$gg \to 4\ell$ with POWHEG and color singlet production via gluon fusion in GENEVA

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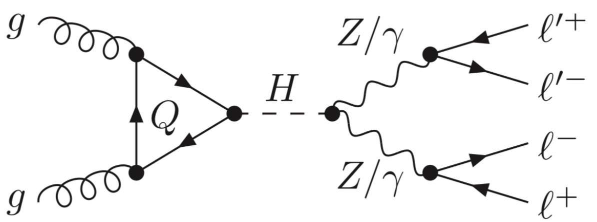
Outline

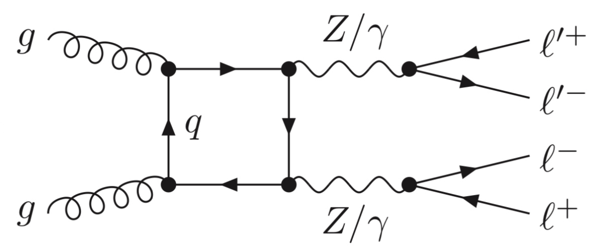
- $gg \to 4\ell$ at NLO+PS in POWHEG-BOX-RES
- Improving precision of MC event generators to NNLO+PS
- Loop-induced color singlet production in GENEVA

Structure of the NLO $gg \to 4\ell$ calculation

- Separately calculate Higgs-mediated amplitude $gg \to H \to 4\ell$ (signal), background and their interference

$$|A|^2 = |A_{\rm signal}|^2 + |A_{\rm bkgd}|^2 + 2{\rm Re}\left(A_{\rm signal}A^*_{\rm bkgd}\right).$$



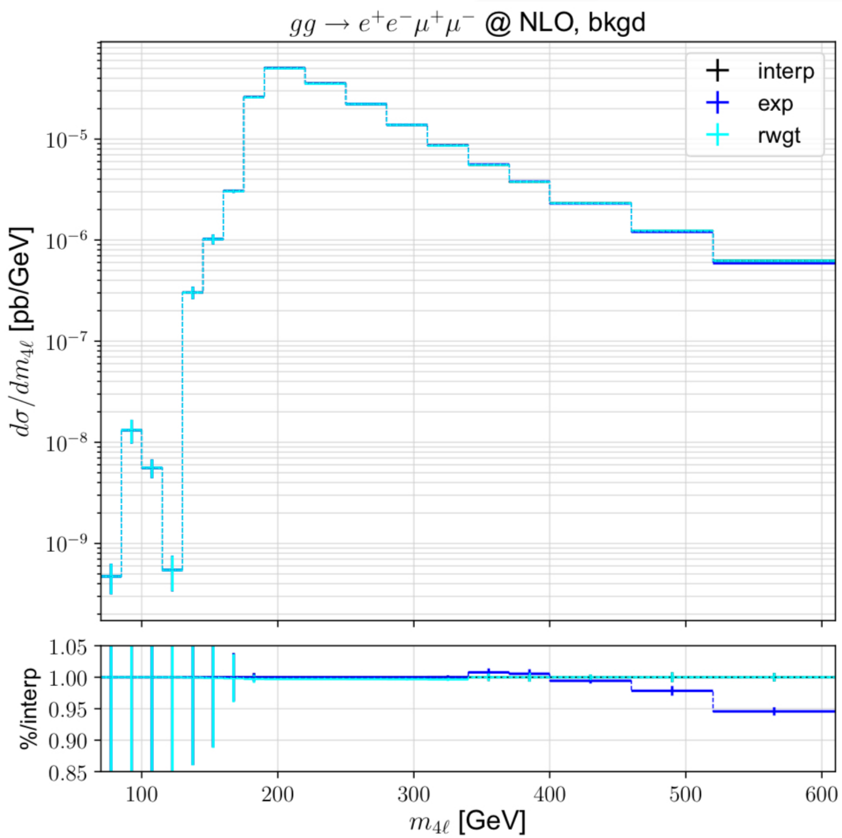


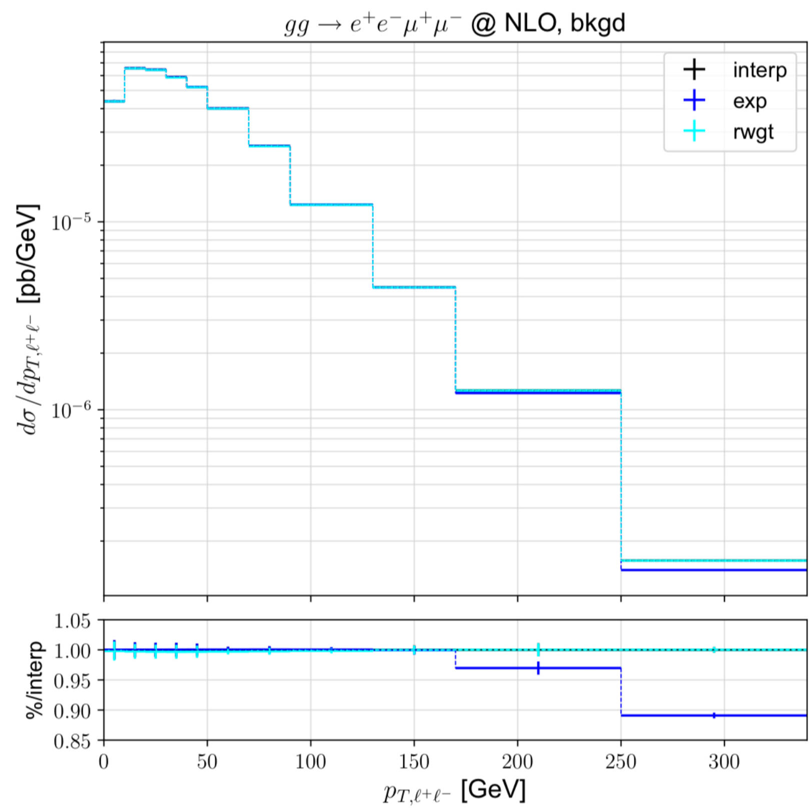
- Loop-induced calculation, `ggVVamp` for massless loops.
- Mass effects difficult to include or only known for on shell Z at 2 loops. [Agarwal et al. '20]
- For ZZ background, top-loop effects included through systematically-improvable $1/m_t$ expansion. Applicability limited to $m_{4\ell} \leq 2m_t, p_{T,\ell\ell} < m_t$ [Caola et al. '15, SA et al. '16]

Structure of the NLO $gg \to 4\ell$ calculation

- Can be extended via reweighting

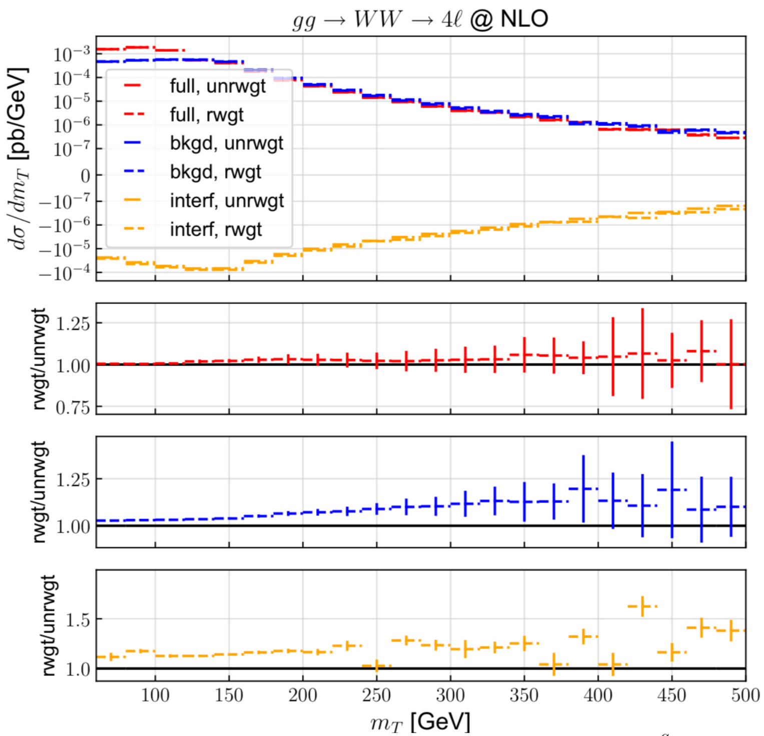
$$\mathcal{A}^{(2),ZZ}_{\rm bkgd} \approx \mathcal{A}^{(2),ZZ}_{\rm bkgd}(d,u,s,c,b) \times \frac{\mathcal{A}^{(1),ZZ}_{\rm bkgd}(d,u,s,c,b,\mathbf{t})}{\mathcal{A}^{(1),ZZ}_{\rm bkgd}(d,u,s,c,b)},$$

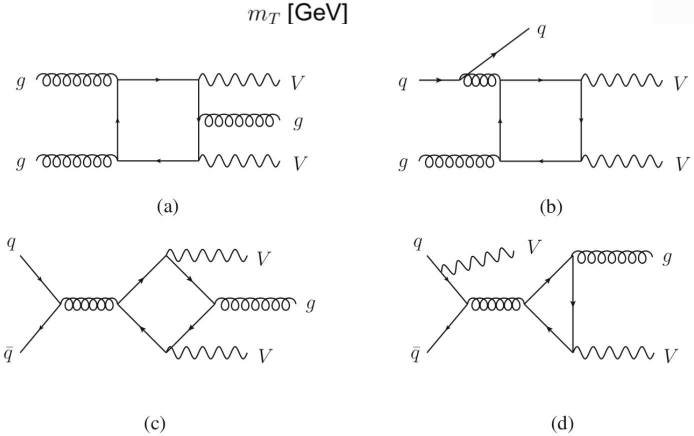




- Differences not so marked for value slightly above threshold

Structure of the NLO $gg \to 4\ell$ calculation





- For WW top and bottom quarks mix in the loops, so no clear distinction between massless and massive loops with $n_f = 5$

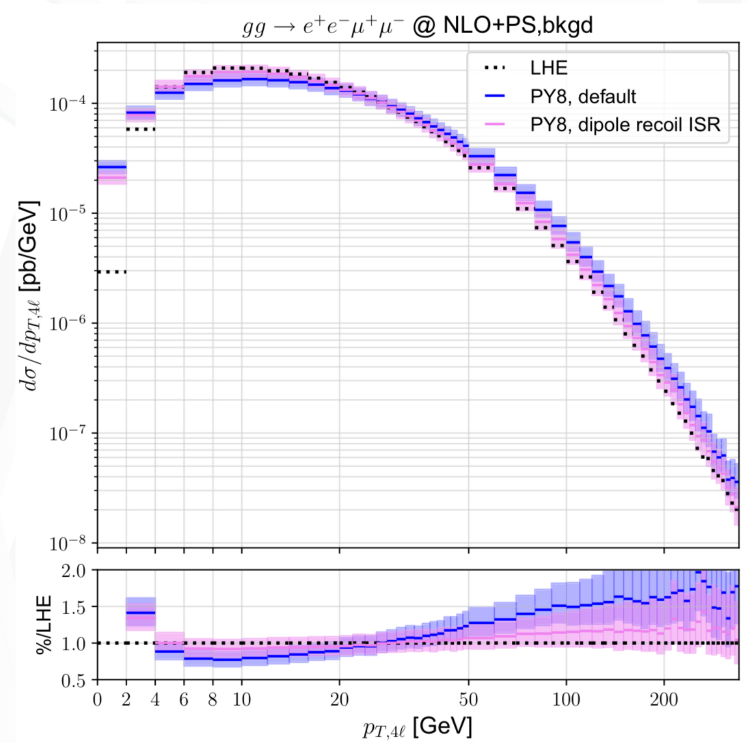
$$\mathcal{A}^{(2),WW}_{\text{bkgd}} \approx \mathcal{A}^{(2),WW}_{\text{bkgd}}(d,u,s,c) \times \frac{\mathcal{A}^{(1),WW}_{\text{bkgd}}(d,u,s,c,b,\mathbf{t})}{\mathcal{A}^{(1),WW}_{\text{bkgd}}(d,u,s,c)},$$

- Real emissions also includes $\mathcal{O}(\alpha_s^3)$ corrections to $q\bar{q} \to 4\ell$
- Top-quark mass dependence exactly included in reals via OpenLoops

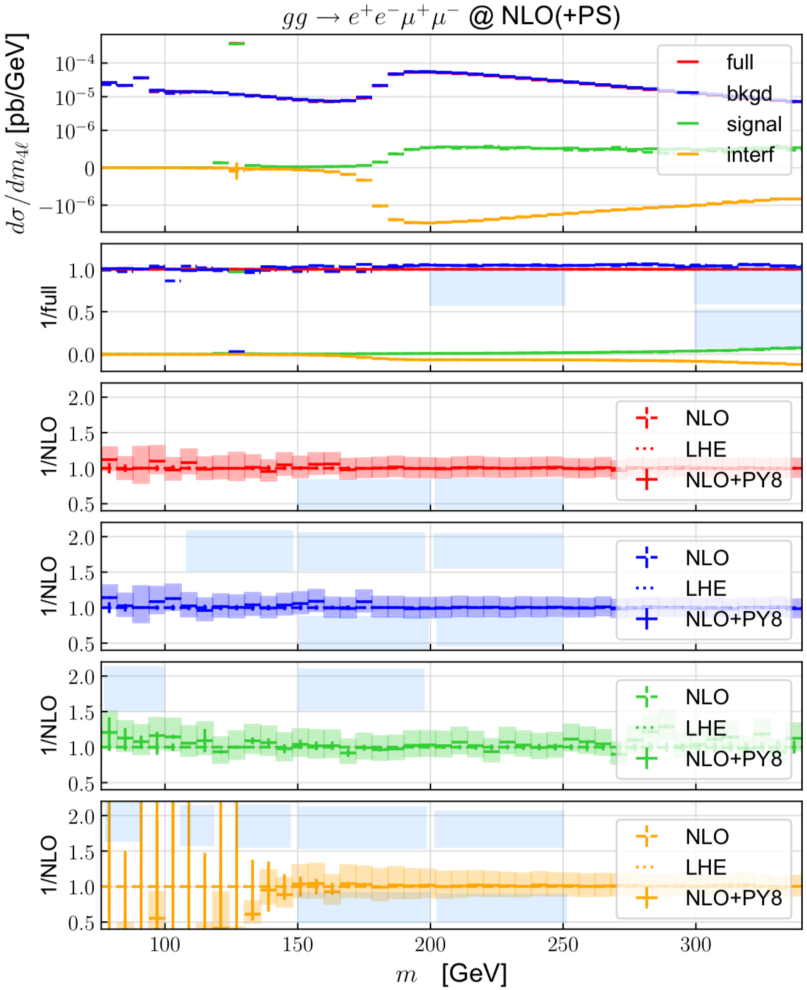
Implementation in POWHEG-BOX-RES

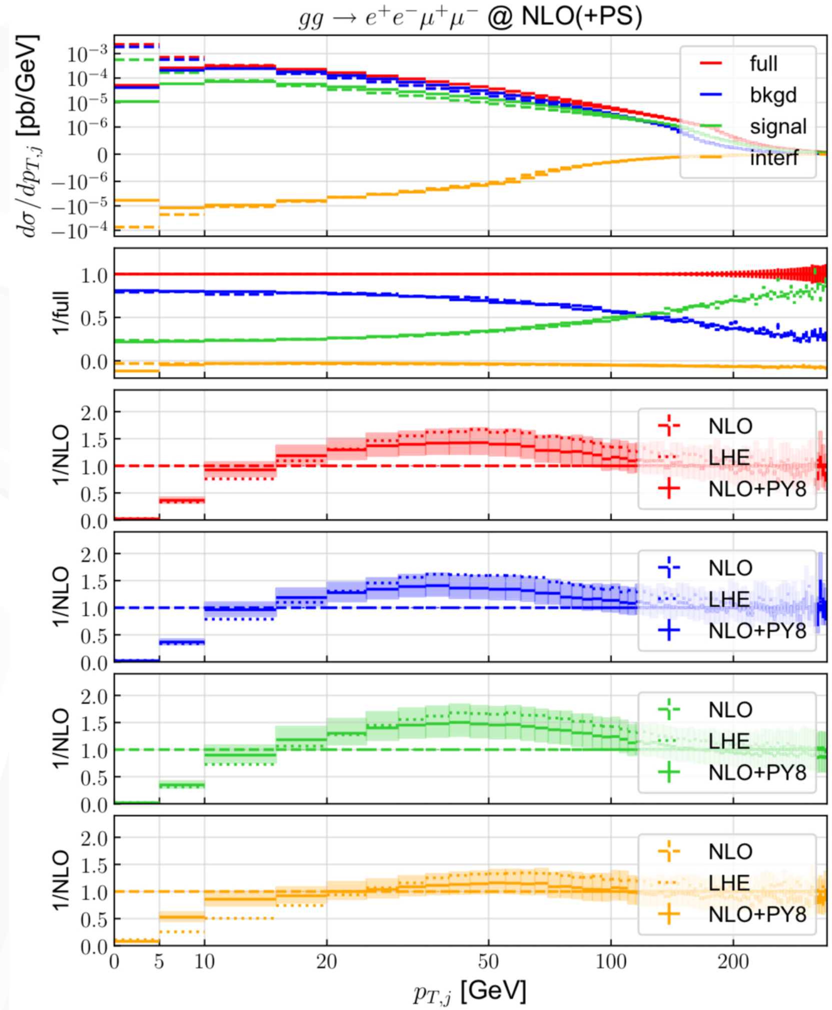
[SA et al. '21]

- Chosen RES for better sampling of resonance structure, despite no colored resonances present.
- POWHEG framework extended to be able to handle event generation with NEGATIVE cross-sections appearing in interference contribution.
- Cut $p_T^{\ell\ell} > 100$ MeV to tame instabilities
- NLO calculation interface to PYTHIA8 parton shower with different recoil schemes



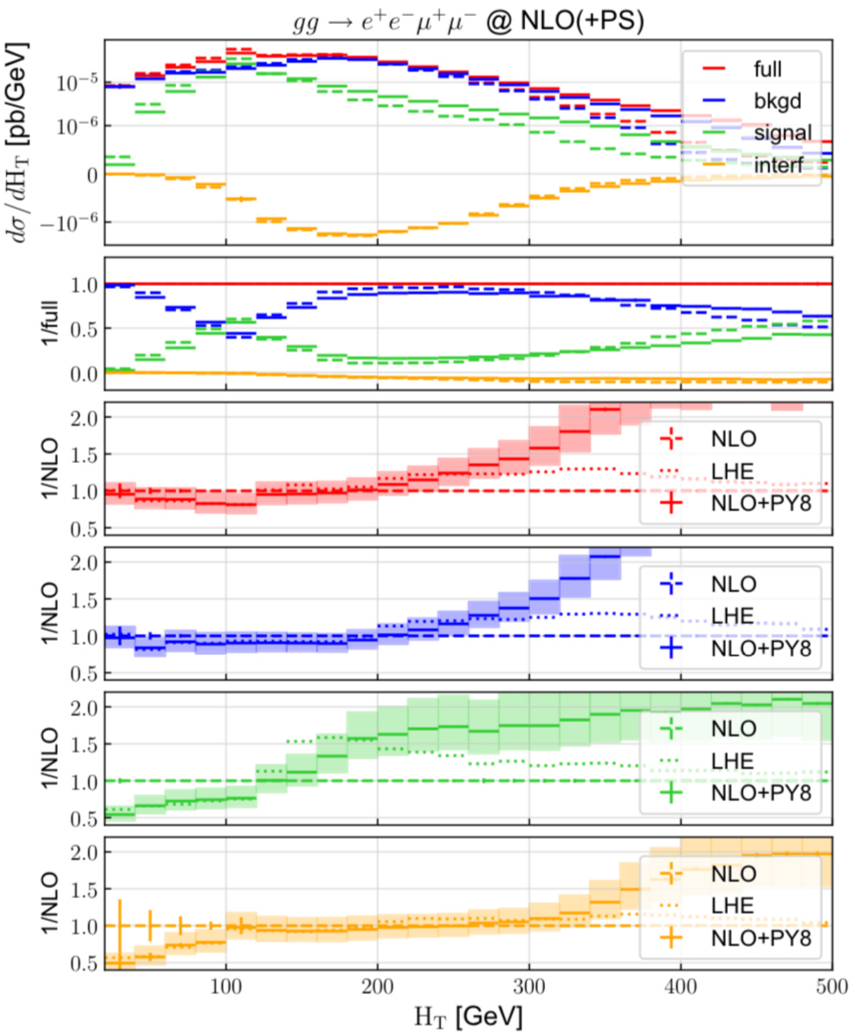
Results for ZZ channel

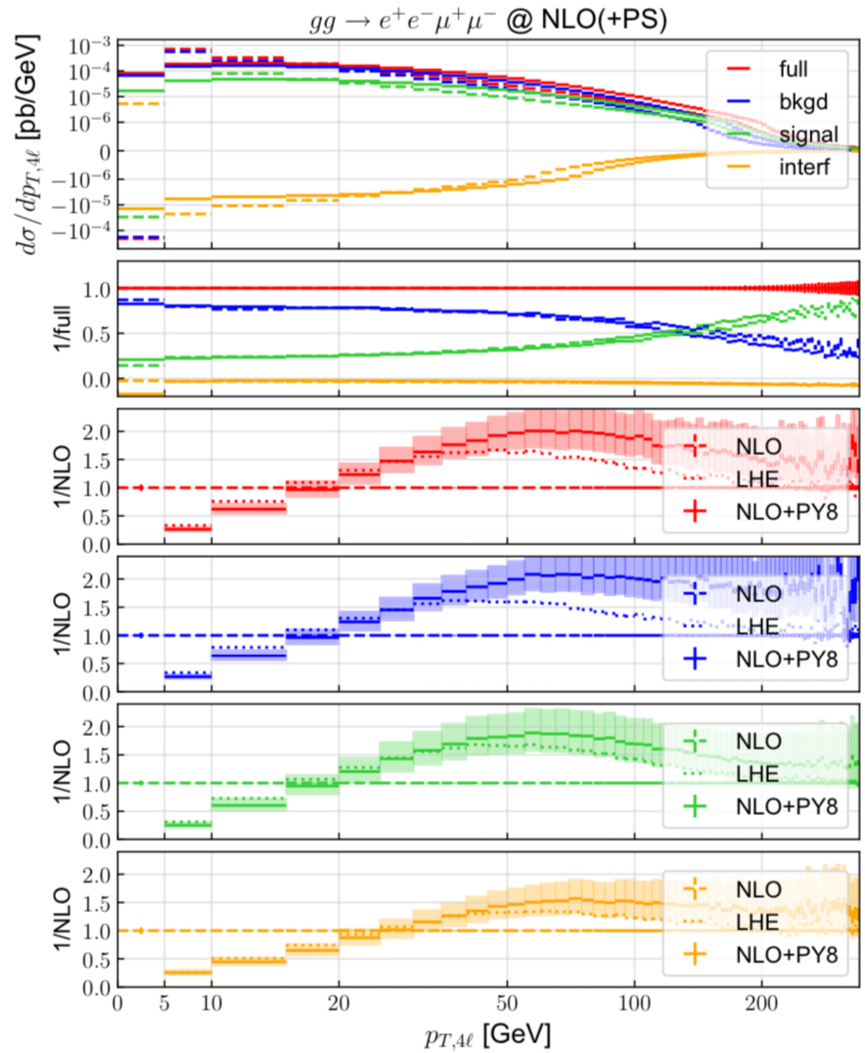




- Expected effects for inclusive quantities.

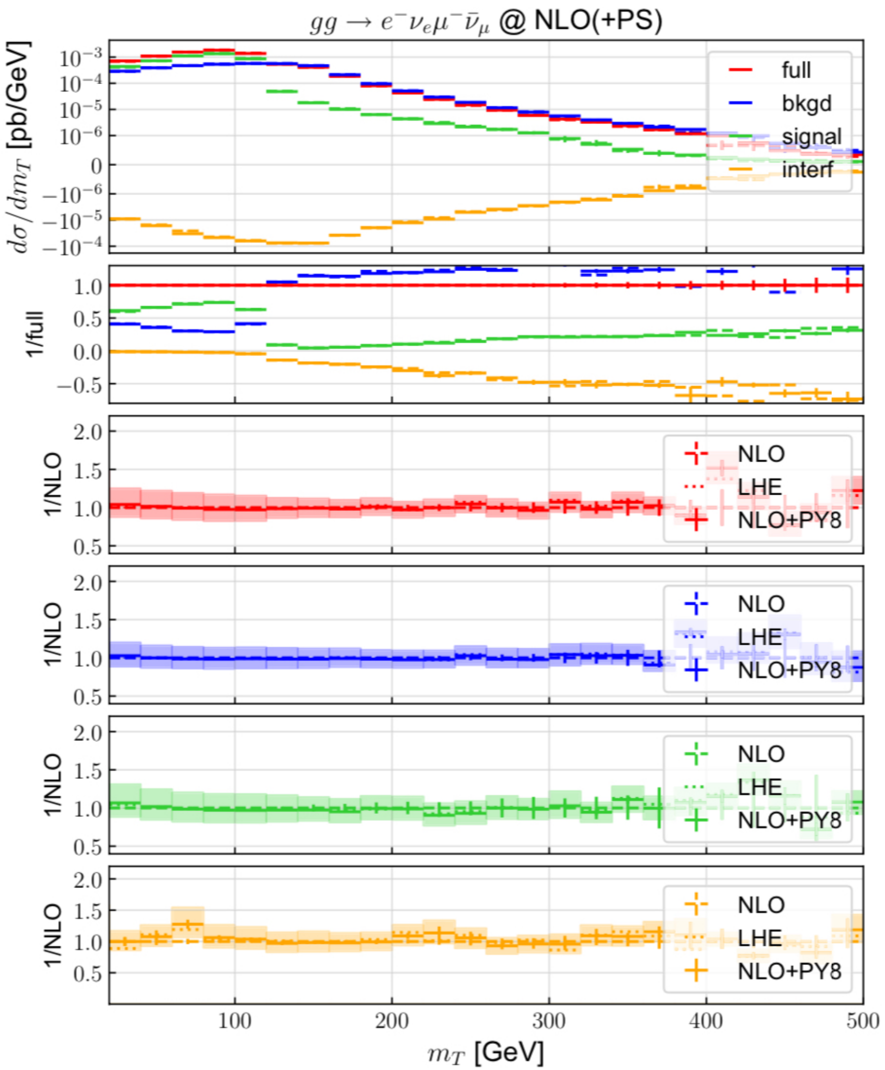
Results for ZZ channel

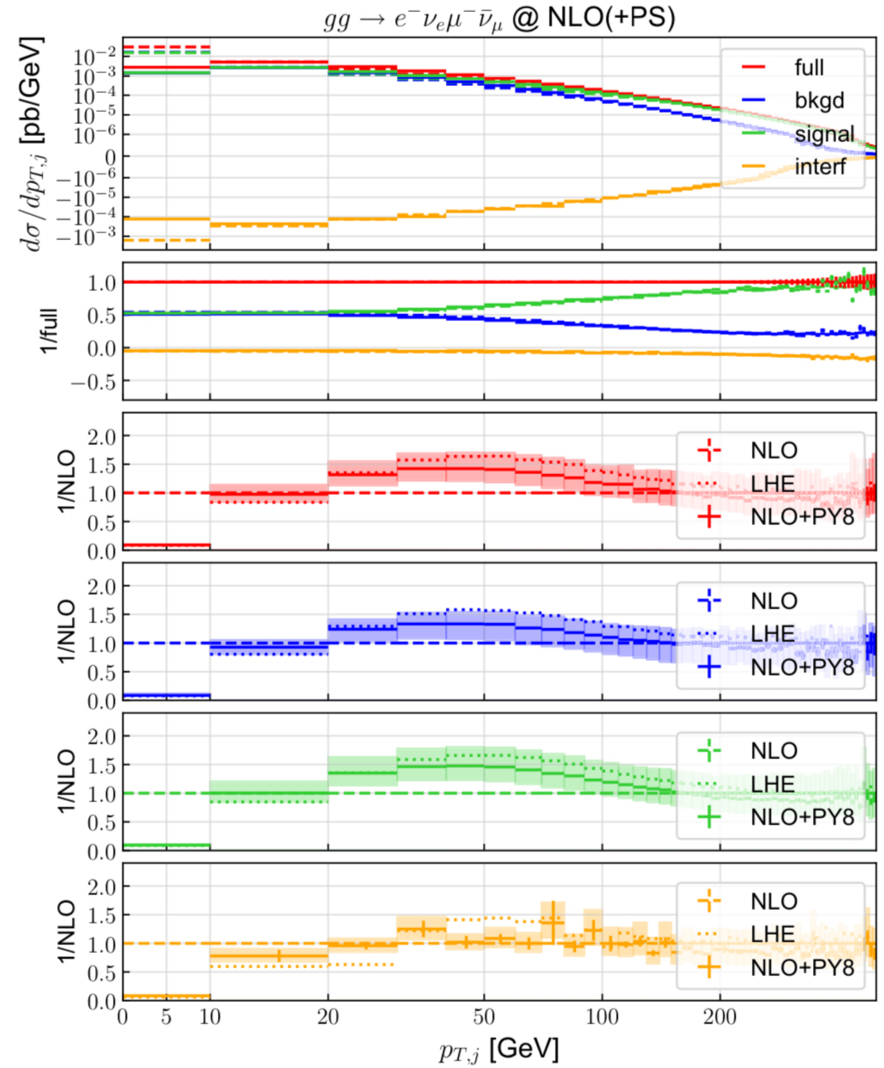




- More marked difference after showering exclusive quantities.

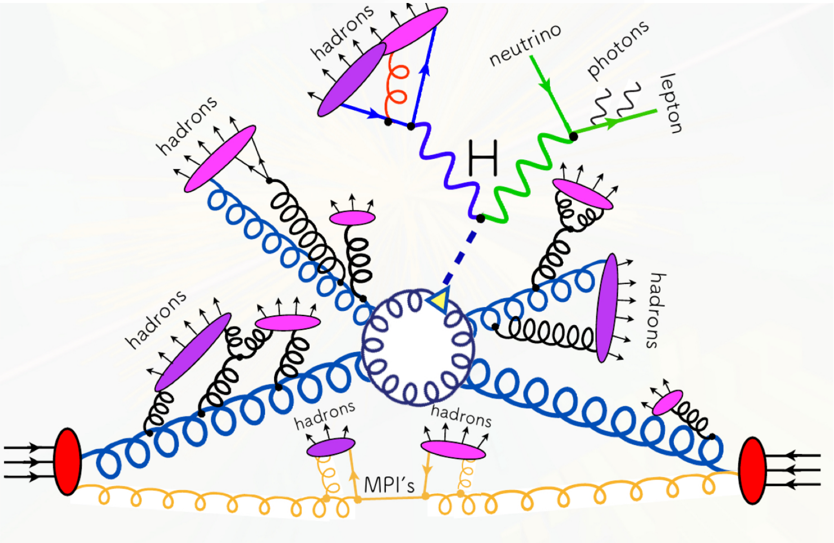
Results for WW channel





- Same behaviour observed for WW channel .

What is a precision MC ?



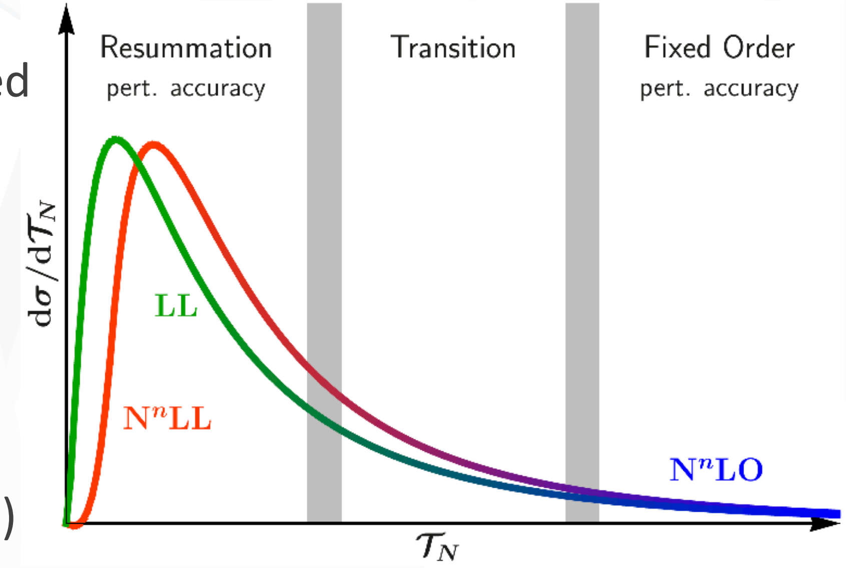
- Fully differential event generator producing hadronic final states, at high accuracy

- Precision enters in multiple ways:

- Perturbative accuracy of integrated total xs (N^{n}LO)

- Perturbative description of radiation pattern (resumm./ shower)

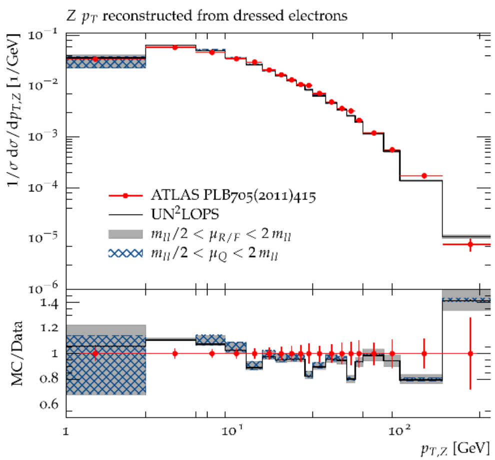
- Description of hard tails (multi-jet)



Increasing event generator accuracy

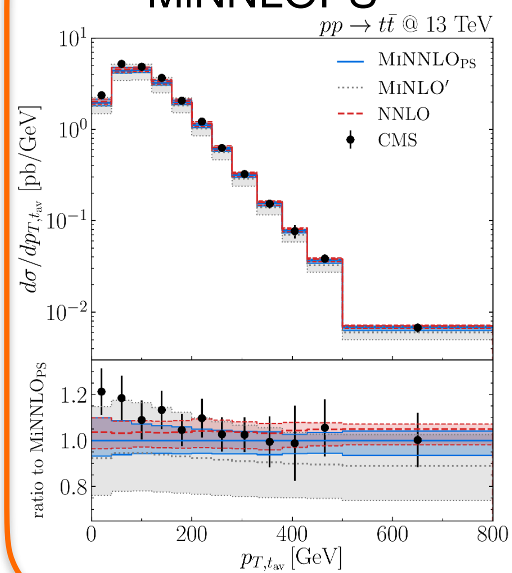
- The increasing experimental precision of LHC measurements challenges existing generators, pushing the request for higher accuracy
- The state-of-the-art is the inclusion of NNLO corrections into parton-shower Monte Carlo
- Three main approach to the problem:

UNNLOPS

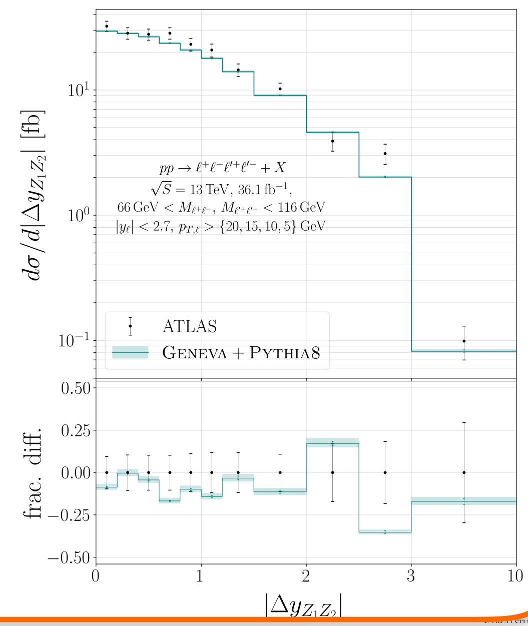


[Hoeche et al. '15]

MiNNLOPS



GENEVA

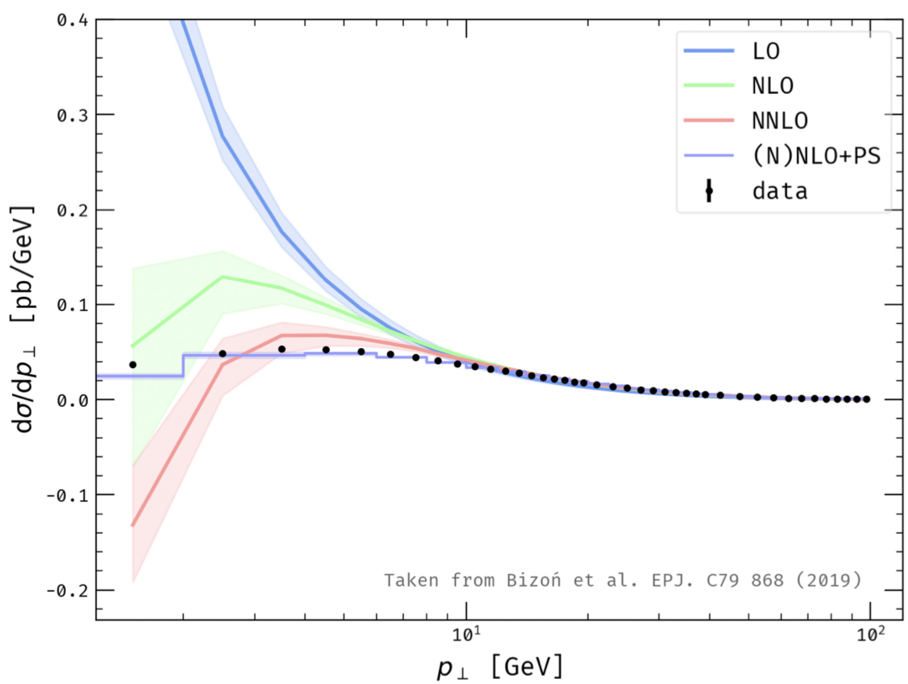


Also NNLO+PS with sector showers available for e^+e^- and $H \to b\bar{b}$

[Campbell et al. 2108.07133]

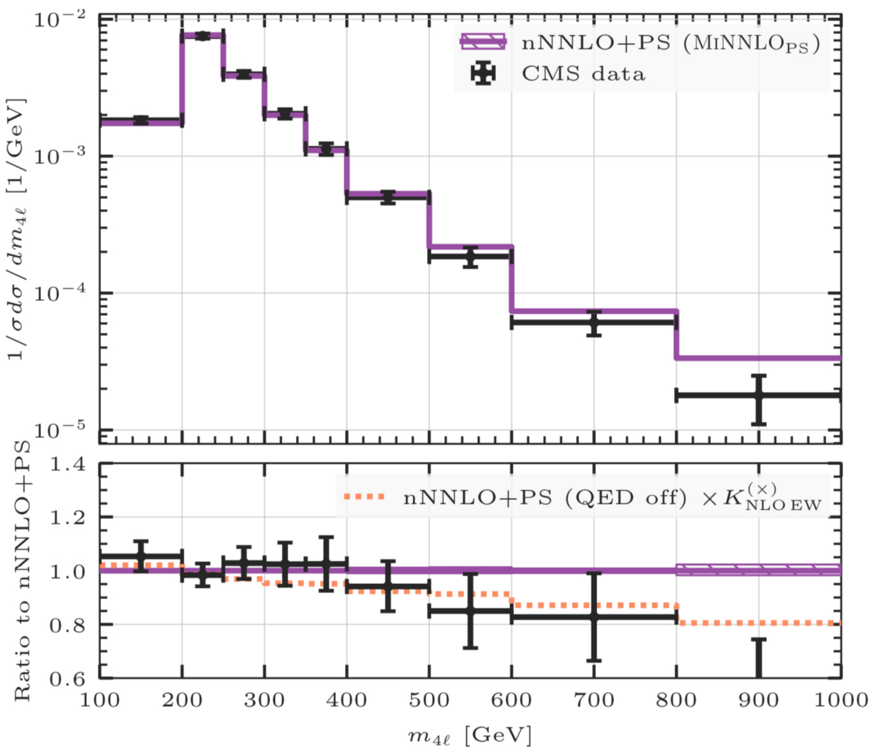
Accuracy goals - Example for $gg \to H$

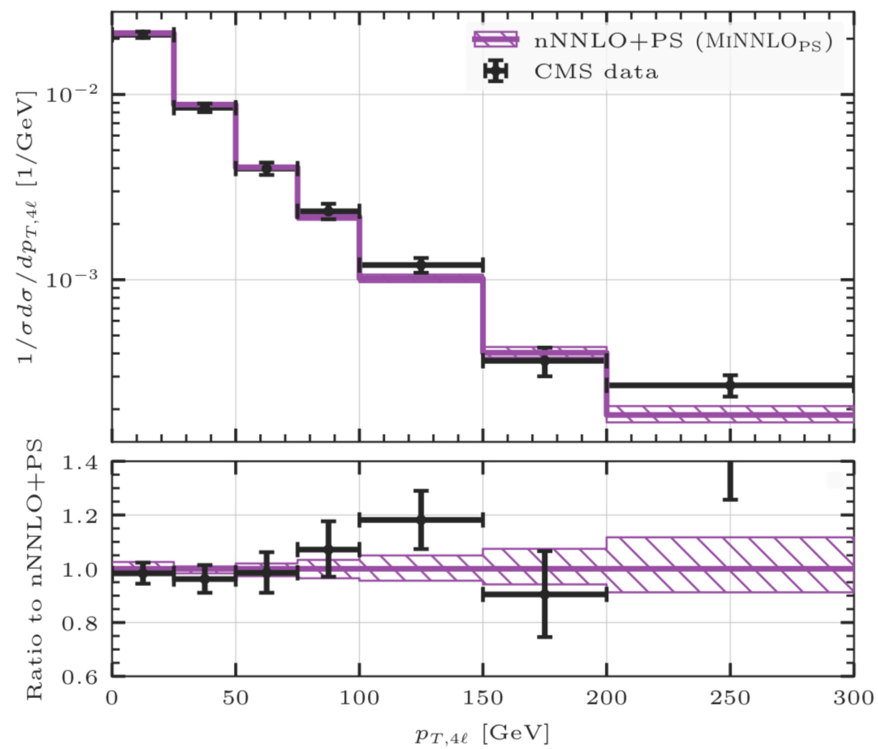
- NNLO accuracy for observables inclusive over extra radiation, e.g. $d\sigma/dy_H$
- NLO accuracy for H+1 jet observables $d\sigma/dp_T^{j_1}$
- LO accuracy for H+2 jet observables $d\sigma/dp_T^{j_2}$ or $d\sigma/dm_{j_1,j_2}$
- Resumm. accuracy (or Shower Sudakov) for small p_T^H
- Further emissions only in shower soft/coll approximation.



MINNLOPS Diboson production

- Independent implementation of NLO $gg \to 4\ell$ included in MiNNLOPS diboson process

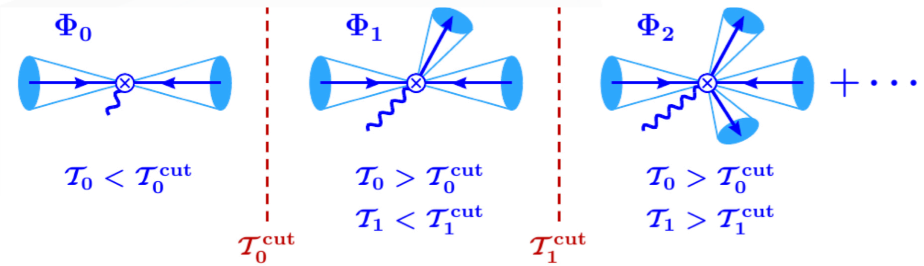


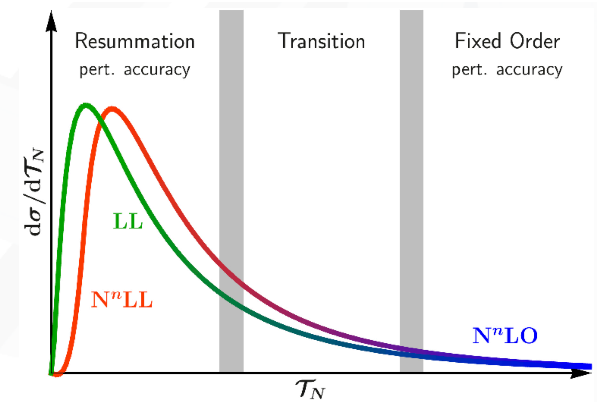


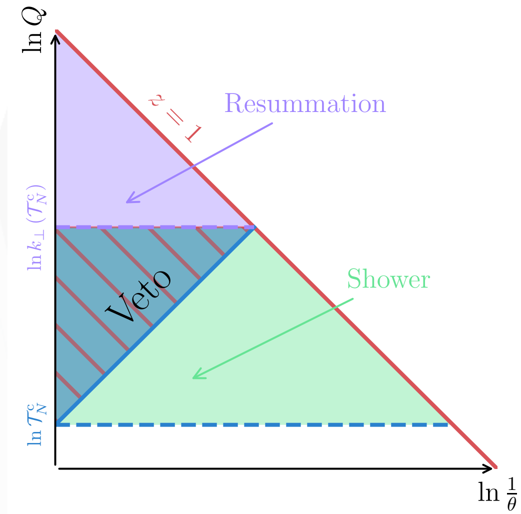
Buonocore et al. '21

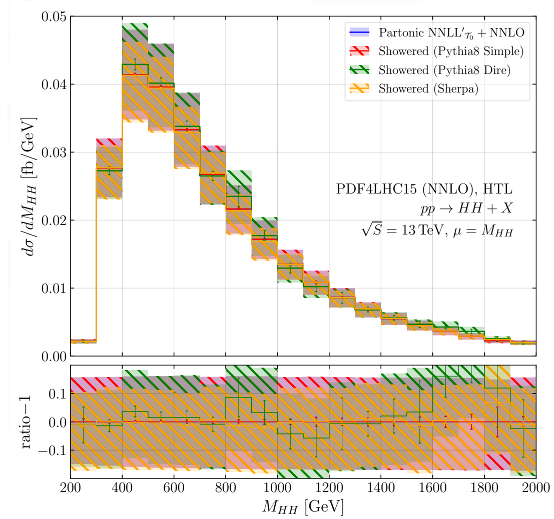
The Geneva method

- Monte Carlo fully-differential event generation at higher-orders (NNLO)
- Resummation plays a key role in the defining the events in a physically sensible way
- Results at partonic level can be further evolved by different shower matching and hadronization models





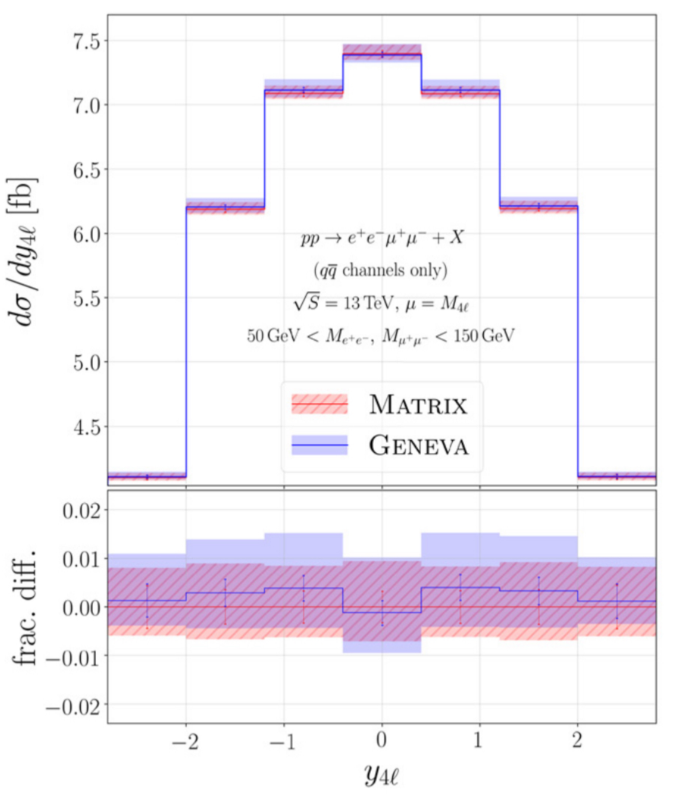


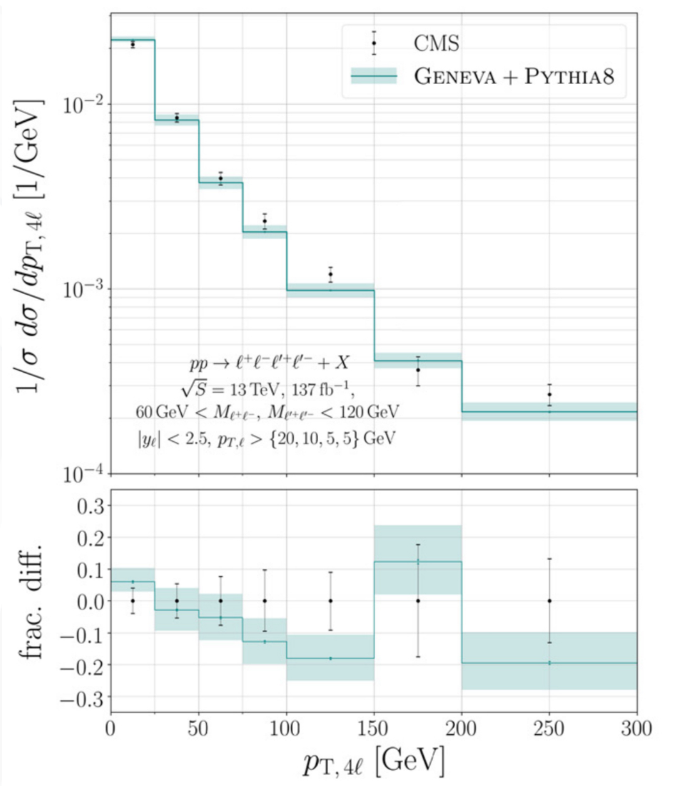


Diboson production in GENEVA

SA et al. '21

- Original NNLO+PS implementation $q\bar{q} \to e^+e^-\mu^+\mu^-$ extended to 4ℓ production.





- NLO gluon-induced channel also included.

Higgs production via gluon fusion

SA et al. '23

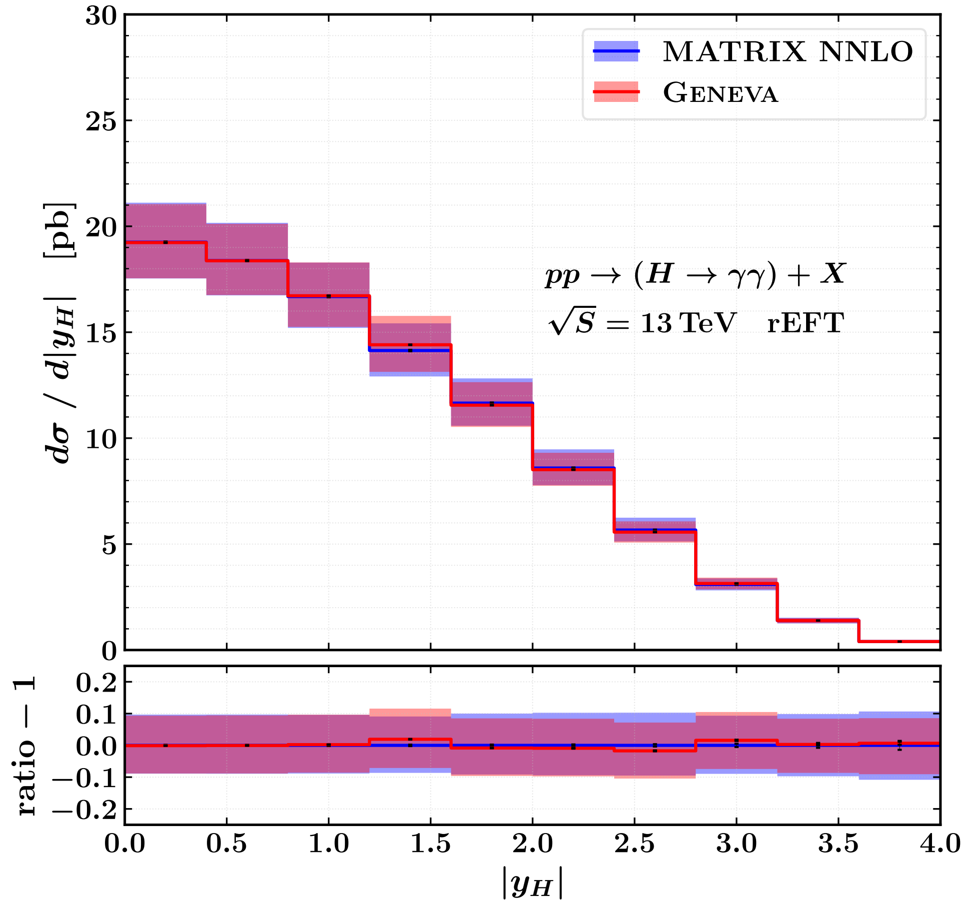
Heavy top-quark limit rescaled with exact LO m_t dependence (rEFT).

NNLL' $\mathscr{T}_0$ resummation requires gluon beam functions

Include 7-point scale variations, introducing explicit μ_F dependence in beam function and their pert. matching coefficients I_{ij}.

Additional variations must be considered also in the resummation region to probe independent μ_B and μ_F changes.

Variations combine in inclusive quantities and give perfect agreement in both central values and FO variations with MATRIX.



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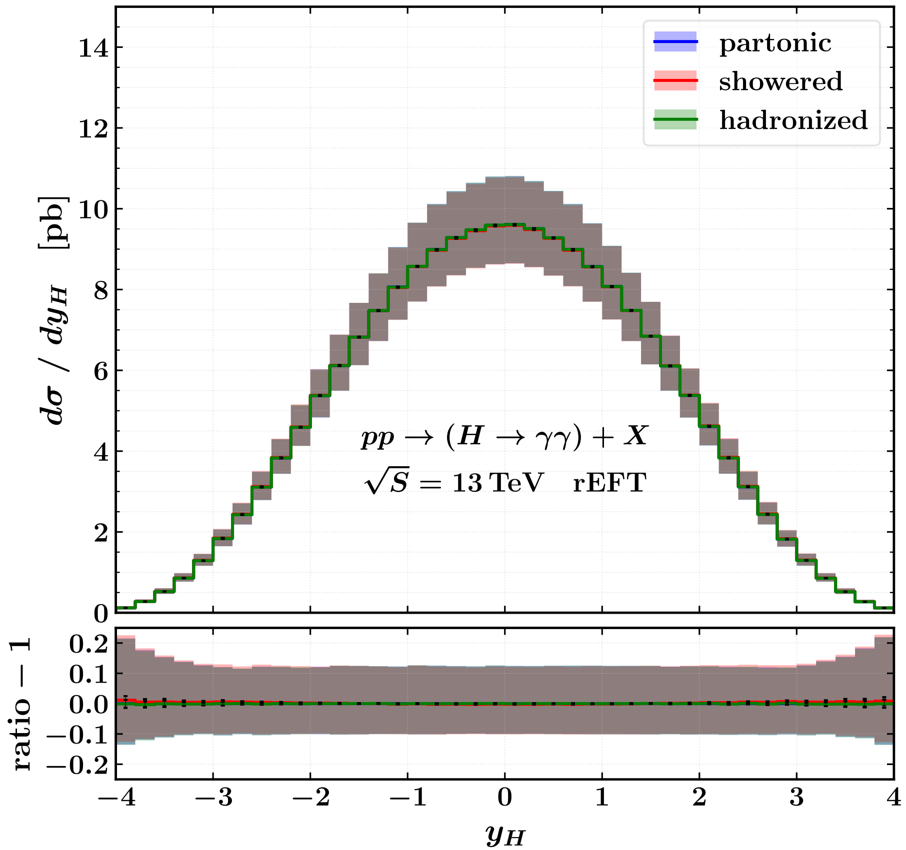
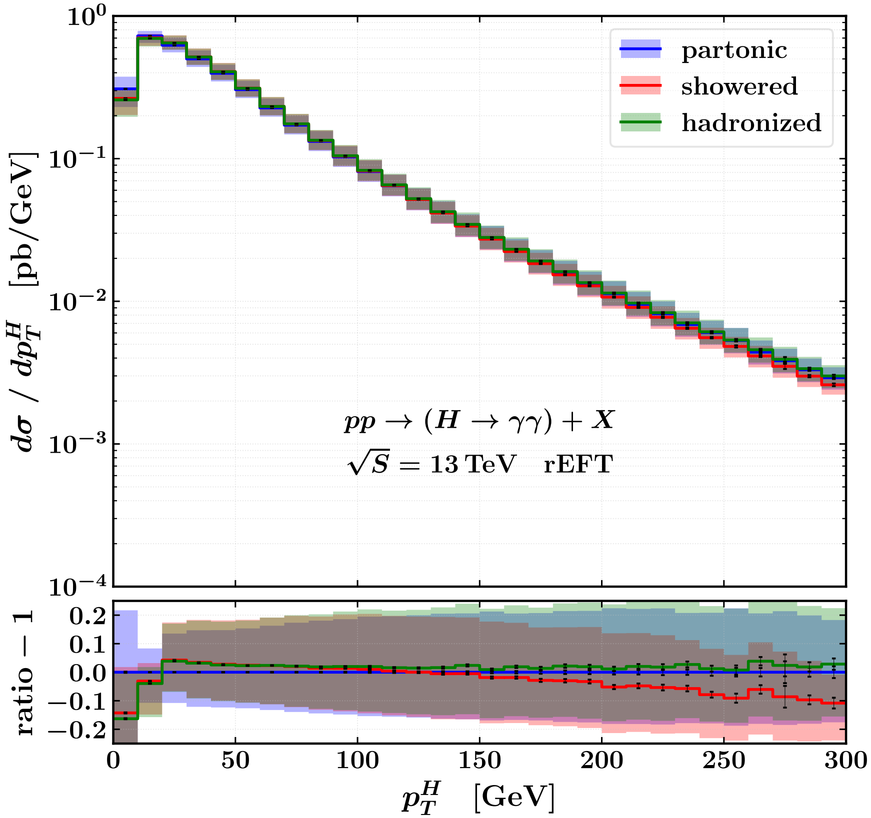
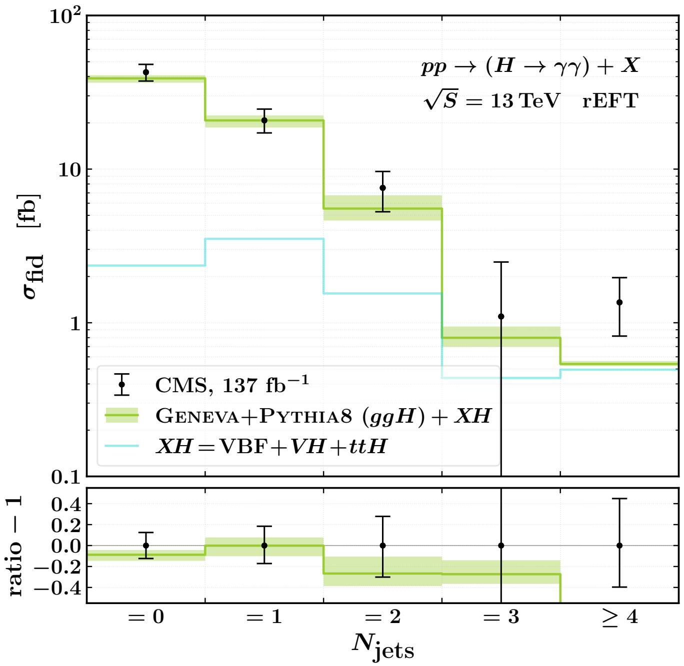
Showered results

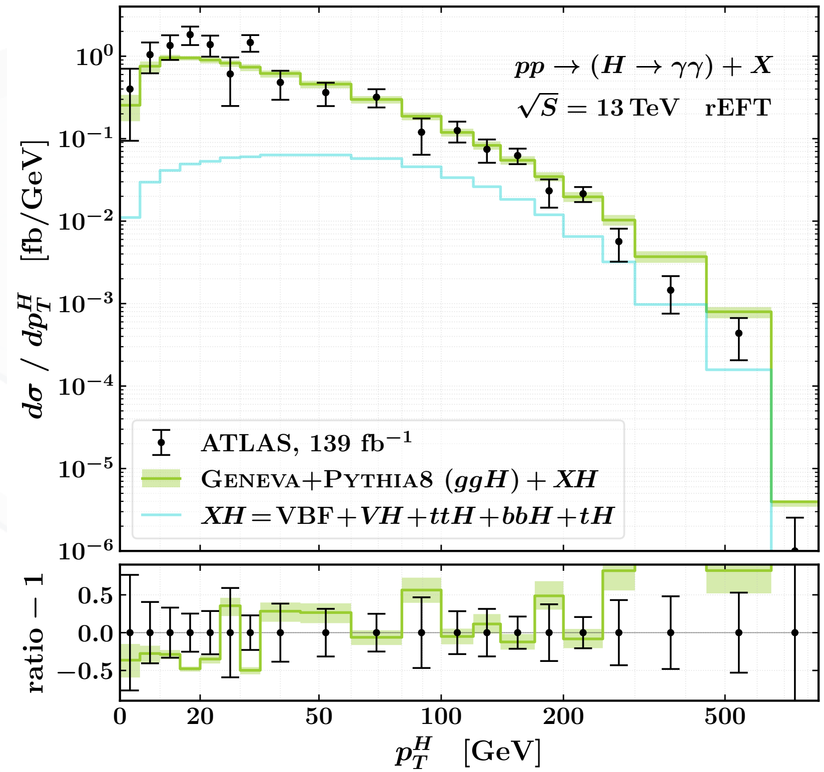
PYTHIA8 showering gives expected results for inclusive quantities.
Reasonable differences for more exclusive ones.
Theoretical uncertainties reasonably small.

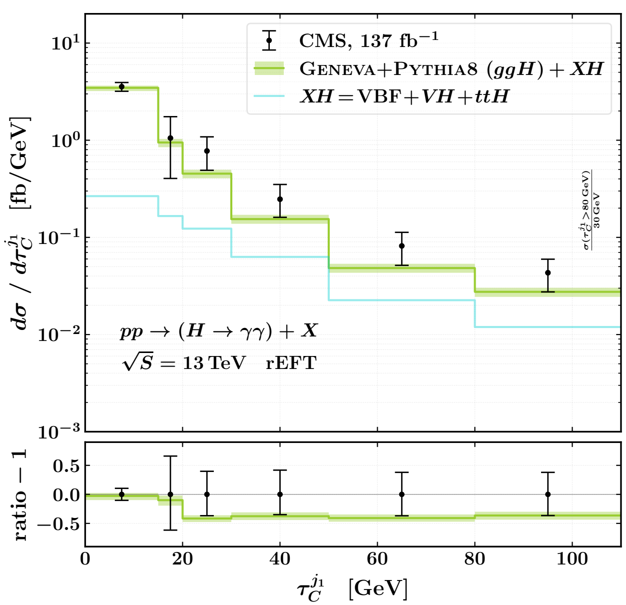




Comparison with LHC data at fiducial level







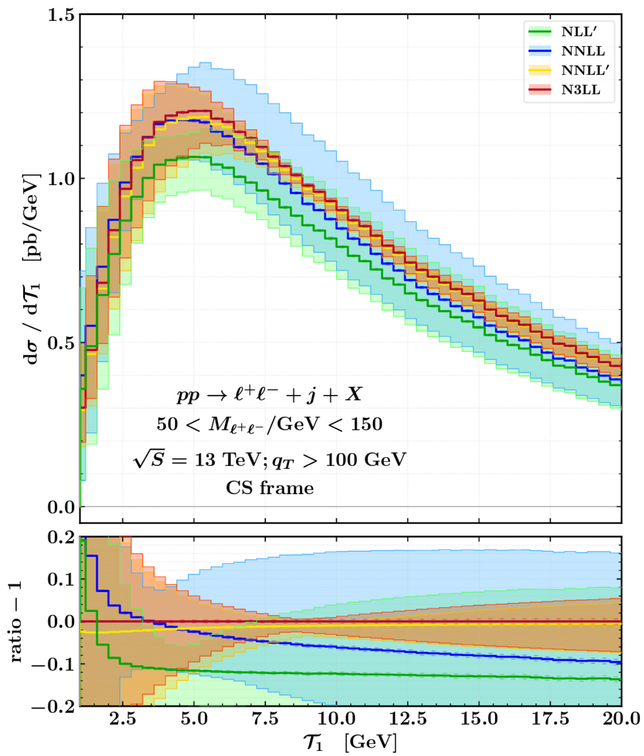
Fiducial cross section affected by resummation, parton shower effects, hadron decays, mainly due to photon isolation requirements, etc…

Comparison with ATLAS shows similar agreement. High p_T tail sensitive to m_t effects.

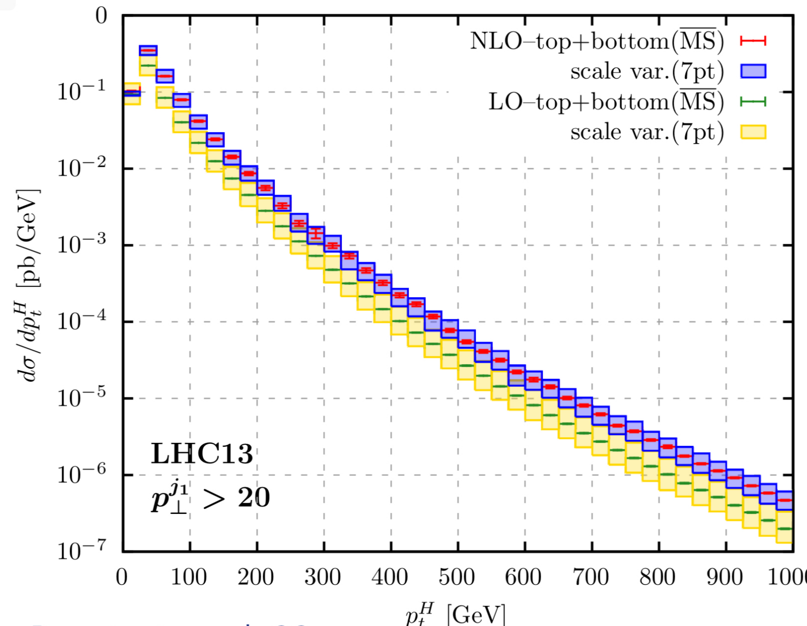
Higgs production via gluon fusion

- Many directions for improvements in high-pT regions.
- Inclusion of top(bottom) quark mass effects. Czakon et al. ‘21, Bonciani et al. ‘22
- Inclusion of EW and mixed QCD-EW corrections Becchetti et al. ‘21, Bonciani et al. ‘22

- Extension to H+j NNLO+PS simulation needs 1-jet resolution.



SA et al. 2312.06496

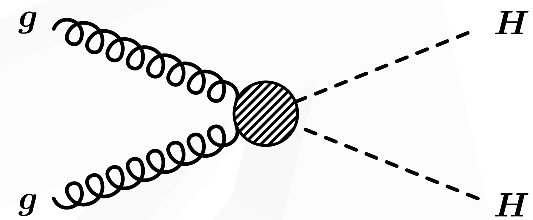


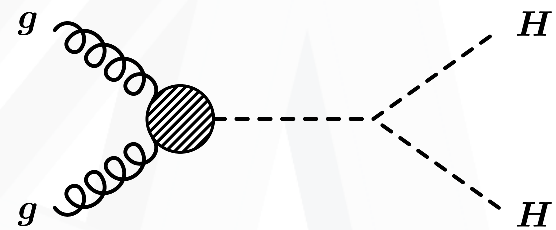
Bonciani, et al. 22

- First step towards this goal is NNLL’ for 1-Jett. Only Z+1jet for now, but H+1jet is next...
- N3LO+PS further ahead.

Double Higgs production

SA et al. '23





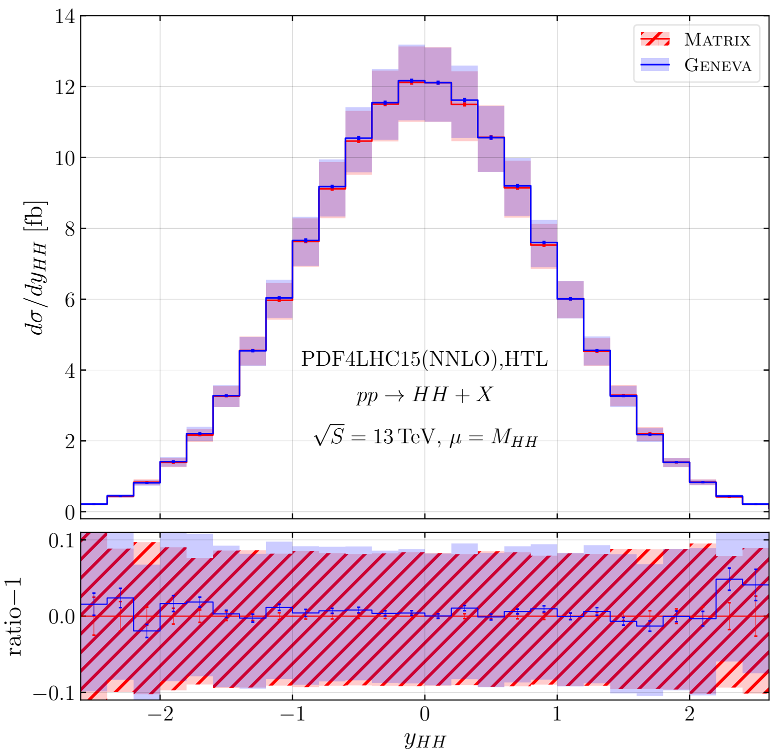
Calculation in infinite top-quark mass limit, not useful for pheno but for validating method $|\log(\mathcal{T}_0/M_{HH})| \gg 1$

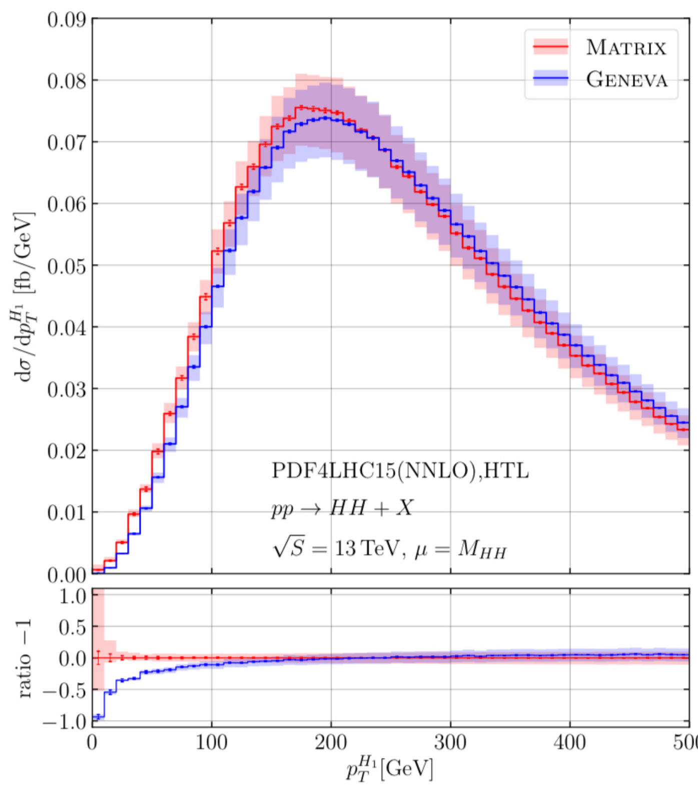
Extensions to full m_t effects possible.

Very good agreement for invariant mass and rapidities

Interesting discrepancy when p_T of the hardest Higgs boson H_1 goes to zero.

Signals inadequacy of fixed-order calculations when $p_{T,HH} \to 0$





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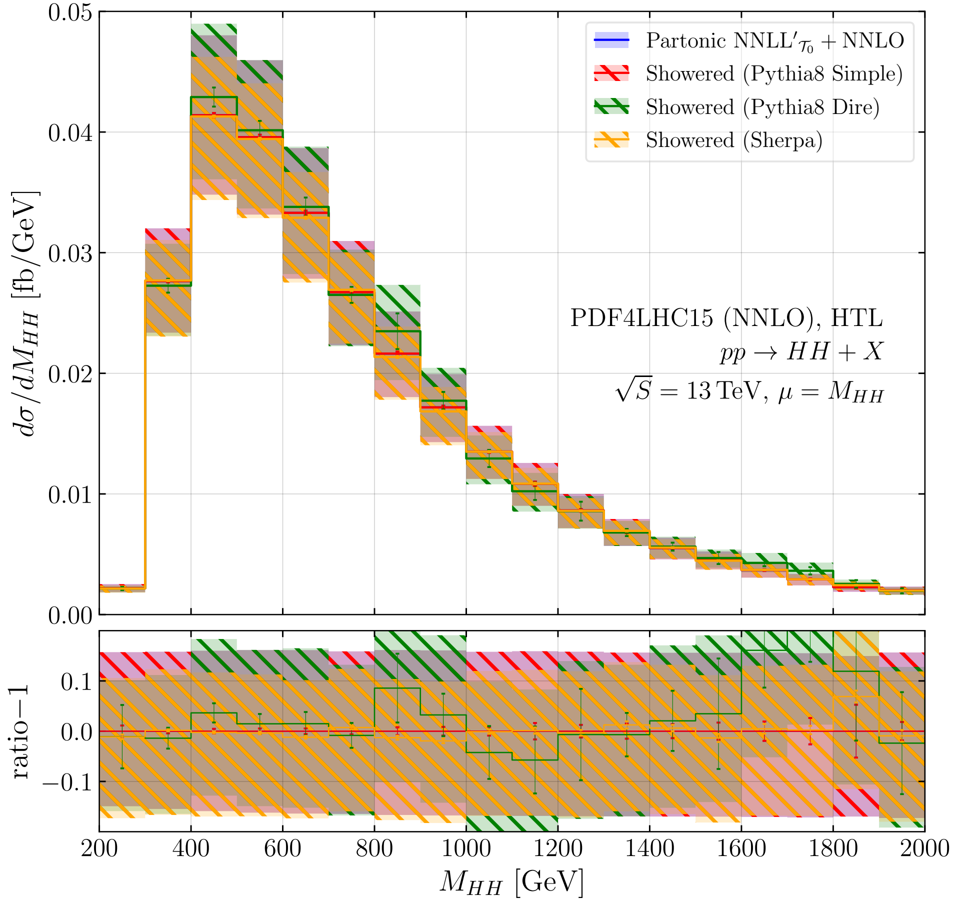
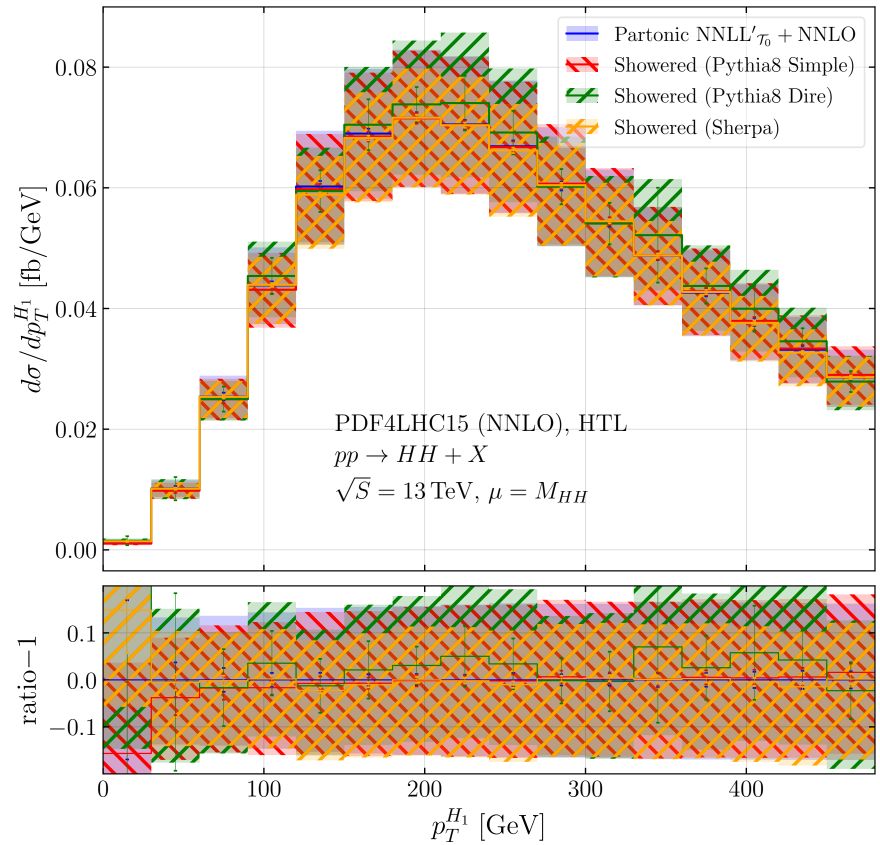
Double Higgs production: showered results

Exploring different shower models: PYTHIA8 standard (simple), DIRE and SHERPA



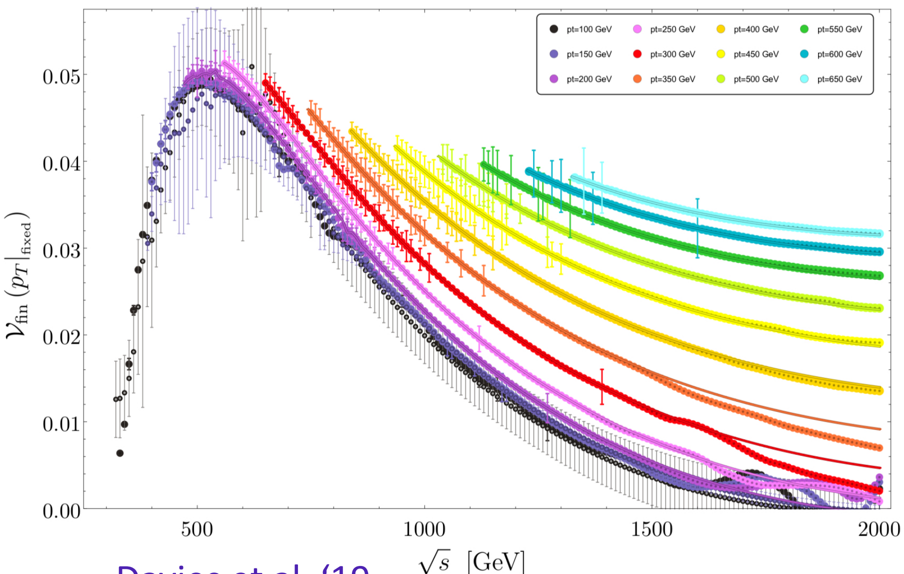


Inclusive quantities correctly described by all showers.

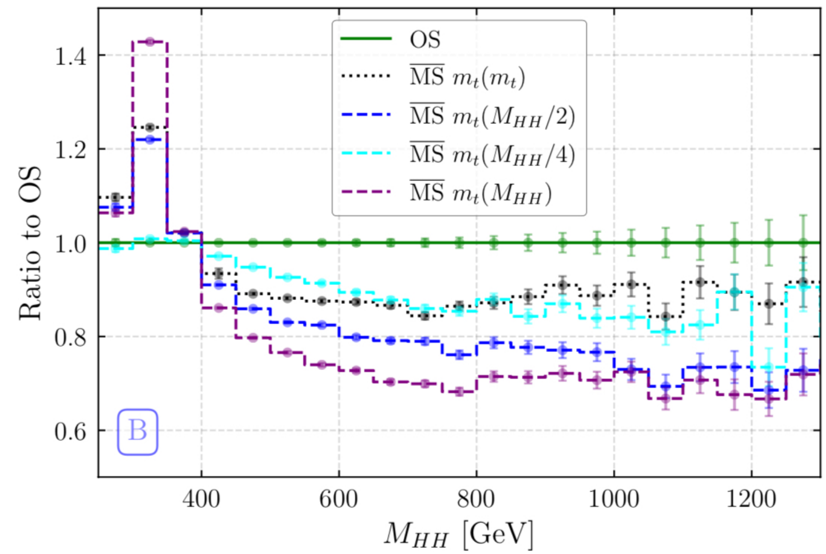
Higgs pair production

- At NLO+PS top mass effects are included matching exact results or small-pT expansion to high-energy expansion.

- Mass-scheme uncertainty on par with scale uncertainties



Davies et al. '19



Bagnaschi et al. '23

- Ongoing effort for top-quark mass effects in FT-approx in NNLO+PS….

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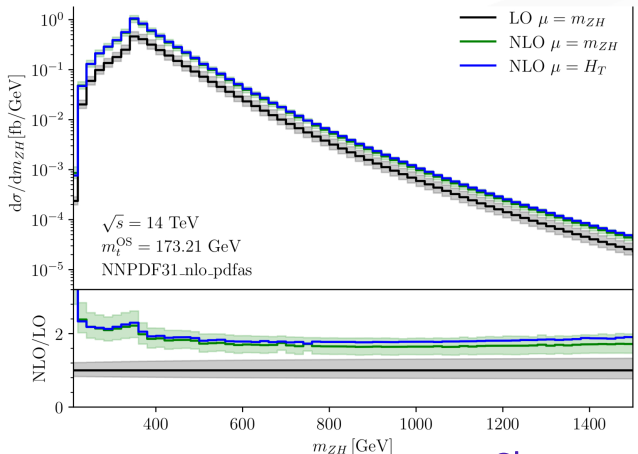
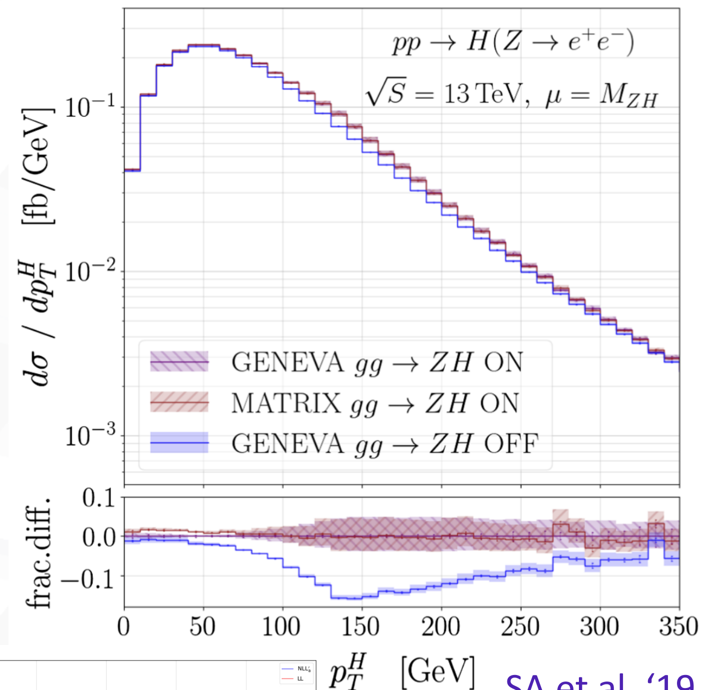
Associated HZ production via gluon fusion

- Gluon channel has large NLO corrections and scale unc.

Chen et al., DeGrassi at al ‘22

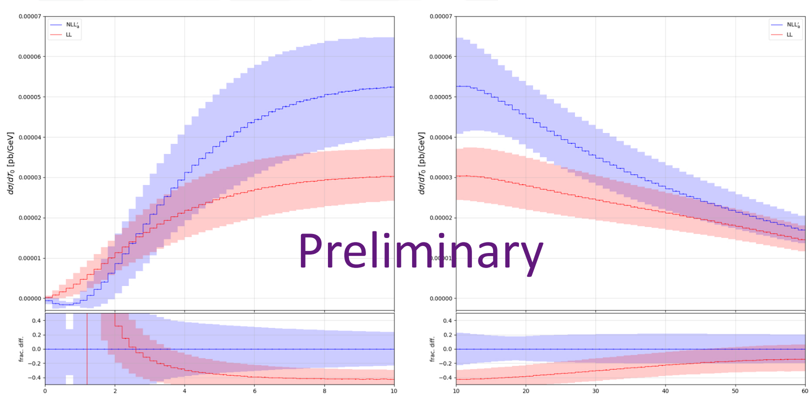


Chen et al. ‘22



SA et al. ‘19

- Strong motivations for NLO+PS. Preliminary results without 2-loop virtuals in GENEVA

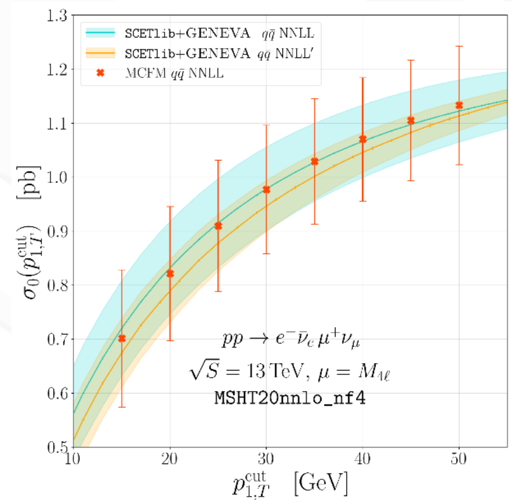


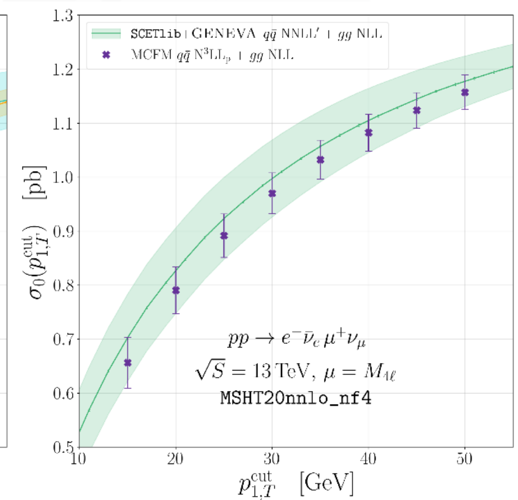
Using the jet pT as resolution variable - WW

GENEVA recently extended to jet veto resummation in [Gavardi et al. 2308.11577].

Focus on $W^+W^- \to \mu^+\nu_\mu e^-\bar{\nu}_e$ with jet veto, in 4-flavor scheme to avoid top contaminations.

We include the resummation of the $q\bar{q}$ channel at NNLL' and the gg channel at NLL



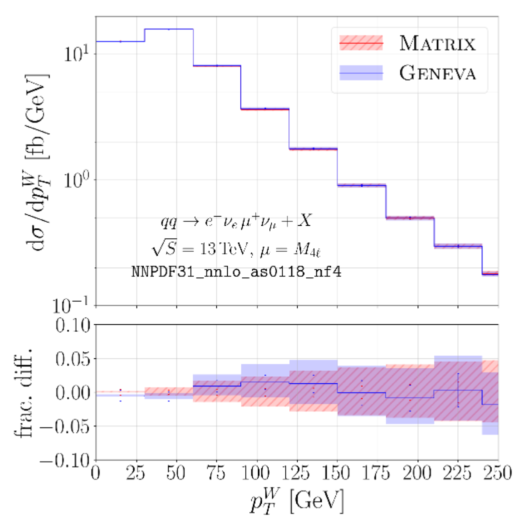


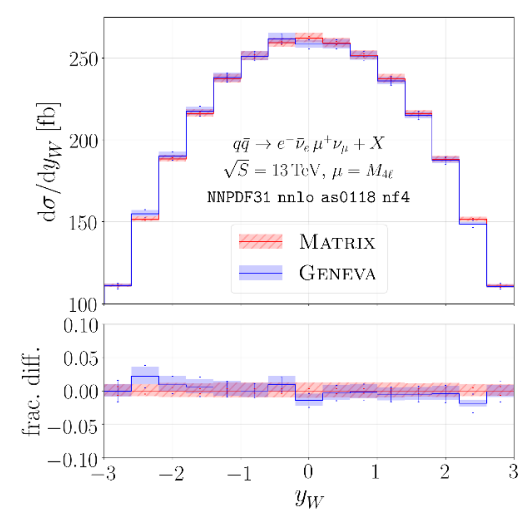
Jet veto resummation available in MCFM up to partial N3LL accuracy. Different treatment of uncertainties.

[Campbell et al. 2301.11768]

NNLO validation against MATRIX

[Grazzini et al. 1711.06631]

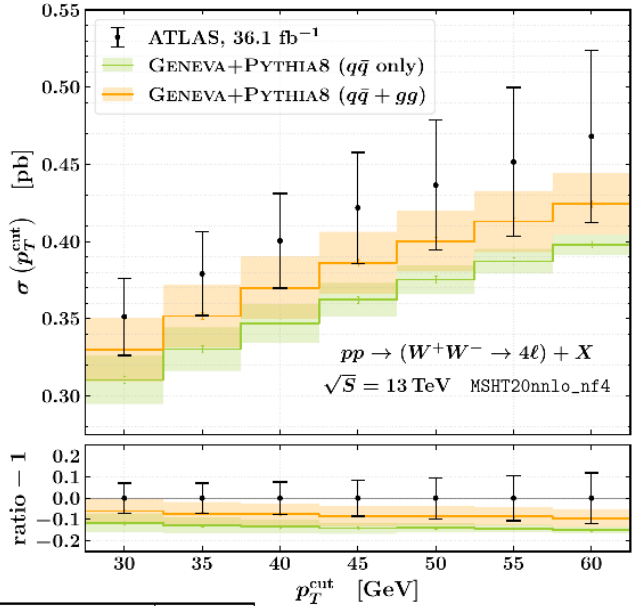


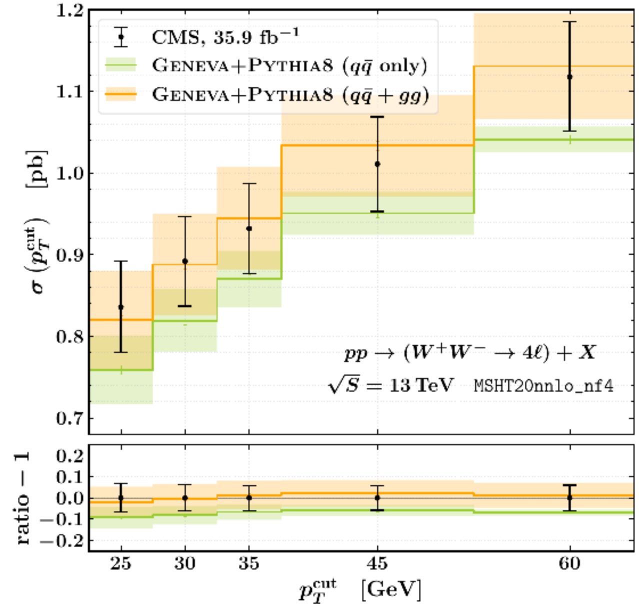


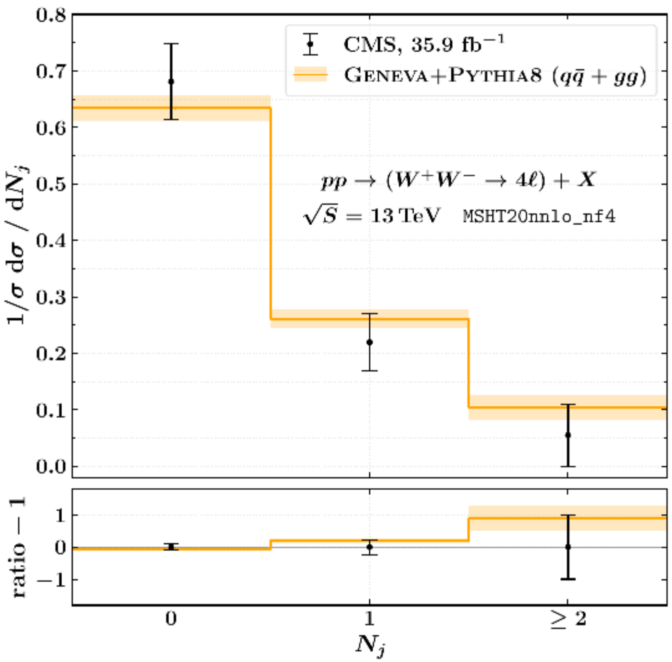
Data comparison

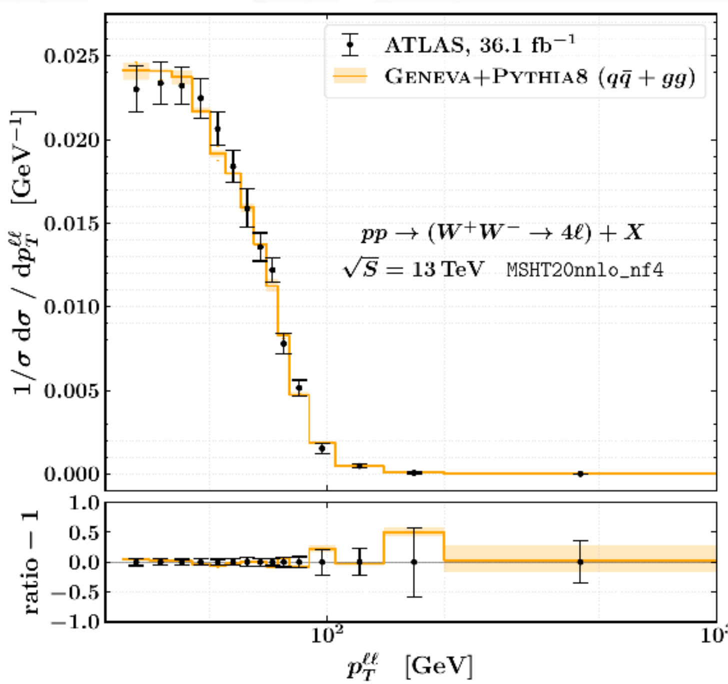
Inclusion of gg channel necessary for agreement with data.

Extension of gg channel to NLO+NLL' ongoing









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Conclusion and outlook

- Precision MCs for the production of Higgs bosons have reached the NNLO+PS stage for many different processes
- NLO $gg \to 4\ell$ production available in POWHEG-BOX-RES. Also available in MINNLOPS and GENEVA diboson processes.
- H and HH gluon-initiated loop-induced color singlet processes available in GENEVA at NNLO+PS. Inclusion of heavy-quark mass effects still not at the same level, but within range.
- Other loop-induced processes which are the current unc. bottleneck should be improved, e.g. $gg \to HZ$
- NNLO+PS are tools that make the most accurate theory predictions available in an easy-to-use event format. Experimental collaborations should try their best to take advantage of their availability.

Thank you for your attention.