Higgs Production with a Jet Veto

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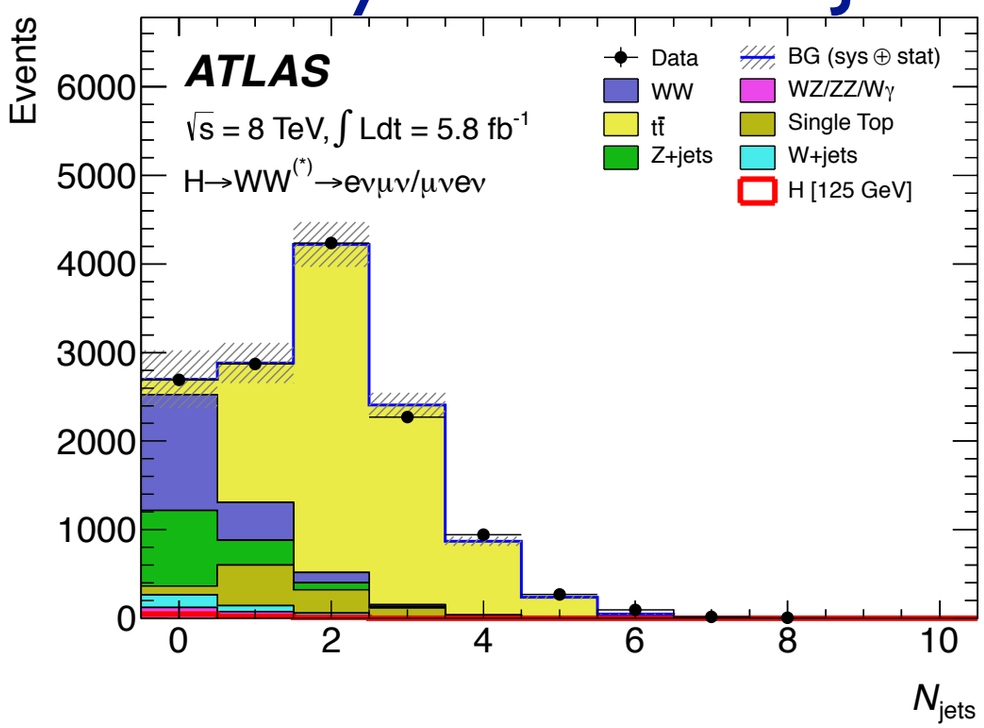
Chicago 2012 Workshop
on LHC Physics

With:
Frank Tackmann and Jon Walsh - arXiv: 1206.4312
Iain Stewart, Frank Tackmann and Jon Walsh

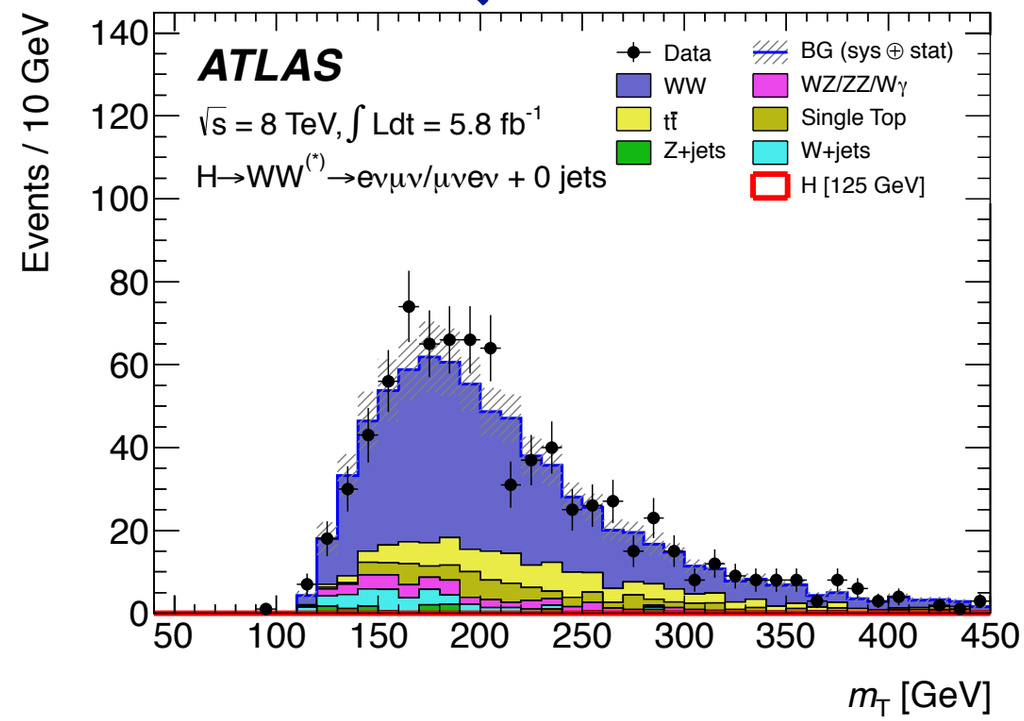
Jet Vetoes in Higgs Analyses

- $pp \to H \to WW^* \to \ell\nu\ell\nu$

Bin by Number of Jets



0-jet bin



Anti-k_T jets R=0.4, $p_T^{jet} < 25$ GeV, $|y| < 4.5$

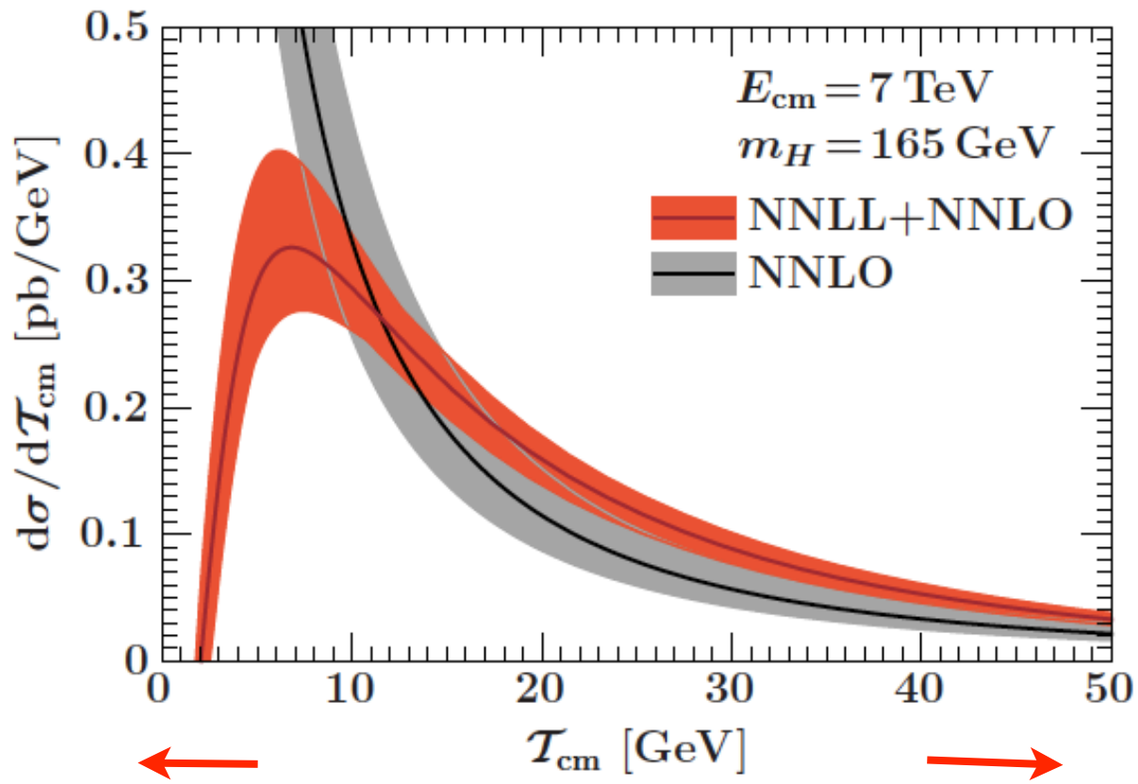
- "The systematic uncertainties that have the largest impact on the sensitivity of the search are the theoretical uncertainties associated with the signal."
  ATLAS **Phys.Lett. B716 (2012) 1-29**

$$\delta\sigma_0 = 17\% \qquad \delta\sigma_1 = 28\%$$

ATLAS-CONF-2012-098

Reducing Theory Uncertainties

Berger et al (1012.4480)



Resummation

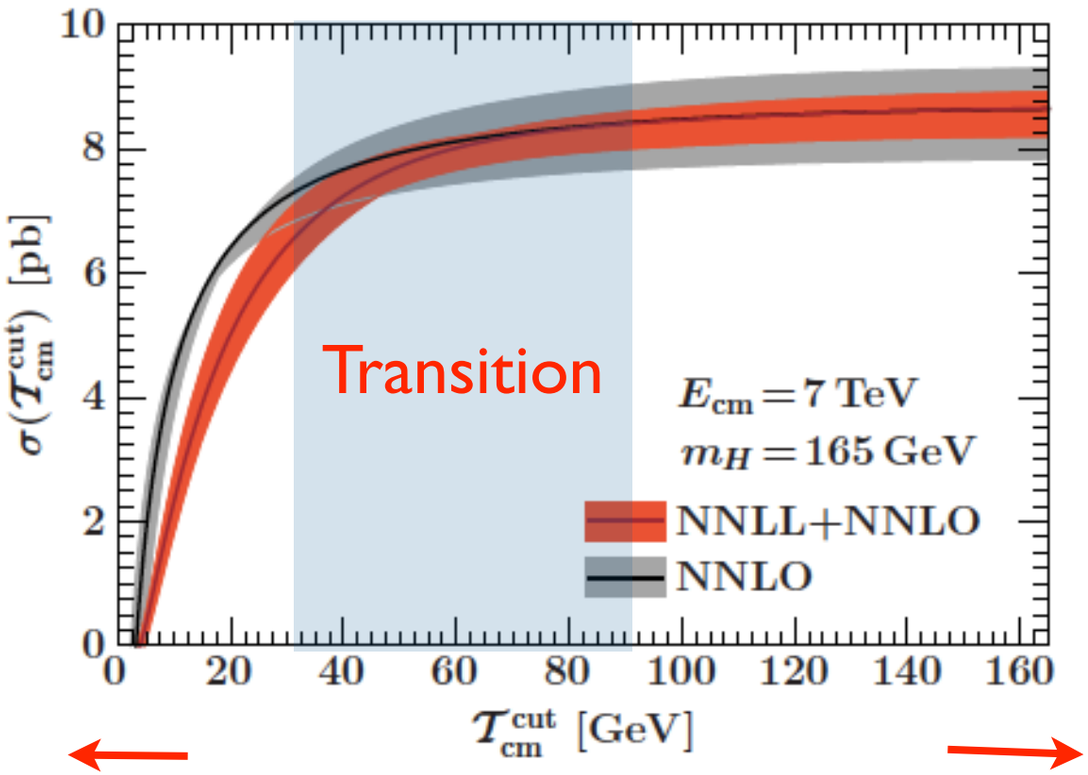
$$\frac{1}{p_T}\,\alpha_s^n \ln^m \frac{p_T}{m_H}$$

Fixed Order

$$\alpha_s^n$$

Reducing Theory Uncertainties

Berger et al (1012.4480)



Resummation

$$\alpha_s^n \ln^m \frac{p_T^{cut}}{m_H}$$

Fixed Order

$$\alpha_s^n$$

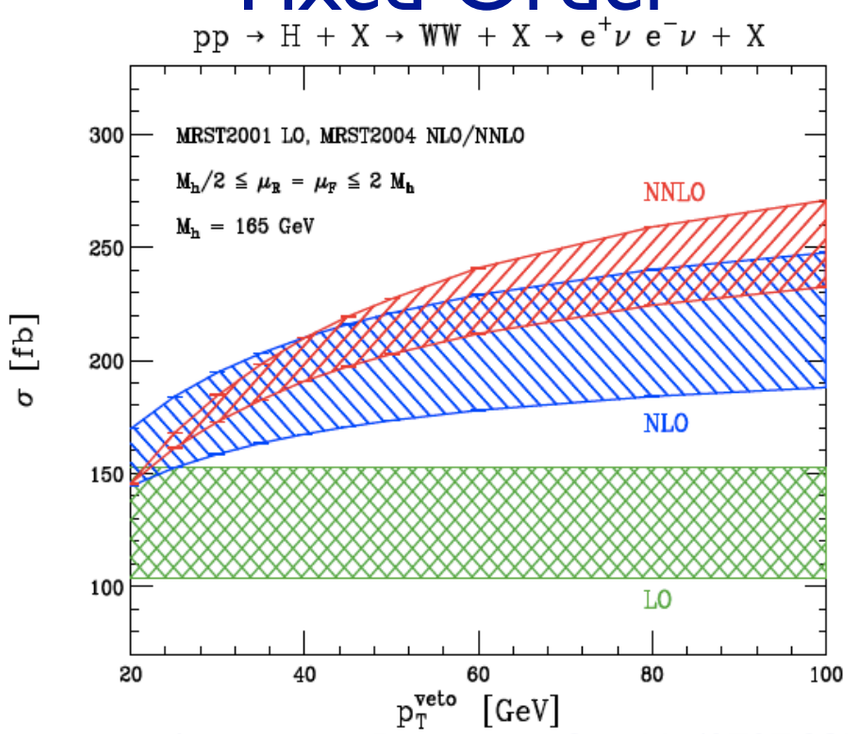
Transition Region:
Phenomenologically important

Need a consistent description of entire region.

Resummation and Fixed Order

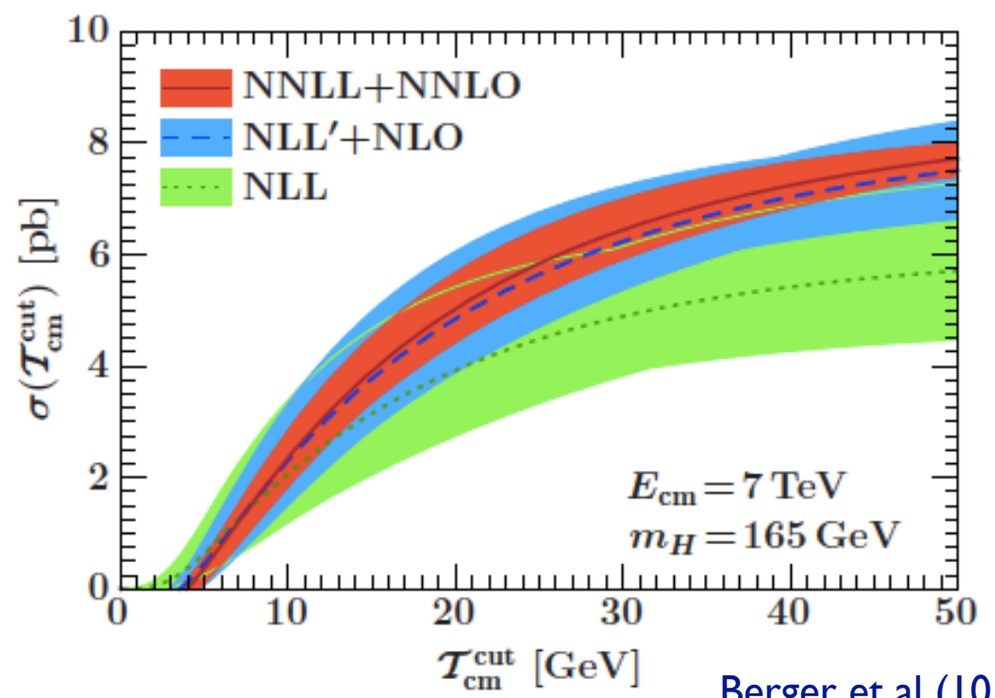
- Resummation + Fixed order reduces scale uncertainty & improves convergence.

Fixed Order



Anastasiou, Dissertori, Stockli (0707.2373)

Resummed+Fixed Order



Berger et al (1012.4480)

Current Status of Jet Veto Resummation

$$L \equiv \ln \frac{p_T^{\rm cut}}{m_H}$$

$$\begin{aligned}
\sigma(p_T^{\rm cut}) \quad &\sim \quad 1 \\
&+ \quad \alpha_s L^2 + \alpha_s L \; + \alpha_s \quad \textbf{NLO} \\
&+ \quad \alpha_s^2 L^4 + \alpha_s^2 L^3 + \alpha_s^2 L^2 + \alpha_s^2 L \; + \alpha_s^2 \quad \textbf{NNLO} \\
&+ \quad \alpha_s^3 L^6 + \alpha_s^3 L^5 + \alpha_s^3 L^4 + \alpha_s^3 L^3 + \alpha_s^3 L^2 + \cdots \\
&\qquad \textbf{LL} \qquad \textbf{NLL} \qquad \textbf{NNLL}
\end{aligned}$$

- MC@NLO/POWHEG : LL + NLO
  Atlas: POWHEG re-weighted to Higgs p_T spectrum NNLL+NNLO Bozzi et al (0508068)

Current Status of Jet Veto Resummation

$$L \equiv \ln \frac{p_T^{\rm cut}}{m_H}$$

$$\begin{aligned}
\sigma_2(p_T^{\rm cut}) \quad &\sim \quad 1 \\
&+ \quad \alpha_s L^2 + \alpha_s L \; + \alpha_s \quad \textbf{NLO} \\
&+ \quad \alpha_s^2 L^4 + \alpha_s^2 L^3 + \alpha_s^2 L^2 + \alpha_s^2 L \; + \alpha_s^2 \quad \textbf{NNLO} \\
&+ \quad \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 \\
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- NNLO Anastasiou, Melnikov, Petriello (0501130)
- NLL+NNLO Banfi, Salam, Zanderighi (1203.5773)
- NNLL+NNLO Banfi et al. (1206.4998), $\delta\sigma_0 \sim 11\%$
  Becher, Neubert (1205.3806v2),
- Extension to H+1 jet NLL resummation

Liu, Petriello (1210.1906)

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  Becher, Neubert (1205.3806v2),
  Stewart, Tackmann, Walsh, SZ (on going)
- Extension to H+1 jet NLL resummation

  Liu, Petriello (1210.1906)

Sources of uncertainties:
Resummation scale variation.
Combining resummed and fixed order.
Higher order jet algorithm effects.

Why Jet Vetoes are Complicated

- Logs are a remnant of soft and collinear divergences. Their structure is determined by

$$\sigma(p_T^{\rm cut}) = \int d\Phi\, \mathcal{A}(\Phi)\, \mathcal{M}\big(p_T^{\rm cut}, \Phi\big)$$

  - Amplitude universal structure in soft and collinear limit.
  - Phase space depends on the way the veto is implemented
    To resum $\alpha_s^n L^m$ need to know structure for *many emissions*

Inclusive vs. Jet Veto

Inclusive Veto

$$E_T = \sum_m |\vec{p}_{Tm}| < p_T^{\rm cut}$$

- Constraint same for **each** particle in final state, independent of α_s
- All orders form simple

$$\widetilde{\mathcal{M}}(x,\Phi) = \prod_i \widetilde{\mathcal{M}}^{(1)}(x,p_i)$$

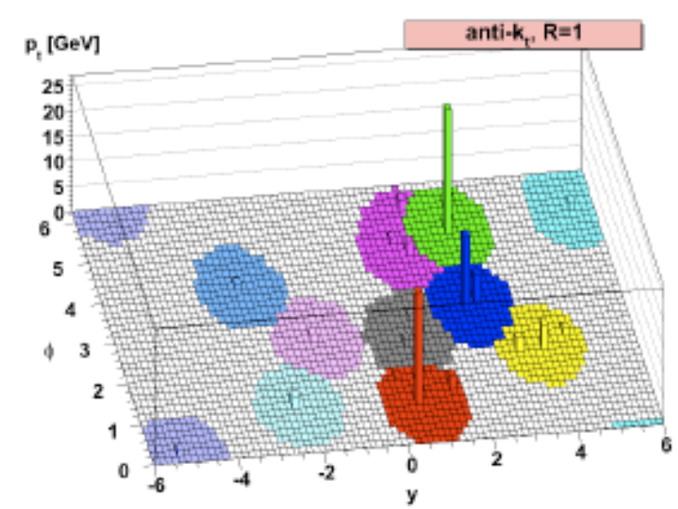
Product of constraint on *single* particle.

Eg. N-jettiness Stewart et al (1004.2489)
Higgs p_T NNLL+NLO resummation
Bozzi et al (0302104)

Jet Veto

$$p_{T\rm jet} = \sum_{m\in\rm jet} |\vec{p}_{Tm}| < p_T^{\rm cut}$$

- Constraint depends on **all** particles in the final state. Changes at each α_s
- All orders form complicated

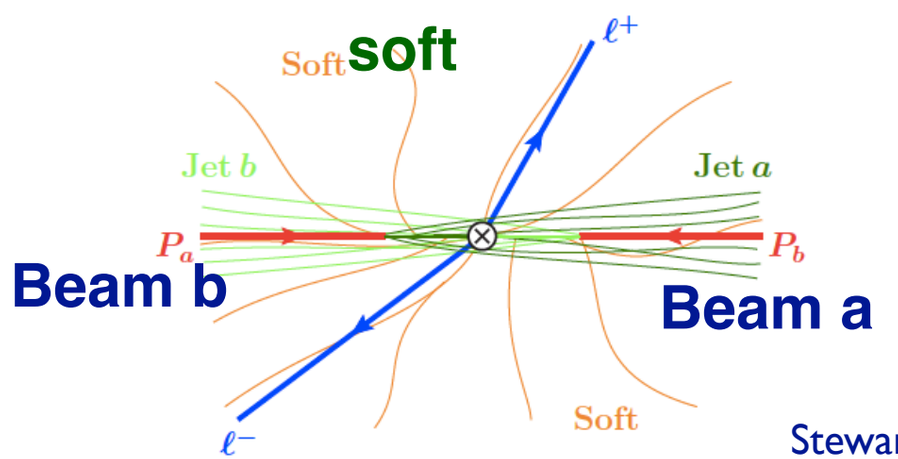


Cacciari, Salam, Soyez (0802.1189)

Factorization

- Start from well-controlled theory limit.
  Factorization:

$$\sigma(p_T^{\rm cut}) \sim H_{gg}(\mu)[B_a(\mu,\nu) \times B_b(\mu,\nu) \times S(\mu,\nu)] + \sigma_{ns}$$



Stewart, Tackmann, Waalewijn (2010)

- Factorization is an all-orders statement (α_s and α_s Ln p_T^{cut}/m_H)

  Systematically improvable way to combine resummation with full fixed order dependence.

Factorization in 3 Steps

1. Match to SCET

$$\lambda \sim \frac{p_T^{\rm cut}}{m_H} \ll 1 \qquad p \sim (p^+, p^-, p_\perp)$$

$$\sigma(p_T^{\rm cut}) \sim H(\mu) \langle \mathcal{O}_{ggH}(\mu)^\dagger \widehat{\mathcal{M}}^{\rm jet}\, \mathcal{O}_{ggH}(\mu) \rangle$$

collinear beam $\quad p_c \sim m_H(1, \lambda^2, \lambda)$

isotropic soft $\quad p_s \sim m_H(\lambda, \lambda, \lambda)$

2. Universal soft-collinear limit of amplitudes in QCD

$$\mathcal{O}_{ggH} \to H \mathcal{O}_a \mathcal{O}_b \mathcal{O}_s$$

Bauer, Pirjol, Stewart (1203.5773)

3. All-orders structure of jet veto

$$\widehat{\mathcal{M}}^{\rm jet} \to \widehat{\mathcal{M}}_a^{\rm jet} \times \widehat{\mathcal{M}}_b^{\rm jet} \times \widehat{\mathcal{M}}_s^{\rm jet} + \underline{\delta \widehat{\mathcal{M}}}$$

Soft-collinear mixing:
Must be suppressed in λ

$$\sigma(p_T^{\rm cut}) \sim H_{gg}(\mu) [B_a(\mu,\nu) \times B_b(\mu,\nu) \times S(\mu,\nu)] + \sigma_{ns}$$

Now understand algorithm effects

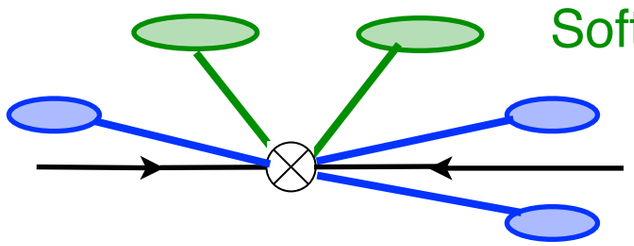
Jet Algorithm Effects

Tackmann, Walsh, SZ (1206.4312)

- Highly non-trivial

$$\widehat{\mathcal{M}}^{\rm jet} \to \widehat{\mathcal{M}}^{\rm jet}_a \times \widehat{\mathcal{M}}^{\rm jet}_b \times \widehat{\mathcal{M}}^{\rm jet}_s + \cancel{\delta\widehat{\mathcal{M}}}$$

$$p \sim (p^+, p^-, p_\perp)$$
$$p_c \sim m_H(1, \lambda^2, \lambda)$$
$$p_s \sim m_H(\lambda, \lambda, \lambda)$$
$$\lambda \sim \frac{p_T^{\rm cut}}{m_H} \ll 1$$



Soft central jets

Forward collinear jets

$$p_{T\,\rm jet} < p_T^{\rm cut}$$

Two sources of algorithm effects:

- Clustering **between** the soft and beam sectors $\delta\widehat{\mathcal{M}}$

  $R \gg p_T^{cut}/m_H \quad \sigma \supset \alpha_s^n R^2$

  Soft-collinear mixing.

- Clustering **within** the soft and beam sectors $\widehat{\mathcal{M}}^{\rm jet}_{a,b}$ $\widehat{\mathcal{M}}^{\rm jet}_s$

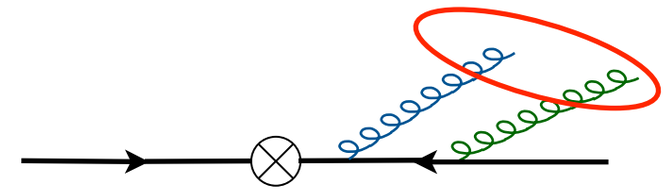
  $R \sim p_T^{cut}/m_H \quad \sigma \supset \alpha_s^n \ln^{n-1} R$

  Clustering logarithms.

*analysis applies to H+N jets

Soft Collinear Mixing

$$\widehat{\mathcal{M}}^{\rm jet} \to \widehat{\mathcal{M}}_a^{\rm jet} \times \widehat{\mathcal{M}}_b^{\rm jet} \times \widehat{\mathcal{M}}_s^{\rm jet} + \delta\widehat{\mathcal{M}}$$



$$|\vec{p}_{Tc} + \vec{p}_{Ts}| < p_T^{\rm cut}$$

$$\delta\sigma_{SC} = -\sigma_{LO}\left(\frac{\alpha_s C_A}{\pi}\right)^2 \frac{2\pi^2}{3} R^2 \ln\frac{m_H}{p_T^{\rm cut}}$$

For R » p_T^{cut}/m_H NNLL

Tackmann, Walsh, SZ (1206.4312)

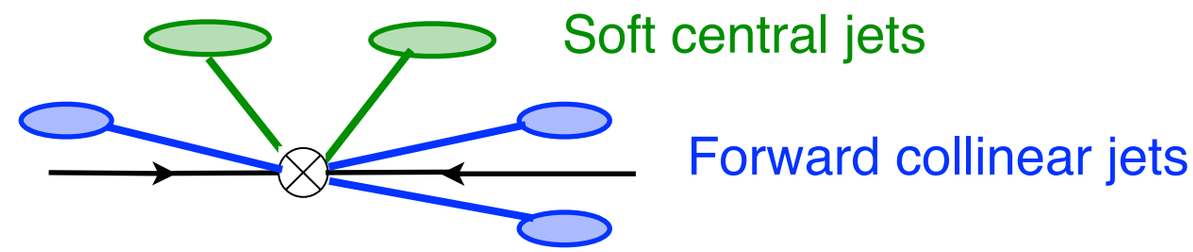
- Violates standard factorization.
- Effect understood to NNLL Banfi, Salam, Zanderighi (1203.5773).
  Include through non-singular terms.

$$\sigma(p_T^{\rm cut}) \sim H_{gg}(\mu)\left[B_a(\mu,\nu)\times B_b(\mu,\nu)\times S(\mu,\nu)\right]\left[1+\delta\sigma_{SC}^{(2)}\right]$$ to NNLL

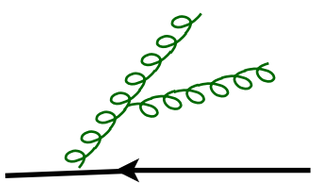
- Phenomenologically not important.

Clustering Logs

$$\widehat{\mathcal{M}}^{\rm jet} \to \widehat{\mathcal{M}}_a^{\rm jet} \times \widehat{\mathcal{M}}_b^{\rm jet} \times \widehat{\mathcal{M}}_s^{\rm jet} + \delta\widehat{\mathcal{M}}$$



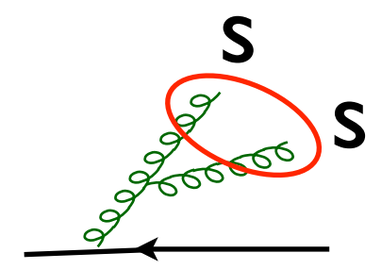
- Useful to consider $\mathcal{M}_s^{\rm jet} = \mathcal{M}_s + \Delta\mathcal{M}_s^{\rm jet}$



Independent of algorithm

$$\theta(p_{T_1} < p_T^{\rm cut})\,\theta(p_{T_2} < p_T^{\rm cut})$$

Clustering Effect



$$\theta(\Delta R_{12} < R)\left[\theta(|\vec{p}_{T_1} + \vec{p}_{T_2}| < p_T^{\rm cut)} - \theta(p_{T_1} < p_T^{\rm cut})\,\theta(p_{T_2} < p_T^{\rm cut})\right]$$

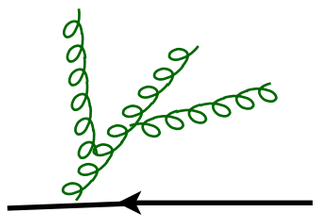
- Clustering log remnant of collinear divergence

$$\frac{1}{\epsilon} \quad - \quad \frac{1}{\epsilon}R^{-2\epsilon} \sim \ln R$$

What is higher order structure?
Not constrained by factorization

Clustering Logarithms

- For ***n*** final state particles there are at most ***n-1*** collinear divergences



General form of clustering logs:

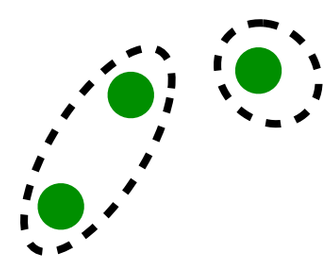
$$\sigma_{LO}\, \alpha_s^n \ln^{n-1} R \ln \frac{m_H}{p_T^{\rm cut}} + \mathcal{O}(R^2)$$

For $R \sim p_T^{cut}/m_H$ NLL effect

- Show using non-abelian exponentiation and collinear singularities in sub-amplitudes

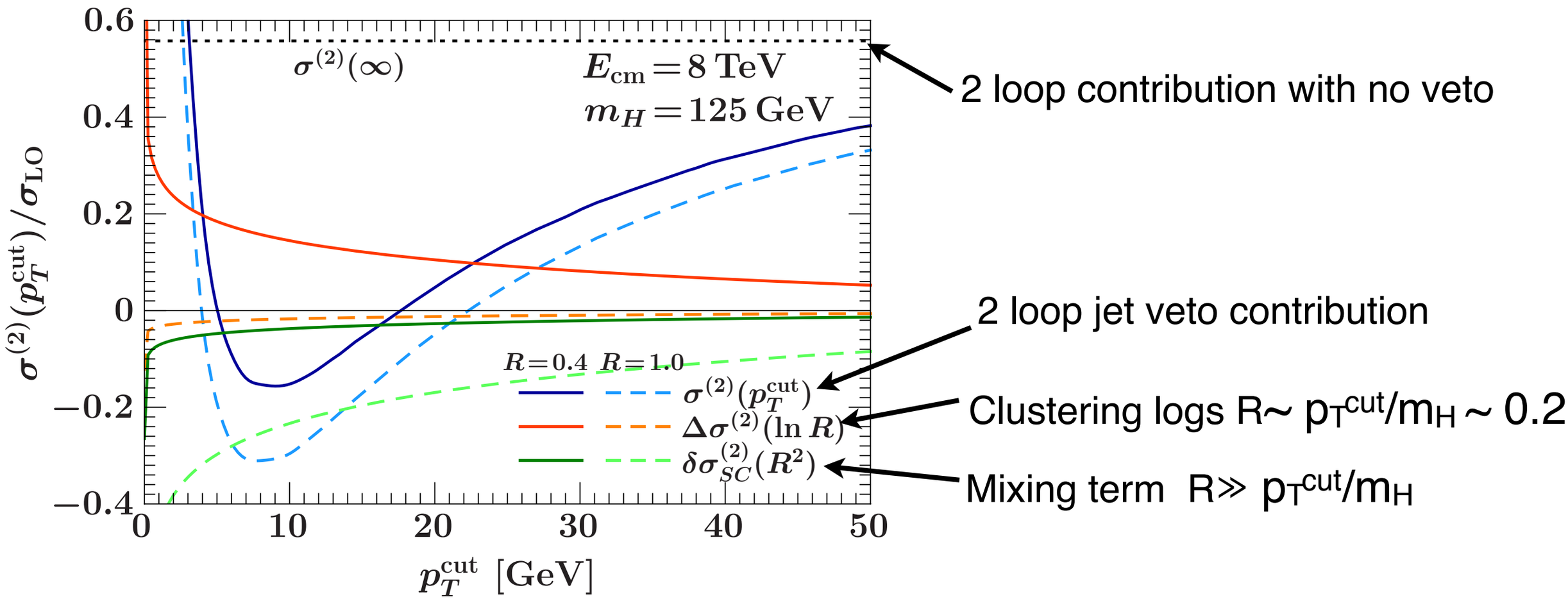
$$\exp\left[\sum_n c_n \alpha_s^n \ln \frac{m_H}{p_T^{\rm cut}} \ln^{n-1} R\right]$$

- Although ln R is exponentiated, the series is not resummed
  In general new coefficient to be calculated at each order in α_s



Numerical Relevance

Tackmann, Walsh, SZ (1206.4312)

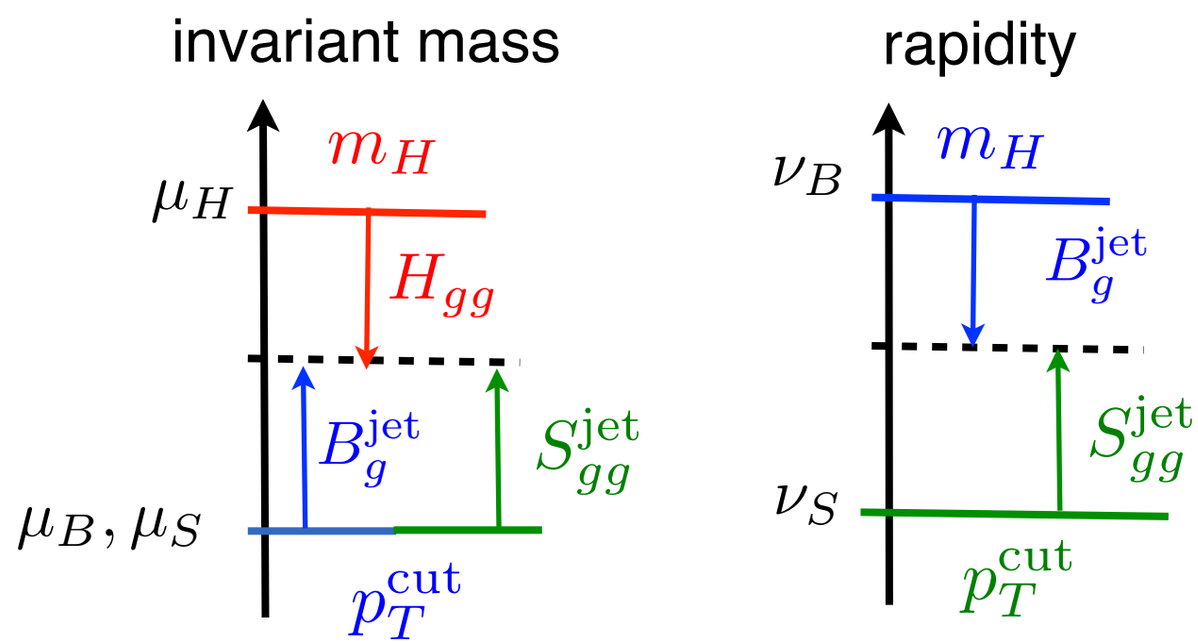


- Algorithm effects are significant fraction of ln m_H/p_T^{cut} contribution at 2 loops
- Important to include clustering effect in uncertainty estimates.

Resummation and Scale Variation

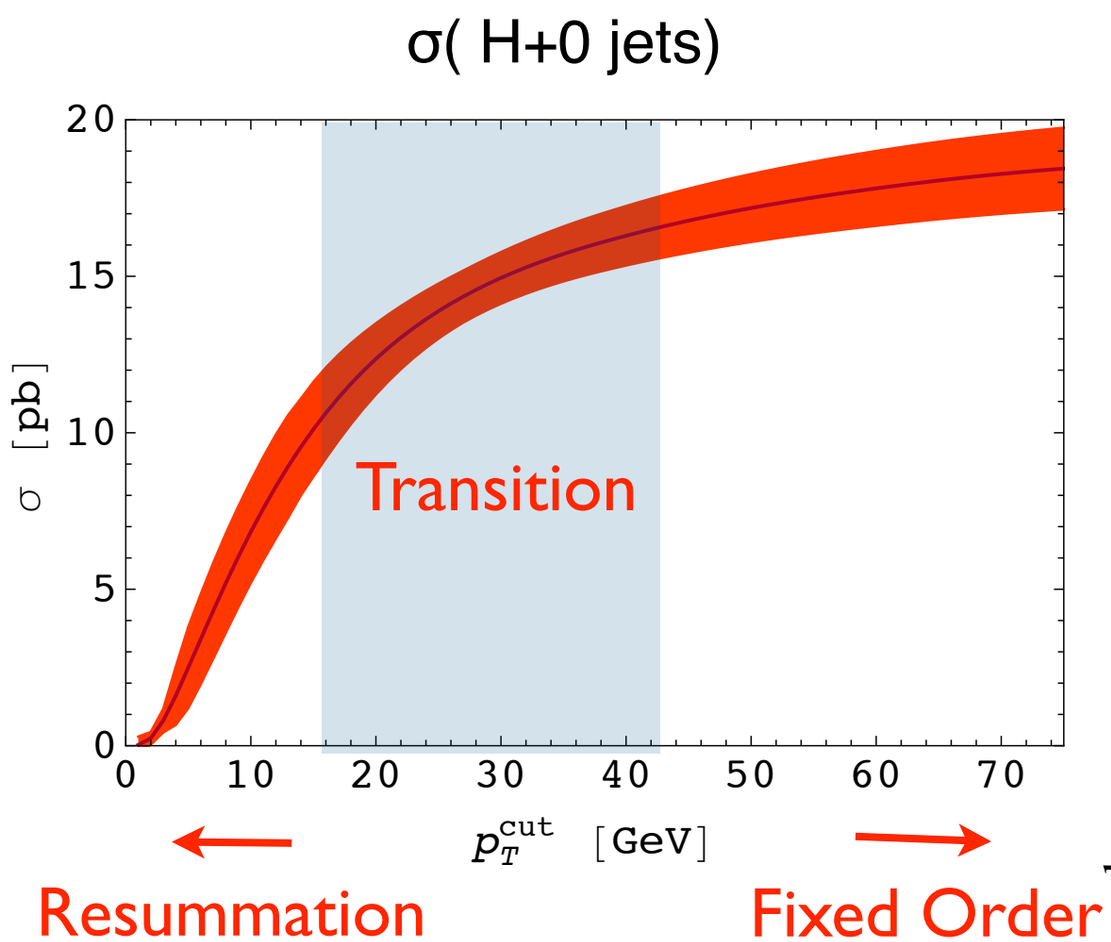
$$\sigma(p_T^{\rm cut}) \sim H_{gg}(\mu)[B_a(\mu,\nu) \times B_b(\mu,\nu) \times S(\mu,\nu)] + \sigma_{ns}(\mu)$$

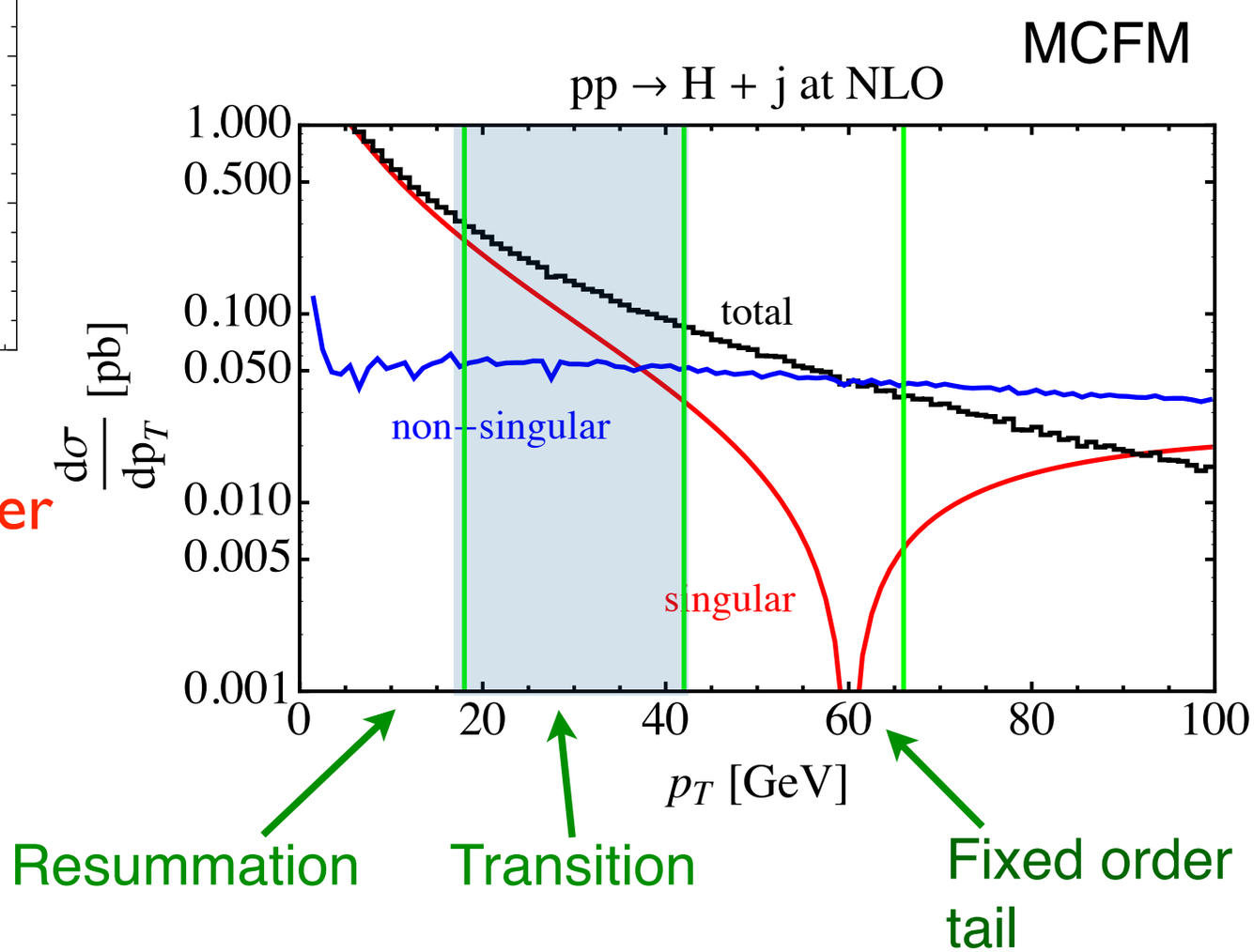
- Factorization separates scales. RG evolve to resum ratio (μ_H, μ_B, μ_S) (ν_B,ν_S) ≡ ln p_T^{cut}/m_H



- Perturbative uncertainties generated by varying scales (μ_H, μ_B, μ_S, ν_B,ν_S)
- Setting low scales (μ_B, μ_S,ν_S) equal to hard scales (μ_H,ν_B) turns off resummation.

Combing Resummation and Fixed Order

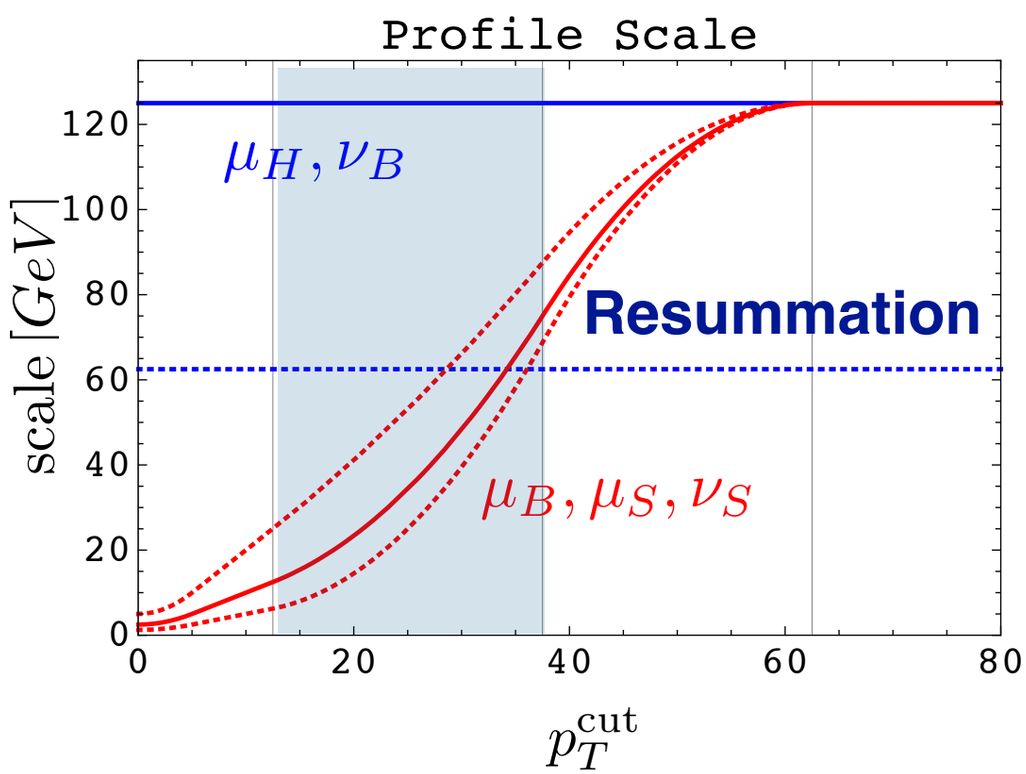




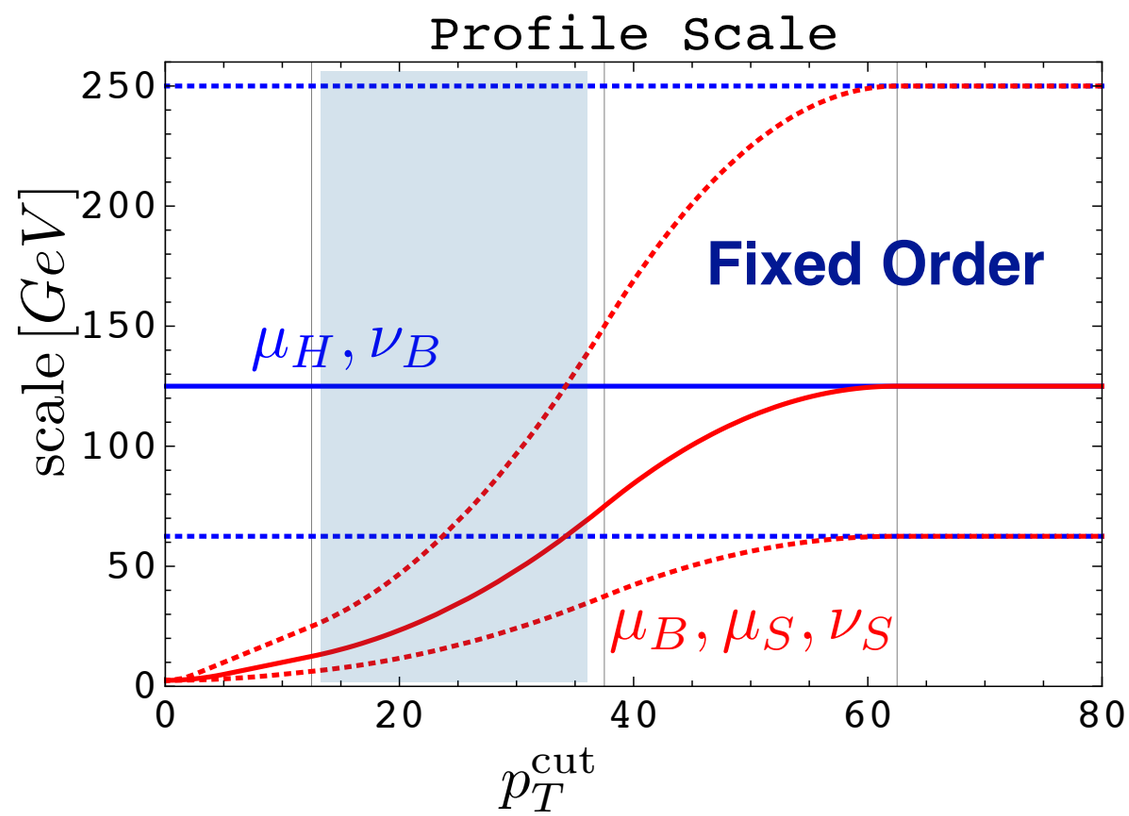
Turn off resummation well below m_H

Combining Scale Uncertainties

- Profile scales control scale variation and how resummation is turned off



Find envelope of **all** low scale variation



High scale (2 m_H,m_H/2) gives fixed order variation

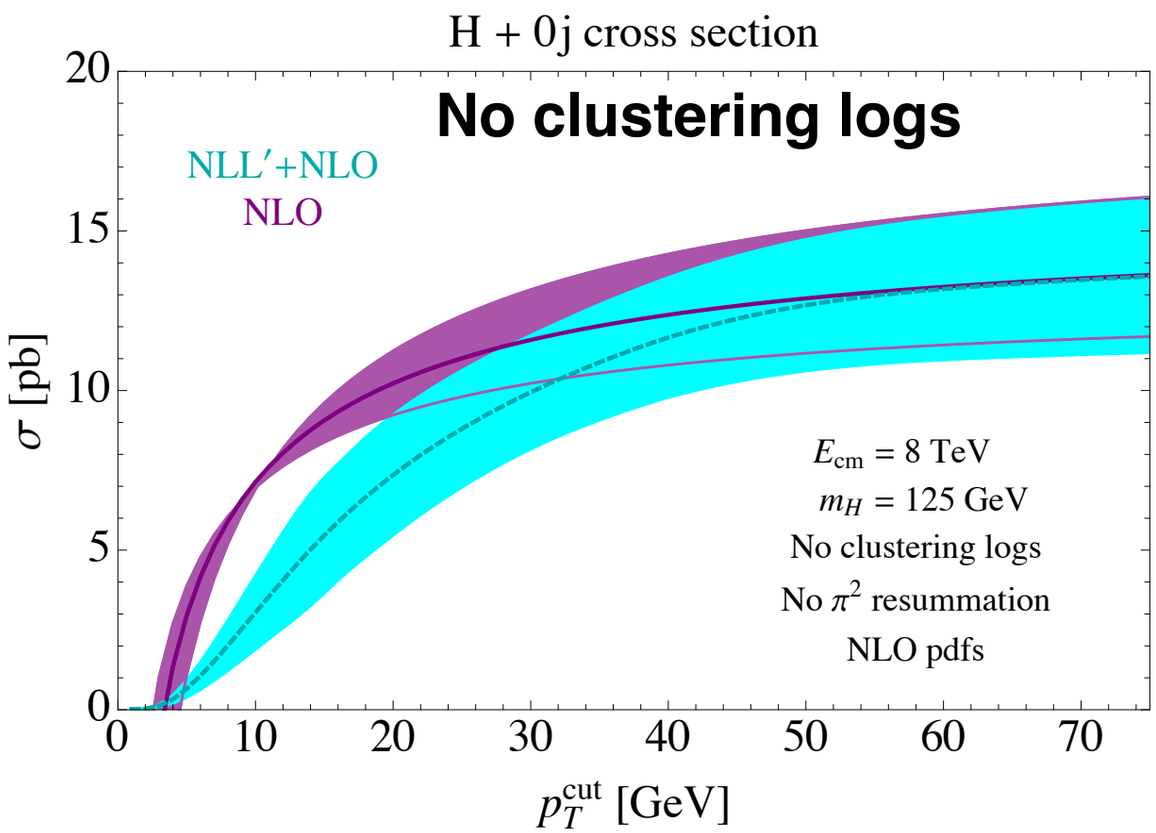
- Combine resummation and fixed order scale uncertainty in quadrature

Stewart, Tackmann (1107.2117)

$$\Delta^2 = \Delta^2_{\rm resum} + \Delta^2_{\rm FO}$$

Resummation with Jet Veto

Preliminary



Resummation with Jet Veto

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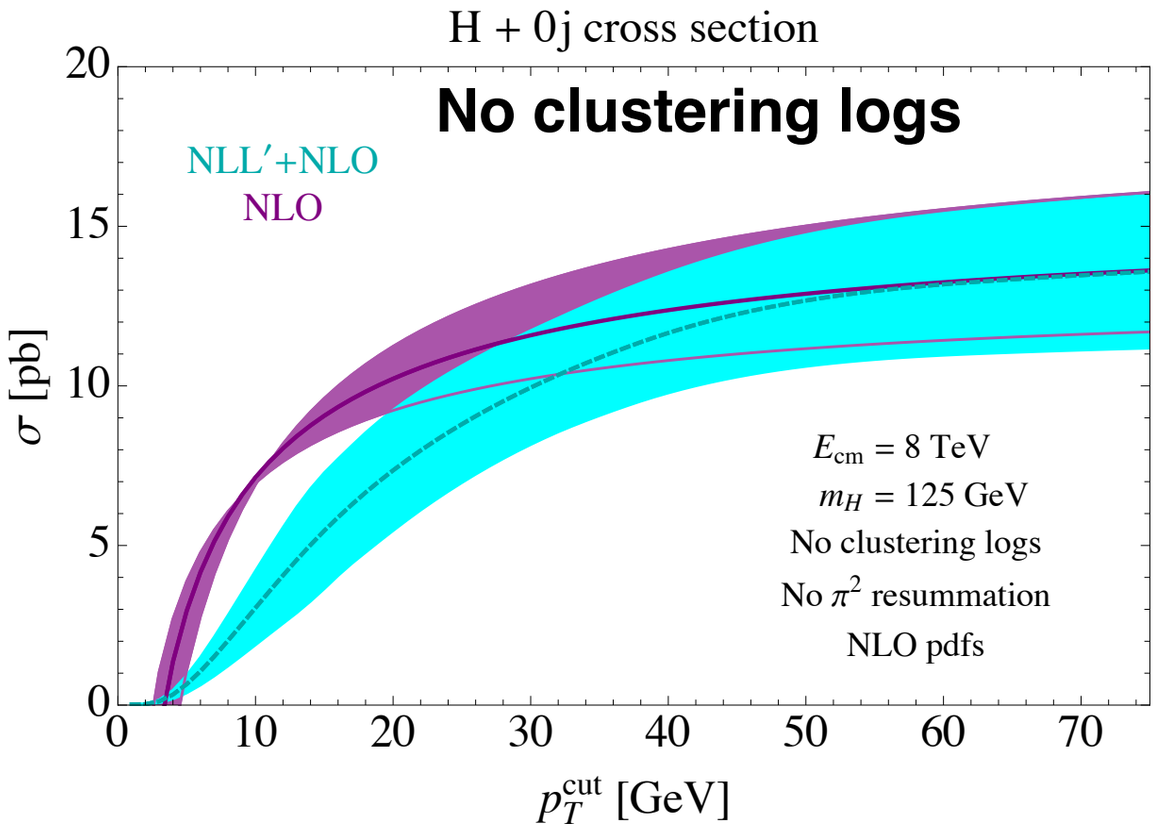

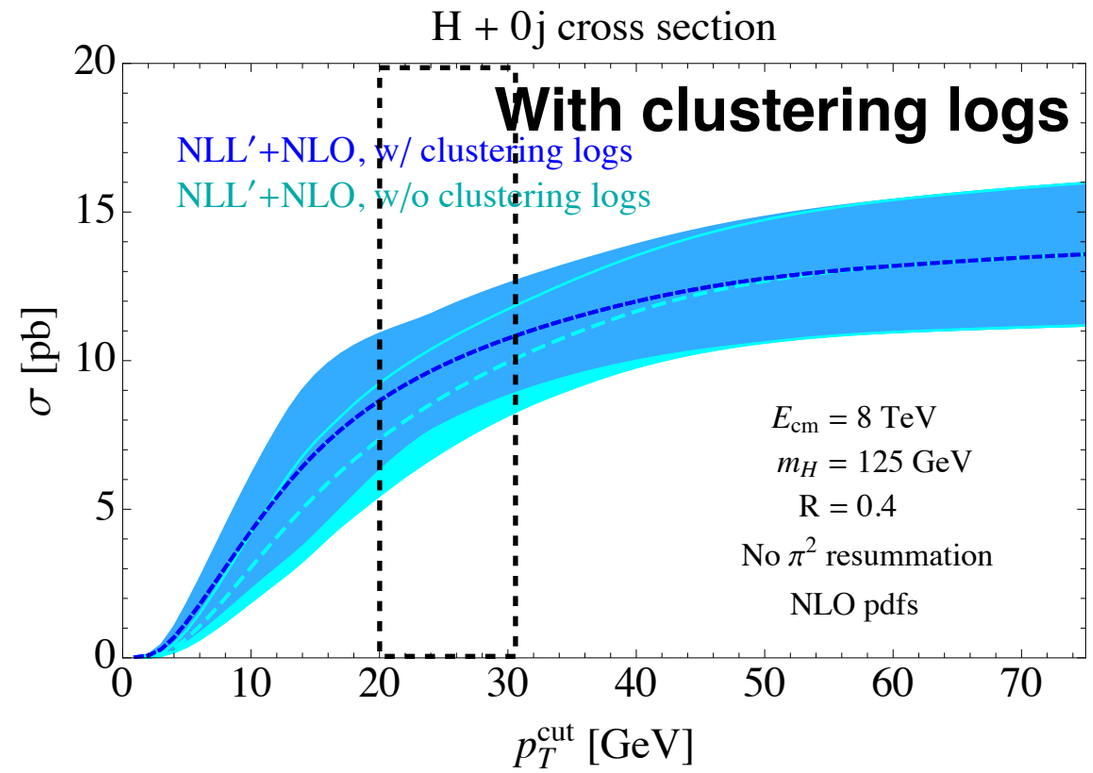

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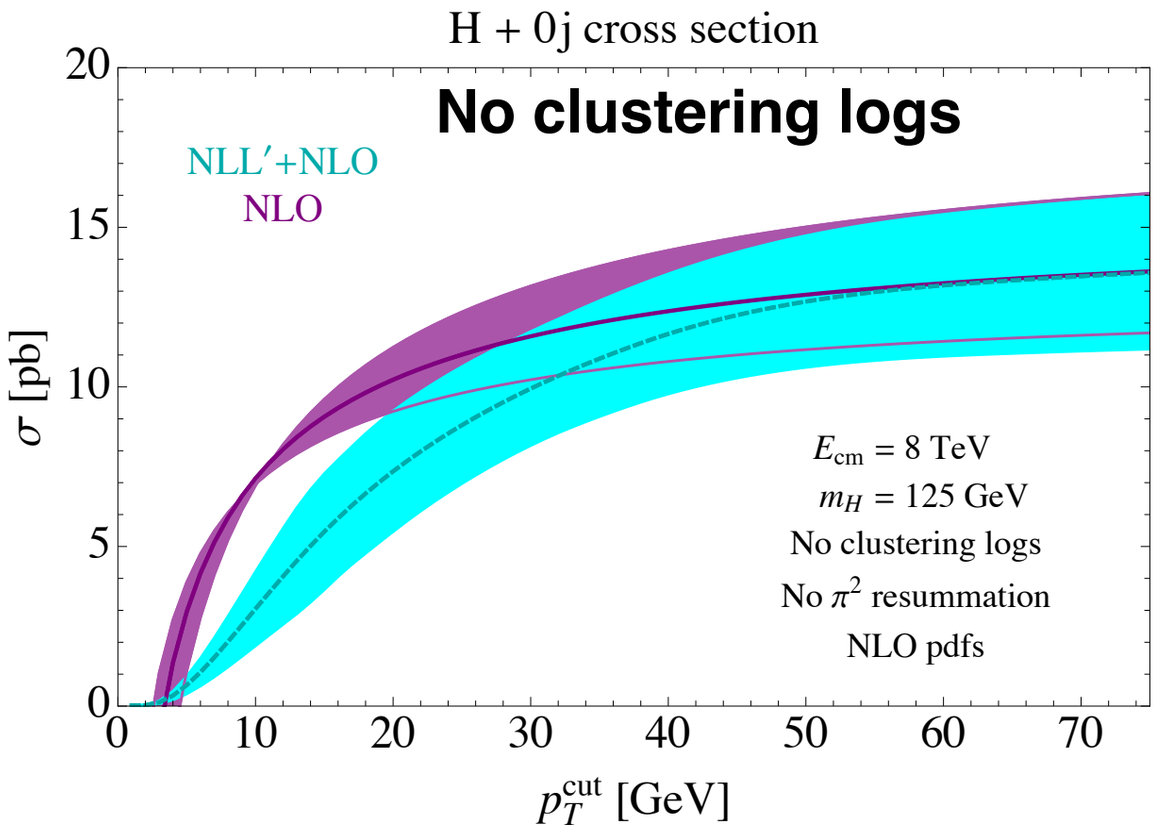

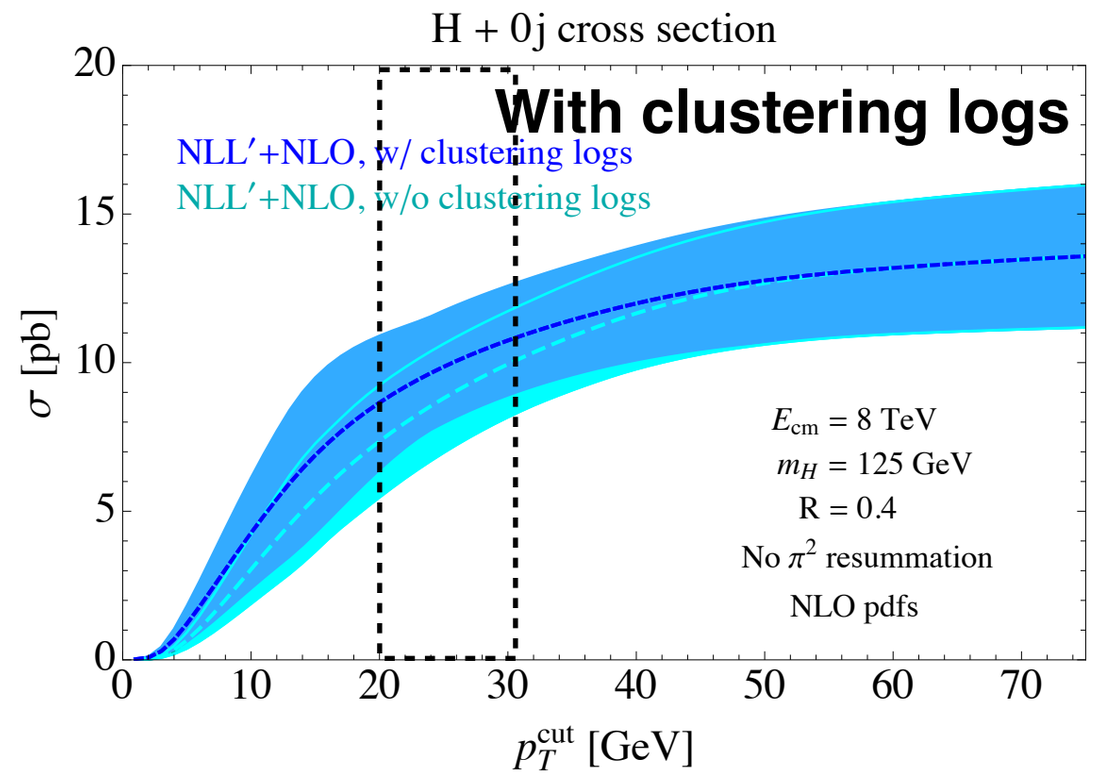

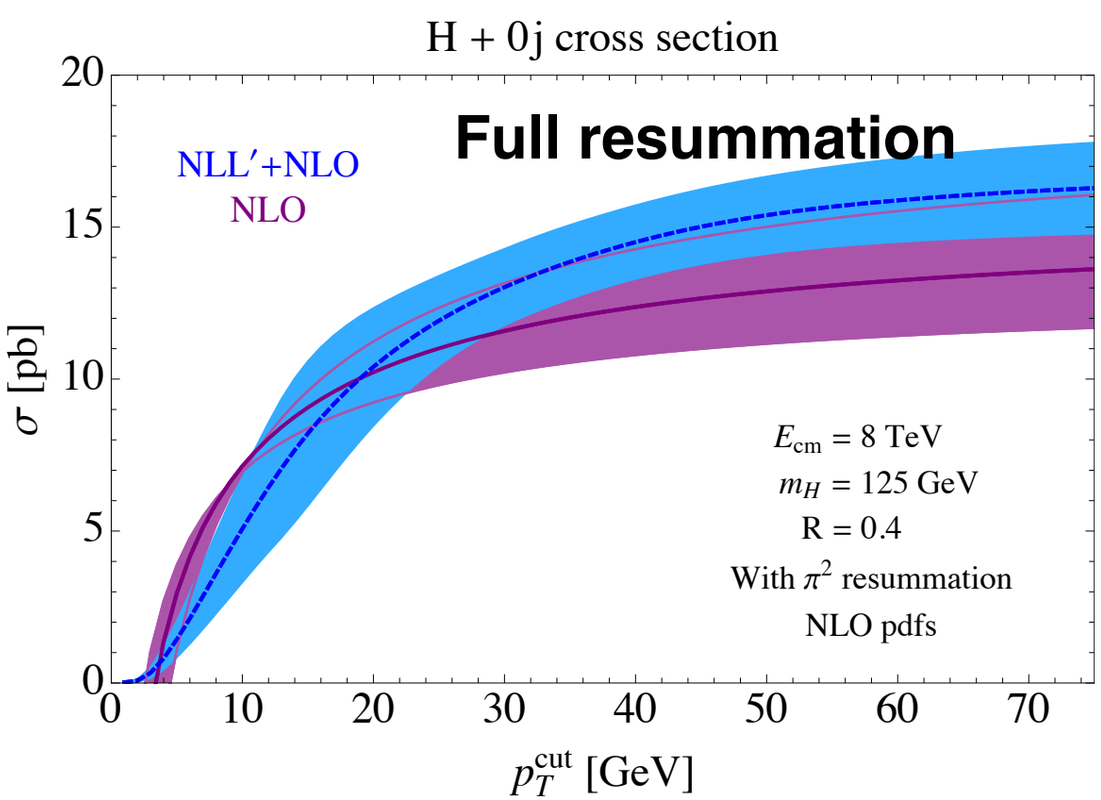

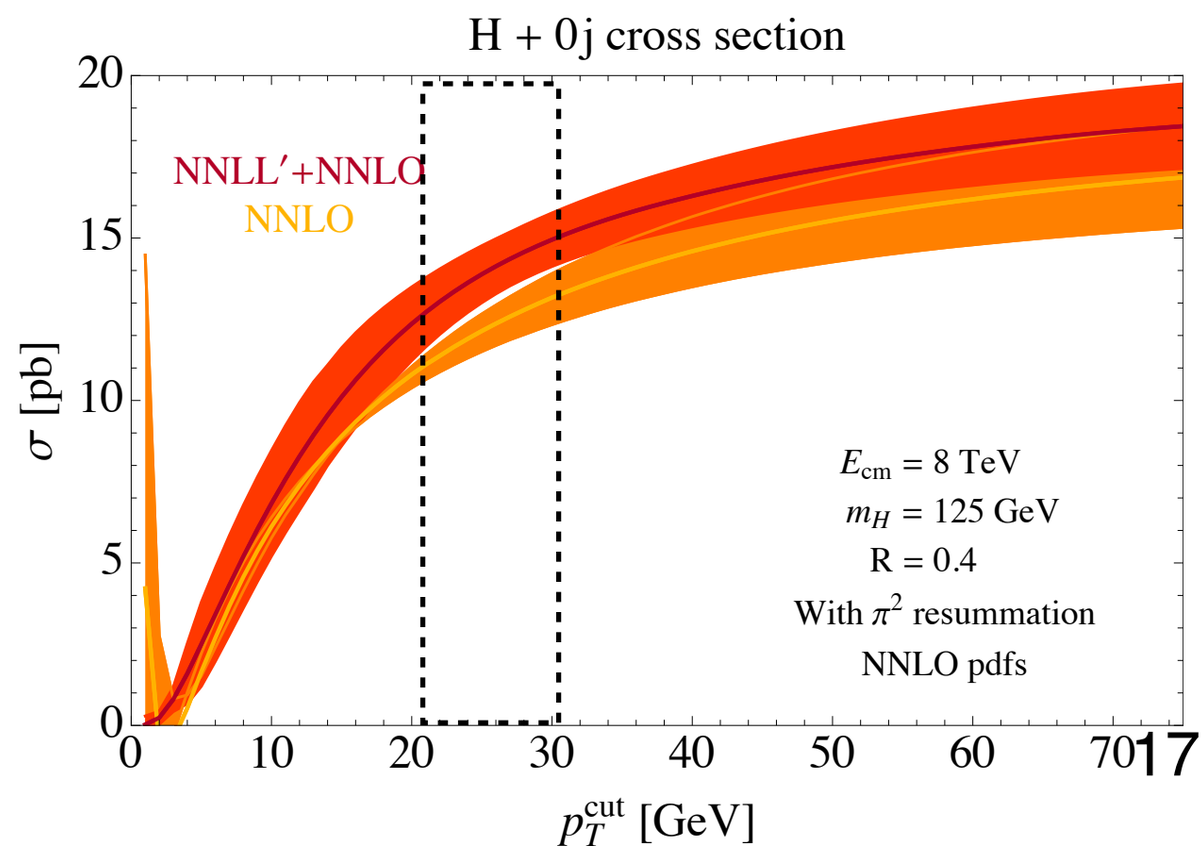

Resummation with Jet Veto

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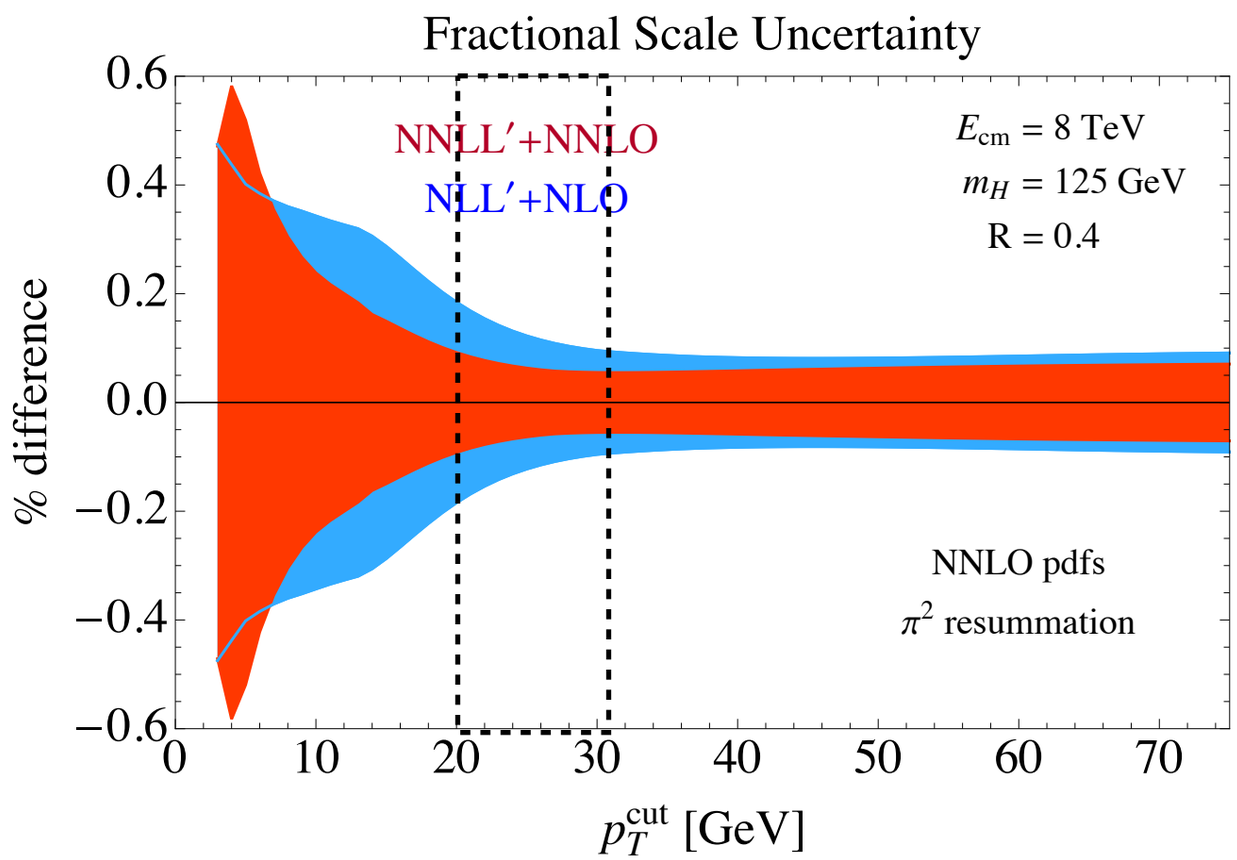


Outlook

- There are *formally* two competing effects make cross sections with a jet vetoes challenging
  - Clustering logarithms $\ln R$ NLL $R \sim p_T^{cut}/m_H$
  - Soft-collinear mixing R^2 NNLL $R \gg p_T^{cut}/m_H$

- Clustering logarithms appear to be phenomenologically relevant.
  Large effect at α_s^2.

  Next step include uncertainties from this effect.
  Size of clustering logs at α_s^3 $\ln^2 R \ln p_T^{cut}/m_H$ very useful.

- Control of scale variation that generates perturbative uncertainties allows combination of resummation and fixed order regions.

  Important: life happens in between!

Additional Slides

Higher Order Structure of Clustering Logs

- Soft function at α_s $$S^{(n)}(p_T^{\rm cut}) = \int d\Phi_n \, \mathcal{A}_n(\Phi_n) \, \mathcal{M}_n(\Phi_n, p_T^{\rm cut})$$

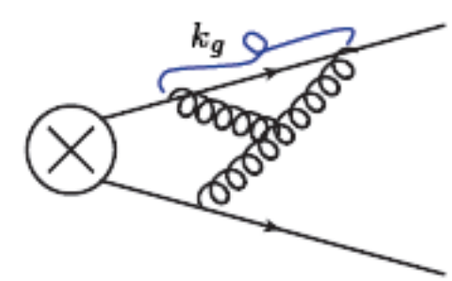
- Non-Abelian exponentiation: eikonal matrix elements exponentiate and can be factorized in to c-webs

$$\mathcal{A}_n(\Phi_n) = \sum_W N_W \left[\prod_{w \in W} \mathcal{A}_w(\Phi_{n_w}) \right]$$

c-web: diagram connecting eikonal lines that cannot be separated into lower order c-webs by cutting two eikonal lines

- Collinear singularities only between final state particles in the same c-web. Clustering between c-webs suppressed

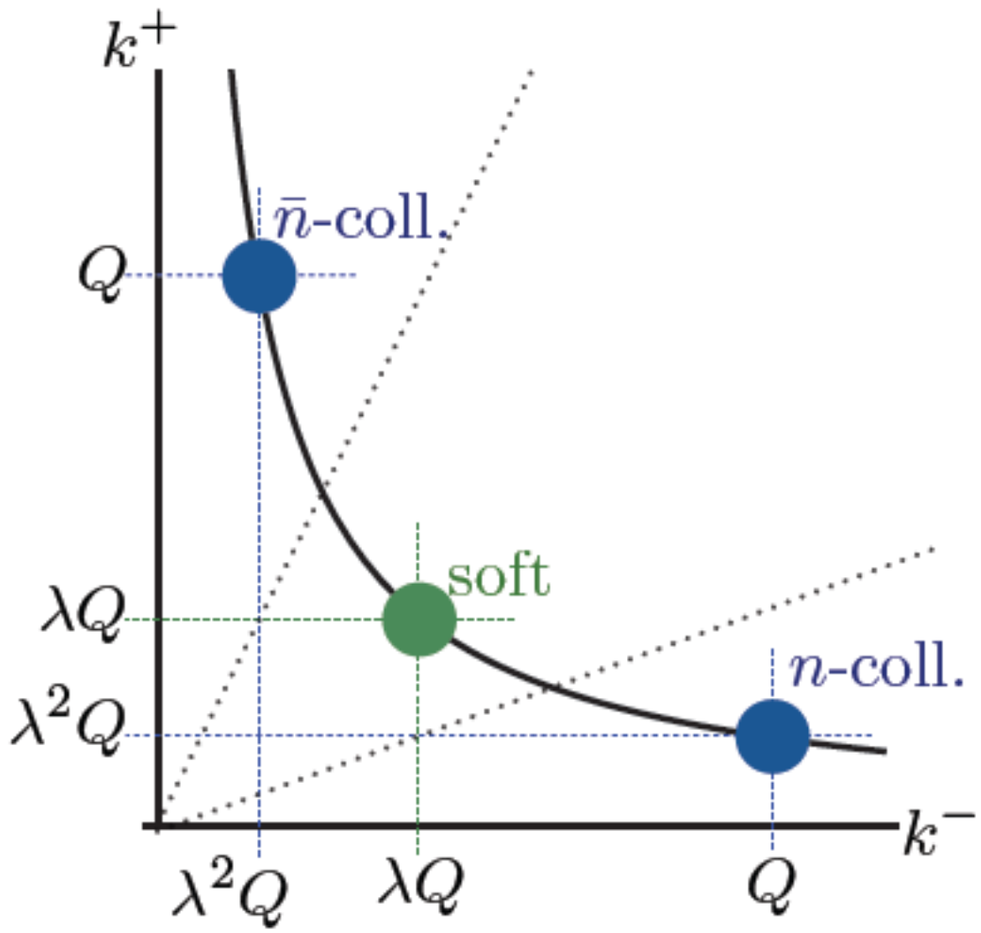
$$\mathcal{M}_n(\Phi_n, p_T^{\rm cut}) = \prod_{w \in W} \mathcal{M}_{n_w}(\Phi_{n_w}) + \mathcal{O}(R^2)$$



- So $$S(p_T^{\rm cut}) = \exp\left[\sum_{\text{c-webs } w} \int d\Phi_{n_w} \mathcal{A}_{n_w}(\Phi_{n_w}) \mathcal{M}_{n_w}(\Phi_{n_w}, p_T^{\rm cut}) \right]$$

- Collinear singularity: clustering log (ln R) $$\exp\left[\sum_{\rm c-webs\, w} \alpha_s^{n_w} \ln \frac{\nu}{p_T^{\rm cut}} \ln^{n_w - 1} R \right]$$

Saba Zuberi, LBL



$$p \sim (p^+, p^-, p_\perp)$$
$$p_c \sim m_H(1, \lambda^2, \lambda)$$
$$p_s \sim m_H(\lambda, \lambda, \lambda)$$