Higgs pT distribution at NNLO + N3LL

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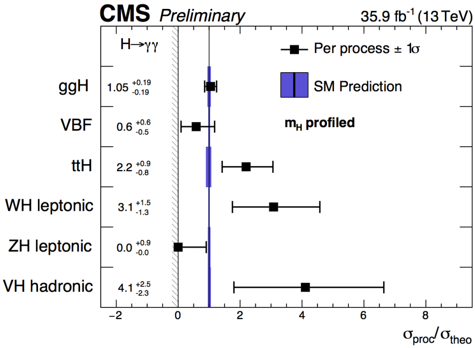
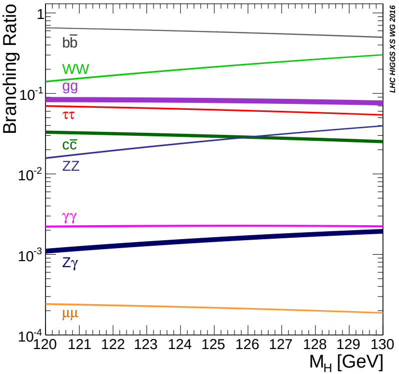
Precision Higgs Measurements

- Outstanding inclusive Higgs boson measurement and predictions.

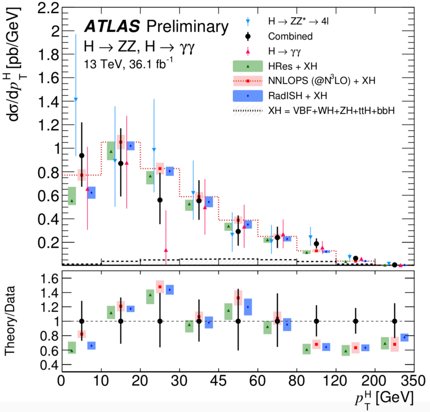


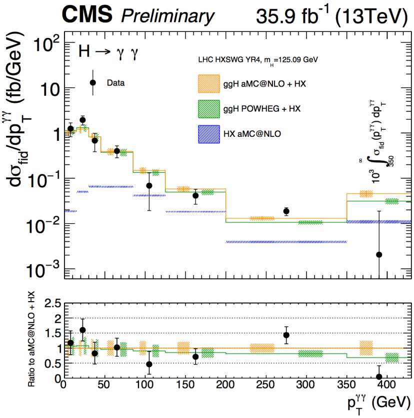


- Higgs production is studied at N3LO for ggF (EFT) C. Anastasiou, B. Mistlberger et. al. and VBF F.A. Dreyer1, A. Karlberg .
- Higgs decay is studied at NLO and some even at NNLO.

Precision Higgs Measurements

- Differential Higgs cross section at LHC
  - Differential corss sections contain detailed information of Higgs properties.
  - $d\sigma/dp_T$ gets more and more interest from both theory and experiment.



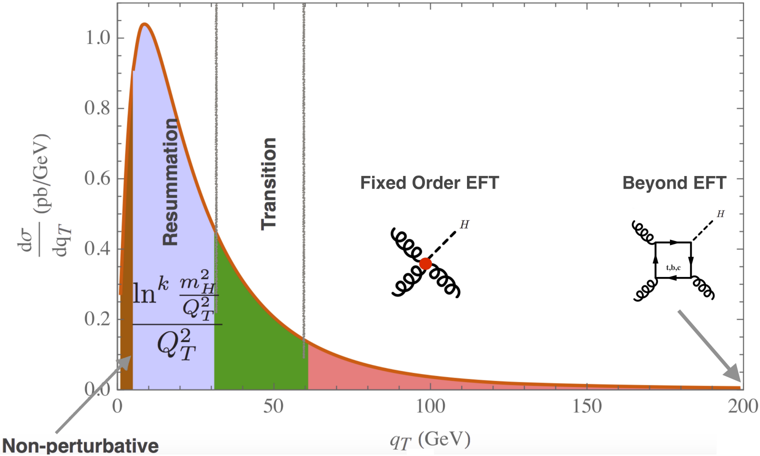


- Full differential predictions for H+J at NNLO (ggF EFT) XC et. al. F. Caola et. al. F. Caola et. al. R. Boughezal et. al. , NLO (ggF SM) S. P. Jones et. al. , H+2J at NNLO (VBF) M. Cacciari et. al.
- NNLO+PS, Resummation, HH production, etc. Sorry for not include everyone!

Higgs pT Distributions Predictions

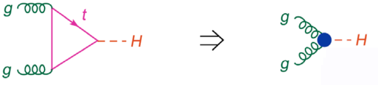
- Focusing on the dominant production channel and inclusive Higgs decay.
- For measured Higgs p_T regions ($[0, 350]$GeV), both FO pQCD (EFT or SM) and resummation are involved (GeV):

  small $p_T \sim [0, 40]$ medium $p_T \sim [40, 200]$ large $p_T > 200$

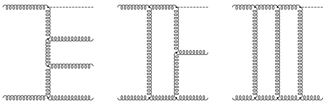


Higgs pT Distributions at Medium pT

- Use effective interaction for ggH vertex in large top mass limit (Example for Higgs production @ LO):



- The state-of-the-art pQCD predictions for medium Higgs p_T region are @ NNLOEFT (same framework of H+J @ NNLOEFT no jet algorithm but with Higgs p_T^{min} 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 $pp \to H + p$ 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

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

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

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

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

- Consistency requirement:

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

$$0 = \int_{d\Phi_{H+3}} d\hat{\sigma}_{NNLO}^{S,H+R} + \int_{d\Phi_{H+2}} d\hat{\sigma}_{NNLO}^{T,H+R} + \int_{d\Phi_{H+1}} d\hat{\sigma}_{NNLO}^{U,H+R}$$

Higgs+jet at (N)(N)LO

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

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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

Antenna Subtraction up to NNLO

- Construct antenna functions using matrix element

$$X_3^0(i,j,k) = \frac{|\mathcal{M}^0_{ijk}|^2}{|\mathcal{M}^0_{IL}|^2}, X_4^0(i,j,k,l) = \frac{|\mathcal{M}^0_{ijkl}|^2}{|\mathcal{M}^0_{IL}|^2}$$

$$X_3^1(i,j,k) = \frac{|\mathcal{M}^1_{ijk}|^2}{|\mathcal{M}^0_{IK}|^2} - X^0_{ijk}\frac{|\mathcal{M}^1_{IK}|^2}{|\mathcal{M}^0_{IK}|^2}$$

- Integrate final state d.o.m of antenna functions

$$\int_{d\Phi_1} X_3^0(i,j,k) = \mathcal{X}_3^0(I,L), \qquad \int_{d\Phi_2} X_4^0(i,j,k,l) = \mathcal{X}_4^0(I,L)$$

Antenna Subtraction up to NNLO

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$$X_3^0(i,j,k) = \frac{|\mathcal{M}^0_{ijk}|^2}{|\mathcal{M}^0_{IL}|^2}, X_4^0(i,j,k,l) = \frac{|\mathcal{M}^0_{ijkl}|^2}{|\mathcal{M}^0_{IL}|^2}$$

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- The NLO antenna subtraction terms for $pp \to H + p$ are

$$d\hat{\sigma}^{S,H+R}_{NLO} \sim X_3^0 d\hat{\sigma}^{B,H+R}_{LO} = X_3^0 |\mathcal{M}^0_{H+3}|^2$$

$$d\hat{\sigma}^{T,H+R}_{NLO} = -\int_{d\Phi_1} d\hat{\sigma}^{S,H+R}_{NLO} = -\mathcal{X}_3^0 |\mathcal{M}^0_{H+3}|^2$$

- Note $d\hat{\sigma}^{S,H+R}_{NLO}$ integrates over $\int_{d\Phi_{H+2}}$ but only contribute to $\int_{d\Phi_{H+1}}$ i.e. Born level kinematics (the reduced ME decides the allocation of weights)

Antenna Subtraction up to NNLO

- The NNLO antenna subtraction terms for $pp \to H$ are

$$d\hat{\sigma}^{S,H}_{NNLO} \sim +X_3^0|\mathcal{M}^0_{H+3}|^2 + X_4^0|\mathcal{M}^0_{H+2}|^2 + X_3^0X_3^0|\mathcal{M}^0_{H+2}|^2$$

$$d\hat{\sigma}^{T,H}_{NNLO} \sim -\mathcal{X}_3^0|\mathcal{M}^0_{H+3}|^2 + X_3^0|\mathcal{M}^1_{H+2}|^2 + X_3^1|\mathcal{M}^0_{H+2}|^2$$

$$d\hat{\sigma}^{U,H}_{NNLO} = -\int_{d\Phi_2} d\hat{\sigma}^{S,H}_{NNLO} - \int_{d\Phi_1} d\hat{\sigma}^{T,H}_{NNLO} \sim \mathcal{X}|\mathcal{M}^{0,1}_{H+2}|^2$$

Antenna Subtraction up to NNLO

- The NNLO antenna subtraction terms for $pp \to H$ are

$$d\hat{\sigma}^{S,H}_{NNLO} \sim + X_3^0|\mathcal{M}^0_{H+3}|^2 + X_4^0|\mathcal{M}^0_{H+2}|^2 + X_3^0 X_3^0|\mathcal{M}^0_{H+2}|^2$$
$$d\hat{\sigma}^{T,H}_{NNLO} \sim - \mathcal{X}_3^0|\mathcal{M}^0_{H+3}|^2 + X_3^0|\mathcal{M}^1_{H+2}|^2 + X_3^1|\mathcal{M}^0_{H+2}|^2$$
$$d\hat{\sigma}^{U,H}_{NNLO} = - \int_{d\Phi_2} d\hat{\sigma}^{S,H}_{NNLO} - \int_{d\Phi_1} d\hat{\sigma}^{T,H}_{NNLO} \sim \mathcal{X}|\mathcal{M}^{0,1}_{H+2}|^2$$

- At LHC, terms proportional to $|\mathcal{M}^{0,1,2}_{H+2}|^2$ have no d.o.m to give Higgs finite p_T
- Compare both ME and antenna subtraction at non-zero p_T one has:

$$d\hat{\sigma}^{H+R}_{NLO} = d\hat{\sigma}^{H}_{NNLO}|_{p_T^H \neq 0}$$

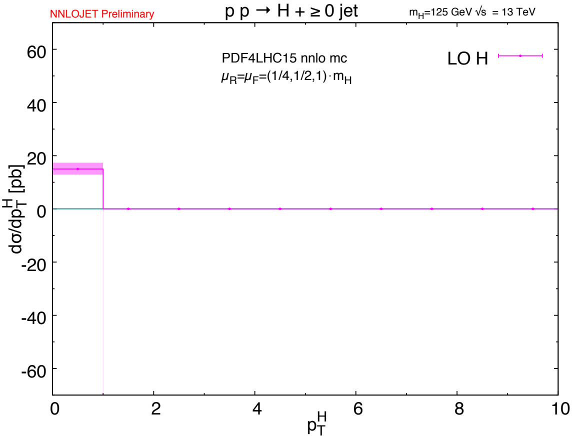
- Same logic holds for higher or lower F.O. that (same idea in ZeLong's talk)

$$d\hat{\sigma}^{H+R}_{LO} = d\hat{\sigma}^{H}_{NLO}|_{p_T^H \neq 0}, \qquad d\hat{\sigma}^{H+R}_{NNLO} = d\hat{\sigma}^{H}_{NNNLO}|_{p_T^H \neq 0}$$

Higgs pT Distributions from F.O.

- $\hat{\sigma}^{H}_{LO} \sim \delta(p^{H}_{T})$

1 min



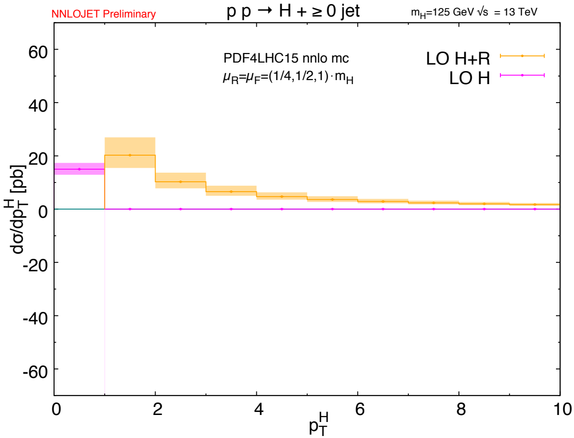
Higgs pT Distributions from F.O.

- $\hat{\sigma}^{H}_{LO} \sim \delta(p^H_T)$

1 min

- $d\hat{\sigma}^{H+R}_{LO}$ with $p^H_T > 1\text{GeV}$

20 min



Higgs pT Distributions from F.O.

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

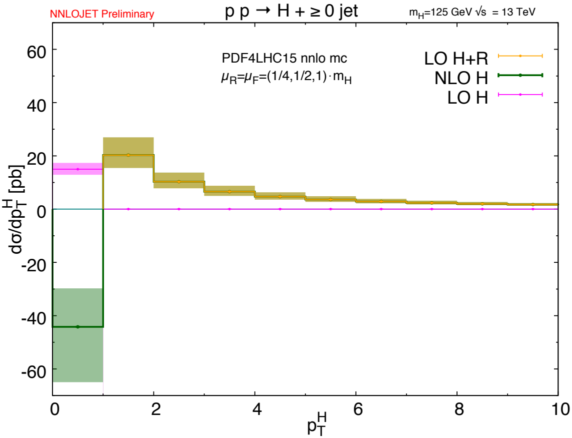
  1 min

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

  20 min

- $d\hat{\sigma}^H_{NLO}$

  30 min



Higgs pT Distributions from F.O.

- $\hat{\sigma}^H_{LO} \sim \delta(p^H_T)$

  1 min

- $d\hat{\sigma}^{H+R}_{LO}$ with $p^H_T > 1\text{GeV}$

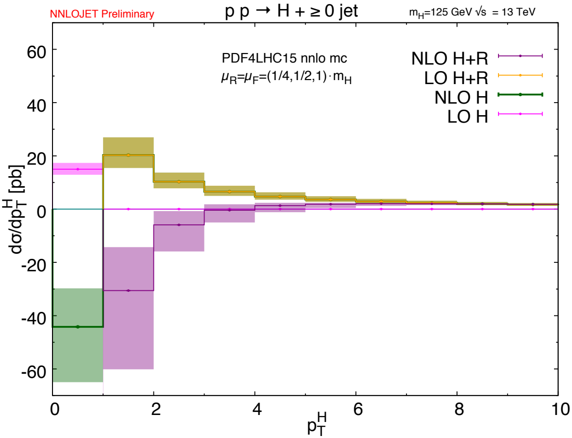
  20 min

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

  30 min

- $d\hat{\sigma}^{H+R}_{NLO}$ with $p^H_T > 1\text{GeV}$

  5 h



Higgs pT Distributions from F.O.

- $\hat{\sigma}^H_{LO} \sim \delta(p^H_T)$

  1 min

- $d\hat{\sigma}^{H+R}_{LO}$ with $p^H_T > 1$GeV

  20 min

- $d\hat{\sigma}^H_{NLO}$

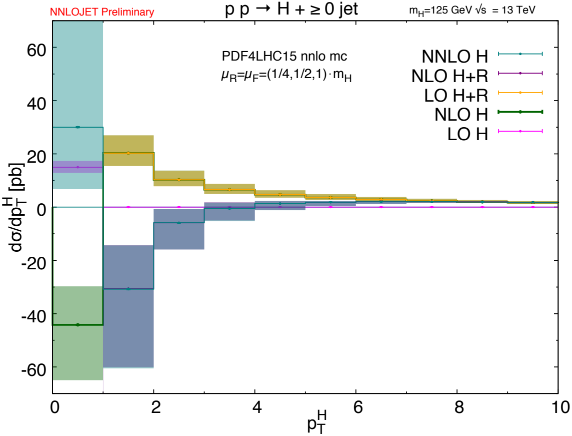
  30 min

- $d\hat{\sigma}^{H+R}_{NLO}$ with $p^H_T > 1$GeV

  5 h

- $d\hat{\sigma}^H_{NNLO}$

  300 h



Higgs pT Distributions from F.O.

- $\hat{\sigma}^{H}_{LO} \sim \delta(p^{H}_{T})$

1 min

- $d\hat{\sigma}^{H+R}_{LO}$ with $p^{H}_{T} > 1\text{GeV}$

20 min

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

30 min

- $d\hat{\sigma}^{H+R}_{NLO}$ with $p^{H}_{T} > 1\text{GeV}$

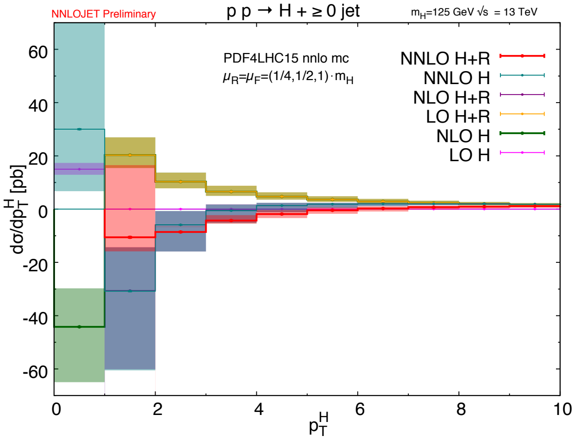
5 h

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

300 h

- $d\hat{\sigma}^{H+R}_{NNLO}$ with $p^{H}_{T} > 1\text{GeV}$

10,000,000 h



Higgs pT Distributions from F.O.

- $\hat{\sigma}^H_{LO} \sim \delta(p^H_T)$

1 min

- $d\hat{\sigma}^{H+R}_{LO}$ with $p^H_T > 1$GeV

20 min

- $d\hat{\sigma}^H_{NLO}$

30 min

- $d\hat{\sigma}^{H+R}_{NLO}$ with $p^H_T > 1$GeV

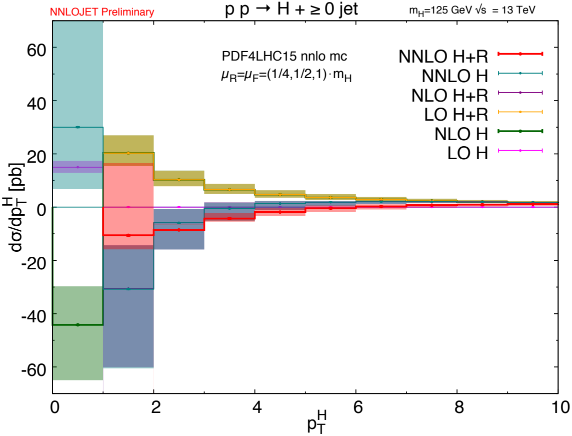
5 h

- $d\hat{\sigma}^H_{NNLO}$

300 h

- $d\hat{\sigma}^{H+R}_{NNLO}$ with $p^H_T > 1$GeV

10,000,000 h



- $d\hat{\sigma}^H_{N3LO}$ at $\delta(p^H_T)$ extract from inclusive X.S.
- $\delta(p^H_T)$ scale variation explodes at high F.O.

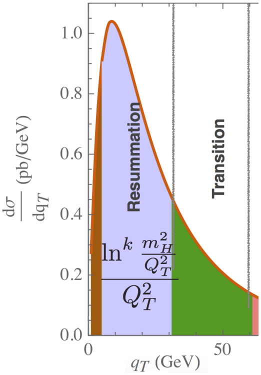
Higgs pT Distributions at Small pT

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

- H+R@NNLO framework is IR divergent as $p_T \to 0$.
- Need to resum log divergence at small Higgs p_T region
- Require matching and merging:

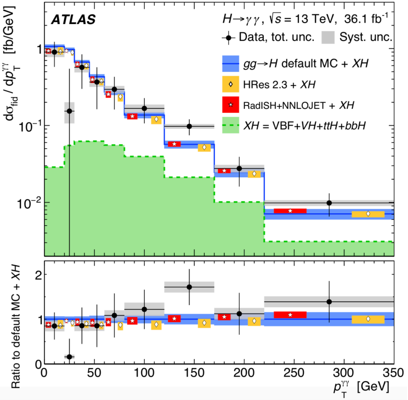
$$d\sigma_{FO} \ominus d\sigma^{CT}_{Resum} \oplus d\sigma_{Resum}$$

  - $d\sigma^{CT}_{Resum}$ and $d\sigma_{Resum}$ depends on resummation scheme
  - Many choices for $\ominus$, $\oplus$ and transition region boundaries
- Recent attempts for matching:
  - NNLO+NNLL: P. Monni, E. Re, et. al. [1604.02191]
  - NNLO+N3LL: W. Bizo, P. Monni, et. al. [1705.09127] also in [1802.04146](RadISH+NNLOJET)

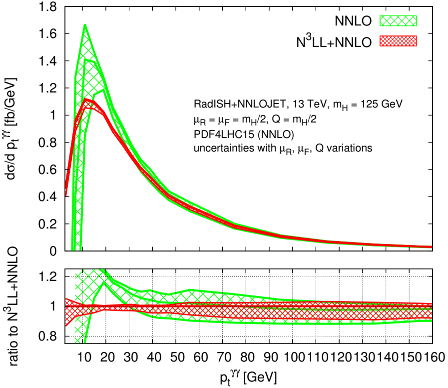


Higgs pT Distributions at Small pT

- Resummed Higgs p_T distributions in $H \to \gamma\gamma$ using RadISH+NNLOJET



[1802.04146]



XC, P. Monni, et. al. [in progress]

  - First bin predictions depend on resummation and inclusive N3LO
    - OK for small bin size. However, current [0,20] GeV region is not trivial (right plot)
  - Detailed study involing photon isolation algorithm not yet available
- New attempts with SCET

Rapidity R.G. Formalism for p_T Resummation

- The small p_T distribution of Higgs boson can be written as

$$\frac{d^2\sigma}{d^2 p_T} = \int dx_a \int dx_b \delta(x_a x_b - \frac{m_H^2}{S}) \sigma_0 \int \frac{d^2\vec{b}}{(2\pi)^2} e^{i\vec{b}\cdot\vec{p}_T} W(x_a, x_b, m_H, \vec{b}, \mu, \nu) \; + \; n.s.$$

- The W kernel can be resummed by choosing RG scale μ and rapidity scale ν to minimize the log dependence and evolving to hard scale $\mathcal{O}(m_H)$ by solving RGE:

$$W(x_a, x_b, m_H, \vec{b}, \mu = b_0/b) = C(m_t, m_H, b_0/b) \exp\left\{ -\int_{b_0^2/b^2}^{m_H^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2} \left[A[\alpha_s(\bar{\mu})] \ln \frac{m_H^2}{\bar{\mu}^2} + B[\alpha_s(\bar{\mu})] \right] \right\}$$

α_s counting	$\ln W(x_a, x_b, m_H, \vec{b}, \mu = b_0/b) \sim$						
α_s	$\ln^2(b^2 m_H^2)$	$\ln(b^2 m_H^2)$	1				$\frac{d\hat{\sigma}^H_{NLO}}{dp_T^H}$
α_s^2	$\ln^3(b^2 m_H^2)$	$\ln^2(b^2 m_H^2)$	$\ln(b^2 m_H^2)$	1			$\frac{d\hat{\sigma}^H_{NNLO}}{dp_T^H}$
α_s^3	$\ln^4(b^2 m_H^2)$	$\ln^3(b^2 m_H^2)$	$\ln^2(b^2 m_H^2)$	$\ln(b^2 m_H^2)$	1		$\frac{d\hat{\sigma}^H_{N^3LO}}{dp_T^H}$
...	...	...	...	...	...	...	...
α_s^k	$\ln^{k+1}(b^2 m_H^2)$	$\ln^k(b^2 m_H^2)$	$\ln^{k-1}(b^2 m_H^2)$	$\ln^{k-2}(b^2 m_H^2)$	...	1	$\frac{d\hat{\sigma}^H_{N^kLO}}{dp_T^H}$
...	...	...	...	...	...	...	...
Resum	LL	NLL	NNLL	N3LL	...	N^{k+1}LL	
A	A_1	A_2	A_3	A_4	...	A_{k+2}	
B		B_1	B_2	B_3	...	B_{k+1}	

- A_3 calculated T. Bechera, M. Neubert. [1007.4005]
- B_3 calculated Y. Li, H.X. Zhu. [1604.01404]

Higgs pT Distributions at Small pT

- Compare large log terms using $d\sigma_{FO} \ominus d\sigma^{CT}_{SCET}$
  XC, Gehrmann, Glover, Huss, Li, Neill, Schulze, Stewart, Zhu [in progress]

- Theoretically one would expect:

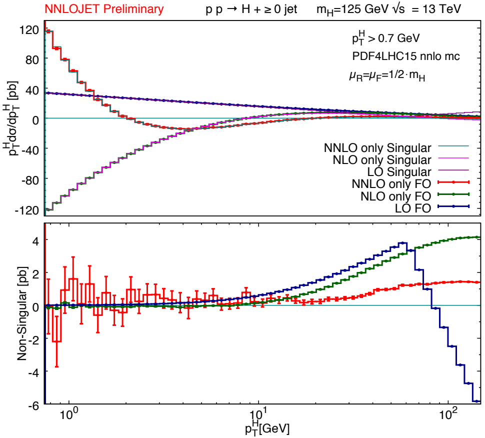
$$d\sigma^{H+R}_{NNLO} - d\sigma^{CT}_{SCET} \xrightarrow{p_T \to 0} 0$$

- Reality needs high numerical stability

- Comparison for $p_T \geq 0.7$ GeV with:
  - $p_T \left[d\sigma^{H+R}_{NNLO}/dp_T - d\sigma^{CT}_{NNLO}/dp_T \right]$
  - with PDF4LHC15 and fixed scale

- Excellent agreement within numerical error ($\sim 1\%$)

- Test the detailed exclusive NNLO behaviour below 15 GeV



Higgs pT Distributions at Small pT

- Matching Higgs p_T spectrum $d\sigma_{NNLO} \ominus d\sigma^{CT}_{SCET}$
  XC, Gehrmann, Glover, Huss, Li, Neill, Schulze, Stewart, Zhu [in progress]

- Linear bin distribution $d\sigma^{H+R}_{NNLO}/dp_T$ also have excellent agreement
- Matching scheme in two folds:
  - Determine the switch off scale

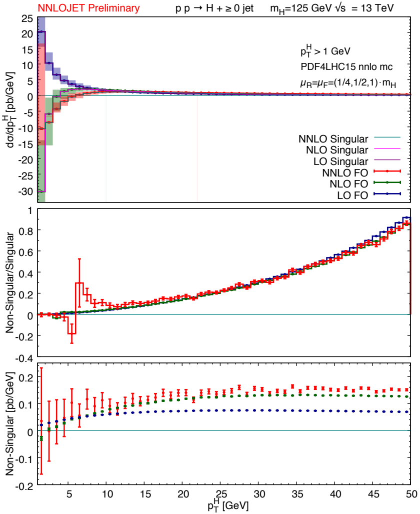
(FO-SCET)/SCET$\sim 85\%$ at 50 GeV

  - Profile function below the switch off scale:D. Neill et. al. [1503.00005]

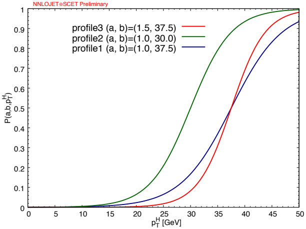
$$P(a,b,p_T) = \frac{1}{2}\left(1+\tanh\left[4a\left(\frac{p_T}{b}-1\right)\right]\right)$$

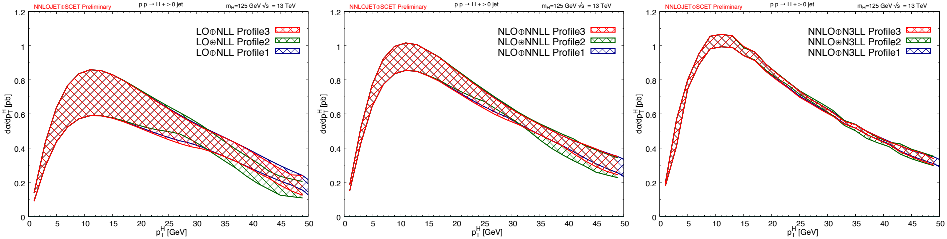
  - Need mannually set a, b:

$$P_1(1, 37.5, p_T)$$
$$P_2(1, 30, p_T)$$
$$P_3(1.5, 37.5, p_T)$$



Higgs pT Distributions at Small pT



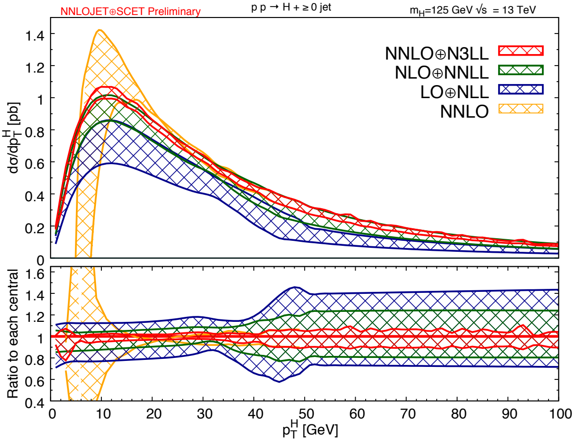


- The distributions become less sensitive to the choice of profile as the order increases, as expected

Higgs pT Distributions at Small pT

- Matched Higgs p_T spectrum $d\sigma_{NNLO} \ominus d\sigma^{CT}_{SCET} \oplus d\sigma_{N3LL}$

- Taking the envelope of the three profiles for resummed distributions (more in future)
- Smooth transition for NNLO⊕N3LL at switch off scale
- Noticeable deviation between NNLO and NNLO⊕N3LL starting from 30 GeV
- Substantial contribution from NNLO⊕N3LL at peak region
- Scale variation reduced by 60% from NLO⊕NNLL to NNLO⊕N3LL



XC, Gehrmann, Glover, Huss, Li, Neill, Schulze, Stewart, Zhu [in progress]

Summary and Outlook

- Precision Higgs measurement is going to focus on p_T distributions
  - ATLAS and CMS analysis for individual as we as combined decay channels
  - Test our understanding of the SM and select candidates of BSM
- Higgs p_T theoretical studies increasingly getting improvements
  - More detailed structures revealed in medium and small p_T region
    - NNLO+N3LL (EFT) accuracy reveal more detailed predictions
  - Large p_T region is sensitive to new physics and Top mass effects
    - H+J@NLO in full theory now available
- Future work
  - Cross check matching NNLOJET with RadISH also at NNLO+N3LL
  - Higgs p_T distribution resumed with decay channel fiducial cuts
  - Higgs large p_T distribution reweighted to NNLO' SM accuracy
  - Fully differential N3LO Higgs production in $q_T \oplus$Antenna Subtraction

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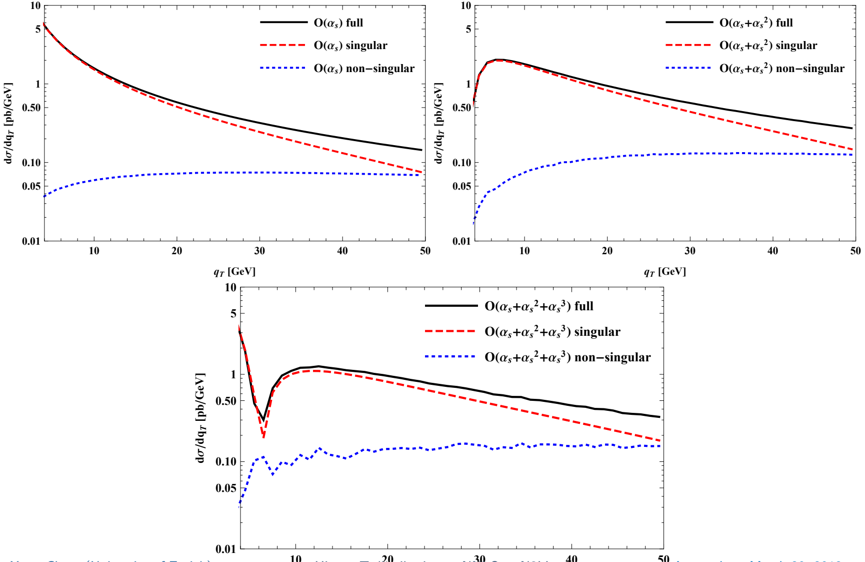
Thank You for Your Attention!

BACK UP SLIDES

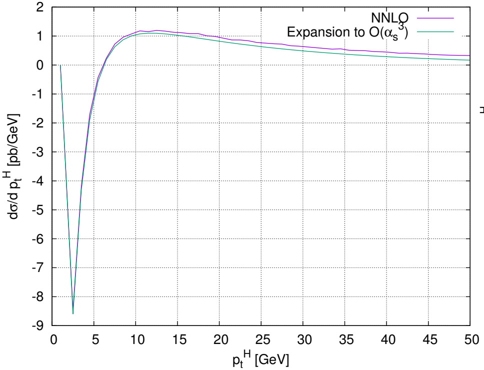
Higgs pT Distributions at Small pT

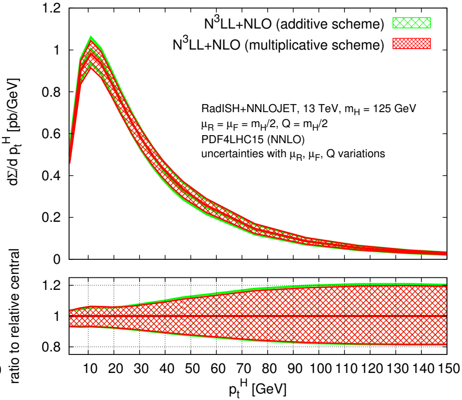
- More about comparing large log terms using $d\sigma_{FO} \ominus d\sigma_{SCET}^{CT}$



Higgs pT Distributions at Small pT

- More about comparison and matching using NNLOJET+RadISH





NNLOJET: $pp \to H$ at $N3LO$

- Towards $pp \to H$ at $N3LO$ using q_T subtraction (fully differential):

$$d\hat{\sigma}^{H}_{N3LO} = \delta^{H}_{N3LO} \otimes d\hat{\sigma}^{H}_{LO} + \left[d\hat{\sigma}^{H+R}_{NNLO} - d\hat{\sigma}^{CT}_{NNLO} \right]_{p_T^H > p_T^{cut}}$$

- $d\hat{\sigma}^{H+R}_{NNLO}$ can be recycled from NNLOJET (removing Jet algorithm)
- $d\hat{\sigma}^{CT}_{NNLO}$ is known for SECT, CSS and momentum-space resummation framework
- δ^{H}_{N3LO} can be factorised as $\mathcal{H} \otimes \mathcal{B} \otimes \mathcal{B} \otimes \mathcal{S}$ using SCET or CSS
    - $\mathcal{H}$ function is known up to 3-loop Anastasiou, Duhr et al
    - $\mathcal{S}$ function at $N3LO$ known Li, Zhu et al
    - Missing $\mathcal{B}$ function (SCET) or $C_n^{(3)}$ coefficient (CSS) at $N3LO$
    - Could numerically back trace $\mathcal{B}$ or $C_n^{(3)}$ at $N3LO$ through inclusive $N3LO$ (similar at NNLO back in 2005 Bozzi, Catani, de Florian, Grazzini)