PROCEEDINGS OF SCIENCE

Dependence of the parton intrinsic transverse momentum on the collision center of mass energy using the Parton Branching Method in Drell-Yan production at NLO

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We investigated the internal motion of partons through its effects on the very low transverse momentum spectra of Drell-Yan pairs produced in hadron-hadron collisions at next-to-leading order (NLO) using the Parton Branching (PB) Method. This method describes the evolution of transverse momentum-dependent parton distributions. Unlike standard Monte Carlo event generators, which require parton intrinsic transverse momentum (intrinsic k_T) distributions to strongly depend on the collision energy, the PB Method does not exhibit such dependence. In order to understand the different behaviour, we try to mimic the parton-shower event generators by imposing a minimal transverse momentum of the radiated parton at a branching at the level of 1-2 GeV, resulting in removal of certain fraction of the soft gluon contribution. It will be shown that the origin of the intrinsic-k_T energy dependence is in the interplay between the two non-perturbative processes: the internal motion and the soft gluon emission.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

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1. Introduction

The transverse momentum spectrum of lepton pairs in Drell-Yan (DY) production provides a sensitive probe into the internal transverse motion of partons and their interactions. At large p_T, the spectrum can be well described using perturbative QCD; however, at low transverse momenta ($p_T \lesssim 1$ GeV), non-perturbative effects such as the intrinsic k_T of partons and multiple soft gluon emissions become dominant. Traditional approaches like collinear parton showers (e.g., PYTHIA, HERWIG) incorporate intrinsic-k_T distributions but impose strong energy dependence on them to describe the data.

In our analyses [1, 2], we apply the Parton Branching method to investigate DY production at NLO and study the intrinsic-k_T distributions across different center-of-mass energies. This method allows soft-gluon resummation through the Sudakov form factor and includes intrinsic-k_T effects in a natural way. We compare our findings to other parton-shower models and explore the energy dependence of the intrinsic-k_T distribution.

2. Theoretical Framework

Transverse momentum dependent parton distribution functions (TMDs) extend the idea of Parton Distribution Functions (PDFs) by including information about the transverse momentum of partons inside a hadron. TMDs describe the probability of finding a parton inside a hadron with both a longitudinal momentum fraction and a transverse momentum component. They are crucial for description of small transverse momentum physics as well as small x physics. The usage of PB method extends the description region, allowing also for higher p_T values to be reached. It provides an iterative solution to the DGLAP evolution equations simulating each branching that can occur during the evolution [3–15]. The evolution equation for a TMD parton density $A_a(x, k_T, \mu^2)$ of a parton a with longitudinal momentum fraction x, transverse momentum k_T, and scale μ is given by:

$$\begin{aligned} A_a(x, \mathbf{k}, \mu^2) &= \Delta_a(\mu^2) A_a(x, \mathbf{k}, \mu_0^2) \\ &+ \sum_b \int \frac{d^2\mathbf{q}'}{\pi \mathbf{q}'^2} \frac{\Delta_a(\mu^2)}{\Delta_a(\mathbf{q}'^2)} \Theta(\mu^2 - \mathbf{q}'^2) \Theta(\mathbf{q}'^2 - \mu_0^2) \\ &\times \int_x^{z_M} \frac{dz}{z} P_{ab}^{(R)}(\alpha_s, z) A_b\left(\frac{x}{z}, \mathbf{k} + (1-z)\mathbf{q}', \mathbf{q}'^2\right) . \end{aligned} \tag{1}$$

The first term on the right-hand side represents the Sudakov form factor contribution, while the second term models resolvable parton emissions during the evolution process. The transverse momentum of the final parton, k_T, results from the vector sum of its initial transverse momentum and all transverse momenta generated in the branchings.

The Sudakov form factor (Δ_a) is central to the PB method as it describes the probability that no additional soft-gluon emissions occur between two scales μ_0 and μ. The form factor for a parton a, evolving between these two scales, is defined as:

$$\Delta_a(\mu^2, \mu_0^2) = \exp\left(- \sum_b \int_{\mu_0^2}^{\mu^2} \frac{dq'^2}{q'^2} \int_0^{z_M} dz\, z\, P_{ab}^{(R)}(\alpha_s, z) \right) . \tag{2}$$

Here, $P^{(R)}_{ab}(\alpha_s, z)$ are the resolvable splitting functions that describe the splitting of a parton b into parton a, and z represents the longitudinal momentum transferred at the branching. The soft gluon resolution scale, z_M, separates resolvable ($z < z_M$) and non-resolvable ($z > z_M$) branching.

It has been shown that the soft-gluon angular ordering provides well defined TMDs which are independent of the choice of the soft-gluon resolution scale when $z_M \to 1$ [1]. The angular ordering connects the branching evolution scale q' to the transverse momentum q_T of the emitted parton:

$$q' = \frac{q_T}{(1-z)} \, . \tag{3}$$

In the PB method, the Sudakov form factor is modified to incorporate both perturbative and non-perturbative contributions through a dynamical cutoff $z_{\rm dyn}$:

$$z_{\rm dyn} = 1 - \frac{q_0}{q'} \, . \tag{4}$$

It dynamically defines the resolution scale for soft gluon emissions, where q_0 is the cutoff parameter. This cutoff distinguishes the perturbative region (where $q_T > q_0$) from the non-perturbative region, where soft-gluon resummation dominates. By introducing q_0, we can probe the sensitivity of DY cross sections to different intrinsic-k_T distributions, allowing comparisons with parton shower approach like PYTHIA and HERWIG, which typically impose a high fixed value of transverse momentum cutoff (1-2 GeV).

At the starting scale μ_0, partons have a non zero intrinsic transverse momentum. This represents the non-perturbative motion of partons inside the hadron, which contributes significantly to the low-p_T region of DY production. The intrinsic-k_T is introduced at the initial scale of the evolution through a Gaussian distribution of width σ. This provides the non-perturbative boundary condition for the PB evolution equation. According to this, the TMD at the starting scale is parameterised as follows:

$$A_0(x, k_T, \mu_0^2) = f_0(x, \mu_0^2) \cdot \exp\left(-\frac{k_T^2}{2\sigma^2}\right) \frac{1}{2\pi\sigma^2} \, . \tag{5}$$

Here, $f_0(x, \mu_0^2)$ represents the collinear parton density at the starting scale. The width σ is related to the parameter $q_s = \sqrt{2}\sigma$, which is used by the CASCADE3, event generator based on TMDs [16].

By introducing larger values for the parameter q_0, the dependence of the intrinsic-k_T width on energy $\sqrt{s}$ can be studied and compared with predictions based on parton shower approach, which exhibit a strong energy dependence in their intrinsic-k_T distributions.

3. Results

In the paper [1] we carried out the study of intrinsic-kT nonperturbative TMD parameter (q_s) from fits of Drell-Yan measurement of differential cross section in function of transverse momentum performed by CMS Collaboration at 13 TeV center-of-mass energy [17]. The measurement is performed in the wide mass range from 50 GeV to 1 TeV. We obtain the optimal q_s value to be

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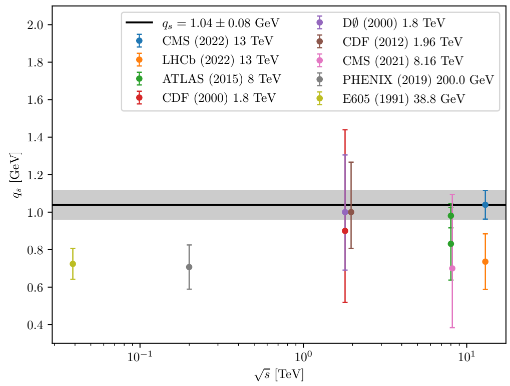
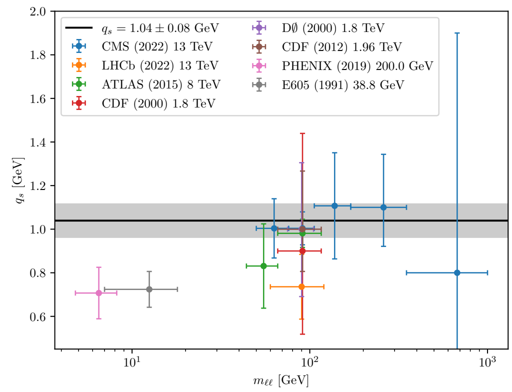
around 1 GeV and as an additional cross check we obtained the value for different centre of mass energies and different DY masses as described in more details in Ref. [1]. The measurement was performed for fixed value of $q_0 = 0.01$ GeV and the q_s values obtained from comparison of data and the prediction are consistent in the wide range in DY pair invariant masses and collision energies, $\sqrt{s}$. The results obtained are presented in Fig. 1.



The value of q_s as a function of $\sqrt{s}$.



The value of q_s as a function of the DY-mass.

Figure 1: The results obtained in [1]. The value of $q_s = 1.04 \pm 0.08\, GeV$ as obtained from the measurements in Ref. [17] is indicated.

In scenarios where the soft-gluon resolution parameter is set to $q_0 = 0.01$ GeV, the intrinsic k_T distribution exhibits minimal dependence on the center-of-mass energy $\sqrt{s}$. This is because nearly all soft gluon emissions are included in the Sudakov form factor, resulting in a universal intrinsic transverse momentum distribution that is largely independent of energy. In contrast, parton shower generators as suggested in Ref. [18], which neglect soft-gluon resummation, require larger intrinsic-k_T values to match data at high energies.

In Ref. [2], to mimic parton-shower behavior, we impose a cutoff on the transverse momentum of the emitted partons (parameter q_0) and vary its value to investigate its effect on the intrinsic-k_T width, q_s. For larger values of q_0, such as 1 GeV or 2 GeV, the intrinsic k_T distribution becomes more sensitive to the center-of-mass energy. By introducing the q_0 cut, soft gluon emissions below this threshold are excluded, resulting in a broader intrinsic k_T distribution to account for the missing transverse momentum. As a result, the width of the intrinsic k_T distribution increases with $\sqrt{s}$, aligning with the behavior seen in parton-shower generators like PYTHIA and HERWIG, where larger values of intrinsic k_T are required at higher energies. The results obtained in this study are presented on Fig. 2

4. Conclusion

This study highlights the critical role of intrinsic transverse momentum and soft gluon emissions in the low p_T region of Drell-Yan production. By varying a minimal transverse momentum of a radiated parton in the branching, q_0, we observe that the intrinsic k_T distribution remains largely energy-independent for small q_0, but exhibits an energy dependence for larger, unphysical, q_0 values ($q_0 \sim 1 - 2$ GeV).

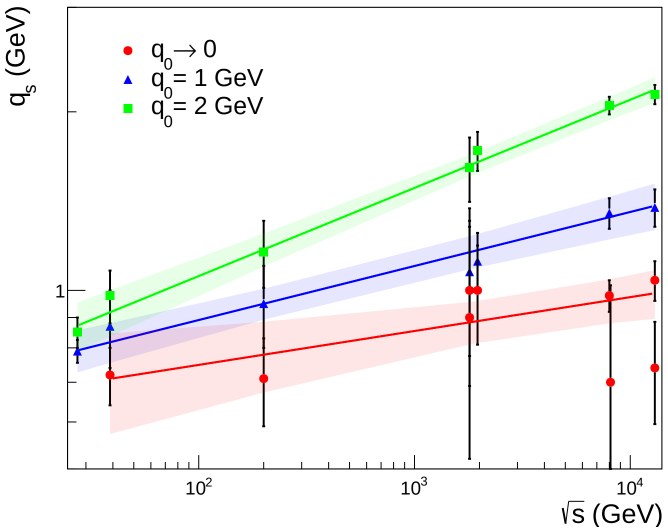


Figure 2: The q_s values as a function of the collision energy, $\sqrt{s}$, obtained from the measurements used in [2] for $q_0 = 1$ GeV and $q_0 = 2$ GeV. Additionally, results from Ref. [1] for $q_0 \to 0$ GeV are included. Each line shows the linear fit of $\log(q_s)$ vs. $\log(\sqrt{s})$.

The inclusion of the non-perturbative Sudakov form factor and proper treatment of soft gluons allows the PB method to describe the low p_T spectrum more accurately than traditional parton-shower approaches. Future studies could further refine these results by exploring more sophisticated models for intrinsic k_T and its energy dependence.

Acknowledgments

I thank my colleagues and CASCADE group members for their contributions to these results. I extend my gratitude to Ministry of Education, Science and Innovation of Montenegro for supporting our ongoing research and ULB (IIHE) for their funding support for ICHEP2024. This work was also supported by the European Union's Horizon 2020 (STRONG-2020, No. 824093).

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