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Study of Intrinsic-kt in the Parton Branching Method

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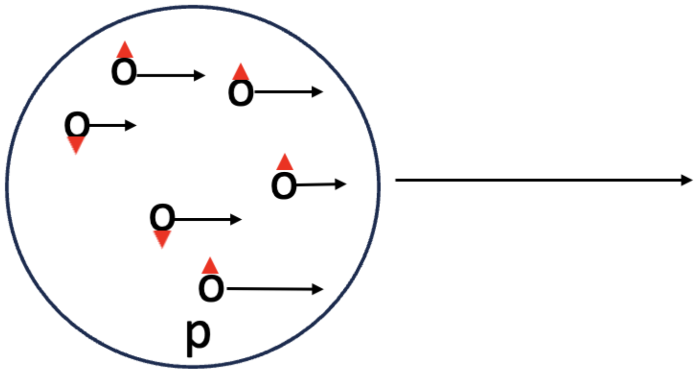
This talk is mainly focused on the recently obtained results shown in:

arXiv:2404.04088

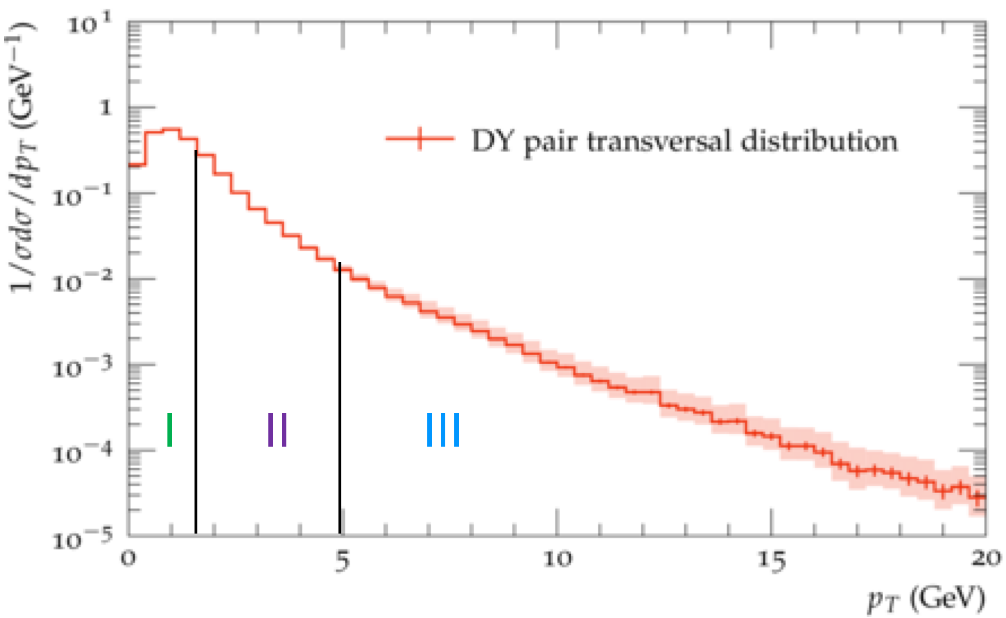
arxiv:2312.08655
Eur.Phys.J.C 84 (2024) 2, 154

Intrinsic-k_T



- The largest part of the initial partons momenta inside a hadron is the longitudinal momentum, but beside it, they have also **transverse momentum due to their internal (Fermi) motion – intrinsic k_T**

- 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

Why Parton Branching (PB) method ?

- The main goal of all theoretical predictions in HEP nowdays is to improve unceratinties at all levels

  → Test consistency of Standard Model and point to the deviations which could indicate a new physics

- BUT, the problem of soft gluon emissions treatment and their resummation in collinear generators persists

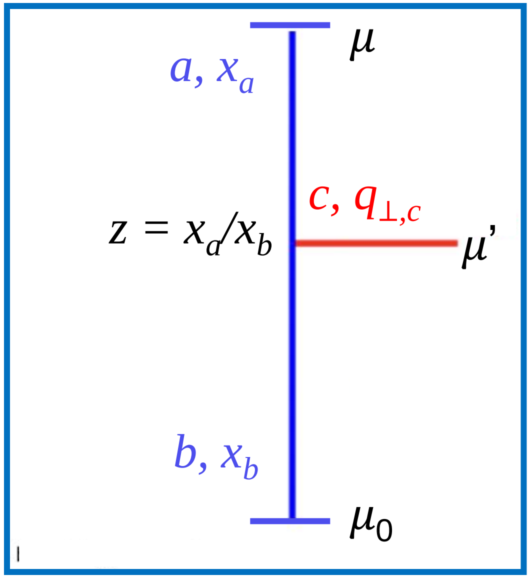
  → Development of the PB Method which follows a different approach by introducing the transverse degree of freedom (k_T – parton transverse momentum) from the beginning instead of treating it as a higher order corrections

- The PB Method – describes partons from colliding hadron via Transverse Momentum Dependent (TMD) parton distribution functions (PDF) → TMDs

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

  → TMDs for all flavors in a wide kinematic range obtained from the TMD evolution equation

Parton branching



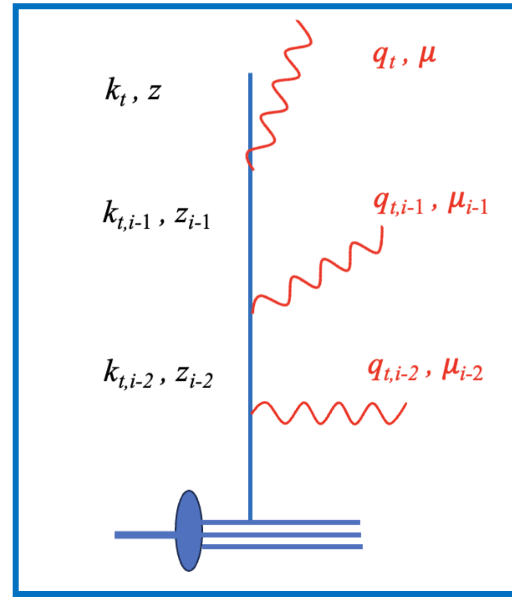
One branching

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 $\rightarrow$ 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

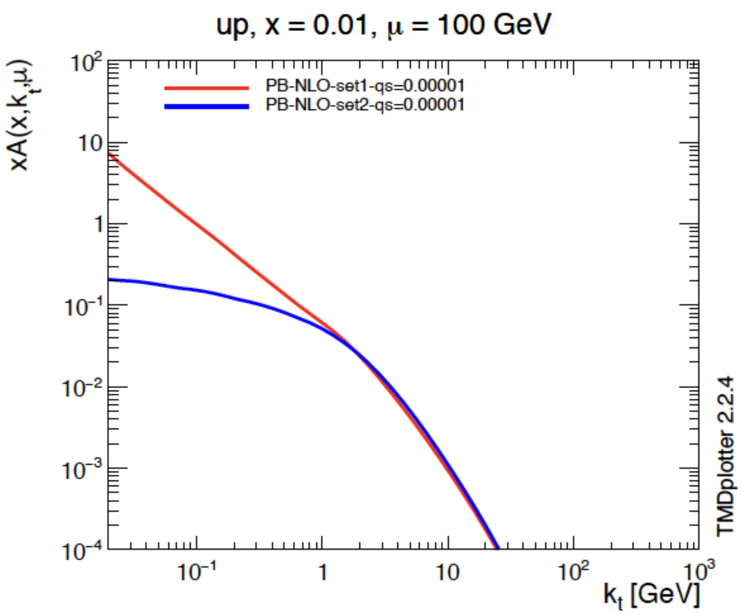
- $z_M \rightarrow 1$ gives the exact solution of the DGLAP evolution
- Integration of $\mathcal{A}_a(x,\mathbf{k},\mu^2)$ over all **k** gives collinear PDFs - $f_a(x,\mu^2)$

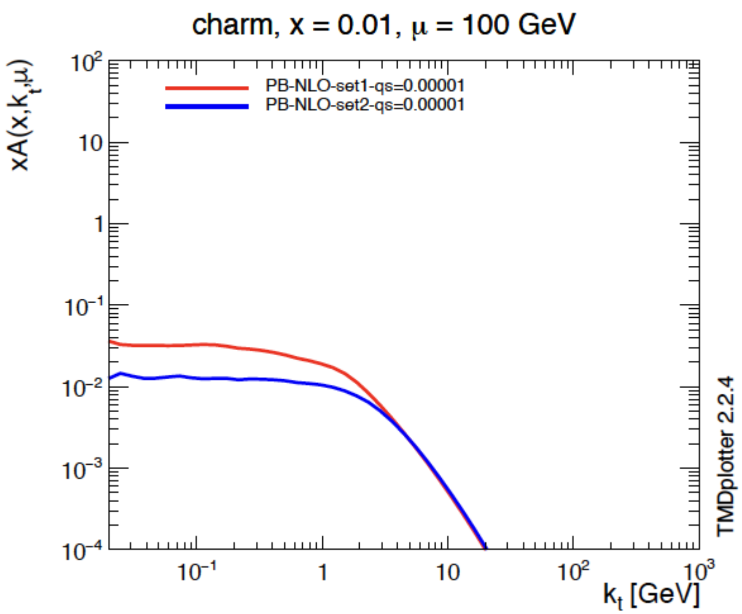
α_s scale

- 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**

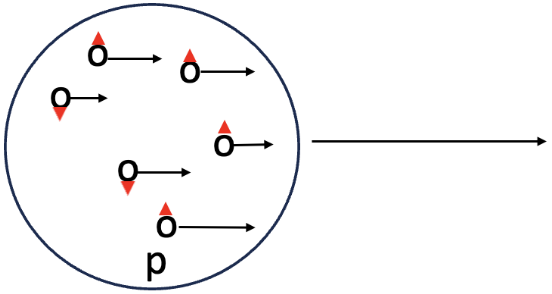




- Significant difference at low transverasal momenta of partons

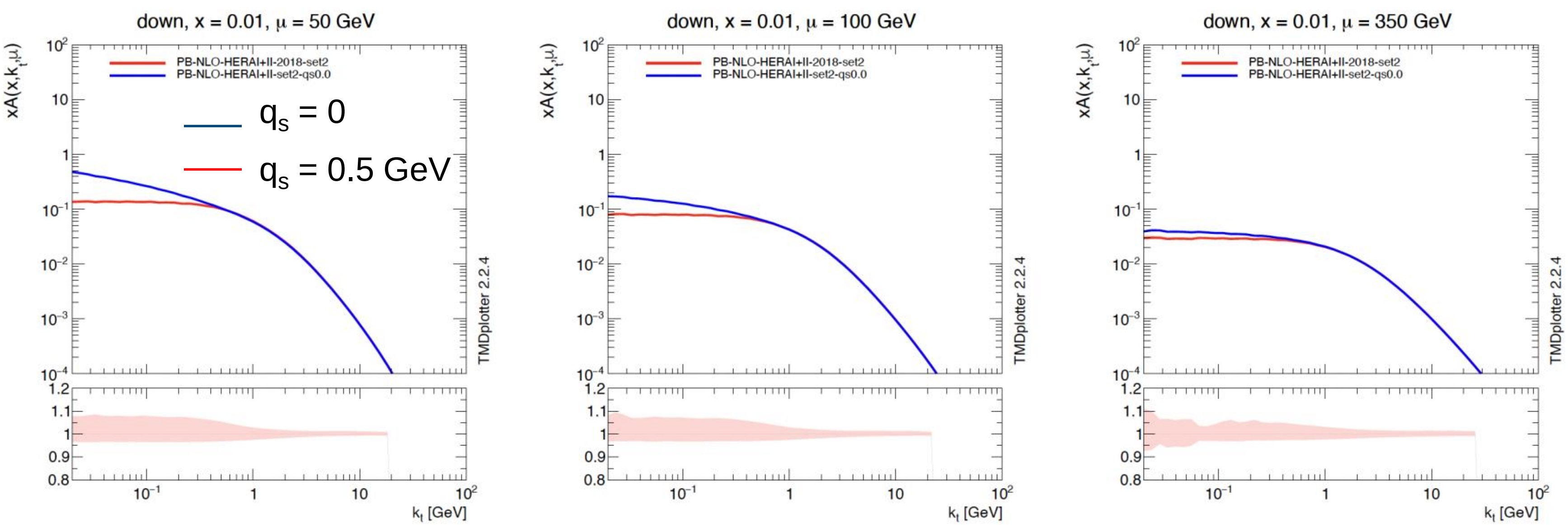
- For heavy flavors the difference much smaller since they are only generated dynamically

Intrinsic k_T in TMDs



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

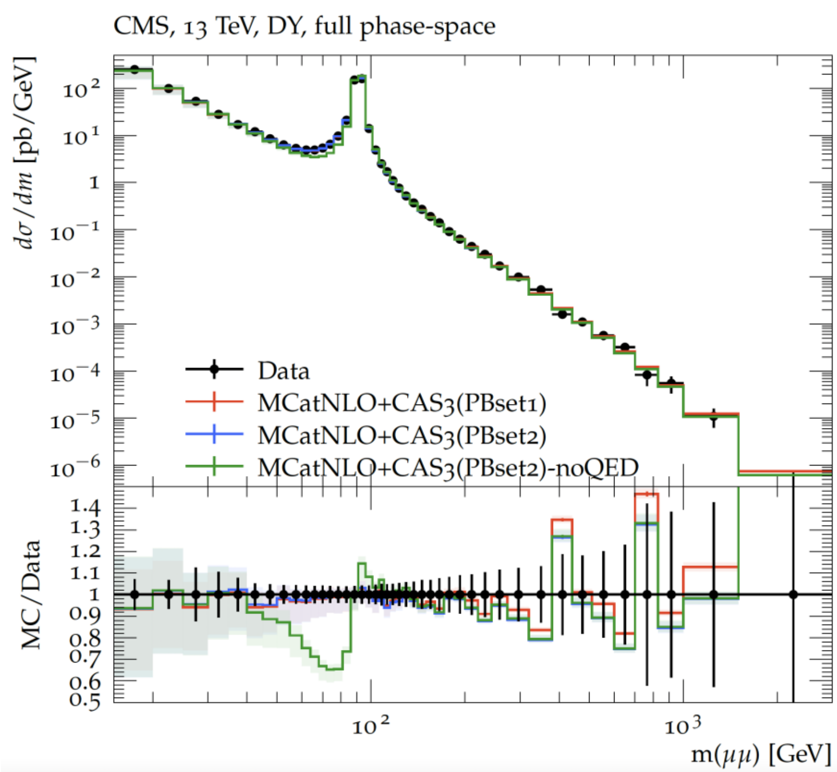
$$A_a(x,\mathbf{k}_0,\mu_0^2) = f_a(x,\mu_0^2)\cdot \exp(-|k_0^2|/q_s^2)/(\pi q_s^2)^{1/2}$$



- Significant effect of the intrinsic-k_T at low scales

DY invariant mass distribution

- For theoretical prediction - PB TMD Monte Carlo event generator CASCADE3 based on PB-NLO-2018 Set1 or PB-NLO-2018 Set2 is used
  (default - q_s = 0.5 GeV, $q_T > q_0$ = 0.01 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



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- CMS measurement [1]
- Rivet package used for calculation of the final distributions
- The inclusion of QED radiation (photon radiation in final state) is essential in the region bellow Z peak

DY transveral momentum distribution

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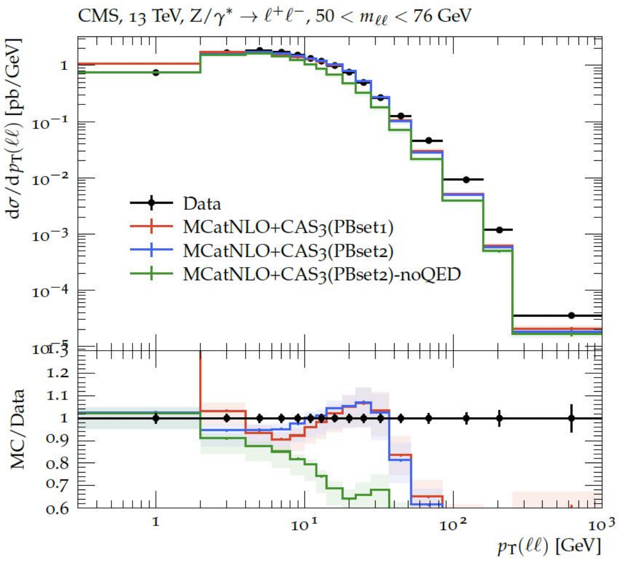
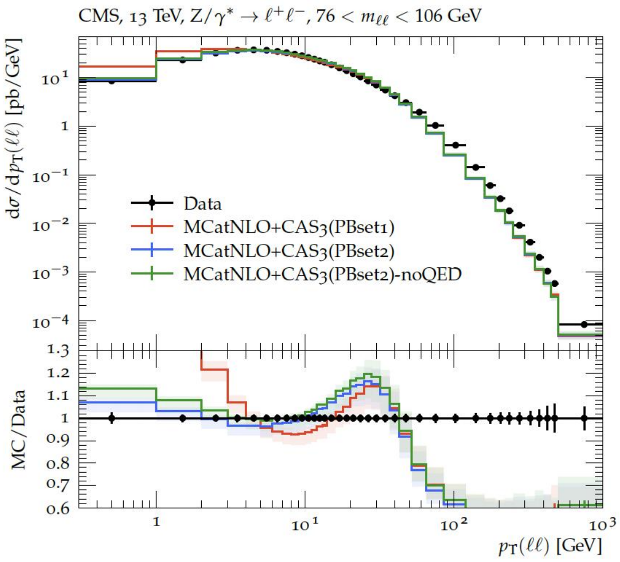
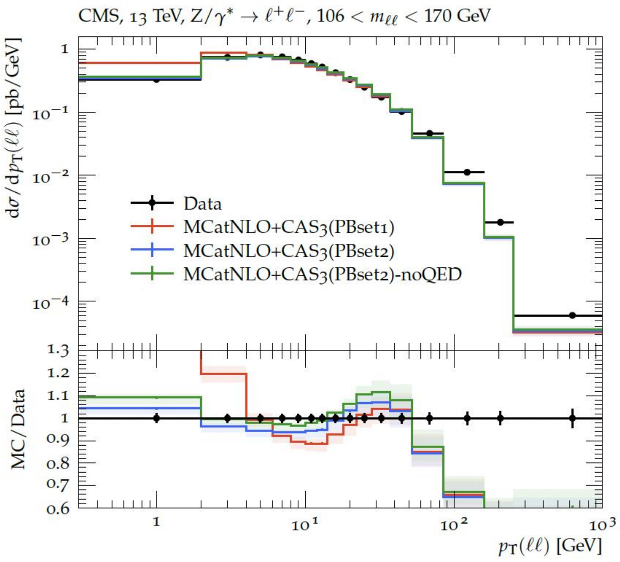
- CMS measurement [2]





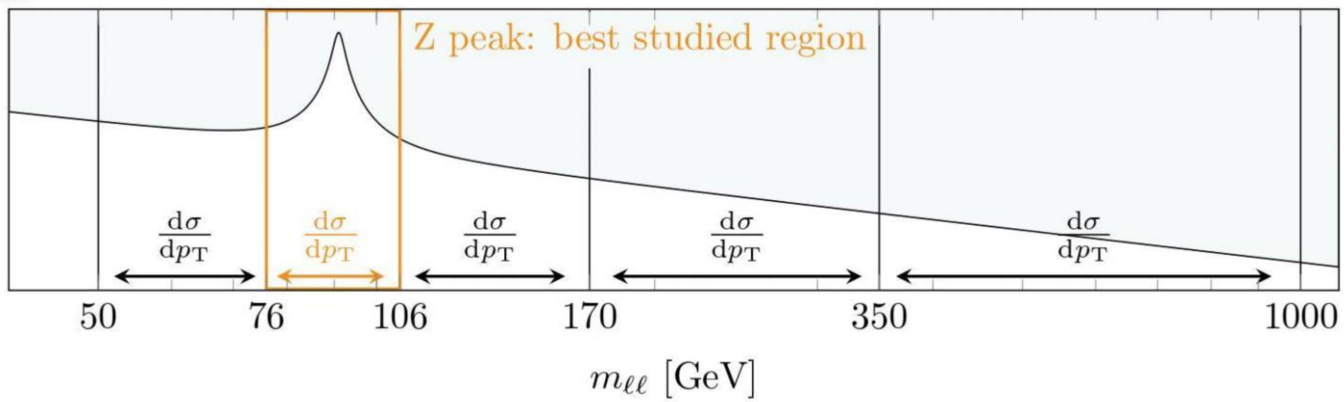


q_s = 0.5 GeV

- Too high contribution at small DY transverse momenta using the PB-NLO-2018 Set1 while PB-NLO-2018 Set2 describes the measurements rather well
- QED changes not only the total cross section but rather strongly modifying the shape of the transverse momentum distribution especially at low DY masses
- Too low cross section predicted with the calculations at large transverse momentum due to missing higher-order contributions in the matrix element

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

- 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

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

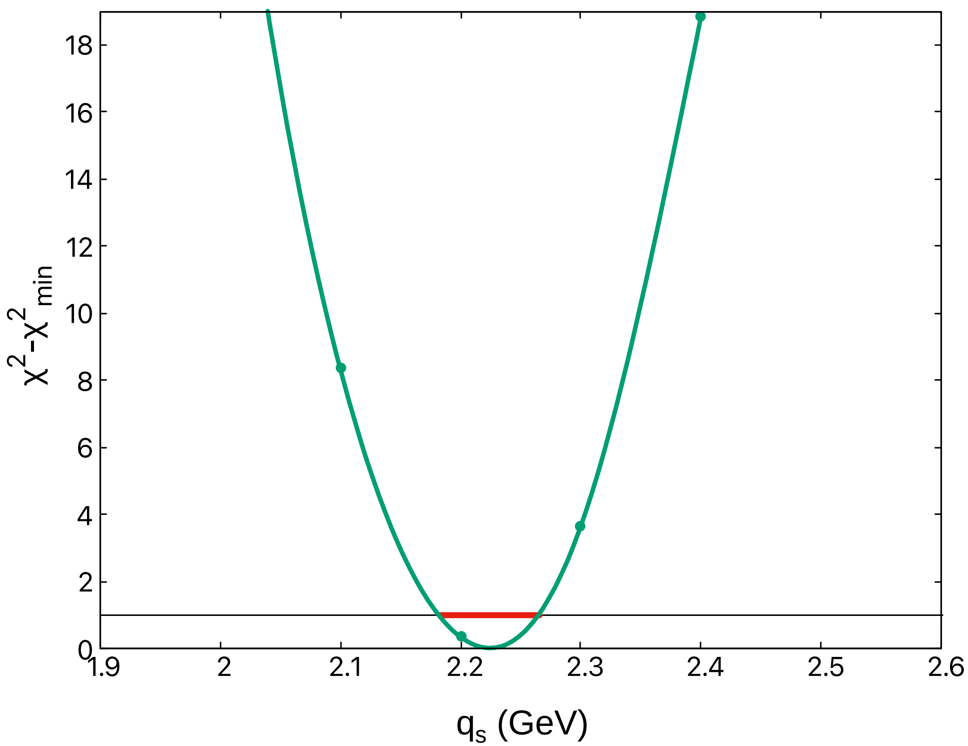
- The covariance matrix C_{ik} consists of a component describing the uncertainty in the measurement, $C_{ik}^{measurement}$, and the statistical (bin by bin stat. unc) and scale uncertainties in the prediction

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

- For each invariant mass region obtained in the measurement, only the region most sensitive to q_s considered , $p_T(ll) < 8$ GeV

Determination of the Gaussian width q_s

- The q_s determined for each mass bins while taking care to obtain a value of $\chi^2 \approx$ ndf for each mass bin (by adjusting the number of pair pt bins considered)
- One-sigma confidence obtained as the region of q_s values for which $\chi^2 < \chi^2_{min}+1$ with



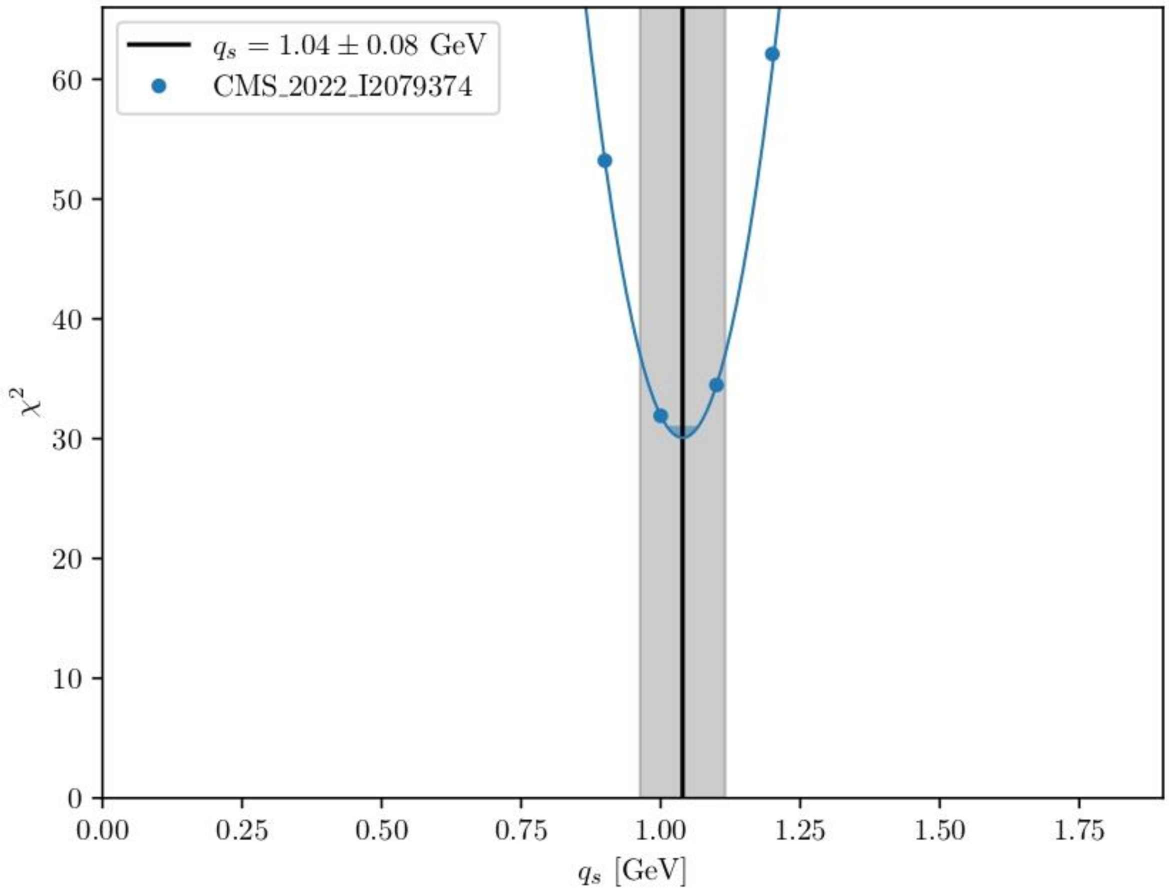
- There are two additional uncertainties added on top of the data one. These are "systematics" related to the scan itself

➢ 0.05 GeV which accounts for the scan resolution (one half of scan-step up and down)

➢ A variable amount to account for changes when considered bins are added or removed

The Gaussian width q_s from the combined CMS data

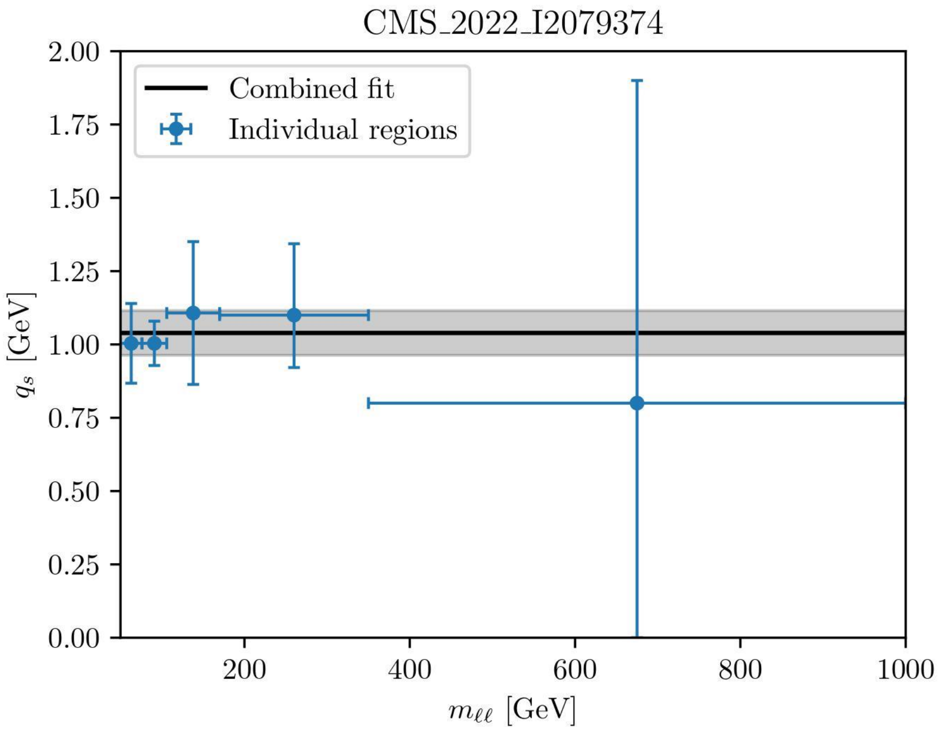
- ❑ The optimal q_s obtained considering bins in all mass ranges Eur.Phys.J.C 84 (2024) 2,154
  - ➢ A new covariance matrix $C_{ik}^{comb.}$ constructed as a sum over the 650 uncertainty sources included in the detailed breakdown



$$q_s = 1.04 \pm 0.03\ (\text{data}) \pm 0.05\ (\text{scan}) \pm 0.05\ (\text{binning})\ \text{GeV} = 1.04 \pm 0.08\ \text{GeV}$$

Intrinsic k_T-width depending on DY mass at $\sqrt{s}$ = 13 TeV

m_{DY} region	Best χ^2	n.d.f.	Best fit q_s [GeV]
50–76 GeV	2.45	3	$1.00 \pm 0.08(\text{data}) \pm 0.05(\text{scan}) \pm 0.1(\text{bins})$
76–106 GeV	11.4	7	$1.03 \pm 0.03(\text{data}) \pm 0.05(\text{scan}) \pm 0.05(\text{bins})$
106–170 GeV	6.46	4	$1.11 \pm 0.13(\text{data}) \pm 0.05(\text{scan}) \pm 0.2(\text{bins})$
170–350 GeV	4.62	4	$1.1^{+0.24}_{-0.18}(\text{data})$
350–1000 GeV	1.04	4	< 1.9



- The q_s values obtained from each mass bin are consistent
- The sensitivity at high mass affected mainly from larger statistical uncertainties in the measurement

→ No mass dependence of the q_s at $\sqrt{s}$ = 13 TeV

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DY production 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	$\sqrt{s}$	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 = 0.01 GeV - minimal parton transverse momentum emitted at a branching

$z_M = 1 - \varepsilon$ ($\varepsilon = 10^{-3}$) → soft gluon contributions included

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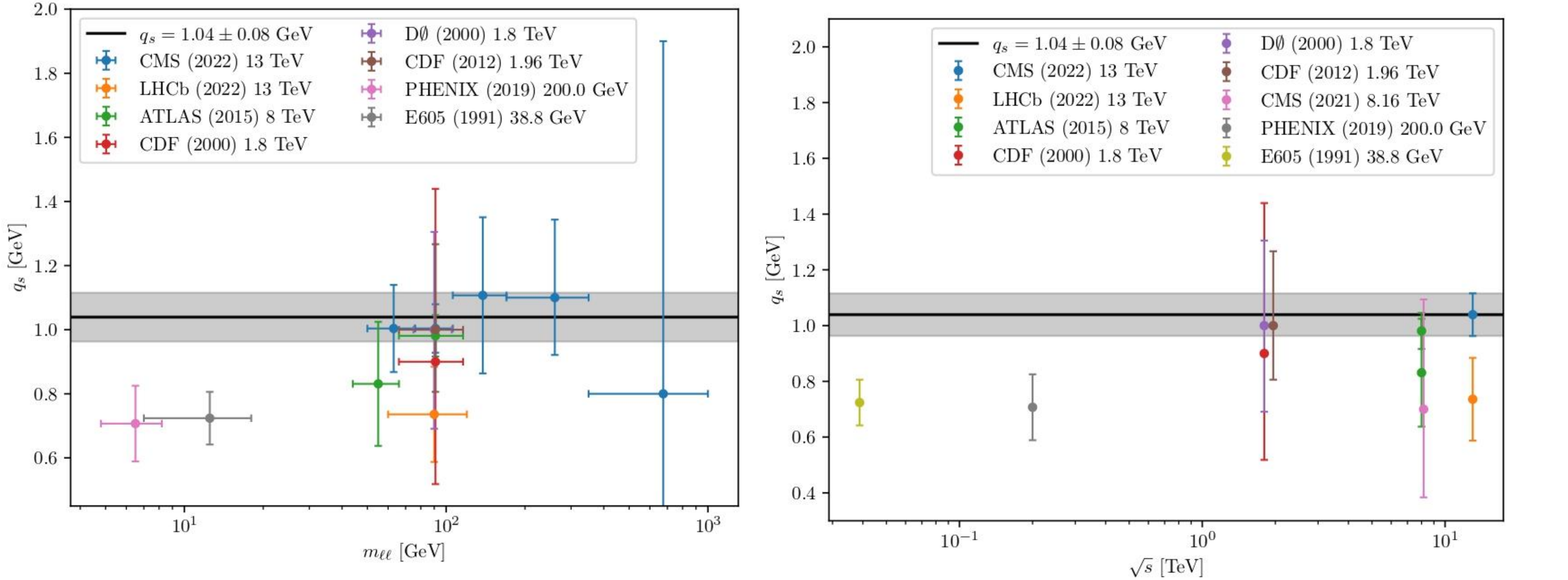


The result of proper treatment of soft contributions:

→ 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) emitted at a branching

- The angular ordering leads to two different regions: a perturbative region, with $q_T > q_0$, and a non-perturbative region of $q_T < q_0$, where α_s is frozen at 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

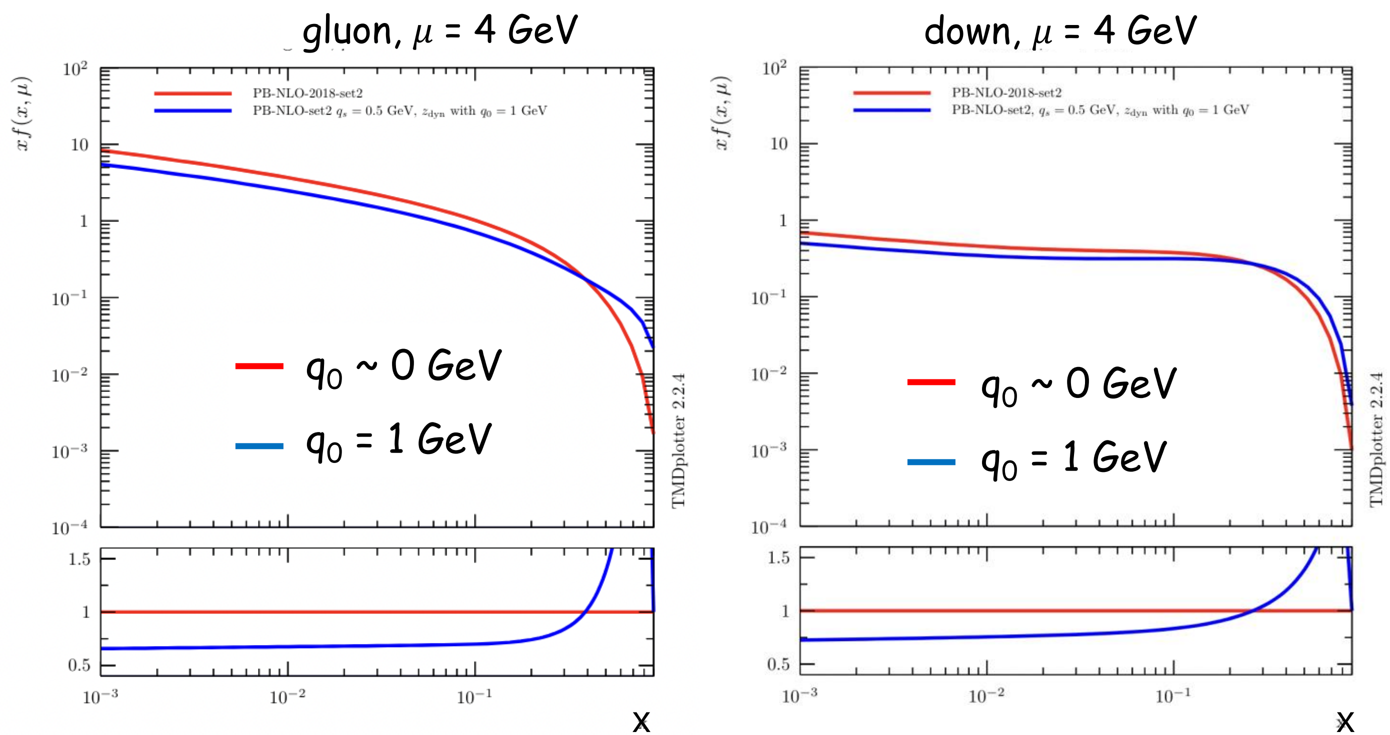
$$
\begin{aligned}
\Delta_a(\mu^2,\mu_0^2) &= \exp\left(-\sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mathbf{q}'^2}{\mathbf{q}'^2} \int_0^{z_{\rm dyn}} dz\ z\ P_{ba}^{(R)}(\alpha_s,z)\right) \\
&\quad \times \exp\left(-\sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mathbf{q}'^2}{\mathbf{q}'^2} \int_{z_{\rm dyn}}^{z_{\rm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

Impact of q_0 cut on integrated parton density

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

→ $\Delta_a^{(NP)}$ - neglected

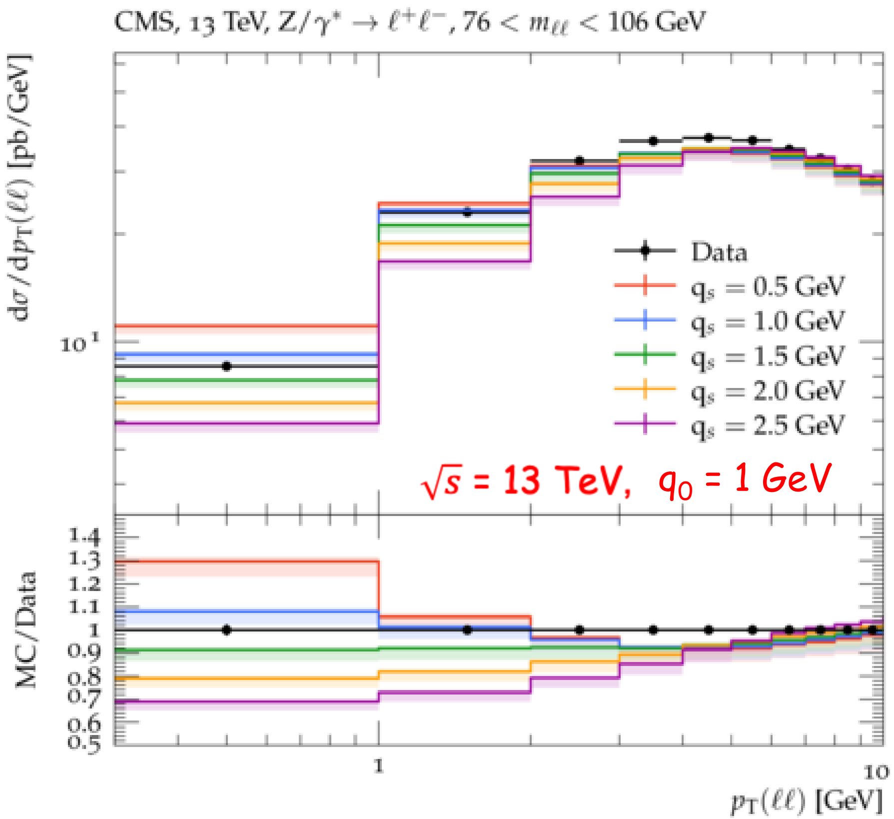
→ Real emissions with $z > 1 - q_0/\mu'$ - neglected

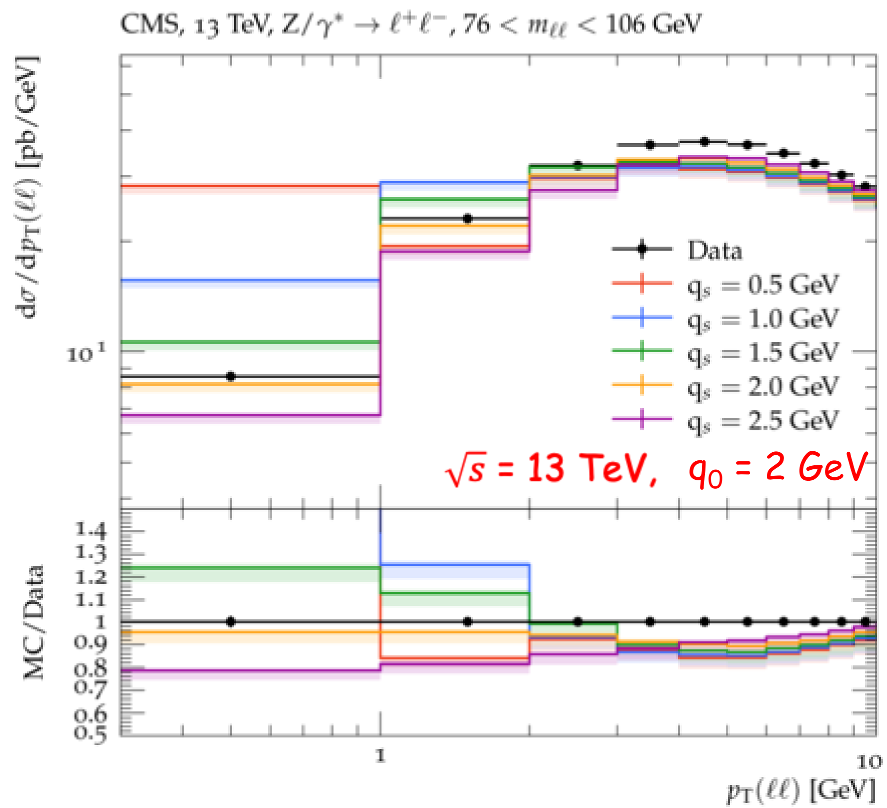


❑ Integrated parton distributions very different for the two cases

→ soft contributions important also for collinear distributions

Impact of intrinsic-k_T on DY pair low p_T distribution vs q_0

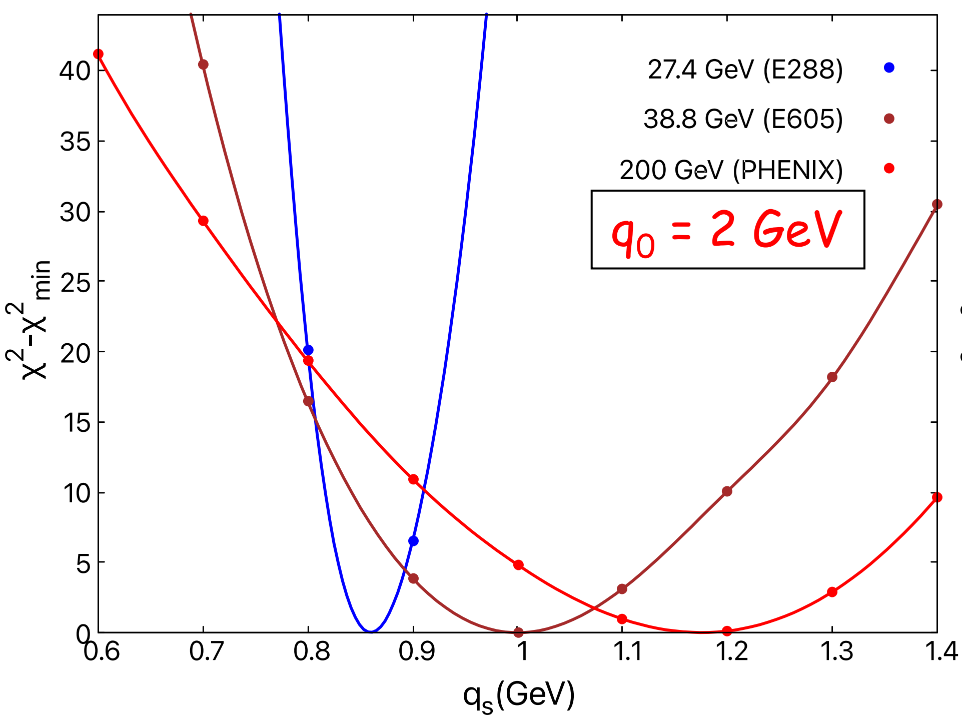


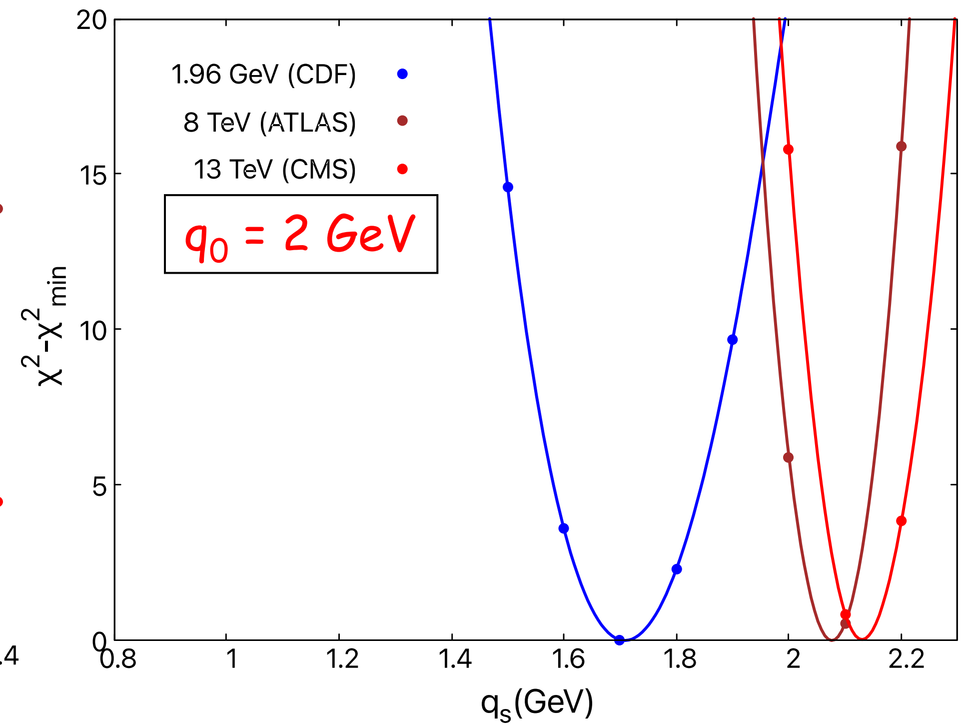


- Sensitivity of the DY cross section on the intrinsic-k_T increases at small pair p_T and with increasing of q_0 value

Determination of intrinsic-k_T (q_s width) for certain q_0

- Measured DY cross section dependence on pair p_T compared with the prediction and χ^2 dependence on qs obtained for each q_0 (1 and 2 GeV) at different collision energies
- The uncertainties are treated as being uncorrelated





$\longrightarrow \sqrt{s}$

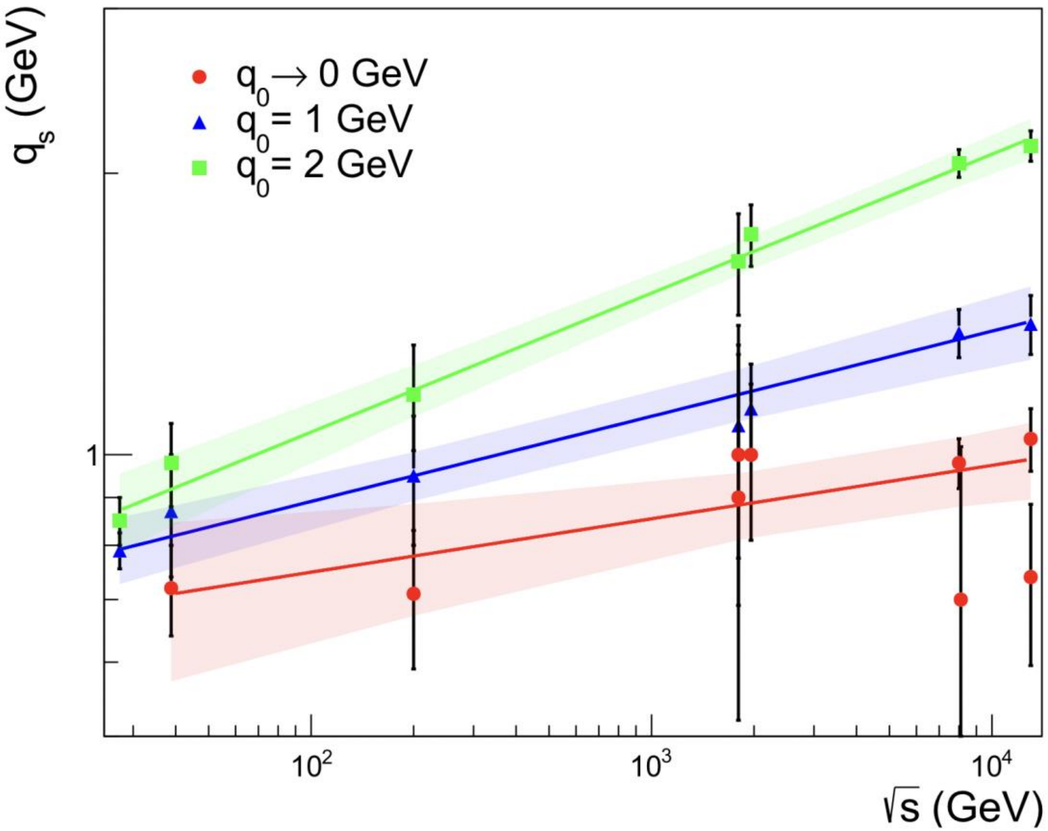
→ Intrinsic-k_T width – q_s for which χ^2 distribution has minimum

→ Intrinsic-k_T width uncertainty - q_s range for which $\chi^2 < \chi^2_{min}+1$

q_s dependence on $\sqrt{s}$ for different q_0

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

arXiv:2404.04088



- ❑ 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
- ❑ Smaller uncertainty band at larger q_0 due to larger sensitivity on intrinsic-k_T

Summary

- The intrinsic-k_T parameter of q_s = 1.04 ± 0.08 GeV extracted from the latest CMS measurement on DY p_T spectra over the wide mass range which provides a detailed uncertainty breakdown

- In contrast to other approaches, the width of the intrinsic-k_T distribution is independent of the mass of the DY pair and independent of the center-of-mass energy $\sqrt{s}$

- The energy scaling of q_s with collision energy, $\sqrt{s}$, was introduced by requiring minimal transverse momentum of emitted parton in a branching, q_0, to mimic collinear parton shower approach

- log (q_s) increases nearly linearly with log ($\sqrt{s}$)

- The slope log (q_s) vs log ($\sqrt{s}$) increases with q_0

→ The intrinsic-k_T increases to compensate for missing soft gluon contributions

- The inclusion of soft gluons, in particularly the non-perturbative Sudakov, is crucial for providing $\sqrt{s}$-independent intrinsic-k_T

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

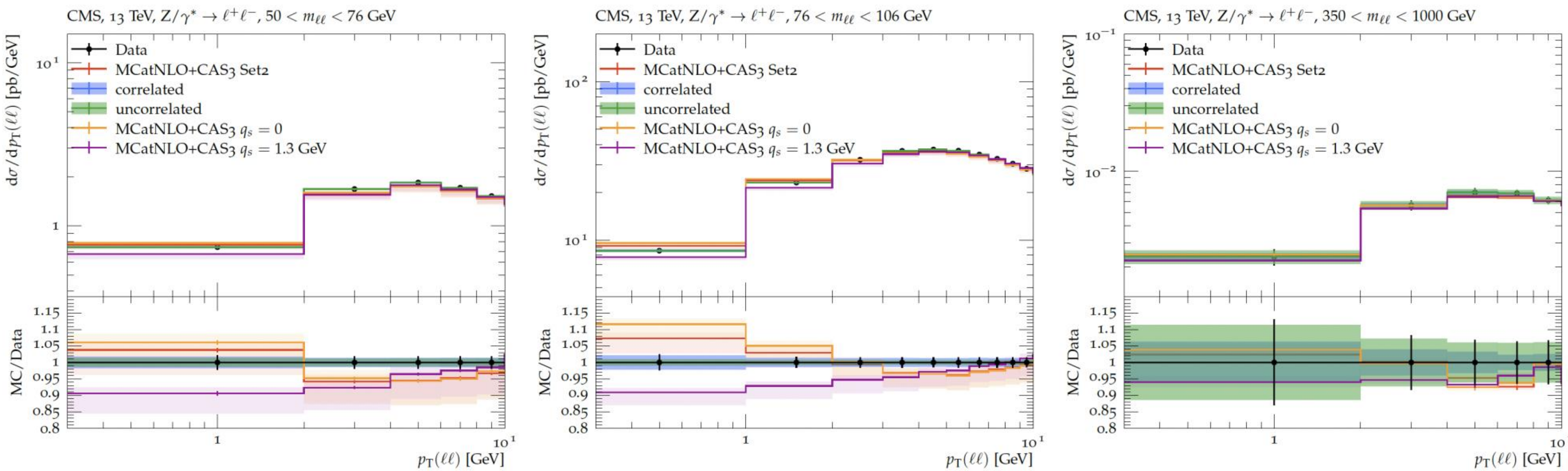
[8] https://arxiv.org/abs/hep-ex/9907009

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

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

Impact of the intrinsic k_T on DY transverse momentum distributions

- Compare the latest CMS [2] results on mass dependent DY pt distributions with the predictions based on PB-NLO-2018 Set 2 with:
  - q_s = 0 GeV
  - q_s = 0.5 GeV
  - q_s = 1.3 GeV



- The differences between no intrinsic-kT distribution and the default value (q_s = 0.5 GeV) is rather small, while a significant effect is observed for large q_s
- In the region of the largest DY invariant masses measured - the sensitivity to the intrinsic-k_T distribution quite small

The Gaussian widths q_s obtained using all analysed DY data