Tools for understanding semi-inclusive deep-inelastic scattering measurements

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Investigating the inner structure of the proton

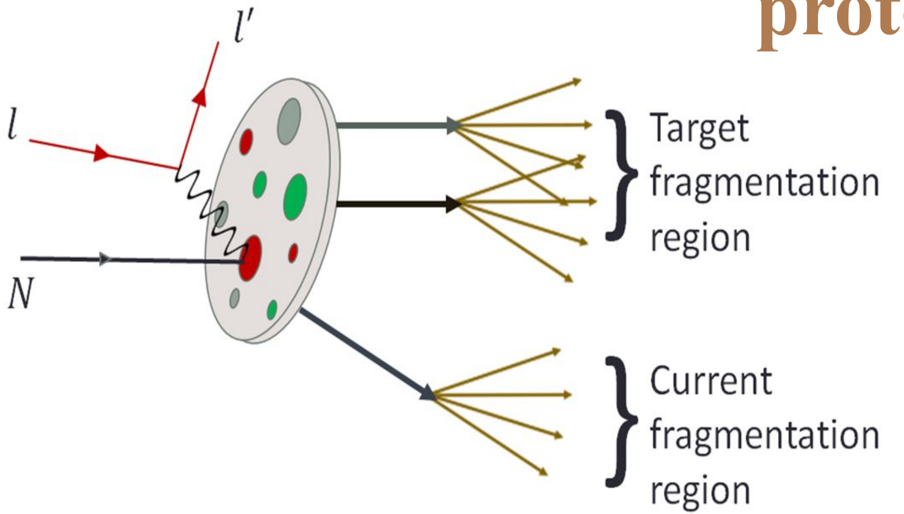


Figure 1: Schematic diagram of semi-inclusive deep inelastic scattering (**SIDIS**): a high-energy electron knocks a quark out of the nucleon. The quark or spectators from the proton forms a pion in the final state, which is detected along with the scattered electron

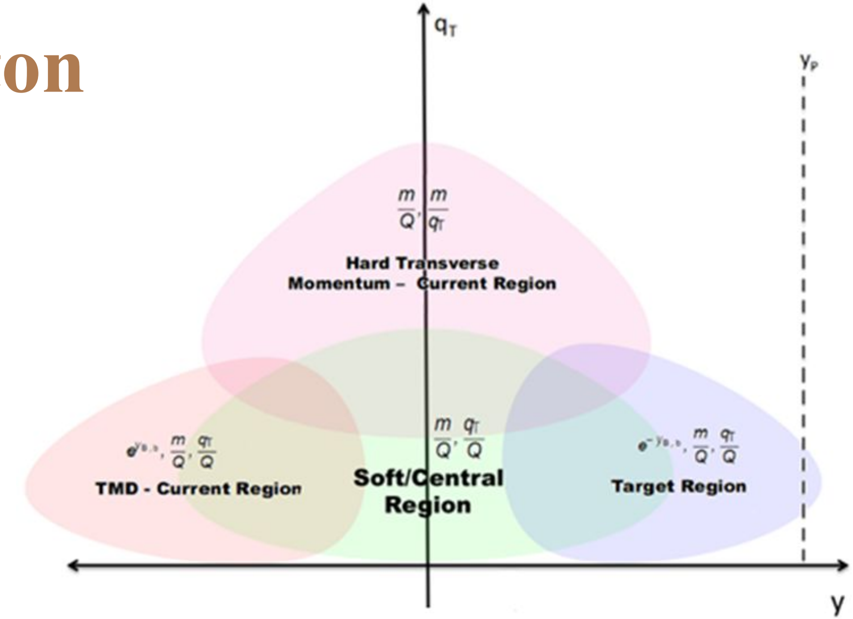
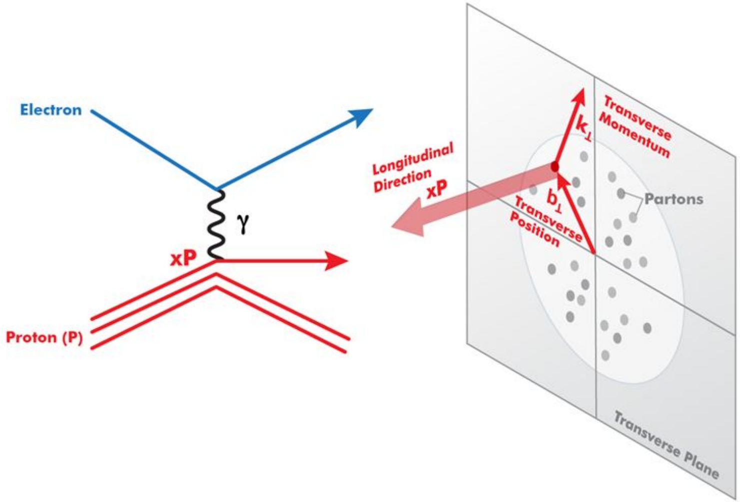


Figure 2: New affinity tool to quantify the proximity of any experimental kinematic bin to a particular hadron production region, e.g., TMD - Current Region.

What are TMDs?

3D imaging in space and momentum



3D imaging of quarks and gluons

longitudinal structure (PDF)

+ transverse momentum information (TMDs)

TMDs are studied in SIDIS

Momentum densities of quarks in a nucleon

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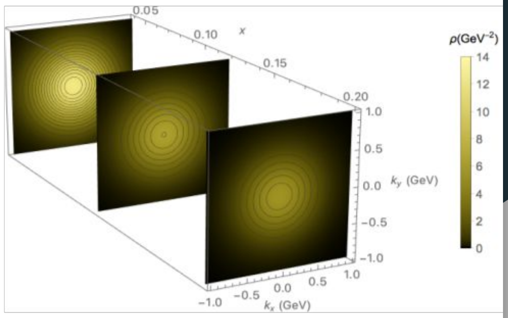
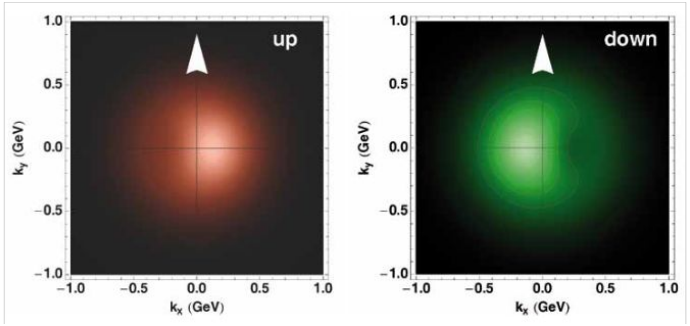


Momentum distributions in a transversely polarized nucleon

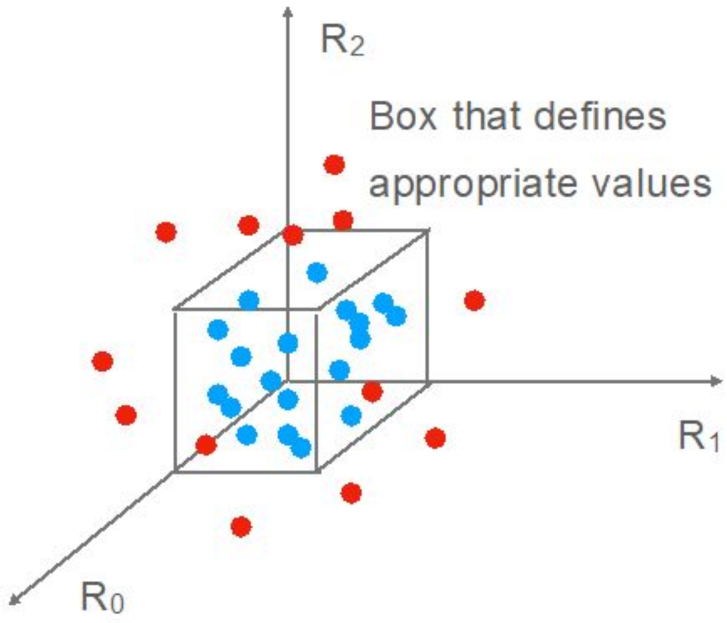


Goals for the project

- To study the paper "New tool for kinematic regime estimation in semi-inclusive deep-inelastic scattering" and the affinity tool;
- To study the influence of these parameters on the affinity results and see how reliable these results are in order to guide experiments and phenomenological studies of nucleon structure.
- Set whether there are any dominant parameters that most affect the result.
- Writing new software using Jupyter Notebooks for studies of the parameter space.

Affinity tool

Sample kinematics bins for ratios based on Monte Carlo method



Box size Estimated, using existing TMD phenomenology for guidance.

Affinity ranges from 0% to 100% and indicates affinity of a bin of a measurement to a particular kinematic region.

Affinity = **# times in** / **(#times in** + **#times out**)

Kinematic Regions in SIDIS and Region Indicators R_i

Ratio		Definition	
R_0	general hardness	$\max\left(\left\lvert\frac{k_i^2}{Q^2}\right\rvert, \left\lvert\frac{k_f^2}{Q^2}\right\rvert, \left\lvert\frac{\delta k_T^2}{Q^2}\right\rvert\right)$	Partonic description requires $R_0 << 1$.
R_1	collinearity	$\frac{P_h \cdot k_f}{P_h \cdot k_i}$	Small for current region, large for central and target region.
R_1'	target proximity	$\frac{P_h \cdot P}{Q^2}$	Small for target region.
R_2	transverse hardness	$\frac{\lvert k^2\rvert}{Q^2}$	Small for $2 \rightarrow 1$ process.
R_3	spectator virtuality	$\frac{\lvert k_X^2\rvert}{Q^2}$	Small for low order pQCD to be applicable. Large for high order pQCD to be applicable.
R_4	large transverse momentum	$\max\left(\left\lvert\frac{k_i^2}{k^2}\right\rvert, \left\lvert\frac{k_f^2}{k^2}\right\rvert, \left\lvert\frac{\delta k_T^2}{k^2}\right\rvert, \left\lvert\frac{k_{iT}^2}{k^2}\right\rvert\right)$	Small for collinear region.

Taken from the article "New tool for kinematic regime estimation in semi-inclusive deep-inelastic scattering" (https://inspirehep.net/literature/2021571)

The region indicators R_i depend on SIDIS measurements and parameters from non-perturbative QCD that are not well known.

Our four nonperturbative parameters are defined as follows:

```
params['delta_k_t'] =  np.random.uniform(lower,upper,size)
params['k_i_t']     =  np.random.uniform(lower,upper,size)
params['M_ki']      =  np.random.uniform(lower,upper,size)
params['M_kf']      =  np.random.uniform(lower,upper,size)
```

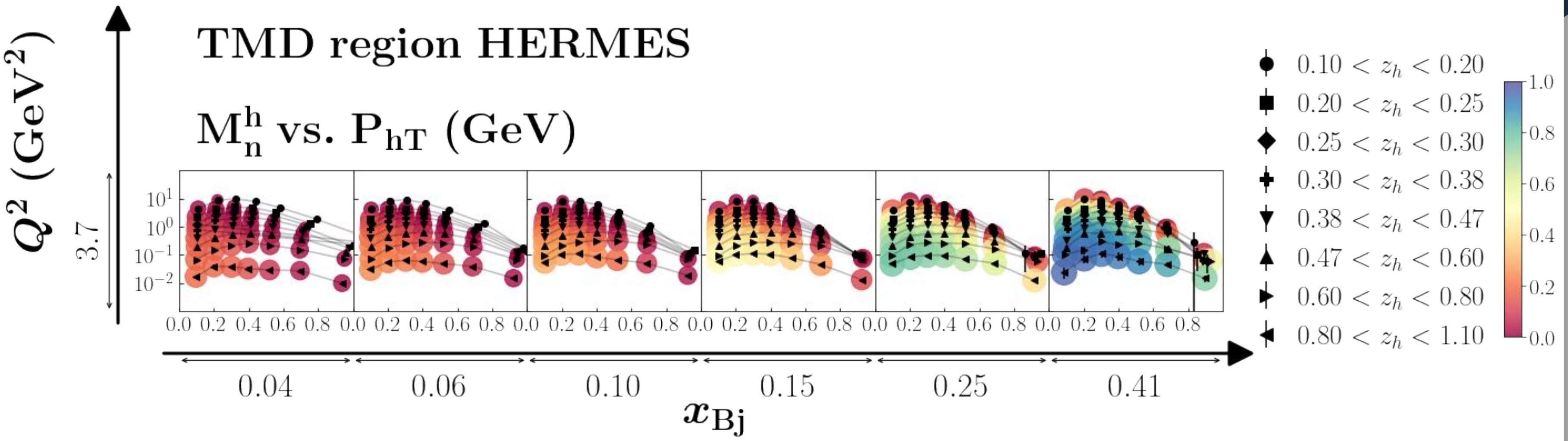
Therefore, there were two types of changes:

- Fixing the value of one parameter to find out which parameter has the greatest influence on the affinity results;
- Changing the value of the first variable (*lower boundary of the output interval*) for one parameter to confirm or disprove guesses that it is it that affects the affinity result.

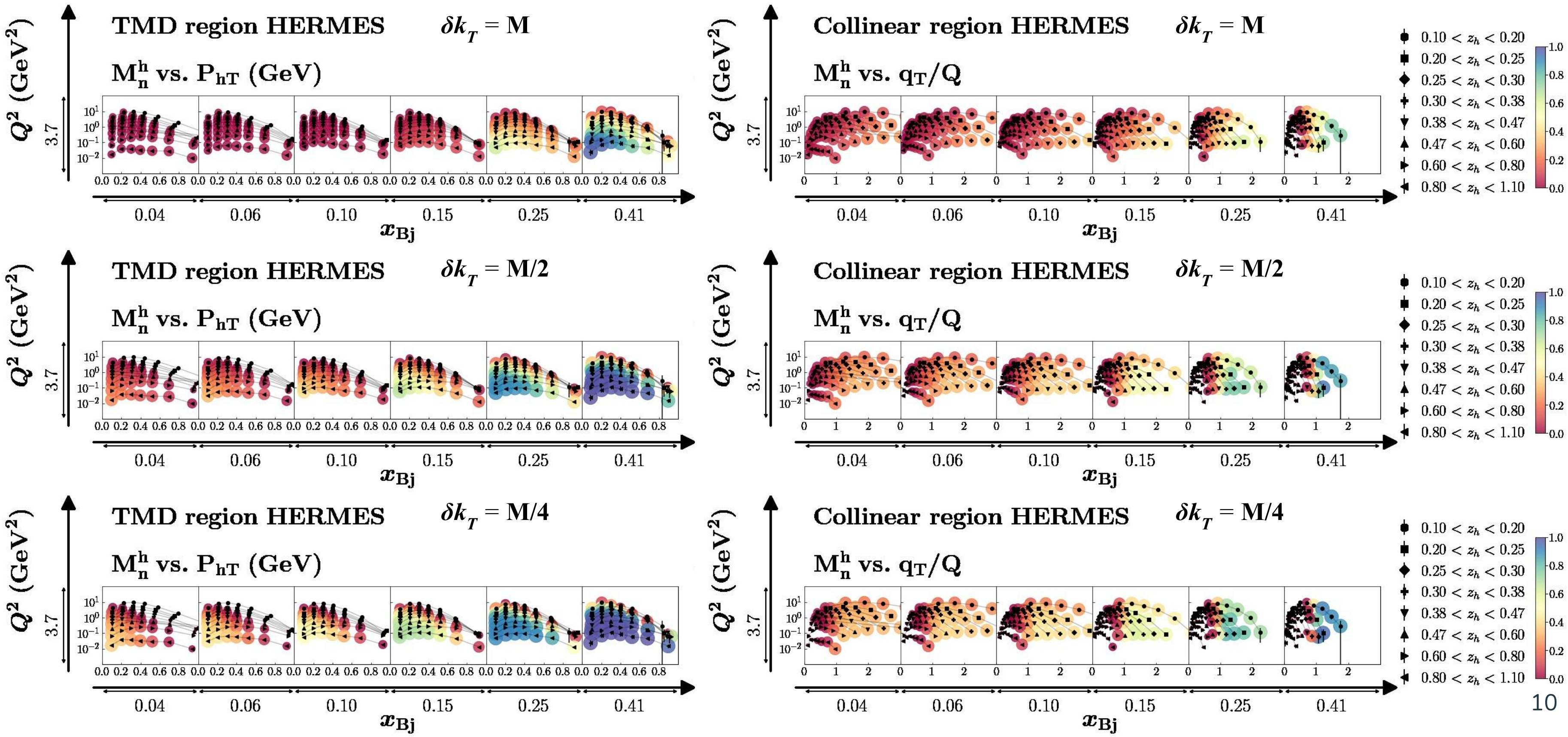
Software used

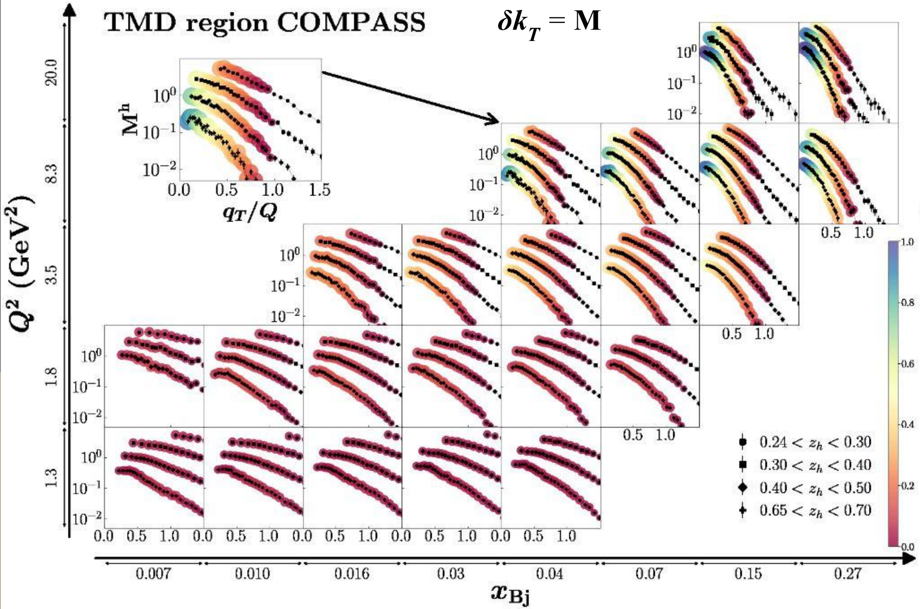
- ❖ Jupyter Notebook tested at JupyterLab at Jefferson Lab, allows to easily share notebook and results with colleagues;
- ❖ Python libraries:
  - ➢NumPy
  - ➢Matplotlib
  - ➢Pandas

Plot format to present affinity results for a multitude of kinematic bins

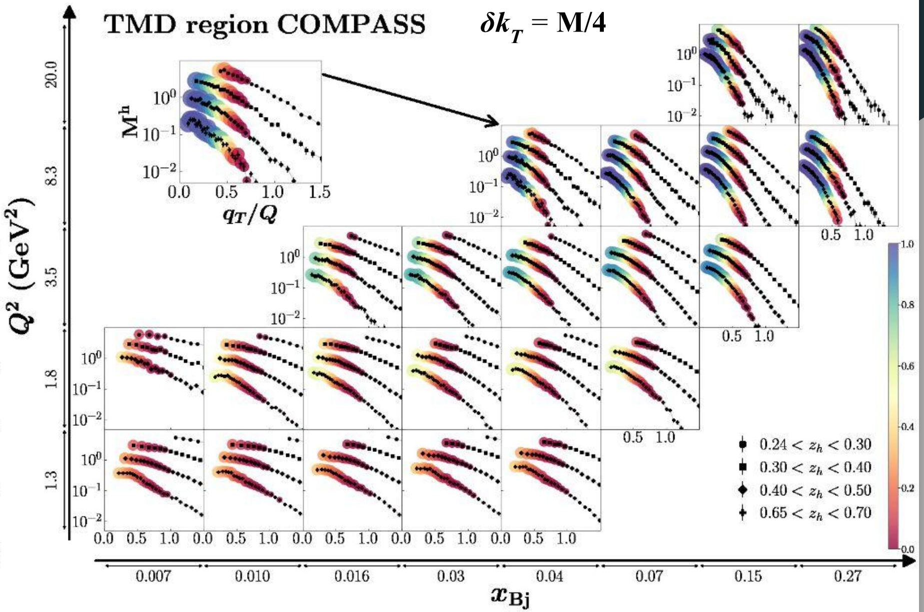


The resulting graphs

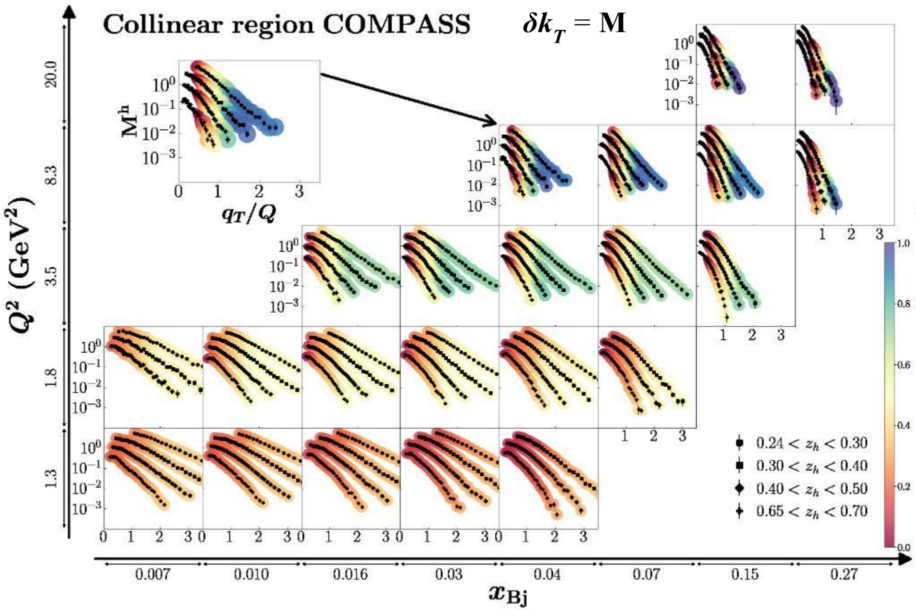


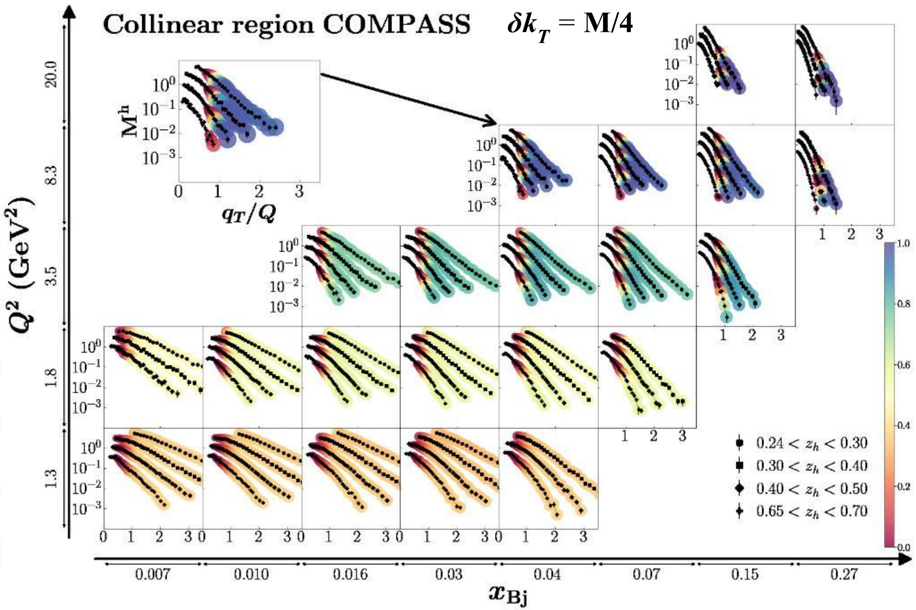


TMD region COMPASS
δk_T = M
Q^2 (GeV^2)
x_{Bj}
q_T/Q
$0.24 < z_h < 0.30$
$0.30 < z_h < 0.40$
$0.40 < z_h < 0.50$
$0.65 < z_h < 0.70$



TMD region COMPASS
δk_T = M/4
Q^2 (GeV^2)
x_{Bj}
q_T/Q
$0.24 < z_h < 0.30$
$0.30 < z_h < 0.40$
$0.40 < z_h < 0.50$
$0.65 < z_h < 0.70$


Collinear region COMPASS
δk_T = M
Q^2 (GeV^2)
20.0
8.3
3.5
1.8
1.3
M^h
q_T/Q
x_{Bj}
0.007
0.010
0.016
0.03
0.04
0.07
0.15
0.27
$0.24 < z_h < 0.30$
$0.30 < z_h < 0.40$
$0.40 < z_h < 0.50$
$0.65 < z_h < 0.70$


Collinear region COMPASS
δk_T = M/4
Q^2 (GeV^2)
20.0
8.3
3.5
1.8
1.3
M^h
q_T/Q
x_{Bj}
0.007
0.010
0.016
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$0.24 < z_h < 0.30$
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$0.65 < z_h < 0.70$

Conclusions

- One parameter was found that most affects the result of affinity. This parameter is δk_T, which is good for characterizing an intrinsic relative transverse momentum in the large Q limits.
- It was also found that indeed only one variable, δk_T, has the strongest influence on the result of plottings.
- When examining the graphs for the collinear and TMD regions, it turned out that in the area where the highest affinity matches for the TMD region is, the same area will have the smallest matches in the Collinear. This means that there is a kind of clear separation of these areas.

What IRIS-HEP Fellowship program gave me

This program gave me these opportunities:

- to work in a team studying semi-inclusive deep inelastic scattering (SIDIS):
  - Mariaelena Boglione (University of Turin and INFN)
  - Markus Diefenthaler (Jefferson Lab)
  - Leonard Gamberg (Penn State Berks)
  - Wally Melnitchouk (Jefferson Lab)
  - Alexei Prokudin (Penn State Berks)
  - Nobuo Sato (Jefferson Lab);
- learn the Python programming language and the advantages of interactive Jupyter Notebooks, because before that I was only familiar with C and Fortran;
- learn more about the parton theory that describes SIDIS;