

Improved understanding of offshell effects in four-lepton production in gluon fusion ($gg \rightarrow 4l$)



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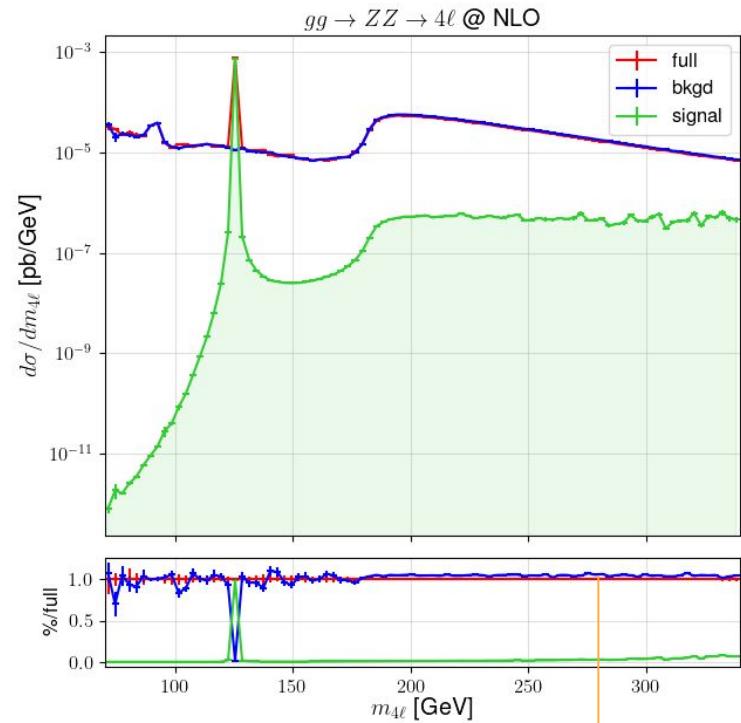
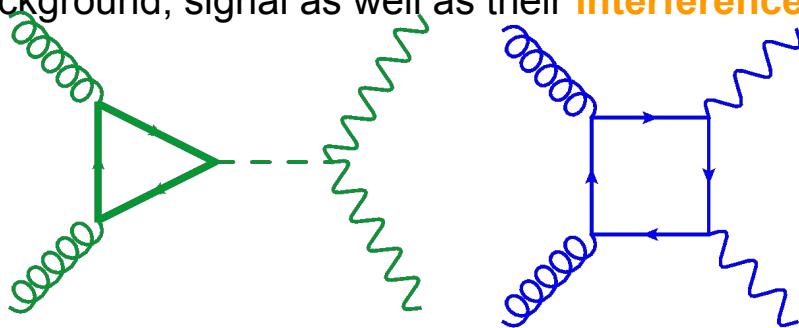


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based on [Eur. Phys. J. C 81, 687 \(2021\)](https://doi.org/10.1140/epjc/s10050-021-01007-0), [2102.07783], S. Alioli, S.F.R., J.M. Lindert and R. Röntsch

Anatomy of $gg \rightarrow H \rightarrow VV \rightarrow 4l$

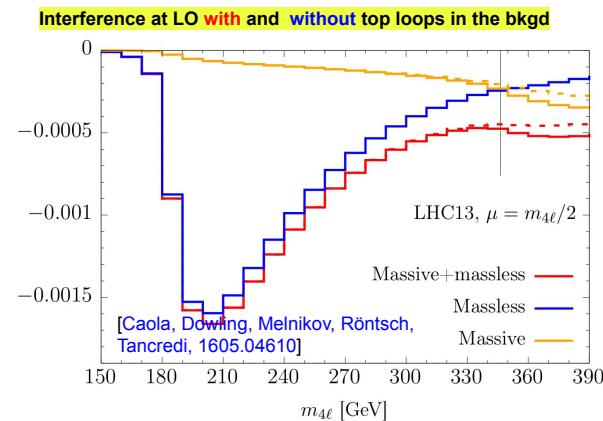
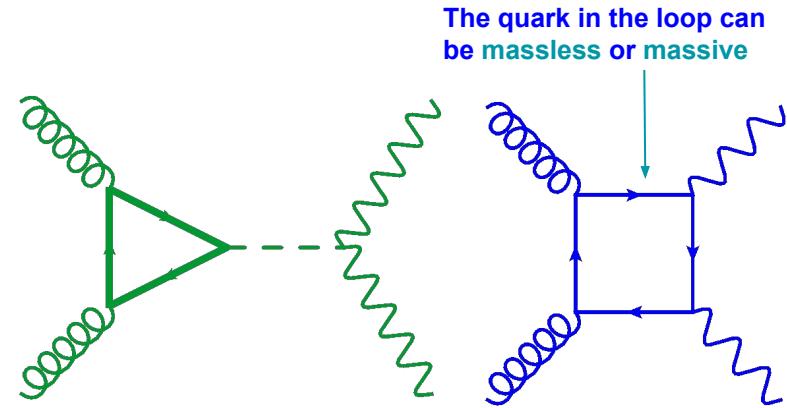
- **Gluon fusion** is the dominant mechanism for Higgs production at the LHC
- The detectors resolution prevents us from measuring directly Γ_H from the m_{VV} distribution.
- $H \rightarrow VV$ sensitive to the **Higgs - gauge bosons** coupling, and a non-negligible ($\sim 10\%$) fraction of $gg \rightarrow H \rightarrow VV$ is from the **off-shell region** $m_{VV} \gg m_H$
- Measure simultaneously σ_{onshell} and σ_{offshell} to get Γ_H and the gauge bosons **Yukawas** independently
- **QCD background** $gg \rightarrow VV$ is dominant at large m_{VV} and cannot be distinguished from the **signal**
- The **full** contribution is given by the sum of background, signal as well as their **interference**



Sizeable and negative
interference for large m_{VV}

Status of $gg \rightarrow VV \rightarrow 4l$ @ NLO

- The **full** contribution is given by the sum of **background**, **signal** as well as their **interference**
- The calculation of the **background** is complicated by the presence of **top-quark** loops, as well as massless. In the **interference**, the contribution of top-loops is enhanced as they couple more to longitudinally-polarized V bosons .
- The **massless** two-loop helicity amplitudes for the **fully offshell** process $gg \rightarrow V^*V^* \rightarrow 4 \text{ leptons}$ are known, and can be taken e.g. from ggvamp (**von Manteuffel, Tancredi, 1503.08835**)
- The **massive** ones have been computed exactly only for **onshell ZZ** [**Agarwal, Jones, von Manteuffel, 2011.15113, Brønnum-Hansen, Wang, 2101.12095**] and **WW** [**Brønnum-Hansen, Wang, arXiv:2102.07783**]
- The **fully offshell** two-loop amplitudes for $gg \rightarrow Z^*Z^* \rightarrow 4l$ with top loops were computed in the **large m_t** limit [**Caola, Dowling, Melnikov, Röntsch, Tancredi, 1605.04610**]



Status of $pp \rightarrow VV \rightarrow 4l$

- $gg \rightarrow VV$ contributes to the **NNLO QCD** corrections to $pp \rightarrow VV$, and can be computed **separately**

Contribution	σ [fb]
LO	$36.8^{+2.9}_{-2.6}$
NLO	$49.0^{+1.5}_{-1.4}$
NNLO (no gg)	$52.1^{+0.7}_{-0.7}$
gg @ LO	$4.3^{+1.1}_{-0.8}$
gg @ NLO	$7.8^{+1.3}_{-1.1}$

ATLAS fiducial cuts for $gg \rightarrow ZZ \rightarrow 4l$ @ 13 TeV,
1902.05892

Grazzini, Kallweit, Wiesemann, Yook '21

$O(\alpha_s^2) = 3.1 + 4.3$ pb, the gluon-fusion channel is enhanced by the large gluon luminosity

A lot of recent activity!

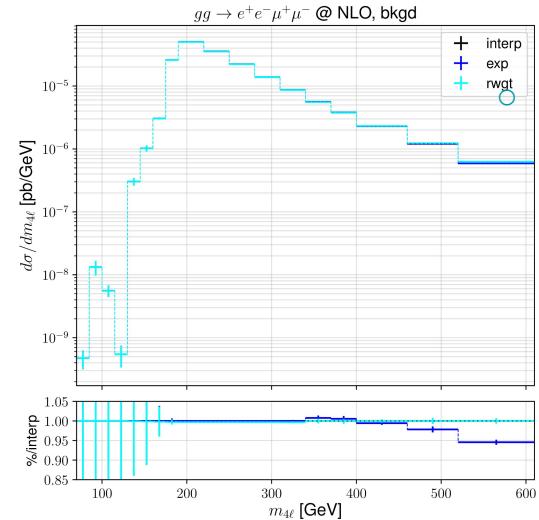
Large NLO corrections (top-mass dependence in the bkgd two-loop amplitudes via LO rwgt)

- $pp \rightarrow WW \rightarrow 4l$ ([MiNNLO_{ps}](#), Lombardi, Wiesemann, Zanderighi '21, [Re, Wiesemann, Zanderighi '18]) and $pp \rightarrow ZZ \rightarrow 4l$ ([GENEVA](#), Alioli, Broggio, Gavardi, Kallweit, Lim, Nagar, Napoletano '21; [MiNNLO_{ps}](#); Buonocore, Koole, Lombardi, Rottoli, Wiesemann, Zanderighi '21) are both known at [NNLOPS](#).
- In this talk: $gg \rightarrow VV \rightarrow 4l$ at **NLOPS** in **POWHEG BOX RES**, with spin correlations, interferences and off-shell effects are included exactly, top-quark mass effects are included approximately in the QCD bkgd ([S. Alioli, S.F.R., J.M. Lindert and R. Röntsch '21](#))

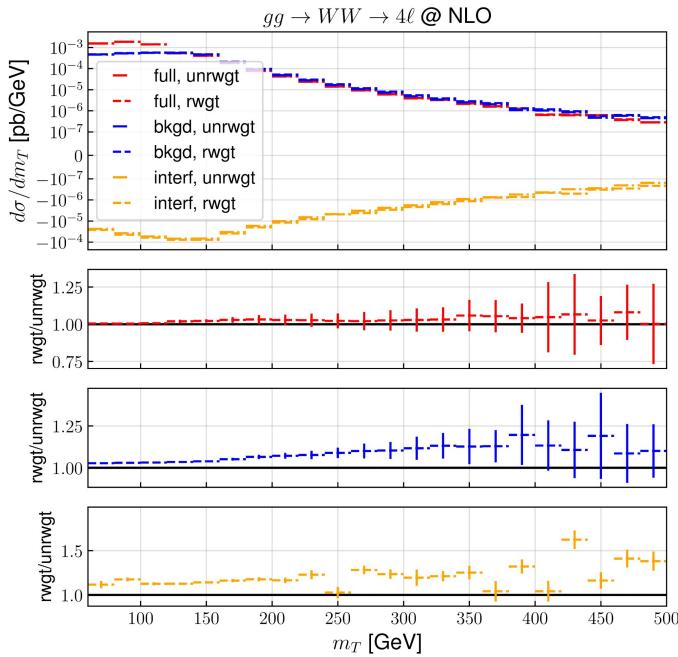
gg4l @ NLO in POWHEG BOX RES

- First NLOPS for $gg \rightarrow VV \rightarrow 4l$ including off-shell effects, **interference** between the **Higgs mediated signal** and the **QCD background**. Exact one-loop matrix elements from **OpenLoops** and two loops from **Caola et al, 2016** and **ggVVamp**:
 - VV = WW:** **top-mass effects** for the virtual **bkgd** ampl obtained using LO reweighting (@ fixed helicity, **MCFM**)

$$\mathcal{A}_{\text{bkgd}}^{(2),WW} = \mathcal{A}_{\text{bkgd}}^{(2),WW}(u, d, s, c) \frac{\mathcal{A}_{\text{bkgd}}^{(1),WW}(u, d, s, c, b, t)}{\mathcal{A}_{\text{bkgd}}^{(1),WW}(u, d, s, c)}$$



VV = ZZ: **top-mass effects** for the virtual **background** amplitude obtained using large- m_t expansion from **Caola et al, 2016**. LO rwgt also available for large m_{4l} region, as well as interpolation between the two options.

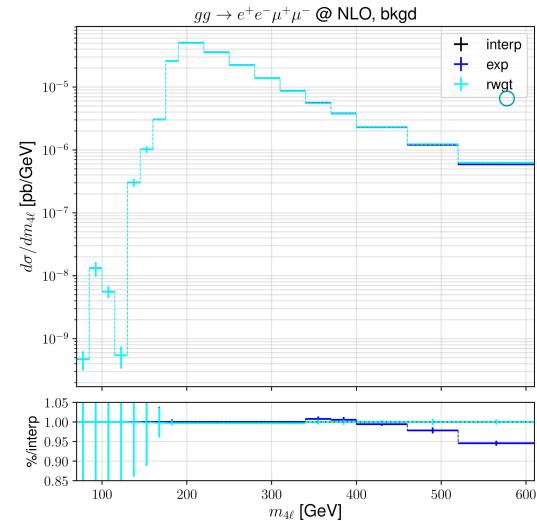


Top-mass effects in **bkgd** ampl important for the **interference**: offshell Higgs decays preferentially to longitudinal Z's, which couple more with top quark loops than with massless loops

gg4I @ NLO in POWHEG BOX RES

- First NLOPS for $gg \rightarrow VV \rightarrow 4l$ including off-shell effects, **interference** between the **Higgs mediated signal** and the **QCD background**. Exact one-loop matrix elements from **OpenLoops** and two loops from **Caola et al, 2016** and **ggVVamp**:
 - VV = WW:** top-mass effects for the virtual **bkgd** ampl obtained using LO reweighting (@ fixed helicity **MCFM**)

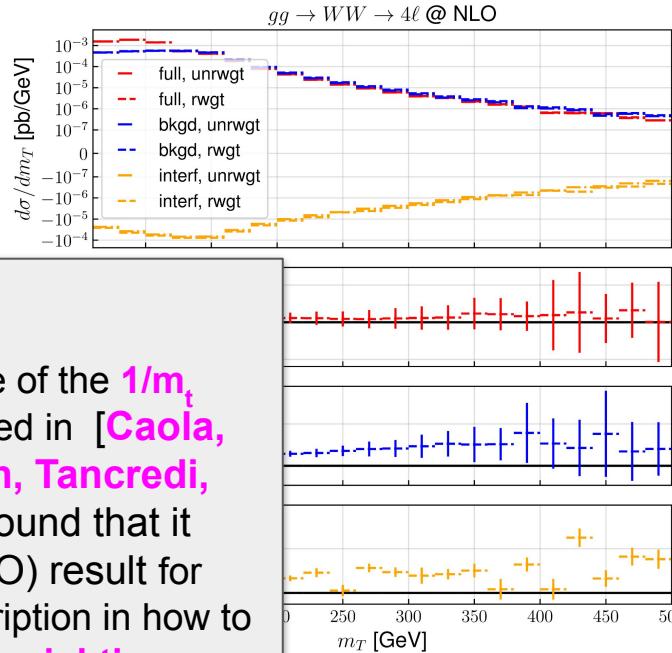
$$\mathcal{A}_{\text{bkgd}}^{(2),WW} = \mathcal{A}_{\text{bkgd}}^{(2),WW}(u, d,$$



the
am
large
eta
LO
 $m_{4\ell}$
interpolation between the two
options.

WARN!!

The uncertainty due to the use of the $1/m_t$ expansion was carefully assessed in [**Caola, Dowling, Melnikov, Röntsch, Tancredi, 1605.04610**], where it was found that it reproduces well the exact (LO) result for $m_{zz} < 2m_t$. There is no clear prescription in how to assess the **quality of the reweighting procedure**, besides just noticing that it agrees with the $1/m_t$ expansion for $m_{zz} < 2m_t$.

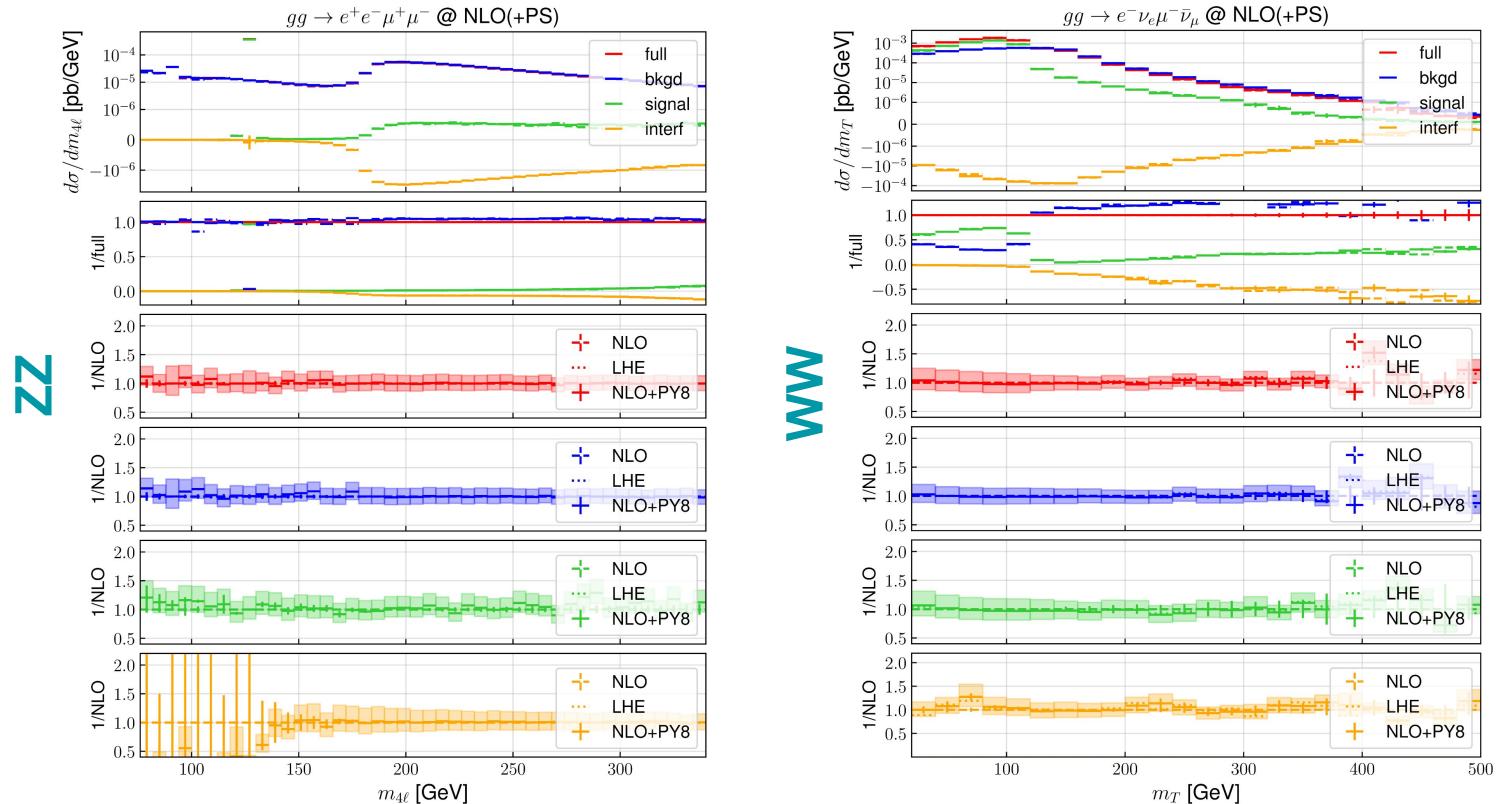


bkgd ampl important
offshell Higgs
coupling to longitudinal Z's,
which couple more with top quark loops
than with massless loops

gg4l @ NLOPS in POWHEG BOX RES: setup

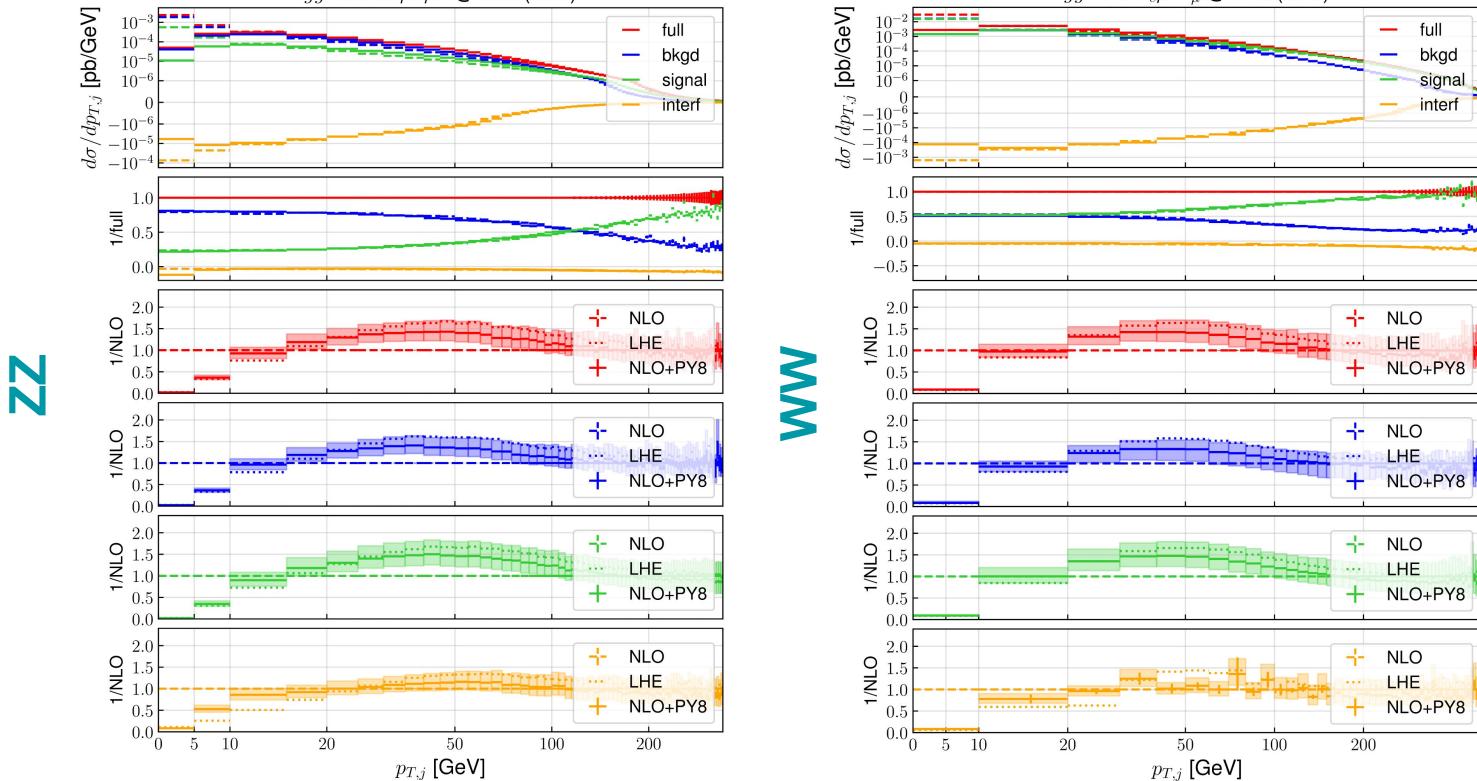
- pp collisions @ **13 TeV**
- Central renormalization and factorization scale $\mu = m_{4l}/2$
- **ZZ** channel:
 - 5 GeV < m_{ll} < 180 GeV;
 - 10 GeV < m_{4l} < 340 GeV; [where we have good control of our approximations]
- Les Houches level (LHE) predictions by POWHEG matched to the **PYTHIA8.2** general purpose Monte Carlo event generator (**default shower, PowhegHooks** class to veto emissions harder than the POWHEG one)

gg4I @ NLOPS in POWHEG + PYTHIA: m_{ZZ} & m_{TWW}



Invariant (transverse) mass of the VV system left unchanged by the parton shower. The relative size of the **signal** and of its **interference** with the QCD **background** increases in the tail.

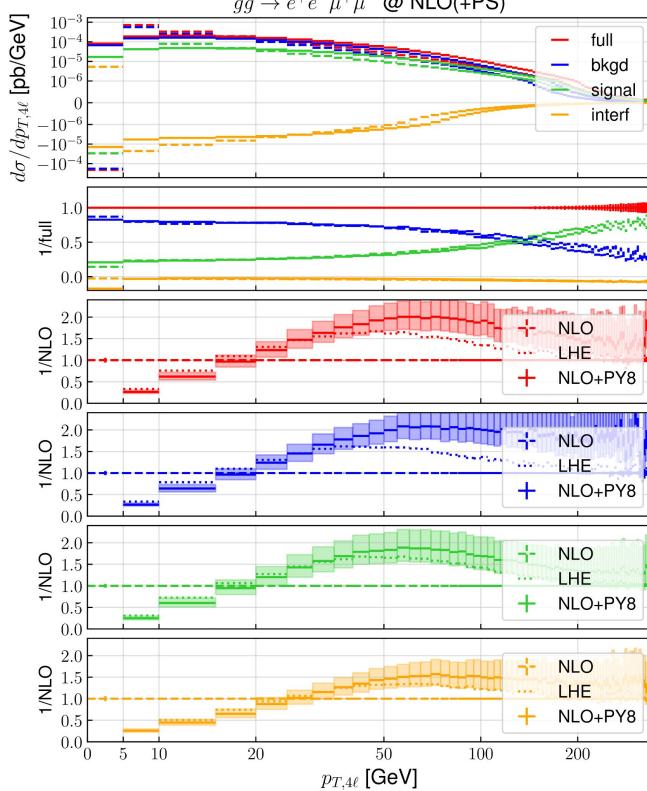
gg4l @ NLOPS in POWHEG + PYTHIA: $p_{T,j}$



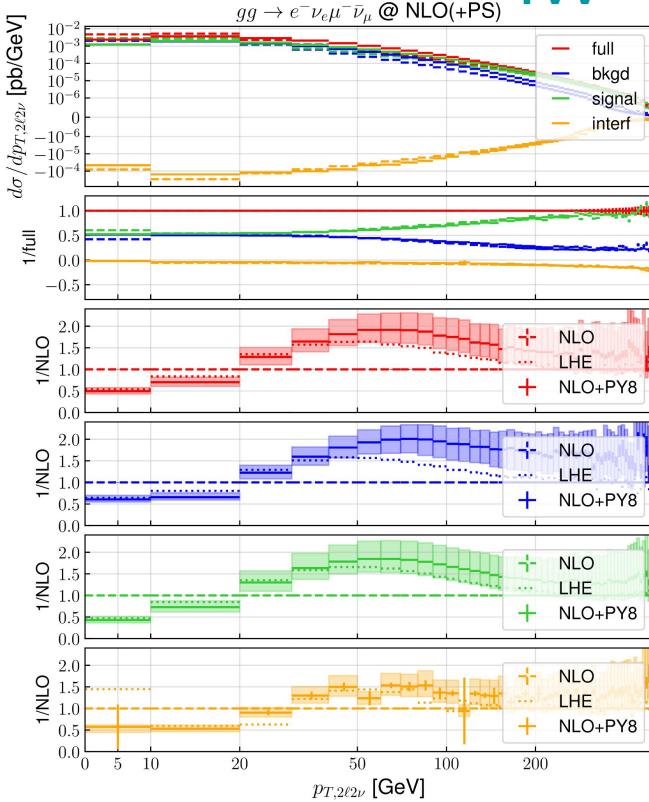
Resummation effects in LHE and NLOPS distributions sizeable for small values of the hardest jet p_T , in the tail agreement with fixed order.

gg4I @ NLOPS in POWHEG + PYTHIA: p_{TVV}

ZZ

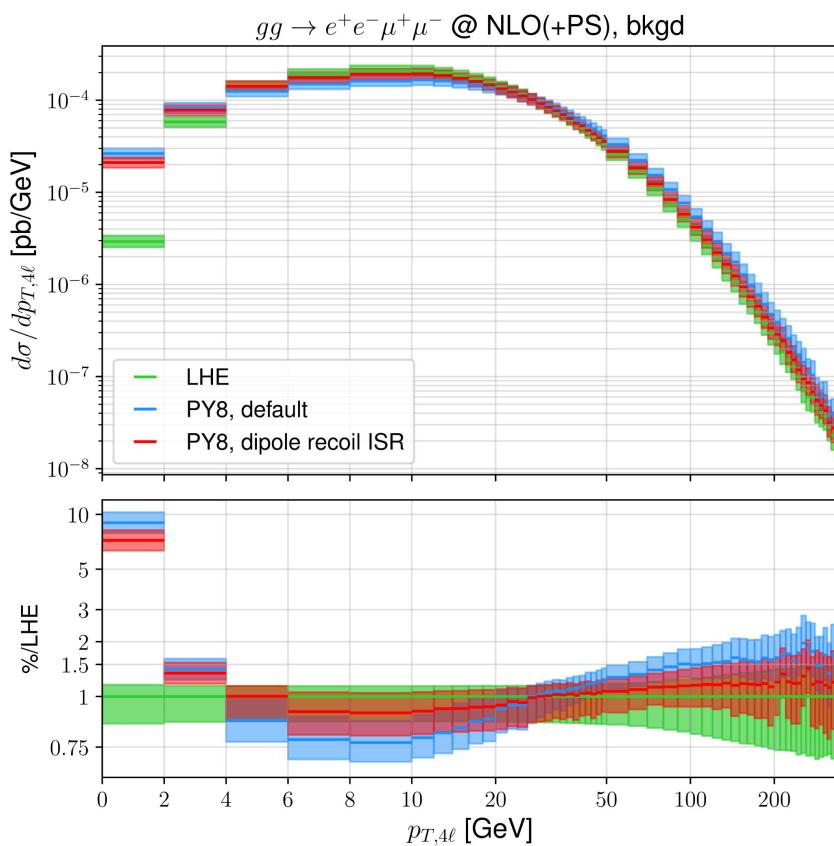


WW

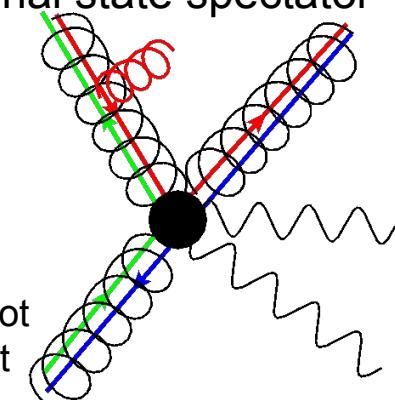


At NLO and LHE, $p_{\text{TVV}} = p_{\text{Tj}}$. The PS enhances significantly the tail, where scale variations are large.

gg4I @ NLOPS in POWHEG + PYTHIA: p_{TVV}



+50% PS corrections in the tail of p_{TVV} depend on the PS recoil scheme, and the differences are as large as scale variations. By **default**, transverse momentum imbalance due to ISR always absorbed by the final state. In the **Catani-Seymour shower**, if the incoming emitter is in an initial-final dipole, the final state spectator takes the recoil. For small p_{TVV} , differences are at **next-to-leading log**.



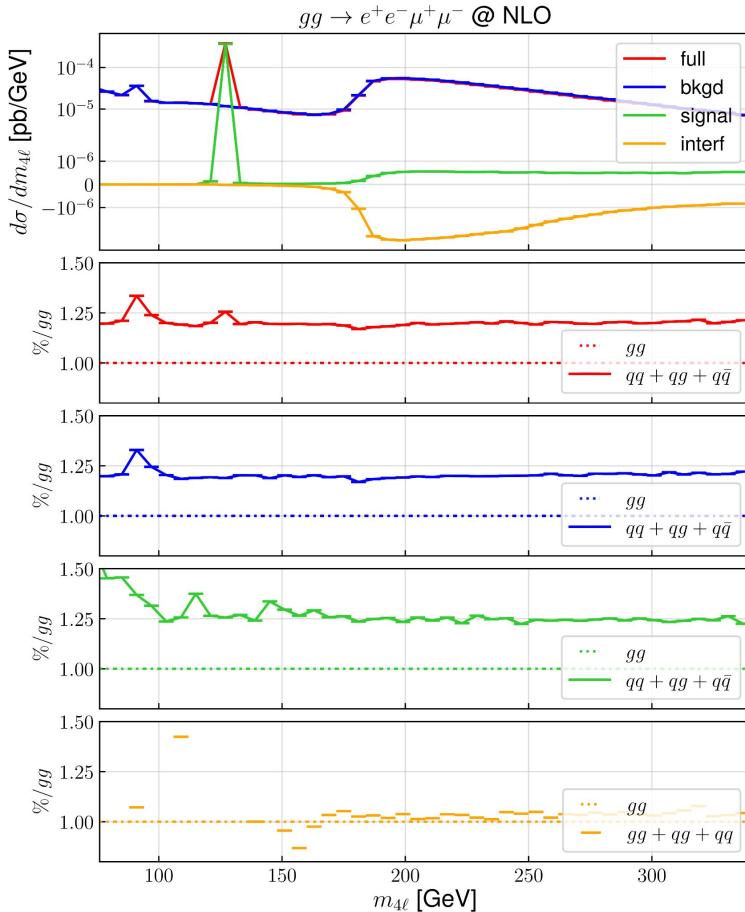
First NLL dipole-showers (not yet public) for colour-singlet production presented in
[van Beekveld, S.F.R., Salam, Soto-Ontoso, Soyez, Verheyen, 2205.02237]

Summary and conclusions

- $gg \rightarrow H \rightarrow VV$ important to probe the HVV coupling: 10% of the cross-section comes from the region $m_{VV} \gg m_V$, which can be used also for Γ_H determinations.
- The main challenge in state-of-the art fixed-order calculations is the inclusion of the **top-mass** dependence in the **two-loops background virtual amplitude**
- We have implemented in POWHEG BOX RES the **first NLOPS generator for off-shell VV production**, with leptonic V decay, in **gluon fusion** including the Higgs mediated **signal**, his QCD **background** and their **interference**.
- One loop matrix elements are exact, some approximations are made for the **top-mass** dependence of the **bkgd** amplitude at two loops: **we can easily replace them once the exact calculation becomes available.** [**Use the exact on-shell two loop amplitudes? Rwg to get offshell effects?**]
- We performed a phenomenological study at 13 TeV: **PS effects** are sizable e.g. for pT_{4l} and H_T .
- Large dependence on the PS recoil scheme in the tail of the pT_{4l} distributions, whose accuracy is only LO+LL. (But NLL showers will soon be a reality!)
- **THE CODE IS PUBLIC** and can be downloaded with:

BACKUP

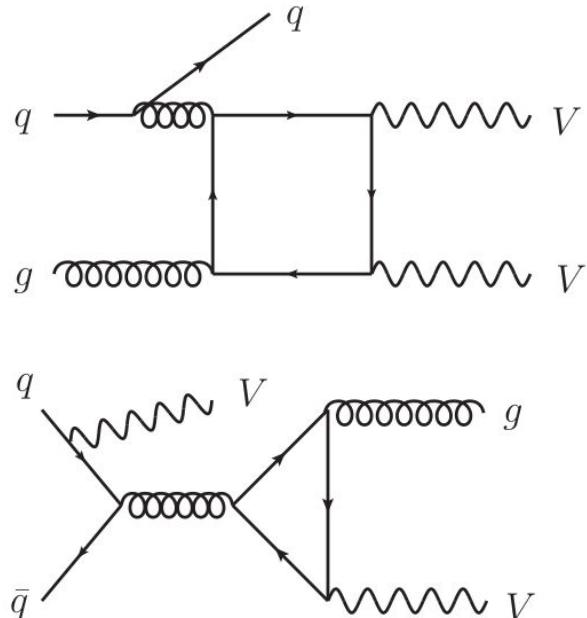
gg4l @ NLO in POWHEG BOX RES



- Singular qg-initiated and regular qq-initiated contributions are included in the real corrections and contribute to the 20% of the **total**

Sizeable impact
(but scale
variations
unchanged)

Regular,
negligible



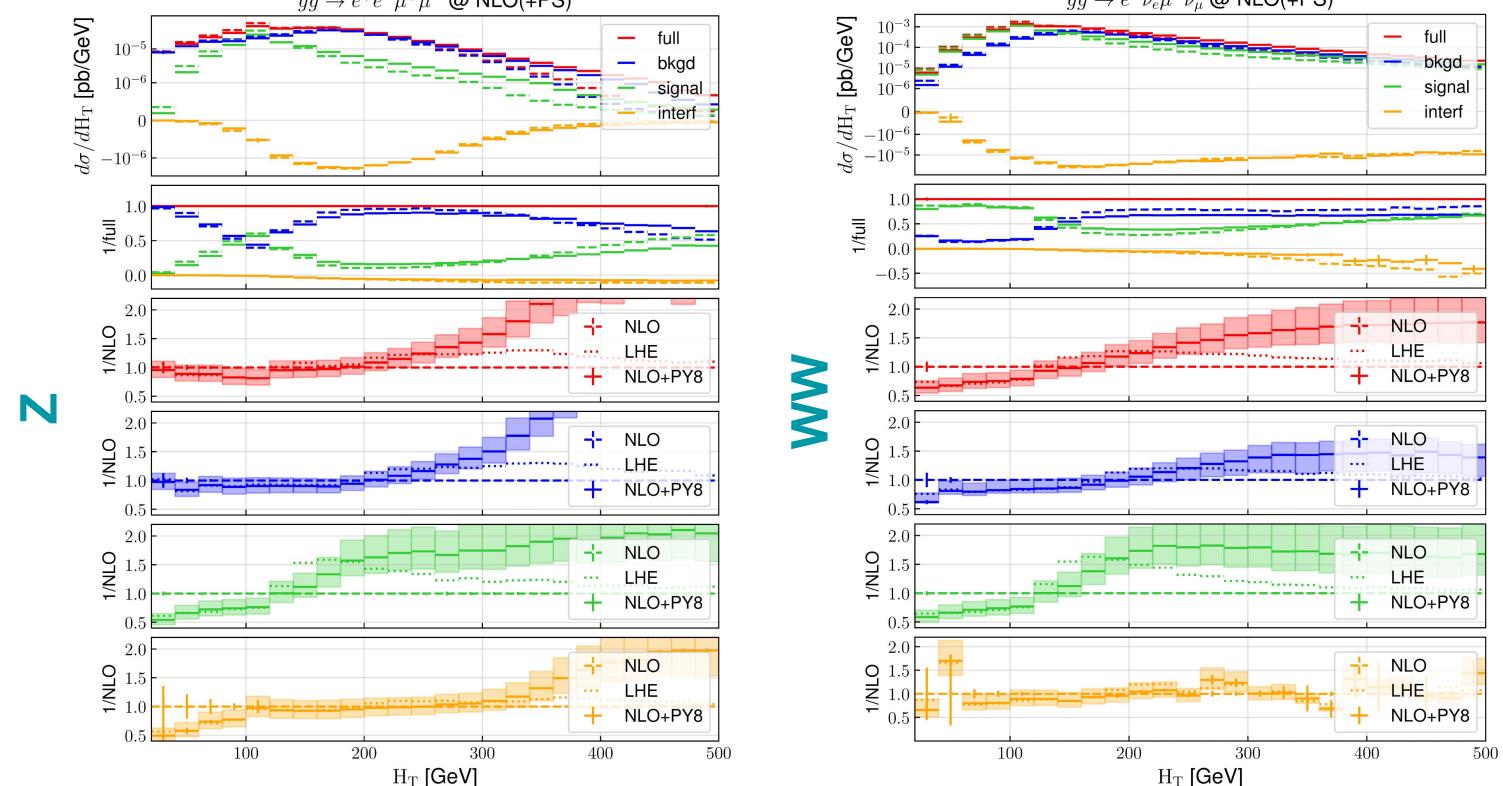
gg4l @ NLOPS in POWHEG BOX RES: setup

- pp collisions @ **13 TeV**
- **NNPDF31_nlo_as_0118** PDF set
- Central renormalization and factorization scale $\mu = m_{4l}/2$
- $m_b = 0$ (**5 flavour** scheme) $m_t = 173.2$ GeV
- **ZZ** channel: $5 \text{ GeV} < m_{\parallel} < 180 \text{ GeV}$; $m_{4l} < 340 \text{ GeV}$
- **WW** channel: $m_{2l2\nu} > 1 \text{ GeV}$
- **Jets**: anti-kt, R=0.4, pT > 20 GeV
- POWHEG matching with **bornzerdamp** and **hdamp=100 GeV** to separate the real contribution into singular and not singular

$$d\sigma = \left[B(\Phi_b) + V(\Phi_b) + \int d\Phi_{\text{rad}} R_s(\Phi_b, \Phi_{\text{rad}}) \right] \left[\Delta^{\text{pwg}}(p_{\perp \min}) + \frac{R_s(\Phi_b, \Phi_{\text{rad}})}{B(\Phi_b)} \Delta^{\text{pwg}}(p_{\perp}(\Phi_{\text{rad}})) \right] + R_{ns}(\Phi_{b+1})$$

- Les Houches level (LHE) predictions by POWHEG matched to the **PYTHIA8.2** general purpose Monte Carlo event generator (**default shower**, **PowhegHooks** class to veto emissions harder than the POWHEG one)

gg4I @ NLOPS in POWHEG + PYTHIA: H_T



Large impact of multiple PS emissions for the tail of $H_T = \sum_{l,\nu,j} p_\perp$, particularly for the **signal**, which at f.o. is peaked at smaller values.