HGamma Couplings and 4-lepton Combination at 13 TeV.

ATLAS Analyses presented at ICHEP 2016

ATLAS-CONF-2016-067

ATLAS-CONF-2016-081

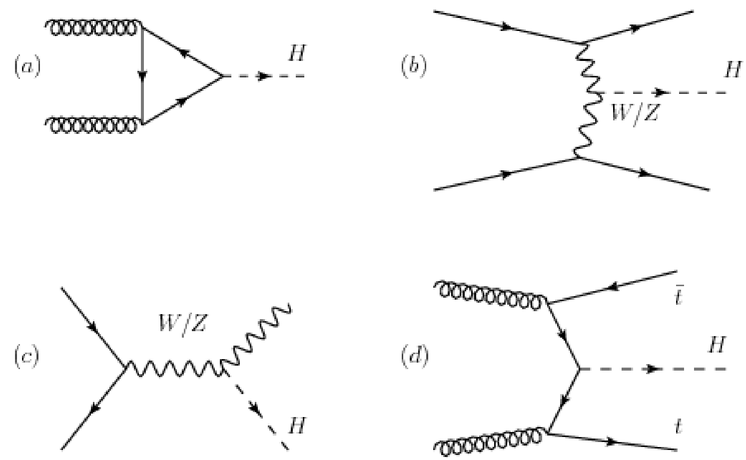
N. Styles
Higgs/B9 Meeting,
26/09/2016

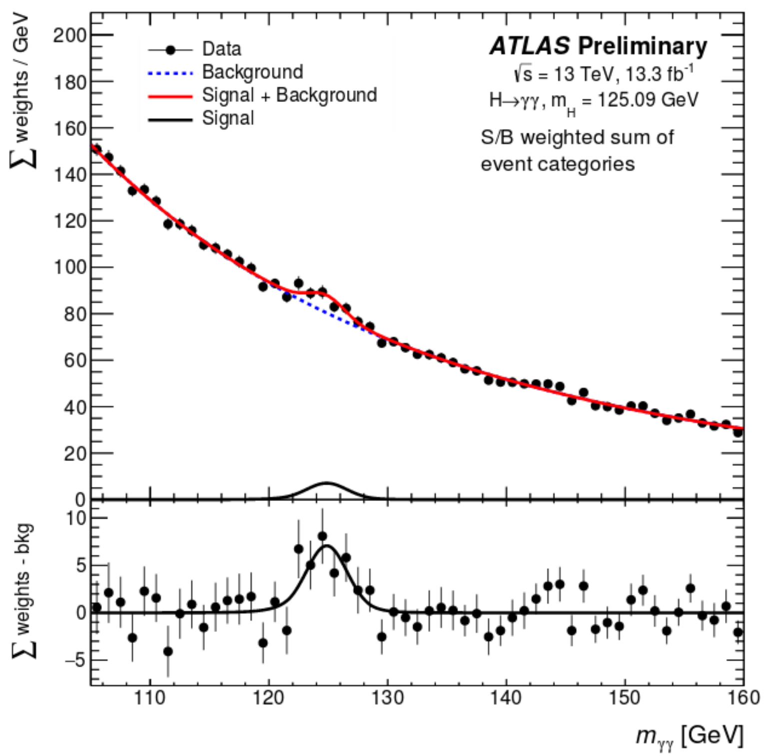
HELMHOLTZ GEMEINSCHAFT

DESY

Motivation

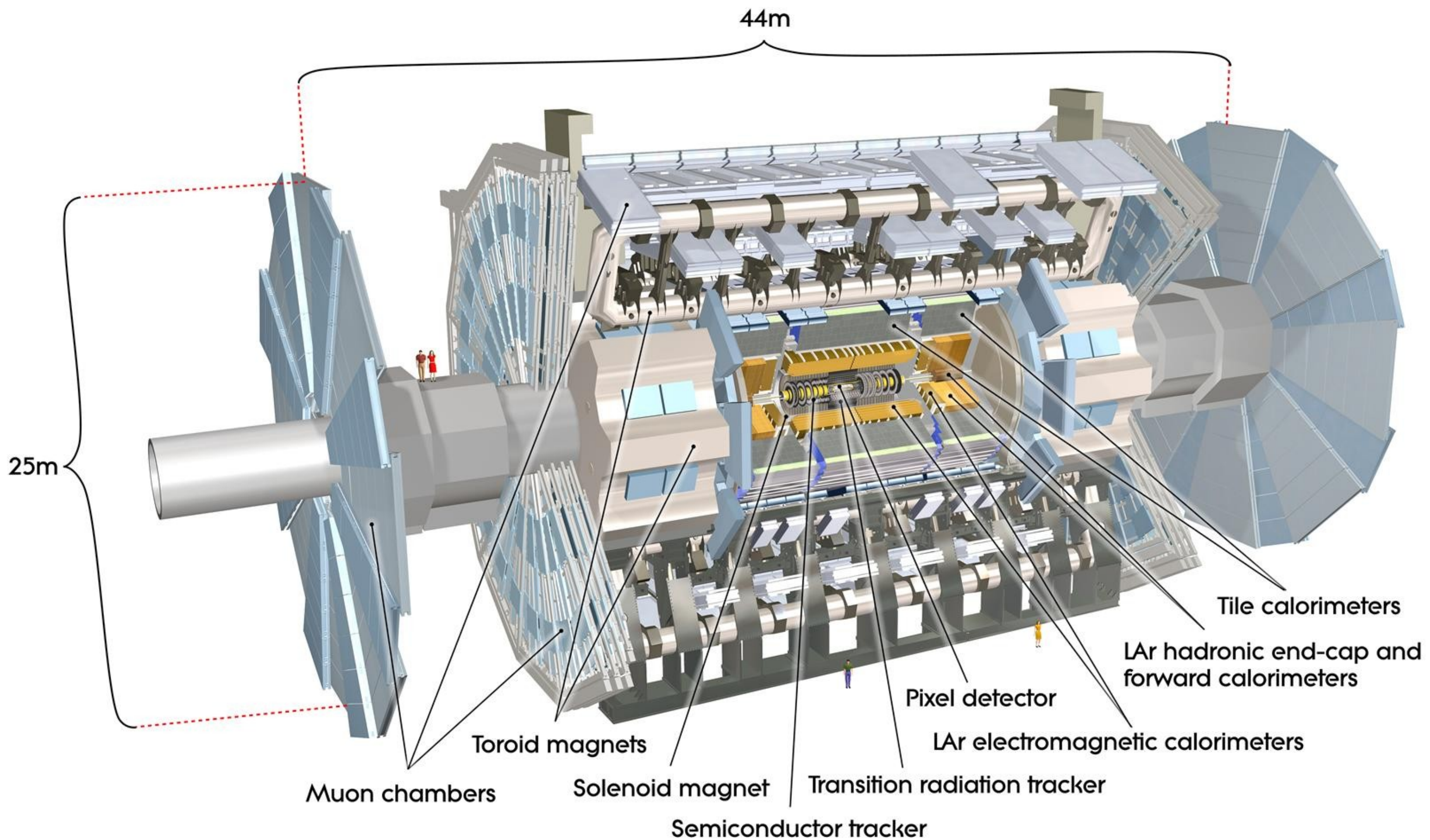
- Aim to investigated coupling of Higgs boson to other particles
  - Design analysis to be sensitive to which production mode is responsible for an event
  - Perform global fit to extract information on couplings



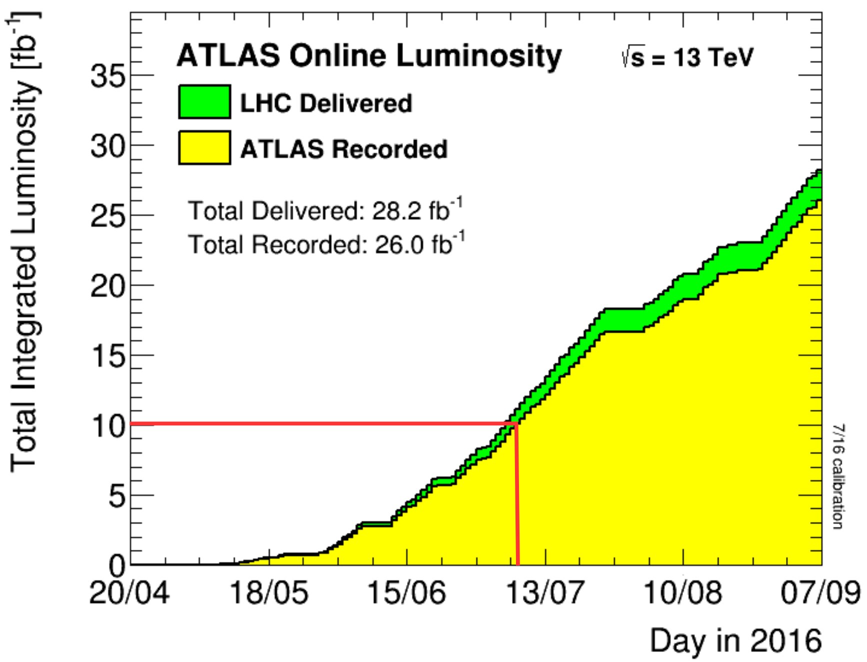


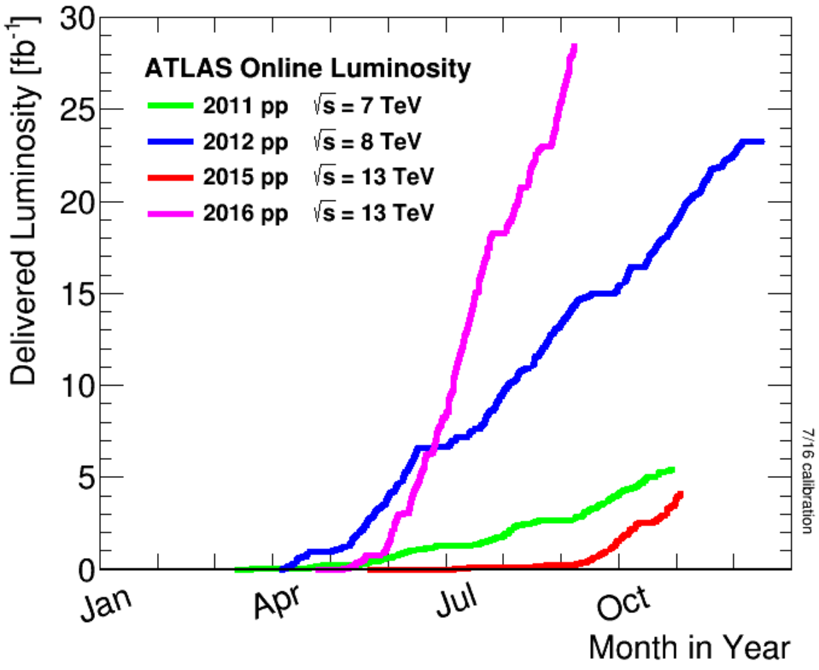
- a) Gluon gluon fusion (ggH)
- b) Vector boson fusion (VBF)
- c) Associated production (VH)
- d) $t\bar{t}H$

ATLAS Detector



LHC and ATLAS Dataset





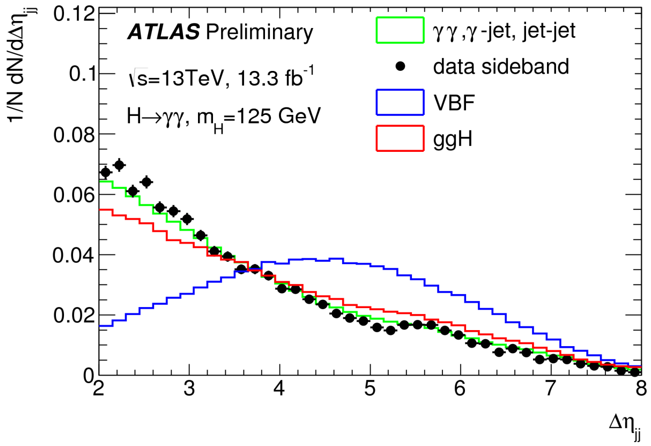
> Total dataset of 13.3 fb^{-1} $\sqrt{s}$=13 TeV pp collisions used

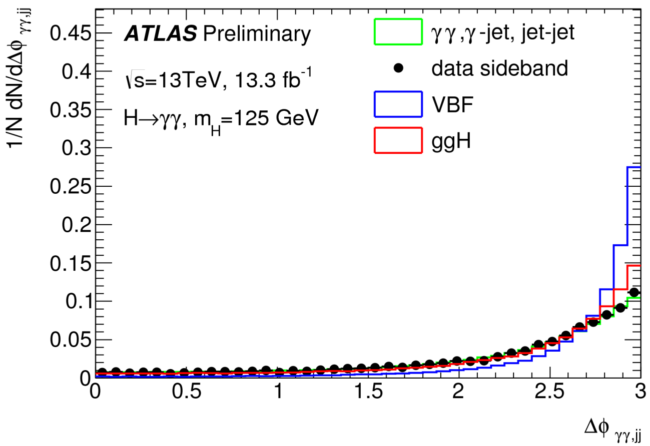
- Combination of 3.2 fb^{-1} 2015 and 10.1 fb^{-1} 2016 data
- Only data with stable beam conditions and fully operational detector are considered
- Events selected by diphoton trigger with 35/25 GeV leading/subleading E_T threshold

Monte Carlo Signal

- ggH, VBF: Powheg Box (NLO), CT10 PDF, Pythia 8 AZNLO tune
  - ggH p_T spectrum re-weighted to HRES; Normalised to N3LO QCD with NLO EW corrections
  - VBF Normalised to NNLO QCD with NLO EW corrections
- VH: Pythia 8 (LO), NNPDF2.3LO PDF, A14 Tune
  - Normalised to NNLO QCD with NLO EW corrections
- TtH: MG5_aMC (NLO), NNPDF2.3 PDF, Pythia 8 A14 tune
  - Normalised to NLO QCD with NLO EW corrections
- Using full (Geant4) ATLAS detector simulation and reconstruction
  - Including overlay of pile-up events
- Single mass point m_H=125 GeV, Γ_H=4.07 MeV

Monte Carlo Backgrounds





> High-statistics Sherpa samples (CT10 PDF, default tune) used for generating non-resonant continuum backgrounds
  - 'Fast Simulation' techniques used to facilitate sufficient sample sizes being produced

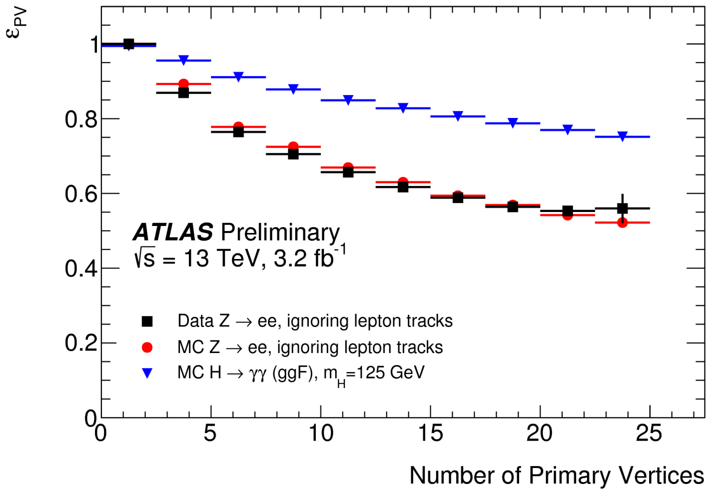
> Generally good data/MC agreement in sideband regions
  - Additional systematics introduced to cover regions where data/MC agreement has issues

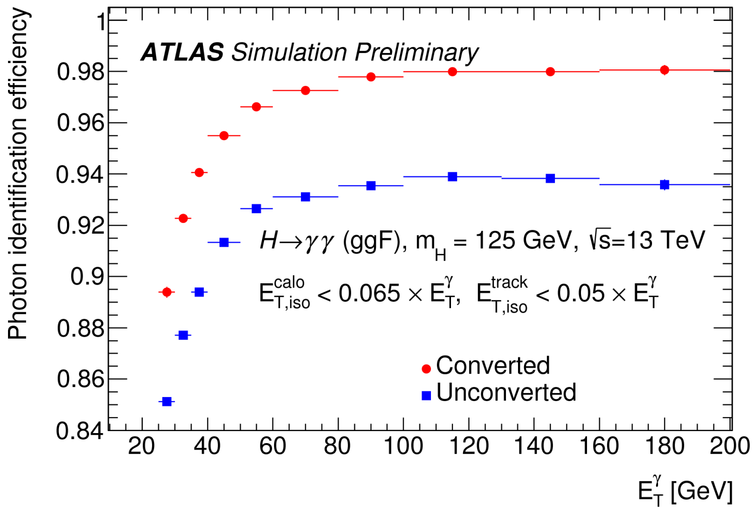
Common Hgamma Event Selection

> Preselection:
  - events with at least 2 loose photons, E_T> 25 GeV, |η|<2.37 (excluding 1.37 – 1.52)

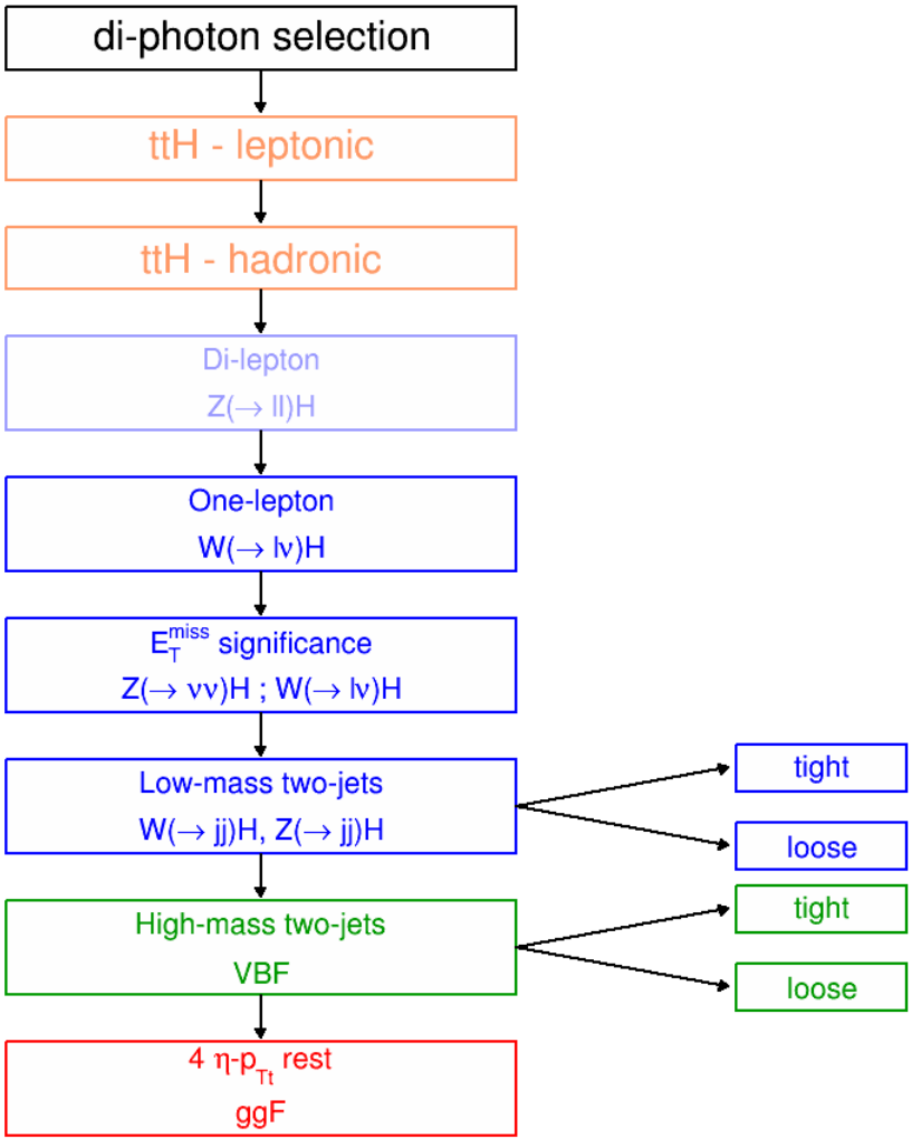
> Primary Vertex selection:
  - Take 2 highest ET photons as diphoton pair
  - Use Neural Network to select diphoton primary vertex, based on vertex, track, and calorimeter pointing information

> Photon selection:
  - $E_T/m_{\gamma\gamma}$ >0.35/0.25 (leading/subleading)
  - Tight identification, isolation
  - 105 < $m_{\gamma\gamma}$ < 160 GeV



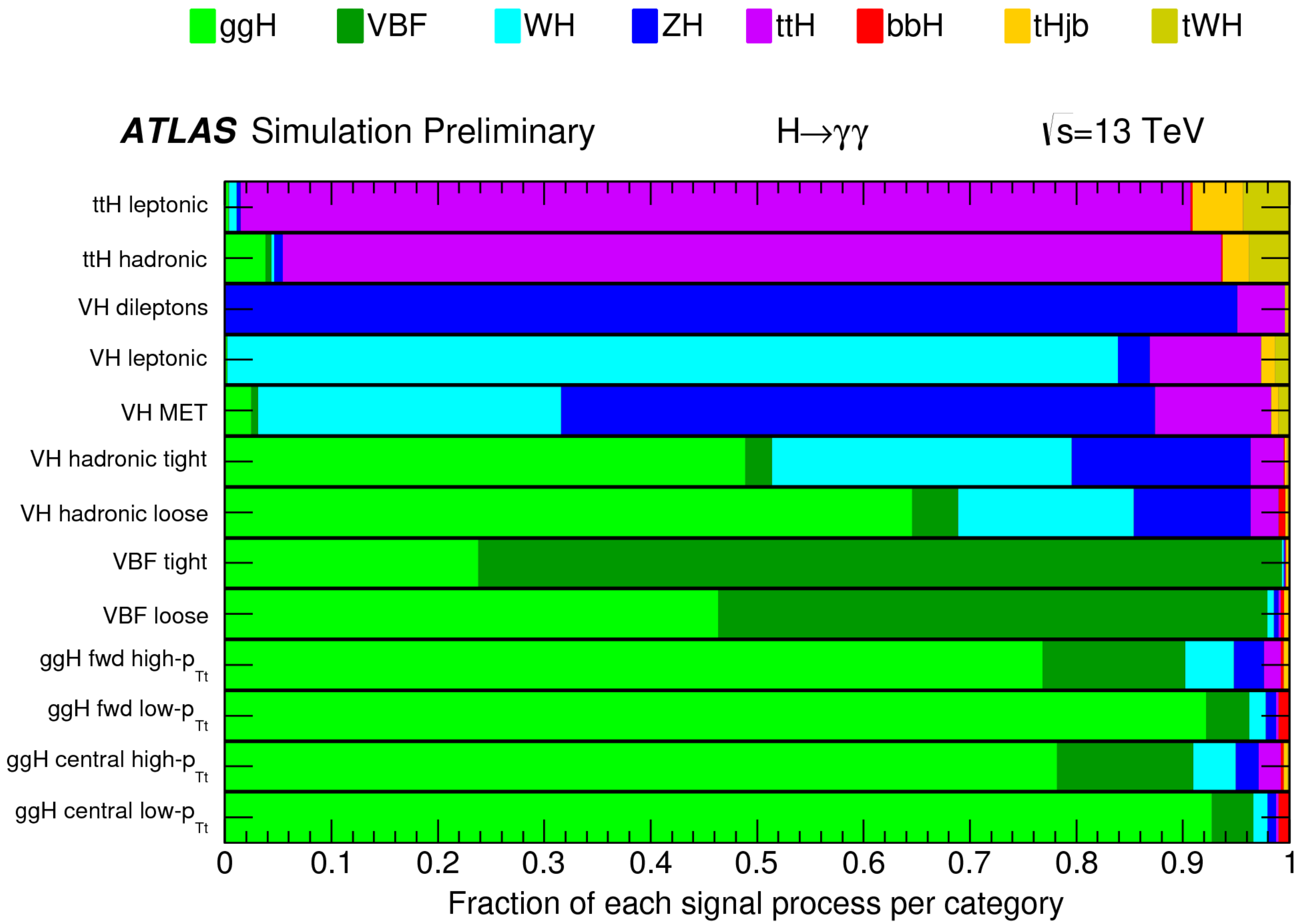


Couplings Categorization



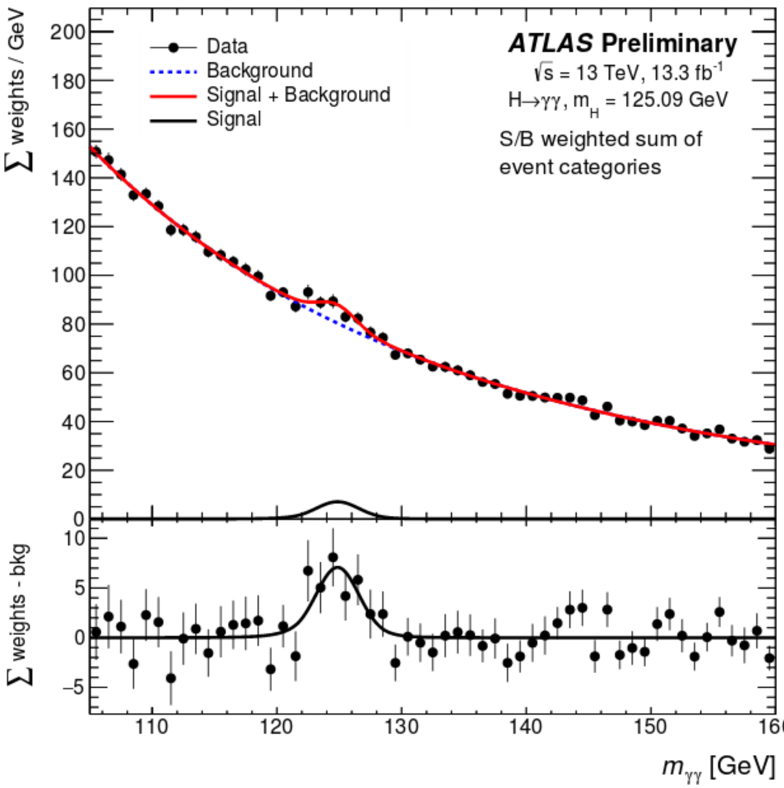
- Define categories optimised to be sensitive to a specific category of events
- Apply categorization criteria in 'reverse-order' of expected SM yields
  - i.e. look at rarest processes first
- Events appear only in one category
  - Once they pass one set of criteria, they are removed from consideration for the rest
  - Each category is an independent dataset

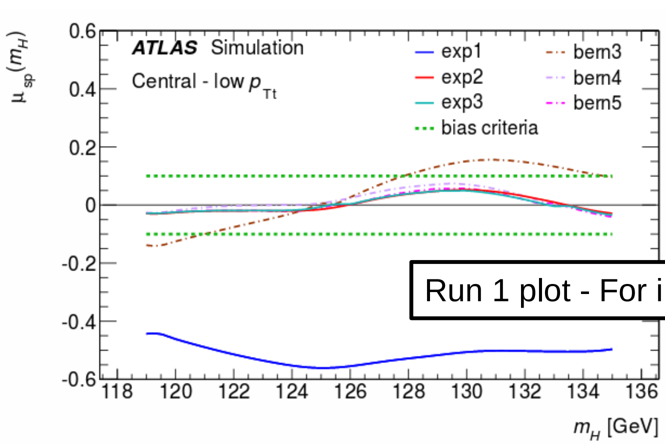
Categories



ggH
VBF
WH
ZH
ttH
bbH
tHjb
tWH
ATLAS Simulation Preliminary
H→γγ
√s=13 TeV
ttH leptonic
ttH hadronic
VH dileptons
VH leptonic
VH MET
VH hadronic tight
VH hadronic loose
VBF tight
VBF loose
ggH fwd high-p_Tt
ggH fwd low-p_Tt
ggH central high-p_Tt
ggH central low-p_Tt
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Fraction of each signal process per category

Signal and Background modeling





Run 1 plot - For illustration only!

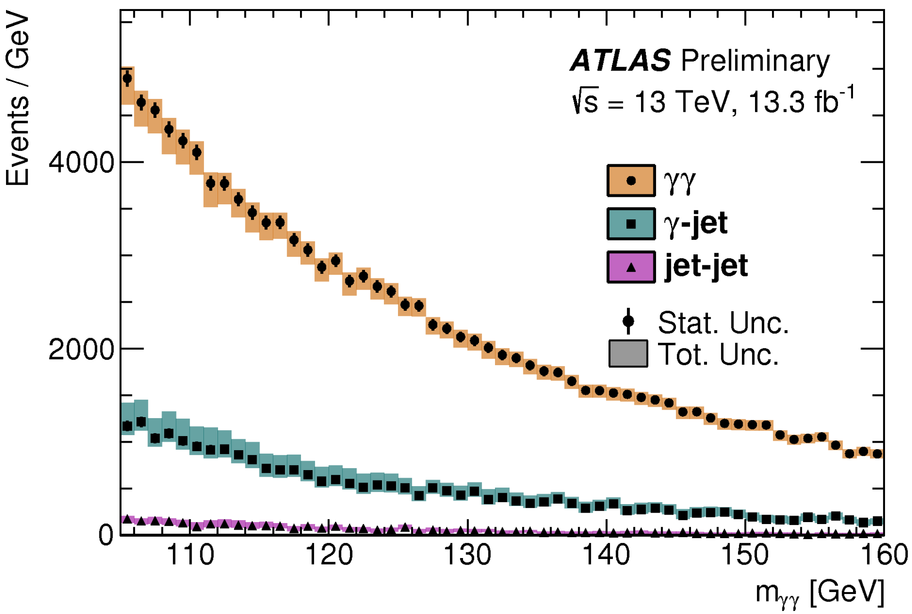
> Fit signal peak on smooth background

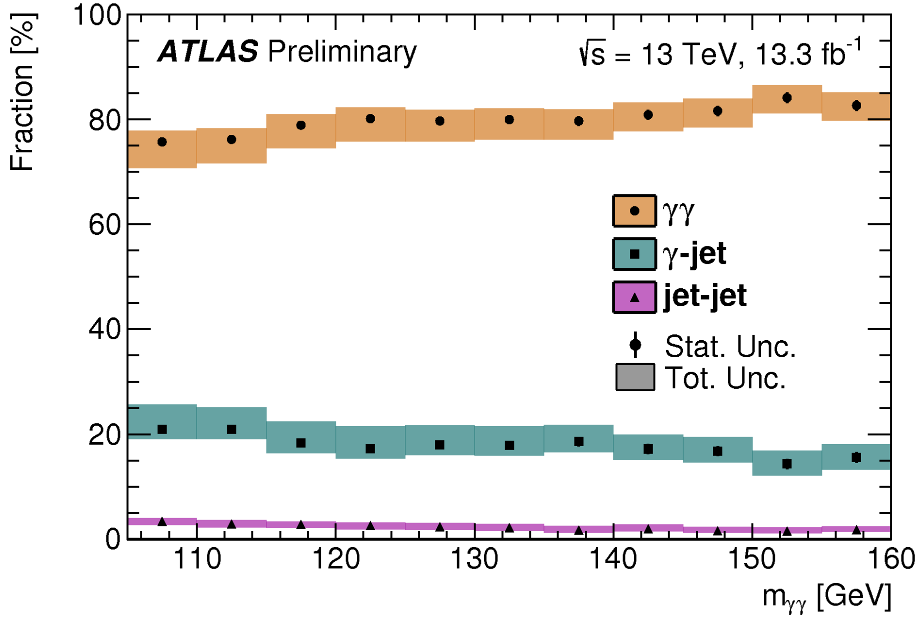
- Signal:Double-sided Crystal Ball

> Background shapes chosen by so-called 'Spurious Signal' method

- Consider 2 families of function: Exp poly and Bernstein poly, with different ndof
- Simplest (fewest ndof) which fulfils Spurious Signal criteria is chosen
- Criteria: When fitting a background-only sample, signal extracted is < 10% expected signal yield OR < 20% of uncertainty on signal yield
- For most categories, background-only sample is MC. For ttH, data sidebands

Background Composition





> Derived using data-driven, 2X2D sideband method

- Reversing Identification and Isolation requirements

Coupling Fit

$$N_k^{\text{sig}} = \sum_i \sigma_i \cdot \mathcal{B}(H \to \gamma\gamma) \cdot \underbrace{\epsilon_{ik}}_{\text{efficiency}} \cdot \underbrace{A_{ik}}_{\text{acceptance}} \cdot \int L\,\mathrm{d}t$$

> Number of events in a category k, for process i

$$\mathcal{L} = \prod_k \mathcal{L}_k = \prod_k \underbrace{P(n_k|N_k(\theta))}_{\text{poisson}} \cdot \prod_{j=1}^{n_k} \underbrace{\mathcal{F}_k(m_{\gamma\gamma}^j, \theta)}_{\text{mass distribution}} \cdot \prod_l \underbrace{G_l(\theta)}_{\text{gaussian constraints}}$$

> Likelihood function; product of individual likelihoods for each category k

- n_k observed events; N_k expected events; θ nuisance parameters

$$\mathcal{F}_k(m_{\gamma\gamma}^j) = \left[\left(\sum_i N_{ik}^{\text{sig}}(\theta_{ik}^{\text{yield}}, \theta_{ik}^{\text{mig}}, m_H) + N_k^{\text{spur}} \cdot \theta_k^{\text{spur}}\right) \cdot \mathcal{F}_k^{\text{sig}}(m_{\gamma\gamma}^j, \theta_k^{\text{sshape}}) + N_k^{\text{bkg}} \cdot \mathcal{F}_k^{\text{bkg}}(m_{\gamma\gamma}^j, \theta_k^{\text{bshape}})\right] / N_k$$

> Mass distribution

- F_k are PDFs; 'spur' is spurious signal; other systematics discussed later
- Higgs mass fixed to ATLAS+CMS combination, 125.09 GeV

Systematic Uncertainties

> Signal & Background parameterisation

- Photon Energy Scale & Resolution (affect peak position and width respectively)
- Background uncertainty from Spurious Signal

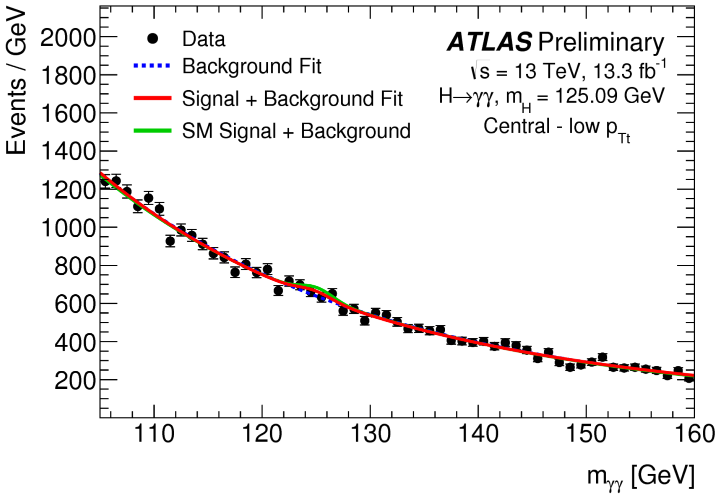
> Yields

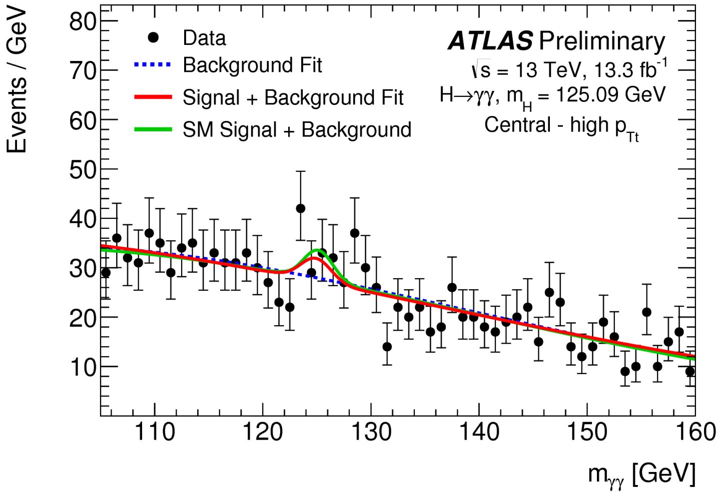
- Object calibration, reconstruction, identification, isolation
- Trigger, luminosity, pile-up modeling
- Additional missing E_T uncertainties to account for data/MC agreement issues in sidebands

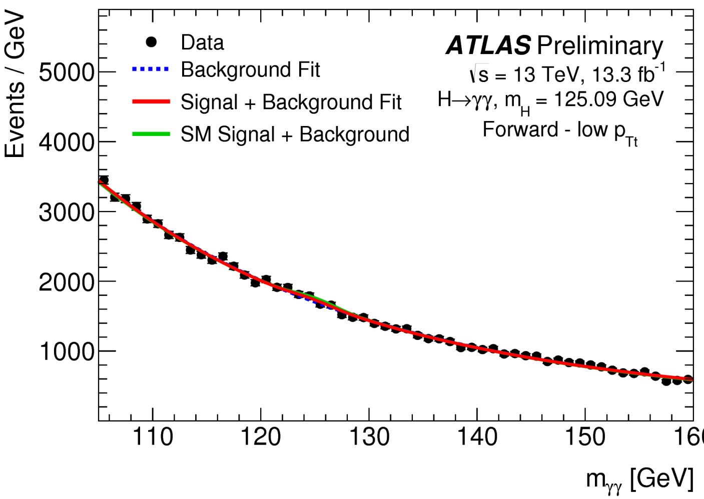
> Theoretical and Modeling

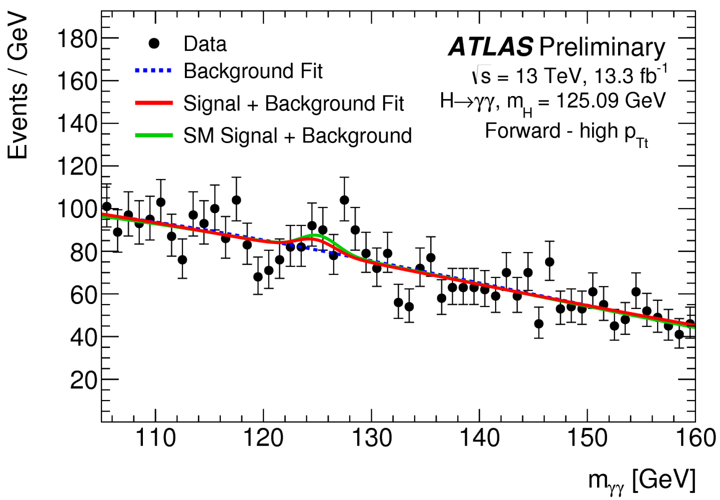
- PDF from (original) PDF4LHC recommendations
- MPI on/off
- Higgs p_T
- H+2j contribution in VBF (via Stewart-Tackmann)
- Normalisation of other productions modes in ttH, uncertainty on MC estimate of VH dileptonic yields

Results in Categories

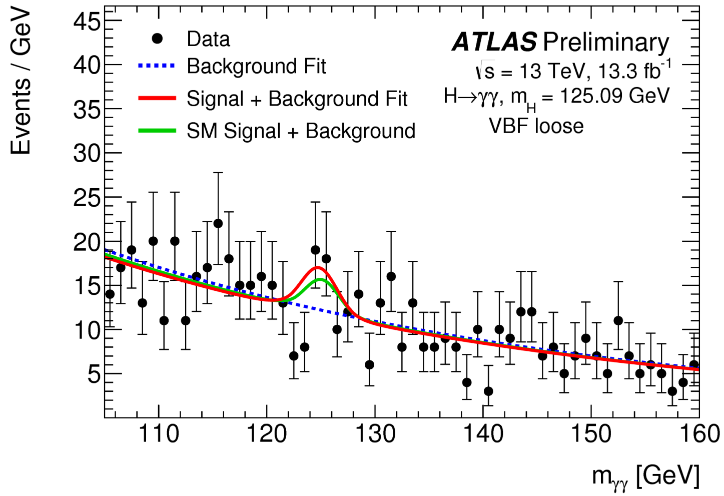


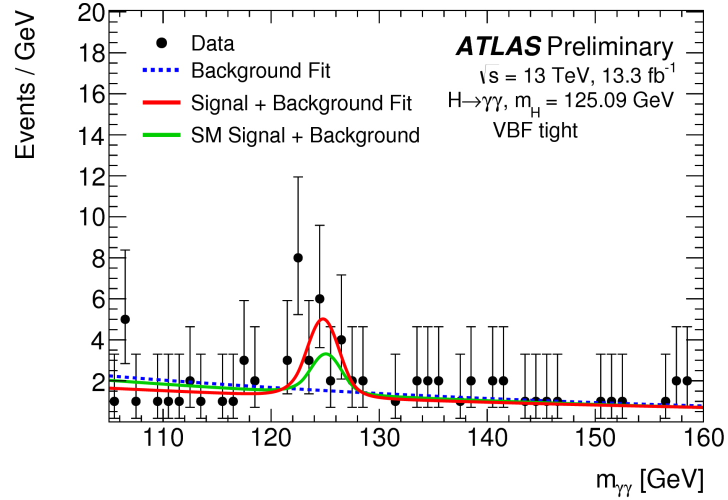


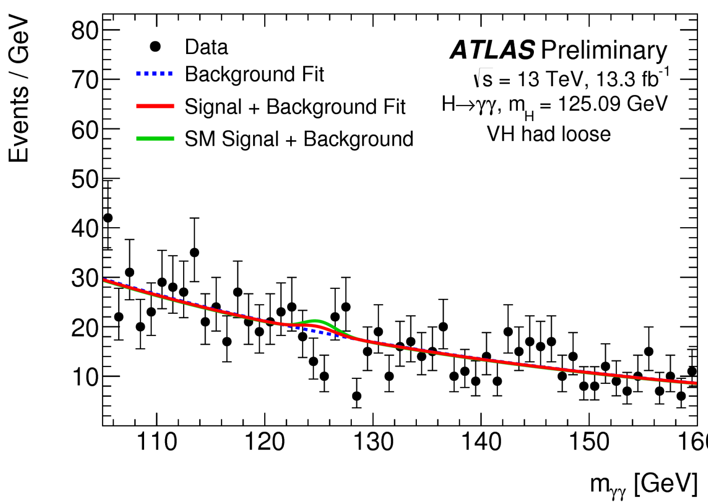


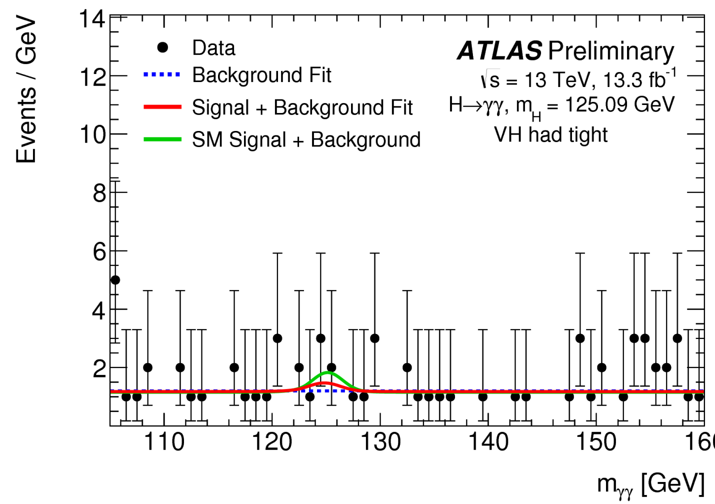


Results in Categories









Fit Results

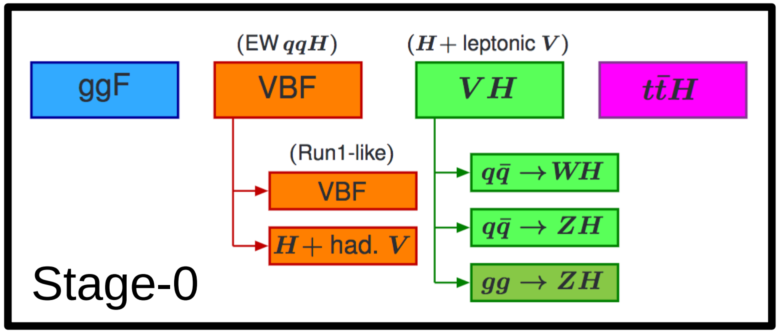
Category	Events	B_{90}	S_{90}	f_{90}	Z_{90}	S_{90}^{fit}
Central low-$p_{\text{T}t}$	31907	3500	180	0.05	3.04	120
Central high-$p_{\text{T}t}$	1319	140	20	0.13	1.66	15
Forward low-$p_{\text{T}t}$	85129	13000	310	0.02	2.73	200
Forward high-$p_{\text{T}t}$	3977	540	33	0.06	1.38	25
VBF loose	604	76	15	0.16	1.62	21
VBF tight	76	8.8	7.3	0.45	2.19	13
VH hadronic loose	937	120	8.9	0.07	0.81	4.7
VH hadronic tight	66	6.7	2.3	0.26	0.86	1.0
VH E_T^{miss}	20	2.4	0.81	0.26	0.50	0.18
VH one-lepton	8	1.0	0.57	0.37	0.53	0.12
VH dilepton	3	0.4	0.30	0.43	0.43	0.07
$t\bar{t}H$ hadronic	72	8.1	1.8	0.18	0.60	-0.23
$t\bar{t}H$ leptonic	19	2.3	1.3	0.36	0.78	-0.18

- S_{90}, B_{90}: Number of events fitted signal/background events in smallest interval expected to contain 90% of SM signal
  - f_{90} is purity, Z_{90} is significance

Cross Section Fits

Simplified Template Cross Sections

$$\begin{aligned}
\sigma_{ggH} \times \mathcal{B}(H \to \gamma\gamma) &= 63\ ^{+30}_{-29}\ \text{fb} \\
\sigma_{\text{VBF}} \times \mathcal{B}(H \to \gamma\gamma) &= 17.8\ ^{+6.3}_{-5.7}\ \text{fb} \\
\sigma_{\text{VHlep}} \times \mathcal{B}(H \to \gamma\gamma) &= 1.0\ ^{+2.5}_{-1.9}\ \text{fb} \\
\sigma_{\text{VHhad}} \times \mathcal{B}(H \to \gamma\gamma) &= -2.3\ ^{+6.8}_{-5.8}\ \text{fb} \\
\sigma_{t\bar{t}H} \times \mathcal{B}(H \to \gamma\gamma) &= -0.3\ ^{+1.4}_{-1.1}\ \text{fb}
\end{aligned}$$



Total Production Cross Sections

$$\begin{aligned}
\sigma_{ggH} \times \mathcal{B}(H \to \gamma\gamma) &= 65\ ^{+32}_{-31}\ \text{fb} \\
\sigma_{\text{VBF}} \times \mathcal{B}(H \to \gamma\gamma) &= 19.2\ ^{+6.8}_{-6.1}\ \text{fb} \\
\sigma_{VH} \times \mathcal{B}(H \to \gamma\gamma) &= 1.2\ ^{+6.5}_{-5.4}\ \text{fb} \\
\sigma_{t\bar{t}H} \times \mathcal{B}(H \to \gamma\gamma) &= -0.3\ ^{+1.4}_{-1.1}\ \text{fb}
\end{aligned}$$

> Ratio of WH/ZH fixed to SM
  - Both q and g initial states

> |y|<2.5

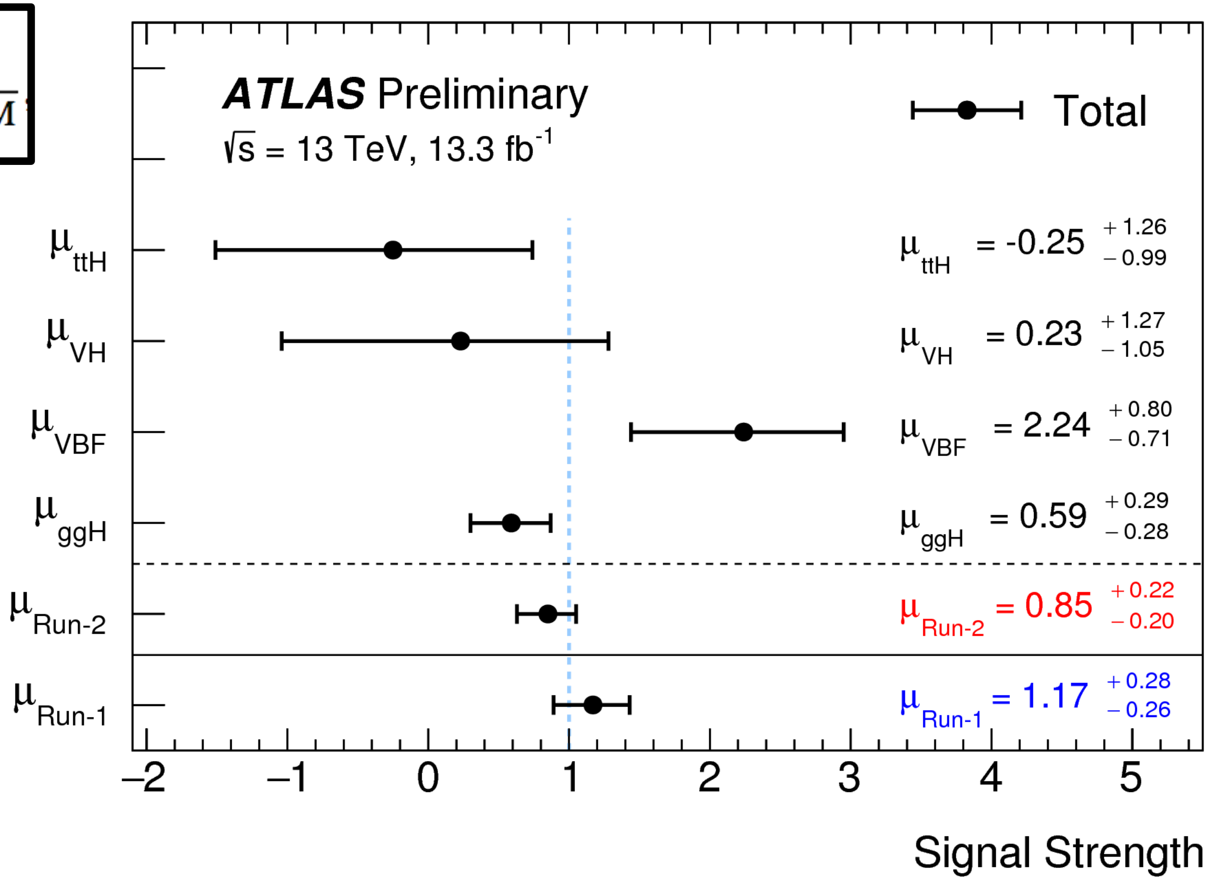
> Ratio of WH/ZH fixed to SM
  - Both q and g initial states

> VHlep: Z → ll/νν, W → lν

> VHhad: hadronic decays only

Signal Strength Fits

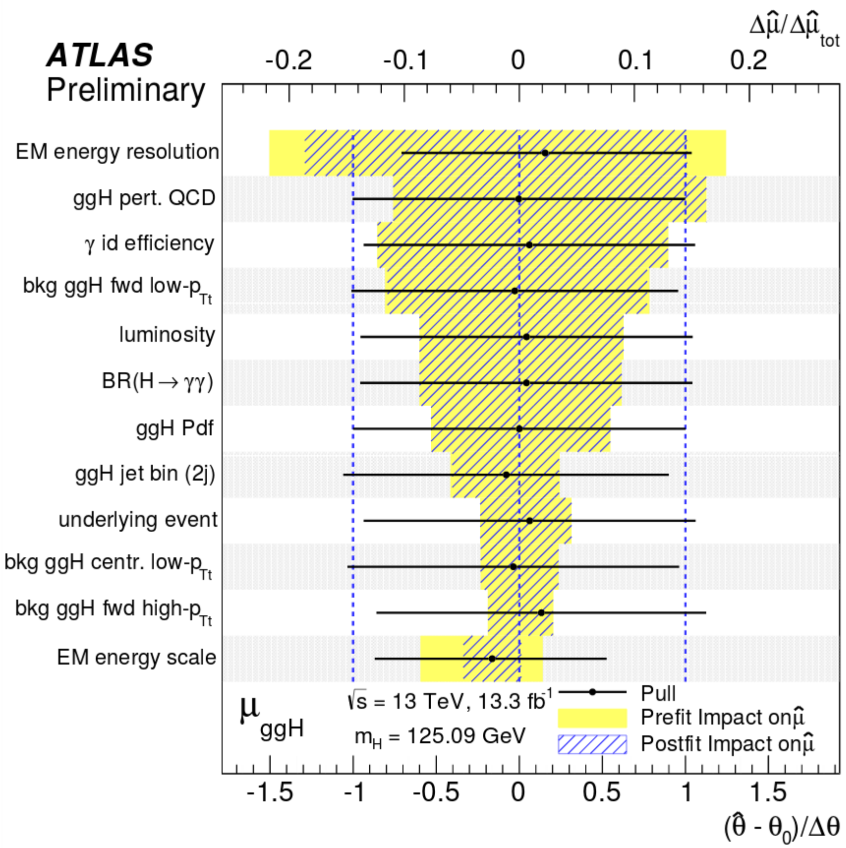
$$\mu = \frac{\sigma \times B}{(\sigma \times B)^{SM}}$$

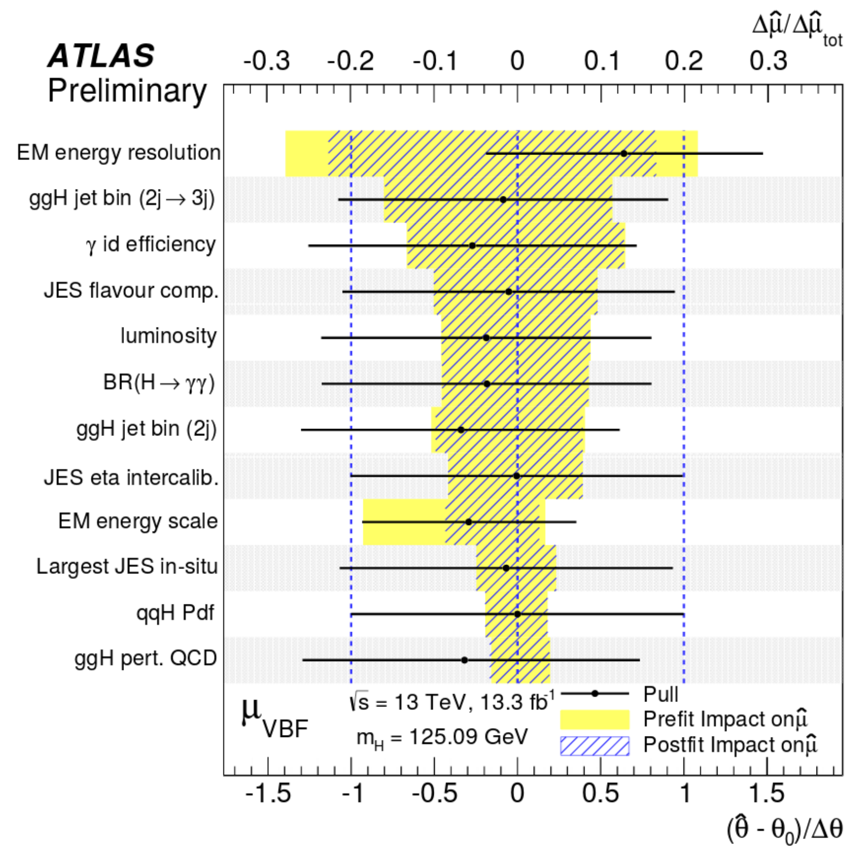


> Reminder: Signal Strength, μ, is ratio of observed signal to SM expectation

- Included mainly for comparability with Run 1 results

Impact of Uncertainties





> Systematic uncertainties with largest effect on fit

- EM resolution slightly pulled – Higgs mass floated in fit to see effect
- Effect on signal strengths within small fraction of statistical uncertainty
- Fitted mass agrees with assumed mass within statistical uncertainty

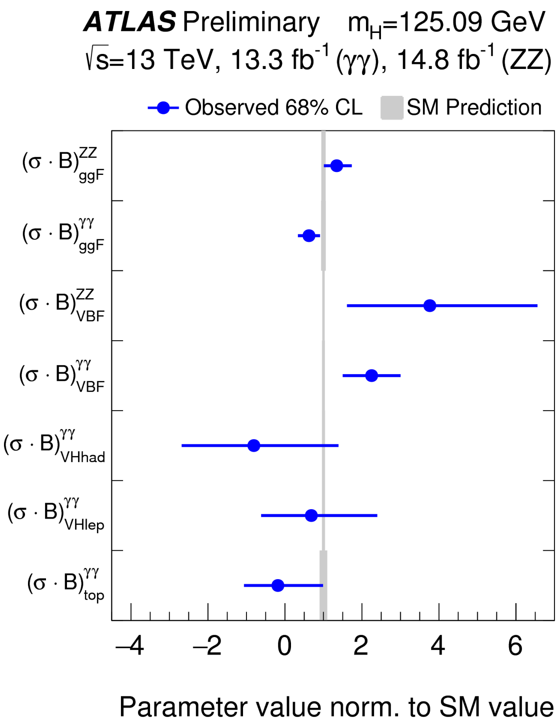
Combination with H → ZZ* → 4l

$H \to ZZ^* \to 4\ell$		$H \to \gamma\gamma$	
Category	Target	Category	Target
VH-leptonic	VHlep	$t\bar{t}H$ leptonic	top
0-jet	ggF	$t\bar{t}H$ hadronic	top
1-jet	ggF	VH dilepton	VHlep
2-jet VBF-like	VBF	VH one-lepton	VHlep
2-jet VH-like	VHhad	VH Emiss	VHlep
		VH hadronic loose	VHhad
		VH hadronic tight	VHhad
		VBF loose	VBF
		VBF tight	VBF
		ggH central low-p_{Tt}	ggF
		ggH central high-p_{Tt}	ggF
		ggH fwd low-p_{Tt}	ggF
		ggH fwd high-p_{Tt}	ggF

Full details in:
ATLAS-CONF-2016-079

- 4l analysis proceeds in conceptually similar way to γγ
- Single event category per process
  - Based on lepton/jet multiplicities
  - VBF and VHhad distinguished based on di-jet mass
- $118 < m_{4l} < 129$ GeV
- Signal extracted through binned fit to BDT discriminant
  - VHlep through event counting
- Background estimation from Monte Carlo
  - Data control regions for Z+jets and $t\bar{t}$

Assuming independent products of σ and BR



		$H \to ZZ^*$	$H \to \gamma\gamma$
ggF	Best fit value (pb)	$1.58^{+0.46}_{-0.39}$	$0.063^{+0.030}_{-0.029}$
	SM prediction (pb)	1.18 ± 0.07	0.101 ± 0.006
VBF	Best fit value (fb)	350^{+260}_{-200}	18^{+6}_{-6}
	SM prediction (fb)	93.0 ± 2.8	8.00 ± 0.29
VHhad	Best fit value (fb)	fixed to SM	$-2.5^{+6.8}_{-5.8}$
	SM prediction (fb)	36.0 ± 1.2	3.09 ± 0.12
VHlep	Best fit value (fb)	fixed to SM	$1.0^{+2.5}_{-1.9}$
	SM prediction (fb)	17.0 ± 0.5	1.46 ± 0.05
top	Best fit value (fb)	fixed to SM	$-0.3^{+1.6}_{-1.2}$
	SM prediction (fb)	15.9 ± 1.5	1.36 ± 0.13

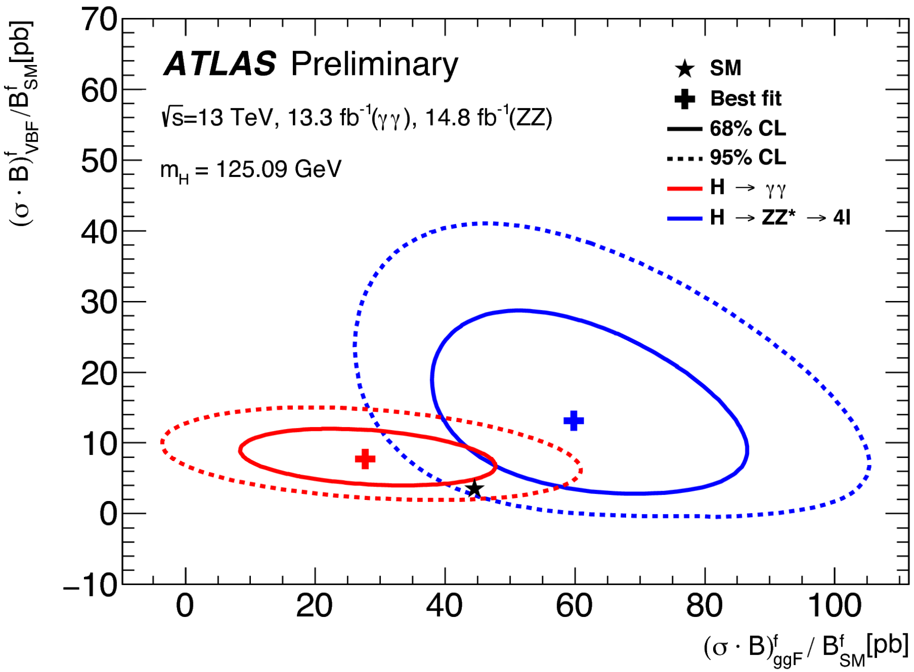
Some processes fixed to SM predictions in fit, if not sufficiently constrained

Process	Contributing to	$\sigma_i(\lvert y_H \rvert < 2.5)/\sigma_i$
$gg \to H$	ggF	0.907
$qq' \to qq'H$	VBF	0.932
$q\bar{q}' \to WH(W \to \text{had.})$	VHhad	0.870
$q\bar{q}/gg \to ZH(Z \to \text{had.})$	VHhad	0.900
$q\bar{q}' \to WH(W \to \text{lep.})$	VHlep	0.869
$q\bar{q} \to ZH(Z \to \text{lep.})$	VHlep	0.900
$gg \to ZH(Z \to \text{lep.})$	VHlep	0.965
$q\bar{q}/gg \to t\bar{t}H$	top	0.985

Ratio of 'central' to total cross sections calculated from Monte Carlo – uncertainties due to sample size ~5%

- > W and Z merged separately for VHhad and VHlep
- > Ratio of of bbH/ggH and tH/ttH (reported together as top) fixed to SM expectations
- > Small differences to numbers from H→γγ due to correlations of experimental uncertainties

Assuming independent products of σ and BR



> Best precision for ggH and VBF

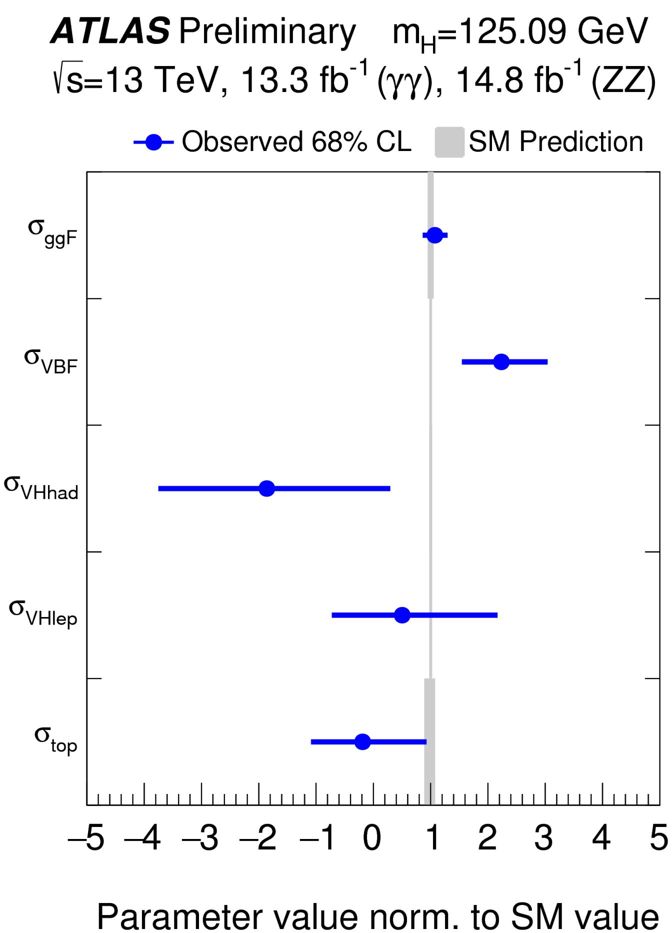
> 'Cross-contribution' from both processes in both categories

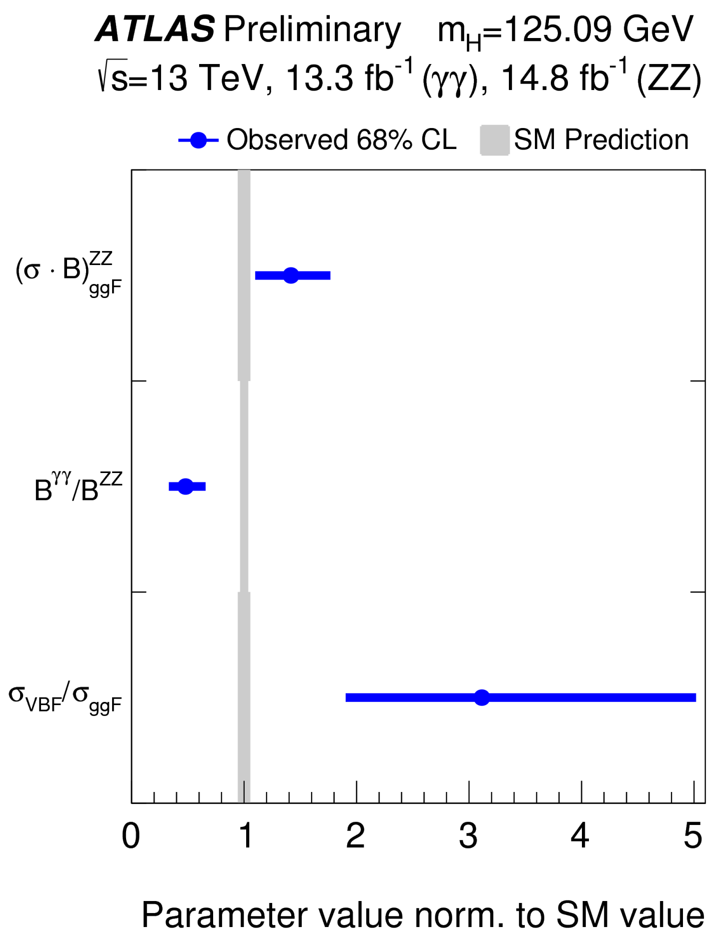
- => Correlated

> Other parameters of interest profiled

SM compatibility p_{SM} = 11%

Independent σ, SM BR; Ratios





- Normalise σ_i to ggF
- Normalise B_f to ZZ
- Profile ratios without sensitivity

$$(\sigma \cdot \mathrm{B})_i^f = (\sigma \cdot \mathrm{B})^{ZZ}_{\mathrm{ggF}} \cdot \left(\frac{\sigma_i}{\sigma_{\mathrm{ggF}}}\right) \cdot \left(\frac{\mathrm{B}^f}{\mathrm{B}^{ZZ}}\right)$$

- Setting BRs to SM values
  - p_{SM} = 21%

Conclusions and Next Steps

- Measured Signal Strengths, Total Cross Sections and STXS for $H\rightarrow\gamma\gamma$ in 13.3 fb^{-1} $\sqrt{s}$ = 13 TeV pp data
- Combined these with measurements of $H\rightarrow ZZ\rightarrow 4l$ through various parameterizations
  - Local significance for Higgs boson production ~ 10 (8.6 expected)
  - Evidence for VBF production with local significance ~4 (1.9 expected)
  - Global signal strength measured to be $\mu=1.13$ +0.18/-0.17
- No significant deviations from SM
- With further Run 2 data will aim to make increasing precise measurements
  - Increased data sample will facilitate 'Stage 1' splitting into further STXS categories