Precision Higgs Phenomenology at N^{3}LO

LoopFest XVII

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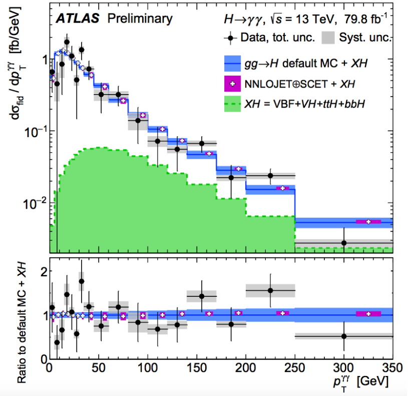
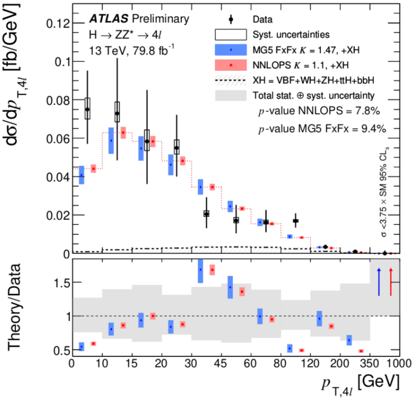
Michigan State University, July 18, 2018

Differential Higgs phenomenology at 80 fb^{-1}

- Precision Higgs measurements is progressing rapidly in the differential sector.

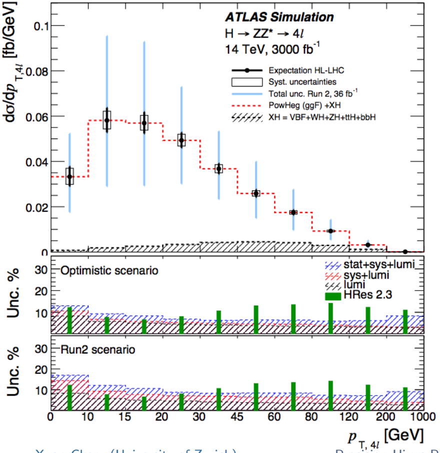


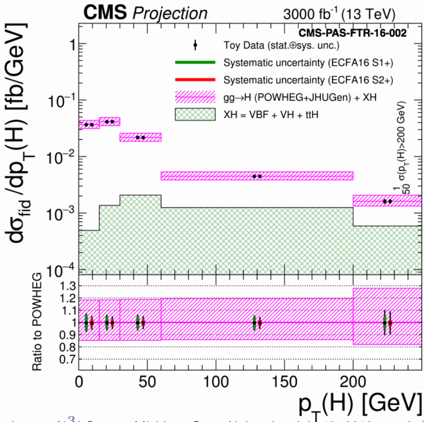


- New discoveries for Higgs production and decay → more differeital results.
- Combined measurements at 40 fb^{-1} improve statistics (about $\pm$ 40% error).

Projection to the future

- LHC run II $\geq$ 300 fb^{-1}
  - p_T^H error within $\pm 15\%$
  - Resolving the difference from NLO+NNLL to NNLO+N^{3}LL.
- HL-LHC $\geq$ 3000 fb^{-1}
  - p_T^H error within $\pm 8\%$ (dominant by sys. & lumi. error)
  - Resolving the theoretical uncertainty at NNLO+N^{3}LL.



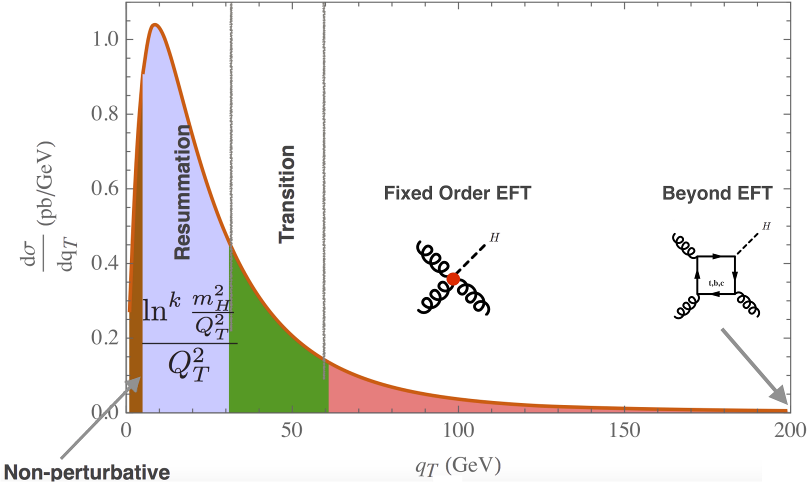


Recent progress of precision SM Higgs phenomenology

- Higgs production from gluon fusion in heavy top EFT
  - Exact total cross section at N^{3}LO. B. Mistlberger [1802.00833]
  - Towards fully differential N^{3}LO (Falko's talk tomorrow) F. Dulat et. al. [1802.00827]
  - Higgs p_T distribution at NNLO+N^{3}LL. XC et. al. [1805.00736]; W. Bizoń et. al. [1805.05916]
- Higgs production from gluon fusion with top mass effect
  - NLO H+J with m_t expansion at large Higgs p_T from MCFM. T. Neumann [1802.02981]
  - NLO H+J with full SM m_t dependence (next talk by Stephen). S. P. Jones et. al. [1802.00349]
  - NLO+NNLL Higgs p_T distribution with m_t expansion and top-bottom interference. F. Caola, J. M. Lindert, K. Melnikov, P. F. Monni, L. Tancredi and C. Wever [1804.07632]
- Higgs pair production from gluon fusion
  - Impressive progress (talks before the coffee break)
  - NNLO HH EFT combined with NLO HH SM. M. Grazzini, G. Heinrich et. al. [1803.02463]
- Other Higgs production channels
  - VBF to H + JJ at NNLO (cross check). J. Cruz-Martinez et. al. [1802.02445]
  - Associated WH production with H$\rightarrow b\bar{b}$ at NNLO (cross check). F. Caola et. al. [1712.06954]
- Many other important progress but not enough space to list.
- This talk focuss on the EFT gg fusion and inclusive Higgs decay.

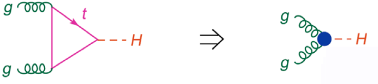
Higgs pT distributions predictions

- For measured Higgs p_T regions ($[0, 350]$GeV), both FO pQCD (EFT or SM) and resummation are involved (GeV):
  small $p_T \sim [0, 40]$ medium $p_T \sim [40, 200]$ large $p_T > 200$

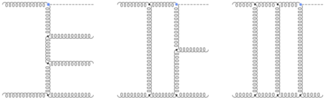


Higgs p_T distributions at medium p_T

- Use effective interaction for ggH vertex in large top mass limit (Higgs production @ LO → only $\delta(p_T)$ contribution):



- The state-of-the-art FO predictions for medium Higgs p_T region are @ NNLOEFT (same framework of H+J @ NNLOEFT no jet algorithm but with small Higgs p_T^{cut})



- One of the first NNLO processes done with three different subtraction schemes
  - pp → H + J Antenna subtraction. XC, Gehrmann, Glover and Jaquier [1408.5325], [1604.04085], [1607.08817]
  - pp → H + J Sector Improved Decomposition subtraction. Boughezal, Caola, Melnikov, Petriello, Schulze [1302.6216], [1504.07922], [1508.02684]
  - pp → H + J N-jettiness subtraction. Boughezal, Focke, Giele, Liu, Petriello [1505.03893]

Higgs + Jet at (N)(N)LO

- Structure of parton level $pp \to H + J$ up to NNLO (subtraction approach):

$$\hat{\sigma}^{H+R}_{LO} = \int_{d\Phi_{H+1}} d\hat{\sigma}^{B,H+R}_{LO}$$

$$\hat{\sigma}^{H+R}_{NLO} = \int_{d\Phi_{H+2}} (d\hat{\sigma}^{R,H+R}_{NLO} - d\hat{\sigma}^{S,H+R}_{NLO}) + \int_{d\Phi_{H+1}} (d\hat{\sigma}^{V,H+R}_{NLO} - d\hat{\sigma}^{T,H+R}_{NLO})$$

$$\hat{\sigma}^{H+R}_{NNLO} = \int_{d\Phi_{H+3}} (d\hat{\sigma}^{RR,H+R}_{NNLO} - d\hat{\sigma}^{S,H+R}_{NNLO}) + \int_{d\Phi_{H+2}} (d\hat{\sigma}^{RV,H+R}_{NNLO} - d\hat{\sigma}^{T,H+R}_{NNLO}) + \int_{d\Phi_{H+1}} (d\hat{\sigma}^{VV,H+R}_{NNLO} - d\hat{\sigma}^{U,H+R}_{NNLO})$$

Higgs + Jet at (N)(N)LO

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$$\hat{\sigma}_{NLO}^{H+R} = \int_{d\Phi_{H+2}} (d\hat{\sigma}_{NLO}^{R,H+R} - d\hat{\sigma}_{NLO}^{S,H+R}) + \int_{d\Phi_{H+1}} (d\hat{\sigma}_{NLO}^{V,H+R} - d\hat{\sigma}_{NLO}^{T,H+R})$$

$$\hat{\sigma}_{NNLO}^{H+R} = \int_{d\Phi_{H+3}} (d\hat{\sigma}_{NNLO}^{RR,H+R} - d\hat{\sigma}_{NNLO}^{S,H+R}) + \int_{d\Phi_{H+2}} (d\hat{\sigma}_{NNLO}^{RV,H+R} - d\hat{\sigma}_{NNLO}^{T,H+R}) + \int_{d\Phi_{H+1}} (d\hat{\sigma}_{NNLO}^{VV,H+R} - d\hat{\sigma}_{NNLO}^{U,H+R})$$

- Consistency requirement:

$$0 = \int_{d\Phi_{H+1}} d\hat{\sigma}_{NLO}^{T,H+R} + \int_{d\Phi_{H+2}} d\hat{\sigma}_{NLO}^{S,H+R}$$

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- Subtraction terms mimic the divergent behaviour of matrix elements
- Each bracket is IR divergent until apply Jet algorithm $H + R \to H + J$
- The construction of red terms depends on different subtraction schemes

Higgs + Jet framework in NNLOJET

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   /    /    / /__/ /_/ / // / _/  / /
  /_/|_/_/|_/____/\____/\___/___/ /_/

********************************************************************************
*                                                                              *
* NNLOJET: A multiprocess parton level event generator at O(alpha_s^3)*
*                                                                              *
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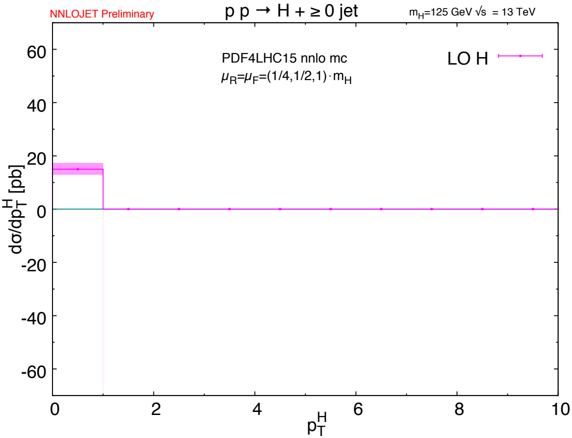
XC, J. Cruz-Martinez, J. Currie, R. Gauld, A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, M. Höhfer, A. Huss, I. Majer, J. Mo, T. Morgan, J. Niehues, J. Pires, D. Walker

- Based on antenna subtraction method at NNLO
- Analytical subtraction terms for process with initial and final colour particles
- Remove Jet algorithm for H + J production at NNLO and apply $p_T^{cut} > 0$ for H
  - P.S. integration is divergent as $p_T^{cut} \to 0$
  - Fully inclusive for Higgs production at $p_T > p_T^{cut}$
  - Challenges due to large dynamic region of scales (large numerical cancellations)

Higgs pT Distributions from F.O.

- $\sigma^H_{LO} \sim \delta(p_T)$

1 min



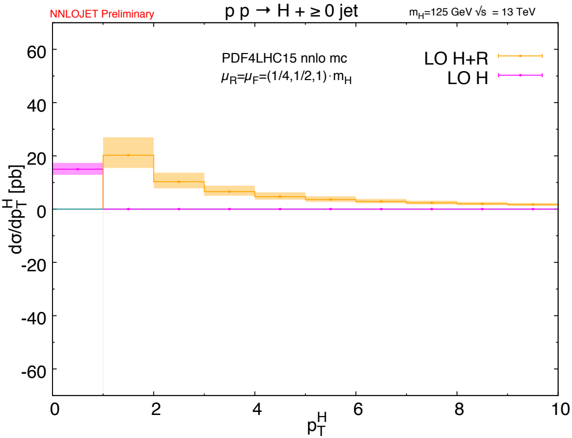
Higgs pT Distributions from F.O.

- $\sigma^H_{LO} \sim \delta(p_T)$

1 min

- $d\sigma^{H+R}_{LO}$ with $p_T^{cut} = 1\text{GeV}$

20 min



Higgs pT Distributions from F.O.

- $\sigma_{LO}^{H} \sim \delta(p_T)$

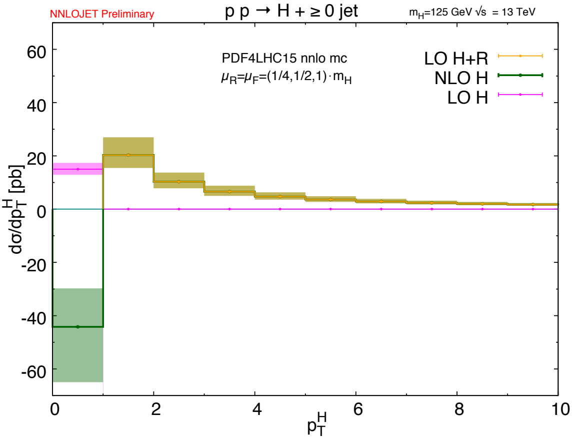
  1 min

- $d\sigma_{LO}^{H+R}$ with $p_T^{cut} = 1\text{GeV}$

  20 min

- d_{NLO}^{H}

  30 min



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1 min

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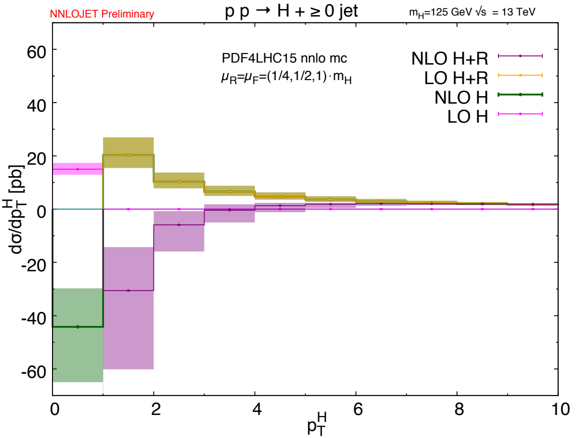
20 min

- $d\sigma^{H}_{NLO}$

30 min

- $d\sigma^{H+R}_{NLO}$ with $p_T^{cut} = 1\text{GeV}$

5 h



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20 min

- $d\sigma^{H}_{NLO}$

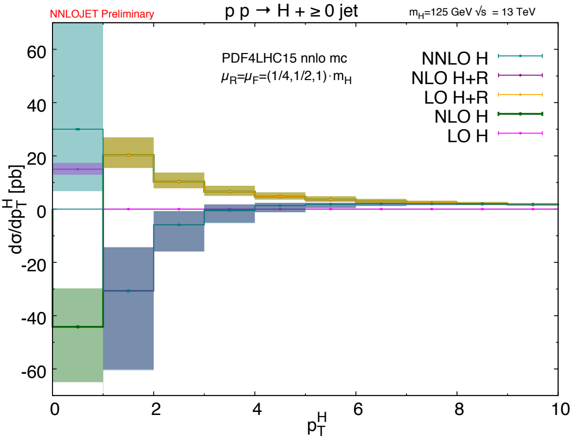
30 min

- $d\sigma^{H+R}_{NLO}$ with $p_T^{cut} = 1\text{GeV}$

5 h

- $d\sigma^{H}_{NNLO}$

100 h



Higgs pT Distributions from F.O.

- $\sigma^H_{LO} \sim \delta(p_T)$

1 min

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20 min

- $d\sigma^H_{NLO}$

30 min

- $d\sigma^{H+R}_{NLO}$ with $p_T^{cut} = 1\text{GeV}$

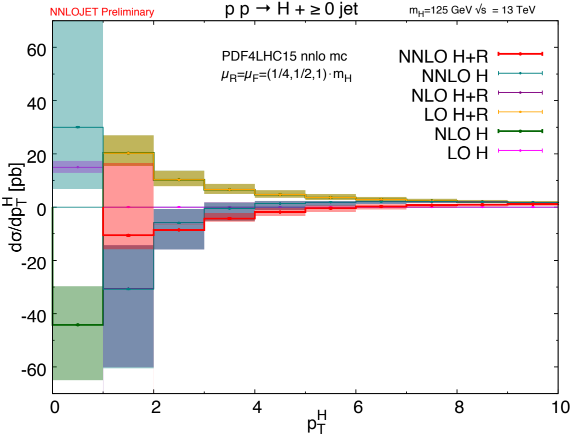
5 h

- $d\sigma^H_{NNLO}$

100 h

- $d\sigma^{H+R}_{NNLO}$ with $p_T^{cut} = 1\text{GeV}$

10,000,000 h



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1 min

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- $d\sigma^{H+R}_{NLO}$ with $p_T^{cut} = 1\text{GeV}$

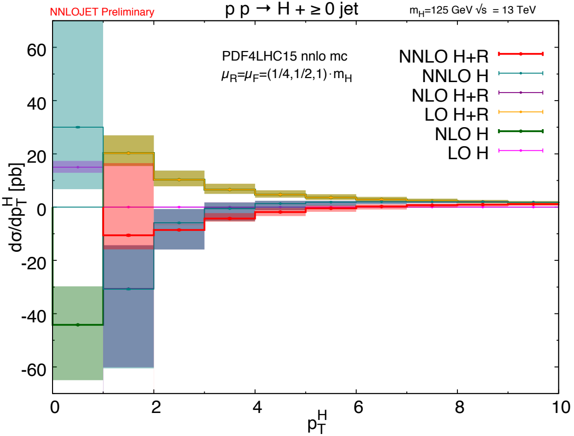
5 h

- $d\sigma^{H}_{NNLO}$

100 h

- $d\sigma^{H+R}_{NNLO}$ with $p_T^{cut} = 1\text{GeV}$

10,000,000 h



- Small p_T^H scale variation explodes
- Compensation at $\delta(p_T^H)$ for finite total X.S.

Higgs pT distributions at small pT

- Higgs production scale is $\mathcal{O}(M_H)$ but the scale at 1 GeV p_T is 10^{-2} different
- Large log terms $\ln^k(M_H^2/p_T^2)/p_T^2$ dominant at small p_T (singular terms $d\sigma^s$)

- Non-singular contribution $d\sigma^n = d\sigma^f \ominus d\sigma^s$ is unphysical
- Resum log divergence in $d\sigma^r$ at small p_T
- Match non-singluar and resummed contribution for physical p_T distributions:

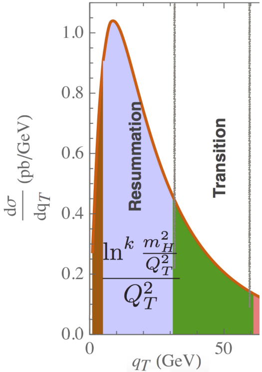
$$d\sigma^f \ominus d\sigma^s \oplus d\sigma^r$$

  - $d\sigma^s$ and $d\sigma^r$ depends on resummation scheme
  - Many choices for $\ominus$, $\oplus$ and transition region

- First focus on $d\sigma^n$, theoretically one would except

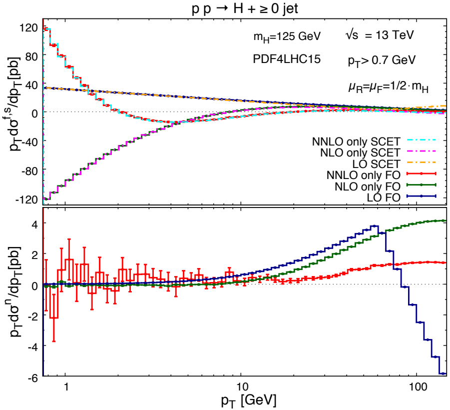
$$d\sigma^f - d\sigma^s \xrightarrow{p_T \to 0} 0$$

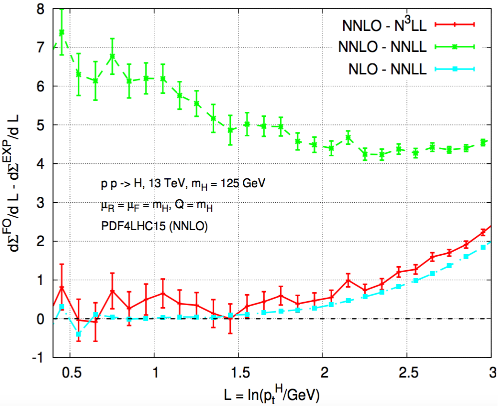
  - P.S. integration of $d\sigma^f$ at small p_T has large numerical cancellations from asympotic tri-soft, quard-collinear etc.
  - Reality needs high numerical stability and careful validation



Small pT singular behaviour validation

- Compare asympotic divergent behaviour from log terms between $d\sigma^f$ and $d\sigma^s$





$d\sigma^s$ from SCET

XC, T. Gehrmann, N. Glover, A. Huss, Y. Li, D. Neill, M. Schulze, I. Stewart, H.X. Zhu [1805.00736]

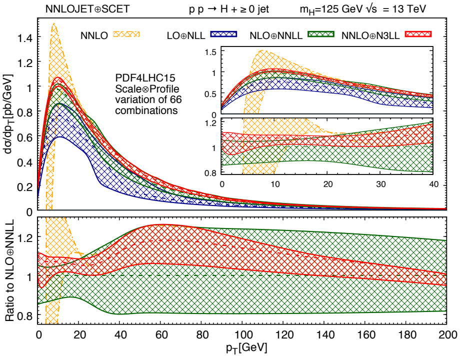
$d\sigma^s$ from RadISH

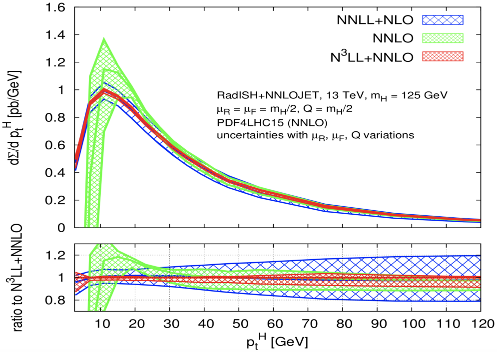
W. Bizoń, XC, A. Gehrmann-De Ridder, T. Gehrmann, N. Glover, A. Huss, P. Monni, E. Re, L. Rottoli, P. Torrielli [1805.05916]

- Calculate $d\sigma^n$ for $p_T \geq 0.7$ GeV with or without p_T reweighting
- Excellent agreement between $d\sigma^f$ and $d\sigma^s$ within numerical error ($\sim 1\%$)

Higgs pT distributions at small and medium p_T

- Matched Higgs p_T spectrum: $d\sigma^{f}_{NNLO} \ominus d\sigma^{s}_{NNLO} \oplus d\sigma^{r}_{N3LL}$





Additive matching with SCET

XC, T. Gehrmann, N. Glover, A. Huss, Y. Li, D. Neill, M. Schulze, I. Stewart, H.X. Zhu [1805.00736]

Multiplicative matching with RadISH

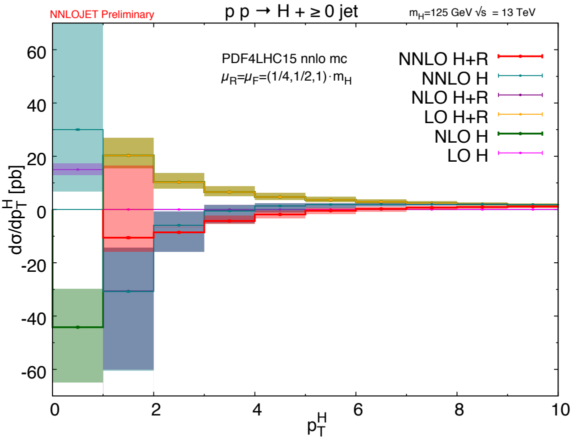
W. Bizoń, XC, A. Gehrmann-De Ridder, T. Gehrmann, N. Glover, A. Huss, P. Monni, E. Re, L. Rottoli, P. Torrielli [1805.05916]

- Smooth transition for NNLO⊕N3LL and NNLO⊗N3LL
- Scale variation reduced to $\sim \pm 10\%$ at NNLO⊕N3LL
- More details for NNLO⊗N3LL in Emanuele's talk tomorrow

Towards fully differential N^3LO

- $d\sigma^{H+R}_{NNLO}$ with $p_T^{cut} = 1\text{GeV}$

10,000,000 h

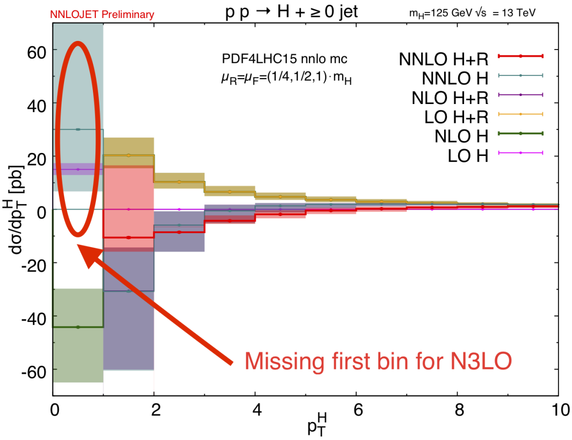


Towards fully differential N^{3}LO

- $d\sigma^{H+R}_{NNLO}$ with $p_T^{cut} = 1$GeV

10,000,000 h

- Compare to N^{3}LO Higgs production, everything above p_T^{cut} is under control
- Only missing piece is the contribution below p_T^{cut}



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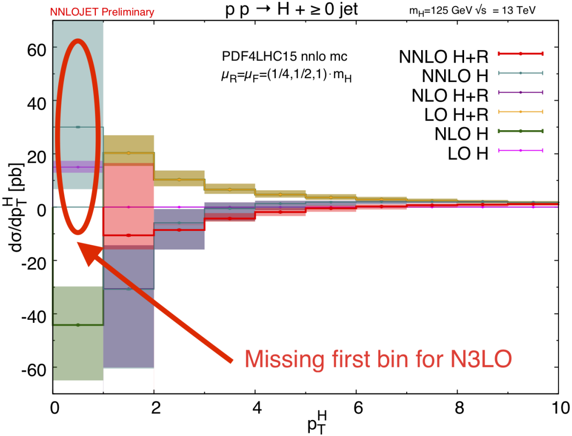

- Transverse momentum subtraction formalism (q_T subtraction) is the ideal tool!
- First established in 2007 for colour singulet procuction at hadron collinders
- Automation in MATRIX and matching to PS (Marius' talk yesterday)
- Extension to $t\bar{t}$ resummation (Massimiliano's talk yesterday)

q_T subtraction at N^{3}LO

XC, L. Cieri, T. Ghermann, N. Glover, A. Huss (in progress)

- q_T subtraction for Higgs production at general F.O. has the following structure:

$$d\sigma^H_{N^nLO} = \mathcal{H}^H_{N^nLO} \otimes d\sigma^H_{LO}\Big|_{\delta(p_T)} + \Big[d\sigma^{H+R}_{N^{n-1}LO} - d\sigma^{H;s}_{N^nLO}\Big]_{p_T > p_T^{cut}}$$

- In principle, $\delta(p_T)$ contains form factor of Higgs and integrated $d\sigma^{H;s}_{N^nLO}$
- Design $d\sigma^{H;s}_{N^nLO} \to \Sigma^H_{N^nLO} \otimes d\sigma^H_{LO}$ that $\delta(p_T)$ has the resummation form:

G. Bozzi, S. Catani et. al. [hep-ph/0508068]; S. Catani and M. Grazzini [hep-ph/0703012]; S. Catani, L. Cieri et. al. [1311.1654]

$$\left(\Sigma^H_{gg\leftarrow a_1a_2}\left(\frac{p_T^2}{M_H^2};\frac{M_H^2}{\hat{s}};\alpha_s\right) + \mathcal{H}^H_{gg\leftarrow a_1a_2}\left(\frac{M_H^2}{\hat{s}};\alpha_s\right)\right) \otimes d\sigma^H_{LO} = \frac{M_H^2}{s}\int \frac{b}{2}db$$

$$\times J_0(bp_T) S_c(M_H,b) \prod_{i=1,2}\int_{x_i}^1 \frac{dz_i}{z_i} f_{a_i/h_i}(z_i,b) \otimes d\hat{\sigma}^{H;(0)}_{gg} \otimes [H^H C_1 C_2]_{gg\leftarrow a_1a_2}$$

$$S_c(M_H,b) = \exp\left\{-\int_{b_0^2/b^2}^{M_H^2} \frac{dq^2}{q^2}\left[A_g(\alpha_s(q^2))\ln\frac{M_H^2}{q^2} + B_g(\alpha_s(q^2))\right]\right\}$$

$$[H^H C_1 C_2]_{gg\leftarrow ab} = H^H_g(\alpha_s)[C_{ga}(z_1;\alpha_s)C_{gb}(z_2;\alpha_s) + G_{ga}(z_1;\alpha_s)G_{gb}(z_2;\alpha_s)]$$

q_T subtraction at N^{3}LO

XC, L. Cieri, T. Ghermann, N. Glover, A. Huss (in progress)

- The factorisation of $\mathcal{H}^H_{N^nLO} \otimes d\sigma^H_{LO}$ depends on resummation scheme choice
- Above formulae is invariant under the following scheme transformation:

$$H^H_g(\alpha_s) \to H^H_g(\alpha_s)[h(\alpha_s)]^{-1}$$
$$A_g(\alpha_s) \to A_g(\alpha_s)$$
$$B_g(\alpha_s) \to B_g(\alpha_s) - \beta(\alpha_s)\frac{d\ln h(\alpha_s)}{d\ln\alpha_s}$$
$$C(G)_{ga}(z;\alpha_s) \to C(G)_{ga}(z;\alpha_s)[h(\alpha_s)]^{1/2}$$

- Above ingredients can be expressed in series expasion of α_s
- Exact formulae from SCET, CSS or hard resummation schemes are transferable
- Collect results from different schemes and transfrom into hard scheme
  - All analytical formulae known for NNLO Higgs production
  - For N^{3}LO Higgs production, we only know some of the ingredients
    $A^{(3)}_g$ →(SCET) T. Becher, M. Neubert [1405.4827]
    $B^{(3)}_g$ → (SCET, CSS) Y. Li, H.X. Zhu [1604.01404]; A.A. Vladimirov [1610.05791]
    $\tilde{H}^{H;(3)}_g = H^{H;(3)}_g - [H^{H;(3)}_g]_{\delta^{p_T}_{(2)}}$ →(CSS) S. Catani, L. Cieri et. al. [1311.1654]

q_T subtraction at N^{3}LO

XC, L. Cieri, T. Ghermann, N. Glover, A. Huss (in progress)

- The currently unknown pieces are inside $\mathcal{H}^{H}_{gg\leftarrow ab}(z;\alpha_s)$ with following structure:

$$\delta_{ga}\delta_{gb}\delta(1-z)[H_g^{H;(3)}]_{\delta^{p_T}_{(2)}} + \delta_{ga}C^{(3)}_{gb}(z) + \delta_{gb}C^{(3)}_{ga}(z) + \left(G^{(1)}_{ga}\otimes G^{(2)}_{gb}\right)(z) + \left(G^{(2)}_{ga}\otimes G^{(1)}_{gb}\right)(z) \rightarrow C_{N3}\delta_{ga}\delta_{gb}\delta(1-z)$$

- Use C_{N3} to approximate the unknown pieces
  - C_{N3} is process dependent but independent of scale choices
  - C_{N3} contains exact unknown pieces propotional to $\delta(1-z)$

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- Use C_{N3} to approximate the unknown pieces
  - C_{N3} is process dependent but independent of scale choices
  - C_{N3} contains exact unknown pieces propotional to $\delta(1-z)$
- C_{N3} can be numerically determined using following strategy (N^{3}LO exclusive):

$$C_{N3}\otimes\sigma^H_{LO} = \sigma^H_{N^3LO} - \tilde{\mathcal{H}}^H_{N^3LO}\otimes\sigma^H_{LO}\Big|_{\delta(p_T)} - \left[d\sigma^{H+R}_{NNLO} - d\sigma^{H;s}_{N^3LO}\right]_{p_T>p_T^{cut}}$$

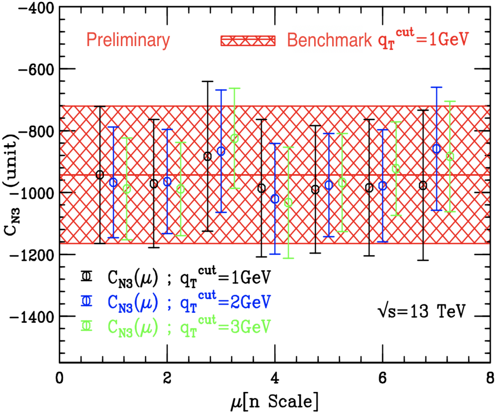
  - Terms in black are available from previous discussions
  - $\sigma^H_{N^3LO}$ is taken from Higgs total cross section at N^{3}LO using ihixs 2

B. Mistlberger [1802.00833]; F. Dulat, A. Lazopoulos and B. Mistlberger [1802.00827]

Extraction of C_{N3}

XC, L. Cieri, T. Ghermann, N. Glover, A. Huss (in progress)

- Numerical abstraction of C_{N3} using newly developed package HN3LO:
  - $\sqrt{s} = 13$TeV, $M_H = 125$ GeV
  - PDF4LHC15,$\alpha_s(M_z) = 0.118$
  - Central scale $\mu_R = \mu_F = M_H/2$
  - With 7-point scale variaitons
  - $p_T^{cut} = 1, 2, 3, 4, 5 \cdots$ GeV
- C_{N3} independent of scale choices
- C_{N3} independent of p_T^{cut} at 1, 2, 3 GeV
- Benchmark value of C_{N3} is recommended at central scale

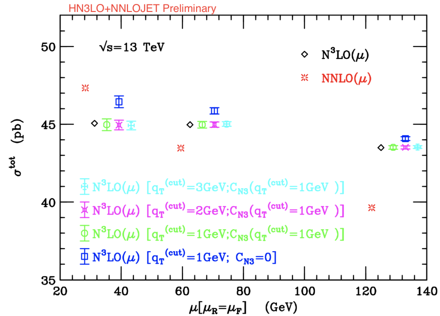


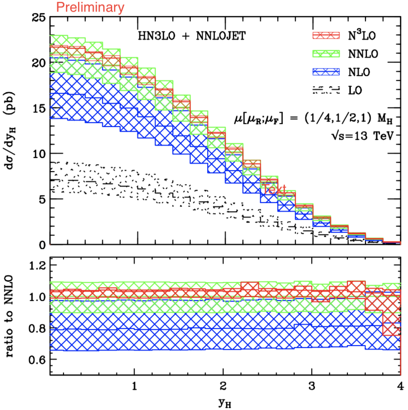
$$C_{N3} = -942 \pm 222$$

N^3LO Higgs total cross section and rapidity distribution

XC, L. Cieri, T. Ghermann, N. Glover, A. Huss (in progress)

- With C_{N3} approximation, the $\sigma^H_{N^3LO}$ and $d\sigma^H_{N^3LO}/dy^H$ distributions are:





- Total XS agree with exact results at level of 0.02%
- y^H distribution take uncertainties from p_T^{cut}, 7-scales and C_{N3} uncertainty
- Uncertainty reduction $> 50\%$, flat k factor (~ 1.04 central) same as total XS
- High rapidity region uncertainty mainly due to limited numerical statistics

Summary and Outlook

- Precision Higgs phenomenology progress rapidly in the past years
  - Current $\int d\mathcal{L} \sim 80$ fb^{-1} results on H differential distributions
  - Theory tools include quark mass effect, EFT, resummation etc. include more and more orders of α_s expansion
- Higgs p_T distribution at small and medium p_T is now at NNLO+N^{3}LL accuracy
  - Logarithmic divergent behaviour at $p_T \to 0$ stablized in NNLOJET for NNLO
  - Challenging resummation at N^{3}LL in SCET and p-space factorisation formalism
  - Different matching procedures result in almost idential NNLO+N^{3}LL distributions
- Higgs production at approximated N^{3}LO with C_{N3}
  - Extend q_T subtraction method to N^{3}LO
  - $p_T \neq 0$ calculated using H+J@NNLO from NNLOJET package
  - $\delta(p_T)$ calculated using HN3LO package
  - Numerical approximation of unknown ingrediants using exact total cross section
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  - Preliminary y^H distribution indicate consistent results
  - More differential distributions at N^{3}LO in the future

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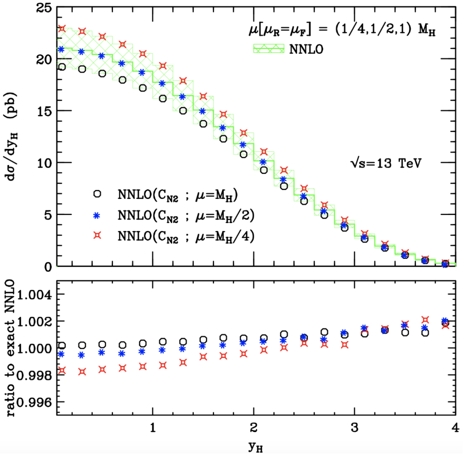
Thank You for Your Attention!

BACK UP SLIDES

Validation of y_H with C_{n2}

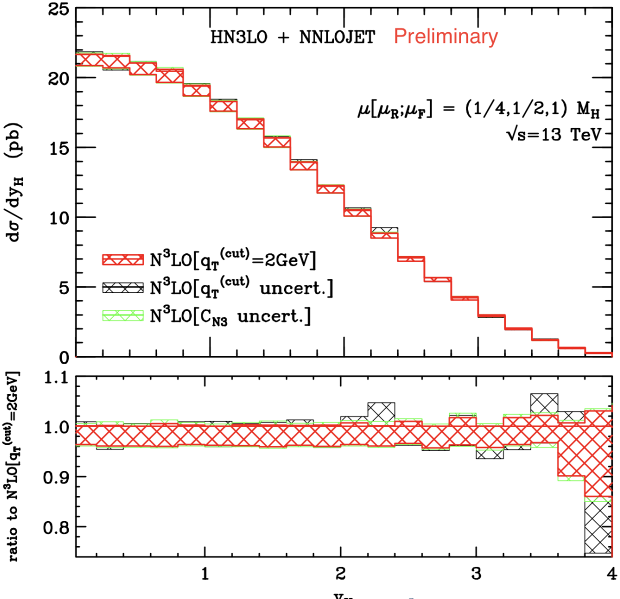
- Without available fully differential N^{3}LO calculations, one could refer to one order lower and test the C_{N2} approximation against exact NNLO results
  - Three scale results devided by exact NNLO distributions
  - Approximation with C_{N2} deviate from exact NNLO by maximum $\sim 0.2\%$ through out $y_H \subset [0, 4]$ for all three scales



$$C_{N2}\delta_{ga}\delta_{gb}\delta(1-z) \leftarrow \delta_{ga}\delta_{gb}\delta(1-z)[H_g^{H;(2)}]_{\delta^{p_T}_{(1)}}$$

$$+\,\delta_{ga}C_{gb}^{(2)}(z) + \delta_{gb}C_{ga}^{(2)}(z) + \left(G_{ga}^{(1)} \otimes G_{gb}^{(1)}\right)(z)$$

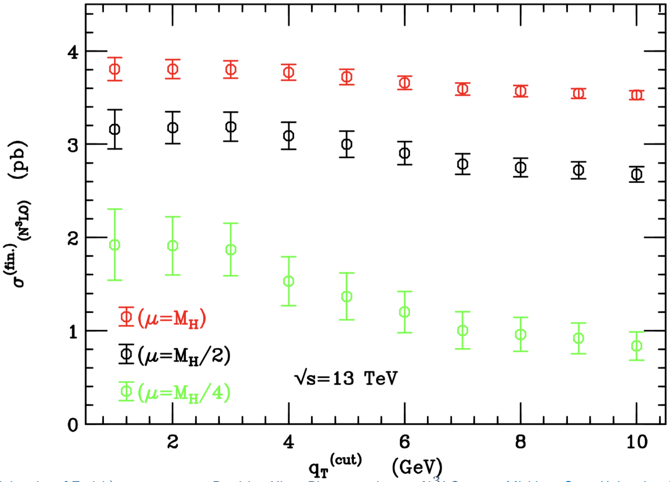
Uncertainties in N^{3}LO Higgs y^H distribution



Higgs pT Distributions at Small pT

- Accumulated finite (non-singular) contribution above p_T^{cut} (=1,2,3 GeV)

$$\int_{p_T>p_T^{cut}} \left[d\sigma^{H+R}_{NNLO} - d\sigma^{H;s}_{N^3LO} \right]$$



Higgs p_T anatomy at NNLO

- Contribution from fixed order, singular and non-singular contributions to Higgs p_T in ggH EFT