Bjorken x weighted Energy-Energy Correlators from the Target Fragmentation Region to the Current Fragmentation Region

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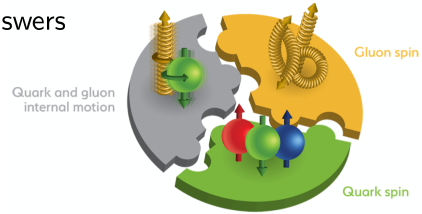
Outline

- Conventional approach to nucleon structure
- Concept and feature of the Bjorken x weighted EEC
- Numerical result
- Summary and Outlook

Why are we interested in Nucleon Structure?

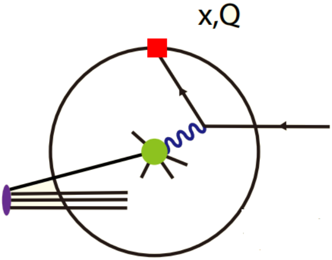
- Still many question yet to answers
  - Partons hadronize
  - Spin components
  - Mass decomposition
  - gluon saturation
  - ...
- Major focus of EIC, EicC

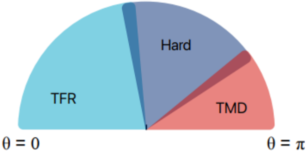


Conventional approach to nucleon structure

Parton distribution function(PDF)

- Inclusive
- Clean in both experiment and theory
- Lose information



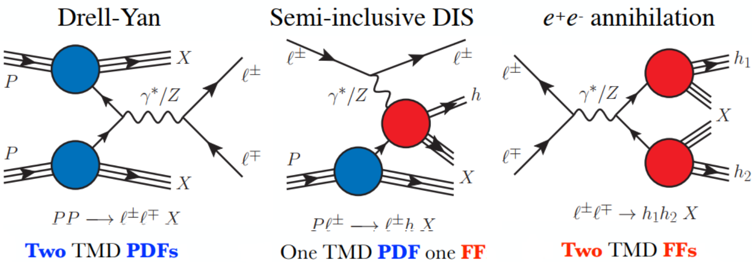


Conventional approach to nucleon structure

Transverse Momentum Dependent (TMD) Distribution

TMD Handbook, arxiv:2303.01530

- Two TMD ;
- Sudakov suppression.



The Nucleon Energy Correlators

Nucleon EEC X.Liu and H.X.Zhu, PRL 130,091901 (2023) 9,9
–Bjorken x weighted EEC of the target fragmentation region.

- The active parton k_t unconstrained,not TMD;
- Energy weighted collinear PDF;
- Transverse dynamics through energy flow operator $\mathcal{E}$;
- Insensitive to soft radiations, no Sudakov suppression

$$f_{q,EEC}(z,\theta) = \int \frac{dy^-}{4\pi} e^{-izP^+ \frac{b^-}{2}} \langle p|\bar{\chi}_n(y^-) \frac{\gamma^+}{2} \hat{\mathcal{E}}(\theta) \chi_n(0)|P\rangle$$

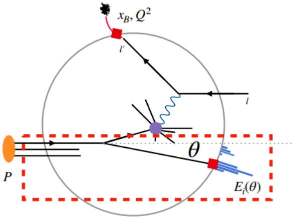
$$\mathcal{E}(\hat{\boldsymbol{n}}) = \int_0^\infty \mathrm{d}t \lim_{r\to\infty} r^2 n^i T_{0i}(t, r\hat{\boldsymbol{n}})$$

$$\hat{\mathcal{E}}(\theta)|X\rangle = \sum_{i\in X} \frac{E_i}{E_P} \Theta(\theta - \theta_i)|X\rangle$$

The Nucleon Energy Correlators

- NEEC can be observed through the following process

$$\Sigma(x_B, Q^2, \theta) = \sum_i \int \frac{E_i}{E_P} d\sigma(x_B, Q^2, p_i)\Theta(\theta - \theta_i)$$



- When $\theta Q \ll Q$, factorization can be shown using SCET

H.T.Cao, X.Liu, H.X.Zhu, Phys.Rev.D 107 (2023) 11,114008

$$\Sigma(x_B, Q^2, \theta) = \int_{x_B}^1 \frac{dz}{z} \hat{\sigma}_i(\frac{x_B}{z}, Q^2, \mu) f_{i,EEC}(z, \theta, \mu)$$

The Nucleon Energy Correlators

- $\theta \ll 1$, hard($p_H \sim Q(1,1,1)$), soft($p_S \sim Q(\theta^a,\theta^a,\theta^a)$), collinear($p_C \sim Q(1,\theta^2,\theta)$)

$$\hat{\mathcal{E}}(\theta)|X\rangle = \frac{1}{E_P}\sum_{i\in X}\Big(E_{H,i}\Theta(\theta-\theta_{H,i}) + E_{C,i}\Theta(\theta-\theta_{C,i}) + E_{S,i}\Theta(\theta-\theta_{S,i})\Big)|X_H,X_C,X_S\rangle$$

- $\Lambda_{QCD} \ll \theta Q$, hard collinear mode($C_1$),$p_t \sim Q(1,\theta^2,\theta)$ $\mathrm{SCET_{II}}$ mode (C_2), $p_t \sim Q(1,\lambda^2,\lambda)$.

$$\hat{\mathcal{E}}(\theta)|X\rangle = \frac{1}{E_P}\sum_{i\in C_1, j\in C_2}(E_{C_{1,i}}\Theta(\theta-\theta_{C_{1,i}}) + E_{C_{2,j}}\Theta(\theta-\theta_{C_{2,j}}))|X_{C_1}X_{C_2}\rangle$$
$$= \frac{1}{E_P}\sum_{i\in X}(E_X - E_{C_{1,i}}\Theta(\theta_{C_{1,i}}-\theta))|X_{C_1}X_{C_2}\rangle$$

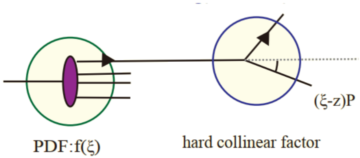
The Nucleon Energy Correlators

- NEEC can be futher matched to pdf.

$$f_{i,EEC}(z, ln\frac{Q\theta}{u\mu}) = f_i(z) - \int_z^1 \frac{d\xi}{\xi} I_{i,j}(\frac{z}{\xi}, ln\frac{Q\theta}{u\mu})\xi f_j(\xi)$$

- We can understand why this object is called NEEC, which is obvious from the fix order calculation.

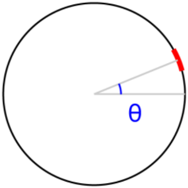
$$\frac{df^{(1)(z,\theta)}_{EEC}}{d\theta} \propto \xi f(\xi)[(1-\frac{z}{\xi})\frac{1}{\theta}P(\frac{z}{\theta})]$$



The Nucleon Energy Correlators

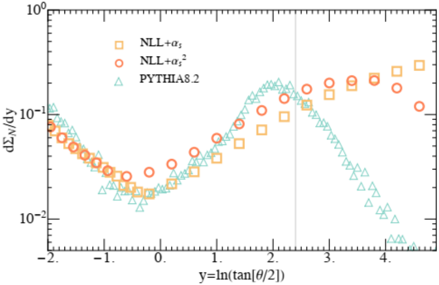
- When the angle theta is very small, we expect to see the region of the free hadron gas phase. In this phase, the energy is evenly distributed.

$$\frac{d\Sigma(\theta)}{d\theta} \propto \theta$$



TFR to the CFR

- Target Fragmentation Region(TFR)



- Current Fragmentation Region(CFR)
  The observed particles result from the fragmentation of the parton struck by the virtual photon.
  - TMD region
  - Hard region

TMD Region

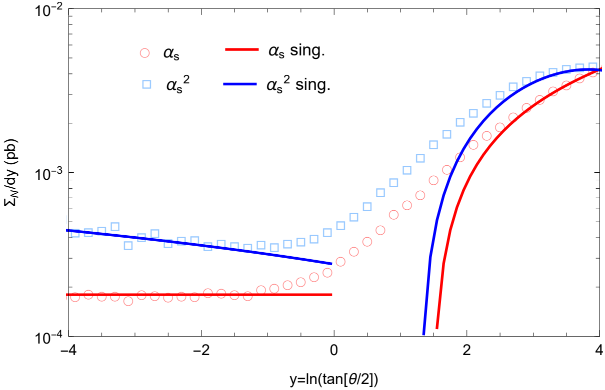
- When $\pi - \theta \ll 1$, the factorization theorem for this observation in this region has already been derivedas follows:

H.T.Li, Makris, Vitev, Phys.Rev.D 103 (2021) 9,094005

$$\frac{d\Sigma_N(Q^2,\theta)}{d\theta} = \int dx_B x_B^N H(Q^2) \int d^2\boldsymbol{q}_T \frac{d^2\boldsymbol{b}}{(2\pi)^2} \exp[-i\boldsymbol{q}_T \cdot \boldsymbol{b}] \\ \times B_{f/p}(b, x_B) S(b) J_{f,\mathrm{EEC}}(b) \delta\left(\frac{2|\boldsymbol{q}_T|}{Q} - \theta\right)$$

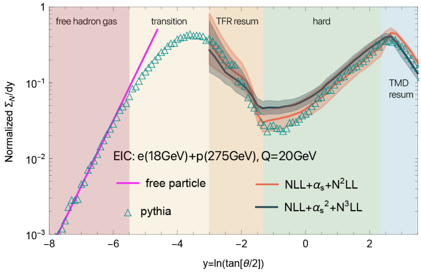
Numerical result

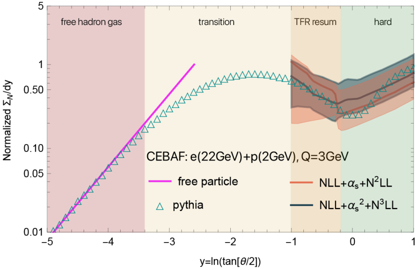
- Comparison between the lnθ leading singular contributions with the fixed-order calculations.



Numerical result

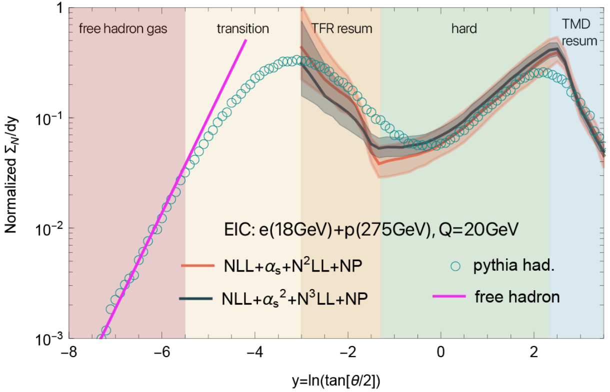
- Comparison between the result of fixed-order calculation + resummation + free hadron gas model and the Pythia simulation result at the partonic level.





Numerical result

- The comparison of EEC between the SCET predictions with hadronic PYTHIA simulations for EIC kinematics.



Summary and Outlook

- Provides a new window into nucleon structure, bridging CFR and TFR.
- It is factorizable, measurable, and computable within SCET.
- Application: Unraveling the gluon saturation by small-x physics

  H.-Y.Liu, X.Liu, F.Yuan, H.X.Zhu, Phys.Rev.L 130 (2023) 18,18
- Application: Exhibits linearly polarized gluons inside the nucleon

  X.L.Li, X.Liu, F.Yuan, H.X.Zhu, Phys.Rev.D 108 (2023) 9,L0915028
- Future work will includes higher-order calculations.

Thanks for your attention!

Matching Scheme

- In EIC kinematics

$$\frac{d\Sigma_N}{dQ^2dy} = (1-f^2)\left.\frac{d\Sigma_N}{dQ^2dy}\right|_{\text{QCD}} + f^2\left(\left.\frac{d\Sigma_N}{dQ^2dy}\right|_{\text{non-sing}} + \left.\frac{d\Sigma_N}{dQ^2dy}\right|_{res}\right)$$

where

$$f = \frac{1}{2}\left[\cos\left(\frac{\cos\theta - a}{a-b}\pi\right)+1\right] \quad (2.3 < y < 3)$$
$$f = \frac{1}{2}\left[\cos\left(\frac{\cos\theta - c}{c-d}\pi\right)+1\right] \quad (-2 < y < -1.3)$$

a, b, c, d equal to cosθ with θ associated with $y = 3, 3.2, -2, -1.3$

- In CEBAF kinematics

$$f = \frac{1}{2}\left[\cos\left(\frac{\cos\theta - a}{a-b}\pi\right)+1\right]$$

a and b equal to cosθ with θ associated with $y = 0.2, 0.1$