Transverse spectra of gauge bosons

Varun Vaidya[1]

[1]Los Alamos National Lab
In collaboration with D. Kang and C. Lee

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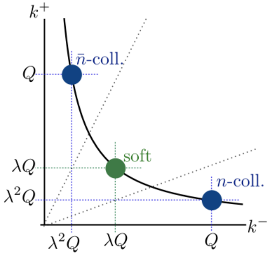
Outline

Factorization

- P+P $\to$ H+X, P+P $\to$ $l^+ + l^-$ +X.



$$p_c \sim \mathrm{Q}\,(1, \lambda^2, \lambda)\,,$$
$$p_{\bar{c}} \sim \mathrm{Q}\,(\lambda^2, 1, \lambda)\,,$$
$$p_s \sim \mathrm{Q}\,(\lambda, \lambda, \lambda)\,,$$
$$\lambda = \mathrm{qT} / \mathrm{Q}$$

Figure: IR modes have the same virtuality.

- The gauge boson recoils against soft and collinear radiation
- Need a regulator ν that breaks boost invariance to factorize the Soft from the collinear sector

Factorization

Transverse momentum cross section

$$\frac{d\sigma}{dq_T^2 dy} \propto H(\frac{\mu}{Q}) \times \int d^2\vec{p_T} S(\vec{q_{Ts}}, \mu, \nu) \times$$
$$f_1^{\perp}(x_1, \vec{q_{T1}}, \mu, \nu, Q) f_2^{\perp}(x_2, \vec{q_{T2}}, \mu, \nu, Q) \delta^2(\vec{q_T} - \vec{q_{Ts}} - \vec{q_{T1}} - \vec{q_{T2}})$$

- Virtuality of hard modes $\sim$ Q
- Virtuality of IR modes spread over a wide range of transverse momentum. Collinear sector has the scale Q.
- RG equations in momentum space are convolutions of distributions functions and hard to solve directly.

Factorization

b space formulation

$$\frac{d\sigma}{dq_T^2 dy} \propto H(\frac{\mu}{Q}) \int bdbJ_0(bq_T) S(b,\mu,\nu) f_1^{\perp}(x_1, b, \mu, \nu, Q) f_2^{\perp}(x_2, b, \mu, \nu, Q)$$

RG equations in b space are simple

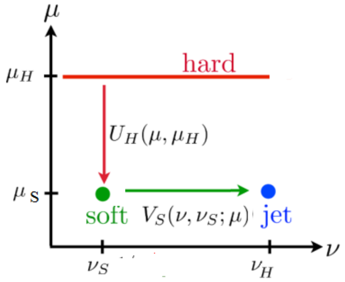
$$\mu \frac{d}{d\mu} F_i(\mu, \nu, b) = \gamma_\mu^i F_i(\mu, \nu, b), \qquad F_i \in (H, S, f_i^{\perp})$$

$$\nu \frac{d}{d\nu} G_i(\mu, \nu, b) = \gamma_\nu^i G_i(\mu, \nu, b), \qquad G_i \in (S, f_i^{\perp})$$

$$\sum_{F_i} \gamma_\mu^i = \sum_{G_i} \gamma_\nu^i = 0$$

Resummation

- Resum large logarithms of the form $log(Q/q_T)$
- b space resummation: Default choice of $\mu = \nu = 1/b$,1007.2351 De Florian et.al., 1503:00005 V. Vaidya et. al
- Momentum space resummation:Both μ, ν in momentum space, distributional scale setting, 1611.08610 Tackmann et.al., 1604.02191 P. Monni et. al.
- Hybrid: μ in momentum space(1007.4005, 1109.6027 Becher et.al.)



Scale choice in momentum space

Can we choose a particular physical scales in momentum space for μ and ν?

Running the Hard function in μ

- Assume a power counting $\alpha_s \log(Q/\mu_L), \log(\mu_L b_0) \sim 1$ [a]

$$\frac{d\sigma}{dq_t^2} \propto U_H^{LL}(H, \mu_L)\left(\alpha_s(\mu_L)\log(Q/q_T)\right)$$

[a] $b_0 = be^{-\gamma_E}/2$

- The leading large logarithm $\alpha_s(\mu_L)\log(Q/q_T)$ goes unresummed.
- Resummation of $log(Q/q_T)$ happens entirely in the IR sector

Scale choice in momentum space

Attempt at NLL → running Soft function in ν

$$
\begin{aligned}
\frac{d\sigma}{dq_t^2} &\propto U_H^{NLL}(H,\mu_L)\int dbbJ_0(bq_t)U_S(\nu_H,\nu_L,\mu_L) \\
&= U_H^{NLL}(H,\mu_L)\int dbbJ_0(bq_t)\left(\mu_L^2 b_0^2\right)^{\Gamma_{cusp}^{(0)}\frac{\alpha(\mu_L)}{2\pi}\log(\frac{\nu_H}{\nu_L})} \\
&= 2U_H^{NLL}(H,\mu_L)e^{-2\omega_s\gamma_E}\frac{\Gamma[1-\omega_s]}{\Gamma[\omega_s]}\frac{1}{\mu_L^2}\left(\frac{\mu_L^2}{q_T^2}\right)^{1-\omega_s}, \\
\omega_s &= -\Gamma_{cusp}^{(0)}\frac{\alpha(\mu_L)}{2\pi}\log(\frac{\nu_H}{\nu_L})
\end{aligned}
$$

- Still does not work, singular at $\omega_s \sim 1$

Scale choice in momentum space

- Divergence caused due to single log structure ($log(\mu_L b)$) in the Soft exponent
- Contribution from highly energetic soft contributions.
- Need damping at low b to stabilize b space exponent.
- $\mu_H, \nu_H \sim Q$ fixed at the hard scale in momentum space.

Scale choice in momentum space

- Resum all logarithms of the form $\alpha_s \log^2(\mu_L b_0)$

A choice for ν in b space $\rightarrow$ include sub-leading terms

$$\nu_L = \frac{\mu_L^n}{b_0^{1-n}}, \qquad n = \frac{1}{2}\left(1 - \alpha(\mu_L)\frac{\beta_0}{2\pi}\log(\frac{\nu_H}{\mu_L})\right)$$

Soft exponent at NLL $\rightarrow$ Quadratic in $\log(\mu_L b_0)$

$$\log(U_S^{NLL}(\nu_H, \nu_L, \mu_L)) = 2\Gamma_{cusp}^{(0)}\frac{\alpha(\mu_L)}{2\pi} \times$$
$$\left(\log(\frac{\nu_H}{\mu_L})\log(\mu_L b_0) + \frac{1}{2}\log^2(\mu_L b_0) + \alpha(\mu_L)\frac{\beta_0}{4\pi}\log^2(\mu_L b_0)\log(\frac{\nu_H}{\mu_L})\right)$$

Scale choice in momentum space

A choice for μ_L in momentum space

- A choice that justifies the power counting $log(\mu_L b_0) \sim 1$
- A choice that will minimize contributions from residual fixed order logs $log^n(\mu_L b_0)$.
- Scale shifted away from q_T due to the scale Q in b space exponent.

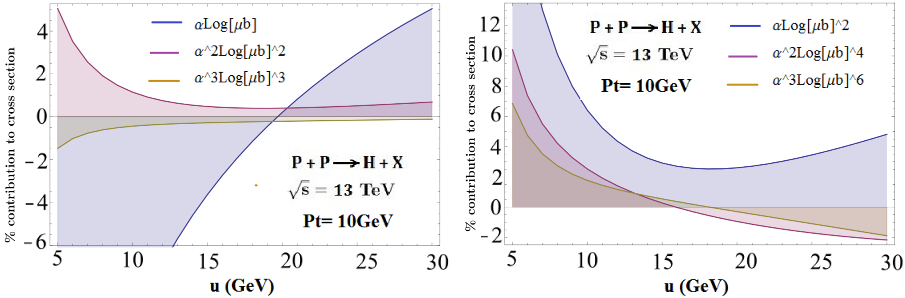
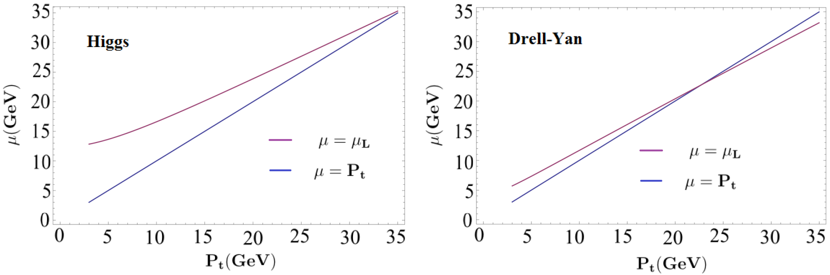


Figure: Percentage contribution of the fixed order logs as a function of the scale

Scale choice in momentum space



- $\mu_L \sim 1/b^*$, b^* is the value at which b space integrand peaks.

$$\frac{d}{db}\left(bJ_0(bq_T)U_{soft}(b)\right)\Big|_{(b=1/\mu_L)} = 0$$

Analytical expression for cross section

Mellin-Barnes representation of Bessel function

- Polynomial integral representation for Bessel function is needed

$$J_0(z) = \frac{1}{2\pi i}\int_{c-i\infty}^{c+i\infty} dt \frac{\Gamma[-t]}{\Gamma[1+t]}\left(\frac{1}{2}z\right)^{2t}$$

b space integral

$$U_S = C_1 Exp[-A\log^2(Ub)]$$

$$I_b = \int_0^{\infty} dbbJ_0(bq_T)U_S \qquad \text{No Landau pole}$$

$$= C_1 \int_{-i\infty}^{i\infty} dt \frac{\Gamma[-t]}{\Gamma[1+t]}\int_0^{\infty} dbb(\frac{bq_T}{2})^{2t} Exp[-A\log^2(Ub)]$$

Analytical expression for cross section

$$
\begin{aligned}
I &= \frac{2C_1}{iq_T^2}\frac{1}{\sqrt{4\pi A}}\int_{c-i\infty}^{c+i\infty} dt \frac{\Gamma[-t]}{\Gamma[1+t]} Exp[\frac{1}{A}(t-t_0)^2] \\
t_0 &= -1 + A\log(2U/q_T) \rightarrow \text{saddle point}
\end{aligned}
$$

- Path of steepest descent is parallel to the imaginary axis
- Suppression controlled by 1/A $\sim \frac{4\pi}{\alpha_s} 1/\Gamma^{(0)}_{cusp}$
- $t = c + ix$

$$
I = \frac{2C_1}{q_T^2}\frac{1}{\sqrt{4\pi A}}\int_{-\infty}^{\infty} dx \frac{\Gamma[-c-ix]}{\Gamma[1+c+ix]} Exp[-\frac{1}{A}(x-i(c-t_0))^2]
$$

- Saddle point weak in resummation region; very strong in Fixed order limit A$\rightarrow$ 0.

Analytical expression for cross section

- What choice do we make for c? Obvious choice $c = t_0$? c depends on A and hence on the details of the process.
- For percent level accuracy, we need info about $F(x) = \frac{\Gamma[-c-ix]}{\Gamma[1+c+ix]}$ out to $x_l \sim \sqrt{2A\log(10)}$
- Worst case scenario A $\sim$0.5 $\implies x_l \sim 1.5$
- A Taylor series expansion around the saddle point is not enough.
- Choose c = -1, the saddle point in the limit $A \to 0$ for all observables and use a more suitable basis for expanding F(x)

Analytical expression for cross section

Guidelines for choosing a basis for expansion

- Fixed order cross section

$$I_{exact}^{O(\alpha_s)} = -2\Gamma_{cusp}^{(0)}\frac{\alpha(\mu_L)}{4\pi}\frac{2}{q_T^2}\left(F'[0]\log\left(\frac{\mu_L e^{-\gamma_E}}{q_T}\right)+\frac{F''[0]}{4}\right)$$

- To correctly reproduce the fixed order cross section upto α_s^n, we need $2n^{th}$ derivative of the expansion to match the exact function F(x)
- We need the expansion in a basis to be accurate upto $x \sim 1.5$
- The basis functions for the expansion should be chosen so as to yield a rapidly converging and analytical result.

Analytical expression for cross section

An expansion for $F(x) = \Gamma[-1 - ix]/\Gamma[ix]$

A general basis $x^n e^{\alpha x^2 + \beta x}$ for expansion

$$\hat{F}_R(x) = g_1(Exp[-g_2 x^2] - \cos[g_3 x])$$

$$\hat{F}_I(x) = f_1 \sin[f_2 x] + f_3 \sinh(f_4 x)$$

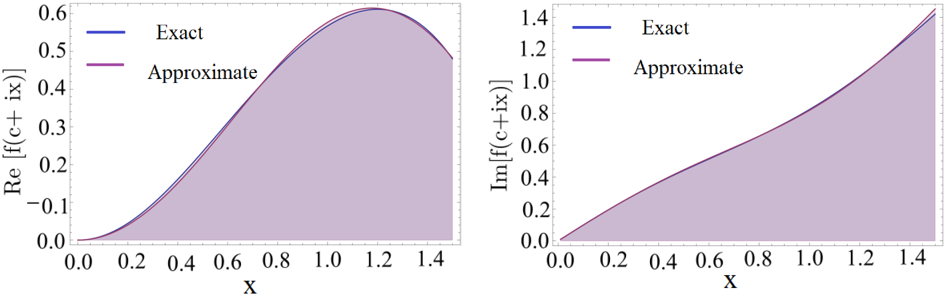


Figure: Expansion for real and imaginary parts of f(t), c is chosen to be -1

Analytical expression for cross section

Expression for resummed Soft function

$$I_b(A,L) = \frac{2C_1}{q_T^2} e^{-AL^2}\Big[-g_1 e^{-\frac{Ag_3^2}{4}} \cosh[ALg_3] + \frac{g_1 e^{\frac{A^2L^2g_2}{1+Ag_2}}}{\sqrt{1+Ag_2}}$$

$$+ \quad f_1 e^{-\frac{Af_2^2}{4}} \sinh[ALf_2] + f_3 e^{\frac{Af_4^2}{4}} \sin[ALf_4]\Big]$$

Parameters at NLL

$$A = -2\Gamma^{(0)}_{cusp} \frac{\alpha(\mu_L)}{4\pi}\left(1 + \frac{\alpha(\mu_L)\beta_0}{2\pi}\log(\frac{\nu_H}{\mu_L})\right)$$

$$C_1 = Exp[A\log^2(\eta)], \quad U = \mu_L \eta e^{-\gamma_E}/2$$

$$\eta = Exp\Big[\frac{\log(\nu_H/\mu_L)}{1+\frac{\alpha(\mu_L)\beta_0}{2\pi}\log(\frac{\nu_H}{\mu_L})}\Big], \quad L = \log(\frac{2U}{q_T})$$

Analytical expression for cross section

Fixed order terms

- I_b acts as a generating function for residual fixed order logs

$$
\begin{aligned}
I_{even} &= C_1 \int bdbJ_0(bq_T) \log^{2n}(Ub) Exp[-A \log^2(Ub)] \\
&= (-1)^n \frac{d^n}{dA^n} I_b(A, L) \\
I_{odd} &= C_1 \int bdbJ_0(bq_T) \log^{2n+1}(Ub) Exp[-A \log^2(Ub)] \\
&= (-1)^n \frac{d^n}{dA^n} \frac{(-1)}{2A} \frac{d}{dL} I_b(A, L)
\end{aligned}
$$

Numerical results

- Easily extended to NNLL, b space exponent kept quadratic in $\log(\mu b)$

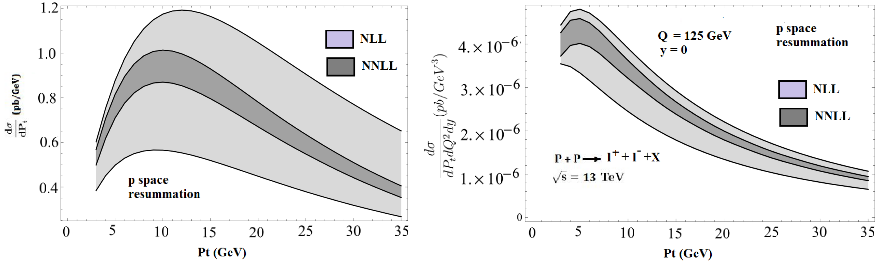


Figure: Resummation in momentum space.

- Excellent convergence for both the Higgs and Drell-Yan spectrum
- No arbitrary b space cut-off while estimating perturbative errors.

Comparison with b space resummation

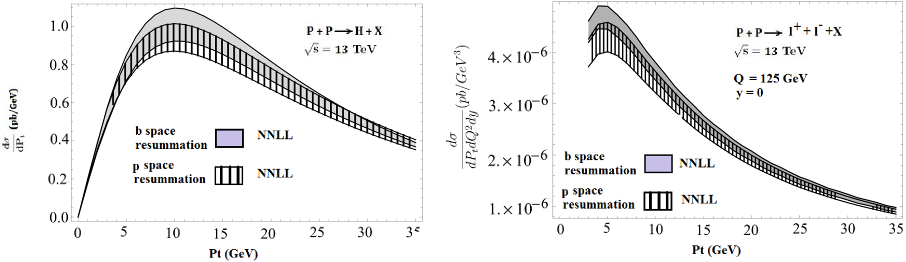


Figure: comparison of nnll cross section in two schemes

- Difference of the order of sub-leading terms.
- More reliable perturbative error estimation in the absence of Landau pole.

Matching to fixed order

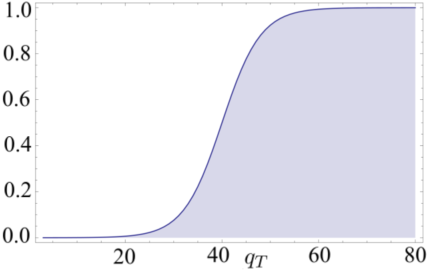
- Implement profiles in μ and ν to turn off resummation

$$S = S_L^{(1-z(q_T))} Q^{z(q_T)} \qquad \mathrm{S} \in \mu, \nu$$

- Soft exponent scales as $(1 - z(q_T))$

$$U_S = Exp[(1-z)\gamma_S^{\nu} log\left(\frac{Q}{\nu_L}\right)]$$

- This is equivalent to A $\rightarrow$ A(1-z) in I_b(A,L)



$$z(q_T) = \frac{1}{2}\left(1 + \tanh\left[r\left(\frac{q_T}{t} - 1\right)\right]\right)$$

Summary

- Implementation momentum space resummation for transverse spectra of gauge bosons
- Rapidity choice in impact parameter space
- Virtuality choice in momentum space.
- Analytical expression for cross section across the entire range of q_T obtained for the first time.
- Numerical accuracy controlled by the accuracy of the expansion for process independent function $\frac{\Gamma[-t]}{\Gamma[1+t]}$
- Outlook
  - Promising approach for other observables with similar factorization structure.
  - Non-perturbative effects need to be included for low Q as well as the low q_T regime.

Backup

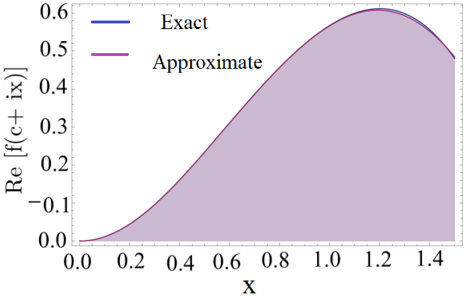
(A more accurate) Analytical expression for cross section

An expansion for $F(x)=\Gamma[-1-ix]/\Gamma[ix]$

A general basis $x^n e^{\alpha x^2+\beta x}$ for expansion

$$\hat{F}_R(x) = g_1(Exp[-g_2x^2] - \cos[g_3x]) + g_4x^2 Exp[-g_5x^2]$$

$$\hat{F}_I(x) = f_1 \sin[f_2x^2] + f_3 \sinh(f_4x)$$



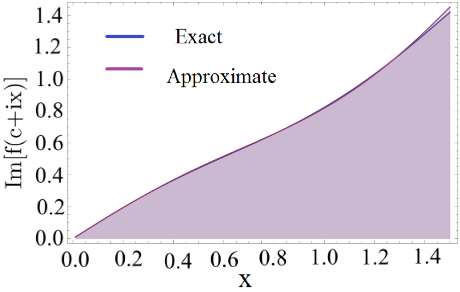


Figure: (Expansion for real and imaginary parts of f(t), c is chosen to be -1