Monte Carlo Analysis of TMD Factorization in SIDIS

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Semi-Inclusive Deep Inelastic Scattering

- Deep inelastic scattering (DIS): $e^- + p \to e^- + X$
- In the *parton* model, e^- interacts with a single quark in the proton

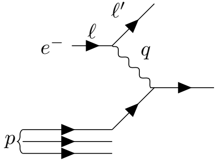

Figure: In DIS, an electron interacts with one of the quarks in a proton via a virtual photon.

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- Deep inelastic scattering (DIS): $e^- + p \to e^- + X$
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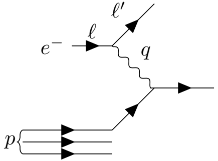
- Semi-inclusive deep inelastic scattering (SIDIS): $e^- + p \to e^- + h + X$



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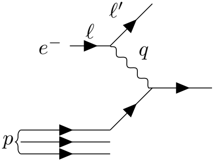
- In the *parton* model, e^- interacts with a single quark in the proton
- Semi-inclusive deep inelastic scattering (SIDIS): $e^- + p \rightarrow e^- + h + X$
- Typical case: $h = \pi^+$



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SIDIS Variables

- DIS is described by variables related to the electron-quark scattering:

$$Q^2 = -(k - k')^2 \equiv -q^2 = \text{photon virtuality}$$

$$x = \frac{Q^2}{2p \cdot q} = \text{quark momentum fraction}$$

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- SIDIS requires additional variables to describe the final product:

$$P_T = \text{transverse momentum of } h$$
$$\eta = \tanh^{-1} \frac{P_z(h)}{E(h)} = \text{rapidity of } h$$

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- The rapidity η is related to the more familiar $z = \frac{P_h \cdot q}{p \cdot q}$, but is more useful for delineating kinematic regions (Boglione et al. 2017)

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Parton Distributions

- Hadrons are built from partons (quarks and gluons)
- Parton structure of hadrons characterized through:

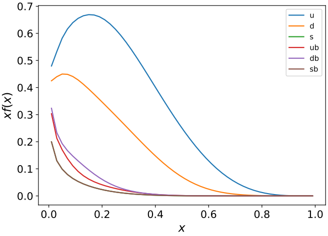

Figure: The CJ15 parton distribution functions for the proton.

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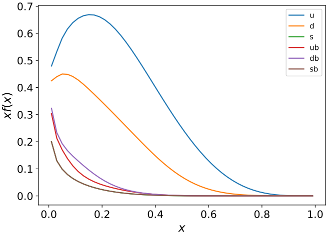
  - Longitudinal momentum. The *parton distribution function* (PDF) records the fraction of longitudinal momentum that is found in a parton species



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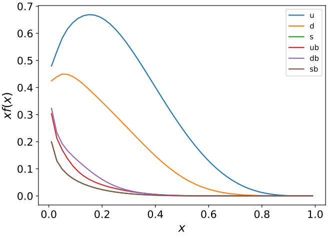
  - Longitudinal momentum. The *parton distribution function* (PDF) records the fraction of longitudinal momentum that is found in a parton species
  - Transverse momentum. Various TMD-PDFs determine how transverse momentum is distributed among the partons in the hadron



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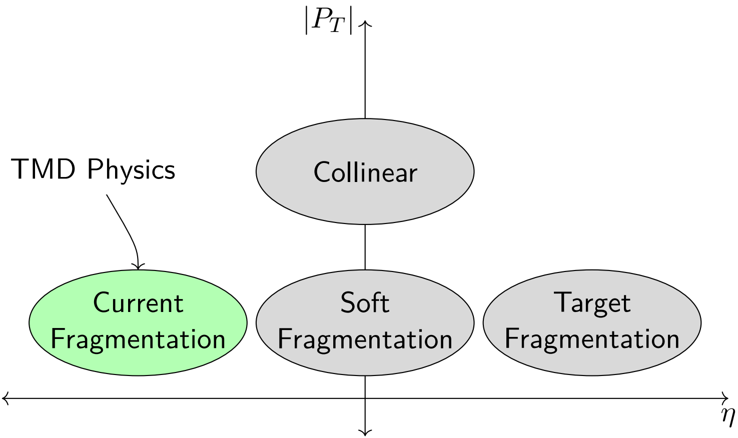
SIDIS Regions

- TMD-PDFs can be extracted from the current fragmentation region, with small p_T and large negative η (Boglione et al. 2017)



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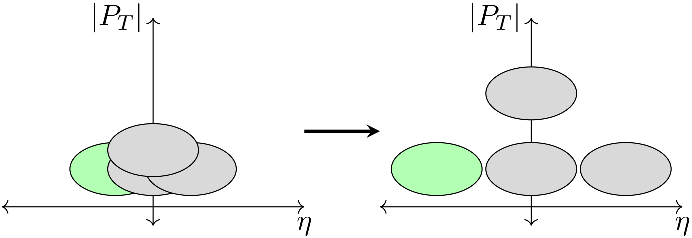
Questions

- How do the SIDIS regions shift with energy?
- Can we distinguish the current fragmentation region from other regions at JLab energies?



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Pythia

- Pythia 8 is a Monte Carlo event generator for high-energy collisions of particles
- Using a combination of Standard Model theory and phenomenological models constrained by data, produces realistic collision events at sufficiently high energies

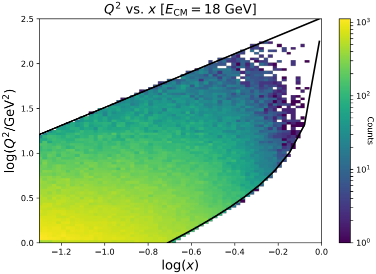

Figure: Events generated with $Q^2 \geq 1\,\mathrm{GeV}^2$, $W^2 \geq 5\,\mathrm{GeV}^2$, and $E_{\mathrm{cm}} = 18\,\mathrm{GeV}$ (COMPASS energy).

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Rapidity Plateau I

- The overall distribution of events in rapidity shows a plateau, with a spike at $\eta = 0$ for soft and collinear events

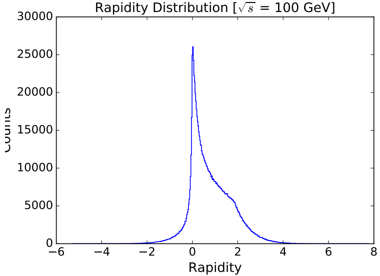

Figure: Rapidity distribution at $\sqrt{s} = 100\,\text{GeV}$.

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Rapidity Plateau II

- At low W, dominated by central and target fragmentation; at high W, current fragmentation becomes dominant (Boglione et al. 2017)
- This contributes to a widening of the rapidity distribution at sufficiently high W

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Evolution of Rapidity Distribution

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Evolution of Rapidity-p_T Distribution

- The splitting of the regions can be seen in rapidity-p_T space

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Region Splitting

- At sufficiently high W, we can see two peaks in the rapidity distribution, and measure the separation between them
- This separation has been used experimentally as a proxy for the isolation of the current region (Berger criterion)

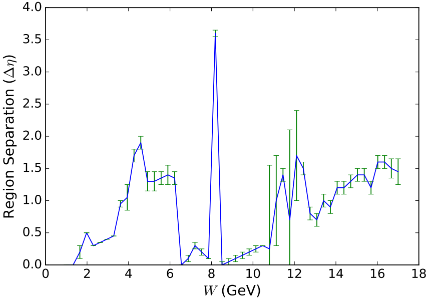

Figure: Rapidity spread is erratic at low W.

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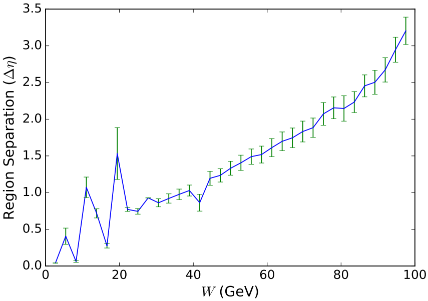

Figure: Rapidity spread eventually grows linearly with W.

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SIDIS Experiments

- Different experiments vary widely in the amount of region separation they can expect

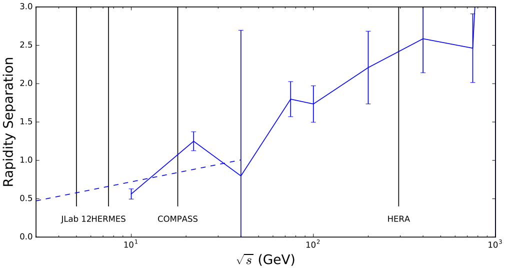

Figure: Higher energy SIDIS experiments will see clearer separation of regions.

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Factorization I

- The unpolarized SIDIS cross section takes the form Anselmino et al. 2014

$$\frac{d\sigma^{\text{SIDIS}}}{dx\, dQ^2\, dz\, dP_T^2} = \frac{2\pi^2\alpha^2}{(xs)^2}\frac{1+(1-y)^2}{y^2}\sum_q e_q^2 A_q,$$

where

$$A_q = \int d^2p_T\, d^2k_T\, \delta(P_T - zk_T - p_T) f_{q/p}(x, k_T) D_{h/q}(z, p_T)$$

- This expresses the final-state P_T as a combination of the quark transverse momentum k_T and the hadron momentum p_T

Factorization II

- We assume, following Anselmino et al. 2014, that the PDFs and fragmentation functions factorize:

$$f_{q/p}(x, k_T) = f_{q/p}(x) \frac{e^{-k_T^2/\langle k_T^2 \rangle}}{\pi \langle k_T^2 \rangle},$$

$$D_{h/q}(z, p_T) = D_{h/q}(z) \frac{e^{-k_T^2/\langle p_T^2 \rangle}}{\pi \langle p_T^2 \rangle}$$

- By the convolution theorem,

$$A_q = f_{q/p}(x) D_{h/q}(z) \frac{e^{-P_T^2/\langle P_T^2 \rangle}}{\pi \langle P_T^2 \rangle}$$

where $\langle P_T^2 \rangle = \langle p_T^2 \rangle + z^2 \langle k_T^2 \rangle$

Model Fit I

- At fixed x, Q^2, and z, this simple factorization model predicts

$$\frac{d\sigma^{\text{SIDIS}}}{dx\, dQ^2\, dz\, dP_T^2} \propto \exp\left(-\frac{P_T^2}{\langle P_T^2 \rangle}\right)$$

- Fitting this distribution at various values of z, we should see a quadratic increase in the parameter $\langle P_T^2 \rangle$

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Model Fit II

- Anselmino et al. find this increase in COMPASS data with $\langle p_T^2 \rangle = 0.12\,\text{GeV}^2$ and $\langle k_T^2 \rangle = 0.68\,\text{GeV}^2$.

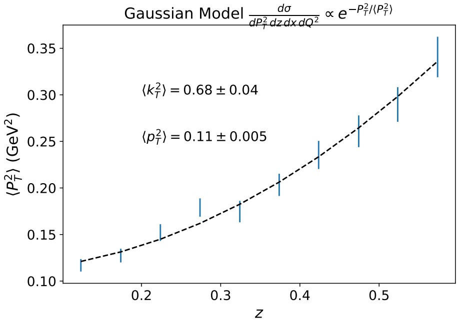

Figure: The parameter $\langle P_T^2 \rangle$ is given by $\langle p_T^2 \rangle + z^2 \langle k_T^2 \rangle$ with $\langle p_T^2 \rangle = 0.11\,\text{GeV}^2$ and $\langle k_T^2 \rangle = 0.68\,\text{GeV}^2$.

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- Pythia is an effective tool for exploring SIDIS kinematic regions
- SIDIS regions are sensitive to energy, and isolating the current fragmentation region may require high energy
- Simple factorization schemes, e.g. Anselmino et al. 2014, show promising agreement with Monte Carlo data

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- SIDIS regions are sensitive to energy, and isolating the current fragmentation region may require high energy
- Simple factorization schemes, e.g. Anselmino et al. 2014, show promising agreement with Monte Carlo data
- Ongoing work:
  - Evaluate the validity of factorization across rapidity-p_T space
  - Suggest improvements to the Berger criterion for isolating the current fragmentation region

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