Status of TMD studies

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Introduction

In last years significant progress in studies of TMD structure has been made.
The field is pushed to qualitatively new level

- TMD evolution, and perturbative computations
- extractions, and global data analysis
- new tools
- TMD factorization for new processes

AV

- TMD evolution
- unpolarized TMDs

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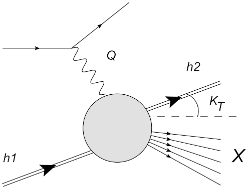
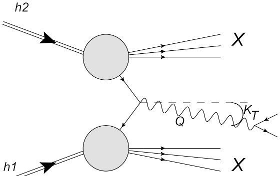
- polarized TMDs

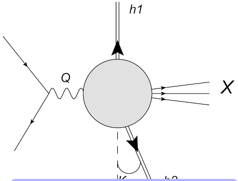
Transverse momentum dependent = TMD



Drell-Yan



SIDIS



$e^+e^- \to h_1 + h_2 + X$

q is momentum of initiating EW-boson
$q^2 = \pm Q^2$
q_T^μ transverse component

$$\begin{cases} Q^2 \gg \Lambda^2_{QCD} \\ Q^2 \gg q_T^2 \end{cases}$$

Many other processes

- TMDs with jets (in jets)
- TMDs in di-hadron production
- TMDs in quarkonia production

[many groups]

TMD factorization

In position space properties of TMD are **MUCH simpler**

$$F(x,b;\mu,\zeta)=\mathcal{F}.\mathcal{T}.[F(x,k_T;\mu,\zeta)]$$

$$\boxed{\frac{d\sigma}{d^2\mathbf{q}_T}=\sum_{ff'}H_{ff'}\Big(\frac{Q}{\mu_Q}\Big)\int d^2b\,e^{i(\mathbf{b}\cdot\mathbf{q}_T)}\,R[b;\mu_Q\to(\mu,\zeta)]F_{f\leftarrow h}(x,b;\mu,\zeta)D_{f'\leftarrow h}(z,b;\mu,\zeta)}$$

- Each data-point is a product (convolution) of **three independent universal non-perturbative** functions
- Each function is responsible for a separate kinematic variable
  - Rapidity AD = CS kernel: $\mathcal{D}$ $\rightarrow$ Q and b
  - TMD PDF: F $\rightarrow$ x and b
  - TMD FF: D $\rightarrow$ z and b

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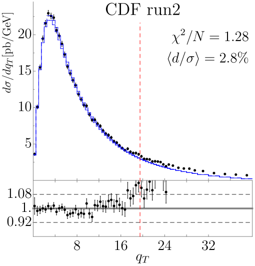
Power corrections $\leftrightarrow$ Domain of applicability

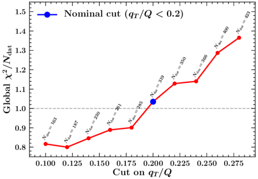
Large Q finite q_T

Power corrections

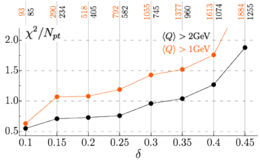
- Theory studies: [Balitsky,Tarasov,17-19],[Ebert,et al,19-20],[Moos,AV,20]
- Phenomenological studies: [Scimemi,AV,17,19],[Bacchetta,et al,19]

$$\frac{q_T^2}{Q^2}_{\text{DY}}, \quad \frac{p_T^2}{z^2Q^2}_{\text{SIDIS}} \quad \lesssim \mathbf{0.2} \;\; \mathbf{-} \;\; \mathbf{0.25}$$



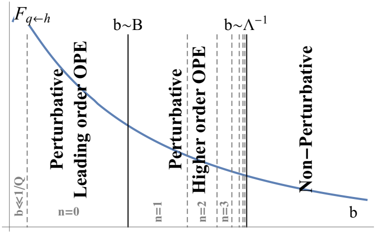


[Bacchetta,et al,19]



[Scimemi,AV,17,19]

Perturbative computations
TMDs and TMD evolution are perturbative at small-b



Great progress in last 2-3 years

- TMD evolution (CS kernel) **N^{3}LO**
  [AV,17; Li,Zhu,17]
- unpolarized TMDs at **N^{3}LO**
  [Ebert,et al,20; Luo,et al,19]
- twist-3/4 computations

table from [Moos,AV,20]

Name	Function	Twist of leading matching	Twist-2 distributions in matching	Twist-3 distributions in matching	Order of leading power coef.function	Ref.
unpolarized	$f_1(x,b)$	tw-2	$f_1(x)$	–	N^{3}LO (α_s^3)	[21, 22]
Sivers	$f_{1T}^{\perp}(x,b)$	tw-3	–	$T(-x,0,x)$	NLO (α_s^1)	[23]
helicity	$g_{1L}(x,b)$	tw-2	$g_1(x)$	$\mathcal{T}_g(x)$	NLO (α_s^1)	[16, 17]
worm-gear T	$g_{1T}(x,b)$	tw-2/3	$g_1(x)$	$\mathcal{T}_g(x)$	LO (α_s^0)	[13, 14]
transversity	$h_1(x,b)$	tw-2	$h_1(x)$	$\mathcal{T}_h(x)$	NNLO (α_s^2)	[19]
Boer-Mulders	$h_1^{\perp}(x,b)$	tw-3	–	$\delta T_\epsilon(-x,0,x)$	LO (α_s^0)	[14]
worm-gear L	$h_{1L}^{\perp}(x,b)$	tw-2/3	$h_1(x)$	$\mathcal{T}_h(x)$	LO (α_s^0)	[13, 14]
pretzelosity	$h_{1T}^{\perp}$	tw-3/4	–	$\mathcal{T}_h(x)$	LO (α_s^0)	eq.(4.8)

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Numerical implementation

artemide

- ζ-prescription
- (unpolarized) NNLO+N^3LL
- (polarized) lin.pol.gluons (NNLO), transversity (NNLO), Sivers ...
- Drell-Yan, SIDIS, SSA's, ...

Nanga Parbat: a TMD fitting framework

- CSS-like
- (unpolarized) NNLO+N^3LL (+N^3LO)
- Drell-Yan

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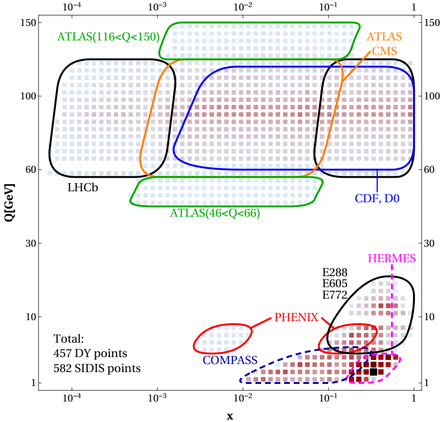
New global extractions = SV19, Pavia19

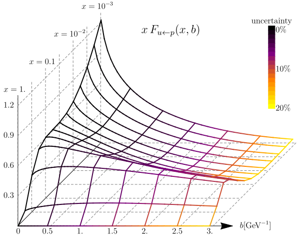
[Scimemi,AV,1912.06532][Bacchetta,et al,1912.07550]

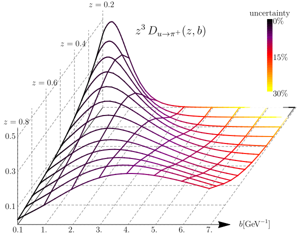


- $2 < Q < 150$GeV
- NNLO+N^{3}LL
- Drell-Yan (**LHC**,Tevatron, PHENIX, fix targets)
- SIDIS (Hermes, Compass)
- πDY (Vpion19) [AV,1907.10356]

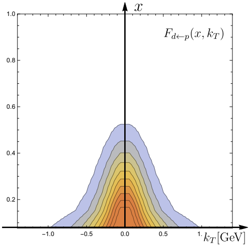
(Do) We know unpolarized TMDs! (?)

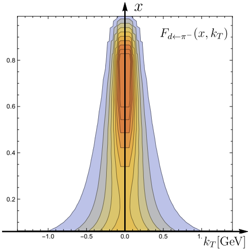
TMDs in b-space





TMDs in k_T-space





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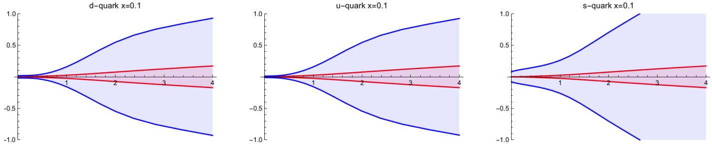
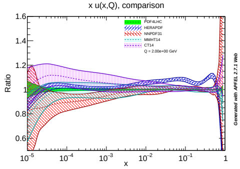
TMDs meet PDFs

$$F(x,b;\mu,\zeta) \simeq \int_x^1 \frac{dy}{y} \underbrace{\left(\delta(1-y) + \alpha_s \left[p(x)\ln\left(\mu^2 b^2\right) + ...\right] + \alpha_s^2 ...\right)}_{\text{known up to N}^3\text{LO}} f_1\left(\frac{x}{y},\mu\right) + b^2...$$

uncertainty band for TMDPDFs





- Impact of PDF input to TMDs is huge, but almost unknown
- This is only the most obvious source o uncertainty

table from [SV19]

PDF set	χ^2/N_{pt}
HERA20	0.97
NNPDF31	1.14
MMHT14	1.34
PDF4LHC	1.53
CT14	1.59
HERA20(N^{3}LO)	1.06
NNPDF31(N^{3}LO)	1.13

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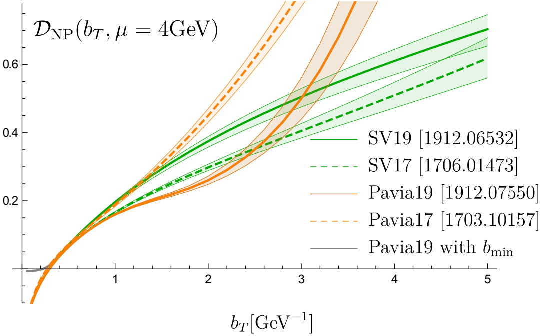
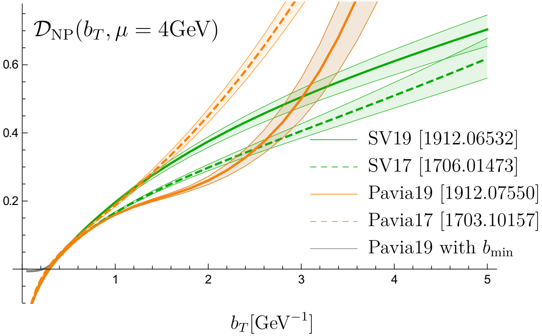
Non-perturbative TMD evolution ⇔ Collins-Soper kernel



- Strong universality: SIDIS, DY, Sivers Asym.
- Obvious disagreement!
- No data that could fix $b > 1.5\text{GeV}^{-1}$.

Non-perturbative TMD evolution ⇔ Collins-Soper kernel



- Strong universality: SIDIS, DY, Sivers Asym.
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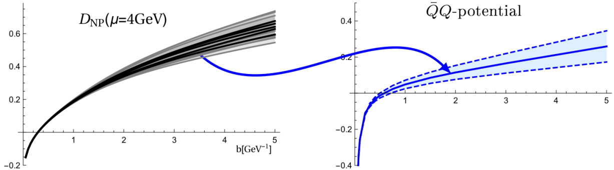
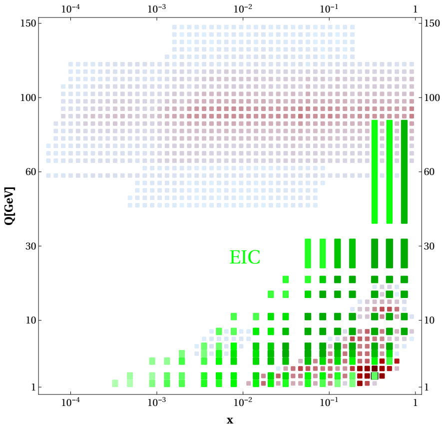
CS-kernel is the function that directly measures properties of **QCD vacuum**

[AV,2003.02288]



EIC will measure TMDs with unprecedented accuracy



- Main channel: SIDIS
- Jets
- Di-hadrons

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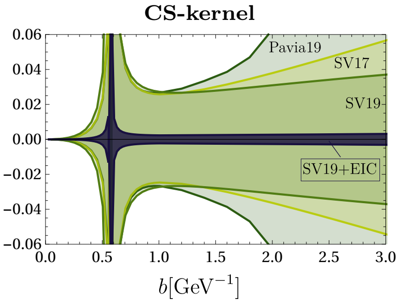
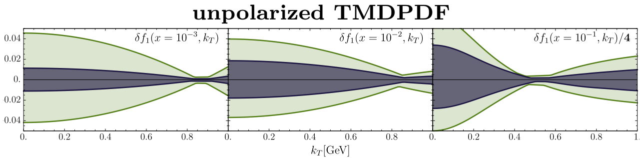
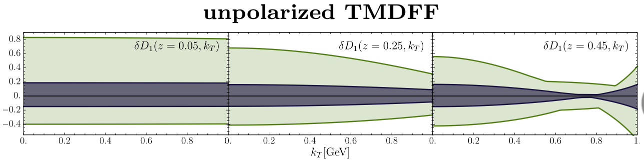


- Huge reduction of uncertainties for CS-kernel
- Large reduction for TMDFF and TMDPDF





Conclusion: unpolarized TMDs

- A lot of new works in theory
- Principally new level of fits and extractions (SV19, Pavia19)
- Joined non-contradictory fits of Drell-Yan and SIDIS

Plenty of direction to investigate

- New ways to measure TMDs
- Incorporation of TMD framework into global QCD picture
- Lattice
- Interpretation

New data

- (close future) LHC, Compass, RHIC, JLAB 12GeV
- (distant future) EIC

This is only unpolarized sector

Polarized→