PROCEEDINGS OF SCIENCE

Intrinsic k_T in shower-based event generators: focus on PYTHIA

Itana Bubanja[a,b,*]

[a] *Faculty of Science and Mathematics, University of Montenegro, Podgorica, Montenegro*

[b] *Interuniversity Institute for High Energies (IIHE), Université libre de Bruxelles, Belgium*

E-mail: itana.bubanja@cern.ch

We explore the role of intrinsic transverse momentum - intrinsic–k_T and its energy dependence in parton shower models used in Monte Carlo event generators. Understanding intrinsic–k_T has long been a challenge: it is typically modeled with a Gaussian distribution, yet in practice, Monte Carlo generators require an intrinsic width that increases with collision energy, reaching unphysical values at high energies. We investigate this behavior in PYTHIA8 and demonstrate that it arises from the interplay between two non–perturbative effects: the intrinsic transverse motion of partons and soft–gluon emissions. These effects become particularly significant in Drell–Yan production at low transverse momentum, which serves as one of the most sensitive probes of initial–state parton evolution. By analyzing the impact of the Sudakov form factor on the required intrinsic–k_T width, we clarify the origin of this unexpected energy dependence and provide new insights into parton shower modeling.

QCD at the Extremes (QCDEX2025)
1–5 Sept 2025
Online

*Speaker

 ISSN 1824-8039 . Published by SISSA Medialab.

PoS(QCDEX2025)009

1. Introduction

In Drell–Yan (DY) production, the transverse momentum spectrum of the lepton pair provides a sensitive probe of several QCD effects. Partons inside a hadron carry both longitudinal and transverse momentum. The transverse momentum arising from their internal Fermi motion is referred to as intrinsic–k_T. At large p_T, the DY spectrum is well described by perturbative QCD, whereas at low transverse momenta non-perturbative effects dominate, including intrinsic–k_T and multiple soft-gluon emissions.

In parton-shower Monte Carlo generators such as Pythia8 and Herwig, the width of the intrinsic–k_T distribution depends on the center-of-mass energy $\sqrt{s}$, increasing with $\sqrt{s}$ as shown in Ref. [1]. In contrast, the Parton Branching (PB) method [2, 3], which uses Transverse Momentum Dependent (TMD) parton distributions, can describe the DY cross section [4, 5] as a function of the pair transverse momentum $p_T(\ell\ell)$ with an intrinsic–k_T distribution that is nearly independent of $\sqrt{s}$, as shown in Refs. [6, 7]. Within TMD factorization, both the hard-scattering matrix element and the parton distribution functions depend on the partons' transverse momentum, ensuring a consistent flow of k_T. However, when the PB method excludes the non-perturbative region near the soft-gluon resolution boundary, a dependence of the intrinsic–k_T width on $\sqrt{s}$ appears, as shown in Refs. [8–11] suggesting the interplay between instrinsic–k_T and soft gluon emissions. This $\sqrt{s}$ dependence resembles the behavior observed in parton-shower Monte Carlo generators.

To investigate in detail the interplay between soft–gluon emissions and intrinsic–k_T at low p_T, Pythia has been tuned to reproduce as closely as possible the setup used within the PB–TMD method to study if this tuning results in a significantly improved agreement with data and leads to a much milder dependence of the extracted intrinsic-k_T width on $\sqrt{s}$ [12].

2. Pythia Tune

In the PB method [8], perturbative and non-perturbative emissions are separated through the Sudakov form factor. In contrast, Pythia includes soft emissions but suppresses non-perturbative ones using the ISR cut-off parameter `SpaceShower:pT0Ref`, which default value is 2 GeV. Lowering `pT0Ref` therefore allows more soft radiation, similar to the PB approach. To study its impact on the energy dependence of the intrinsic transverse-momentum width, we vary this cut-off. The intrinsic k_T is introduced as a non-perturbative Gaussian with width σ, corresponding to the parameter `BeamRemnants:primordialKThard` in Pythia8.

Figure 1 shows the Drell–Yan p_T spectrum in the Z peak region at $\sqrt{s}$ = 13 TeV using the Pythia Monash 2013 tune, for `pT0Ref` = 0.5 and 2.0 GeV. The influence of intrinsic k_T is largest at the lowest p_T, and the sensitivity decreases when the ISR cut-off is reduced.

The baseline analysis for this study was recent precision measurement of Drell Yan production cross section at 13 TeV [15]. To obtain the best agreement with data, a modified Monash tune is used. Monash uses the NNPDF2.3 LO set with $\alpha_s(m_Z) = 0.130$ and $\alpha_s(m_Z) = 0.1365$ for both ISR and FSR. Its default non-perturbative parameters are `pT0Ref` = 2.0 GeV and σ = 1.8 GeV. The optimised tune was obtained by modifying the value of $\alpha_s(m_Z) = 0.130$ in the Monash tune and by using the lowest accessible value pT0Ref=0.5 GeV in Pythia8 and adjusting the intrinsic–k_T width to best describe the lowest measured p_T region[12]. The width of the intrinsic–k_T distribution is

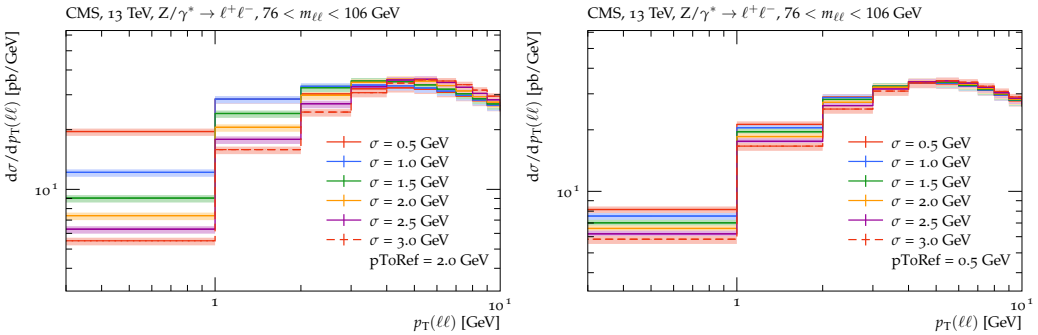

Figure 1: pT0Ref=2 GeV (left) and pT0Ref=0.5 GeV (right), σ values of 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 GeV . The CMS measurement [15] was used. *The plot is taken from Ref.[12] with the kind permission of The European Physical Journal C.*

obtained by fitting the predicted DY cross section to the measured $p_T(ll)$ spectrum. Predictions are generated with MCatNLO interfaced to the optimized tune parton shower, and compared to data using Rivet. The parameter `primordialKThard` is varied and the value corresponding to the minimum of χ^2(`primordialKThard`) is taken [12]. Because detailed uncertainty breakdown are not available for most measurements, the experimental uncertainties are treated as uncorrelated.

3. Results

A detailed description of the parton-shower framework can be found in Refs. [16, 17]. Here is briefly outlined the role of the Sudakov form factor $\Delta(Q_1^2, Q_2^2)$, which gives the probability of no radiation between the evolution scales Q_1^2 and Q_2^2. For backward evolution it is written as

$$\log \Delta_{bw}(Q_1^2, Q_2^2) = -\sum_a \int_{Q_1^2}^{Q_2^2} \frac{\alpha_s(Q^2)}{2\pi} \frac{dQ^2}{Q^2} \int_x^{z_{\rm dyn}} dz\, P_{ab}(z)\, \frac{x'\, f_b(x', Q^2)}{x\, f_a(x, Q^2)}\,, \qquad (1)$$

where $P_{ab}(z)$ is the DGLAP splitting function, $x = x'z$ and the scale Q^2 is related to the transverse momentum by $p_\perp^2 = (1-z)Q^2$, so large z corresponds to small $p_\perp$. The upper limit $z_{\rm dyn} < 1$ is set by the dipole kinematics. Soft emissions are suppressed at small $p_\perp$ by the factor $p_\perp^2/(p_\perp^2 + p_{\perp 0}^2)$, with $p_{\perp 0}$ = `pT0Ref`, and the shower is limited by the hard scale μ such that $Q_2 < \mu$. The Sudakov form factor therefore depends on `pT0Ref` through both the z limit and the scale behaviour in Eq. (1).

To study the effect of pT0Ref and energy dependence, the intrinsic–k_T width σ was plotted against `pT0Ref` obtained at different center-of-mass energies: LHC data [15], Tevatron data [18], and data from lower energies [19, 20] (Fig. 2). With increasing $\sqrt{s}$, the number of both perturbative and soft branchings grows, so for a fixed `pT0Ref` the intrinsic-k_T width increases with energy. In the range 0.5–2.0 GeV, σ rises approximately linearly with `pT0Ref`. At lower energies (38.8 and 200 GeV), soft gluons around $p_\perp \sim 0.5$ GeV dominate, so σ varies only weakly with the cut-off. At higher energies, the rise with `pT0Ref` is more visible, but the slope is similar across TeV-scale measurements ($\sqrt{s}$ = 1.96 TeV and 13 TeV).

The soft emissions should predominately contribute at low scale. In order to test the width parameter σ dependence on `pT0Ref` in low mass region, ratio plots of the simulated cross sections

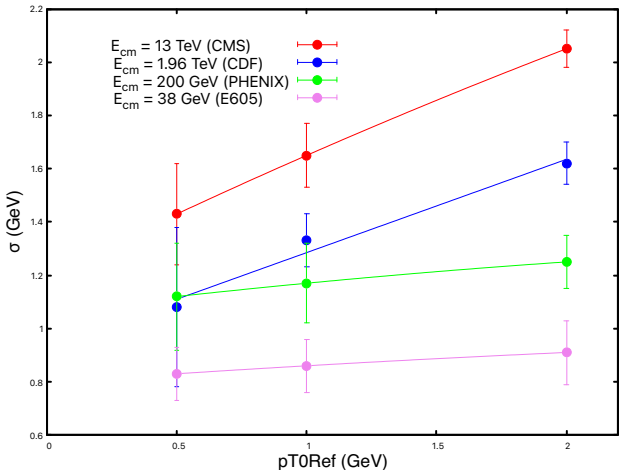

Figure 2: Dependence of the intrinsic–k_T width, σ, on the ISR cut-off parameter `pT0Ref` used in Pythia tune for different collision center of mass energies [15, 18–20]. *The plot is taken from Ref.[12] with the kind permission of The European Physical Journal C.*

obtained with Pythia for two ISR cut-off values, `pT0Ref` = 0.5 GeV and 2.0 GeV were obtained, as shown on Fig. 3. As expected, the difference between the two simulations grows as m_{DY} decreases.

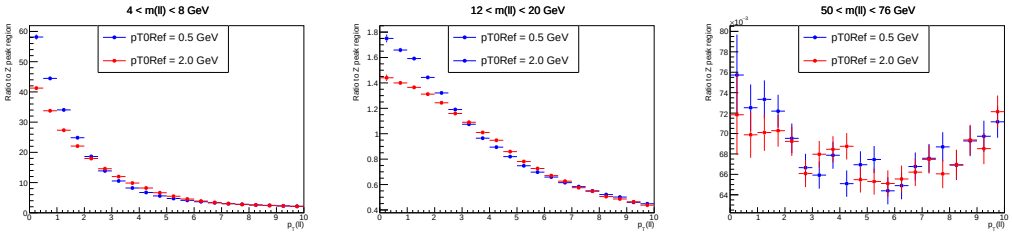

Figure 3: The ratio of the predicted $p_T(ll)$ spectrum to the Z-peak region, evaluated in different Drell–Yan invariant-mass bins, for two ISR cut-off values, `pT0Ref` = 0.5 GeV and 2.0 GeV. *The plot is taken from Ref.[12] with the kind permission of The European Physical Journal C.*

4. Conclusion

A detailed study was performed to model the Drell–Yan $p_T(ll)$ spectrum using Pythia simulations, with emphasis on the lowest $p_T(ll)$ region where non-perturbative effects, intrinsic parton transverse momentum and soft gluon emissions, are most significant. The results confirm that the $\sqrt{s}$ dependence of the intrinsic–k_T width originates from soft gluon emissions, regulated by the ISR transverse-momentum cut-off.

In the range $0.5 <$ `pT0Ref` $< 2.0\,GeV$, the intrinsic–k_T width increases approximately linearly with the ISR cut-off, demonstrating a direct link to the no-emission probability encoded in the Sudakov form factor. The observed dependence of the width σ on m_{DY}, especially pronounced at low m_{DY}, confirms the Q-dependent part of the Sudakov form factor. These results suggest that the energy dependence of the intrinsic–k_T width in Monte Carlo event generators arises from soft, non-perturbative gluon emissions during parton evolution and the parton shower.

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 support in funding.

References

[1] CMS Collaboration, "Energy-scaling behavior of intrinsic transverse-momentum parameters in Drell-Yan simulation", *Phys. Rev. D* **111** (2025) 7,DOI: 10.1103/PhysRevD.111.072003.

[2] F. Hautmann et al., "Collinear and TMD quark and gluon densities from Parton Branching solution of QCD evolution equations", *JHEP* **01** (2018) 070, arXiv:1708.03279.

[3] F. Hautmann et al., "Soft-gluon resolution scale in QCD evolution equations", *Phys. Lett. B* **772** (2017) 446, arXiv:1704.01757.

[4] A. Bermudez Martinez et al., "Production of Z-bosons in the parton branching method", *Phys. Rev. D* **100** (2019) 074027, arXiv:1906.00919.

[5] A. Bermudez Martinez et al., "The transverse momentum spectrum of low mass Drell–Yan production at next-to-leading order in the parton branching method", *Eur. Phys. J. C* **80** (2020) 598, arXiv:2001.06488.

[6] I. Bubanja et al., "The small k_{T}region in Drell-Yan production at next-to-leading order with the parton branching method", *Eur. Phys. J. C* **84** (2024) 154, DOI: 10.1140/epjc/s10052-024-12507-0.

[7] N. Raičević, "The Impact of Intrinsic Motion of Partons in Drell–Yan Production at NLO with the Parton Branching Method", *Moscow Univ. Phys.* **79**, 455 (2024), DOI: 10.3103/S0027134924701285.

[8] I. Bubanja et al., "Center-of-mass energy dependence of intrinsic-kT distributions obtained from Drell-Yan production", *Eur. Phys. J. C* **85** (2025) 278, DOI: 10.1140/epjc/s10052-025-14021-3.

[9] N. Raičević, "Study of intrinsic-kT in the Parton Branching Method", *Nucl. Part. Phys. Proc.* **347**, 12 (2024), DOI:10.1016/j.nuclphysbps.2024.09.005.

[10] N. Raičević, "The Role of the Intrinsic-kT and Soft Gluon Contributions in Drell–Yan Production", *Phys. Part. Nuclei Lett.* **22**, 156 (2025), DOI: 10.1134/S1547477124702017.

[11] N. Raičević, "Non-perturbative contributions to low transverse momentum Drell- Yan pair production using the Parton Branching Method", *Phys. Scripta* **100**, No 4 (2025), DOI: 10.1088/1402-4896/adc163.

[12] I. Bubanja et al.,"Interplay of intrinsic motion of partons and soft gluon emissions in Drell–Yan production studied with PYTHIA", *The European Physical Journal C* **85** (2025) 363, DOI: 10.1140/epjc/s10052-025-14066-4.

[13] A. Bermudez Martinez, F. Hautmann, and M. L. Mangano, "TMD evolution and multi-jet merging", *Phys. Lett. B* **822** (2021) 136700, arXiv:2107.01224.

[14] R. Angeles-Martinez et al., "Transverse Momentum Dependent (TMD) parton distribution functions: status and prospects", *Acta Phys. Polon. B* **46** (2015), no. 12, 2501, arXiv:1507.05267.

[15] CMS Collaboration, "Measurement of the mass dependence of the transverse momentum of lepton pairs in Drell-Yan production in proton-proton collisions at $\sqrt{s}$ = 13 TeV", *Eur. Phys. J. C* **83** (2023) 628, arXiv:2205.04897.

[16] M. Bengtsson, T. Sjostrand, and M. van Zijl, "Initial state radiation effects on W and jet production", *Z. Phys. C* **32** (1986) 67.

[17] C. Bierlich et al., "A comprehensive guide to the physics and usage of PYTHIA 8.3", *SciPost Phys. Codeb.* **2022** (2022) 8, arXiv:2203.11601.

[18] CDF Collaboration, "Transverse momentum cross section of e^+e^- pairs in the Z-boson region from $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV", *Phys. Rev. D* **86** (2012) 052010, arXiv:1207.7138.

[19] PHENIX Collaboration, "Measurements of $\mu\mu$ pairs from open heavy flavor and Drell-Yan in $p + p$ collisions at $\sqrt{s}$ = 200 GeV", *Phys. Rev. D* **99** (2019) 072003, arXiv:1805.02448.

[20] G. Moreno et al., "Dimuon production in proton - copper collisions at $\sqrt{s}$ = 38.8 GeV", *Phys. Rev. D* **43** (1991) 2815.