

THE HIGGS DOUBLECROSS EXOTIC PRODUCTION OF THE 126 GeV HIGGS

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[arXiv:1307.xxxx]

5th TLEP Workshop, Fermilab
July 26, 2013

Motivation and starting point

- A key question for our community:

WHAT IS THE NATURE OF THE HIGGS?

- The answer requires a comprehensive program to measure precisely the mass, couplings, *CP* properties of the Higgs
- Has inspired many (many!) papers discussing “model-independent” frameworks
 - Fit for coupling ratios, effective operators, etc.
- Fantastic motivation for a future Higgs factory

Model-independence?

- SM Higgs production at hadron colliders arises from a few nominally dominant modes
 - Namely, gluon fusion, VBF, VBA, ttH
- As a result, can parameterize modified couplings as rescalings affecting production and decay simultaneously

$$\begin{aligned}\mathcal{L}_{eff} = & c_V \frac{2m_W^2}{v} h W_\mu^+ W_\mu^- + c_V \frac{m_Z^2}{v} h Z_\mu Z_\mu - c_b \frac{m_b}{v} h \bar{b}b - c_\tau \frac{m_\tau}{v} h \bar{\tau}\tau - c_c \frac{m_c}{v} h \bar{c}c \\ & + c_g \frac{\alpha_s}{12\pi v} h G_{\mu\nu}^a G_{\mu\nu}^a + c_\gamma \frac{\alpha}{\pi v} h A_{\mu\nu} A_{\mu\nu} - c_{inv} h \bar{\chi}\chi .\end{aligned}$$

Model-independence?

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$$(\sigma \cdot \text{BR}) (ii \rightarrow H \rightarrow ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}$$

$$(\sigma \cdot \text{BR}) (gg \rightarrow H \rightarrow \gamma\gamma) = \sigma_{\text{SM}}(gg \rightarrow H) \cdot \text{BR}_{\text{SM}}(H \rightarrow \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

Model-independence? *No!*

- SM Higgs production at hadron colliders arises from a few nominally dominant modes
 - Namely, gluon fusion, VBF, VBA, ttH
- As a result, can parameterize modified couplings as rescalings affecting production and decay simultaneously
- Yet these share a common assumption that there are no New Physics production modes for the Higgs!

Exotic production modes for SM Higgs

- Arise as cascade decays of heavy new particles
 - Collider signature is $h + X$ (X includes leptons, jets, photons, and/or MET)
 - Many past studies focused on kinematic regimes where the SM Higgs is boosted

Datta, Djouadi, Guchait, Moortgat (0303095)
Huitu, et. al. (0808.3094)
Gori, Schwaller, Wagner (1103.4138)
Kribs, Martin, Roy, Spannowsky (0912.4731, 1006.1656)
Baer, Barger, Lessa, Sreethawong, Tata (1201.2949)
Ghosh, Guchait, Sengupta (1202.4937)
Byakti, Ghosh (1204.0415)
Howe, Saraswat (1208.1542)
Arbey, Battaglia, Mahmoudi (1212.6865)
Bharucha, Heinemeyer, von der Pahlen (1307.4237)
+ many more

Exotic production modes for SM Higgs

- Arise as cascade decays of heavy new particles
 - Collider signature is $h + X$ (X includes leptons, jets, photons, and/or MET)
 - Many past studies focused on kinematic regimes where the SM Higgs is boosted
- Generally, there is a region of parameter space where the initial signature of NP is exotic Higgs production
 - If SM Higgs is not too boosted, then dedicated boosted Higgs searches are not sensitive
 - Instead, these Higgses show up in current searches
 - Will show two examples from vanilla SUSY as proof of principle

MSSM illustration: chargino-neutralino production

- Use Softsusy + SUSYHIT for spectrum generation and decay tables, Prospino for NLO xsec
- All other SUSY particles are heavy

Model A	
χ_1^+	195.8 GeV
χ_2^0	197.4 GeV
χ_3^0	253.9 GeV
χ_1^0	65.7 GeV
$\text{Br}(\chi_1^+ \text{ to } W^+ \chi_1^0)$	100%
$\text{Br}(\chi_2^0 \text{ to } Z \chi_1^0)$	38.9%
$\text{Br}(\chi_2^0 \text{ to } h \chi_1^0)$	61.1%
NLO xsec ($\chi_1^+ \chi_2^0$) @ 8 TeV	0.429 pb

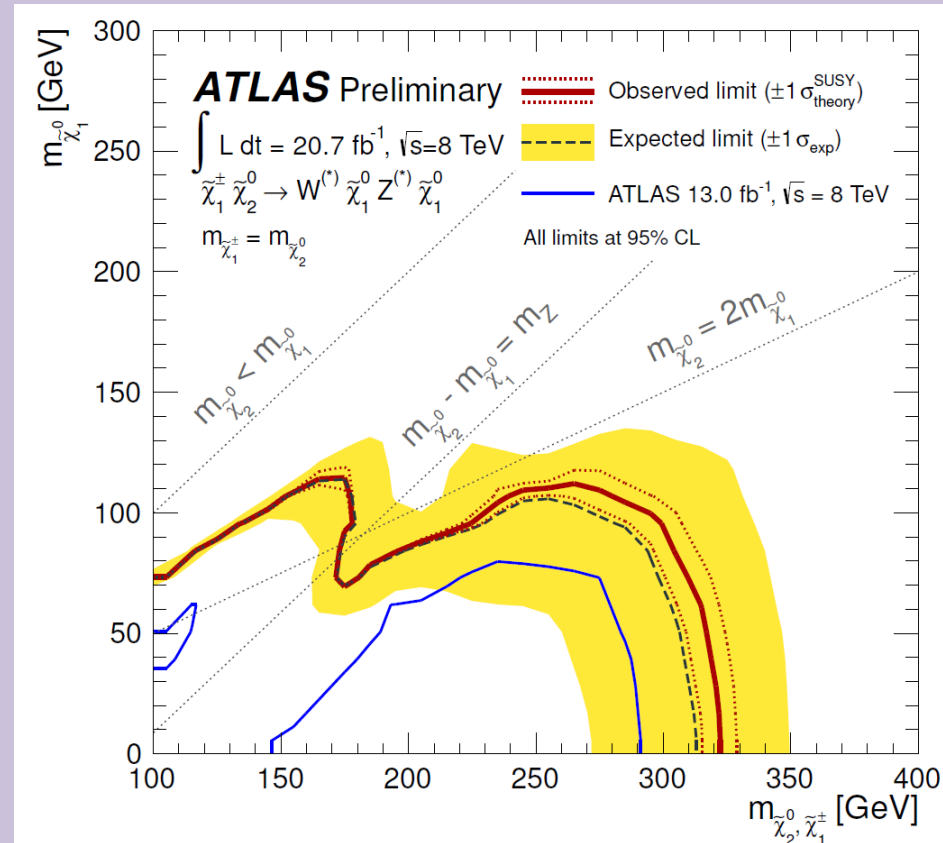
Model B	
χ_1^+	231.7 GeV
χ_2^0	231.5 GeV
χ_1^0	98.6 GeV
$\text{Br}(\chi_1^+ \text{ to } W^+ \chi_1^0)$	100%
$\text{Br}(\chi_2^0 \text{ to } Z \chi_1^0)$	17.7%
$\text{Br}(\chi_2^0 \text{ to } h \chi_1^0)$	82.3%
NLO xsec ($\chi_1^+ \chi_2^0$) @ 8 TeV	0.364 pb

MSSM illustration: chargino-neutralino production

- Use Softsusy + SUSYHIT for spectrum generation and decay tables, Prospino for NLO xsec
- All other SUSY particles are heavy (decoupling limit for MSSM Higgs sector)

Model A and B are safe from current direct search bounds

Main signature contaminates SM Higgs searches



Other considerations

- Real SM Higgses in the final state
 - not imposters!
- ... with non-standard kinematics
 - Cannot be mapped onto an enhanced SM production mechanism
- New physics assumed to have negligible effect on Higgs partial widths
 - Decays of the Higgs are not affected
 - ... up to changes in signal efficiency arising from non-SM kinematics

Other considerations

- Three categories for exotic Higgs production
 - Large NP xsec compared to SM xsecs, but tiny efficiency
 - Comparable NP xsec to SM xsecs, comparable efficiency
 - Subdominant NP xsec
 - Also includes subdominant SM production modes

Mode	Xsec (pb)	QCD scale (%)	QCD scale (%)	PDF + α_s (%)	PDF + α_s (%)
ggF	18.82	+7.2	-7.8	+7.5	-6.9
VBF	126.5	1.558	+0.2	-0.2	+2.6
WH	0.6767	+1.0	-1.0	+2.3	-2.3
ZH	0.4000	+3.2	-3.2	+2.5	-2.5
ttH	0.1247	+3.8	-9.3	+8.1	-8.1

At 8 TeV, $m = 126.5$ GeV

From <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt8TeV>

Other considerations

- ~~Three~~ Four! categories for exotic Higgs production
 - Large NP xsec compared to SM xsecs, but tiny efficiency
 - Comparable NP xsec to SM xsecs, comparable efficiency
 - Subdominant NP xsec
 - Also includes subdominant SM production modes
 - Can (and should) study simultaneous presence of new physics production and modified decays!
 - Measure SM-like rates but could have simultaneous suppression of ggF and NP production mimicking ggF
 - Would have been truly double-crossed

MSSM illustration: chargino-neutralino production

- Use MadGraph 5 for signal generation
- Implement ATLAS and CMS diphoton, ZZ and WW cut-based analyses
- Illustrate how this exotic production mode is categorized under current search strategy

MSSM illustration: chargino-neutralino production efficiencies in diphoton analyses

- Need SM efficiencies from expts. for validation*

ATLAS diphoton	Model A	Model B
lepton	7.58%	7.55%
MET	29.94%	33.59%
VBA mjj	2.22%	1.85%
VBF	0.23%	0.18%
ggF	17.49%	14.88%

CMS diphoton	Model A	Model B
muon	6.38%	6.50%
electron	6.29%	6.28%
tight VBF	0.10%	0.12%
loose VBF	0.42%	0.39%
MET	20.43%	24.75%
untagged	31.78%	27.41%

*Also advocated in Boudjema, et. al. (1307.5865)

Expanding to more models

- Other models with similar kinematics and cascade decay objects will give similar efficiencies
- RPC SUSY will be typically limited by MET signal region contamination

Category	N_D	N_B	N_S	ggF	VBF	WH	ZH	$t\bar{t}H$
Untagged	14248	13582	350	320	19	7.0	4.2	1.0
Loose high-mass two-jet	41	28	5.0	2.3	2.7	< 0.1	< 0.1	< 0.1
Tight high-mass two-jet	23	13	7.7	1.8	5.9	< 0.1	< 0.1	< 0.1
Low-mass two-jet	19	21	3.1	1.5	< 0.1	0.92	0.54	< 0.1
E_T^{miss} significance	8	4	1.2	< 0.1	< 0.1	0.43	0.57	0.14
Lepton	20	12	2.7	< 0.1	< 0.1	1.7	0.41	0.50
All categories (inclusive)	13931	13205	370	330	27	10	5.8	1.7

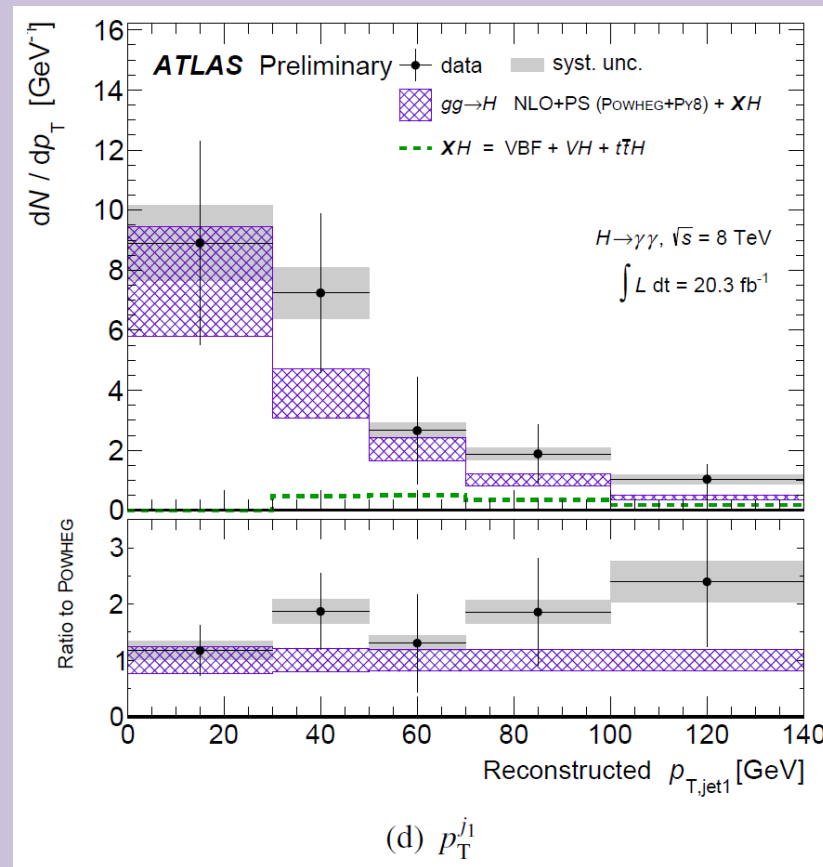
8 TeV counts in diphoton analysis and breakdown into expected background and SM signal contributions

Expanding to more models

- Other models with similar kinematics and cascade decay objects will give similar efficiencies
- RPC SUSY will be typically limited by MET signal region contamination
- RPV SUSY will not have this issue
 - Can readily construct models that are dominantly contaminate gluon fusion
 - More motivation for continued theory work in reducing cross section uncertainties

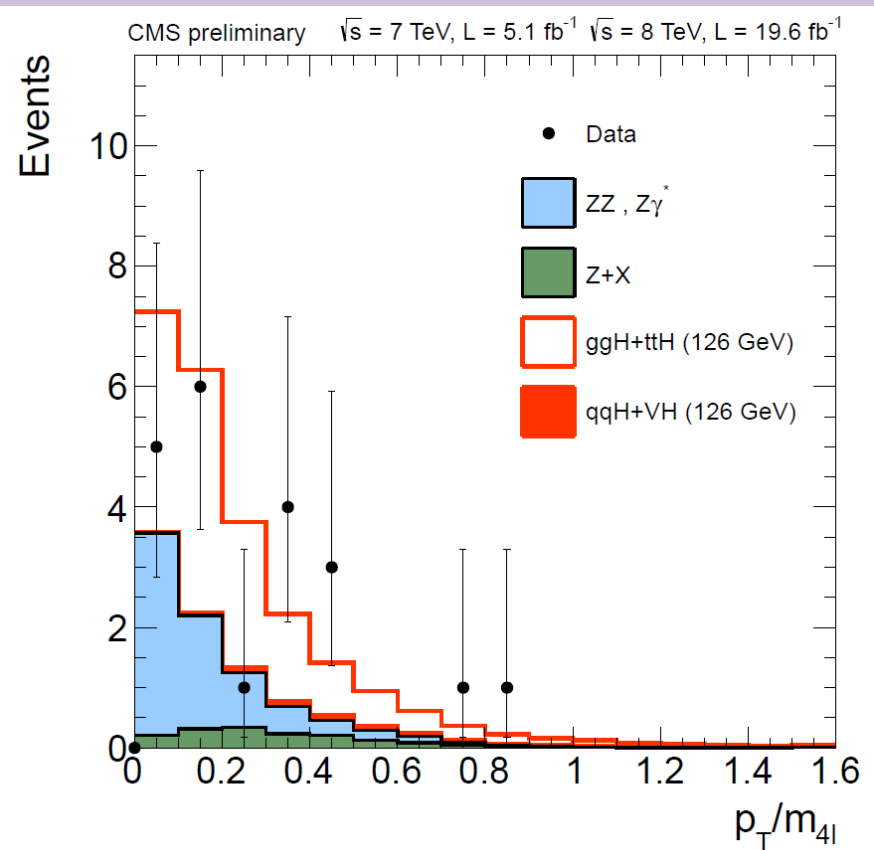
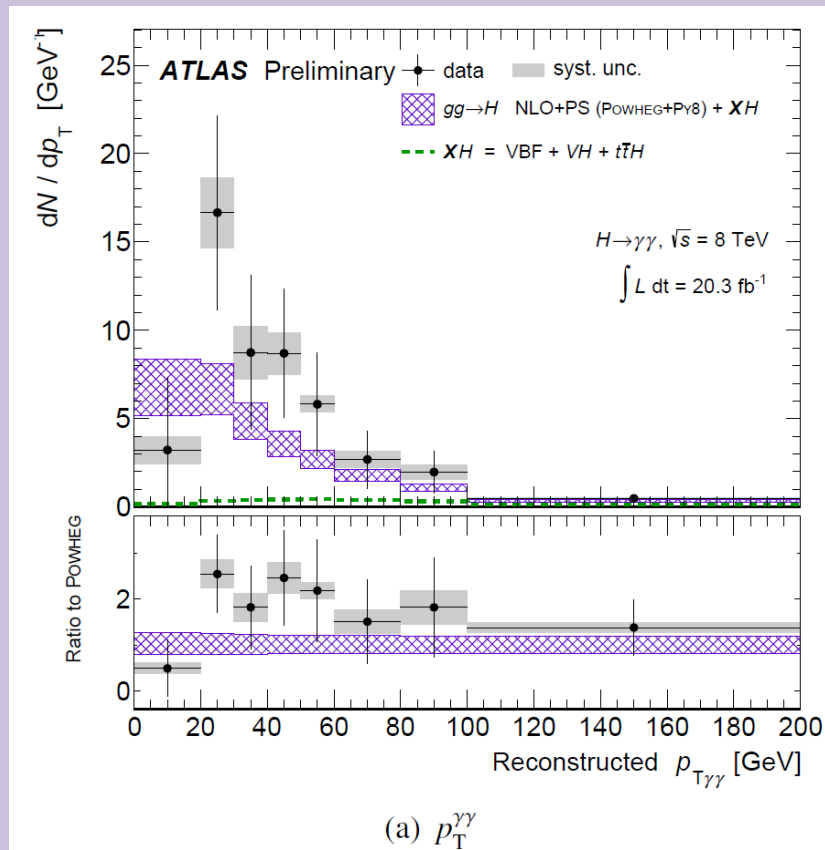
Testing for exotic production

- For $h+X$ from new physics, should test counts and kinematics X (= leptons, jets, photons, MET)



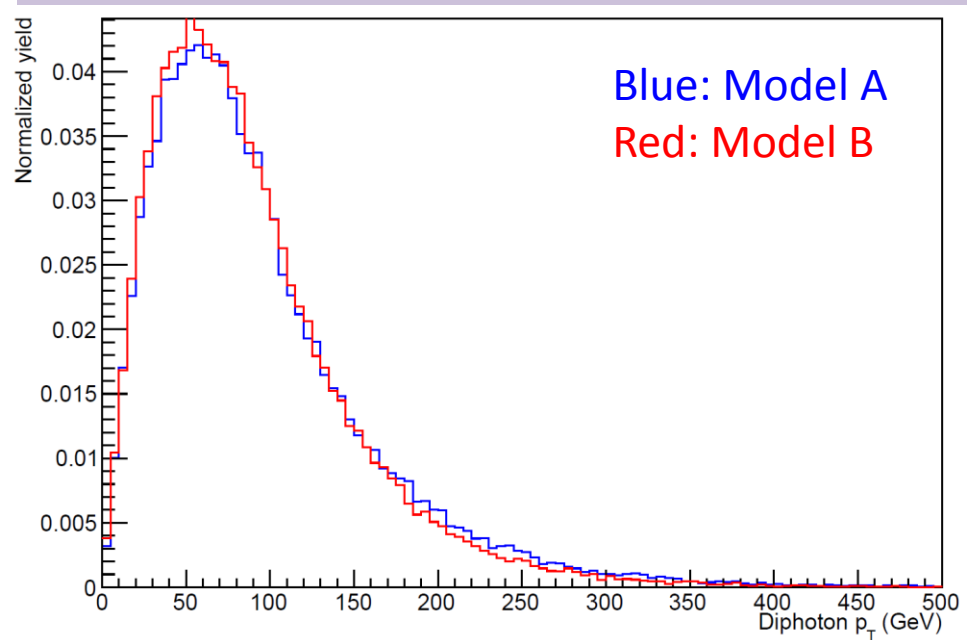
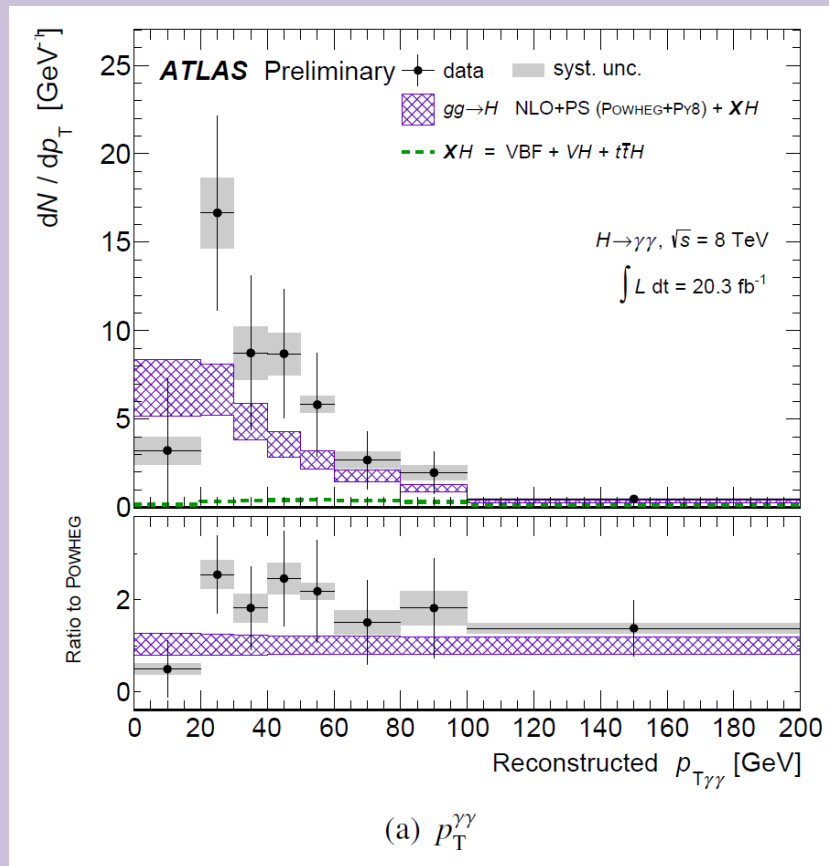
Testing for exotic production

- Also should test the p_T of the Higgs candidates
 - Need continued theory work on differential distributions



Testing for exotic production

- Also should test the p_T of the Higgs candidates
 - Need continued theory work on differential distributions



Diphoton spectrum (no detector effects) after all cuts

Connection to precision measurements

Facility	LHC	HL-LHC	ILC	Full ILC	CLIC	LEP3 (4 IP)	TLEP (4 IP)
Energy (GeV)	14,000	14,000	250	250+500+1000	350+500+1500	240	240+350
$\int \mathcal{L} dt$ (fb ⁻¹)	300/expt	3000/expt	250	250+500+1000	500+500+1500	2000	10000+1400
N_H produced	1.7×10^7	1.7×10^8	80,000	370,000	618,000	600,000	3,200,000
Measurement precision							
m_H (MeV)	100	50	35	35	70	26	7
$\Delta\Gamma_H$	—	—	11%	6%	6%	4%	1.3%
BR _{inv}	NA	NA	<0.8%	<0.8%	NA	<0.7%	<0.3%
$\Delta g_{H\gamma\gamma}$	5.1 – 6.5%	1.5 – 5.4%	18%	4.1%	NA	3.4%	1.4%
Δg_{Hgg}	5.7 – 11%	2.7 – 7.5%	6.4%	1.8%	NA	2.2%	0.7%
Δg_{HWW}	2.7 – 5.7% [†]	1.0 – 4.5% [†]	4.8%	1.4%	1%	1.5%	0.25%
Δg_{HZZ}	2.7 – 5.7% [†]	1.0 – 4.5% [†]	1.3%	1.3%	1%	0.25%	0.2%
$\Delta g_{H\mu\mu}$	< 30%	< 10%	—	16%	15%	14%	7%
$\Delta g_{H\tau\tau}$	5.1 – 8.5%	2.0 – 5.4%	5.7%	2.0%	3%	1.5%	0.4%
Δg_{Hcc}	—	—	6.8%	2.0%	4%	2.0%	0.25%
Δg_{Hbb}	6.9 – 15%	2.7 – 11%	5.3%	1.5%	2%	0.7%	0.22%
Δg_{Htt}	8.7 – 14%	3.9 – 8.0%	—	4.0%	3%	—	30%
Δg_{HHH}	—	30% [‡]	—	26%	16%	—	—

Note: with the luminosity upgrade, the ILC coupling precision improves by a factor of ~ 2 .

[†] assuming the same deviation for the HWW and HZZ couplings. [‡] two experiments.

Hadron vs. lepton colliders

- The assumption about SM production modes at hadron colliders must be tested!
 - Apart from NP, expect subdominant SM production modes (single top, triple boson, di-Higgs) at high luminosity
- Lepton colliders have a clean SM production mode
 - Easy to test via scanning over \sqrt{s}
 - Higgs samples are not contaminated by possible exotic production modes
- The hadron and lepton Higgs datasets are truly orthogonal and complementary
 - Discrepancies between central values of extracted couplings can be resolved by exotic Higgs production

Summary and final comments

- Exotic Higgs production is a realistic prospect for hadron colliders
 - Possible contamination of Higgs samples by NP production modes is significant a caveat in hadron vs. lepton collider comparison
 - Probing exotic production via lepton colliders is limited by energy threshold
- Improving theory uncertainties in SM inclusive and differential distributions are key to testing exotic production modes and understanding discrepancies