Resummation of b-Quark Mass Effects for the $b\bar{b}H$-Induced Higgs Production Cross Section

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bbH cross section sub-group kick-off meeting

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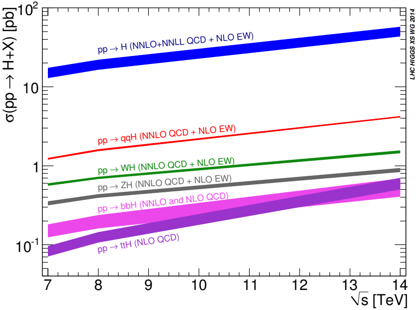
Outline

Combining Flavour Schemes

$b\bar{b}H$ to NLO

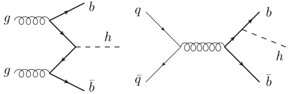
Conclusions & Outlook



Disclaimer: this is not a comparison of 4F vs 5F!

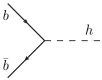
Flavour Schemes

4-flavour scheme



- finite-m_b effects ✓
- no b-PDF: no resummation of potentially large logs ✗
- logs not as large as one naïvely would think [Maltoni,Ridolfi,Ubiali]
- NLO: [Dittmaier et. al; Dawson et al]
- NLO+PS: [Wiesemann et al]

5-flavour scheme



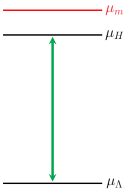
- DGLAP resummation of $\log(m_b/m_H)$ via effective b-quark PDF ✓
- mass power-corrections dropped ✗
- NNLO: [Harlander, Kilgore, Bühler et al.]
- NLO+PS: [Wiesemann et al]

- theoretically consistent approach combining virtues of 4F and 5F schemes <u>missing</u>
    - current prescription: 'Santander Matching' [Harlander,Krämer,Schumacher]
    - for DIS consistent approaches include (S-)ACOT / FONLL / TR

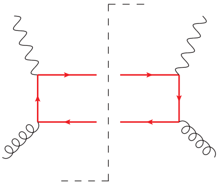
Scale Hierarchies & Matching: $m_b \sim Q$

Consider simplest case of DIS and ignore light quarks for now:

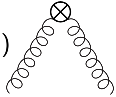
$\mu_m \sim \mu_H$



- single hard scale $\mu_H \sim m_b \sim Q$ (pretend $m_b \sim m_H$ here)
- at μ_H match full QCD $\rightarrow$ theory of collinear gluons
- b-quark integrated out at hard scale and effects of mass only present in Wilson coefficient, C_g
- $\sigma \sim C_g(\mu_H; m_b)\langle O_g(\mu_H)\rangle$
  $\sim C_g(\mu_H; m_b) U_{gg}(\mu_H, \mu_\Lambda) f_g(\mu_\Lambda) = C_g(\mu_H; m_b) f_g(\mu_H)$

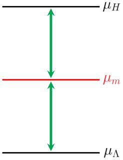


$= C_g^{(1)}(\mu_H; m_b)$



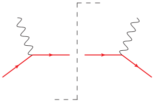
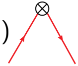
Scale Hierarchies & Matching: $m_b \ll Q$

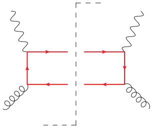
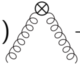
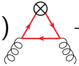
$\mu_m \ll \mu_H$



- 2 relevant scales: $\mu_H \sim Q$ and $\mu_m \sim m_b$
- at μ_H match full QCD $\rightarrow$ theory of collinear gluons and b-quarks
- $\sigma \sim C_b(\mu_H; m_b = 0)\langle O_b(\mu_H)\rangle + C_g(\mu_H; m_b = 0)\langle O_g(\mu_H)\rangle + \mathcal{O}(\frac{m_b^2}{Q^2})$
- genuine mass power-corrections can be absorbed into C_g

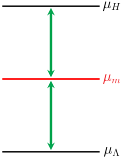
at μ_H:

 $= C_b^{(0)}(\mu_H)$ 

 $= C_g^{(1)}(\mu_H)$  $+ C_b^{(0)}(\mu_H)$  $+ \mathcal{O}\left(\frac{m_b^2}{m_H^2}\right)$

Scale Hierarchies & Matching: $m_b \ll Q$

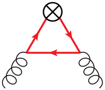
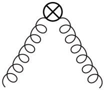
$\mu_m \ll \mu_H$



- 2 relevant scales: $\mu_H \sim Q$ and $\mu_m \sim m_b$
- evolve down to μ_m:

$$\sigma \sim C_b(\mu_H)\left(U_{bb}\langle O_b(\mu_m)\rangle + U_{bg}\langle O_g(\mu_m)\rangle\right)$$
$$+\, C_g(\mu_H)\left(U_{gg}\langle O_g(\mu_m)\rangle + U_{gb}\langle O_b(\mu_m)\rangle\right)$$

- at μ_m integrate out b-quark: match onto theory of collinear gluons
- $\langle O_b(\mu_m)\rangle = \mathcal{M}_{bg}(\mu_m)\langle O'_g(\mu_m)\rangle = \mathcal{M}_{bg}(\mu_m) f_g(\mu_m) \quad =$ "b-pdf"

at μ_m:  $= \mathcal{M}^{(1)}_{bg}(\mu_m)$ 

PERTURBATIVE COUNTING

standard 4F counting: $f_b \sim 0,\ f_g \sim 1$
standard 5F counting: $f_b \sim f_g \sim 1$
} + count orders in α_s in coefficient fn

But, for $\mu_m \ll \mu_H$:

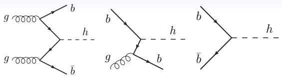
$$\begin{array}{c} \quad\sim 1 \qquad\qquad \sim 1 \cdot \alpha_s \qquad\qquad\qquad \sim \alpha_s \cdot 1 \\ \sigma = C_b^{(0)}\Big[\, U_{bb}(\mu_H,\mu_m)\mathcal{M}_{bg}^{(1)}(\mu_m) \;+\; U_{bg}(\mu_H,\mu_m)\mathcal{M}_{gg}^{(0)}(\mu_m)\,\Big] f_g(\mu_m) \\ + C_g^{(1)}\Big[\, U_{gg}(\mu_H,\mu_m)\mathcal{M}_{gg}^{(0)}(\mu_m) \;+\; U_{gb}(\mu_H,\mu_m)\mathcal{M}_{bg}^{(1)}(\mu_m)\,\Big] f_g(\mu_m) \\ \sim \alpha_s \qquad\qquad \sim 1 \cdot 1 \qquad\qquad\qquad \sim \alpha_s \cdot \alpha_s \end{array}$$

- b-initiated term dominates in limit $m_b/\mu_H \to 0$ (practically $\mu_H > 1$ TeV)
- otherwise b- & g-initiated contributions comparable ($\alpha_s \log \frac{\mu_H}{\mu_m} \sim \alpha_s$)

In this intermediate region more appropriate counting holds:

- $f_b \sim \alpha_s$
- apply counting at level of $f_i \otimes C_i$ (not simply to C_i)

$b\bar{b}H$ setup to NLO



Construction of cross-sections:

$$\sigma = C^{(2)}_{gg} f_g f_g + C^{(1)}_{bg} f_b f_g + C^{(0)}_{b\bar{b}} f_b f_b + q\bar{q}\text{-channel} \quad \sim \alpha_s^2$$
$$+ C^{(3)}_{gg} f_g f_g + C^{(2)}_{bg} f_b f_g + C^{(1)}_{b\bar{b}} f_b f_b + q\bar{q}/qg/bq\text{-channels} \quad \sim \alpha_s^3$$

Construct NLO Coefficient functions

- $C^{(3)}_{gg}$, $C^{(2)}_{q\bar{q}}$, $C^{(2)}_{qg}$ MadGraph5_aMC@NLO [Alwall et al.]
- $C^{(2)}_{bg}$, $C^{(1)}_{b\bar{b}}$, $C^{(2)}_{bq}$ [Harlander, Kilgore]
- + subtractions (in-house)

LO	$C^{(2)}_{gg}$, $C^{(2)}_{q\bar{q}}$, $C^{(1)}_{bg}$, $C^{(0)}_{b\bar{b}}$
NLO	$C^{(3)}_{gg}$, $C^{(2)}_{q\bar{q}}$, $C^{(2)}_{qg}$, $C^{(2)}_{bg}$, $C^{(1)}_{b\bar{b}}$, $C^{(2)}_{bq}$

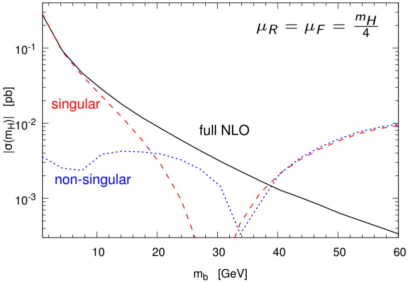
NLO mass-matching & PDFs: constructed from

- $\mathcal{M}^{(2)}_{ij}(\mu_m)$ [Buza et al.]
- implement in Apfel [Bertone et al.] for general μ_m
- create LHAPDF grid files for each m_b and μ_m (initial conditions from available PDFs)

LO	$\mathcal{M}^{(1)}_{ij}(\mu_m)$
NLO	$\mathcal{M}^{(2)}_{ij}(\mu_m)$

Logarithmic Structure of Fixed-Order

- examine cross-section varying m_b, at fixed-order (4F) :



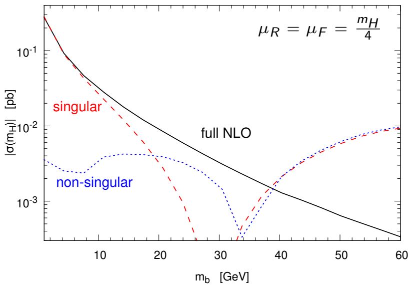
$$\sigma^{\text{tot, 4F}}(\mu_H) = \sigma^{\text{sing.}}(\mu_H) + \sigma^{\text{non-sing.}}(\mu_H)$$

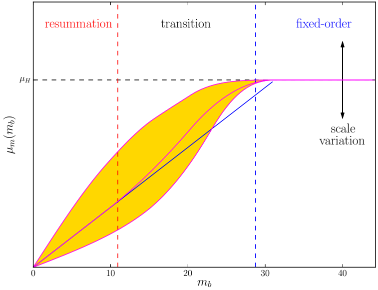
$$\sigma^{\text{sing.}}(\mu_H) = \sum_{m \leq n} C_{nm}\, \alpha_s^n \log^m\left(\frac{m_b}{\mu_H}\right)$$

(convolutions/PDFs implicit)

- large m_b, large cancellations between singular & non-singular
  $\Rightarrow$ must use fixed order (no resummation!)
- small m_b, singular contributions dominate cross-section
  $\Rightarrow$ resummation of logarithms important

Controlling Transition between Resummation & Fixed-Order

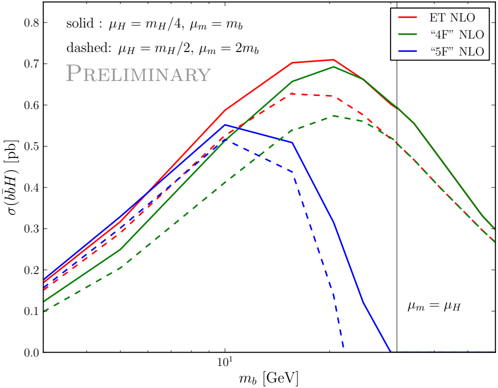




- control transition by promoting $\mu_m \to \mu_m(m_b)$ (profiles)
- $m_b \to \mu_H$ need $\mu_m \to \mu_H$ to switch off resummation
- $m_b \to 0$ need $\mu_m \to m_b$ to resum logs appearing in fixed-order result
- varying shape of profile allows one to estimate resummation uncertainty and uncertainty in transition

$b\bar{b}H$-Induced Cross-Section: fix $m_H = 125$ GeV, vary m_b

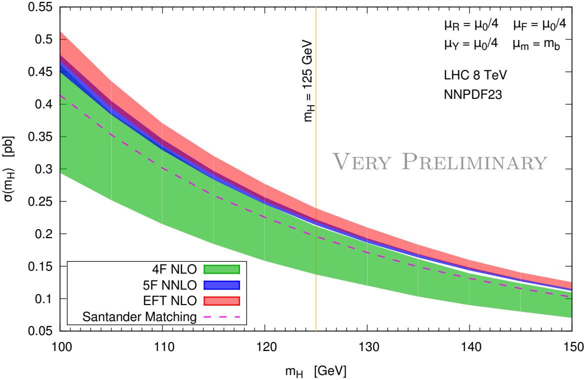
- perform a strict expansion to $\mathcal{O}(\alpha_s^3)$ at level of $C_{ij} \otimes \mathcal{M}_{ij}$ to ensure resummation switched off continuously!



- very good transition between fixed-order ("4F") and resummation ("5F") regions

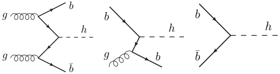
$b\bar{b}H$-Induced Cross-Section: fix $m_b = 4.75$ GeV, vary m_H

- $\mu_H = \mu_0 = (m_H + 2m_b)/4$, & vary by factor 2
  (i.e. $\mu_F = \mu_R = \mu_Y$ simultaneously varied)



- Santander Matched result lies (by construction) between 4F and 5F
- EFT result seems to sit above Santander Matching on average
- we are still working on how best to combine uncertainties

Conclusions & Outlook



Conclusions:

- a theoretically consistent method that includes resummation of large logarithms and mass-effects for the $b\bar{b}H$-induced cross-section is possible
- appropriate counting: $f_b \sim \alpha_s$ holds for values of $m_H \lesssim 1$ TeV
- keep in mind that PDFs matched at a threshold scale $\mu_m \sim m_b$
- exploiting μ_m allows for a controlled transition between resummation and fixed-order regions
- varying μ_m provides a way to assess this additional source of (resummation) scale uncertainty

Outlook:

- full comparison to 4F, 5F and Santander Matched predictions
- disentangling resummation uncertainties through proper use of profiles
- generalize approach for differential observables and $H + J_b$ production