Jets in Higgs Searches – Theory Overview

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Newly Formed Jets Subgroup

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Different Uses for Jets in Higgs Searches (see Bruce' talk next)

- Jet binning to increase sensitivity:
  - Suppress backgrounds: e.g. jet veto in $H \to WW$ to kill $t\bar{t}$
  - Distinguish Higgs production mechanisms: VBF vs. ggF
- Higgs decay products: $H \to b\bar{b}$

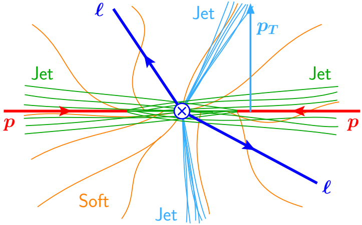
Some common issues that appear in all uses of jets

- Jet definition and jet selection cuts $\longrightarrow$ perturbative uncertainties
- Impact of underlying event $\longrightarrow$ nonperturbative uncertainties
- Experimental issues: pile-up, resolution, jet-energy scale

Large Logarithms from Jet Selection

Jet selection cuts (or any other type of exclusive cut) are sensitive to additional soft and collinear emissions

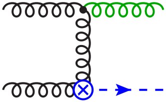
⇒ Restricting or cutting into soft radiation, ISR, or FSR causes large logarithms



Example: $gg \to H + 0$ jets

- Jet veto restricts ISR $\longrightarrow$ t-channel singularities produce Sudakov double logarithms

$$\sigma_0(p_T^{\rm cut}) = \sigma_B\Big(1 - \frac{\alpha_s}{\pi}\, 6\ln^2\frac{p_T^{\rm cut}}{m_H} + \cdots\Big)$$



⇒ Perturbative corrections get large at small $p_T^{\rm cut}$

- Nonperturbative effects and pile-up become more important at small $p_T^{\rm cut}$

Perturbative Structure of Jet Bin Cross Sections

$$\sigma_{\text{total}} = \underbrace{\int_0^{p^{\text{cut}}} \mathrm{d}p \, \frac{\mathrm{d}\sigma}{\mathrm{d}p}}_{\sigma_0(p^{\text{cut}})} + \underbrace{\int_{p^{\text{cut}}}^{\infty} \mathrm{d}p \, \frac{\mathrm{d}\sigma}{\mathrm{d}p}}_{\sigma_{\geq 1}(p^{\text{cut}})}$$

$$\sigma_{\text{total}} = 1 + \alpha_s + \alpha_s^2 + \cdots$$

$$\sigma_{\geq 1}(p^{\text{cut}}) = \alpha_s(L^2 + L + 1) + \alpha_s^2(L^4 + L^3 + L^2 + L + 1) + \cdots$$

$$\sigma_0(p^{\text{cut}}) = \sigma_{\text{total}} - \sigma_{\geq 1}(p^{\text{cut}})$$

$$= \left[1 + \alpha_s + \alpha_s^2 + \cdots\right] - \left[\alpha_s(L^2 + \cdots) + \alpha_s^2(L^4 + \cdots) + \cdots\right]$$

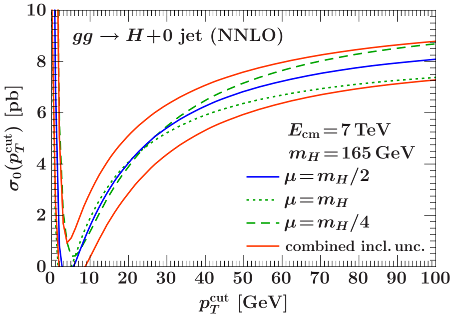
where $L = \ln(p^{\text{cut}}/Q)$

- Logarithms are important for $p^{\text{cut}} \ll Q \sim$ hard-interaction scale
- *Same* logarithms appear in the exclusive 0-jet and inclusive ($\geq$ 1)-jet cross section (and cancel in their sum)

$gg \longrightarrow$ Higgs + 0 Jets

blue: central scale choice
green: standard scale variation (method A)
orange: including estimate of the size of $p_T^{\rm cut}$-logarithms (method B)

Higgs + 0 Jets



[HNNLO, FEHiP, MCFM]

- Logs at small $p_T^{\rm cut}$ degrade fixed-order perturbation theory
- Resummation of exclusive logs can give improved predictions and uncertainty estimates

Perturbative Uncertainties in Jet Bins

$$\sigma_{\rm total} \quad = \quad \sigma_0(p^{\rm cut}) \quad + \quad \sigma_{\geq 1}(p^{\rm cut})$$

Consider theory "covariance matrix" for $\{\sigma_0(p^{\rm cut}), \sigma_{\geq 1}(p^{\rm cut})\}$

$$C = \begin{pmatrix} \Delta_0^2 & \Delta_0\, \Delta_{\geq 1} \\ \Delta_0\, \Delta_{\geq 1} & \Delta_{\geq 1}^2 \end{pmatrix} + \begin{pmatrix} \Delta_{\rm cut}^2 & -\Delta_{\rm cut}^2 \\ -\Delta_{\rm cut}^2 & \Delta_{\rm cut}^2 \end{pmatrix}$$

In general it will have a

- Correlated component with $\Delta_{\rm total} = \Delta_0 + \Delta_{\geq 1}$
- Anti-correlated component $\Delta_{\rm cut}$ induced by $p^{\rm cut}$ which cancels from $\Delta_{\rm total}$

$\Rightarrow$ The question is how to evaluate each piece.

Using Fixed-Order Scale Uncertainties

In fixed-order perturbation theory, we can use two pieces of information from scale variation

$$\Delta_{\mu\,\mathrm{total}} \quad \text{and} \quad \Delta_{\mu\geq 1} \quad \text{with} \quad \Delta_{\mu 0} = \Delta_{\mu\,\mathrm{total}} - \Delta_{\mu\geq 1}$$

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Method A: Take $\Delta_{\mathrm{cut}} = 0$ and use $\Delta_i = \Delta_{\mu i}$

$$C_A = \begin{pmatrix} \Delta_{\mu 0}^2 & \Delta_{\mu 0}\,\Delta_{\mu\geq 1} \\ \Delta_{\mu 0}\,\Delta_{\mu\geq 1} & \Delta_{\mu\geq 1}^2 \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}$$

$\Rightarrow$ Okay for large p^{cut}, but at small p^{cut} one cannot neglect Δ_{cut}

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$\Rightarrow$ Okay for large p^{cut}, but at small p^{cut} one cannot neglect Δ_{cut}

Method B: Take $\Delta_{\mathrm{cut}} = \Delta_{\mu\geq 1}$ and $\Delta_{\geq 1} = 0$ so $\Delta_0 = \Delta_{\mu\,\mathrm{total}}$

$$C_B = \begin{pmatrix} \Delta_{\mu\,\mathrm{total}}^2 & 0 \\ 0 & 0 \end{pmatrix} + \begin{pmatrix} \Delta_{\mu\geq 1}^2 & -\Delta_{\mu\geq 1}^2 \\ -\Delta_{\mu\geq 1}^2 & \Delta_{\mu\geq 1}^2 \end{pmatrix}$$

$\Rightarrow$ Better for small p^{cut}

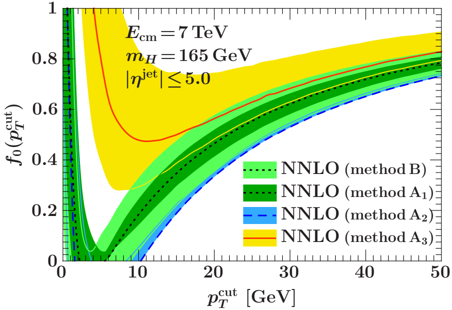
$\Rightarrow$ Reproduces Method A at large p^{cut} (since $\Delta_{\mu\geq 1}$ becomes small)

Event Fraction

Consider event fraction (jet-veto efficiency)

$$f_0(p^{\text{cut}}) = \frac{\sigma_0(p^{\text{cut}})}{\sigma_{\text{total}}} = 1 - \frac{\sigma_{\geq 1}(p^{\text{cut}})}{\sigma_{\text{total}}}$$

- Treat as a derived quantity with either method A or B (option 1)
- Alternative: Treat as the fundamental quantity and reexpand different $\mathcal{O}(\alpha_s^3)$ terms (options 2 and 3) [Banfi, Salam, Zanderighi]



- Use spread of central values from options 1, 2, 3 as uncertainty estimate

⇒ Agrees very well with method B uncertainties

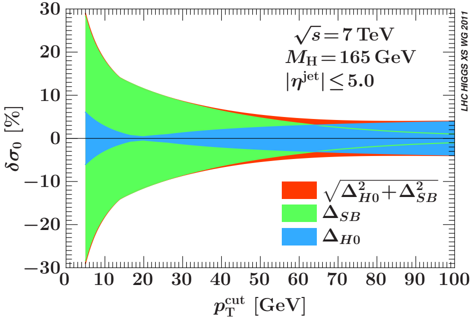
Using Uncertainties from Resummation

Method C: Resummation of exclusive logs provides additional information

$\Rightarrow$ Allows one to directly estimate different components

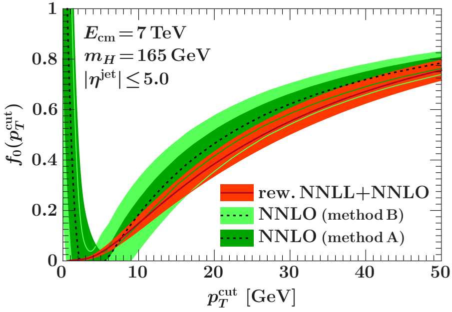
$$C_C = \begin{pmatrix} \Delta_{H0}^2 & \Delta_{H0}\,\Delta_{H\geq1} \\ \Delta_{H0}\,\Delta_{H\geq1} & \Delta_{H\geq1}^2 \end{pmatrix} + \begin{pmatrix} \Delta_{SB}^2 & -\Delta_{SB}^2 \\ -\Delta_{SB}^2 & \Delta_{SB}^2 \end{pmatrix}$$

- Δ_{Hi} from hard scale variation, with $\Delta_{\mu\,\mathrm{total}} = \Delta_{H0} + \Delta_{H\geq1}$
- $\Delta_{\mathrm{cut}} = \Delta_{SB}$ from soft and collinear scale variations

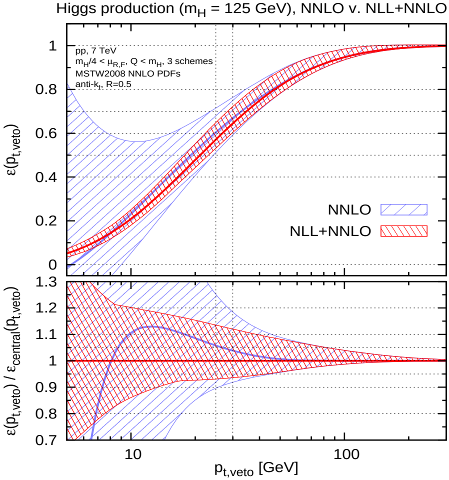


Comparison of Resummed and Fixed-Order Methods

Estimate of Δ_{cut} in method B is consistent with resummation



- orange: MC@NLO reweighted to partonic NNLL+NNLO beam thrust spectrum
  [Stewart, FT, Waalewijn]



- red: NLL+NNLO for p_T^{cut}
  [Banfi, Salam, Zanderighi]

More Comments on Resummation

What does NNLL mean?

- NNLL always means the same: $\ln\sigma = \alpha_s^n L^{n+1}(1 + \alpha_s + \alpha_s^2)$

  which requires 3-loop cusp, 2-loop non-cusp, and 1-loop matching
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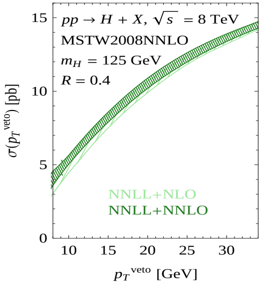
Very recent NNLL+NNLO for p_T^{cut} [Becher, Neubert]

- Uncertainties seem quite optimistic
- Transition from resummation region (small p_T^{cut}) to fixed-order region (large p_T^{cut}) not studied



Generalization to More Jets

Basic principle is the same for other cases and more jets

$$\sigma_{\geq N} = \underbrace{\int_0^{p_{N+1}^{\mathrm{cut}}} \mathrm{d}p_{N+1} \frac{\mathrm{d}\sigma_{\geq N}}{\mathrm{d}p_{N+1}}}_{\sigma_N(p_{N+1}^{\mathrm{cut}})} + \underbrace{\int_{p_{N+1}^{\mathrm{cut}}}^{\infty} \mathrm{d}p_{N+1} \frac{\mathrm{d}\sigma_{\geq N}}{\mathrm{d}p_{N+1}}}_{\sigma_{\geq N+1}(p_{N+1}^{\mathrm{cut}})}$$

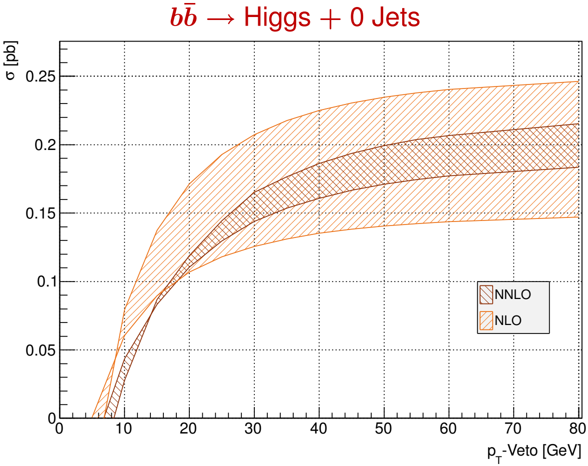
- Same logs $\ln(p_{N+1}^{\mathrm{cut}}/Q)$ appear in exclusive N-jet and corresponding inclusive ($\geq$ N+1)-jet cross section and cancel in their sum
- $\sigma_{\geq N}$ may have its own *unrelated* series of logs $\ln(p_N^{\mathrm{cut}}/Q)$

Impact of logs needs to be studied on case-by-case basis

- Typically larger for gluons than quarks
- Can get larger with additional hard jets (mostly for $gg \to H$)

$b\bar{b} \longrightarrow$ Higgs + 0 Jets

$E_{\mathrm{cm}} = 8\,\mathrm{TeV}$, $m_H = 125\,\mathrm{GeV}$ [Buehler, Herzog, Lazopoulos, Mueller]



- Same effect for incoming quarks but at somewhat lower p_T^{cut}

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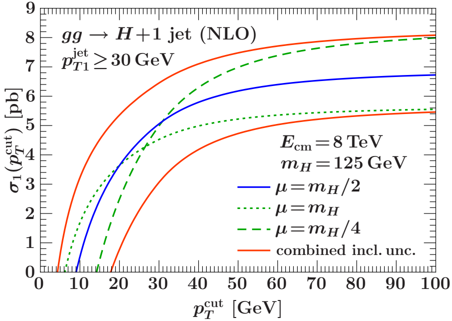
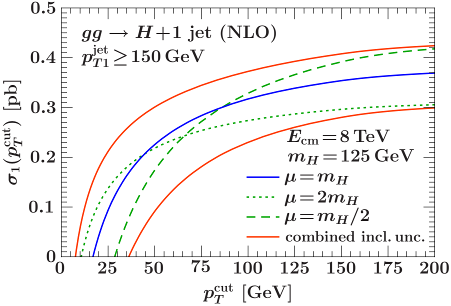
Higgs + 1 Jet



Higgs + 1 Jet



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- Logs get stronger with an additional hard jet (as expected)

VBF and $gg \to$ Higgs + 2 Jets

Central jet veto (CJV) in VBF selection is a (non-trivial) jet binning

$$\sigma_{\geq 2}^{\text{VBF cuts}} = \sigma_{2}^{\text{VBF cuts}}(\text{CJV}) + \sigma_{\geq 3}^{\text{VBF cuts}}(\text{inverse CJV})$$

- VBF signal process looks safe (color structure and incoming quarks)
- $gg \to H$ contribution needs to be studied carefully
  - Impact of VBF selection cuts (m_{jj}, $\Delta\eta$, etc.)
  - Can use NLO $gg \to H + 2j$ (MCFM) for this exercise

Interplay with $gg \to H + 0, 1$ jet selections. Currently:

- Use $\sigma_{\geq 2}^{\text{VBF cuts}}$ at NLO when it is removed from 0,1-jet selections (since typically $\sigma_{\geq 2}^{\text{VBF cuts}} \ll \sigma_{\geq 1}$)
- Use $\sigma_{\geq 2}$ at LO when it corresponds to a genuine veto on ≥ 2 jets

$\Rightarrow$ Needs to be studied more carefully

Some Remarks on Prescriptions and Timelines ...

Theory uncertainties are subtle

- Carefully estimating them is part of our job description as theorists
- For various reasons in practice experiments often have to evaluate them, so they would like to get a prescription

However

- Any real progress and discussion needs to be given the appropriate amount of time
- There is no such thing as a simple general prescription for evaluating theory uncertainties
- If you want to get meaningful input from theorists, we need to be allowed to see enough intermediate details
  (not to check on you but on the “prescription” ...)

Beyond ICHEP

Currently

- Central values for jet-bin cross sections from POWHEG+Pythia reweighted to HqT reweighted to NNLO σ_{total}
- Perturbative uncertainties are evaluated at fixed order using method B

$\Rightarrow$ Probably sufficient for limits and the time being

For measuring couplings above mix is sub-optimal (you may call it inconsistent)

- Perturbative uncertainties really apply to “their” respective calculation
- Central values matter

Correlations between perturbative jet-bin uncertainties from same production mode in different analyses/decay channels

- Again probably not important right now for limits
- But will likely become relevant for global coupling fits

Things to Think About Next

How to make best use of additional information provided by resummed calculations

- Relations and comparisons between different resummed variables: Higgs p_T, inclusive beam thrust, jet p_T, jet beam thrust, inclusive E_T
- Relation to MCs and intrinsic uncertainties in reweighting procedures (numerically seems to improve things, but formally destroys NNLL accuracy)

Is it feasible to go from few jet (or other) bins/categories to differential spectra?

- Important to validate theoretical description and understanding
- Might also help to further increase sensitivity?

More Things

- Interplay of additional kinematic cuts with jet-binning uncertainties
- Interplay of underlying event with jet definition/selection/binning

Final Thoughts

What should this group do?

- Rei's personal point of view:
  "It would be better to have Jets restaurant rather than Pizza (Jets) delivery service."

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- My personal translation:

  "A place to wait and discuss and in the end get something carefully prepared rather than getting a quick (half-baked) delivery after calling a hotline."

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The question remains what the menu should be

- There are obviously many issues and overlaps, so we are hoping to have close discussions with other subgroups
- We are open to suggestions on menu items (including priority)
- Everybody is invited to contribute