Jet p_T Resummation in Higgs Production

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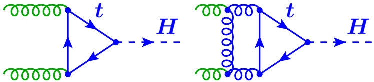
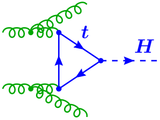
work with Iain Stewart, Jon Walsh, Saba Zuberi
(arXiv:1307.1808)

Higgs Production and Decay is a QCD Laboratory

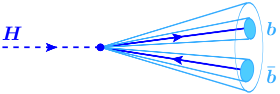
- Large QCD corrections in gluon fusion



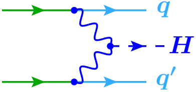
- Jets from initial-state radiation



- Jets from (boosted) decays



- Associated signal jets in weak boson fusion



Jets are used extensively in Higgs measurements

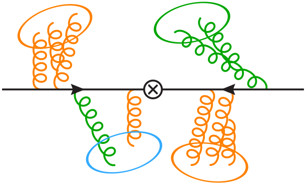
- Jet selection and jet kinematics are important in event categorization to separate different Higgs production and decay channels, which is essential to measure Higgs couplings.

Standard Example of Jet Binning: $H \to WW$

Exclusive 0-jet and 1-jet bins are crucial to control top background in $H \to WW$

Source (0-jet)	Signal (%)	Bkg. (%)
Inclusive ggF signal ren./fact. scale	13	-
1-jet incl. ggF signal ren./fact. scale	10	-
PDF model (signal only)	8	-
QCD scale (acceptance)	4	-
Jet energy scale and resolution	4	2
W+jets fake factor	-	5
WW theoretical model	-	5
Source (1-jet)	**Signal (%)**	**Bkg. (%)**
1-jet incl. ggF signal ren./fact. scale	26	-
2-jet incl. ggF signal ren./fact. scale	15	-
Parton shower/ U.E. model (signal only)	10	-
b-tagging efficiency	-	11
PDF model (signal only)	7	-
QCD scale (acceptance)	4	2
Jet energy scale and resolution	1	3
W+jets fake factor	-	5
WW theoretical model	-	3

[ATLAS-CONF-2012-158]



$p_T^{\rm jet} \leq p_T^{\rm cut} \simeq 25 - 30\,\mathrm{GeV}$

for $|\eta^{\rm jet}| \leq 4.5 - 5$

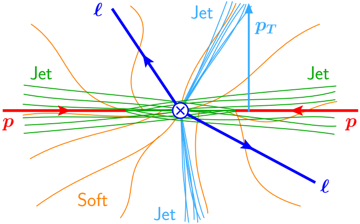
Perturbative QCD uncertainties are dominant syst. unc. in 0-jet and 1-jet bins [ATLAS, similar for CMS]

- $\Delta\sigma_0/\sigma_0 = 17\%$
- $\Delta\sigma_1/\sigma_1 = 30\%$

Large Logarithms from Jet Selection

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

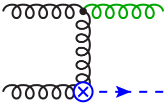
$\Rightarrow$ Restricting or cutting into soft radiation, ISR, or FSR causes large logarithms



Example: $gg \to H + 0$ jets

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

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



$\Rightarrow$ Perturbative corrections get large for small $p_T^{\rm cut}$

$\Rightarrow$ Should be reflected in perturbative uncertainties and better yet resummed

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)

Theory Uncertainties in Jet Binning

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

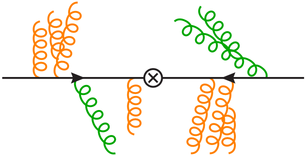
Complete description requires full theory covariance matrix for $\{\sigma_0, \sigma_{\geq 1}\}$

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

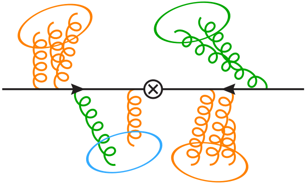
$$C = \begin{pmatrix} (\Delta_0^{\mathrm{y}})^2 & \Delta_0^{\mathrm{y}} \, \Delta_{\geq 1}^{\mathrm{y}} \\ \Delta_0^{\mathrm{y}} \, \Delta_{\geq 1}^{\mathrm{y}} & (\Delta_{\geq 1}^{\mathrm{y}})^2 \end{pmatrix} + \begin{pmatrix} \Delta_{\text{cut}}^2 & -\Delta_{\text{cut}}^2 \\ -\Delta_{\text{cut}}^2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

- Absolute "yield" uncertainty is fully correlated between bins
  - $\Delta_{\text{total}}^{\mathrm{y}} = \Delta_0^{\mathrm{y}} + \Delta_{\geq 1}^{\mathrm{y}}$
- "Migration" unc. Δ_{cut} due to binning (must drop out in sum $\sigma_0 + \sigma_{\geq 1}$)
  - Fixed-order region ($p^{\text{cut}} \sim Q$): Δ_{cut} small and can be neglected
  - Resummation region ($p^{\text{cut}} \ll Q$): Δ_{cut} important and associated with uncertainties in p^{cut} log series

Jet-Veto Observables



"Global Veto" restricts $\sum$ of all emissions



"Local Veto" restrict (local chunks of) individual emissions

SCET-I	beam thrust	"jet beam thrust"
(p^+-like scaling)	$\mathcal{T} = \sum_i E_i - \lvert p_i^z \rvert$	$\mathcal{T}^{\rm jet} = \sum_{i \in \rm jet} E_i - \lvert p_i^z \rvert$
SCET-II	"beam broadening"	jet p_T
($p_\perp$-like scaling)	$E_T = \sum_i p_{Ti}$	$\vec{p}_T^{\rm jet} = \sum_{i \in \rm jet} \vec{p}_{Ti}$

⇒ All are jet vetoes and technology exists to resum them (to at least NNLL)

Resummation for p_T^{jet}

Various complications to deal with

- Jet-algorithm effects (R dependence)
- p_T requires renormalization of rapidity divergences in SCET-II [Chiu et al.]
- Matching to fixed order result at intermediate and large p_T^{jet}
- Estimation of pert. uncertainties (including correlations)

Similar work by other groups

- H + 0 jets: Banfi, Monni, Salam, Zanderighi [1203.5773, 1206.4998]
- H + 0 jets: Becher, Neubert, Rothen [1205.3806, 1307.0025]
- H + 1 jet: Liu, Petriello [1210.1906, 1303.4405]
- H + 0 + 1 jet: Boughezal, Liu, Petriello, FT, Walsh [1312.4535]
  $\longrightarrow$ see Jon's talk next
- VH + 0 jets: Shao, Li, Li [1309.5015], Liu, Li [1401.2149]

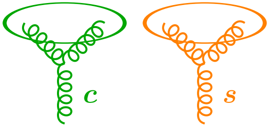
Jet Algorithm Effects in Local Vetoes

Definition of a local veto needs a jet algorithm with jet size R

$$\mathcal{M}^{\rm jet}(p_T^{\rm cut}) = \prod_{{\rm jets}\, j(R)} \theta\big(p_{Tj} < p_T^{\rm cut}\big)$$

Algorithm effects start at $\mathcal{O}(\alpha_s^2)$. Consider correction relative to global veto

$$\mathcal{M}^{\rm jet} = \big(\mathcal{M}_{n_a}^G + \Delta\mathcal{M}_{n_a}^{\rm jet}\big)\big(\mathcal{M}_{n_b}^G + \Delta\mathcal{M}_{n_b}^{\rm jet}\big)\big(\mathcal{M}_{s}^G + \Delta\mathcal{M}_{s}^{\rm jet}\big) + \delta\mathcal{M}^{\rm jet}$$

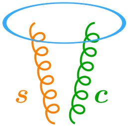


Clustering *within* each sector

$\sim \mathcal{O}(\ln^n R),\ \mathcal{O}(R^n)$

$\Rightarrow$ Relevant for small $R \ll 1$

- Included in beam (collinear) and soft functions



Clustering *between* sectors

$\sim \mathcal{O}(R^n)$

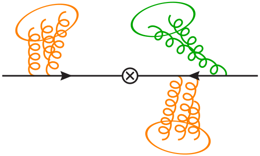
$\Rightarrow$ Relevant for large $R \sim 1$

- Violates simple factorization into collinear and soft

Factorization for Local p_T^{jet} Veto

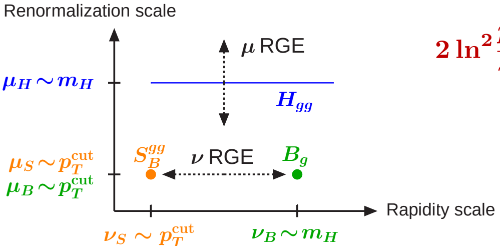
For $R^2 \ll 1$ local jet-veto measurement factorizes into simple product

$$\mathcal{M}^{\mathrm{jet}} = \mathcal{M}^{\mathrm{jet}}_{n_a}\, \mathcal{M}^{\mathrm{jet}}_{n_b}\, \mathcal{M}^{\mathrm{jet}}_{s}$$



$$\sigma_0(p_T^{\mathrm{cut}}) = H(Q,\mu)\, B^{\mathrm{jet}}(R, p_T^{\mathrm{cut}}, \mu, \nu)\, B^{\mathrm{jet}}(R, p_T^{\mathrm{cut}}, \mu, \nu)\, S^{\mathrm{jet}}(R, p_T^{\mathrm{cut}}, \mu, \nu)$$

Logarithms are split apart and resummed using coupled RGEs in μ and ν



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

Resummation Structure and Log 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 matching	full FO	Resummation input $\gamma_{H,B,S}^{\mu,\nu}$	$\Gamma_{\rm cusp}$	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^{3}LL+NNLO	α_s^2	α_s^2	3-loop	4-loop	4-loop

- "matching" are the singular FO corrections that act as starting/boundary conditions in the resummation (FO corrections to H, B, S)
- "full FO" means adding remaining FO terms not included in the resummation

Central Scale Choices

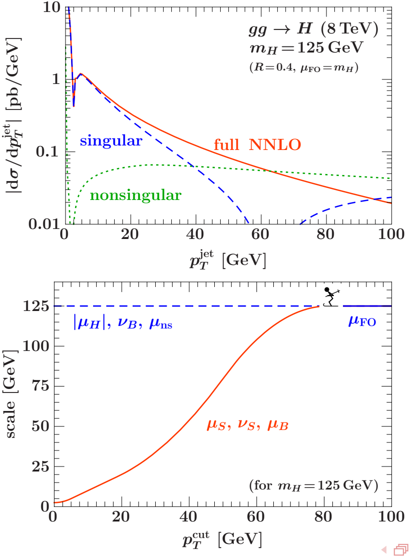
- Resummation region: Logs are resummed using canonical scaling

$$\mu_H \sim -i m_H$$
$$\mu_S \sim p_T^{\rm cut}, \nu_S \sim p_T^{\rm cut}$$
$$\mu_B \sim p_T^{\rm cut}, \nu_B \sim m_H$$

- FO region: Resummation turned off to ensure proper cancellation between singular and nonsingular terms by taking

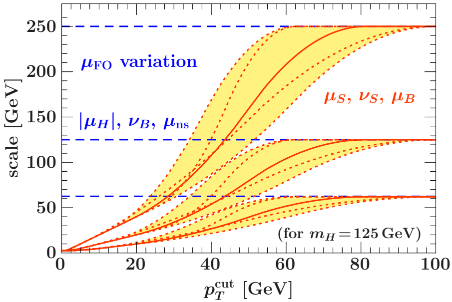
$$\mu_B, \mu_S, \nu_S, \nu_B \to \mu_{\rm FO} \sim m_H$$

- Transition region: Profiles for $\mu_B, \mu_S, \nu_B, \nu_S$ provide smooth transition from resummation to fixed-order region



Perturbative Uncertainties from Scale Variations

Fixed-order scale variations



- Take max of collective up/down variation (+ where resum. turns off)

$\Rightarrow$ Equivalent to overall FO μ variation keeping logs fixed

$\Rightarrow$ Reproduces $\Delta^{\rm FO}_{\geq 0}$ for large $p_T^{\rm cut}$

$\Rightarrow$ $\Delta_i^{\rm y} = \Delta_{\mu i}$

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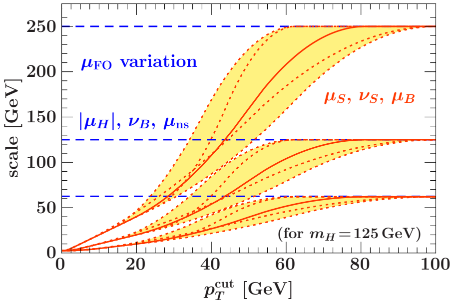

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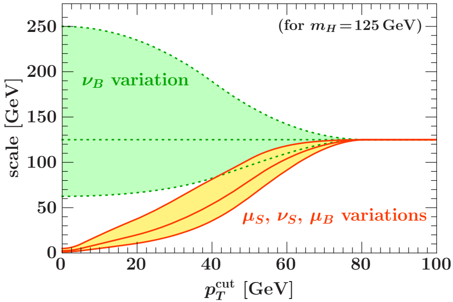
Resummation scale variations

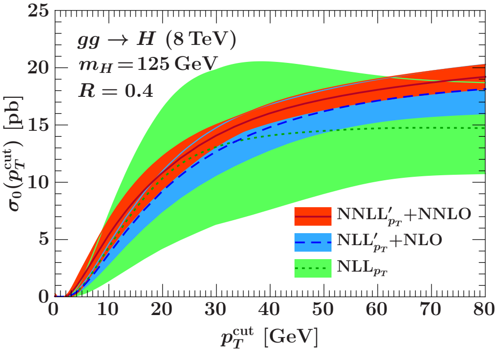


- Take maximum from separately varying all low scales (within canonical constraints)

⇒ Directly estimates size of logs and missing higher log terms

⇒ $\Delta_{\rm cut} = \Delta_{\rm resum}$

Resummed Results



Resummation Transition Fixed Order

(Here NNLL$_{p_T}$ refers to counting logarithms $\ln(p_T^{\rm cut}/m_H)$ only, but not $\ln R^2$)

At NNLL$'_{p_T}$+NNLO

$$\sigma_0(25\,\mathrm{GeV}, R = 0.4)$$
$$= 12.67 \pm 1.22_{\rm pert} (\pm 0.46_{\rm clust})\ \mathrm{pb}$$

$$\sigma_0(30\,\mathrm{GeV}, R = 0.5)$$
$$= 13.85 \pm 0.87_{\rm pert} (\pm 0.24_{\rm clust})\ \mathrm{pb}$$

- Resummed pert. theory shows good convergence and reduced uncertainties compared to fixed (N)NLO

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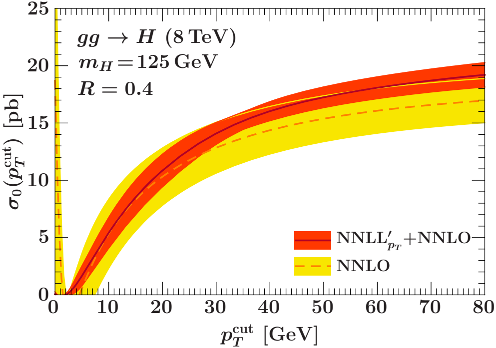

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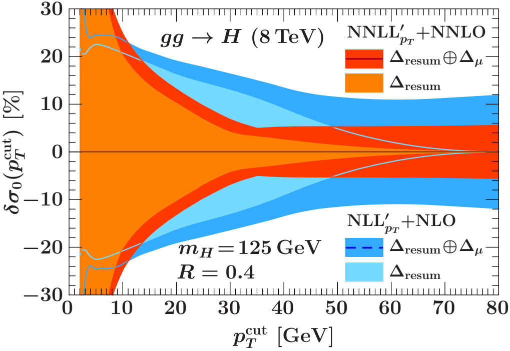

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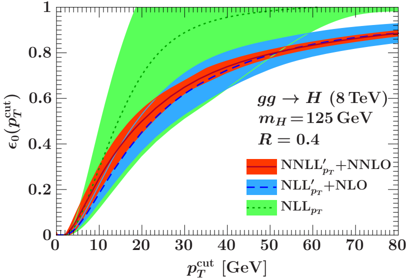
- Resummed pert. theory shows good convergence and reduced uncertainties compared to fixed (N)NLO
- Resummation provides systematic assessment of full theory unc. matrix

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

Resummed Results

green: NLL_{p_T}
blue: NLL'_{p_T}+NLO
orange: NNLL'_{p_T}+NNLO



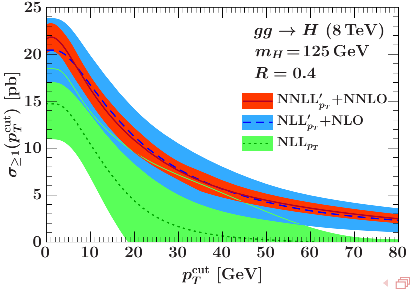
With full unc. matrix we can also make predictions for other quantities

- 0-jet fraction (jet-veto efficiency)

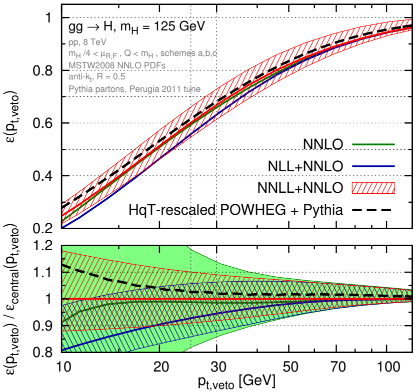
$$\epsilon_0(p_T^{\rm cut}) = \sigma_0(p_T^{\rm cut})/\sigma_{\rm total}$$

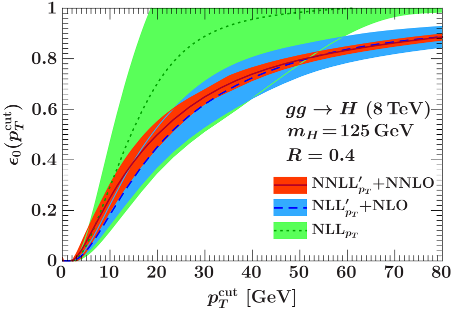
- incl. 1-jet cross section

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



Comparison to BMSZ



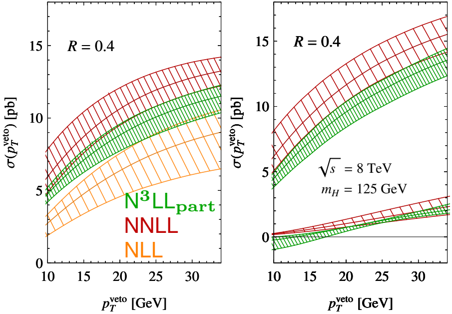


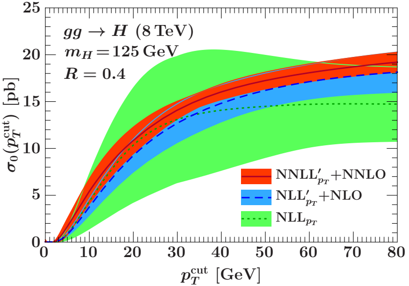
$$\epsilon_0(p_T^{\rm cut}) = \sigma_0(p_T^{\rm cut})/\sigma_{\rm total}$$

Banfi, Monni, Salam, Zanderighi [1203.5773, 1206.4998]

- Consider jet-veto efficiency as the primary quantity to resum
- Use QCD NNLL resummation for p_T^H [Bozzi, Catani, Grazzini] plus necessary correction terms to go from p_T^H to $p_T^{\rm jet}$

Comparison to BNR





Becher, Neubert, Rothen [1205.3806, 1307.0025]

- Use SCET-II together with "collinear anomaly" treatment to exponentiate rapidity logarithms
- Different organization of H, B, S, and nonsingular
  (similar uncertainties at highest order, but much poorer convergence)

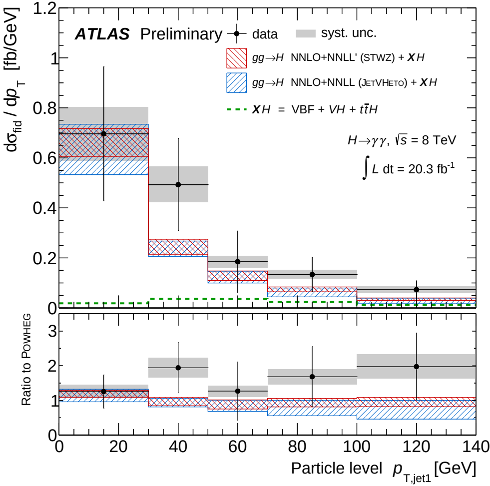
Comparison to ATLAS Data

ATLAS measurement of fiducial cross section in $H \to \gamma\gamma$ in bins of $p_T^{\rm jet}$ and corrected for detector effects

- Crucial transition step from fitting μ-values to measuring fiducial cross sections
  - Presents expt. results as theory independent as possible
  - Can be (almost) directly compared to theory predictions

    red: NNLL′+NNLO
    (Stewart, FT, Walsh, Zuberi)

    blue: NNLL+NNLO
    (Banfi, Monni, Salam, Zanderighi)



Summary

Differential and exclusive jet measurements are key to precision Higgs physics at LHC

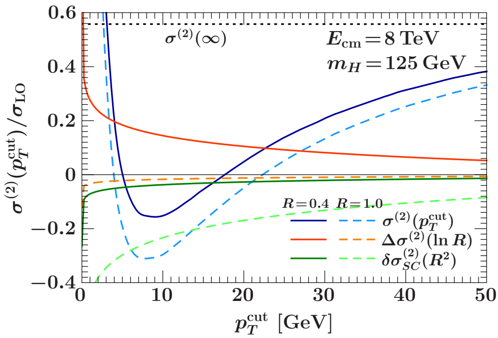
- $gg \to H + 0$ jet cross section determined to full NNLL$'_{p_T}$ +NNLO
  - Resummation is important to reduce uncertainties
  - Consistent treatment of correlations in theory uncertainties required
  - Jet algorithm effects can be sizable
    ($\ln R^2$ terms are formally NLL and not resummable at present)

There are many more things

- √ Consistent combination with resummed $gg \to H + 1$ jet
- √ VH production, boosted $H \to b\bar{b}$
- Other jet-binning/jet-veto variables ($\mathcal{T}^{\rm jet}$, E_T)
- 2-jet selection and VBF vs. gluon fusion separation
- Backgrounds
- ...

Backup Slides

Numerical Jet Algorithm Effects at NNLO



full 2-loop contribution with no veto

full 2-loop contribution with veto

clustering logs

soft-collinear mixing

For $R = 0.4$ (and also $R = 0.5$)

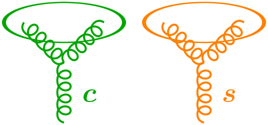
- Clustering $\ln R^2$ contributions are sizable
- Uncorrelated emission contributions (soft-collinear mixing) can safely be treated as $\mathcal{O}(R^2)$ power suppressed

$\Rightarrow$ Suggests that one should count $R^2 \sim p_T^{\rm cut}/m_H \ll 1$

Clustering Logarithms

$$\mathcal{M}^{\rm jet} = \left(\mathcal{M}^G_{n_a} + \Delta\mathcal{M}^{\rm jet}_{n_a}\right)\left(\mathcal{M}^G_{n_b} + \Delta\mathcal{M}^{\rm jet}_{n_b}\right)\left(\mathcal{M}^G_{s} + \Delta\mathcal{M}^{\rm jet}_{s}\right) + \delta\mathcal{M}^{\rm jet}$$

$\Delta\mathcal{M}^{\rm jet}_n$, $\Delta\mathcal{M}^{\rm jet}_s$: Correction from clustering of correlated emissions within soft and beam sectors



Gives rise to logs of R, leading clustering logs are

$$\frac{\Delta\sigma^{(n)}}{\sigma_B} = C_n(R)\left(\frac{\alpha_s C_A}{\pi}\right)^n \ln\frac{m_H}{p_T^{\rm cut}} \ln^{n-1} R^2$$

- For $R^2 \sim p_T^{\rm cut}/m_H \to \alpha_s^n L^n$ NLL series in the exponent that *cannot* be resummed at present
- Full $\alpha_s^2 C_2(R)$ term first computed by BMSZ

$\Rightarrow$ In SCET, these appear in the noncusp anomalous dimensions, allowing one to resum the $\ln(p_T^{\rm cut}/m_H)$ at NNLL$_{p_T}$ [FT, Walsh, Zuberi]