Extraction of TMDs from Data

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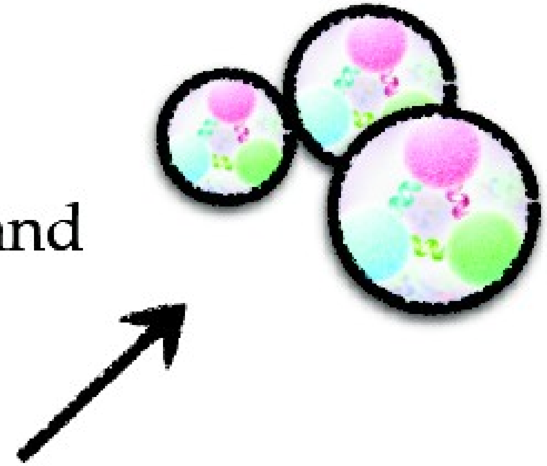
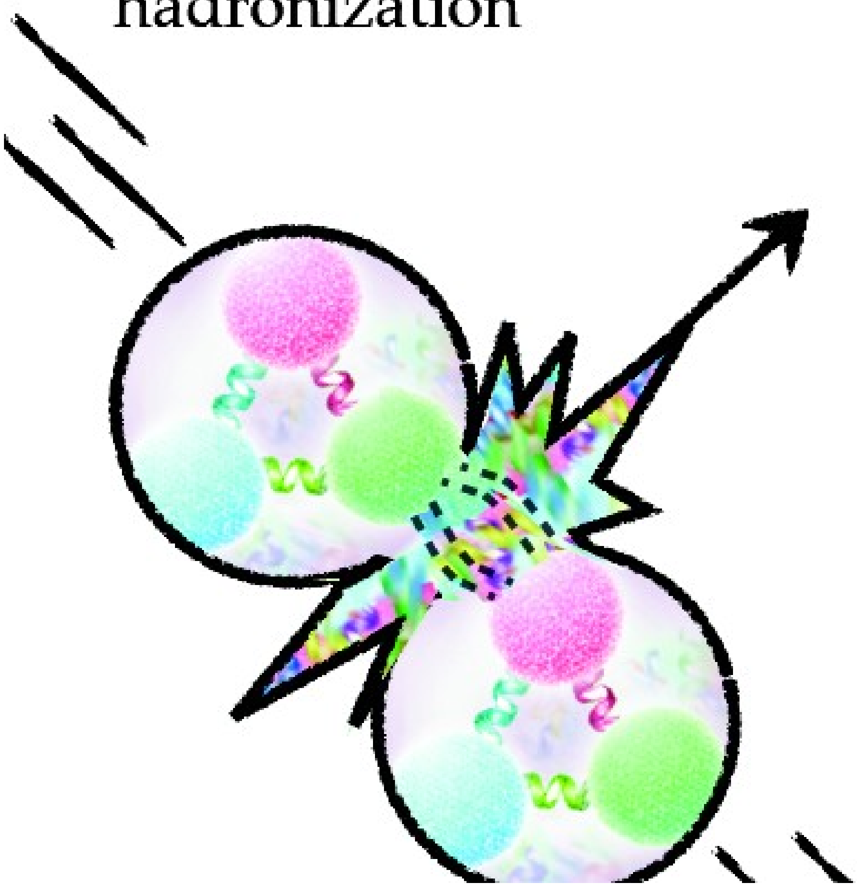
Motivation

At the more fundamental level we would like to learn about confinement and hadronization





factorization theorems, important theoretical tool

Unpolarized SIDIS cross section (current region)

$$\frac{d\sigma^{\ell+p\to\ell' hX}}{dx_{_B}\, dQ^2\, dz_h\, dP_T^2} = \frac{2\,\pi^2\alpha^2}{(x_{_B}\, s)^2}\,\frac{\left[1+(1-y)^2\right]}{y^2}\, F_{UU}$$

$$F_{UU} = \sum_q \mathcal{H}_q \;\text{F.T.}\left\{\tilde{D}_{h/q}(z, z\,\boldsymbol{b}_\perp; Q)\;\tilde{f}_{q/P}(x, \boldsymbol{b}_\perp; Q)\right\}$$

$$+ \text{ large } q_T \text{ corrections} + \text{power suppressed terms}$$

$$\tilde{f}_{q/P}(x,\boldsymbol{b}_\perp;Q)=\sum_j\left[\left(\tilde{C}_{q/j}\otimes f_{j/P}\right)e^{\Gamma_f(Q)}\right]\exp\left\{g_{h/j}(z,b_\perp)+g_K(b_\perp)\log\left(\frac{Q}{Q_0}\right)\right\}$$

$$\tilde{D}_{h/q}(z,\boldsymbol{b}_\perp;Q)=\sum_j\left[\left(\tilde{C}_{j/q}\otimes\frac{d_{h/j}}{z^2}\right)e^{\Gamma_D(Q)}\right]\exp\left\{g_{j/P}(x,b_\perp)+g_K(b_\perp)\log\left(\frac{Q}{Q_0}\right)\right\}$$

$$F_{UU}=\sum_q\mathcal{H}_q\ \text{F.T.}\left\{\tilde{D}_{h/q}(z,z\,\boldsymbol{b}_\perp;Q)\ \tilde{f}_{q/P}(x,\boldsymbol{b}_\perp;Q)\right\}$$

$$+\ \text{large } q_T \text{ corrections} + \text{power suppressed terms}$$

QCD picture

Ultimate goal,
great predictive power.

$$\tilde{f}_{q/P}(x,\boldsymbol{b}_\perp;Q) = \sum_j \left[\left(\tilde{C}_{q/j} \otimes f_{j/P} \right) e^{\Gamma_f(Q)} \right] \exp\left\{ g_{h/j}(z,b_\perp) + g_K(b_\perp) \log\left(\frac{Q}{Q_0} \right) \right\}$$

$$\tilde{D}_{h/q}(z,\boldsymbol{b}_\perp;Q) = \sum_j \left[\left(\tilde{C}_{j/q} \otimes \frac{d_{h/j}}{z^2} \right) e^{\Gamma_D(Q)} \right] \exp\left\{ g_{j/P}(x,b_\perp) + g_K(b_\perp) \log\left(\frac{Q}{Q_0} \right) \right\}$$

$$F_{UU} = \sum_q \mathcal{H}_q \ \text{F.T.} \left\{ \tilde{D}_{h/q}(z, z\,\boldsymbol{b}_\perp;Q) \ \tilde{f}_{q/P}(x,\boldsymbol{b}_\perp;Q) \right\}$$

$$+ \text{ large } q_T \text{ corrections} + \text{power suppressed terms}$$

Several complications in phenomenology

QCD picture

Ultimate goal,
great predictive power.

$$\tilde{f}_{q/P}(x, \boldsymbol{b}_\perp; Q) = \sum_j \left[\left(\tilde{C}_{q/j} \otimes f_{j/P} \right) e^{\Gamma_f(Q)} \right] \exp\left\{ g_{h/j}(z, b_\perp) + g_K(b_\perp) \log\left(\frac{Q}{Q_0} \right) \right\}$$

$$\tilde{D}_{h/q}(z, \boldsymbol{b}_\perp; Q) = \sum_j \left[\left(\tilde{C}_{j/q} \otimes \frac{d_{h/j}}{z^2} \right) e^{\Gamma_D(Q)} \right] \exp\left\{ g_{j/P}(x, b_\perp) + g_K(b_\perp) \log\left(\frac{Q}{Q_0} \right) \right\}$$

Simple partonic picture (useful starting point)

$$f_{q/P}(x, k_\perp) = f_{q/P}(x)\, h_f(k_\perp)$$

$$D_{h/q}(z, p_\perp) = d_{h/q}(z)\, h_d(p_\perp)$$

easy to implement, generally leads to interpretations of limited validity

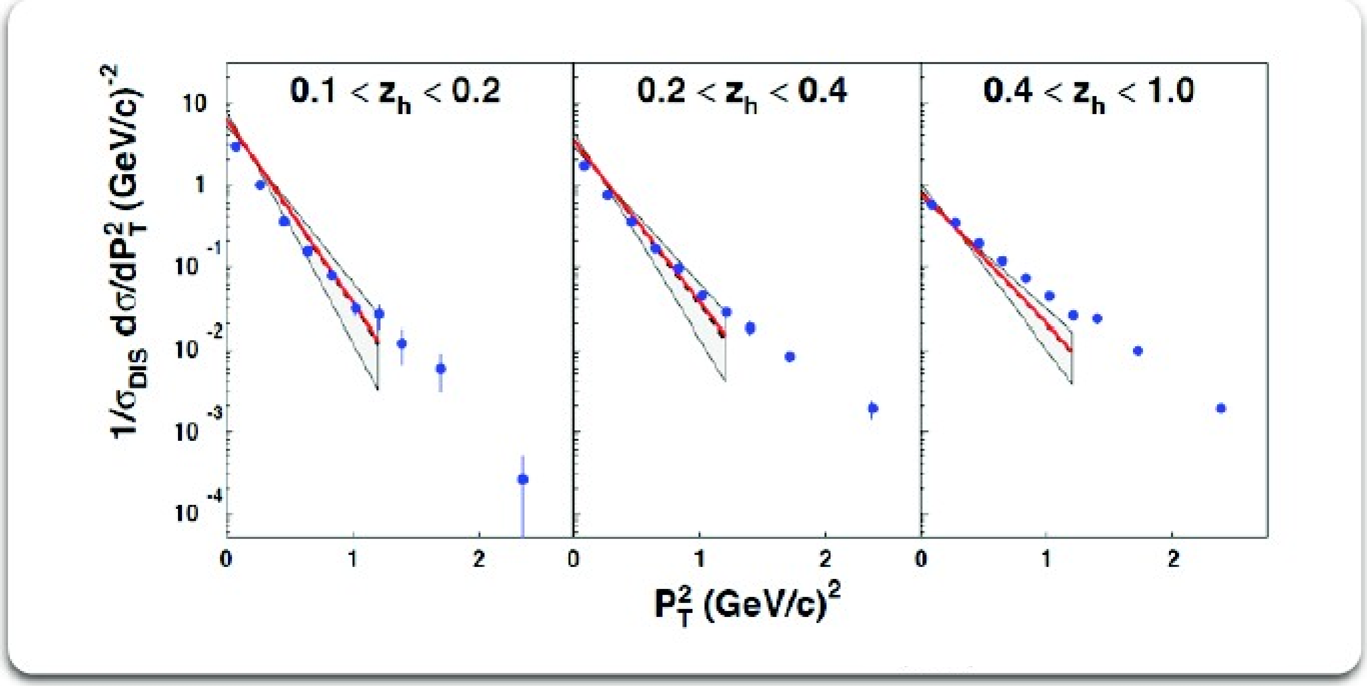
TMD extraction

Simple models: gather as much intel as possible

easy to implement, generally leads to interpretations of limited validity

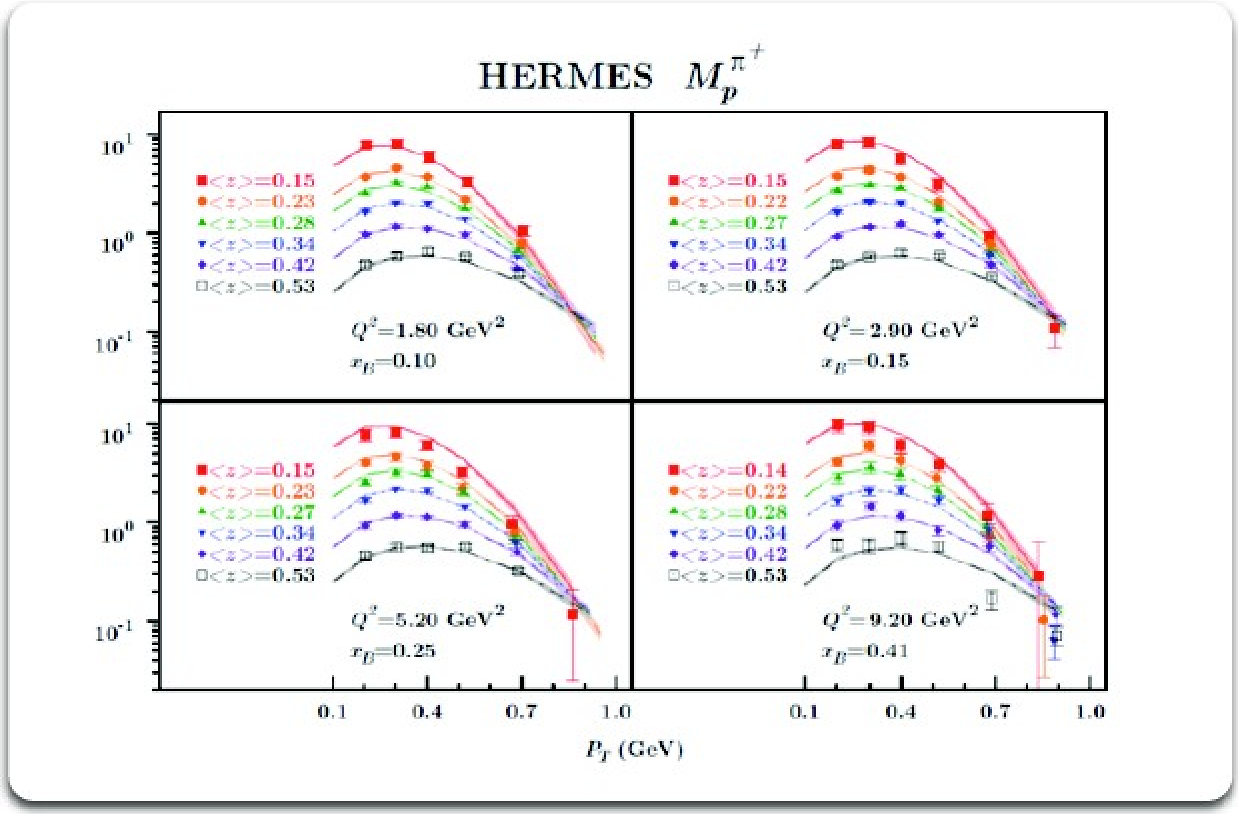
Full QCD picture: perturbative corrections, evolution equations ...

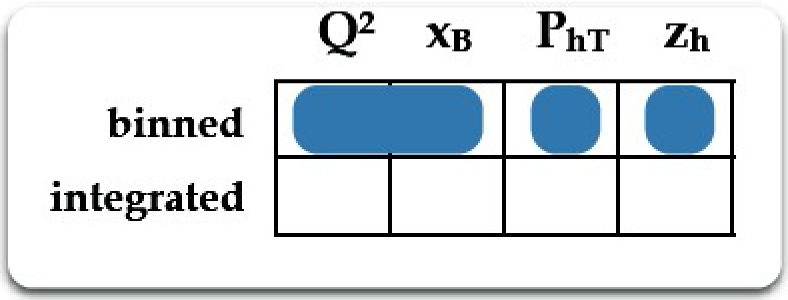
Ultimate goal, great predictive power.



	Q^2	x_B	P_{hT}	z_h
binned			●	
integrated	●	●		●

Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Prokudin, Phys.Rev. D71 (2005) 074006





M. Anselmino, M. Boglione, JOGH, S. Melis, A. Prokudin

JHEP 1404 (2014) 005

Ingredients for extraction of Collins function.

$e^+e^- \to \pi\,\pi\,X$

Unpolarized TMDFF **Collins TMDFF**

$$\frac{d\sigma^{e^+e^-\to h_1 h_2 X}}{dz_1\,dz_2\,d^2\boldsymbol{P}_{1T}\,d\cos\theta_2} = \frac{3\pi\alpha^2}{2s}\left\{\boxed{D_{h_1\,h_2}} + \boxed{N_{h_1\,h_2}}\cos 2\phi_1\right\}$$

$$P_0^{U,L,C} = \frac{N^{U,L,C}}{D^{U,L,C}}$$

Ratio

$$D^U = D_{\pi^+\pi^-} + D_{\pi^-\pi^+} \qquad N^U = N_{\pi^+\pi^-} + N_{\pi^-\pi^+}$$

$$D^L = D_{\pi^+\pi^+} + D_{\pi^-\pi^-} \qquad N^L = N_{\pi^+\pi^+} + N_{\pi^-\pi^-}$$

$$D^C = D^U + D^L \qquad N^C = N^U + N^L\,,$$

$$\frac{A_0^U}{A_0^{L(C)}} \equiv 1 + \cos(2\phi_1)\boxed{A_0^{UL(C)}}$$

Double Ratio

SIDIS

$$\frac{d\sigma^{\ell(S_\ell)+p(S)\to\ell' hX}}{dx_B dQ^2 dz_h d^2\boldsymbol{P}_T d\phi_S} =$$

$$\frac{2\alpha^2}{Q^4}\left\{\frac{1+(1-y)^2}{2}F_{UU} + \quad \cdots\right.$$

$$\left. + S_T(1-y)(\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)}\right\}.$$

$$\boxed{A_{UT}^{\sin(\phi_h+\phi_S)}} \sim \frac{\boxed{F_{UT}^{\sin(\phi_h+\phi_S)}}}{\boxed{F_{UU}}}$$

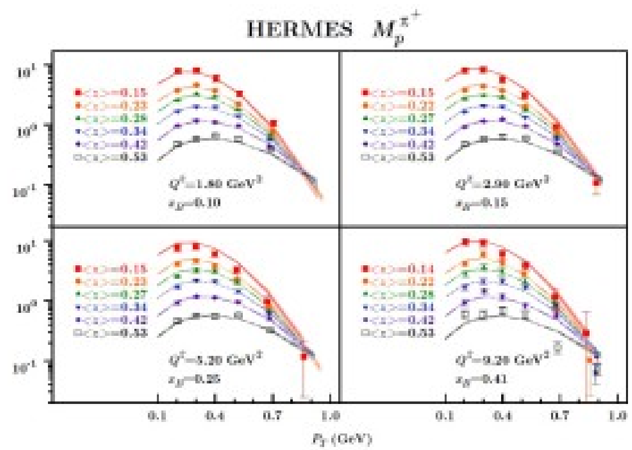
Ratio

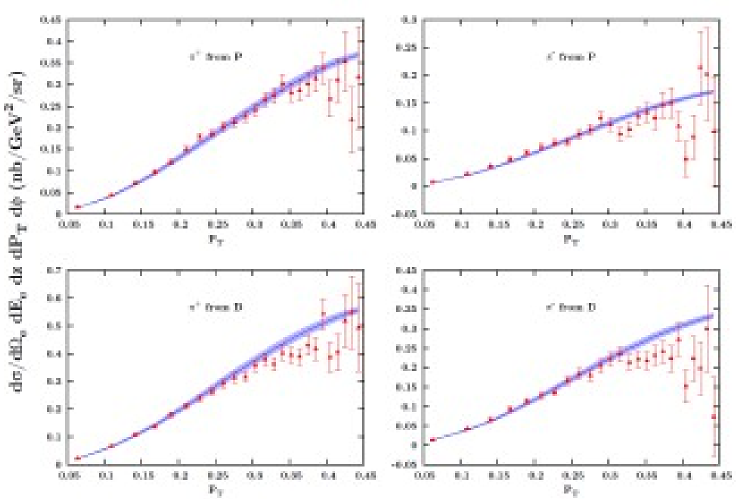
Unpolarized TMDFF &TMDPDF

TMD Transversity & Collins function

Ingredients for extraction of Collins function.

Unpolarized TMDFF &TMDPDF from previous Analysis of SIDIS data





SIDIS

$$\frac{d\sigma^{\ell(S_\ell)+p(S)\to\ell' hX}}{dx_B\, dQ^2\, dz_h\, d^2\boldsymbol{P}_T\, d\phi_S} =$$

$$\frac{2\alpha^2}{Q^4}\left\{\frac{1+(1-y)^2}{2}F_{UU} + \quad \cdots \right.$$

$$\left. + S_T(1-y)(\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)}\right\}.$$

$$A_{UT}^{\sin(\phi_h+\phi_S)} \sim \frac{\boxed{F_{UT}^{\sin(\phi_h+\phi_S)}}}{\boxed{F_{UU}}}$$

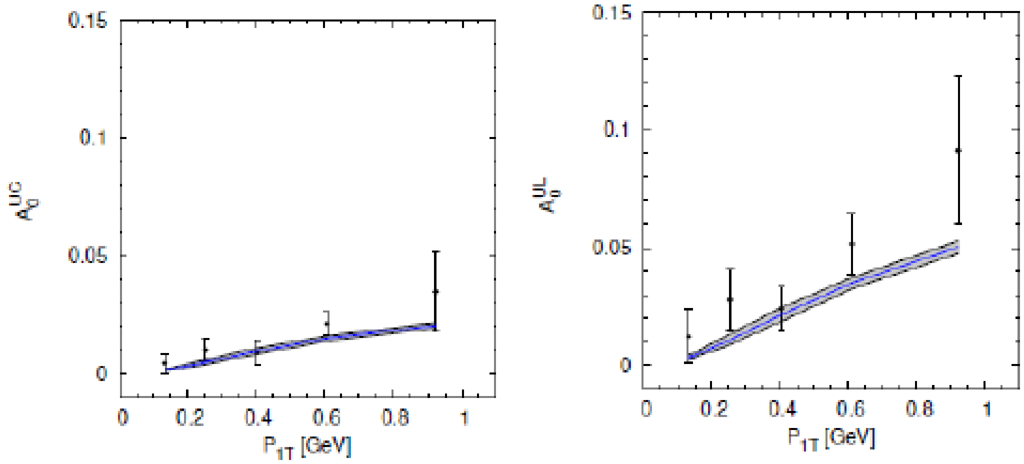
Unpolarized TMDFF &TMDPDF

TMD Transversity & Collins function

M. Anselmino, M. Boglione, JOGH, S. Melis, A. Prokudin JHEP 1404 (2014) 005

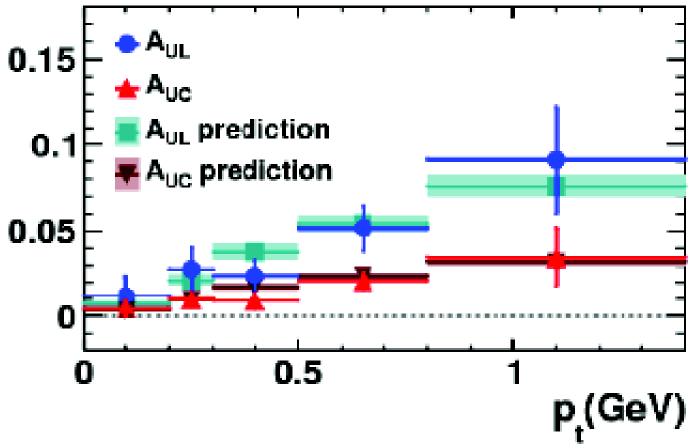
TMD evolution?

Q^2 = 13 GeV^2



Anselmino, Boglione,D'Alesio,JOGH, Melis, Murgia, Prokudin
10.1103/PhysRevD.92.114023

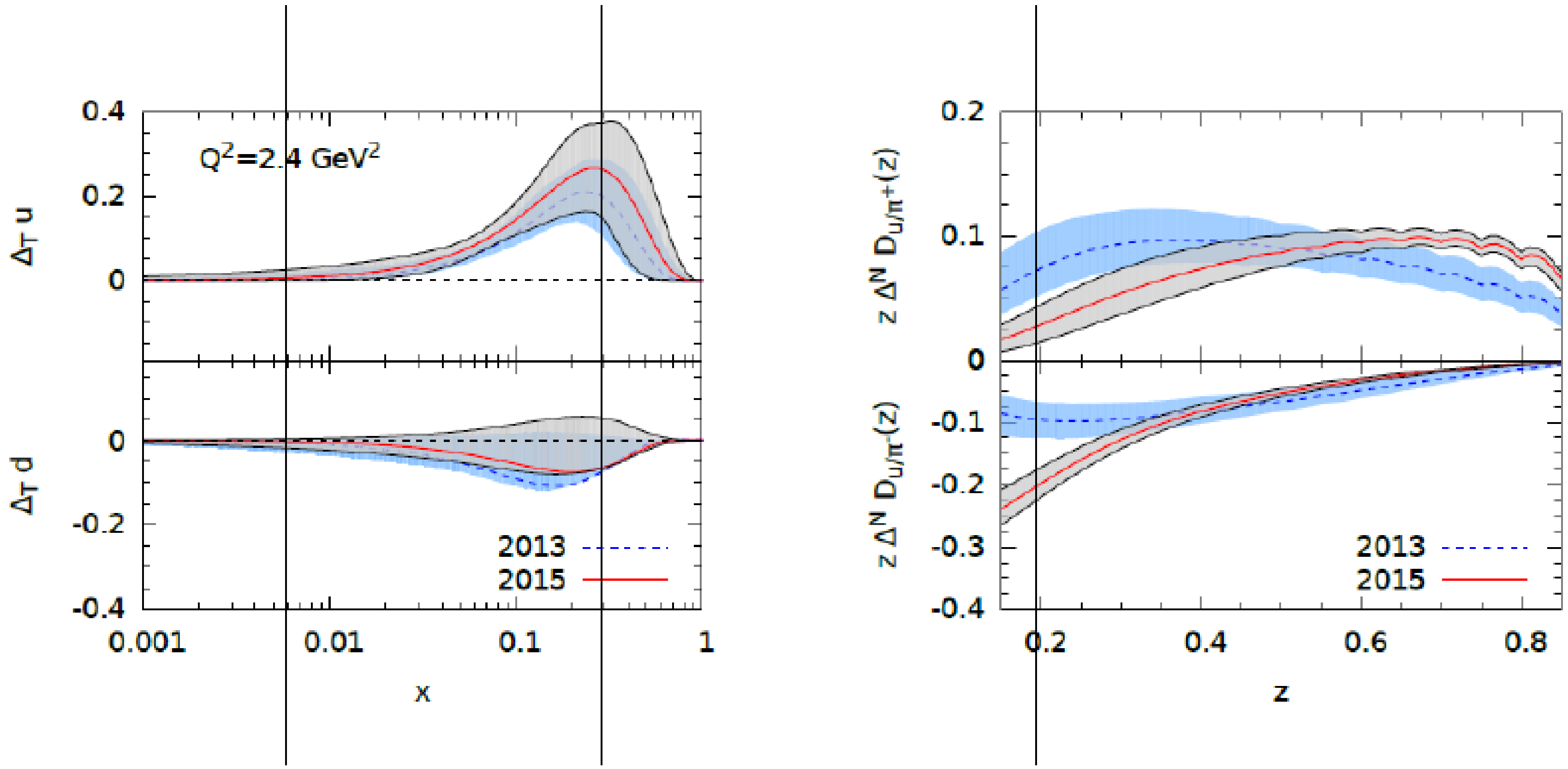
Are current data suitable for TMD evolution studies?



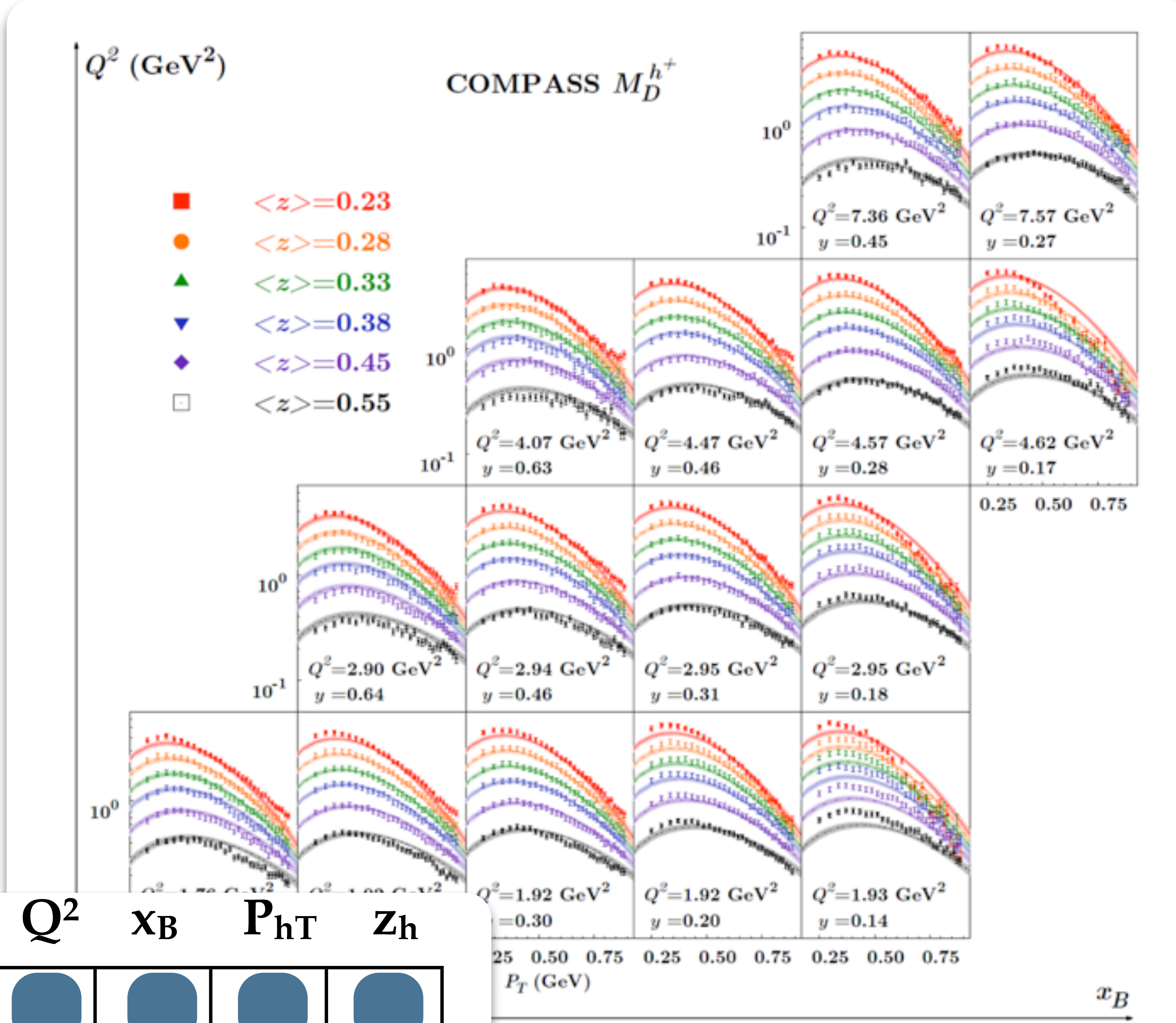
Kang, Prokudin, Sun, Yuan

Phys.Rev. D93 (2016) no.1, 014009
arXiv:1505.05589 [hep-ph] JLAB-THY-15-2044

Results on pion Collins function

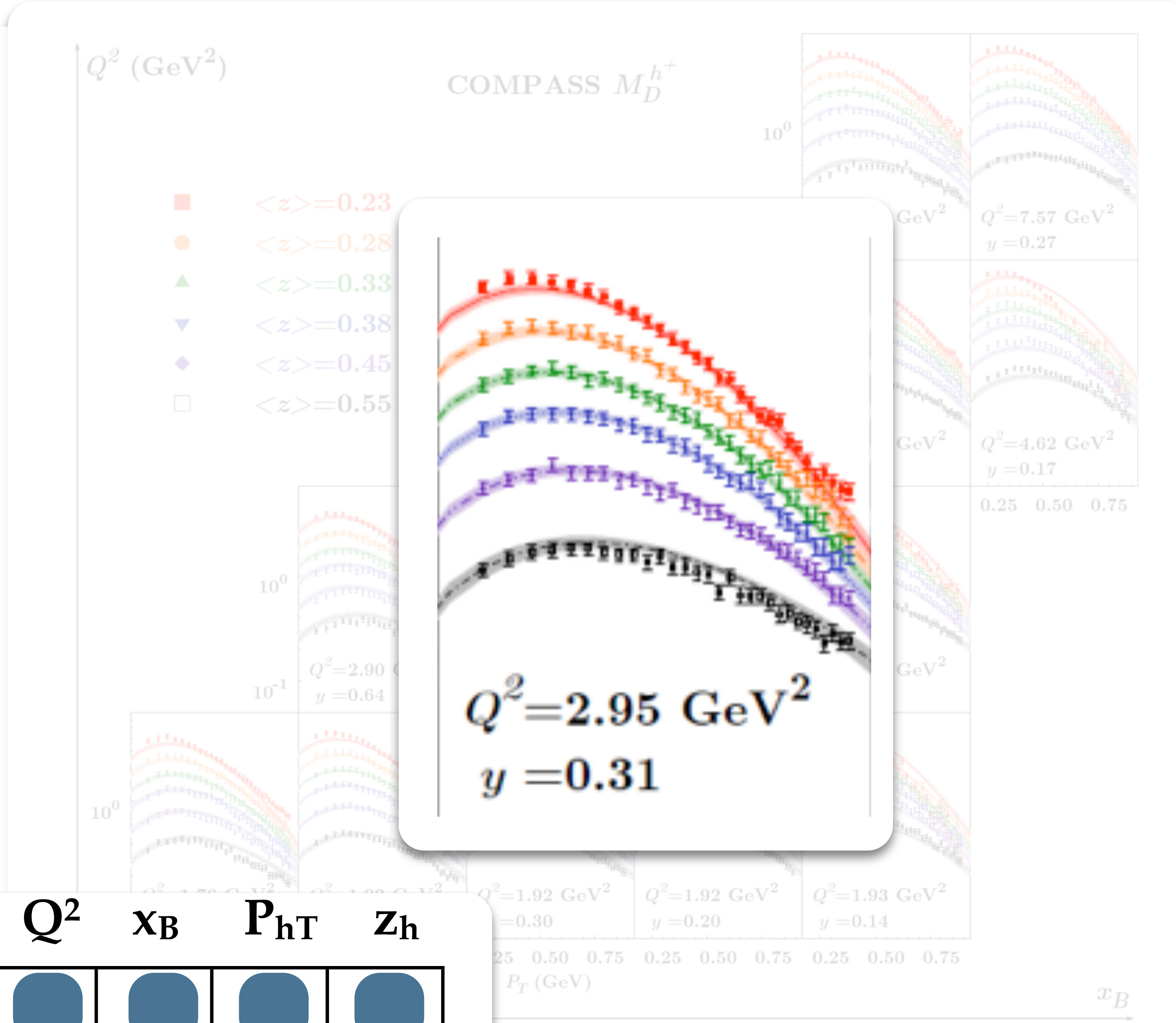


Anselmino, Boglione, D'Alesio, JOGH,
Melis, Murgia, Prokudin
10.1103/PhysRevD.92.114023



	Q^2	x_B	P_{hT}	z_h
binned	●	●	●	●
integrated				

Anselmino, Boglione, JOGH, Melis, Prokudin (2014)



JOGH, et.al. (2013)

	Q^2	x_B	P_{hT}	z_h
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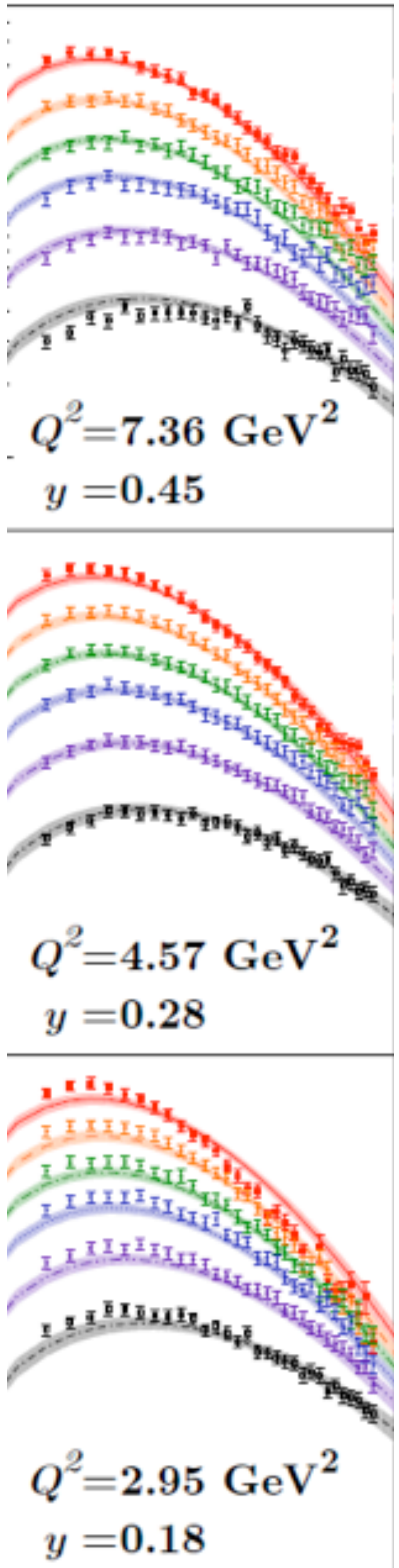
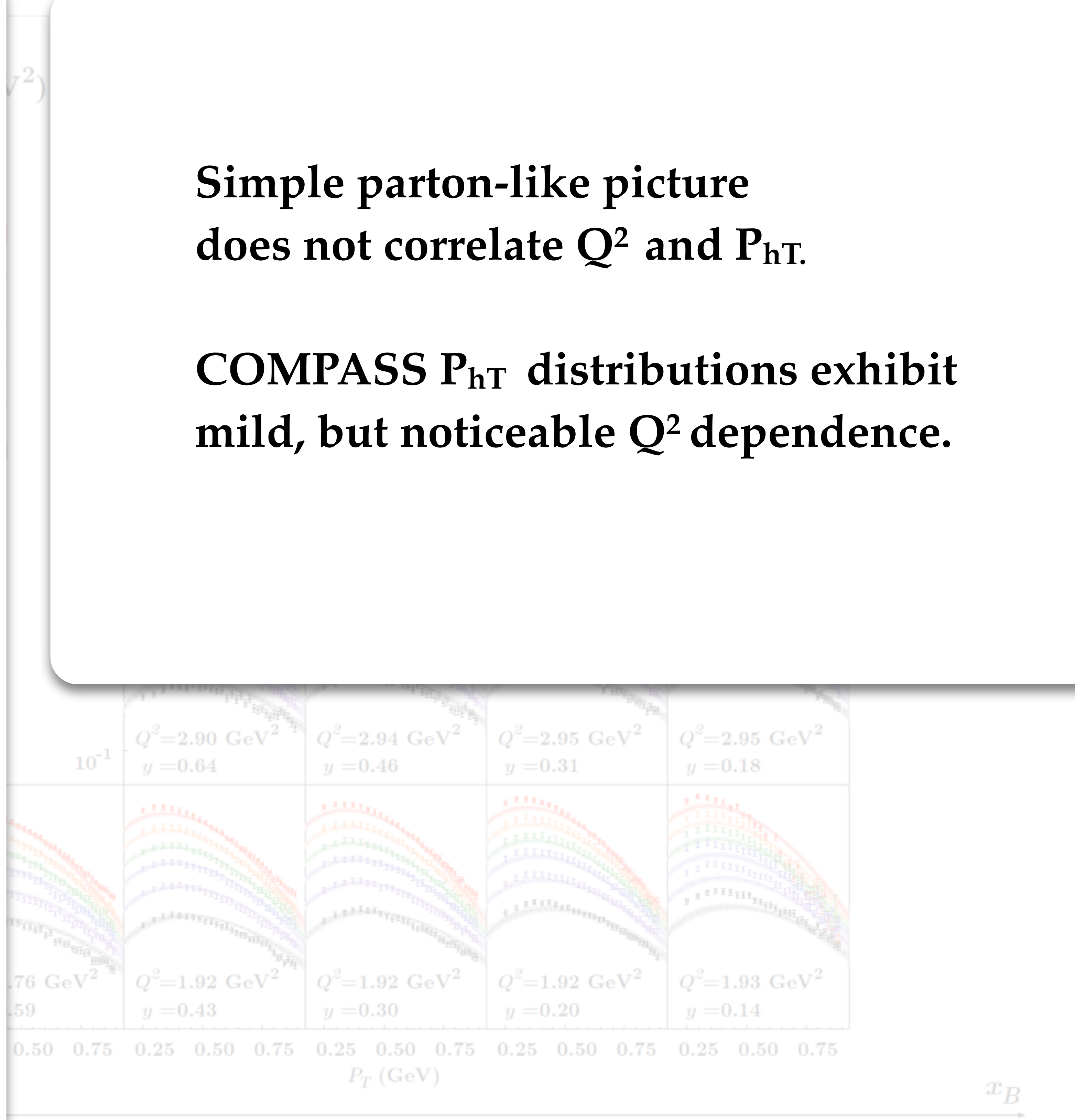


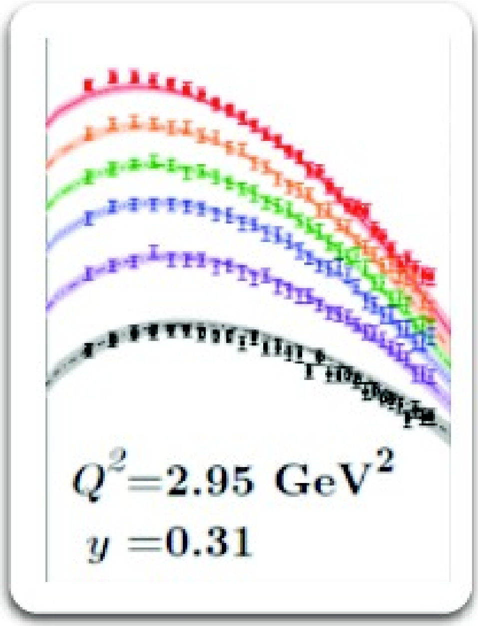
Simple parton-like picture
does not correlate Q^2 and P_{hT}.

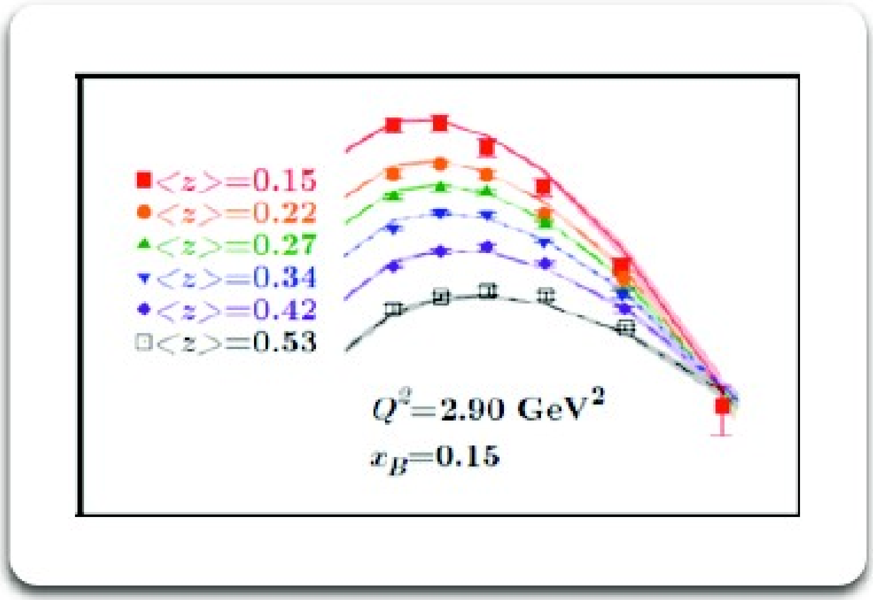
COMPASS P_{hT} distributions exhibit
mild, but noticeable Q^2 dependence.

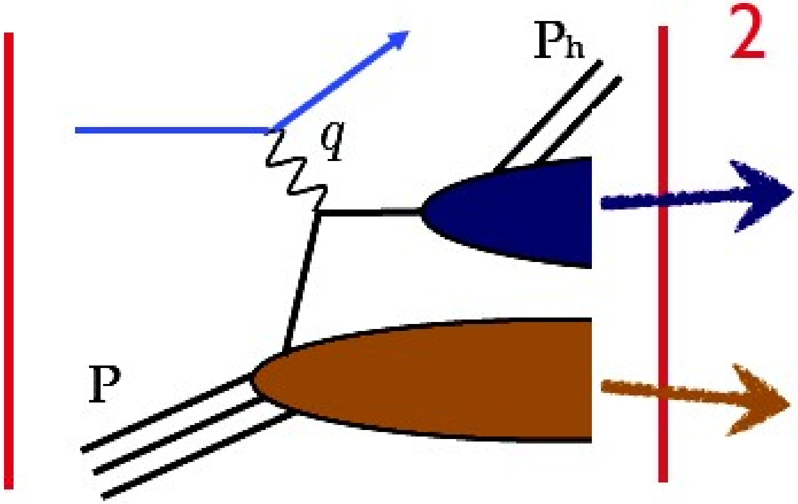


JOGH, et.al. (2013)

Comparing both analyses



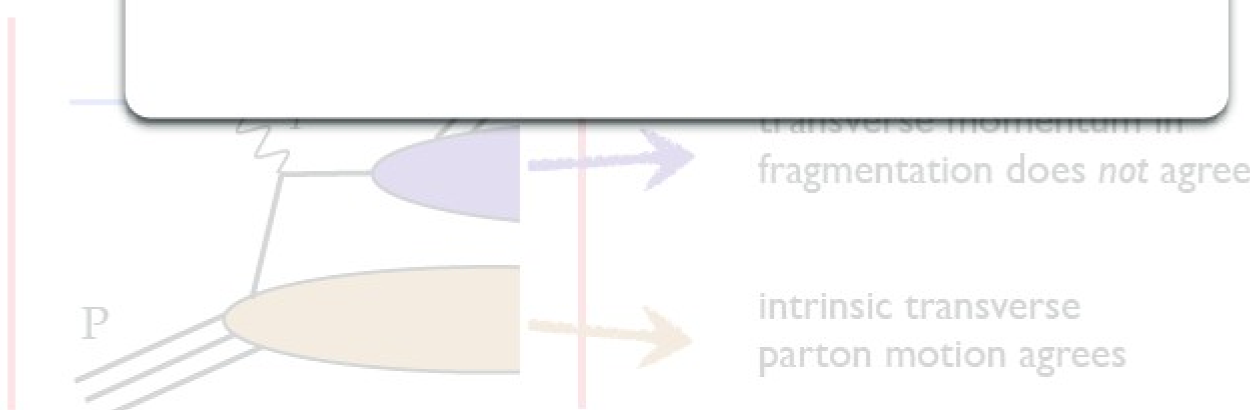




transverse momentum in fragmentation does *not* agree

intrinsic transverse parton motion agrees

Need to consider full QCD picture.



TMD extraction

Simple models: gather as much intel as possible

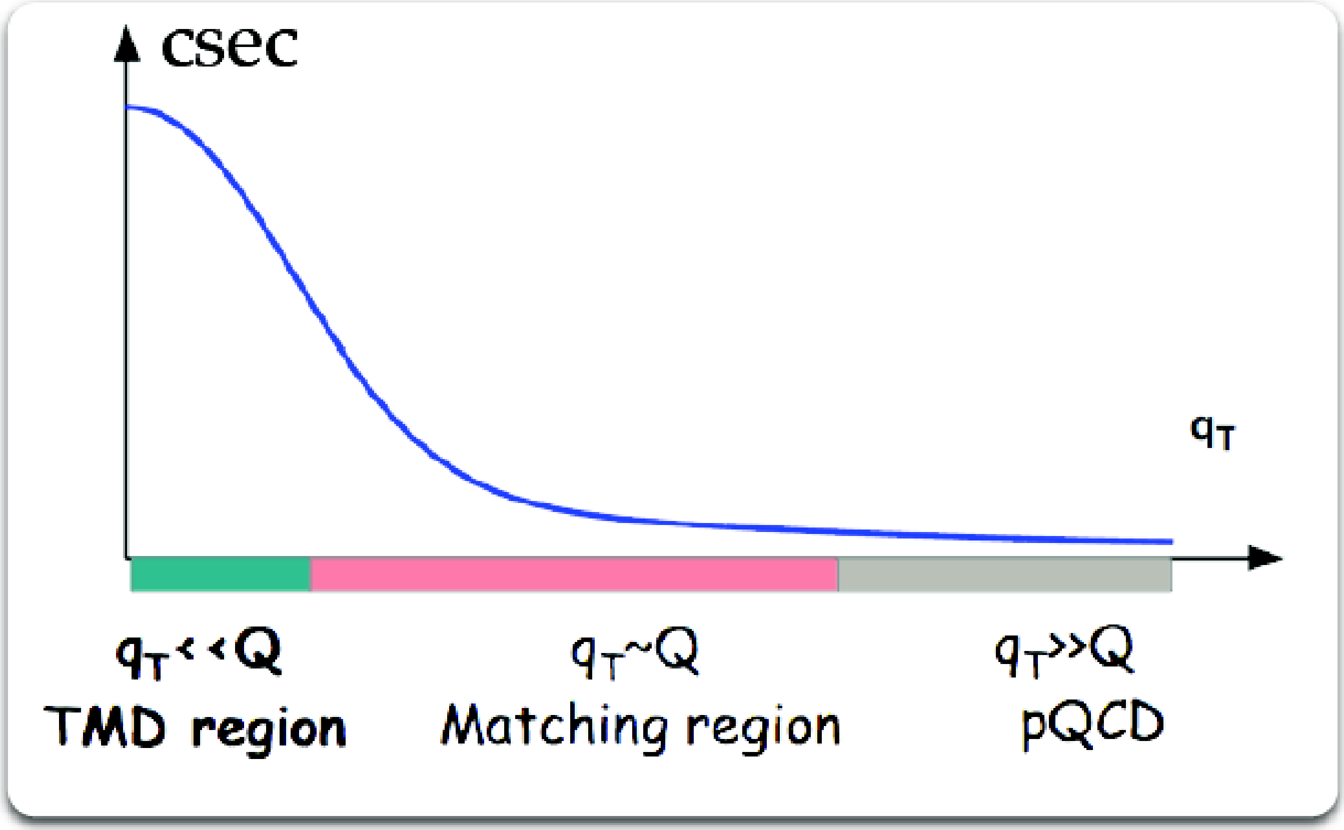
easy to implement, generally leads to interpretations of limited validity

Full QCD picture: perturbative corrections, evolution equations ...

Ultimate goal, great predictive power.

The Matching Problem in SIDIS

$\{Q^2, x_B, P_{hT}, z_h\}$ $\qquad$ $q_T = P_{hT} / z_h$

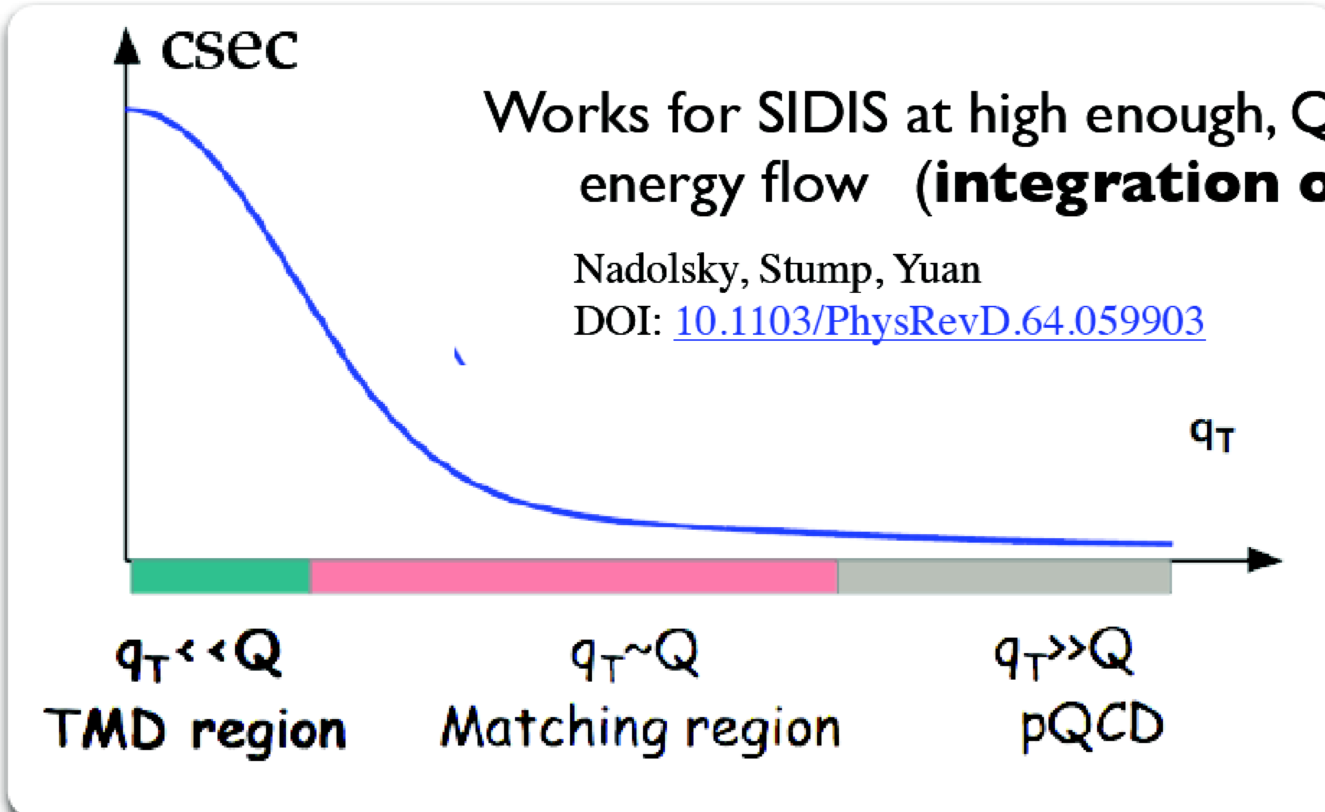


W + Y $\qquad$ gluon radiation

(Collins-Soper-Sterman) $\qquad$ (Collinear Factorization)

The Matching Problem in SIDIS

$\{Q^2, x_B, P_{hT}, z_h\}$ $\qquad$ $q_T = P_{hT} / z_h$



Works for SIDIS at high enough, $Q^2 > 10$ GeV^2, energy flow (**integration over z_h**)

Nadolsky, Stump, Yuan

DOI: 10.1103/PhysRevD.64.059903

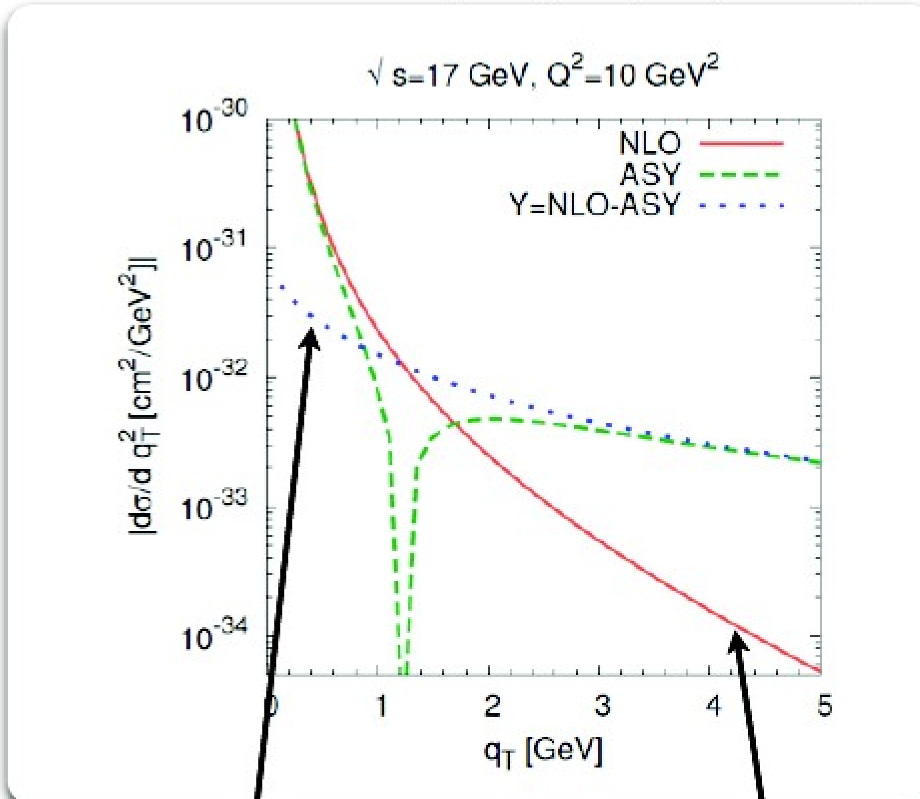
W + Y

(Collins-Soper-Sterman)

gluon radiation

(Collinear Factorization)

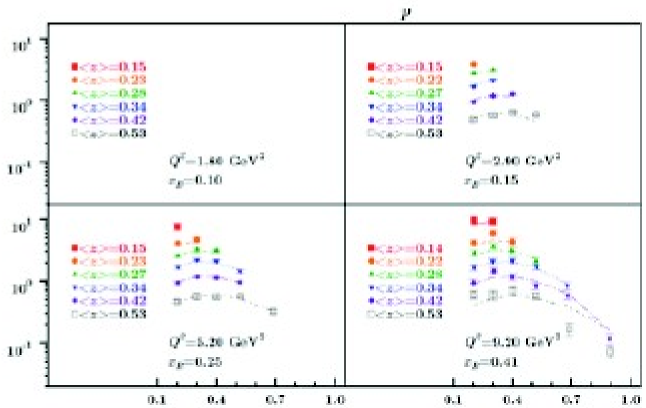
Bogliones, JOGH, Melis, Prokudin, JHEP 1502 (2015) 095

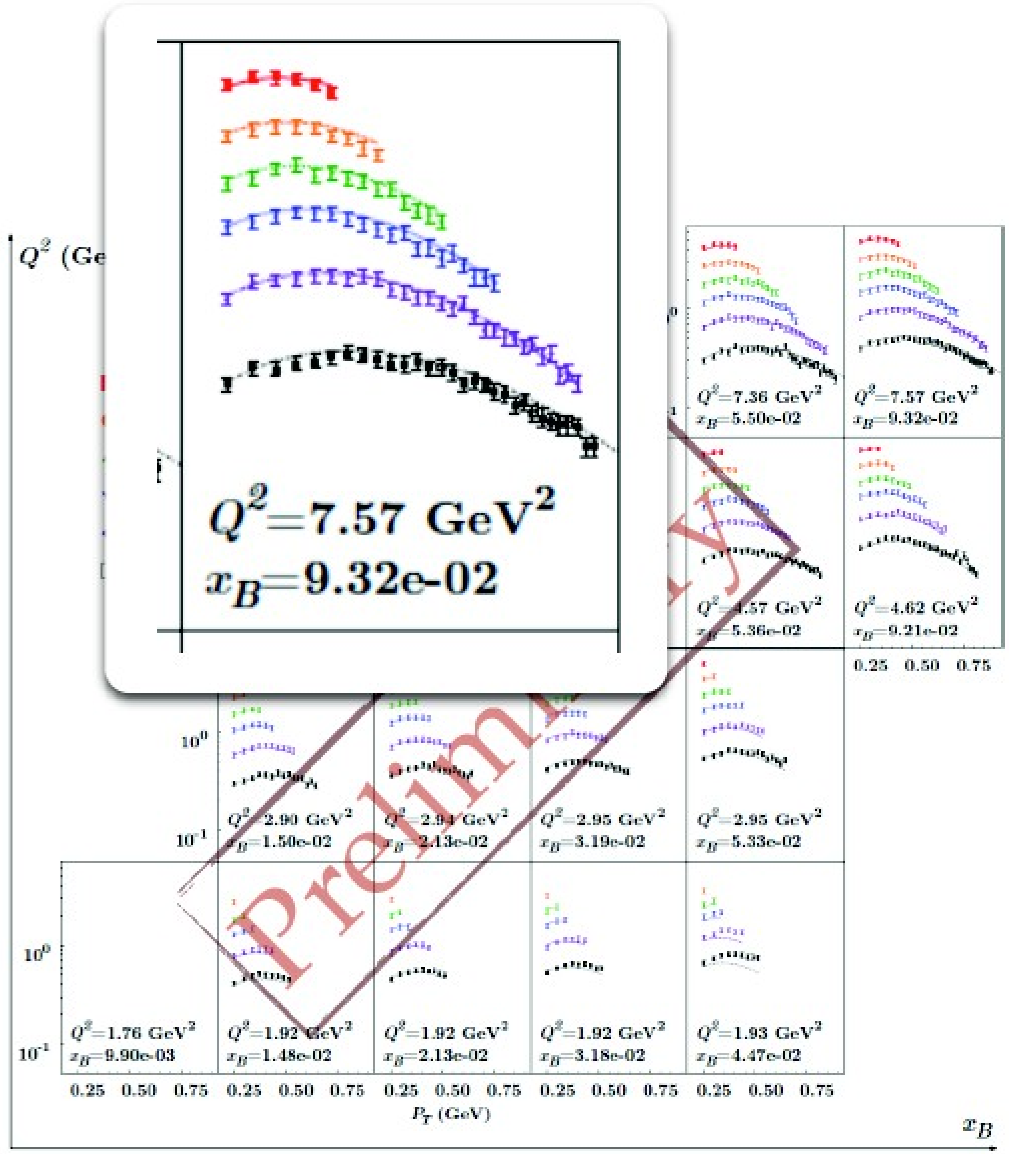


W + Y
(Collins-Soper-Sterman)

gluon radiation
(Collinear Factorization)

W (no Y-term)



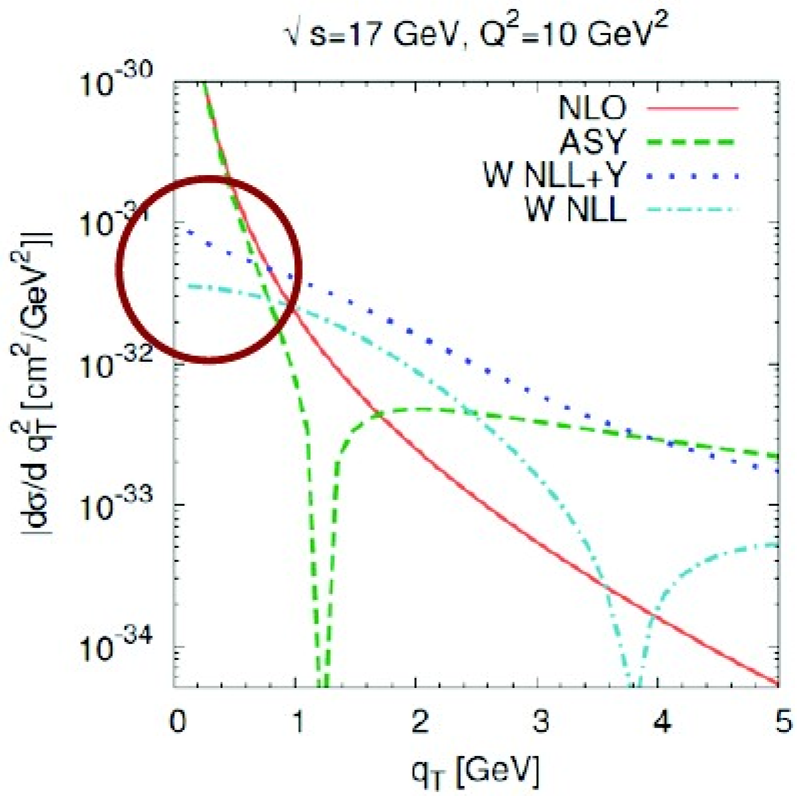


$\chi^2_{tot} = 1.17$

Note:

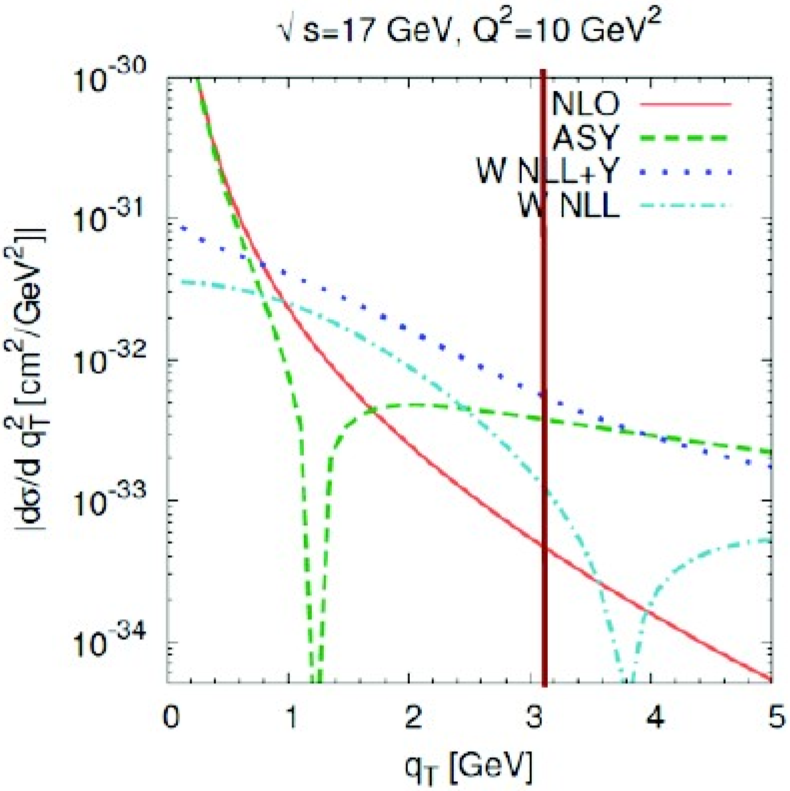
cuts in $q_T = P_T / z_h$

Y-term ?



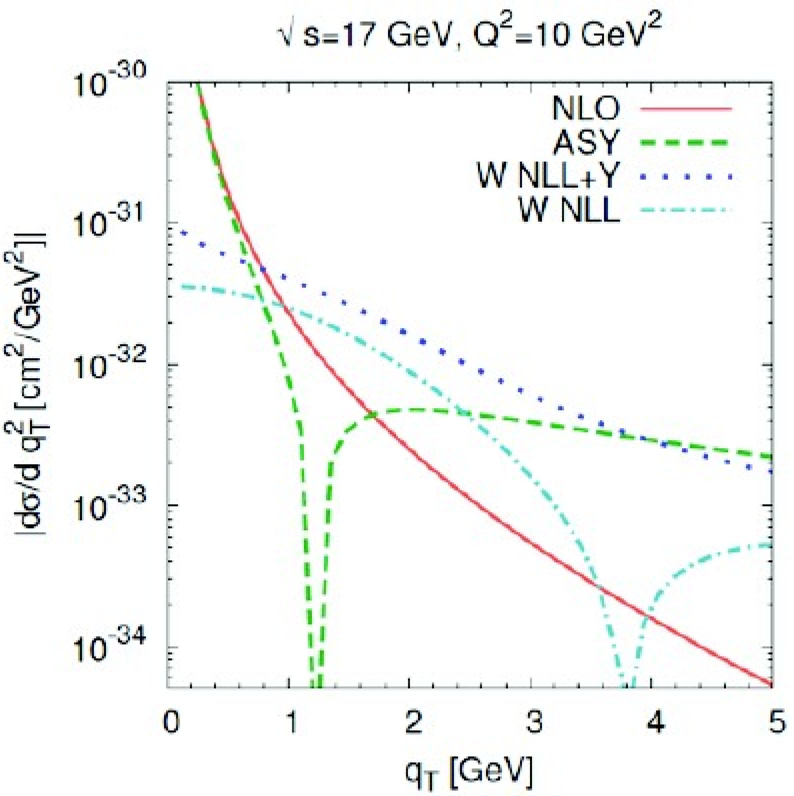
- Large Y-term at small q_T

Y-term ?



- Large Y-term at small q_T
- Small cross section at large q_T
- No smooth matching

Y-term ?



- Large Y-term at small q_T
- Small cross section at large q_T
- No smooth matching
- Delicate kinematics

Some progress..

J. Collins, L. Gamberg, A. Prokudin, T. C. Rogers, N. Sato, and B. Wang Phys. Rev. D **94**, 034014 (2016)

- Large Y-term at small q_T
- Small cross section at large q_T
- No smooth matching
- Delicate kinematics

Improved matching prescription. Still some trouble with sizable Y-term at low q_T

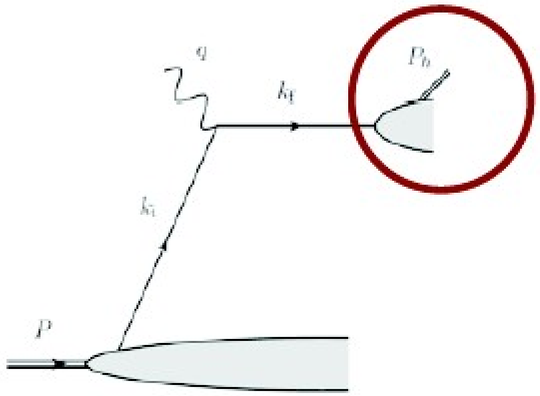
Some progress..

Boglione, Collins, Gamberg, JOGH, Rogers, Sato,

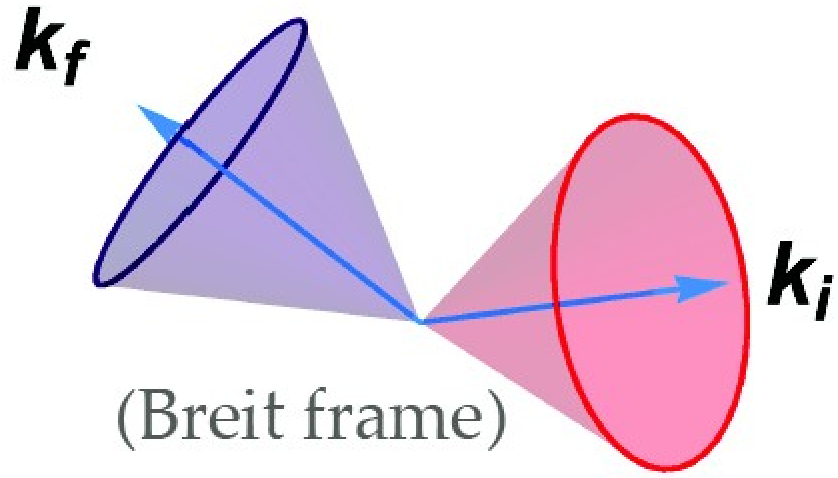
Phys.Lett. B766 (2017) 245-253

Kinematical Region of validity of TMD formalism

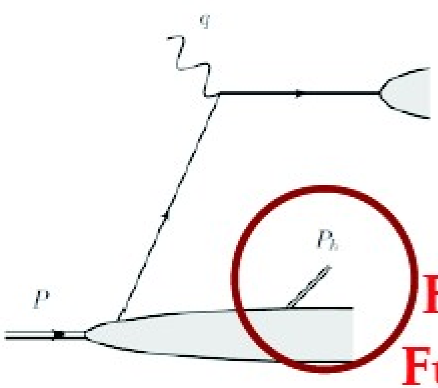
- Large Y-term at small q_T
- Small cross section at large q_T
- No smooth matching
- **Delicate kinematics**



TMDs

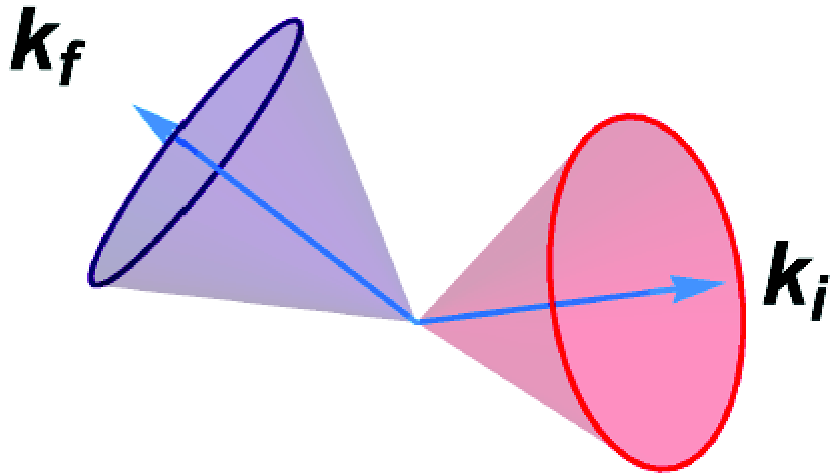


factorization theorems for different leading regions

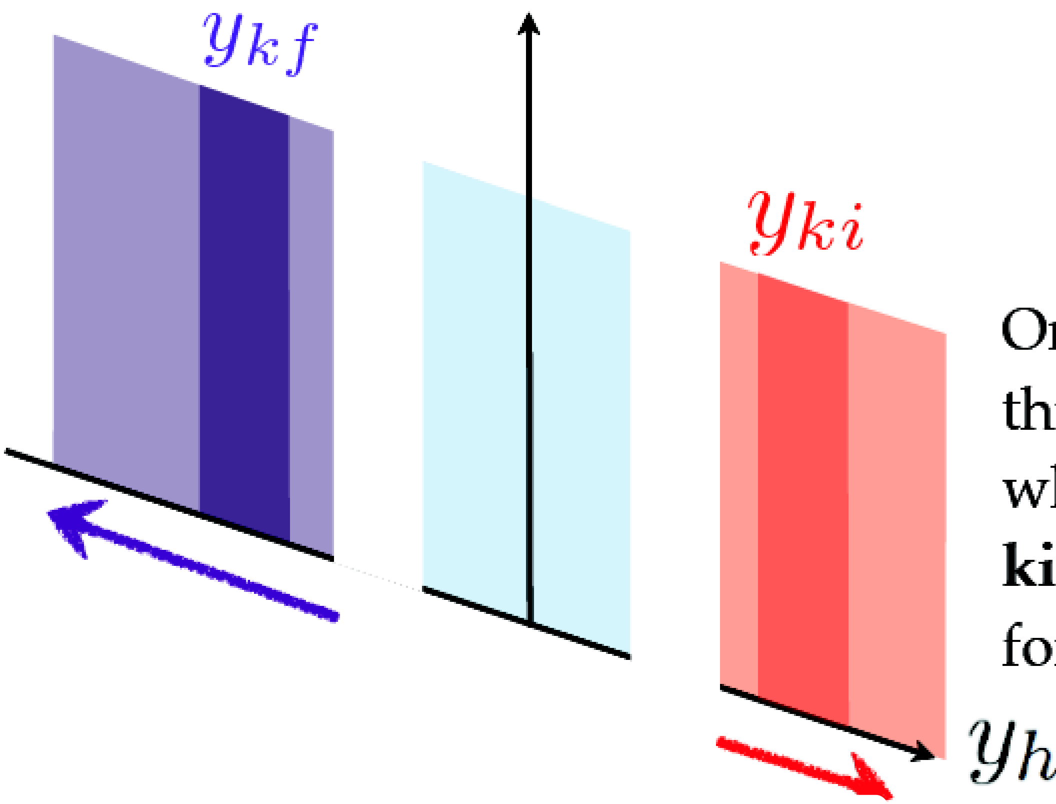


Fracture Functions

$$y_h \equiv \frac{1}{2} \log \frac{P_h^+}{P_h^-}$$

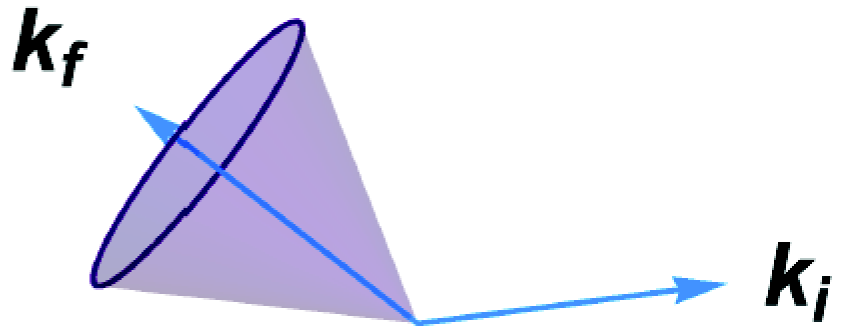


Observable



One may take
this into account, at least
when defining
kinematic limits
for current / target region

Power counting and kinematics of the current region



small masses

$$P_h \cdot k_{\mathrm{f}} = O\left(\boxed{m^2}\right)$$

$$P_h \cdot k_{\mathrm{i}} = O\left(\boxed{Q^2}\right)$$

hard scale

require small values for

$$\boxed{R \equiv \frac{P_h \cdot k_{\mathrm{f}}}{P_h \cdot k_{\mathrm{i}}}}$$

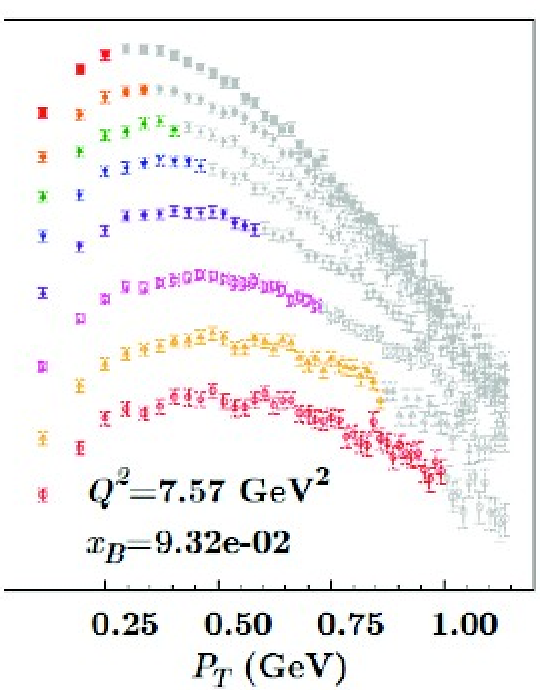
notice quark momenta have to be estimated

a better set of variables?

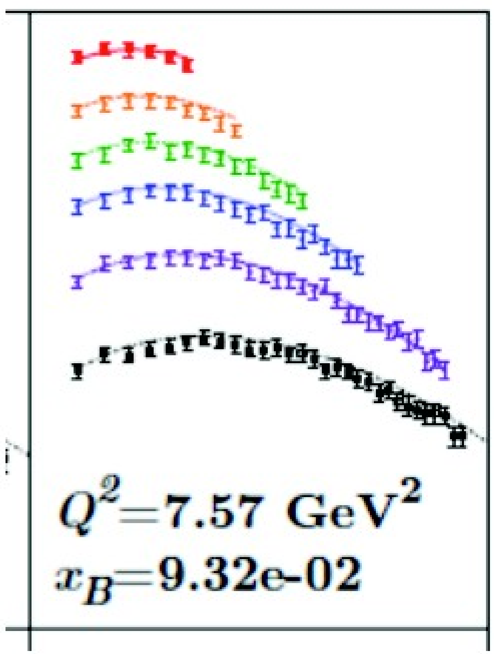
*ONLY AN EXAMPLE

$\{Q^2, x_B, P_{hT}, z_h\}$

$q_T = P_{hT} / z_h$ $\quad y_h$



precise implementation of the R criterion on data is work in progress



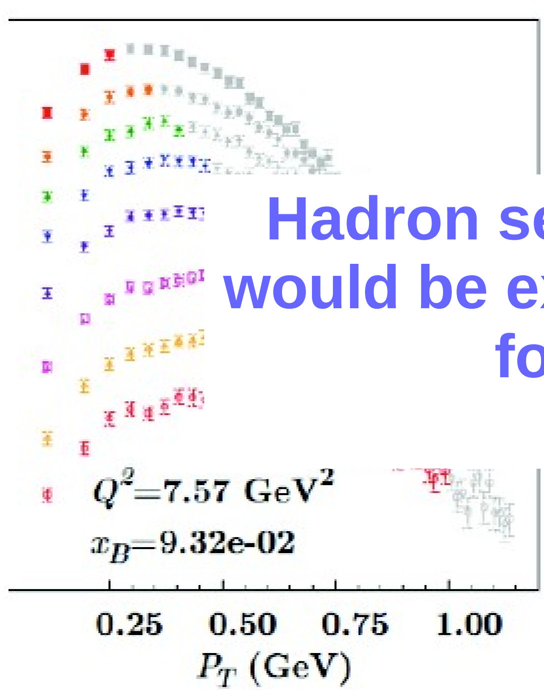
only-W analysis

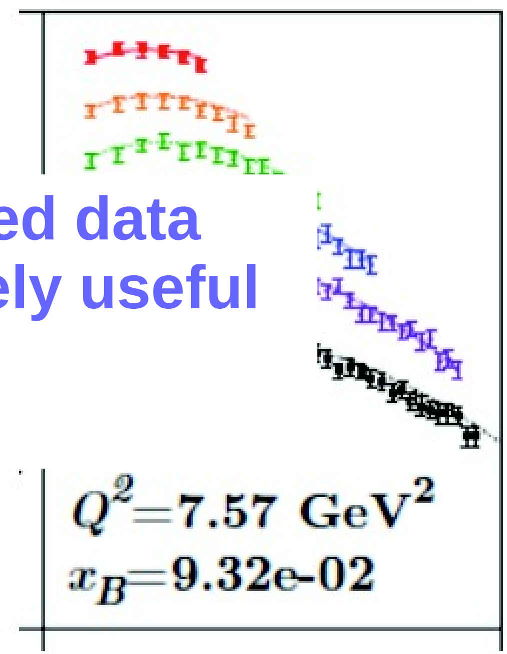
a better set of variables?

$\{Q^2, x_B, P_{hT}, z_h\}$

$q_T = P_{hT} / z_h \qquad y_h$

***ONLY AN EXAMPLE**





only-W analysis

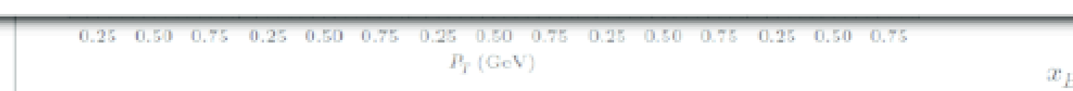
Hadron separated data would be extremely useful for this.

precise implementation of the R criterion on data is work in progress

Ongoing work

some examples of the research in theory and phenomenology motivated by the COMPASS multiplicities

- Large Y-term at small q_T
- Small cross section at large q_T ← B. Wang, N. Sato, T. Rogers, JOGH
- No smooth matching
- Delicate kinematics
  - criterion for TMD region
  - precise implementation on data



Final Remarks

Currently, we are moving from simple parton model pictures to **full QCD picture**.

Need to describe regions of **low and large transverse momenta** simultaneously.

More work to be done, it's important to take a step back and think of the **theoretical issues** (solving the
“matching problem” at delicate kinematics).

Final Remarks

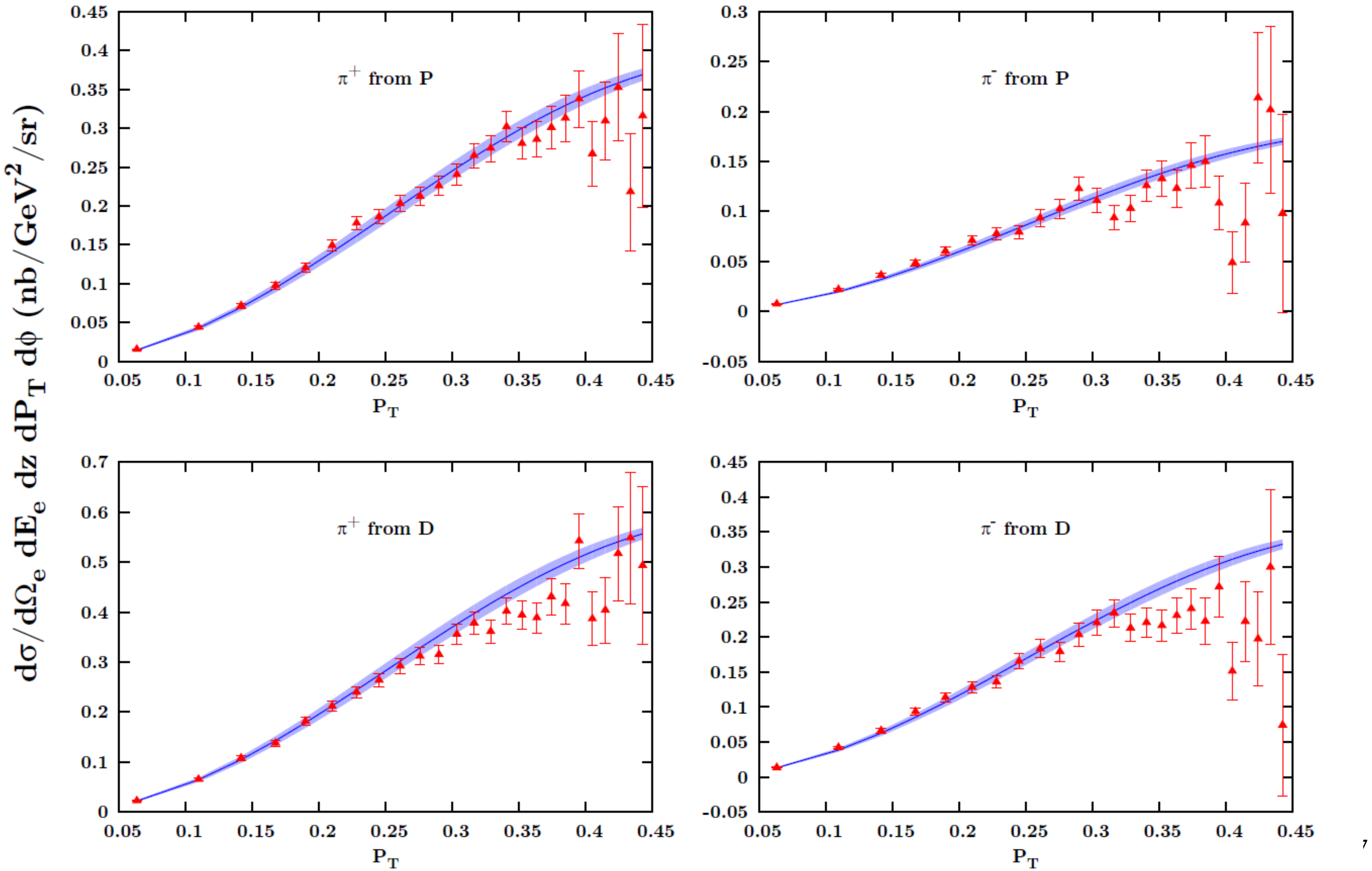
Simple models are still useful. One should be **very careful with interpretations (Think of these as preliminary sketches)**

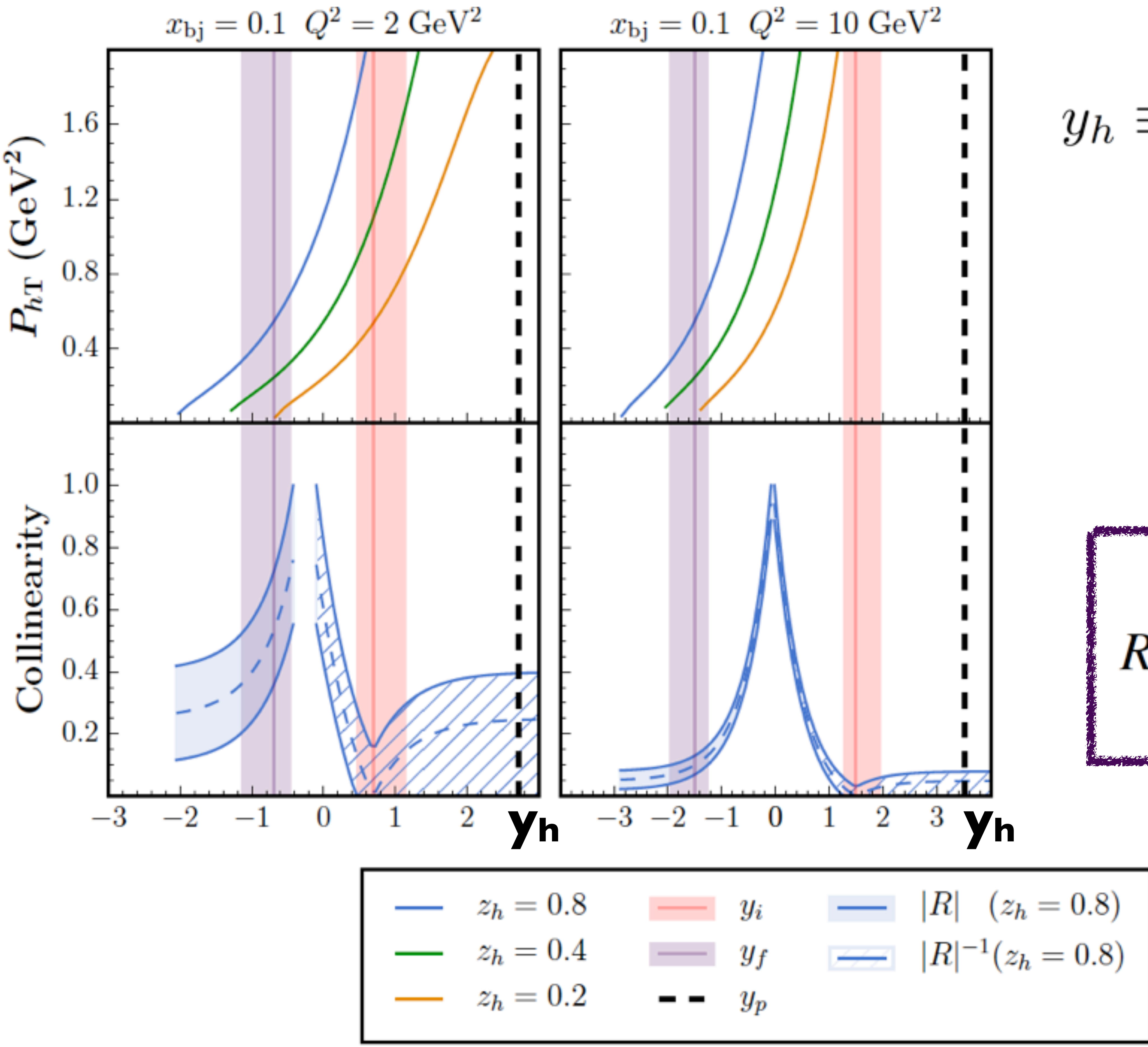
Why does a simple partonic picture is appropriate sometimes?

Is it possible to extend the current TMD formalism?

Thank you.

Jlab SIDIS data (2012) (Parameters from HERMES extraction).

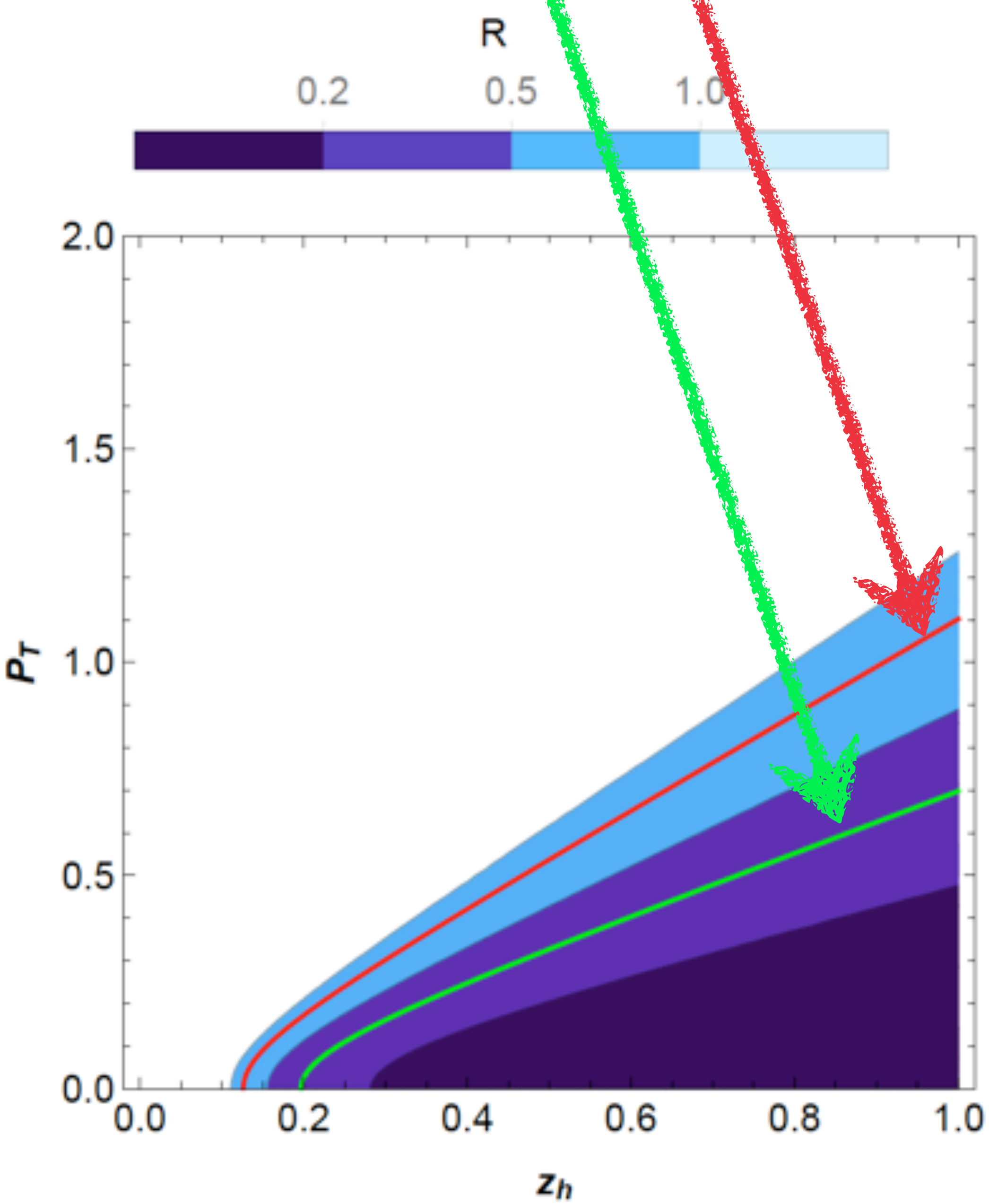


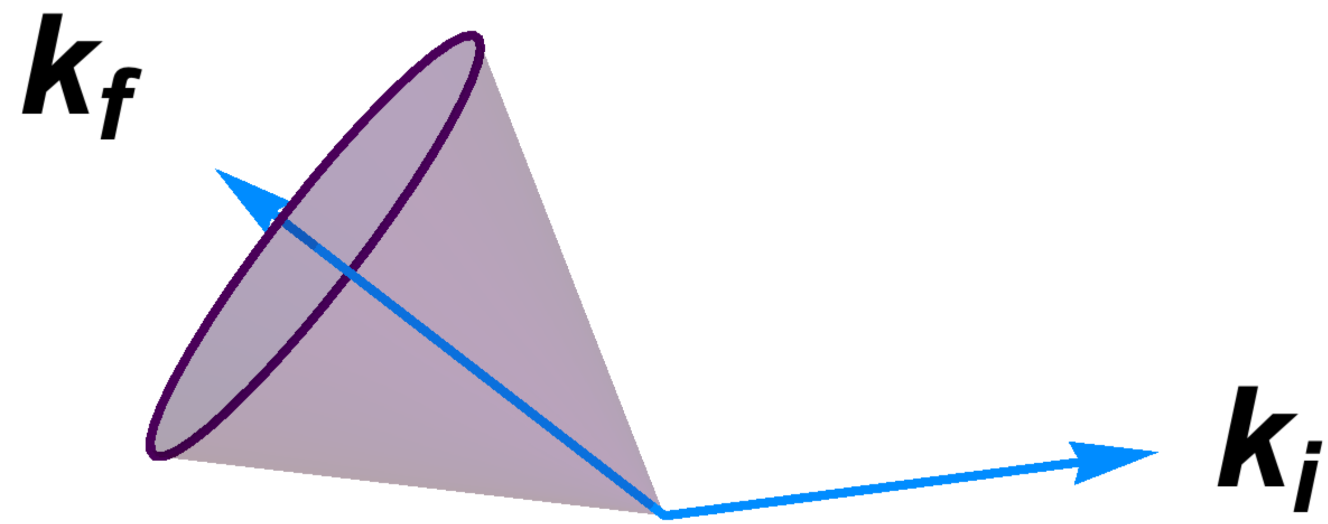


$$y_h \equiv \frac{1}{2} \log \frac{P_h^+}{P_h^-}$$

$$\boxed{R \equiv \frac{P_h \cdot k_{\mathrm{f}}}{P_h \cdot k_{\mathrm{i}}}}$$

Impose
rapidity cuts





current region

Alternatively,
require small values
for

$$\boxed{R \equiv \frac{P_h \cdot k_\mathrm{f}}{P_h \cdot k_\mathrm{i}}}$$

notice quark momenta
have to be estimated