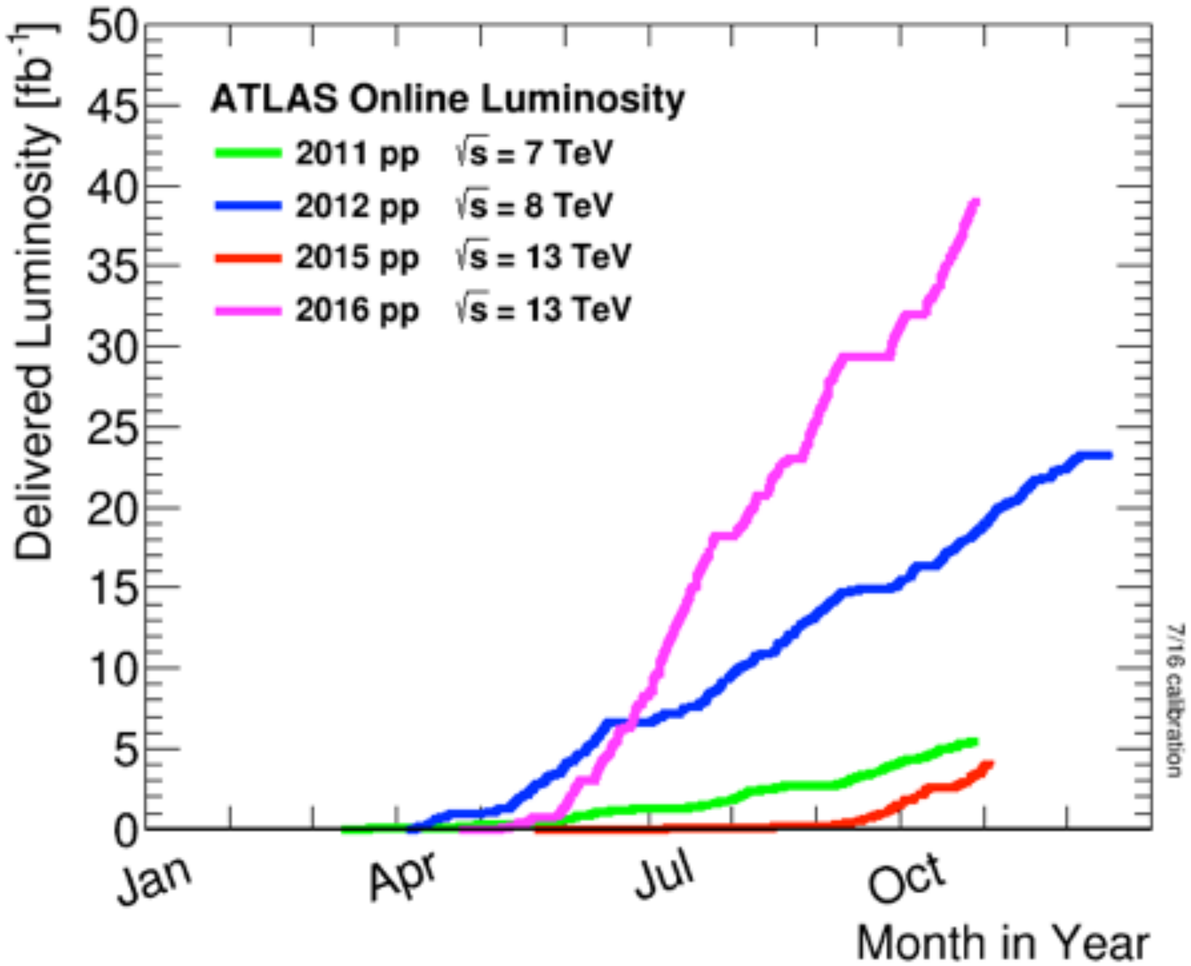
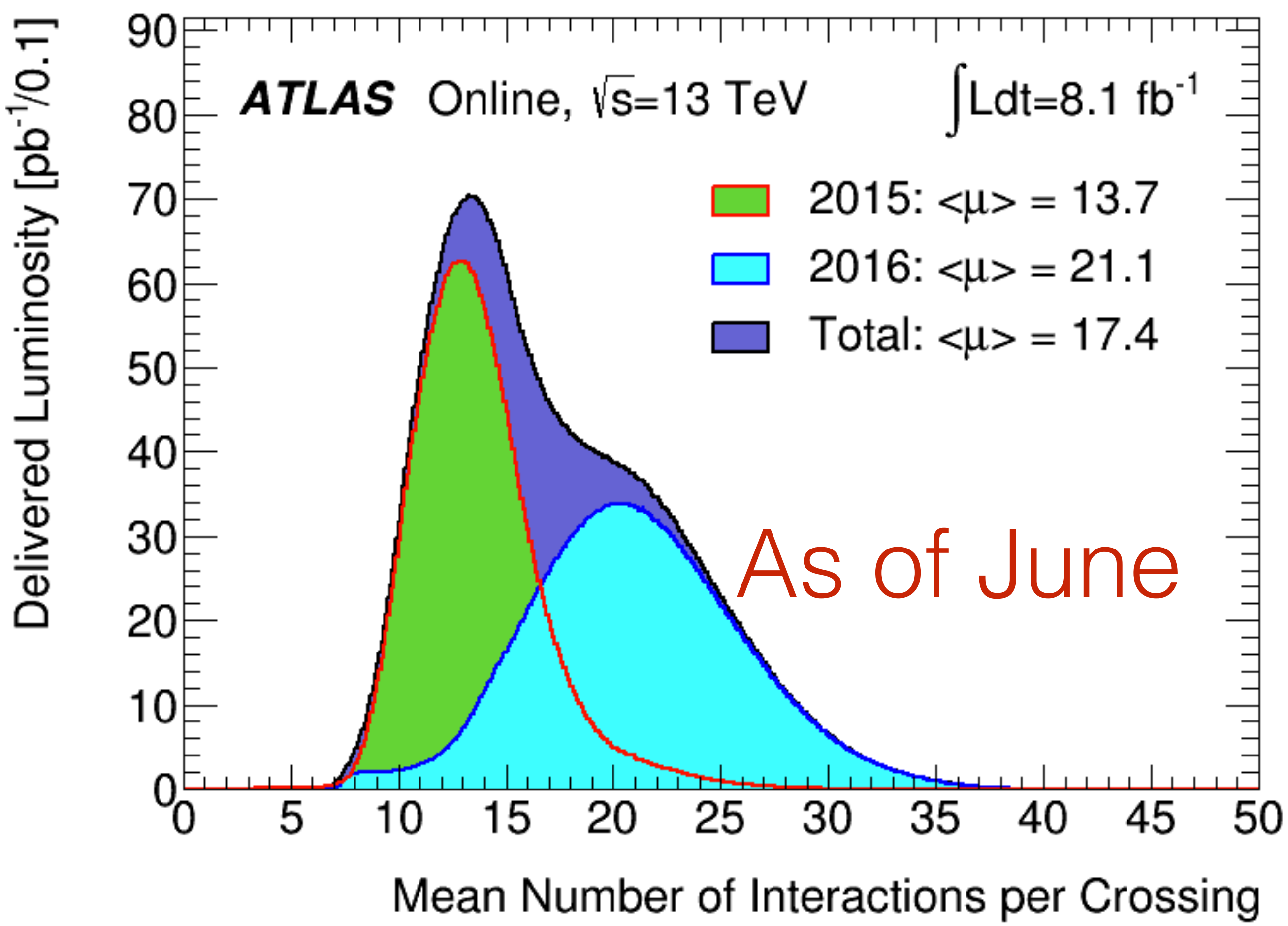
Cross-section and coupling measurements with the ATLAS detector for the 125 GeV Higgs Boson in the diboson decay channels

William Leight
for the ATLAS Collaboration
April 4, 2017

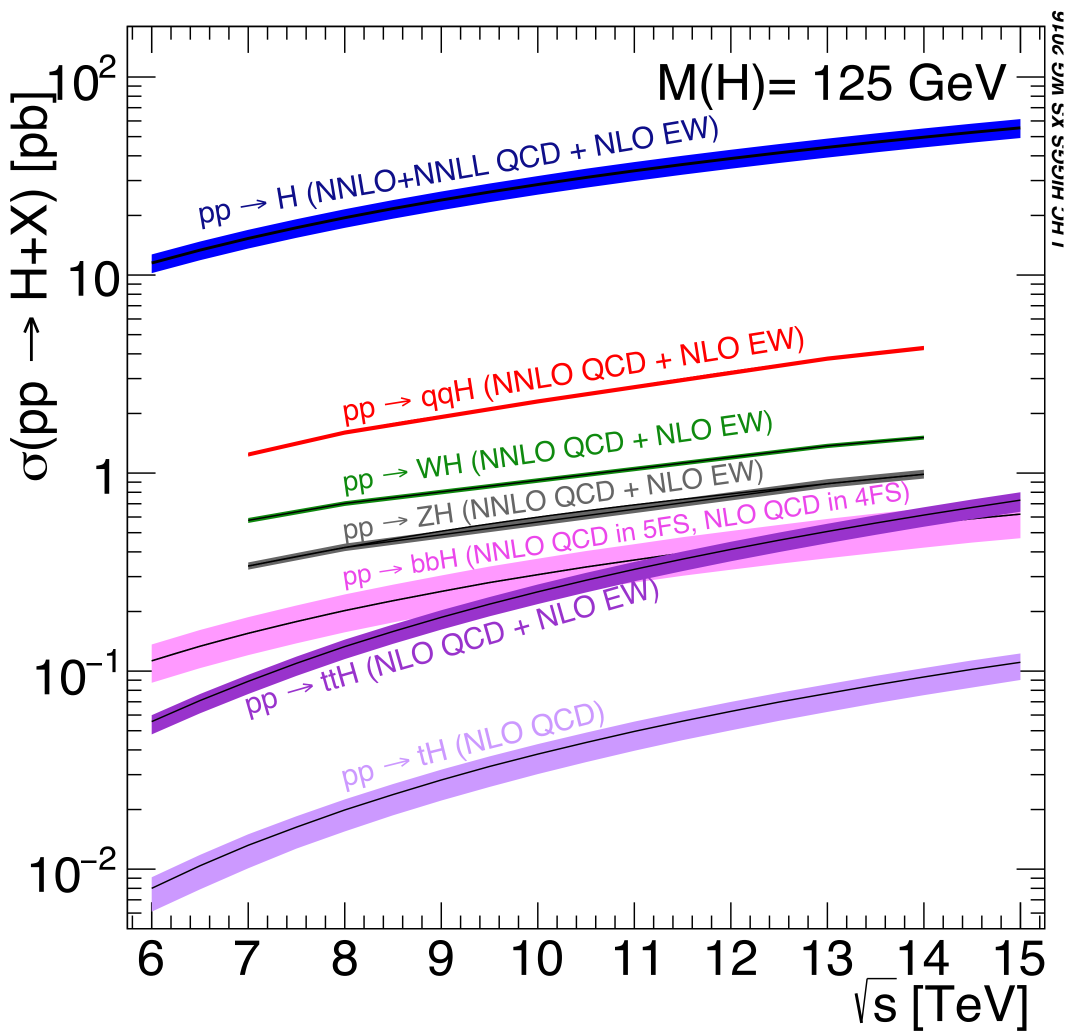
ATLAS and the LHC in Run-2





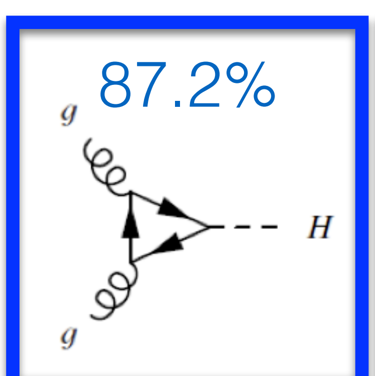
- Excellent performance by the LHC last year.
- The results shown here represent up to 14.8 fb^{-1} of data at 13 TeV recorded in 2015 and up to June of 2016.
  - Our sensitivity to the Higgs is now higher than it was in Run-1.
- Improvements to ATLAS as well
  - Insertable B-layer: new pixel layer at 3.3 cm from the beam
  - Improved Muon Spectrometer coverage

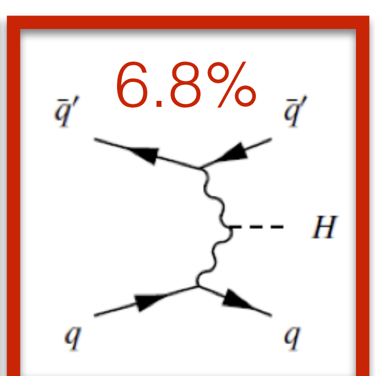
Higgs Boson Production

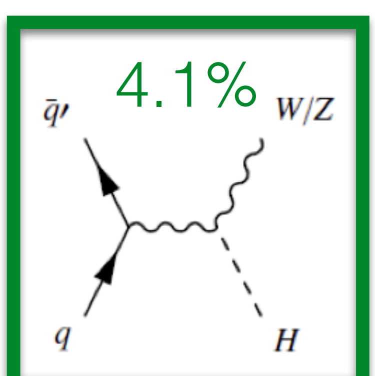


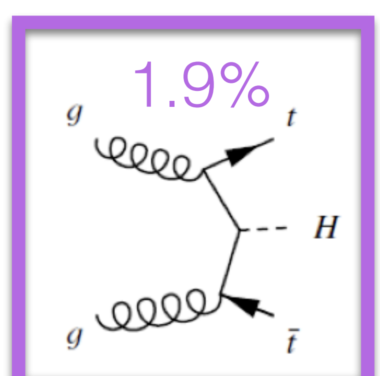
LHC Higgs XS WG

Channel	BR
H->ZZ*->4ℓ	0.013%
H->γγ	0.2%
H->WW*->ℓνℓν	1%



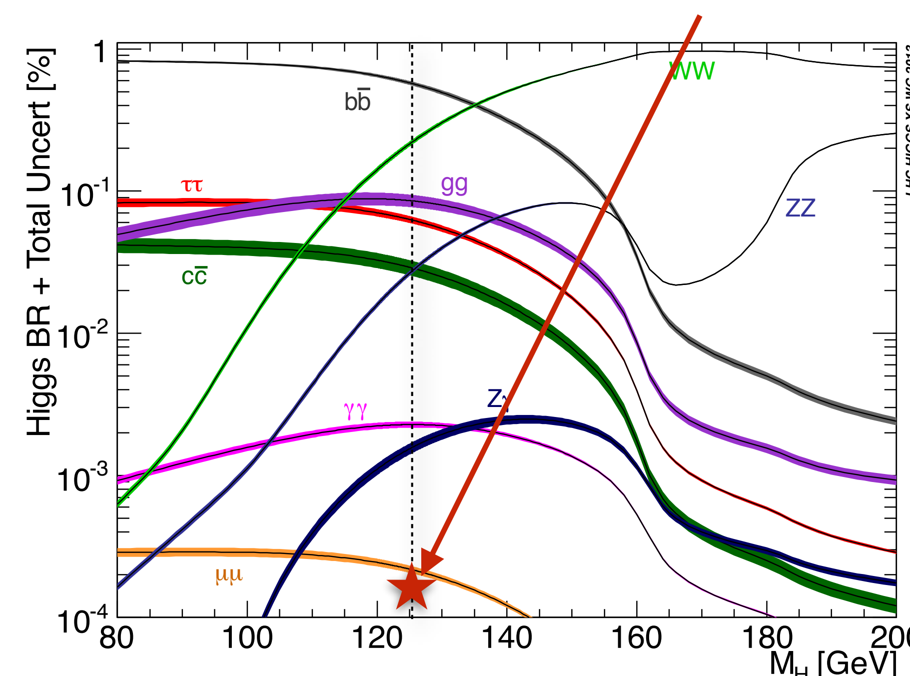






σ_{tot}(13 TeV)~2σ_{tot}(8 TeV)

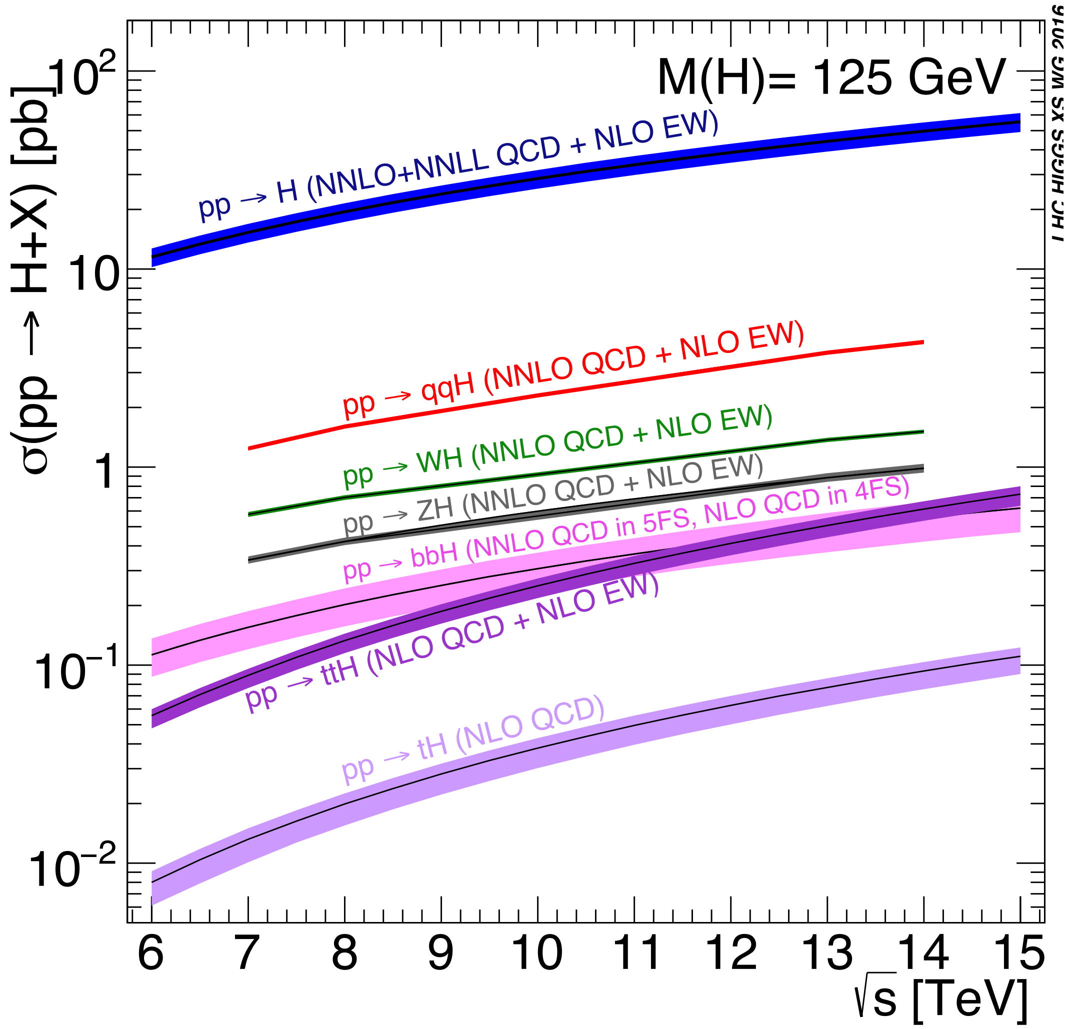
H->ZZ->4ℓ BR~.013%



arxiv 1101.0593

- High S/B
- Low BR

Higgs Boson Production



Channel	BR
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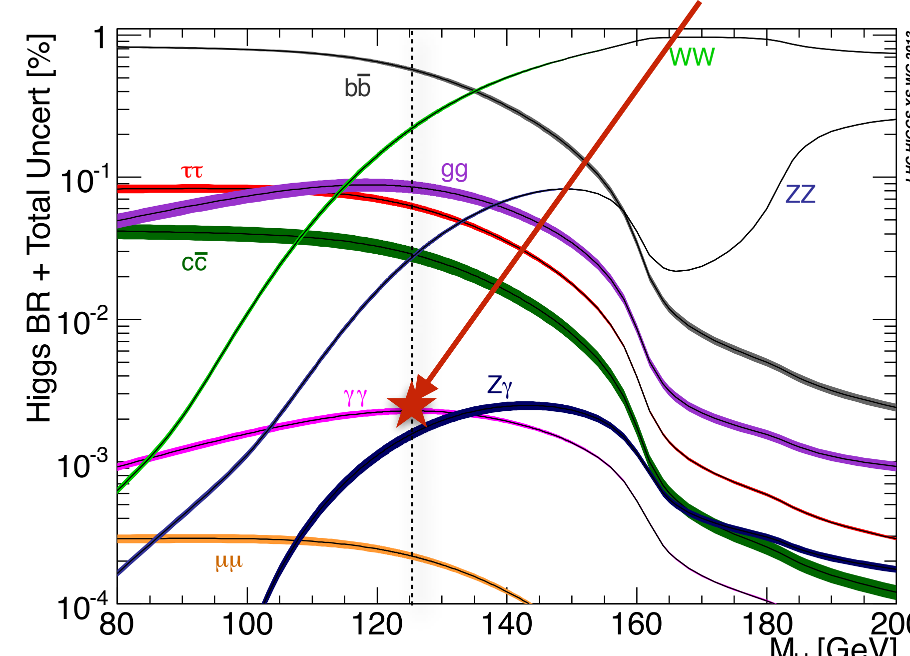
H->WW*->ℓνℓν	1%

LHC Higgs XS WG

H->γγ BR~.2%



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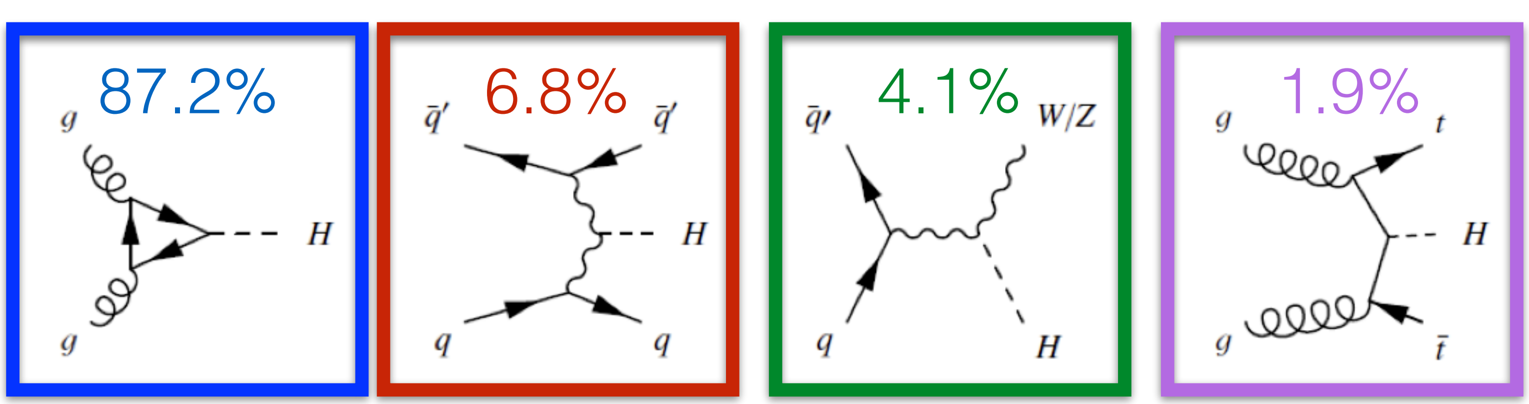
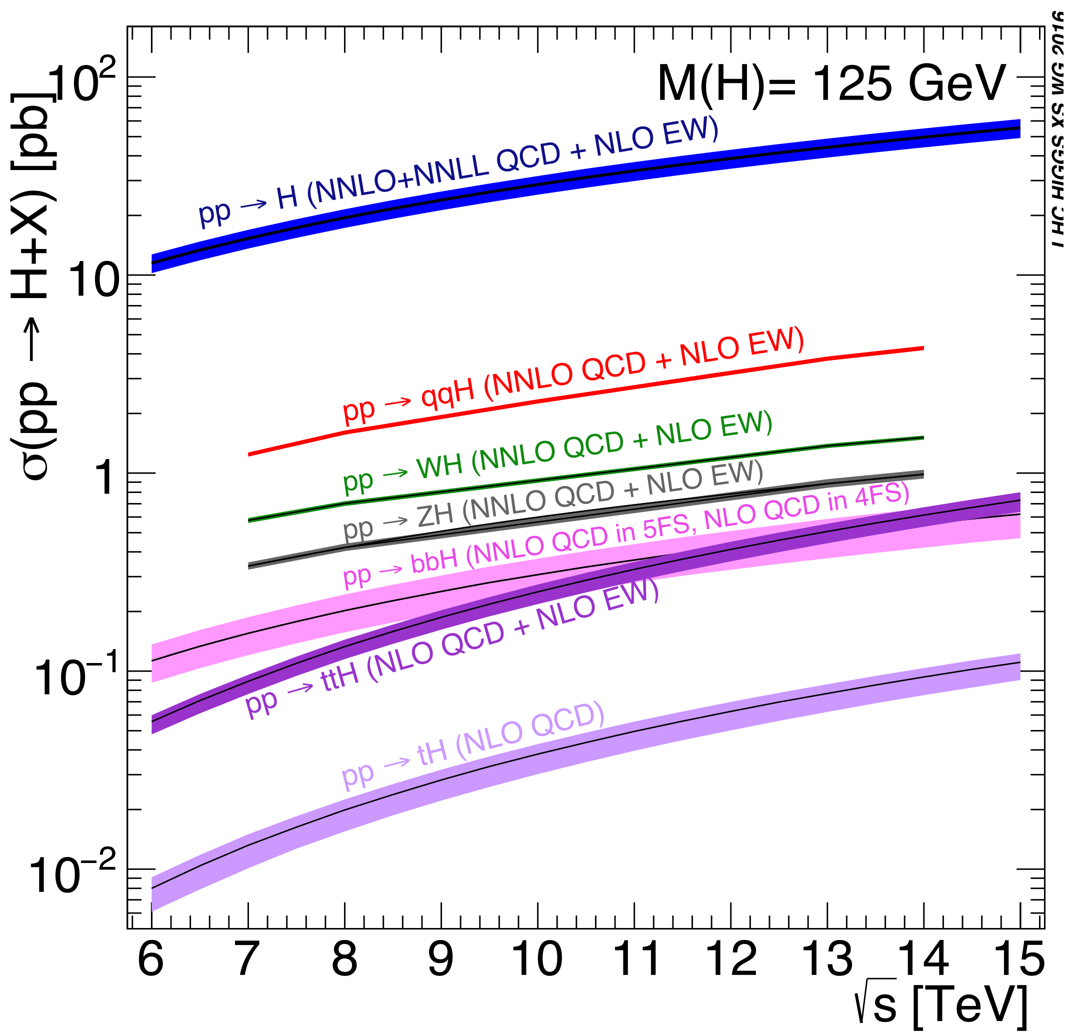


$\boldsymbol{\sigma}_{tot}$(13 TeV)~2$\boldsymbol{\sigma}_{tot}$(8 TeV)

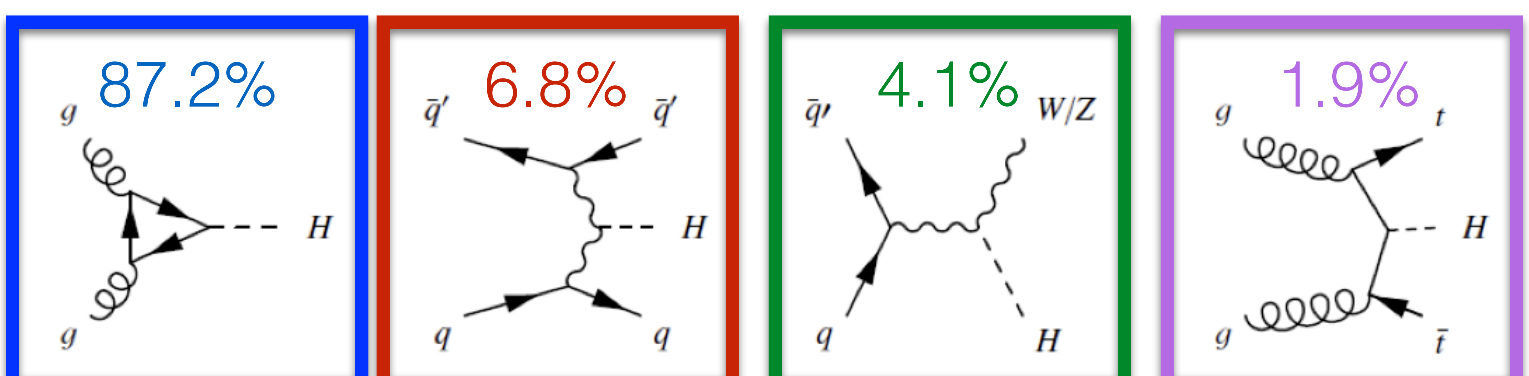
- Larger BR
- Relatively clean signal

Higgs Boson Production



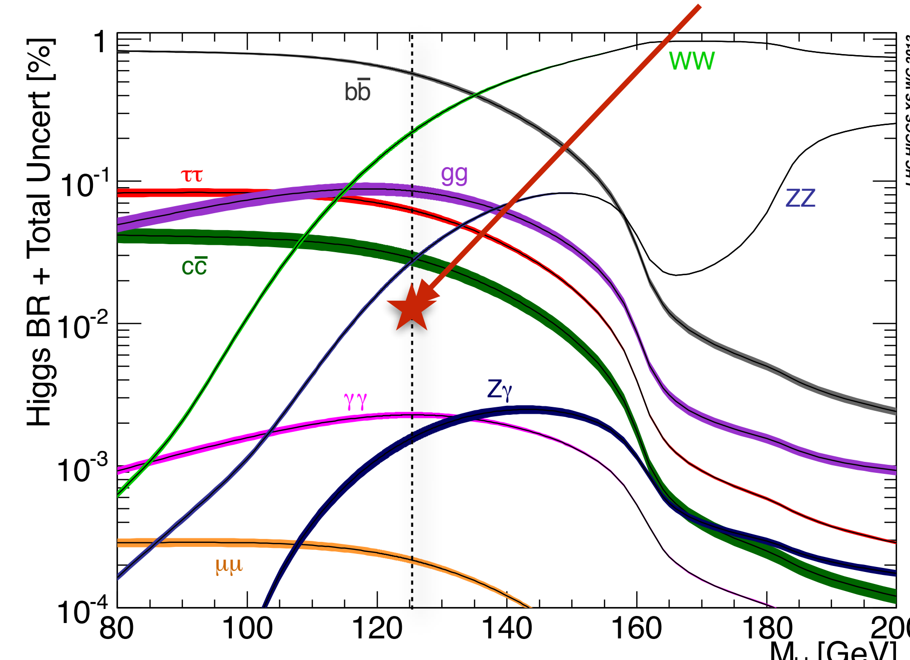
LHC Higgs XS WG

Channel	BR
H->ZZ*->4ℓ	0.013%
H->γγ	0.2%
H->WW*->$\ell\nu\ell\nu$	1%



$\boldsymbol{\sigma}_{tot}$(13 TeV)~2$\boldsymbol{\sigma}_{tot}$(8 TeV)

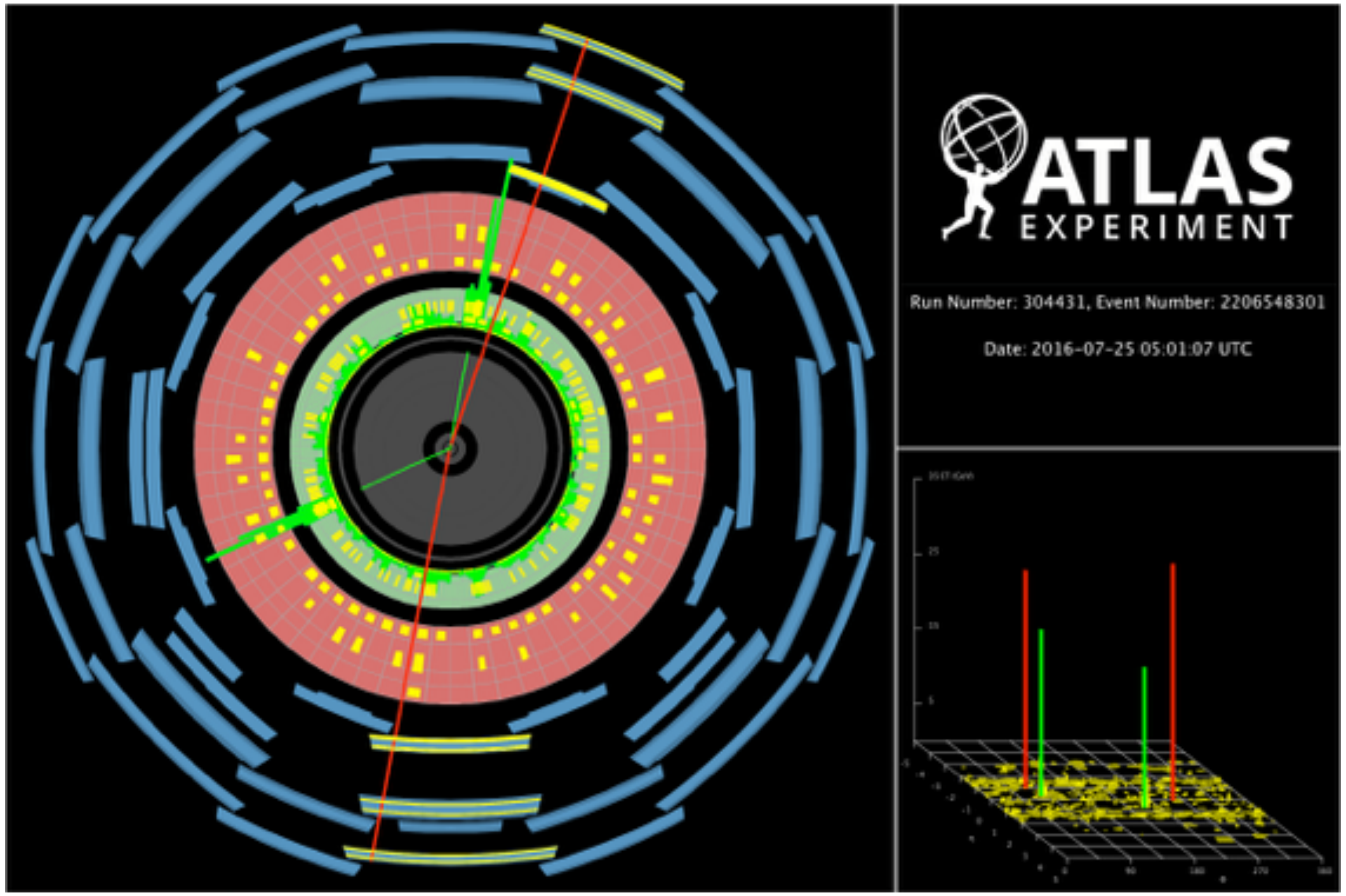
H->WW*->$\ell\nu\ell\nu$ BR~1%



arxiv 1101.0593

- Larger BR, many backgrounds
- Final state not fully reconstructed

H->ZZ*->4ℓ

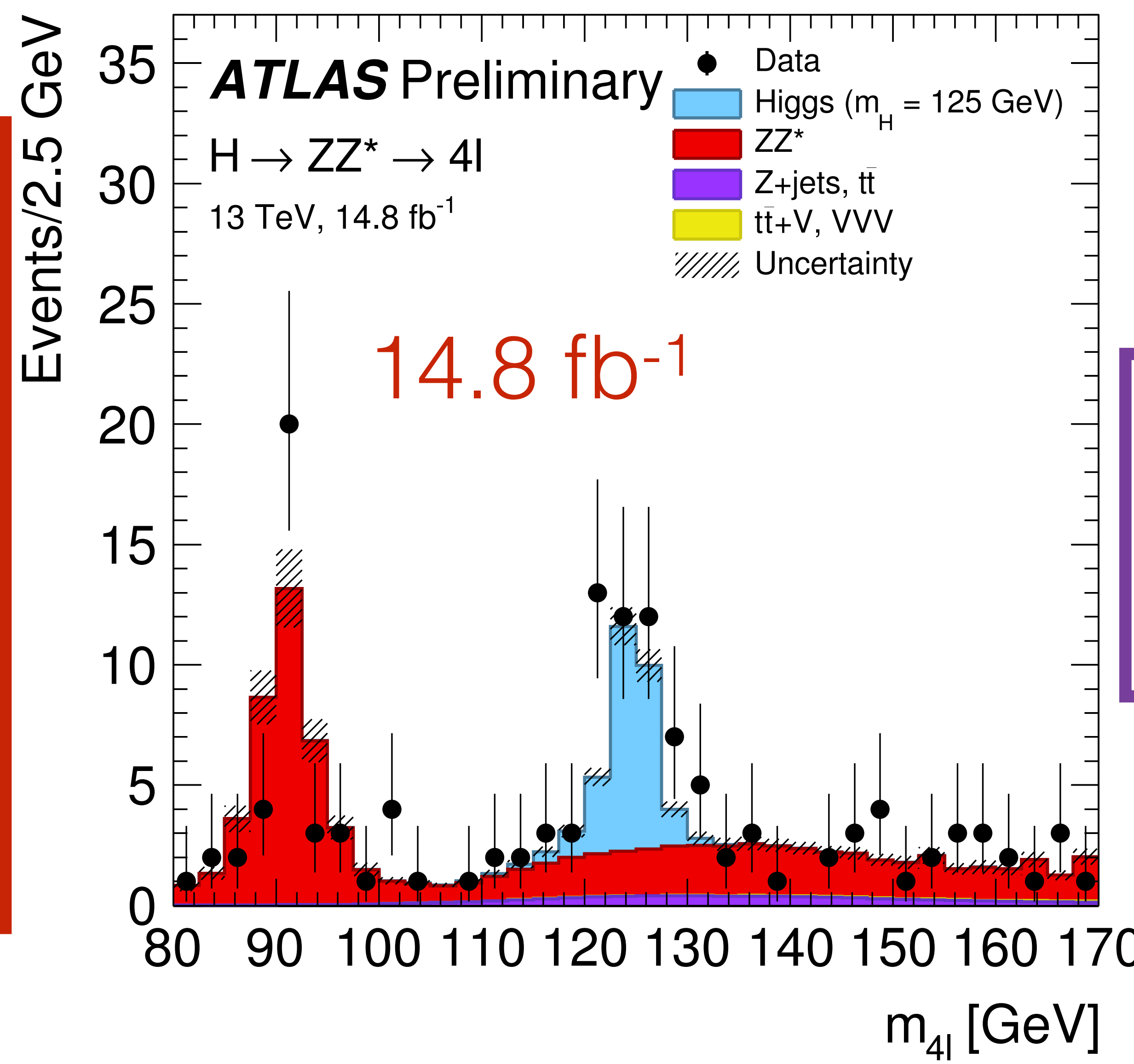


- The “golden channel”
  - S/B of 2
  - But very low branching ratio
  - Acceptance*efficiency of 16%(4e)-31%(4μ)
    - Loose particle ID and isolation selections
- Improvements in Run-2
  - IBL provides superior rejection of electron backgrounds.
  - Muon p_T cut lowered from 6 to 5 GeV, +8% acceptance.

H->ZZ*->4ℓ

ATLAS-CONF-2016-079

- Main background is ZZ* production
  - qq->ZZ simulated at NLO with POWHEG, QCD+EW corrections as function of m_{ZZ}.
  - gg->ZZ simulated at LO with gg2VV, with k-factor for higher-order QCD effects



Reducible background from Z+jets and tt estimated using data-driven methods

- Exploit properties of the event
  - 4ℓ vertexing constraint in event selection.
  - m_{12} (+FSR photons) kinematically constrained to m_Z to improve the resolution.

Fiducial Cross-Section

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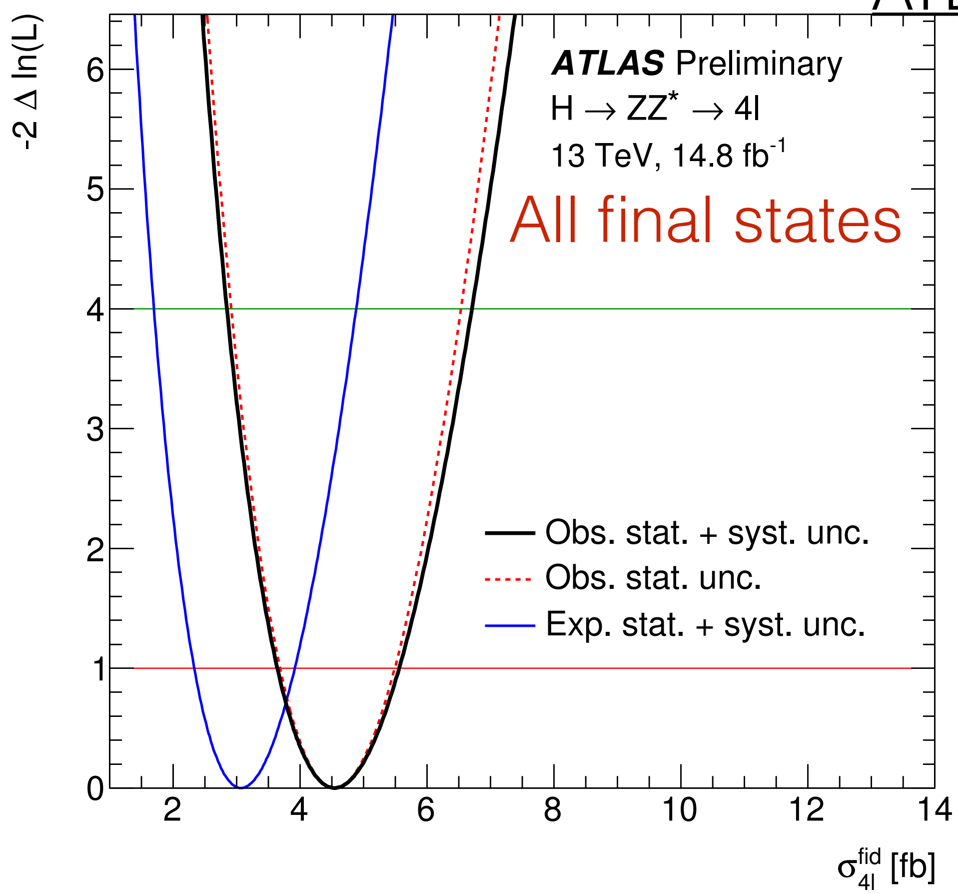

Final state	measured σ_{fid} [fb]	$\sigma_{\mathrm{fid,SM}}$ [fb]
4μ	$1.28\,^{+0.48}_{-0.40}$	$0.93\,^{+0.06}_{-0.08}$
$4e$	$0.81\,^{+0.51}_{-0.38}$	$0.73\,^{+0.05}_{-0.06}$
$2\mu 2e$	$1.29\,^{+0.58}_{-0.46}$	$0.67\,^{+0.04}_{-0.04}$
$2e2\mu$	$1.10\,^{+0.49}_{-0.40}$	$0.76\,^{+0.05}_{-0.06}$

$$\sigma_{\mathrm{tot}} = 81^{+18}_{-16}\ \mathrm{pb}$$

$$\sigma_{\mathrm{tot,SM}} = 55.5^{+3.8}_{-4.4}\ \mathrm{pb}$$

Uncertainties are still statistically dominated.
Compatible with SM at 1.6 σ.

- Fiducial cross-section is independent of assumptions about acceptance or BR.
  - Reduces model dependence
  - Only need to correct for detector efficiencies and resolution (C)
  - Fiducial region based on lepton p_T and η, dilepton masses, and the lepton separation

$$\sigma^{\mathrm{fid}} = \frac{N_s}{C \times \mathcal{L}_{\mathrm{int}}}$$

- Fiducial cross-section is obtained from a likelihood fit to the $m_{4\ell}$ distribution for $115 < m_{4\ell} < 130$ GeV.
  - Total cross-section is then obtained assuming SM BR and acceptance and m_H=125.09 GeV.

Cross-sections by Production Mode

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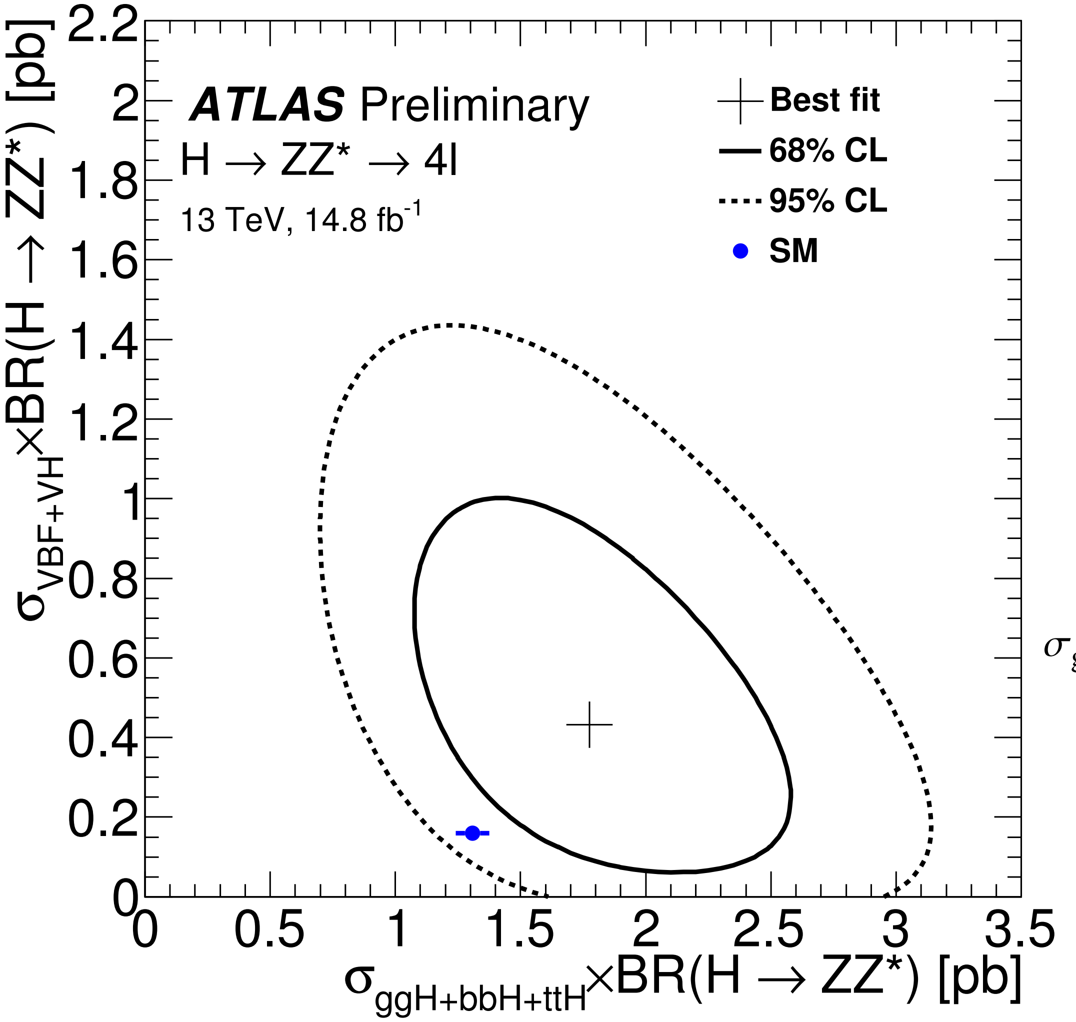
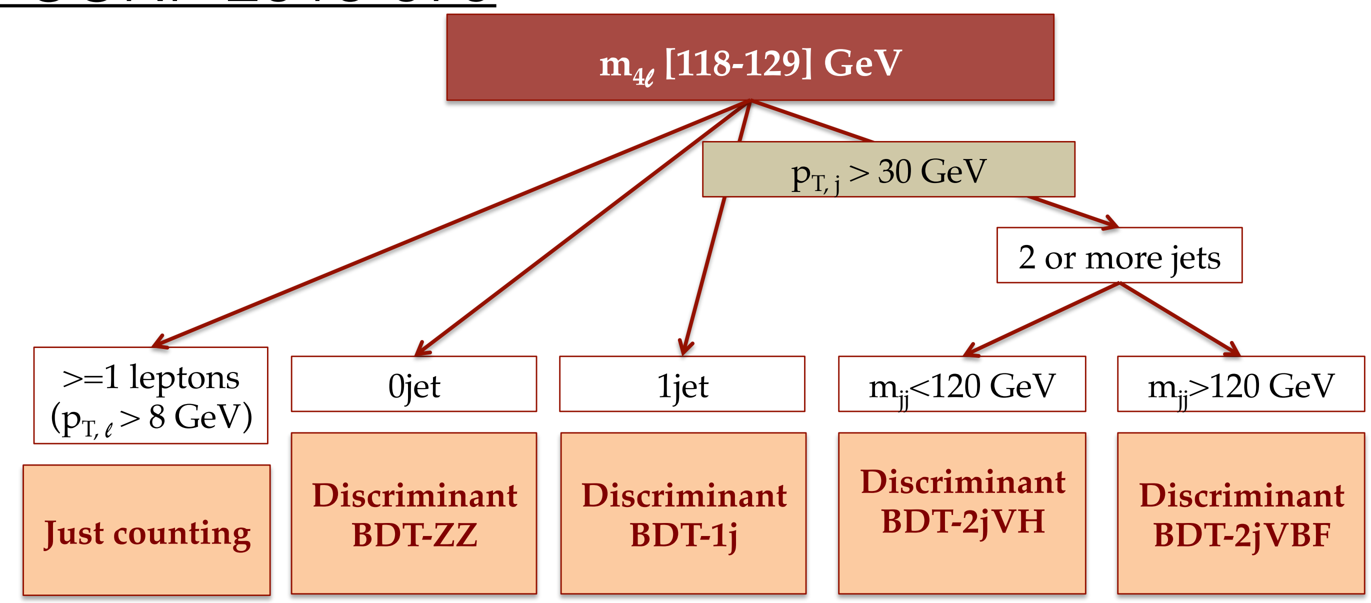




$$\sigma_{\mathrm{ggF}+b\bar{b}H+t\bar{t}H} \cdot \mathcal{B}(H \to ZZ^*) = 1.80^{+0.49}_{-0.44}\ \mathrm{pb}$$
$$\sigma_{\mathrm{VBF}} \cdot \mathcal{B}(H \to ZZ^*) = 0.37^{+0.28}_{-0.21}\ \mathrm{pb}$$
$$\sigma_{\mathrm{VH}} \cdot \mathcal{B}(H \to ZZ^*) = 0^{+0.15}\ \mathrm{pb}$$

$$\sigma_{\mathrm{SM,ggF}+b\bar{b}H+t\bar{t}H} \cdot \mathcal{B}(H \to ZZ^*) = 1.31 \pm 0.07\ \mathrm{pb}$$
$$\sigma_{\mathrm{SM,VBF}} \cdot \mathcal{B}(H \to ZZ^*) = 0.100 \pm 0.003\ \mathrm{pb}$$
$$\sigma_{\mathrm{SM,VH}} \cdot \mathcal{B}(H \to ZZ^*) = 0.059 \pm 0.002\ \mathrm{pb}$$

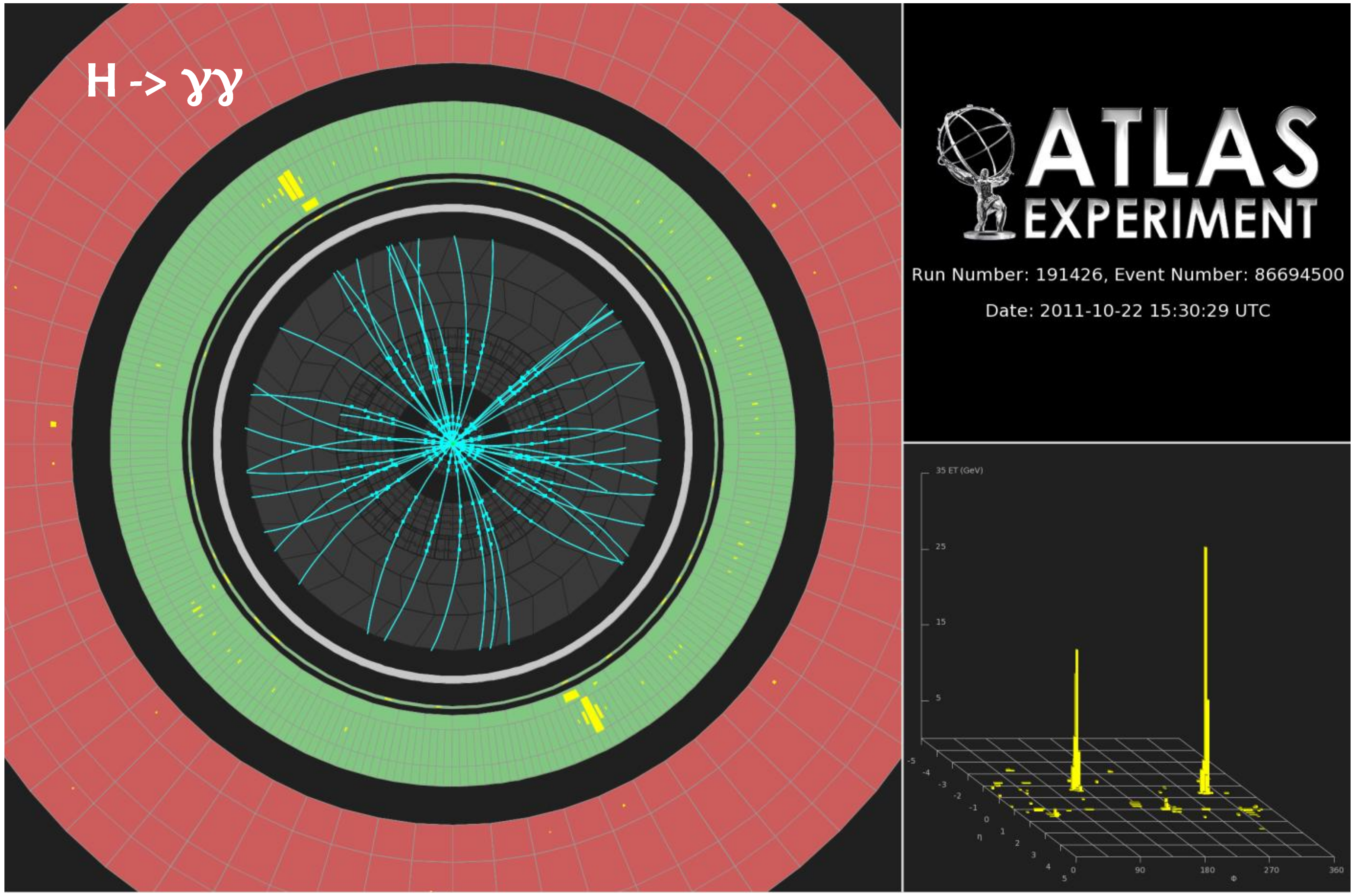
Compatibility to the SM prediction:

$\sigma_{\mathrm{ggF+bbH+ttH}}$*BR(H->ZZ*): 1.1σ

σ_{VBF}*BR(H->ZZ*): 1.4σ

- Events in the $118 < m_{4\ell} < 129$ GeV range are sorted into exclusive categories.
  - Use BDT to enhance sensitivity (except VH-leptonic category).
- Signal obtained from a likelihood fit to the BDT output.
  - Cross-sections obtained assuming $m_H = 125.09$ GeV.

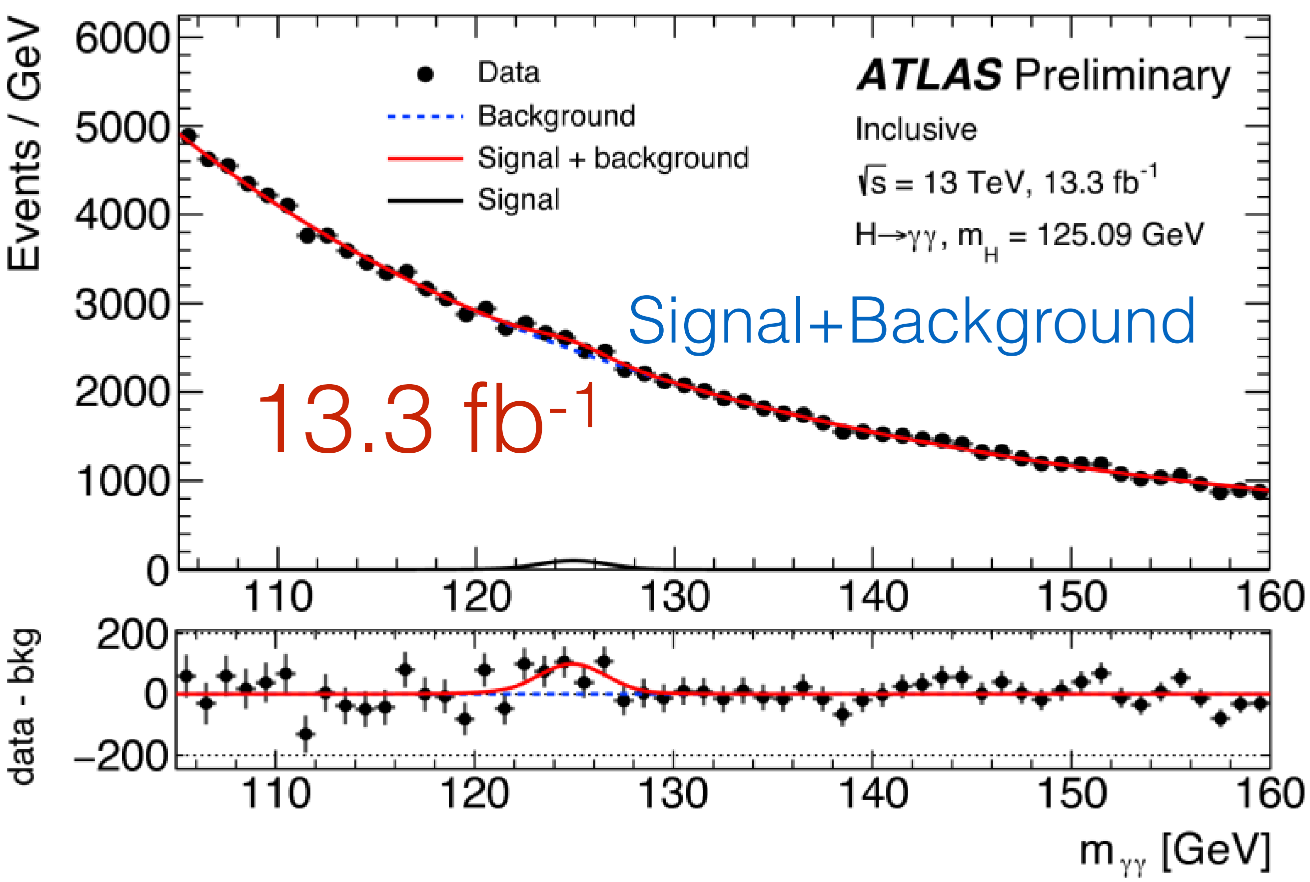
H->γγ

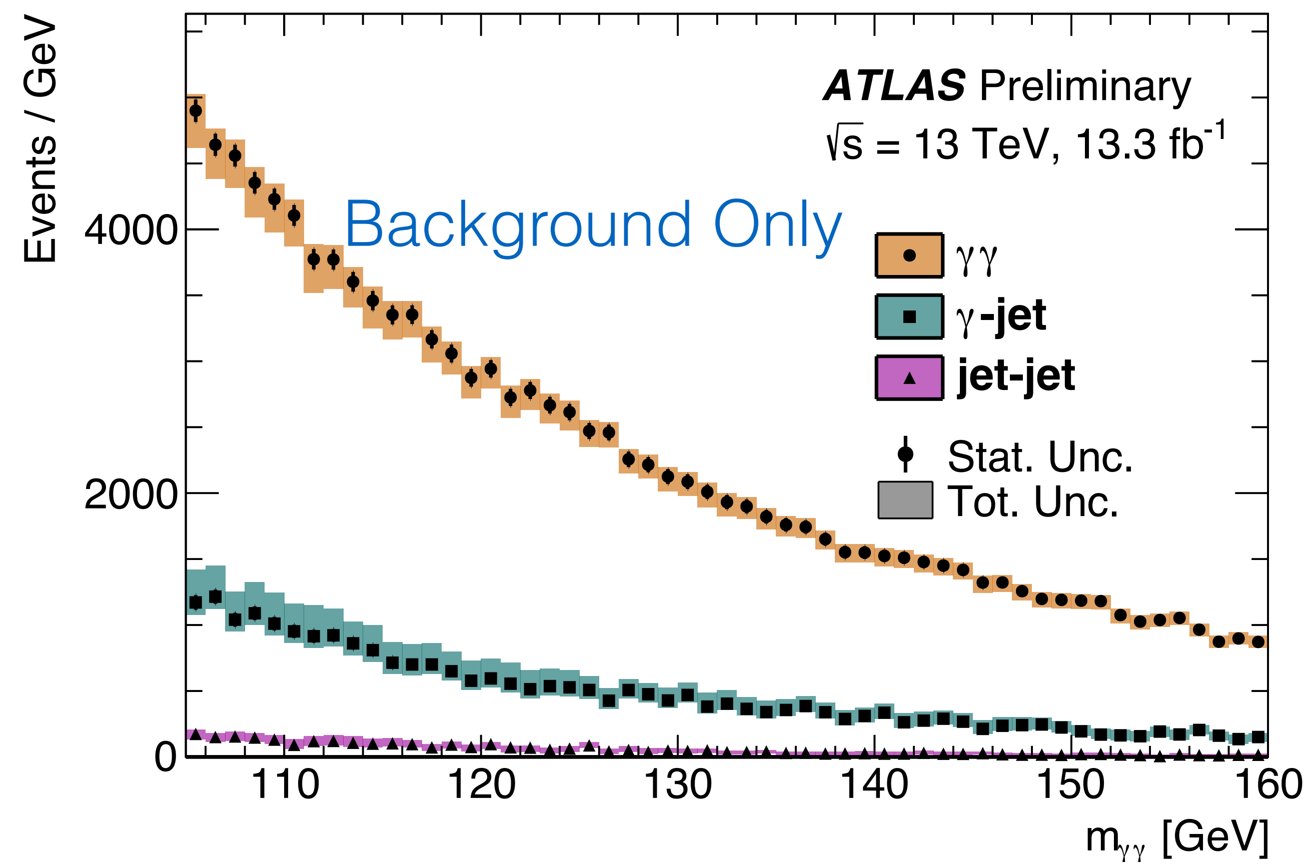


- Tight ID and isolation requirements for the photons.
  - Diphoton vertex found using neural network
  - Acceptance*efficiency of ~30-45% depending on production mode

H->γγ

ATLAS-CONF-2016-067

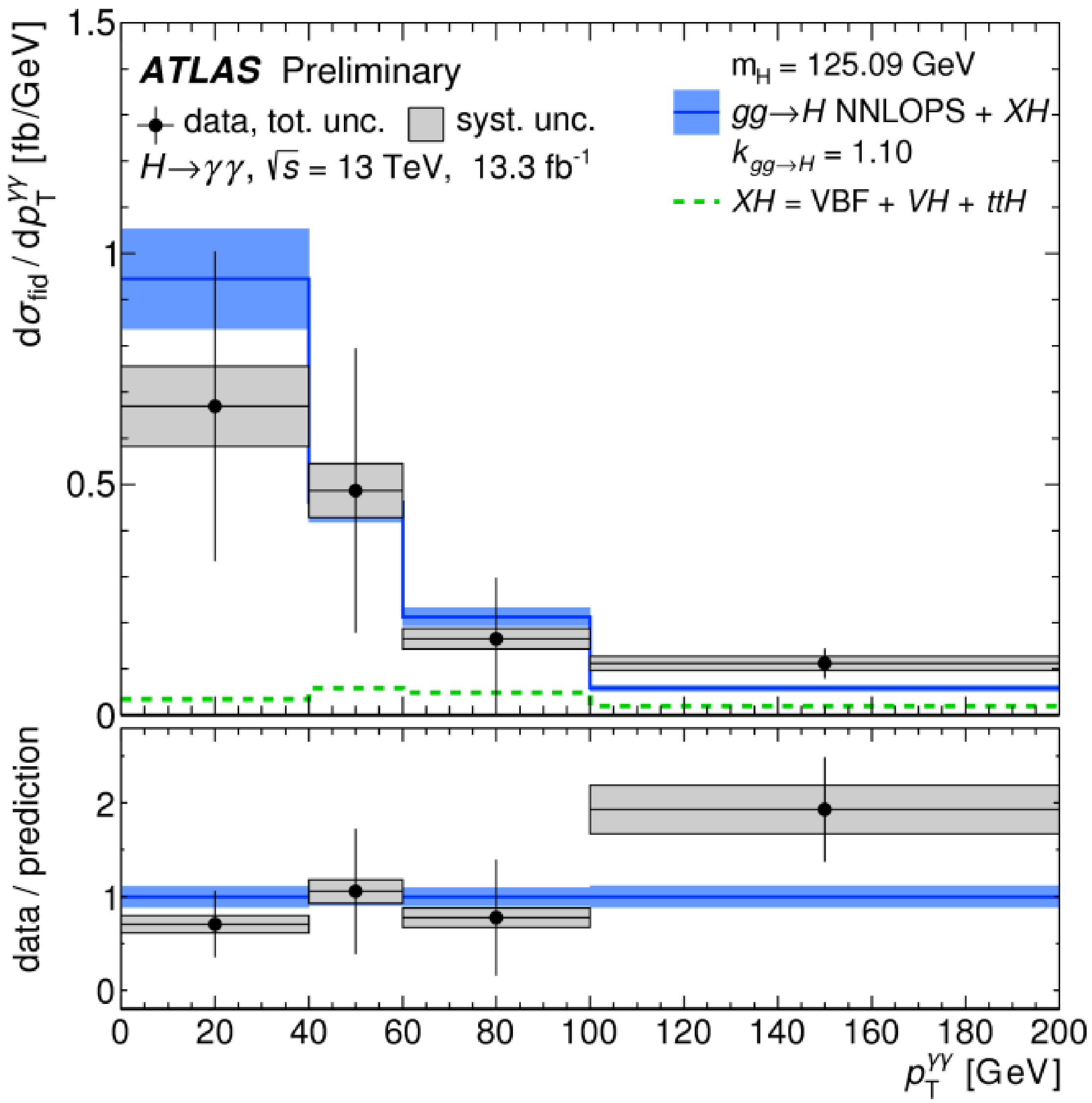


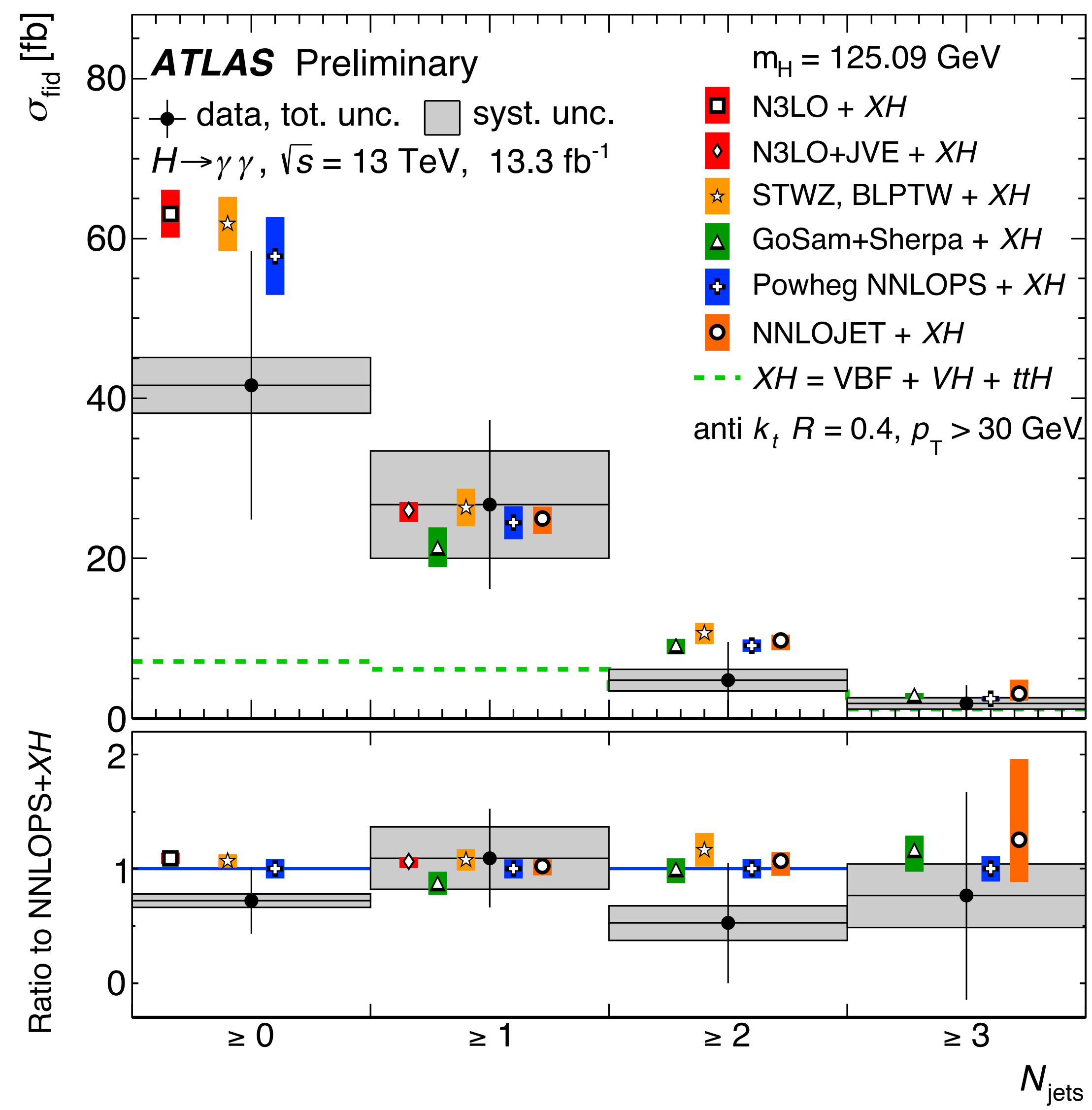


- Higgs peak sits on top of smoothly falling diphoton background.
  - Signal extracted via signal+background fit to $m_{\gamma\gamma}$ distribution.
  - Background from diphoton processes and jets faking photons.
  - Background models chosen to minimize spurious signal.
    - Defined as the amount of measured signal when doing S+B fit to background-only simulation

Fiducial and Differential Cross-Sections

ATLAS-CONF-2016-067

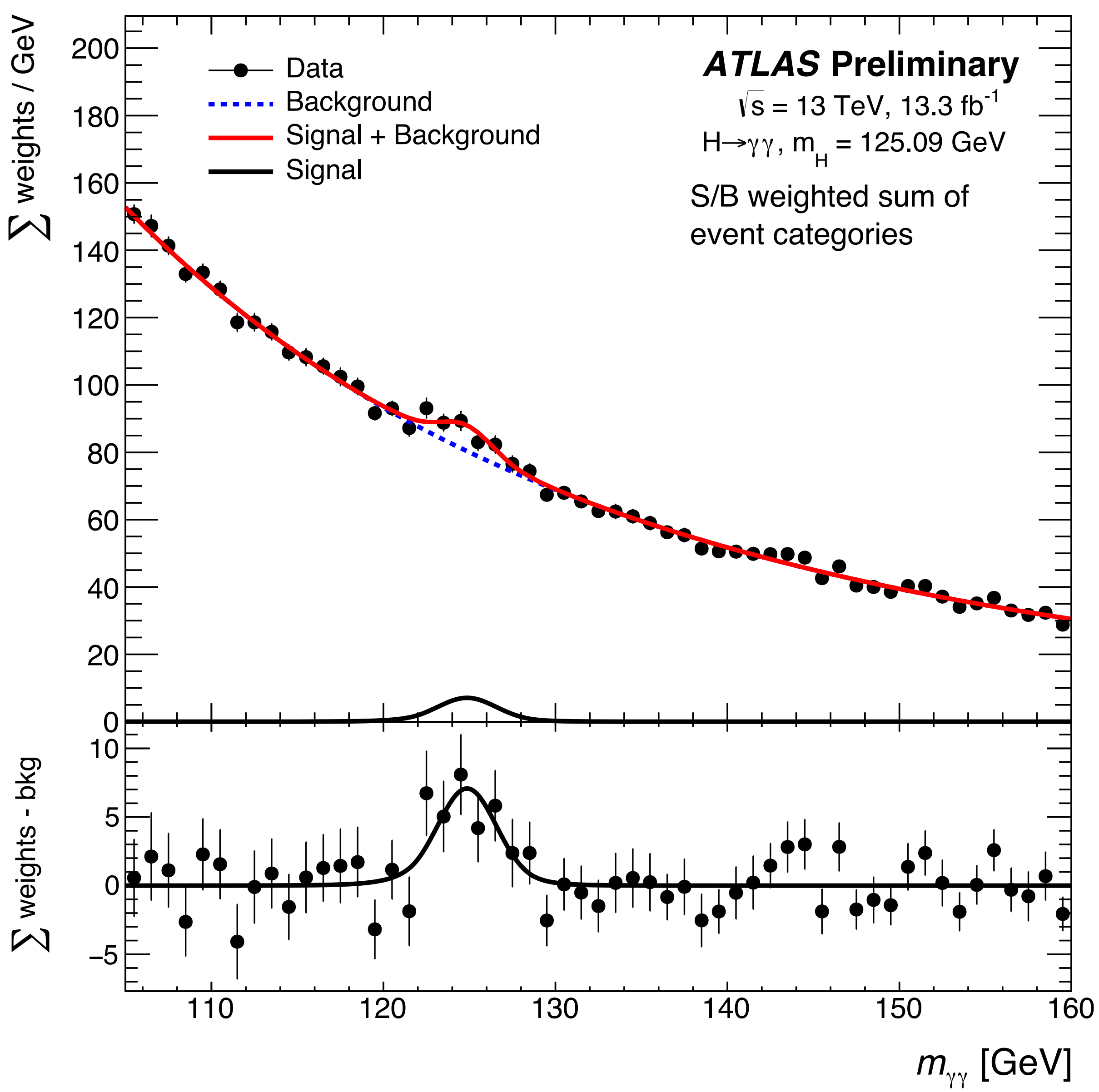


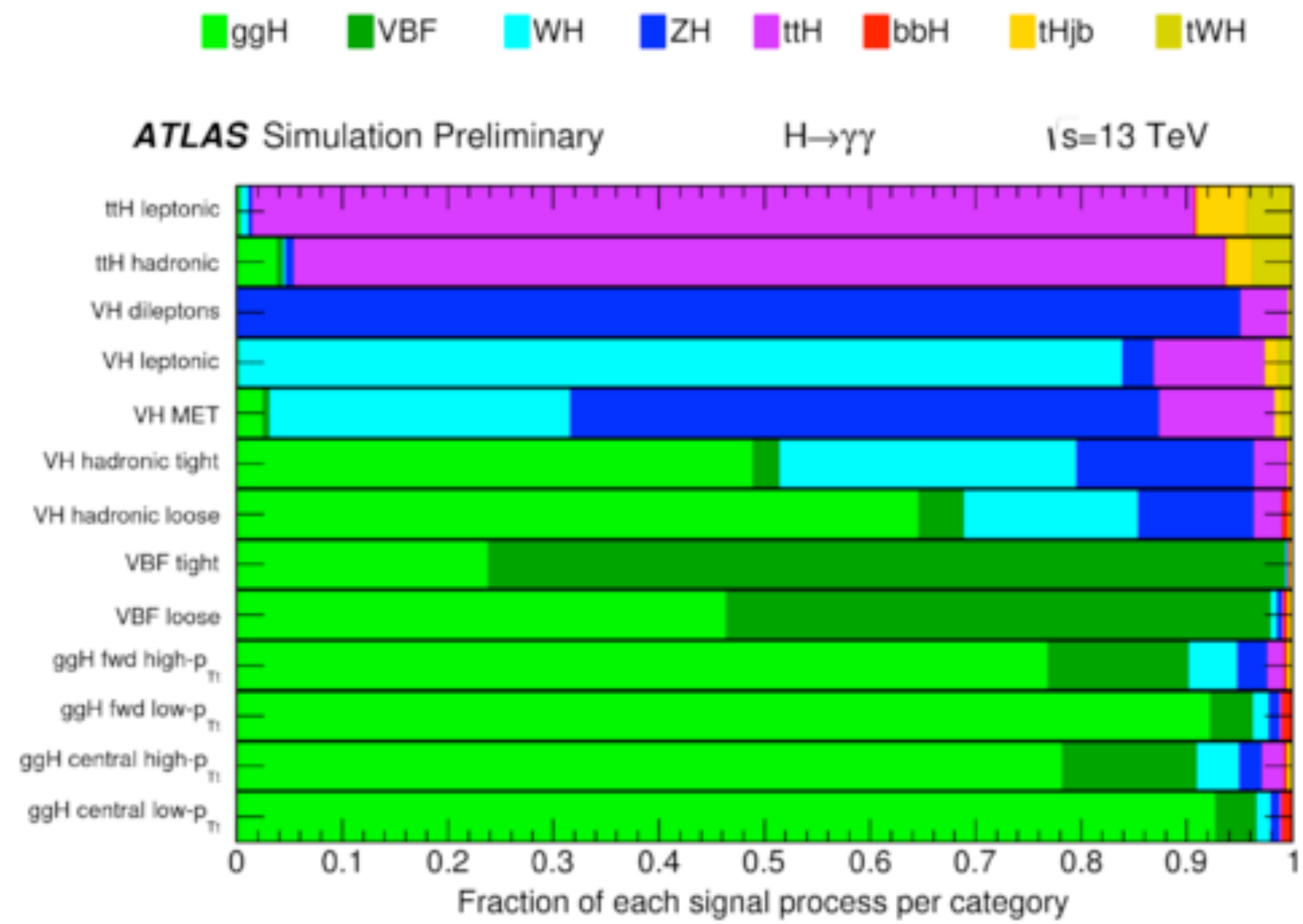


- Cross-sections extracted using bin-by-bin correction factors, assuming m_H=125.09 GeV.
- Fiducial region defined by photon E_T, η, and isolation: σ_{fid}=43.2±14.9 (stat)±4.9 (syst) fb.
    - Agrees with SM prediction $\sigma_{fid,SM}$=62.8+3.4/-4.4 fb
- Differential cross-sections produced for a number of variables, compared to multiple calculations: no significant disagreements with the SM observed.

Production Mode Cross-Sections

ATLAS-CONF-2016-067

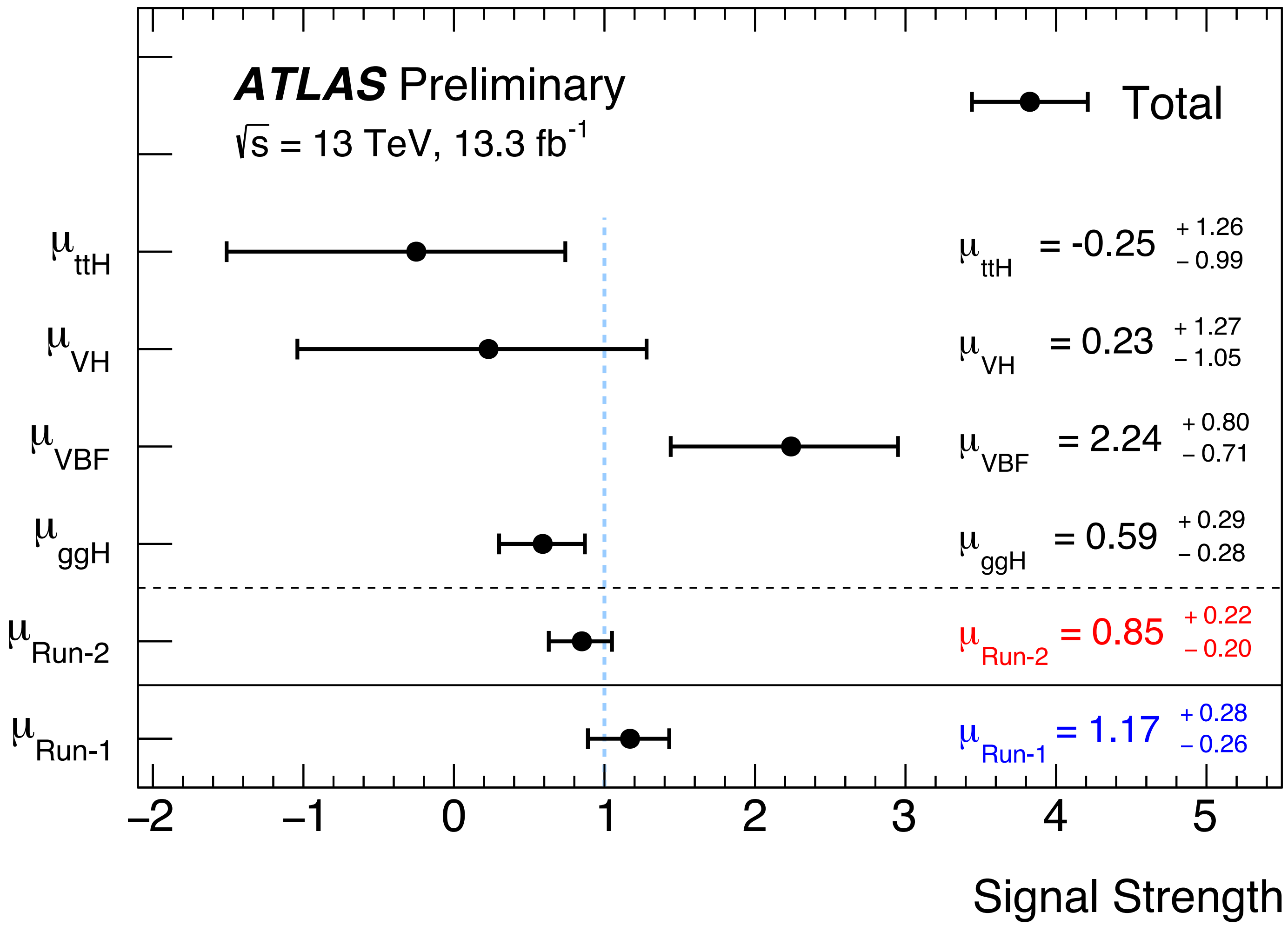




- Reconstructed events are divided into 13 exclusive categories enriched in different production modes.
- A simultaneous fit is performed to the $m_{\gamma\gamma}$ distributions in all categories.

Production Mode Cross-Sections

ATLAS-CONF-2016-067



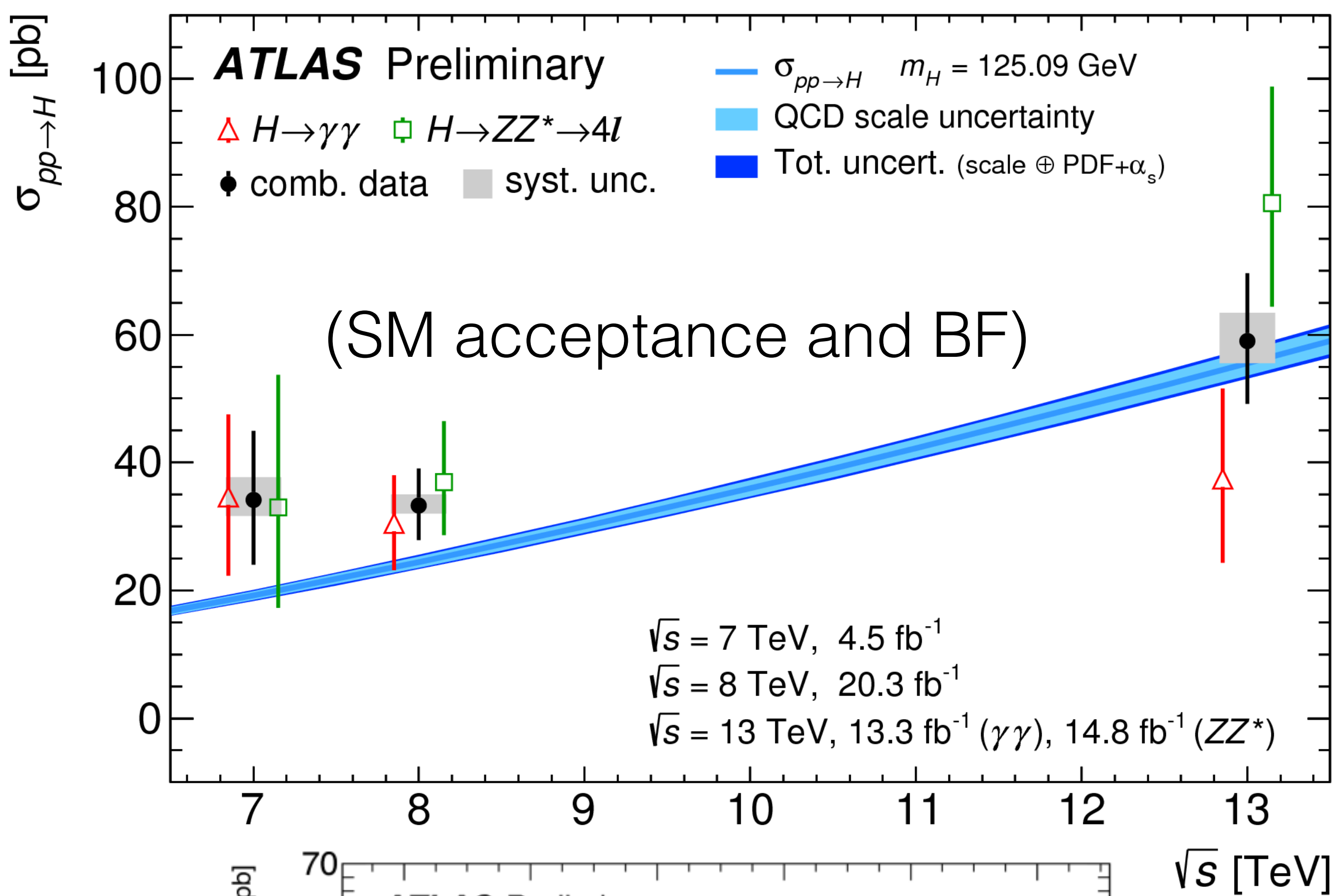
$$\sigma_{ggH} \times \mathcal{B}(H \to \gamma\gamma) = 63\ ^{+30}_{-29}\ \text{fb}$$
$$\sigma_{\text{VBF}} \times \mathcal{B}(H \to \gamma\gamma) = 17.8\ ^{+6.3}_{-5.7}\ \text{fb}$$
$$\sigma_{\text{VHlep}} \times \mathcal{B}(H \to \gamma\gamma) = 1.0\ ^{+2.5}_{-1.9}\ \text{fb}$$
$$\sigma_{\text{VHhad}}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

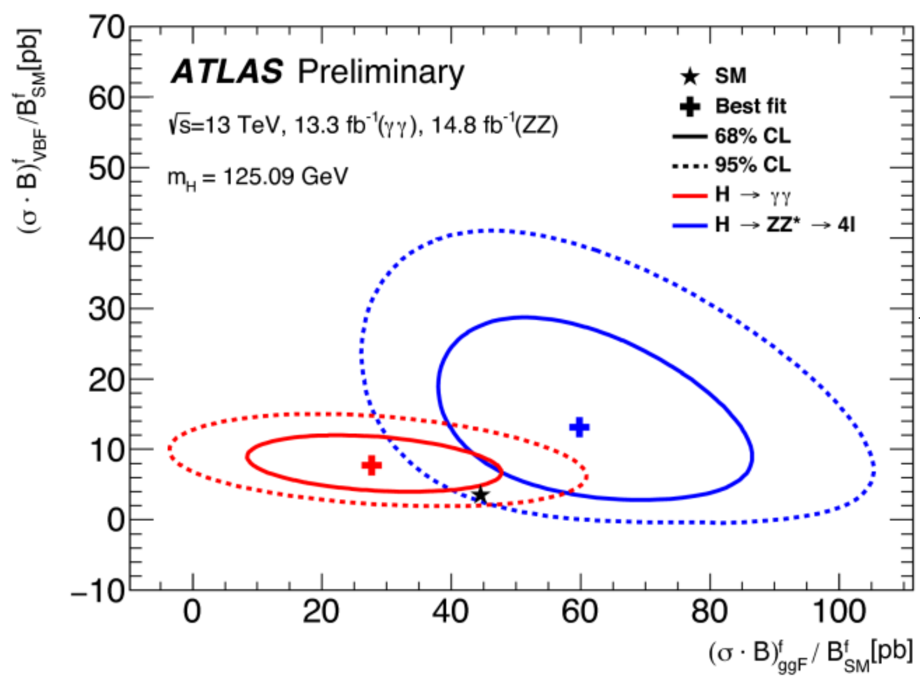
Stage 0 simplified template cross-section measurements

- Signal strength results from Run-1 and Run-2 are not directly comparable
  - N3LO ggH cross-section used in Run-2 is 10% larger
  - For a direct comparison the full Run-1 analysis would have to be re-run
- Stage-0 STXS results are for $|y_H|<2.5$
  - VH assumes WH/ZH production ratio follows the SM
- All results agree with the SM within 1-2 σ

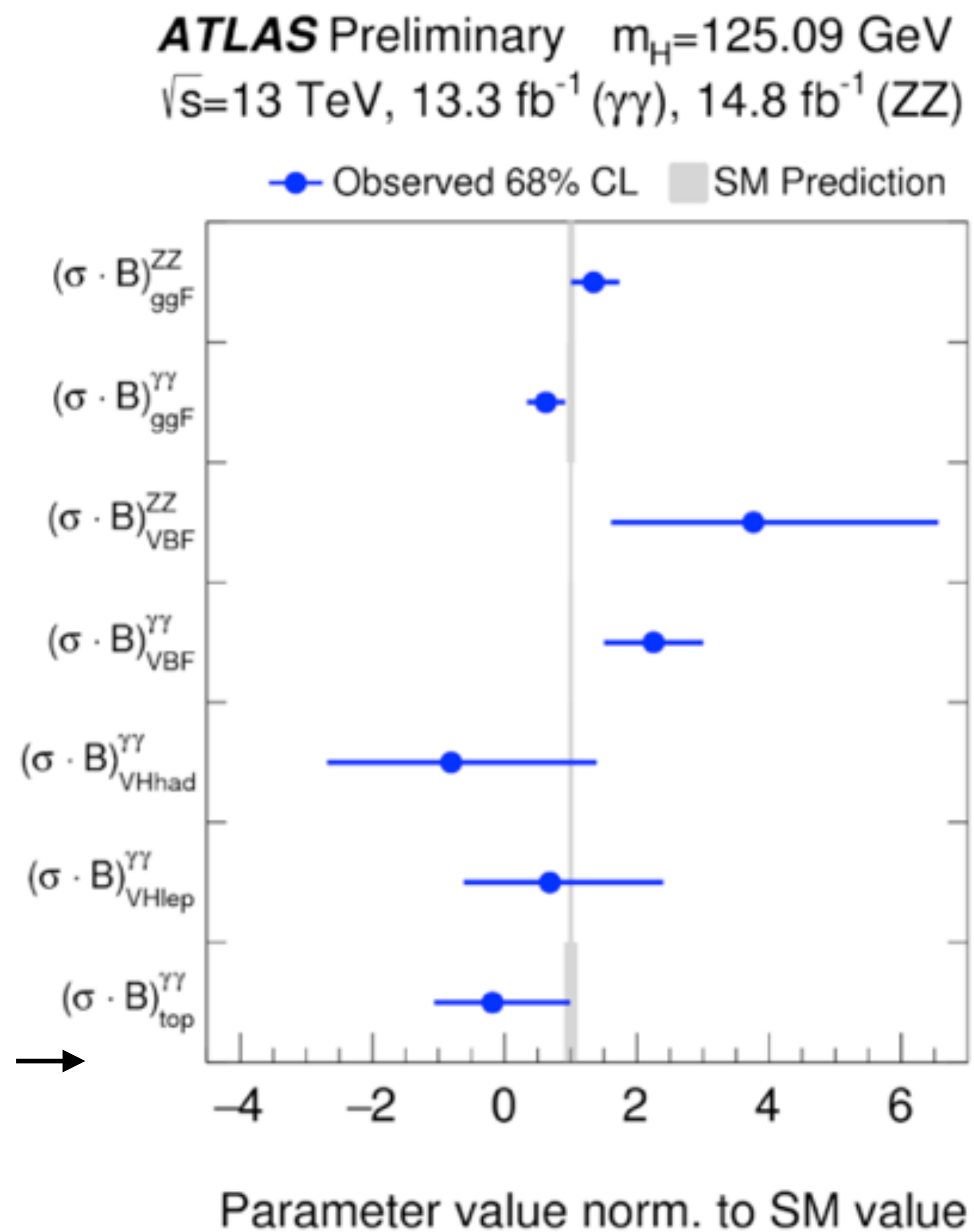
Combined Results

ATLAS-CONF-2016-081





← $|y_H|<2.5$ →



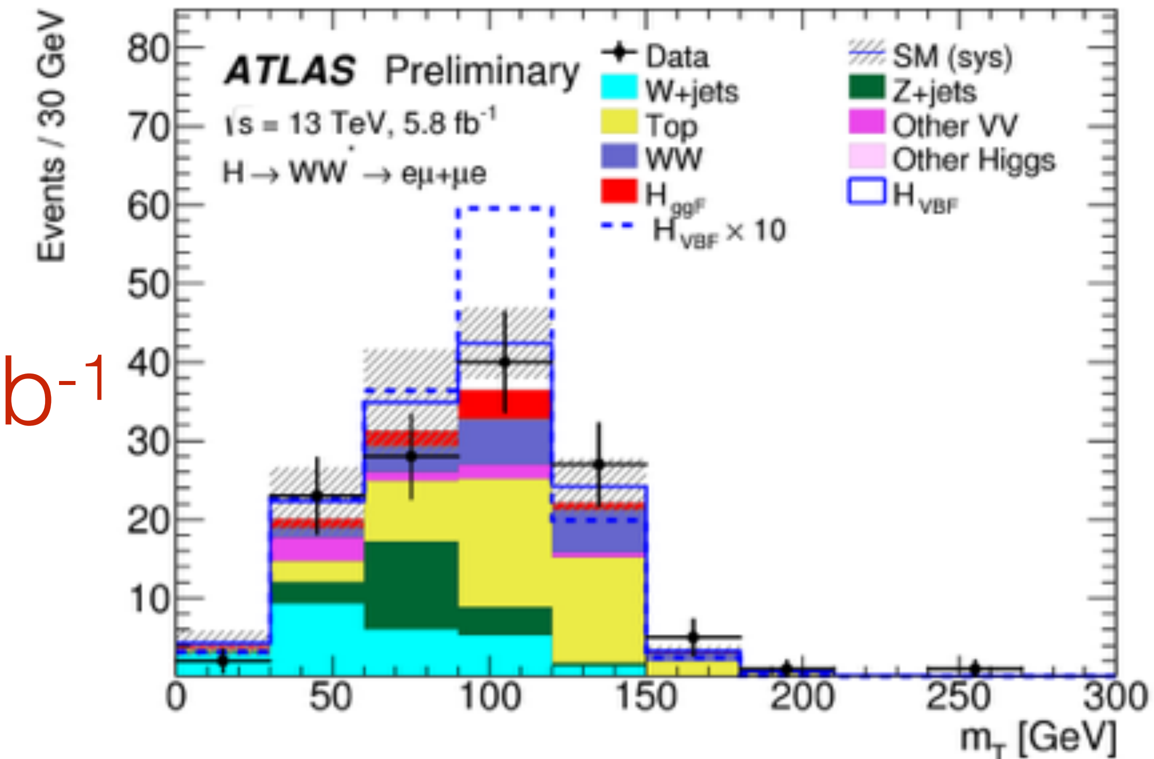
Results are compatible with SM expectations

H->WW*->$\ell\nu\ell\nu$

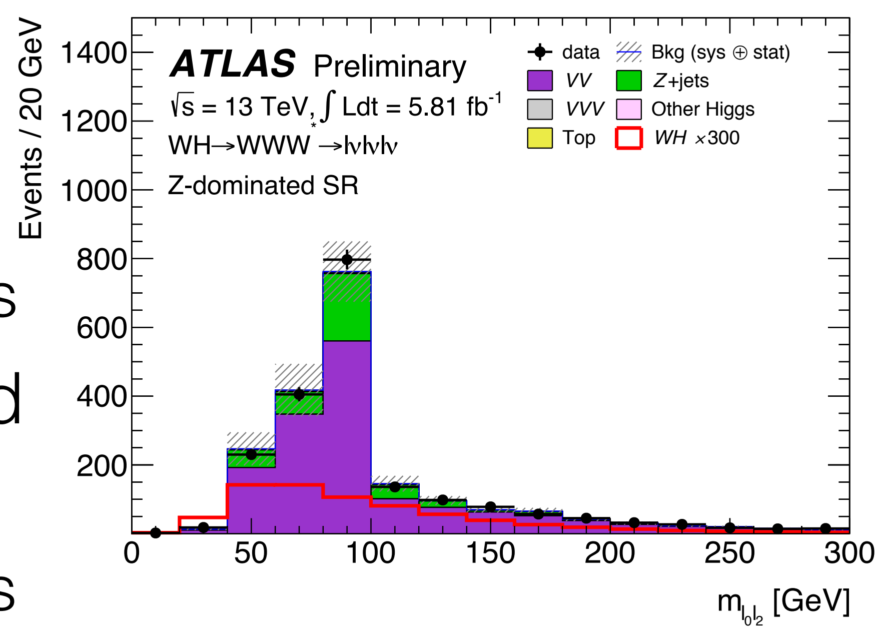
ATLAS-CONF-2016-112

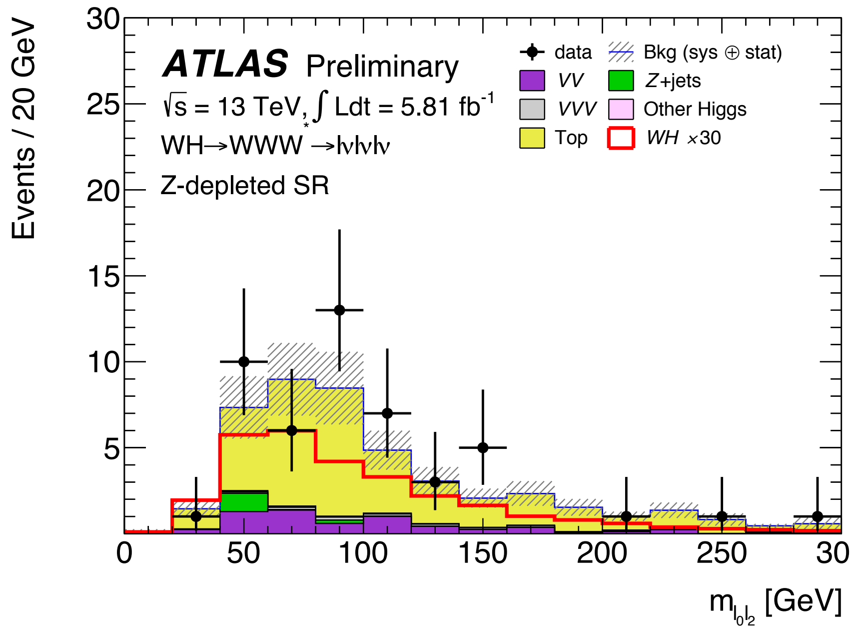
- Highest BF, but very challenging analysis
  - Lots of backgrounds
    - Top, V+jets, WW, Z->$\tau\tau$, ggF, VV
  - Final state not fully reconstructed
- Background suppression is key
  - Use e/μ final state to avoid Drell/Yan backgrounds.
  - Tight lepton ID and isolation
  - b-jet veto against top quarks
- Results here for the VBF and WH production modes only.
  - Extra jet or lepton signatures reduce backgrounds.

5.8 fb^{-1}



Background normalizations are determined in dedicated control regions





WH candidates are split into two categories depending on the dominant backgrounds

Results

ATLAS-CONF-2016-112

- VBF: 2 jets in addition to the eμ pair
  - Both leptons must be between the two jets, which must also have no additional jet between them.
  - Z->$\tau\tau$ is explicitly vetoed, as is a 3rd lepton.
- WH: Exactly three leptons with total charge of ±1
  - Max of 1 jet allowed, Z veto, E_T^{miss}>50 GeV
  - The closest eμ pair must have ΔR<2
- Signals are extracted from a simultaneous fit to signal and control region yields (assuming m_H=125.09 GeV).
  - Control regions chosen to be enriched in leading backgrounds.
  - VBF uses a BDT: the signal region is split in two based on the BDT score.

$$\mu_{\mathrm{VBF}} = 1.7^{+1.0}_{-0.8}(\mathrm{stat})^{+0.6}_{-0.4}(\mathrm{sys})$$

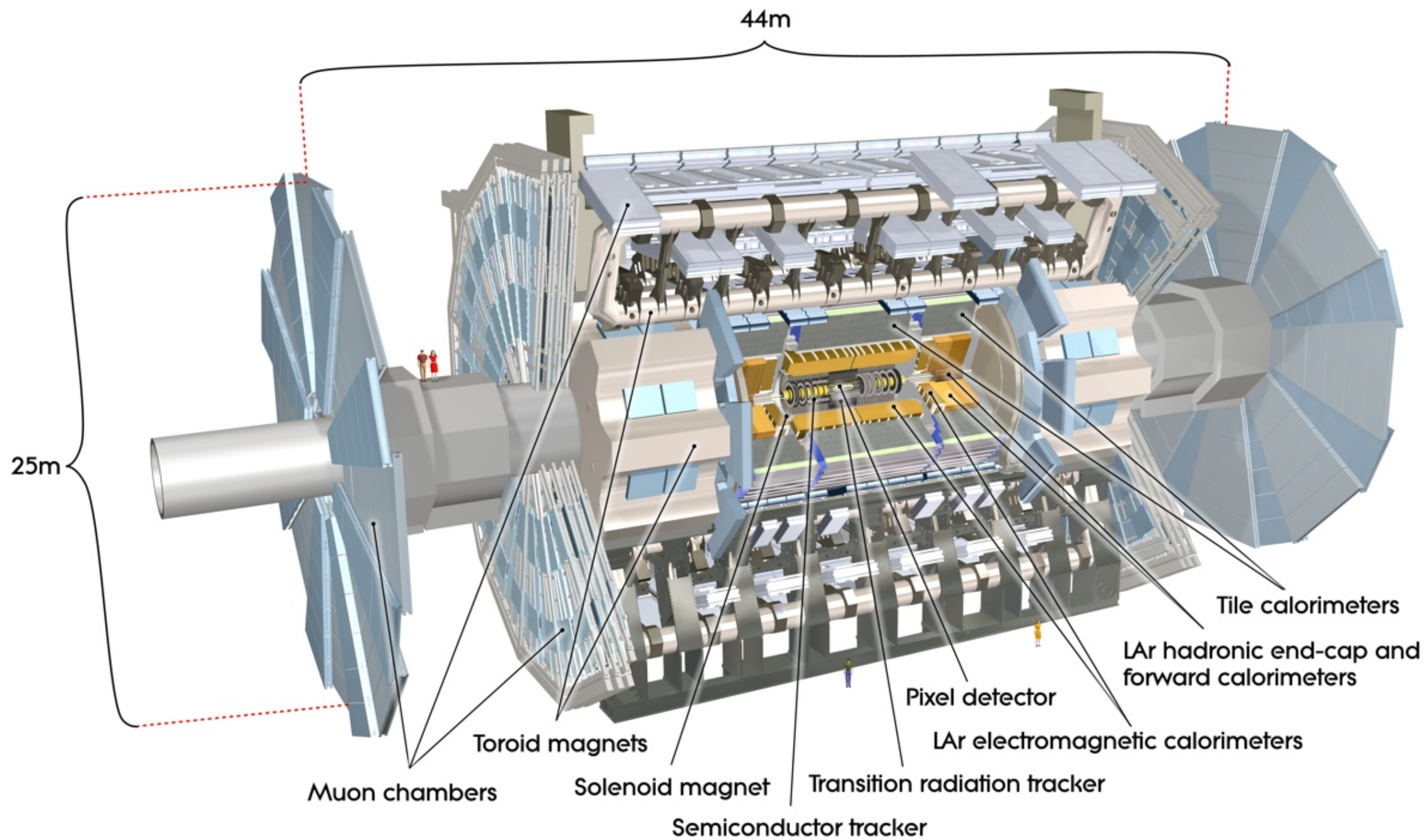
$$\mu_{WH} = 3.2^{+3.7}_{-3.2}(\mathrm{stat})^{+2.3}_{-2.7}(\mathrm{sys})$$

Summary

- Diboson channels continue to provide lots of information about the Higgs boson
- So far, no deviations from the SM observed
- Expecting many interesting new results once the full 2015+2016 dataset of 36.1 fb^{-1} is analyzed.
  - In 2017 our dataset should more than double
  - Lots more to come!

Backup

The ATLAS Detector



- An all-purpose particle detector with excellent detection and reconstruction capabilities.
- New features for Run-2:
  - Inner B-layer: pixel layer at 3.3 cm from the beam
  - Increased muon coverage

H->4ℓ Event Selection

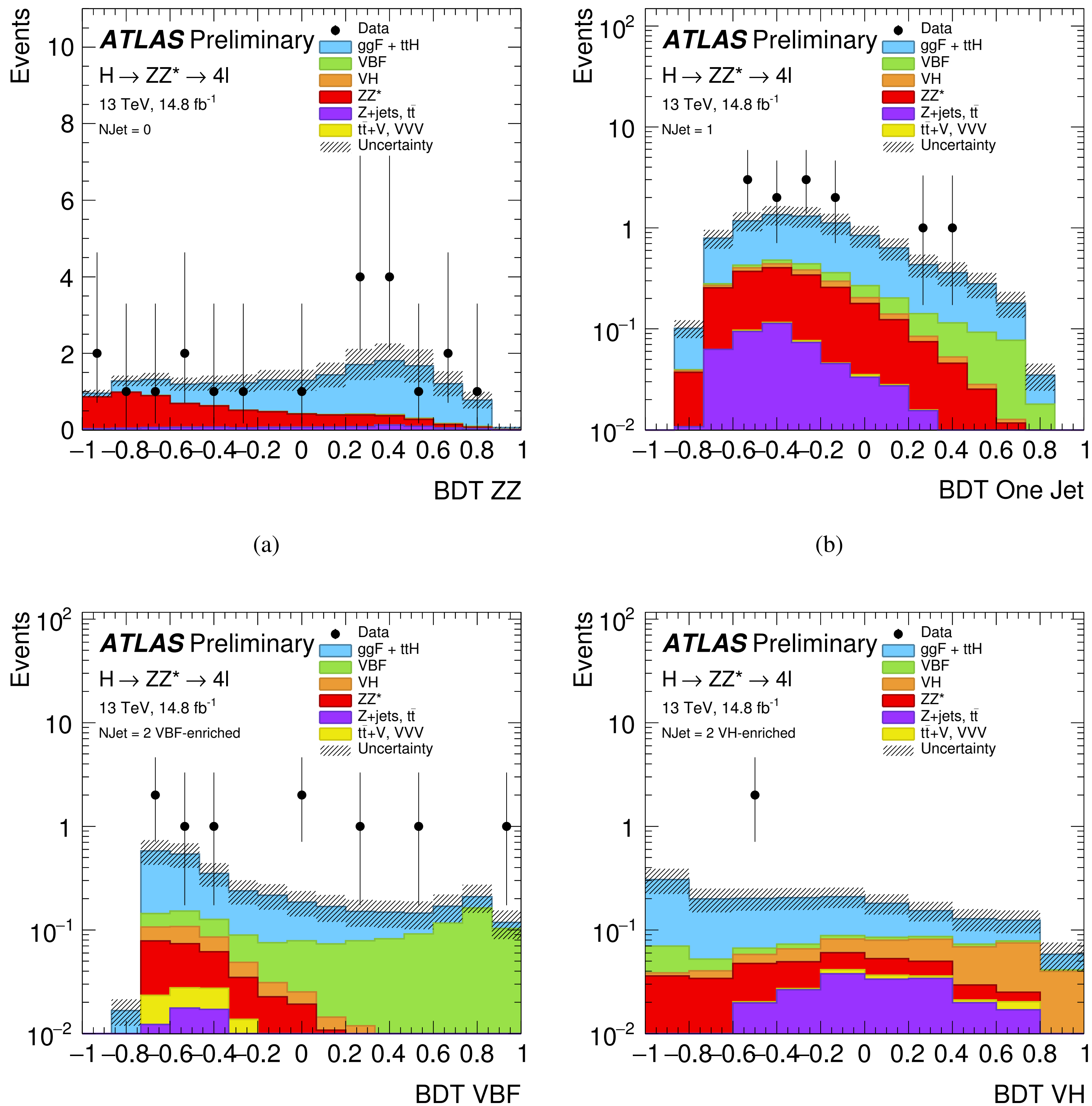
Leptons and Jets requirements
Electrons
Loose Likelihood quality electrons with hit in innermost layer, $E_T > 7$ GeV and $\|\eta\| < 2.47$
Muons
Loose identification $\|\eta\| < 2.7$
Calo-tagged muons with $p_T > 15$ GeV and $\|\eta\| < 0.1$
Combined, stand-alone (with ID hits if available) and segment tagged muons with $p_T > 5$ GeV
Jets
anti-k_t jets with $p_T > 30$ GeV, $\|\eta\| < 4.5$ and passing pile-up jet rejection requirements

Event Selection	
Quadruplet Selection	Require at least one quadruplet of leptons consisting of two pairs of same flavour opposite-charge leptons fulfilling the following requirements: p_T thresholds for three leading leptons in the quadruplet - 20, 15 and 10 GeV Maximum of one calo-tagged or standalone muon per quadruplet Select best quadruplet to be the one with the (sub)leading dilepton mass (second) closest the Z mass Leading dilepton mass requirement: 50 GeV $< m_{12} <$ 106 GeV Sub-leading dilepton mass requirement: $12 < m_{34} <$ 115 GeV Remove quadruplet if alternative same-flavour opposite-charge dilepton gives $m_{\ell\ell} < 5$ GeV $\Delta R(\ell, \ell') > 0.10$ (0.20) for all same(different)-flavour leptons in the quadruplet
Isolation	Contribution from the other leptons of the quadruplet is subtracted Muon track isolation ($\Delta R \leq 0.30$): $\Sigma p_T / p_T < 0.15$ Muon calorimeter isolation ($\Delta R = 0.20$): $\Sigma E_T / p_T < 0.30$ Electron track isolation ($\Delta R \leq 0.20$) : $\Sigma E_T / E_T < 0.15$ Electron calorimeter isolation ($\Delta R = 0.20$) : $\Sigma E_T / E_T < 0.20$
Impact Parameter Significance	Apply impact parameter significance cut to all leptons of the quadruplet. For electrons : $\|d_0/\sigma_{d_0}\| < 5$ For muons : $\|d_0/\sigma_{d_0}\| < 3$
Vertex Selection	Require a common vertex for the leptons χ^2/ndof < 6 for 4μ and < 9 for others.

H->4ℓ Fiducial Selection

Lepton definition	
Muons: $p_{\mathrm{T}} > 5$ GeV, $\|\eta\| < 2.7$	Electrons: $p_{\mathrm{T}} > 7$ GeV, $\|\eta\| < 2.47$
Pairing	
Leading pair:	SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Sub-leading pair:	Remaining SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Event selection	
Lepton kinematics:	Leading leptons $p_{\mathrm{T}} > 20, 15, 10$ GeV
Mass requirements:	$50 < m_{12} < 106$ GeV; $12 < m_{34} < 115$ GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1(0.2)$ for same(opposite)-flavour leptons
J/ψ veto:	$m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs
Mass window:	$115 < m_{4\ell} < 130$ GeV

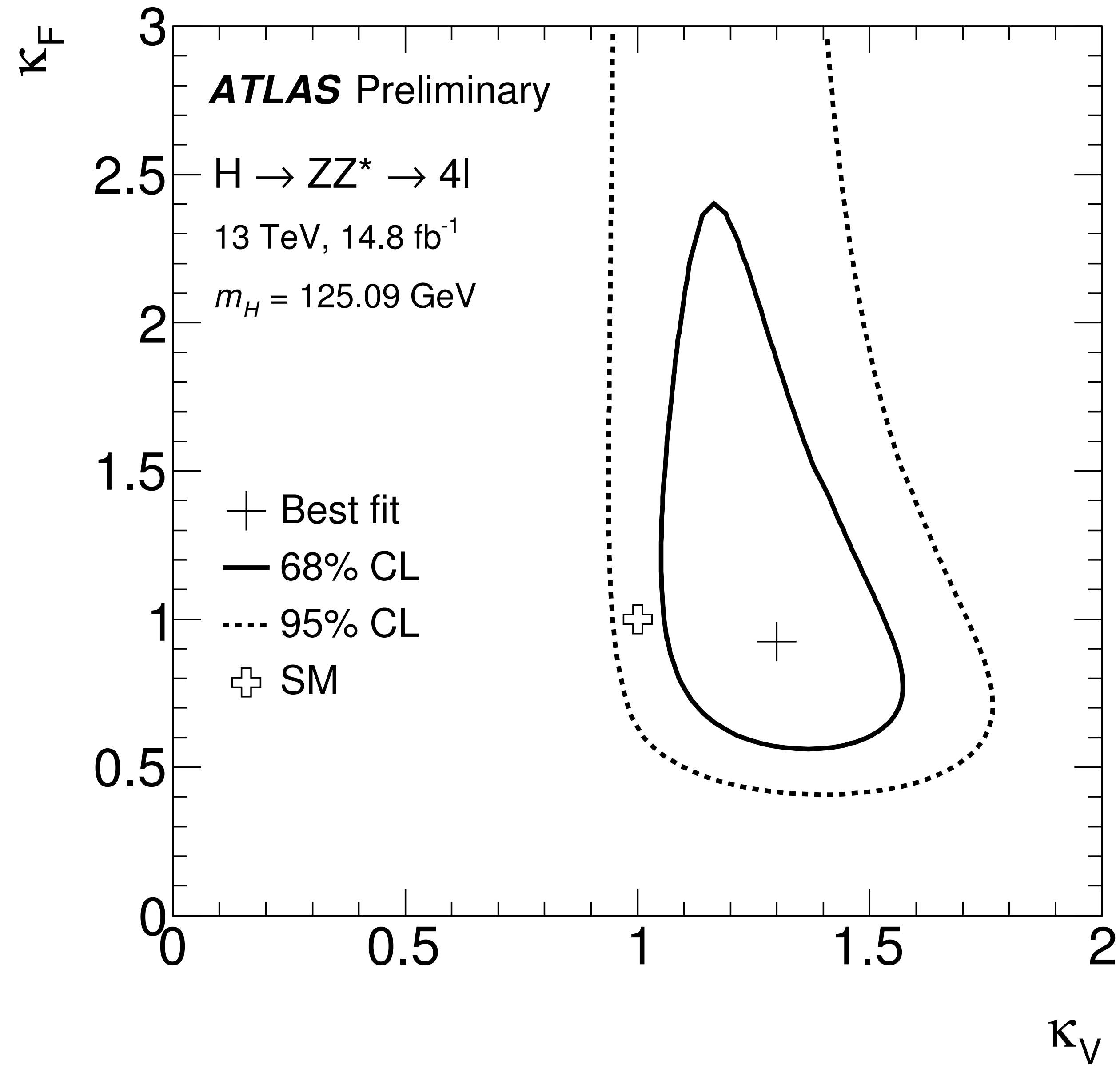
H->4ℓ Category BDT Distributions



(a)

(b)

Interpretation in the κ Framework

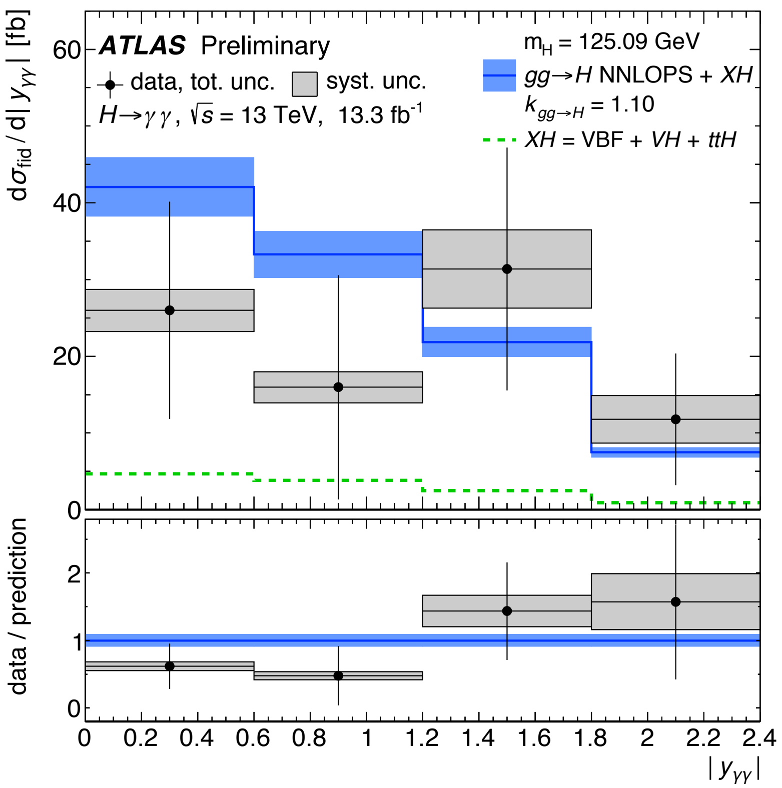


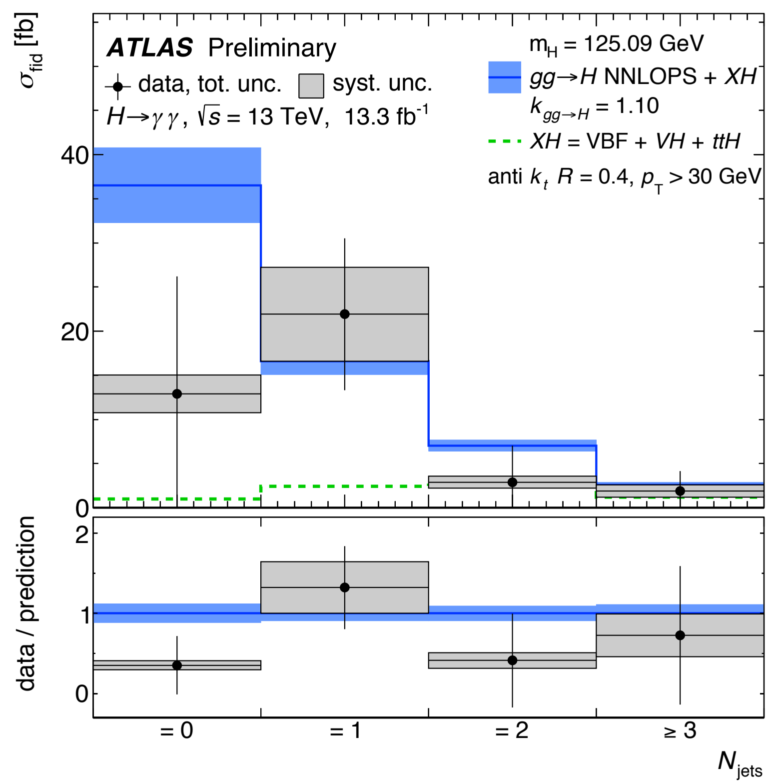
- κ_V parametrizes deviations from the SM in Higgs couplings to vector bosons and κ_F the same but for fermions: it is assumed that no undetected or invisible Higgs decays exist.

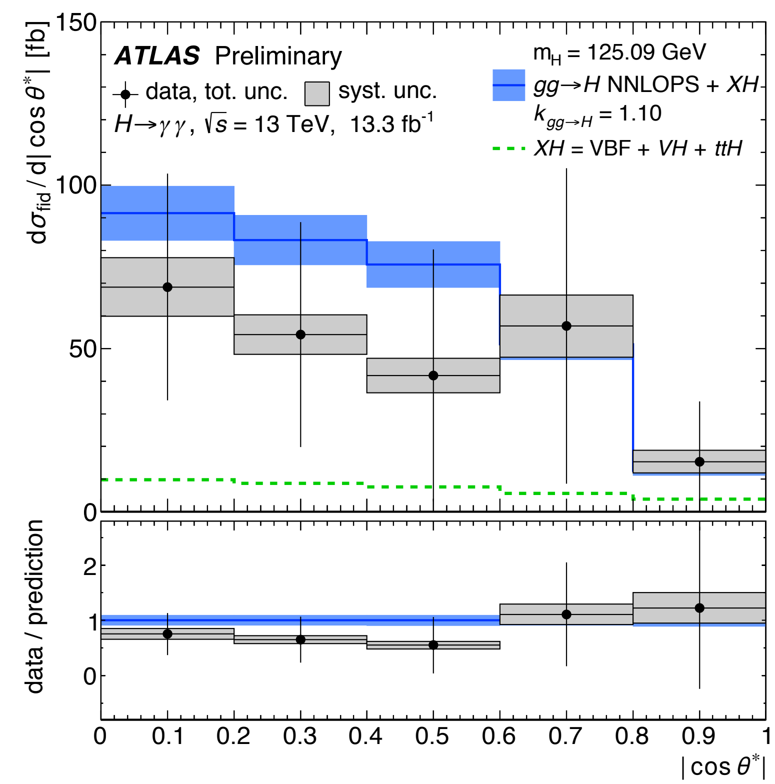
H->ɣɣ Event Selection

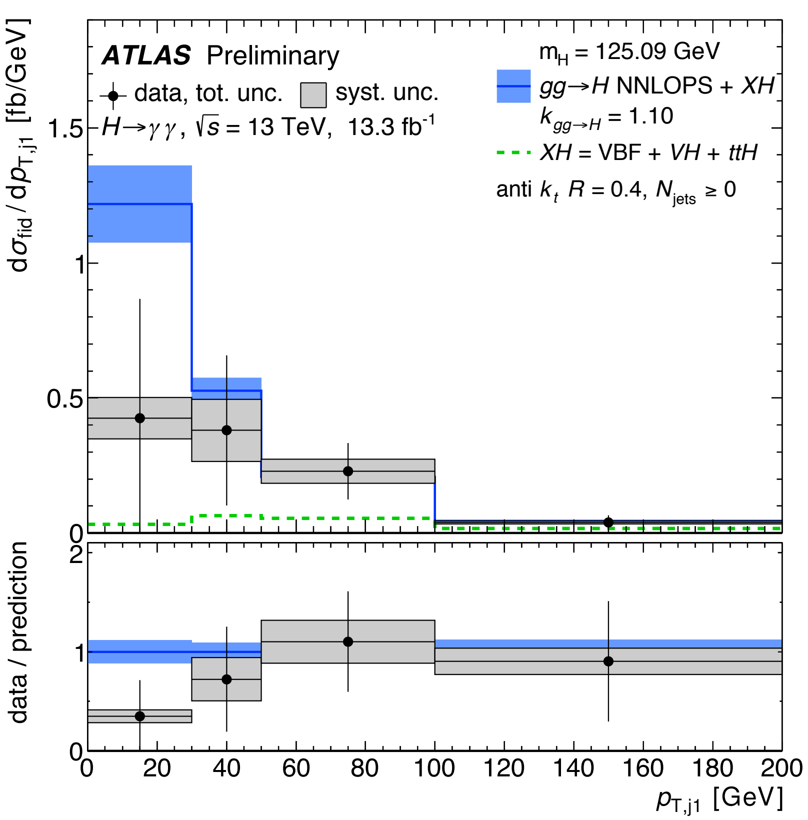
- Two photons with E_T>25 GeV and $|\eta|$<2.37
  - Excluding the region $1.37<|\eta|<1.52$
- Both must pass tight ID and isolation selections
  - Identification is based on shower shape: different for converted and unconverted photons
  - Isolation wrt to both the calorimeter and tracking detectors
- Leading and subleading photons must satisfy $E_T/m_{\gamma\gamma}$>.35 and .25 respectively, once $m_{\gamma\gamma}$ has been determined using the diphoton vertex.

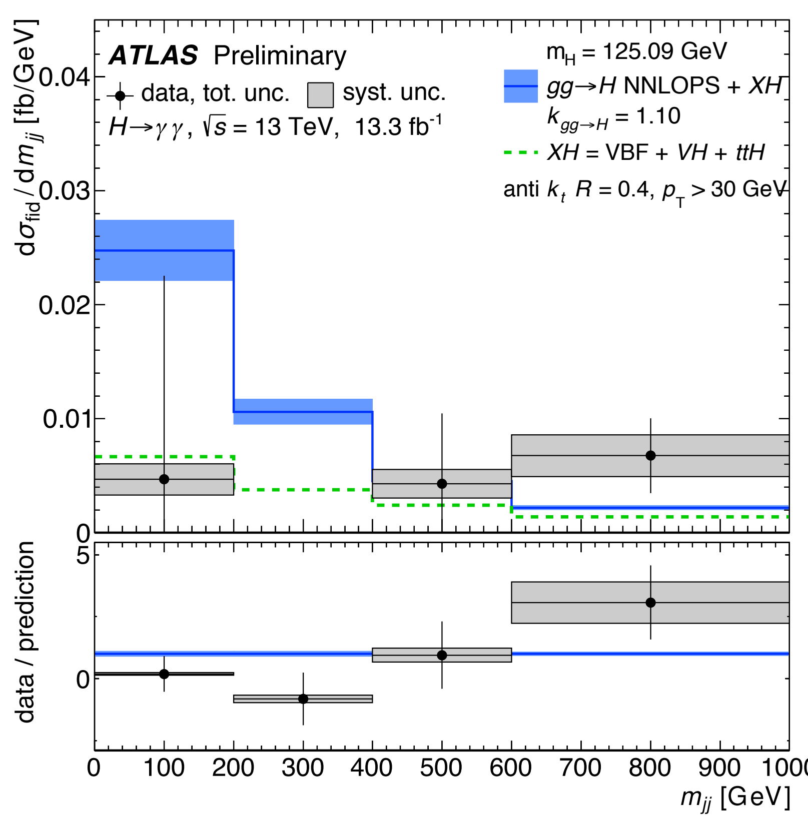
Further H->γγ Differential Cross-Sections

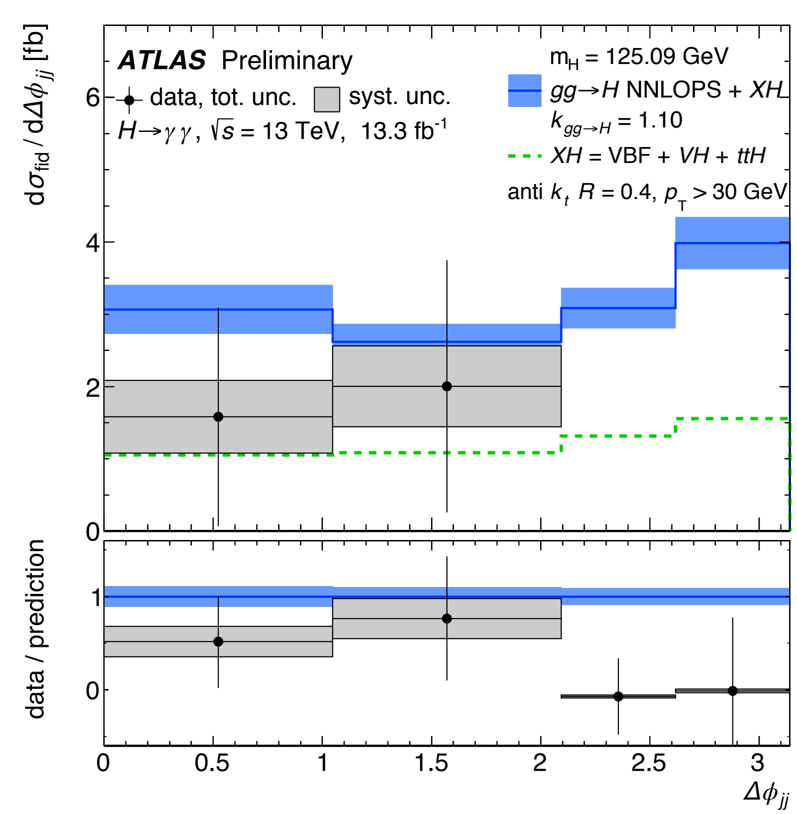




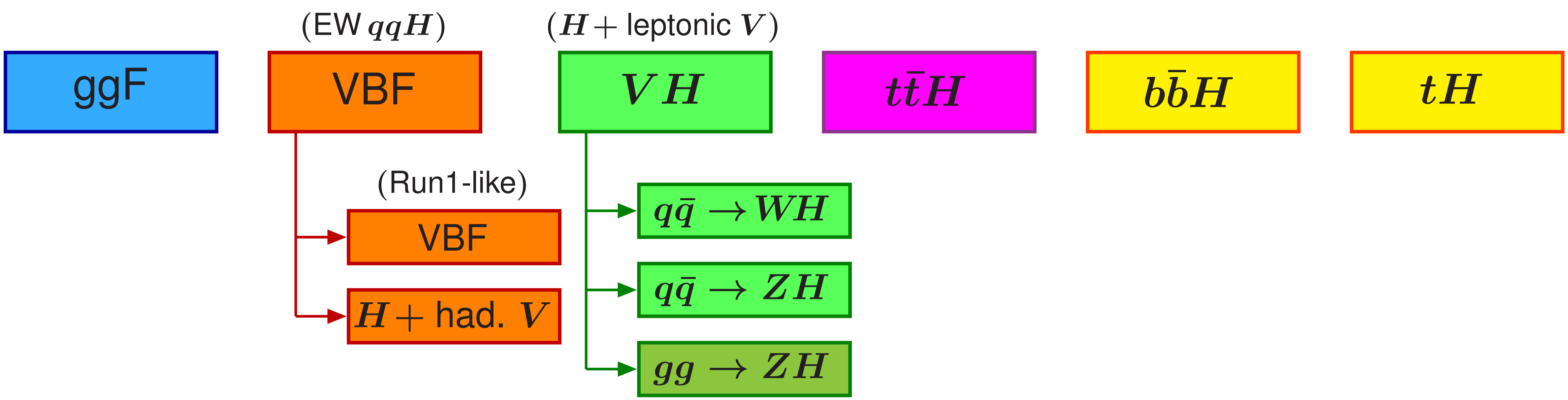








Simplified Template Cross-Section Stage 0



ue to lack of statistics, only one VH leptonic category is measured, and bbH and tH are not measured.

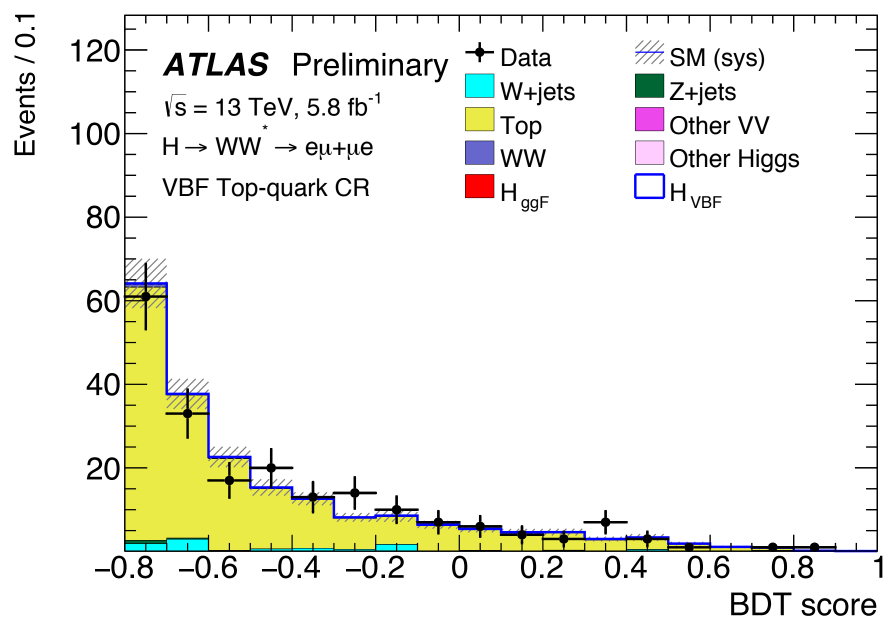
Event Selection for H->WW*->ℓνℓν VBF

	Signal region	$Z \to \tau\tau$ CR	Top-quark CR
Preselection	Two isolated leptons ($\ell = e, \mu$) with opposite charge $p_{\mathrm{T}}^{\mathrm{lead}} > 25\mathrm{GeV}$ ($p_{\mathrm{T}}^{\mathrm{lead}} > 22\mathrm{GeV}$ for muons in 2015), $p_{\mathrm{T}}^{\mathrm{sublead}} > 15\mathrm{GeV}$ $m_{\ell\ell} > 10\mathrm{GeV}$, $N_{\mathrm{jet}} \geq 2$		
	$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} = 1$
A BDT is trained at this level. Eight discriminant variables are used: $\Delta\phi_{\ell\ell}$, $m_{\ell\ell}$, m_{T}, Δy_{jj}, m_{jj}, $p_{\mathrm{T}}^{\mathrm{tot}}$, $\sum_{\ell,j} m_{\ell j}$, and $\eta_{\ell}^{\mathrm{centrality}}$			
Selection	$m_{\tau\tau} < 66.2\mathrm{GeV}$	$\lvert m_{\tau\tau} - m_Z \rvert < 25\mathrm{GeV}$	–
	–	$m_{\ell\ell} < 80\mathrm{GeV}$	–
	OLV applied, CJV applied, BDT > -0.8		
	SR1: $-0.8 <$ BDT ≤ 0.7	–	–
	SR2: $0.7 <$ BDT ≤ 1	–	–

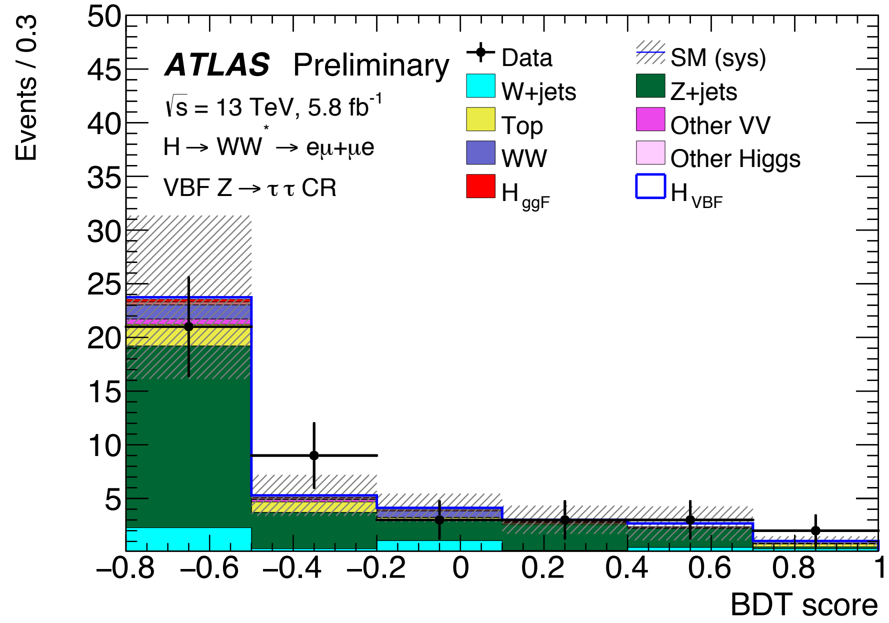
Event Selection for H->WW*->$\ell\nu\ell\nu$ WH

Category	Z-dominated SR ≥ 1 SFOS pair	Z-depleted SR no SFOS pair
Preselection	Three isolated leptons (p_{T} >15 GeV) total charge = ± 1 ≥ 1 lepton matches to the trigger	
Background Rejection	$N_{\mathrm{jet}} \leq 1$, $N_{b\text{-jet}} = 0$	
	$E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV	–
	$\lvert m_{\ell^+\ell^-} - m_Z \rvert > 25$ GeV	$Z/\gamma^* \to ee$ veto
	$m_{\ell^+\ell^-}^{\mathrm{max}} < 200$ GeV	
	$m_{\ell^+\ell^-}^{\mathrm{min}} > 12$ GeV	$m_{\ell^+\ell^-}^{\mathrm{min}} > 6$ GeV
$H \to WW^* \to \ell\nu\ell\nu$ topology	$\Delta R_{\ell_0\ell_1} < 2.0$	

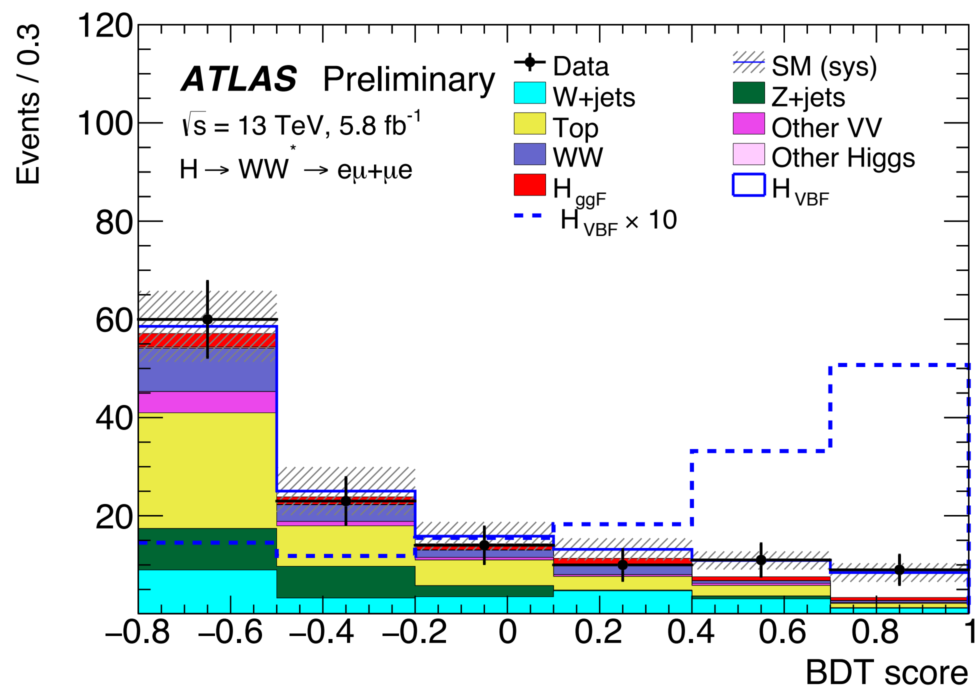
H->WW*->ℓνℓν VBF Backgrounds



(a) Top-quark CR

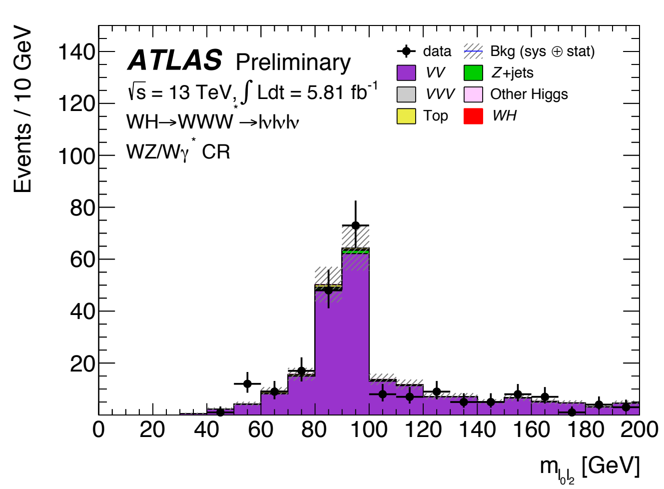


(b) $Z \to \tau\tau$ CR

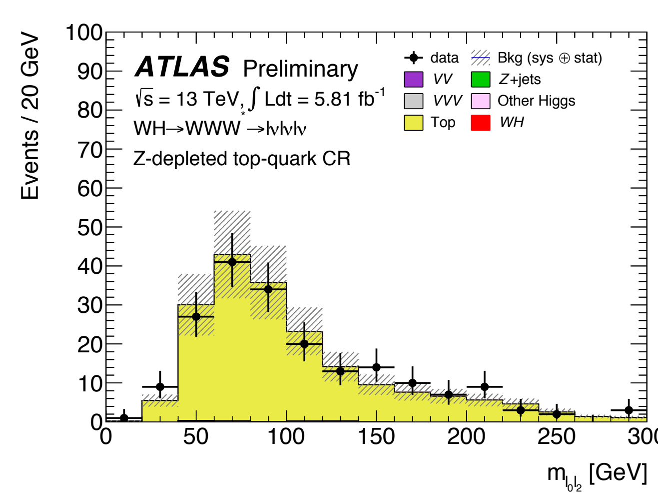


H->WW*->$\ell\nu\ell\nu$ WH Backgrounds

CR	Process	Reference SR	Changes w.r.t. reference SR
CRa	$WZ/W\gamma^*$	Z-dominated	$\geq$ 1 SFOS pair with $\lvert m_{\ell\ell} - m_Z \rvert < 25$ GeV
CRb	$Z\gamma$	Z-dominated	no Z-mass veto $\lvert m_{\ell\ell\ell} - m_Z \rvert < 15$ GeV $E_{\mathrm{T}}^{\mathrm{miss}} < 50$ GeV only eee, $\mu\mu e$
CRc	Z+jets	Z-dominated	$\geq$ 1 SFOS pair with $\lvert m_{\ell\ell} - m_Z \rvert < 25$ GeV $E_{\mathrm{T}}^{\mathrm{miss}} < 50$ GeV $\lvert m_{\ell\ell\ell} - m_Z \rvert > 15$ GeV one lepton without an isolation requirement (NFs are derived for e-fake sample and μ-fake sample separately)
CRd	Top quark	Z-dominated	no $m_{\ell^+\ell^-}^{\max}$ and $\Delta R_{\ell_0\ell_1}$ cuts at least 1 jet one b-jet one lepton without an isolation requirement
CRe	Top quark	Z-depleted	no $m_{\ell^+\ell^-}^{\max}$ and $\Delta R_{\ell_0\ell_1}$ cuts at least 1 jet one b-jet one lepton without an isolation requirement



(a) $WZ/W\gamma^*$ CR



(b) Z-depleted top-quark CR

H->WW*->ℓνℓν Fit Results