Top and Charm

CERN workshop
The top-charm frontier at the LHC

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Dery, Efrati, Hiller, Hochberg, YN, JHEP1308(2013)006

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Hochberg, YN, PRL108(2012)261601

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Plan of Talk

1. Introduction
   The flavorful Higgs
2. 1 is not large statistics
   From V_q to U_ℓ
3. Top-Charm connection?
   From $A^t_{\rm FB}$ to ΔA^D_{CP}
4. Some concluding comments
   Why top? Why charm? Why top&charm?

Introduction

The flavorful Higgs

Questions for the LHC

- What is the mechanism of electroweak symmetry breaking?

- What separates the electroweak scale from the Planck scale?

- What happened at the electroweak phase transition (10^{-11} second after the big bang)?

- What are the dark matter particles?

- How was the baryon asymmetry generated?

- What is the solution of the flavor puzzles?

The flavor puzzles

- The SM flavor puzzle:
  Why is there smallness and hierarchy in the charged fermion flavor parameters?

- The SM flavor puzzle extended:
  Why is the neutrino flavor structure different?

- The NP flavor puzzle:
  If there is TeV-scale NP, why doesn't it affect FCNC?

Can we make progress?

- NP that couples to quarks/leptons $\Longrightarrow$ New flavor parameters (spectrum, flavor decomposition) that can be measured
- The NP flavor structure could be:
  - MFV
  - Related but not identical to SM
  - Unrelated to SM or even anarchical
- The NP flavor puzzle:
  With ATLAS/CMS we will surely understand how it is solved
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- $\boxed{h}$ $\Longrightarrow$ The "NP" is already here!
  $Y_{\bar{f}_i f_j}$ are new flavor parameters that can be measured

Higgs, Top and Charm

- Experimentally:
  - Measure $\sigma(pp \to t\bar{t}h) \Longrightarrow Y_{tt}$
  - Measure $\sigma(pp \to h) \times \mathrm{BR}(h \to c\bar{c}) \Longrightarrow Y_{cc}$
  - Measure $\mathrm{BR}(t \to hc) \Longrightarrow Y_{tc}$

- Theoretically:

Model	$\frac{Y_{tt}}{Y_{tt}^{\mathrm{SM}}}$	$\frac{Y_{cc}/Y_{tt}}{m_c/m_t}$	Y_{ct}/Y_{tt}
SM	1	1	0
2HDM-NFC	c_α/s_β	1	0
2HDM-MFV	$\mathcal{O}(1)$	$\mathcal{O}(1)$	$\mathcal{O}(Y_b^2 V_{cb})$
1HDM-FN	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(V_{cb} v m_t/\Lambda^2)$

1 is not large statistics

From quark to lepton mixing

Quark mixing

- The CKM matrix a-la BABAR/BELLE: Ceccucci et al, PDG(2012)

$$V_q = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & (4.12^{+0.11}_{-0.05}) \times 10^{-2} \\ (8.67 \pm 0.30) \times 10^{-3} & (4.04^{+0.11}_{-0.05}) \times 10^{-2} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

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- The CKM matrix a-la ATLAS/CMS:

$$V_q = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

From quark mixing to lepton mixing

- Quark mixing a-la theorists, qualitatively:

$$V_q = \begin{pmatrix} 1 & \text{small} & \text{small} \\ \text{small} & 1 & \text{small} \\ \text{small} & \text{small} & 1 \end{pmatrix}$$

From quark mixing to lepton mixing

- Quark mixing a-la theorists, qualitatively:

$$V_q = \begin{pmatrix} 1 & \text{small} & \text{small} \\ \text{small} & 1 & \text{small} \\ \text{small} & \text{small} & 1 \end{pmatrix}$$

- The theoretical prejudice for lepton mixing:

$$U_\ell = \begin{pmatrix} 1 & \text{small} & \text{small} \\ \text{small} & 1 & \text{small} \\ \text{small} & \text{small} & 1 \end{pmatrix}$$

Lepton mixing

- The data: Gonzalez-Garcia, PoS ICHEP2012(2013)005

$$|U|_{3\sigma} = \begin{pmatrix} 0.79 - 0.85 & 0.51 - 0.59 & 0.13 - 0.18 \\ 0.20 - 0.54 & 0.42 - 0.73 & 0.58 - 0.81 \\ 0.21 - 0.55 & 0.41 - 0.73 & 0.57 - 0.80 \end{pmatrix}$$

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- Tribimaximal-ists:

$$|U|_{\rm TBM} = \begin{pmatrix} 0.82 & 0.58 & 0 \\ 0.41 & 0.58 & 0.71 \\ 0.41 & 0.58 & 0.71 \end{pmatrix}$$

- Anarch-ists:

$$|U|_{\rm anarchy} = \begin{pmatrix} \mathcal{O}(0.6) & \mathcal{O}(0.6) & \mathcal{O}(0.6) \\ \mathcal{O}(0.6) & \mathcal{O}(0.6) & \mathcal{O}(0.6) \\ \mathcal{O}(0.6) & \mathcal{O}(0.6) & \mathcal{O}(0.6) \end{pmatrix}$$

Summary I

- The attempt to guess from V_q the structure of U_ℓ has failed (1 is not large statistics)
- The attempt to guess from $M_{U,D,E}$ the flavor structure of NP might fail
  (3 is still not large statistics)

Summary I

- The attempt to guess from V_q the structure of U_ℓ has failed
  (1 is not large statistics)
- The attempt to guess from $M_{U,D,E}$ the flavor structure of NP might fail
  (3 is still not large statistics)
- Be suspicious of theoretical prejudices
  (MFV is not an experimental fact)
- Measure as much as you can in $Y_{U,D,E}$
  (In the context of this workshop: Y_{tt}, Y_{cc}, Y_{ct}...)

Top-Charm connection?

From $A_{\rm FB}^t$ to $\Delta A_{\rm CP}^D$

$A_{\rm FB}^t$ and scalar mediation

- $A_{\rm FB}^t(\rm CDF + D0) = 0.18 \pm 0.04$
- $A_{\rm FB}^t(\rm SM) = 0.09 \pm 0.01$
- Suggestive of a new boson-mediated tree-level $u\bar{u} \to t\bar{t}$
- Focus on $\Phi(1,2)_{-1/2}$ with $m \sim 130$ GeV and $\lambda_{\phi ut} \sim 1$; $G_0 \equiv 4|\lambda|^2/m_\phi^2 = (10-30)G_F/\sqrt{2}$
- Note: The CKM misalignment $\Longrightarrow$ Flavor changing couplings are unavoidable

$A^t_{\rm FB}$ and flavor constraints

- $A^t_{\rm FB} - A^t_{\rm FB}({\rm SM}) \sim 0.1 \implies \lambda_{\phi^0 \bar{t} u} \sim 1$:
  - $\overline{t_L} u_R$ or $\overline{t_R} u_L$?
  - Avoid FC couplings in the up (ϕ^0-mediated) or down (ϕ^--mediated) sector?

$A^t_{\rm FB}$ and flavor constraints

- $A^t_{\rm FB} - A^t_{\rm FB}({\rm SM}) \sim 0.1 \implies \lambda_{\phi^0 \bar{t} u} \sim 1$:
  - $\overline{t_L} u_R$ or $\overline{t_R} u_L$?
  - Avoid FC couplings in the up (ϕ^0-mediated) or down (ϕ^--mediated) sector?
- Constraints from $\Delta m_K,\ \Delta m_D,\ {\rm BR}(\overline{B^0} \to \pi^+ K^-)$ dictate:
  - $\overline{t_L} u_R$
  - Avoid FC couplings in the down sector
- The only (flavor-) viable possibility:

$$\boxed{\lambda \left[\overline{b_L} u_R \phi^- + \left(V_{tb}\overline{t_L} + V_{cb}\overline{c_L} + V_{ub}\overline{u_L}\right) u_R \phi^0\right]}$$

Introduction to $\Delta A_{\rm CP}^D$

- $\Delta A_{\rm CP}^D({\rm EXP}) = (-3.3 \pm 1.2) \times 10^{-3}$
- SM: $\Delta A_{\rm CP}^D({\rm SM}) = 1.2 \times 10^{-4} \frac{|P/T| \sin\delta}{0.1}$
- Three logical possibilities:
  - $\Delta A_{\rm CP}^D({\rm EXP})$ will go down
  - Very strong penguin enhancement
  - New Physics

$A_{\rm FB}^t \Rightarrow \Delta A_{\rm CP}^D$

Consider ϕ:

- t-channel tree-level exchange of ϕ^0 generates
  $\frac{4|\lambda|^2}{m_\phi^2}\, V_{ub}V_{cb}^*\, (\overline{u_R}c_L)(\overline{u_L}u_R)$
- Predicts $\Delta A_{\rm CP}^\phi = 2\sqrt{2}(G_0/G_F)I_{\rm CKM}I_{\rm QCD} \sim (0.02-0.07)I_{\rm QCD}$
  - $G_0 \equiv \frac{4|\lambda|^2}{m_\phi^2} = (10-30)\times\frac{G_F}{\sqrt{2}}$
  - $I_{\rm CKM} \equiv 2\mathcal{I}m\left(\frac{V_{ub}V_{cb}^*}{V_{us}V_{cs}^*}\right) \sim 0.001$
- Guess $I_{\rm QCD} \sim 0.5 f_D/m_D \Longrightarrow |\Delta A_{\rm CP}^\phi| \sim 0.003$
- Interesting... but 4σ away from atomic parity violation

Summary II

- The model is radically different from MFV, yet not excluded by flavor
- Are we too much "committed" to MFV?

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- The model is radically different from MFV, yet not excluded by flavor
- Are we too much “committed” to MFV?

- $A^t_{\rm FB}$: scalar-mediated mechanisms involve flavor non-universal couplings in the up sector
- ΔA_{CP}: involves flavor non-universal couplings in the up sector
- The two observables, if BSM, might be related
- Our model provides a specific example; Are there any others?

Concluding Comments

Why top? Why charm? Why top&charm?

Why top?

- The main source of the fine-tuning problem;
  'Top-partners' likely to modify top couplings
- In some models drives EWSB
- Still much to learn about FCNC top decays;
  $t \to qZ$, $t \to q\gamma$, $t \to qg$, $t \to qh$
- At the LHC: Large statistics, 'easy' to identify, rich phenomenology
- Affects Higgs phenomenology in a variety of ways;
  $gg \to h$, $h \to \gamma\gamma$, $h \to gg$, $pp \to t\bar{t}h$

Why charm?

- Flavor in the up sector much less explored
- $\Delta A_{\rm CP}$ – intriguing
- Until now – the charm is elusive:
  Unlike t (and b) – not an easy-to-identify final state
  Unlike u (and d) – not a copious initial state
- The news: charm tagging is possible:
  a new arena for flavor physics!

Why top&charm?

- In most solutions of the fine-tuning problem:
  Not just top-partners, but all fermion-partners
- The top-partners mix with all states with the same color and EM charge:
  Expect top-partner – charm-partner mixing
- May lead to $\mathcal{O}(1)$ modifications in top-partner physics
- In MFV and, more generally, U(2) models:
  Charm and up $\sim$ flavor-doublet $\Longrightarrow$ Small $\tilde{t}-\tilde{c}$ mixing
- But... in FN and, more generally, U(1) models –
  Charm and up are different $\Longrightarrow$ Large $\tilde{t}-\tilde{c}$ mixing possible

Conclusions

- Higgs physics – a new arena for flavor physics
  Third generation couplings: $Y_t,\ Y_b,\ Y_\tau$
  Second generation couplings: $Y_c,\ Y_\mu$
  FC couplings: $Y_{ct},\ Y_{\mu\tau}$
- Don't assume MFV – test it!
  We may be surprised...
- Naturalness seems elusive – maybe it is just somewhat charmed
- Charm tagging – an opportunity