Resummation of jet (veto) observables

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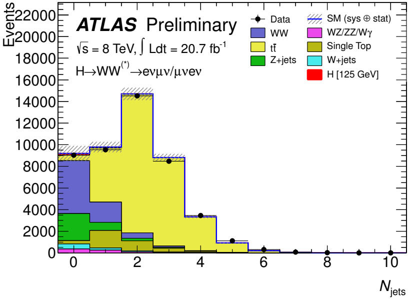
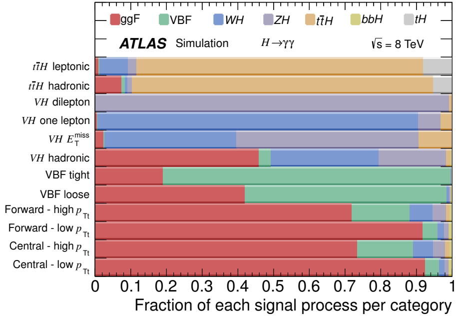
Introduction

Event Categorization

Data separated into exclusive kinematic categories to optimize S/B and gain access to different production channels



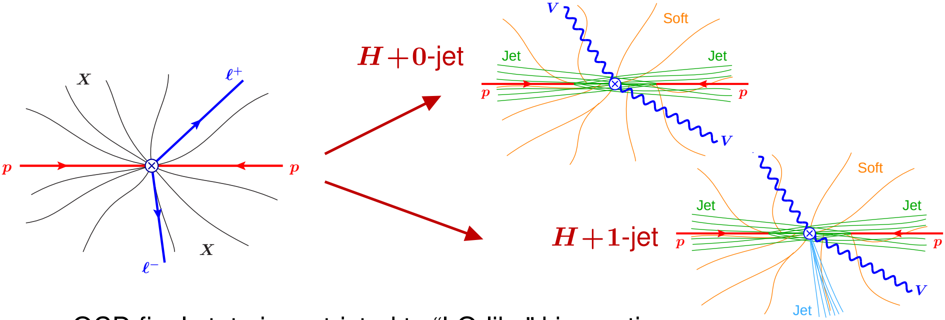


Requires theory predictions for each exclusive category

- Heavily relies on MC predictions
- In the end, want to combine results from all categories

⇒ Consistent theory description, treatment of uncertainties and their correlations are essential

Exclusive Region



- QCD final state is restricted to “LO-like” kinematics
- Only soft or collinear (ISR or FSR) emissions are allowed that turn the primary hard partons into jets (but don’t produce additional hard jets)
  - In MC equivalent to parton-shower regime

Why we care about this region in practice

- Signal region of interest is typically defined by the LO topology
- This is also where most of the signal cross section is

Types of Kinematic Variables

Important to distinguish two types of kinematic variables

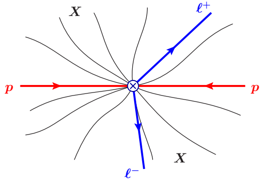
- Hard kinematics: Describe the underlying LO-like kinematics
- "Resolution" variables p_{res}: Determine how exclusive we are, i.e. restrict/characterize additional soft/collinear emissions:
  - Without additional emissions (tree level): $p_{\mathrm{res}} = 0$
  - Forcing $p_{\mathrm{res}} \to 0$ restricts final-state into exclusive LO-like region

For example

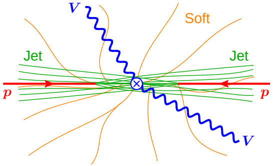
hard process	hard kinematics	resolution variables
$gg \to H$	Y_H	$p_T^H, p_T^{\mathrm{jet1}}$ $(E_T, \mathcal{T}_f^{\mathrm{jet1}}, \ldots)$
$gg \to H + 1$ jet	$Y_H, y_{\mathrm{jet1}}, m_{Hj}$ $p_T^H, p_T^{\mathrm{jet1}}, \ldots$	$p_T^{Hj}, p_T^{\mathrm{jet2}}, m_j, \ldots$

$\Rightarrow$ $p_T^H, p_T^{\mathrm{jet1}}$, ... change role from resolution in H to hard in $H + 1$ jet

Large Logarithms



$p_{\mathrm{res}} \ll m_H$

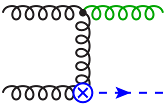


For any type of exclusive measurement or restriction

- Constraining radiation causes large logs of $\alpha_s^n \ln^m(p_{\mathrm{res}}/m_H)$
  (due to sensitivity to soft/collinear divergences)

Example: jet p_T veto in $gg \to H + 0$ jets

- Restricts ISR to $p_{\mathrm{res}} \equiv p_T < p_T^{\mathrm{cut}}$

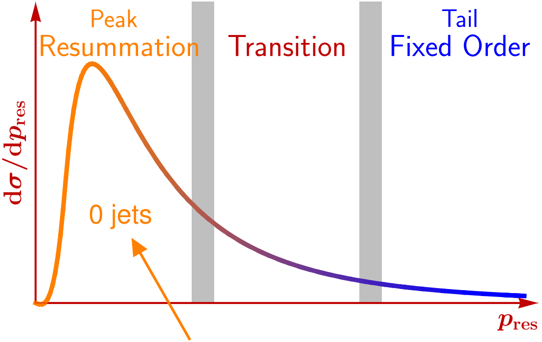


$$\sigma_0(p_T^{\mathrm{cut}}) \propto 1 - \frac{\alpha_s}{\pi} C_A 2 \ln^2 \frac{p_T^{\mathrm{cut}}}{m_H} + \cdots$$

⇒ Perturbative corrections grow large for decreasing p_T^{cut} (stronger restriction)

⇒ Should be resummed to all orders to obtain reliable precise predictions

Perturbative Regions of Phase Space



Here $p_{res} \equiv p_T^H, p_T^{jet1}$, ...

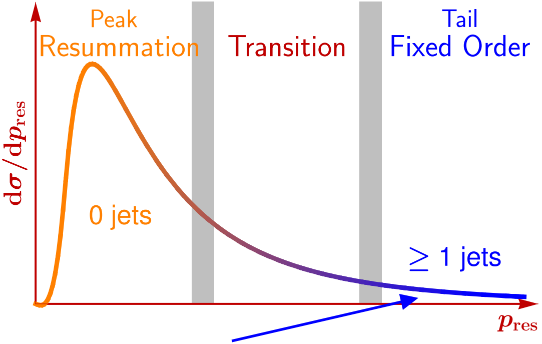
$p_{res} \to 0$:
only soft or collinear emissions

$p_{res} \sim m_H$:
additional hard emissions

Resummation region (in MC: parton shower regime)

- Differential spectrum at low $p_{res} \ll m_H$:
  - resum large logs $\alpha_s^n \ln^m(p_{res}/m_H)$
- Excl. $H+0$-jet cross section: integral up to $p_{res} \leq p^{cut} \ll m_H$
  - resum large logarithms $\alpha_s^n \ln^m(p^{cut}/m_H)$

Perturbative Regions of Phase Space



Here $p_{res} \equiv p_T^H, p_T^{jet1}$, ...

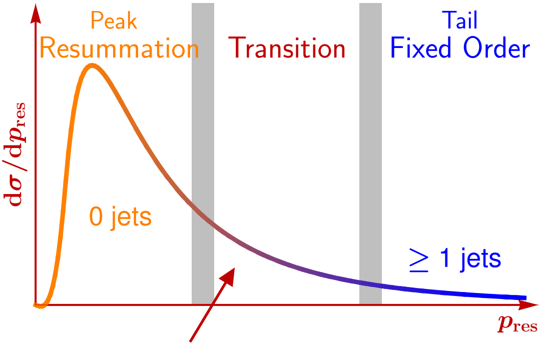
$p_{res} \to 0$:
only soft or collinear emissions

$p_{res} \sim m_H$:
additional hard emissions

Fixed-order region (no logs, in MC: fixed-order matrix elements)

- Differential spectrum at high $p_{res} \sim m_H$:
  - Hard kinematics of inclusive $H + (\geq 1)$-jet process
- Integral up to $p_{res} \leq p^{cut} \sim m_H$
  - Inclusive $H + (\geq 0)$-jets cross section

Perturbative Regions of Phase Space



Here $p_{res} \equiv p_T^H, p_T^{jet1}$, ...

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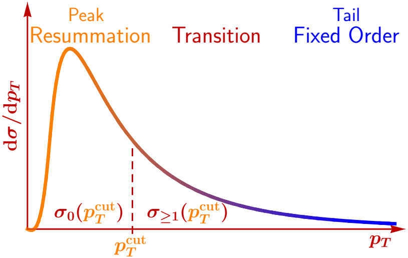
Transition region (in MC: where ME+PS matching comes in)

- Often experimentally the most relevant while theoretically the most subtle
- Best prediction for entire spectrum requires properly matched resummation+fixed order calculation: NLL+NLO, NNLL+NNLO, ...
  - Consistent treatment of theory uncertainties across spectrum (for both differential and integrated in p_{res}) is *very nontrivial* because it requires nontrivial correlations

Theory Uncertainties in Jet Binning

$$\sigma_{\rm total} = \underbrace{\int_0^{p_T^{\rm cut}} dp_T \frac{d\sigma}{dp_T}}_{\sigma_0(p_T^{\rm cut})} + \underbrace{\int_{p_T^{\rm cut}}^{\infty} dp_T \frac{d\sigma}{dp_T}}_{\sigma_{\geq 1}(p_T^{\rm cut})}$$



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

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

$$\sigma_0(p_T^{\rm cut}) = \sigma_{\rm total} - \sigma_{\geq 1}(p_T^{\rm cut})$$

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

where $L = \ln(p_T^{\rm cut}/m_H)$

$\Rightarrow$ *Same* logarithms appear in the exclusive 0-jet and inclusive ($\geq$ 1)-jet cross section and cancel in their sum

Theory Uncertainties in Jet Binning

$$\sigma_{\rm total} = \int_0^{p_T^{\rm cut}} \mathrm{d}p_T \frac{\mathrm{d}\sigma}{\mathrm{d}p_T} + \int_{p_T^{\rm cut}}^{\infty} \mathrm{d}p_T \frac{\mathrm{d}\sigma}{\mathrm{d}p_T} \equiv \sigma_0(p_T^{\rm cut}) + \sigma_{\geq 1}(p_T^{\rm cut})$$

Complete description requires full theory covariance matrix for $\{\sigma_0, \sigma_{\geq 1}\}$

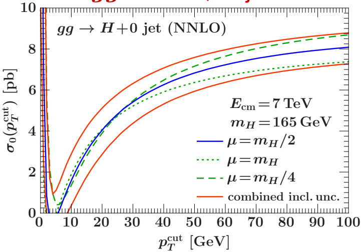
- General physical parametrization in terms of 100% correlated and 100% anticorrelated pieces

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

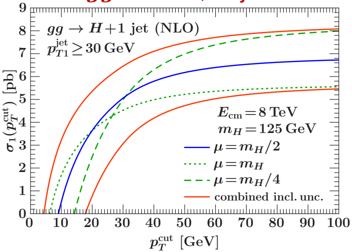
- Overall "yield" uncertainty is fully correlated between bins
  - $\Delta_{\rm total}^{\rm y} = \Delta_0^{\rm y} + \Delta_{\geq 1}^{\rm y}$ reproduces fixed-order uncertainty in $\sigma_{\rm total}$
- "Migration" uncertainty $\Delta_{\rm cut}$
  - Induced by binning cut and drops out in sum $\sigma_0 + \sigma_{\geq 1}$
  - $p_T^{\rm cut} \ll m_H$: $\Delta_{\rm cut} \sim$ uncertainty in $\ln(p_T^{\rm cut}/m_H)$ series

Migration Uncertainty at Fixed Order

$gg \to H + 0$ jet



$gg \to H + 1$ jet



In a pure fixed-order calculation separating $\Delta^{\rm y}$ and $\Delta_{\rm cut}$ is ambiguous so we have to make some assumptions

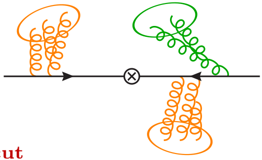
- naive scale variation: sets $\Delta_{\rm cut} = 0$ → becomes wrong for small $p_T^{\rm cut}$
- ST method: take $\Delta_{\rm cut} \equiv \Delta^{\rm FO}(\sigma_{\geq 1})$, $\Delta_0^{\rm y} \equiv \Delta^{\rm FO}(\sigma_{\rm total})$
  - results in treating $\Delta^{\rm FO}(\sigma_{\rm total})$ and $\Delta^{\rm FO}(\sigma_{\geq 1})$ as uncorrelated
- JVE method: take $\Delta_{\rm cut} = \sigma_{\rm total}\Delta(\epsilon_0)$, $\Delta_0^{\rm y} \equiv \epsilon_0 \Delta^{\rm FO}(\sigma_{\rm total})$
  - assumes that $\sigma_{\rm total}$ and 0-jet effiency ϵ_0 are uncorrelated

$\Rightarrow$ Resumming $p_T^{\rm cut}$ logs is necessary to cure bad behavior at small $p_T^{\rm cut}$

Jet p_T Resummation

Resummation for $p_T^{\rm jet}$

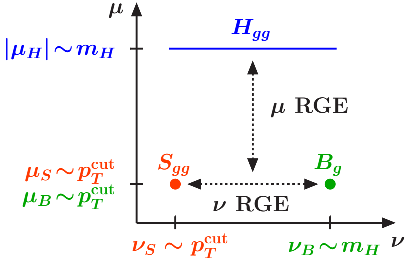
For $R^2 \ll 1$ local jet clustering algorithm factorizes into purely soft and collinear jets
[Becher, Neubert, Rothen; Tackmann, Walsh, Zuberi]



Allowing to factorize cross section for $p_T^{\rm jet} < p_T^{\rm cut}$

$$\sigma_0(p_T^{\rm cut}) = H_{gg}(m_H^2, \mu) B_g(p_T^{\rm cut}, R, \mu, \nu) B_g(p_T^{\rm cut}, R, \mu, \nu) S_{gg}(p_T^{\rm cut}, R, \mu, \nu)$$

Logarithms are split apart and resummed using coupled RGEs in μ and ν
[Using SCET-II with rapidity RGE by Chiu, Jain, Neill, Rothstein]



$$2\ln^2 \frac{p_T^{\rm cut}}{m_H} = 2\ln^2 \frac{m_H}{\mu} + 4\ln\frac{p_T^{\rm cut}}{\mu}\ln\frac{\nu}{m_H} + 2\ln\frac{p_T^{\rm cut}}{\mu}\ln\frac{\mu\, p_T^{\rm cut}}{\nu^2}$$

Profile Scales

[Ligeti, FT, Stewart '08; Abbate et al. '10; Berger et al. '10]

- Resummation region: Large logs are resummed using canonical scaling

$$\mu_H \sim -\mathrm{i}m_H$$

$$\mu_S \sim p_T^{\rm cut}, \nu_S \sim p_T^{\rm cut}$$

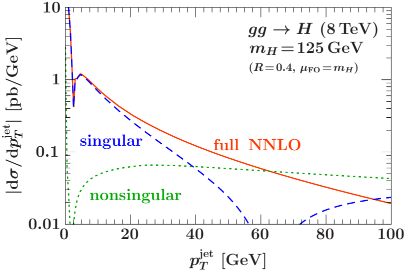
$$\mu_B \sim p_T^{\rm cut}, \nu_B \sim m_H$$

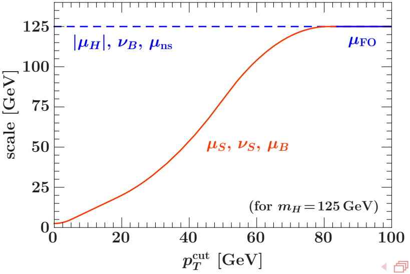
- FO region: Resummation must be turned off by taking

$$\mu_B, \mu_S, \nu_S, \nu_B \to \mu_{\rm FO} \sim m_H$$

- Transition region: Profile scales $\mu_i = \mu_i(p_T^{\rm cut})$ and $\nu_i \equiv \nu_i(p_T^{\rm cut})$ provide smooth matching between both limits

$\Rightarrow$ Ambiguity is a scale uncertainty





Uncertainties from Profile Scale Variations

Resummation framework is flexible and general enough to allow estimating full theory uncertainty matrix [Stewart, FT, Walsh, Zuberi '13]

$$C = \begin{pmatrix} \Delta_{\mu 0}^2 & \Delta_{\mu 0}\,\Delta_{\mu\geq 1} \\ \Delta_{\mu 0}\,\Delta_{\mu\geq 1} & \Delta_{\mu\geq 1}^2 \end{pmatrix} + \begin{pmatrix} \Delta_{\rm resum}^2 & -\Delta_{\rm resum}^2 \\ -\Delta_{\rm resum}^2 & \Delta_{\rm resum}^2 \end{pmatrix}$$

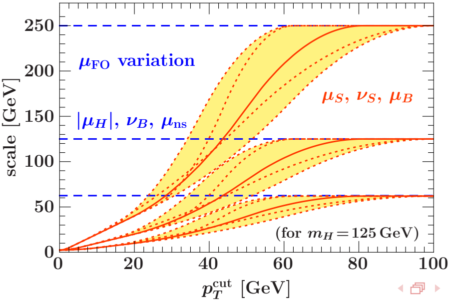
- Requires no assumptions on correlations between cross sections (as are made in JVE or fixed-order ST)
- Can study nontrivial correlations, e.g. between $\sigma_0, \epsilon_0, \sigma_{\rm total}$

$\Delta_{\mu i}$: Collective overall scale variation

(+ where resum. turns off)

- FO unc. within resummed prediction
- leaves scale ratios and resummed logs invariant
- Reproduces usual FO scale variation for large $p_T^{\rm cut}$ and $\sigma_{\rm tot}$

$\Rightarrow$ Naturally identified with yield uncertainty



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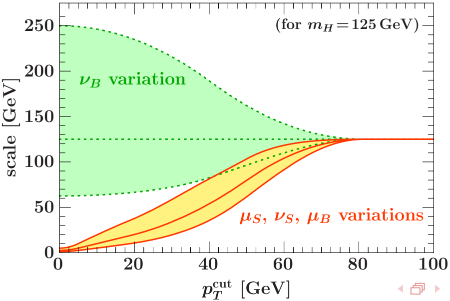
- Requires no assumptions on correlations between cross sections (as are made in JVE or fixed-order ST)
- Can study nontrivial correlations, e.g. between $\sigma_0, \epsilon_0, \sigma_{\text{total}}$

Δ_{resum}: Resummation scale variations

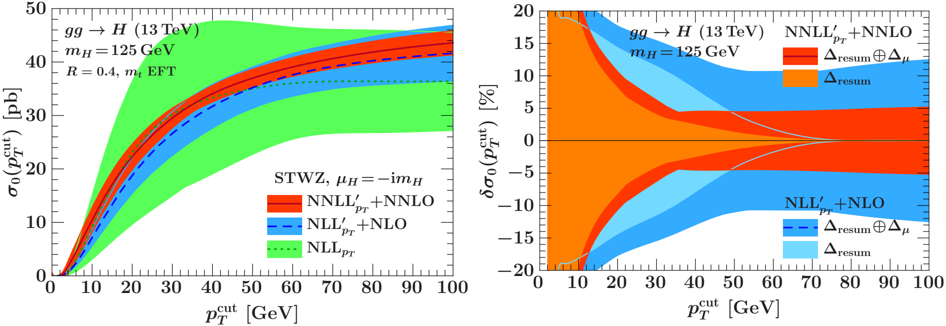
- Envelope of separately varying all profile scales (within canonical constraints)
- Directly probes size of logs and uncertainties in resummed log series
- Vanishes for large p_T^{cut} as resummation turns off

$\Rightarrow$ Naturally identified with Δ_{cut} migration



Resummed Results for Higgs + 0-jet Bin

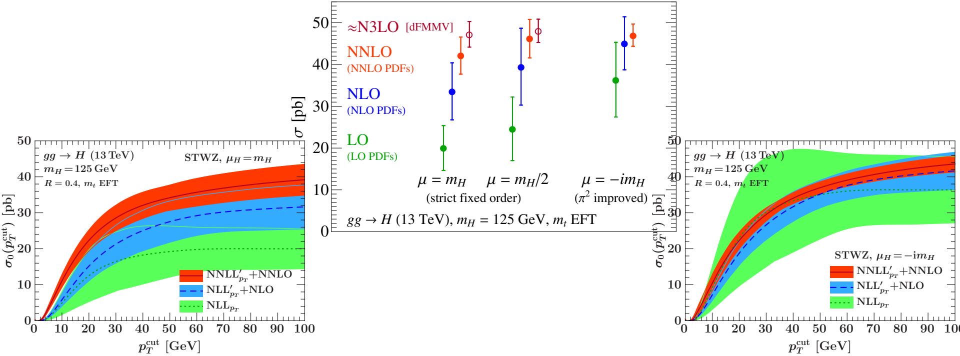
[Stewart, FT, Walsh, Zuberi]



Resummation Transition Fixed Order

- New updated results at $13\,\mathrm{TeV}$ (using MSTW2008, $R = 0.4$, m_t EFT)
- Resummation yields much improved precision: small uncertainties and good convergence
  - PDF+α_s uncertainties are not shown, and start to dominate now

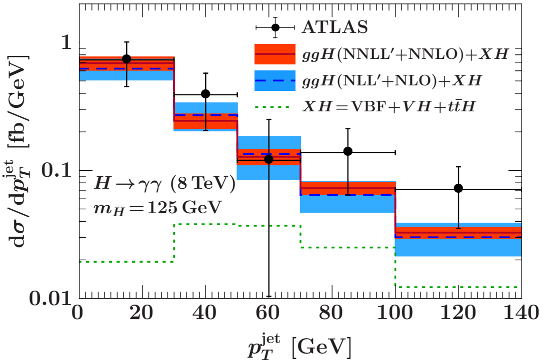
Inclusive Cross Section



Imaginary scale choice avoids large constant terms in gluon form factor (π^2 resummation [Parisi, Sterman, Magnea; Ahrens et al.])

- Significant improvement in exclusive 0-jet region extends to total cross section
- π^2-improved NNLO cross section very consistent with approx. N^{3}LO estimates [see e.g. de Florian, Mazzitelli, Moch, Vogt]

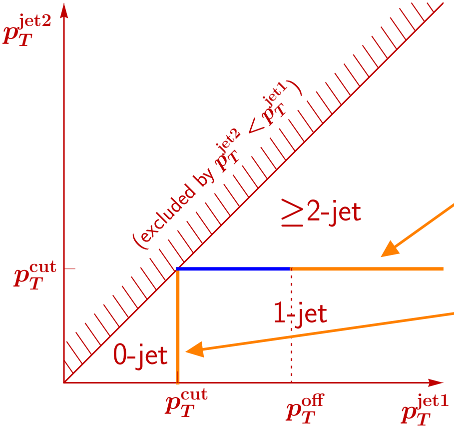
Comparison with ATLAS differential measurements



Direct comparison at cross section level

- No K-factor for total cross section
- Only relevant corrections factors are $\mathrm{BR}(H \to \gamma\gamma)$ and photon acceptance (basically flat in p_T^{jet})
- Uncertainties also include 5% $\mathrm{BR}(H \to \gamma\gamma)$ and flat 8% PDF

Resummation for Higgs + 1-jet Bin



[Liu Petriello; Boughezal, Liu, Petriello, FT, Walsh]

1-jet bin is more complicated due to additional scale involved

$p_T^{\rm jet2}$ resummation
($p_T^{\rm jet1} > p_T^{\rm off}$ treated in fixed order)

$p_T^{\rm jet1}$ resummation ($p_T^{\rm jet1} < p_T^{\rm off}$)
required for consistent combination with resummed 0-jet bin
($p_T^{\rm jet2}$ treated at fixed order)

- Important consistency check: results must be insensitive to $p_T^{\rm off}$
- Uncertainty framework extends to $\{\sigma_0, \sigma_1, \sigma_{\geq 2}\}$ 3x3 case

$$C = C^{\rm yield} + C(0/1\text{-migration}) + C(1/2\text{-migration})$$

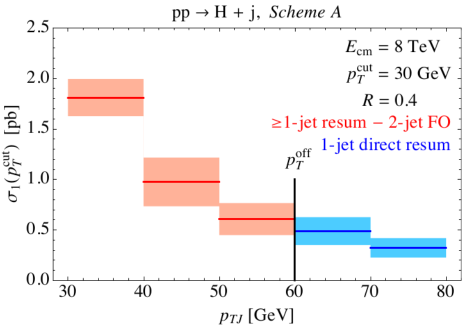
Combined 0-jet and 1-jet Bin Resummation

- 0-jet bin: NNLL′+NNLO with $\mu_H = -\mathrm{i}m_H$
- 1-jet bin: NLL′+NLO plus $H + j$ NNLO$_1$ virtuals

$\Rightarrow$ Getting consistent results depends (sensitively) on how α_s^3 corrections are treated

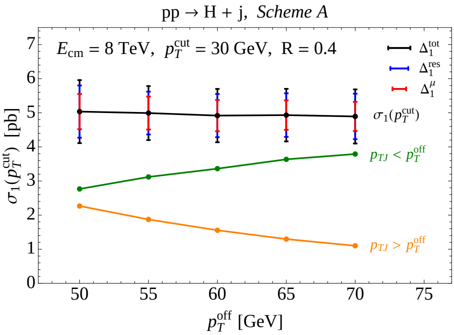
Important consistency checks

$\sigma_1(p_T^{\rm cut})$ in bins of $p_{T1}^{\rm jet}$



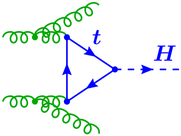
→ smooth transition across $p_T^{\rm off}$

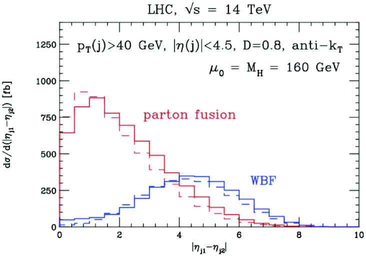
$\sigma_1(p_T^{\rm cut})$ integrated over $p_{T1}^{\rm jet} > p_T^{\rm cut}$

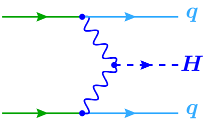


→ independent of $p_T^{\rm off}$ choice

Side Remark: VBF-enhanced Categories







Best VBF sensitivity comes from exclusive 2-jet region with 2 forward jets

- Hard kinematics: Two jets with large m_{jj} and/or $\Delta\eta_{jj}$
- Various possible 2-jet resolution variables: p_T^{jet3}, p_T^{Hjj}, $\pi - \Delta\phi_{H-jj}$

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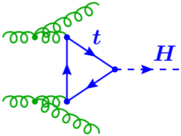

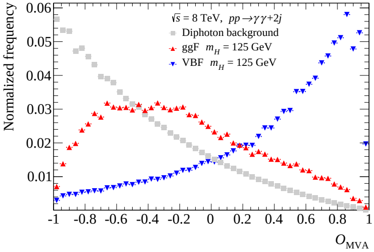

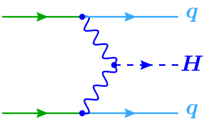

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- Hard kinematics: Two jets with large m_{jj} and/or $\Delta\eta_{jj}$
- Various possible 2-jet resolution variables: $p_T^{\rm jet3}$, p_T^{Hjj}, $\pi - \Delta\phi_{H-jj}$

All of this happens inside a multivariate analysis (MVA)

- Even if MVA only knows hard-kinematics variables, it can construct itself a resolution variable, e.g. $E_T^{Hjj} = p_T^H + p_T^{\rm jet1} + p_T^{\rm jet1}$

⇒ Crucial to ensure that the MVA does not cut arbitrarily into exclusive resummation regions, otherwise one can easily loose all theory control

New Jet Observables

[Shireen Gangal, Maximilian Stahlhofen, FT, arXiv:1412.4792]

Rapidity-Dependent Jet (Veto) Variables

Starting point: Set $J(R)$ of jets clustered with radius R

$$p_{\rm res}: \quad p_T^{\rm jet} = \max_{j \in J(R)} \{p_{Tj}\, \theta(|y_j| < y_{\rm cut})\}$$

$$0\text{-jet bin (jet veto)}: \quad p_T^{\rm jet} < p_T^{\rm cut}$$

$$\geq 1\text{-jet bin}: \quad p_T^{\rm jet} > p_T^{\rm cut}$$

Generalize to include rapidity weighting function $f(y_j)$

define: $\mathcal{T}_{fj} = p_{Tj}\, f(y_j) \qquad \Rightarrow \qquad p_{\rm res}: \quad \mathcal{T}_f^{\rm jet} = \max_{j \in J(R)} \mathcal{T}_{fj}$

Can now classify and veto jets according to $\mathcal{T}_{fj}$

$$0\text{-jet bin (jet veto)}: \quad \mathcal{T}_f^{\rm jet} < \mathcal{T}^{\rm cut}$$

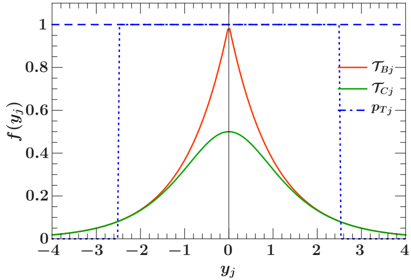
$$\geq 1\text{-jet bin}: \quad \mathcal{T}_f^{\rm jet} > \mathcal{T}^{\rm cut}$$

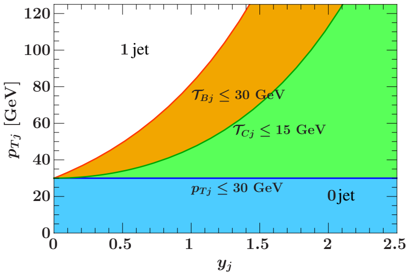
Rapidity Weighting Functions

	in pp cm frame	relative to $Y_H = 0$ rest frame
$\mathcal{T}_{B(\mathrm{cm})}$:	$f(y_j) = e^{-\lvert y_j \rvert}$	$f_(y_j) = e^{-\lvert y_j - Y_H \rvert}$
$\mathcal{T}_{C(\mathrm{cm})}$:	$f(y_j) = \dfrac{1}{2\cosh(y_j)}$	$f(y_j) = \dfrac{1}{2\cosh(y_j - Y_H)}$

Correspond to rapidity-weighted p_{Tj} veto

$\Rightarrow$ insensitive to forward rapidities, resummable to same level as p_T^{jet}





Resummation for $\mathcal{T}_f^{\rm jet}$

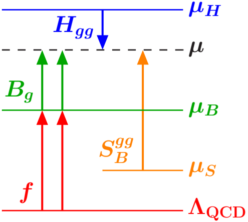
Factorized cross section for $\mathcal{T}_f^{\rm jet} < \mathcal{T}^{\rm cut}$

$$\sigma_0(\mathcal{T}^{\rm cut}) = H_{gg}(m_H^2, \mu)\, [B_g(m_H \mathcal{T}^{\rm cut}, R, \mu)]^2\, S_{gg}^{B,C}(\mathcal{T}^{\rm cut}, R, \mu)$$

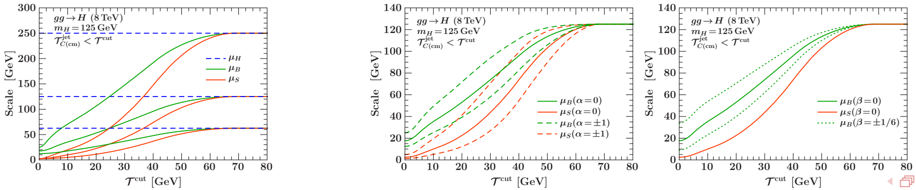
Resummation and unc. framework is the same

$\Rightarrow$ logarithmic/RGE structure very different from $p_T^{\rm jet}$

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

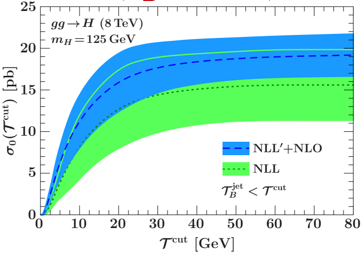


- Canonical: $\mu_H \sim -i m_H$, $\mu_B^2 \sim \mathcal{T}^{\rm cut} m_H$, $\mu_S \sim \mathcal{T}^{\rm cut}$
- Corresponding profile scale variations:

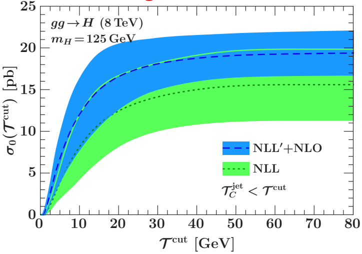


First Results at NLL′+NLO

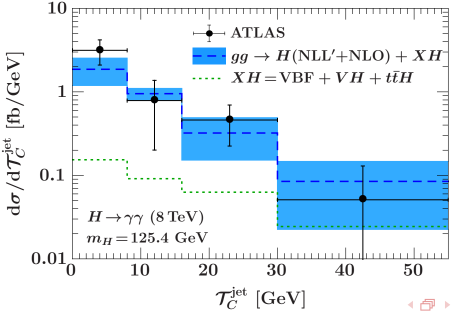
$\sigma_0(\mathcal{T}_B^{\rm jet} < \mathcal{T}^{\rm cut})$



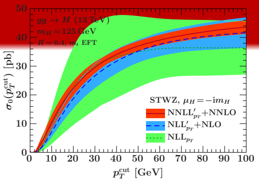
$\sigma_0(\mathcal{T}_C^{\rm jet} < \mathcal{T}^{\rm cut})$

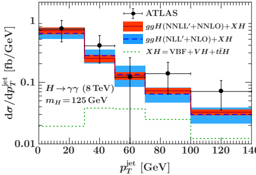


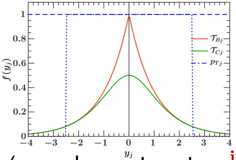
- Full NNLL′+NNLO will come
  - expect significant reduction in unc.
- Comparison to ATLAS differential measurements of $\mathcal{T}_C^{\rm jet}$
  - No K factor for total cross section
  - Same corrections and unc. applied as in $p_T^{\rm jet}$ case



Summary and Outlook







Jet observables can be resummed to high accuracy

- Turning "scale variations" into "theory unc." is nontrivial, *particularly* in resummed perturbation theory
- To "validate" uncertainties need to be able to check convergence and coverage at lower orders

Next steps

- Include full quark mass dependence
- Public code release (likely early next year)
  - Aiming to be fast, modular, and extendable
  - Will have access to full set of profile scale variations for studying uncertainties

Generalized jet (veto) observables

- Provide more general way to divide up phase space (complementary to p_T^{jet})
  - Can be utilized to optimize jet-binning ($\to$ optimal $f(y_j)$?)
  - Also probe a complementary region of theory/resummation space
  - Can be measured/tested in many processes (Higgs, Drell-Yan, diphoton, ...)

Backup Slides

Resummation + FO Matching and Counting

$$\ln \sigma_0(p_T^{\rm cut}) \sim \sum_n \alpha_s^n \ln^{n+1} \frac{p_T^{\rm cut}}{m_H} (1+\alpha_s+\alpha_s^2+\cdots) \sim \text{LL+NLL+NNLL+}\cdots$$

Resummation conventions:	Fixed-order corrections		Resummation input		
	matching (sing.)	full FO (+ nons.)	$\gamma_{H,B,S}^{\mu,\nu}$	$\Gamma_{\rm cusp}$	β
LL	1	-	-	1-loop	1-loop
NLL	1	-	1-loop	2-loop	2-loop
NLL+NLO	1	α_s	1-loop	2-loop	2-loop
NLL′+NLO	α_s	α_s	1-loop	2-loop	2-loop
NNLL+NLO	α_s	α_s	2-loop	3-loop	3-loop
NNLL+NNLO	α_s	α_s^2	2-loop	3-loop	3-loop
NNLL′+NNLO	α_s^2	α_s^2	2-loop	3-loop	3-loop
N^3LL+NNLO	α_s^2	α_s^2	3-loop	4-loop	4-loop

- "matching": singular FO corrections that act as boundary conditions in the resummation (α_s^n corrections to H, B, S reproduces full α_s^n singular)
- "full FO": adds FO nonsingular terms not included in the resummation