Vector boson production in joint resummation

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Introduction

- Electro-weak boson distributions reached percent level uncertainty
  [ATLAS, CMS, LHCb, 15]

- Fixed order computed at NNLO accuracy
  [Gehrmann-De-Ridder, Gehrmann, Glover, Huss, Morgan '15]
  [Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello, '15]

- Differential → Additional scales → Different types of logarithms

- Threshold resummation improved precision and small q_T logarithms

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Joint threshold and Q_T resummation

- Original formalism for joint q_T and threshold
  [Laenen, Sterman, Vogelsang, '00]

- Applied at NLL to prompt photon *[Laenen, Sterman, Vogelsang, '00]*, Higgs and DY *[Kulesza, Sterman, Vogelsang, '02,'03]*, top *[Banfi, Laenen, '05]*, EW SUSY *[Fuks et al., '13]*

- Recent resurgence *[Li, Neill, Zhu, '16]*
  [Lustermans, Waalewijn, Zuene, '16][Forte, Muselli, Ridolfi, '17]

- Parton shower with threshold resummation *[Nagy, Soper, '16]*

- This talk → extension to NNLL *[Marzani, VT, '16]*

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Definition of Threshold

Threshold variable $\hat{\tau} = \frac{Q^2}{\hat{s}}$

Q^2: the invariant mass final state particles

$$1 - \hat{\tau} = 1 - \frac{Q^2}{\hat{s}}$$

$$\sim \frac{\text{energy of the emitted gluons}}{\text{total available energy}}$$

The IR divergences lead to logarithms:

$$(1-\hat{\tau})^{-1-2\epsilon} = -\frac{1}{2\epsilon}\delta(1-\hat{\tau}) + \left(\frac{1}{1-\hat{\tau}}\right)_+ - 2\epsilon\left(\frac{\log(1-\hat{\tau})}{1-\hat{\tau}}\right)_+$$

$$\boxed{\alpha_s^n \left(\frac{\log^m(1-\hat{\tau})}{1-\hat{\tau}}\right)_+}$$

$\log^n(1-\hat{\tau}) \Rightarrow \log^n N$ and threshold $\hat{\tau} \to 1 \sim N \to \infty$

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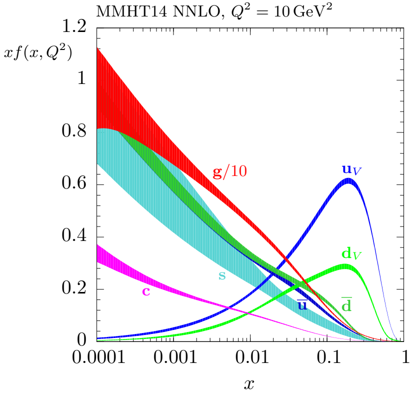
Motivation for threshold resummation

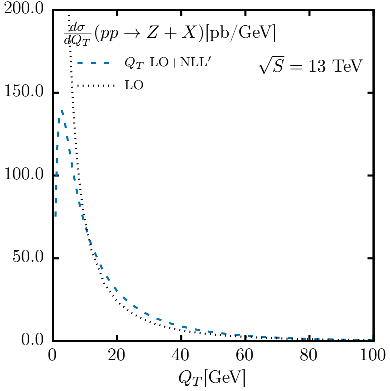
- Not close to hadronic absolute threshold
- PDFs large in low x region
- Close to partonic absolute threshold
- Allows us to go beyond the current scope of fixed order



[Harland-Lang, Martin, Motylinski, Thorne , '14]

Q_T distribution

Q_T resummation needed for Q_T distributions in the small Q_T limit



Fourier transform: $\frac{\log^n(Q_T)}{Q_T} \Rightarrow \log^{n+1} b$ and threshold $Q_T \to 0 \sim b \to \infty$

NLL exponent

Generalizes to:

$$E_{ab}(b,N,Q,\mu_F) = \int_0^{Q^2} \frac{dk_T^2}{k_T^2} \left\{ \sum_{i=a,b} A_i(\alpha_s(k_T)) \left[J_0(bk_T) K_0\left(\frac{2Nk_T}{Q}\right) + \log\left(\frac{\bar{N}k_T}{Q}\right) \right] \right\}$$

$$- \log \bar{N} \int_{\mu_F^2}^{Q^2} \frac{dk_T^2}{k_T^2} \sum_{i=a,b} A_i(\alpha_s(k_T))$$

Approximates to:

$$E_{a\bar{a}}(\chi,N,Q,\mu_F) = 2\int_{Q^2/\chi^2}^{Q^2} \frac{dk_T^2}{k_T^2} A_a(\alpha_s(k_T)) \log\left(\frac{\bar{N}k_T}{Q}\right)$$

$$- 2\log \bar{N} \int_{\mu_F^2}^{Q^2} \frac{dk_T^2}{k_T^2} A_a(\alpha_s(k_T))$$

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Joint function χ

- χ reproduces threshold limit: $\lim_{N\to\infty}\chi(\bar{N},\bar{b}) = \bar{N}$
- χ reproduces q_T limit: $\lim_{b\to\infty}\chi(\bar{N},\bar{b}) = \bar{b} = Qbe^{\gamma_E}/2$
- Function determines power suppressed terms
- Contour needs to avoid poles and branch-cuts

Examples:

- $\chi = \bar{b} + \bar{N}$, simple pole and branch-cut structure, $\bar{N}/\bar{b}$ and $\bar{b}/\bar{N}$ power suppressed terms
- $\chi = \bar{b} + \frac{\bar{N}}{1+\bar{b}\eta/\bar{N}}$, $\eta > 0$, $(\bar{N}/\bar{b})^2$ and $\bar{b}/\bar{N}$ power suppressed terms, more complicated pole and branch-cut structure, angular restrictions for $\eta \neq 1/4$

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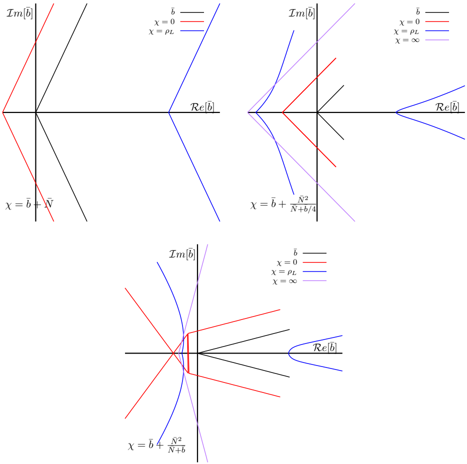
Contour



$\chi = 0$, $\chi = \exp[1/(2\alpha_s b_0)]$, $\chi = \infty$, $\bar{b}$

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Interlude: $\tilde{B}_N$

Usually $\tilde{C}(N, \alpha_s(Q/\chi))$

All hard contributions computed at the same scale (Q), can be described as:

$$\tilde{B}_N(\alpha_s) = B(\alpha_s) + 2\beta(\alpha_s)\frac{d\log C_N(\alpha_s)}{d\log\alpha_s} + 2\gamma(N, \alpha_s)$$

Hard contribution

Difference hard contribution threshold and q_T.

Can be computed based on eikonal integral

$$\Delta\mathcal{H}^{(1)} = A^{(1)}\left[2\log^2\bar{N} + \mathrm{Li}_2\left(-\frac{\bar{b}^2}{\bar{N}^2}\right) + \zeta_2 + 2\log^2\chi - 4\log\chi\log\bar{N}\right]$$

$$= A^{(1)}\left[\zeta_2 + \mathrm{Li}_2\left(-\frac{\bar{b}^2}{\bar{N}^2}\right) + 2\log^2(\chi/\bar{N})\right] \simeq A^{(1)}\left[\zeta_2 - \mathrm{Li}_2\left(\frac{\bar{b}^2}{\chi^2}\right)\right]$$

Changes C_{qq} affects $\tilde{B}$

$$\tilde{B}^{(2)} \to \tilde{B}^{(2)} - 2\beta_0\Delta\mathcal{H}^{(1)}$$

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Overview at NNLL

$$E_{\{I\}}(\alpha_s(\mu_R), b, N, Q^2/\mu_R^2, Q^2/\mu_F^2) =$$

$$-\int_{Q^2/\chi^2}^{Q^2} \frac{dq^2}{q^2}\left[A(\alpha_s(q))\log\frac{Q^2}{q^2} + \tilde{B}(N, b, \alpha_s(q)) + \frac{1}{2}\tilde{D}(\alpha_s(q))\right]$$

$$-\frac{1}{2}\log\left(\frac{\bar{N}^2}{\chi^2}\right)\tilde{D}\left(\alpha_s\left(\frac{Q}{\chi}\right)\right) + 2\int_{\mu_F^2}^{Q^2}\frac{dq^2}{q^2}\gamma_{\text{soft}}(N, \alpha_s(q)),$$

$$\tilde{B}(N, b, \alpha_s) = B(\alpha_s) + 2\beta(\alpha_s)\frac{d\log\tilde{C}(N, b, \alpha_s)}{d\log\alpha_s} + 2\gamma(N, \alpha_s).$$

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Orders of Resummation

Perturbation reordered in α_s and L:

$$\boxed{\tilde{\sigma} \sim \tilde{\sigma}_{LO} \times \mathcal{C}(\alpha_s) \exp[L g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \cdots]}$$

	$\Downarrow$	$\Downarrow$	$\Downarrow$
With orders of precision:	LL	NLL	NNLL
	$\Downarrow$	$\Downarrow$	$\Downarrow$
	$\alpha_s^n L^{n+1}$	$\alpha_s^n L^n$	$\alpha_s^{n+1} L^n$

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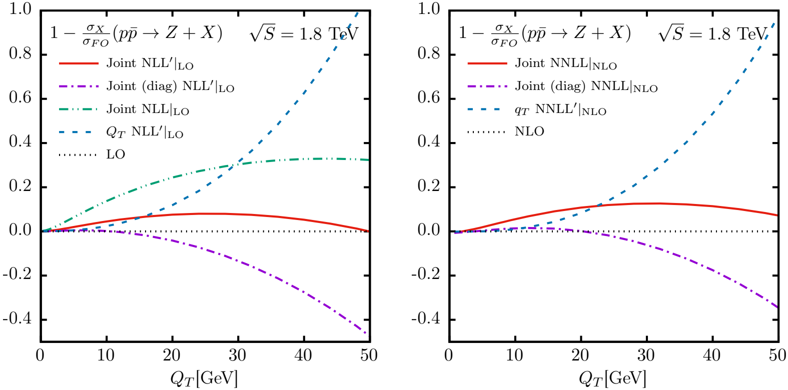
Results

[Marzani, VT, 1612.01432]

PDFs used: CT14



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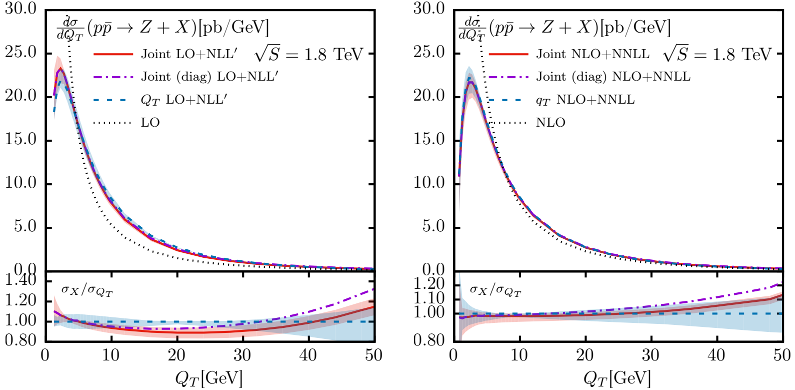

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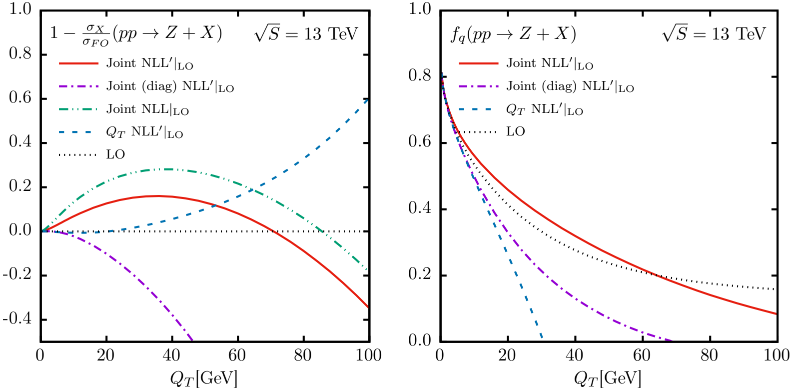

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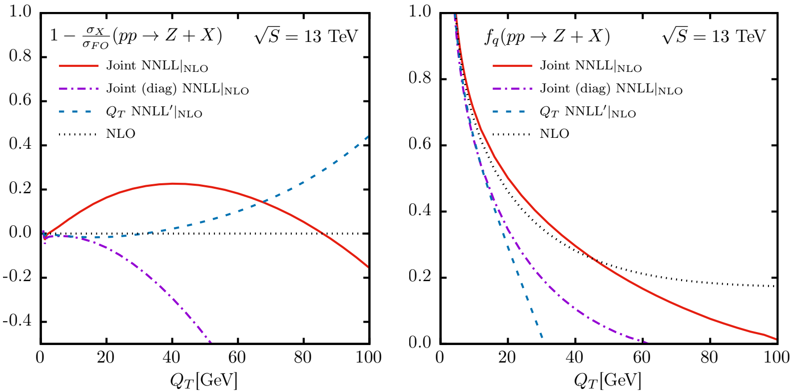

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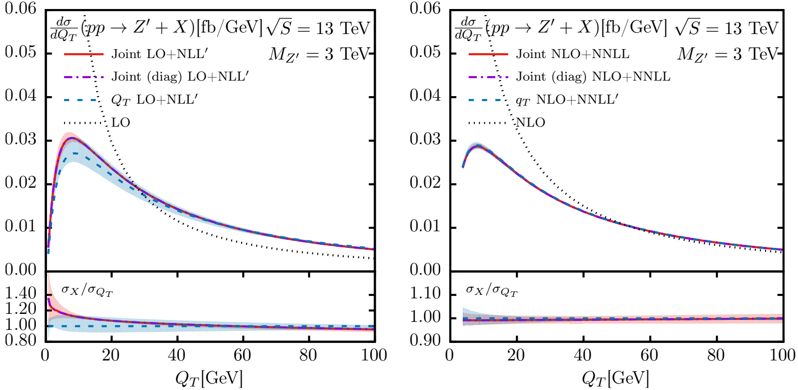

Summary

Conclusions

- Application of joint threshold, Q_T extended to NNLL
- Does not work well for LHC for Z-boson production
- Better agreement to Fixed order
- Lower scale uncertainty mid to high Q_T

Outlook

- Potentially works better for Higgs production
- Application to BSM processes

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Thank you for your attention

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Comparison to threshold and q_T

$$E_{a\bar{a}}(\chi, N, Q, \mu_F) = 2\int_{Q^2/\chi^2}^{Q^2} \frac{dk_T^2}{k_T^2} A_a(\alpha_s(k_T)) \log\left(\frac{\bar{N} k_T}{Q}\right)$$

$$- 2\log \bar{N} \int_{\mu_F^2}^{Q^2} \frac{dk_T^2}{k_T^2} A_a(\alpha_s(k_T))$$

Becomes threshold exponential for $\chi \to \bar{N}$

$$E_{a\bar{a}}(\chi, N, Q, \mu_F) = -\int_{Q^2/\chi^2}^{Q^2} \frac{dk_T^2}{k_T^2} \left[A_a(\alpha_s(k_T)) \log\left(\frac{Q^2}{k_T^2}\right) + B(\alpha_s(k_T))\right]$$

$$+ \int_{\mu_F^2}^{Q^2/\chi^2} \frac{dk_T^2}{k_T^2} \left[-2\log \bar{N} A_a(\alpha_s(k_T)) - B(\alpha_s(k_T))\right]$$

Becomes q_T exponential for $\chi \to \bar{b}$

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Overview at NLL

Written similar to *[Bozzi, Catani, de Florian, Grazzini, '06]*

$$\frac{d\sigma_F^{(\mathrm{res})}}{dQ_T^2} = \int_0^\infty db \frac{b}{2} J_0(bQ_T) \int_{C_T} \frac{dN}{2\pi i} \left(\frac{Q^2}{s}\right)^{-N+1} \tilde{W}^F(b, N, Q)$$

$$\tilde{W}^F(N, b, Q) = \sum_{c,d} \sum_{\{I\}} \mathcal{H}_{cd}^{\{I\},\,F}(N, Q, \alpha_s(\mu_R), Q^2/\mu_R^2, Q^2/\mu_F^2, Q^2/\mu_Q^2)$$

$$\times\ \tilde{f}_{c/h_1}(N, \mu_F^2)\ \tilde{f}_{d/h_2}(N, \mu_F^2)$$

$$\times\ \exp\left\{E_{\{I\}}(\alpha_s(\mu_R), b, N, Q^2/\mu_R^2, Q^2/\mu_Q^2)\right\}$$

$$\mathcal{H}^F(N, Q, \alpha_s(\mu_R), Q^2/\mu_R^2, Q^2/\mu_F^2, Q^2/\mu_Q^2) = \sigma^{(0)}_{a\bar{a}\to F}(\alpha_s(Q)) H_a^F(\alpha_s(Q)) \left(\tilde{C}(N, \alpha_s(Q))\right)^2$$

$$E_{\{I\}}(\alpha_s(\mu_R), b, N, Q^2/\mu_R^2, Q^2/\mu_Q^2) = -\int_{Q^2/\chi^2}^{Q^2} \frac{dq^2}{q^2} \left[A(\alpha_s(q)) \log\frac{Q^2}{q^2} + \tilde{B}_N(\alpha_s(q))\right]$$

$$+ \int_{\mu_F^2}^{Q^2} \frac{dq^2}{q^2} 2\gamma(N, \alpha_s(q))$$

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$$\times\ \tilde{f}_{c/h_1}(N,\mu_F^2)\ \tilde{f}_{d/h_2}(N,\mu_F^2)$$

$$\times\ \exp\Big\{E_{\{I\}}(\alpha_s(\mu_R),b,N,Q^2/\mu_R^2,Q^2/\mu_Q^2)\Big\}$$

$$\mathcal{H}^{\,F}(N,Q,\alpha_s(\mu_R),Q^2/\mu_R^2,Q^2/\mu_F^2,Q^2/\mu_Q^2) = \sigma^{(0)}_{a\bar{a}\to F}(\alpha_s(Q))H_a^F(\alpha_s(Q))\Big(\tilde{C}(N,\alpha_s(Q))\Big)^2$$

$$E_{\{I\}}(\alpha_s(\mu_R),b,N,Q^2/\mu_R^2,Q^2/\mu_Q^2) = -\int_{Q^2/\chi^2}^{Q^2} \frac{dq^2}{q^2}\left[A(\alpha_s(q))\log\frac{Q^2}{q^2} + \tilde{B}_N(\alpha_s(q))\right]$$

$$+\int_{\mu_F^2}^{Q^2} \frac{dq^2}{q^2} 2\gamma(N,\alpha_s(q))$$

Hard contribution

Overview at NLL

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$$\frac{d\sigma_F^{(\mathrm{res})}}{dQ_T^2} = \int_0^\infty db\, \frac{b}{2} J_0(bQ_T) \int_{C_T} \frac{dN}{2\pi i} \left(\frac{Q^2}{s}\right)^{-N+1} \tilde{W}^F(b, N, Q)$$

$$\tilde{W}^F(N, b, Q) = \sum_{c,d} \sum_{\{I\}} \mathcal{H}_{cd}^{\{I\},\,F}(N, Q, \alpha_s(\mu_R), Q^2/\mu_R^2, Q^2/\mu_F^2, Q^2/\mu_Q^2)$$

$$\times\ \tilde{f}_{c/h_1}(N, \mu_F^2)\ \tilde{f}_{d/h_2}(N, \mu_F^2)$$

$$\times\ \exp\Big\{E_{\{I\}}(\alpha_s(\mu_R), b, N, Q^2/\mu_R^2, Q^2/\mu_Q^2)\Big\}$$

$$\mathcal{H}^{\,F}(N, Q, \alpha_s(\mu_R), Q^2/\mu_R^2, Q^2/\mu_F^2, Q^2/\mu_Q^2) = \sigma^{(0)}_{a\bar{a}\to F}(\alpha_s(Q)) H_a^F(\alpha_s(Q)) \Big(\tilde{C}(N, \alpha_s(Q))\Big)^2$$

$$E_{\{I\}}(\alpha_s(\mu_R), b, N, Q^2/\mu_R^2, Q^2/\mu_Q^2) = -\int_{Q^2/\chi^2}^{Q^2} \frac{dq^2}{q^2}\left[A(\alpha_s(q)) \log\frac{Q^2}{q^2} + \tilde{B}_N(\alpha_s(q))\right] + \int_{\mu_F^2}^{Q^2} \frac{dq^2}{q^2} 2\gamma(N, \alpha_s(q))$$

Sudakov factor

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Backup

[Marzani, VT, 1612.01432]

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