

Nucleon tomography in momentum space

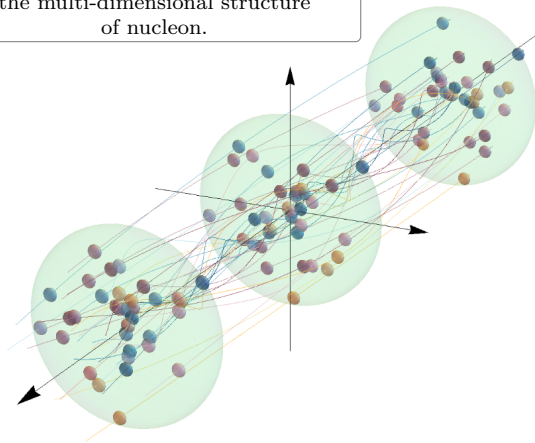
Alexey Vladimirov

IPARCOS meeting **16 June 2022**



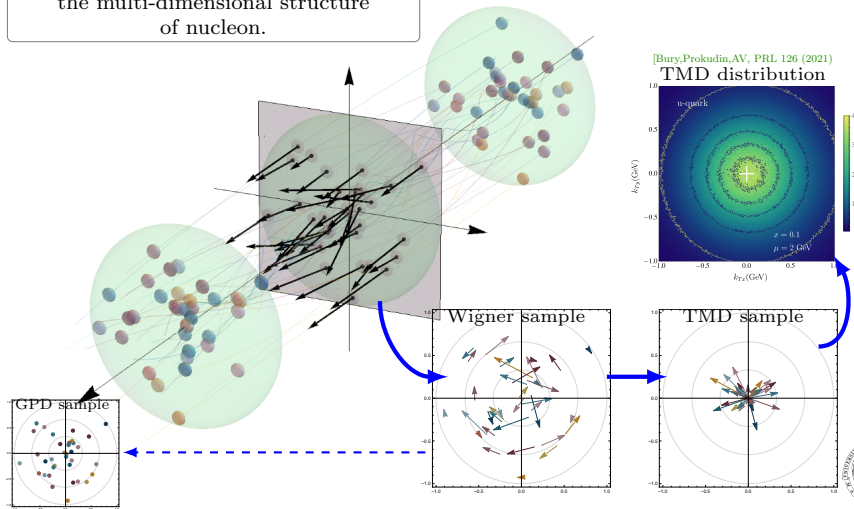
Hadron is a 3D object

Nucleon tomography aims to explore the multi-dimensional structure of nucleon.



Hadron is a 3D object
















Nucleon tomography aims to explore the multi-dimensional structure of nucleon.



There are many TMD distributions
 They describe different correlations between
 quark's and hadron's spin and orbital momenta

Leading Twist TMDs

 : Nucleon Spin  : Quark Spin

		Quark polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = $ 		$h_1^\perp = $  -  Boer-Mulder
	L		$g_1 = $  -  Helicity	$h_{1L}^\perp = $  - 
	T	$f_{1T}^\perp = $  -  Sivers	$g_{1T}^\perp = $  - 	$h_{1T} = $  -  Transversity $h_{1T}^\perp = $  - 

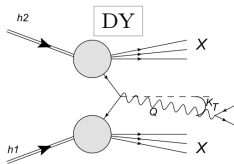
$$F(x, k_T) = f_1(x, k_T^2) - i \frac{(\mathbf{s} \times \mathbf{k}_T)}{M} f_{1T}^\perp(x, k_T^2)$$

- Some TMDs (e.g. Sivers function) do not have analogy in naive/collinear physics



How to extract TMD distributions from the data?

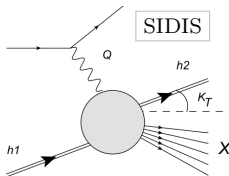




PDF \times PDF

LHC
Tevatron
Fermilab
RHIC

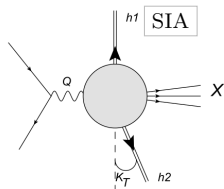
**Best
 studied**



PDF \times FF

COMPASS
HERMES
JLab

**Some
 studies**



FF \times FF

Belle
BES

**Just
 started**



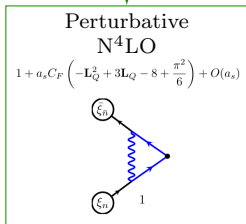
At $Q^2 \gg q_T^2$ structure functions can be expressed via TMD parton distributions
 \Rightarrow **TMD factorization theorem**

$$F_{UU} = \sigma_0 \int \frac{d^2b}{(2\pi)^2} e^{i(bp_T)} C\left(\frac{Q}{\mu}\right) F(x_1, b; \mu, \zeta) F(x_2, b; \mu, \bar{\zeta})$$



At $Q^2 \gg q_T^2$ structure functions can be expressed via TMD parton distributions
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$$F_{UU} = \sigma_0 \int \frac{d^2b}{(2\pi)^2} e^{i(bp_T)} C\left(\frac{Q}{\mu}\right) F(x_1, b; \mu, \zeta) F(x_2, b; \mu, \bar{\zeta})$$



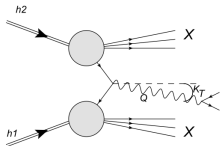
Note: TMDs are defined in b-space (not k_T -space)

Nonperturbative & Universal TMD distributions
 (μ, ζ) -dependence is given by evolution
Leading Twist TMDs

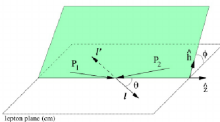
○ : Nucleon Spin ● : Quark Spin

		Quark polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = \odot$		$h_{1T}^\perp = \uparrow - \downarrow$ Boer-Mulder
	L		$g_1 = \odot - \ominus$ Helicity	$h_{1L}^\perp = \odot - \ominus$
	T	$f_{1T}^\perp = \odot - \ominus$ Sivers	$g_{1T}^\perp = \odot - \ominus$	$h_{1T}^\perp = \uparrow - \downarrow$ Transversity





Large amount of structure functions!




$$\begin{aligned}
 \frac{d\sigma}{d^3q d\Omega} &= \frac{\alpha_{em}^2}{Fq^2} \times \text{unpolarized} \\
 &\left\{ \left((1 + \cos^2 \theta) F_{UU}^1 + (1 - \cos^2 \theta) F_{UU}^2 + \sin 2\theta \cos \phi F_{UU}^{\cos \phi} + \sin^2 \theta \cos 2\phi F_{UU}^{\cos 2\phi} \right) \right. \\
 &+ S_{aL} \left(\sin 2\theta \sin \phi F_{LU}^{\sin \phi} + \sin^2 \theta \sin 2\phi F_{LU}^{\sin 2\phi} \right) \\
 &+ S_{bL} \left(\sin 2\theta \sin \phi F_{UL}^{\sin \phi} + \sin^2 \theta \sin 2\phi F_{UL}^{\sin 2\phi} \right) \text{ -- -- -- Sivers} \\
 &+ |\vec{S}_{aT}| \left[\sin \phi_a \left((1 + \cos^2 \theta) F_{TU}^1 + (1 - \cos^2 \theta) F_{TU}^2 + \sin 2\theta \cos \phi F_{TU}^{\cos \phi} + \sin^2 \theta \cos 2\phi F_{TU}^{\cos 2\phi} \right) \right. \\
 &\quad \left. + \cos \phi_a \left(\sin 2\theta \sin \phi F_{TU}^{\sin \phi} + \sin^2 \theta \sin 2\phi F_{TU}^{\sin 2\phi} \right) \right] \\
 &+ |\vec{S}_{bT}| \left[\sin \phi_b \left((1 + \cos^2 \theta) F_{UT}^1 + (1 - \cos^2 \theta) F_{UT}^2 + \sin 2\theta \cos \phi F_{UT}^{\cos \phi} + \sin^2 \theta \cos 2\phi F_{UT}^{\cos 2\phi} \right) \right. \\
 &\quad \left. + \cos \phi_b \left(\sin 2\theta \sin \phi F_{UT}^{\sin \phi} + \sin^2 \theta \sin 2\phi F_{UT}^{\sin 2\phi} \right) \right] \\
 &+ S_{aL} S_{bL} \left((1 + \cos^2 \theta) F_{LL}^1 + (1 - \cos^2 \theta) F_{LL}^2 + \sin 2\theta \cos \phi F_{LL}^{\cos \phi} + \sin^2 \theta \cos 2\phi F_{LL}^{\cos 2\phi} \right) \\
 &+ S_{aL} |\vec{S}_{bT}| \left[\cos \phi_b \left((1 + \cos^2 \theta) F_{LT}^1 + (1 - \cos^2 \theta) F_{LT}^2 + \sin 2\theta \cos \phi F_{LT}^{\cos \phi} + \sin^2 \theta \cos 2\phi F_{LT}^{\cos 2\phi} \right) \right. \\
 &\quad \left. + \sin \phi_b \left(\sin 2\theta \sin \phi F_{LT}^{\sin \phi} + \sin^2 \theta \sin 2\phi F_{LT}^{\sin 2\phi} \right) \right] \\
 &+ |\vec{S}_{aT}| S_{bL} \left[\cos \phi_a \left((1 + \cos^2 \theta) F_{TL}^1 + (1 - \cos^2 \theta) F_{TL}^2 + \sin 2\theta \cos \phi F_{TL}^{\cos \phi} + \sin^2 \theta \cos 2\phi F_{TL}^{\cos 2\phi} \right) \right. \\
 &\quad \left. + \sin \phi_a \left(\sin 2\theta \sin \phi F_{TL}^{\sin \phi} + \sin^2 \theta \sin 2\phi F_{TL}^{\sin 2\phi} \right) \right] \\
 &+ |\vec{S}_{aT}| |\vec{S}_{bT}| \left[\cos(\phi_a + \phi_b) \left((1 + \cos^2 \theta) F_{TT}^1 + (1 - \cos^2 \theta) F_{TT}^2 + \sin 2\theta \cos \phi F_{TT}^{\cos \phi} + \sin^2 \theta \cos 2\phi F_{TT}^{\cos 2\phi} \right) \right. \\
 &\quad + \cos(\phi_a - \phi_b) \left((1 + \cos^2 \theta) \bar{F}_{TT}^1 + (1 - \cos^2 \theta) \bar{F}_{TT}^2 + \sin 2\theta \cos \phi \bar{F}_{TT}^{\cos \phi} + \sin^2 \theta \cos 2\phi \bar{F}_{TT}^{\cos 2\phi} \right) \\
 &\quad + \sin(\phi_a + \phi_b) \left(\sin 2\theta \sin \phi F_{TT}^{\sin \phi} + \sin^2 \theta \sin 2\phi F_{TT}^{\sin 2\phi} \right) \\
 &\quad \left. \left. + \sin(\phi_a - \phi_b) \left(\sin 2\theta \sin \phi F_{TT}^{\sin \phi} + \sin^2 \theta \sin 2\phi F_{TT}^{\sin 2\phi} \right) \right] \right\}. \tag{57}
 \end{aligned}$$



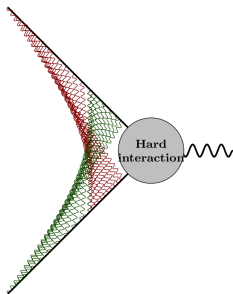
Feature of TMD distributions :
double-scale evolution & **non-perturbative evolution kernel**

$$\mu^2 \frac{d}{d\mu^2} F(x, b; \mu, \zeta) = \gamma_F(\mu, \zeta) F(x, b; \mu, \zeta) \quad \leftarrow \text{UV}$$

$$\zeta \frac{d}{d\zeta} F(x, b; \mu, \zeta) = -\mathcal{D}(b, \mu) F(x, b; \mu, \zeta) \quad \leftarrow \text{Rapidity}$$


CS kernel

This structure comes from the involved form of TMD operator (infinite staple gauge link)



Collins-Soper (CS) kernel
describes long-range forces of QCD.
It is one of the most fundamental observable
which provides us information about QCD vacuum.

[AV, PRL,125 (2020) 19]



Each experimental point is a convolution of
two TMDs and the CS kernel

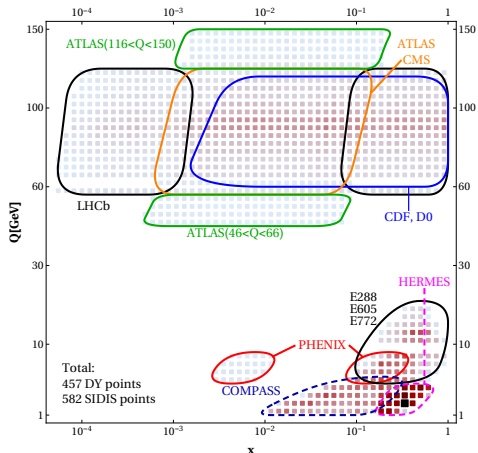
$$\frac{d\sigma}{dX} = \sigma_0 \int \frac{d^2b}{(2\pi)^2} e^{i(bp_T)} C\left(\frac{Q}{\mu}\right) R[\mathcal{D}, \mu, Q] F(x_1, b) F(x_2, b)$$

To disentangle these functions one needs

- ▶ Multi-differential cross-section
- ▶ Large coverage

Requires combining together several experiments





SV19 extraction

► Data

- Large energy span:
 $2 < Q < 150 \text{ GeV}$
- SIDIS+DY
- $q_T < 0.25 Q$

► Theory

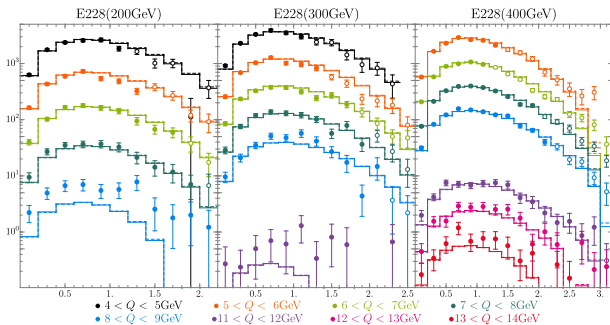
- $N^3\text{LO}$ evolution ← [AV, PRL 118 (2017)]
- NNLO collinear matching ← [Echevarria, Scimemi, AV, JHEP 09 (2018)]
- ζ -prescription ← [Scimemi, AV, JHEP 08 (2018)]

- **artemide** ← github.com/VladimirovAlexey/artemide-public

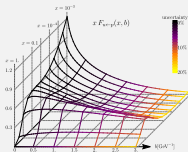
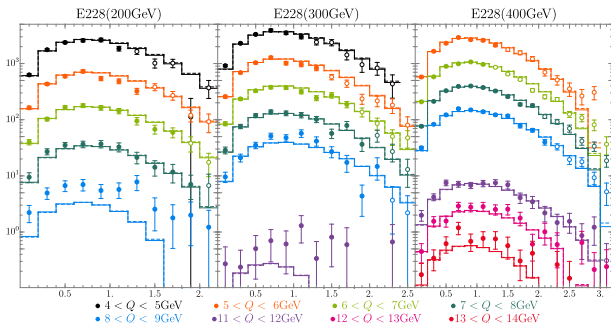


Example of data description

Mid/Low-energy Drell-Yan

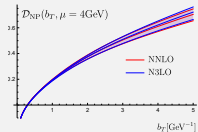


Example of data description Mid/Low-energy Drell-Yan

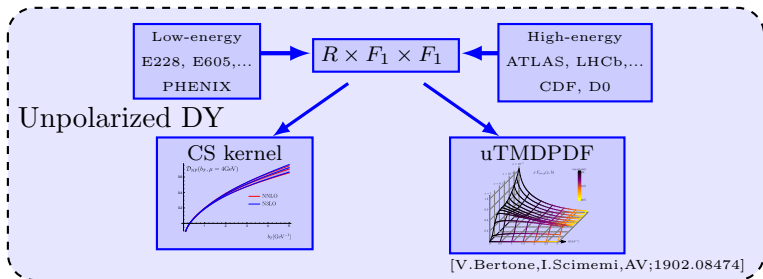


Using DY data we extract
CS-kernel and unpolarized
TMDPDF

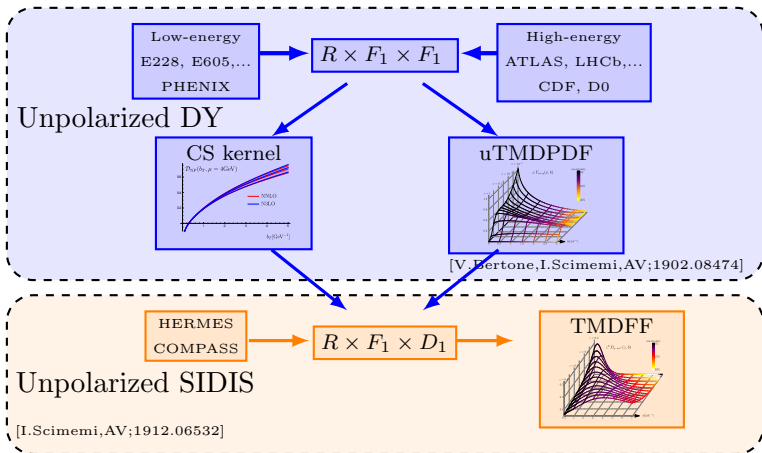
**This is only the first
step!**



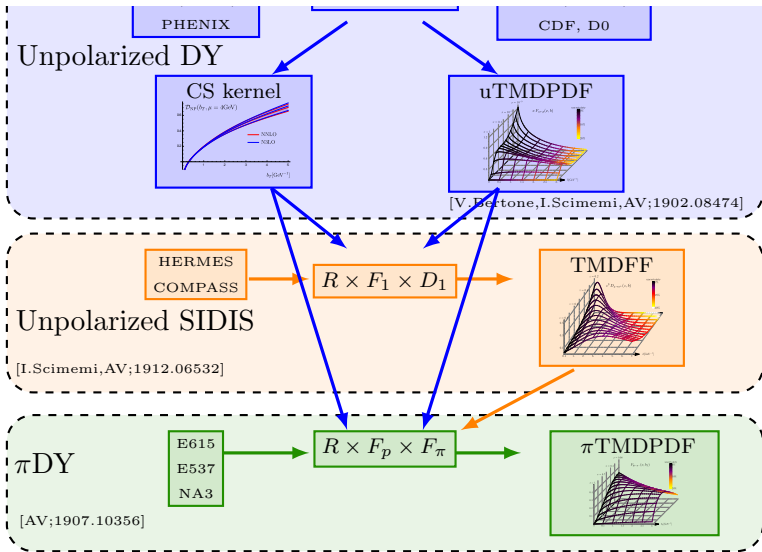
Universality & the chain of extractions



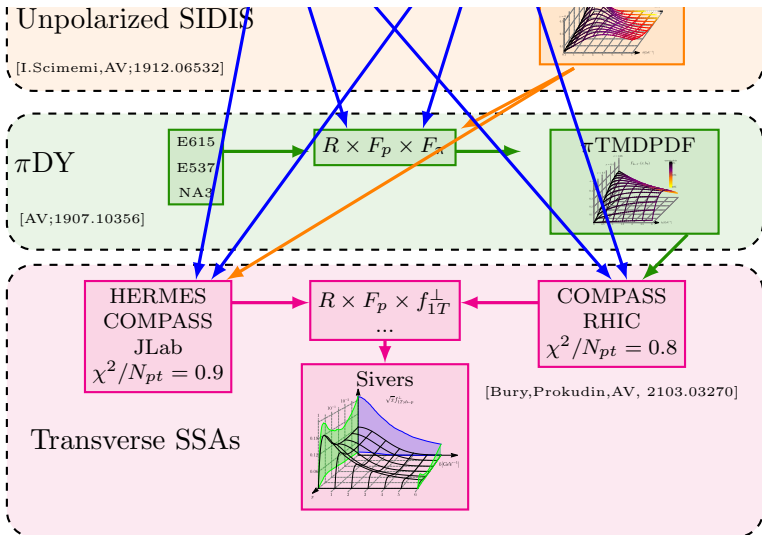
Universality & the chain of extractions



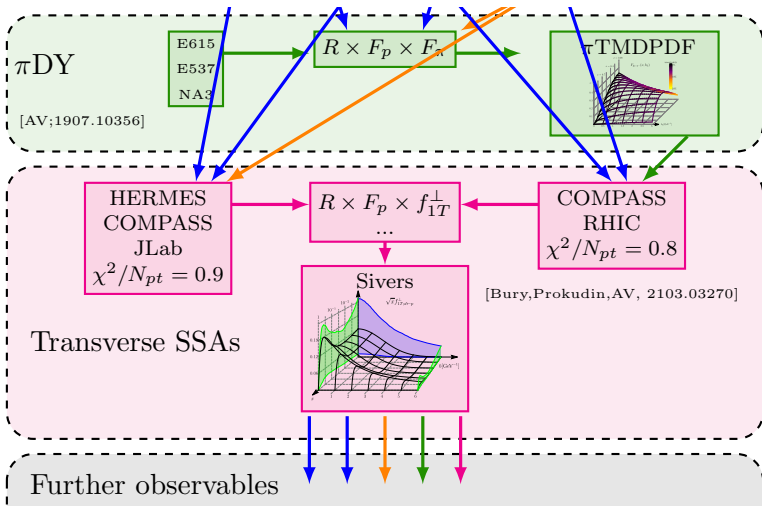
Universality & the chain of extractions



Universality & the chain of extractions



Universality & the chain of extractions

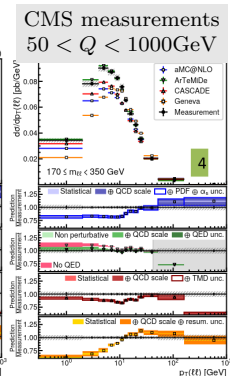
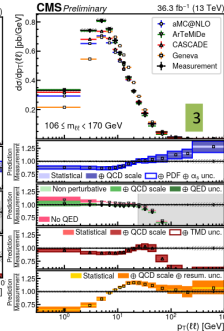
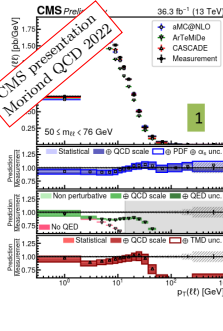


Why is it useful/interesting?
[in two words]



artemide is used by many experiments for generation of predictions

CMS presentation
Moriond QCD 2022



unpol. DY:
CMS
LHCb
RHIC

π DY:
COMPASS

DY-SSA:
RHIC

unpol.SIDIS:
COMPASS
JLab

SIDIS-SSA:
JLab

- aMC@NLO+ Pythia8 gives overall good description
 - Failing to describe the low p_T , failure increasing for higher m_{ll}
- ArTeMiDe gives perfect description in its validity region
 - The QED FSR, added to the prediction from aMC@NLO+ Pythia8 sample, shows the effect of migrations to low mass from the Z peak

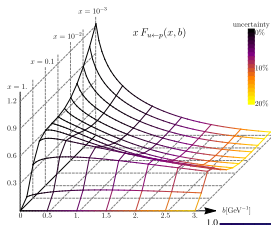


Tomographic picture of nucleon

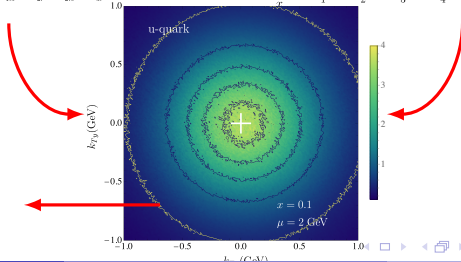
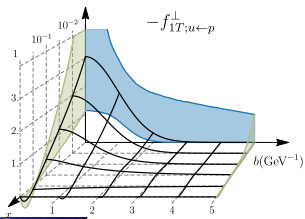
Momentum density of an **unpolarized** quark in a **polarized** hadron

$$\rho_{1; q \leftarrow h^\uparrow}(x, \mathbf{k}_T, \mathbf{S}_T, \mu) = f_{1; q \leftarrow h}(x, k_T; \mu, \mu^2) - \frac{k_T x}{M} f_{1T; q \leftarrow h}(x, k_T; \mu, \mu^2)$$

unpolarized TMDPDF



Sivers TMDPDF

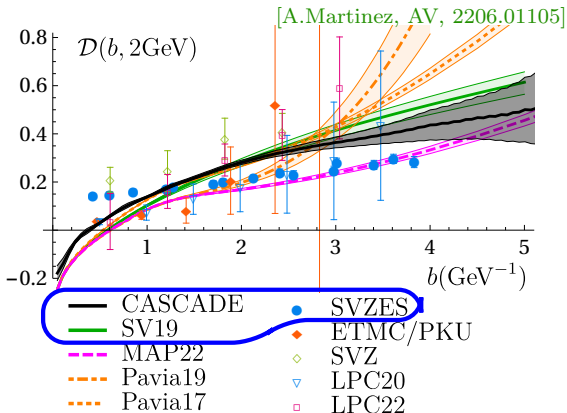


[PDG, 2022]



Collins-Soper kernel
 Exploring QCD vacuum structure with collider data

[AV, PRL,125 (2020) 19]



Lattice calculations

From the ratios of
 “quasi-TMD” distributions

[AV, Schäfer, 2002.07527]

Directly

From the “proper” ratios of
 cross-sections

[A.Martinez, AV, 2206.01105]

Each approach has
 its own systematic
 uncertainties

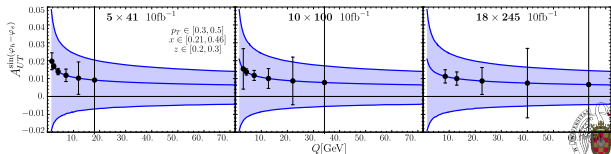
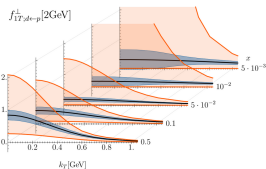


These are only a few examples

- ▶ Collinear distributions
- ▶ Spin and orbital momentum structure
- ▶ Sum-rules [spin, mass, tensor-charge]
- ▶ Beyond SM studies [W-mass]
- ▶ ...

At present **nucleon tomography** has **detailed theory** which is able to describe the **modern generation of experiments**.

But in the (nearest) future, the next generation of experiments will require a **better/more accurate theory/techniques**.



Backup slides



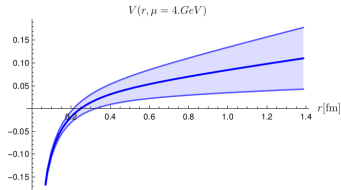
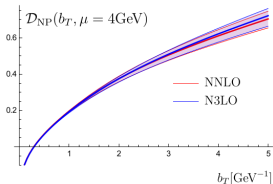
Collins-Soper kernel

- ▶ CS-kernel was introduced long ago [Collins, Soper, Sterman, 1982-1985]
- ▶ The fundamental importance for QCD has been recognized recently
 - ▶ Decorrelation from the TMD distributions [I.Scimemi, AV, JHEP 08 (2018)]
 - ▶ Duality to jet-production [AV, Phys.Rev.Lett. 118 (2017)]

$$\mathcal{D}(b, \epsilon^*) = 2\gamma_{\text{jet}}(\theta(b))$$

- ▶ Definition and interpretation [AV, Phys.Rev.Lett. 125 (2020)]

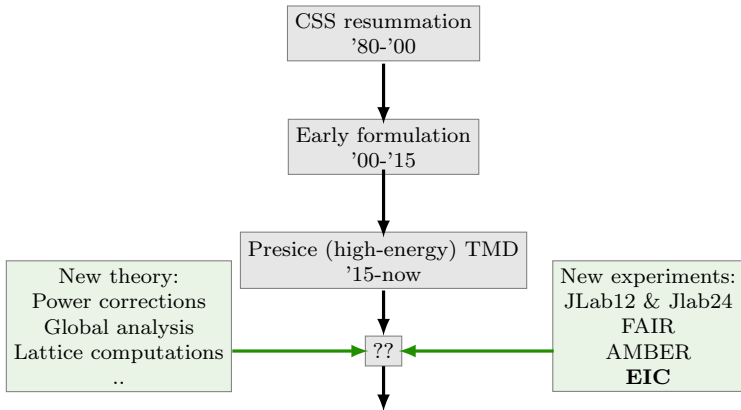
$$\mathcal{D}(b) \simeq \int_0^1 d\beta \langle 0 | b^\nu F_{\nu+}(\beta b) [\text{staple contour}] | 0 \rangle$$



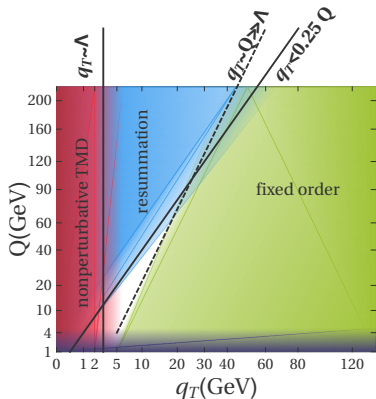
$$V(r) = r \frac{\pi}{4} \mathcal{D}''(0) + \frac{\mathcal{D}'(0)}{2} + \frac{r^2}{2} \int_r^\infty \frac{dx}{x^2} \frac{\mathcal{D}'(x)}{\sqrt{x^2 - r^2}} + \dots$$



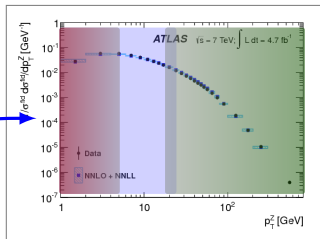
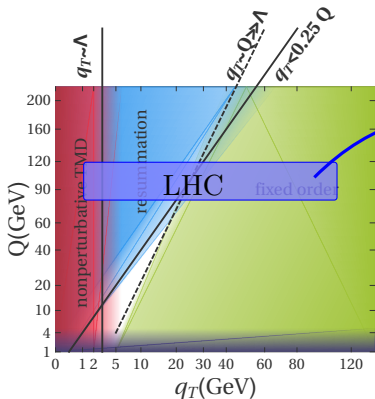
What is next?



TMD factorization is a very developed science
 In fact, it is as good (and even better) than the collinear factorization
 But **there are important limitations**



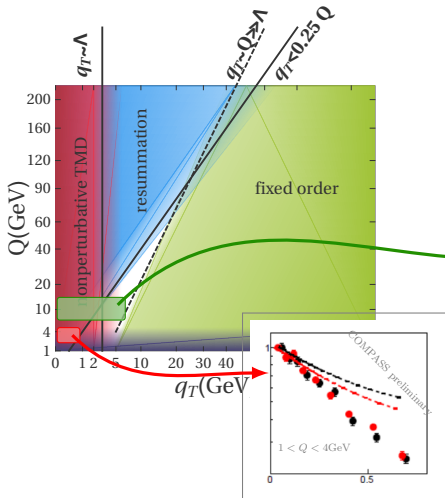
TMD factorization is a very developed science
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 But **there are important limitations**



At high-energy (such as LHC)
 different factorization regions overlap
 therefore, the interpolation makes a good job.

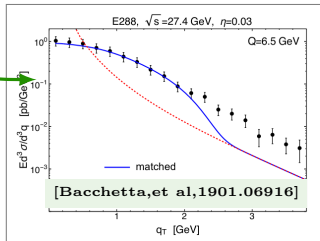


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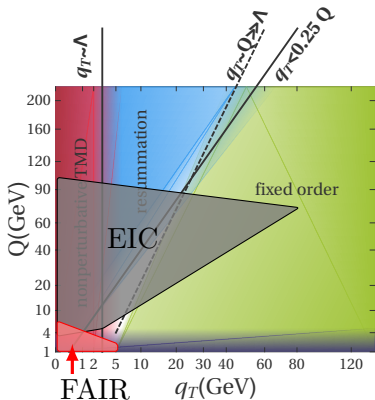


LP TMD factorization has
 limited region of application.

For SIDIS it cuts
the most part of the data



TMD factorization is a very developed science
 In fact, it is as good (and even better) than the collinear factorization
 But **there are important limitations**



Phase space of all future experiments
 are centered directly in
 the transition region

COMPASS, JLab
 have large contribution of power corrections

Important!
 Similar problem is foreseen
 for GPD physics



The key to the problem is power corrections!
However, this is a very difficult problem of QCD (in general), and especially for multi-dimensional measurements.

For the last ~ 2 years I concentrate on power corrections

- ▶ Power corrections to lattice observables [V.Braun,AV,18-21]
- ▶ Target mass corrections to TMDs (all powers!) [V.Moos,AV,JHEP 12 (2020)]
- ▶ **TMD operator expansion** [AV,V.Moos,I.Scimemi,JHEP 01 (2022)]
 - ▶ Novel method for TMD factorization
 - ▶ Next-to-leading power expression at NLO
 - ▶ Operator-level formalism
- ▶ TMDs of twist-3 (the first systematic study) [S.Rodini,AV, 2204.03856]
- ▶ Factorization for lattice-TMD operator at NLP [S.Rodini,AV, in prep.]



	U	L	T_{odd}	T_{even}	T_{odd}	T_{even}
U	β_1	β_2	β_3	β_4	β_5	β_6
L	β_7	β_8	β_9	β_{10}	β_{11}	β_{12}
T_{odd}	β_{13}	β_{14}	β_{15}	β_{16}	β_{17}	β_{18}
T_{even}	β_{19}	β_{20}	β_{21}	β_{22}	β_{23}	β_{24}

Table 1. Quick TFD distribution of reninlike vertex with respect to polarization properties of both the operator (horizontal) and the leading tensor. The labels U, L and T are for the unphysical, longitudinal and transverse polarization. The subscripts J differentiate different angular momentum for the transverse-polarized case. The table is similar to the \mathbb{R}^3 table.

$$P_{\text{odd}}^{\text{TT}}(s_1, s_2, s_3, s_4, s_5, s_6) = -4s_1^2 s_2^2 (s_1, s_2, s_3 - \beta_3 - \beta_4).$$

The PT transformation gives

$$P_{\text{odd}}^{\text{TT}}(s_1, s_2, s_3, s_4, s_5, s_6, s_7, s_8) = -4s_1^2 s_2^2 s_7^2 s_8^2 (s_1, s_2, s_3 - \beta_3 - \beta_4), \quad (4.3)$$

$$P_{\text{even}}^{\text{TT}}(s_1, s_2, s_3, s_4, s_5, s_6, s_7, s_8) = +4s_1^2 s_2^2 s_7^2 s_8^2 (s_1, s_2, s_3 - \beta_3 - \beta_4).$$

Note that, due to the composition of momentum fraction s_i 's in the definition (4.1), the form of the eight spin functions with quark and antiquark labels (4.3) is preserved.

The evolution equations for Φ_4 and Φ_8 are

$$s^2 \frac{d}{ds} \Phi_4^{\text{TT}} = \left(\frac{1}{s} \ln \left(\frac{s}{s_0} \right) + \gamma_{\text{anom}} \right) \Phi_4^{\text{TT}} + 2s \Theta_{\text{anom}} \Phi_4^{\text{TT}} \\ + \beta_{13}^{\text{TT}} \left(s_1^2 s_2^2 s_3^2 s_4^2 s_5^2 + s_1^2 s_2^2 s_3^2 s_4^2 s_6^2 \right) \\ + \beta_{14}^{\text{TT}} \left(s_1^2 s_2^2 s_3^2 s_4^2 s_5^2 + s_1^2 s_2^2 s_3^2 s_4^2 s_6^2 \right), \quad (4.4)$$

$$s^2 \frac{d}{ds} \Phi_8^{\text{TT}} = \left(\frac{1}{s} \ln \left(\frac{s}{s_0} \right) + \gamma_{\text{anom}} \right) \Phi_8^{\text{TT}} - 2s \Theta_{\text{anom}} \Phi_8^{\text{TT}} \\ + \beta_{19}^{\text{TT}} \left(s_1^2 s_2^2 s_3^2 s_4^2 s_5^2 + s_1^2 s_2^2 s_3^2 s_4^2 s_6^2 \right) \\ + \beta_{20}^{\text{TT}} \left(s_1^2 s_2^2 s_3^2 s_4^2 s_5^2 + s_1^2 s_2^2 s_3^2 s_4^2 s_6^2 \right).$$

where it may read that $\gamma_{\text{anom}} = \gamma_{\text{anom}}^{\text{TT}}(s_1, s_2, s_3, s_4, s_5, s_6) = -\Theta_{\text{anom}}^{\text{TT}}(s_1, s_2, s_3, s_4, s_5, s_6) = P_{\text{odd}}^{\text{TT}}(s_1, s_2, s_3, s_4, s_5, s_6) = -\beta_3 - \beta_4$.

In this representation the evolution kernel are real. An amusing feature of these evolution equations is that they mix the functions with different T-parity. However, the mixing terms are proportional to s , which changes sign under $s \rightarrow -s$. Thus the T-parity of each vertex is preserved, and it remains purely independent (up to trivial sign-change for T-odd functions). To our best knowledge, it is the first example of such behavior.

4.2 Parameterization

The discussion is natural enough to allow us to introduce the parameterization for the TFD evolution in the sense of TFD distributions. For each TFD evolution we write all possible spin and tensor structures in accordance to its parity and dimension. As an example of constructing one can see the vertices Φ^{TT} and Φ^{LT} , and the tensors Φ^{TT} and Φ^{LT} . The spin vector is split into the

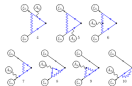


Figure 6. The three-point diagrams contributing to the NLO of the effective operator. The diagrams with β_1, \dots, β_6 , and lines with $\nu = 1$ should be added. The labels indicate the type of background field. The blue lines are the dynamical fields.

As a result¹ of the two-point diagram is

$$s^2 \frac{d}{ds} \left(\frac{1}{s} \ln \left(\frac{s}{s_0} \right) - \frac{\gamma_{\text{anom}}(s)}{s} \right) \frac{d}{ds} \frac{1}{s} \ln \left(\frac{s}{s_0} \right) \\ + 2s^2 \left(\beta_{13}^{\text{TT}} (s_1^2 s_2^2 s_3^2 s_4^2 s_5^2 + s_1^2 s_2^2 s_3^2 s_4^2 s_6^2) + \beta_{14}^{\text{TT}} (s_1^2 s_2^2 s_3^2 s_4^2 s_5^2 + s_1^2 s_2^2 s_3^2 s_4^2 s_6^2) \right) \\ + 4s^2 (1 - \nu) (s^2 - s^2 \nu^2) \beta_{13}^{\text{TT}} (s_1^2 s_2^2 s_3^2 s_4^2 s_5^2 + s_1^2 s_2^2 s_3^2 s_4^2 s_6^2) \\ + 4s^2 (1 - \nu) (s^2 - s^2 \nu^2) \beta_{14}^{\text{TT}} (s_1^2 s_2^2 s_3^2 s_4^2 s_5^2 + s_1^2 s_2^2 s_3^2 s_4^2 s_6^2). \quad (4.5)$$

The operators for vertex diagrams is equal to eq. (4.4) with $s \rightarrow -s$. Note, that the last two lines can be rewritten with tensor derivatives, reproducing the operator J_2^{TT} eq. (3.10).

The operator in the second line of eq. (4.5) is the $\mathcal{O}_2^{\text{TT}}$ current of eq. (3.10). As expected, the coefficient functions for all terms of J_2^{TT} are the same, such that the current conservation eq. (3.12) is preserved. Since the contributions to NLP part is the result of the combination of several diagrams, it gives a strong check of our computation.

Three-point diagrams

The three-point diagrams are shown in fig. 6. The diagrams 7-10 are specific for the composite background field and would be absent in the usual background field computation. Note, that the three-gluon vertex that appears in diagrams 6 and 7 is not equal to three-gluon vertex in QCD but has a modification that comes from the background-gauge gauge-fixing condition.

The computation of these diagrams is straightforward and described in details in appendix B. Here we present the final expression for the sum of three-point diagrams. For convenience we add the $\mathcal{O}_2^{\text{TT}}$ part of the two-point diagrams, such that the result is the full expression for the coefficient

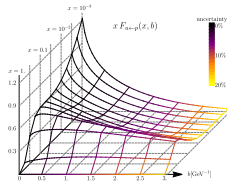
So far, pure theory



$$\lim_{b \rightarrow 0} F(x, b) \simeq C(x, \ln(b^2)) \otimes f(x) + \text{power corrections}$$

[Echevarria, Scimemi, AV, 1604.07869]
 [Gutierrez-Reyes, et al, AV, 1907.03780]
 [Scimemi, Tarasov, AV, 1901.04519]
 [Moos, AV, 2008.01744]
 ...

unpolarized TMDPDF

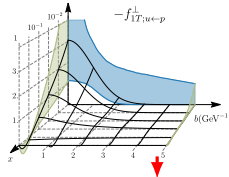


PDF are used as input
PDF - bias

[AV, et al, 2201.07114]

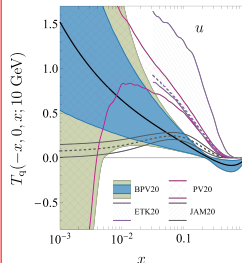
Joined analysis of
 TMD + collinear data

Sivers TMDPDF



Determining twist-3 PDF

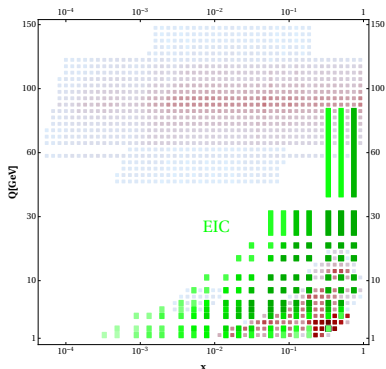
$$T_q \sim \langle h | \bar{q} F q | h \rangle$$



Next generation of experiments

EIC, FAIR, AMBER, JLab24, EICC

Each of them has a research program dedicated to nucleon tomography



Complimentary

Altogether EIC, FAIR, AMBER, JLab24 will be able to measure relevant cross-section with **unprecedented precision in a wide kinematic range**

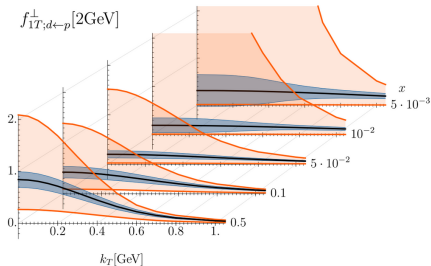
- ▶ from low energy [FAIR]
- ▶ till high energy [EIC]



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