# Higgs Production at High Transverse Momentum

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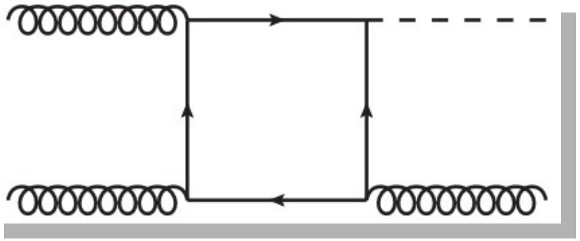
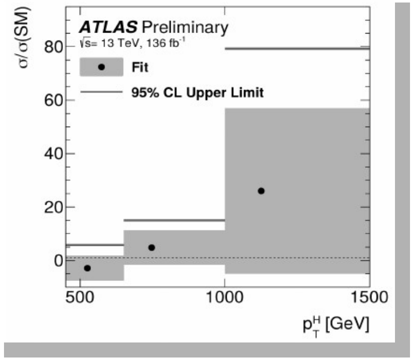
# GLUON FUSION

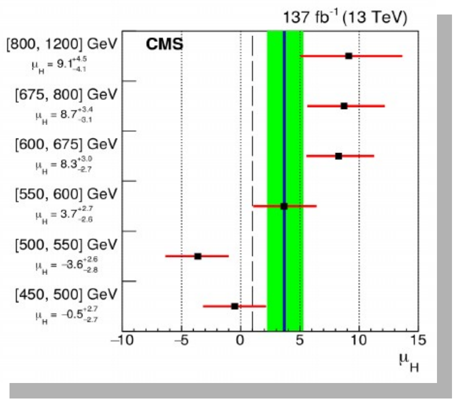
# Motivation

- Study Higgs production at high $p_T \gtrsim 340\ \mathrm{GeV}$ → Explore Higgs in a new kinematic regime.



- Allow us to look inside loop:
  - Probe Higgs couplings to SM quarks;
  - Probe of potential New Physics in loop.

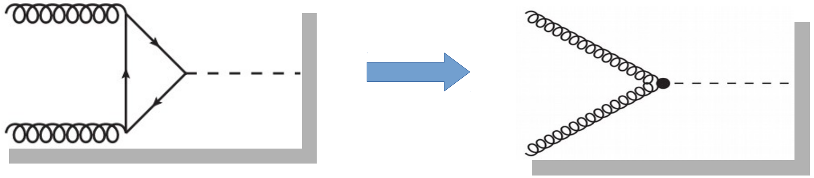


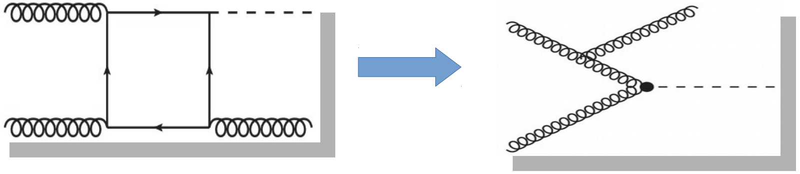




- Studies by ATLAS and CMS.
  [ATL-CONF-2021-010; JHEP 2012 085]
  [Talk by Christina Reissel]
  - Limited by available statistics → looking forward to more data!

# Theoretical Calculations

- Calculations of gluon fusion Higgs production use **H**eavy **E**ffective **F**ield **T**heory: integrate out top loops.





✔ H @ N3LO [Anastasiou *et al.*, '16; Mistlberger, '18]

✔ H+j @ NNLO [Boughezal, Caola, Melnikov, Petriello, Schulze, '13, '15; Chen, Gehrmann, Glover, Jaquier, '15; Boughezal, Focke, Giele, Liu, Petriello, '15]

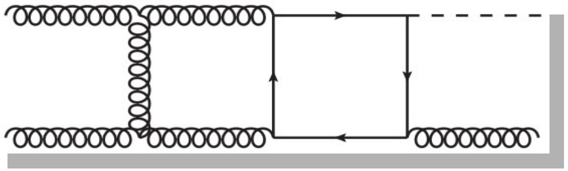
- High-$p_T$: top mass no longer largest scale:
  - HEFT not valid.
  - Full (top) mass effects need to be taken into account.

# Current Status

- LO results for *H+j, H+jj, H+3j* known.

[Ellis, Hinchliffe, Soldate, van der Bij, '88; Baur, Glover, '90; Del Duca, Kilgore, Oleari, Schmidt, Zeppenfeld, '01; Campanario, Kubocz, '13; Greiner *et al.*, '17]

- NLO corrections to *H+j* require two-loop massive amplitudes:



→ **Extremely challenging!**

  - Approximate treatments (reweighting, jet merging, ...):

    [Buschmann *et al.*, '14; Maltoni, Vryonidou, Zaro, '14; Hamilton, Nason, Zanderighi, '15; Chen, Cruz-Martinez, Gehrmann, Glover, Jaquier, '16; Frederix, Frixione, Vryonidou,Wiesemann, '16; Neumann, Williams, '17; Neumann, '18]

  - Progress towards exact analytic amplitudes.

    [Bonciani *et al.*, '16; Frellesvig, Hidding, Maestri, Moriello, Salvator,i '20]

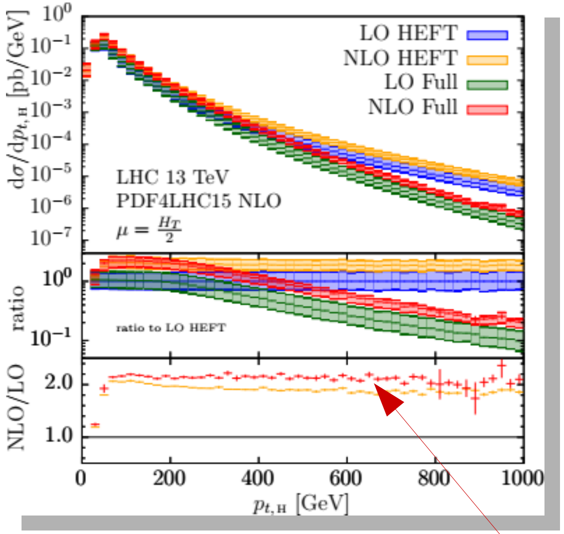
  - Analytic results using $p_{T,H} \gg m_t, m_H$ [Kudashkin, Melnikov, Wever, '17 + Lindert, '18]

  - Exact numerical results. [Jones, Kerner, Luisoni, '18]

# $H$+$j$: Results at NLO

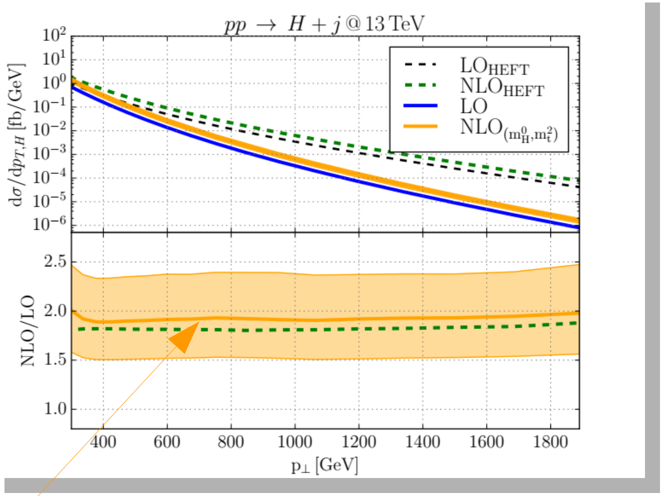
## Exact results

[Jones, Kerner, Luisoni, '18]




## Approximation $p_{T,H} \gg m_t, m_H$

[Kudashkin, Lindert, Melnikov, Wever, '18]

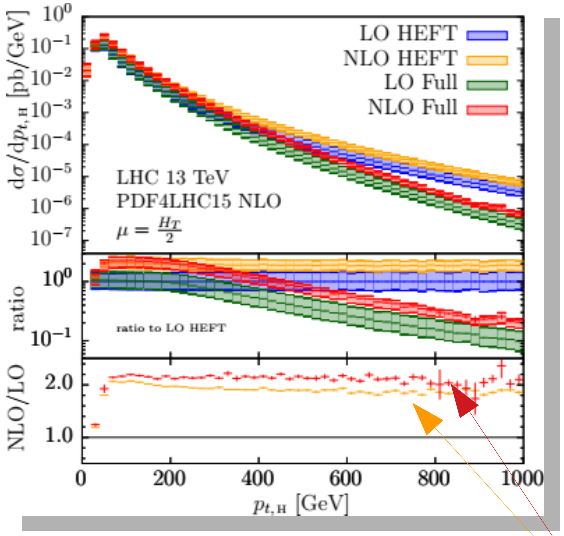



1. K-factors from exact and approximate results show similar behavior
   → important validation!

# $H$+$j$: Results at NLO

## Exact results

[Jones, Kerner, Luisoni, '18]

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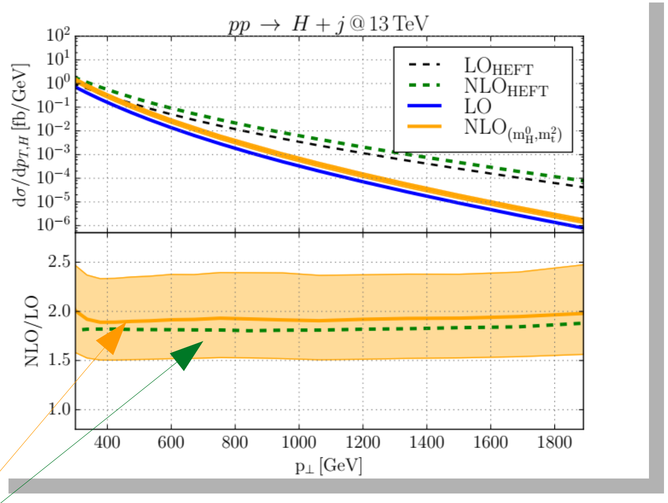
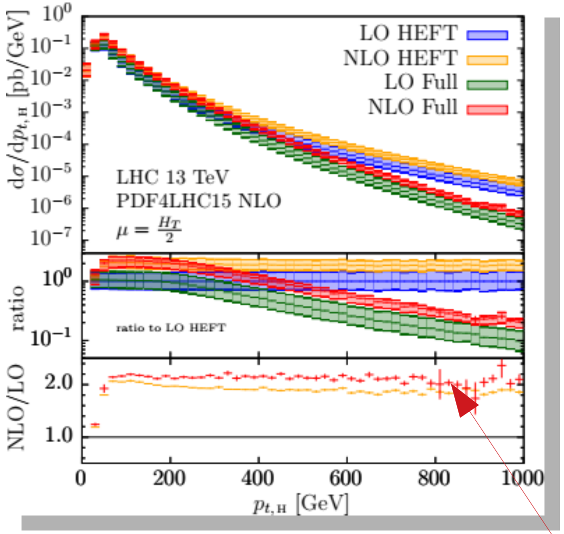



2. K-factors slightly larger than k-factors using HEFT, but quite flat in both cases!

# $H$+$j$: Results at NLO

## Exact results

[Jones, Kerner, Luisoni, '18]

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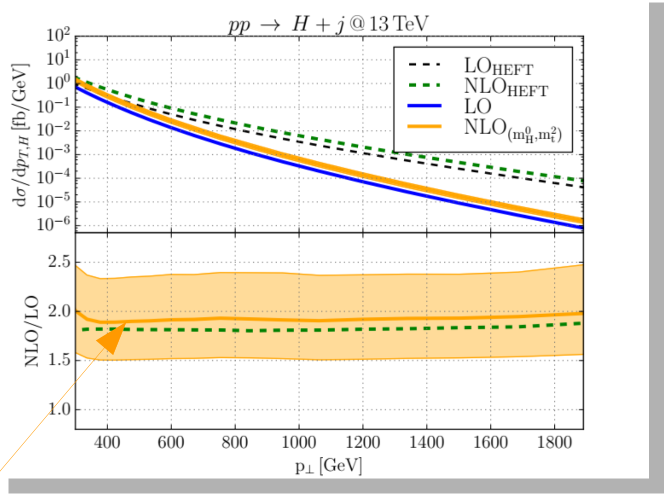
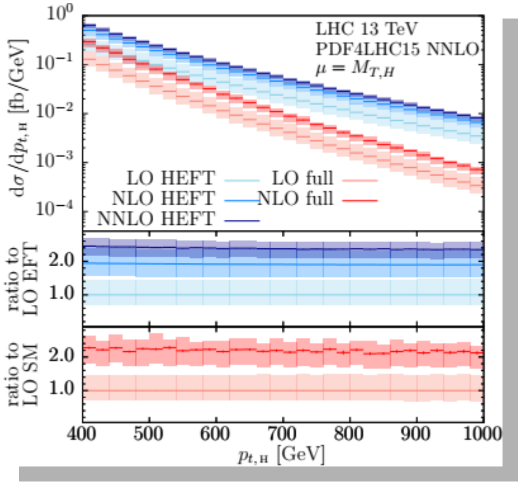



3. Corrections are large (k ≈ 2) and scale uncertainty large (~ 20%)

# $H+j$: Beyond NLO

- Increased precision and reduced theoretical uncertainty: combine HEFT NNLO results with exact NLO results.




[Becker *et al.*, LHCHXSWG note, '20]

- Flat k-factors: NLO and NNLO corrections in HEFT and exact NLO corrections don't alter shape of distribution.
- "Born-improved": Mass effects at NNLO accounted for by reweighting HEFT results using exact results.

[Chen, Gehrmann, Glover, Jaquier '15]

$$\Sigma(p_{T,\mathrm{cut}}) = \int_{p_T^{\mathrm{cut}}}^{\infty} \frac{d\sigma}{dp'_T} dp'_T$$

(Mass effects at LO)

$$\Sigma^{\mathrm{HEFT\ imp.(0),NNLO}}(p_T^{\mathrm{cut}}) = \frac{\Sigma^{\mathrm{exact,\ LO}}(p_T^{\mathrm{cut}})}{\Sigma^{\mathrm{HEFT,\ LO}}(p_T^{\mathrm{cut}})} \Sigma^{\mathrm{HEFT,\ NNLO}}(p_T^{\mathrm{cut}})$$

$$= \frac{\Sigma^{\mathrm{HEFT,\ NNLO}}(p_T^{\mathrm{cut}})}{\Sigma^{\mathrm{HEFT,\ LO}}(p_T^{\mathrm{cut}})} \Sigma^{\mathrm{exact,\ LO}}(p_T^{\mathrm{cut}})$$

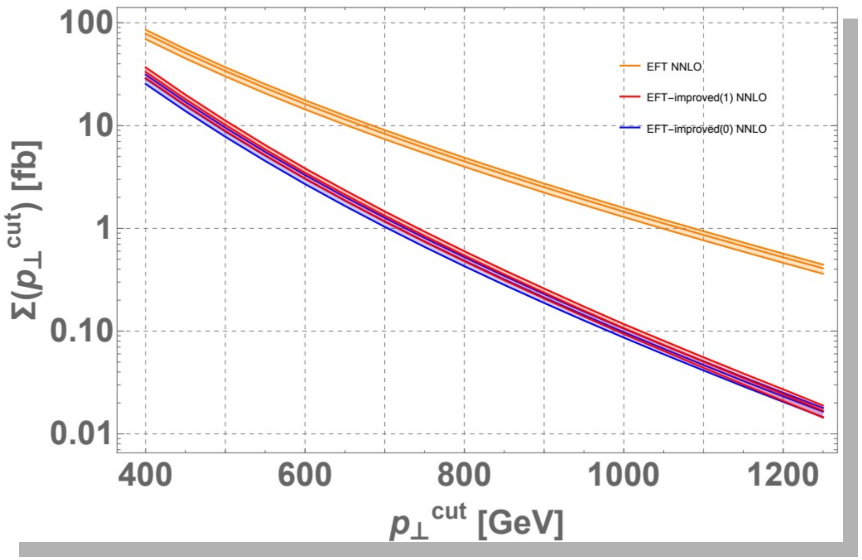
(NNLO corrections in HEFT)

# $H$+$j$: Beyond NLO

- Use exact results at NLO

[Becker *et al.*, LHCHXSWG note, '20]

$$\Sigma^{\text{HEFT imp.(1),NNLO}}(p_T^{\text{cut}}) = \frac{\Sigma^{\text{exact, NLO}}(p_T^{\text{cut}})}{\Sigma^{\text{HEFT, NLO}}(p_T^{\text{cut}})} \Sigma^{\text{HEFT, NNLO}}(p_T^{\text{cut}})$$



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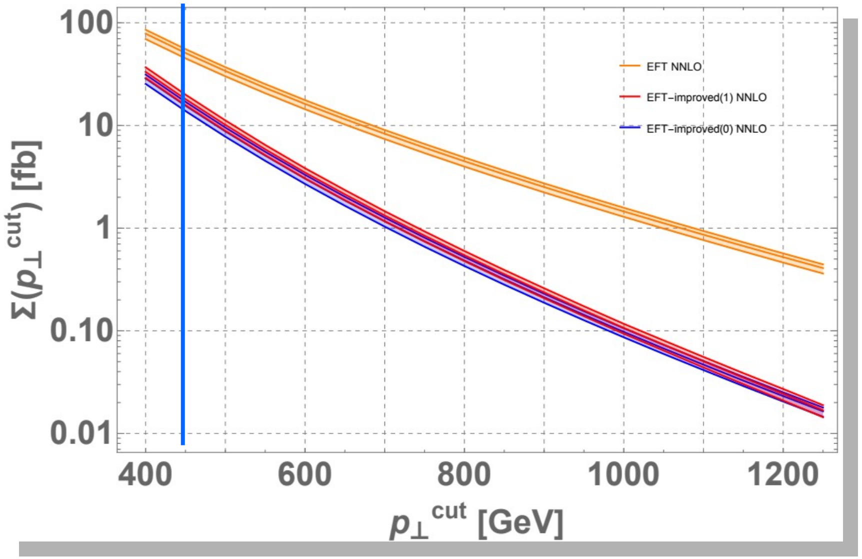


$$p_T^{\text{cut}} = 450 \text{ GeV}:$$

$$\Sigma^{\text{exact, LO}} = 6.5^{+45\%}_{-29\%} \text{ fb} \qquad \Sigma^{\text{exact, NLO}} = 14.4^{+15\%}_{-21\%} \text{ fb}$$

$$\Sigma^{\text{HEFT, NNLO}} = 51^{+9\%}_{-11\%} \text{ fb}$$

Unphysical number

$$\Sigma^{\text{EFT imp.(1), NNLO}} = 18.1^{+11\%}_{-13\%} \text{ fb}$$

# $H$+$j$: Beyond NLO

- Use exact results at NLO

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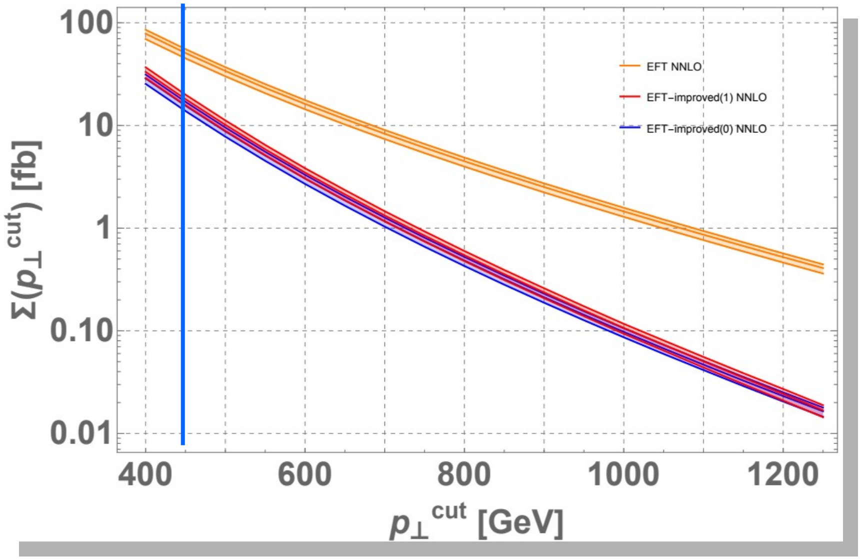


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$$\Sigma^{\text{HEFT, NNLO}} = 51^{+9\%}_{-11\%} \text{ fb}$$

Reduced theoretical uncertainty

$$\Sigma^{\text{EFT imp.(1), NNLO}} = 18.1^{+11\%}_{-13\%} \text{ fb}$$

# Generators

[Becker *et al.*, LHCHXSWG note, '20]

Before matching to PS

| Fixed order level | Total | $p_\perp^{cut} > 400$ GeV | $p_\perp^{cut} > 450$ GeV | $p_\perp^{cut} > 500$ GeV |
|---|---|---|---|---|
| $\texttt{ggh}^{\text{hfact}=104}_{\text{m}_t=\infty}$ | $30.3^{+6.1}_{-4.7}$ | 0.0730 | 0.0507 | 0.0362 |
| HJ $m_t = \infty$, 5 GeV gen. cut | – | 0.0643 | 0.0413 | 0.0278 |
| HJ $m_t = \infty$, 50 GeV gen. cut | – | 0.0644 | 0.0416 | 0.0277 |
| HJ-MiNLO $m_t = \infty$ | $32.1^{+11}_{-4.9}$ | 0.0778 | 0.0509 | 0.0343 |
| HJ-MiNLO $m_t = 171.3$ GeV | $33.8^{+11.4}_{-5.2}$ | 0.0281 | 0.0153 | 0.0089 |

After matching to PS

| Fixed order level | Total | $p_\perp^{cut} > 400$ GeV | $p_\perp^{cut} > 450$ GeV | $p_\perp^{cut} > 500$ GeV |
|---|---|---|---|---|
| $\texttt{ggh}^{\text{hfact}=104}_{\text{m}_t=\infty}$ | $30.3^{+6.1}_{-4.7}$ | $0.0829^{+0.0451}_{-0.0266}$ | $0.0577^{+0.0325}_{-0.019}$ | $0.0408^{+0.0236}_{-0.0137}$ |
| HJ $m_t = \infty$, 5 GeV gen. cut | – | $0.0651^{+0.0156}_{-0.0131}$ | $0.0417^{+0.01}_{-0.0084}$ | $0.0279^{+0.0067}_{-0.0057}$ |
| HJ $m_t = \infty$, 50 GeV gen. cut | – | $0.0651^{+0.0156}_{-0.0131}$ | $0.0418^{+0.01}_{-0.0085}$ | $0.0278^{+0.0066}_{-0.0056}$ |
| HJ-MiNLO $m_t = \infty$ | $32.1^{+11}_{-4.9}$ | $0.0803^{+0.9087}_{-0.0164}$ | $0.0524^{+0.0118}_{-0.0107}$ | $0.0353^{+0.0078}_{-0.0072}$ |
| HJ-MiNLO $m_t = 171.3$ GeV | $33.8^{+11.4}_{-5.2}$ | $0.029^{+0.007}_{-0.006}$ | $0.0161^{+0.0036}_{-0.0033}$ | $0.0091^{+0.0021}_{-0.0018}$ |

As expected, small impact from PS (2%-5%)

# Generators

[Becker *et al.*, LHCHXSWG note, ‘20]

HEFT

Top mass through reweighting

| Fixed order level | Total | $p_\perp^{cut} > 400$ GeV | $p_\perp^{cut} > 450$ GeV | $p_\perp^{cut} > 500$ GeV |
|---|---|---|---|---|
| $\mathtt{ggh}^{\mathrm{hfact}=104}_{\mathrm{m_t}=\infty}$ | $30.3^{+6.1}_{-4.7}$ | 0.0730 | 0.0507 | 0.0362 |
| HJ $m_t = \infty$, 5 GeV gen. cut | – | 0.0643 | 0.0413 | 0.0278 |
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- `MG5_MC@NLO` also includes mass effects:

  exact in Born and real-radiation corrections; through reweighting in virtual matrix elements.

[Alwall *et al.*, ‘14; Frederix, Frixione, Vryonidou, Wiesemann ‘16]

- `MG5_MC@NLO`, `HJ-MiNLO` and approx. NNLO results agree within uncertainties

  → can be used for high-$p_T$ simulations.

| $p_\perp^{cut}$ | $\mathrm{NNLO}^{\mathrm{approximate}}_{\mathrm{quad.unc.}}$ [fb] | HJ-MINLO [fb] | MG5_MC@NLO [fb] |
|---|---|---|---|
| 400 GeV | $33.3^{+10.9\%}_{-12.9\%}$ | $29^{+24\%}_{-21\%}$ | $31.5^{+31\%}_{-25\%}$ |
| 430 GeV | $23.0^{+10.8\%}_{-12.8\%}$ | - | $21.8^{+31\%}_{-25\%}$ |
| 450 GeV | $18.1^{+10.8\%}_{-12.8\%}$ | $16.1^{+22\%}_{-21\%}$ | $17.1^{+31\%}_{-25\%}$ |

# Top Mass Scheme Dependence and EW Corrections

Other source of theoretical uncertainty:

- EW corrections: unknown, expected to be large.
- Scheme and scale choice for top quark mass in loops.
  - Exact NLO results for $m_t = 173.055$ GeV– pole mass. [Jones, Kerner, Luisoni '18]
  - Different scheme choice: $\overline{\text{MS}}$ mass at given scale, .e.g. $\overline{m}_t(\overline{m}_t) \approx 163$ GeV
  - Scheme and scale choice significant for *HH* production: [Baglio *et al.*, '18; Baglio *et al.*, '20]

$$\frac{\mathrm{d}\sigma^{\mathrm{LO}}(gg \to HH)}{\mathrm{d}Q}(Q = 300\ \mathrm{GeV}) = 0.01656^{+62\%}_{-2.4\%}\,\mathrm{fb/GeV}$$

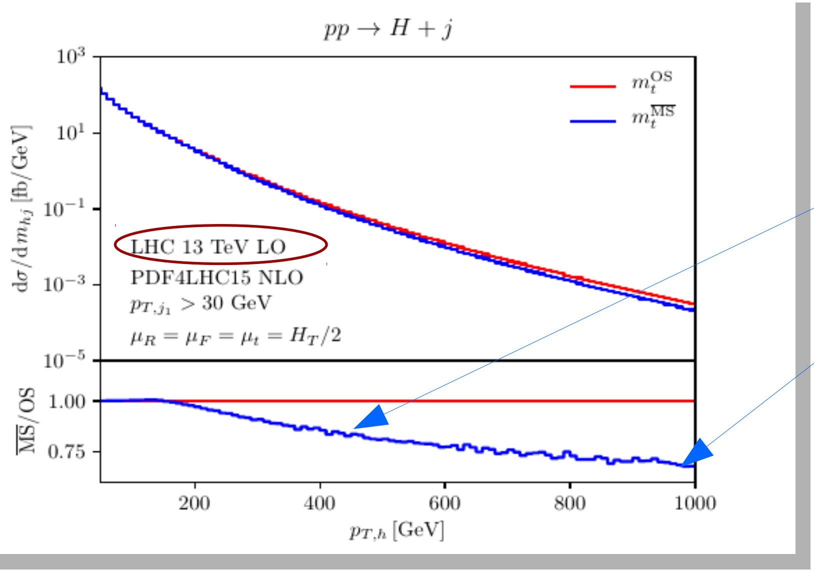
$$\frac{\mathrm{d}\sigma^{\mathrm{NLO}}(gg \to HH)}{\mathrm{d}Q}(Q = 300\ \mathrm{GeV}) = 0.02978^{+6\%}_{-34\%}\,\mathrm{fb/GeV}$$

[Jones, Spira; LH2019 SMWG Report]

  - NLO corrections reduce uncertainty due to scheme and scale choice by factor of ~ 2.
  - Still comparable to scale uncertainty for *HH* production.

# Top Mass Scheme Dependence and EW Corrections

Similar situation for high-pT Higgs: [Jones, Spira; LH2019 SMWG Report]

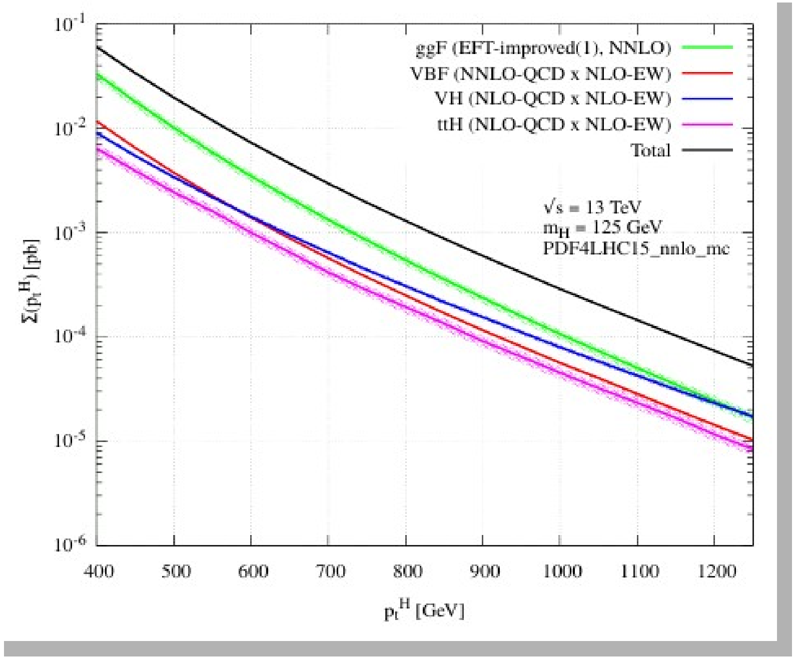


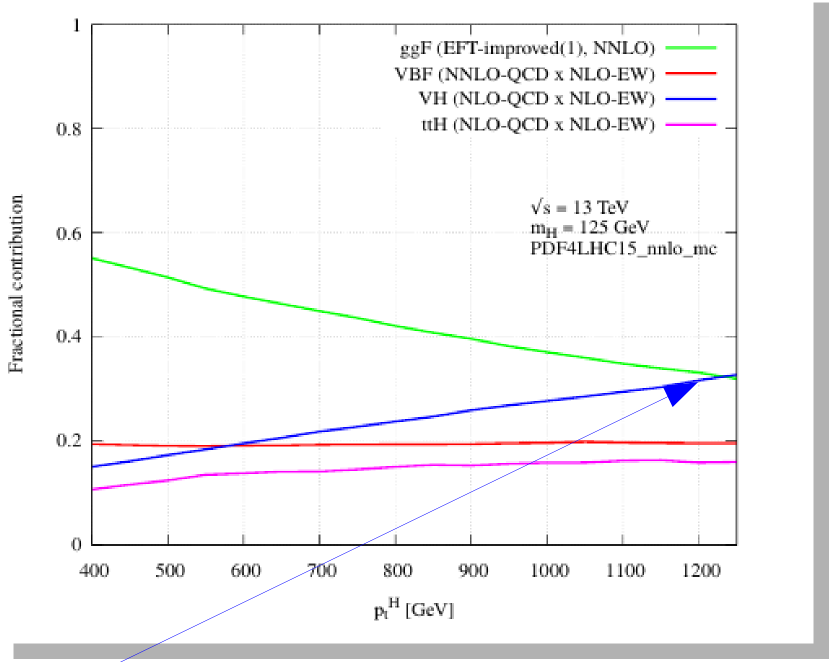

- ~ 15% at 400 GeV – comparable to scale uncertainty.
- ~30% at 1 TeV.

- NLO corrections might reduce this, but still likely to be an important source of theoretical uncertainty.

# OTHER PRODUCTION MODES

# Impact of Different Production Modes

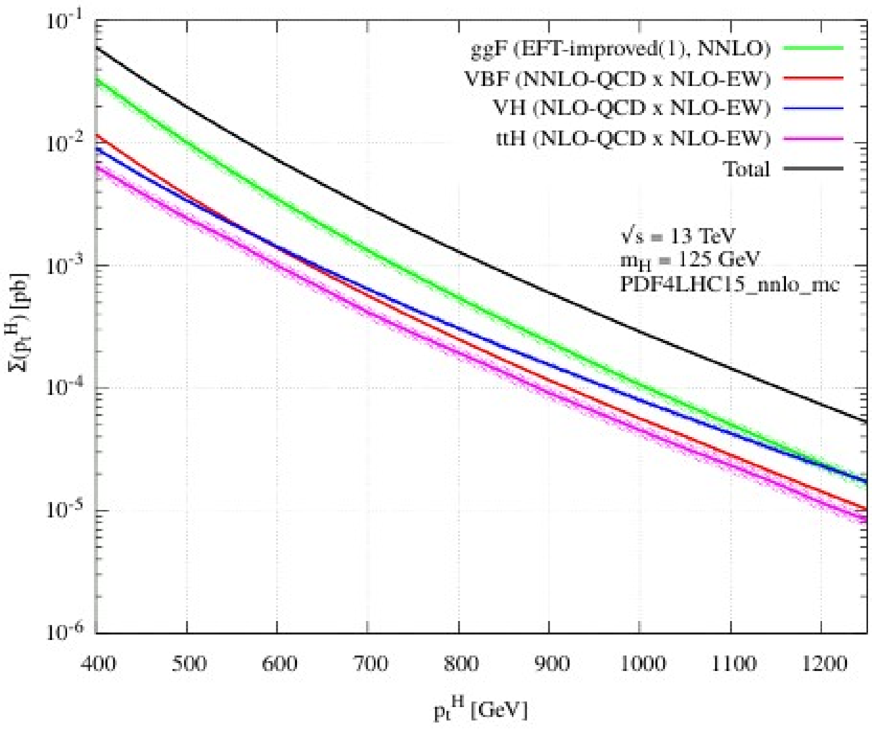



[Becker *et al.*, LHCHXSWG note, ‘20]

- Other production modes, esp. *VH*, become important at pT ~ 1 TeV.

# Theoretical Uncertainties of Different Production Modes




[Becker *et al.*, LHCHXSWG note, '20]

## Theoretical uncertainties:

- VBF: < 1%.
- *VH*: ~ 5%.
  - Further decreased by (known) NNLO corrections.
  - *ZH:* large contribution from gluon fusion; corrections to this unknown but likely sizeable.
  - PS effects may become significant when jet vetoes applied.

  [Astill, Bizoń, Re, Zanderighi, '18]
- *$t\bar{t}H$*:~ 10%-15%
  - NNLO corrections unknown.
- EW corrections ~ 20%-30% for *VH* and VBF, ~7%-12% for *$t\bar{t}H$*.

# SUMMARY

# Summary

- Higgs production at high-$p_T$ is important to probe Higgs couplings to quarks and potential BSM effects.
- Dominant contribution from gluon fusion:
  - NLO results with exact top mass dependence available → k-factor of ~2.
  - Combined with NNLO results in HEFT → scale uncertainty ~ 10%.
  - Generators available including mass effects at higher orders, allowing for reliable event simulations.
  - Other important sources of error: EW corrections, top mass scheme and scale choice.
- Other production modes important, especially *VH* at $p_T \sim 1$ TeV.
  - Different patterns of radiative corrections.

# THANK YOU FOR YOUR ATTENTION

# BACKUP SLIDES

# ESTIMATING THEORETICAL UNCERTAINTY

Approx. NNLO results:

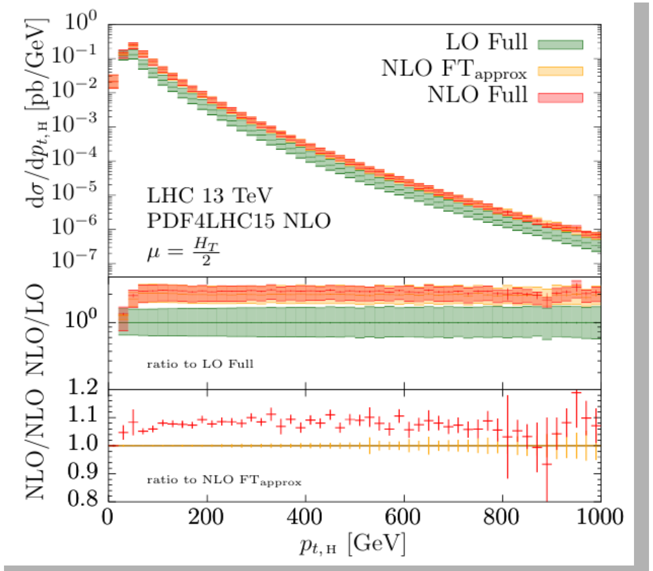
$$\Sigma^{\text{HEFT imp.(1),NNLO}}(p_T^{\text{cut}}) = \frac{\Sigma^{\text{exact, NLO}}(p_T^{\text{cut}})}{\Sigma^{\text{HEFT, NLO}}(p_T^{\text{cut}})} \Sigma^{\text{HEFT, NNLO}}(p_T^{\text{cut}})$$

- 7-point envelope by varying scale uncertainties by factor of 2.
- Combine linearly and quadratically.
- Assume uncertainty due to mass effects in NNLO EFT obtained by rescaling by impact of relative mass corrections at NLO:

$$\delta\text{NNLO}_{m_t} = \frac{\delta\Sigma^{\text{SM,NLO}} - \delta\Sigma^{\text{SM,imp.(0),NLO}}}{\delta\Sigma^{\text{SM,imp.(0),NLO}}} \times \delta\Sigma^{\text{SM,imp.(0),NNLO}}$$

- Uncertainties added quadratically and linearly.

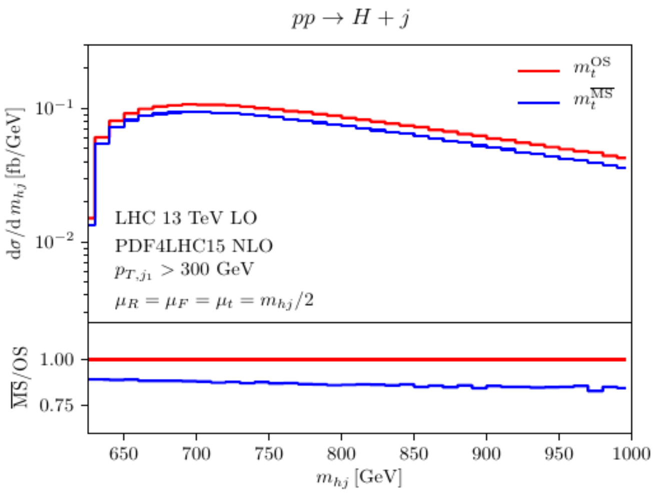
# Additional Plots




[Jones, Kerner, Luisoni, '18]

- NLO results with full top mass dependence vs. results with reweighted virtual amplitudes, exact Born and real amplitudes.

[Maltoni, Vryonidou, Zaro, '14]




- Impact of top mass scheme and scale choice on *Hj* invariant mass.

[Jones, Spira; LH2019 SMWG Report]