Higgs+jet production in bottom quark annihilation

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Bergische Universität Wuppertal

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Outline

1. Introduction
   - SM Higgs production
   - Motivation $pp \to (b\bar{b})H$
   - Review: associated $b\bar{b}H$ production

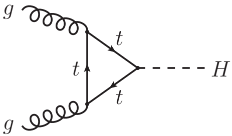
2. Higgs+jet production in bottom quark annihilation at NLO

3. $b\bar{b} \to H$ with upper cut on p_T^H at NNLO

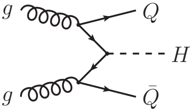
4. Higgs production with a jet veto

SM Higgs production

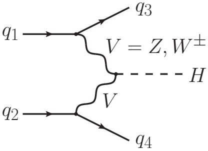
- gluon fusion $gg \to H$:



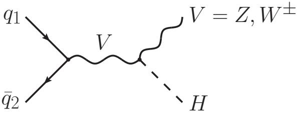
- associated $Q\bar{Q}H$ production
  $pp \to (Q\bar{Q})H$ (SM: $Q = t$):



- weak boson fusion (WBF)
  $q_1 q_2 \to q_3 q_4 H$:

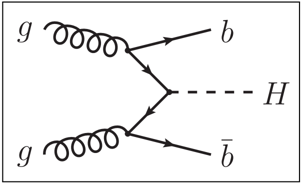


- Higgs Strahlung $q_1 \bar{q}_2 \to VH$:



Why Higgs production in bottom quark annihilation?

- Higgs production in bottom quark annihilation:



- small cross section in SM ($y_{b\bar{b}H} = \frac{m_b}{v} \ll \frac{m_t}{v} = y_{t\bar{t}H}$)
- enhanced coupling in MSSM:

$$\frac{y_{b\bar{b}H}}{y_{t\bar{t}H}} \sim \tan\beta = \frac{v_2}{v_1}$$

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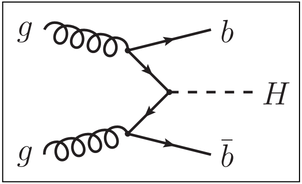

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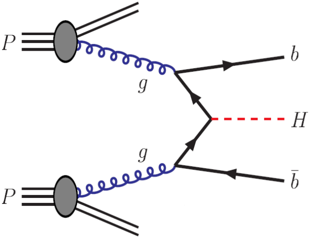
- enhanced coupling in MSSM:

$$\frac{y_{b\bar{b}H}}{y_{t\bar{t}H}} \sim \tan\beta = \frac{v_2}{v_1}$$

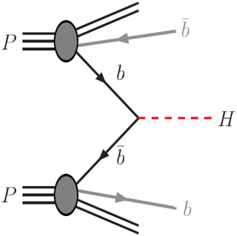
$\rightarrow$ associated $b\bar{b}H$ production can be dominant

4-FS vs. 5-FS

4-flavour scheme



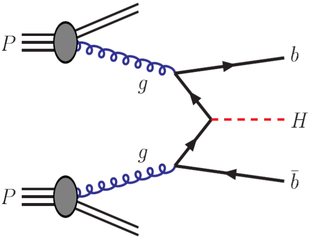
5-flavour scheme



- same contribution, different ordering of terms
- 5-FS: large $\ln\left(\frac{m_b}{m_H}\right)$ resummed in bottom PDFs

4-FS vs. 5-FS

4-flavour scheme

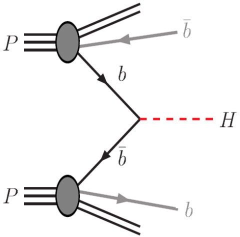


- exclusive up to NLO

  [Dittmaier, Krämer, Spira '04]

  [Dawson, Jackson, Reina, Wackeroth '04]

5-flavour scheme



- inclusive up to NLO

  [Dicus, Willenbrock '89]

  [Dicus, Stelzer, Sullivan, Willenbrock '99]

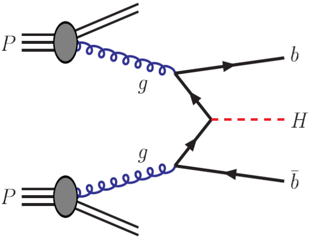
  [Maltoni, Sullivan, Willenbrock '03]

- inclusive up to NNLO

  [Harlander, Kilgore '03]

4-FS vs. 5-FS

4-flavour scheme



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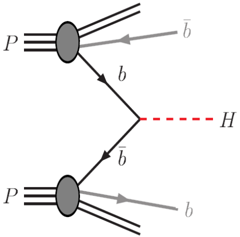
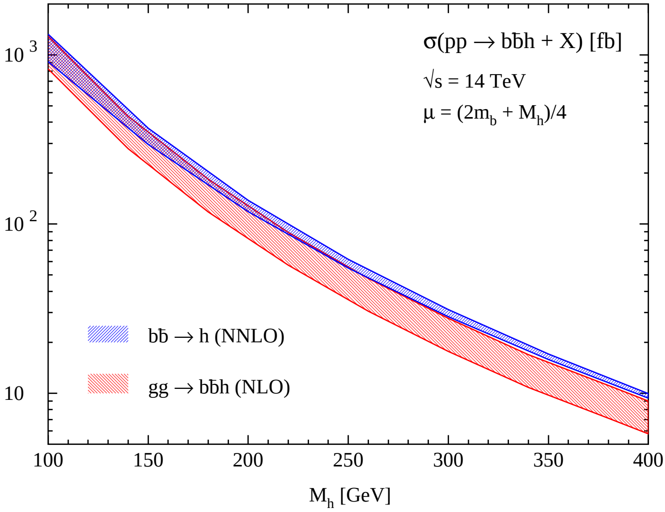


- same contribution, different ordering of terms
- 5-FS: large $\ln\left(\frac{m_b}{m_H}\right)$ resummed in bottom PDFs
- 5-FS: "natural" factorization scale $\mu_F = \frac{m_H}{4}$

[Harlander, Kilgore '03], [Plehn '03], [Maltoni, Sullivan, Willenbrock '03], [Boos, Plehn '04]

4-FS vs. 5-FS


σ(pp → bb̄h + X) [fb]
√s = 14 TeV
μ = (2m_b + M_h)/4
bb̄ → h (NNLO)
gg → bb̄h (NLO)
10 3
10 2
10
100
150
200
250
300
350
400
M_h [GeV]

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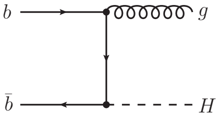
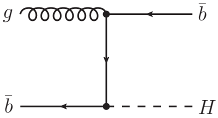
$(b\bar{b})H + jet$ calculation

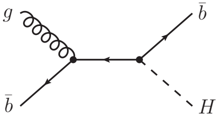
LO

$b\bar{b}$:



gb:



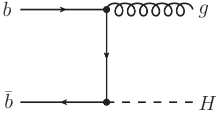


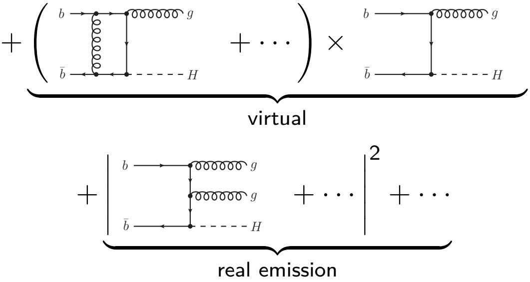
$(b\bar{b})H + jet$ calculation

LO

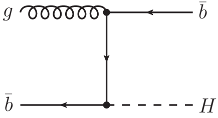
NLO

$b\bar{b}$:

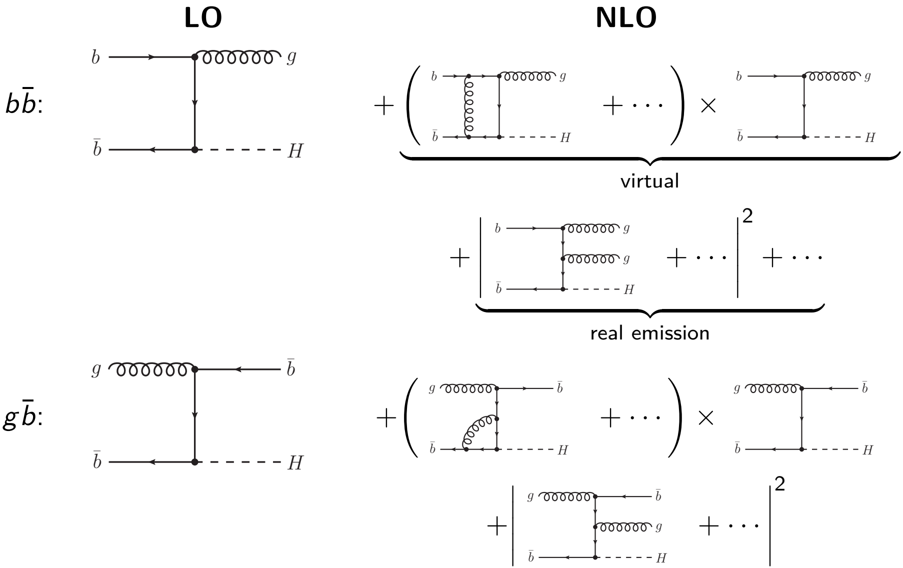




$g\bar{b}$:



$(b\bar{b})H + jet$ calculation



LO

NLO

$b\bar{b}$:

virtual

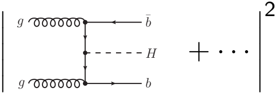
real emission

$g\bar{b}$:

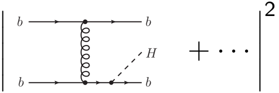
$(b\bar{b})H + jet$ calculation

LO **NLO**

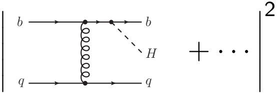
gg: —



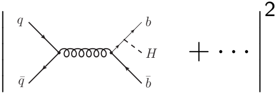
bb: —



gq: —



$q\bar{q}$: —



Catani Seymour dipole subtraction

$$\sigma = \sigma^{LO} + \sigma^{NLO} = \underbrace{\int_m d\sigma^B}_{=\sigma^{LO}} + \underbrace{\int_{m+1} d\sigma^R + \int_m d\sigma^V}_{=\sigma^{NLO}}$$

Catani Seymour dipole subtraction

$$\sigma = \sigma^{LO} + \sigma^{NLO} = \underbrace{\int_m d\sigma^B}_{=\sigma^{LO}} + \underbrace{\int_{m+1} d\sigma^R + \int_m d\sigma^V}_{=\sigma^{NLO}}$$

- introduce a subtraction term that approximates the real emission

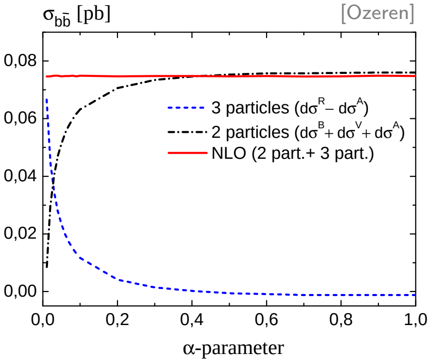
$$\Rightarrow \quad \sigma^{NLO} = \int_{m+1} \left[\left(d\sigma^R \right)_{\varepsilon=0} - \left(d\sigma^A \right)_{\varepsilon=0} \right] + \int_m \left[d\sigma^V + \int_1 d\sigma^A \right]_{\varepsilon=0}$$

- each term in squared brackets finite
  → phase-space integration in $d = 4\,(\varepsilon = 0)$ dimensions
- dipole factorization was used to calculate the subtraction term
  [Catani, Seymour '97]

Checks

- α-parameter independence

  [Nagy, Trócsányi '00], [Nagy '03]



- virtual corrections checked

  [Campbell, Ellis, Maltoni, Willenbrock '03]

- small p_T behaviour checked numerically against resummed expression

  [Belyaev, Nadolsky '06]

- most important: numerical comparison to an analytic evaluation of the p_T and y distribution

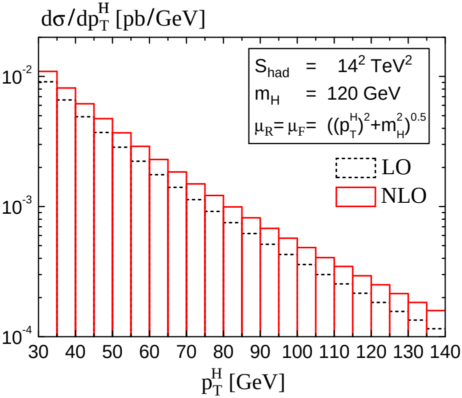
  [Ozeren '10]

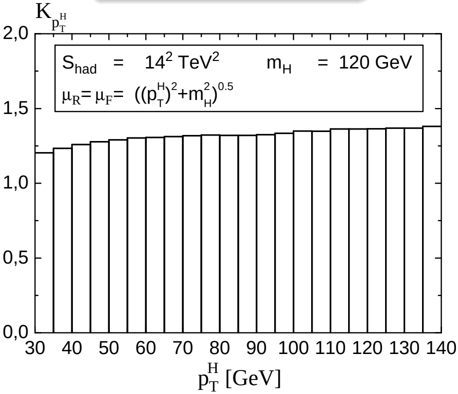
Higgs+jet production in bottom quark annihilation at NLO

Transverse momentum distribution:

[Harlander, Ozeren, MW '10]

$$K_{p_T^H} \equiv \frac{\left(d\sigma/dp_T^H\right)_{NLO}}{\left(d\sigma/dp_T^H\right)_{LO}}$$





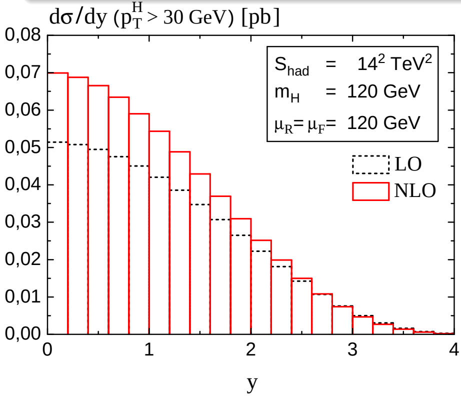
Higgs+jet production in bottom quark annihilation at NLO

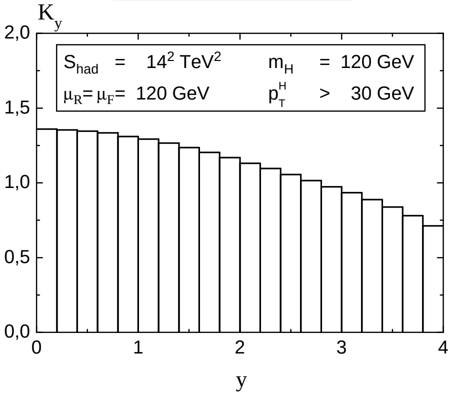
Rapidity distribution:

[Harlander, Ozeren, MW '10]

$$\sigma(p_T^H > p_{T,\text{cut}}) = \int_{p_T^H > p_{T,\text{cut}}} \frac{d\sigma}{dp_T^H}\, dp_T^H$$

$$K_y \equiv \frac{(d\sigma/dy)_{NLO}}{(d\sigma/dy)_{LO}}$$





Higgs+jet production in bottom quark annihilation at NLO

Scale dependence:

[Harlander, Ozeren, MW '10]

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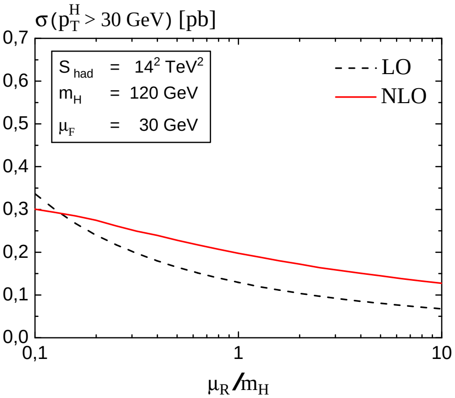

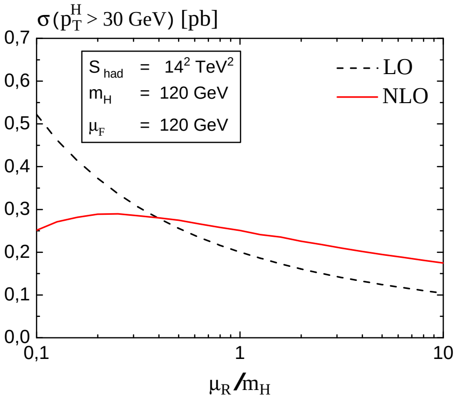

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$b\bar{b} \to H$ with upper cut on p_T^H at NNLO

- σ^{tot} known up to NNLO

  [Harlander, Kilgore '03]

- evaluate NNLO cross section with an upper cut on p_T^H:

$$\sigma(p_T^H < p_{T,\text{cut}}) = \sigma^{\text{tot}} - \int_{p_T^H > p_{T,\text{cut}}} \frac{d\sigma^{H+\text{jet}}}{dp_T^H}\, dp_T^H$$

$b\bar{b} \to H$ with upper cut on p_T^H at NNLO

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- $p_{T,\text{cut}} \gtrsim 30$ GeV to avoid large $\ln(p_T^H/M_H)$

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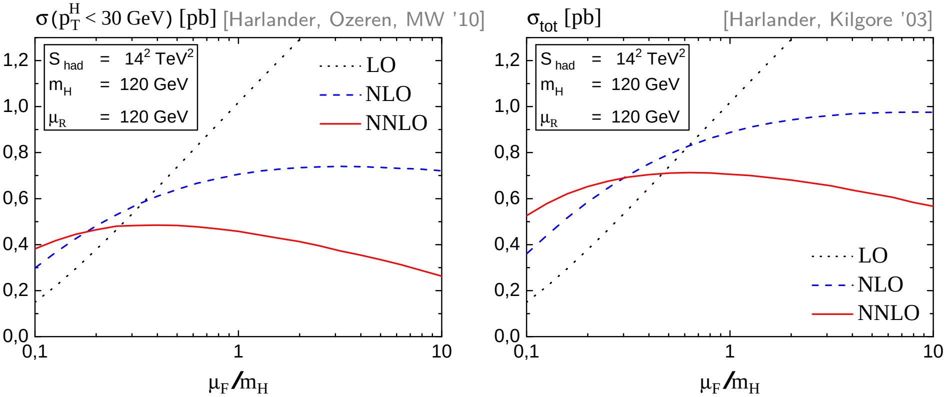
- $p_{T,\text{cut}} \gtrsim 30$ GeV to avoid large $\ln(p_T^H/M_H)$
- use NNLO PDFs and couplings

$b\bar{b} \to H$ with upper cut on p_T^H at NNLO

Scale dependence:

$$\sigma(p_T^H < p_{T,\text{cut}}) = \sigma^{\text{tot}} - \int_{p_T^H > p_{T,\text{cut}}} \frac{d\sigma^{H+\text{jet}}}{dp_T^H}\, dp_T^H$$



[Harlander, Ozeren, MW '10]

[Harlander, Kilgore '03]

$b\bar{b} \to H$ with upper cut on p_T^H at NNLO

$p_{T,cut}$ dependence:

[Harlander, Ozeren, MW '10]

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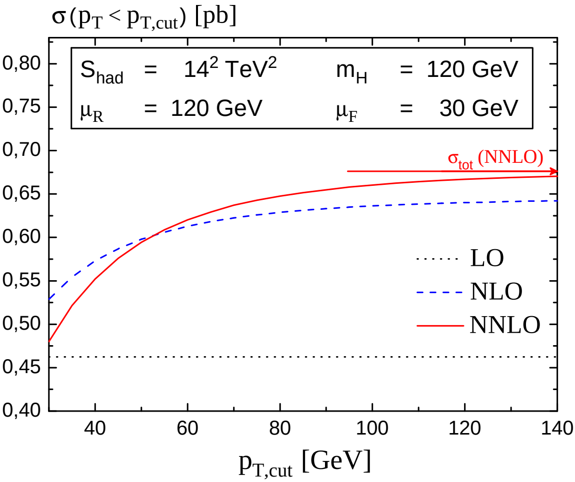

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Why Higgs production with jet veto?

- Higgs production in gluon fusion with jet veto at NNLO:
  [Catani, de Florian, Grazzini '01]
  - $gg \to H \to W^+W^- \to l^+l^-\nu\bar{\nu}$ important channel
  - background: $t\bar{t}$- and tW-production
  - with $t \to l\bar{\nu}b$ high p_T^{jet} b-jets in final state
  - if b's not identified → veto cut on p_T^{jet} to enhance signal/background
  - essential at Tevatron and the LHC
- here: application to $b\bar{b} \to H$

Why Higgs production with jet veto?

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  - $gg \to H \to W^+W^- \to l^+l^-\nu\bar{\nu}$ important channel
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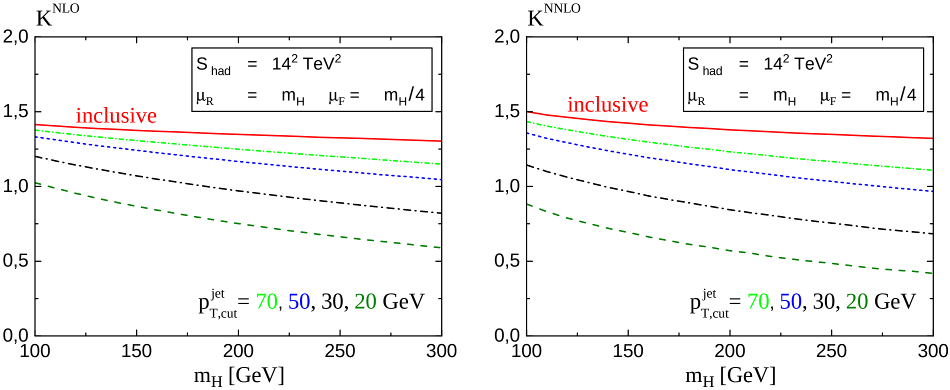
  - if b's not identified → veto cut on p_T^{jet} to enhance signal/background
  - essential at Tevatron and the LHC
- here: application to $b\bar{b} \to H$
- evaluation of jet vetoed cross section:

$$\sigma^{\text{veto}}(p_T^{\text{jet}} < p_{T,\text{cut}}^{\text{jet}}) = \sigma^{\text{tot}} - \sigma^{H+\text{jet}}[\text{1-jet}](p_T^{\text{jet}} > p_{T,\text{cut}}^{\text{jet}}) \\ - \sigma^{H+\text{jet}}[\text{2-jet}](p_{T,1}^{\text{jet}}, p_{T,2}^{\text{jet}} > p_{T,\text{cut}}^{\text{jet}})$$

Associated $(b\bar{b})H$ production with jet veto at NNLO

Higgs mass dependence:

[Harlander, Ozeren, MW '10]



Conclusions and Outlook

Conclusions:

- $b\bar{b}H + jet$ production up to NLO (fully differential)
- factorization scale $\mu_F = \frac{m_H}{4}$ less motivated
- NNLO with upper p_T^H cut calculated
- NNLO jet vetoed cross section calculated

$\Big\}$ similar results

- K-factors rather flat, similar to gluon fusion, but different from inclusive ones

Outlook:

- full NNLO Monte Carlo ?
- parton shower ?
- combination with Higgs+jet in gluon fusion – interference terms ?

BackUp

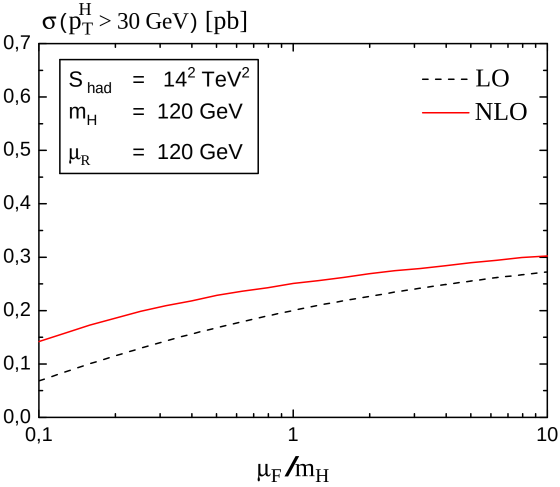
BackUp

Higgs+jet production in bottom quark annihilation at NLO

Scale dependence:

[Harlander, Ozeren, MW '10]

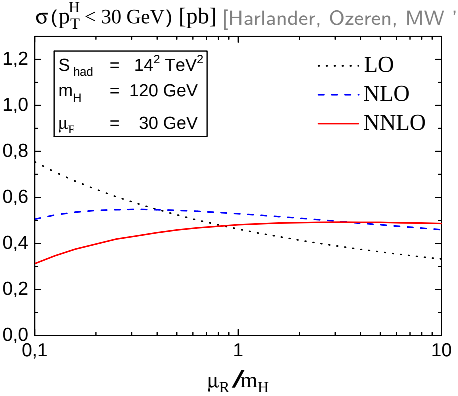
$$\sigma(p_T^H > p_{T,\text{cut}}) = \int_{p_T^H > p_{T,\text{cut}}} \frac{d\sigma}{dp_T^H}\, dp_T^H$$



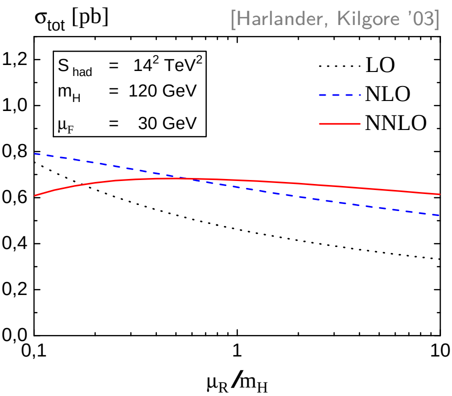
$b\bar{b} \to H$ with upper cut on p_T^H at NNLO

Scale dependence:

$$\sigma(p_T^H < p_{T,\mathrm{cut}}) = \sigma^{\mathrm{tot}} - \int_{p_T^H > p_{T,\mathrm{cut}}} \frac{d\sigma^{H+\mathrm{jet}}}{dp_T^H}\, dp_T^H$$



[Harlander, Ozeren, MW '10]



[Harlander, Kilgore '03]

$b\bar{b} \to H$ with upper cut on p_T^H at NNLO

Higgs mass dependence:

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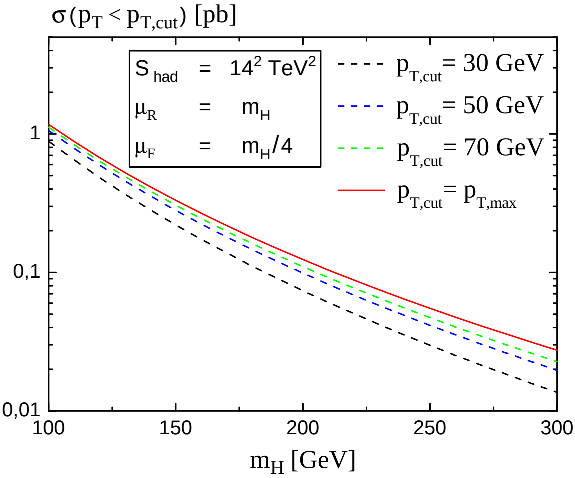

Jet Algorithm

- In General: m partons in final state → how many jets?

1. Clustering part — clustering of jets:

   jets $= m - n$ (if n times two jets have to be clustered into one jet according to the considered jet definition)

   The momenta of the clustered jets are recombined according to the recombination Scheme (e.g. E-Scheme: $p_i \oplus p_j = p_i + p_j$).

2. Acceptance part — performing cuts on the momenta of the $(m - n)$ jets (e.g. $p_{T,\mathrm{cut}},\ y_{\mathrm{cut}}, \ldots$):

   jets $= (m - n) - k$ (if k of the $(m - n)$ jets do not survive the cuts)

→ contributes to the $[(m - k - l)$-jet$]$ cross section

Jet Algorithm

- we want to calculate the [1-jet] and the [2-jet] cross section with a minimum cut ($p_{T,\text{cut}}$) on the transverse momentum of the jets

LO-kinematics: 1 parton with momentum p_1 (trivial)

if($p_1 > p_{T,\text{cut}}$) → contribution to [1-jet] c.s.
if($p_1 < p_{T,\text{cut}}$) → discard event

NLO-kinematics: 2 partons with momenta p_1 and p_2

Jet Algorithm

- we want to calculate the [1-jet] and the [2-jet] cross section with a minimum cut ($p_{T,\text{cut}}$) on the transverse momentum of the jets

NLO-kinematics: 2 partons with momenta p_1 and p_2

Cone algorithm: define

$$R_{12}^2 = ((\phi_1 - \phi_2)^2 + (\eta_1 - \eta_2)^2)$$

```
if($R_{12} < R$) → cluster to one jet $k_{\text{jet}} = p_1 + p_2$
    if($k_{\text{jet}} > p_{T,\text{cut}}$) → contribution to [1-jet] c.s.
    if($k_{\text{jet}} < p_{T,\text{cut}}$) → discard event
```

Jet Algorithm

- we want to calculate the [1-jet] and the [2-jet] cross section with a minimum cut ($p_{T,\text{cut}}$) on the transverse momentum of the jets

NLO-kinematics: 2 partons with momenta p_1 and p_2

Cone algorithm: define

$$R_{12}^2 = ((\phi_1 - \phi_2)^2 + (\eta_1 - \eta_2)^2)$$

```
if($R_{12} < R$) $\rightarrow$ cluster to one jet $k_{\text{jet}} = p_1 + p_2$
    if($k_{\text{jet}} > p_{T,\text{cut}}$) $\rightarrow$ contribution to [1-jet] c.s.
    if($k_{\text{jet}} < p_{T,\text{cut}}$) $\rightarrow$ discard event
if($R_{12} > R$) $\rightarrow$ 2 jets with $k_1 = p_1$ and $k_2 = p_2$
    if($k_1 \wedge k_2 > p_{T,\text{cut}}$) $\rightarrow$ contr. to [2-jet] c.s.
    if($k_1 \wedge k_2 < p_{T,\text{cut}}$) $\rightarrow$ discard event
    else $\rightarrow$ contribution to [1-jet] c.s.
```

Jet Algorithm

- we want to calculate the [1-jet] and the [2-jet] cross section with a minimum cut ($p_{T,\text{cut}}$) on the transverse momentum of the jets

NLO-kinematics: 2 partons with momenta p_1 and p_2

k_T-algorithm: define

[Catani, Dokshitzer, Seymour, Webber '93]

$$d_1 = p_{T,1}^2, \quad d_2 = p_{T,2}^2$$

$$d_{12} = \min(d_1, d_2) \cdot ((\phi_1 - \phi_2)^2 + (\eta_1 - \eta_2)^2)$$

```
if($d_1 \wedge d_2 \wedge d_{12} > p_{T,\text{cut}}$) → contr. to [2-jet] c.s.
if($d_{12} = \min(d_1, d_2, d_{12})$) → cluster $k_{\text{jet}} = p_1 + p_2$
        if($k_{\text{jet}} > p_{T,\text{cut}}$) → contribution to [1-jet] c.s.
        if($k_{\text{jet}} < p_{T,\text{cut}}$) → discard event
else if($d_1 \wedge d_2 < p_{T,\text{cut}}$) → discard event
else → contribution to [1-jet] c.s.
```

Jet vetoed cross section

- using the jet algorithm → jet vetoed cross section at NNLO:

$$\sigma^{\text{veto}}(p_T^{\text{jet}} < p_{T,\text{cut}}^{\text{jet}}) = \sigma^{\text{tot}} - \sigma^{H+\text{jet}}[\text{1-jet}](p_T^{\text{jet}} > p_{T,\text{cut}}^{\text{jet}}) - \sigma^{H+\text{jet}}[\text{2-jet}](p_{T,1}^{\text{jet}}, p_{T,2}^{\text{jet}} > p_{T,\text{cut}}^{\text{jet}})$$

- use NNLO PDFs and couplings
- Higgs+jet calculation fully exclusive

  → vetoed cross section with

  - additional experimental cuts on jets (e.g. rapidity cut)
  - different jet definitions

  possible