Description of unpolarized Drell-Yan and SIDIS processes within TMD factorization

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Introduction

I present the joined fit of the DY and SIDIS data
and the extraction non-perturbative TMD distributions

Main messages:

- Joined description of DY and SIDIS is consistent and does not meet any problem
- We do not see any tension between HERMES and COMPASS SIDIS data
- TMD non-perturbative evolution is universal

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TMD factorization formula (in ζ-prescription)

Rapidity anomalous dimension

$\mathcal{D} \sim \langle 0|F_{+b}[\text{staple link}]|0\rangle$

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

$F \sim \langle P|\bar{q}[\text{staple link}]q|0\rangle$

$$\frac{d\sigma}{dxdzdQ^2d^2\mathbf{q}_T} = \sum_{ff'} H_{ff'}\left(\frac{Q}{\mu}\right) \int d^2b\, e^{i(\mathbf{b}\cdot\mathbf{q}_T)} \left(\frac{Q^2}{\zeta_\mu[\mathcal{D}]}\right)^{-2\mathcal{D}(b,\mu)} F_{f\leftarrow h}(x,b) D_{f'\leftarrow h}(z,b)$$

- Each data-point is a product (convolution) of **three independent non-perturbative** functions
- Functions do not "cross-talk" and could be modeled independently
- Each function is responsible for a separate kinematic variable
  - Rapidity AD: $\mathcal{D} \;\; \rightarrow \;\; Q$ and b
  - TMD PDF: $F \;\; \rightarrow \;\; x$ and b
  - TMD FF: $D \;\; \rightarrow \;\; z$ and b

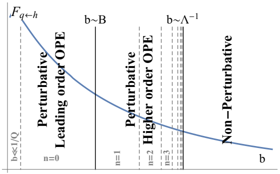
Theory input

Hard part and TMD evolution

NNLO & N^{3}LO

Model for RAD

$$\mathcal{D}(b,\mu) = -\frac{K(b,\mu)}{2} = \underbrace{\mathcal{D}_{\text{pert}}(b^*(b),\mu)}_{\substack{\text{NNLO \& N}^3\text{LO} \\ \text{resummed}}} + c_0 b \cdot b^*(b), \qquad b^* = b(1+b^2/B_{NP}^2)^{-1/2}$$



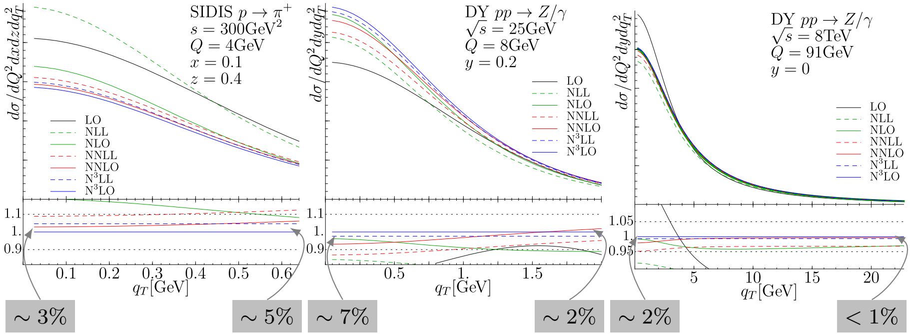
Model for (optimal) TMD distribution

$$F(x,b) = \underbrace{C(x,b)\otimes f_1(x)}_{\text{NNLO \& N}^3\text{LO}} f_{NP}(x,b)$$

Resummation equivalent: NNLL' & N^{3}LL(?)

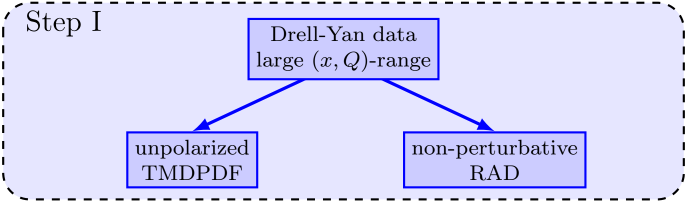
In ζ-prescription: $\mu \sim Q$

Matching scales $\mu_{\rm OPE}$ are intrinsic for each function

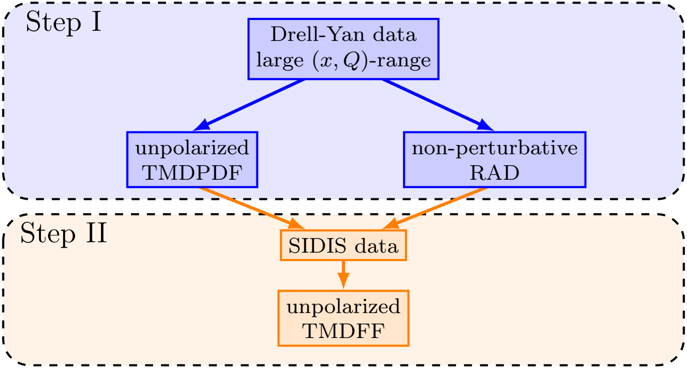


Difference between NNLO and N^{3}LO is not that important

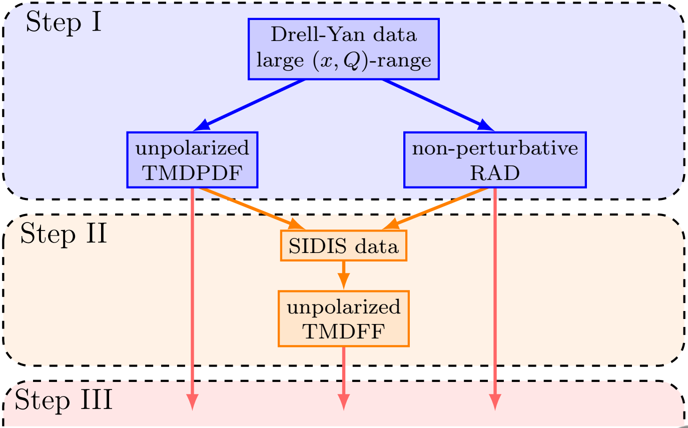
Fit strategy and the test of universality



Fit strategy and the test of universality



Fit strategy and the test of universality



Check of universality

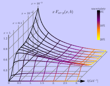
Step I

Low-energy
E228, E605,...
PHENIX

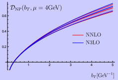
→ **Drell-Yan fit** $\chi^2/N_{pt} = 1.2$ ←

High-energy
ATLAS, LHCb,...
CDF, D0

uTMDPDF (5 params +PDF)



RAD (2 params)



[V.Bertone,I.Scimemi,AV;1902.08474]

Step I

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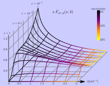
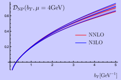


RAD (2 params)



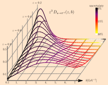
[V.Bertone,I.Scimemi,AV;1902.08474]

Step II

HERMES
COMPASS

→ **SIDIS fit** $\chi^2/N_{pt} = 1.0$

TMDFF (4 params)



[I.Scimemi,AV;in prep.]

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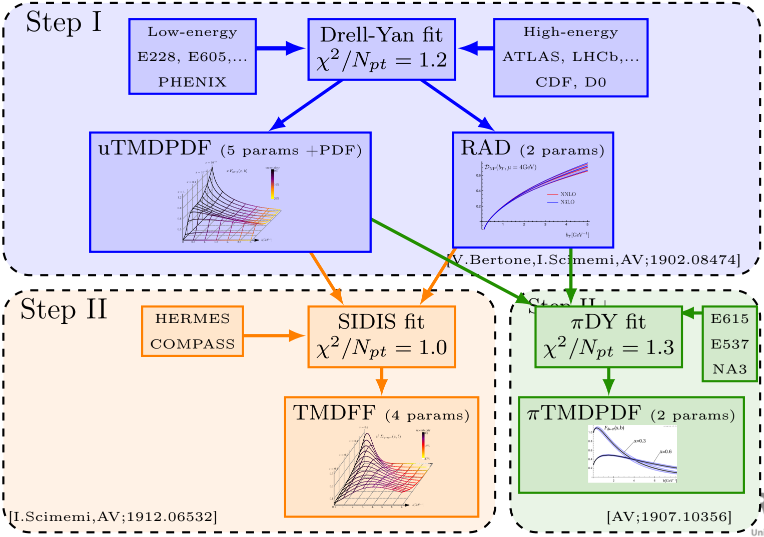
Check of universality



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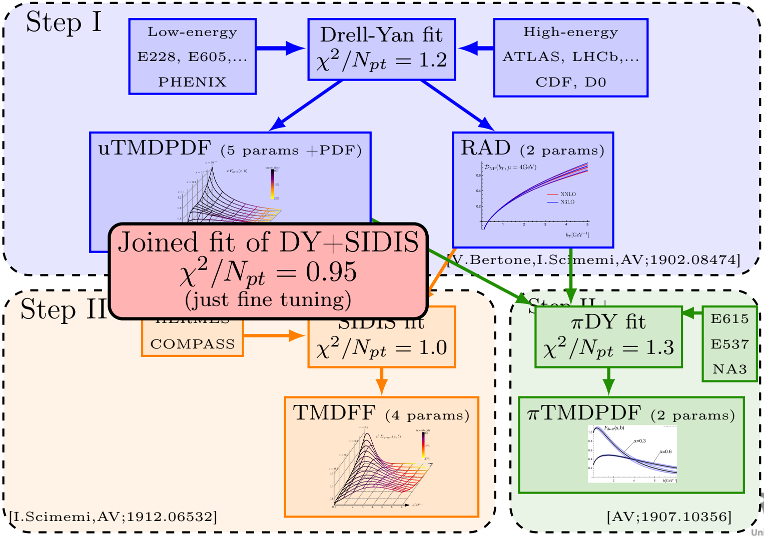
Check of universality



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There are plenty of details/questions

- How to cut the data?
- Where is the limit of TMD factorization?
- Power corrections:
  - Induced (ATLAS, LHCb) (linear in q_T ?)
  - Kinematic
  - In the definition of collinear frame
  - Target mass and produced mass
- Universality and correlations
- ... many others ...
- What do we learn from it?

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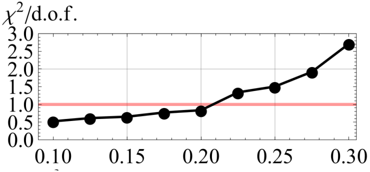
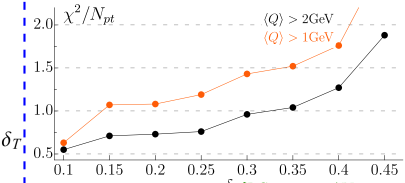
Test by inclusion of the data with $q_T < \delta \cdot Q$

unpolarized DY



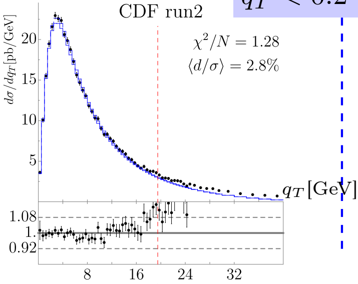
[I.Scimemi,AV,1706.01473]

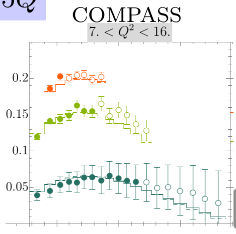
unpolarized SIDIS



[I.Scimemi,AV,in prep.]

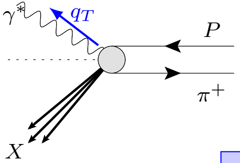
$$q_T < 0.2 - 0.25Q$$



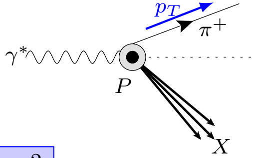


Proof of factorization is done in the Breit frame

Breit frame



Lab frame



$$q_T^2 = \frac{p_T^2}{z^2}\frac{1+\gamma^2}{1-\varsigma^2}$$

$$\gamma = \frac{2Mx}{Q}$$

$$\varsigma = \gamma\frac{m}{zQ}$$

$$x_1 = -x\frac{2}{\gamma^2}\left(1-\sqrt{1+\gamma^2\left(1-\frac{\mathbf{q}_T^2}{Q^2}\right)}\right), \qquad z_1 = z\frac{x_1}{x}\frac{1+\sqrt{1-\varsigma^2}}{2\left(1-\frac{\mathbf{q}_T^2}{Q^2}\right)}$$

In practice: $q_T < 0.25Q$

- Most part of data is not TMD factorisable.
- Low z's are not accessible
- H1, ZEUS data have no TMD points, too low z.

Test of importance of power correction

These are not all power corrections,
but only those that we know how to account

include (m/Q)	yes	**no**	yes	yes	**no**	**no**
include (M/Q)	yes	yes	**no**	yes	**no**	**no**
include (q_T/Q) in kinematics	yes	yes	yes	**no**	**no**	**no**
include (q_T/Q) in x_S, z_S	yes	yes	yes	yes	yes	**no**
χ^2/N_{pt}	1.00	1.00	1.09	1.06	1.16	1.31

Most important corrections are $\frac{M}{Q}$ and $\frac{q_T}{Q}$ from the rotation Breit$\to$Lab

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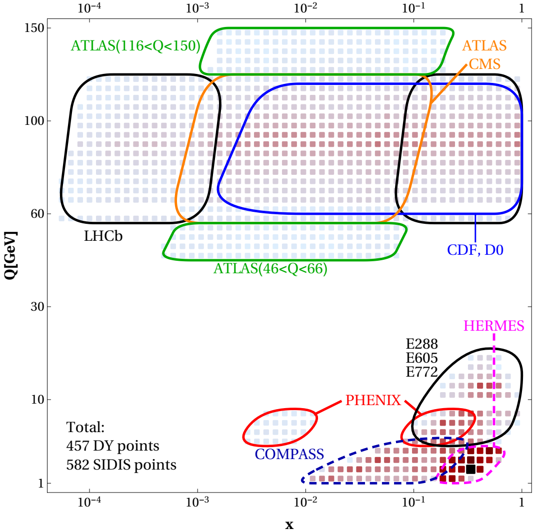
Data survived after the cut

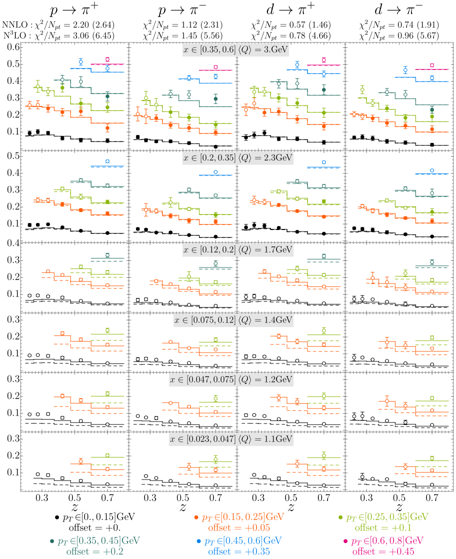


High energy DY:	194 points
Low energy DY:	263 points
(Low energy) SIDIS:	582 points
TOTAL:	1039 points

NNLO: $\chi^2_{global}/N_{pt} = 0.95$

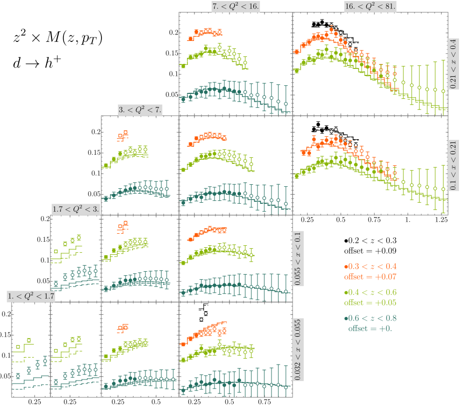
N^{3}LO: $\chi^2_{global}/N_{pt} = 1.05$

`artemide` v.2.02



Example of SIDIS data

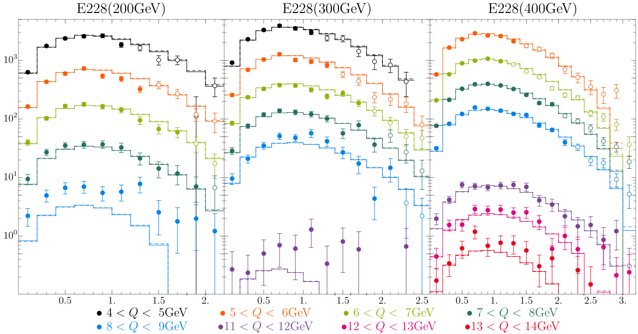
No contradiction between HERMES and COMPASS

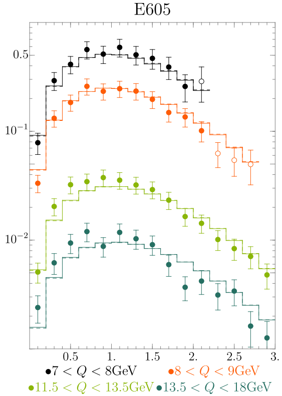


Example of low-energy DY

Some problem with normalization

Large-x, nuclear corrections,...



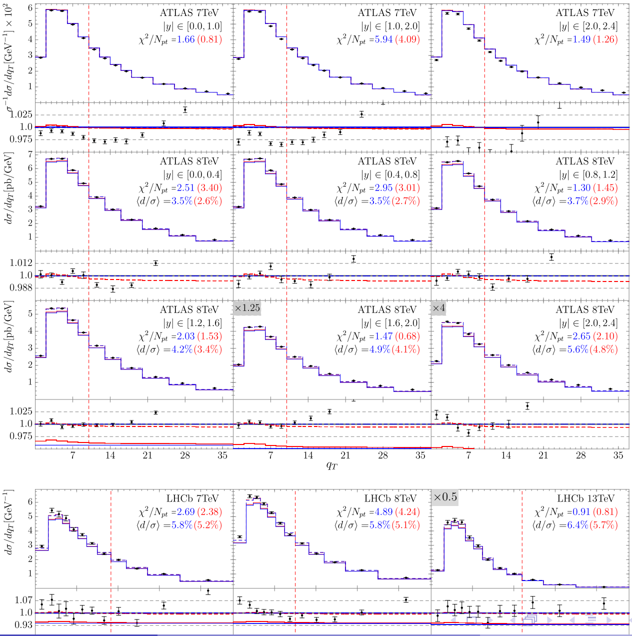


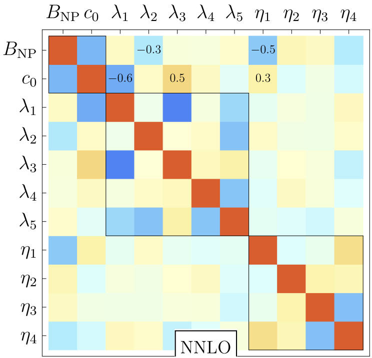
+30% +25% +15%

Norm.error of data 25%

+15%

LHC data within TMD factorization



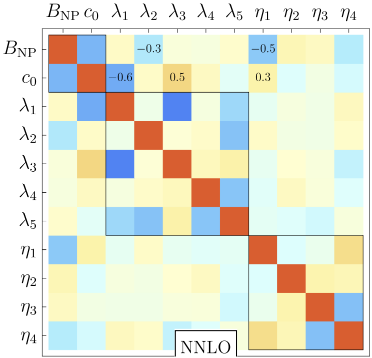


Evolution : 2 parameters
TMDPDF : 5 parameters + PDF
TMDFF : 4 parameters + NNFF

Different NP functions are almost decorrelated

$$f_{NP}(x,b) = \exp\left(-\frac{\lambda_1(1-x)+\lambda_2 x + x(1-x)\lambda_5}{\sqrt{1+\lambda_3 x^{\lambda_4}\boldsymbol{b}^2}}\boldsymbol{b}^2\right),$$

$$D_{NP}(x,b) = \exp\left(-\frac{\eta_1 z+\eta_2(1-z)}{\sqrt{1+\eta_3(\boldsymbol{b}/z)^2}}\frac{\boldsymbol{b}^2}{z^2}\right)\left(1+\eta_4\frac{\boldsymbol{b}^2}{z^2}\right),$$



Evolution : 2 parameters
TMDPDF : 5 parameters + PDF
TMDFF : 4 parameters + NNFF

Different NP functions are almost decorrelated

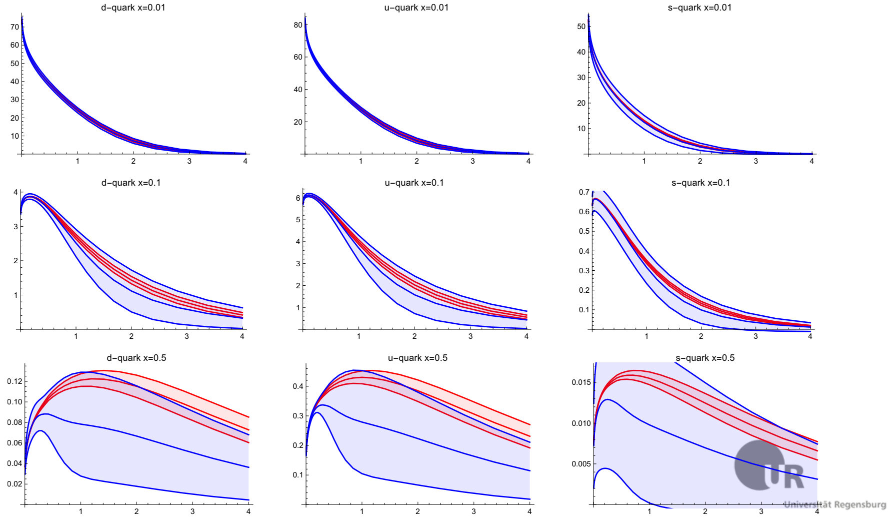
Fit quality essentially depends on the collinear input.

Vary NNPDF within the 1σ band

$$\chi^2/N_{pt} \in [0.8, 6.]$$

We cannot estimate accurately the PDF uncertainty.

$$F(x,b) = C(x,b,\mu_{OPE}) \otimes \underbrace{f_1(x,\mu_{OPE})}_{\pm\delta f(\text{reweighted})} \underbrace{f_{NP}(x,b)}_{\pm\delta f_{NP}}$$



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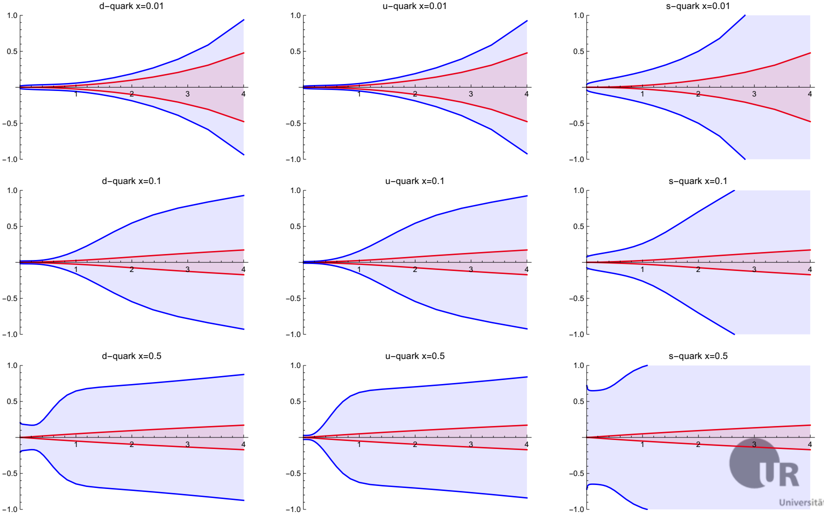
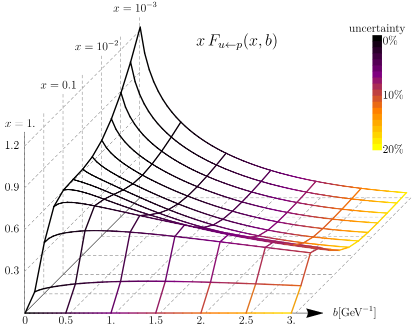
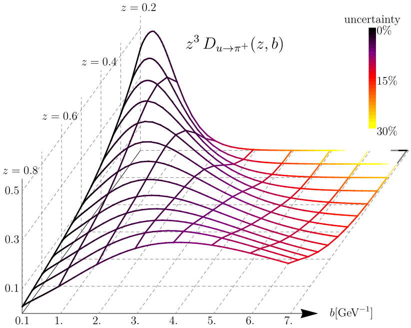


unpolarized TMD-distributions

unpolarized TMDPDF



unpolarized TMDFF



... systematic error 10-20%

... evolution does not have this systematics

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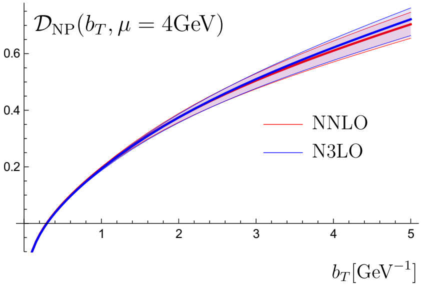
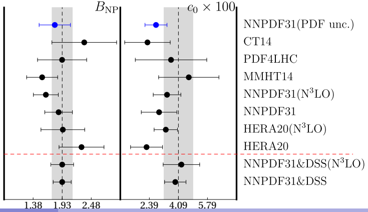
Universal TMD evolution kernel

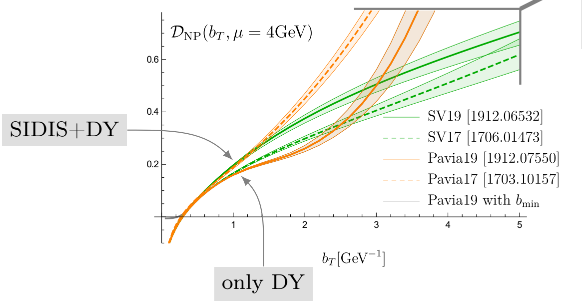


$$\mathcal{D}_{\rm NP}(b,\mu) = \mathcal{D}_{\rm perp}(b^*,\mu) + c_0 b b^*, \qquad b^* = b/\sqrt{1 + b^2/B_{NP^2}}$$

- Linear asymptotic at $b \to \infty$ (ed.assumption)
- RAD is independent on PDF set



Universal TMD evolution kernel
Comparison



- SV19 $\sim b$
- SV17 $\sim b^2$
- Pavia19 $\sim b^4$
- Pavia17 $\sim b^2$

Conclusion

TMD factorization is consistent and universal approach

- Large bulk of data DY+SIDIS described by same TMD distribution (+πDY)
- Extracted NP-functions are (almost) uncorrelated
- Previous estimation of limits for TMD factorization confirmed $q_T/Q < 0.25$
- Perfect perturbative stability
- Target mass corrections and proper definition of the kinematic variables helps
- Strong sensitivity to collinear input (restriction to PDFs?)
- Definite model bias
- Lack external information on distributions (models,lattice,...)

`artemide` v2.02 $\rightarrow$ v2.03 (soon)

https://github.com/VladimirovAlexey/artemide-public

- Bug fixing
- Growing functionality: DY, SIDIS, different in/out-states
- New tools to estimate uncertainties.