PROCEEDINGS OF SCIENCE

Intrinsic k_T and soft gluons in Monte Carlo event generators

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Experimental measurements of the transverse momentum of Drell-Yan lepton pairs are sensitive to non-perturbative physics associated with the intrinsic parton transverse momentum k_T. We discuss recent determinations of intrinsic k_T in the context of transverse momentum dependent (TMD) parton branching calculations and collinear parton-shower Monte Carlo generators. We illustrate the influence of the soft-gluon resolution scale and the non-perturbative Sudakov region on the intrinsic k_T extraction. We emphasize the relevance of the correct treatment of correlated uncertainties between different transverse momentum bins in TMD fits and present an application to the determination of the intrinsic k_T in the forward rapidity region.

The European Physical Society Conference on High Energy Physics EPS-HEP2025
7-11 July 2025
Marseille, France

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ISSN 1824-8039. Published by SISSA Medialab.

PoS(EPS-HEP2025)256

Introduction The intrinsic transverse momentum k_T of partons in hadronic states at high energies is one of the most important contributions to non-perturbative physics in production processes at hadron colliders. The intrinsic k_T measures transverse degrees of freedom of the strong interactions for low mass scales in the QCD evolution [1]. It is taken into account in parton-shower Monte Carlo event generators [2] which are used in analyses of experimental data at colliders, as well as in QCD calculations based on factorization and evolution of transverse momentum dependent (TMD) parton distributions [3, 4].

The intrinsic k_T distribution can be extracted from comparisons of theory predictions with experimental measurements of the transverse momentum p_T of lepton pairs in the Drell-Yan (DY) process. This has recently been carried out for the Herwig [5] and Pythia [6] collinear parton showers [7] and for the parton branching (PB) [8–11] formulation of TMD evolution [12]. A good description of the low-p_T experimental data is achieved in both cases. For parton showers, this necessitates a value of the intrinsic-k_T parameter that rises steeply with energy (Fig. 1 left). This is not needed in the PB TMD approach (Fig. 1 right).

In these proceedings, we discuss two aspects of these studies and the determination of intrinsic k_T parameters. First, we recall the results of Ref. [16], interpreting the different behaviors seen in Fig. 1 from the standpoint of including (or not) the evolution of the partonic transverse momentum in the parton cascade [17] through TMD distributions, and in particular the role of QCD emissions beyond the soft-gluon resolution scale [18].

The second aspect concerns the value of the intrinsic k_T parameter q_s extracted from the analysis of LHCb measurements [19] shown in Fig. 1 (right), which appears to be about 30% lower than values obtained from the analysis of CMS [15, 20] and ATLAS [21] measurements at similar energies. We revisit the study of the LHCb dataset [22] presenting new results which take into account a number of potentially significant factors, including the contribution of forward rapidities to the transverse momentum distribution, the treatment of final-state radiation, the role of experimental uncertainties and especially correlations in the extraction of the intrinsic k_T parameters.

All PB TMD results shown in these proceedings use the Cascade [23, 24] Monte Carlo generator. The hard scattering is simulated at next-to-leading order with MadGraph5_aMC@NLO [25], matched to the TMD parton distributions and initial-state shower as described in Refs. [26–29]. Final-state radiation and hadronization are simulated with Pythia 6 [30].

Soft gluons at low k_T We analyze the difference between the two panels of Fig. 1 in terms of the partonic branching phase space [18] shown in Fig. 2 (left). In this diagram, the vertical axis represents the transverse momentum q_T of the emitted parton, with hard emissions at the top. Along this axis, emissions with $q_\perp < q_0 \sim 1$ GeV are considered soft and non resolvable. The horizontal axis corresponds to the longitudinal momentum fraction z carried by the emitting parton after a splitting, which is kinematically limited by the energy scale at the branching μ (diagonal lines). The evolution is carried out between the hard scale μ and the small scale $\mu_0 \sim 1$ GeV at which non-perturbative structure of the hadron is parameterized.

An essential feature of the PB TMD is its treatment of soft, non resolvable branchings (gray region in the diagram), which corresponds to non-perturbative Sudakov effects. This region dominates the PB TMD results for the rapidity evolution kernel [31, 32] at large transverse distances b.

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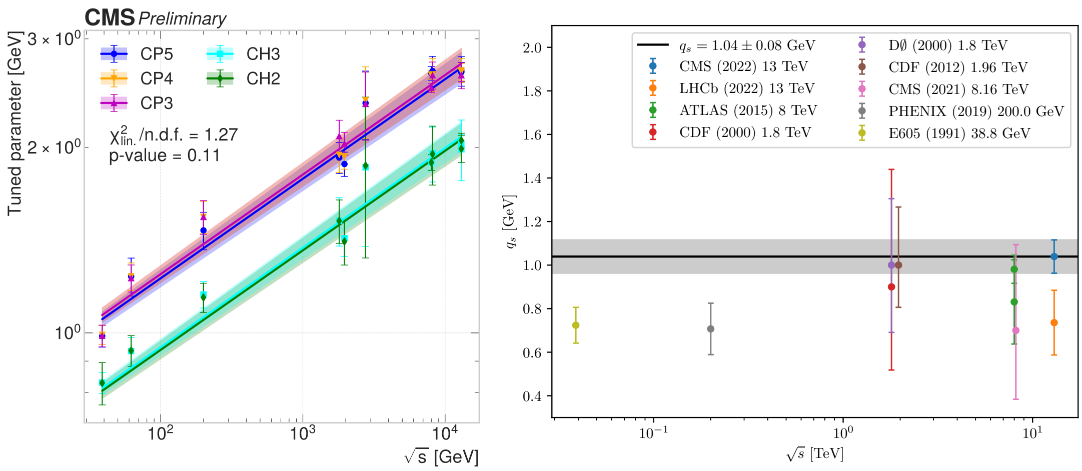

Figure 1: Extraction of intrinsic k_T parameters from measurements of DY transverse momentum distributions at varying center-of-mass energies. The plot on the left-hand side [7] is based on the collinear parton-shower Monte Carlo generators Herwig [5] and Pythia [6], with underlying-event tunes CH2 and CH3 [13] and CP3 through CP5 [14], respectively. The plot on the right-hand side [12] is based on the PB TMD method, with the horizontal line based on CMS 13 TeV data [15].

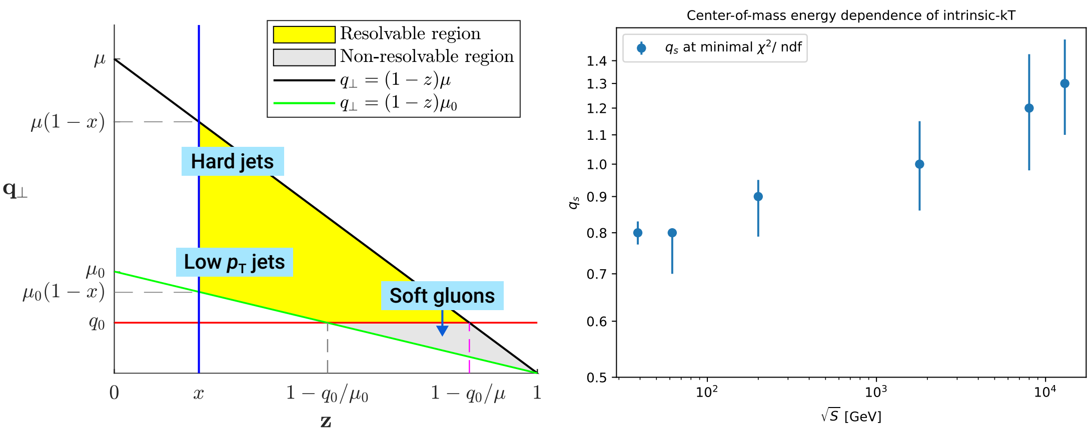

Figure 2: Partonic branching phase space diagram (left, adapted from Ref. [18]) and intrinsic k_T parameter extracted from fits of PB TMD to DY p_T using dynamic soft-gluon resolution scale [16] with $q_0 = 1$ GeV (right).

Such results may be compared with analogous ones from fits of DY data [33–35] and from lattice calculations [36–41] (in particular, regarding the asymptotic large-b behavior [42–45]).

The dependence of PB results in the treatment of the soft, non resolvable region is highlighted in Ref. [16] by stopping the evolution at the "dynamical" soft-gluon resolution scale z_{dyn} [18] that corresponds to the red line in Fig. 2 (left). First, it is verified by an `xFitter` [46] analysis that precision deep inelastic scattering (DIS) measurements are well described by applying the soft-gluon resolution z_{dyn} in the TMD evolution. Second, the analysis of Fig. 1 is repeated to extract the parameter controlling the intrinsic k_T behavior. The results, shown in Fig. 2 (right), exhibit an increase in the value of the extracted intrinsic k_T with energy, similar to Herwig and Pythia. A similar study [47] demonstrates that the slope increases with larger q_0.

Correlated uncertainties and the forward region As mentioned in the introduction, one can see in Fig. 1 (right) that the PB TMD fits to the LHCb measurements [19], as well as to some of the lower-energy measurements, favor lower values of intrinsic k_T. This raises the question of possible physical effects which may be responsible for this: e.g., the impact of large-x parton distributions in the forward LHCb region and at low energy, the TMD flavor dependence in the valence and sea quark sectors, or the interplay of large-x and small-x effects on transverse momentum in the forward-rapidity asymmetric kinematics.

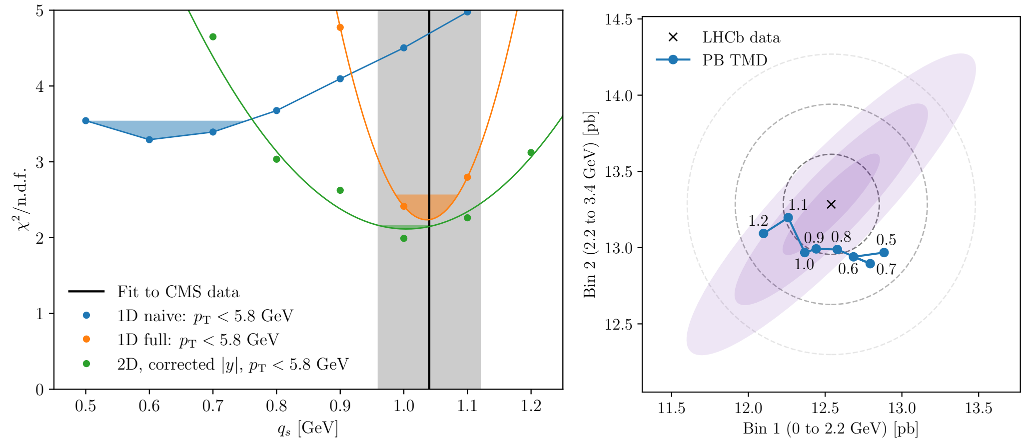

Figure 3: (Left) intrinsic-k_T values extracted from fits to LHCb data: (blue) no correlations; (orange) including correlations; (green) including correlations and correcting the rapidity distribution. (Right) the effect of including correlations in the case of the LHCb dataset [19]: dashed lines corresponds to no correlations, shaded areas correspond to correct correlations included.

In Ref. [22] we focus on the LHCb measurement. The approach followed for the result shown in Fig. 1 (right) is based on minimizing the χ^2 between the measurement and the predicted p_T distributions, neglecting correlations among uncertainties in the measurement made in the different bins. We start by qualitatively reproducing these results (blue line in Fig. 3) using the first four bins of the p_T distribution. We then make two changes to obtain the orange line: we scale the prediction to match the measured total cross section, and we take correlations into account. Finally, we fit the 2D measured p_T-rapidity distribution to obtain the green curve; for this result, we include a correction of the inclusive rapidity distribution predicted by the PB TMD. We make two observations: a) in our fits, the minimum is shifted to a value compatible with the main result of Ref. [12] extracted from the CMS DY measurement [15], and b) the minimum is steeper, resulting in a more precise determination of the intrinsic k_T parameter.

The reason for these changes is illustrated in the right panel of Fig. 3. The LHCb measurement is projected to the plane formed by the first two bins of the p_T distribution. The PB TMD prediction for different values of the intrinsic k_T parameter is represented as a blue line. The experimental uncertainty, accounting for correlations, is shown as the diagonal ellipses for $\chi^2 = 1, 2,$ and 3. The dashed lines show the correspond to the same uncertainty without accounting for the correlation between the bins. Without the correlation, the $\chi^2 < 1$ region includes values of q_s between 0.8 and

1.1 GeV. Accounting for the correlation reduces this to a fraction of the interval between 1.0 and 1.1 GeV. Taking correlations into account is thus essential to fully exploit the constraining power of a measurement.

Summary and outlook We presented two effects influencing extractions of the intrinsic k_T parameters of Monte Carlo generators. We first illustrated that the treatment of soft, non resolvable gluon emissions has an impact on the center-of-mass-energy dependence of the extracted parameters. Then, we turned to experimental effects and highlighted the importance of a correct treatment of correlated uncertainties in fits. In Ref. [22], we find that other effects are important for the description of the LHCb data, including the treatment of QED final-state radiation and background processes. Once these effects are taken into account, good sensitivity to nonperturbative TMD dynamics can be achieved in the forward region.

Acknowledgments We thank the organizers of EPS-HEP2025 for the excellent conference and the kind invitation. We acknowledge useful conversations with A. Bermudez Martinez, H. Jung, H. Li, M. Mangano, N. Raicevic and H. Yin. L. Moureaux acknowledges support by the DFG under Germany's Excellence Strategy 390833306 – EXC 2121: Quantum Universe. A. Lelek acknowledges funding by Research Foundation-Flanders (FWO) (1278325N). L. Favart is supported by the "Fonds de la Recherche Scientifique – FNRS".

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