Higgs production in the MSSM: Transverse momentum resummation

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HP2 : High Precision for Hard Processes, Florence (Italy)

3-5 August, 2014

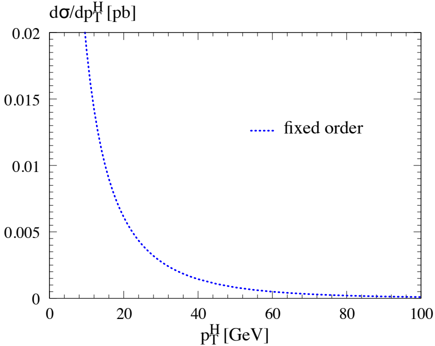
Outline

1. Transverse momentum resummation
2. SM vs. MSSM Higgs production
3. $b\bar{b}H$: NNLO+NNLL distribution in the 5FS
4. Gluon fusion: NLO+NLL distribution in the MSSM

p_T resummation

- 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 $p_T \ll M$

$$\alpha_s: \quad \ln(p_T^2/M^2),\ \ln^2(p_T^2/M^2)$$
$$\alpha_s^2: \quad \ln(p_T^2/M^2),\ \ln^2(p_T^2/M^2),\ \ln^3(p_T^2/M^2),\ \ln^4(p_T^2/M^2)$$
$$\ldots$$



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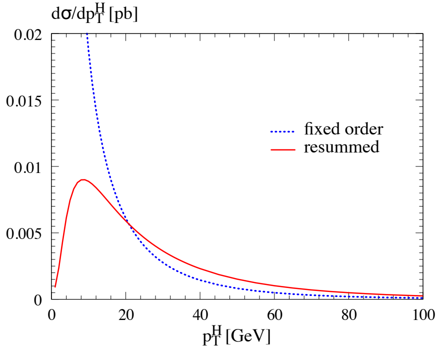
- solution: all order resummation



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]

$$\frac{d\sigma_N^{(\text{res})}}{dp_T^2} \sim \int db\,\frac{b}{2}\,J_0(b\,p_T)\,S(b,A,B)\,\mathcal{H}_N\,f_N\,f_N, \quad \mathcal{H}_N = H_N\,C_N\,C_N$$

- we use newer formulation including various improvements:

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

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

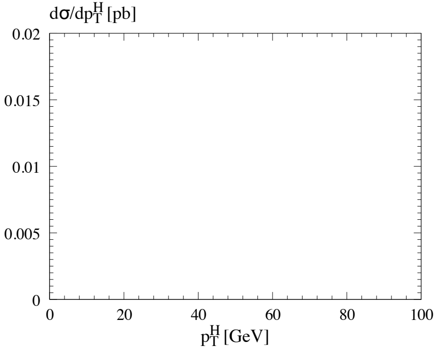
    $\rightarrow$ reduction of impact at high p_T (low b)

    $\rightarrow$ 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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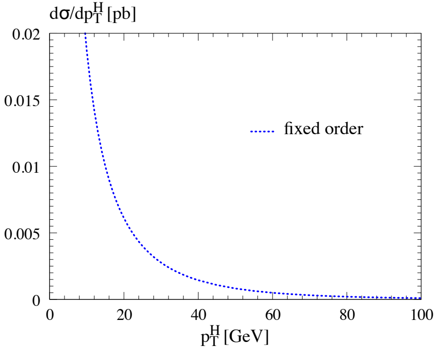

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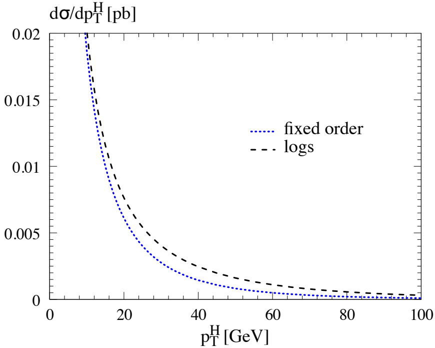

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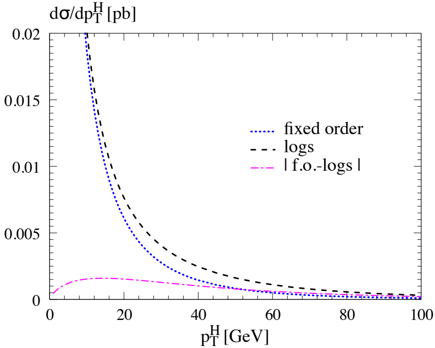

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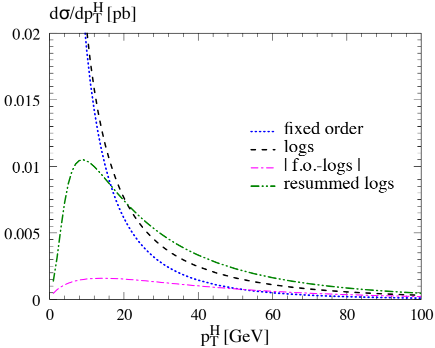

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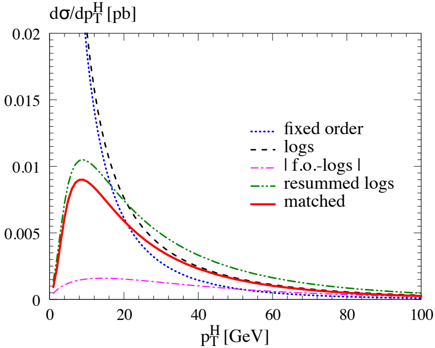
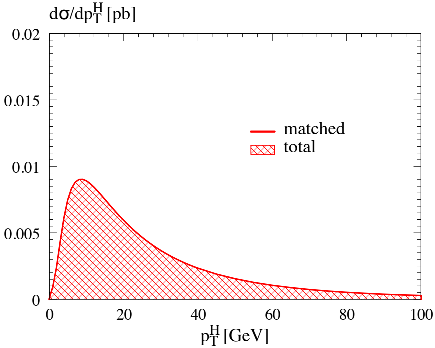


Matching

- 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

- SM 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]
- SM Higgs production through gluon fusion with full mass dependence
  [Mantler, MW '12], [Grazzini, Sargsyan '13]

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- SM Higgs production through gluon fusion with full mass dependence
  [Mantler, MW '12], [Grazzini, Sargsyan '13]
- Recently: Higgs production through bottom annihilation
  [Harlander, Tripathi, MW '14]
- new: MSSM Higgs production in gluon fusion
  [Harlander, Mantler, MW '14]

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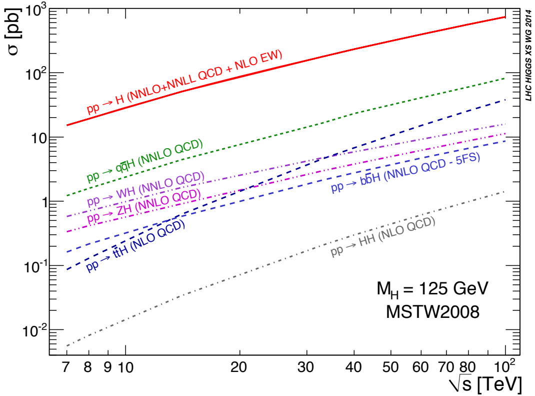

- SM:
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  - $b\bar{b}H$ sizeable only with b-tagging

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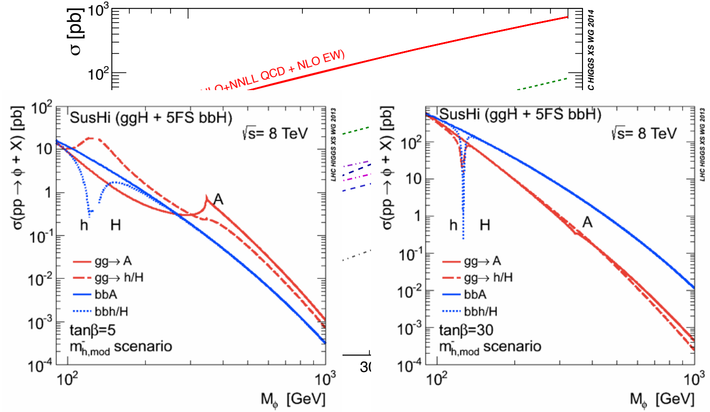

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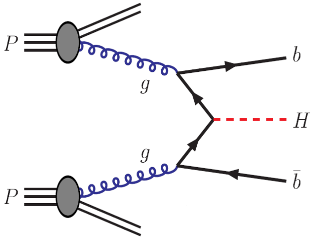
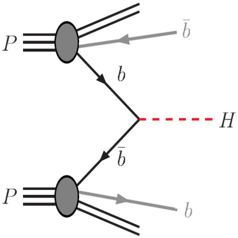
  - gluon fusion by far dominant
  - $b\bar{b}H$ sizeable only with b-tagging
- MSSM/2HDM:
  - 3 neutral Higgs: h, H and A
  - y_b/y_t enhanced by $\tan\beta$
  - h: constrained to be SM-like
  - $b\bar{b}H/A$ dominant for large $\tan\beta$

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

<u>4-flavour scheme</u>



<u>5-flavour scheme</u>



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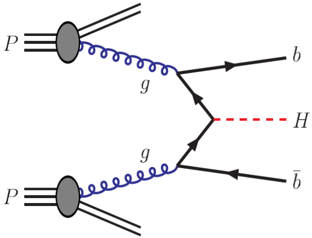

- exclusive up to NLO

  [Dittmaier, Krämer, Spira '04]

  [Dawson, Jackson, Reina, Wackeroth '04]

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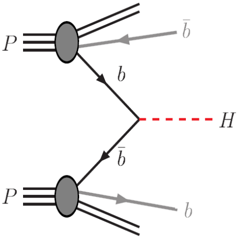

- inclusive up to NNLO

  [Harlander, Kilgore '03]

- exclusive up to NNLO

  [Buehler, Herzog, Lazopoulos, Mueller '12]

- NLO+NLL p_T resummation

  [Belyaev, Nadolsky, Yuan '06]

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$b\bar{b}H$: 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 [Ozeren '10]

α_s:

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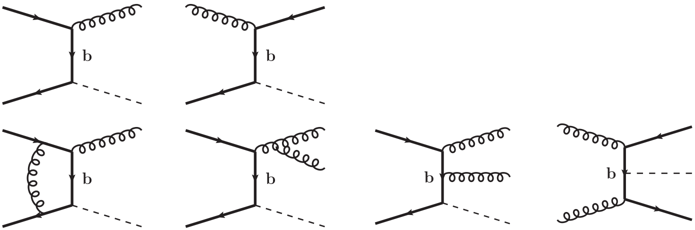

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  $A^{(1)}$, $A^{(2)}$, $B^{(1)}$ [Kodaira, Trentadue '82], $C^{(1)}$ [Davies, Stirling '84],
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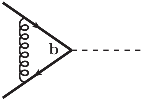
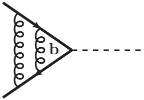


- new: [Harlander, Tripathi, MW '14]
  $H^{b\bar{b}H(2)} = 10.47 \pm 0.08$ (numerical result)

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



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

  → see Leandro's talk

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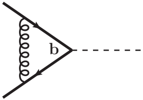

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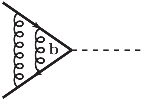

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- $+\ H^{b\bar{b}H(1)}$ and $H^{b\bar{b}H(2)}$
- third term: modified version of `HqT`

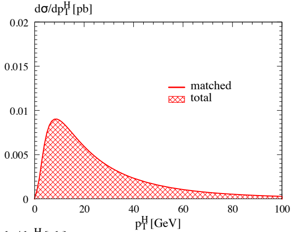
[Bozzi, Catani, de Florian, Grazzini '03 '05]

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

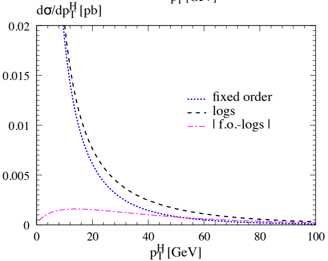
$b\bar{b}H$: Checks

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

- unitarity: $\int \frac{d\sigma}{dp_T} dp_T = \text{total}$
  - 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}

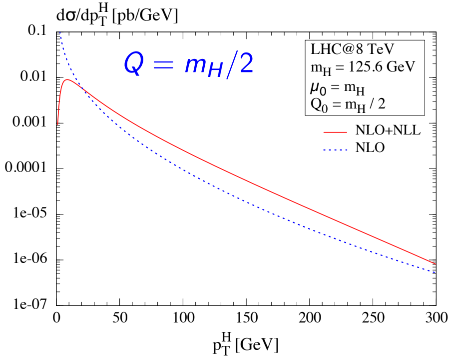


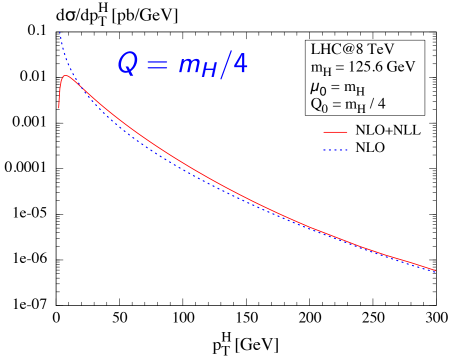
$b\bar{b}H$: Results

NLO+NLL distribution:

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

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





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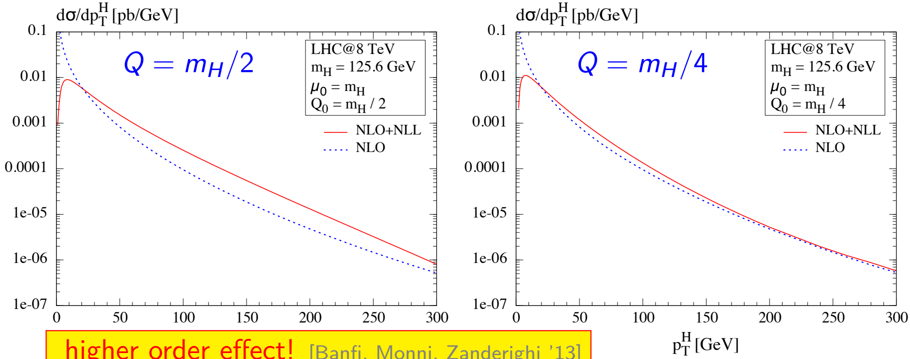

higher order effect! [Banfi, Monni, Zanderighi '13]

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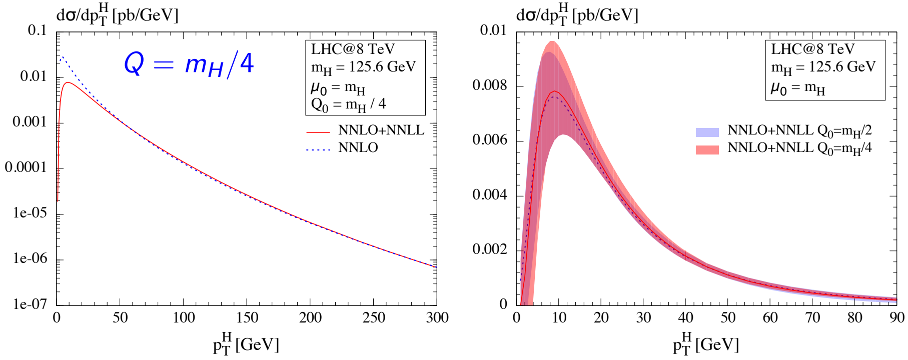

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Scale uncertainties:

[Harlander, Tripathi, MW '14]

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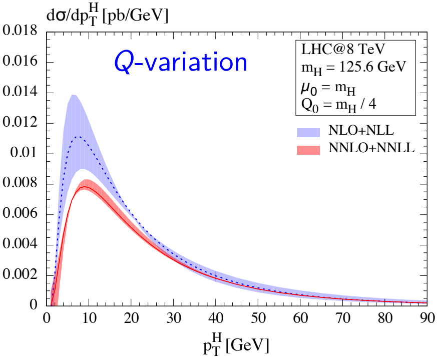

$b\bar{b}H$: Results

Comparison to 5FS NLO+PS:

[Frederix, Frixione, Maltoni, Torielli, MW]

analytic resum:

$\mu_F = \mu_R = m_T/4$

NLO+PS:

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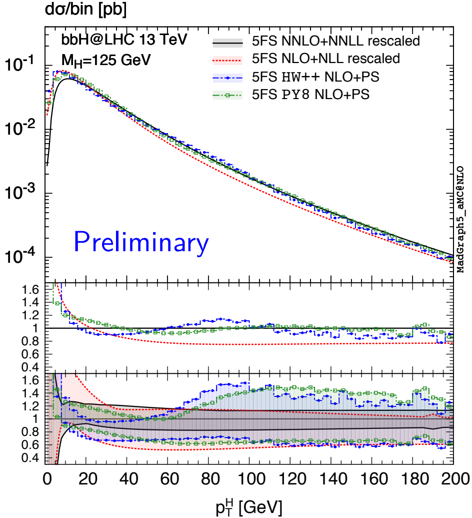

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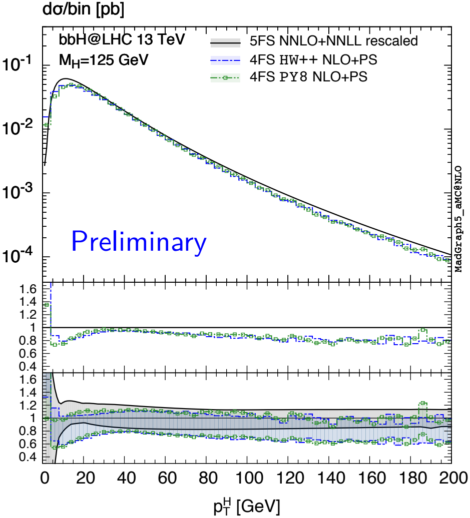

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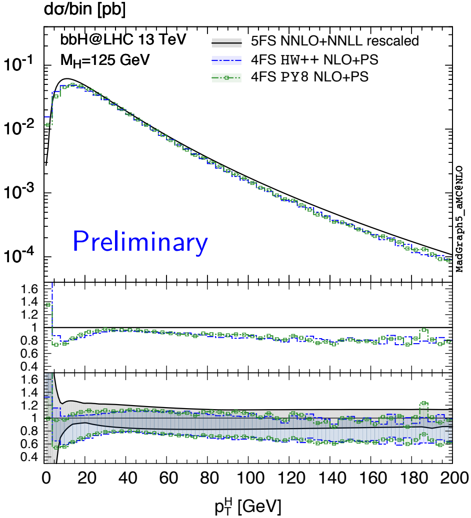
NLO+PS:

$\mu_F = \mu_R = H_T/4$



→ Q_{shower} significantly lower than Higgs mass (peak around 45 GeV, similar to μ_F)

(default shower scale in MG5_aMC distribution peaks around 190 GeV)

1. Transverse momentum resummation

2. SM vs. MSSM Higgs production

3. $b\bar{b}H$: NNLO+NNLL distribution in the 5FS

4. Gluon fusion: NLO+NLL distribution in the MSSM

Gluon fusion: Ingredients of the calculation

- NNLO+NNLL in heavy-top limit [Bozzi, Catani, de Florian, Grazzini '05]
- MSSM effects? $\rightarrow$ new: `MoRe-SusHi` (on sushi.hepforge.org)

$$\frac{d\sigma}{dp_T} = \frac{d\sigma^{\text{f.o.}}}{dp_T} - \frac{d\sigma^{\text{logs}}}{dp_T} + \frac{d\sigma^{\text{res}}}{dp_T}$$

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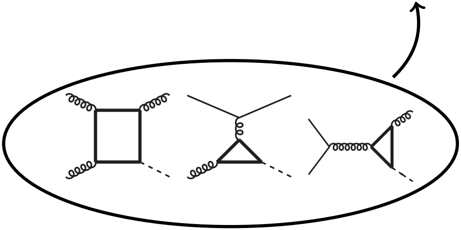

Amplitudes from `SusHi`

[Harlander, Liebler, Mantler '12]

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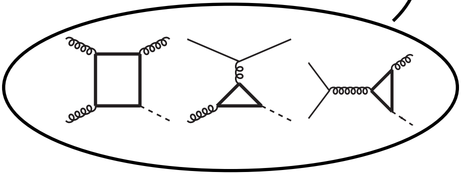
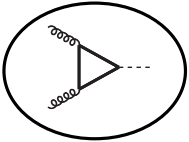


$\sigma^{(0)}_{\text{t+b}}$



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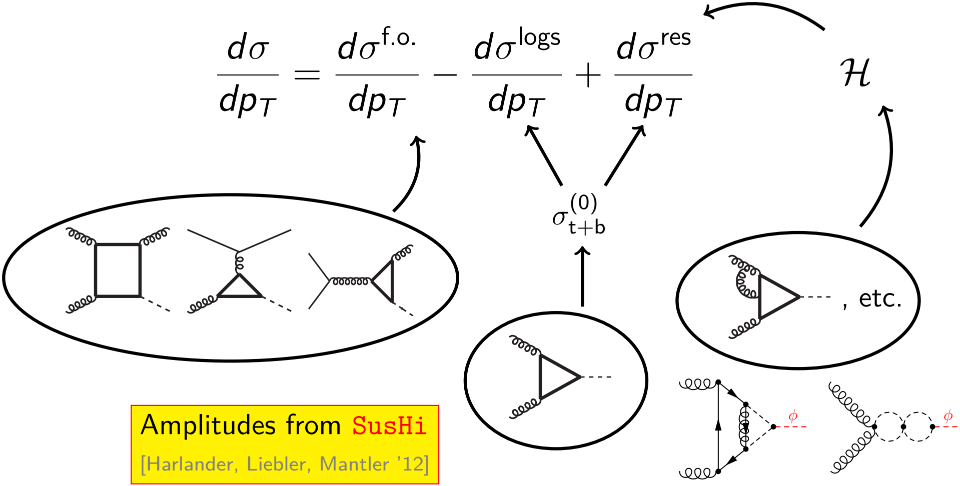


Amplitudes from SusHi
[Harlander, Liebler, Mantler '12]

Gluon Fusion: Results

NLO+NLL ratio in the MSSM/SM (light Higgs):

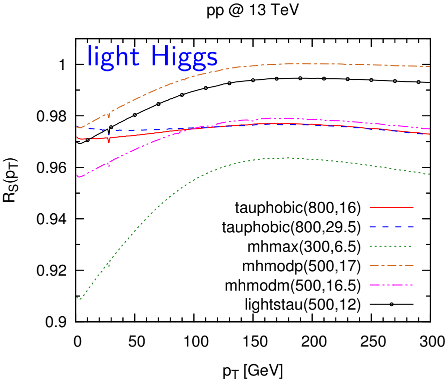
[Harlander, Mantler, MW '14]

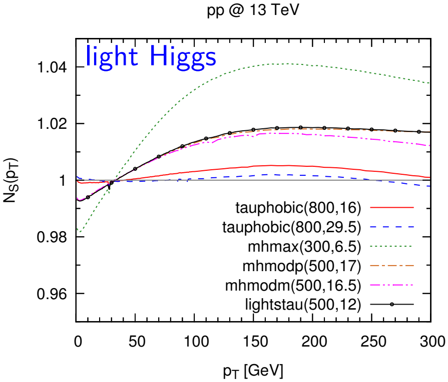
$$R_{\mathcal{S}}(p_T) = \frac{\mathrm{d}\sigma_{\mathcal{S}}/\mathrm{d}p_T}{\mathrm{d}\sigma_{\mathrm{SM}}/\mathrm{d}p_T}$$

ratio to SM

$$N_{\mathcal{S}}(p_T) = \frac{\mathrm{d}\sigma_{\mathcal{S}}/\mathrm{d}p_T}{\mathrm{d}\sigma_{\mathrm{SM}}/\mathrm{d}p_T} \cdot \frac{\sigma_{SM}}{\sigma_{\mathcal{S}}}$$

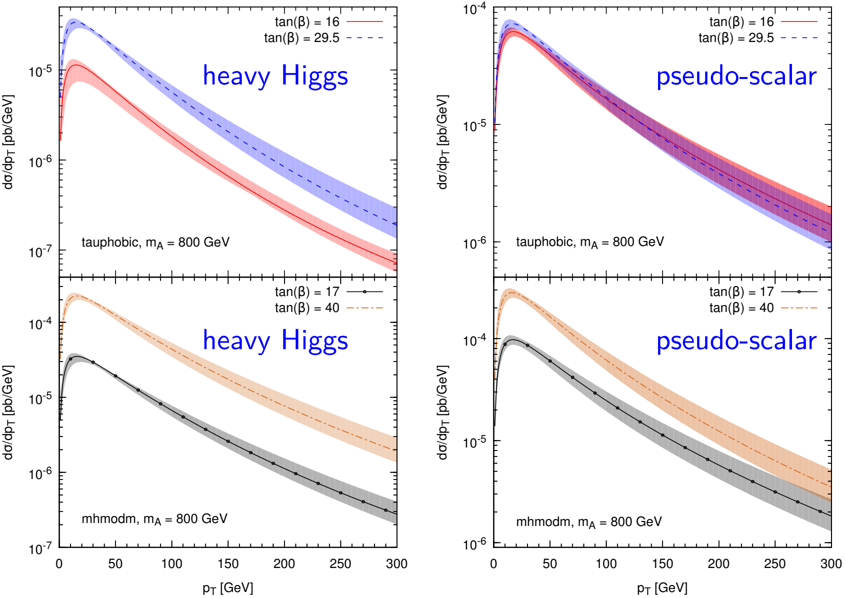
shape-ratio to SM





Benchmark Scenarios from [Carena, Heinemeyer, Stål, Wagner, Weiglein '13]

Gluon Fusion: Results

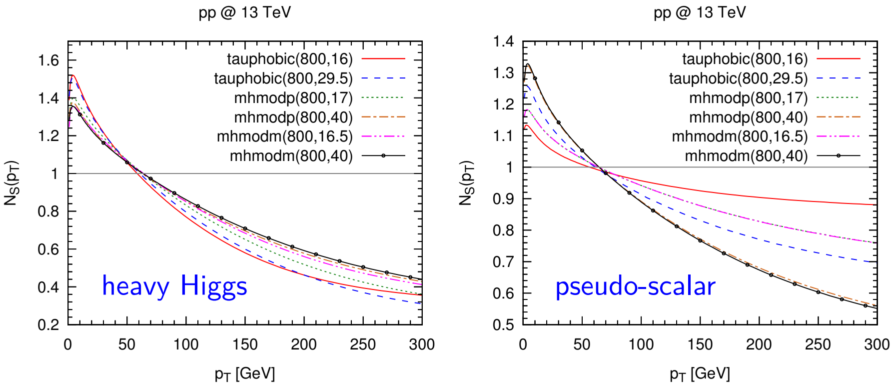


Gluon Fusion: Results

NLO+NLL distribution in the MSSM (left: heavy, right: pseudo-scalar):

[Harlander, Mantler, MW '14]

$$N_{\mathcal{S}}(p_T) = \frac{\mathrm{d}\sigma_{\mathcal{S}}/\mathrm{d}p_T}{\mathrm{d}\sigma_{\mathrm{SM}}/\mathrm{d}p_T} \cdot \frac{\sigma_{SM}}{\sigma_{\mathcal{S}}}$$



Conclusions and Outlook

Conclusions:

- $b\bar{b}H$ and gluon fusion crucial in MSSM/2HDM

$b\bar{b}H$:

- 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
- consistent with NLO+PS results
- remarkable agreement of 5FS NNLO+NNLL with 4FS NLO+PS

gluon fusion:

- `MoRe-SusHi`: MSSM effects included in analytic resummation
- h: quite SM-like
- H/A: significant shape/normalization distortion from b-loop

Outlook:

- first NLO+PS in 4FS
- complete differential comparison 4FS and 5FS for $H(b\bar{b})$
- inclusion of $b\bar{b}H$ into `MoRe-SusHi`

BackUp

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:

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

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

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

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

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

- recently: universal Form of $H^{(2)}$ determined

  [Catani, Cieri, de Florian, Grazzini '13]

  $\rightarrow$ for both gg- and $q\bar{q}$-initiated processes

  $\rightarrow$ process dependence: finite part of virtuals

- anlytical result from two-loop virtuals:

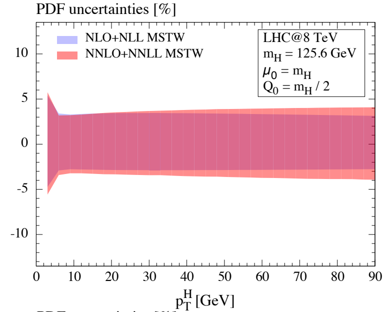
  [Harlander, Tripathi, MW '14]

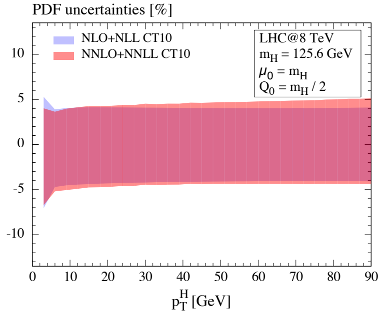
$$H_b^{b\bar{b}H,(2)} = C_F \Big[\left(\frac{321}{64} - \frac{13}{48}\pi^2\right) C_F + \left(-\frac{365}{288} + \frac{\pi^2}{12}\right) N_f + \left(\frac{5269}{576} - \frac{5}{12}\pi^2 - \frac{9}{4}\zeta_3\right) C_A \Big] = 10.52\ldots$$

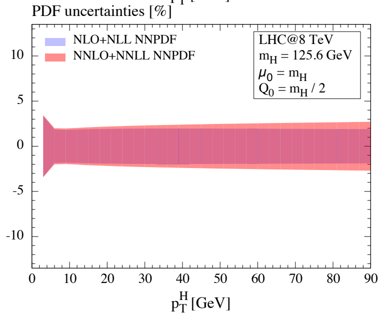
Results

PDF+α_s uncertainties:

[Harlander, Tripathi, MW '14]





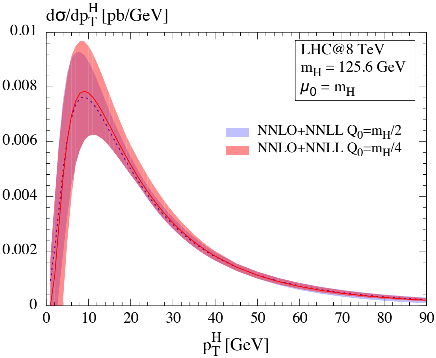


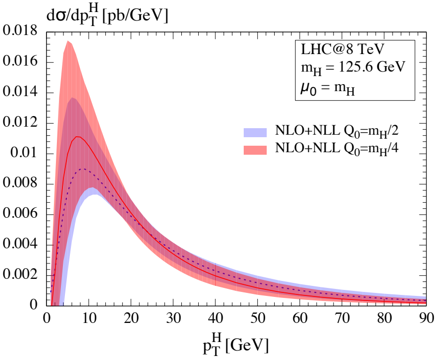
$b\bar{b}H$: Results

$Q = m_H/2$ vs. $Q = m_H/4$:

[Harlander, Tripathi, MW '14]

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





p_T resummation

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

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

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

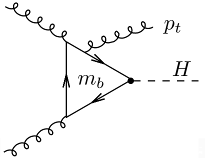
- known for Drell-Yan and $gg \to H$ up to NNLL

  [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]

Gluon fusion: Choosing the resummation scale

- $Q_b \equiv Q_{tb} = m_b$ in SM suggested due to appearance of terms
  [Grazzini, Sargsyan '13]

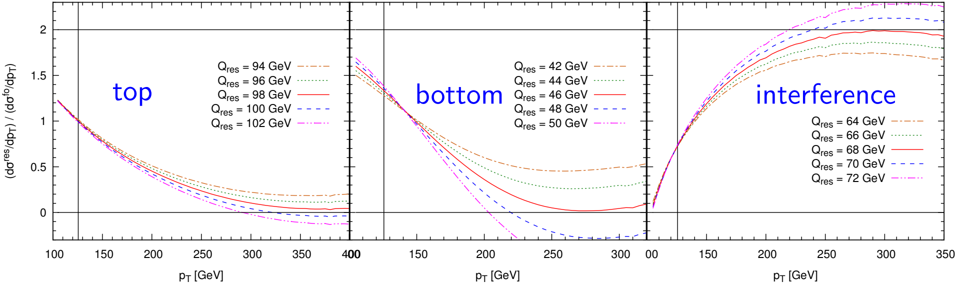
  $$\sim ln(m_b/p_T)$$



  - vanish as $p_T \to 0 \Rightarrow$ no factorization breaking, no Sudakov logs
  - directly related to $\ln(m_b/m_H)$ in total rate
  - HOWEVER: could spoil collinear/soft approximation
    $\Rightarrow$ Sudakov resummation would be unsufficient
  - BUT: if small, treated as all other finite terms (power corrections in p_T)
- choosing Q_b (and Q_{tb}) – 2 proposals:
  1. analyze size of finite terms
     [Banfi, Monni, Zanderighi '13]
  2. consider validity of collinear/soft approximation
     [Bagnaschi, Vicini]

Gluon fusion: Choosing the resummation scale

- bad high p_T matching for large Q
- due to unitarity: cross section will even become negative
- pragmatic way to determine Q: [Harlander, Mantler, MW '14]
  require that cross section remains positive for $Q = 2\,Q_0$



high p_T matching $\rightarrow$ $Q_t = 49\,\text{GeV}$, $Q_b = 23\,\text{GeV}$, $Q_{tb} = 34\,\text{GeV}$

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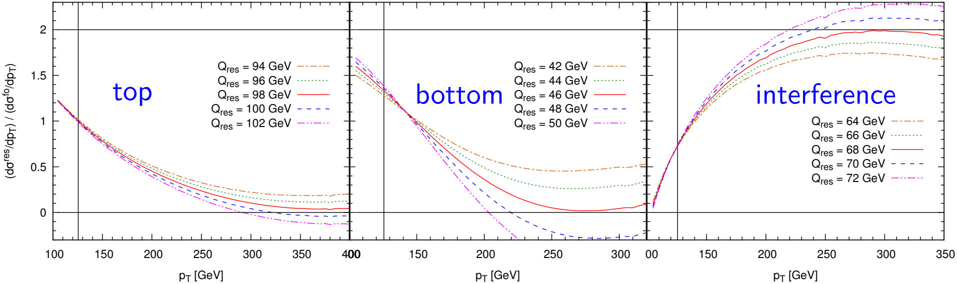
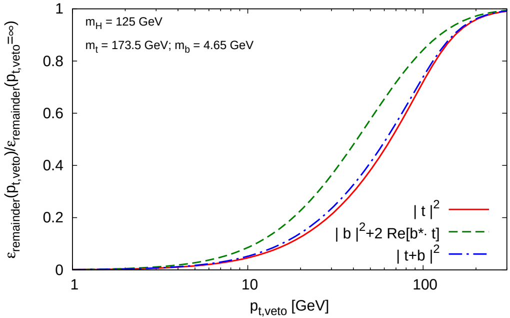


high p_T matching $\rightarrow$ $Q_t = 49$ GeV, $Q_b = 23$ GeV, $Q_{tb} = 34$ GeV
finite terms (for p_T^{veto}) $\rightarrow$ $Q_t \sim 60$ GeV, $Q_b \equiv Q_{tb} \sim 35$ GeV
soft/collinear approx (10%) $\rightarrow$ $Q_t \sim 55$ GeV, $Q_b \sim 25$ GeV

1. size of finite terms

- considered for $p_{T,\mathrm{veto}}^{\mathrm{jet}}$ efficiencies
  [Banfi, Monni, Zanderighi '13]

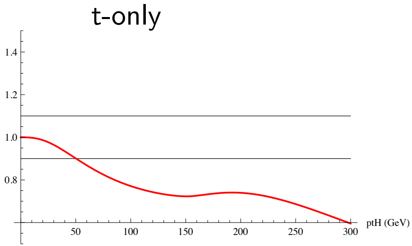


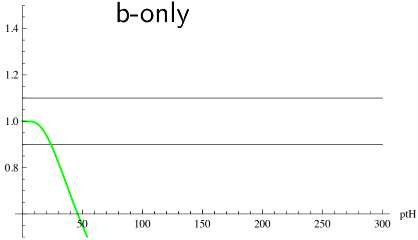
finite terms $\leq 50\%$ $\rightarrow$ $Q_t \sim 60\,\mathrm{GeV},\ Q_b \equiv Q_{tb} \sim 35\,\mathrm{GeV}$

2. validity of collinear approximation

- at matrixelement level for p_T Higgs → more in Alessandro's talk

  [Bagnaschi, Vicini]





max 10% deviation → $Q_t \sim 55\,\text{GeV},\ Q_b \sim 25\,\text{GeV}$

Gluon Fusion: Results

NLO+NLL distribution in the SM:

[Harlander, Mantler, MW '14]

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