Higgs coupling measurements with ATLAS

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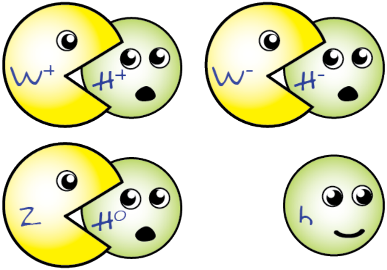
Higgs Mechanism



- For Higgs mechanism potential chosen such that electroweak symmetry is hidden
  - Higgs field gets **non-zero vacuum expectation value**
  - Three degrees of freedom give W^+, W^-, Z mass, one gives new scalar boson - **the Higgs boson**

- $SU(2)_L \otimes U(1)_Y$ describes electroweak sector in terms of **massless gauge bosons**
- In the SM a complex scalar doublet is introduced

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

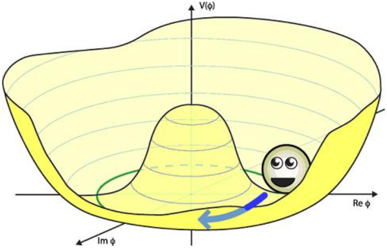
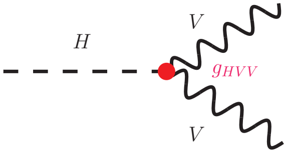


Image credit: Philip Tanedo

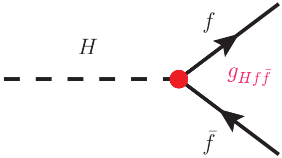
Higgs Mechanism: Scalar Couplings Structure

Bosonic sector:

- **EWSB** gives mass to W^+, W^-, Z bosons
- Higgs couplings proportional to $m^2_{W/Z}$



$$g_{HVV} = \frac{2m_V^2}{v}$$



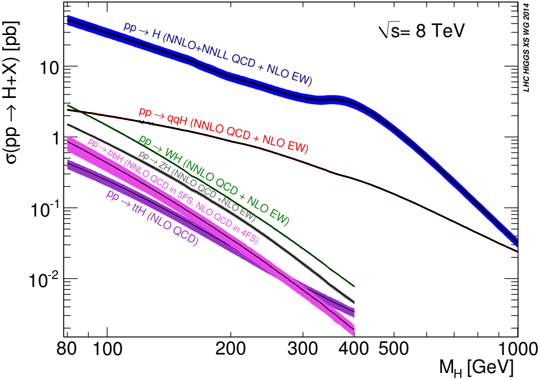
Fermionic sector:

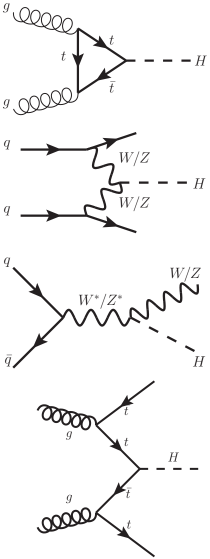
- After introducting Higgs field, can add **Yukawa terms** to Lagrangian
- Higgs couplings proportional to fermion mass

$$g_{Hf\bar{f}} = Y_f = \frac{m_f}{v}$$

- v is Higgs field vacuum expectation value
- Loops (e.g. γ, gluon) sensitive to BSM physics

Higgs Production at the LHC





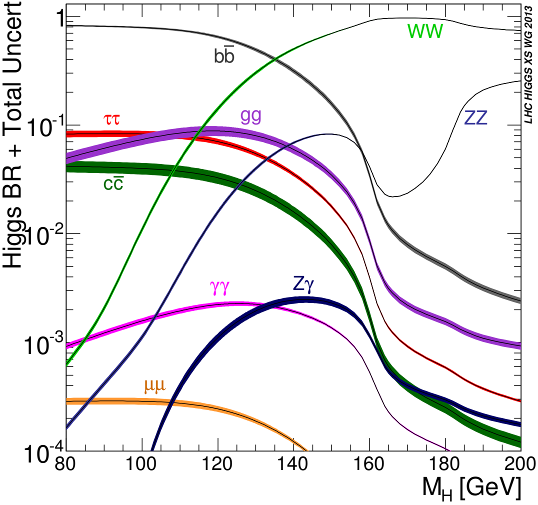
- Gluon fusion mode dominates
- Subleading modes essential to tag more difficult decay modes and measure couplings

Higgs Decays at the LHC

- $H \to b\bar{b}$ has highest rate but challenging due to very large background

- $H \to WW^{(*)} \to l\nu l\nu$, $H \to \tau\tau$ also have relatively high rates but complex final states

- $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ challenging because of low rates but clean final states



Possible Extensions to SM Higgs Sector

- In the SM EWSB is achieved through a **single complex scalar doublet** but many extensions possible

Additional EW singlet

- Mixing between singlet original Higgs doublet $\rightarrow$ two CP-even bosons
- Couple to SM particles in a similar way to SM Higgs

Two Higgs Doublet

- Predict 5 Higgs Bosons: 2 neutral CP-even, one neutral CP odd, 2 charged
- e.g. MSSM
- Typically require that models satisfy Glashow-Weinberg condition, e.g:
  - Type I: one doublet couples to vector bosons, one to fermions
  - Type II: one doublet couples to up-type quarks, the other to down-type and leptons

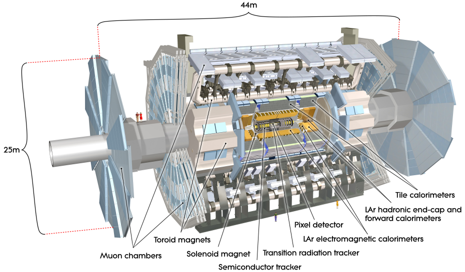
How does new physics modify Higgs couplings?

- New physics (e.g. extended Higgs sectors) can modify the Higgs couplings
- Modifications depend on mass scale of new physics
- For new physics at 1 TeV scale modifications are typically $\sim$ 1 - 10 %

Model	κ_V	κ_b	κ_γ
Singlet mixing	$\sim$ 6%	$\sim$ 6%	$\sim$ 6%
2HDM	$\sim$ 1%	$\sim$ 10%	$\sim$ 1%
Decoupling MSSM	$\sim$ -0.001%	$\sim$ 1.6%	$\sim$ -0.4%
Composite	$\sim$ -3%	$\sim$ -(3-9)%	$\sim$ -9%
Top Partner	$\sim$ -2%	$\sim$ -2%	$\sim$ +1%

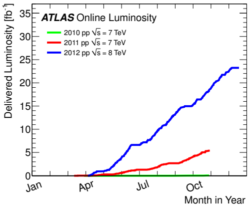
From Snowmass Higgs Working Group Report

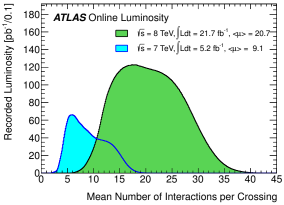
ATLAS detector



- **Successful operation** of ATLAS detector in run I
  - 4.6 fb^{-1} at $\sqrt{s} = 7\,TeV$, 20.3 fb^{-1} at $\sqrt{s} = 8\,TeV$
  - $\simeq$ 95% of recorded luminosity good for physics

- Strong detector performance achieved in challenging environment
  - Average 21 interactions per bunch crossing
  - **Higher than design pileup**





Atlas Higgs physics programme

- ATLAS has published a broad selection of results in the Higgs sector in run I
  - Mass
  - Couplings
  - Spin/CP
  - Differential distributions
  - Rare decays
  - and more ...

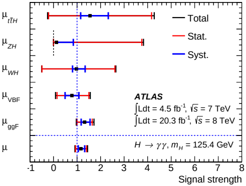
- Focus on measurement of **coupling properties** today

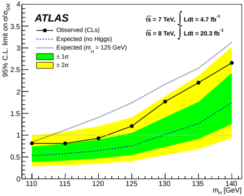
- Don't have time to discuss individual analyses in detail
  - Instead a selection of highlights from main inputs to ATLAS combined coupling measurements
  - For *bb* see Paul Thompson's recent seminar

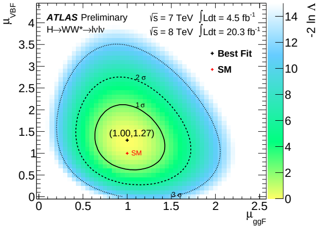
ATLAS Higgs couplings measurements

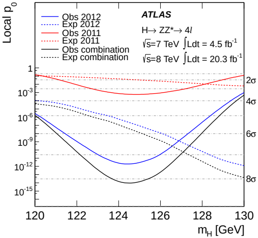
ATLAS has recently released updated results for the five most sensitive SM channels using full run I data:

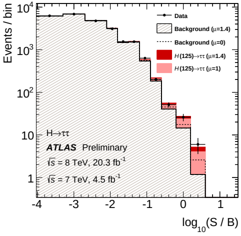
- $H \to 4\ell$
- $H \to \gamma\gamma$
- $VH, H \to b\bar{b}$
- $H \to WW$
- $H \to \tau\tau$











'Signal Strength' μ

- Measured rates reported relative to **SM prediction**
- **Signal strength** defined as:

$$\mu = \frac{\sigma \cdot BR}{\sigma_{SM} \cdot BR_{SM}}$$

- Measured in decay modes and also for their combination
- Also able to measure rates for **specific production modes**
  - Typically denoted with a subscript

$$\mu_{ggF} = \frac{\sigma(ggF) \cdot BR}{\sigma_{SM}(ggF) \cdot BR_{SM}}$$

- Often combine bosonic/fermionic production modes
  - $\mu_{ggF+ttH}$, μ_{VBF+VH}

Statistical techniques

- Confidence intervals based on **profile likelihood ratio**

$$\Lambda(\alpha) = \frac{L(\alpha, \hat{\hat{\theta}}(\alpha))}{L(\hat{\alpha}, \hat{\theta})} = \frac{\text{Maximum likelihood for given } \alpha}{\text{Global maximum likelihood}}$$

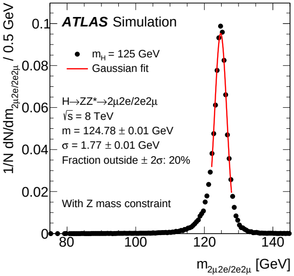
- Depends on one of more parameters of interest, α
  - e.g. (μ, m_H), (μ_{ggF}, μ_{VBF})
- Systematic uncertainties modelled using nuisance parameters, θ
  - Typically constrained by gaussians
  - Model uncertainties and their correlations
- Likelihood functions built using sums of signal and background pdfs in discriminating variables

$H \to ZZ^{(*)} \to 4\ell$ analysis

- **Low rates** but final state with **good mass resolution** (1.6 - 2.2 GeV) and **high S/B** (0.7 - 1.8)
  - $\sigma \times BR \simeq 2.9$ fb for $m_H = 125.5$ GeV

- Two same-flavour, opposite sign lepton pairs

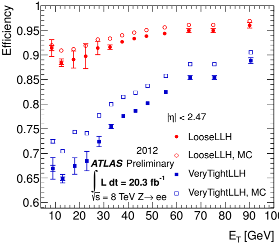
- Low p_T electron/muon performance critical
  - $p_T > 7$ (6) GeV for electrons (muons)
  - Isolation and impact parameter requirements to reduce background

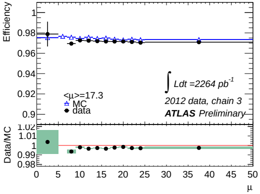


- m_Z constrained kinematic fit for m_{12}

- FSR photon recovery for m_{12} candidates

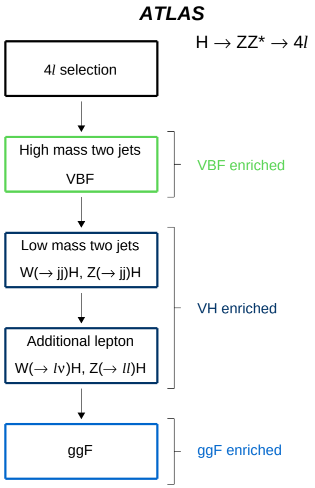
- E-p combination for $p_T^e < 30$ GeV





$H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ categorisation and fit model

- Multi-observable fit in **production-tagged** categories
  - Exploit use of **BDTs**



ggF categories:

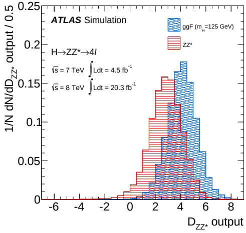
- Fit $m_{4\ell}$ and BDT with LO matrix element kinematic discriminant, $p_T^{4\ell}, \eta^{4\ell}$

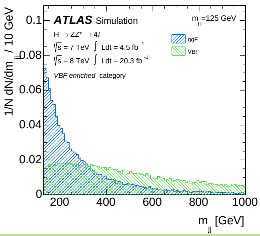
VBF category:

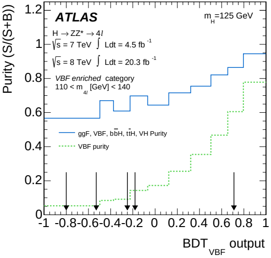
- Fit $m_{4\ell}$ and BDT with jet kinematic variables

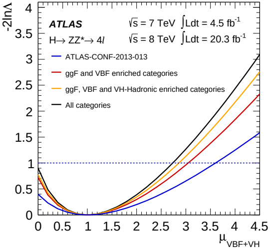
VH categories:

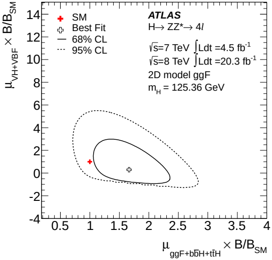
- 1D fit to $m_{4\ell}$











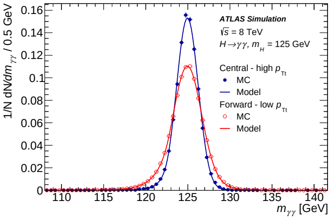
- 5 events in VBF-enriched category, 1 with $BDT_{VBF} \simeq 0.7$

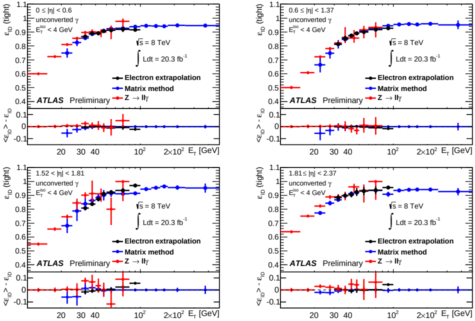
$$\mu_{ggF+bbH+ttH} \times B/B_{SM} = 1.7^{+0.5}_{-0.4}$$
$$\mu_{VBF+VH} \times B/B_{SM} = 0.3^{+1.6}_{-0.9}$$

- Uncertainties dominated by statistical component
- Expected uncertainty on μ_{VBF+VH} reduced by $\simeq$ 40% compared to preliminary result

$H \to \gamma\gamma$ analysis

- $H \to \gamma\gamma$ decays through t and W loops in SM
  - Negative interference between t and W contributions
- Two isolated, high p_T photons
- Search for narrow peak (mass resolution 1.3 - 1.8 GeV) on top of background (S/B $\simeq$ 3%)

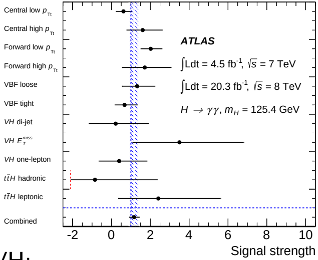




- Diphoton invariant mass: $m^2_{\gamma\gamma} = 2E_1E_2(1 - cos\alpha)$
  - Neural network based identification of primary interaction vertex
- Backgrounds $\gamma\gamma(75\%)$, γj, jj
  - Estimated from sideband fit

$H \to \gamma\gamma$ categories

Comprehensive categorisation scheme targetting 5 main production mechanisms



Untagged:

- Split based on p_{Tt} and position in detector

VBF:

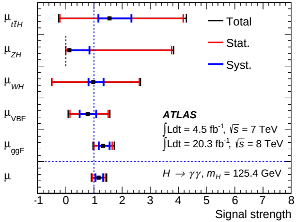
- Cut on output of BDT
- Loose and tight categories

VH:

- Sensitivity to separate WH and ZH
- Hadronic, leptonic and E_T^{miss} signatures

ttH:

- Hadronic and leptonic top decays



Signal strength for each production mode
consistent with SM

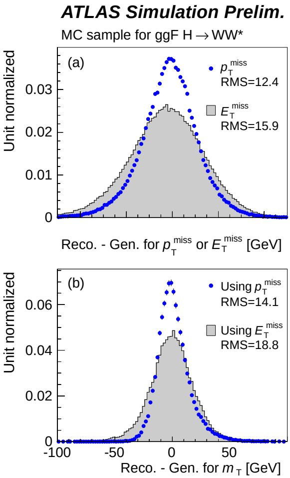
$H \to WW^{(*)} \to \ell\nu\ell\nu$ analysis

- High rate, relatively clean final state ($ee, e\mu, \mu\mu$ with E_T^{miss}/p_T^{miss})
  - Mass resolution $\simeq$ 15 GeV
    $\Rightarrow$ background control crucial

- Several background sources
  - WW,W+jets,tt,single top, $Z\gamma^*$, Z$\to \ell\ell$ estimated in data using control regions
  - Other diboson process estimate using MC
  - Background composition depends on lepton flavour, N_{jets}

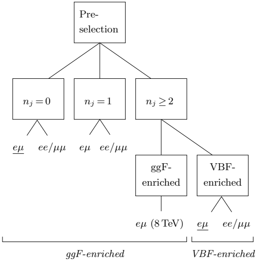
- Improvements with respect to preliminary analysis
  - Track-based missing E_T
  - Electron Likelihood ID
    - Reduce lepton E_T threshold 15 $\to$ 10 GeV
  - Optimised event categorisation

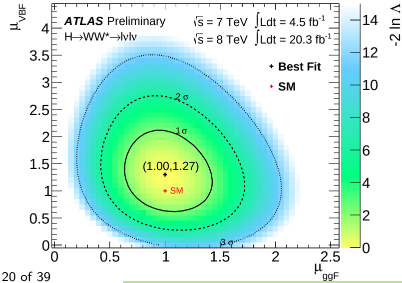
- Overall **30% reduction of uncertainties** on μ w.r.t preliminary results

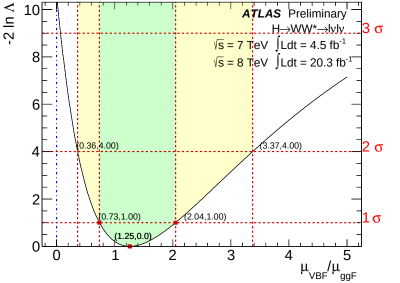


$H \to WW^{(*)} \to \ell\nu\ell\nu$ categories and fit model

- Transverse mass m_T used as discriminant in fit
  - In VBF categories use *BDT* instead
  - Fit in several signal and control regions
- Rates for ggF and VBF processes **consistent with SM**
- Observe VBF production with 3.2σ significance

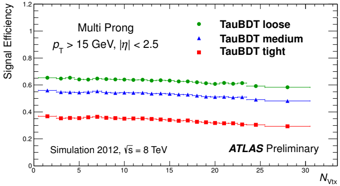


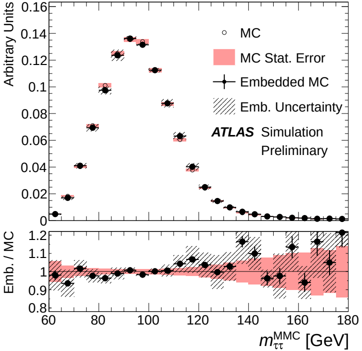




$H \to \tau\tau$ analysis

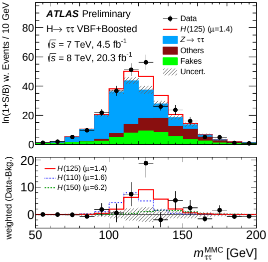
- Three final states used in analysis depending on τ decays:
  - $\tau_{lep}\tau_{lep}$
  - $\tau_{lep}\tau_{had}$
  - $\tau_{had}\tau_{had}$
- $Z \to \tau\tau$ and fake τ backgronds dominate
- Use missing mass calculator
  - Use visible τ decay products and E_T^{miss} to find most-likely $m_{\tau\tau}$
- $Z \to \tau\tau$ background from $Z \to \mu\mu$ embedding method
- BDT used as a discriminating variable in a 6 category (VBF and boosted for each final state) fit
  - Cut-based analysis as cross check

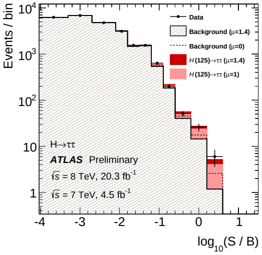


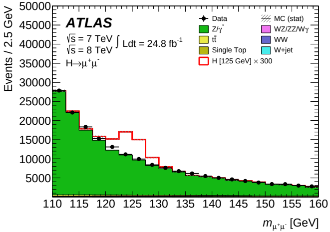


$H \to \tau\tau$: evidence for Higgs decays to fermions

- **Direct evidence for coupling to fermions** at 4.5σ level (3.5σ exp)
- $\mu = 1.42^{+0.44}_{-0.38}$ consistent with SM Yukawa coupling prediction



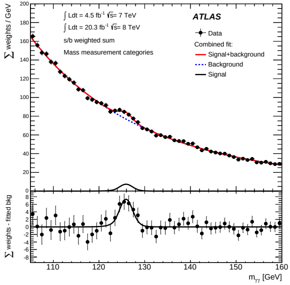


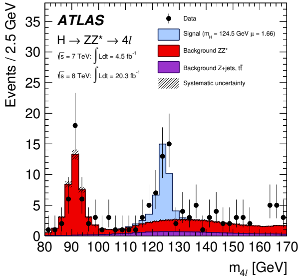


- ATLAS also searches for $H \to \mu\mu$
- No observed excess of events
- In SM $BR(\tau\tau)/BR(\mu\mu) \simeq 300$
  $\Rightarrow$ The Higgs does not couple universally to different flavour leptons

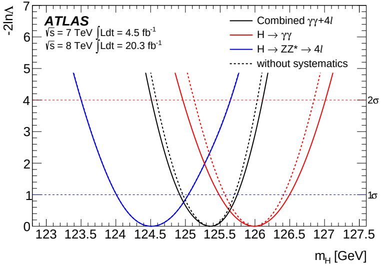
Higgs mass measurement

- Precise measurement of m_H important for determining couplings
  - For a shift in mass $\Delta m_H = 400$ MeV, $\sigma \times BR(ZZ)$ changes by $\simeq 3\%$
- ATLAS m_H measurement uses **high resolution modes** $H \to \gamma\gamma$ $H \to ZZ^{(*)} \to 4\ell$
- Improvements with respect to preliminary results
  - Significantly improved **e/γ calibration**
    - Systematic on m_H in $\gamma\gamma$ due to photon energy scale reduced by factor 2.5
  - Improved **lepton performace**
    - Likelihood-based electron ID
    - E-p combination for electrons
    - S/B for $2\mu 2e$ final state improved from $1.2 \to 1.8$
  - **Multivariate techniques** in $H \to ZZ^{(*)} \to 4\ell$
    - BDT as additional observable in fit $\to$ 8% improvement compared to 1D





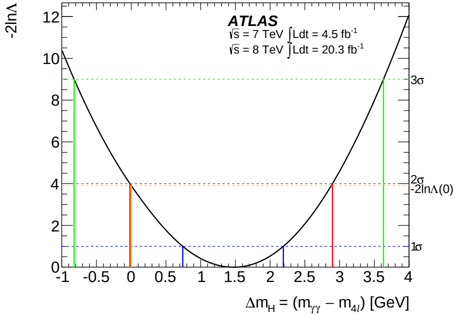
Higgs mass measurement



$H \to \gamma\gamma$: $m_H = 125.98 \pm 0.42(stat) \pm 0.28(sys)$

$H \to 4\ell$: $m_H = 124.51 \pm 0.52(stat) \pm 0.06(sys)$

Comined : $\mathbf{m_H = 125.36 \pm 0.37(stat) \pm 0.18(sys)}$



- Combined mass from a simultaneous max. likelihood fit, where $\mu_{\gamma\gamma}$ and $\mu_{4\ell}$ treated as independent free parameters
- Individual measurements **compatibility** $\simeq \mathbf{2.0}\sigma$
  - Compatibility in preliminary result was 2.5σ

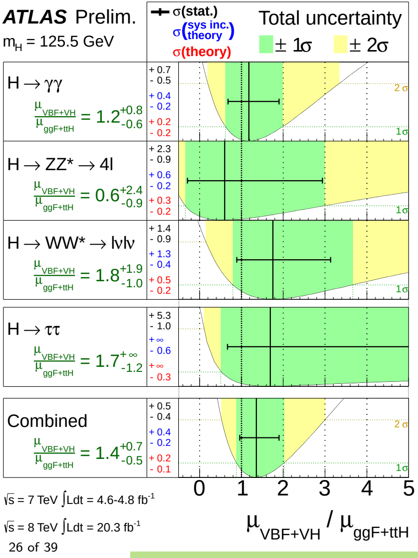
Measuring coupling properties

- Most recent ATLAS couplings combination released March 2014
  - $\gamma\gamma$, $ZZ^{(*)} \to 4\ell, WW^{(*)} - \to l\nu l\nu, \tau^+\tau^-, b\bar{b}$
  - Also use combination to put constraints on new phenomena
  - Many of the results shown so far today **not yet included** in combination
- Note measuring absolute couplings depends on total width:

$$\sigma \times BR(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

- In SM $\Gamma_H \simeq 4$ MeV!
  - Not possible to measure directly at the LHC
- Alternatively, measure **ratios of couplings**
  - Dependence on Γ_H cancels
- **Updated couplings combination** with final results planned
  - Possibility to include searches for rare decays and $t\bar{t}H$ production in future combinations

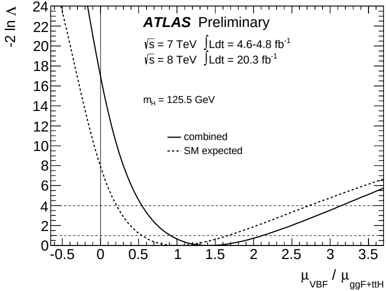
Production mode rates



- No combination of μ_{ggF}, μ_{VBF} possible between decay modes
  - Can't distinguish between production and decay for deviations
- Combine ratio instead

$$\mu_{VBF}/\mu_{ggF+ttH} = 1.4^{+0.5}_{-0.4}(stat)^{+0.4}_{-0.3}(sys)$$

- 4.1σ evidence for VBF Higgs production



κ-framework

- Framework for couplings based on LHC Higgs Cross Section Working Group recommendations
- **Leading order framework** for a single, SM-like Higgs boson under **specific assumptions**:
  - Single resonance with a mass near 125 GeV
  - Zero width approximation holds
  - Tensor structure of couplings assumed to be the same as SM
    - $J^P = 0^+$
- Define couplings scale factors κ :

$$\sigma \cdot BR(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H} = \frac{\sigma_i^{SM} \cdot \Gamma_f^{SM}}{\Gamma_H^{SM}} \cdot \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

- $\kappa_i = 1$ corresponds to the SM

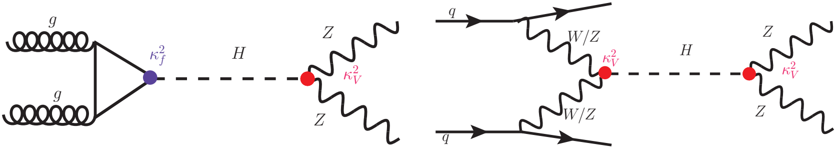
$\Rightarrow$ Idea is to Look for deviations from SM rates

κ-framework

- Framework makes **no specific assumptions on additional states of new physics** which could interact with the state at $\simeq$ 125 GeV, in particular on:
  - Additional Higgs bosons
  - Additional fermions, vector bosons or others scalars (which don't acquire a VEV)
  - Invisible decay modes
- Test **benchmark scenarios** based on this framework
- Fermion vs vector couplings:
  - Tests EWSB, Yukawa coupling model
  - One scale factor for vector bosons and one for fermions
- Fermion structure:
  - Many SM extensions (e.g. 2HDMs) predict deviations in fermion sector
  - One scale factor for up-type fermions and one for down-type
  - One scale factor for quarks and one for leptons
- Several other benchmarks also tested

Vector boson vs fermion couplings: $H \to ZZ^{(*)}$ example

- Benchmark model with one scale factor for all vector bosons (κ_V), one for all fermions (κ_F)



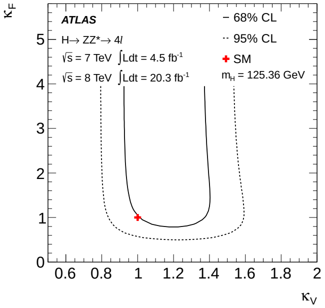
$$\mu_{ggF;H\to ZZ} = \frac{\sigma(ggF)\cdot BR(H\to ZZ)}{\sigma_{SM}(ggF)\cdot BR_{SM}(H\to ZZ)}$$

$$\to \frac{\kappa_F^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_F^2, \kappa_V^2)}$$

$$\mu_{VBF;H\to ZZ} = \frac{\kappa_V^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_F^2, \kappa_V^2)}$$

- $\kappa_H(\kappa_F, \kappa_V)$ is a scale factor for Γ_H^{total}

$$\kappa_H^2(\kappa_F^2, \kappa_V^2) = \alpha \cdot \kappa_F^2 + \beta \cdot \kappa_V^2$$



Vector boson vs fermion couplings

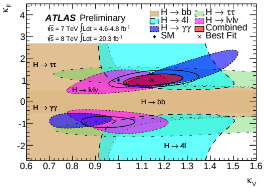
- Total width is sum of known SM Higgs decay modes
  - Modified appropriately with κ_V and κ_F

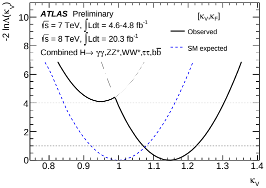
$$\kappa_V = 1.15 \pm 0.08$$
$$\kappa_F = 0.99^{+0.17}_{-0.15}$$

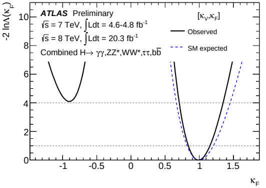
- Only relative sign physical $\rightarrow$ set $\kappa_V > 0$
- Sensitivity to relative sign from interference in $H \rightarrow \gamma\gamma$ decays
- 2D compatibility of SM with best fit 10%

Free parameters:

κ_V, κ_F





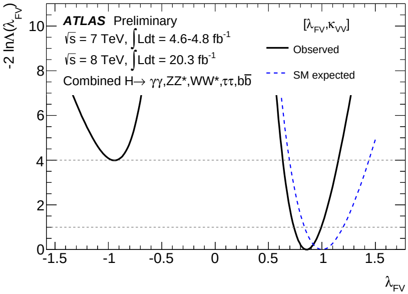


Vector boson vs fermion couplings

- Assumption on total width gives strong constraint on κ_F
  - Total width in SM dominated by b, τ and gluon decay widths
- Relax assumption by measuring ratios of scale factors

- Take ratio of fermion and vector scale factors λ_{FV}
- Then κ_{VV} is an overall scale factor which applies to all rates

$$\lambda_{FV} = 0.86^{+0.14}_{-0.12}$$
$$\kappa_{VV} = 1.28^{+0.16}_{-0.15}$$



Free parameters:

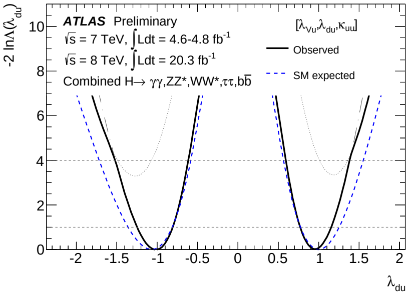
$$\lambda_{FV} = \kappa_F / \kappa_V, \; \kappa_{VV} = \kappa_V \cdot \kappa_V / \kappa_H$$

Up-type vs down-type fermions

- One scale factor for up-type fermions and one for down-type
- Some SM extensions (e.g some 2HDMs) predict different couplings for up- and down-type fermions
  - e.g. MSSM
- Take ratio of down and up scale factors λ_{du}

$$\lambda_{du} = 0.95^{+0.20}_{-0.18}*$$
$$\lambda_{Vu} = 1.21^{+0.24}_{-0.26}$$
$$\kappa_{uu} = 0.86^{+0.41}_{-0.21}$$

*For positive minima



- Little sensitivity to relative sign
- 3D compatibility with SM 20%
- 3.6σ evidence for coupling to down-type fermions

Free parameters:

$\lambda_{du} = \kappa_d/\kappa_u$, $\lambda_{Vu} = \kappa_V/\kappa_u$, $\kappa_{uu} = \kappa_u \cdot \kappa_u/\kappa_H$

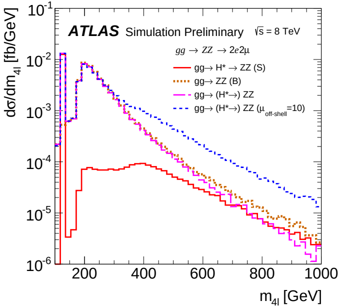
Off shell Higgs couplings

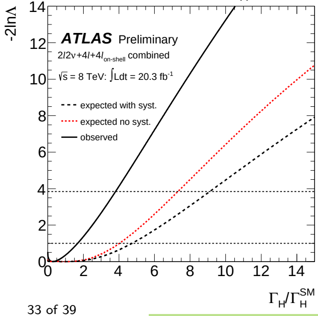
- $H \to VV$ high mass region has **sensitivity to off-shell Higgs production**

$$\frac{d\sigma_{pp\to H\to ZZ}}{dM^2_{4\ell}} \sim \frac{g^2_{Hgg} g^2_{HZZ}}{(M^2_{4\ell} - m^2_H) + m^2_H \Gamma^2_H}$$

- Using κ language

$$\mu_{on-shell} = \frac{\kappa^2_g \kappa^2_Z}{\kappa^2_H} \quad \mu_{off-shell} = \kappa^2_g \kappa^2_Z$$





- Combining on- and off-shell results, can interpret as **measurement of Γ_H**
- Measurement performed by ATLAS using $H \to ZZ^{(*)} \to 4\ell$ and $H \to ZZ^{(*)} \to 2\ell 2\nu$
- $\frac{\Gamma_H}{\Gamma_H^{SM}} < 5.7$ at 95% CL

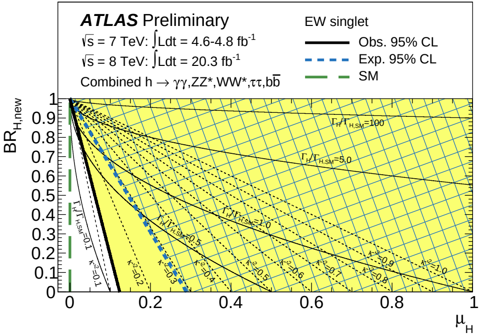
Constraints on new phenomena I: Additional Electroweak singlet

- Two Higgs bosons, one light (h), one heavy(H)
- Couple to vector bosons and fermions similar to SM but modified by scale factors
  - $\kappa + \kappa' = 1$
- h couplings same as SM, modified by κ
- H couplings modified to take into account new decay modes (e.g. $H \rightarrow hh$)

$$\mu_H = \kappa'^2 (1 - BR_{H,new})$$

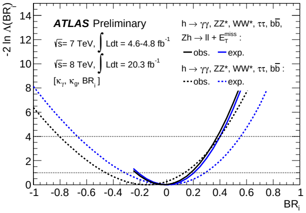
$$\kappa'^2 = 1 - \mu_h$$

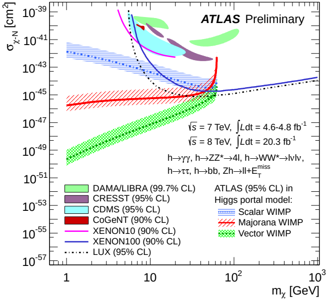
- Best fit at $\kappa'^2 = -0.30^{+0.17}_{-0.18}$
  - 1.5σ from physical boundary $\kappa'^2 \geq 0$
- Set limits in μ_H, $BR_{H,new}$ plane



Constraints on new phenomena II: Invisible branching ratio and dark matter portals

- Derive upper limits on Higgs BR to invisible final states
- Uses couplings combination combined with upper limits on $ZH \to \ell\ell + E_T^{miss}$ process
- $BR_i < 0.37$ at 95% CL

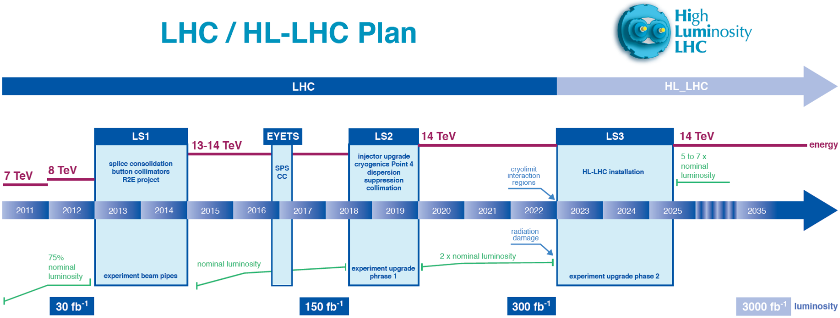




- Higgs portal models introduce weakly-interacting massive particles as dark matter candidates
  - Assumed to interact weakly with SM particles except Higgs boson
- Can compare limits with direct dark matter searches
  - Assuming $m_{WIMP} < 0.5 \cdot m_H$ and $H \to 2WIMPs$ accounts for all of BR_i

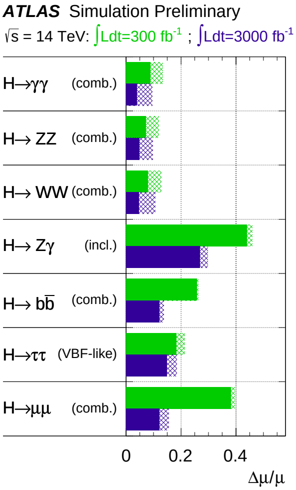
LHC upgrade timescale

- HL-LHC upgrade proposed
  - Goal to collect 3000 fb^{-1} by 2035



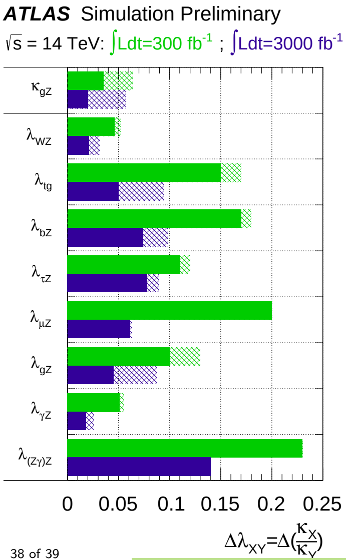
- Corresponding proposals for upgrades of the LHC experiments
  - Central feature of ATLAS upgrade programme a new, all silicon tracking system

Prospects for Higgs coupling measurements at a HL-LHC

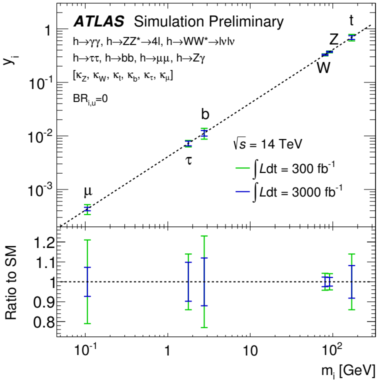


- ATLAS has studied the prospects for Higgs coupling studies with 3000 fb^{-1}
- Generator-level MC with parameterised model for detector efficiency and resolution
  - Parameterisations from Geant4 simulation
    - 140 interactions per bunch crossing
  - Systematic uncertainties same as run I
    - Data-driven uncertainties scaled with int lumi
- Hashed bands: theoretical uncertainties at their current level
- Projections typically based on older versions of analyses - do not include recent improvements
- Possible to measure decay rates to sub 10% level

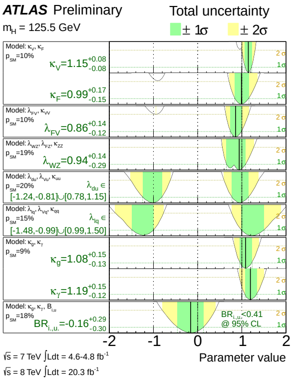
Prospects for Higgs coupling measurements at a HL-LHC



- Potential to measure coupling ratios down to few % level with 3000 fb^{-1}
- Projections in terms of scaling of couplings as for run I, but likely to move to a more general framework, e.g. effective field theory



Conclusion



- So far no significant deviation from SM
- Increased precision anticipated during next LHC runs and beyond

- ATLAS used LHC run I dataset to probe the coupling properties of the Higgs
  - Results suggest that a non-zero VEV of a scalar doublet is indeed responsible for EWSB
  - Evidence for Higgs decays to fermions also seen in $\tau\tau$ final state
    - Observed rates agree with SM Yukawa coupling prediction