$b\bar{b}H$ report and plans (theory)

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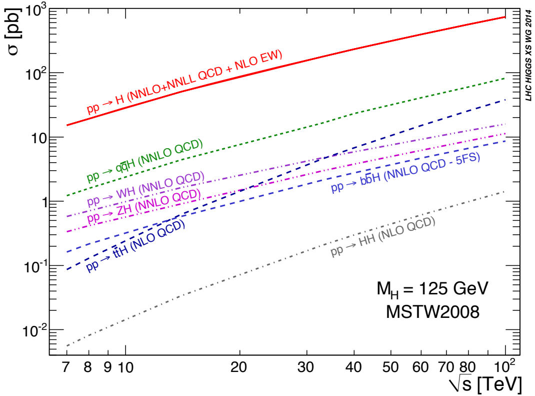
Outline

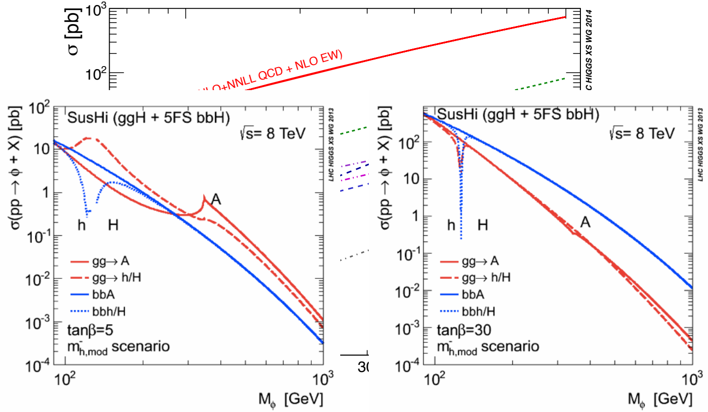
1. Motivation
2. Schemes
3. Cross Section
4. Current status and ongoing studies
5. Plans and Outlook

SM vs. MSSM Higgs production



- SM:
  - gluon fusion by far dominant
  - $b\bar{b}H$ sizeable only with b-tagging

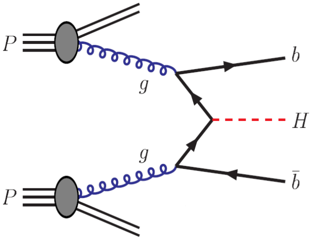
SM vs. MSSM Higgs production



- SM:
  - 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 $\tan\beta$

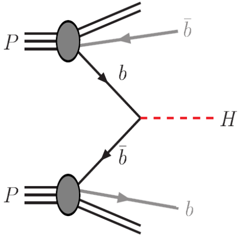
Associated $H(b\bar{b})$ production

4-flavour scheme



- massive b's
- potentially large logs $\ln(m_b/Q)$
- power terms $(m_b/Q)^n$
- involved $2 \to 3$ at LO
- 2 exclusive b's at LO
- b(-tag) well defined

5-flavour scheme



- massless b's
- resummation into b-PDFs
- —
- simple $2 \to 1$ at LO
- exclusive b's at higher orders
- b part of light jets

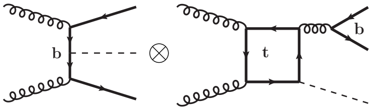
4-flavour scheme

- inclusive (exclusive) up to NLO
  [Dittmaier, Krämer, Spira '04]
  [Dawson, Jackson, Reina, Wackeroth '04]
- exclusive NLO+PS
  [MW, Frederix, Frixione, Hirschi, Maltoni, Torrielli '14],
  [Sherpa: Krauss, Schönherr... work in progress]

5-flavour scheme

- inclusive up to NNLO
  [Harlander, Kilgore '03]
- towards N^{3}LO
  [Ahmed, Rana, Ravindran '14], [Ahmed, Mandal, Rana, Ravindran '14], [Gehrmann, Kara '14]
- exclusive H+b at NLO
  [Campbell, Ellis, Maltoni, Willenbrock '03]
- exclusive H+n-jet ($n = 0/1/2$)
  [Harlander, Ozeren, MW '10],[Harlander, MW '11]
- exclusive up to NNLO
  [Buehler, Herzog, Lazopoulos, Mueller '12]
- p_T resummation
  NLO+NLL [Belyaev, Nadolsky, Yuan '06]
  NNLO+NNLL [Harlander, Tripathi, MW '14]
- exclusive NLO+PS
  [MW, Frederix, Frixione, Hirschi, Maltoni, Torrielli '14]

The $b\bar{b}H$ cross section



y_b^2-term at NLO

$y_b\, y_t$-term at NLO

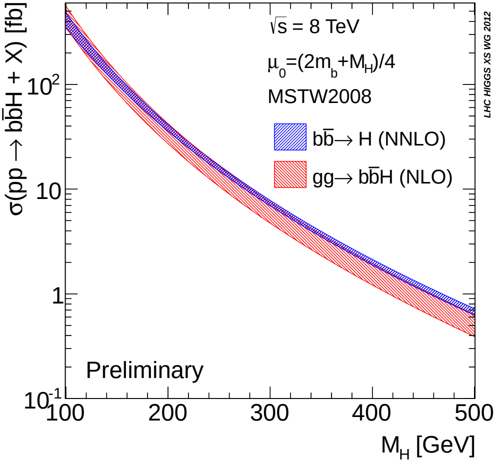
y_t^2-term at NNLO

$$\sigma^{4FS}_{b\bar{b}H} = \alpha_s^2\, y_b^2\, \Delta^{(0)}_{y_b^2} + \alpha_s^3 \left(y_b^2\, \Delta^{(1)}_{y_b^2} + y_b\, y_t\, \Delta^{(1)}_{y_b y_t} \right) + \alpha_s^4 \left(y_b^2\, \Delta^{(2)}_{y_b^2} + y_b\, y_t\, \Delta^{(2)}_{y_b y_t} + y_t^2\, \Delta^{(2)}_{y_t^2} \right) + \mathcal{O}(\alpha_s^5)$$

$$\sigma^{5FS}_{b\bar{b}H} = y_b^2\, \Delta^{(0)}_{y_b^2} + \alpha_s\, y_b^2\, \Delta^{(1)}_{y_b^2} + \alpha_s^2 \left(y_b^2\, \Delta^{(2)}_{y_b^2} + y_t^2\, \Delta^{(2)}_{y_t^2} \right) + \mathcal{O}(\alpha_s^3)$$

- $y_b\, y_t$-term enters at NLO:
  - interference with (contamination from) gluon fusion
  - no double counting with gluon fusion cross section!
- y_t^2-term enters at NNLO:
  - part of gluon fusion cross section
  - sizable in SM $\sim 40\%$ (LO – large uncertainties)
  - e.g., with MG5@LO in 4FS HEFT; agreement with full theory

4FS vs. 5FS: Inclusive cross section



4FS NLO:

[Dittmaier, Krämer, Spira '04]

[Dawson, Jackson, Reina, Wackeroth '04]

grids $m_\phi = 80 - 1000$ GeV for y_b^2 and $y_b\, y_t$ produced by M. Spira ($y_b\, y_t$ negligible for large $\tan\beta$)

5FS NNLO:

[Harlander, Kilgore '03]

grids $m_\phi = 80 - 1000$ GeV for y_b^2 and produced with SusHi

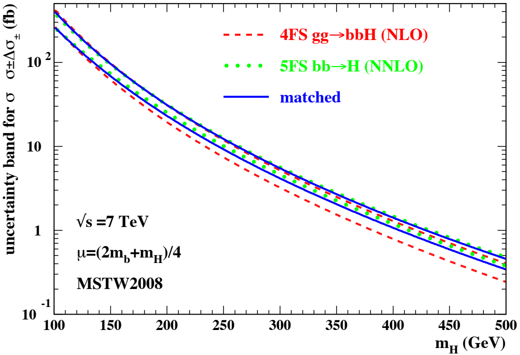
[Harlander, Liebler, Mantler '13]

MSSM: Δ_b approximation and resummation through y_b-reweighting (captures dominant effects) [Dawson, Jackson, Reina, Wackeroth '05], [Dittmaier, Häfliger, Krämer, Spira, Walser '14]

4FS vs. 5FS: Santander matching

$$\sigma = \frac{\sigma^{4FS} + w\,\sigma^{4FS}}{1+w}, \quad w = ln(m_\phi/m_b) - 2$$

[Harlander, Krämer, Schumacher '11]



combined grids available on:
http:\\twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt8TeV

– **now:** $y_b\, y_t$ included (crucial for large-y_t scenarios)

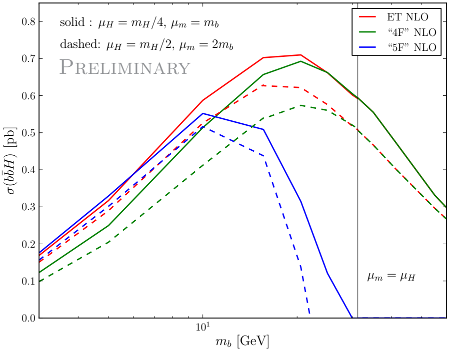
– e.g, SM: $y_b\, y_t \sim -10\%$

– y_t^2 simply from gluon fusion

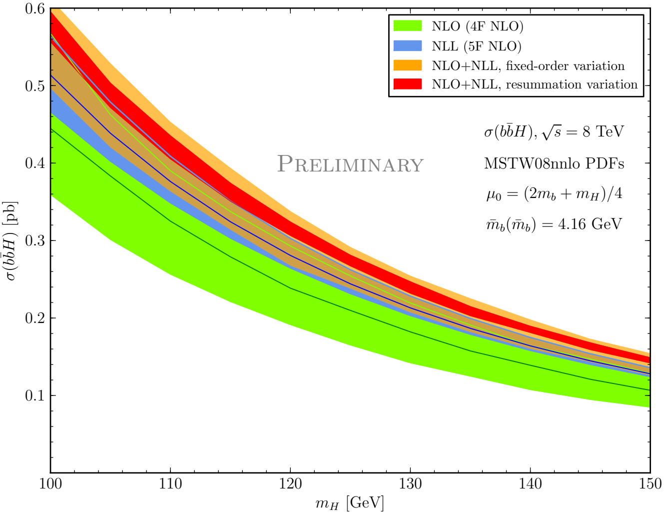
Alternative matching scheme: [Bonvini, Papanastasiou, Tackmann] work in progress...

$b\bar{b}H$-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



NLO (4F NLO)
NLL (5F NLO)
NLO+NLL, fixed-order variation
NLO+NLL, resummation variation
$\sigma(b\bar{b}H)$, $\sqrt{s} = 8$ TeV
MSTW08nnlo PDFs
$\mu_0 = (2m_b + m_H)/4$
$\bar{m}_b(\bar{m}_b) = 4.16$ GeV
PRELIMINARY
$\sigma(b\bar{b}H)$ [pb]
0.1
0.2
0.3
0.4
0.5
0.6
100
110
120
130
140
150
m_H [GeV]

Tools for exclusive $b\bar{b}H$ cross section and distributions

- Higgs distributions (inclusive over b's)
  - 5FS y^H at NNLO: private code
    [Bühler, Herzog, Lazopoulos, Müller '12]
  - 5FS $p_T(H)$ at NNLO+NNLL: private code by M. Wiesemann
    [Harlander, Tripathi, MW '14]
  - 4FS at NLO: private codes by M. Spira and M. Krämer
    [Dittmaier, Krämer, Spira '04]
  - 4FS at NLO+PS: MG5_aMC with $y_b^{\overline{MS}}$
    [MW, Frederix, Frixione, Hirschi, Maltoni, Torielli '14]
- exclusive cross section with b-tagging
  - 4FS at NLO+PS: MG5_aMC with $y_b^{\overline{MS}}$ (both y_b^2 and $y_b\, y_t$)
    [MW, Frederix, Frixione, Hirschi, Maltoni, Torielli '14]
    process folder publicly available on:
    https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/bbH

- work in progress: new developments in Sherpa

Exclusive $b\bar{b}H$ cross section

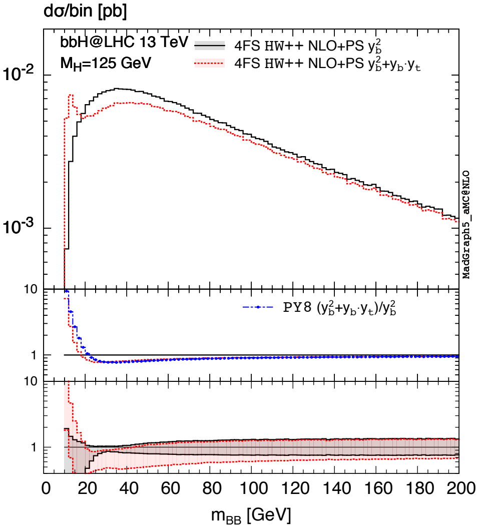
SM NLO+PS with `Pythia 8`; $\mu_F = \mu_R = H_T/4$;
shower scale according to [MW, Frederix, Frixione, Hirschi, Maltoni, Torielli '14]

- significantly reduced residual uncertainty at NLO
- $y_b\, y_t$ always $\sim -10\%$ with large uncertainty (effectively LO)
- b-tag reduces cross section by factor of 3 – 4
- second b-tag by additional factor of 10

	NLO			LO
σ[pb]	y_b^2	$y_b\, y_t$	$y_b^2 + y_b\, y_t$	y_b^2
inclusive	$0.448^{+19.8\%}_{-20.8\%}$	$-0.0365^{+35.5\%}_{-62.8\%}$	$0.411^{+24.6\%}_{-28.4\%}$	$0.478^{+59.0\%}_{-34.6\%}$
$\geq 1j_b$	$0.133^{+16.7\%}_{-17.3\%}$	$-0.0148^{+35.0\%}_{-60.1\%}$	$0.118^{+23.5\%}_{-26.8\%}$	$0.150^{+55.9\%}_{-32.8\%}$
$\geq 2j_b$	$0.0133^{+13.7\%}_{-16.0\%}$	$-0.00147^{+34.3\%}_{-58.8\%}$	$0.0118^{+20.0\%}_{-25.1\%}$	$0.0168^{+54.4\%}_{-32.7\%}$

m_{BB}: y_b^2 vs. $y_b\, y_t$ (4FS)

[MW, Frederix, Frixione, Hirschi, Maltoni, Torielli '14]



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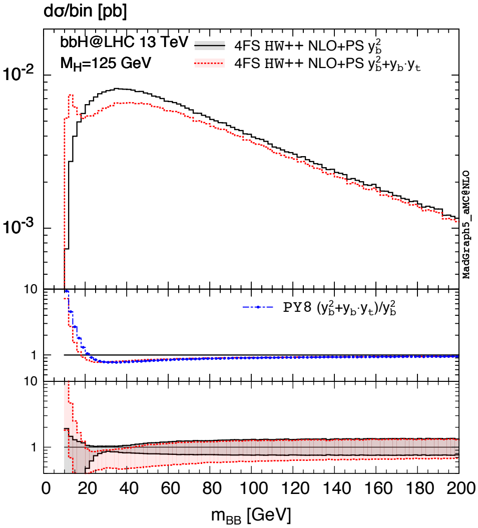
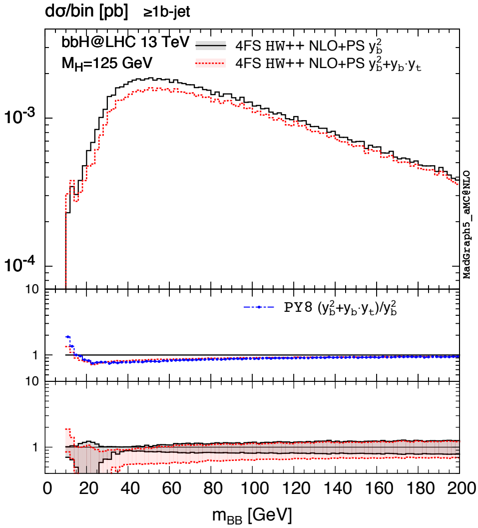
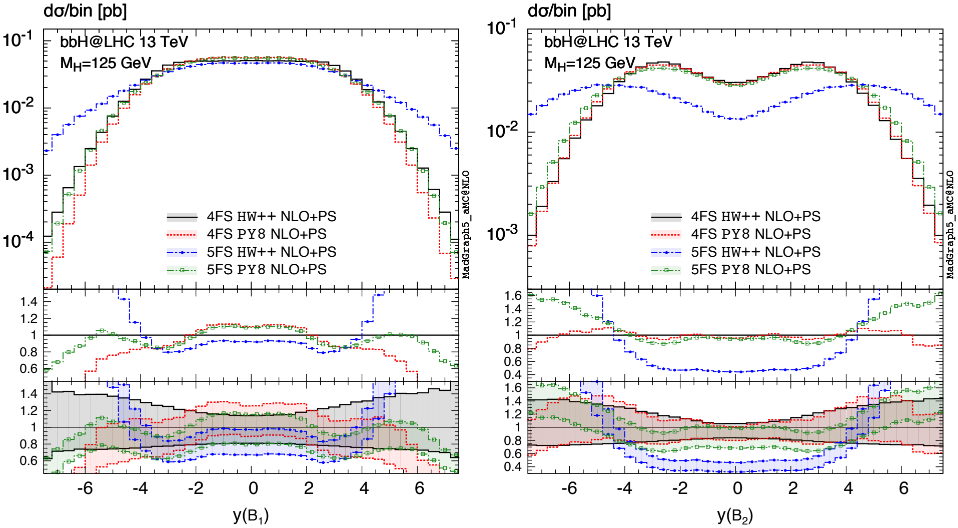




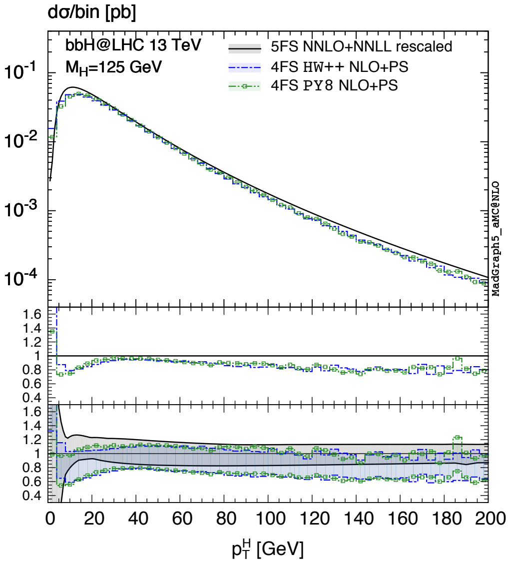
y_B: 4FS vs. 5FS

[MW, Frederix, Frixione, Hirschi, Maltoni, Torielli '14]



p_T^H: 4FS vs. 5FS NNLO+NNLL

[MW, Frederix, Frixione, Hirschi, Maltoni, Torielli '14], [Harlander, Tripathi, MW '14]



analytic resummation:
$\mu_F = \mu_R = m_T/4$

NLO+PS:
$\mu_F = \mu_R = H_T/4$

New developments in Sherpa

very preliminary so far:

[Krauss, Schönherr]

4FS:

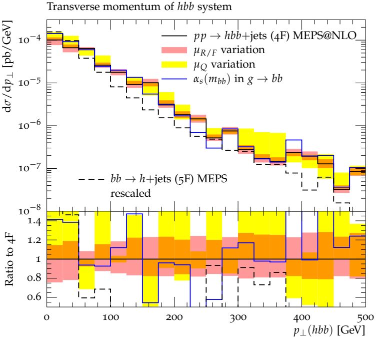
- 0-jet NLO+PS merged with 2-jet LO
- scales: $\alpha_s^2(\mu_R) = \alpha_s(m_h)\,\alpha_s(t)$; $\mu_F = \mu_Q = m_T(h)$
- on-shell y_b
- virtuals from OpenLoops

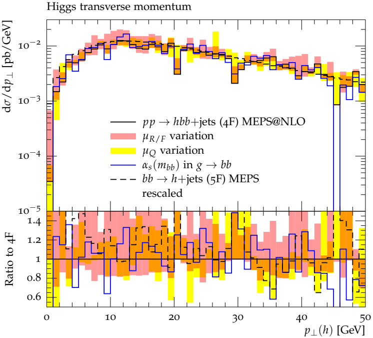
5FS:

- merged 0,1,2,3-jet LO
- $\mu_F = \mu_R = \mu_Q = m_h$
- on-shell y_b
- virtuals from OpenLoops

work in progress...

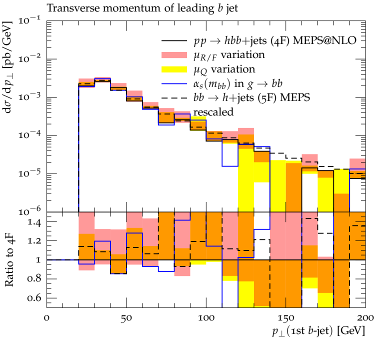
very preliminary results

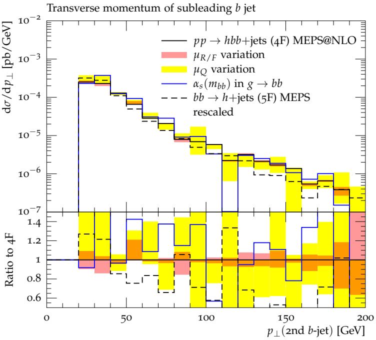




- $p_\perp(hbb)$ is somewhat softer in 5F
- hardly any impact of choice of scale in $g \to bb$ splitting
  $\to$ most likely because leading b-jets couple to Higgs
  $\to$ hardly any contribution from soft $g \to bb$ splittings

very preliminary results





- good agreement for $p_\perp$(1st b-jet)
- $p_\perp$(2nd b-jet) is somewhat softer in 5F
- hardly any impact of choice of scale in $g \to bb$ splitting

Summary: current recommended tools for $b\bar{b}H$

- inclusive cross section
  - 4FS at NLO: private code by M. Spira, MG5_aMC with $y_b^{\overline{MS}}$
  - 5FS at NNLO: SusHi (bbh@nnlo)
- Higgs distributions (inclusive over b's)
  - 5FS y^H at NNLO: private code [Bühler, Herzog, Lazopoulos, Müller '12]
  - 5FS $p_T(H)$ at NNLO+NNLL: private code by M. Wiesemann
  - 4FS at NLO: private code by M. Spira [Dittmaier, Krämer, Spira '04]
  - 4FS at NLO+PS: MG5_aMC with $y_b^{\overline{MS}}$
- exclusive cross section with b-tagging
  - 4FS at NLO+PS: MG5_aMC with $y_b^{\overline{MS}}$

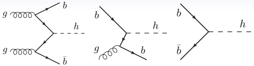
disclaimer: will be updated once ongoing studies are finalized (e.g. Sherpa)

Plans for YR4

- **total cross section:**
  - comparison: 4FS/5FS combination vs. existing results
  - update recommendation (if required): scales, inputs (e.g. y_b)
- **exclusive cross sections:**
  - having (at least) two MC's (MG5, Sherpa) beyond LO
  - MC and 4FS vs 5FS comparison
  - validation with similar processes ($b\bar{b}Z$, single top)
  - recommendation: scales, inputs (consistent with total)
  - uncertainty estimation (and recommendation):
    - perturbative (μ_R, μ_F)
    - shower matching (Q)
    - merging (Sherpa)
  - studies for larger Higgs masses (so far mostly 125 GeV)
  - gluon fusion contribution

BackUp

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



Construction of cross-sections:

$$\sigma = C^{(2)}_{gg} f_g f_g + C^{(1)}_{bg} f_b f_g + C^{(0)}_{b\bar{b}} f_b f_b + q\bar{q}\text{-channel} \qquad \sim \alpha_s^2$$

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

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

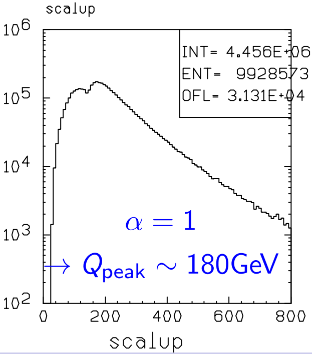
shower scale in MG5_aMC

- shower scale Q event-wise chosen from distribution
- interval of distribution determined from inputs $(\alpha,\ f_1,\ f_2)$:

$$\alpha f_1 \sqrt{s_0} \leq Q \leq \alpha f_2 \sqrt{s_0}, \qquad s_0 : \text{LO center of mass energy}$$

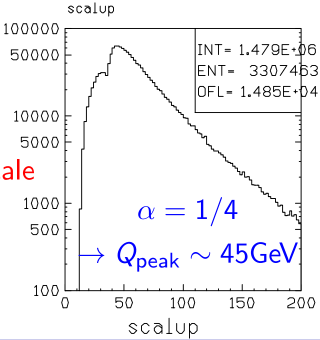
default values: $\alpha = 1,\ f_1 = 0.1,\ f_2 = 1$

- peaked at $Q_{\text{peak}} \sim \alpha(f_1 + f_2)\sqrt{\langle s_0 \rangle}/2$
- for $b\bar{b}H$ in 4FS follows:



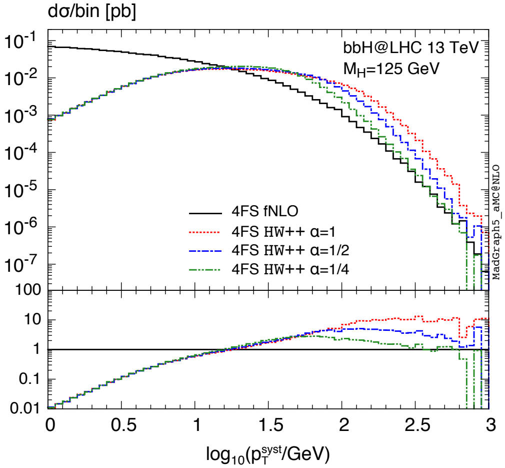
NOTE: related scale

$$\mu_F \sim \frac{m_\phi + 2m_b}{4} \sim 34\text{GeV}$$



4FS: choosing the shower scale

[MW, Frederix, Frixione, Hirschi, Maltoni, Torielli '14]



$\alpha = 1 \quad \widehat{=}\ Q_{\text{peak}} \sim 180\text{GeV}$

$\alpha = 1/2\ \widehat{=}\ Q_{\text{peak}} \sim 90\text{GeV}$

$\alpha = 1/4\ \widehat{=}\ Q_{\text{peak}} \sim 45\text{GeV}$

Q event-wise from a distribution peaked at $Q_{\text{peak}} \sim \alpha(f_1 + f_2)\sqrt{\langle s_0 \rangle}/2$
in an interval: $\alpha f_1 \sqrt{s_0} \leq Q \leq \alpha f_2 \sqrt{s_0}$, $\quad f_1 = 0.1,\ f_2 = 1,\ s_0$: LO c.m.e.

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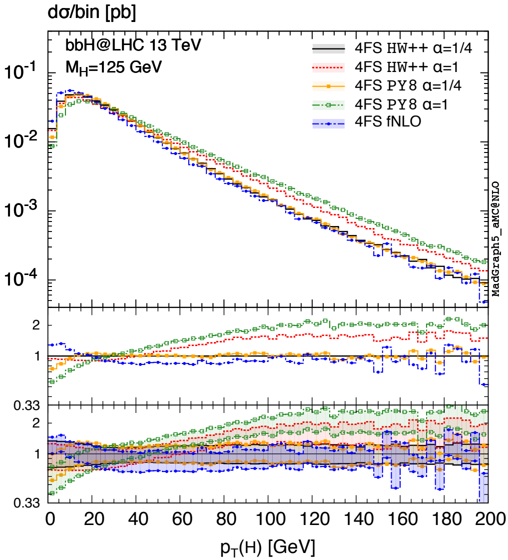

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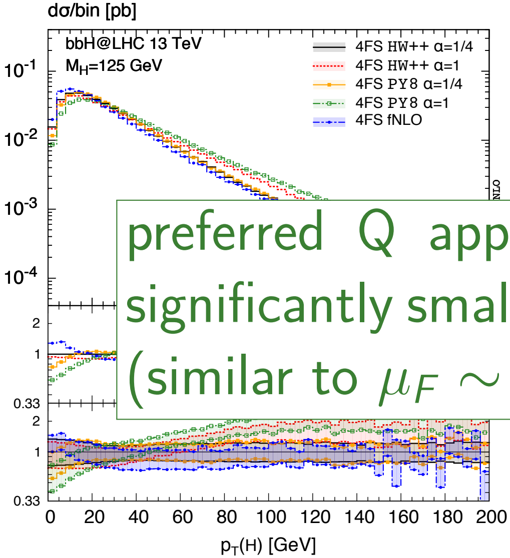

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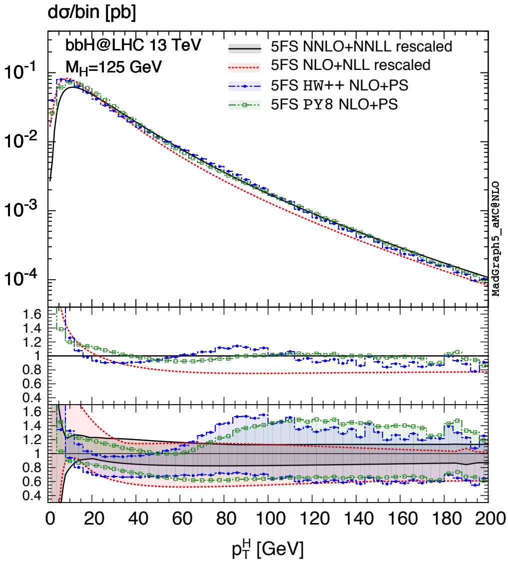
preferred Q appears to be significantly smaller than m_ϕ (similar to $\mu_F \sim m_\phi/4$)

p_T^H in 5FS: NLO+PS vs. analytic resummation

[MW, Frederix, Frixione, Hirschi, Maltoni, Torielli '14]



analytic resummation:

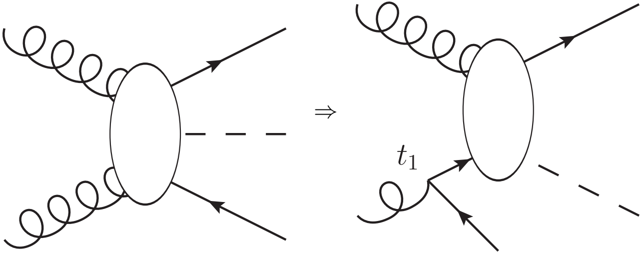
$\mu_F = \mu_R = m_T/4$

NLO+PS:

$\mu_F = \mu_R = H_T/4$

Parton shower starting conditions for $pp \to Xb\bar{b}$

One way of addressing the above issue is through clustering in CKKW approach. Reduce



$\rightarrow$ starting scale needs to be of the order of t
$\rightarrow$ set starting scale on $2 \to 2$ to $\mu_Q = m_\perp(h)$
in the following also use for μ_R the solution of $\alpha_s^2(\mu_R) = \alpha_s(m_h)\alpha_s(t)$ and $\mu_F = \mu_Q$