Offshell Status

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22ND Workshop of LHC Higgs Working Group

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Introduction

- Focus on Higgs boson produced at high invariant masses $p_H^2 \gg m_H^2$
- E.g: $gg \to H \to VV$:

  10% of events above the $2\, m_V$ threshold. [Kauer, Passarino '12]
- Large offshell rates also in EW production. [Campbell, Ellis '15; Gritsan *et al.* '20]

- Contrary to expectations from narrow width approximation:

$$\frac{\Gamma_H}{m_H} \simeq \frac{4\ \text{MeV}}{125\ \text{GeV}} \sim 10^{-5}$$

  → Expect a very narrow resonance and hence offshell cross section highly suppressed.

- Due to Higgs boson restoring unitarity in massive scattering amplitudes

  ➞ offshell Higgs production allows us to probe unitarization behavior.

✓ Indirect constraints on Higgs width by comparing onshell and offshell Higgs rates. [Caola, Melnikov (2013)]

$\sigma_{\text{on}} \propto g_i^2 g_f^2 / \Gamma_H$ $\sigma_{\text{off}} \propto g_i^2 g_f^2$

✓ Probe Higgs in a different kinematic regime.

Latest ATLAS results

- Full Run 2 measurement in the $H \to ZZ^* \to 4\ell$ decay channel using neural simulation-based inference.
- Unbinned measurement with optimal observable for all values of the off-shell signal strength .

  Rept. Prog. Phys. 88(5), 057803 (2025) and arXiv:2412.01600

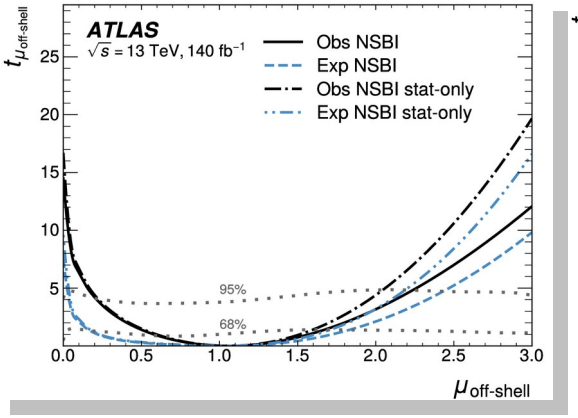
  $$\Gamma_H = 4.3^{+2.7}_{-1.9}\ \text{MeV}$$

- Full Run 2 measurement in the decay channel $H \to ZZ^* \to 2\ell 2\nu$ based on the $m_{T,ZZ}$ distribution in ggF (0 and 1 jets) and VBF regions (2+ jets).

  Phys. Lett. B 846 (2023) 138223

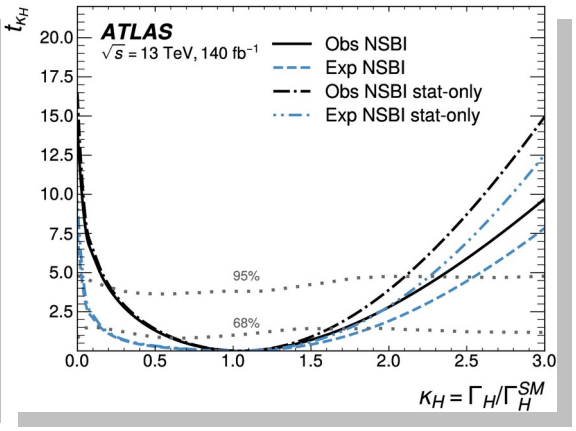
		68% CL interval		95% CL interval	
Parameter	Value	Observed	Expected	Observed	Expected
Γ_H [MeV]	4.29	[2.41, 6.95]	[0.66, 7.61]	[0.76, 9.66]	[0.12, 10.50]

(off-shell) Higgs signal strength

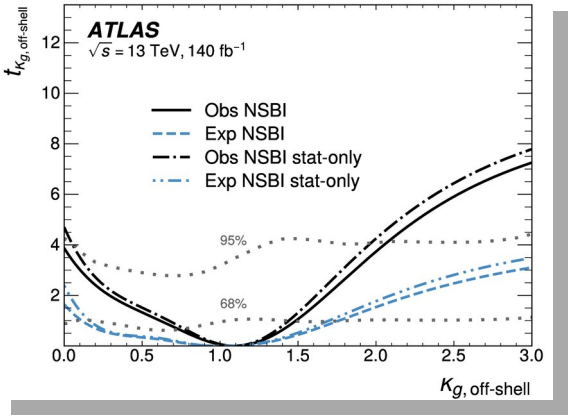


Higgs width interpretation using on-shell

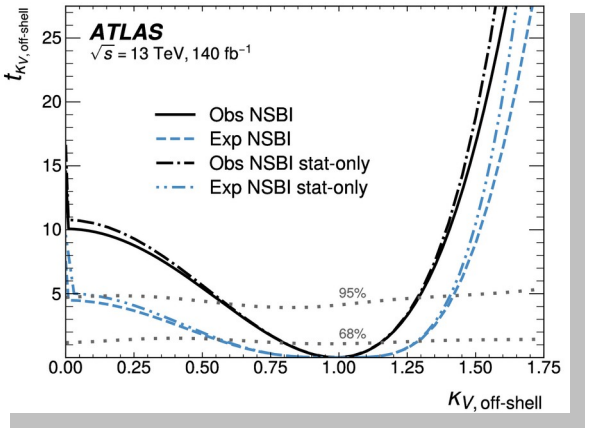
Eur. Phys. J. C 80 (2020) 957



(off-shell) Higgs – gluon coupling

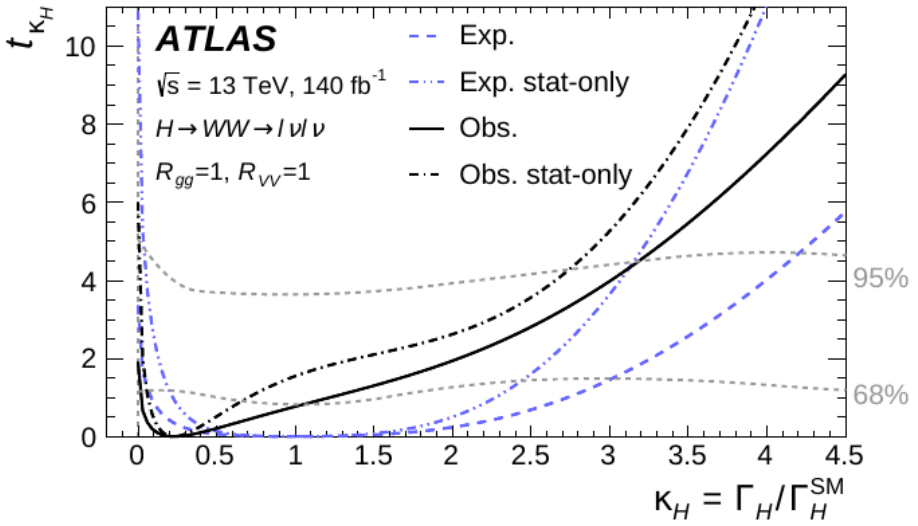


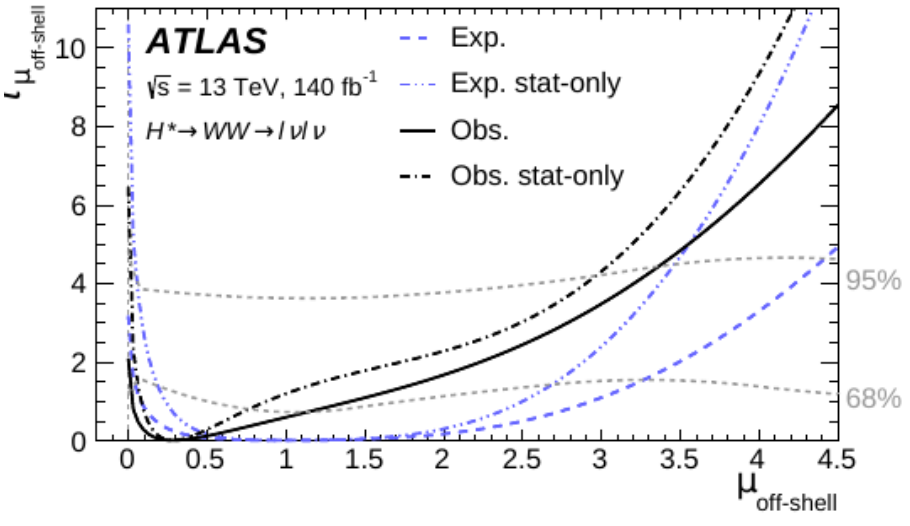
(off-shell) Higgs – vector boson coupling



Latest ATLAS results

Full Run 2 measurement in the $H \to WW^* \to 2\ell 2\nu$ decay channel. [Phys.Lett.B 870 (2025) 139898]





$$\Gamma_H = 0.9^{+3.4}_{-0.9}\ \text{MeV}\ @\ 95\%\ \text{CL}$$

$$\mu^{\text{offshell}} = 0.3^{+0.9}_{-0.3}$$

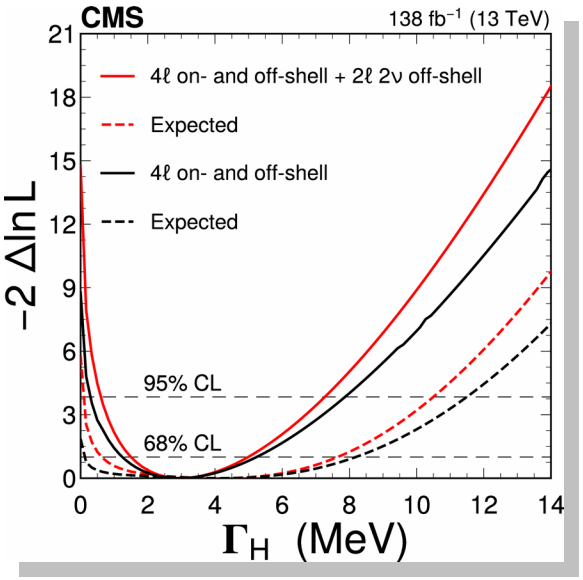
Statistical uncertainty	52%
MC stat. uncertainty	15%
Theory uncertainty	39%
- Theory background	22%
- Theory signal	34%
Experimental uncertainty	25%
- Jets	19%
- Leptons	5.3%
- Others	6.8%
- Misidentified leptons	3.1%
Background normalisation	7.6%

Latest CMS results

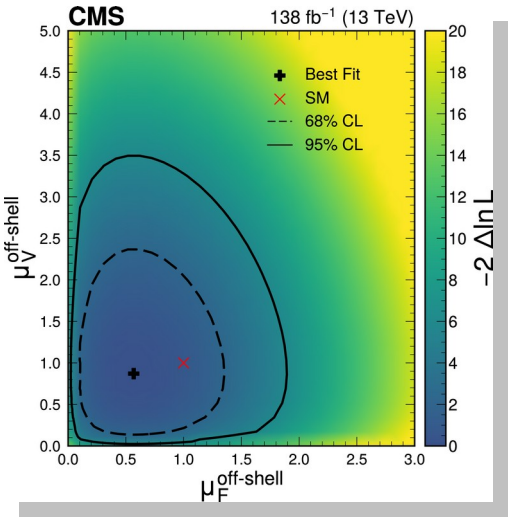
- Full Run 2 measurement in the $H \to ZZ^* \to 4\ell$ and $H \to ZZ^* \to 2\ell 2\nu$ decay channels.

Phys. Rev D 111 (2025) 9, 092014

Nature Phys. 18 (2022) 11, 1329-1334



Measured width and signal strength consistent with SM prediction.



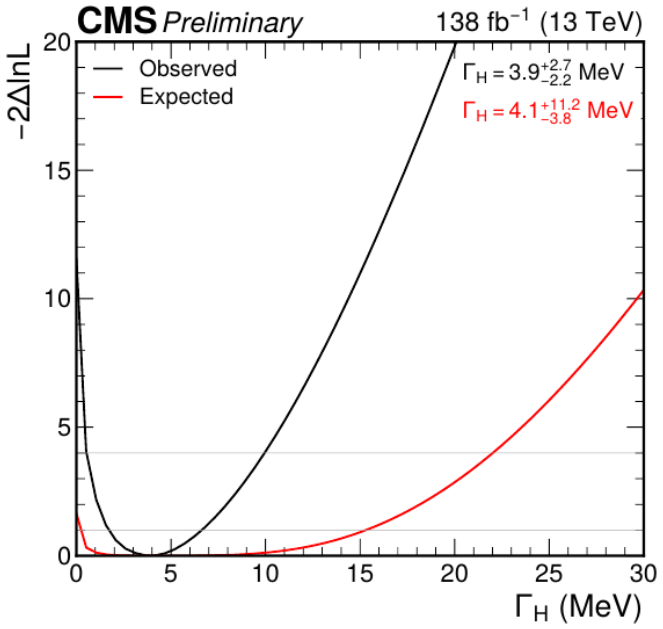
Channel	Observed Γ_H (MeV)	Expected Γ_H (MeV)
4ℓ on- and off-shell	$2.9^{+2.3}_{-1.7}$ [0.3, 7.9]	4.1 ± 4.0 [< 11.5]
4ℓ on- and off-shell + $2\ell 2\nu$ off-shell	$3.0^{+2.0}_{-1.5}$ [0.6, 7.3]	4.1 ± 3.5 [0.1, 10.5]

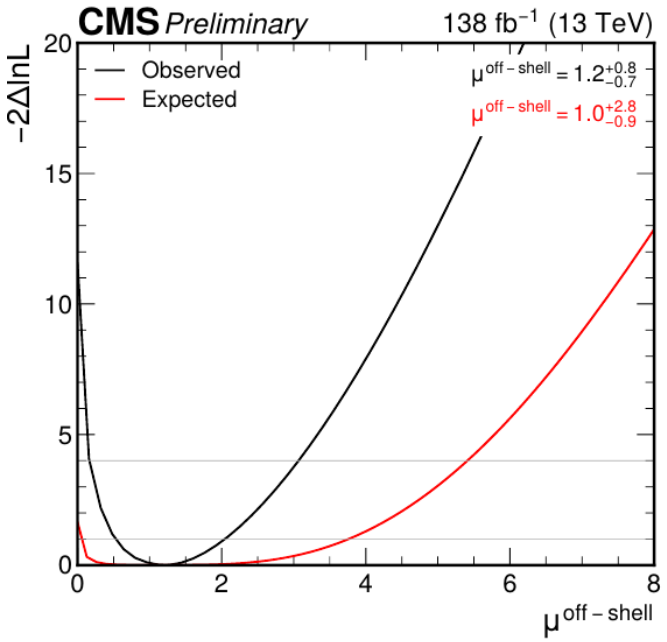
68% CL 95% CL

Parameter	Observed	Expected
$\mu^{\text{off-shell}}$	$0.67^{+0.42}_{-0.32}$ [0.14, 1.54]	$1.00^{+0.83}_{-0.84}$ [0.02, 2.46]
$\mu_F^{\text{off-shell}}$	$0.57^{+0.50}_{-0.36}$ [0.04, 1.61]	$1.00^{+0.90}_{-0.98}$ [<2.62]
$\mu_V^{\text{off-shell}}$	$0.87^{+0.93}_{-0.57}$ [0.05, 2.90]	$1.00^{+1.95}_{-0.89}$ [<4.34]

Latest CMS results

Full Run 2 measurement in the $H \to WW^* \to 2\ell 2\nu$ decay channels. CMS PAS HIG-24-011





Talk by Pedro

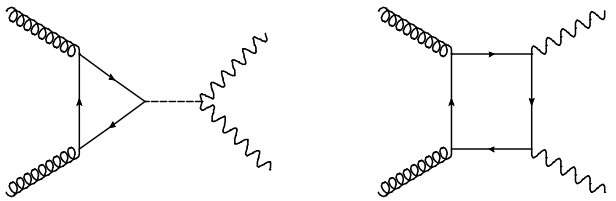
Parameter	c.v.	Observed		Expected	
		68% CL	95% CL	68% CL	95% CL
$\mu_{\text{on-shell}}$	1.25	1.09, 1.44	0.94, 1.65	0.85, 1.18	0.72, 1.38
$\mu_{\text{ggF}}^{\text{off-shell}}$	1.19	0.48, 2.15	< 3.40	< 4.31	< 6.21
$\mu_{\text{VBF}}^{\text{off-shell}}$	1.25	0.16, 3.09	< 5.59	< 6.41	< 11.2
$\mu^{\text{off-shell}}$	1.21	0.53, 2.05	0.17, 3.08	0.06, 3.75	< 5.4
Γ_H (MeV)	3.91	1.72, 6.61	0.54, 9.94	0.25, 15.3	< 22.0

Best fit $\mu^{\text{offshell}} = 1.2^{+0.8}_{-0.7}$

Uncertainty	Contribution to r	Contribution to $\mu_{\text{off-shell}}$
Luminosity	2%	3%
Theoretical	27%	29%
Experimental	8%	6%
Statistical	56%	56%
Other	4%	3%

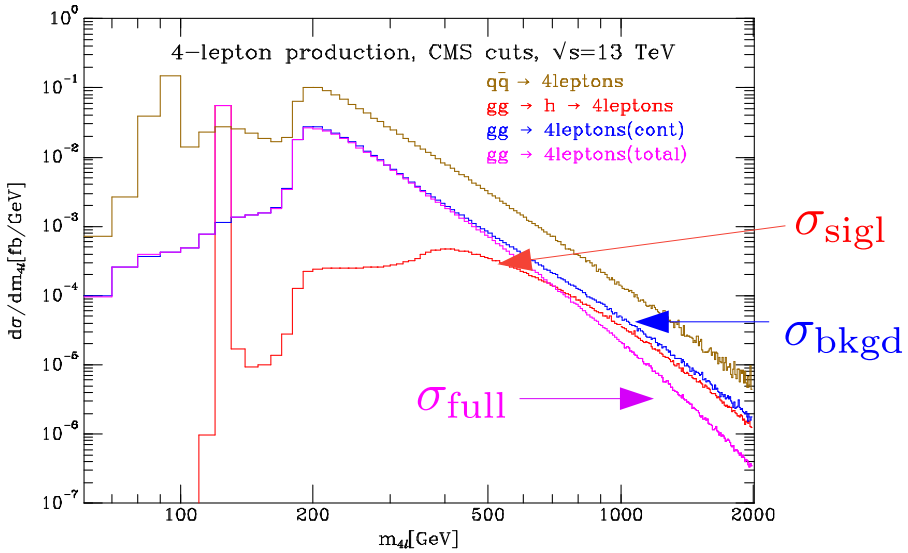
Offshell Calculations

- Need to consider:
  - Signal
  - Background
  - Interference
  - Full (physical) result SBI



A_s A_b

$$|A_{ZZ}|^2 = |A_s|^2 + |A_b|^2 + 2\mathrm{Re}[A_s A_b^*] \quad \rightarrow \sigma_{\mathrm{full}} = \sigma_{\mathrm{sigl}} + \sigma_{\mathrm{bkgd}} + \sigma_{\mathrm{intf}}$$

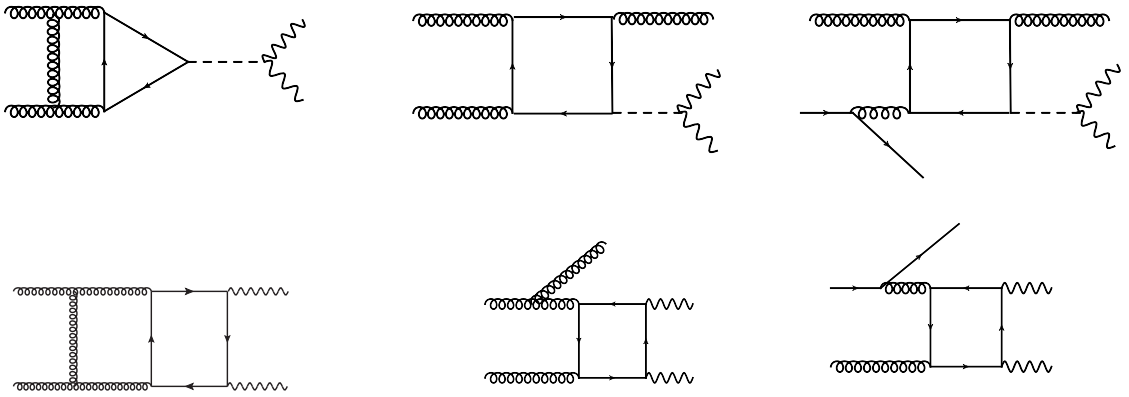


[Campbell, Ellis, Williams (2013)]

Large destructive interference at high energies – sign of Higgs unitarizing massive scattering amplitudes.

NLO Corrections

- Need to include corrections to signal and background.
  - Include effects of top mass in loops.
- Bottleneck: two-loop corrections to background with massive quark loops



Approximations:

- Expansion in $1/m_t$ – valid for $m_{VV} < 2m_t$

  [Dowling, Melnikov '15; Czakon, Campbell, Kirchner, Ellis '16; Caola, Dowling, Melnikov, RR, Tancredi '16]

- Matched to PS in POWHEG.

  [Alioli, Ferrario Ravasio, Lindert, RR '21]

- Expansion in high energy limit $m_{VV} > 750$ GeV

  [Davies, Mishima, Steinhauser, Wellmann '20]

- Combination with threshold approximation

  [Gröber, Maier, Rauh '17; '19]

- Reweighting of massive one-loop amplitudes

  [Grazzini, Kallweit, Wiesemann, Yook '18; '21]

- Expansion in p_{TZ} + merging with high-energy expansions using Padé approximants

  [Degrassi, Gröber, Vitti '24]

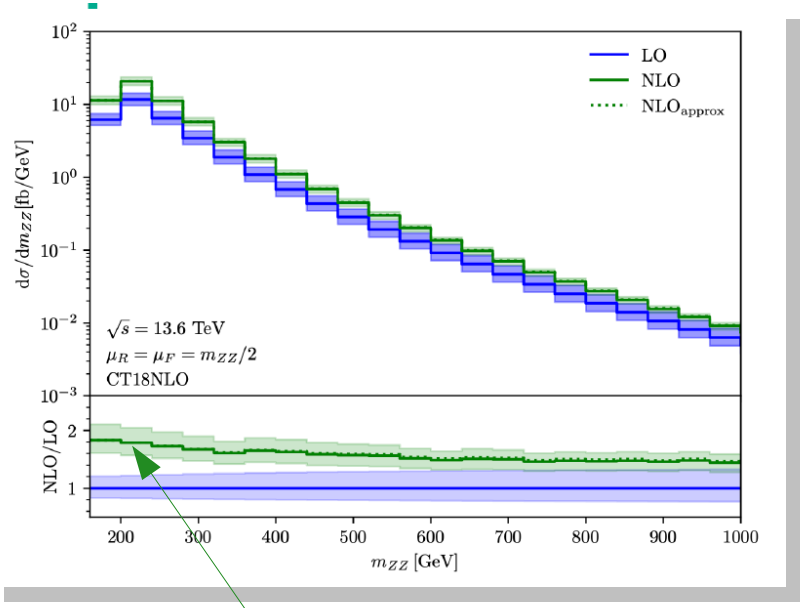
Exact NLO Results

Exact NLO amplitudes:

[Brønnum-Hansen, Wang ‘20; ‘21; Agarwal, Jones, von Manteuffel ‘20]

Exact NLO results

[Agarwal, Jones, Kerner, von Manteuffel ‘24]



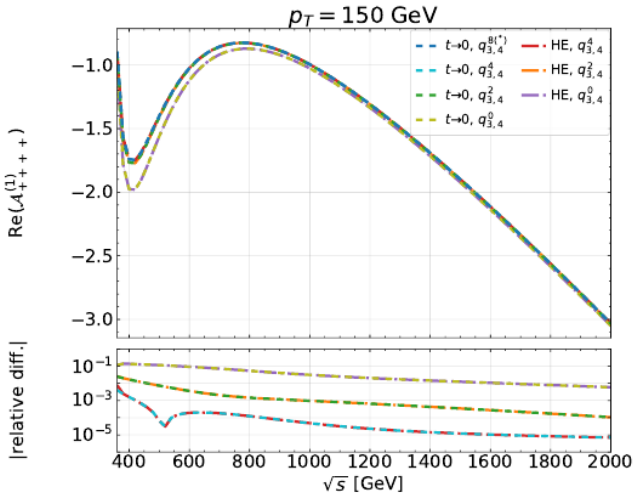
- Evaluation of two-loop amplitudes relatively expensive (~ 10 mins/point)
  - Up to ~ 1000 minutes for low-p_T events.
- Use one-loop results for massive quark loops to generate sampling grid of ~ 3000 points.
- Better than per-mille precision for most of phase space.
- Use qT subtraction scheme: minimize contribution of two-loop amplitudes

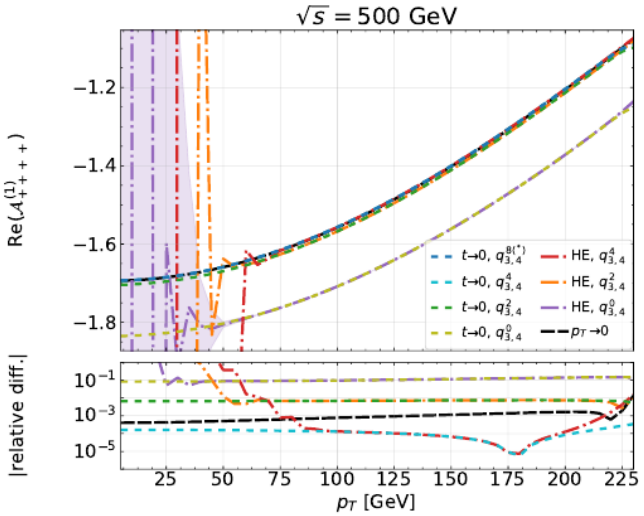
- Differential k-factor ~ 2 for near $2m_{Z,}$ relatively flat after $2m_{t.}$
- Reweighting captures massive two-loop contributions extremely well!
- Signal + massive quark loops decreases cross section by ~ 2%.

NLO Corrections

- Combination of high energy and forward expansions for two-loop amplitudes for $gg \to Z^* Z^*$ [Davies et al, '25]
  - Many terms retained:
    - Padé approximants in high-energy limit with m_t^{100}
    - $t^{n_t}(q_3^2)^{n_3}(q_4^2)^{n_4}$ with $n_t + n_3 + n_4 \leq 4$

$q_{3,4}^2$: Invariant mass of Z bosons





- Excellent agreement with exact results at one-loop.
- Very fast numerical evaluation
- Flexible (can change parameters, renormalization scheme, ...)

Modelling additional radiation

- Going beyond NLO is very demanding → include additional radiation through parton showers.
- Combine with fixed-order either through merging or jet matching.

➡ Tuned comparison of merged NLO+PS (`POWHEG+PYTHIA`) vs. LO 0+1 jet matching (`MadGraph+PYTHIA` (MLM) and `Sherpa (CSShower)` (CKKW-L)).

SciPost Phys. Comm. Rep. 12 (2025)

Theoretical modeling of QCD radiation in off-shell Higgs production through gluon fusion

Rafael Coelho Lopes de Sá[1⋆], Martina Javurkova[1,2†], Matteo Lazzeretti[3‡] and Raoul Röntsch[3,4◦]

See also [Li et al (2020)]

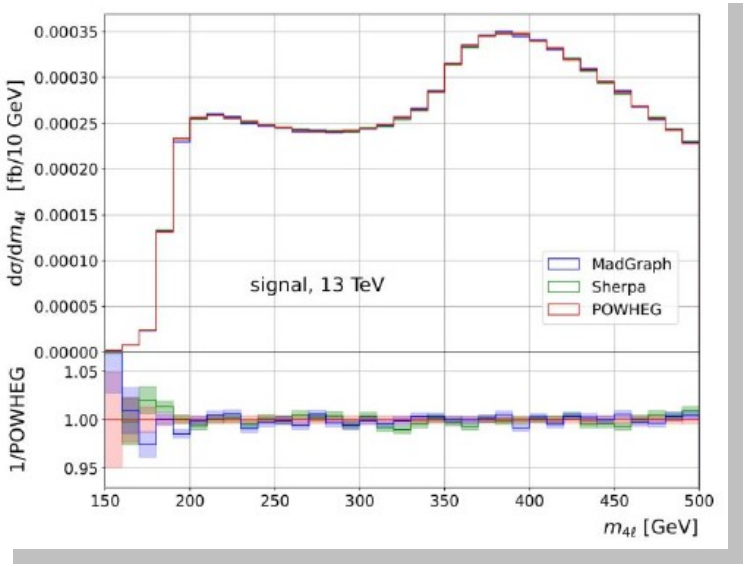
Contribution to Report 5

Modelling additional radiation

- Going beyond NLO is very demanding → include additional radiation through parton showers.
- Combine with fixed-order either through merging or jet matching.

➡ Tuned comparison of merged NLO+PS (`POWHEG+PYTHIA`) vs. LO 0+1 jet matching (`MadGraph+PYTHIA` (MLM) and `Sherpa (CSShower)` (CKKW-L)).

Compare results at LO (no PS) to tune parameters: any difference beyond LO due to additional QCD radiation.



Process	POWHEG LO	SHERPA LO	MADGRAPH LO
Signal	0.08745(5)	0.08741(5)	0.08742(1)
Background	2.725(1)	2.726(1)	2.724(1)
SBI	2.617(1)	2.616(1)	2.617(1)

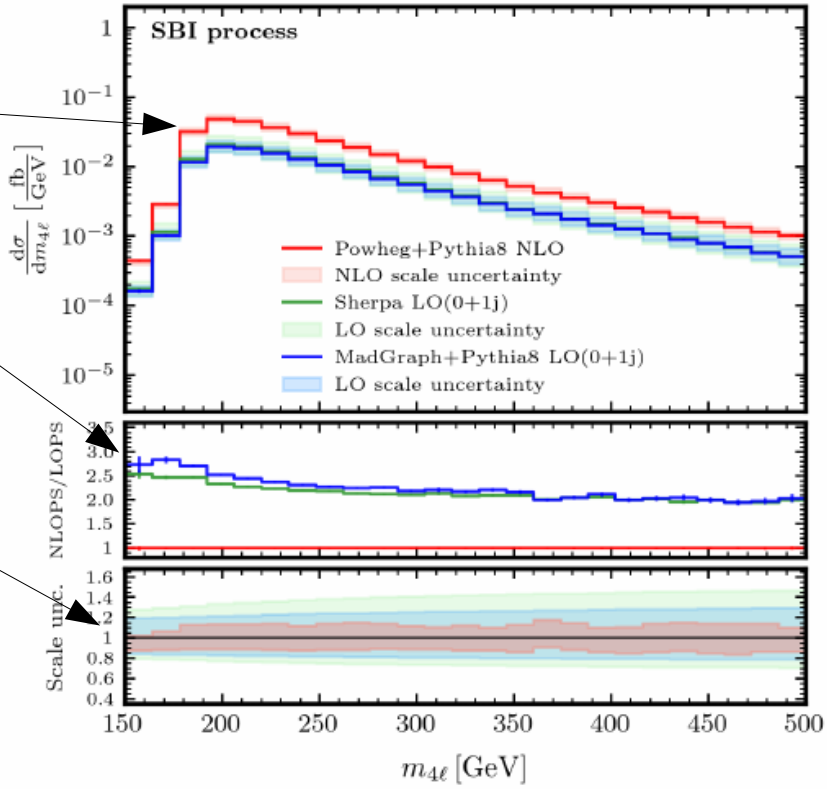
Table 1: Comparison of fixed-order LO cross-sections (in fb) for signal, background, and inclusive processes as calculated by POWHEG, SHERPA, and MADGRAPH.

Talk by Matteo Lazzeretti

Modelling additional radiation

Merged NLO+PS (POWHEG) vs LO 0+1 jet matching (MadGraph and Sherpa).

- Large contribution from missing NLO (virtual) pieces in LO+PS.
- Shape similar across all MC generators (expected for inclusive observable).
- Smaller scale uncertainties (~ 18%) for NLO+PS than for LO+PS (27%, 43%).



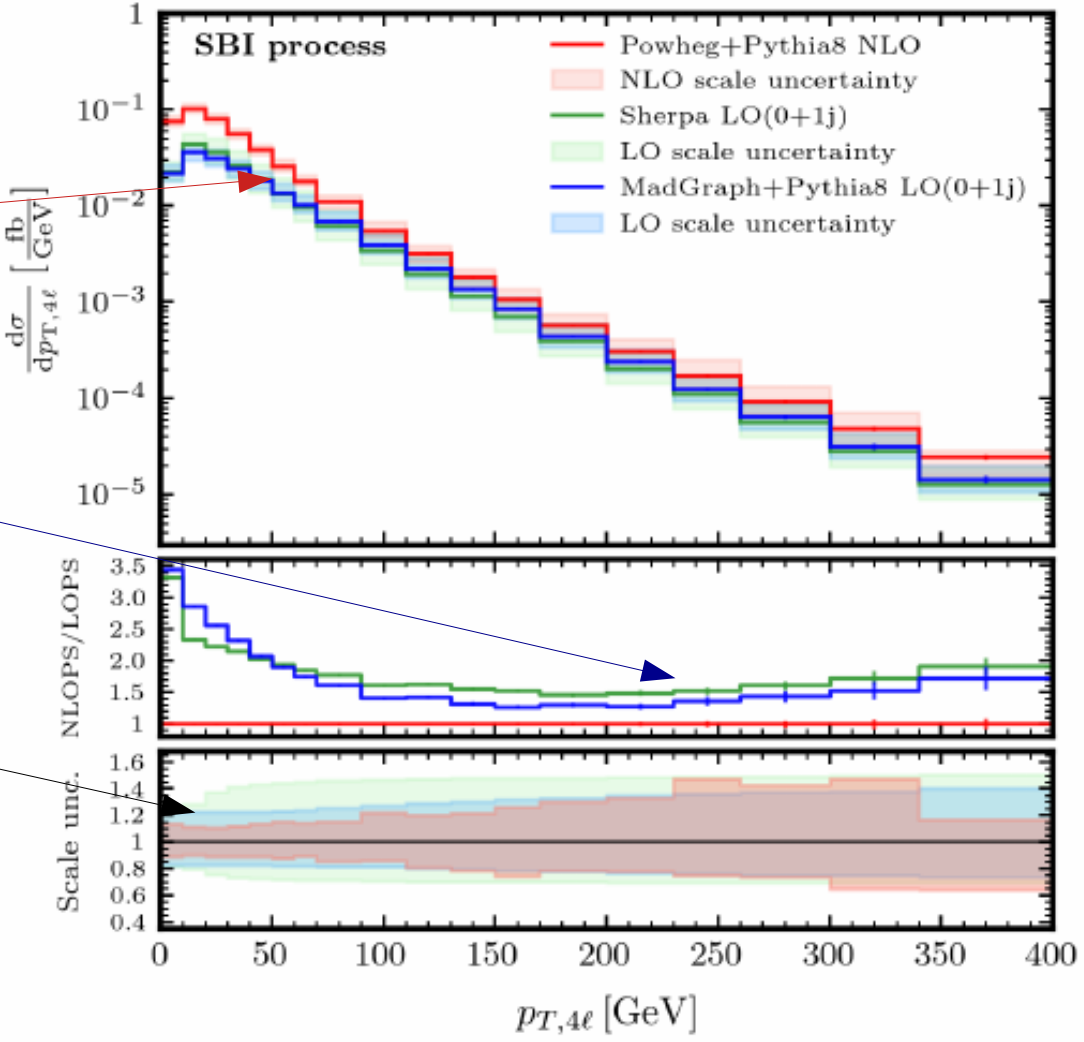
Process	POWHEG NLO+PS	SHERPA LO(0+1j)+PS	MADGRAPH LO(0+1j)+PS
Signal	0.1759(5)	0.09300(4)	0.09125(8)
Background	4.74(1)	2.102(1)	1.914(4)
SBI	4.49(1)	2.005(1)	1.892(3)

Table 2: Comparison of cross-sections (in fb) considering QCD effects beyond fixed-order LO for POWHEG (NLO+PS), and for SHERPA and MADGRAPH (LO(0+1j)+PS), showing the large increases from LO to NLO.

Modelling additional radiation

Merged NLO+PS (POWHEG) vs LO 0+1 jet matching (MadGraph and Sherpa).

- POWHEG results at small $p_{T,4\ell}$ enhanced by virtual corrections, then spread out over $p_{T,4\ell}$ --> softer distribution.
- Agreement improves slightly for $p_{T,4\ell} \simeq 200$ GeV, then worse in tail,
  - Interplay of different treatments of radiation
- ~ 15% difference between MadGraph and Sherpa
  - CKKW vs MLM?
- Theoretical uncertainties similar (LO control on this observable).



Modelling additional radiation

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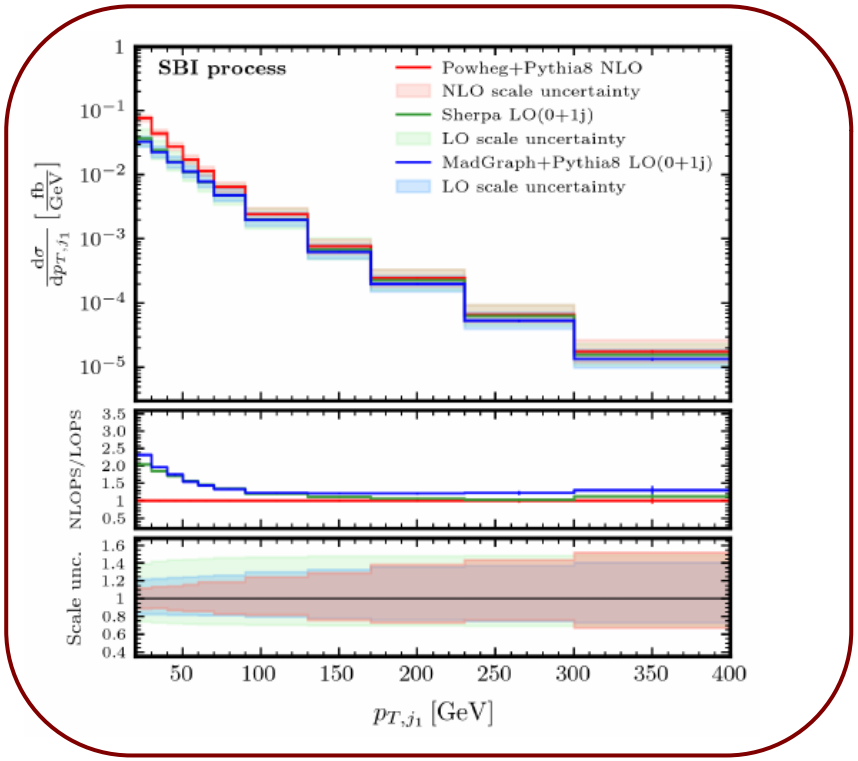
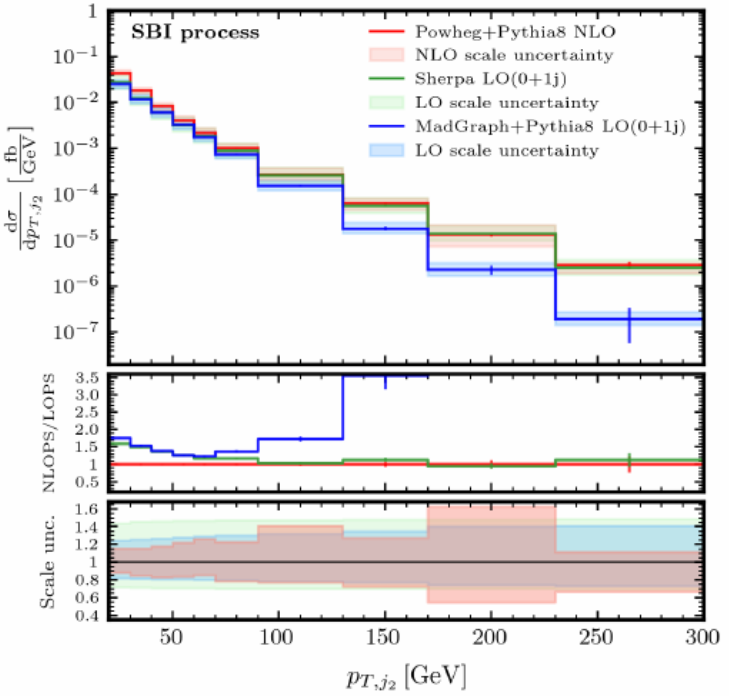
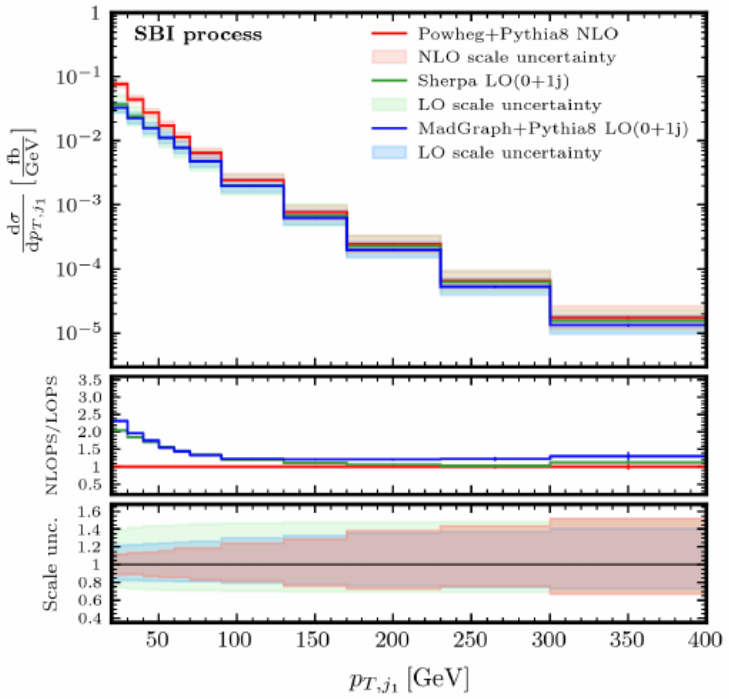


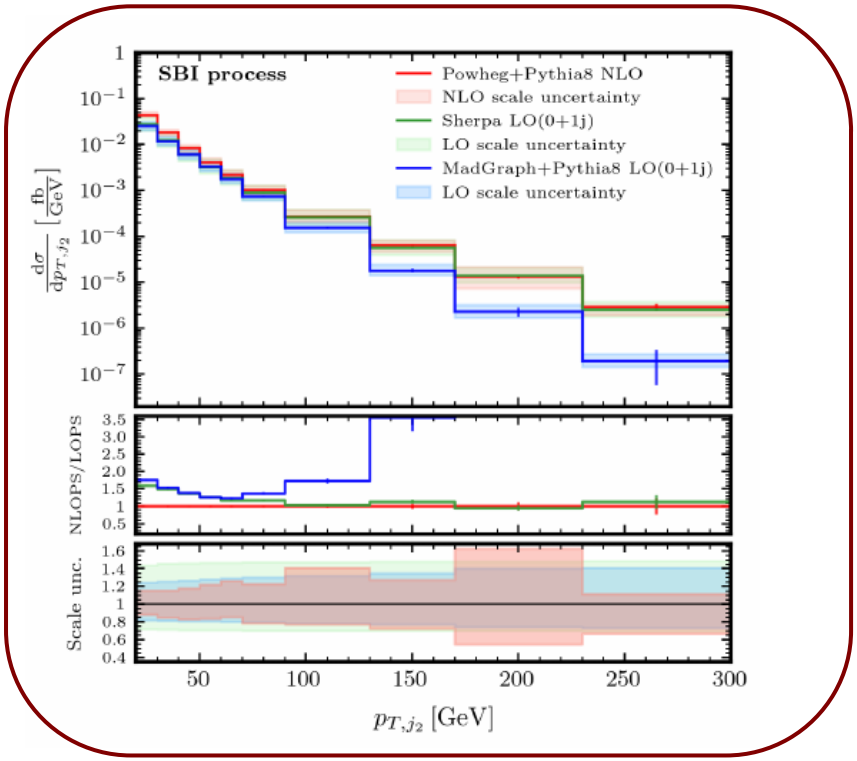


- Results for leading jet p_T similar to $p_{T,4\ell}$ -> differences driven by inclusion of virtual corrections in POWHEG, rather than by treatment of additional radiation.
- Smaller differences in high-p_T tail.
- MadGraph and Sherpa almost identical – observable is insensitive to details of merging procedure and PS.

Modelling additional radiation

Merged NLO+PS (POWHEG) vs LO 0+1 jet matching (MadGraph and Sherpa).





- Behavior of subleading jet is especially relevant for offshell measurements through EW production.
- Subleading jet p_T similar for POWHEG and Sherpa, severely underpopulated by MadGraph.
  - Both POWHEG and MadGraph use PYTHIA for PS. Details of MLM merging?

Theoretical Uncertainty Impact

Vary key parameters in matching/merging procedures as proxy to assess theoretical uncertainty.

- POWHEG: $h_{\mathrm{damp}} = \{75,\ 100,\ 150\}$ GeV $\mu_0 = \{m_{4\ell}/4, m_{4\ell}/2, m_{4\ell}\}$

  (amount of radiation exponentiated in Sudakov factor). (ISR renorm. scale)

- MadGraph & Sherpa: $Q_{\mathrm{cut}} = \{15, 20, 30\}$ GeV

  (transition between jets generated by matrix element and PS).

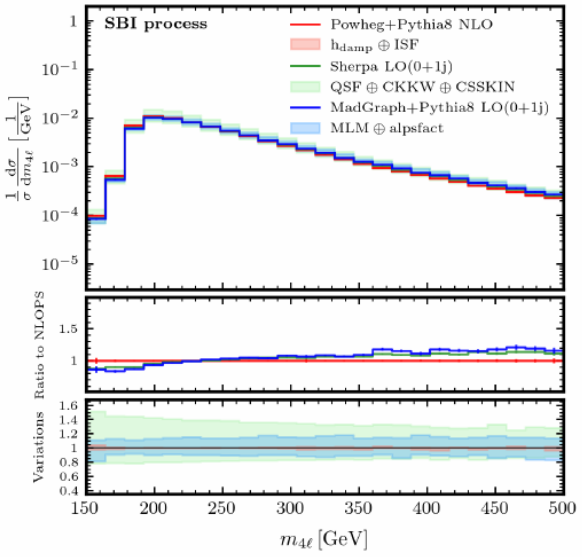
- MadGraph: `alpfact` = {0.5, 1.0, 2.0}

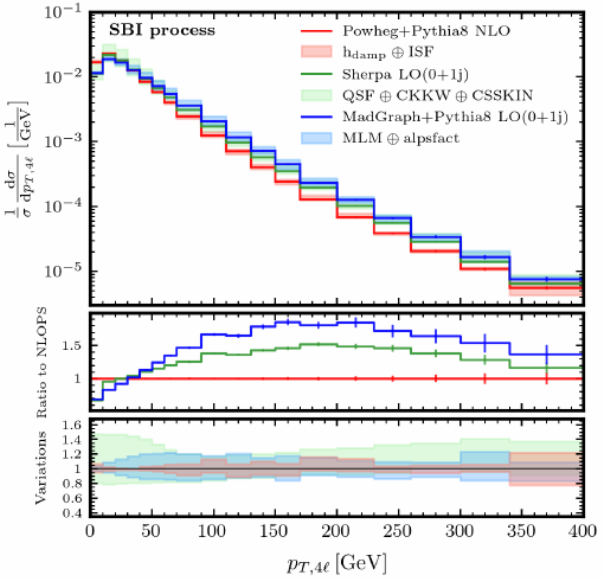
  (scales strong coupling at start of PS)

- Sherpa: `QSF` = $\mu_R = \{m_{4\ell}/4, m_{4\ell}/2, m_{4\ell}\}$ `CSSKIN` = {0, 1}

  (scales renormalization/factorization scale in PS) (recoil scheme)

Theoretical Uncertainty Impact

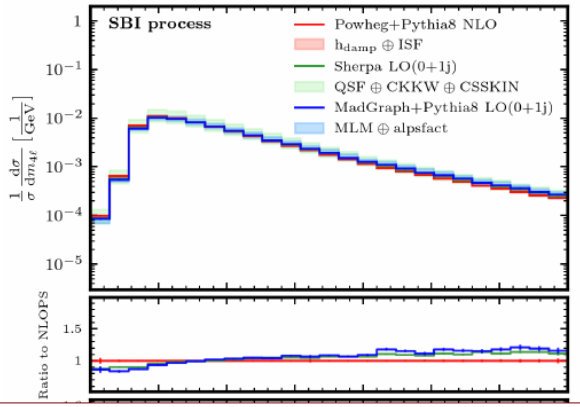




- `QSF` parameter has biggest impact across all $m_{4\ell}$ and low $p_{T,4\ell}$ (up to 40%-50%).
- h_{damp} mostly affects $p_{T,4\ell}$, especially at intermediate values.
- `CKSSKIN` becomes significant at high $p_{T,4\ell}$.
- `MadGraph` has lowest uncertainties for $p_{T,4\ell}$ at most 15%.

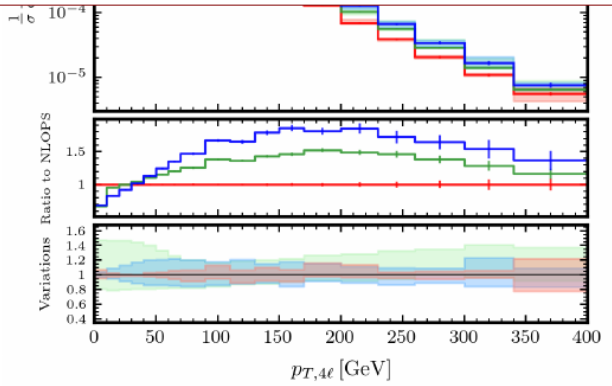
- Uncertainties larger than differences between generators for $m_{4\ell}$, smaller for $p_{T,4\ell}$:
  - Conservative for $m_{4\ell}$, but underestimate for $p_{T,4\ell}$

Theoretical Uncertainty Impact



- QSF parameter has biggest impact across all $m_{4\ell}$ and low $p_{T,4\ell}$ (up to 40%-50%).
- h_{damp} mostly affects $p_{T,4\ell}$, especially at intermediate values.
- CKSSKIN becomes significant at high $p_{T,4\ell}$.

pears to be the largest for both the observables studied. Thus the NLO+PS generator provided by POWHEG appears to give the most robust theoretical predictions for off-shell Higgs boson studies. However, as already observed in Ref. [24], the impact of the parton shower in POWHEG at large $p_{T,4\ell}$ is quite large, due to the choice of the default recoil scheme in PYTHIA8. Additionally, the uncertainty estimated from the variation of the damping parameter can be a substantial source of modeling uncertainty in future measurements.



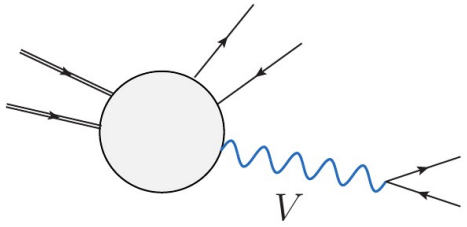
- Conservative for $m_{4\ell}$, but underestimate for $p_{T,4\ell}$

Polarized Dibosons

- Interference / unitarization in offshell Higgs production deeply connected with boson polarization.

Talk by Giovanni

Natural definition for resonant diagrams (in PA/NWA) [Denner GP 2006.14867]



$$\begin{aligned}\mathcal{A}^{\text{unpol}} &= \mathcal{P}_\mu \frac{-g^{\mu\nu}}{k^2 - M_V^2 + iM_V\Gamma_V} \mathcal{D}_\nu \\ &= \mathcal{P}_\mu \frac{\sum_{\lambda'} \varepsilon^\mu_{\lambda'} \varepsilon^{*\nu}_{\lambda'}}{k^2 - M_V^2 + iM_V\Gamma_V} \mathcal{D}_\nu \\ \longrightarrow \quad &\mathcal{P}_\mu \frac{\varepsilon^\mu_\lambda \varepsilon^{*\nu}_\lambda}{k^2 - M_V^2 + iM_V\Gamma_V} \mathcal{D}_\nu = \mathcal{A}_\lambda\end{aligned}$$

$$|\mathcal{A}^{\text{unpol}}|^2 = \underbrace{\sum_\lambda |\mathcal{A}_\lambda|^2}_{\text{incoherent sum}} + \underbrace{\sum_{\lambda \neq \lambda'} \mathcal{A}^*_\lambda \mathcal{A}_{\lambda'}}_{\text{interference terms}} \longrightarrow |\mathcal{A}_\lambda|^2 \propto \text{polarised cross section}$$

(1) Non-resonant diagrams regarded as non-resonant background.

(2) Resonant diagrams treated with

DPA: double-pole approximation [Denner et al. 0006307]

NWA: spin-correlated narrow-width approximation [Artoisenet et al. 1212.3460]

(3) Separate polarisations

Polarized Dibosons

Talk by Giovanni

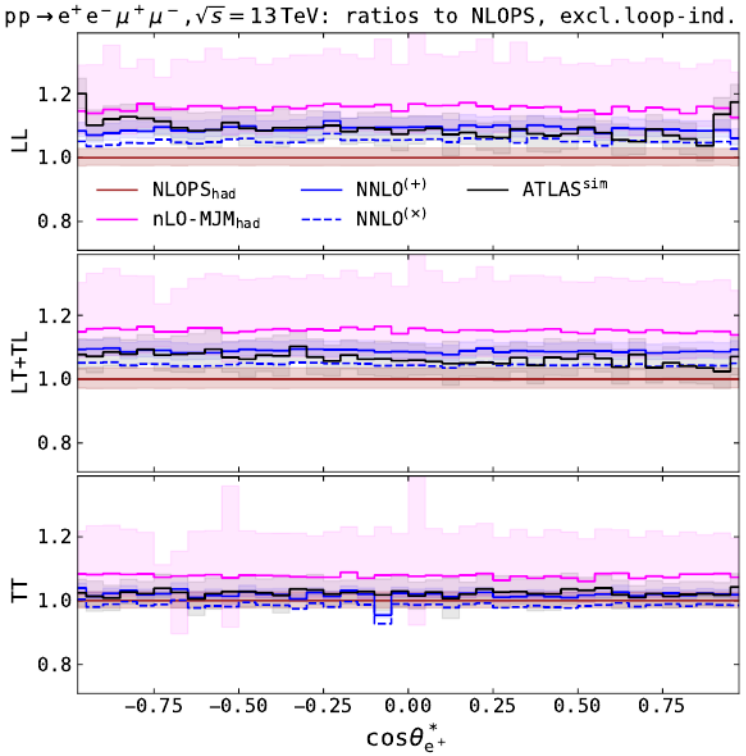
- → $W^+(\ell^+\nu_\ell)\,W^-(\ell'^-\bar{\nu}_{\ell'})$: NNLO QCD [Denner GP 2006.14867, Poncelet Popescu 2102.13583], NLO EW [Denner Haitz GP 2311.16031, Dao Le 2311.17027, 2409.06396]
- → $W^\pm(\ell^\pm\nu_\ell)\,Z(\ell'^+\ell'^-)$: NLO QCD + EW [Denner GP 2010.07149, Le Baglio 2203.01470, 2208.09232]
- → $Z(\ell^+\ell^-)\,Z(\ell'^+\ell'^-)$: NNLO QCD + NLO EW [Denner GP 2107.06579, Carrivale GP et al. 2505.09686]
- → $W^\pm(\ell^\pm\nu_\ell)$ +j: NNLO QCD [Pellen et al. 2109.14336]
- → $W^\pm$(jj/J) $Z(\ell'^+\ell'^-)$: NLO QCD [Denner Haitz GP 2211.09040]
- → $W^+(\ell^+\nu_\ell)\,W^+(\ell'^+\nu_{\ell'})$ +jj: NLO EW + QCD [Denner Haitz GP 2409.03620]

A lot of activity in last ~ 4 years!

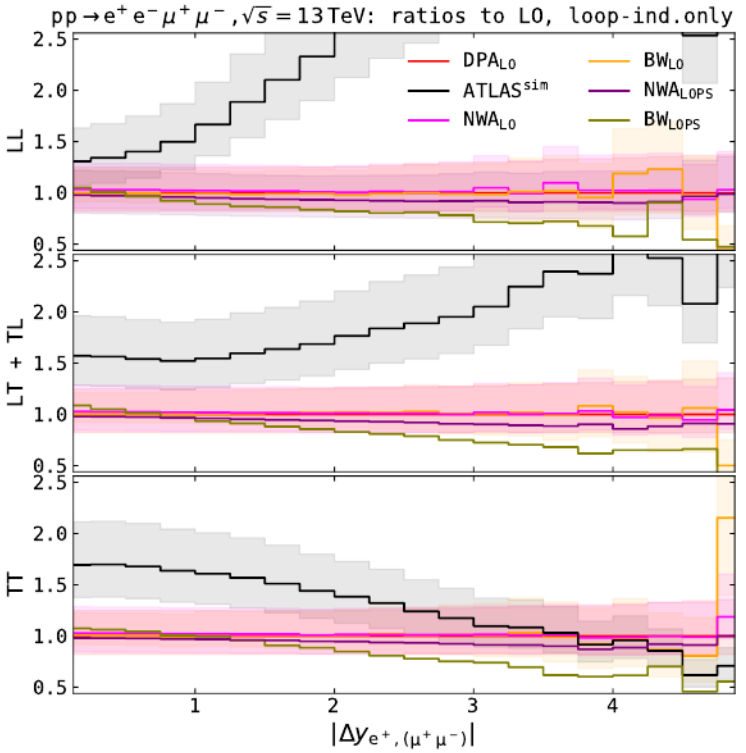
Polarized Dibosons

Talk by Giovanni

Best predictions [Carrivale GP et al. 2505.09686] vs ATLAS modelling [ATLAS 2310.04350]:



(qq) agreement, small QCD unc.



(gg) NLO QCD urgent

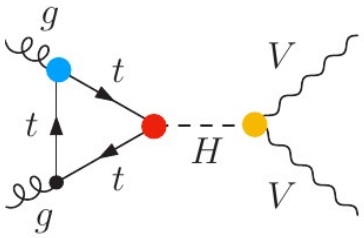
Interpretation in EFT

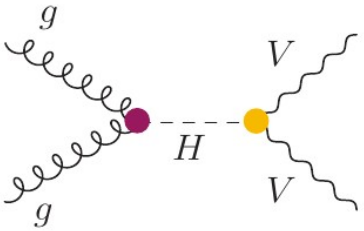
- Underlying assumption in Higgs width determination: onshell couplings are the same as offshell couplings.
- New Physics could change the behavior of the couplings in such a way that the Higgs width is the same as in SM!

[Englert, Spannowksy ('14); Englert, Soreq, Spannowsky ('14); Corbett et al '15; Azatov,Grojean, Paul, Salvioni ('16); Rossia, Thomas, Vryonidou '23; Azatov et al '22 (HWG Note)]

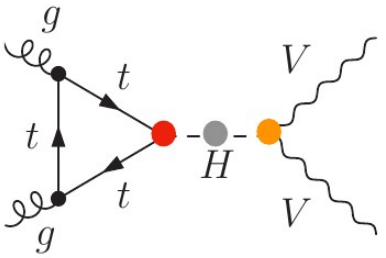
- Parametrize couplings using EFT and perform simultaneous determinations of these and Higgs width using offshell data.
  - Higher dimensional operators change couplings.

- SMEFT:





- HEFT:



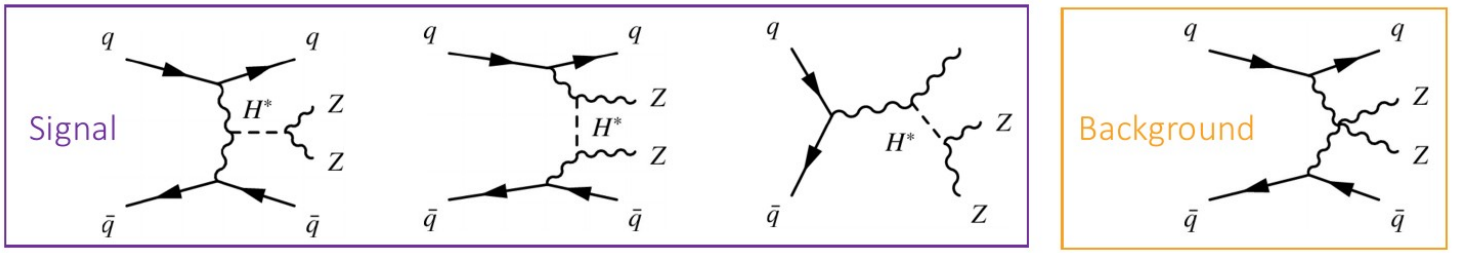
Talk by Anisha

[Anisha, Englert, Kogler, Spannowsky '24]

Offshell Higgs through electroweak production

- ATLAS & CMS studying offshell Higgs through EW production (*VH*+VBF) with signal strength ~ 50% - 100%
- ✓ Width extraction with no assumptions on BSM physics in top quark loop.
- ✗ No clear distinction between signal and background.

Talk by Robin Hayes



- Modelling becoming important – include higher order corrections with relevant kinematic cuts

Summary

- New ATLAS and CMS results: $H \to WW^* \to 2\ell 2\nu$ decay channel.
  - Both ATLAS & CMS have analyses with full Run 2 data for $H \to ZZ^* \to 4\ell$, $H \to ZZ^* \to 2\ell 2\nu$, $H \to WW^* \to 2\ell 2\nu$
- Improved approximation methods, now for offshell Z bosons.
- Tuned comparison of NLO+PS and jet merging tools (`POWHEG/MadGraph/Sherpa`)

  -> contribution to Report 5.

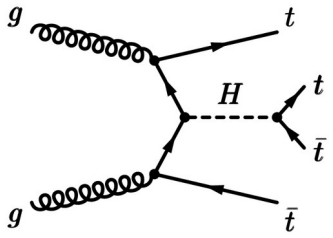
Thanks to everyone who has contributed, given talks, etc.

We welcome new ideas and contributors!

THANK YOU FOR YOUR ATTENTION

Latest ATLAS results

- Based on 4-top search in ATLAS



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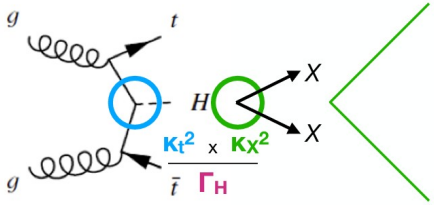
- Compare with (on-shell) $t\bar{t}H$ measurement to do Higgs width interpretation.

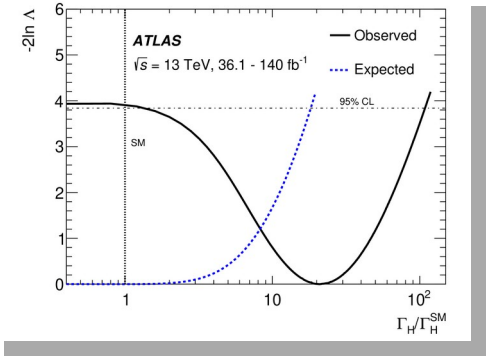


On-shell measurement

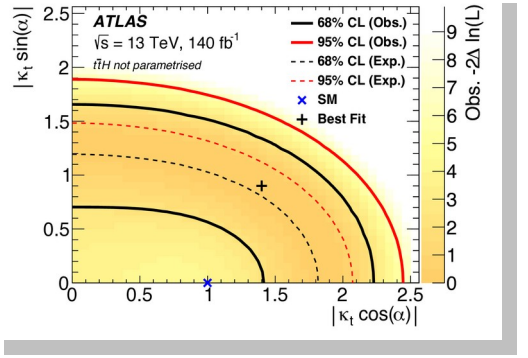
Production	Decay	ecay
ggF, VBF, WH, ZH, $t\bar{t}H$, tH	$H \to \gamma\gamma$	$\to \gamma\gamma$
$t\bar{t}H + tH$	$H \to b\bar{b}$	$\to b\bar{b}$
WH, ZH	$H \to b\bar{b}$	$\to b\bar{b}$
VBF	$H \to b\bar{b}$	$\to b\bar{b}$
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \to ZZ$	$\to ZZ$
ggF, VBF	$H \to WW$	$\to WW$
WH, ZH	$H \to WW$	$\to WW$
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \to \tau\tau$	$\to \tau\tau$
ggF+ $t\bar{t}H + tH$, VBF+ $WH + ZH$	$H \to \mu\mu$	$\to \mu\mu$
Inclusive	$H \to Z\gamma$	$\to Z\gamma$

- Several measurements used to constrain other (not Higgs-top) couplings.
- Results vary significantly if ggH and $H\gamma\gamma$ loops are used to constrain on-shell Higgs-top coupling.

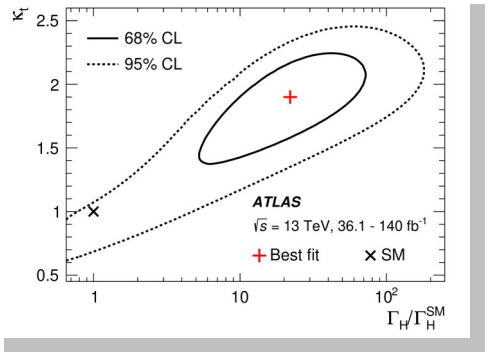
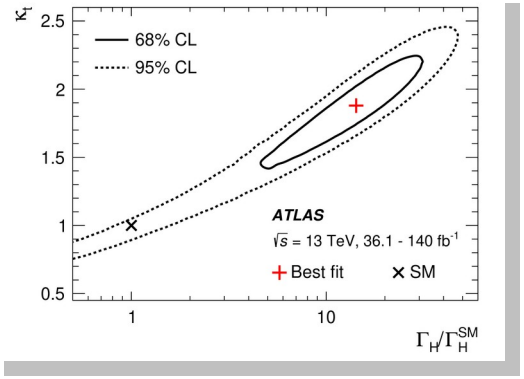
Higgs width interpretation



(off-shell) Higgs – top coupling



Higgs – top coupling width



Higgs – top coupling width (resolving loops)