ETH zürich

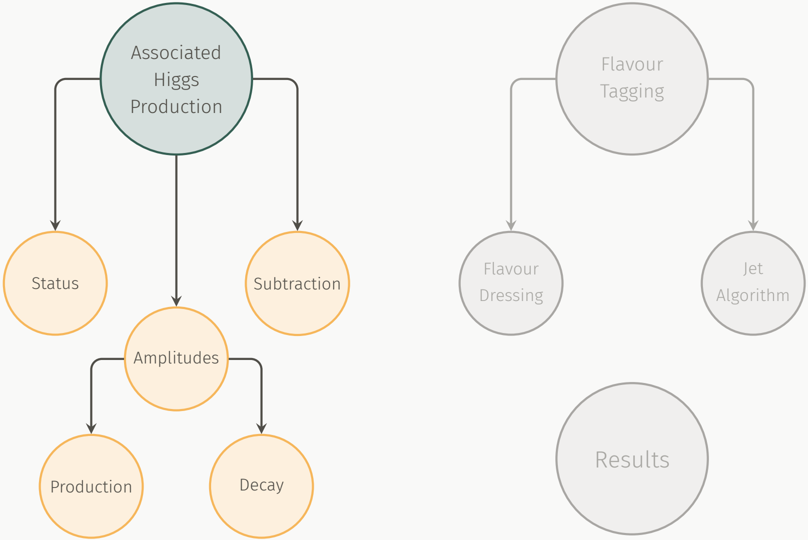
ASSOCIATED HIGGS BOSON PRODUCTION VIA FLAVOUR TAGGING IN *NNLOJET*

Imre Majer

with R. Gauld, A. Gehrmann–De Ridder, E. W. N. Glover, and A. Huss

from the *NNLOJET* collaboration

LoopFest XVIII, 2019 August 14


Associated Higgs Production
Status
Amplitudes
Subtraction
Production
Decay
Flavour Tagging
Flavour Dressing
Jet Algorithm
Results

Associated Higgs Production

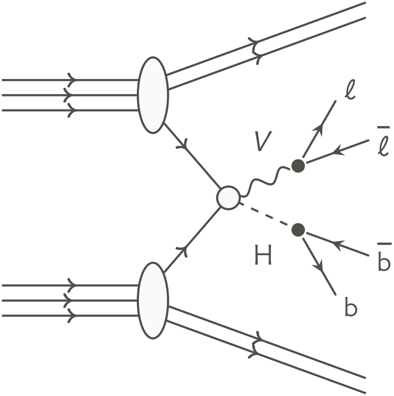
Estimated 5% of Higgs production

Clear leptonic signature

$H \to b\bar{b}$ main decay channel ($\mathcal{B}r = 58\%$)

Experiment Status

Theory Status



ASSOCIATED HIGGS BOSON PRODUCTION STATUS

Associated Higgs Production

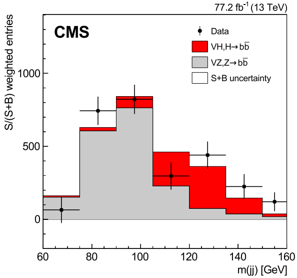
Experiment Status

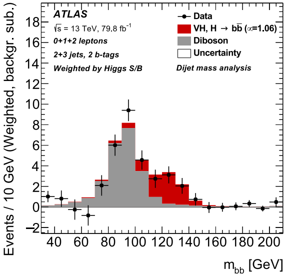
Evidence for $H \to b\bar{b}$ through the VH channel

ATLAS: 5.3σ significance [arXiv:1808.08238]
CMS: 5.6σ significance [arXiv:1808.08242]

Measurements as a function of p_T^V [arXiv:1903.04618]

Theory Status





Associated Higgs Production

Experiment Status

Theory Status

NNLO Production × NLO Decay

[G. Ferrera, M. Grazzini, F. Tramontano, arXiv:1407.4747]

NNLO Production × NNLO Decay

[G. Ferrera, G. Somogyi, F. Tramontano, arXiv:1705.10304]

[F. Caola, G. Luisoni, K. Melnikov, R. Röntsch, arXiv:1712.06954]

NNLO Decay with massive b quarks

[W. Bernreuther, L. Chen, Z.-G. Si, arXiv:1805.06658]

N^3LO Decay with massless b quarks

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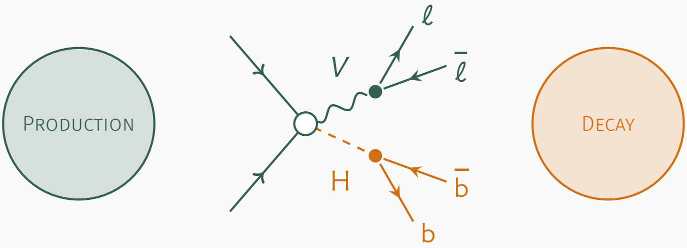
Our Calculations in *NNLOJET*...

NNLO Production × NNLO Decay

- include off-shell propagators with full spin correlations.
- utilize extensive scale variations.
- demonstrate a general flavour-tagging infrastructure.
- employ a streamlined flavour-sensitive jet algorithm.
- validated against W^-H total cross section of [F. Caola, G. Luisoni, K. Melnikov, R. Röntsch, arXiv:1712:06954].

arXiv:1907.05836

VH process setup: production × decay



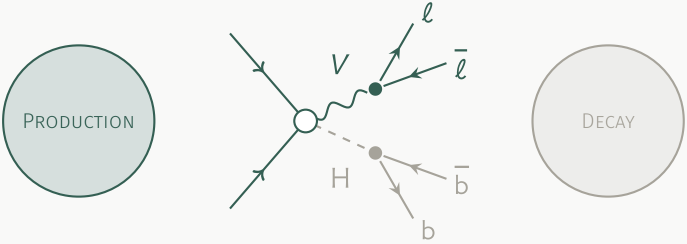
Factorization

- No cross-talk between production and decay amplitudes.
- Differential cross sections are assembled as

$$\mathrm{d}\sigma^{\mathrm{N}^k\mathrm{LO}} = \sum_{i,j=0}^{k} \mathrm{d}\sigma_{VH}^{(i)} \times \mathrm{d}\sigma_{\mathrm{H}\to\mathrm{b}\bar{\mathrm{b}}}^{(j)}.$$

- $\mathcal{O}(\alpha_s)$ power counting: keep only $i + j \leq k$ terms.
- Yukawa couplings: top + $\mathcal{O}(\overline{y}_{\mathrm{b}}^2)$ for bottom (i.e. only in decay).
- Different renormalization scales for production and decay.

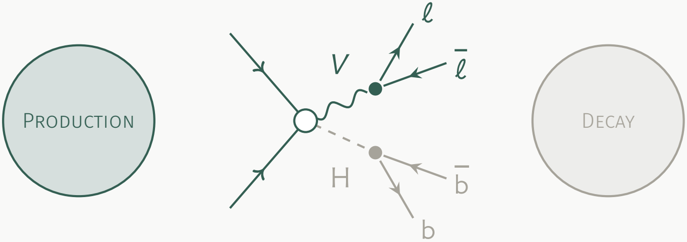
VH Process Setup: Production × Decay



Drell–Yan-like Amplitudes

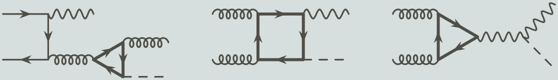
- Refit non-momentum conserving Drell–Yan-like amplitudes.
- Off-shell vector boson effects with full spin correlations present.

VH PROCESS SETUP: PRODUCTION × DECAY

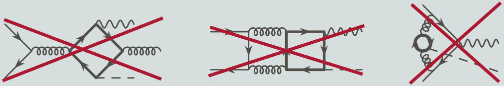


Top-loop Contributions

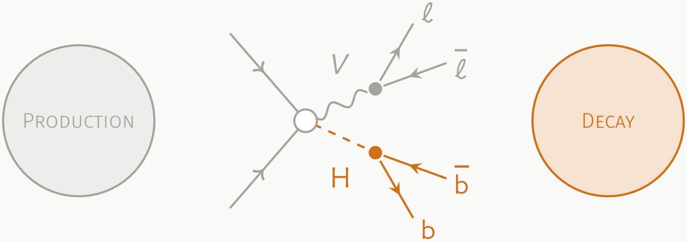
- Contributions of $\mathcal{O}(y_t)$ starting from NNLO.



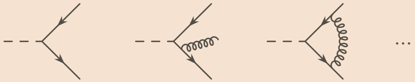
- gg-induced amplitudes are dominant (only ZH).
- Neglect sub-permille amplitudes or those only known in EFTs.



VH PROCESS SETUP: PRODUCTION × DECAY



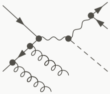
Decay Through Yukawa Coupling



- Running of $\overline{y}_{\mathrm{b}} = \overline{y}_{\mathrm{b}}(\mu^{\mathrm{dec.}})$ in $\overline{\mathrm{MS}}$ scheme.
- Kinematic mass $m_{\mathrm{b}} = 0$.

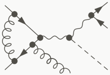
Integrate $d\sigma$! But...

$$\sigma^{\mathrm{NNLO}} = \int_{d\Phi_{VH+2}}$$



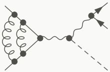
☹ Unresolved limits!

$$+ \int_{d\Phi_{VH+1}}$$



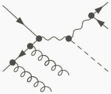
☹ Unresolved limits $1/\epsilon^2$ and $1/\epsilon$ poles!

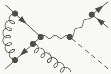
$$+ \int_{d\Phi_{VH}}$$

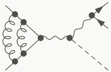


☹ $1/\epsilon^4 \ldots 1/\epsilon$ poles!

Integrate $\mathrm{d}\sigma$! But...

$$\sigma^{\mathrm{NNLO}} = \int_{\mathrm{d}\Phi_{VH+2}} \Big[$$

$$- \mathrm{d}\sigma^{\mathrm{S}} \Big]$$
☺ Well-behaved!

$$+ \int_{\mathrm{d}\Phi_{VH+1}} \Big[$$

$$- \mathrm{d}\sigma^{\mathrm{T}} \Big]$$
☺ Well-behaved! No poles!

$$+ \int_{\mathrm{d}\Phi_{VH}} \Big[$$

$$- \mathrm{d}\sigma^{\mathrm{U}} \Big]$$
☺ No poles!

Integrate $d\sigma$! But...

$$\sigma^{\mathrm{NNLO}} = \int_{d\Phi_{VH+2}} \left[d\sigma^{RR} \quad - d\sigma^{S} \right]$$ ☺ Well-behaved!

$$+ \int_{d\Phi_{VH+1}} \left[d\sigma^{RV} \quad - d\sigma^{T} \right]$$ ☺ Well-behaved! No poles!

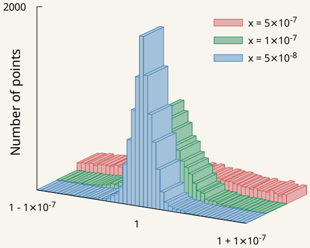
poles!

Unresolved limits: $x \to 0$

$d\sigma^{RR} \longrightarrow d\sigma^{S}$

$d\sigma^{RV} \longrightarrow d\sigma^{T}$

Ratio peaks at 1!



Integrate $d\sigma$! But...

$$\sigma^{NNLO} = \int_{d\Phi_{VH+2}} \left[d\sigma^{RR} - d\sigma^{S} \right]$$ ☺ Well-behaved!

$$+ \int_{d\Phi_{VH+1}} \left[d\sigma^{RV} - d\sigma^{T} \right]$$ ☺ Well-behaved! No poles!

$$+ \int_{d\Phi_{VH}} \left[d\sigma^{VV} - d\sigma^{U} \right]$$ ☺ No poles!

Analytic pole cancellation!

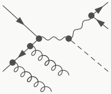
$$\text{Poles}\left(d\sigma^{RV} - d\sigma^{T}\right) = 0$$

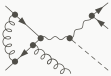
$$\text{Poles}\left(d\sigma^{VV} - d\sigma^{U}\right) = 0$$

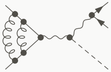
```
/scratch/majeri/nnlojet/maple/process/VH
❯ form autoqgB0g2WHxBy0g0HU.frm
FORM 4.2 (Sep 14 2017) 64-bits
    #-

   poles = 0;

  6.54 sec out of 6.59 sec
```

INFRARED SINGULARITIES—SUBTRACTION

Integrate $\mathrm{d}\sigma$!

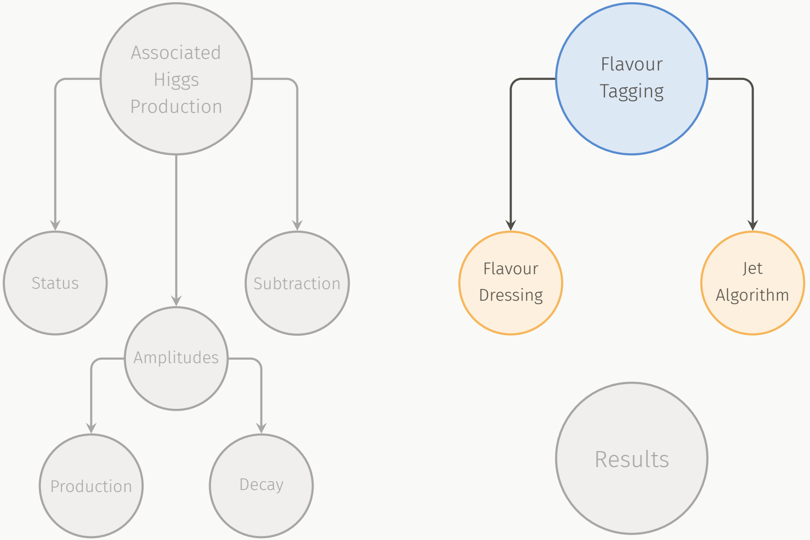
$$\sigma^{\mathrm{NNLO}} = \int_{\mathrm{d}\Phi_{VH+2}} \Big[$$

$$- \mathrm{d}\sigma^{\mathrm{S}} \Big]$$
☺ Well-behaved!

$$+ \int_{\mathrm{d}\Phi_{VH+1}} \Big[$$

$$- \mathrm{d}\sigma^{\mathrm{T}} \Big]$$
☺ Well-behaved! No poles!

$$+ \int_{\mathrm{d}\Phi_{VH}} \Big[$$

$$- \mathrm{d}\sigma^{\mathrm{U}} \Big]$$
☺ No poles!

NNLOJET: “A multiprocess parton level event generator.”

- Uses antenna subtraction.
- Can numerically integrate each subtracted line.


Associated Higgs Production
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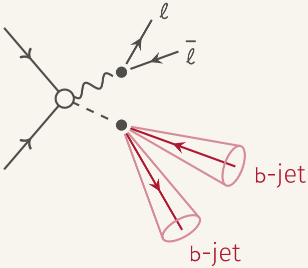
Flavour Dressing
Jet Algorithm
Results

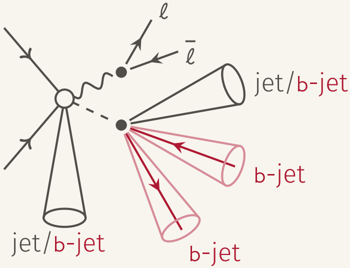
Necessary for $H \to b\bar{b}$

- Two b-jets at leading order.



Necessary for $H \to b\bar{b}$

- Two b-jets at leading order.
- More emissions at higher order.



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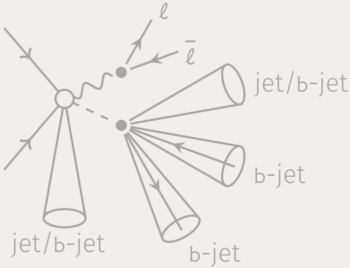


General

Applicable to all processes present in *NNLOJET* for arbitrary flavours.

"Flavour dressing"

Flavour-sensitive jet reconstruction

NLO Example

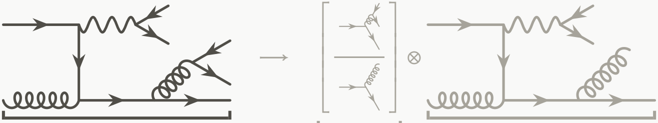
$$\mathrm{d}\hat{\sigma}_{ij,\mathrm{NLO}} = \int_{n+1} \left[\mathrm{d}\hat{\sigma}^{R}_{ij,\mathrm{NLO}} - \mathrm{d}\hat{\sigma}^{S}_{ij,\mathrm{NLO}} \right] + \int_{n} \left[\mathrm{d}\hat{\sigma}^{V}_{ij,\mathrm{NLO}} - \mathrm{d}\hat{\sigma}^{T}_{ij,\mathrm{NLO}} \right]$$

$\mathrm{d}\hat{\sigma}^{R}_{ij,\mathrm{NLO}}$ — real contributions

$\mathrm{d}\hat{\sigma}^{S}_{ij,\mathrm{NLO}}$ — real subtraction terms

$\mathrm{d}\hat{\sigma}^{V}_{ij,\mathrm{NLO}}$ — virtual contributions

$\mathrm{d}\hat{\sigma}^{T}_{ij,\mathrm{NLO}}$ — virtual subtraction terms



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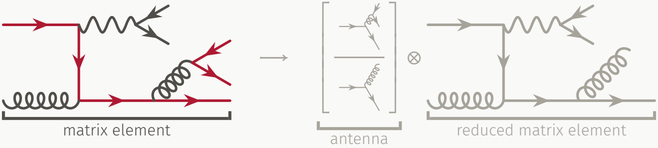
Real Amplitudes

$$d\hat{\sigma}^{R}_{ij,\mathrm{NLO}} = \mathcal{N}^{R}_{\mathrm{NLO}} \, d\Phi_{n+1}\left(\{p_3, \ldots, p_{n+3}\}; p_1, p_2\right) \frac{1}{S_{n+1}}$$
$$\times \left[M^{0}_{n+3}\left(\{p_{n+3}\}\right) \, J^{(n+1)}_{n}(\{p_{n+1}\}) \right]$$



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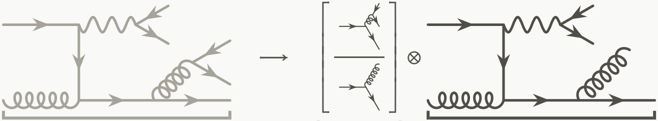
$$\times \left[M^{0}_{n+3}\left(\{p_{n+3}\},\{f_{n+3}\}\right) J^{(n+1)}_{n}\left(\{p_{n+1}\},\{f_{n+1}\}\right)\right]$$

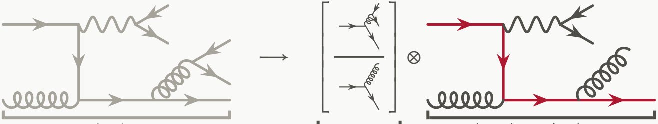


NLO Example

$$d\hat{\sigma}_{ij,\mathrm{NLO}} = \int_{n+1} \left[d\hat{\sigma}^{R}_{ij,\mathrm{NLO}} - d\hat{\sigma}^{S}_{ij,\mathrm{NLO}} \right] + \int_{n} \left[d\hat{\sigma}^{V}_{ij,\mathrm{NLO}} - d\hat{\sigma}^{T}_{ij,\mathrm{NLO}} \right]$$

Real Subtraction Terms

$$d\hat{\sigma}^{S}_{ij,\mathrm{NLO}} = \mathcal{N}^{R}_{\mathrm{NLO}} \sum_{k} d\Phi_{n+1}\left(\{p_3, \ldots, p_{n+3}\}; p_1, p_2\right) \frac{1}{S_{n+1}}$$
$$\times \left[X^0_3(\cdot, k, \cdot)\, M^0_{n+2}\left(\{\tilde{p}_{n+2}\}\right)\, J^{(n)}_n\left(\{\tilde{p}_n\}\right) \right]$$



NLO Example

$$\mathrm{d}\hat{\sigma}_{ij,\mathrm{NLO}} = \int_{n+1} \left[\mathrm{d}\hat{\sigma}^{R}_{ij,\mathrm{NLO}} - \mathrm{d}\hat{\sigma}^{S}_{ij,\mathrm{NLO}} \right] + \int_{n} \left[\mathrm{d}\hat{\sigma}^{V}_{ij,\mathrm{NLO}} - \mathrm{d}\hat{\sigma}^{T}_{ij,\mathrm{NLO}} \right]$$

Real Subtraction Terms

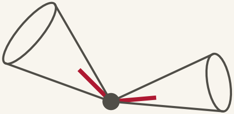
$$\mathrm{d}\hat{\sigma}^{S}_{ij,\mathrm{NLO}} = \mathcal{N}^{R}_{\mathrm{NLO}} \sum_{k} \mathrm{d}\Phi_{n+1}\left(\{p_3, \ldots, p_{n+3}\}; p_1, p_2\right) \frac{1}{S_{n+1}}$$
$$\times \left[X^0_3(\cdot, k, \cdot)\, M^0_{n+2}\left(\{\tilde{p}_{n+2}\}, \{\tilde{f}_{n+2}\}\right)\, J^{(n)}_n\left(\{\tilde{p}_n\}, \{\tilde{f}_n\}\right) \right]$$

Similarly for NLO virtual and all NNLO contributions.

Massless bottom quarks ($n_f = 5$ scheme)

⇒ Infrared safe jet algorithm is necessary for a working subtraction scheme.

Truth-tagging of (anti-)k_t Jets



$$d_{ij} = \frac{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}{R^2} \min(k_{ti}^{2p}, k_{tj}^{2p})$$

$$d_{iB} = k_{ti}^{2p} \qquad \text{with } p = \pm 1$$

flavour insensitive

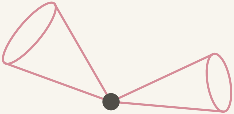
Wide-angle soft $b\bar{b}$ splitting at double real level:

- b and $\bar{b}$ *can* be clustered to different jets
- subtraction term has no b quark

Massless bottom quarks ($n_f = 5$ scheme)

$\Rightarrow$ Infrared safe jet algorithm is necessary for a working subtraction scheme.

Truth-tagging of (anti-)k_t Jets



$$d_{ij} = \frac{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}{R^2} \min(k_{ti}^{2p}, k_{tj}^{2p})$$

$d_{iB} = k_{ti}^{2p}$ with $p = \pm 1$

flavour insensitive

Wide-angle soft $b\bar{b}$ splitting at double real level:

- b and $\bar{b}$ *can* be clustered to different jets
  - → two b-jets in final state
- subtraction term has no b quark
  - → no flavoured jet in final state

$\Rightarrow$ mismatch between amplitude and subtraction term

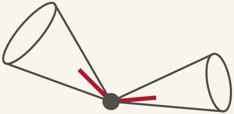
Not infrared safe!

FLAVOUR-SENSITIVE JET ALGORITHM

Massless bottom quarks ($n_f = 5$ scheme)

$\Rightarrow$ Infrared safe jet algorithm is necessary for a working subtraction scheme.

Flavour-k_t Jets



Wide-angle soft $b\bar{b}$ splitting at double real level:

- soft $b\bar{b}$ combined first
- jet is flavoured iff. $\left|\#b - \#\bar{b}\right| \pmod 2 \neq 0$

$$d_{ij} = \frac{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}{R^2} \begin{cases} \max(k_{ti}^2, k_{tj}^2) & \text{softer of } i, j \text{ is flavoured} \\ \min(k_{ti}^2, k_{tj}^2) & \text{softer of } i, j \text{ is unflavoured} \end{cases}$$

$$d_{iB} = \begin{cases} \max(k_{ti}^2, k_{tB}^2(y_i)) & \text{softer of } i, j \text{ is flavoured} \\ \min(k_{ti}^2, k_{tB}^2(y_i)) & \text{softer of } i, j \text{ is unflavoured} \end{cases}$$

similarly for $d_{i\bar{B}}$

$$k_{tB}(y) = \sum_i k_{ti} \left[\Theta(y_i - y) + \Theta(y - y_i)\, e^{(y_i - y)}\right]$$

$$k_{t\bar{B}}(y) = \sum_i k_{ti} \left[\Theta(y - y_i) + \Theta(y_i - y)\, e^{(y - y_i)}\right]$$

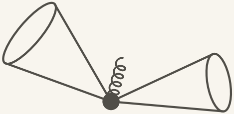
[A. Banfi, G. P. Salam, G. Zanderighi, arXiv:hep-ph/0601139]

FLAVOUR-SENSITIVE JET ALGORITHM

Massless bottom quarks ($n_f = 5$ scheme)

$\Rightarrow$ Infrared safe jet algorithm is necessary for a working subtraction scheme.

Flavour-k_t Jets



Wide-angle soft $b\bar{b}$ splitting at double real level:

- soft $b\bar{b}$ combined first
- jet is flavoured iff. $\left|\#b - \#\bar{b}\right| \pmod 2 \neq 0$

  $\rightarrow$ no flavoured jets in final state

  Infrared safe!

$$d_{ij} = \frac{\Delta y_{ij}^2 + \Delta\phi_{ij}^2}{R^2} \begin{cases} \max(k_{ti}^2, k_{tj}^2) & \text{softer of } i, j \text{ is flavoured} \\ \min(k_{ti}^2, k_{tj}^2) & \text{softer of } i, j \text{ is unflavoured} \end{cases}$$

$$d_{iB} = \begin{cases} \max(k_{ti}^2, k_{tB}^2(y_i)) & \text{softer of } i, j \text{ is flavoured} \\ \min(k_{ti}^2, k_{tB}^2(y_i)) & \text{softer of } i, j \text{ is unflavoured} \end{cases}$$

similarly for $d_{i\bar{B}}$

$$k_{tB}(y) = \sum_i k_{ti} \left[\Theta(y_i - y) + \Theta(y - y_i)\, e^{(y_i - y)}\right]$$

$$k_{t\bar{B}}(y) = \sum_i k_{ti} \left[\Theta(y - y_i) + \Theta(y_i - y)\, e^{(y - y_i)}\right]$$

[A. Banfi, G. P. Salam, G. Zanderighi, arXiv:hep-ph/0601139]

Even-tag Exclusion

$$\text{Jet is flavoured iff. } \left|\#b - \#\bar{b}\right| \bmod 2 \neq 0$$

$\bmod 2$ is optional but experimentally more feasible:

- IR safety requires $b\bar{b}$ quark ($B\bar{B}$ hadron) pair to be flavourless!
- most experimental studies sensitive to absolute flavour only
- even number of b (B) and/or $\bar{b}$ ($\bar{B}$) in jet ⇒ unflavoured!
- charge tagging is possible via semi-leptonic B-hadron decay
  - $\mathrm{Br}(B \to \ell + X) \approx 10\%$

→ reduction in event statistics but little information gain

Transverse Momentum of the Beam

Non-QCD particles ⇒ k_{tB} and $k_{t\bar{B}}$ modified

In case of VH production $V \to \ell\bar{\ell}$ included as

$$\tilde{k}_{tB}(y) = k_{tB}(y) + E_{t,V}\left[\Theta(y_V - y) + \Theta(y - y_V)\, e^{(y_V - y)}\right]$$
$$\tilde{k}_{t\bar{B}}(y) = k_{t\bar{B}}(y) + E_{t,V}\left[\Theta(y - y_V) + \Theta(y_V - y)\, e^{(y - y_V)}\right]$$

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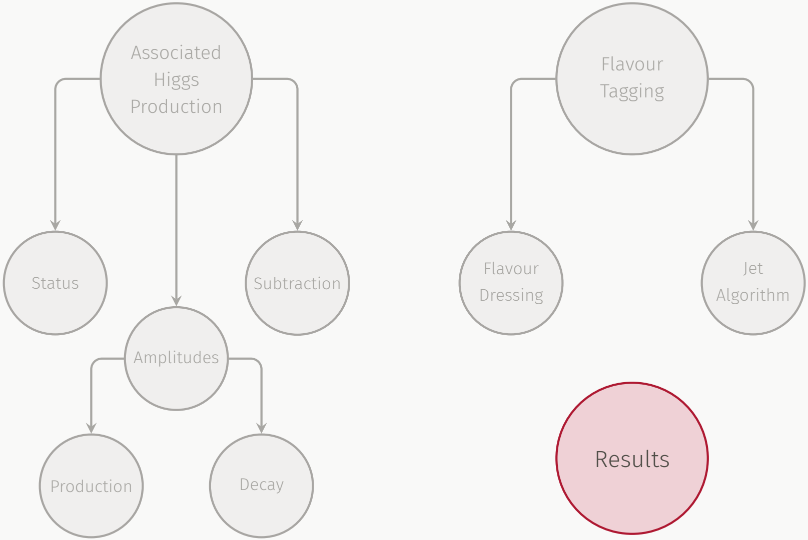

Associated Higgs Production
Status
Amplitudes
Subtraction
Production
Decay
Flavour Tagging
Flavour Dressing
Jet Algorithm
Results

Run Parameters

$\sqrt{s}$	13 TeV
PDF	NNPDF31_nnlo_as_0118
ΔR_{jet}	0.5
min. 2 b-jets:	$p_{\perp,\text{b}} > 25$ GeV
	$\lvert y_\text{b}\rvert < 2.5$
leptons:	$p_{\perp,\text{e}^\pm} > 15$ GeV
	$\lvert y_{\text{e}^\pm}\rvert < 2.5$
	$E_{\perp,\text{miss}} > 15$ GeV (for $\text{W}^\pm\text{H}$)

Uncertainty Estimate

Extensive 21-point scale variation

- production: dynamic scale M_{VH}

$$\mu_F = M_{\text{VH}} \times \left[2, 1, \frac{1}{2}\right]$$

$$\mu_R = M_{\text{VH}} \times \left[2, 1, \frac{1}{2}\right]$$

- decay: fixed scale m_{H}

$$\mu_R = m_{\text{H}} \times \left[2, 1, \frac{1}{2}\right]$$

Fiducial Cross Sections

	W^+H	W^-H	ZH
σ_{LO} [fb]	$18.06^{+2.87}_{-2.41}$	$11.96^{+1.90}_{-1.60}$	$4.83^{+0.77}_{-0.65}$
σ_{NLO} [fb]	$21.52^{+0.88}_{-1.08}$	$14.21^{+0.58}_{-0.71}$	$5.71^{+0.22}_{-0.28}$
σ_{NNLO} [fb]	$20.68^{+0.16}_{-0.46}$	$13.64^{+0.11}_{-0.31}$	$5.92^{+0.13}_{-0.16}$

$\mathcal{O}(5\%)$ decrease for $\text{W}^\pm$H@NNLO

$\mathcal{O}(4\%)$ increase for ZH@NNLO

→ top-loop contributions

$\mathcal{O}(2\text{–}3\%)$ theoretical uncertainty

VH@NNLO—NUMERICAL SCALE VARIATIONS VS. ANALYTIC RUNNING

Check against analytic running of renormalization scales:

1. fix decay scale, vary production scale
2. fix production scale, vary decay scale
3. vary both scales together

1

$$\mu_R^{\text{dec.}} = m_\text{H}$$

$$\mu_R^{\text{prod.}} = K_R^{\text{prod.}} \times M_{V\text{H}}$$

$$\text{with } K_R^{\text{prod.}} \in \left[\tfrac{1}{2}, 2\right]$$

2

$$\mu_R^{\text{prod.}} = M_{V\text{H}}$$

$$\mu_R^{\text{dec.}} = K_R^{\text{dec.}} \times m_\text{H}$$

$$\text{with } K_R^{\text{dec.}} \in \left[\tfrac{1}{2}, 2\right]$$

3

$$\mu_R^{\text{prod.}} = K_R \times M_{V\text{H}}$$

$$\mu_R^{\text{dec.}} = K_R \times m_\text{H}$$

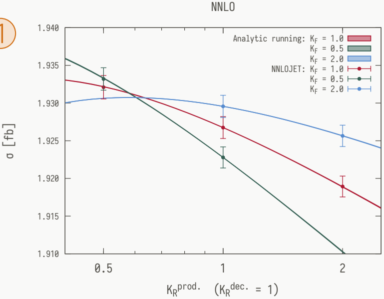
$$\text{with } K_R \in \left[\tfrac{1}{2}, 2\right]$$

Check against analytic running of renormalization scales:

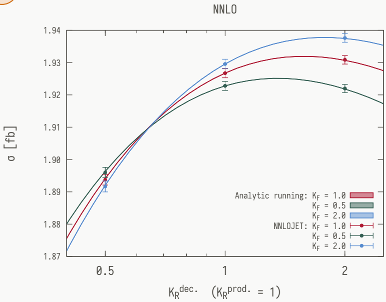
1. fix decay scale, vary production scale
2. fix production scale, vary decay scale
3. vary both scales together

→ e.g. single bin of $M_{WH} \in [220, 230]$ GeV

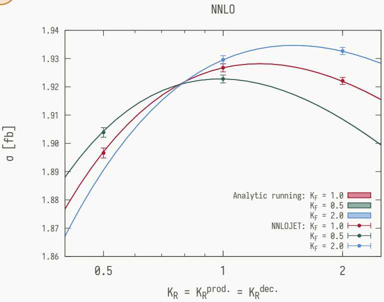
1



2



3



In the literature decay is often scaled to a fixed branching ratio $\mathrm{Br}(H \to b\bar{b})$:

$$
\begin{aligned}
d\sigma^{\text{scaled}}_{\text{NNLO}} &= d\sigma^{(0)}_{VH} \times \left(d\sigma^{(0)}_{H\to b\bar{b}} + d\sigma^{(1)}_{H\to b\bar{b}} + d\sigma^{(2)}_{H\to b\bar{b}} \right) \times K^{(2)} \\
&+ d\sigma^{(1)}_{VH} \times \left(d\sigma^{(0)}_{H\to b\bar{b}} + d\sigma^{(1)}_{H\to b\bar{b}} \right) \times K^{(1)} \\
&+ d\sigma^{(2)}_{VH} \times \left(d\sigma^{(0)}_{H\to b\bar{b}} \right) \times K^{(0)}
\end{aligned}
$$

with $K^{(i)} = \frac{\mathrm{Br}(H \to b\bar{b})\,\Gamma_H}{\sum_{j=0}^{i} \Gamma^{(j)}_{H\to b\bar{b}}}$

Fiducial Cross Sections

	naïve (unscaled)			scaled		
	W^+H	W^-H	ZH	W^+H	W^-H	ZH
σ_{LO} [fb]	$18.06^{+2.87}_{-2.41}$	$11.96^{+1.90}_{-1.60}$	$4.83^{+0.77}_{-0.65}$	$22.52^{+0.63}_{-0.80}$	$14.91^{+0.42}_{-0.54}$	$6.02^{+0.17}_{-0.21}$
σ_{NLO} [fb]	$21.52^{+0.88}_{-1.08}$	$14.21^{+0.58}_{-0.71}$	$5.71^{+0.22}_{-0.28}$	$22.87^{+0.76}_{-0.87}$	$15.11^{+0.51}_{-0.58}$	$6.06^{+0.20}_{-0.23}$
σ_{NNLO} [fb]	$20.68^{+0.16}_{-0.46}$	$13.64^{+0.11}_{-0.31}$	$5.92^{+0.13}_{-0.16}$	$20.93^{+0.61}_{-0.73}$	$13.80^{+0.41}_{-0.49}$	$6.10^{+0.31}_{-0.31}$

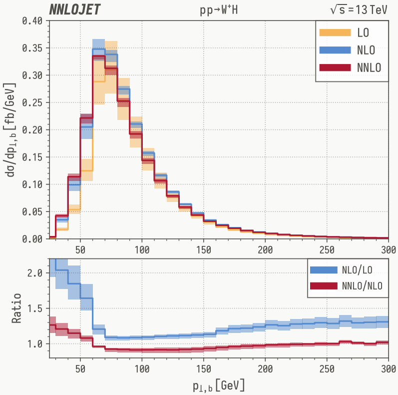
→ Barely any difference at NNLO between naïve and scaled values!

→ No reduction in theoretical uncertainties for the scaled cross sections!

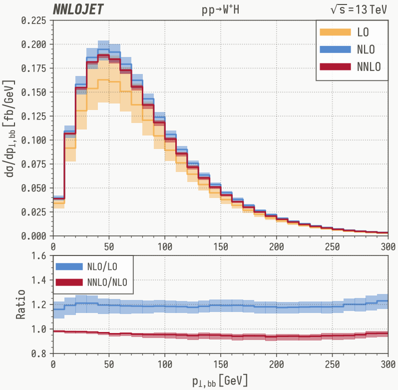
- $K^{(i)}$ divide out the Yukawa coupling $\overline{y}_b$.
- Different factors accompany different *production* orders.

W^+H@NNLO distributions

Leading b-jet transverse momentum



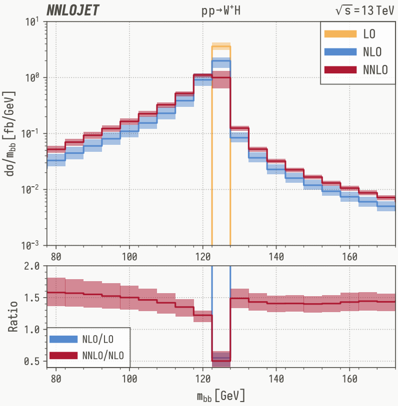
b-jet pair transverse momentum (m_{bb} closest to m_H)



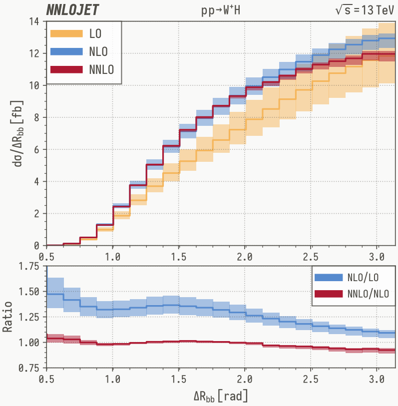
- Reduction of scale uncertainties, stabilization of the predictions at NNLO.

W$^+$H@NNLO DISTRIBUTIONS

b-jet pair invariant mass
(m_{bb} closest to m_H)



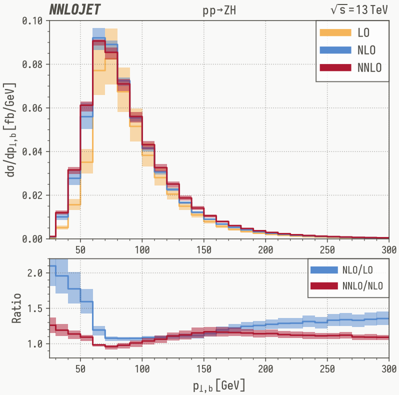
b-jet pair angular separation
(m_{bb} closest to m_H)



- Reduction of scale uncertainties, stabilization of the predictions at NNLO.
- m_{bb} left shoulder: decay corrections; right shoulder: production corrections

ZH@NNLO DISTRIBUTIONS

Leading b-jet transverse momentum



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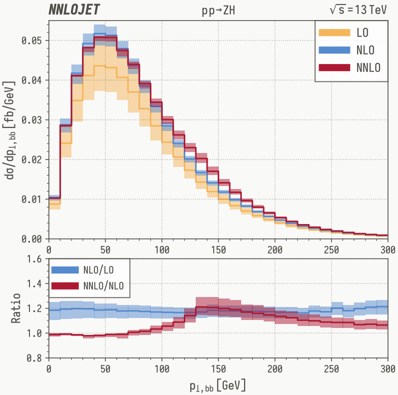
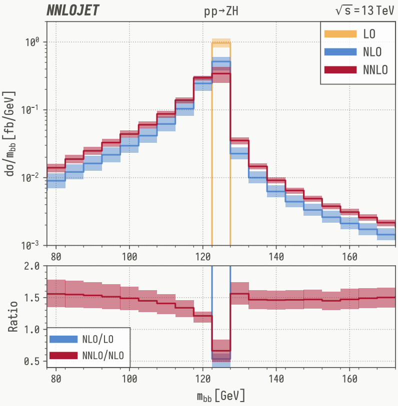


- Difference compared to $W^{\pm}H$: gg-induced top loops at NNLO.

→ Top quark threshold effects in central regions.

b-jet pair invariant mass
(m_{bb} closest to m_H)



b-jet pair angular separation
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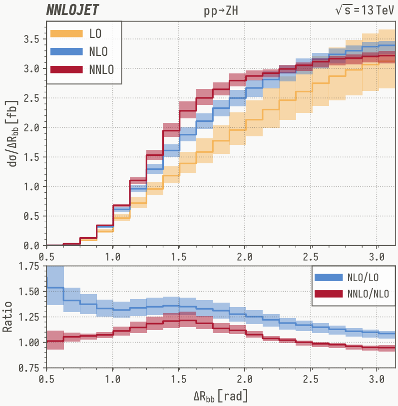

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→ Top quark threshold effects in central regions.

NNLOJET ♡ Flavour Tagging

- Associated Higgs production with $\mathrm{H} \to \mathrm{b}\bar{\mathrm{b}}$ decay at NNLO
  - prefer naïve assembly of production × decay
- Flavour-k_t jet algorithm
  - required by IR safety for massless b quarks
  - experimental feasibility: even-tag exclusion
- General purpose flavour-tagging implementation in *NNLOJET*

  → More processes to come: e.g. $V+$ heavy flavour, ...

THANK YOU!