Off-shell Higgs signal strength measurement in ATLAS

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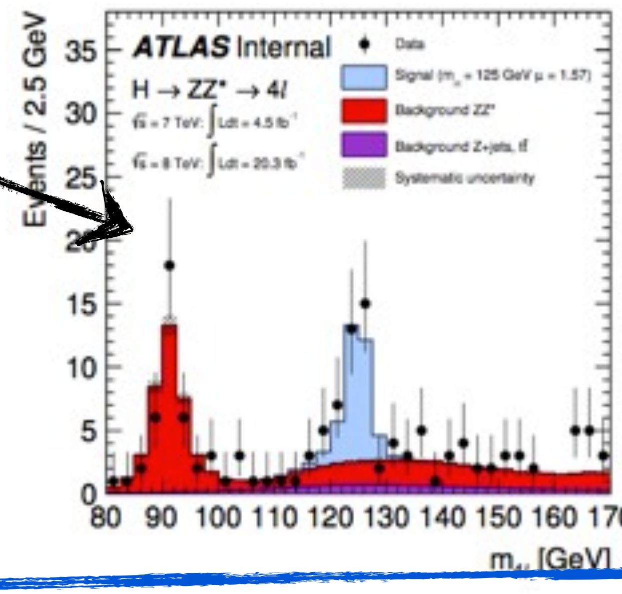
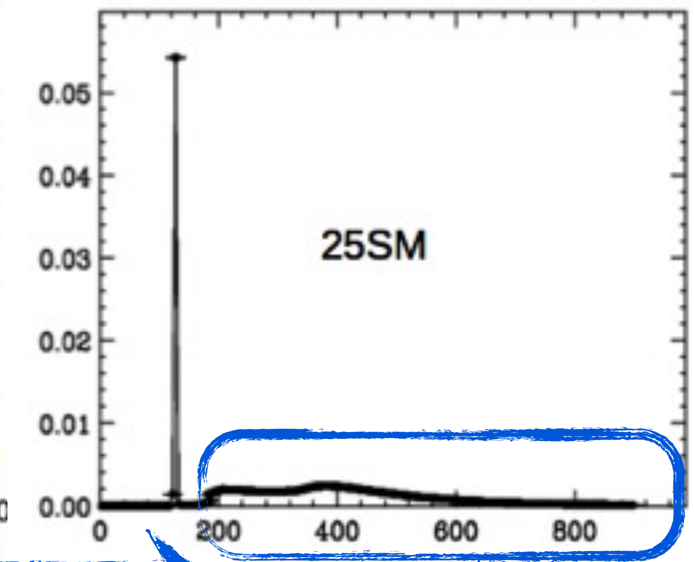
Off-peak Higgs signal strength

- 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:
  - $\sigma_{on\text{-}peak} \sim g^2_{ggH}\, g^2_{HZZ} / \Gamma^2_H$
- In the off-shell regions (where the Higgs acts as a propagator), the cross section is:
  - $\sigma_{off\text{-}peak} \sim g^2_{ggH}\, g^2_{HZZ}$ (the cross-section is independent of the total Higgs width)

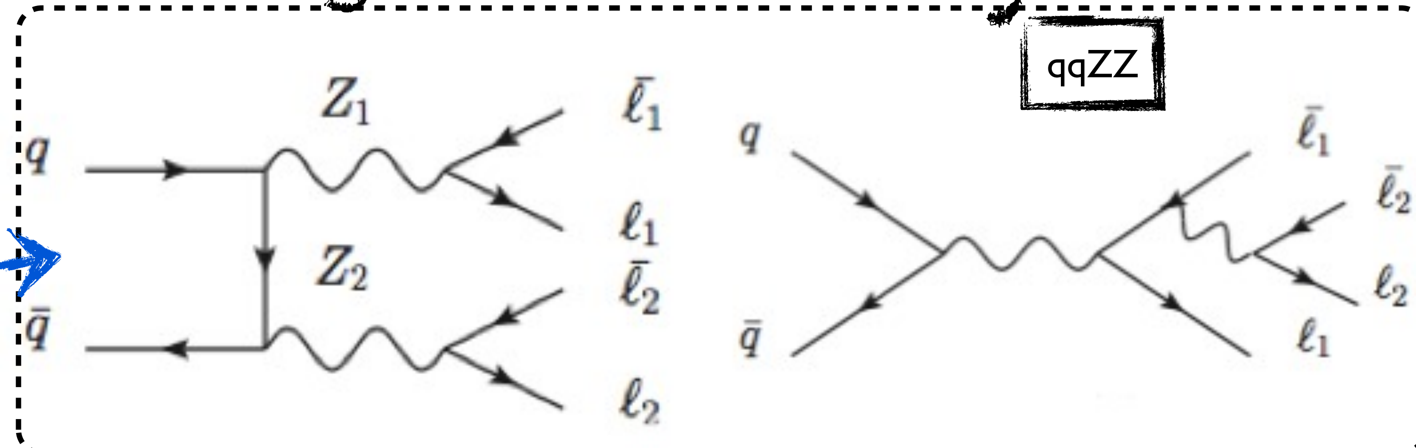
- The ratio of off-shell and on-shell production cross sections will lead to a direct measurement of the μ_offShell and consequently the Higgs width, as long as the product of the coupling to initial and final states remains constant

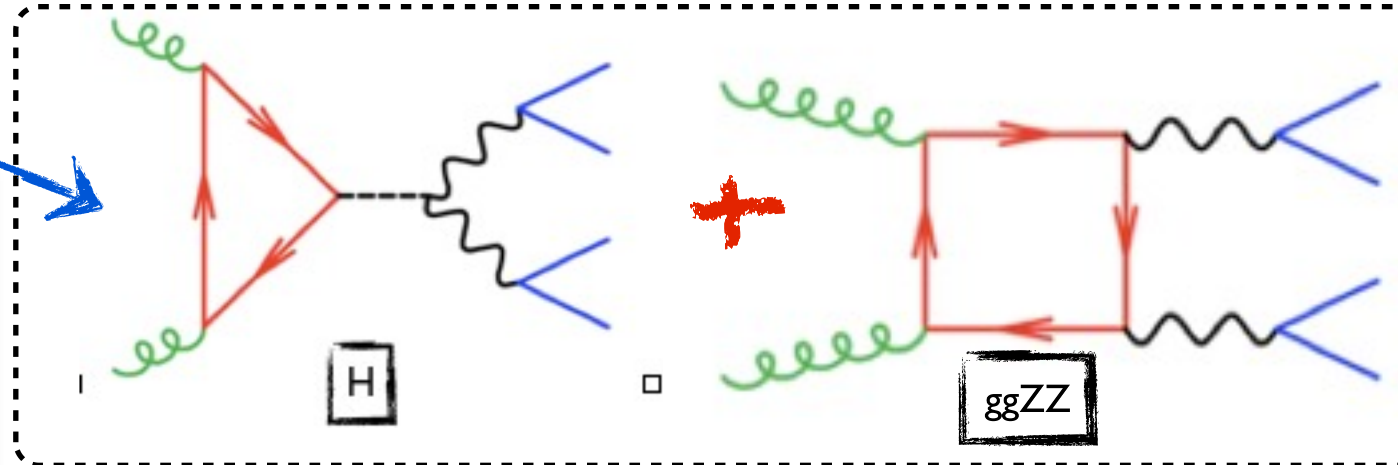
↓

- 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

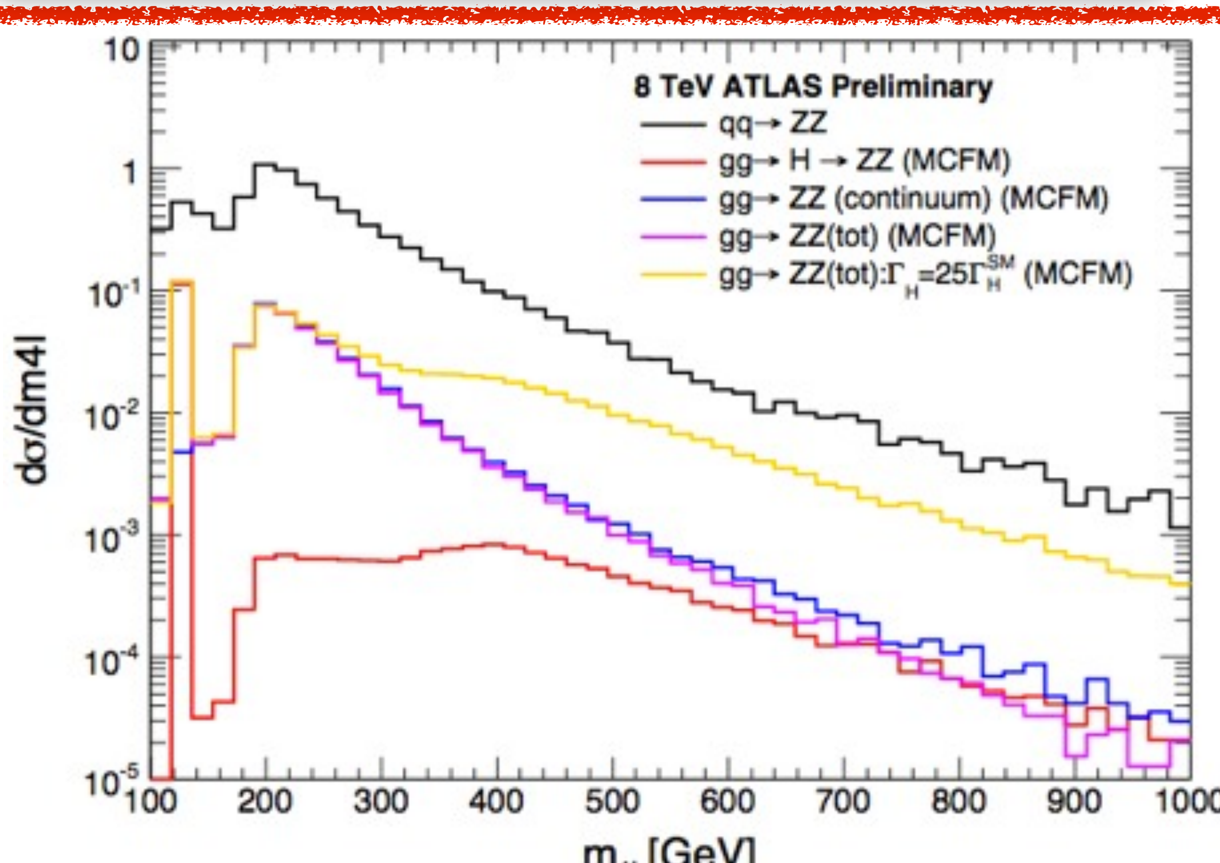
Off-peak Higgs signal strength - The analysis

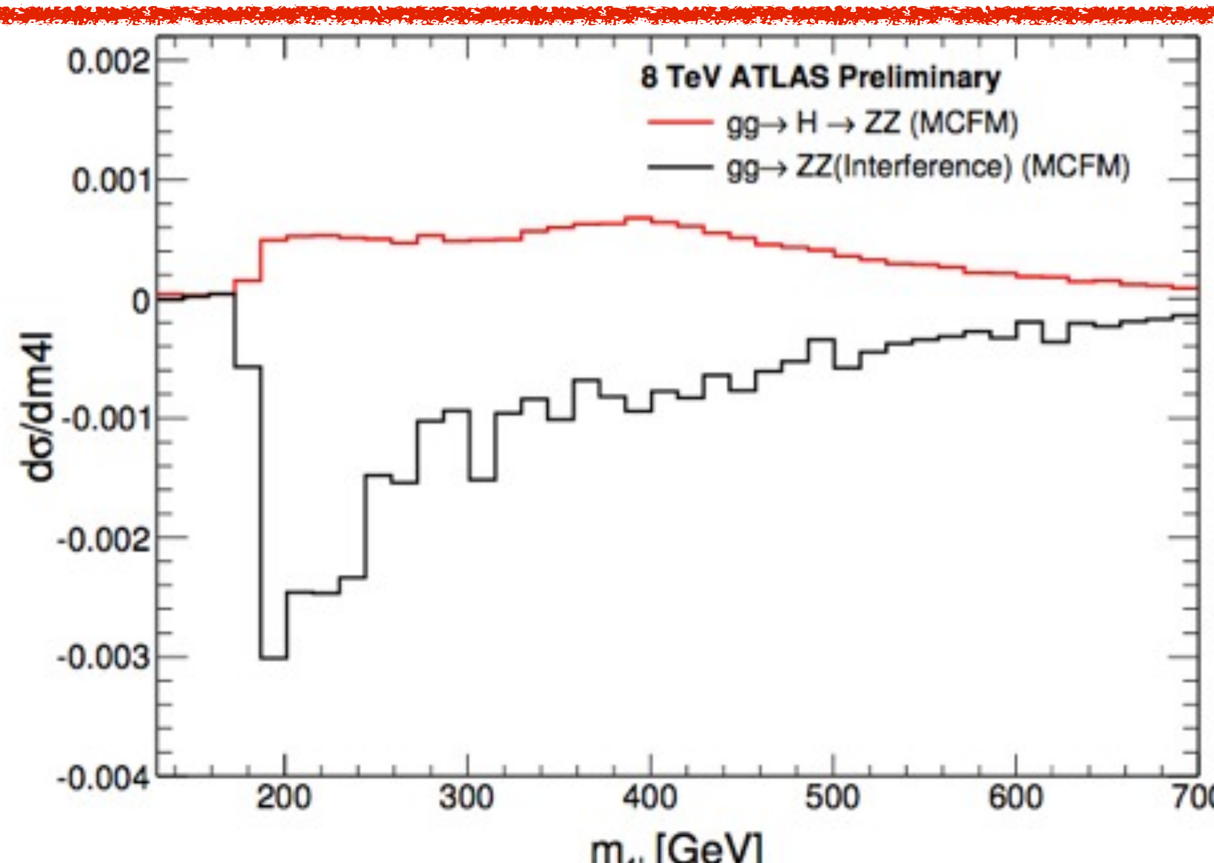
- Signal: gg→H→ZZ (the VBF production mechanism has been explored as well)
- Backgrounds: gg→ZZ, qq→ZZ (dominant contribution)
- Quantum (negative) interference effects between the same-initial-state diagrams gg→H→ZZ and gg→ZZ





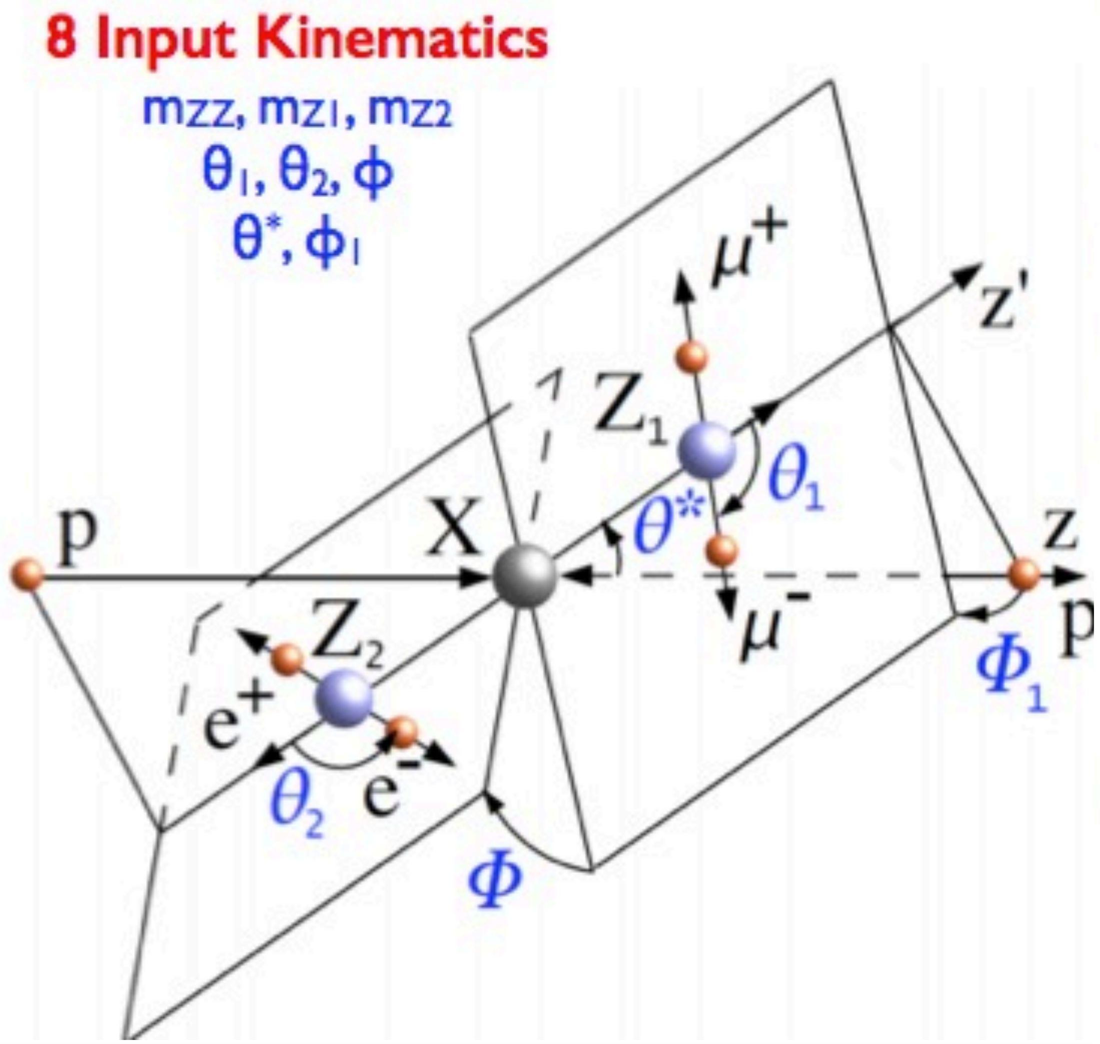
- Large theory uncertainties:
  - gg→(H)→ZZ currently known at LO
  - results given for K(gg→ZZ)/K(gg→H→ZZ) between 0.5 and 2 (the same in the soft collinear approximation)

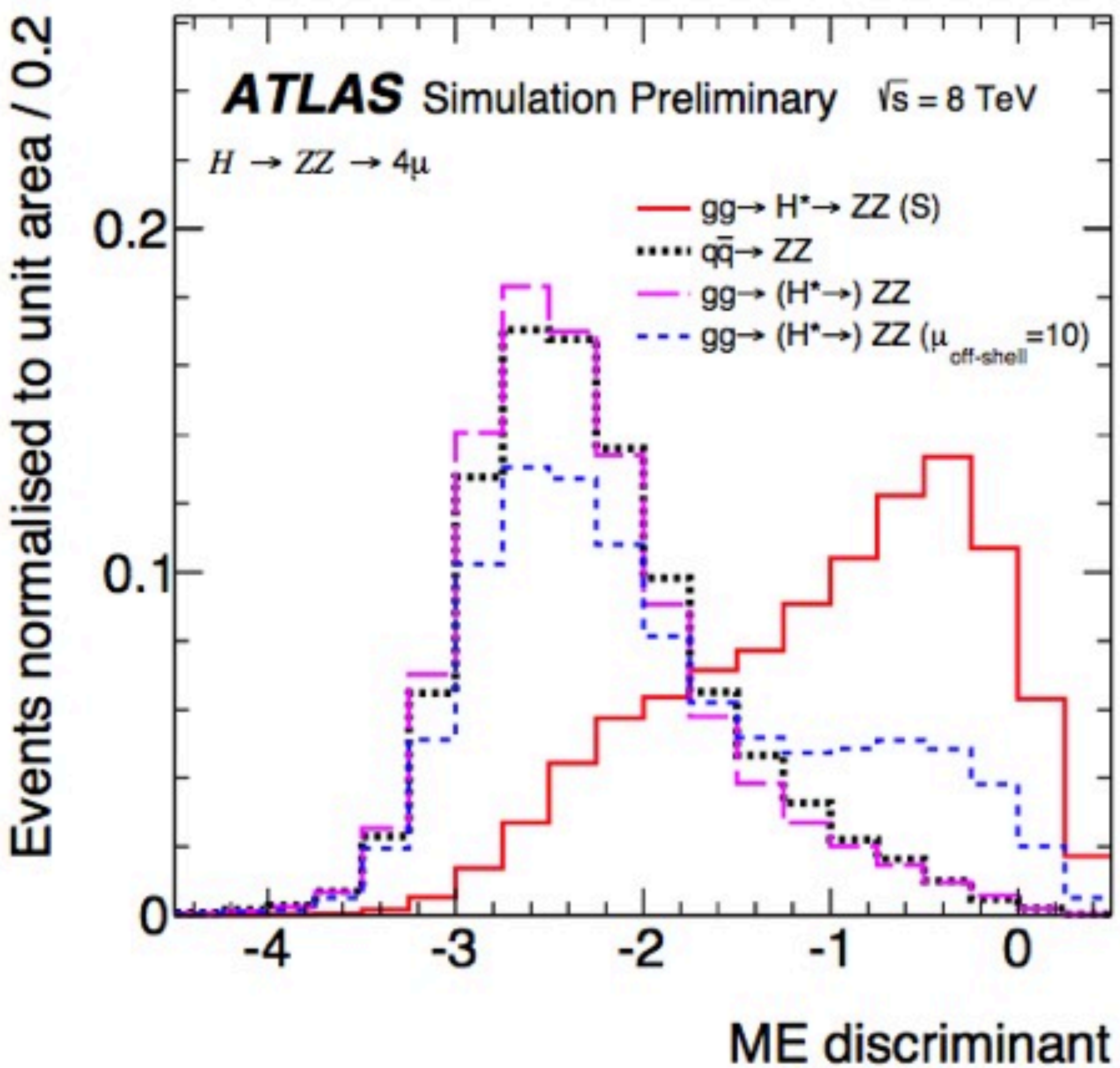




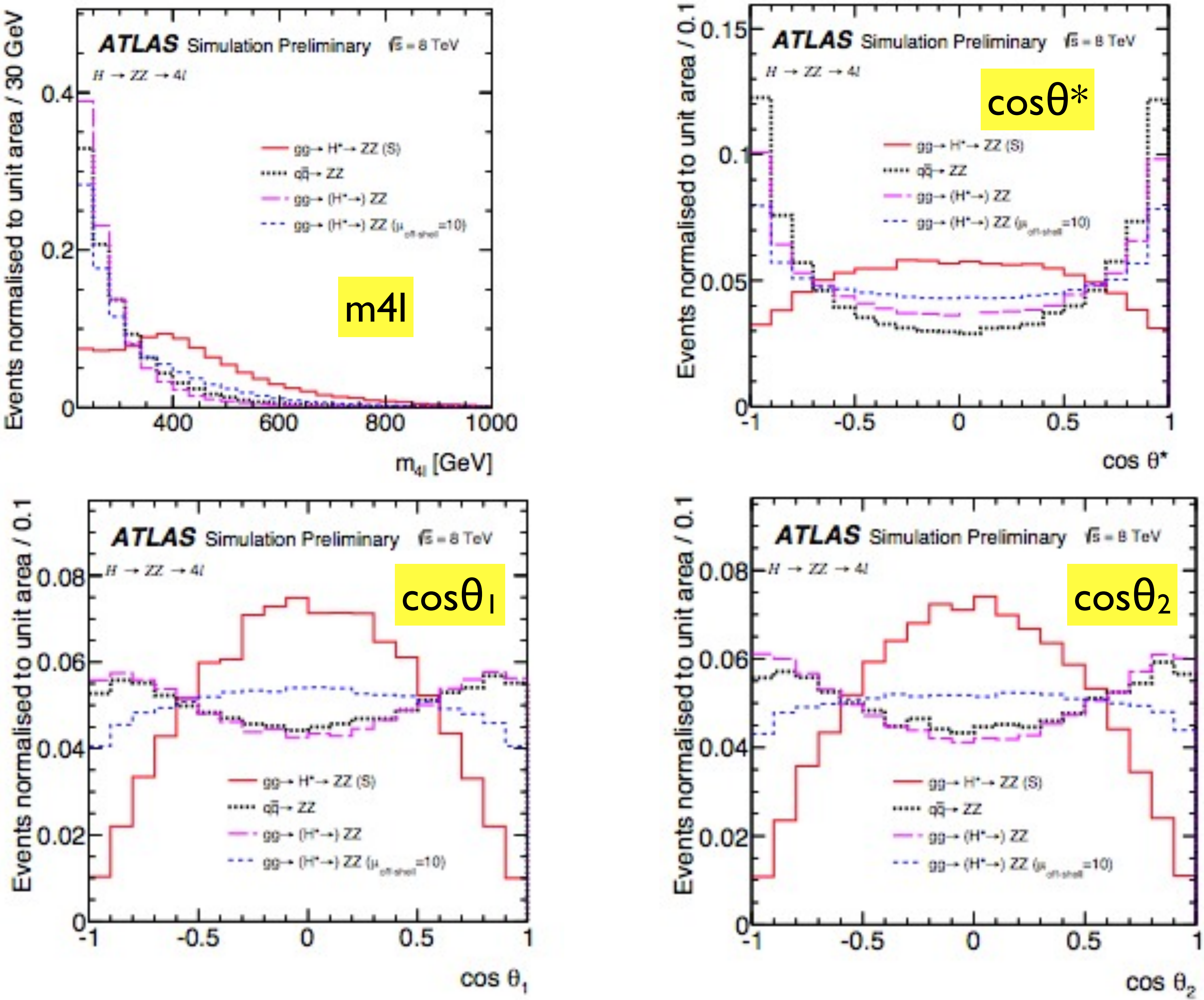
The analysis strategy (4l)

- The analysis is performed in the off-shell ZZ region (m4l>220 GeV) keeping the same low mass kinematic selection
- We try to reject the qqZZ background using simple (cut-based) or shape-based methods (Matrix Element)
- For a given event, we evaluate $|ME|^2$ for process hypotheses
  - $P(H\rightarrow ZZ)$, $P(gg\rightarrow ZZ)$, $P(qq\rightarrow ZZ)$ and Pint.
  - To be combined to construct a kinematic discriminant against main background qqZZ





Key input variables to the ME discriminant (4l)



Shape-based analysis (4l)

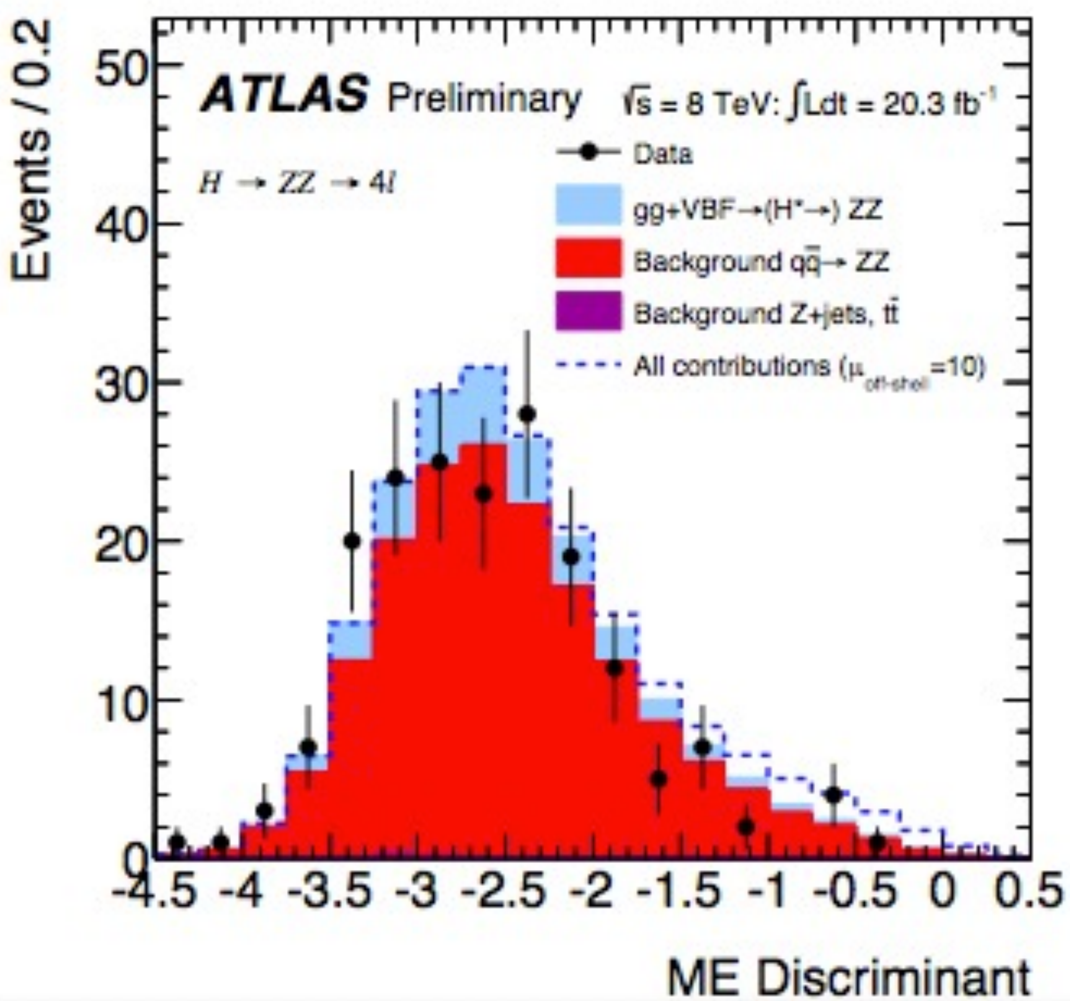
- Unbinned maximum likelihood fit to extract the constraint on the off-shell Higgs couplings and the total width

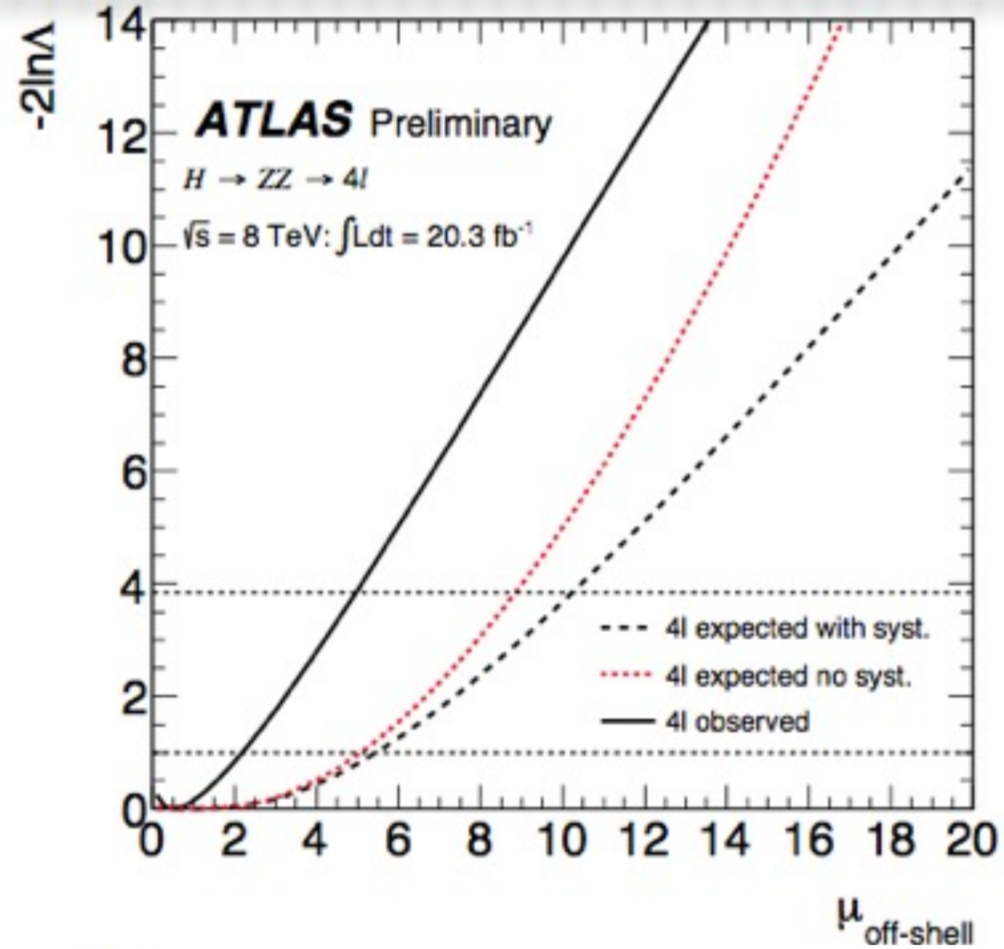
- The PDFs are built from MC templates assuming SM Higgs hypothesis (μ_offshell =1) .
  - $|P^{SM}_{gg\to H\to ZZ}|$ (gluon-gluon → Higgs →ZZ contribution only)
  - $|P^{cont}_{gg\to ZZ}|$ (ZZ continuum only)
  - $|P^{SM}_{gg\to H\to ZZ} + P^{cont}_{gg\to ZZ}| = P^{SM}_{gg\to ZZ}$ (including Higgs, interference and continuum)
  - *defining* $P^{SM}_{interference} = P^{SM}_{gg\to ZZ} - P^{cont}_{gg\to ZZ} - P^{SM}_{gg\to H\to ZZ}$
  - for $\mu_{offShell} \neq 1 \Rightarrow P_{gg\to ZZ}(\mu_{offShell}) = P^{SM}_{gg\to H\to ZZ} \cdot \mu\_offshell + P_{Interference} \cdot \sqrt{(\mu\_offshell)} + P^{cont}_{gg\to ZZ}$
  - $P_{gg\to ZZ}(\mu_{offShell}, x) = \sqrt{(\mu_{offShell})} \cdot P^{SM}_{gg\to ZZ}(x) + (\mu_{offShell} - \sqrt{\mu_{offShell}}) \cdot P^{SM}_{gg\to H\to ZZ}(x) + (1-\sqrt{\mu_{offShell}}) \cdot P^{cont}_{gg\to ZZ}(x)$

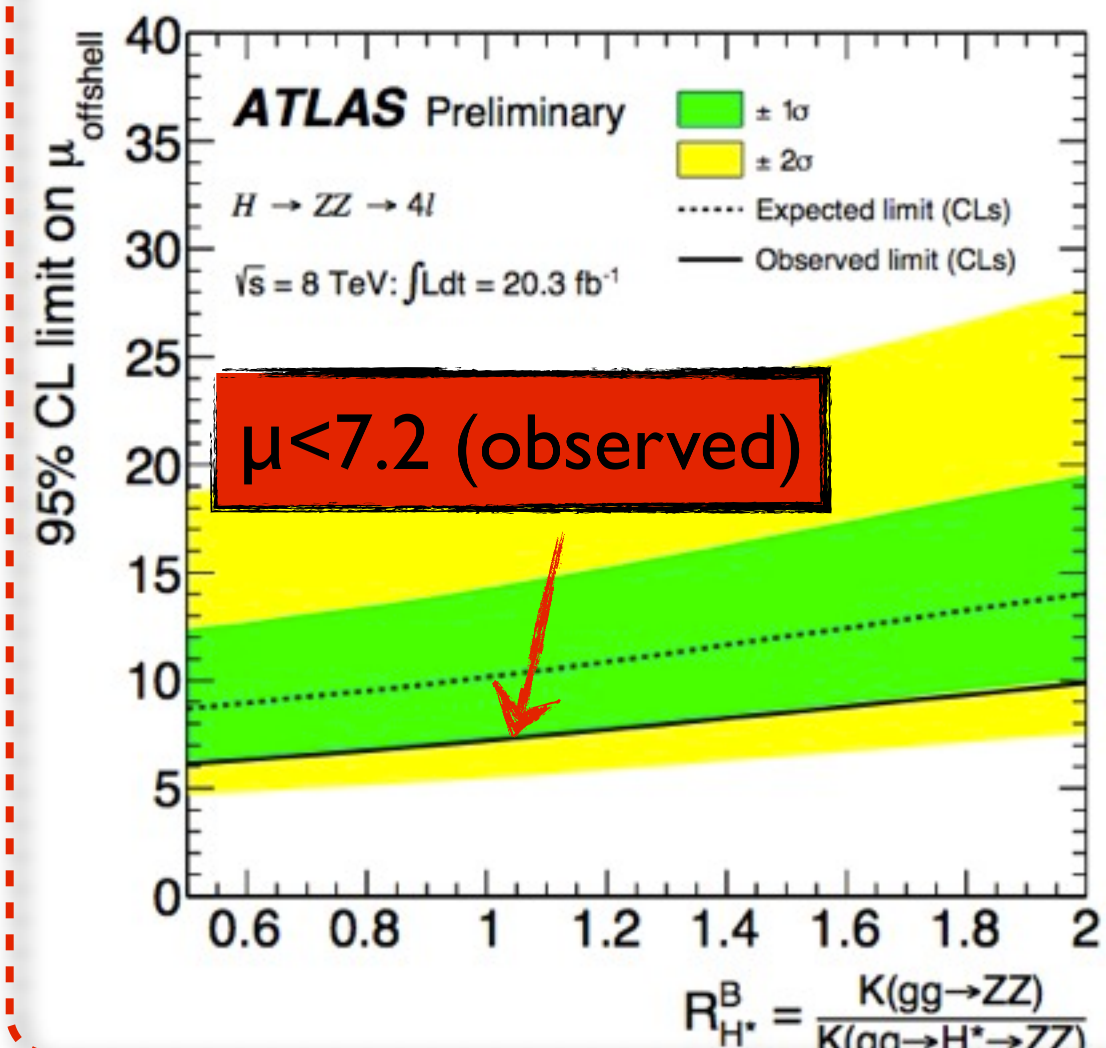
- The 3 templates are extracted from MC
  - Closure test performed between the MC distributions (generated at $\mu_{OffShell}$=10 and $\mu_{OffShell}$=25) and the PDFs extracted with the formula above
  - Assuming the same on and off-shell couplings, the above-defined parametrizations can be fitted in μ and this gives a limit on the ratio Γ/Γ SM

Results (4l)

- Use CLs method to extract 95% CL limit on μoffShell (4l)
  - We can interpret it as a limit on the width
  - Results presented as a function of K (gg→ZZ)/K(gg→H→ZZ).
  - The systematic uncertainties are dominated by the QCD scale of gg→ZZ, qq→ZZ and gg→H→ZZ.







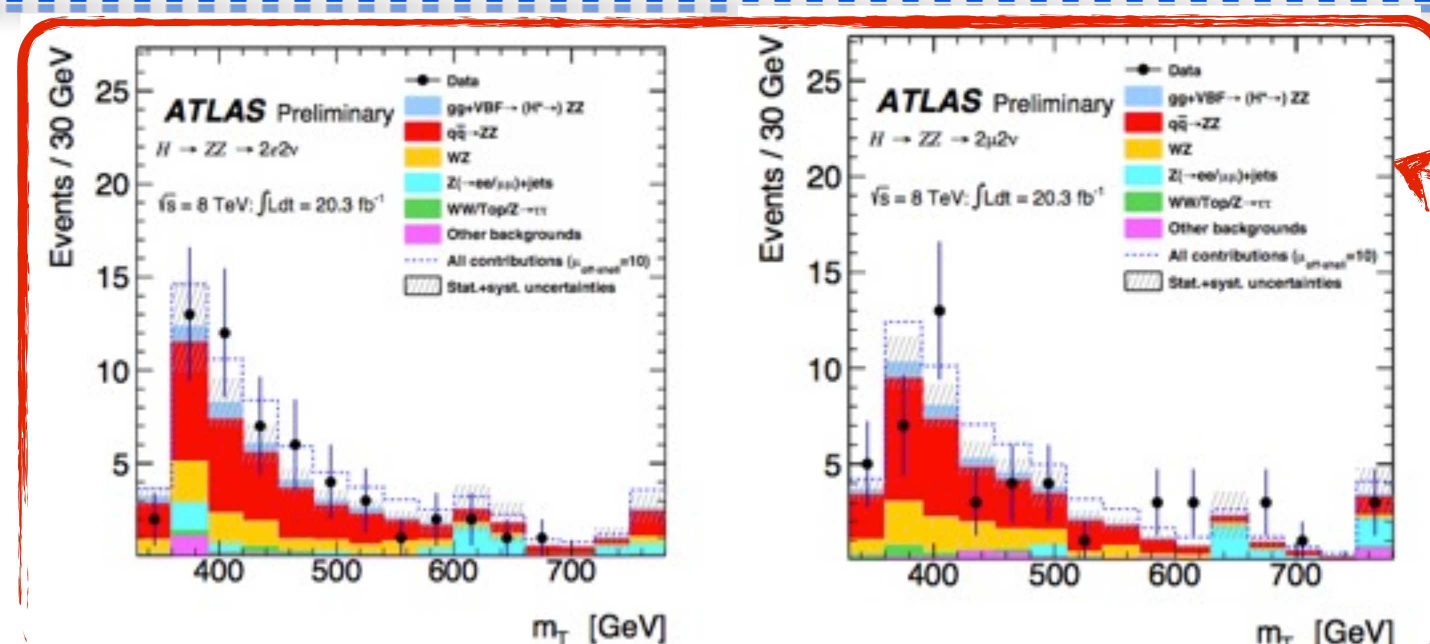
Cut-based analysis as a cross-check (4l)

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

	Observed			Median expected		
$R^B_{H^*}$	0.5	**1.0**	2.0	0.5	**1.0**	2.0
cut-based	10.8	**12.2**	14.9	13.6	**15.6**	19.9
ME-based discriminant analysis	6.1	**7.2**	9.9	8.7	**10.2**	14.0

The analysis strategy (llνν)

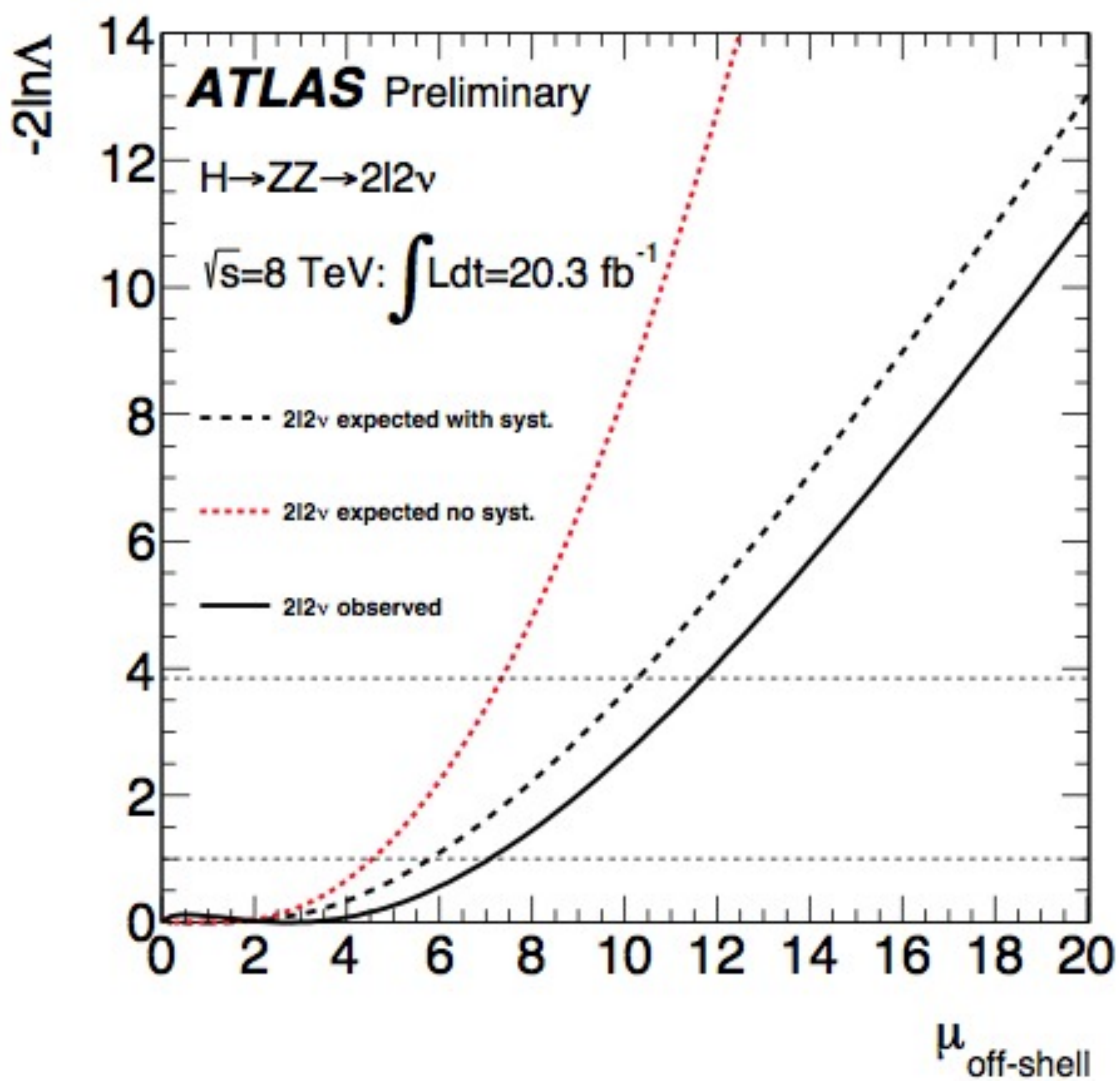
- Kinematic selection (off-peak region m_T^{ZZ}>350 GeV)
  - (76<mll<106) GeV, MET>150 GeV
  - Veto on the 3rd lepton to reject WZ, b-jet veto to reject top
  - |pt(Z)-MET|/pt(Z) <0.3, ΔΦ (MET, ptMiss)<0.5 to reject top and Z+jets background
- Background estimation:
  - WZ: estimated in MC and validated with data in a 3-lepton CR
  - ZZ: extracted from MC (NLO EW corrections applied to ZZ and WZ - it reduces the yield of 8% and 6% for ZZ and WZ)
  - 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

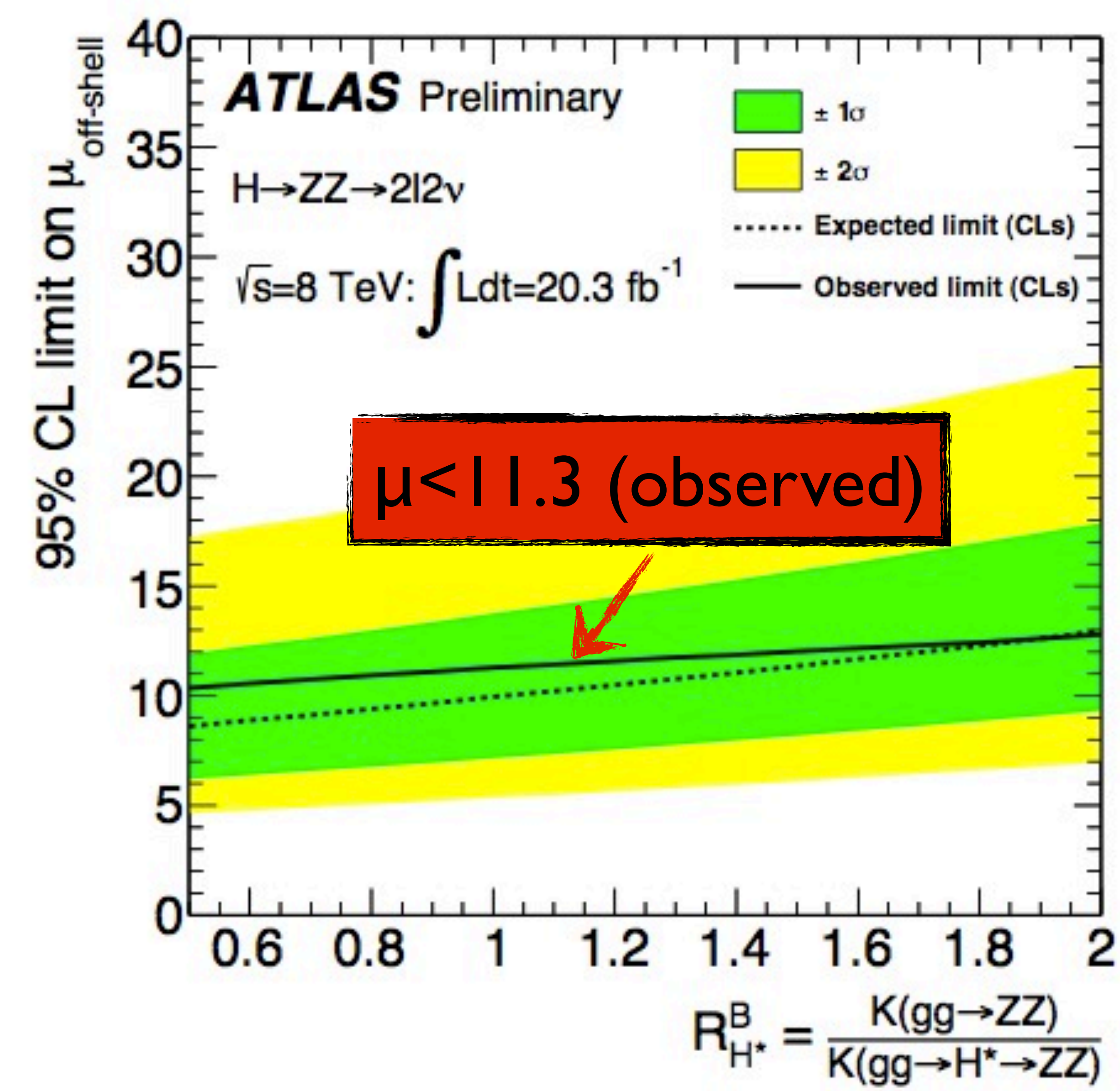


2e2ν, 2μ2ν final states

Results (llνν)

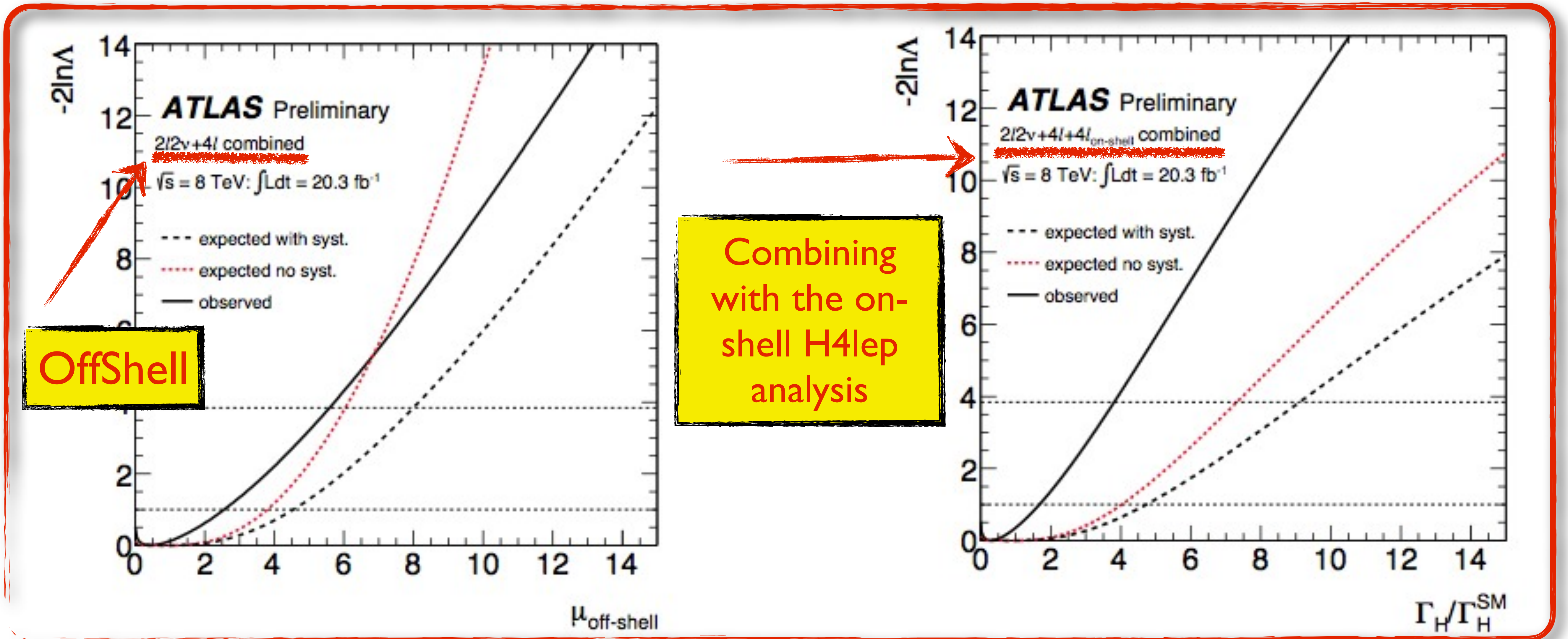
- Use CLs method to extract 95% CL limit on μoffShell (2l2ν)
  - cut-based analysis on m_T^{ZZ}
  - As for the 4l case, the systematic uncertainties are dominated by the QCD scale of gg→ZZ, qq→ZZ and gg→H→ZZ.
  - Small excess observed when comparing data with the expectations from the SM → slightly weaker observed limit compared to the expected values (compatible within 1σ)





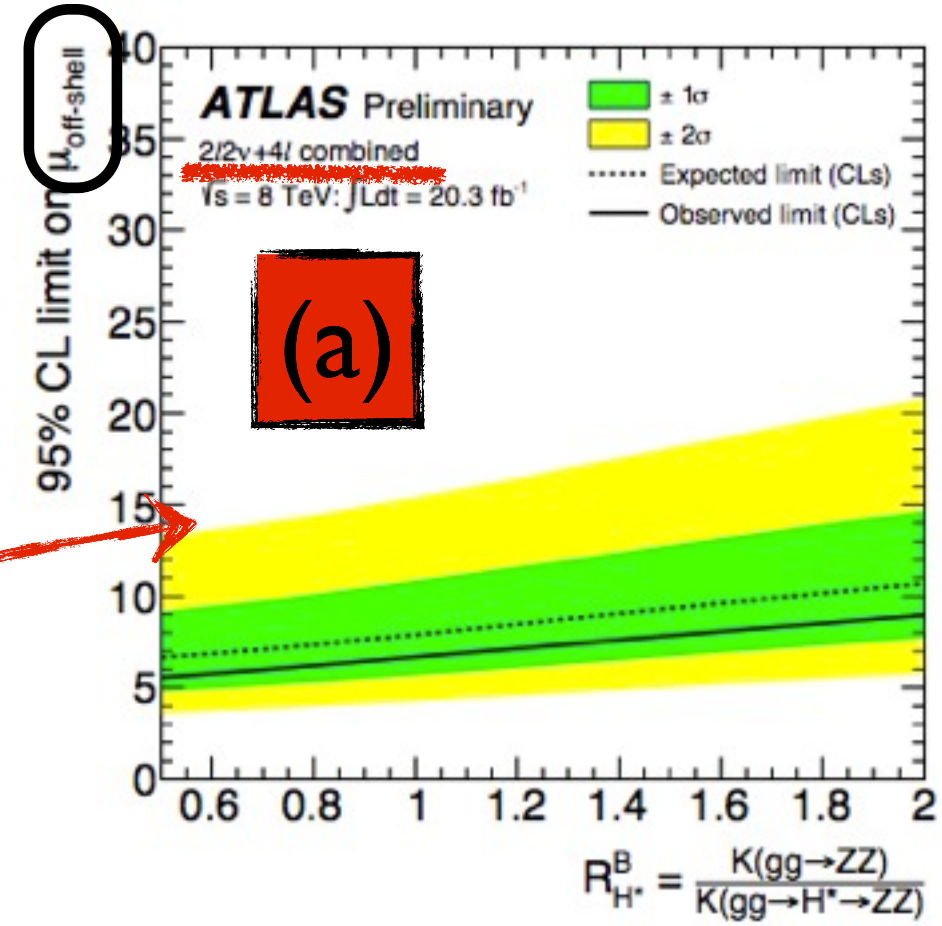
Combined results (4l+llvv)

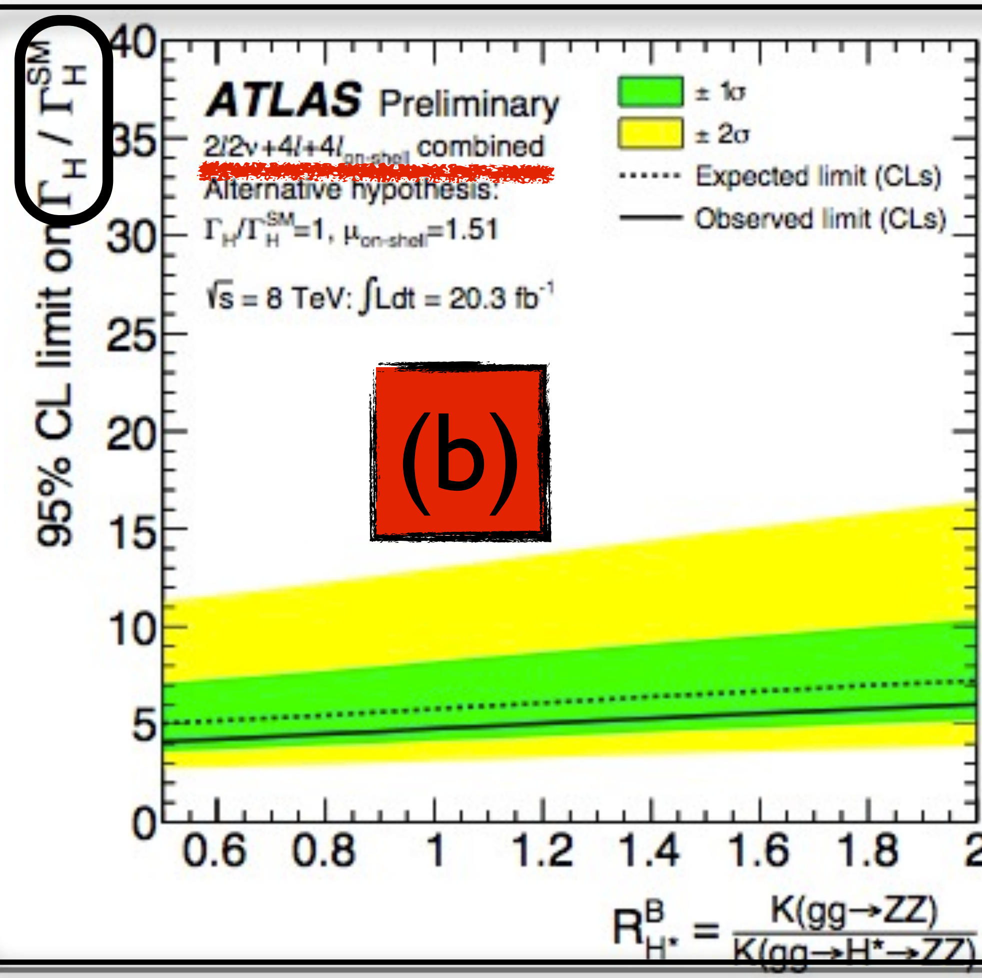
- Simultaneous binned maximum likelihood fit to extract μ(Off-Shell)
- Assuming identical on and off shell couplings, likelihood fit extended to include the low mass H4lep
    - Simultaneously measuring μ off-shell and on-shell → Interpretation of the measurement of the off-shell coupling as a limit on the Higgs width
    - Experimental sys uncertainties are treated as correlated between on and off-shell H4lep
    - QCD scale uncertainties on signal and qq →ZZ are treated as correlated between on and off-shell H4lep, whereas the PDF-related systematics are not

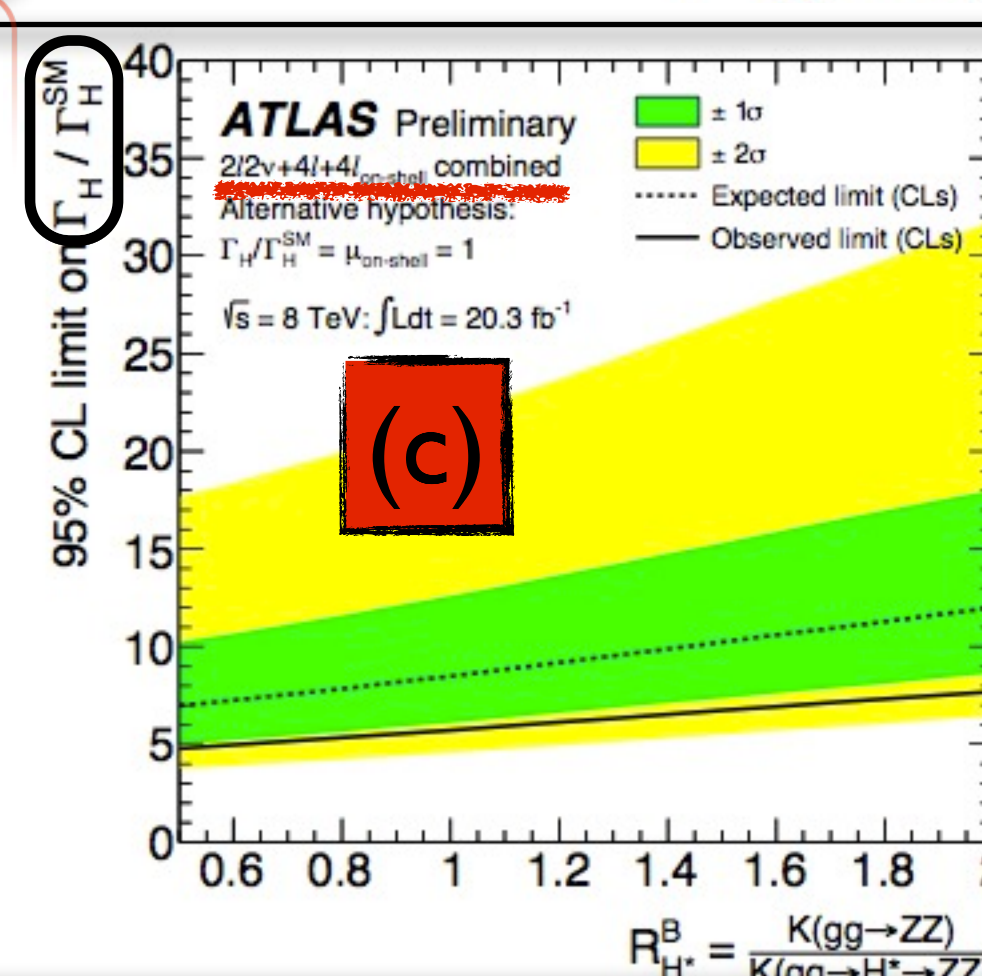


Combined results (4l+llvv) - 2

- The upper limit are evaluated using the CLs method including all the various systematic uncertainties
  - $\mu_{OffShell}$, $\Gamma H/\Gamma SM$ (when including H4lep on-shell)
- The alternative hypothesis for the measurement are
  - R= $\mu_{OffShell}$ =1 (a);
  - $\mu_{OnShell}$ =1.51 (b) - as measured in data
  - $\mu_{OnShell}$ =1 (c) - as expected from SM







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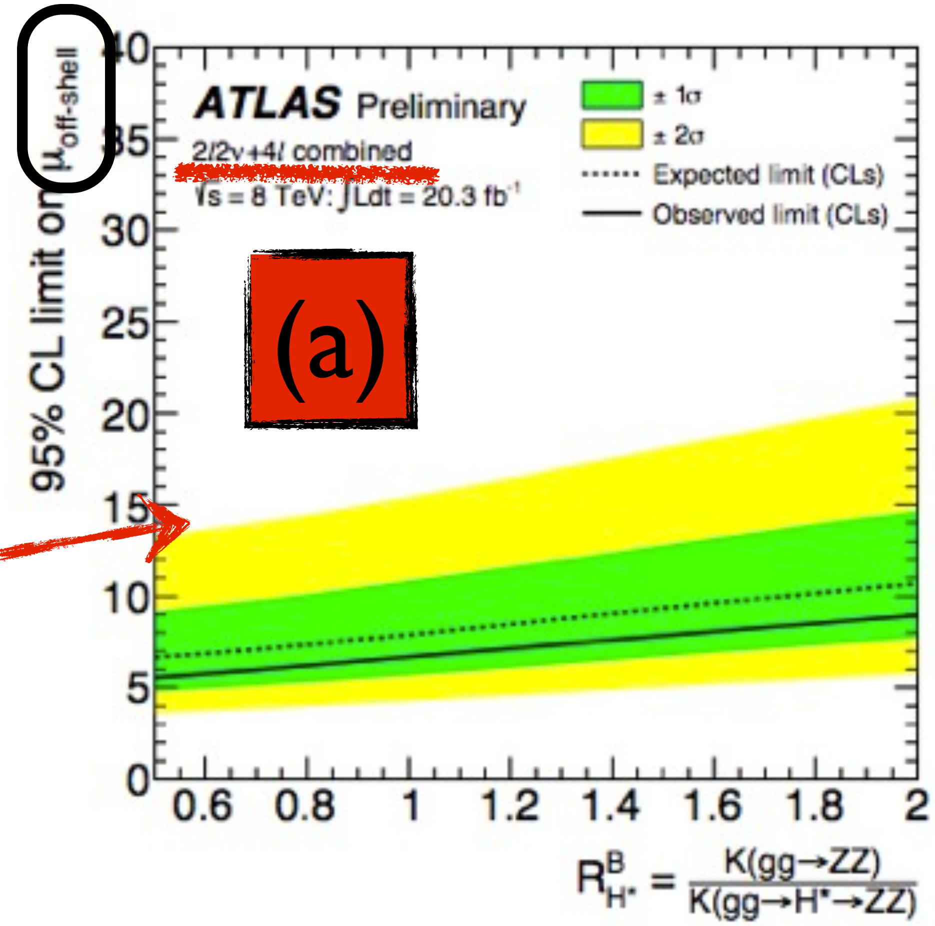
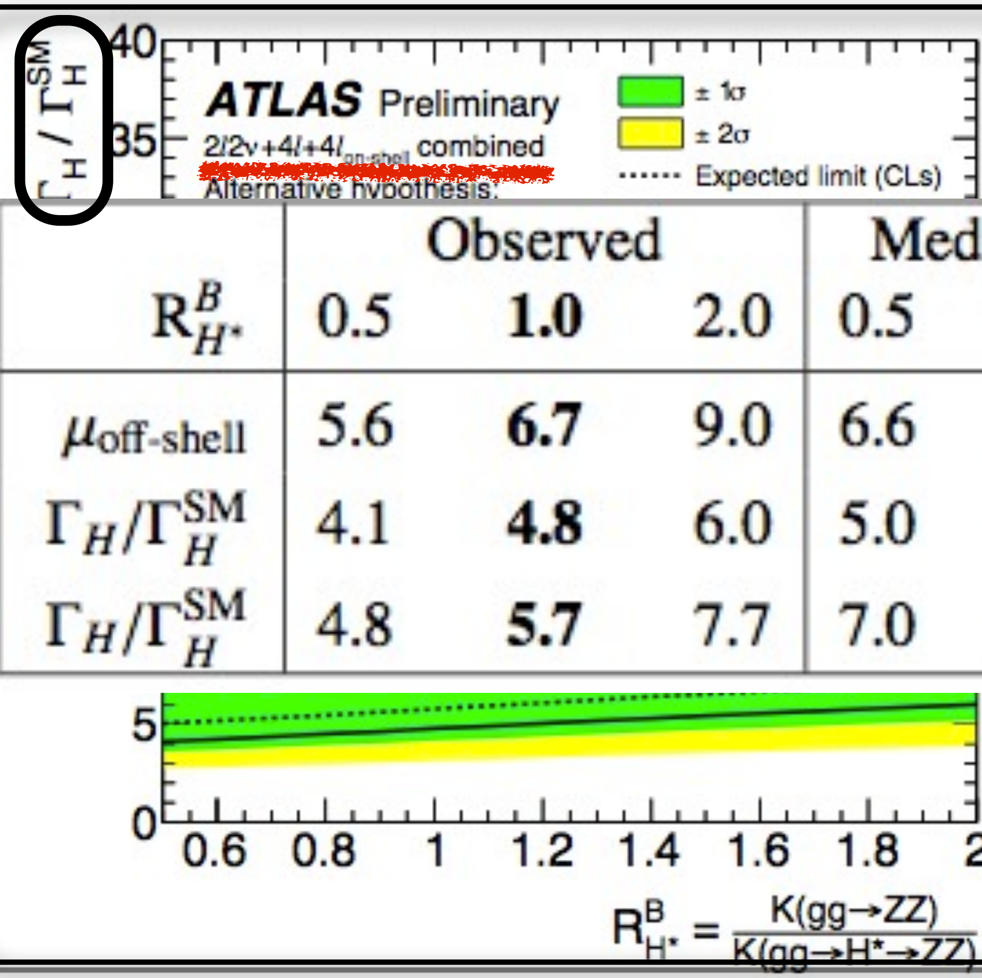
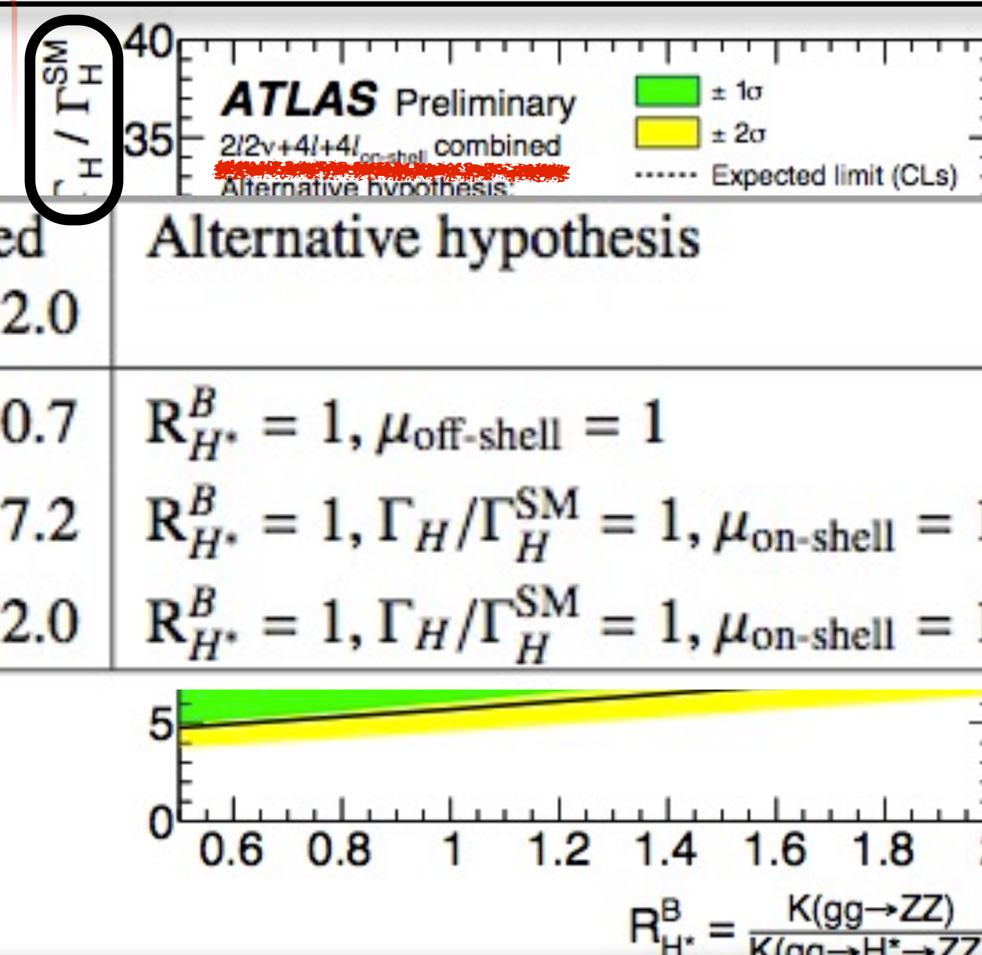






	Observed			Median expected			Alternative hypothesis
$R^B_{H^*}$	0.5	**1.0**	2.0	0.5	**1.0**	2.0	
$\mu_{\text{off-shell}}$	5.6	**6.7**	9.0	6.6	**7.9**	10.7	$R^B_{H^*} = 1, \mu_{\text{off-shell}} = 1$
Γ_H/Γ_H^{SM}	4.1	**4.8**	6.0	5.0	**5.8**	7.2	$R^B_{H^*} = 1, \Gamma_H/\Gamma_H^{SM} = 1, \mu_{\text{on-shell}} = 1.51$
Γ_H/Γ_H^{SM}	4.8	**5.7**	7.7	7.0	**8.5**	12.0	$R^B_{H^*} = 1, \Gamma_H/\Gamma_H^{SM} = 1, \mu_{\text{on-shell}} = 1$

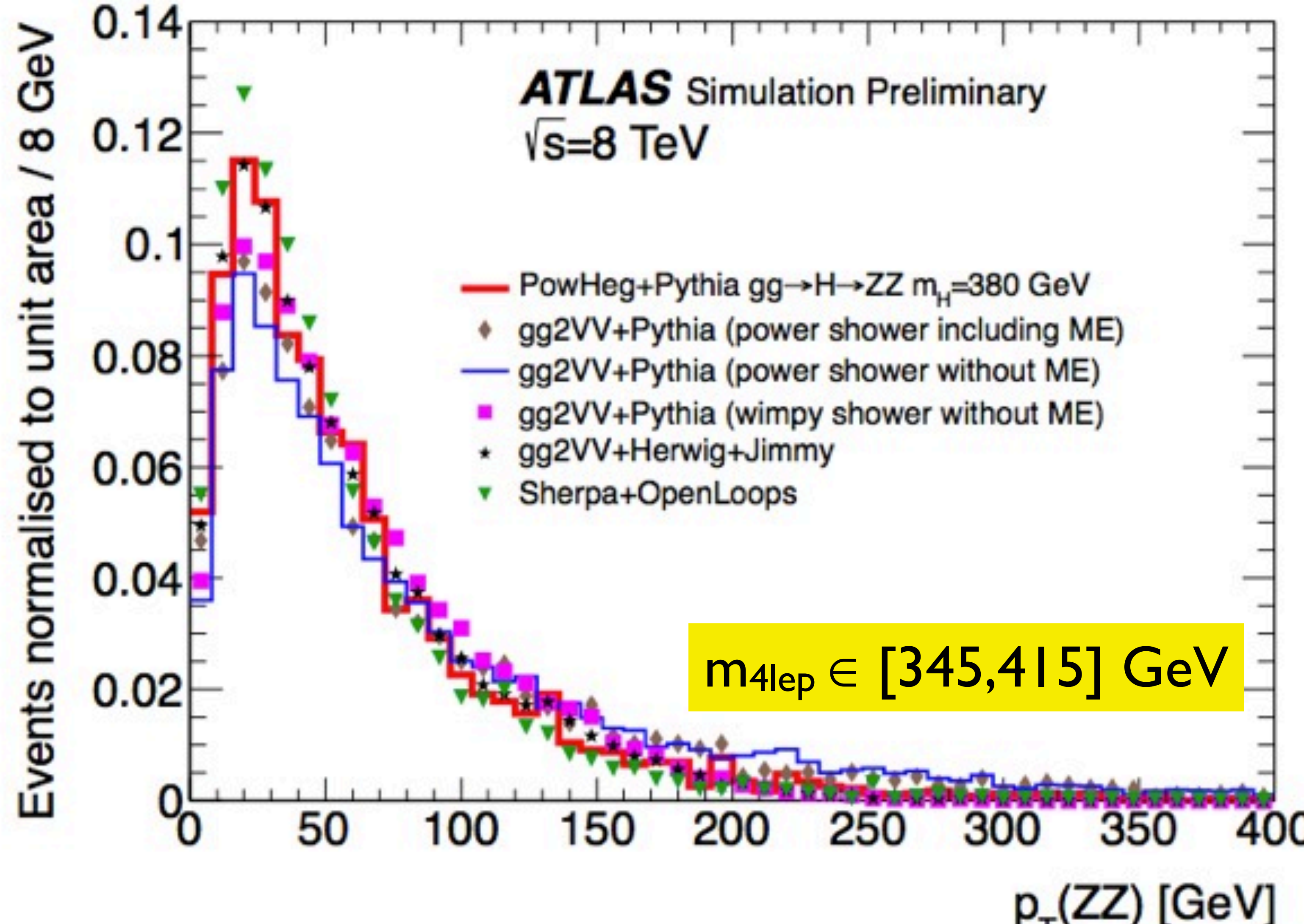
Treatment of the systematic uncertainties

- The largest systematic arises from theoretical uncertainties on $gg \to H \to ZZ$ and $gg \to ZZ$
- The experimental uncertainties are negligible both in 4lep and llvv
- Uncertainty on the signal contribution:
  - missing higher order QCD and EW: k-factor as a function of mZZ. The uncertainty is ~ 20-30%
- Treatment of the $gg \to ZZ$ continuum background uncertainty
  - NLO and NNLO QCD calculations are not available
  - results are given as a function of the ratio of the K-factors for signal and background (K-factor of the signal is applied to the gluon-induced background)
- The interference uncertainty has been taken into account as well

Treatment of the acceptance systematics

- 4lep analysis is inclusive in QCD observables - no further acceptance uncertainties are assigned
- llvv does not apply explicit jet categorization, yet the selection has an indirect influence on jet emissions and pt (ZZ) spectra
- gg2VV is a LO MC → Approach: comparing several parton showers and hadronization options:
  - Pythia8 "power" and "wimpy" showers (with and w/o a ME correction on the 1st jet emission)
  - Jimmy+Herwig
- ...compared to Powheg NLO signal (m_H=380 GeV) and Sherpa+OpenLoops background (LO+ 0 and 1j merged ME calculation)

- In llvv, the acceptance of the LO-based signal is reweighted to the Powheg sample
- Acceptance systematics: full difference gg2VV+Pythia8 power shower (default) and Sherpa - approximately 5% effect



Wrapping-up and conclusions

- Determination of the off-shell signal strength in the high mass $H \to ZZ^* \to 4l$ and $H \to ZZ^* \to 2l2\nu$ performed

- The analysis in the 4l channel employs a likelihood fit on the ME discriminant while the 2l2v channel exploits a cut-based approach in an enriched signal region

- Results are presented as a function of the ratio of background ($gg \to ZZ$) and signal ($gg \to H \to ZZ$) k-factors as no NLO QCD calculation is available for $gg \to ZZ$

- 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:

  - 95% CL observed (expected) limit on $\mu_{OffShell} < 6.7$ (7.9)

  - under the same assumptions: $\Gamma_H/\Gamma_{SM} < 5.7$ (8.5).

- *Currently working on the paper (will be most likely released by the beginning of 2015)*

Additional Slides

Breakdown of the systematic uncertainties

4l

Source of systematic uncertainties	95% CL on $\mu_{\text{off-shell}}$
QCD scale for $gg \rightarrow ZZ$	9.5
QCD scale for the $gg \rightarrow (H^* \rightarrow)ZZ$ interference	9.2
QCD scale for $q\bar{q} \rightarrow ZZ$	8.8
PDF for $pp \rightarrow ZZ$	8.7
EW for $q\bar{q} \rightarrow ZZ$	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 $\mu_{off-shell}$
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