Jet Physics for Higgs

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Higgs@DESY Discussion
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Emmy Noether-Programm
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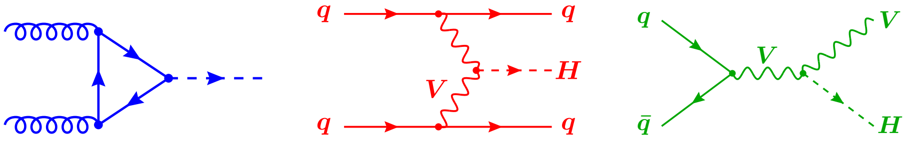
Higgs and Jets

Higgs Production and Decay is a QCD Laboratory



Jets are used extensively in Higgs searches/measurements

- Jet selections and categorization of events used to increase sensitivity to various production and decay channels
  - Suppress backgrounds: Jet veto in $gg \to H \to WW$ to kill $t\bar{t}$
  - Distinguish Higgs production mechanisms: VBF vs. ggF
  - Higgs decay: boosted $H \to b\bar{b}$ is prime example of a jet substructure analysis

⇒ Recently formed Jets subgroup in the Higgs cross section working group
Conveners: B. Mellado (ATLAS), D. del Re (CMS), G. Salam, FT

Overview

Main issues that appear in all uses of jets

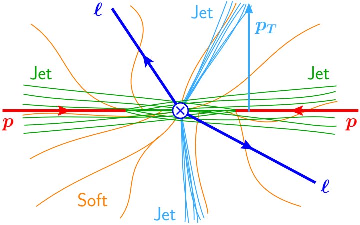
- Jet definition and jet selection cuts, improved theory predictions and uncertainty estimates
  - Our main focus at the moment
- Impact of underlying event, nonperturbative corrections and uncertainties
  - Something to really think about
- Experimental issues: pile-up, resolution, jet-energy scale
  - I'd be curious if there are things theory could help?

Fixed-Order Studies

Large Logarithms from Jet Selection

Jet selection cuts (or other types of exclusive measurements) can be sensitive to additional soft and collinear emissions

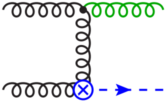
⇒ Restricting or cutting into soft radiation, ISR, or FSR causes large logarithms



Example: $gg \to H + 0$ jets

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

$$\sigma_0(p_T^{\text{cut}}) \propto 1 - \frac{\alpha_s}{\pi} 6 \ln^2 \frac{p_T^{\text{cut}}}{m_H} + \cdots$$



⇒ Perturbative corrections get large at small cuts

⇒ Should be reflected in perturbative uncertainties

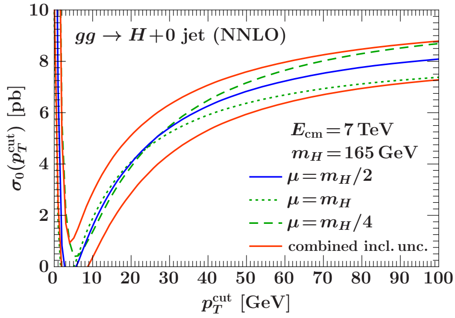
$gg \to$ Higgs + 0 Jets

blue: central scale choice

green: standard scale variation

orange: including estimate of the size of p_T^{cut}-logarithms

Higgs + 0 Jets



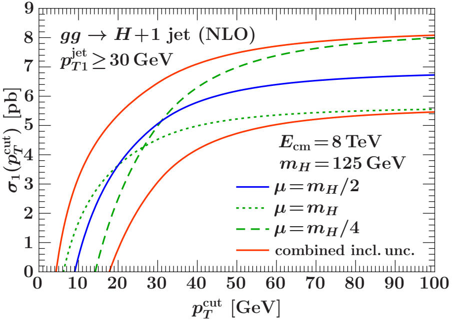
- Typical experimental range $p_T^{\mathrm{cut}} = 20 - 40\,\mathrm{GeV}$
- Logs at small p_T^{cut} degrade fixed-order perturbation theory
- Resummation of exclusive logs can give improved predictions and uncertainty estimates (→ see later)

[using fixed-order programs: HNNLO, FEHiP, MCFM]

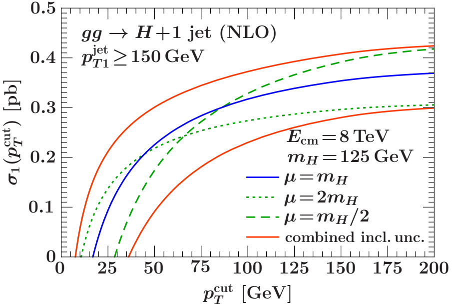
$gg \to$ Higgs + 1 Jet

blue: central scale choice
green: standard scale variation
orange: including estimate of the size of p_T^{cut}-logarithms

Higgs + 1 Jet



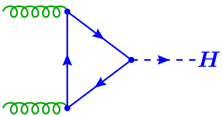
Higgs + 1 Jet

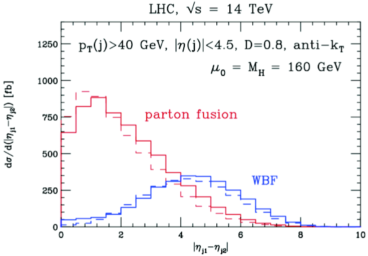


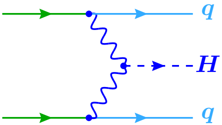
[HNNLO, FEHiP, MCFM]

- 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 (nontrivial) 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 to VBF selection needs to be studied carefully
  - Important question how much $gg \to H$ "dilutes" the VBF signal both in terms of purity and theory uncertainties
  - Something we have started to look into

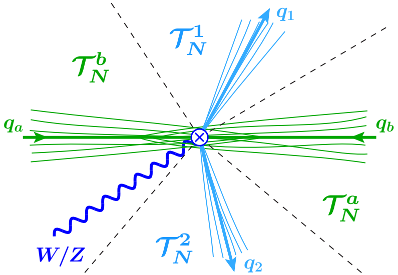
New Jet Variables and Resummation

N-Jettiness Event Shape

$$\mathcal{T}_N = \sum_k |\vec{p}_{kT}| \min\left\{ \frac{2q_a \cdot p_k}{Q_a}, \frac{2q_b \cdot p_k}{Q_b}, \frac{2q_1 \cdot p_k}{Q_1}, \frac{2q_2 \cdot p_k}{Q_2}, \dots, \frac{2q_N \cdot p_k}{Q_N} \right\}$$

$$\equiv \mathcal{T}_N^a + \mathcal{T}_N^b + \mathcal{T}_N^1 + \cdots + \mathcal{T}_N^N$$

- $Q_{a,b}$, Q_j: determine distance measure of particle k to beam and jet directions
- $q_{a,b}$, q_j: light-like reference directions from overall minimization (or other jet algorithm like anti-kT)
- Divides phase space into N jet regions and 2 beam regions



For small $\mathcal{T}_N \ll Q$ final state contains exactly N jets (+ 2 ISR jets)

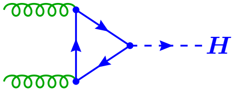
(Generalization of thrust for $e^+e^- \to$ 2 jets to $pp \to$ N jets)

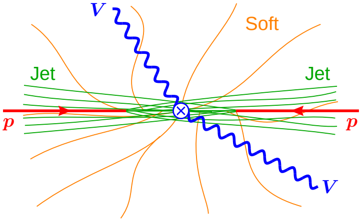
Example: Higgs + 0 Jets Using 0-Jettiness

0-jettiness $\mathcal{T}_0$ is equivalent to "beam thrust" $\mathcal{T}_{\mathrm{cm}}$

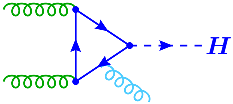
$$\mathcal{T}_{\mathrm{cm}} = \sum_k |\vec{p}_{kT}| e^{-|\eta_k|} = \sum_k (E_k - |p_k^z|)$$

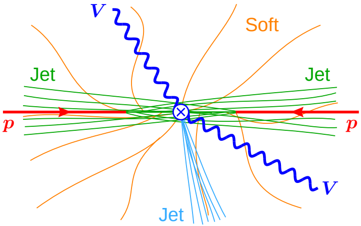
$\mathcal{T}_{\mathrm{cm}} \ll m_H$: 0 hard central jets





$\mathcal{T}_{\mathrm{cm}} \sim m_H$: *at least* 1 hard central jet

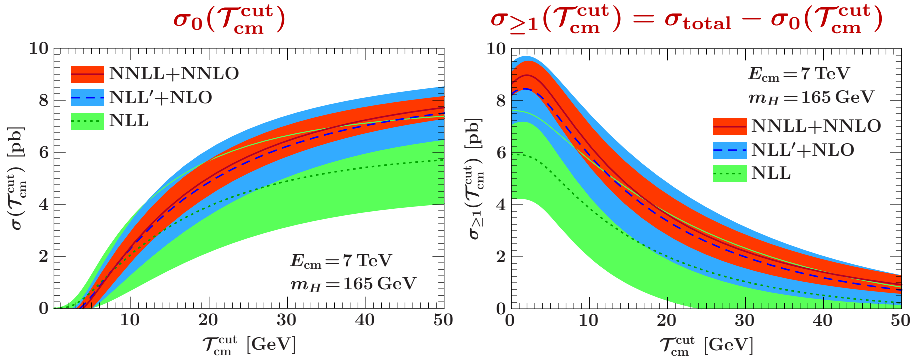




Resummed Higgs + 0 and $\geq$ 1 Jets

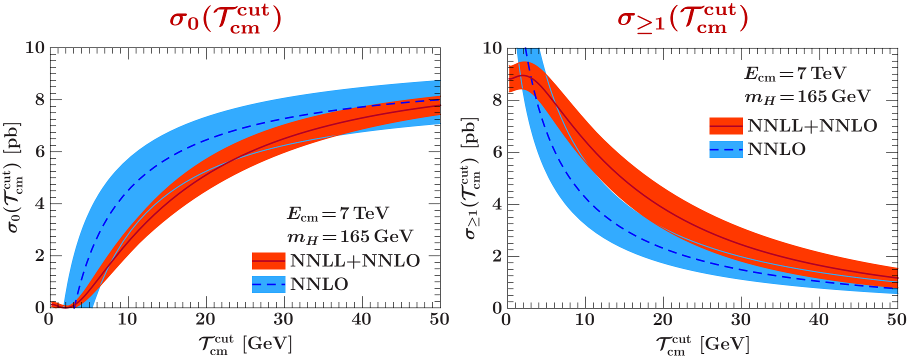
N-Jettiness has a very simple and well-understood perturbative structure

- Factorization and resummation is known to NNLL+(N)NLO (2 orders beyond parton shower)
- Allows reliable estimates of perturbative uncertainties



Comparison to Fixed-Order

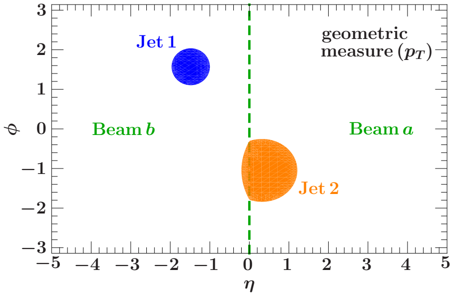
blue: fixed NNLO, orange: including resummation to NNLL



- It is feasible to further reduce uncertainties by going to N^{3}LL
- Irreducible backgrounds with the same cut can be computed as well
- Working on extension to more jets
- Studying resummation for more exclusive jet variables: $\mathcal{T}^{jet}, p_T^{jet}$

N-Jettiness as Exclusive Jet Algorithm

$$\mathcal{T}_N = \sum_k |\vec{p}_{kT}| \min\left\{ \frac{2q_a \cdot p_k}{Q_a}, \frac{2q_b \cdot p_k}{Q_b}, \frac{2q_1 \cdot p_k}{Q_1}, \frac{2q_2 \cdot p_k}{Q_2}, \ldots, \frac{2q_N \cdot p_k}{Q_N} \right\}$$



$Q_{a,b} = x_{a,b} E_{\mathrm{cm}} \quad Q_j = p_T^{\mathrm{jet}\,i}$ $\qquad$ $Q_{a,b} = x_{a,b} E_{\mathrm{cm}} \quad Q_j = E^{\mathrm{jet}\,i}$

Provides a theoretically ideal *exclusive* N-jet algorithm

- Yields jets with regular shape (similar to anti-kT)

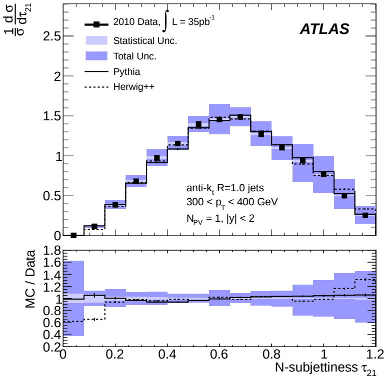
$\Rightarrow$ Try using directly for exclusive jet selection, e.g. VBF selection

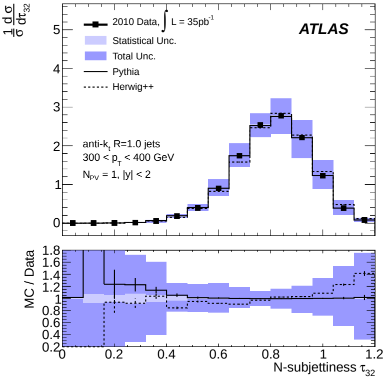
Application to Jet Substructure: N-Subjettiness

Restricting sum to a given large jet makes it a jet shape: N-subjettiness τ_N

[Thaler, Van Tilburg]

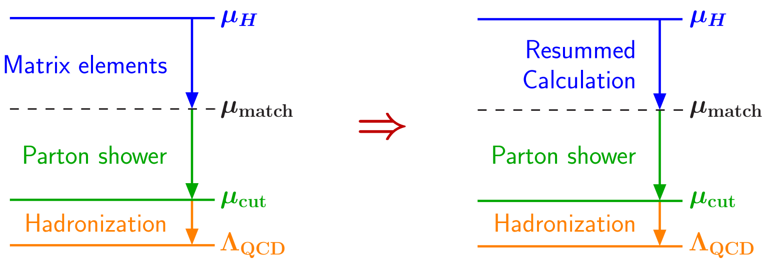
- τ_2/τ_1 can be used to identify boosted $W/Z/H$
  - Feasible to compute and resum for $H \to b\bar{b}$
- τ_3/τ_2 can be used as a boosted top tagger





GENEVA Monte Carlo Framework

GENEVA



GENEVA

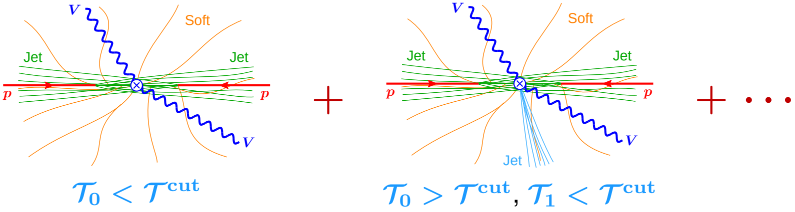
"GENerate EVents Analytically"

[Alioli, Bauer, Berggren, Hornig, FT, Vermilion, Walsh, Zuberi]

Constructing a Monte-Carlo framework based on resummed calculations

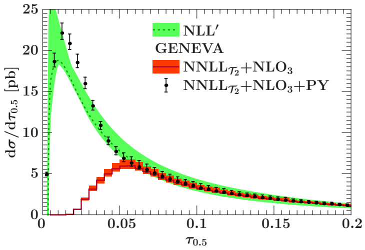
- Make resummed calculations directly usable by experiments
- Use benefits of resummation to improve Monte-Carlo itself
  - Higher-order corrections: N^{n}LL, N^{m}LO
  - Better control and estimate of perturbative uncertainties

Going Beyond Standard NLO+PS Merging



Using N-Jettiness as jet resolution variable in the Monte Carlo

- NNLL resummation allows to combine *several* jet-multiplicities at NLO
- MC with event-by-event theory uncertainties
- Looks very promising for e^+e^-



Goal: Full implementation of $pp \to H + 0, 1, 2$ jets at $\mathrm{NNLL}_{\mathcal{T}}$+(N)NLO

The End

Backup

Perturbative Structure of Jet Cross Sections

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

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

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

$$\begin{aligned}\sigma_0(p^{\text{cut}}) &= \sigma_{\text{total}} - \sigma_{\geq 1}(p^{\text{cut}}) \\ &= \left[1 + \alpha_s + \alpha_s^2 + \cdots\right] - \left[\alpha_s(L^2 + \cdots) + \alpha_s^2(L^4 + \cdots) + \cdots\right]\end{aligned}$$

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 N-jet and inclusive ($\geq$ N+1)-jet cross section (and cancel in their sum)

Higher-Order Logarithmic Structure

Log-counting is defined in the exponent: $\ln\sigma = \alpha_s^n L^{n+1}(1+\alpha_s+\alpha_s^2+\cdots)$

Corresponding terms in the cross section

$$
\begin{array}{lllllllll}
\sigma = 1 & & & & & & & & \\
+ \ \alpha_s L^2 & + \ \alpha_s L & + \ \alpha_s + \alpha_s n_1(p^{\text{cut}}) & & & & & & \text{NLO} \\
+ \ \alpha_s^2 L^4 & + \ \alpha_s^2 L^3 & + \ \alpha_s^2 L^2 & + \ \alpha_s^2 L & + \ \alpha_s^2 + \alpha_s^2 n_2(p^{\text{cut}}) & & & & \text{NNLO} \\
+ \ \alpha_s^3 L^6 & + \ \alpha_s^3 L^5 & + \ \alpha_s^3 L^4 & + \ \alpha_s^3 L^3 & + \ \alpha_s^3 L^2 & + \ \alpha_s^3 L & + & \cdots & \\
+ \ \vdots & + \ \vdots & + \ \vdots & + \ \vdots & + \ \vdots & + \ \vdots & + & \ddots & \\
\text{LL} & \text{NLL} & \text{NNLL} & & \text{N}^3\text{LL} & & & &
\end{array}
$$

- Parton shower resums LL (plus some NLL)
- NLO+PS MCs combine parton-shower LL with NLO [MC@NLO, POWHEG]

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$$
\begin{aligned}
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&+ \alpha_s L^2 + \alpha_s L + \alpha_s + \alpha_s n_1(p^{\text{cut}}) && \text{NLO} \\
&+ \alpha_s^2 L^4 + \alpha_s^2 L^3 + \alpha_s^2 L^2 + \alpha_s^2 L + \alpha_s^2 + \alpha_s^2 n_2(p^{\text{cut}}) && \text{NNLO} \\
&+ \alpha_s^3 L^6 + \alpha_s^3 L^5 + \alpha_s^3 L^4 + \alpha_s^3 L^3 + \alpha_s^3 L^2 + \alpha_s^3 L + \cdots \\
&+ \vdots + \vdots + \vdots + \vdots + \vdots + \vdots + \ddots \\
& \quad \text{LL} \quad \text{NLL} \quad \text{NNLL} \quad \text{N}^3\text{LL}
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&+ \vdots + \vdots + \vdots + \vdots + \vdots + \vdots + \ddots \\
&\quad \text{LL} \quad \text{NLL} \quad \text{NNLL} \quad \text{N}^3\text{LL}
\end{aligned}
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- NLO+PS MCs combine parton-shower LL with NLO [MC@NLO, POWHEG]
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$\Rightarrow$ We want to go (at least) to full NNLL where fixed NLO formally enters