Modelling of higher order QCD corrections in the gg→VV process

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Outline of the talk

- Several studies have shown that the high-mass off-peak regions in the H→ZZ and H→WW channels above the VV mass threshold have sensitivity to off-shell Higgs production and interference effects - this feature is exploited to characterize the Higgs boson signal strength and its associated couplings

★ The main core of the talk will cover the treatment of the QCD-related systematic uncertainties related to the Monte Carlo modelling of the gg→(H*)→VV related processes

☑ many available tools for LO background and interference, i.e. gg2VV, MCFM, MadGraph,....

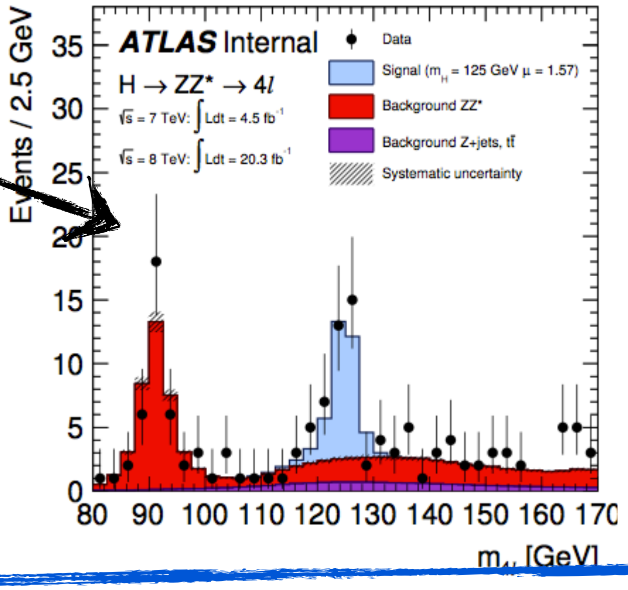
- Parton shower dependence on higher order QCD corrections are investigated
- Higher order QCD corrections to the VV system are studied using SherpaOpenLoops which includes matrix-element calculations for the first hard jet emission
- Impact of the QCD scale (renormalization, factorization and resummtion scales) variations worked out

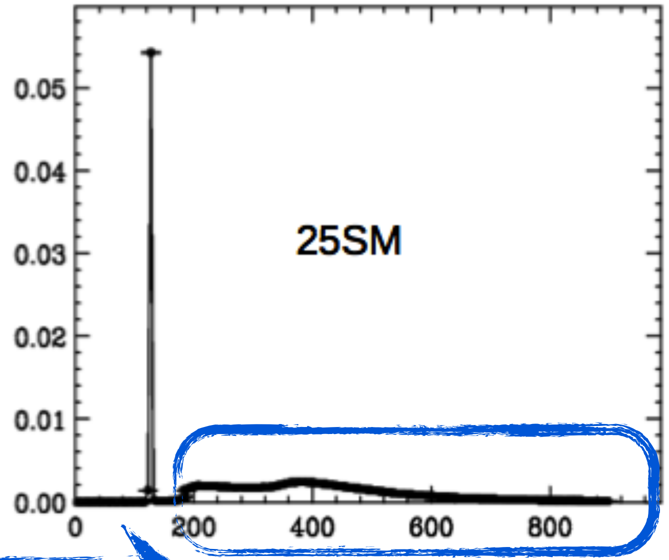
★ A brief overview of the analysis strategy is presented as well as a quick glance to the final results on the off-shell signal strength extraction and the Higgs boson width (published in EPJC-75-2014-335)

➡ Final results published (with $\sqrt{s}$=8 TeV dataset) for an ATLAS Note (http://cds.cern.ch/record/2127515/files/ATL-PHYS-PUB-2016-006.pdf) and in the Handbook of the LHC Cross Section 4: Deciphering the Nature of the Higgs sector (https://arxiv.org/abs/1610.07922)

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)

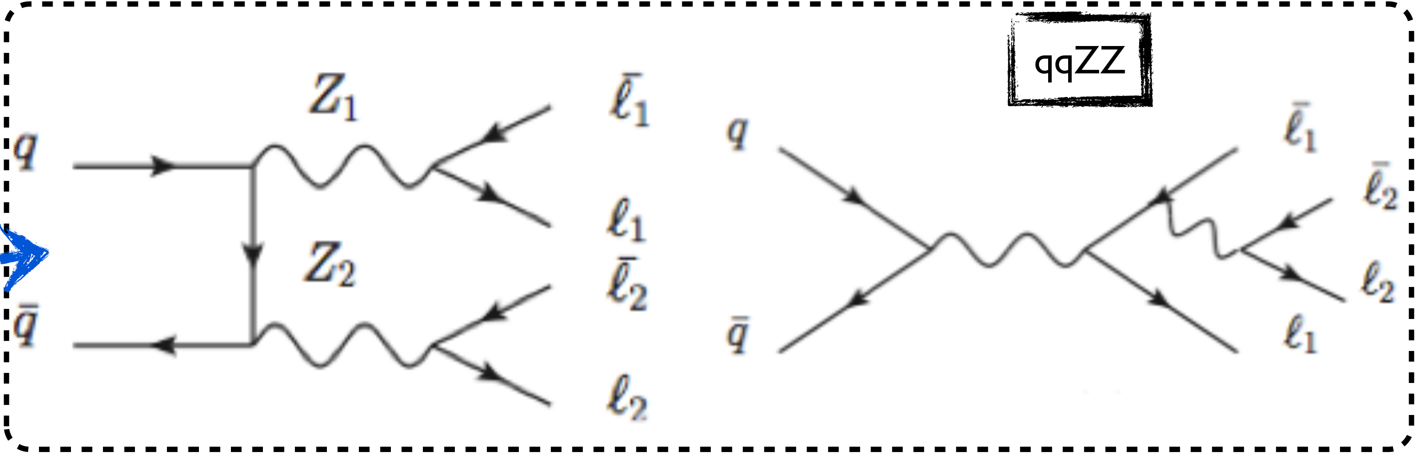
- The ratio of off-shell and on-shell production cross sections will lead to an indirect measurement of the μ_offShell and consequently the Higgs width, as long as the product of the coupling to initial and final states remains constant

☑ Limit on the off-shell couplings (μ_{Offshell}) in the high mass region

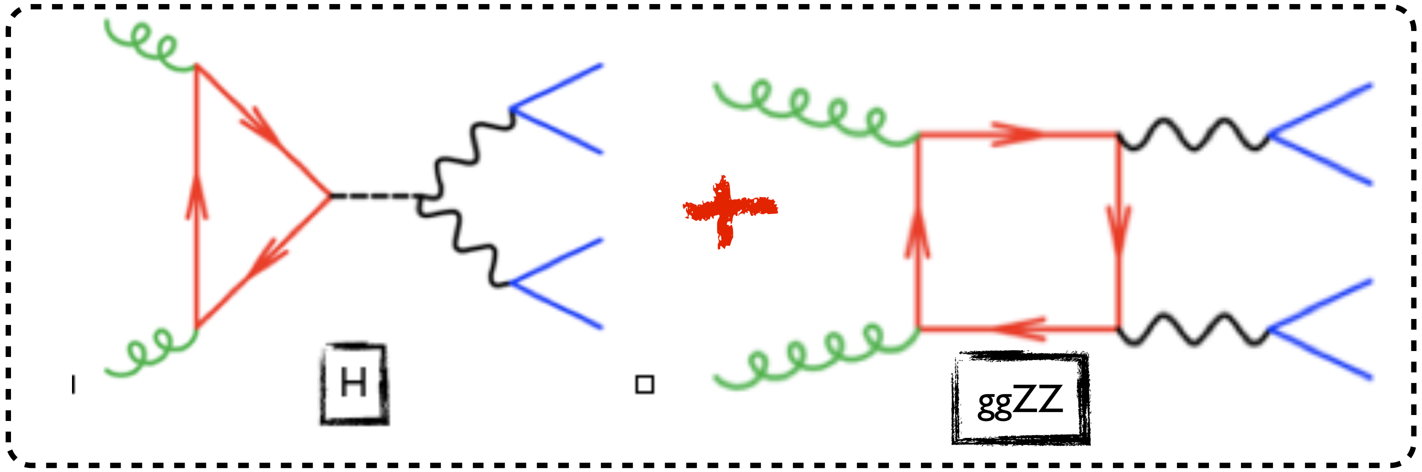
☑ We'll interpret this off-shell limit as a limit on Γ_H ($\Gamma_{H,SM}$=4.2 MeV) when combining with the on-shell (low mass) measurement

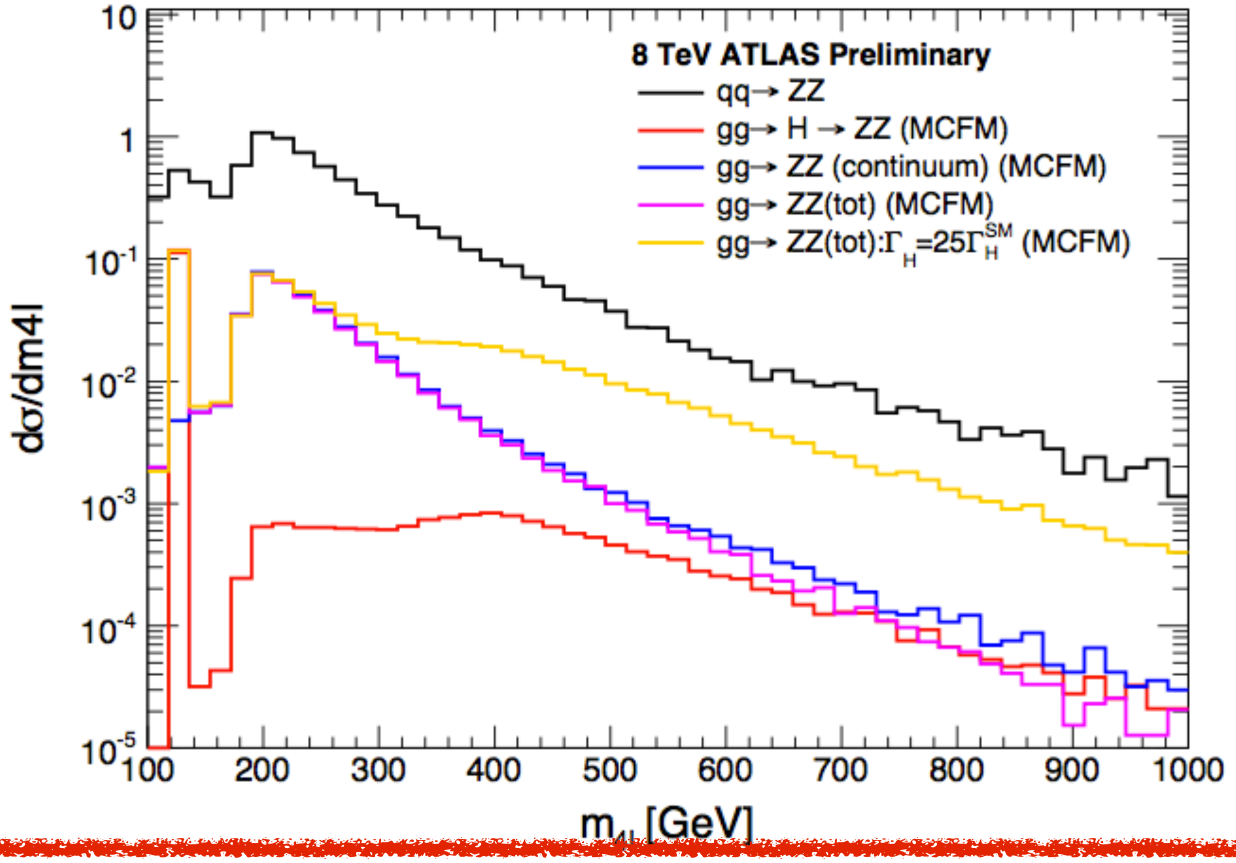
Off-peak Higgs signal strength - The Run1 analysis

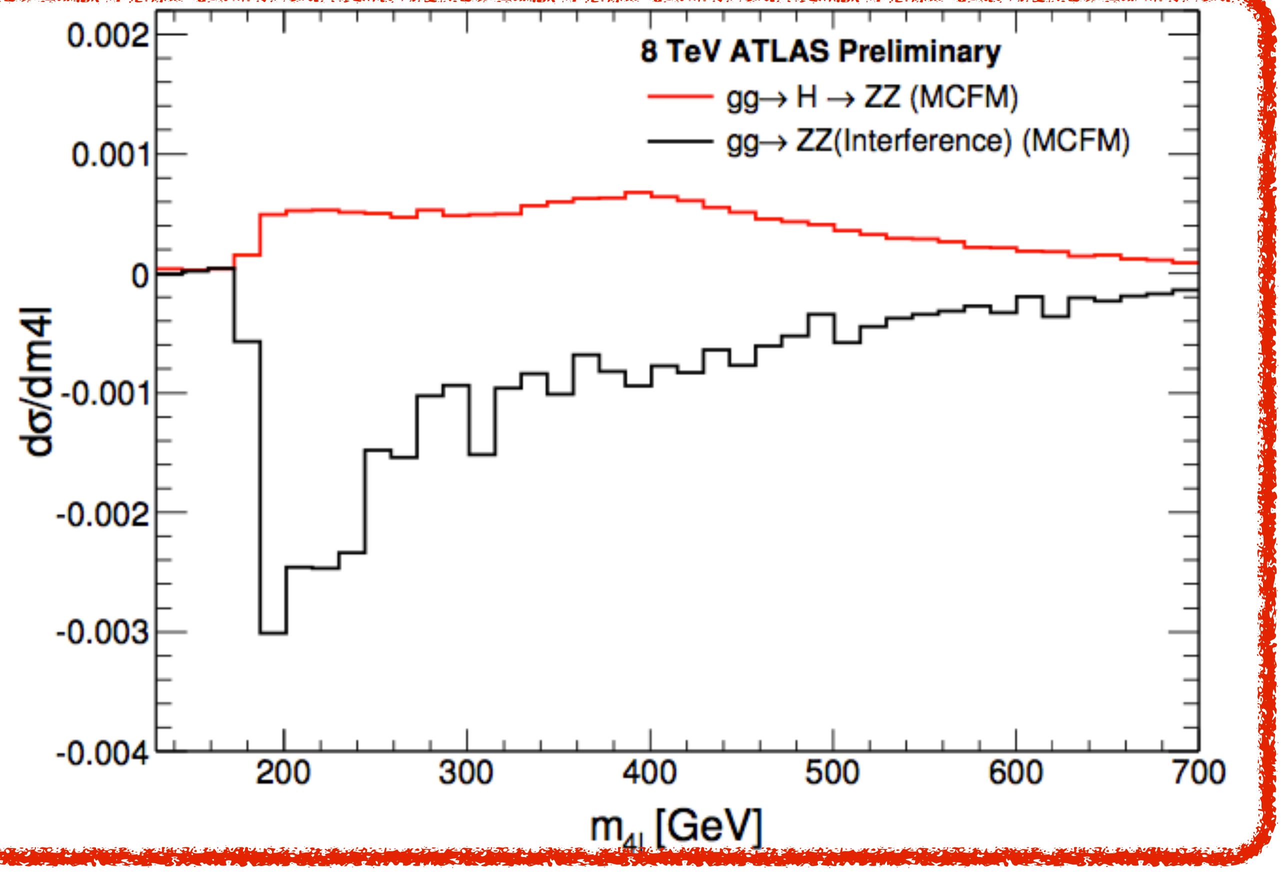
- Signal: gg→H→VV (VBF - Phantom) with gg2VV or MCFM
- Backgrounds: gg→VV, qq→VV (m_{4l} -dependent k-factor applied to POWHEG NLO to match NNLO)
- Quantum (negative) interference effects between gg→H→ZZ and gg→ZZ



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





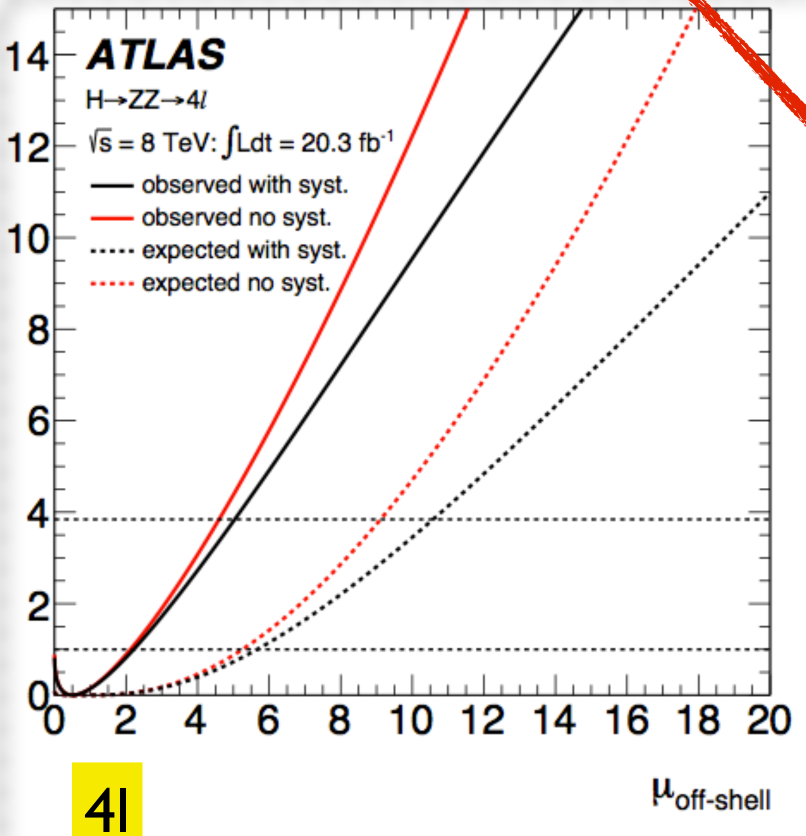


Run1 results off-shell analysis (4l + 2l2v + WW→lvlv)

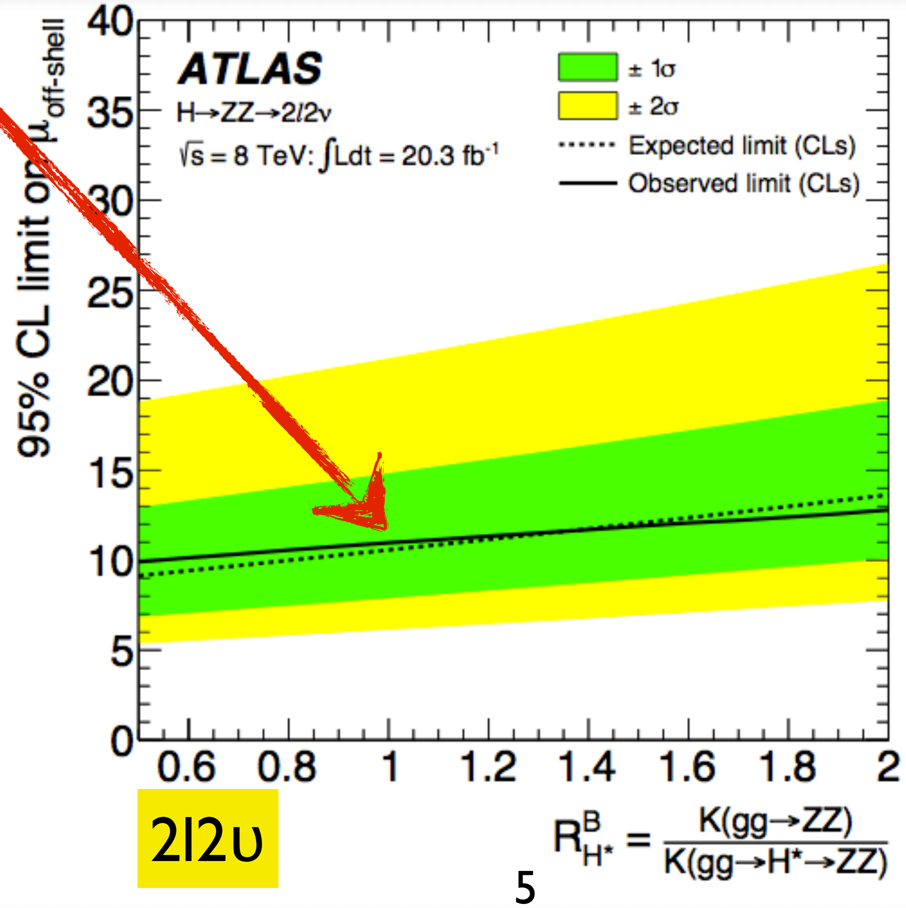
- CLs method to extract 95% CL limit on $\mu_{Offshell}$ (combination of 4l, 2l2v and WW→lvlv)
    - Results presented as a function of R_B=K(gg→VV)/K(gg→H→VV)
    - The systematic uncertainties are dominated by the QCD scale of gg→VV, qq→VV and gg→H→VV

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

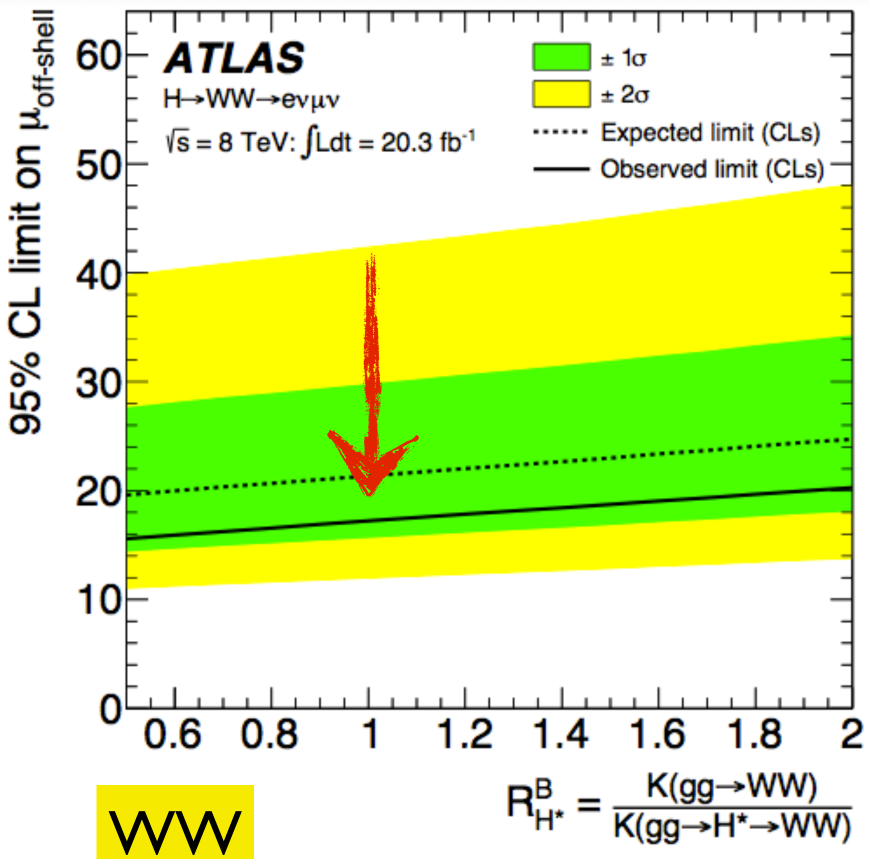
	Observed			Median expected		
$R^B_{H^*}$	0.5	**1.0**	2.0	0.5	**1.0**	2.0
$ZZ \to 4\ell$ analysis	6.1	**7.3**	10.0	9.1	**10.6**	14.8
$ZZ \to 2\ell\, 2\nu$ analysis	9.9	**11.0**	12.8	9.1	**10.6**	13.6
$WW \to e\nu\,\mu\nu$ analysis	15.6	**17.2**	20.3	19.6	**21.3**	24.7



4l



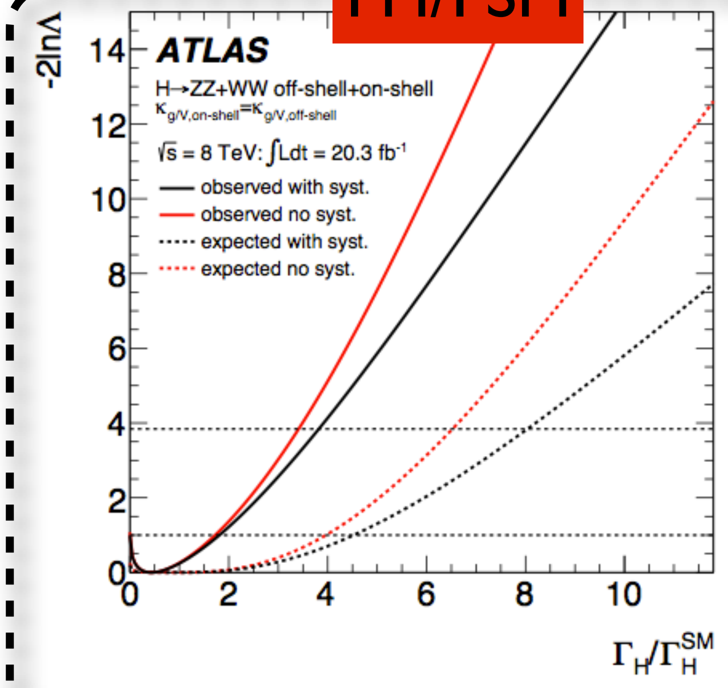
2l2υ

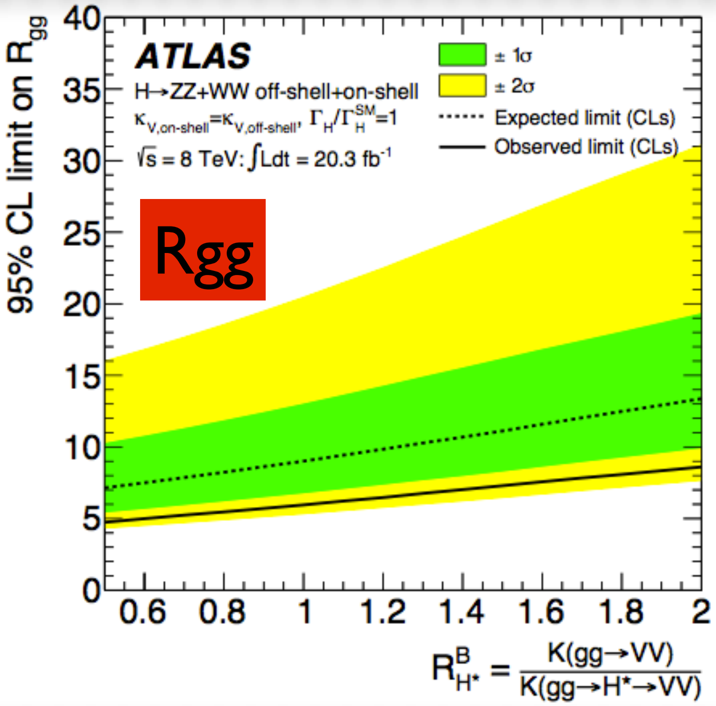


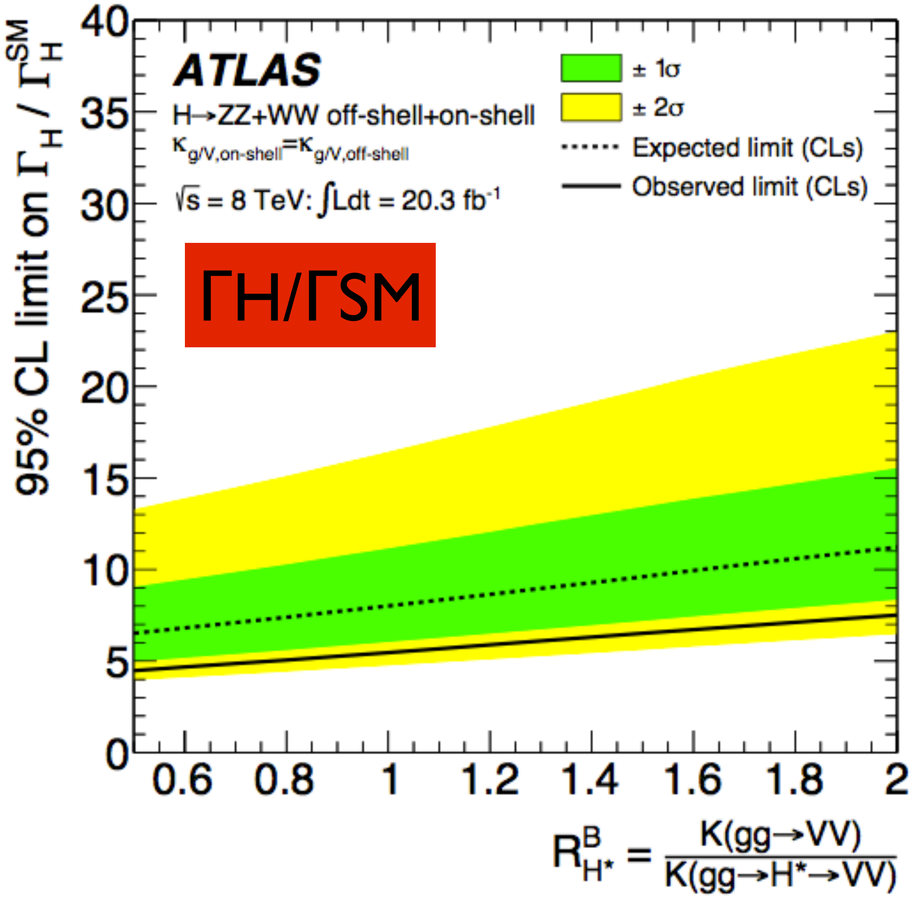
WW

Run 1 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 $R_{gg}=\mu_{ggF}(\text{off-shell})/\mu_{ggF}(\text{on-shell})$ - sensitive to possible modification of the gluon couplings in the high mass range - assuming $\Gamma_H/\Gamma_{SM}=1$


ΓH/ΓSM


Rgg


ΓH/ΓSM

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)

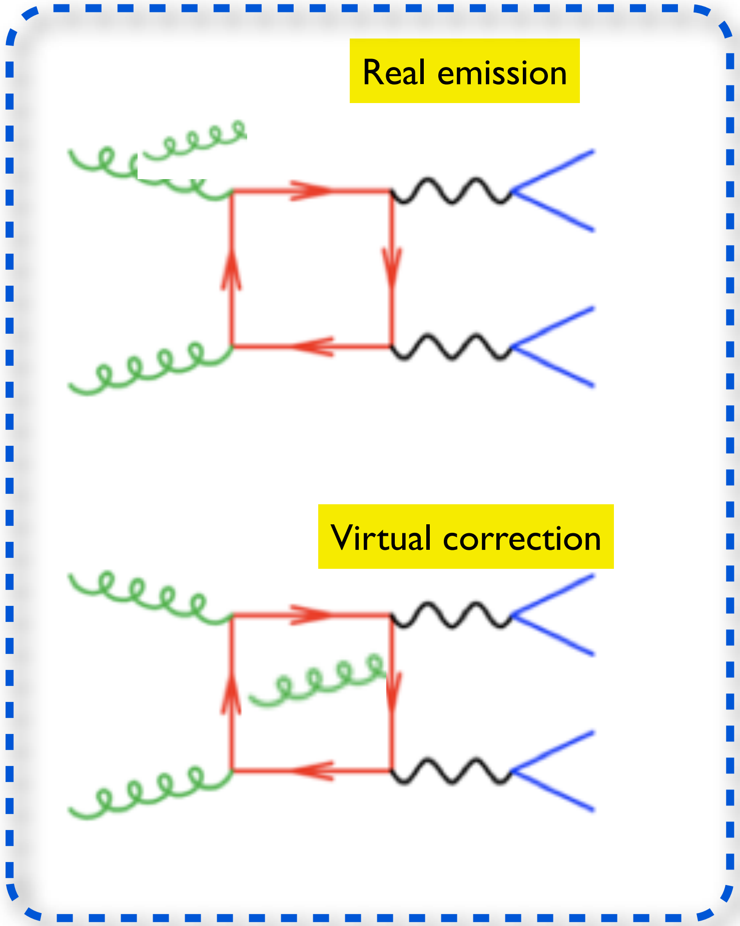
	Observed			Median expected		
$R^B_{H^*}$	0.5	**1.0**	2.0	0.5	**1.0**	2.0
Γ_H/Γ_H^{SM}	4.5	**5.5**	7.5	6.5	**8.0**	11.2
$R_{gg} = \kappa^2_{g,\text{off-shell}}/\kappa^2_{g,\text{on-shell}}$	4.7	**6.0**	8.6	7.1	**9.0**	13.4

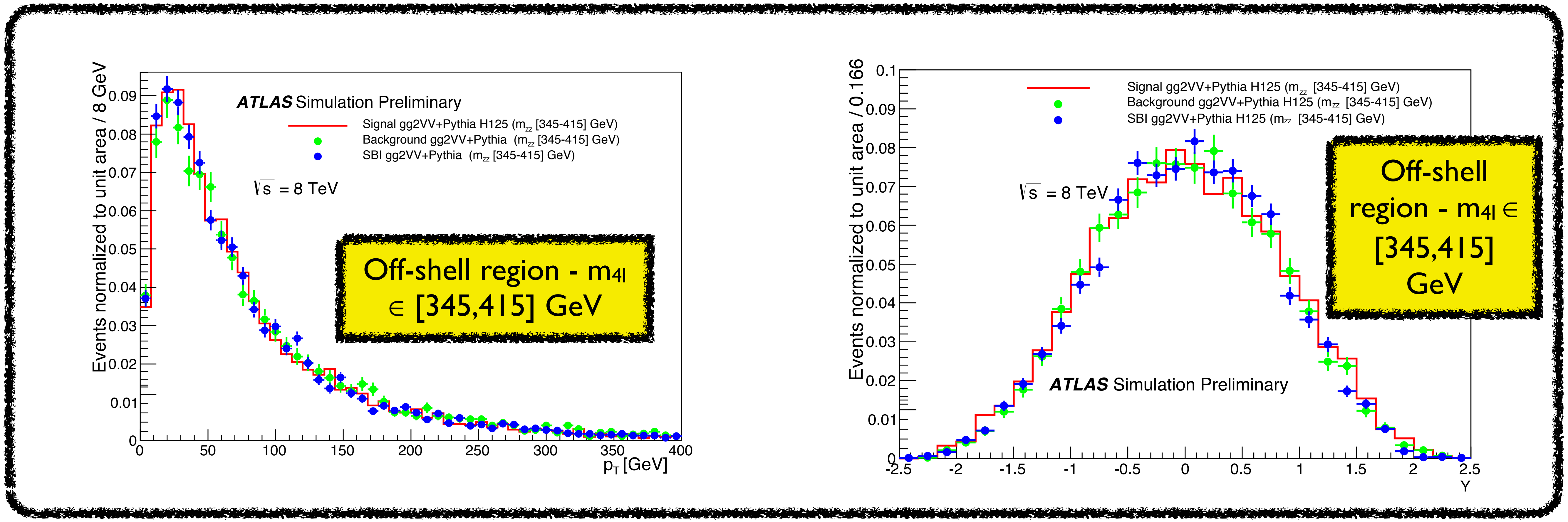
How to approximate NLO-like behaviour for the gg background

➡ Main issue: NLO calculations for gg→ZZ is not available

✓ gg2VV (+Pythia) MC generator: LO +PS (no virtual or real QCD corrections) Sherpa (+ OpenLoops): ggVV+1 jet (at LO) + PS - best approximation - not a complete NLO generator because the real QCD corrections are included but not the virtual ones (it contains the LO gg→ZZ process+ 1j and merges this LO+gg→ZZ + 0j matrix-element)

✓ Test performed on the agreement between Sherpa signal (LO+0/1 j) and Powheg signal (complete NLO) for the signal in the on and off-shell → Signal is the only way to test NLO





Off-shell region - $m_{4l} \in [345,415]$ GeV

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Parton Shower Scheme dependency

✓ No higher order matrix element calculations are available for the gg-initiated processes (gg2VV or MCFM)

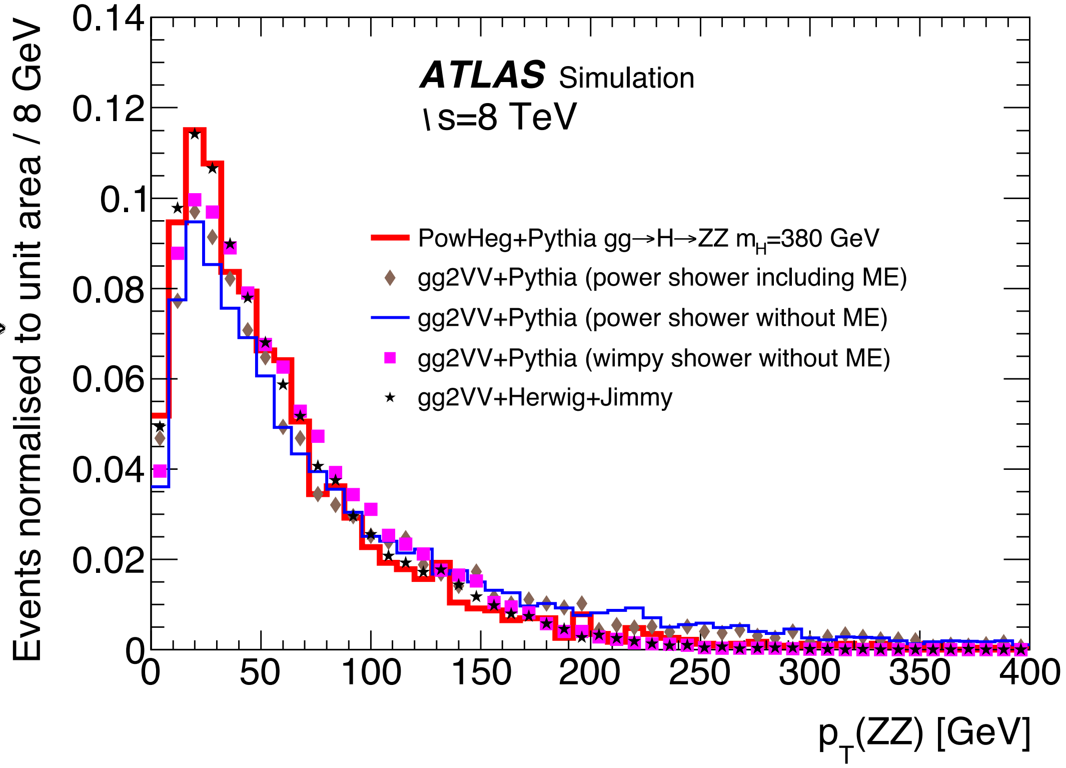
- ➡ simulation of the QCD radiation with parton shower
- ➡ the generation is done at LO, hence no clear prescriptions to evaluate the uncertainties on the QCD scale

☐ The 4l analysis is inclusive in QCD observables → no acceptance systematics are applied (impact of the acceptance on ptZZin 4l found to be negligible)

☑ The 2l2v is not inclusive in QCD (dependence of the QCD-related observables on the kinematic cuts of the analysis)

- ☑ gg2VV (LO) central value of ptZZ is reweighted to POWHEG (NLO).
- ☑ Difference between gg2VV (LO) with PYTHIA 8 power shower (default) and the full NLO Powheg is regarded as the acceptance systematics on gg2VV

- Powheg NLO is generated at mH=380 GeV
- gg2VV is showered with:
  - Pythia power and wimpy showers (jet pt scale emission of the PS)
  - Herwig+Jimmy



Higher order QCD corrections

✓ Higher order QCD corrections for the $gg \to ZZ$ processes studied using Sherpa+OpenLoops (LO $gg \to ZZ$+1-jet matrix-element, LO $gg \to ZZ$+0-jet matrix-element)

- comparisons deployed to a full-accuracy Monte Carlo generator, i.e. Powheg reweighted to HRes2.1 predictions to reach NNLO+NNLL
- second comparison against a pure LO+PS generator, gg2VV+Pythia8

▶ Systematic uncertainties on the distributions are drawn as shaded boxes and extracted from scale variations of Sherpa+OpenLoops and HRes2.1 as detailed later in the talk

✓ Set of requirements on kinematics applied in the generation phase space (grid-stage)

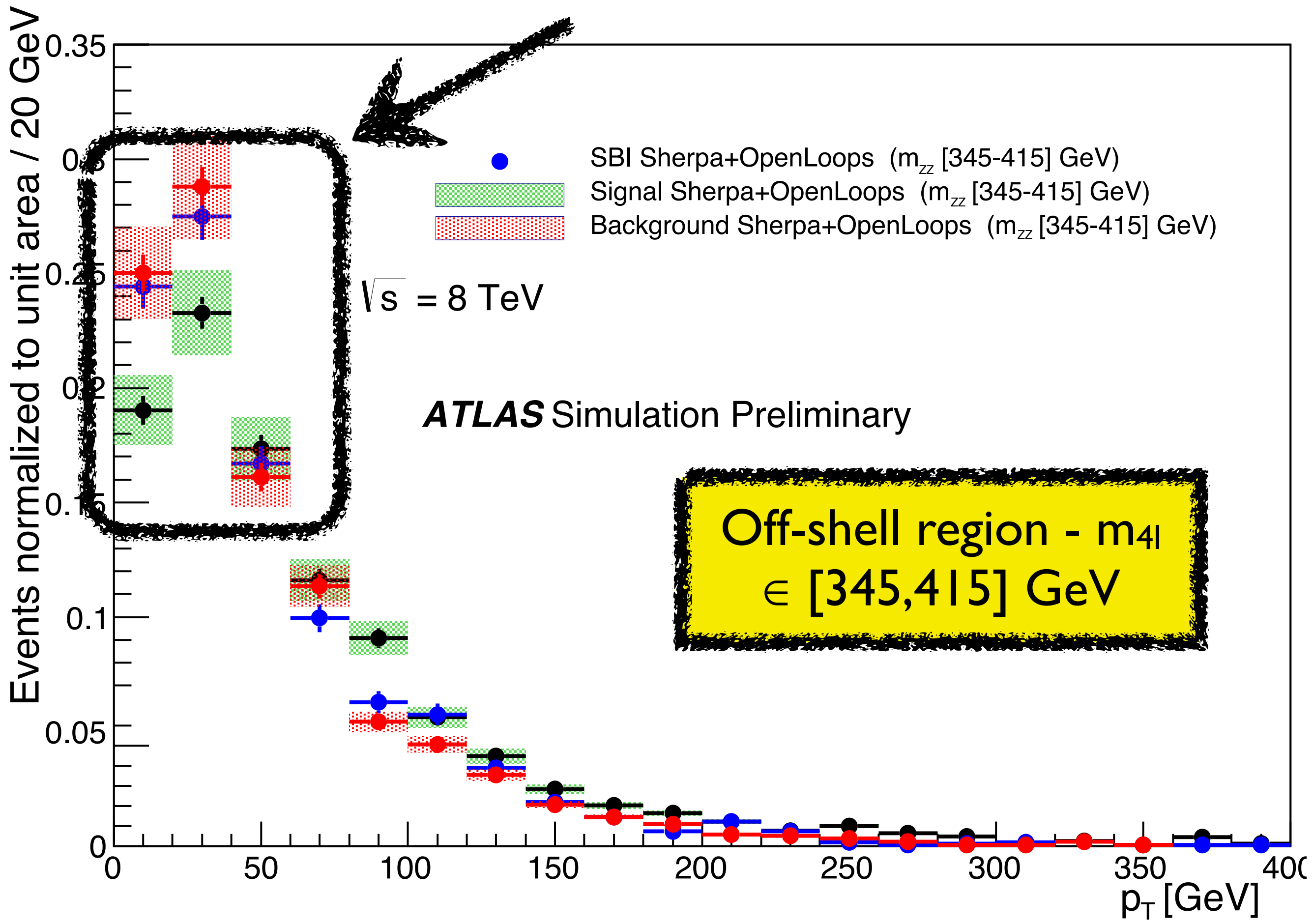
○ $m_{4l}>100$ GeV, $p_{T_l}>3$ GeV, $|\eta_l|<2.8$, $m_{Zl,Z2}>4$ GeV

➡ additional selection criteria are applied on the final state quadruplet, i.e.

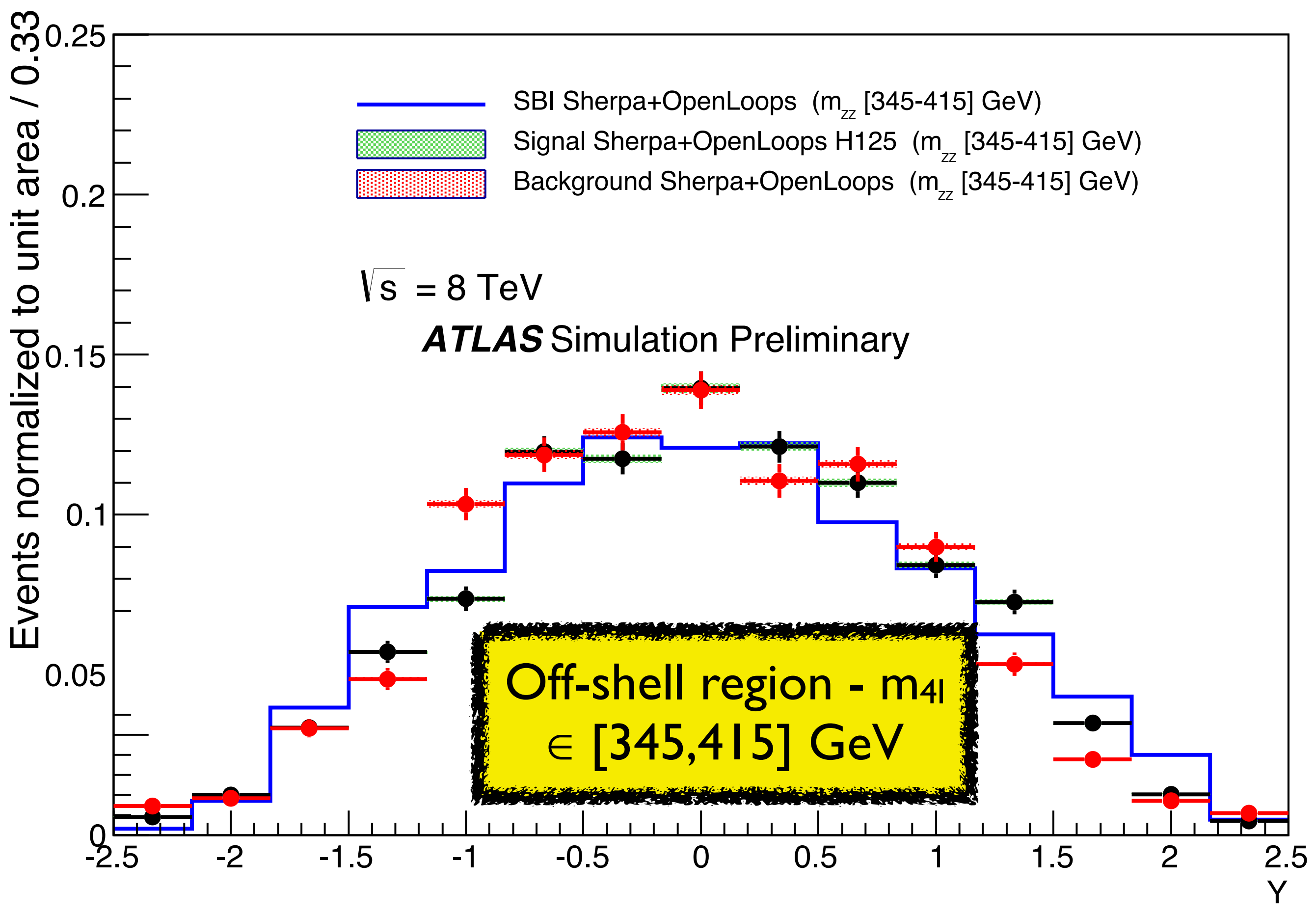
- ○ $p_T>20, 10, 15, 5$ (6) GeV,
- ○ $|\eta|<2.5$
- ○ $(50<m_{Z1}<106)$ GeV,
- ○ if $m_{4l}<140$ GeV → $m_{Z2}>12$ GeV, $140<m_{4l}<190$ GeV → $m_{Z2}>0.76\cdot(m_{4l}-140)+12$ GeV, $m_{4l}>190$ GeV → $m_{Z2}>50$ GeV

Characterization of Sherpa+OpenLoops

- Comparison of the gg→ZZ signal processes (signal, background and the full component comprising signal, background and interference) shows a significantly harder pt spectrum for the signal term and larger jet multiplicity
  - ✓ caused by the presence of the additional matrix-element correction to the first-jet emission triggering different treatments of signal/background components
  - ✓ validation performed by explicitly removing the 1-jet matrix element computation from the Sherpa+OpenLoops generation→full compatibility found between signal and background



Off-shell region - m_{4l} ∈ [345,415] GeV



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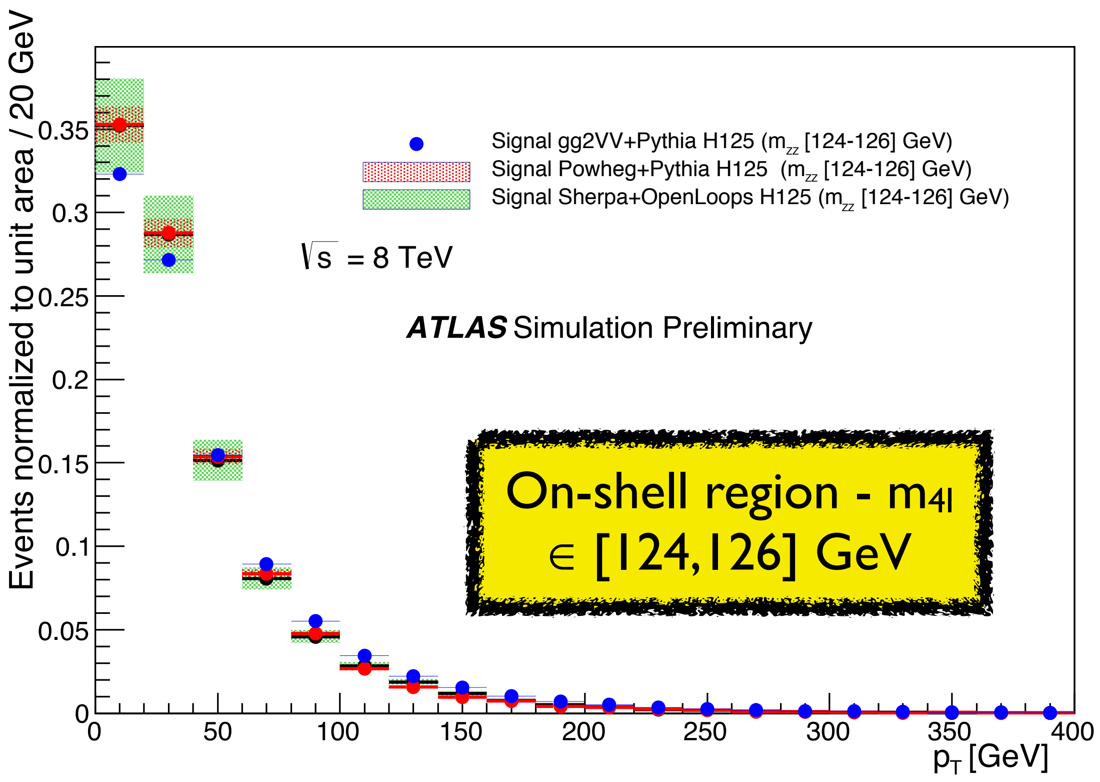
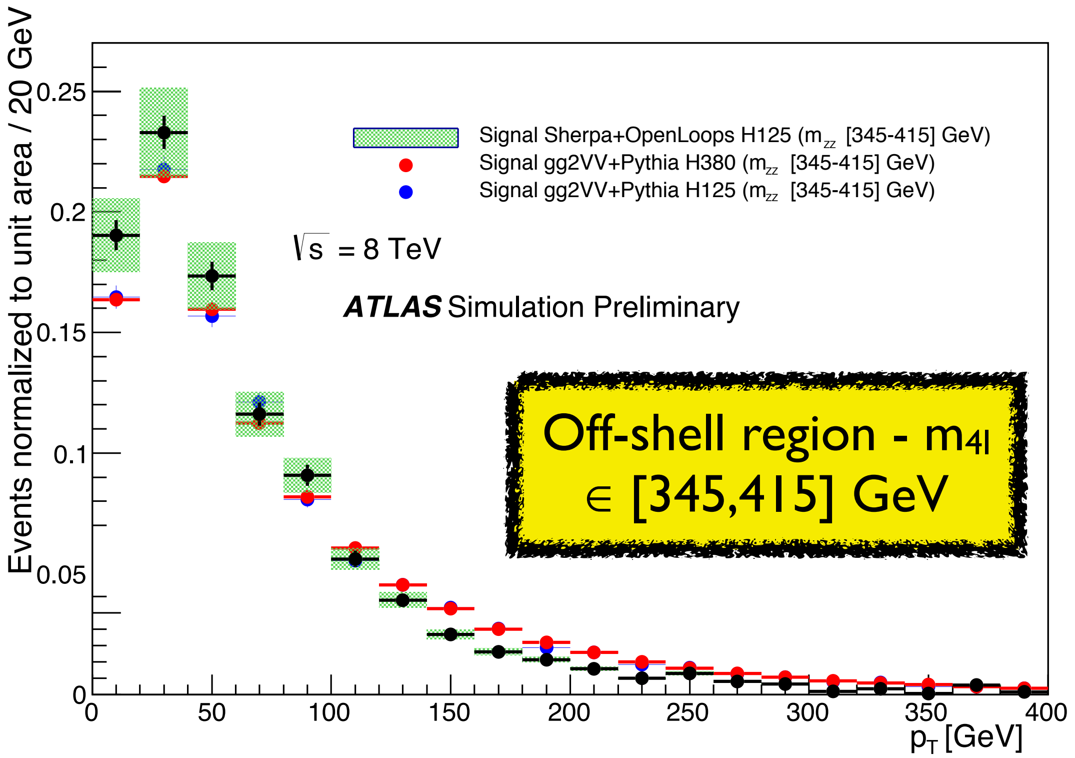
Higher order QCD corrections



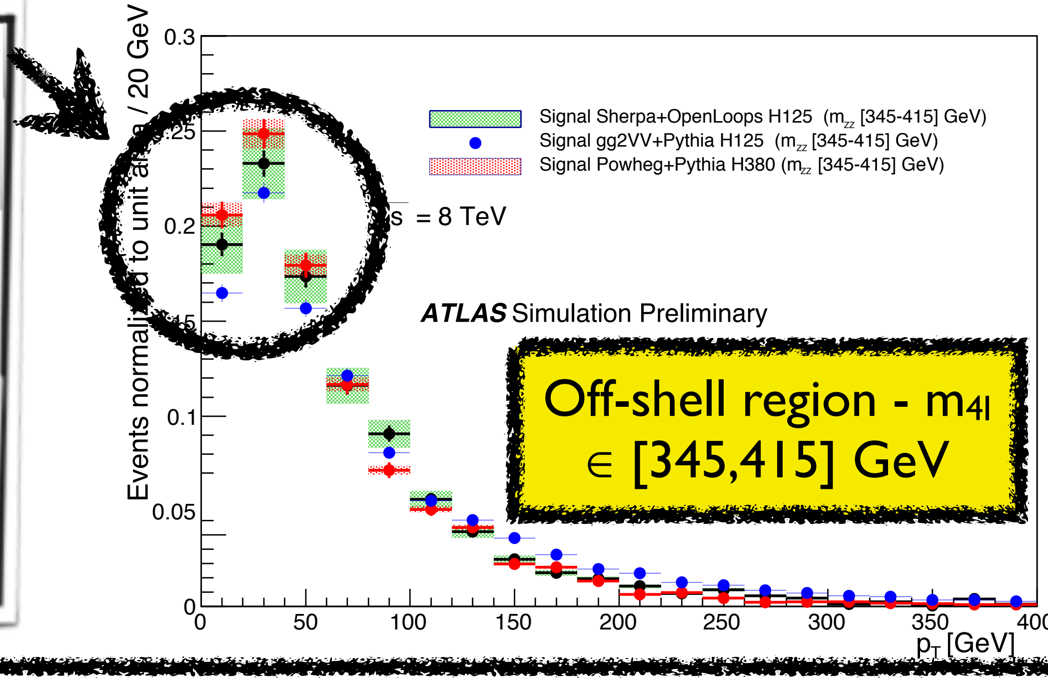
On-shell region - m_{4l} ∈ [124,126] GeV



Off-shell region - m_{4l} ∈ [345,415] GeV

- ✓ Lack of higher order QCD calculations in gg2VV results in different pt spectra (order of 20% in the relevant kinematic region) compared to the higher order Powheg and Sherpa+OpenLoops MC samples
- ✓ In the high-mass region, the on- and off-shell gg2VV components (m_H=380 GeV and 125 GeV) agree fairly well

- Differences in transverse momentum between Sherpa and gg2VV in the off-shell mass region not covered by the uncertainties assigned to Sherpa+OpenLoops
  - ➡ given the better treatment of the first hard-jet emission exploited by Sherpa+OpenLoops, the gg2VV pt is reweighted to the Sherpa+OpenLoops
  - ➡ no reweighting in Y as no significant mis-modelling is found

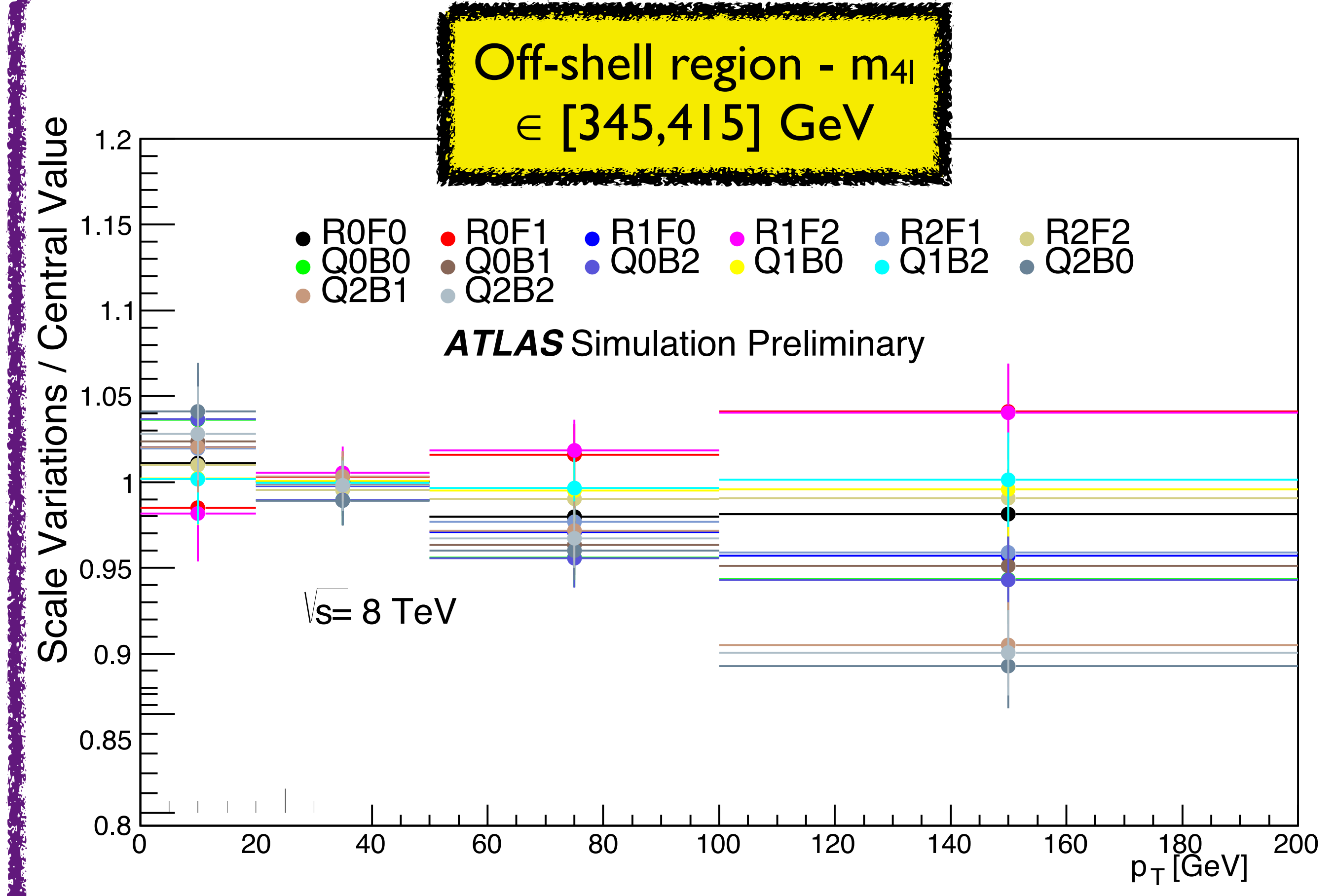


Off-shell region - m_{4l} ∈ [345,415] GeV

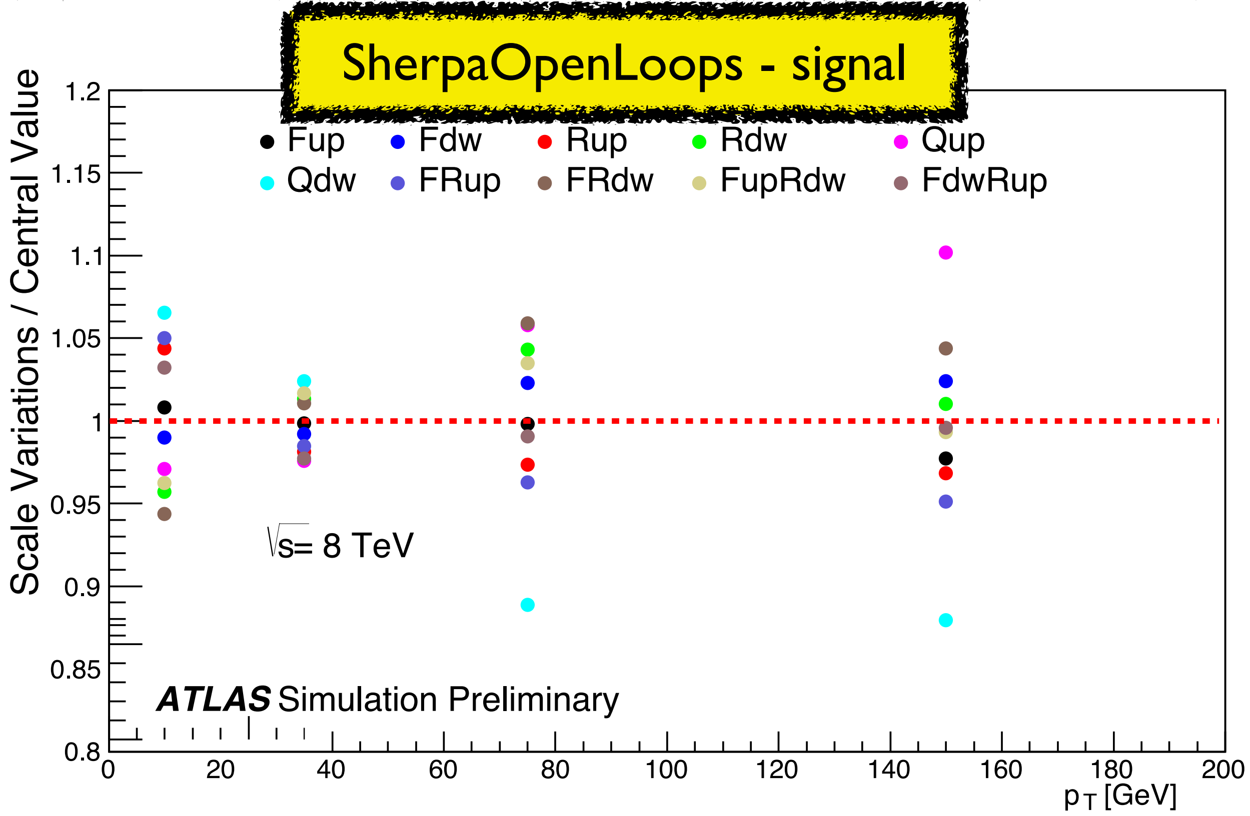
QCD scale variations

- To evaluate the systematic effects on the uncertainties of pT/η in the ZZ frame, QCD scale variations (factorisation, resummation and renormalization) are generated
- Impact of PDF uncertainties also evaluated: nominal PDF set CT10 applied on the signal is compared to MSTW2008 and with NNPDF2.3 in bins of ZZ transverse momentum and rapidity → impact found to be negligible (less than 3%)
- 5/10% effect on Sherpa+OpenLoops QCD scales (dominated by the resummation scale)
- Sherpa uncertainty encompass HRes2.1 →Sherpa does not contain the full NNLO calculation

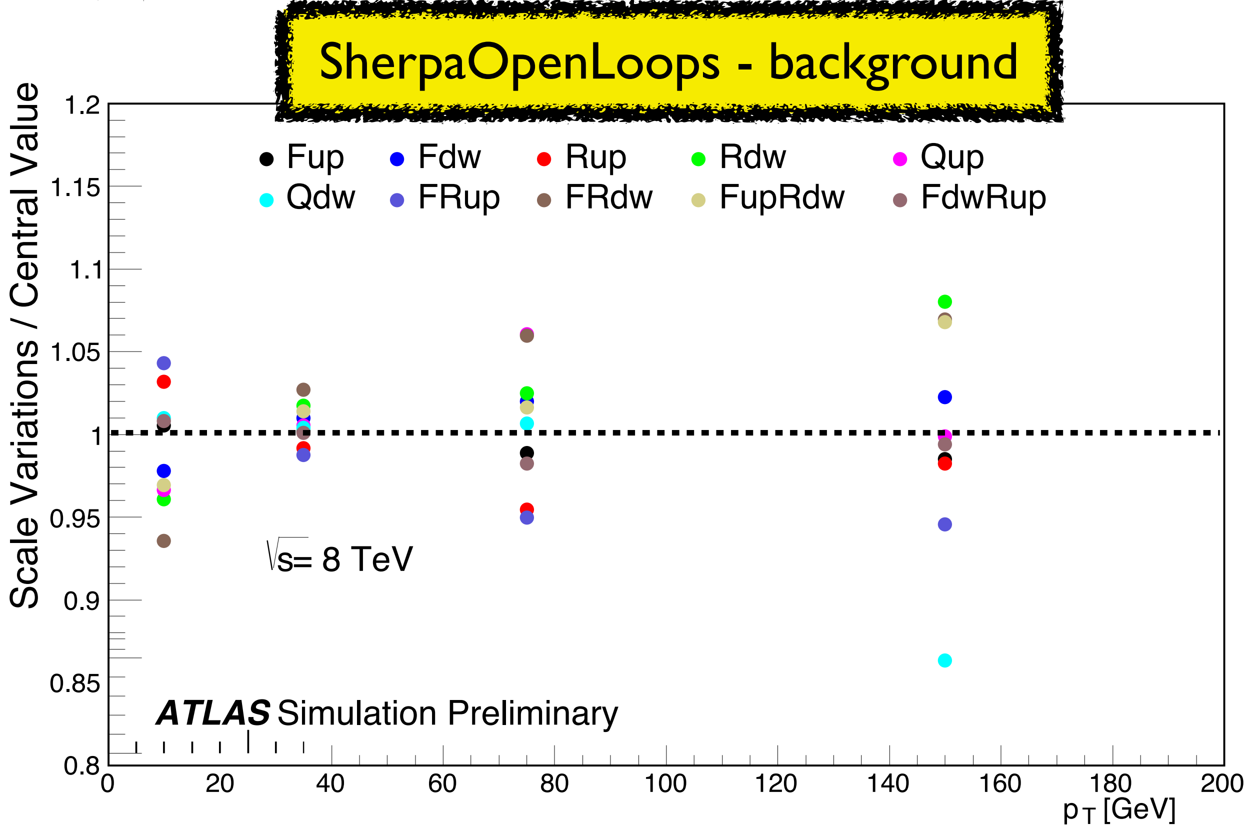
Off-shell region - $m_{4l} \in [345,415]$ GeV



SherpaOpenLoops - signal



SherpaOpenLoops - background



Wrapping up and conclusions

- ✓ Higher order QCD corrections to the transverse momentum and the rapidity of the VV system are studied using Sherpa+OpenLoops which includes matrix-element calculations for the first hard jet emissions

- ✓ A difference of order 20% in the relevant kinematic region is observed when comparing the pt distribution of LO+PS generator to Sherpa+OpenLoops while the difference in rapidity is negligible

- ✓ This difference in pt of the VV system can modify the kinematic observables used in the analysis leading to variations in both the kinematic shapes and acceptance
    - to account for these effects, the LO generators can be reweighted to Sherpa +OpenLoops in pt of the VV system
    - The systematic uncertainties associated with the Sherpa-based reweighting are assessed by varying the typical QCD scales (renormalisation, factorisation and resummation) while the PDF uncertainty was found to be small

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Thanks for your attention!!!

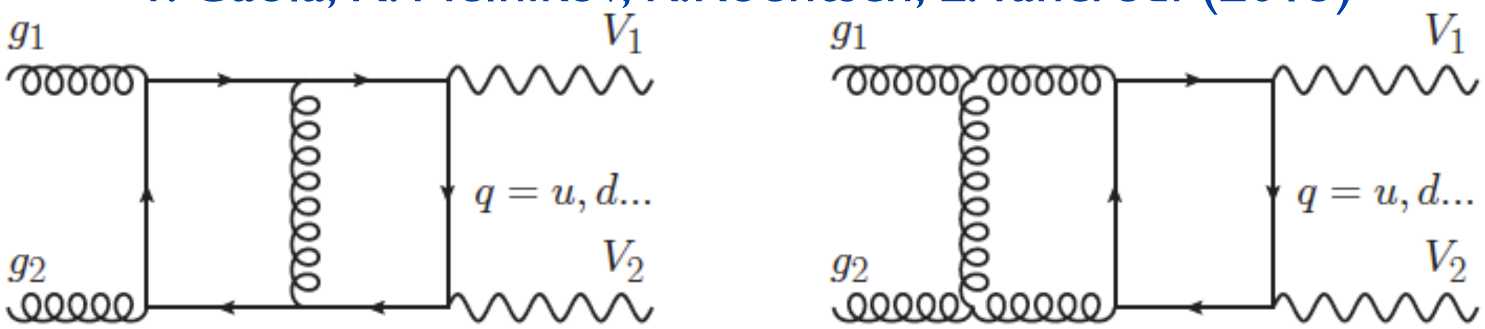
Additional slides

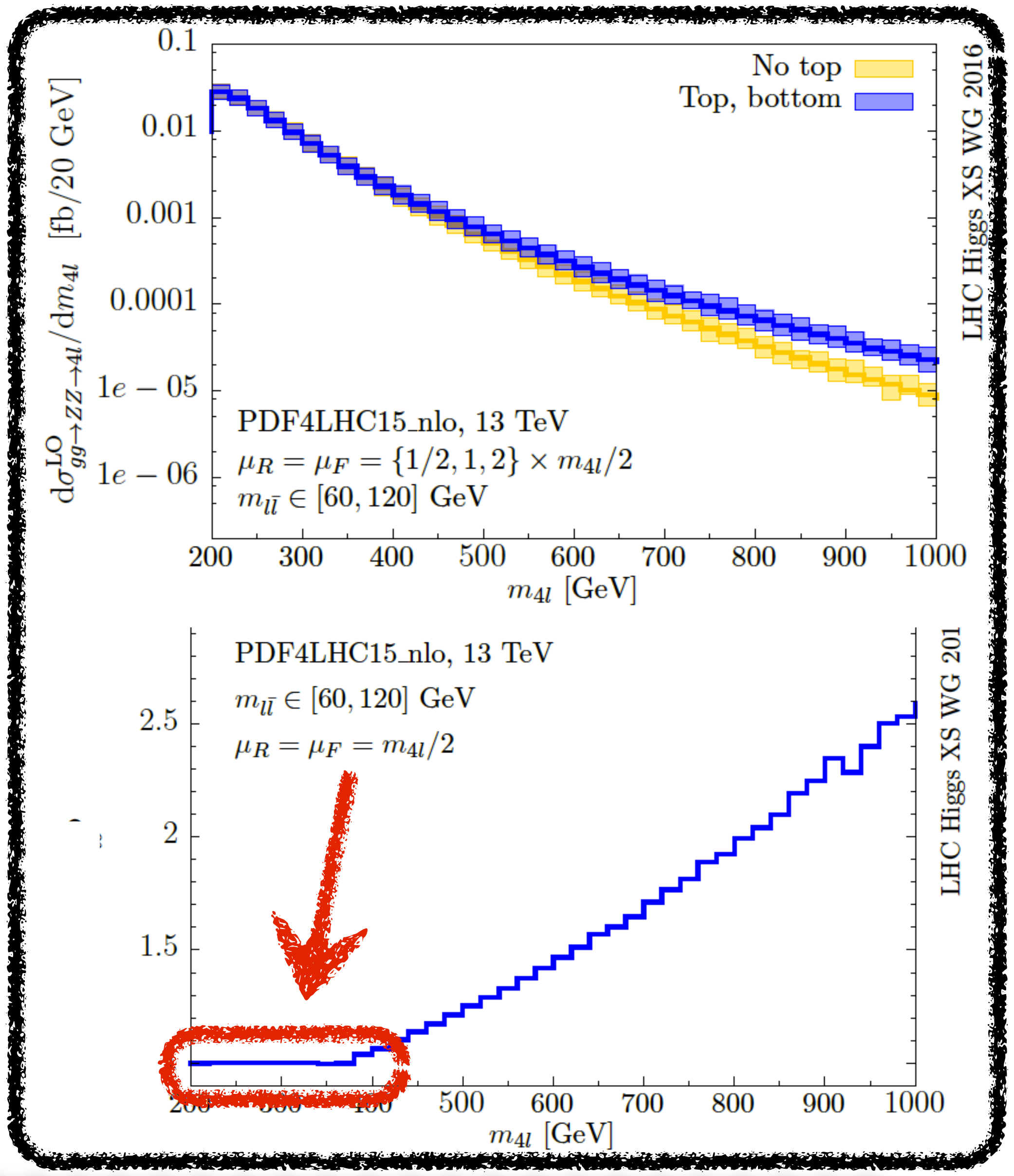
A glance on the current status of the higher order calculations

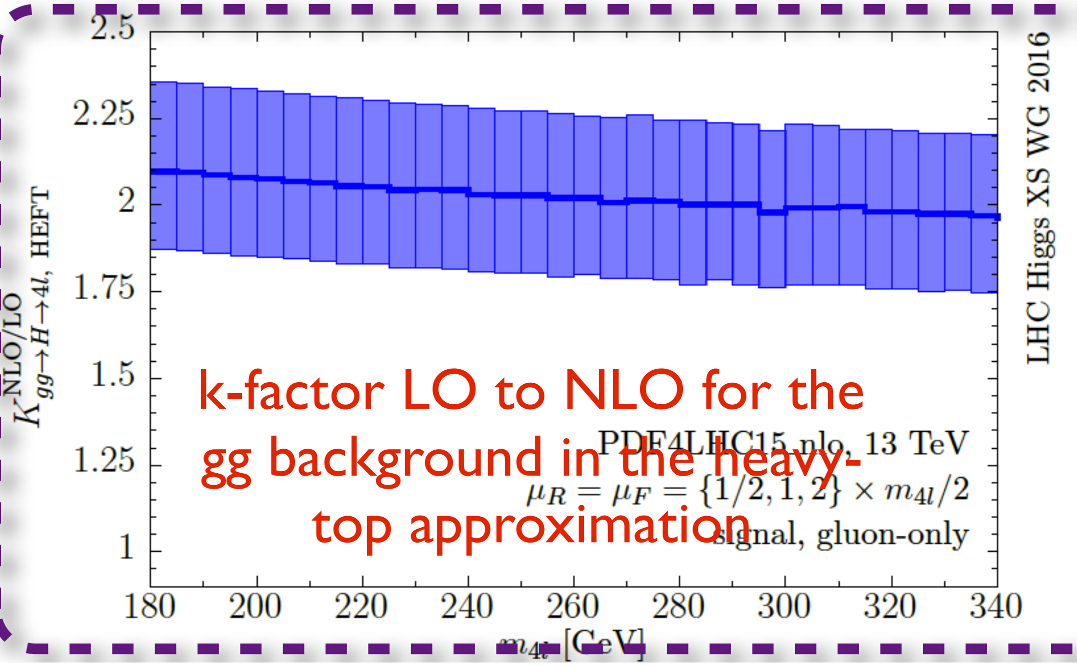
- Computing NLO corrections to gg→VV is highly non-trivial as it involves the knowledge of two-loop diagrams with both external and internal massive particles

- NLO QCD corrections for gg→VV processes are now available in case of massless quarks running in the loop
  - this approximation is expected to hold quite well below $m_{4l} < 2m_t = 350$ GeV

F. Caola, K. Melnikov, R.Roentsch, L. Tancredi (2015)







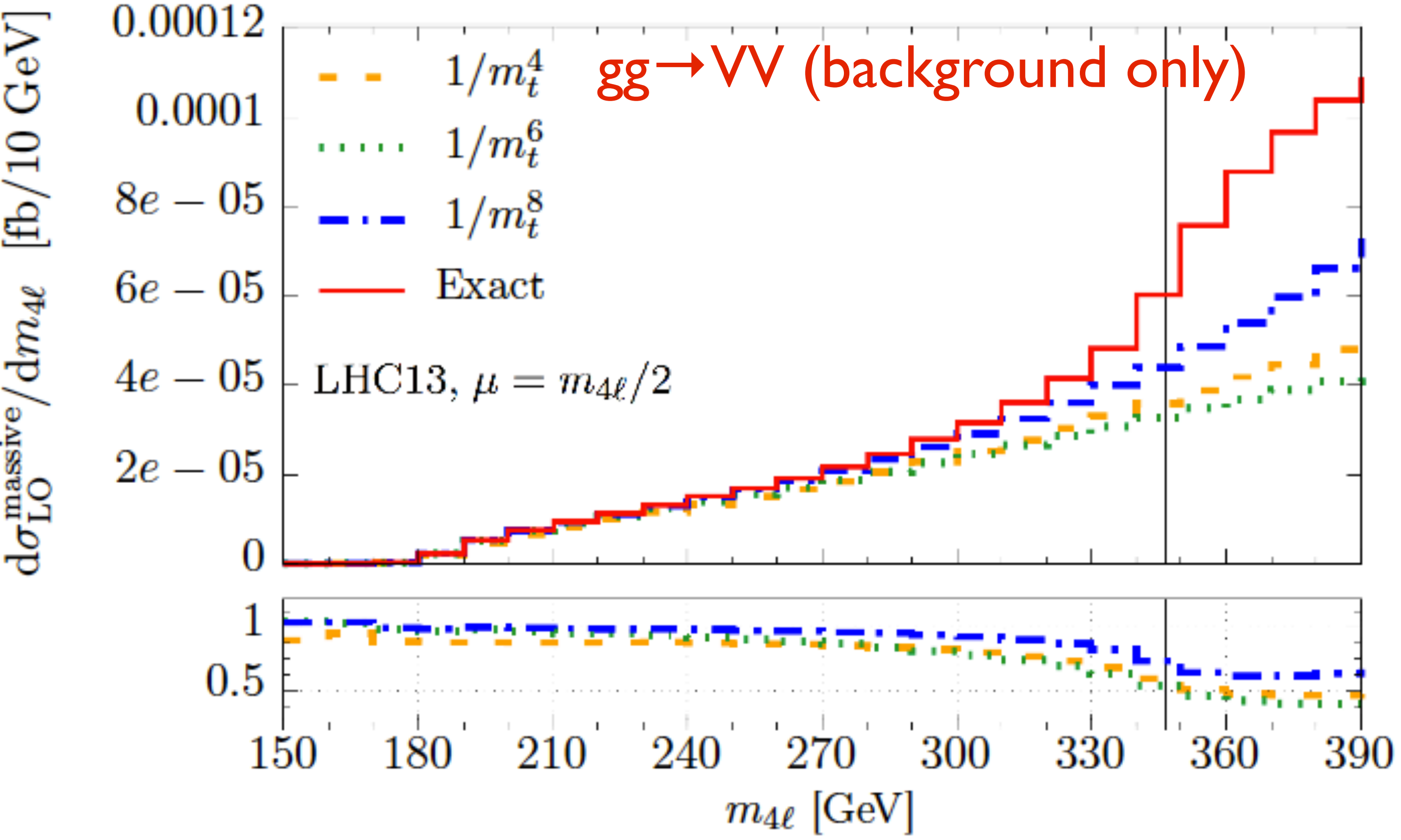
k-factor LO to NLO for the gg background in the heavy-top approximation

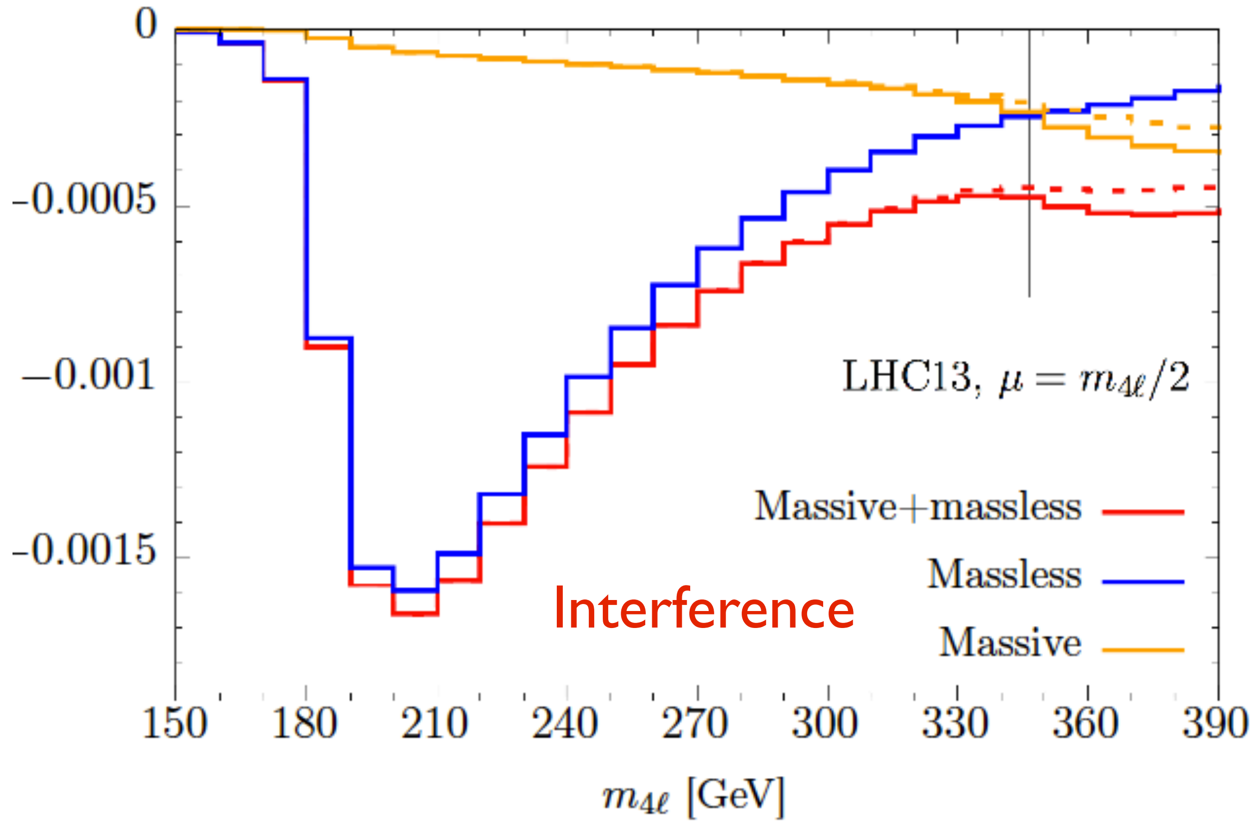
- Effect of finite top quark mass in the loop evaluated (expansion for $m_t \to \infty$ limit - Large Mass Expansion, LME)

- Close to the VV threshold, accurate within 20%

K. Melnikov, M. Dowling (2015)

Precision predictions for interference in the LME calculation





- LO 4-lepton invariant mass distribution with different LME calculations

Scale variations

Process	MC	Nominal Scales	Scale variations	# Variations
$gg \to H \to ZZ$	HRes	$\mu_R = \mu_F = \frac{m_{ZZ}}{2}$	$(\frac{1}{2}\mu_{R/F}, 2\mu_{R/F}), \frac{1}{2} \leq \mu_F/\mu_R \geq 2$	6
		$\mu_Q = m_{ZZ}/2, \mu_B = m_b$	$(\frac{1}{2}\mu_Q, 2\mu_Q), (\frac{1}{4}\mu_B, 4\mu_B)$	8
$gg \to H \to ZZ$	Sherpa	$\mu_R = \mu_F = \frac{m_{ZZ}}{2}$	$(\frac{1}{2}\mu_{R/F}, 2\mu_{R/F}), \frac{1}{2} \leq \mu_F/\mu_R \geq 2$	6
		$\mu_Q = m_{ZZ}/2, \mu_B = m_b$	$(\frac{1}{\sqrt{2}}\mu_Q, \sqrt{2}\mu_Q)$	2
$q\bar{q} \to ZZ$	Powheg	$\mu_R = \mu_F = m_{ZZ}$	$(\frac{1}{2}\mu_{R/F}, 2\mu_{R/F})$	6