Higgs and Flavor: Theory Status

Felix Yu
Johannes Gutenberg University, Mainz

Based, in part, on FY, JHEP **1702** (2017) 083 [1609.06592]

Workshop on the Physics of HL-LHC, and Perspectives on HE-LHC
CERN – June 19, 2018

Hard problem: the SM flavor puzzle

- Recall: SM global symmetry $U(3)^5$ broken by SM Yukawa interactions
  - CKM provides only expected tree-level generation-changing interactions
  - Alignment of fermion mass and Yukawa matrices as well as vanishing FCNCs in Z and Higgs interactions are strong prediction from SM Higgs mechanism
- No explanation for hierarchy of fermion masses, why 3 generations, near-unity nature of CKM

Harder problem: the NP flavor puzzle

- New matter fields can have, in principle, different breaking patterns of SM global symmetry
  - After integrating out heavy fields (e.g. 2HDM, VL fermions)

$$\mathcal{L} \supset y_u \bar{Q}_L \tilde{H} u_R + y'_u \frac{H^\dagger H}{\Lambda^2} \bar{Q} \tilde{H} u_R + y_d \bar{Q}_L H d_R + y'_d \frac{H^\dagger H}{\Lambda^2} \bar{Q} H d_R + \text{ h.c.}$$

  - In dim-6 SMEFT, diagonalize the mass combination

$$m_f = \frac{y_f v}{\sqrt{2}} + \frac{y'_f v^3}{2\sqrt{2}\Lambda^2}$$

- Resulting Yukawa interactions are not necessarily diagonal nor CP-conserving, nor aligned with mass

$$\frac{y_{f,\text{ eff}}}{\sqrt{2}} = \frac{y_f}{\sqrt{2}} + \frac{3y'_f v^2}{2\sqrt{2}\Lambda^2} = \frac{m_f}{v} + \frac{2y'_f v^2}{2\sqrt{2}\Lambda^2}$$

NP flavor puzzle, non-standard Yukawas

- Effective Yukawa interactions can strongly deviate from SM expectations

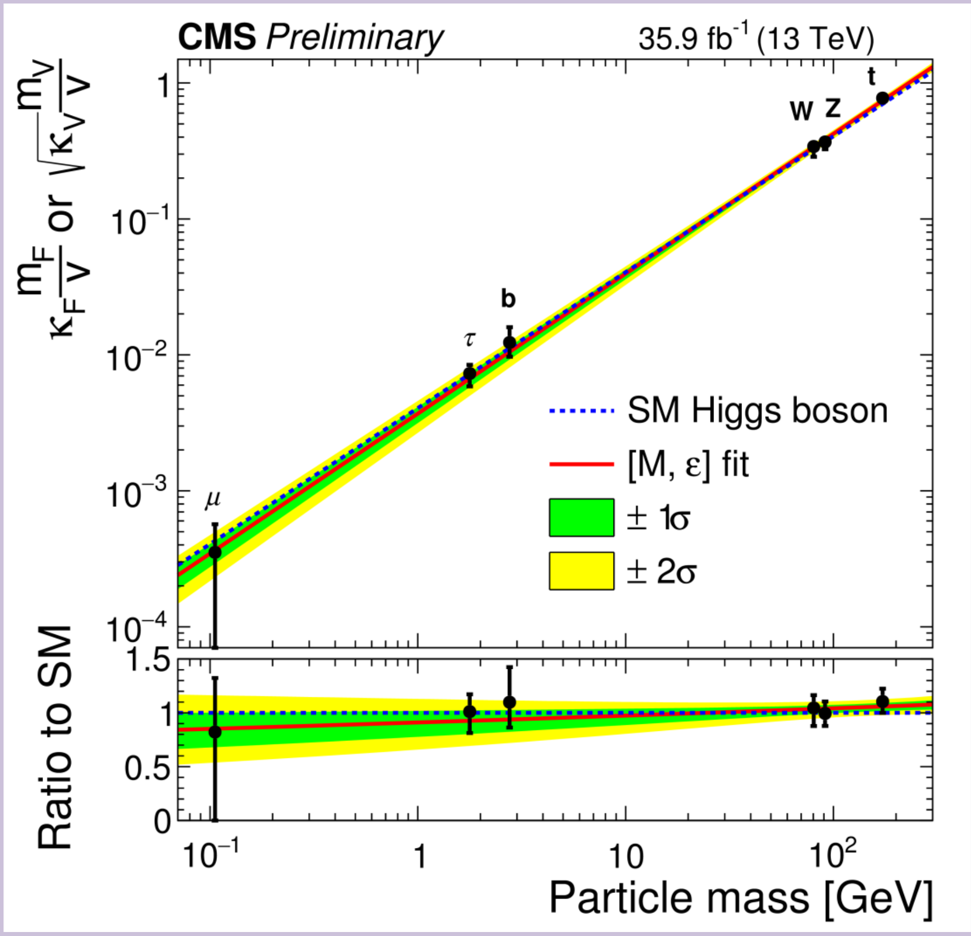
$$\left(\frac{y_{f,\text{ eff}}}{\sqrt{2}}\right)_{ij} = \left(\frac{m_i}{v}\right)\delta_{ij} + \left(\frac{2y'_f v^2}{2\sqrt{2}\Lambda^2}\right)_{ij}$$

  – Competition of SM and NP global symmetry breaking patterns – NP flavor puzzle
- Main consequences
  – Break the mass-Yukawa proportionality
    - For light quarks, dominant Yukawa contribution can come from higher dimensional operator
  – New flavor-violating Higgs interactions
  – New CP-violating Higgs interactions

Suite of Higgs NP signatures

CMS-PAS-HIG-17-031

- Test for deviations from predicted SM decays
- Test for presence of forbidden/vanishingly small SM decays
  - Light fermions (cc, μμ, ee)
  - Flavor violating
  - CP-violating
- (Test for presence of BSM states)
  - (Invisible decay, exotic decays, exotic production)



See slides by B. Nachman, T. Stefaniak; Curtin, et. al. [1312.4992]; FY [1404.2924]

Outline

- Testing mass-Yukawa proportionality
  - In production: Wh charge asymmetry; $p_T(h)$, $p_T(j)$, $y(h)$
  - In decays: charm tagging, rare decays
- Briefly: testing Higgs FCNCs and CPV
- Conclusions

Phenomenology of diagonal Higgs Yukawas

- Recall that top Yukawa coupling provides leading contribution for Higgs production ($y_t \approx 1$)
  - Theory uncertainty in ggF at N3LO is 4.6-6.7%
    Anatasiou, et. al. [1602.00695]
  - Enhanced light quark Yukawas can induce
    - New *s*-channel Higgs production modes
    - Associated Higgs+j modes
    - Interference in inclusive and exclusive ggF
    - Deviations in Wh charge asymmetry
- Bottom Yukawa coupling provides leading contribution for Higgs decay ($y_b \approx 1/60$ at $\mu_R = 125$ GeV)
  - Growth in total Higgs width is an irreducible effect from enhanced light quark Yukawas

Phenomenology of diagonal Higgs Yukawas

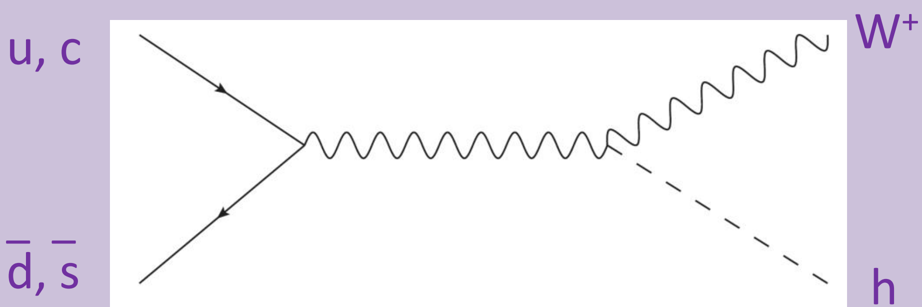
- Competition between enhanced production (leveraging quark PDFs) and depleted signal strength
  - Differentiates production-based probes vs. exclusive decays
  - Generally expect modifications to both total rates and differential distributions, if precision is attainable
- Production-based studies flesh out observable consequences of enhanced Yukawa coupling – agnostic to overall signal strength

Quark Yukawas, $W^{\pm}h$ charge asymmetry

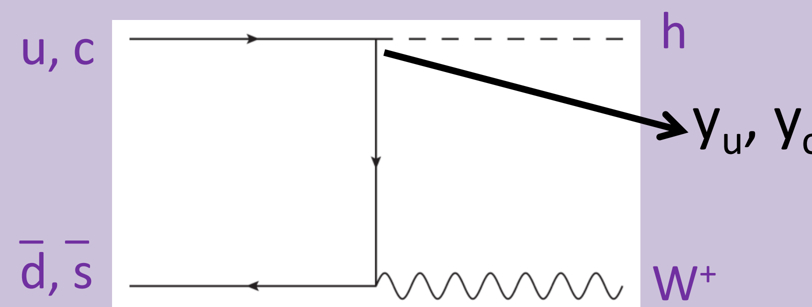
- $W^{\pm}h$ production asymmetric at LHC
  - Asymmetry driven by proton PDFs
  - Consider $W^{+}h$:
    - (Unitarity violation requires NP completion)

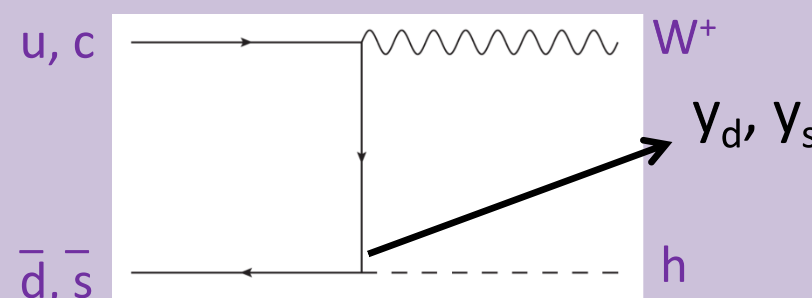
14 TeV: $W^{+}H$ (pb)	$W^{-}H$ (pb)
0.922	0.591

Higgs XSWG



Insensitive to Yukawas





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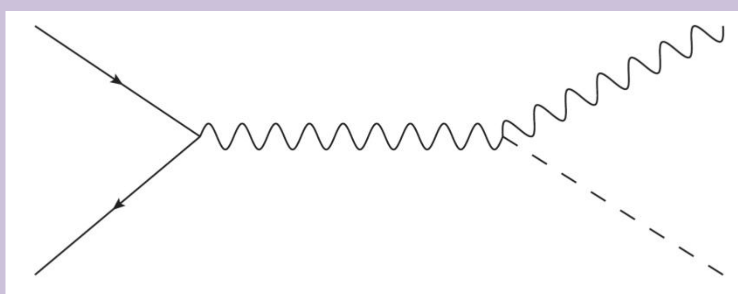

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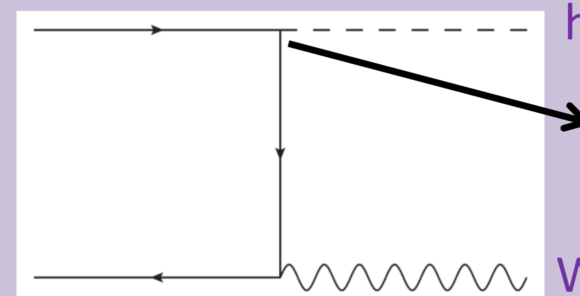
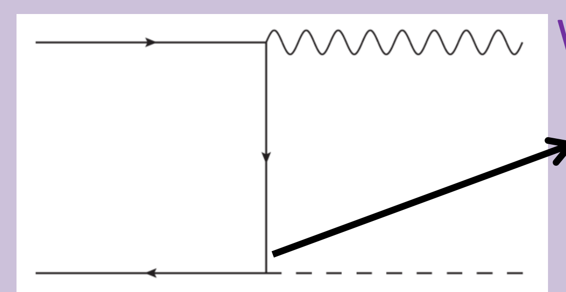
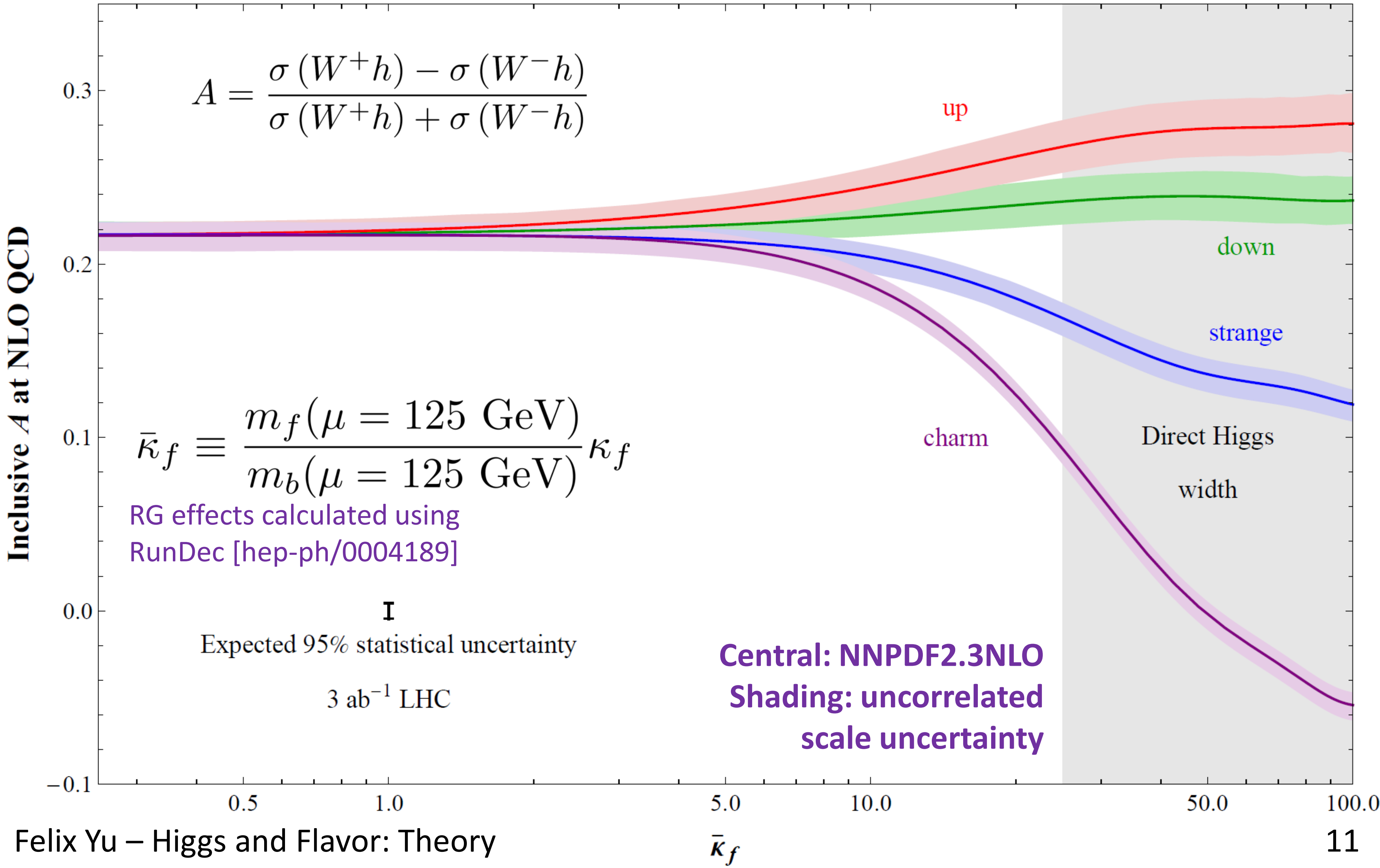




NLO Inclusive charge asymmetry



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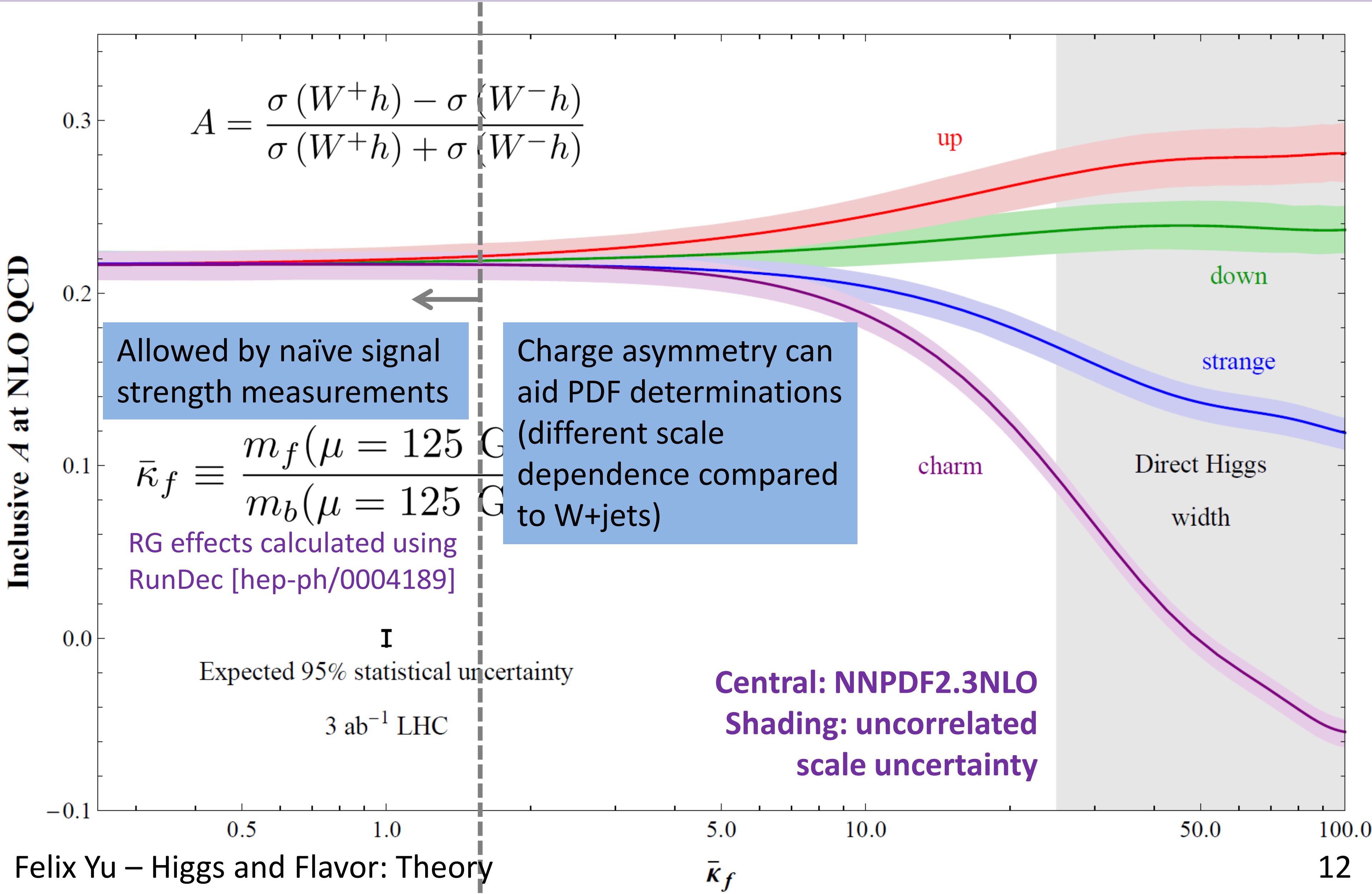


Allowed by naïve signal strength measurements

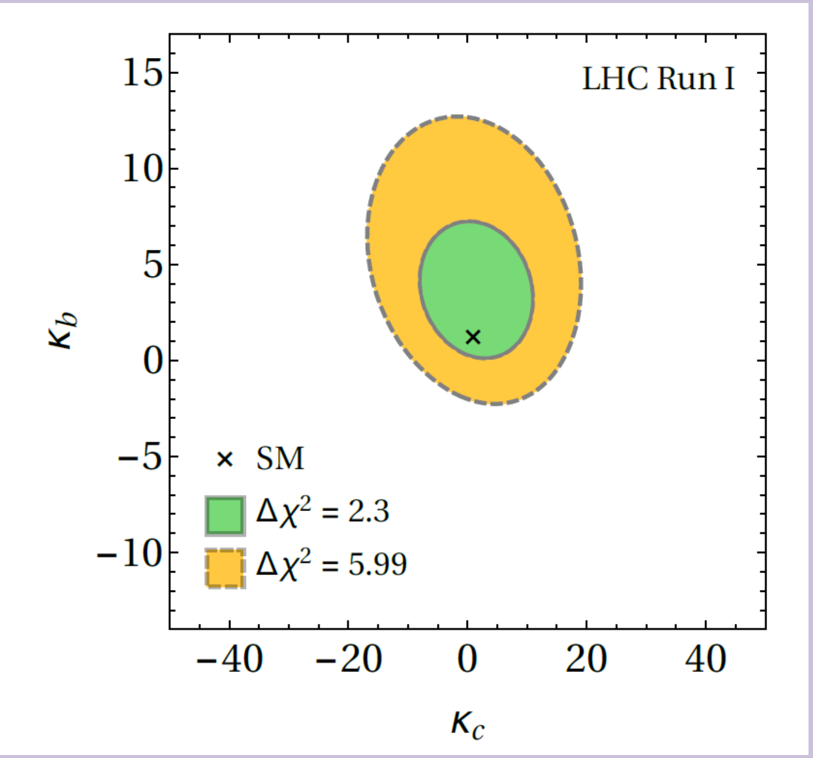
Charge asymmetry can aid PDF determinations (different scale dependence compared to W+jets)

RG effects calculated using RunDec [hep-ph/0004189]

Central: NNPDF2.3NLO
Shading: uncorrelated scale uncertainty

Phenomenology of diagonal Higgs Yukawas

- Modifying light quark Yukawas changes interference effect with top Yukawa in ggF
  - Use $p_{T,\,h}$ and leading jet p_T distributions



 Bishara, Haisch, Monni, Re [1606.09253]

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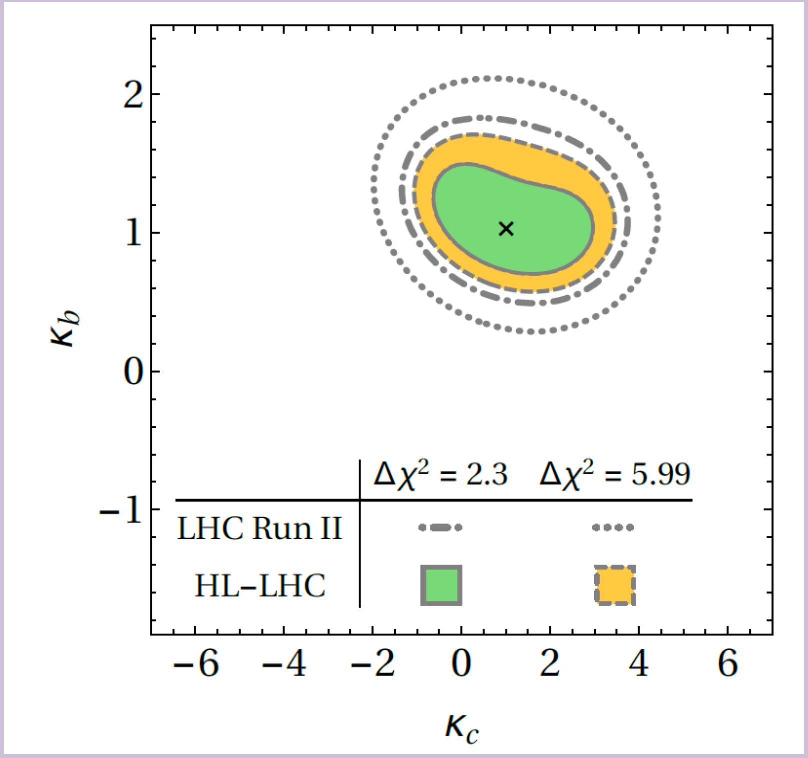


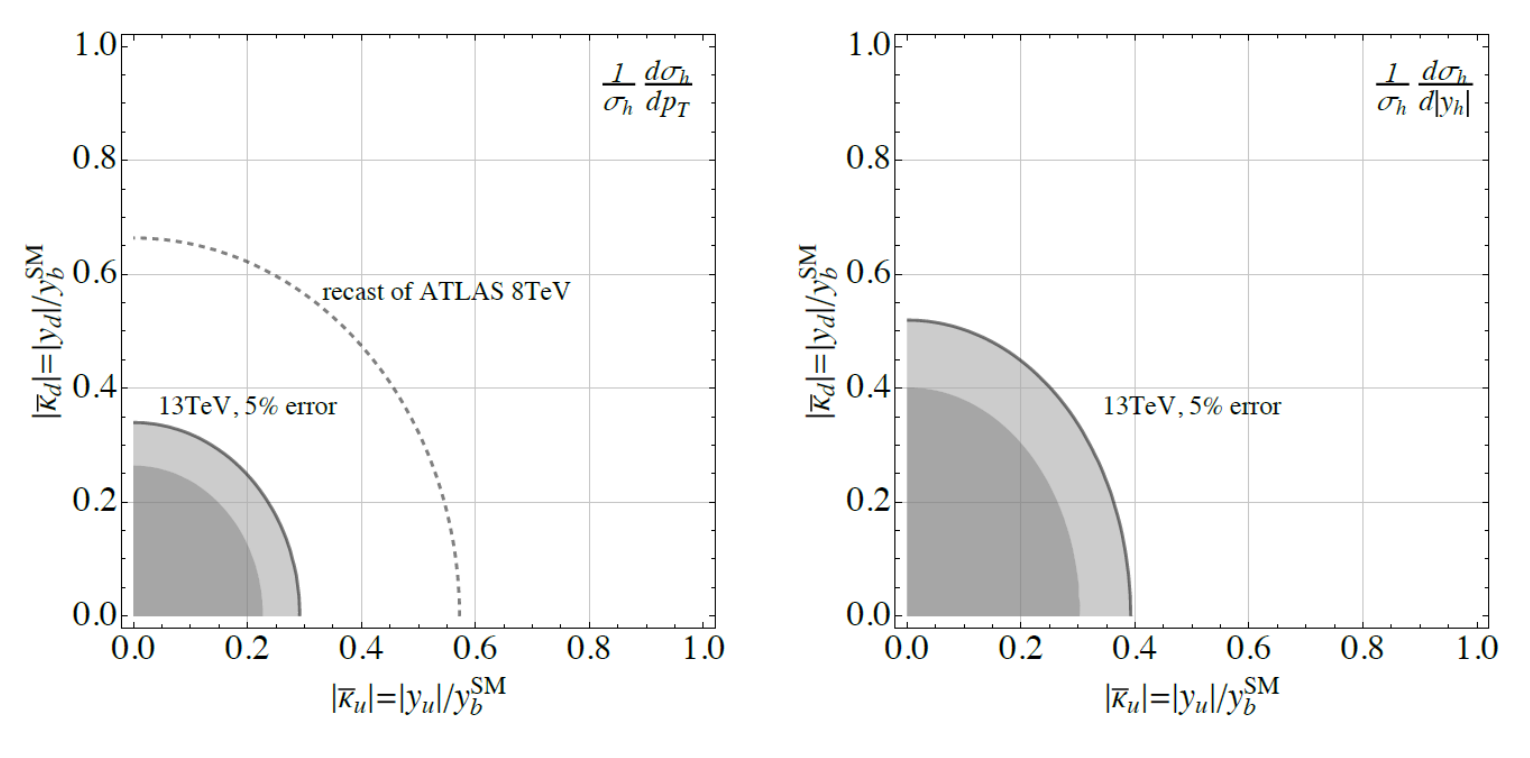
$$\kappa_c \sim [-2.9, 4.2] \quad \text{HL-LHC}$$

Bishara, Haisch, Monni, Re [1606.09253]

Phenomenology of diagonal Higgs Yukawas

– Use $p_{T,h}$ and y_h distributions

- Continuing theory calculations needed to push uncertainties



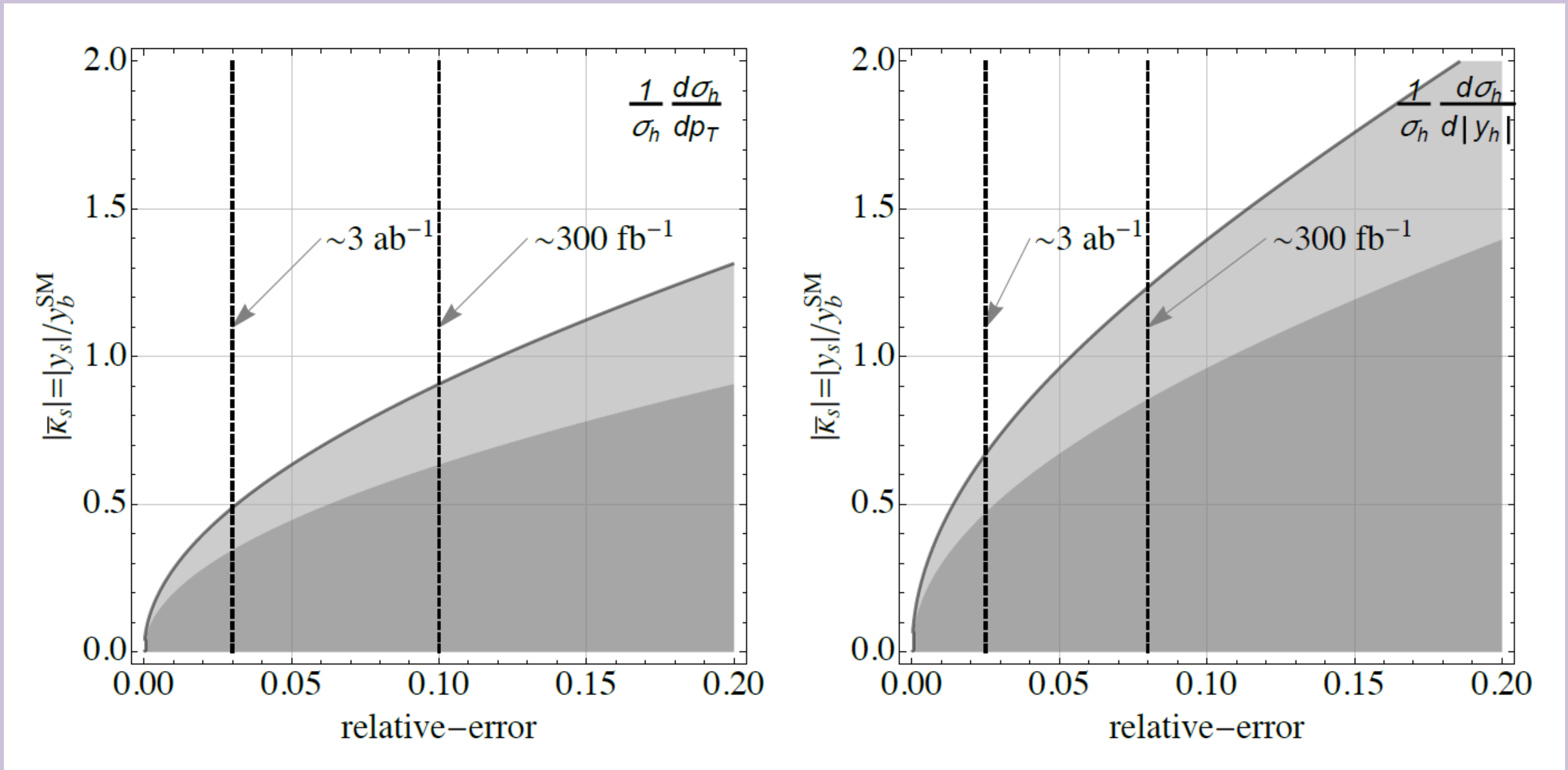
$$p_T : \quad \bar{\kappa}_u < 0.27, \bar{\kappa}_d < 0.31 \quad 2\ \text{ab}^{-1}$$

$$y : \quad \bar{\kappa}_u < 0.36, \bar{\kappa}_d < 0.47 \quad 2\ \text{ab}^{-1}$$

Soreq, Zhu, Zupan [1606.09621]

Phenomenology of diagonal Higgs Yukawas

- Bin-to-bin relative error effect

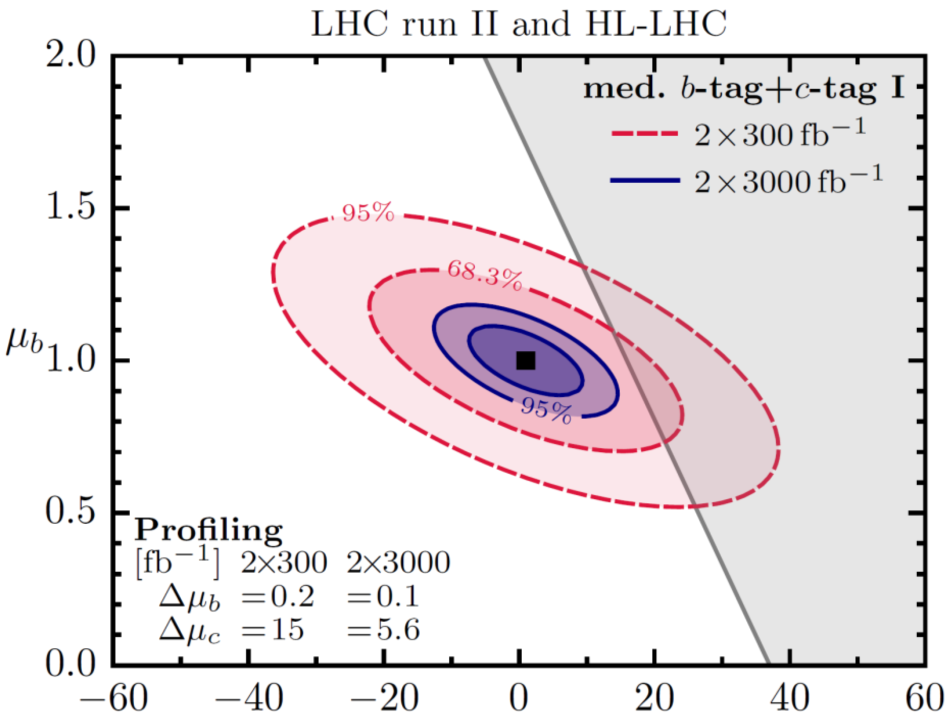


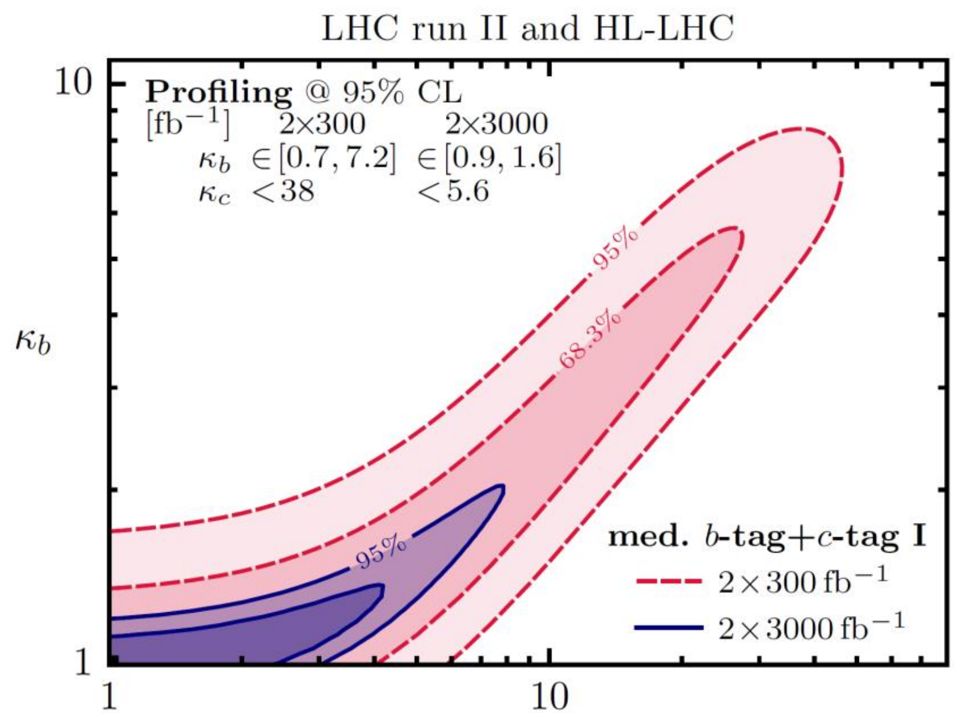
Soreq, Zhu, Zupan [1606.09621]

Testing quark Yukawas in Higgs decays

	ϵ_b	ϵ_c	ϵ_l
b-tagging	70%	20%	1.25%
c-tagging I	13%	19%	0.5%
c-tagging II	20%	30%	0.5%
c-tagging III	20%	50%	0.5%

- Directly measure in $q\bar{q}$ decays
  - Use bottom and charm tagging in tandem, profile over enhanced *c* content in Higgs decays





Perez, et. al. [1505.06689]

See slides by E. Reynolds, P. Ilten

Enhanced charm Yukawa in rare decays

- Indirectly measure in rare decays: *e.g.* h → J/ψ γ
  - Yukawa contribution interferes with loop-induced vertex with virtual γ/Z

Isidori, Manohar, Trott [1305.0663]
Kagan, Perez, Petriello, Soreq, Stoynev, Zupan [1406.1722]
Bodwin, Chung, Ee, Lee, Petriello [1407.6695]
Perez, Soreq, Stamou, Tobioka [1503.00290, 1505.06689]
König, Neubert [1505.03870]

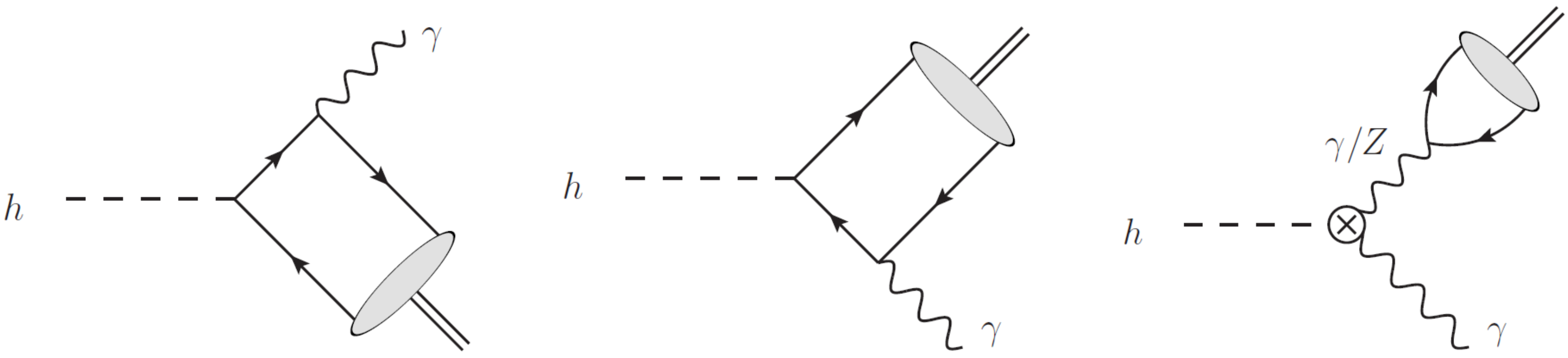


Fig. from König, Neubert [1505.03870]

Small SM rates, clean final state

$$\mathrm{Br}(h \to \phi\gamma) = (2.31 \pm 0.03_{f_\phi} \pm 0.11_{h\to\gamma\gamma}) \cdot 10^{-6}$$

$$\mathrm{Br}(h \to J/\psi\gamma) = (2.95 \pm 0.07_{f_{J/\psi}} \pm 0.06_{\text{direct}} \pm 0.14_{h\to\gamma\gamma}) \cdot 10^{-6}$$

$$\mathrm{Br}(h \to \Upsilon(1S)\gamma) = (4.61 \pm 0.06_{f_{\Upsilon(1S)}}\,{}^{+1.75}_{-1.21}{}_{\text{direct}} \pm 0.22_{h\to\gamma\gamma}) \cdot 10^{-9}$$

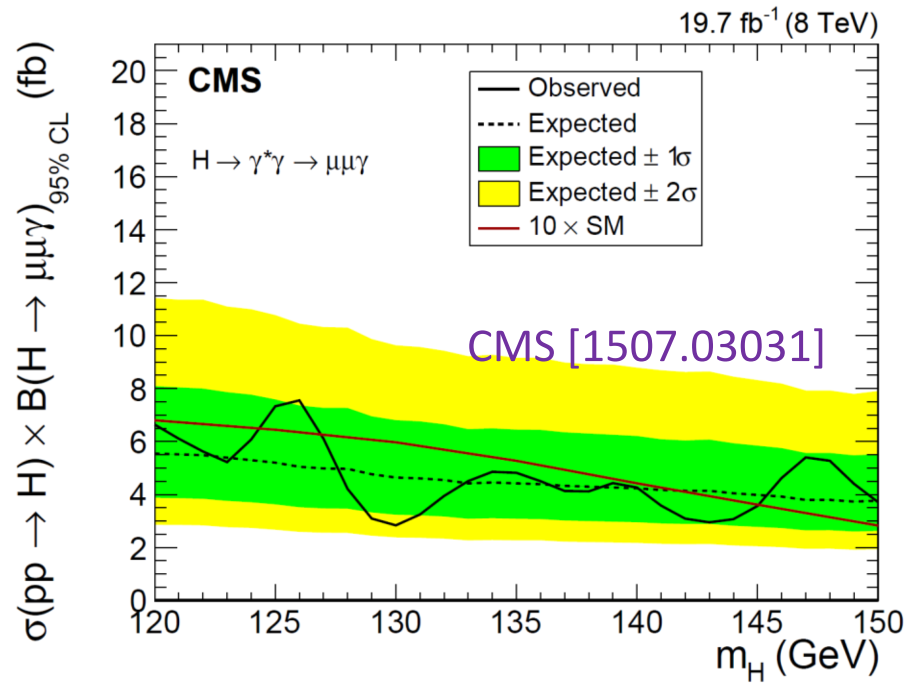
König, Neubert [1505.03870]

	95% CL Upper Limits				
	J/ψ	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\sum_n \Upsilon(nS)$
$\mathcal{B}(Z \to \mathcal{Q}\gamma)$ [10^{-6}]					
Expected	$2.0^{+1.0}_{-0.6}$	$4.9^{+2.5}_{-1.4}$	$6.2^{+3.2}_{-1.8}$	$5.4^{+2.7}_{-1.5}$	$8.8^{+4.7}_{-2.5}$
Observed	2.6	3.4	6.5	5.4	7.9
$\mathcal{B}(H \to \mathcal{Q}\gamma)$ [10^{-3}]					
Expected	$1.2^{+0.6}_{-0.3}$	$1.8^{+0.9}_{-0.5}$	$2.1^{+1.1}_{-0.6}$	$1.8^{+0.9}_{-0.5}$	$2.5^{+1.3}_{-0.7}$
Observed	1.5	1.3	1.9	1.3	2.0
$\sigma(pp \to H) \times \mathcal{B}(H \to \mathcal{Q}\gamma)$ [fb]					
Expected	26^{+12}_{-7}	38^{+19}_{-11}	45^{+24}_{-13}	38^{+19}_{-11}	54^{+27}_{-15}
Observed	33	29	41	28	44

Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to \phi\gamma)$ [10^{-3}]	$1.5^{+0.7}_{-0.4}$	1.4
$\mathcal{B}(Z \to \phi\gamma)$ [10^{-6}]	$4.4^{+2.0}_{-1.2}$	8.3

ATLAS [1501.03276]; [1607.03400]

$$\mathcal{B}(\mathrm{H} \to (\mathrm{J}/\psi)\gamma) < 1.5 \times 10^{-3}$$



CMS [1507.03031]

Higgs FCNCs and Higgs CPV

- FCNCs
  - Recall LHC searches of $h \to \tau\mu$ and $h \to \tau e$
  - LHC provides leading constraints on possible $t \to hc$ decays
- CPV
  - Observation of ttH invites study of Higgs CPV in top Yukawa coupling (apart from indirect constraint in eEDM)
  - Numerous possibilities for CPV in Higgs to taus

Harnik, Martin, Okui, Primulando, FY [1308.1094], refs. therein;
see slides by A. Martin from FNAL HL/HE-LHC in April, FY from CERN HL/HE-LHC in 2017

- Higgs width studies also critical for quark Yukawas
- Prospects for HE-LHC still unknown

Summary

- The SM flavor puzzle is ripe for testing by inventive Higgs physics searches
  - Not only searches for "known" decays, but also decays absent in the SM
- NP flavor puzzle is a critical open question – violation of SM flavor breaking pattern is generic
  - CPV connections with baryogenesis and EW phase transition
  - cf. possible connections with B-flavor anomalies?

CPV at dimension 6

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$(H^\dagger D_\mu H)^* (H^\dagger D_\mu H)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H\, W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8: (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \epsilon_{jk} (\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r) \epsilon_{jk} (\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r) \epsilon_{jk} (\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r) \epsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$

Alonso, Jenkins, Manohar, Trott [1312.2014]