Combining Resummed Higgs Predictions Across Jet Bins

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SM@LHC
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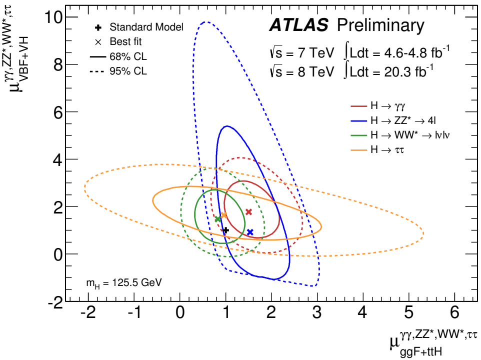
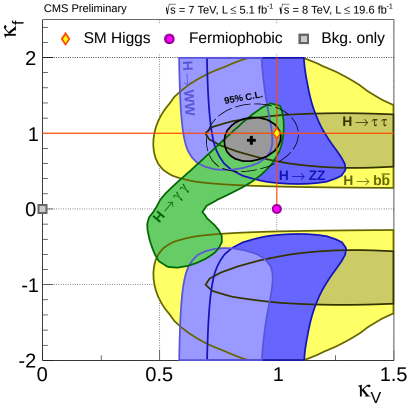
Determining Higgs Couplings





So far consistent with the SM Higgs

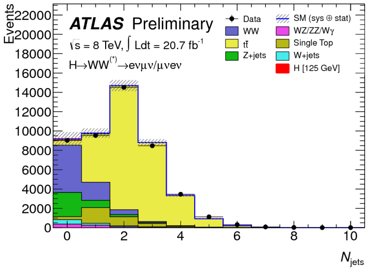
- Every measurement is also an indirect search

⇒ Discovering BSM effects in Higgs couplings at the few to $\mathcal{O}(10\%)$ level requires detailed and precise control of QCD effects at the same level including reliable theory uncertainties and correlations.

Event Categorization and Jet Binning

Separating data into exclusive categories is advantageous when backgrounds depend on kinematics and jet multiplicity

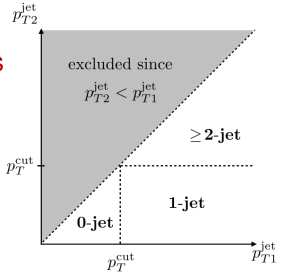
- Substantial gain by optimizing analysis in each category or jet bin
- $H \to WW$: Exclusive 0-jet and 1-jet bins important to control top background



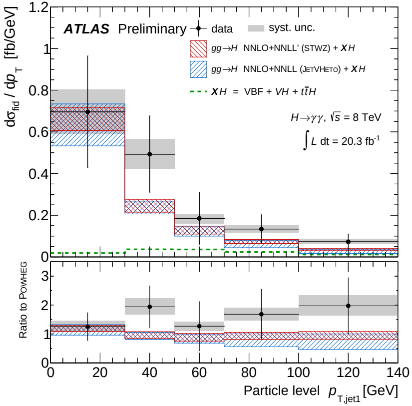
Ultimately, the relevant quantities that are measured and thus to be predicted are the fiducial cross sections in each category or jet bin

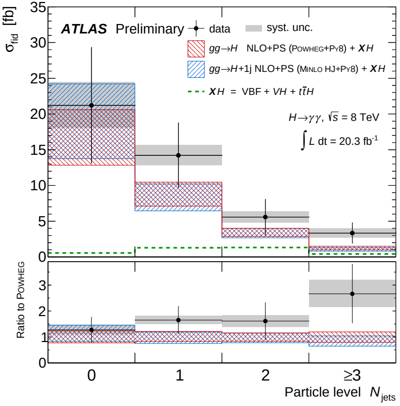
- In the end, we want to combine results from all jet bins (and in fact from all categories and channels)

⇒ Consistent theory description, uncertainties & correlations are essential



Differential Cross Section Measurements





- It is invaluable to have measurements of the actual fiducial cross sections (actually more important than μ-values, at least in my mind)

Substantial Theory Progress over the Last Years

Resummation and uncertainties for excl. jet cross sections

- Beam thrust: Berger, Marcantonini, Stewart, FT, Waalewijn [0910.0467, 1012.4480]
- FO jet-bin uncertainties: Stewart, FT [1107.2117], Bernlochner, Gangal, Gillberg, FT [1302.5437, 1307.1347]

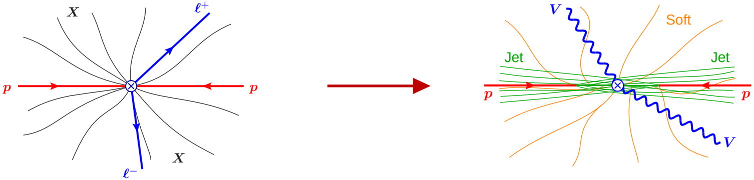
Jet algorithms and jet p_T

- $H+0$ jets: Banfi, Monni, Salam, Zanderighi [1203.5773, 1206.4998, 1308.4634]
- $H+0$ jets: Becher, Neubert, Rothen [1205.3806, 1307.0025]
- → $H+0$ jets: Stewart, FT, Walsh, Zuberi [1206.4312, 1307.1808]
- → $H+1$ jets: Liu, Petriello [1210.1906, 1303.4405]
- α_s^3 jet clustering effects: Alioli, Walsh [1311.5234]
- $VH+0$ jets: Shao, Li, Li [1309.5015]
- $VH+0$ jets: Liu, Li [1401.2149]

This talk

- combined 0+1 jet resummation: Boughezal, Liu, Petriello, FT, Walsh [1312.4535]

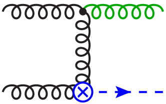
Large Logarithms



For any type of exclusive measurement or restriction

- Constraining radiation into soft and collinear regions causes large logs (due to sensitivity to soft/collinear divergences)

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



- Restricts ISR to $p_T < p_T^{\rm cut}$ ($\to$ Sudakov double logs from t-channel sing.)

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

$\Rightarrow$ Perturbative corrections increase for smaller $p_T^{\rm cut}$ (stronger restriction)

$\Rightarrow$ Should be resummed to all orders to obtain reliable precise predictions

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 $\{\sigma_0, \sigma_{\geq 1}\}$

[Berger, Marcantonini, Stewart, FT, Waalewijn; Stewart, FT]

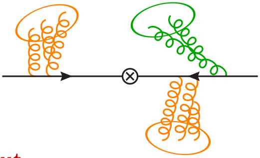
- General physical parametrization in terms of 100% correlated and 100% anticorrelated pieces

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

- Absolute "yield" uncertainty is fully correlated between bins
  - $\Delta_{\rm total}^{\rm y} = \Delta_0^{\rm y} + \Delta_{\geq 1}^{\rm y}$ reproduces uncertainty in $\sigma_{\rm total}$
- "Migration" unc. $\Delta_{\rm cut}$ due to binning (must drop out in sum $\sigma_0 + \sigma_{\geq 1}$)
  - $p_T^{\rm cut} \sim m_H$: $\Delta_{\rm cut}$ small and can be neglected (FO region)
  - $p_T^{\rm cut} \ll m_H$: $\Delta_{\rm cut}$ important, associated with unc. in $p_T^{\rm cut}$ log series

Resummation for p_T^{jet}

For $R^2 \ll 1$ local jet clustering algorithm factorizes into purely soft and collinear jets

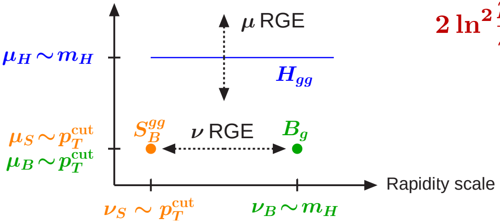


Allowing to factorize cross section for $p_T^{\mathrm{jet}} < p_T^{\mathrm{cut}}$

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

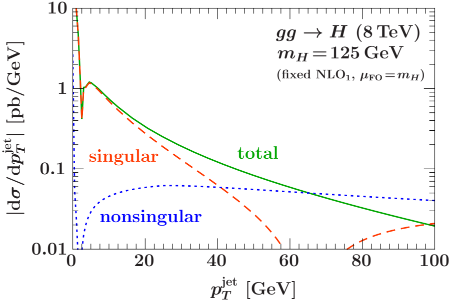
Logarithms are split apart and resummed using coupled RGEs in μ and ν

[Using SCET-II with rapidity RGE by Chiu, Jain, Neill, Rothstein]

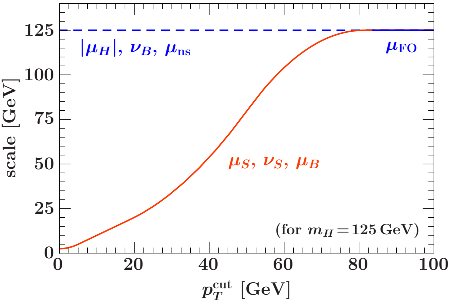


$$2\ln^2 \frac{p_T^{\mathrm{cut}}}{m_H} = 2\ln^2 \frac{m_H}{\mu} + 4\ln\frac{p_T^{\mathrm{cut}}}{\mu}\ln\frac{\nu}{m_H} + 2\ln\frac{p_T^{\mathrm{cut}}}{\mu}\ln\frac{\mu\, p_T^{\mathrm{cut}}}{\nu^2}$$

Perturbative Regions and Profile Scales



Resummation



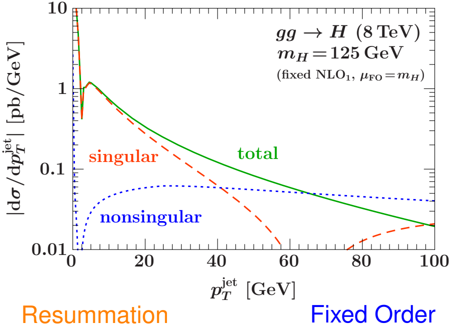
Resummation

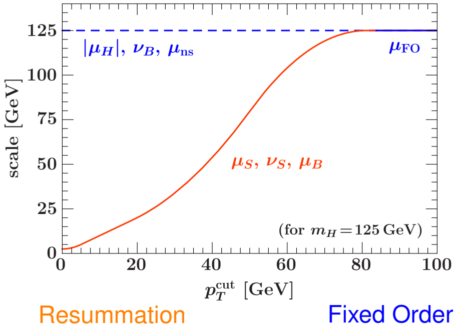
Resummation region

- Logs ("singular") dominate and are resummed to all orders
  (remaining "nonsingular" are power-suppressed)

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

Perturbative Regions and Profile Scales



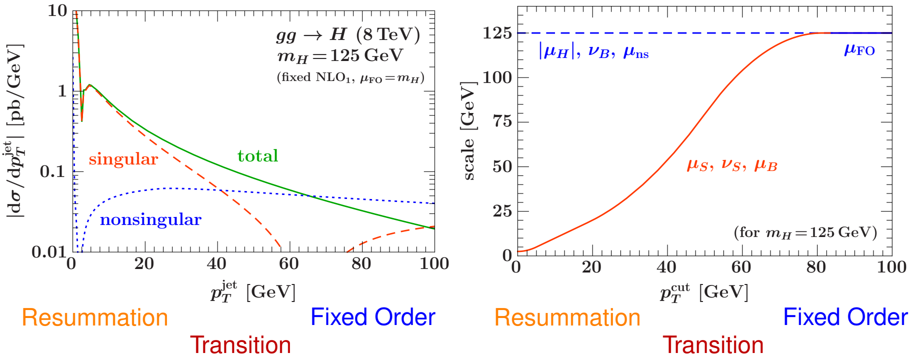


Fixed-order region

- Fixed-order expansion for $H+1$ hard jet applies
- Resummation must be turned off (singular/nonsingular separation becomes arbitrary with large cancellations between them)

$$\mu_B, \mu_S, \nu_S, \nu_B \to |\mu_H| = \mu_{FO} \sim m_H$$

Perturbative Regions and Profile Scales



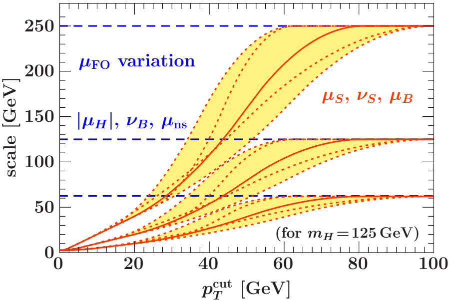
Transition region

- Theoretically the most subtle but often the most relevant in practice
- Profile scales for $\mu_B, \mu_S, \nu_B, \nu_S$ provide smooth transition between resummation and fixed-order limits

  $\Rightarrow$ Ambiguity is a *scale* uncertainty $\to$ reduces going to higher orders

Uncertainties from Profile Scale Variations

Fixed-order scale variations

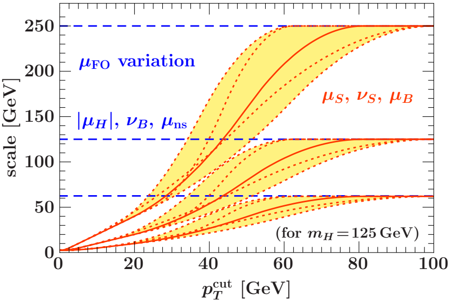


- Take max of collective up/down variation (+ where resum. turns off)
  - Equivalent to overall FO μ variation keeping logs fixed
  - Reproduces $\Delta^{\rm FO}_{\geq 0}$ for large $p_T^{\rm cut}$

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

Uncertainties from Profile Scale Variations

Fixed-order scale variations



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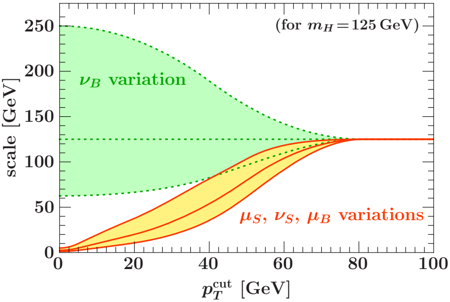
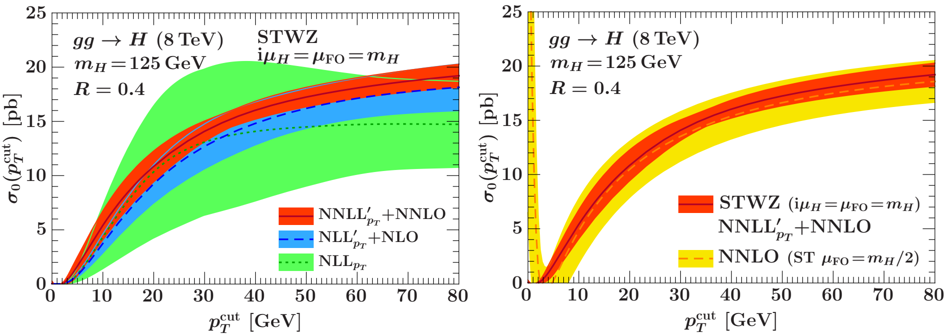
Resummation scale variations



- Take maximum from separately varying all low scales
  - Constrained to preserve canonical scaling relations
  - Probes unc. in log series

$\Rightarrow$ Migration unc. $\Delta_{\rm cut} = \Delta_{\rm resum}$

Resummed Results for 0-jet Bin



Resummation Transition Fixed Order

- Resummed pert. theory shows good convergence
  (NNLL$_{p_T}$ refers to counting logarithms $\ln(p_T^{cut}/m_H)$ only, but not $\ln R^2$)

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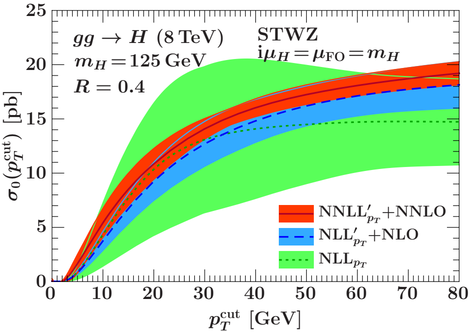
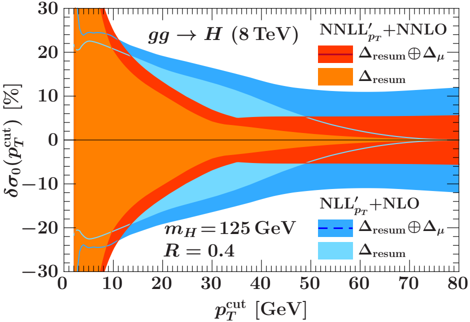


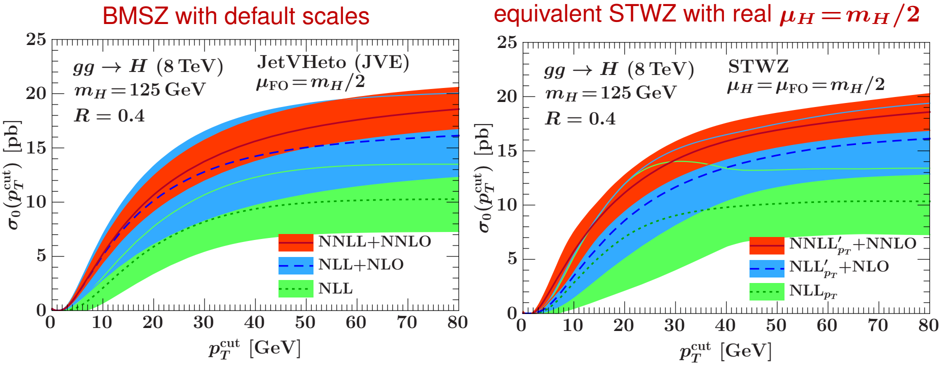


Resummation Transition Fixed Order

- Resummed pert. theory shows good convergence
  (NNLL$_{p_T}$ refers to counting logarithms $\ln(p_T^{cut}/m_H)$ only, but not $\ln R^2$)
- Resummation framework allows assessment of full theory unc. matrix
  (i.e. *without* any assumptions on correlations between different cross sections)

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

Comparison to BMSZ

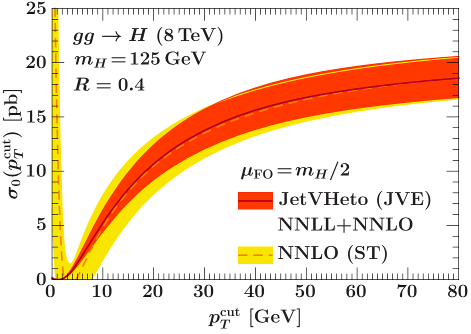


Banfi, Monni, Salam, Zanderighi [1203.5773, 1206.4998]

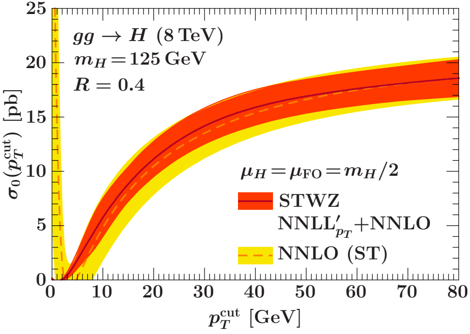
- Use QCD NNLL resummation for p_T^H [Bozzi, Catani, Grazzini] plus necessary correction terms to go from p_T^H to p_T^{jet}
- Consider jet-veto efficiency as the primary quantity to resum, assume efficiency and total cross section as uncorrelated

Comparison to BMSZ

BMSZ with default scales



equivalent STWZ with real $\mu_H = m_H/2$



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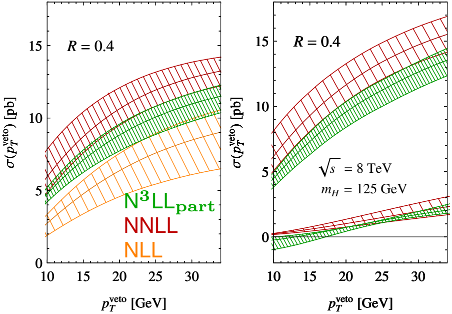
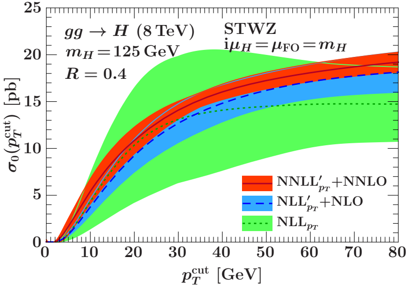
Comparison to BNR





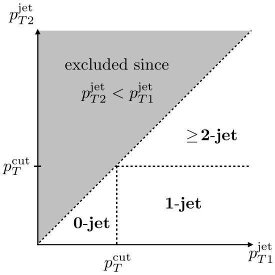
Becher, Neubert, Rothen [1205.3806, 1307.0025]

- 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)

Exclusive Higgs + 1 jet bin

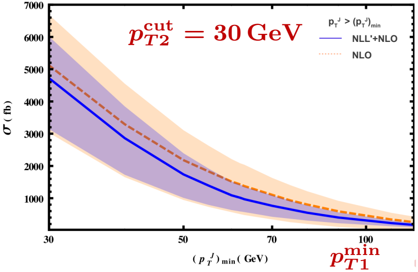
Resummation for 1-2 jet boundary $p_{T2}^{\mathrm{jet}} < p_{T2}^{\mathrm{cut}}$
is more tricky than for 0-1 jet boundary $p_{T1}^{\mathrm{jet}} < p_{T1}^{\mathrm{cut}}$

- multiple scales: $p_{T2}^{\mathrm{jet}} \leq p_T^{\mathrm{cut}} < p_{T1}^{\mathrm{jet}} < m_H$
- Jet-algorithm dependence from both the signal jet and the vetoed jet



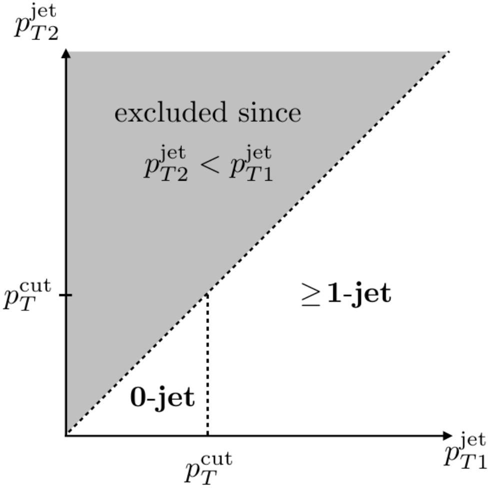
For $p_{T2}^{\mathrm{cut}} \ll p_{T1}^{\mathrm{jet}} \sim m_H$ [Liu, Petriello]

- Analogous setup using $\mu - \nu$ RGE with profile scales applies
- Resummation to NLL$'$+NLO

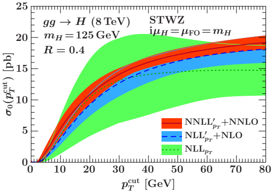


0-jet Bin Resummation

Resummation for leading jet p_T provides

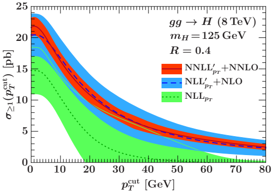


- 0-jet bin: $\sigma_0(p_T^{\rm cut})$



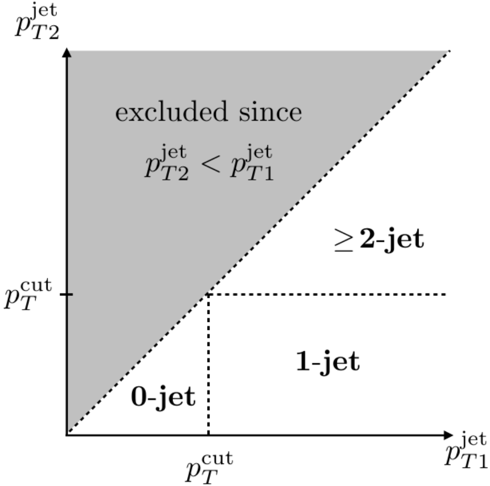
- $\geq$ 1-jet bin:

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



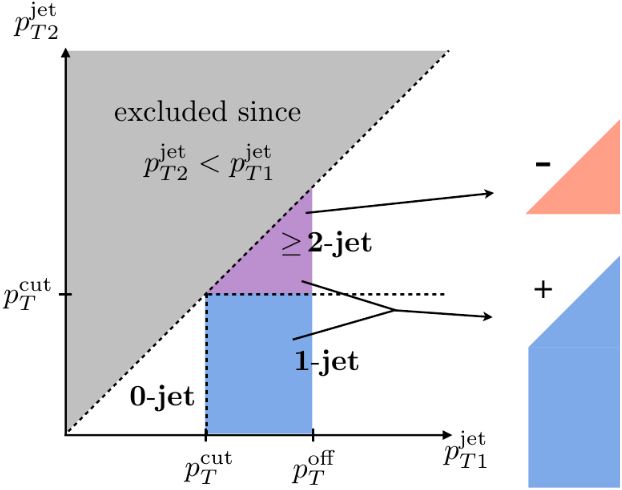
1-jet Bin Resummation

Exclusive 1-jet bin is a multi-scale problem: $p_{T2}^{\rm jet} \le p_T^{\rm cut} < p_{T1}^{\rm jet} < m_H$



1-jet Bin Resummation: Low Leading Jet p_T

Split it apart: $p_T^{\rm cut} < p_{T1}^{\rm jet} < p_T^{\rm off} \to$ $p_{T1}^{\rm jet}$ resummed, $p_{T2}^{\rm jet}$ at fixed order



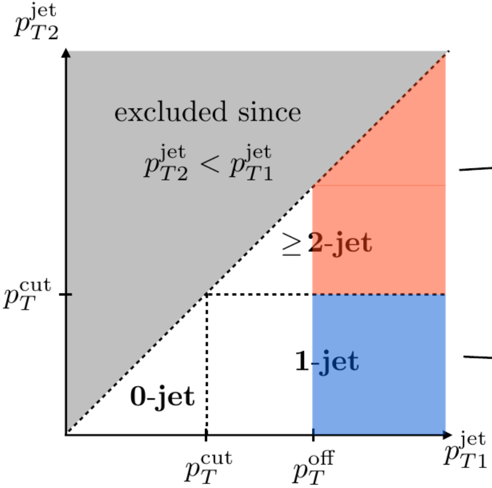
Indirect approach:

≥ 2-jet bin
fixed-order contribution
(small correction from ≥ 1-jet to exclusive 1-jet bin)

≥ 1-jet bin
resummed result

1-jet Bin Resummation: High Leading Jet p_T

Split it apart: $p_T^{\mathrm{off}} < p_{T1}^{\mathrm{jet}} \to p_{T1}^{\mathrm{jet}}$ fixed order, p_{T2}^{jet} resummed



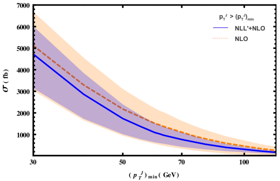
Direct approach:

≥ 2-jet bin:

$\sigma_{\geq 2}(p_T^{\mathrm{cut}}) = \sigma_{\geq 1} - \sigma_1(p_T^{\mathrm{cut}})$

1-jet bin direct resummation:

$\sigma_1(p_T^{\mathrm{cut}})$ for $p_{T1}^{\mathrm{jet}} > p_T^{\mathrm{off}}$



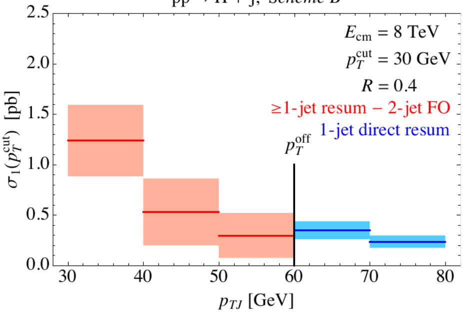
Combined 1-jet Bin Resummation

Scheme B: Everything matched to strict α_s^2

- 0-jet bin: NNLL′+NNLO with real $\mu_H = m_H$
- 1-jet bin: NLL′+NLO

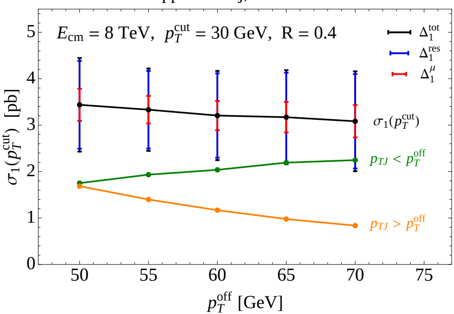
Important consistency checks

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



smooth transition across p_T^{off} (of sorts)

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



independent of p_T^{off} choice

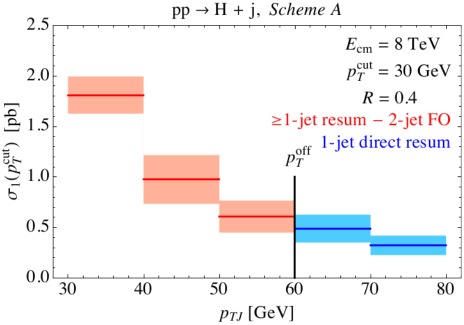
Combined 1-jet Bin Resummation

Scheme A (default): Include important α_s^3 virtual corrections

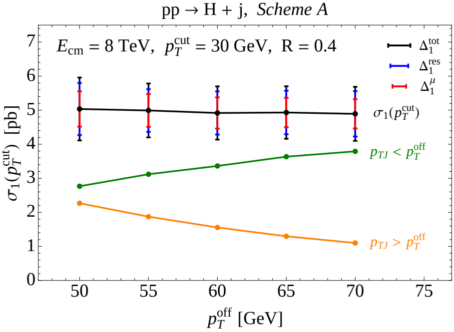
- 0-jet bin: NNLL′+NNLO with complex $\mu_H = -i m_H$
- 1-jet bin: NLL′+NLO plus $H + j$ NNLO$_1$ virtuals

Important consistency checks

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



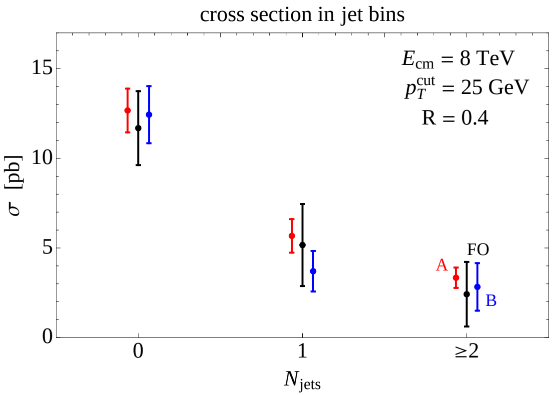
$\sigma_1(p_T^{cut})$ integrated over $p_{T1}^{jet} > p_T^{cut}$



smooth transition across p_T^{off}

independent of p_T^{off} choice

Final results for 0, 1, $\geq$ 2-jet Bins



red: default scheme (A)

blue: scheme B

black: fixed-order to α_s^2

- Reduces theory uncertainties on signal yield in $H \to WW$ by about factor of 2
- Framework allows us to estimate full 3x3 theory correlation matrix
  - General parametrization in terms of yield, 0-1 migration, and 1-2 migration

Summary

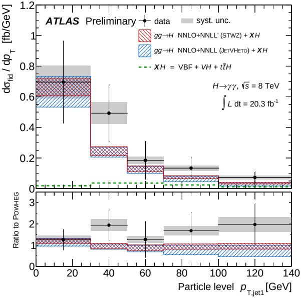
For detailed Higgs measurements

- Differential and exclusive jet measurements are of key importance
  - Requires precise resummed calculations
  - Precision demands reliable unc. and correlations (just small is not enough...)

Higher-order resummation for p_T^{jet}

- $H+$0-jet cross section known to NNLL$'$+NNLO
- $H+$1-jet cross section known to NLL$'$+NLO

$\Rightarrow$ Framework to combine both including uncertainties and correlations (ready to be used ...)



Ultimate dream/goal:

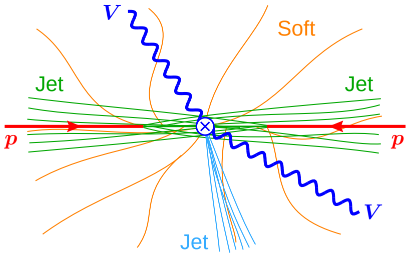
- Global coupling fit using fully corrected fiducial cross sections

$\Rightarrow$ Requires experiments to measure them and theory to compute them ...

Backup Slides

Soft-Collinear Effective Theory (SCET)

Physical picture: Contributions at different energy scales



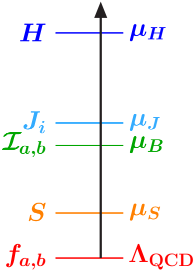
Hard interaction

ISR and FSR

Collinear to incoming and outgoing primary partons

Soft radiation

no preferred direction



$\rightarrow$ *Factorization:* $\mathrm{d}\sigma = \text{Hard} \otimes \text{PDFs} \otimes \text{ISR} \otimes \text{FSR} \otimes \text{Soft}$

SCET is the effective field theory of QCD in the soft and collinear limit

[Bauer, Fleming, Pirjol, Stewart; Rothstein, Beneke, Chapovsky, Diehl, Feldmann]

- Power counting and expansion in soft and collinear limits manifest at the Lagrangian level
- Systematic separation of different relevant energy scales

Soft-Collinear Factorization (Schematically)

Cross section after matching from QCD onto SCET

$$\sigma = \sum_{k,l} C_k^\dagger C_l \, \langle O_k^\dagger \, \mathcal{M} \, O_l \rangle$$

- Matching coeffs C_i contain process dependence and hard kinematics
- Measurement function $\mathcal{M}$ defines observable

SCET operators factorize into soft and collinear (universal)

$$O_k = O_{n_{a,b}} \times O_{n_j} \times O_s$$

Soft-collinear factorization requires that $\mathcal{M}$ also factorizes to all orders

$$\mathcal{M} = \mathcal{M}_{n_{a,b}} \otimes \mathcal{M}_{n_j} \otimes \mathcal{M}_s + \text{power corrections}$$

Together this factorizes the cross section

$$\sigma = \underbrace{|C|^2}_{H} \times \underbrace{\langle O^\dagger_{n_{a,b}} \mathcal{M}_{n_{a,b}} O^\dagger_{n_{a,b}} \rangle}_{B_{a,b}} \otimes \underbrace{\langle O^\dagger_{n_J} \mathcal{M}_{n_j} O^\dagger_{n_j} \rangle}_{J_j} \otimes \underbrace{\langle O^\dagger_{n_s} \mathcal{M}_s O^\dagger_s \rangle}_{S}$$

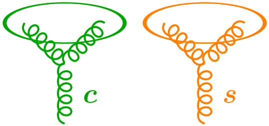
Jet Algorithm Effects

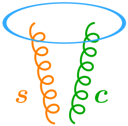
"Local" jet veto depends on a jet clustering algorithm with jet size R

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

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

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





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

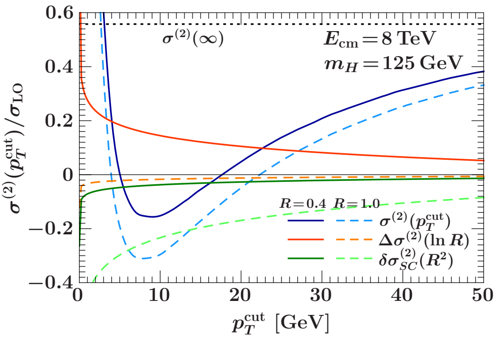
Clustering *between* sectors

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

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

- Violates simple factorization into collinear and soft

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

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

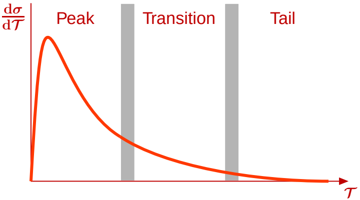
Perturbative Structure – Singular vs. Nonsingular

Differential/integrated spectrum in some IR-sensitive variable τ

thrust: $\tau = 1 - T = \mathcal{T}_2/Q$

jet-mass: $\tau = m_J^2/p_{T\mathrm{jet}}^2$

jet-veto: $\tau = p_{T\mathrm{jet}}/Q$



$$\frac{d\sigma}{d\tau} = \sum_k \alpha_s^k \left\{ c_{k,-1}\delta(\tau) + \sum_{n=0}^{2k-1} c_{kn}\left[\frac{\ln^n \tau}{\tau}\right]_+ + f_k^{\mathrm{ns}}(\tau) \right\}$$

$$\sigma(\tau^{\mathrm{cut}}) = \sum_k \alpha_s^k \left\{ c_{k,-1} + \sum_{n=0}^{2k-1} c_{kn}\frac{\ln^{n+1}\tau^{\mathrm{cut}}}{n+1} + F_k^{\mathrm{ns}}(\tau^{\mathrm{cut}}) \right\}$$

singular — nonsingular

singular: large logs to be resummed

- constant $c_{k,-1}$ belongs to singular

nonsingular: $\mathcal{O}(\tau)$ power corrections

- $f_k^{\mathrm{ns}}(\tau)$ at most integrable divergent
- $F_k^{\mathrm{ns}}(\tau^{\mathrm{cut}} \to 0) \to 0$

Resummation + Fixed Order Matching

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

Resummation conventions:	Fixed-order corrections: matching (sing.)	full FO (+ nons.)	Resummation input: $\gamma^{\mu,\nu}_{H,B,S}$	$\Gamma_{\rm cusp}$	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