Higgs production in bottom annihilation: Transverse momentum spectrum at NNLO+NNLL

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Outline

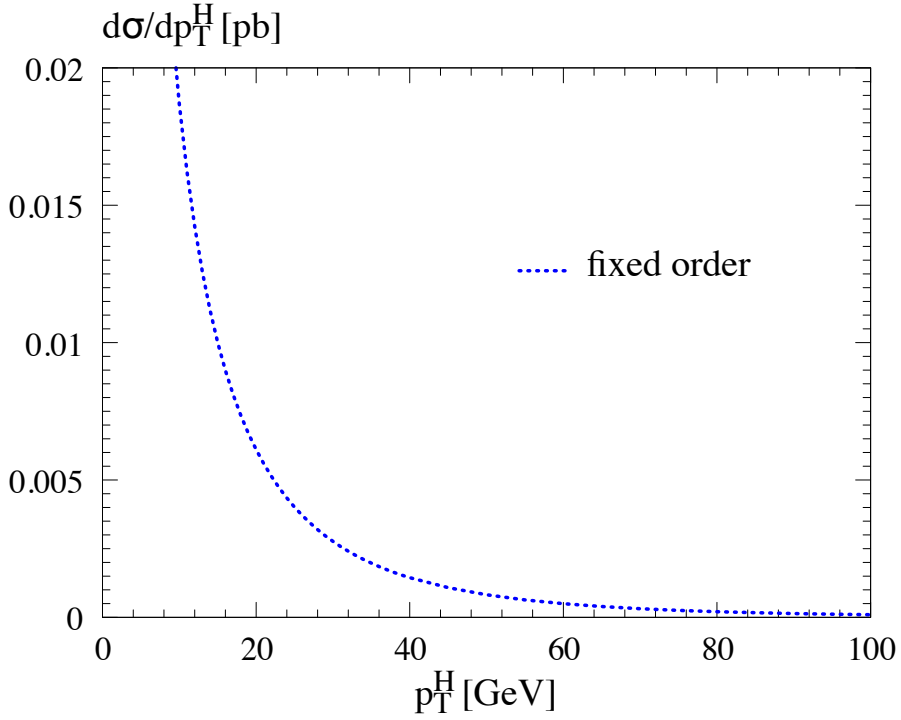
1. Transverse momentum resummation

2. Associated $H(b\bar{b})$ production

3. Resummed p_T distribution in the 5FS

p_T resummation

- production of colorless particle (mass M)
- problem: p_T distribution diverges at $p_T \to 0$



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- production of colorless particle (mass M)
- problem: p_T distribution diverges at $p_T \to 0$
- reason: large logs $\ln p_T^2/M^2$ for $p_T \ll M$

$$\begin{aligned}
\alpha_s: &\quad \ln(p_T^2/M^2),\ \ln^2(p_T^2/M^2) \\
\alpha_s^2: &\quad \ln(p_T^2/M^2),\ \ln^2(p_T^2/M^2),\ \ln^3(p_T^2/M^2),\ \ln^4(p_T^2/M^2) \\
\ldots &
\end{aligned}$$

- solution: all order resummation

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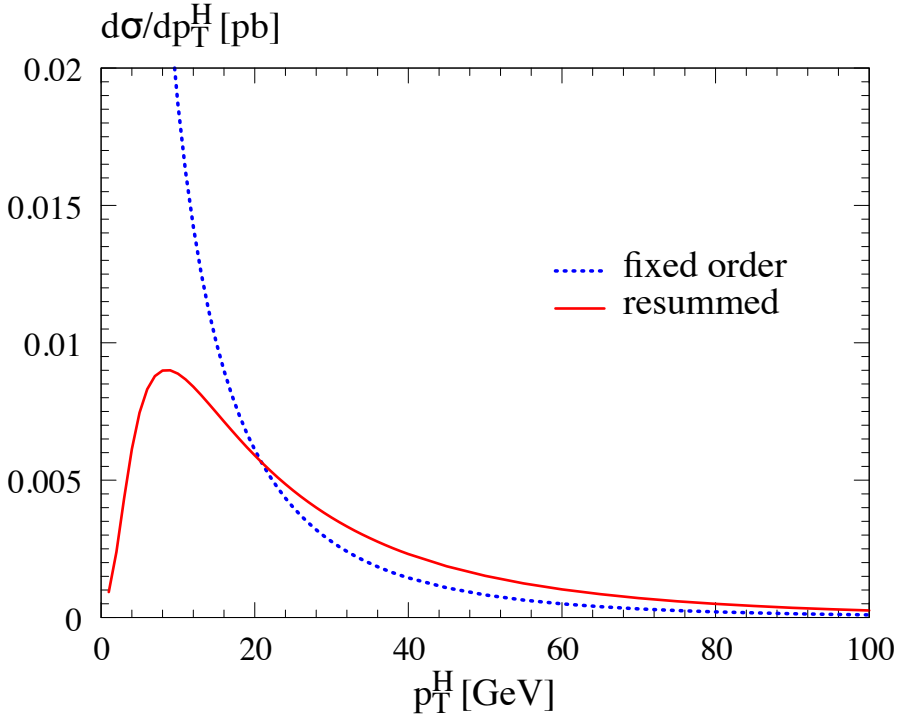

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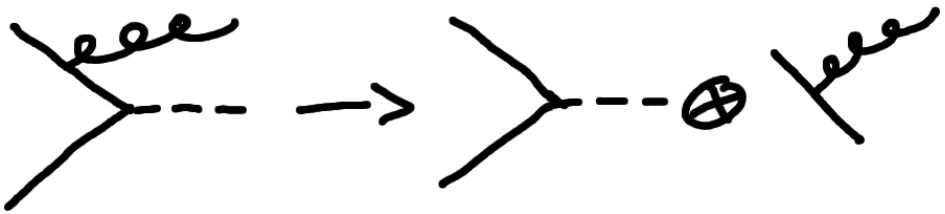
- solution: all order resummation
  - factorization of soft and collinear radiation in matrixelements

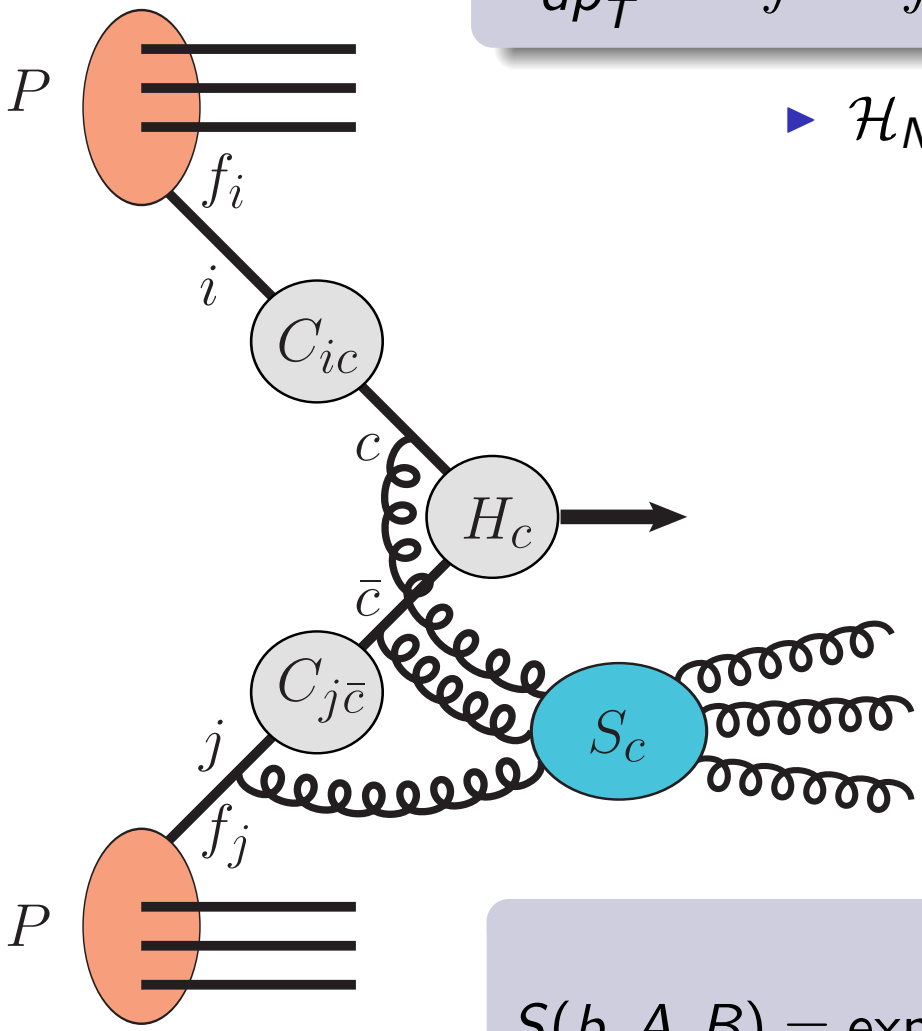


$\to$ allows for resummation

  - done in impact parameter (b) space

$$\frac{d\sigma_N^{(\mathrm{res})}}{dp_T^2} \sim \int dy \int db \, \frac{b}{2} \, J_0(b\, p_T) \, S(b, A, B) \, \mathcal{H}_N \, f_N \, f_N$$

- $\mathcal{H}_N = H_N \, C_N \, C_N$



$$S(b, A, B) = \exp\left\{ -\int_{b_0^2/b^2}^{m_H^2} \frac{dq^2}{q^2} \left[A \ln\left(\frac{m_H^2}{q^2}\right) + B \right] \right\}$$

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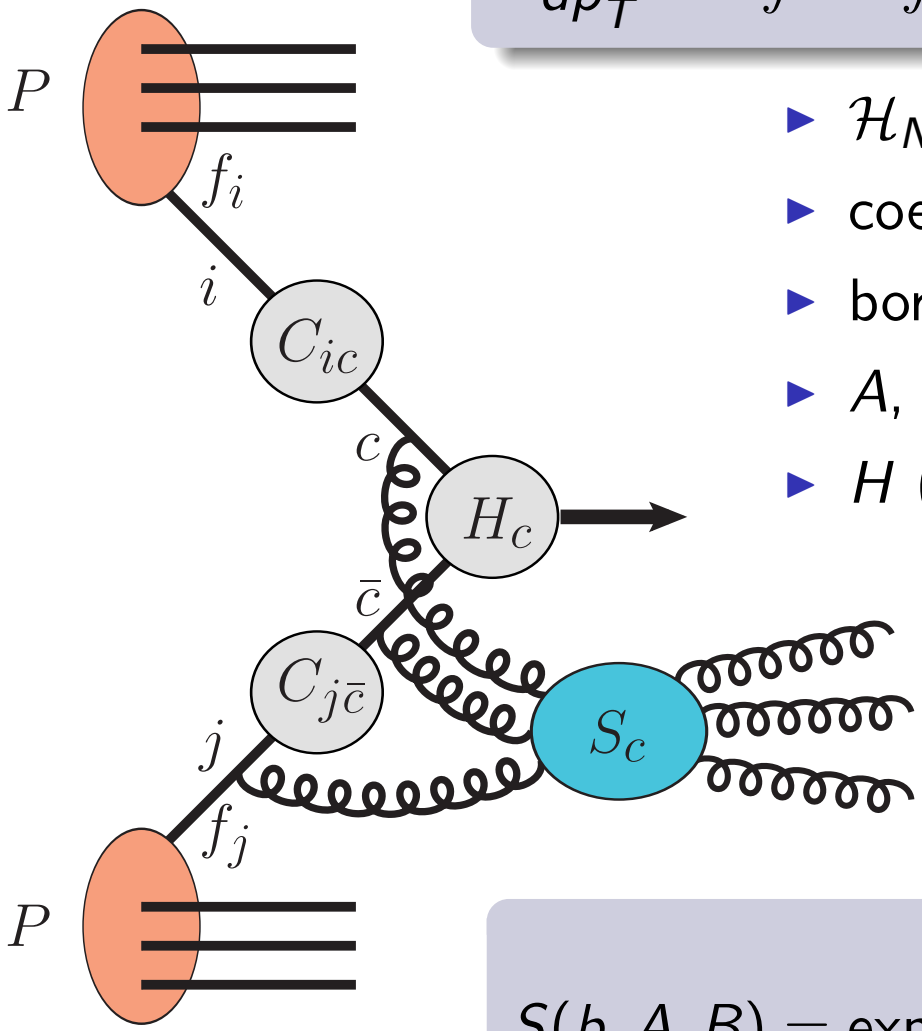


- $\mathcal{H}_N = H_N \, C_N \, C_N$
- coefficients A, B, C, H ($\mathcal{H}$) perturbative
- born initial state gg or $q\bar{q}$
- A, B, C process independent
- H ($\mathcal{H}$) process dependent

$$S(b, A, B) = \exp\left\{ -\int_{b_0^2/b^2}^{m_H^2} \frac{dq^2}{q^2} \left[A \ln\left(\frac{m_H^2}{q^2}\right) + B \right] \right\}$$

Transverse momentum resummation

- developed already 30 years ago

  [Parisi, Petronzio '79], [Dokshitzer, Diakonov, Troian '80], [Curci, Greco, Srivastava '79], [Bassetto, Ciafaloni, Marchesini '80], [Kodaira, Trentadue '82], [Collins, Soper, Sterman '85]

- we use newer formulation including various improvements:

  [Catani, de Florian, Grazzini '01], [Bozzi, Catani, de Florian, Grazzini '06]

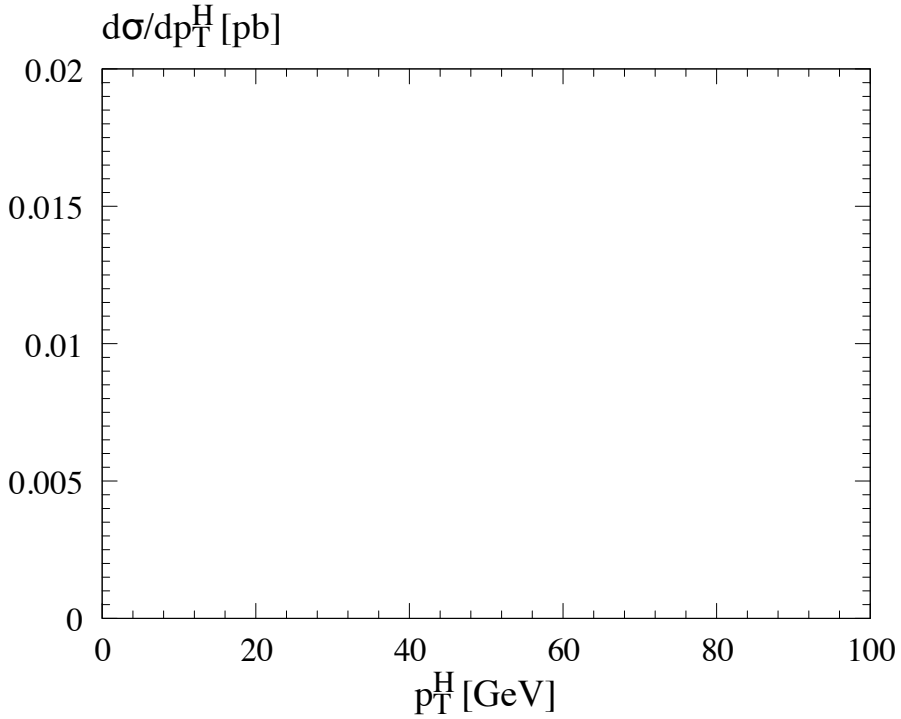
  - H embodies whole process dependence
  - $L = \ln(Q^2\, b^2/b_0^2) \to L' = \ln(Q^2\, b^2/b_0^2 + 1)$

    $\to$ reduction of impact at high p_T (low b)
    $\to$ unitarity constraint

Matching

- matched (resummed) cross section:

$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} =$$



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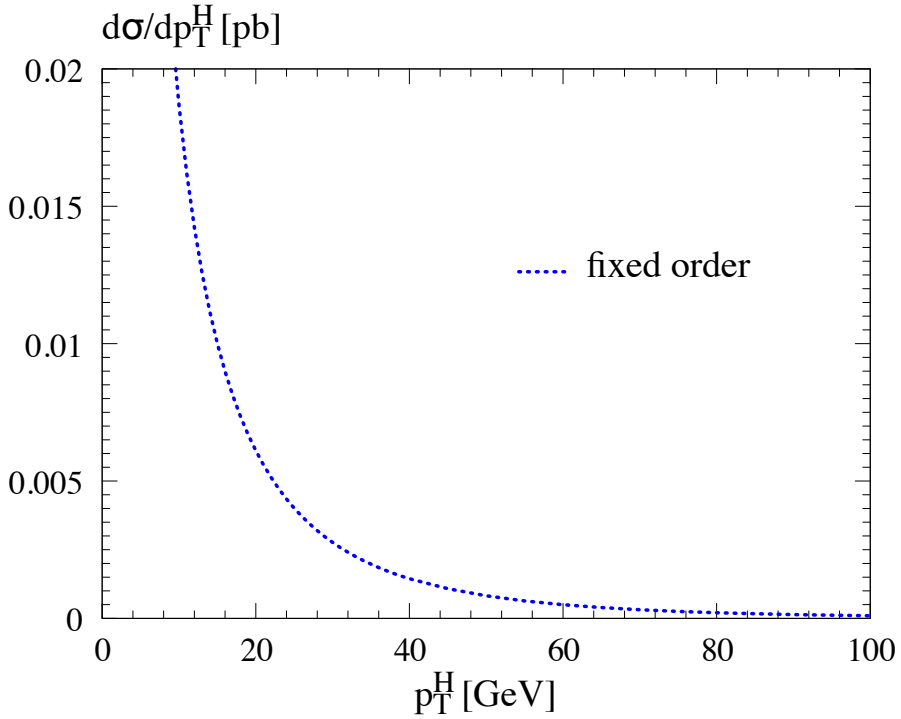

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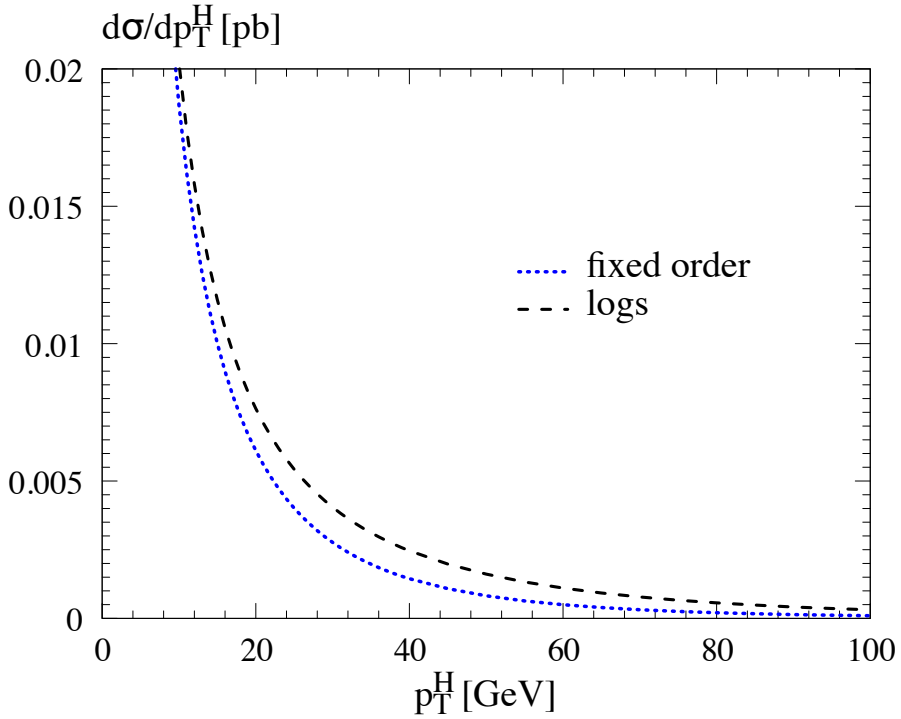

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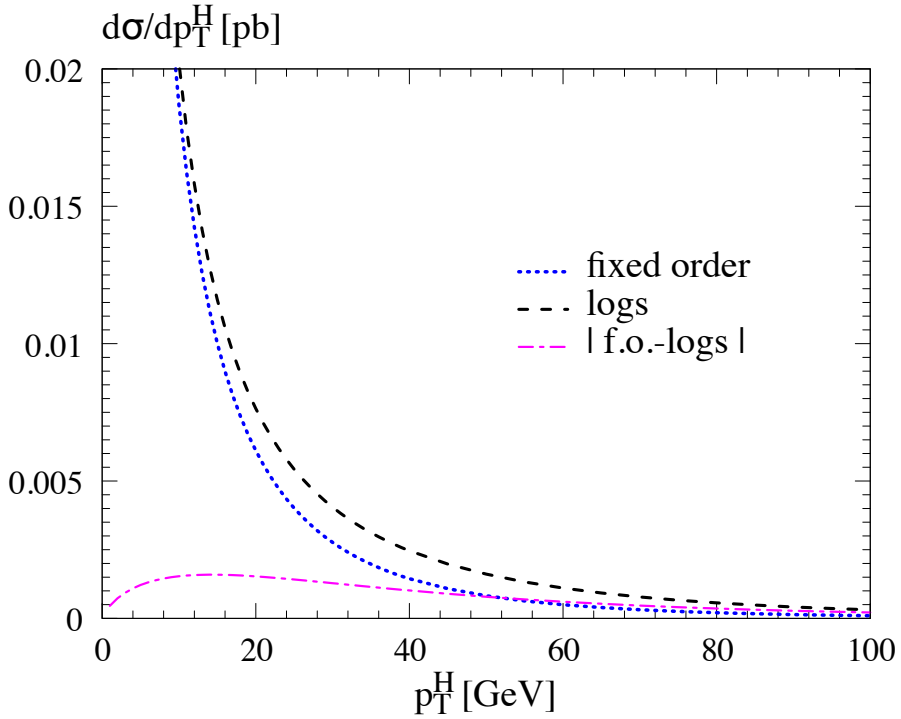

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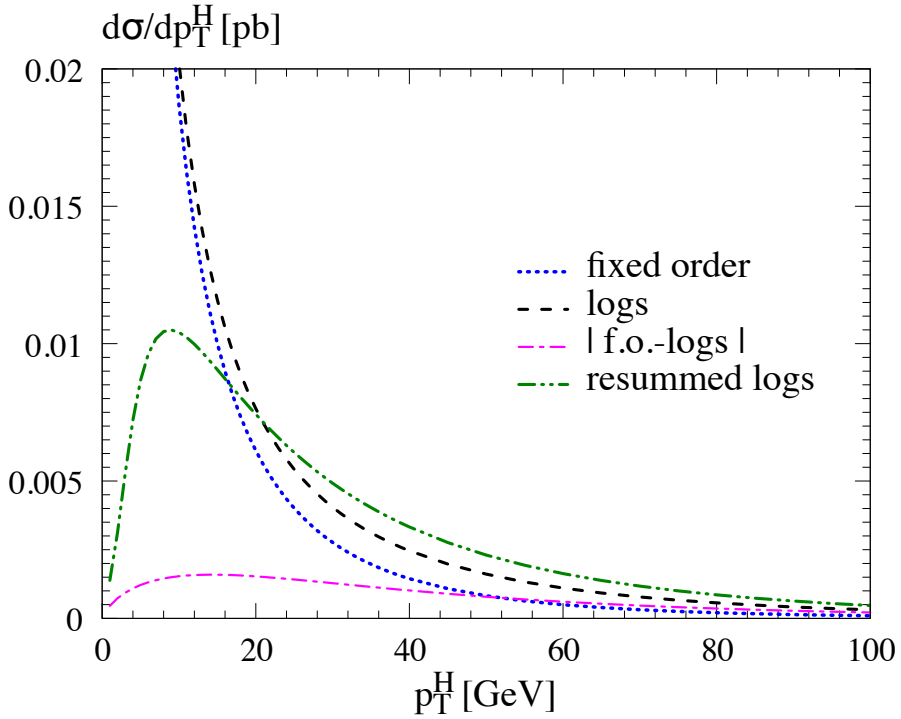

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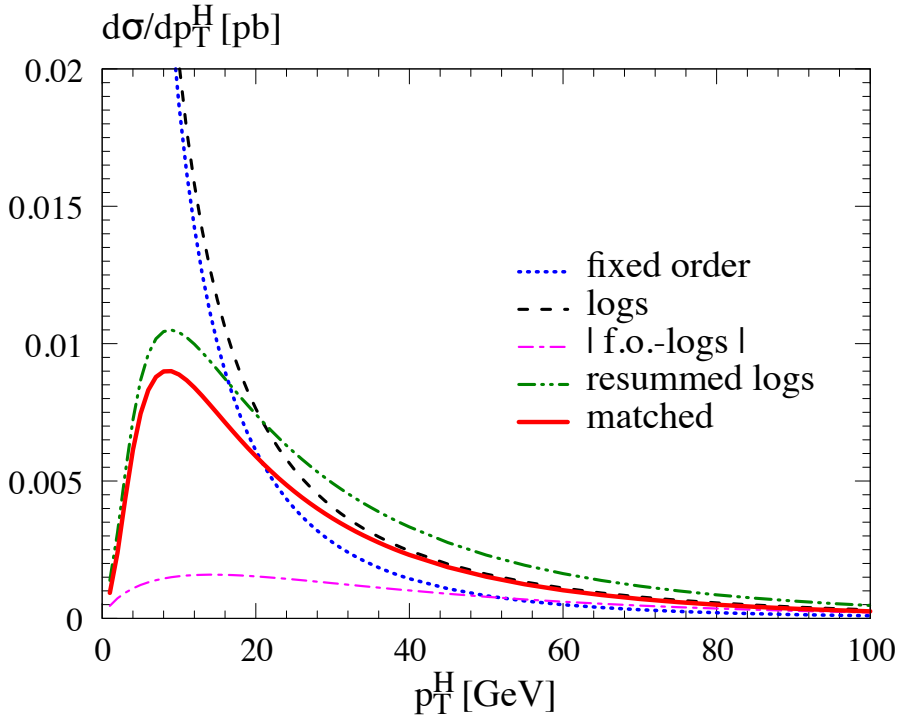
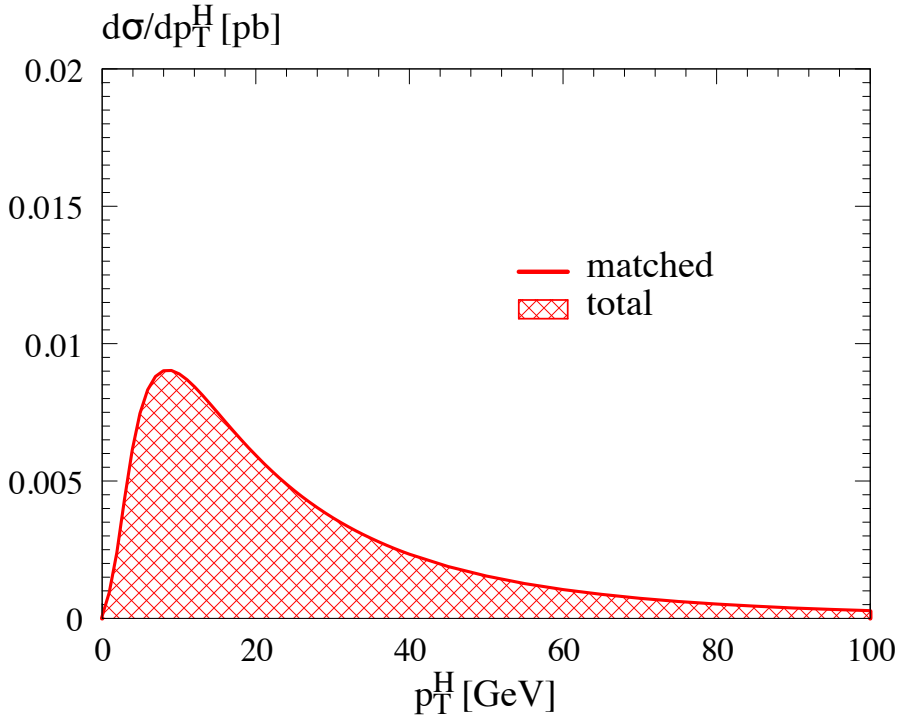


Matching

- unitarity (due to $L \to L'$):

$$\int \mathrm{d}p_T^2 \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} \equiv \left[\sigma^{(\text{tot})}\right]_{\text{f.o.}} .$$



Applications

- Higgs production through gluon fusion (heavy-top limit)

  [Bozzi, Catani, de Florian, Grazzini '06]

- Slepton pair production

  [Bozzi, Fuks, Klasen '06]

- Vector boson pair production: WW and ZZ

  [Grazzini '06], [Grazzini, Frederix '08]

- Drell-Yan

  [Bozzi, Catani, Ferrera, de Florian, Grazzini '10]

- Higgs production through gluon fusion with full mass dependence

  [Mantler, MW '12], [Grazzini, Sargsyan '13]

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  [Mantler, MW '12], [Grazzini, Sargsyan '13]
- new: Higgs production through bottom annihilation

  [Harlander, Tripathi, MW '14]

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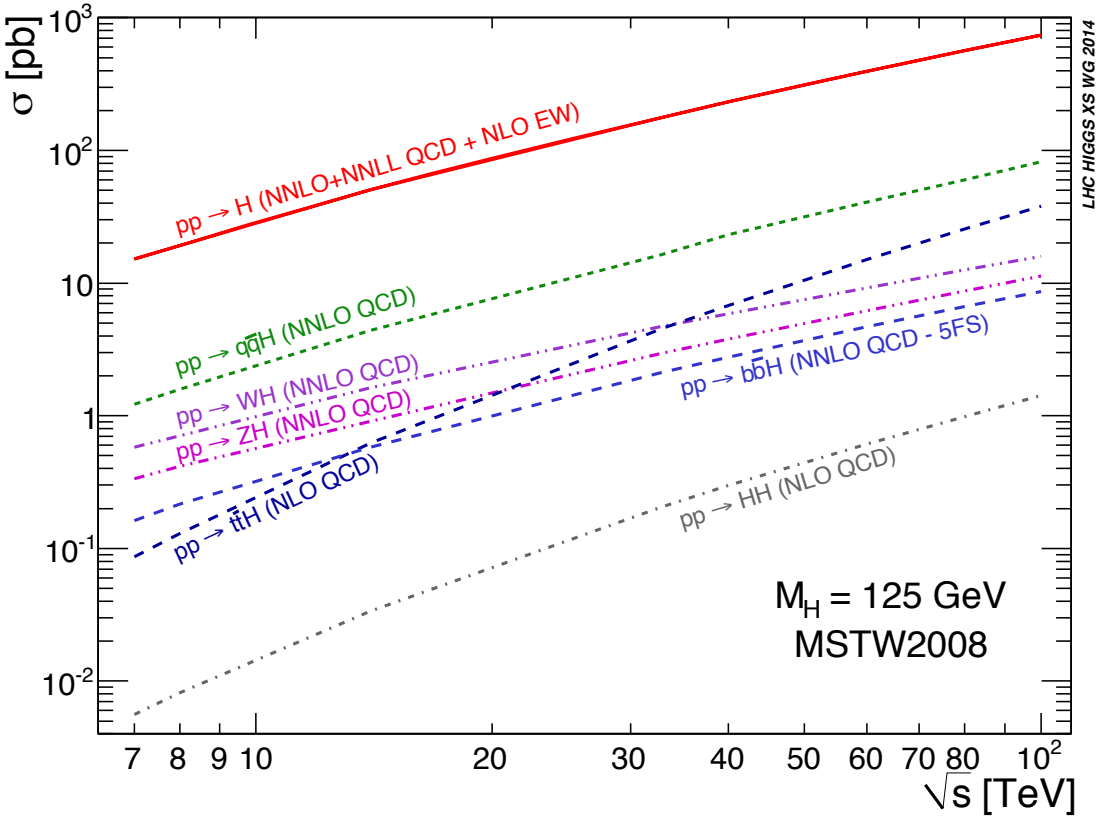
3. Resummed p_T distribution in the 5FS

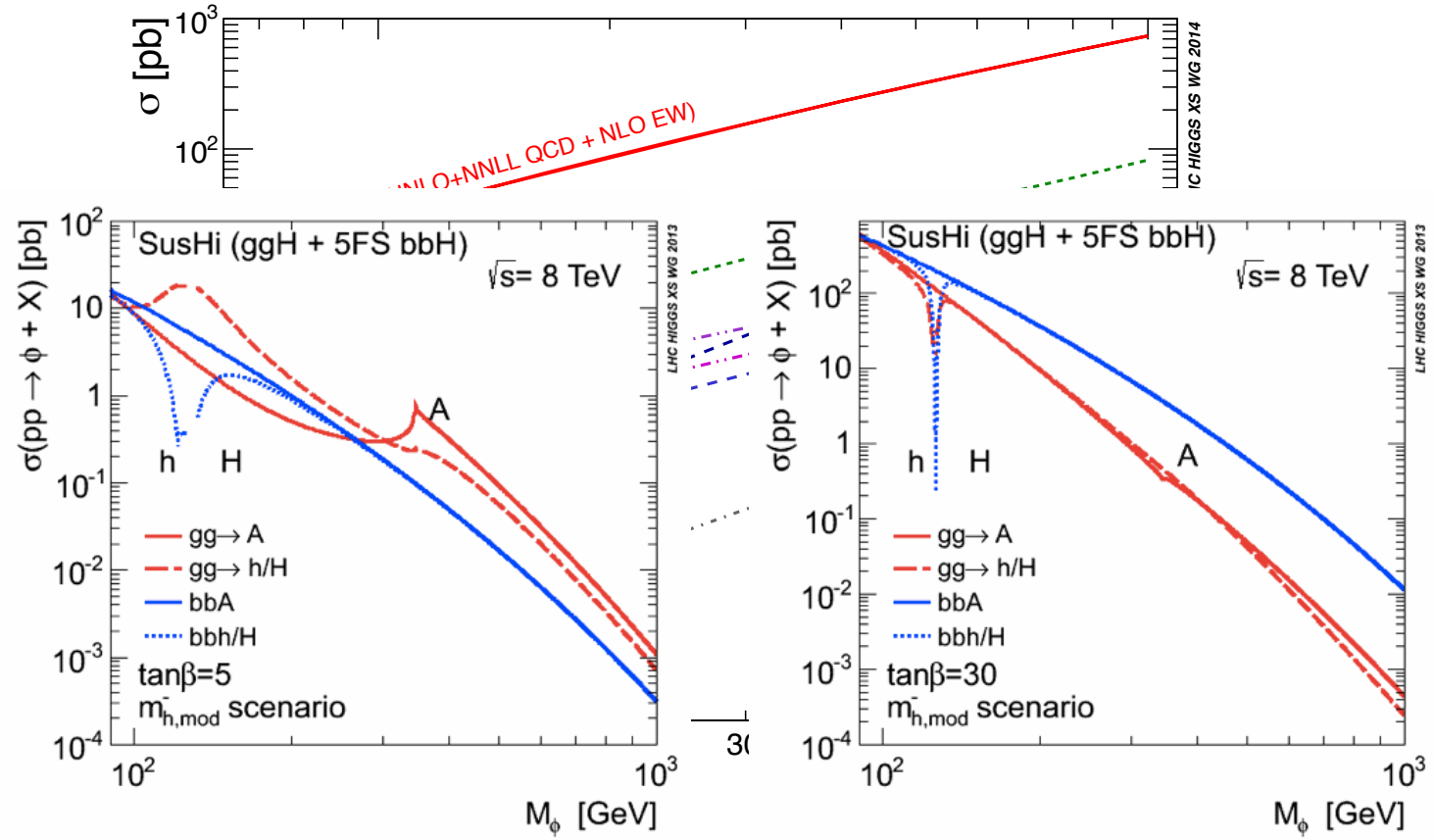
Associated $H(b\bar{b})$ production



- SM:
  - inclusively negligible
  - sizeable with b-tagging:

    $H + b$ and $H + b\bar{b}$

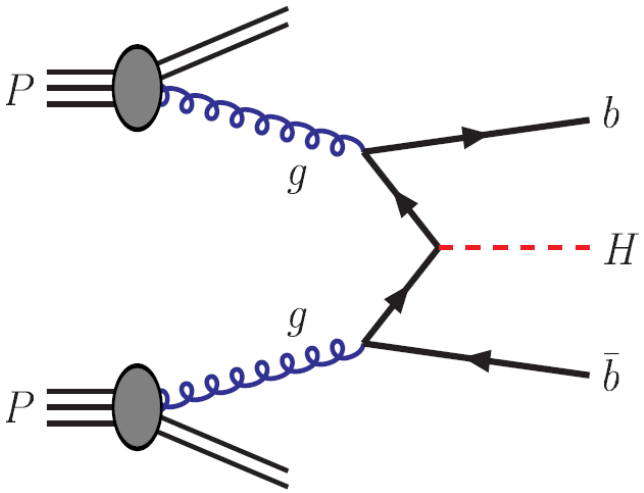
Associated $H(b\bar{b})$ production



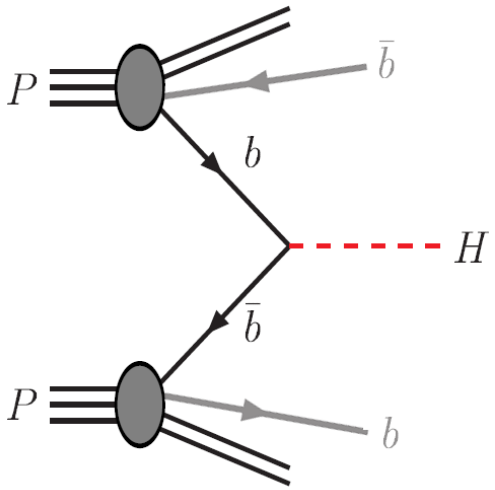
- SM:
  - inclusively negligible
  - sizeable with b-tagging: $H + b$ and $H + b\bar{b}$
- MSSM/2HDM:
  - 3 neutral Higgs: h, H and A
  - y_b/y_t enhanced by $\tan\beta$
  - h: constrained to be SM-like
  - H, A: dominant for large $\tan\beta$

Associated $H(b\bar{b})$ production: 4FS vs. 5FS

4-flavour scheme



5-flavour scheme



Associated $H(b\bar{b})$ production: 4FS vs. 5FS

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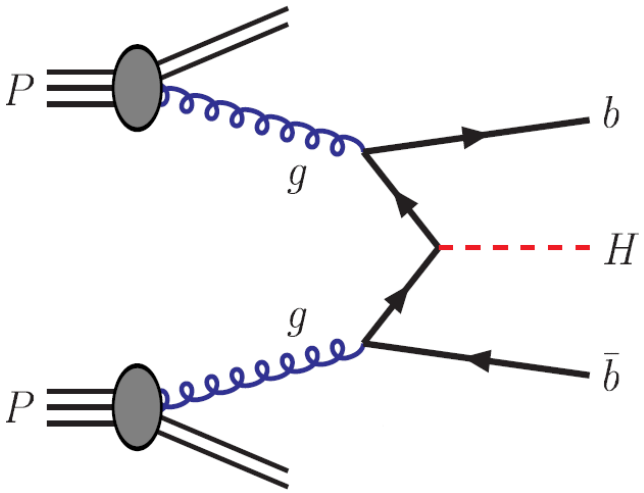

- exclusive up to NLO

  [Dittmaier, Krämer, Spira '04]

  [Dawson, Jackson, Reina, Wackeroth '04]

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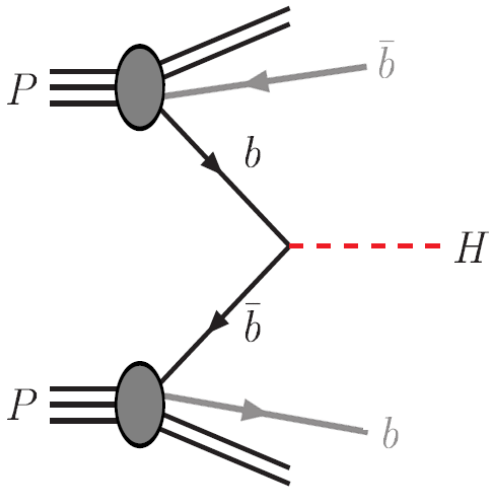

- inclusive up to NNLO

  [Harlander, Kilgore '03]

- exclusive up to NNLO

  [Buehler, Herzog, Lazopoulos, Mueller '12]

- NLO+NLL p_T resummation

  [Belyaev, Nadolsky, Yuan '06]

1. Transverse momentum resummation

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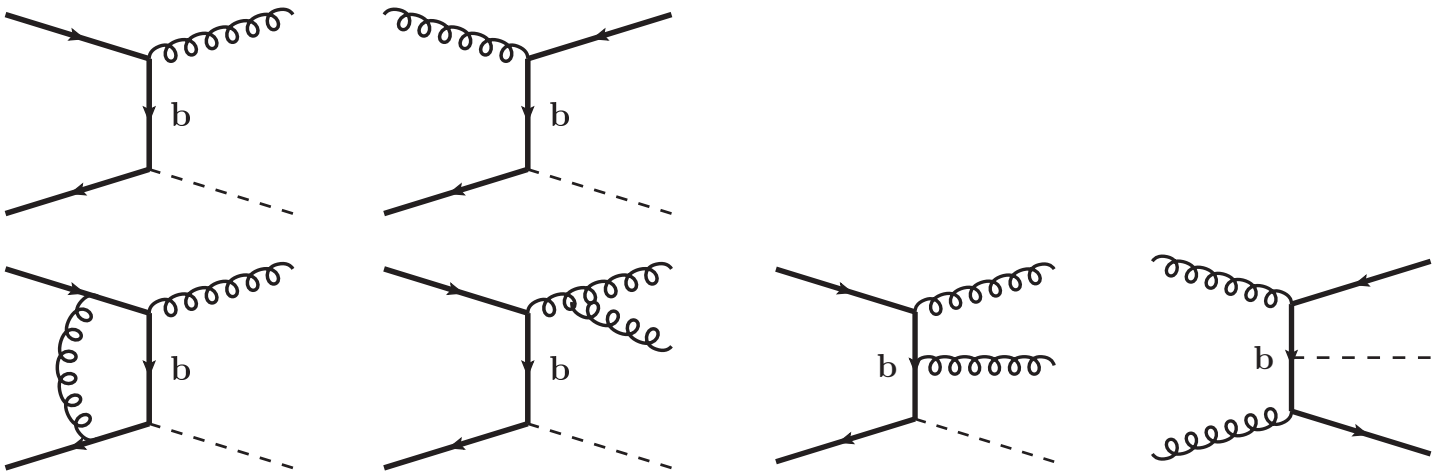
Ingredients of the calculation

$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.+l.a.}} = \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\text{f.o.}}$$

- analytic p_T-distribution at NNLO [Ozeren '10]

α_s:

α_s^2:



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  $A^{(1)}$, $A^{(2)}$, $B^{(1)}$ [Kodaira, Trentadue '82], $C^{(1)}$ [Davies, Stirling '84],
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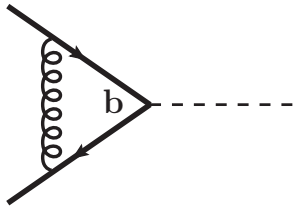
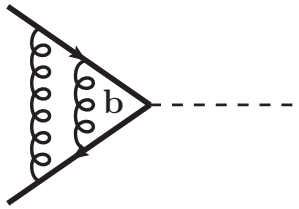


- new: [Harlander, Tripathi, MW '14]
  $H^{b\bar{b}H(2)} = 10.47 \pm 0.08$ (numerical result)
  $$H^{b\bar{b}H(2)} = C_F\left[\left(\frac{321}{64} - \frac{13}{48}\pi^2\right) C_F + \left(-\frac{365}{288} + \frac{\pi^2}{12}\right) N_f + \left(\frac{5269}{576} - \frac{5}{12}\pi^2 - \frac{9}{4}\zeta_3\right) C_A\right]$$



from universal form of $H^{(2)}$ [Catani, Cieri, de Florian, Grazzini '13]

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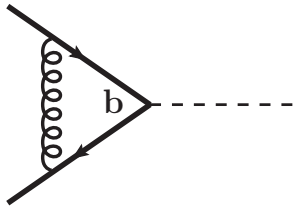

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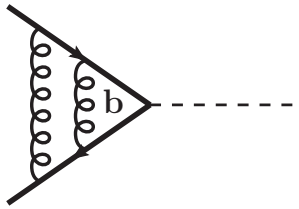

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- $+$ $H^{b\bar{b}H(1)}$ and $H^{b\bar{b}H(2)}$
- third term: modified version of `HqT`

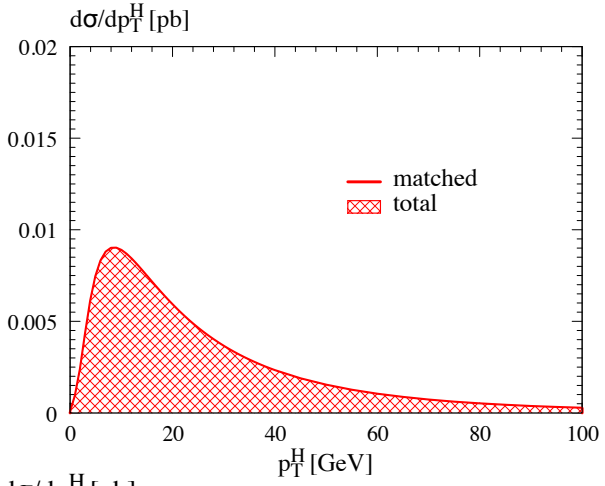
  [Bozzi, Catani, de Florian, Grazzini '03 '05]

  [de Florian, Ferrera, Grazzini, Tommasini '11]

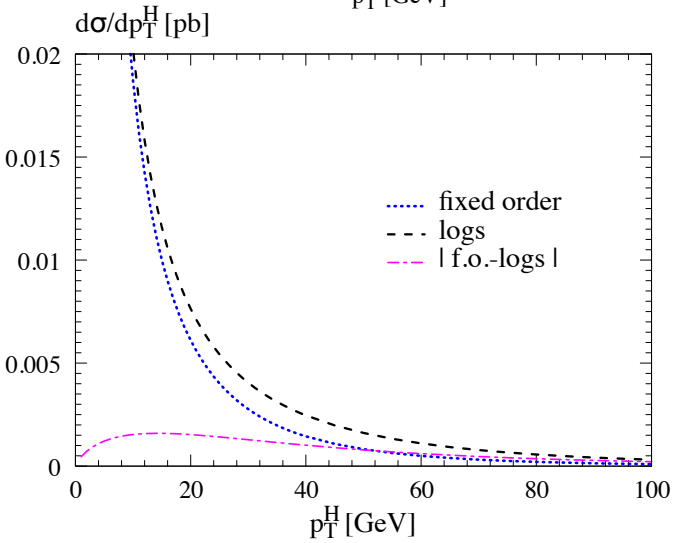
Checks

- analytic NNLO p_T-distribution checked against numerical $H + jet$ calculation at NLO [Harlander, Ozeren, MW '10]

- integral of matched cross section = total
  - for various μ_F, μ_R values
  - integral Q_{res}-independent



- fixed order ($p_T \to 0$) = logs ($p_T \to 0$)
  - for various μ_F, μ_R values
  - independent of Q_{res}

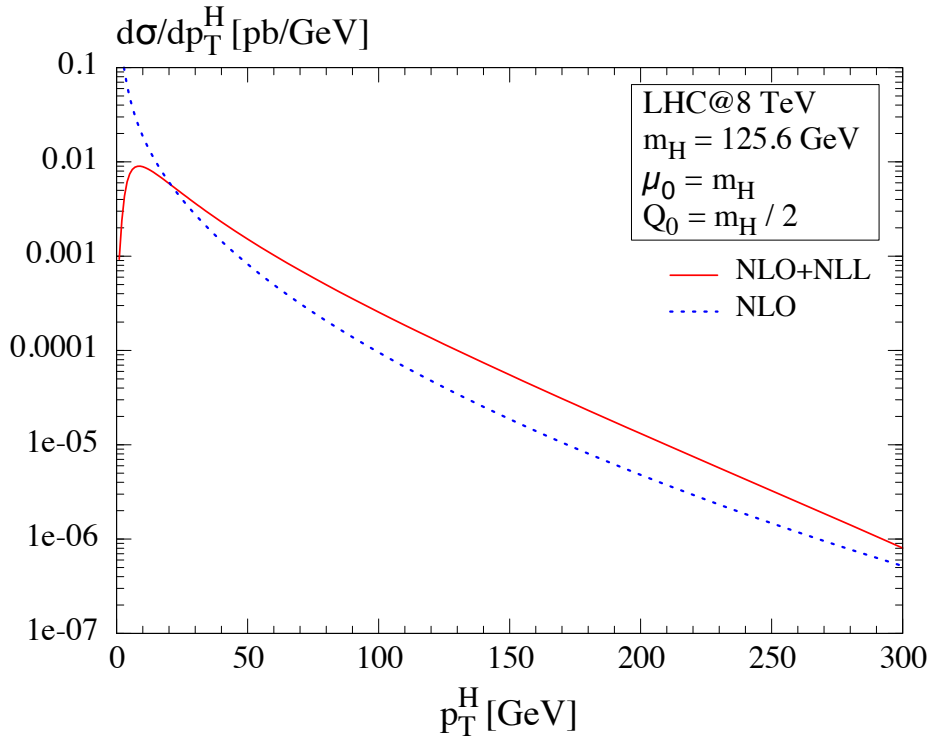


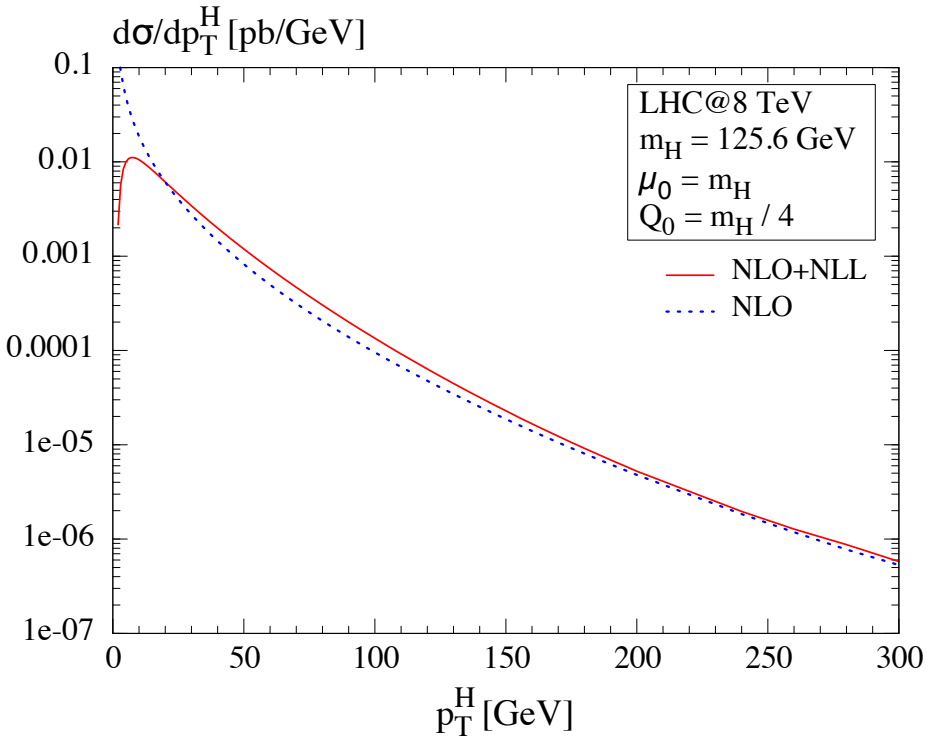
Results

p_T distribution at NLO+NLL (left: $Q = m_H/2$, right: $Q = m_H/4$):

[Harlander, Tripathi, MW '14], [Belyaev, Nadolsky, Yuan '06]

$$\left[\frac{d\sigma}{dp_T^2}\right]_{\text{NLO+NLL}} = \left[\frac{d\sigma}{dp_T^2}\right]_{\text{NLO}} - \left[\frac{d\sigma^{(\text{res})}}{dp_T^2}\right]_{\text{NLO}} + \left[\frac{d\sigma^{(\text{res})}}{dp_T^2}\right]_{\text{NLL}}$$





Results

p_T distribution at NLO+NLL (left: $Q = m_H/2$, right: $Q = m_H/4$):

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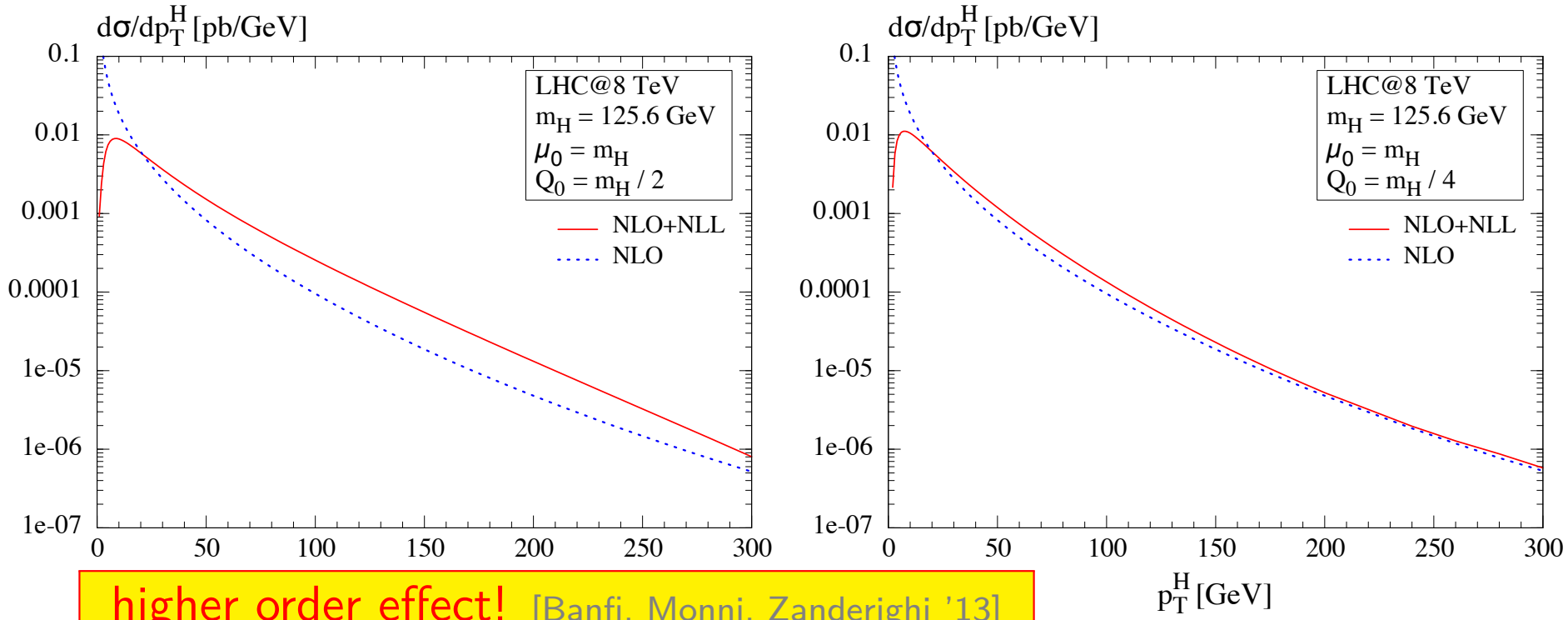

higher order effect! [Banfi, Monni, Zanderighi '13]

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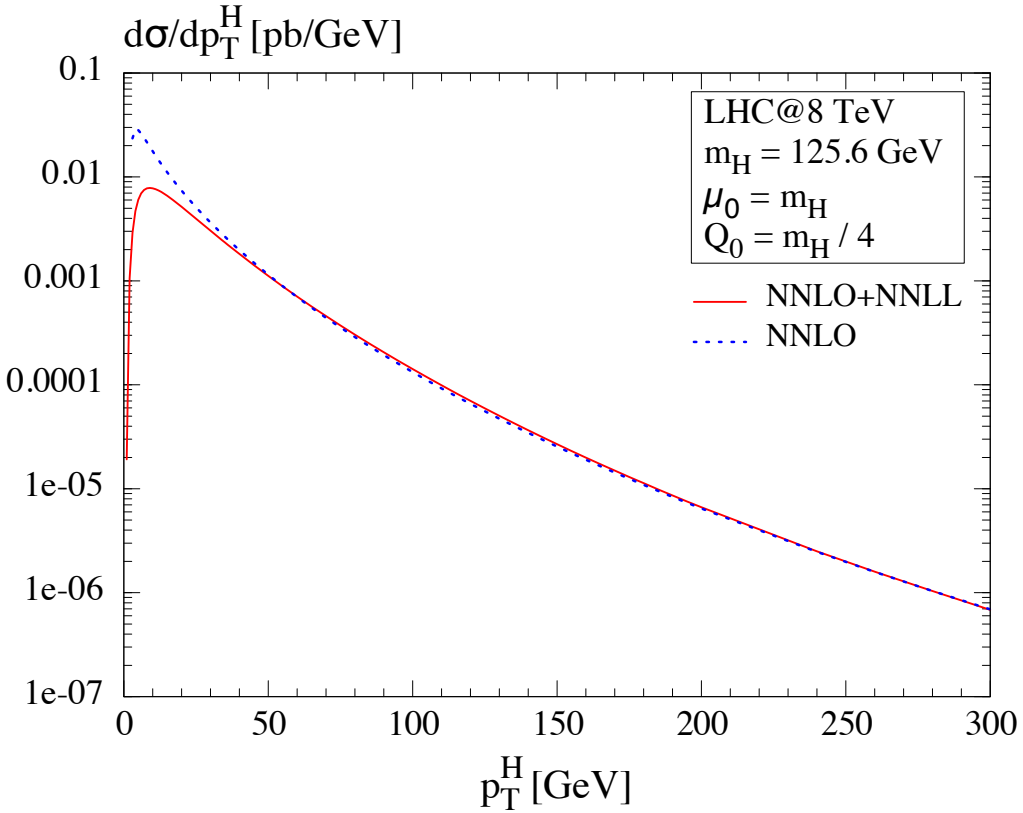

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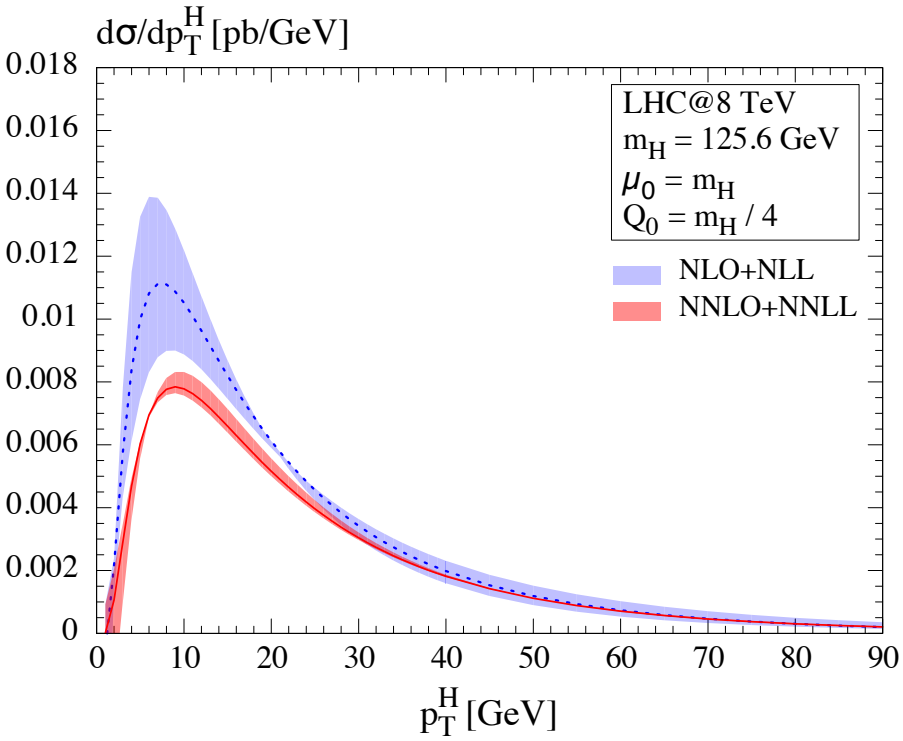

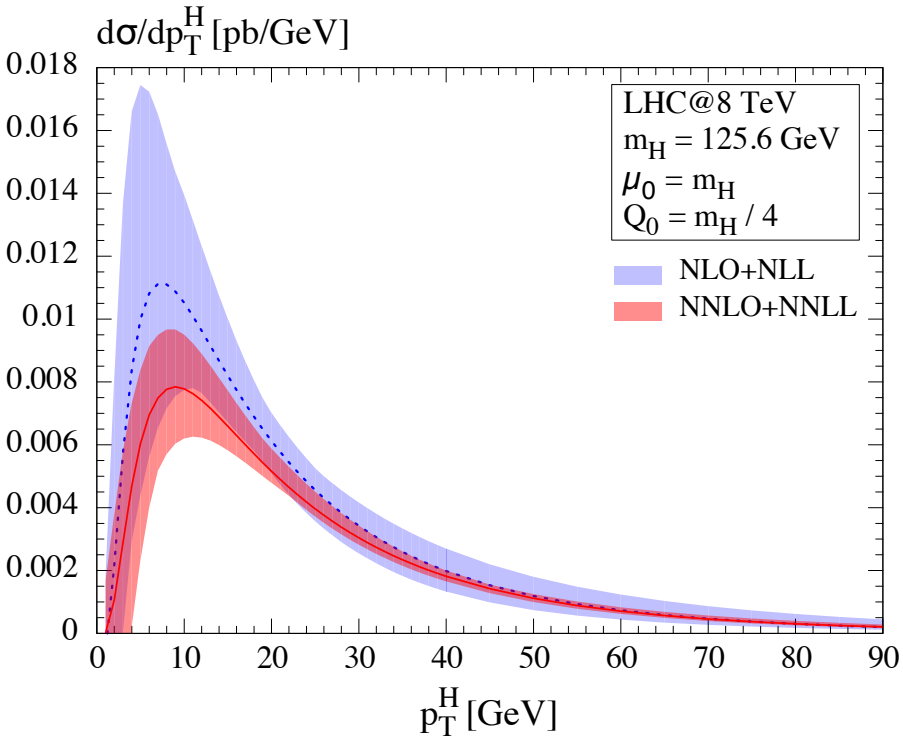

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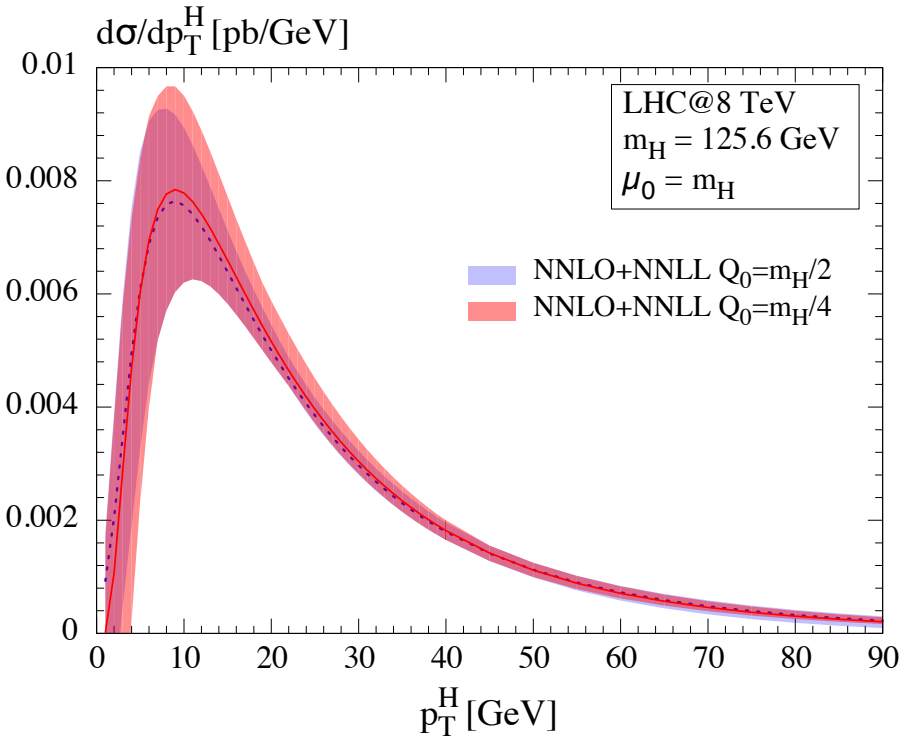

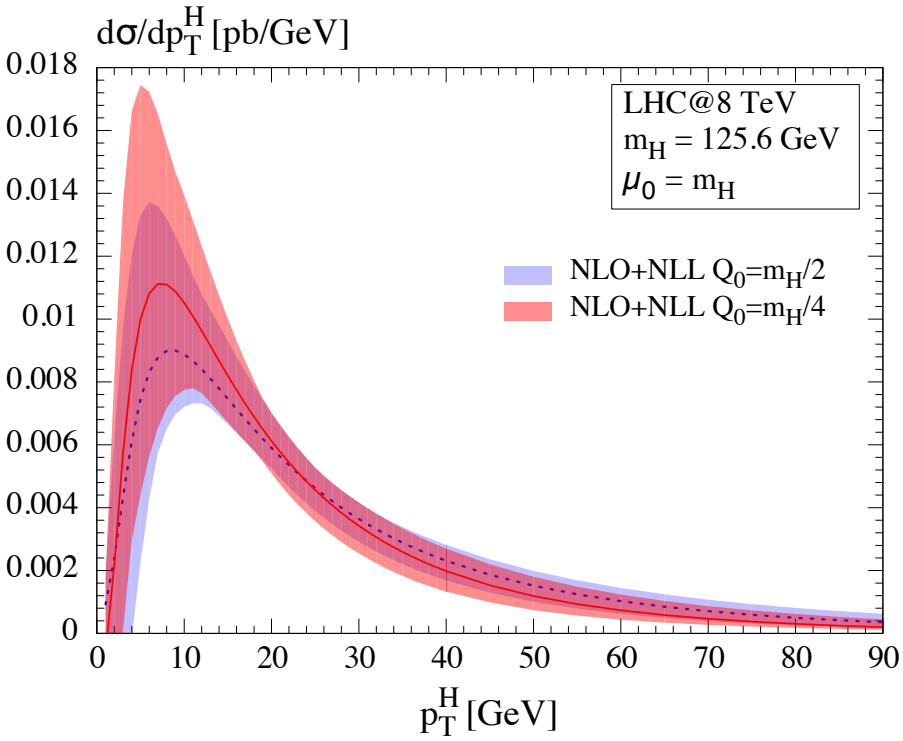

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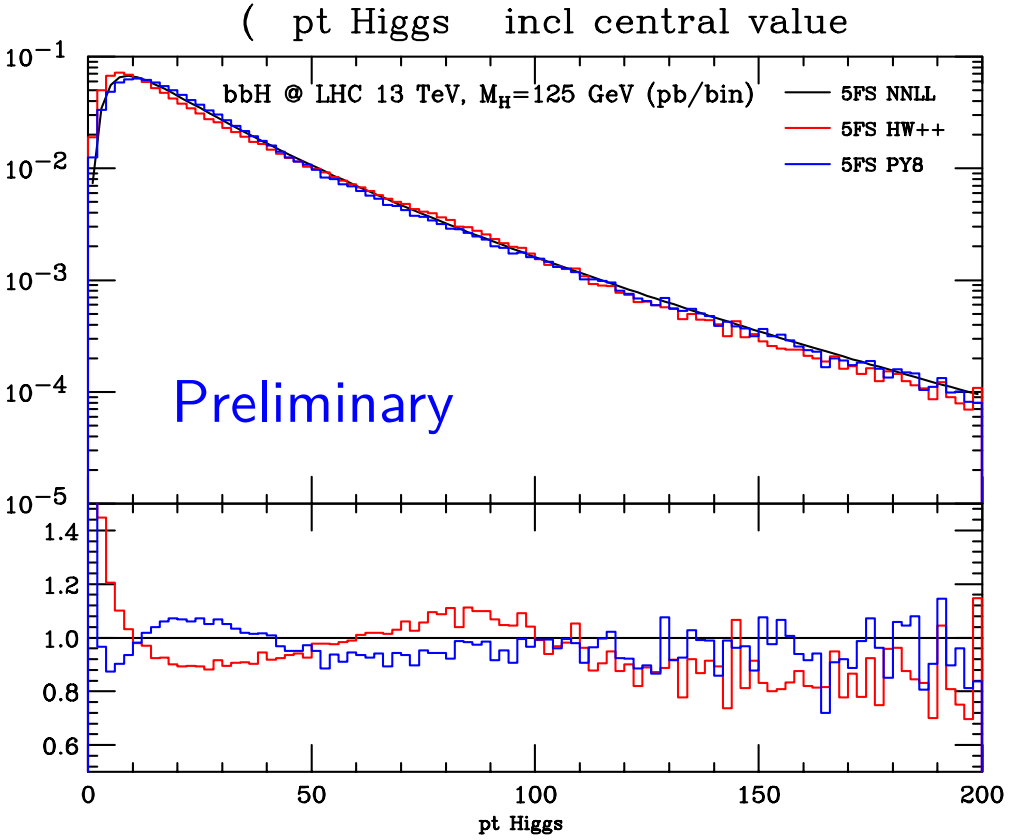
Comparison to 5FS NLO+PS:

[Frederix, Frixione, Hirschi, Maltoni, Torielli, MW]

normalized curves!



Results

Comparison to 4FS and 5FS NLO+PS:

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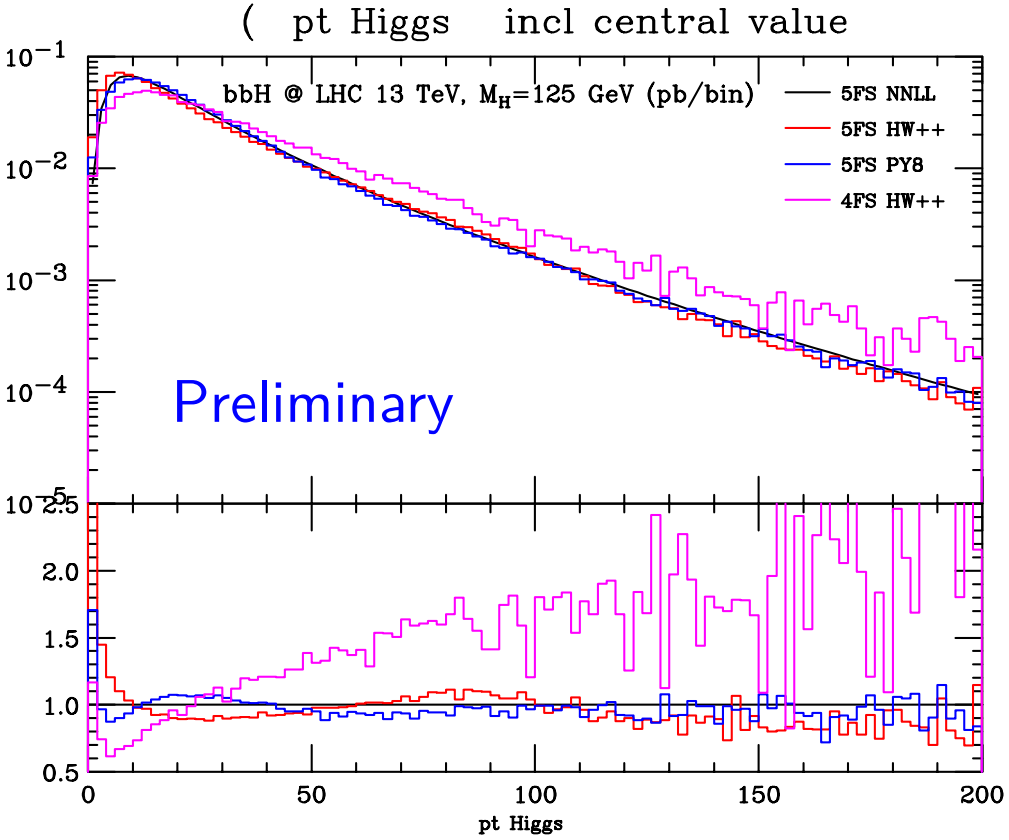

Conclusions and Outlook

Conclusions:

- $H(b\bar{b})$ production important for H and A in MSSM/2HDM
- missing hard coefficient at two-loop for $H(b\bar{b})$ determined
- first calculation of NNLL p_T-effects for $H(b\bar{b})$ production
- strong reduction of resummation scale dependence
- perfect matching at NNLO+NNLL for $Q = m_H/4$
- remarkable agreement of 5FS NNLO+NNLL with NLO+PS
- spectrum in 4FS significantly harder

Outlook:

- first NLO+PS in 4FS
- complete differential comparison 4FS and 5FS for $H(b\bar{b})$
- fully differential NNLO for $b\bar{b} \to H$

BackUp

Resummation coefficients: determination of $H_b^{b\bar{b}H,(2)}$

- DY resummation coefficients known up to NNLL and universal

  LL: $A^{(1)}$

  NLL: $A^{(2)}$, $B^{(1)}$, $C^{(1)}$

  NNLL: $A^{(3)}$, $B^{(2)}$, $C^{(2)}$
- except $H_b^{b\bar{b}H,(1)}$ and $H_b^{b\bar{b}H,(2)}$
- $H_b^{b\bar{b}H(1)} = 3\, C_F$
- <u>new:</u> $H_b^{b\bar{b}H(2)}$

Resummation coefficients: determination of $H_b^{b\bar{b}H,(2)}$

- hard-collinear function:

$$\mathcal{H}^{b\bar{b}H(2)}_{b\bar{b}\leftarrow b\bar{b}}(z) = H_b^{b\bar{b}H(2)}\,\delta(1-z) + \text{known}$$

[Catani, Cieri, de Florian, Ferrera, Grazzini '12]

- use unitarity:

$$\left[\hat{\sigma}^{(\text{tot})}_{b\bar{b}}\right]_{\text{f.o.}} = \int \mathrm{d}p_T^2 \left\{ \left[\frac{\mathrm{d}\sigma_{b\bar{b}}}{\mathrm{d}p_T^2}\right]_{\text{f.o.}} - \left[\frac{\mathrm{d}\sigma^{(\text{res})}_{b\bar{b}}}{\mathrm{d}p_T^2}\right]_{\text{f.o.}} \right\} + \underbrace{\int dp_T^2 \left[\frac{\mathrm{d}\sigma^{(\text{res})}_{b\bar{b}}}{\mathrm{d}p_T^2}\right]_{\text{l.a.}}}_{=z\,\hat{\sigma}^{(0)}_{b\bar{b}}\,\mathcal{H}^{b\bar{b}H(2)}_{b\bar{b}\leftarrow b\bar{b}}}$$

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$\rightarrow$ numerical result: $H_b^{b\bar{b}H,(2)} = 10.47 \pm 0.08$

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  [Harlander, Tripathi, MW '14]

$$H_b^{b\bar{b}H,(2)} = C_F \left[\left(\frac{321}{64} - \frac{13}{48}\pi^2 \right) C_F + \left(-\frac{365}{288} + \frac{\pi^2}{12} \right) N_f + \left(\frac{5269}{576} - \frac{5}{12}\pi^2 - \frac{9}{4}\zeta_3 \right) C_A \right]$$

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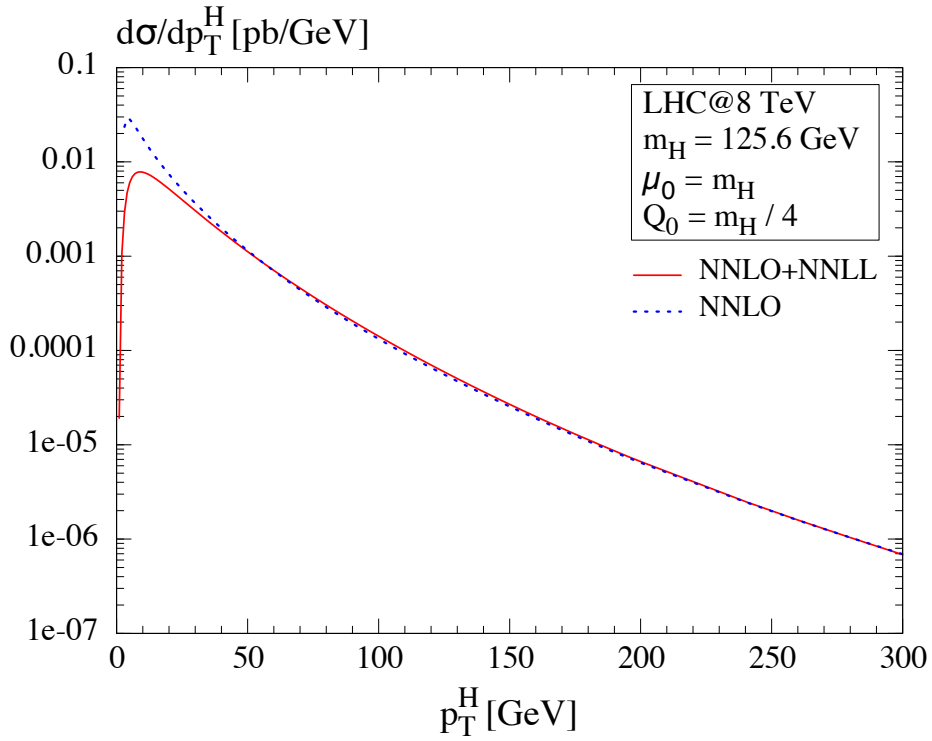
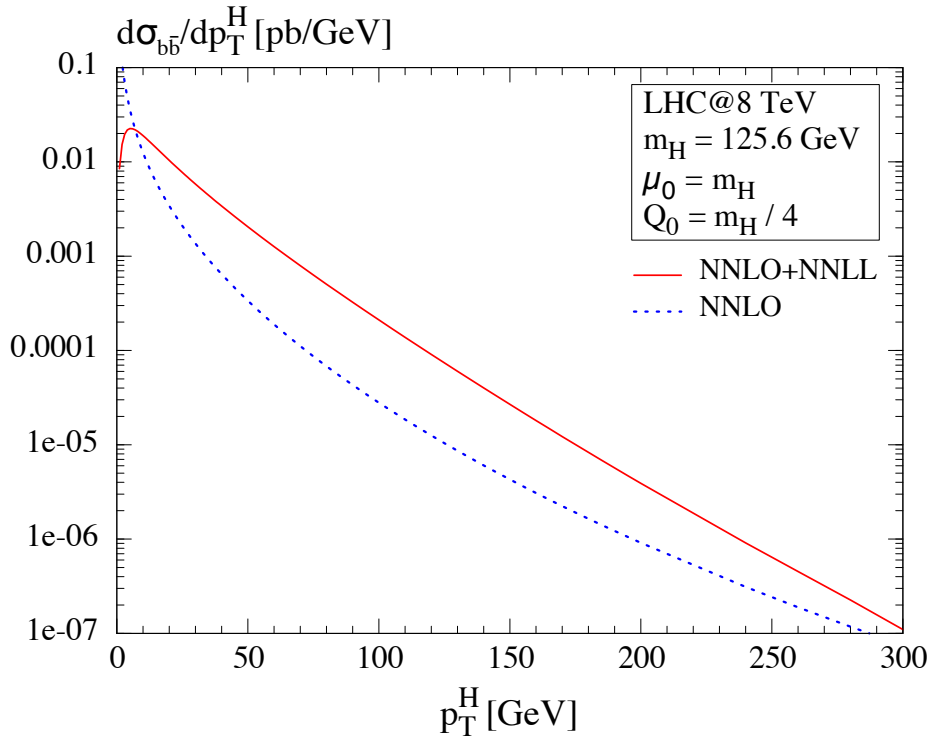
$$\left[\frac{d\sigma}{dp_T^2}\right]_{\text{NNLO+NNLL}} = \left[\frac{d\sigma}{dp_T^2}\right]_{\text{NNLO}} - \left[\frac{d\sigma^{(\text{res})}}{dp_T^2}\right]_{\text{NNLO}} + \left[\frac{d\sigma^{(\text{res})}}{dp_T^2}\right]_{\text{NNLL}}$$





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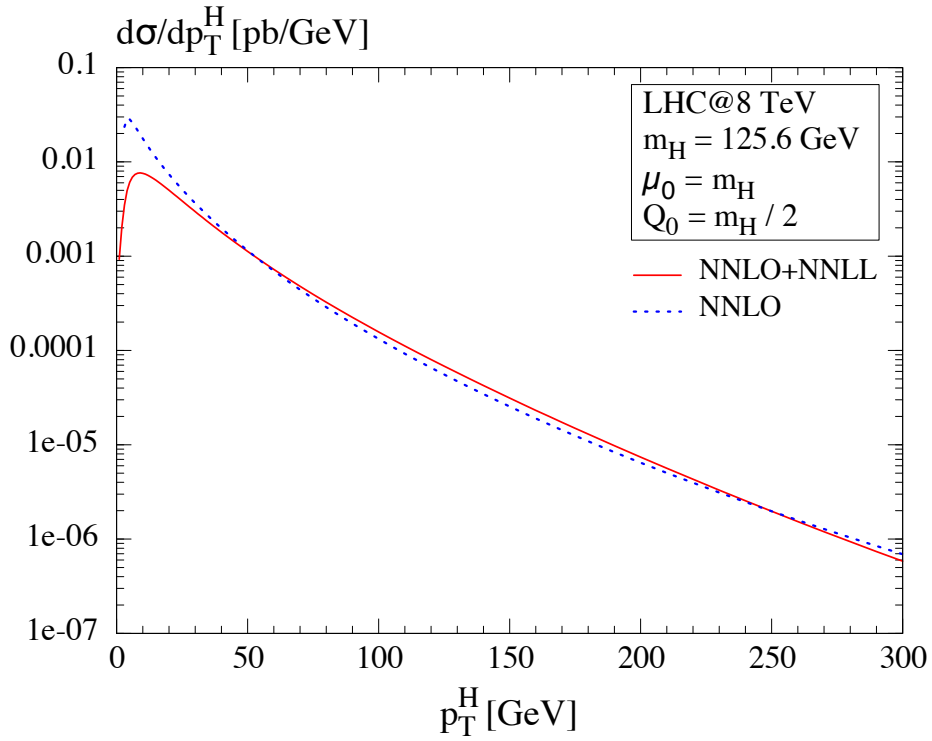

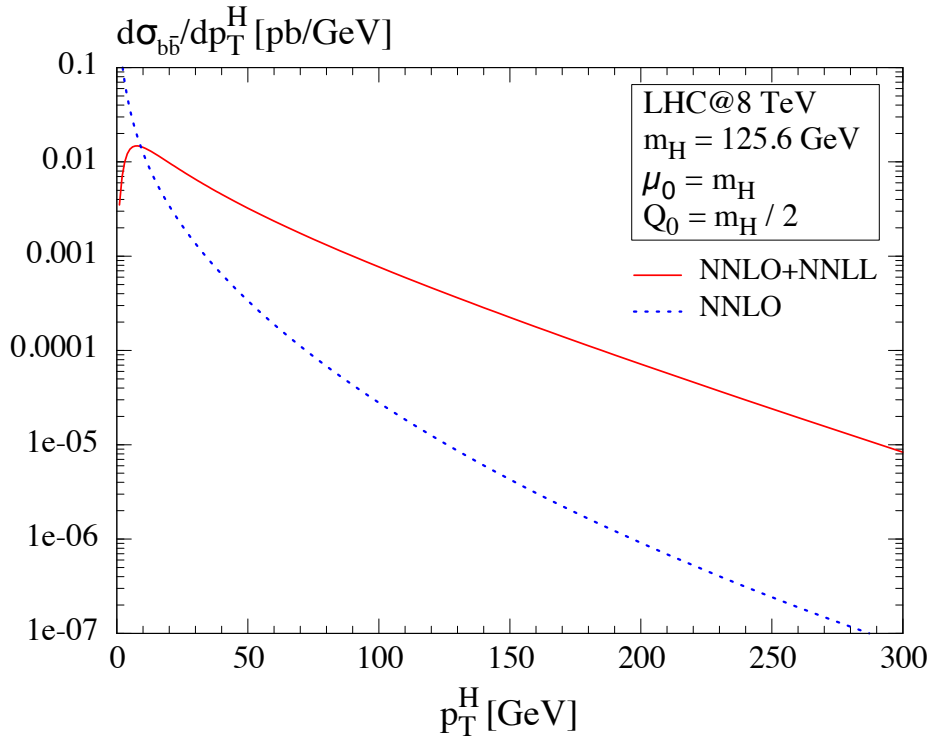

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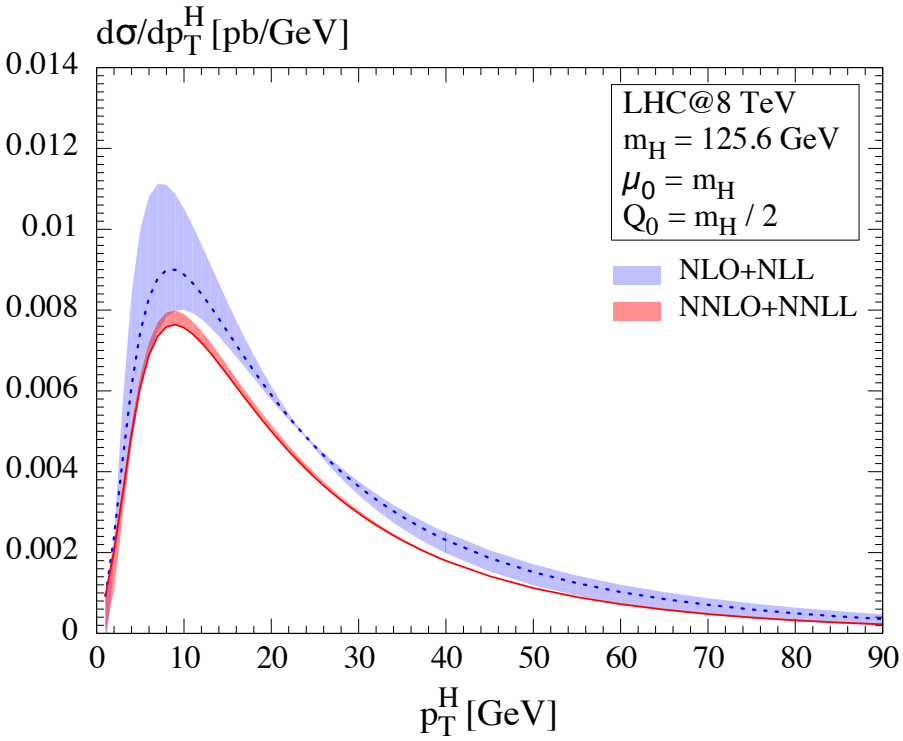
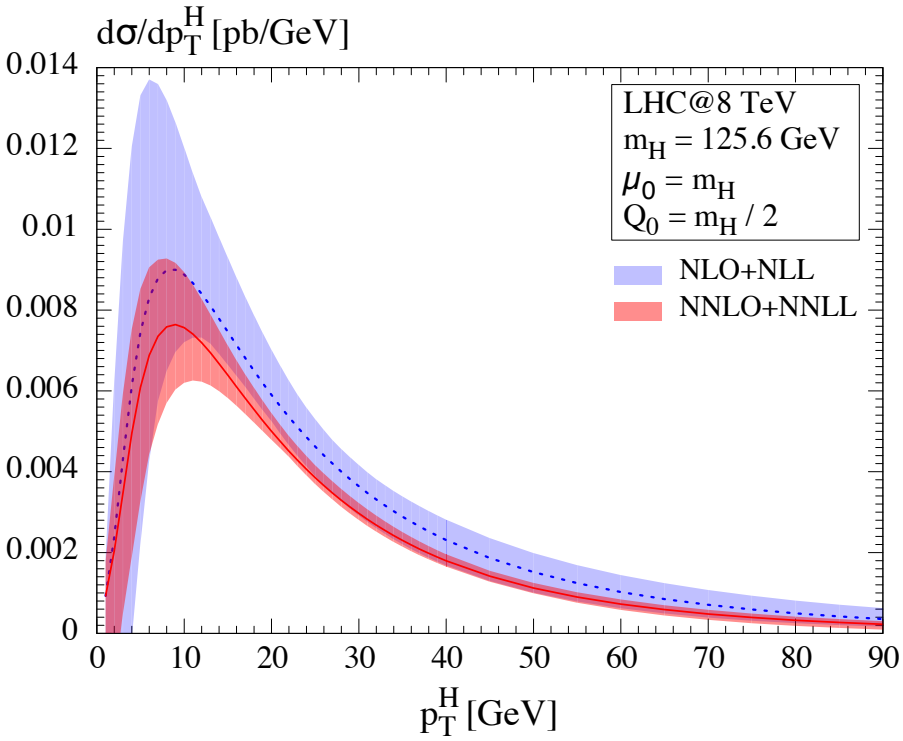
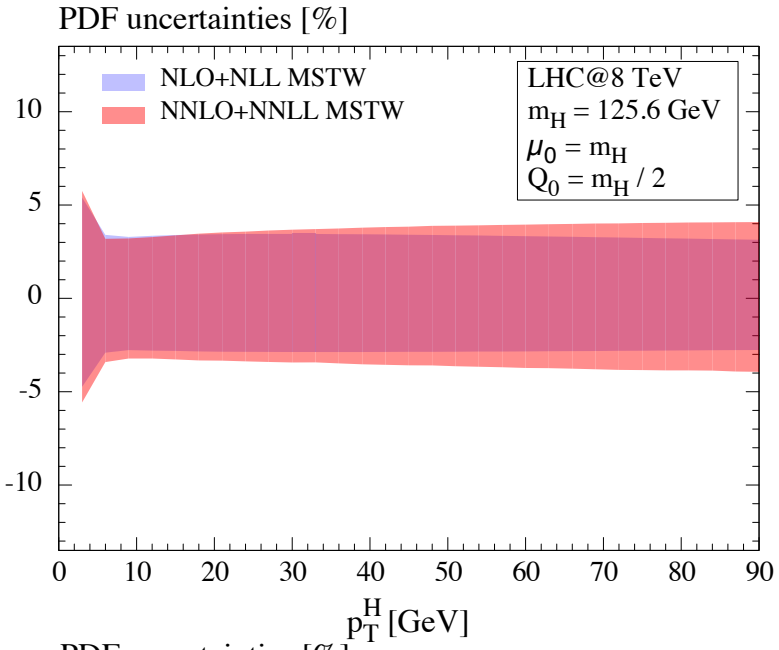


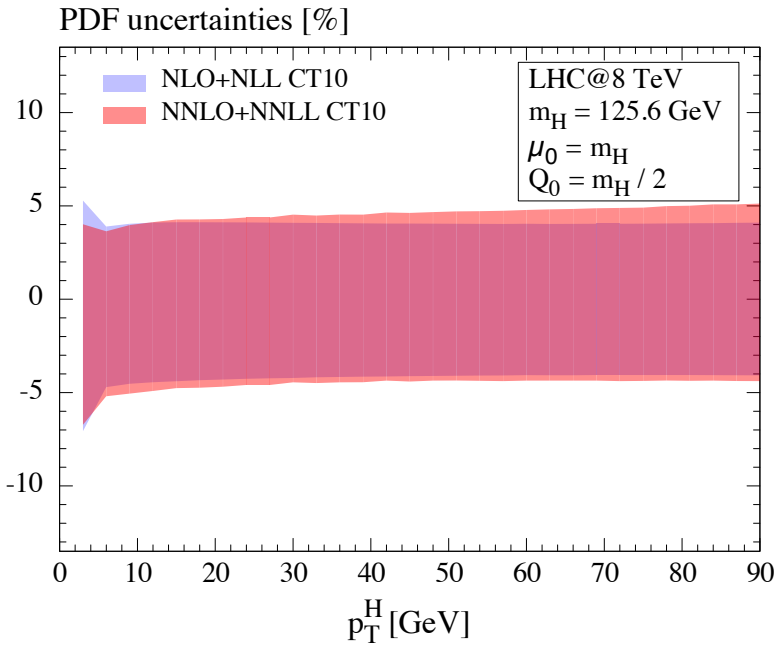


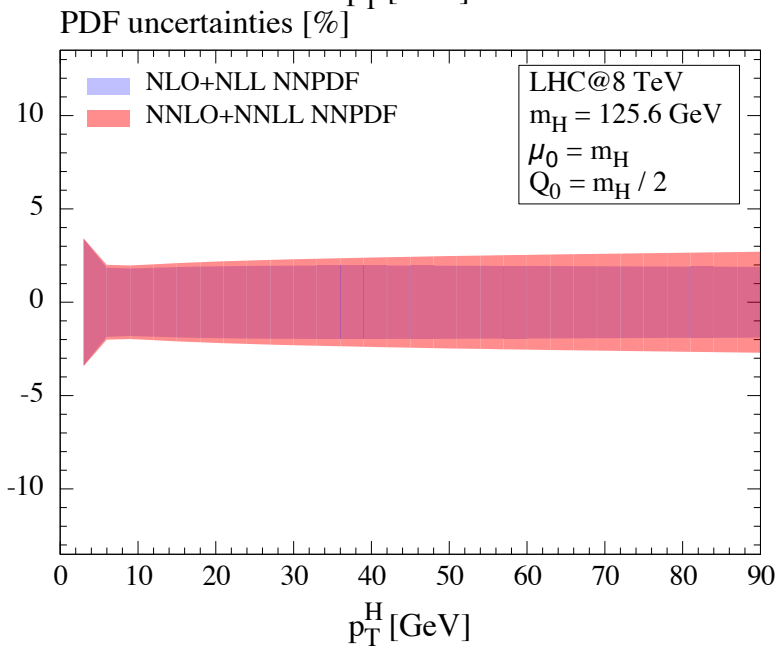
Results

PDF+α_s uncertainties:

[Harlander, Tripathi, MW '14]







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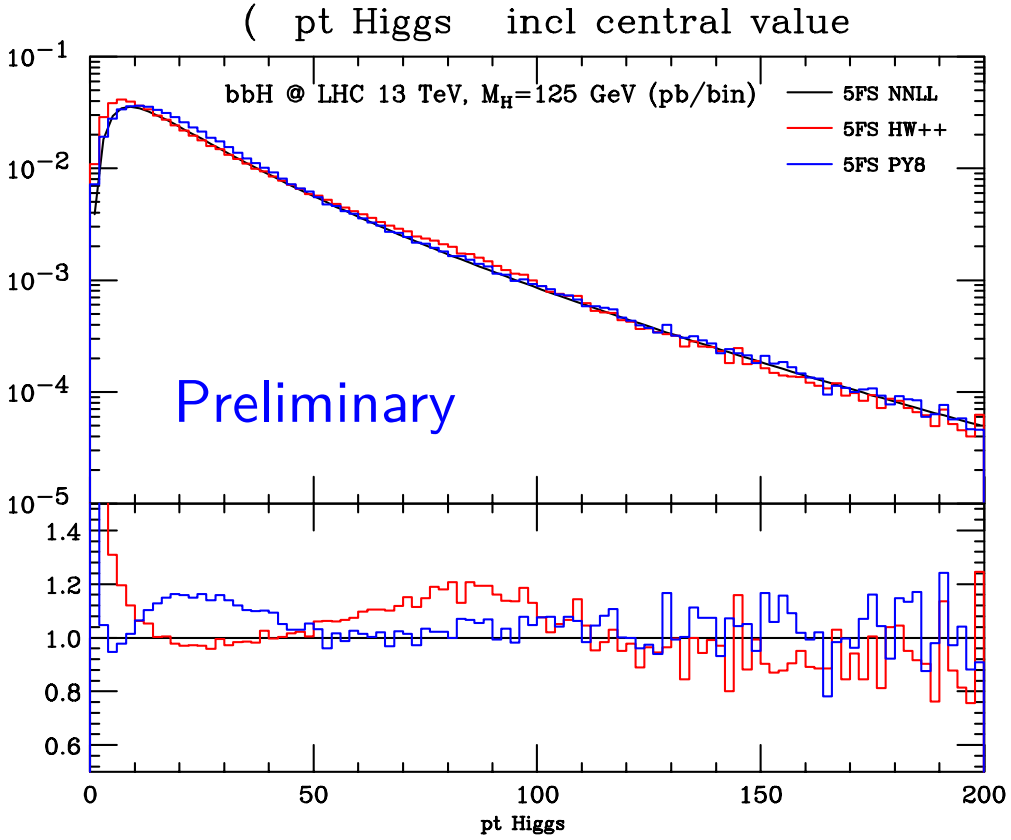

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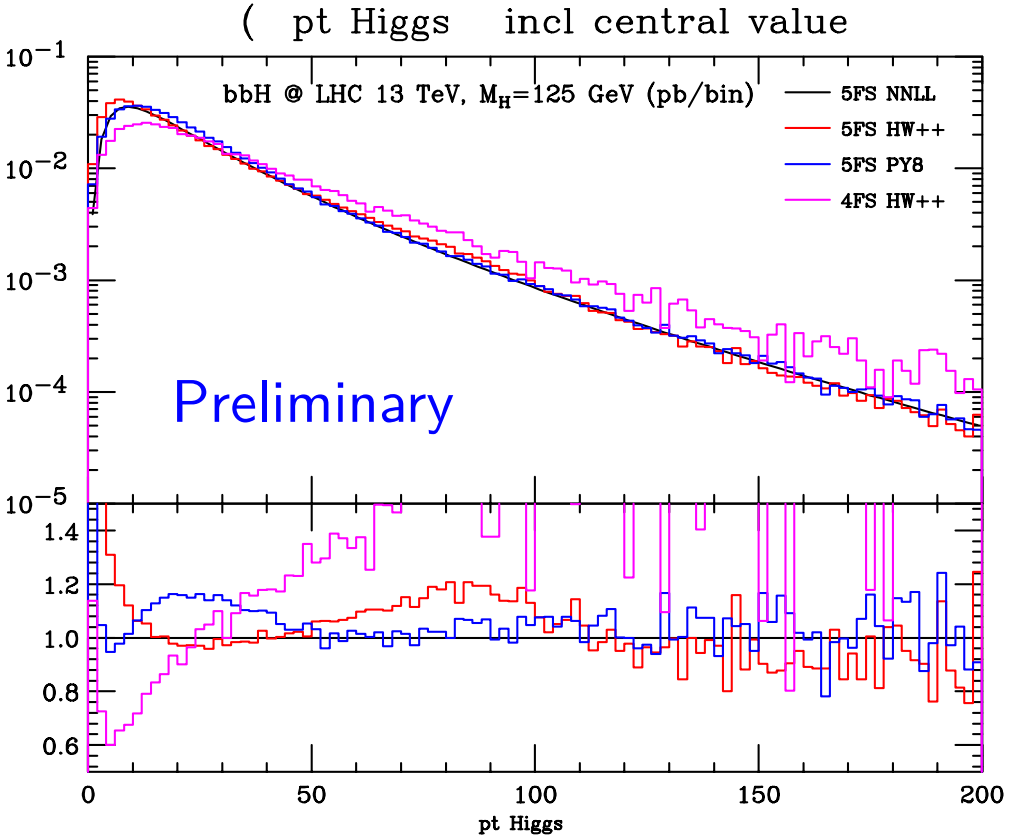

p_T resummation

- sudakov: $\alpha_s L \sim \mathcal{O}(1)$

$$S_c(A,B) = \exp\Big\{ \underbrace{\underbrace{\underbrace{L\, g^{(1)}(\alpha_s L)}_{LL} + g^{(2)}(\alpha_s L)}_{NLL} + \alpha_s g^{(3)}(\alpha_s L)}_{NNLL} + \alpha_s^2 \cdots \Big\}$$

- $L = \ln(Q^2\, b^2/b_0^2) \quad \widehat{=} \quad \ln(Q^2/p_T^2)$, Q: resummation scale
- LL: $g^{(1)} \to A^{(1)}$
  NLL: $g^{(2)} \to A^{(2)},\ B^{(1)},\ C^{(1)}$
  NNLL: $g^{(3)} \to A^{(3)},\ B^{(2)},\ C^{(2)}$

p_T resummation

- determination of resummation coefficients:
  - expand resummation formula in α_s
  - compare to small p_T region of fixed order cross section
  - $Q_0 \ll M$:

$$\alpha_s: \quad \int_0^{Q_0^2} \left[\frac{\mathrm{d}\sigma^{(\mathrm{res})}}{\mathrm{d}p_T^2}\right]_{NLO} \mathrm{d}p_T^2 \stackrel{!}{=} \int_0^{Q_0^2} \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{NLO} \mathrm{d}p_T^2$$

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$$f(A^{(1)}, B^{(1)}, C^{(1)}, H^{(1)}) = K_2 \ln^2(Q_0^2/M^2) + K_1 \ln(Q_0^2/M^2) + K_0 + \mathcal{O}(Q_0^2/M^2)$$

- known for Drell-Yan and $gg \to H$ up to NNLL

  [Kodaira, Trentadue '82], [Davies, Stirling '84], [Catani, D'Emilio, Trentadue '88], [de Florian, Grazzini '01], [Becher, Neubert '11], [Catani, Grazzini '11], [Catani, Cieri, de Florian, Ferrera, Grazzini '12]