Resummation of jet veto observables in Higgs production

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Outline

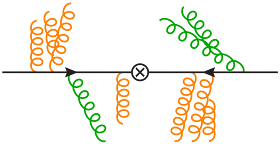
Introduction

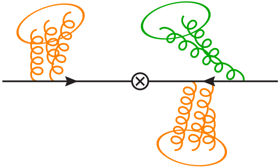
- Precision measurement of the Higgs boson properties at the LHC : Accurate theoretical prediction of cross section is required.
- Experimental analyses separate the data into jet bins. Eg: In H $\rightarrow$ W W* : any hard jets with $p_T^{jet} > p_T^{\rm cut} \sim 20 - 30\,{\rm GeV}$ are vetoed.
- Jet vetoes induce large Sudakov (double) logs: $\alpha_s^n \log^m [p_T^{\rm cut}/m_H]$ that need to be resummed.
- Eg: gg $\rightarrow H + 0$ jet

$$\sigma_0(p_T^{\rm cut}) \propto \sigma_B(1 - 2\frac{\alpha_s C_A}{\pi} \log^2 \frac{p_T^{\rm cut}}{m_H} + ...)$$

- Perturbative corrections get large at small $p_T^{\rm cut} \ll m_H$.
- Resummation of logs give improved prediction and uncertainty estimates.

Jet veto Observables





Global Veto
restricts $\sum$ of all emissions

"beam broadening"

$$E_T = \sum_i |\vec{p_{Ti}}|$$

"beam thrust"

Local Veto
restrict (local chunks of) individual emissions

"jet p_T"

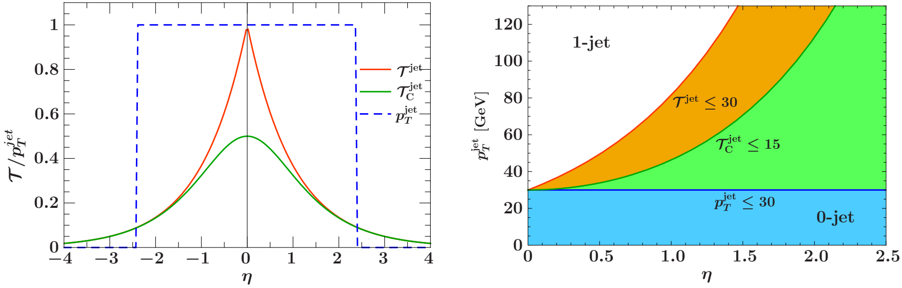
$$\vec{p}_T^{jet} = \max_{i \in \text{jets}} |\vec{p}_{Ti}|$$

"jet beam thrust"

$$\mathcal{T} = \sum_i |\vec{p_T}_i| e^{-|y_i - Y|} \qquad \mathcal{T}^{\text{jet}} = \max_{i \in \text{jets}} |\vec{p_T}_i| e^{-|y_i - Y|} \qquad \mathcal{T}_C^{\text{jet}} = \max_{i \in \text{jets}} \frac{|\vec{p_T}_i|}{2\cosh(y_i - Y)}$$

(y_i and Y are the jet and Higgs rapidity respectively.)

Jet veto Observables

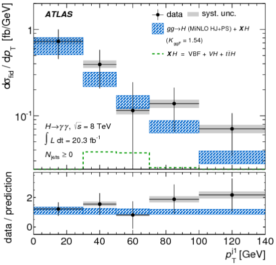


$$\vec{p}_T^{\,jet} = \max_{i \in \text{jets}} |\vec{p}_{Ti}| \qquad \mathcal{T}^{\rm jet} = \max_{i \in \text{jets}} |\vec{p}_{T\,i}| e^{-|y_i - Y|} \qquad \mathcal{T}_C^{\rm jet} = \max_{i \in \text{jets}} \frac{|\vec{p}_{T\,i}|}{2\cosh(y_i - Y)}$$

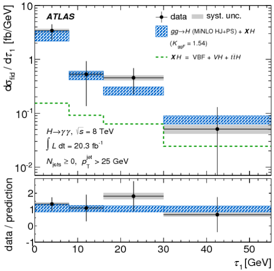
- $\mathcal{T}^{\rm jet}$ and $\mathcal{T}_C^{\rm jet}$ are rapidity weighted jet veto observables and provide different 0-jet phase space compared to $p_T^{\rm jet}$.
- $\mathcal{T}_C^{\rm jet}$ is a tighter jet veto at central rapidities and weaker at forward rapidities.

Jet veto Observables

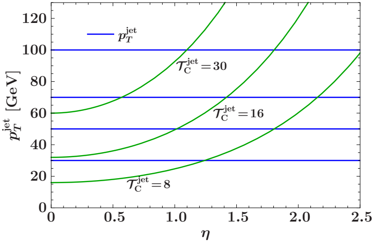
p_T^{jet}



$\mathcal{T}_C^{\text{jet}}$



p_T^{jet} and $\mathcal{T}_C^{\text{jet}}$ binning



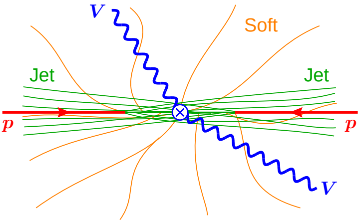
- Resummation of various jet veto observables has been done:
  1. Beam Thrust resummation: [Berger, Marcantonini, Stewart, Tackmann, Waalewijn]
  2. p_T^{jet} resummation: [Banfi, Monni, Salam, Zanderighi ; Becher, Neubert, Rothen; Stewart,Tackmann, Walsh, Zuberi.]
- $\mathcal{T}_{(C)}^{\text{jet}}$ is a rapidity weighted p_T and has different resummation structure.
- Resummation of $\mathcal{T}_{(C)}^{\text{jet}}$ provides complimentary information in the exclusive 0-jet region. We now focus on this.

Soft-collinear Factorization and Resummation

The cross section in SCET for $gg \to H$:

$$d\sigma_0 = |C_{ggH}|^2 \langle p_a p_b | O^\dagger_{ggH} M^{veto} O_{ggH} | p_a p_b \rangle$$

$$O_{ggH} \sim H O_a O_s O_b \sim H B^\mu_{n_a} T[Y^\dagger_{n_a} Y_{n_b}] B_{n_b \mu}$$



Measurement function M^{veto}

- Implements phase space constraints due to jet veto.
- Soft-collinear factorization implies

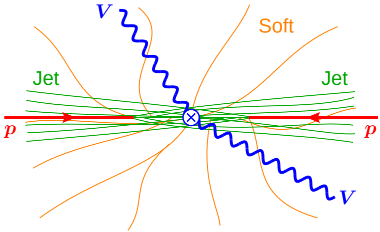
$$M^{veto} = M^{veto}_a \times M^{veto}_b \times M^{veto}_s + O(R^2)$$

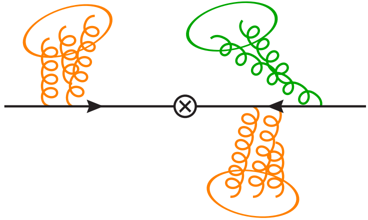
- Matrix elements factorize into independent soft and collinear matrix elements

$$B_{a,b}(\mu) = \langle p_a | O^\dagger_{a,b} M_{a,b} O_{a,b} | p_b \rangle$$

$$S_{a,b}(\mu) = \langle 0 | O^\dagger_s M_s O_s | 0 \rangle$$

Soft collinear Factorization and Resummation





Factorized cross section for $gg \to H$ with a jet veto $\mathcal{T}^{jet} < \mathcal{T}^{cut}$ derived in SCET: [Tackmann, Walsh, Zuberi]

$$\sigma_0(\mathcal{T}^{cut}) = H_{ggH}(m_H, \mu) B_g^{jet}(R, m_H \mathcal{T}^{cut}, x_a, \mu) B_g^{jet}(R, m_H \mathcal{T}^{cut}, x_b, \mu) S^{jet}(R, \mathcal{T}^{cut}, \mu) + \sigma_0^{ns}(\mathcal{T}^{cut}, \mu) + \sigma_0^{Rsub}(\mathcal{T}^{cut}, R)$$

Analogous for $\mathcal{T}_C^{jet} < \mathcal{T}^{cut}$:

$$\sigma_0(\mathcal{T}^{cut}) = H_{ggH}(m_H, \mu) B_g^{jet}(R, m_H \mathcal{T}^{cut}, x_a, \mu) B_g^{jet}(R, m_H \mathcal{T}^{cut}, x_b, \mu) S_C^{jet}(R, \mathcal{T}^{cut}, \mu) + \sigma_0^{ns}(\mathcal{T}^{cut}, \mu) + \sigma_0^{Rsub}(\mathcal{T}^{cut}, R)$$

Soft collinear Factorization and Resummation

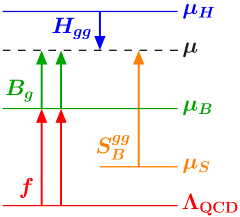
Factorized Cross section:

$$\sigma_0(\mathcal{T}^{cut}) = H_{ggH}(m_H,\mu) B_g^{jet}(R, m_H\mathcal{T}^{cut}, x_a, \mu) B_g^{jet}(R, m_H\mathcal{T}^{cut}, x_b, \mu)$$
$$S_{(C)}^{jet}(R, \mathcal{T}^{cut}, \mu) + \ldots$$

- Logarithms are split apart and resummed using RGE

$$\ln^2 \frac{\mathcal{T}^{cut}}{m_H} = 2\ln^2 \frac{m_H}{\mu} - \ln^2 \frac{\mathcal{T}^{cut} m_H}{\mu^2} + 2\ln^2 \frac{\mathcal{T}^{cut}}{\mu}$$

- Natural scales for Hard, beam and soft functions:
  $\mu_H \simeq m_H$, $\mu_B \simeq \sqrt{\mathcal{T}^{\rm cut} m_H}$, $\mu_S \simeq \mathcal{T}^{\rm cut}$
- Hard function contains: $\ln^2\left[-m_H^2/\mu_H^2\right]$
- Beam functions: $\ln^2\left[m_H \mathcal{T}^{cut}/\mu_B^2\right]$
- Soft function: $\ln^2\left[\mathcal{T}^{cut}/\mu_S\right]$



Soft collinear Factorization and Resummation

- Resummation Structure:

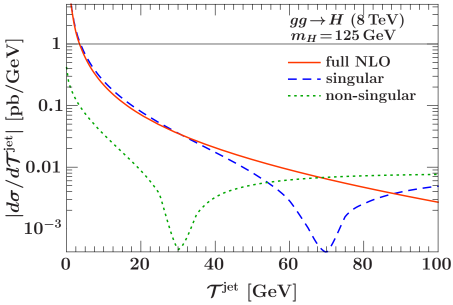
$$\ln \sigma_0(\mathcal{T}^{\rm cut}) \sim \sum_n \alpha_s^n \ln \left[\frac{\mathcal{T}^{\rm cut}}{m_H}\right]^{n+1} (1+\alpha_s+\alpha_s^2+\cdots) \sim \text{LL} + \text{NLL} + \text{NNLL} + \cdots$$

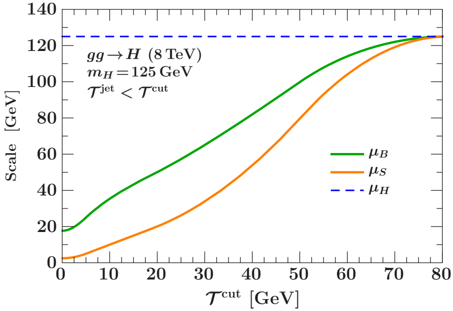
- Including the RGE running the resummed cross section for $\mathcal{T}^{jet}$

$$\sigma_0(\mathcal{T}^{cut}) = H_{ggH}(m_H, \mu_H)\, U_H(m_H, \mu_H, \mu) \times \left[B_g^{jet}(R, \mathcal{T}^{cut}, \mu_B)\, U_B(m_H, \mu_B, \mu)\right]^2 \times S_{(C)}^{jet}(R, \mathcal{T}^{cut}, \mu_S)\, U_S(\mu_S, \mu) + \ldots$$

Log counting:	Fixed-order corrections matching	nonsingular	Resummation input $\gamma^{\mu}_{H,B,S}$	$\Gamma_{\rm cusp}$	β
NLL	1	-	1-loop	2-loop	2-loop
NLL′+ NLO	NLO	NLO	1-loop	2-loop	2-loop
NNLL′+NNLO	NNLO	NNLO	2-loop	3-loop	3-loop

Resummation scales and Perturbative Uncertainties





- Resummation region: Logs are resummed using canonical scaling

$$|\mu_H| \sim m_H \qquad \mu_S \sim \mathcal{T}^{\mathrm{cut}} \qquad \mu_B \sim \sqrt{m_H \mathcal{T}^{\mathrm{cut}}}$$

- FO region: Resummation is turned off to get the right FO cross section at large $\mathcal{T}^{\mathrm{cut}}$

$$\mu_B, \mu_S \to \mu \sim m_H$$

- Transition region: Profiles for μ_B, μ_S provide smooth transition from resummation to fixed-order region.

Perturbative Uncertainties in Jet Binning

$$\sigma_{\text{total}} = \int_0^{\mathcal{T}^{\text{cut}}} \mathrm{d}\mathcal{T}^{\text{jet}} \frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{T}^{\text{jet}}} + \int_{\mathcal{T}^{\text{cut}}}^{\infty} \mathrm{d}\mathcal{T}^{\text{jet}} \frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{T}^{\text{jet}}}$$
$$\equiv \sigma_0(\mathcal{T}^{\text{cut}}) + \sigma_{\geq 1}(\mathcal{T}^{\text{cut}})$$

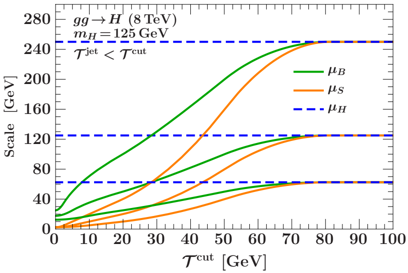
- Uncertainties in the jet binning described in general by fully correlated (yield unc.) and fully anticorrelated (migration unc.) components of a covariance matrix $\{\sigma_0, \sigma_{\geq 1}\}$

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

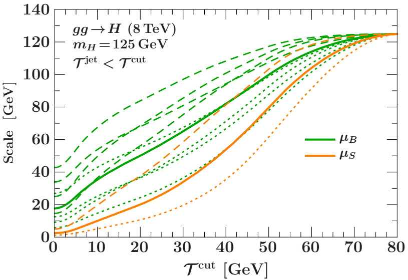
- FO region ($\mathcal{T}^{cut} \sim Q$) : $\Delta^y = \Delta^{FO}$
- Resummation region ($\mathcal{T}^{cut} << Q$) : $\Delta_{cut} = \Delta_{\text{resum}}$
- Δ_{resum} is the intrinsic uncertainty in the resummed $\mathcal{T}^{cut}$ logarithmic series caused by the binning cut.

Perturbative Uncertainties

FO scale uncertainty



Resummation uncertainty

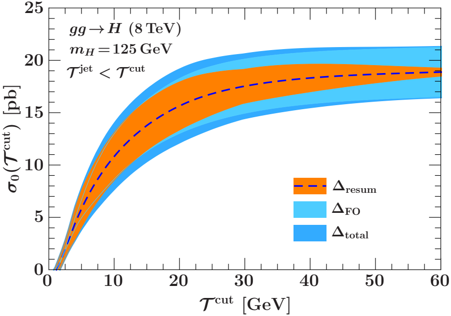


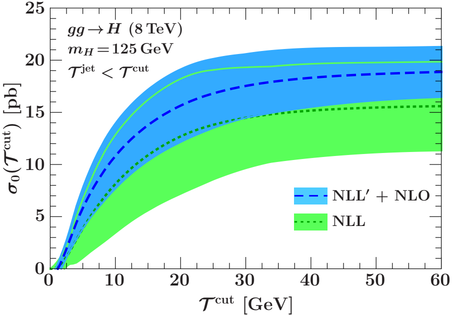
- Fixed Order Uncertainty Δ_{FO}:
  - Maximum of collective variation of all scales by a factor of 2 keeping scale ratios fixed.
  - Reproduces the inclusive cross section uncertainty for large $\mathcal{T}^{\rm cut}$.
- Resummation Uncertainty $\Delta_{\rm resum}$:
  - Varying the argument of logs estimates their size and missing higher log terms.
  - These variations are smoothly turned off at large $\mathcal{T}^{cut}$ where the resummation turns off.

Resummation results for Higgs +0 jet

$$\Delta_{tot} = \sqrt{\Delta^2_{\text{resum}} + \Delta^2_{FO}}$$

$$\mathcal{T}^{\text{jet}} = \max_{i \in \text{jets}} |\vec{p_T}_i| e^{-|y_i - Y|}$$



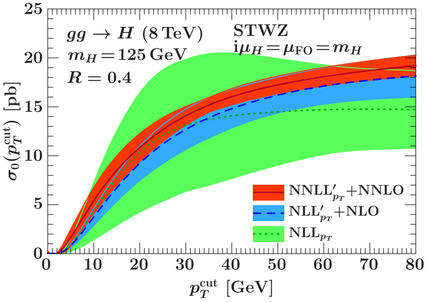


- Total Uncertainty dominated by resummation unc. till $\mathcal{T}^{cut} \sim 20\,\text{GeV}$ and by FO unc. at larger $\mathcal{T}^{cut}$.
- Good perturbative convergence.

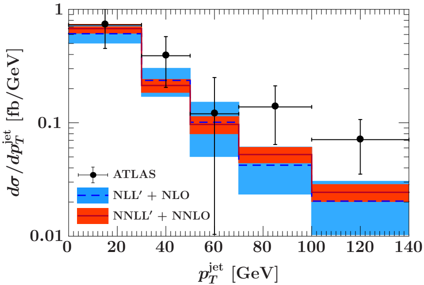
Comparison to ATLAS $H \to \gamma\gamma$ data

- The resummed results for different jet veto observables can be directly compared to the ATLAS measurements.
- p_T^{jet} resummation at NNLL$'$+ NNLO (Stewart,Tackmann,Walsh, Zuberi.):

$$\vec{p}_T^{\,jet} = \max_{i \in \text{jets}} |\vec{p}_{Ti}|$$



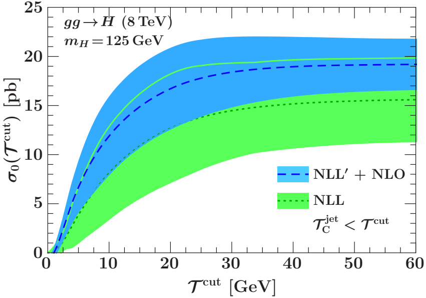
First comparison to the ATLAS measurement of fiducial cross section in $H \to \gamma\gamma$



Comparison to ATLAS $H \to \gamma\gamma$ data

- NLL′+ NLO resummation for $\mathcal{T}_C^{jet} < \mathcal{T}^{cut}$:

$$\mathcal{T}_C^{\text{jet}} = \max_{i \in \text{jets}} \frac{|\vec{p_T}_i|}{2\cosh(y_i - Y)}$$



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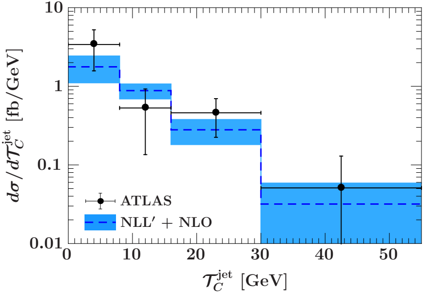
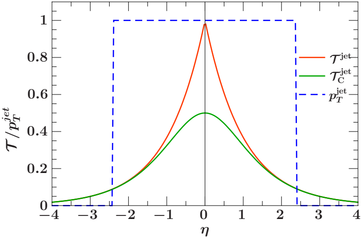


Summary

- Exclusive jet cross section measurements are key to precision Higgs physics at the LHC.
- Resummation of jet veto logs: important for accurate cross section predictions.
- Resummation of different jet veto observables provides complementary information: In this talk $\mathcal{T}^{\mathrm{jet}}$, $\mathcal{T}_C^{\mathrm{jet}}$.



- Outlook : $\mathcal{T}^{\mathrm{jet}}$ resummation to NNLL$'$+ NNLO

BackUp slides

Non-singular Contribution

- In the large $\mathcal{T}$ limit, the resummed results should reproduce the correct FO cross section.

$$\frac{d\sigma^{FO}}{d\mathcal{T}dY} = \sigma_0 \alpha_s^2(\mu^2) \int \frac{d\xi_a}{\xi_a}\frac{d\xi_b}{\xi_b} \sum_{ij} C_{ij}(x_a/\xi_a, x_b/\xi_b, \mathcal{T}, Y) f_i(\xi_a, \mu) f_j(\xi_b, \mu)$$

- The coefficients C_{ij} for the FO cross section can be thought of as:

$$C_{ij}^{\text{FO}} = |M_{ij}|^2 \times \text{(phase space factor)} \times M^{\text{veto}}$$

- M^{veto} depends on the jet-veto observable.
- The FO cross section is a sum of the singular and the non-singular parts.

$$\frac{d\sigma^{ns,FO}}{d\mathcal{T}} = \frac{d\sigma^{FO}}{d\mathcal{T}} - \frac{d\sigma^{s,FO}}{d\mathcal{T}}$$

Theory Uncertainties in Jet Binning

- Peturbative Structure of jet bin cross sections:

$$\sigma_{\geq 0} = \sigma_B\big[1 + \alpha_s + \alpha_s^2 + \cdots\big]$$
$$\sigma_{\geq 1}(p_T^{\rm cut}) = \sigma_B\big[\alpha_s(L^2 + L + 1) + \alpha_s^2(L^4 + L^3 + L^2 + L + 1) + \cdots\big]$$
$$\sigma_0(p_T^{\rm cut}) = \sigma_B\big\{\big[1 + \alpha_s + \alpha_s^2 + \cdots\big] - \big[\alpha_s(L^2 + L + 1) + \alpha_s^2 L^4 + \cdots\big]\big\}$$

where $L = Log[p_T^{cut}/Q]$

- Central profiles:

$$\mu_B = \mu_s = \mu_{FO} f_{run}(\mathcal{T}^{cut})$$

- Variation of beam and soft scales performed with a multiplicative factor $f_{\rm vary}(\mathcal{T}^{\rm cut})$:

$$\mu_S(\mathcal{T}^{\rm cut}) = f_{\rm vary}^{\alpha}(\mathcal{T}^{\rm cut})\mu_S^{central}, \quad \mu_B = \mu^{1/2+\beta}(\mu_S(\mathcal{T}^{\rm cut}))^{1/2-\beta}$$