Determination of the off-shell Higgs boson signal strength in the high mass ZZ and WW final states with the ATLAS detector

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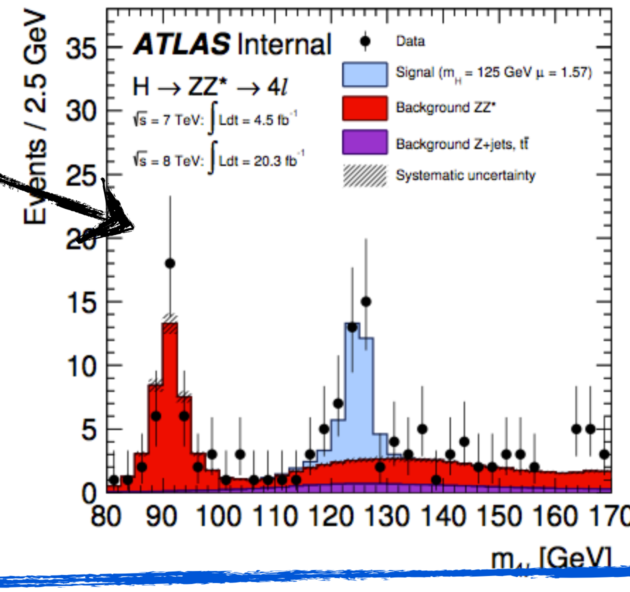
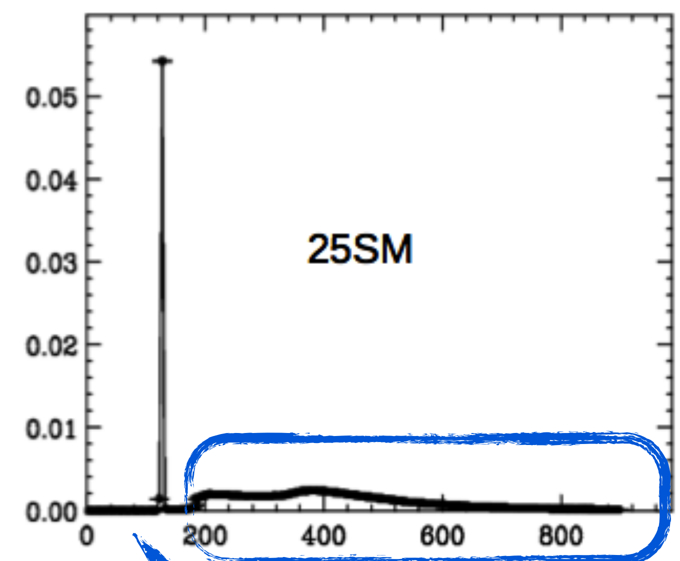
Off-peak Higgs signal strength

- We used to search the Higgs as a new on-shell particle (peak on the final state invariant mass spectrum)
- Recently, N. Kauer and G. Passarino explained the possible inadequacy of the zero-width approximation → The Higgs has also contributions as a virtual particle (propagator) and can be therefore measured in the high mass region.





- In the 0-width approximation (no off-peak contribution), the integrated cross section is given by:
    - $\sigma_{\text{on-peak}} \sim g^2_{ggH}\, g^2_{HVV} / \Gamma^2_H$
- In the off-shell regions (where the Higgs acts as a propagator), the cross section is:
    - $\sigma_{\text{off-peak}} \sim g^2_{ggH}\, g^2_{HVV}$ (the cross-section is independent of the total Higgs width)

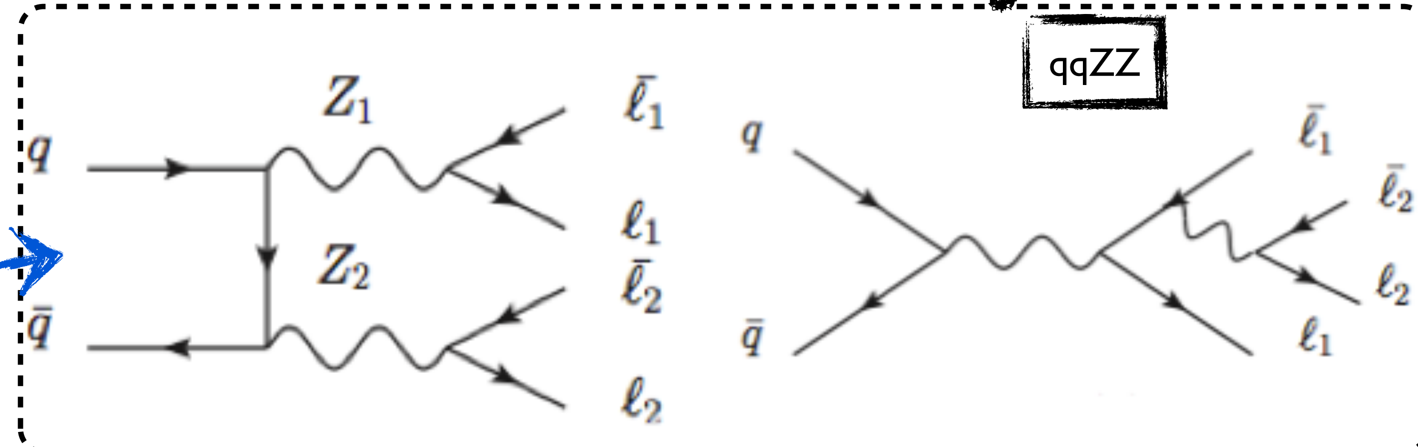
- The ratio of off-shell and on-shell production cross sections will lead to a direct measurement of the μ_offShell and consequently the Higgs width, as long as the product of the coupling to initial and final states remains constant

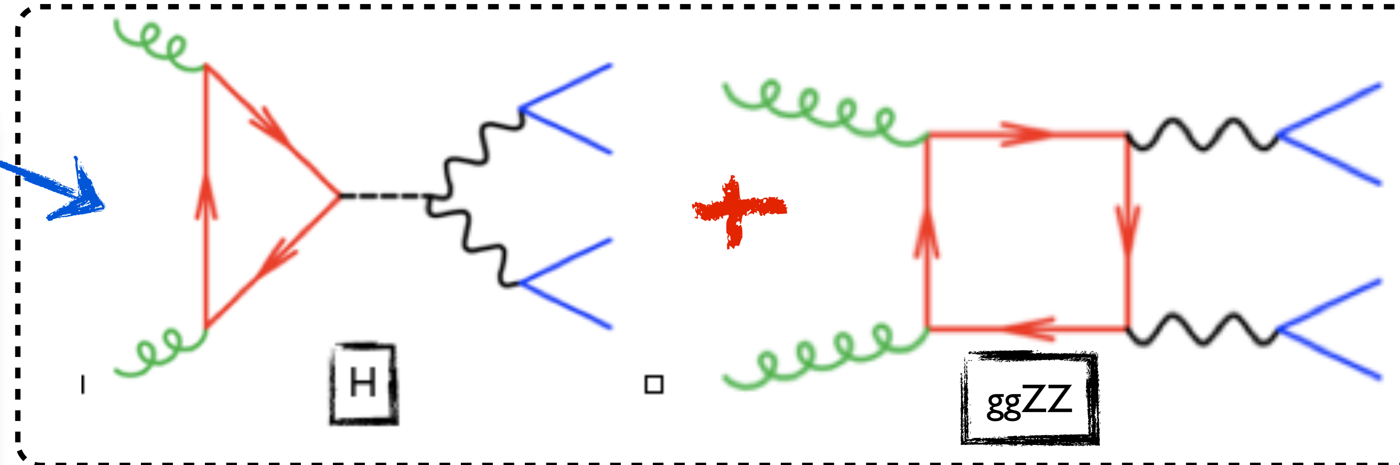
ATLAS: arXiv:1503.01060 (published on EPJC)

- Limit on the off-shell couplings (μ_offshell) in the high mass region
- We'll interpret this off-shell limit as a limit on ΓH (ΓH_SM=4.2 MeV) when combining with the on-shell (low mass) measurement

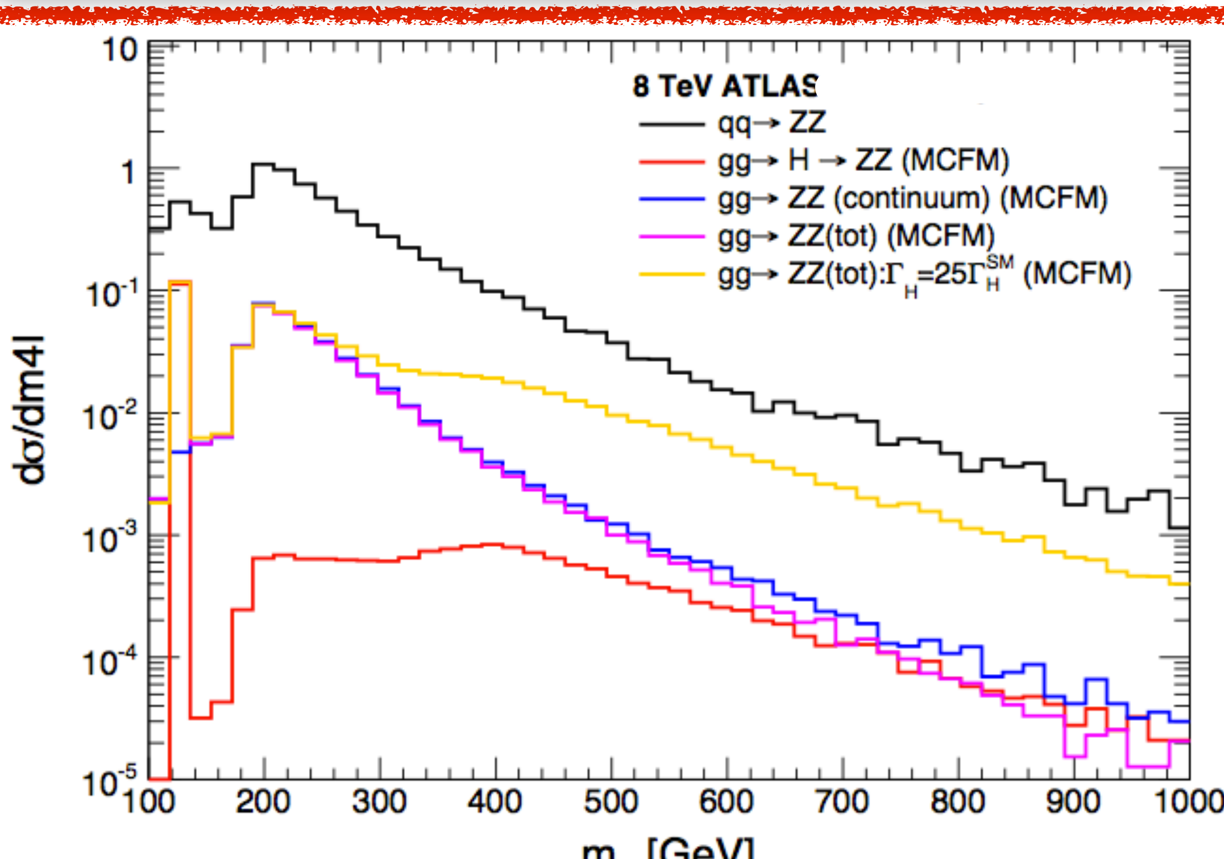
Off-peak Higgs signal strength - The analysis

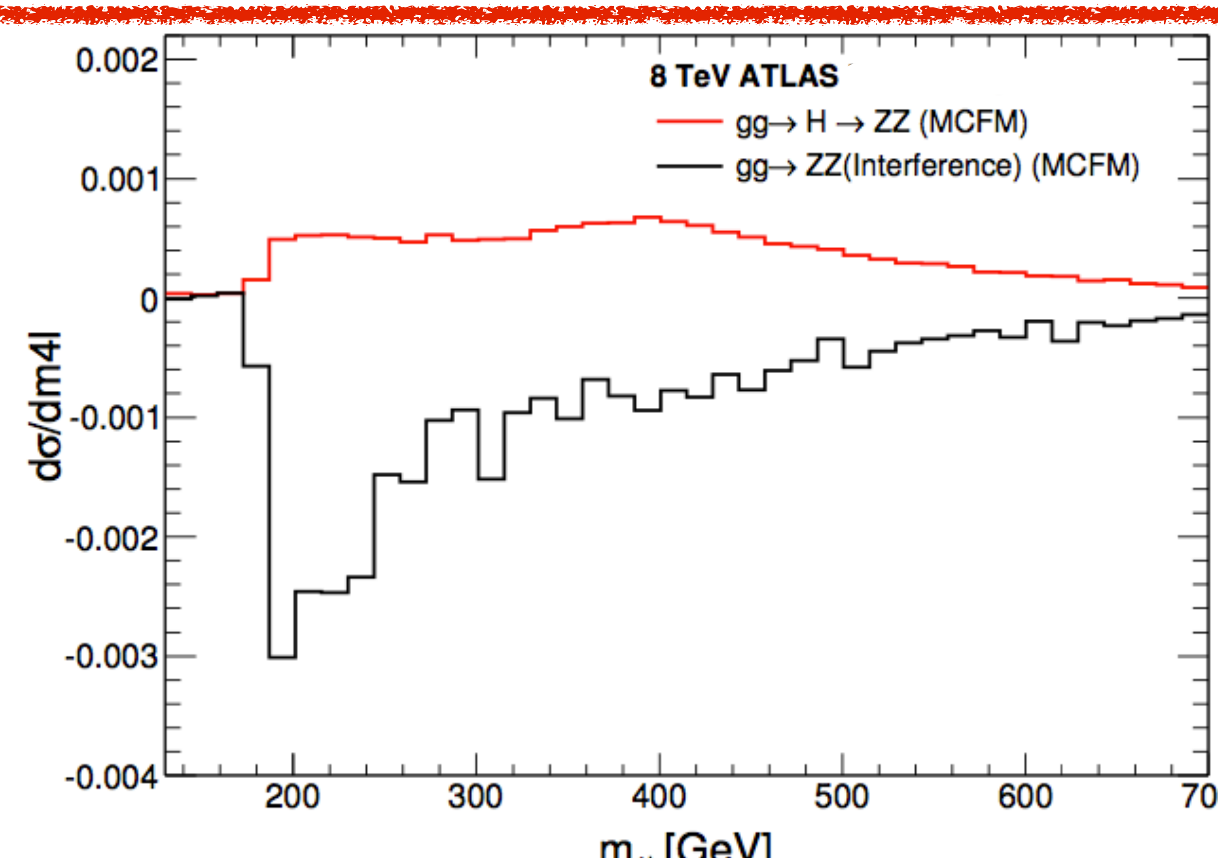
- Signal: gg→H→VV (the VBF production mechanism has been explored as well)
- Backgrounds: gg→VV, qq→VV (dominant contribution)
- Quantum (negative) interference effects between gg→H→ZZ and gg→ZZ





- gg→(H)→VV currently known at LO
- K-factor for the signal process available to match NNLO accuracy (mZZ dependence)
- No k-factors available for the background process, gg→VV

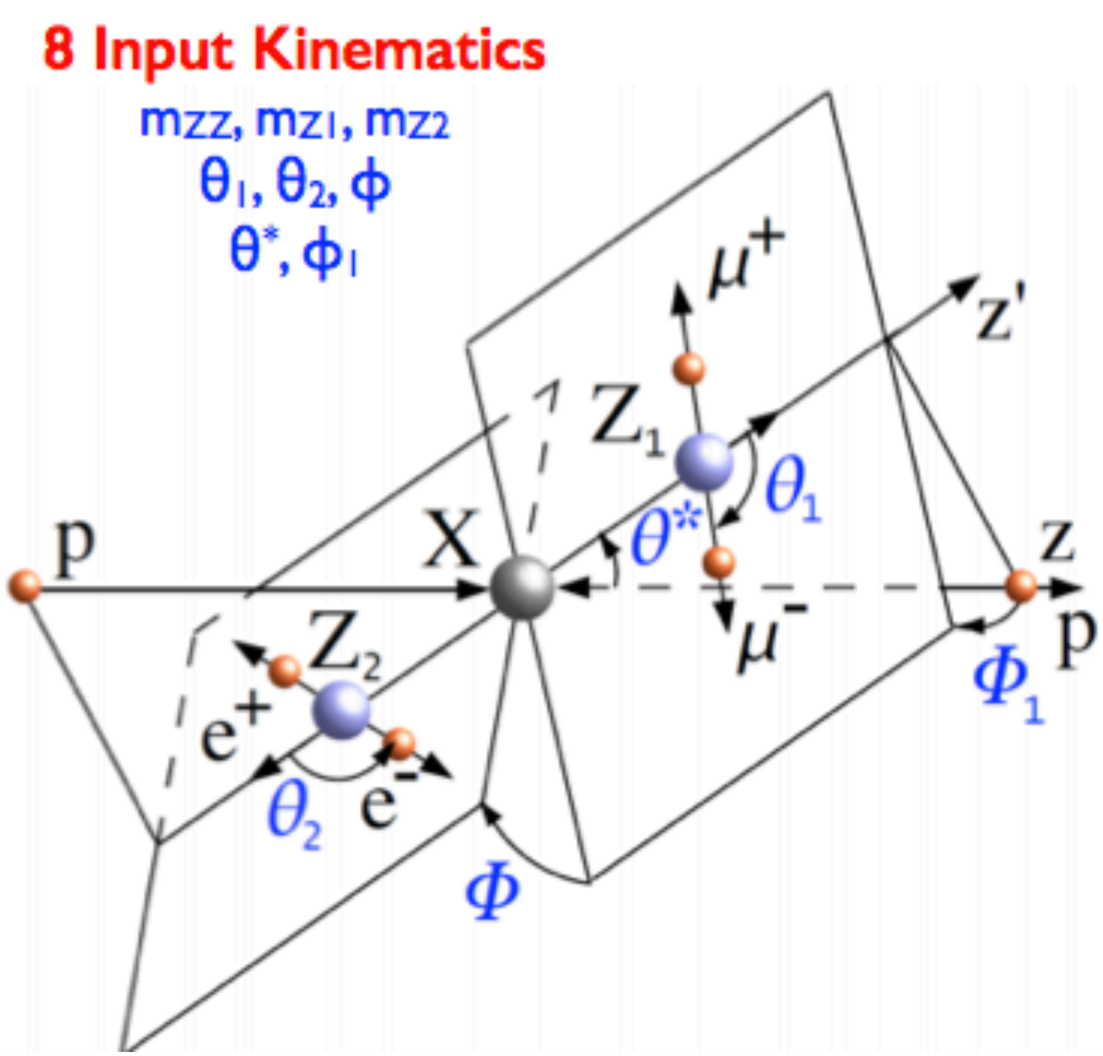


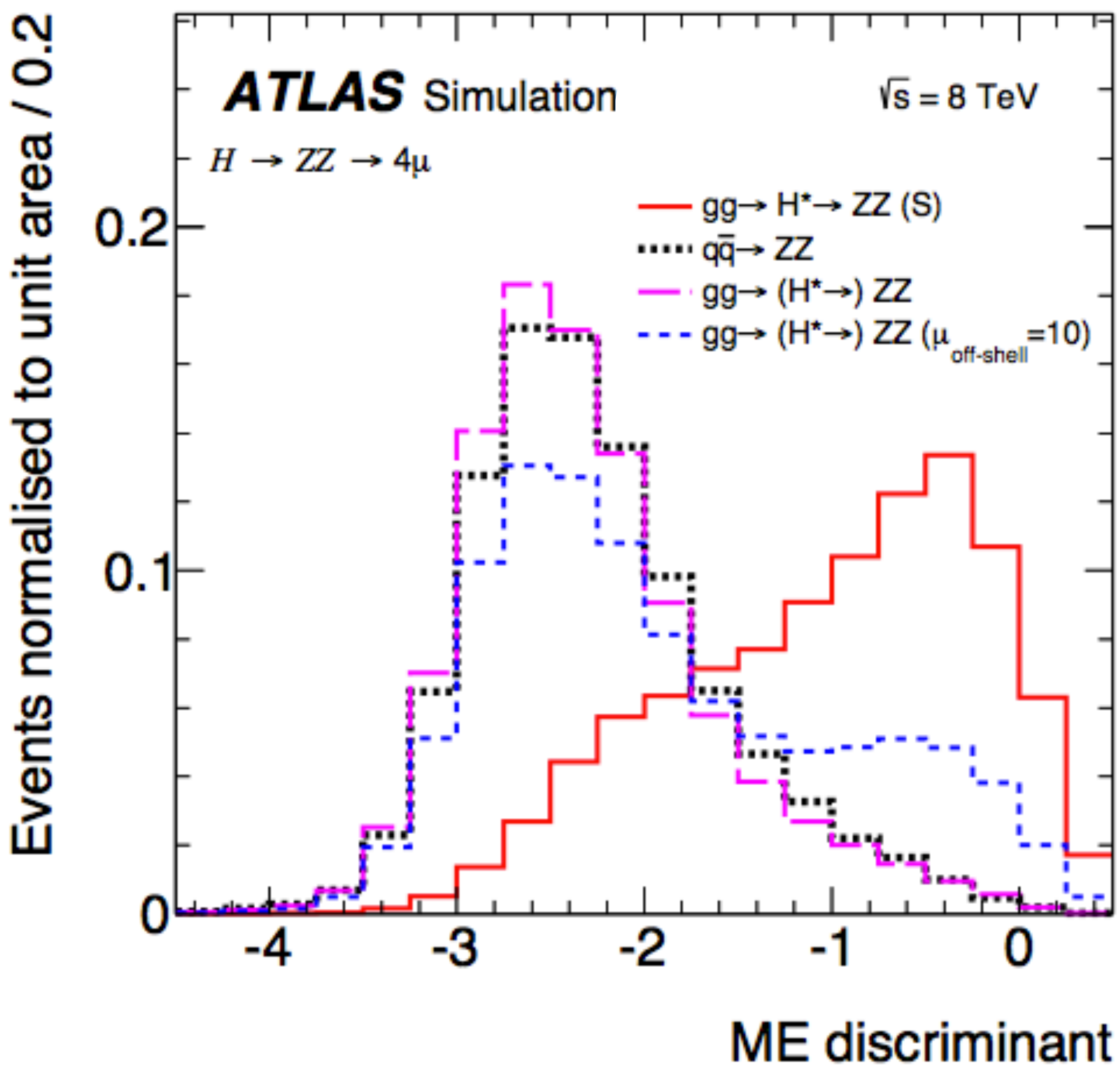


The analysis strategy in the 4l channel

- The analysis is performed in the off-shell ZZ region (m4l>220 GeV) keeping the same low mass kinematic selection

- For a given event, we evaluate $|ME|^2$ for process hypotheses
  - P(H→ZZ), P(gg→ZZ), P(qq→ZZ) and Pint.
  - To be combined to construct a kinematic discriminant against main background qq→ZZ





Shape-based analysis ($ZZ \rightarrow 4l$)

- Calculating the distributions of the various physics processes for an arbitrary value of μ_offshell
- The PDFs of the physics processes are built from MC templates assuming SM Higgs hypothesis (μ_offshell =1) .
  - $|P^{SM}_{gg \rightarrow H \rightarrow ZZ}|$ (gluon-gluon → Higgs →ZZ contribution only)
  - $|P^{cont}_{gg \rightarrow ZZ}|$ (ZZ continuum only)
  - $|P^{SM}_{gg \rightarrow H \rightarrow ZZ} + P^{cont}_{gg \rightarrow ZZ}| = P^{SM}_{gg \rightarrow ZZ}$ (including Higgs, interference and continuum)
  - *defining* $P^{SM}_{interference} = P^{SM}_{gg \rightarrow ZZ} - P^{cont}_{gg \rightarrow ZZ} - P^{SM}_{gg \rightarrow H \rightarrow ZZ}$

$$\mu_{offShell} \neq 1 \Rightarrow P_{gg \rightarrow ZZ}(\mu_{offShell}) = P^{SM}_{gg \rightarrow H \rightarrow ZZ} \cdot \mu\_offshell + P_{Interference} \cdot \sqrt{(\mu\_offshell)} + P^{cont}_{gg \rightarrow ZZ}$$

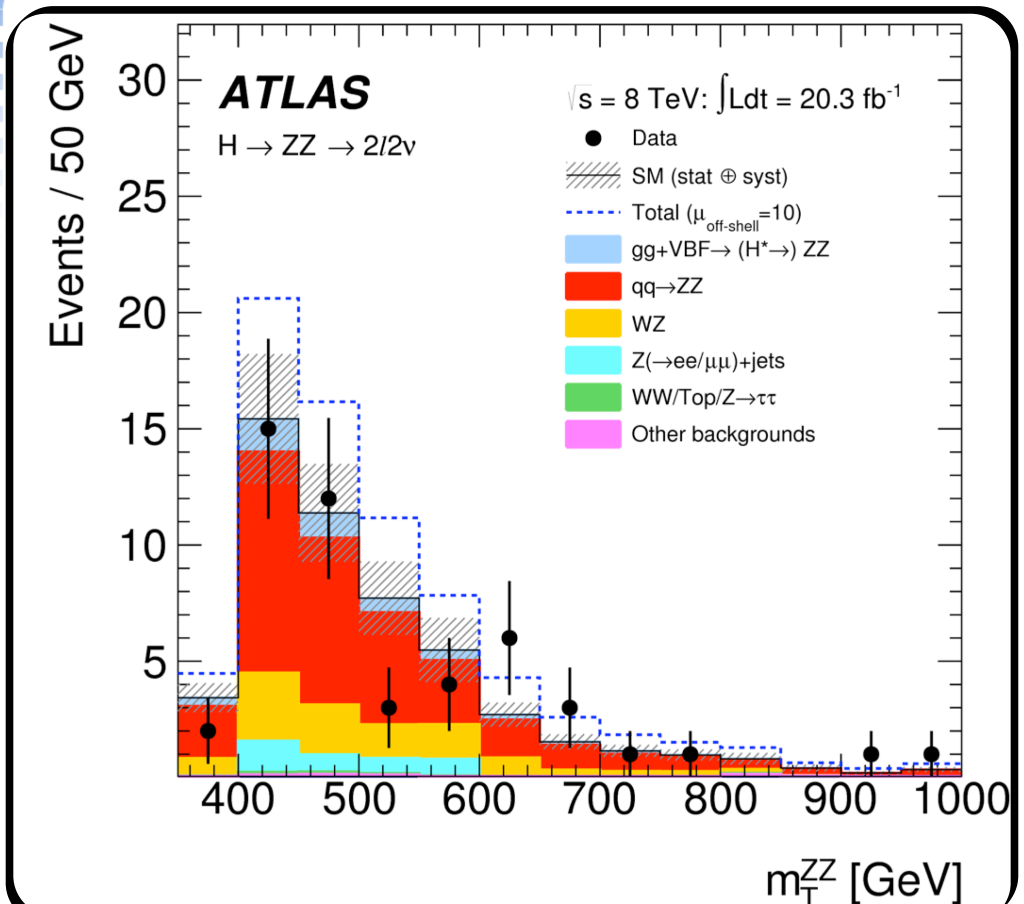
$$P_{gg \rightarrow ZZ}(\mu_{offShell}) = \sqrt{(\mu_{offShell})} \cdot P^{SM}_{gg \rightarrow ZZ} + (\mu_{offShell} - \sqrt{\mu_{offShell}}) \cdot P^{SM}_{gg \rightarrow H \rightarrow ZZ} + (1 - \sqrt{\mu_{offShell}}) \cdot P^{cont}_{gg \rightarrow ZZ}$$

Closure test performed between the MC distributions (generated at $\mu_{OffShell}=10$ and $\mu_{OffShell}=25$) and the PDFs extracted with the formula above

The analysis strategy in the ZZ→2l2ν channel

- 2 oppositely-charged leptons of the same flavour compatible with a Z boson decay + large MET from neutrinos

- Background estimation:
  - WZ: estimated in MC and validated with data in a 3-lepton CR
  - ZZ: extracted from MC
  - WW, tt, Wt, Z→ττ: calculated in data using the flavour simmetry in a eμ control region
  - Z→ee, Z→μμ: computed in data using 2D sidebands (fractional pt difference and ΔΦ cuts are reversed)
  - W+jets, multijet: estimated in data using fake factors methods

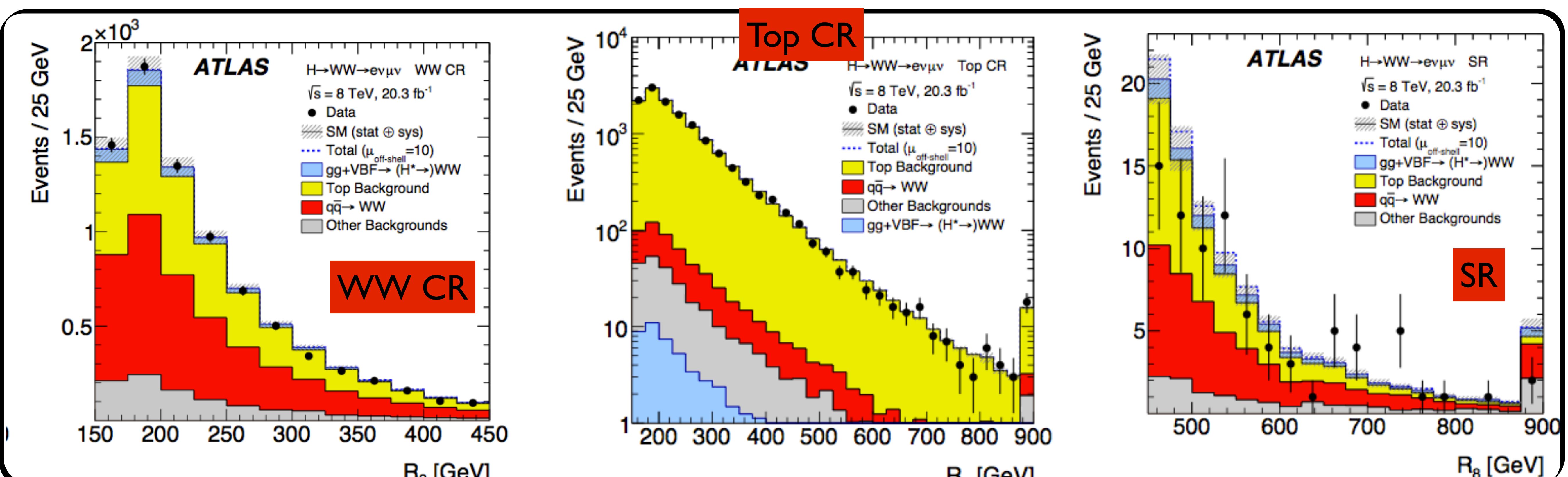


$$m_T^{ZZ} \equiv \sqrt{\left(\sqrt{m_Z^2 + |p_T^{\ell\ell}|^2} + \sqrt{m_Z^2 + |E_T^{\text{miss}}|^2}\right)^2 - |p_T^{\ell\ell} + E_T^{\text{miss}}|^2}$$

- Kinematic selection (off-peak region m_T^{ZZ}>350 GeV)
  - (76<mll<106) GeV, MET>150 GeV
  - Veto on the 3rd lepton to reject WZ, b-jet veto to reject top
  - |pt(Z)-MET|/pt(Z) <0.3, ΔΦ (MET, ptMiss)<0.5 to reject top and Z+jets background

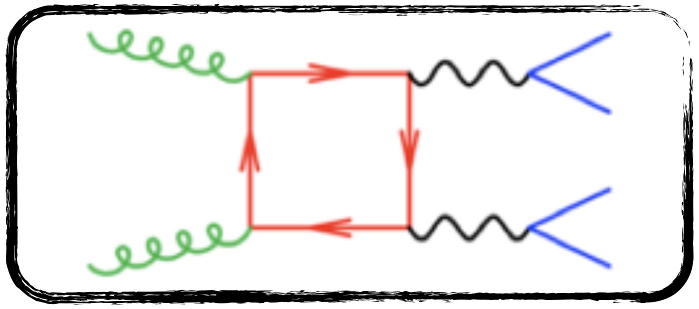
The analysis strategy in the WW→eνμν channel

- Same kinematic selection of the mass paper in the low mass region
  - <u>No explicit jet binning</u>
- In order to isolate the off-shell Higgs signal production in the high mass region, a new variable, R_8, is introduced:
  - $R_8 > \sqrt{m^2_{ll} + (a \cdot m^T_{WW})^2}$ where a=0.8 and $R_8 > 450$ GeV (optimized for the off-shell sensitivity)
- <u>Background components:</u>
  - top quark, and non-resonant qq → WW production are the dominant backgrounds (extracted in data CR)
  - W+jets and multijet production estimated from Monte Carlo simulations



Treatment of the systematic uncertainties

- The largest systematics arise from theoretical uncertainties on gg→H→VV and gg→VV
- The experimental systematics are negligible
- qqVV: PDF and scales variations + EW correction
- Uncertainty on the signal contribution:
  1
  - missing order QCD and EW: k-factor as a function of mVV (20-30% uncertainty)
  - PDF uncertainties for the signal process as a function of mVV (10-20% in the high mass)
- No higher order QCD calculations for the gg-initiated background available
  2
  - Results shown as a function of the ratio of the signal-to-background k-factors. Uncertainty: quadratic difference between the full signal k-factor and the gg-induced signal k-factor



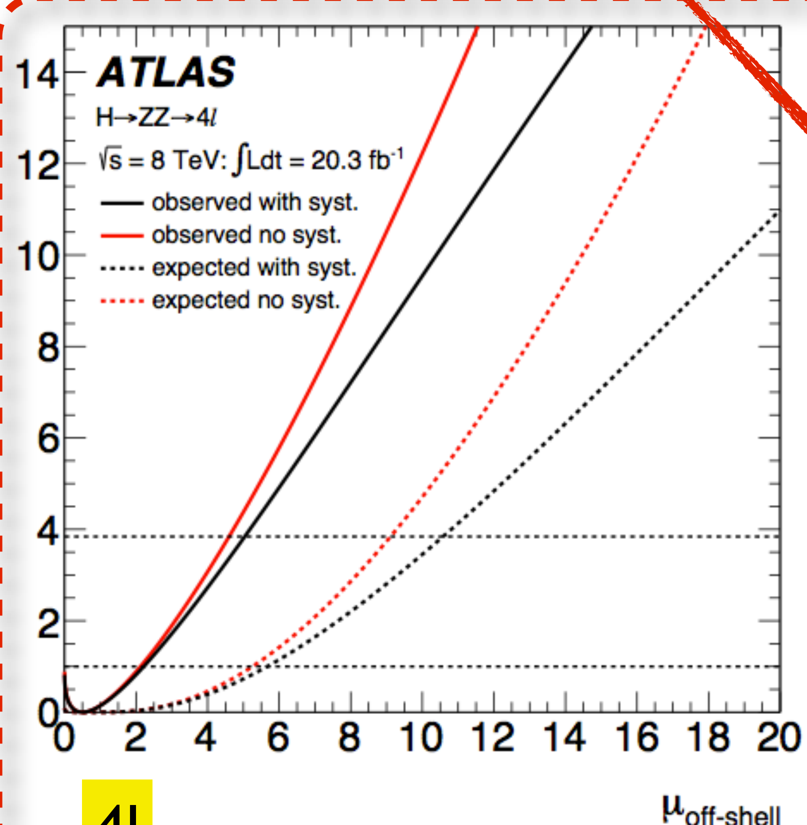
- Uncertainty on the interference term:
  - conservative 30% uncertainty on the terms with the square root
- Sherpa (LO+0-1j)-based ptVV reweighting of gg2VV (pure LO+ Parton Shower, PS)
  3
  - resummation, renormalization and factorisation scales on the gg processes (S, SBI, B) - Larger in value between the scale variations and the pt difference between Sherpa and gg2VV is taken as acceptance sytematics

Results off-shell analysis (4l + 2l2ν + WW→lνlν)

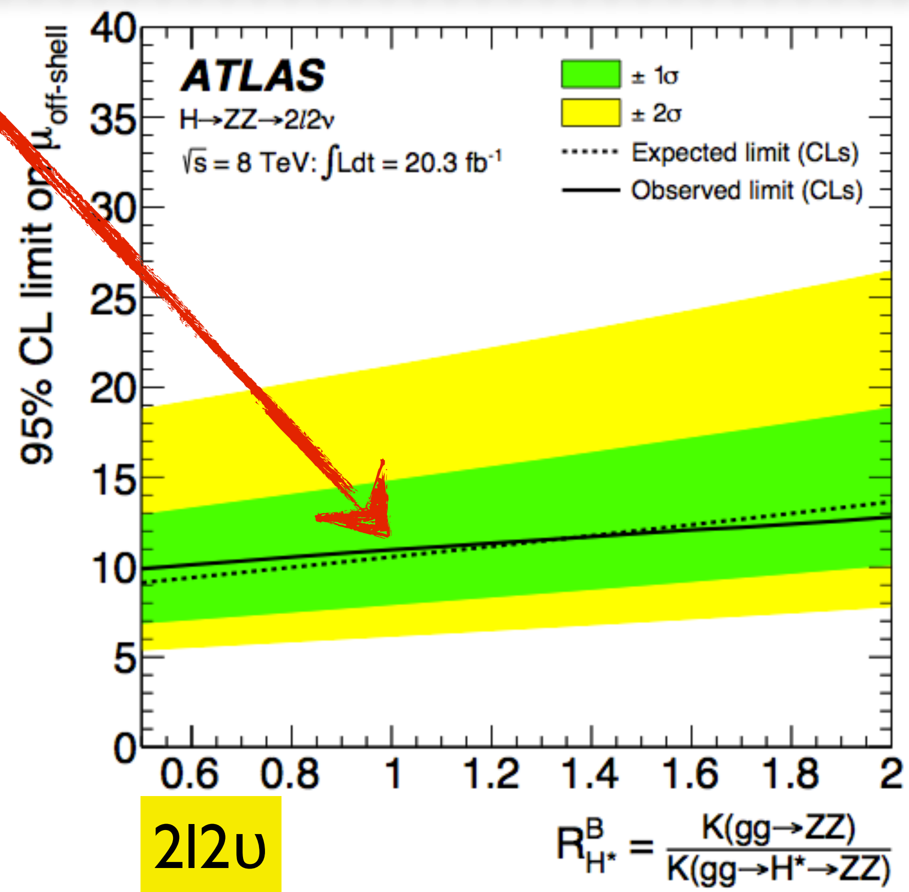
- CLs method to extract 95% CL limit on $\mu_{Offshell}$ (combination of 4l, 2l2ν and WW→lνlν)
  - Results presented as a function of R_B=K(gg→VV)/K(gg→H→VV)
  - The systematic uncertainties are dominated by the QCD scale of gg→VV, qq→VV and gg→H→VV

Soft collinear approximation: signal-to-background k-factor, R_{H*}^B, is 1

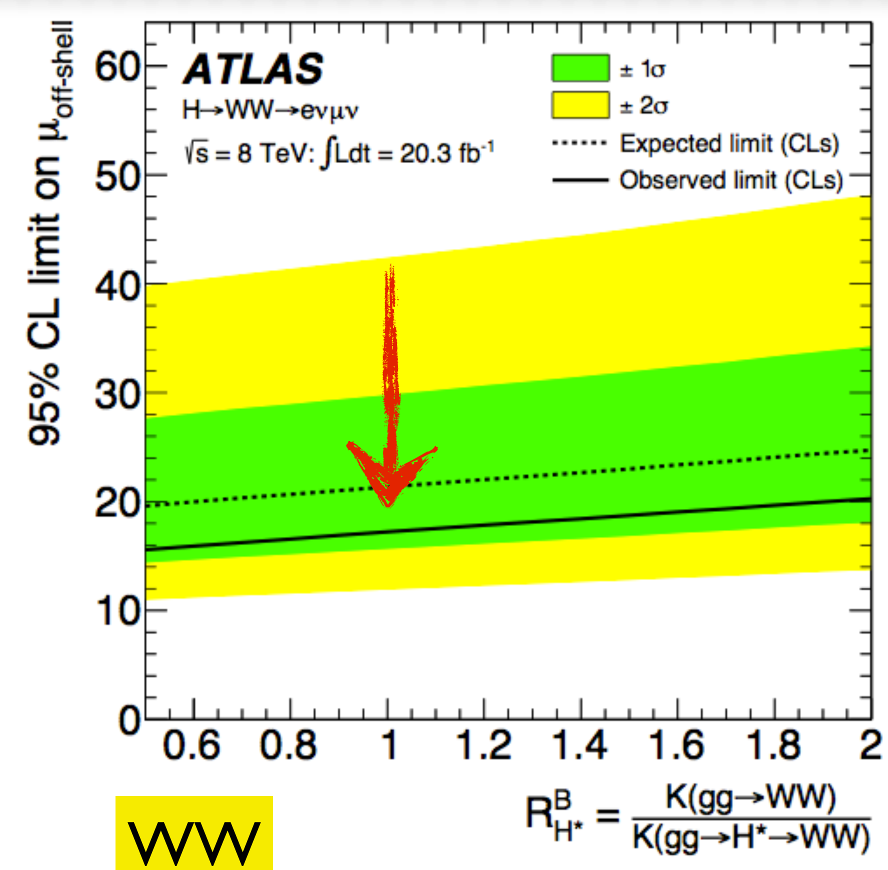
$R^B_{H^*}$	Observed 0.5	Observed 1.0	Observed 2.0	Median expected 0.5	Median expected 1.0	Median expected 2.0
$ZZ \to 4\ell$ analysis	6.1	**7.3**	10.0	9.1	**10.6**	14.8
$ZZ \to 2\ell 2\nu$ analysis	9.9	**11.0**	12.8	9.1	**10.6**	13.6
$WW \to e\nu\mu\nu$ analysis	15.6	**17.2**	20.3	19.6	**21.3**	24.7



4l



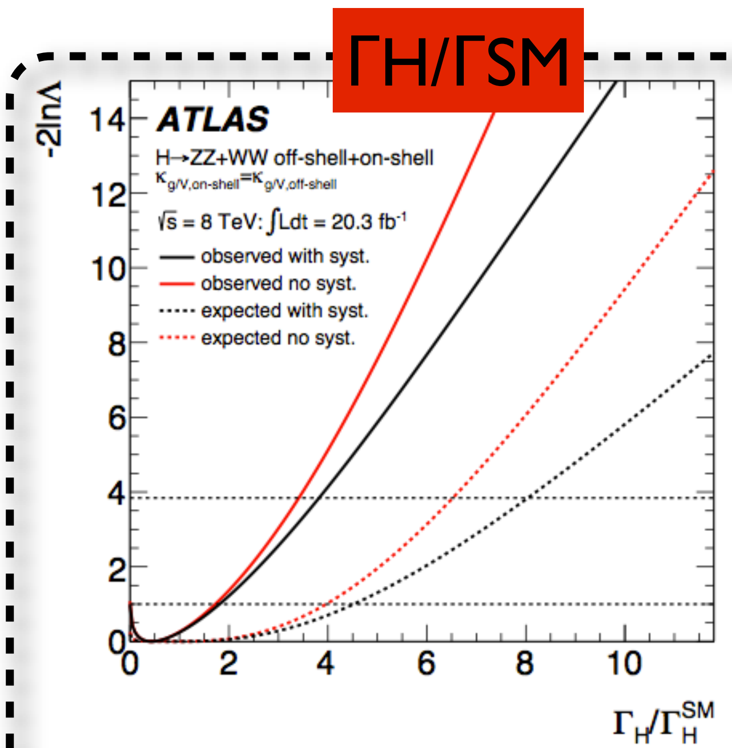
2l2υ

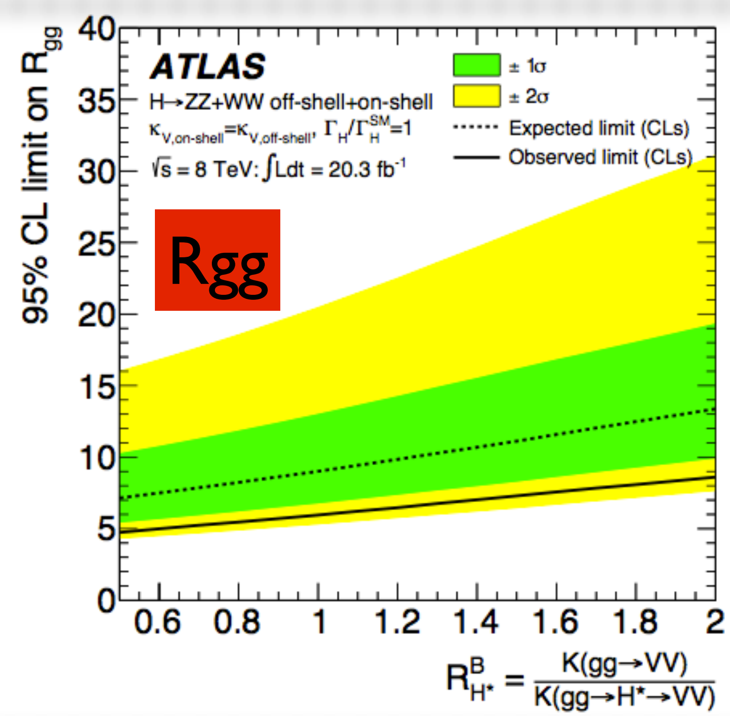


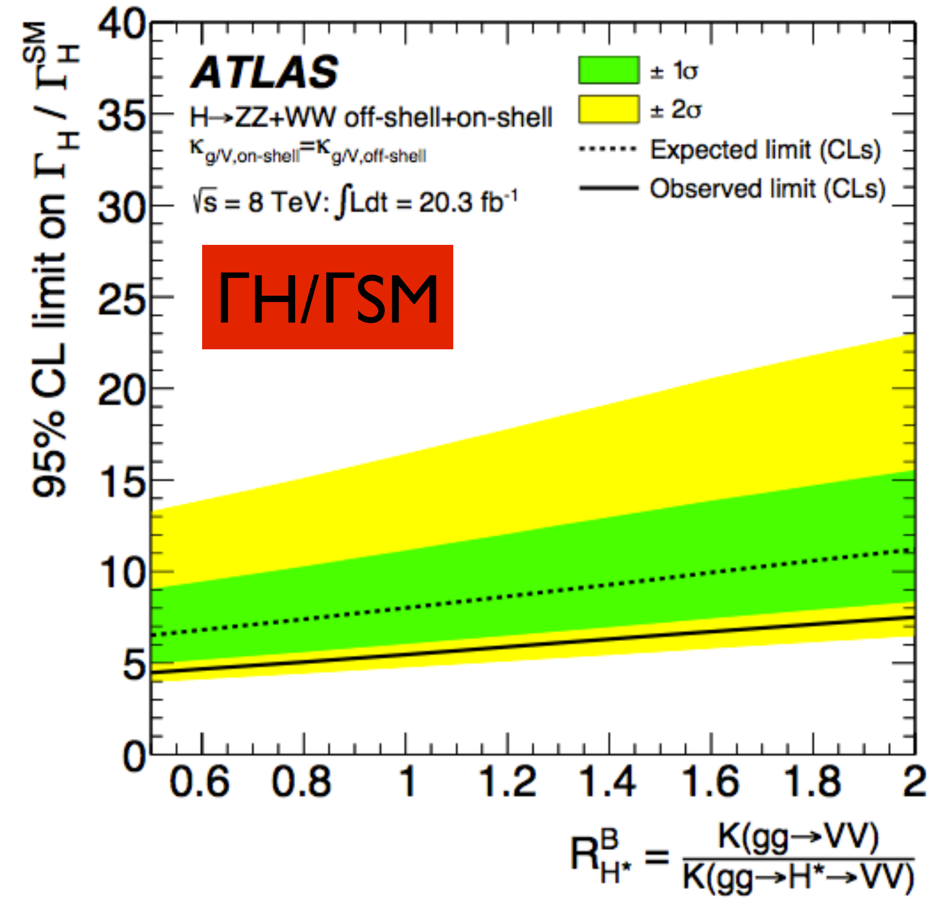
WW

Limits on the total Higgs boson width

- Combination of the off-shell analyses with the on-shell → limit on Γ_H/Γ_{SM}
    - determination of Γ_H/Γ_{SM} assuming identical on and off-shell couplings (no dependency on Γ_H in the off-shell cross section)
    - extraction of $R_{gg}=\mu_{ggF}$(off-shell)/μ_{ggF}(on-shell) - sensitive to possible modification of the gluon couplings in the high mass range - assuming $\Gamma_H/\Gamma_{SM}=1$







Combining the 4l, 2l2ν and the WW channels, a limit is observed (expected) on the total width - $\Gamma_H/\Gamma_{SM}<5.5$ (8.0)

	Observed			Median expected		
$R^B_{H^*}$	0.5	**1.0**	2.0	0.5	**1.0**	2.0
Γ_H/Γ_H^{SM}	4.5	**5.5**	7.5	6.5	**8.0**	11.2
$R_{gg}=\kappa^2_{g,\text{off-shell}}/\kappa^2_{g,\text{on-shell}}$	4.7	**6.0**	8.6	7.1	**9.0**	13.4

Wrapping-up and conclusions

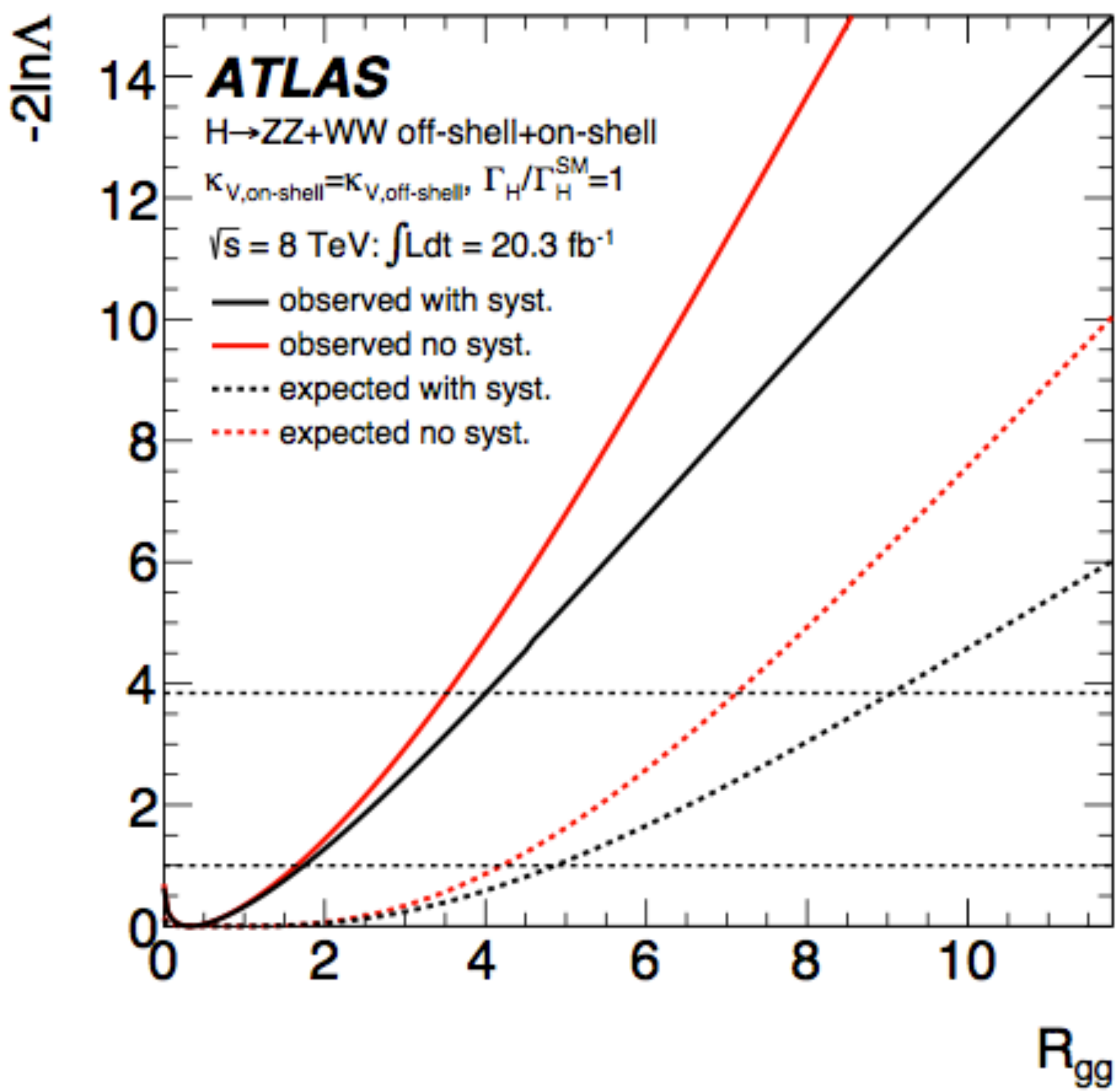
- Determination of the off-shell signal strength in the high mass ZZ and WW performed by ATLAS and CMS
- Combination with the on-shell signal strength results in a limit on the Higgs width
- ATLAS presents results as a function of the ratio of background-to-signal k-factor as no NLO QCD calculation is available for gg → VV,

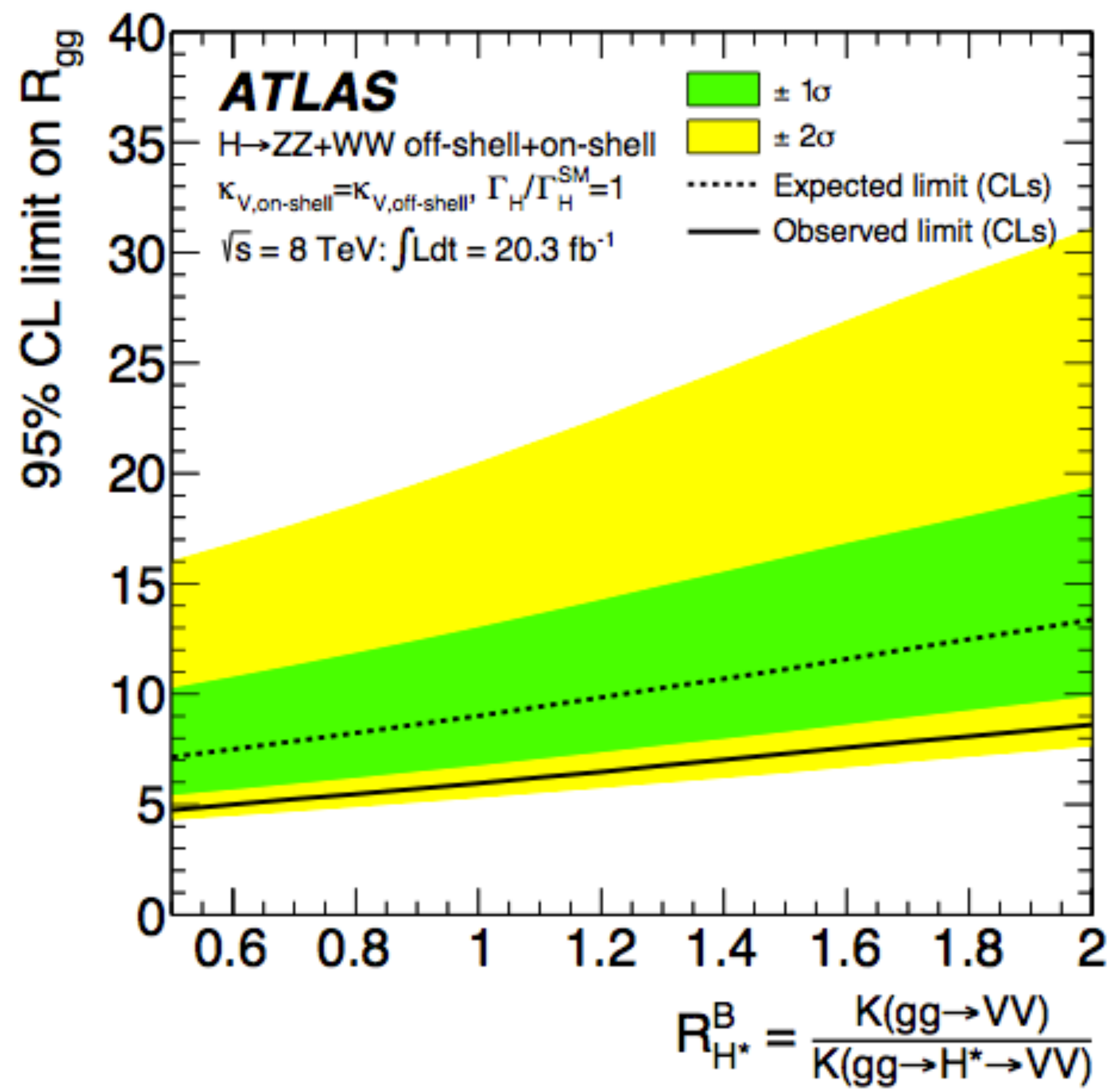
- Assuming identical coupling strength for on and off-shell:
  - interpreting this off-shell limit as a constraint on the total Higgs width when combining with the on-shell measurement
- Assuming identical k-factors for signal and background:
  - expected (observed) limit on $\Gamma_H/\Gamma_{SM}<5.4$ (8.0)
    - Observed upper limits on the Higgs boson width $\Gamma_H<22$ MeV at 95 % CL ($\Gamma_H=4.2$ MeV)

- This result (under the hypothesis of constant HVV couplings) improves by more than two order of magnitude previous experimental constraints on the Higgs boson decay width from the direct measurement of the resonance peak

Additional Slides

Fit on Rgg

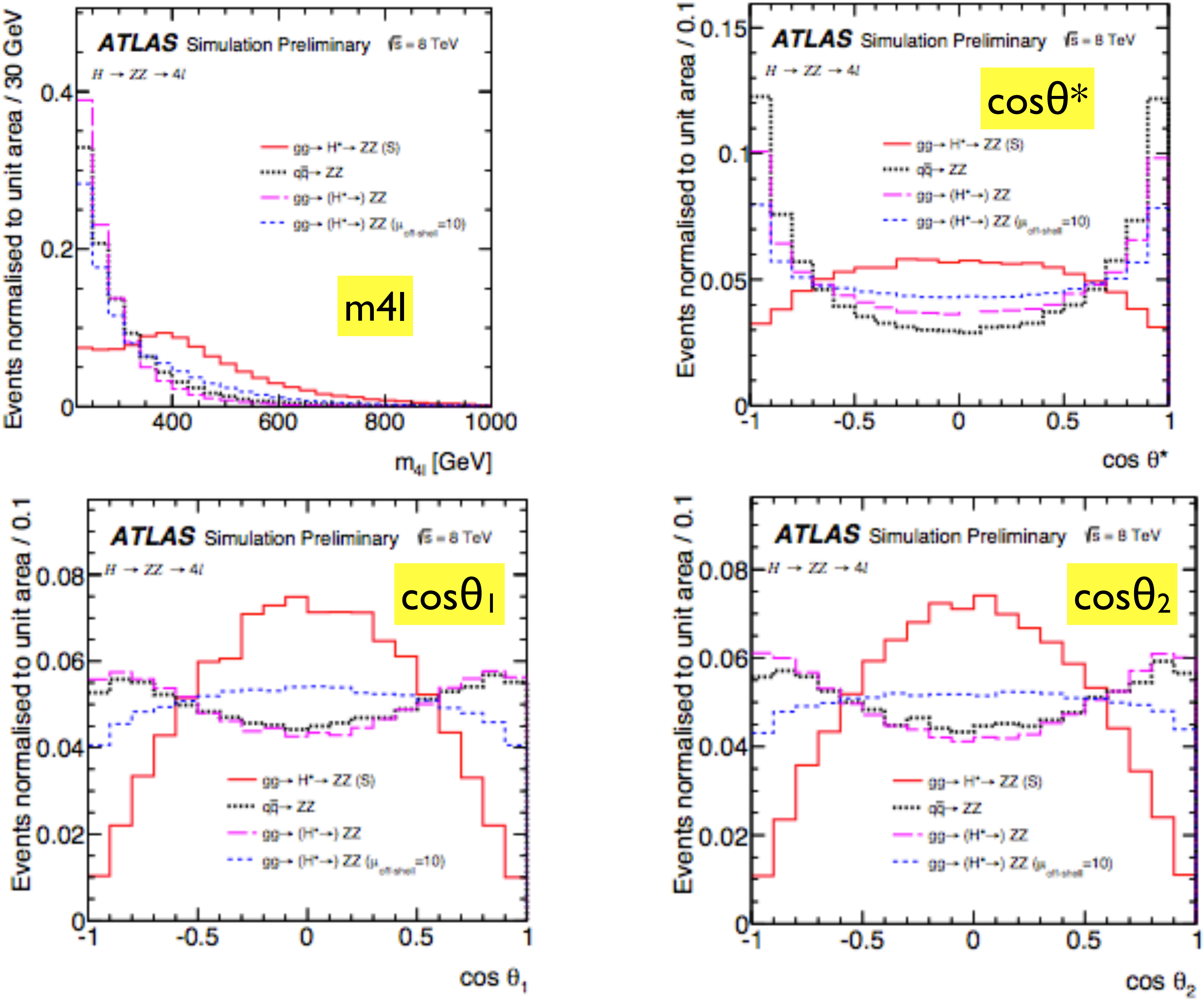

ATLAS
H→ZZ+WW off-shell+on-shell
κV,on-shell=κV,off-shell, ΓH/ΓH SM=1
√s = 8 TeV: ∫Ldt = 20.3 fb-1
observed with syst.
observed no syst.
expected with syst.
expected no syst.
-2lnΛ
Rgg


ATLAS
H→ZZ+WW off-shell+on-shell
κV,on-shell=κV,off-shell, ΓH/ΓH SM=1
√s = 8 TeV: ∫Ldt = 20.3 fb-1
± 1σ
± 2σ
Expected limit (CLs)
Observed limit (CLs)
95% CL limit on Rgg
R B H* = K(gg→VV) / K(gg→H*→VV)

Cut-based analysis as a cross-check (4l)

Process	220 GeV < $m_{4\ell}$ < 1000 GeV	400 GeV < $m_{4\ell}$ < 1000 GeV
$gg \to H^* \to ZZ$ (S)	2.2 ± 0.5	1.1 ± 0.3
$gg \to ZZ$ (B)	30.7 ± 7.0	2.7 ± 0.7
$gg \to (H^* \to)ZZ$	29.2 ± 6.7	2.3 ± 0.6
$gg \to (H^* \to)ZZ$ ($\mu_{\text{off-shell}} = 10$)	40.2 ± 9.2	9.0 ± 2.5
VBF $H^* \to ZZ$ (S)	0.2 ± 0.0	0.1 ± 0.0
VBF ZZ (B)	2.2 ± 0.1	0.7 ± 0.0
VBF $(H^* \to)ZZ$	2.0 ± 0.1	0.6 ± 0.0
VBF $(H^* \to)ZZ$ ($\mu_{\text{off-shell}} = 10$)	3.0 ± 0.2	1.4 ± 0.1
$q\bar{q} \to ZZ$	168 ± 13	21.3 ± 2.1
Reducible backgrounds	1.4 ± 0.1	0.1 ± 0.0
Total Expected (SM)	200 ± 15	24.3 ± 2.2
Observed	182	18

Key input variables to the ME discriminant (ZZ→4l)



Breakdown of the systematic uncertainties

4l

Source of systematic uncertainties	95% CL on $\mu_{\text{off-shell}}$
QCD scale for $gg \to ZZ$	9.5
QCD scale for the $gg \to (H^* \to)ZZ$ interference	9.2
QCD scale for $q\bar{q} \to ZZ$	8.8
PDF for $pp \to ZZ$	8.7
EW for $q\bar{q} \to ZZ$	8.7
Luminosity	8.8
electron efficiency	8.7
μ efficiency	8.7
All systematic	10.2
No systematic	8.7

Breakdown of the systematic uncertainties

llvv

Source of systematic uncertainties	95% CL on $\mu_{\text{off-shell}}$
QCD scale for $gg \to ZZ$	7.9
QCD scale for the $gg \to (H^* \to)ZZ$ interference	7.7
QCD scale for $q\bar{q} \to ZZ$	7.6
PDF for $pp \to ZZ$	7.2
EW for $q\bar{q} \to ZZ$	7.1
Parton showering	7.1
Z BG systematic	7.4
Luminosity	7.3
Electron energy scale	7.1
Electron ID efficiency	7.1
Muon reconstruction efficiency	7.1
Jet energy scale	7.1
Sum of remaining systematic uncertainties	7.1
All systematic	9.9
No systematic	7.1

Breakdown of the systematic uncertainties

4L +llvv

Source of systematic uncertainties	95% CL on $\mu_{\text{off-shell}}$
QCD scale for $gg \to ZZ$	6.7
QCD scale for the $gg \to (H^* \to)ZZ$ interference	6.7
QCD scale for $q\bar{q} \to ZZ$	6.4
Z BG systematic	6.2
Luminosity	6.2
PDF for $pp \to ZZ$	6.1
Sum of remaining systematic uncertainties	6.2
No systematic	6.0
All systematic	7.9

K-factor (LO to NNLO) for the signal