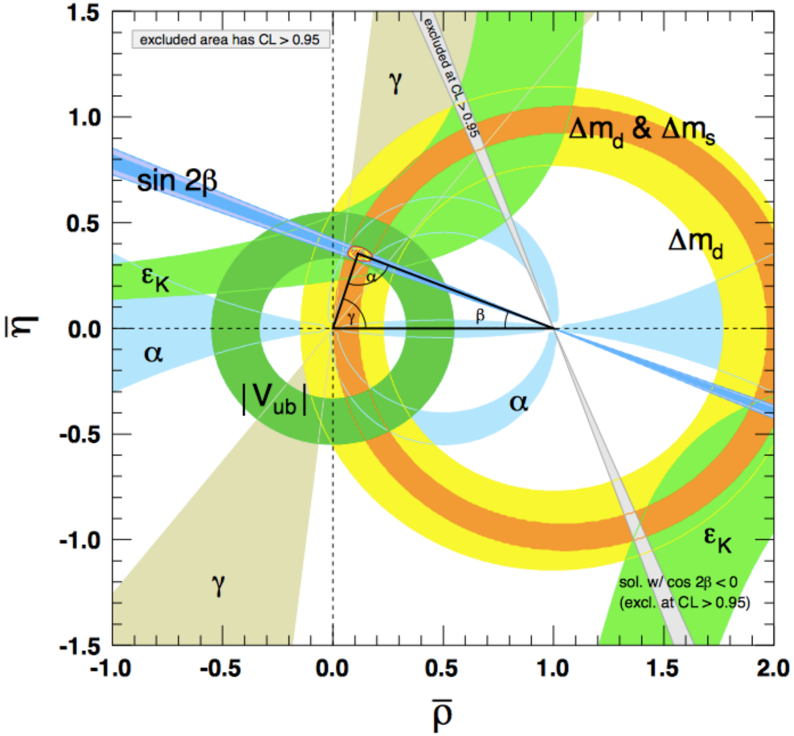
If neutrinos are of Majorana type, for the PMNS matrix one should include an additional diagonal

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 | Neutrino Mixing

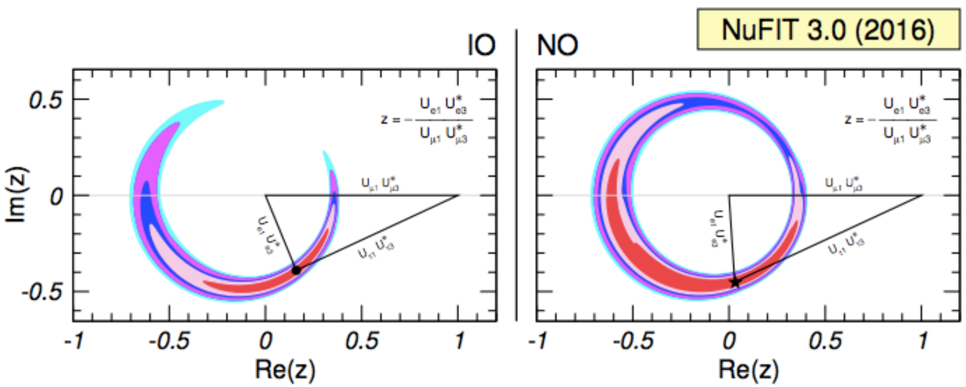
$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$



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

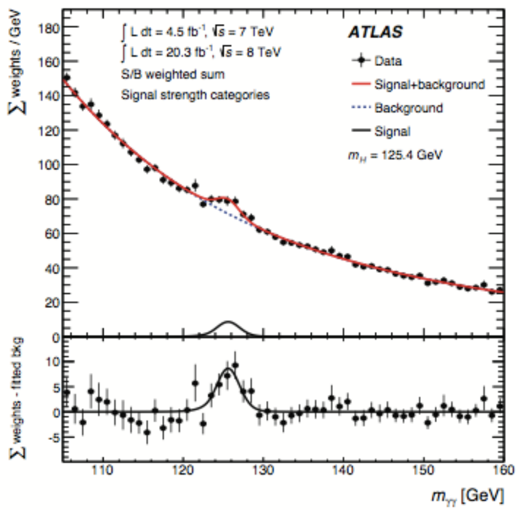
$\Delta m^2 = m_3^2 - (m_2^2 + m_1^2)/2$. Thus, $\Delta m^2 = \Delta m_{31}^2 - \Delta m_{21}^2/2 > 0$, if $m_1 < m_2 < m_3$ and $\Delta m^2 = \Delta m_{32}^2 + \Delta m_{21}^2/2 < 0$ for $m_3 < m_1 < m_2$.

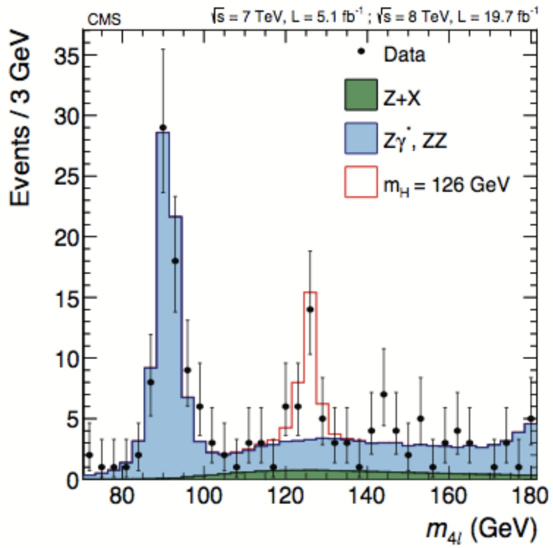
Parameter	best-fit	3σ
Δm_{21}^2 [10^{-5} eV ^{2}]	7.37	6.93 – 7.97
$\lvert\Delta m^2\rvert$ [10^{-3} eV ^{2}]	2.50 (2.46)	2.37 – 2.63 (2.33 – 2.60)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	0.437	0.379 – 0.616
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	0.569	0.383 – 0.637
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	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))

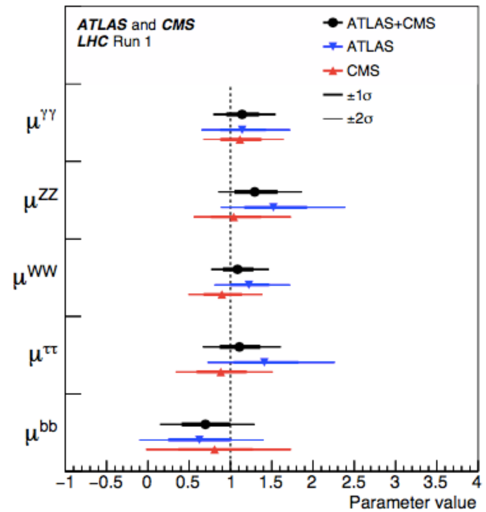


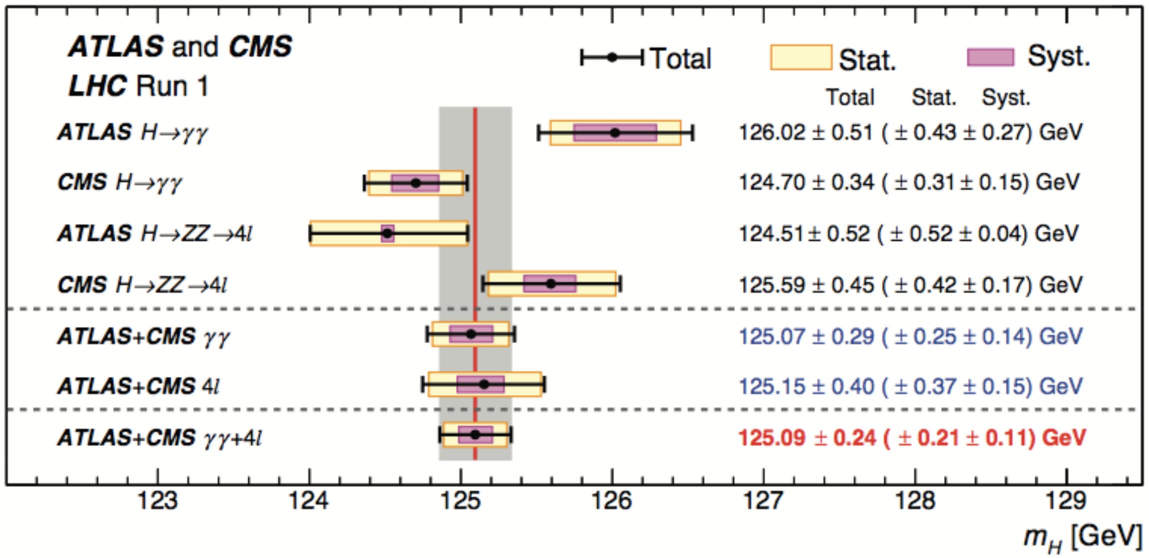
Why they mix the pattern shown above? Some understanding.

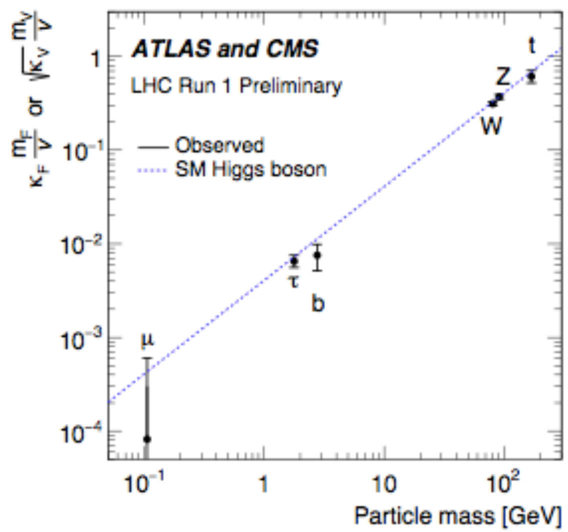
The 125 GeV Higgs is consistent with SM one!











SM explains many particle phenomena well,

but there are anomalies.

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**

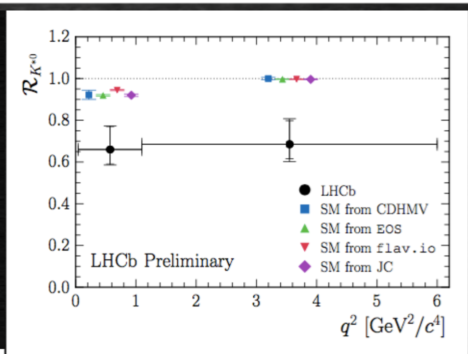
$$\mathcal{R}_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$

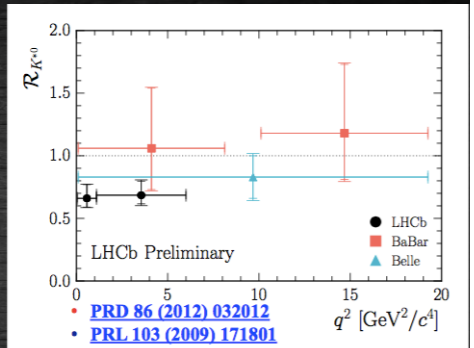
› **Control of the absolute scale of the efficiencies** via the ratio

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

which is expected to be unity and measured to be

$$1.043 \pm 0.006\,(\text{stat}) \pm 0.045\,(\text{syst})$$





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

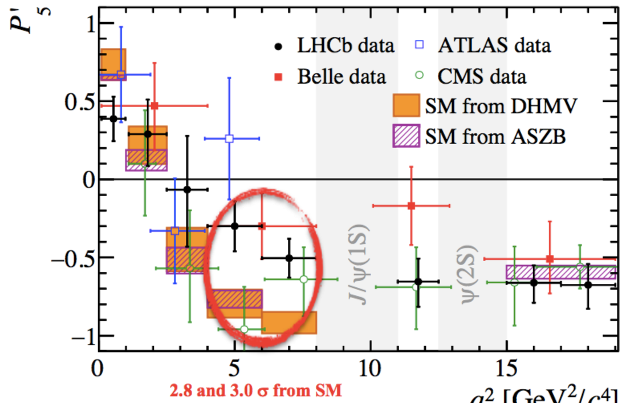
› The compatibility of the result in the **low-q²** with respect to the SM prediction(s) is of **2.2-2.4** standard deviations

› The compatibility of the result in the **central-q²** with respect to the SM prediction(s) is of **2.4-2.5** standard deviations

$$R_{K^{*0}} = \begin{cases} 0.66\,^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\ \text{GeV}^2/c^4\,, \\ 0.69\,^{+\,0.11}_{-\,0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 \quad < q^2 < 6.0\ \text{GeV}^2/c^4\,. \end{cases}$$

LHCb arXiv: 1705.05802

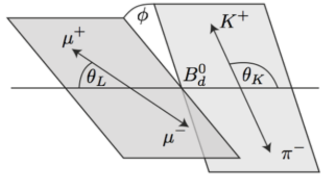
More B physics anomalies



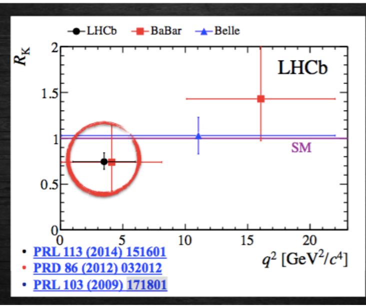
- JHEP 02 (2016) 104
- PRL 118 (2017)
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{d\cos\theta_L\, d\cos\theta_K\, d\phi\, dq^2} = \frac{9}{32\pi}\Big[\frac{3(1-F_L)}{4}\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1-F_L}{4}\sin^2\theta_K\cos 2\theta_L$$
$$-F_L\cos^2\theta_K\cos 2\theta_L + S_3\sin^2\theta_K\sin^2\theta_L\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_L\cos\phi + S_5\sin 2\theta_K\sin\theta_L\cos\phi$$
$$+S_6\sin^2\theta_K\cos\theta_L + S_7\sin 2\theta_K\sin\theta_L\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_L\sin\phi + S_9\sin^2\theta_K\sin^2\theta_L\sin 2\phi\Big].$$

$$P_1 = \frac{2S_3}{1-F_L}$$
$$P_2 = \frac{2}{3}\frac{A_{FB}}{1-F_L}$$
$$P_3 = -\frac{S_9}{1-F_L}$$
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}.$$



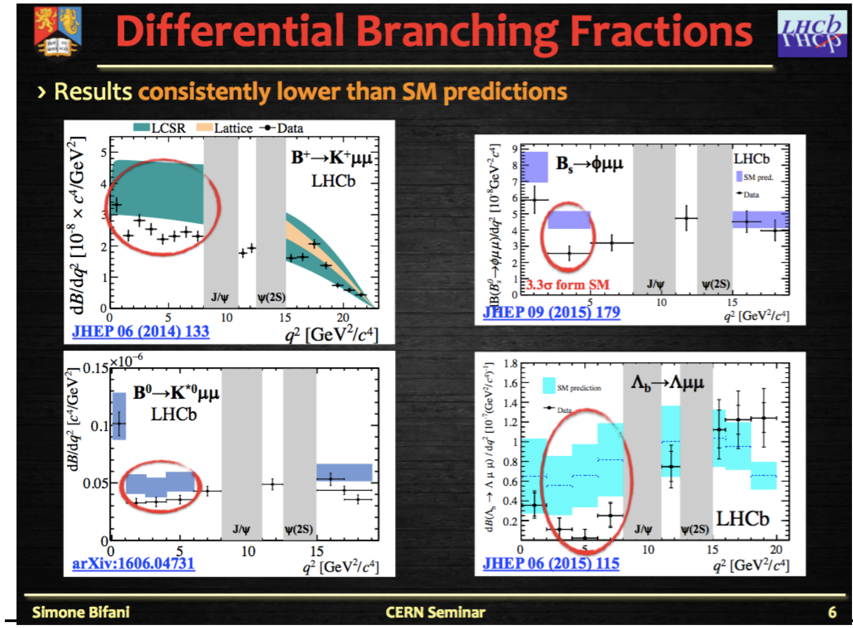
$$\mathcal{R}_K = \frac{\mathcal{B}(B^+\to K^+\mu^+\mu^-)}{\mathcal{B}(B^+\to K^+J/\psi(\to\mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+\to K^+e^+e^-)}{\mathcal{B}(B^+\to K^+J/\psi(\to e^+e^-))}$$

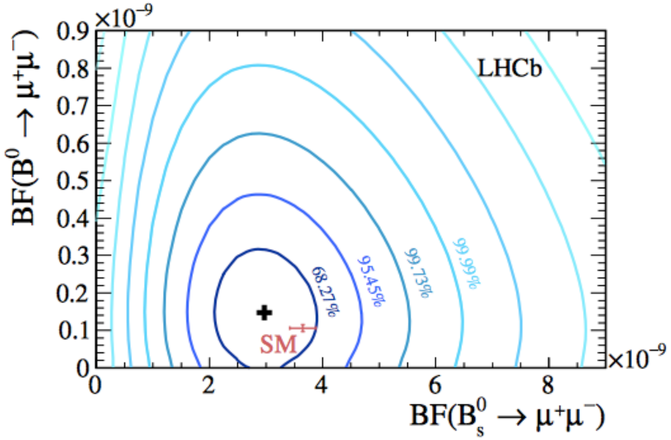


- PRL 113 (2014) 151601
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

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

$1\ \text{GeV}^2 < q^2 < 6\ \text{GeV}^2,$





LHCb arXiv:1705.03274

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

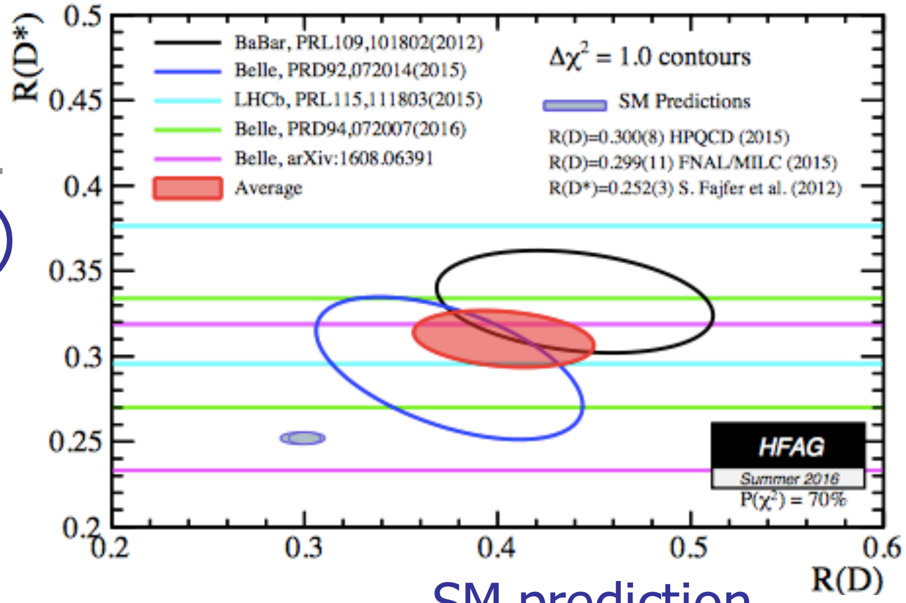
Combined effects are now about 4σ !

More

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

	$R(D)$	$R(D^*)$
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

4σ effects!



SM prediction

$$R(J/\psi) = \frac{B(B_c^+ \to J/\psi\tau^+\nu_\tau)}{B(B_c^+ \to J/\psi\mu^+\nu_\mu)} = 0.71 \pm 0.17 \pm 0.18$$

$$R(J/\psi) = 0.283 \pm 0.048$$

R. Aaij *et al.* [LHCb Collaboration], arXiv:1711.05623 [hep-ex]

R. Watanabe, arXiv:1709.08644 [hep-ph]

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

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

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

PDG

To solve these anomalies, one needs to go beyond SM.

Most of the models will come with additional Higgs bosons.

Higgs sector is the less known part of the SM.

May be a good place to look for new physics:

- Direct search at high energy colliders

- Precision measurements, such in flavor physics

2. Beyond SM Higgs Couplings to Fermions

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

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

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

There is no flavor changing Higgs interaction with fermions in the SM

When going beyond SM, there many ways to introduce FCNC Higgs interactions

Examples: Multi-Higgs doublet model, higher dimensional operators.

Model independent dimension 6 operators analysis

Grzadkowski, Iskrzynski, Misiak and Rosiek, JHEP 10(2010)085

At dimension 6 order, there are 59 independent operators. Only the ones on the right Higgs interacts with fermions.

Only the top 3 operators can generate tree level single Higgs interaction with fermions.

$\psi^2\varphi^3$	
$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$

$\psi^2\varphi^2 D$	
$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

General Higgs couplings to fermions

$$L_6 = -\frac{1}{\Lambda^2}(H^\dagger H)\bar{f}_L g_f H f_R \,, \rightarrow L_6 = -\frac{v^2}{2\sqrt{2}\Lambda^2}\bar{f}_L g_f v(1+3\frac{h}{v})f_R \,,$$

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

$$Y_f = \sqrt{2}\frac{M_f}{v} + (\delta Y_f + \delta Y_f^\dagger) \,, \;\; \tilde{Y}_f = -i(\delta Y_f - \delta Y_f^\dagger) \,, \;\; \delta Y = \frac{v^2}{2\Lambda^2}S_f^\dagger g_f T_f \,.$$

Or

$$\mathcal{L}_Y^f = -\frac{1}{\sqrt{2}}\bar{f}_L \bar{Y}_f f_R v - \frac{1}{\sqrt{2}}\bar{f}_L\left(\bar{Y}_f - \frac{v^2}{\Lambda^2}C_{fH}\right)f_R h + h.c. \,.$$

$$Y_l = \begin{pmatrix} Y_{ee} & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & Y_{\mu\mu} & Y_{\mu\tau} \\ Y_{\tau e} & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix}$$

$$\bar{Y}_f = Y_f - \frac{1}{2}\frac{v^2}{\Lambda^2}C_{fH} \,. \qquad Y_L = Y_R^\dagger$$

$$\bar{Y}_l = \begin{pmatrix} \bar{Y}_{ee} & \bar{Y}_{e\mu} & \bar{Y}_{e\tau} \\ \bar{Y}_{\mu e} & \bar{Y}_{\mu\mu} & \bar{Y}_{\mu\tau} \\ \bar{Y}_{\tau e} & \bar{Y}_{\tau\mu} & \bar{Y}_{\tau\tau} \end{pmatrix}$$

$$\mathcal{L}_Y = -\frac{1}{\sqrt{2}}\bar{f}(Y_L P_L + Y_R P_R) f h,$$

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

Minimal Flavor Violation
A Systematic way for organizing FCNC interactions

$$\bar{Y}_f = Y_f - \frac{1}{2}\frac{v^2}{\Lambda^2}C_{fH} .$$

is an arbitrary 3x3 matrix, many free parameters
May be all originate from minimal SM V_{KM}, V_{PMNS}
MFV hypothesis D'Ambrosio, Giudice, Isidori, Strumia, arXiv: 0207036

The MFV framework for quarks

L_K and L_m are formally invariant under a global group

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

$\mathrm{U}(3)_Q \times \mathrm{U}(3)_U \times \mathrm{U}(3)_D = G_q \times U(1)_Q \times U(1)_U \times U(1)_D$.

with $G_q = \mathrm{SU}(3)_Q \times \mathrm{SU}(3)_U \times \mathrm{SU}(3)_D$.

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

$Q_{i,L}$, $U_{i,R}$, 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

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

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

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

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

MFV: Only terms are singlet under G_q is allowed in the effective Largrangian

How to construct such terms?

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).

$\mathsf{A}_q = Y_u Y_u^\dagger$, $\mathsf{B}_q = Y_d Y_d^\dagger$, transforming as $(1 + \bar{8}, 1, 1)$

polynomials of A and B, which are denoted by $f(\mathsf{A}, \mathsf{B})$,

general forms of the $(\mathbf{3}, \bar{\mathbf{3}}, \mathbf{1})$ and $(\mathbf{3}, \mathbf{1}, \bar{\mathbf{3}})$ tensors are $f_u(\mathsf{A}, \mathsf{B}) Y_u$ and $f_d(\mathsf{A}, \mathsf{B}) Y_d$,

$C_{dH} = f_d(\mathsf{A}, \mathsf{B}) Y_d$ and $C_{uH} = f_u(\mathsf{A}, \mathsf{B}) Y_u$. allowed!

$f(\mathsf{A}, \mathsf{B}) = \sum_{ijk\ldots} \xi_{ijk\ldots} A^i B^j A^k \ldots$ infinite!

Cayley-Hamilton indentyt tfor 3x3 matrix,

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

Resume into 17 terms

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

For pratical analysis, the first two terms are sufficient.

$$f_u(\mathsf{A}, \mathsf{B}) \approx \epsilon_0^u \mathbb{1} + \epsilon_1^u \mathsf{A} + \epsilon_2^u \mathsf{A}^2 \quad \text{and} \quad f_d(\mathsf{A}, \mathsf{B}) \approx \epsilon_0^d \mathbb{1} + \epsilon_1^d \mathsf{A} + \epsilon_2^d \mathsf{A}^2 .$$

$$\bar{Y}_f = Y_f - \frac{1}{2}\frac{v^2}{\Lambda^2}C_{fH}$$

Previous one $$C_{dH} = \left[\epsilon_0^u \mathbb{1} + \epsilon_1^u Y_u Y_u^\dagger + \epsilon_2^u (Y_u Y_u^\dagger)^2\right] Y_d$$

Redefined to be $$C_{dH} = \left[\epsilon_0^u \mathbb{1} + \epsilon_1^u \bar{Y}_u \bar{Y}_u^\dagger + \epsilon_2^u (\bar{Y}_u \bar{Y}_u^\dagger)^2\right] \bar{Y}_d + \mathcal{O}(v^2/\Lambda^2)$$

$$\mathcal{L}_Y^d = -\frac{1}{\sqrt{2}}\bar{d}_L\left[(1-\hat{\epsilon}_0^d)\lambda_d - \hat{\epsilon}_1^d V^\dagger \lambda_u^2 V \lambda_d\right] d_R h + h.c.\,,$$

$$\mathcal{L}_Y^u = -\frac{1}{\sqrt{2}}\bar{u}_L(1-\hat{\epsilon}_0^u)\lambda_u u_R h + h.c.\,.$$

These are the leading Higgs flavor couplings in MFV

MFV for the lepton sector

Cirigliano, Grinstein, Isidori, arXiv:0507001

the global group is $U(3)_L \times U(3)_\nu \times U(3)_E = G_\ell \times U(1)_L \times U(1)_\nu \times U(1)_E$ with $G_\ell = SU(3)_L \times SU(3)_\nu \times SU(3)_E$.

$L_{i,L}$, $\nu_{i,R}$, 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.

$$-(Y_e)_{jk}\,\overline{L_j}P_R E_k H - (Y_\nu)_{jk}\,\overline{L_j}P_R N_k \tilde{H} - \tfrac{1}{2}(M_N)_{jk}\,\overline{(N_j)^c}P_R N_k$$

$$Y_\nu \sim (3,\bar{3},1) \text{ and } Y_e \sim (3,1,\bar{3})$$

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

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

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

O offers a potentially important new source of CP violation.

$$\mathcal{L}_Y^\ell = -\frac{1}{\sqrt{2}}\bar{\ell}_L\left[(1-\hat{\epsilon}_0^\ell)\lambda_\ell - \hat{\epsilon}_1^\ell \mathsf{A}_\ell \lambda_\ell - \hat{\epsilon}_2^\ell \mathsf{A}_\ell^2 \lambda_\ell\right]\ell_R h$$

The most general leading order Higgs couplings to quarks and charged leptons are

$$\mathcal{L}_Y = -\frac{1}{\sqrt{2}}\bar{f}(Y_L P_L + Y_R P_R) f h, \qquad Y_L = Y_R^\dagger$$

Y_L are arbitrary 3x3 matrices

With MFV the leading order Higgs couplings are

$$Y_R^d = (1 - \hat{\epsilon}_0^d)\lambda_d - \hat{\epsilon}_1^d V^\dagger \lambda_u^2 V \lambda_d \,,$$

$$Y_R^u = (1 - \hat{\epsilon}_0^u)\lambda_u \,,$$

$$Y_R^\ell = (1 - \hat{\epsilon}_0^\ell)\lambda_\ell - \hat{\epsilon}_1^\ell \mathsf{A}_\ell \lambda_\ell - \hat{\epsilon}_2^\ell \mathsf{A}_\ell^2 \lambda_\ell$$

Relevant processes to be discussed,

constraints and predictions

$B_s - \bar{B}_s$, $B_d - \bar{B}_d$ and $K^0 - \bar{K}^0$ $\quad \ell_i \to \ell_j \gamma$ and $\mu - e$ conversion

OBSERVABLE	SM	EXP
$\mathcal{B}(h \to e\mu)$	-	$< 3.5 \times 10^{-4}$
$\mathcal{B}(h \to e\tau)$	-	$< 6.1 \times 10^{-3}$
$\mathcal{B}(h \to \mu\tau)$	-	$< 2.5 \times 10^{-3}$
$\mathcal{B}(\mu \to e\gamma)$	-	$< 4.2 \times 10^{-13}$
$\mathcal{B}(\tau \to e\gamma)$	-	$< 3.3 \times 10^{-8}$
$\mathcal{B}(\tau \to \mu\gamma)$	-	$< 4.4 \times 10^{-8}$
$\mathcal{B}(\mu \to eee)$	-	$< 1.0 \times 10^{-12}$
$\mathcal{B}(\tau \to eee)$	-	$< 2.7 \times 10^{-8}$
$\mathcal{B}(\tau \to \mu\mu\mu)$	-	$< 2.1 \times 10^{-8}$
$\mathcal{B}(\mu\mathrm{Au} \to e\mathrm{Au})$	-	$< 7.0 \times 10^{-13}$

$B_{s,d} \to \ell_1 \ell_2 \quad B_{s,d} \to \ell_1 \ell_2$

Experimental data

$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)[10^{-9}]$	3.43 ± 0.19	3.1 ± 0.7
$\Delta m_d[\mathrm{ps}^{-1}]$	$0.607^{+0.075}_{-0.075}$	0.5064 ± 0.0019
$\Delta m_s[\mathrm{ps}^{-1}]$	$19.196^{+1.377}_{-1.341}$	17.757 ± 0.021
$\phi_s[\mathrm{rad}]$	$-0.042^{+0.003}_{-0.003}$	-0.021 ± 0.031
$\Delta m_K[10^{-3}\,\mathrm{ps}^{-1}]$	4.40 ± 1.77	5.293 ± 0.009
$\lvert\varepsilon_K\rvert[10^{-3}]$	2.10 ± 0.30	2.228 ± 0.011

Input parameters

Input	Value	Unit
$\alpha_s^{(5)}(m_Z)$	0.1181 ± 0.0011	
m_t^{P}	173.1 ± 0.9	GeV
$\lvert V_{cb}\rvert$ (semi-leptonic)	$41.00 \pm 0.33 \pm 0.74$	10^{-3}
$\lvert V_{ub}\rvert$ (semi-leptonic)	$3.98 \pm 0.08 \pm 0.22$	10^{-3}
$\lvert V_{us}\rvert f_+^{K\to\pi}(0)$	0.2165 ± 0.0004	
γ	$72.1^{+5.4}_{-5.8}$	[°]
$f_+^{K\to\pi}(0)$	$0.9681 \pm 0.0014 \pm 0.0022$	

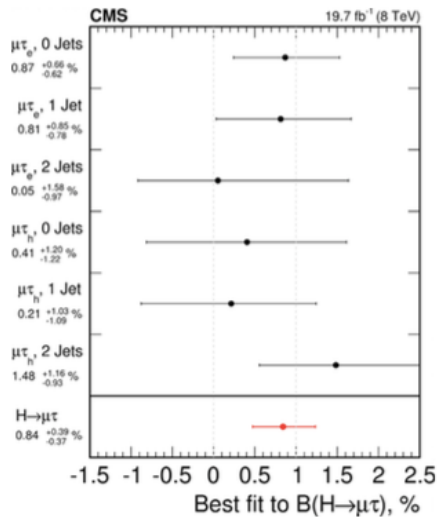
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$ $(0.554^{+0.023}_{-0.033})$	
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$ $(0.02227^{+0.00074}_{-0.00074})$	
δ_{CP}	234^{+43}_{-31} (278^{+26}_{-29})	[°]
Δm^2_{21}	$7.40^{+0.21}_{-0.20}$	$10^{-5}\,\mathrm{eV}^2$
$\Delta m^2_{3\ell}$	$+2.494^{+0.033}_{-0.031}$ $(-2.465^{+0.032}_{-0.031})$	$10^{-3}\,\mathrm{eV}^2$
f_{B_s}	228.4 ± 3.7	MeV
f_{B_d}	192.0 ± 4.3	MeV
$f_{B_s}\sqrt{\hat{B}_s}$	274 ± 8	MeV
$f_{B_d}\sqrt{\hat{B}_d}$	225 ± 9	MeV
$1/\Gamma_s^{\mathrm{H}}$	1.609 ± 0.010	ps
$\Delta\Gamma_s/\Gamma_s$	0.128 ± 0.009	

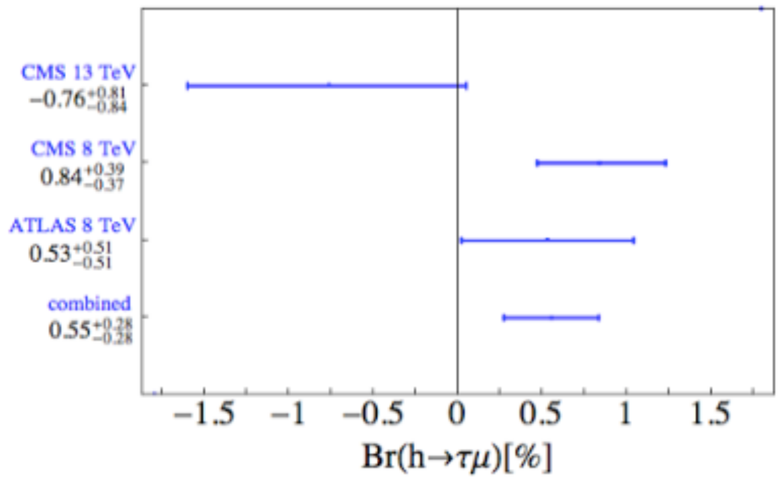
3. Flavor Violating Higgs Interaction without MFV

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

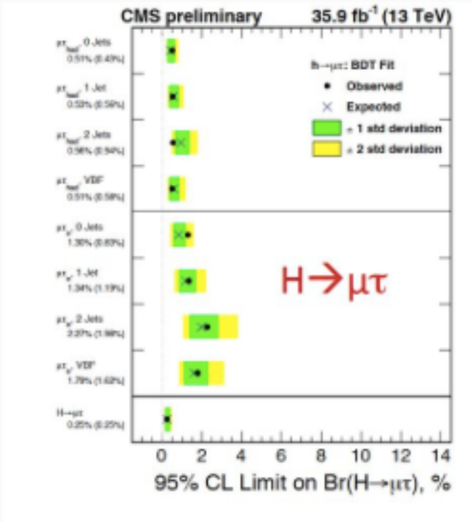
With the new CMS result

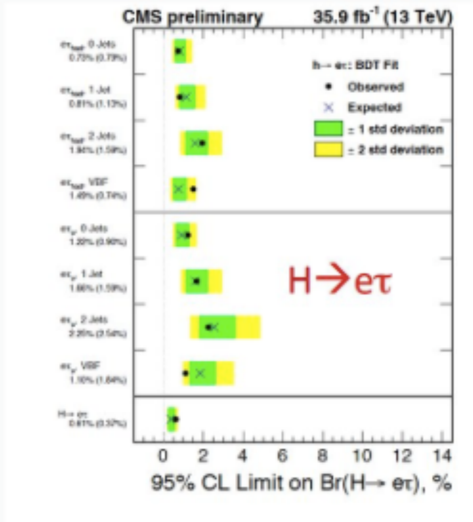
Channel	Coupling	95% CL Limit Pre-LHC	95% CL Limit CMS	95% CL Limit ATLAS
H→ μe	$\sqrt{\lvert Y_{\mu e}\rvert^2 + \lvert Y_{e\mu}\rvert^2}$	$3.6 \cdot 10^{-6}$	$5.4 \cdot 10^{-4}$	-
H→ $\mu\tau$	$\sqrt{\lvert Y_{\mu\tau}\rvert^2 + \lvert Y_{\tau\mu}\rvert^2}$	0.016	**0.00316**	0.0035
H→ $e\tau$	$\sqrt{\lvert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

$$\mathcal{B}(h \to e\mu) < 3.5 \times 10^{-4}$$

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

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

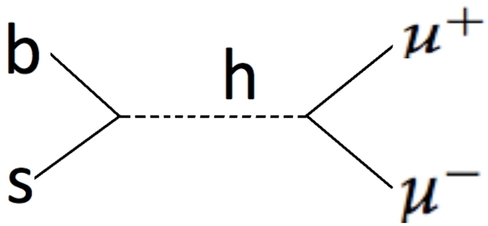
$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.43 \times 10^{-3}$$

$$\sqrt{|Y_L^{e\tau}|^2 + |Y_R^{e\tau}|^2} < 3.0 \times 10^{-3}$$

$$\sqrt{|Y_L^{e\mu}|^2 + |Y_R^{e\mu}|^2} < 7.2 \times 10^{-4}$$

Higgs contribution to $B_s \to \mu^+\mu^-$ and Bs-antiBs mixing

$$\mathcal{H}_{\rm eff} = -\frac{G_F}{\sqrt{2}}\frac{\alpha_{em}}{\pi s_W^2} V_{tb}V_{ts}^* \left(C_A\mathcal{O}_A + C_S\mathcal{O}_S + C_P\mathcal{O}_P + C_S'\mathcal{O}_S' + C_P'\mathcal{O}_P'\right)$$



$$\mathcal{O}_A = (\bar{q}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu\gamma_5\mu)\ , \quad \mathcal{O}_S = m_b(\bar{q}P_R b)(\bar{\mu}\mu)\ , \quad \mathcal{O}_P = m_b(\bar{q}P_R b)(\bar{\mu}\gamma_5\mu)\ ,$$

$$\mathcal{O}_S' = m_b(\bar{q}P_L b)(\bar{\mu}\mu)\ , \quad \mathcal{O}_P' = m_b(\bar{q}P_L b)(\bar{\mu}\gamma_5\mu)\ ,$$

$$C_A^{\rm SM}(\mu_b) = -0.4690\left(\frac{m_t^{\rm P}}{173.1\ {\rm GeV}}\right)^{1.53}\left(\frac{\alpha_s(m_Z)}{0.1184}\right)^{-0.09}$$

$$\kappa = \frac{\pi^2}{2G_F^2}\frac{1}{V_{tb}V_{ts}^*}\frac{1}{m_b m_h^2 m_W^2}\ .$$

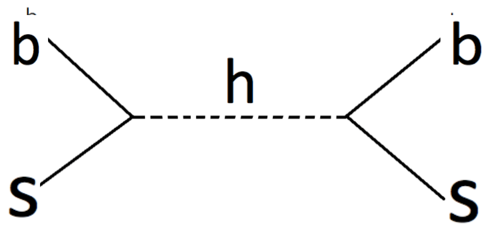
$$C_S^{\rm NP} = \kappa(Y_{sb} + i\bar{Y}_{sb})Y_{\mu\mu}\ , \qquad C_P^{\rm NP} = i\kappa(Y_{sb} + i\bar{Y}_{sb})\bar{Y}_{\mu\mu}\ ,$$

$$C_S'^{\rm NP} = \kappa(Y_{sb} - i\bar{Y}_{sb})Y_{\mu\mu}\ , \qquad C_P'^{\rm NP} = i\kappa(Y_{sb} - i\bar{Y}_{sb})\bar{Y}_{\mu\mu}\ ,$$

$$P \equiv C_A + \frac{m_{B_s}^2}{2m_\mu}\left(\frac{m_b}{m_b + m_s}\right)(C_P - C_P')\ ,$$

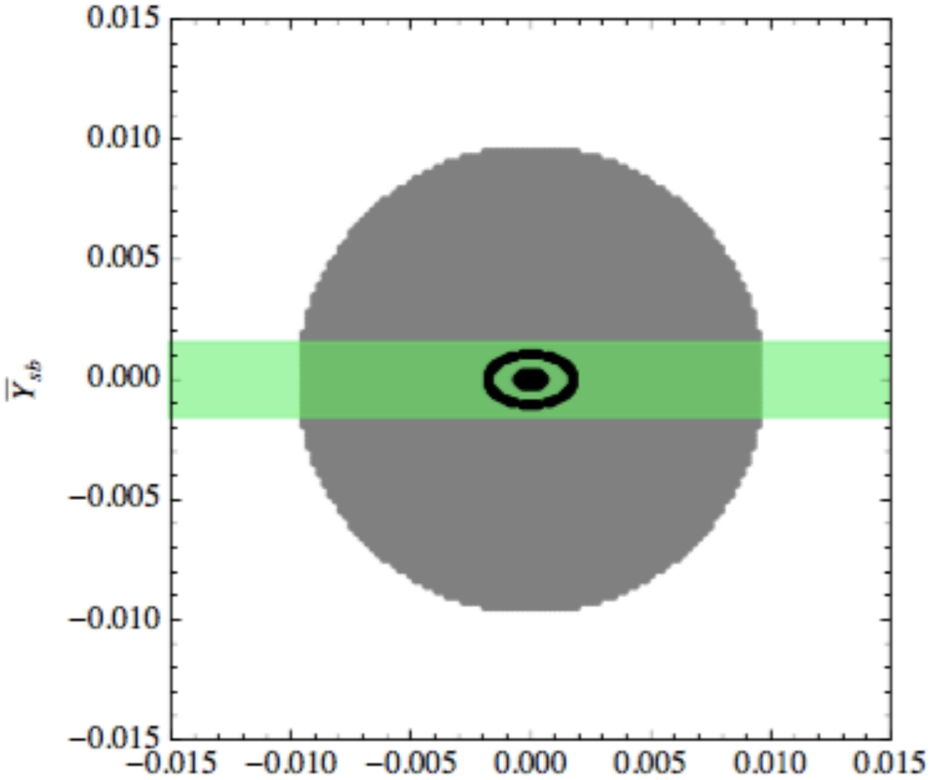
$$S \equiv \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}}\frac{m_{B_s}^2}{2m_\mu}\left(\frac{m_b}{m_b + m_s}\right)(C_S - C_S')\ .$$

Constraint from B_s –antiB_s mixing



Constraints

Predictions



$$\frac{\mathcal{B}(B_s \to \ell_1 \ell_2)}{\mathcal{B}(h \to \ell_1 \ell_2)} \approx 2.1 |\bar{Y}_{sb}|^2$$

$$\Gamma(h \to sb) < 0.17\,\mathrm{MeV}$$

$$\mathcal{B}(B_s \to e\mu) < 2.1 \times 10^{-9}$$

$$\mathcal{B}(B_s \to e\tau) < 3.7 \times 10^{-8}$$

$$\mathcal{B}(B_s \to \mu\tau) < 1.5 \times 10^{-8}$$

FIG. 1: Allowed region of $(Y_{sb}, \bar{Y}_{sb})$, assuming real Y_{sb} and $\bar{Y}_{sb}$ couplings. The black region corresponds to the allowed space by $B_s - \bar{B}_s$ mixing. The green region is allowed by $\mathcal{B}(B_s \to \mu^+\mu^-)$ with the assumption $(Y_{\mu\mu}, \bar{Y}_{\mu\mu}) = (Y_{\mu\mu}^{\mathrm{SM}}, 0)$. In the dark region, $\Gamma(h \to sb) < 1.4\,\mathrm{MeV}$.

$\mathcal{B}(h \to \text{new}) < 34\%$ at 95%CL

l_i -> l_j γ

$$\Gamma(\ell_i \to \ell_j \gamma) = \frac{\alpha_e m_i^5}{64\pi^4}(|c_L|^2 + |c_R|^2)$$

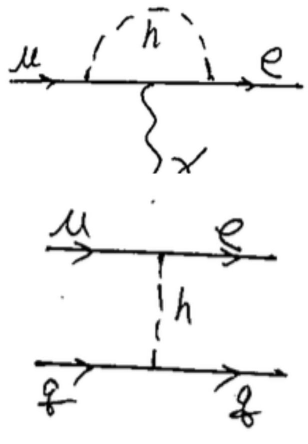
$$c_L^{1-\text{loop}} = \sum_{f=e,\mu,\tau} F(m_i, m_f, m_j, 0, Y), \quad c_R^{1-\text{loop}} = \sum_{f=e,\mu,\tau} F(m_i, m_f, m_j, 0, Y^\dagger),$$

$$F(m_i, m_f, m_j, q^2, Y) = \frac{1}{8m_i}\int_0^1 dx dy dz \delta(1-x-y-z) \; \frac{xzm_j Y_R^{jf} Y_L^{fi} + yzm_i Y_L^{jf} Y_R^{fi} + (x+y)m_f Y_L^{jf} Y_L^{fi}}{zm_h^2 - xzm_j^2 - yzm_i^2 + (x+y)m_f^2 - xyq^2}$$

$$c_L^{2-\text{loop}} \approx \frac{1}{\sqrt{2}m_h^2}\frac{m_\tau}{m_i} Y_L^{ji}(-0.058 Y_R^{tt} + 0.11),$$

$$c_R^{2-\text{loop}} \approx \frac{1}{\sqrt{2}m_h^2}\frac{m_\tau}{m_i} Y_R^{ji}(-0.058 Y_R^{tt} + 0.11),$$

μ – e conversions



$$\mathcal{B}(\mu N \to eN) = \frac{\Gamma(\mu N \to eN)}{\Gamma_{\text{capt.}\,N}},$$

$$\Gamma_{\text{capt. Au}} = 1.307 \times 10^7\,\text{s}^{-1}$$

$$\Gamma_{\text{capt. Al}} = 7.054 \times 10^5\,\text{s}^{-1}$$

$$\Gamma(\mu N \to eN) = \left| -\frac{e}{16\pi^2} c_R D + \tilde{g}_{LS}^{(p)} S^{(p)} + \tilde{g}_{LS}^{(n)} S^{(n)} + \tilde{g}_{LV}^{(p)} V^{(p)} \right|^2.$$

$$\tilde{g}_{LS,RS}^{(p)} = \sum_q g_{LS,RS}^q \frac{m_p}{m_q} f^{(q,p)}, \qquad \tilde{g}_{LS,RS}^{(n)} = \sum_q g_{LS,RS}^q \frac{m_n}{m_q} f^{(q,n)},$$

$$f^{(u,p)} = f^{(d,n)} = 0.024,$$

$$f^{(d,p)} = f^{(u,n)} = 0.033,$$

$$f^{(s,p)} = f^{(s,n)} = 0.25.$$

$$(D, V^{(p)}, S^{(p)}, S^{(n)}) = \begin{cases} 0.1890, 0.0974, 0.0614, 0.0167 & \text{for Au}, \\ 0.0362, 0.0161, 0.0155, 0.0918 & \text{for Al}, \end{cases}$$

$$g^q_{LS} = -\frac{1}{m_h^2} Y_R^{e\mu} \mathrm{Re}(Y_R^{qq}), \qquad g^q_{RS} = -\frac{1}{m_h^2} Y_L^{e\mu} \mathrm{Re}(Y_R^{qq}).$$

$$g^q_{LV} = -\frac{\alpha_e Q_q}{2\pi q^2} \sum_{f=e,\mu,\tau} [G(m_\mu, m_f, m_e, q^2, Y) - G(m_\mu, m_f, m_e, 0, Y)],$$

$$G(m_i, m_f, m_j, q^2, Y) = \int_0^1 dx \int_0^{1-x} dy \Big\{ + Y_R^{jf} Y_L^{fi} \log\Delta - \frac{1}{\Delta}(m_i m_j z^2 Y_L^{jf} Y_R^{fi}) - \frac{1}{\Delta}\Big[m_f m_j z Y_L^{jf} Y_L^{fi} + m_f m_i z Y_R^{jf} Y_R^{fi} + (q^2 xy + m_f^2) Y_R^{jf} Y_L^{fi} \Big] \Big\}$$

$$\Delta \equiv z m_h^2 - xz m_j^2 - yz m_i^2 + (x+y) m_f^2 - xyq^2 \text{ and } z \equiv 1 - x - y.$$

μ to e γ and μ – e conversion constrain the couplings will discuss related next section when discussing constraints with MFV.
The general case has some unknown parameters at two loop.

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)

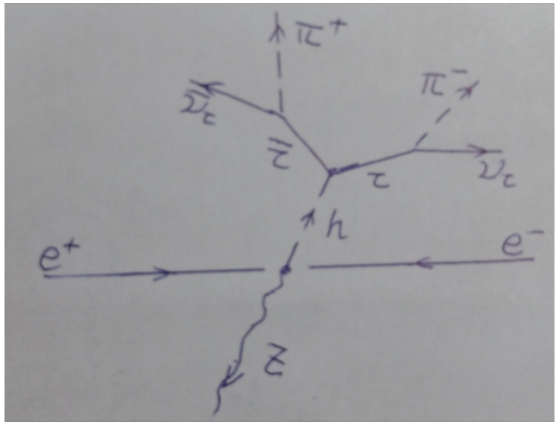
$$L_Y = -\bar{L}_L[y\frac{v}{\sqrt{2}} + (y+\delta y)\frac{h}{\sqrt{2}}]E_R$$

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

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

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

one can construct T odd operator $O_\pi = \vec{p}_\tau \cdot (\vec{p}_\pi^{\,+} \times \vec{p}_\pi^{\,-})$, Br(h ->ττ) ~ 5×10^{-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))

4. Flavor Violating Higgs Interaction with MFV

The most general leading order couplings to quarks and charged leptons are

$$\mathcal{L}_Y = -\frac{1}{\sqrt{2}}\bar{f}(Y_L P_L + Y_R P_R) f h, \qquad Y_L = Y_R^\dagger$$

Y_L are arbitrary 3x3 matrices

With MFV the leading order Higgs couplings are

$$Y_R^d = (1-\hat{\epsilon}_0^d)\lambda_d - \hat{\epsilon}_1^d V^\dagger \lambda_u^2 V \lambda_d\,,$$

$$Y_R^u = (1-\hat{\epsilon}_0^u)\lambda_u\,,$$

$$Y_R^\ell = (1-\hat{\epsilon}_0^\ell)\lambda_\ell - \hat{\epsilon}_1^\ell \mathsf{A}_\ell \lambda_\ell - \hat{\epsilon}_2^\ell \mathsf{A}_\ell^2 \lambda_\ell$$

$$\left(\epsilon_0^u,\ \epsilon_0^d,\ \epsilon_1^d,\ \epsilon_0^\ell,\ \epsilon_1^\ell,\ \epsilon_2^\ell\right)$$

$$\text{Scenario I}: -0.5 < \epsilon_{0,1,2}^\ell < +0.5$$

$$\epsilon_0^u = \epsilon_0^d = 0$$

$$\text{Scenario II}: -1.0 < \epsilon_{0,1,2}^\ell < +1.0$$

$$-1.0 < \epsilon_0^u < +1.0$$

$$-1.0 < \epsilon_0^d < +1.0$$

Scenario I the quark sector is the same as in the SM. Scenario II is general case.

Higgs couplings to quarks

Flavor conserving constraint
from Higgs properties global fit

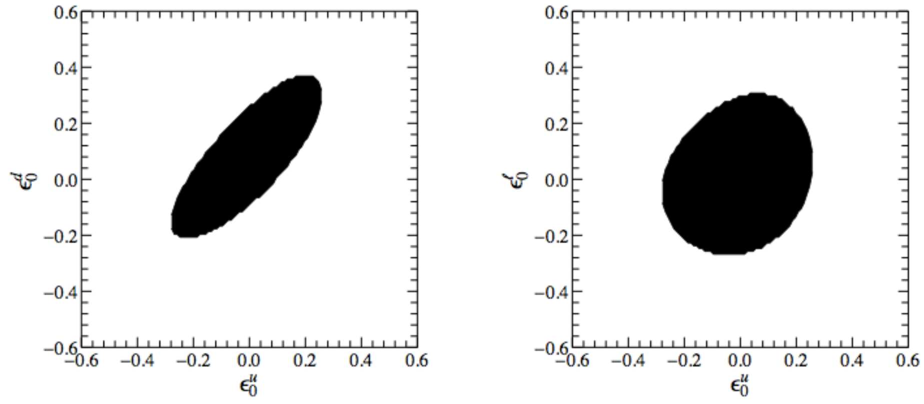


FIG. 2: Allowed region of $(\epsilon_0^u, \epsilon_0^d, \epsilon_0^\ell)$ by the LHC Higgs data at 90% CL, plotted in the $(\epsilon_0^u, \epsilon_0^d)$ (left) and $(\epsilon_0^u, \epsilon_0^\ell)$ (right) plane.

$B_s - \bar{B}_s$, $B_d - \bar{B}_d$ and $K^0 - \bar{K}^0$ mixing. Constrain FCNC

$B_s - \bar{B}_s$: Constrain FCNC the strongest with $|\epsilon_1^d| < 0.59$.

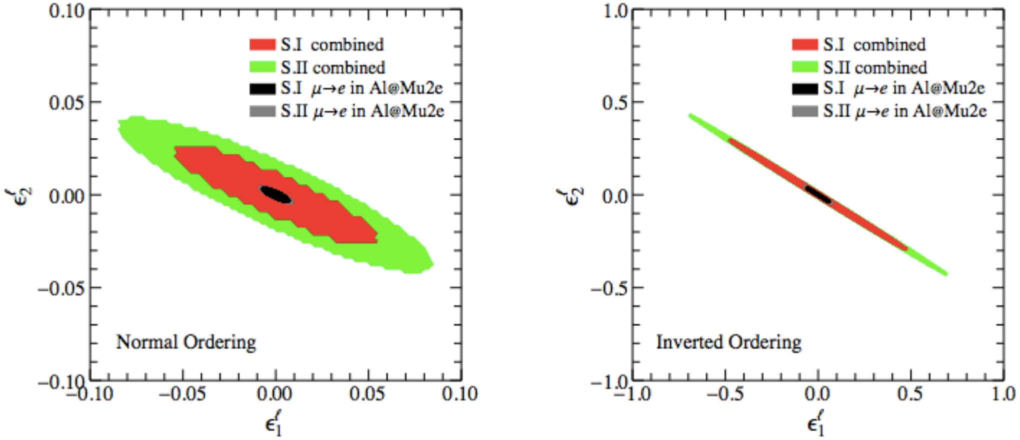
Predictions:

$$\Gamma(h \to sd) < 7.4 \times 10^{-11}\ \mathrm{MeV},$$

$$\Gamma(h \to sb) < 2.0 \times 10^{-3}\ \mathrm{MeV},$$

$$\Gamma(h \to db) < 9.4 \times 10^{-5}\ \mathrm{MeV},$$

μ to e γ and μ – e conversion constraints



Combined=Data from MEG II
μ to e γ
and
Au μ – e conversion constraints

FIG. 3: Combined constraints at 95% CL, plotted in $(\epsilon_1^\ell, \epsilon_2^\ell)$ plane, in the NO (Left) and IO (Right) cases. The black and gray regions are the allowed parameter space in Scenario. I and II, respectively. The tiny black and gray regions indicate the future constraints from the $\mu \to e$ conversion in Al at Mu2e experiment.

Current Au μ – e conversion data weaker than MEG II μ to e γ .

But future Al data will provide much better constraints.

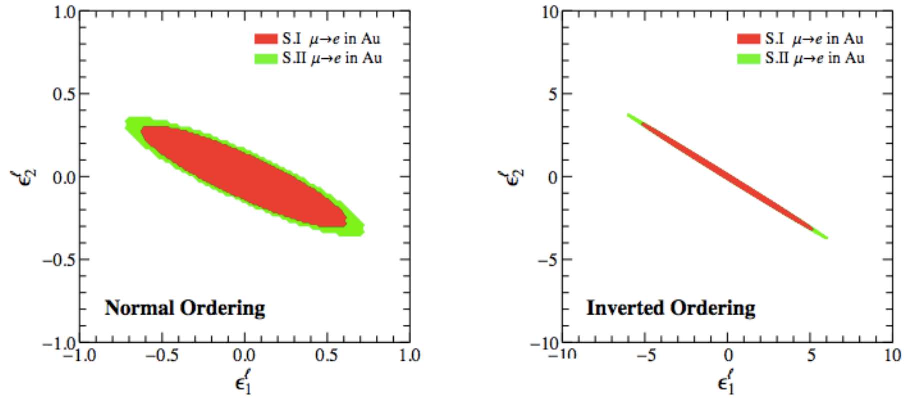
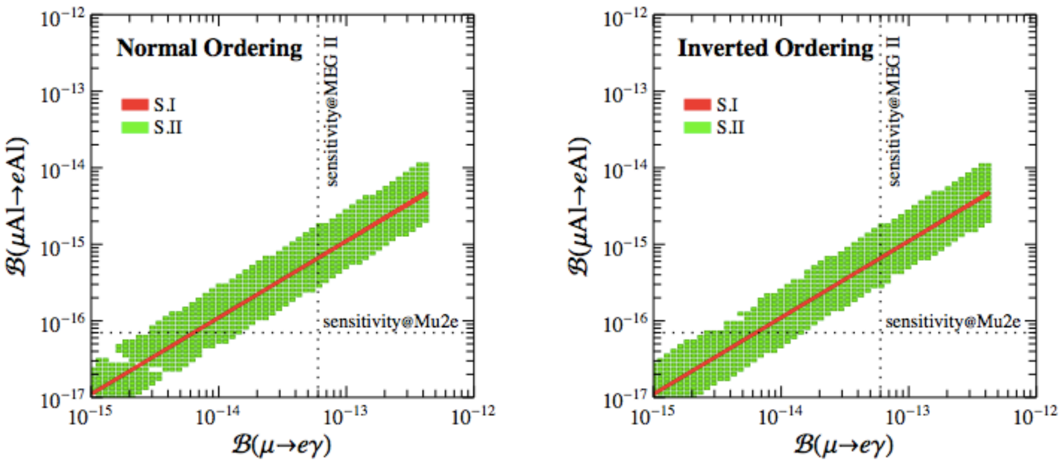


FIG. 4: The same as Fig. 3, but only under the constraint of $\mu \to e$ conversion in Au.

Predictions

		$\Gamma(h \to e\mu)$	$\Gamma(h \to e\tau)$	$\Gamma(h \to \mu\tau)$	$\mathcal{B}(B_s \to e\mu)$	$\mathcal{B}(B_s \to e\tau)$	$\mathcal{B}(B_s \to \mu\tau)$
NO	S.I	1.2×10^{-8}	1.3×10^{-5}	9.0×10^{-5}	2.4×10^{-16}	2.6×10^{-13}	1.8×10^{-12}
NO	S.II	2.2×10^{-8}	2.4×10^{-5}	1.7×10^{-4}	4.6×10^{-16}	5.0×10^{-13}	3.5×10^{-12}
IO	S.I	1.2×10^{-8}	4.7×10^{-6}	7.1×10^{-5}	2.4×10^{-16}	9.6×10^{-14}	1.4×10^{-12}
IO	S.II	2.2×10^{-8}	8.7×10^{-6}	1.3×10^{-4}	4.5×10^{-16}	1.8×10^{-13}	2.6×10^{-12}

TABLE III: Upper bounds on $\Gamma(h \to \ell_i \ell_j)$ [MeV] and $\mathcal{B}(B_s \to \ell_i \ell_j)$ at 90%CL.



5. Conclusions

Higgs property studies is entering "precision" measurement era.
Recent LHC searches for Bs → $l_1 l_2$ and h → $l_1 l_2$, has interesting implications for Higgs FCNC interactions with fermions.

With and without the MFV hypothesis, we investigate effects on B_s – antiB_s, B_d – antiB_d and K^0 – antiK^0 mixing, $l_i \to l_j$ g, and μ → e conversion

Without MFV (assuming 4 MeV for Higgs width) With MFV

$$\mathcal{B}(h \to sb) < 4.1 \times 10^{-2},$$

$$\frac{\mathcal{B}(B_s \to \ell_1 \ell_2)}{\mathcal{B}(h \to \ell_1 \ell_2)} \approx 2.1 |\bar{Y}_{sb}|^2,$$

$$\mathcal{B}(h \to sb) < 4.9 \times 10^{-4},$$

$$\mathcal{B}(h \to \mu\tau) < 4.2\,(3.2) \times 10^{-5},$$

$$\mathcal{B}(B_s \to e\mu) < 2.1 \times 10^{-9},$$

$$\mathcal{B}(B_s \to e\mu) < 4.6\,(4.5) \times 10^{-16},$$

μ-e conversion future Al data will provide very strong constraints.

More precise data can tell more