# Drell-Yan at NLO in the Parton Branching Method

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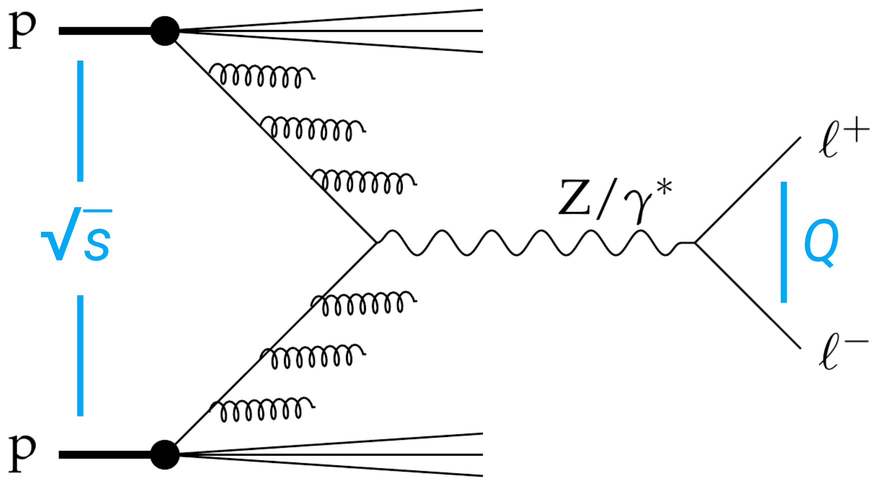
# Drell-Yan

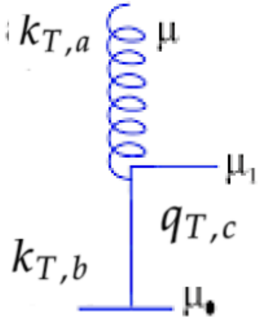
Z boson: important particle at the LHC

- Color singlet: facilitates theory
- Easy experimental signature with leptonic decay
- Rich platform for QCD in the initial state
- **TMD effects** in $p_T$(Z) distribution



# Parton Branching TMDs

JHEP 01 (2018) 070




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

Idea: $k_T$ accumulates through repeated parton *branchings*

- Start at a small scale and evolve
- Branchings governed by scale evolution
- Every branching generates some $k_T$
- Non-resolvable branchings: Sudakov form factors

Related to CSS formalism:

- Non-resolvable Sudakov FF ⇄ Collins-Soper kernel
- More in PoS EPS-HEP2023 (2024) 270

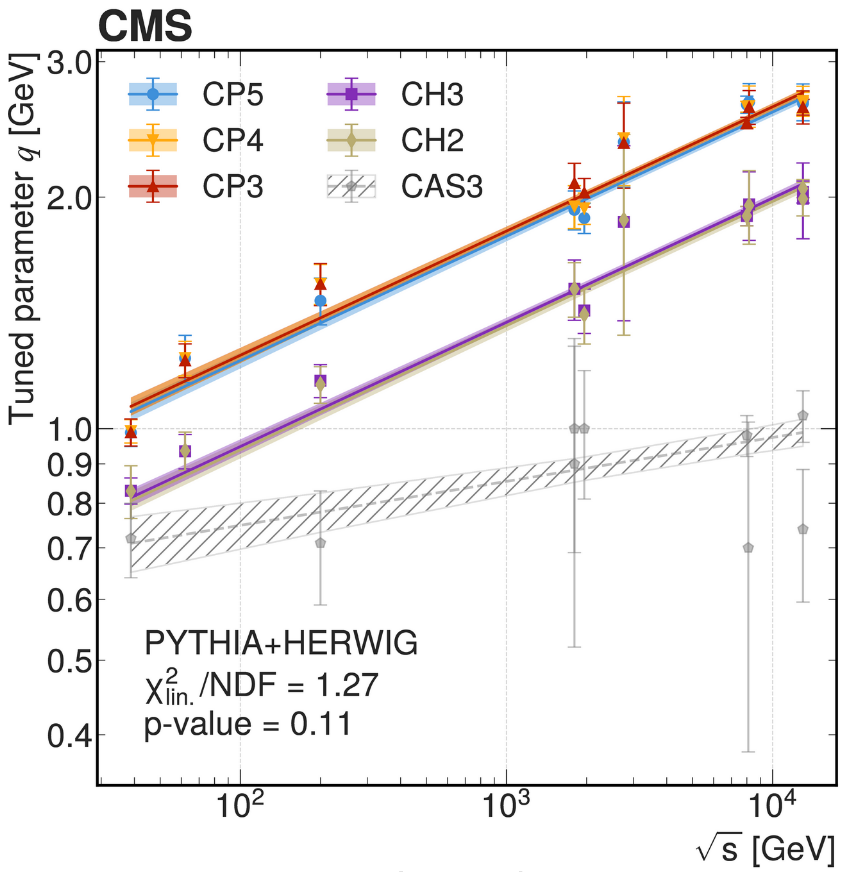
# Intrinsic $k_T$

Parton $k_T$ distribution at small scale

- Present in all formalisms
- In TMDs: identified with the parton "orbital momentum"

No predictions:

- Extracted from data
- Usually simple Gaussian
- Major unknown: width of this distribution
- Tuned from data




CMS-GEN-22-001, submitted to PRL

# CASCADE 3

Website; manual: EPJ C 81, 425 (2021)

*CASCADE generates a full hadron event record according to the HEP common standards.*

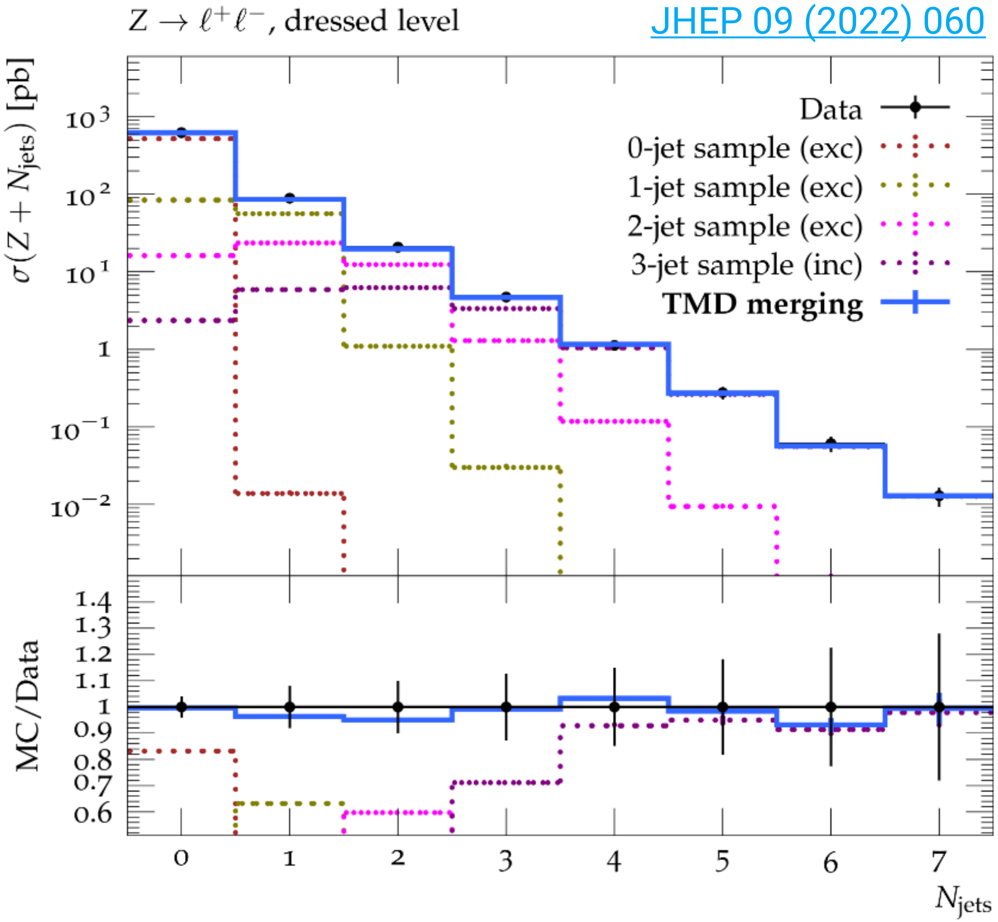
- Full TMD initial-state shower (with TMDlib 2103.09741)
- Pythia final-state shower
- e—p and p—p initial states
- On/off-shell matrix elements
- Arbitrary processes via LHE files ← Essential for experiments!
- Multileg via TMD merging JHEP 09 (2022) 060

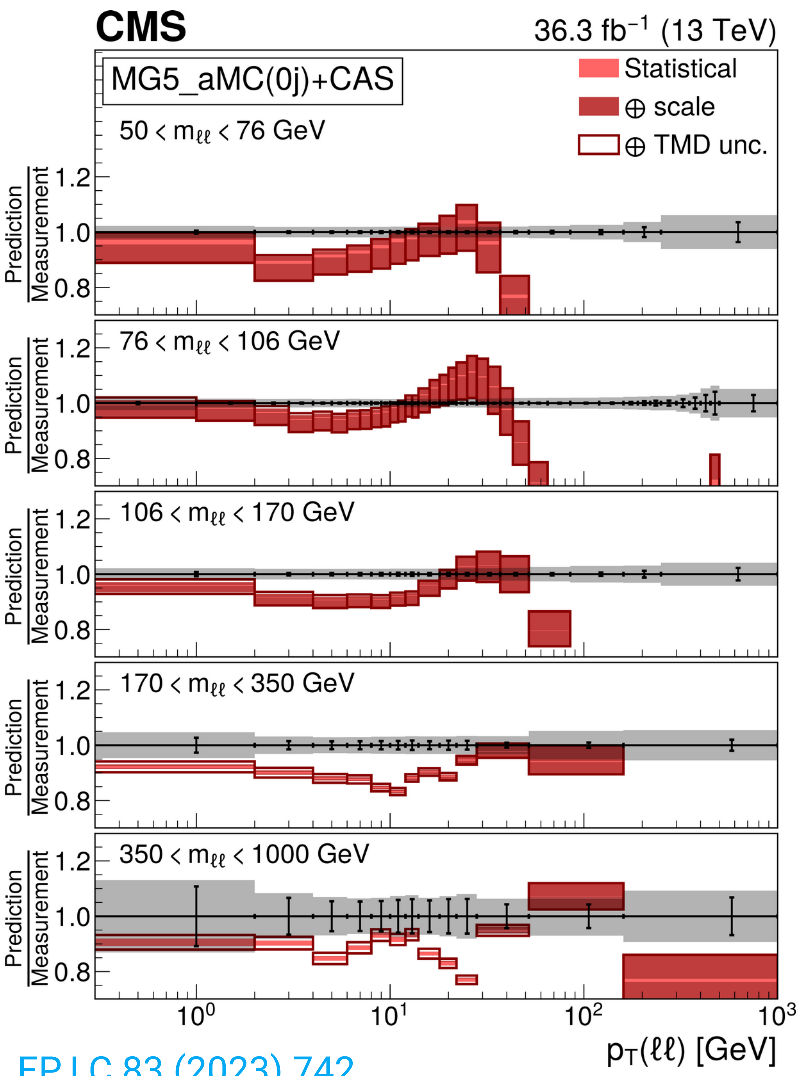
# Showcase: Z + jets

## CASCADE with TMD merging

- Compared to ATLAS data [EPJ C 77 (2017) 361]
- 0–3 jets in matrix element
- Excellent agreement up to 7 (!) jets

JHEP 09 (2022) 060






[EPJ C 83 (2023) 742](https://doi.org/)

# Transverse momentum

CMS compared their Z $p_T$ measurement to CASCADE

- Five $Q^2$ intervals
- No prediction at high $p_T$ (expected)
- Low-$p_T$ behavior could be improved

⇒ Fit the TMD model

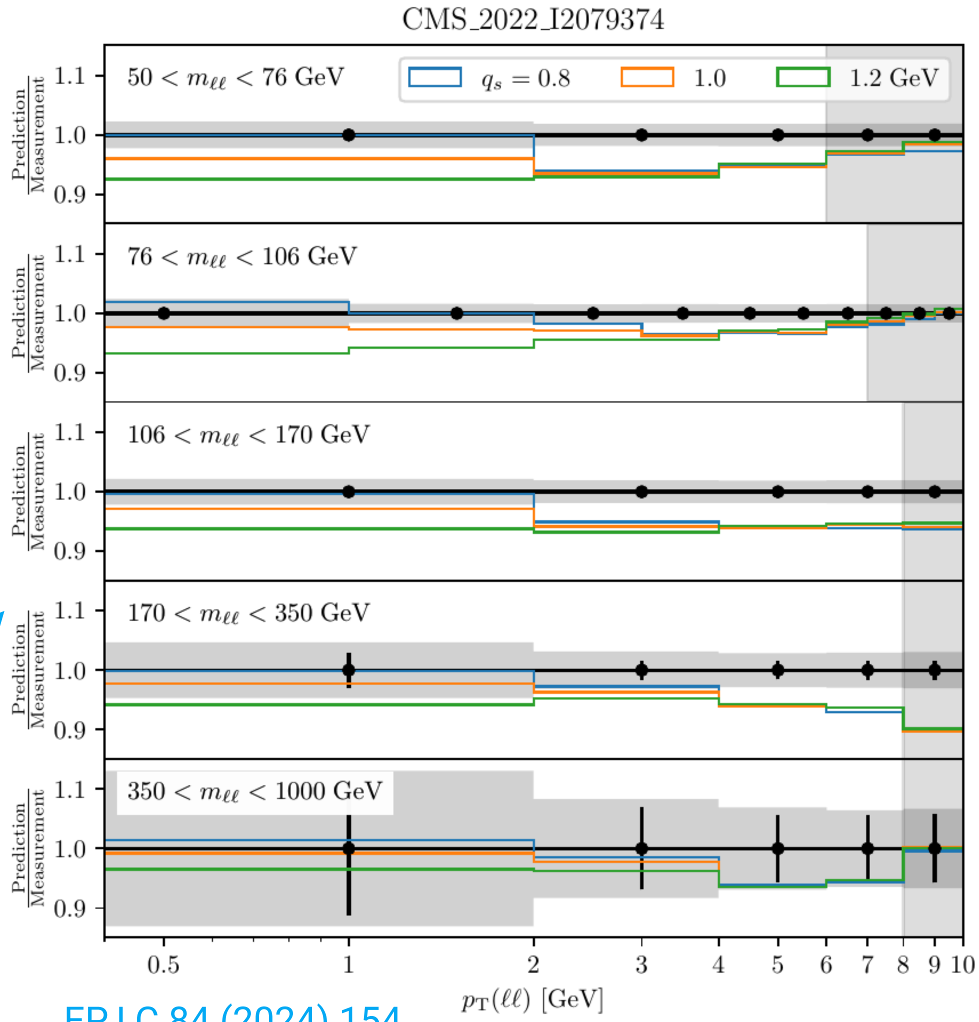
# Intrinsic $k_T$ determination

Low-$p_T$ DY data is sensitive to the quark $k_T$ distributions

In PB TMD:

- Gaussian distribution at $\mu_0$ = 1 GeV
- Width given by $\sigma = q_s / \sqrt{2}$
- Evolved to the scale of interest

CMS data sensitivity

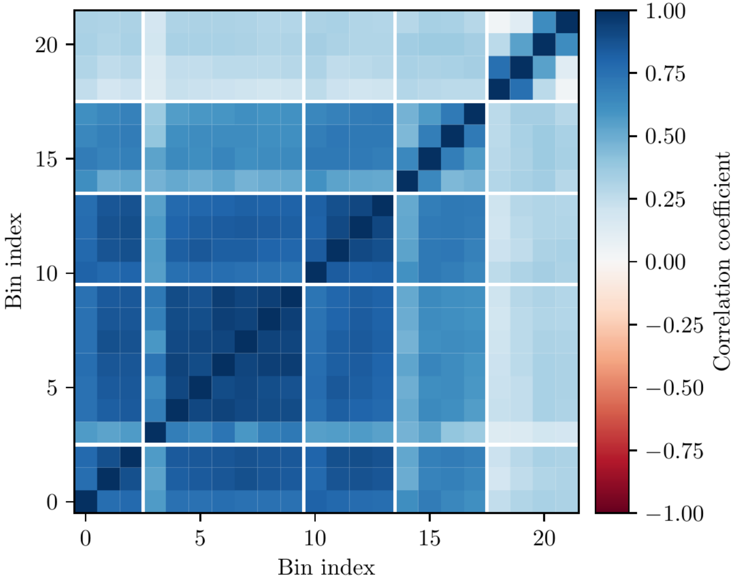



EPJ C 84 (2024) 154

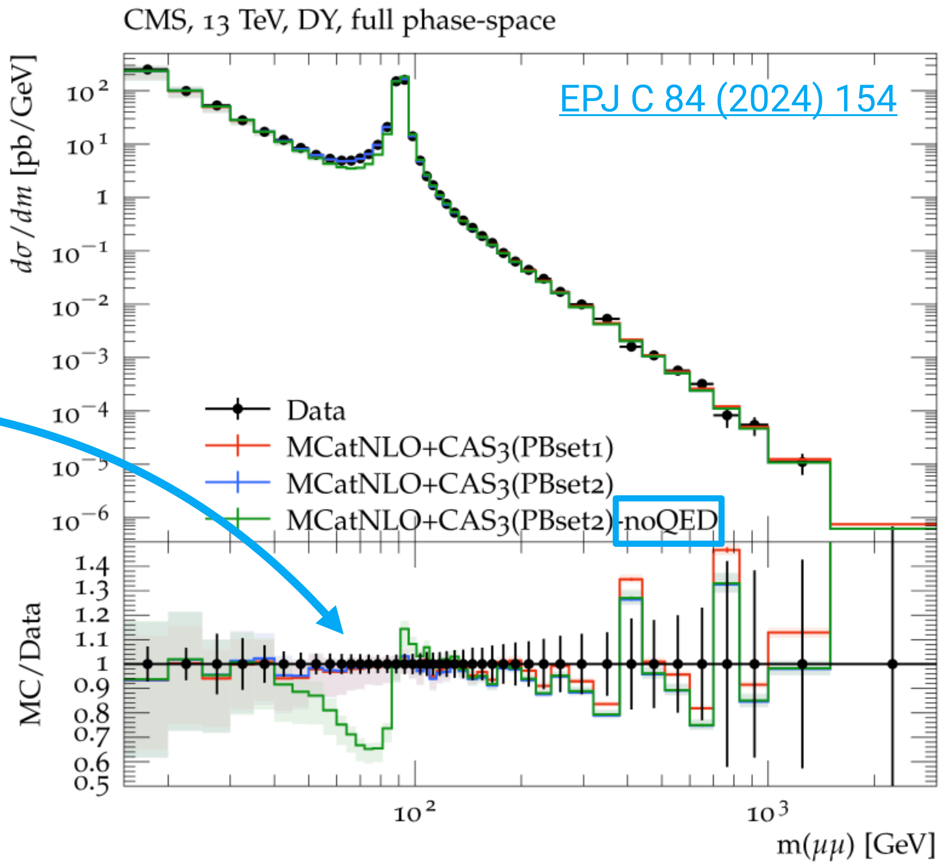
# Input data

CMS results from [EPJ C 83 (2023) 628](EPJ C 83 (2023) 628):

- $d\sigma/dp_T(Z)\, dQ^2$ in five $Q^2$ bins
- Sensitive to QED FSR
- Detailed systematics & correlations




Correlation matrix for bins used in the fit



# Fitting procedure

Code for combined χ²

Using the first few $p_T$ bins in each $Q^2$ bin

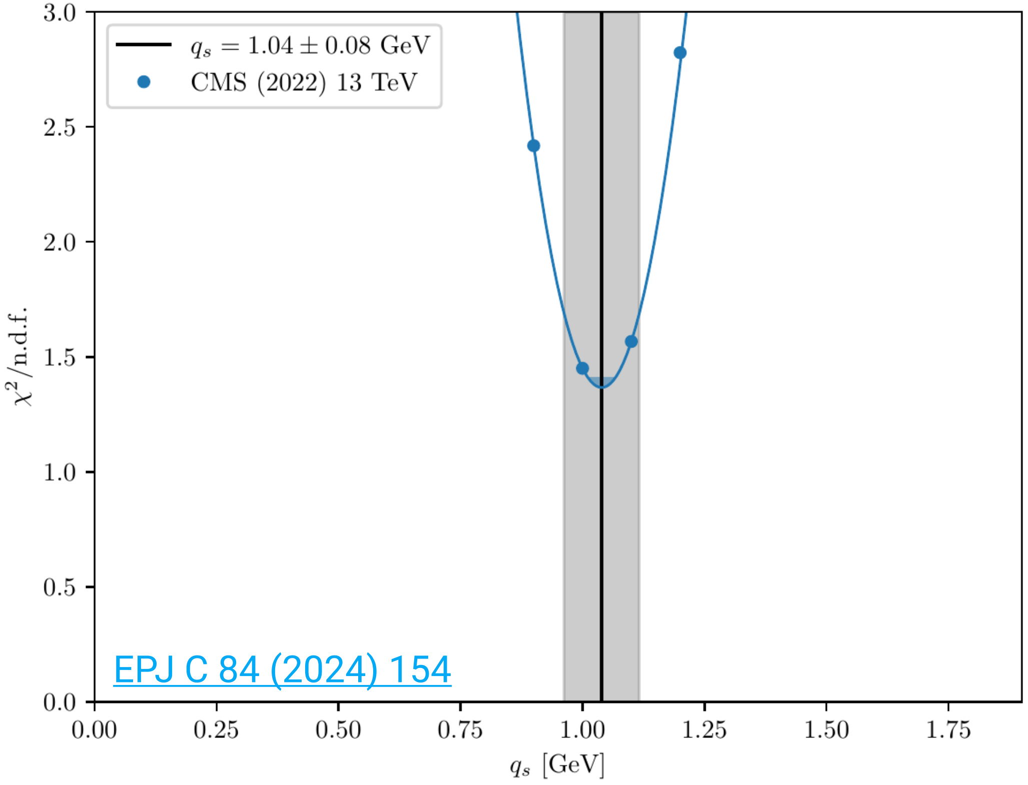
Minimize a joint $\chi^2$ statistic with all bins

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

$C_{ik}$ includes measurement & prediction errors

Fit result at $\sqrt{s}$ = 13 TeV:

**$q_s$ = 1.04 ± 0.08 GeV**



# Other experiments

Fitted Drell-Yan measurements at different $\sqrt{s}$ with consistent results

| Analysis | $\sqrt{s}$ | Collision types | n.d.f |
|---|---|---|---|
| CMS_2022_I2079374 [17] | 13 TeV | pp | 25 |
| LHCb_2022_I1990313 [58] | 13 TeV | pp | 5 |
| CMS_2021_I1849180 [67] | 8.1 TeV | pPb | 5 |
| ATLAS_2015_I1408516 [61] | 8 TeV | pp | 8 |
| CDF_2012_I1124333 [64] | 1.96 TeV | p$\bar{p}$ | 6 |
| CDF_2000_S4155203 [63] | 1.8 TeV | p$\bar{p}$ | 5 |
| D0_2000_I503361 [62] | 1.8 TeV | p$\bar{p}$ | 4 |
| PHENIX_2019_I1672015 [65] | 200 GeV | p$\bar{p}$ | 12 |
| E605_1991_I302822 [66] | 38.8 GeV | pp | 11 |
| Total | | | 81 |

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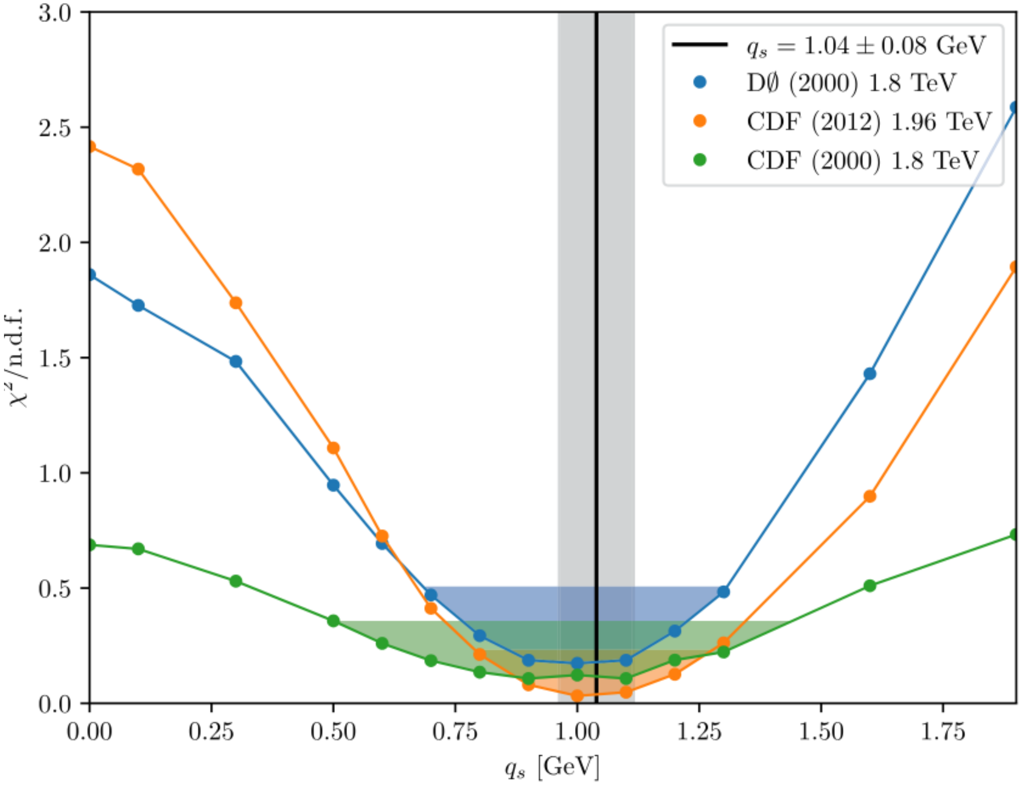
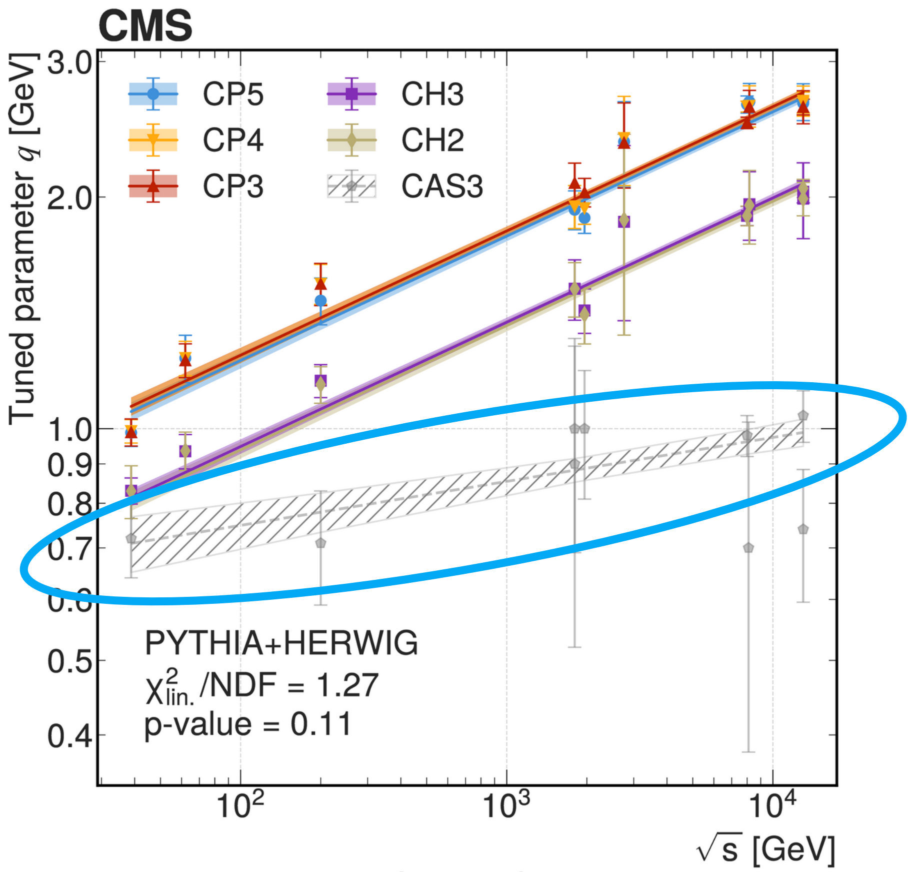


# Scaling

CMS suggests a scaling of $q_s$ w.r.t. $\sqrt{s}$

- Observed for Herwig and Pythia
- Our PB TMD fit is much more stable

**Why?**

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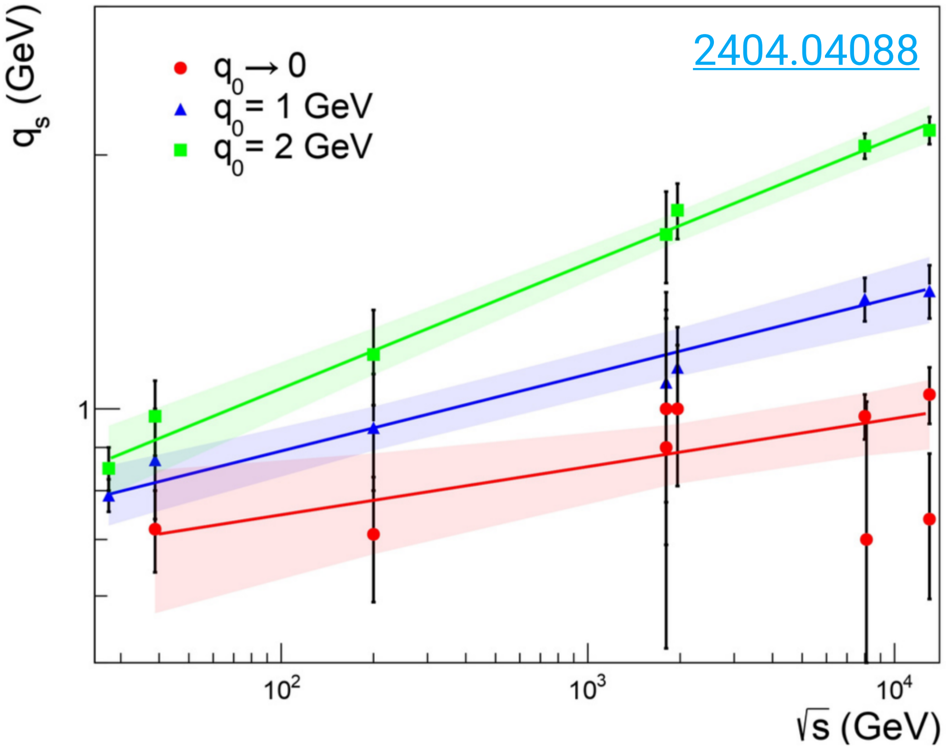
# Impact of $q_0$

Experiment to understand the effect:

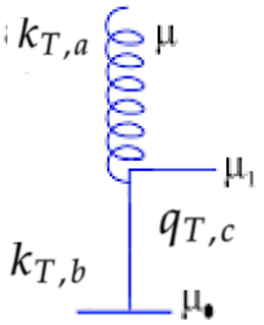
- Increase minimum branching scale $q_0$ in PB TMD (neglecting soft gluons < $q_0$)
- Extract $q_s$ vs $\sqrt{s}$ dependence
- Recovers the $q_s$ scaling seen by CMS!



# Discussion

Increasing $q_0$ leads to $\sqrt{s}$ dependence for intrinsic $k_T$

- Corresponds to making more branchings non-resolvable
- Thus making the non-perturbative Sudakov FF more important




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

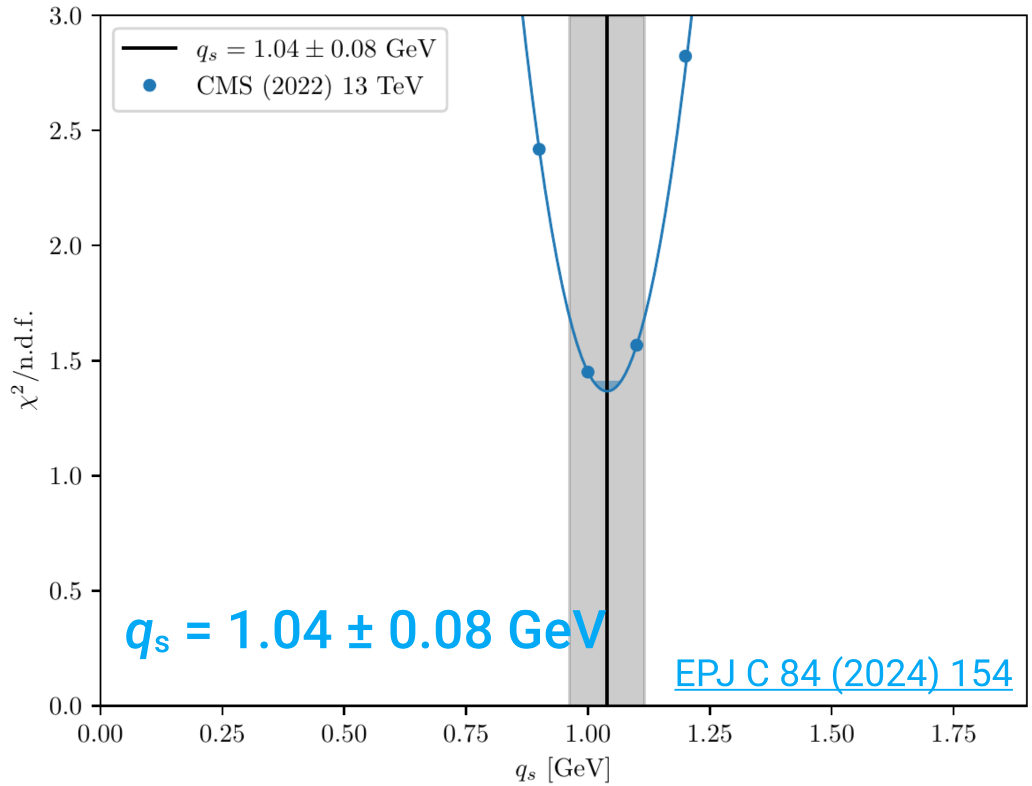
**Non-resolvable Sudakov FF ⇄ Collins-Soper kernels are essential for evolution, with measurable effects in high-energy DY data**

Neglecting them leads to artificial constrains on intrinsic $k_T$ and $\sqrt{s}$ dependence

# Summary

Parton Branching TMDs

- Implemented in the CASCADE general-purpose MC
- Successful description of LHC data




Extracted the "intrinsic $k_T$" parameter

- Mild $\sqrt{s}$ dependence observed
- Much less than parton showers 👍
- Governed by non-resolvable Sudakov FF ⇄ Collins-Soper kernel in evolution

# Thank you