Direct determination of the rapidity anomalous dimension. Experimental and phenomenological applications.

European Physical Society Conference on High Energy Physics 2023

21.08.2023

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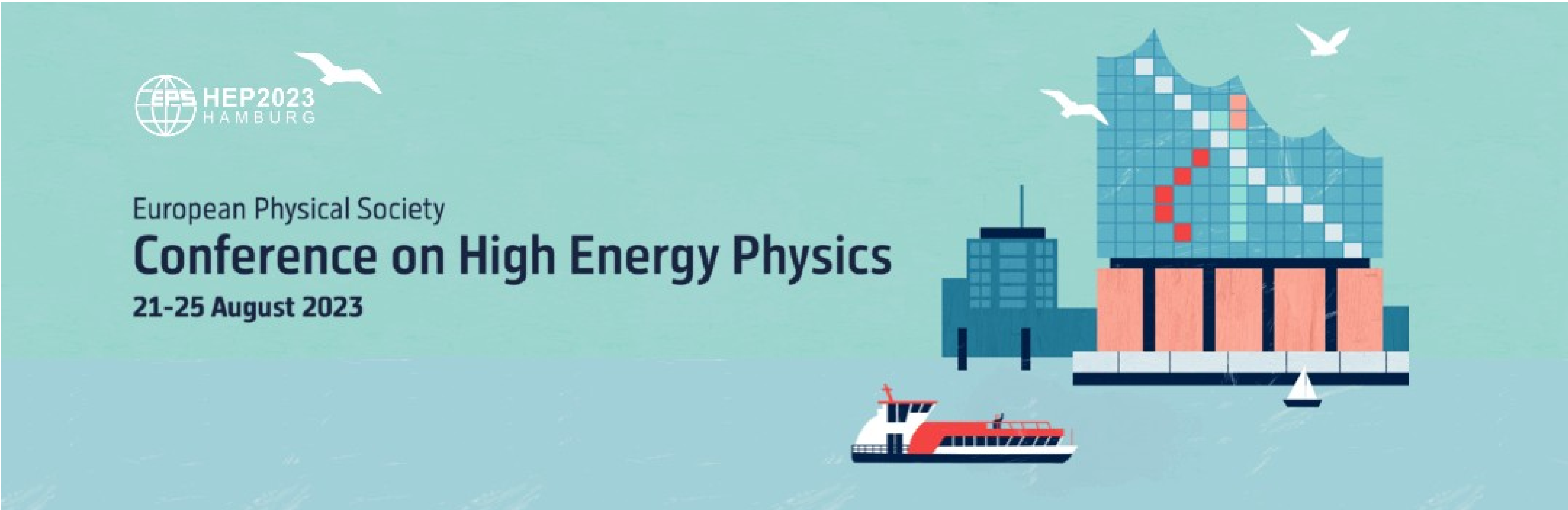
Based on the recent work:

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

arXiv:2307.06704

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

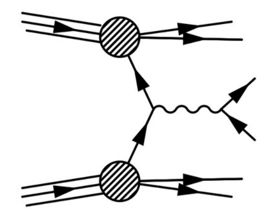


From factorization to nucleon tomography

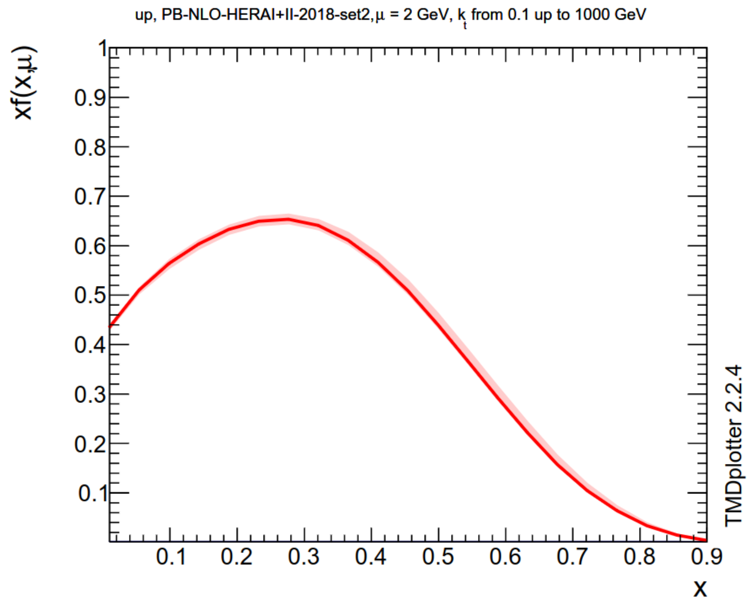
From factorization to nucleon tomography

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

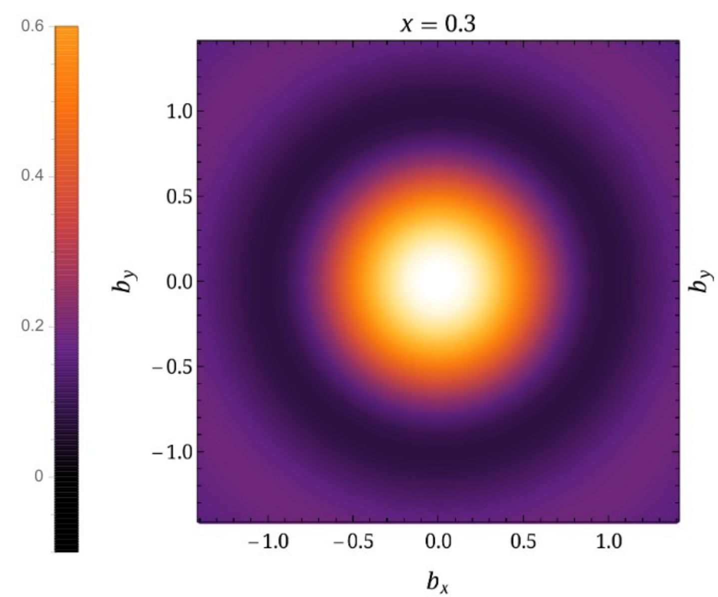
$$\frac{d\sigma}{dp_T} = \sigma_0 \int \frac{d^2b}{(2\pi)^2} e^{i(bp_T)} C\left(\frac{Q}{\mu}\right) F_1(x_1, b; \mu, \zeta) F_2(x_2, b; \mu, \zeta)$$



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



Eur.Phys.J.C 81 (2021) 8, 752



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

From factorization to nucleon tomography

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

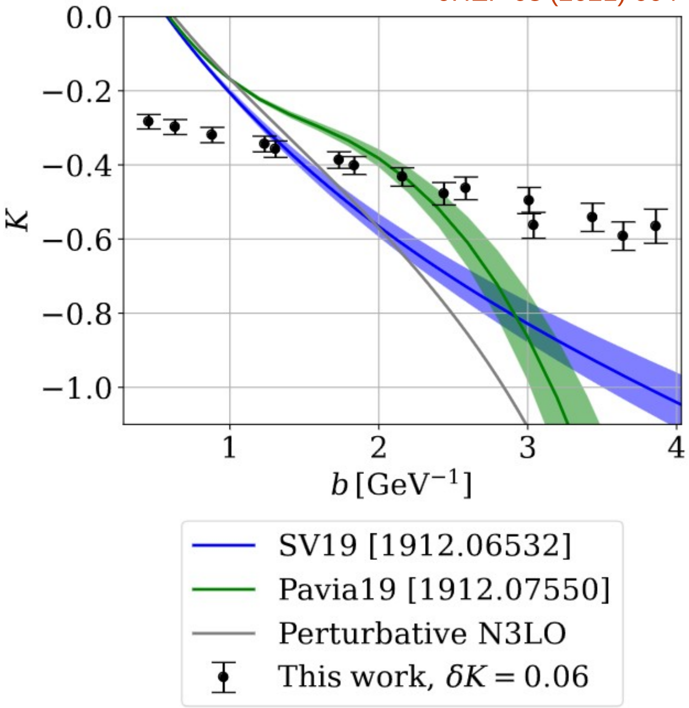
$$\frac{df_{q,h}(x,b;\mu,\zeta)}{d\ln\mu^2} = \frac{\gamma_F(\mu,\zeta)}{2} f_{q,h}(x,b;\mu,\zeta),$$
$$\frac{df_{q,h}(x,b;\mu,\zeta)}{d\ln\zeta} = -\boxed{\mathcal{D}(b,\mu)} f_{q,h}(x,b;\mu,\zeta).$$

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

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

  - RAD has been studied extensively
  - Yet, only QCD function which is largely unknown

JHEP 08 (2021) 004



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- **A direct measurement of RAD would imply:**

  - Stringent test of factorization and universality of the 3D structure
  - Higher precision imaging of hadrons
  - Higher precision for measurements, e.g W mass
  - Input to probe parton spin-orbit correlations

  ...

Novel method to determine RAD

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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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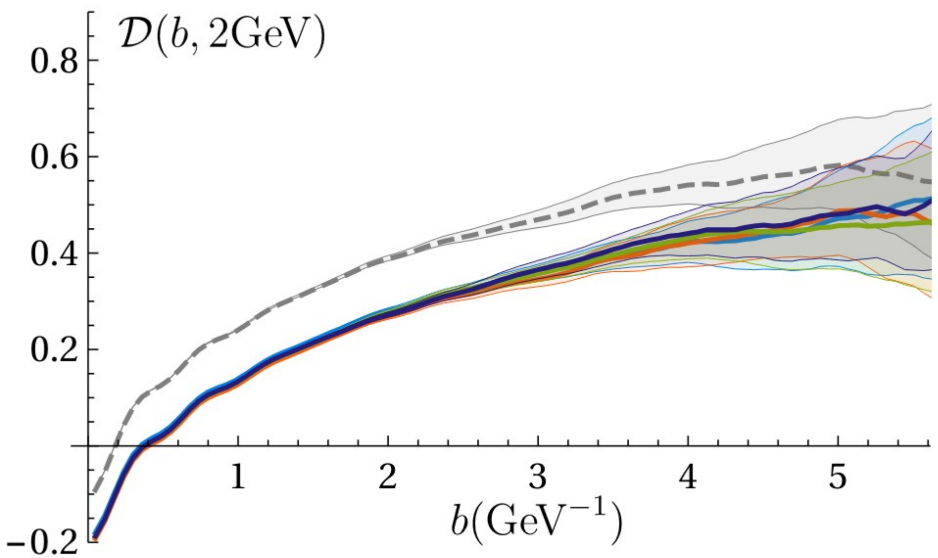
- We get the master formula:

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

measurement perturbative terms

- Things to remember:

- No dependence on the chosen scales
- No dependence on process
- Cancellation of the longitudinal part



Ultimate test of factorization ansatz

Applying the method to simulated data

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Applying the method to simulated data

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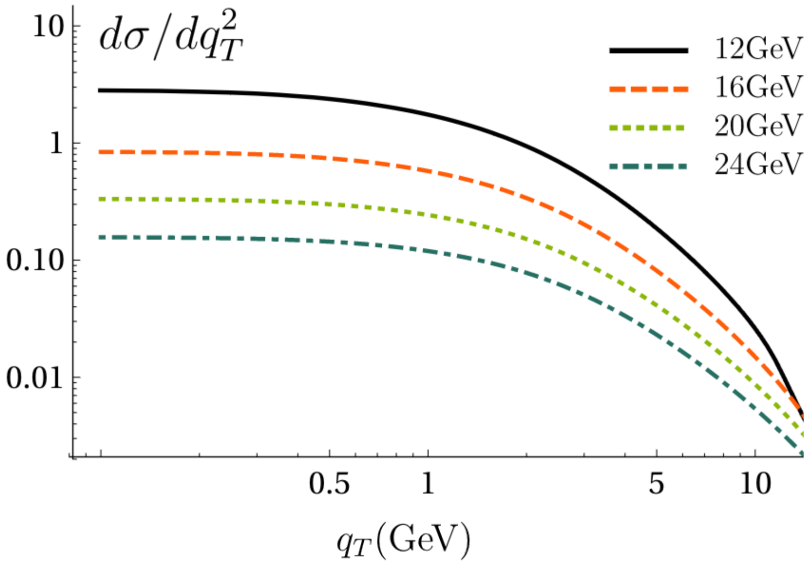
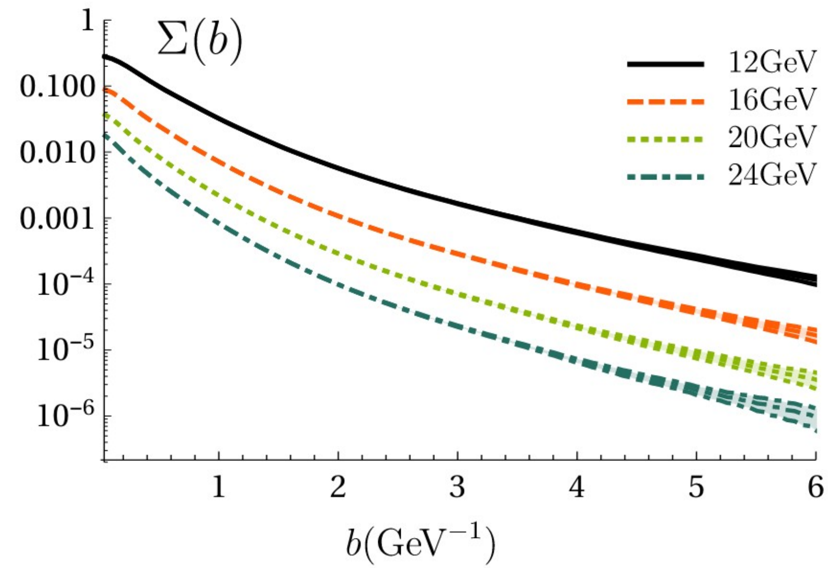
- Master formula can be used with data, provided:
  - small q_T and Q bin sizes
  - choices of y, Q and center-of-mass energy ensure same x range
  - Q below Z peak
- Simulation using the CASCADE MC generator:



Inverse Hankel



Applying the method to simulated data

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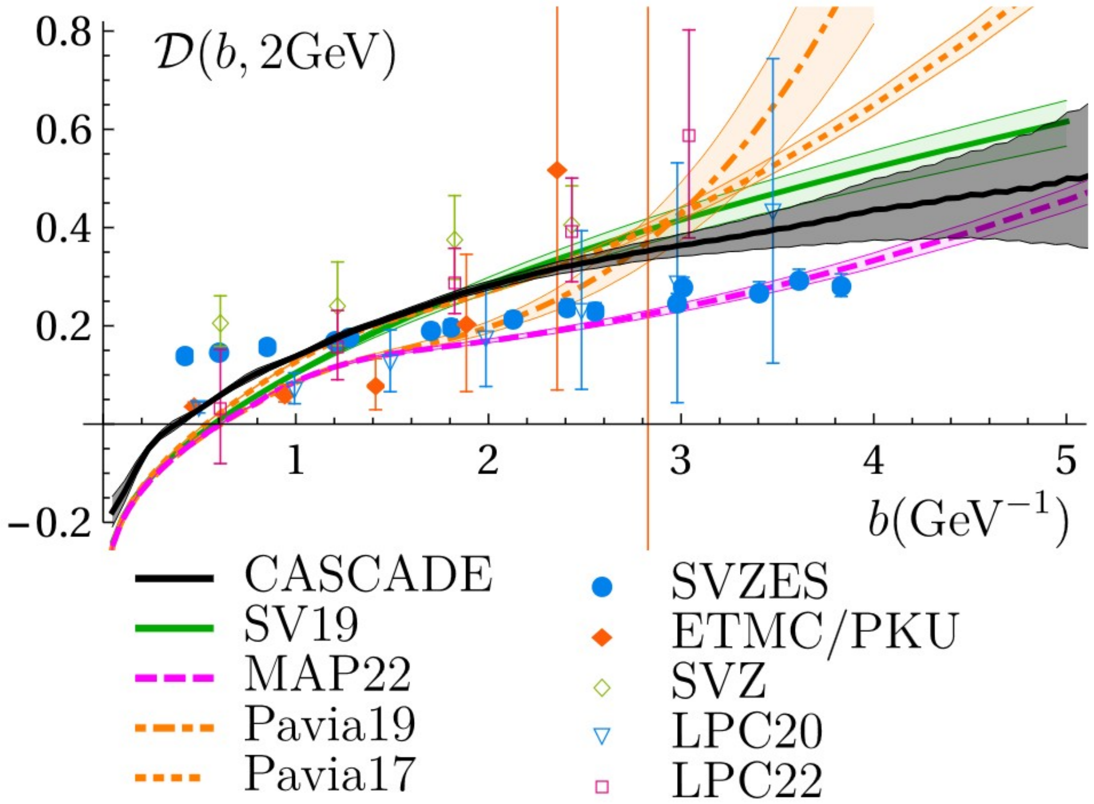
- All properties of RAD, like universality, are observed for the PB approach
- This non-trivially supports both factorization and PB approaches, sets the stage for a comparison
- The method can be applied to the experimental data!



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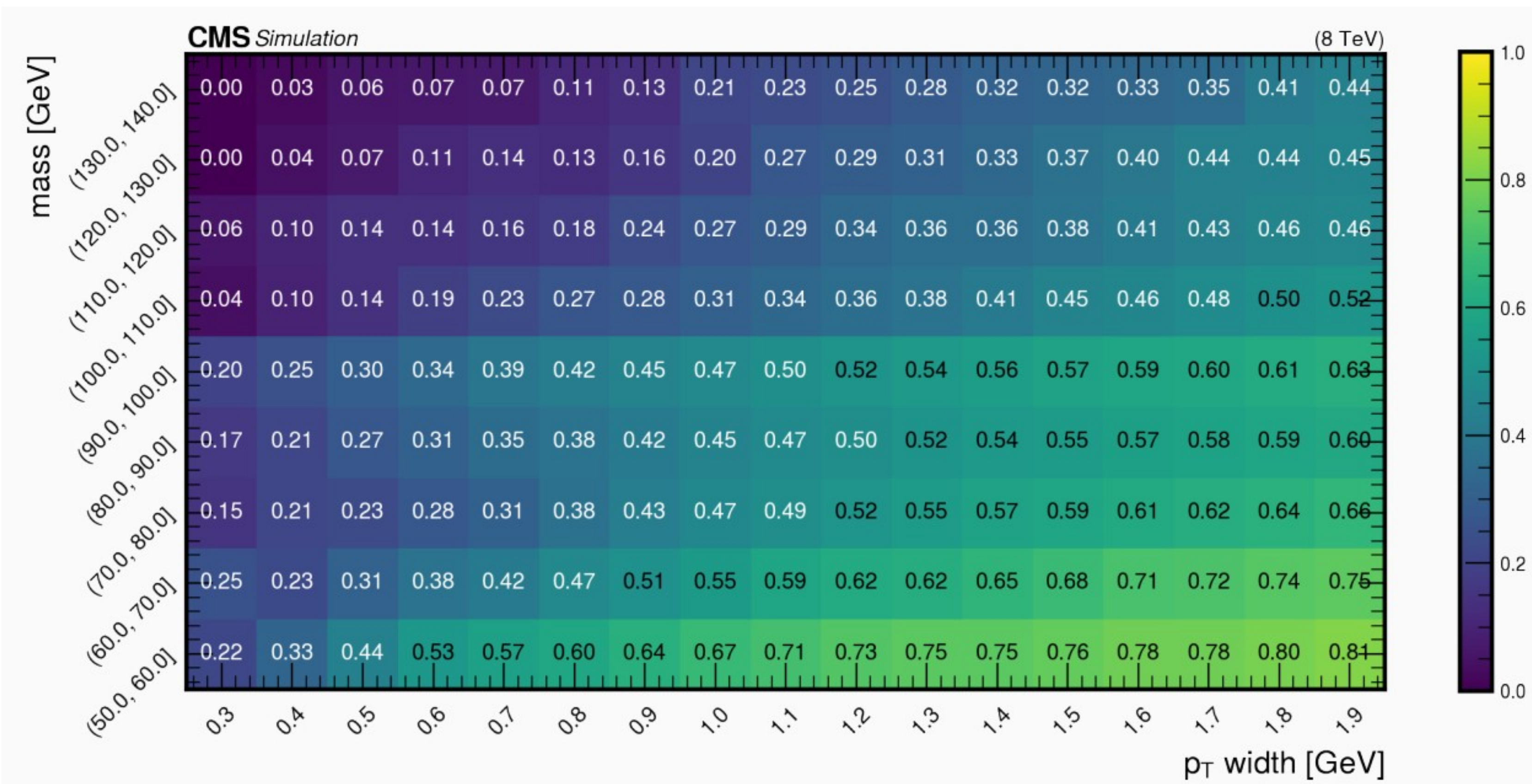
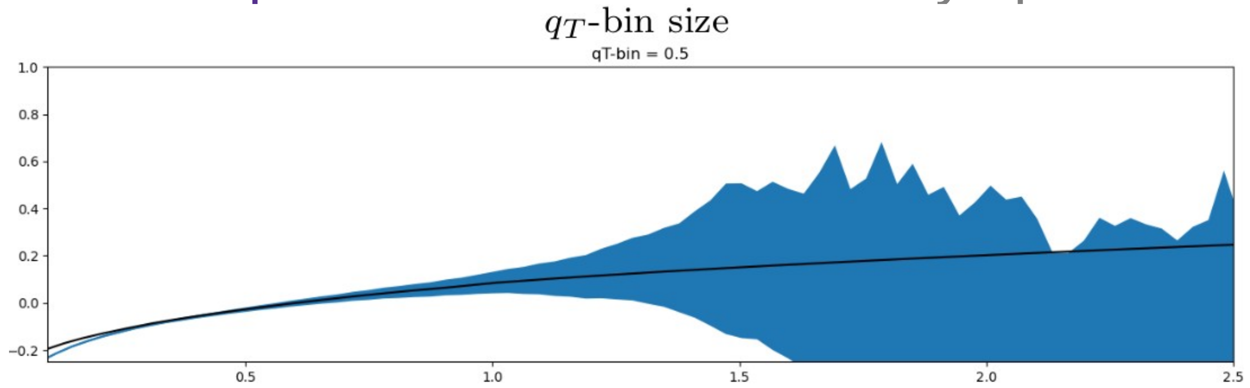
- CMS provides a excellent muon capabilities
- High quality data at 7, 8, 13, 13.5 TeV
- Feasibility studies on the di-muon resolution show promising results:

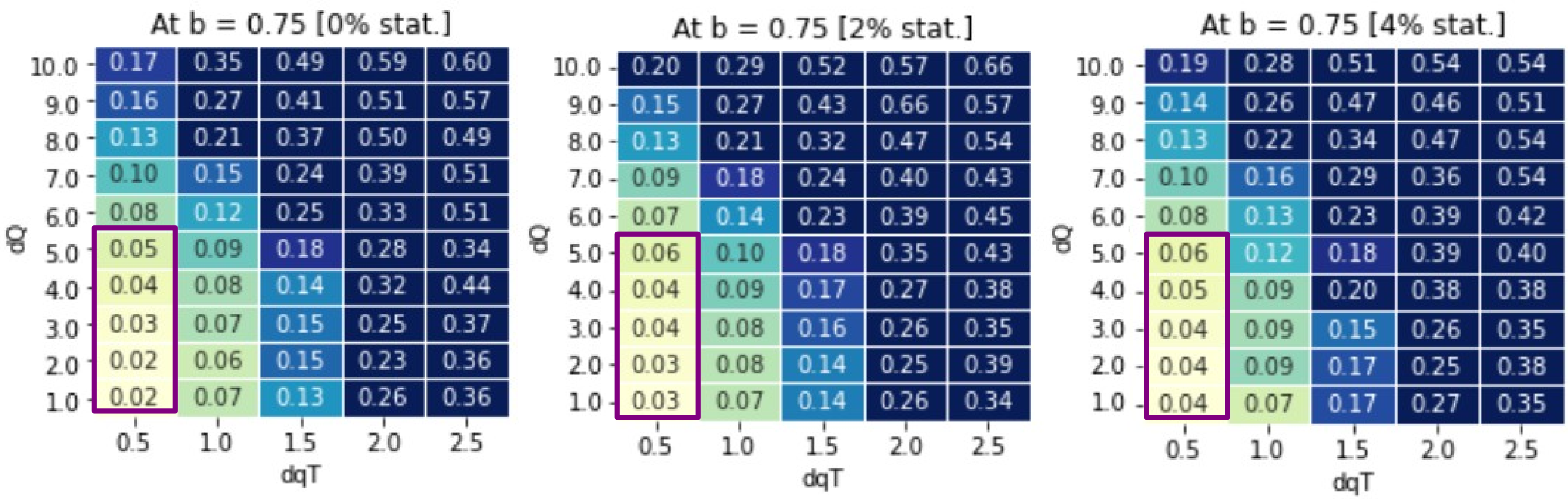


Applying the method to **experimental** data

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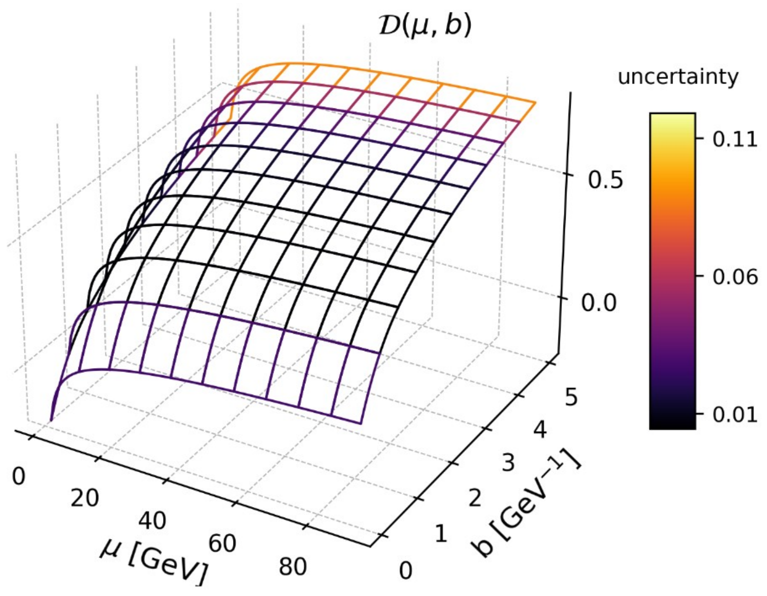
- This is a long standing problem
- Evolution of a TMD can be expressed as:

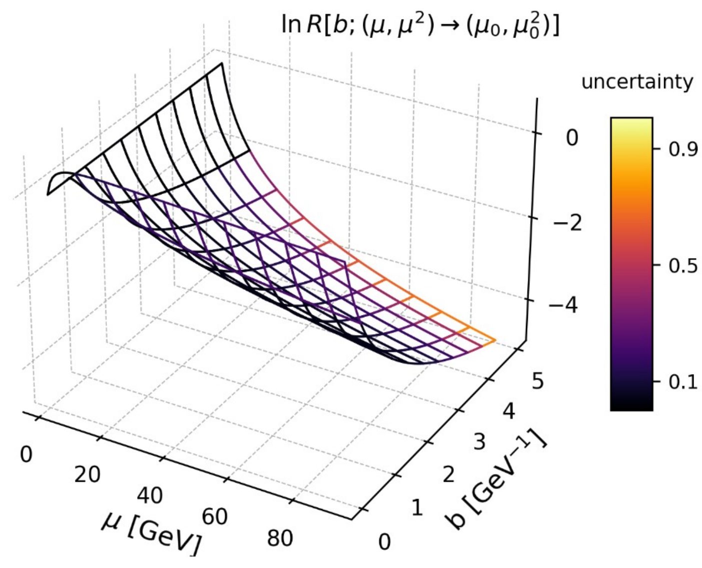
Evolution factor

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

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

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





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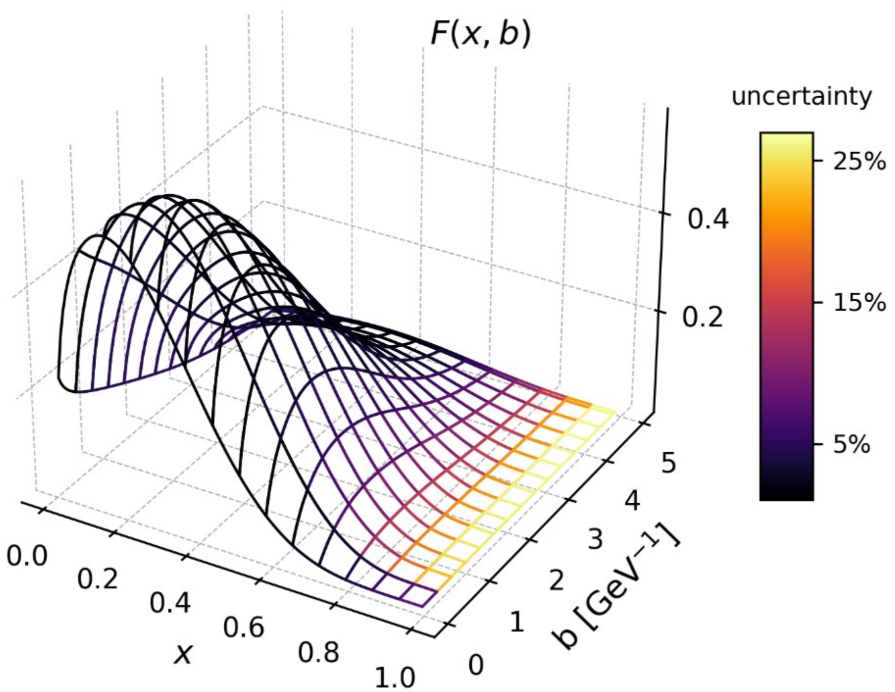
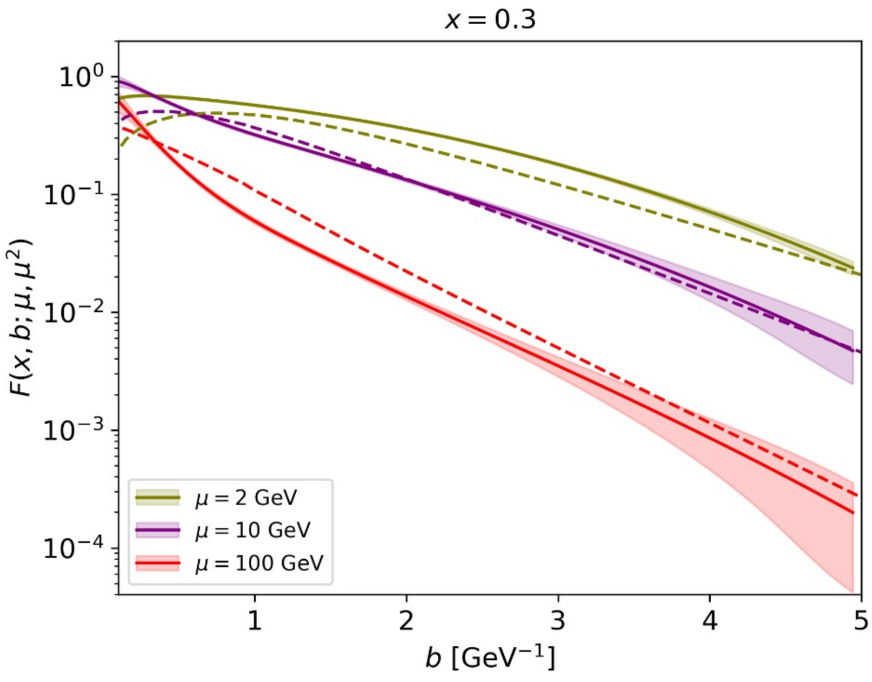
Evolution factor

- 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