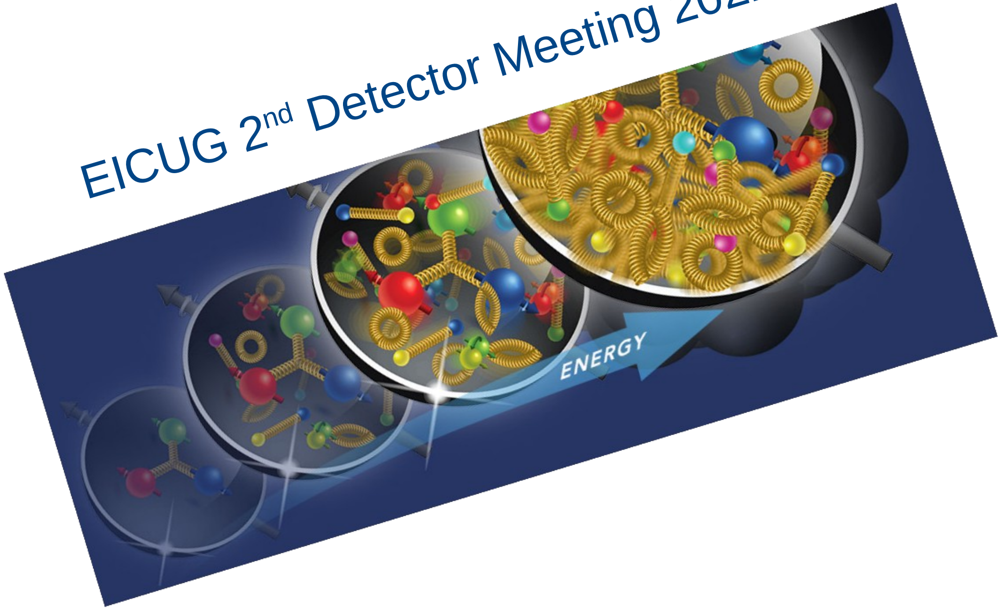
TMDs@EIC

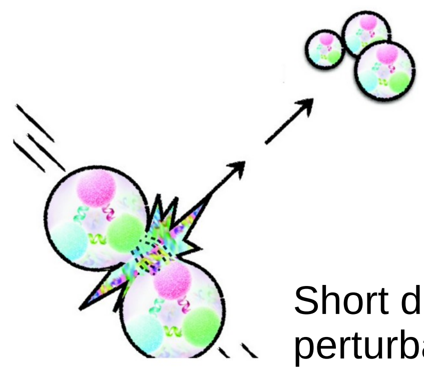
M. Boglione

EICUG 2nd Detector Meeting 2022



QCD@EIC

QCD
- Confinement
- Asymptotic Freedom

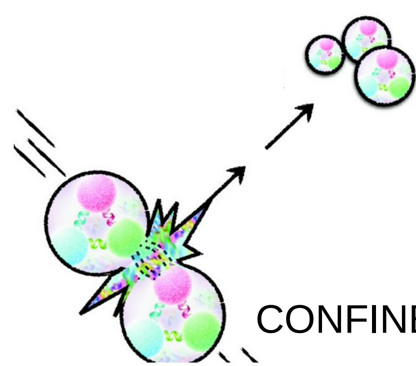


Long distance physics, non-perturbative structure functions.

Short distance effects, perturbative QCD

QCD
- Perturbative regime (computable but process dependent terms)
- Non perturbative regime (non computable but universal terms)

Strong interactions: **hadron structure** is a playground for QCD@Work !



HADRONIZATION

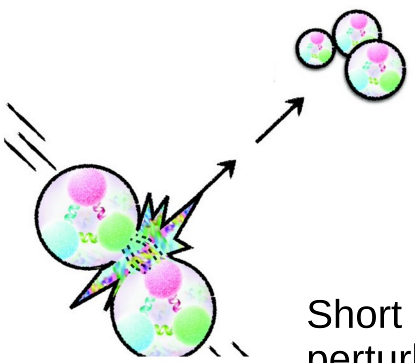
CONFINEMENT

QCD@EIC

QCD

Non perturbative regime (non computable but universal terms)

Perturbative regime (computable but process dependent terms)



Long distance physics, non-perturbative structure functions.

Short distance effects, perturbative QCD

- The interplay between **perturbative** and **non-perturbative** regimes is currently one of the most challenging aspects in phenomenology, which will be explored at the EIC
- **Factorization** allows to separate the perturbative content of an observable from its non-perturbative content. At large Q and small m, the non-perturbative contributions are separated out from anything that can be computed by using perturbative techniques, and identified with universal quantities (structure functions).
- **Factorization** restores the predictive power of QCD

Factorization: region classification

J. Collins, Foundations of perturbative QCD (Cambridge University Press, 2011)

Particles are classified according to how they propagate in space, i.e. according to their virtuality.

Momentum regions:

HARD

$k \sim (Q,\, Q,\, Q)$

Short-distance contributions → Large virtuality

Long-distance contributions → Low virtuality

SOFT

$k \sim (\lambda_S,\, \lambda_S,\, \lambda_S)$

$$\lambda_S = \lambda^2/Q$$

COLLINEAR

$k \sim (Q,\, \lambda^2/Q,\, \lambda)$

Factorization theorem

General structure of a generic factorization theorem:

$$\mathcal{O} = H \times \boxed{S \times \prod_j C_j} + p.s.$$

IR-safe hard contribution

Soft and collinear contributions, accounting for non-perturbative effects

Power suppressed terms

- Each term is equipped with proper subtractions.
- The soft factor S encodes the *correlation* among the various collinear parts.
- While H can be computed in pQCD, S and C have to be determined using non perturbative methods. For instance they can be modeled and extracted from experimental data, or computed in lattice QCD

TMD observables

The 3D hadron structure and transverse momentum dependence (TMD)

- Observables that carry information about the **transverse motion** of partons inside the hadrons are of primary interest in modern studies of QCD, as they encode very rich information about the 3D hadron structure and transverse spin effects.
- The **TMD factorization** of such observables is one of the most important and challenging approach to investigate the non-perturbative core of QCD, as well as spin-spin and spin-momentum correlations between the hadrons and their constituents.

Quark-quark correlation matrix

$$\Phi_{i\,j}(k,P,S) = \mathrm{F.T.}\langle P\,S|\overline{\psi}_j(0)\,W[0,\xi]\,\psi_i(\xi)|P\,S\rangle$$

- Dirac algebra expansion
- $\xi = \left(0, \xi^-, \vec{\xi}_T\right)$
- Leading Twist (Twist-2)

Contributions @ LP
(power counting)

quark pol.

nucleon pol.	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

8 TMD PDFs at leading twist

TMD observables

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U	f_1		$h_1^\perp$
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T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

8 TMD PDFs at leading twist

quark pol.

hadron pol.	U	L	T
U	D_1		$H_1^\perp$
L		G_{1L}	$H_{1L}^\perp$
T	$D_{1T}^\perp$	G_{1T}	$H_1,\ H_{1T}^\perp$

8 TMD FFs at leading twist

Collinear factorization

J. Collins, Foundations of perturbative QCD (Cambridge University Press, 2011)

$q_T \gtrsim Q$

There is *enough* transverse momentum to produce jets at wide angles in the final state.

The low transverse momenta of the struck parton, the fragmenting parton and soft radiation are totally negligible

The soft factor becomes a trivial unit matrix in color space

All the hard jets are included into the hard part

Typical collinear factorization

Terms that encode non-perturbative effects:

- Collinear factor associated with the **target**
- Collinear factor associated with the **detected hadron**

None of them carry TMD information.

$$d\sigma = \sum_{j,j'} H_{j,j'} \otimes f_{j,\,h_1}(x) \otimes d_{j',\,h_2}(z)$$

TMD factorization

J. Collins, *Foundations of perturbative QCD* (Cambridge University Press, 2011)

$q_T \ll Q$ → The production of hard jets with high transverse momentum is strongly suppressed → The low transverse momenta of the struck parton, the fragmenting parton and soft radiation are *relevant*

The soft factor is a vacuum expectation value of Wilson lines

The hard part accounts for the sole virtual radiation.

Soft radiation correlates collinear terms

Terms that encode the non-perturbative effects:

- Collinear factor associated with the **target**
- Collinear factor associated with the **detected hadron**
- Soft factor correlating them.

All of them carry TMD information.

$$\widetilde{d\sigma} = \sum_{j,j'} H_{j,\,j'} F_{j,\,h_1}(x, b_T)\, S(b_T)\, D_{j',\,h_2}(z, b_T)$$

Rapidity divergences

- Rapidity divergences are introduced by the approximations induced by factorization
- Problematic for TMD factorization.
- Rapidity divergences are ultimately associated to Wilson lines along the light-cone:

Eikonal propagators $\sim \dfrac{1}{k^+ + i\,0}$ and $y = \dfrac{1}{2} \log \dfrac{k^+}{k^-}$

Collins' regulator: soft Wilson lines are tilted off the light-cone:

$(1,\, 0,\, \vec{0}_T) \to (1,\, -e^{-2\,y_1},\, \vec{0}_T),$ $\quad y_1$ Large and positive

$(0,\, 1,\, \vec{0}_T) \to (-e^{2\,y_2},\, 1,\, \vec{0}_T),$ $\quad y_2$ Large and negative

Analogous to introducing a **rapidity cut-offs**

$$\widetilde{d\sigma} = \sum_{j,j'} H_{j,\,j'} \underbrace{F_{j,\,h_1}(x, b_T)}_{-\infty < y < y_2} \underbrace{S(b_T)}_{y_2 < y < y_1} \underbrace{D_{j',\,h_2}(z, b_T)}_{y_1 < y < +\infty}$$

The dependence on rapidity cut-offs is cancelled in the final result

Soft factor and soft/collinear subtraction

$$\frac{d\sigma}{dq_T} = \mathcal{H}_{\text{proc.}} \int \frac{d^2\vec{b}_T}{(2\pi)^2} e^{i\vec{q}_T\cdot\vec{b}_T} \, F(b_T)\, S(b_T)\, D(b_T)$$

TMDs are defined through the **factorization definition**:

$$D(z,\, b_T,\, y_1) = \lim_{\hat{y}\to-\infty} \frac{D^{\text{uns.}}(z,\, b_T,\, y_P - \hat{y})}{S(b_T,\, y_1 - \hat{y})}$$

From quark-quark correlation matrix

Subtraction of soft-collinear overlapping

The soft factor (included the subtraction term) is defined as:

$$S(b_T,\, y_1 - y_2) = \frac{\text{Tr}}{N_C} \langle 0|W^{\dagger}_{n_2}[\vec{b_T}/2,\infty]\, W_{n_1}[\vec{b_T}/2,\infty] \times W_{n_2}[-\vec{b_T}/2,\infty]\, W^{\dagger}_{n_1}[-\vec{b_T}/2,\infty]|0\rangle$$

The soft factor of the process and the soft factor of subtractions are the same function!

Square root definition of TMDs

S. M. Aybat and T. C. Rogers, Phys.Rev. D83, 114042 (2011)

sqrt.

$$\frac{d\sigma}{dq_T} = \mathcal{H}_{\text{proc.}} \int \frac{d^2\vec{b}_T}{(2\pi)^2} e^{i\vec{q}_T\cdot\vec{b}_T}\, F(b_T)\, \cancel{\mathbb{S}_{2\text{-h}}}(b_T)\, D(b_T) =$$

sqrt.

Recasting terms

Parton model-like

$$= \mathcal{H}_{\text{proc.}} \int \frac{d^2\vec{b}_T}{(2\pi)^2} e^{i\vec{q}_T\cdot\vec{b}_T}\, F^{\text{sqrt}}(b_T)\, D^{\text{sqrt}}(b_T)$$

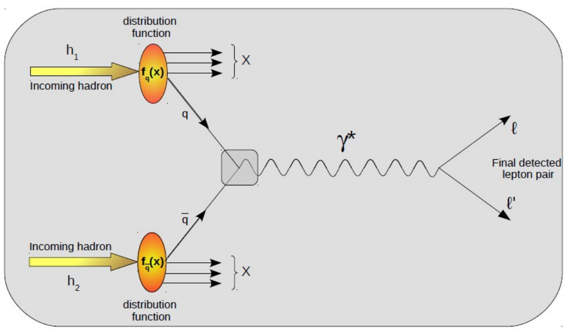
See also talk by Sergio Leal Gomez

Square-root definition of the TMD:

$$D^{\text{sqrt}}(z,\, b_T,\, y_n) = \lim_{\substack{\widehat{y}_1\to+\infty \\ \widehat{y}_2\to-\infty}} D^{\text{uns.}}(z,\, b_T,\, y_P - \widehat{y}_2)\sqrt{\frac{S(b_T,\, \widehat{y}_1 - y_n)}{S(b_T,\, \widehat{y}_1 - \widehat{y}_2)\, S(b_T,\, y_n - \widehat{y}_2)}}$$

Where do we learn about TMDs?

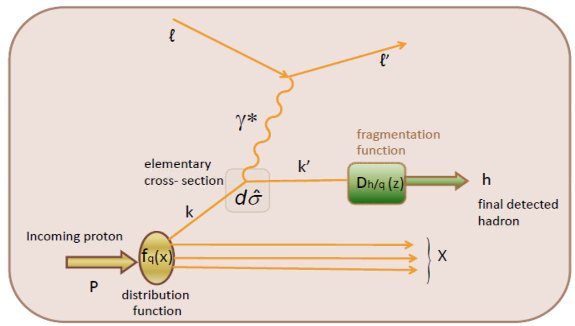
Unpolarized and Polarized Drell-Yan scattering



$$\sigma_{Drell-Yan} = f_q(x,k_\perp) \otimes f_{\bar{q}}(x,k_\perp) \otimes \hat{\sigma}^{q\bar{q}\to \ell\ell'}$$

Allows extraction of distribution functions

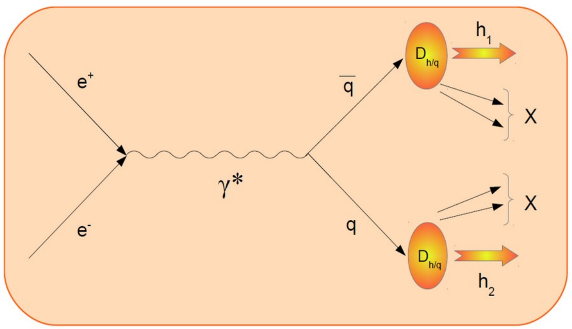
Unpolarized and Polarized SIDIS scattering



$$\sigma_{SIDIS} = f_q(x) \otimes \hat{\sigma} \otimes D_{h/q}(z)$$

Allows extraction of distribution and fragmentation functions

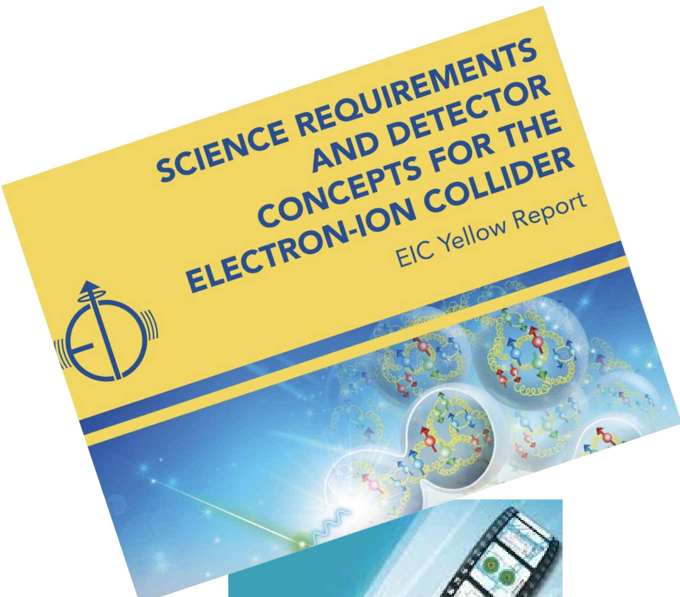
$e^+ e^- \to h_1\, h_2\, X$

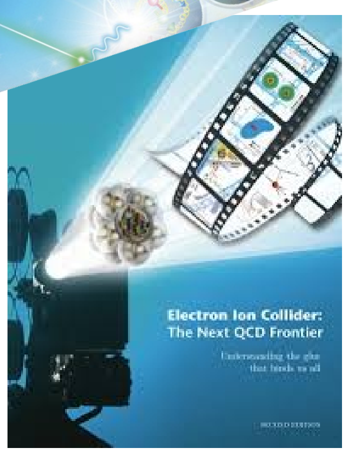


$$\sigma_{h1\,h2} \propto D(z_1) \otimes D(z_2) \otimes \hat{\sigma}$$

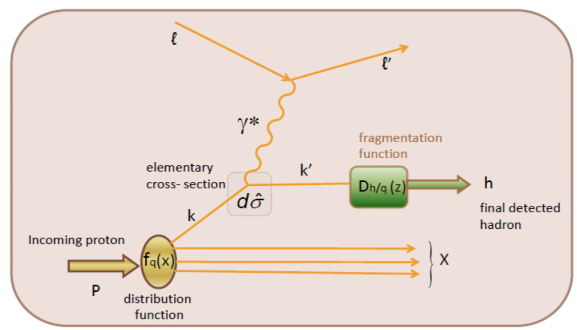
Allows extraction of fragmentation functions

Where do we learn about TMDs?





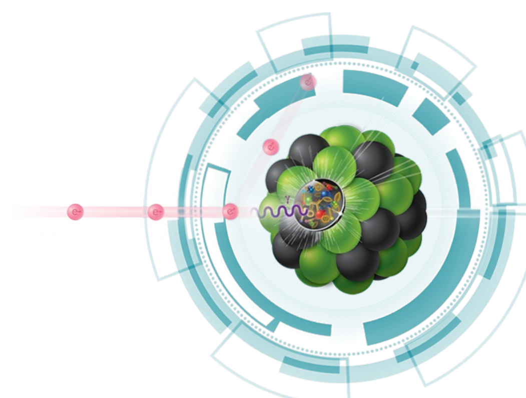
Unpolarized and Polarized SIDIS scattering



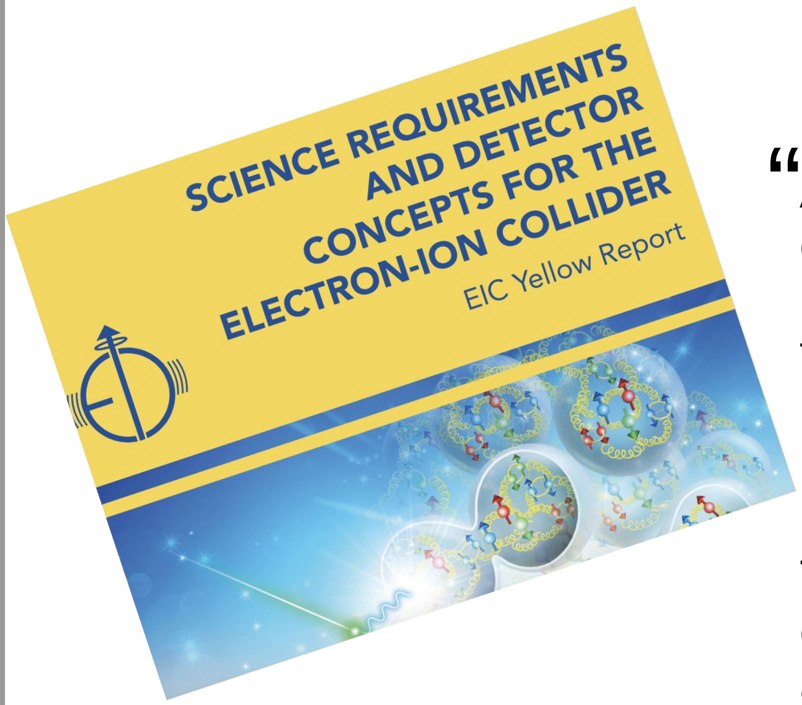
$$\sigma_{SIDIS} = f_q(x) \otimes \hat{\sigma} \otimes D_{h/q}(z)$$

Allows extraction of distribution and fragmentation functions

Electron-Ion Collider



TMDs@EIC



EIC Yellow Report

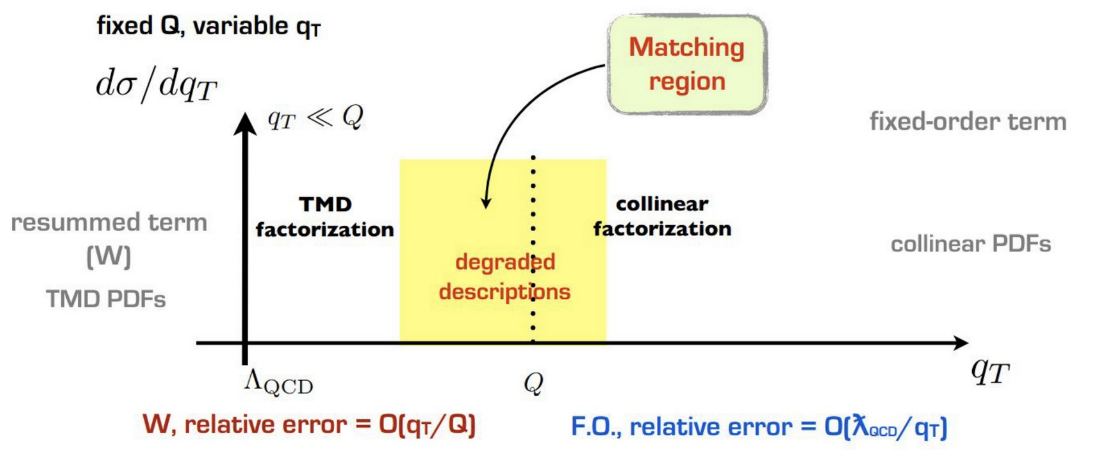
Nucl.Phys.A 1026 (2022) 122447

"An essential aspect of TMDs concerns their scale-dependence (evolution) as predicted in QCD, which is considerably more involved than the evolution of the 1D PDFs. There is, therefore, substantial interest in a quantitative understanding of the TMD evolution.

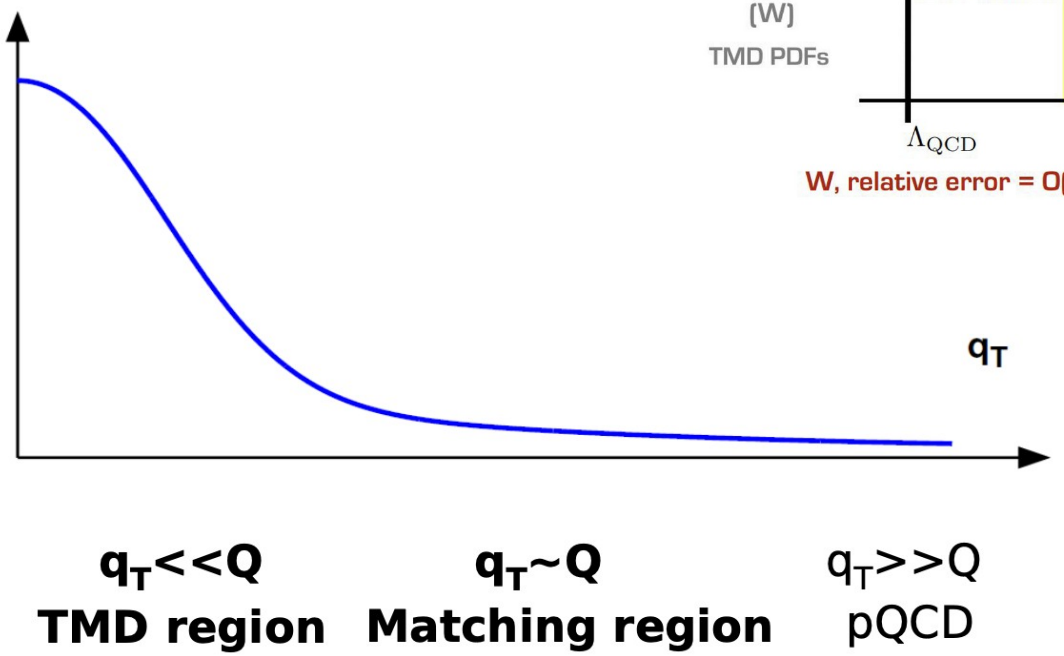
The EIC will be ideal for such studies, complementing the high precision data becoming available from JLab at larger values of x. It allows to explore SIDIS observables over an extensive range in Q^2 while covering transverse momenta of the final-state hadrons over a wide range from low non perturbative values to high (perturbative) values."

TMD vs Collinear kinematic regions

How do we know where the boundaries of the kinematic regions are?



Plot credit: A. Signori

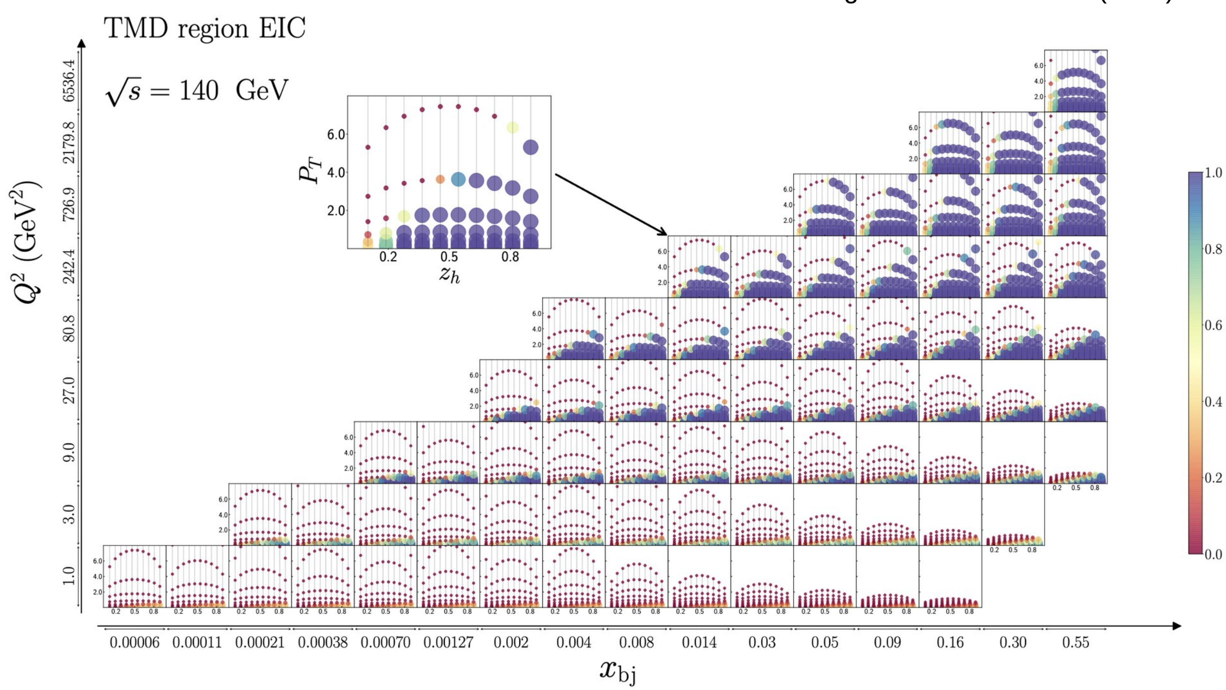


Plot credit: J.O. Gonzalez-Hernandez

Affinity – TMD region at EIC

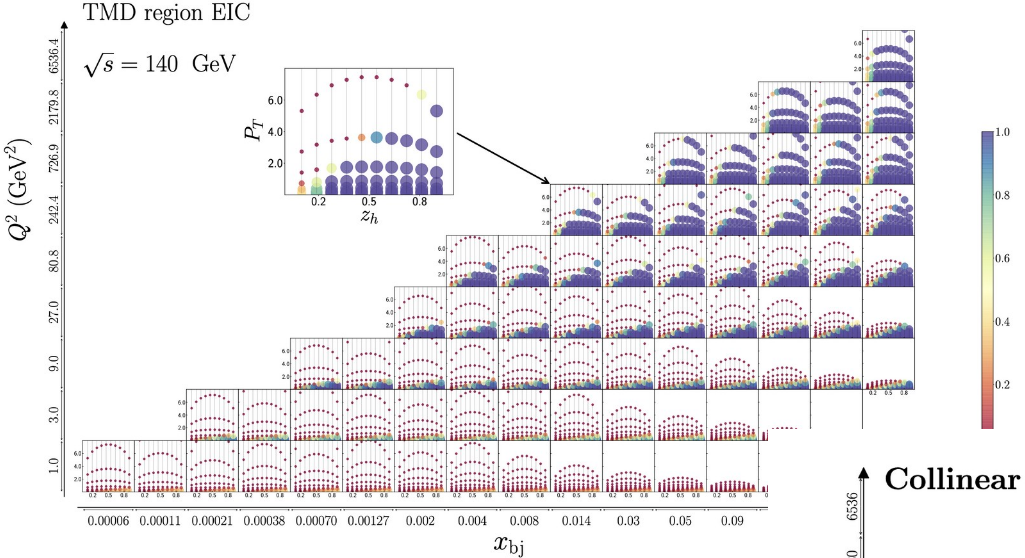
- Affinity is a phenomenological tool based on momentum region indicators to guide the analysis and interpretation of SIDIS measurements.
- The new tool, referred to as "affinity", is devised to help visualize and quantify the proximity of any experimental kinematic bin to a particular hadron production region, such as that associated with transverse momentum dependent factorization.

Boglione et al. JHEP 04 (2022) 084

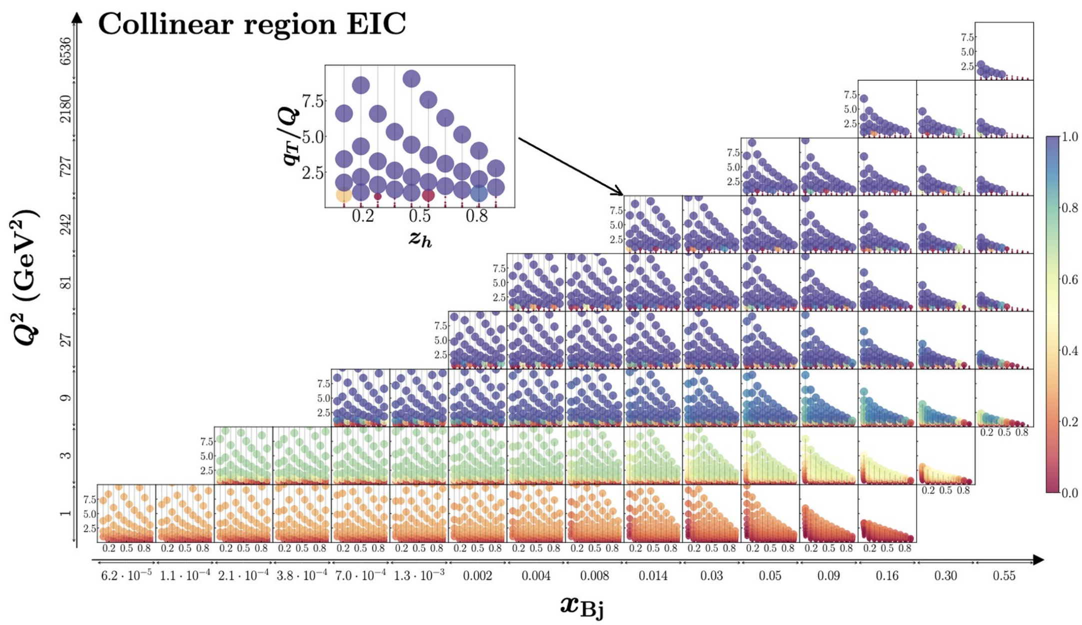


Bin centers are located in the points corresponding to the bin averaged values of x_{Bj} and Q^2, and in each of these bins various values of z_h and q_T/Q can be measured. In each bin of fixed z and q_T/Q, the affinity is indicated by a dot with size proportional to the corresponding affinity value. The affinity is color coded according to the scheme on the right of the panels: red (and smaller) symbols correspond to low TMD affinity, while dark blue (and larger) symbols correspond to high TMD affinity

Affinity – TMD region at EIC

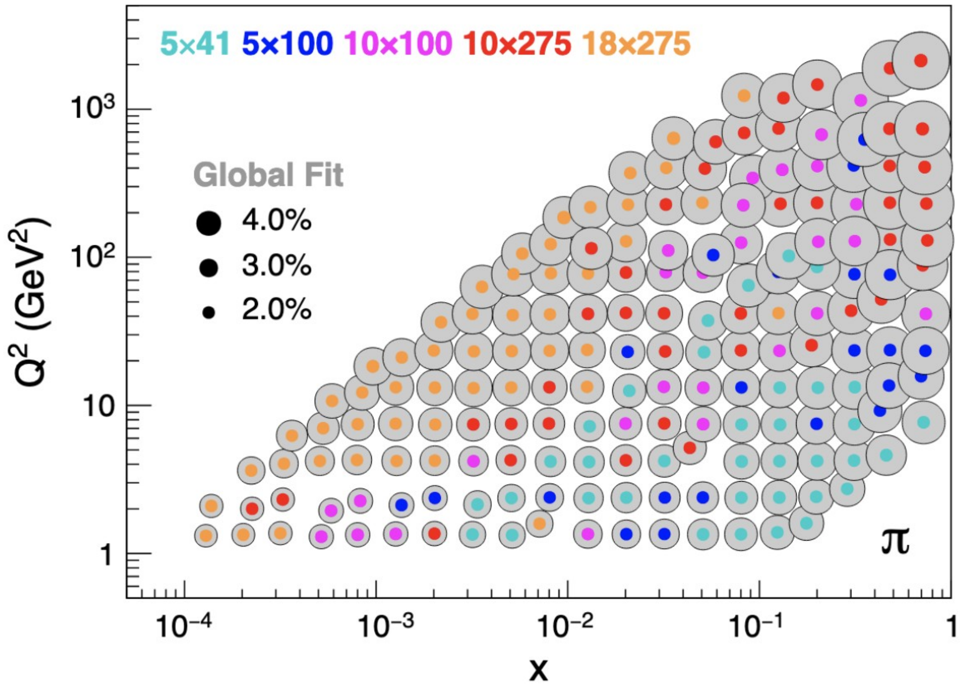


Boglione et al. JHEP 04 (2022) 084



TMD and Collinear regions appear to be consistently complementary

Impact of EIC measurements on TMD extraction



Impact of the EIC measurements on the coverage and precision in extracting the unpolarized TMD distribution function.

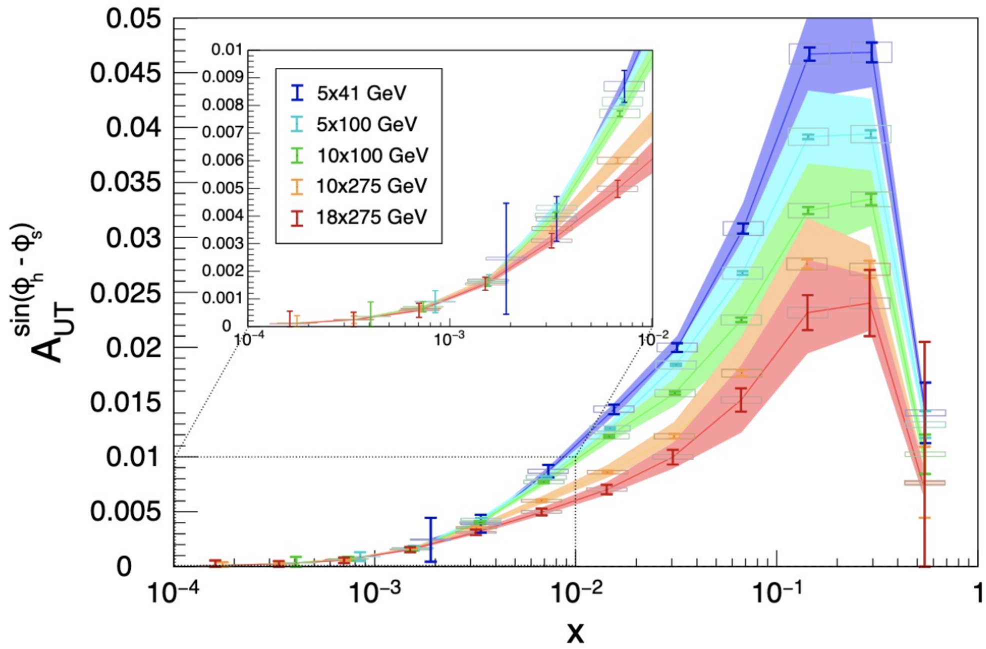
"ATHENA detector proposal — a totally hermetic electron nucleus apparatus proposed for IP6 at EIC"

ATHENA Collaboration

JINST 17 (2022) 10, P10019, 2210.09048 [physics.ins-det]

- Projected uncertainties for the unpolarized cross sections measured with ATHENA, compared to present uncertainties in TMD PDF extraction.
- Over a significant part of the phase space the total uncertainty on the ATHENA pseudodata is dominated by the 2% systematic point-to-point and 3% scale uncertainty, whereas the theory uncertainties are dominated by the poorly known non-perturbative part of the TMD **evolution.**
- The different colors represent the different energy combinations. The size of the markers show the uncertainties of the corresponding datasets.

Impact of EIC measurements on TMD extraction



Impact of the EIC measurements on the coverage and precision in extracting the Sivers distribution function.

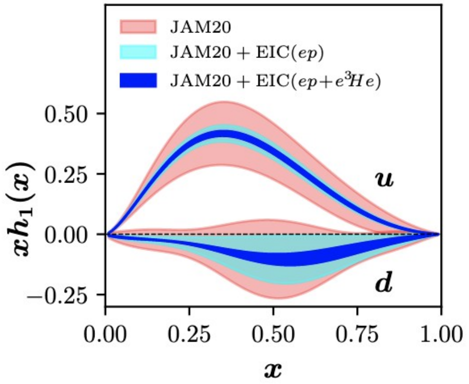
"ATHENA detector proposal — a totally hermetic electron nucleus apparatus proposed for IP6 at EIC"

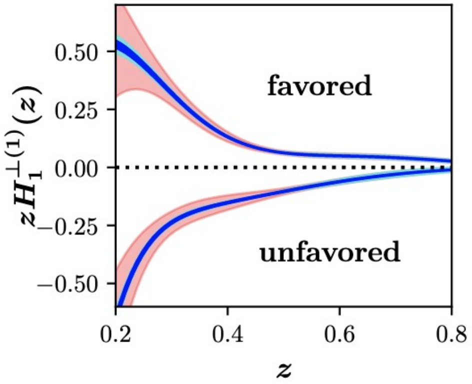
ATHENA Collaboration

JINST 17 (2022) 10, P10019, 2210.09048 [physics.ins-det]

- Projected Sivers asymmetries extracted from ATHENA pseudodata compared to projections from present extraction for charged pions.
- The ATHENA data will be powerful in constraining the shape of this TMD as well as its evolution. The uncertainties of the individual datasets were scaled to 100 fb1 of 10 GeV electron collisions with 275 GeV protons assuming equal data taking time for each center-of-mass-energy.
- 2% point-to-point uncertainty and 1.5% scale uncertainty are assumed

Impact of EIC measurements on TMD extraction

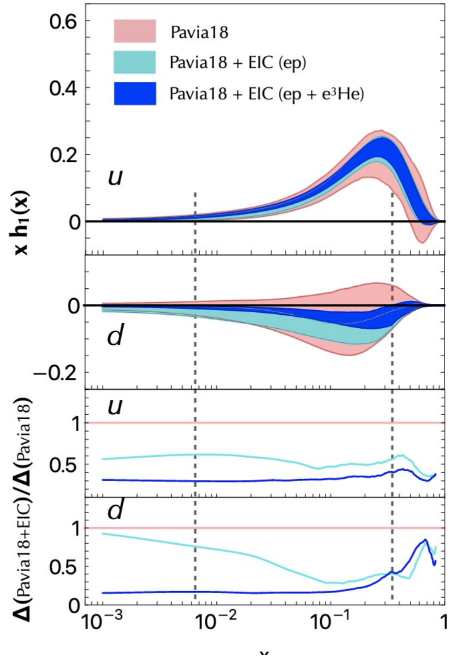




Impact of the EIC measurements on the coverage and precision in extracting transversity and Collins TMD distribution functions.

EIC Yellow Report

Nucl.Phys.A 1026 (2022) 122447

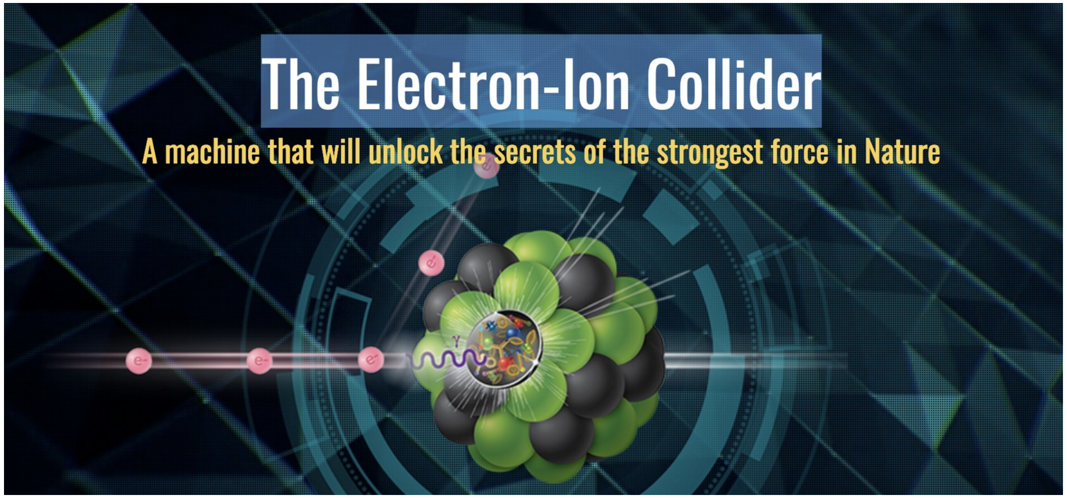


- The transversity distribution and Collins TMDs as a function of x at $Q^2 = 2.4$ GeV^2 for up and down valence quarks and for favoured and disfavoured contributions, respectively. Uncertainty bands for 68% of all fitted replicas of data.
- Comparison between pink and blue bands show the impact of the future EIC data on the precision of the extraction of transversity.
- Vertical dashed lines indicate the x-range covered by existing data.

Conclusions and Outlook

The EIC will allow for an unprecedented

- knowledge of the non perturbative aspects of the scale Q evolution of TMDs and on the soft physics involved
- precision in the extraction of TMDs and a better and better map of the 3D nucleon structure



Conclusions and Outlook

The Soft Factor acquires a central role

The focus of phenomenological analyses moves from the TMDs considered as a whole, to the Soft Factor contribution (which encloses the full process dependent part of the TMD).

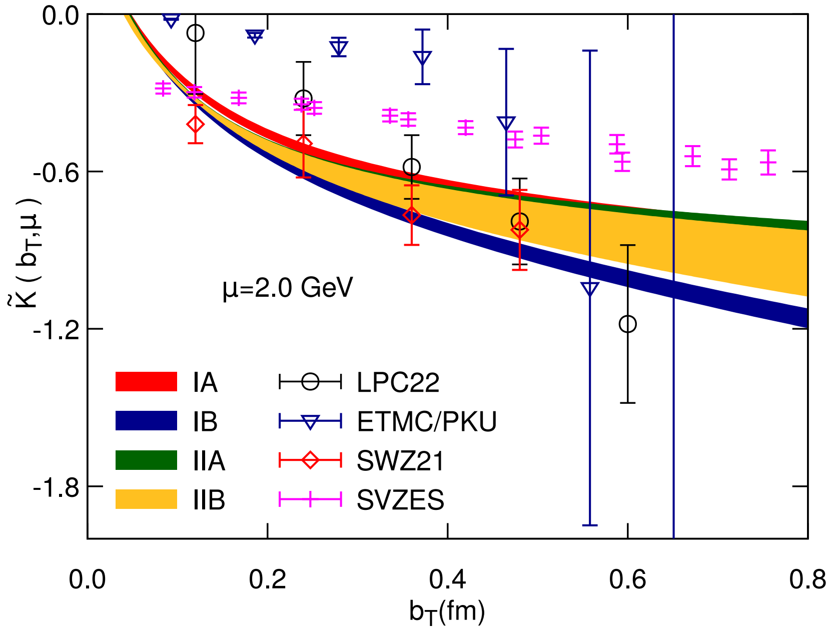
The Collins-Soper kernel acquires a central role

The focus of phenomenological analyses moves from the TMDs considered as a whole, to the g_K function (which embeds the non-perturbative essence of the TMD evolution).

Collins-Soper kernel: comparison to other analyses

M. Boglione, J.O. Gonzalez-Hernandez, A. Simonelli, 2206.08876 [hep-ph]

Our extraction of the Collins-Soper Kernel compared to corresponding lattice computations



M.-H. Chu et al. (LPC22), arXiv:2204.00200 [hep- lat]

Y. Li et al.,(ETMC/PKU) Phys. Rev. Lett. 128, 062002 (2022),

P. Shanahan et al. (SVZ21) Phys. Rev. D 104, 114502 (2021),

M. Schlemmer et al. (SVZES) JHEP 08, 004 (2021),

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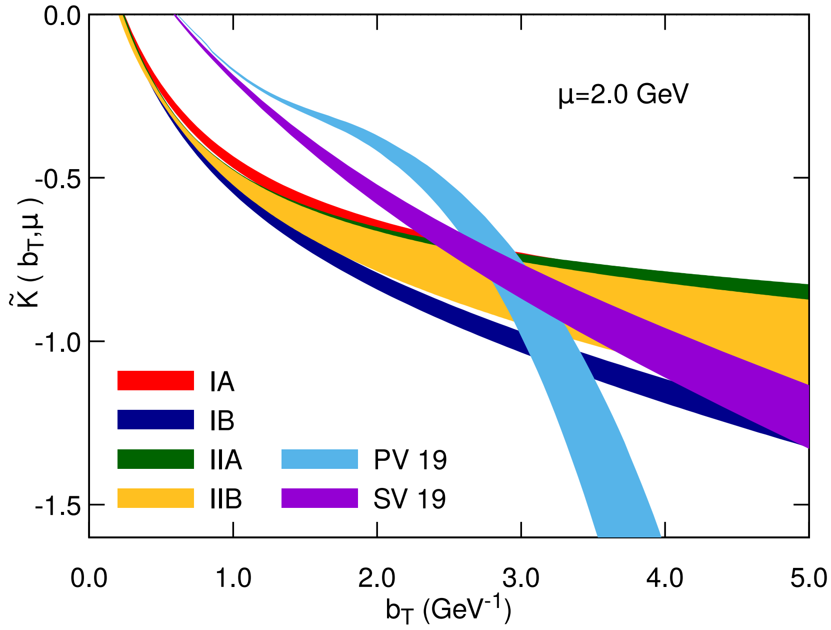

I. Scimemi and A. Vladimirov, (SV19) JHEP 06, 137 (2020)

A. Bacchetta, et al. (PV19) JHEP 07, 117 (2020)