ATLAS Higgs off-shell and interferometry in Run 1 and wish list for Run 2

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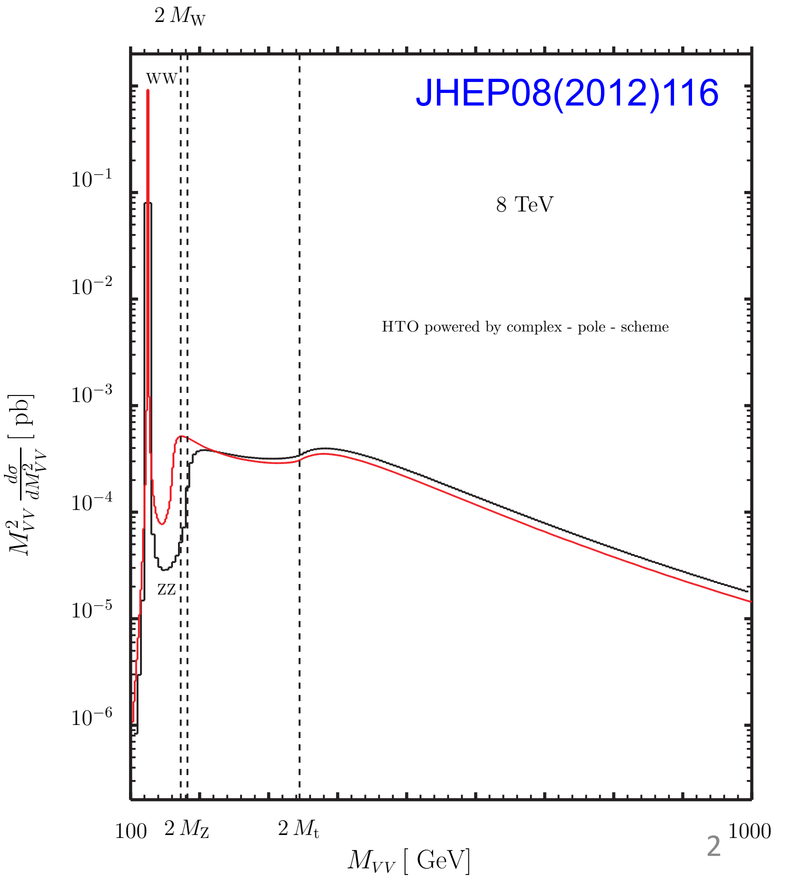
Introduction

- High mass region of H→ VV above the $2m_V$ threshold sensitive to the Higgs boson production through off-shell and background interference effects
  - characterize the properties of the Higgs boson through off-shell signal strength and off-shell Higgs boson couplings
  - Sensitivity to new physics that change interaction between the Higgs and SM particle in this region
- $\boldsymbol{\sigma_{offshell} \sim g_g^2 g_V^2}$ and not depends on total width Γ_H as $\sigma_{onshell}$
  - In terms of couplings modifiers

$$\frac{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell}}}{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell, SM}}} = \mu_{\text{off-shell}} = \kappa^2_{g,\text{off-shell}} \cdot \kappa^2_{V,\text{off-shell}}$$

$$\frac{\sigma^{gg\to H\to ZZ}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ}_{\text{on-shell, SM}}} = \mu_{\text{on-shell}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$$

- Assuming the on-peak and off-peak couplings are the same, we can reinterpret the limit on $\mu_{offshell}$, combined with $\mu_{onshell}$ measurement, as a **limit on Γ_H**
  - direct limits with H→ZZ*→4l and H→γγ
    $\boldsymbol{\Gamma_H < 600\ \Gamma_H^{SM}}$



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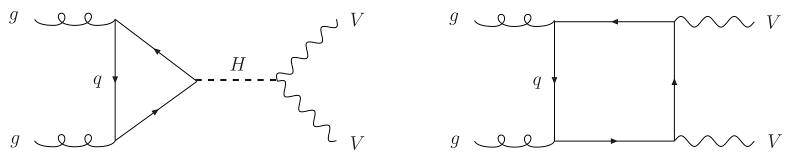
Interference effects and MC generators

- In the high mass region off-shell Higgs production and non resonant gg→ VV background (box diagram)



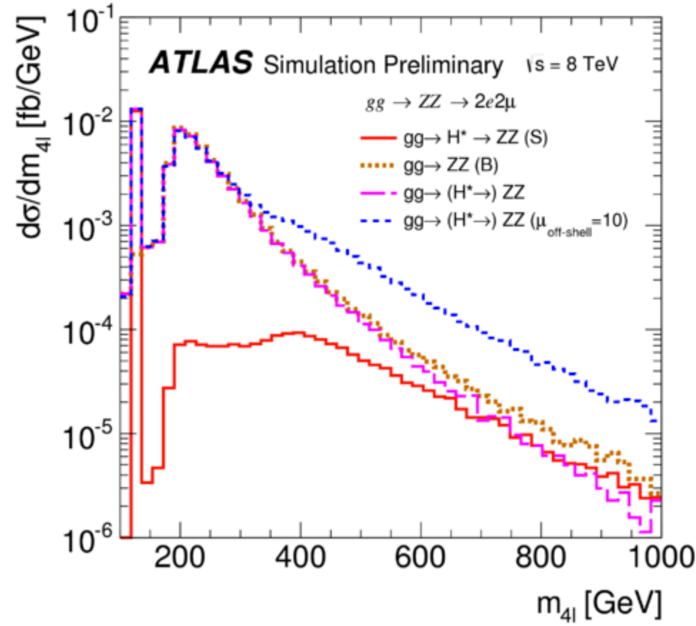
- Interference between the two processes sizable and negative in SM
  - Taken into account in the analysis
- Similar for qq→VV+2j and VBF production

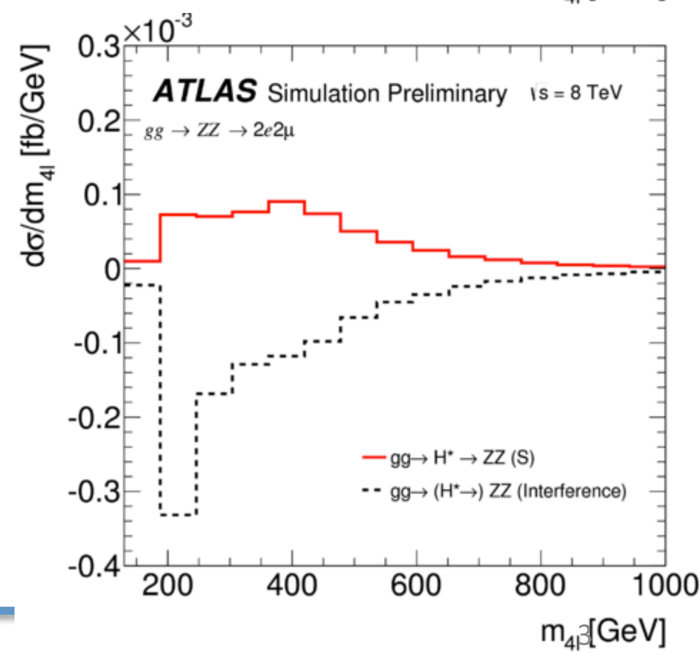
ggF production mechanism

- MCFM and gg2VV (LO, $\mu R \mu F = m_{ZZ}/2$)
  - gg→(H*)→ ZZ gg→H*→ ZZ , gg→ZZ
- Sherpa (0j+1j) for $p_{T(ZZ)}$ description

VBF production mechanism

- MG5 and Phantom used
- Other production mechanisms (VH,ttH) negligible





$\mu_{offshell}$ dependence and K-factors

- Possible to obtain a sample with an arbitrary value of $\mu_{offshell}$ combining the SM expectations for $gg\rightarrow(H^*)\rightarrow ZZ$ $gg\rightarrow H^*\rightarrow ZZ$ and $gg\rightarrow ZZ$

$$\begin{aligned} \mathrm{MC}_{gg\to(H^*\to)ZZ}(\mu_{\text{off-shell}}) = & \left(\mathrm{K}^{H^*}(m_{ZZ})\cdot\mu_{\text{off-shell}} - \mathrm{K}^{H^*}_{gg}(m_{ZZ})\cdot\sqrt{\mathrm{R}^B_{H^*}\cdot\mu_{\text{off-shell}}}\right)\cdot \mathrm{MC}^{\mathrm{SM}}_{gg\to H^*\to ZZ} \\ & + \mathrm{K}^{H^*}_{gg}(m_{ZZ})\cdot\sqrt{\mathrm{R}^B_{H^*}\cdot\mu_{\text{off-shell}}}\cdot \mathrm{MC}^{\mathrm{SM}}_{gg\to(H^*\to)ZZ} \\ & + \mathrm{K}^{H^*}_{gg}(m_{ZZ})\cdot\left(\mathrm{R}^B_{H^*} - \sqrt{\mathrm{R}^B_{H^*}\cdot\mu_{\text{off-shell}}}\right)\cdot \mathrm{MC}^{\mathrm{cont}}_{gg\to ZZ}, \end{aligned}$$

- $K^{H*}(m_{ZZ})$: NNLO/LO K factor for the signal
  - Includes contribution from qg qq initial states
  - Calculated inclusively (integrated over jet p_T and $p_T(ZZ)$ induced by higher order QCD corrections)
  - 20-30% QCD scale uncertainty
- $K^{H*}_{gg}(m_{ZZ})$: NNLO/LO K factor for the gg initiated process
  - Only gg contribution and larger uncertainty wrt $K^{H*}(m_{ZZ})$
  - $K^{H*}(m_{ZZ})$ scale uncertainties applied correlated for $K^{H*}(m_{ZZ})$ and $K^{H*}_{gg}(m_{ZZ})$ and the difference in quadrature scorrelated for $K^{H*}_{gg}(m_{ZZ})$

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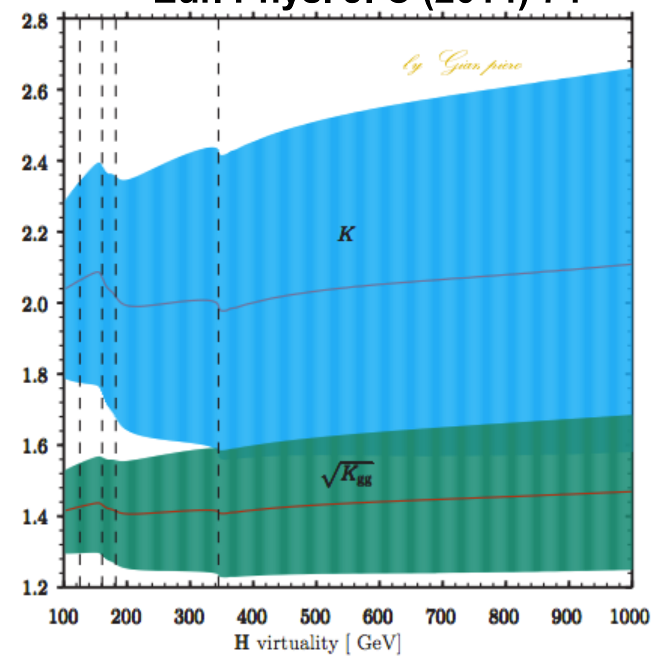

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- **R^{B}_{H*}** : $K^{B}/K^{H*}_{gg}(m_{ZZ})$
  - Kfactor for $gg\rightarrow ZZ$ unknown
  - In soft collinear approximation ~1 with 10% uncertainty on K^{B}
    - » Studied in Phys. Rev. D88 (2013) 034032 for WW process
  - ATLAS result given as function of R^{B}_{H*} [0.5-2]
- Additional 30% uncertainty considered for the interference terms
  - Uncorrelated with of R^{B}_{H*} (otherwise cancellation between the negative interference and positive gg background)

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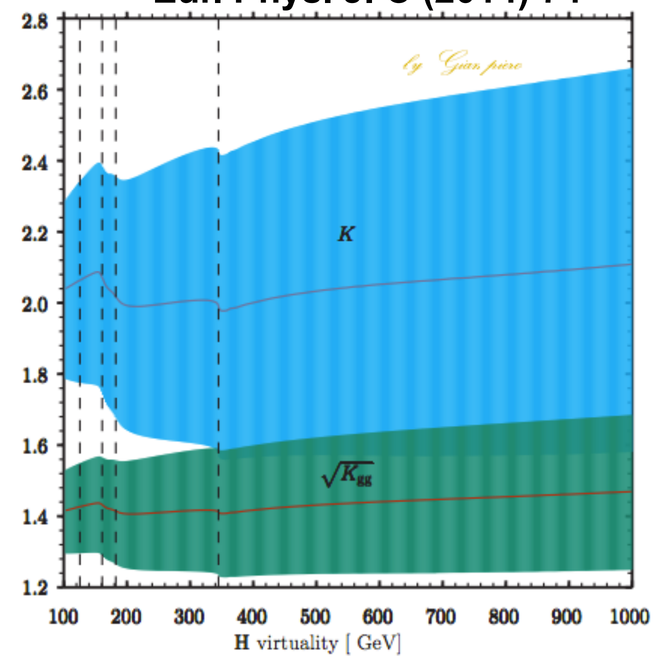
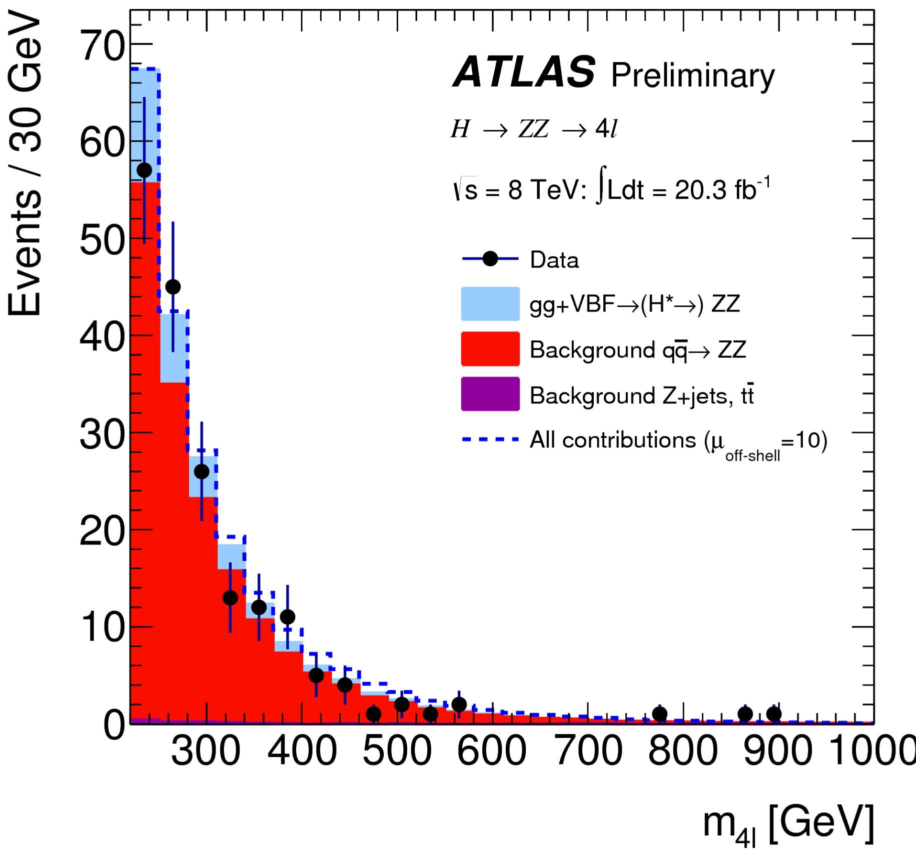


ATLAS Higgs off-shell production measurement (ZZ final state)

ATLAS-CONF-2014-042

4l analysis

- 4l analysis designed to be mostly inclusive wrt additional QCD activity
- Selection similar as the one used for the on-shell coupling results
- 4 leptons (e/μ) with p_T>20,15,10,6(7) GeV
- m_{ll}>50GeV and compatible with m_Z
- Measurement of the $\mu_{offshell}$ performed in the region 220 GeV<m_{4l}<1 TeV
- Main backgrounds (gg→ ZZ and qq→ ZZ) from MC simulation
  - NLO EW and NNLO QCD correction (m_{ZZ}) available for qq→ ZZ
  - Reducible background (Z+X,tt) <0.5% of the total background → neglected
- Sensitivity improved by using ME
- 4 channels combined (4e, 4μ, 2e2μ, 2μ2e)



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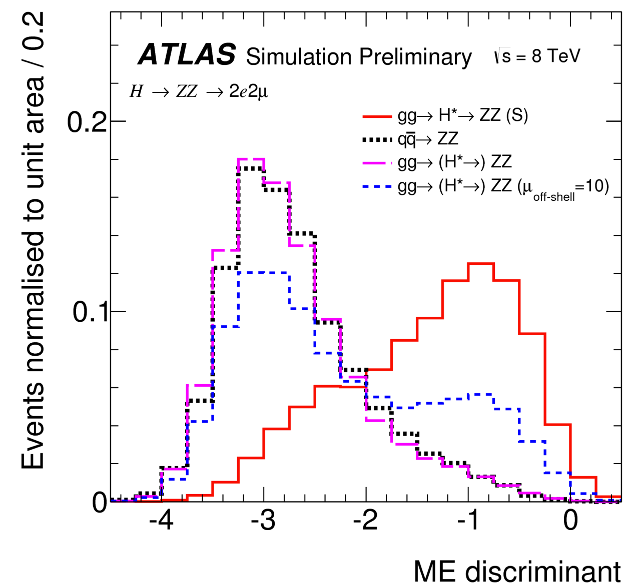
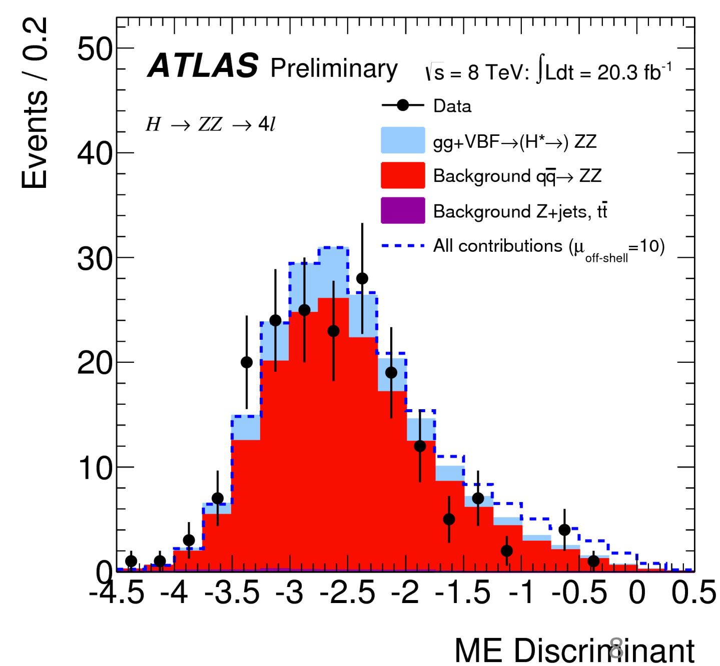
ME discriminant for 4l analisys

- A LO ME based discriminant used to enhance the sensitivity to the $gg \to H^* \to ZZ$ signal
  - Wrt the $gg \to ZZ$ and $qq \to ZZ$ backgrounds
- m_{4l} m_{Z1} m_{Z2} and 5 production/decay angles used to calculate the ME for the different processes with MCFM

$$\mathrm{ME} = \log_{10}\left(\frac{P_H}{P_{gg} + c \cdot P_{q\bar{q}}}\right)$$

- $P_H = gg \to H^* \to ZZ \to 4l$
- $P_{gg} = gg \to (H^*) \to ZZ \to 4l$
- $P_{qq} = qq \to ZZ \to 4l$
  - c=0.1 to balance the SBI and qqZZ xsec
- MLE fit to the ME discriminant shape to extract the limit on $\mu_{offshell}$





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4l analysis Results

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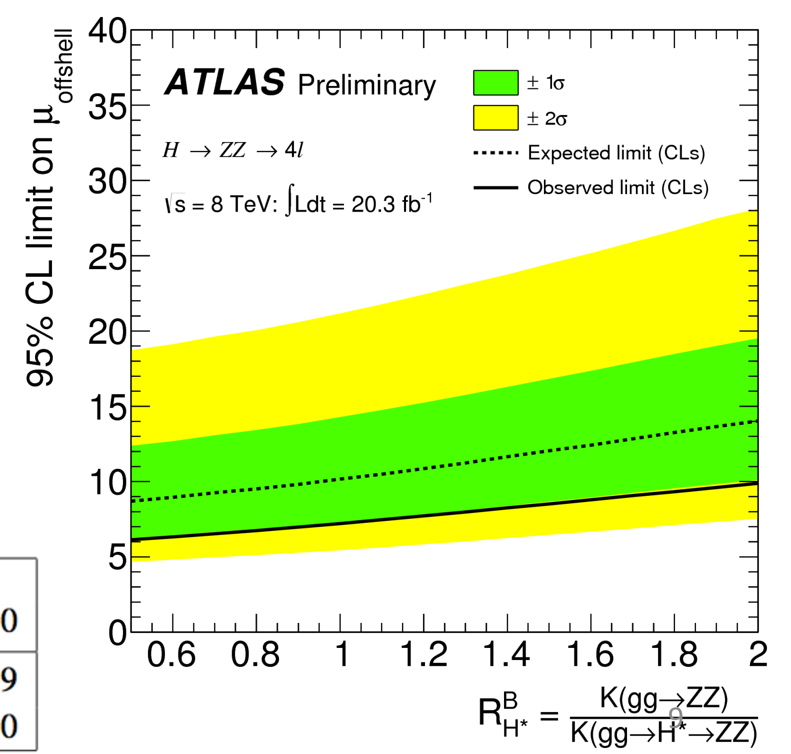
- Event yield expected and observed for m_{4l}>220 GeV and for the signal region (m_{4l}>400 GeV)
  – Deficit observed wrt SM expectations

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

- Limit on $\mu_{offshell}$ given as function of the relative gg→ZZ background K-factor R^B_{H*}
  – Limit observed lower than expected
  – Poorly dependent on R^B_{H*}
  – R^B_{H*}~1 in the soft collinear approximation
- Small impact of the experimental uncertainties



	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

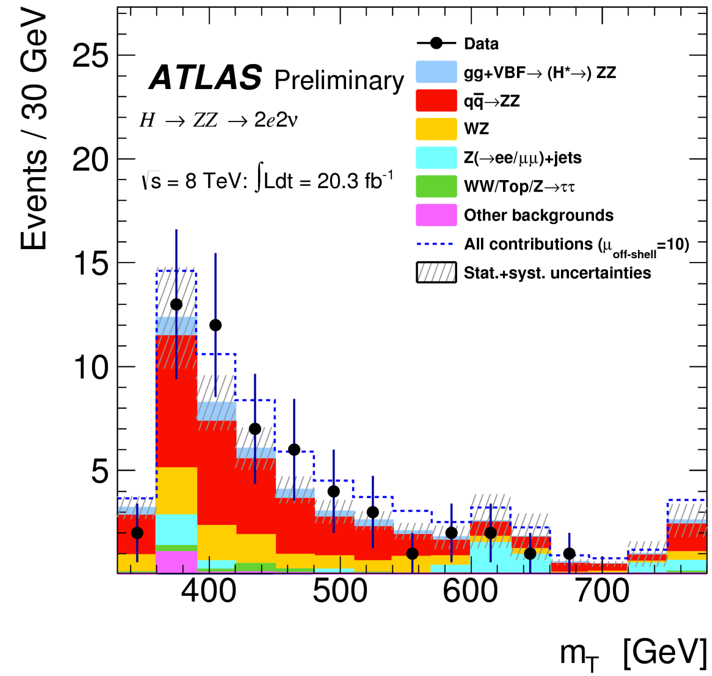
Systematic uncertainties in 4l analysis

- Impact of systematic uncertainties considered (theoretical and experimental) on the 95% CL limit on $\mu_{offshell}$ (K^{B}_{H*}=1)
  - Limit worst by 17% due to the systematic uncertainties
- Negligible impact on the limit of the experimental uncertainties
- Main impact of QCD scale systematic uncertainties for $gg \to ZZ$ and $gg \to (H^*) \to ZZ \to 4l$ interference

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

2l2ν analysis

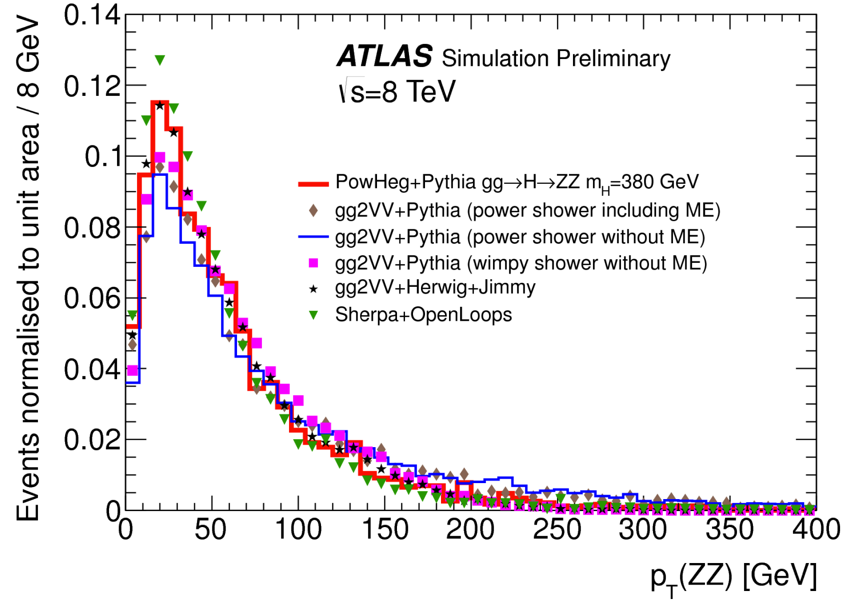
- Similar sensitivity as the 4l analysis
  - Profit of factor 6 higher BR
- Selection cuts:
  - E_T^{miss}>150 GeV, 76<m_{ll}<106 GeV
  - Signal region: 350GeV<m_T<1TeV
- Simple cut based analysis
- Main backgrounds
  - qq→ZZ: MC based estimation
  - WZ: MC based estimation
  - WW/tt/Z$\tau\tau$: estimated inclusively with eμ events
  - Z+jets: data-driven with ABCD method
- Slightly more events observed in the signal region wrt the SM expectation

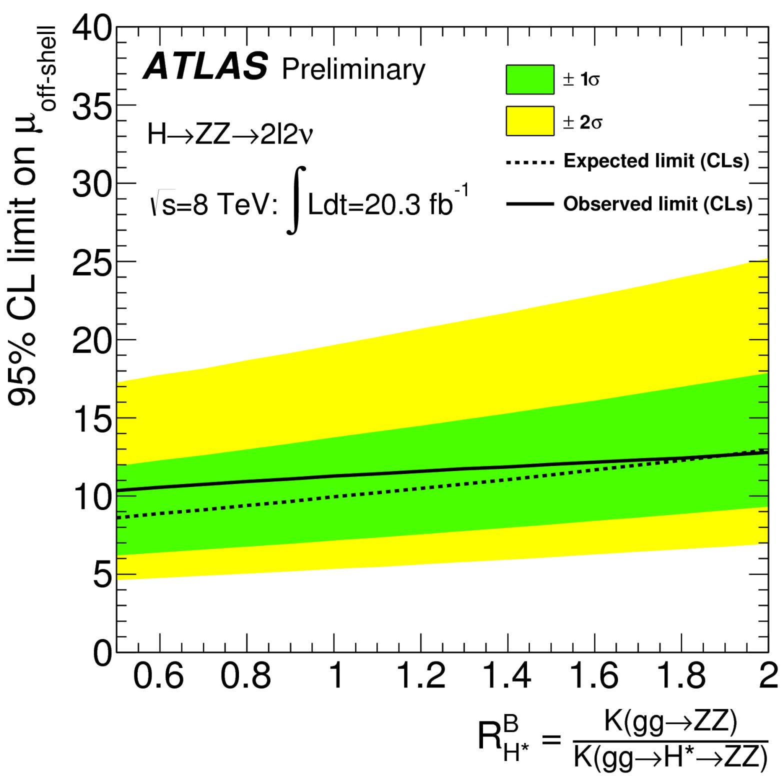


Process	Total
$gg \to H^* \to ZZ$ (S)	4.8 ± 0.04 ± 1.5
$gg \to ZZ$ (B)	9.2 ± 0.8 ± 2.7
$gg \to (H^* \to)ZZ$	7.4 ± 0.1 ± 2.2
$gg \to (H^* \to)ZZ(\mu_{off-shell} = 10)$	34.7 ± 0.2 ± 10.4
VBF $H^* \to ZZ$ (S)	0.5 ± 0.07 ± 0.02
VBF ZZ (B)	1.8 ± 0.1 ± 0.1
VBF $(H^* \to)ZZ$	1.4 ± 0.1 ± 0.1
VBF $(H^* \to)ZZ(\mu_{off-shell} = 10)$	3.7 ± 0.2 ± 0.1
$q\bar{q} \to ZZ$	54.4 ± 0.9 ± 5.7
WZ	21.1 ± 0.7 ± 2.3
WW, $t\bar{t}$, Wt, and $Z \to \tau\tau$	2.8 ± 1.7 ± 0.2
$Z \to ee, \mu\mu$	9.6 ± 3.5 ± 4.0
Other backgrounds	3.3 ± 0.8 ± 0.4
Total Expected (SM)	100 ± 4 ± 10
Observed	104

2l2ν analysis result

- Event selection for the 2l2ν indirect influence on jet emission and $p_T(ZZ)$
  - Additional acceptance uncertainty
  - LO vs 0j+1J (Sherpa+OpenLoops)
    - Knowledge of signal and bkg processes at higher order is crucial



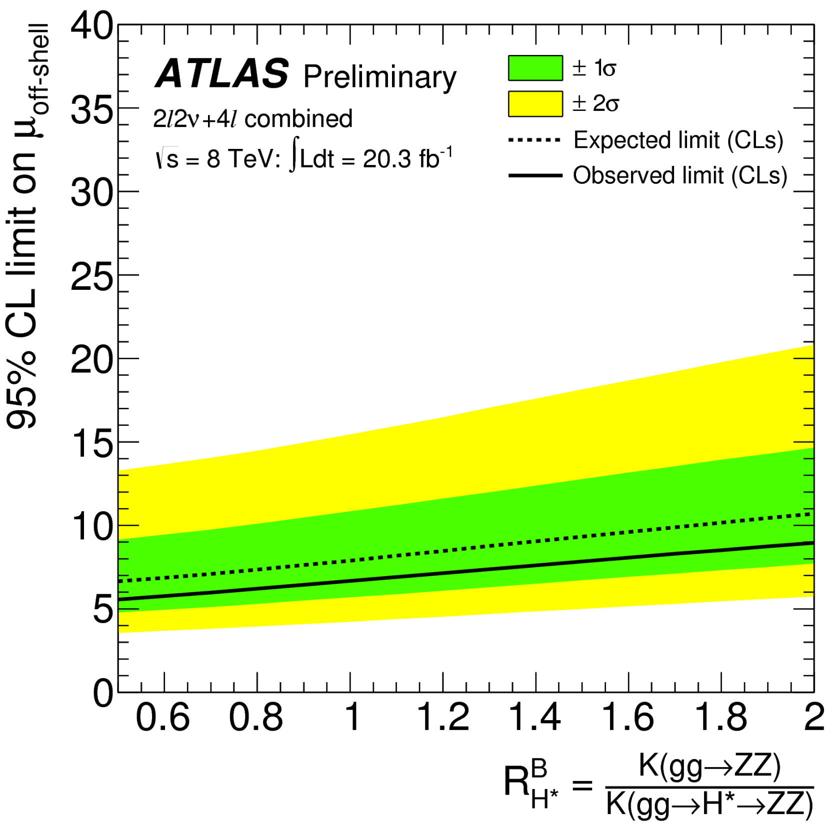


- Limit on $\mu_{offshell}$ from 2l2ν final state given as function of the relative gg→ZZ background K-factor $R^B{}_{H*}$

- **$\mu_{offshell}$ < 11.3** at 95% CL for $R^B{}_{H*}=1$
  - Expected: $\mu_{offshell} < 9.9$ @ 95% CL

Combined result

- $\mu_{offshell}$ < 6.7   95% CL for R^B_{H*}=1
  - Expected: $\mu_{offshell}$ < 7.9 @ 95% CL

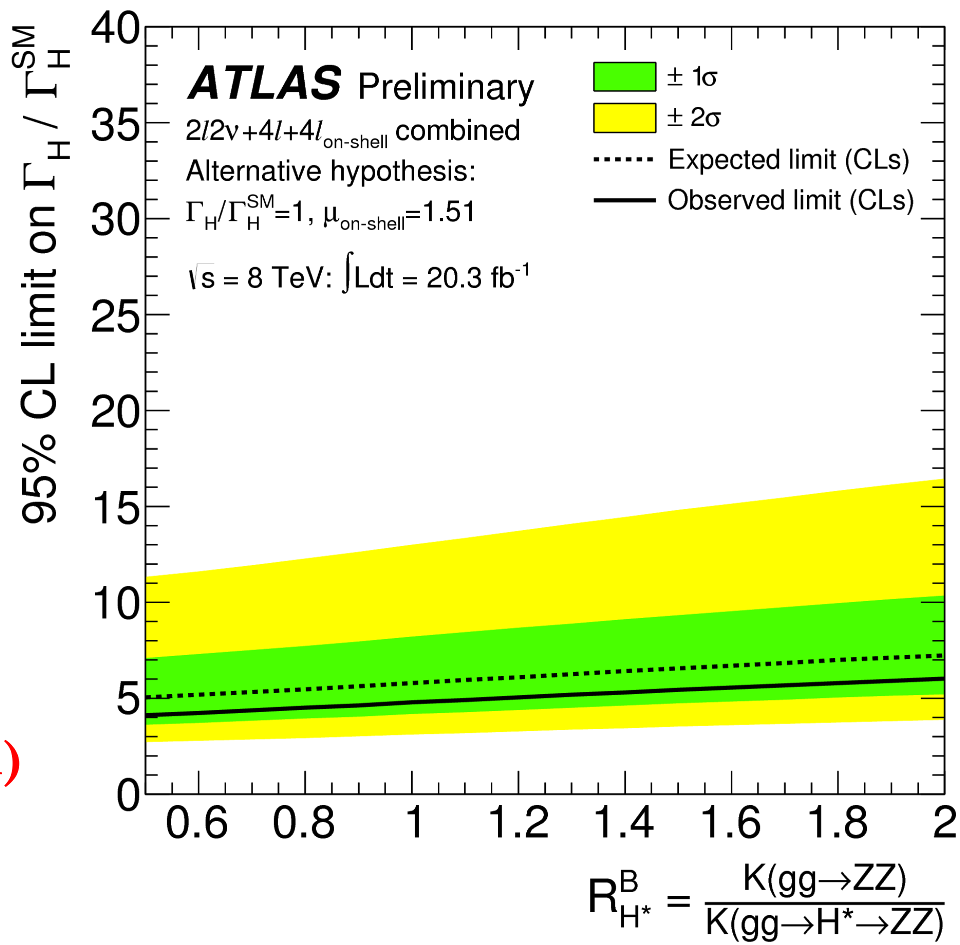


Source of systematic uncertainties	95% CL on $\mu_{\mathrm{off-shell}}$
QCD scale for $gg \to ZZ$	6.7
QCD scale for the $gg \to (H^* \to)ZZ$ interference	6.7
QCD scale for $q\bar{q} \to ZZ$	6.4
Z BG systematic	6.2
Luminosity	6.2
PDF for $pp \to ZZ$	6.1
Sum of remaining systematic uncertainties	6.2
No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

- Limit on $\mu_{offshell}$ obtained with the combination of the 4l and 2l2ν analyses
- Main theoretical uncertainties from QCD scale for the qq and gg initiated processes
- Main experimental uncertainties:
  - Luminosity
  - Z bg estimate for the 2l2ν channel

Limit on the Higgs width

- Obtained by combining the on-shell 4l and off-shell 4l-llvv signal strength measurements
  - measured $\mu_{onshell}$=1.5 with $H \rightarrow ZZ^* \rightarrow 4l$
- Limit valid under the assumption that on-peak and off-peak couplings are the same
  - Assumed μ_{ggf}/μ_{VBF}=1
  - Other approaches possible i.e. profiling μ_{ggf} and μ_{VBF} from 8 TeV coupling measurement
- **$\Gamma_H / \Gamma_{H,SM} < 4.8$ at 95% CL (R^B_{H*}=1)**
  - **< 6 @ 95% CL for R^B_{H*}=2**
  - **Expected (R^B_{H*}=1, $\mu_{onshell}$=1.5):**
    - $\Gamma_H / \Gamma_{H,SM}$**< 5.8 @ 95% CL**



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RUN 2 needs

- Precious lesson from Run 1 analysis
- During Run 2 same sensitivity will be reached with ~10fb^{-1}
- With the increase of the statistics, it will be crucial to have as best as possible accurate theoretical prediction
  - Theoretical uncertainties on cross-section and shapes of the different components
- Essential to move from LO to NLO MC development for $gg \rightarrow VV$ process
  - Introduce less "QCD-inclusive" analysis
  - Might help if category for VBF and VH-like production modes introduced
- Equally important the development of MC generators for the main $qq \rightarrow VV$ background
  - $pp \rightarrow WW/ZZ^*$ at NNLO cross sections and NNLO MC development

Looking forward…

- Increasing integrated luminosity → high statistical power of the measurement
- Simple scaling of the current 1σ stat only uncertainty at 14 TeV assuming ~2.7 higher xsec for the signal

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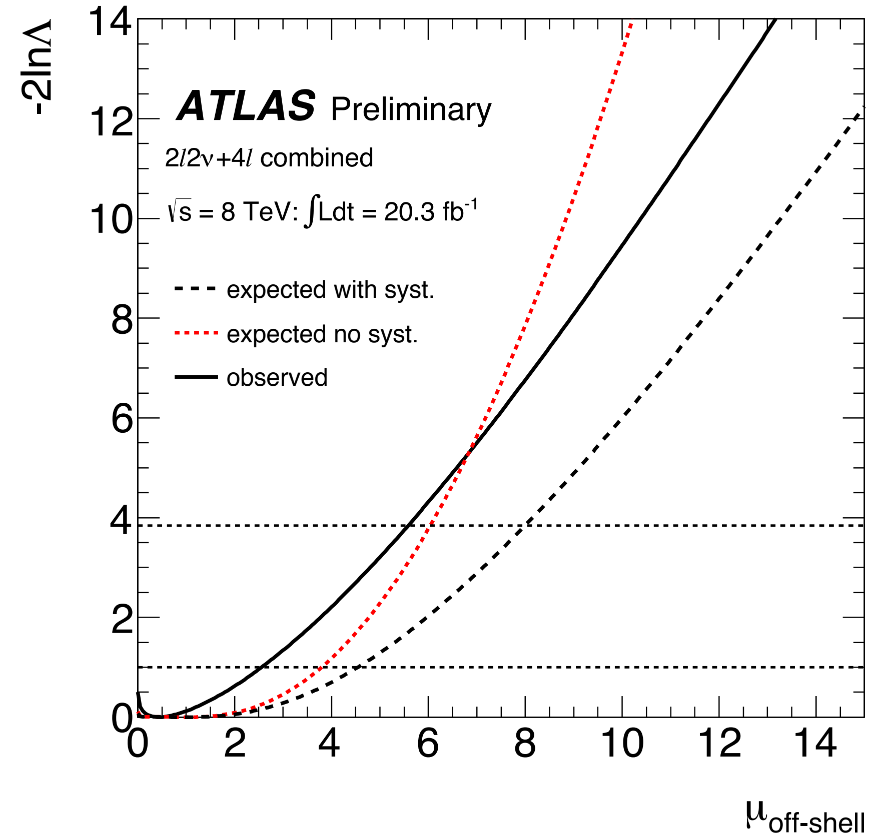
- $\mu_{offshell}$ measurement @ 20-30% level (stat only) with 3000fb $^{-1}$

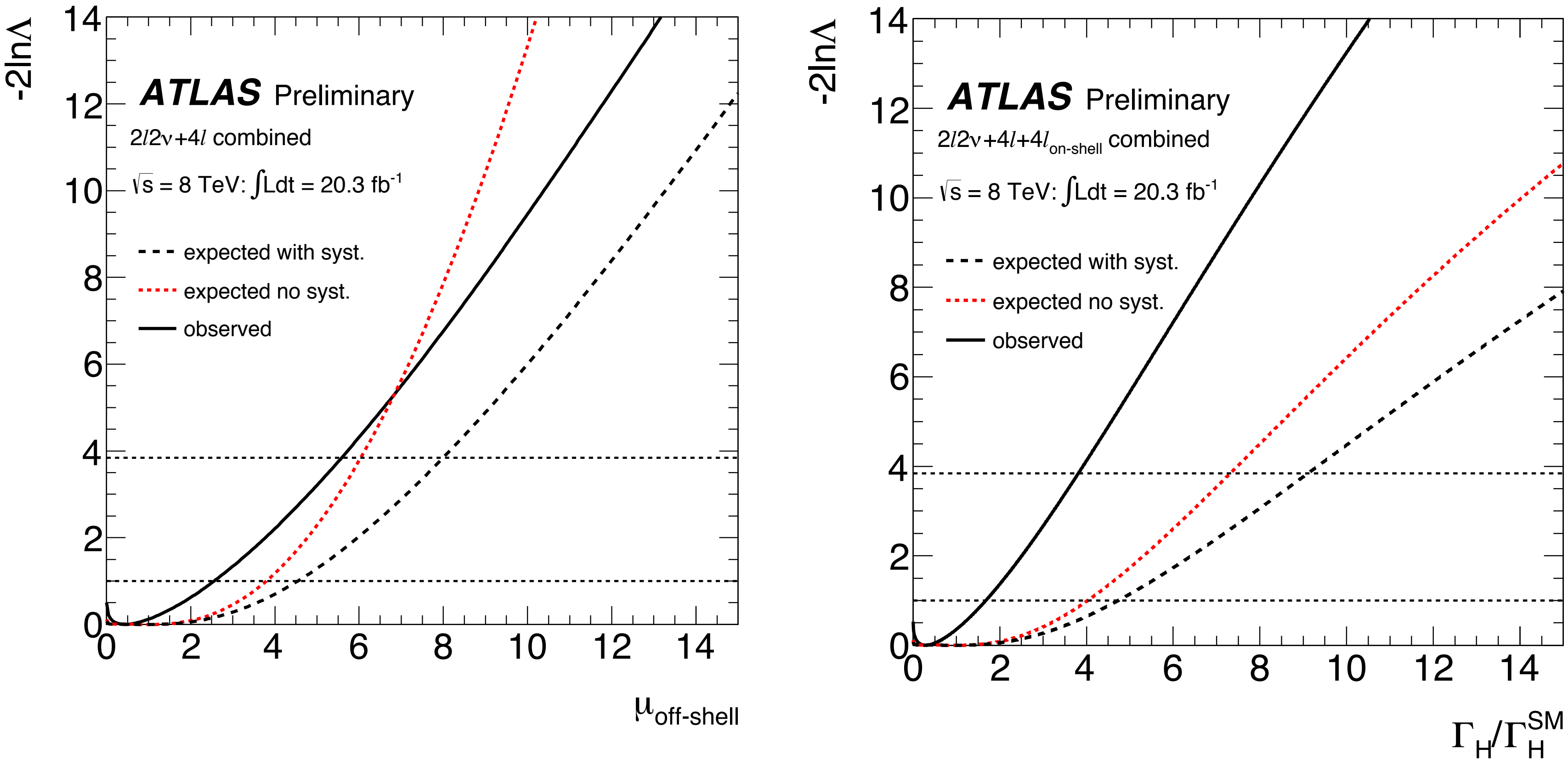
- "differential" knowledge (ME,m_{ZZ},m_T) of the signal and background processes will be more and more crucial
  - Shape analysis solve the two possible solution from simple cut and count analysis
  - i.e. higher order EW corrections need to be taken also into account



Conclusions

- Off-shell production of the Higgs boson gives interesting extra information of the coupling structure of the Higgs boson
- Analysis performed by ATLAS using the 8TeV data (20.3 fb^{-1}) with the 4l and llvv final states
  - Similar sensitivities
  - **$\mu_{offshell} < 6.7$ 95% CL for $R^{B}_{H*}=1$**
    - Studied also as function of the R^{B}_{H*} [0.5 , 2]
- With theoretical caveats, this might interpret as a limit on the Higgs width when off-shell and on-shell measurement are combined together
  - **$\Gamma_{H} / \Gamma_{H,SM} < 4.8$ at 95% CL**
  - ~2 order of magnitudes better than direct limits on the width
  - Similar limit for CMS
- Very interesting measurement to perform with RUN2 data (and HL-LHC)
  - $\mu_{offshell}$ measurement sensitivity @ 20-30% level with 3000fb^{-1} (stat only)
  - Very important the theoretical knowledge of the $gg\rightarrow(H^{*})\rightarrow VV$ process and the backgrounds at higher orders in QCD

backup



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