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Dependence of intrinsic kT on the collision center of mass energy using the Parton Branching Method in Drell-Yan production at NLO

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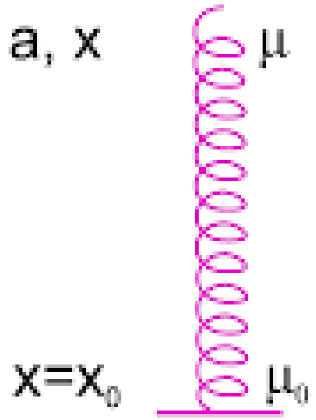
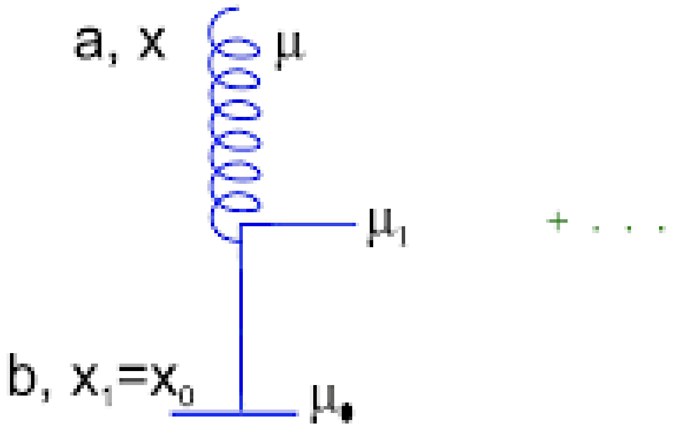
Soft contributions and Sudakov form factor

- The transverse momentum dependent parton distribution functions (**TMD PDFs**) play an important role in the description of **small transverse momentum physics as well as small x physics**
- The **parton branching (PB) method** - successful description up to the higher pT values
- The **PB method** is an **iterative procedure** using the concept of **resolvable and non-resolvable branching** and applying **Sudakov form factors** to describe the probability for non resolvable branchings from one evolution scale to another

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

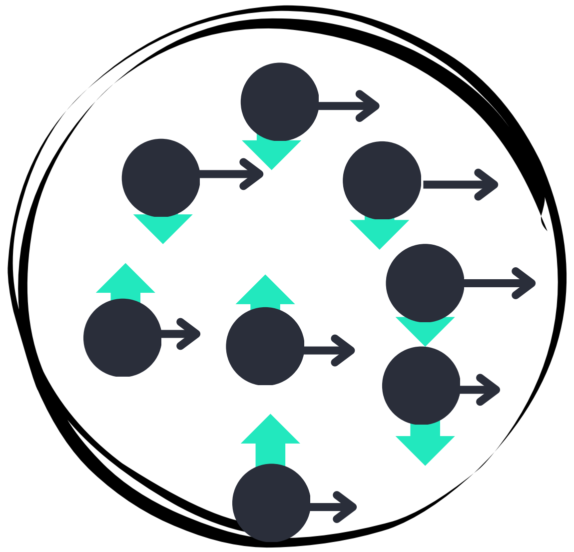


0 branching

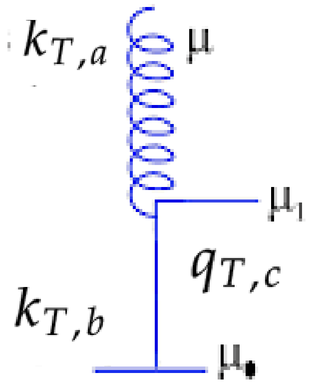


1 branching

Intrinsic kT



- At the initial state partons have not only longitudinal momentum, but also transverse momentum due to their internal (Fermi) motion – intrinsic kT
- **Total transverse momentum** of the parton is that intrinsic transverse momentum + all the transverse momentum **qT** of the parton emitted at the branching

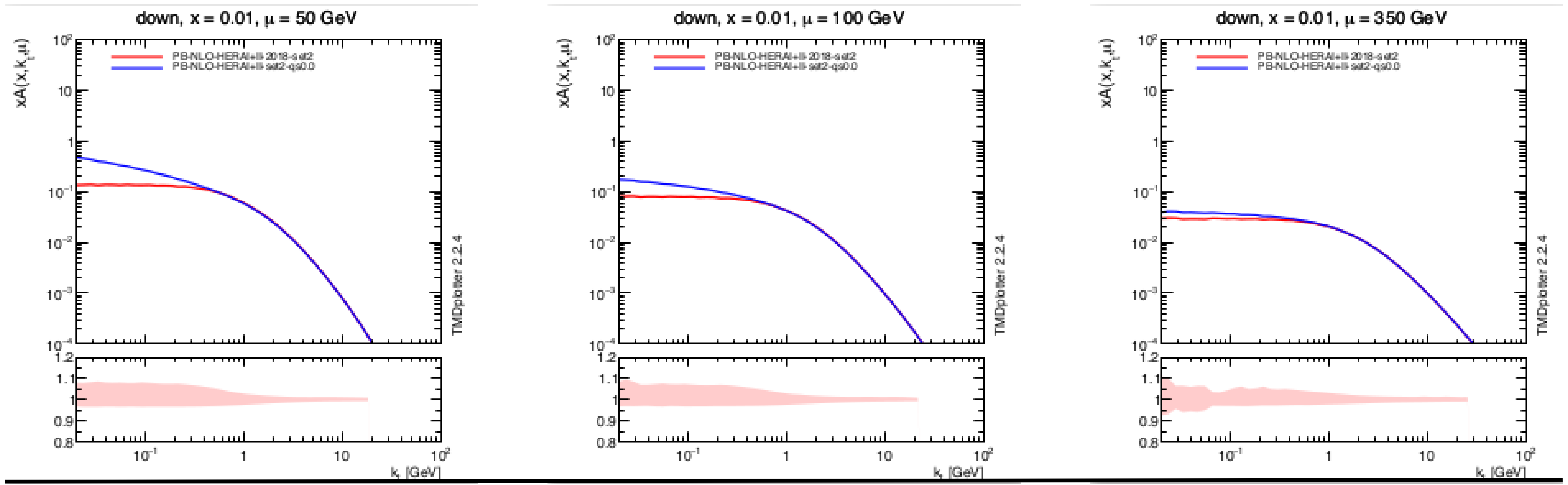


$$k_T = k_{T,0} + \sum_c q_{T,c}$$

- At the starting scale, parameter generated from **a Gaussian distribution with zero mean and a width** σ expressed via parameter qs in the PB model:

$$A_{0,a}(x, \mathbf{k_T}^2, \mu_0^2) = f_{0,a}(x, \mu_0^2)(1/2\pi\sigma^2)e^{-(|k_T^2|/2\sigma^2)}$$

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



- **Scale dependence** - a much smaller sensitivity to the intrinsic-kT distribution at high Drell-Yan mass
- The intrinsic-kT interplays with the nonperturbative soft gluon contributions

Soft contributions

- **z** – longitudinal momentum transferred at the branching, 0 < z < zM , zM → 1
- **qT** - the transverse momentum of the parton emitted at the branching

$$\alpha_s = \alpha_s\,(qT) \rightarrow q0$$

$$qT = (1 - z)|q'|$$

$$z_{dyn} = 1 - q0/|q'|$$

- Angular ordering
  - αs is frozen
  - Two different regions:
    - perturbative region, with qT > q0
    - non-perturbative region of qT < q0

=> qT - minimal parton transverse momentum emitted at a branching
=> zdyn - the dynamical resolution scale associated with the angular ordering

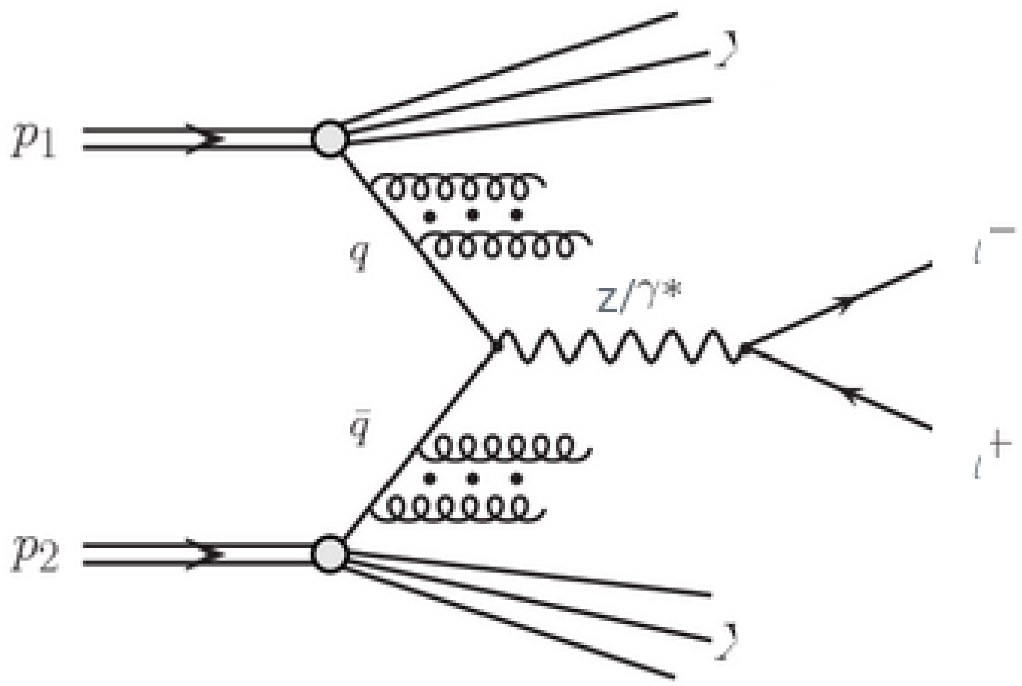
- Two regions of z:
  - a perturbative region, with 0 < z < zdyn (qT > q0)
  - a non-perturbative region with zdyn < z < zM (qT < q0)
    - Soft gluon resolution scale zM separates resolvable (z < zM) and non-resolvable (z > zM) branchings

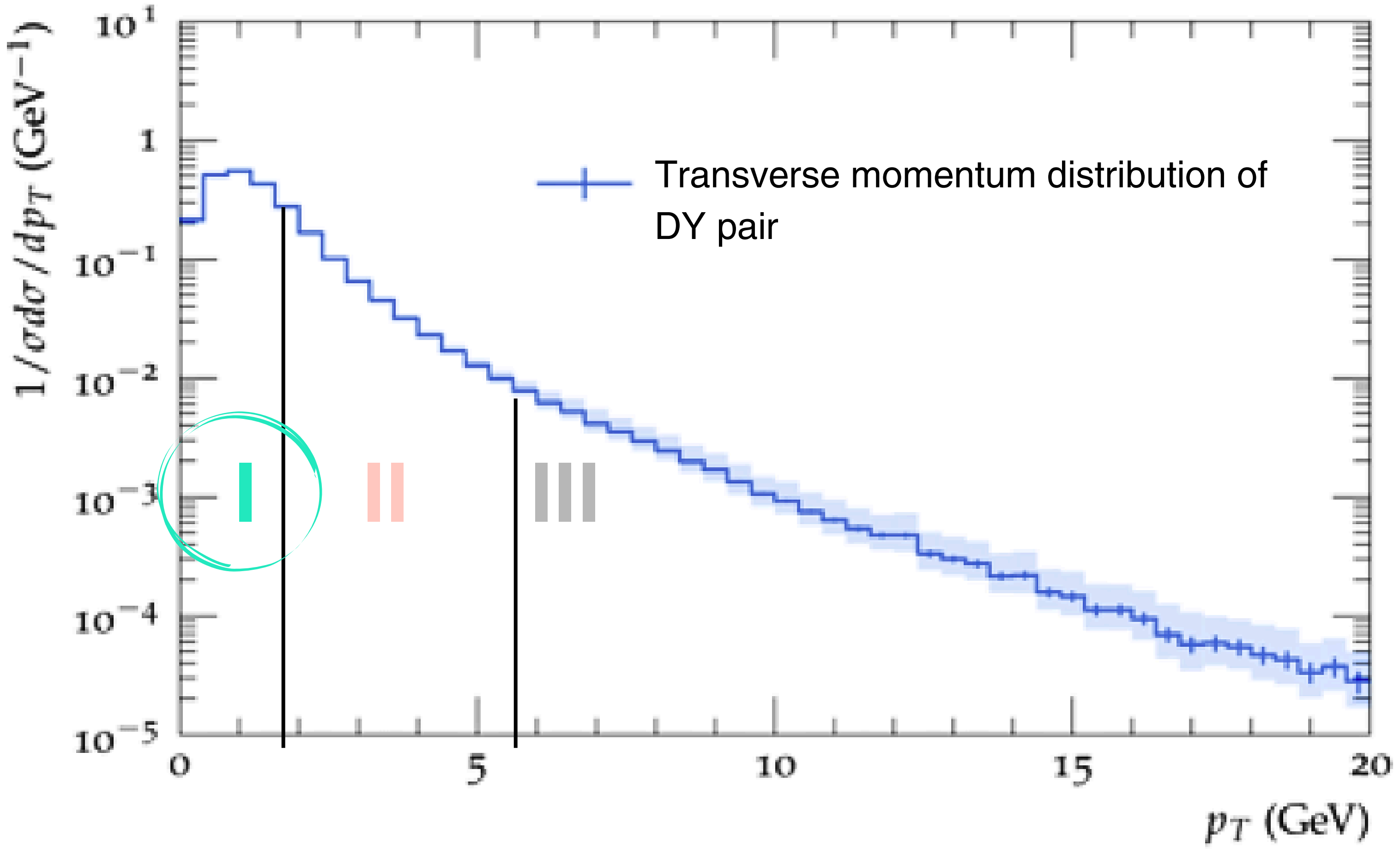
=> Define a perturbative (P) and non-perturbative (NP) (zdyn < z < zM, zM → 1)
Sudakov form factors

$$\Delta_a\left(\mu^2,{\mu_0}^2\right) = exp\left(-\sum_b \int_{{\mu_0}^2}^{\mu^2} \frac{d{q'}^2}{{q'}^2} \int_0^{z_{dyn}} z dz P_{ba}^{(R)}(\alpha_s, z)\right) exp\left(-\sum_b \int_{{\mu_0}^2}^{\mu^2} \frac{d{q'}^2}{{q'}^2} \int_{z_{dyn}}^{z_{M\approx 1}} z dz P_{ba}^{(R)}(\alpha_s, z)\right)$$

$$= {\Delta_a}^{(P)}\left(\mu^2,{\mu_0}^2,{q_0}^2\right) \cdot {\Delta_a}^{(NP)}\left(\mu^2,{\mu_0}^2,{q_0}^2\right)$$

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
  - **Clean final state** - no QCD final-state radiation, easily measured decay products
  - Three pT regions:
    - Non-perturbative region
    - Transition region
    - Perturbative region dominated by higher-order contributions
- Low pT region significant for our analysis
  - intrinsic motion of partons
  - non-perturbative region
  - resummation of multiple soft gluon emissions
- DY production at NLO studied using the Parton Branching (PB) Method

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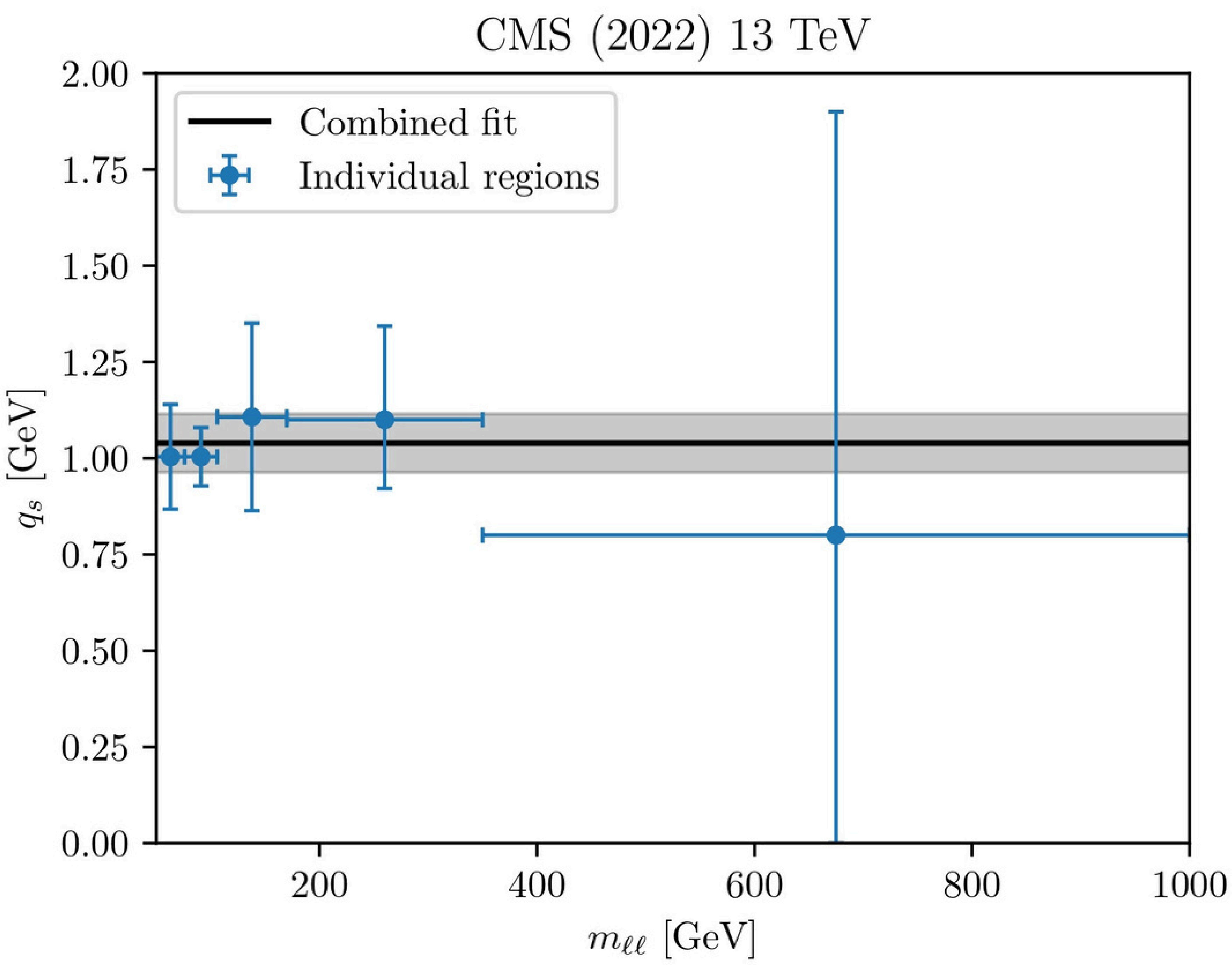
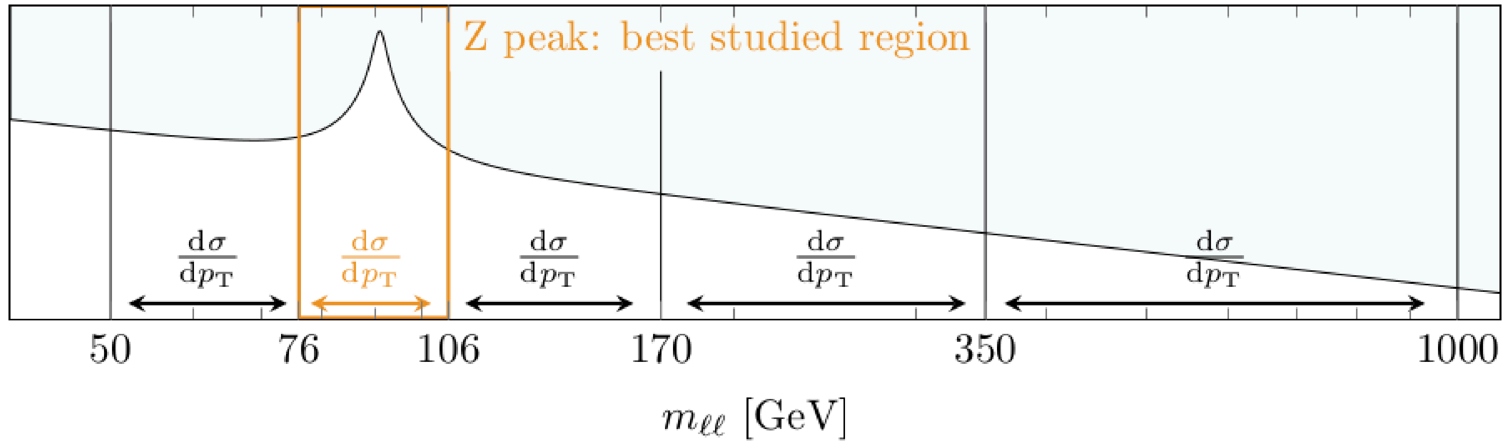
Invariant mass dependance at √s = 13 TeV

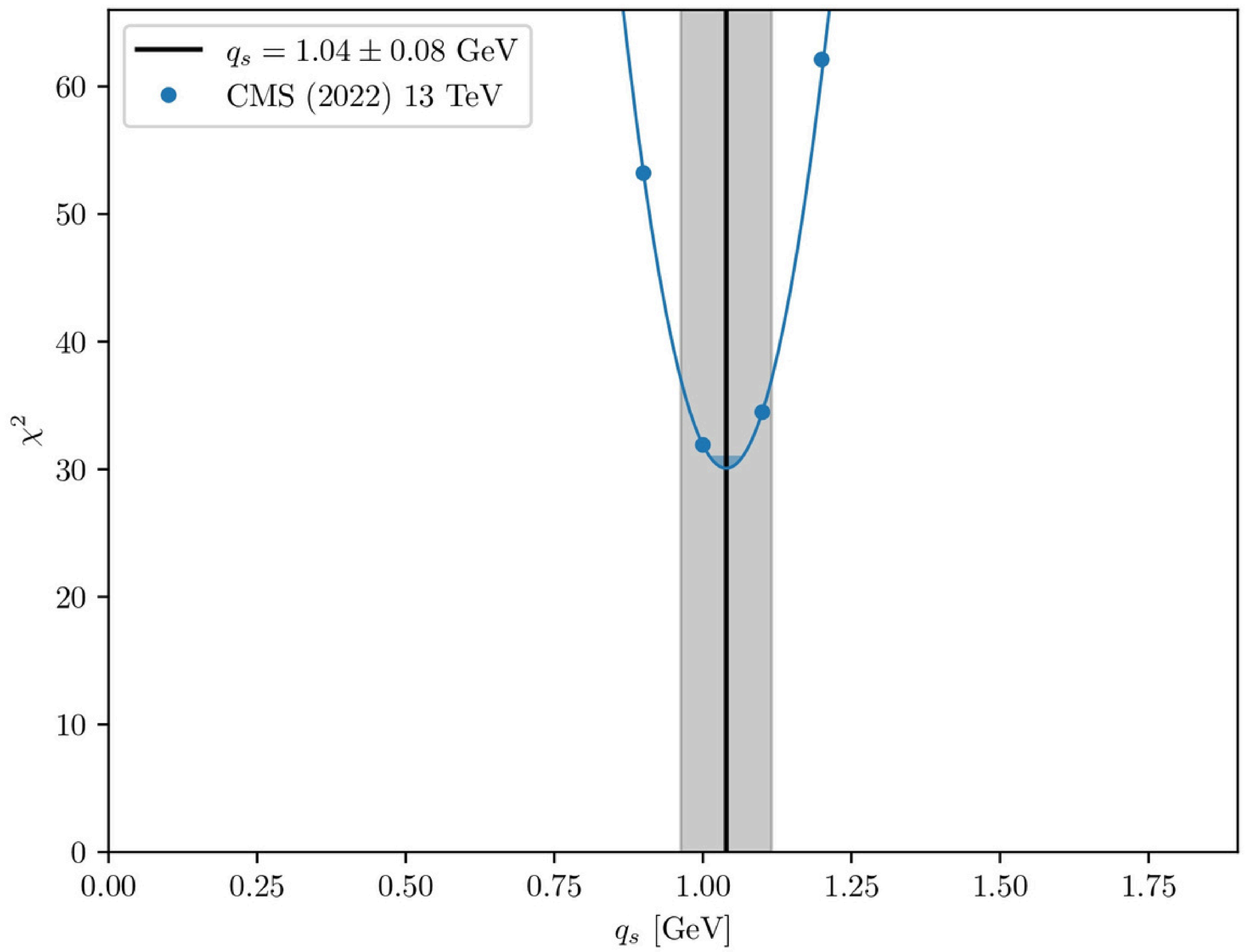




- We used as baseline analysis the public CMS measurement **Eur. Phys. J. C 83 (2023) 628**
- **Detailed uncertainty breakdown**: complete treatement of experimental uncertainties + correlations between bins of the measurement
  - The qs values obtained from **each mass bin are compatible with each other**
  - **The most precise** determination is obtained from the **Z peak region**
  - **The sensitivity at high mass** affected mainly **from larger statistical uncertainties** in the measurement
  - The optimal qs obtained considering bins in all mass ranges:

$$q_s = 1.04 \pm 0.08\ GeV$$

Invariant mass dependance at $\sqrt{s}$ = 13 TeV



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DY production at different centre-of-mass energies

Analysis	√s	Collision types	Bins
CMS (2022) (shown before)	13 TeV	pp	25
LHCb (2022)	13 TeV	pp	5
CMS (2021)	8.1 TeV	pPb	5
ATLAS (2015)	8 TeV	pp	8
CDF (2012)	1.96 TeV	$p\bar{p}$	6
CDF (2000)	1.8 TeV	$p\bar{p}$	5
D0 (2000)	1.8 TeV	$p\bar{p}$	4
PHENIX (2019)	200 GeV	$p\bar{p}$	12
Total			81

- For the other measurements all uncertainties treated as being uncorrelated

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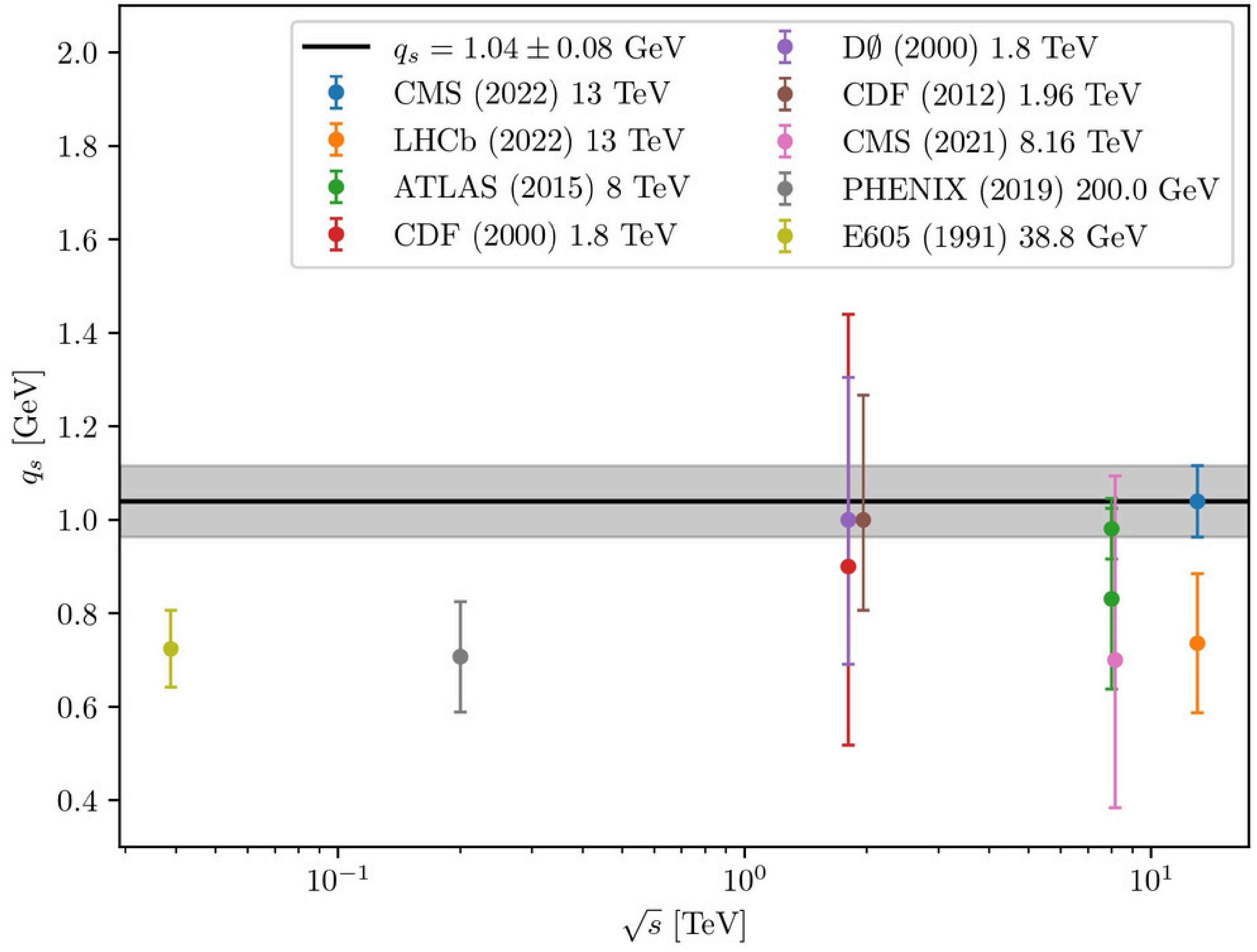
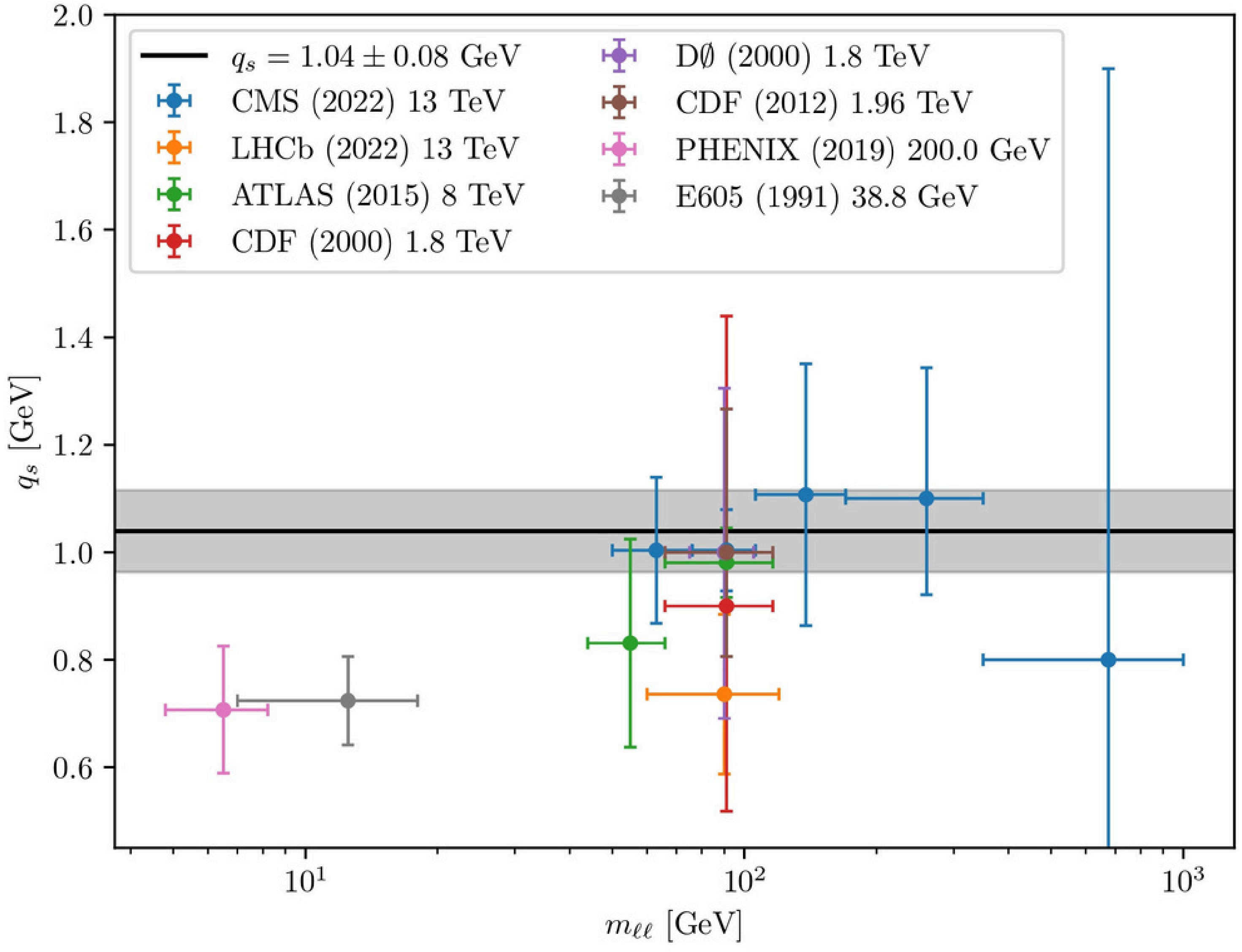
Intrinsic kT-width dependence on √s and invariant mass

q0 = 0.01 GeV - minimal parton transverse momentum emitted at a branching

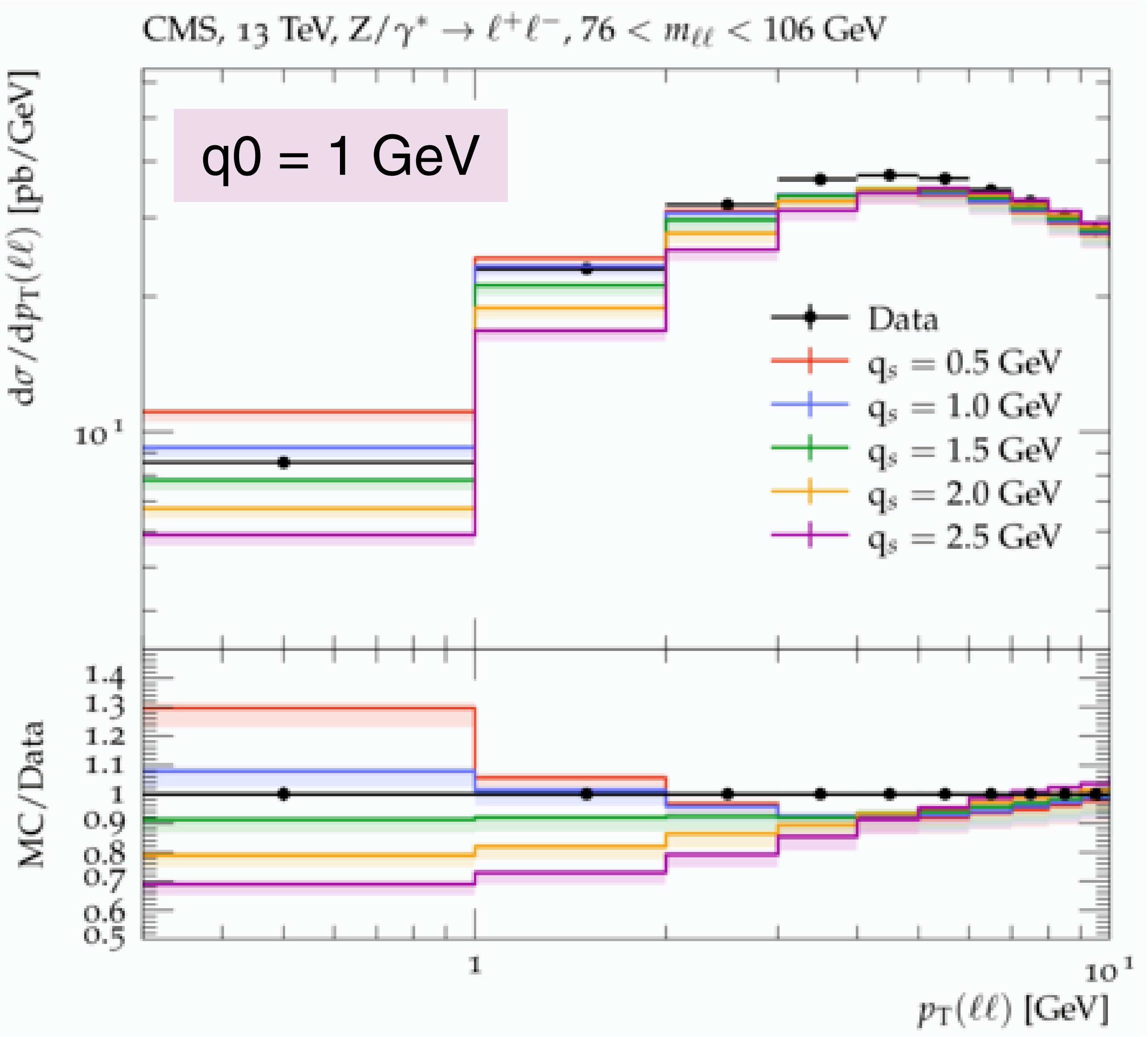


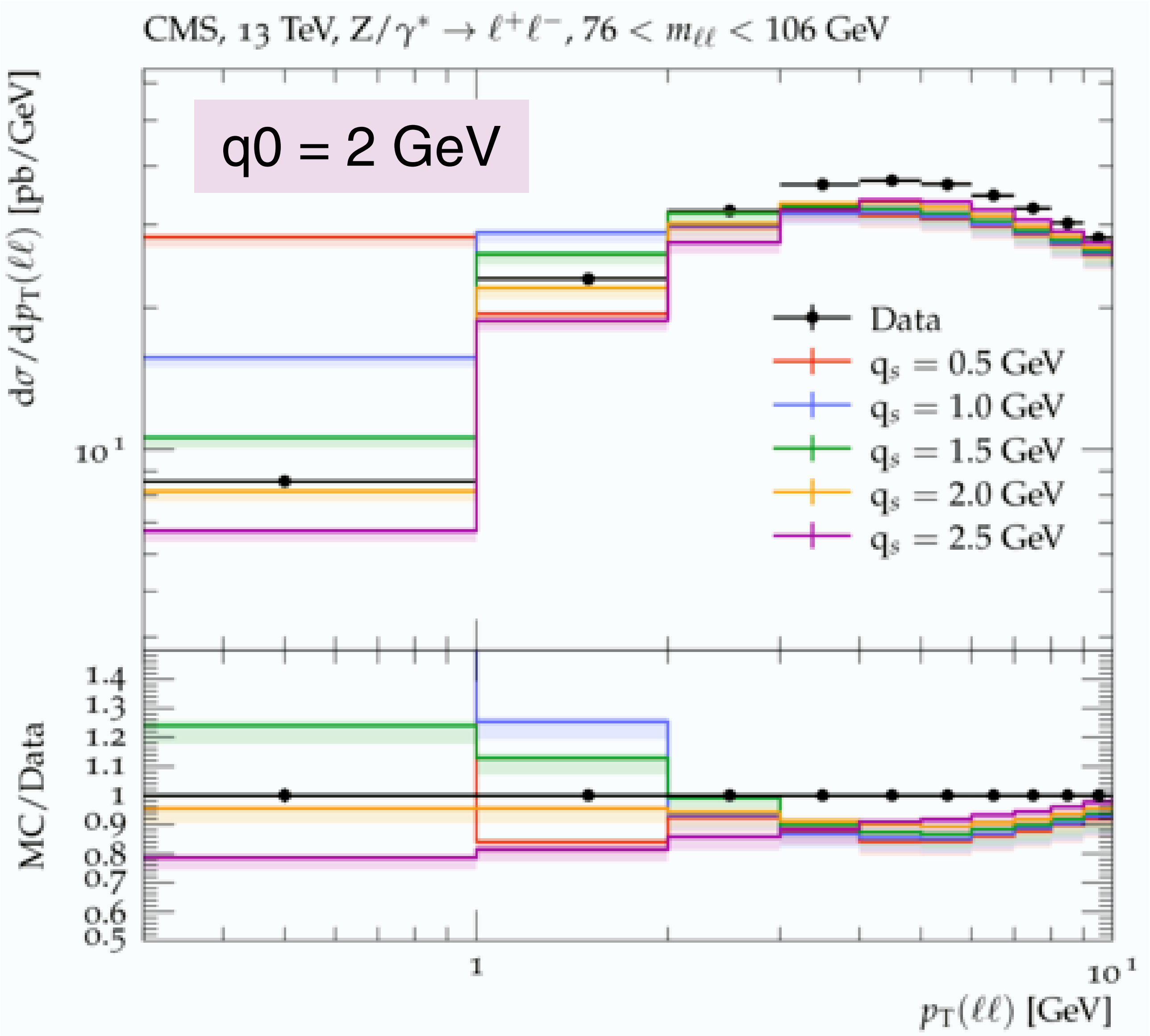


- Consistent values of qs for a large range of DY pair invariant masses
- Standard Monte Carlo event generators need a strongly increasing intrinsic-kT width with $\sqrt{s}$
- Strong center-of-mass energy dependence is not observed

Introducing energy dependence of the intrinsic-kT in PB

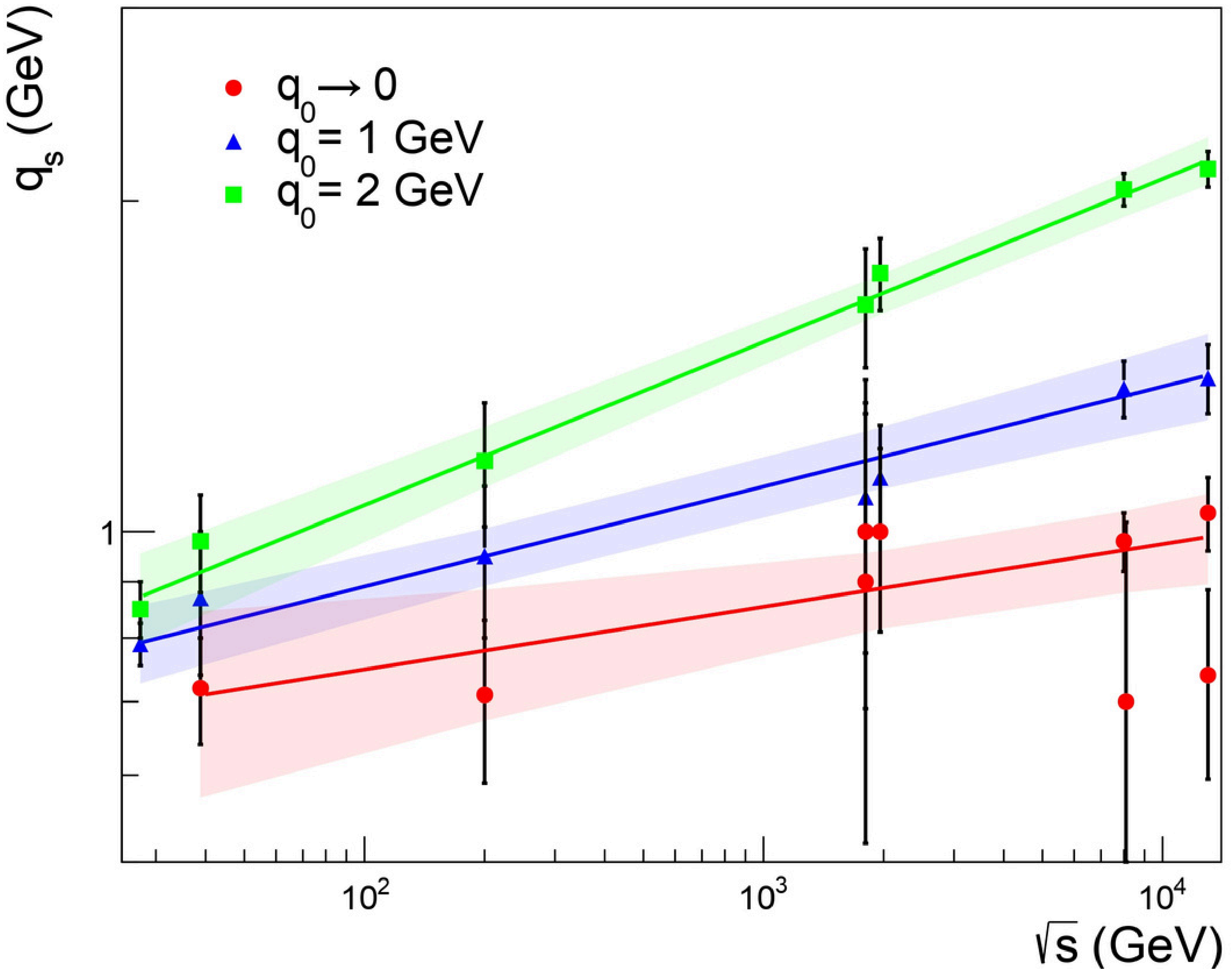
- Mimic parton-shower event generators by demanding a minimal parton transverse momentum
- q0 = 1 and 2 GeV
  - qT > q0
- Non-perturbative part neglected





- Sensitivity of the DY cross section on the intrinsic-kT increases at small pair pT and with increasing of q0 value

Introducing energy dependence of the intrinsic-kT in PB

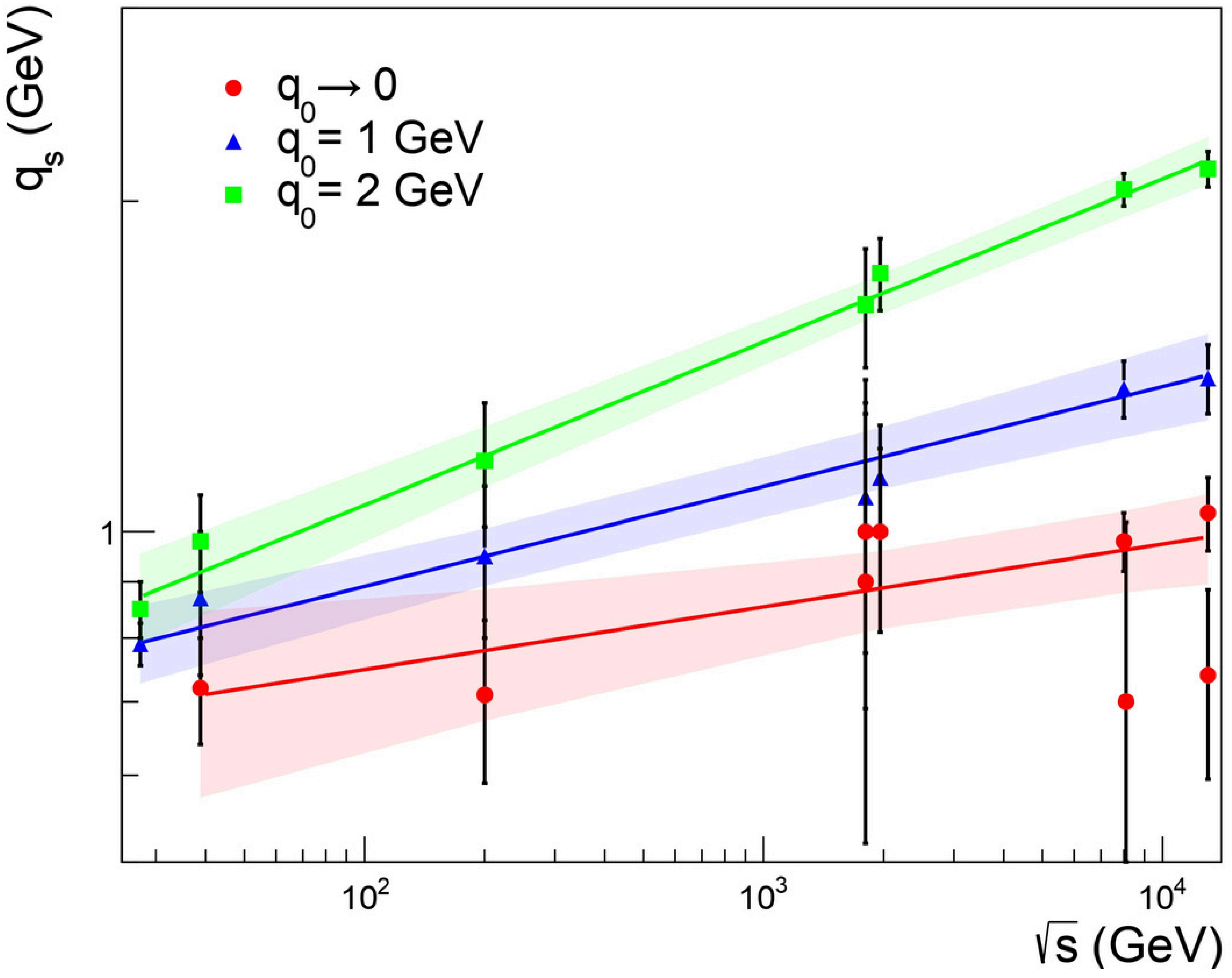


- qs dependence on center-of-mass energy for the cases with q0 = 1 GeV and q0 = 2 GeV and q0 → 0 GeV
- The uncertainty is estimated as a range of qs in which:

$$\chi^2 (q_s) - \chi^2{}_{min} < 1$$

- We have performed a linear fit for the relation $log\left(q_s\right) - log\left(\sqrt{s}\right)$
- The uncertainty bands around the fitted lines correspond to the 95% CL band

Introducing energy dependence of the intrinsic-kT in PB



- The slope increases as q0 increases
- **Larger q0** means that **more soft contributions** are excluded
  - Larger intrinsic-kT needed to compensate missing contribution from soft gluons
    - Higher q0 values lead to an **increased sensitivity to the intrinsic kT-distribution**, resulting in **smaller uncertainty bands**

Summary

- DY production at NLO obtained with the **MADGRAPH5_AMC@NLO** event generator matched with the PB TMD distributions **PBNLO-2018 Set2**
- We study Fermi-motion of partons inside proton parameterized by a Gauss distribution of width $\sigma = q_s/\sqrt{2}$
- Proper treatment of the soft contributions in PB method leads to the intrinsic-kT width which does not depend on collision center-of-mass collision energy
    - The inclusion of soft gluons, in particularly the non-perturbative Sudakov, is crucial for providing $\sqrt{s}$ -independent intrinsic-kT

Thank you for your attention!