Higgs Theory

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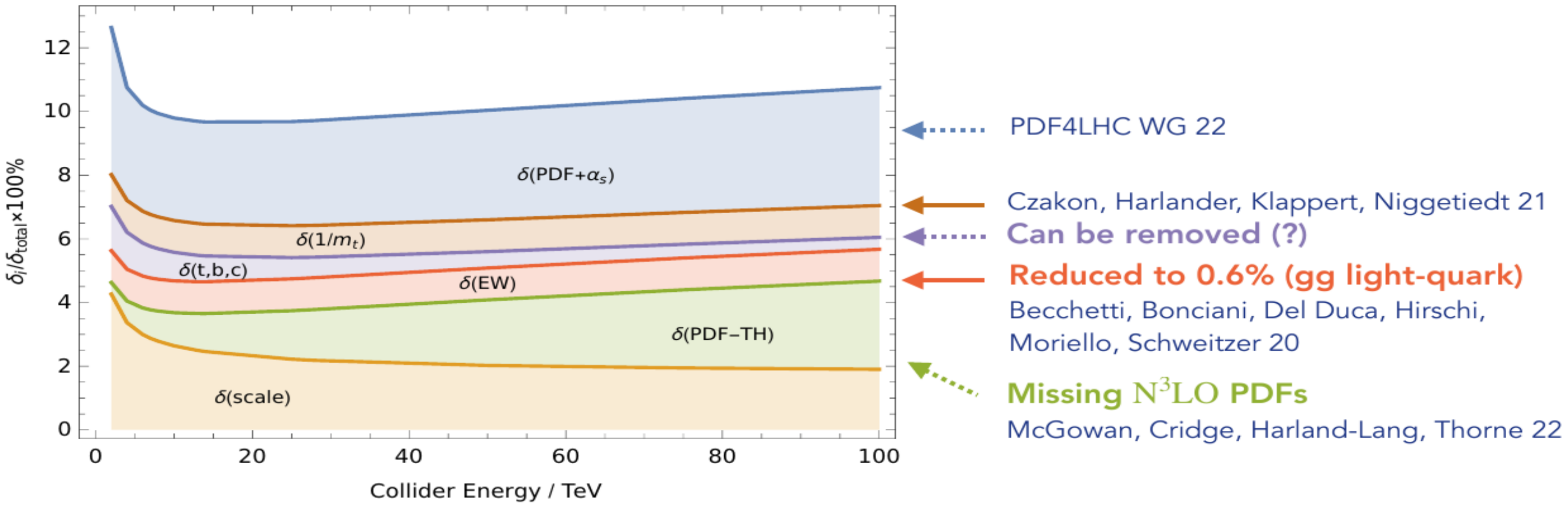
Les Houches Session I

13 June 2023

Outline

- Lots of progress over last two years:
  - Higher-order predictions (add one "N") calculated.
  - Other approximations / issues being addressed.
- Gluon fusion:
  - Hjj at NLO using FTApprox.
  - Top mass contribution; impact of aN3LO pdfs; mass scheme uncertainties.
- VBF:
  - NLL matching.
  - Non-factorizable NNLO corrections; EW Hjj production in PS.
- *VH*
  - N3LO cross sections; VH+j @ NNLO; VH (+ decay) NNLO+PS.
  - *gg → ZH.*
- $t\bar{t}H$
  - NNLO corrections.

Gluon Fusion



iHixs2: Dulat, Lazopoulos, Mistlberger 18

$\mathrm{N^3LO_{HTL}}$ - use iHixs2 Dulat, Lazopoulos, Mistlberger 18 (+ n3loxs Baglio, Duhr, Mistlberger, Szafron 22 ?)

$\delta(1/m_t)$ - NNLO QCD w/ m_T use Czakon et al. 21 (mass-scheme uncert. estimate?)

$\delta(t,b,c)$ - Not yet in literature ($m_q \sim 0$, m_b & m_t) (asked Czakon et al. if timeline available)

$\delta(\mathrm{EW})$ - gg-channel light-quark contributions use Becchetti et al 20. (asked for timeline for other channels)

$\delta(\mathrm{PDF-TH})$ - estimate with individual sets (PDF4LHC21 has no NLO set), separate comparison to $\mathrm{aN^3LO}$

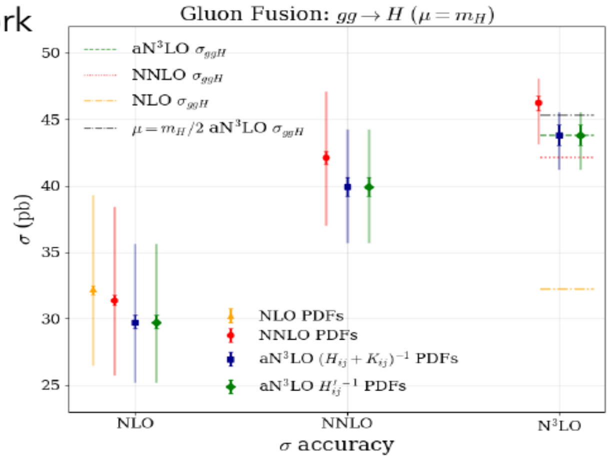
Run 3 update to ggF WG recommendation now underway, both TH conveners here and happy for input/feedback

Gluon Fusion

Approximate N3LO PDFs available with MSHT framework have sizeable impact on ggF

McGowan, Cridge, Harland-Lang, Thorne 22

σ order	PDF order	$\sigma + \Delta\sigma_+ - \Delta\sigma_-$ (pb)	σ (pb) $+ \Delta\sigma_+ - \Delta\sigma_-$ (%)
		PDF uncertainties	
N^3LO	aN^3LO (no theory unc.)	$45.296 + 0.723 - 0.545$	$45.296 + 1.60\% - 1.22\%$
	aN^3LO ($H_{ij} + K_{ij}$)	$45.296 + 0.832 - 0.755$	$45.296 + 1.84\% - 1.67\%$
	aN^3LO (H'_{ij})	$45.296 + 0.821 - 0.761$	$45.296 + 1.81\% - 1.68\%$
	NNLO	$47.817 + 0.558 - 0.581$	$47.817 + 1.17\% - 1.22\%$
NNLO	NNLO	$46.206 + 0.541 - 0.564$	$46.206 + 1.17\% - 1.22\%$



Previous procedure, take half the difference of NNLO with (N)NLO PDFs:

$$\delta(\mathrm{PDF-TH})_{\mathrm{NNLO}} = \pm \frac{1}{2} \left| \sigma^{(2)}_{\mathrm{NNLO}} - \sigma^{(2)}_{\mathrm{NLO}} \right| \sim \pm 1.2 - 1.4\,\% \text{ @ 13 TeV}$$

Can now compute:

$$\Delta_1 = \left| \sigma^{(3)}_{\mathrm{aN^3LO}} - \sigma^{(3)}_{\mathrm{NNLO}} \right| \sim 5.3\,\%$$

$$\Delta_2 = \left| \sigma^{(3)}_{\mathrm{aN^3LO}} - \sigma^{(2)}_{\mathrm{NNLO}} \right| \sim 2\,\%$$

Complications: No NLO set in PDF4LHC21, aN^3LO includes some MHOU in errors already, need aN^3LO input from other groups and input on procedure

Gluon Fusion

GENEVA Refinements to NNLO+PS matching

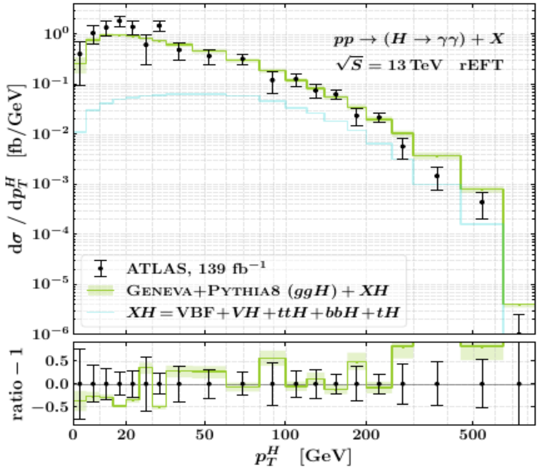
Improved treatment of splitting functions

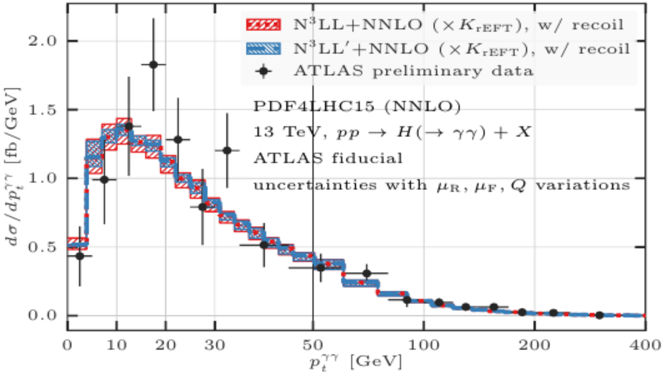
Disentangling μ_R, μ_F uncertainties

Handling time-like logs (improves pert. converge.)

Also studied to HH @ NNLO+PS in HTL

Alioli, Billis, Broggio, Gavardi, Kallweit, Lim, Marinelli, Nagara, Napoletano 23 (x 2)





RadISH N3LL/N3LL' + NNLO fiducial predictions

TH uncertainty in resummation region 5-7%

Re, Rottoli, Torrielli 21

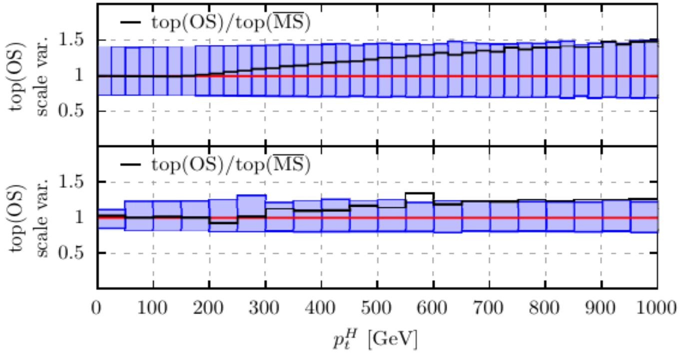
Important to continue addressing PS/matching uncertainties which are large/ dominant sources of TH uncertainty for many Higgs processes

Gluon Fusion

Updates since last Les Houches:

1) Mass scheme uncertainties known at NLO

Bonciani, et al. 22

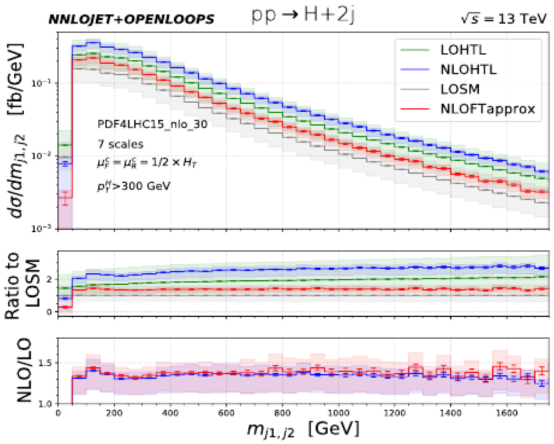


2) Boosted Higgs note needs an update

- Mixed QCD-EW Corrections
- Parton Shower updates for HJ, HJJ
- HJ mass scheme uncertainties
- All channels contributing

3) Progress towards NNLO w/ m_T and N3LO HTL

Henn, Lim, Bobadilla 23; Gehrmann, Jakubčík, Mella, Syrrakos, Tancredi 23



Higgs + 2 Jets @ NLO FTApprox

Know $gg \rightarrow Hggg$ @ 1-loop with m_T

2300s/ps to <1s/ps (OTTER) Lang

Chen, Huss, Jones, Kerner, Lang, Lindert, Zhang 21

Could be interesting for estimating ggF background to VBF?

Vector boson fusion

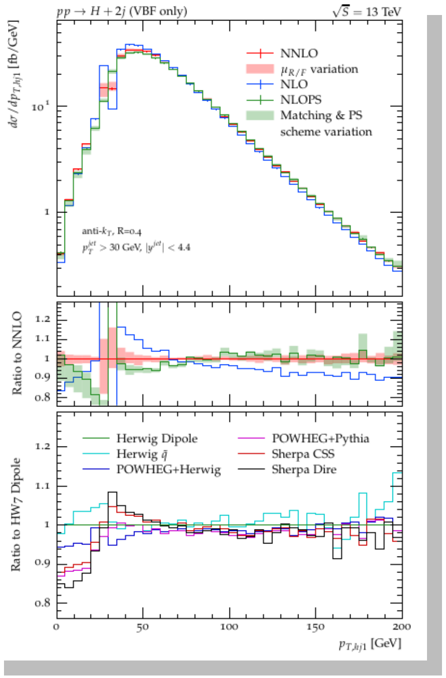
- Les Houches 2019 study published:

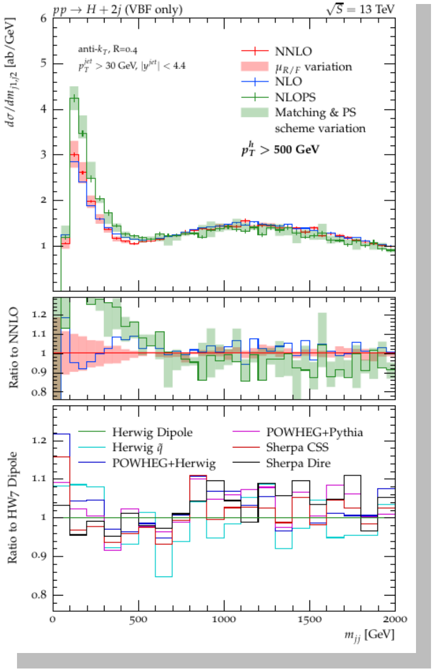
  A comparative study of Higgs boson production from vector-boson fusion

  A. Buckley,[1] X. Chen,[2,3,4] J. Cruz-Martinez,[5] S. Ferrario Ravasio,[6,7] T. Gehrmann,[2] E.W.N. Glover,[7] S. Höche,[8] A. Huss,[9] J. Huston,[10] J. M. Lindert,[11] S. Plätzer,[12] and M. Schönherr[7]

  [2105.11399]

- Extensive study of:
  - ✔ NNLO and NLO+PS results (`NNLOJET`, `HERWIG`, `PYTHIA`, `SHERPA`, `POWHEG`)
  - ✔ Different PS approaches (additive/multiplicative matching)
  - ✔ Dependence on jet radius
  - ✔ High-pT region
  - ✔ Discrimination between VBF, VH and ggF production modes
- Generally good agreement between NNLO and NLO+PS.
- Global jet veto preferable to central jet veto.



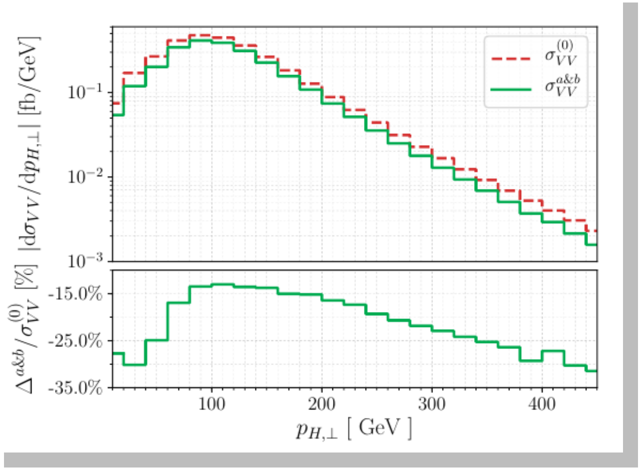


Vector boson fusion

- A lot of activity in last ~ 2 years! [VBF Subgroup Workshop, Nov '22]
- NNLO results beyond factorization approximation:
  - Leading eikonal approximation (two-loop): non-factorizable effects: -0.5% to -1%

    [Liu, Penin, Melnikov, '19]
  - Real-real and real-virtual results negligible. [Asteriadis, Brønnum-Hansen, Melnikov '23]
  - Next-to-leading eikonal corrections: -15% to -30% of leading eikonal approximation.

    [Long, Melnikov, Quarroz '23]
  - *"Since the non-factorizable contribution itself is just O(1) percent of the total WBF cross section, the remaining uncertainties stemming from the imprecise knowledge of the two-loop virtual amplitude are irrelevant."*

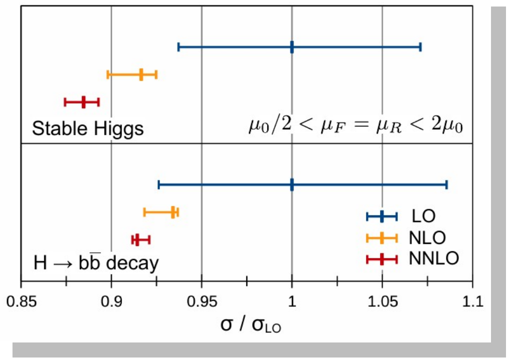


Vector boson fusion

- NNLO including Higgs decay

  [Asteriadis, Caola, Melnikov, RR, ‘21]

  - NNLO results with $H \to b\bar{b}$ decay:
    - Scale uncertainty and perturbative convergence better than for stable Higgs.
    - Impact of decay ~ 3% at NNLO – comparable with size of NNLO corrections.
    - Effects milder with $H \to WW \to$ leptons, can be captured by overall k-factor.



$$\frac{\sigma^H_{\rm NLO}}{\sigma^H_{\rm LO}} = 0.917(1) \quad \xrightarrow{-3.2\%} \quad \frac{\sigma^H_{\rm NNLO}}{\sigma^H_{\rm LO}} = 0.885(1)$$

$\downarrow$ +1.7% $\qquad\qquad$ $\downarrow$ +2.9%

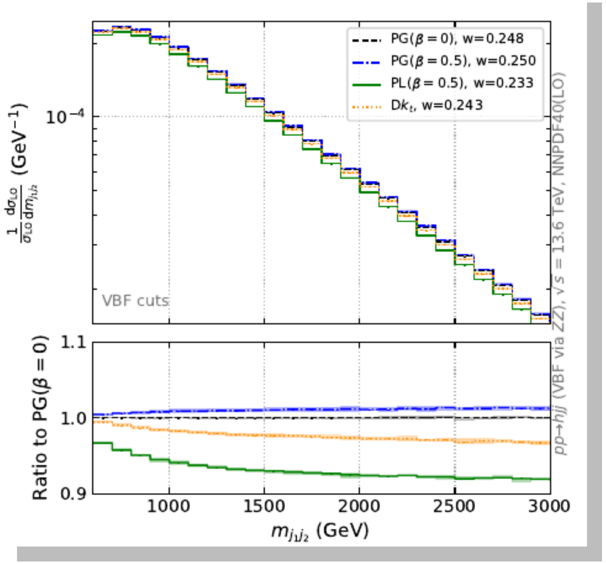
$$\frac{\sigma^{b\bar{b}}_{\rm NLO}}{\sigma^{b\bar{b}}_{\rm LO}} = 0.934(1) \qquad \frac{\sigma^{b\bar{b}}_{\rm NNLO}}{\sigma^{b\bar{b}}_{\rm LO}} = 0.914(2)$$

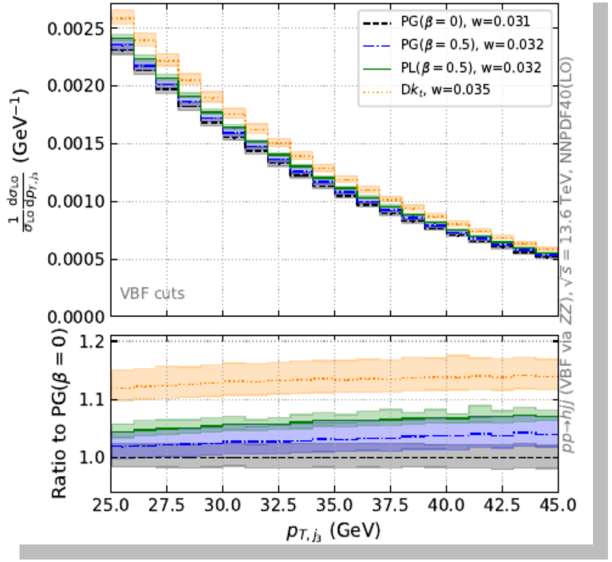
Vector boson fusion

- PS results at NLL:

[Van Beekveld, Ferrario Ravasio, ‘23]

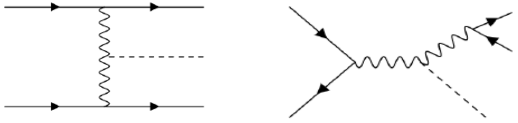
- NLL-accurate resummation for global and non-global observables in VBF.
- Two-jet observables: mild dependence on NLL shower, agreement with LL shower.
- Three-jet observables: discrepancies as high as 10% between LL and NLL showers.



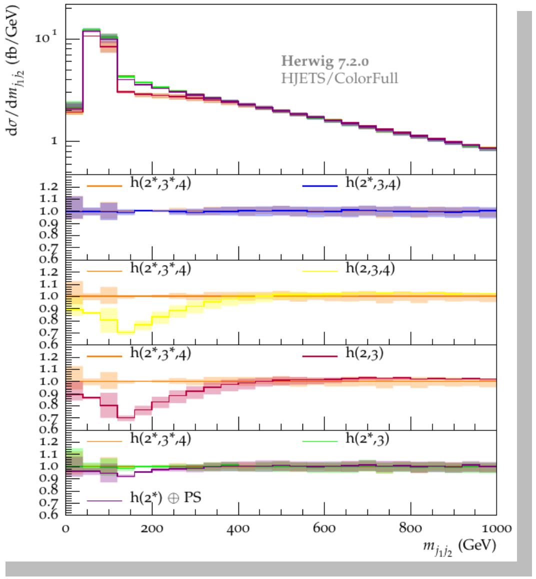


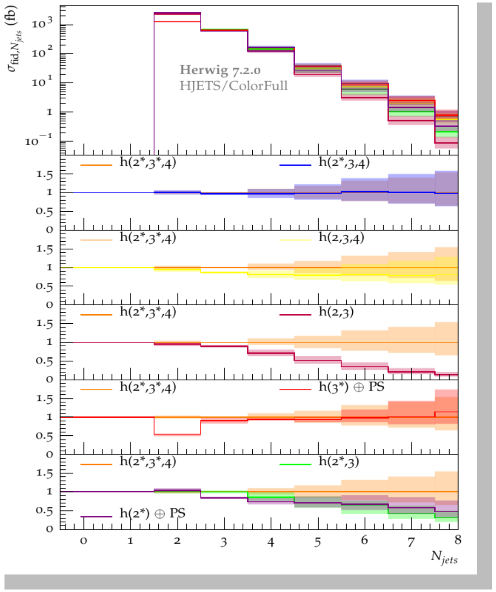
Vector boson fusion

- PS results beyond the VBF approximation:
  - First PS prediction using EW H+jj production in both t- and s-channel.
    [Chen, Figy, Plätzer '21]



  - H+2,3 jets at NLO; H+4 jets at LO
  - Matching and merging in `Herwig7`.
  - Good agreement between matching and merging for 2-jet observables.
  - Disagreements as high as 20% for third-jet observables.
  - NLO-QCD and NLO-EW matched to PS in POWHEG-BOX
    [Jäger, Scheller, '22]





Vector boson fusion

- Non-perturbative soft QCD effects:
  - Not clear how to quantify uncertainties.
  - Variation of MPI and color-reconnection parameters : uncertainty in third-jet observables comparable to perturbative uncertainties.

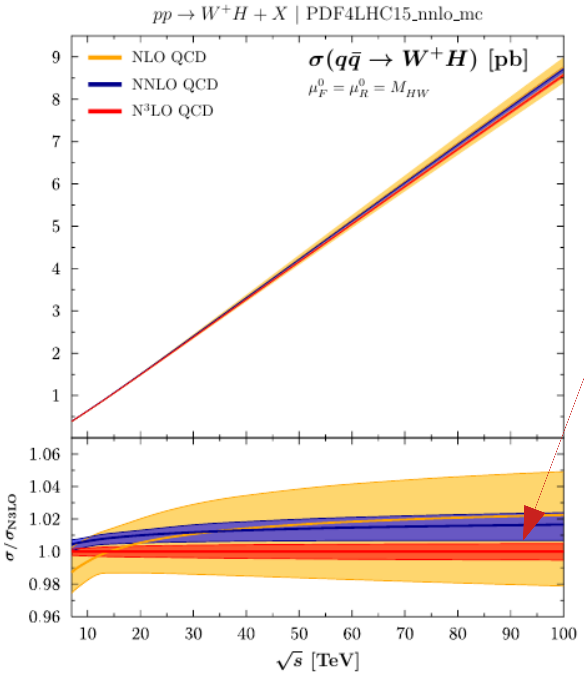
    [Bittrich et al., ‘21]

- Matching and merging in PYTHIA
  - Comparison of DGLAP and dipole recoil showers with antenna shower in VINCIA.
  - At LO, large discrepancies between DGLAP and dipole/antenna showers in observables sensitive to additional radiation.
  - Discrepancies persist at NLO for observables sensitive to > 3 jet multiplicities.
  - Higher multiplicity matrix elements included through CKKW-L scheme.

  [Höche et al., ‘21]

VH Production

- Inclusive cross section computed to N3LO



[Baglio, Duhr, Mistlberger, Szafron ‘22]

- Scale uncertainties < 0.5%.
- Scale uncertainties similar to NNLO and N3LO results lie outside of NNLO scale variations.
- Error budget dominated by PDF and strong coupling determination.
- Publicly available in `n3loxs`.

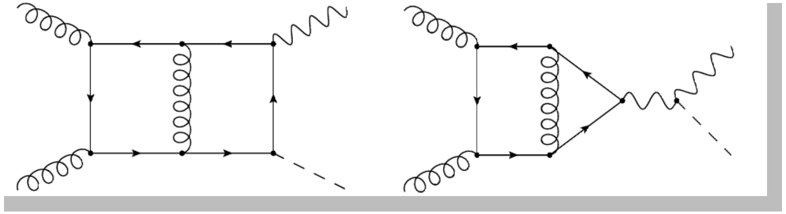
Process	σ^{N^3LO} [pb]	δ(PDF) [%]	$\delta(\text{PDF} + \alpha_S)$ [%]	δ(PDF-TH) [%]
W^+H	0.884	±1.59	±1.80	±1.45
W^-H	0.559	±1.76	±1.92	±1.63
ZH	0.786	±1.77	±1.95	±1.53

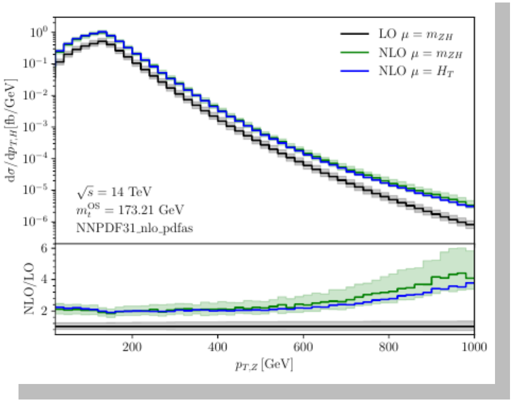
VH Production

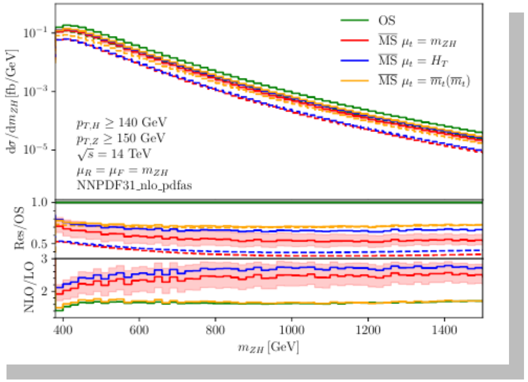
- NLO corrections to $gg \to ZH$ computed

  [Chen et al., '22]

  - Two-loop amplitudes computed exactly by [Chen et al '20]
  - Two-loop amplitudes also available in several expansions*.
  - Now combined and used for pheno study.
  - Very large k-factors ~ 2.
  - Results consistent with [Wang, Xu, Xu, Wang '21] using small m_Z and m_H expansion.
  - Top mass scheme dependence also large.







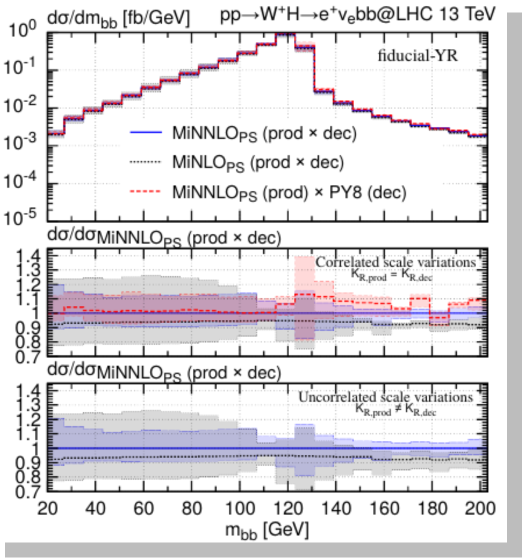
* [Hasselhuhn, Luthe, Steinhauser '16; Davies, Mishima, Steinhauser '20; Alasfar et al, '21; Bellafronte et al '22; Wang et al '20; Wang, Xu, Xu, Yang '21]

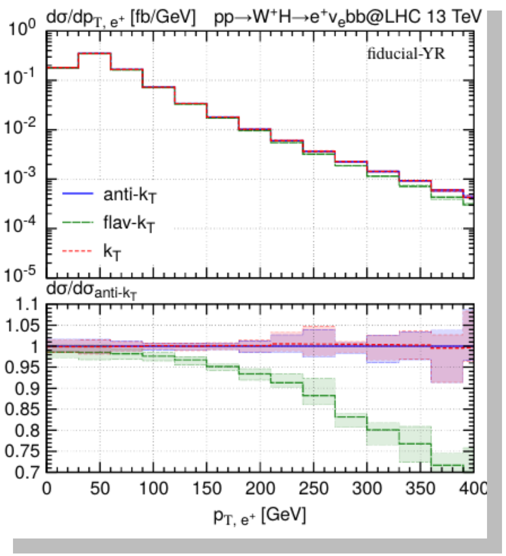
VH Production

- NNLO matched to PS using MINNLOPS

[Zanoli et al, '21]

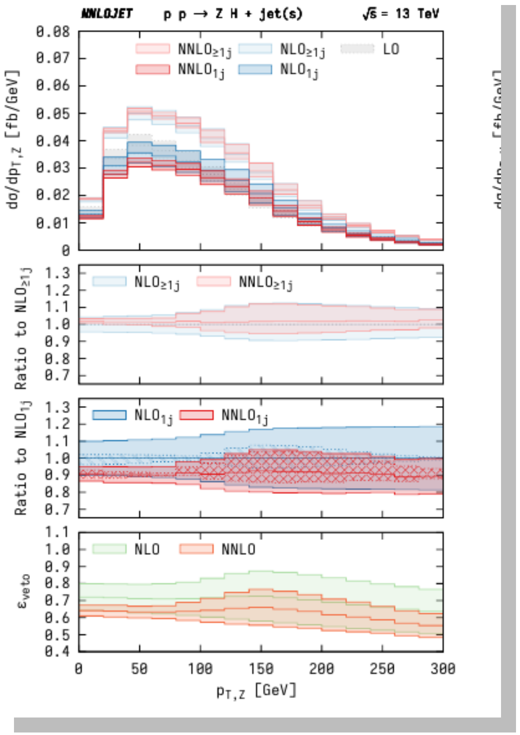
- NNLO+PS accuracy for $H \to b\bar{b}$ decay in WH production
- Increases cross section relative to MINLO' by ~ 5% (inclusive and with fiducial cuts).
- Scale uncertainties reduced using MINNLOPS,
- MINNLOPS result does not lie in correlated scale uncertainty band of MINLO' – uncorrelated production and decay scale uncertainties preferable.
- Effect of jet definition also studied (using massive b-quarks in shower allows use of anti-kT)

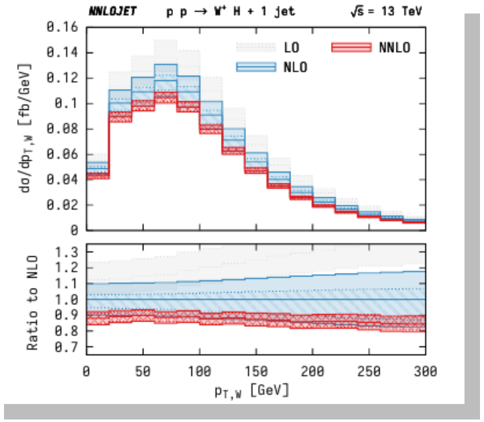




VH Production

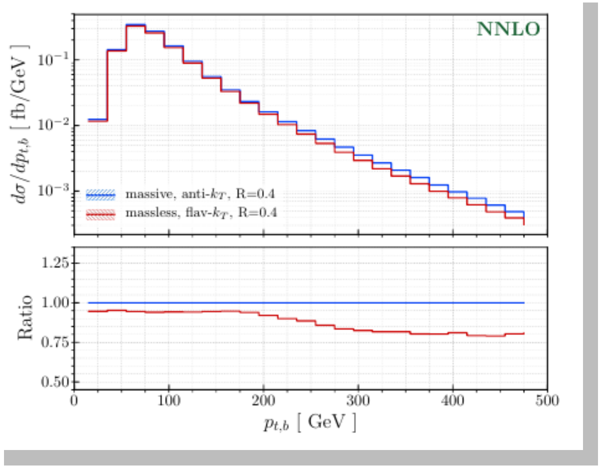
- VH+j production computed to NNLO QCD [Gauld et al, '22]
  - Inclusive production in *WH+j:* NNLO corrections ~ percent and constant across distributions
  - Inclusive production in *ZH+j:* shape distortion from gluon-induced heavy quark loops.
  - These increase the inclusive NNLO cross section by ~ 15%.
  - Larger corrections in exclusive production.





VH Production

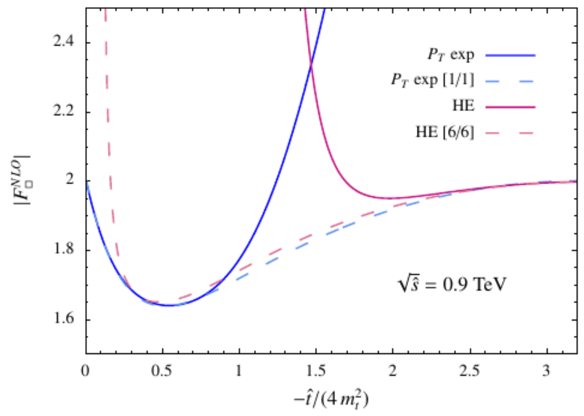
- $H \to b\bar{b}$ decay first observed in VH production.
- NNLO results for $VH(\to b\bar{b})$ employed flavour-kT algorithm. [Banfi, Salam, Zanderighi '07]
- Significant effects from jet algorithm:
  - $H \to b\bar{b}$ with massive b-quarks & anti-kT vs. $H \to b\bar{b}$ massless with flavor kT

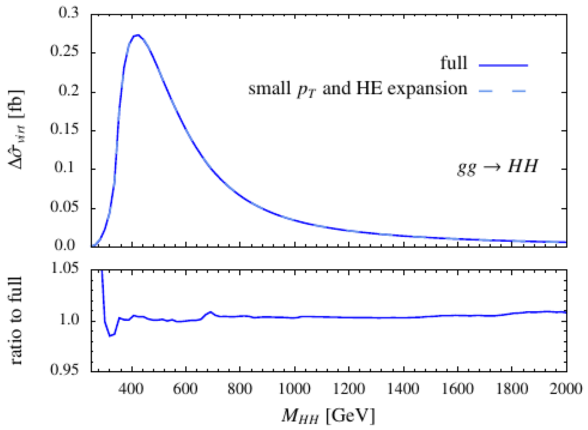


[Behring et al, '22]

- A natural testing-ground for new generation of flavor-sensitive jet algorithms?

HH/ZH Expansions





Bellafronte, Degrassi, Giardino, Gröber, Vitti 22

Several 2-loop $2 \to 2$ amplitudes known in expansions that cover the phase-space

Small-p_T / Small-t Bonciani, Degrassi, Giardino, Gröber 18; Davies, Mishima, Schönwald, Steinhauser 23

High-energy Davies, Mishima, Steinhauser, Wellmann 18

+ combining expansions Bellafronte, Degrassi, Giardino, Gröber, Vitti 22

Will be interesting to see if this can eventually be used to produce approximate NNLO (3-loop) results for gluon induced processes

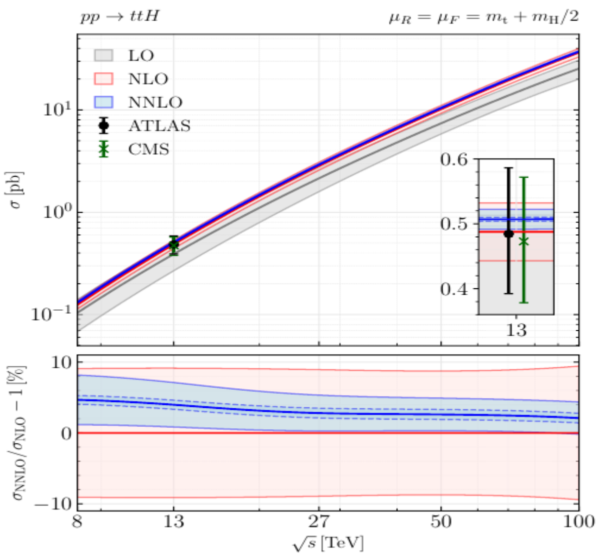
$t\bar{t}H$ production

$ab \to t\bar{t}H + X$, off-diagonal contributions
$(qg,\ qq, qq', q\bar{q}' \quad (q \neq q'))$ obtained @ NNLO
Catani, Fabre, Grazzini, Kallweit 21

$a\bar{a} \to t\bar{t}H + X$, diagonal contributions
$(a = q, \bar{q}, g)$ @NNLO with soft Higgs approx.
Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini 23

Obtained using q_T subtraction method

	$\sqrt{s} = 13$ TeV		$\sqrt{s} = 100$ TeV	
σ [fb]	gg	$q\bar{q}$	gg	$q\bar{q}$
σ_{LO}	261.58	129.47	23055	2323.7
$\Delta\sigma_{\mathrm{NLO,H}}$	88.62	7.826	8205	217.0
$\Delta\sigma_{\mathrm{NLO,H}}\vert_{\mathrm{soft}}$	61.98	7.413	5612	206.0
$\Delta\sigma_{\mathrm{NNLO,H}}\vert_{\mathrm{soft}}$	−2.980(3)	2.622(0)	−239.4(4)	65.45(1)



2-loop amplitudes for diagonal contributions approximated using soft H factorisation formula extended to NNLO
@NLO full gg/qq result ~40/5% larger than soft approx
@NNLO whole correction is 1% of LO

Conclusions

- Remarkable progress from all directions – congratulations!
- No time to mention:
  - Higgs decay
  - EFT / anomalous couplings in Higgs sector
  - Offshell Higgs
  - ...
- What we have learned tells us what we still don't understand – many interesting things to explore!

Comments & suggestions for LH studies are welcome!

Great to be back at Les Houches!