FUTURE HIGGS MEASUREMENTS AT COLLIDERS

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Central Importance of Higgs Physics

- Ultimate challenge/opportunity of Higgs physics: $|H|^2$ operator
  - Higgs potential provides the only scale in EW Lagrangian
  - Renormalization of $|H|^2$ (D=2) operator in D=4 QFT underpins hierarchy problem
  - Simplest gauge invariant operator gives attractive motivation for Higgs portal physics
- Many outstanding problems in the SM arise from Higgs sector
  - EWSB and perturbative unitarity
  - Chiral fermion masses
  - EW phase transition and CP violation for baryogenesis
  - Neutrino masses
  - Vacuum stability

Central Importance of Higgs Physics

- Ultimate challenge/opportunity of Higgs physics: $|H|^2$ operator
  - – SUSY is best candidate for stabilizing the weak scale
    - Elegantly embeds SM Higgs into chiral superfield, with corresponding chiral symmetry removes the quadratic divergence
  - – Composite Higgs softens the divergence by prescribing a lower cutoff of the theory and reducing the anomalous dimension
  - – [More recent proposals, a la relaxion, focus on dynamical interplay between cosmological evolution and scalar field excursion, not specific to Higgs potential]

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)
  - Vector coupling-induced decays
    - 4l, lνlν, lνqq
  - Loop-induced decays
    - gg, γγ, Zγ
  - Rare decays
    - J/ψ γ, ϒγ, ϕγ

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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

Phenomenological perspective

- Moreover, huge variety of “SM zeroes” which can also be tested in Higgs physics
  - Flavor violating decays (τμ, τe, …)
  - CP-violation (VV*, ττ, ttH)
  - Invisible decays to DM particles
  - Exotic production modes

Example: new physics flavor puzzle and the |H|^2 thorn

- Consider $N_f = 3$ dim-6 Lagrangian

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

- The flavor structures of y_u', y_l', y_d' are not governed by any gauge symmetry
  - Have not expanded the global symmetry structure either

Example: new physics flavor puzzle and the |H|^2 thorn

- Consider $N_f = 3$ dim-6 Lagrangian
- One linear combination of Yukawa matrices gives diagonal masses

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

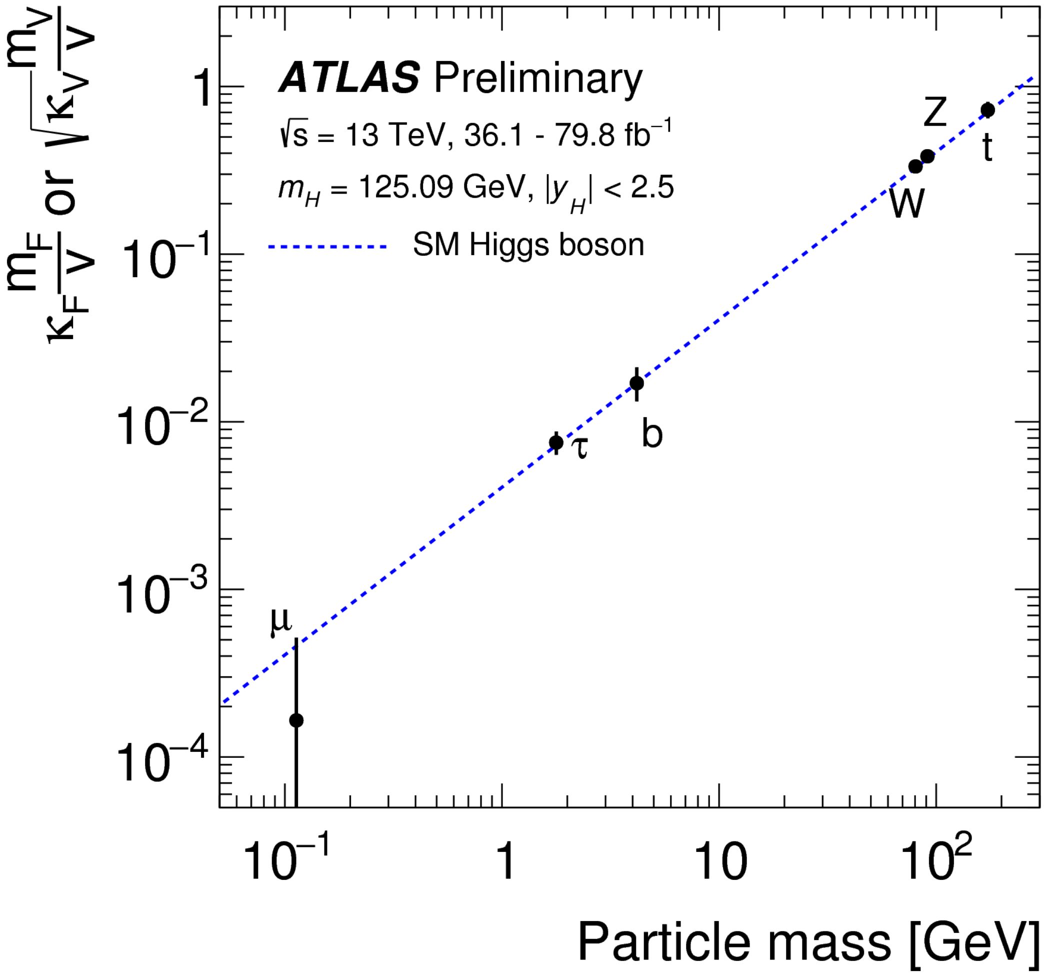
- Corresponding effective Yukawa interactions are generally not diagonal, CP-conserving, aligned

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

  - Fine-tune mass generation ↔ large BSM effects
- – In particular, $m_f / v \approx 10^{-5} – 10^{-1.5}$: why are SM decays falling into line?

Harnik, Martin, Okui, Primulando, FY [1308.1094]; FY [1609.06592]

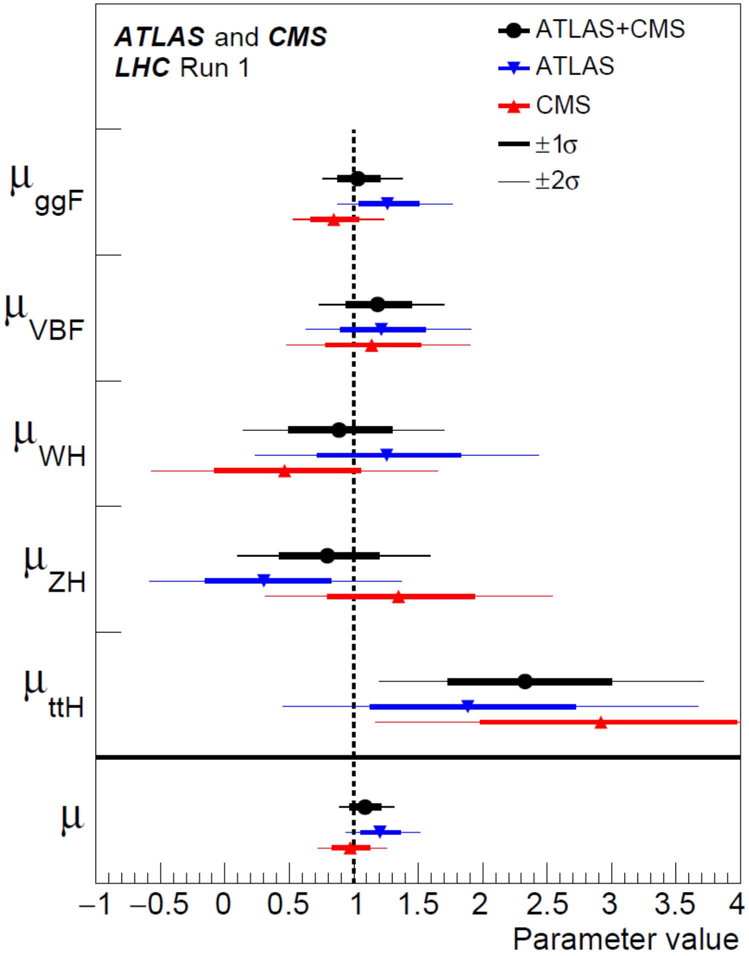
Reminder: Current status



Reminder: Current status

ATLAS, CMS [1606.02266]

- Recall ggF (and diphoton decay) is non-decoupling for new chiral matter
  - cf. Low energy theorem
  - If deviation is observed that is not quantized in units of SM chiral matter, *must* have a new mass scale beyond EW scale



$$\mu = 1.09 \pm 0.07\,(\mathrm{stat}) \pm 0.04\,(\mathrm{expt})$$
$$\pm 0.03\,(\mathrm{thbgd})^{+0.07}_{-0.06}\,(\mathrm{thsig})$$

Collider difference: pp vs. ee vs. ep

- At pp, ep colliders, longitudinal boost is not fixed
  - Leads to ambiguity of COM frame for 2-to-N production
- At ee colliders, COM is lab frame
  - For desired process e+e- → Zh, can choose events with $(p_{e+} + p_{e-} - p_Z)^2 = (125\ \text{GeV})^2$ to select a *fully inclusive* Higgs event selection [recoil-mass method]
- For given final state, get

$$N_{\text{events}} = \mathcal{L}\sigma \times B \propto \frac{g_p^2 g_d^2}{\Gamma_{\text{tot}}} \sim \frac{g_p^2 g_d^2}{\sum_i \Gamma_{i,\text{vis}} + \Gamma_{\text{unobs}}}$$

Collider difference: pp vs. ee vs. ep

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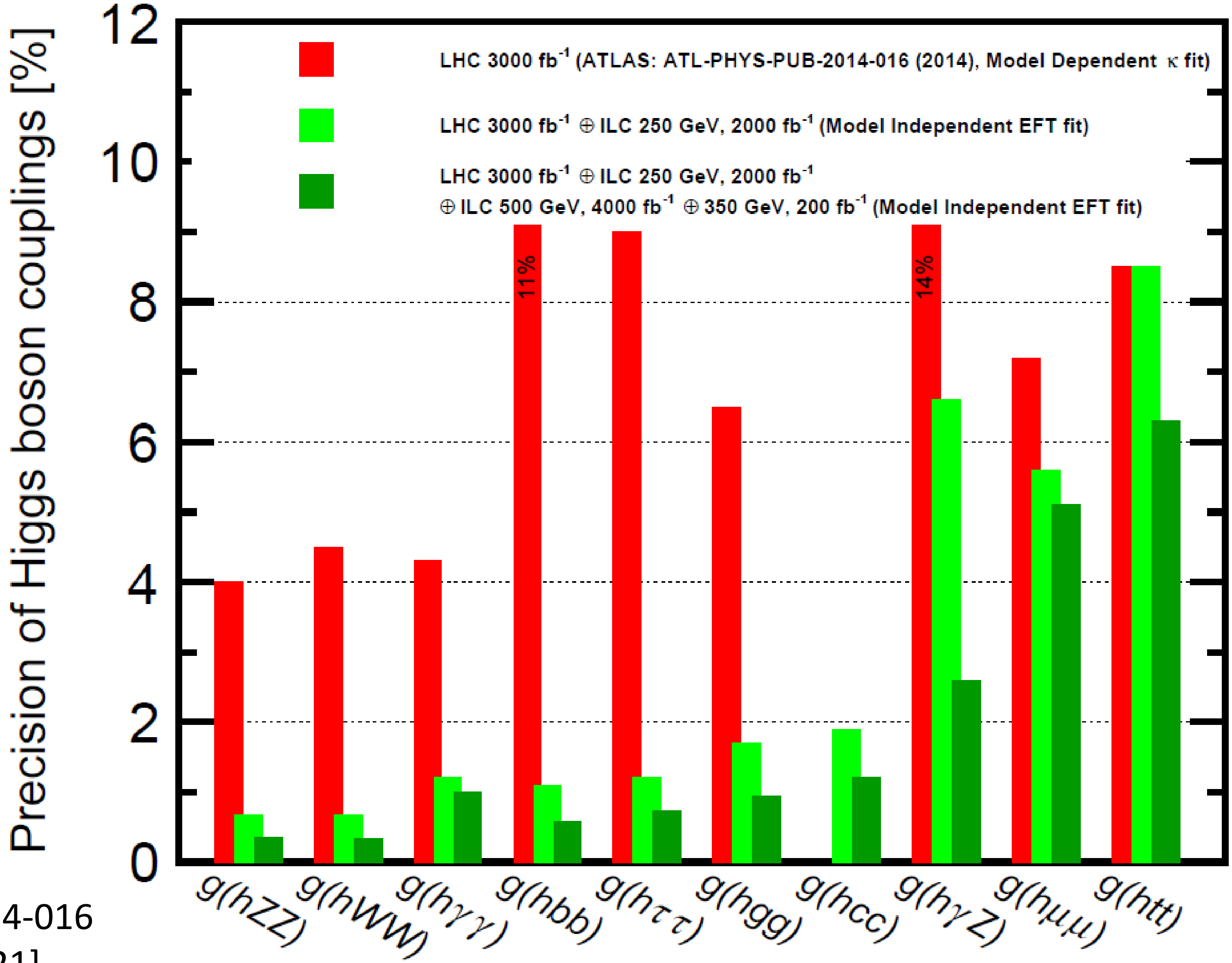
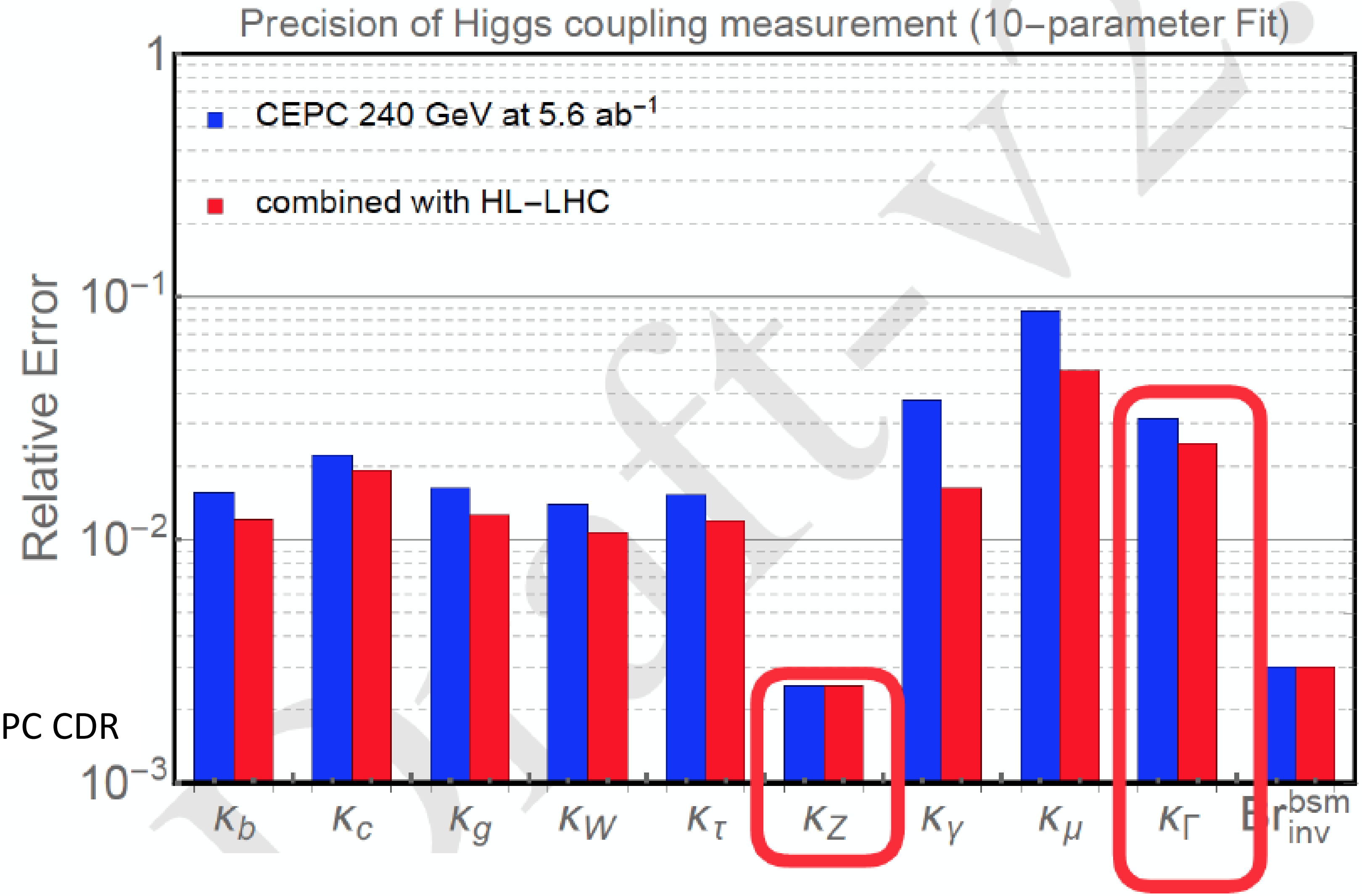
  - At pp, ep colliders, require additional assumption about contribution of Γ_{unobs} to extract Higgs couplings
  - At ee collider, simply measure h→ZZ* and take ratio to extract total width
- Model-indepent width extraction is a key aspect of ee collider Higgs physics compared to pp, ep

Collider difference: pp vs. ee vs. ep



ATL-PHYS-PUB-2014-016
and ILC [1710.07621]

Collider difference: pp vs. ee vs. ep



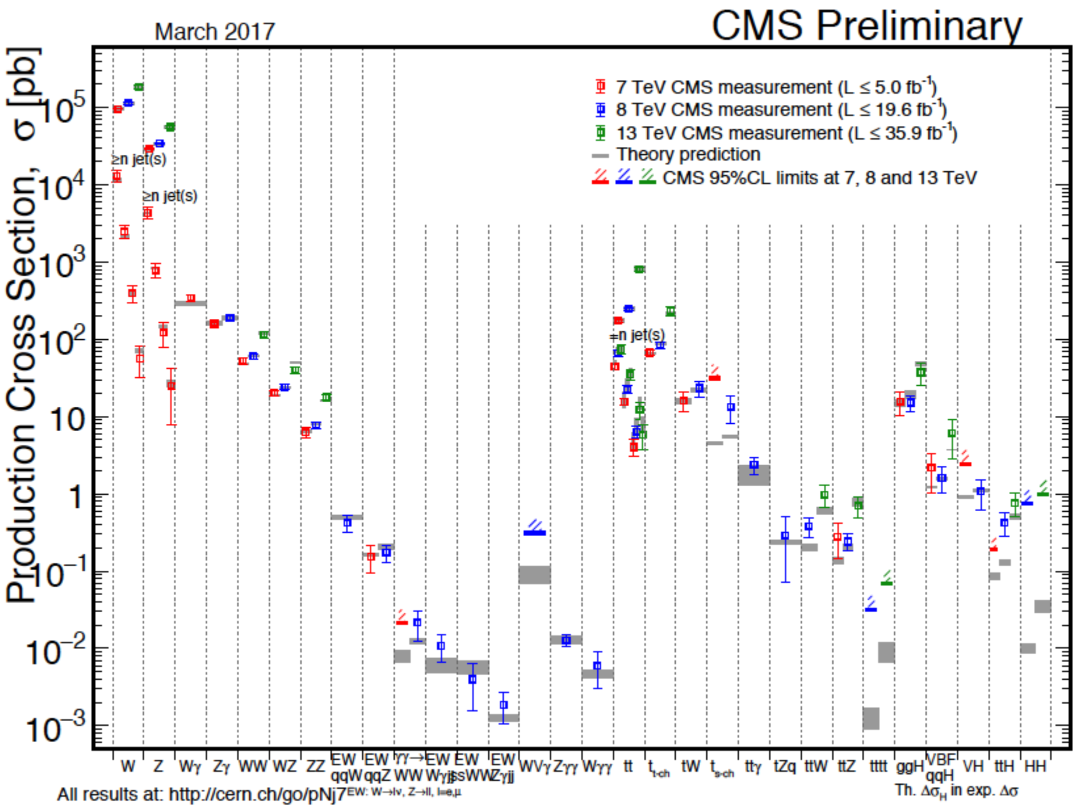
See slides by
M. Ruan or
upcoming CEPC CDR

Collider difference: pp vs. ee vs. ep

- On the other hand, rare decays, exotic production are better probed at pp colliders
  - Simply reflects huge statistics (O(500k-1M) Higgs bosons @ ee vs. O(150M) HL-LHC)
- Many additional directions motivate deviations in Higgs physics
    - Additional scalars – Rui Santos
    - VH discussion – Andreas Papaefstathiou
    - Triple Higgs coupling – Julien Baglio
    - Higgs portal – Rohini Godbole

Recap

- Every discovery machine has been followed by a precision machine
- The Standard Model $|H|^2$ is the most difficult operator we have; progress begs the best precision we can obtain with future colliders



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], talk by Sakurai
  - 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

Dimension 6 CPV

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

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			CP-odd		
		n_g	1	3	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

CPV in HVV interactions at future colliders

- Comparison for e^+e^- and pp

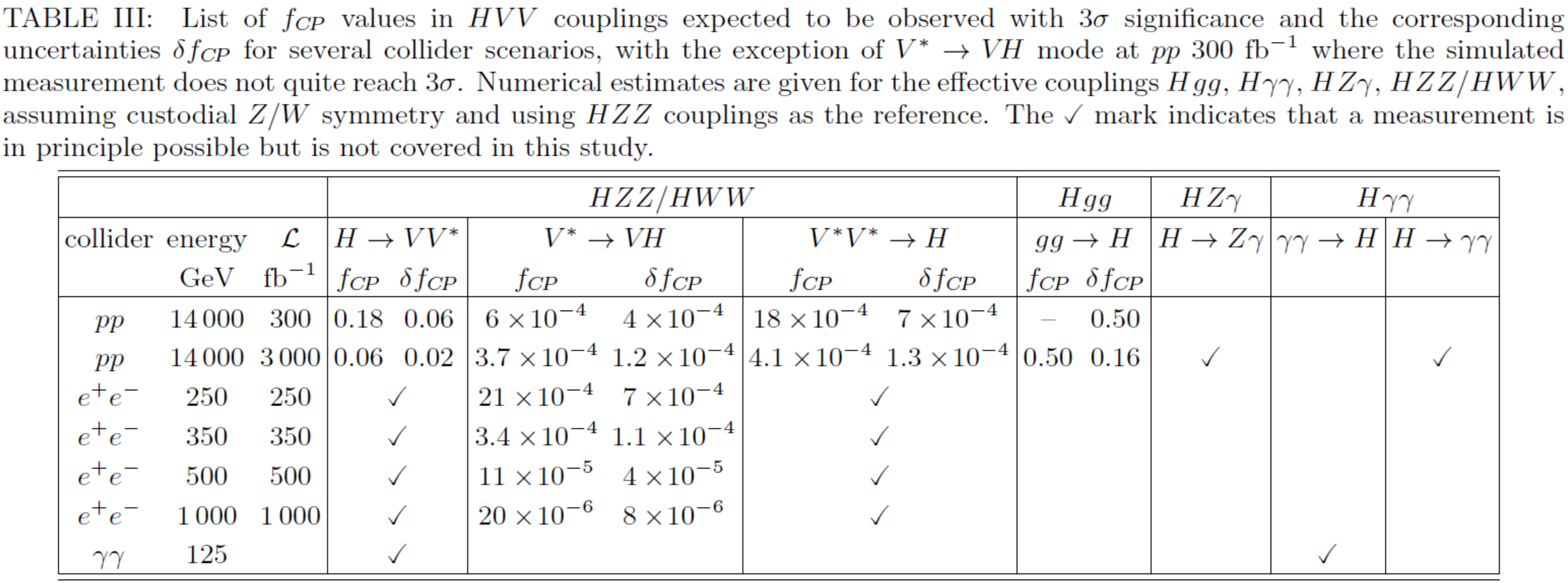


TABLE III: List of f_{CP} values in HVV couplings expected to be observed with 3σ significance and the corresponding uncertainties δf_{CP} for several collider scenarios, with the exception of $V^* \to VH$ mode at pp 300 fb^{-1} where the simulated measurement does not quite reach 3σ. Numerical estimates 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]