SIDIS Kinematic regions

and their role in giving the correct theory interpretation to experimental measurements

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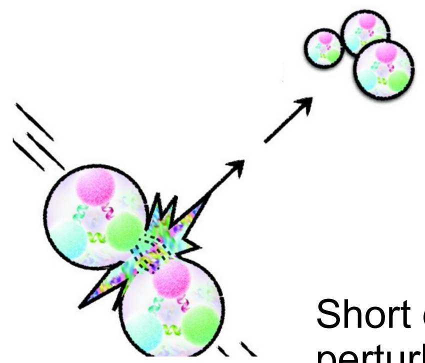
QCD and Factorization

QCD

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



- The interplay between **perturbative** and **non-perturbative** regimes is currently one of the most challenging aspects in phenomenology, which will be explored at JLab22
- **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

Resummation / TMD evolution

$$\frac{1}{\sigma_0}\frac{d\sigma}{dQ^2dydq_T^2} = \int \frac{d^2\boldsymbol{b}_T e^{i\boldsymbol{q}_T\cdot\boldsymbol{b}_T}}{(2\pi)^2}\sum_j \underbrace{e_j^2 W_j(x_1,x_2,b_T,Q)}_{\text{Resummed term}} + \underbrace{Y(x_1,x_2,q_T,Q)}_{\text{Finite term}}$$

$$\boxed{Y = \sigma^{FO} - \sigma^{ASY}}$$

- The W term is designed to work well at low and moderate q_T, when $q_T << Q$. (Notice that W is devised to work down to $q_T \sim 0$, however collinear-factorization works up to $q_T > M$; therefore, TMD-factorization and collinear-factorization can be simultaneously applied only when $q_T >> M$).
- The W term becomes unphysical at larger q_T, when $q_T \geq Q$, where it becomes negative (and large).
- The Y term corrects for the misbehaviour of W as q_T gets larger, providing a consistent (and positive) q_T differential cross section.
- The Y term should provide an effective smooth transition to large q_T, where fixed order perturbative calculations are expected to work.

TMD vs Collinear regions

- For this scheme to work, 4 distinct kinematic regions have to be identified
- They should be large enough and well separated

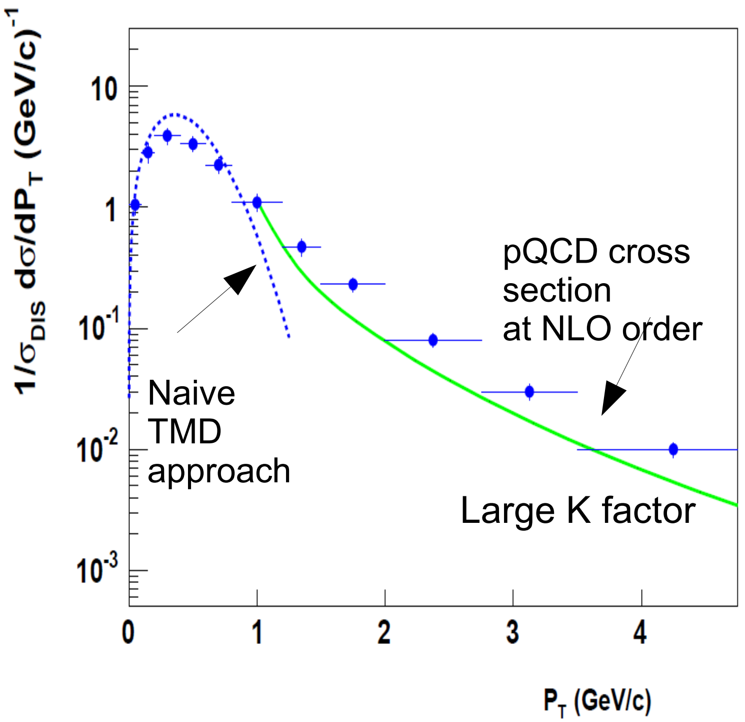
TMD evolution		Matching region (Y factor)	Fixed Order collinear QCD
$q_T \sim \lambda_{QCD}$	$q_T << Q$	$q_T \sim Q$	$q_T \geq Q$
Intrinsic q_T	Soft gluon radiation		Hard gluon emission

$$q_T = \frac{P_T}{z_h}$$

Resummation in SIDIS

Factorization regions

- fixed order pQCD calculation describe the SIDIS cross section at large q_T
- the cross section at small q_T is dominated by non perturbative
  it is well described by TMD factorization (complemented with non perturbative modeling)
- The intermediate region is the "matching region"

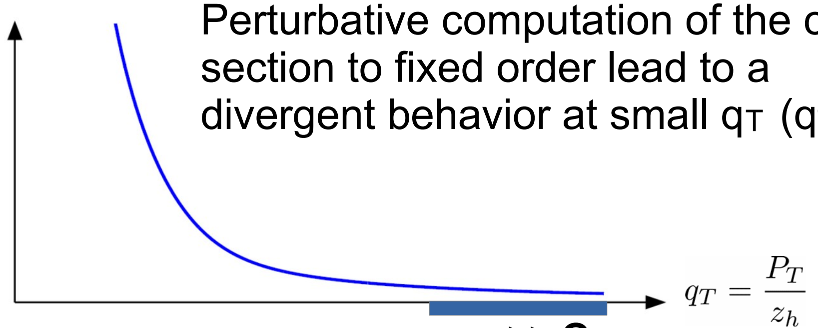


Anselmino, Boglione, Prokudin, Turk, Eur.Phys.J. A31 (2007) 373-381

ZEUS Collaboration (M. Derrick), Z. Phys. C 70, 1 (1996)

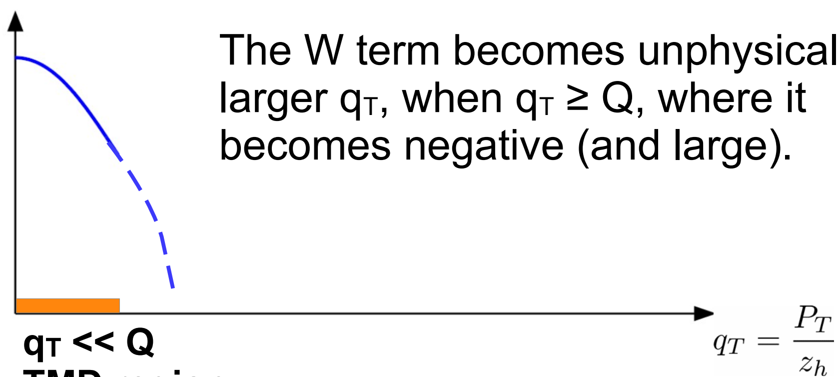
Factorization

Perturbative computation of the cross section to fixed order lead to a divergent behavior at small q_T (q_T<<Q)

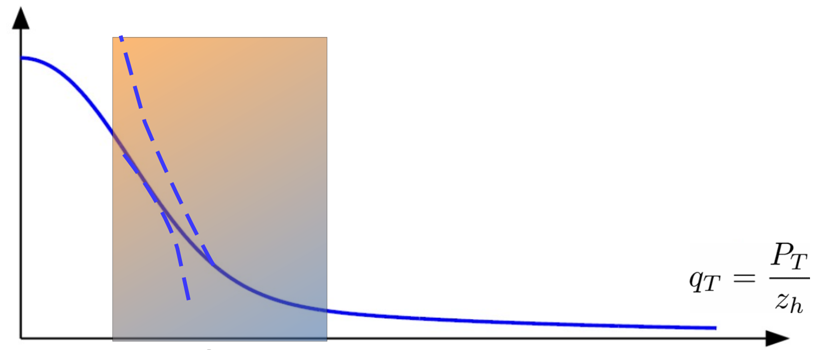


q_T >> Q
collinear region
pQCD

The W term becomes unphysical at larger q_T, when $q_T \geq Q$, where it becomes negative (and large).



q_T << Q
TMD region
non-pQCD



q_T ~ Q
matching region

Matching region is where TMD and collinear cross sections are expected to be matched

$$\sigma \simeq W + Y$$

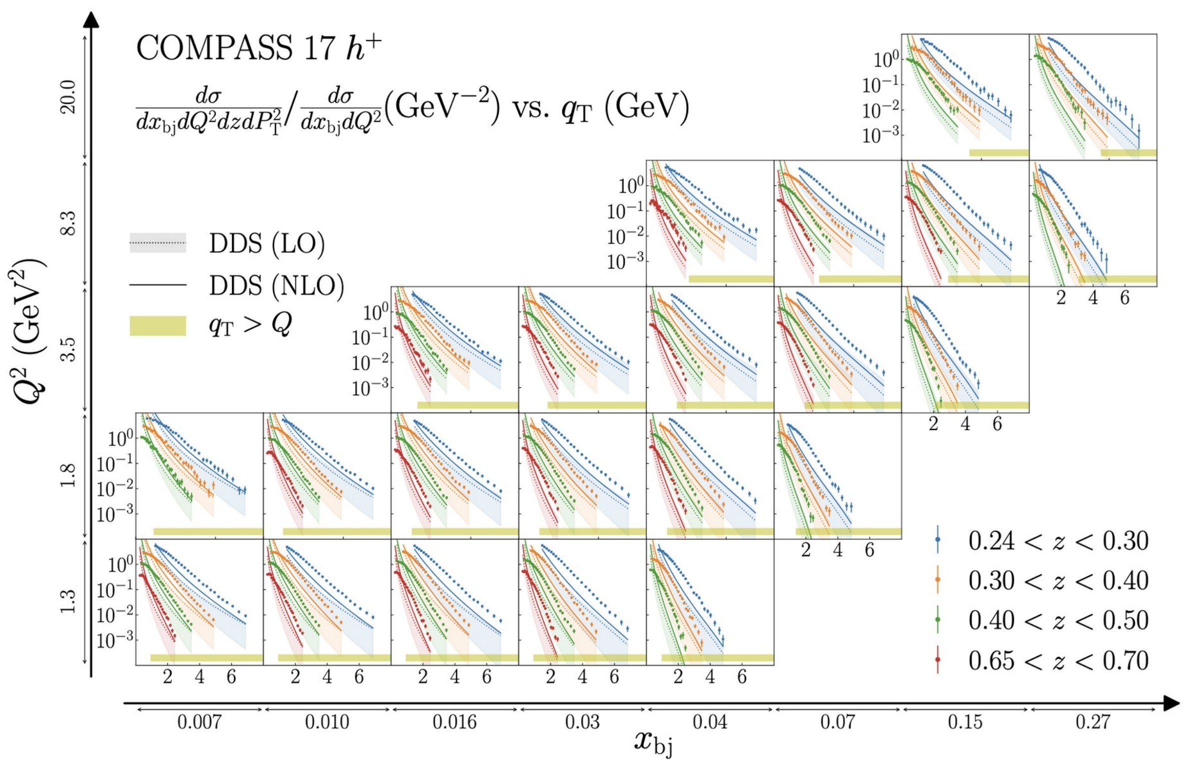
The Y term corrects for the misbehavior of W as q_T gets larger, providing a consistent (positive) q_T differential cross section.

The Y term should provide an effective smooth transition to large q_T, where fixed order perturbative calculations are expected to work.

Serious Issues

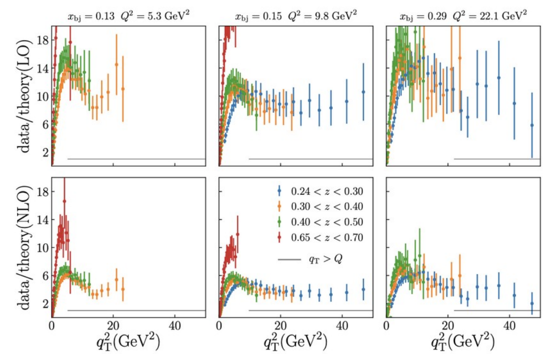
Issue 1: collinear cross section at large q_T

★ At high q_T the collinear formalism should be valid, but large discrepancies are observed



Gonzalez-Hernandez, Rogers, Sato, Wang, Phys.Rev.D 98 (2018) 11, 114005

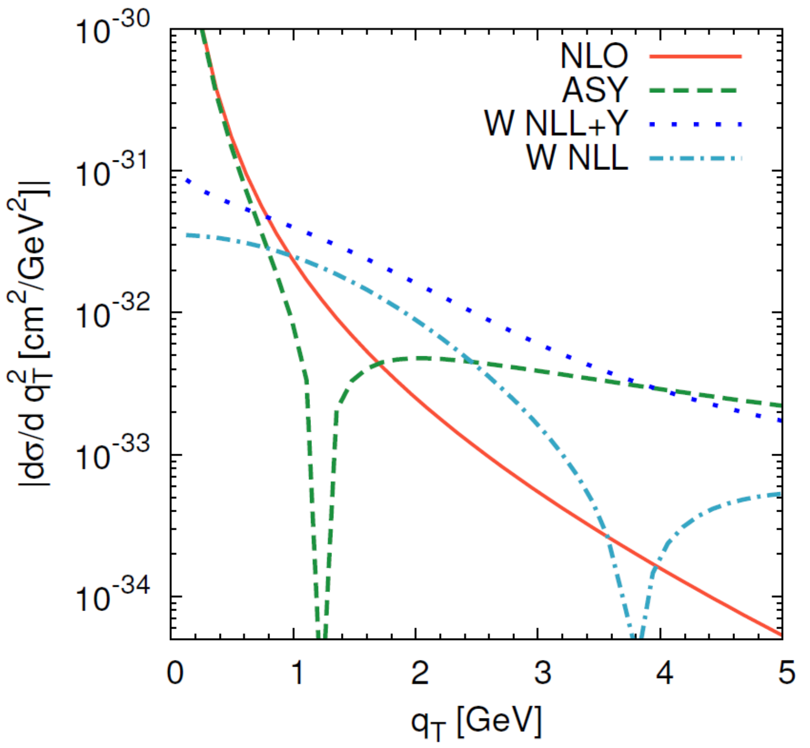
Discrepancy is about one order of magnitude



$$q_T = \frac{P_T}{z_h}$$

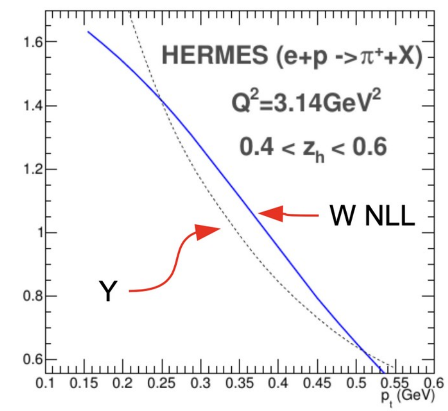
Issue 2: SIDIS - Y factor

Boglione, Gonzalez, Melis, Prokudin, JHEP 02 (2015) 095



$$\boxed{\frac{d\sigma^{\rm NLO}}{dx\,dy\,dz\,dq_T^2} = \frac{d\sigma^{\rm ASY}}{dx\,dy\,dz\,dq_T^2} + Y}$$

- The Y factor should not be neglected
- The Y factor is very large (as large as the cross section itself) even at low q_T



Sun et al arXiv:1406.3073

- However, it could be affected by large theoretical uncertainties

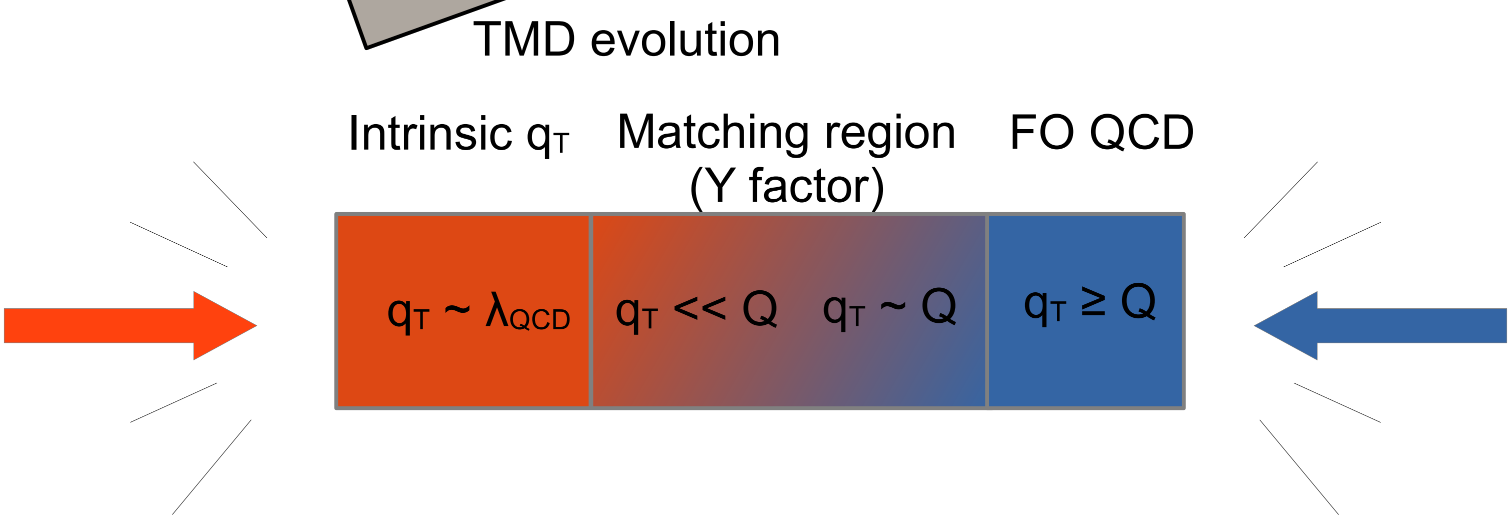
see for example
Echevarria et al, Phys.Lett.B 781 (2018) 161-168

$\sigma^{ASY} = Q^2/q_T^2$ [A $\mathrm{Ln}(Q^2/q_T^2)$ + B + C]

Kinematic regions

- For this scheme to work, 4 distinc ... have to be identified
- They should be larg ...

Does not work in SIDIS (HERMES, COMPASS, JLAB12)



The role of Jlab 22

- How does QCD manifest itself in the “matching region”?
- Is the “matching region” just a transition region?
- Does this region need a new theoretical approach of its own, not just an attempt to stretch the TMD and collinear schemes to match each other?
- To learn about this new kinematic region we need new, high statistics data which populate this exact kinematics. This is something that JLab22 could do in a unique way.
- Jlab 22 experimental data will explore this intermediate region, helping us to study an energy and transverse momentum range which is crucial to improve the current understanding of QCD in term of factorization.

Affinity

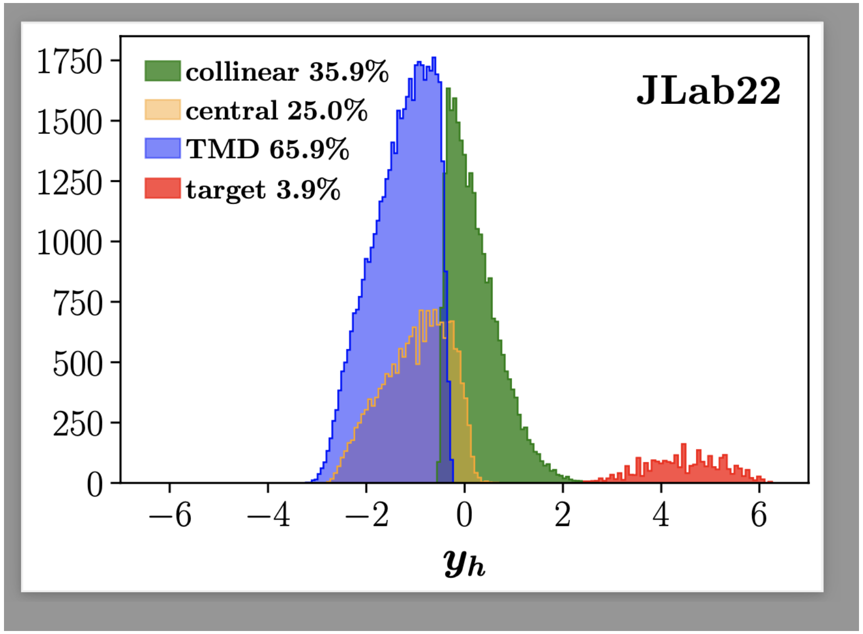
- Affinity is phenomenological tool based on momentum region indicators to guide the analysis and interpretation of SIDIS measurements.
- It is devised to help visualize and quantify the proximity of any experimental kinematic bin to a particular hadron production region, such as that associated with TMD factorization, collinear factorization, etc …
- It is based on region indicators

Ratio		Definition
R_0	general hardness	$\max\left(\left\lvert\frac{k_i^2}{Q^2}\right\rvert, \left\lvert\frac{k_f^2}{Q^2}\right\rvert, \left\lvert\frac{\delta k_T^2}{Q^2}\right\rvert\right)$
R_1	collinearity	$\frac{P_h \cdot k_f}{P_h \cdot k_i}$
R_1'	target proximity	$\frac{P_h \cdot P}{Q^2}$
R_2	transverse hardness	$\frac{\lvert k^2\rvert}{Q^2}$
R_3	spectator virtuality	$\frac{\lvert k_X^2\rvert}{Q^2}$
R_4	large transverse momentum	$\max\left(\left\lvert\frac{k_i^2}{k^2}\right\rvert, \left\lvert\frac{k_f^2}{k^2}\right\rvert, \left\lvert\frac{\delta k_T^2}{k^2}\right\rvert, \left\lvert\frac{k_{iT}^2}{k^2}\right\rvert\right)$

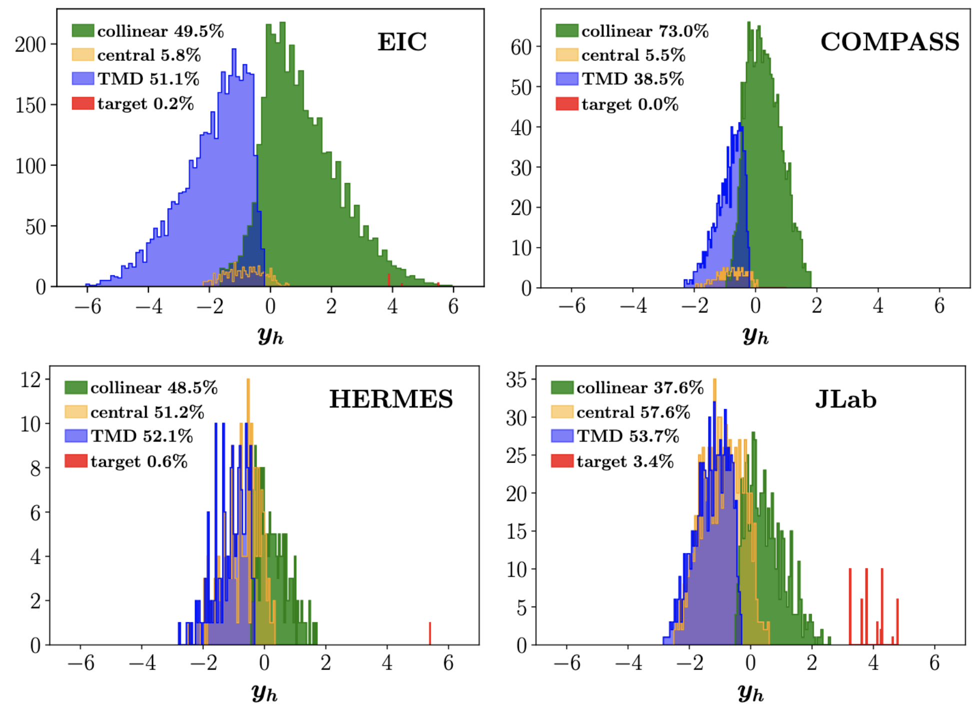
Region	R_0	R_1	R_1'	R_2	R_3	R_4
TMD	small	small	$\times$	small	$\times$	$\times$
matching	small	small	$\times$	small	$\times$	$\times$
collinear	small	small	$\times$	large	small (LO pQCD) large (HO pQCD)	small
target	small	large	small	$\times$	$\times$	$\times$
central	small	not small	not small	small	$\times$	$\times$

- It requires some number of non-perturbative parameters (which have to be appropriately tuned)

Affinity



$$y_h = \frac{1}{2}\log\left(\frac{P_h^+}{P_h^-}\right)$$

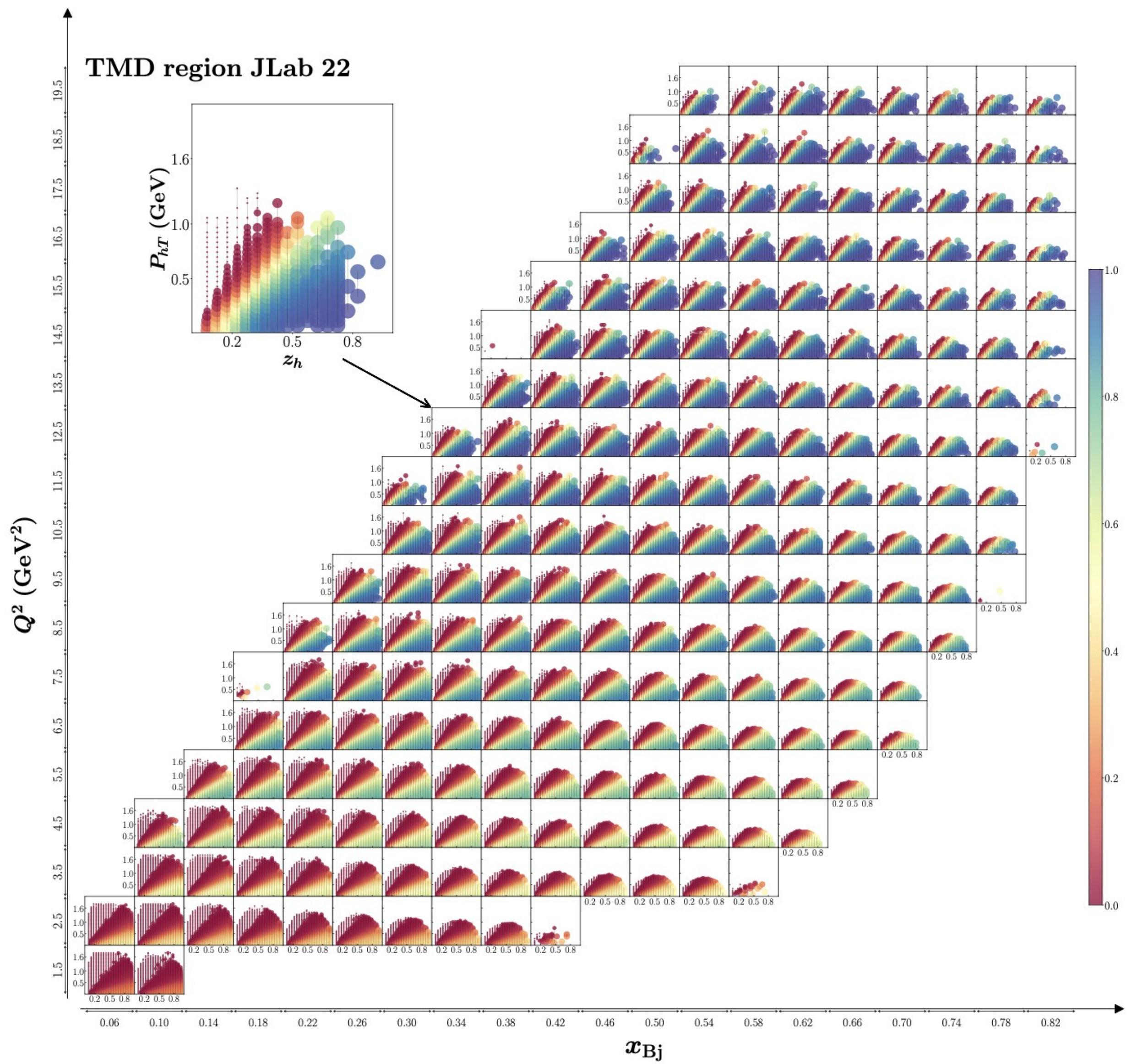


Phase space in rapidity y_h of produced hadron, with for TMD, collinear, central and target regions indicated.

The legends show the percentage of all bins with corresponding affinity above 5%

- EIC and COMPASS offer little access to the central region
- Jlab 22, with its amazing statistics, will be a magnifying glass on the central region

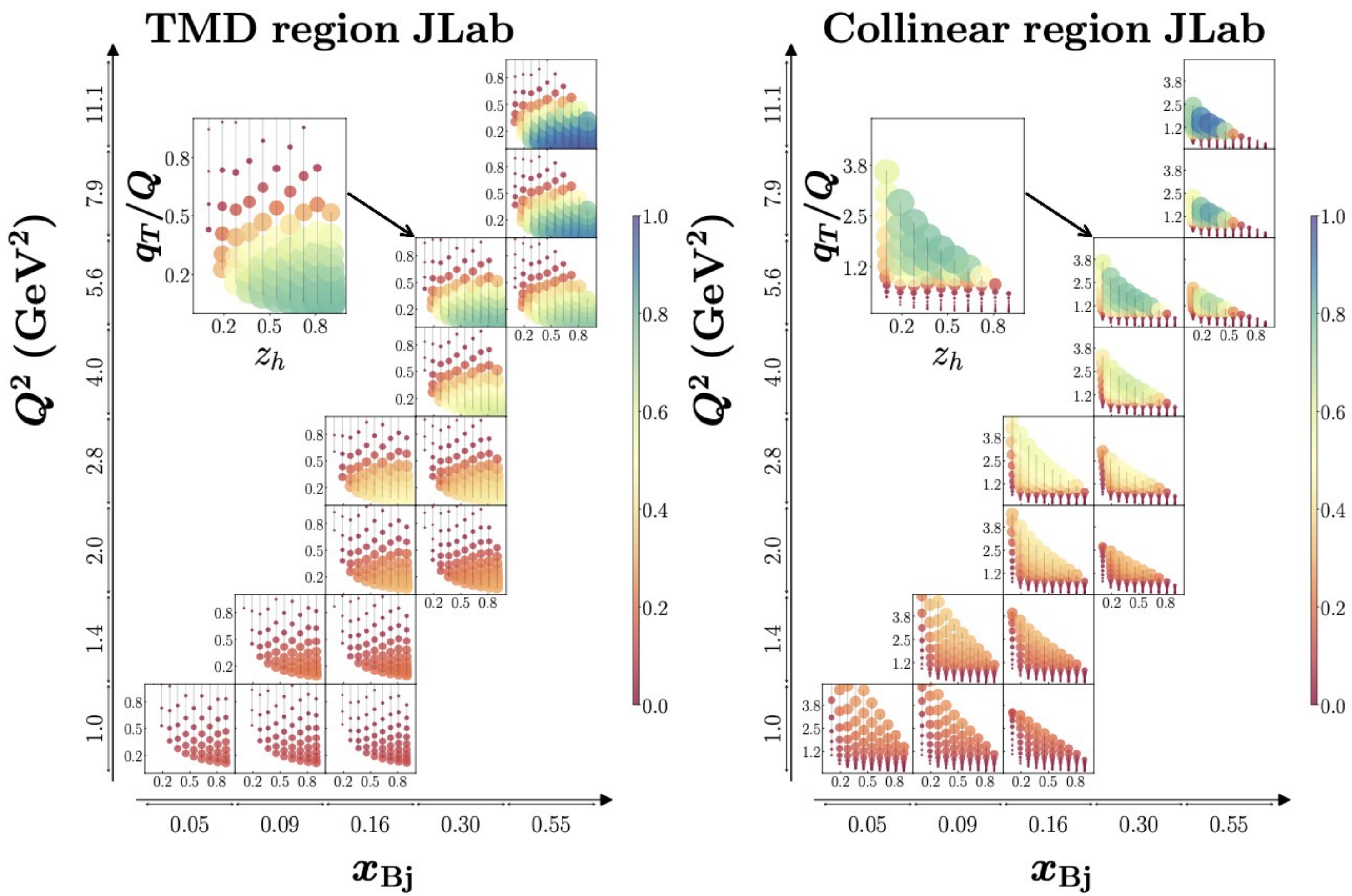
TMD-Affinity@JLab22



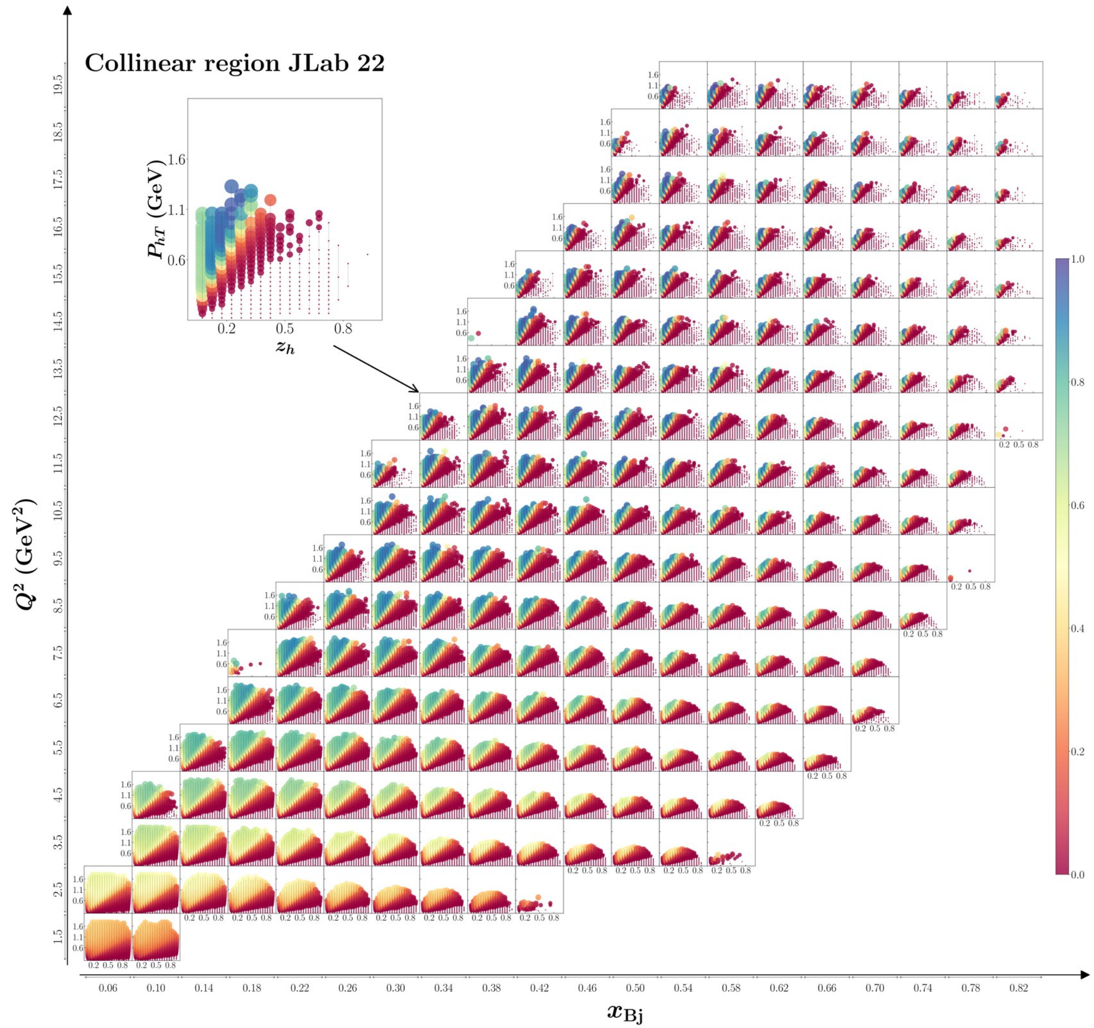
- Very high statistics and fine binning will improve the 3D maps of hadron structure
- **TMD region** will be accessible (large Q, large z, **small P_T**)
- **Collinear region** will be accessible (large Q, moderate z, **large P_T**)
- A unique feature of Jlab22 is that it will offer an unprecedented insight onto the **matching region,** which cannot be explored in any other SIDIS experiment
- Extended reach in x will be crucial

Many thanks to Alexei Prokudin, who produced these plots in high speed mode

TMD region@JLab12



Collinear-Affinity@JLab22



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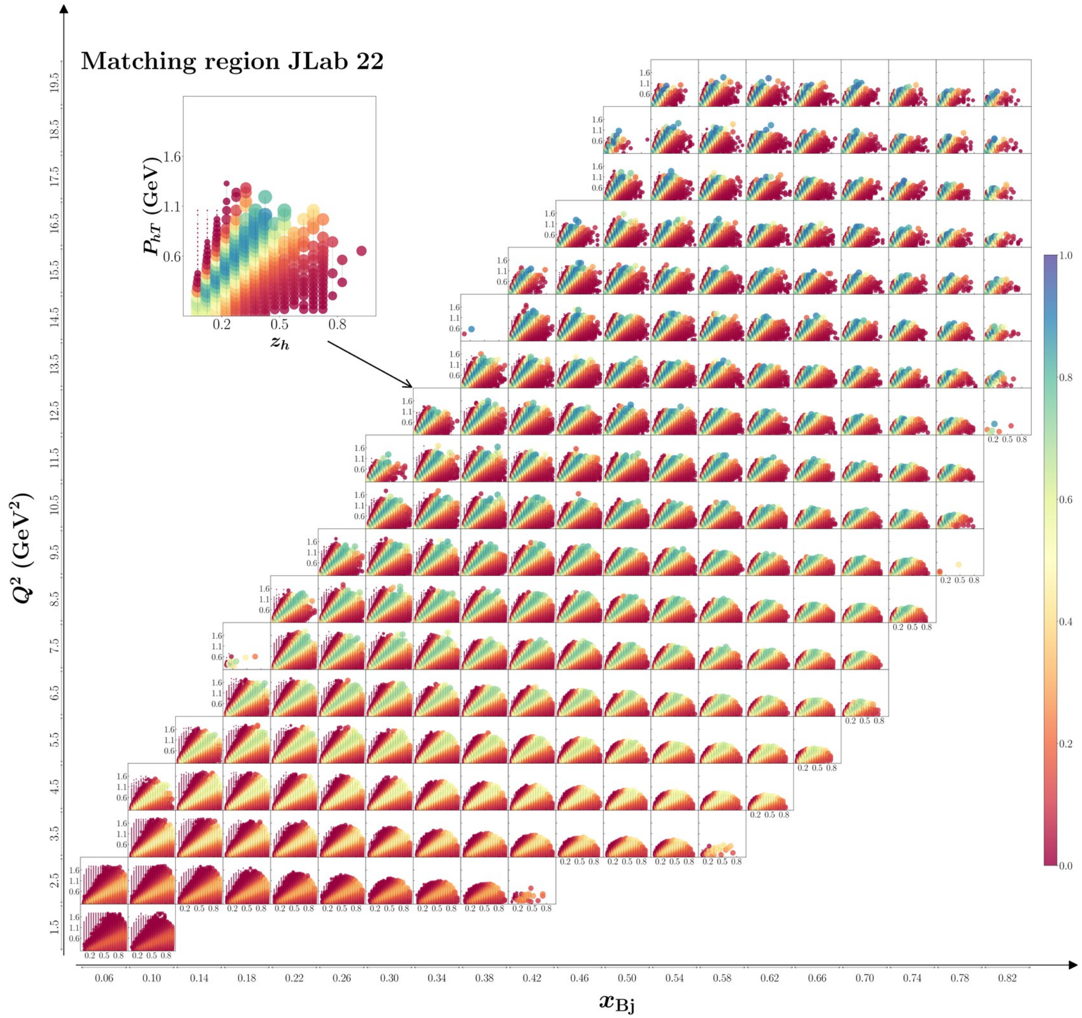
Affinity to matching region @JLab22



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Issues and future perspectives

- Phenomenological studies of TMD factorization and evolution have come a long way. Many aspects of the interplay between perturbative and non-perturbative contributions are now better understood. But the matching region needs a dedicated, more detailed theoretical treatment.

- Until very recently, we expected TMD factorization to work at very low P_T, collinear factorization to work at large P_T and a fusion/overlap of the two schemes to be enough for the description the transition region which, for this exact reason, we always called "matching region".

- Hermes, Compass and JLab12 measurements have shown us that this is hardly the case.

- P_T distributions of SIDIS cross sections over the full P_T range will have to be further investigated (flexibility of models, number of free parameters)

  - Y factor and matching region are crucial ingredients, which JLAB22 will help to explore

- Data selection is crucial in global fitting:

  - not too many
    (only data belonging to the kinematic region described by the appropriate scheme should be considered)
  - not too few
    (too strict a selection can bias the fit results and neglect important information from experimental data)

  - Affinity is a tool that needs refining, but it can help phenomenologists in performing consistent data selection