High-precision SIDIS at intermediate energies: Exploring the limits of precocious scaling at HERMES and beyond.

http://www-hermes.desy.de/multiplicities

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April 23, 2013

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Section 1

About factorization and precocious scaling
What happens in a High Energy Collision?
What happens in a High Energy Collision?
What happens in a High Energy Collision?

Sylvester J. Joosten (HERMES, Illinois)
What happens in a High Energy Collision?
What happens in a High Energy Collision?

SIDIS at HERMES

April 23, 2013
What happens in a High Energy Collision?
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What happens in a High Energy Collision?

HADRONS are formed, in “JETS”

Confinement at Work!

Creation of hadrons from the struck quark: the fragmentation process
A hadron $h$ is detected in coincidence with the scattered lepton.

**Factorization of the cross section**

$$d\sigma^h \propto \sum_q e_q^2 f^q_1(x) \otimes \hat{\sigma} \otimes D^h_q(z)$$
Semi-Inclusive Deep-Inelastic Scattering (SIDIS)

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- Perturbative
  - Cross section for the hard photon-quark subprocess
  - Asymptotic freedom, can calculate!
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\[
\text{Factorization of the cross section}
\]

\[
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- Parton Distribution Function
  - Momentum distribution of a quark $q$ within the proton
  - In principle calculable (lattice!)
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- **Fragmentation Function**
  - Momentum distribution of the hadrons \( h \) formed from \( q \)
  - Not calculable...
A hadron $h$ is detected in coincidence with the scattered lepton:

Factorization of the cross section

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Scaling, evolution and factorization scale

Naive Quark Parton Model:

- Scattering off free point-like quark
- Expect no dependence of proton structure on photon virtuality $Q^2$ (i.e. scaling)
Scaling, evolution and factorization scale

- **Naive Quark Parton Model:**
  - Scattering off free **point-like quark**
  - Expect no dependence of proton structure on photon virtuality \( Q^2 \) (i.e. scaling)

- **BUT: Scaling violation!**

**HERA \( F_2 \)**

![Graph showing HERA \( F_2 \) data with various fits and data points for different \( x \) and \( Q^2 \).]
Scaling, evolution and factorization scale

- **Naive Quark Parton Model:**
  - Scattering off free point-like quark
  - Expect no dependence of proton structure on photon virtuality $Q^2$ (i.e. scaling)

- **BUT: Scaling violation!**

- **QCD evolution:**
  - PDFs depend on factorization scale $\mu \sim Q$
  - $\mu$ separates structure from dynamics
  - Observables independent of $\mu \rightarrow$ evolution equations for PDFs (DGLAP)
Complications arise when the hard scale $Q$ is not really hard (towards $Q \sim M$)

- Mass effects
- Higher order terms in $\alpha_s$ become larger
- Initial- and final-state interactions start to play a larger role
- Higher twist terms in become larger
- ...

- Only break factorization if not properly taken into account
- **Simple interpretation** through intuitive QPM-like LO factorization not possible anymore
Clear separation of current and target “jet” seems to be needed...

**Factorization of the cross section**

\[ d\sigma^h \propto \sum_q e_q^2 f_1^q(x) \otimes \hat{\sigma} \otimes D_q^h(z) \]

- \( D_q^h \) only depends on the struck quark.
  - Independent of target and process
  - Only depends on fractional hadron momentum \( z = P_h/\nu \).
Limits of factorization: SIDIS

- **Clear separation of current and target** “jet” seems to be needed...

EMC, PR162 (1988)

- Jet **FWHM: 2 units of rapidity $\gamma$.**
Limits of factorization: SIDIS

- **Clear separation of current and target** "jet" seems to be needed...
- Jet **FWHM: 2 units of rapidity** $y$.
- **Lower rapidity limit** required to fully disentangle the forward and backward hemisphere.
Clear separation of current and target “jet” seems to be needed...

Full separation: need 4 units of rapidity between jets

This requires:

- **Lower limit in** $W$ (invariant mass of the $\gamma^* p$ system)
- $y^h = \ln(2P^h/M^h) \rightarrow$ also **lower limit in** $z$
27.6 GeV HERA $e^\pm$ beam

- Forward spectrometer
  - Pure H and D atomic gas target
  - Clean lepton-hadron identification
  - Very good $\pi - K$ separation with RICH
HERMES as a measure of future challenges

SOLID

$E_{\text{beam}} = 12$ GeV
$\sqrt{s} = 4.9$ GeV
$2 \text{ GeV} < W < 4.8 \text{ GeV}$

CLAS12

$E_{\text{beam}} = 12$ GeV
$\sqrt{s} = 4.9$ GeV
$2 \text{ GeV} < W < 4.8 \text{ GeV}$

HERMIES

$E_{\text{beam}} = 27.6$ GeV
$\sqrt{s} = 7.43$ GeV
$3.2 \text{ GeV} < W < 7.43 \text{ GeV}$

$W_{\text{MAX}} = \sqrt{s}$
HERMES as a measure of future challenges

SOLID

12 GeV SoLID forward
12 GeV SoLID large angle
6 GeV Transversity

$E_{\text{beam}} = 12$ GeV
$\sqrt{s} = 4.9$ GeV
2 GeV < $W$ < 4.8 GeV

CLAS12

$E_{\text{beam}} = 12$ GeV
$\sqrt{s} = 4.9$ GeV
2 GeV < $W$ < 4.8 GeV

HERMES

$E_{\text{beam}} = 27.6$ GeV
$\sqrt{s} = 7.43$ GeV
3.2 GeV < $W$ < 7.43 GeV

$W_{\text{MAX}} = \sqrt{s}$

Berger criterion:

- Full separation for $y_{\text{max}}^h = 4$
- $y_{\text{max}}^h \approx \ln(W/M_h) = 4$
- for $\pi: W > 7.6$ GeV
- for $K: W > 27$ GeV

Problematic!?!?

- But...
  Factorization seems to work for HERMES?
Factorization and precocious scaling

Precocious scaling

Factorized QCD appears to be working in energy regimes down to \( Q \sim M \)… and for SIDIS far below the Berger threshold...

Independent of \( z \)

Simple QPM-like factorization holds at HERMES

Caveat:
  - Model dependent extraction, depends on FFs, isospin symmetry, ...
  - Low statistics
  - Can we do better?
Section 2

Multiplicity analysis: Experimental
SIDIS Multiplicities: New HERMES Results

- High statistics
- 3D analysis \( x(Q^2), z, P_{h\perp} \)

![Graphs of SIDIS Multiplicities](image-url)

- **High statistics**
- **3D analysis** $(x(Q^2), z, P_{h\perp})$

**sophisticated analysis** required:
- Corrections for trigger inefficiencies
- Charge-symmetric background correction
- **RICH unfolding**
- Correction for exclusive vector mesons (optional)
- Multidimensional **smearing-unfolding** for radiative effects, limited acceptance and detector smearing
- Final results corrected to $4\pi$ Born (single-photon exchange).

**Systematics dominated**
- Highly correlated, challenge to properly estimate and understand
Exclusive vector meson contamination

- **Diffractive $\rho^0$ and $\phi$** contaminate the SIDIS $\pi$ and $K$ sample
  - Correction obtained from tuned PYTHIA
    - Applied at the fully differential level
    - Most of the correction canceled by the corresponding inclusive correction
    - **systematic $< 1\%$**

- **results** available both with and without this correction

This presentation: with VM correction
A raw measurement does not give experiment-independent information:

- Usually not known if any **radiative effects** occurred (e.g., ISR and FSR)
- Detector has less than full $4\pi$ coverage
- Detector has a finite **resolution**

### Relation between true and measured quantities

\[
\nu_i = \mu_{\text{tot}} \sum_{j=1}^{M} \frac{\int_{\text{bin } i} dX \int_{\text{bin } j} dY \int d\vec{Y} f(Y) \rho(\vec{Y}|Y) A(\vec{Y}) M(\vec{Y}|X)}{\int_{\text{bin } j} dY f(Y)} \mu_j + \beta_i
\]

- **Physics distribution** $f$
- **Background** from outside the acceptance $\beta$
Smearing-unfolding in SIDIS

Relation between true and measured quantities

\[ \nu_i = \mu_{\text{tot}} \sum_{j=1}^{M} \frac{\int_{\text{bin } i} dX \int_{\text{bin } j} dY \int d\overline{Y} f(Y) \rho(\overline{Y}|Y) A(\overline{Y}) M(\overline{Y}|X)}{\int_{\text{bin } j} dY f(Y)} \mu_j + \beta_i \]

- Has the shape of a matrix equation

\[ \nu_i = \sum_{j=1}^{M} S_{ij} \mu_j + \beta_i \]
Smearing-unfolding in SIDIS

Relation between true and measured quantities

\[ \nu_i = \mu_{\text{tot}} \sum_{j=1}^{M} \frac{\int_{\text{bin } i} dX \int_{\text{bin } j} dY \int d\bar{Y} f(Y) \rho(\bar{Y}|Y) A(\bar{Y}) M(\bar{Y}|X) \left( \mu_j + \beta_i \right)}{\int_{\text{bin } j} dY f(Y)} \]

- Has the shape of a **matrix equation**
- **Smearing matrix** \( S \) is calculated using **two MC** simulations
- **Solve** for true data by simple **matrix inversion**

\[ \mu_j = \sum_{i=1}^{M} S_{ji}^{-1} (\nu_i - \beta_i) \]
**Smearing-unfolding in SIDIS**

**Relation between true and measured quantities**

\[ \nu_i = \mu_{\text{tot}} \sum_{j=1}^{M} \int_{\text{bin } i} dX \int_{\text{bin } j} dY \int d\bar{Y} f(\bar{Y}) \rho(\bar{Y}|Y) A(\bar{Y}) M(\bar{Y}|X) \frac{1}{\int_{\text{bin } j} dY f(Y)} \mu_j + \beta_i \]

- **Smearing matrix** $S$ is calculated using **two MC** simulations.
- Completely **model-independent if either**:
  - Acceptance function $A$ is flat within each bin
  - Distribution $f$ is flat within each bin
- If this is **not the case**, a **reasonable** (better than 10% level) **model for $f$** is required.
- This analysis: systematic uncertainty from the $1\sigma$ contour in MC parameter space.
Importance of a multidimensional approach

- Neglecting to unfold in $z$ changes the $x$ dependence dramatically.
- The momentum cut has a similar effect.

$3D$ vs $1D$ (and $P$ cut)
Importance of a **multidimensional approach**

- Neglecting to unfold in $z$ changes the $x$ dependence dramatically.
- The **momentum cut** has a similar effect.

3D vs 1D (and $P$ cut)
Unfolding and MC Model Systematic

- Caused by **finite bin width**.
- **Estimate:**
  - Vary the LUND MC tune over its $1\sigma$ contour.
  - Unfold with each of the $1\sigma$ tunes.
  - Compare final multiplicities.
Unfolding and MC Model Systematic

- Caused by **finite bin width**.
- **Estimate:**
  - Vary the LUND MC tune over its $1\sigma$ contour.
  - Unfold with each of the $1\sigma$ tunes.
  - Compare final multiplicities.
  - Generally $\sim 2 - 3\%$.
Systematics breakdown

- **Dominant** contributions to the systematic:
  - $\cos N\phi$ modulations
  - MC Model
  - RICH
  - time dependence

![Graph showing systematics breakdown](attachment:graph.png)
**Systematics breakdown**

- **Dominant** contributions to the systematic:
  - $\cos N\phi$ modulations
  - MC Model
  - RICH
  - time dependence

![Graph showing systematics breakdown](image-url)
Systematics breakdown

- **Systematics dominated!** Even without the 2006-2007 data!
Providing the data

arXiv:1212.5407v1 [hep-ex]

http://www-hermes.desy.de/multiplicities
Providing the data: the multiplicity website

- Provides all datafiles and available figures.
- Multiplicities (differential and in various projections)
- Asymmetries and ratios
- Both with and without the correction for exclusive vector mesons
- Proper handling of the correlated systematics
Browse the data files

View and download available figures

Use filters for intuitive file selection

Download the final results
- Understand what version of the data you have.

File name structure

hermes.(TARGET).[BINNING].(PROJECTION).[OPTION].WHAT.list.gz

- TARGET: Either proton or deuteron. Blank in case of the target asymmetries.
- BINNING: Can be z-3D, zp-3D, zp2-3D, zx-3D or zxp-3D. The binning codes are defined below in PROJECTION: Blank in case of the 3D data without projection, or VARIABLE-proj for projected data. For exa projection versus z or zx-proj for a 2D projection versus x in z slices.
- OPTION: Results with the vector meson contribution subtracted are labelled vsub, results without this correction.
- WHAT:
  - The covariance matrices for the multiplicities are labelled covmat_mults.
  - Target asymmetry files are labelled as asym PARTICLE (for example: asym pplus).
  - The covariance matrices for the target asymmetries are labelled covmat asym.

- Detailed description of the different binnings.

High resolution in z

- Name: z-3D
- Profile: x: 2 / z: 10 / P_h,⊥: 5
- Use for: The projection versus z, and for analyses that benefit from the full binning.
- Edges:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Edges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q^2 [GeV]</td>
<td>&gt; 1</td>
</tr>
<tr>
<td>x</td>
<td>0.023 - 0.085 - 0.6</td>
</tr>
<tr>
<td>z</td>
<td>0.1 - 0.15 - 0.25 - 0.3 - 0.4 - 0.5 - 0.6 - 0.7 - 0.8 - 1.1</td>
</tr>
<tr>
<td>P_h,⊥ [GeV]</td>
<td>0.0 - 0.1 - 0.3 - 0.45 - 0.6 - 1.2</td>
</tr>
</tbody>
</table>

High resolution in P_h,⊥ with z slices

- Name: zp-3D
- Profile: x: 2 / z: 6 / P_h,⊥: 9
- Use for: The projection versus P_h,⊥. The projection versus z and P_h,⊥, and for analysis.
- Edges:

<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
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<td>0.1 - 0.2 - 0.3 - 0.4 - 0.6 - 0.8 - 1.1</td>
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<td>P_h,⊥ [GeV]</td>
<td>0.0 - 0.1 - 0.2 - 0.3 - 0.4 - 0.5 - 0.6 - 0.7 - 0.8 - 1.2</td>
</tr>
</tbody>
</table>

High resolution in x with z slices

- Get an overview of what is available.
Section 4

The final HERMES multiplicities

A little sampler.
Multiplicities: Projected vs $z$

- $u$-quark dominance.
- Deuteron has less $u$-quarks.
- $K^-$ pure sea object ($s\bar{u}$).

- Systematic uncertainties between particles/targets correlated.
- Asymmetries and ratios increase precision even further.

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One dimensional comparison with LO predictions

- Good agreement CTEQ6+DSS for $\pi^+$ and $K^+$ up to medium $z$.
- CTEQ6+Kretzer performs well for pions.
- Larger deviations for $\pi^-$ and $K^-$. 
- Room for improvement at high $z$, and in the disfavored sector.

*DSS, de Florian et al, PRD 75 (2007)*
CTEQ6L+DSS perform very well up to medium $z$.

Larger discrepancies at high $z$. 

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**$K/\pi$ and strangeness suppression**

- **Very good agreement** with the LO prediction.
- $u$ dominance: $K^+/\pi^+$ at high $z$ shows the extra cost of producing an $s\bar{s}$ compared to a $d\bar{d}$.
- **Strangeness suppresion larger** than previous fits.
- Also observed during the HERMES LUND MC tuning.
$K/\pi$ in 2 dimensions

- **LO parametrizations** predict the $\pi/K$ ratio very well up to medium $z$.
- At high $z$, LO calculations overshoot the measurement for the entire valence region.
Pushing the envelope

Applicability QPM-like factorization and the limits of precocious scaling.
QPM-like factorization is intuitive

Valence ratio $d_v/u_v$

\[
\frac{d_v}{u_v} \approx \frac{4R^\pi + 1}{4 + R^\pi}
\]

\[
R^\pi = 2 \frac{\sigma^+ - \sigma^-}{\sigma^+_p - \sigma^-_p} - 1
\]

Light sea asymmetry

\[
\frac{\bar{d} - \bar{u}}{u - d} \approx \frac{4k^{\text{sea}} - \rho^\pi}{1 - k^{\text{sea}} \rho^\pi}
\]

\[
\rho^\pi = \frac{\sigma^-_d - \sigma^-_p}{\sigma^+_p - \sigma^+_d}
\]

\[
k^{\text{sea}} = \frac{4 - \eta}{4\eta - 1} \quad \text{where} \quad \eta = \frac{D_{\text{unf}}}{D_{\text{fav}}}
\]

- Both should **depend on** $x$, not $z$:
  - **Signature of factorization.**
- Light sea asymmetry requires $D_{\text{unf}}/D_{\text{fav}}$ as input.
Where are the limits of QPM-like factorization?

HERMES, PRL81 (1998)

- Important result but **not ideal test** due to higher model dependence
- $\int d_v / \int u_v$ finally possible!
  - RICH and RICH unfolding.
  - Multi-dimensional smearing-unfolding.
  - Near-perfect grasp of interplay between the different systematics.
- High $z$ exclusive, low $z$ backward hemisphere.
Where are the limits of QPM-like factorization?

**LO access**

\[
R^\pi(z) \equiv \frac{2 \int_{Acc.} dxdQ^2 (\sigma^+_{d} - \sigma^-_{d})}{\int_{Acc.} dxdQ^2 (\sigma^+_{p} - \sigma^-_{p})} - 1 \approx \frac{\int_{Acc.} dxdQ^2 (u_v - 4k^{val} d_v)}{\int_{Acc.} dxdQ^2 (d_v - 4k^{val} u_v)}
\]

\[
\rightarrow \frac{\int_{Acc.} dxdQ^2 d_v}{\int_{Acc.} dxdQ^2 u_v} \approx \frac{4k^{val} R^\pi + 1}{4k^{val} + R^\pi}
\]

- \( k^{val} \equiv \frac{D^+_{u} - D^+_{\bar{u}}}{D^+_{d} - D^+_{\bar{d}}} \rightarrow 1 \) (isospin symmetry).

- Pushes the experimental precision to a limit:
  - A proper treatment of the **correlated systematics** is crucial.

- Very **sensitive to theoretical assumptions**:
  - Applicability of the LO, leading twist framework.
  - Additional assumptions (eg. isospin symmetry, cf. DSS).

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Where are the limits of QPM-like factorization?

\[
R^\pi = 2 \frac{\sigma^\pi_d - \sigma_d^+}{\sigma^\pi_p - \sigma_p^+} - 1
\]

\[
\int_{\text{Acc}} dx dQ^2 \frac{d\nu(x, Q^2)}{\int_{\text{Acc}} dx dQ^2 u(x, Q^2)}
\]

Cropped for dramatic effect
Where are the limits of QPM-like factorization?

- Very good agreement for mid-to-high $z$.
- Lowest point $> 3\sigma$ from the prediction:
  - Target remnant or theory?
  - Realistic FF assumption (DSS) lessens the discrepancy,
  - Probably mix.
- Results generally systematics dominated.
- CTEQ curve below 0.5 due to the integral over the HERMES acceptance (see page 9).
Where are the limits of QPM-like factorization?

### Lessons:
- **Discrepancy HAS to occur at low $z$.** This should be carefully considered when moving towards that limit.
- **Precocious scaling** holds very well mid-to-high $z$.
- More **precise knowledge of FF symmetries** required.

### SYSTEMATICS!
- Going higher in statistics doesn’t make sense anymore.
- **On to CEBAF!**
- **Multi-D binning key** for unfolding and interpretation.
Bonus: Transverse momentum dependence of the multiplicities
Transverse momentum dependence

- The multidimensional results provide leverage in the **quest to unfold intrinsic quark** $p_T$ and **fragmentation** $k_T$ from the **transverse hadron momentum** $P_{h\perp}$
  - Leverage the simultaneous binning in $P_{h\perp}$, $z$ and $x$ (or $Q^2$)
  - Access the shape of the unpolarized TMD
  - Provide a handle on flavor separation
  - Constrain TMD models and calculations

**$P_{h\perp}$ dependence in the LO TMD formalism**

\[
\frac{d^5\sigma^h}{dx dQ^2 dz d^2\vec{P}_{h\perp}} \propto \sum_q e^2_q \int d^2\vec{p}_T d^2\vec{k}_T \delta^2(\vec{P}_{h\perp} - \vec{k}_T - z\vec{p}_T) f^q_1(x, Q^2, p_T) D^h_q(z, Q^2, k_T)
\]
The shape of $P_{h\perp}$ in $z$ slices

- Superficially consistent with the **Gaussian ansatz**
- **Average and width** function of kinematics and hadron type.
\[ \langle P_{h\perp} \rangle \text{ as a function of } z \]

- Rising function of \( z \)
- \( \langle P_{h\perp} \rangle \) for \( K \text{ higher than } \pi \) at larger \( z \)
  - Point-to-point significance of 2\( \sigma \)
  - Strangeness suppression: at high \( z \), \( K \) sample contains (relatively) more sea events than \( \pi \)
  - Could hint at higher intrinsic \( \langle p_T \rangle \) for the sea?
\[ \langle P_{h\perp} \rangle \text{ in 2 dimensions} \]

- Slightly falling function of \( x \)
  - Also hints at higher intrinsic \( \langle p_T \rangle \) for the sea
Hadron charge asymmetry

- Numerator contains proportionally more valence than the denominator
- Especially at higher $z$
- Ratio encodes information about the shape of the intrinsic $p_T$ distribution

$A_h^+ = \frac{\pi^+ - \pi^-}{\pi^+ + \pi^-}$

$K^+ - K^- / K^+ + K^-$

$0.2 < z < 0.3$

$0.3 < z < 0.4$

$0.4 < z < 0.6$

$0.6 < z < 0.8$
Summary

- Unique set of 3D high-precision SIDIS multiplicities for $\pi^{\pm}$ and $K^{\pm}$ on $p$ and $d$ are presented

Enabling:
- **Evaluation of the quality** of FF (and PDF) parametrizations
- **Input** for the **next generation** of parametrizations
- Access to the **transverse distributions**

What do these high-precision results teach us?
- Crucial to consider the **fully differential case**
- Systematics have to be carefully considered
- If possible, take into account the correlations in the systematic uncertainties when calculating derived quantities

Precocious scaling continues down to HERMES energy!

Get the data at [http://www-hermes.desy.de/multiplicities](http://www-hermes.desy.de/multiplicities)
**BACKUP:** Proton-deuteron multiplicity asymmetry

**definition:**

\[ A_{d-p}^h \equiv \frac{M_d^h - M_p^h}{M_d^h + M_p^h} \]

- Reflects different valence quark content
- **Improved precision by cancellations** in the systematic uncertainty
BACKUP: Effect of the correction for exclusive VM

![Graph showing the effect of the correction for exclusive VM](image)

- Multiplicity for 
  - \( \pi^+ \)
  - \( \pi^- \)
  - \( K^+ \)
  - \( K^- \)

- Ratio for 
  - \( \pi^+ \)
  - \( \pi^- \)
  - \( K^+ \)
  - \( K^- \)

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SIDIS at HERMES
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Discrepancy is a function of $z$

- Lessons
  - More precise knowledge of FF symmetries required
  - Possible target remnant influence should be carefully considered when analyzing data near the low-$z$ limit
  - The framework holds surprizingly well mid-to-high $z$ at intermiate energies
EMC FFs

HERMES multiplicities
1996-97 data