Jet-vetoed Higgs cross section in gluon fusion at $N_3\text{LO}+NNLL+\text{LL}_R$

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University of Oxford

Work in collaboration with A. Banfi, F. Caola, F. Dreyer, G. Salam, G. Zanderighi, F. Dulat

[1511.02886]

Rencontres de Moriond - La Thuile, 24 March 2016
Jet vetoes

• Jet-bins categorisation of events is used in Higgs analyses and serves as a way to separate different production modes

• In some final states (WW and $\tau\tau$), exclusive-jet cross sections are measured in order to separate different background compositions

• Specifically, in the $H \rightarrow WW$ 0-jet cross section the top-induced background is dramatically suppressed by requiring no jets with a $p_{t,\text{veto}} > 25 - 30$ GeV

• Analogously, many signal events (mainly ggF in the 0-jet bin) are discarded by the veto requirement, and knowing the precise fraction of events that survive (jet veto efficiency) is relevant for precision studies of the cross section and determination of the Higgs couplings
Possible theoretical issues

• Stringent constraints on the QCD radiation may give rise to large logarithms which must be resummed to all orders in the strong coupling when $p_{t,\text{veto}} \ll m_H$

• e.g. soft-collinear emission

$$\Sigma(p_{t,\text{veto}}) \simeq \sigma^{(0)} \left(1 - 2 C_A \frac{\alpha_s}{\pi} \ln^2 \frac{m_H}{p_{t,\text{veto}}} \right)$$

• Commonly used values of $p_{t,\text{veto}}$ do not lead to the appearance of dramatically large logarithms, but all-order treatment relevant for accurate predictions (also for leading jet’s pt distribution) and precise error assessment
NNLO+NNLL predictions at Run I

- Lessons learnt at Run I:
  
  - Veto scales used in practical studies (25 - 30 GeV) do not lead to sizeable logarithms (logarithmic terms are the leading part of the fixed-order series, yet not too large)
  
  - These jet-veto scales are at the edge of the region where Sudakov effects become important, it’s hard to establish a priori whether one is misestimating the theoretical uncertainties in the vetoed cross section

Existing studies at NNLO+NNLL showed significant residual uncertainties (~10%) suggesting that N3LO corrections could be sizeable
NNLO+NNLL predictions at Run I

- Possible sizeable higher-order corrections are also allowed by the early comparison to data
Sources of H.O. (QCD) corrections

NNLL resummation
Sources of H.O. (QCD) corrections

NNLL resummation

H+1jet @ NNLO

>5% increase at 25-30 GeV for \( \mu_R = \mu_F = m_H/2 \)

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Full NLO and HEFT for NNLO

N3LO corrections

[Boughezal, Caola, Melnikov, Petriello, Schulze 1504.07922]
[Boughezal, Focke, Giele, Liu, Petriello 1505.03893]
[Chen, Gehrmann, Glover, Jaquier 1408.5325 (gluons only)]
Sources of H.O. (QCD) corrections

NNLL resummation

- Total cross section @ N3LO
- H+1jet @ NNLO

>3% increase at 13 TeV for $\mu_R = \mu_F = m_H/2$

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LHC 13 TeV [pb]

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Full NLO and HEFT for NNLO N3LO corrections

1-2% effect on the 0-jet cross section

References:

- [Anastasiou, Duhr, Dulat, Herzog, Mistlberger 1503.06056]
- [Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger 1602.00695]
- [Boughezal, Caola, Melnikov, Petriello, Schulze 1504.07922]
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H+1jet @ NNLO

>5% increase at 25-30 GeV for $\mu_R = \mu_F = m_H/2$

>3% increase at 13 TeV for $\mu_R = \mu_F = m_H/2$

Full NLO and HEFT for NNLO N3LO corrections

LHC 13 TeV, anti-$k_t$ R = 0.4

HEFT, $\mu_0 = m_H/2$, scale variations
PDF4LHC15 (NNLO), $\alpha_s = 0.118$
Sources of H.O. (QCD) corrections

- Total cross section @ N3LO
  
  >3% increase at 13 TeV for $\mu_R = \mu_F = m_H/2$

- NNLL resummation
  
  >5% increase at 25-30 GeV for $\mu_R = \mu_F = m_H/2$

- H+1jet @ NNLO

- LL small-R resummation

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- Total cross section @ N3LO
  - >3% increase at 13 TeV for \( \mu_R = \mu_F = m_H/2 \)
- NNLL resummation
  - H+1jet @ NNLO
    - >5% increase at 25-30 GeV for \( \mu_R = \mu_F = m_H/2 \)
- Quark-mass effects
  - [Banfi, Monni, Zanderighi 1308.4634]
  - [Grazzini, Sargsyan 1306.4581]
- LL small-R resummation
  - [Dasgupta, Dreyer, Salam, Soyez 1411.5182]
Theoretical uncertainties

- It is known that scale variation becomes unreliable at small pt because of accidental cancellations due to the presence of large logarithms.

- In this region, resummation provides a better handle on different sources of uncertainty and cancellations are avoided.

- However, one would like to have a method for assessing the uncertainties in exclusive cross sections which is:
  - robust against the inclusion of sizeable unknown effects (e.g. exact quark-mass effects)
  - reliable (i.e. resilient to accidental cancellations) even when the resummation is not available (e.g. combination of different jet multiplicities)
  - Not overly conservative in any kinematic regime
Uncertainties with the JVE method

• Jet Veto Efficiency (JVE) method’s synopsis:
  - JVE is a ratio of perturbative quantities - i.e. it admits a number of possible definitions at each perturbative order

\[
\epsilon_{n\text{LO}}^{(a)}(p_{t,\text{veto}}) = \frac{\sum^{(0)}(p_{t,\text{veto}}) + \cdots + \sum^{(n)}(p_{t,\text{veto}})}{\sigma^{(0)} + \cdots + \sigma^{(n)}}, \quad \sum^{(0)}(p_{t,\text{veto}}) = \sigma^{(0)}
\]

\[
\epsilon_{n\text{LO}}^{(b)}(p_{t,\text{veto}}) = \frac{\sum^{(0)}(p_{t,\text{veto}}) + \cdots + \sum^{(n)}(p_{t,\text{veto}}) - \sigma^{(n)}}{\sigma^{(0)} + \cdots + \sigma^{(n-1)}},
\]

\vdots

• In the large-logarithms region, JVE’s uncertainty dominated by Sudakov effects - uncertainties uncorrelated with the error in the total cross section (scale variation)

\[
\sum(p_{t,\text{veto}}) = \epsilon(p_{t,\text{veto}})\sigma_{\text{tot}} \quad \delta\sum(p_{t,\text{veto}}) = \sqrt{\epsilon^2\delta^2\sigma_{\text{tot}} + \delta^2\epsilon^2\sigma_{\text{tot}}^2}
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• Extension to the resummed case obtained by defining a set of multiplicative matching schemes corresponding to different efficiency schemes
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Uncertainty in scheme (a) obtained by varying all perturbative scales (see backup for details)
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Additional schemes could be in principle considered if the relative geometric expansion is justified (moderate K factors)
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  \]

  Extendable to any jet multiplicity

- Extension to the resummed case obtained by defining a set of multiplicative matching schemes corresponding to different efficiency schemes

Additional schemes could be in principle considered if the relative geometric expansion is justified (moderate K factors)
Basics of leading jet resummation

- Consider ensemble of independent (abelian) emissions with strong angular ordering (i.e. no clusterings). Consider kt-ordered emissions ($k_{t,1} > k_{t,2} > \ldots$)

\[
\Sigma(p_{t,veto}) \sim \sigma_0 \int dk_{t,1} p(k_{t,1}) p(\{k_{t,i}\}|k_{t,1}) = \sigma_0 e^{-\int [dk_1] |M(k_1)|^2 \Theta(k_{t,1} - p_{t,veto})}
\]
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• Consider ensemble of independent (abelian) emissions with strong angular ordering (i.e. no clusterings). Consider $k_t$-ordered emissions ($k_{t,1} > k_{t,2} > \ldots$)

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- The 0-jet cross section can be obtained as

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Probability of emitting the hardest gluon

Probability of emitting the remaining radiation given the veto on the hardest emission (jet) (1 if $p_{t,veto} > k_{t,1}$, 0 otherwise)
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(1 if $p_{t,veto} > k_{t,1}$, 0 otherwise)

At NNLL a number of corrections to this toy model must be considered (accurate Sudakov, treatment of parton luminosity, corrections to the strong angular ordering for a pair of emissions) - final result known analytically

[Banfi, Monni, Salam, Zanderighi 1206.4998]
Also in SCET: [Becher, Neubert, Rothen 1307.0025]
[Stewart, Tackmann, Walsh, Zuberi 1307.1808]
Jet radius logarithms

- Jet radius dependence in jet’s pt resummation enters at NNLL through the contributions describing the clustering (declustering) of an independent (correlated) pair of emissions.

\[ F_{\text{clust}}(R) = \frac{4\alpha_s^2(p_{t,\text{veto}})C_A^2}{\pi^2} L \left( -\frac{\pi^2 R^2}{12} + \frac{R^4}{16} \right) \]

\[ F_{\text{correl}}(R) = \frac{4\alpha_s^2(p_{t,\text{veto}})C_A L}{\pi^2} \left( f_1 \ln \frac{1}{R} + f_{\text{reg}}(R) \right) \]

- Small values of R lead to large collinear logarithms which could spoil the resummation accuracy already at NLL, and should be resummed.

[Dasgupta, Dreyer, Salam, Soyez 1411.5182]

[Initial value of the jet radius in the evolution
Conventionally set to one, and varied to probe size of subleading terms]

- Resummation of jet-radius leading logarithms can be performed by replacing the correlated contribution \( F_{\text{correl}}(R) \) with the all-order result.

\[ F_{\text{LLR}}(R) = \exp \left[ -\frac{4\alpha_s(p_{t,\text{veto}})C_A L}{\pi} \mathcal{Z}(t(R_0, R, p_{t,\text{veto}})) \right] - 1 \]

\[ + \frac{4\alpha_s^2(p_{t,\text{veto}})C_A L}{\pi^2} \left( f_1 \ln \frac{1}{R_0} + f_{\text{reg}}(R) \right) \]

[LL approximation for the first logarithmic moment of the momentum fraction carried by the hardest small-R jet arising from the fragmentation of a gluon]

[Tackmann, Walsh, Zuberi 1206.4312]
Jet radius logarithms

- In addition to the other perturbative uncertainties, the error associated with small-R resummation is estimated by varying \(1/2 \leq R_0 \leq 2\)

- Small impact (~1%) with \(R=0.4\)
- Slight increase in uncertainty band due to larger \(Q\) dependence of the all-order correlated contribution
- \(R_0\) dependence moderate (backup)
Quark-mass effects

- When exact mass loops are considered, the bottom-quark amplitude is enhanced by logarithms of the ratio $p_t/m_b$ in the regime $m_b^2 << p_t^2 << m_H^2$

- e.g. at NLO (currently the state-of-the-art prediction for the full process), the 0-jet cross section features terms of the type

  $$\alpha_s \frac{m_b^2 m_t^2}{m_H^4} \ln^2 \frac{p_{t,\text{veto}}}{m_b} \ln \frac{p_{t,\text{veto}}}{m_H}$$

  (interference)

  $$\alpha_s \frac{m_b^4}{m_H^4} \ln^4 \frac{p_{t,\text{veto}}}{m_b} \ln^2 \frac{p_{t,\text{veto}}}{m_H}$$

  (bottom squared)

- These logarithms do not exist for $p_t \leq m_b$ (HQEFT picture), therefore QCD factorisation is preserved in the limit $p_t \to 0$ (i.e. the new logarithms are never divergent and come with a bunch of other regular terms $\sim \mathcal{O}(p_t^2)$)

  $$|\mathcal{M}({\tilde{p}}, k_1, \ldots, k_n)|^2 = |M_{\text{Born}}({\tilde{p}})|^2 |M_{\text{div}}(k_1, \ldots, k_n)|^2 + \text{regular terms}$$

- At normal jet-veto scales their contribution is potentially large, and an all-order treatment is preferable.

  Recent progress in [Melnikov, Penin 1602.09020]
Quark-mass effects

• Full resummation of mass logarithms still unknown, therefore one needs to stick to a prescription for the time being. Allow for a different resummation scale (possibly smaller) for the bottom contribution

\[ \Sigma_{\text{matched}}(p_t, \text{veto}) = \Sigma_t^{\text{matched}}(p_t, \text{veto}, Q) + \Sigma_{t,b}^{\text{matched}}(p_t, \text{veto}, Q_b) - \Sigma_t^{\text{matched}}(p_t, \text{veto}, Q_b) \]

• Two prescriptions for the resummation are available:
  • Treat new logs on the same footing as other regular terms which vanish when \( p_t \to 0 \)
  • Switch off resummation around \( m_b \) for the bottom contribution (i.e. set \( Q_b \sim m_b \))

• Difference between the two prescriptions is negligible above 20 GeV therefore we choose to set \( Q_b = Q = m_H/2 \)

• NNLO calculation desirable - will also help establish which prescription is more appropriate

[Banfi, Monni, Zanderighi 1308.4634]
[Mantler, Wiesemann 1210.8263]
[Grazzini, Sargsyan 1306.4581]

Use mass effects up to NLO and HEFT at higher orders.
Jet Veto Efficiency at LHC13

- Jet-veto efficiency with $\mu_R = \mu_F = m_H/2$

  - Moderate corrections w.r.t. NNLO+NNLL (~1-2%) - consistently, theory uncertainty reduced by more than a factor of two (~8% → ~3%)

  - Impact of resummation w.r.t. N3LO at the 1-2% level - similar uncertainties (this is peculiar of this scale, doesn’t occur at e.g. $m_H$)
0-jet Cross Section at LHC13

- 0-jet cross section with $\mu_R = \mu_F = m_H/2$

- Moderate increase in the 0-jet cross section (~2%) w.r.t. NNLO+NNLL - significant reduction of the theory uncertainty
i-jet Cross Section at LHC13

- Inclusive 1-jet cross section with $\mu_R = \mu_F = m_H/2$

- very moderate effects in the inclusive 1-jet cross section
- JVE not too conservative at high pt
Predictions at 13 TeV LHC ($\mu_0 = m_H/2$)

### 0-jet efficiency and cross section

<table>
<thead>
<tr>
<th>LHC 13 TeV</th>
<th>$\epsilon^{N^3LO+NNLL+LL_R}$</th>
<th>$\Sigma_{0\text{-jet}}^{N^3LO+NNLL+LL_R}$ [pb]</th>
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<td>$p_{t,\text{veto}} = 25$ GeV</td>
<td>0.534$^{+0.017}_{-0.008}$</td>
<td>24.0$^{+0.8}_{-1.0}$</td>
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<td>23.6$^{+2.5}_{-3.6}$</td>
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<tr>
<td>$p_{t,\text{veto}} = 30$ GeV</td>
<td>0.607$^{+0.016}_{-0.008}$</td>
<td>27.2$^{+0.7}_{-1.1}$</td>
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### 1-jet cross section

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<td>$p_{t,\text{min}} = 25$ GeV</td>
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<td>17.6$^{+0.4}_{-1.0}$</td>
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All uncertainties obtained with the new JVE prescription
Conclusions

- State-of-the-art predictions for the jet-veto efficiency and 0-jet cross section in H production includes:
  - N3LO corrections to the total cross section
  - NNLO corrections to the inclusive 1-jet cross section
  - NNLL resummation for jet-veto logarithms
  - small-R resummation effects at LL accuracy
  - heavy-quark mass effects

[Code JetVHeto-v3.0 at https://jetvheto.hepforge.org/]

- JVE method has been revisited to take into account the good convergence shown by N3LO effects, and to fix some convergence issues at higher energies (see backup slides)

- Corrections w.r.t. to the previous NNLO+NNLL predictions are at the ~2% level - theoretical uncertainties are reduced to ~3% (efficiency)/~4% (0-jet cross section)

- At this level of precision other effects (may) become as important (quark masses at NNLO, EW, non-perturbative corrections) - PDF and strong coupling uncertainties of the same order, need for a precise assessment
Uncertainties with the JVE method @ NNLO

- e.g. at NNLO, three different efficiency schemes are available

\[
\epsilon_{\text{NNLO}}^{(a)}(p_{t,veto}) = 1 + \frac{1}{\sigma_{\text{tot},2}} \sum_{i=1}^{2} \tilde{\sum}^{(i)}(p_{t,veto}),
\]

\[
\epsilon_{\text{NNLO}}^{(b)}(p_{t,veto}) = 1 + \frac{1}{\sigma_{\text{tot},1}} \sum_{i=1}^{2} \tilde{\sum}^{(i)}(p_{t,veto}),
\]

\[
\epsilon_{\text{NNLO}}^{(c)}(p_{t,veto}) = 1 + \frac{1}{\sigma_{\text{tot},0}} \left[ \sum_{i=1}^{2} \tilde{\sum}^{(i)}(p_{t,veto}) - \frac{\sigma^{(1)}}{\sigma_{\text{tot},0}} \tilde{\sum}^{(1)}(p_{t,veto}) \right]
\]

- Resummation fits in naturally (each efficiency scheme corresponds to a different matching scheme), providing a better control of Sudakov effects, e.g. reducing the spread between different efficiency schemes
Uncertainties with the JVE method @ NNLO

- Prescription at NNLO+NNLL (a.k.a. old JVE method): uncertainty for JVE as the envelope of the following variations

  - with scheme (a), vary scales $\mu_R/\mu_F$ by a factor of 2 in either direction while keeping $1/2 \leq \mu_R/\mu_F \leq 2$

  - with central $\mu_R/\mu_F$, vary the resummation scale $Q$ by a factor of 2

  - with central scales, switch to schemes (b), (c)

Final uncertainty in the 0-jet cross section slightly larger (but not overly conservative) than the $Q$, renorm./fact. scales variations. Slightly conservative estimate reasonable considering the large corrections at NNLO.
Potential issues of the JVE method

• Possible issues can appear when the perturbative series for the total cross section features a very poor convergence, and the geometric expansion which defines the efficiency schemes can be badly defined.

• This feature shows up already at NNLO for scheme (c) at larger c.o.m. energies —> NLO $\frac{\sigma^{(1)}}{\sigma^{(0)}}$ factor grows from $\sim 1.2$ (8 TeV) to $\sim 1.3$ (13 TeV).
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- This feature shows up already at NNLO for scheme (c) at larger c.o.m. energies —> NLO factor grows from ~1.2 (8 TeV) to ~1.3 (13 TeV). Scheme (c)’s efficiency increases with the energy (unphysical).
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• Possible issues can appear when the perturbative series for the total cross section features a very poor convergence, and the geometric expansion which defines the efficiency schemes can be poorly defined.

• This feature shows up already at NNLO for scheme (c) at larger c.o.m. energies —> NLO K factor grows from ~1.2 (8 TeV) to ~1.3 (13 TeV).

- Scheme (c)'s efficiency becomes larger than one at high scales. Overly large uncertainty also in the tail of the leading jet's pt spectrum.
JVE method at N3LO

• 5 schemes for the jet-veto efficiency available at this order

\[ \sigma^{(3)} \rightarrow \text{[Anastasiou, Duhr, Dulat, Herzog, Mistlberger 1503.06056]} \]

\[ \sum^{(3)}(p_{t,\text{veto}}) \rightarrow \text{[Boughezal, Caola, Melnikov, Petriello, Schulze 1504.07922]} \]

\[
\begin{align*}
\epsilon^{(a)}(p_{t,\text{veto}}) &= 1 + \frac{1}{\sigma_{\text{tot},3}} \sum_{i=1}^{3} \bar{\Sigma}^{(i)}(p_{t,\text{veto}}) \\
\epsilon^{(b)}(p_{t,\text{veto}}) &= 1 + \frac{1}{\sigma_{\text{tot},2}} \sum_{i=1}^{3} \bar{\Sigma}^{(i)}(p_{t,\text{veto}}), \\
\epsilon^{(c)}(p_{t,\text{veto}}) &= 1 + \frac{1}{\sigma_{\text{tot},1}} \left[ \sum_{i=1}^{3} \bar{\Sigma}^{(i)}(p_{t,\text{veto}}) - \frac{\sigma^{(2)}}{\sigma_{\text{tot},0}} \sum^{(1)}(p_{t,\text{veto}}) \right], \\
\epsilon^{(c')}(p_{t,\text{veto}}) &= 1 + \frac{1}{\sigma_{\text{tot},1}} \left[ \sum_{i=1}^{3} \bar{\Sigma}^{(i)}(p_{t,\text{veto}}) - \frac{\sigma^{(2)}}{\sigma_{\text{tot},1}} \sum^{(1)}(p_{t,\text{veto}}) \right], \\
\epsilon^{(d)}(p_{t,\text{veto}}) &= 1 + \frac{1}{\sigma_{\text{tot},0}} \left[ \sum_{i=1}^{3} \bar{\Sigma}^{(i)}(p_{t,\text{veto}}) - \frac{\sigma^{(1)}}{\sigma_{\text{tot},0}} \left( \sum^{(1)}(p_{t,\text{veto}}) + \bar{\Sigma}^{(2)}(p_{t,\text{veto}}) \right) \right. \\
& \left. + \frac{\sigma^{(1)}\sigma^{(1)} - \sigma^{(0)}\sigma^{(2)}}{(\sigma_{\text{tot},0})^2} \sum^{(1)}(p_{t,\text{veto}}) \right].
\end{align*}
\]

Schemes (c) and (d) are sensible only if the NLO K factor is small, therefore show the same issues as scheme (c) at NNLO

Therefore:

\[ \sigma_{\text{tot},1} = \sigma^{(0)} + \sigma^{(1)} \]
JVE method at N3LO

- Spread between schemes (c) and (d) @ N3LO not consistent with the change in efficiency from NNLO to N3LO (little uncertainty reduction inconsistent with the good perturbative convergence)
- Issues exacerbated when mass effects are included (larger NLO K factor)
Resummation & uncertainties

- Matching to NNLL resummation of jet-veto logarithms is performed by means of two multiplicative matching schemes which correspond to the two efficiency schemes (a) and (b) respectively.

- In addition to $\mu_R/\mu_F$ scales ($\times 2$) and schemes (a,b) variations, the size of subleading logarithmic terms is estimated by varying the resummation scale $Q$ around its central value $Q_0 = m_H/2$:
  - The old variation range $1/2 \leq Q/Q_0 \leq 2$ is conservative and allows for resummation effects up to $\sim m_H$ (larger uncertainty band in tail of jet’s pt spectrum).
Resummation & uncertainties

• Matching to NNLL resummation of jet-veto logarithms is performed by means of two multiplicative matching schemes which correspond to the two efficiency schemes (a) and (b) respectively.

• In addition to scales ($x^2$) and schemes (a,b) variations, the size of subleading logarithmic terms is estimated by varying the resummation scale around its central value.

  - The old variation range is conservative and allows for resummation effects up to $\sim m_H$ (larger uncertainty band in tail of jet's pt spectrum).

  - Given the good convergence observed with the inclusion of N3LO leading logarithmic corrections, we use the variation range $2/3 \leq Q/Q_0 \leq 3/2$ which gives a less conservative uncertainty at large pt.

  - The $Q$ dependence is reduced everywhere along the spectrum.
JVE prescription

- New uncertainty prescription for the JVE:
  - with scheme (a), vary scales $\mu_R/\mu_F$ by a factor of 2 in either direction while keeping $1/2 \leq \mu_R/\mu_F \leq 2$ (7 points)
  - keeping renormalisation and factorisation scales to their respective central values, vary the resummation scale ($Q_b = Q$) in the range $2/3 \leq Q/Q_0 \leq 3/2$
  - keeping central scales, switch to matching scheme (b)
  - with scheme (a) and keeping central scales, vary $R_0$ by a factor of 2
  - final uncertainty defined as the envelope of the above variations

- Uncertainty in the 0-jet cross section obtained by combining in quadrature with the error in the total cross section

$$
\Sigma(p_{t,\text{veto}}) = \epsilon(p_{t,\text{veto}}) \sigma_{\text{tot}}
$$

$$
\delta \Sigma(p_{t,\text{veto}}) = \sqrt{\epsilon^2 \delta^2 \sigma_{\text{tot}} + \delta^2 \epsilon \sigma_{\text{tot}}^2}
$$
Breakdown of uncertainties
New JVE prescription at NNLO+NNLL 8 TeV

- Uncertainty reduction due to smaller range of $Q$ variation at small $p_t$, and absence of scheme (c) at high $p_t$
- Moderate impact on the 0-jet cross section
fixed-order JVE vs. ST 13 TeV LHC

[Stewart, Tackmann 1107.2117]
fixed-order JVE vs. scale 13 TeV LHC

N$^3$LO jet veto cross section

scale variation

JVE

pp 13 TeV, anti-$k_t$ $R = 0.4$
Finite $m_{t,b}$, $\mu_0 = m_H/2$
PDF4LHC15 (NNLO), $\alpha_s = 0.118$
Comparison to $N_3LL+NLL$ @ 13 TeV LHC

Gluon branching is resolved at NNLL, and carries a significant resummation-scale dependence.