Four-lepton production in gluon fusion at NLO matched to parton showers

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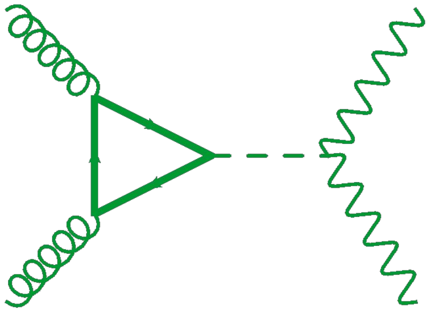
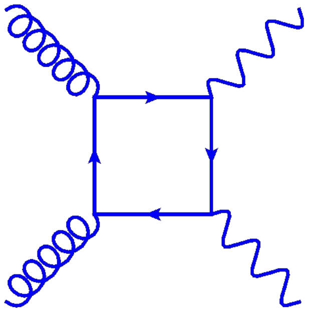
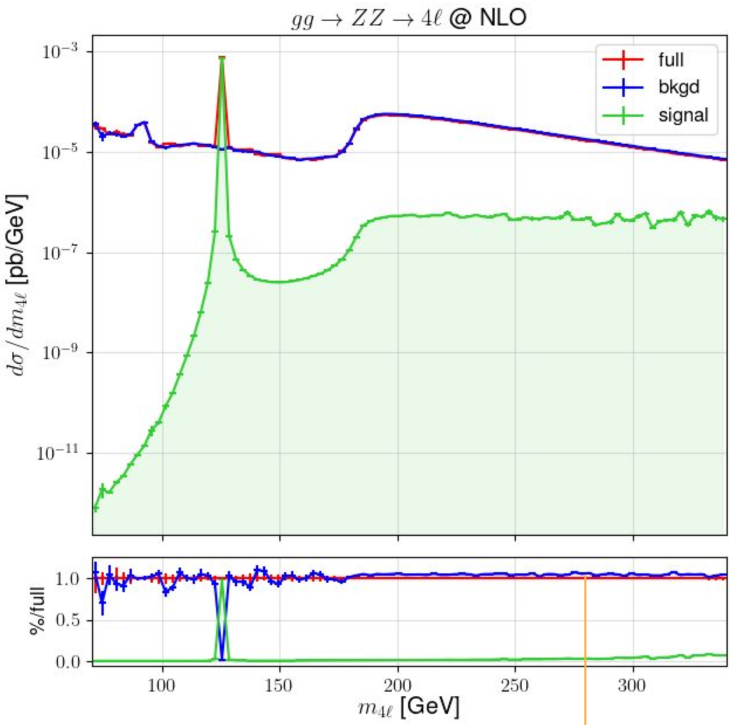
based on *Eur. Phys. J. C* **81, 687 (2021)**, [2102.07783], S. Alioli, S.F.R., J.M. Lindert and R. Röntsch

Anatomy of gg→H→VV

- Gluon fusion is the dominant mechanism for Higgs production at the LHC
- H→VV sensitive to the Higgs - gauge bosons coupling
- Roughly 10% of **gg→H→VV** comes from $m_{VV} > m_V$
- Offshell Higgs cross section important to determine $\Gamma_H \ll$ detector resolutions
- **QCD bakground gg→VV** is dominant 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}

Anatomy of pp→VV →4l

- **gg→VV** contributes to the NNLO QCD corrections to pp→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 → ZZ →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

Large NLO corrections

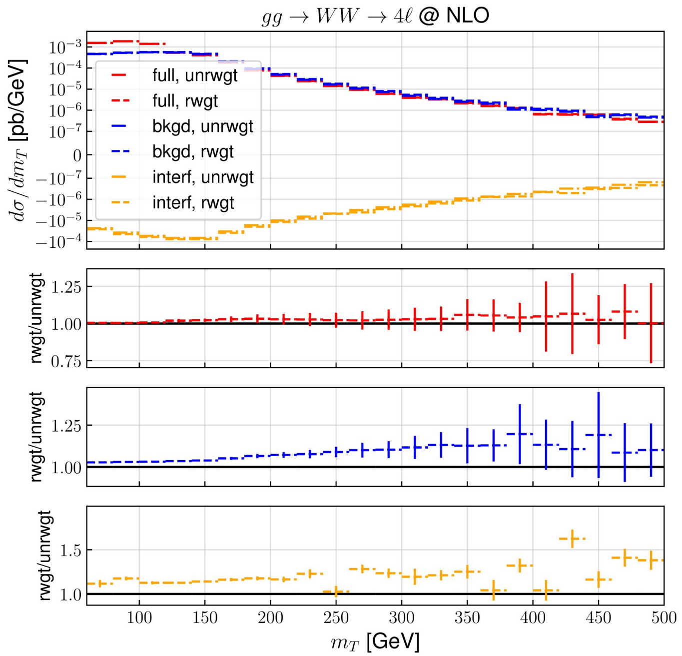
A lot of recent activity!

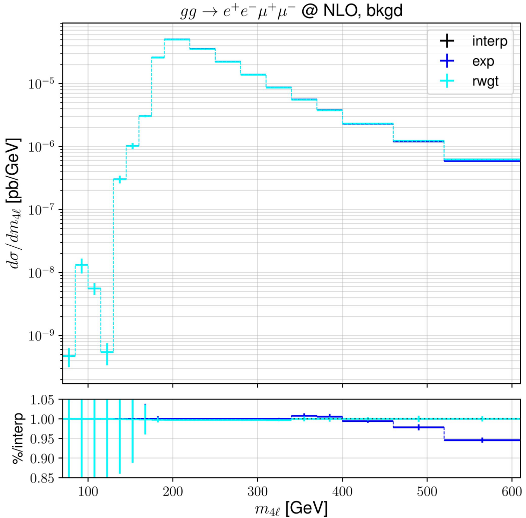
- **pp→WW→4l** (**MiNNLO$_{PS}$**, Lombardi, Wiesemann, Zanderighi '21, [Re, Wiesemann, Zanderighi '18]) and **pp→ZZ→4l** (**GENEVA**, Alioli, Broggio, Gavardi, Kallweit, Lim, Nagar, Napoletano '21; **MiNNLO$_{PS}$**; Buonocore, Koole, Lombardi, Rottoli, Wiesemann, Zanderighi '21) are both known at **NNLOPS**.
- In this talk: **gg→VV→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→VV→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 etal, 2016** (and **ggVVamp**).
- **VV = WW**: **top-mass effects** for the virtual **bkgd** ampl obtained using LO reweighting (@ fixed helicity, **MCFM**)

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

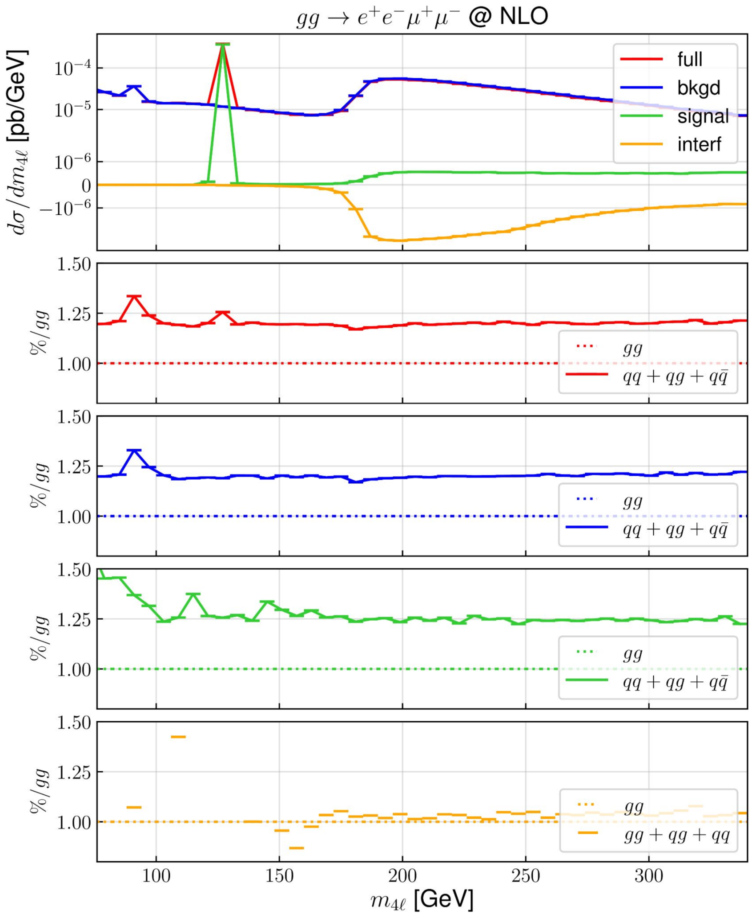




- **VV = ZZ**: **top-mass effects** for the virtual **background** amplitude obtained using large-m_t expansion from **Caola etal, 2016**. (LO rwgt also available for large m_{4l} region, as well as interpolation between the two options)

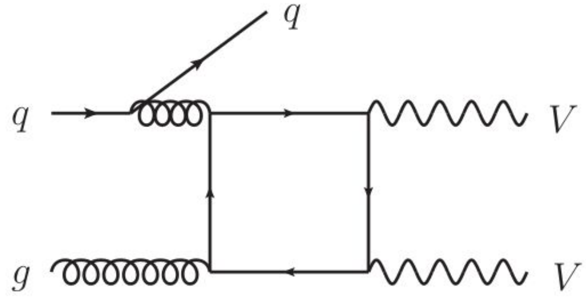
Top-mass effects in **bkgd** ampl important for the **interference**: offshell Higgs decays preferentially to longitudinal Z's, which couple more with top quark loops than with massless loops

gg4l @ NLO in POWHEG BOX RES

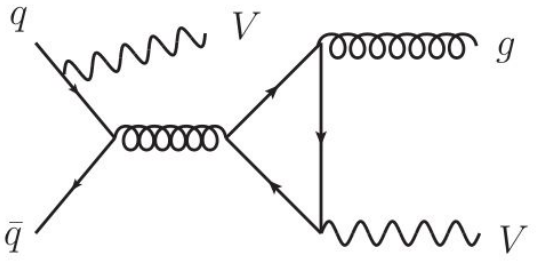


- **Singular qg-initiated** and **regular qq-initiated** contributions are included in the real corrections and contribute to the 20% of the **total**

Sizeable impact (but scale variations unchanged)



Regular, negligible



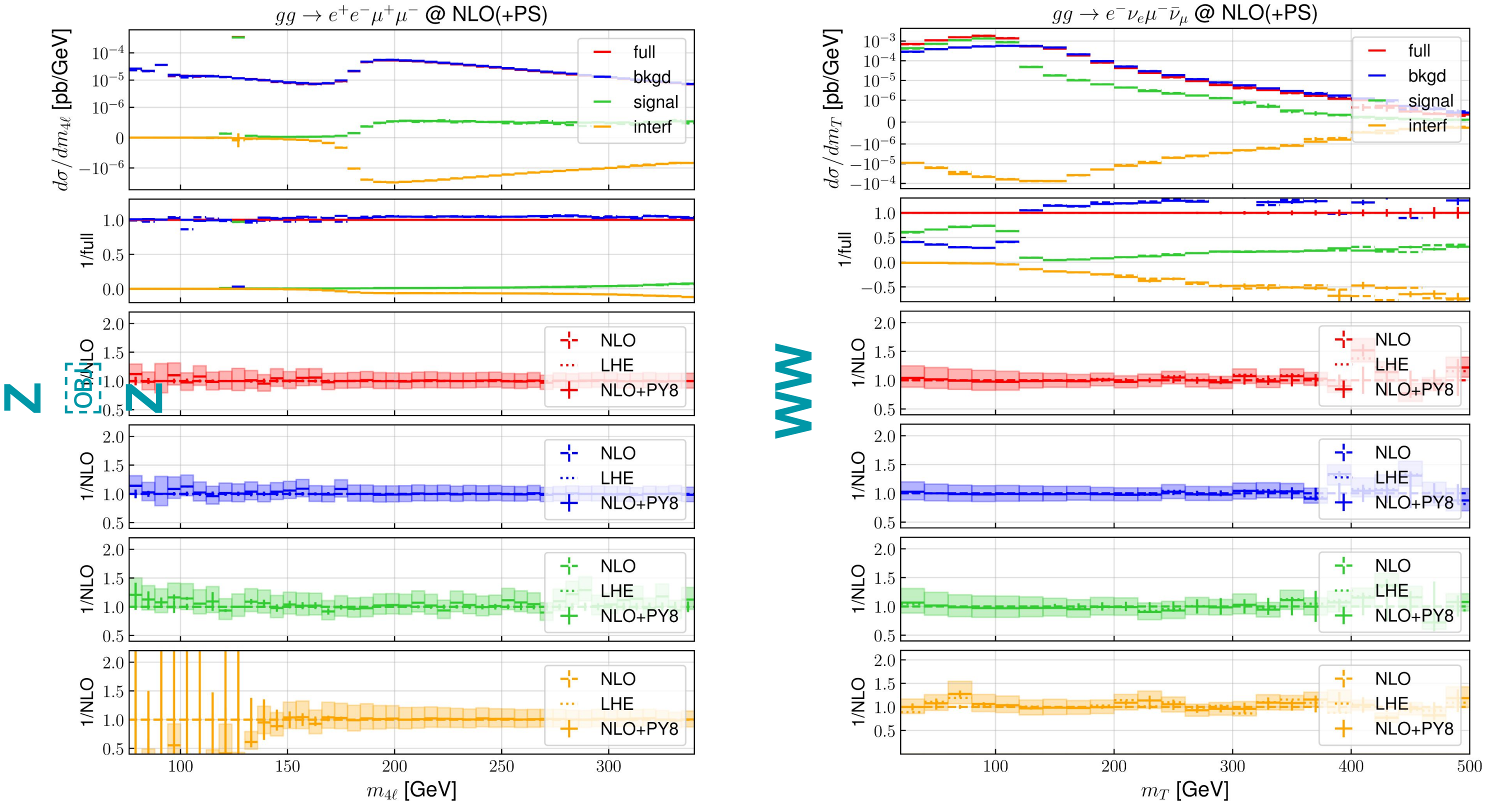
gg4l @ NLOPS in POWHEG BOX RES: setup

- pp collistions @ **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 GeV < m_{ll} < 180 GeV; m_{4l} < 340 GeV
- **WW** channel: $m_{2l2\nu}$ > 1 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

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

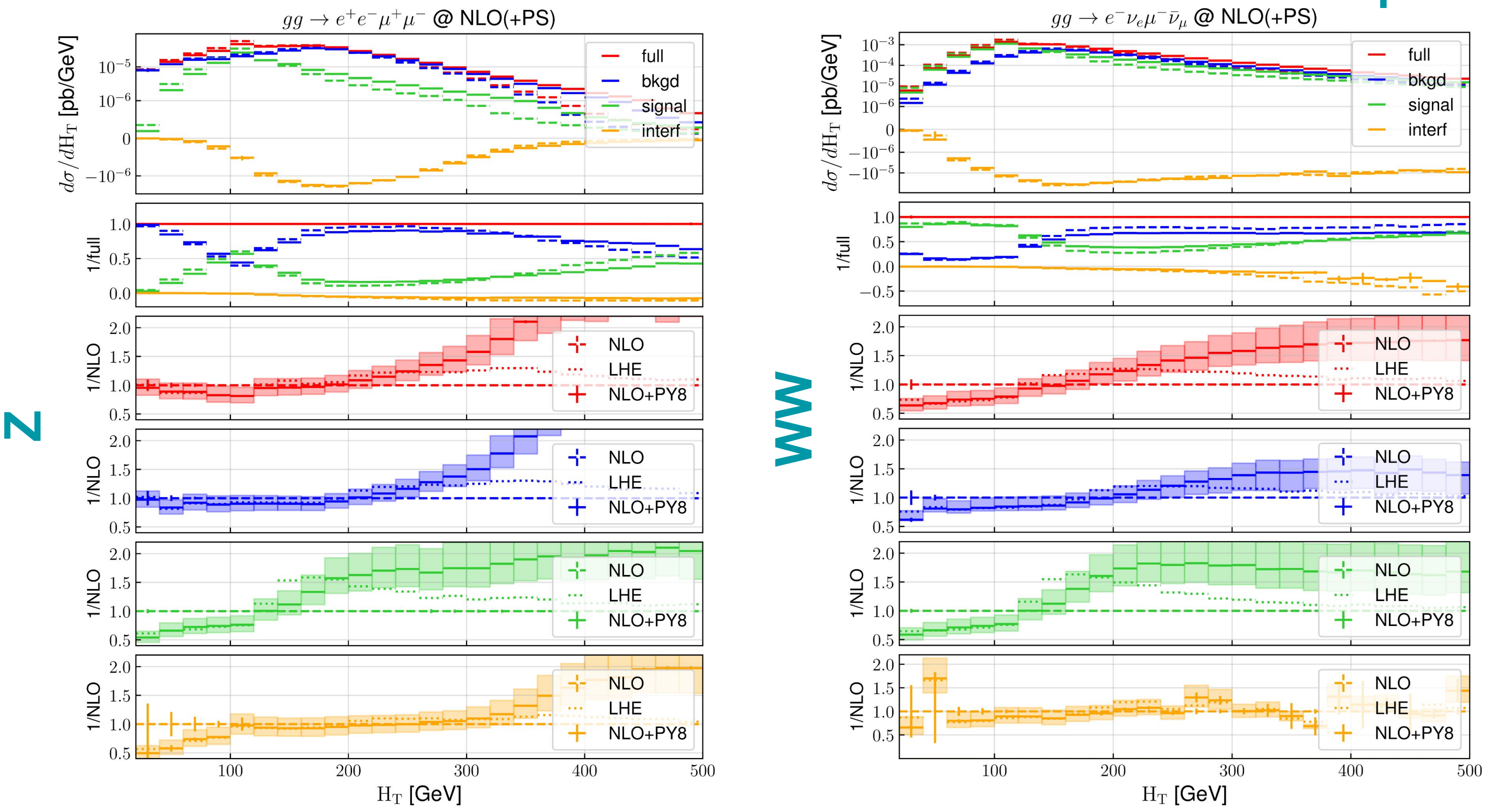
- Les Houches level (LHE) predictions by POWHEG matched to the **PYTHIA8.2** general purpose Monte Carlo event generator (**default shower**, **PowhegHooks** class to veto emissions harder than the POWHEG one)

gg4l @ NLOPS in POWHEG + PYTHIA: m_{ZZ} & m_{TWW}



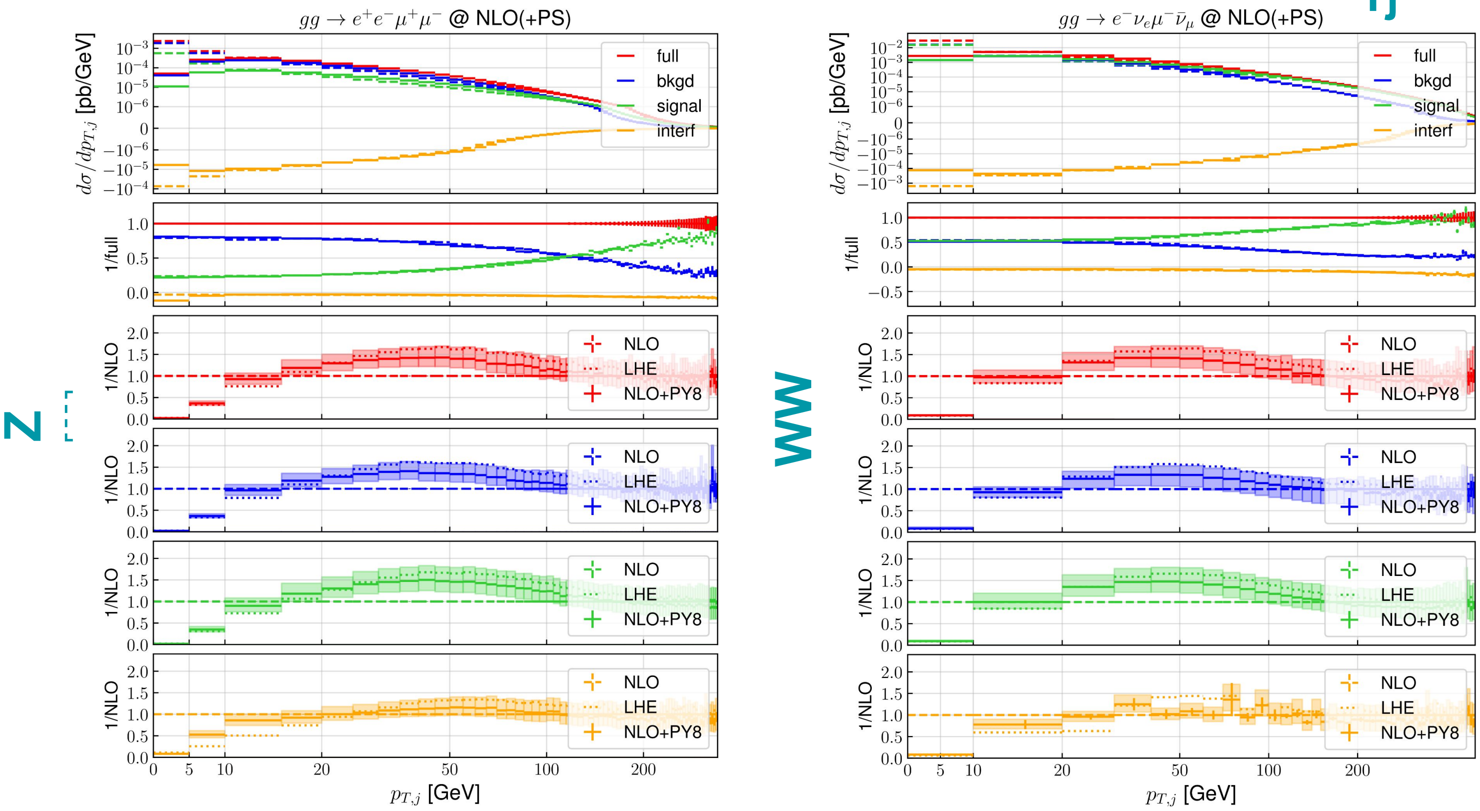
Invariant (transverse) mass of the VV system left unchanged by the parton shower. The relative size of the **signal** and of its **interference** with the QCD **background** increases in the tail.

gg4l @ NLOPS in POWHEG + PYTHIA: H_T



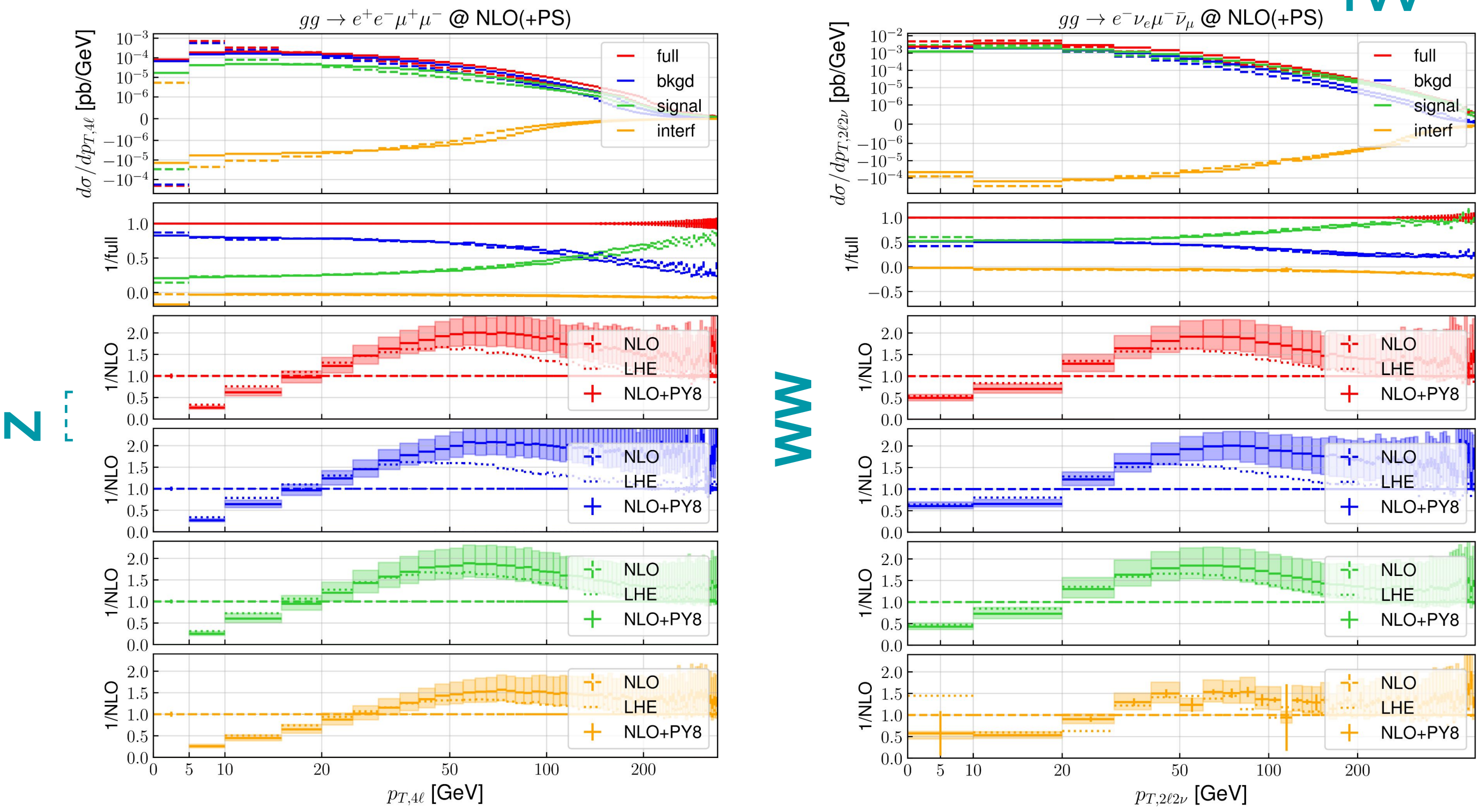
Large impact of multiple PS emissions for the tail of $H_T = \sum_{l,\nu,j} p_\perp$, particularly for the **signal**, which at f.o. is peaked at smaller values.

gg4l @ NLOPS in POWHEG + PYTHIA: p_{Tj}



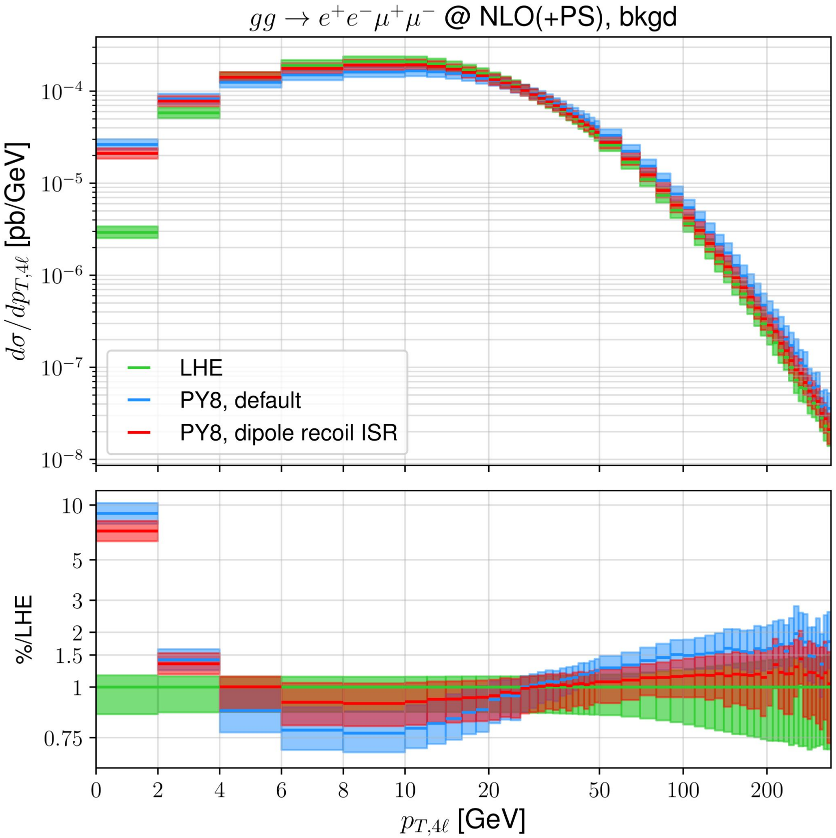
Resummation effects in LHE and NLOPS distributions sizeable for small values of the hardest jet pT, in the tail agreement with fixed order.

gg4l @ NLOPS in POWHEG + PYTHIA: p_{TVV}



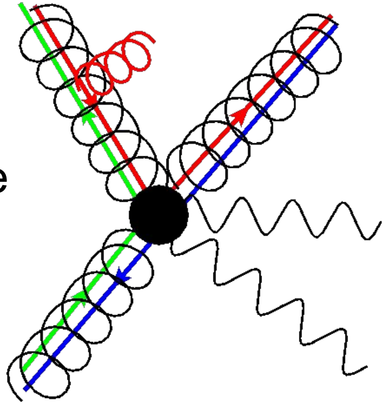
At NLO and LHE, $p_{TVV} = p_{Tj}$. The PS enhances significantly the tail, where scale variations are large.

gg4l @ NLOPS in POWHEG + PYTHIA: p_{TVV}



+50% PS corrections in the tail of p_{TVV} depend on the PS recoil scheme. 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.

Differences are at **next-to-leading log** accuracy and as large as scale variations.



Summary and conclusions

- **gg→H→VV** important to probe the HVV coupling: 10% of the cross-section comes from the region $m_{VV} >> m_V$, which can be used also for Γ_H determinations.
- 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 replace them once the exact calculation becomes available.
- 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.
- The code will be released in a couple of weeks:

svn co --username anonymous --password anonymous svn://powhegbox.mib.infn.it/trunk/User-Processes-RES/gg4l