ASSOCIATED HIGGS BOSON PRODUCTION VIA FLAVOUR-TAGGING IN *NNLOJET*

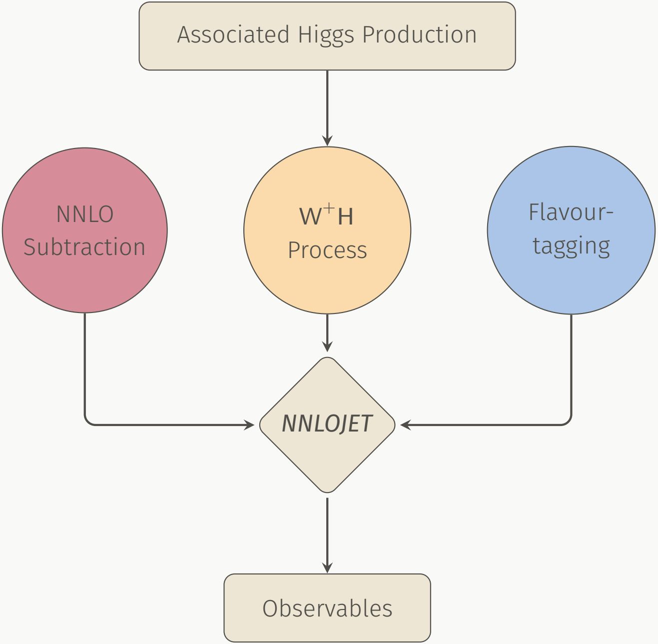
ETH zürich

Imre Majer

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

from the *NNLOJET* collaboration

Higgs Couplings, 29th November 2018


Associated Higgs Production
NNLO Subtraction
W^+H Process
Flavour-tagging
NNLOJET
Observables

Associated Higgs Production

Estimated 5% of Higgs production.

Clear leptonic signature.

$\mathrm{H} \to \mathrm{b}\bar{\mathrm{b}}$ main decay channel (BR = 58%)

Experiment Status

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

- CMS: 5.6σ significance. [arXiv:1808.08242]
- ATLAS: 5.3σ significance. [arXiv:1808.08242]

Theory Status

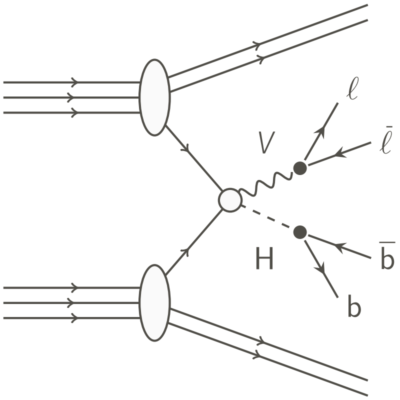
NNLO Production × NLO Decay

[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]



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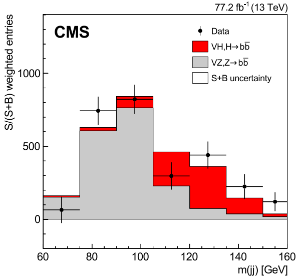

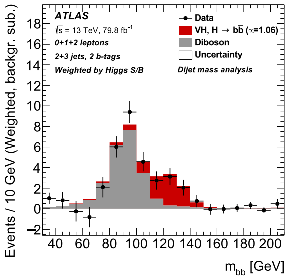

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Validation against W^-H total cross section of [F. Caola, G. Luisoni, K. Melnikov, R. Röntsch]. ✓

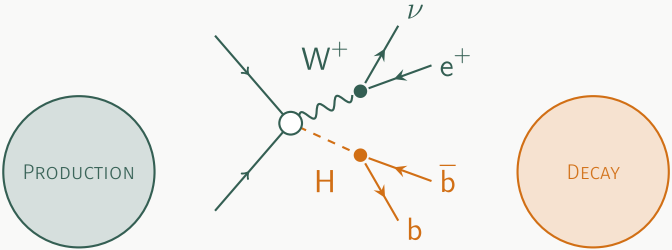
Our calculations . . .

→ include offshell propagators.

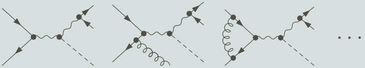
→ do extensive scale variations.

→ demonstrate a general flavour-tagging infrastructure

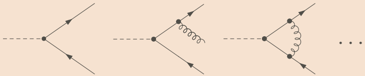
WH process setup: Production × Decay



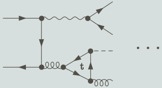
Drell–Yan-like amplitudes



Yukawa coupling $y_b = y_b(\mu)$



Top-loop contributions

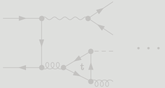


Differential Cross Sections

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

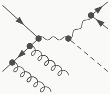
$\mathcal{O}(\alpha_s)$ power counting: keep only $i + j \leq k$ terms.

Top-loop contributions



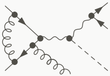
Integrate $\mathrm{d}\sigma$! But...

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



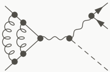
☹ Unresolved limits!

$$+ \int_{\mathrm{d}\Phi_{\mathrm{WH}+1}}$$



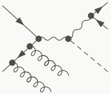
☹ Unresolved limits $1/\epsilon^2$ and $1/\epsilon$ poles!

$$+ \int_{\mathrm{d}\Phi_{\mathrm{WH}}}$$



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

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

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

$$- \mathrm{d}\sigma^{\mathrm{S}} \Big]$$

☺ Well-behaved!

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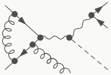
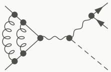

$$- \mathrm{d}\sigma^{\mathrm{T}} \Big]$$

☺ Well-behaved! No poles!

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

$$- \mathrm{d}\sigma^{\mathrm{U}} \Big]$$

☺ No poles!

INFRARED SINGULARITIES—SUBTRACTION

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

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

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

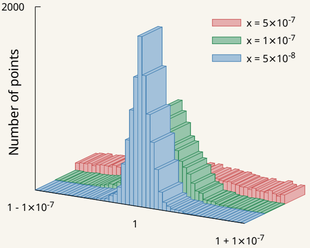
$-$ ... poles!

Unresolved limits: $x \to 0$

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

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

Ratio peaks at 1!



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Analytic pole cancellation!

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

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

```
/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
```

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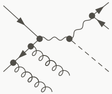
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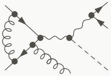
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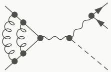
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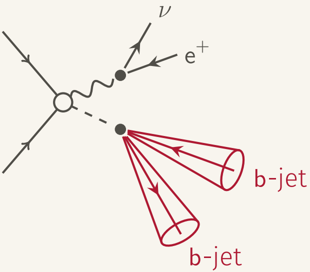
☺ No poles!

NNLOJET: “A multiprocess parton level event generator.”
Numerically integrate each subtracted line!

Partonic flavour-tracking

- Two b-jets at leading order.



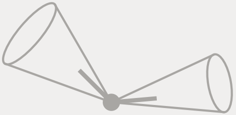
In *NNLOJET*

- Any existing process.
- All flavours: e.g. `TAG_FLAVOUR 5`

Flavoured jet reconstruction

- Massless b quarks ($n_f = 5$).
- Truth-tagging in (anti-)k_t jets:

e.g. soft $\mathrm{b}\bar{\mathrm{b}}$ splitting



Not infrared safe!

- Flavour-k_t: soft $\mathrm{b}\bar{\mathrm{b}}$ combined first

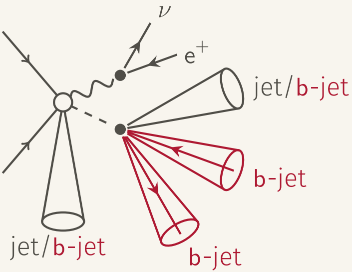
$$\left|\#\mathrm{b} - \#\bar{\mathrm{b}}\right| \neq 0 \Leftrightarrow \text{flavoured}$$

Infrared safe!

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

Partonic flavour-tracking

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



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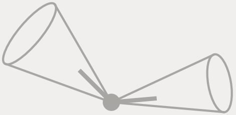

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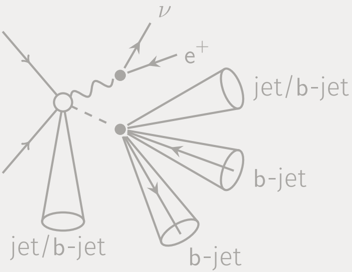

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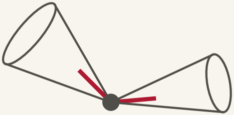

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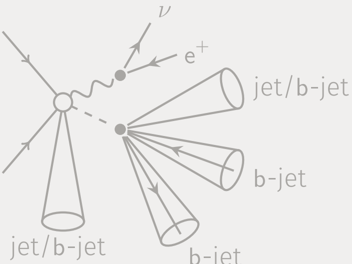

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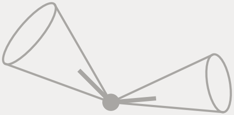

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Run parameters

$\sqrt{s}$	13 TeV
PDF	`NNPDF31_nnlo_as_0118`
ΔR_{jet}	0.5
b-jets:	minimum 2 (flavour-k_t)
	$p_{\perp,\mathbf{b}} > 25$ GeV
	$\lvert y_{\mathbf{b}} \rvert < 2.5$
leptons:	$p_{\perp,\mathbf{e}^+} > 15$ GeV
	$\lvert y_{\mathbf{e}^+} \rvert < 2.5$
	$E_{\perp,\text{miss}} > 15$ GeV

[arXiv:1610.07922, page 102]

Scale variations

production: dynamic scale M_{WH}

$$\mu_F = M_{\mathrm{WH}} \times \left(2, 1, \frac{1}{2}\right)$$

$$\mu_R = M_{\mathrm{WH}} \times \left(2, 1, \frac{1}{2}\right)$$

decay: fixed scale m_{H}

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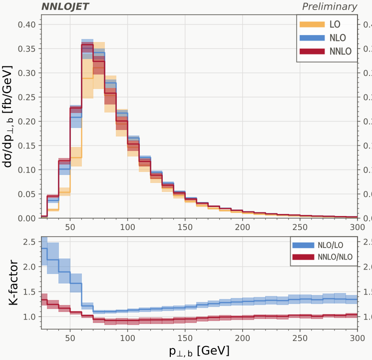
Fiducial cross section

$$\sigma^{\mathrm{LO}} = 18.61^{+2.93}_{-2.46}\ \text{fb}$$

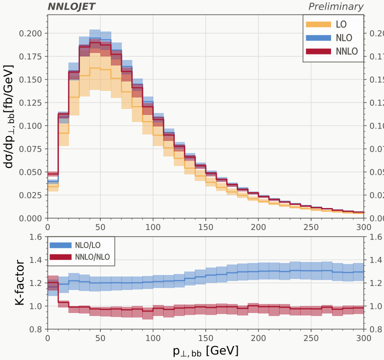
$$\sigma^{\mathrm{NLO}} = 22.70^{+1.03}_{-1.17}\ \text{fb}$$

$$\sigma^{\mathrm{NNLO}} = 22.36^{+0.47}_{-1.34}\ \text{fb}$$

Leading **b**-jet $p_\perp$



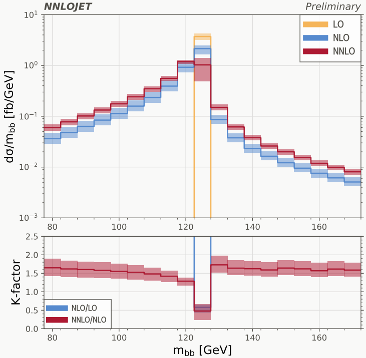
b-jet pair $p_\perp$
(m_{bb} closest to m_{H})



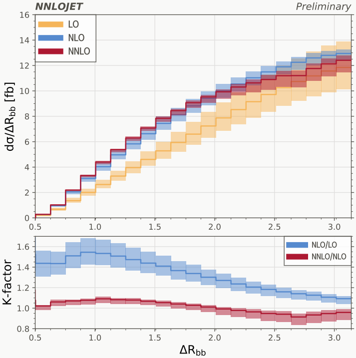
- Overall reduction of scale uncertainties.
- Regions where new NNLO channels are important can have larger scale bands.

CROSS SECTION & DISTRIBUTIONS

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



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



- Overall reduction of scale uncertainties.
- m_{bb} left shoulder dominated by decay corrections.
  m_{bb} right shoulder dominated by production corrections.

NNLOJET ♡ flavour-tagging

- Fixed-order Monte Carlo event generator $\cdots$
- $\cdots$ equipped with general-purpose flavour-tagging.
- Demonstrated $\mathrm{W^+H}$ at NNLO.
- More processes: $\mathrm{W^-H},\ \mathrm{ZH},\ \mathrm{Z+b},\ \mathrm{W+c}\cdots$
- Flavour-k_t: infrared safety, but not used in experiments.

THANK YOU!