Drell–Yan Production Using a New Approach PDF2ISR in the PYTHIA Event Generator

Dušan Subotić [1], Hannes Jung [2] and Nataša Raičević [1]

1 University of Montenegro, Faculty of Science and Mathematics, Montenegro

2 DESY, Hamburg, Germany

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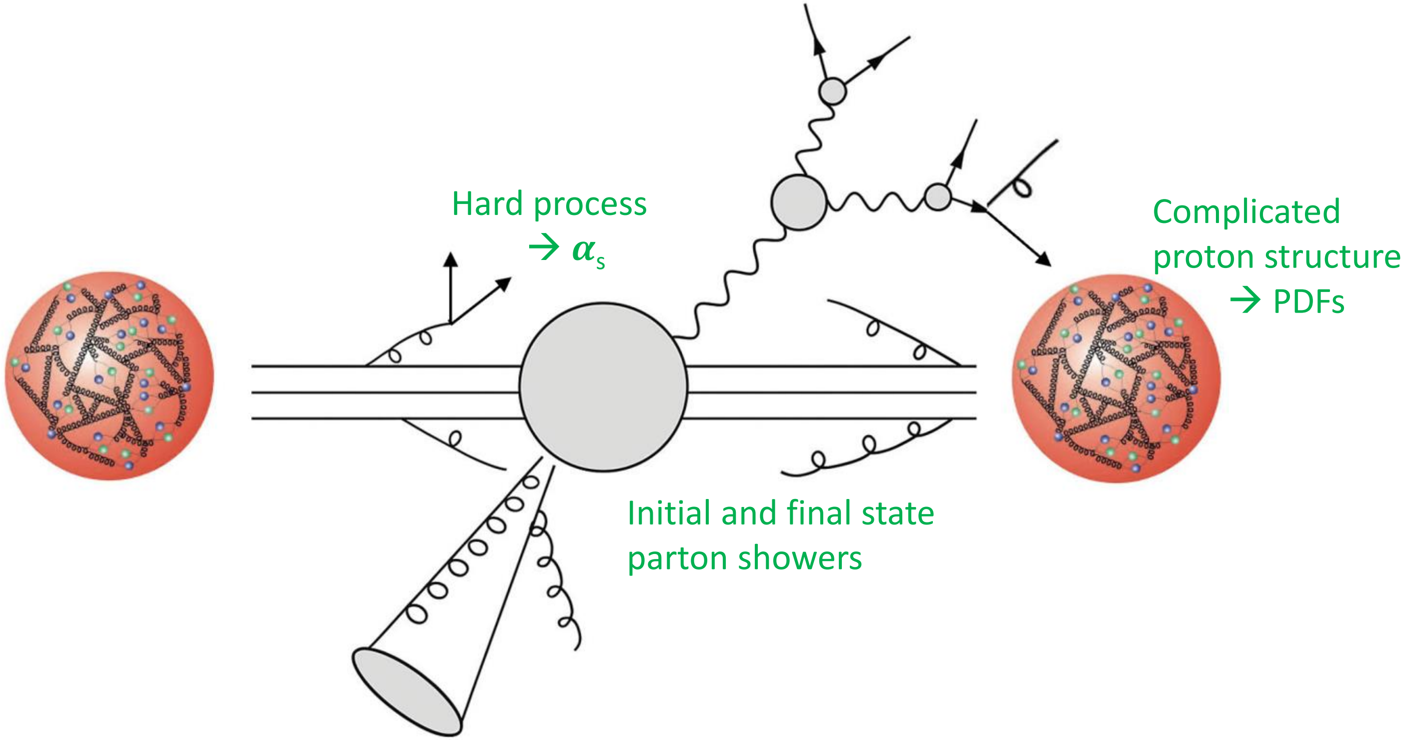
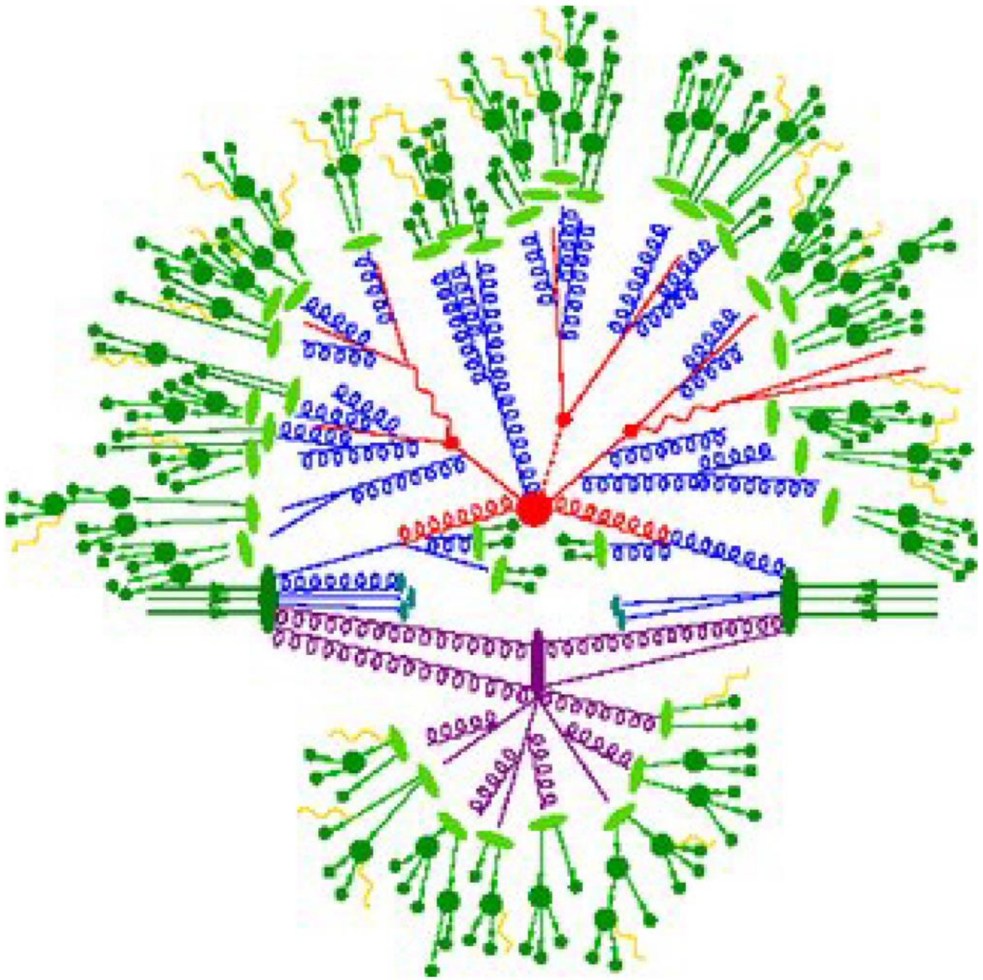
Outline

- **Parton Branching Method (PB)**
  - Transverse Momentum Dependent parton density functions (TMDs) as a key ingredient
  - Consistent treatment of collinear and transverse dynamics
- **Motivation for a new approach**
  - Limitations of standard MC event generators in describing non-perturbative effects
  - Need for a more consistent treatment of parton evolution and transverse momentum dynamics
- **PDF2ISR approach**
  - Toy model study based on parton fusion into a hypothetical “Boson”
- **Validation studies of the PDF2ISR approach**
  - Study using real Drell–Yan samples

QCD (Quantum ChromoDynamics) process



- At high energy, hard interactions occur between quasi-free partons originating from hadrons
- Addidtional processes both precede and follow the hard scattering
- Partons inside protons also undergo internal motion which gives them additional transverse momentum



Hard Scattering

Parton Shower (PS)

Hadronization

Decays of hadrons

Multi-parton interactions (MPI)

Final State Radiation (FSR)

Why Parton Branching (PB) method?

- The main goal of all theoretical predictions in HEP nowdays is to reduce uceratinties at all levels

  → Testing the consistency of the Standard Model and identify potential deviations that could signal new physics

- However, the challenge of treating soft gluon emissions and their resummation in collinear parton shower generators still persists

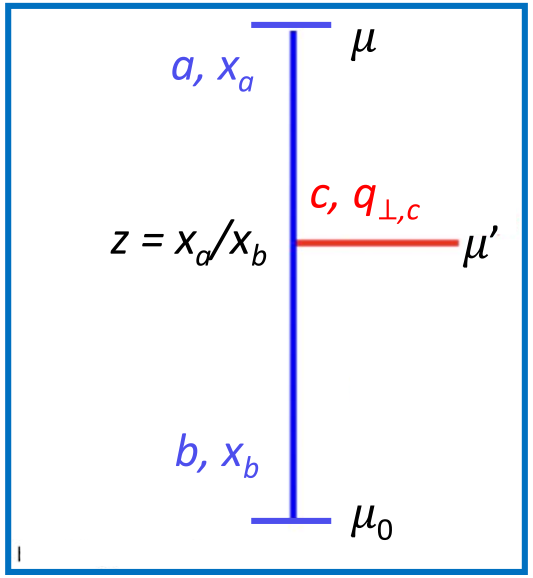
  → The development of the PB Method which takes a different approach by introducing the transverse degree of freedom (k_T – parton transverse momentum) already at the parton distribution level

- The PB Method also allows to determine transverse momentum dependent PDFs - TMDs

  $A_a(x,k_T,\mu^2)$ – gives the probability of finding a parton **a** with a hadron momentum fraction x, transverse momentum k_T and at the evolution scale μ

  → TMDs for all flavours across a wide kinematic range obtained from the TMD evolution equation

Parton Branching



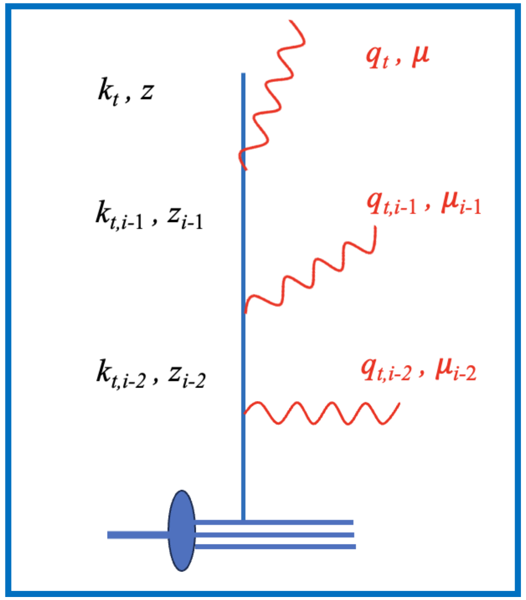
One branching

$b \rightarrow a + c$

$q_{\perp,c} \sim \mu'$ – branching variable

z – longitudinal momentum transfered at the branching ($0 < z < z_M$)

+ ....



More branchings

- ❑ z_M – soft gluon resolution parameter defining resolvable ($z < z_M$) and non-resolvable ($z > z_M$) parton branchings

- ➢ PB method takes into account *angular ordering* based on colour coherence in QCD according to which the angles of partons with respect to an initial hadron increase in the subsequent branching

$\mu' = |\boldsymbol{\mu}'| = q_\perp/(1-z)$ – angular ordering is independent of the choice of the soft-gluon resolution scale when $z_M \rightarrow 1$

TMDs

- Parton evolution is expressed in terms of resolvable, real emission DGLAP splitting functions, P_{ab} for parton splitting b → a, and Sudakov form factors (Δ_a) which give the probability to evolve from one scale to another scale without resolvable branching
- The TMD for a parton a, with the longitudinal momentum fraction x of the proton and the transverse momentum **k**, evaluated at a scale μ:

$$\mathcal{A}_a(x,\mathbf{k},\mu^2) = \Delta_a(\mu^2)\,\mathcal{A}_a(x,\mathbf{k},\mu_0^2) + \sum_b \int_{\mu_0}^{\mu} \frac{d^2\mu'}{\pi\mu'^2} \frac{\Delta_a(\mu^2)}{\Delta_a(\mu'^2)}\,\Theta(\mu^2-\mu'^2)\,\Theta(\mu'^2-\mu_0^2) \times \int_x^{z_M} \frac{dz}{z} P_{ab}^{(R)}(\alpha_s,z)\,\mathcal{A}_b\left(\frac{x}{z},\mathbf{k}+(1-z)\,\boldsymbol{\mu}',\mu'^2\right)$$

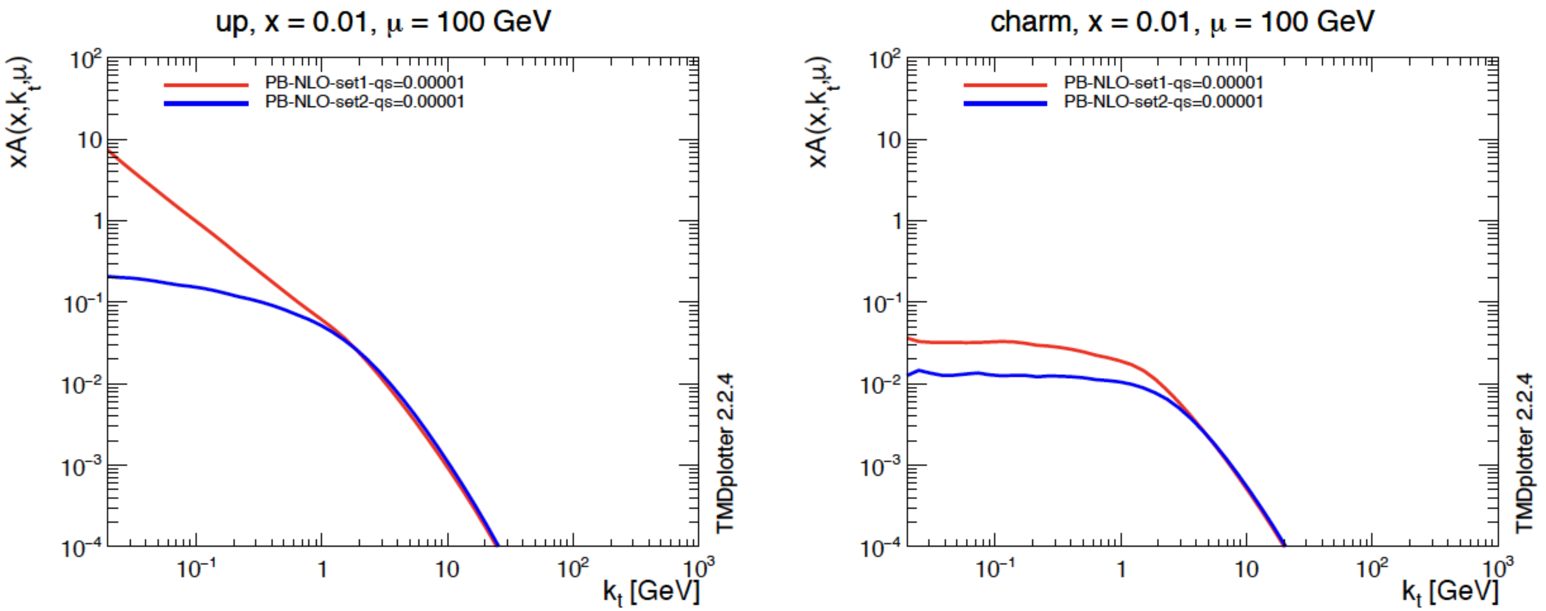
$$\Delta_a(z_M,\mu^2,\mu_0^2) = \exp\left(-\sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \int_0^{z_M} dz\; z\; P_{ba}^{(R)}(\alpha_s,z)\right)$$

$\mathcal{A}_a(x,\mathbf{k},\mu_0^2)$ - the TMD at the starting scale μ_0 is a nonperturbative boundary condition to the evolution equation and is determined from experimental data

- z_M → 1 gives the exact solution of the DGLAP evolution
- Integration of $\mathcal{A}_a(x,\mathbf{k},\mu^2)$ over all **k** gives collinear PDFs - $f_a(x,\mu^2)$

α_s scale

- The scale at which α_s should be evaluated in the PB evolution equations is a function of the branching variable μ'
- $\alpha_s = \alpha_s(\mu'^2)$ → **PB-NLO-2018 set 1**
- $\alpha_s = \alpha_s(\mu'^2(1-z)^2) = \alpha_s(q_T^2)$ → **PB-NLO-2018 set 2**



- Significant difference at low transverse momenta of partons
- For heavy flavours the difference is much smaller since they are only generated dynamically

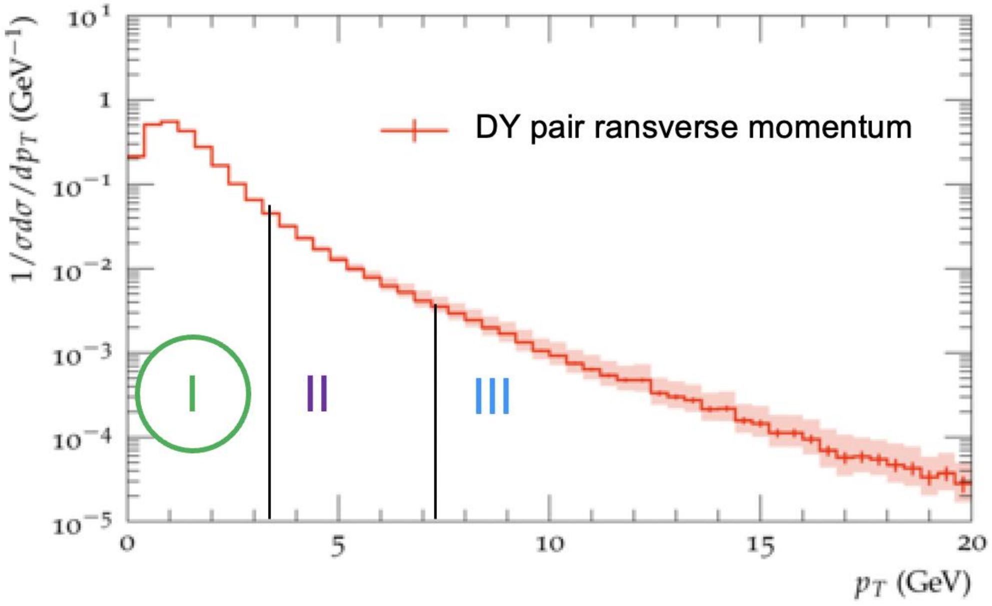
Non-perturbative processes in the parton evolution in the initial state

- Intrinsic-kT

  The largest component of an initial parton's momenta inside a hadron is its longitudinal momentum, received from the parent parton. However, in addition to this, partons also possess **transverse momentum due to their internal (Fermi) motion – known as intrinsic k_T**

- Multiple soft gluon emmissions

- The production of **Drell-Yan (DY) lepton pairs** in hadron collisions - excellent process to study various QCD effects



I – Non-perturbative region

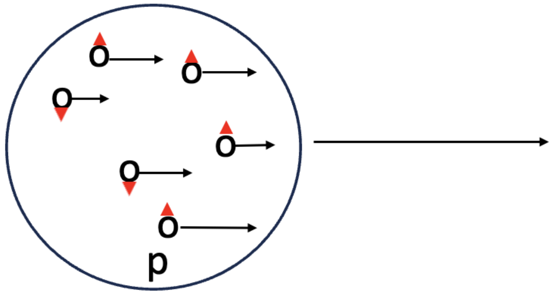
- intrinsic motion of partons
- resummation of multiple soft gluon emissions

II – Transition region

III - Perturbative higher-order contributions dominating

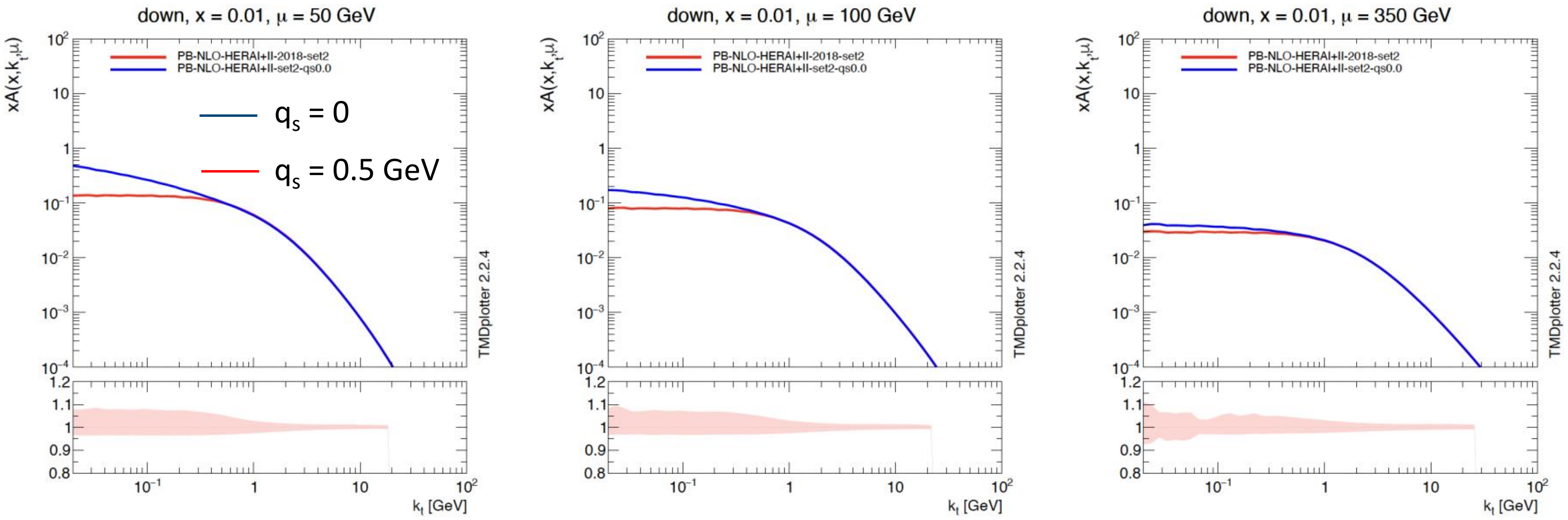
➢ Eur.Phys.J.C 84 (2024) 2, 154 → low p_T DY distributions at LHC data well described with **PB-NLO-2018 set 2**

Intrinsic k_T in TMDs



- In the evolution, intrinsic k_T is introduced as a non-perturbative parameter and is generated from a Gaussian distribution with width σ which is expressed in the PB Model via the parameter $\mathbf{q_s}$: $\sigma^2 = q_s^2/2$

$$A_a(x, k_0, \mu_0^2) = f_a(x, \mu_0^2) \cdot \frac{\exp\left(-\frac{|k_0^2|}{q_s^2}\right)}{(\pi q_s^2)^{1/2}}$$

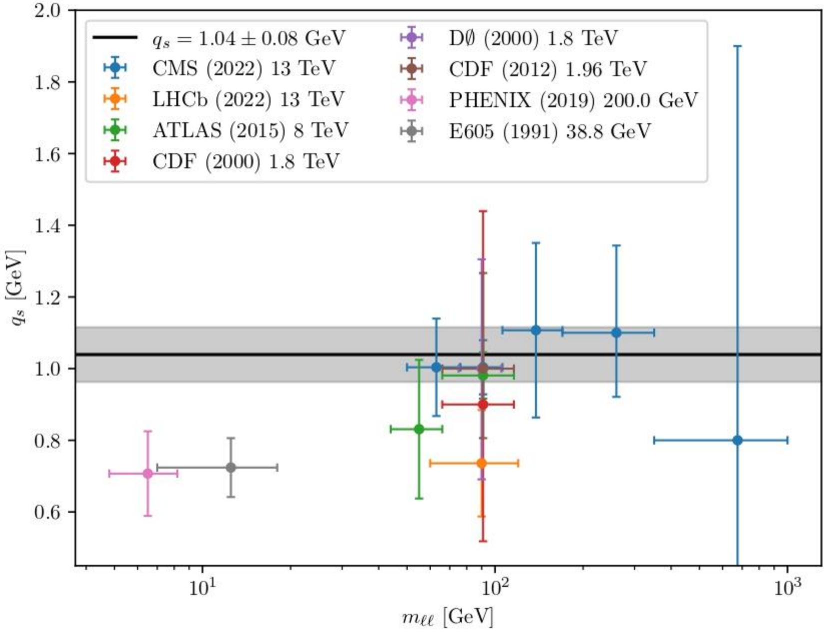


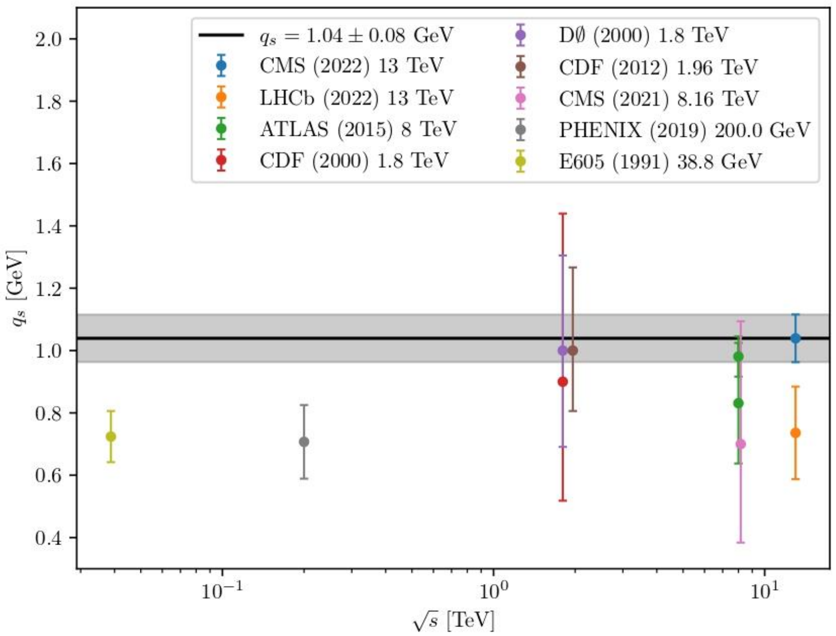
- Significant effect of the intrinsic-k_T at low scales

Intrinsic k_T-width depending on $\sqrt{s}$ and DY mass

I. Bubanja et al, Eur.Phys.J.C 84 (2024) 2, 154

- $q_0 = 10^{-2}$ GeV - minimal parton transverse momentum emitted at a branching
- $q_T > q_0$ → soft contributions included





→ Consistent values of q_s are observed across a wide range of DY pair invariant masses

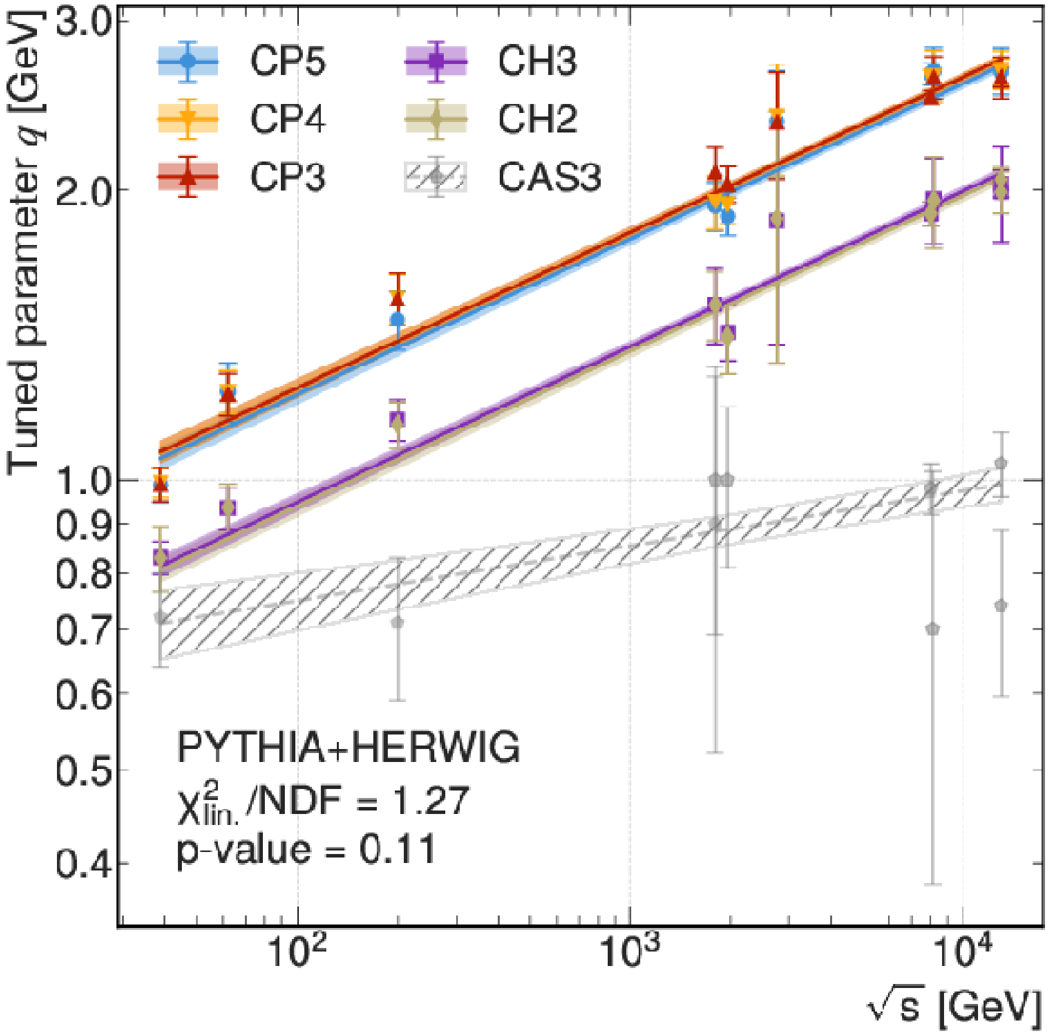
→ No trend in centre-of-mass energy dependence of q_s is observed

→ The result stands in contrast to those from standard Monte Carlo event generators which require a strongly increasing intrinsic k_T width with $\sqrt{s}$

T. Sjostrand, Peter Z. Skands, JHEP 03 (2004) 053; Stefan Gieseke, Michael H. Seymour, Andrzej Siodmok, JHEP 06 (2008) 001;
CMS, *GEN-22-001, 2024*

Centre-of-mass dependence of the k_T width in the shower-based generators

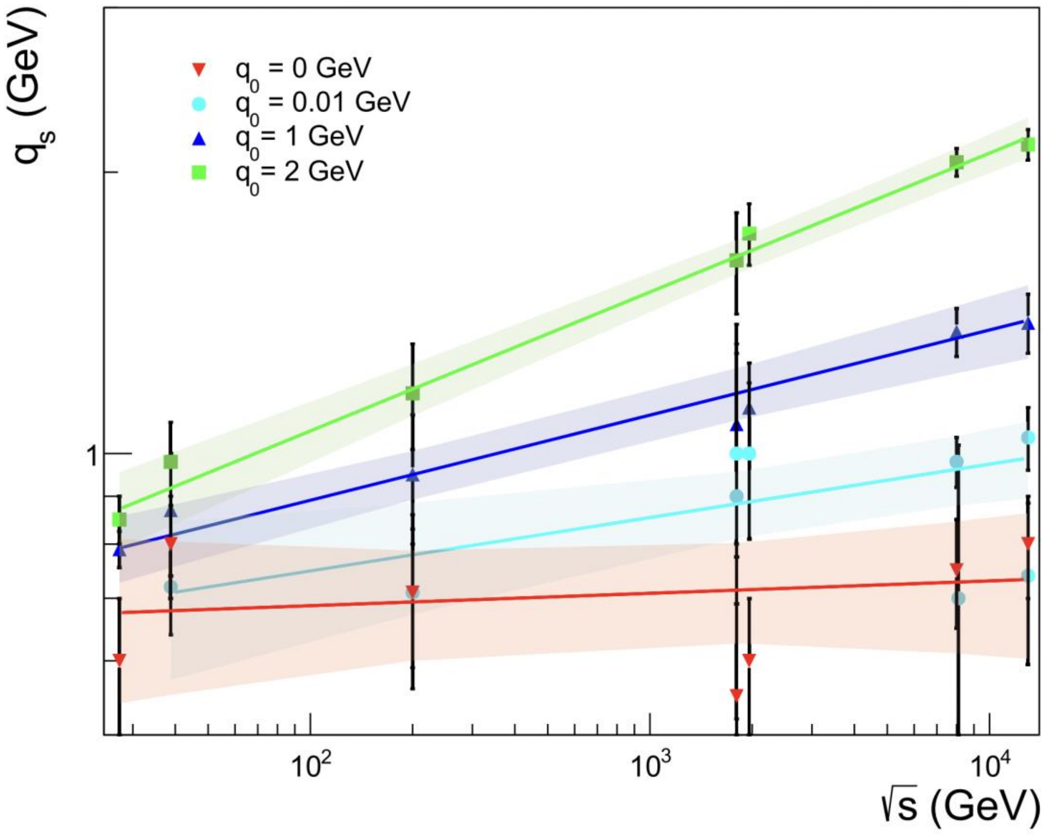
CMS Collaboration, *Phys.Rev.D* 111 (2025) 7, 072003



- In standard shower-based event generators such as **PYTHIA** and **HERWIG**, the intrinsic-k_T width increases with energy independently of the tune
- In contrast, the result from CASCADE3 (which is based on the PB Method), when fitted with the same function form, shows only a very mild dependence
- A possible reason for this difference could be the exclusion of soft gluon emissions in PYTHIA and HERWIG, aimed at avoiding potential divergences
- The origin of this energy dependence has been studied using the CASCADE3 event generator by varying the contribution from soft gluon emissions

Explanation of the centre-of-mass energy dependence of k_T

I. Bubanja et al, Eur. Phys. J. C 85 (2025) 3, 278



By mimicking standard shower-based event generators within the PB method, it was concluded that:

- The intrinsic-k_T width parameter increases with the collision energy for $q_0 > 0$ GeV
- The slope od the dependence increases as q_0 increases
- Larger q_0 means that more soft contributions are excluded

  → Larger intrinsic-k_T needed to compensate missing contribution from soft gluons

→ Implement the PB Method in PYTHIA, and develop a procedure for obtaining an initial-state parton shower model in which the (backward) evolution is fully consistent with the (forward) evolution of the collinear parton density used

➢ A parton shower consistent with parton densities at LO and NLO: PDF2ISR proposed in arXiv:2504.10243

PDF2ISR

H. Jung et al, arXiv:2504.10243

- PDF2ISR approach constructs the initial-state radiation (ISR) simulated as a parton shower to exactly follow the evolution of the collinear parton density, using the PB Method

- The PB-TMD distributions are, by construction, consistent with the collinear distributions upon integration over the transverse momentum

→ TMD parton densities are ideal for testing the consistency between the evolution and the parton shower, as they can be obtained from both approaches

- The default initial-state parton shower in PYTHIA8 is modified to use the parameters of the collinear PB parton distribution and to follow the same kinematic constraints as in the parton evolution, in order to obtain effective TMD distributions

- Consistent results can be achieved when using the same settings in PYTHIA as it is in PB Method

- The transverse momentum ordering ($\mu' = q_T$) is replaced by angular ordering ($\mu' = \frac{q_T}{1-z}$)

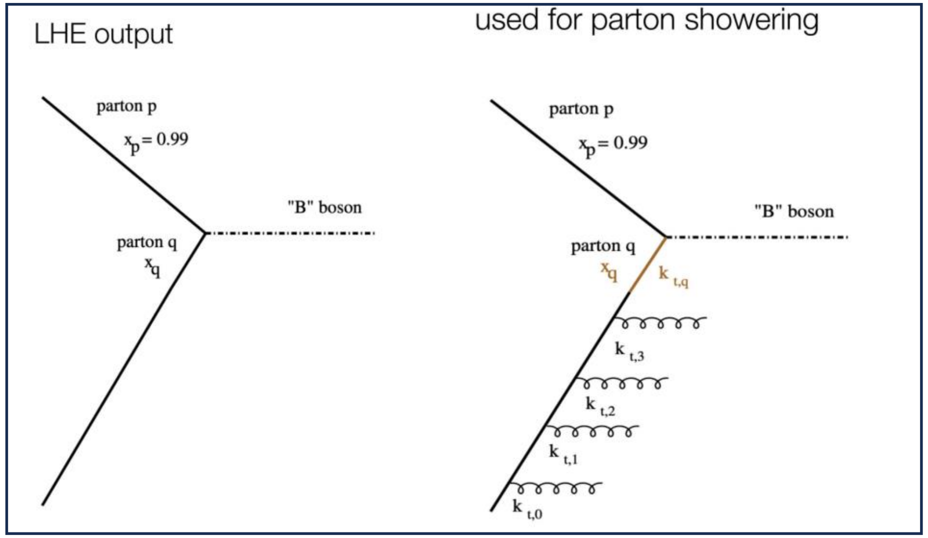
- α_s is treated the same way as in the PB method

- When considering TMDs at NLO obtained with the PB-method, NLO splitting functions must be used

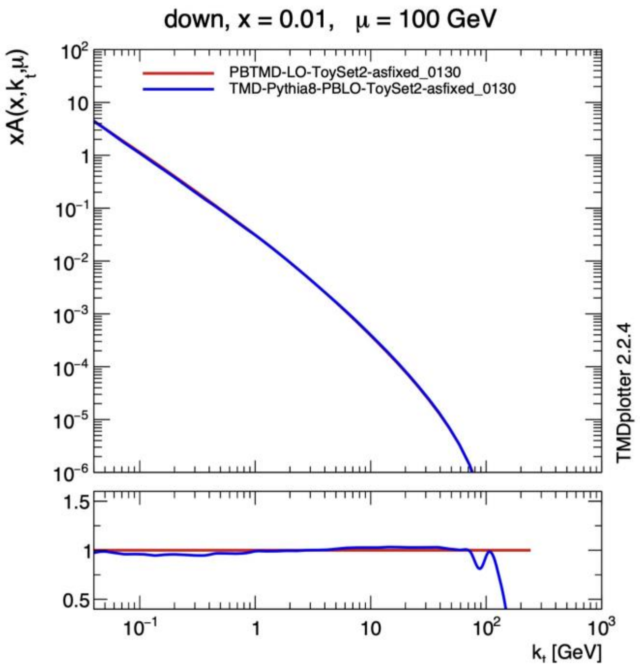
→ High level of consistency achieved between the TMDs in PB and those in PYTHIA as shown in the next slide

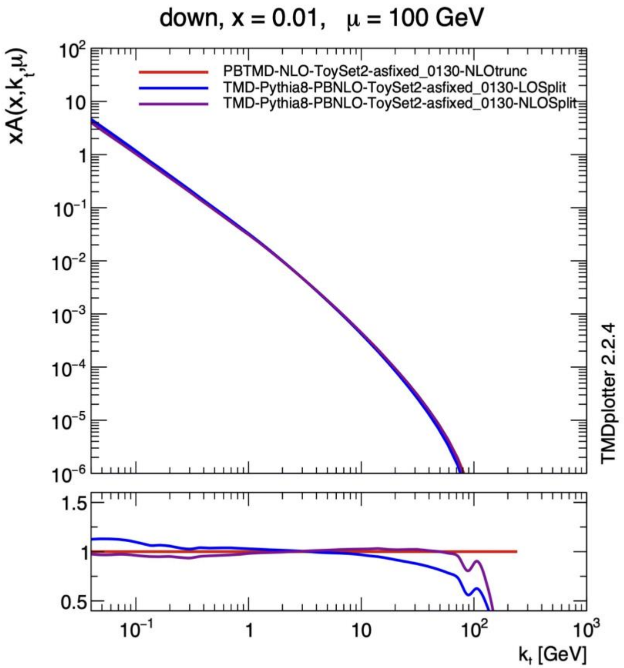
Results from the Toy Model used for studying PDF2ISR

H. Jung et al, arXiv:2504.10243



- ❑ Toy model: B-boson (unphysical, couples to quarks and gluons)
- ➢ LHE files produced with given collinear PDF, for different scales μ and different x_q while keeping x_p fixed
- ➢ allow parton shower only from one leg
  → B-boson transverse momentum $k_{T,q}$
- ➢ $\sqrt{s} = 5 \cdot 10^3\ TeV$ to ensure appropriate coverage of the phase space



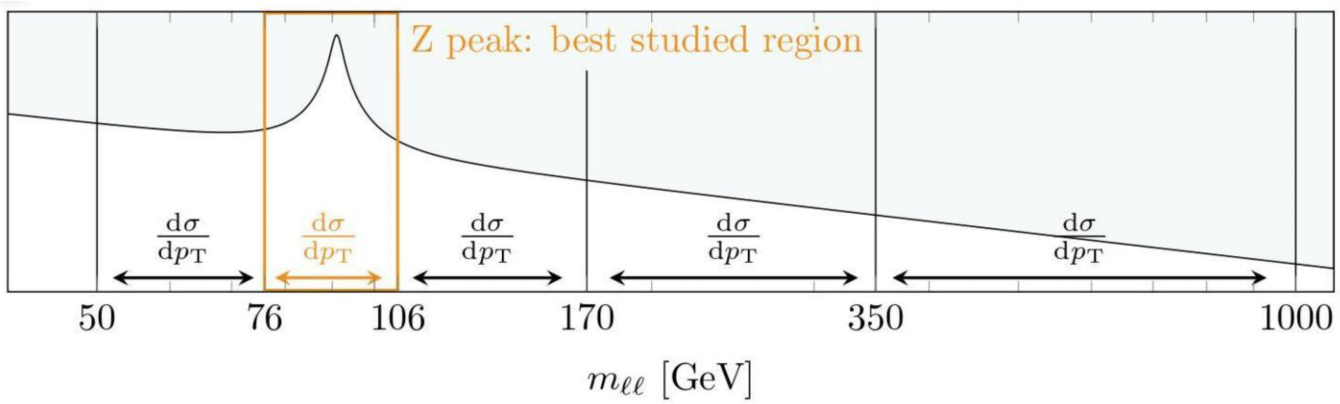


- ❑ Very good agreement between the TMDs from the PB and PYTHIA-PB at LO
- ❑ For the NLO case
- ➢ with NLO splitting functions in PYTHIA → good agreement
- ➢ Using LO splitting functions in PYTHIA (even with NLO α_s) → large differences
- ➢ NLO splitting functions essential for consistent treatment with NLO pdf

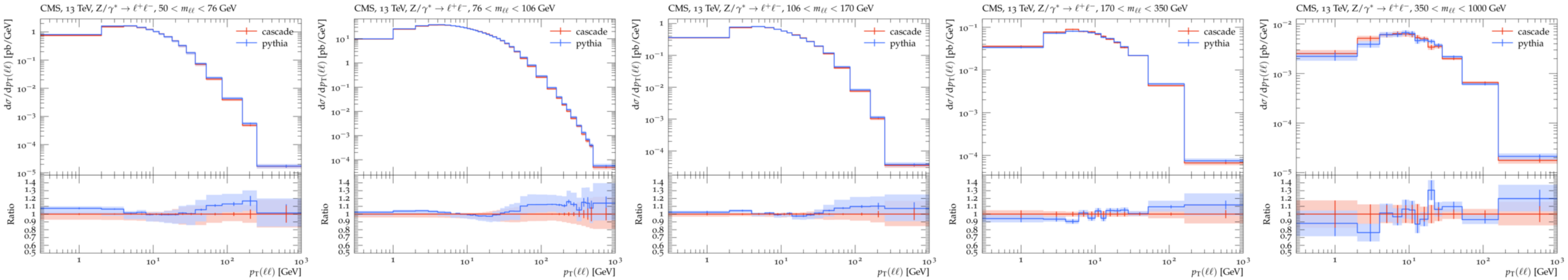
Compare real DY p_T from PB and PYTHIA-PB at NLO at 13 TeV

- Use phase space recently measured by the CMS at 13 TeV

Eur. Phys. J. C 83 (2023) 628

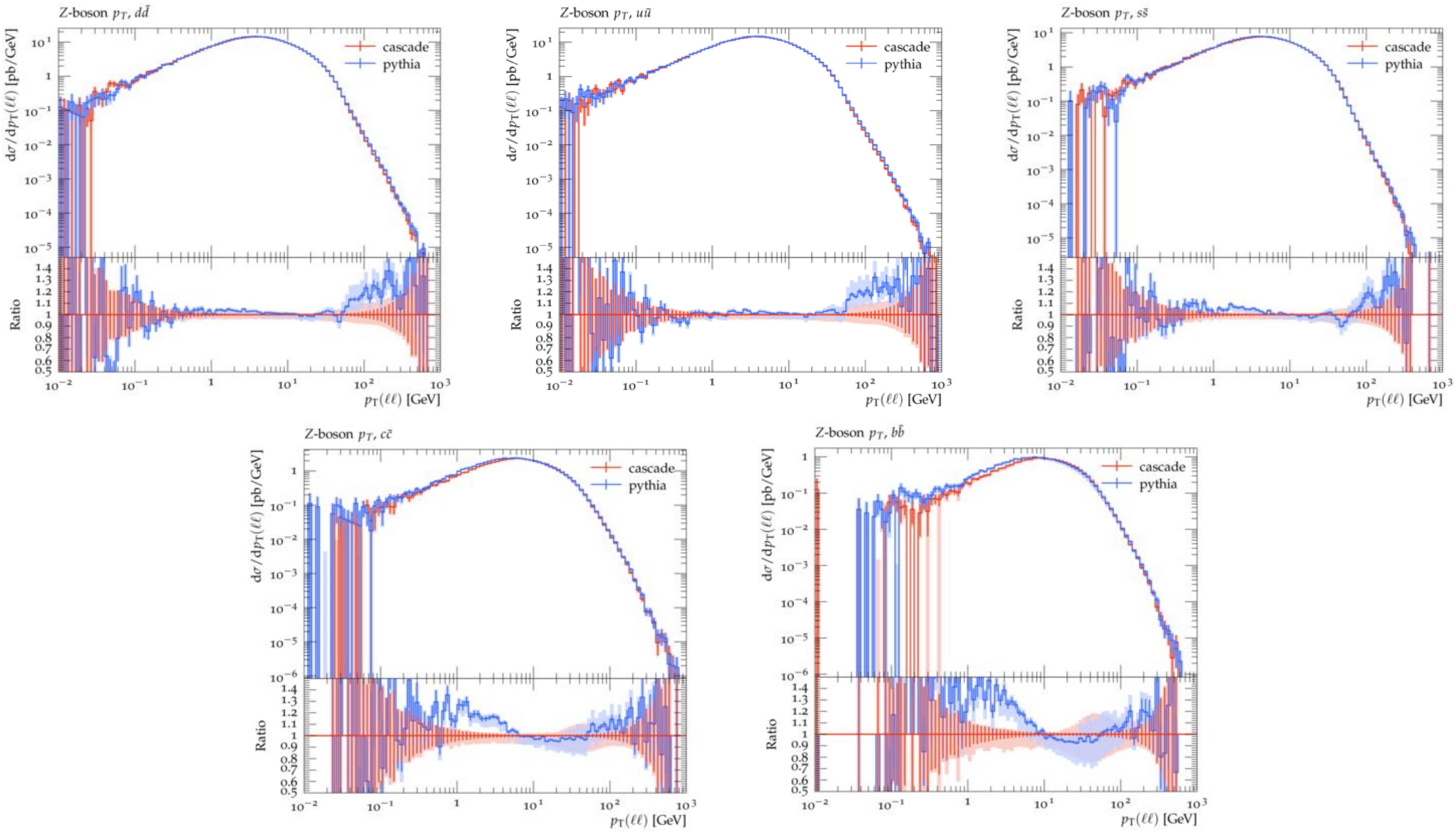


- All the processes switched-off but ISR

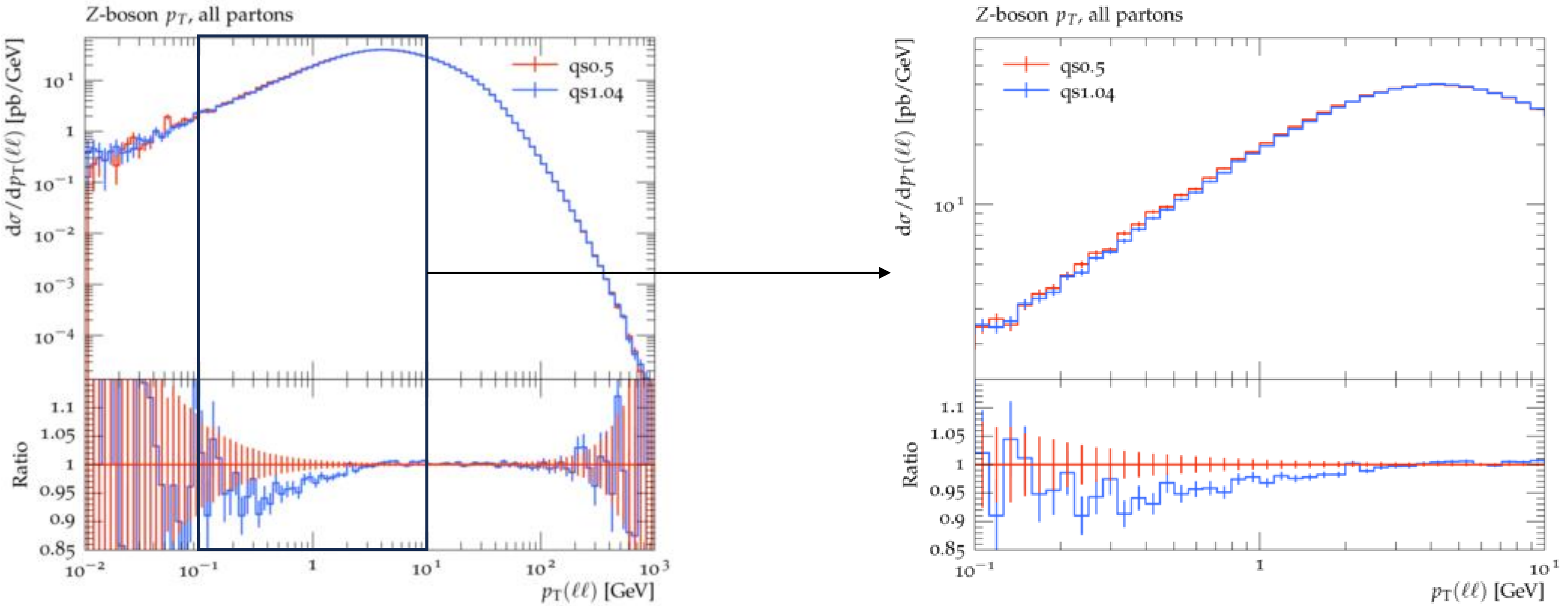


> The distributions in the bins measured in the CMS collaboration agree well

Individual quark flavours forming a DY pair in a pp collision at 13 TeV



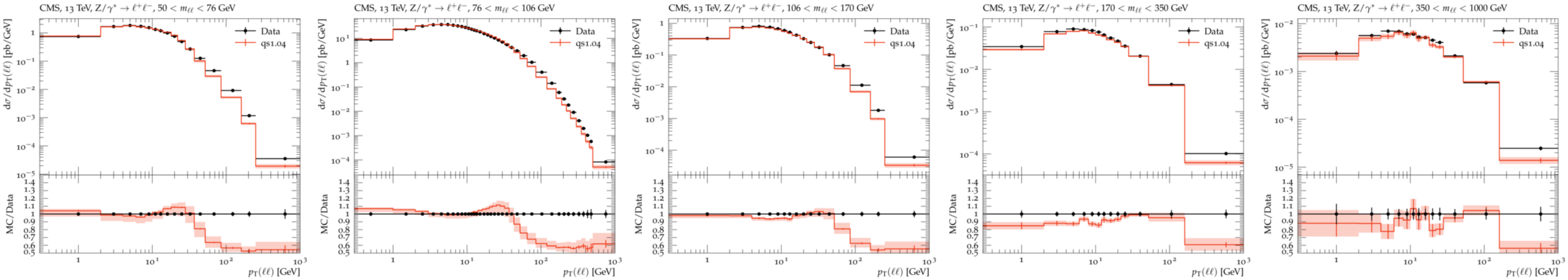
Influence of intrinsic k_T on DY p_T distribution



- Cross-section at low p_T decreases when increasing width q_s
- The decrease is not big because $q_0 \sim 0$

PYTHIA-PB at NLO at 13 TeV compared with the data

- Use the value of the intrinsic transverse momentum of 1.04 GeV (as determined in **Eur. Phys. J. C (2024) 84:154**)
- Turn on FSR



- The data well described by the PDF2ISR approach
- The calculations predicts too low a cross section at large transverse momentum due to missing higher-order contributions in the matrix element

Summary and outlook

- A detailed study of the PDF2ISR approach has been carried out using DY pair production as a benchmark process, due to its high sensitivity to initial-state parton showers.

- A very good agreement is observed between the DY pair p_T distributions obtained using the PB Method and PDF2ISR approach
- The distributions of all quark flavours show very good consistency between the two approaches
- Experimental data from LHC well described by the PDF2ISR approach

- Outlook

- Apply and validate PDF2ISR at lower centre-of-mass energies
- Extend the use of PDF2ISR to describe other physics processes