Jet-veto efficiencies at all orders in QCD

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Why jet-veto efficiencies in Higgs searches

QCD predictions for jet-veto efficiencies
  - Fixed order calculations
  - NLL resummation

Comparisons with other theoretical approaches
  - NNLL transverse momentum resummation (HqT)
  - Parton shower MC (POWHEG + PYTHIA)

Missing theoretical ingredients (multi-jet configurations, NNLL resummation, etc.)

[Fresh from the press: AB Salam Zanderighi arXiv:1203.5773]
Low-mass Higgs searches

Experimental data collected so far at the LHC give us hints that the Standard Model Higgs can be light.

One of the channels that is sensitive to a low-mass Higgs is $H \rightarrow WW^*$.

In case of a discovery, this channel will be crucial to determine the nature of the Higgs, e.g. its coupling to SM particles.
Jet-veto cross sections

In order to suppress the background from coloured particles (top), it is useful to separate events with different jet multiplicities.

In particular, the 0-jet bin is the least contaminated by W’s from top-antitop production.

The 0-jet cross section, the quantity we want to compute with high accuracy, is the cross section for Higgs production with no jets with $p_t > p_{t,veto}$.
The most obvious way to estimate jet-veto cross sections is via QCD fixed order calculations, nowadays NNLO

\[ \Delta \sigma^2[0 \text{ jets}] = \Delta \sigma^2[\text{all jets}] + \Delta \sigma^2[\geq 1 \text{ jet}] \]

\[ \sigma[0 \text{ jets}] = \sigma[\text{inclusive}] - \sigma[\geq 1 \text{ jet}] \sim \sigma_0 \left( K - 2CA \frac{\alpha_s}{\pi} \ln^2 \frac{M_H}{p_T^{\text{cut}}} \right) \]

\[ \sigma[0 \text{ jets}] \text{ affected by cancellation between large K-factor and large logarithms } \Rightarrow \text{ scale variations underestimate uncertainty} \]

\[ E_{cm} = 7 \text{ TeV } \]

\[ m_H = 165 \text{ GeV } \]

\[ |\eta^{\text{jet}}| \leq 3.0 \]

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Jet-veto efficiencies

An alternative way to account for different sources of uncertainties is to consider the jet-veto efficiency

The efficiency $\epsilon(p_{t,\text{veto}})$ is the fraction of events in which all jets have $p_t < p_{t,\text{veto}}$

$$\sigma[0\text{ jets}] = \sigma[\text{inclusive}] \times \epsilon(p_{t,\text{veto}})$$

- large K-factor
- large logarithms

Uncertainties in $\sigma[\text{inclusive}]$ reflect our ignorance of NNNLO terms in the perturbative expansion

Uncertainties in $\epsilon(p_{t,\text{veto}})$, especially at low $p_{t,\text{veto}}$, are related to missing logarithms $\ln(M_H/p_{t,\text{veto}})$ of Sudakov origin

In the following we will concentrate on the jet-veto efficiency and consider uncertainties of $\sigma[\text{inclusive}]$ and $\epsilon(p_{t,\text{veto}})$ uncorrelated
Fixed-order jet-veto efficiencies have extra source of uncertainties related to how they are defined in terms of basic cross sections

$$\sigma[\text{inclusive}] \equiv \sigma = \sigma_0 + \sigma_1 + \sigma_2$$

$$\sigma[0 \text{ jets}] \equiv \Sigma(p_{t,veto}) = \sigma_0 + \Sigma_1(p_{t,veto}) + \Sigma_2(p_{t,veto})$$

$$\Sigma_i(p_{t,veto}) = \sigma_i + \Sigma_i(p_{t,veto}) \quad \bar{\Sigma}_i(p_{t,veto}) = -\int_{p_{t,veto}}^{\infty} dp_t \frac{d\Sigma_i}{dp_t}$$

We propose three schemes for $\epsilon(p_{t,veto})$, equivalent at NNLO

$$\epsilon^{(a)}(p_{t,veto}) = \frac{\sigma_0 + \Sigma_1(p_{t,veto}) + \Sigma_2(p_{t,veto})}{\sigma_0 + \sigma_1 + \sigma_2}$$

Naive definition

$$\epsilon^{(b)}(p_{t,veto}) = \frac{\sigma_0 + \Sigma_1(p_{t,veto}) + \Sigma_2(p_{t,veto})}{\sigma_0 + \sigma_1}$$

$$1 - \frac{\sigma_{NLO}[1 \text{ jet}]}{\sigma_{NLO}[\text{all jets}]}$$

$$\epsilon^{(c)}(p_{t,veto}) = 1 + \left(1 - \frac{\sigma_1}{\sigma_0}\right) \frac{\bar{\Sigma}_1(p_{t,veto})}{\sigma_0} + \frac{\bar{\Sigma}_2(p_{t,veto})}{\sigma_0}$$

Strict fixed order expansion of $\epsilon(p_{t,veto})$
For Higgs the three schemes differ significantly at the reference values $p_{t,veto} = 25 - 30 \text{ GeV}$ (ATLAS - CMS)

In Z production, our control case, the 3 schemes give similar results, due to a better convergence of the PT series for $\sigma[\text{inclusive}]$

Part of the uncertainty in Higgs production can be removed via an all-order resummation of large logarithmic contributions

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NLL resummation

- Resummation is a reorganisation of the PT series for $\epsilon(p_{t,\text{veto}})$ that gives a physically sensible answer for any value of $p_{t,\text{veto}}$

\[
\epsilon(p_{t,\text{veto}}) = \exp\left[ Lg_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \ldots \right]
\]

Here $L = \ln\left(\frac{M_B}{p_{t,\text{veto}}}\right)$, with $M_B$ the boson (Higgs, Z) mass

- The jet-veto efficiency is just the cumulative distribution in the transverse momentum $p_{t,\text{jet}}$ of the leading jet $\Rightarrow$ within the scope of the Computer Automated Expert Semi-Analytical Resummer (CAESAR)

- Given a subroutine that computes a function $V(k_1, \ldots, k_n)$ of final state momenta $k_1, \ldots, k_n$ (e.g. $p_{t,\text{jet}}$), CAESAR
  - checks whether $V(k_1, \ldots, k_n)$ is resummable at NLL accuracy
  - performs the NLL resummation using a general master formula

[AB Salam Zanderighi '05]
Since $p_{t,\text{jet}}$ satisfies CAESAR’s applicability conditions, the jet-veto efficiency, at NLL accuracy, can be written in the form

$$\epsilon(p_{t,\text{veto}}) \sim \mathcal{L}(p_{t,\text{veto}}) e^{-R(p_{t,\text{veto}})} \mathcal{F}(R') \quad R' = -p_{t,\text{veto}} \frac{dR(p_{t,\text{veto}})}{dp_{t,\text{veto}}},$$

The Sudakov exponent $R(p_{t,\text{veto}})$ embodies virtual corrections at a scale larger than $p_{t,\text{veto}}$

$$R(p_{t,\text{veto}}) = 2C \int_{p_{t,\text{veto}}^2}^{M_B^2} \frac{dk_t^2}{k_t^2} \frac{\alpha_s^{CMW}(k_t)}{\pi} \left[ \ln \frac{M_B}{k_t} + B \right]$$

$$C = \frac{C_A}{C_A} \quad \text{or} \quad C_F \quad B = -\frac{4\pi\beta_0}{C_A} \quad \text{or} \quad -\frac{3}{4}$$

$\mathcal{F}(R')$, a pure NLL function, accounts for the effect of multiple soft and collinear emissions: $\mathcal{F}(R') = 1$ for a perfectly factorisable observable $V(k_1, \ldots, k_n) = \max_i V(k_i)$

In the NLL limit $p_{t,\text{veto}} \to 0$ emissions are widely separated in rapidity, no recombination occurs and $p_{t,\text{jet}} = \max_i k_{ti} \Rightarrow \mathcal{F}(R') = 1$ $\epsilon(p_{t,\text{veto}})$ is a pure Sudakov form factor
Uncertainties in resummed calculations are estimated via
“traditional” variation of renormalisation and factorisation
scales, which we pick up in the range

\[ \frac{M_B}{4} \leq \mu_F, \mu_R \leq M_B \]
\[ \frac{1}{2} \leq \frac{\mu_R}{\mu_F} \leq 2 \]

resumming \( L = \ln(Q/p_{t,veto}) \) and letting \( M_B/4 \leq Q \leq M_B \)

Resummed calculations are unphysical for large \( p_{t,veto} \) ⇒
matching to fixed order needed

Variation of matching schemes gives an extra handle we can use

to estimate theoretical uncertainties

[AB Salam Zanderighi arXiv:1203.5773 ]
We propose three different matchings that correspond to the three schemes a, b, and c adopted for \( \epsilon(p_{t,veto}) \) at fixed order.

**Total uncertainty:** scale variations + central value of schemes b, c
**Comparison to NNLO**

- **NLL+NNLO** gives in general a lower efficiency with respect to pure NNLO, with 50% reduction of uncertainty at $p_{t,veto} = 25$ GeV.

Difference among schemes is NNNLL, only moderate improvement expected from NNLL at intermediate $p_{t,veto}$.
Our resummed calculation considers partonic jets, detected at all possible rapidities (jet-veto efficiency is global)

Hadronisation and finite acceptance corrections are much less than theoretical uncertainties in the reference region
The observable used for validation of MC event generators is the Higgs $p_t$, for which we have NNLL+NNLO (HqT).

In the reference region, size of uncertainties of NNLL Higgs and NLL jet veto is comparable ⇒ matching corrections dominate.

Consistency between our resummation and NNLL Higgs $p_t$ with addition of NNLL corrections from Higgs+2jet@NLO.

[Bozzi Catani de Florian Grazzini ’03]
Experimental analyses use POWHEG+PYTHIA, rescaled so that it agrees with HqT resummation. Overall agreement within uncertainties in the reference region, although our resummation gives lower efficiency.
Using CAESAR’s approach we can compute the only NNLL corrections that depend on the jet radius $R$:

$$\epsilon(p_t, \text{veto}) \sim e^{-R_{\text{NNLL}}(p_t, \text{veto})} (1 + F_{\text{correl}} + F_{\text{indep}})$$

$F_{\text{correl}}$ accounts for the effects of two partons coming from the splitting of a soft gluon:

$$F_{\text{correl}} = R' \alpha_s(p_t, \text{veto}) \times \left[ C_A F_A(R) + n_f F_f(R) \right]$$

$F_{\text{indep}}$ accounts for two independent emissions that are clustered into the same jet:

$$F_{\text{indep}} = R' \frac{C \alpha_s(p_t, \text{veto})}{\pi} \left( -\frac{\pi^2 R^2}{12} + \frac{R^4}{16} \right)$$
Conclusions

- We have argued that uncertainties on total Higgs cross-section and jet-veto efficiency are uncorrelated.
- We have introduced fixed-order prescriptions as extra handles to estimate theoretical uncertainties for jet-veto efficiencies.
- Fixed-order uncertainties are in general reduced by matching NNLO to NLL resummation (performed with CAESAR).
- In the reference region ($p_{t,veto} \sim 20 - 30$ GeV) resummation does not have a huge impact, matching corrections are important.
- NNLO+NLL predictions for the efficiency are consistent with those obtained with other theoretical tools (HqT+MCFM, POWHEG+PYTHIA).
- Issues that should be addressed (corrections of order 5%)
  - Impact of NLO corrections to H+2jets.
  - Relation between Higgs $p_t$ and jet-veto at NNLL.
EXTRA SLIDES
NLL resummability

An observable $V(k_1, \ldots, k_n)$ is resummable at NLL accuracy if

After a single emission $k$, soft and collinear to any hard leg $\ell$, the observable behaves as

$$V(k) = d_\ell \left( \frac{k_t}{Q} \right)^{a_\ell} e^{-b_\ell \eta^{(\ell)}} g_\ell(\phi)$$

For $V(k) = p_{t,jet}/M_B$ we have $a_\ell = d_\ell = g_\ell = 1$ and $b_\ell = 0$

$V$ is continuously global, sensitive to emissions in the whole of the phase space ⇒ satisfied since $p_{t,jet} \sim k_t$ everywhere

$V$ is recursively IR and collinear safe, a non-trivial condition on the observable’s scaling with multiple emissions ⇒ also satisfied for $p_{t,jet}$, which can then be resummed with CAESAR

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