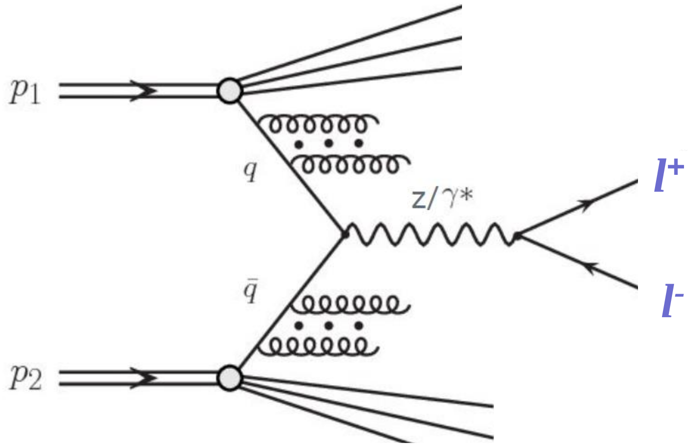
Non-perturbative contributions to the low transverse momentum Drell-Yan pair production at NLO using the Parton Branching Method

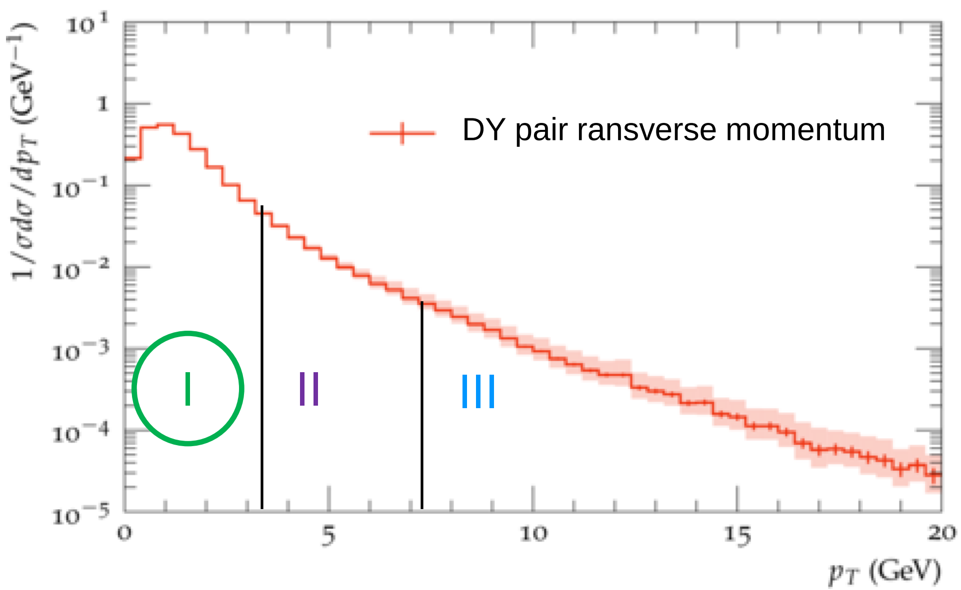
Nataša Raičević
on behalf of the CASCADE group

University of Montenegro, Faculty of Science and Mathematics

Drell-Yan pair production in hadron-hadron collisions



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



I – Non-perturbative region

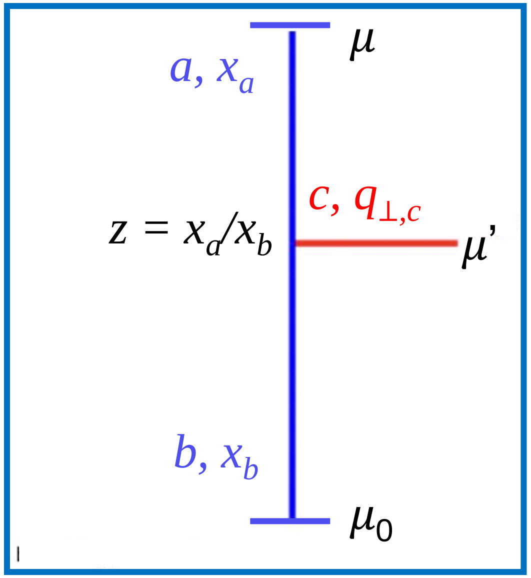
- intrinsic motion of partons
- resummation of multiple soft gluon emissions

II – Transition region

III - Perturbative higher-order contributions dominating

- DY production at NLO studied using the **Parton Branching (PB) Method which** introduces a transverse degree of freedom (k_T – parton transverse momentum) from the beginning instead of treating it as a higher order corrections

Parton branching



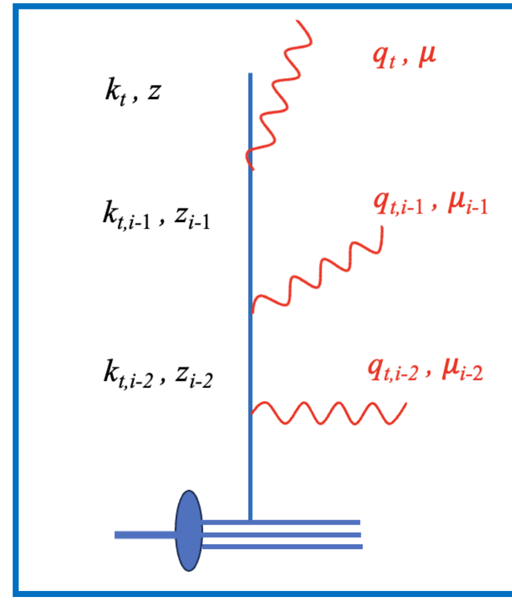
One branching

$b \rightarrow a + c$

$q_{\perp,c} \sim \mu'$ – 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

$$\mu' = |\boldsymbol{\mu}'| = q_\perp/(1-z)$$

Transverse Momentum Dependent (TMD) parton densities

- Parton evolution is expressed in terms of resolvable, real emission DGLAP splitting functions, P_{ab} for parton splitting $b \to a$, 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 hadron and the transverse momentum **k**, evaluated at a scale μ:

$$\mathcal{A}_a(x,\mathbf{k},\mu^2) \;=\; \Delta_a(\mu^2)\; \mathcal{A}_a(x,\mathbf{k},\mu_0^2) + \sum_b \int_{\mu_0}^{\mu} \frac{d^2\mu'}{\pi\mu'^2}\, \frac{\Delta_a(\mu^2)}{\Delta_a(\mu'^2)}\, \Theta(\mu^2-\mu'^2)\; \Theta(\mu'^2-\mu_0^2)$$

$$\times \int_x^{z_M} \frac{dz}{z}\, P_{ab}^{(R)}(\alpha_s,z)\, \mathcal{A}_b\left(\frac{x}{z}, \mathbf{k}+(1-z)\,\boldsymbol{\mu}', \mu'^2\right)$$

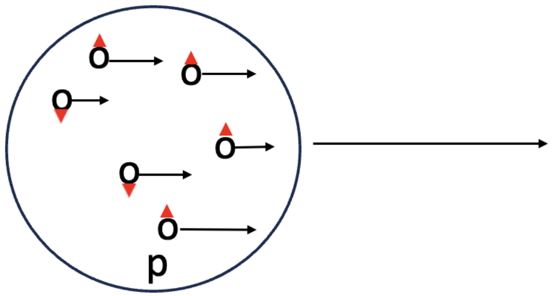
$$\Delta_a(z_M,\mu^2,\mu_0^2) = \exp\left(-\sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \int_0^{z_M} dz\; z\; P_{ba}^{(R)}(\alpha_s,z)\right)$$

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

- Integration of $\mathcal{A}_a(x,\mathbf{k},\mu^2)$ over all **k** gives collinear PDFs - $f_a(x,\mu^2)$
- $z_M \to 1$ gives the exact solution of the DGLAP evolution
- With angular ordering, TMDs well defined and independent of the choice of the soft-gluon resolution scale when $z_M \to 1$

Impact of the internal motion on k_T distributions

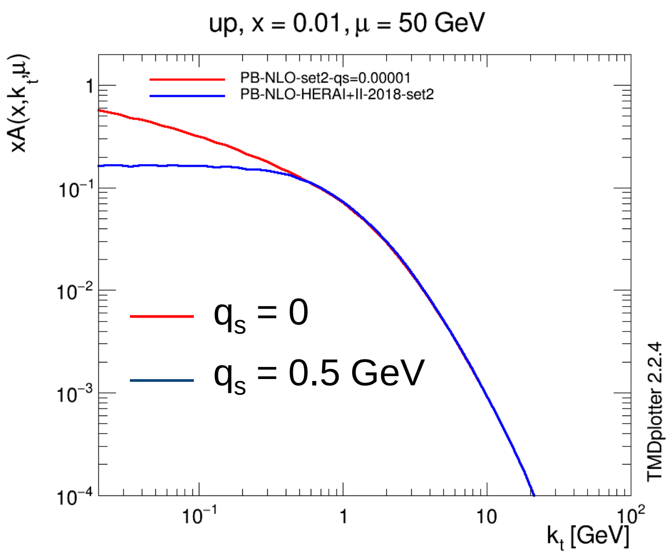
- Intrinsic k_T - transverse momentum which posses parton inside a hadron due to its internal (Fermi) motion

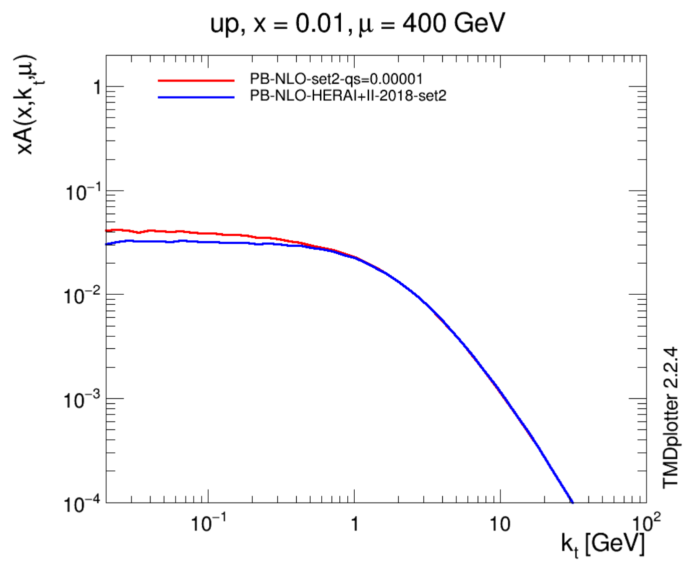


- In the evolution, it is introduced as a non-perturbative parameter and is generated from a Gaussian distribution of of the width σ which is expressed via parameter q_s in the PB model: $\sigma^2 = q_s^2/2$

$$A_a(x,\mathbf{k}_0,\mu_0^2) = f_a(x,\mu_0^2)\cdot \exp(-|k_0^2|/q_s^2)/(\sqrt{\pi} q_s)$$

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





- Significant effect of the intrinsic-k_T at low k_T and low scales

Soft contributions and Sudakov form factor

- Since $\alpha_s = \alpha_s(q_T) \rightarrow q_0$ where α_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:

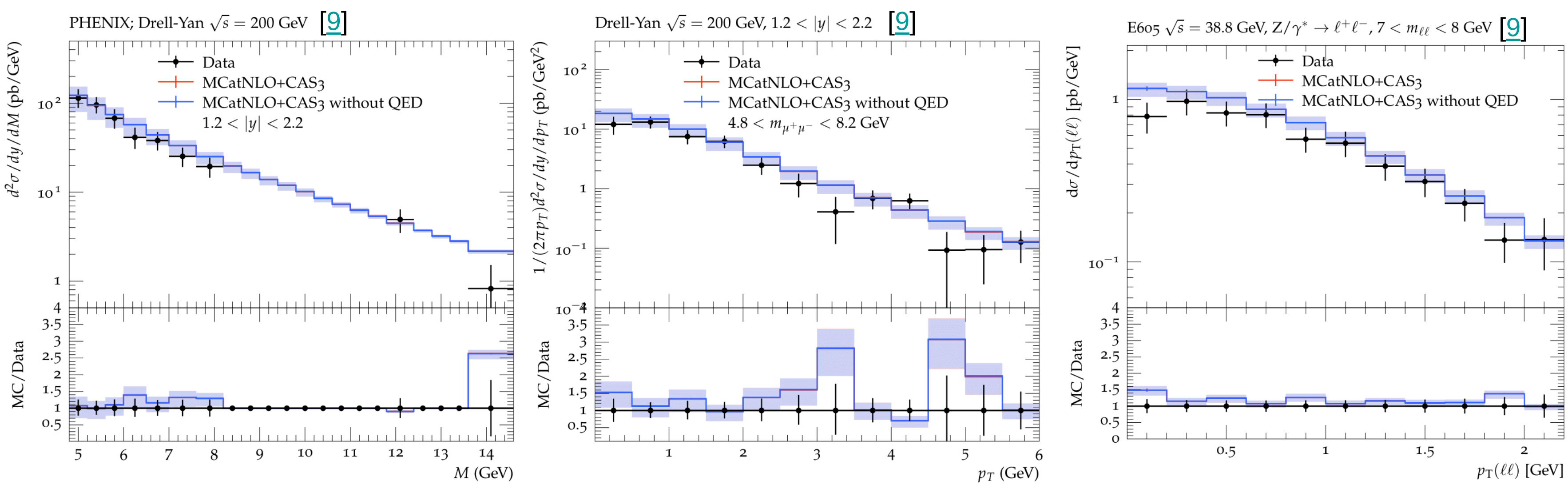
  - a perturbative region, with $0 < z < z_{dyn}$ ($q_T > q_0$)
  - a non-perturbative region with $z_{dyn} < z < z_M$ ($q_T < q_0$)

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

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

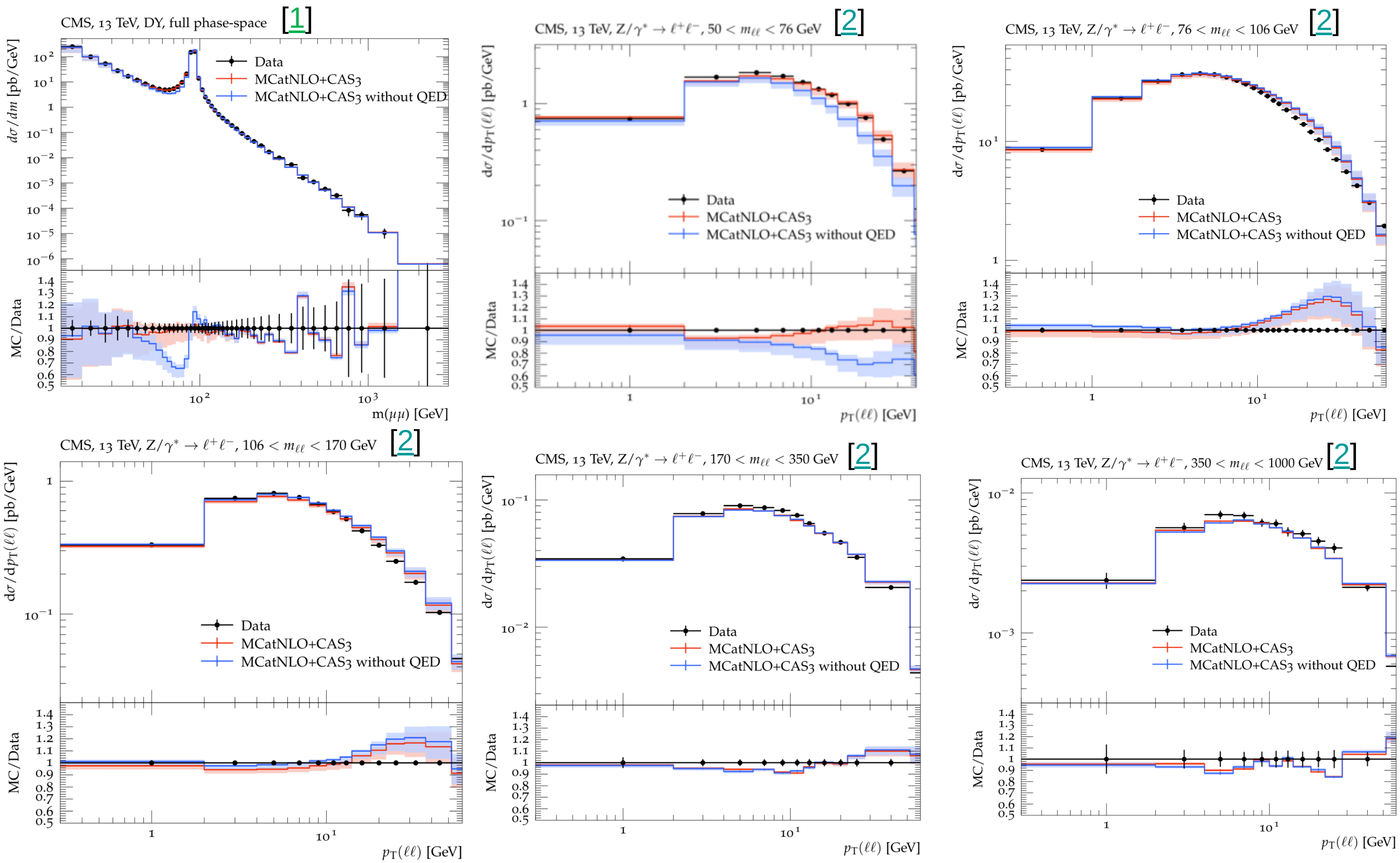
DY pairs with low invariant mass

- For theoretical prediction - PB TMD Monte Carlo event generator CASCADE3 based on PB-NLO-2018 Set2 is used (default - q_s = 0.5 GeV, $q_T > q_0 \simeq 0$ GeV)
- Matrix elements are obtained from the MADGRAPH5_AMC@NLO event generator at next-to-leading (NLO) and are matched with TMD parton distributions and showers obtained from PB evolution
- The final state parton shower in CASCADE3 is generated from PYTHIA since here are no PB-fragmentation functions available yet



- QED radiation not contributing to the low DY invariant mass and low pair p_T region
- Fair description of the low DY pair invariant mass and transverse momentum distributions obtained in hadron-hadron collisions at low energies.

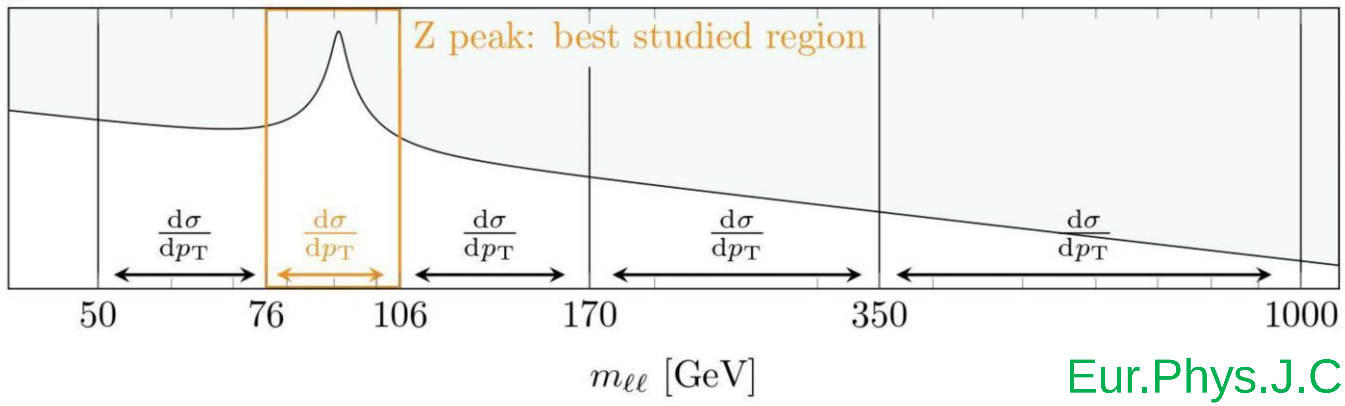
DY pair production at the LHC and the impact of QED



- QED plays important role in the mass region bellow the Z peak down to about 40 GeV
- PB provides a good description of experimental DY invariant mass and transverse momentum distributions in the wide range of center-of-mass collision energies

Determination of the Gaussian width q_s

- The recent publication from CMS on transverse momentum distribution in a wide DY invariant mass [2] provides a detailed uncertainty breakdown



→ the basic data for the determination of the intrinsic-k_T parameter q_s

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

➢ χ^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

- ❑ No full error breakdown is available for the other measurements
- ➢ All uncertainties treated as being uncorrelated and do not include any systematic uncertainty coming from the scale variation in the theoretical calculation

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

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

$q_0 = 10^{-2}$ GeV - minimal parton transverse momentum emitted at a branching

$q_T > q_0$ → soft contributions included

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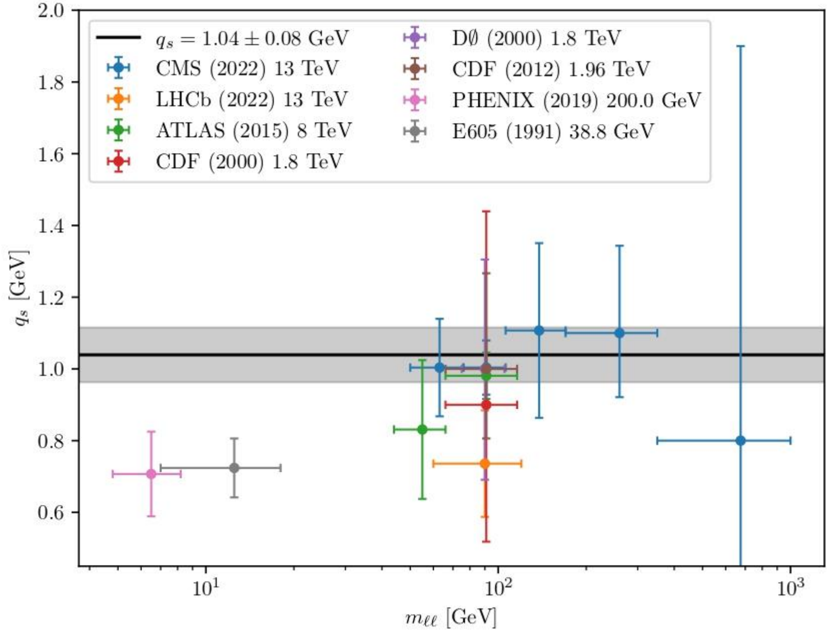
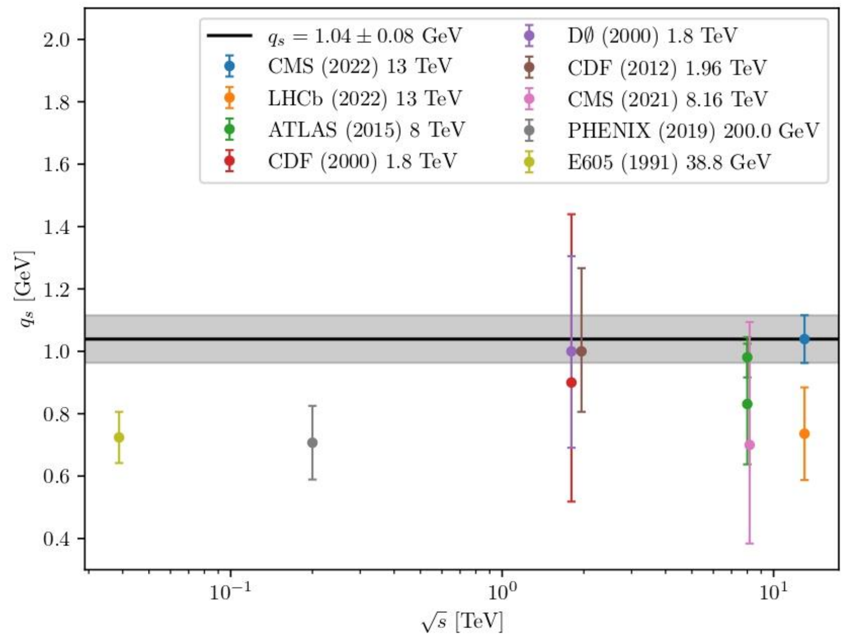




→ Consistent values of q_s for a large range of DY pair invariant masses

→ Very mild or no centre-of-mass energy dependence of q_s

→ The result in contrast to the ones obtained from standard Monte Carlo event generators which need 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*

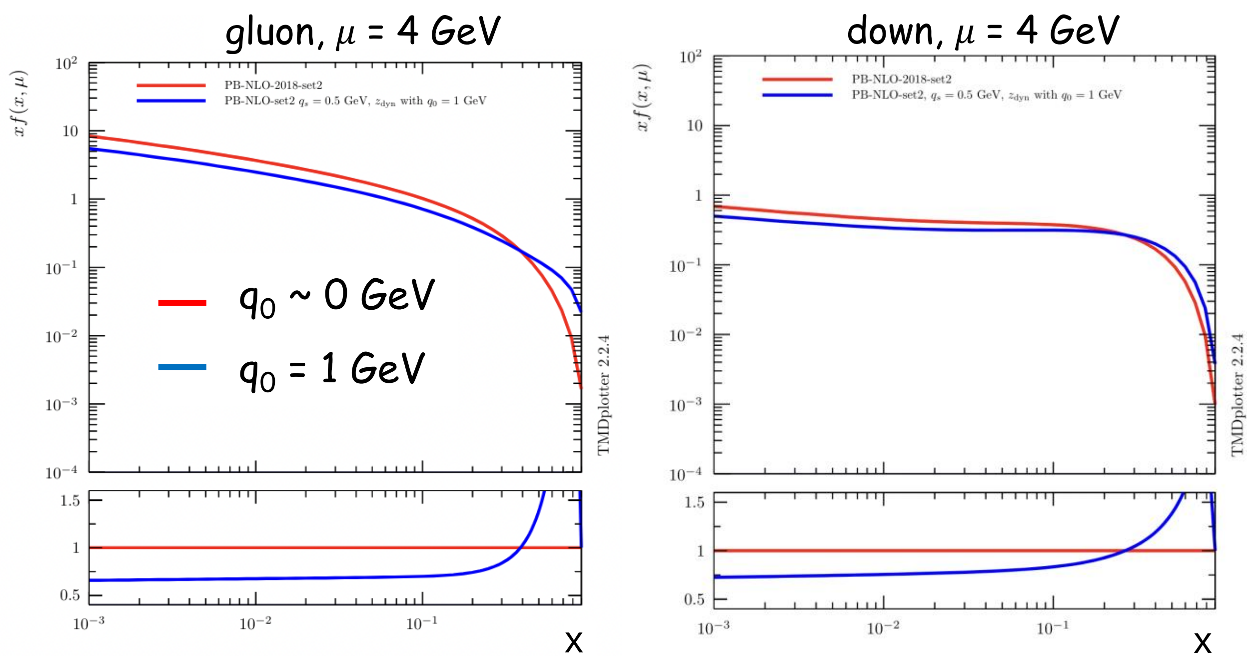
Try to introduce energy dependence of the intrinsic-k_T in PB

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

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

→ Real emissions with $z > 1 - q_0/\mu'$ - neglected



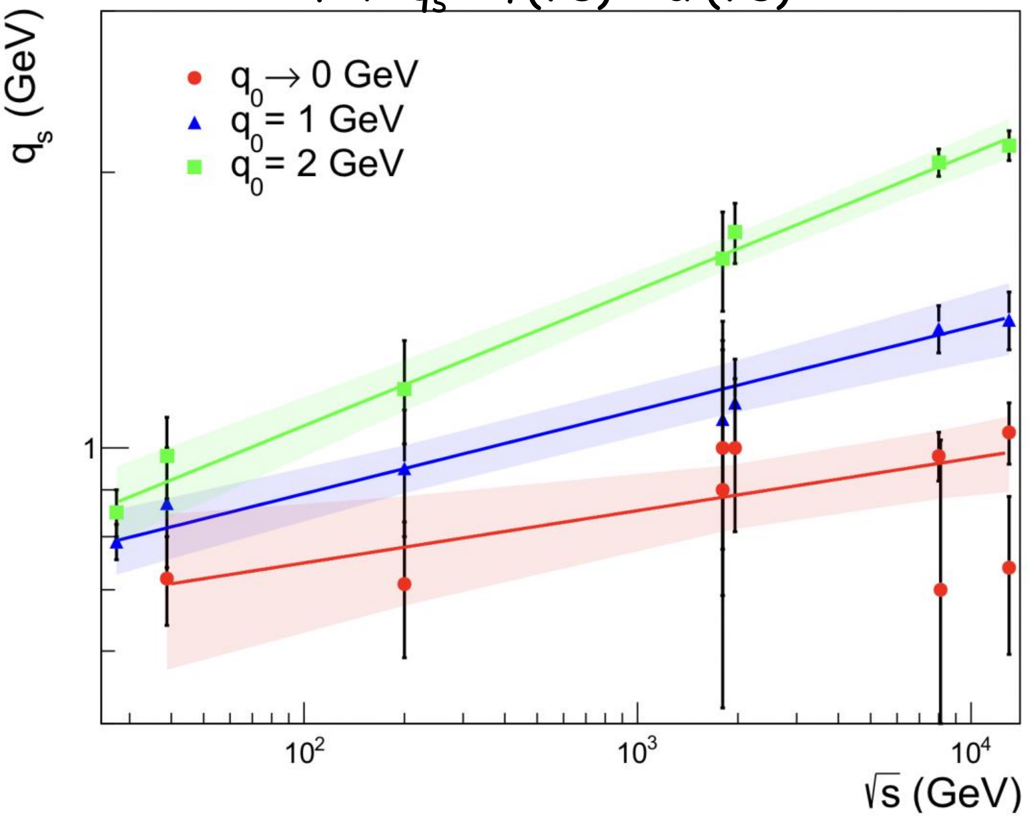
- Integrated parton distributions very different for the two cases

→ soft contributions important also for collinear distributions

q_s vs $\sqrt{s}$ for different q_0

arXiv:2404.04088

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

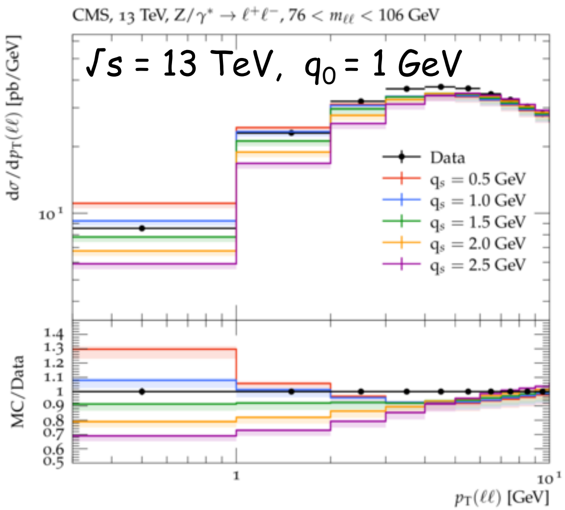


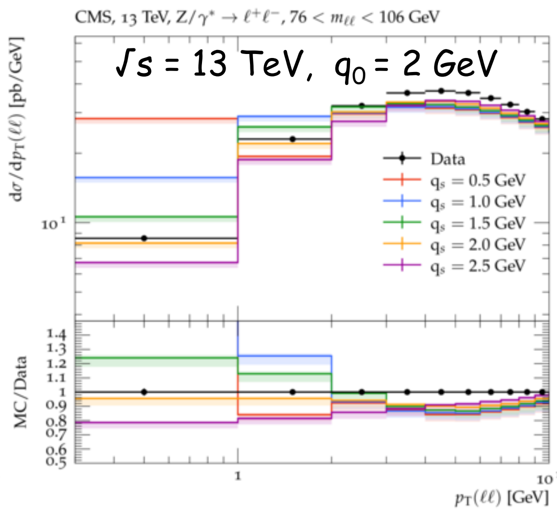
- The intrinsic-k_T width parameter increases with the collision energy
- The slope od the dependence increases as q_0 increases
- Larger q_0 means that more soft contributions are excluded

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

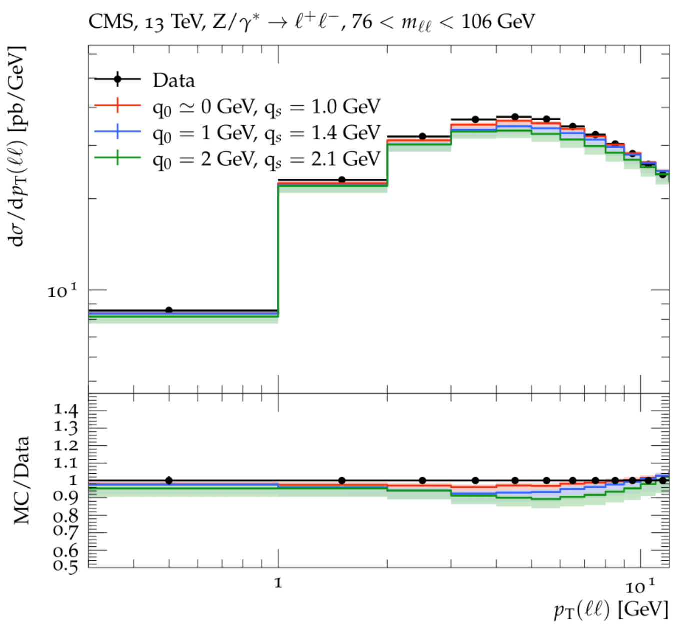
Closer look into DY pair low p_T distributions with different q_0

arXiv:2404.04088



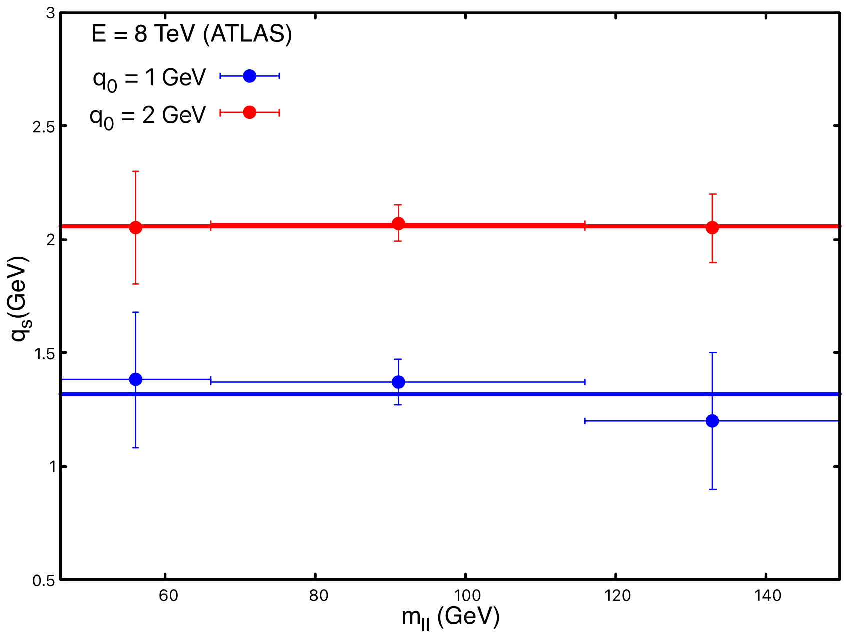


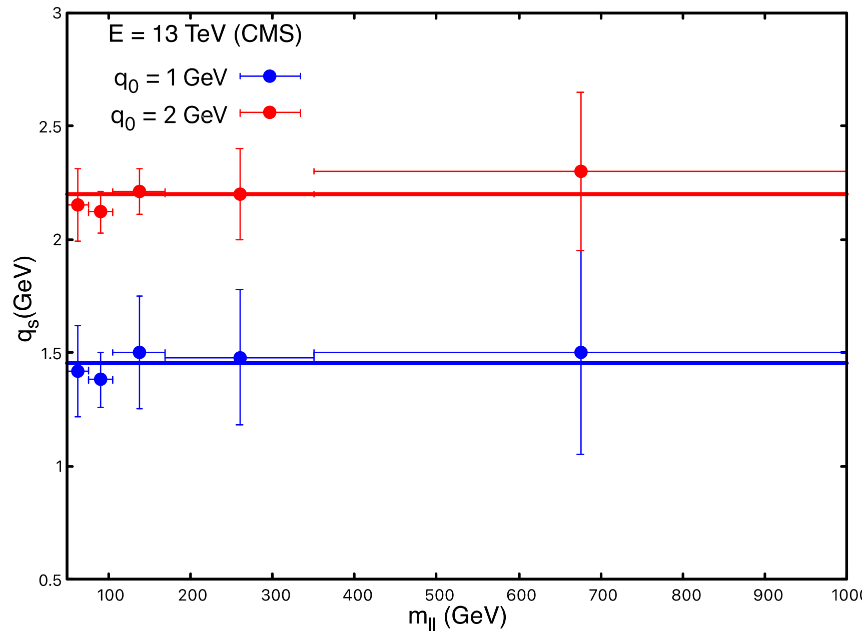
- The largest impact of the intrinsic k_T at very low DY pair p_T (up to 2-3 GeV)
- The sensitivity of the pair p_T distributions on the intrinsic-k_T width increases with q_0 cut



- The data and the prediction distributions obtained for the three values of q_0 (0, 1, 2 GeV) with optimal values of q_s (1, 1.4, 2.1 GeV) for each q_0
- The (small) difference in the transition region ($p_T(ll) \gtrsim 4$ GeV) influenced by the missing soft gluon contribution which is larger at higher q_0

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

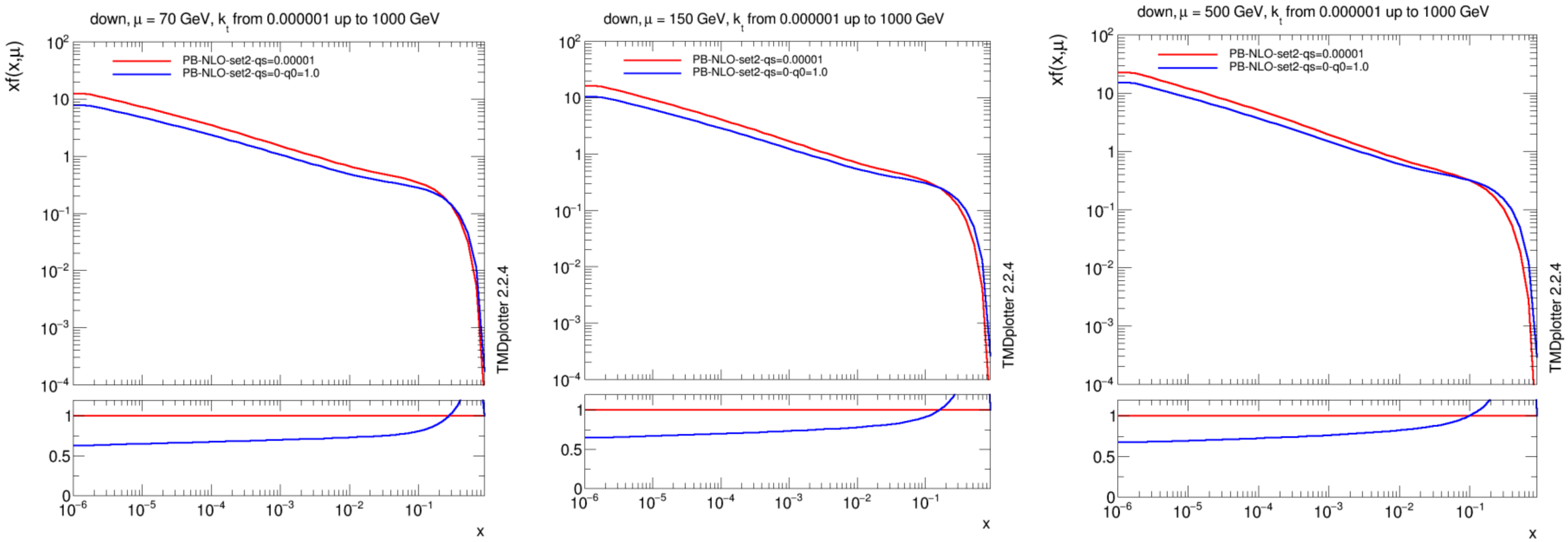




- <u>From the available measurements and existing uncertainties</u>: q_s remains independent of the DY pair invariant mass for $q_0 \lesssim 2$ GeV

  → 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



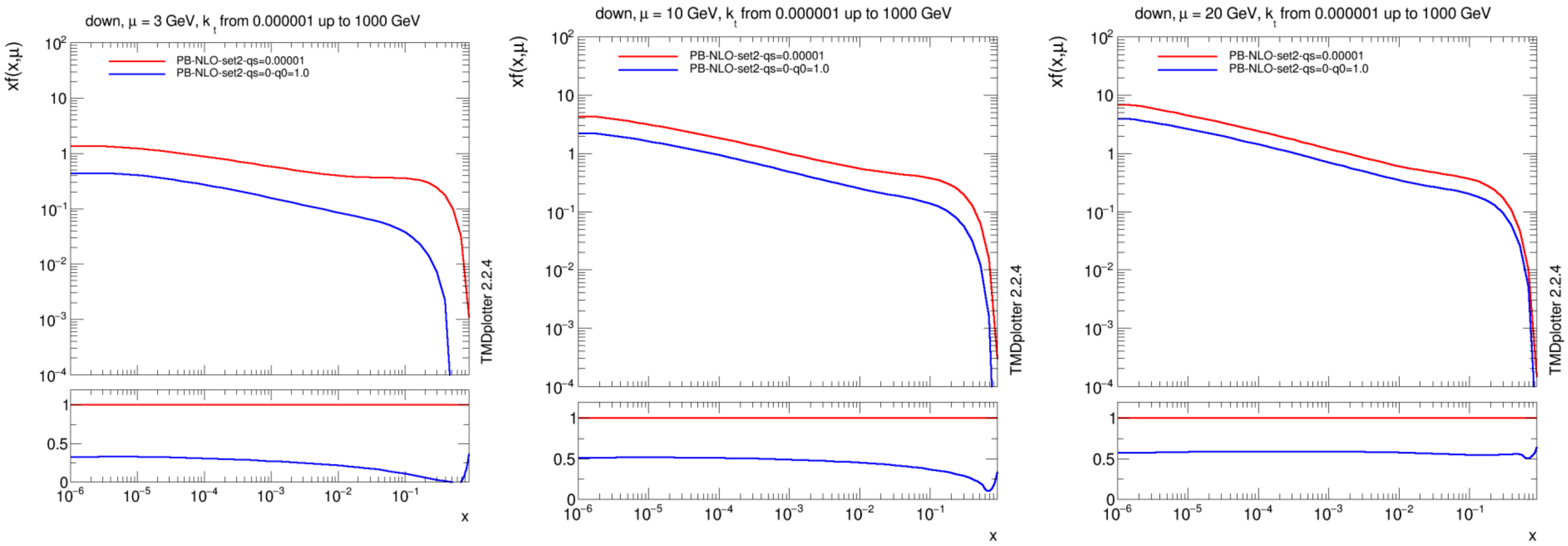
The scale values relevant for available measurements from LHC

- 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 slide) and changes slowly with μ in the region of μ ~ 100 GeV where measurements from the LHC have been performed

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

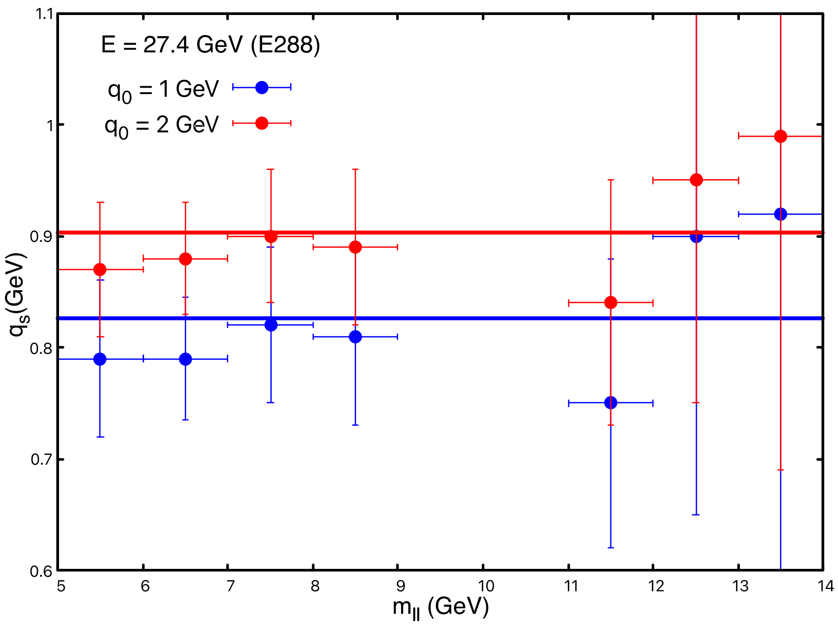
- The change in the integrated PDFs by introducing the q_0 ~ 1 GeV cut varies rapidly with the μ scale relevant for DY pair masses ~10 GeV

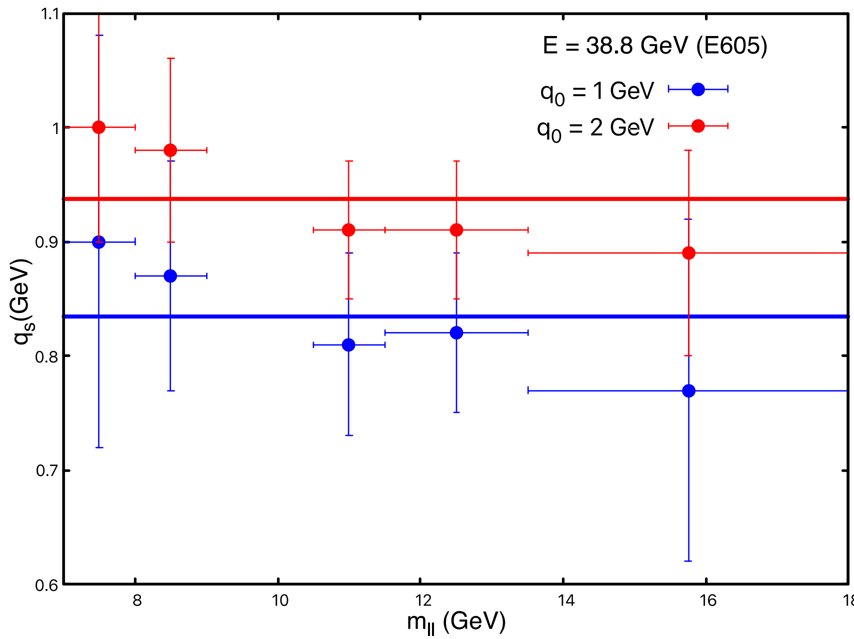
  → The relative amount of soft gluons removed by the cut changes significantly at low scales and the measurable changes in the value of q_s could be expected at low DY pair invariant masses

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

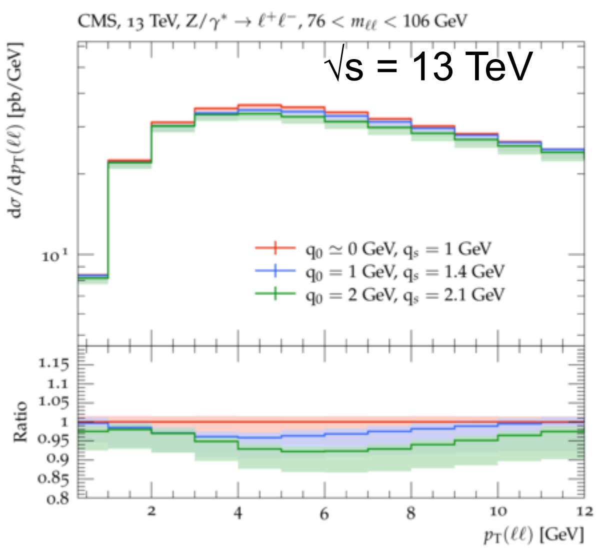


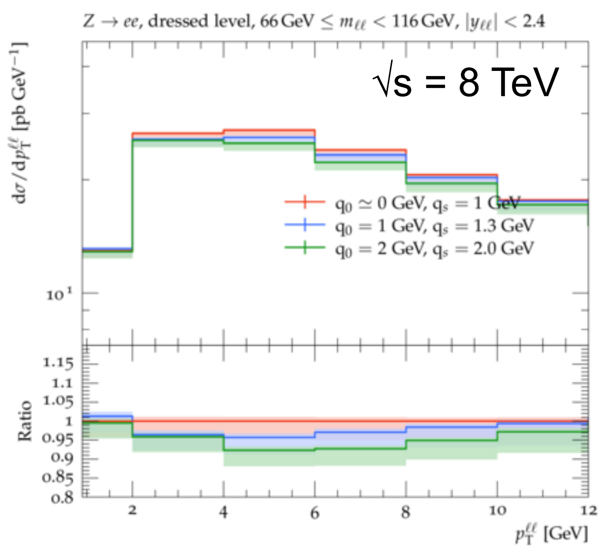


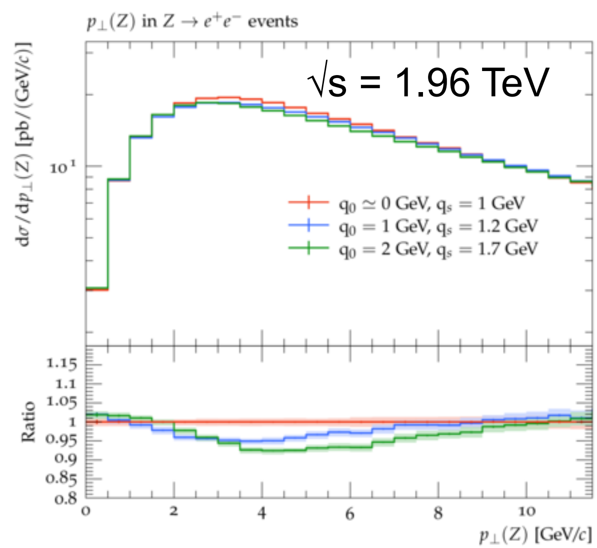
→ Although the errors are large and it is not possible to draw a firm conclusion, the trend of change of the q_s with m(ll) is noticeable in the measurements obtained from the E605

Z peak region for different q_0

- The prediction distributions obtained at different center of mass collision energies for the three values of q_0 (0, 1, 2 GeV) with optimal values of q_s







- Similar relative contribution of soft emissions in the transition region at different collision energies

- The cut on the transverse momentum of the radiated parton in the branching, q_0, up to 2 GeV does not affect the distribution of the transverse momentum of the Drell-Yan pair with $p_T(ll) \gtrsim$ 10-15 GeV

Summary

- The PB method provides a measurement of the intrinsic-k_T width that does not depend on the invariant mass of the DY pair, nor on the center-of-mass collision energy $\sqrt{s}$
  - The inclusion of soft gluons is crucial for providing $\sqrt{s}$-independent intrinsic-k_T
- We learned the following about the soft gluons contribution to DY pair production in hadron-hadron collisions:
  - There is an interplay between the internal transverse motion and soft gluon contribution in the non-perturbative region of the DY transverse momentum distribution
  - The relative contribution of the soft gluon emissions which interplays with internal parton transverse motion increases with the collision energy
  - With the available measurements and existing uncertainties, we still cannot confirm the dependency of the relative soft gluon contribution on the DY pair invariant mass
    → consistent with the behaviour (the small sensitivity) of the non-perturbative Sudakov FF in the measured regions
- The intrinsic-k_T contribution can be disentangled from the non-perturbative Sudakov one only by the proper treatment of the non-perturbative processes which can be provided by the PB Method due to its sensitivity to non-perturbative TMD contributions

Thank you very much for your attention

References

[1] https://arxiv.org/abs/1812.10529

[2] https://arxiv.org/abs/2205.04897

[3] https://arxiv.org/abs/2112.07458

[4] https://arxiv.org/abs/2102.13648

[5] https://arxiv.org/abs/1512.02192

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

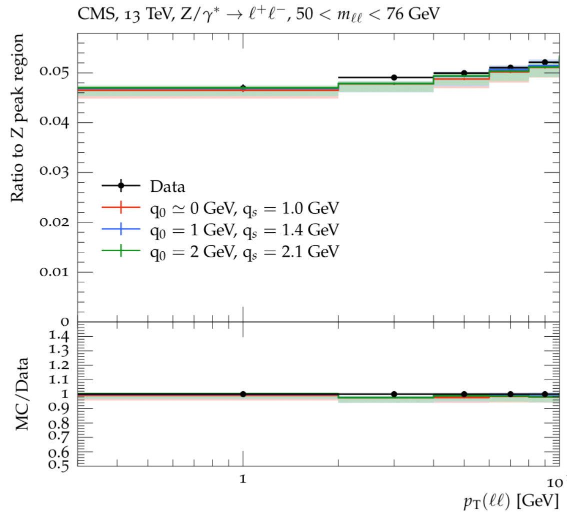
[7] https://arxiv.org/abs/hep-ex/0001021

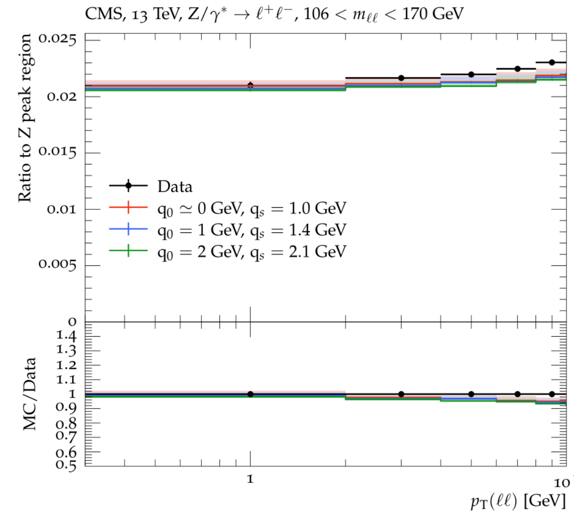
[8] https://arxiv.org/abs/hep-ex/9907009

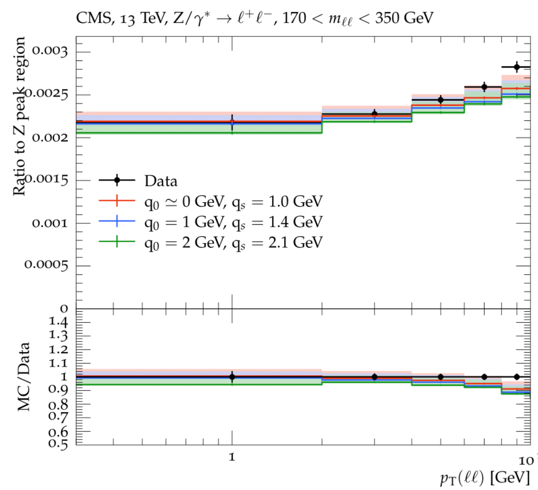
[9] https://arxiv.org/abs/1805.02448

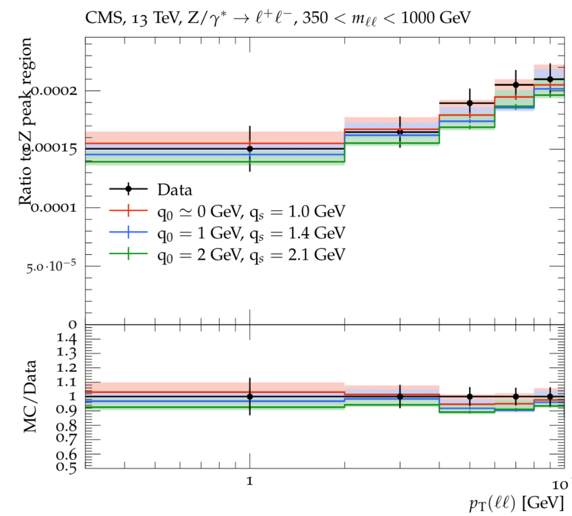
[10] https://journals.aps.org/prd/abstract/10.1103/PhysRevD.43.2815

The ratio of the cross section to Z peak region for different q_0









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