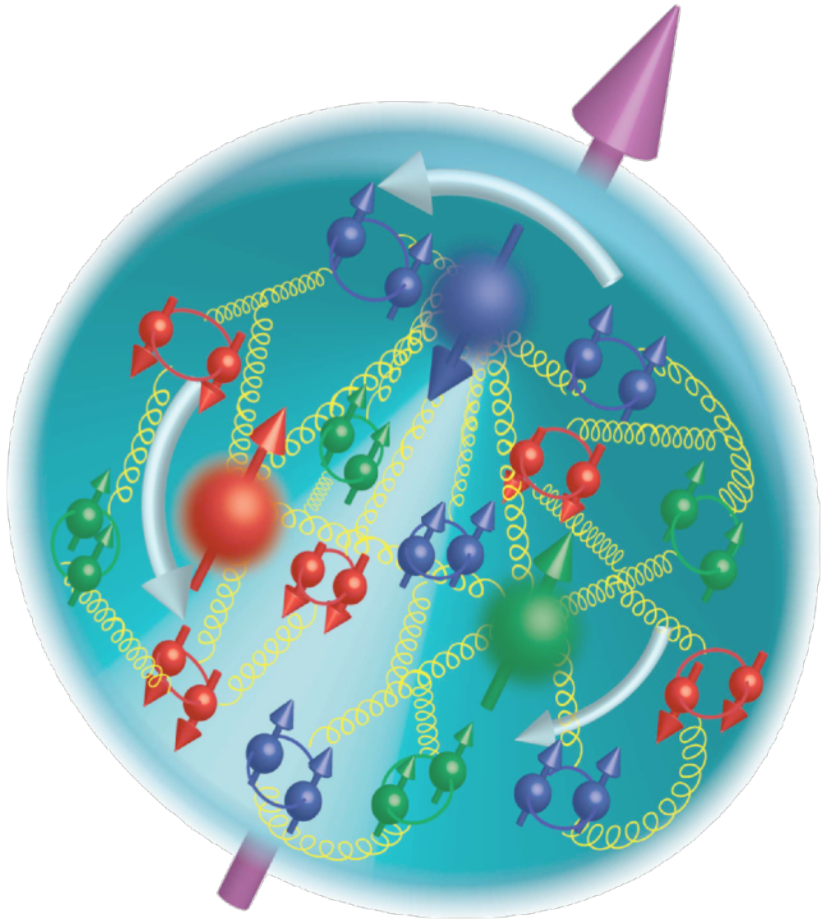
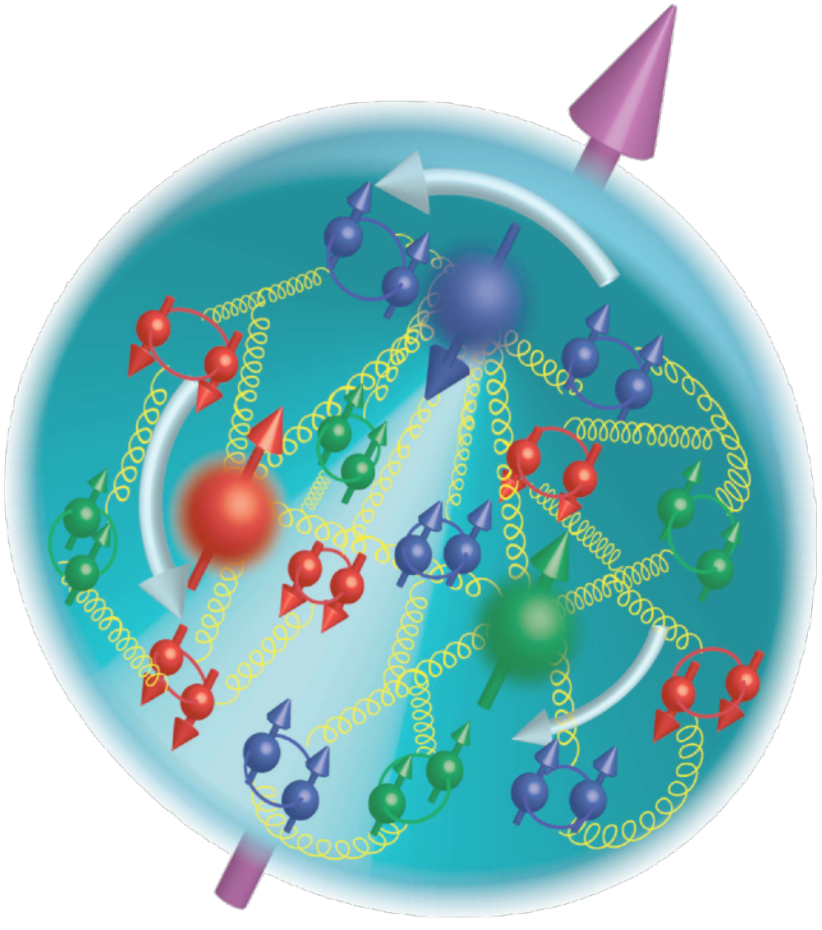


REGIONS IN SIDIS

Alexei Prokudin



In collaboration with: M. Boglione, M. Diefenthaler, S. Dolan, L. Gamberg, S. Gordon, W. Melnitchouk, D. Pitonyak, T. Rogers, N. Sato

SEMI INCLUSIVE DEEP INELASTIC SCATTERING

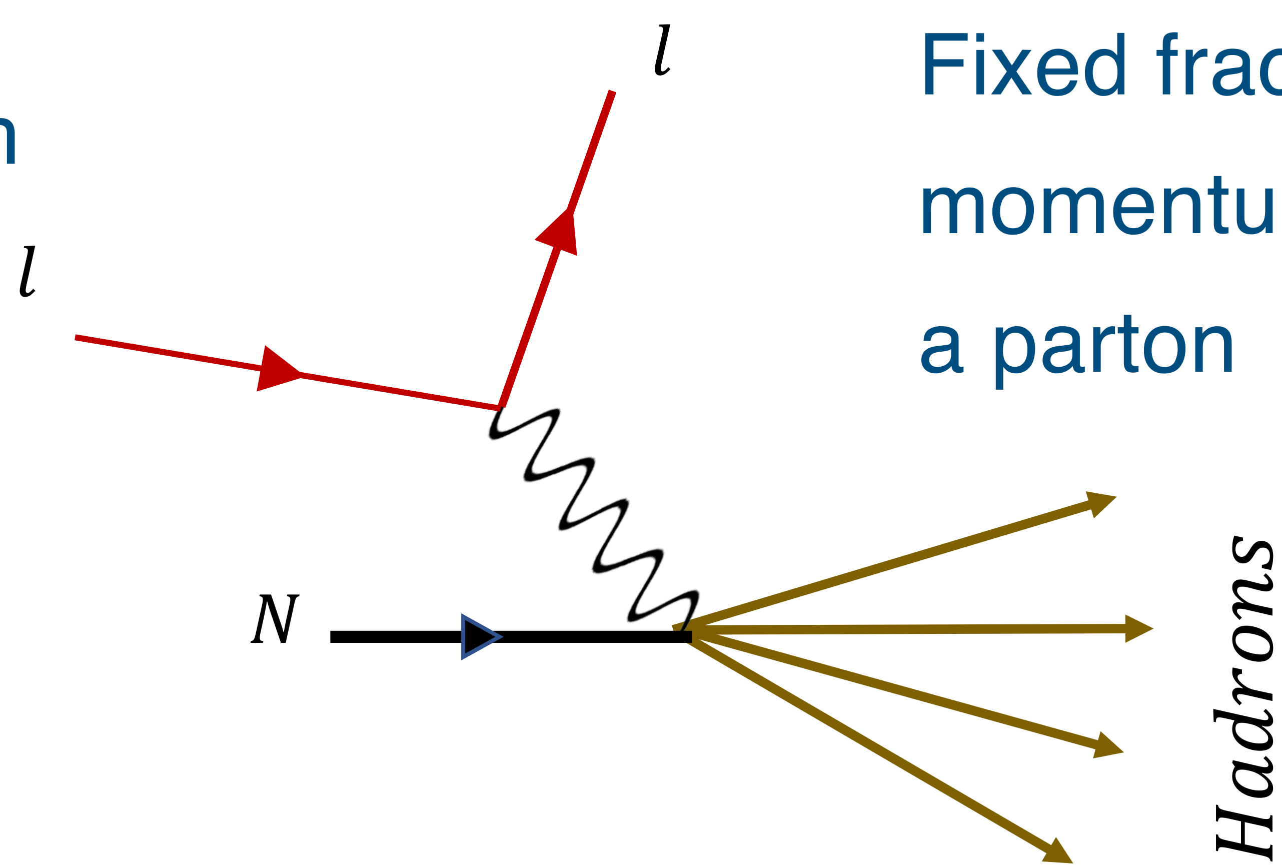
Consider electron - hadron collisions in DIS regime

$$Q^2 \to \infty$$

Transverse resolution < 1 fm

$$x_{Bj} = \frac{Q^2}{2P \cdot q} = const$$

Fixed fraction of momentum carried by a parton



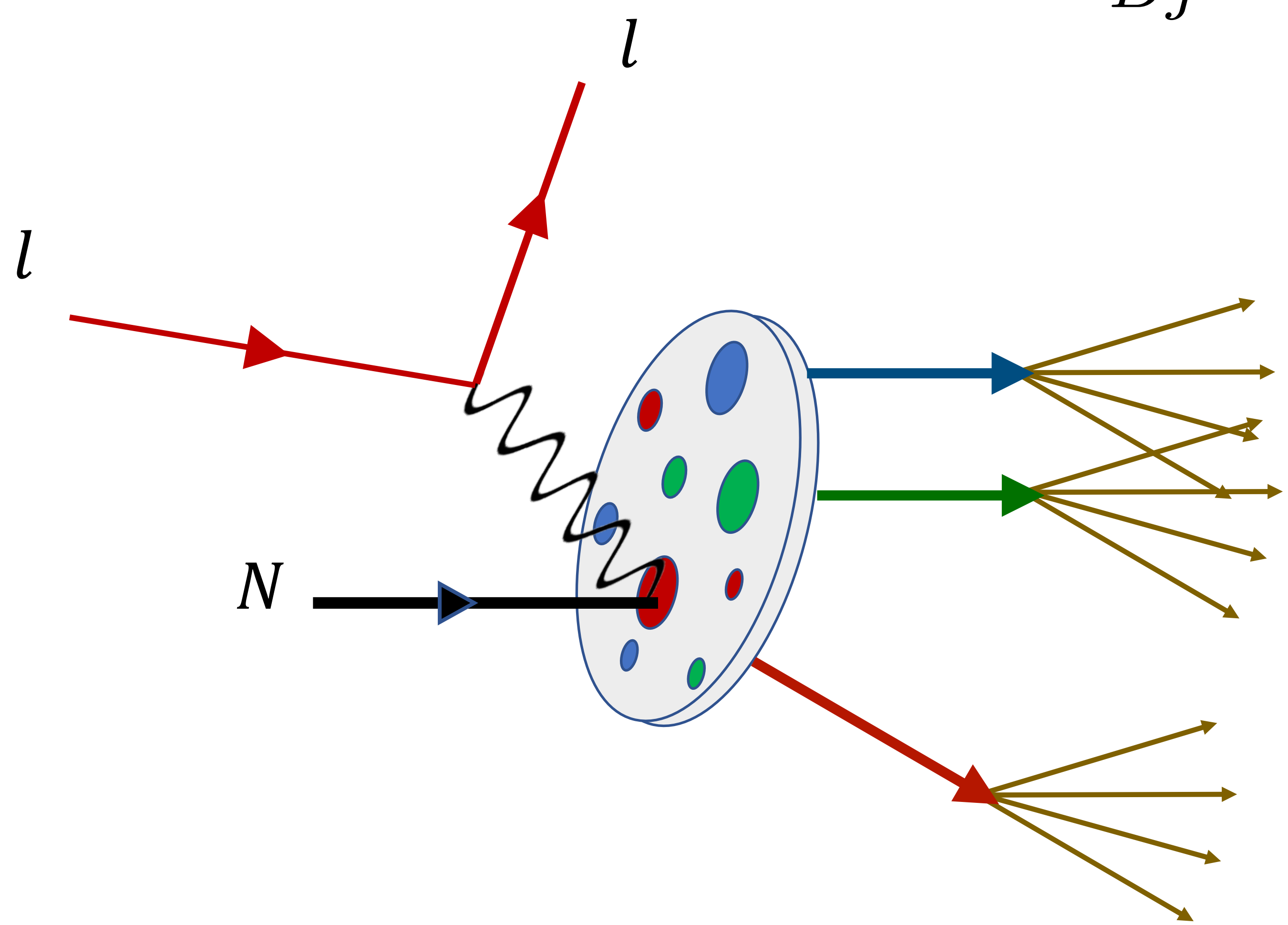
Detect a pion in the final state

SEMI INCLUSIVE DEEP INELASTIC SCATTERING

Consider electron - hadron collisions in DIS regime

$$Q^2 \to \infty$$

$$x_{Bj} = \frac{Q^2}{2P \cdot q} = const$$

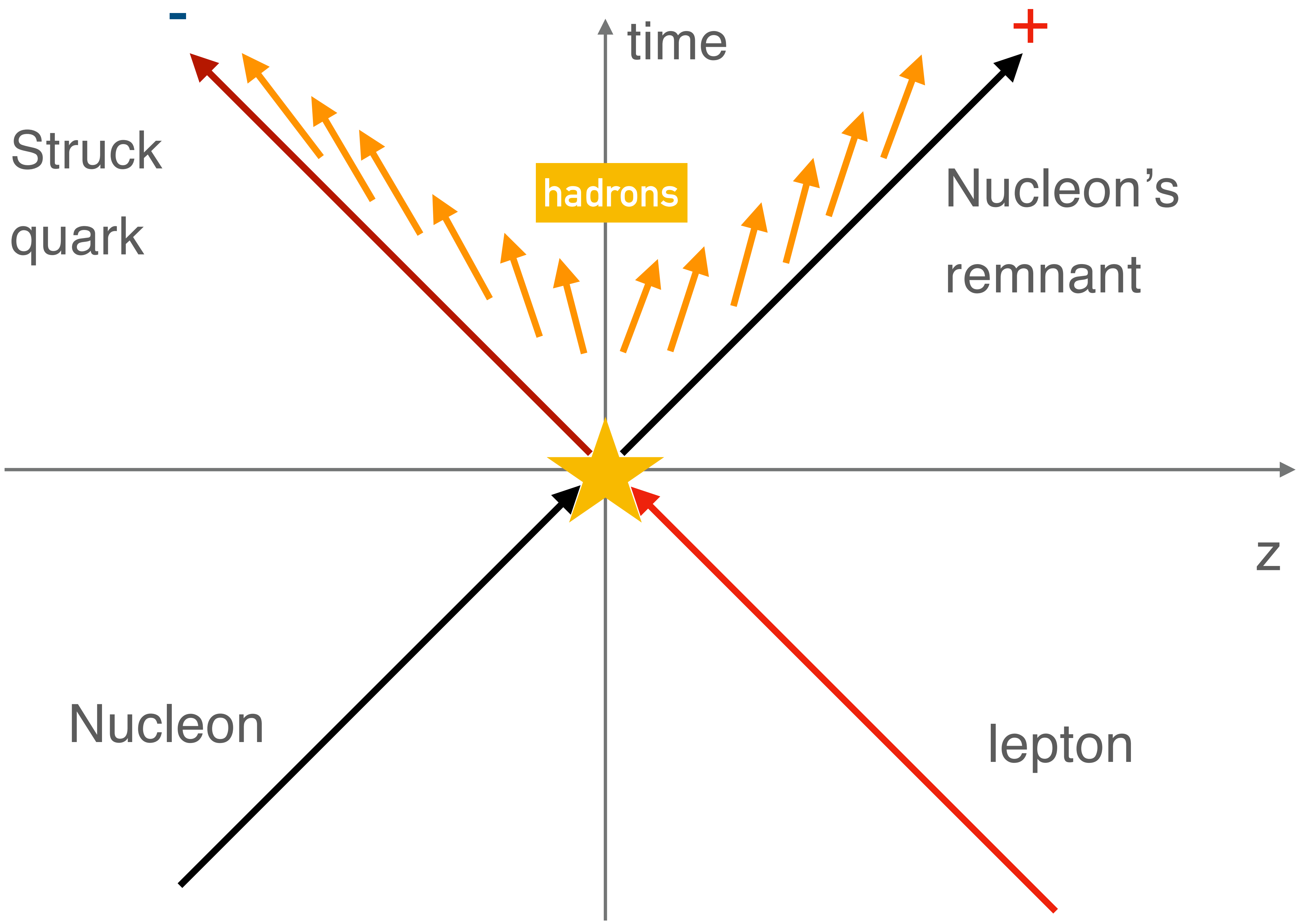


Target fragmentation region

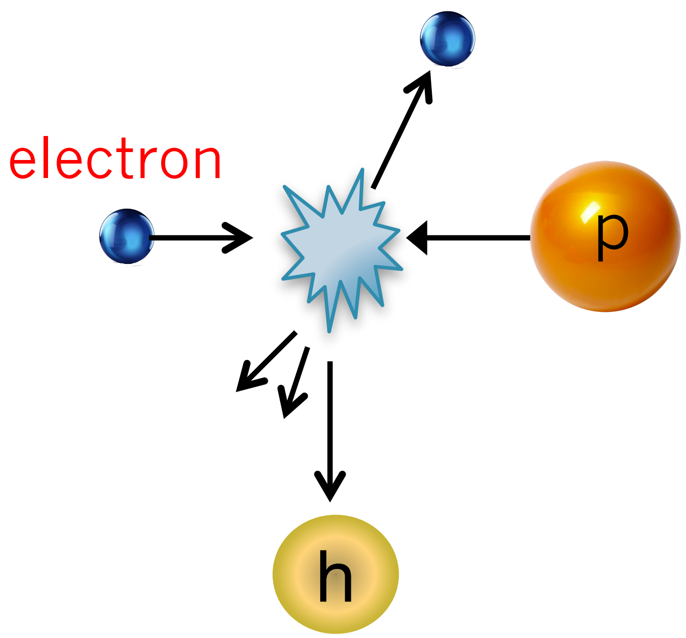
Current fragmentation region

Detect a pion in the final state

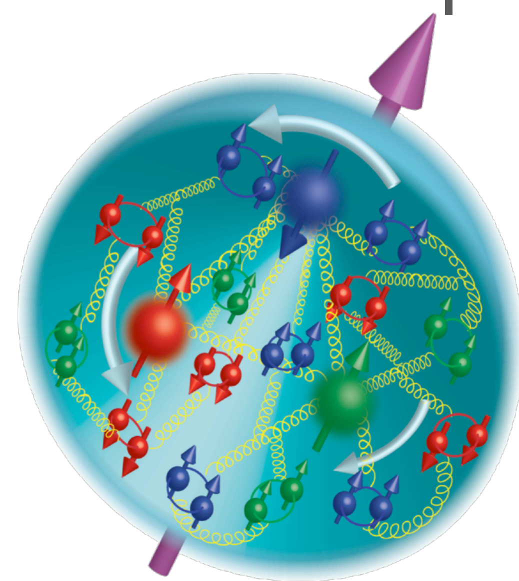
SPACE-TIME PICTURE OF THE COLLISION



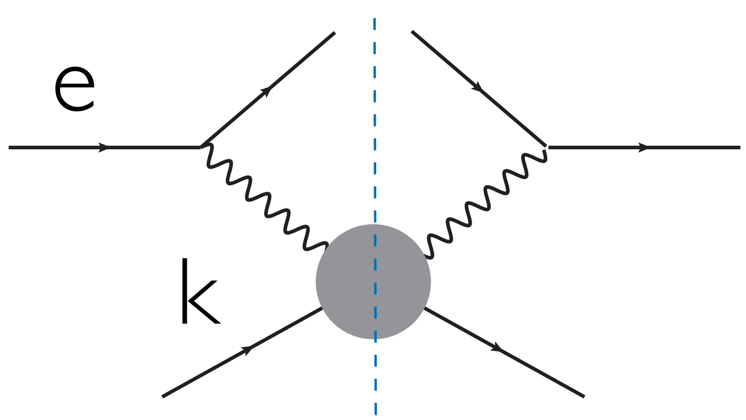
QCD FACTORIZATION IS THE KEY!



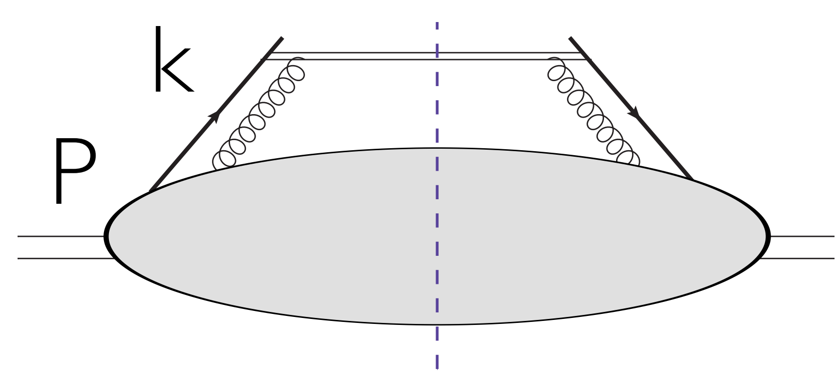
We need a probe to “see” quarks and gluons



$\sigma \approx$



$\otimes$

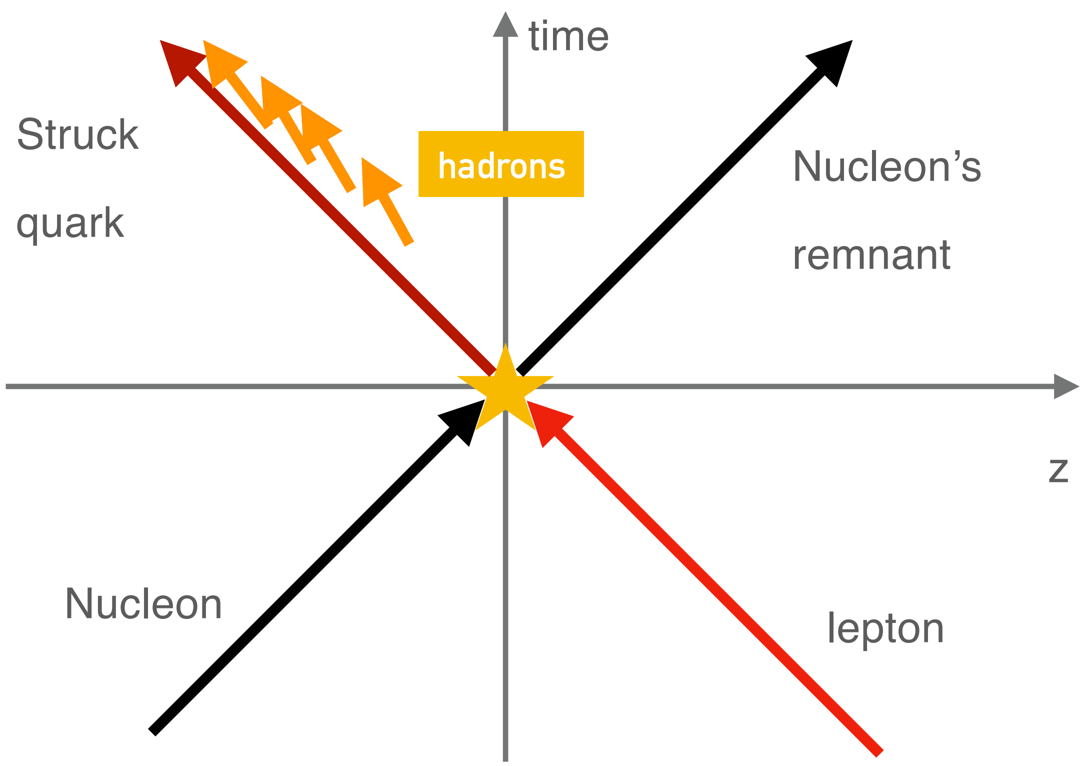


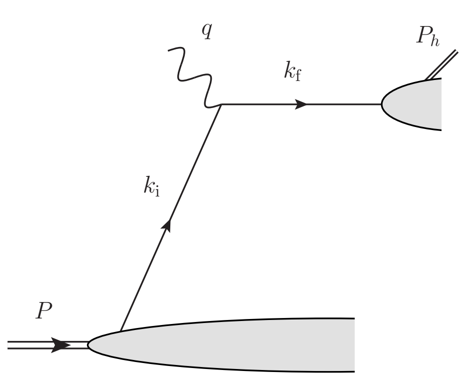
$+\mathcal{O}\left(\frac{M^2}{Q^2}\right)$

Factorization Probe Structure Power corrections

CURRENT REGION FACTORIZATION

$$\sigma \sim \sigma_0 \; f_{q/N}(x_{Bj}) \otimes D_{q/h}(z_h)$$





Boglione et al, 1611.10329

- Libby-Sterman analysis (Collins 2011 Ch.5) suggests that classical trajectories dominate
- Produced hadrons are close in rapidity to the fragmenting quark

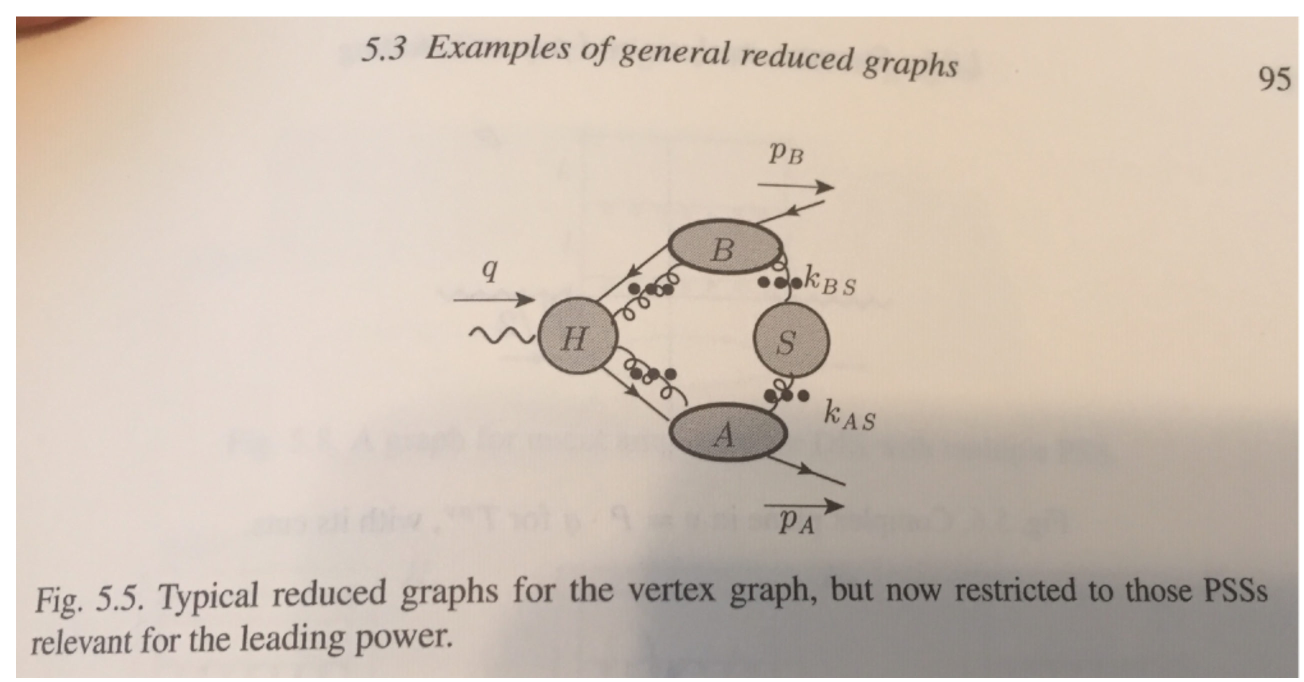

5.3 Examples of general reduced graphs 95

Fig. 5.5. Typical reduced graphs for the vertex graph, but now restricted to those PSSs relevant for the leading power.

Example of pinch-singular surfaces for e+e-

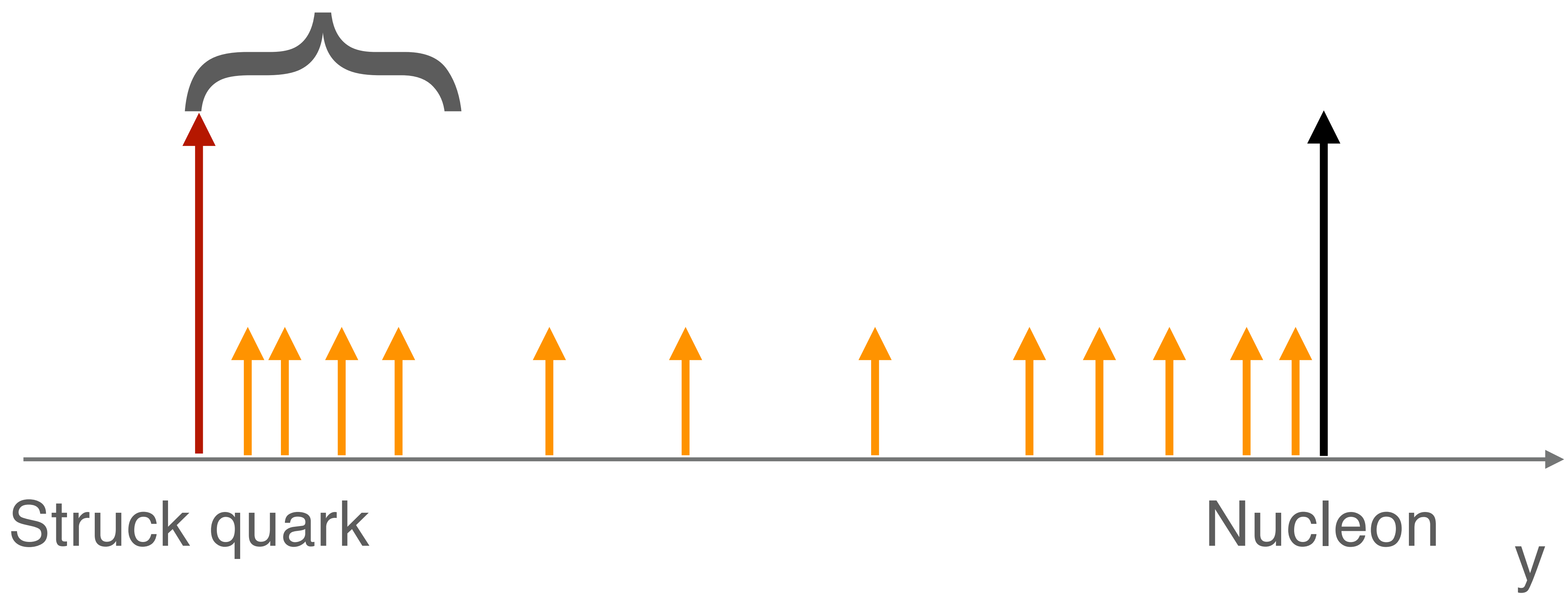
Boglione et al, 1611.10329

CURRENT REGION FACTORIZATION

$\sigma \sim \sigma_0 \, f_{q/N}(x_{Bj}) \otimes D_{q/h}(z_h)$ Rapidity of the hadron is important

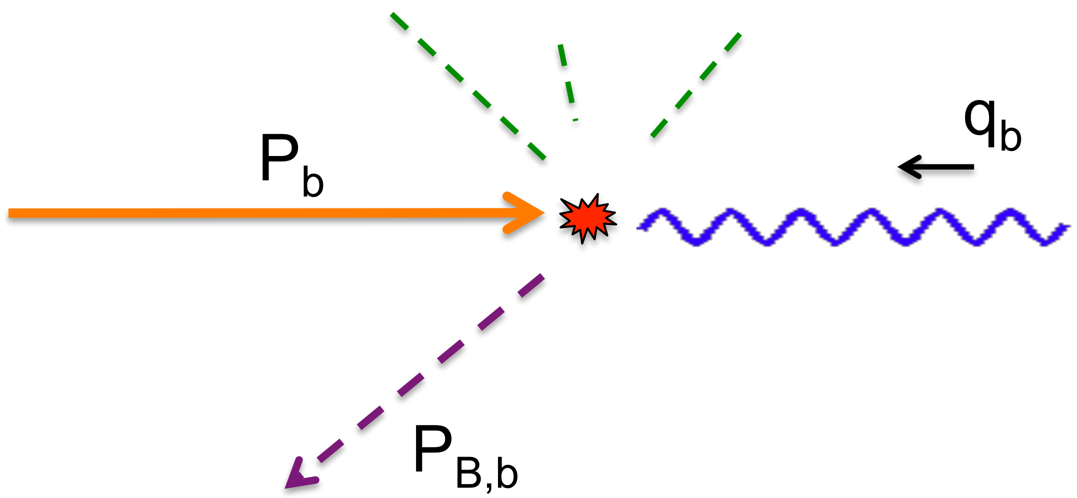
$$y = \frac{1}{2} \ln \left| \frac{V^+}{V^-} \right|, V = \left[\frac{M_T}{\sqrt{2}} e^y, \frac{M_T}{\sqrt{2}} e^{-y}, \mathbf{V}_T \right], M_T = \sqrt{|M^2 + \mathbf{V}_T^2|}$$

Current fragmentation region

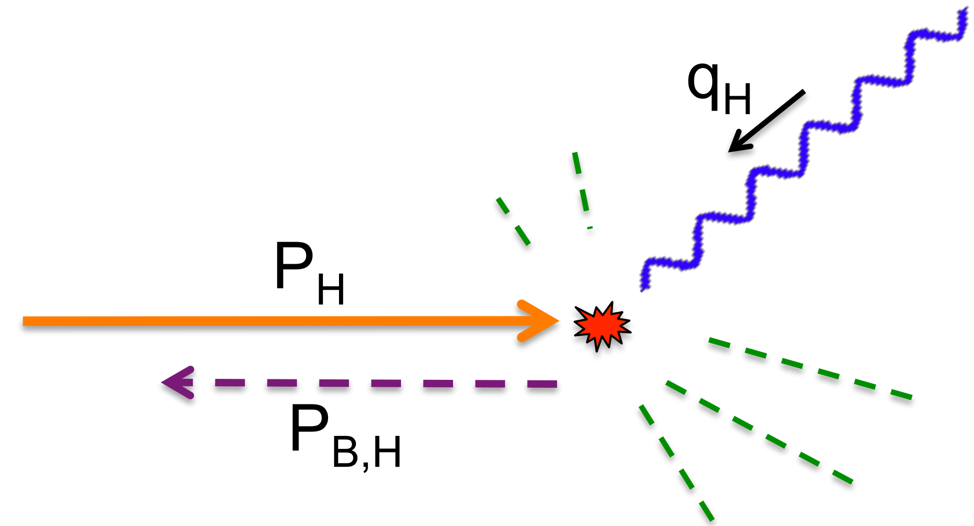


Boglione et al, 1904.12882

REFERENCE FRAMES



(a)



(b)

Photon Breit frame

$$q_{\rm b} = \left(-\frac{Q}{\sqrt{2}}, \frac{Q}{\sqrt{2}}, \mathbf{0}_{\rm T} \right) ,$$

$$P_{\rm b} = \left(\frac{Q}{x_{\rm N}\sqrt{2}}, \frac{x_{\rm N} M^2}{\sqrt{2} Q}, \mathbf{0}_{\rm T} \right) = \left(\frac{M}{\sqrt{2}}\, e^{y_{P,\rm b}}, \frac{M}{\sqrt{2}} e^{-y_{P,\rm b}}, \mathbf{0}_{\rm T} \right) .$$

$$P_{\rm B,b} = \left(\frac{M_{\rm B,T}^2}{2 P_{\rm B,b}^-}, P_{\rm B,b}^-, \mathbf{P}_{\rm B,b,T} \right) = \left(\frac{M_{\rm B,T}}{\sqrt{2}}\, e^{y_{\rm B,b}}, \frac{M_{\rm B,T}}{\sqrt{2}}\, e^{-y_{\rm B,b}}, \mathbf{P}_{\rm B,b,T} \right)$$

$$P_{\rm B,b} = \left(\frac{M_{\rm B}^2 + z_{\rm N}^2 \mathbf{q}_{\rm T}^2}{\sqrt{2} z_{\rm N} Q}, \frac{z_{\rm N} Q}{\sqrt{2}}, -z_{\rm N} \mathbf{q}_{\rm T} \right)$$

Rapidity interval boost invariant

Hadron frame

$$q_{\rm H} = \left(q_{\rm H}^+, q_{\rm H}^-, \mathbf{q}_{\rm H,T} \right) ,$$

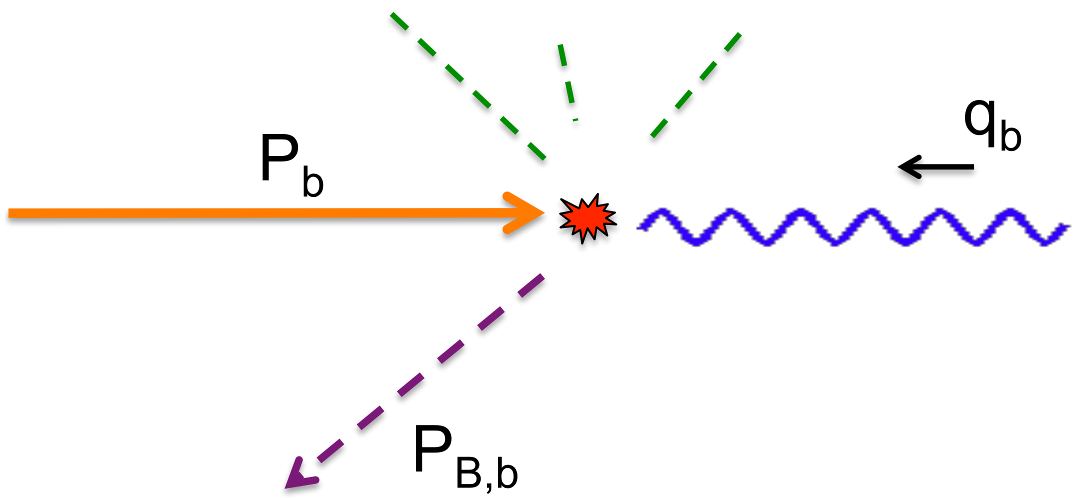
$$P_{\rm H} = \left(P_{\rm H}^+, \frac{M^2}{2 P_{\rm H}^+}, \mathbf{0}_{\rm T} \right) ,$$

$$P_{\rm B,H} = \left(\frac{M_{\rm B}^2}{2 P_{\rm B,H}^-}, P_{\rm B,H}^-, \mathbf{0}_{\rm T} \right) .$$

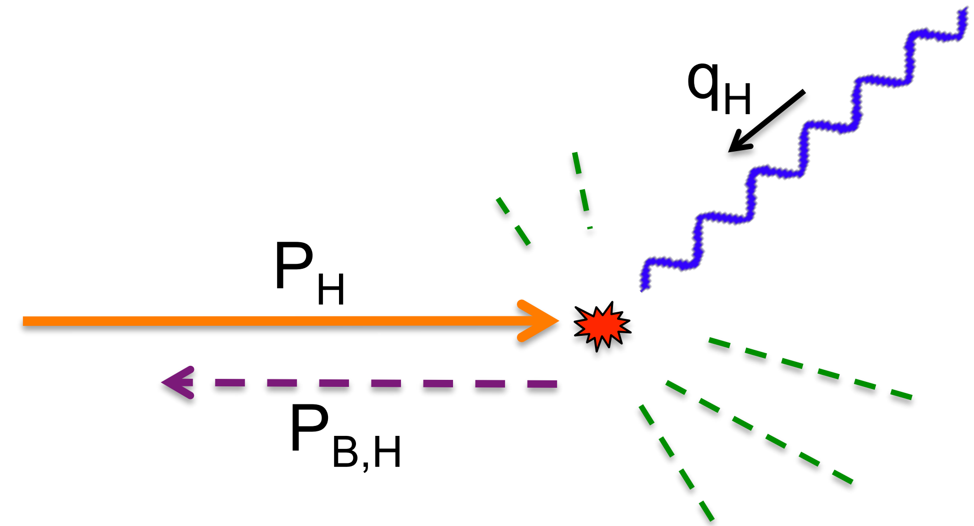
Useful for factorization

Boglione et al, 1904.12882

REFERENCE FRAMES



(a)



(b)

Photon Breit frame

$$z_{\mathrm{N}} = \frac{x_{\mathrm{N}} z_{\mathrm{h}}}{2 x_{\mathrm{Bj}}} \left(1 + \sqrt{1 - \frac{4 M^2 M_{\mathrm{B,T}}^2 x_{\mathrm{Bj}}^2}{Q^4 z_{\mathrm{h}}^2}} \right) \approx z_{\mathrm{h}} \, .$$

$$\mathbf{q}_{\mathrm{H,T}} \approx - \frac{\mathbf{P}_{\mathrm{B,b,T}}}{z_{\mathrm{h}}} \approx \mathbf{q}_{\mathrm{T}} \, ,$$

up to $\mathcal{O}\left(\frac{M}{Q} \right)$

Hadron frame

$$q_{\mathrm{H}} = \left(q_{\mathrm{H}}^{+}, q_{\mathrm{H}}^{-}, \mathbf{q}_{\mathrm{H,T}} \right) \, ,$$

$$P_{\mathrm{H}} = \left(P_{\mathrm{H}}^{+}, \frac{M^2}{2 P_{\mathrm{H}}^{+}}, \mathbf{0}_{\mathrm{T}} \right) \, ,$$

$$P_{\mathrm{B,H}} = \left(\frac{M_{\mathrm{B}}^2}{2 P_{\mathrm{B,H}}^{-}}, P_{\mathrm{B,H}}^{-}, \mathbf{0}_{\mathrm{T}} \right) \, .$$

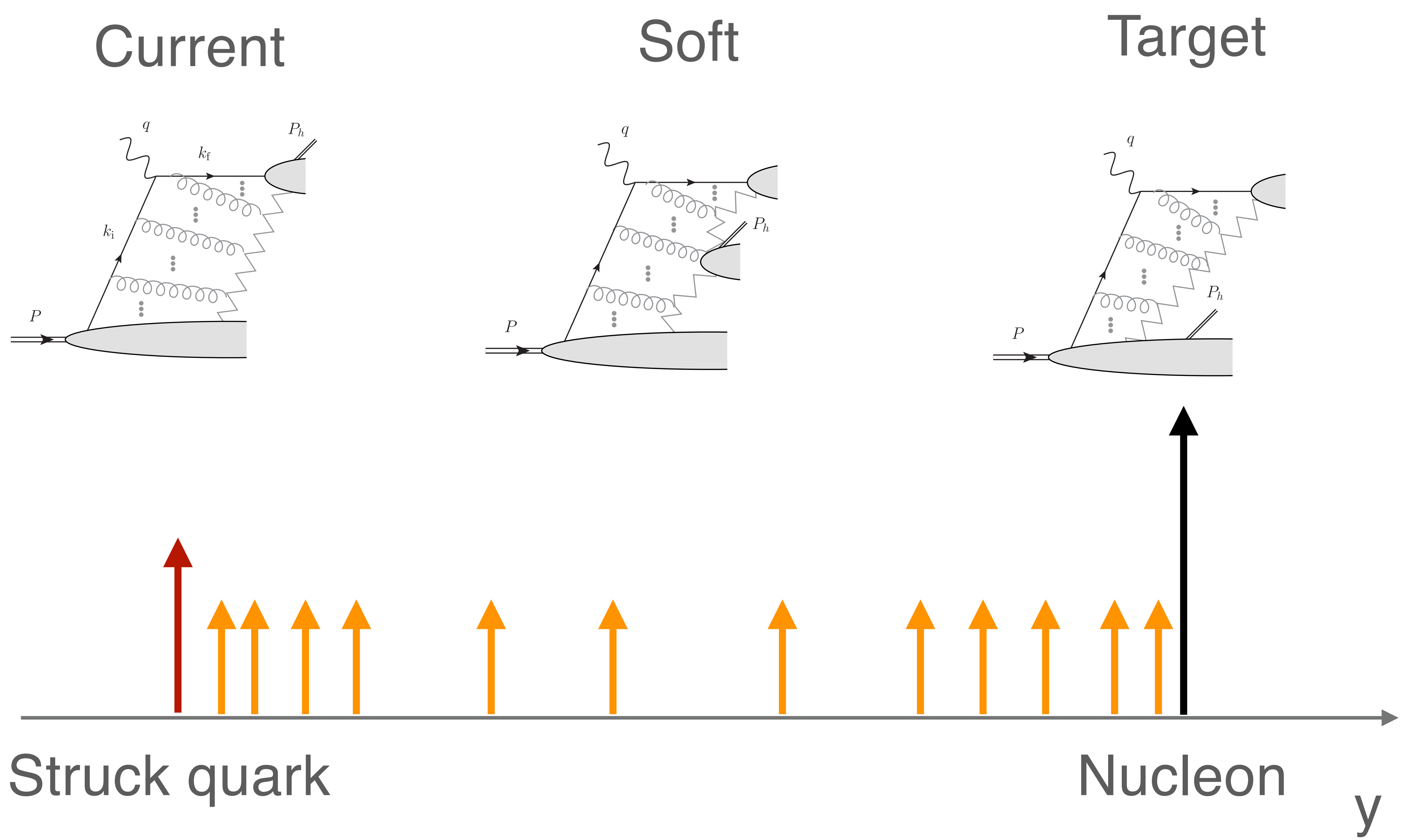
Useful for factorization

Boglione et al, 1611.10329

CURRENT REGION FACTORIZATION

Fresh look:

Define ratios of kinematical variables and identify regions



Boglione et al, 1611.10329

CURRENT REGION FACTORIZATION

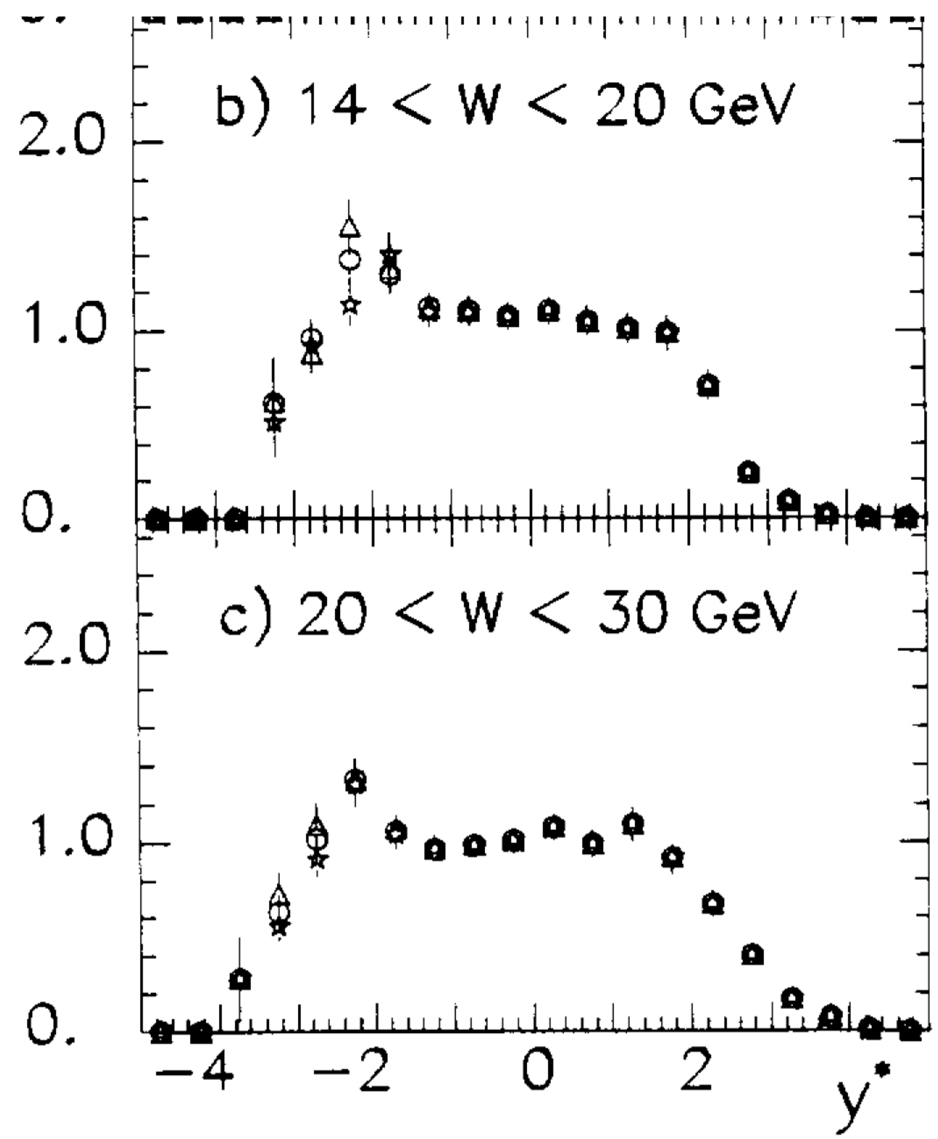
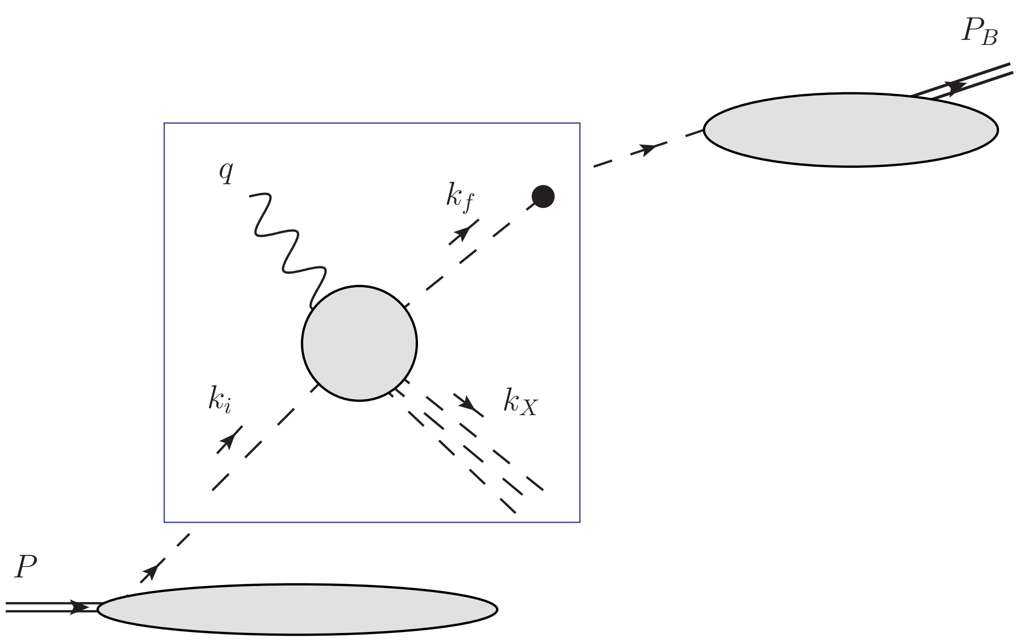


Figure 8.1: Normalized CM-rapidity distribution of positive hadrons in three bins of W from μXe-scattering at E665. The different markers refer to variants of the PID procedure not relevant to the current discussion. The target jet (negative rapidity) and current jet (positive rapidity) are hard to distinguish from each other due large amount of additional hadrons filling the gap between both jets. The situation becomes slightly better at higher values of W. See also Fig. 8.2. Figure from [139].

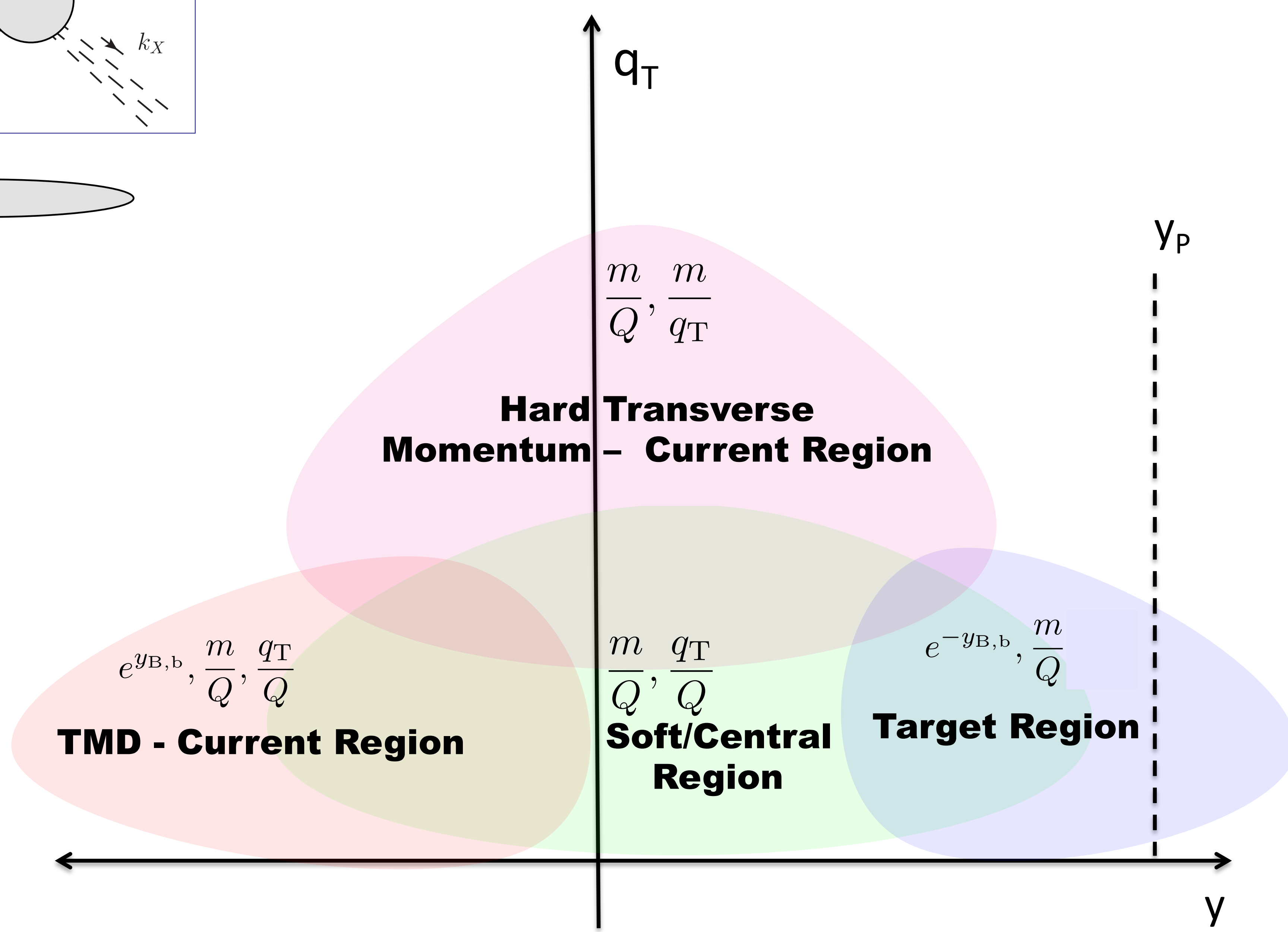
- E665 data rapidity distribution
- From S. Joosten Ph.D. thesis

REGIONS IN SIDIS AND RATIOS

Boglione et al, 1611.10329
Boglione et al, 1904.12882

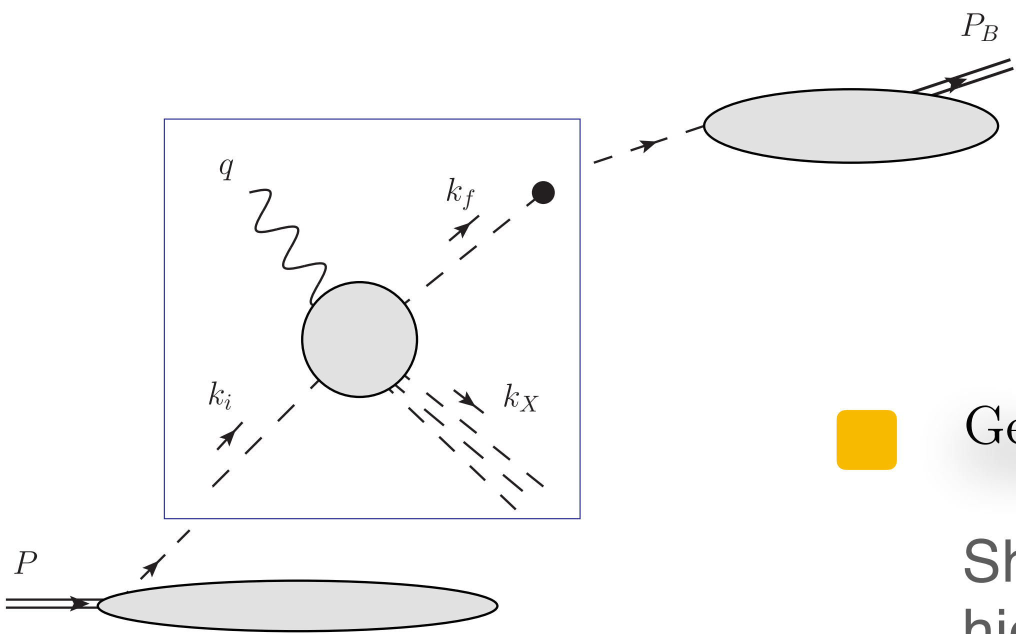


- Define ratios
- Identify regions



REGIONS IN SIDIS AND RATIOS

Boglione et al, 1611.10329
Boglione et al, 1904.12882



$$R_2 \propto \frac{q_T^2}{Q^2}$$

Used already in phenomenology

Bacchetta et al, 1912.07550

Vladimirov et al, 1912.06532

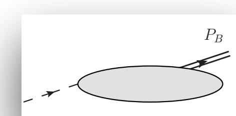
- Define ratios
- Identify regions

- General Hardness Ratio $= R_0 \equiv \max\left(\left|\frac{k_\mathrm{i}^2}{Q^2}\right|, \left|\frac{k_\mathrm{f}^2}{Q^2}\right|, \left|\frac{\delta k_\mathrm{T}^2}{Q^2}\right|\right)$.

  Should be small for partonic description to hold, high off-shelness = short distance

- Collinearity $= R_1 \equiv \frac{P_\mathrm{B} \cdot k_\mathrm{f}}{P_\mathrm{B} \cdot k_\mathrm{i}}$,

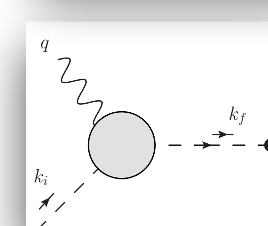
  Should be small for current region, large for target region

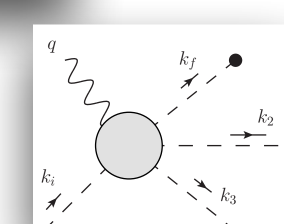


- Transverse Hardness Ratio $= R_2 \equiv \frac{|k^2|}{Q^2}$.

  $$k \equiv k_\mathrm{f} - q\,.$$

  Should be small for 2—> 1 process



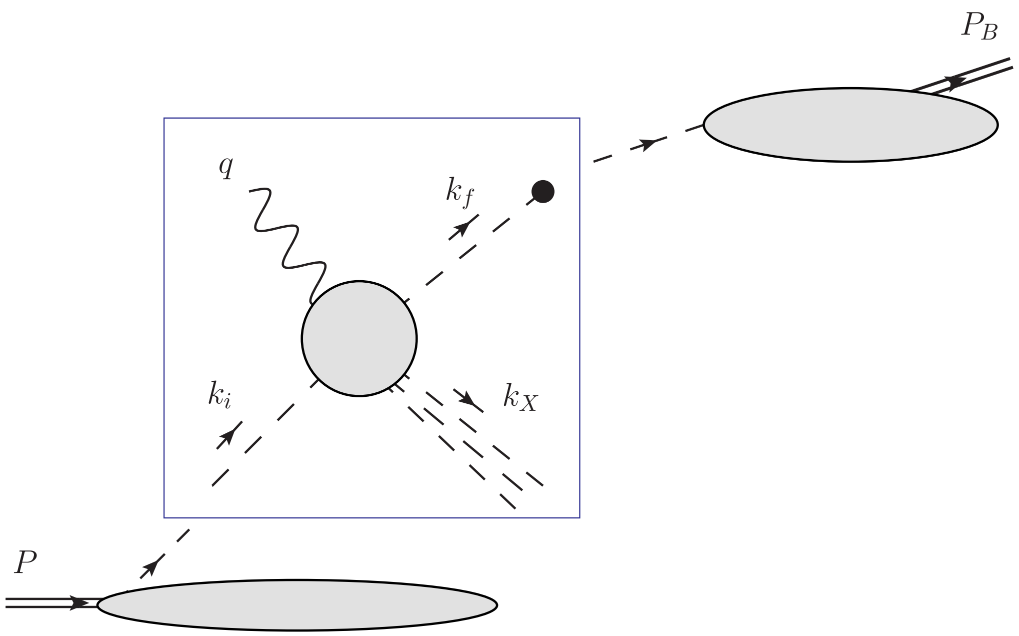


- Spectator Virtuality Ratio $= R_3 \equiv \frac{|k_\mathrm{X}^2|}{Q^2}$.

  Small for lowest order QCD to be applicable

REGIONS IN SIDIS AND RATIOS

Boglione et al, 1611.10329
Boglione et al, 1904.12882



- Define ratios
- Identify regions

	R_0	R_1	R_2	R_3
TMD Current region	small	small	small	X
Hard region	small	small	large	small (low order pQCD)
	small	small	large	large (high order pQCD)
Target region	small	large	X	X
Soft region	small	large	small	X

Table 1: Examples for sizes of ratios corresponding to particular regions of SIDIS. The "X" means "irrelevant or ill-defined." This ranking should be viewed as schematic since "small" and "large" need to be defined quantitatively and can in general be scale-dependent.

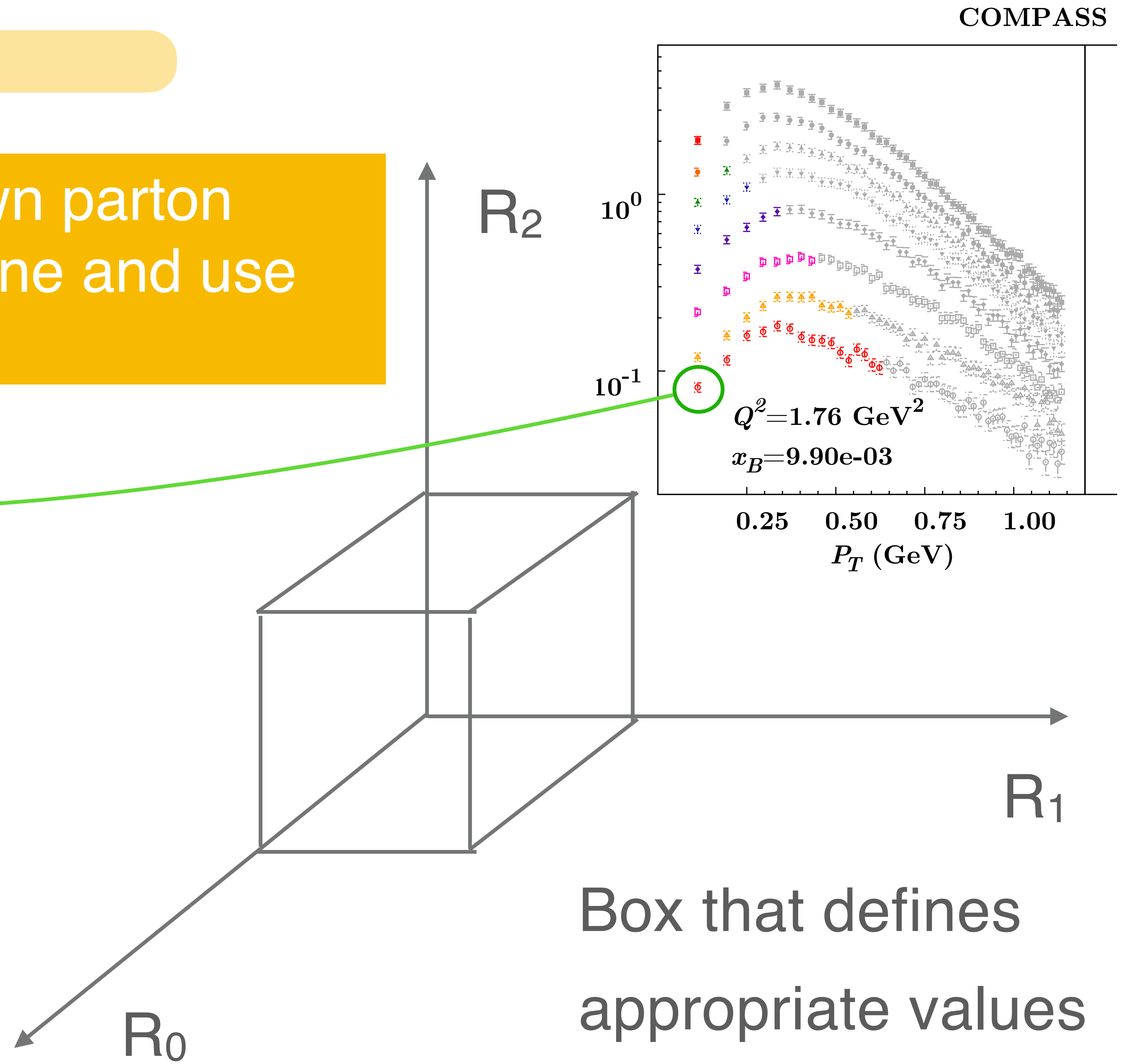
REGIONS IN SIDIS AND RATIOS

Boglione et al, 1611.10329
Boglione et al, 1904.12882
Current study

➤ Define ratios

Ratios depend on unknown parton momenta. Ho can we define and use them?

Where does this bin belong?



- Use a Monte Carlo* with parton momenta
- Sample experimental bins for ratios

Box that defines appropriate values

* by saying Monte Carlo we do not intend Pythia!

REGIONS IN SIDIS AND RATIOS

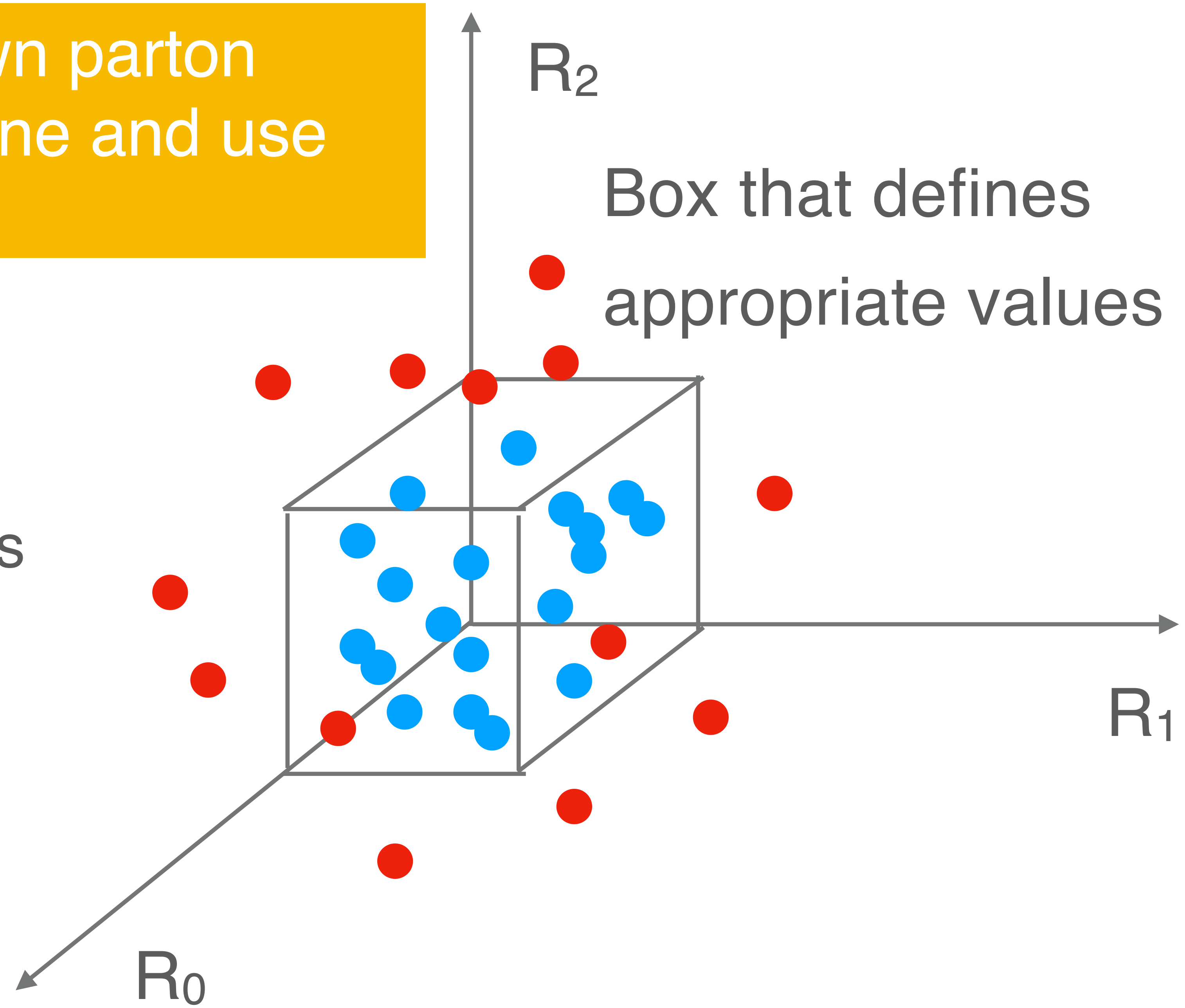
Boglione et al, 1611.10329
Boglione et al, 1904.12882
Current study

➤ Define ratios

Ratios depend on unknown parton momenta. Ho can we define and use them?

➤ Use a Monte Carlo* with parton momenta

➤ Sample experimental bins for ratios



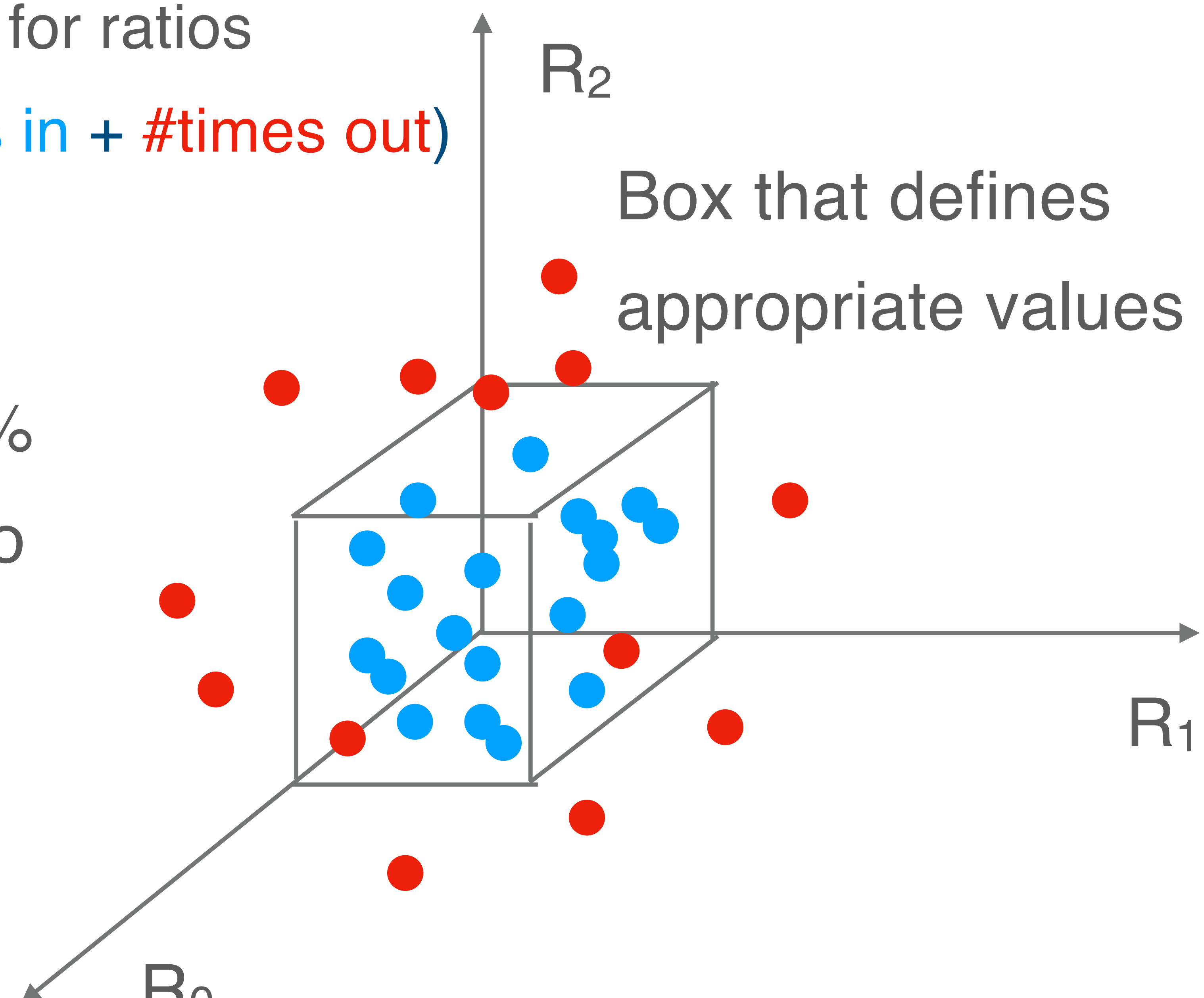
* by saying Monte Carlo we do not intend Pythia!

AFFINITY

Boglione et al, 1611.10329
Boglione et al, 1904.12882
Current study

- Use a Monte Carlo* with parton momenta
- Sample experimental bins for ratios
- Affinity = #times in/(#times in + #times out)

Affinity is from 0% to 100% indicates affinity of a bin to a particular region



* by saying Monte Carlo we do not intend Pythia!

AFFINITY

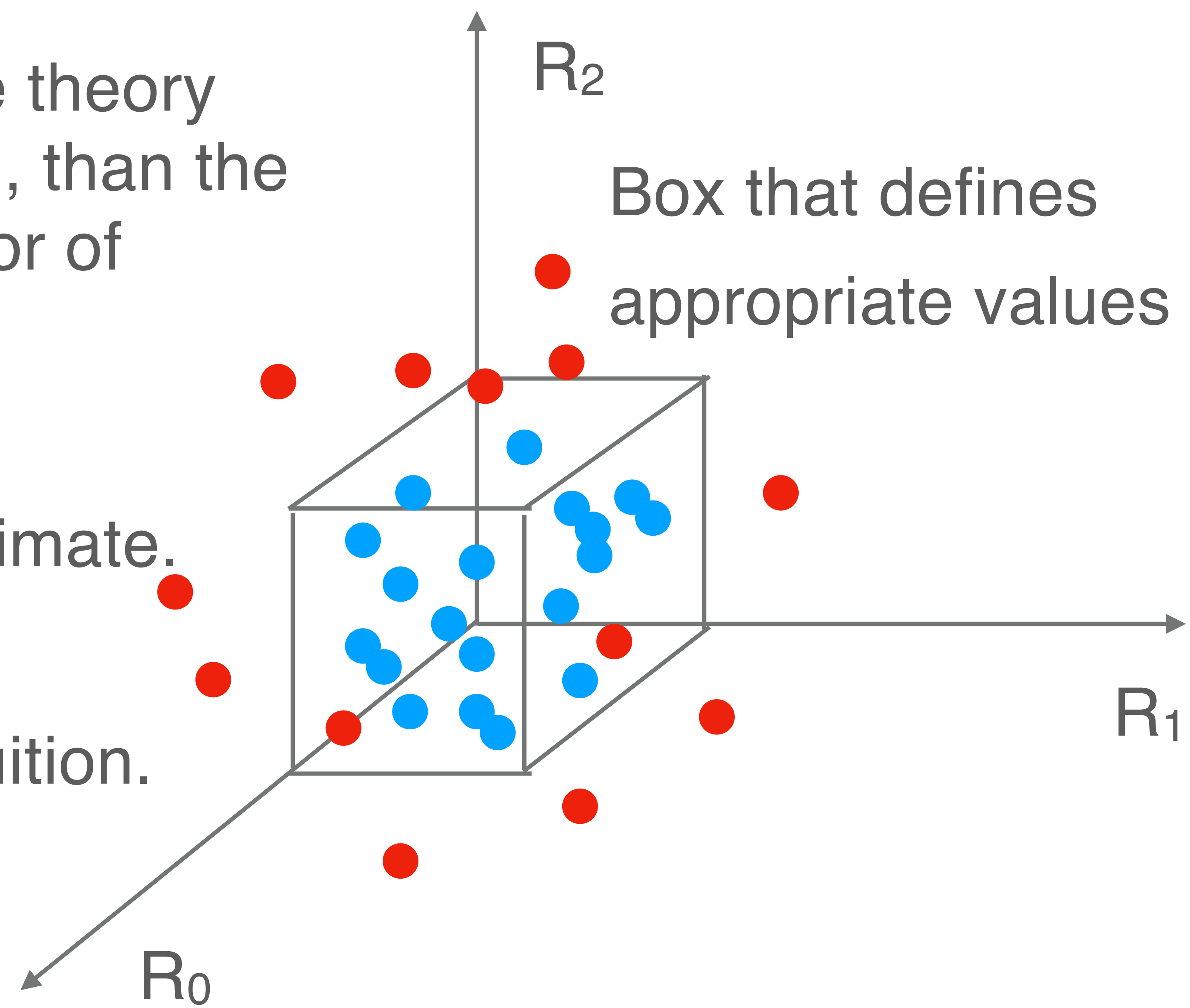
Boglione et al, 1611.10329
Boglione et al, 1904.12882
Current study

➤ What about size of the box?

If rigorous expansion of the theory in terms of Rs is performed, than the size is ~ to the relative error of factorization.

In our case it is only an estimate.

The tool is to guide our intuition.



MONTE CARLO

Boglione et al, 1611.10329
Boglione et al, 1904.12882
Current study

$$y_{\rm i}^{\rm b} = \frac{1}{2}\ln\left(\left|\frac{Q^2}{\hat{x}_{\rm N}^2(k_{\rm i}^2 + \mathbf{k}_{\rm i,T}^2)}\right|\right), \qquad y_{\rm f}^{\rm b} = \frac{1}{2}\ln\left(\left|\frac{\hat{z}_{\rm N}^2 q_{\rm T}^2 + \delta k_{\rm T}^2 - 2\hat{z}_{\rm N}\mathbf{q}_{\rm T}\cdot\delta\mathbf{k}_{\rm T} + k_{\rm f}^2}{\hat{z}_{\rm N}^2 Q^2}\right|\right).$$

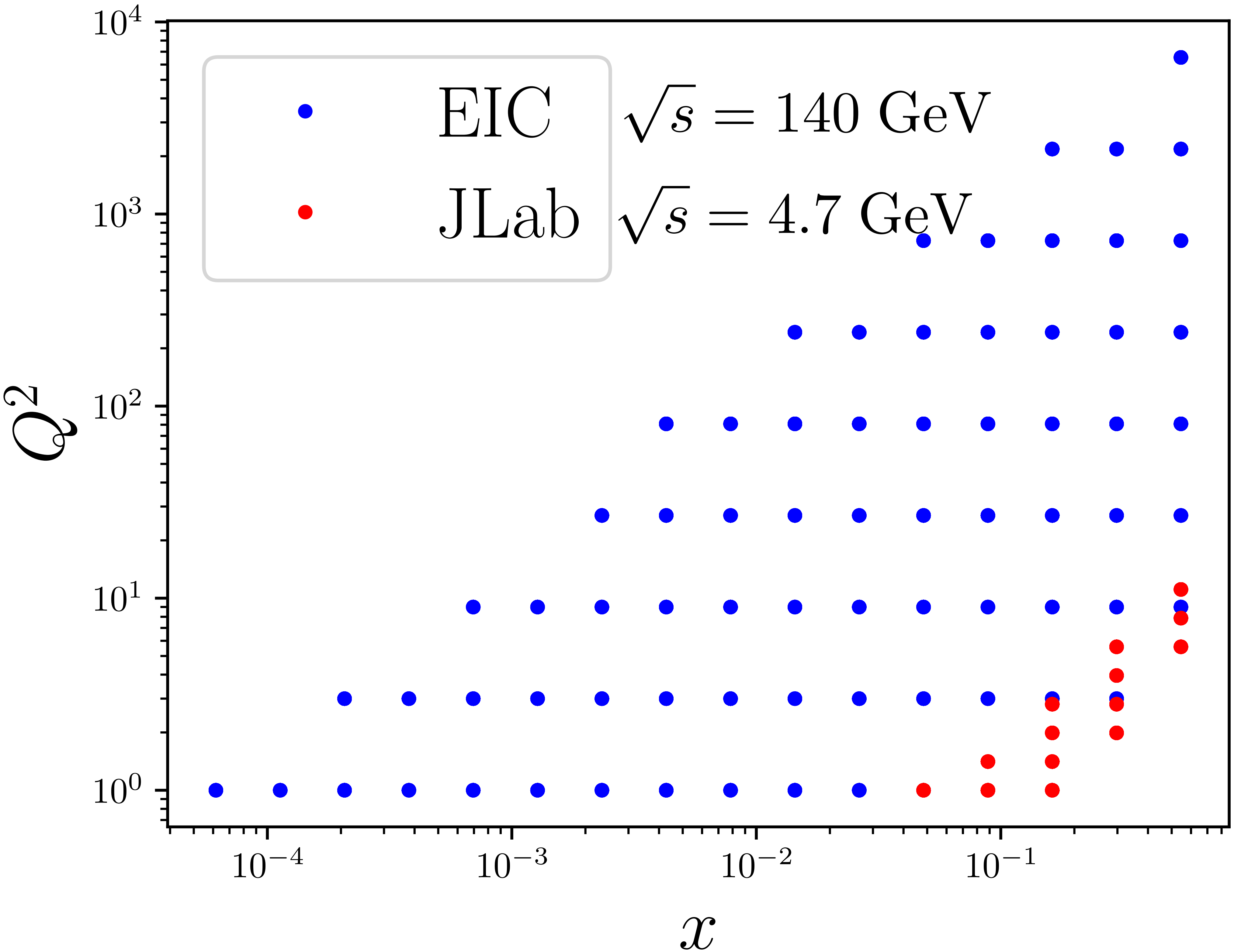
$$R_1 = \frac{M_{\rm B,T}M_{\rm f,b,T}\left(e^{y_{\rm B,b}-y_{\rm f}^{\rm b}} + e^{y_{\rm f}^{\rm b}-y_{\rm B,b}}\right) - 2z_{\rm N}\hat{z}_{\rm N}q_{\rm T}^2 + 2z_{\rm N}\mathbf{q}_{\rm T}\cdot\delta\mathbf{k}_{\rm T}}{M_{\rm B,T}M_{\rm i,b,T}\left(e^{y_{\rm i}^{\rm b}-y_{\rm B,b}} - e^{y_{\rm B,b}-y_{\rm i}^{\rm b}}\right) + 2z_{\rm N}\mathbf{q}_{\rm T}\cdot\mathbf{k}_{\rm i,T}},$$

where $M_{\rm i,b,T} = \sqrt{|k_{\rm i}^2 + \mathbf{k}_{\rm i,T}^2|}$ and $M_{\rm f,b,T} = \sqrt{k_{\rm f}^2 + \mathbf{k}_{\rm f,T}^2}$.

Parton kinematics is sampled in a particular region [0,0.8] GeV

JEFFERSON LAB 12 AND EIC

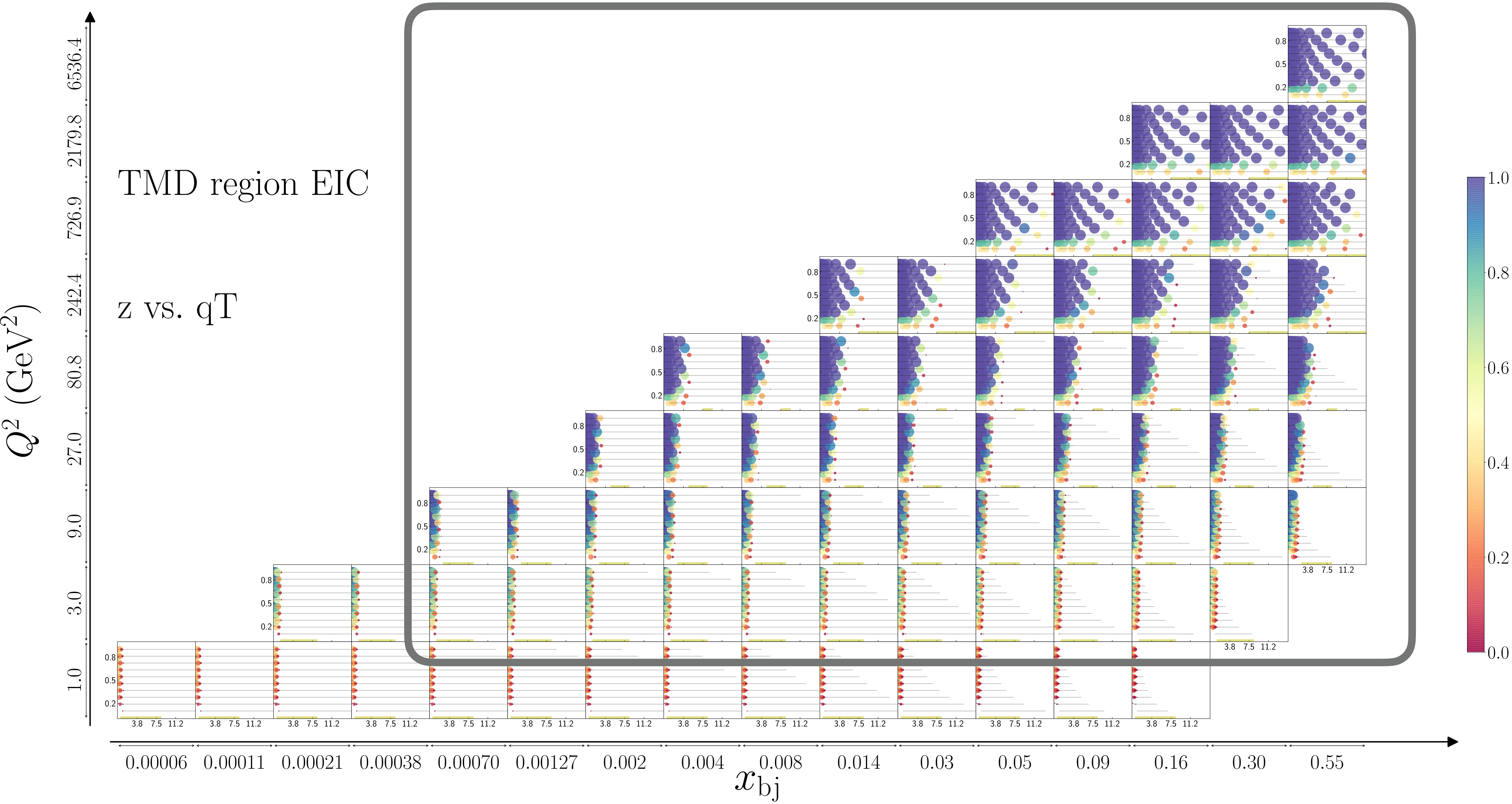
Current study



EIC: CURRENT REGION

Current study

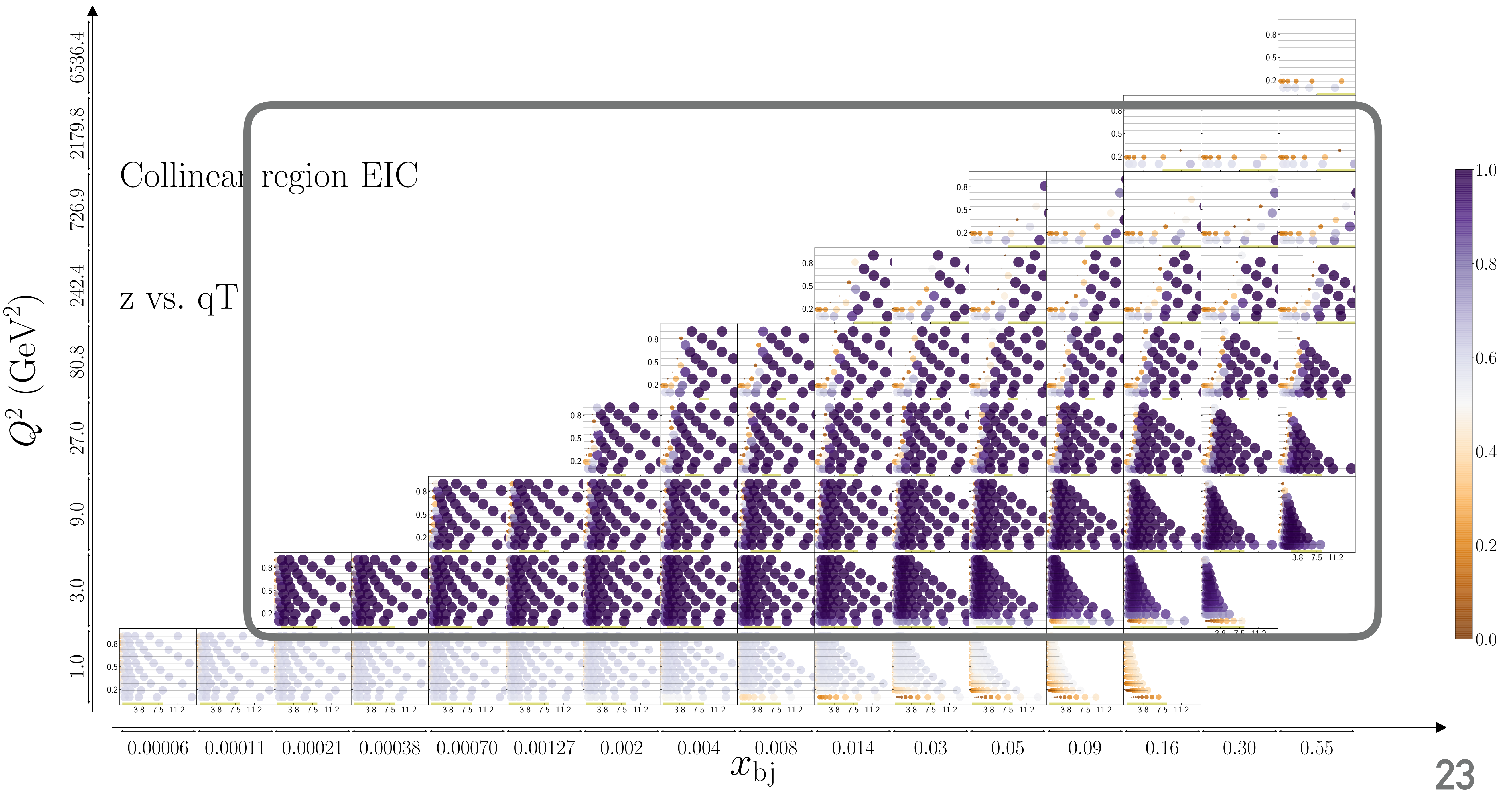
Relatively large x_{Bj}, z_h, Q



EIC: CURRENT REGION

Current study

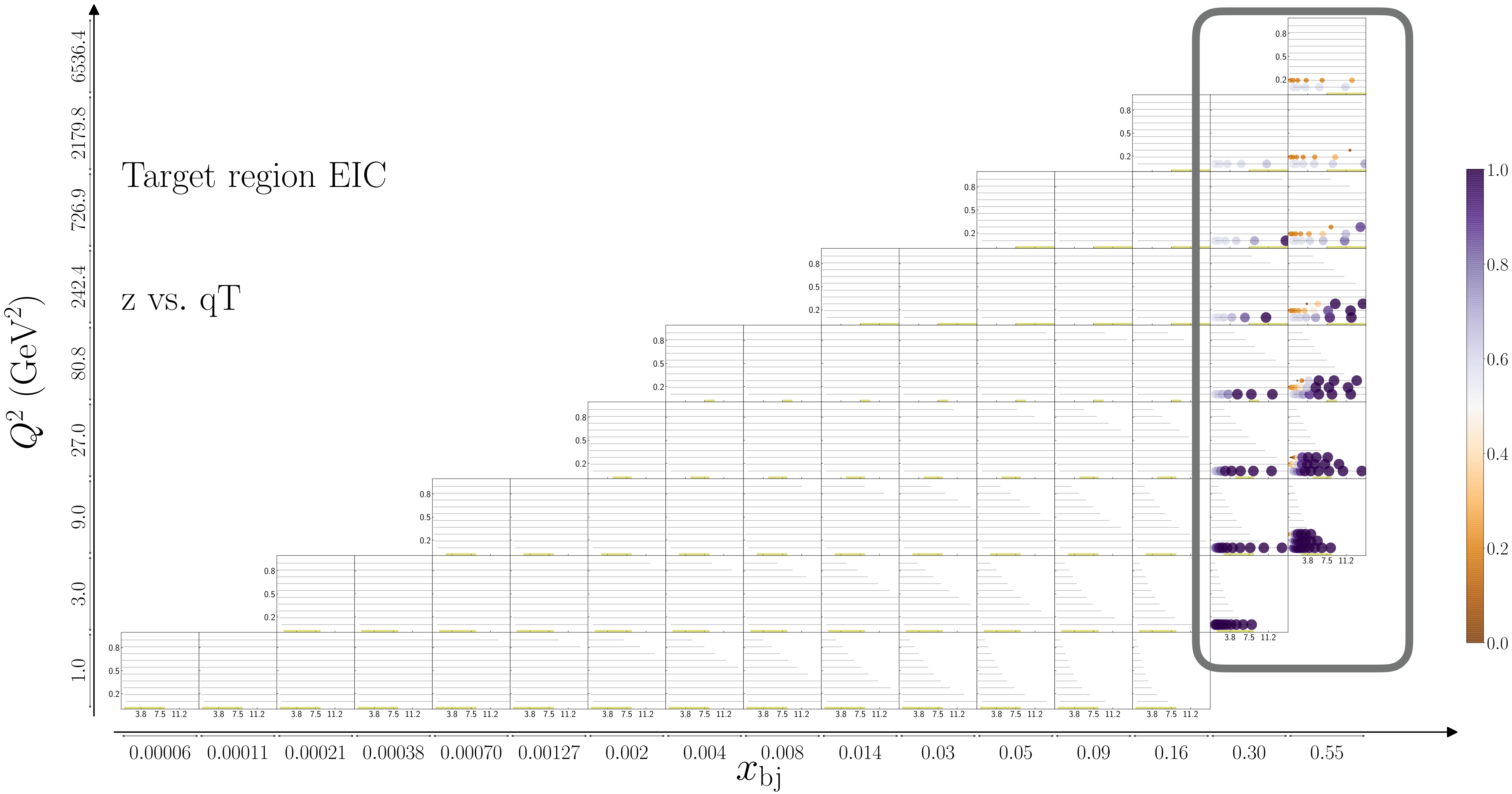
Relatively large x_{Bj}, z_h, Q



EIC: TARGET REGION

Current study

Large x_{Bj} and small z_h, Q



THEORETICAL AND PHENOMENOLOGICAL DEVELOPMENT

- We have studies regions in SIDIS and identified TMD, Target, Soft and Hard regions
- New tool to guide our intuition is provided
- Further phenomenological and theoretical studies to follow