INTRINSIC TRANSVERSE MOMENTUM AND PARTON BRANCHING TMD

DRELL-YAN & TMD WORKSHOP

Itana Bubanja
on behalf of the CASCADE Group
Université libre de Bruxelles
& University of Montenegro

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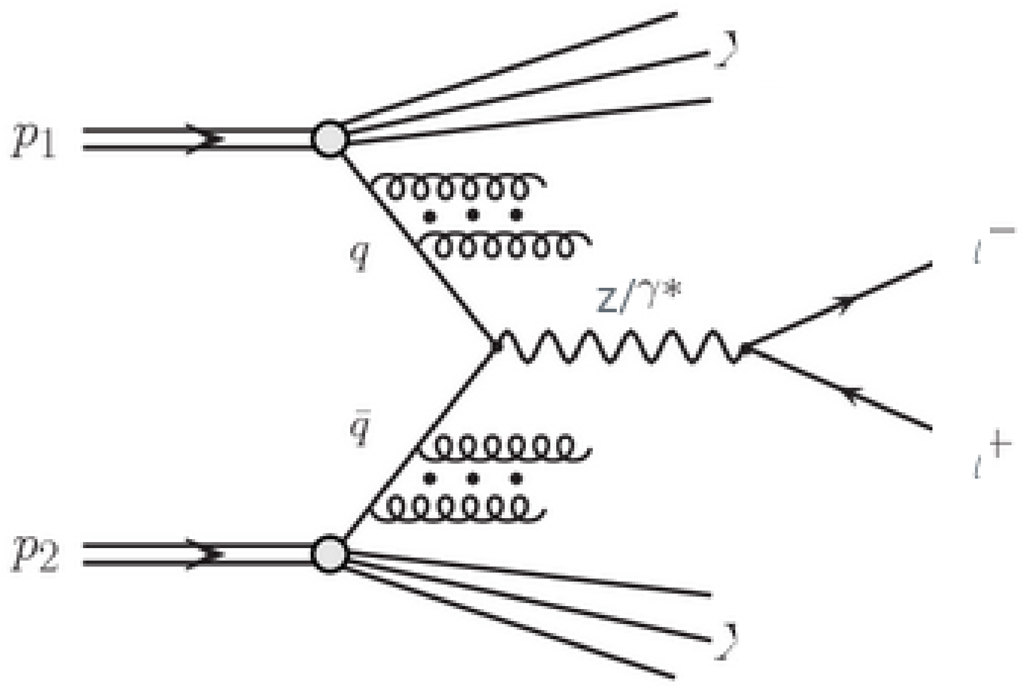
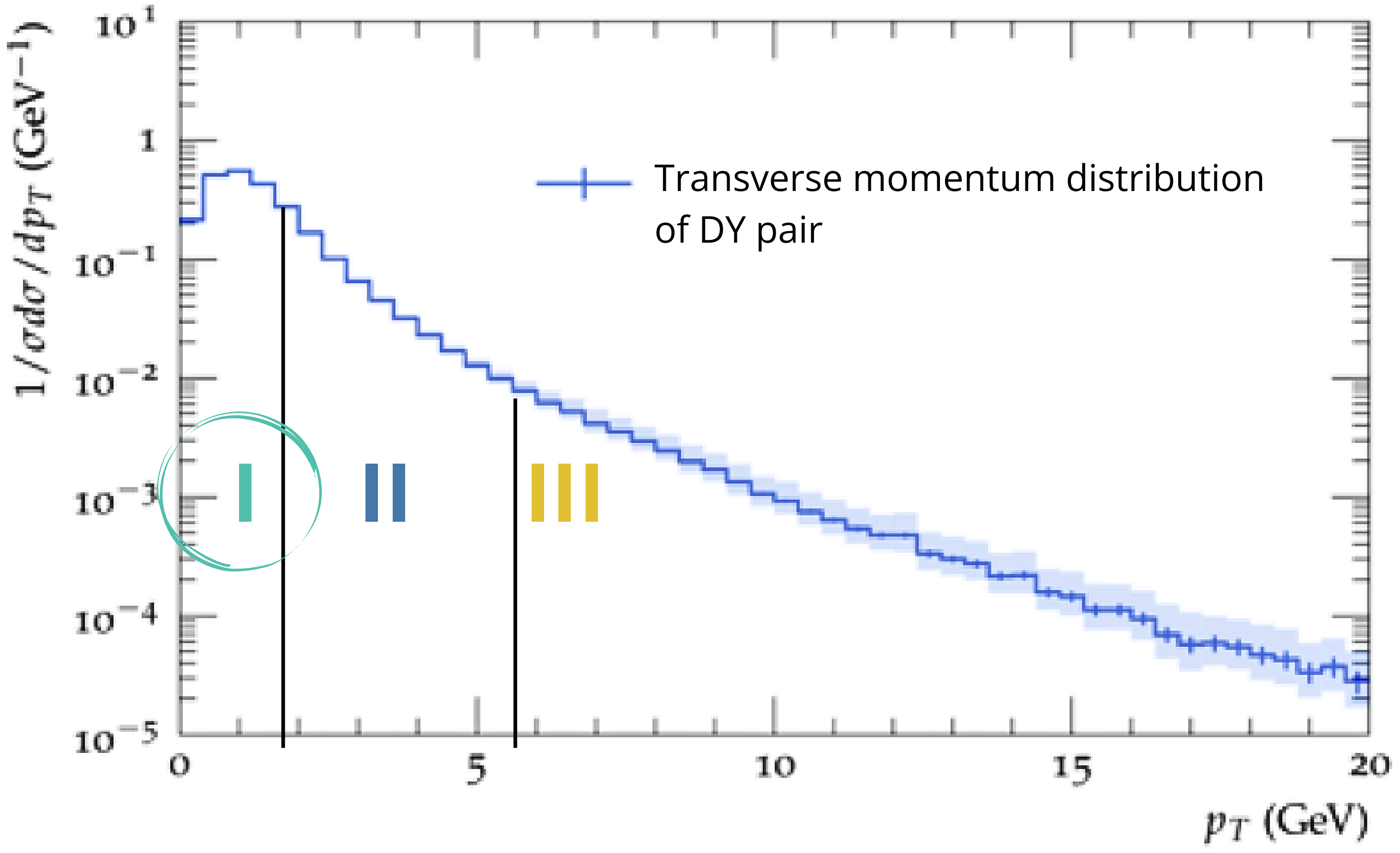
Why the Drell–Yan Process?

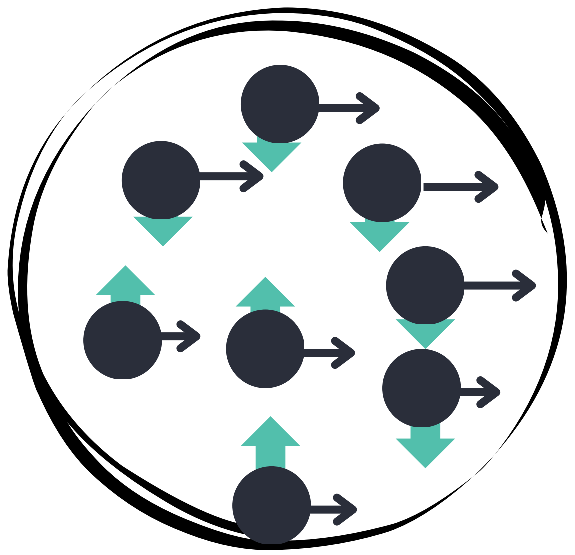




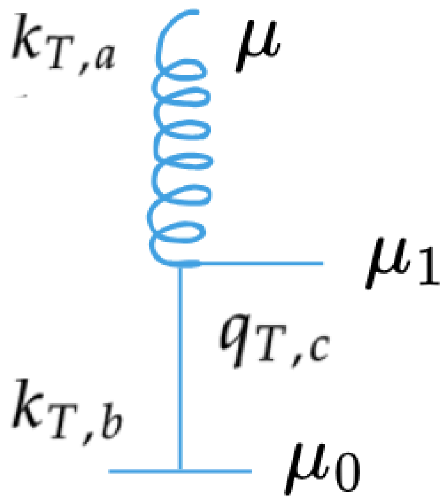
- Precise description of parton motion is vital for accurate predictions
  - Reduces theoretical uncertainties in collider experiments
  - Key to testing the Standard Model with high precision
  - Helps identify potential signatures of new physics
  - Improves modeling in Monte Carlo event generators

- 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
  - resummation of multiple soft gluon emissions
- DY production at NLO studied using the Parton Branching (PB) Method

Introduction



- 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



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

- 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

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

$$A_{0,a}(x, \mathbf{k}_T^2, \mu_0^2) = f_{0,a}(x, \mu_0^2) \cdot \left(\frac{1}{2\pi\sigma^2}\right) e^{-|\mathbf{k}_T^2|/(2\sigma^2)} \qquad \sigma^2 = q_s^2/2$$

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

$\alpha_s \rightarrow \alpha_s(q_0)$ for small q_t

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

$$z_{dyn} = 1 - q_0/|q'|$$

- Angular ordering
  - Two different regions:
    - perturbative region, with qT > q0
    - non-perturbative region of qT < q0
- αs is frozen for qT < q0
  - in order to avoid the divergency at the Landau pole.

=> qT - 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

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

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

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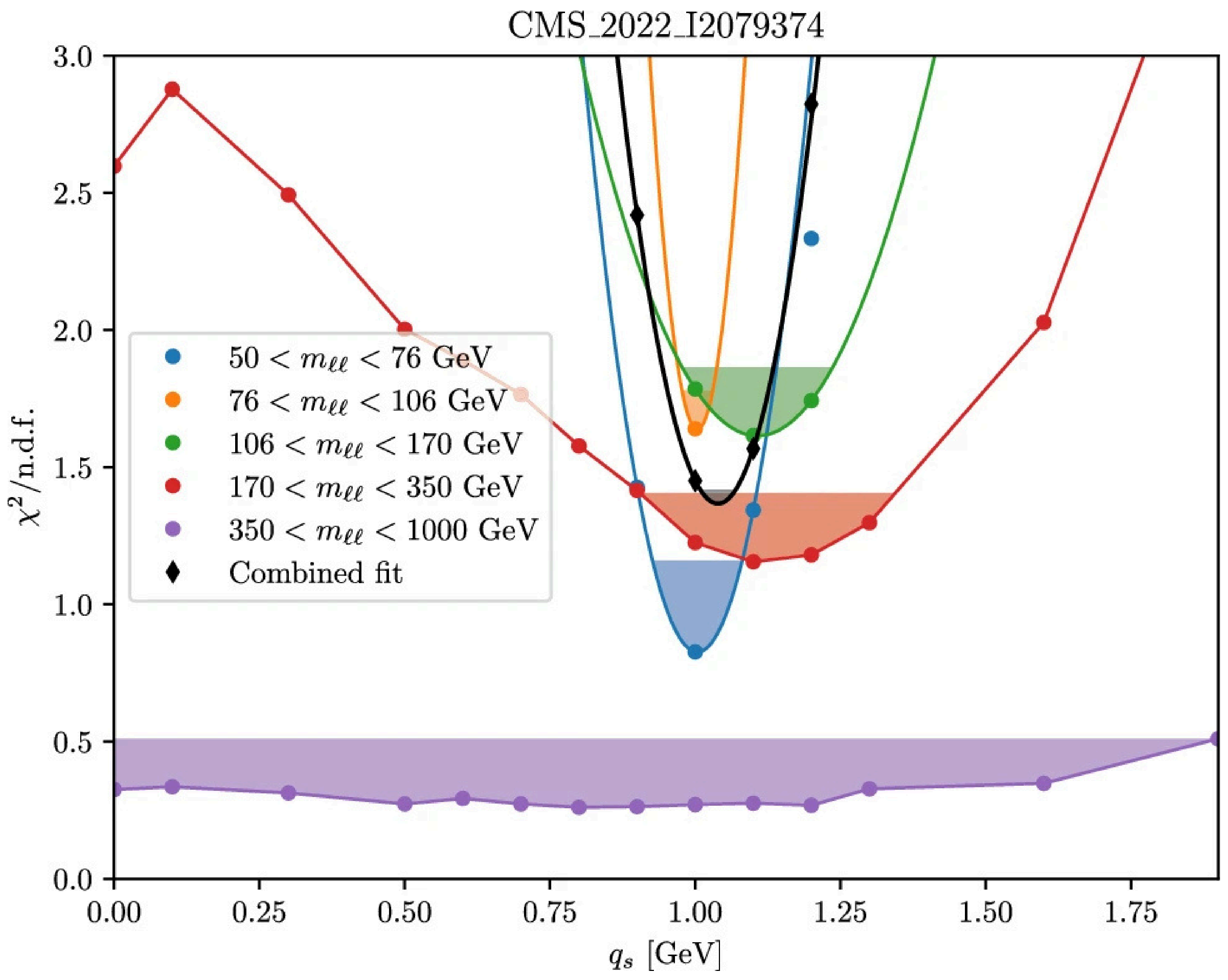
Intrinsic kT-width dependence on invariant mass at √s = 13 TeV



- The reduced chi2 (chi2/n.d.f) distribution as a function of qs for different regions obtained from a comparison of the MCatNLO+CAS3 prediction with the measurement by CMS

- 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:

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

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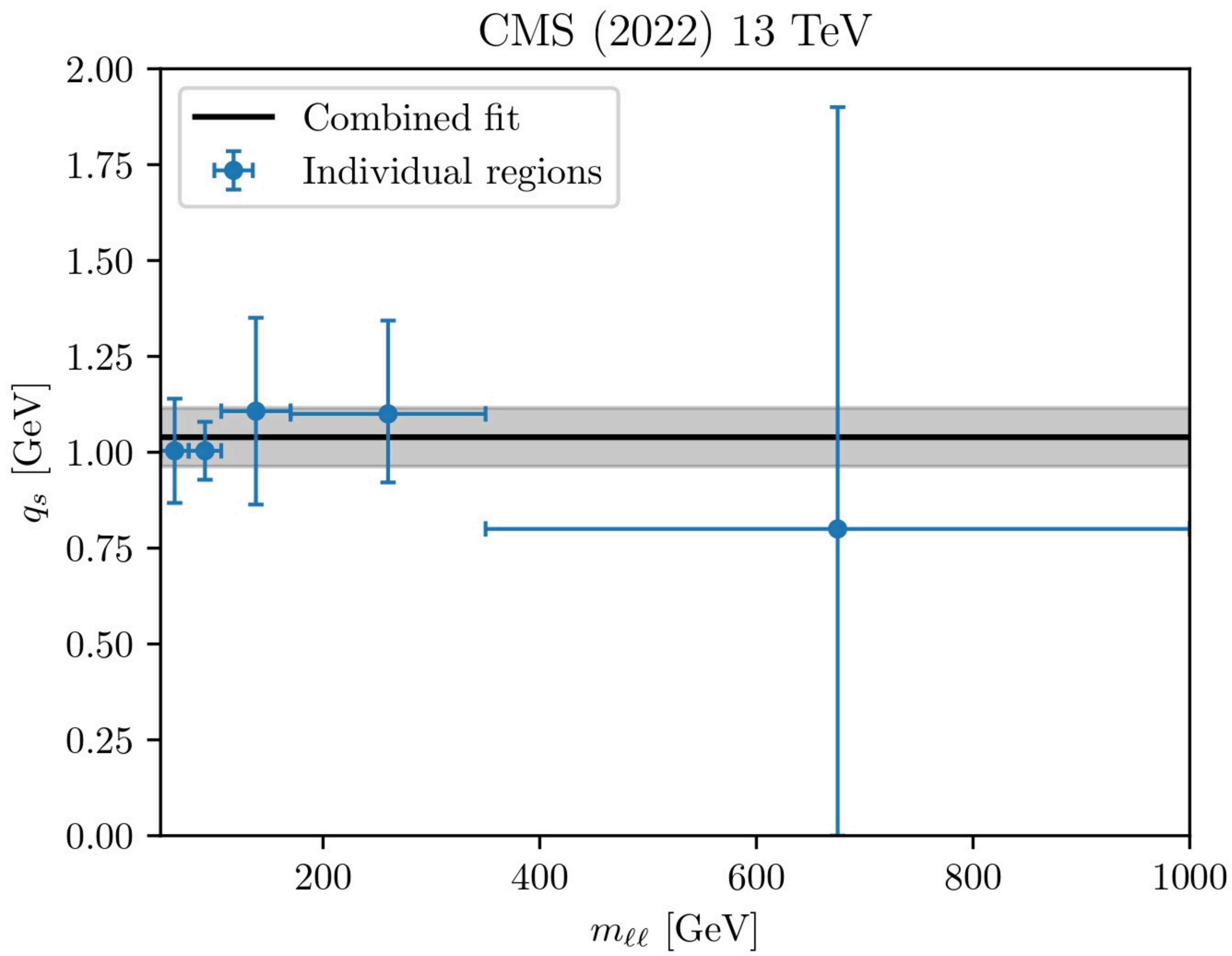

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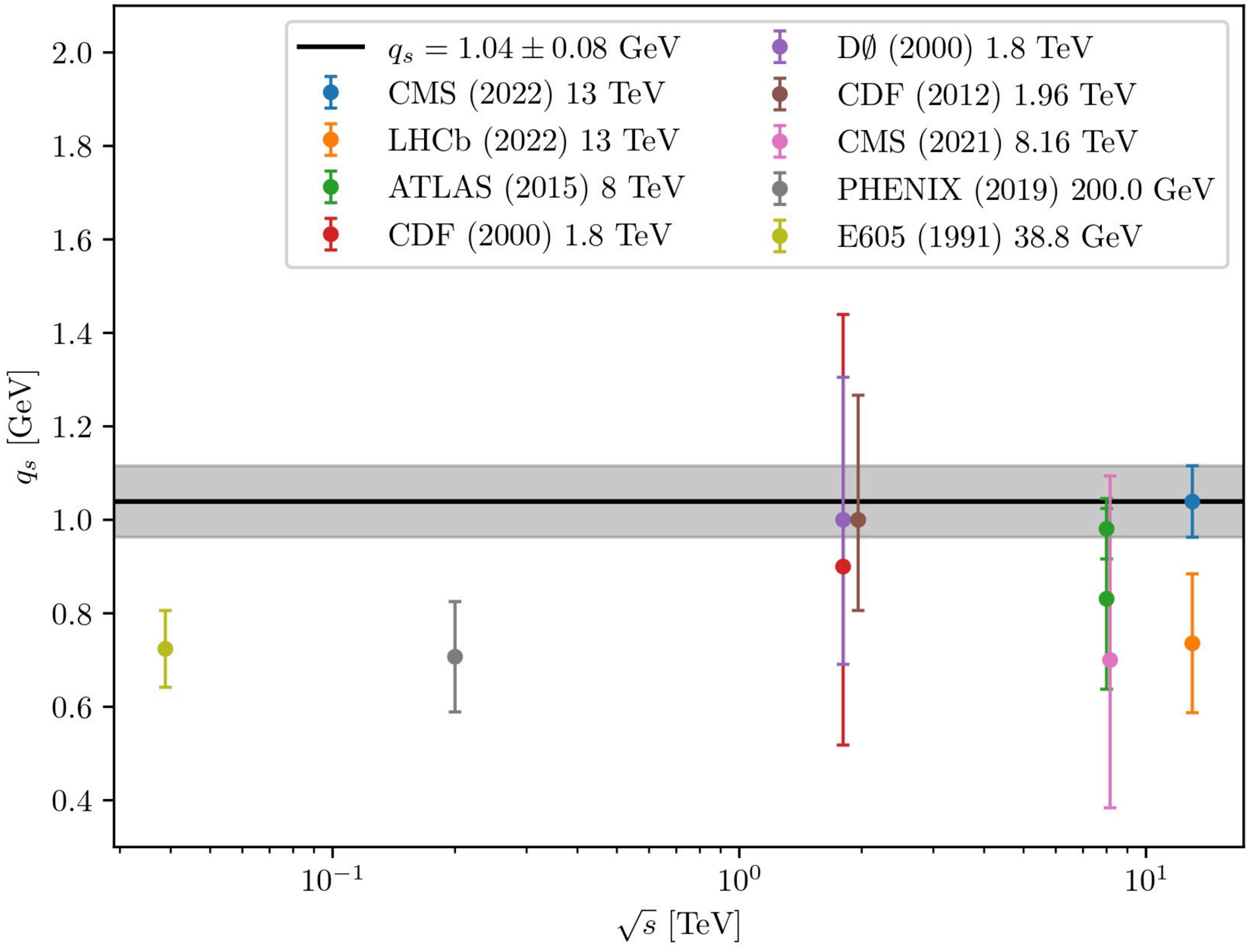
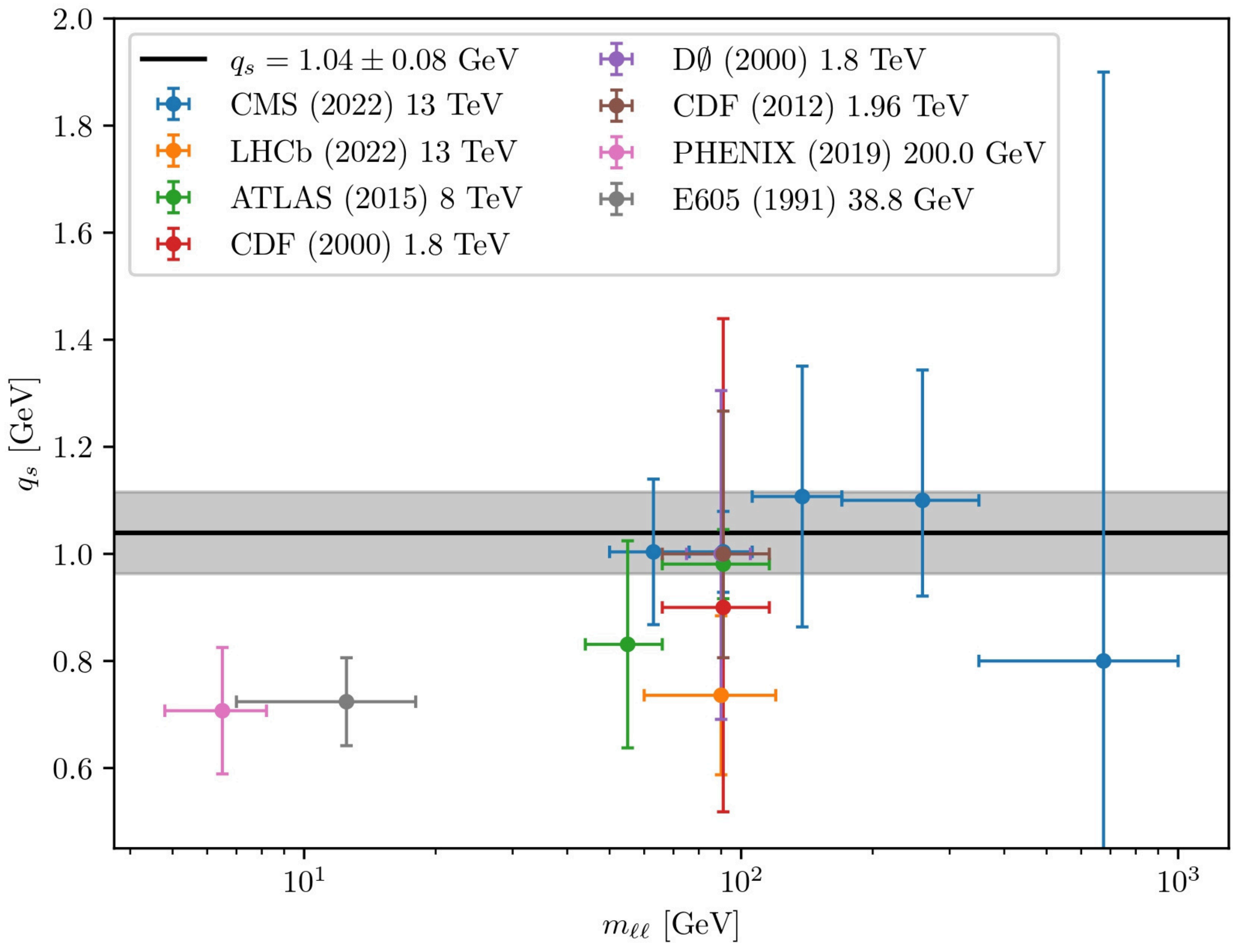
Intrinsic kT-width dependence on √s





- Standard Monte Carlo event generators need a strongly increasing intrinsic-kT width with $\sqrt{s}$
- Strong center-of-mass energy dependence is not observed

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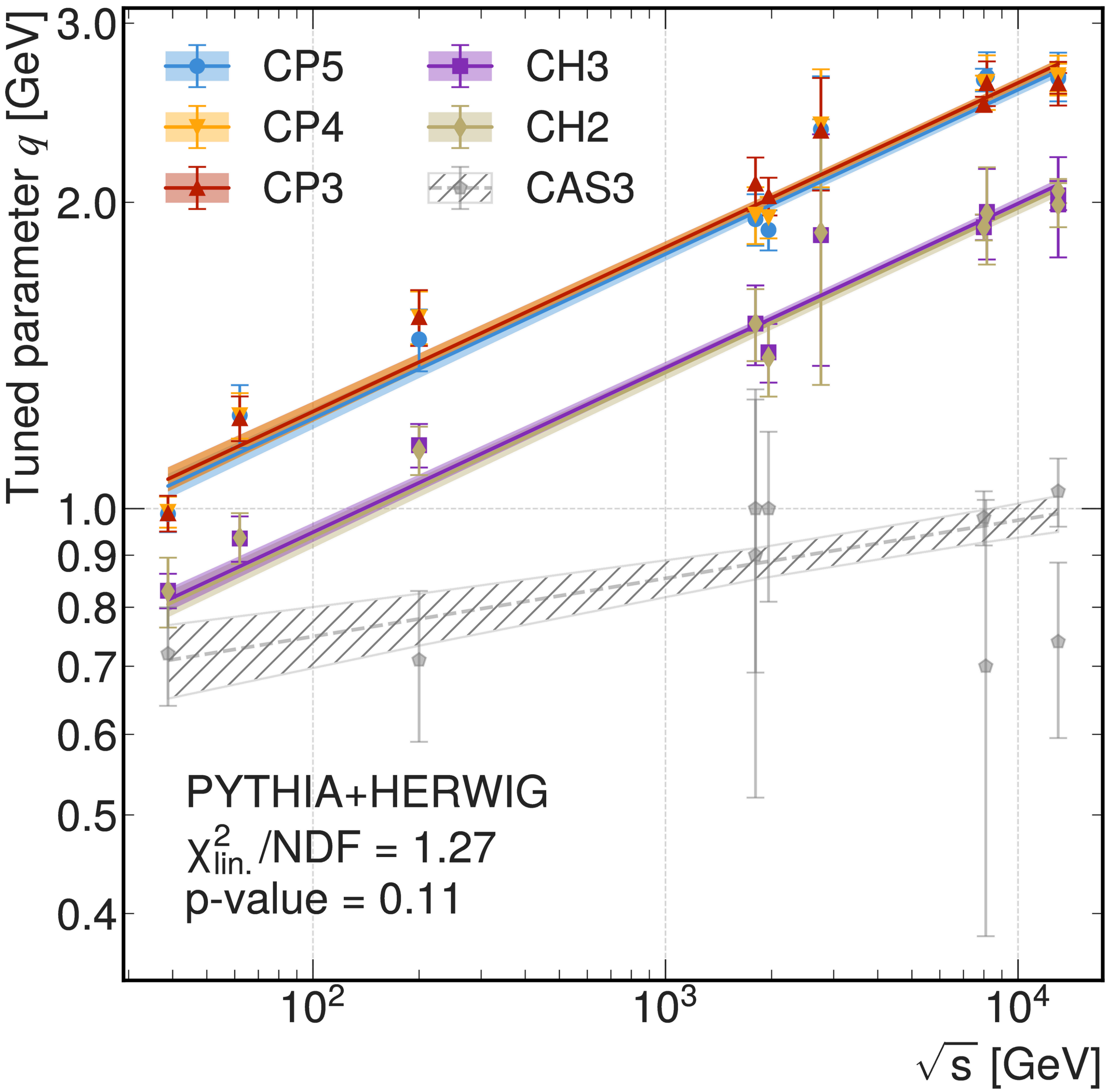
Center-of mass dependence of the intrinsic-kT width in the shower-based generators



- In PYTHIA and HERWIG (shower-based generators):
  - Intrinsic-kT width increases strongly with energy, regardless of tune
- As previously shown in CASCADE3 only a very mild energy dependence is observed
  - **PYTHIA/HERWIG exclude soft gluon emissions to avoid divergences**
- Our next step - study with CASCADE3:
  - **Origin of the dependence analyzed by varying soft gluon contributions**

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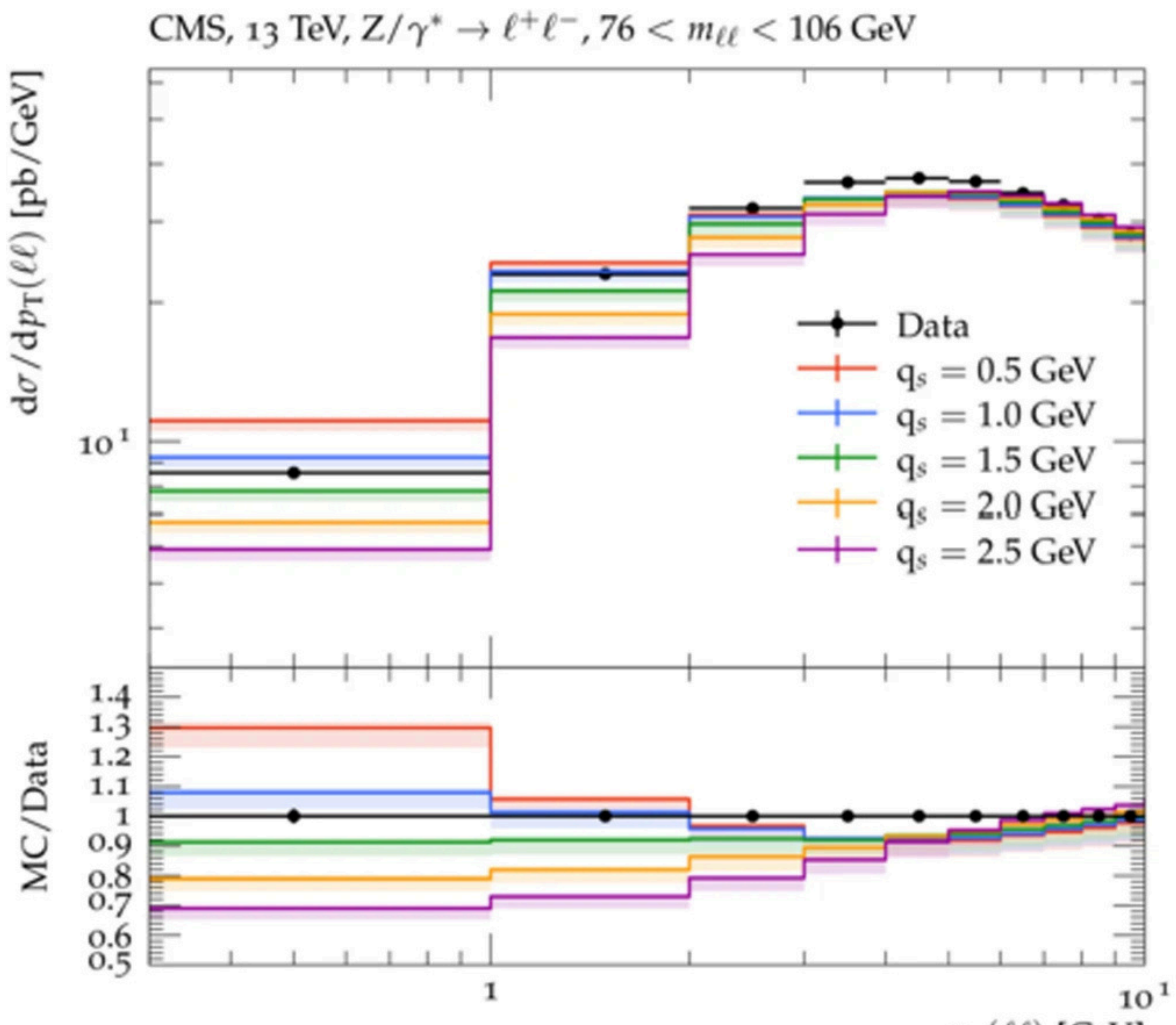
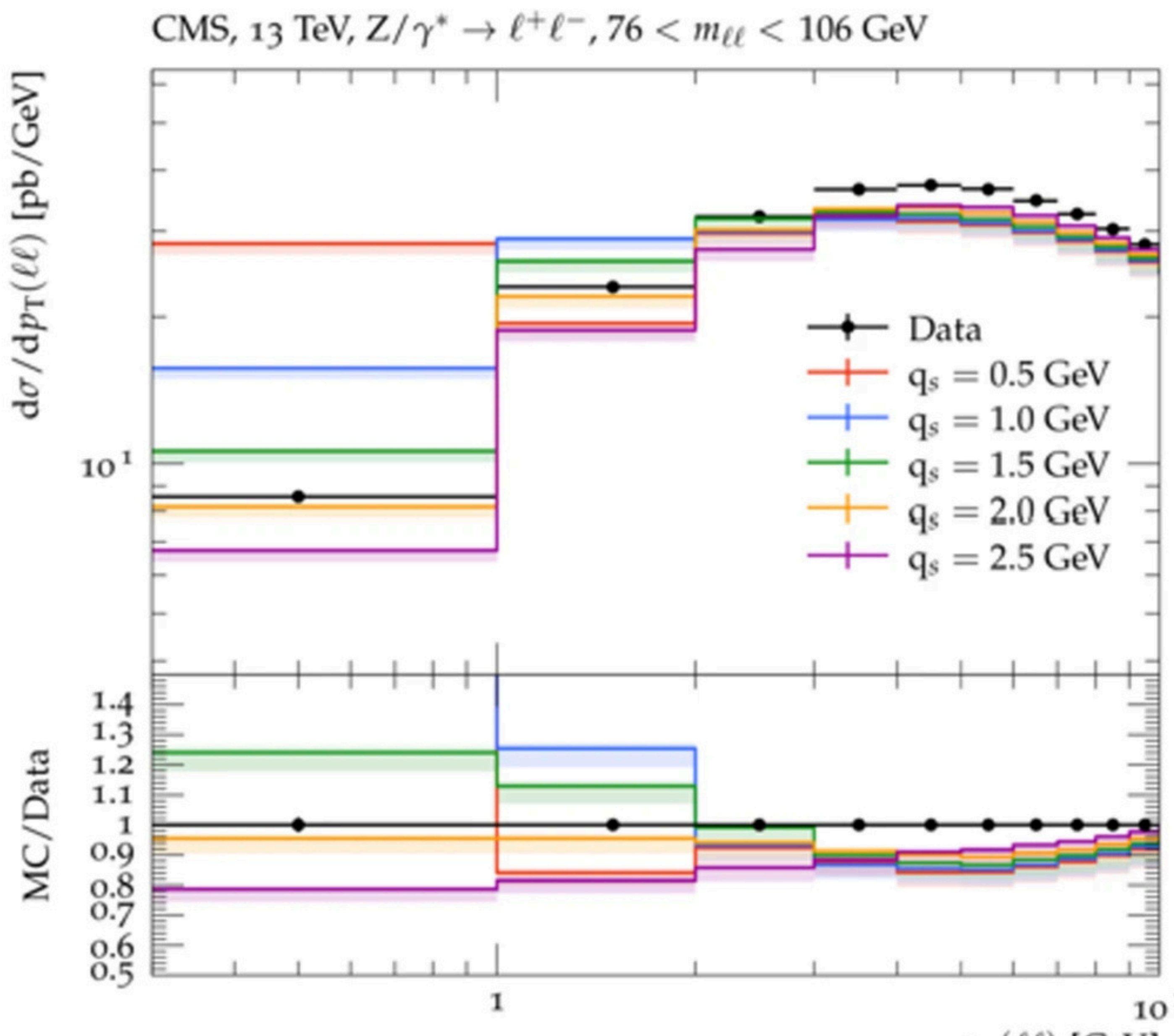
Introducing energy dependence of the intrinsic-kT in PB

- Mimic parton-shower event generators by demanding a minimal parton transverse momentum
- **q0 = 1 and 2 GeV**
    - qT > q0
- Non-perturbative part neglected
- A comparison of DY transverse momentum distribution, measured by CMS at TeV in the peak region.



q0 = 1 GeV



q0 = 2 GeV

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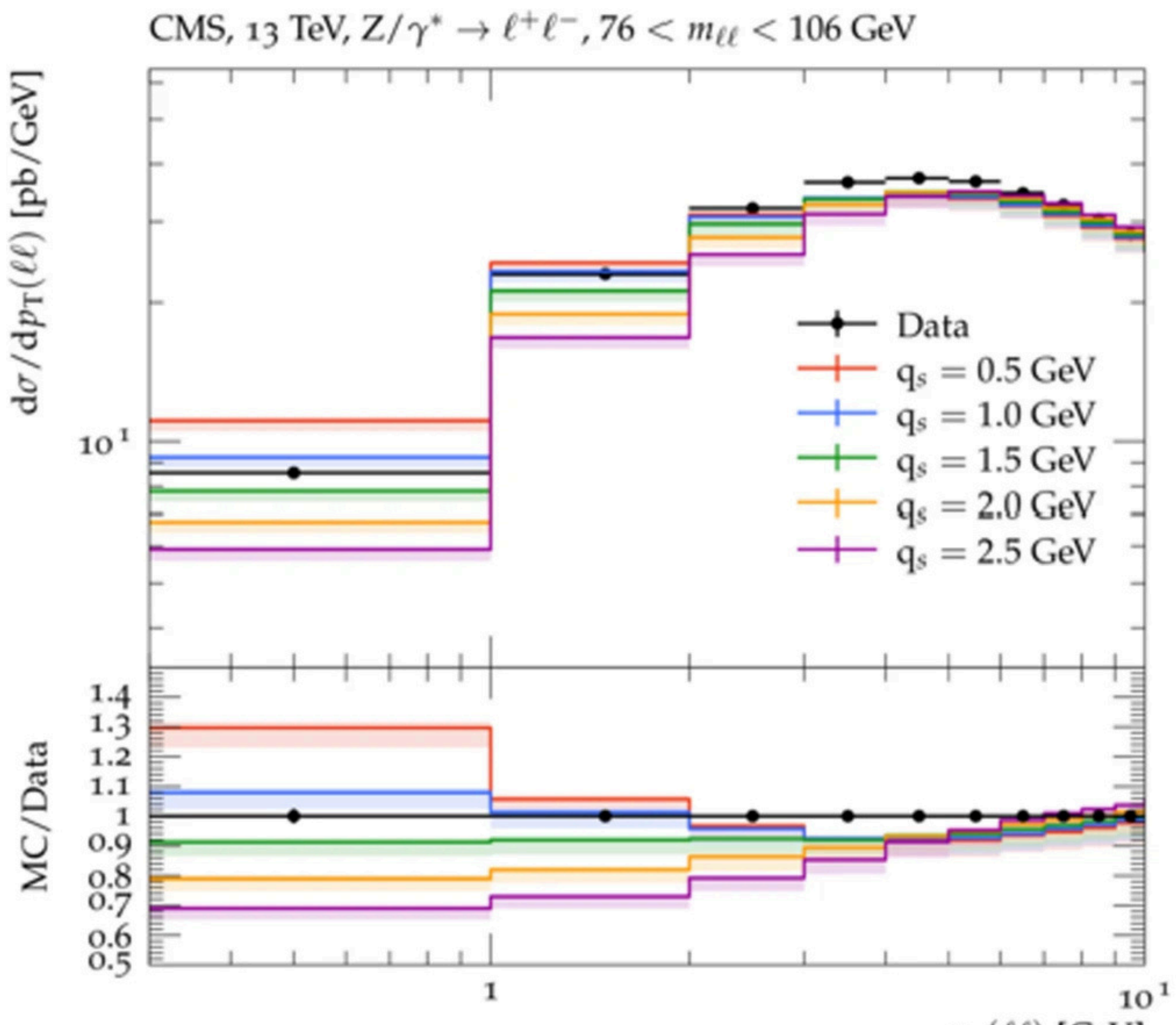

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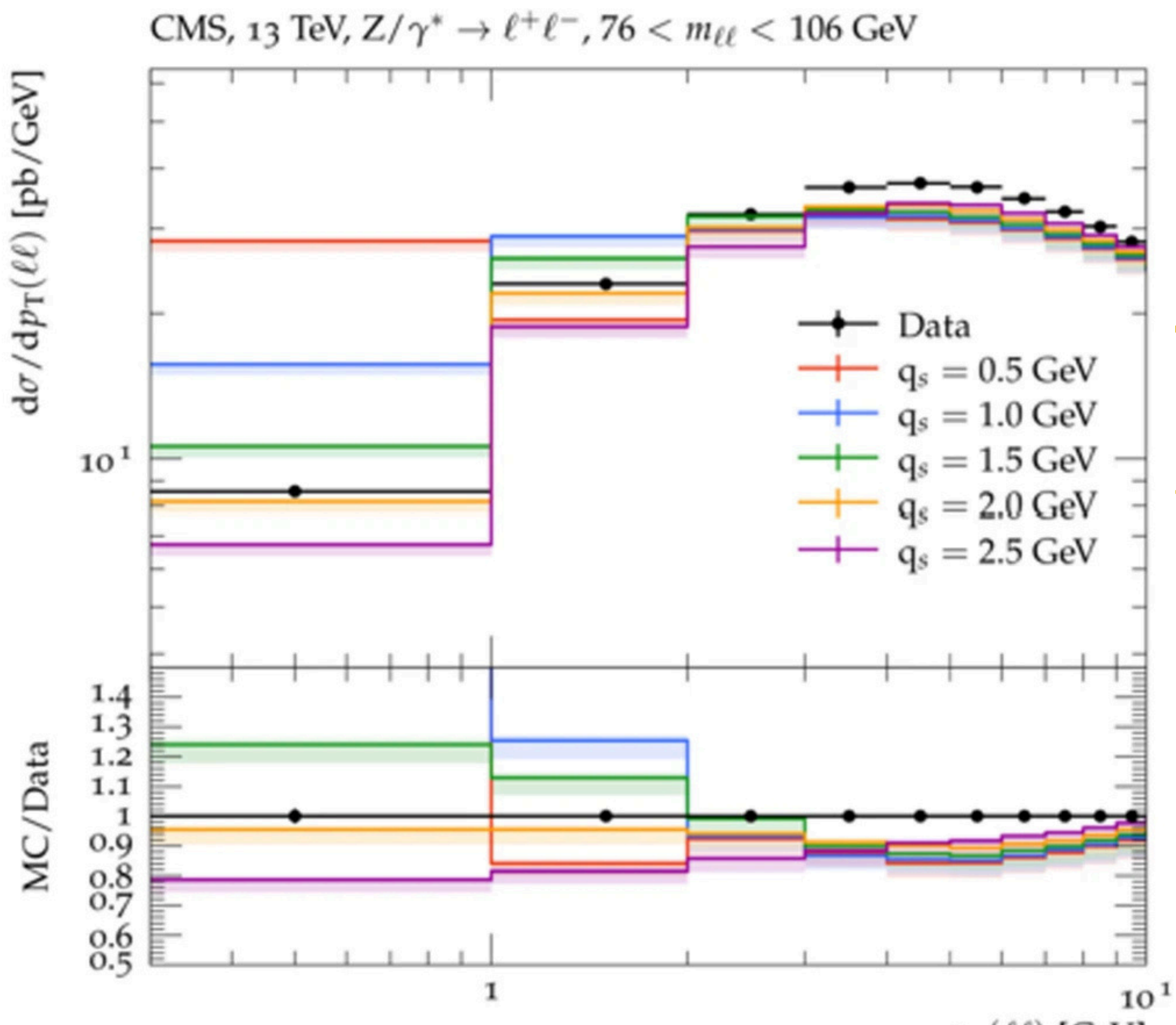

q0 = 2 GeV

The sensitivity of the DY cross section on the intrinsic-kT increases with increasing cut-off q0

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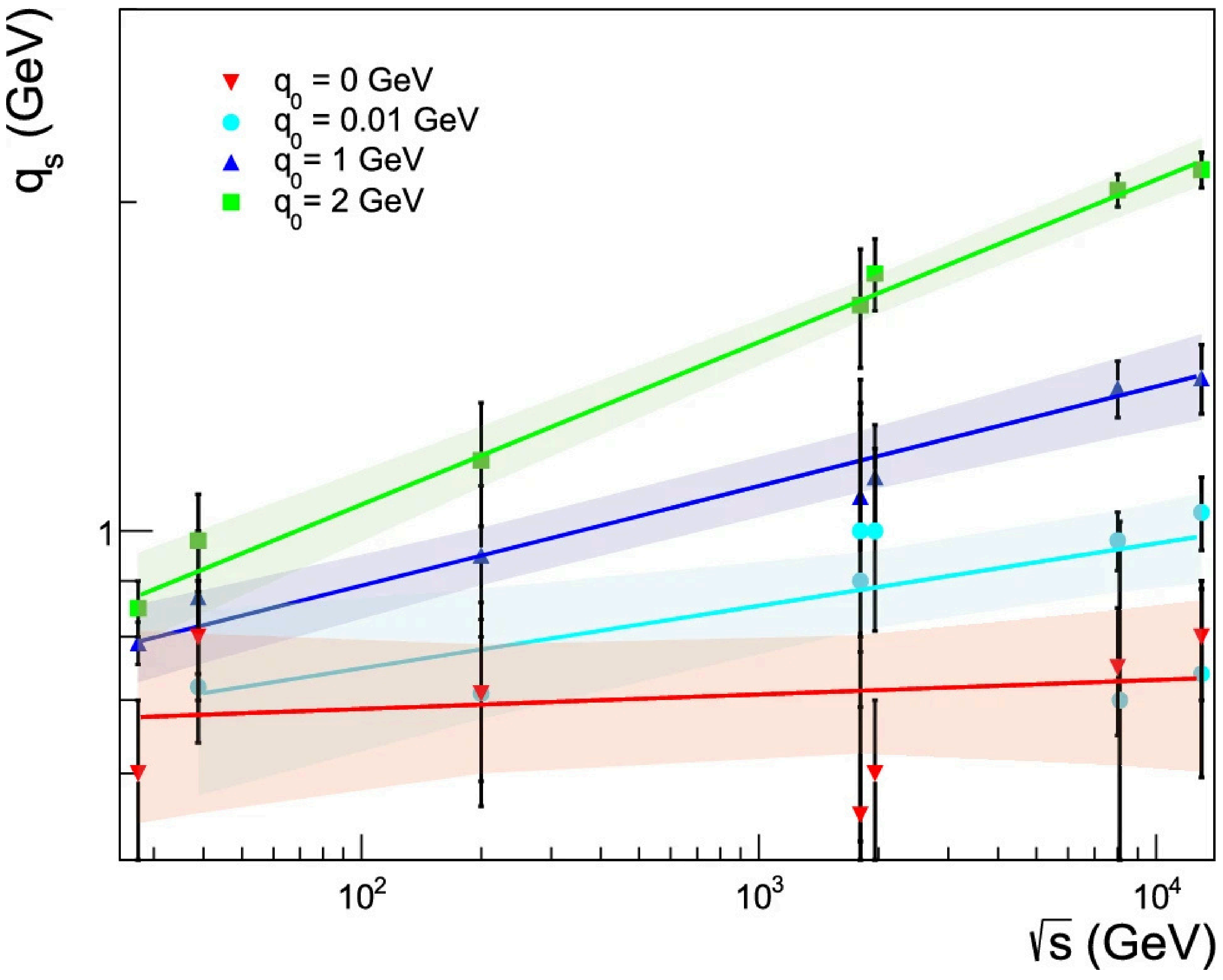

- qs dependence on center-of-mass energy for the cases with q0 = 1 GeV, q0 = 2 GeV, q0 = 0 GeV and q0 = 0.01 GeV
- The slope increases as q0 increases
- **Larger q0** means that **more soft contributions** are excluded
  - Larger intrinsic-kT needed to compensate missing contribution from soft gluons
    - Higher q0 values lead to an **increased sensitivity to the intrinsic kT-distribution**, resulting in **smaller uncertainty bands**

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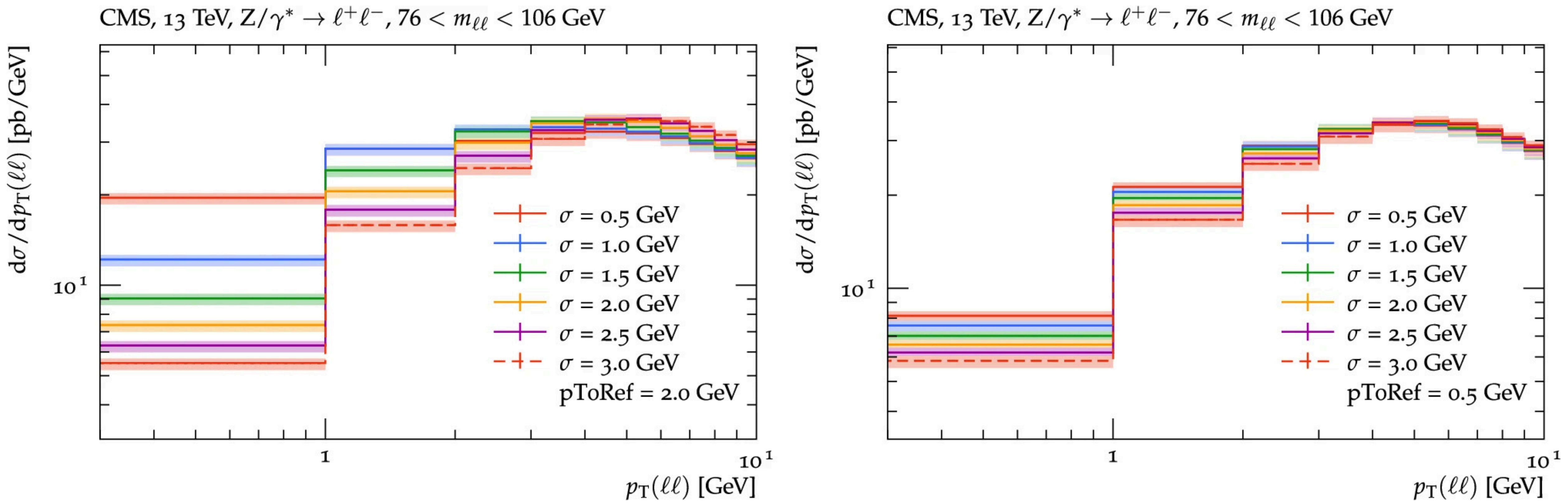
Interplay of intrinsic motion of partons and soft gluon emissions with PYTHIA

- Varied the ISR cutoff parameter (pT0Ref) = 0.5, 1.0, 2.0 GeV to test sensitivity of kT to the treatment of soft gluons.
- Default PYTHIA settings:
  - ISR cutoff pT0Ref = 2.0 GeV
  - Intrinsic-kT width ≈ 2 GeV



- Drell–Yan cross section in the Z-peak region from Pythia8, shown for two ISR cutoff values: pT0Ref = 2 GeV (left) and pT0Ref = 0.5 GeV (right). Results are compared for intrinsic-kT widths of 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 GeV.

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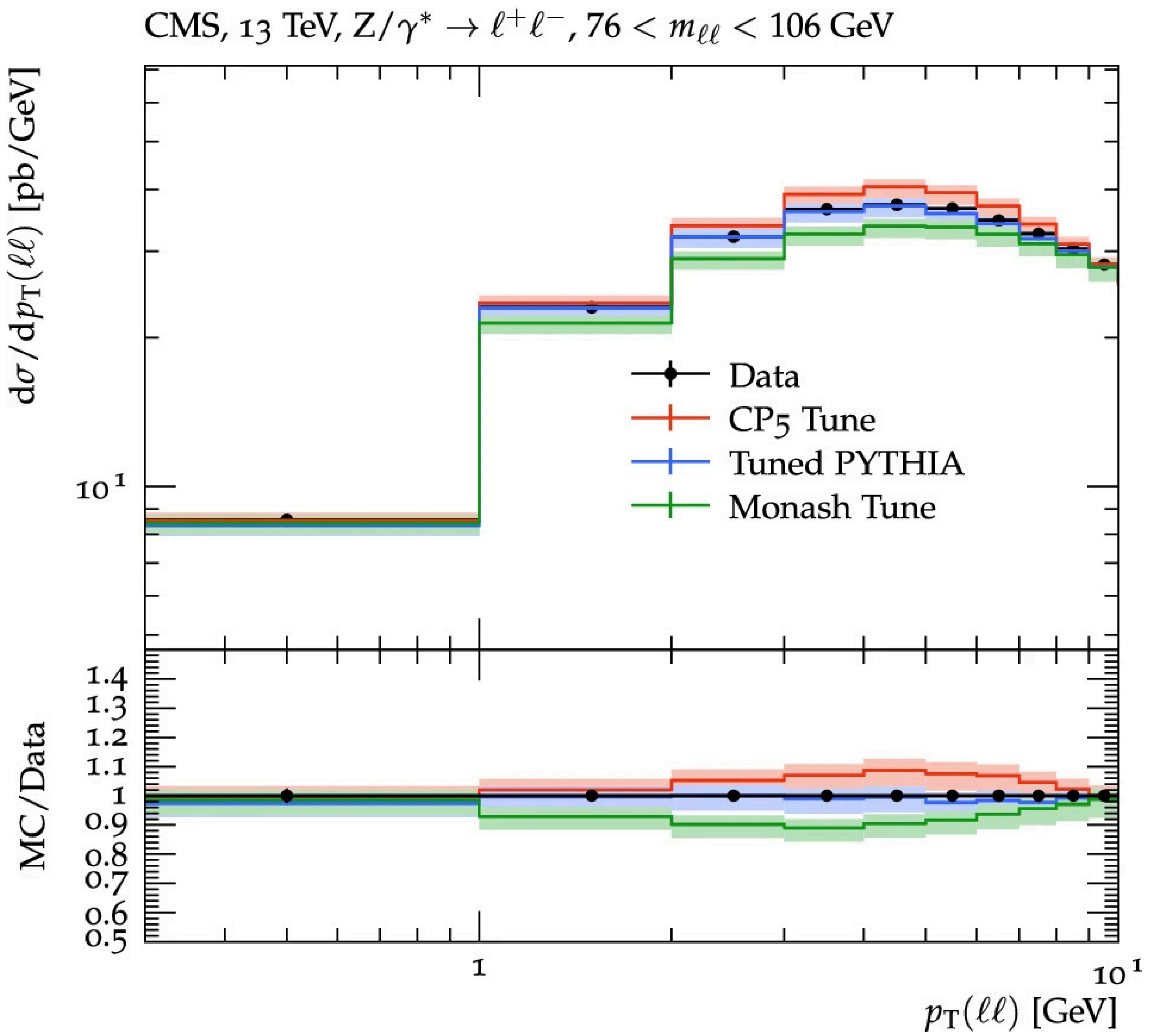
Pythia8 Tunes and DY Cross Section



- Comparison with LHC DY data (Z-peak):
  - Monash tune → underestimates cross section (2–5 GeV region)
  - CP5 tune → overestimates cross section (2–5 GeV region)
  - Optimized Monash (with pT0Ref = 0.5 GeV and tuned intrinsic-kT width) → excellent agreement with data
- DY data in the Z-peak region are very sensitive to ISR cutoff and intrinsic-kT modeling
- An intrinsic-kT-optimized tune is required for accurate description

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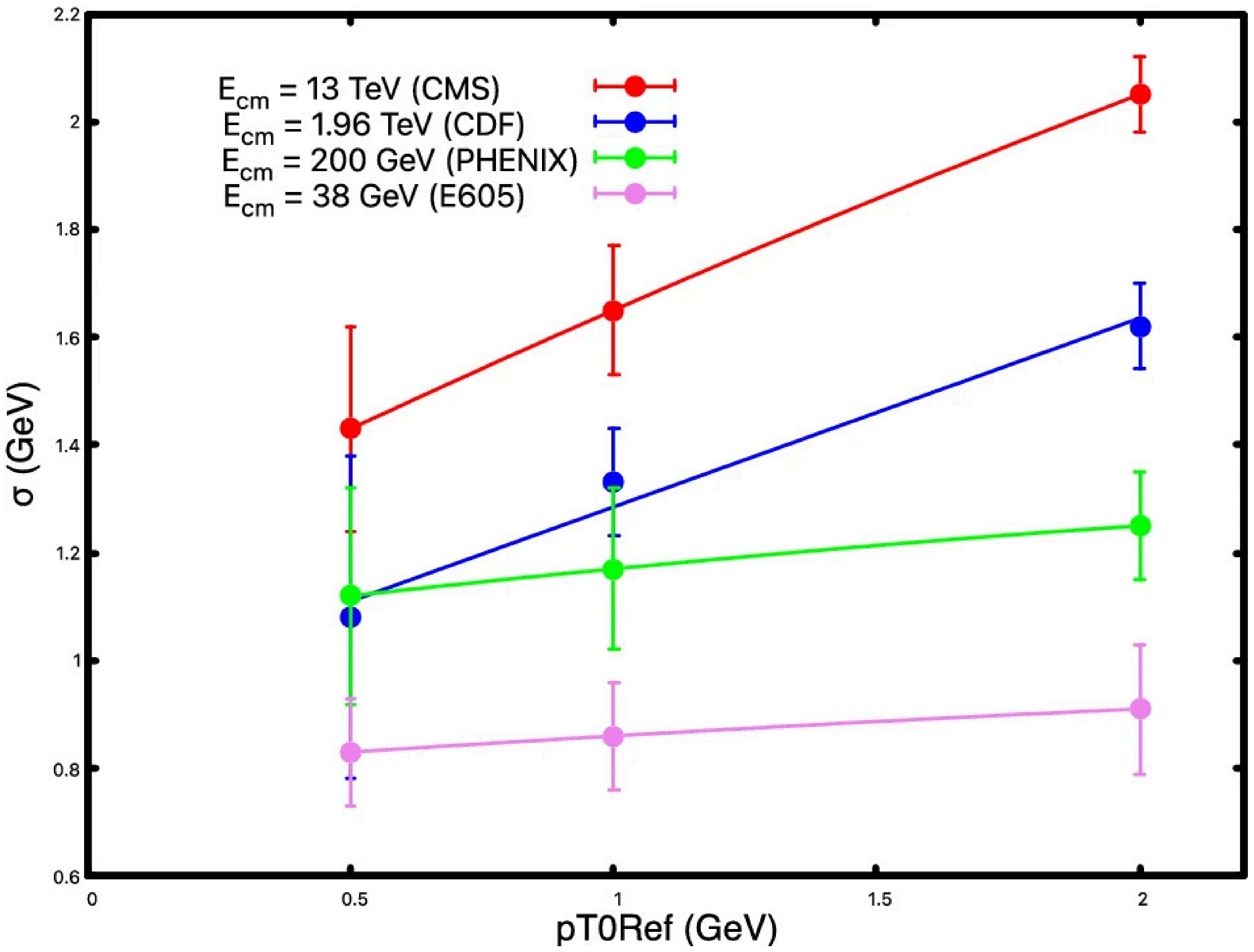
Intrinsic-kT Width vs ISR Cutoff and Energy



- Dependence of the intrinsic width on the ISR cut-off parameter pT0Ref, as determined in the intrinsic-optimized tune from comparisons with measurements at various collision center-of-mass energies. Linear fits are shown for each energy.

- Trend with ISR cutoff (pT0Ref):
  - Intrinsic-kT width grows nearly linearly with pT0Ref

- Energy dependence:
  - For the same cutoff, higher center of mass energy → larger intrinsic-kT width
  - Increased number of branchings at high energy:
    - More perturbative emissions
    - More soft, non-perturbative emissions

- Low-energy measurements (38.8 GeV, 200 GeV):
  - Contribution dominated by soft gluons with very low pT (~0.5 GeV)
  - Width shows only small variations with cutoff

- At higher energies(1.96 TeV, 13 TeV), the rate of increase of the width with pT0Ref becomes more pronounced. This rate is similar across experiments

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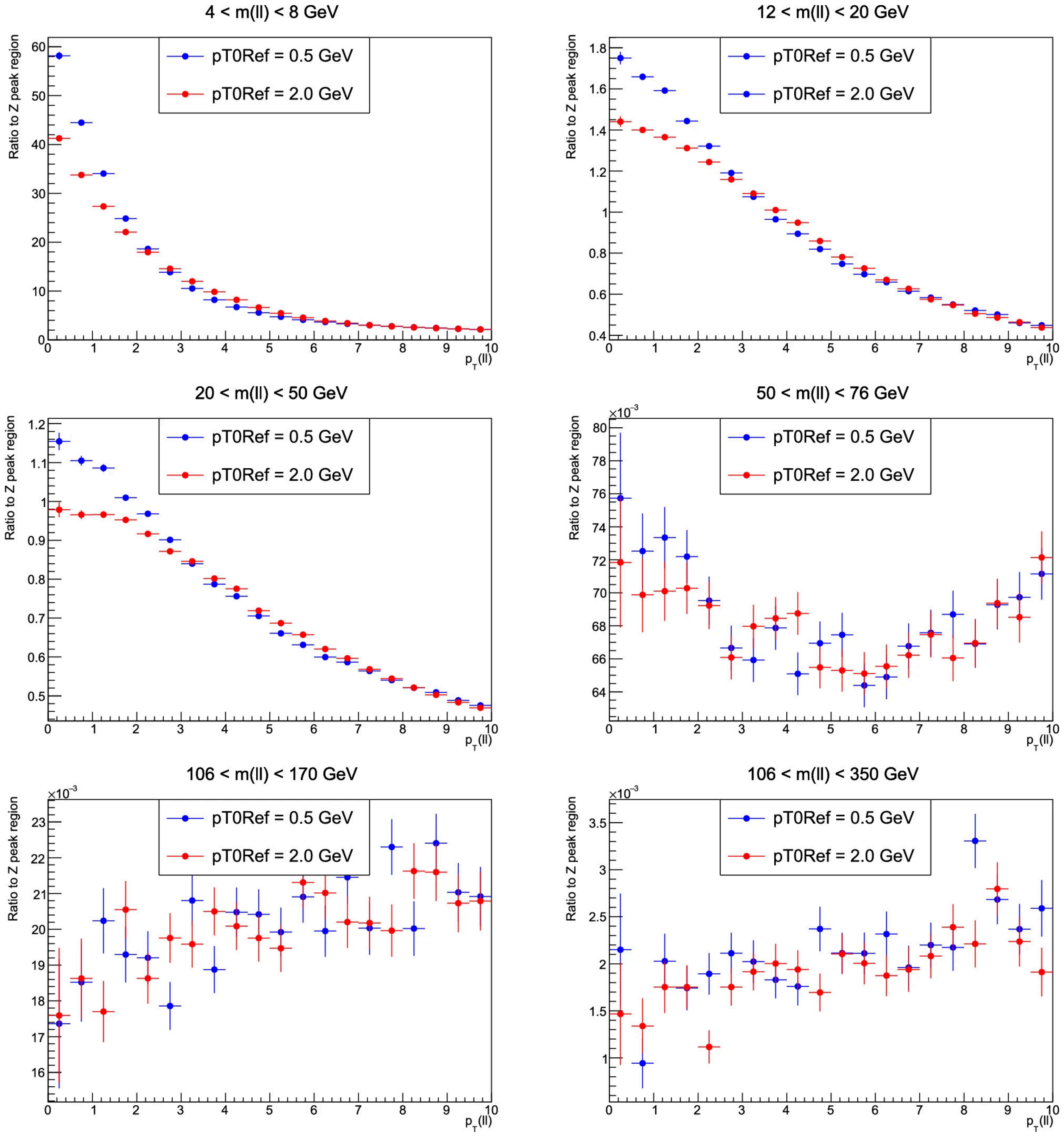
Cross Section Ratio from Pythia Predictions



- Ratio of DY cross section as a function of pT to Z-peak region,
- High invariant masses: Width parameter shows no significant dependence on cutoff
- At lower invariant masses a clear dependence appears
- Difference between the two cutoff settings grows as mDY decreases
  - Confirms that soft gluon emissions dominate at low scales

Conclusion

- Drell–Yan low-pT is the key probe of intrinsic motion + soft gluon dynamics.
- CASCADE includes soft contributions → gives stable, universal intrinsic kT across different center of mass energies and DY mass.
- Energy dependence of intrinsic kT in Pythia/Herwig is not physical → caused by excluded soft gluons.
- Proper treatment of soft non-perturbative emissions is essential for reliable event generator tuning and precision QCD.

Thank you!