Structure of Yukawa couplings and prospects for Higgs flavour physics era

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CERN

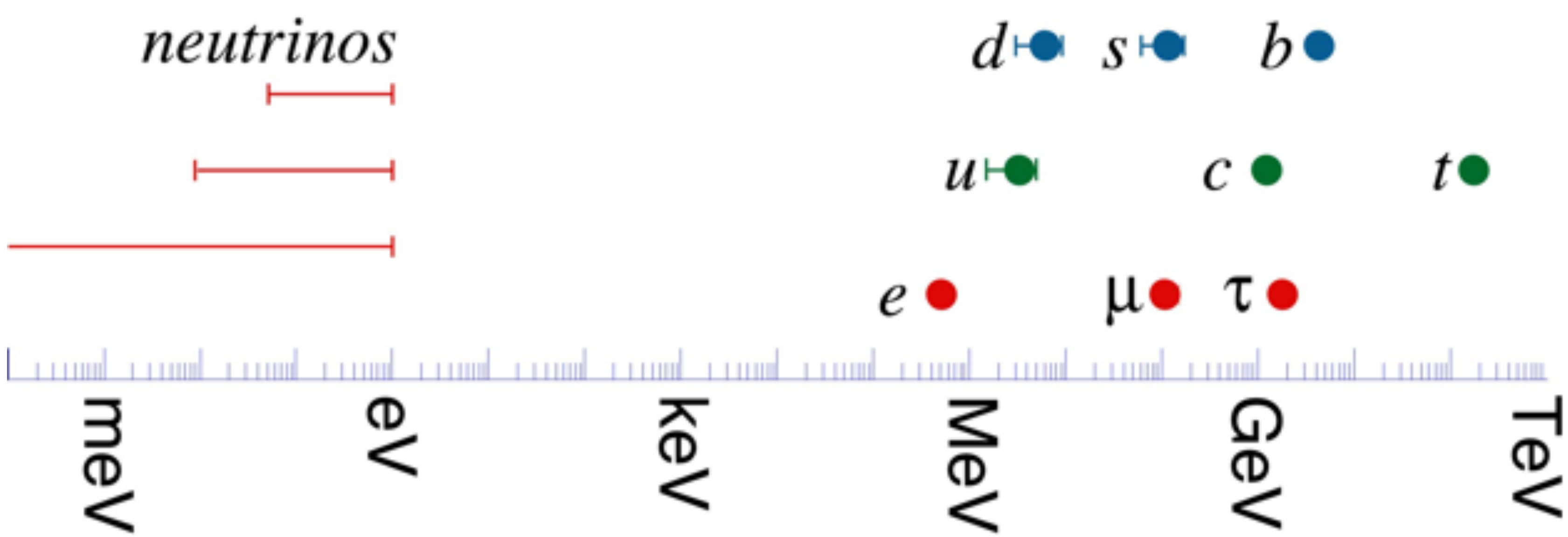
31 March 2017, Current Trends in Flavour Physics, Paris

Outline

- Structure of the Yukawa couplings
  1. Flavour Symmetries
  2. Dynamics (Partial Compositeness)
- Higgs Flavour Physics (@ LHC)
- Conclusions

Standard Model Flavour Puzzle

- Why this pattern of masses (and mixing)?



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  1. Radiative stability
  2. Setting the values (theoretical prejudice: O(1) couplings)

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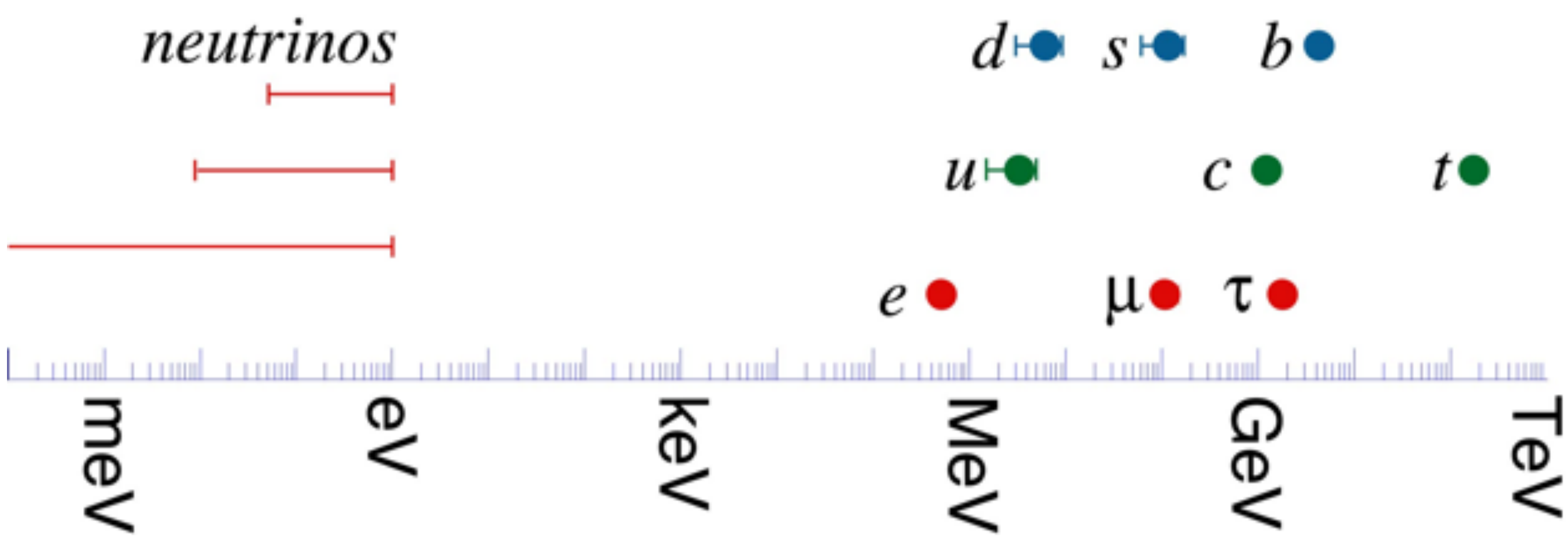

- Understanding the hierarchy requires to address two issues

1. Radiative stability
2. Setting the values (theoretical prejudice: O(1) couplings)

- Stability of the Yukawa coupling is guaranteed by symmetries

"We conjecture that the following dogma should be followed: at any scale M, a physical parameter a(M) is allowed to be very small if the replacement a(M)=0 would increase the symmetry of the system"

[G. 't Hooft, Proceedings NATO, 1980]

Standard Model Flavour Puzzle

- Indeed in the SM:

$$\mathcal{L}_{SM} = \mathcal{L}_{\rm kin} + V(H) + \mathcal{L}_{\rm Yukawa}$$

$$\mathcal{L}_{\rm Yukawa} = Y^U_{ij}\, \overline{Q}^i_L U^j_R H + Y^D_{ij}\, \overline{Q}^i_L D^j_R \tilde{H} + Y^E_{ij}\, \overline{L}^i_L E^j_R \tilde{H} + {\rm h.c.}$$

- Global symmetry: $U(1)_e \times U(1)_\mu \times U(1)_\tau \times U(1)_B$

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- Switching off the Yukawa $Y_U, Y_D, Y_E \to 0$

$$\mathcal{L}_{\rm kin} \supset \sum_f i f^\dagger \sigma^\mu D_\mu f$$ invariant under $U(3)^5$

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- A possible approach to the SM Flavour Problem: don't do anything

- More ambitious: understand this pattern in theories with parameters of the same size

Froggatt-Nielsen mechanism

- There is an Abelian symmetry that distinguishes the different families
- A scalar field (the flavon) is responsible for the spontaneous symmetry breaking of this symmetry
- An example with the 2HDM (adapted from 1605.00433)

$$\begin{aligned} H(\bar{Q}_i) &= H(U_i) = H(E_i) = (2,1,0), \\ H(\bar{L}_i) &= H(D_i) = (0,0,0), \end{aligned}$$

$$H(\phi) = -1$$

$$\mathcal{L} \supset c_{ij}^U \left(\frac{\phi}{M}\right)^{H(\bar{Q}_i)+H(U_j)} \overline{Q}_L^i U_R^j H_u + \ldots$$

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- Afters spontaneous symmetry breaking $\epsilon \equiv \dfrac{\langle\phi\rangle}{M} = 0.05$

$$Y^u \sim \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix}, \quad Y^d \sim (Y^e)^T \sim \begin{pmatrix} \epsilon^2 & \epsilon^2 & \epsilon^2 \\ \epsilon & \epsilon & \epsilon \\ 1 & 1 & 1 \end{pmatrix}$$

$$\begin{aligned} Y_t &\sim 1, \quad Y_c \sim \epsilon^2, \quad Y_u \sim \epsilon^4, \\ Y_b &\sim 1, \quad Y_s \sim \epsilon, \quad Y_d \sim \epsilon^2, \\ Y_\tau &\sim 1, \quad Y_\mu \sim \epsilon, \quad Y_e \sim \epsilon^2, \\ |V_{us}| &\sim \epsilon, \quad |V_{cb}| \sim \epsilon, \quad |V_{ub}| \sim \epsilon^2, \quad \delta_{\mathrm{KM}} \sim 1. \end{aligned}$$

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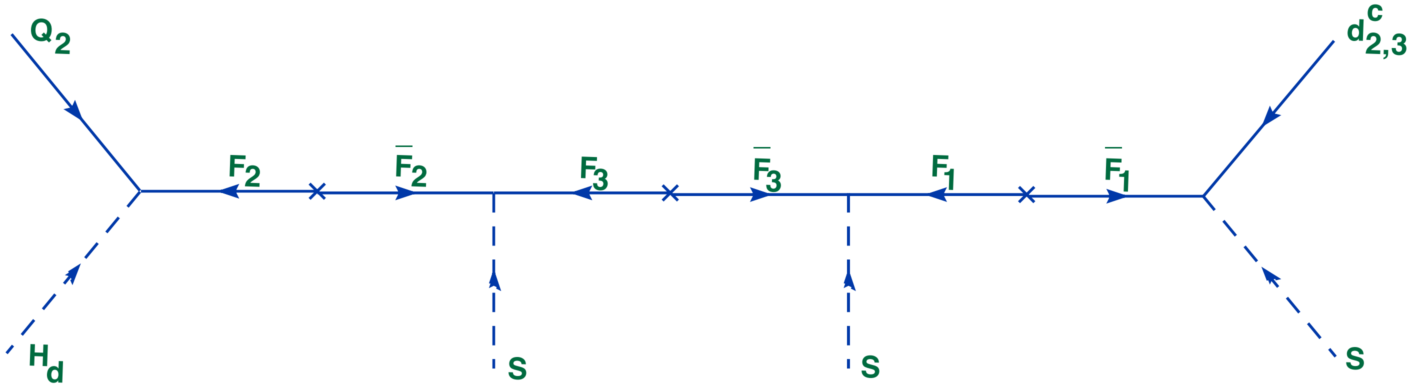
- all parameters are natural O(1)
- How to test this idea?

Froggatt-Nielsen mechanism



- The dream: directly probe the flavon interactions at the scale M

- Physics of fermion and gauge mediators

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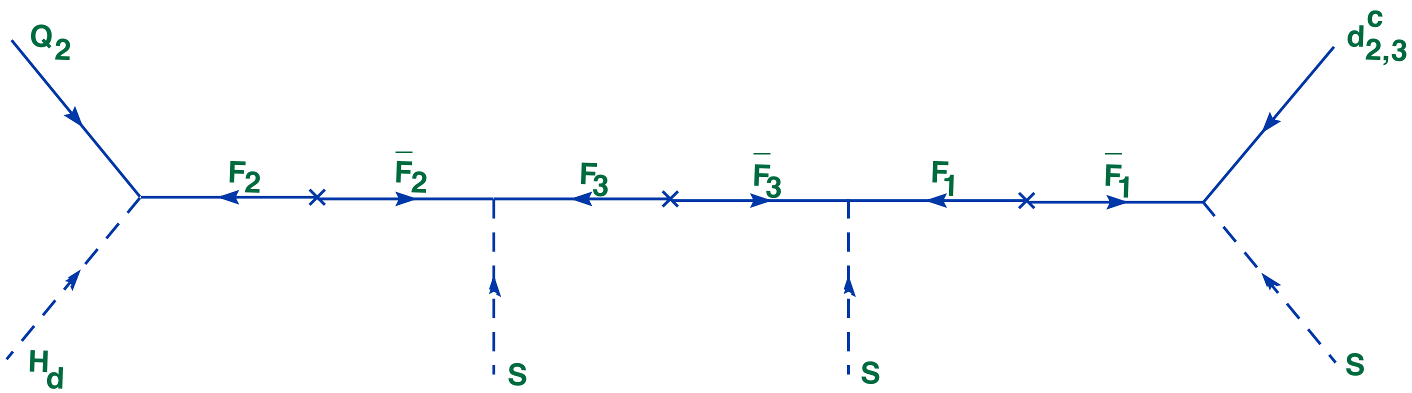

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• However possible effects in other flavour observables (analysis with spurions)

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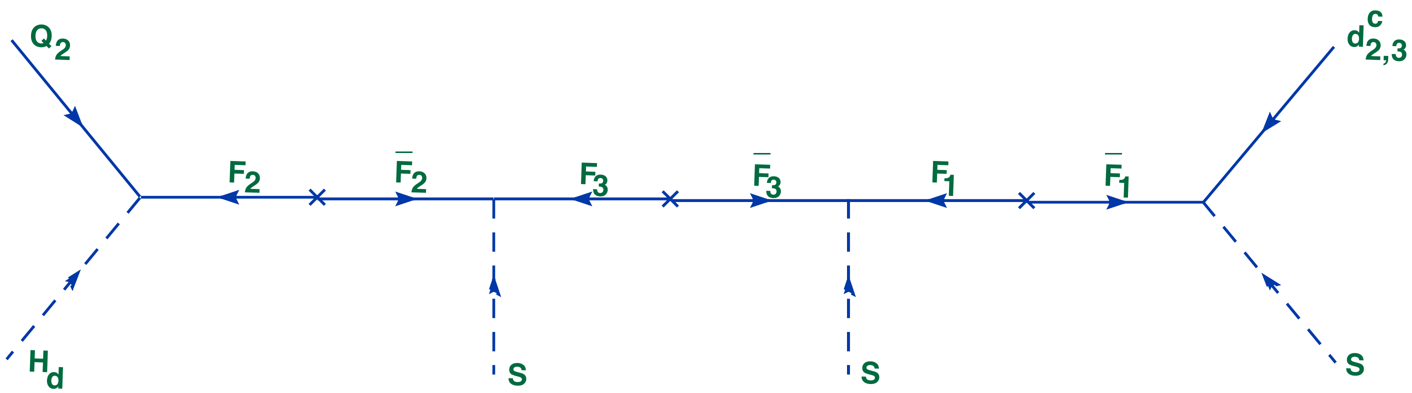

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- Deviation from the Standard Model prediction in Higgs physics [hep-ph/9502418]

1. Flavour violation $\quad Y_{\mu\tau} = \mathcal{O}\left(\frac{|U_{23}| v m_\tau}{\Lambda^2}\right) \qquad Y_{\tau\mu} = \mathcal{O}\left(\frac{v m_\mu}{|U_{23}|\Lambda^2}\right)$

2. Different diagonal couplings $\quad Y_\tau \approx \frac{\sqrt{2} m_\tau}{v}\left[1 + \mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)\right]$

Beyond the Abelian case

- The Effective Field Theory (EFT) approach to flavour symmetry is based on

(i) a flavour group $U(1)_{\rm FN} \supseteq G \supseteq SU(3)^5$

(ii) a set of irreducible symmetry breaking terms (spurions)

- Get O(1) prediction assuming the full EFT is formally invariant with respect to the flavour symmetry

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}(\text{SM fields}). \qquad c_i^d = c_i^d(X_i)$$

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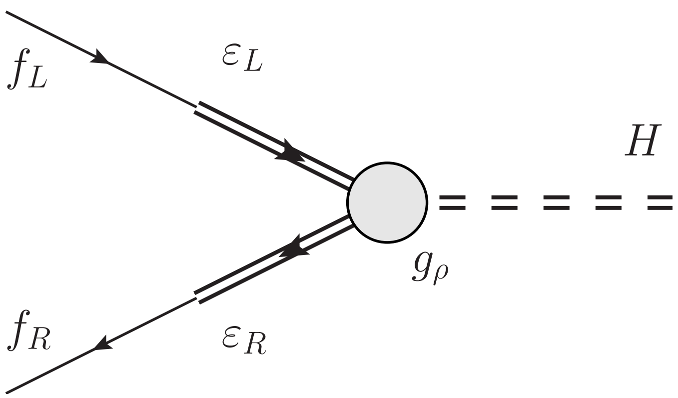
- Deviation in Higgs flavour observable are typically small, observable effects require a scale of New Physics to be very low

$$Y^{NP} = Y^{SM}\left(1 + \mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)\right)$$

Partial Compositeness in CH models

- Yukawa sector:

Georgi, Kaplan (1984)
Contino, 1005.4269
Bellazzini, Csaki, Serra 1401.2457



$$\mathcal{L}_{\rm elem} = i\overline{f}\gamma^\mu D_\mu f$$

$$\mathcal{L}_{\rm comp} = \mathcal{L}_{\rm comp}(g_\rho, m_\rho, H)$$

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$$Y^{ij} = c_{ij}\,\epsilon_L^i \epsilon_R^j\, g_\rho \longrightarrow Y^{ij} \sim \epsilon_L^i \epsilon_R^j g_\rho$$

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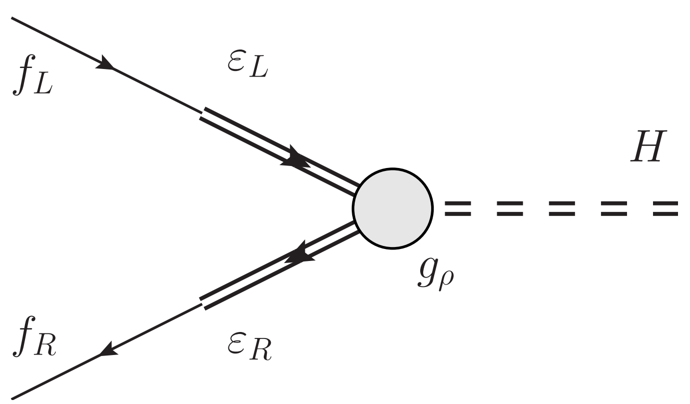

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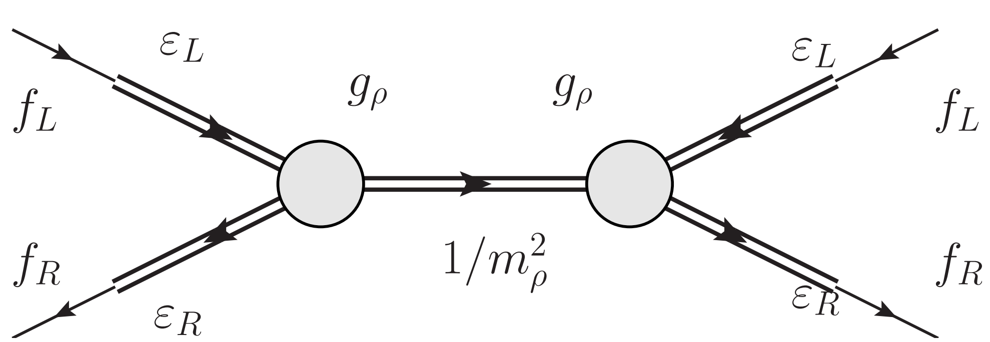
- Flavor violation beyond the CKM one is generated:



$$\sim \frac{g_\rho^2}{m_\rho^2} \epsilon_L^i \epsilon_R^i \epsilon_L^j \epsilon_R^j$$

FV related to the SM one but not in a Minimal FV way

Mixing parameters

- Mixing parameters are related to values of fermion masses and mixing

$$(Y_u)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^u \qquad (Y_d)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^d \qquad (Y_e)_{ij} \sim g_\rho \epsilon_i^\ell \epsilon_j^e,$$

- In the quarks sector everything is fixed up to 2 parameters, (g_ρ, ϵ_3^q)
- In the lepton sector parameters cannot be univocally connected to physical inputs, due to our ignorance on neutrino masses, will assume that left and right mixing have similar size

Mixing Parameter	Value
$\epsilon_1^q = \lambda^3 \epsilon_3^q$	$1.15 \times 10^{-2}\, \epsilon_3^q$
$\epsilon_2^q = \lambda^2 \epsilon_3^q$	$5.11 \times 10^{-2}\, \epsilon_3^q$
$\epsilon_1^u = \frac{m_u}{v g_\rho} \frac{1}{\lambda^3 \epsilon_3^q}$	$5.48 \times 10^{-4}/(g_\rho \epsilon_3^q)$
$\epsilon_2^u = \frac{m_c}{v g_\rho} \frac{1}{\lambda^2 \epsilon_3^q}$	$5.96 \times 10^{-2}/(g_\rho \epsilon_3^q)$
$\epsilon_3^u = \frac{m_t}{v g_\rho} \frac{1}{\epsilon_3^q}$	$0.866/(g_\rho \epsilon_3^q)$
$\epsilon_1^d = \frac{m_d}{v g_\rho} \frac{1}{\lambda^3 \epsilon_3^q}$	$1.24 \times 10^{-3}/(g_\rho \epsilon_3^q)$
$\epsilon_2^d = \frac{m_s}{v g_\rho} \frac{1}{\lambda^2 \epsilon_3^q}$	$5.29 \times 10^{-3}/(g_\rho \epsilon_3^q)$
$\epsilon_3^d = \frac{m_b}{v g_\rho} \frac{1}{\epsilon_3^q}$	$1.40 \times 10^{-2}(g_\rho \epsilon_3^q)$
$\epsilon_1^\ell = \epsilon_1^e = \left(\frac{m_e}{g_\rho v}\right)^{1/2}$	$1.67 \times 10^{-3}/g_\rho^{1/2}$
$\epsilon_2^\ell = \epsilon_2^e = \left(\frac{m_\mu}{g_\rho v}\right)^{1/2}$	$2.43 \times 10^{-2}/g_\rho^{1/2}$
$\epsilon_3^\ell = \epsilon_3^e = \left(\frac{m_\tau}{g_\rho v}\right)^{1/2}$	$0.101/g_\rho^{1/2}$

The 4D picture

Λ^{cutoff} $\mathcal{L} = \epsilon_i f_i \mathcal{O}_i + \ldots$

$$\epsilon_i = \mathcal{O}(1)$$

~ conformal

$$\epsilon_i\left(\mu\right) \sim \epsilon_i\left(\Lambda\right)\left(\frac{\mu}{\Lambda}\right)^{\Delta_{\mathcal{O}_i} - 5/2}$$

$$\epsilon_1 \ll \epsilon_2 \ll \epsilon_3$$

natural explanation of flavor hierarchy!

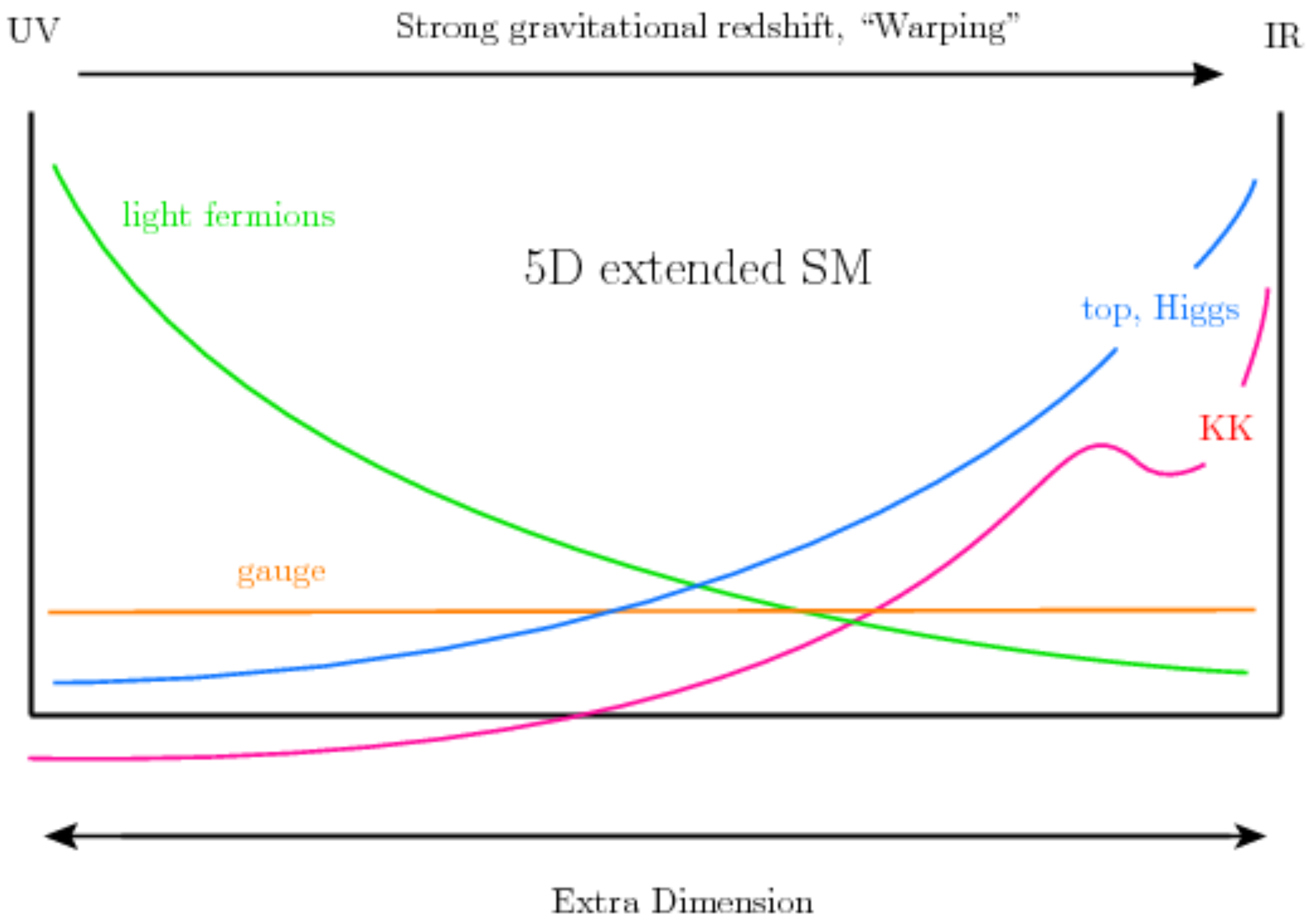
m_ρ $\mathcal{L}_{\text{SM}} \underbrace{+ \ldots}$

Higher Dim. Operators controlled by m_ρ
(here focus on Flavor Violation)

- Use Naive Dimensional Analysis to estimate the Wilson Coefficients:

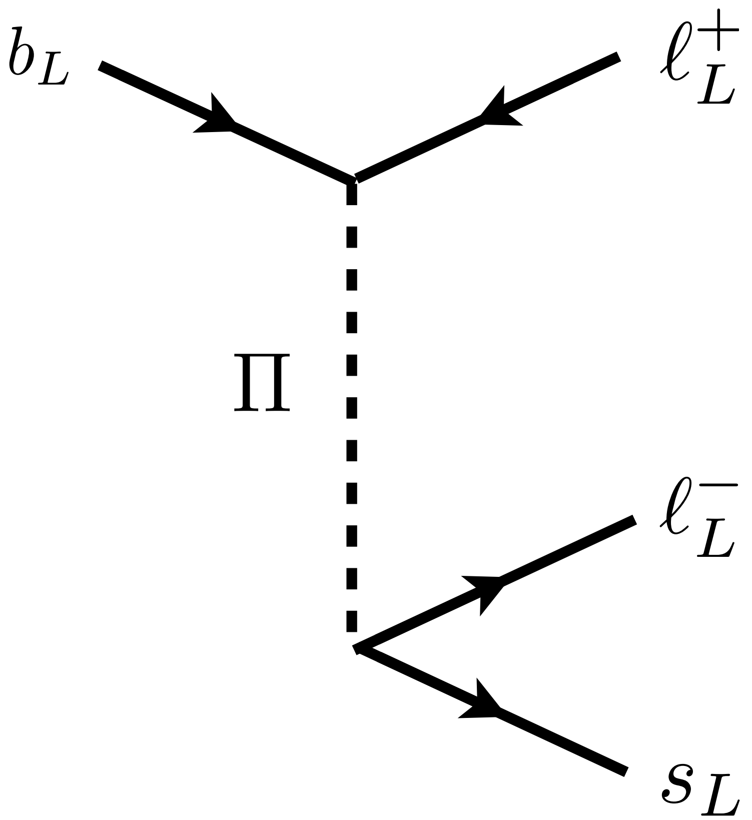
$$\mathcal{L}_{\text{NDA}} = \frac{m_\rho^4}{g_\rho^2}\left[\mathcal{L}^{(0)}\left(\frac{g_\rho \epsilon_i^a f_i^a}{m_\rho^{3/2}}, \frac{D_\mu}{m_\rho}, \frac{g_\rho H}{m_\rho}\right) + \frac{g_\rho^2}{16\pi^2}\mathcal{L}^{(1)}\left(\frac{g_\rho \epsilon_i^a f_i^a}{m_\rho^{3/2}}, \frac{D_\mu}{m_\rho}, \frac{g_\rho H}{m_\rho}\right) + \ldots\right]$$

The 5D picture



$b \to s\ell\ell$

- A leptoquark interpretation



- Quantum number of the new states, uniquely determined by the the Left-Left structure

$$\Pi \sim (\overline{\mathbf{3}}, \mathbf{3}, 1/3)$$

$$\lambda_{ij}\, \overline{q}^c_{Lj} i\tau_2 \tau_a \ell_{Li}\, \Pi$$

- Anomalies are fitted when $\dfrac{\lambda_{b\mu}\lambda_{s\mu}}{m_\Pi^2} \approx \dfrac{1}{(30\,\mathrm{TeV})^2}$
- Just two, non-vanishing leptoquark coupling
- Scale of New Physics not predicted
- No connection with FV in the SM

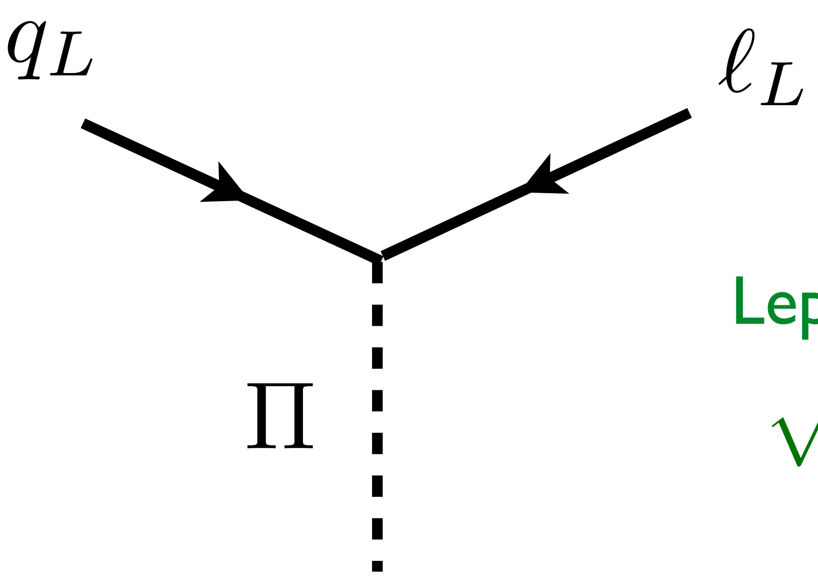
Flavour Violation & Leptoquarks

- Partial compositeness predicts the strength of the couplings

1412.5942, JHEP,
With B. Gripaios and S. Renner

- Relevant Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + (D^\mu \Pi)^\dagger D_\mu \Pi - M^2 \Pi^\dagger \Pi + \lambda_{ij}\, \overline{q}^c_{Lj} i\tau_2 \tau_a \ell_{Li}\, \Pi + \text{ h.c.}$$



Quarks →

Leptons ↓ $\sqrt{Y_\ell}$

$\lambda_{ij}/(c_{ij} g_\rho^{1/2} \epsilon_3^q)$	$j=1$	$j=2$	$j=3$
$i=1$	1.92×10^{-5}	8.53×10^{-5}	1.67×10^{-3}
$i=2$	2.80×10^{-4}	1.24×10^{-3}	2.43×10^{-2}
$i=3$	1.16×10^{-3}	5.16×10^{-3}	0.101

- c are O(1) parameters

- Only 3 fundamental parameters reduced to a single combination in all the flavour observable

$$(g_\rho, \epsilon_3^q, M) \longrightarrow \sqrt{g_\rho}\epsilon_3^q/M$$

A bottom up approach

- Regardless of any theoretical input/prejudice, it is crucial to extract as the maximum information as possible from experiment.

- From a bottom up approach we can place bound on the Yukawa coupling of the following EFT:

$$\mathcal{L}_Y = -m_i \bar{f}_L^i f_R^i - Y_{ij}(\bar{f}_L^i f_R^j)h + h.c. + \cdots$$

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- In general $$Y_{ij} \neq \frac{m_i}{v} \delta_{ij}$$

- Possible deformations respect to the Standard Model :

1. Proportionality $$Y_{ii} \neq \frac{m_i}{v}$$

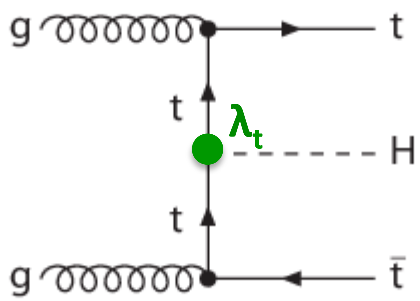
2. Flavour Violation $$Y_{ij} \neq 0$$

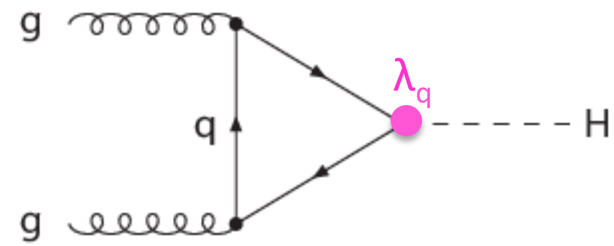
3. CP violation $$\mathrm{Im}(Y_{ij}) \neq 0$$

Coupling to the top quark

G. Petrucciani,
Moriond EW 2017

- SM ttH cross section at 13 TeV: **507 fb**: ~1/96th of ggH
  - small, but top quarks in the final state provide good handles to trigger and select the events





	ATLAS Run 2		CMS Run 2		
bb	**2.1**	**+1.0 −0.9**	**−0.2**	**+0.8 −0.8**	*PAS HIG 16-038*
multilep	**2.5**	**+1.3 −1.1**	**1.5**	**+0.5 −0.5**	*PAS HIG 17-004 **(35.9 fb^{-1})***
γγ	**−0.3**	**+1.2 −1.0**	**1.9**	**+1.5 −1.2**	*PAS HIG 16-020*
4ℓ			**0.0***	**+1.2* −0.0***	*PAS HIG 16-041 **(35.9 fb^{-1})***
comb.	**1.8** *ATLAS-CONF-2016-068*	**+0.7 −0.7**			

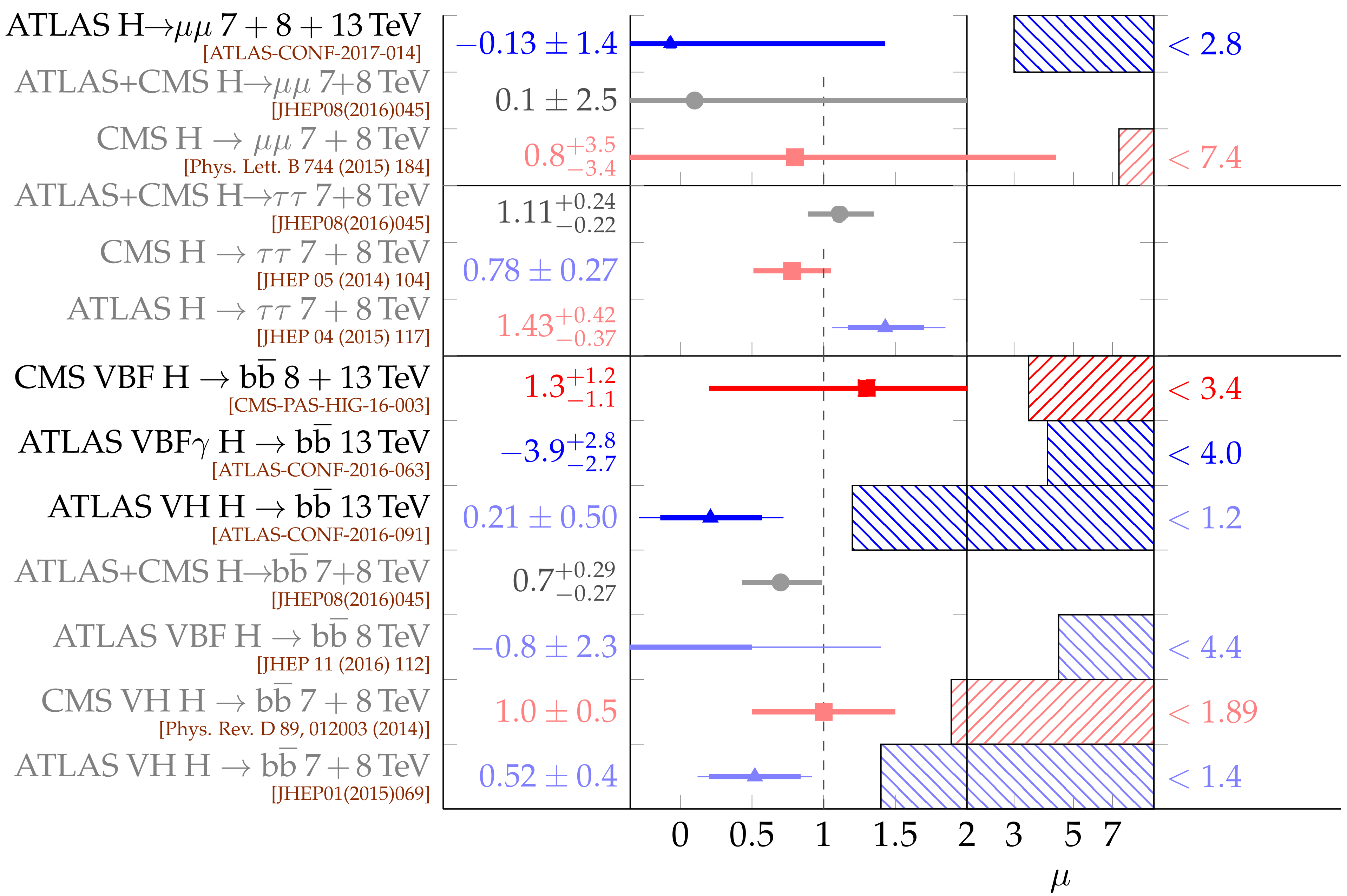
(*) $-2\Delta\ln L = 1$ interval with $\mu \geq 0$ constraint

Run1 comb. *JHEP 08(2016) 045*	**2.3**	**+1.2 −1.0**

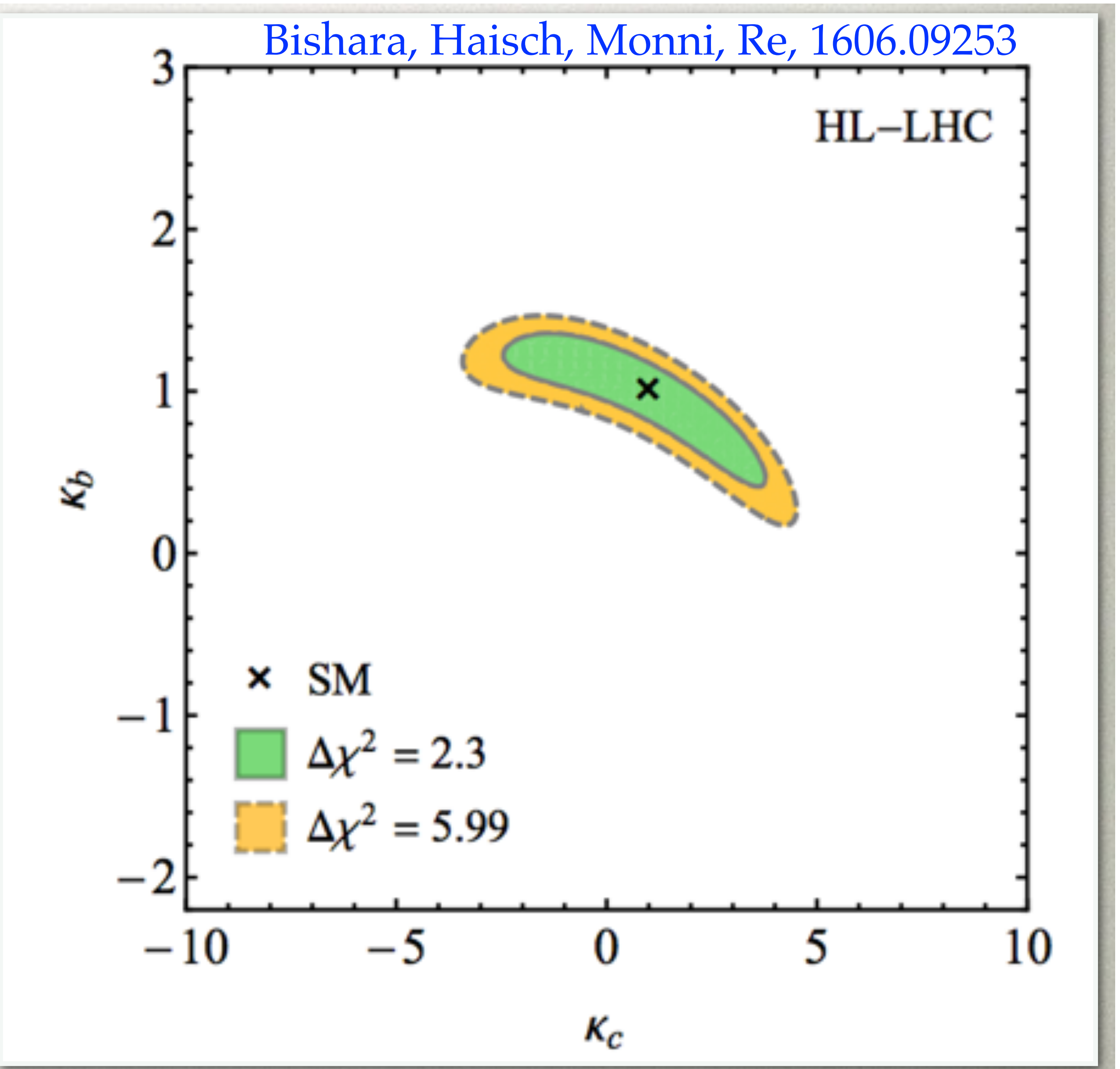
Status after Moriond EW

2nd, 3rd generation couplings

Measured signal strength μ and 95% CL limit on $\sigma \times \mathrm{Br}$ relative to the SM expectation for $m_{\mathrm{H}} = 125\,\mathrm{GeV}$:



Charm Yukawa



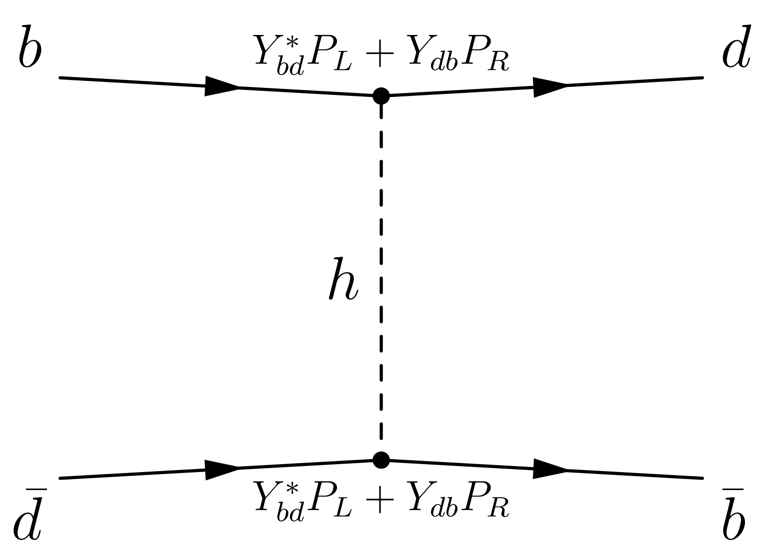
- 3fb^{-1} HL-LHC could probe models of *O(1)* enhanced charm Yukawas
- compare with LHCb
  - present (8 TeV, 1.98fb^{-1}): $\kappa_c<80$ LHCb-CONF-2016-006
  - future HL-LHCb (13 TeV, 300fb^{-1}, simple scaling): $\kappa_c \lesssim 4$

using LHCb-CONF-2016-006+C.Parkes's talk

Flavour Violation

- If $Y_{ij} \neq 0$ various indirect probes have to be considered

Harnik, Kopp, Zupan 1209.1397



Technique	Coupling	Constraint
D^0 oscill. [48]	$\|y_{uc}\|^2$, $\|y_{cu}\|^2$	$< 1.0 \times 10^{-8}$
	$\|y_{uc}y_{cu}\|$	$< 1.5 \times 10^{-9}$
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B^0_s oscill. [48]	$\|y_{sb}\|^2$, $\|y_{bs}\|^2$	$< 3.6 \times 10^{-6}$
	$\|y_{sb}y_{bs}\|$	$< 5.0 \times 10^{-7}$
K^0 oscill. [48]	$\mathrm{Re}(y^2_{ds})$, $\mathrm{Re}(y^2_{sd})$	$[-1.2 \ldots 1.2] \times 10^{-9}$
	$\mathrm{Im}(y^2_{ds})$, $\mathrm{Im}(y^2_{sd})$	$[-5.8 \ldots 3.2] \times 10^{-12}$
	$\mathrm{Re}(y^*_{ds}y_{sd})$	$[-1.1 \ldots 1.1] \times 10^{-10}$
	$\mathrm{Im}(y^*_{ds}y_{sd})$	$[-2.8 \ldots 5.6] \times 10^{-13}$

- Rate $h \to q_i q_j$ suppressed, also difficult to discriminate among jets of different flavour

Flavour Violation

- If $Y_{ij} \neq 0$ various indirect probes have to be considered

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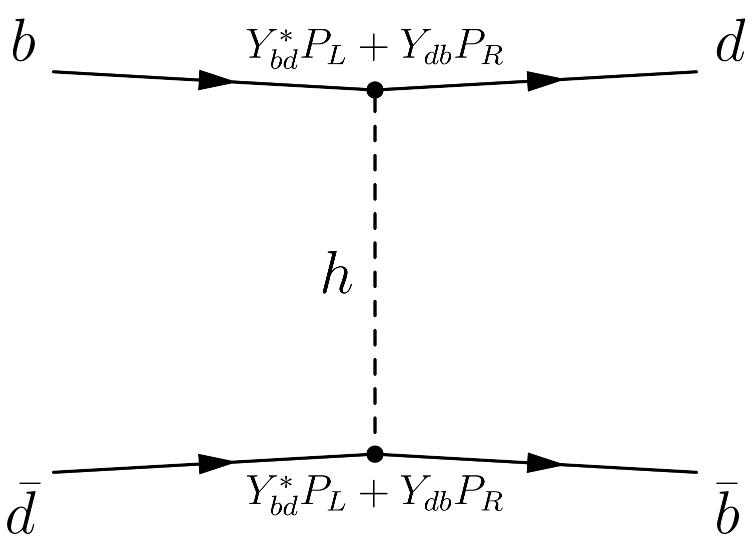

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- Bounds in the lepton sector

Channel	Coupling	Bound on coupling	Bound on BR	C.L.
$\mu \to e\gamma$	$\sqrt{\lvert Y^h_{\mu e}\rvert^2 + \lvert Y^h_{e\mu}\rvert^2}$	3.6×10^{-6}	2.4×10^{-12}	90%
$\mu \to e\gamma$	$\left(\lvert Y^h_{\tau\mu}Y^h_{\tau e}\rvert^2 + \lvert Y^h_{\mu\tau}Y^h_{e\tau}\rvert^2\right)^{1/4}$	3.4×10^{-4}	2.4×10^{-12}	90%
$\tau \to e\gamma$	$\sqrt{\lvert Y^h_{\tau e}\rvert^2 + \lvert Y^h_{e\tau}\rvert^2}$	0.014	3.3×10^{-8}	90%
$\tau \to \mu\gamma$	$\sqrt{\lvert Y^h_{\tau\mu}\rvert^2 + \lvert Y^h_{\mu\tau}\rvert^2}$	0.016	4.4×10^{-8}	90%

Lepton Flavour Violation

- An interesting anomaly in the Higgs sector $h \to \tau\mu$
- CMS : $Br(h \to \tau\mu) = (0.89 \pm 0.39)\%$ 1502.07400
- ATLAS : $Br(h \to \tau\mu) = (0.53 \pm 0.51)\%$ 1604.07730
- Run 2 data, CMS $Br(h \to \tau\mu) < 1.20\%$ $(1.62\%$ expected$)$ CMS-PAS-HIG-16-005

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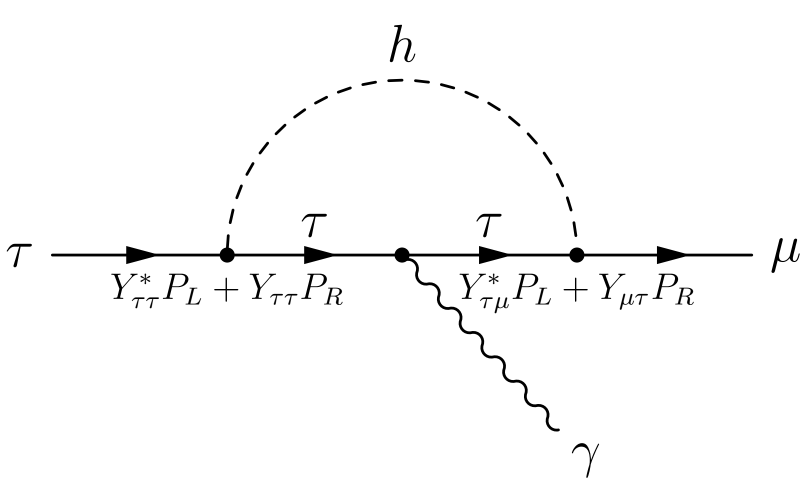
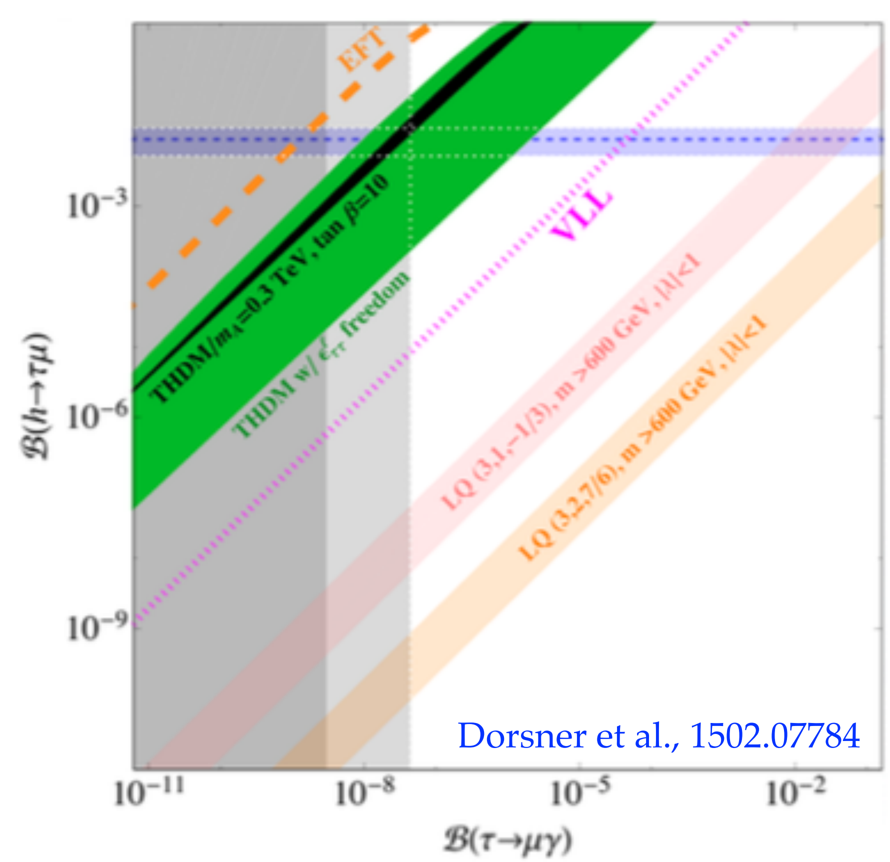
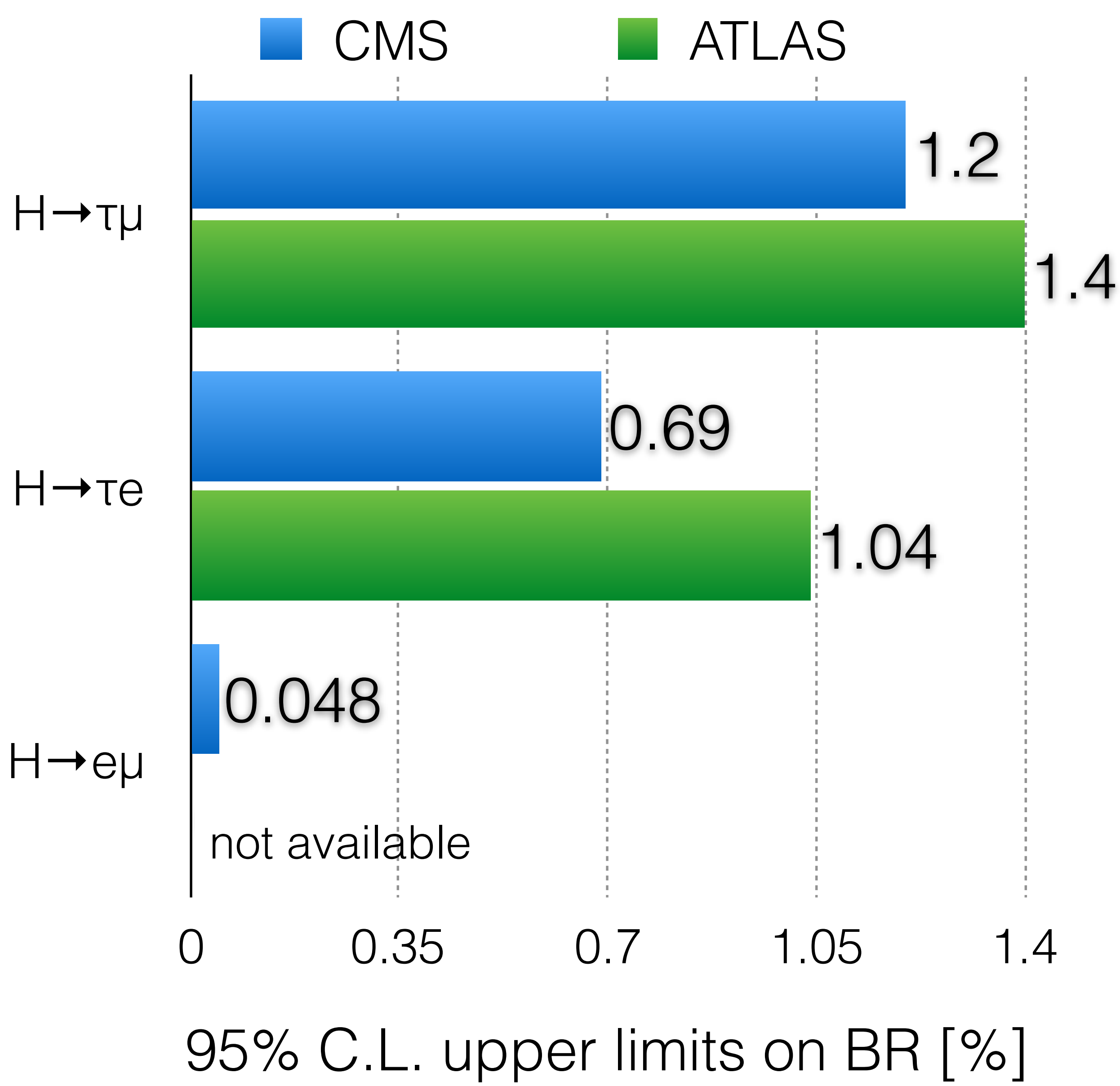


- Model building severely constricted by LFV radiative decay
- Only one motivated model survive: type III 2HDM



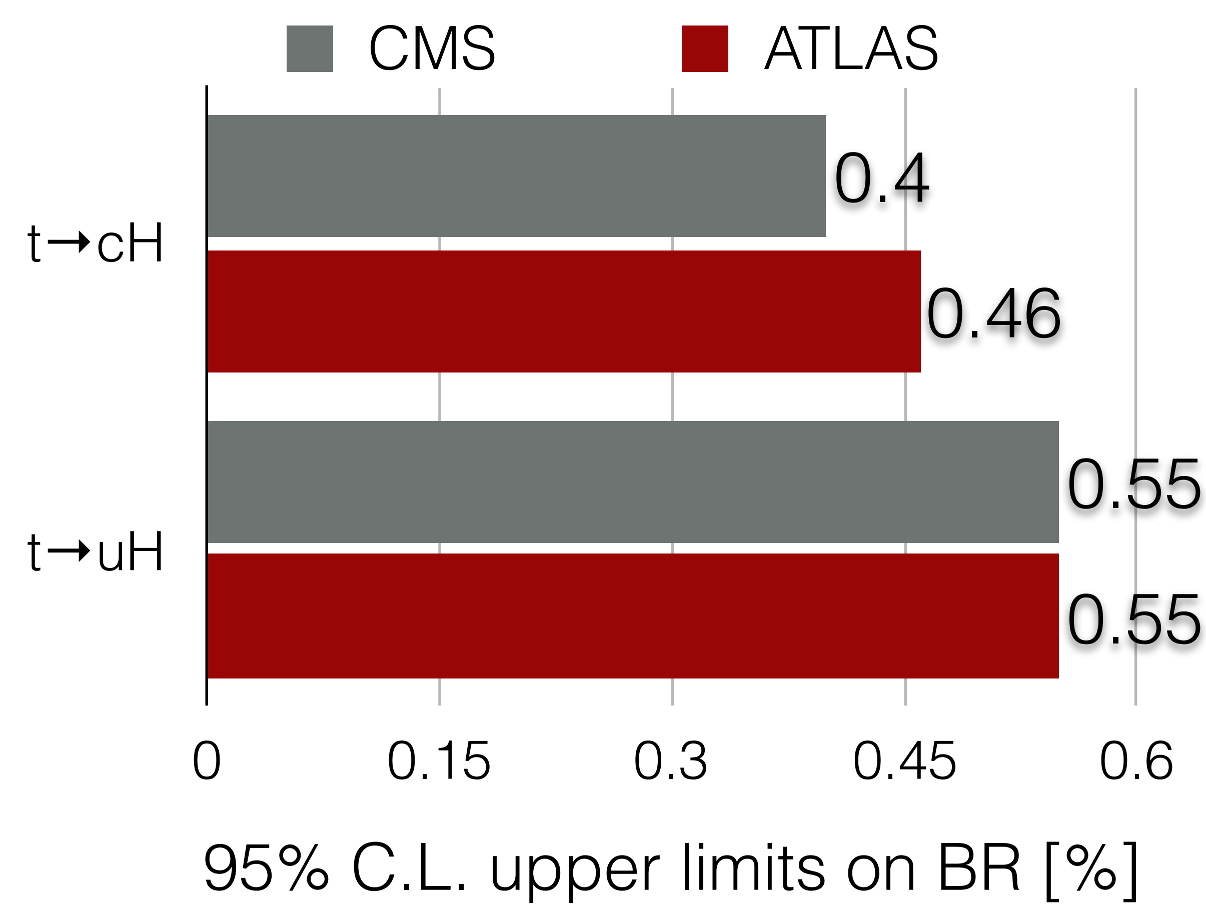
Flavour Violation

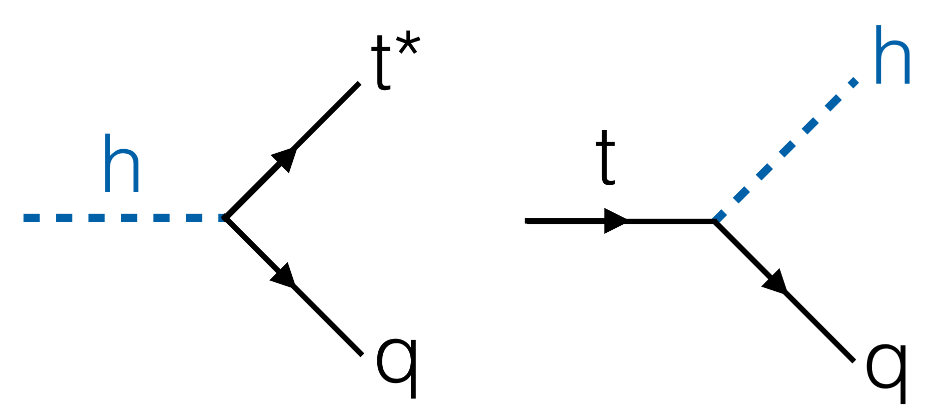
Lepton Couplings



CMS arXiv:1502.07400, arXiv:1607.03561, CMS-PAS-HIG-16-005
ATLAS arXiv:1508.03372, arXiv:1601.03567, arXiv:1604.07737
CMS arXiv:1410.2751, arXiv:1610.04857
ATLAS arXiv:1403.6293, arXiv:1509.06047

Quark Couplings

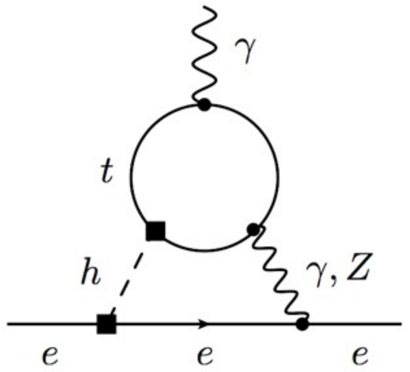




Both are sensitive to $|Y_{tq}|^2+|Y_{qt}|^2$

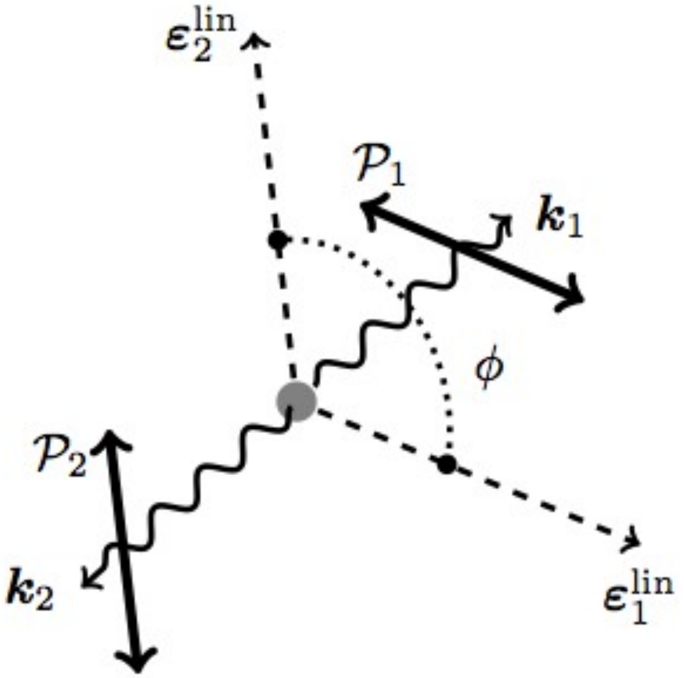
CP violation

- Indirect, example neutron/electron EDM



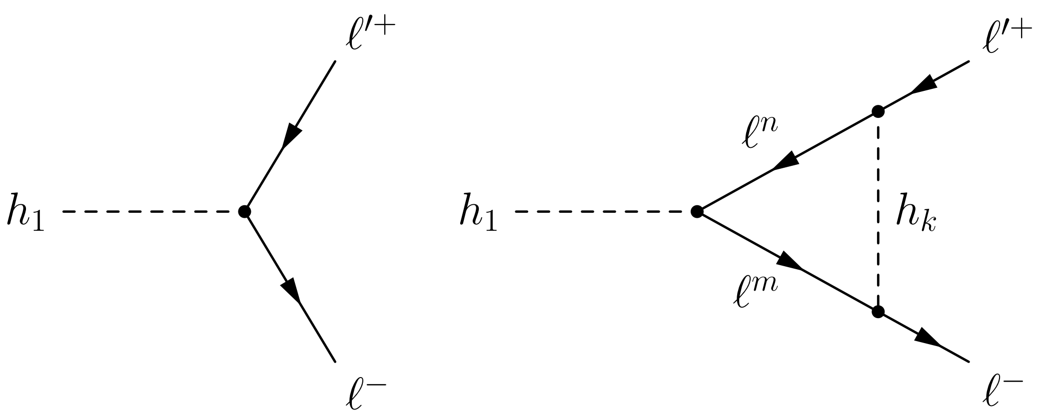
- T-violation

$$\mathcal{H}_{\text{eff}} = -\hat{c}\frac{\alpha}{\pi v} h F_{\mu\nu} F^{\mu\nu} - \frac{\tilde{c}}{2}\frac{\alpha}{\pi v} h F_{\mu\nu} \tilde{F}^{\mu\nu}$$



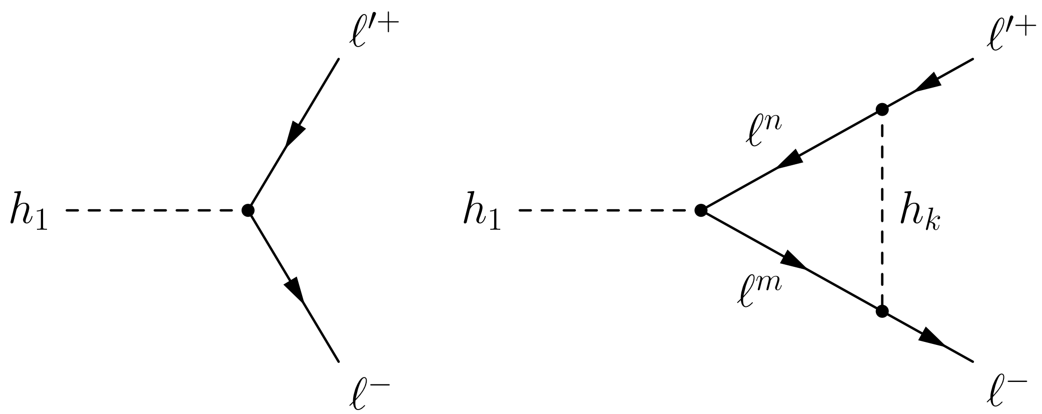
- Direct

$$A_{CP}^{\ell^i \ell^j} \equiv \frac{\Gamma(h \to \ell^{i-} \ell^{j+}) - \Gamma(h \to \ell^{i+} \ell^{j-})}{\Gamma(h \to \ell^{i-} \ell^{j+}) + \Gamma(h \to \ell^{i+} \ell^{j-})}$$



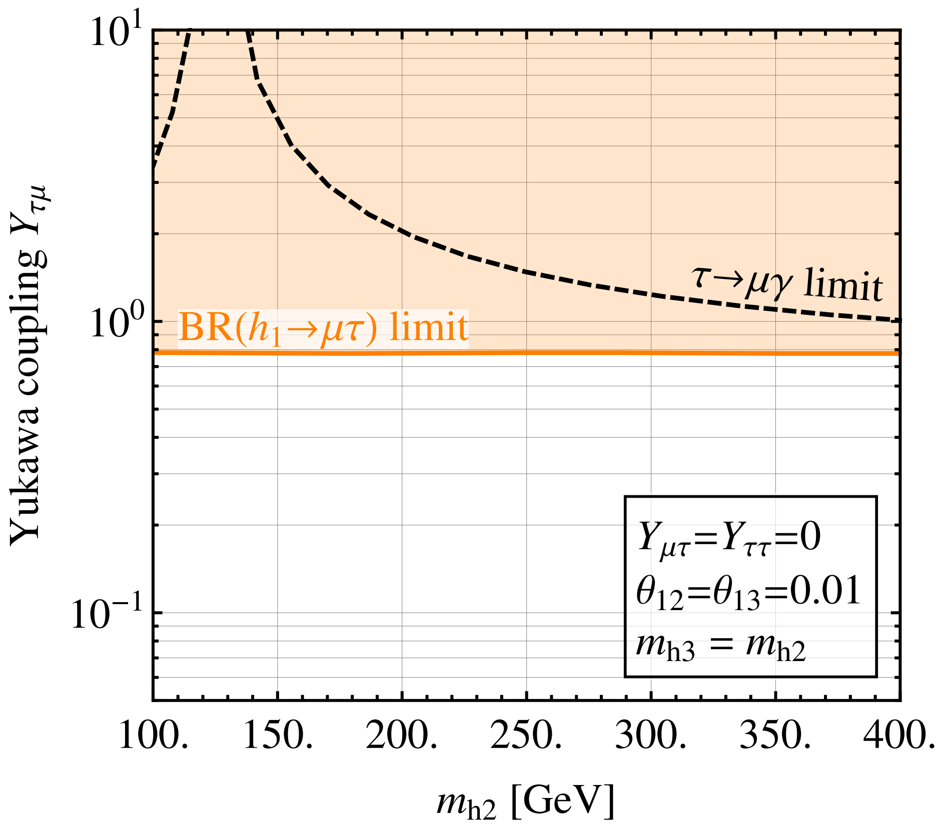
Flavour and CP violating H decays

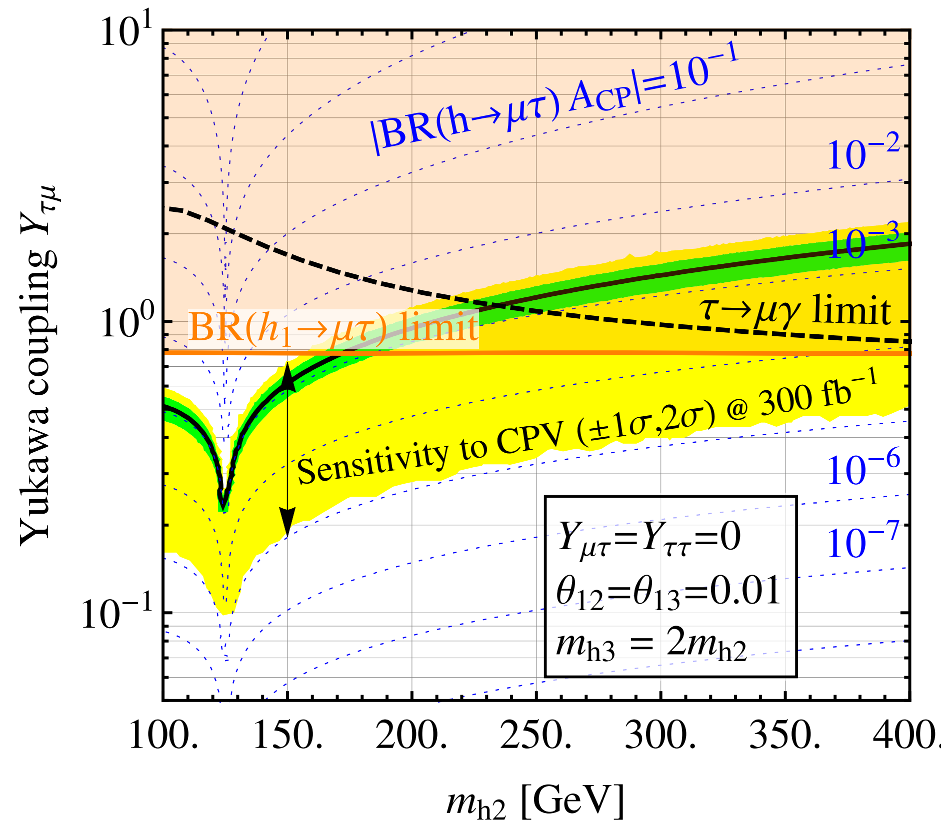
With J.Kopp,
JHEP, 1406.5303



$$A_{CP}^{\ell^i\ell^j} \approx 2\frac{Im\left[c_0 c_1^*\right]}{|c_0|^2}\frac{Im\left[\int \mathcal{A}_0\mathcal{A}_1^* d\Phi^2\right]}{\int d\Phi^2}$$

$$\Gamma(h_1\to\tau^+\mu^-)\times A_{CP}^{\mu\tau} \simeq -\frac{m_{h_1}}{64\pi^2}\theta_{12}\theta_{13}|Y_{\tau\mu}|^4\times\sum_{\alpha=2,3}(-1)^\alpha\left[g\left(\frac{m_{h_1}^2}{m_{h_\alpha}^2 a}\right)+\frac{m_{h_1}^2}{m_{h_1}^2-m_{h_\alpha}^2}\right]$$





Conclusions

- Structure of the Yukawa couplings calls for a (non-compulsory!) explanation

- Symmetries or dynamics could explain this pattern

- Possible anomalous effects in flavour observables might shed some light on the SM flavour puzzle

- The Higgs is now a new probe for flavour physics

- With Run 2 we are testing the Yukawa coupling of the SM (third family at 20-30%)

Predictions

- We expect large effects coming from third families of leptons

Lepton $\sqrt{Y_\ell}$ ↓

$\lambda_{ij}/(c_{ij} g_\rho^{1/2} \epsilon_3^q)$	$j=1$	$j=2$	$j=3$
$i=1$	1.92×10^{-5}	8.53×10^{-5}	1.67×10^{-3}
$i=2$	2.80×10^{-4}	1.24×10^{-3}	2.43×10^{-2}
$i=3$	1.16×10^{-3}	5.16×10^{-3}	0.101

- Decay channels with taus are difficult to be reconstructed $b \longrightarrow s\tau^+\tau^-$

- More interesting are channels with tau neutrinos in the final state

Buras et al. arXiv:1409.4557

$$R_K^{*\nu\nu} \equiv \frac{\mathcal{B}(B \to K^* \nu\overline{\nu})}{\mathcal{B}(B \to K^* \nu\overline{\nu})_{SM}} < 3.7,$$

$$R_K^{\nu\nu} \equiv \frac{\mathcal{B}(B \to K \nu\overline{\nu})}{\mathcal{B}(B \to K \nu\overline{\nu})_{SM}} < 4.0.$$

- Considering just $B \longrightarrow K^* \overline{\nu}_\mu \nu_\mu$ gives
$$\Delta R_K^{(*)\nu\nu} < \text{ few } \%$$

- Including $\mathrm{BR}(B \longrightarrow K \nu_\tau \overline{\nu}_\tau)$, large deviation $\Delta R_K^{(*)\nu\nu} \sim 50\%$

Testable at Belle II

See 1002.5012

Predictions

- Rare Kaon decay

Hurt et al 0807.5039
NA62 1411.0109

$$\mathcal{B}(K^+ \to \pi^+ \nu\nu) = 8.6(9) \times 10^{-11}[1 + 0.96\delta C_{\nu\bar{\nu}} + 0.24(\delta C_{\nu\bar{\nu}})^2]$$

Present bound $\delta C_{\nu\bar{\nu}} \in [-6.3, 2.3]$ NA62 expected sensitivity $\delta C_{\nu\bar{\nu}} \in [-0.2, 0.2]$

Composite leptoquark prediction $\delta C_{\nu\bar{\nu}} = 0.62 \ \mathrm{Re}(c_{31}c_{32}^*) \left(\frac{g_\rho}{4\pi}\right) (\epsilon_3^q)^2 \left(\frac{M}{\mathrm{TeV}}\right)^{-2}$

- Radiative decay $\mu \longrightarrow e\gamma$

$$|c_{23}^* c_{13}| < 1.4 \left(\frac{4\pi}{g_\rho}\right) \left(\frac{M}{\mathrm{TeV}}\right)^2 \left(\frac{1}{\epsilon_3^q}\right)^2$$