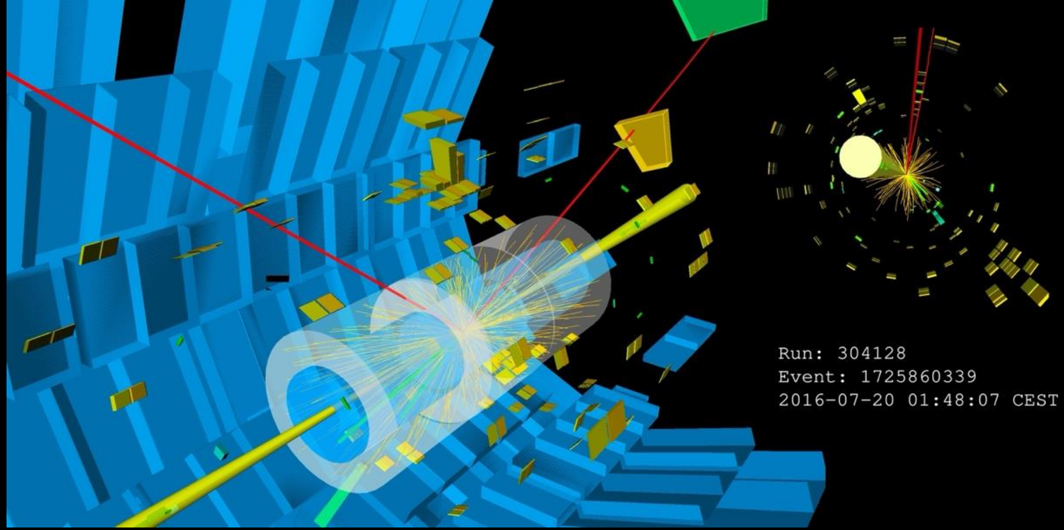


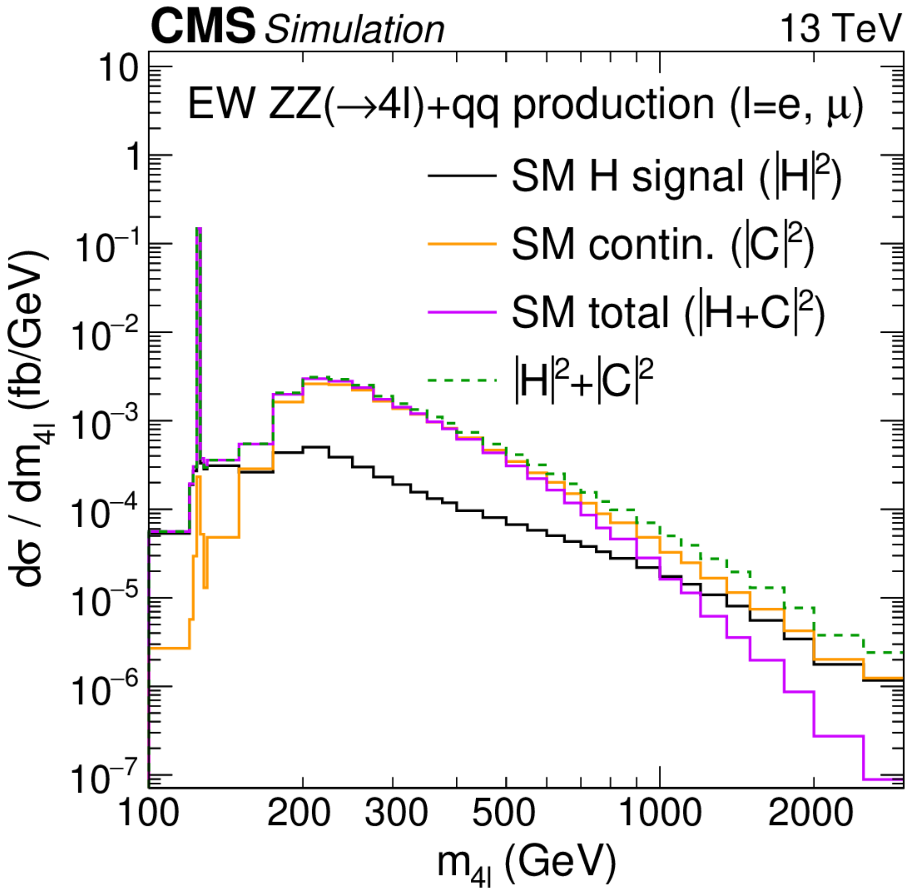
Vector Boson Fusion Offshell Higgs Measurements

Theory considerations from the experiments

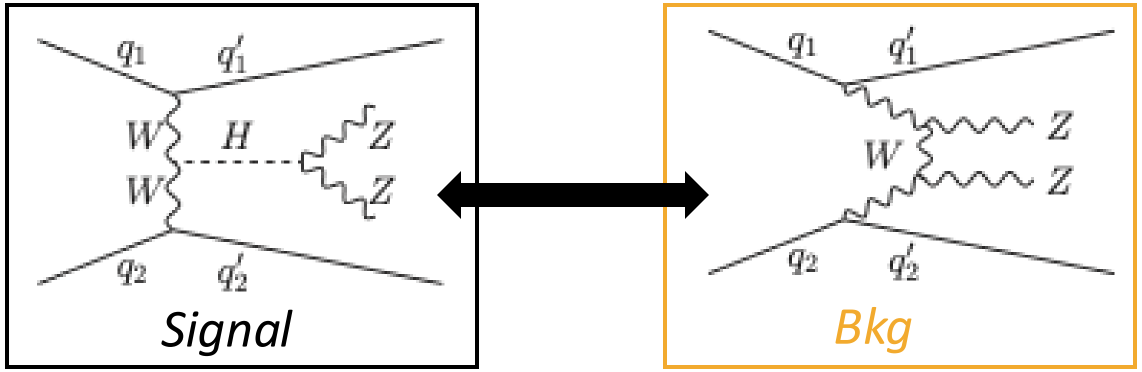
Robin Hayes
LHCHWG Offshell Subgroup Meeting
Nov. 19 2024

VBF in Offshell $H^* \to VV$

$H^* \to VV$ production has been used at the LHC to probe offshell Higgs production and constrain the Higgs width.



Dominant channel is $gg \to H^* \to VV$ (ggF), but electroweak $qq \to H^* \to VVqq$ (VBF) is increasingly well-measured.



Offshell VBF Higgs signal and continuum VBS background interfere.

VBF in Offshell Higgs

In this talk:

- Glimpse of current offshell Higgs VBF measurements
  - Sensitivity and strategy

- Modelling VBF in analysis
  - Generators and uncertainties

- Moving forward: effect of higher-order corrections on VBF
  - How can we improve our current treatment?

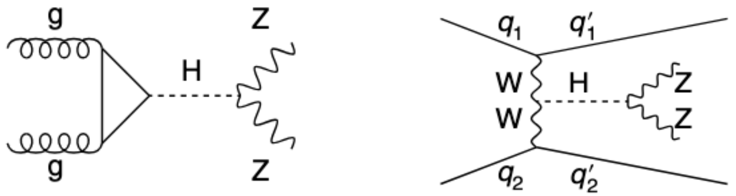
Hope to set the stage by discussing experimental sensitivity and needs, ahead of next talk covering theory status.

Recent Offshell Higgs Measurements

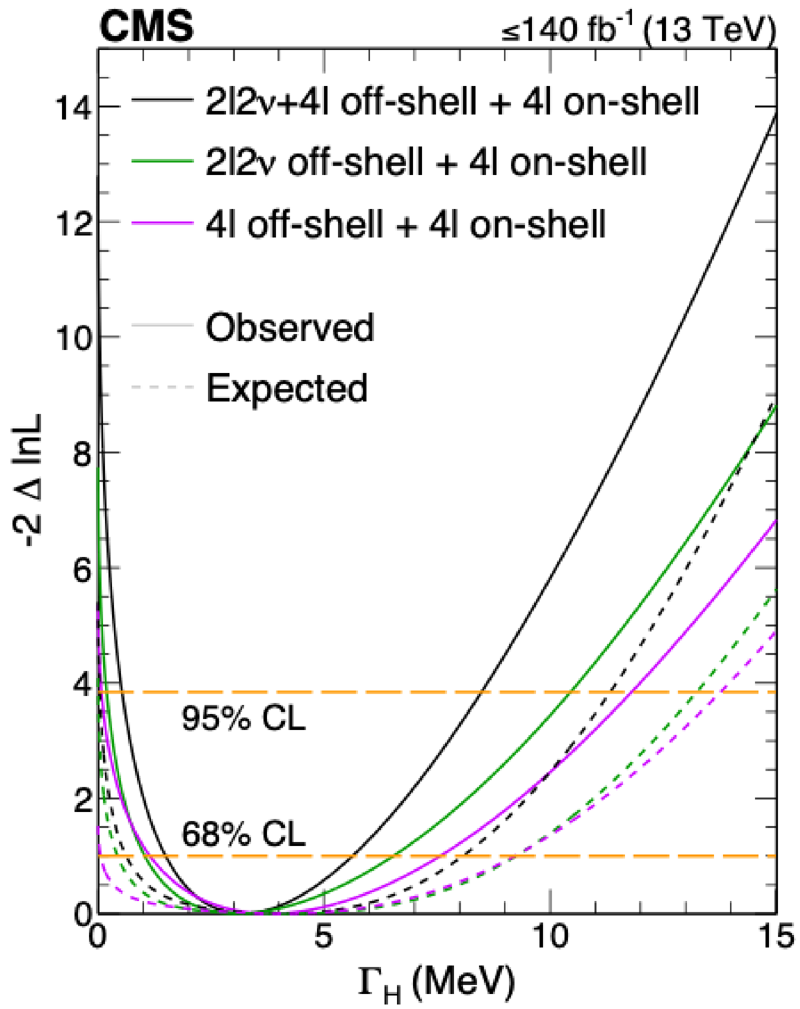
Start with a quick look at recent measurement, to give a sense of experimental sensitivity:

CMS

- ggF and VBF production
- $H \rightarrow ZZ \rightarrow 2\ell 2\nu$ and 4ℓ Run 2 paper (and update of onshell measurement in HIG-21-019)



Γ_H=3.2(+2.4,−1.7) MeV at 68% CL
μ_{VBF}=0.90(+0.9,−0.59) at 68% CL
μ_{ggF}=0.62(+0.68,−0.45) at 68% CL



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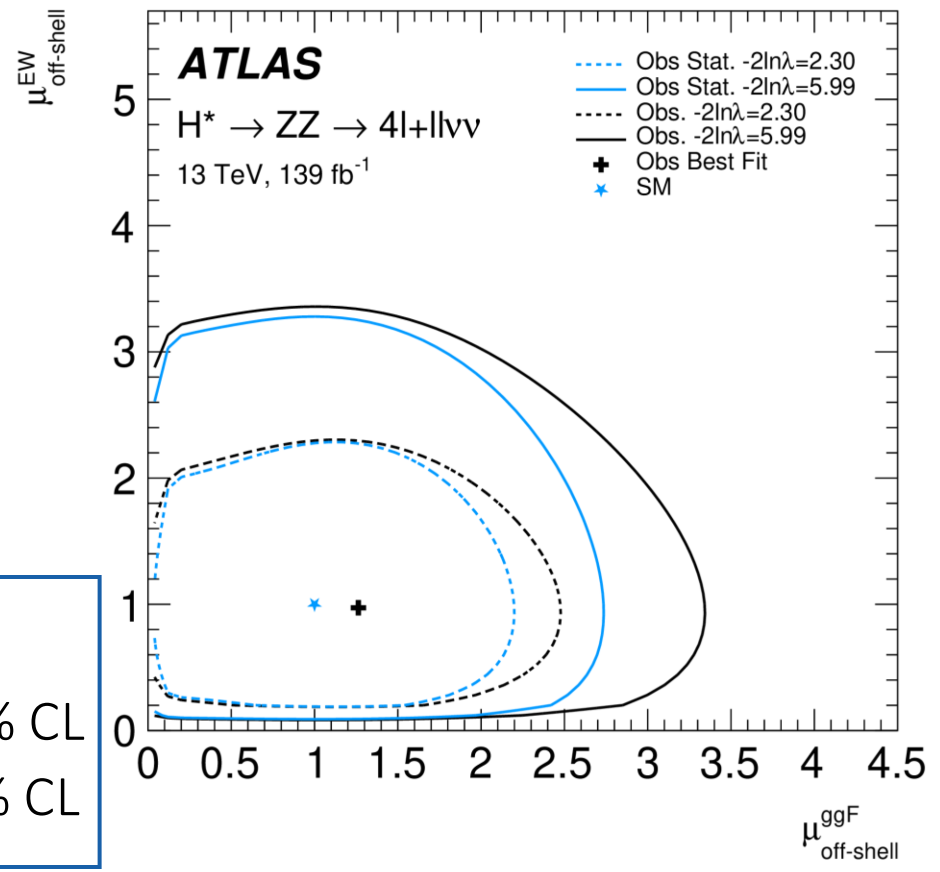
Recent Offshell Higgs Measurements

Start with a quick look at recent measurement, to give a sense of experimental sensitivity:

ref

ATLAS:

- ggF and VBF production
- $H \to ZZ \to 2\ell 2\nu$ and 4ℓ Run 2 paper
- $H \to ZZ \to 4\ell$ with simulation-based inference (SBI) combined with above $2\ell 2\nu$ in CONF note
- $H \to WW \to \ell\nu\ell\nu$ also investigated in Run 1 paper



ZZ paper:

Γ_H=4.5(+3.3,−2.5) MeV at 68% CL

μ_{off}=1.1(+0.7,−0.6) at 68% CL

ZZ CONF (SBI):

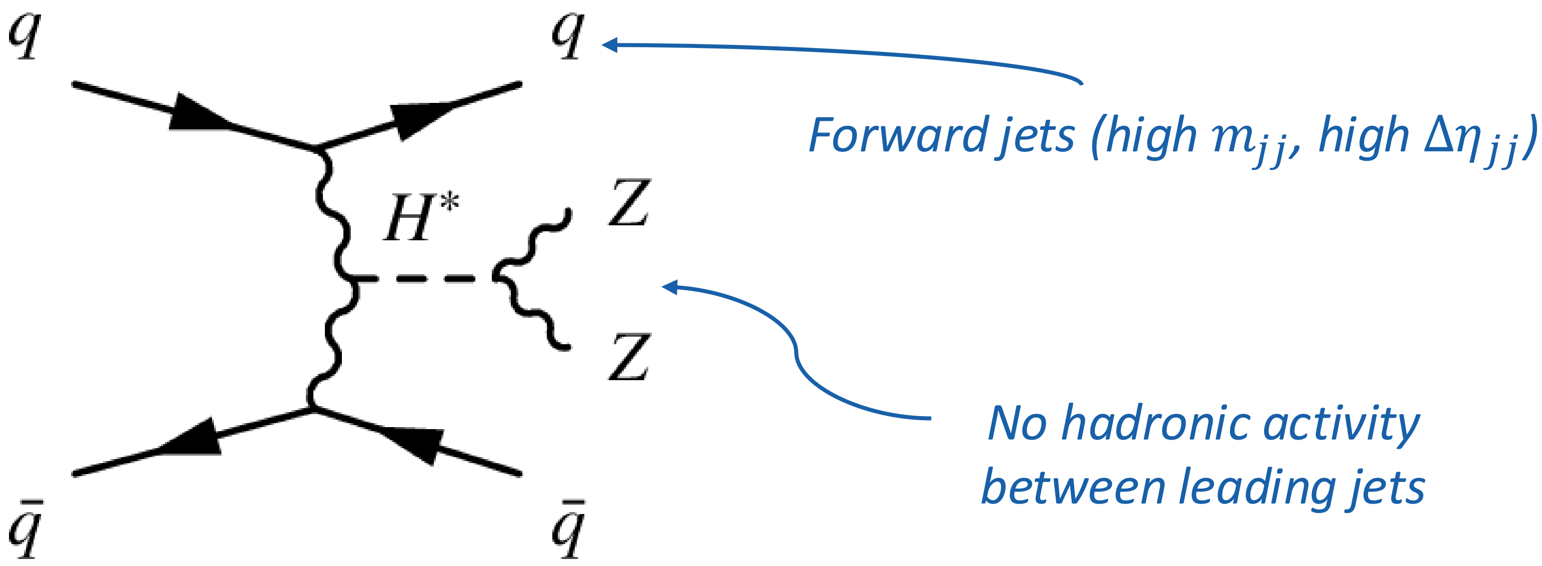
Γ_H=4.3(+2.7,−1.9) MeV at 68% CL

μ_{off}=1.06(+0.62,−0.45) at 68% CL

Measuring Offshell VBF Higgs

Key takeaway: Offshell VBF Higgs being studied by both experiments in all recent measurements, with signal strength measured with $\vartheta(50 - 100\%)$ precision.

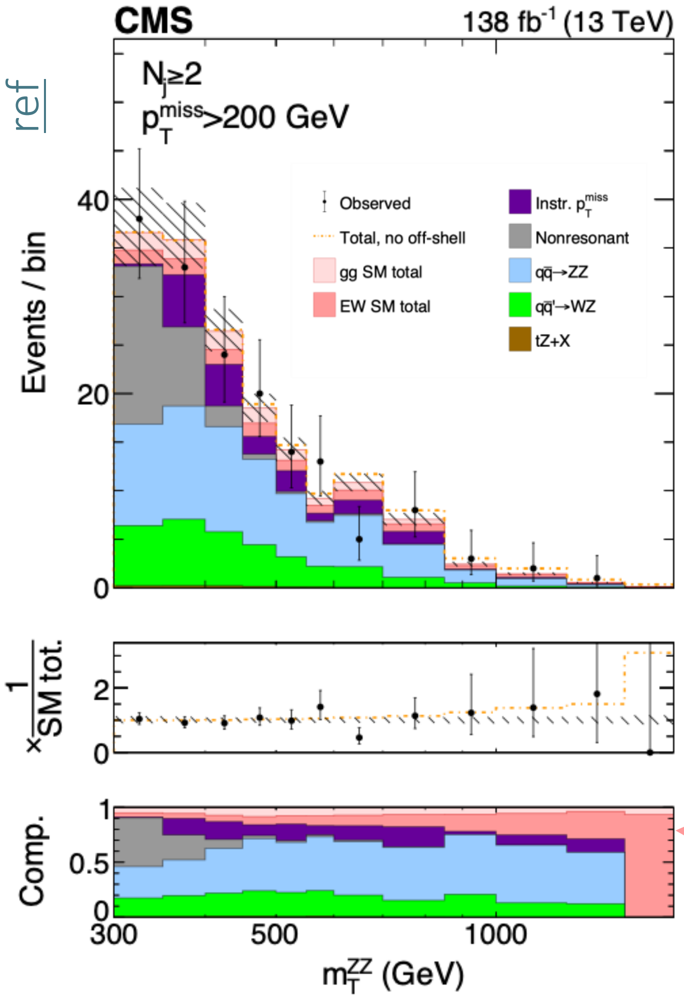
- Comparable to ggF, despite 1/10th the cross-section → equally important for width constraints.
- Some key advantages experimentally and theoretically:
  - Distinctive production mode features → especially important for $H \to WW \to l\nu l\nu$
  - Different couplings than ggF → no assumptions needed on BSM physics on top loop.



Targeting VBF in the Measurements

VBF signal typically targeted via a mix of **cuts** and **machine learning.**

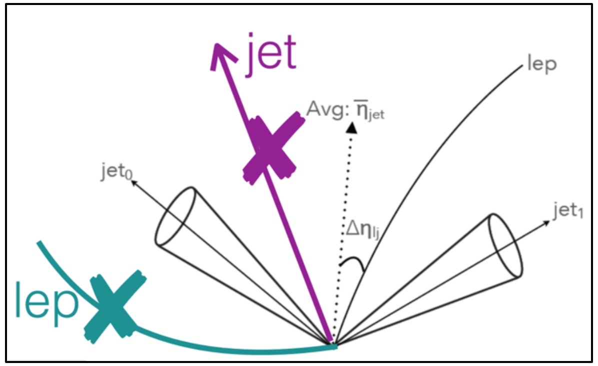
ref



VBF signal (in SR targeting VBF)

Typical cuts include:

- **b-veto** for top background rejection
- **Invariant mass cuts** to select offshell phase space
- **Mass or kinematic cuts** to select leptons from V decays.
- **MET** (for $2l2\nu$ final states)
- **Jet multiplicity division**; 2j targets VBF
- **VBF topological cuts**, eg. $\Delta\eta_{jj}$, central jet veto, outside lepton veto.



Targeting VBF in the Measurements

VBF signal typically targeted via a mix of **cuts** and **machine learning.**

4L CONF note

Variable	Definition
$m_{4\ell}$	quadruplet mass
m_{Z1}	Z_1 mass
m_{Z2}	Z_2 mass
$\cos\theta^*$	cosine of the Higgs boson decay angle $[\mathbf{q}_1 \cdot \mathbf{n}_z/\lvert\mathbf{q}_1\rvert]$
$\cos\theta_1$	cosine of the Z_1 decay angle $[-(\mathbf{q}_2)\cdot\mathbf{q}_{11}/(\lvert\mathbf{q}_2\rvert\cdot\lvert\mathbf{q}_{11}\rvert)]$
$\cos\theta_2$	cosine of the Z_2 decay angle $[-(\mathbf{q}_1)\cdot\mathbf{q}_{21}/(\lvert\mathbf{q}_1\rvert\cdot\lvert\mathbf{q}_{21}\rvert)]$
Φ_1	Z_1 decay plane angle $[\cos^{-1}(\mathbf{n}_1\cdot\mathbf{n}_{sc})\,(\mathbf{q}_1\cdot(\mathbf{n}_1\times\mathbf{n}_{sc})/(\lvert\mathbf{q}_1\rvert\cdot\lvert\mathbf{n}_1\times\mathbf{n}_{sc}\rvert)]$
Φ	angle between Z_1, Z_2 decay planes $[\cos^{-1}(\mathbf{n}_1\cdot\mathbf{n}_2)\,(\mathbf{q}_1\cdot(\mathbf{n}_1\times\mathbf{n}_2)/(\lvert\mathbf{q}_1\rvert\cdot\lvert\mathbf{n}_1\times\mathbf{n}_2\rvert)]$
$p_T^{4\ell}$	quadruplet transverse momentum
$y^{4\ell}$	quadruplet rapidity
n_{jets}	number of jets in the event
m_{jj}	leading dijet system mass
$\Delta\eta_{jj}$	leading dijet system pseudorapidity
$\Delta\phi_{jj}$	leading dijet system azimuthal angle difference

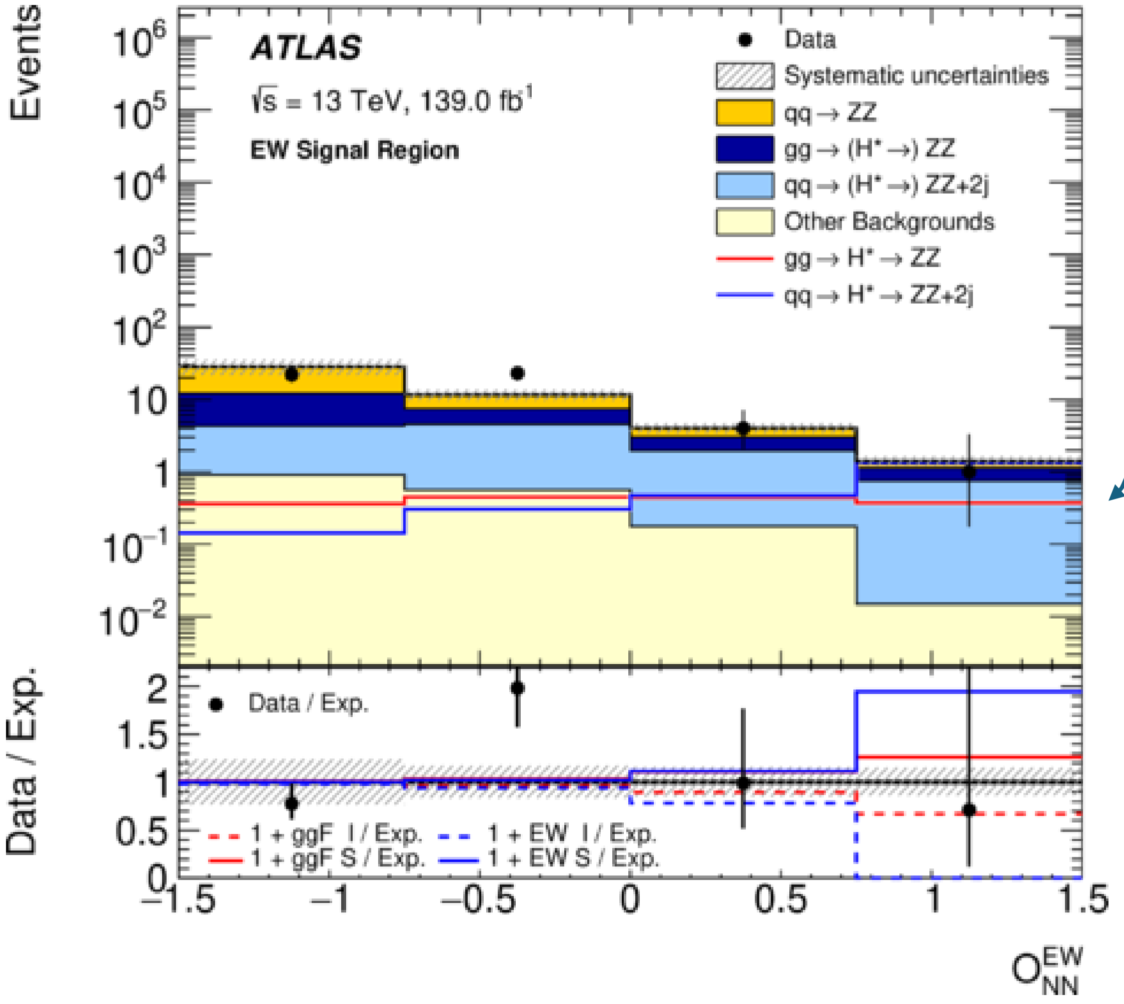
Variables used in NN discriminant

Neural networks applied in several ways:

- Histogram-based analyses use NNs as final discriminants and to classify events into SRs.
- SBI-based analysis performs unbinned analysis using likelihood built from density ratios.
- In either case: NNs generally rely on **wide range of lepton and jet kinematic features**.

Modelling Offshell Higgs

paper



Monte Carlo simulations are crucial for optimizing cuts, and training NNs, and predicting signal yields.

ATLAS and CMS strategies differ a bit here:

1. Both: Generate S with available MC generator

2a. ATLAS: With same generator, also generate B and I (or SBI, SBI20) for VV sample with S, B and I contributions

2b. CMS: Use matrix-element reweighting (MELA) for VV sample with S, B and I contributions.

3. Both: Reweight S, B, I to higher order, differentially if available, or inclusively.

VBF Modelling Details

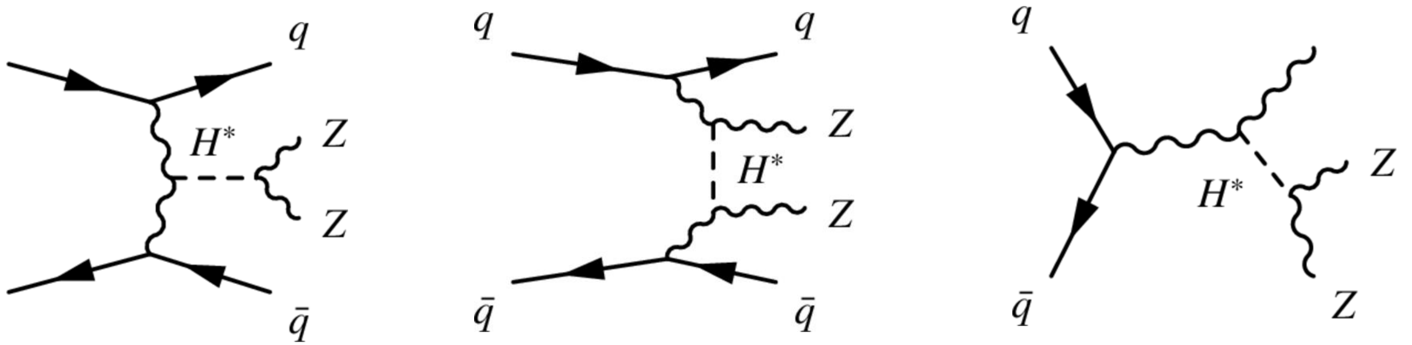
CMS

- Powheg (NLO QCD, LO EW) + JHUGen decay for wide-resonance signals with pole masses from 125 GeV to 3 TeV.
- Reweight for B and I with MELA package (JHUGen and MCFM LO MEs)

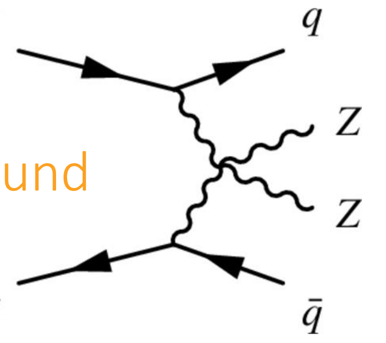
ATLAS

- MadGraph (LO QCD, LO EW) + Pythia8 for B, SBI, SBI20
  - SBI20 = offshell cross-section and width scaled by factor of 20 → onshell contribution suppressed.
  - Can't generate S sample alone due to diagrams beyond s-channel one.

Signal



Background



No further higher-order corrections applied by either experiment.

VBF Theory Uncertainties

Theory uncertainties on VBF capture the effect of:

- Parton shower: Internal weight variations (ISR, FSR, A14 tune parameters).
- QCD scale variations: 7-point variations of μ_R, μ_F
- PDF+α_S: standard deviation of NNPDF3.0 set, and α_S variations.

Some details:

- All uncertainties evaluated at reco-level (after detector simulation).
- Impact evaluated separately for SBI, SBI20 and B samples.
- NPs correlated across all three samples.

Impact of Theory Uncertainties

Measurement of $\mu_{offshell}$ and Γ_H are generally dominated by:

- Statistics
- ggF parton shower uncertainty.
- Final-state-dependent uncertainties: background theory, experimental uncertainties.

4L CONF note

Process	Uncertainty	Final State	Value (%)
2-jet Signal Region			
$q\bar{q} \to ZZ$	QCD Scale	4ℓ	18–26
$q\bar{q} \to ZZ$	QCD Scale	$2\ell 2\nu$	8–32
$gg \to H^* \to ZZ$	Parton Shower	4ℓ	27
$gg \to H^* \to ZZ$	QCD Scale	$2\ell 2\nu$	14-18
$gg \to ZZ$	Parton Shower	4ℓ	38
$gg \to ZZ$	QCD Scale	$2\ell 2\nu$	18–20
$WZ+2j$	QCD Scale	$2\ell 2\nu$	20–22
$q\bar{q} \to ZZ+2j$	QCD Scale	4ℓ	8–14
$q\bar{q} \to ZZ+2j$	QCD Scale	$2\ell 2\nu$	8–16

Effect of VBF theory uncertainties are more important in dedicated phase space.

- QCD scale tends to be largest.
- But still subleading compared to other uncertainty sources.

Updating VBF Theory Treatment

- VBF offshell Higgs measurements are becoming less stat-limited and more sensitive.
  → Modelling matters more and more.
- Current MC simulations are at LO or NLO QCD, and LO EW.
  → What is the effect of missing higher-order corrections on VBF S, B and I?

Look at recent HO calculations for $qq \rightarrow (H^*) \rightarrow VVqq$ for a sense of the impact:

JHEP06(2022)098

NLO QCD and EW corrections to vector-boson scattering into W^+W^- at the LHC

Ansgar Denner, Robert Franken, Timo Schmidt and Christopher Schwan

JHEP11(2020)110

NLO QCD and EW corrections to vector-boson scattering into ZZ at the LHC

Ansgar Denner,[a] Robert Franken,[a] Mathieu Pellen[b] and Timo Schmidt[a]

Robert Franken will speak about this next; I will just briefly motivate experiments' interest.

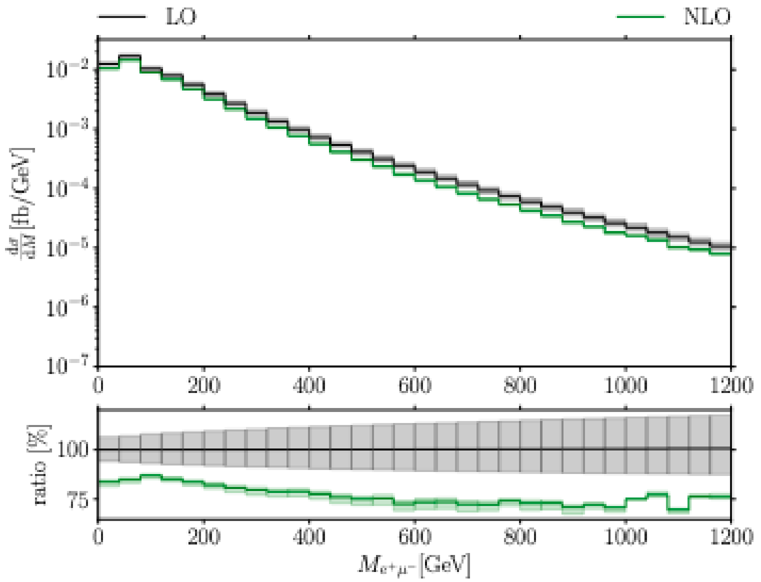
Expectations from VBS Calculations

NLO QCD and EW corrections on the full process are sizable in VBS phase spaces:

closest to our offshell analyses; more later.

VBS W^+W^-:

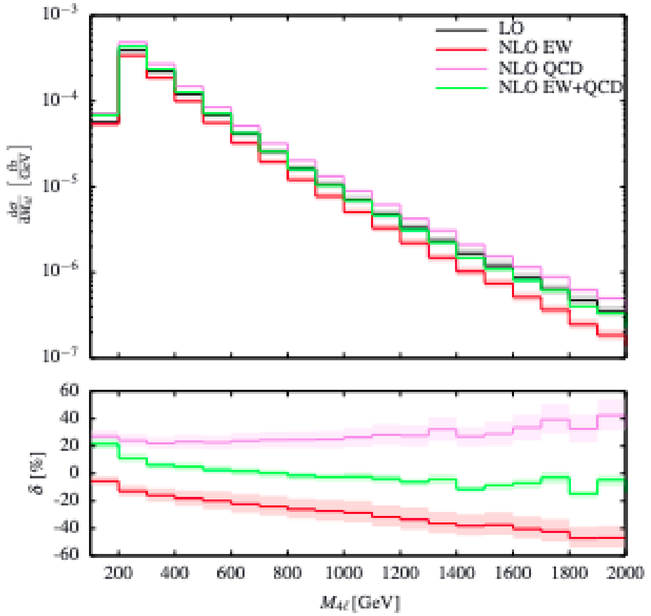
- Higgs resonance included: -11.4% (EW), -5.1% (QCD)
- Higgs resonance cut out: -13.2% (EW), -0.4% (QCD)



JHEP06(2022)098

VBS ZZ:

- mJJ>100 GeV: -15.9% (EW), 23.6% (QCD)
- mJJ>500 GeV: -17.6% (EW), 0.1% (QCD)



JHEP11(2020)110

Impact of H.O. Corrections on VBF Offshell

How much would the **norm** and **shape** components of such a correction matter?

Normalization change (overall xsec): probably not so much.

- Scaling signal down could hurt a little (less of already-small signal).
  - Background and interference would also be scaled down (discussion point...).

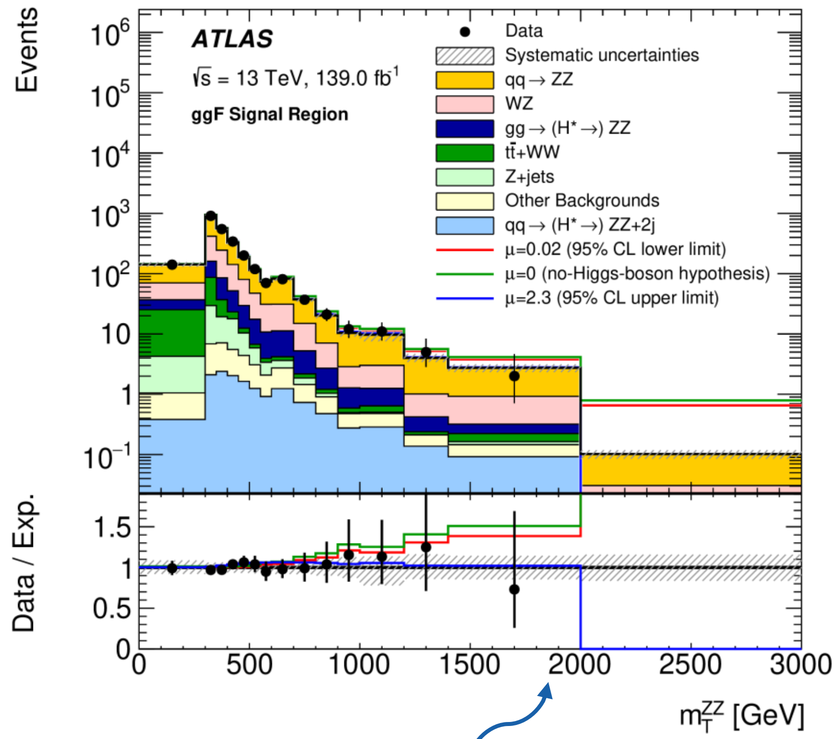
- (If full correction not available): Applying extra uncertainty to account for effect of missing NLO EW corrections on xsec would have a small effect:
  - Leading ggF theory uncertainties are 20-40%, but stat uncertainties still dominate our measurements for now. And VBF is even more stats-limited.
  - Current largest VBF theory uncertainties are ~10%, similar size to NLO EW correction, and they don't rank highly.

Impact of H.O. Corrections on VBF Offshell

How much would the **norm** and **shape** components of such a correction matter?

m_{VV} **shape correction:** likely more, but hard to say.

- Shape information is crucial for distinguishing S (higher mVV) from B and I (lower mVV).
- S and I dominate sensitivity over different m_{VV} and μ ranges → altering their yields and shapes has non-trivial affect on sensitivity.



Expected event yield shows deficit or excess across different mVV ranges depending on mu hypothesis.

Toward H.O Corrections for VBF Offshell

Conclusion: probably not a large effect *yet*, but somewhat non-trivial to say for sure, and will be increasingly important as stats and sensitivity improve.

Some considerations toward applying (or checking) these corrections in offshell analyses:

- NLO corrections calculated for S, B and I inclusively.
  - We separate these (via templates and via selections) → corrections equally applicable to all?
- VBS phase spaces not identical to those of either analysis
  - eg. no central jet veto in WW paper
- m_{VV} dependence is large, so corrections should likely be applied differentially.
  - Practically, how to do this? Implementation in FO calculator, application at truth-level?
- The $qq \rightarrow VVqq$ background-only process enters onshell $H \rightarrow VV$ analyses.
  - Ensure consistent treatment → affects offshell-onshell width combinations.

Toward H.O Corrections for VBF Offshell

How to move forward?

Lots of questions on previous slide.

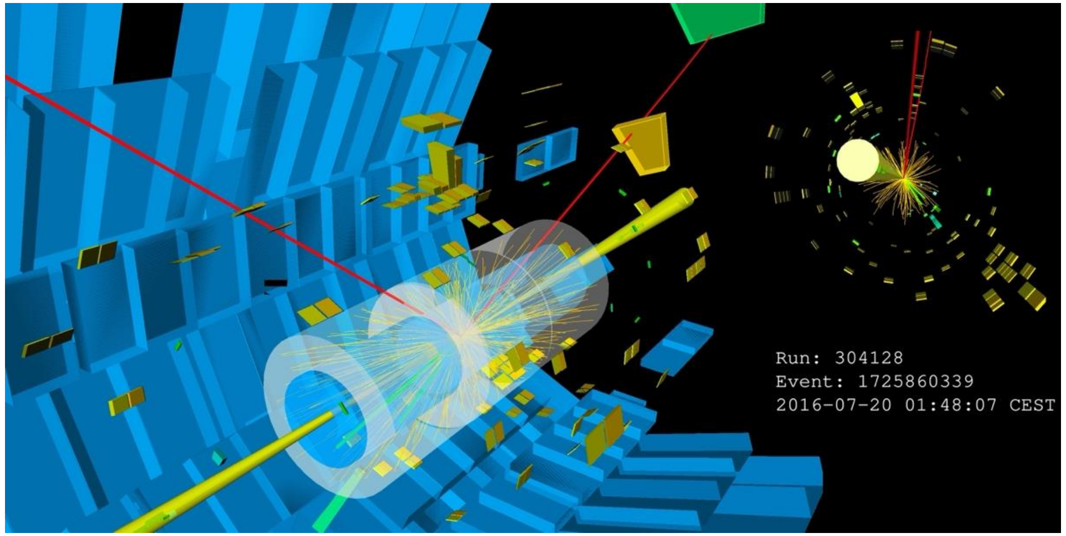
Arising from discussions with LHCHWG offshell SGCs and experimentalists on ATLAS

Some thoughts on moving toward answers (and makes sense to discuss more after Robert's talk):

- Would it be possible to have the implementation of these corrections in either a) a FO calculator (could apply mVV corrections to nominal sample at truth-level), or b) a generator matched to PS (allows running the sample through whole analysis including NN)?
- Alternatively, would authors be willing to: 1) re-run calculations with more typical offshell analysis selections, 2) isolate S, B and I components, and 3) provide m_{VV}-differential corrections in usable form?
- NLO QCD corrections for VBF high-mass signal available in Powheg (used by CMS) and MadGraph (but tricky/computationally-expensive). NLO EW available as automated corrections in Sherpa+Recola – is this usable/recommended for VBF offshell Higgs?

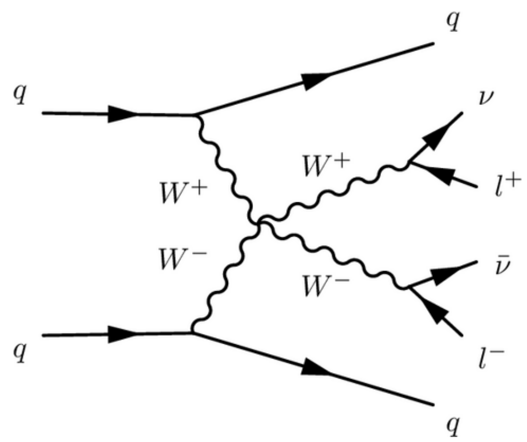
Conclusion

- Offshell Higgs analyses are becoming increasingly sensitive to VBF production.
- Want to make sure we are correctly modelling signal, background and interference for this process.
- Looking forward to discussion now and after the next talk.

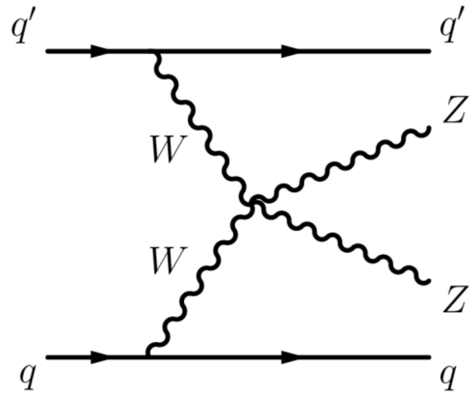


Backup: VBS in Other Measurements

VBS measurements performed in ATLAS and CMS. How do they treat higher-order corrections?



Observation of EW W+W- [STDM-2022-06 and SMP-21-001-pas]
- ATLAS: Signal sample is NLO QCD, LO EW.
- CMS: Signal sample is LO QCD and EW.
- Neither reports any H.O corrections or related uncertainty.



Observation of EW ZZ [STDM-2017-19 and SMP-20-001]:
- ATLAS: Signal sample is NLO QCD, LO EW.
- CMS: Signal sample is LO QCD and EW
- Neither reports any H.O corrections or related uncertainty.