From factorization to proton tomography: direct determination of the rapidity anomalous dimension.

Low-x Workshop 2023

08.09.2023

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Based on the recent work:

Phys.Rev.D 106 (2022) 9, L091501

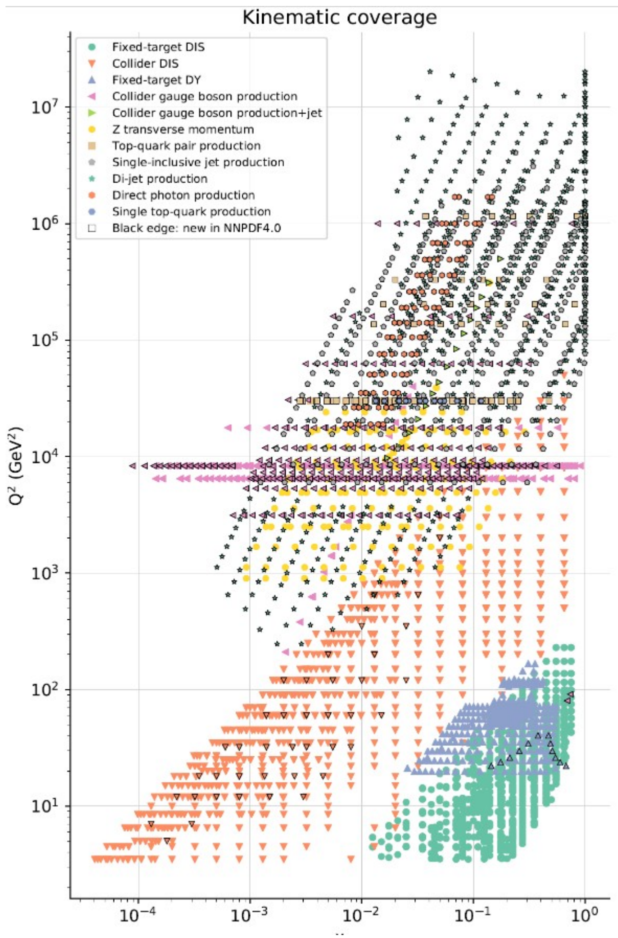
arXiv:2307.06704

https://www.desy.de/f/students/2022/reports/David.Gutierrez.pdf

Motivation

Motivation: factorization

recall Amanda's talk



The HERA data are the 'backbone of all PDF fits

BUT what could HERA not do?
High-x gluon and sea flavour detail s,c
What other data can we use?

- Drell-Yan data from fixed target DIS and the Tevatron and LHC
- W,Z rapidity spectra from Tevatron and LHC
- Jet pT spectra from Tevatron and LHC
- Top-anti-top differential cross-sections from LHC
- W and Z +jet spectra, or Z pt spectra from LHC
- W and Z +heavy flavours from LHC

- Beware: there may be new physics at high scale that we 'fit away'
- Further warning, this additional information comes from many different groups– often there is no clarity on the correlations of experimental systematic uncertainties between differing LHC

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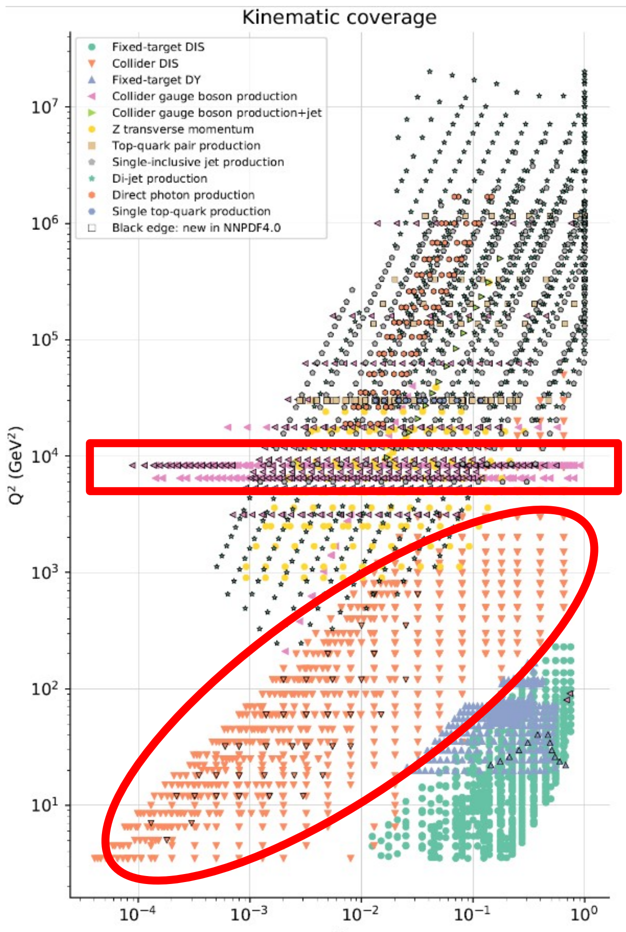

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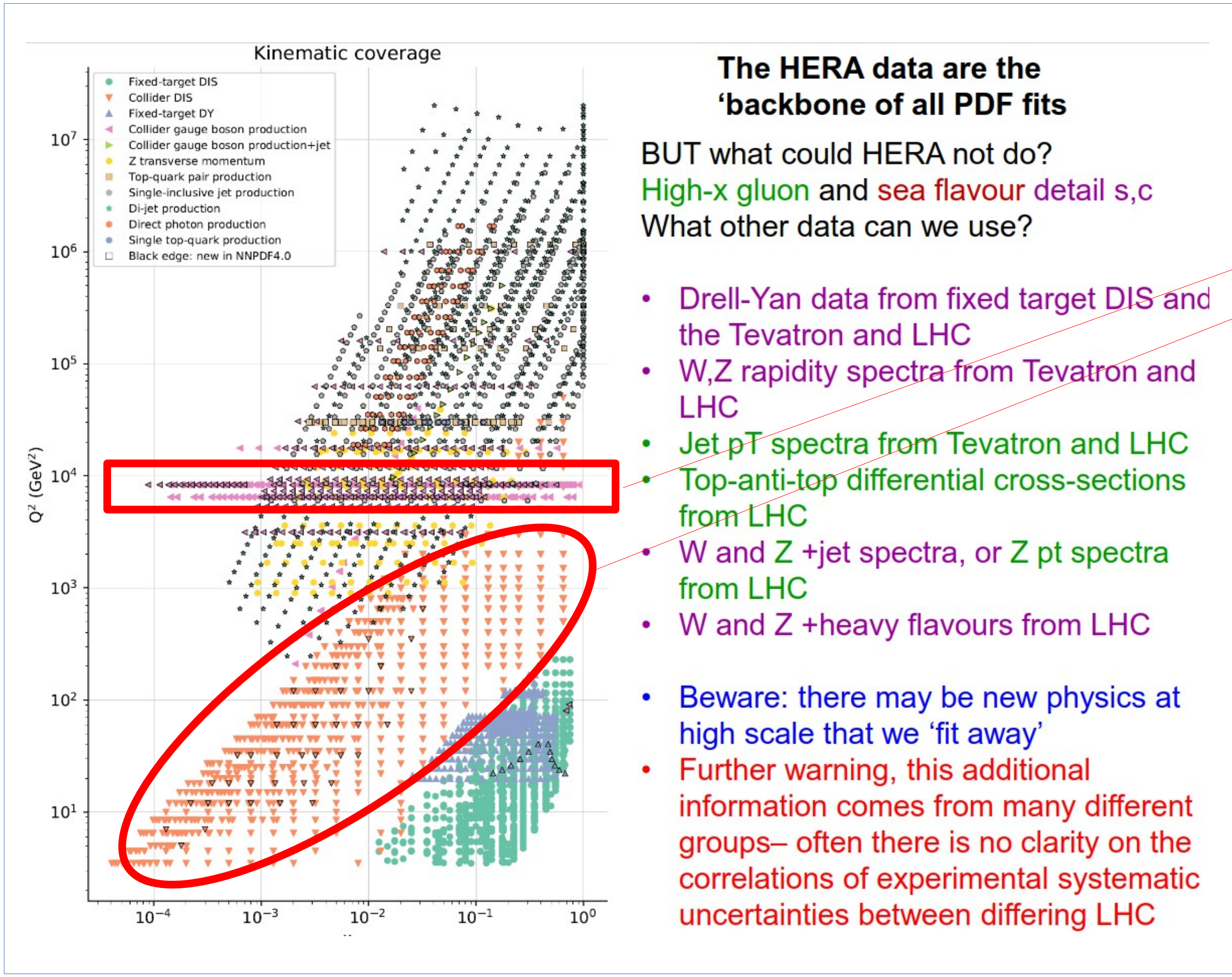

Proven factorization for sufficiently inclusive observables

This is a very small fraction of observables we measure

Up to what extend is this correct?

Are we fitting away breaking effects, NP?

Motivation: factorization

Imagine the case in which factorization dictates:

$$\sigma_1 = H_1 \times PDF(x\ range;\ \mu_1)$$

$$\sigma_2 = H_2 \times PDF(x\ range;\ \mu_2)$$

And now assume it also dictates:

$$PDF(x\ range;\ \mu_2) = PDF(x\ range;\ \mu_1)\ \mathbf{x\ R}$$

It would meant we could construct the observable:

$$\mathbf{R} \propto \sigma_2/\sigma_1$$

- R would depend neither on the scale choices, x range, PDF, nor on the process → clear way of testing factorization

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And now assume it also dictates:

$$PDF(x \text{ range}; \mu_2) = PDF(x \text{ range}; \mu_1) \times \mathbf{R}$$

It would meant we could construct the observable:

RAD hidden in here ← $\mathbf{R} \propto \sigma_2/\sigma_1$

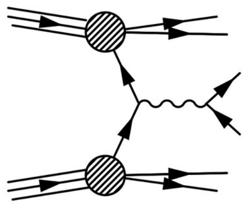
- R would depend neither on the scale choices, x range, PDF, nor on the process → clear way of testing factorization

  This case scenario exists in Drell Yan, at low transverse momentum

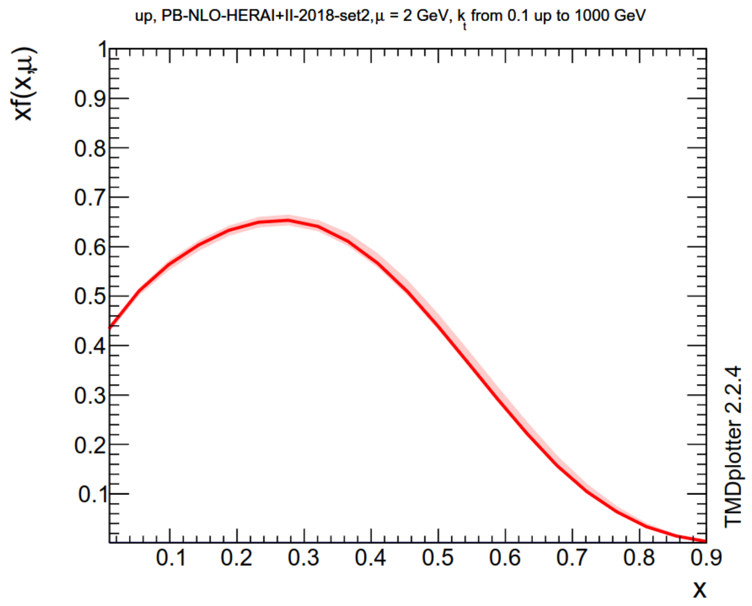
Motivation: nucleon tomography

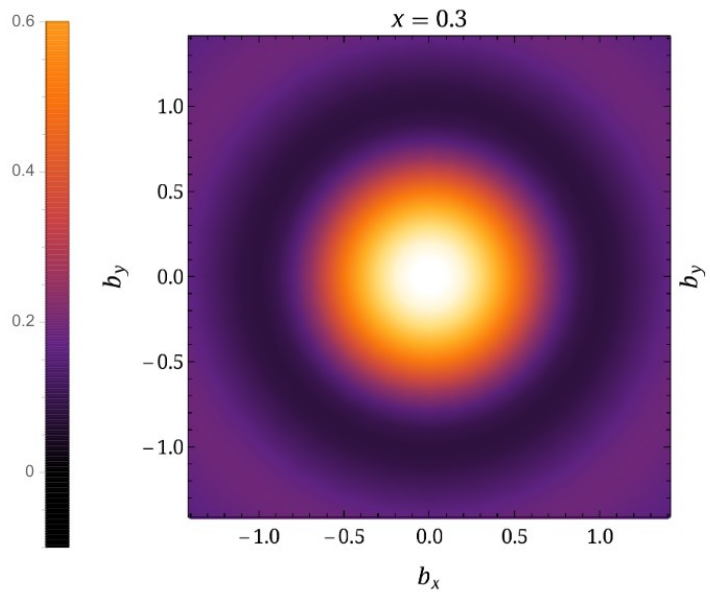
- Modern factorization theorems separate the hadron structure from the low distance hard scattering

$$\frac{d\sigma}{dp_T} = \sigma_0 \int \frac{d^2b}{(2\pi)^2} e^{i(bp_T)} C\left(\frac{Q}{\mu}\right) F_1(x_1, b; \mu, \zeta) F_2(x_2, b; \mu, \zeta)$$



- More complete description, going beyond the simplest 1D parton structure





Phys.Rev.Lett. 127 (2021) 18, 182001

Motivation: nucleon tomography

- A new function emerges and it dictates the evolution of the parton distributions:

$$\frac{df_{q,h}(x,b;\mu,\zeta)}{d\ln\mu^2} = \frac{\gamma_F(\mu,\zeta)}{2} f_{q,h}(x,b;\mu,\zeta),$$

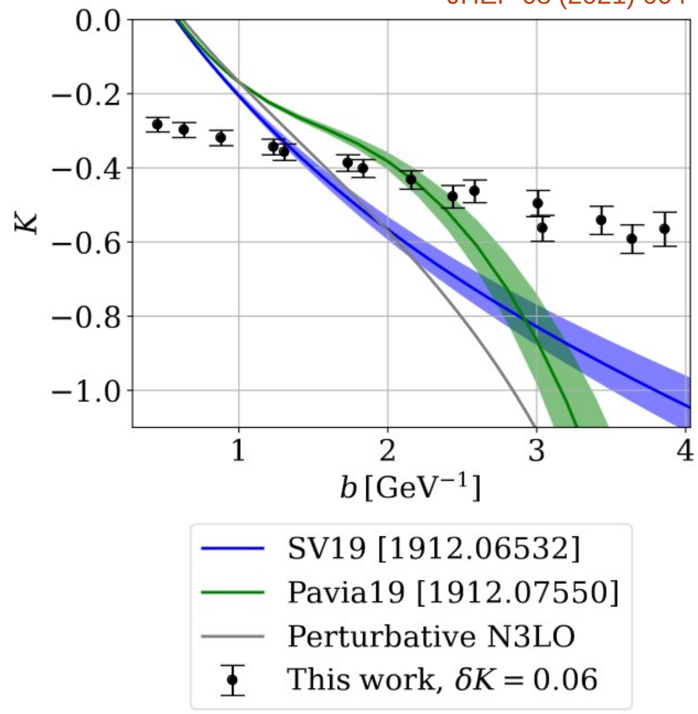
$$\frac{df_{q,h}(x,b;\mu,\zeta)}{d\ln\zeta} = -\boxed{\mathcal{D}(b,\mu)} f_{q,h}(x,b;\mu,\zeta).$$

- It is a self-contained object with new non-perturbative information

Phys. Rev. Lett. 125, 192002 (2020)

- Exclusively sensitive to QCD vacuum
  - RAD has been studied extensively
  - Yet, only QCD function which is largely unknown

JHEP 08 (2021) 004



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- Exclusively sensitive to QCD vacuum
- **A direct measurement of RAD would imply:**
  - Stringent test of factorization and universality of the TMDs
  - Higher precision imaging of hadrons
  - Higher precision for measurements, e.g W mass
  - Input to probe parton spin-orbit correlations
  - information on confinement and hadronization

…

Novel method to determine RAD

Phys.Rev.D 106 (2022) 9, L091501

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- Start from the factorization formula:

$$\frac{d\sigma}{dQ^2 dy dq_T^2} = \frac{2\pi}{9}\frac{\alpha_{\rm em}^2(Q)}{sQ^2} W_{f_1 f_2}(x_1, x_2, Q, q_T),$$

- Apply the inverse Hankel transform:

$$\Sigma(y, Q; b) = \frac{2\pi}{9}\frac{\alpha_{\rm em}^2(Q)}{sQ^2}|C_V(Q)|^2 \sum_q e_q^2 f_{q_1}(x_1, b; Q, Q^2) f_{q_2}(x_2, b; Q, Q^2)$$

- Evolve the parton distribution to a reference scale:

$$\Sigma(y, Q; b) = \frac{2\pi}{9}\frac{\alpha_{\rm em}^2(Q)}{sQ^2}|C_V(Q)|^2 e^{2\Delta(b; Q\to(\mu_0,\zeta_0))} \sum_q e_q^2 f_{q_1}(x_1, b; \mu_0, \zeta_0) f_{q_2}(x_2, b; \mu_0, \zeta_0)$$

disposable

the target

- Build ratios of the cross sections at different scales:

$$\frac{\Sigma_1}{\Sigma_2} = \frac{\frac{\alpha_{\rm em}^2(Q_1)}{s_1 Q_1^2}|C_V(Q_1)|^2 e^{2\Delta(b; Q_1\to(\mu_0,\zeta_0))}}{\frac{\alpha_{\rm em}^2(Q_2)}{s_2 Q_2^2}|C_V(Q_2)|^2 e^{2\Delta(b; Q_2\to(\mu_0,\zeta_0))}} \frac{\sum e_q^2 f_{q_1}(x_1, b; \mu_0, \zeta_0) f_{q_2}(x_2, b; \mu_0, \zeta_0)}{\sum e_q^2 f_{q_1}(x_1, b; \mu_0, \zeta_0) f_{q_2}(x_2, b; \mu_0, \zeta_0)}$$

Novel method to determine RAD

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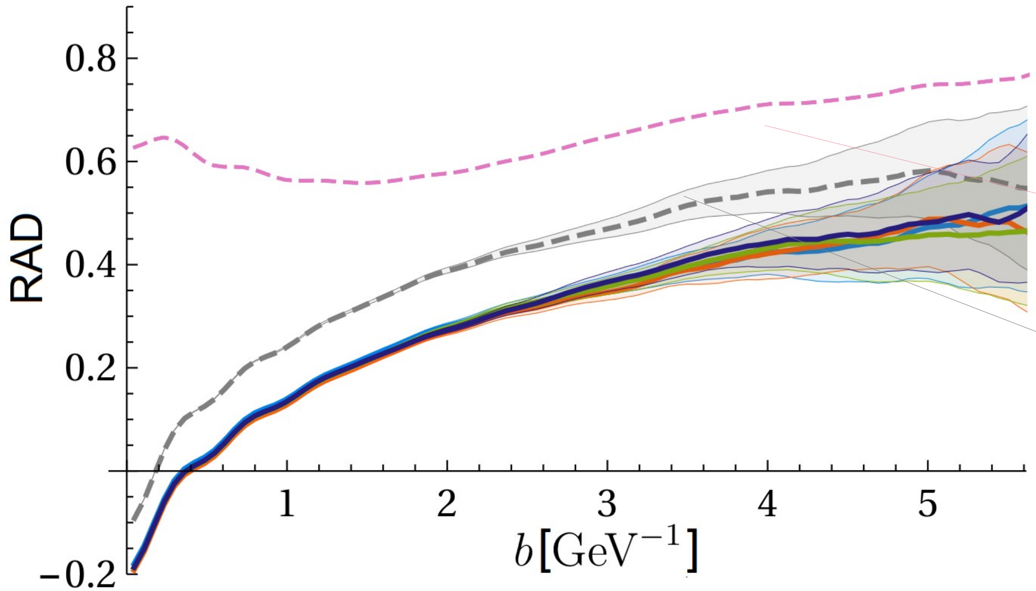
- We get the master formula:

$$\mathcal{D}(b,\mu_0) = \frac{\ln\left(\frac{\Sigma_1}{\Sigma_2}\right) - \ln Z(Q_1,Q_2) - 2\Delta_R(Q_1,Q_2;\mu_0)}{4\ln(Q_2/Q_1)} - 1$$

measurement — perturbative terms

- Things to remember:
  - No dependence on the chosen scales
  - No dependence on process
  - Cancellation of the longitudinal part



Clear test of factorization premise

Different x range

Different PDF

Applying the method to simulated data

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Applying the method to simulated data

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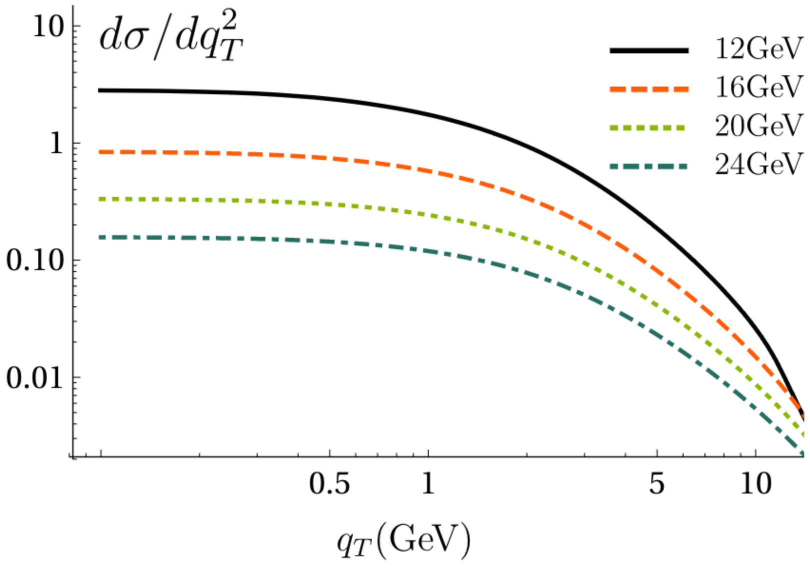
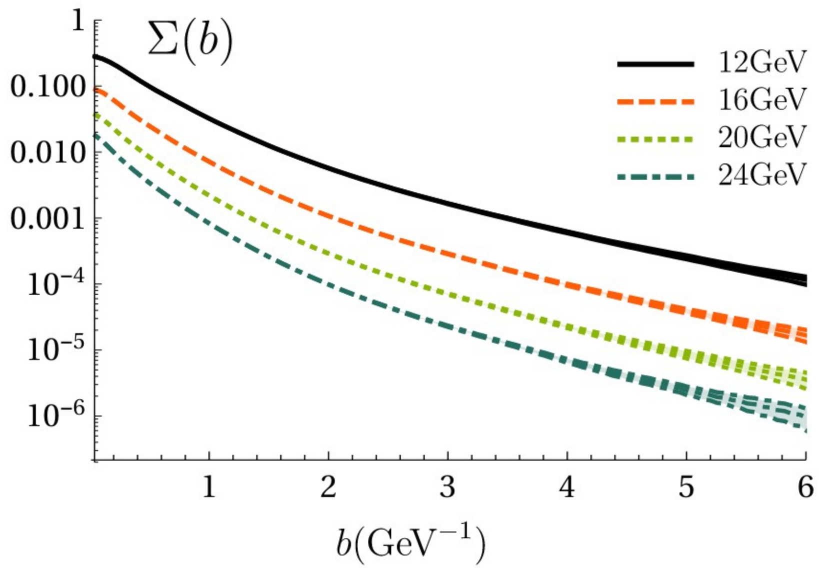
- Master formula can be used with data, provided:
  - small q_T and Q bin sizes
  - choices of y, Q and center-of-mass energy ensure same x range
  - Q below Z peak
- Simulation using the CASCADE MC generator:



Inverse Hankel



Applying the method to simulated data

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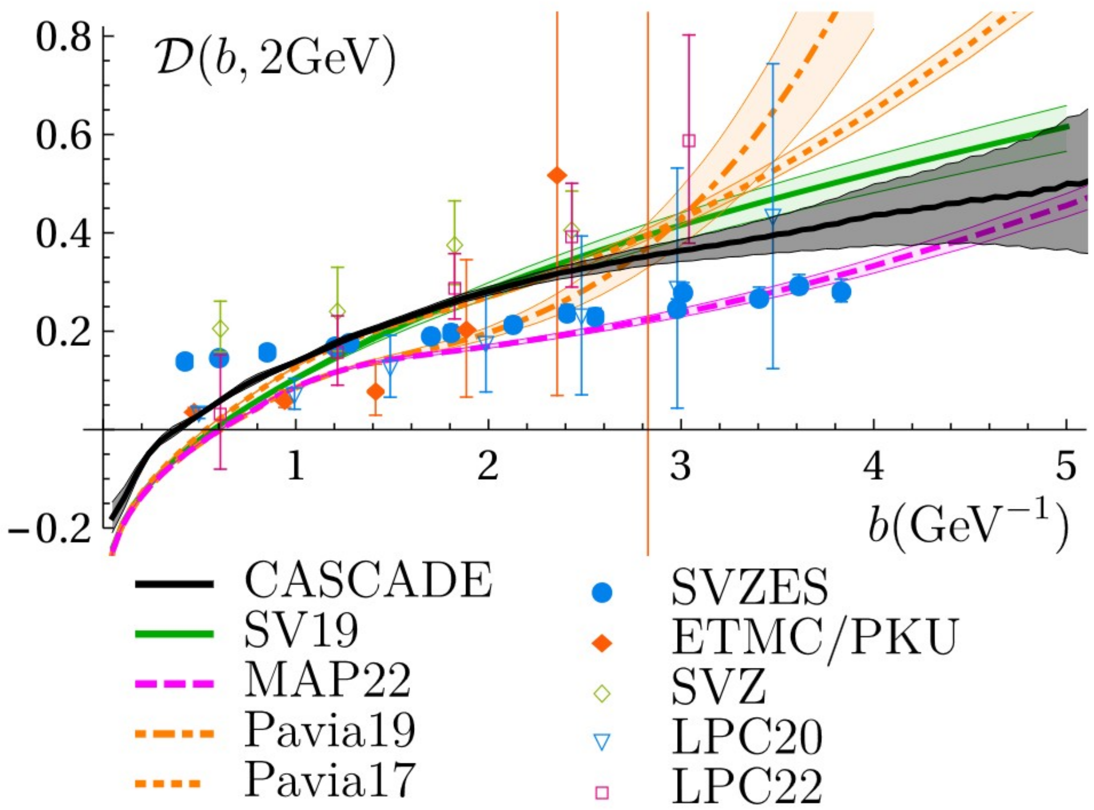
- All properties of RAD, like universality, are observed for the PB approach
- This non-trivially supports both factorization and PB approaches, sets the stage for a comparison
- The method can be applied to the experimental data!



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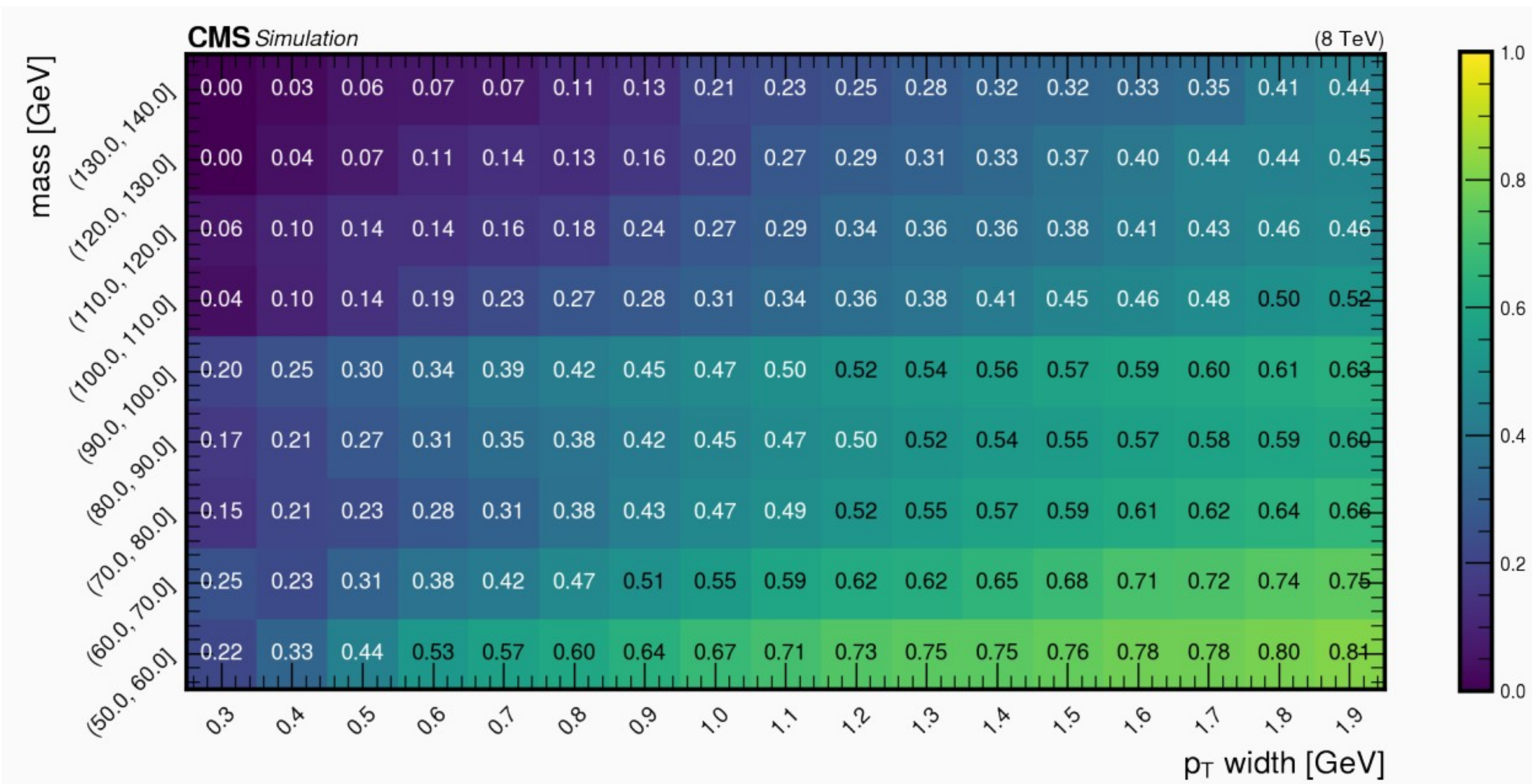
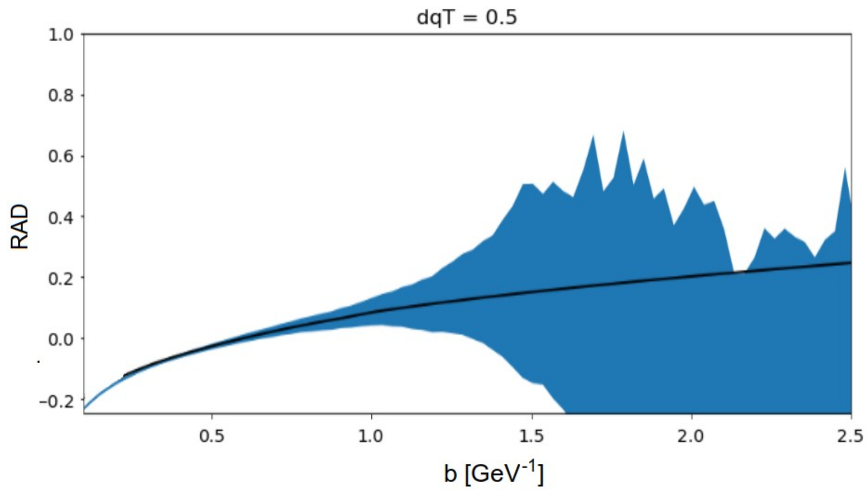
- CMS provides a excellent muon capabilities
- High quality data at 7, 8, 13, 13.5 TeV
- Feasibility studies on the di-muon resolution show promising results:

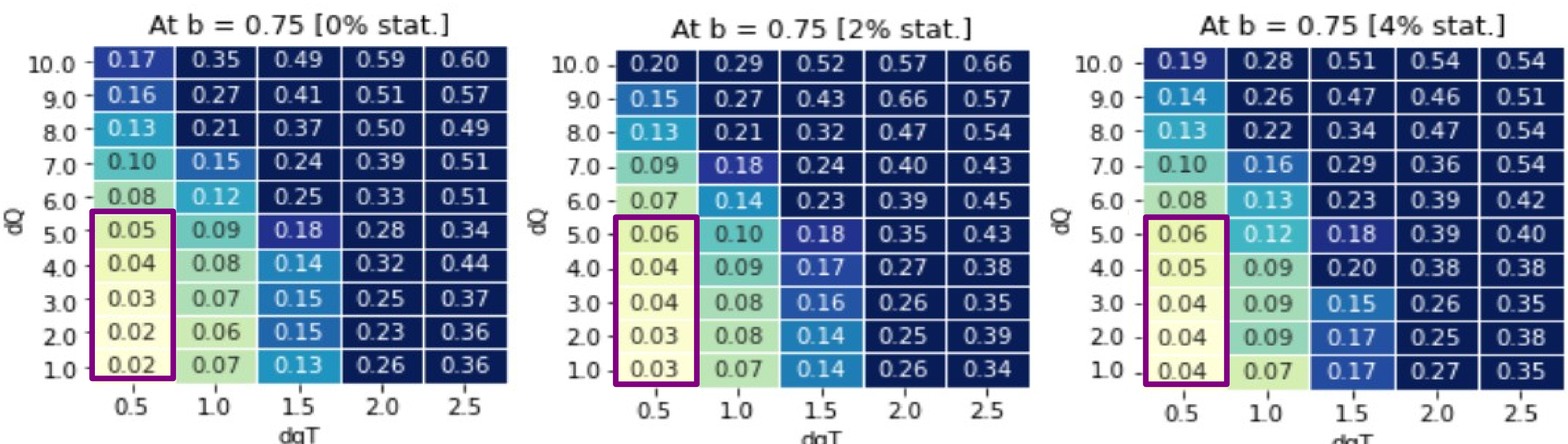


Applying the method to **experimental** data

- As an example Q1, Q2 = 28, 46 GeV
- Small q_T bin size ensure sensitivity up to around b = 1.5



- Adding statistical and dQ uncertainties:



- Statistical uncertainty mild, main uncertainty from q_T binning

Applying the method to transform PB TMDs to CSS

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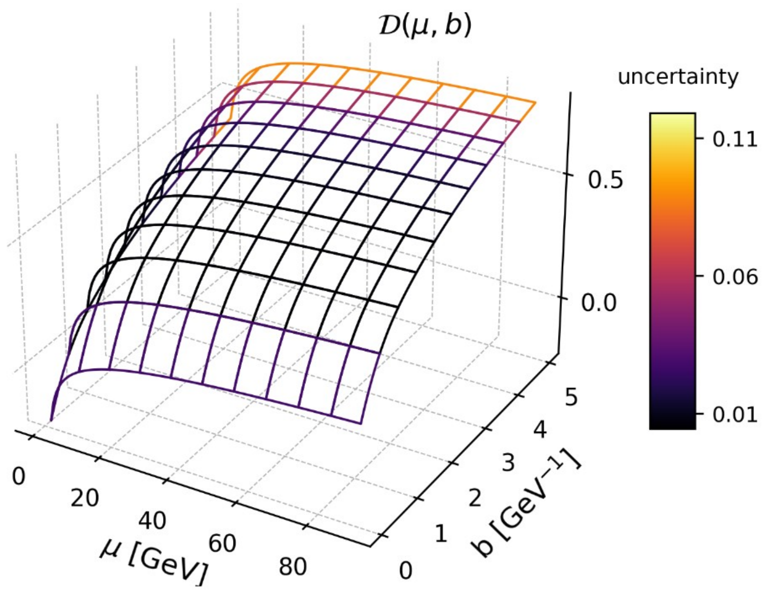
- This is a long standing problem
- Evolution of a TMD can be expressed as:

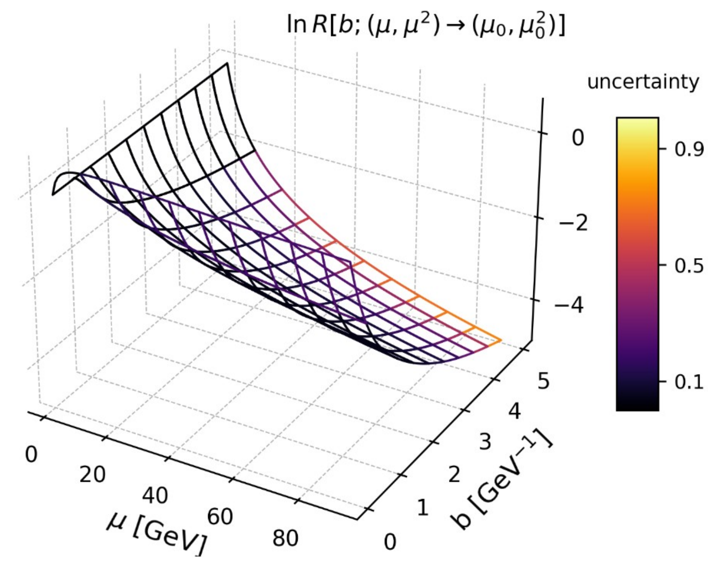
Evolution factor

$$F(x, b; \mu, \zeta) = R[b; (\mu, \zeta) \to (\mu_0, \zeta_0)] F(x, b)$$

- $$R[b; (\mu, \mu^2) \to (\mu_0, \mu_0^2)] = \exp\left\{ -\int_{\mu_0}^{\mu} \frac{d\mu'}{\mu'} (2\mathcal{D}(\mu', b) + \gamma_V(\mu')) \right\}$$

- We use the method to determine RAD from DY in CASCADE:





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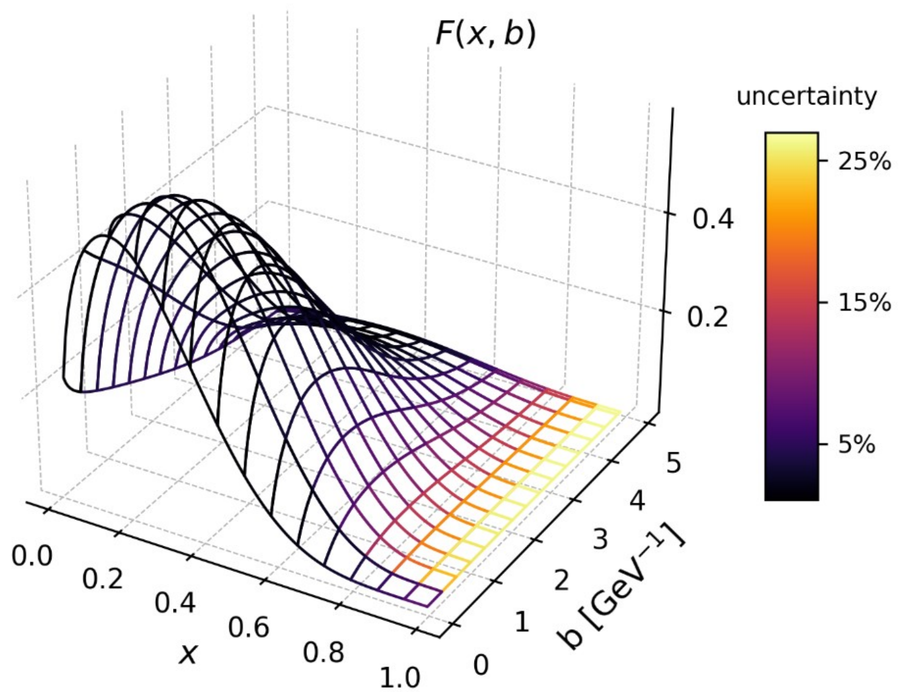
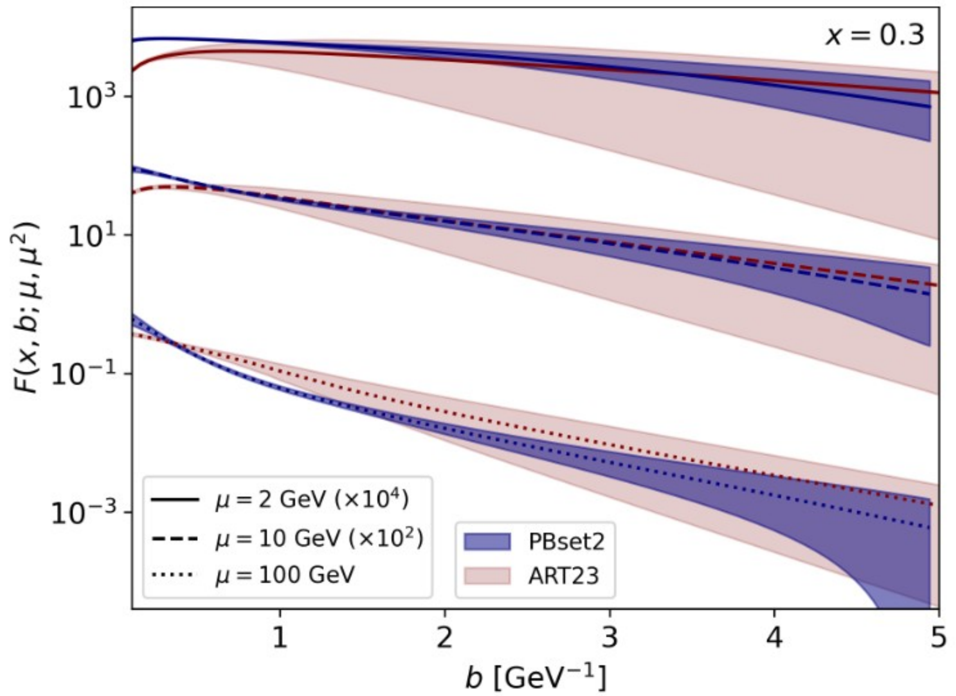
Evolution factor

- Comparing PB TMD set2 to MAPP22





Summary and conclusions

- Determination of RAD would be a stringent test of factorization and can have a deep impact on hadron 3D imaging
- Novel method to determine RAD was introduced
- Its application to simulated data from PB approach has solved long standing problem of comparison between factorization and PB
- Feasibility studies using CMS full simulated public data have shown promising results