Intrinsic k_T in Monte Carlo generators

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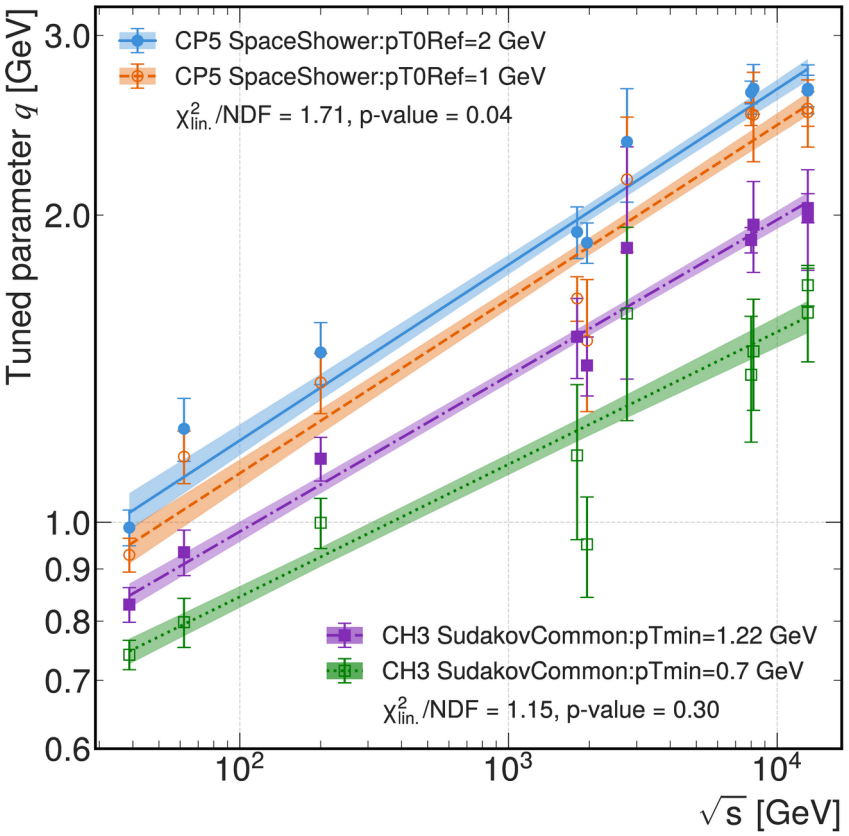
Intrinsic k_T in parton showers

- Most predictions for LHC experiments done with Pythia/Herwig
- They have an “initial” k_T parameter
- Inconsistent values depending on $\sqrt{s}$

TMDs provide a well-motivated framework to address this issue.

CMS-GEN-22-001



Intrinsic k_T from Drell-Yan measurements

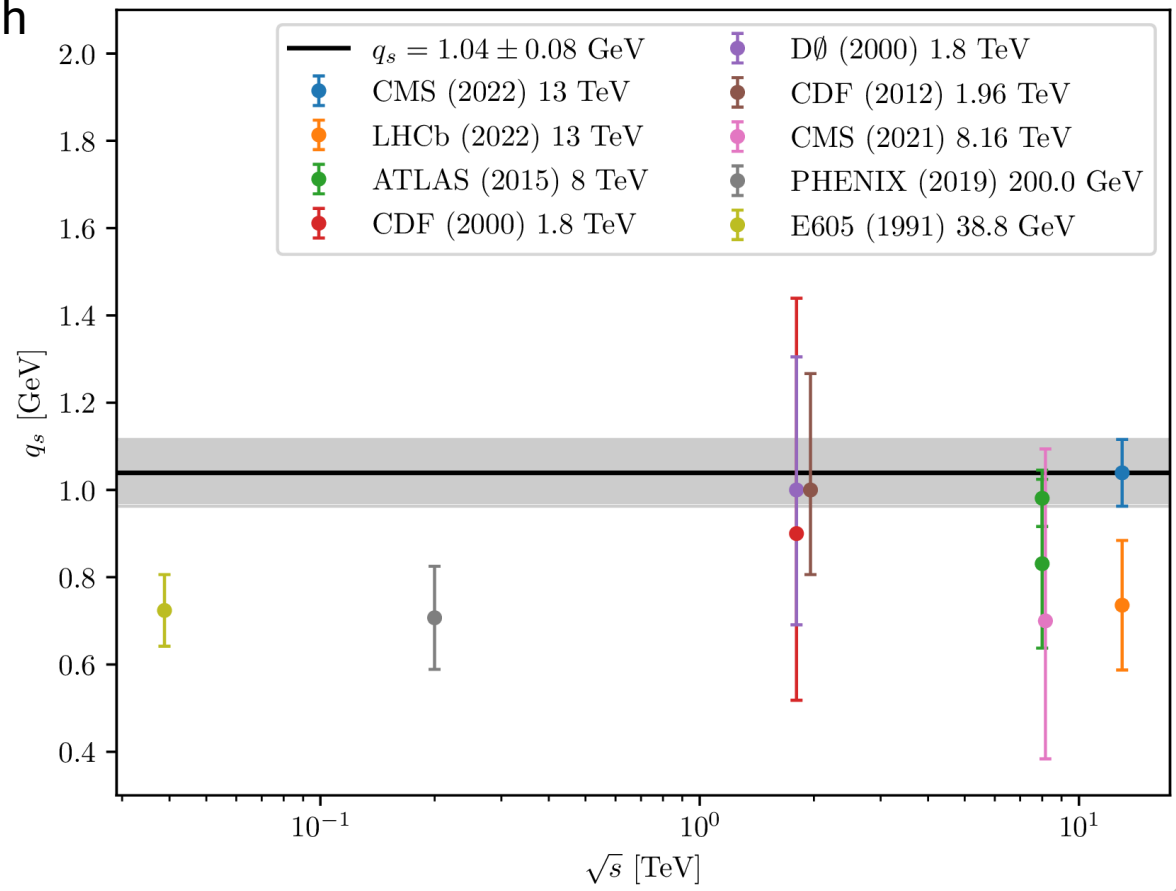
EPJ C 84 (2024) 154 (I. Bubanja, ..., LM, ...)

We use the parton branching approach

- Intrinsic k_T has a Gaussian distribution at low scale
- Only parameter:
  q_s = width of the distribution
- We obtained:

  q_s = (1.04 ± 0.08) GeV

  from PB TMD fit to CMS
  13 TeV data
- Consistent across experiments



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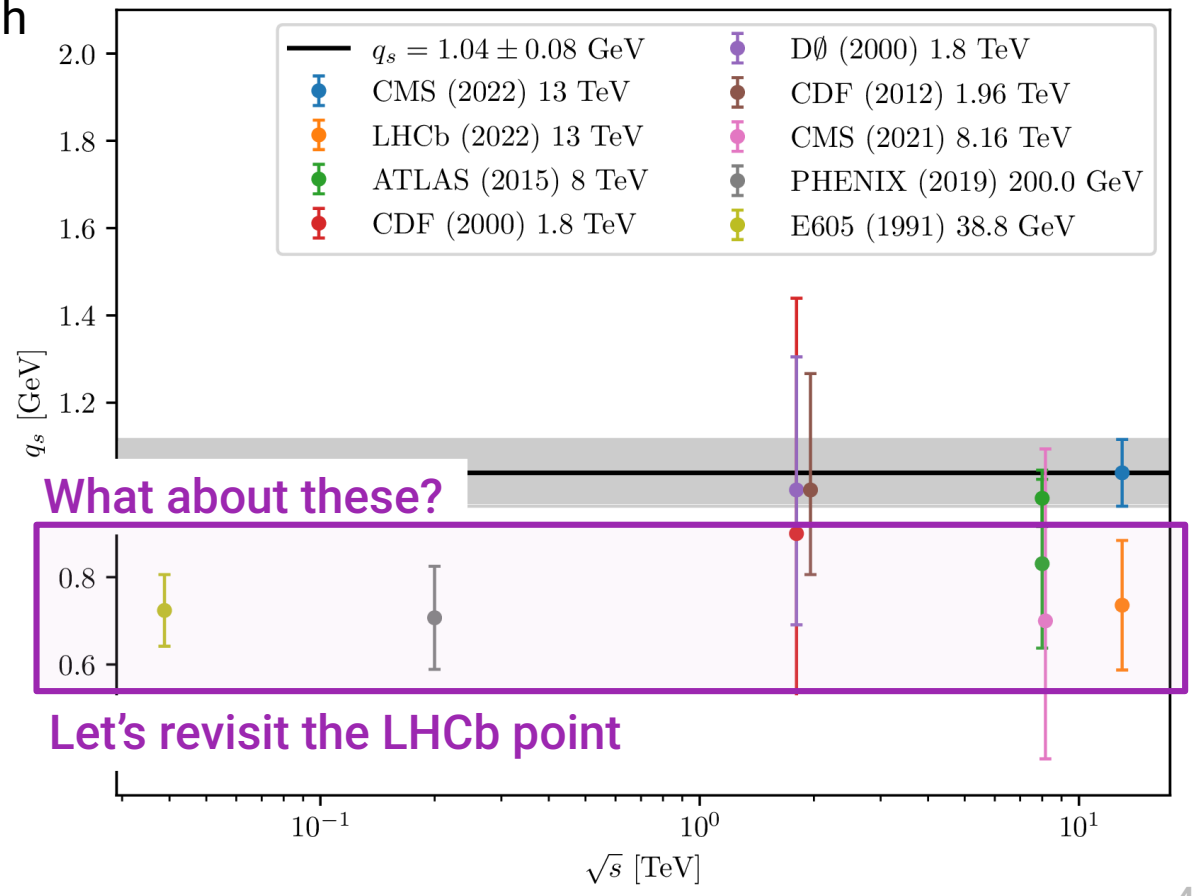
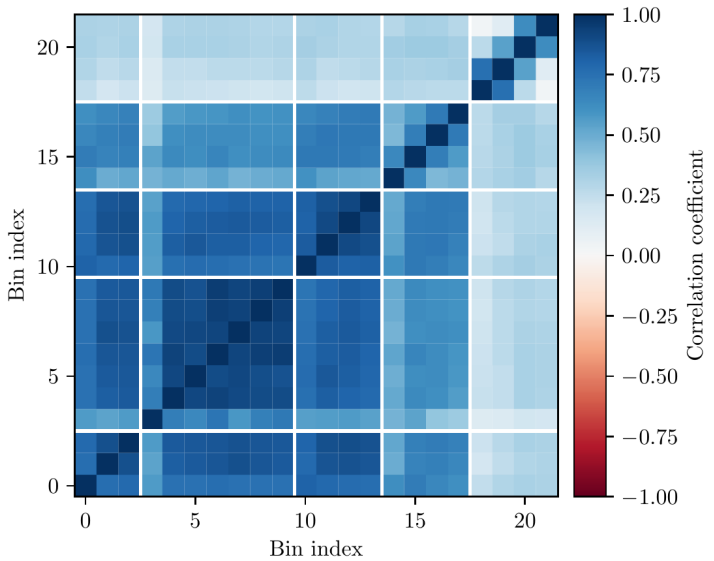


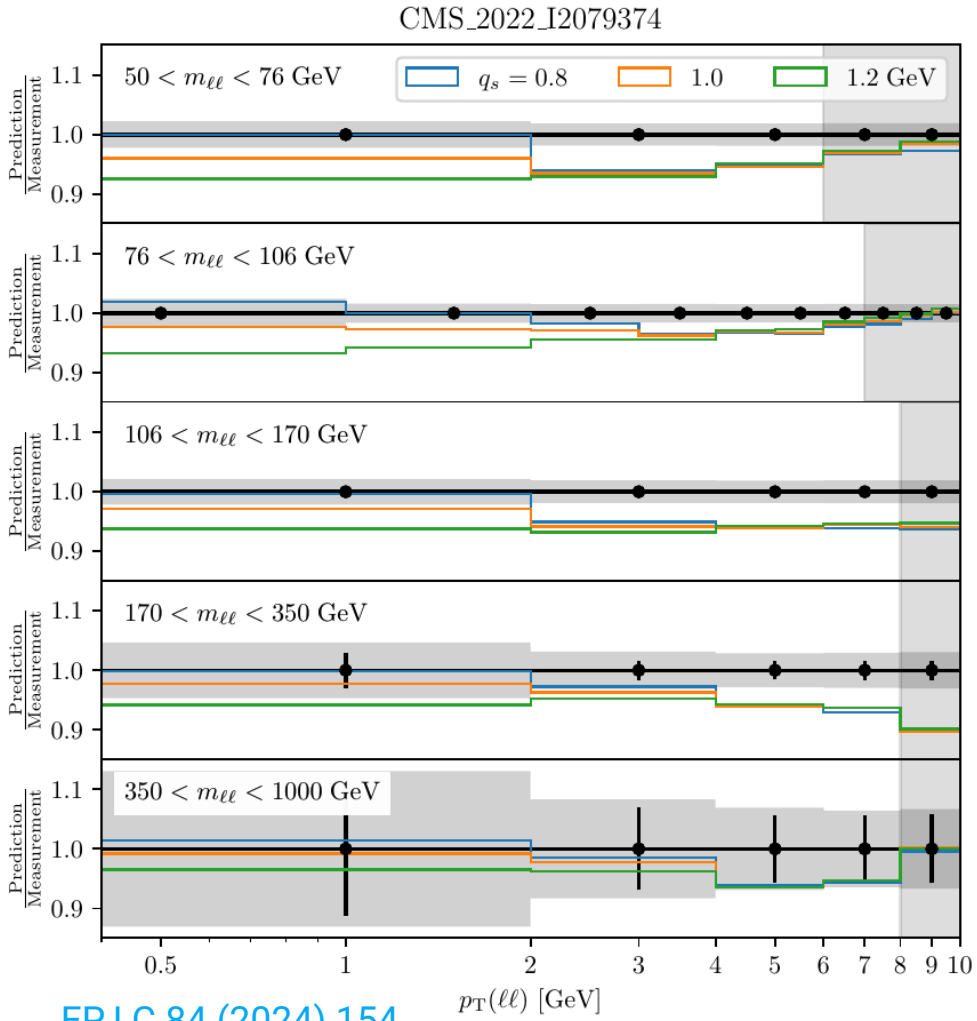
Recap of fit to CMS data

We used low-p_T Drell-Yan

Detailed fit taking the complete correlation matrix into account:



Simpler approach used for the LHCb point



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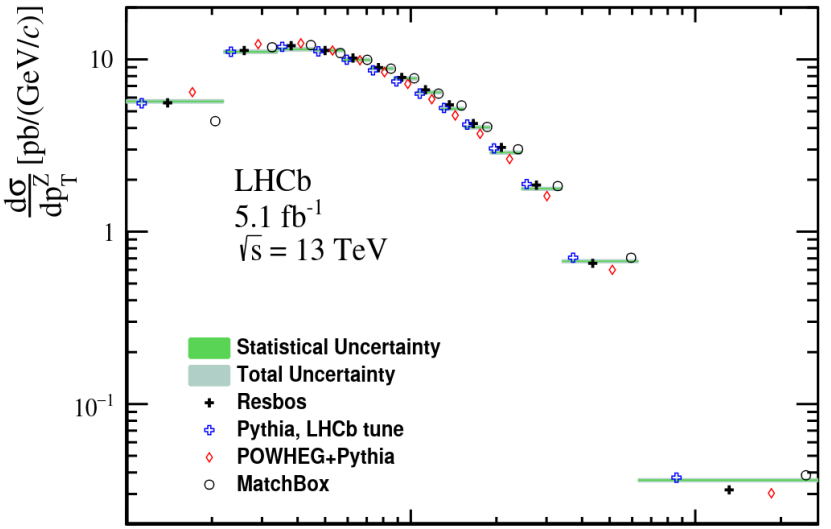
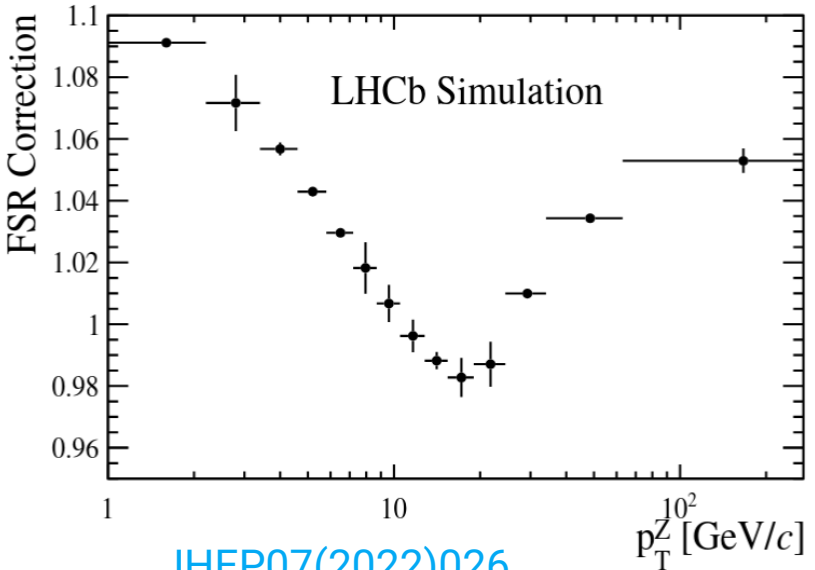
What LHCb provides

HepData record

- Total cross section
- Transverse momentum p_T: TMD effects
- Rapidity y: PDF effects
- 2D p_T—y: eventually we want to fit this
- Uncertainty breakdown
- Correlations for selected uncertainties

FSR correction:
Published results are at Born level





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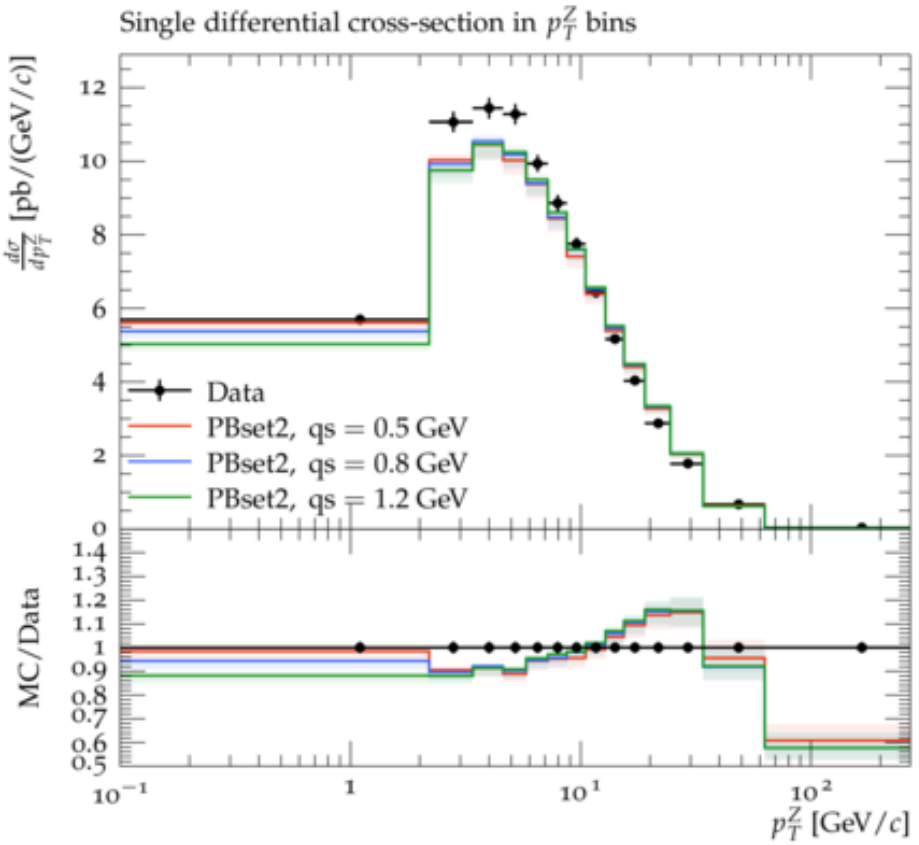
A first look



Comparing PB TMD predictions for **different q_s** to the data

In the TMD region (first bins):

- Good shape agreement
- Normalization is off

At higher Z p_T:

- Shoulder around 15 GeV
- Missing higher orders in the tail

Fitting procedure

We use a “simple” χ^2 metric: $\chi^2 = \sum_{i,j=1}^{d} (x_i - p_i)(C^{-1})_{ij}(x_j - p_j)$

data

prediction

covariance matrix

The covariance matrix accounts for experimental and theory uncertainties

Uncertainty	Treatment
Statistical	Correlation matrix from HepData
Efficiency	Correlation matrix from HepData
Luminosity	Full correlation
Alignment	Full correlation
Closure	Full correlation
Background	Uncorrelated
Unfolding	Uncorrelated
FSR	Uncorrelated

⊕ MC statistics ⊕ scale uncertainties

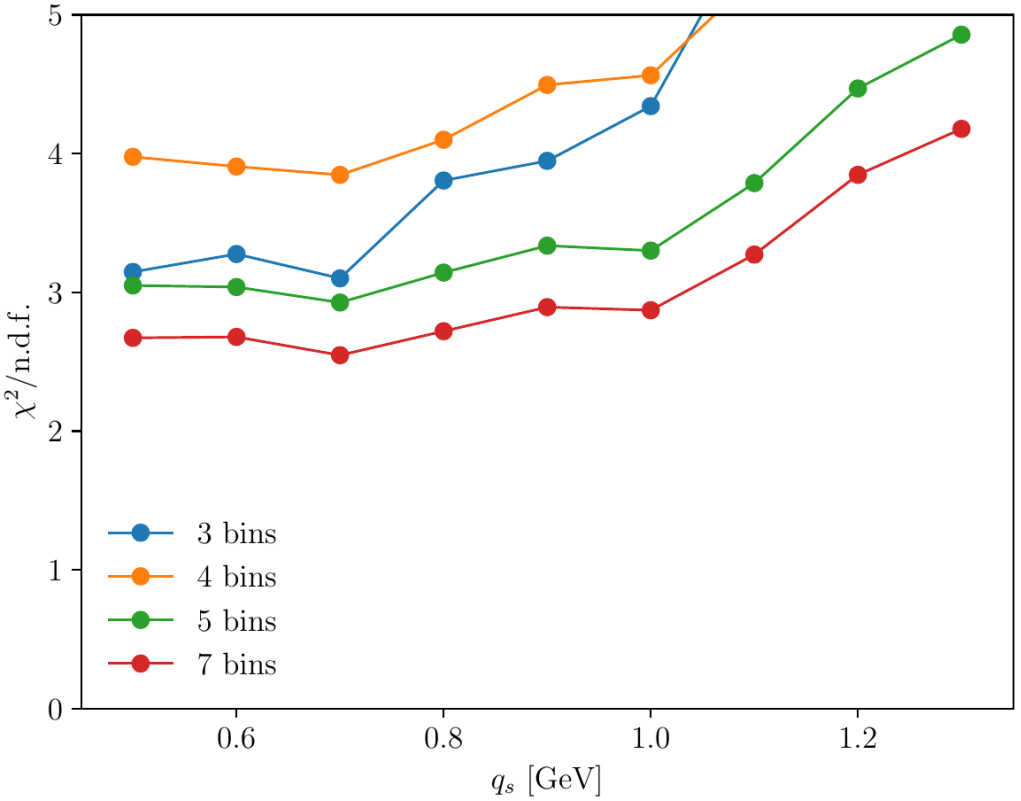
Then: find model parameters that minimize χ^2

- Extract $\hat{q}_s$ at the minimum
- Uncertainties from $\Delta\chi^2 = 1$

Fitting

We start by **neglecting correlations,** with **different numbers of bins.**

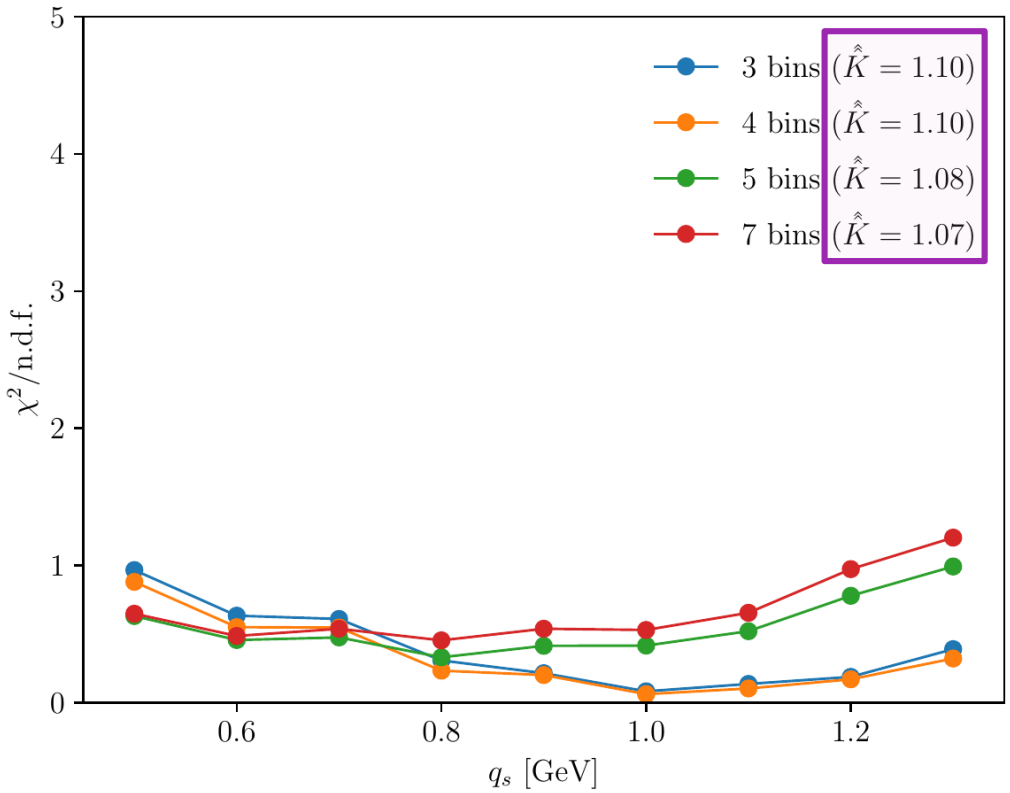
- Fit quality is OK
- q_s is not well constrained
- Let's improve this



Effect of normalization

Normalization is off at low p_T, so:

- Introduce a *k*-factor
- *Profile* it to find the best *k*-factor for each value of q_s
- Leads to very good agreement
- But little sensitivity



Correlations

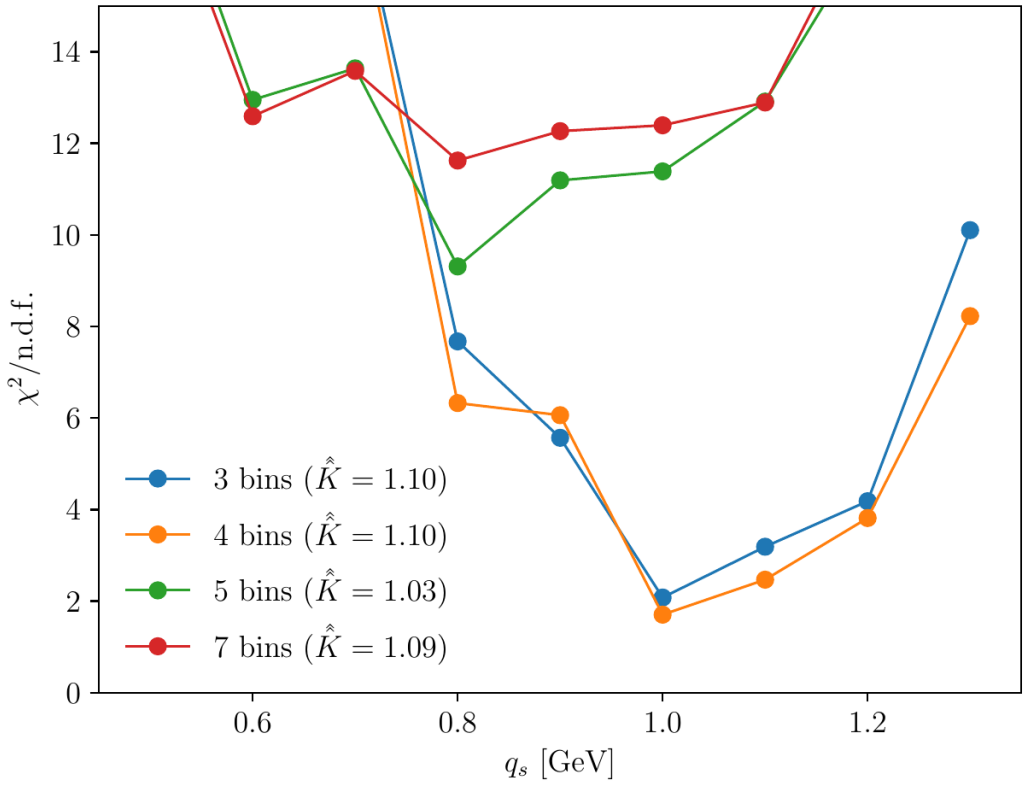
To gain sensitivity, account for correlations in the fit:

$$\chi^2 = \sum_{i,j=1}^{d} (x_i - p_i)(C^{-1})_{ij}(x_j - p_j)$$

Non-diagonal C

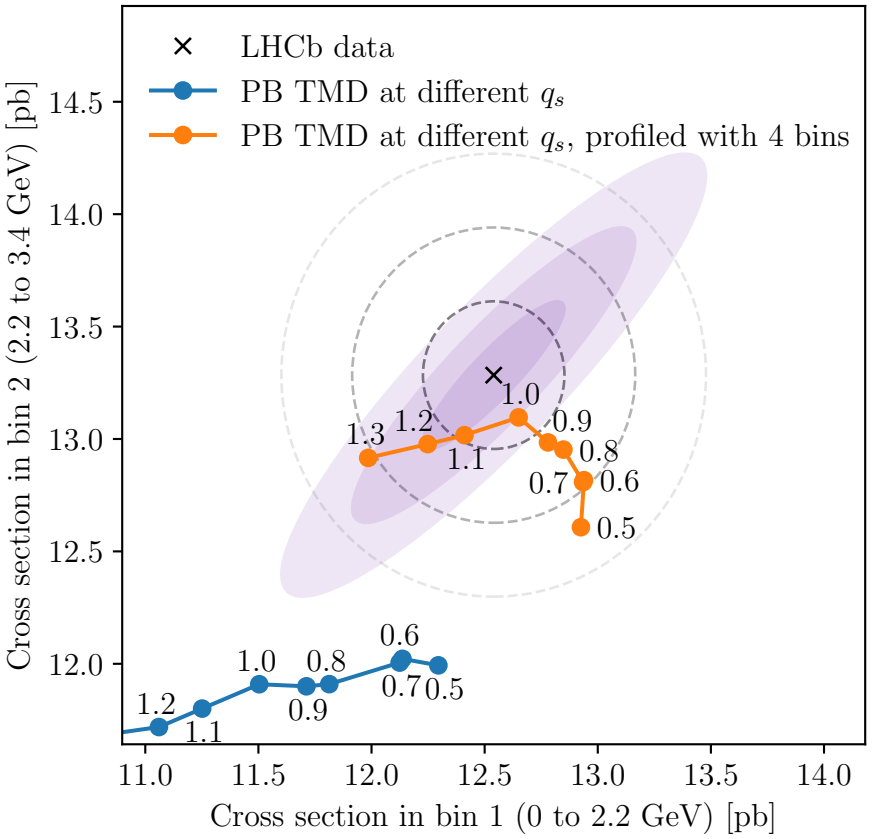
- Greatly improved sensitivity
- Bad fits for 5 and 7 bins

Our new baseline:
4 bins with correlations



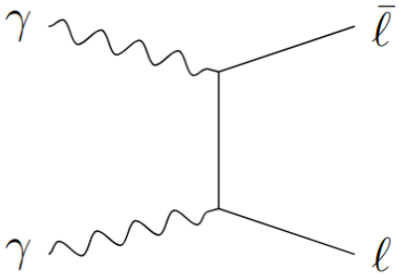
Why do correlations matter so much?

With multiple bins, we need to think of uncertainties in a multidimensional space



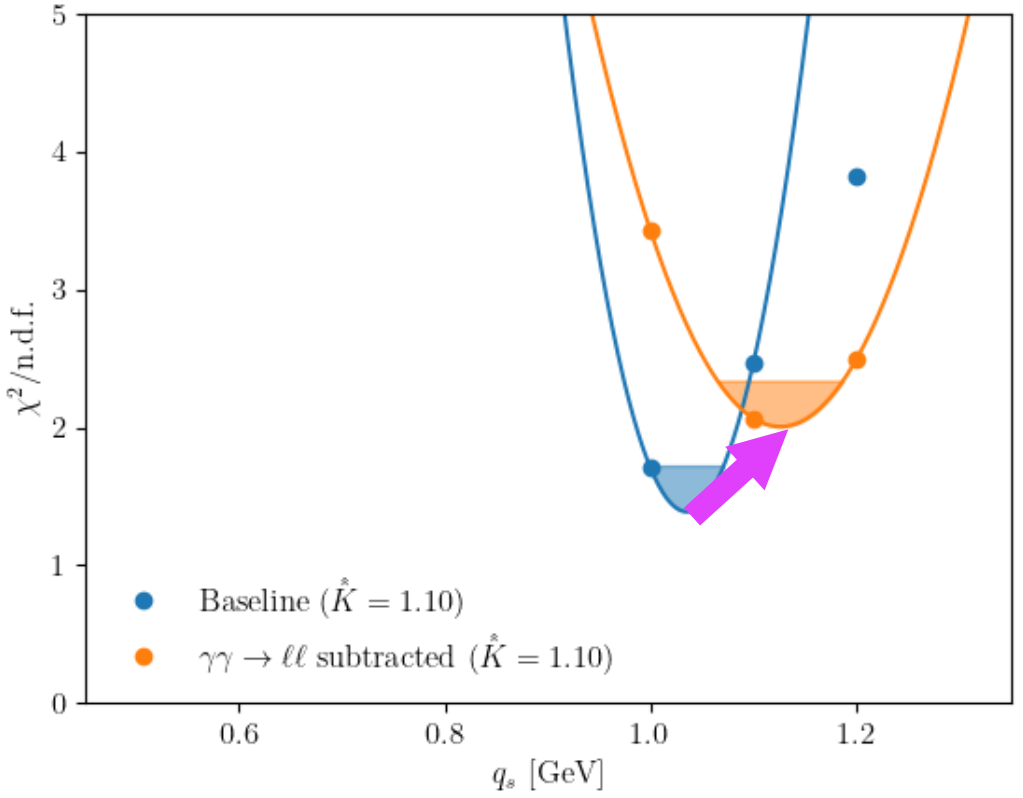
Other effects: Photon-induced background

LHCb neglected photon-induced lepton pair production:



Generate our own sample and subtract it from the measurement

➔ **q_s shifts by 1σ to the right!**

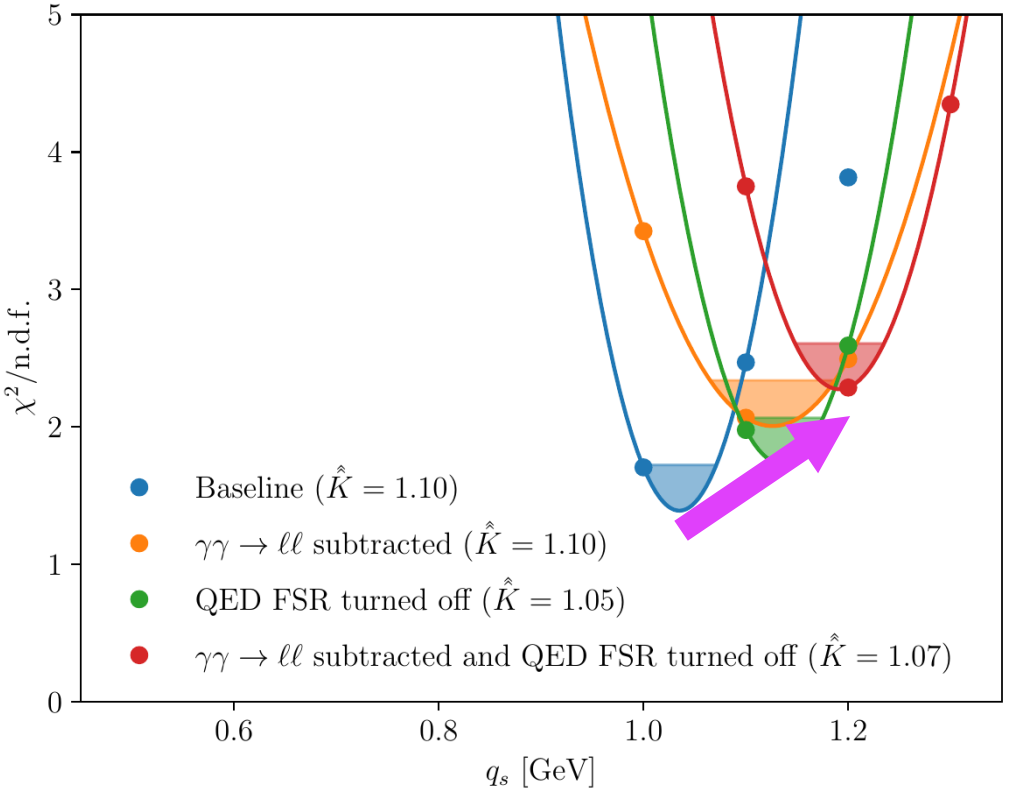


Other effects: QED final-state radiation

The LHCb results are unfolded to Born level ➔ corrected for QED FSR

Our baseline prediction includes QED FSR ➔ disable it...

➔ q_s moves again! **Now 3σ to the right!**



Other effects: Matching to matrix element

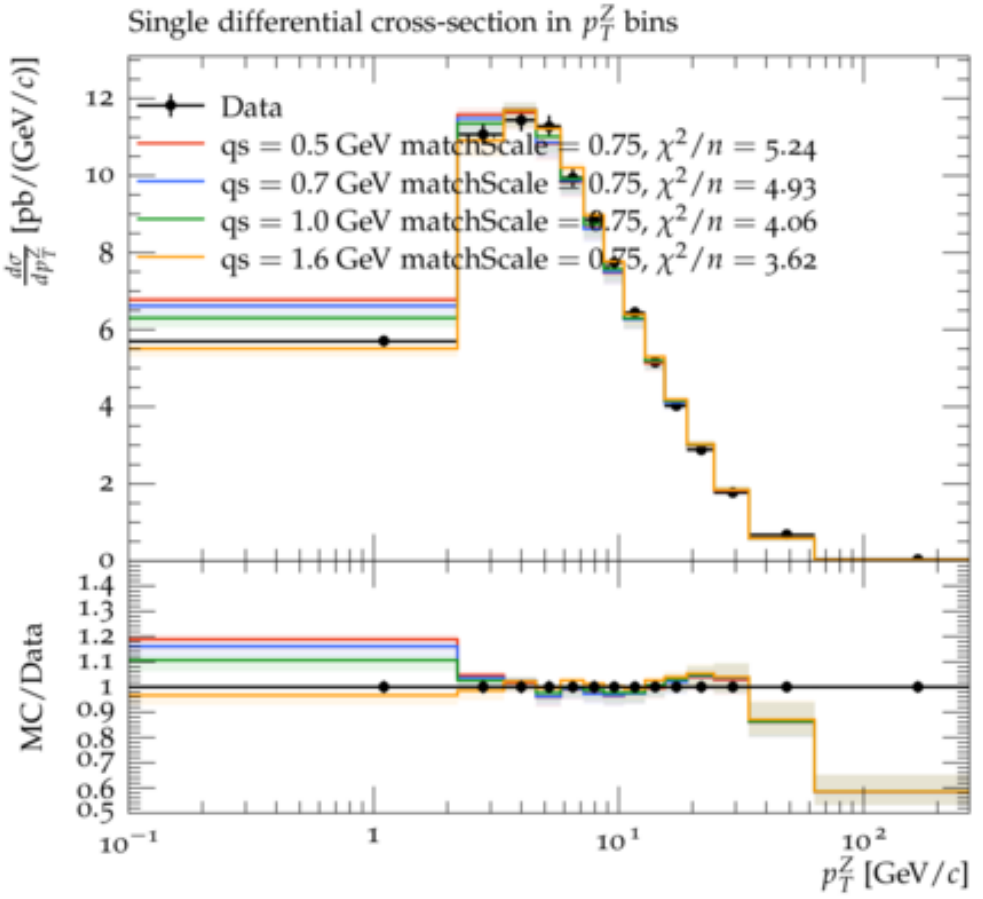
We had a shape disagreement at high p_T

Can we fix it?
Does it affect q_s?

➔ Change the matching scale

➔ Greatly improved agreement

➔ **Much larger q_s (1.6 GeV)!**

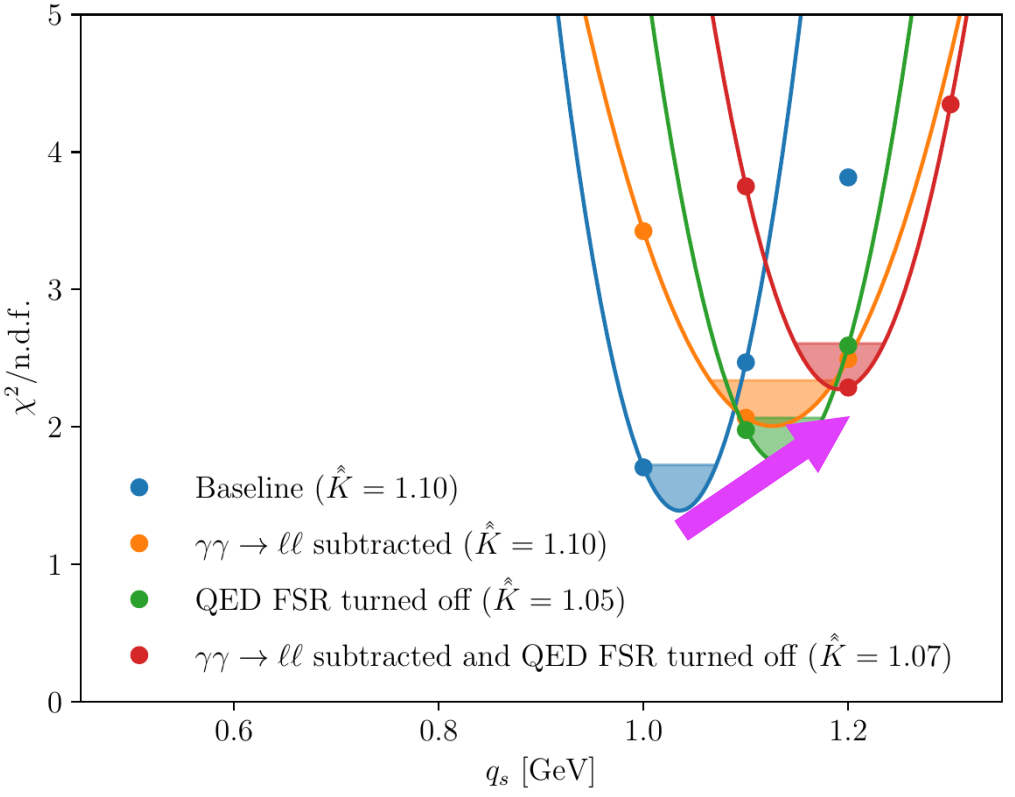


Conclusion

LHC measurements already greatly constain TMD models.

Even QED effects are larger than data uncertainties!

We call for:

- Full clarity in the phase space description by experiments
- Caution when fitting

What can we learn from PDF fitters?