Unpolarized TMD extraction from HERMES and COMPASS SIDIS data

Jose Osvaldo Gonzalez Hernandez

INFN Torino

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In collaboration with

M. Anselmino (Torino)

M. Boglione (Torino)

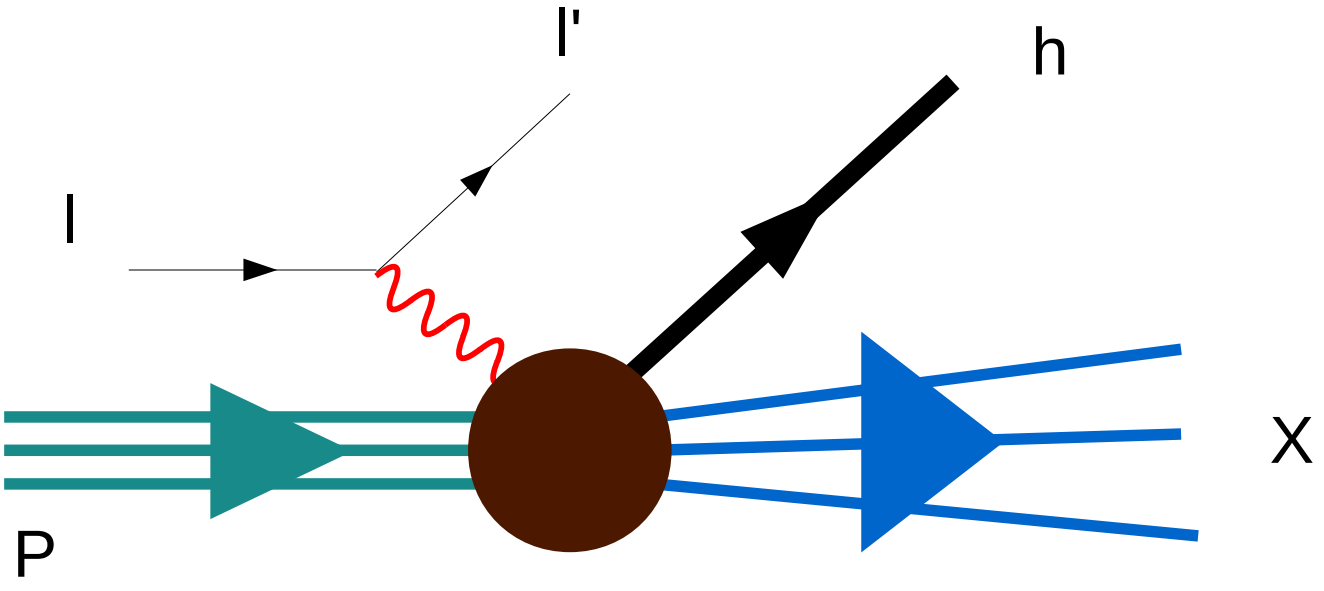
S. Melis (Torino)

V. Barone (Alessandria)

A. Prokudin (JLab)

OUTLINE

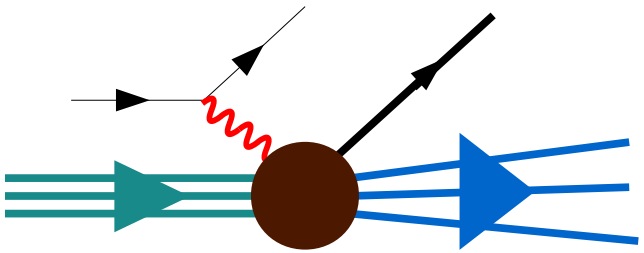
- General Comments on TMD extraction.
- Unpolarized TMD extraction from HERMES Multiplicities.
- Unpolarized TMD extraction from COMPASS Multiplicities.
- Towards a Global Fit : Azimuthal Moments



What can we really learn?

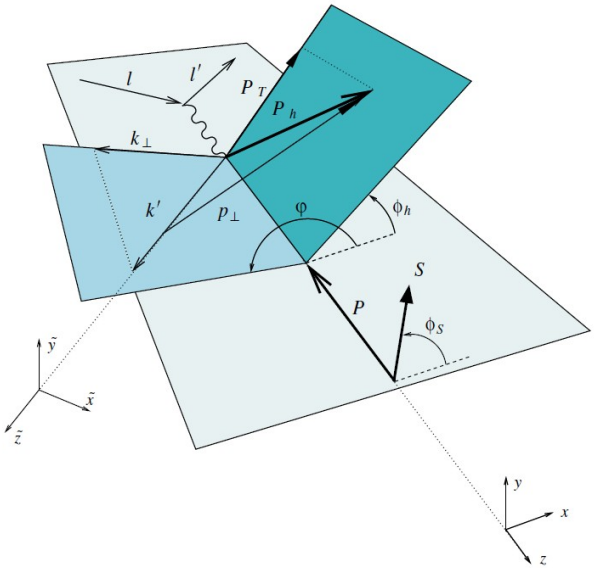
Model for Non-Perturvative Functions

Dynamics...



$$\sum_q e_q^2 \int d^2\boldsymbol{k}_\perp f_q(x_B, k_\perp) \frac{2\pi\alpha^2}{x_B^2 s^2} \times \frac{\hat{s}^2 + \hat{u}^2}{Q^4} D_q^h(z_h, p_\perp),$$

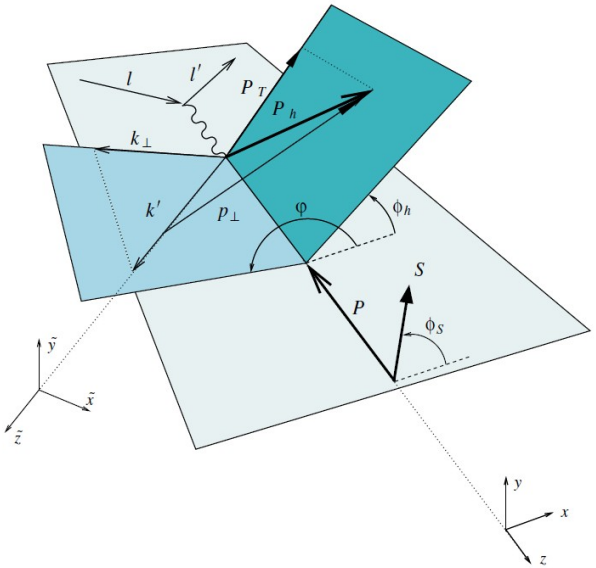
Kinematics...



$$\boldsymbol{P}_T = z\,\boldsymbol{k}_\perp + \boldsymbol{p}_\perp$$

Intrinsic limitation on what we observe

Kinematics...

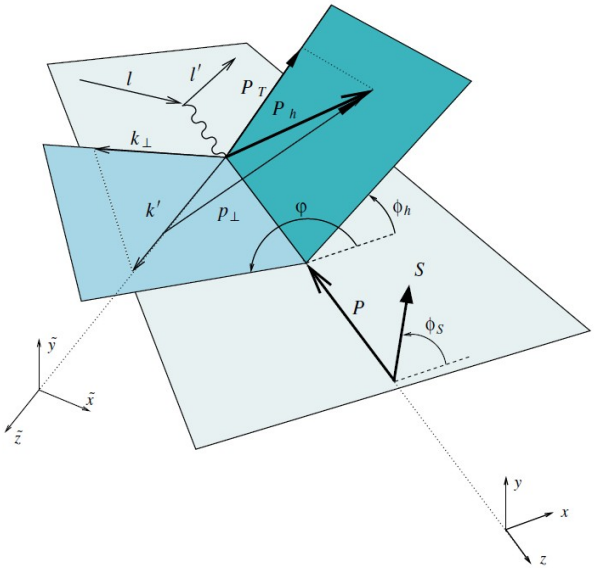


$$\boldsymbol{P}_T = z\,\boldsymbol{k}_\perp + \boldsymbol{p}_\perp$$

Intrinsic limitation on what we observe

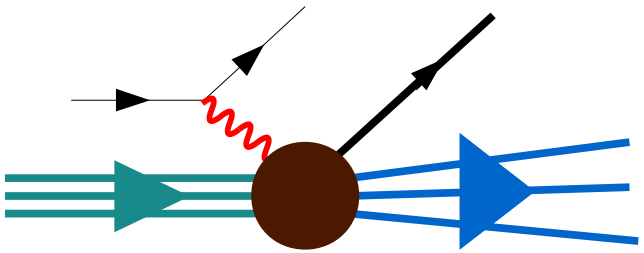
Easier to see in a model, say, for instance...

Kinematics...



Gaussian model:

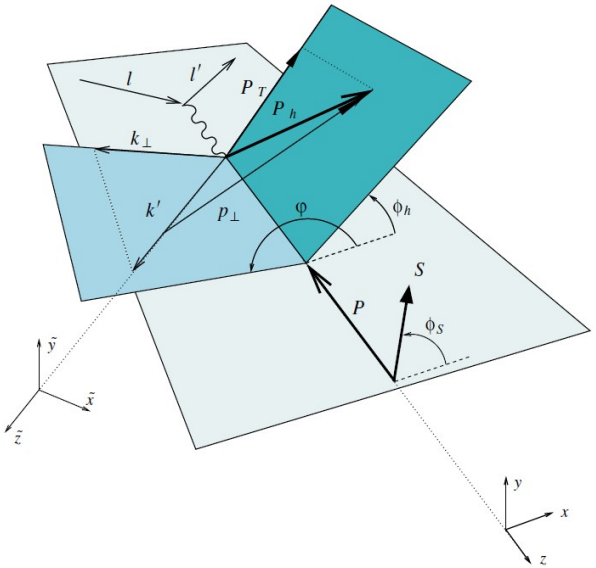
Dynamics...



$$f_q(x, k_\perp) = f_q(x) \frac{1}{\pi \langle k_\perp^2 \rangle} e^{-k_\perp^2/\langle k_\perp^2 \rangle}$$

$$D_q^h(z, p_\perp) = D_q^h(z) \frac{1}{\pi \langle p_\perp^2 \rangle} e^{-p_\perp^2/\langle p_\perp^2 \rangle}$$

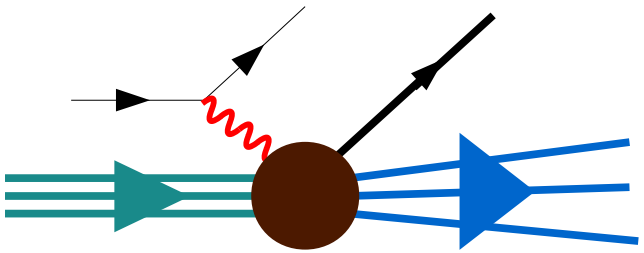
Kinematics...



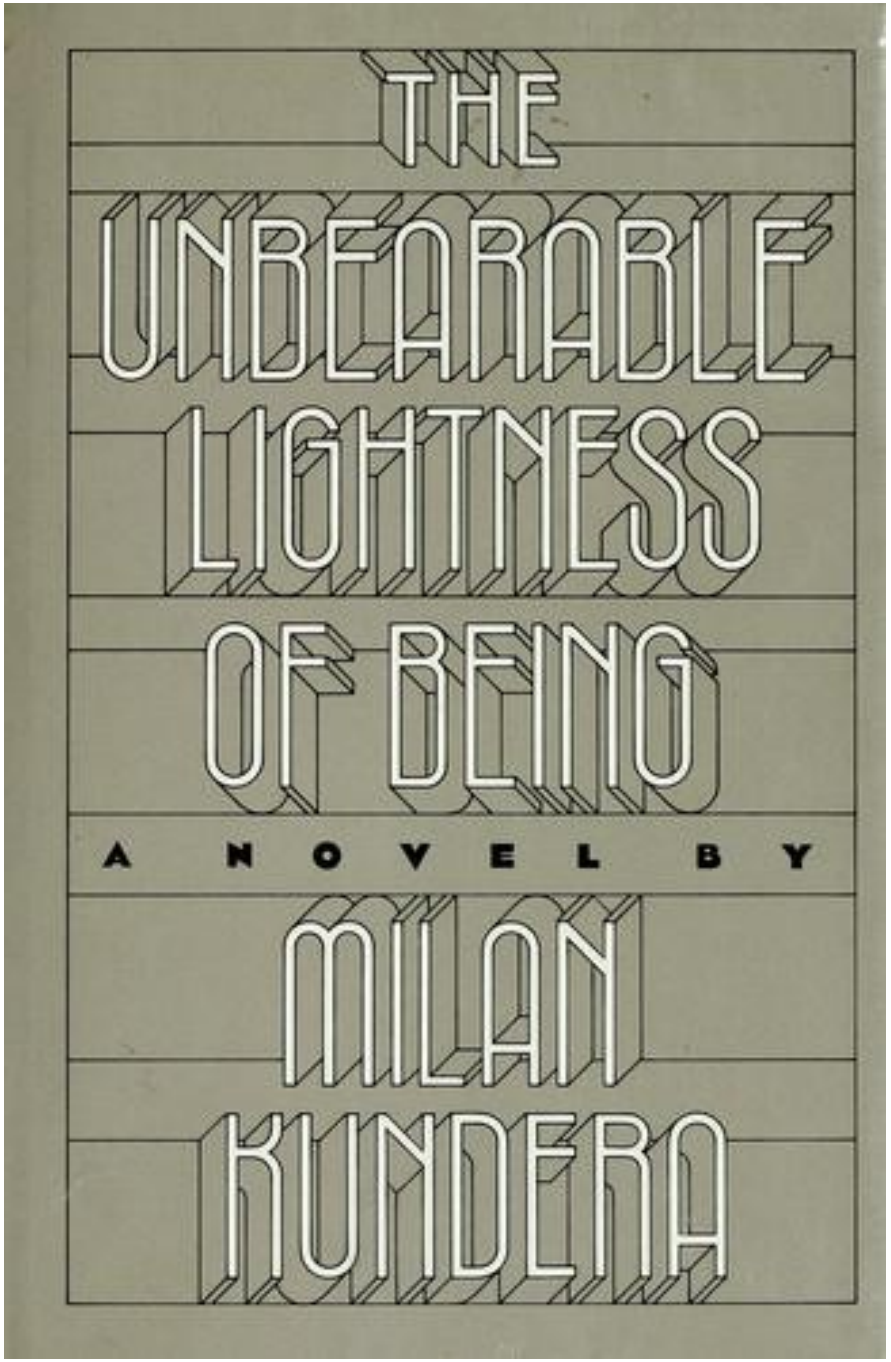
Gaussian model:

$$\langle P_T^2 \rangle = \langle p_\perp^2 \rangle + z_h^2 \langle k_\perp^2 \rangle.$$

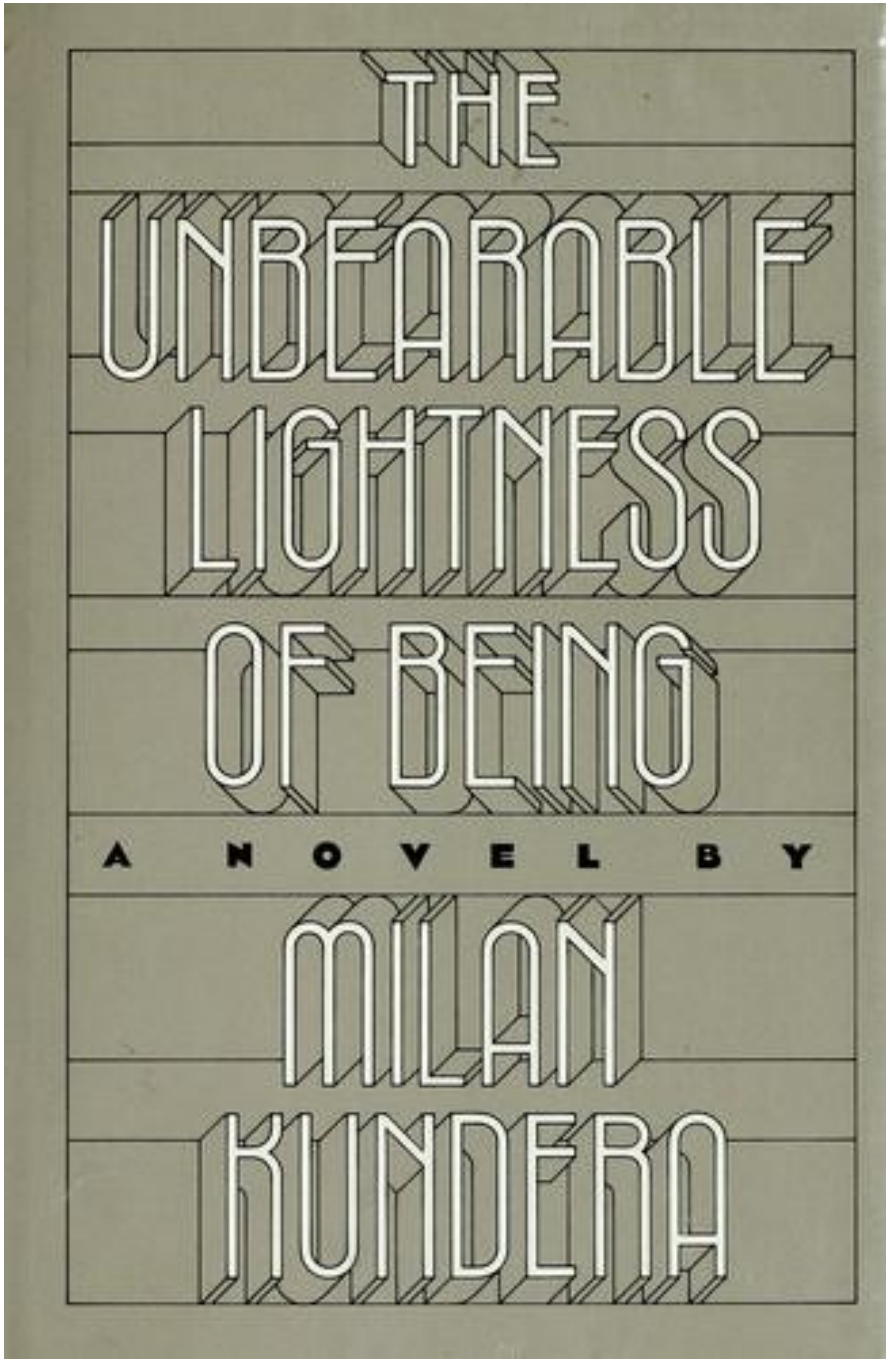
Dynamics...



$$\sigma \propto \frac{1}{\pi \langle P_T^2 \rangle} e^{-P_T^2/\langle P_T^2 \rangle}$$



$$\langle P_T^2 \rangle = \langle p_\perp^2 \rangle + z_h^2 \langle k_\perp^2 \rangle.$$

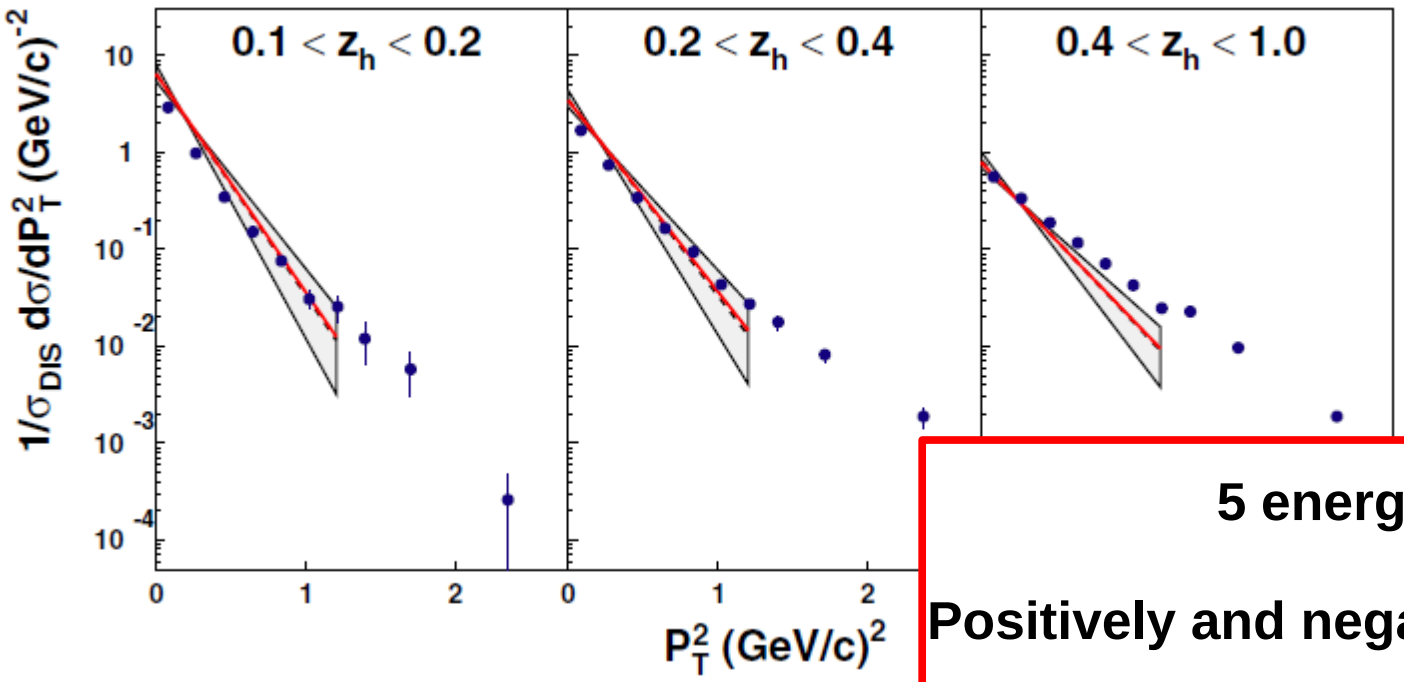


$$\langle P_T^2 \rangle = \langle p_\perp^2 \rangle + z_h^2 \langle k_\perp^2 \rangle.$$

Previous Extraction (2005).

From EMC data:
Ashman, J. et al. Z.Phys. C52 (1991) 361-388 CERN-PPE-91-53

$$\langle k_\perp^2 \rangle = 0.25 \ \mathrm{GeV}^2 \qquad \langle p_\perp^2 \rangle = 0.20 \ \mathrm{GeV}^2$$



Anselmino, M. et al. Phys.Rev. D71 (2005)

5 energies,

Positively and negatively charged particles . . .

. . . 1 data set.

Recent data releases.

HERMES
Airapetian, A. et al. Phys.Rev. D87 (2013) 074029

COMPASS
Adolph, C. et al. Eur.Phys.J. C73 (2013) 2531

Multidimensional data → An opportunity
to explore new things.

Recent data releases.

HERMES

Airapetian, A. et al. Phys.Rev. D87 (2013) 074029

COMPASS

Adolph, C. et al. Eur.Phys.J. C73 (2013) 2531

Results presented here have been published in:

DOI: 10.1007/JHEP04(2014)005

Extraction from HERMES

and COMPASS data.

Model

$$f_q(x, k_\perp) = f_q(x) \frac{1}{\pi \langle k_\perp^2 \rangle} e^{-k_\perp^2 / \langle k_\perp^2 \rangle}$$

$$D_q^h(z, p_\perp) = D_q^h(z) \frac{1}{\pi \langle p_\perp^2 \rangle} e^{-p_\perp^2 / \langle p_\perp^2 \rangle}$$

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Kinematical Cuts

$$Q^2 > 1.69 \text{ GeV}^2$$

$$0.2 < P_T < 0.9 \text{ GeV}$$

$$z < 0.6$$

Extraction from HERMES

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Kinematical Cuts

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$$0.2 < P_T < 0.9 \text{ GeV}$$
$$z < 0.6$$

Processes included

π^+ and π^- production from both P and D targets.

h^+ and h^- production from D.

Extraction from HERMES data.

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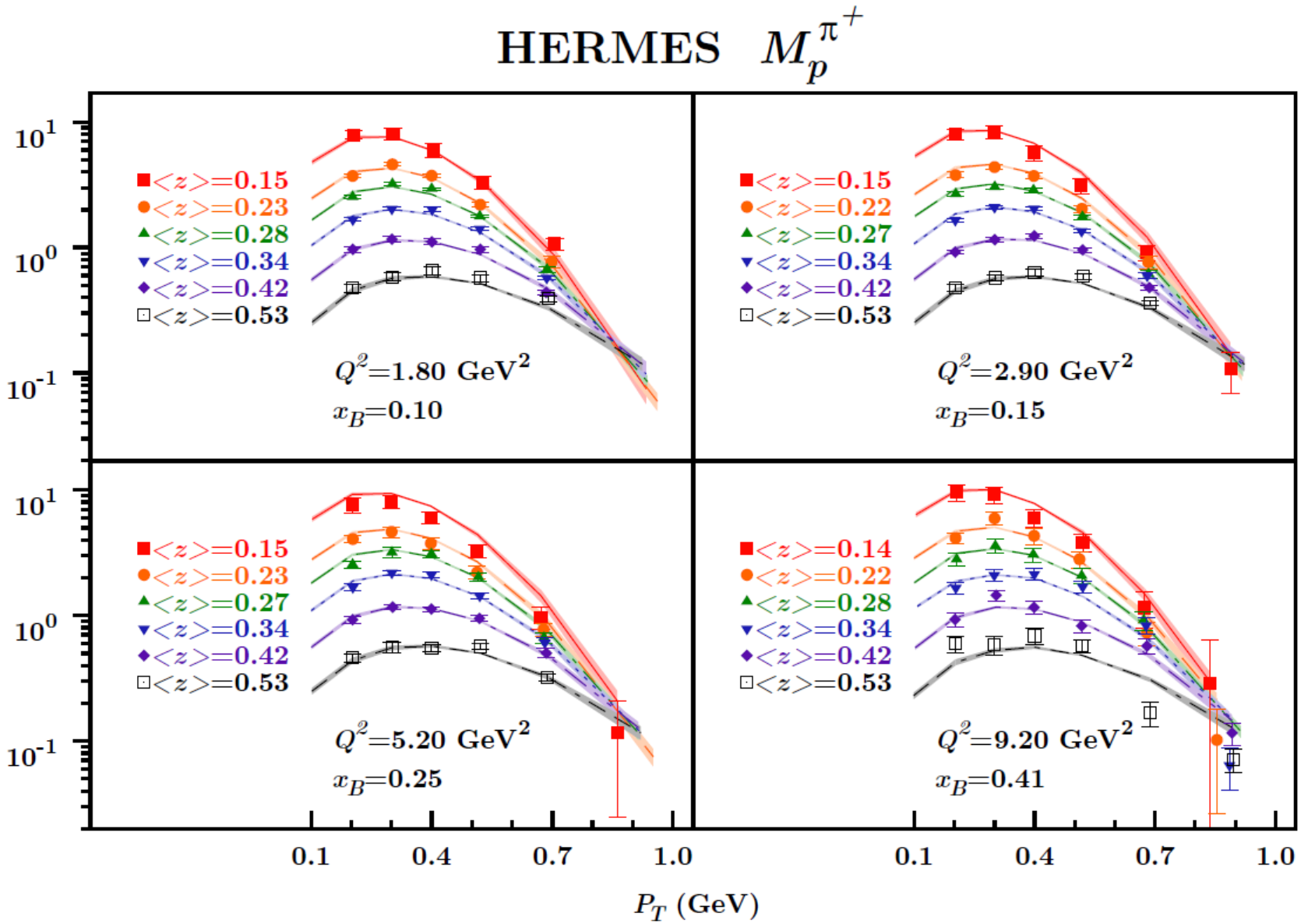


Extraction from HERMES data.

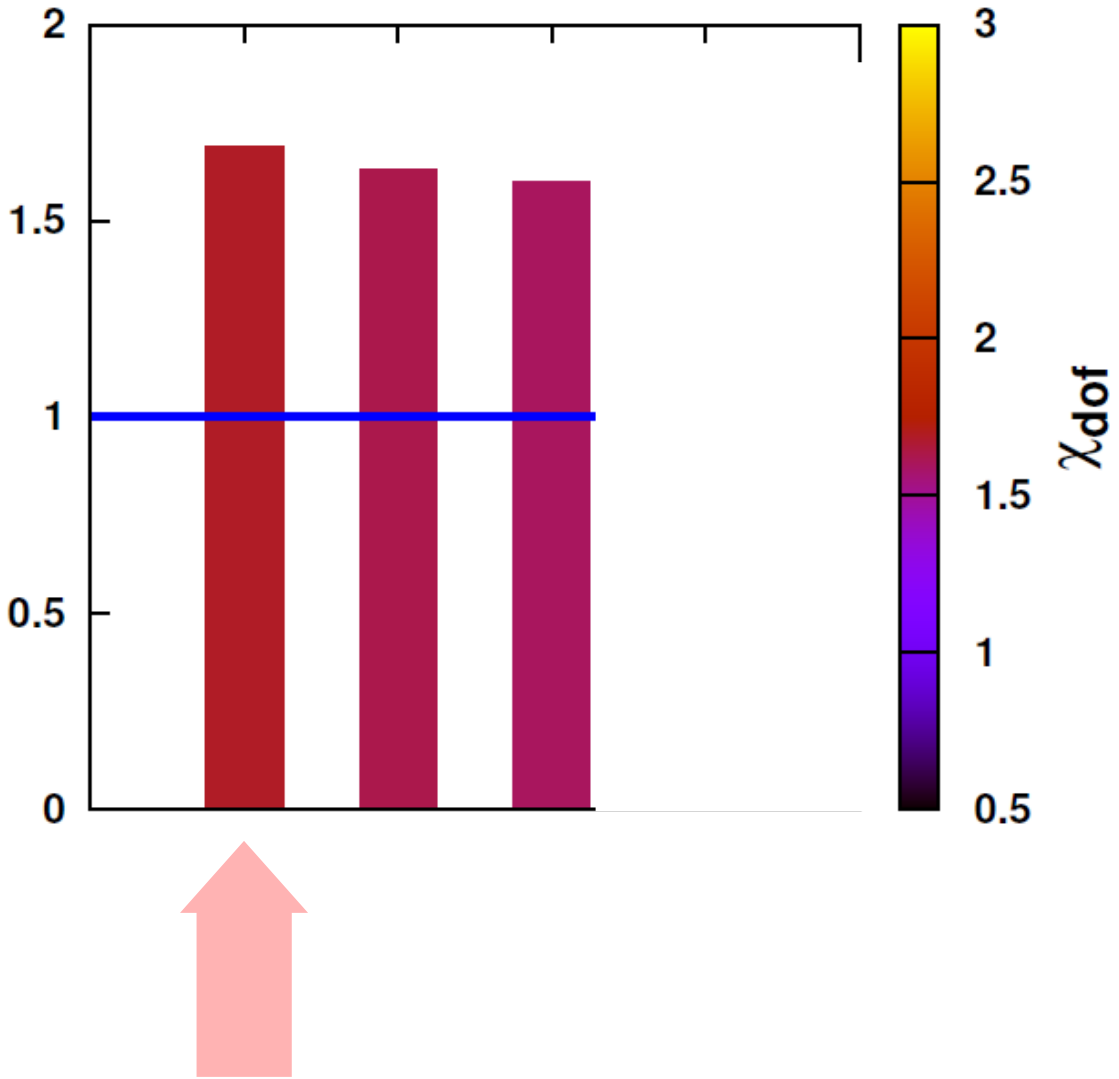
HERMES					
Cuts	χ^2_{pts}	n. points	$[\chi^2_{pts}]^{\pi^+}$	$[\chi^2_{pts}]^{\pi^-}$	Parameters
$Q^2 > 1.69$ GeV^2 $0.2 < P_T < 0.9$ GeV $z < 0.6$	1.69	497	1.93	1.45	$\langle k_\perp^2 \rangle = 0.57 \pm 0.08$ GeV^2 $\langle p_\perp^2 \rangle = 0.12 \pm 0.01$ GeV^2

Extraction from HERMES data.

Gaussian Model

(Simple)

2 parameters.

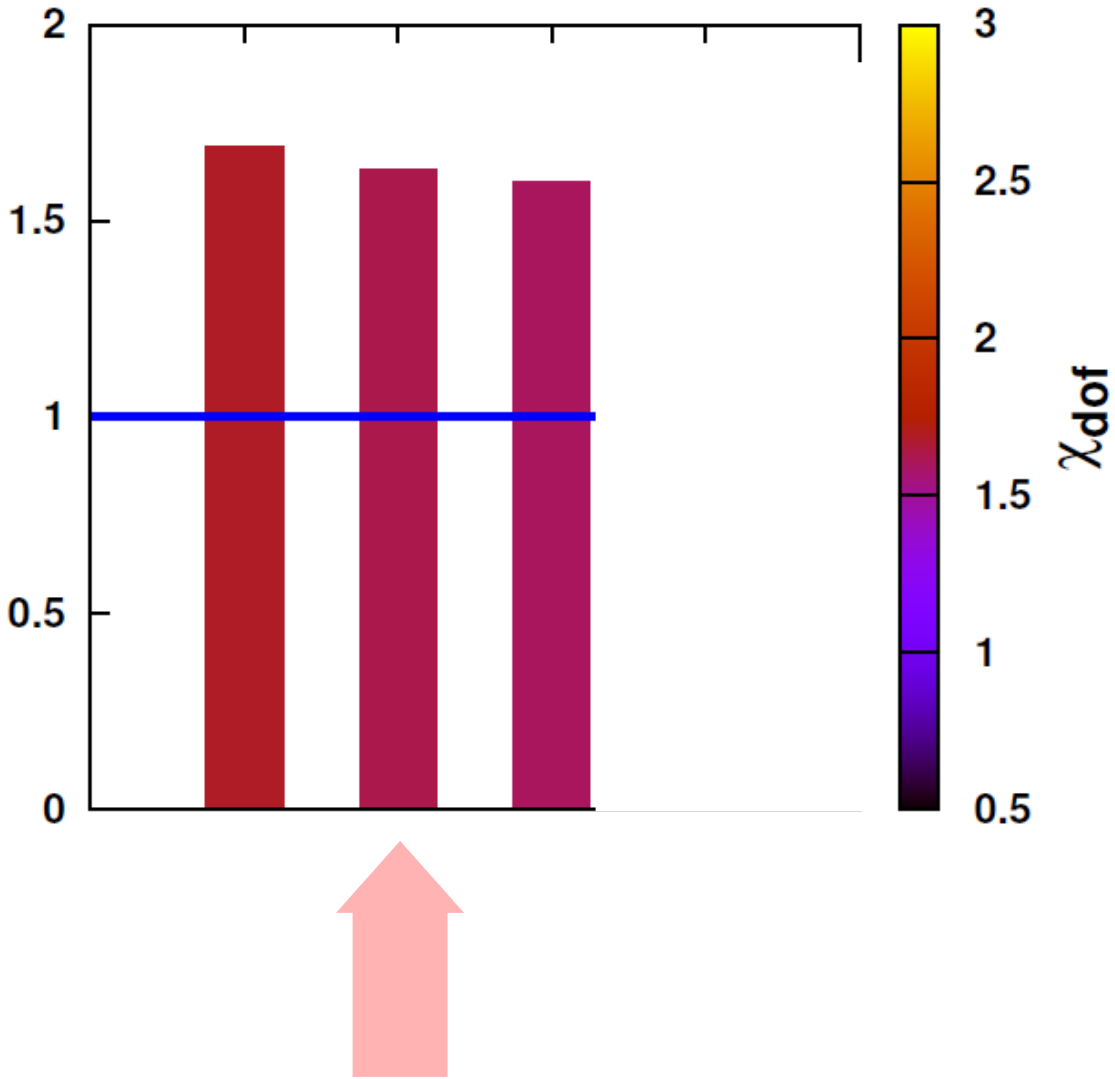


Extraction from HERMES data.

Gaussian Model

(z-dependent TMDFF)

4 parameters.

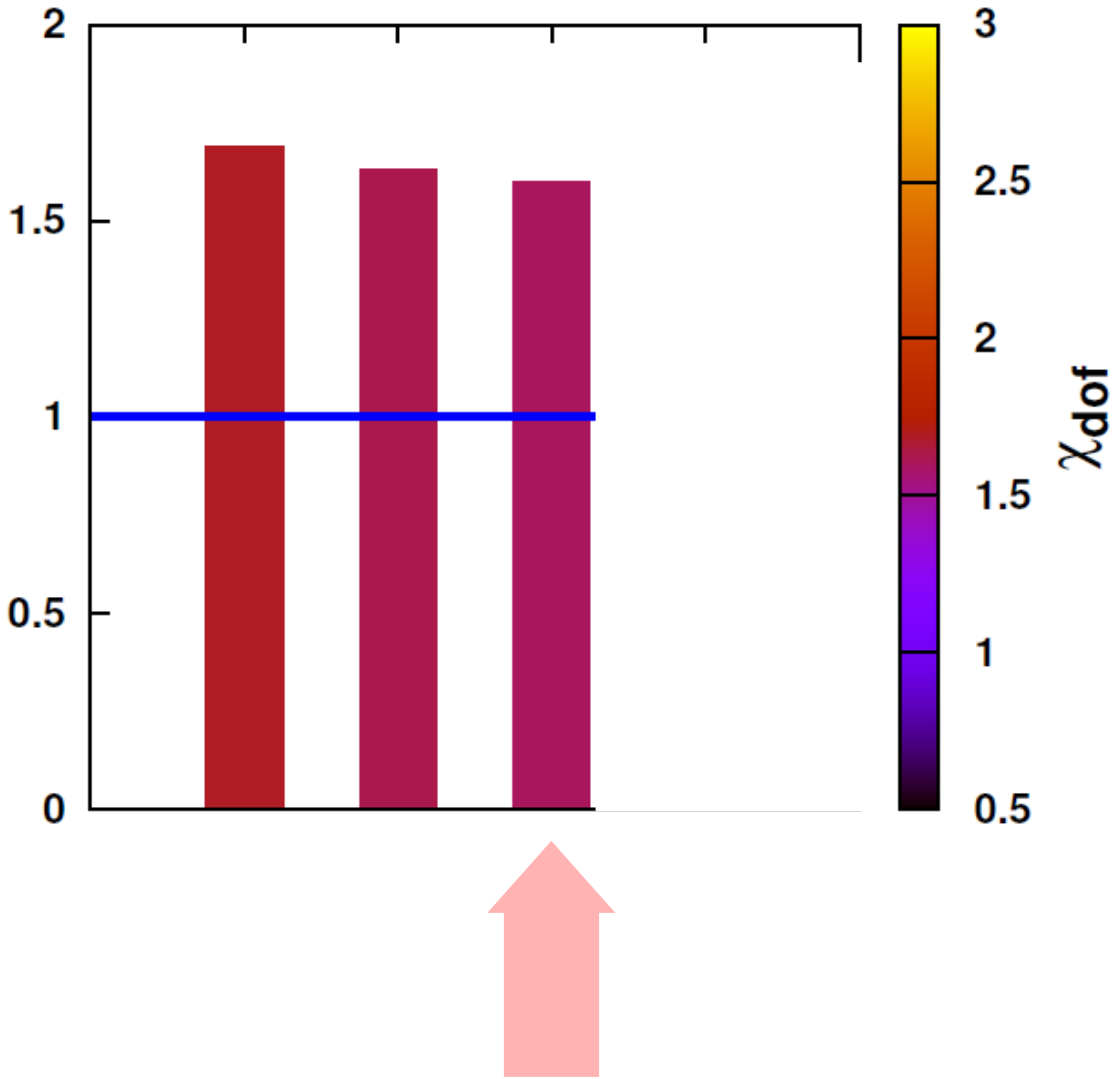


Extraction from HERMES data.

Gaussian Model

(Flavor-dependent TMDFF)

3 parameters.

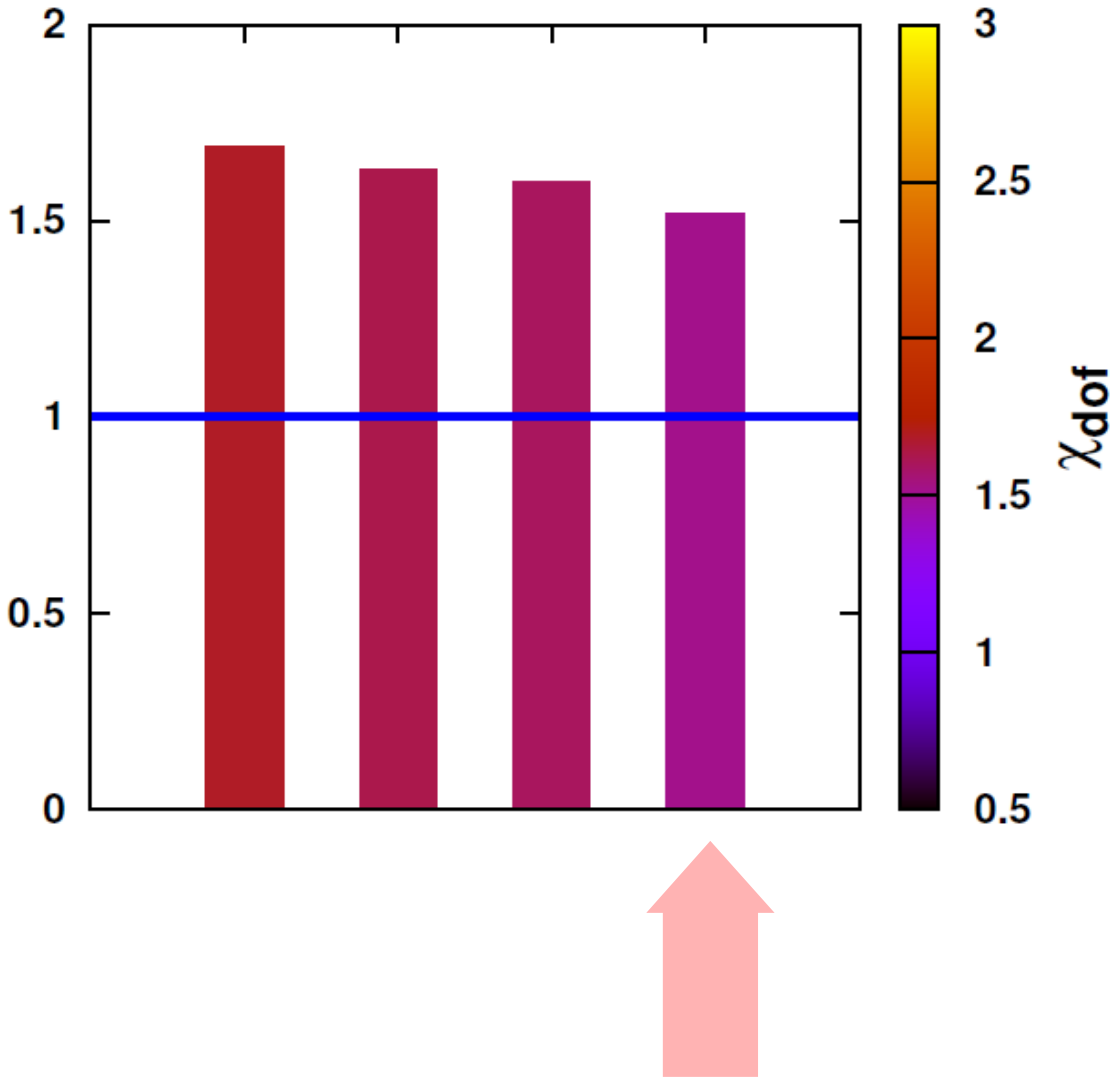


Extraction from HERMES data.

Other Simple Model

(Academic Example)

2 parameters.



Extraction from COMPASS data.

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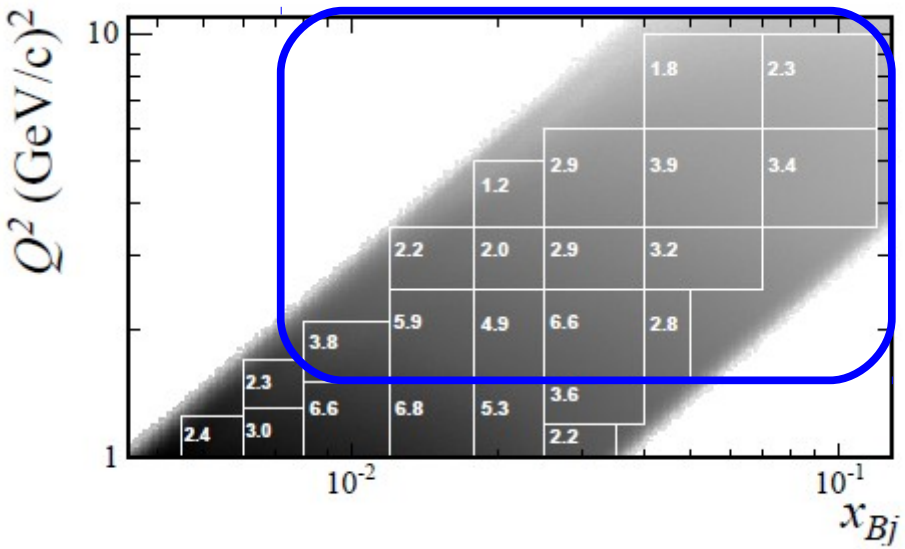
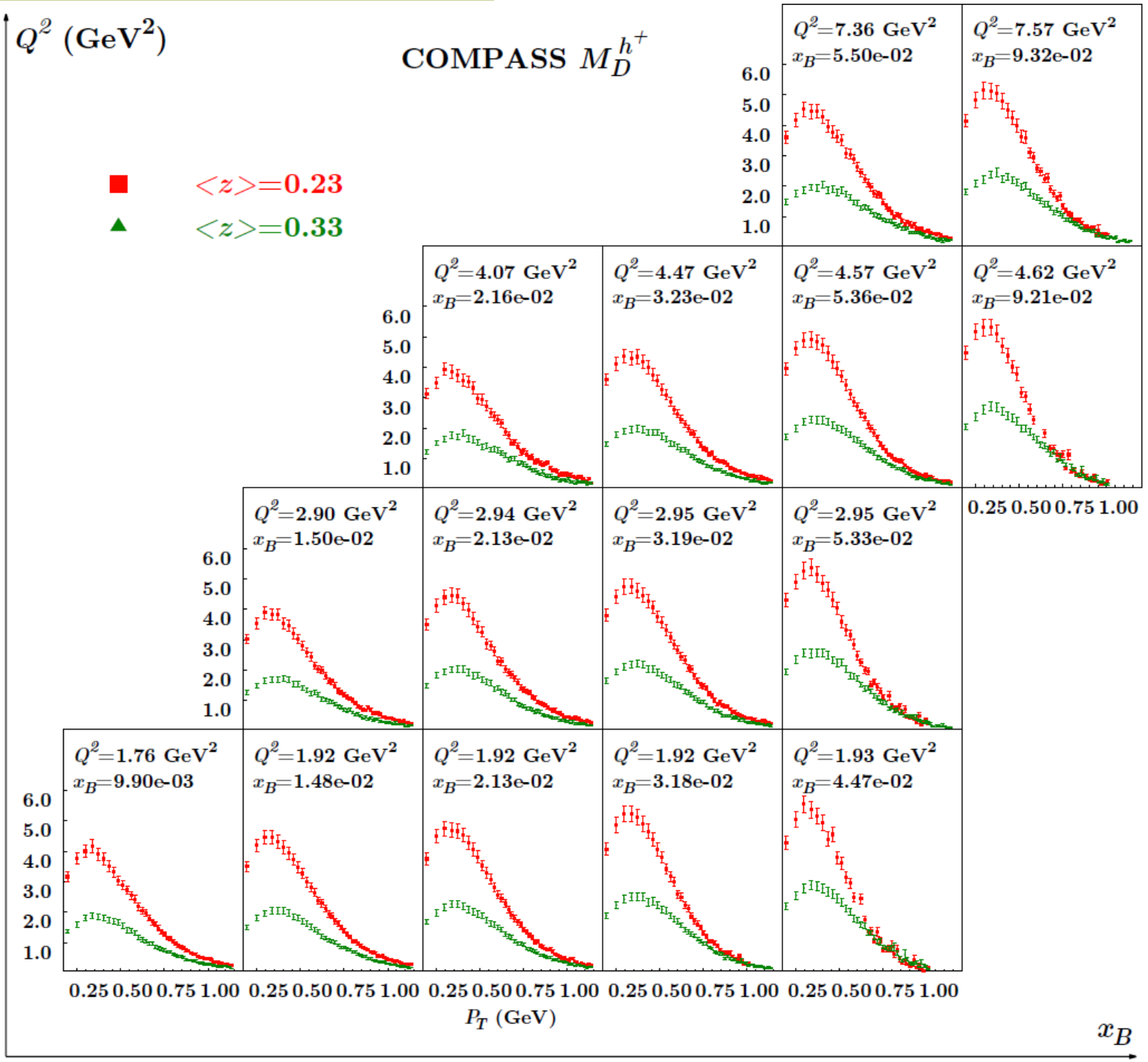


Figure from: Adolph, C. et al. Eur.Phys.J. C73 (2013) 2531

COMPASS data

- From Deuteron only
- No hadron separation
- 4D-binning: $\mathbf{Q^2}$, $\mathbf{x_B}$, z , P_T
- Total number of points: **18624**

Extraction from COMPASS data.



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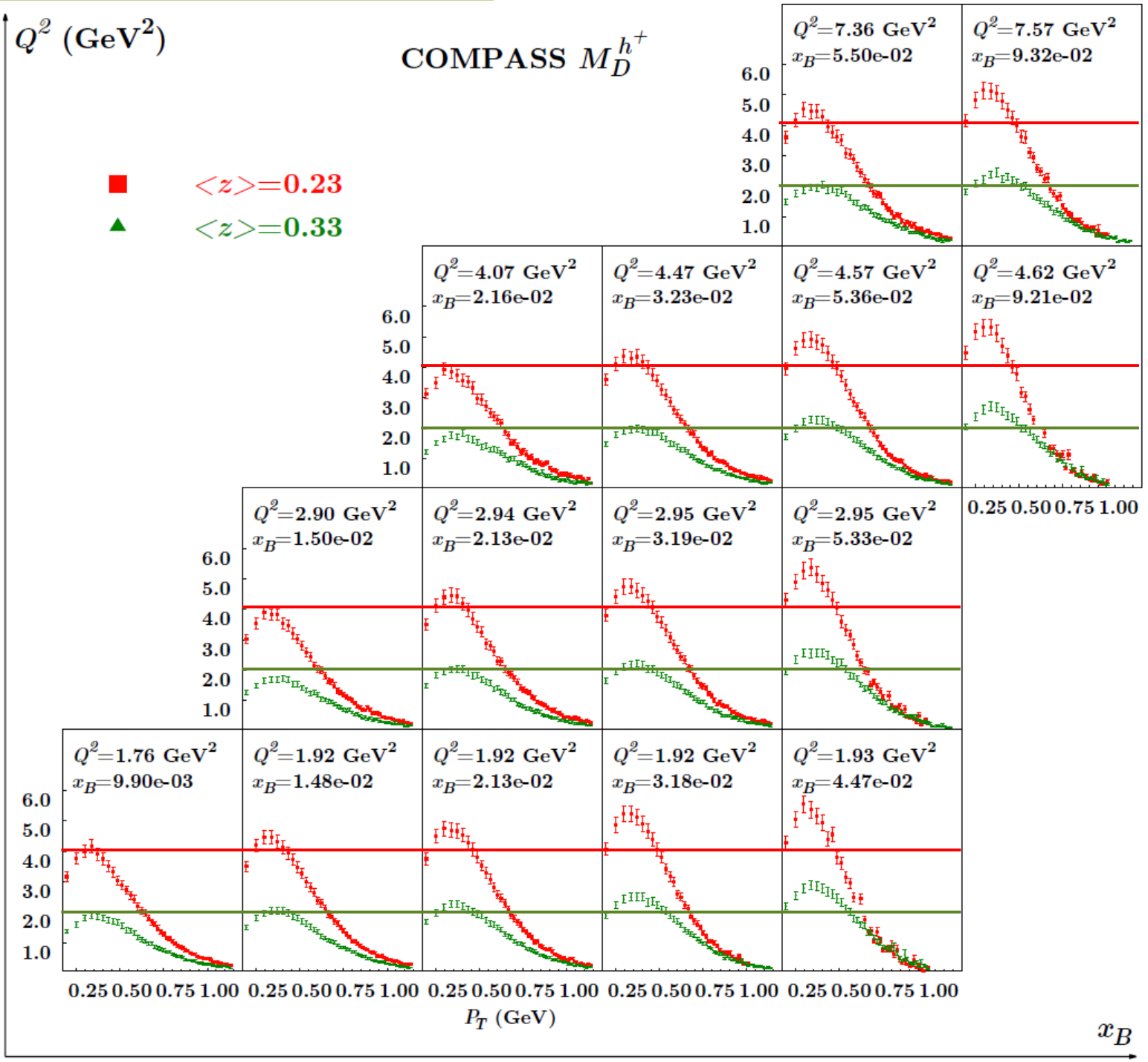

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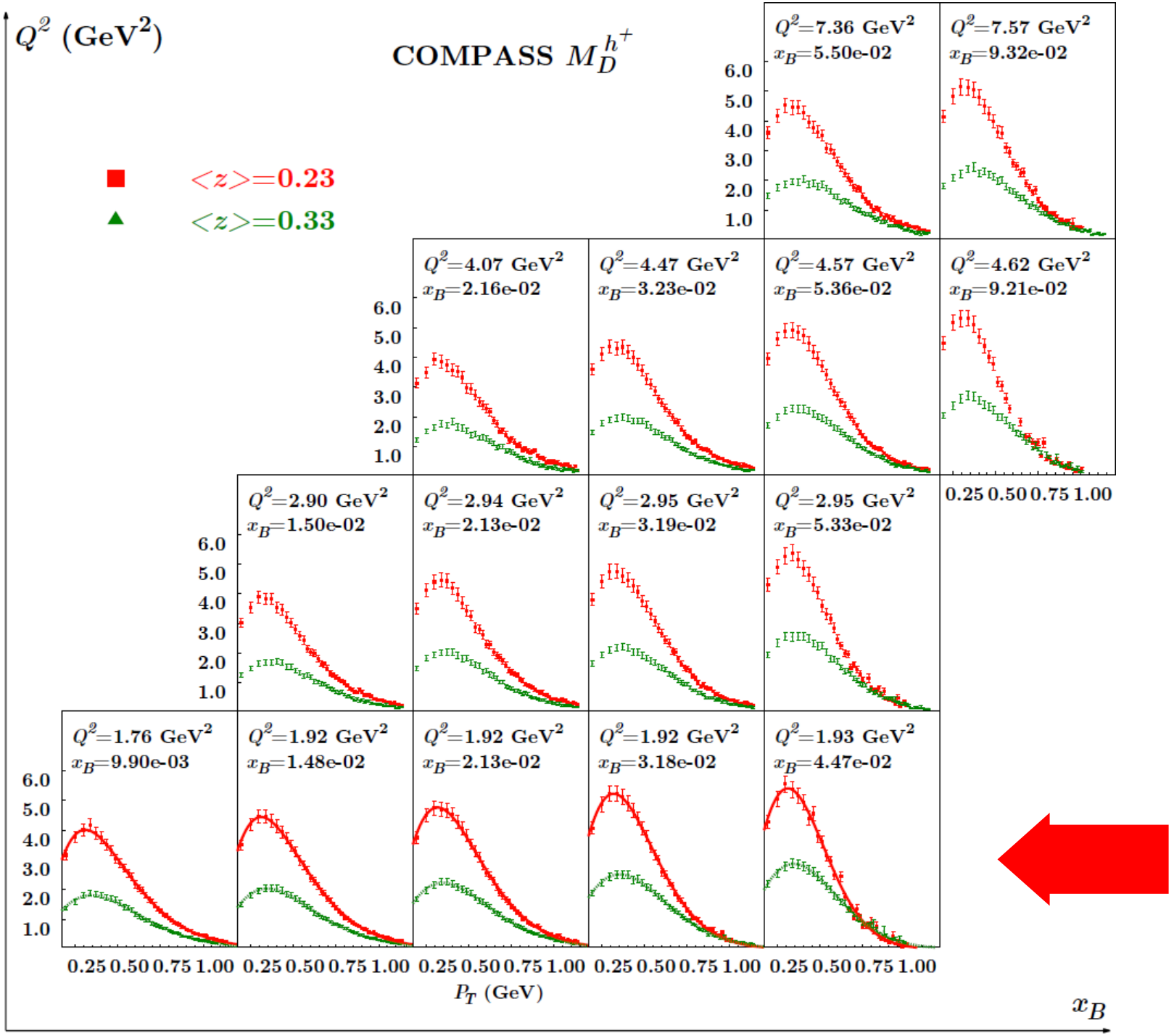

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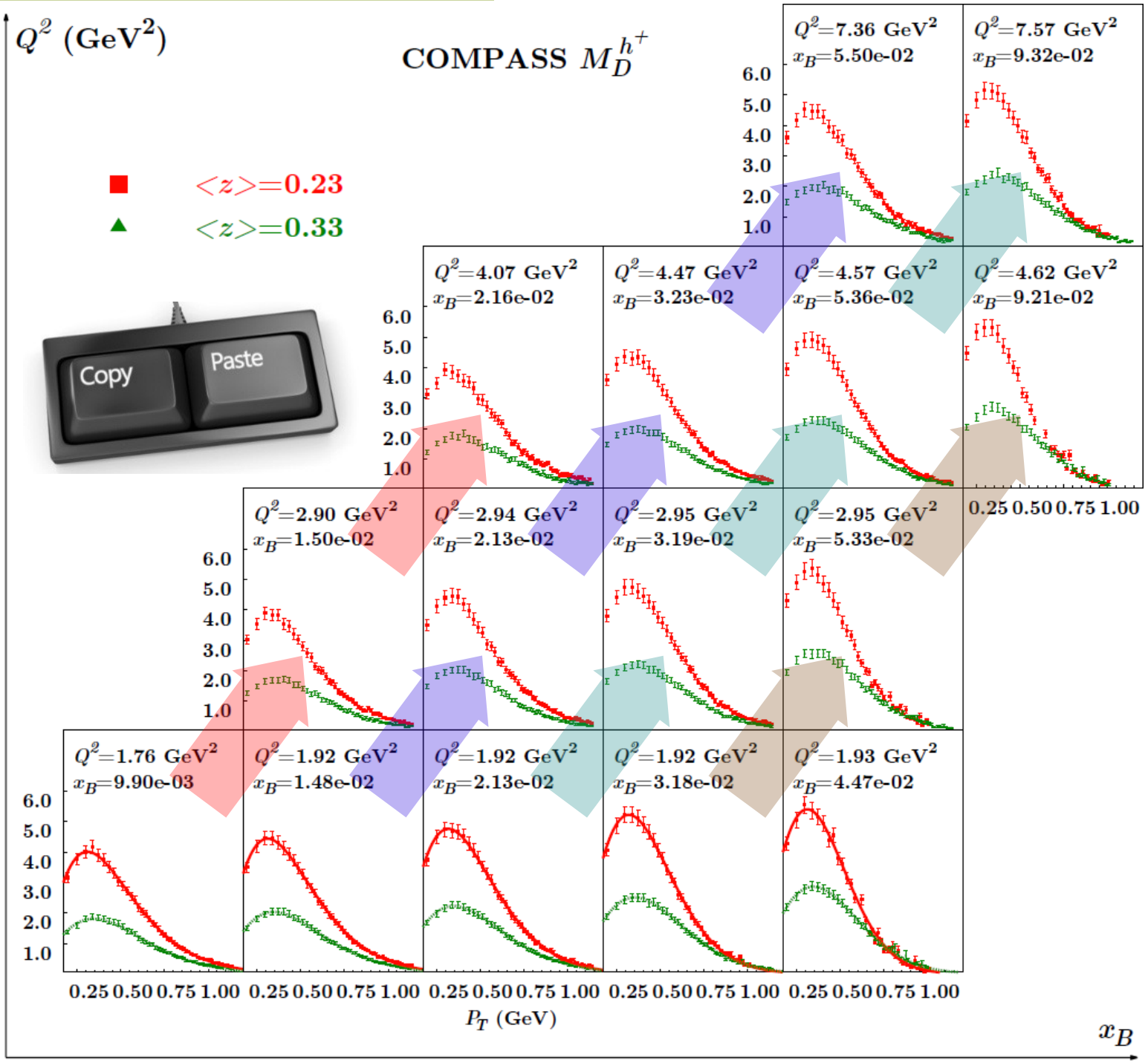

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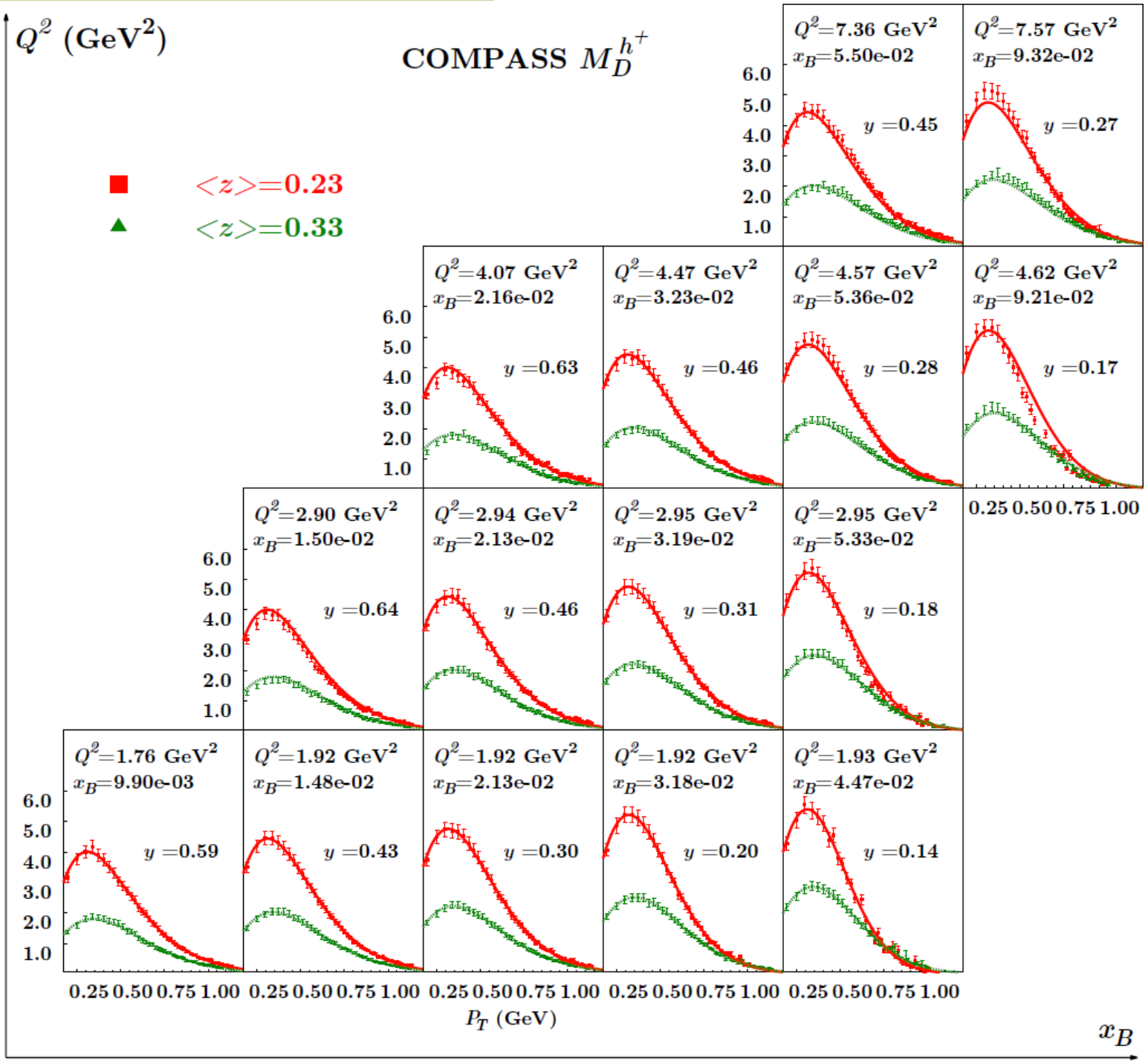

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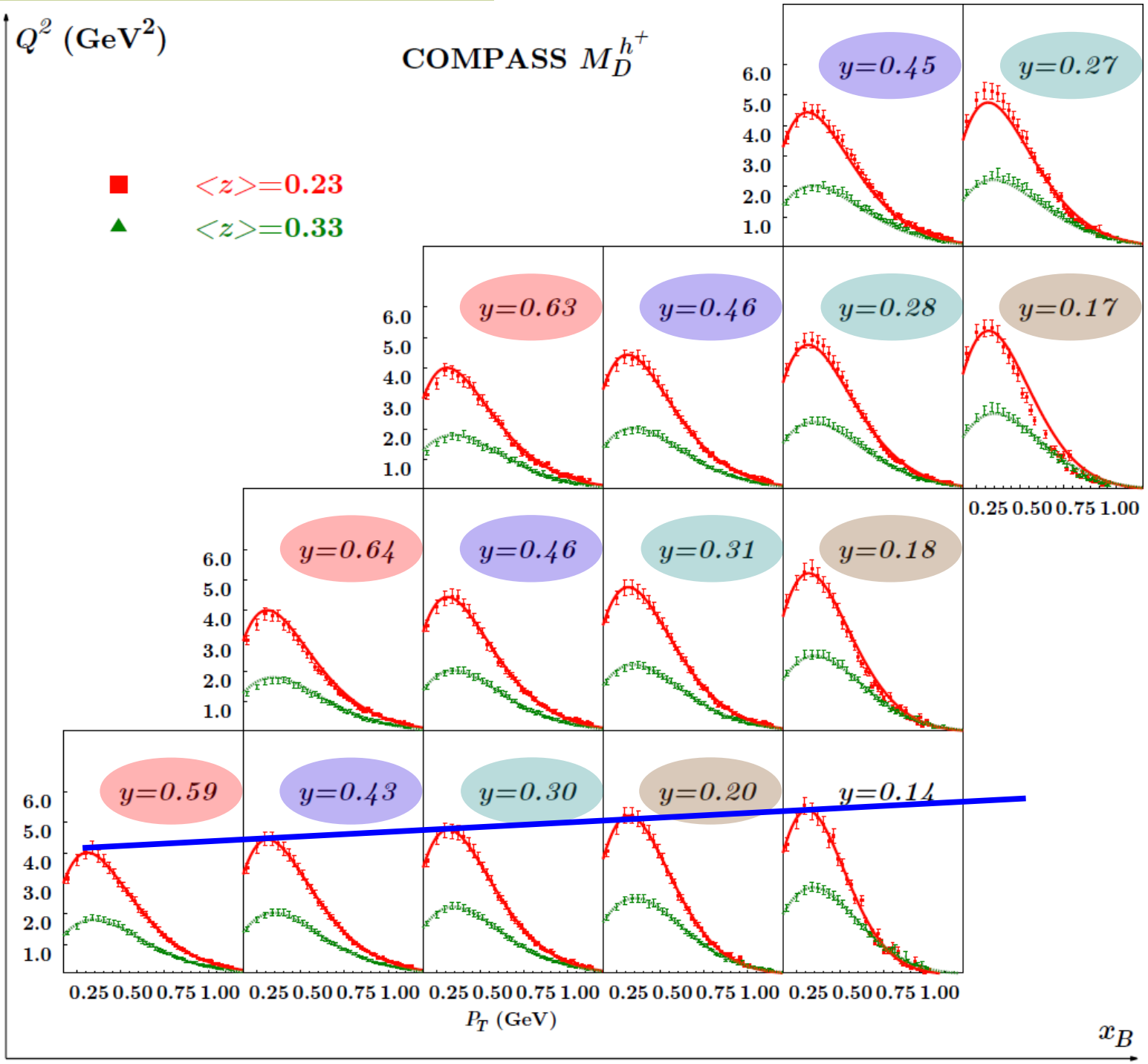

Extraction from COMPASS data.

COMPASS					
Cuts	$\chi^2_{\rm dof}$	n. points	$[\chi^2_{\rm dof}]^{h^+}$	$[\chi^2_{\rm dof}]^{h^-}$	Parameters
$Q^2 > 1.69$ GeV^2 $0.2 < P_T < 0.9$ GeV $z < 0.6$	8.54	5385	8.94	8.15	$\langle k_\perp^2 \rangle = 0.61 \pm 0.20$ GeV^2 $\langle p_\perp^2 \rangle = 0.19 \pm 0.02$ GeV^2

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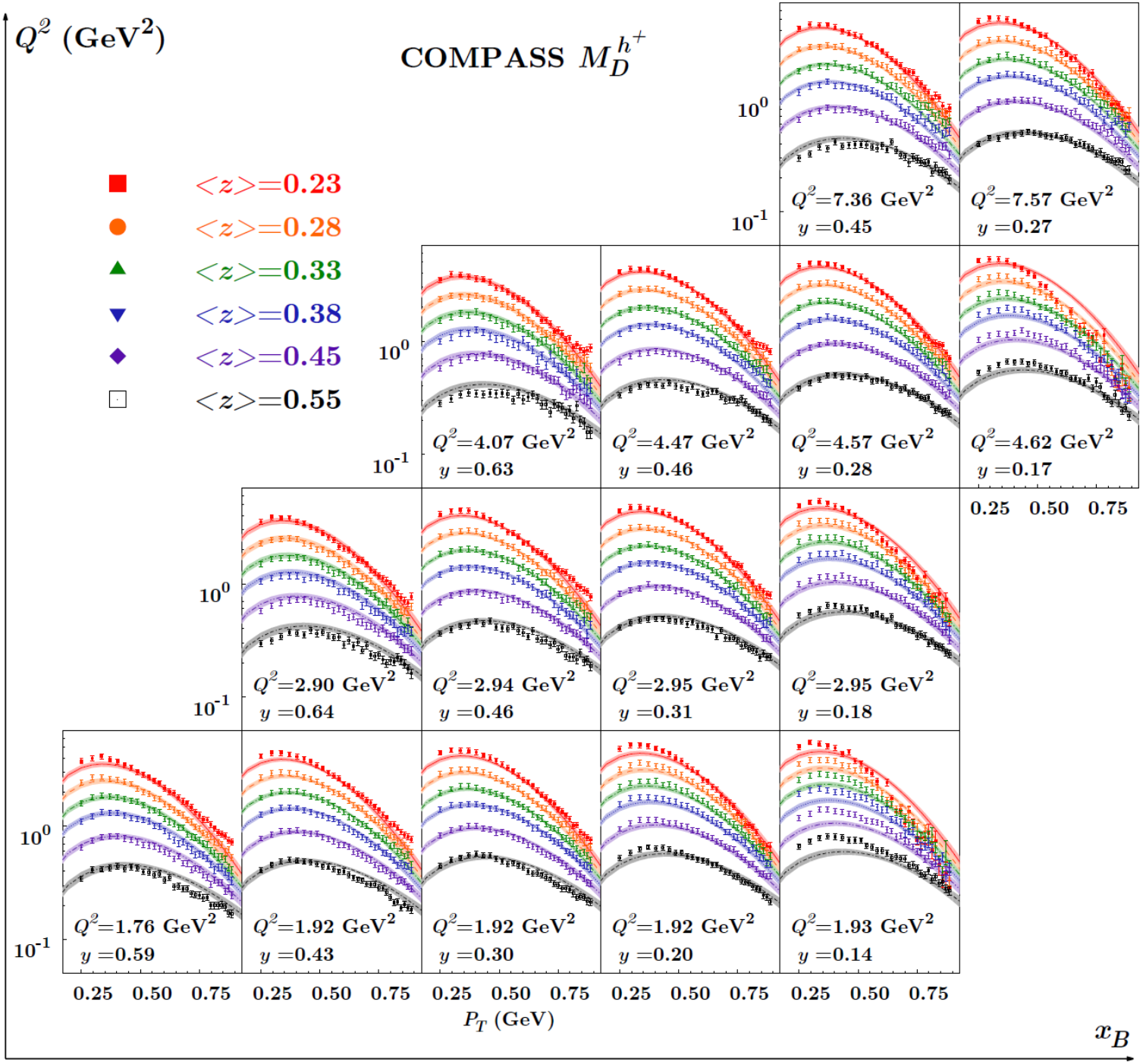
$Q^2 > 1.69$ GeV^2 $0.2 < P_T < 0.9$ GeV $z < 0.6$ $N_y = A + B\,y$	3.42	5385	3.25	3.60	$\langle k_\perp^2 \rangle = 0.60 \pm 0.14$ GeV^2 $\langle p_\perp^2 \rangle = 0.20 \pm 0.02$ GeV^2 $A = 1.06 \pm 0.06$ $B = -0.43 \pm 0.14$

Extraction from COMPASS data.



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$$\sigma \propto \frac{1}{\pi \langle P_T^2 \rangle} e^{-P_T^2/\langle P_T^2 \rangle}$$

Constrained Normalization, similarly to the TMDs

Extraction from COMPASS data.

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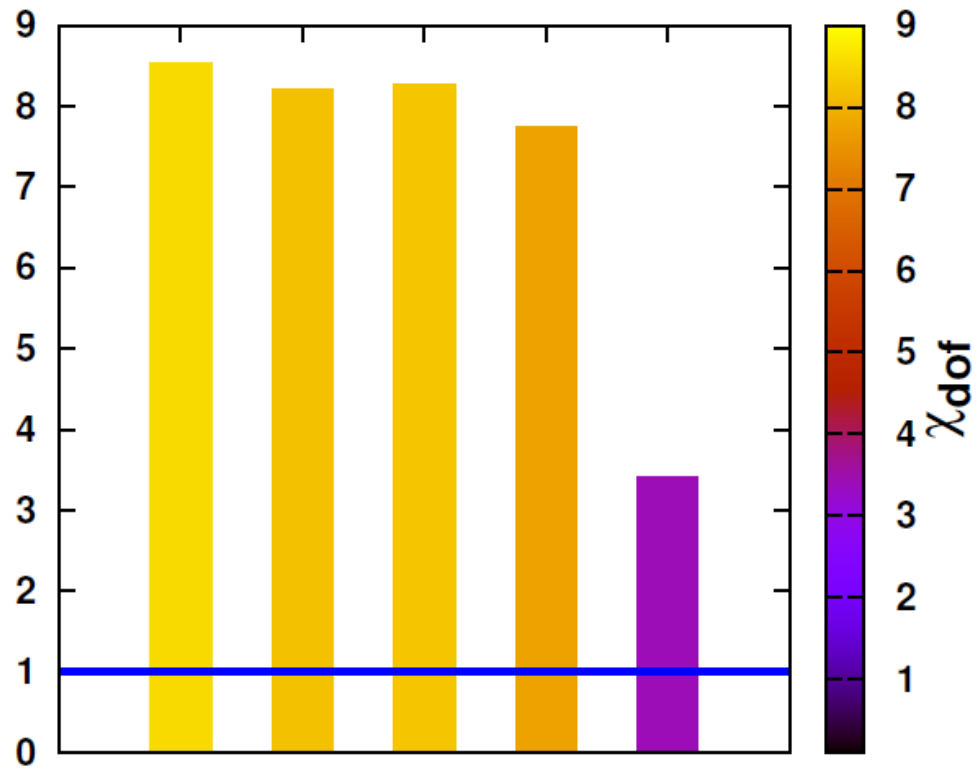
Other Models for Gaussian width?

Extraction from COMPASS data.

$$\langle k_\perp^2 \rangle = g_1$$

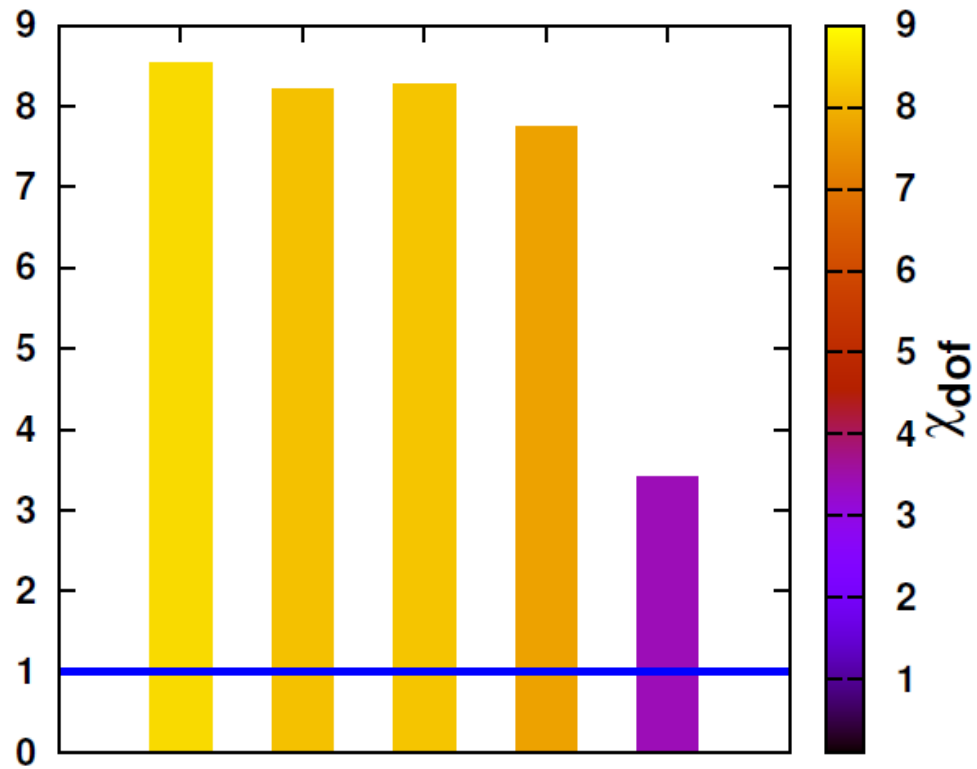
$$\langle p_\perp^2 \rangle = g_1'$$



Extraction from COMPASS data.

$$\langle k_\perp^2 \rangle = g_1 + g_2 \ln\left(Q^2/Q_0^2\right) + g_3 \ln\left(10ex\right)$$

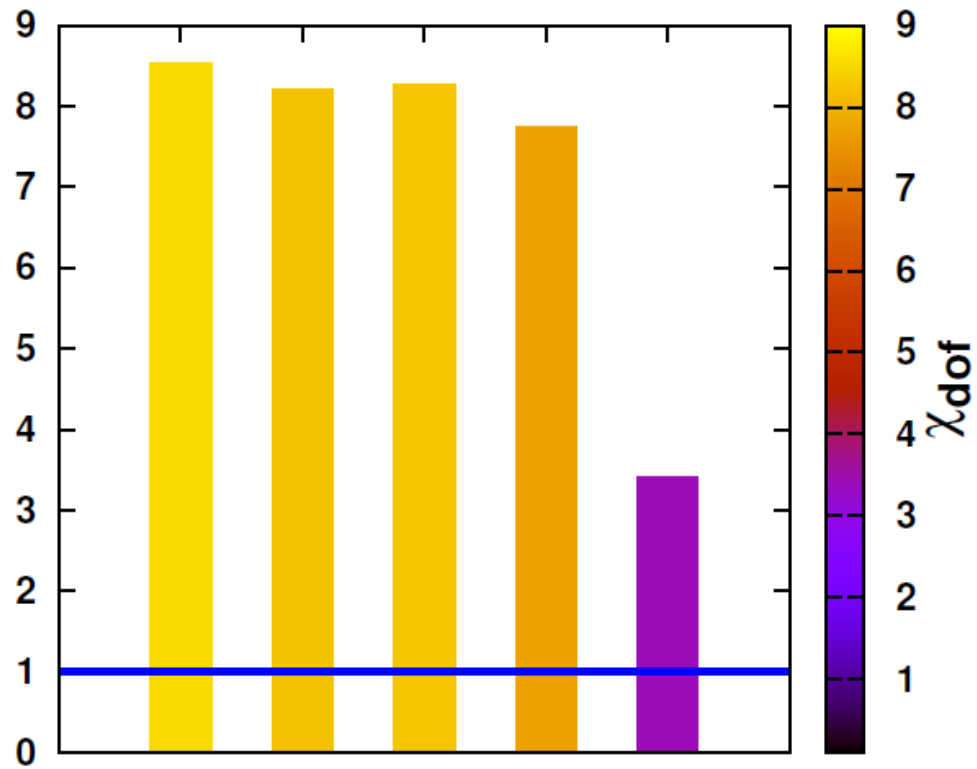
$$\langle p_\perp^2 \rangle = g_1' + z^2 g_2' \ln\left(Q^2/Q_0^2\right)$$



Extraction from COMPASS data.

$$\langle k_\perp^2 \rangle = a_1 + a_2 \ln(10y)$$

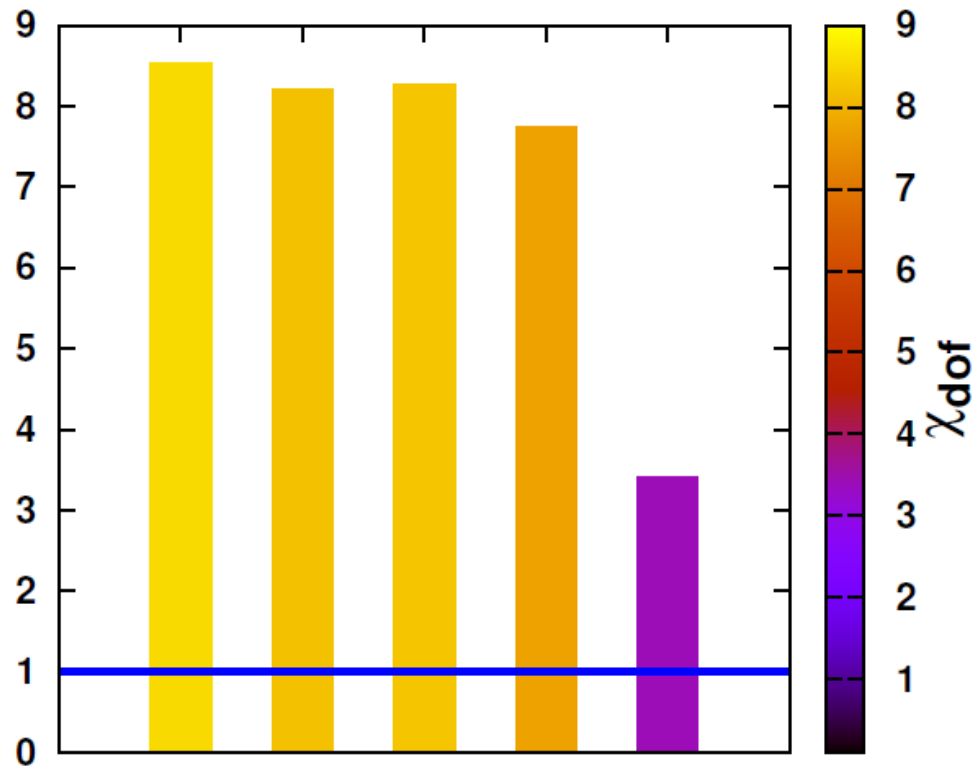
$$\langle p_\perp^2 \rangle = a_1' + a_2' \ln(10y)$$



Extraction from COMPASS data.

$$\langle k_\perp^2 \rangle = a_1 + a_2 \ln(10y)$$

$$\langle p_\perp^2 \rangle = a_1' + a_2' \ln(10y) + a_3' \sqrt{y}$$

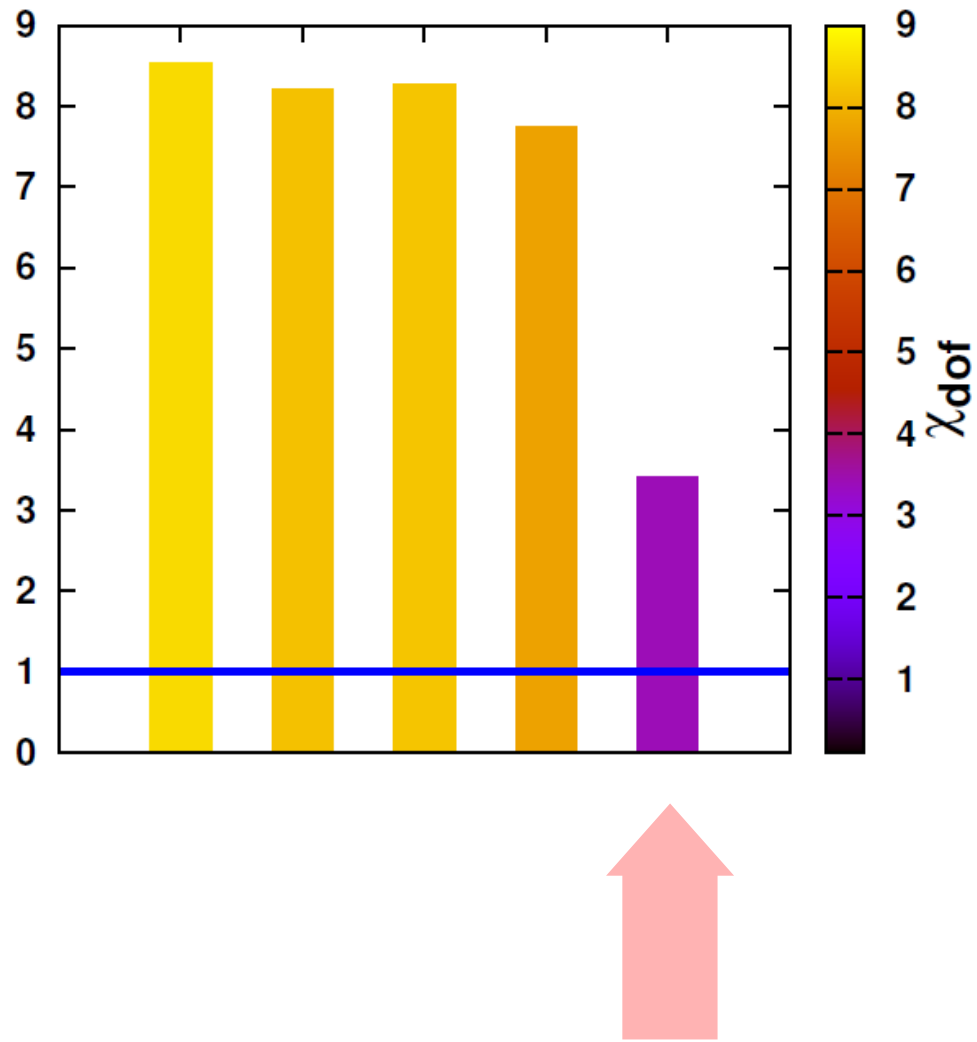


Extraction from COMPASS data.

$$\langle k_\perp^2 \rangle = g_1$$

$$\langle p_\perp^2 \rangle = g_1'$$

$$N = A + By$$



Towards a global fit: Azimuthal Moments.

Azimuthal Moments.

The Goal
In Progress

$$A^{\cos\phi} = 2\langle\cos\phi_h\rangle = 2\frac{\int d\phi_h\, d\sigma \cos\phi_h}{\int d\phi_h\, d\sigma}$$

$$F_{UU}^{\cos\phi_h}|_{Cahn} = -2\sum_q \int d^2\boldsymbol{k}_\perp \frac{(\boldsymbol{k}_\perp\cdot\boldsymbol{h})}{Q} f_q(x,k_\perp) D_q(z,p_\perp)$$

$$F_{UU}^{\cos\phi_h}|_{BM} = \sum_q \int d^2\boldsymbol{k}_\perp \frac{k_\perp}{Q}\frac{\Delta^N f_{q^\uparrow/p}(x,k_\perp)\Delta^N D_{h/q^\uparrow}(z,p_\perp)}{p_\perp}[P_T - z_h(\boldsymbol{k}_\perp\cdot\boldsymbol{h})]$$

$$A^{\cos 2\phi} = 2\langle\cos 2\phi_h\rangle = 2\frac{\int d\phi_h\, d\sigma \cos 2\phi_h}{\int d\phi_h\, d\sigma}$$

$$F_{UU}^{\cos 2\phi_h}|_{Cahn} = 2\sum_q \int d^2\boldsymbol{k}_\perp \frac{2(\boldsymbol{k}_\perp\cdot\boldsymbol{h})^2 - k_\perp^2}{Q^2} f_q(x,k_\perp) D_q(z,p_\perp)$$

$$F_{UU}^{\cos 2\phi_h}|_{BM} = \sum_q \int d^2\boldsymbol{k}_\perp \frac{-\Delta^N f_{q^\uparrow/p}(x,k_\perp)\Delta^N D_{h/q^\uparrow}(z,p_\perp)}{2k_\perp p_\perp}\left\{P_T(\boldsymbol{k}_\perp\cdot\boldsymbol{h}) + z_h\left[k_\perp^2 - 2(\boldsymbol{k}_\perp\cdot\boldsymbol{h})^2\right]\right\} \quad ($$

Azimuthal Moments.

Connection with Multiplicities

$$A^{\cos\phi} = 2\langle\cos\phi_h\rangle = 2\frac{\int d\phi_h\, d\sigma \cos\phi_h}{\int d\phi_h\, d\sigma}$$

$$F_{UU}^{\cos\phi_h}|_{Cahn} = -2\sum_q \int d^2\boldsymbol{k}_\perp \frac{(\boldsymbol{k}_\perp\cdot\boldsymbol{h})}{Q} f_q(x,k_\perp) D_q(z,p_\perp)$$

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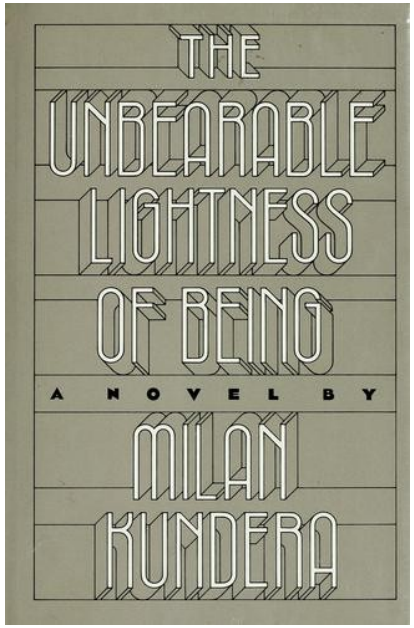
$$F_{UU}^{\cos 2\phi_h}|_{BM} = \sum_q \int d^2\boldsymbol{k}_\perp \frac{-\Delta^N f_{q^\uparrow/p}(x,k_\perp)\Delta^N D_{h/q^\uparrow}(z,p_\perp)}{2k_\perp p_\perp}\left\{P_T(\boldsymbol{k}_\perp\cdot\boldsymbol{h}) + z_h\left[k_\perp^2 - 2(\boldsymbol{k}_\perp\cdot\boldsymbol{h})^2\right]\right\} \quad ($$

Azimuthal Moments.



Must be careful when interpreting Parameters!!!

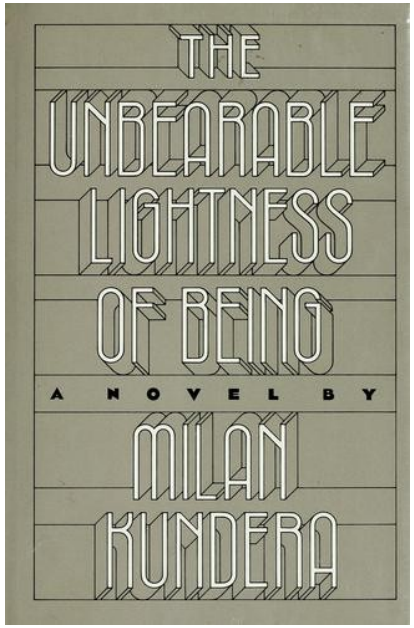
Again, consider the Gaussian Model

Multiplicities → $\langle P_T^2 \rangle = \langle p_\perp^2 \rangle + z_h^2 \langle k_\perp^2 \rangle.$

Azimuthal Asymmetries → $\langle P_T^2 \rangle \quad \langle k_\perp^2 \rangle.$

Azimuthal Moments.

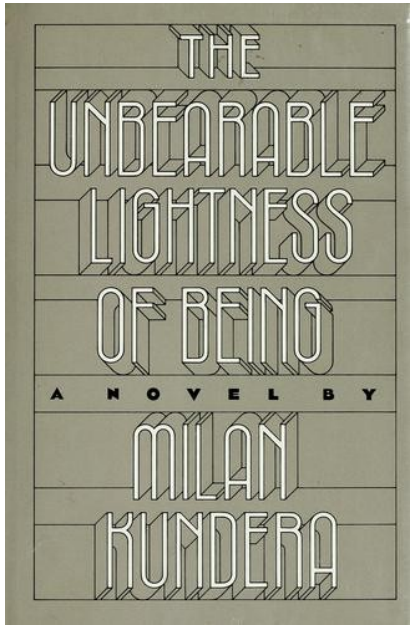
$\langle p_\perp^2 \rangle \rightarrow A$



Multiplicities → $\langle P_T^2 \rangle = \langle p_\perp^2 \rangle + z_h^2 \langle k_\perp^2 \rangle.$

Azimuthal Asymmetries → $\langle P_T^2 \rangle \quad \langle k_\perp^2 \rangle.$

Azimuthal Moments.



$$\langle p_\perp^2 \rangle \rightarrow A + B\, z^2$$

Multiplicities → $\langle P_T^2 \rangle = \langle p_\perp^2 \rangle + z_h^2 \langle k_\perp^2 \rangle.$

Azimuthal Asymmetries → $\langle P_T^2 \rangle \quad \langle k_\perp^2 \rangle.$

Work in progress...

Azimuthal Moments.

Analysis to be completed soon

Final Remarks

- Neither HERMES nor COMPASS data suggest a strong correlation between transverse momenta and x or z (within our kinematical cuts).
- HERMES and COMPASS data do not seem to be compatible.
- HERMES Multiplicities do not show sign of Q2-dependence. Simple Gaussian reasonably describes Multiplicities.
- COMPASS Multiplicities (seemingly) exhibit a y-dependence in the normalization. This deserves further study. Simple Gaussian model does good job in describing the “width” of the data.
- Interpretation of the parameters should be done always very carefully. Must always keep in mind the fundamental limitations of each observable. Multiple observables helpful to disentangle different “components” (i.e. intrinsic momentum).
- In the near future results on azimuthal asymmetries analysis.

Thank you.

Thank you.

Thank you.

TABLE I. Minimal χ^2 values for the COMPASS multiplicities and different versions of the Gaussian model. The numbers in the right column are obtained by introducing an overall y-dependent normalization in the multiplicities.

COMPASS		
	$\chi^2_{d.o.f}$	
	$N = 1.0$	$N = A + By$
$\langle k_\perp^2 \rangle = g_1$ $\langle p_\perp^2 \rangle = g_1'$	8.54	3.42 $A = 1.06 \quad B = -0.43$
$\langle k_\perp^2 \rangle = g_1 + g_2 \ln(Q^2/Q_0^2) + g_3 \ln(10ex)$ $\langle p_\perp^2 \rangle = g_1' + z^2 g_2' \ln(Q^2/Q_0^2)$	8.21	2.74 $A = 1.10 \quad B = -0.53$
$\langle k_\perp^2 \rangle = a_1 + a_2 \ln(10y)$ $\langle p_\perp^2 \rangle = a_1' + a_2' \ln(10y)$	8.27	2.00 $A = 1.13 \quad B = -0.62$
$\langle k_\perp^2 \rangle = a_1 + a_2 \ln(10y)$ $\langle p_\perp^2 \rangle = a_1' + a_2' \ln(10y) + a_3' \sqrt{y}$	7.75	1.81 $A = 1.12 \quad B = -0.59$

Comparing extractions

Extraction from EMC data (2005)

$$\langle k_\perp^2 \rangle = 0.25 \text{ GeV}^2 \qquad \langle p_\perp^2 \rangle = 0.20 \text{ GeV}^2$$

Extraction from HERMES data (2013)

$$\langle k_\perp^2 \rangle = 0.57 \pm 0.08 \text{ GeV}^2 , \qquad \langle p_\perp^2 \rangle = 0.124 \pm 0.008 \text{ GeV}^2$$

Extraction from COMPASS data (2013)

$$\langle k_\perp^2 \rangle = 0.61 \pm 0.20 \text{ GeV}^2 \qquad \langle p_\perp^2 \rangle = 0.19 \pm 0.02 \text{ GeV}^2$$

Going back to HERMES data...

z dependence?

Other kinematical dependences.

π only, simplest model

$\langle k_\perp^2 \rangle = 0.57 \pm 0.08$ GeV^2

$\langle p_\perp^2 \rangle = 0.12 \pm 0.01$ GeV^2

$\chi^2_{pt} = 1.69$

π only, z dependence

$\langle p_\perp^2 \rangle \rightarrow A\,(1-z)^B\, z^C$

$\langle k_\perp^2 \rangle = 0.48 \pm 0.54$ GeV^2

$A = 0.21 \pm 0.60$ GeV^2

$B = 0.34 \pm 6.42$

$C = 0.27 \pm 0.73$

$\chi^2_{pt} = 1.63$

Flavor Dependence. HERMES.

#pts = 497 chi2pt = 1.60 chi2 = 794.89

#optimal parameters: YES

#TMDPDF version 0 : k2avg = a

#TMDFF version 0 : pt2avg = A

#name	free	val	err	lim	min	max
a	1	5.91e-01	3.79e-02	1	0.00e+00	1.00e+00
b	0	0.00e+00	0.00e+00	0	0.00e+00	1.00e+00
c	1	1.16e-01	4.92e-03	1	0.00e+00	1.00e+00
A	1	1.36e-01	6.35e-03	1	0.00e+00	1.00e+00

Flavor Dependence. COMPASS.

#pts = 5385 chi2pt = 3.42 chi2 = 18436.98

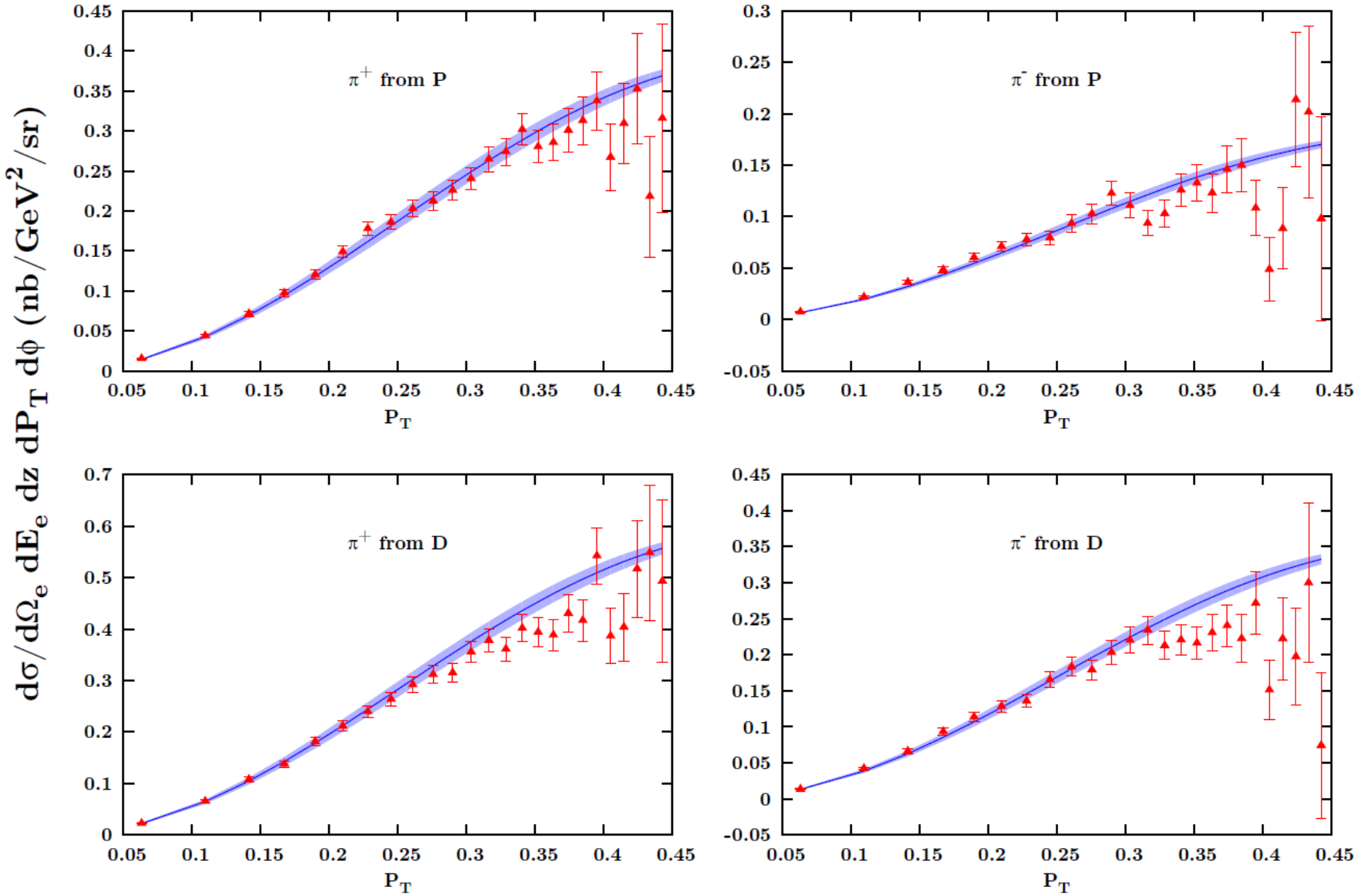
#optimal parameters: YES

#TMDPDF version 0 : k2avg = a

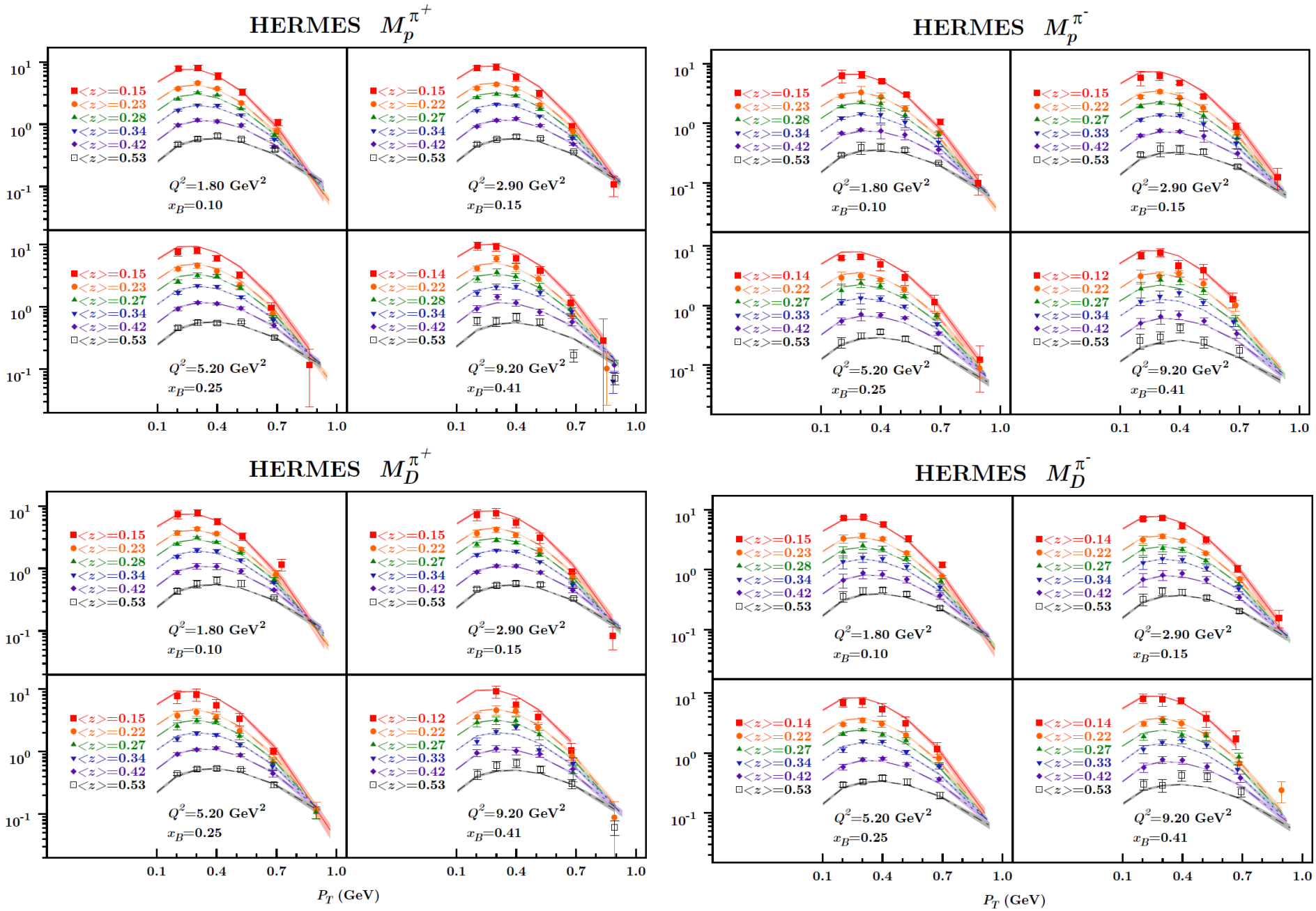
#TMDFF version 0 : pt2avg = A

#name	free	val	err	lim	min	max
a	1	6.04e-01	1.68e-02	1	0.00e+00	1.00e+00
b	0	0.00e+00	0.00e+00	0	0.00e+00	1.00e+02
c	1	1.98e-01	4.31e-03	1	0.00e+00	1.00e+00
A	1	2.02e-01	5.40e-03	1	0.00e+00	1.00e+00

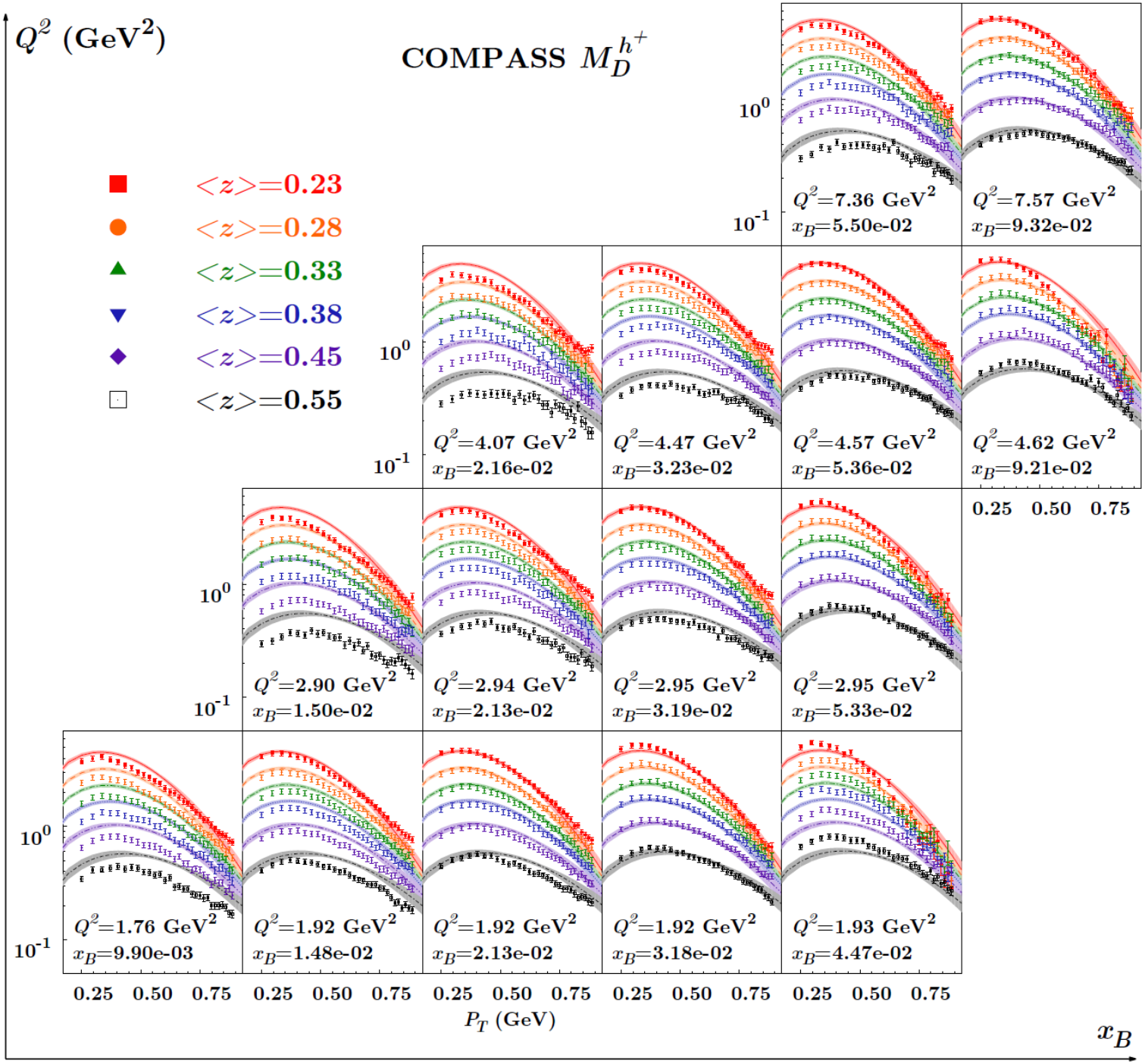
Jlab SIDIS data (2012).



Extraction from HERMES data.



Extraction from COMPASS data.



Extraction from COMPASS data.

$$N_y \sim 1 - y/2$$