Calculations with CSS based generator reSolve and PB based generator Cascade

Maxim Pavlov

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Universiteit Antwerpen

Introduction

- Analytical and numerical comparison between CSS and PB formalism
- Using MC generator reSolve to obtain results for CSS
- Phenomenological analysis with data from ATLAS

CSS formalism

- Well-established formalism that provides analytical expression for inclusive processes
- Only valid for $q_T << Q$, need matching with a finite term for higher q_T
- The resummation of the large logarithms $\alpha_S^n \log^m(Q^2/q_T^2)$ is contained within the Sudakov form factor S_c, which can be expanded in terms of $\alpha_S^n \log^{n+1}(Q^2/q_T^2)$ (LL), $\alpha_S^n \log^n(Q^2/q_T^2)$ (NLL), $\alpha_S^n \log^{n-1}(Q^2/q_T^2)$ (NNLL), ...

Sudakov form factors

$$\text{CSS:}\ \exp\Big\{-\int_{b_0^2/b^2}^{Q^2}\frac{dq^2}{q^2}\Big[\log(\frac{Q^2}{q^2})A_a(\alpha_S(q^2))+B_a(\alpha_S(q^2))\Big]\Big\}$$

$$\text{PB:}\ \exp\Big\{\int_{\mu_0^2}^{\mu^2}\frac{d\bar{\mu}^2}{\bar{\mu}^2}\int_0^{z_M(\bar{\mu}^2)}dz\ \Big[\frac{k_a(\alpha_S(\bar{\mu}^2))}{1-z}-d_a(\alpha_S(\bar{\mu}^2))\delta(1-z)\Big]\Big\}$$

with expansions:

$$A_a(\alpha_S)=\sum_{n=1}^{\infty}\left(\frac{\alpha_S}{\pi}\right)^n A_a^{(n)};\qquad k_a(\alpha_S)=\sum_{n=1}^{\infty}\left(\frac{\alpha_S}{2\pi}\right)^n k_a^{(n-1)}$$

and similar for the other functions
$\Rightarrow$ A_a comparable with k_a and B_a comparable with d_a after rewriting PB Sudakov

Analytical comparison CSS and PB

- LL order:

$$A_q^{(1)} = C_F \quad , \qquad\qquad k_q^{(0)} = 2C_F$$

- NLL order:

$$\begin{aligned}
A_q^{(2)} &= C_F C_A \left(\frac{67}{18} - \frac{\pi^2}{6} \right) - \frac{5}{9} N_f C_F \\
B_q^{(1)} &= -\frac{3}{2} C_F \\
k_q^{(1)} &= 2 C_F C_A \left(\frac{67}{18} - \frac{\pi^2}{6} \right) - \frac{10}{9} N_f C_F \\
d_q^{(0)} &= \frac{3}{2} C_F
\end{aligned}$$

At LL and NLL, coefficients from CSS and PB coincide, apart from a factor 2 caused by difference in perturbative expansion

Analytical comparison CSS and PB

- NNLL order:

$$B_q^{(2)} + \frac{1}{2} d_q^{(1)} = 4\pi C_F \beta_0 (\zeta(2) - 1)$$

This difference can be explained with the resummation scheme transformation in CSS, which leaves the expression for the cross section invariant. Expanding the B_c and H_c^F functions gives:

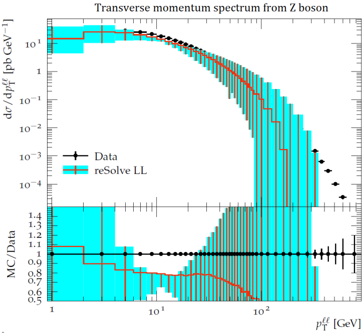
$$B_c^F(\alpha_S) = B_c(\alpha_S) - \beta(\alpha_S) \frac{d \log H_c^F(\alpha_S)}{d \log \alpha_S}$$

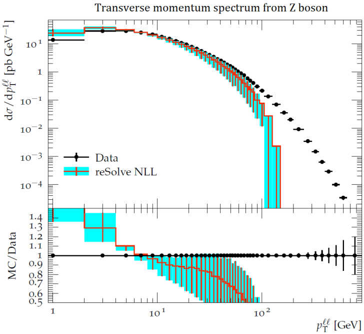
$$\Rightarrow B_q^{(2)F} = B_q^{(2)} + \pi \beta_0 H_c^{(1)F}$$

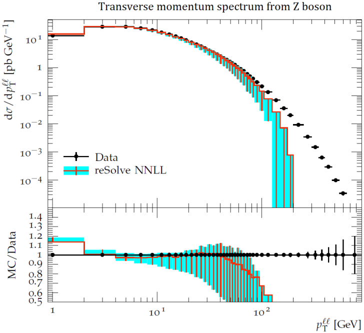
Numerical comparison

- p_T spectrum of Z boson in Drell-Yan produced for both formalisms
- CSS results: reSolve, recently-developed C++ program that implements the CSS resummation
  [F. Coradeschi and T. Cridge, Comput. Phys. Commun. 238 (2019) 262-294.]
- PB results: CASCADE to combine TMD PDF (TMDlib) with matrix element (PYTHIA for LO, MC@NLO for NLO)
  [H. Jung et al., Eur. Phys. J. C 70, 1237-1249 (2010).]
- Phenomenological analysis of results from PB TMD and reSolve, compared to each other and to ATLAS data at 8 TeV

Different orders within reSolve

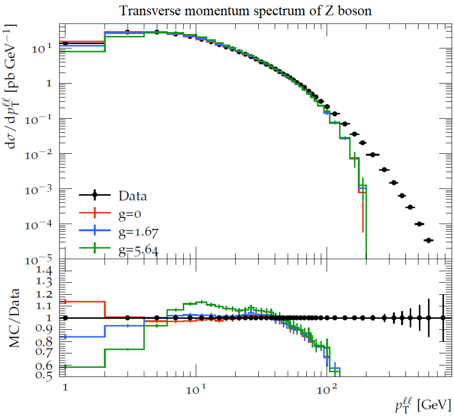






- Uncertainty band originates from resummation scale variation
- Matching procedure not present in reSolve, unreliable results at high p_T
- Using higher logarithmic accuracy improves results

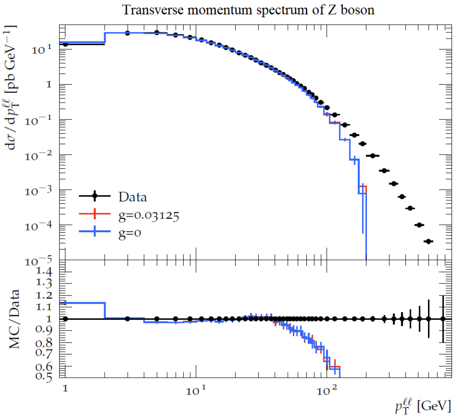
Influence of the non-perturbative smearing in reSolve



- reSolve uses a Gaussian smearing $S_{NP} = \exp\left(-g_{NP}^q b^2\right)$ for the non-perturbative contributions
- Value for g_{NP}^q not yet fitted to data
- Used values are taken from Bozzi et al, but these are only applicable for gluon-gluon fusion

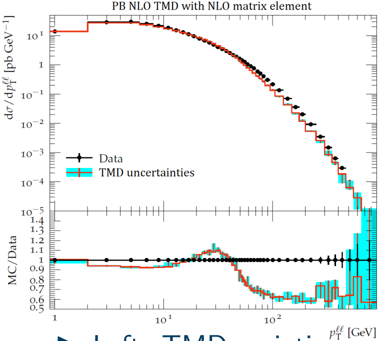
[G. Bozzi, S. Catani, D. de Florain, M. Grazzini, Nucl.Phys. B737, 73-120 (2006) arXiv:hepph/0508068v1.]

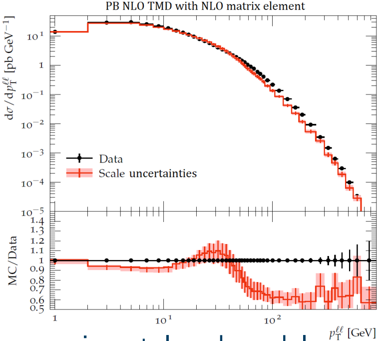
Influence of the non-perturbative smearing in reSolve



- Attempt to use similar smearing as in the PB calculations, which was $G = \exp\left(-\frac{\mathbf{k}_T^2}{\sigma^2}\right)$ with $\sigma^2 = 0.125$ GeV^2
- Using the properties of Fourier transformation to go from b-space to k_T-space, this value of σ^2 would correspond to g_{NP}^q=0.03125 GeV^2

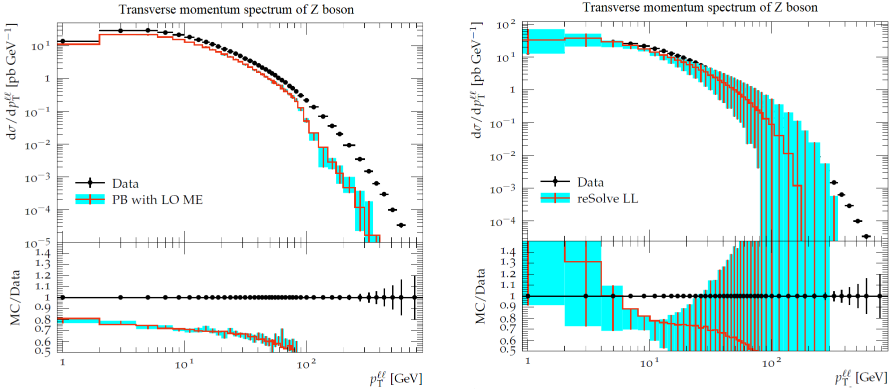
Uncertainty band on PB results





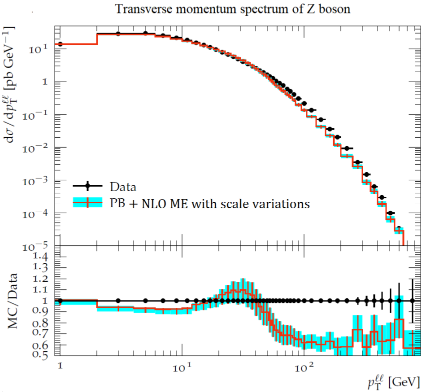
- Left: TMD variations, caused by experimental and model alterations when performing fit
- Right: Scale variations by varying the renormalization and factorization scale with a factor 2 up/down from the default value to obtain 9-point scale variation

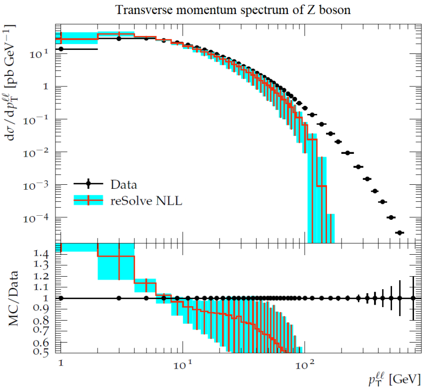
Comparison PB and reSolve: LO vs LL



- TMD uncertainty on PB results, not able to do scale variation for LO matrix element
- Uncertainty on reSolve results caused by varying resummation scale
- Integrated PB PDF set used in reSolve
- Central value PB differs from data because the spectrum is not normalized

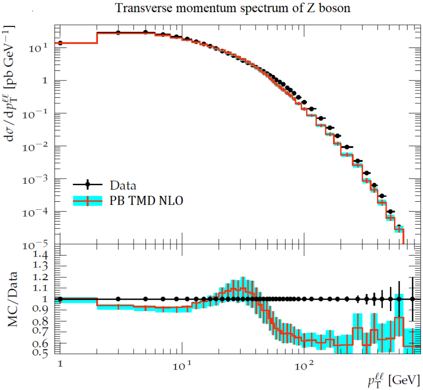
Comparison PB and reSolve: NLO vs NLL

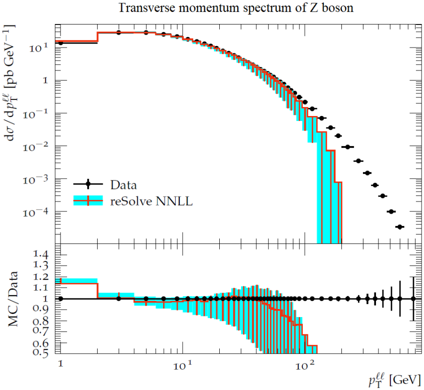




- High p_T: outside resummation region, need matching in reSolve for better shape of CSS predictions
- Low p_T: lowest bins = non-perturbative region
- NNLL results are improvement, therefore worth to compare PB NLO with NNLL

Comparison PB and reSolve: NLO vs NNLL





- Same issues in low and high p_T region
- PB can produce results of similar quality as CSS
- Similarity between the two results can be explained with the analytical comparison: both $B^{(2)}$ and $d^{(1)}$ coefficients are used in the calculations
  $\rightarrow$ similar virtual contributions are taken into account

Current work

- Performing a similar 9-point scale variation with the reSolve calculations by varying renormalization, factorization and resummation scales

- Testing g^{q}_{NP}=2.67 GeV^2 (number obtained from T. Cridge, co-author of reSolve) to see if the reSolve results improve at low p_T

Conclusions

- Comparison between two formalisms, analytically and numerically, and a phenomenological analysis with data from ATLAS
- Numerical results show that PB produces results of similar quality as the well-established CSS formalism
- Part of NNLL resummation is present in the NLO predictions from the PB method
- Current work tries to improve reSolve results

Backup slides

Resummation scale

- Argument of resummed logarithms can be rescaled:

$$\log Q^2 b^2 = \log Q^2/\mu_S^2 + \log \mu_S^2 b^2$$

- μ_S = resummation scale

- Rescaling valid when $\mu_S \sim Q$, in reSolve default value is $Q/2$