INTERPLAY OF HIGGS AND FLAVOR PHYSICS

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KAIST-KAIX Workshop for Future Particle Accelerators
KAIST – July 11, 2019

The Higgs and Flavor Connection

- Prima facie connection
  - Higgs Yukawa couplings break global flavor symmetry of SM: $U(3)^5 \rightarrow U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$
  - Yukawa matrices provide the only flavored interactions in SM, resulting in CKM matrix for charged current

$$\mathcal{L} \supset \bar{Q}_L \, y_u \, \tilde{H} u_R + \bar{Q}_L H \, y_d \, d_R + \text{ h.c.}$$

$$= \bar{Q}_L V_u^\dagger \tilde{H} V_u \, y_u \, U_u^\dagger U_u u_R + \bar{Q}_L V_d^\dagger H V_d \, y_d \, U_d^\dagger U_d d_R + \text{ h.c.}$$

$$= \bar{Q}_L^m \tilde{H} \, y_u^{\text{diag}} \, u_R^m + \bar{Q}_L^m H \, y_d^{\text{diag}} \, d_R^m + \text{ h.c.}$$

$$V_{\text{CKM}} = V_u V_d^\dagger$$

The Higgs and Flavor Connection

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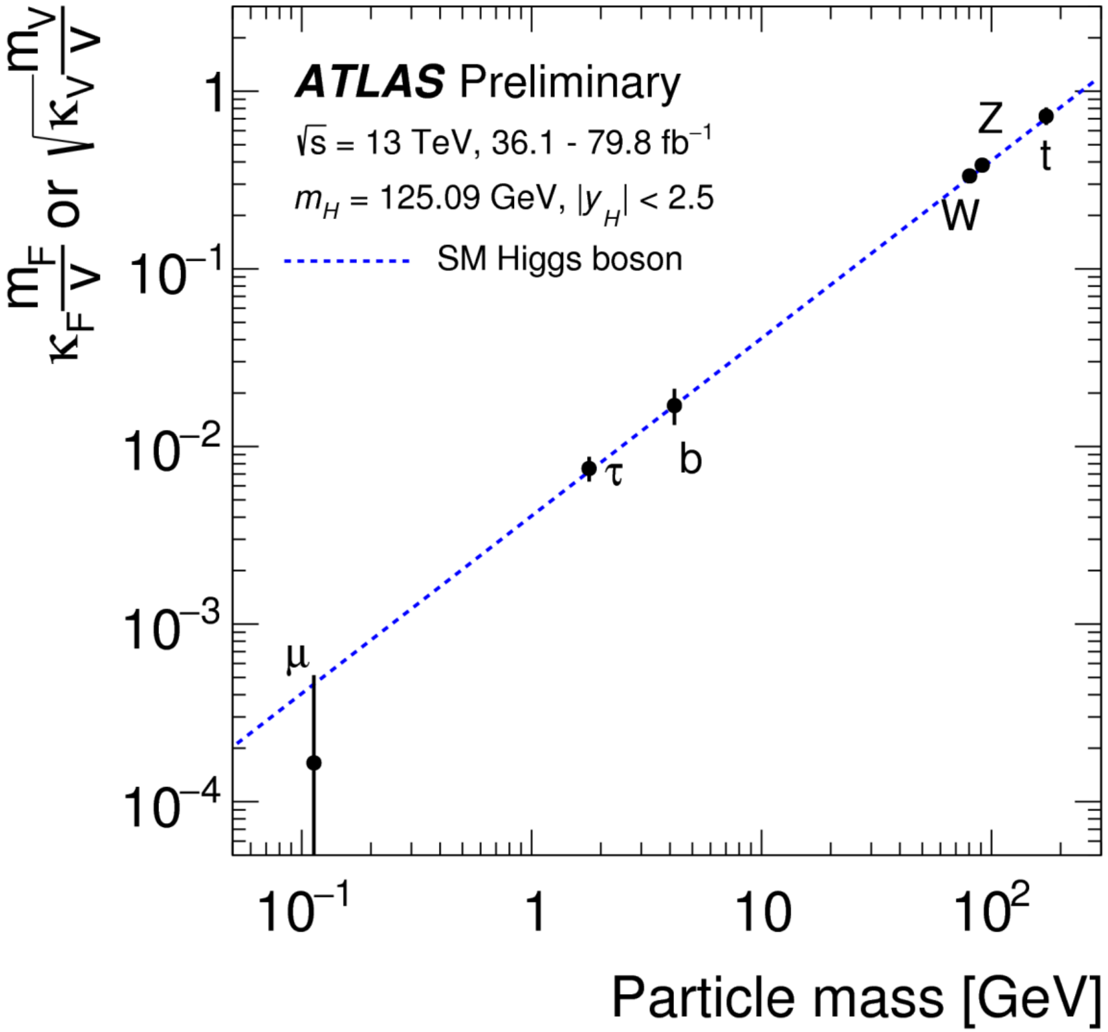
  - Yukawa matrices provide the only flavor interactions in SM, resulting in CKM matrix
- Yet, *inescapable* mechanism at play
  - No matter the Yukawa matrices (in gauge basis), large SM global symmetry structure dictates mass-coupling degeneracy for Higgs-fermion interactions
  - And guarantees absence of tree-level FCNCs

The SM Flavor Puzzle

ATLAS Higgs WG, Combined Summary Plot

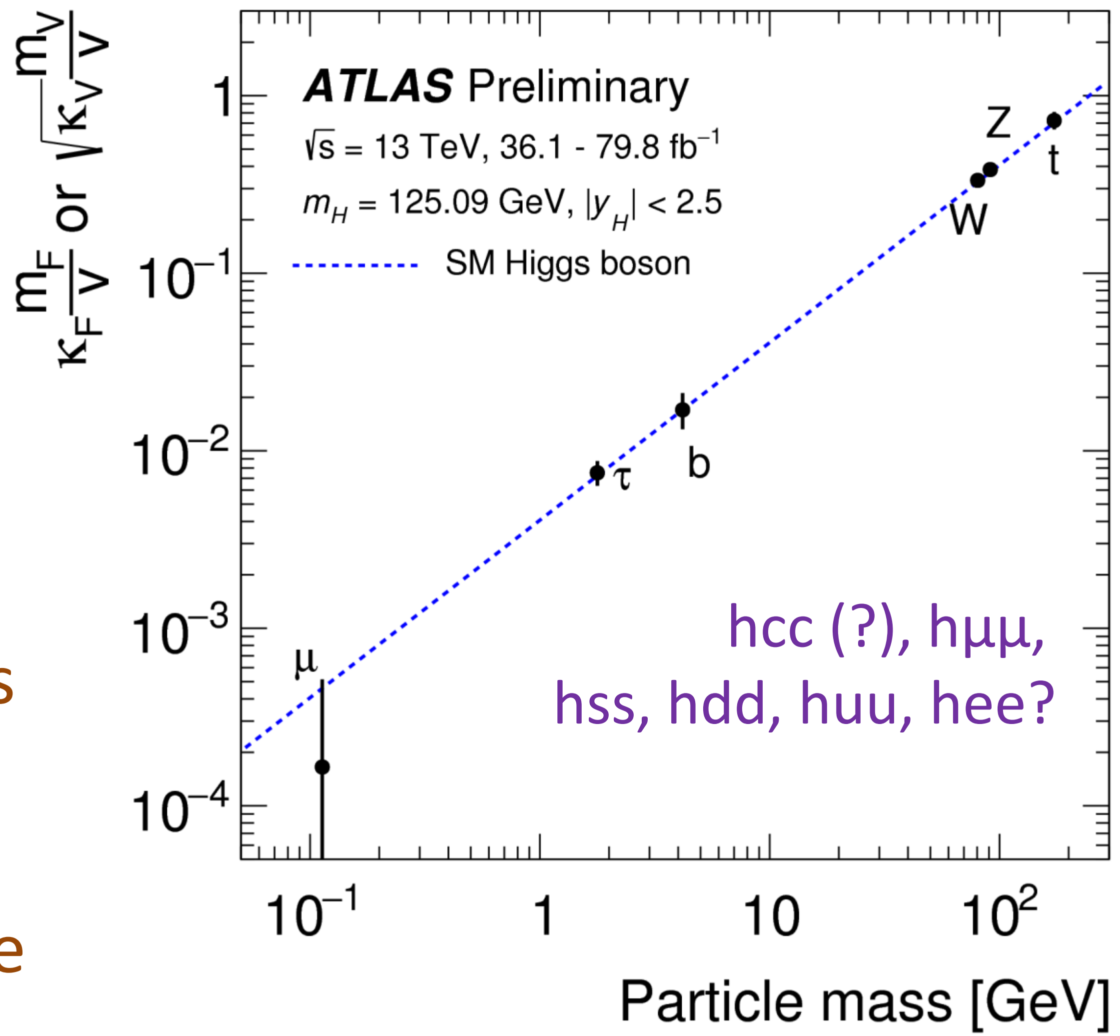
- Mass-coupling degeneracy well-supported by Higgs data
  - Known hierarchy in fermion masses, patterns of CKM mixing lack dynamical explanation



The SM Flavor Puzzle

ATLAS Higgs WG, Combined Summary Plot

- Mass-coupling degeneracy well-supported by Higgs data
  - Nevertheless, should continue program as far as we can go and cover all SM fermions possible



hcc (?), hμμ, hss, hdd, huu, hee?

Motivating non-standard Yukawas

- κ-framework to rescale SM Yukawa couplings seems innocuous – can simply write dim-4, renormalizable Higgs interactions
- In fact, any $\kappa \neq 1$ scenario provides no-lose scenario for New Physics

Motivating non-standard Yukawas

- SM fermions are chiral → mismatch between Yukawa coupling and mass leads to unitarity violation in $f\bar{f} \to VV$ scattering

Appelquist, Chanowitz, PRL **59**, 2405 (1987)

  - For example, W^+W^- scattering breaks unitarity at

$$E_f \simeq \frac{8\pi v^2}{\zeta |m_f - y_f v|}, \quad \begin{array}{ccll} \zeta & = & \sqrt{3} & \text{quarks} \\ \zeta & = & 1 & \text{leptons} \end{array}$$

    - As an example, bare top quark mass breaks unitarity at about 5 TeV

- UV completion needed to satisfy perturbative unitarity
  - e.g. 2HDM, vector-like fermion partners

Effects of non-standard Yukawas

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

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

  - 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

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

New Physics Flavor Problem

- One of the most significant problems in BSM pheno
  - In dim-6 SMEFT, can only exercise the global flavor rotations once
    - Recall that the form of the SM Yukawa matrices did not matter – guaranteed vanishing of FCNCs, mass-coupling degeneracy
    - Now, y_u, y_u', y_d, and y_d' are *each* arbitrary – not governed by any gauge symmetry

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

    - No dynamical expectation for an alignment between these matrices

D'Ambrosio, et al [hep-ph/0207036]

      - [Minimal flavor violation is an ansatz, not an answer]

Effects of 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 generically gives strongly constrained flavor effects
  - Break the mass-Yukawa proportionality
    - For light fermions, dominant Yukawa contribution can come from higher dimensional operator
    - In particular, $m_f / v \approx 10^{-5} - 10^{-1.5}$: why are SM decays falling into line?
  - New flavor-violating Higgs interactions
  - New CP-violating Higgs interactions

Dimension 6 CPV

Alonso, Jenkins, Manohar, Trott [1312.2014]
Also see Grzadowski, Iskrzynski, Misiak, Rosiek [1008.4884]
Henning, Lu, Melia, Murayama [1512.03433]

i.e. How expansive the NP flavor problem is

1: X^3	2: H^6	3: H^4D^2	4: X^2H^2
5: $\psi^2H^3 +$ h.c.	6: $\psi^2XH +$ h.c.	7: ψ^2H^2D	
8: $(\bar{L}L)(\bar{L}L)$	8: $(\bar{R}R)(\bar{R}R)$	8: $(\bar{L}L)(\bar{R}R)$	
8: $(\bar{L}R)(\bar{R}L) +$ h.c.	8: $(\bar{L}R)(\bar{L}R) +$ h.c.		

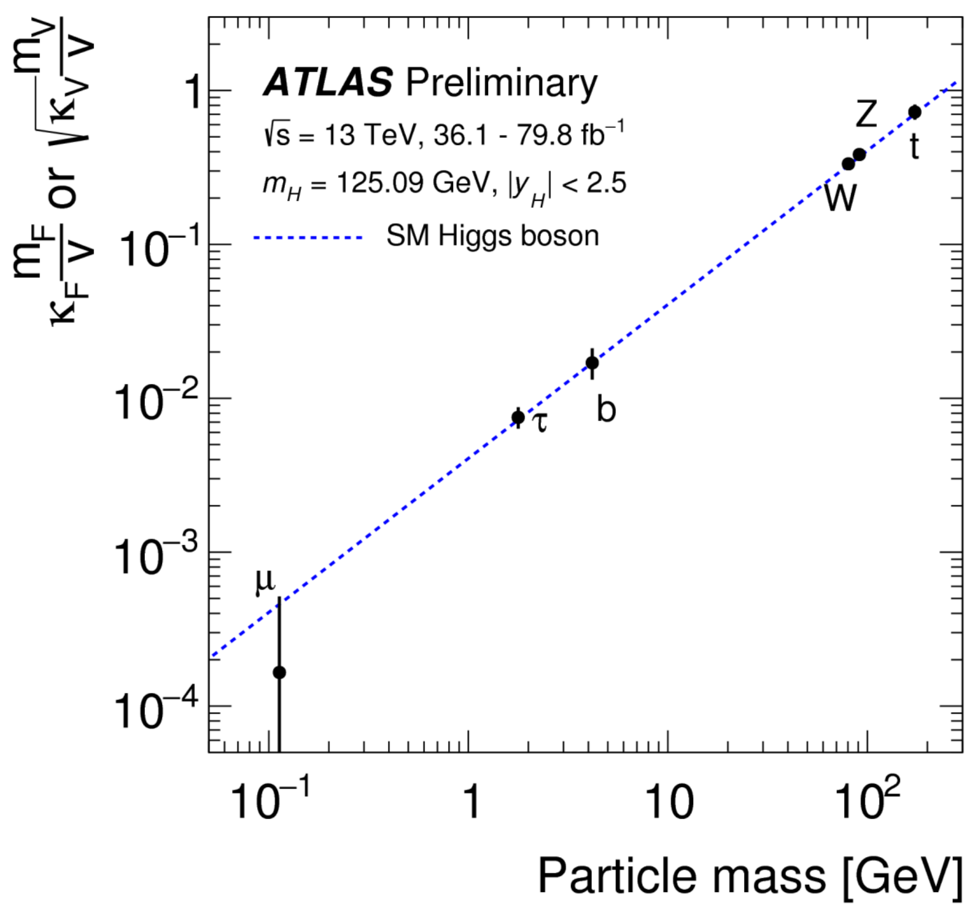
1350 CP-even, 1149-CP odd operators (B-conserving)

Class	N_{op}	CP-even n_g	1	3	CP-odd n_g	1	3
1	4	2	2	2	2	2	2
2	1	1	1	1	0	0	0
3	2	2	2	2	0	0	0
4	8	4	4	4	4	4	4
5	3	$3n_g^2$	3	27	$3n_g^2$	3	27
6	8	$8n_g^2$	8	72	$8n_g^2$	8	72
7	8	$\frac{1}{2}n_g(9n_g+7)$	8	51	$\frac{1}{2}n_g(9n_g-7)$	1	30
8 : $(\overline{L}L)(\overline{L}L)$	5	$\frac{1}{4}n_g^2(7n_g^2+13)$	5	171	$\frac{7}{4}n_g^2(n_g-1)(n_g+1)$	0	126
8 : $(\overline{R}R)(\overline{R}R)$	7	$\frac{1}{8}n_g(21n_g^3+2n_g^2+31n_g+2)$	7	255	$\frac{1}{8}n_g(21n_g+2)(n_g-1)(n_g+1)$	0	195
8 : $(\overline{L}L)(\overline{R}R)$	8	$4n_g^2(n_g^2+1)$	8	360	$4n_g^2(n_g-1)(n_g+1)$	0	288
8 : $(\overline{L}R)(\overline{R}L)$	1	n_g^4	1	81	n_g^4	1	81
8 : $(\overline{L}R)(\overline{L}R)$	4	$4n_g^4$	4	324	$4n_g^4$	4	324
8 : All	25	$\frac{1}{8}n_g(107n_g^3+2n_g^2+89n_g+2)$	25	1191	$\frac{1}{8}n_g(107n_g^3+2n_g^2-67n_g-2)$	5	1014
Total	59	$\frac{1}{8}(107n_g^4+2n_g^3+213n_g^2+30n_g+72)$	53	1350	$\frac{1}{8}(107n_g^4+2n_g^3+57n_g^2-30n_g+48)$	23	1149

Suite of Higgs NP signatures

- Test for deviations from predicted SM decays (Z. Liu, J. Gu talk)
- Test for presence of forbidden/vanishingly small SM decays
  - Light fermions (cc, μμ, ee)
  - Flavor violating
  - CP-violating (Stamou talk)
- (Test BSM states)
  - (Invisible/exotic decays, exotic production)

ATLAS Higgs WG, Combined Summary Plot



Curtin, et. al. [1312.4992]; FY [1404.2924]

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 FY [1609.06592]
- 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

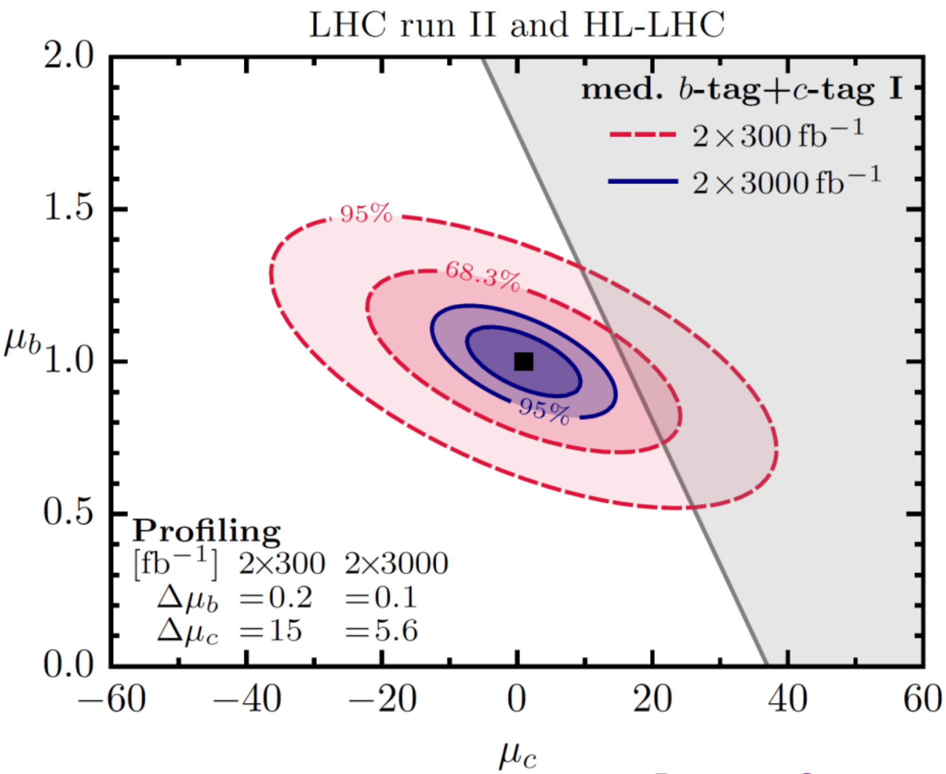
Phenomenology of diagonal Higgs Yukawas

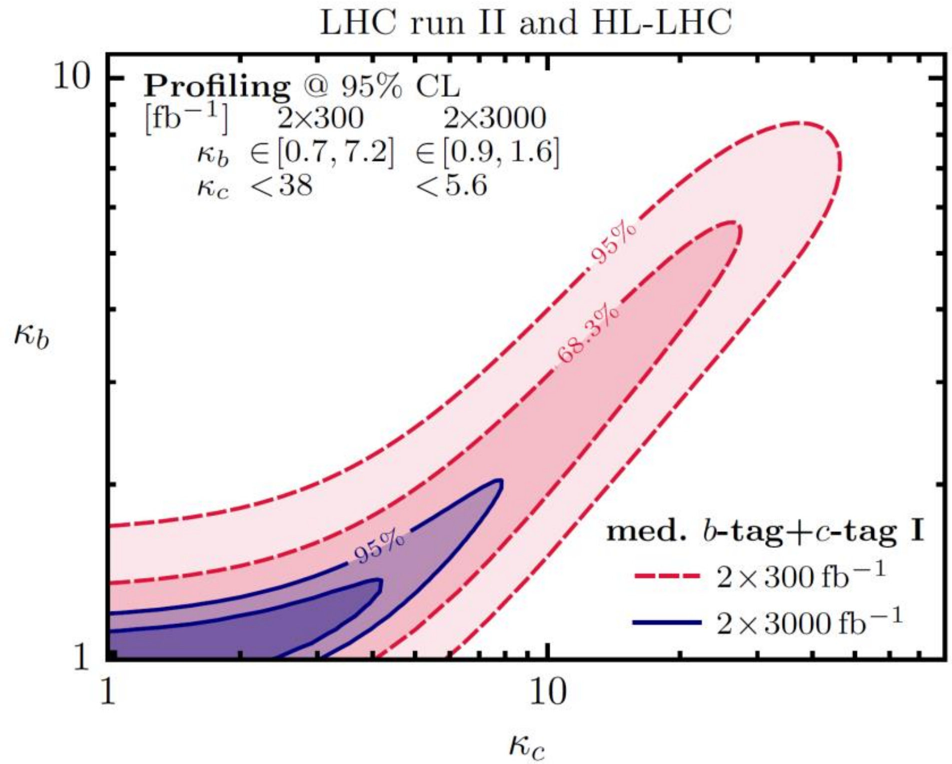
- Competition between enhanced production (leveraging quark PDFs) and depleted signal strength
  - Differentiates production-based probes vs. exclusive decays
  - Generally expect modifications to both total rates and differential distributions, if precision is attainable
- Production-based studies flesh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

Testing quark Yukawas in Higgs decays

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





Perez, Soreq, Stamou, Tobioka [1505.06689]

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]
Han, Wang [1704.00790]

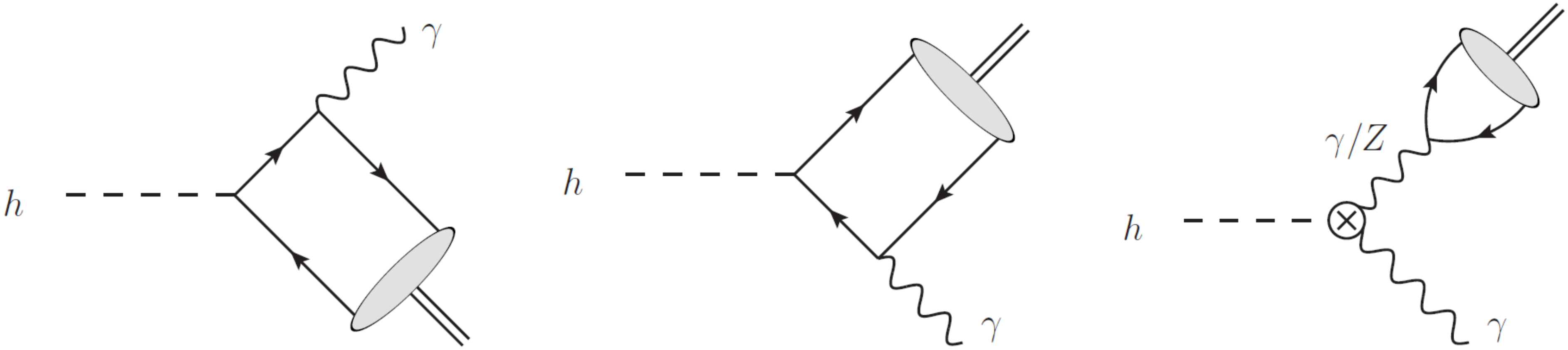


Fig. from König, Neubert [1505.03870]

Small SM rates, clean final state

König, Neubert [1505.03870]

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

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

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

ATLAS [1807.00802]

Branching fraction limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to J/\psi\,\gamma)\,[\,10^{-4}\,]$	$3.0^{+1.4}_{-0.8}$	3.5
$\mathcal{B}(H \to \psi(2S)\,\gamma)\,[\,10^{-4}\,]$	$15.6^{+7.7}_{-4.4}$	19.8
$\mathcal{B}(Z \to J/\psi\,\gamma)\,[\,10^{-6}\,]$	$1.1^{+0.5}_{-0.3}$	2.3
$\mathcal{B}(Z \to \psi(2S)\,\gamma)\,[\,10^{-6}\,]$	$6.0^{+2.7}_{-1.7}$	4.5
$\mathcal{B}(H \to \Upsilon(1S)\,\gamma)\,[\,10^{-4}\,]$	$5.0^{+2.4}_{-1.4}$	4.9
$\mathcal{B}(H \to \Upsilon(2S)\,\gamma)\,[\,10^{-4}\,]$	$6.2^{+3.0}_{-1.7}$	5.9
$\mathcal{B}(H \to \Upsilon(3S)\,\gamma)\,[\,10^{-4}\,]$	$5.0^{+2.5}_{-1.4}$	5.7
$\mathcal{B}(Z \to \Upsilon(1S)\,\gamma)\,[\,10^{-6}\,]$	$2.8^{+1.2}_{-0.8}$	2.8
$\mathcal{B}(Z \to \Upsilon(2S)\,\gamma)\,[\,10^{-6}\,]$	$3.8^{+1.6}_{-1.1}$	1.7
$\mathcal{B}(Z \to \Upsilon(3S)\,\gamma)\,[\,10^{-6}\,]$	$3.0^{+1.3}_{-0.8}$	4.8

CMS [1810.10056]

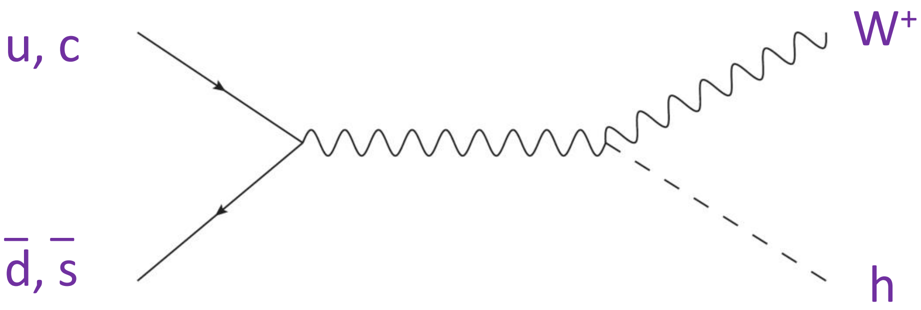
Channel	Polarization	σ (fb) at 95% CL	$\mathcal{B}(\mathrm{Z\ (H)} \to \mathrm{J}/\psi\gamma)$ at 95% CL	$\frac{\mathcal{B}(\mathrm{Z\ (H)}\to\mathrm{J}/\psi\gamma)}{\mathcal{B}_{\mathrm{SM}}(\mathrm{Z\ (H)}\to\mathrm{J}/\psi\gamma)}$
	Unpolarized	$4.6\ (5.3^{+2.3}_{-1.6})$	$1.4\ (1.6^{+0.7}_{-0.5}) \times 10^{-6}$	15 (18)
$\mathrm{Z} \to \mathrm{J}/\psi\gamma$	Transverse	$5.0\ (5.9^{+2.5}_{-1.7})$	$1.5\ (1.7^{+0.7}_{-0.5}) \times 10^{-6}$	16 (19)
	Longitudinal	$3.9\ (4.6^{+2.0}_{-1.4})$	$1.2\ (1.4^{+0.6}_{-0.4}) \times 10^{-6}$	13 (15)
$\mathrm{H} \to \mathrm{J}/\psi\gamma$	Transverse	$2.5\ (1.7^{+0.8}_{-0.5})$	$7.6\ (5.2^{+2.4}_{-1.6}) \times 10^{-4}$	260 (170)

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

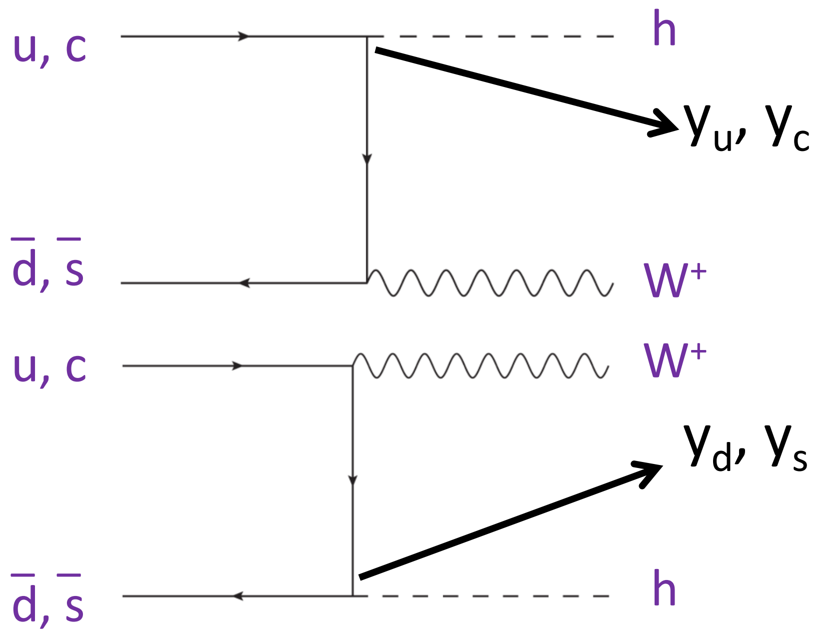
- $W^\pm h$ production asymmetric at LHC
  - Asymmetry driven by proton PDFs
  - Consider $W^+ h$:
    - (Unitarity violation requires NP completion)

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

Higgs XSWG



Insensitive to Yukawas



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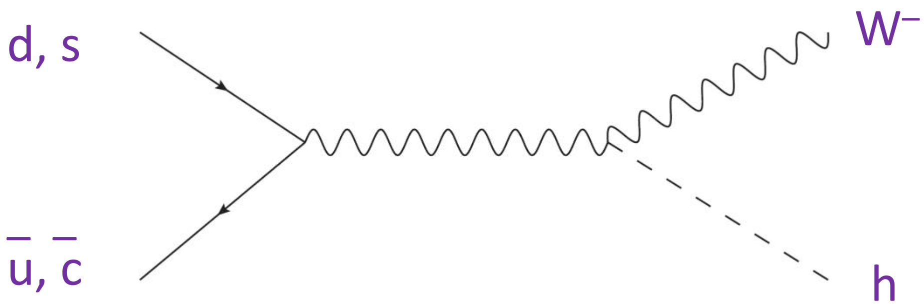

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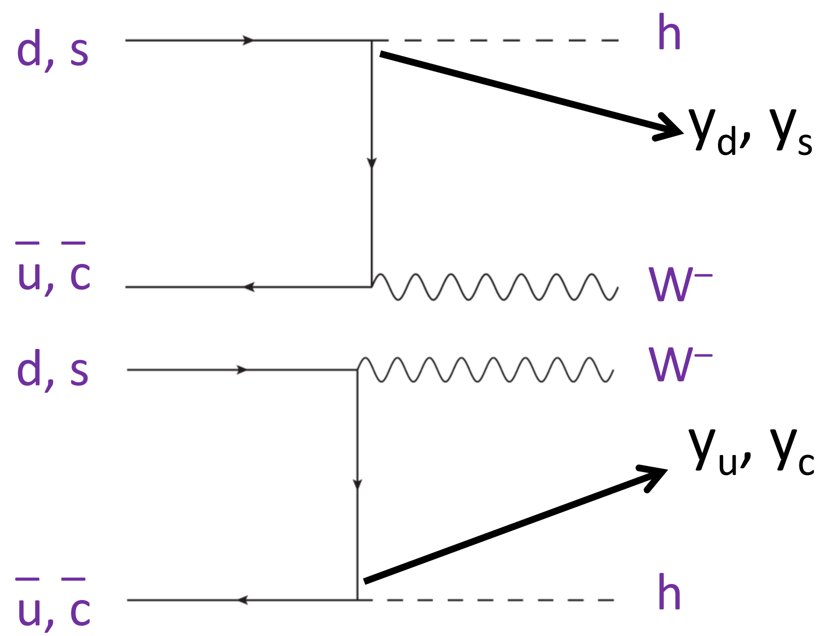
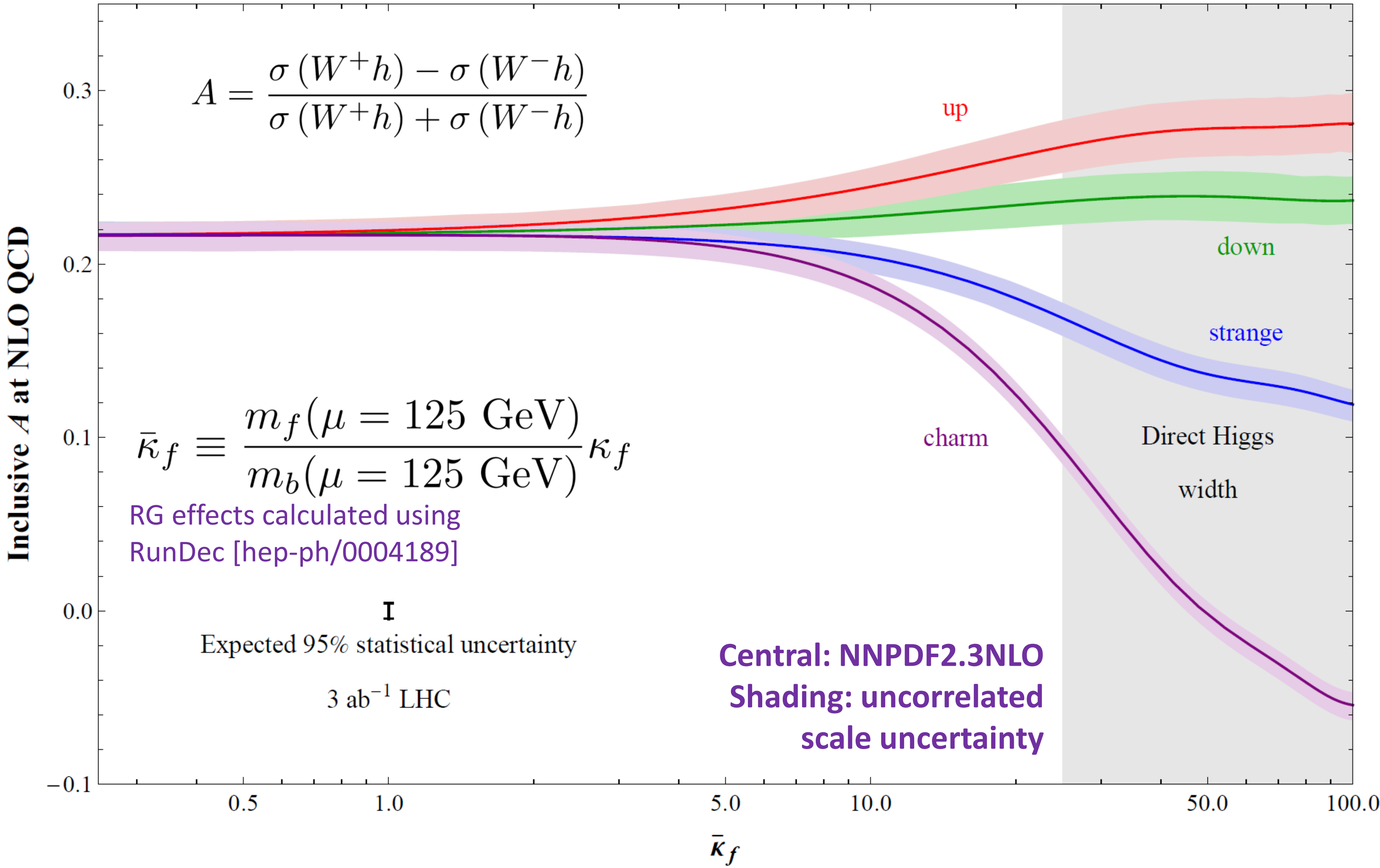


NLO Inclusive charge asymmetry



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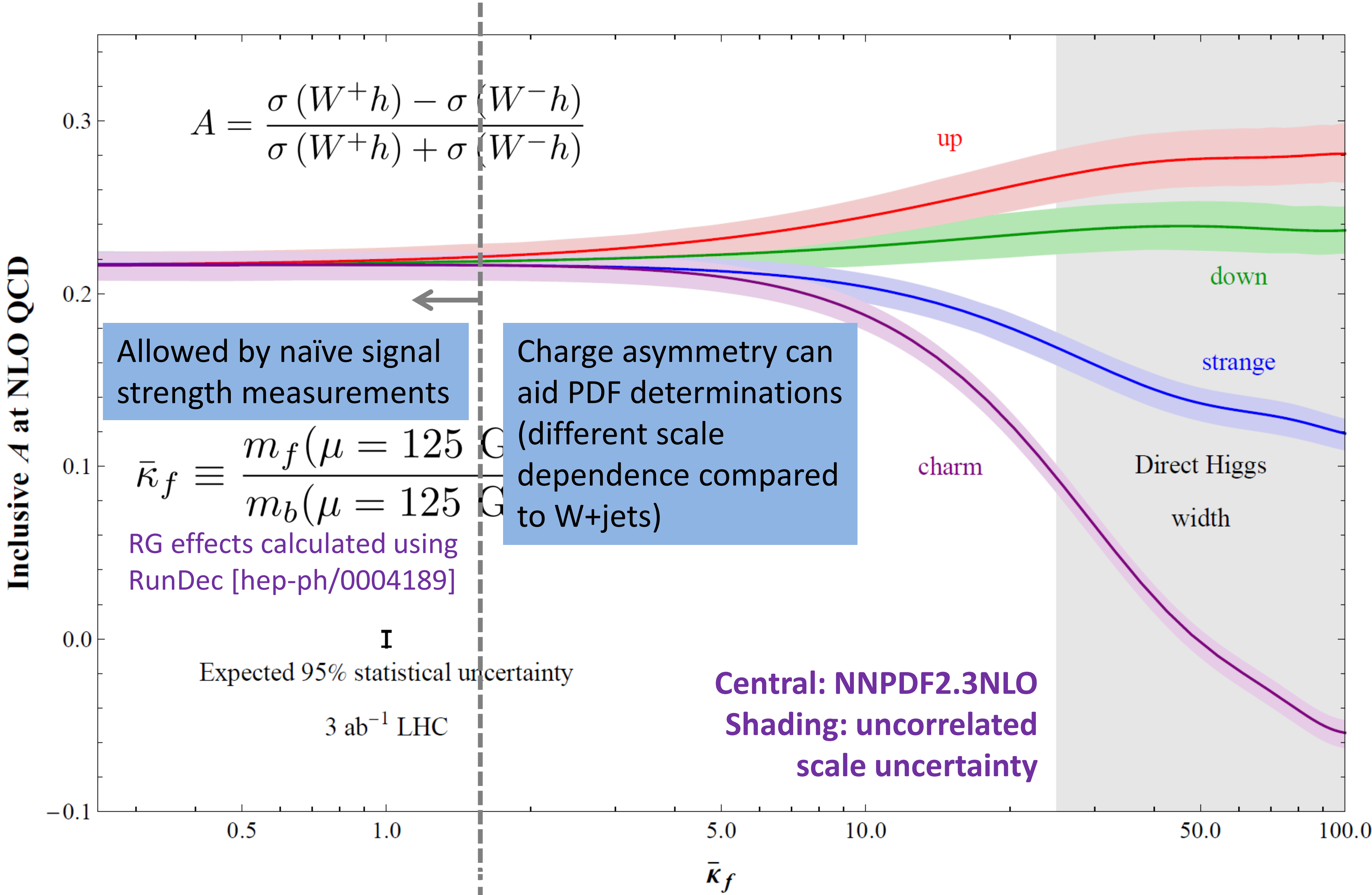
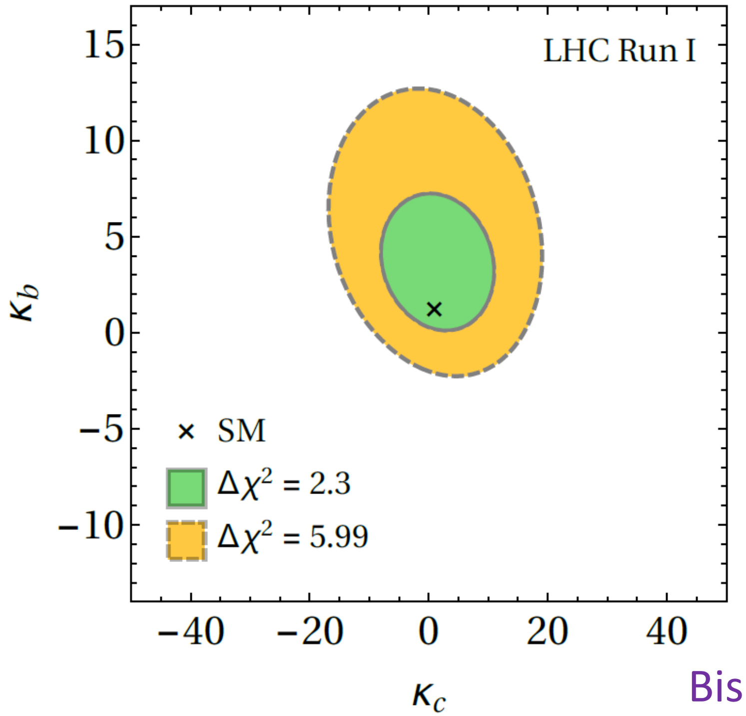


Phenomenology of diagonal Higgs Yukawas

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



Bishara, Haisch, Monni, Re [1606.09253]

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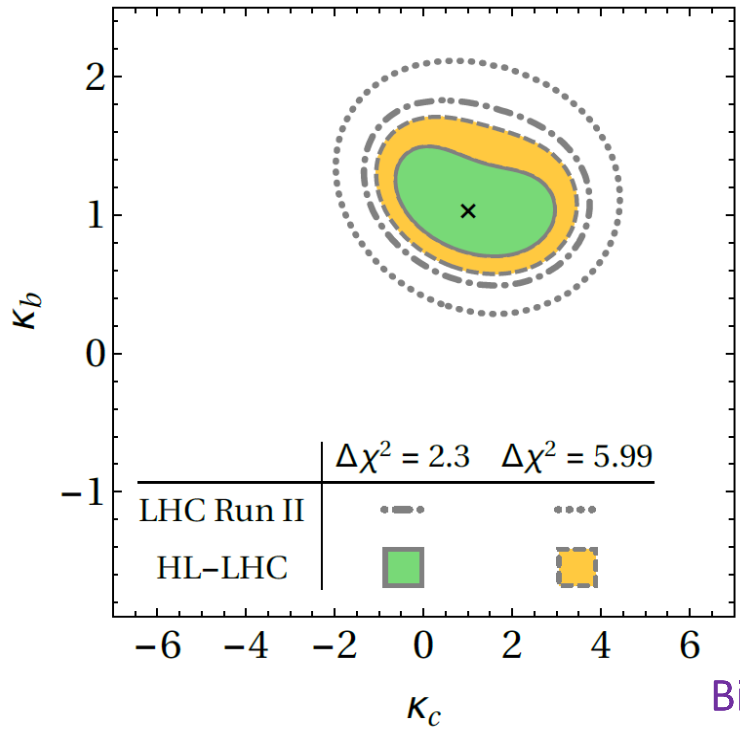
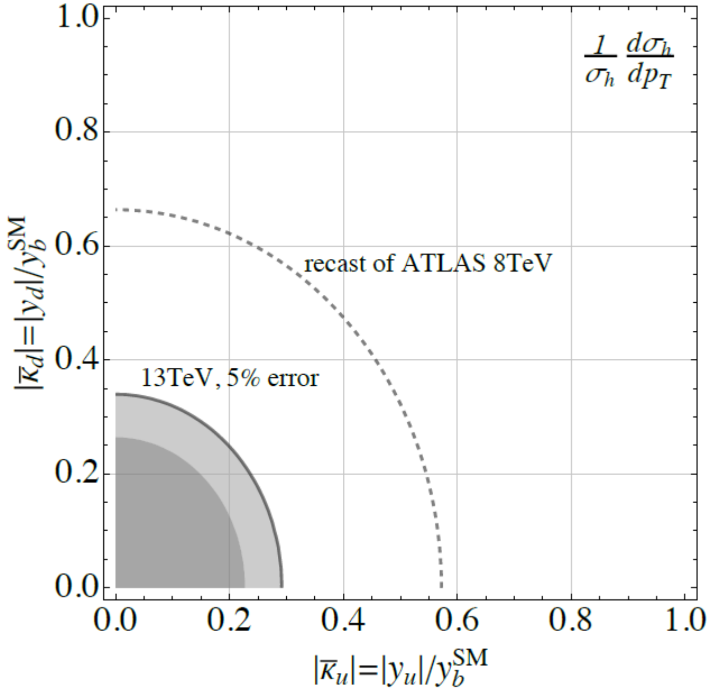


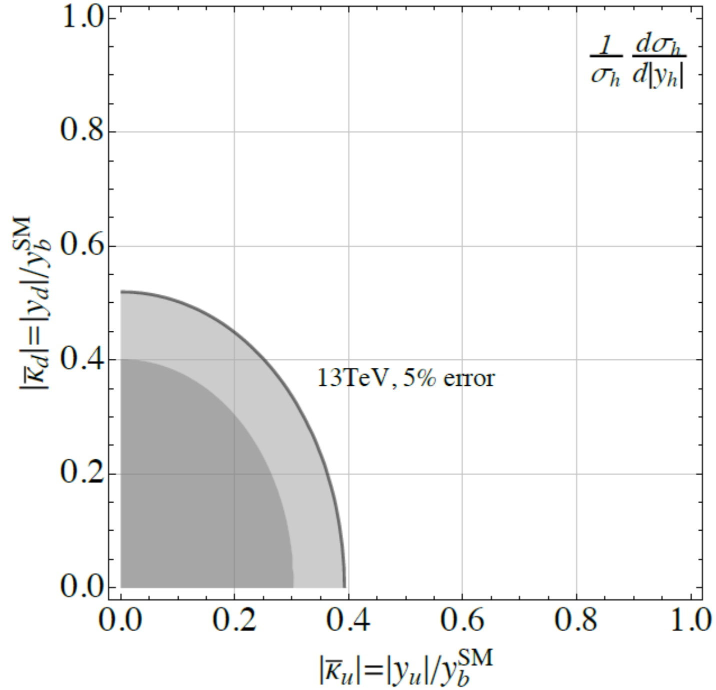
$\kappa_c \sim [-2.9, 4.2]$ HL-LHC

Bishara, Haisch, Monni, Re [1606.09253]

Phenomenology of diagonal Higgs Yukawas

- Use normalized $p_{T,h}$ and y_h distributions
  - Continuing theory calculations needed to push uncertainties





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

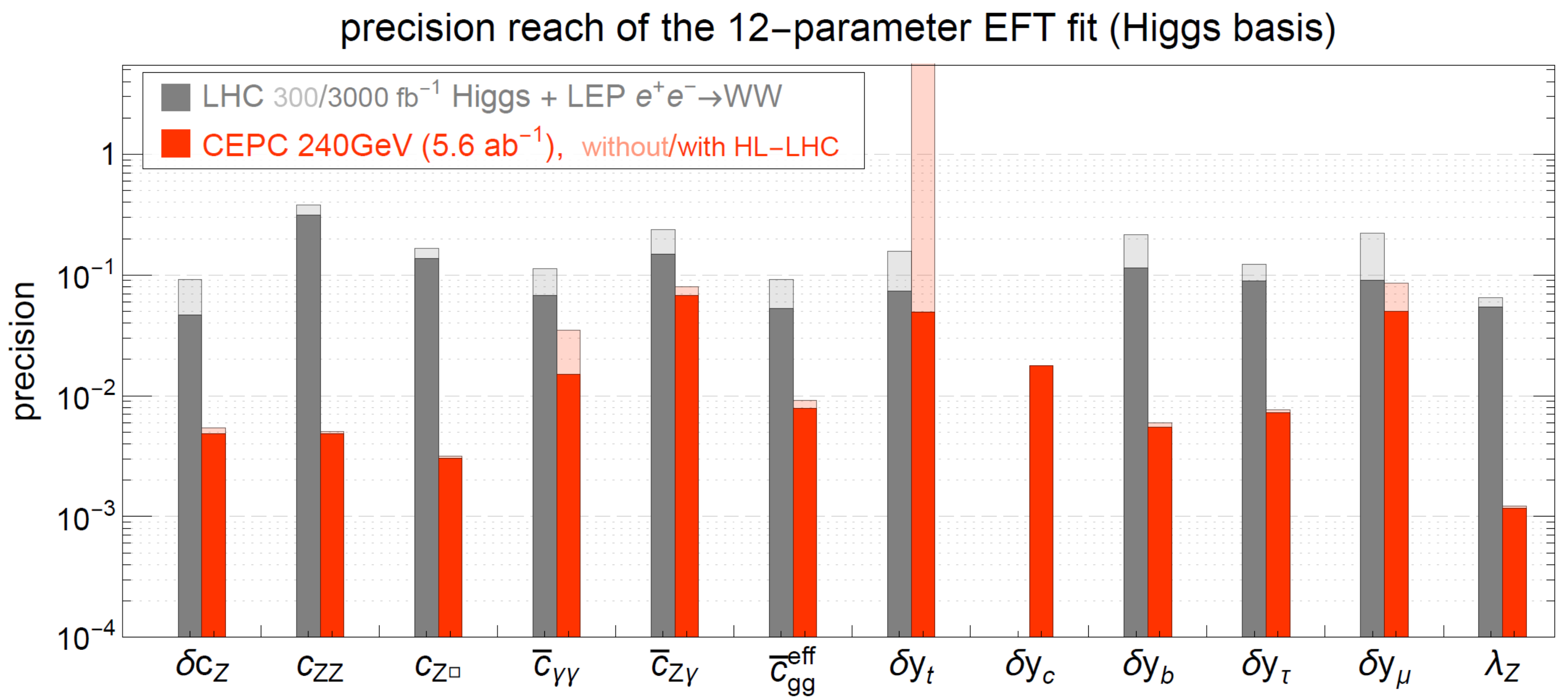
$$y: \quad \bar{\kappa}_u < 0.36, \bar{\kappa}_d < 0.47 \quad 2\ \mathrm{ab}^{-1}$$

Soreq, Zhu, Zupan [1606.09621]

Future collider sensitivity

CEPC CDR [1811.10545]

- Much better sensitivity to charm and muon at e^+e^- machine



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

    Ibrahim, Itani, Nath, Zorik [1703.04457]
  - Clean e^+e^- environment can access $h \to bs$, bd decays

    Barducci, Helmboldt [1710.06657]
- 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;
    - ATLAS estimates ±18° (aggressive), ±33° (conservative) at HL-LHC, assuming only stat. uncertainty

    ATL-PHYS-PUB-2019-008
- Higgs width studies also critical for quark Yukawas

Summary

- Huge variety of "SM zeroes" which can also be tested in Higgs physics
  - Light 2nd and 1st generation Yukawa couplings
    - Most studies focus on (HL-)LHC reach, selective attention on for future colliders
  - FCNCs, CPV – studied in conjunction with low energy probes
- Higgs-Flavor program at Higgs factory still under progress
- NP flavor problem 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?

Any $\kappa \neq 1$ discovery provides no-lose scenario for New Physics – ties discovery at Higgs factory with (very) high energy machine

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}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
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}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
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}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

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

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
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]

Phenomenological perspective

- SM is entirely predictive for a huge range of possible Higgs production and decay channels
  - Yukawa-mediated two-body decays
    - bb, cc, ττ, μμ, ee (tt, ss, uu, dd)

    Test Yukawa patterns, CPV phases
  - Vector coupling-induced decays
    - 4l, lνlν, lνqq

    Test EWSB, probe VV unitarization, additional Higgs states, CPV
  - Loop-induced decays
    - gg, γγ, Zγ

    Test new colored states, new EM charged states
    Mass generation/mixing of new matter
  - Rare decays
    - J/ψ γ, ϒγ, ϕγ

    Test Yukawa couplings, loop-induced couplings

Suite of Higgs modes to study

- EW dibosons — See, e.g. Anderson, *et. al.* [1309.4819]
  - Probe in both decays and production, especially VBF and VH (using crossing symmetry)
  - Part of general study of differential distributions to test momentum-dependent form factors
- ttH — See, e.g. Buckley, Goncalves [1507.07926]
  - Dileptonic tt final state with H→bb jet substructure
- Zγ — Farina, Grossman, Robinson [1503.06470]
  - Take advantage of interference between continuum background and signal from gluon initiated events
- gg — Dolan, Harris, Jankowiak, Spannowsky [1406.3322]
  - Use associated jets for angular analysis
- γγ — Bishara, Grossman, Harnik, Robinson, Shu, Zupan [1312.2955]
  - Require converted photons (detector material) and angular resolution on leptonic opening angles
- bb, cc, etc. — Galanti, Giammanco, Grossman, Kats, Stamou, Zupan [1505.02771]
  - Can possible overcome QCD wash-out of quark polarization

CPV in HVV interactions at future colliders

- Comparison for e^+e^- and pp

TABLE III: List of f_{CP} values in HVV couplings expected to be observed with 3σ significance and the corresponding uncertainties δf_{CP} for several collider scenarios, with the exception of $V^* \to VH$ mode at pp 300 fb^{-1} where the simulated measurement does not quite reach 3σ. Numerical estimates are given for the effective couplings Hgg, $H\gamma\gamma$, $HZ\gamma$, HZZ/HWW, assuming custodial Z/W symmetry and using HZZ couplings as the reference. The ✓ mark indicates that a measurement is in principle possible but is not covered in this study.

			HZZ/HWW						Hgg		$HZ\gamma$	$H\gamma\gamma$	
collider	energy	$\mathcal{L}$	$H \to VV^*$		$V^* \to VH$		$V^*V^* \to H$		$gg \to H$		$H \to Z\gamma$	$\gamma\gamma \to H$	$H \to \gamma\gamma$
	GeV	fb^{-1}	f_{CP}	δf_{CP}	f_{CP}	δf_{CP}	f_{CP}	δf_{CP}	f_{CP}	δf_{CP}			
pp	14 000	300	0.18	0.06	6×10^{-4}	4×10^{-4}	18×10^{-4}	7×10^{-4}	–	0.50			
pp	14 000	3 000	0.06	0.02	3.7×10^{-4}	1.2×10^{-4}	4.1×10^{-4}	1.3×10^{-4}	0.50	0.16	✓		✓
e^+e^-	250	250	✓		21×10^{-4}	7×10^{-4}	✓						
e^+e^-	350	350	✓		3.4×10^{-4}	1.1×10^{-4}	✓						
e^+e^-	500	500	✓		11×10^{-5}	4×10^{-5}	✓						
e^+e^-	1 000	1 000	✓		20×10^{-6}	8×10^{-6}	✓						
$\gamma\gamma$	125		✓									✓	

Anderson, *et. al.* [1309.4819]