Direct determination of Collins-Soper kernel.

Physics in Collision 2023

12.09.2023

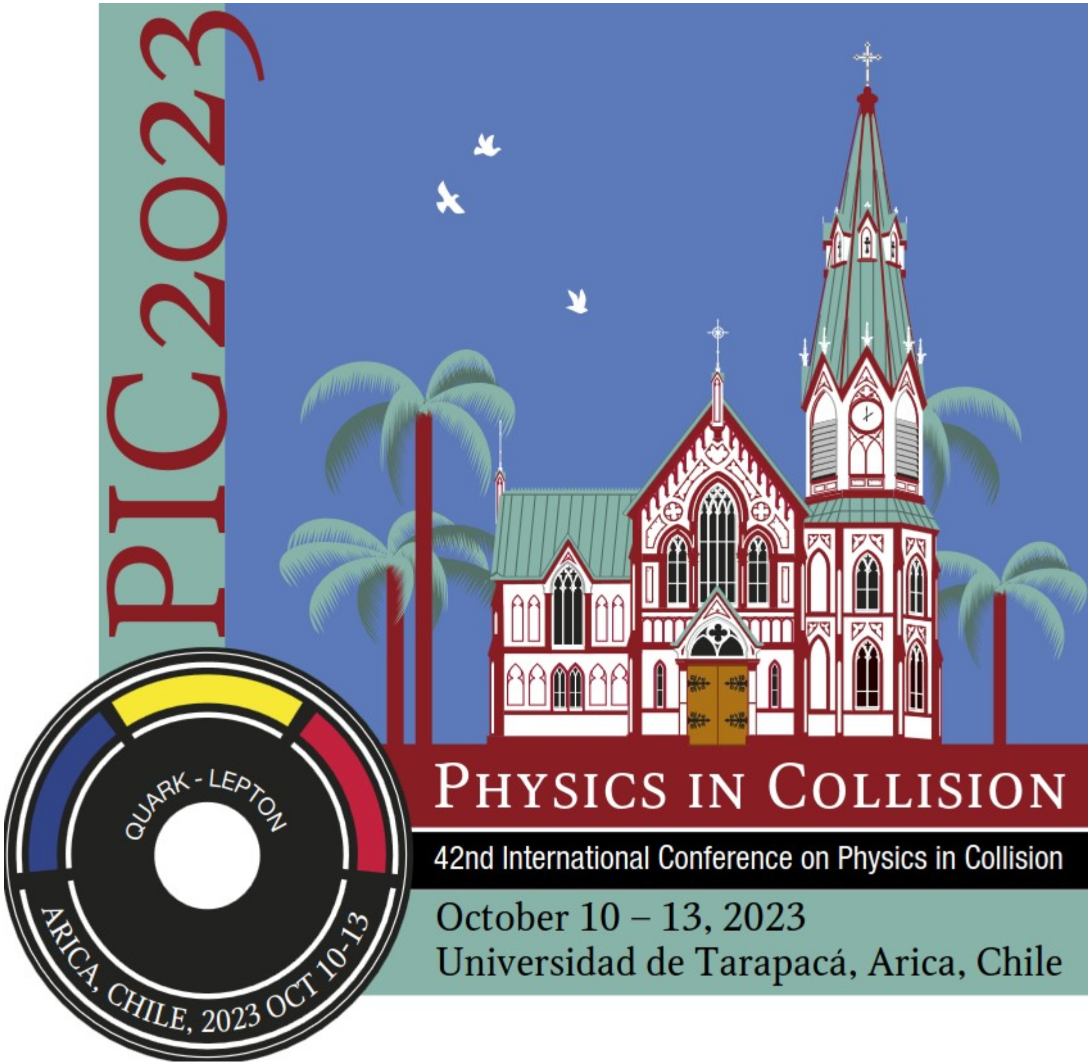
Armando Bermúdez Martínez

Based on the recent work:

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

Phys. Lett. B 845 (2023) 138182

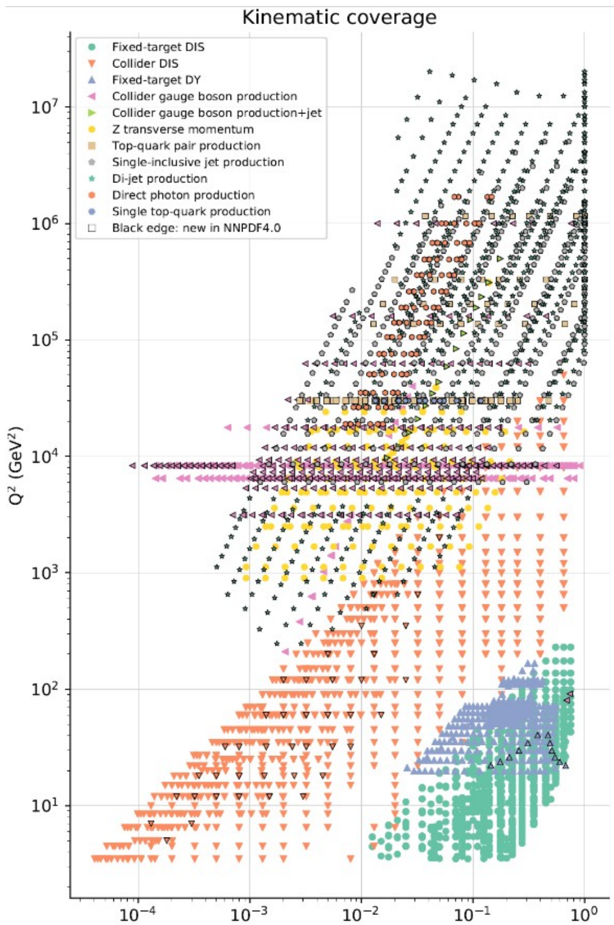
https://www.desy.de/f/students/2022/reports/David.Gutierrez.pdf



Motivation

Motivation: factorization

A. Sarkar's slide at Low-x workshop



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
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- 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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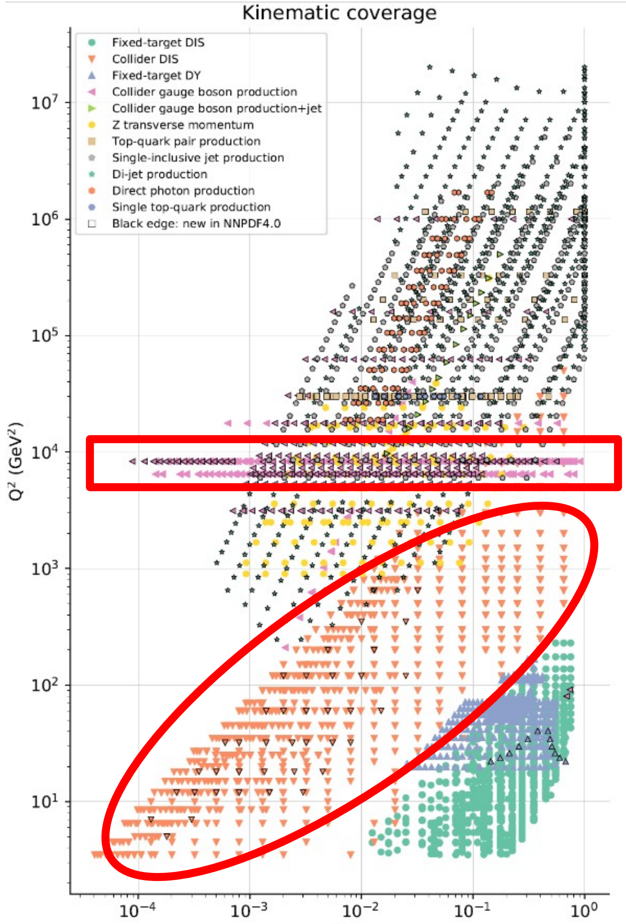

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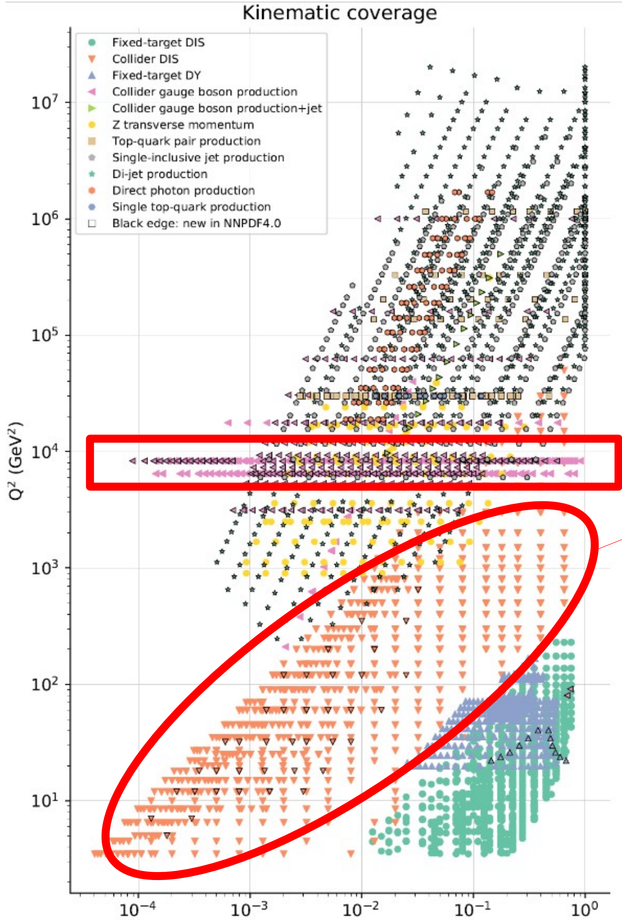

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Proven factorization for sufficiently inclusive observables

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:

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

It would meant we could construct the observable:

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

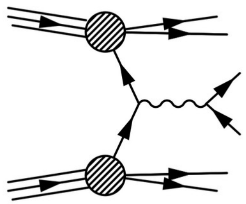
- R would depend neither on the scale choices, x range, PDF, nor on the process → clear way of testing factorization

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

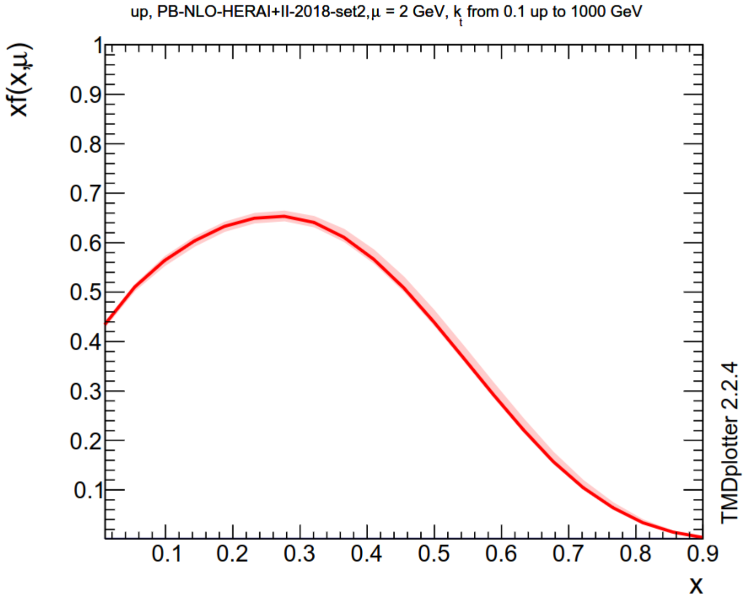
Motivation: nucleon tomography

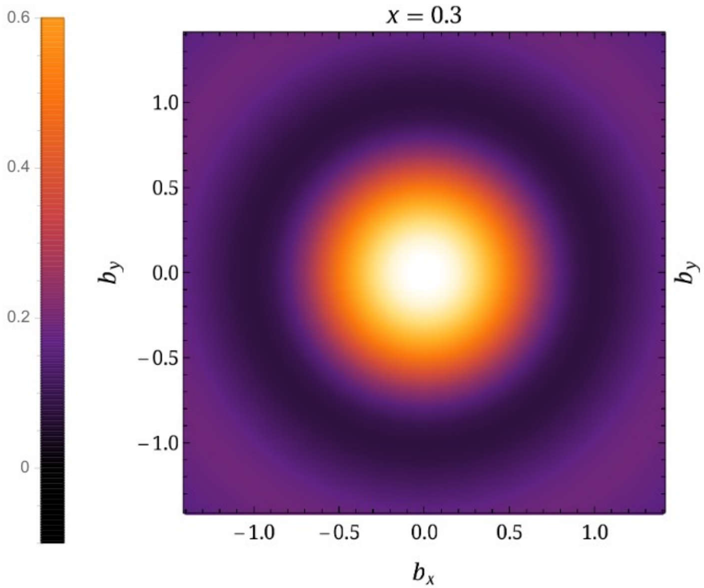
- Modern factorization theorems separate the 3D hadron structure from the low distance hard scattering

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



- More complete description, going beyond the simplest 1D parton structure
  - e.g. information on parton angular momentum contribution to proton spin





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

Motivation: nucleon tomography

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

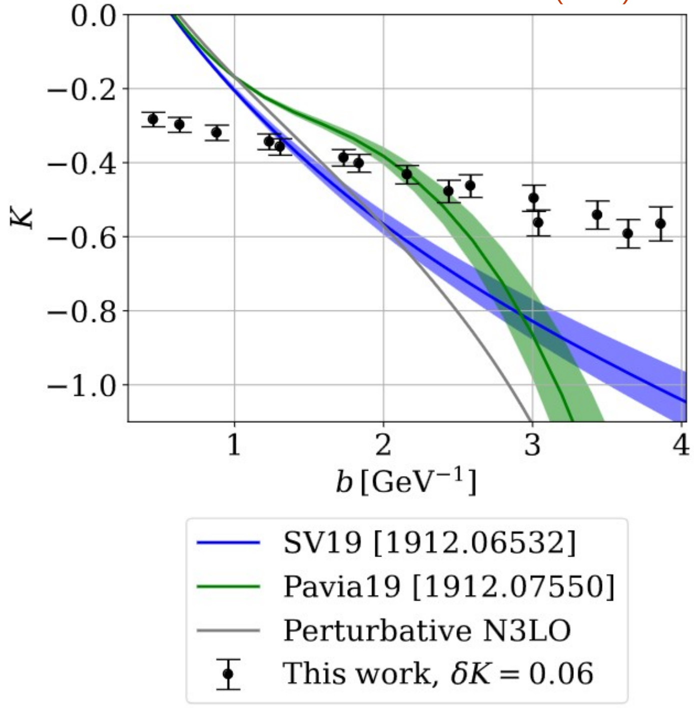
$$\frac{df_{q,h}(x,b;\mu,\zeta)}{d\ln\mu^2} = \frac{\gamma_F(\mu,\zeta)}{2} f_{q,h}(x,b;\mu,\zeta),$$
$$\frac{df_{q,h}(x,b;\mu,\zeta)}{d\ln\zeta} = -\boxed{\mathcal{D}(b,\mu)} f_{q,h}(x,b;\mu,\zeta).$$

- 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

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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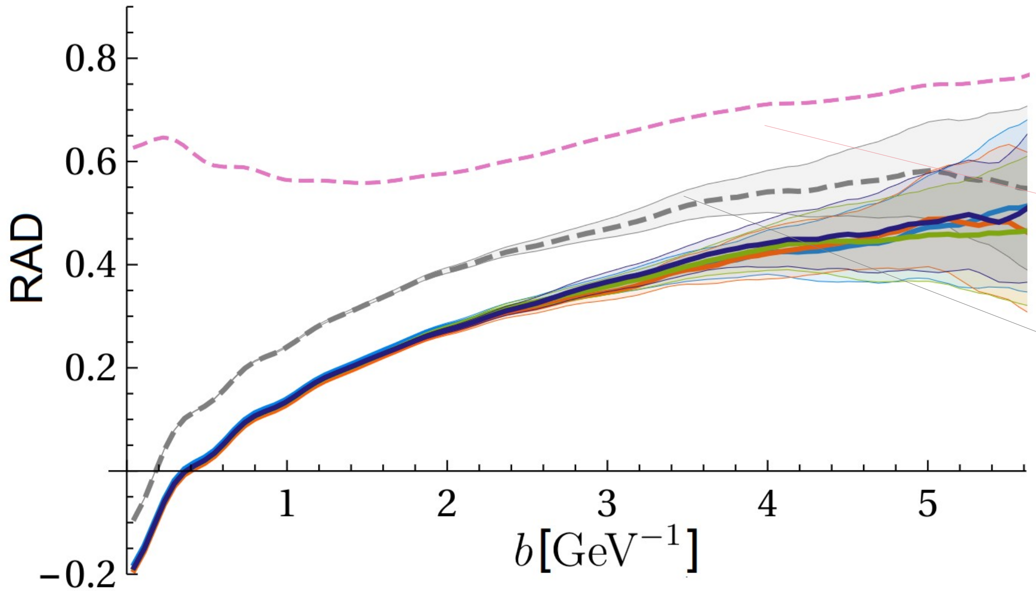
- We get the master formula:

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

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

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

Applying the method to simulated data

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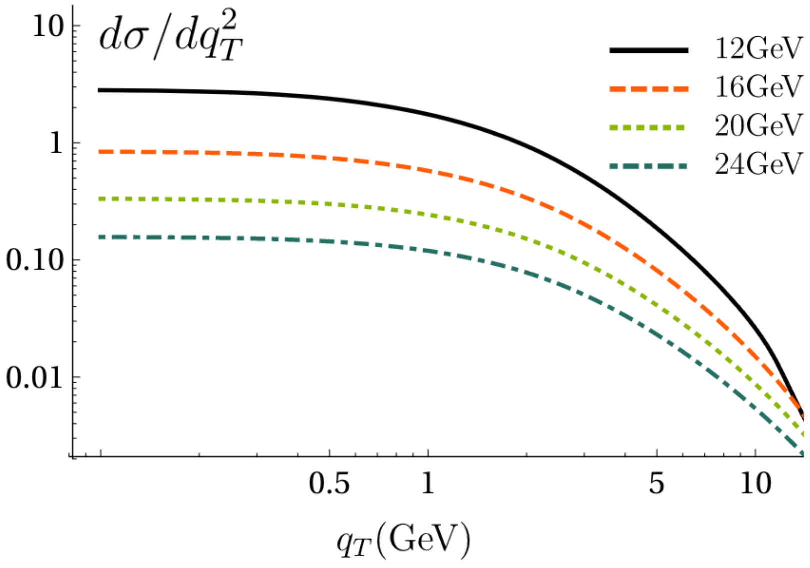
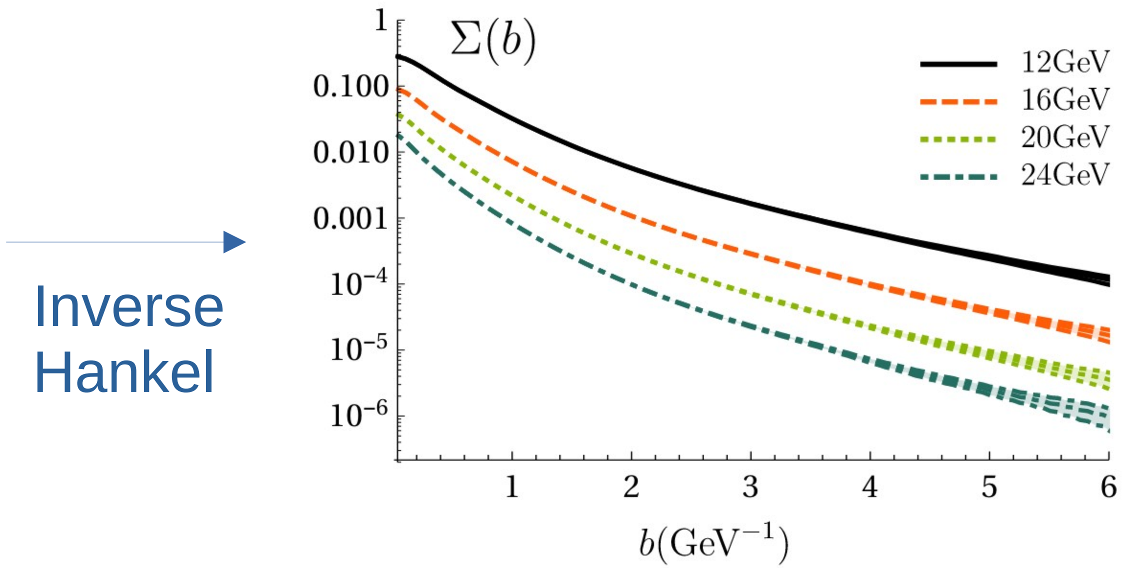
- Master formula can be used with data, provided:
  - small q_T and Q bin sizes
  - choices of y, Q and center-of-mass energy ensure same x range
  - Q below Z peak
- Simulation using the CASCADE MC generator:





Applying the method to simulated data

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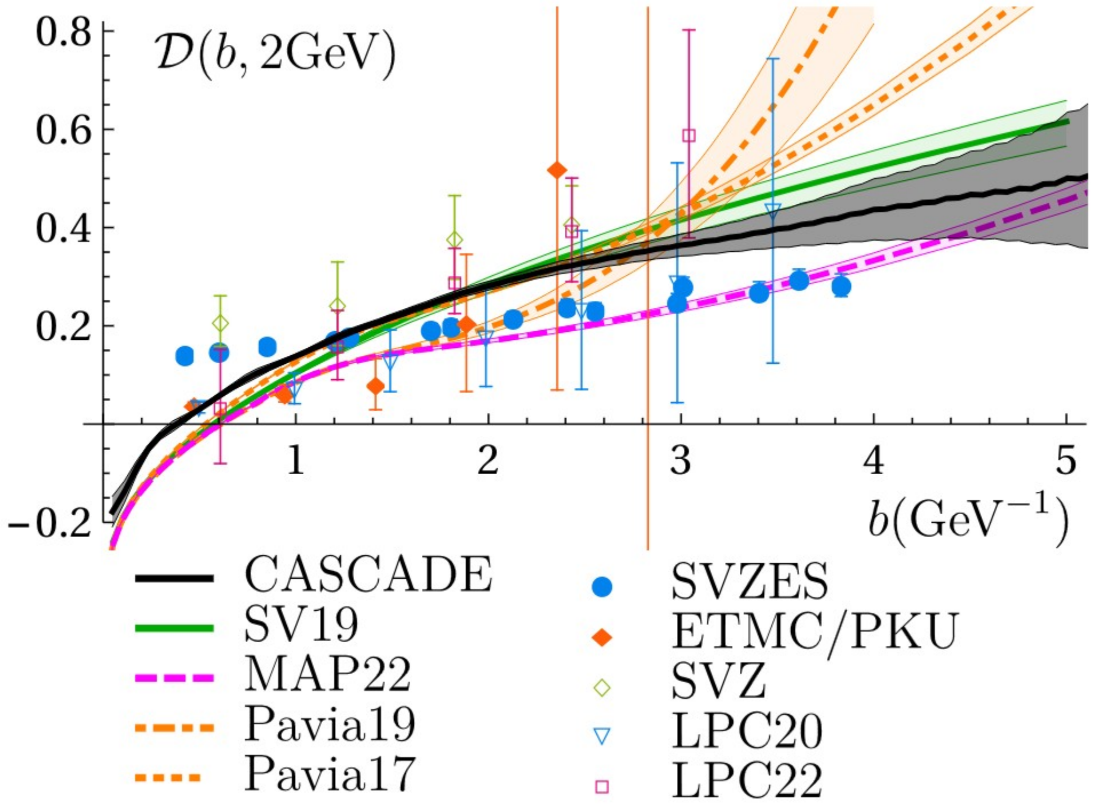
- All properties of RAD, like universality, are observed for the PB approach
- This non-trivially supports both factorization and PB approaches, sets the stage for a comparison
- The method can be applied to the experimental data!



Applying the method to **experimental** data

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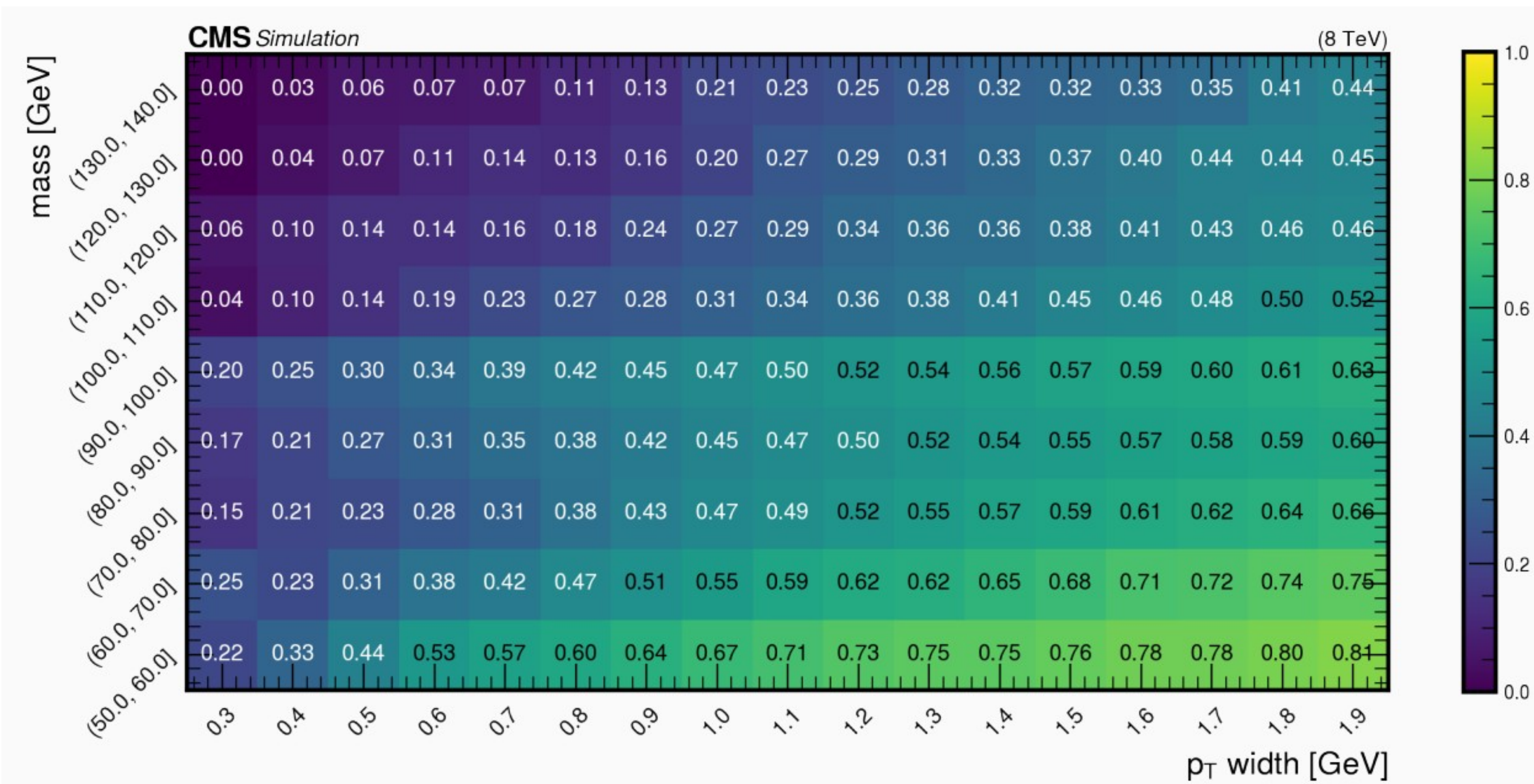
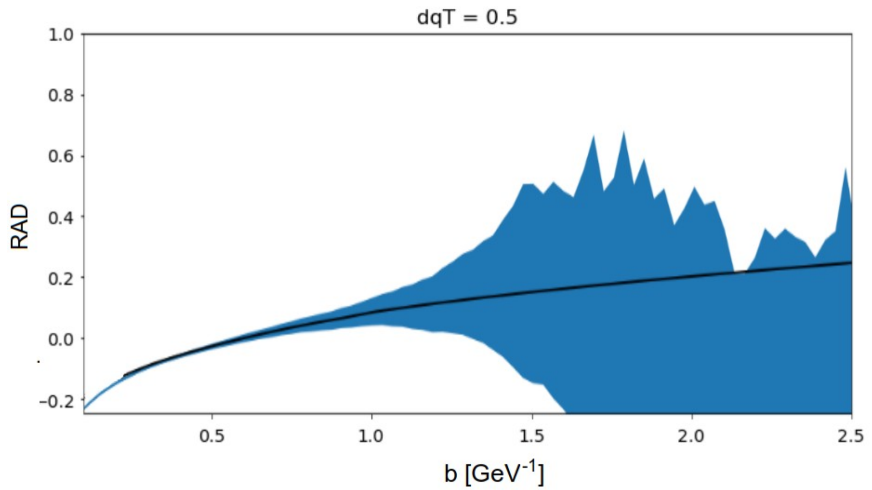
- CMS provides a excellent muon capabilities
- High quality data at 7, 8, 13, 13.5 TeV
- Feasibility studies on the di-muon resolution show promising results:



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:

At b = 0.75 [0% stat.]

dQ \ dqT	0.5	1.0	1.5	2.0	2.5
10.0	0.17	0.35	0.49	0.59	0.60
9.0	0.16	0.27	0.41	0.51	0.57
8.0	0.13	0.21	0.37	0.50	0.49
7.0	0.10	0.15	0.24	0.39	0.51
6.0	0.08	0.12	0.25	0.33	0.51
5.0	0.05	0.09	0.18	0.28	0.34
4.0	0.04	0.08	0.14	0.32	0.44
3.0	0.03	0.07	0.15	0.25	0.37
2.0	0.02	0.06	0.15	0.23	0.36
1.0	0.02	0.07	0.13	0.26	0.36

At b = 0.75 [2% stat.]

dQ \ dqT	0.5	1.0	1.5	2.0	2.5
10.0	0.20	0.29	0.52	0.57	0.66
9.0	0.15	0.27	0.43	0.66	0.57
8.0	0.13	0.21	0.32	0.47	0.54
7.0	0.09	0.18	0.24	0.40	0.43
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At b = 0.75 [4% stat.]

dQ \ dqT	0.5	1.0	1.5	2.0	2.5
10.0	0.19	0.28	0.51	0.54	0.54
9.0	0.14	0.26	0.47	0.46	0.51
8.0	0.13	0.22	0.34	0.47	0.54
7.0	0.10	0.16	0.29	0.36	0.54
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2.0	0.04	0.09	0.17	0.25	0.38
1.0	0.04	0.07	0.17	0.27	0.35

- Statistical uncertainty mild, main uncertainty from q_T binning

Applying the method to transform PB TMDs to CSS

Phys. Lett. B 845 (2023) 138182

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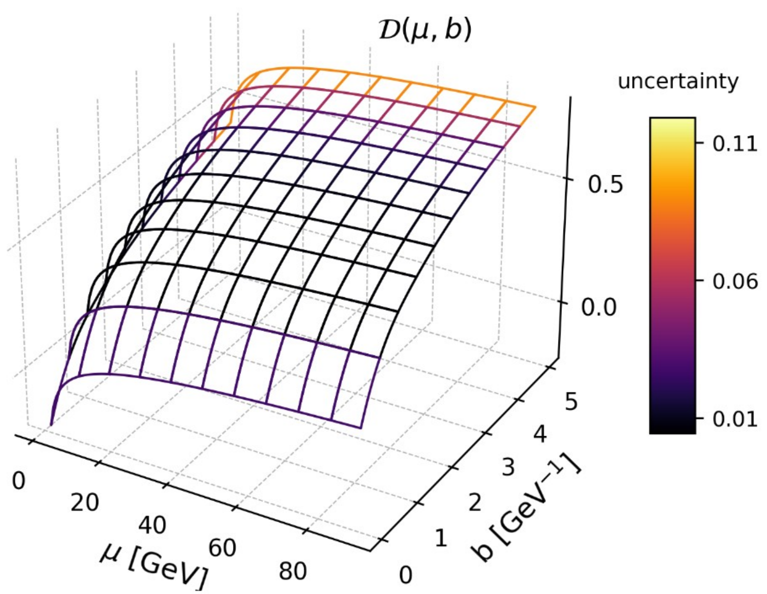
- This is a long standing problem
- Evolution of a TMD can be expressed as:

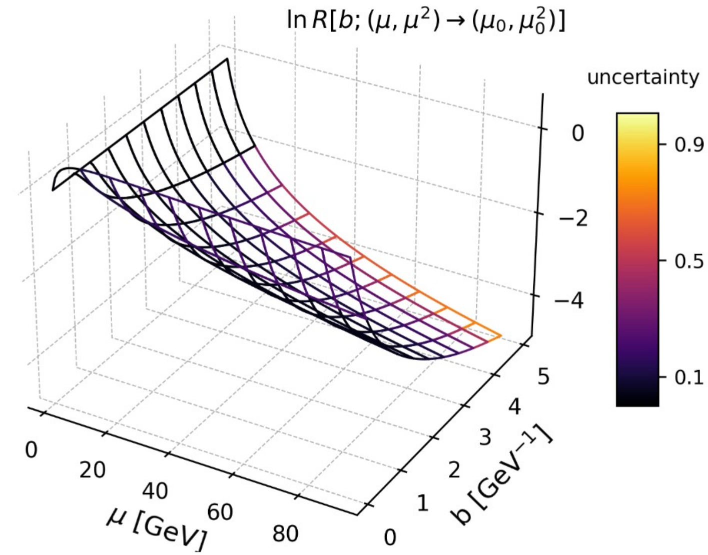
Evolution factor

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

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

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





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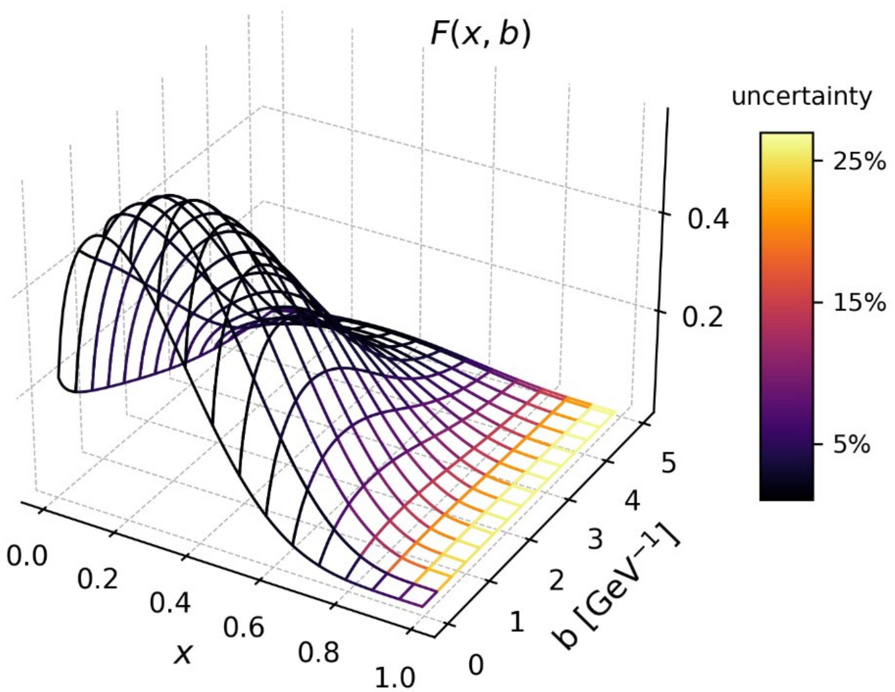
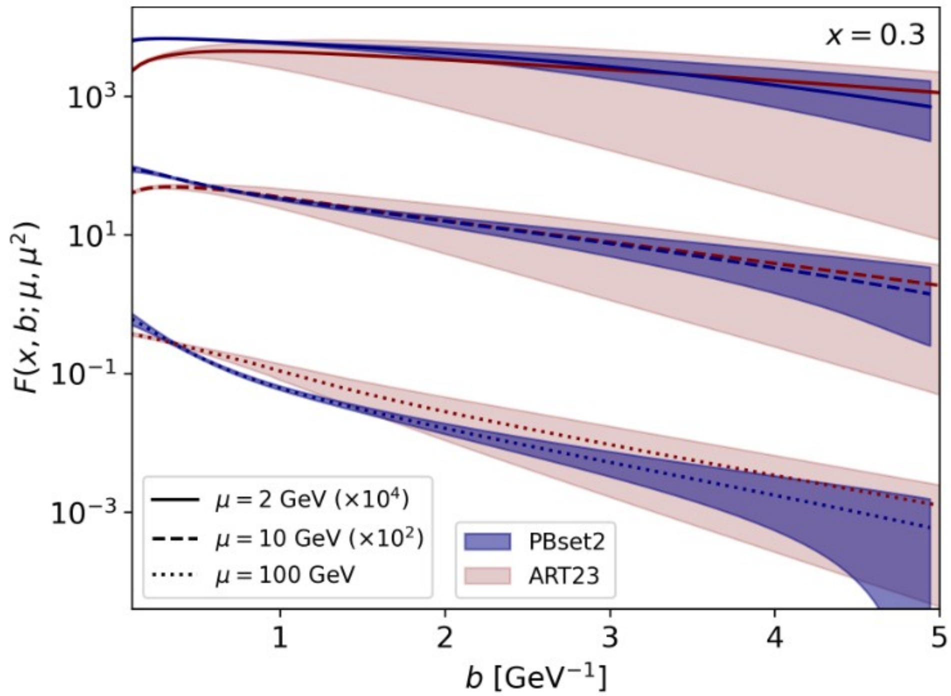
Evolution factor

- 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