Energy dependence of intrinsic k_T with the Parton Branching Method

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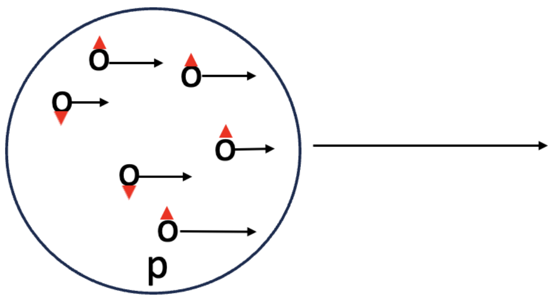
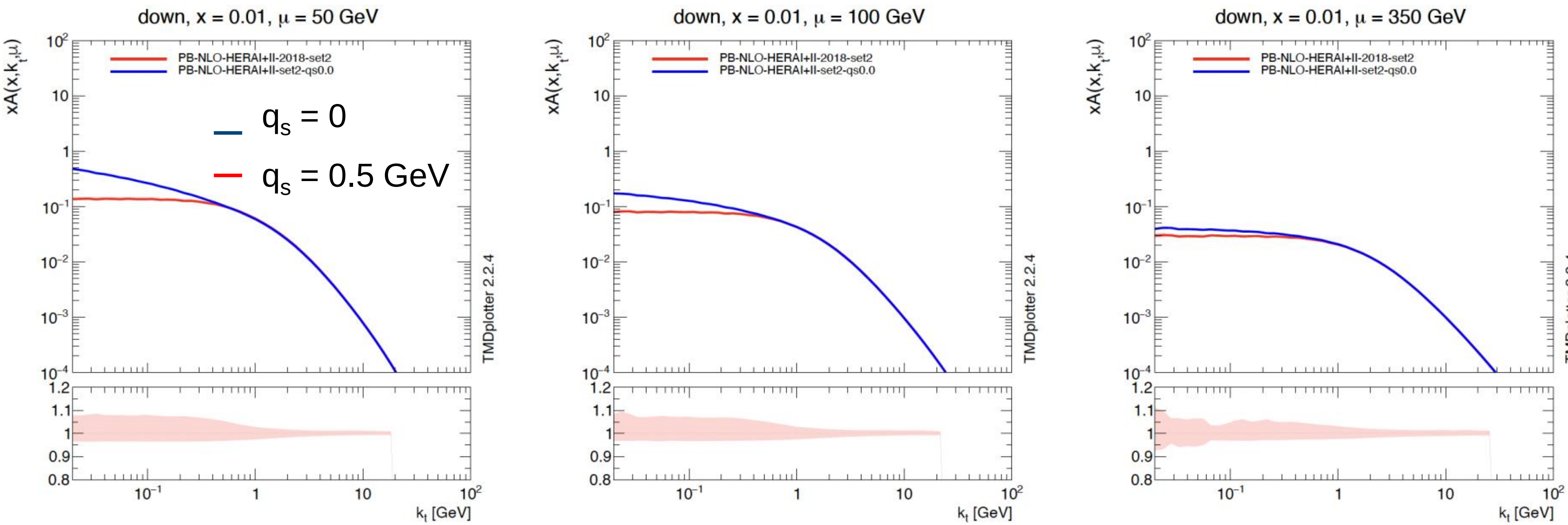
Impact of the internal motion on k_T distributions in the PB method



- In the evolution, the intrinsic-k_T 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: $\sigma^2 = q_s^2/2$

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



- Significant effect of the intrinsic-k_T at small k_T at low scales
- The intrinsic-k_T interplays with the nonperturbative soft gluon contributions

Soft contributions and Sudakov form factor

Sudakov FF → $\Delta_a(\mu^2, \mu_0^2) = \exp\left(-\sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mathbf{q}'^2}{\mathbf{q}'^2} \int_0^{z_M} dz\, z\, P_{ab}^{(R)}(\alpha_s, z)\right)$

- z – longitudinal momentum transferred at the branching, $0 < z < z_M$, $z_M \to 1$
- Ang. ordering → $\alpha_s = \alpha_s(q_T)$ → 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 $q_T < q_0$

AO → $z_{dyn} = 1 - q_0/q'$

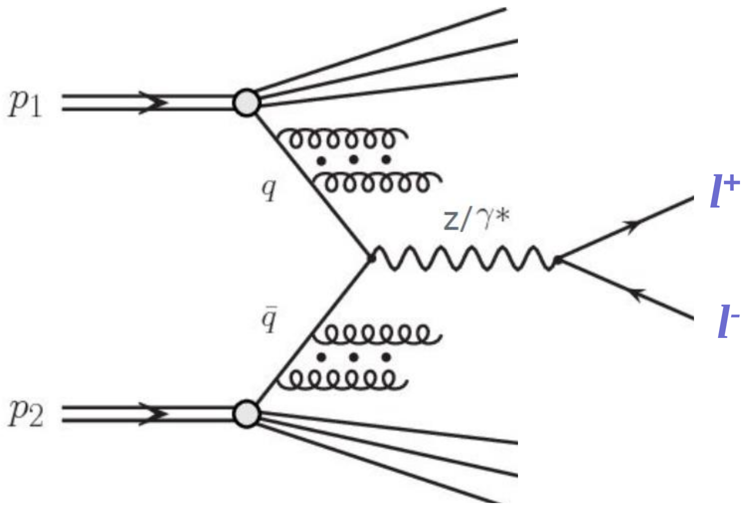
→ Two regions of z:

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

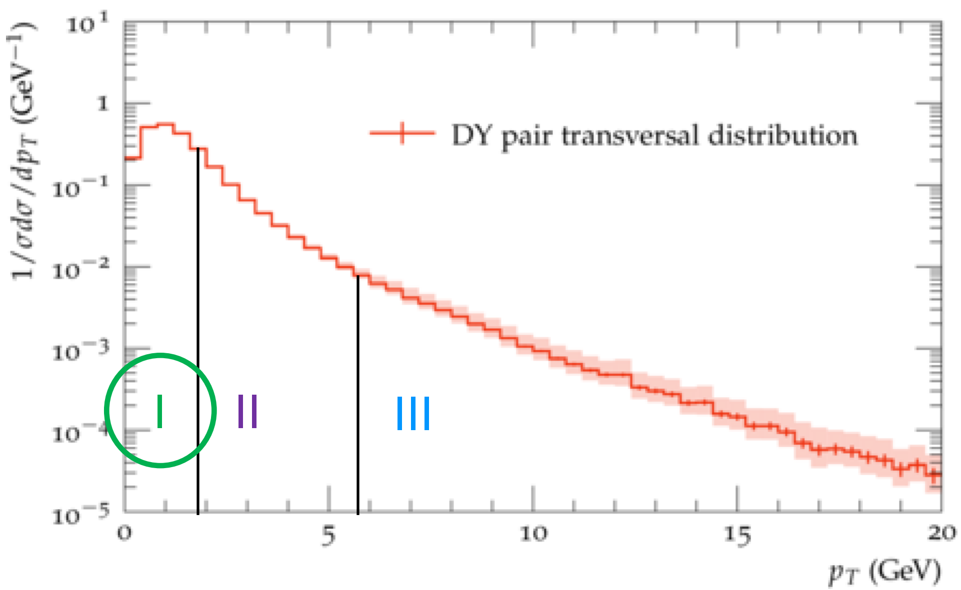
➢ define a perturbative (**P**) and non-perturbative (**NP**) ($z_{dyn} < z < z_M$, $z_M \to 1$) Sudakov form factors

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

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

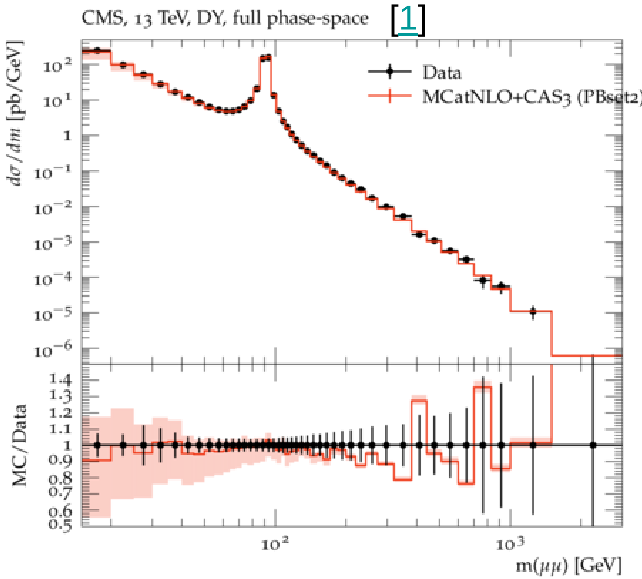
- intrinsic motion of partons
- resummation of multiple soft gluon emissions

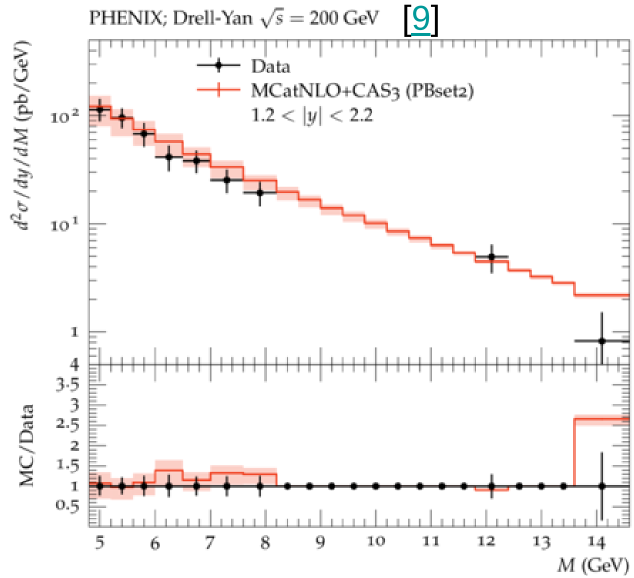
II – Transition region

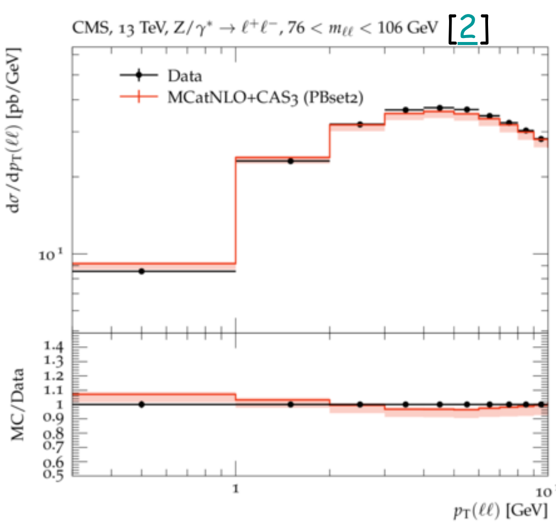
III - Perturbative higher-order contributions dominating

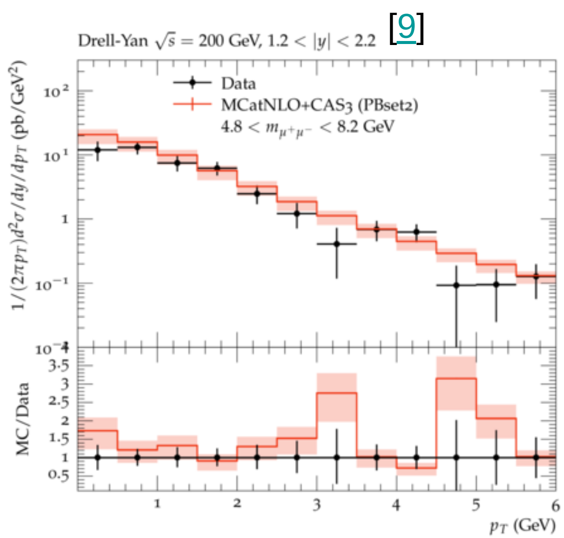
- DY production at NLO studied using the Parton Branching (PB) Method

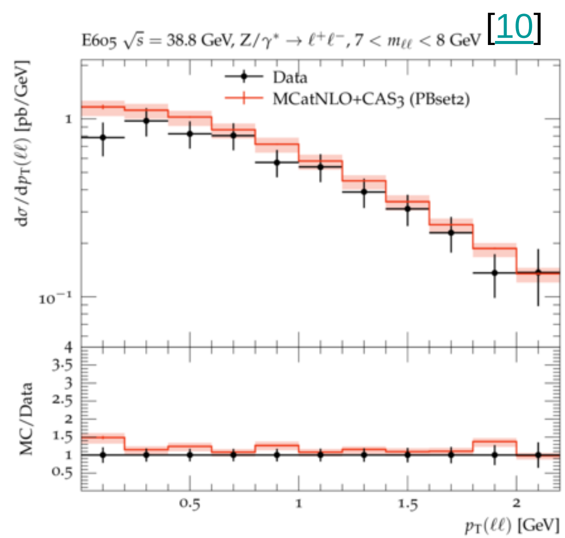
DY mass and p_T distributions in the wide range of $\sqrt{s}$











→ Good description of the entire mass range by the PB method

→ Low p_T region well understood

The Gaussian width q_s determined from the DY CMS data [2]

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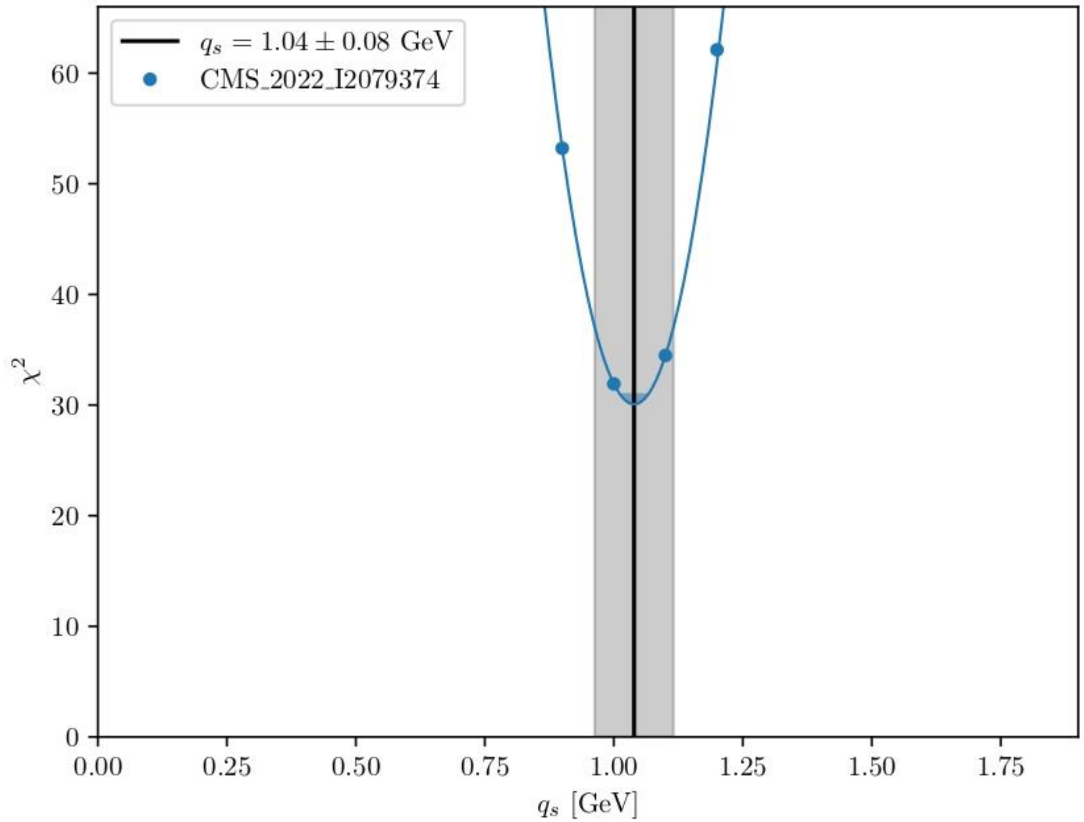
- The optimal q_s obtained considering bins in all mass ranges

- 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 ± 0.08 GeV

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	√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

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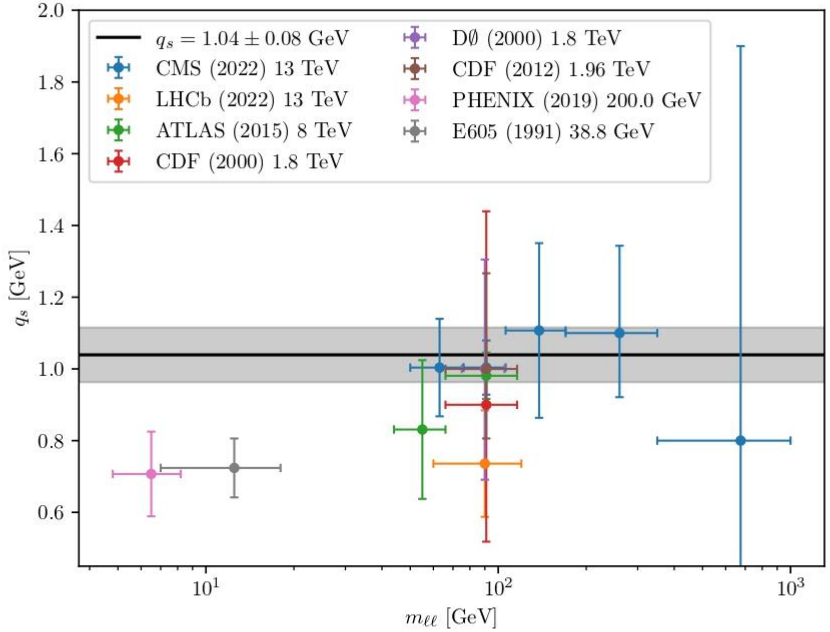
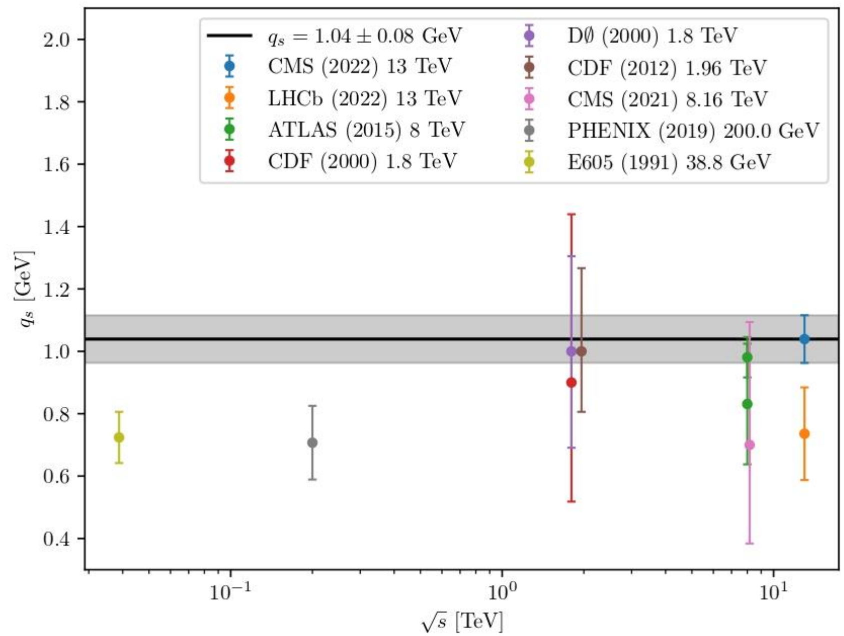
$q_0 = 10^{-2}$ GeV - minimal parton transverse momentum emitted at a branching





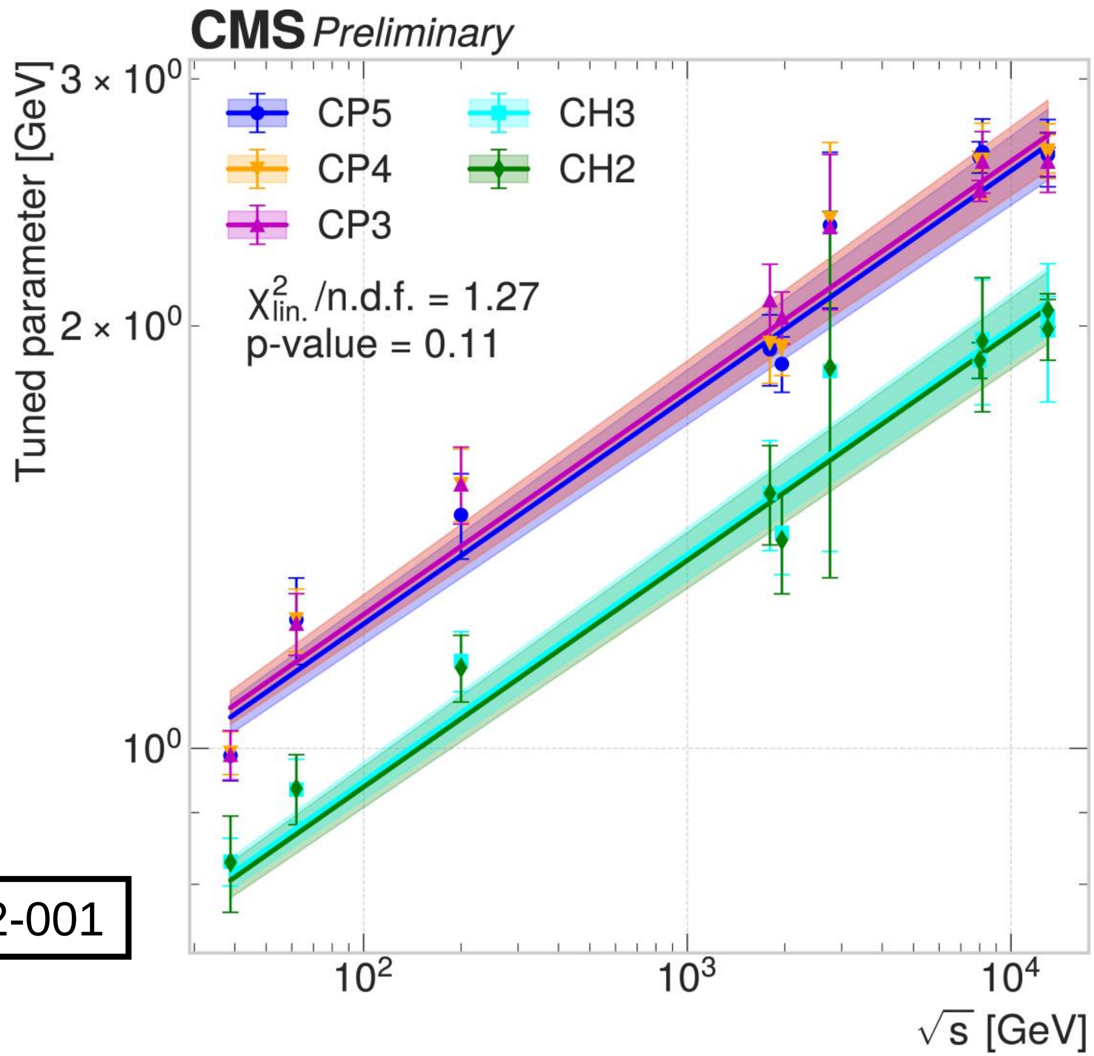
→ Consistent values of q_s for a large range of DY pair invariant masses

→ 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*

CMS preliminary result of energy dependence on the intrinsic-k_T



CMS, GEN-22-001

PYTHIA 8 - CP3, CP4 and CP5 tunes

HERWIG 7 – CH2 and CH3 tunes

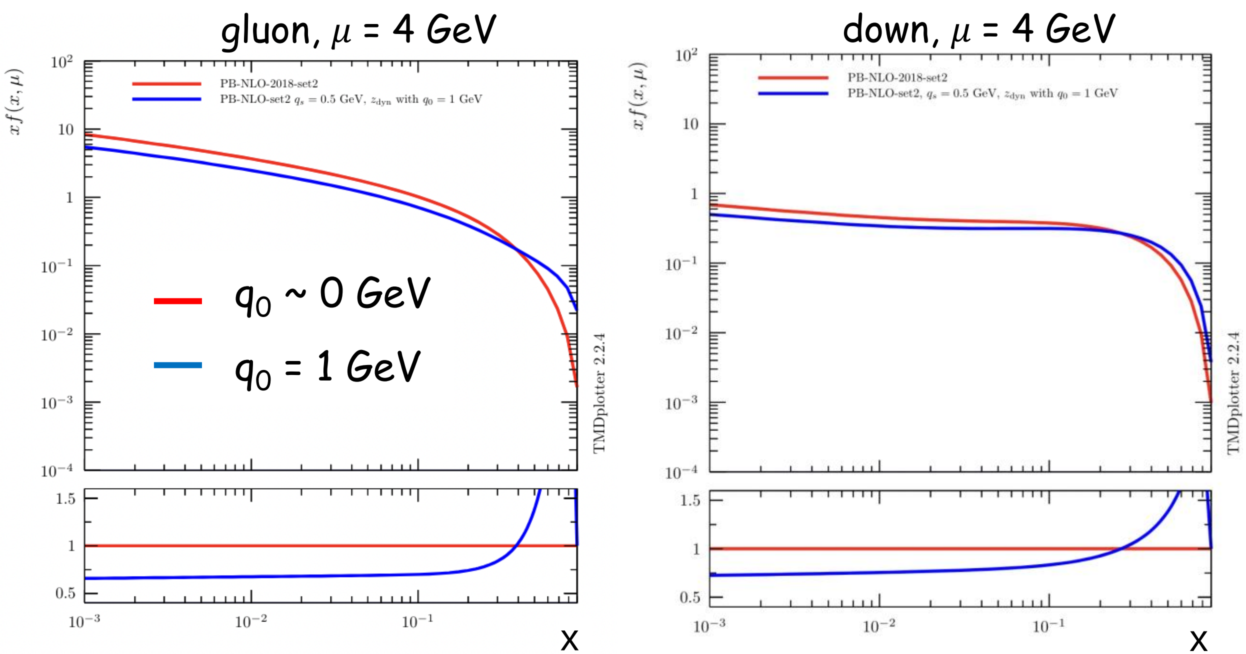
Try to introduce energy dependence of the intrinsic-k_T in PB

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

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

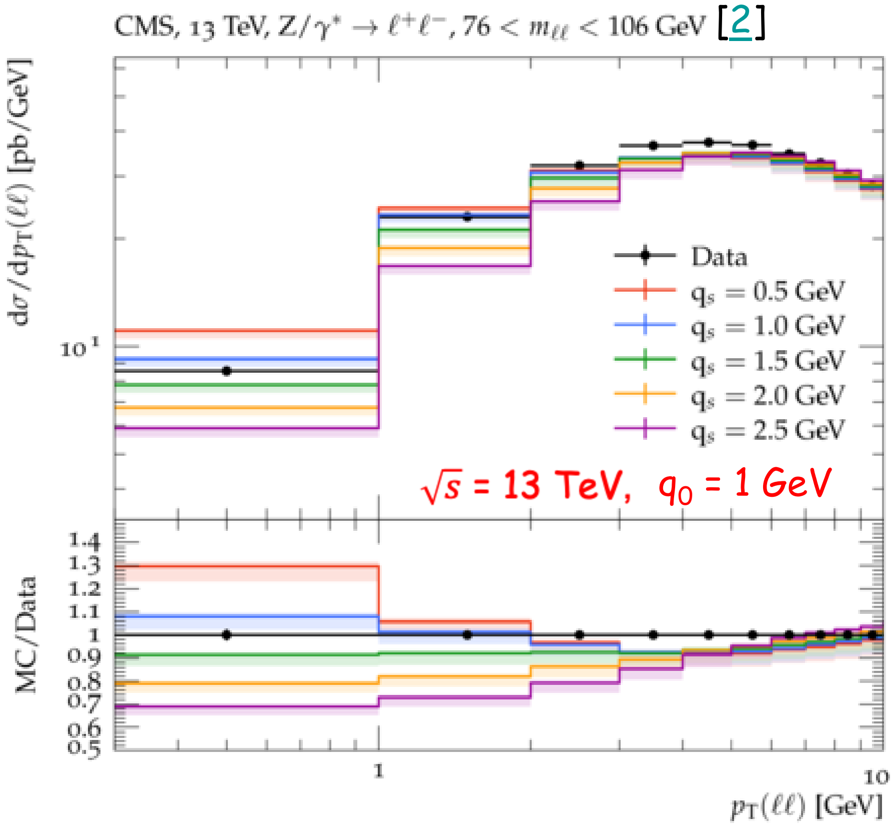
→ Real emissions with $z > 1 - q_0/\mu'$ - neglected

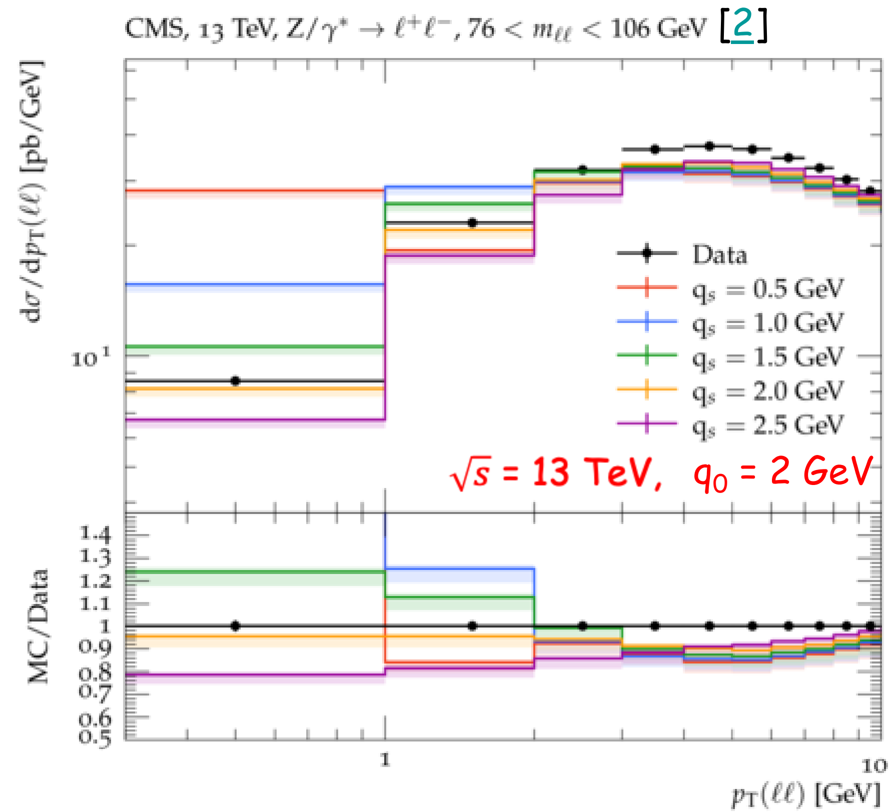


- Integrated parton distributions very different for the two cases

  → soft contributions important also for collinear distributions

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



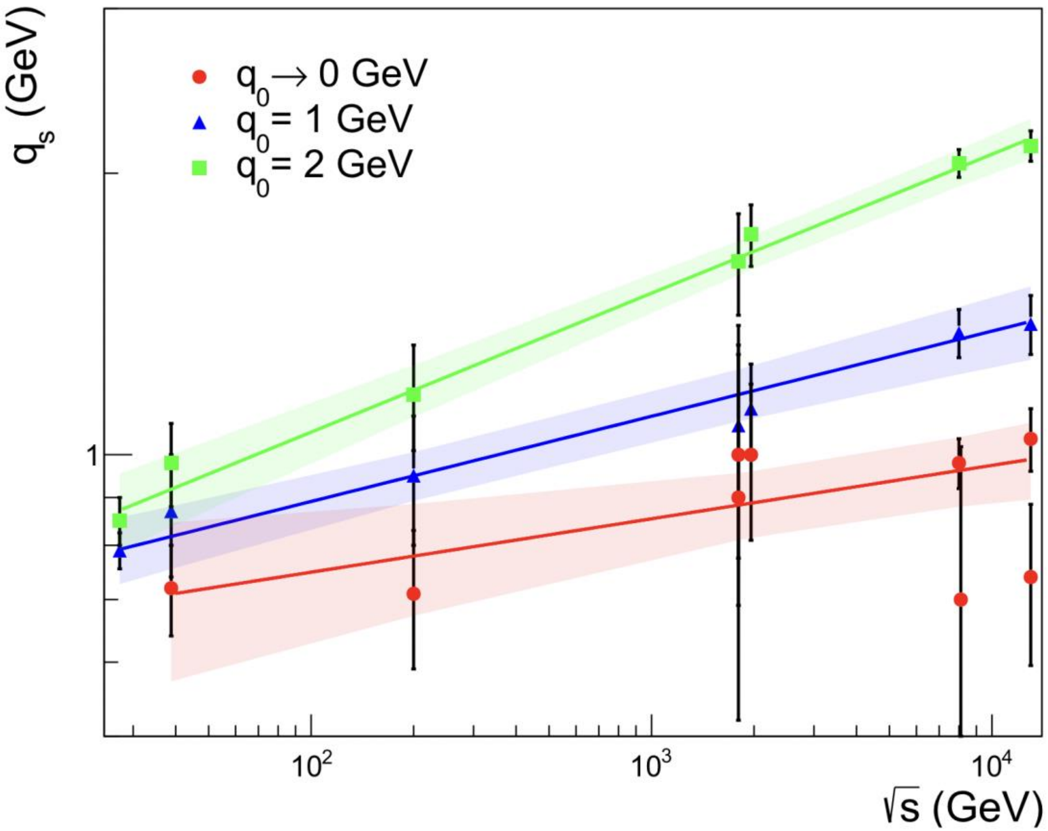


- Sensitivity of the DY cross section on the intrinsic-k_T increases at small pair p_T and with increasing of q_0 value

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

Summary

- By the proper treatment of the soft contributions, PB method allows to measure the intrinsic-k_T width which does not depend on DY hard-scattering scale, neither on center-of-mass collision energy $\sqrt{s}$

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

- The intrinsic-k_T contribution can be disentangled from the nonperturbative Sudakov one only by the proper treatment of the nonperturbative processes which is achieved in PB method due to the sensitivity to nonperturbative TMD contributions

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

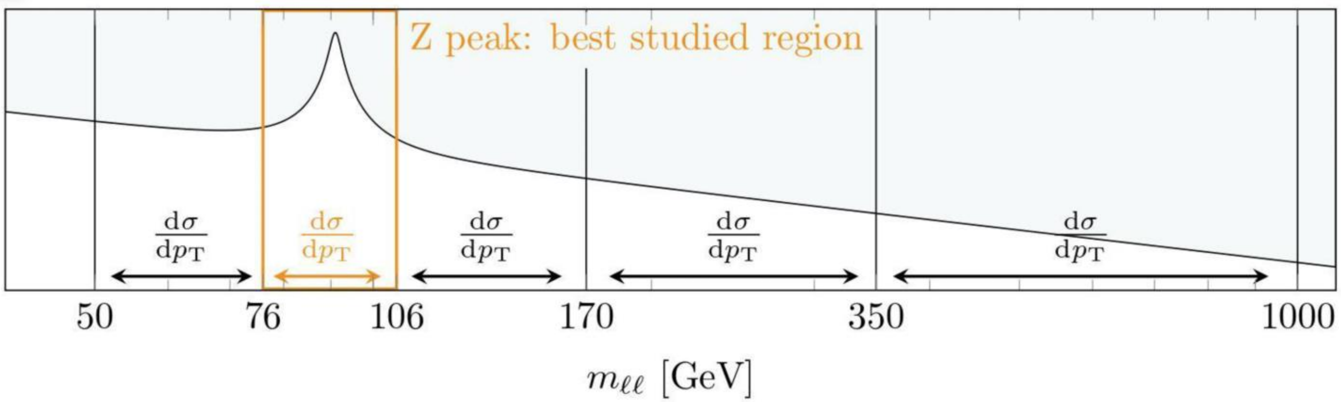
[8] https://arxiv.org/abs/hep-ex/9907009

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

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

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

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

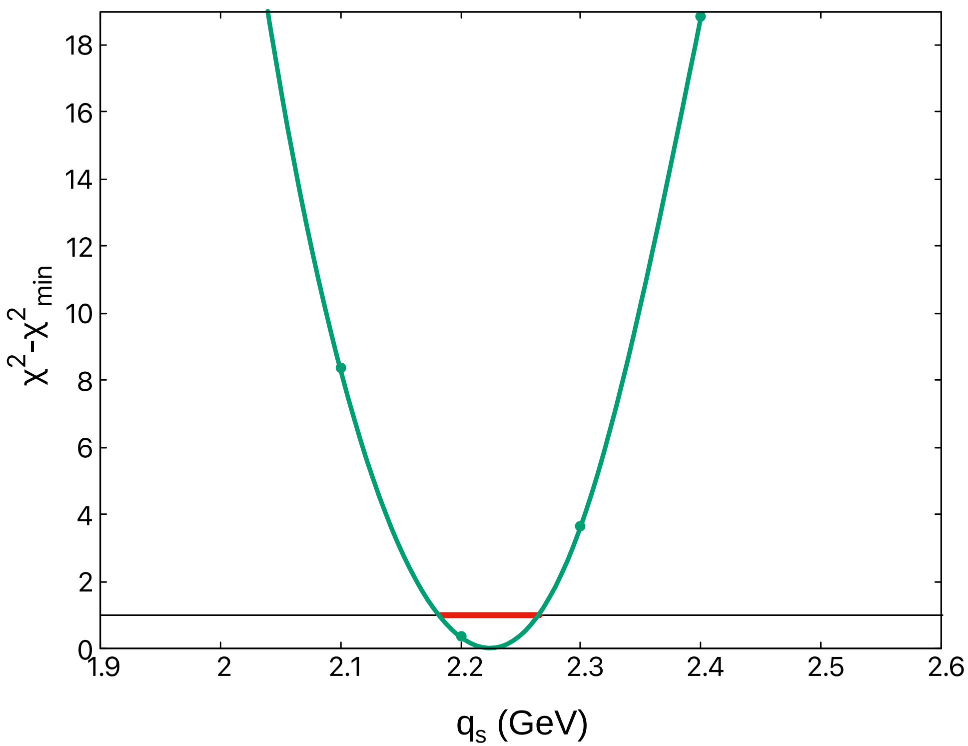
- The covariance matrix C_{ik} consists of a component describing the uncertainty in the measurement, $C_{ik}^{measurement}$, and the statistical (bin by bin stat. unc) and scale uncertainties in the prediction

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

- 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



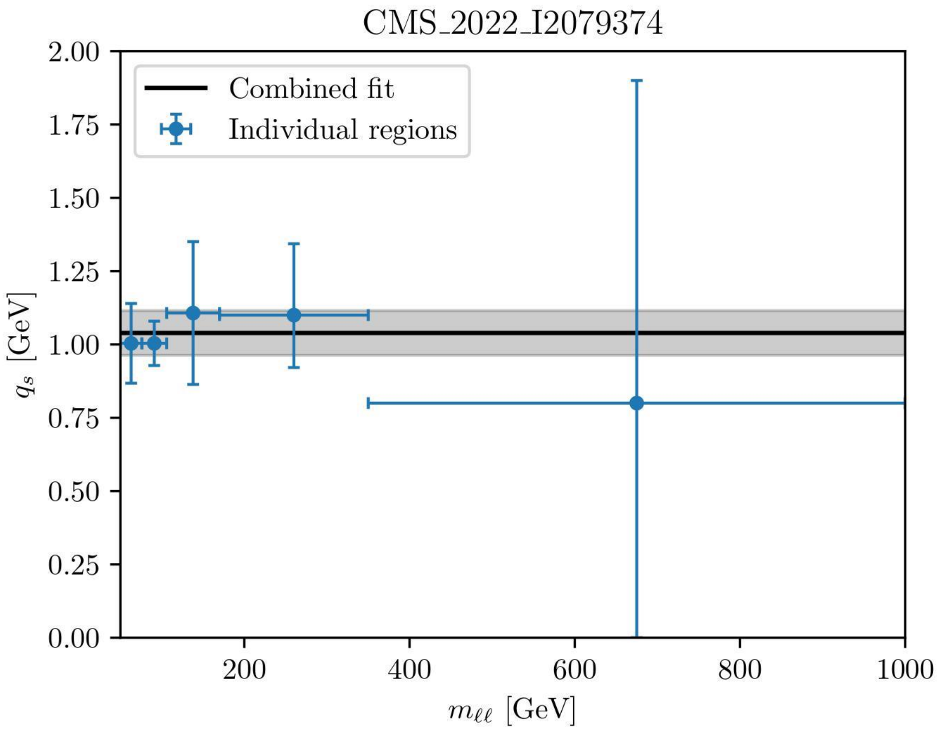
- There are two additional uncertainties added on top of the data one. These are "systematics" related to the scan itself

> 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

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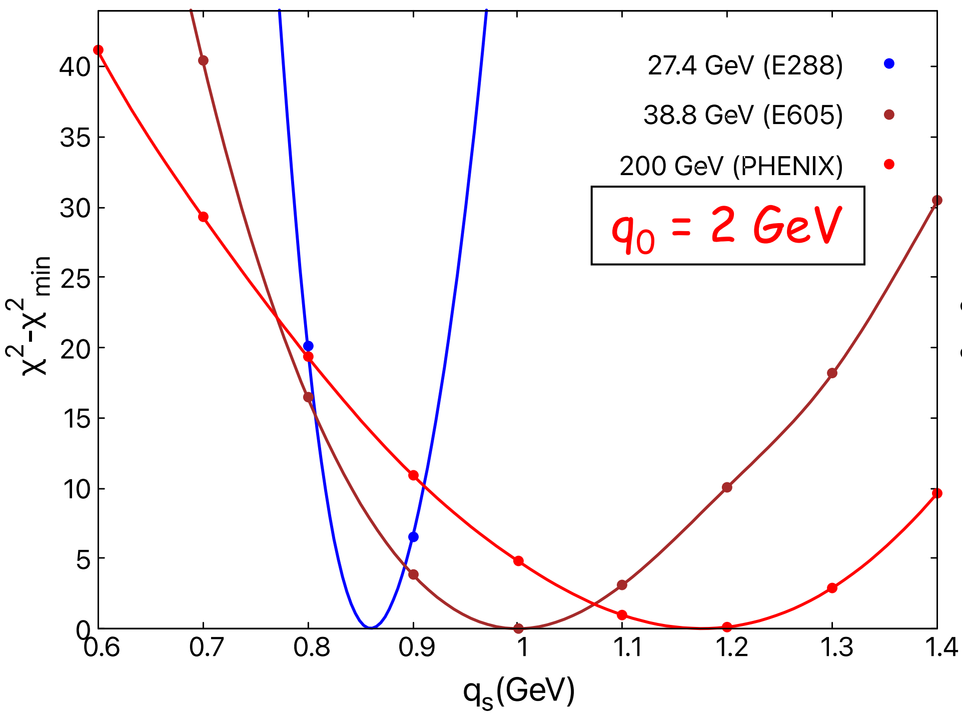
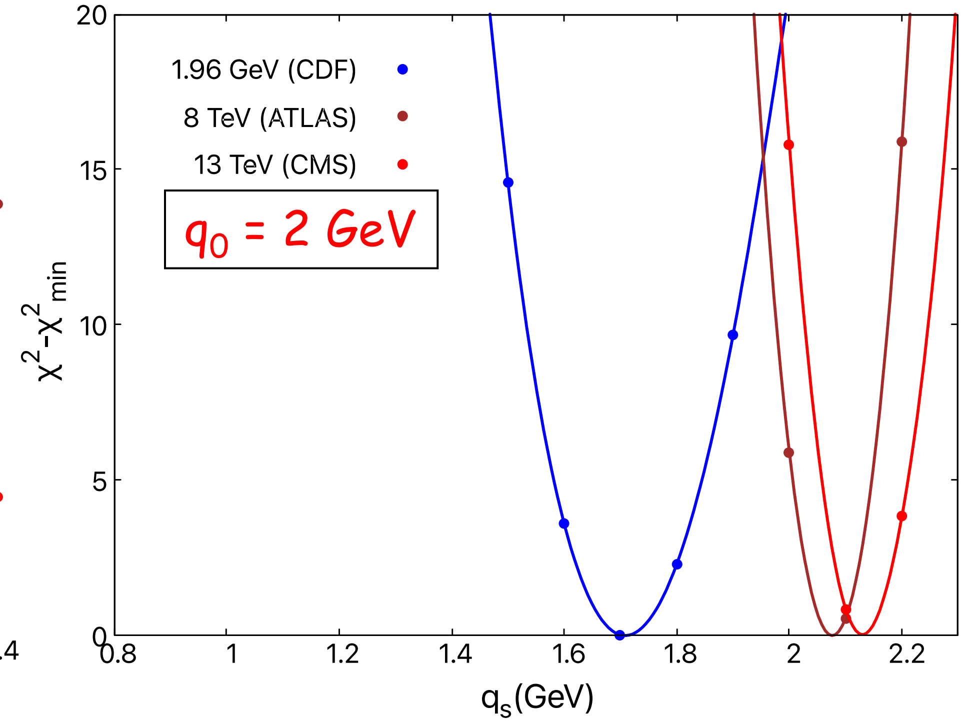
Determination of intrinsic-k_T (q_s width) for certain q_0

- 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 $\chi^2 < \chi^2_{min}+1$