# Internal transverse motion described by TMD based and shower based generators


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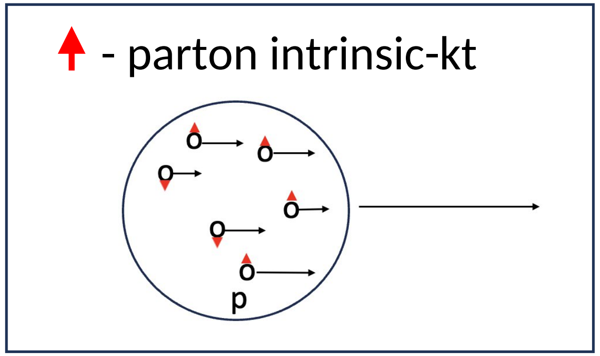
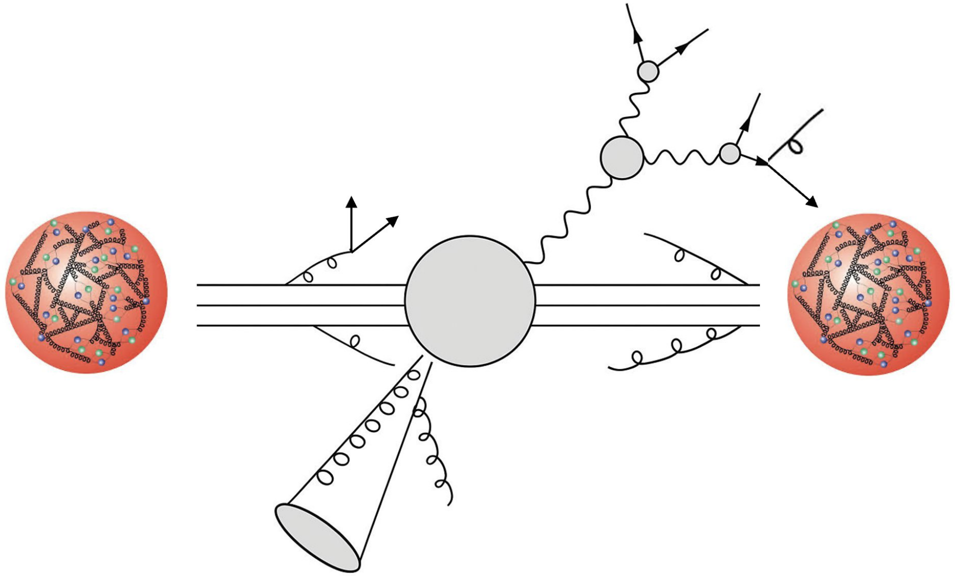
MOSCOW STATE UNIVERSITY

# Outline




➢ 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 posses **transverse momentum due to their internal (Fermi) motion – known as intrinsic $k_T$**

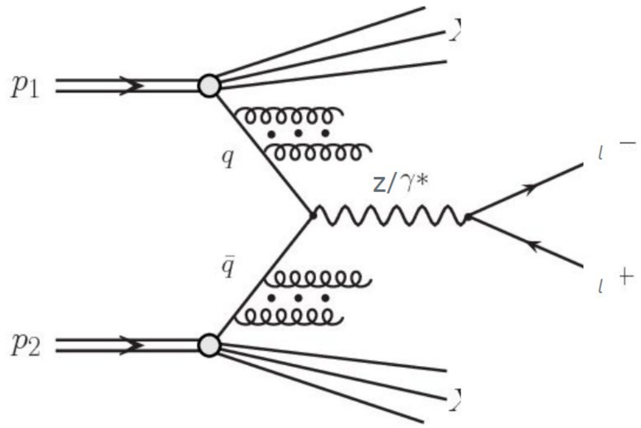


- Study of the internal parton motion with the Parton Branching (PB) method
- Recent studies of the internal parton motion with shower based Monte-Carlo event generators
- Validation studies of the new PDF2ISR approach – PB framework implemented in PYTHIA event generator

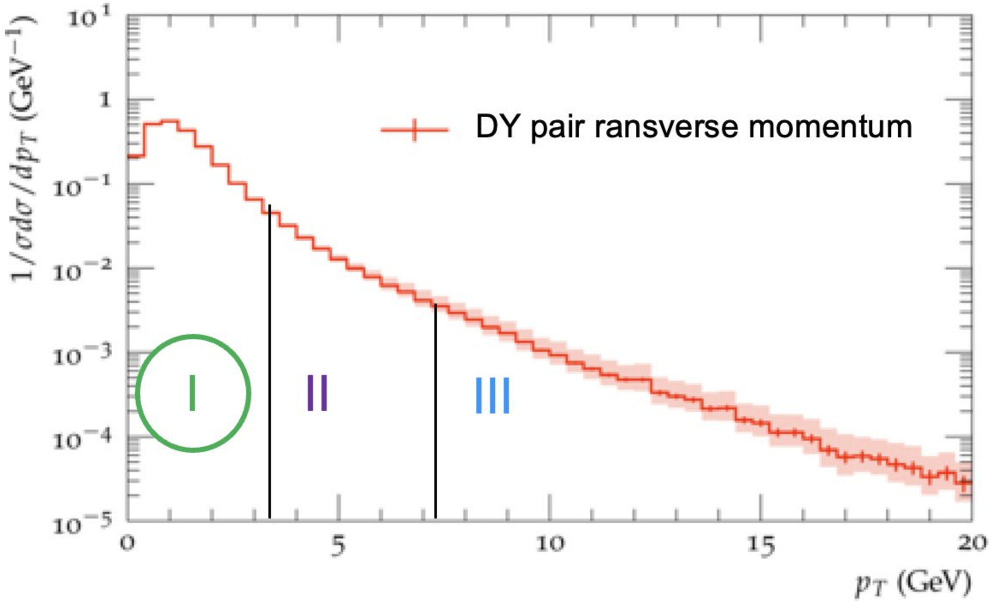
# Non-perturbative processes in the parton evolution in the initial state

- ❑ Intrinsic motion of partons
- ❑ Multiple soft gluon emmissions

Direct impact on the transverse momentum distribution of Drell-Yan (DY) pairs produced in hadron-hadron collisions




- ❑ The production of **DY lepton pairs** in hadron collisions - excellent process to study various QCD effects




I – Non-perturbative region

- Intrinsic-kT
- resummation of multiple soft gluon emissions

II – Transition region

III - Perturbative higher-order contributions dominating

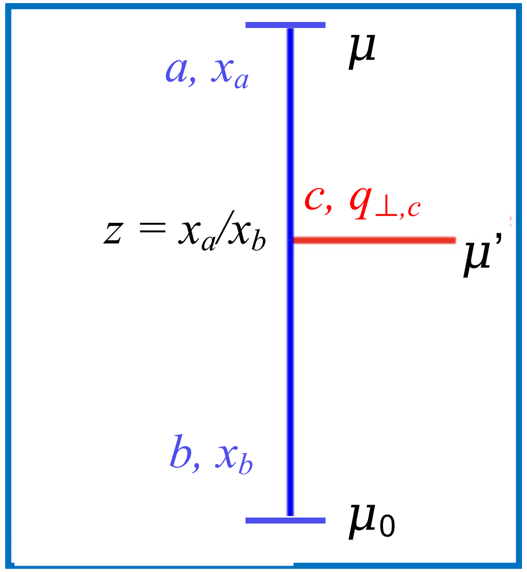
# Why Parton Branching (PB) method ?

- 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 already at the parton level ($k_T$ – parton transverse momentum)
- The PB Method describes partons from colliding hadron via Transverse Momentum Dependent (TMD) parton distribution functions (PDF) - 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 $\mu$

  - TMDs for all flavors across a wide kinematic range obtained from the TMD evolution equation

# Parton branching



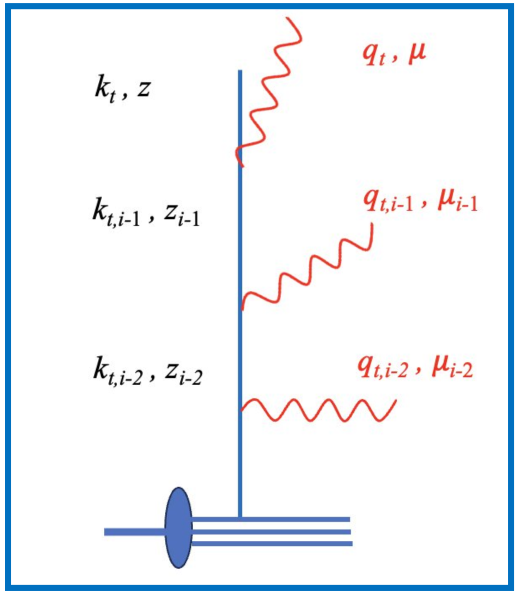

One branching

b ☾ $a$ + 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 $z_M \to 1$

# 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 ($\Delta_a$) 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:

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

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

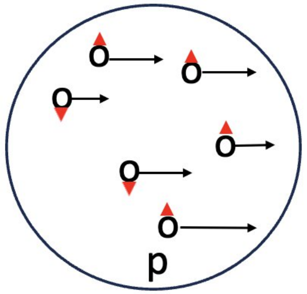
$\mathcal{A}_a(x,\mathbf{k},\mu_0^2)$ - the TMD at the starting scale $\mu_0$ is a nonperturbative boundary condition to the evolution equation and is determined from experimental data

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



- $\alpha_s = \alpha_s(\mu'^2(1-z)^2) = \alpha_s(q_T^2)$ ☾ the TMD set termed as PB-NLO-2018 set 2

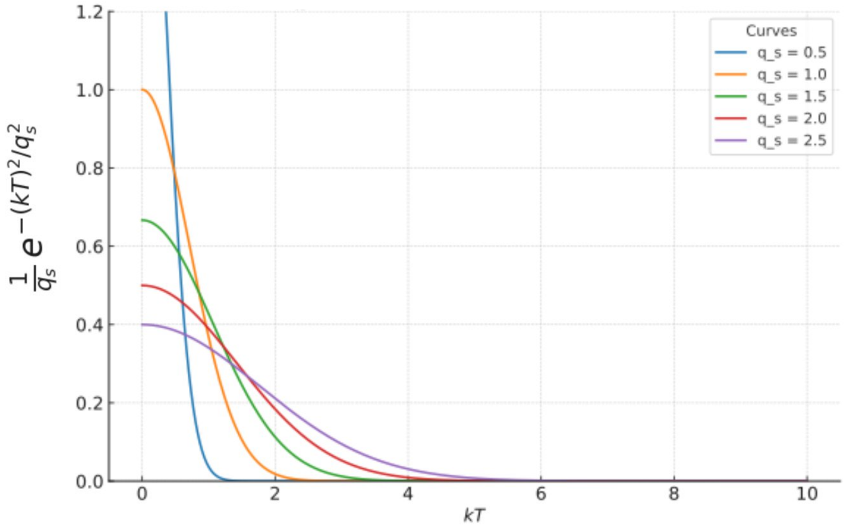
# Intrinsic-$k_T$ in TMDs

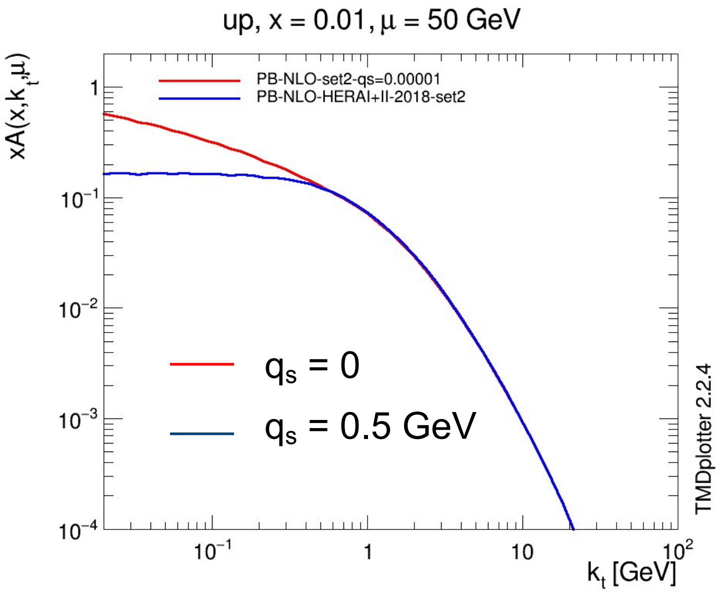


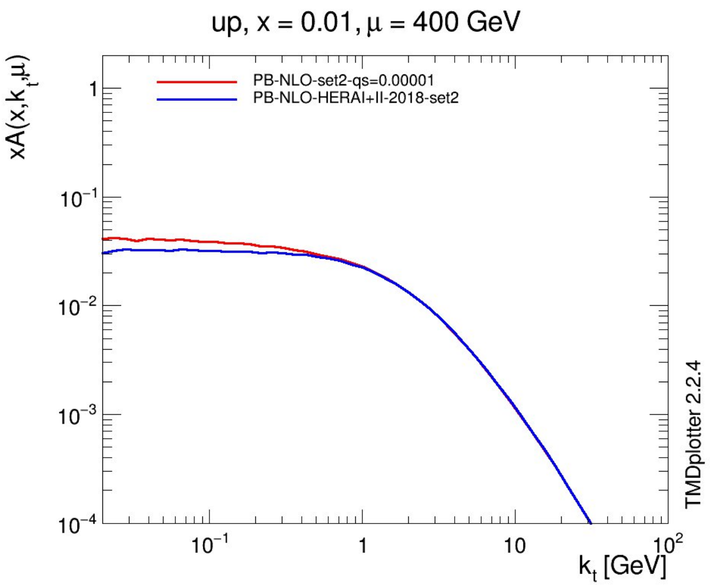

In the evolution, intrinsic $k_T$ is introduced as a non-perturbative parameter and is generated from a Gaussian distribution with width $\sigma$ which is expressed in the PB Model via the parameter $\mathbf{q_s}$:

$$\sigma^2 = q_s^2/2$$

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




- ➢ Significant effect of the intrinsic-$k_T$ at low scales

# Soft contributions and Sudakov form factor

- Since $\alpha_s = \alpha_s(q_T)$ ☾ $q_0$ where $\alpha_s$ is frozen leads to two different regions:
  a perturbative region, with $q_T > q_0$ , and and non-perturbative region of $q_T < q_0$

  $z_{dyn} = 1 - q_0/\mu'$

  ☾ Two regions of z:

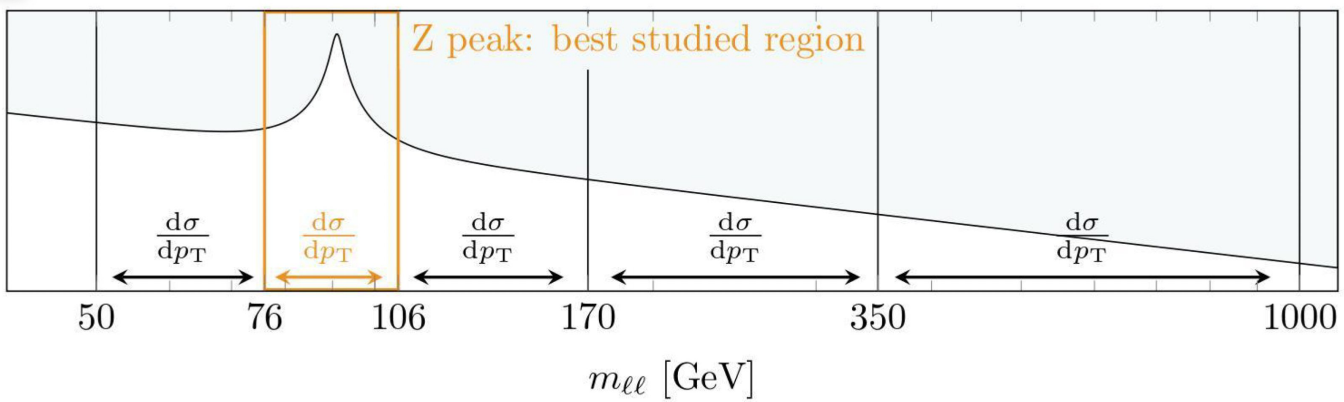
  - a perturbative region, with $0 < z < z_{dyn}$ ($q_T > q_0$)
  - a non-perturbative region with $z_{dyn} < z < z_M$ ($q_T < q_0$)

➢ define a perturbative (**P**) and non-perturbative (**NP**) ($z_{dyn} < z < z_M$, $z_M \to 1$ ) Sudakov form factors

$$\begin{aligned}\Delta_a(\mu^2,\mu_0^2) &= \exp\left(-\sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mathbf{q}'^2}{\mathbf{q}'^2} \int_0^{z_{\rm dyn}} dz\ z\ P_{ba}^{(R)}(\alpha_s,z)\right) \\ &\quad\times \exp\left(-\sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mathbf{q}'^2}{\mathbf{q}'^2} \int_{z_{\rm dyn}}^{z_{\rm M}\approx 1} dz\ z\ P_{ba}^{(R)}(\alpha_s,z)\right) \\ &= \Delta_a^{(\rm P)}\left(\mu^2,\mu_0^2,q_0^2\right) \cdot \Delta_a^{(\rm NP)}\left(\mu^2,\mu_0^2,q_0^2\right) .\end{aligned}$$

# Determination of the Gaussian width $q_s$

- The recent publication from CMS on transverse momentum distribution in a wide DY invariant mass [1] provides a detailed uncertainty breakdown




☾ the basic data for the determination of the intrinsic-$k_T$ parameter $q_s$

- $q_s$ parameter in PB-NLO-2018 Set 2 is varied and compared to the measurement

➢ $\chi^2$ is calculated to quantify the model agreement to the measurement

$$\chi^2 = \sum_{i,k} (m_i - \mu_i) C_{ik}^{-1} (m_k - \mu_k)$$

- The covariance matrix $C_{ik}$ consists of a component describing the uncertainty in the measurement, $C_{ik}^{measurement}$, and the statistical (bin by bin stat. unc) and scale uncertainties in the prediction

$$C_{ik} = C_{ik}^{measurement} + C_{ik}^{model-stat.} + C_{ik}^{scale}$$

$q_s$ = 1.04 ± 0.08 GeV

# DY data at lower energies

- Most of the published experimental data do not include a detailed breakdown of uncertainties
- The experimental uncertainties are treated as uncorrelated

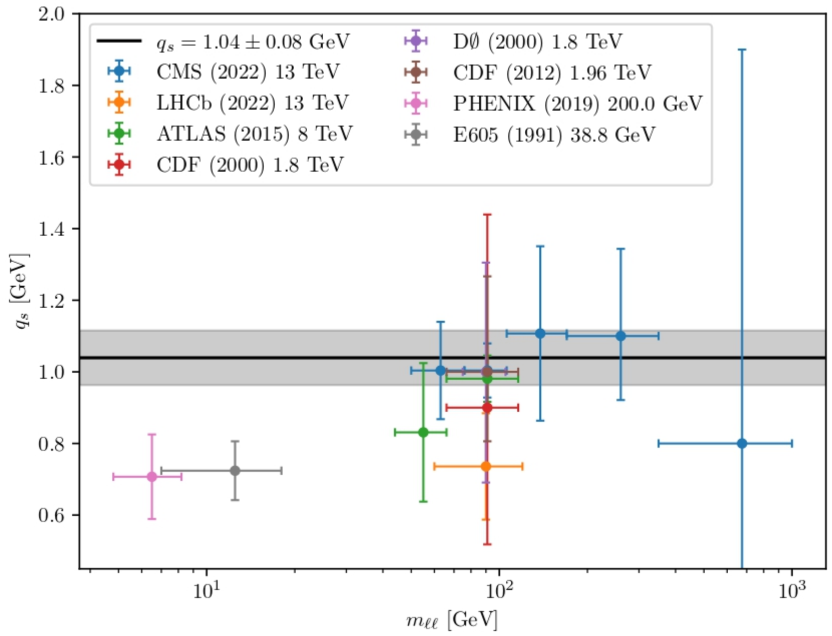
| Analysis | $\sqrt{s}$ | Collision type |
|---|---|---|
| CMS (2022) [1] | 13 TeV | pp |
| LHCb (2022) [2] | 13 TeV | pp |
| CMS (2021) [3] | 8.1 TeV | pPb |
| ATLAS (2015) [4] | 8 TeV | pp |
| CDF (2012) [5] | 1.96 TeV | $p\bar{p}$ |
| CDF (2000) [6] | 1.8 TeV | $p\bar{p}$ |
| D0 (2000) [7] | 1.8 TeV | $p\bar{p}$ |
| PHENIX (2019) [8] | 200 GeV | $p\bar{p}$ |
| E605 (1991) [9] | 38.8 GeV | PN |
| E277 (1981) [10] | 27.4 GeV | pN |

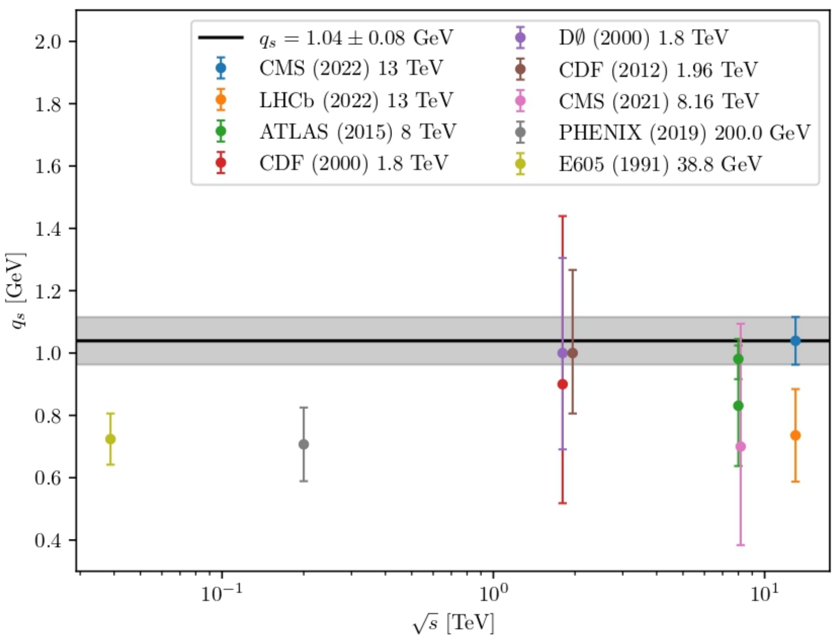
# Intrinsic-kT width depending on √s and DY mass

I. Bubanja et al,
Eur.Phys.J.C 84 (2024) 2, 154
arXiv:2312.08655

$q_0 = 10^{-2}$ 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

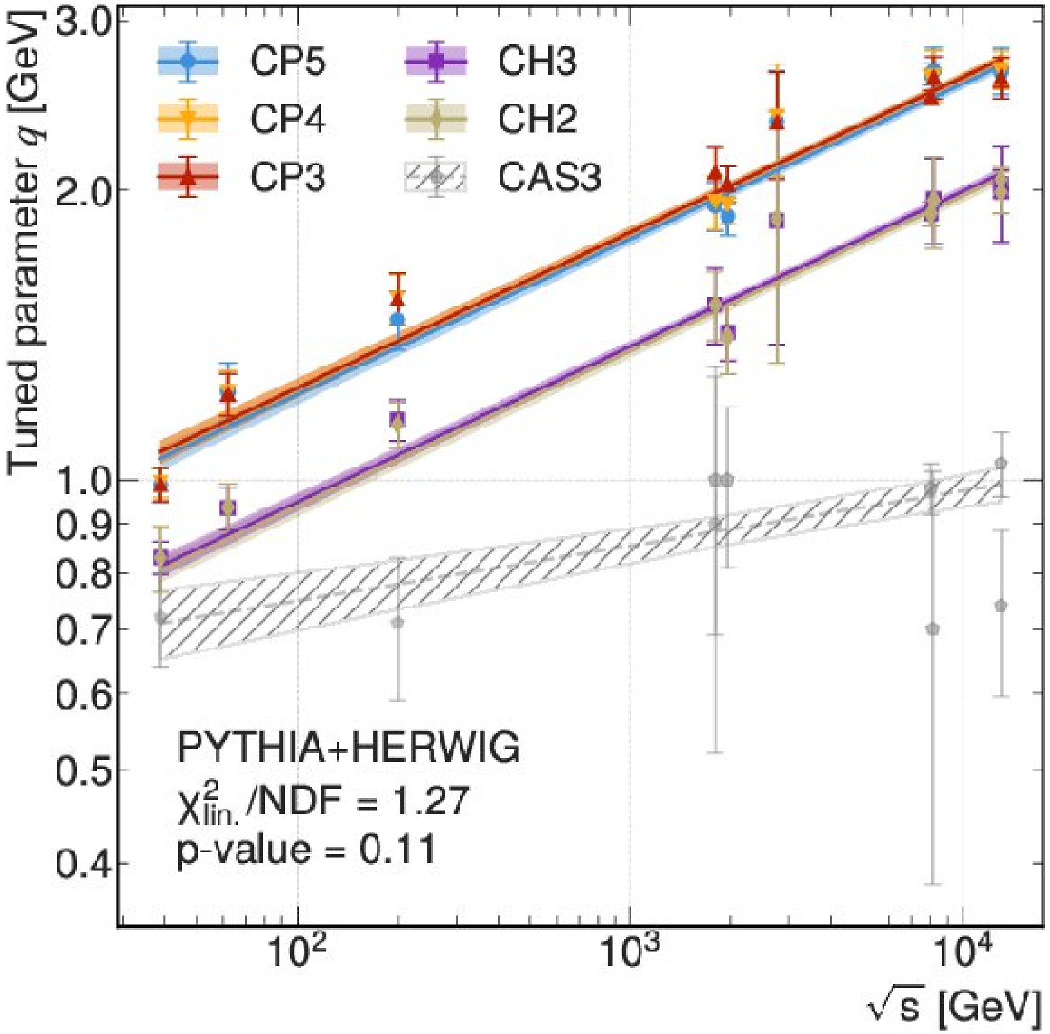
à No trend in centre-of-mass energy dependence of $q_s$ is observed

à The result stands in contrast to those from standard Monte Carlo event generators which require a strongly increasing intrinsic-$k_T$ width with √s

# Center-of mass dependence of the intrinsic-$k_T$ width in the shower-based generators

CMS Collaboration, *Phys.Rev.D* 111 (2025) 7, 072003
arXiv:2409.17770

Fit: $q = f(\sqrt{s}) = a \cdot (\sqrt{s})^b$




- 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, show 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

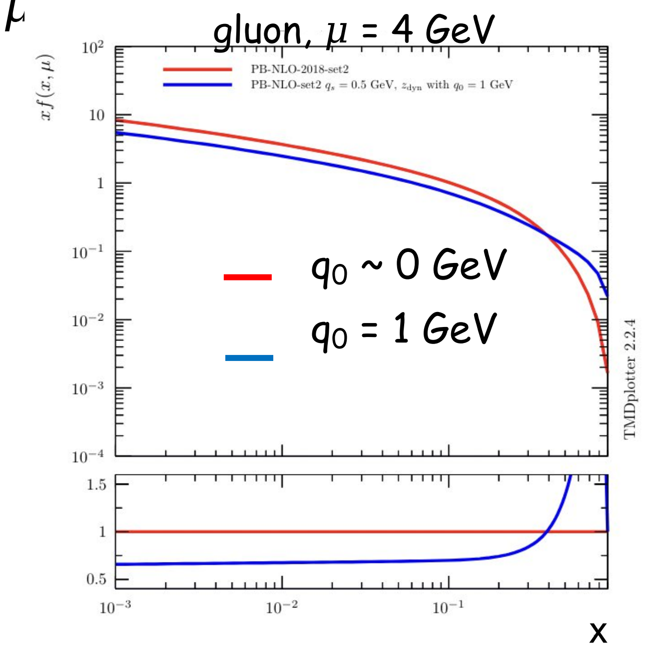
# Try to introduce the energy dependence of the intrinsic-$k_T$ in PB

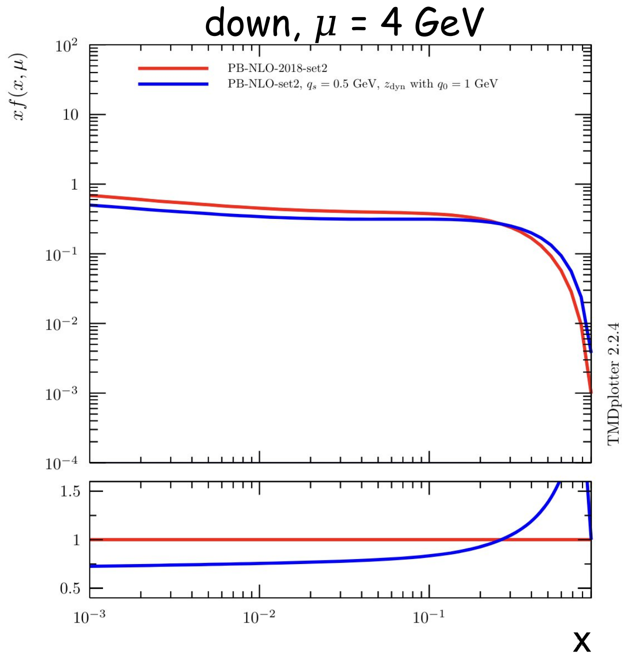
- Try to mimic parton-shower event generators by demanding a minimal parton transverse momentum ($q_0$ = 1 and 2 GeV) ☾ $q_T > q_0$

  ☾ $z_M$ constrained: $z_M = z_{dyn} = 1 - q_0/\mu' < 1$

à $\Delta_a^{(\mathrm{NP})}\left(\mu^2, \mu_0^2, q_0^2\right) = \exp\left(-\sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \int_{z_{\mathrm{dyn}}}^{z_{\mathrm{M}}} dz\, z\, P_{ba}^{(R)}(\alpha_s, z)\right)$ - neglected

à Real emissions with $z > 1 - q_0/\mu'$ ...



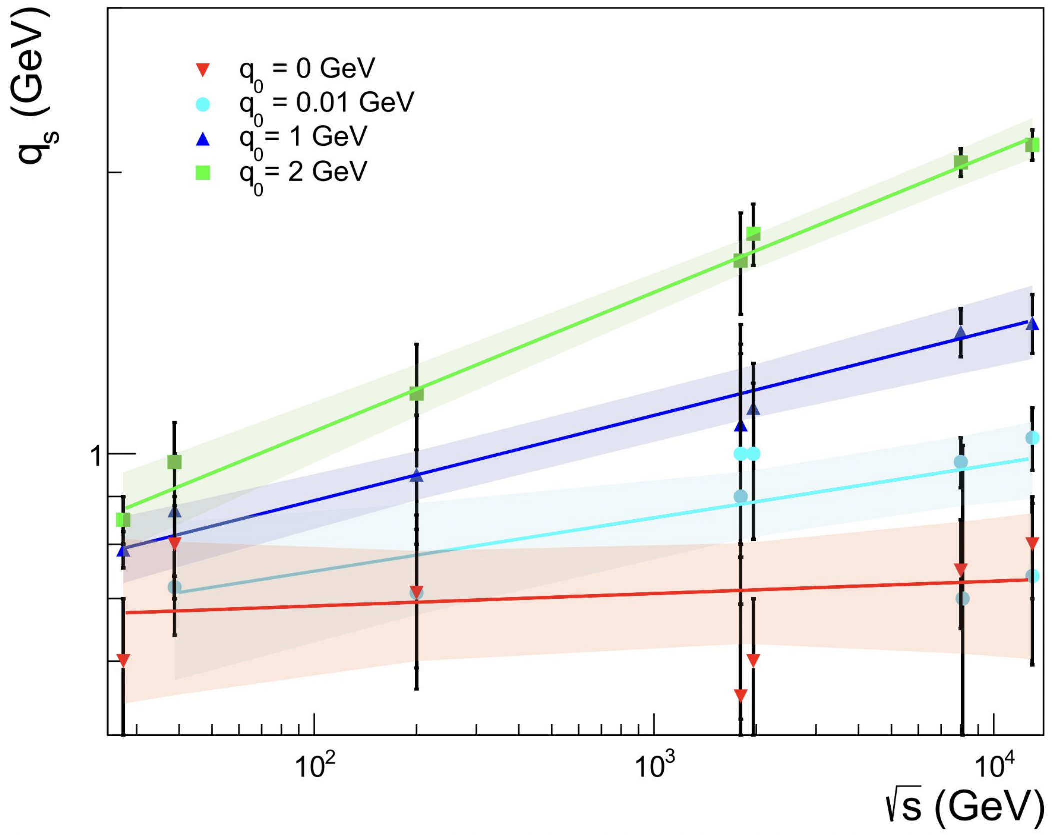

- Integrated parton distributions very different for the two cases

  ☾ soft contributions important also for collinear distributions

# $q_s$ vs √s for different $q_0$ in the PB

I. Bubanja et al,
Eur.Phys.J.C 85 (2025) 3, 278
arXiv:2404.04088

Fit: $q_s = f(\sqrt{s}) = a \cdot (\sqrt{s})^b$




- The intrinsic-$k_T$ width parameter increases with the collision energy
- 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

# Dependence of the intrinsic-$k_T$ width on the hard scale

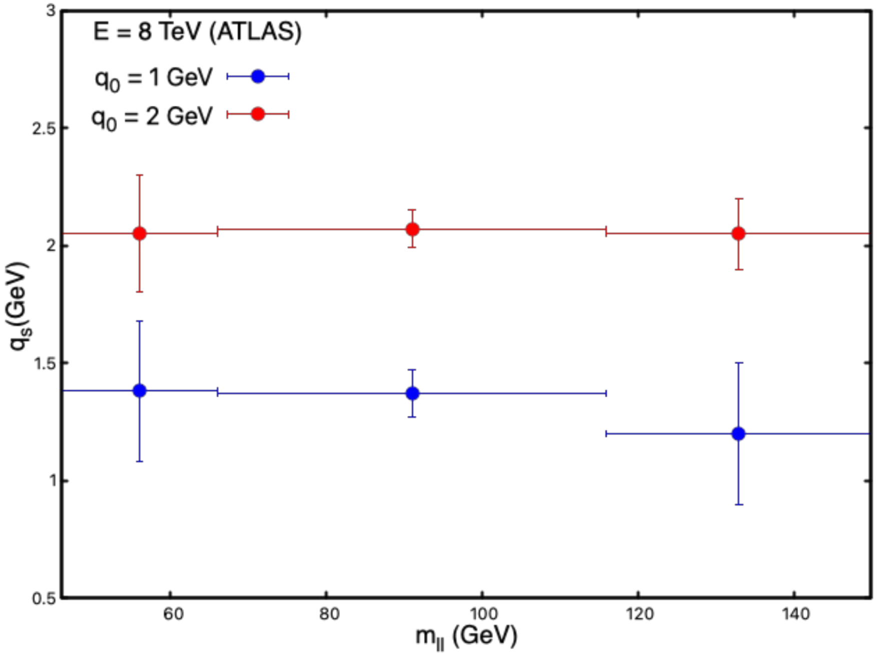
N. Raičević

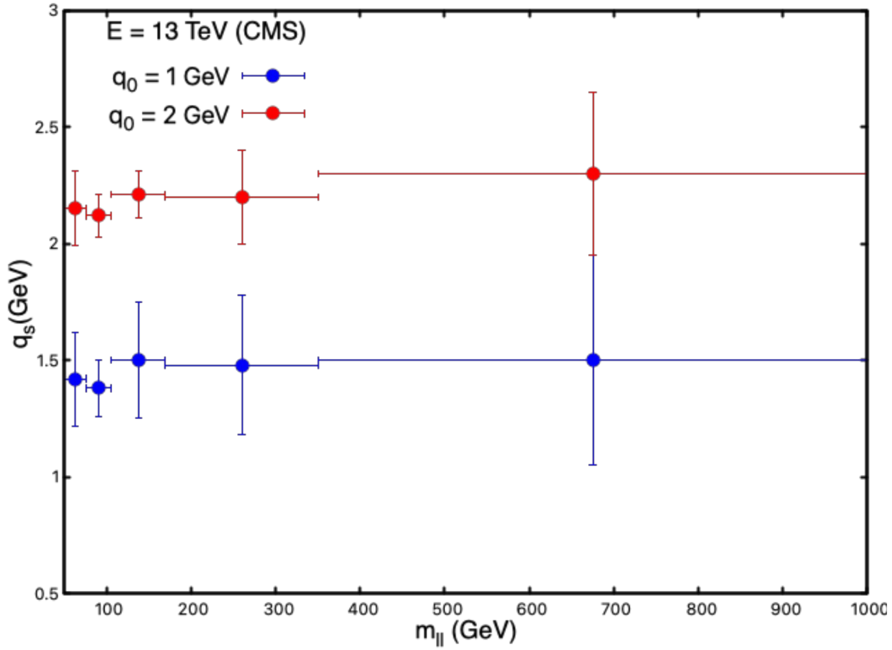
Phys. Scr. **100 (2025)** 045306

arXiv:2412.00892

# $q_s$ as a function of DY pair invariant mass with a $q_0$ cut at LHC

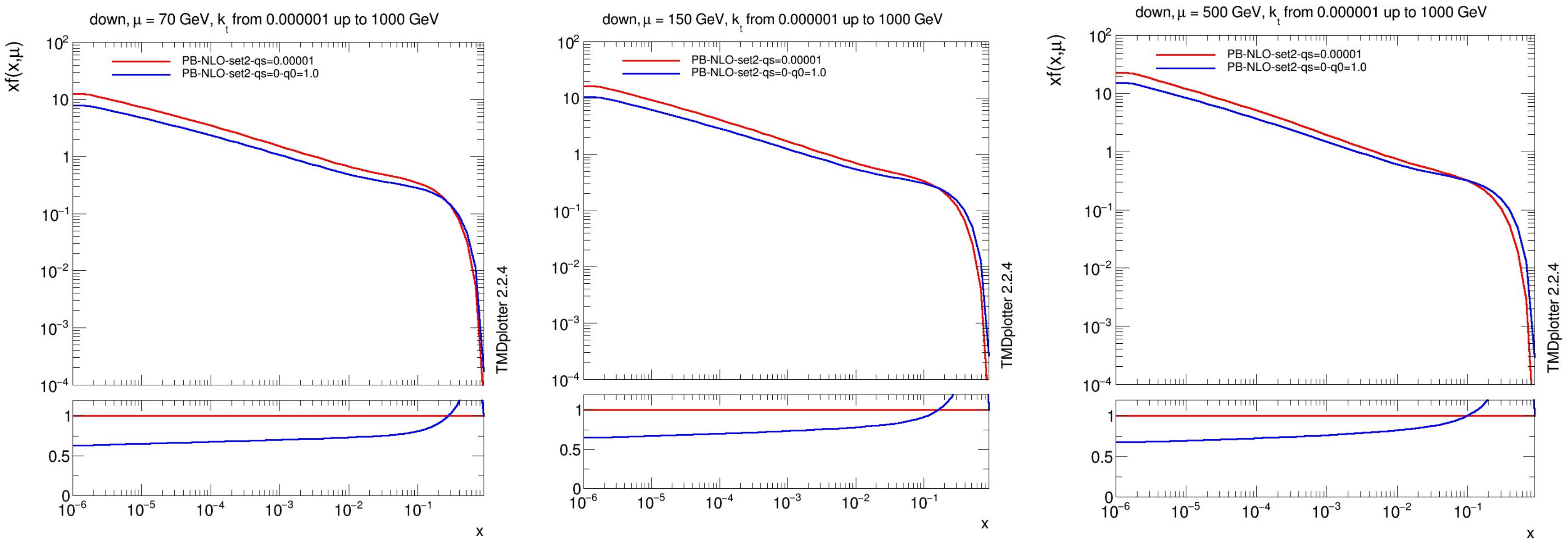
- The evolution scale directly linked to the DY-pair invariant mass ($m_{ll}$)




- From the available measurements and existing uncertainties: $q_s$ remains independent of the DY pair invariant mass for $q_0 \lesssim 2$ GeV
  - the fraction of soft parton contributions with the transverse momentum ~1 GeV which populate the DY $p_T$ region up to 2-3 GeV similar for different mass regions

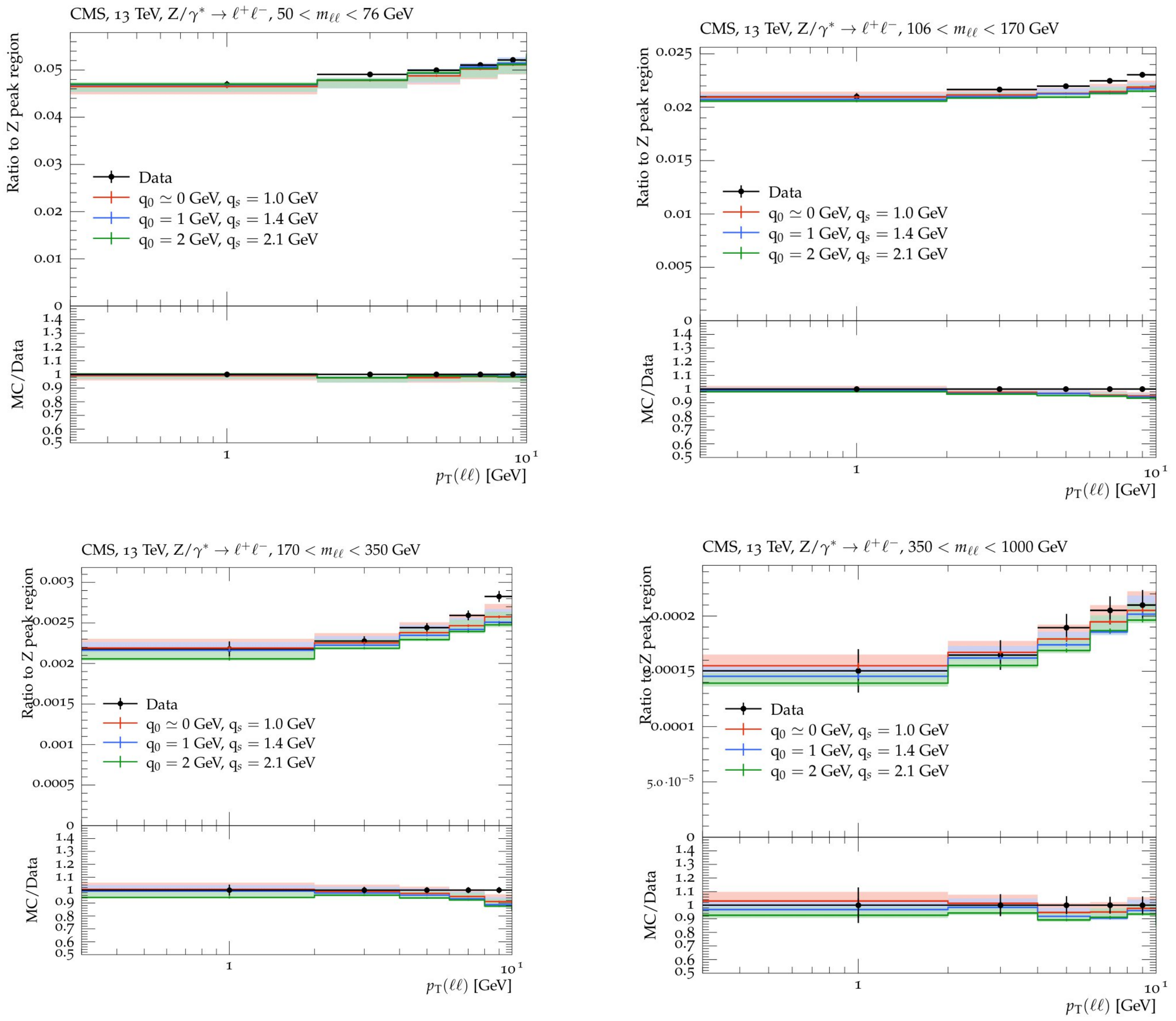
# Integrated PDFs with a $q_0$ cut at high scales




The scale values relevant for available measurements from LHC

- The change of the integrated PDFs by introducing a cut of $q_0$ ~ 1 GeV is similar for different scale values, μ, relevant for the available measurements at the LHC
  - Consistent with the result of $q_s$ vs m(ll) from the available measurements from LHC
  - Consistent with the non-perturbative Sudakov FF which is sensitive at small values of μ (the next slides) and changes slowly with μ in the region of μ ~ 100 GeV where measurements from the LHC have been performed

# The ratio of the cross section to Z-peak region as a function of DY-$p_T$ at different scales




$q_0$ = 0.01 GeV ($q_s$ = 1.0 GeV)

$q_0$ = 1 GeV ($q_s$ = 1.4 GeV)

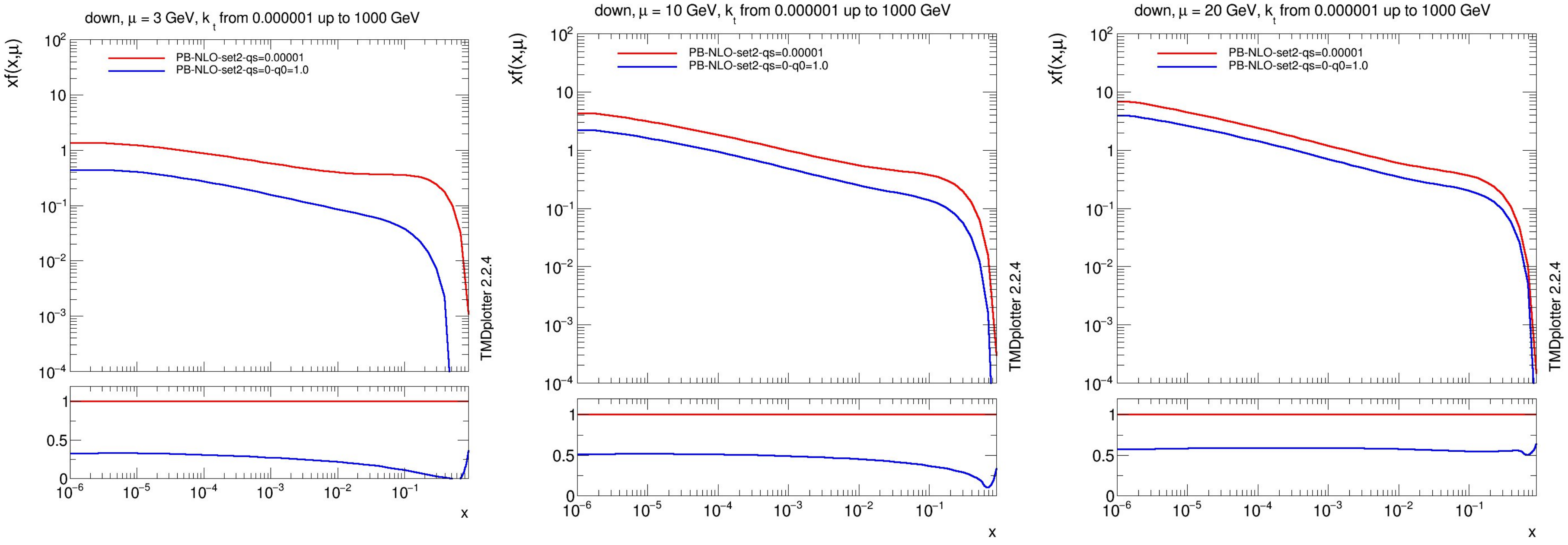
$q_0$ = 2 GeV ($q_s$ = 2.1 GeV)

- The ratio of the cross section to the Z peak similar for different DY pair invariant mass regions for $q_0 \lesssim 2$ GeV

- The ratio is well described by the predictions, which use the same $q_s$ width for each mass bin, and that the distributions obtained for different values of $q_0$ are similar.

  - The relative contributions of soft gluons are quite similar across different invariant mass bins, not only in the non-perturbative region but also in the transition region ($4 \lesssim pT(ll) \lesssim 15$ GeV).

# Integrated PDFs with $q_0$ cut at low scales



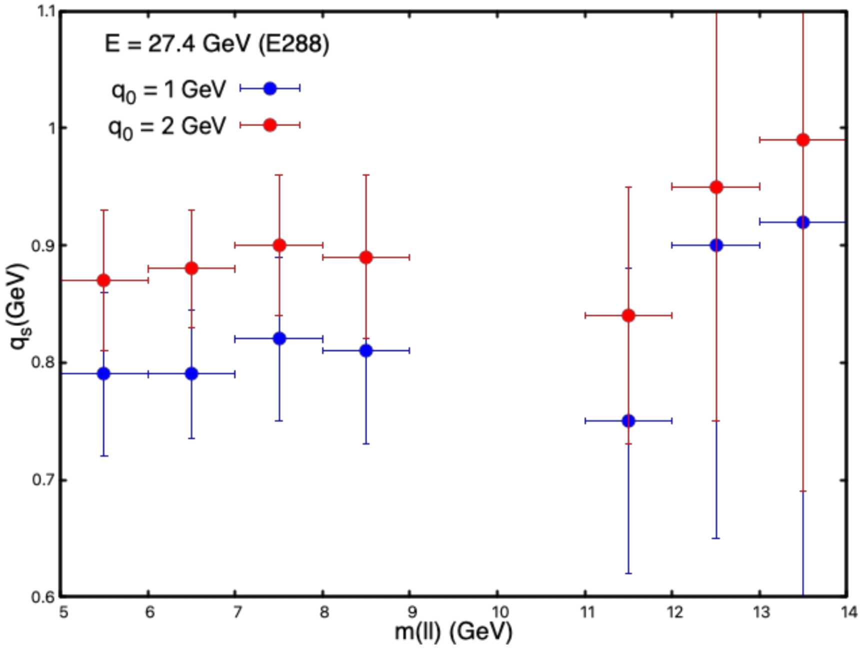

- Different trend at low μ which corresponds to the measurements of the pair-$p_T$ at low invariant masses not yet available at the LHC

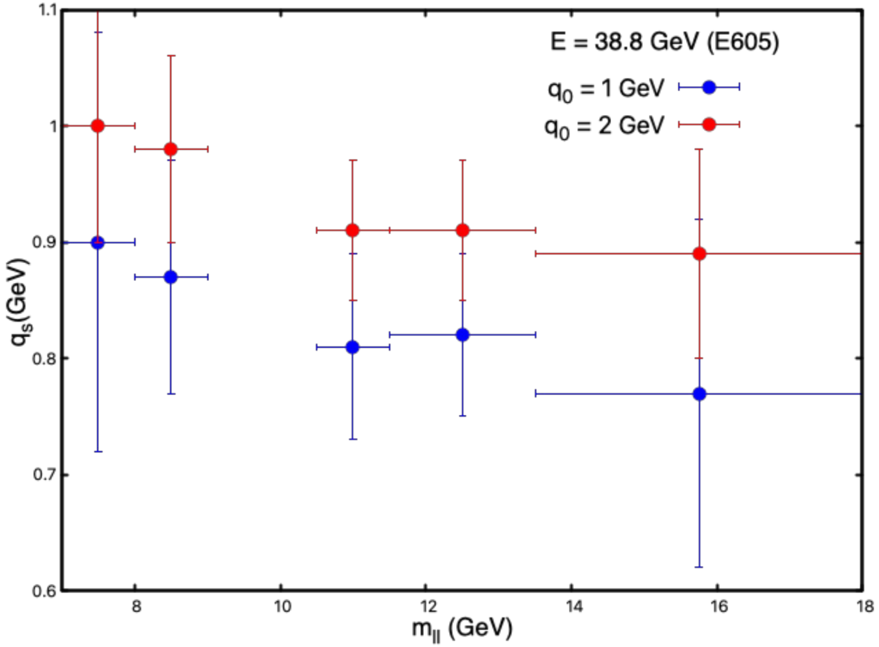
- The integrated PDFs by introducing the $q_0$ ~ 1 GeV cut varies rapidly with the μ scale relevant for DY pair masses ~10 GeV
  - The relative amount of soft gluons removed by the cut changes significantly at low scales and the measurable changes in the value of $q_s$ could be expected at low DY pair invariant masses for collision energies available at LHC

# $q_s$ as a function of DY pair invariant mass with a $q_0$ cut at small $\sqrt{s}$

- At the collision energies of 27.4 GeV (E288) and 38.8 GeV (E605), the DY pairs with the low inv. mass are mainly produced at high x from the valence contributions

- One cannot expect measurable dependence of $q_s$ on DY pair invariant mass



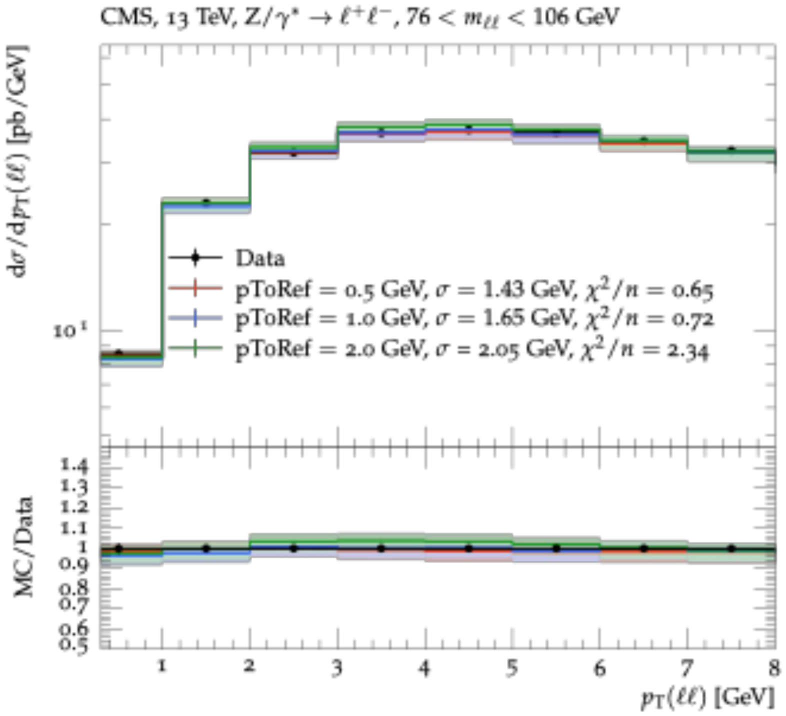

- Although the errors are large and it is not possible to draw a firm conclusion, the trend of change of the $q_s$ with m(ll) is noticeable in the measurements obtained from the E605

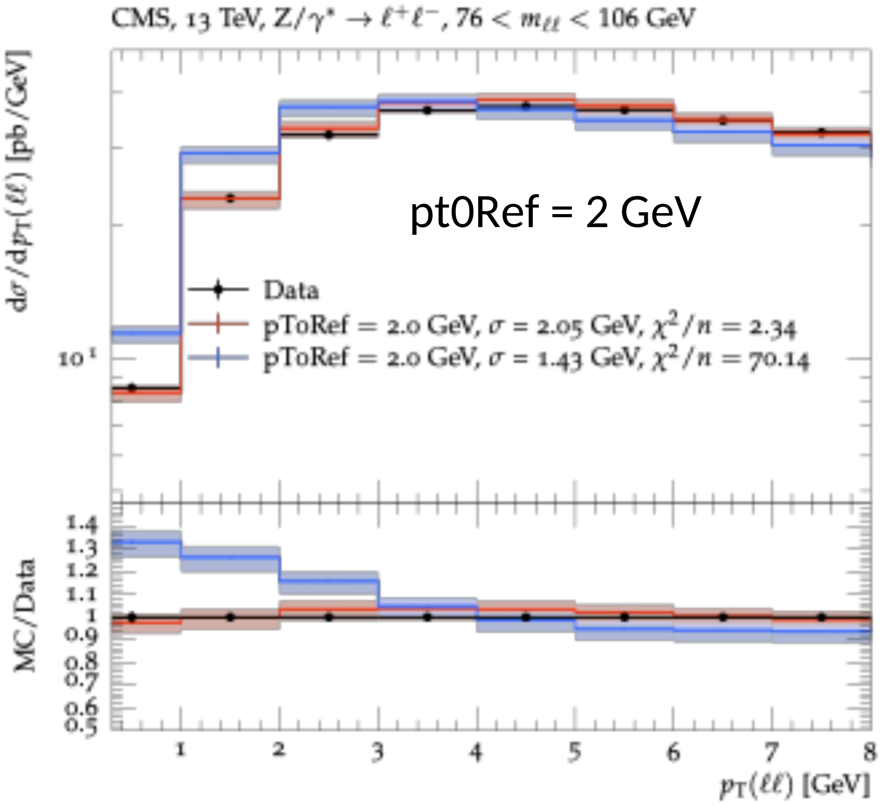
# Study of the non-perturbative effects with PYTHIA

I. Bubanja et al,
Eur.Phys.J.C 85 (2025) 3, 363
arXiv:2412.05221

# DY-pT distributions with different ISR cut-off parameter in PYTHIA

- pt0ref – minimum $q_T$ (similar to $q_0$ in PB) – ISR cut-off parameter in PYTHIA
- $\sigma$ – width of the Gaussian for intrinsic- $k_T$ (similar to $q_s$)



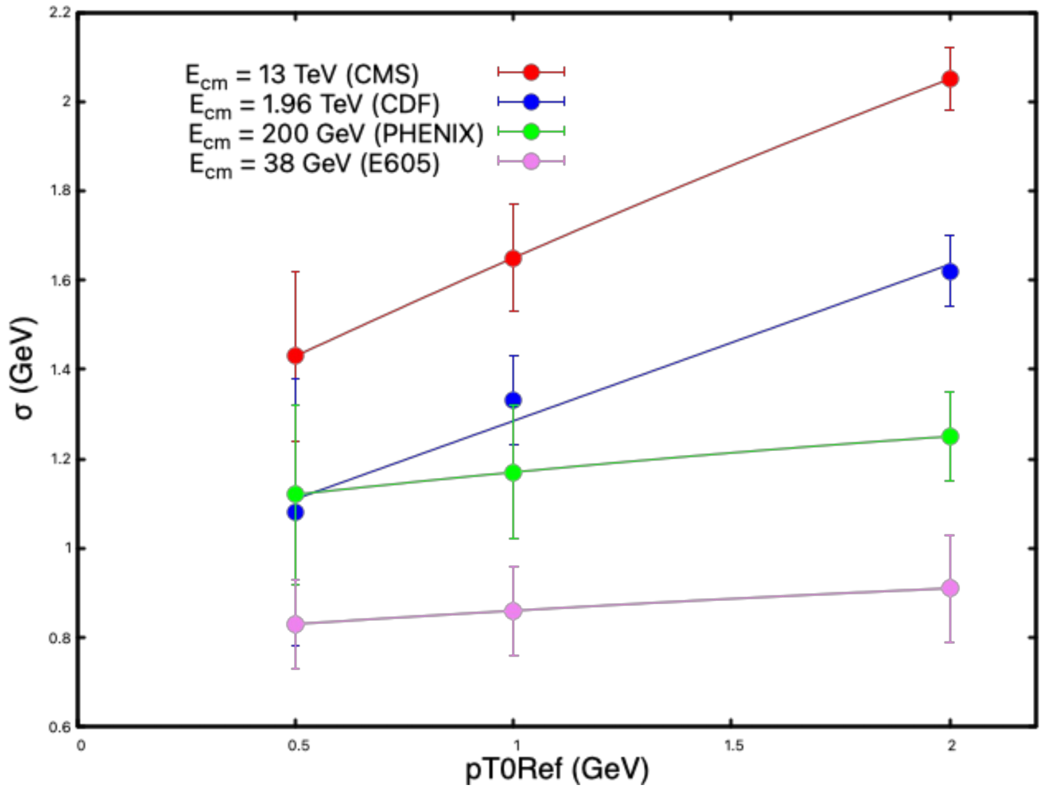




Optimal intrinsic-kT widths:

- (red) $\sigma$ = 1.43 GeV for pt0Ref = 0.5 GeV
- (blue) $\sigma$ = 1.65 GeV for pt0Ref = 1.0 GeV
- (green) $\sigma$ = 2.05 GeV for pt0Ref = 2.0 GeV

- (blue) $\sigma$ = 1.43 GeV
- (red) $\sigma$ = 2.05 GeV

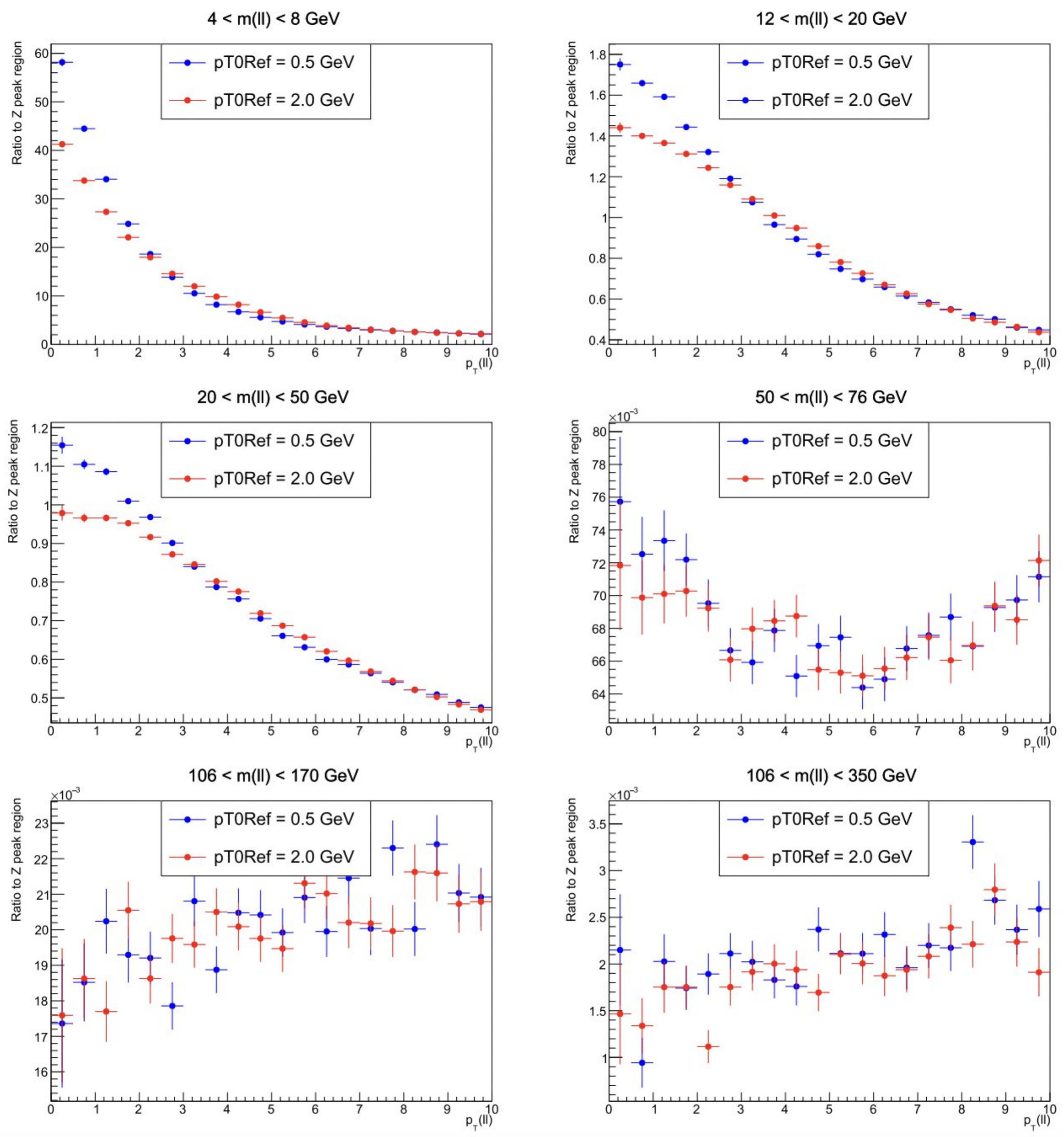
## Dependence of the intrinsic-kT width on the ISR cut-off parameter




The intrinsic-kT width, reflecting the interplay between two non-perturbative processes (internal transverse motion inside the hadrons and soft gluon emissions), increases approximately linearly with the ISR cut-off parameter in the range 0.5 < pT0Ref < 2.0 GeV.

- clear evidence that the energy dependence is related to the no-emission probability, Sudakov form factor, through its dependence on pT0Ref.

# The ratio of the cross section to Z-peak region as a function of DY-$p_T$ at different scales




- The ratio of the cross section as a function of pT(ll) to Z-peak region from PYTHIA predictions in different DY pair invariant mass bins, shown for the two values of the ISR cut-off parameter:

  — pT0Ref = 0.5 GeV and

  — pT0Ref = 2.0 GeV

- For high $m_{DY}$ values as measured at the LHC - no significant dependence of the width parameter σ, while extending the mass range to smaller values, such a dependence is clearly visible.

- The difference between the simulations with pT0Ref = 2 GeV and pT0Ref = 0.5 GeV increases as mDY decreases.

- Consistent with the expectation that most of the contribution from the soft emissions arise at low scales

# A new approach: **PDF2ISR** – implementation of the PB Method framework in PYTHIA

H. Jung et al, Eur. Phys. J. C (2025) 85:870, arXiv:2504.10243

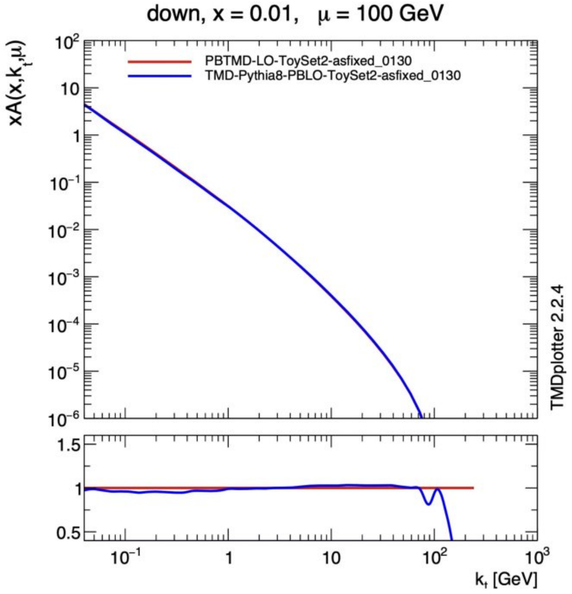
- Implement the TMDs from PB Method in PYTHIA, and develop a procedure for obtaining an initial-state parton shower model in which the (backward) evolution is fully consistent with the (forward) evolution of the collinear parton density used

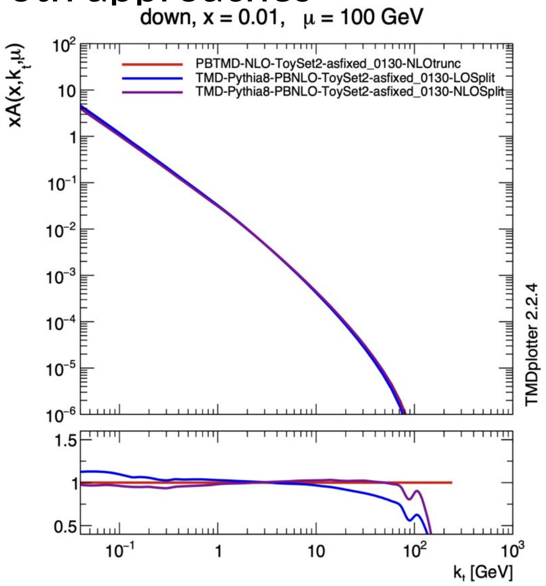
➢ A parton shower consistent with parton densities at LO and NLO

- PDF2ISR 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

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




- By using dedicated Toy Model

à Very good agreement between the TMDs from the PB and PYTHIA-PB at LO and NLO

[NLO splitting functions essential for consistent treatment with NLO PDF]

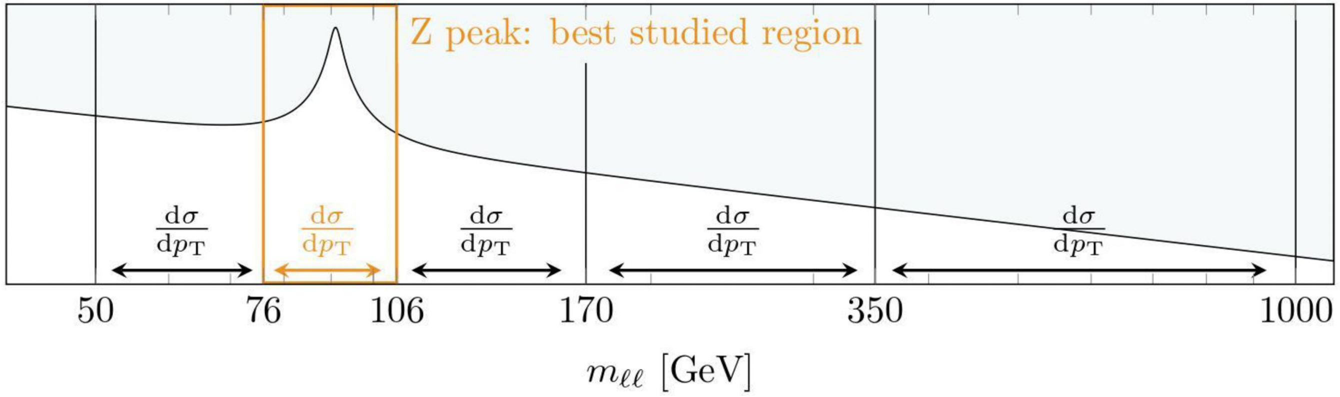
➢ Perform validation studies of the PDF2ISR implemented in PYTHIA event generator by applying on real DY pairs

# Validation studies of the PDF2ISR approach

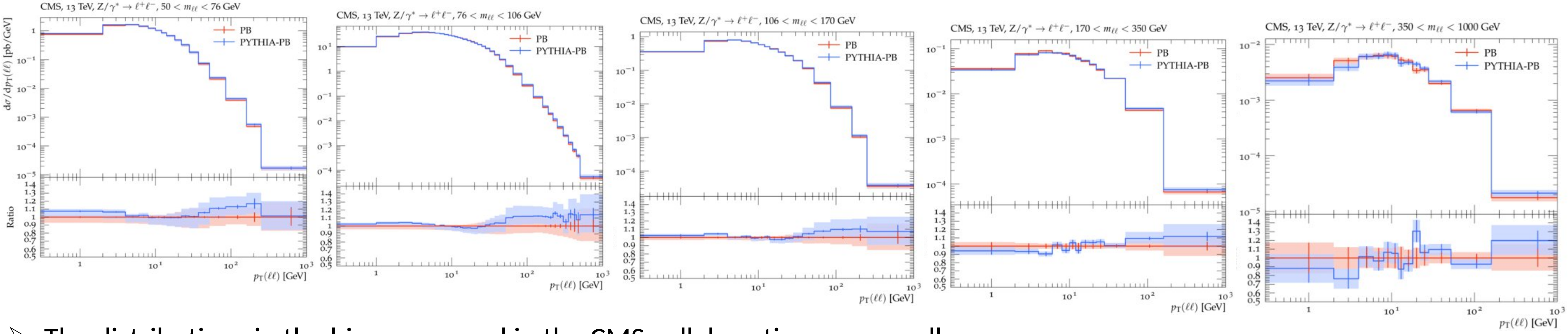
D. Subotić, H. Jung and N. Raičević
12th International Congress of the Balkan Physical Union (July, 2025)

# Compare real DY $p_T$ from PB and PDF2ISR (PYTHIA-PB) at NLO at 13 TeV

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



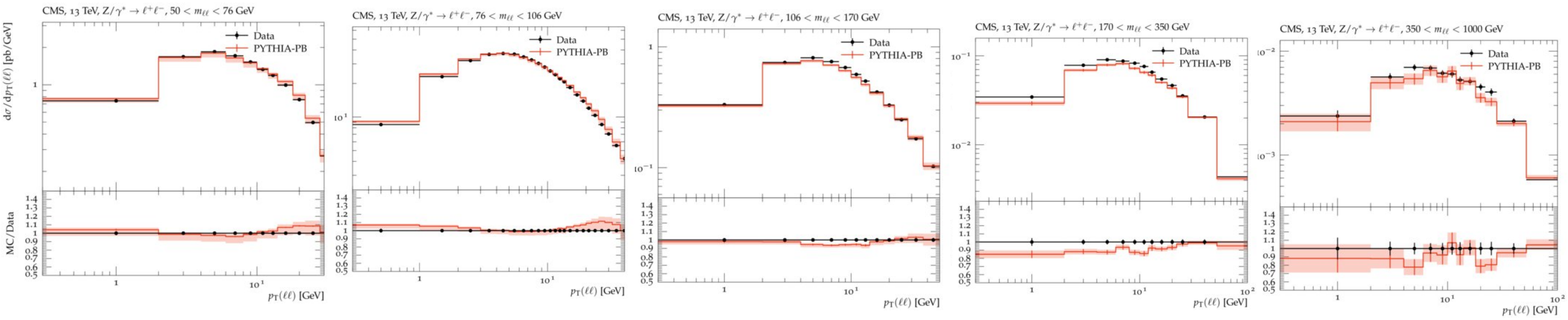

- All the processes switched-off but ISR




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

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

- Use the value of the intrinsic transverse momentum of 1 GeV
- Turn on FSR




- The data well described by the PDF2ISR approach

# Summary

- A detailed study of non-perturbative processes and their interplay was performed using DY pair production with the PB Method

- The limitations of standard event generators in describing and distinguishing non-perturbative processes were identified

  - The intrinsic-kT width is found to increase with both the ISR cut-off parameter and the collision energy, due to the interplay between intrinsic transverse motion and multiple soft-gluon emissions in the non-perturbative region of DY production
  - The intrinsic-$k_T$ contribution can be disentangled from the non-perturbative Sudakov contribution only through a proper treatment of non-perturbative processes, which the PB Method enables due to its sensitivity to non-perturbative TMD contributions

- Using the recent results on DY production at the LHC, validation studies of a new approach, named **PDF2ISR**, were performed, in which the TMD framework from the PB Method was implemented into the PYTHIA event generator

  - very good agreement is observed between the DY-pair $p_T$ distributions obtained using the PB Method and those from the PDF2ISR approach
  - Experimental data from the LHC are well described by the PDF2ISR approach

**Thank you very much**
**for**
**your attention**

References for the data used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[4] https://arxiv.org/abs/1512.02192

[5] https://arxiv.org/abs/1207.7138

[6] https://arxiv.org/abs/hep-ex/0001021

[7] https://arxiv.org/abs/hep-ex/9907009

[8] https://arxiv.org/abs/1805.02448

[9] https://journals.aps.org/prd/abstract/10.1103/PhysRevD.43.2815

[10] https://journals.aps.org/prd/abstract/10.1103/PhysRevD.23.604