Higgs Coupling Measurements and BSM Sensitivity at a High-Luminosity LHC with ATLAS

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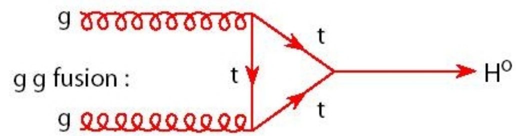
Introduction

- Measured Higgs couplings with combination of all decay channels ($\gamma\gamma$, ZZ, WW, $\tau\tau$, bb) using up to ~25 fb^{-1} of data at sqrt(s) = 7 and 8 TeV
- ATLAS conference notes on Higgs coupling measurements: ATLAS-CONF-2013-034, ATLAS-CONF-2012-127
- Couplings consistent with SM-like Higgs boson within large uncertainties
  - Small deviations in couplings predicted by BSM models like two-Higgs-doublet model e.g. MSSM, an additional EW singlet, and dark matter
- **Snowmass goals:**
  - Derive expected precision on Higgs couplings with 300 and 3000 fb^{-1} at 14 TeV
  - Translate into sensitivity to various BSM scenarios
- New ATLAS results in final stages of Collaboration approval
  - Illustrate here with existing public ATLAS results and schematic examples

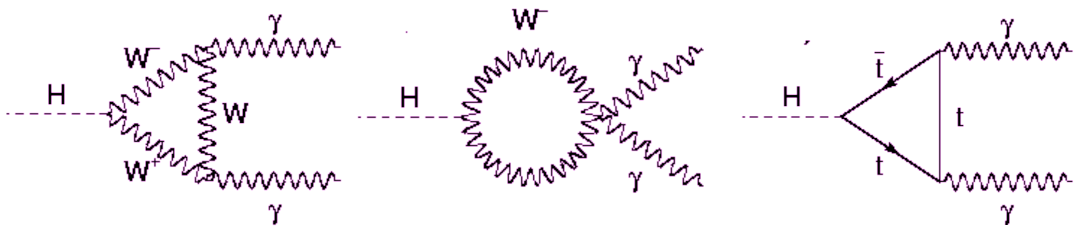
Framework to probe couplings

- Define signal strength $\mu = (\sigma * BR)/(\sigma * BR)_{SM}$
  - Similarly for each coupling g_i , measure strength in "units" of SM value: $\kappa_i = g_i / g_{i\,,\,SM}$
- Scale each production or decay mode *i* by $\kappa_i^2 = g_i^2 / g_{i,\,SM}^2$
- Scale total width by κ_H^2

[LHC HXSWG (arXiv:1209.0040)](arXiv:1209.0040)



$\sim \kappa_g^2 \sim f_t \kappa_t^2 + f_b \kappa_b^2 + f_{tb} k_t k_b + \ldots$ (top quark dominates loop coupling to gluons)



$\sim \kappa_\gamma^2 = |1.28\, \kappa_W - 0.28\, \kappa_t + \ldots|^2$

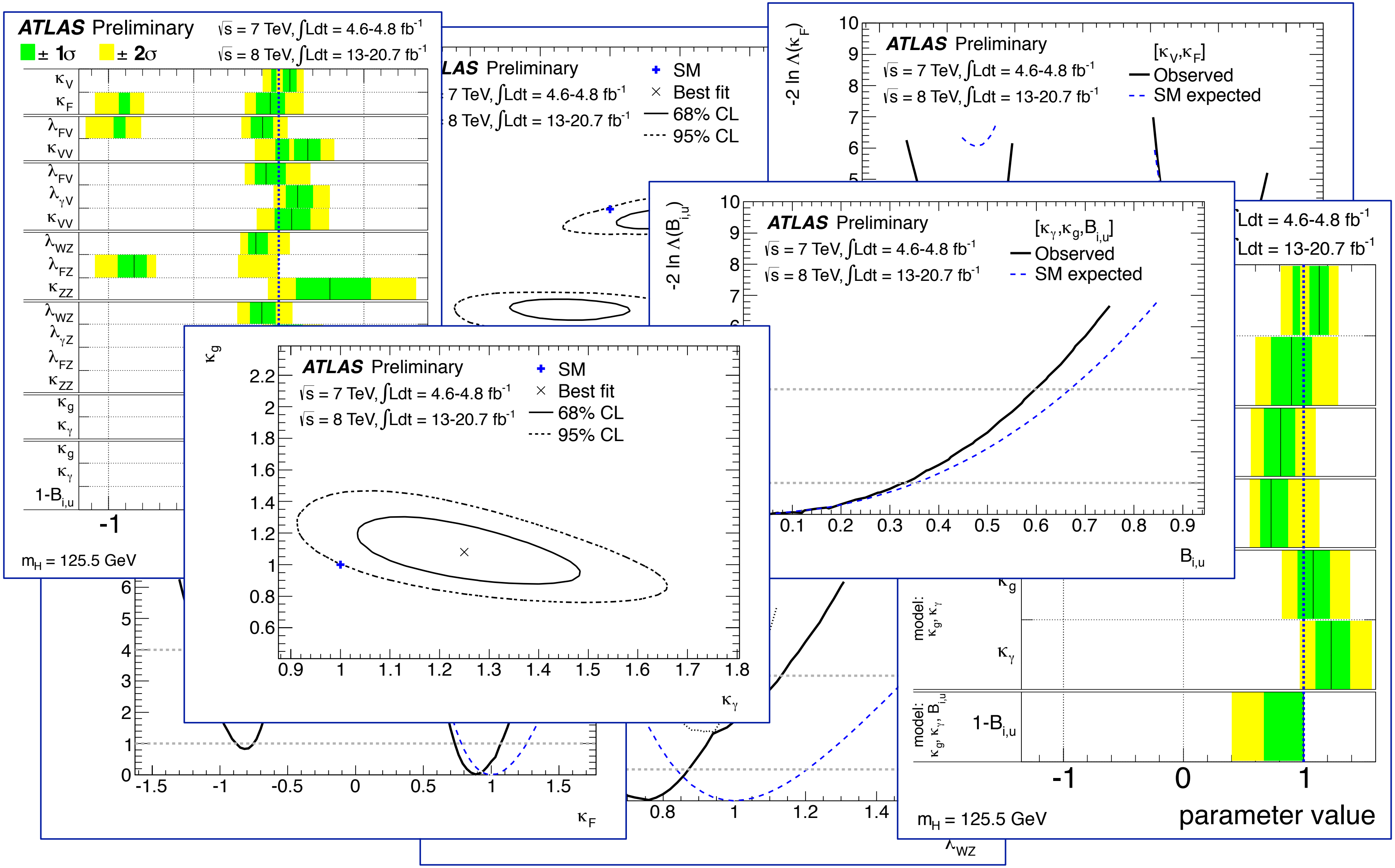
(W and top interfere in loop coupling to photons)

- Example:

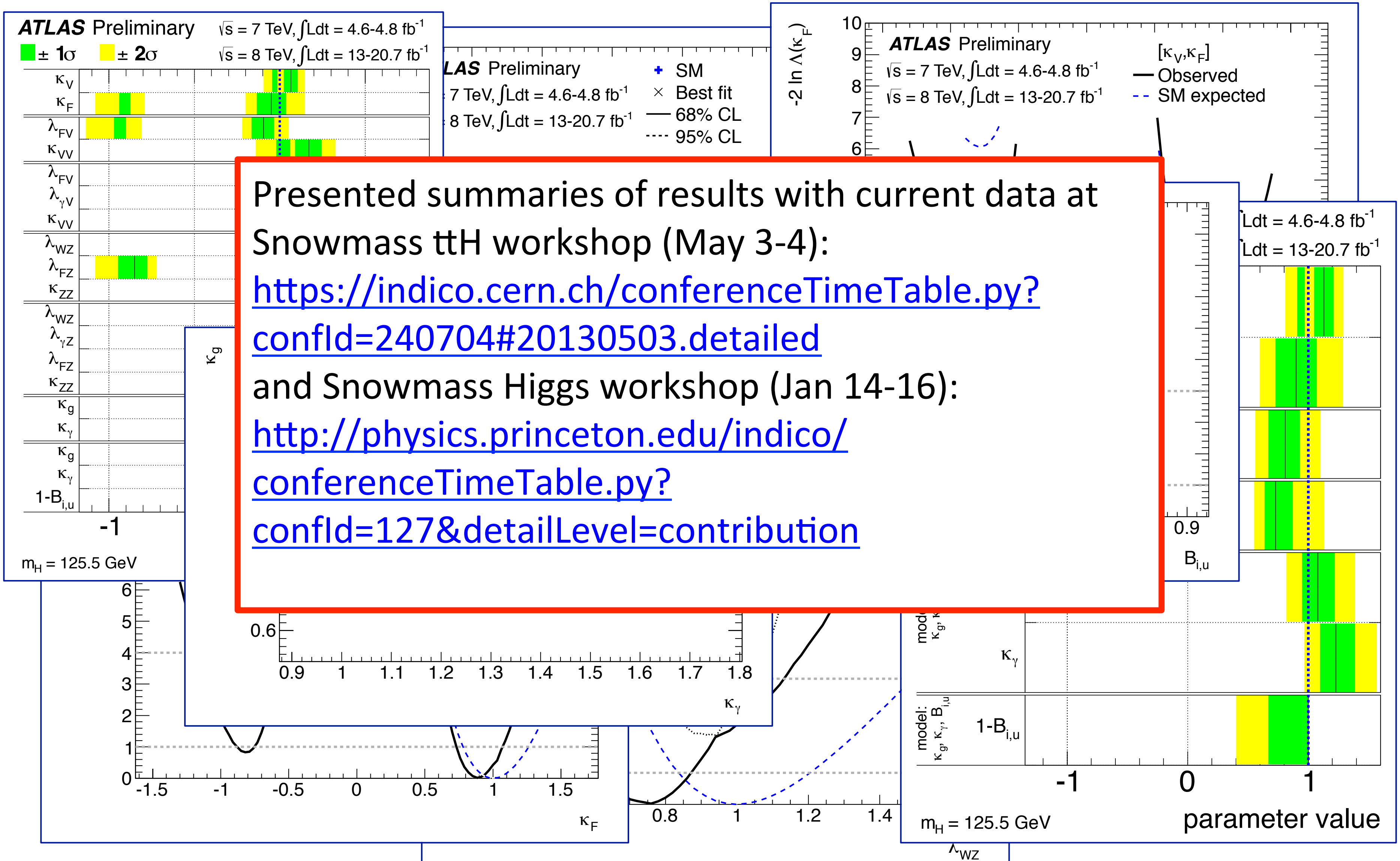
$$(\sigma \cdot \mathrm{BR})(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot \mathrm{BR}_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

$$\kappa_H^2(\kappa_i, m_H) = \sum_{\substack{j = WW^{(*)}, ZZ^{(*)}, b\bar{b}, \tau^-\tau^+, \\ \gamma\gamma, Z\gamma, gg, t\bar{t}, c\bar{c}, s\bar{s}, \mu^-\mu^+}} \frac{\Gamma_j(\kappa_i, m_H)}{\Gamma_H^{SM}(m_H)}$$

Higgs couplings with current data



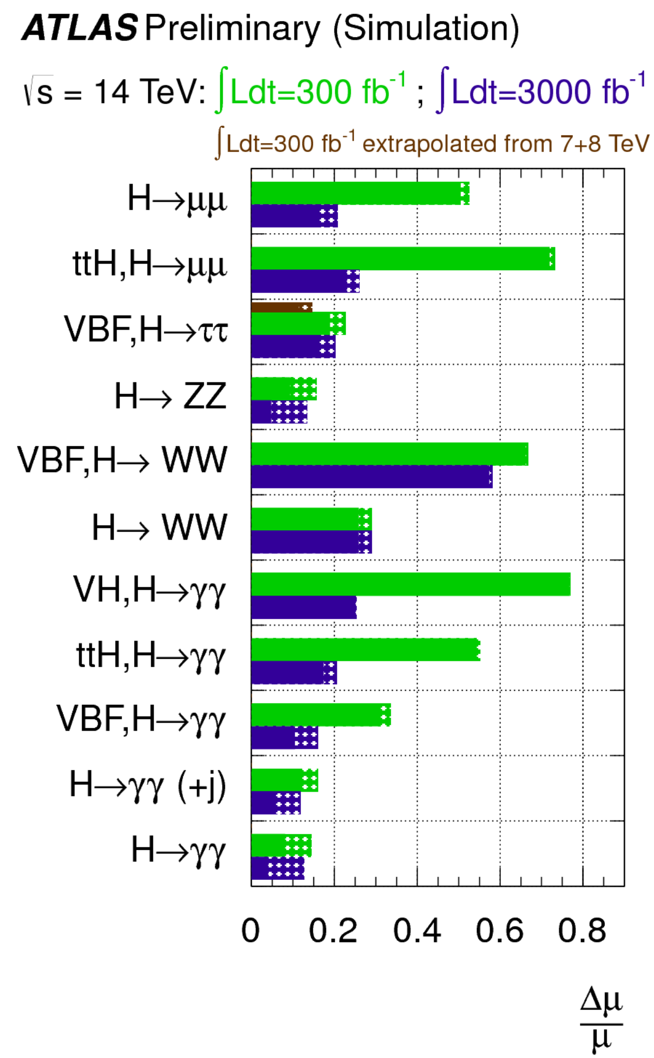
Higgs couplings with current data



Presented summaries of results with current data at Snowmass ttH workshop (May 3-4):
https://indico.cern.ch/conferenceTimeTable.py?confId=240704#20130503.detailed
and Snowmass Higgs workshop (Jan 14-16):
http://physics.princeton.edu/indico/conferenceTimeTable.py?confId=127&detailLevel=contribution

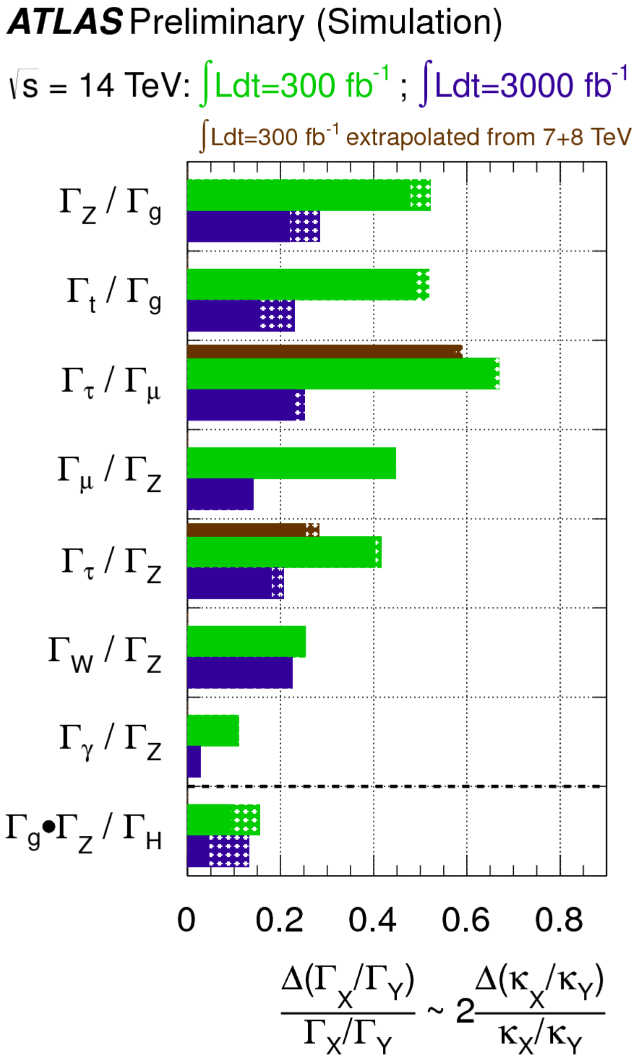
Input channels for HL-LHC

- Expected precision with 300 & 3000 fb^{-1} @ 14 TeV studied by Eur. Strategy group
  - ATL-PHYS-PUB-2012-004
- Parametrized detector inefficiencies and resolutions to model object performance with higher pileup
  - Up to 150 simultaneous *pp* interactions
- Further improvements in H->γγ, ZZ, WW, and ττ final states
  - bb not included due to heavy dependence on b-tagging performance and JER
- Expected measurement precision with 300 & 3000 fb^{-1} @ 14 TeV on Higgs
  - Signal strengths, μ_i, and partial widths, Γ_i (proportional to squared coupling constants)
  - Hashed areas indicate theoretical uncertainties
  - No assumptions on Higgs total width (BSM)



Coupling prospects at HL-LHC

- Uncertainties on ratios of couplings will decrease to as low as ~5% with 300 fb^{-1} at 14 TeV, and as low as couple percent with 3000 fb^{-1} at HL-LHC
- Γ_γ / Γ_Z provides constraint on new physics in H->γγ loop to couple level at 3000 fb^{-1}
- 25% precision on Γ_τ / Γ_μ probes couplings of 2nd and 3rd generation fermions



Coupling prospects at HL-LHC

- Precision on ratios of couplings
  - No interpretation: identical to official ATLAS numbers
  - No assumption on Higgs total width, which cancels out in ratios of couplings
- Very conservative results as experimental systematic uncertainties are treated as uncorrelated between different channels
  - Saturate the performance at high luminosity, whereas in reality will partially cancel and result in further improvement in performance
- Correlations in theoretical uncertainties between channels are included
  - Improvement in this area would also be critical for further progress
- For perspective, even more conservative than CMS Scenario 1
  - Consistent numbers if use more optimistic (realistic) assumptions

Model	300 fb^{-1}	3000 fb^{-1}
κ_W / κ_Z	12%	11%
κ_t / κ_g	26%	11%
κ_b / κ_Z	N/A	N/A
κ_τ / κ_Z	21%	10%
κ_μ / κ_Z	22%	7%
κ_g / κ_Z	26%	14%
κ_γ / κ_Z	5%	1%
$\kappa_g \kappa_Z / \kappa_H$	8%	7%

κ_τ / κ_μ	33%	12%

Uncertainties on couplings

- Uncertainties on couplings determined for many benchmark models
  - Some have simplifying assumptions, e.g. (k_V, k_F)
  - Others are fully general – no simplifications: (κ_Z, κ_W, κ_t, κ_b, κ_τ, κ_μ, κ_g, κ_γ)
- Results in final stages of ATLAS approval process
  - Expected to become public as ATLAS PUB note within couple weeks
  - Will also be included in ATLAS white paper

ATLAS NOTE

ATL-PHYS-PUB-2013-XXX

Higgs Couplings Precision and Sensitivity to New Phenomena with the ATLAS Detector at a High-Luminosity LHC

The ATLAS Collaboration

Higgs couplings precision at 14 TeV

- Parametrizations studied assuming BR_{inv}=0
  - Ratios also probed without assumption
- First with photon and gluon rates expressed as rescaled loops of above couplings
- Overall coupling strength
- Vector bosons vs. fermions to probe quadratic vs. linear mass dependence
- Gauge sector
  - W vs. Z bosons to test custodial symmetry
- Yukawa sector
  - Up-type vs. down-type fermions to test Type II 2HDMs, e.g. MSSM
  - Leptons vs. quarks to test Type III and IV 2HDMs
  - Muons vs. taus to test 2nd vs. 3rd generation fermions
- General 6-dimensional fit to all couplings to massive particles (κ_b not determined)

Coupling	300 fb^{-1}	3000 fb^{-1}
κ		
κ_V		
κ_F		
κ_Z		
λ_{WZ}		
κ_F		
κ_V		
κ_u		
λ_{du}		
κ_V		
κ_3		
λ_{23}		
κ_Z		
κ_W		
κ_t		
κ_b		
κ_τ		
κ_μ		

Higgs couplings precision at 14 TeV

- Also perform fits with effective loop couplings to gluons and photons
  - More model-independent because absorb arbitrary contributions from new diagrams from BSM phenomena
- Simplified probe of vector vs. fermion couplings, but with effective loop couplings
- General 8-dimensional fit of all couplings to massive and massless particles
  - κ_b not determined

- Since ATLAS update not available yet, provide in following slides *personal* (i.e. my own) interpretation of public ATLAS results for illustrative purposes
  - Actual ATLAS results not determined by such simplified reasoning, but rather using full-blown fits

Coupling	300 fb^{-1}	3000 fb^{-1}
κ_V		
κ_F		
κ_g		
κ_γ		
κ_Z		
κ_W		
κ_t		
κ_b		
κ_τ		
κ_μ		
κ_g		
κ_γ		

W and Z couplings

- **Disclaimer: Personal interpretation of public ATLAS results**
- W and Z coupling precisions are similar at 300 fb^{-1}
  - Experimental and statistical uncertainties uncorrelated so divide by sqrt(2)
- W performance saturates at 3000 fb^{-1} (treated very conservatively), while Z coupling precision expected to further improve wrt W coupling shown

Model	300 fb^{-1}	3000 fb^{-1}
κ_W / κ_Z	12%	11%
κ_t / κ_g	26%	11%
κ_b / κ_Z	N/A	N/A
κ_τ / κ_Z	21%	10%
κ_μ / κ_Z	22%	7%
κ_g / κ_Z	26%	14%
κ_γ / κ_Z	5%	2%
$\kappa_g \kappa_Z / \kappa_H$	8%	7%

→

Model	300 fb^{-1}	3000 fb^{-1}
κ_W	8.5%	8%
κ_t / κ_g	26%	11%
κ_b / κ_Z	N/A	N/A
κ_τ / κ_Z	21%	10%
κ_μ / κ_Z	22%	7%
κ_g / κ_Z	26%	14%
κ_γ / κ_Z	5%	2%
$\kappa_g \kappa_Z / \kappa_H$	8%	7%

Top quark coupling

- **Disclaimer: Personal interpretation of public ATLAS results**
- Top coupling from ttH($\gamma\gamma$, $\mu\mu$) is statistically limited at 300 fb^{-1}
  - Systematics become relevant at 3000 fb^{-1}
  - In both scenarios, top-quark uncertainty dominates that on gluon (ggF)
- Additional ttH with decays to WW, bb, etc under study but not included here

Model	300 fb^{-1}	3000 fb^{-1}
κ_W / κ_Z	12%	11%
κ_t / κ_g	26%	11%
κ_b / κ_Z	N/A	N/A
κ_τ / κ_Z	21%	10%
κ_μ / κ_Z	22%	7%
κ_g / κ_Z	26%	14%
κ_γ / κ_Z	5%	2%
$\kappa_g \kappa_Z / \kappa_H$	8%	7%

→

Model	300 fb^{-1}	3000 fb^{-1}
κ_W	8.5%	8%
κ_t	26%	11%
κ_b / κ_Z	N/A	N/A
κ_τ / κ_Z	21%	10%
κ_μ / κ_Z	22%	7%
κ_g / κ_Z	26%	14%
κ_γ / κ_Z	5%	2%
$\kappa_g \kappa_Z / \kappa_H$	8%	7%

b-quark coupling

- **Disclaimer: Personal interpretation of public ATLAS results**
- No sensitivity projections given for H->bb
  - Studies of b-jet performance and sensitivity in boosted regime on-going
  - May provide an update by ECFA in October, but unlikely for Snowmass
- BR(Γ->bb) ~ 57% for SM Higgs so important for absolute couplings

Model	300 fb^{-1}	3000 fb^{-1}
κ_W / κ_Z	12%	11%
κ_t / κ_g	26%	11%
κ_b / κ_Z	N/A	N/A
κ_τ / κ_Z	21%	10%
κ_μ / κ_Z	22%	7%
κ_g / κ_Z	26%	14%
κ_γ / κ_Z	5%	2%
$\kappa_g \kappa_Z / \kappa_H$	8%	7%

→

Model	300 fb^{-1}	3000 fb^{-1}
κ_W	8.5%	8%
κ_t	26%	11%
κ_b	N/A	N/A
κ_τ / κ_Z	21%	10%
κ_μ / κ_Z	22%	7%
κ_g / κ_Z	26%	14%
κ_γ / κ_Z	5%	2%
$\kappa_g \kappa_Z / \kappa_H$	8%	7%

Tau coupling

- **Disclaimer: Personal interpretation of public ATLAS results**
- Tau precision dominates ratio of tau and Z couplings
  - Precision on H->tautau signal strength about 50% better than H->ZZ, not including additional power for Z coupling from VBF and ZH

Model	300 fb^{-1}	3000 fb^{-1}
κ_W / κ_Z	12%	11%
κ_t / κ_g	26%	11%
κ_b / κ_Z	N/A	N/A
κ_τ / κ_Z	21%	10%
κ_μ / κ_Z	22%	7%
κ_g / κ_Z	26%	14%
κ_γ / κ_Z	5%	2%
$\kappa_g \kappa_Z / \kappa_H$	8%	7%

→

Model	300 fb^{-1}	3000 fb^{-1}
κ_W	8.5%	8%
κ_t	26%	11%
κ_b	N/A	N/A
κ_τ	21%	10%
κ_μ / κ_Z	22%	7%
κ_g / κ_Z	26%	14%
κ_γ / κ_Z	5%	2%
$\kappa_g \kappa_Z / \kappa_H$	8%	7%

Muon coupling

- **Disclaimer: Personal interpretation of public ATLAS results**
- Muon coupling is statistically limited and trivially dominates Z coupling precision
  - Precision on H->tautau signal strength about 50% better than H->ZZ, not including additional power for Z coupling from VBF and ZH

Model	300 fb^{-1}	3000 fb^{-1}
κ_W / κ_Z	12%	11%
κ_t / κ_g	26%	11%
κ_b / κ_Z	N/A	N/A
κ_τ / κ_Z	21%	10%
κ_μ / κ_Z	22%	7%
κ_g / κ_Z	26%	14%
κ_γ / κ_Z	5%	2%
$\kappa_g \kappa_Z / \kappa_H$	8%	7%

Model	300 fb^{-1}	3000 fb^{-1}
κ_W	8.5%	8%
κ_t	26%	11%
κ_b	N/A	N/A
κ_τ	21%	10%
κ_μ	22%	7%
κ_g / κ_Z	26%	14%
κ_γ / κ_Z	5%	2%
$\kappa_g \kappa_Z / \kappa_H$	8%	7%

Gluon coupling

- **Disclaimer: Personal interpretation of public ATLAS results**
- Precision on gluon coupling in similar ballpark as Z coupling
  - Gluon coupling from gluon fusion – high rate
  - Z coupling from ZZ fusion and ZH production – lower rates but higher S/B

Model	300 fb^{-1}	3000 fb^{-1}
κ_W / κ_Z	12%	11%
κ_t / κ_g	26%	11%
κ_b / κ_Z	N/A	N/A
κ_τ / κ_Z	21%	10%
κ_μ / κ_Z	22%	7%
κ_g / κ_Z	26%	14%
κ_γ / κ_Z	5%	2%
$\kappa_g \kappa_Z / \kappa_H$	8%	7%

→

Model	300 fb^{-1}	3000 fb^{-1}
κ_W	8.5%	8%
κ_t	26%	11%
κ_b	N/A	N/A
κ_τ	21%	10%
κ_μ	22%	7%
κ_g	18%	10%
κ_γ / κ_Z	5%	2%
$\kappa_g \kappa_Z / \kappa_H$	8%	7%

Photon coupling

- **Disclaimer: Personal interpretation of public ATLAS results**
- Diphoton channel is most precise (1-jet & 2-jet) measured (even better than ZZ)
  - Fine resolution and smoothly falling background improves with luminosity
- For both $\gamma\gamma$ and ZZ, theoretical uncertainty is about 50% (75%) of total uncertainty at 300 (3000) fb^{-1}
  - Canceled in ratio of couplings, but would persist in absolute couplings

Model	300 fb^{-1}	3000 fb^{-1}
κ_W / κ_Z	12%	11%
κ_t / κ_g	26%	11%
κ_b / κ_Z	N/A	N/A
κ_τ / κ_Z	21%	10%
κ_μ / κ_Z	22%	7%
κ_g / κ_Z	26%	14%
κ_γ / κ_Z	5%	1%
$\kappa_g \kappa_Z / \kappa_H$	8%	7%

→

Model	300 fb^{-1}	3000 fb^{-1}
κ_W	8.5%	8%
κ_t	26%	11%
κ_b	N/A	N/A
κ_τ	21%	10%
κ_μ	22%	7%
κ_g	18%	10%
κ_γ	10%	4%
$\kappa_g \kappa_Z / \kappa_H$	8%	7%

Higgs coupling precision at HL-LHC

- **Disclaimer: Personal interpretation of public ATLAS results**
- Therefore arrive at crude table approximating expected ATLAS precision
  - Conservative but agrees with actual ATLAS results well within ~50%
- Precision on most couplings improves by around a factor of 2 with 3000 fb^{-1}
  - Z coupling not shown (extracted as ratio wrt Z) but also expected to improve
- Coupling precisions between roughly 5-10% can be attained with 3000 fb^{-1}

Model	300 fb^{-1}	3000 fb^{-1}
κ_W	8.5%	8%
κ_t	26%	11%
κ_b	N/A	N/A
κ_τ	21%	10%
κ_μ	22%	7%
κ_g	18%	10%
κ_γ	10%	4%
$\kappa_g \kappa_Z / \kappa_H$	8%	7%

Motivation for BSM sensitivity

- Joint discussions between Higgs and New Physics working groups at BNL Snowmass Energy Frontier workshop (April 3-6)
- Plenary summary below by Snowmass Higgs WG conveners
  - Action item applies to both spin/CP and couplings

Projects to be finished by June 30

2) Quantify the reach in New Physics sensitivity for a given precision of Higgs-coupling measurement

Decide on NP/Higgs benchmarks!
Compute significance of benchmark Higgs deviations from expt inputs

Solicit benchmarks for NP reach from loop-induced Higgs couplings
Solicit some NMSSM benchmark points from Pittsburgh/Arizona group

Survey double Higgs production studies for NP sensitivity

Heather Logan (Carleton U) *Higgs WG summary* *Snowmass EF workshop BNL*
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1) Two Higgs Doublet Models (2HDMs)

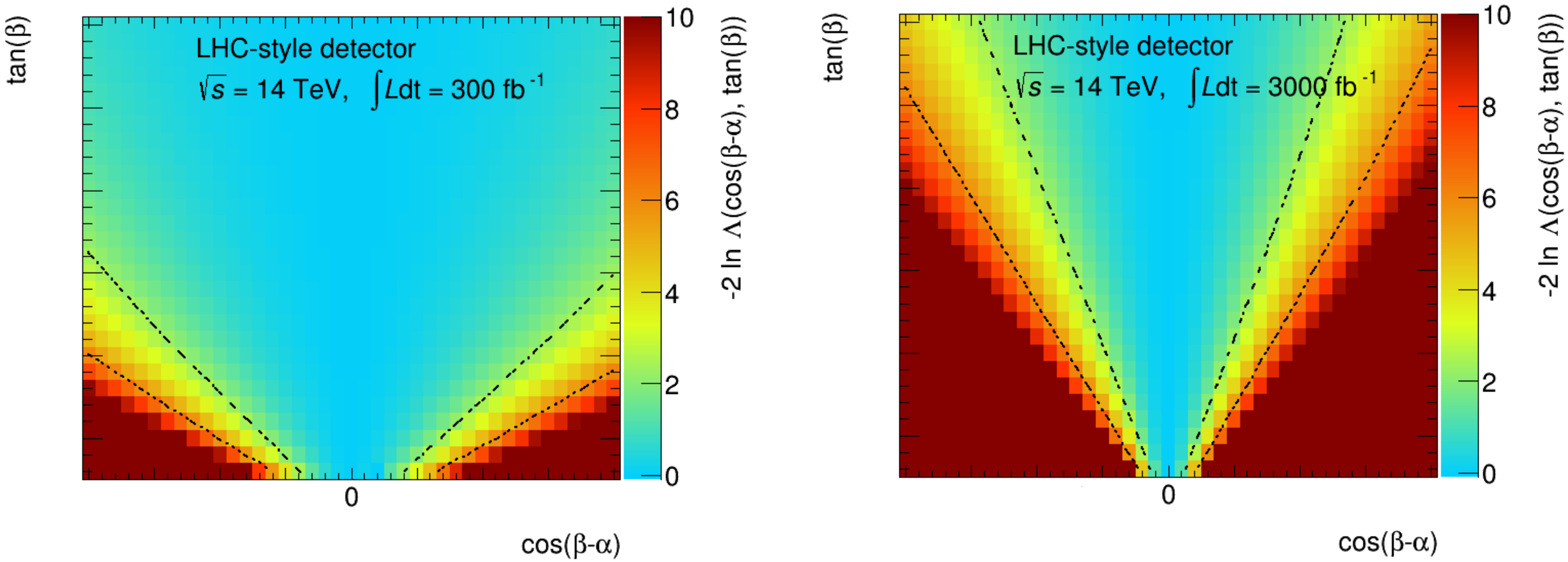
- Consider model with additional Higgs doublet
- Four types (I, II, III, IV) of two Higgs-doublet models satisfy Glashow-Weinberg condition
  - No tree-level flavor changing neutral currents
- Light Higgs couplings are function of two parameters:
  - Mixing angle α between neutral Higgses (h, H)
    Ratio of vacuum expectation values: $\tan(\beta)=v_2/v_1$

e.g. N. Craig et al. arXiv:1210.0559

$y_{2\mathrm{HDM}}/y_{\mathrm{SM}}$	2HDM I	2HDM II	2HDM III	2HDM IV
hVV	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
hQu	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
hQd	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
hLe	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$

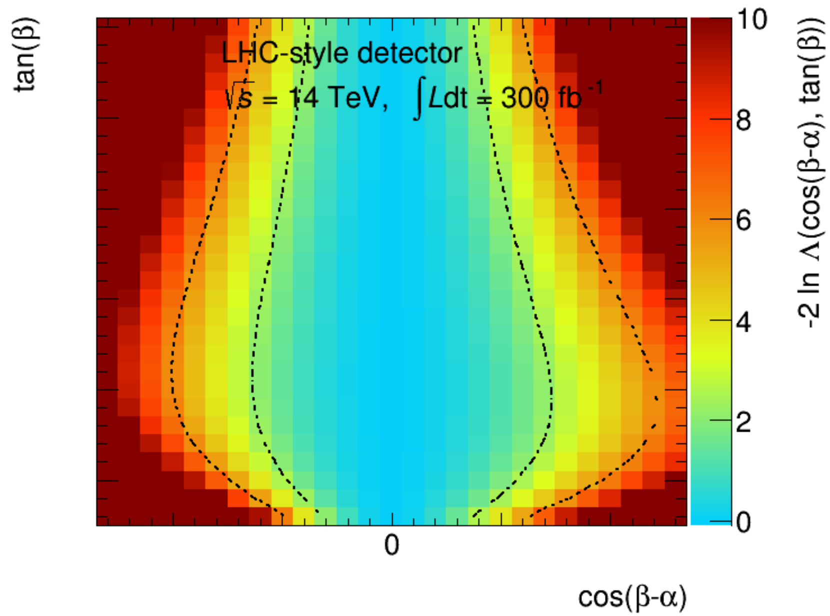
Limits on 2HDM Type I

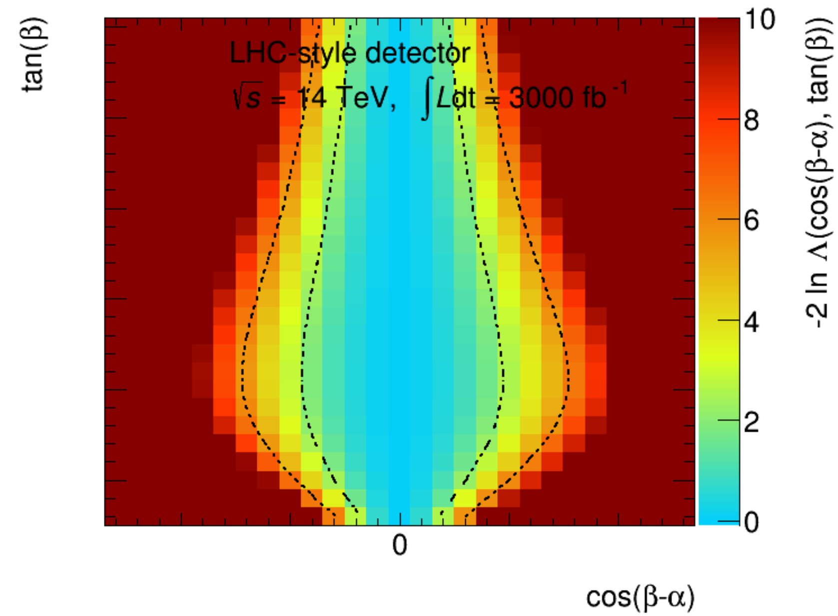
- **Disclaimer: Schematic illustration with LHC-style detector (not ATLAS)**
- Expected limits on 2HDM Type I with 300 (left) and 3000 (right) fb^{-1} at 14 TeV
- Type I: "Fermiophobic" i.e. decreased fermion couplings for first Higgs doublet
  - SM decoupling limit at $\cos(\beta-\alpha)=0$
  - Regions with $-2 \ln \Lambda > 6.0$ excluded at 95% CL
- At "low" $\tan(\beta)$, reach in $\cos(\beta-\alpha)$ improves by factor ~2 with 3000 fb^{-1}



Limits on 2HDM Type II

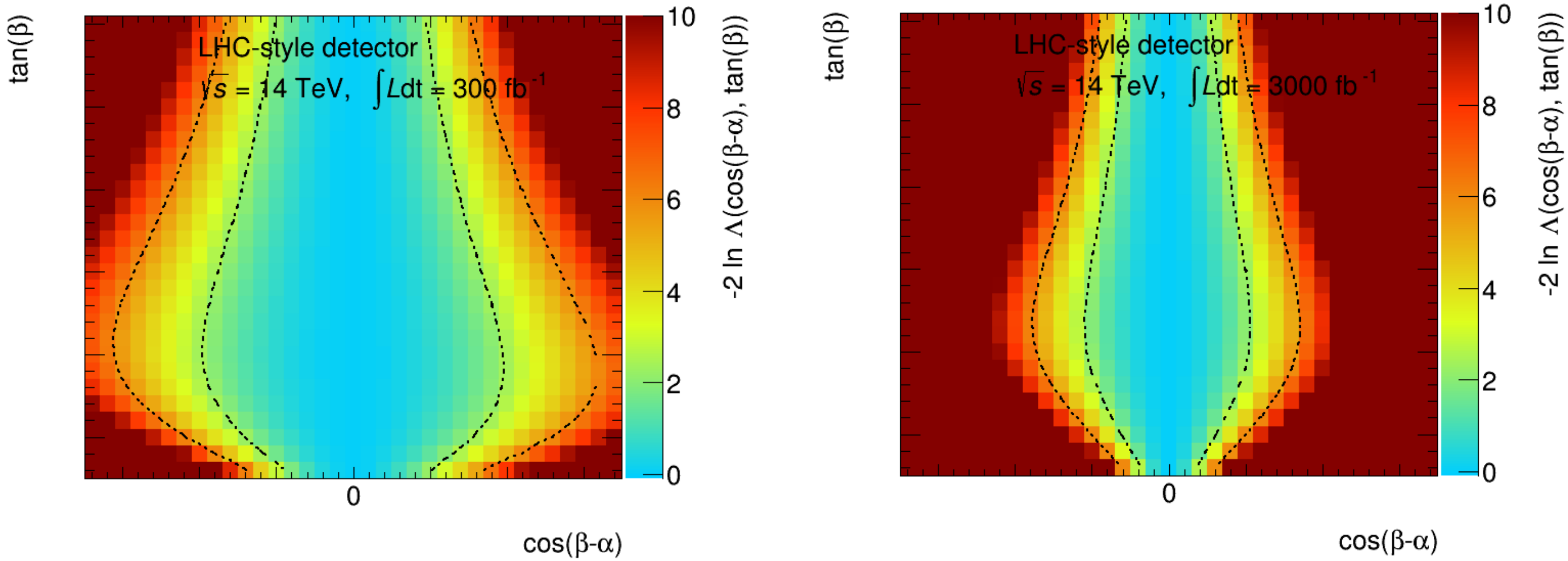
- **Disclaimer: Schematic illustration with LHC-style detector (not ATLAS)**
- Expected limits on 2HDM Type II with 300 (left) and 3000 (right) fb^{-1} at 14 TeV
- Type II: "MSSM-like" i.e. two doublets couple separately to up & down-type
  - SM decoupling limit at $\cos(\beta-\alpha)=0$
  - Regions with $-2 \ln \Lambda > 6.0$ excluded at 95% CL
- At "low" $\tan(\beta)$, reach in $\cos(\beta-\alpha)$ improves by factor ~2 with 3000 fb^{-1}





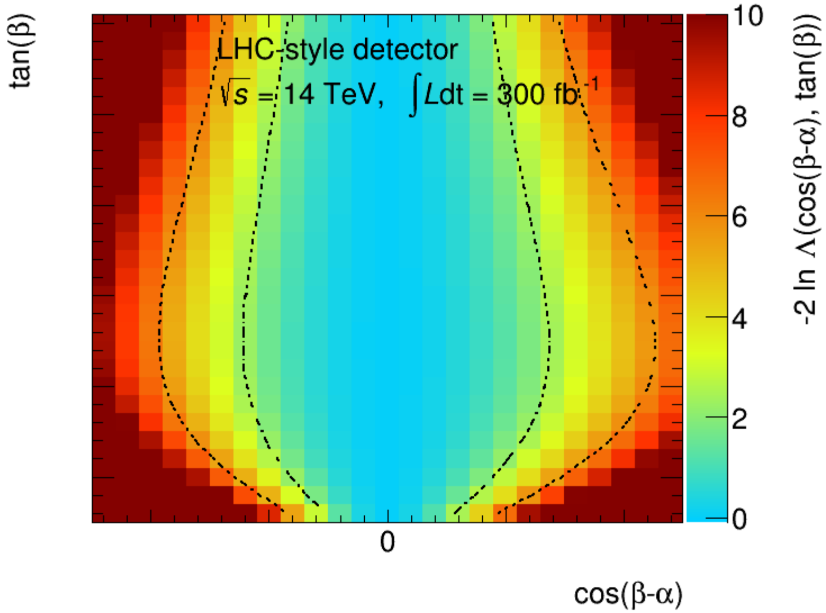
Limits on 2HDM Type III

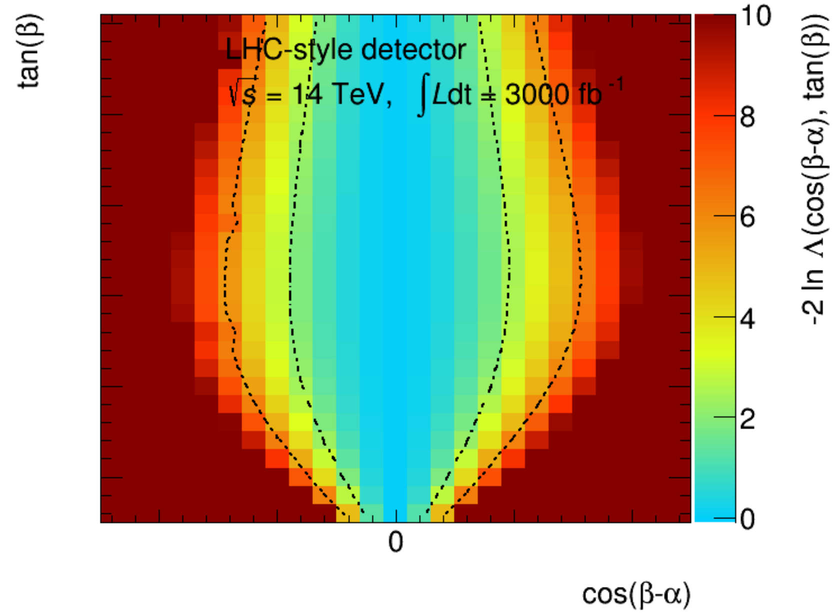
- **Disclaimer: Schematic illustration with LHC-style detector (not ATLAS)**
- Expected limits on 2HDM Type III with 300 (left) and 3000 (right) fb^{-1} at 14 TeV
- Type III: "Lepton-specific" i.e. lepton couplings inverted wrt Type I
  - SM decoupling limit at $\cos(\beta-\alpha)=0$
  - Regions with $-2 \ln \Lambda > 6.0$ excluded at 95% CL
- At "low" $\tan(\beta)$, reach in $\cos(\beta-\alpha)$ improves by factor ~2 with 3000 fb^{-1}



Limits on 2HDM: Type IV

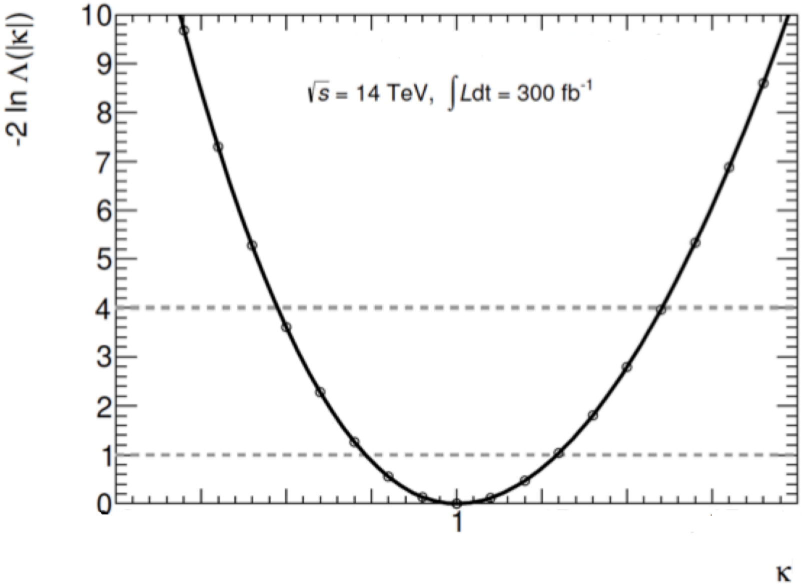
- **Disclaimer: Schematic illustration with LHC-style detector (not ATLAS)**
- Expected limits on 2HDM Type IV with 300 (left) and 3000 (right) fb^{-1} at 14 TeV
- Type IV: "Flipped" i.e. lepton couplings flipped wrt Type II
  - SM decoupling limit at $\cos(\beta-\alpha)=0$
  - Regions with $-2 \ln \Lambda > 6.0$ excluded at 95% CL
- At "low" $\tan(\beta)$, reach in $\cos(\beta-\alpha)$ improves by factor ~2 with 3000 fb^{-1}

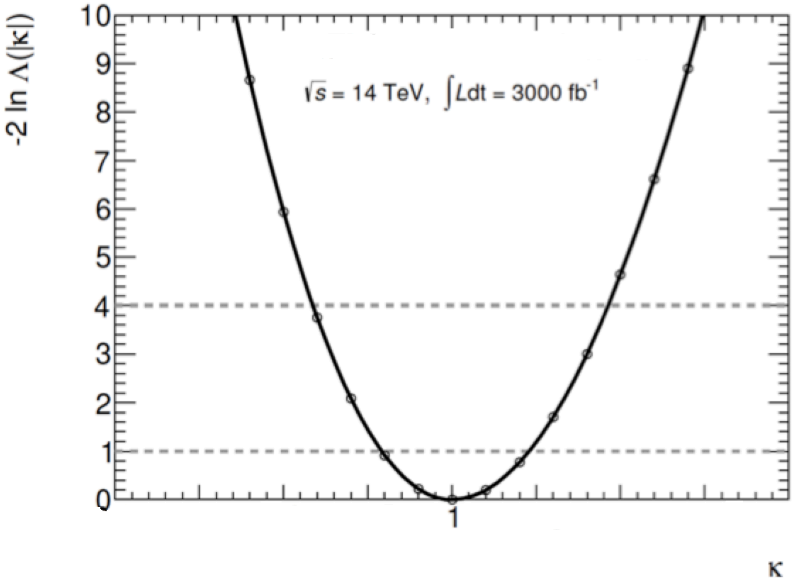




2) Additional electroweak singlet

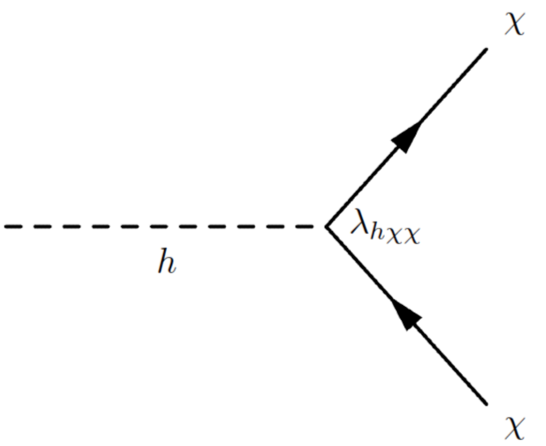
- BSM models could also include additional EW singlet:
  e.g. G. Pruna, T. Robens. arXiv:1303.1150
- Modifies all Higgs couplings by factor κ
  - Uncertainty on κ expected to decrease significantly from 300 to 3000 fb^{-1}
- Expected upper limit on coupling $\kappa' = \mathrm{sqrt}(1 - \kappa^2)$ to EW singlet improves proportionally to that on κ
  - Example below: 50% improvement on precision of Higgs κ with 3000 fb^{-1} would bring a 50% improvement on the upper limit on EW singlet κ'





3) Higgs portal to dark matter / hidden sector

- "Higgs portal" model extends SM to include dark matter WIMP, with coupling to Higgs boson as additional DOF
  - e.g. Djouadi et al. arXiv:1112.3299.
- Higgs resonant decays to dark matter pairs if $m_{DM} < 2\ m_H$
- Translate upper limit on invisible partial width into upper limit on Higgs coupling to WIMP as function of WIMP mass given either scalar, vector, or Majorana fermion:



$$\Gamma^{\rm inv}_{h\to SS} = \frac{\lambda^2_{hSS} v^2 \beta_S}{64\pi m_h} \ ,$$

$$\Gamma^{\rm inv}_{h\to VV} = \frac{\lambda^2_{hVV} v^2 m_h^3 \beta_V}{256\pi M_V^4} \left(1 - 4\frac{M_V^2}{m_h^2} + 12\frac{M_V^4}{m_h^4}\right) ,$$

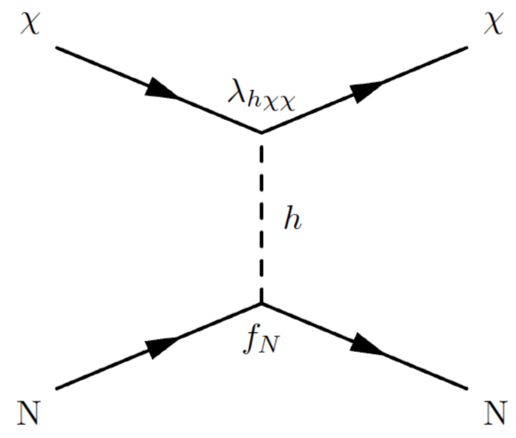
$$\Gamma^{\rm inv}_{h\to\chi\chi} = \frac{\lambda^2_{hff} v^2 m_h \beta_f^3}{32\pi\Lambda^2} \ ,$$

where:

$$\beta_X = \sqrt{1 - 4M_X^2/m_h^2}$$

Limit on WIMP-Nucleon cross-section

- Convert to upper limit on WIMP-nucleon scattering cross-section (via Higgs exchange), which is proportional to invisible branching ratio, as function of WIMP mass
  - Form factor for Higgs coupling to nucleons, f_N, computed using lattice QCD



$$\sigma^{SI}_{S-N} = \frac{\lambda^2_{hSS}}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(M_S + m_N)^2} ,$$

$$\sigma^{SI}_{V-N} = \frac{\lambda^2_{hVV}}{16\pi m_h^4} \frac{m_N^4 f_N^2}{(M_V + m_N)^2} ,$$

$$\sigma^{SI}_{f-N} = \frac{\lambda^2_{hff}}{4\pi \Lambda^2 m_h^4} \frac{m_N^4 M_f^2 f_N^2}{(M_f + m_N)^2} ,$$

- Below half the Higgs mass, indirect limit from LHC far more stringent than direct searches in astroparticle experiments
  - HL-LHC would further extend these upper limits on the cross-section
  - For example, improvement of 50% precision of upper limit on invisible decays with 3000 fb^{-1} would improve the upper limit on WIMP-nucleon cross-section by 50%

Conclusions

- ATLAS PUB note and white paper on expected gain at HL-LHC for Higgs coupling precision & indirect constraints on BSM physics will be public soon
- Higgs coupling uncertainties will (conservatively) decrease to as low as ~10% with 300 fb^{-1} at 14 TeV, and as low as ~5% with 3000 fb^{-1} at HL-LHC
  - *Private interpretation here of existing public results*
- Expected limits (and discovery reach) for various new phenomena can be significantly enhanced with higher luminosity:
  - 2HDM: Reach in $\cos(\beta-\alpha)$ and $\tan(\beta)$ for types I-IV, including MSSM-like Type II, could be improved by roughly factor of 2
  - EW singlet: Upper limit on coupling κ' proportional to coupling precision
  - Dark matter: WIMP-nucleon cross-section upper limit better than limits from direct detection and improves proportionally with BR_{inv}
- Very conservative assumptions regarding projected detector performance (e.g. H->WW), and not including expected reductions in theory uncertainties
  - Improvements would scale expected limits correspondingly
- Higgs coupling precision and corresponding reach for new physics at HL-LHC comparable to those of Stage I at an ILC
  - HL-LHC is complementary and worthwhile investment given lower cost

Additional information

References (I)

- ATLAS Collaboration. "Combined coupling measurements of the new Higgs-like boson with the ATLAS detector using up to 25 fb-1 of *pp* collision data." ATLAS-CONF-2013-034, CERN. March 2013.
- ATLAS Collaboration. "Coupling properties of the new Higgs-like boson observed with the ATLAS detector at the LHC". ATLAS-CONF-2012-127, CERN. September 2012.
- ATLAS Collaboration. "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC." Phys. Lett. B 716, 1 (2012).
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- ATLAS Collaboration. Physics at a High-Luminosity LHC with ATLAS. ATL-PHYS-PUB-2012-001, CERN.
- LHC Higgs Cross Section Working Group. "LHC HXSWG interim recommendations to explore the coupling structure of a Higgs-like particle." arXiv:1209.0040 (2012).

References (II)

- CMS Collaboration. "Measurements of the properties of the new boson with a mass near 125 GeV." CMS-PAS-HIG-13-005, CERN. April 2013.
- CMS Collaboration. "Combination of Standard Model Higgs boson searches and measurements of the properties of the new boson with a mass new 125 GeV." CMS-HIG-12-045, CERN. November 2012.
- CMS Collaboration. "Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC". Phys. Lett. B 716, 30 (2012).
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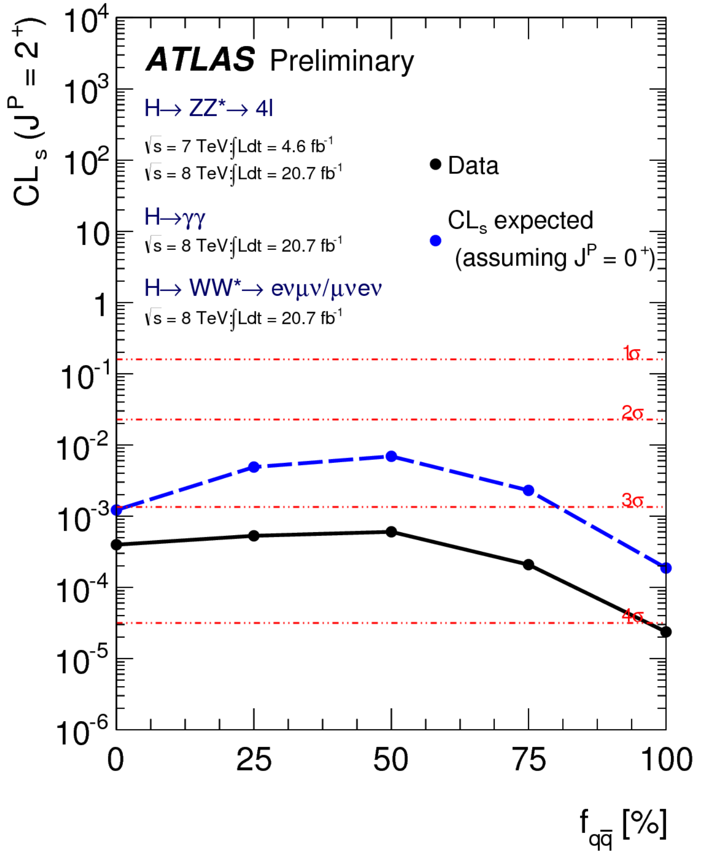
- M. J. Dolan, C. Englert, M. Spannowsky. "Higgs self-coupling measurements at the LHC". arXiv:1206.5001v2 (2012).
- U. Baur, T.Plehn, D, Rainwater. Probing the Higgs self-coupling at hadron colliders using rare decays, Phys. Rev. D69, 053004 (2004).

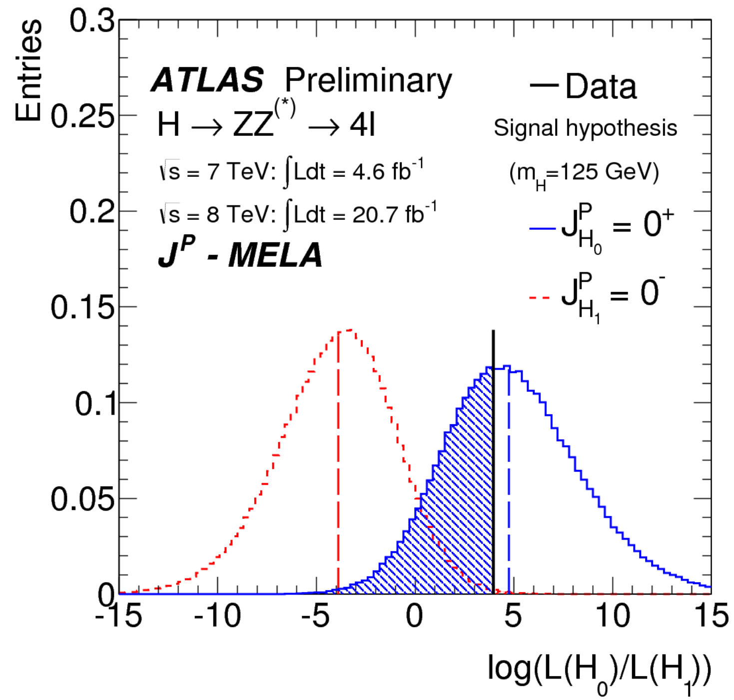
Spin and charge-parity

- New, neutral boson appears to have spin 0 and even CP
  - 2^+ and 0^- hypotheses excluded at >95% CL, , but mixed parity not ruled out
  - Does not appear to be KK graviton, pure CP-odd A, etc.
- Consistent with a Higgs boson, but is it the SM Higgs?



ATLAS-CONF-2013-040

ATLAS-CONF-2013-013



Input data for ATLAS measurements

Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int L\,dt$ [fb^{-1}]	Ref.
		2011 $\sqrt{s}$ =7 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu$, 2-jet VBF, ℓ-tag$\}$	4.6	[8]
$H \to \gamma\gamma$	–	10 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes$ conversion$\} \oplus \{$2-jet VBF$\}$	4.8	[7]
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{$0-jet, 1-jet, 2-jet VBF$\}$	4.6	[9]
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{e\mu\} \otimes \{$0-jet$\} \oplus \{\ell\ell\} \otimes \{$1-jet, 2-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, $VH\}$	4.6	[10]
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes \{$0-jet, 1-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, 2-jet$\}$	4.6	
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{$1-jet, 2-jet$\}$	4.6	
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200$ GeV$\} \otimes \{$2-jet, 3-jet$\}$	4.6	[11]
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	4.7	
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	4.7	
		2012 $\sqrt{s}$ =8 TeV		
$H \to ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu 2e, 4\mu$, 2-jet VBF, ℓ-tag$\}\}$	20.7	[8]
$H \to \gamma\gamma$	–	14 categories $\{p_{\mathrm{Tt}} \otimes \eta_\gamma \otimes$ conversion$\} \oplus \{$2-jet VBF$\} \oplus \{\ell$-tag, $E_{\mathrm{T}}^{\mathrm{miss}}$-tag, 2-jet VH$\}$	20.7	[7]
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu e, \mu\mu\} \otimes \{$0-jet, 1-jet, 2-jet VBF$\}$	20.7	[9]
$H \to \tau\tau$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\{\ell\ell\} \otimes \{$1-jet, 2-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, $VH\}$	13	[10]
	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\{e, \mu\} \otimes \{$0-jet, 1-jet, $p_{\mathrm{T},\tau\tau} > 100$ GeV, 2-jet$\}$	13	
	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\{$1-jet, 2-jet$\}$	13	
$VH \to Vbb$	$Z \to \nu\nu$	$E_{\mathrm{T}}^{\mathrm{miss}} \in \{120-160, 160-200, \geq 200$ GeV$\} \otimes \{$2-jet, 3-jet$\}$	13	[11]
	$W \to \ell\nu$	$p_{\mathrm{T}}^{W} \in \{< 50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	13	
	$Z \to \ell\ell$	$p_{\mathrm{T}}^{Z} \in \{< 50, 50-100, 100-150, 150-200, \geq 200$ GeV$\}$	13	

Production modes

- Coupling strengths for production modes

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ggH}}} = \begin{cases} \kappa_{\mathrm{g}}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, m_H) \\ \kappa_{\mathrm{g}}^2 \end{cases}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma^{\mathrm{SM}}_{\mathrm{VBF}}} = \kappa_{\mathrm{VBF}}^2(\kappa_{\mathrm{W}}, \kappa_{\mathrm{Z}}, m_H)$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma^{\mathrm{SM}}_{\mathrm{WH}}} = \kappa_{\mathrm{W}}^2$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma^{\mathrm{SM}}_{\mathrm{ZH}}} = \kappa_{\mathrm{Z}}^2$$

$$\frac{\sigma_{\mathrm{t\bar{t}H}}}{\sigma^{\mathrm{SM}}_{\mathrm{t\bar{t}H}}} = \kappa_{\mathrm{t}}^2$$

Decay modes

- Coupling strengths for decay modes and total width

$$\frac{\Gamma_{\mathrm{WW}^{(*)}}}{\Gamma^{\mathrm{SM}}_{\mathrm{WW}^{(*)}}} = \kappa_{\mathrm{W}}^2$$

$$\frac{\Gamma_{\mathrm{ZZ}^{(*)}}}{\Gamma^{\mathrm{SM}}_{\mathrm{ZZ}^{(*)}}} = \kappa_{\mathrm{Z}}^2$$

$$\frac{\Gamma_{\mathrm{b\bar{b}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{b\bar{b}}}} = \kappa_{\mathrm{b}}^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{\mathrm{SM}}_{\tau^-\tau^+}} = \kappa_{\tau}^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{\mathrm{SM}}_{\gamma\gamma}} = \begin{cases} \kappa_{\gamma}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_H) \\ \kappa_{\gamma}^2 \end{cases}$$

$$\frac{\Gamma_{\mathrm{Z}\gamma}}{\Gamma^{\mathrm{SM}}_{\mathrm{Z}\gamma}} = \begin{cases} \kappa_{(\mathrm{Z}\gamma)}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_H) \\ \kappa_{(\mathrm{Z}\gamma)}^2 \end{cases}$$

$$\frac{\Gamma_{\mathrm{t\bar{t}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{t\bar{t}}}} = \kappa_{\mathrm{t}}^2$$

$$\frac{\Gamma_{\mathrm{gg}}}{\Gamma^{\mathrm{SM}}_{\mathrm{gg}}} = \begin{cases} \kappa_{(\mathrm{H}\to\mathrm{gg})}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, m_H) \\ \kappa_{\mathrm{g}}^2 \end{cases}$$

$$\frac{\Gamma_{\mathrm{c\bar{c}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{c\bar{c}}}} = \kappa_{\mathrm{t}}^2$$

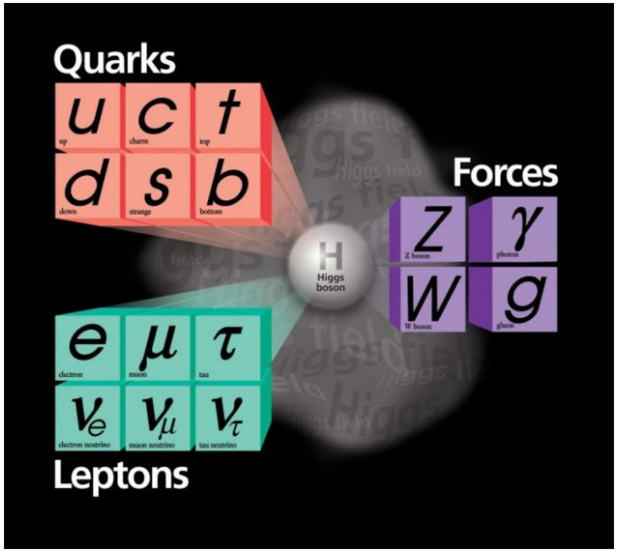
$$\frac{\Gamma_{\mathrm{s\bar{s}}}}{\Gamma^{\mathrm{SM}}_{\mathrm{s\bar{s}}}} = \kappa_{\mathrm{b}}^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma^{\mathrm{SM}}_{\mu^-\mu^+}} = \kappa_{\tau}^2$$

$$\frac{\Gamma_{\mathrm{H}}}{\Gamma^{\mathrm{SM}}_{\mathrm{H}}} = \begin{cases} \kappa_{\mathrm{H}}^2(\kappa_i, m_H) \\ \kappa_{\mathrm{H}}^2 \end{cases}$$

Simplified benchmark models

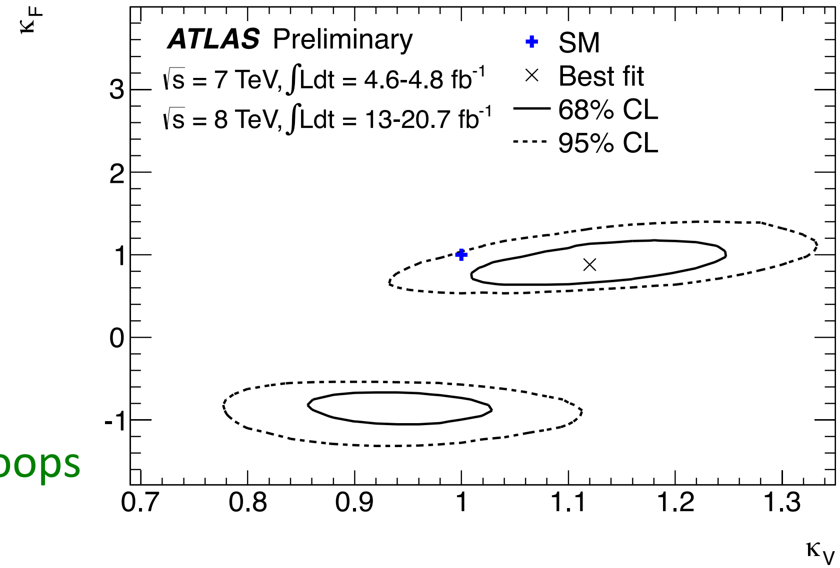
- Probed 7 symmetries, each with and without Higgs total width fixed = 14 models:
  - Fewer DOF's gives greater statistical precision in combined fit
  - Primary goal is to test SM (null hypothesis)
    - Possible bias from model assumptions not important

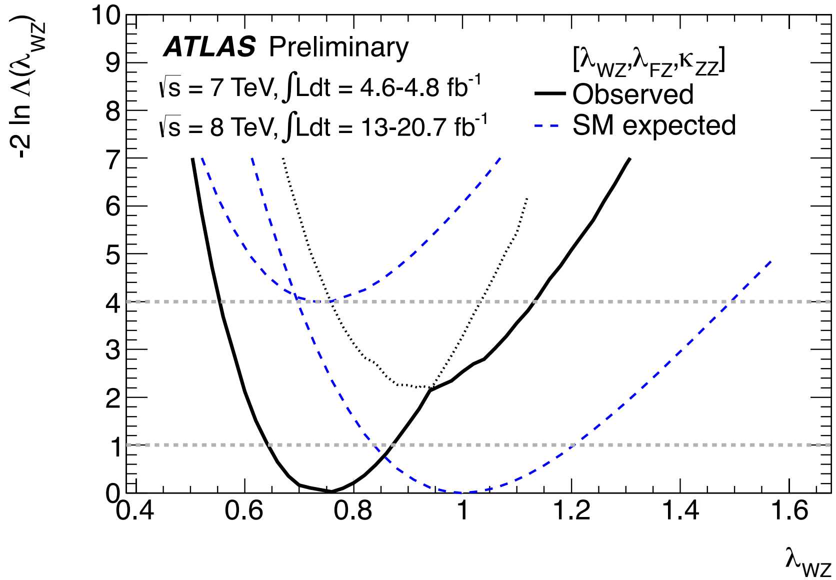


- Benchmark models defined by LHC Higgs XS WG: arXiv:1209.0040
  - **κ = sqrt(μ):** Universal scaling of couplings to all particles
  - **κ_V vs. κ_F:** Spin, vector bosons vs. fermions
  - **κ_W vs. κ_Z:** Custodial symmetry, W vs. Z boson
  - **κ_q vs. κ_l:** Fermion flavor, quarks vs. leptons
  - **κ_u vs. κ_d:** Fermion type, up vs. down
  - **κ_g vs. κ_γ:** Effective loop couplings for effects of heavy BSM particles
  - **κ_H & BR_{inv}:** Allow decays to light invisible BSM particles
- More complex models, including some targeting top coupling, will be accessible at 300 and 3000 fb^{-1}

Higgs couplings with current data

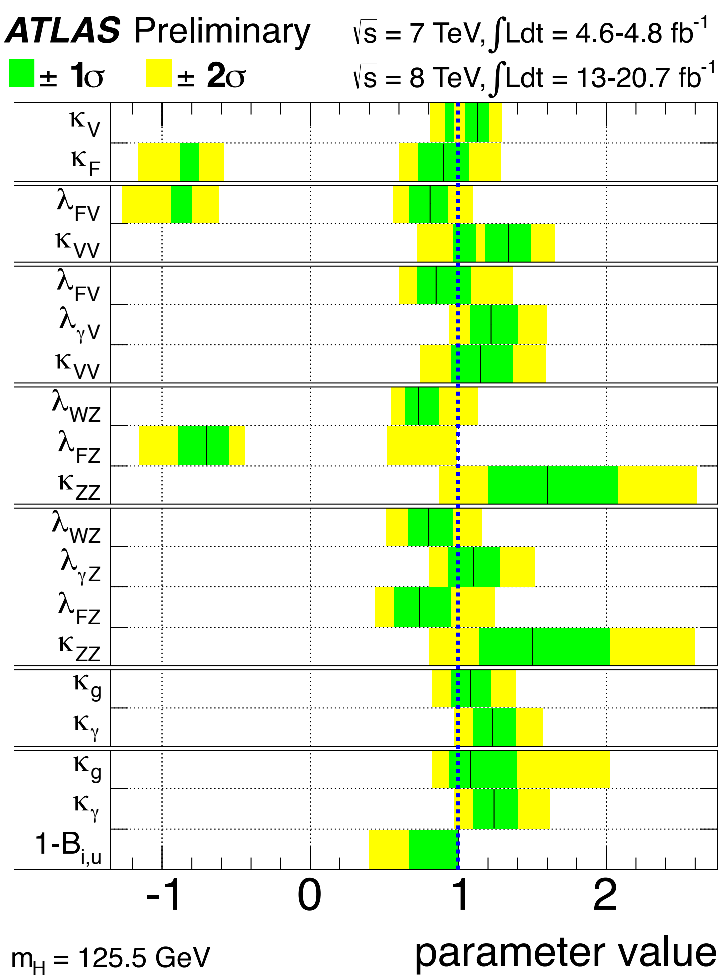
- Simplified model where couplings to weak vector bosons scaled by same strength:
  $\kappa_V = \kappa_W = g_W / g_{W,SM}$
  $= \kappa_Z = g_Z / g_{Z,SM}$
  and separate strength for fermions:
  $\kappa_f = \kappa_t = \kappa_b = \kappa_\tau = \ldots$
  - Assume no invisible decays
  - Recast gluon & photon couplings with loops of scaled tree-level couplings (W, t, etc)
  - **Couplings compatible with SM Higgs within 2σ -- not radion, dilaton, etc**
- Now repeat but giving W and Z boson couplings separate strengths
  - Independent of Higgs width
  - $\lambda_{WZ} = \kappa_W / \kappa_Z = 0.75 +/- 0.12$ consistent with SM within ~1.5σ
  - No significant violation of custodial symmetry observed
  - **Indirect indication "Higgs-like" boson is EW doublet since λ_{WZ}=0.5 for triplet**

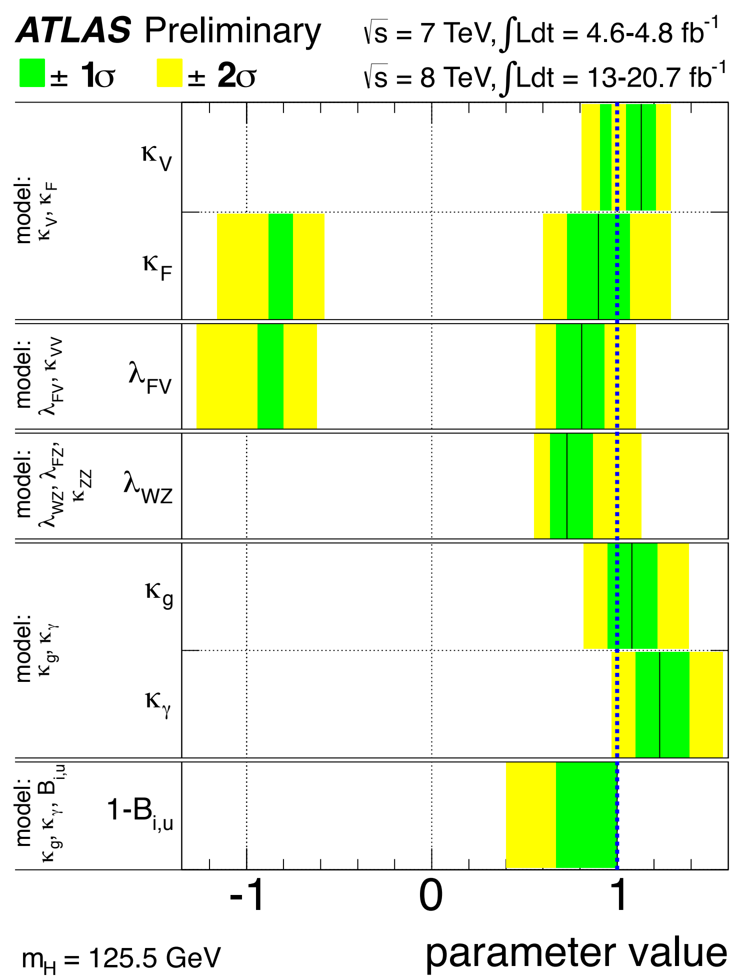




Summary of ATLAS fit results

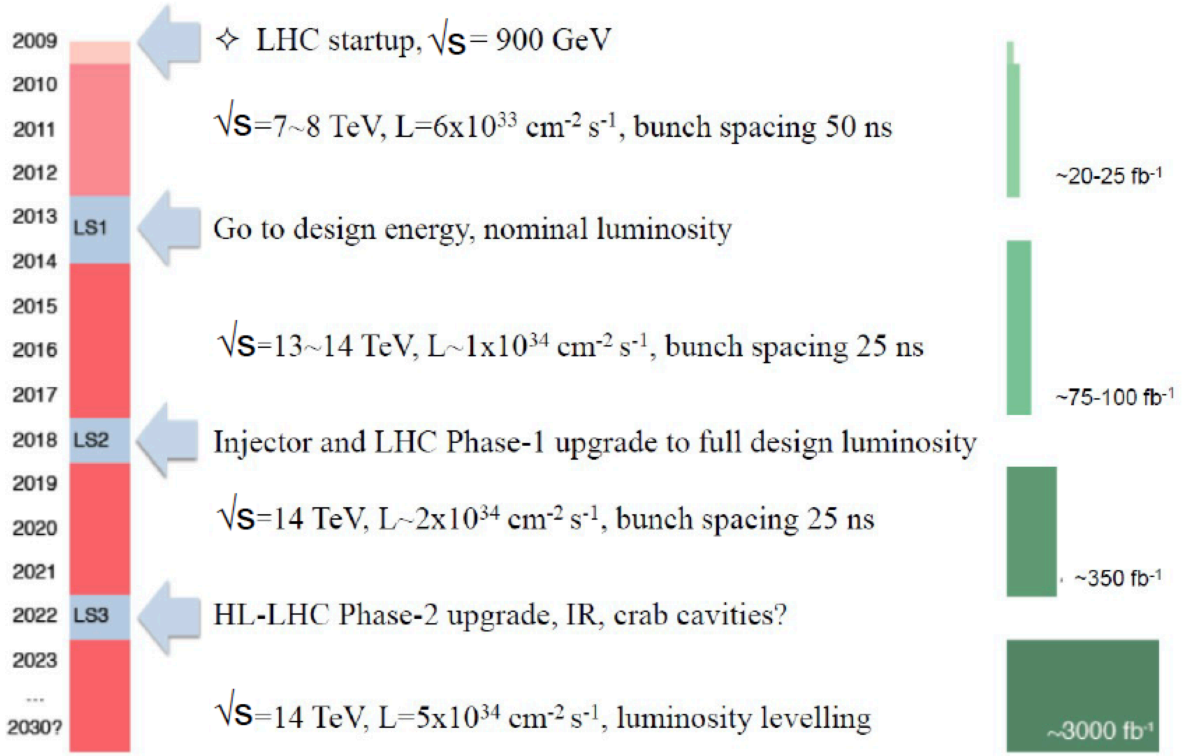
- Good agreement in most models
  - Note models are strongly correlated





LHC / High-lumi LHC schedule

- LHC schedule from Chamonix 2012
  - After LS3: ~140 collisions/bunch-crossing with luminosity-leveling
- Milestones:
  - 2022: 300 fb^{-1}
  - 2030: 3000 fb^{-1}



Theoretical uncertainties

- Precisions at high lumi with and without theoretical uncertainties

Model	300 fb^{-1}	3000 fb^{-1}
λ_{Zg}	26 (24)%	14 (11)%

λ_{tg}	26 (24)%	11 (7)%
$\lambda_{\tau\mu}$	33 (33)%	12 (11)%

$\lambda_{\mu Z}$	22 (22)%	7 (7)%
$\lambda_{\tau Z}$	21 (20)%	10 (9)%
λ_{WZ}	12 (12)%	11 (11)%

$\lambda_{\gamma Z}$	5 (5)%	1.5 (1.5)%
κ_{gZ}	8 (5)%	7 (2.5)%