Precisions MCs for Higgs: status and new developments

Higgs 2023 conference - Beijing

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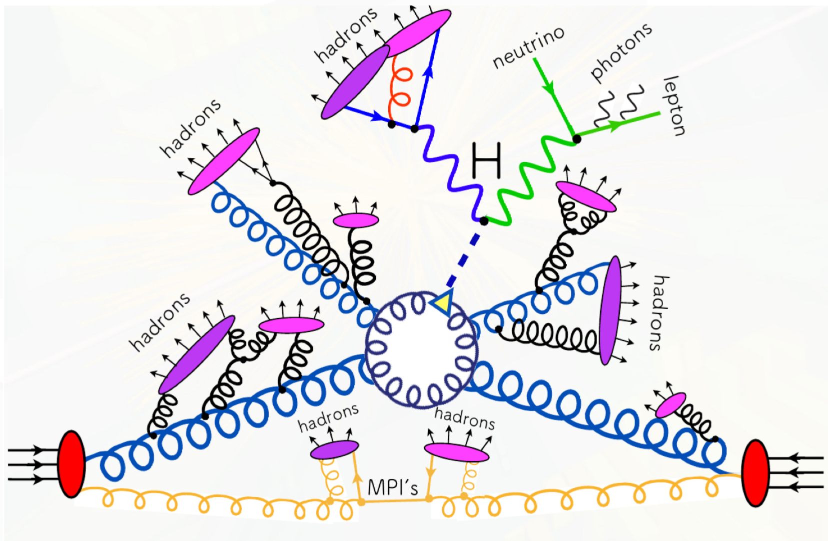
Outline

- Review of precision MCs for Higgs production
- Discuss ingredients for a precise MC
- Focus on NNLO + PS and some other high-accuracy results.
- Discussion of recent developments and improvements
- Outlook and conclusions

Apologies for the biased selection of topics and for not covering other interesting developments

What is a precision MC ?



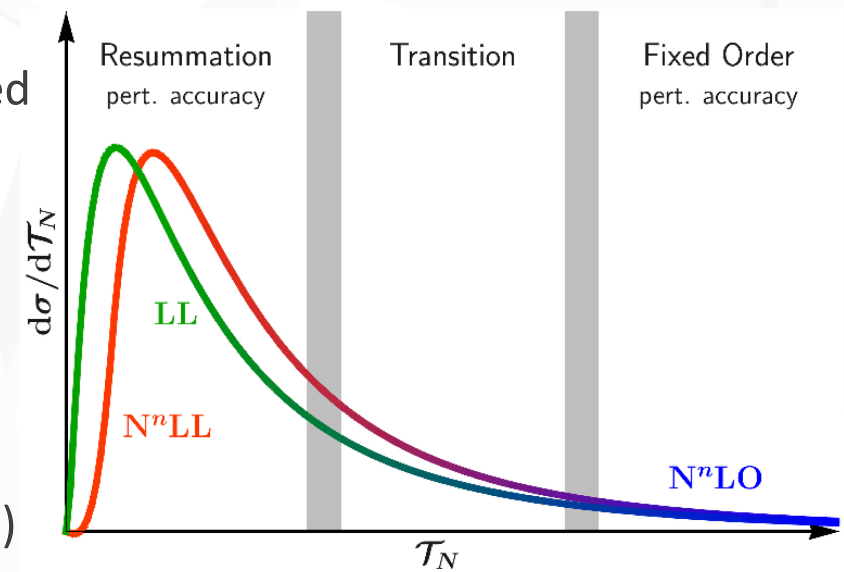
- Fully differential event generator producing hadronic final states, at high accuracy

- 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)



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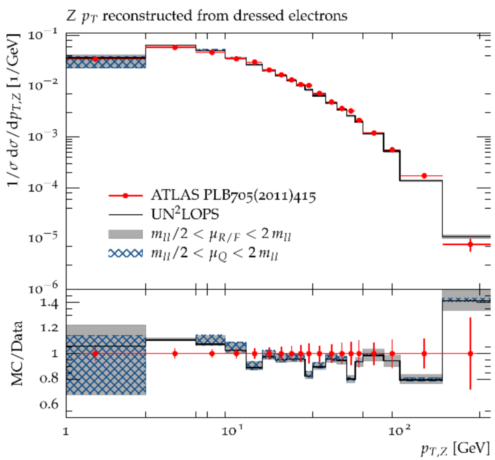
NNLO matched to parton showers

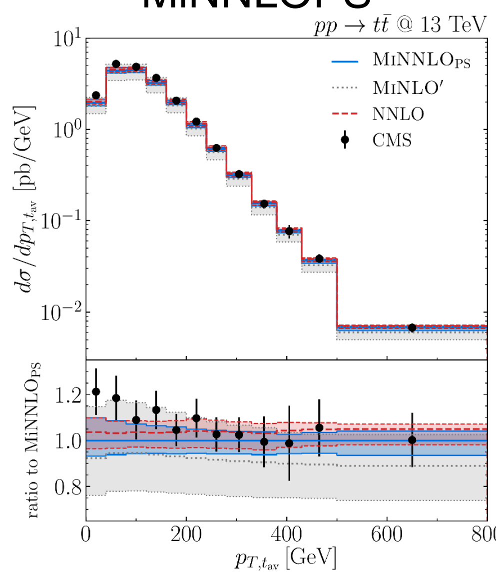
- The increasing experimental precision of LHC measurements challenges existing generators, pushing the request for higher accuracy
- The state-of-the-art is the inclusion of NNLO corrections into parton-shower Monte Carlo
- Three main approach to the problem:

UNNLOPS



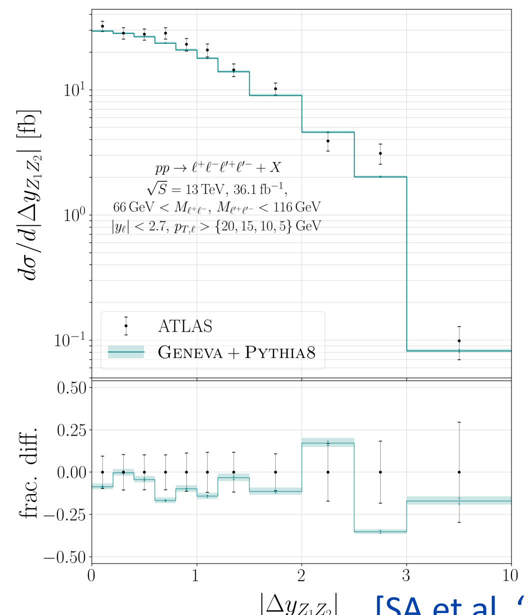
[Hoeche et al. ‘15]

MiNNLOPS



[Nason et al. ‘12 - ‘23]

GENEVA



[SA et al. ‘15 - ‘23]

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

[Campbell et al. 2108.07133]

Introduction

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- Three main approach to the problem:

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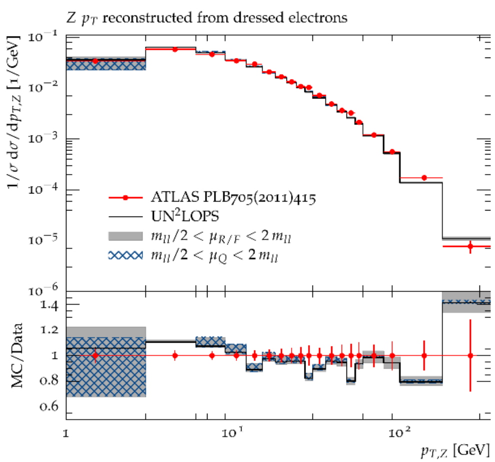
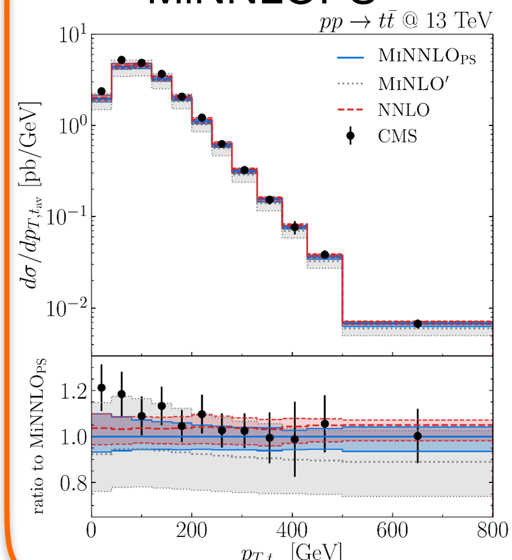
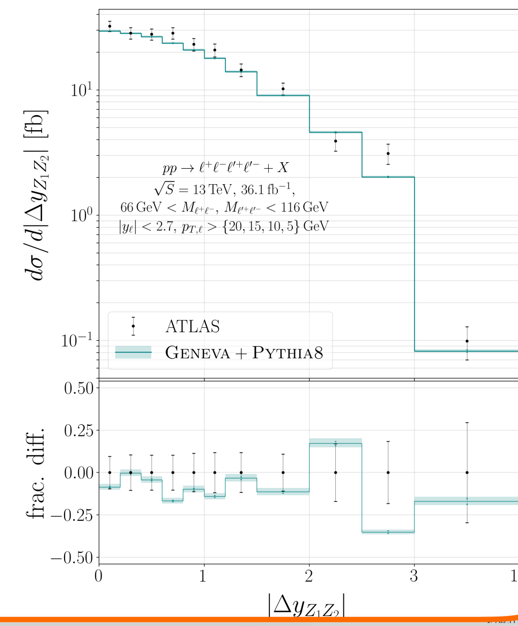


[Hoeche et al. '15]

MiNNLOPS



GENEVA



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[Campbell et al. 2108.07133]

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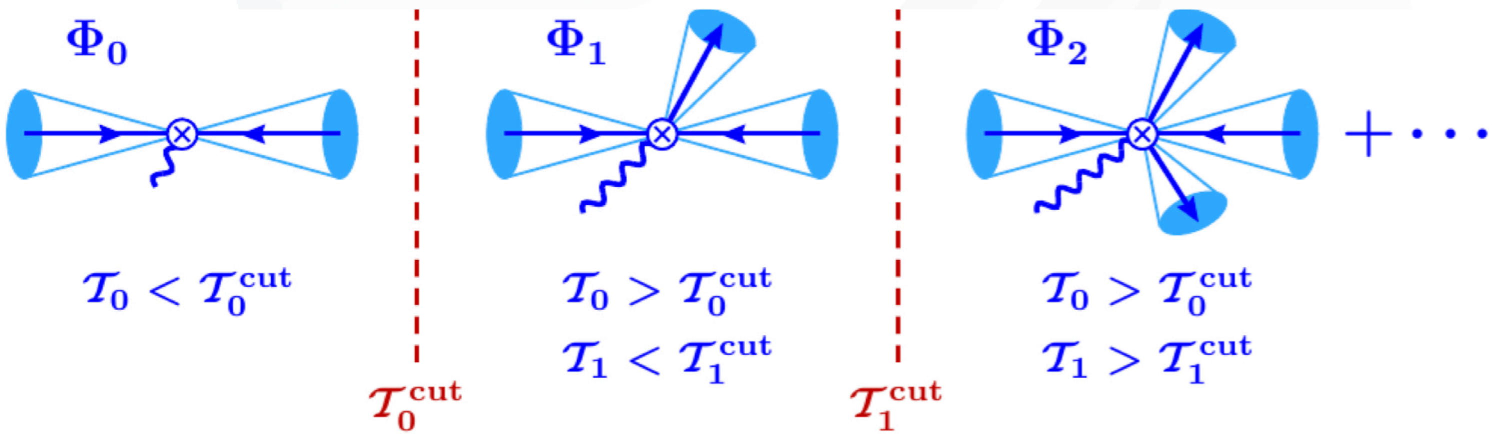
How to build a NNLO + PS

- Need a set of resolution parameters to measure hardness of first emission $p_T^H, p_T^{j_1}, \mathscr{T}_0$. For second emission $p_T^{j_2}, \mathscr{T}_1 \ldots$

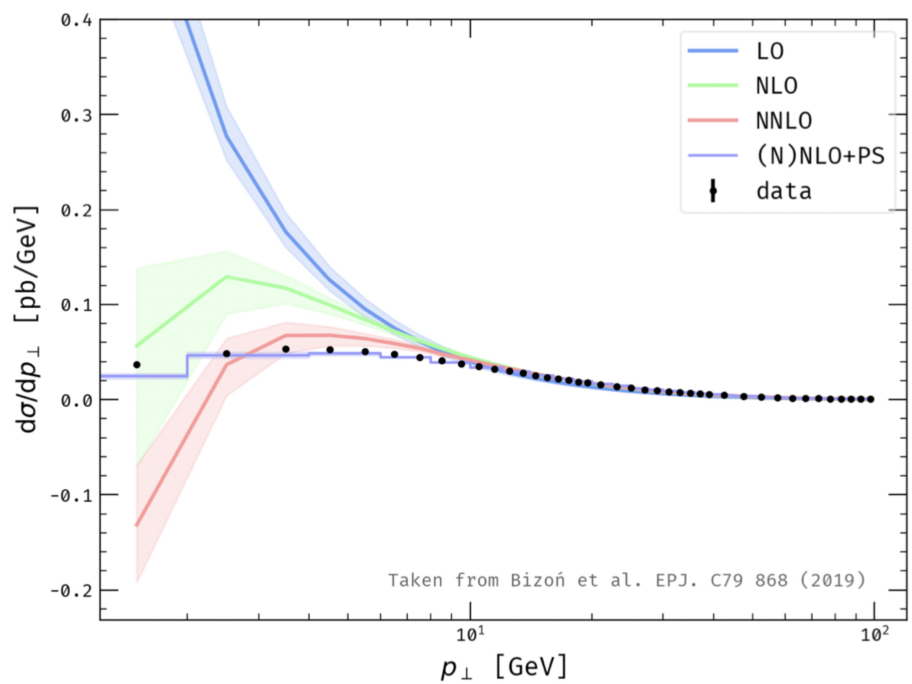


- Partonic fixed-order weights have a log dependence on the resolution parameters
- Dependence is resummed either explicitly or by the shower Sudakov

- Results at partonic level can be further evolved by different shower matching and hadronization models

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.



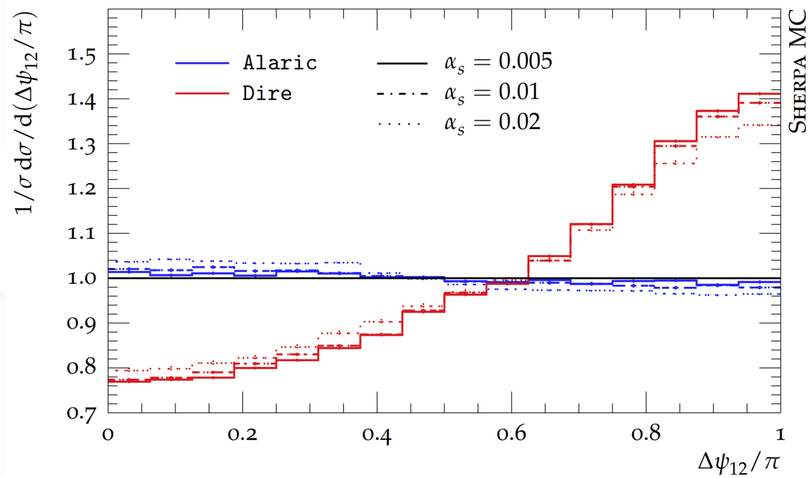
Improvement in the parton shower

- Recent progress on shower formal accuracy by various groups: Panscales, Alaric, Herwig …

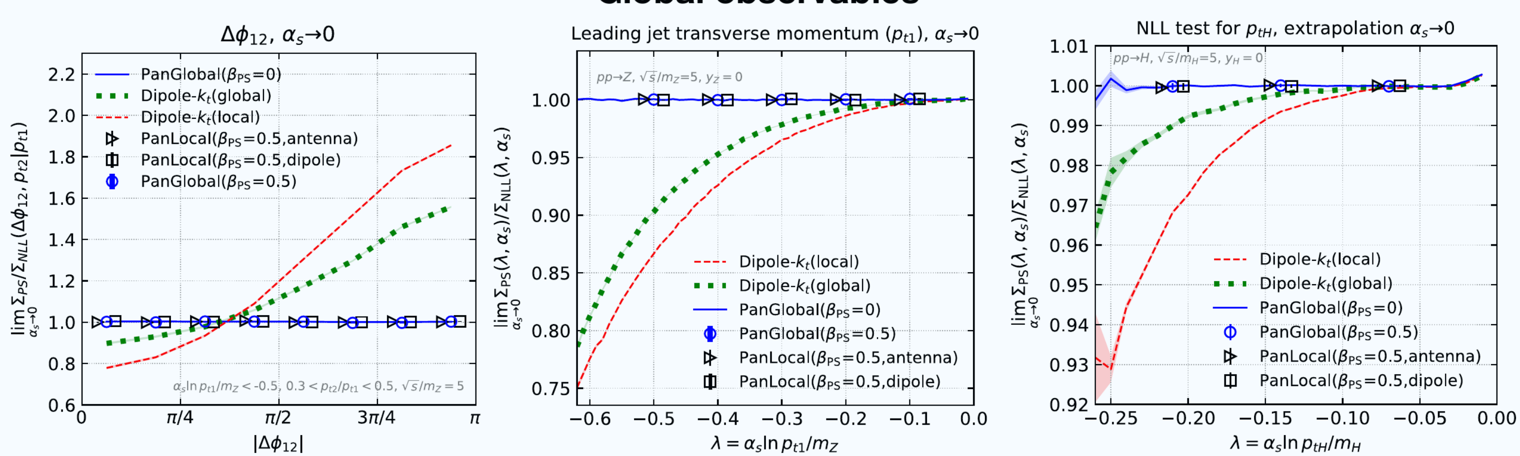
Tested by taking $\lim_{\alpha_s \to 0} \frac{\Sigma^{PS}(\alpha_s L)}{\Sigma^{NLL/NDL}(\alpha_s L)}$

(While keeping the size of $\lambda = \alpha_s L$ fixed)

Herren et al. '22



Global observables



van Beekveld et al. '22

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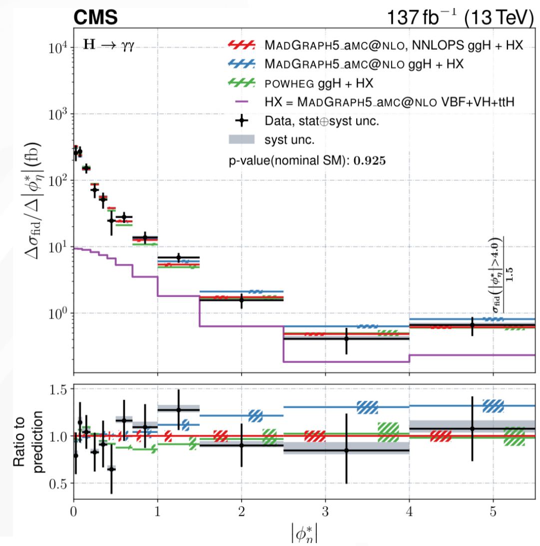
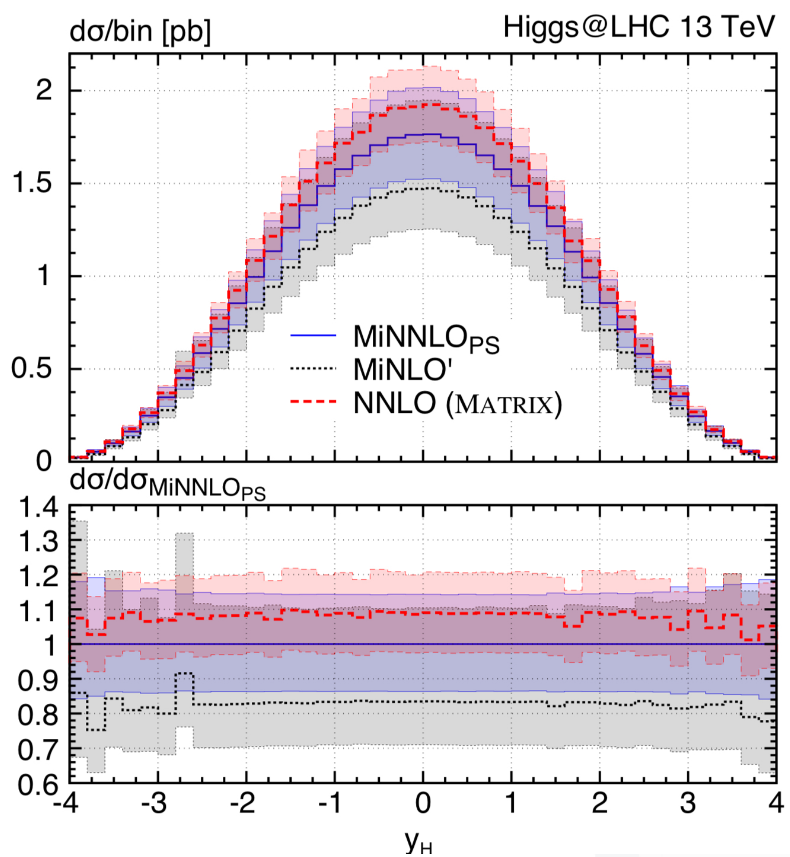
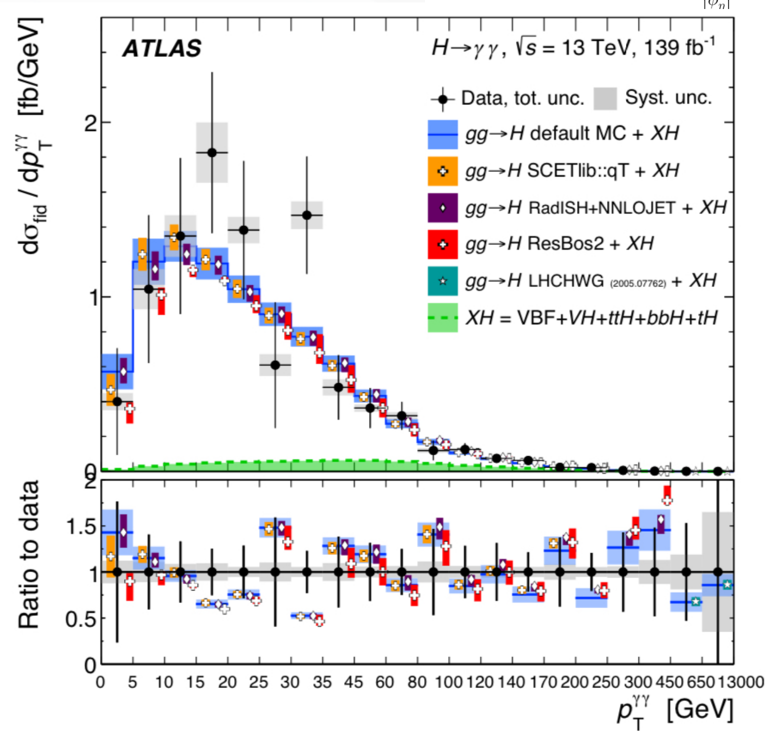
Higgs production via gluon fusion

- MINNLO’ original approach replaced by MINNLOPS
- Adopted by exp. collaborations



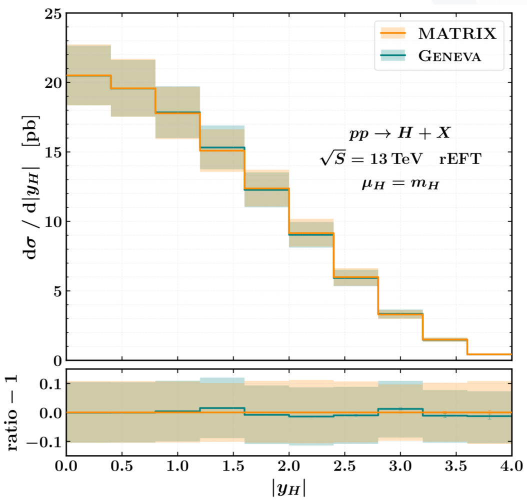


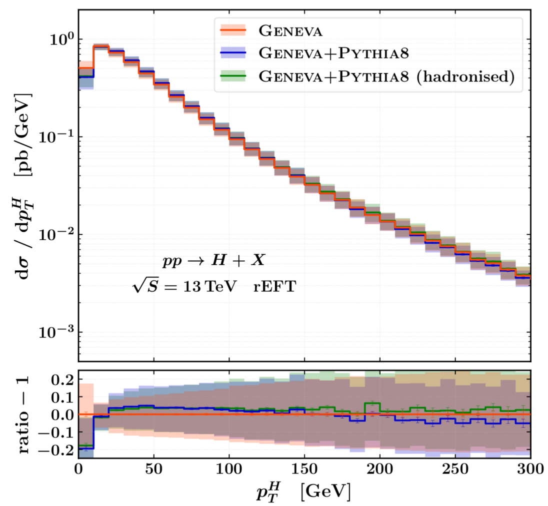


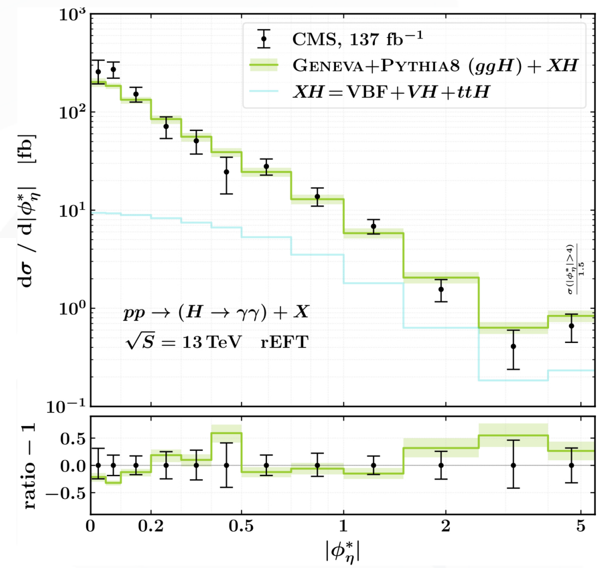
Higgs production via gluon fusion

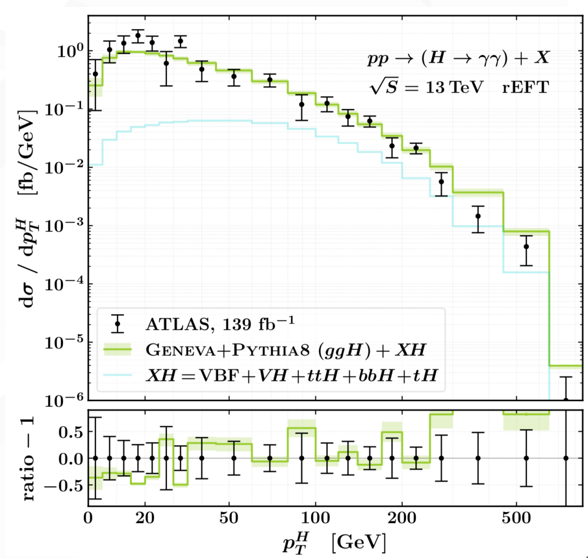
- Recently implemented in GENEVA

SA et al. '23









- Extensive comparison with LHC data, showing very good agreement.
- Small theoretical scale unc.

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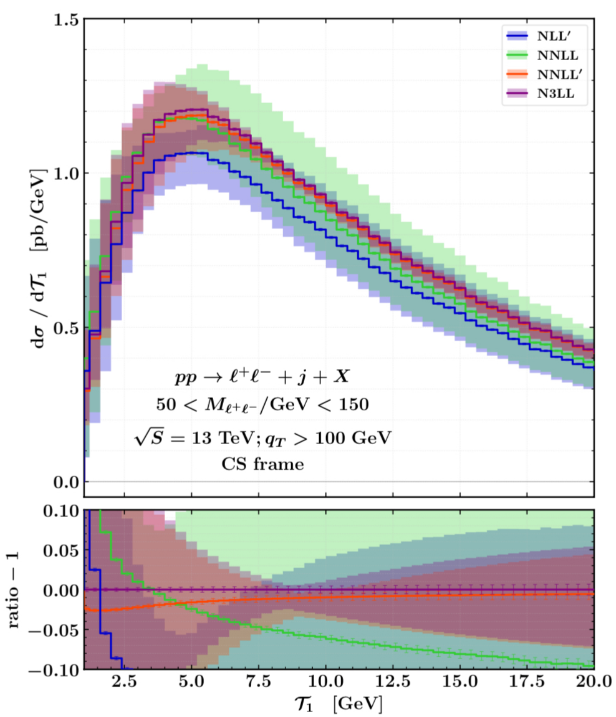
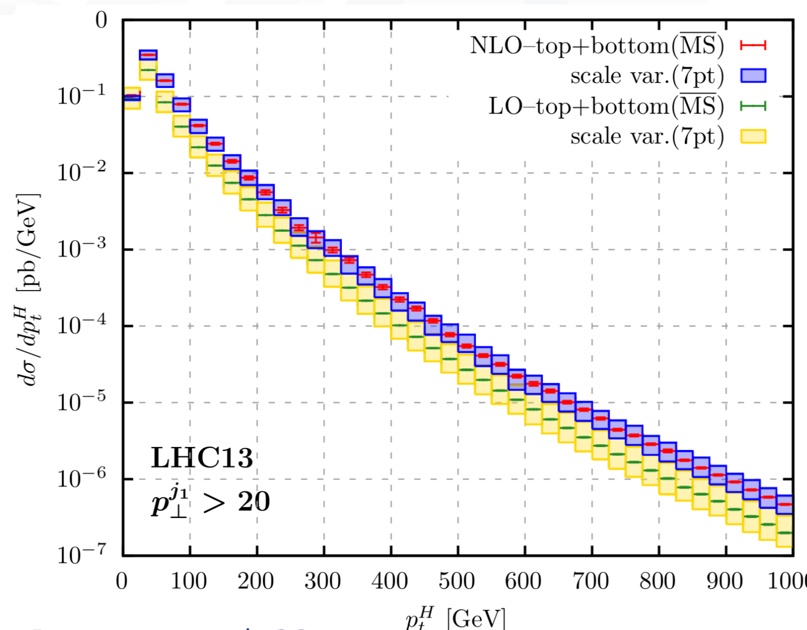
Higgs production via gluon fusion

- 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., to appear



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.

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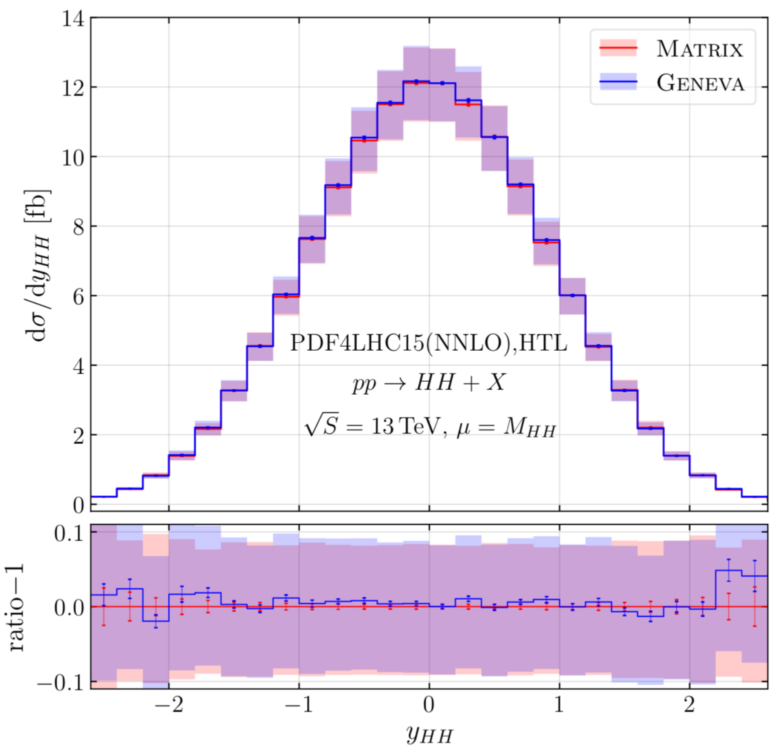
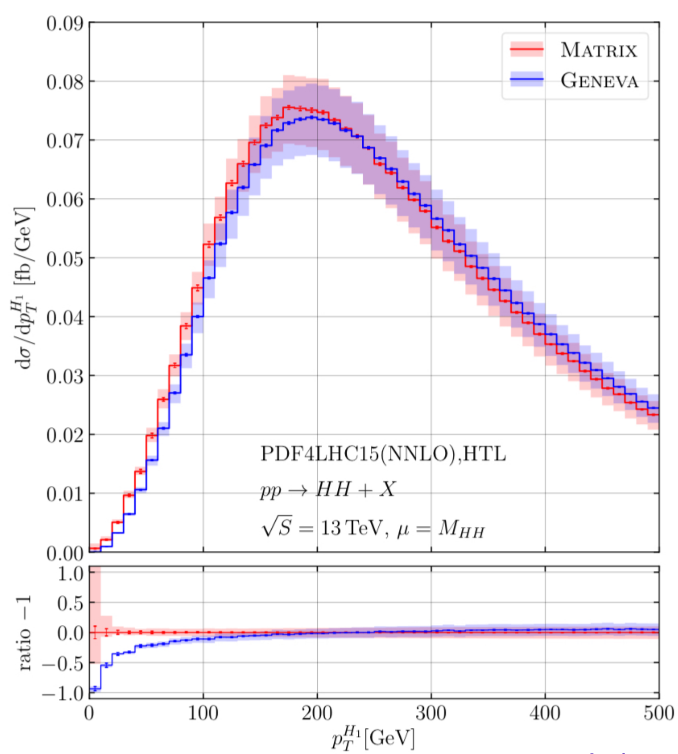
Higgs pair production

- Recently implemented in GENEVA using NNLO + $\mathrm{NNLL}'_{\mathcal{T}_0}$ in HTL
- Effects of resummation also visible inclusive quantities, in pathological regions for fixed-order calculations

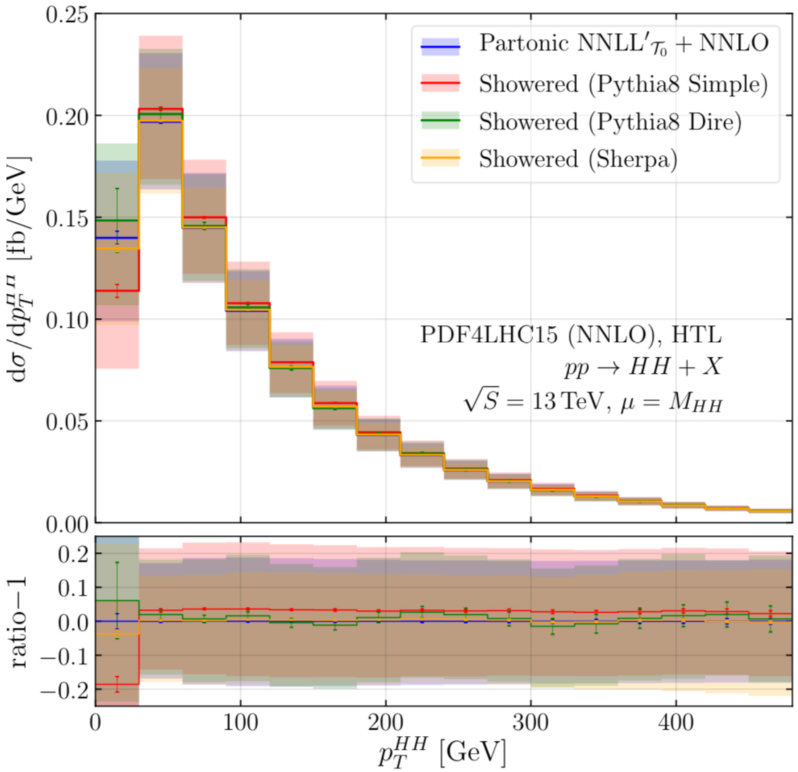


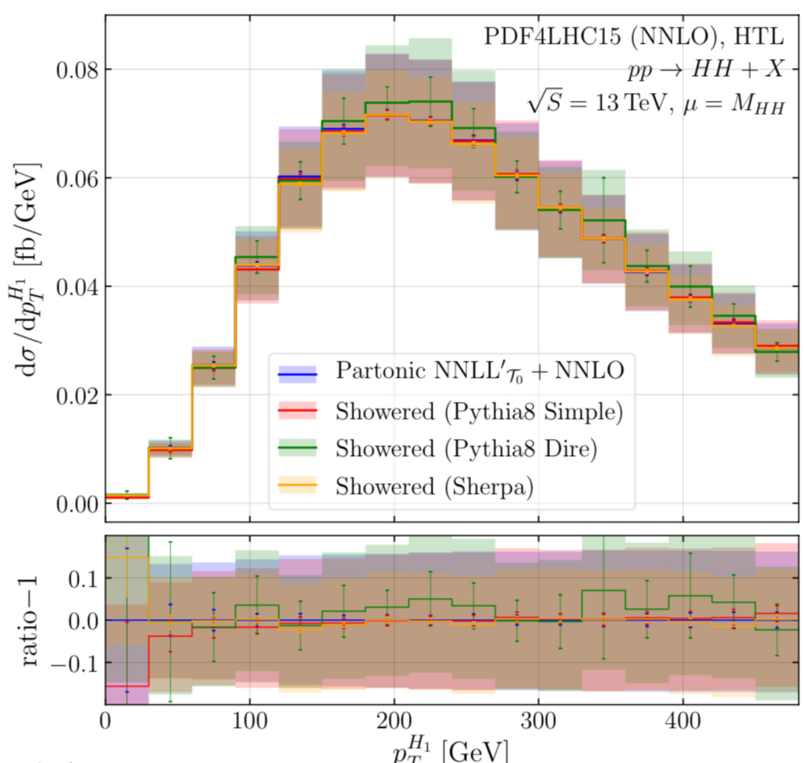


SA et al. ‘22

Higgs pair production

- Study interface with different shower models: inclusive quantities not much affected, expected differences for more exclusive ones.



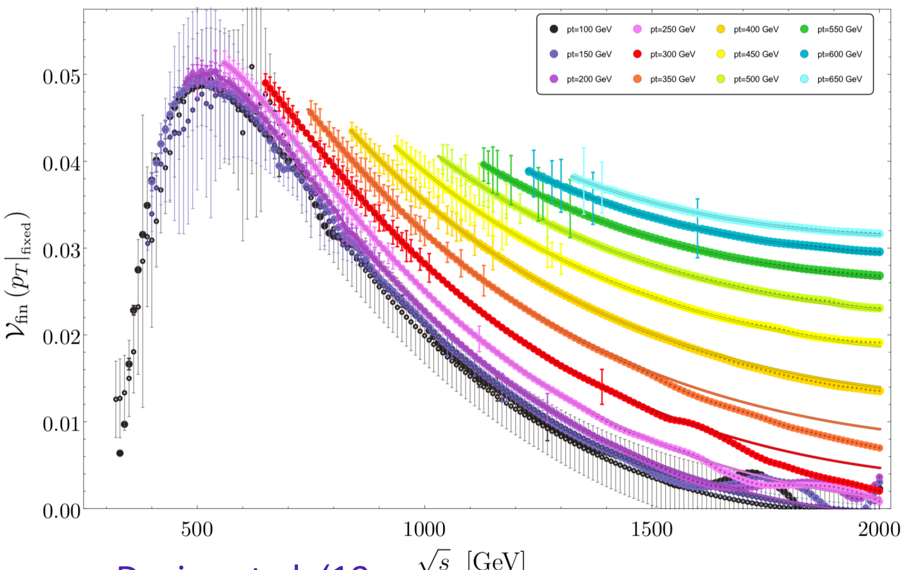


SA et al. '22

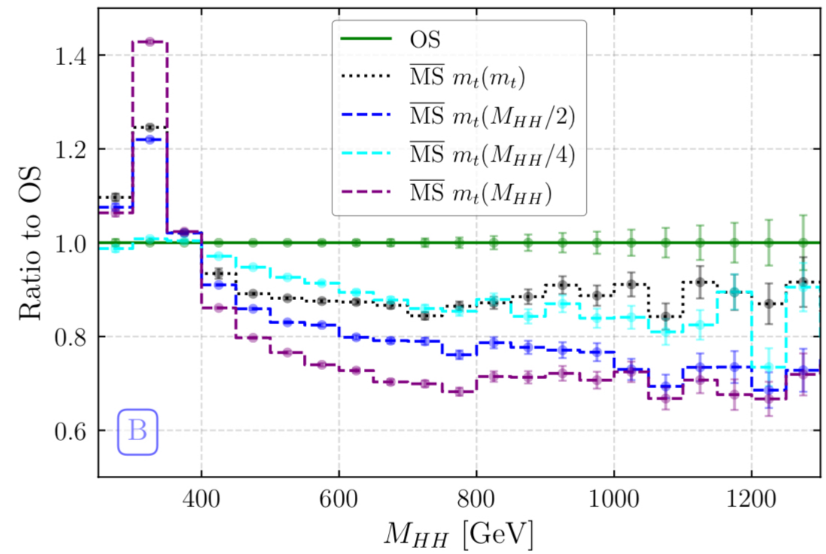
Higgs pair production

- 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 FTapprox in NNLO+PS….

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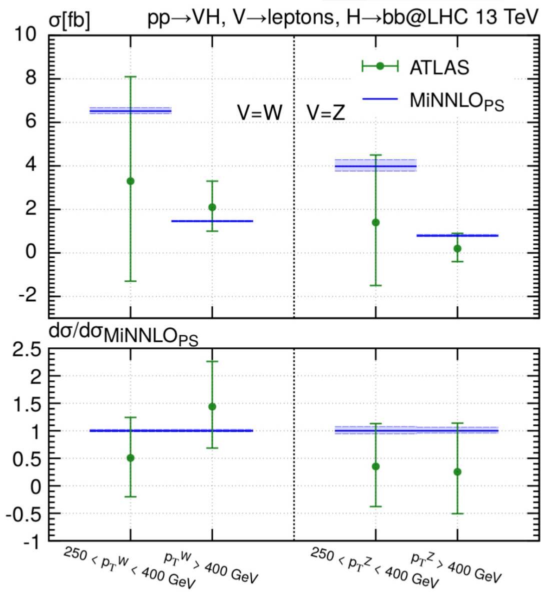
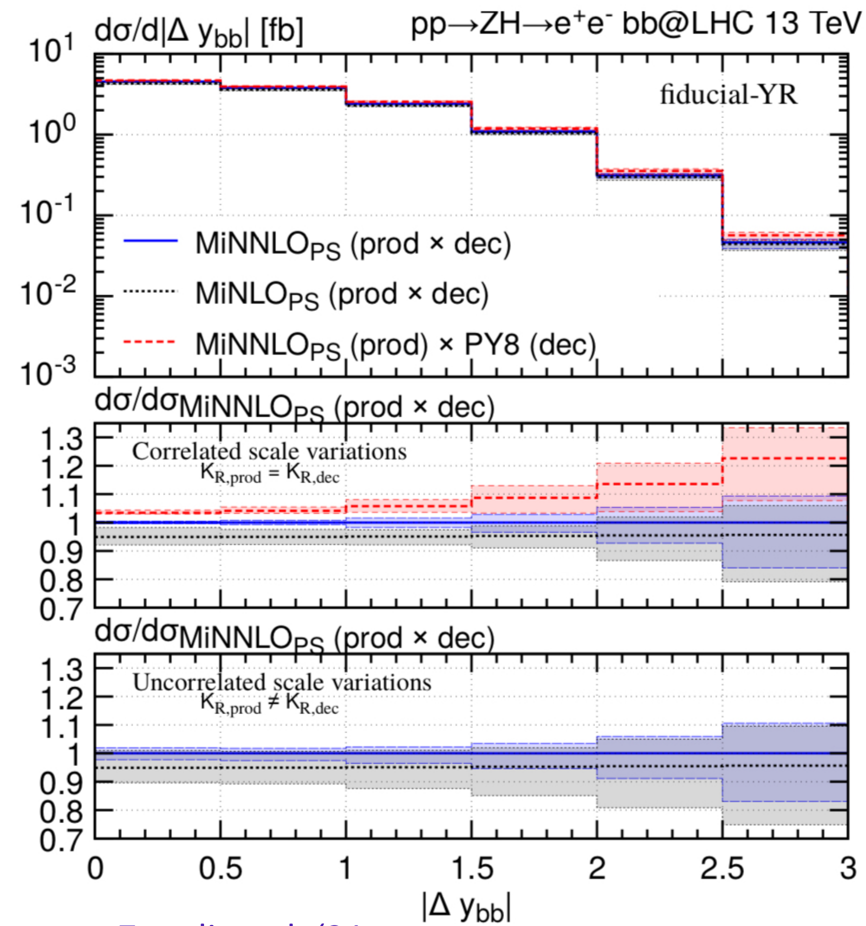
Higgsstrahlung HZ, HW

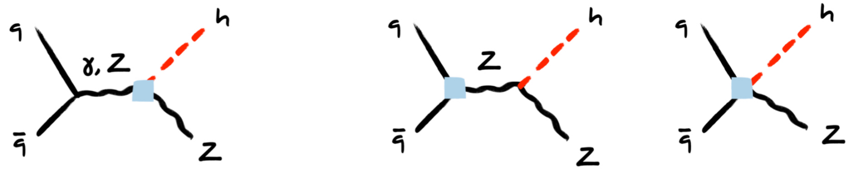
- MINNLOPS merging NNLO corrections to production and $H \to b\bar{b}$ decay





Zanoli et al. ‘21

Higgsstrahlung HZ, HW

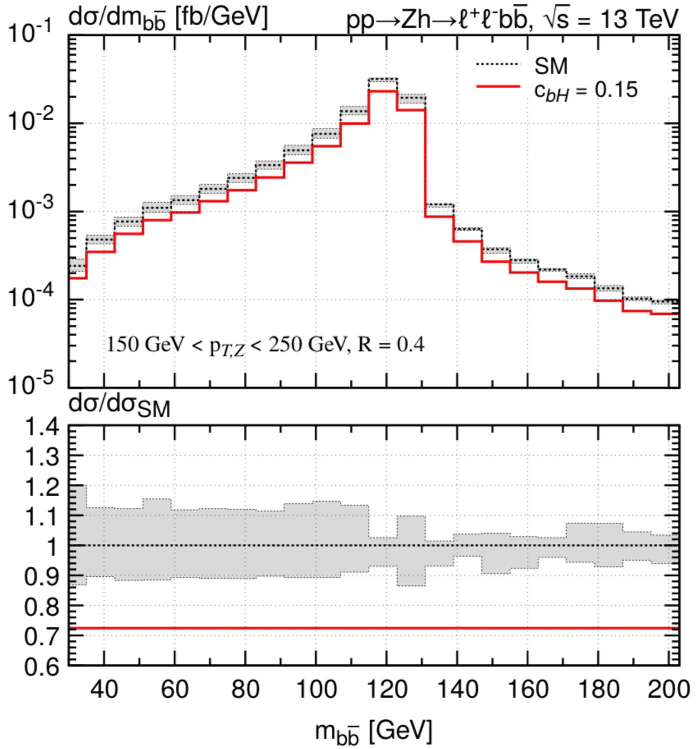


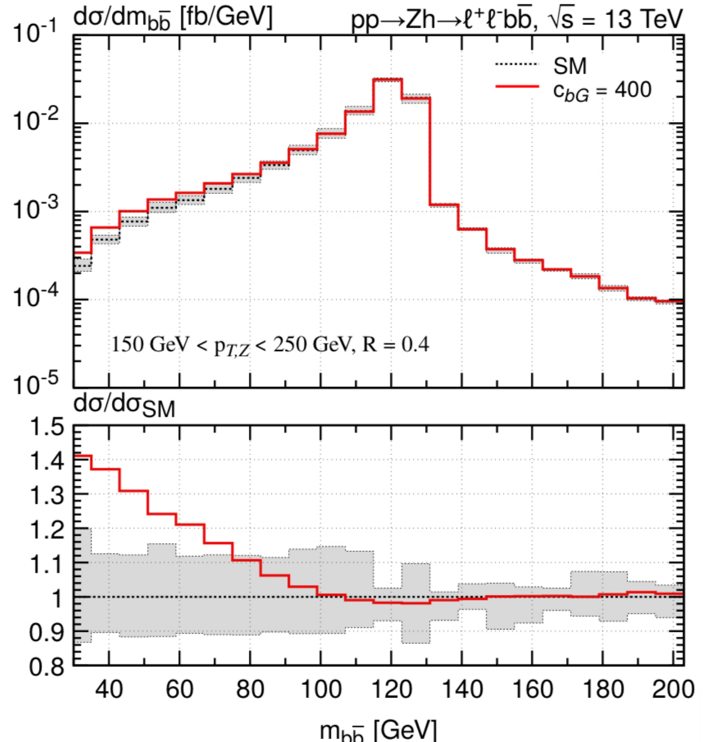
- Study of SMEFT effects at NNLOPS

Haisch, Gauld et al. '22, '23

$$Q_{bH} = y_b (H^\dagger H)\, \bar{q}_L b_R H\,,$$

$$Q_{bG} = \frac{g_s^3}{(4\pi)^2}\, y_b\, \bar{q}_L \sigma_{\mu\nu} T^a b_R H G^{a,\mu\nu}$$



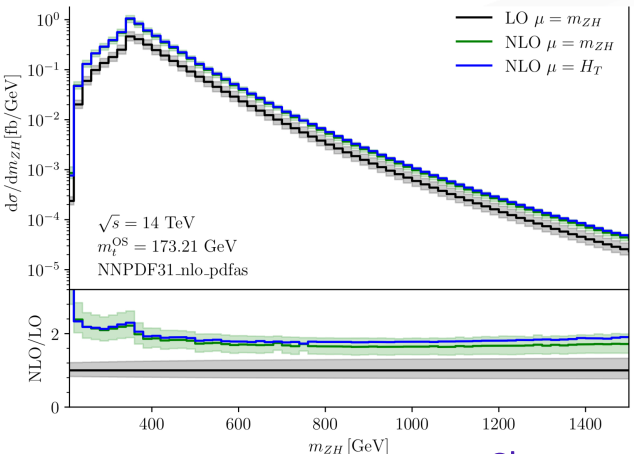


Haisch et al. '22

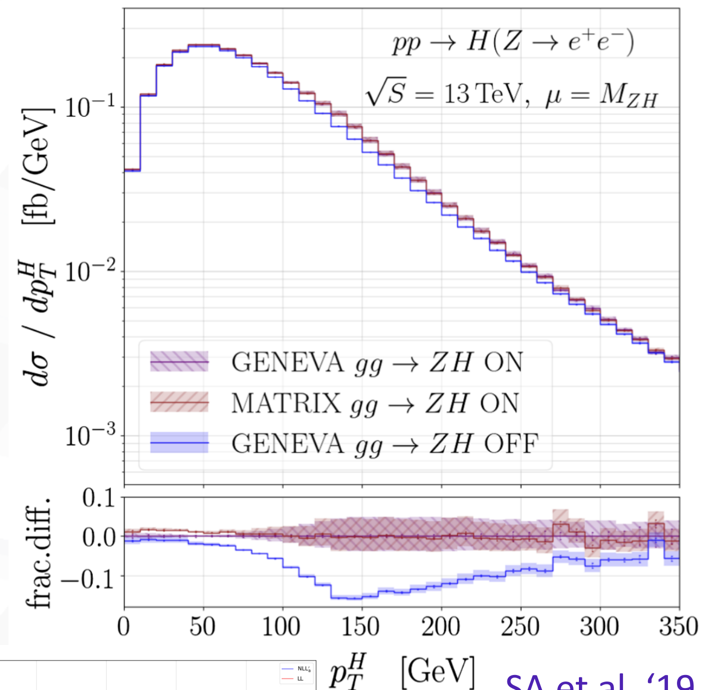
Associated HZ production via gluon fusion

- Gluon channel has large NLO corrections and scale unc.

Chen et al., DeGrassi at al ‘22

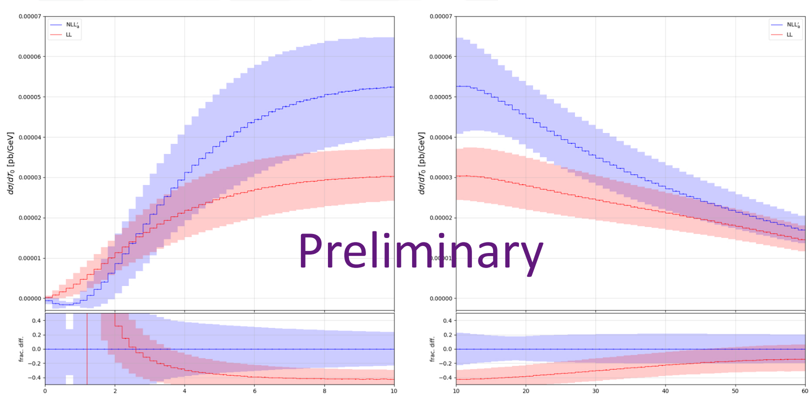


Chen et al. ‘22



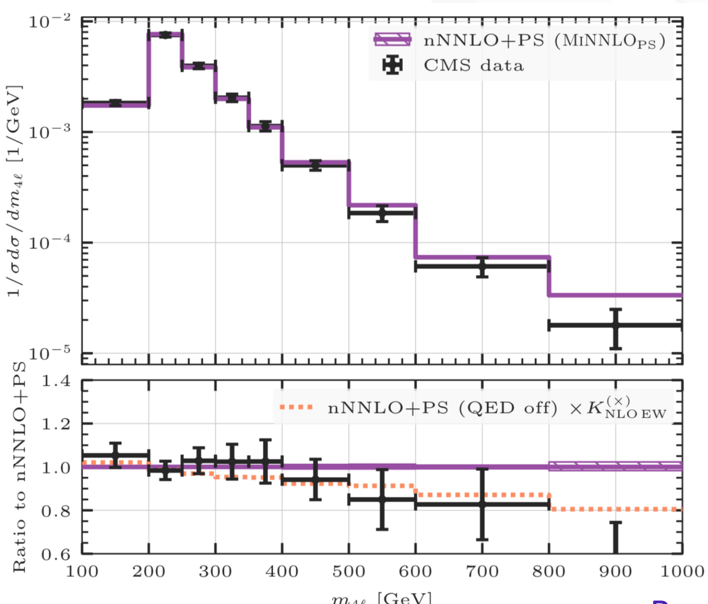
SA et al. ‘19

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

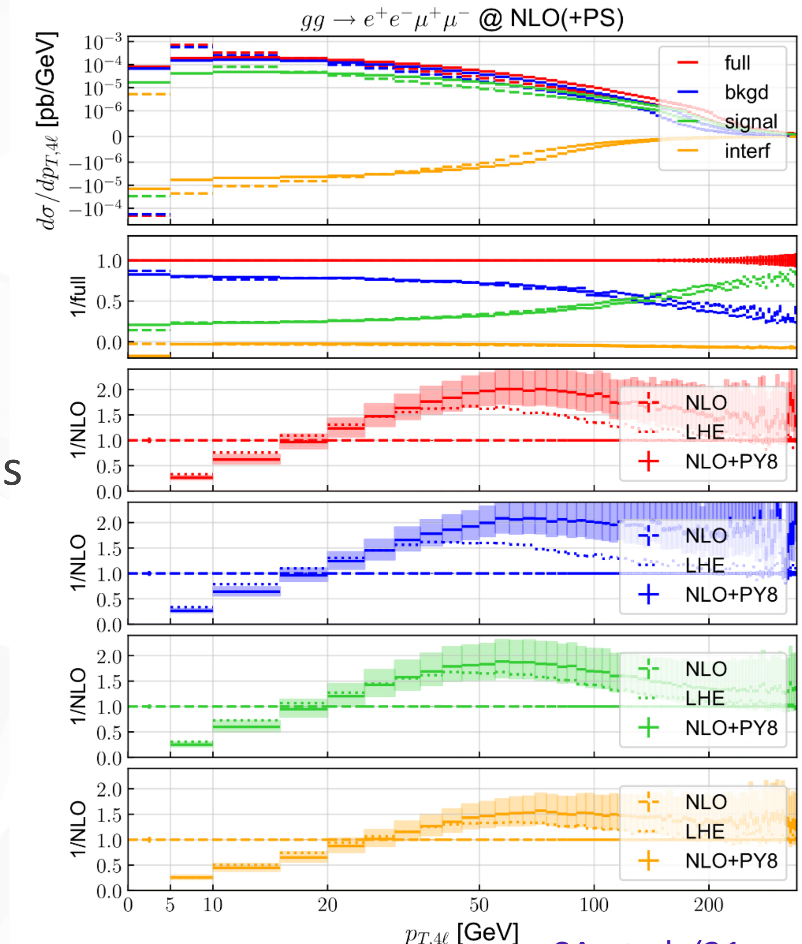


Signal-background interference in gg4l

- Full Higgs-mediated contribution and interference with ZZ and WW production, studied in POWHEG at NLO+PS accuracy.
- Precise modeling important for determination of Higgs width
- Included in MiNNLOPS diboson process



Buonocore et al. '21



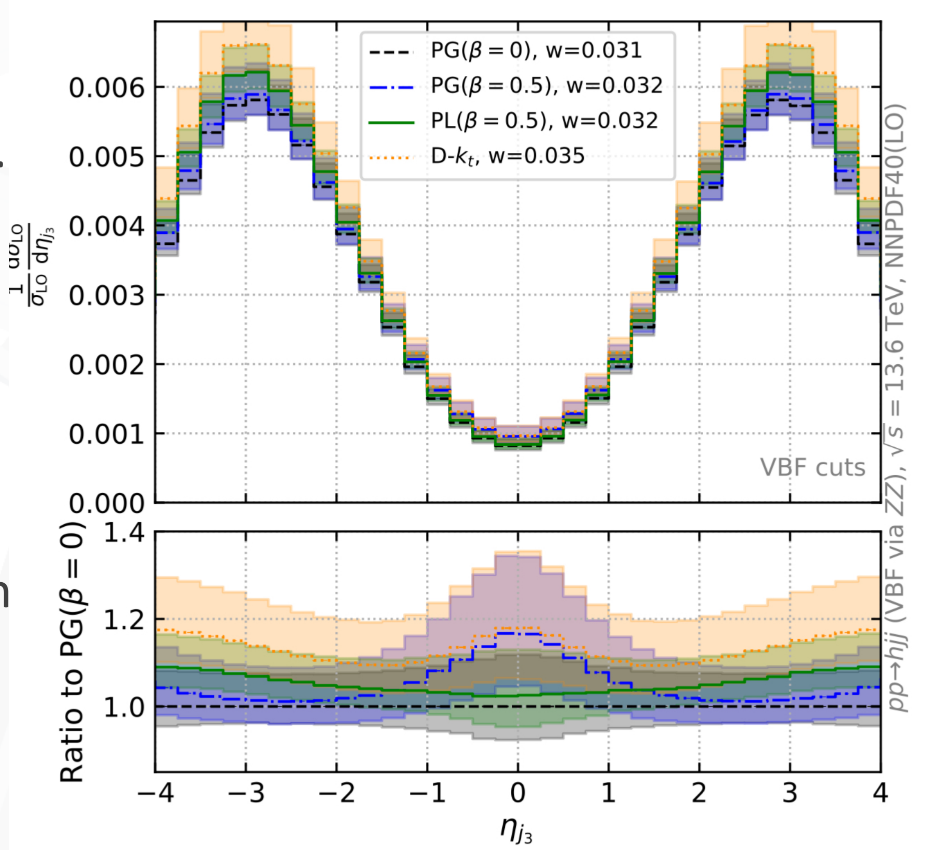
SA et al. '21

Vector boson fusion

- Color coherence strongly suppresses radiation in central rapidity region.
- Shower algorithms with global recoil (default PYTHIA) struggling with this.
- Matching procedures up to NLO+PS only fixes the 3rd jet, same problem for 4th jet.
- Uncertainty between shower modeling largest theo. unc.

- Recently studied with NLL showers, in factorized approach by Panscales
- Observed reduced spread among different shower predictions

- Challenge is to include this in a NNLOPS

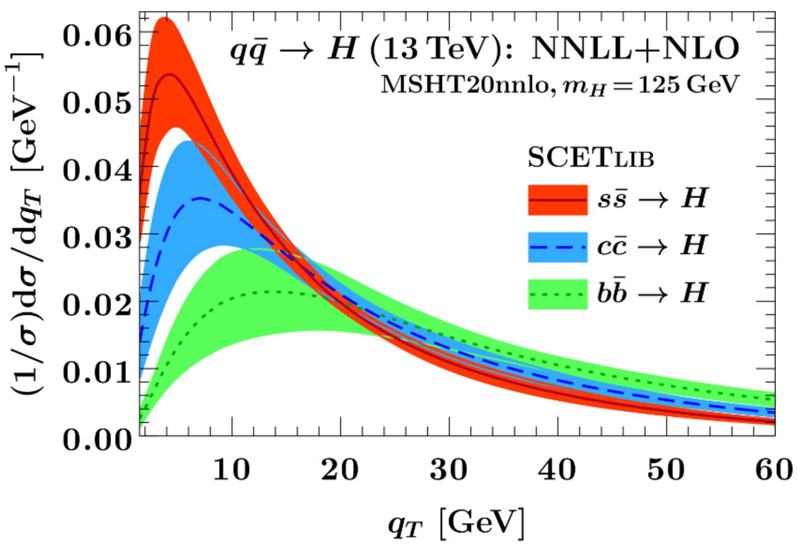


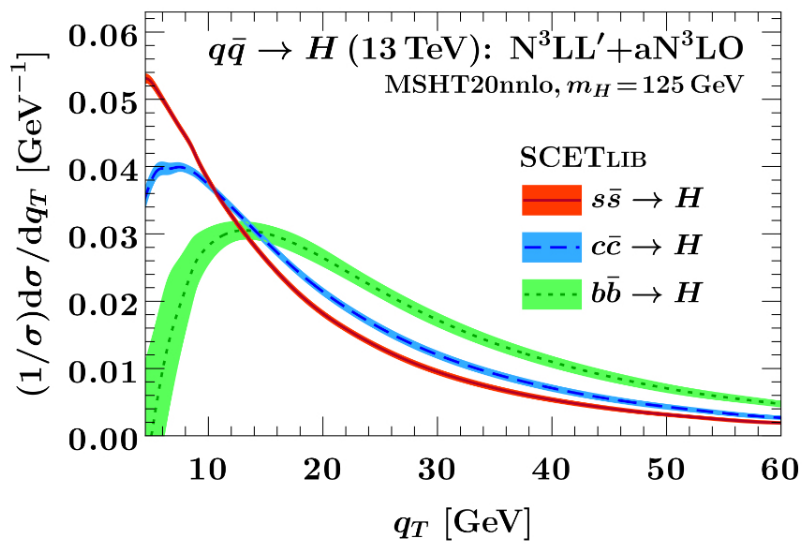
Van Beekveld, Ferrario-Ravasio. '23

Higgs production via $q\bar{q}$ annihilation

- Direct access to Yukawa from production rather than decay but measurement seems hopeless at LHC
- However different contributions to Higgs transverse momentum spectrum makes it possible to extract them
- Studied theoretically at high accuracy

Cal et al. '23





- Interesting to investigate how shower matching will change this picture

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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
- Inclusion of heavy-quark mass effects still not at the same level, but within range.
- Description of hard tails will also be improved by NNLO H+1jet, when that will be available in a NNLO+PS
- Other loop-induced processes which are the current unc. bottleneck should be improved, e.g. $gg \to HZ$
- Advancements in shower accuracy should be incorporated in NNLO+PS
- 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.