Transverse momentum resummation for supersymmetric Higgs production

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Outline

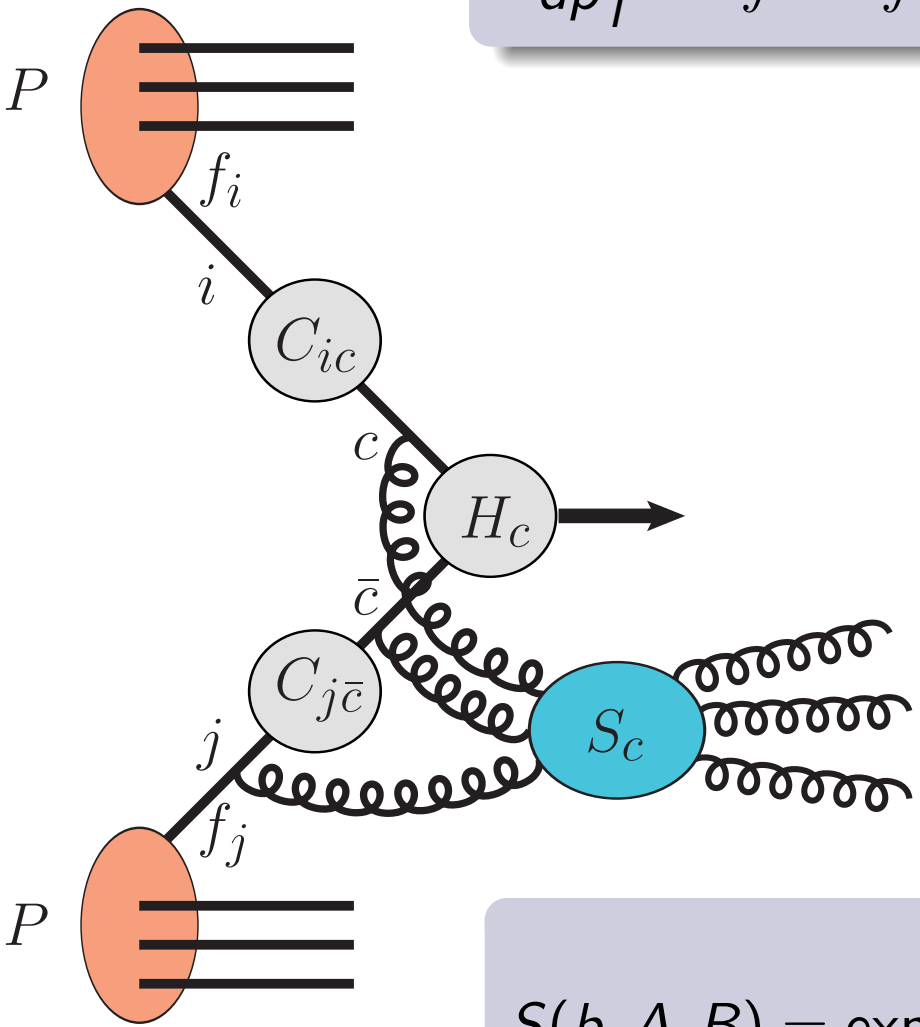
Transverse momentum resummation

- problem: fixed order p_T-distribution diverges for $p_T \to 0$
- reason: soft gluon emission produces large terms $1/p_T \ln^n(m_H/p_T)$
- solution: resummation to all orders
- 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:

  [Bozzi, Catani, de Florian, Grazzini '06]
  - single coefficient embodies whole process dependence
  - $\ln(b^2\, m_H^2/b_0^2) \to \ln(b^2\, m_H^2/b_0^2 + 1)$
    $\to$ reduction of impact at high p_T (low b)
    $\to$ unitarity constraint

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



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

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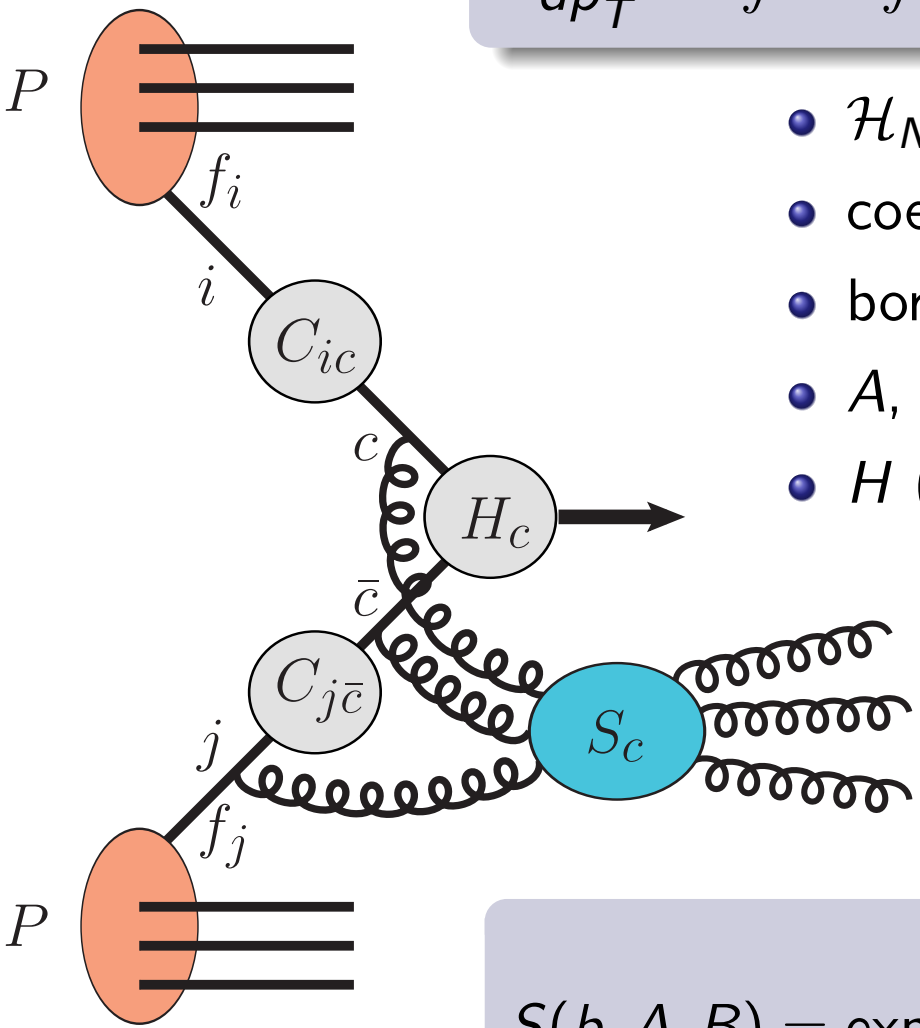

- $\mathcal{H}_N = H_N\, C_N\, C_N$
- coefficients A, B, C, H $(\mathcal{H})$ perturbative
- born initial state gg or $q\bar{q}$
- A, B, C process independent
- H $(\mathcal{H})$ process dependent

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Matched cross section

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

$\rightarrow$ finite for $p_T \rightarrow 0$

- unitary:

$$\int dp_T \, \frac{d\sigma}{dp_T} = \sigma_{tot} \quad \text{through} \quad \int dp_T \, \frac{d\sigma^{\text{res}}}{dp_T} \sim \mathcal{H}$$

Applications

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

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

- Slepton pair production

  [Bozzi, Fuks, Klasen '06]

- Vector 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]

Higgs production through gluon fusion

Transverse momentum resummation

- NLO+NNLL in heavy-top limit (htl), `HqT` [Bozzi, Catani, de Florian, Grazzini '05]
- SUSY effects? $\rightarrow$ not included

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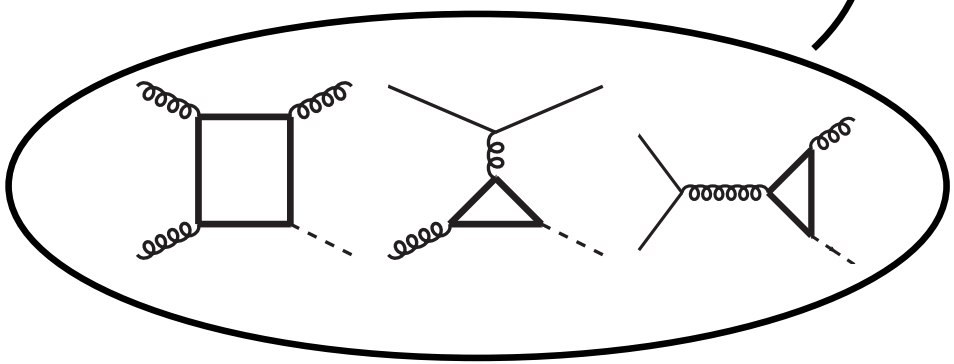

Amplitudes from `SusHi`

[Harlander, Liebler, Mantler '12]

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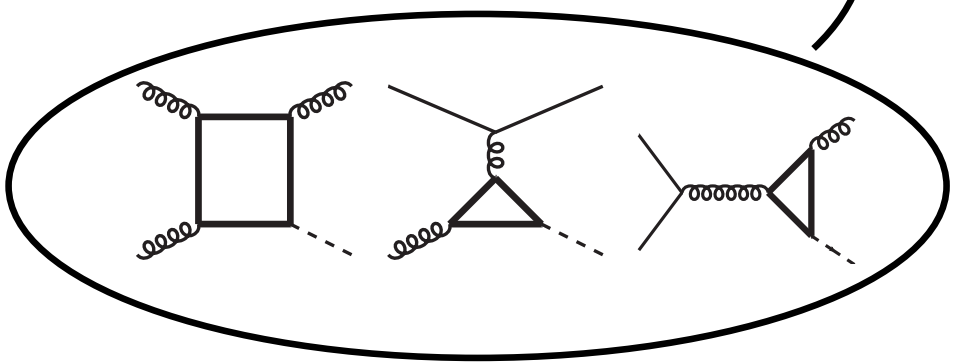
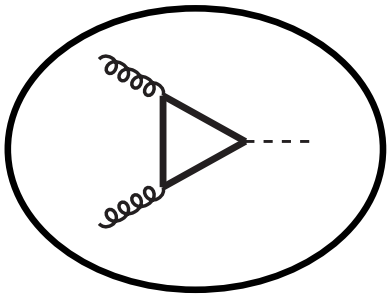


$\sigma^{(0)}_{\text{t+b}}$



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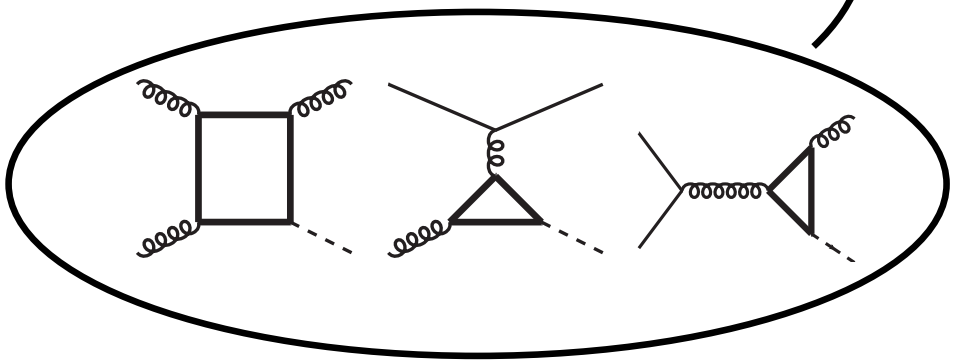

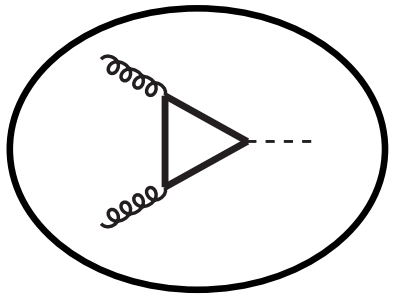

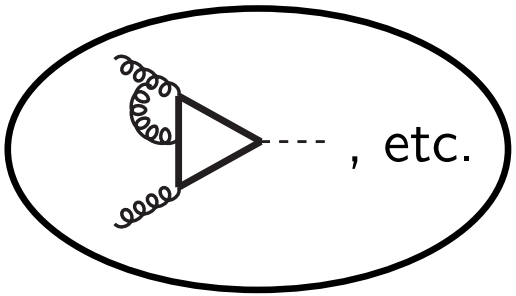

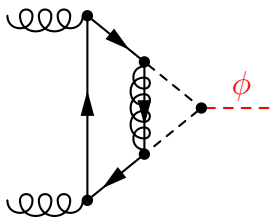

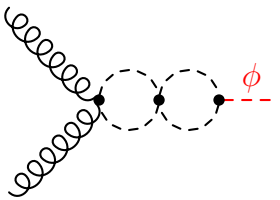

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Introducing a second resummation scale

- problem: three scales p_T, m_b and $m_H \sim m_t$
- reason: bottom contribution (including interference term)
- proposed solution: introduce second scale $Q_b \sim m_b$ for bottom contribution (while $Q_t \sim m_H$ remains for top contribution)

  [Grazzini, Sargsyan '13]
- BUT: problem only shifted
  - dominant contribution from bottom is interference term
  - logarithms $\ln(m_H/p_T)$, $\ln(m_t/p_T)$ not correctly resummed, allthough they are big
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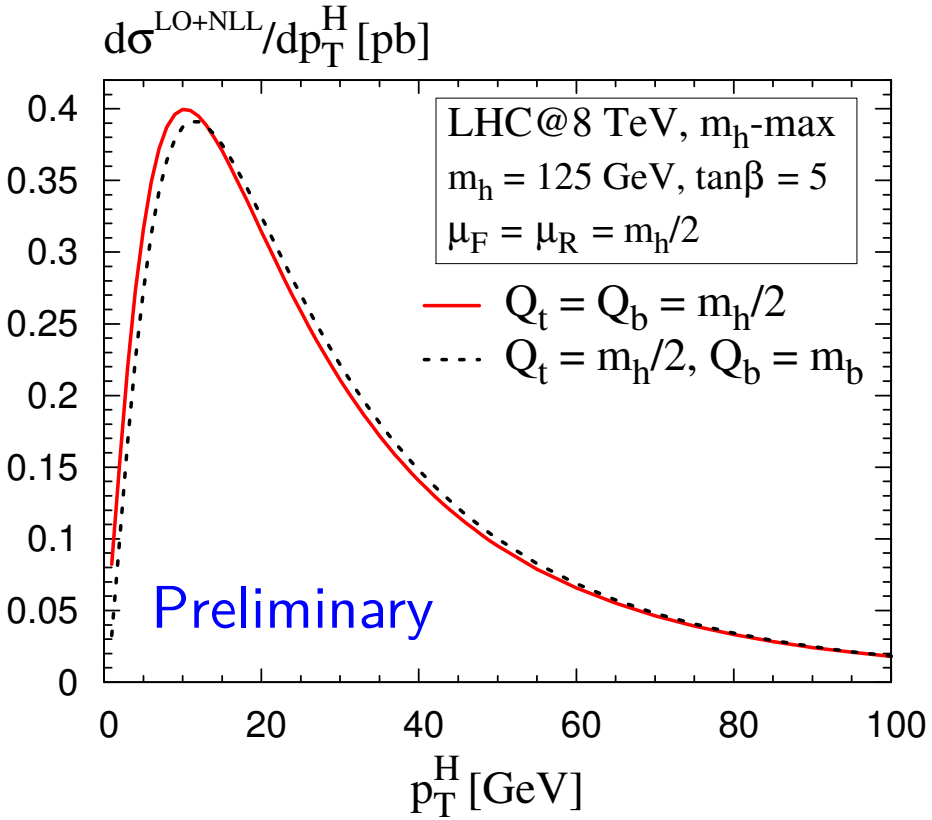
$\rightarrow$ particularly important for SUSY

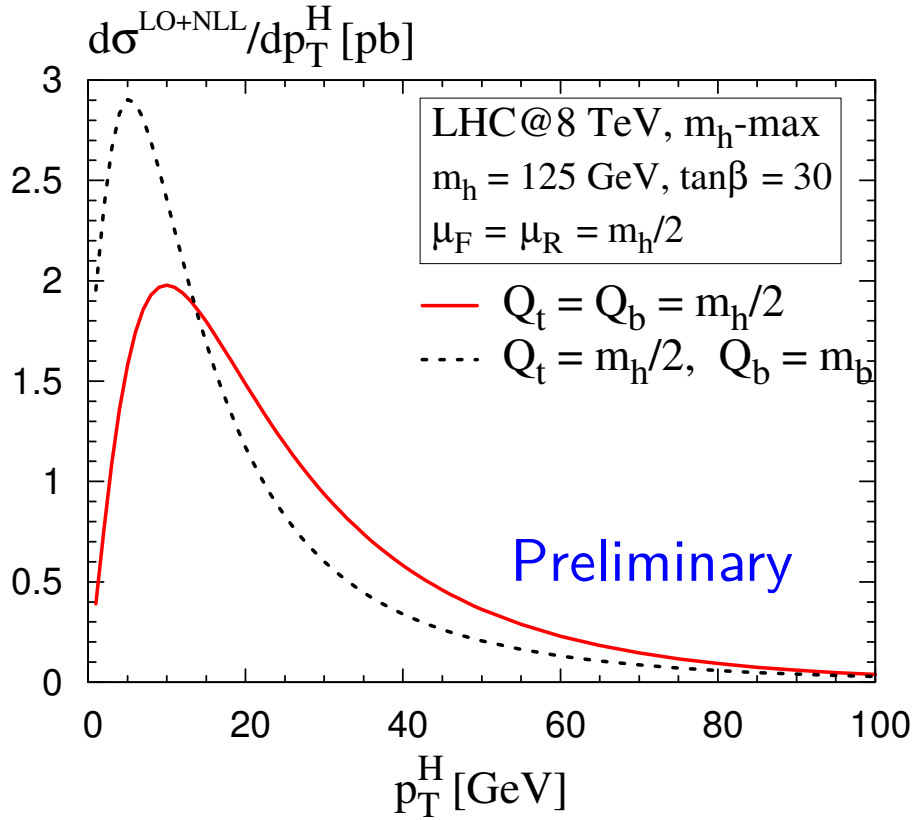
Resummed cross section

p_T distribution at LO+NLL:

[Harlander, Mantler, MW '12]

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





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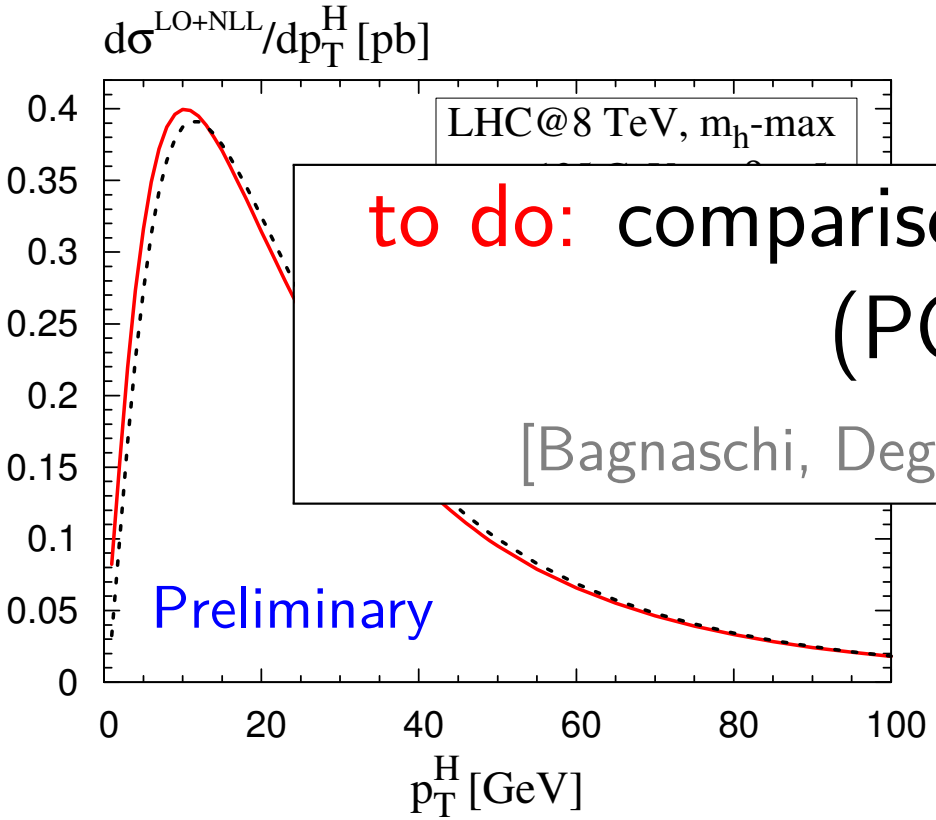
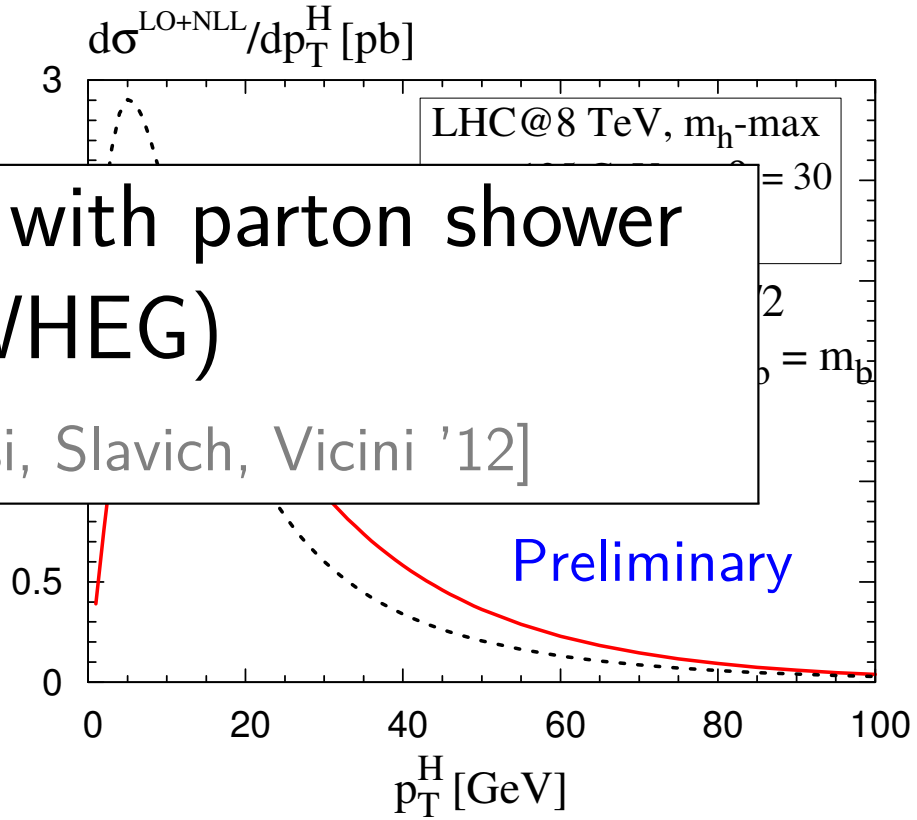




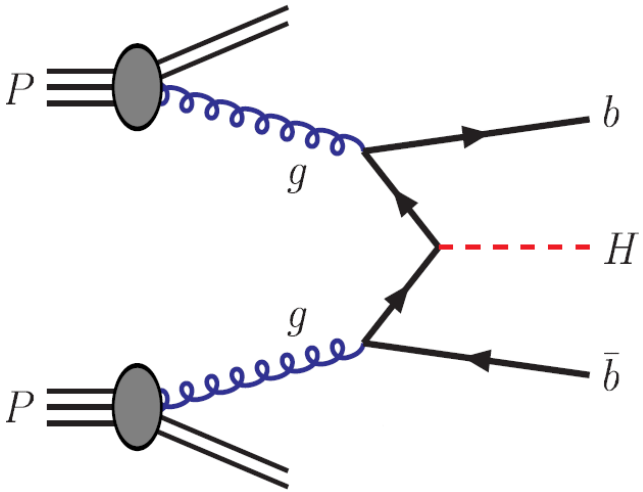
to do: comparison with parton shower (POWHEG)

[Bagnaschi, Degrassi, Slavich, Vicini '12]

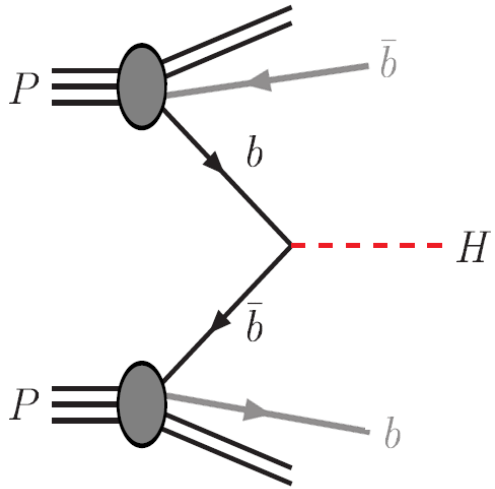
Higgs production in bottom-annihilation

4-FS vs. 5-FS

4-flavour scheme



5-flavour scheme



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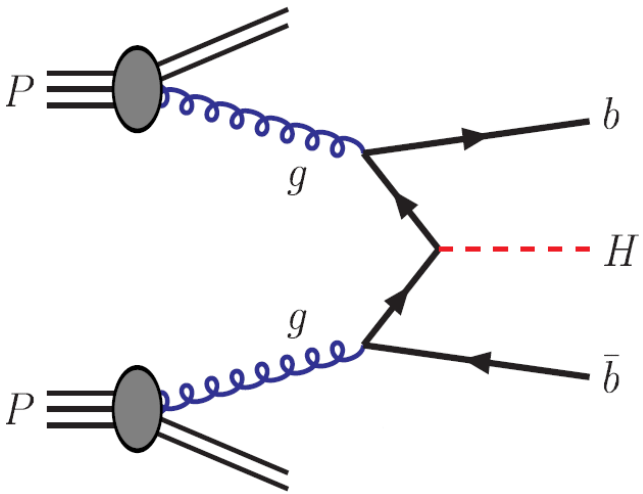

- exclusive up to NLO

  [Dittmaier, Krämer, Spira '04]

  [Dawson, Jackson, Reina, Wackeroth '04]

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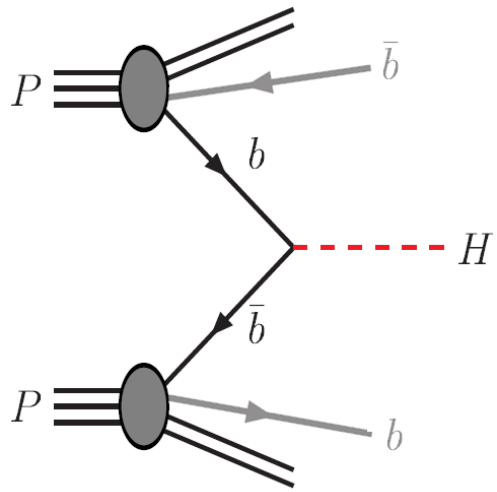

- inclusive up to NNLO

  [Harlander, Kilgore '03]

- exclusive up to NNLO

  [Buehler, Herzog, Lazopoulos, Mueller '12]

- resummation at LO+NLL

  [Belyaev, Nadolsky, Yuan '06]

4-FS vs. 5-FS

- 5-FS advantages
  - small scale dependence (because NNLO available)
  - logs resummed
  - `bbh@nnlo` fast and publicly available
  - ...
- BUT:
  - p_T-resummation only at LO+NLL
- HERE:
  - first results for resummed p_T-distribution at NLO+NNLL

Determination of $\mathcal{H}_{b\bar{b}\leftarrow b\bar{b}}$

- resummation-scheme: $H_q^{DY} = 1$ $(H_q^{DY(1)} = H_q^{DY(2)} = \cdots = 0)$
- from DY: LL: $A_q^{(1)}$; NLL: $A_q^{(2)}$, $B_q^{(1)}$, $C_{ci}^{(1)}$; NNLL: $A_q^{(3)}$, $B_q^{(2)}$, $C_{ci}^{(2)}$
- $H_b^{b\bar{b}H(1)} = 3\,C_F$
- unknown: $H_b^{b\bar{b}H(2)}$

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- $H_b^{b\bar{b}H(1)} = 3\,C_F$
- unknown: $H_b^{b\bar{b}H(2)}$
- hard-collinear function:

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

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

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- use unitarity:

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

$\rightarrow$ numerical evaluation of $H_b^{b\bar{b}H(2)}$, without approximations

Universal Form of the hard factor

- 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 virtual

  $\Rightarrow$ going to compare with our numerical result for $H^{b\bar{b}H(2)}$

Ingredients of the calculation

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

- analytic p_T-distribution at NLO
  [Ozeren '10]
- resummation coefficients from Drell-Yan
  $A^{(1)}$, $A^{(2)}$, $B^{(1)}$ [Kodaira, Trentadue '82]
  $C^{(1)}$ [Davies, Stirling '84]
  $A^{(3)}$ [Becher, Neubert '11]
  $C^{(2)}$ $(\mathcal{H}^{(2)})$ [Catani, Cieri, de Florian, Grazzini '12]
- $+$ $H^{b\bar{b}H(1)}$ and $H^{b\bar{b}H(2)}$
- third term: modified version of HqT [Bozzi, Catani, de Florian, Grazzini '05]

Checks

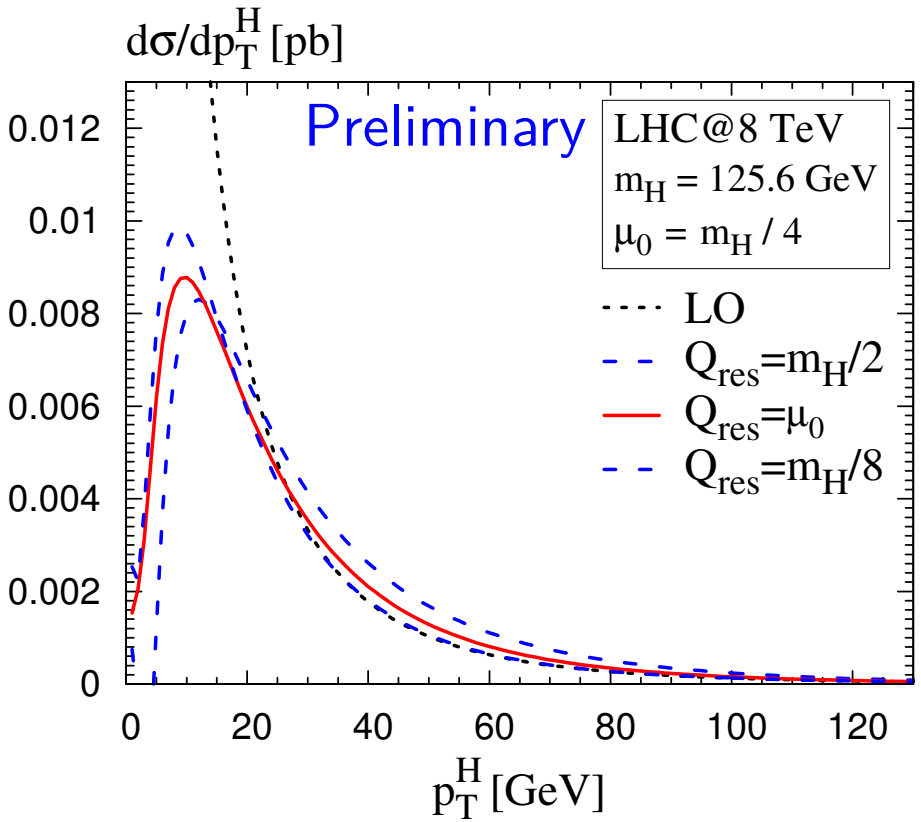
- p_T-distribution checked against numerical $H + jet$ calculation at NLO
  [Harlander, Ozeren, MW '10]
- integral over p_T = total (including full μ_F, μ_R dependence)
- integral over p_T Q_{res}-independent
- small p_T behaviour of logs = f.o. (including full μ_F, μ_R dependence)
- small pT behaviour of logs Q_{res}-independent

Results: Higgs production through bottom-annihilation

p_T distribution at LO+NLL:

[Harlander, Tripathi, MW]

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



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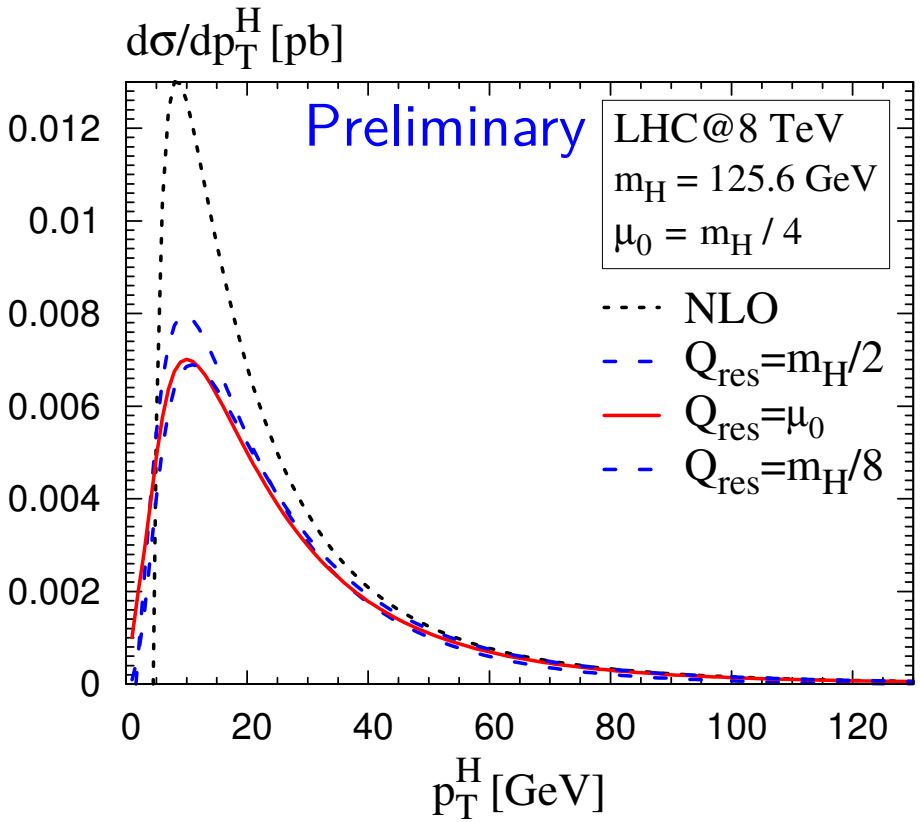


Conclusions and Outlook

Conclusions:

- gluon-fusion at LO+NLL for supersymmetric Higgs
- choice of Q_b even more problematic
- missing hard coefficient at two-loop for $b\bar{b}H$ determined numerically
- first calculation of NNLL effects for $b\bar{b}H$ production
- strong reduction of resummation scale dependence

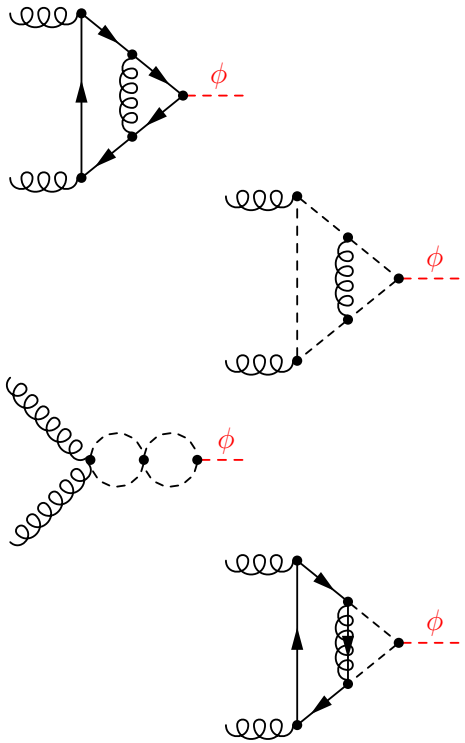
Outlook:

- 2HDM studies for $gg \to H$
- comparison analytic resummation and parton shower for $gg \to H$
- comparison 4- and 5-FS for $b\bar{b} \to H$
- fully differential NNLO for $b\bar{b} \to H$

BackUp

Virtual corrections

- Quark-gluon known analytically
  (at higher orders)
  [Spira, Djouadi, Graudenz, Zerwas '95; Harlander, Kant '05]
- Squark-gluon/squark
  known analytically
  [Anastasiou, Beerli, Bucherer, Daleo, Kunszt '06;
  Aglietti, Bonciani, Degrassi, Vicini '06; Mühlleitner, Spira '06]
- Quark-squark-gluino
  semi-analytically known,
  but no public code
  [Anastasiou, Beerli, Daleo '08; Mühlleitner, Rzehak, Spira '10]



- Taylor expansion in the Higgs mass: $m_\phi \ll m_q, m_{\tilde{q}_1}, m_{\tilde{q}_2}, m_{\tilde{g}}$
  [Harlander, Steinhauser '03 '04 + Hofmann '05; Degrassi, Slavich '08]
  $\longrightarrow$ top-stop-gluino
- Expansion in SUSY masses: $m_\phi, m_q \ll m_{\tilde{q}_1}, m_{\tilde{q}_2}, m_{\tilde{g}}$
  for $m_{\tilde{q}_1} = m_{\tilde{q}_2} = m_{\tilde{g}}$ [Harlander, Hofmann, HM '10]
  for arbitrary SUSY masses [Degrassi, Slavich '10 + Di Vita '11 '12]
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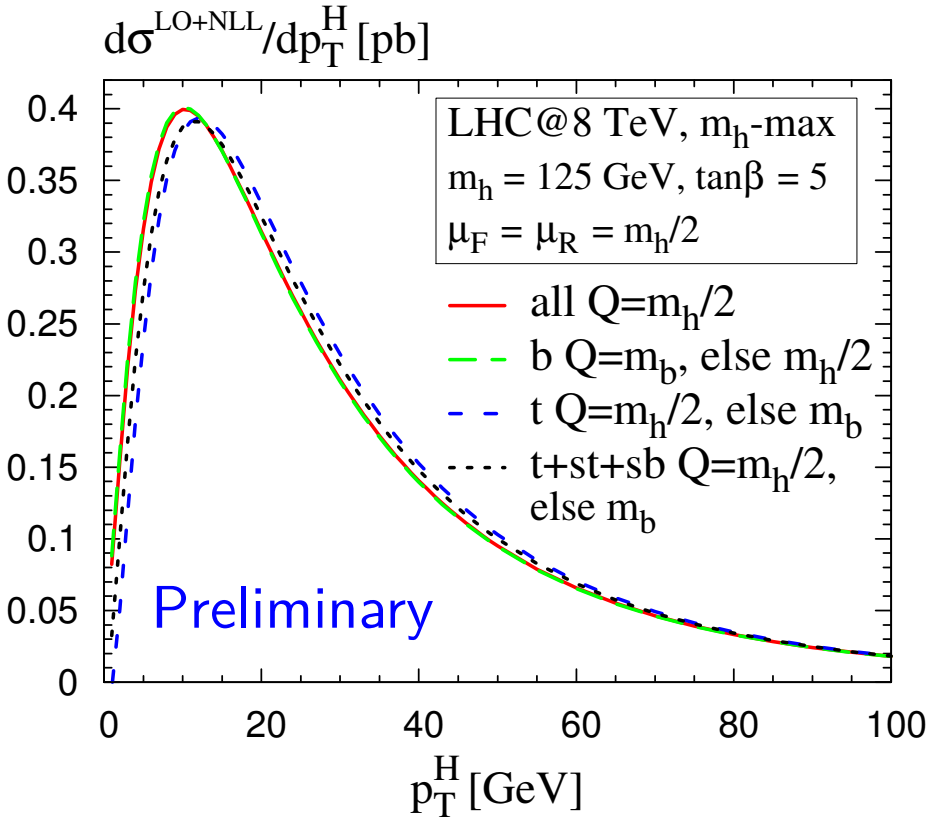
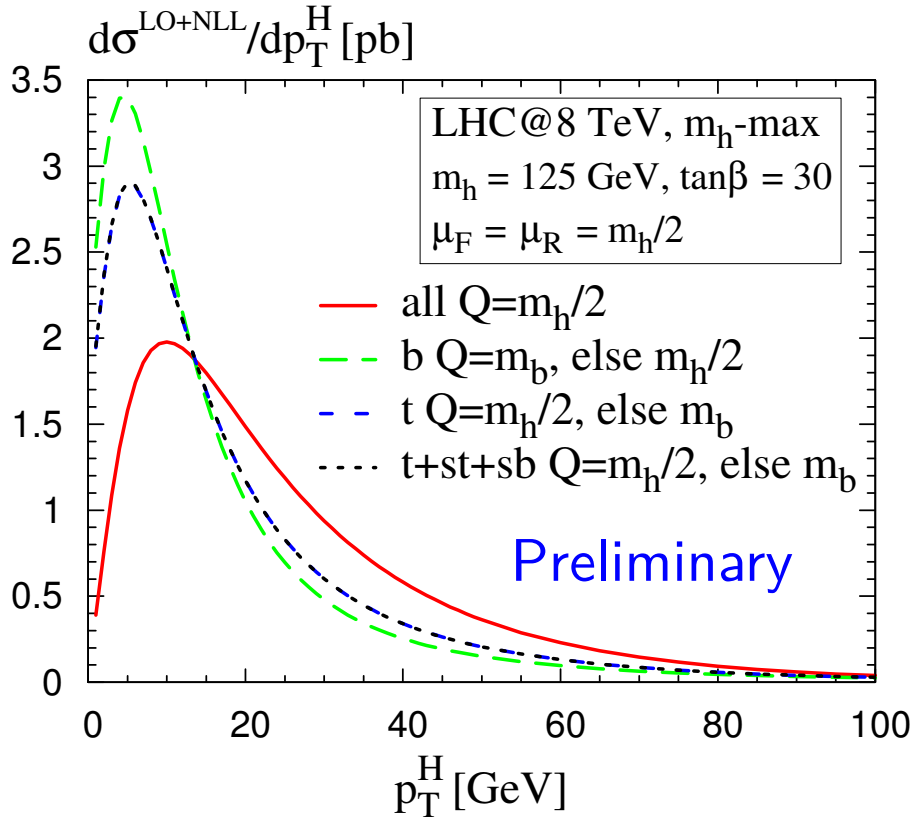
[Harlander, Mantler, MW '12]

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



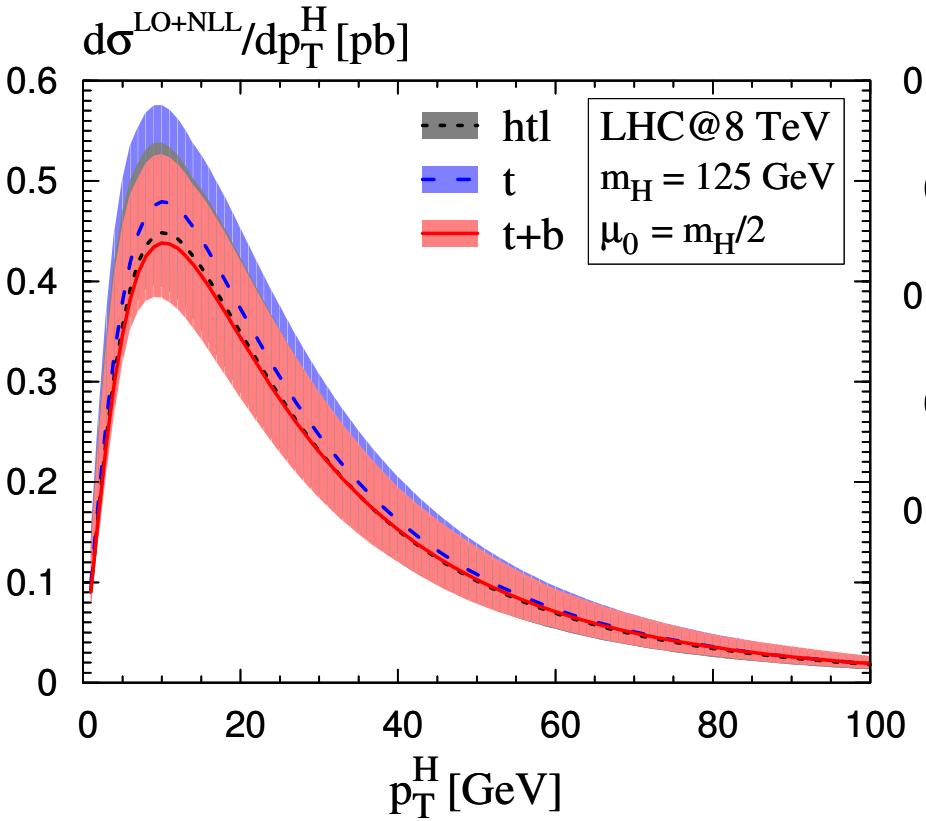


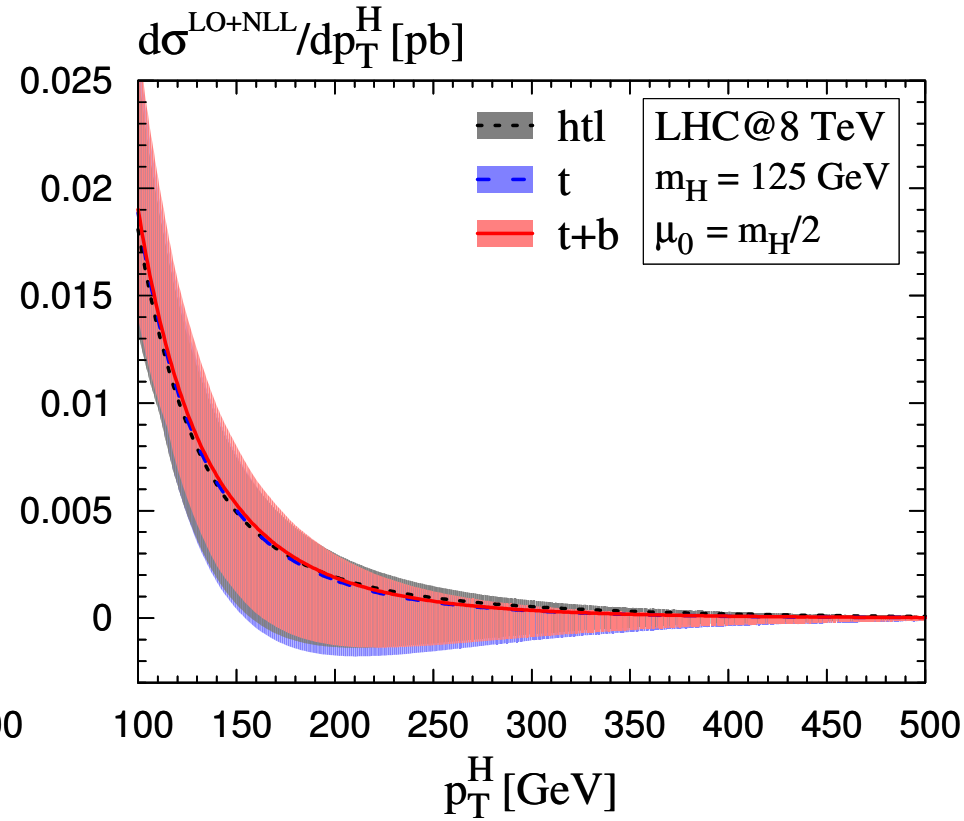
Resummed cross section

p_T distribution at LO+NLL:

[Mantler, MW '12]

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

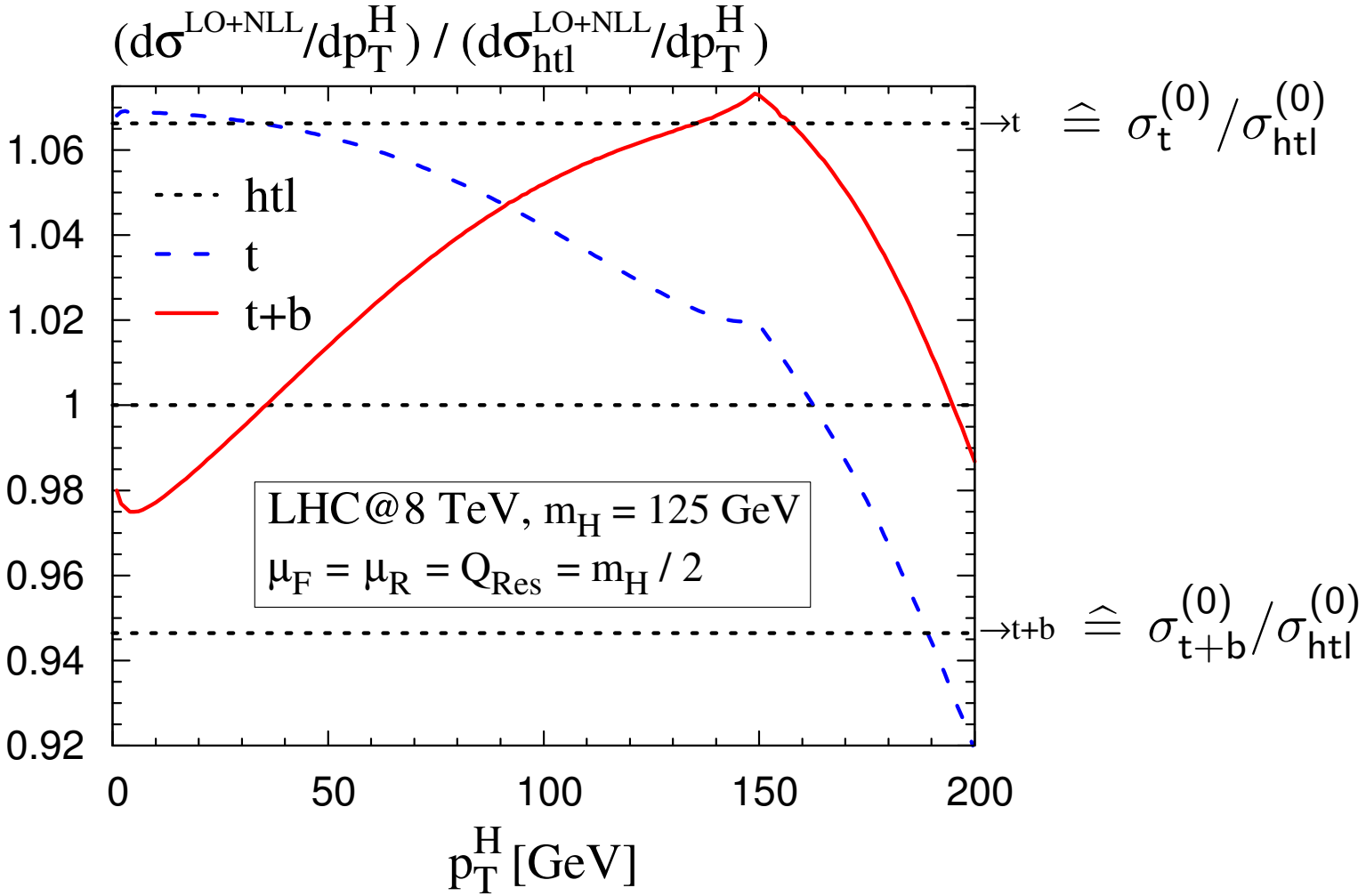




Resummed cross section

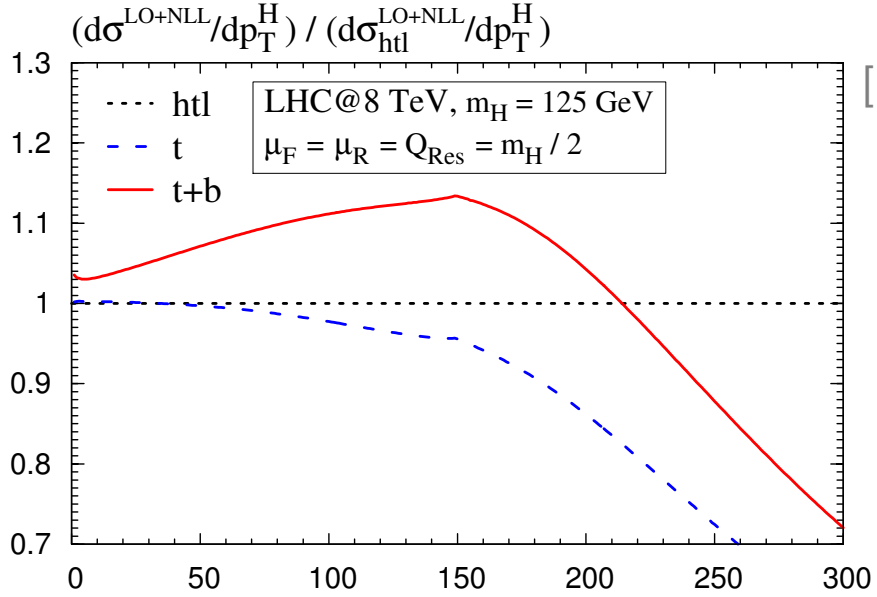
Mass effects at LO+NLL:

[Mantler, MW '12]



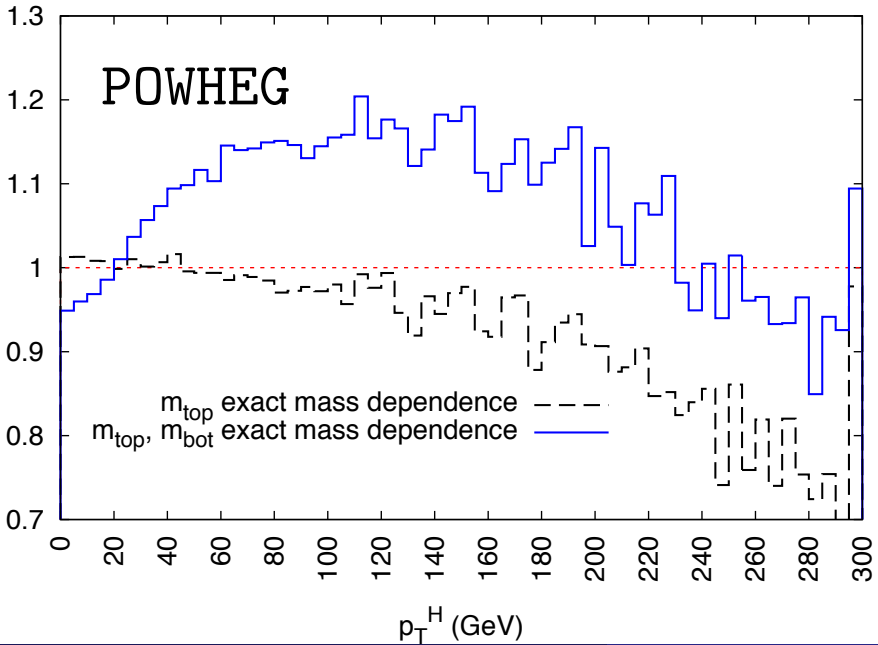
Analytic resummation vs. POWHEG vs. MC@NLO

Mass effects:

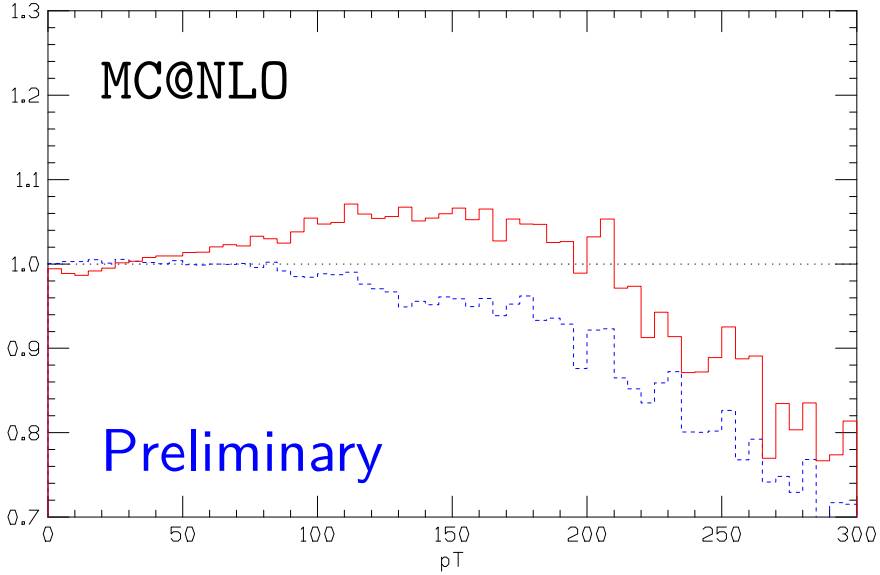


[Mantler, MW '12]

[Bagnaschi, Degrassi, Slavich, Vicini '12]

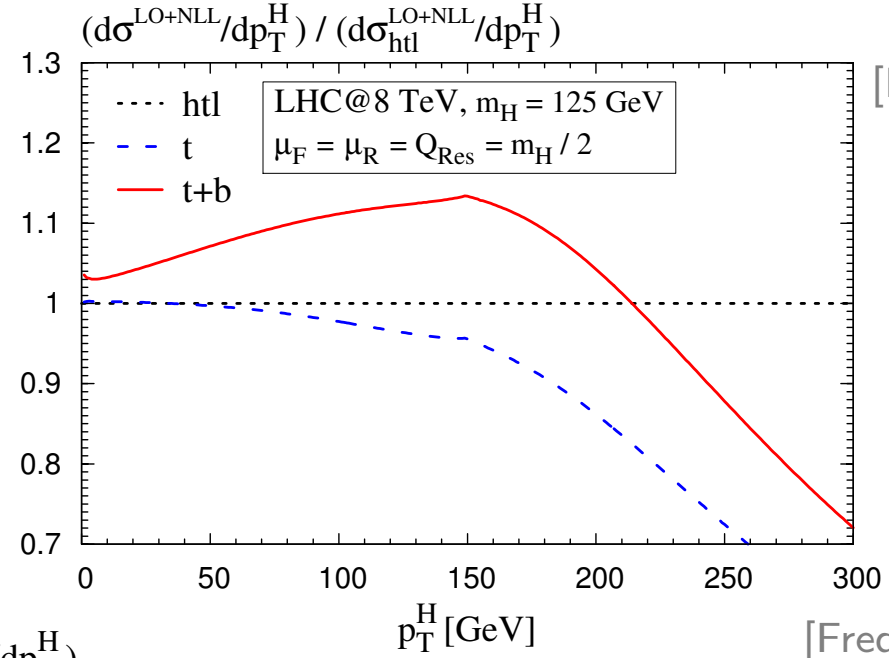


[Frederix, Frixione, Maltoni]



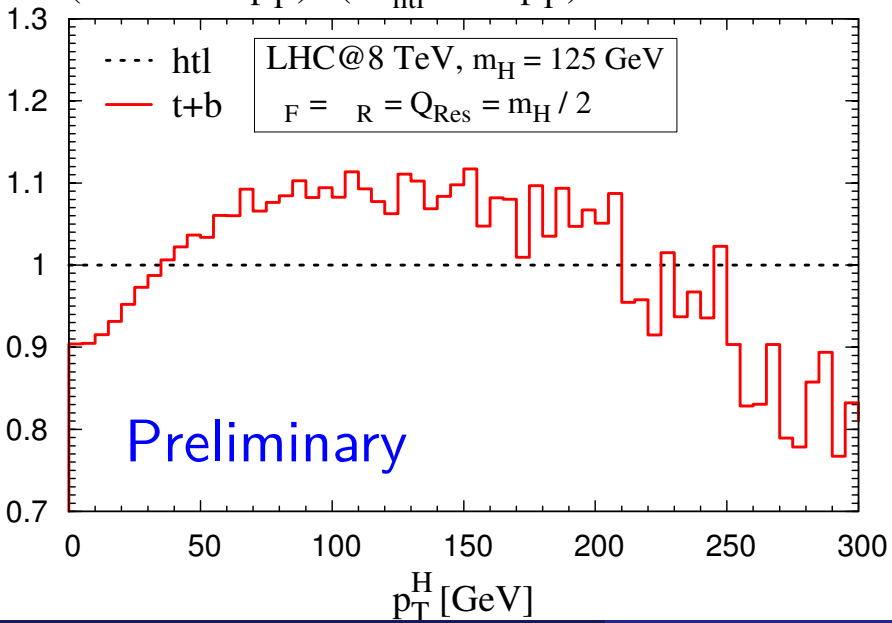
Analytic resummation vs. POWHEG vs. MC@NLO

Mass effects:

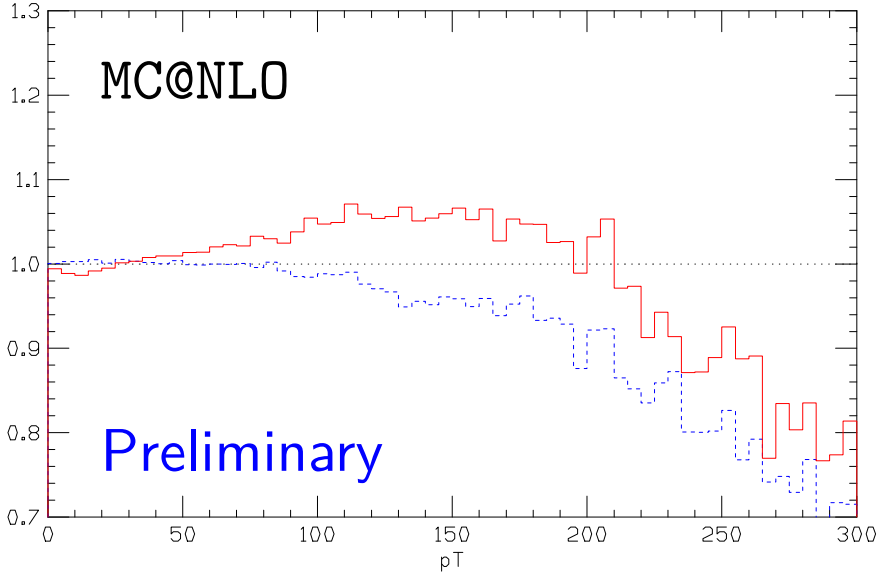


[Mantler, MW '12]

[Mantler, MW]



[Frederix, Frixione, Maltoni]



Analytic resummation vs. POWHEG vs. MC@NLO