Extraction of TMDs from hard scattering data

Andrea Signori

3D nucleon tomography workshop

March 16th 2017

Jefferson Lab

Outline of the talk

1) Transverse Momentum Dependent distributions (TMDs)

2) phenomenology : **latest extraction** of unpolarized TMDs

3) **what's next** - formalism and phenomenology

Disclaimer :
the focus is on the latest extraction

- we should keep in mind the full picture -
(room for discussion during this workshop!)

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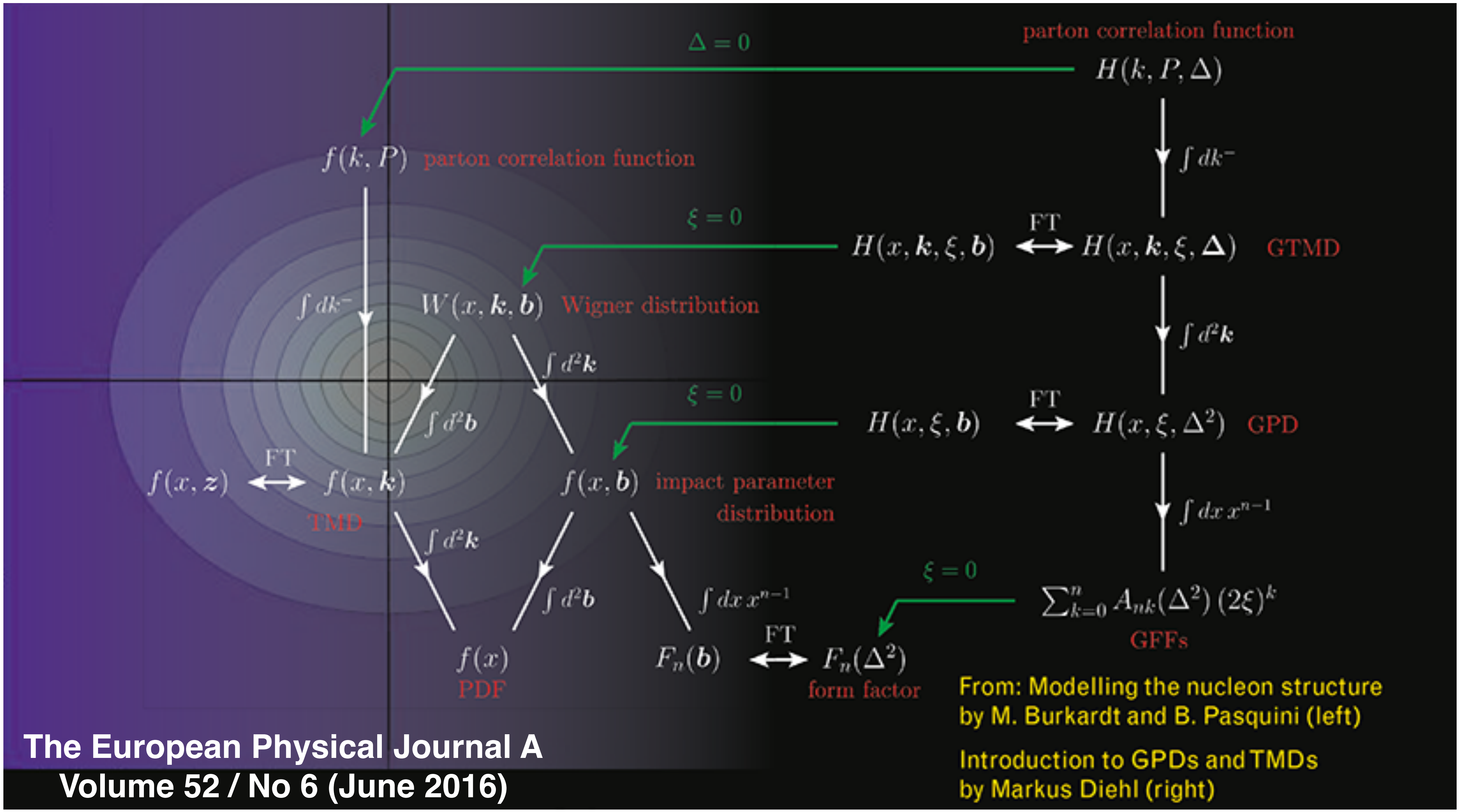
TMDs

Which hadron structure ?



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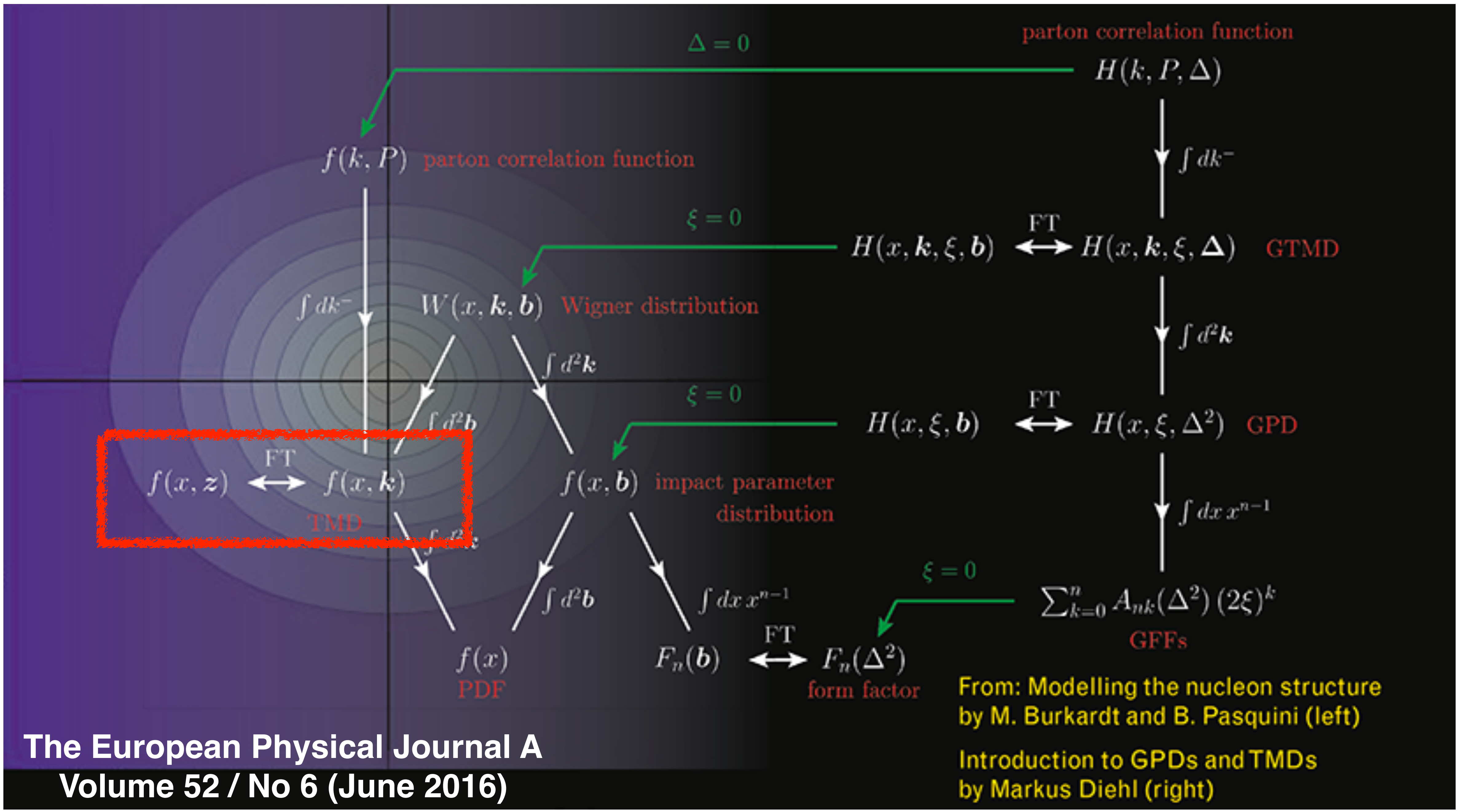
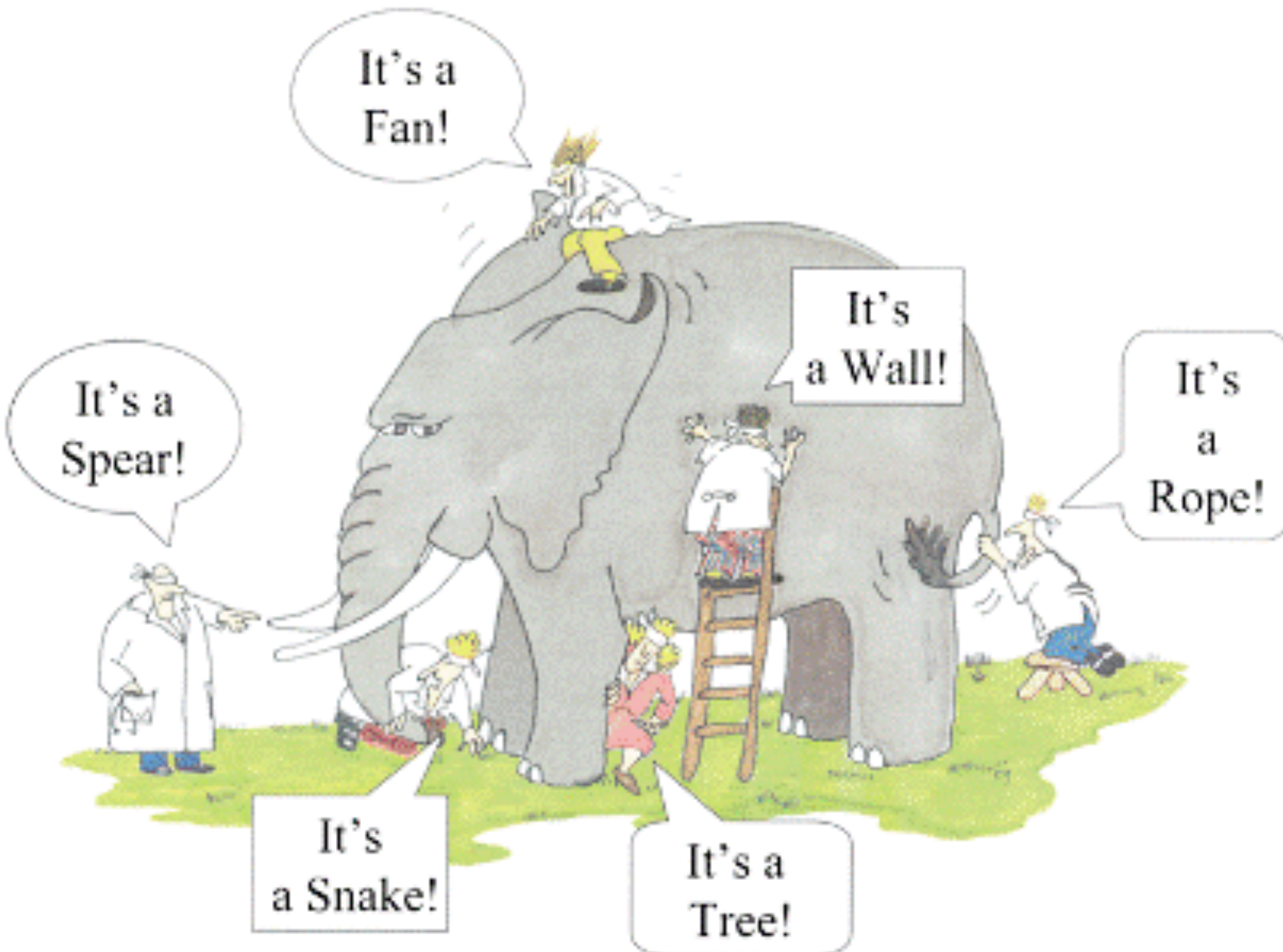
Which hadron structure ?



Which hadron structure ?



each projection carries only a portion of the complete picture

complementary information (TMDs, GPDs, etc.) is essential to have a global understanding

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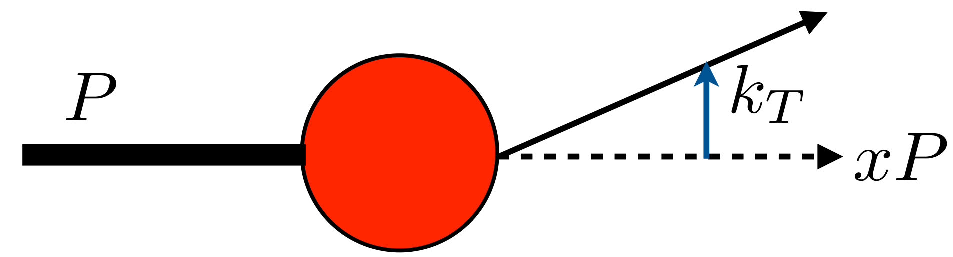
quark TMD PDFs

$$\Phi_{ij}(k, P; S\ \ ) \sim \text{F.T.}\ \langle PS\ \ |\ \bar{\psi}_j(0)\ U_{[0,\xi]}\ \psi_i(\xi)\ |PS\ \ \rangle_{|LF}$$

Quarks	γ^+	$\gamma^+\gamma^5$	$i\sigma^{i+}\gamma^5$
U	$\boldsymbol{f_1}$		$h_1^\perp$
L		$\boldsymbol{g_1}$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$\boldsymbol{h_1},\ h_{1T}^\perp$



extraction of a **quark**
not collinear with the proton

bold : also collinear
red : time-reversal odd (universality properties)

quark TMD PDFs

$$\Phi_{ij}(k,P;S,T) \sim \text{F.T.}\ \langle PST|\ \bar{\psi}_j(0)\ U_{[0,\xi]}\ \psi_i(\xi)\ |PST\rangle_{|LF}$$

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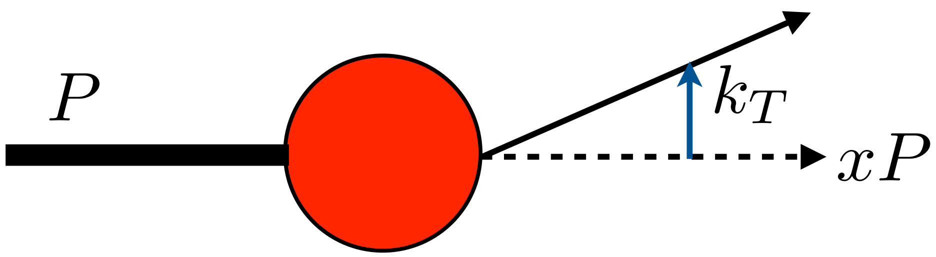
U	$\boldsymbol{f_1}$		$h_1^\perp$
L		$\boldsymbol{g_1}$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$\boldsymbol{h_1}$, $h_{1T}^\perp$
LL	$\boldsymbol{f_{1LL}}$		$h_{1LL}^\perp$
LT	f_{1LT}	g_{1LT}	h_{1LT}, $h_{1LT}^\perp$
TT	f_{1TT}	g_{1TT}	h_{1TT}, $h_{1TT}^\perp$



extraction of a **quark**
not collinear with the proton

a similar scheme holds for
TMD FFs and gluons

bold : also collinear
red : time-reversal odd (universality properties)

Extraction of unpolarized TMDs

In collaboration with:

- A. Bacchetta, F. Delcarro, C. Pisano, M. Radici
  Pavia University, IT

Why studying unpolarized TMDs ?

1) **Nucleon tomography**:
improve our knowledge of 1D and 3D hadron structure (focus on high-x from JLab)

2) this program is **fundamental** for **high-energy phenomenology** to predict q_T spectra and to improve our investigations of **BSM** physics.

Open questions :

1) what is the **functional form** of TMDs at low transverse momentum ?

2) what is its **kinematic** and **flavor** dependence ?

3) how can we separate the descriptions at **low** and **high** transverse momenta ?

4) how can we **match TMD** and **collinear** factorization ?

5) can we test the generalized **universality** of TMDs ?

6) can we perform a **global fit** of TMDs ?

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Where : hard scattering data

Where can we access TMDs **today**?

LHC ...

... and **tomorrow** ?

EIC ...

Where : hard scattering data

Where can we access TMDs **today**?

LHC ...

... and tomorrow ?

EIC ...

SIDIS at low Q: multi-dim. data (x, z, Q, P_{hT})

Fixed-target DY and Z production (Tevatron)

here: only unpolarized

crucial information in order to access the structure of the nonperturbative part

What do we know ?

(a selection of results)

	Framework	HERMES	COMPASS	DY	Z production	N of points
KN 2006 hep-ph/0506225	LO-NLL	✘	✘	✔	✔	98
Pavia 2013 (+Amsterdam, Bilbao) arXiv:1309.3507	No evo (QPM)	✔	✘	✘	✘	1538
Torino 2014 (+JLab) arXiv:1312.6261	No evo (QPM)	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
DEMS 2014 arXiv:1407.3311	NLO-NNLL	✘	✘	✔	✔	223
EIKV 2014 arXiv:1401.5078	LO-NLL	1 (x,Q^2) bin	1 (x,Q^2) bin	✔	✔	500 (?)

[courtesy A. Bacchetta]

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Pavia 2017 (+JLab)	LO-NLL	✔	✔	✔	✔	8059

[courtesy A. Bacchetta]

Features

	Framework	HERMES	COMPASS	DY	Z production	N of points
Pavia 2017 (+JLab)	LO-NLL	✔	✔	✔	✔	8059

PROs

almost a **global fit** of quark unpolarized TMDs

includes **TMD evolution**

replica methodology

kinematic dependence in intrinsic part of TMDs

intrinsic momentum: **beyond the Gaussian assumption**

CONs

no “pure” info on TMD FFs

accuracy of TMD evolution : not the state of the art

only “low” transverse momentum (no fixed order and Y-term)

flavor separation : problematic

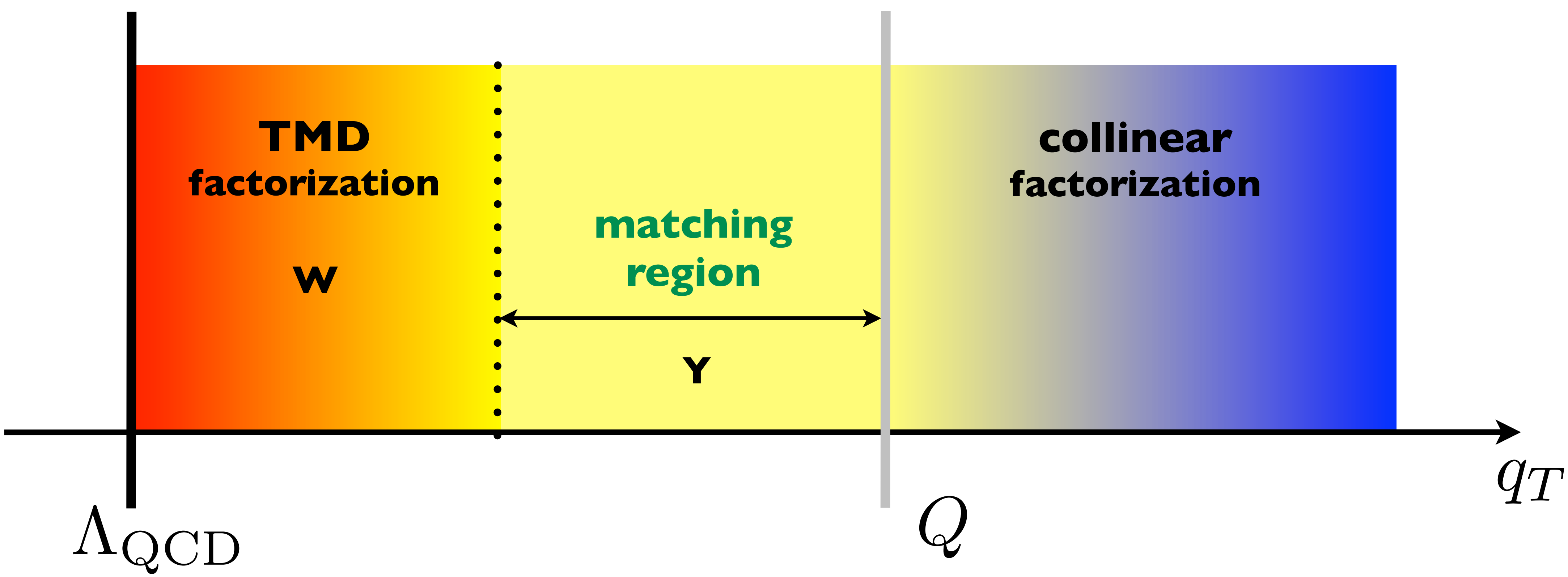
How : factorization

TMD factorization :

W-term : a hard part (H) and two TMDs (F) matching

$$d\sigma \sim \mathcal{H}\ F_{i/A}(x, k_T; \mu, \zeta_A) \otimes F_{j/B}(x, k_T; \mu, \zeta_B) + Y(q_T; Q) + \mathcal{O}(\Lambda/Q)$$

power corrections



What : perturbative & nonperturbative

choosing the scales:

$$\tilde{F}_i(x, b_T; Q, Q^2) = \tilde{F}_i(x, b_T, \mu_{\hat{b}}, \mu_{\hat{b}}^2) \times$$

$$\exp\left\{ \int_{\mu_{\hat{b}}}^{Q} \frac{d\mu}{\mu} \gamma_F[\alpha_s(\mu), Q^2/\mu^2] \right\} \left(\frac{Q^2}{\mu_{\hat{b}}^2} \right)^{-K(\hat{b}_T; \mu_{\hat{b}}) - g_K(b_T; \{\lambda\})}$$

Sudakov form factor : perturbative and **nonperturbative** contributions

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What : perturbative & nonperturbative

FT of TMDs :

$$\tilde{F}_i(x, b_T; Q, Q^2) = \tilde{F}_i(x, b_T, \mu_{\hat{b}}, \mu_{\hat{b}}^2) \times \exp\left\{ \int_{\mu_{\hat{b}}}^{Q} \frac{d\mu}{\mu} \gamma_F[\alpha_s(\mu), Q^2/\mu^2] \right\} \left(\frac{Q^2}{\mu_{\hat{b}}^2} \right)^{-K(\hat{b}_T;\mu_{\hat{b}}) - g_K(b_T;\{\lambda\})}$$

Sudakov form factor : perturbative and **nonperturbative** contributions

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Collinear distribution!

(input) TMD distribution : Wilson coefficients and **intrinsic part**

$$\tilde{F}_i(x, b_T; \mu_{\hat{b}}, \mu_{\hat{b}}^2) = \sum_{j=q,\bar{q},g} C_{i/j}(x, \hat{b}_T; \mu_{\hat{b}}, \mu_{\hat{b}}^2) \otimes f_j(x; \mu_{\hat{b}}) \tilde{F}_{i,NP}(x, b_T; \{\lambda\})$$

Nonperturbative parts defined in a "negative" way : **observed-calculable**

Nonperturbative models

Distribution for intrinsic transverse momentum (and its FT):

$$\tilde{F}_{i,NP}(x, b_T; \{\lambda\})$$

a Gaussian ?

Soft gluon emission

$$g_K(b_T; \{\lambda\})$$

Nonperturbative models

Distribution for intrinsic transverse momentum (and its FT):

$$\tilde{F}_{i,NP}(x, b_T; \{\lambda\})$$

a Gaussian ?

Soft gluon emission

$$g_K(b_T; \{\lambda\})$$

Separation of **b_T regions**

$$\hat{b}_T(b_T; b_{\min}, b_{\max}) \sim \begin{cases} b_{\max}\,, & b_T \to +\infty \\ b_T\,, & b_{\min} \ll b_T \ll b_{\max} \\ b_{\min}\,, & b_T \to 0 \end{cases}$$

High b_T limit : avoid Landau pole

Low b_T limit : recover fixed order expression

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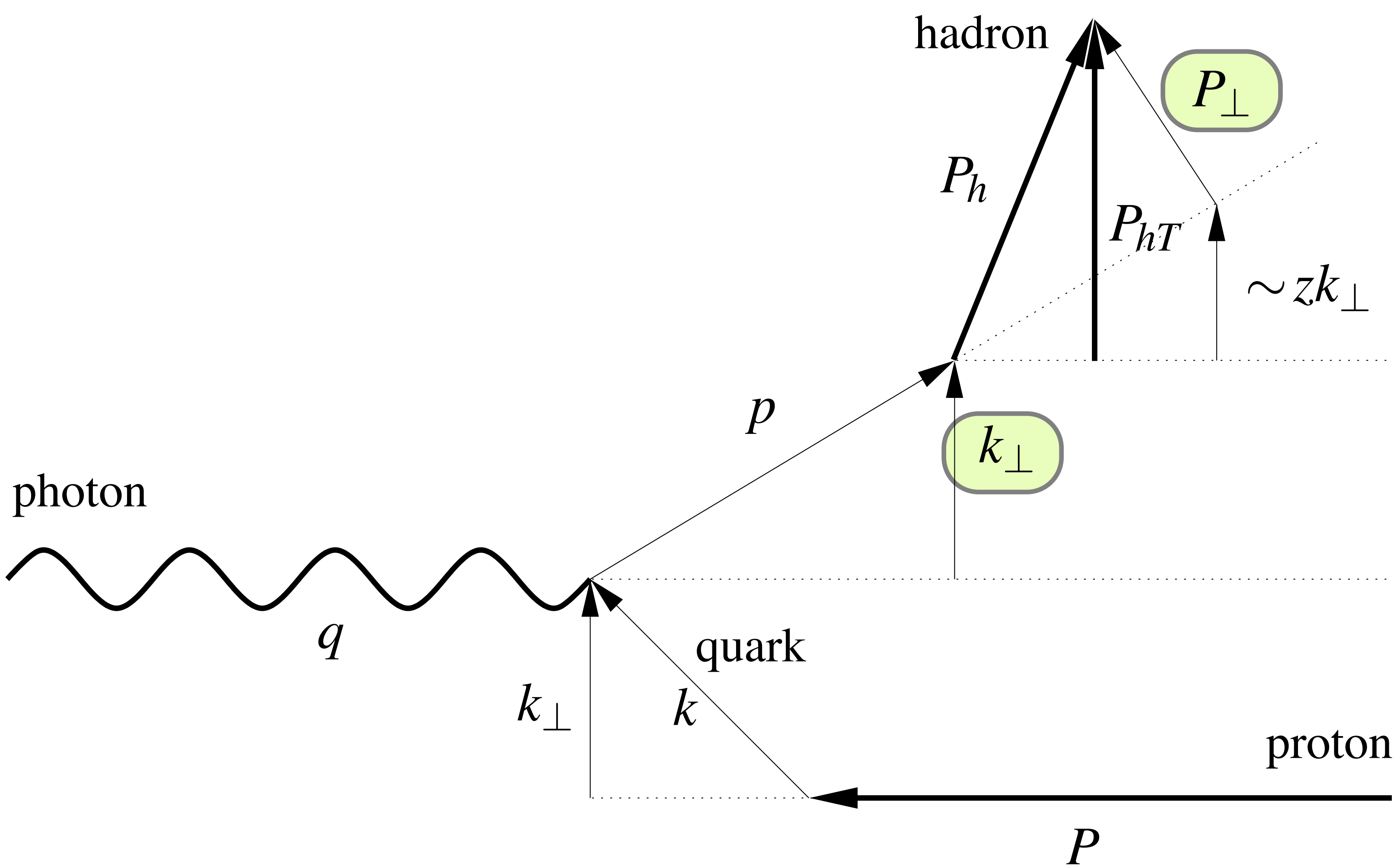
Transverse momenta

SIDIS



TMD FF

TMD PDF

Intrinsic transverse momentum

$$f_{1\mathrm{NP}}^{a}(x,\boldsymbol{k}_\perp^2) = \frac{1}{\pi}\,\frac{\left(1+\lambda \boldsymbol{k}_\perp^2\right)}{\langle \boldsymbol{k}_{\perp a}^2\rangle + \lambda\,\langle \boldsymbol{k}_{\perp a}^2\rangle^2}\; e^{-\frac{\boldsymbol{k}_\perp^2}{\langle \boldsymbol{k}_{\perp a}^2\rangle}}$$

$$\langle \boldsymbol{k}_{\perp a}^2\rangle(x) = \langle \hat{\boldsymbol{k}}_{\perp a}^2\rangle\,\frac{(1-x)^\alpha\; x^\sigma}{(1-\hat{x})^\alpha\;\hat{x}^\sigma}$$

$$\hat{x} = 0.1$$

weighted sum of two Gaussians

same widths for distributions, **different widths** fragmentations

$$D_{1\mathrm{NP}}^{a\to h}(z,\boldsymbol{P}_\perp^2) = \frac{1}{\pi}\,\frac{1}{\langle \boldsymbol{P}_{\perp a\to h}^2\rangle + \left(\lambda_F/z^2\right)\langle \boldsymbol{P}_{\perp a\to h}'^2\rangle^2}\left(e^{-\frac{\boldsymbol{P}_\perp^2}{\langle \boldsymbol{P}_{\perp a\to h}^2\rangle}} + \left(\lambda_F/z^2\right)\boldsymbol{P}_\perp^2\; e^{-\frac{\boldsymbol{P}_\perp^2}{\langle \boldsymbol{P}_{\perp a\to h}'^2\rangle}}\right)$$

$$\langle \boldsymbol{P}_{\perp a\to h}^2\rangle(z) = \langle \hat{\boldsymbol{P}}_{\perp a\to h}^2\rangle\,\frac{(z^\beta+\delta)\;(1-z)^\gamma}{(\hat{z}^\beta+\delta)\;(1-\hat{z})^\gamma}$$

$$\hat{z} = 0.5$$

Inspired from diquark models
(Eur.Phys.J. A45 (2010) 373-388)

For f_{1NP} and D_{1NP} we have 10 free parameters
(flavor independent case)

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Models - evolution and b_T regions

$$g_K(b_T; g_2) = -g_2 \frac{b_T^2}{2}$$

$$\hat{b}(b_T; b_{\min}, b_{\max}) = b_{\max} \left(\frac{1 - e^{-b_T^4/b_{\max}^4}}{1 - e^{-b_T^4/b_{\min}^4}} \right)$$

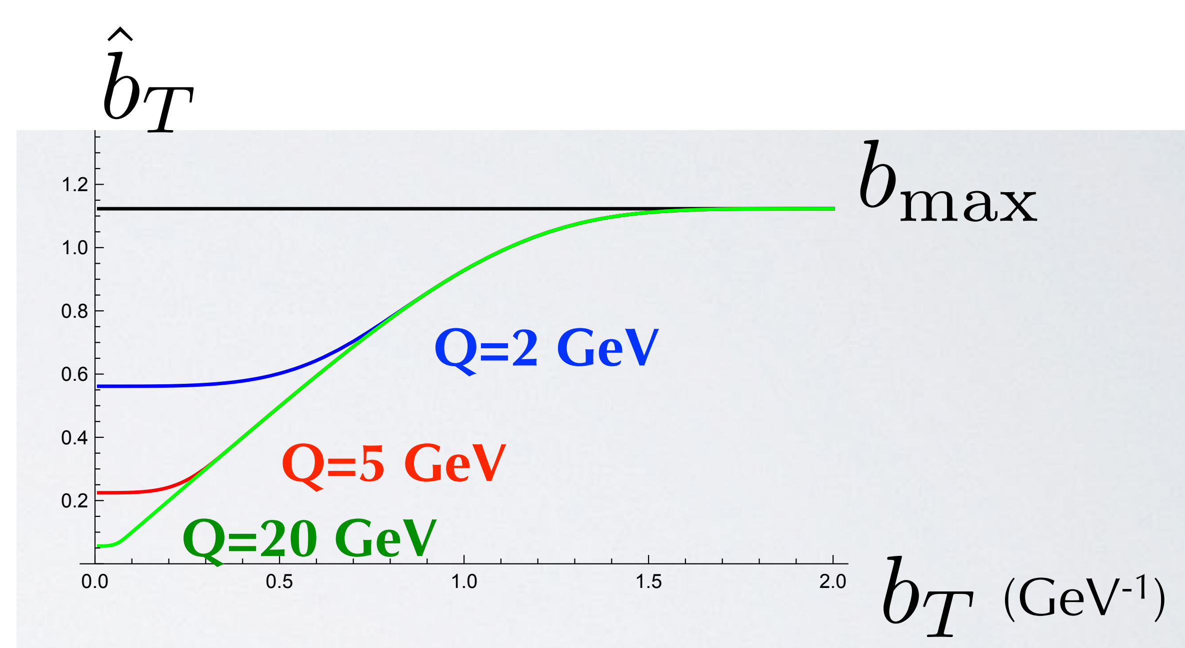
$\nearrow$ $b_{\max}\ , \quad b_T \to +\infty$

$\searrow$ $b_{\min}\ , \quad b_T \to 0$

$$b_{\max} = 2e^{-\gamma_E}$$

$$b_{\min} = 2e^{-\gamma_E}/Q$$

These choices guarantee that for Q=1 GeV the TMD coincides with the NP model



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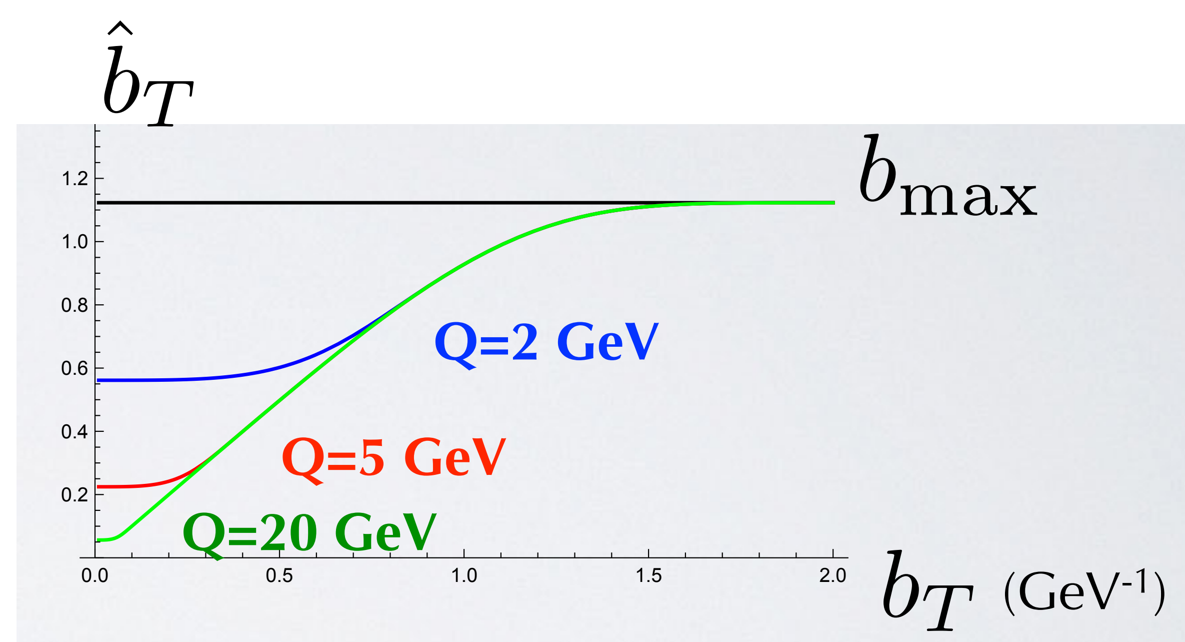
$\nearrow b_{\max} \,, \quad b_T \to +\infty$

$\searrow b_{\min} \,, \quad b_T \to 0$

$b_{\min} \sim 1/Q \,, \quad \mu_{\hat{b}} < Q$

The phenomenological importance of $b_{\min}$ is a signal that -especially in SIDIS data at **low Q**- we are exiting the proper TMD region and approaching the region of collinear factorization



Data sets and selections

SIDIS

	HERMES $p \to \pi^+$	HERMES $p \to \pi^-$	HERMES $p \to K^+$	HERMES $p \to K^-$
Reference	[61]			
Cuts	$Q^2 > 1.4$ GeV^2 $0.2 < z < 0.7$ $P_{hT} < \text{Min}[0.2\ Q, 0.7\ Qz] + 0.5$ GeV			
Points	190	190	189	187
Max. Q^2	9.2 GeV^2			
x range	$0.06 < x < 0.4$			

TMD factorization ($P_{hT}/z \ll Q^2$)

avoid target fragmentation (low z)
and exclusive contributions (high z)

In order to avoid the problems
with the normalization in COMPASS data
(see Compass coll., Erratum)

	HERMES $D \to \pi^+$	HERMES $D \to \pi^-$	HERMES $D \to K^+$	HERMES $D \to K^-$	COMPASS $D \to h^+$	COMPASS $D \to h^-$
Reference	[61]				[62]	
Cuts	$Q^2 > 1.4$ GeV^2 $0.2 < z < 0.7$ $P_{hT} < \text{Min}[0.2\ Q, 0.7\ Qz] + 0.5$ GeV					
Points	190	190	189	189	3125	3127
Max. Q^2	9.2 GeV^2				10 GeV^2	
x range	$0.06 < x < 0.4$				$0.006 < x < 0.12$	
Notes					Observable: $m_{\text{norm}}(x, z, \boldsymbol{P}_{hT}^2, Q^2)$, eq. (38)	

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Data sets and selections

	E288 200	E288 300	E288 400	E605
Reference	[65]	[65]	[65]	[66]
Cuts	$q_T < 0.2\ Q + 0.5$ GeV			
Points	45	45	78	35
$\sqrt{s}$	19.4 GeV	23.8 GeV	27.4 GeV	38.8 GeV
Q range	4-9 GeV	4-9 GeV	5-9, 11-14 GeV	7-9, 10.5-18 GeV
Kin. var.	y=0.4	y=0.21	y=0.03	$-0.1 < x_F < 0.2$

TMD factorization ($q_T \ll Q^2$)

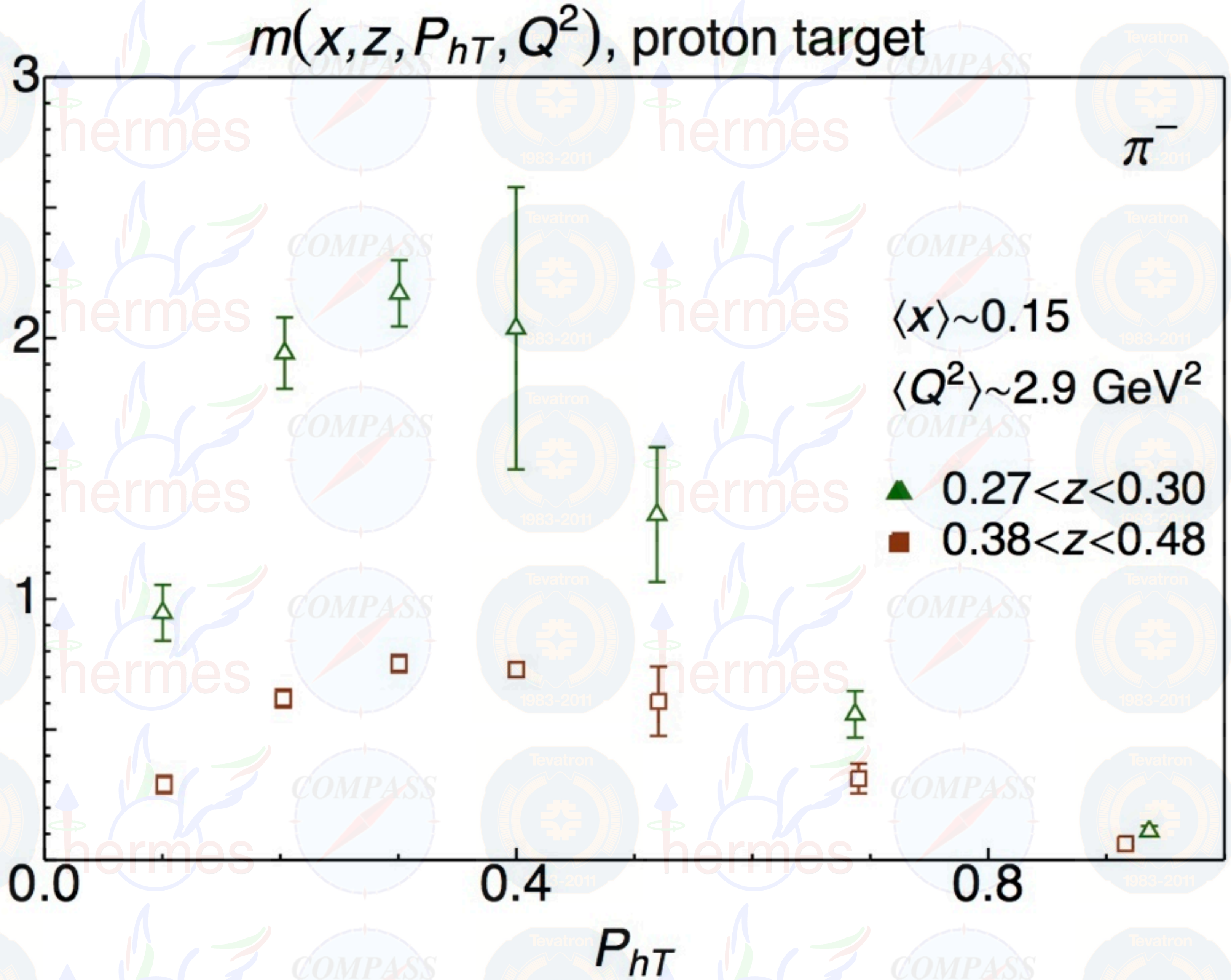
Drell-Yan

	CDF Run I	D0 Run I	CDF Run II	D0 Run II
Reference	[67]	[68]	[69]	[70]
Cuts	$q_T < 0.2\ Q + 0.5$ GeV $= 18.7$ GeV			
Points	31	14	37	8
$\sqrt{s}$	1.8 TeV	1.8 TeV	1.96 TeV	1.96 TeV
Normalization	1.114	0.992	1.049	1.048

Z

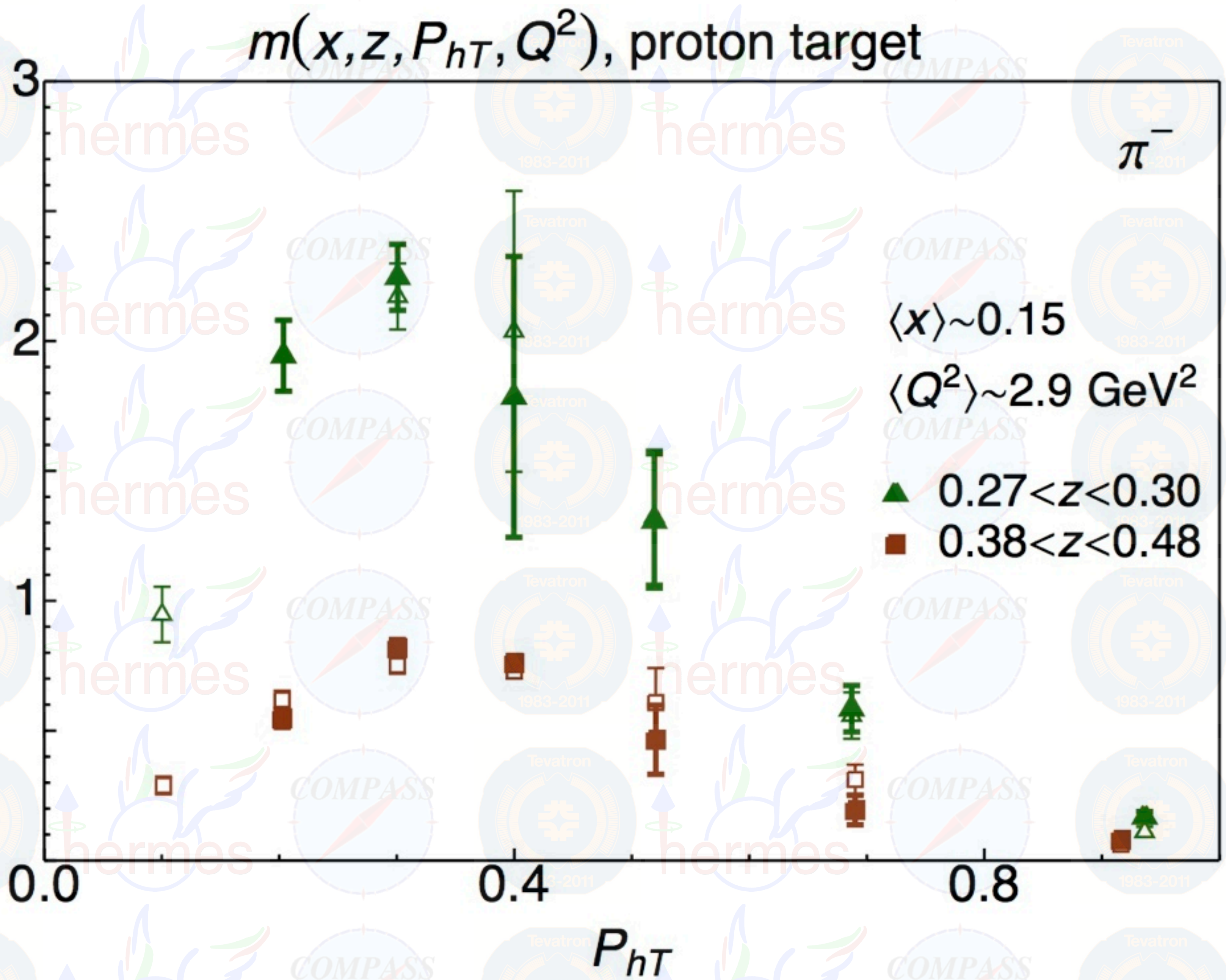
normalization :
fixed from DEMS fit,
different from exp.
(not really relevant for TMD
parametrizations)

The replica method



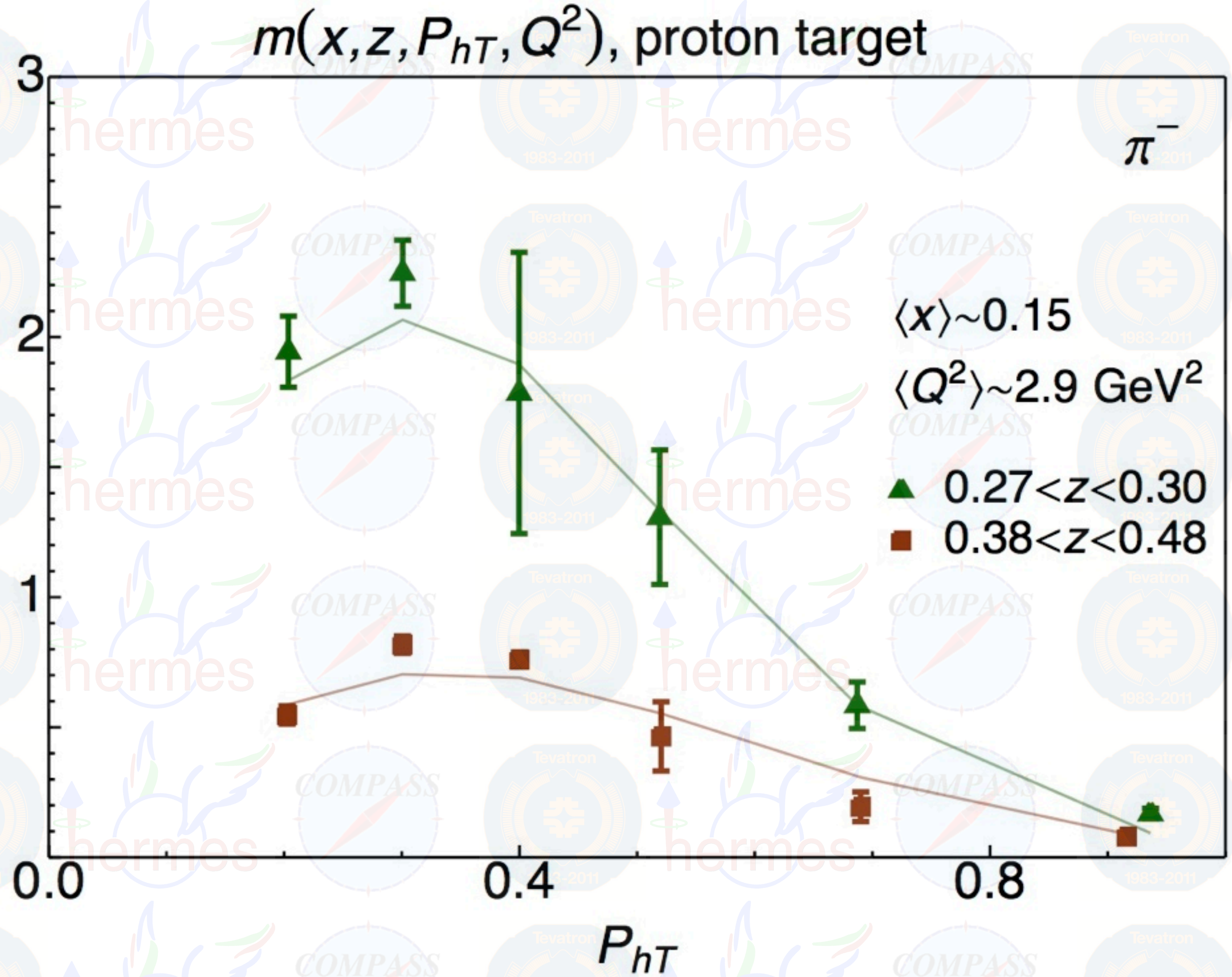
Sample of original data

The replica method



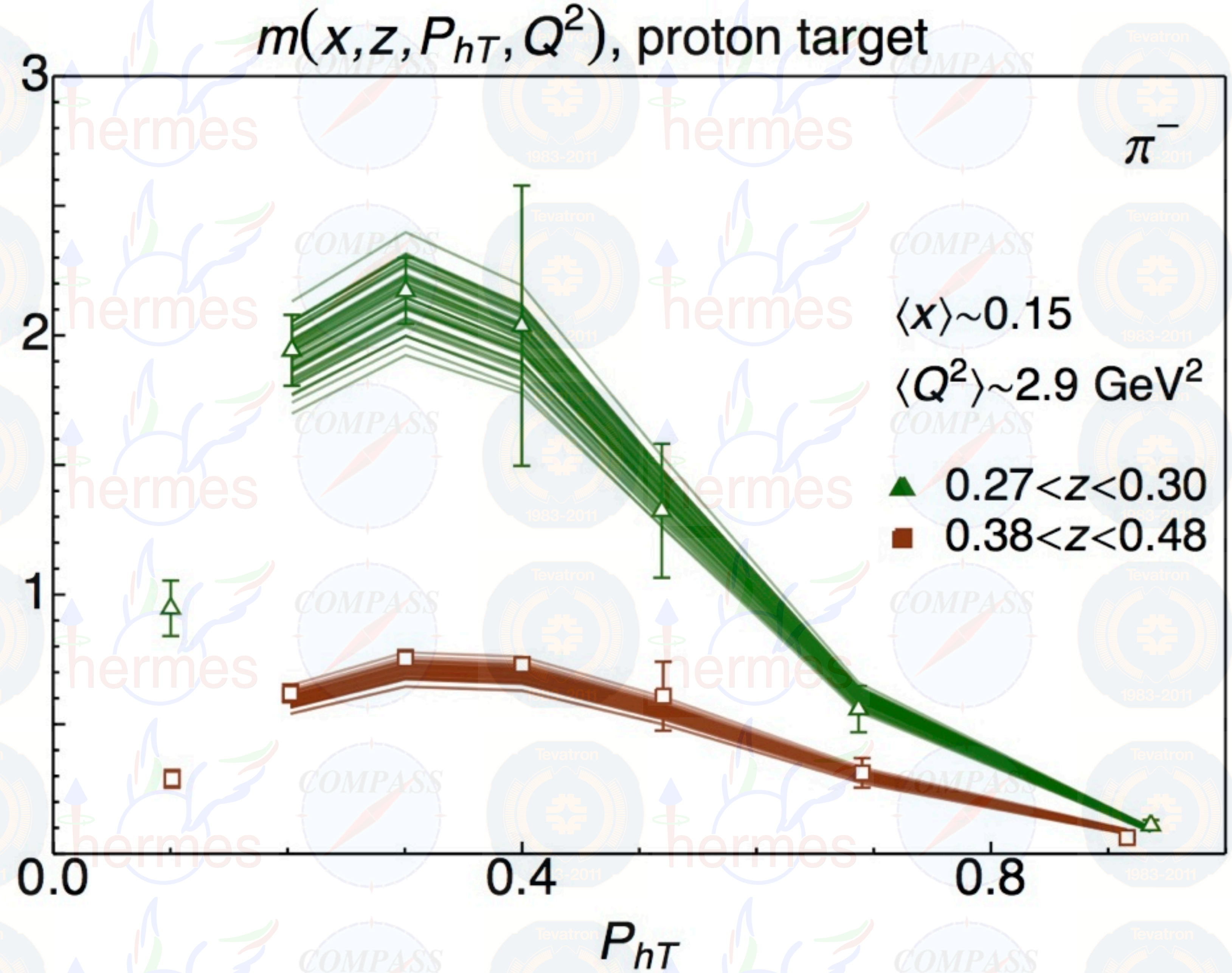
Replica of the original data with Gaussian noise

The replica method



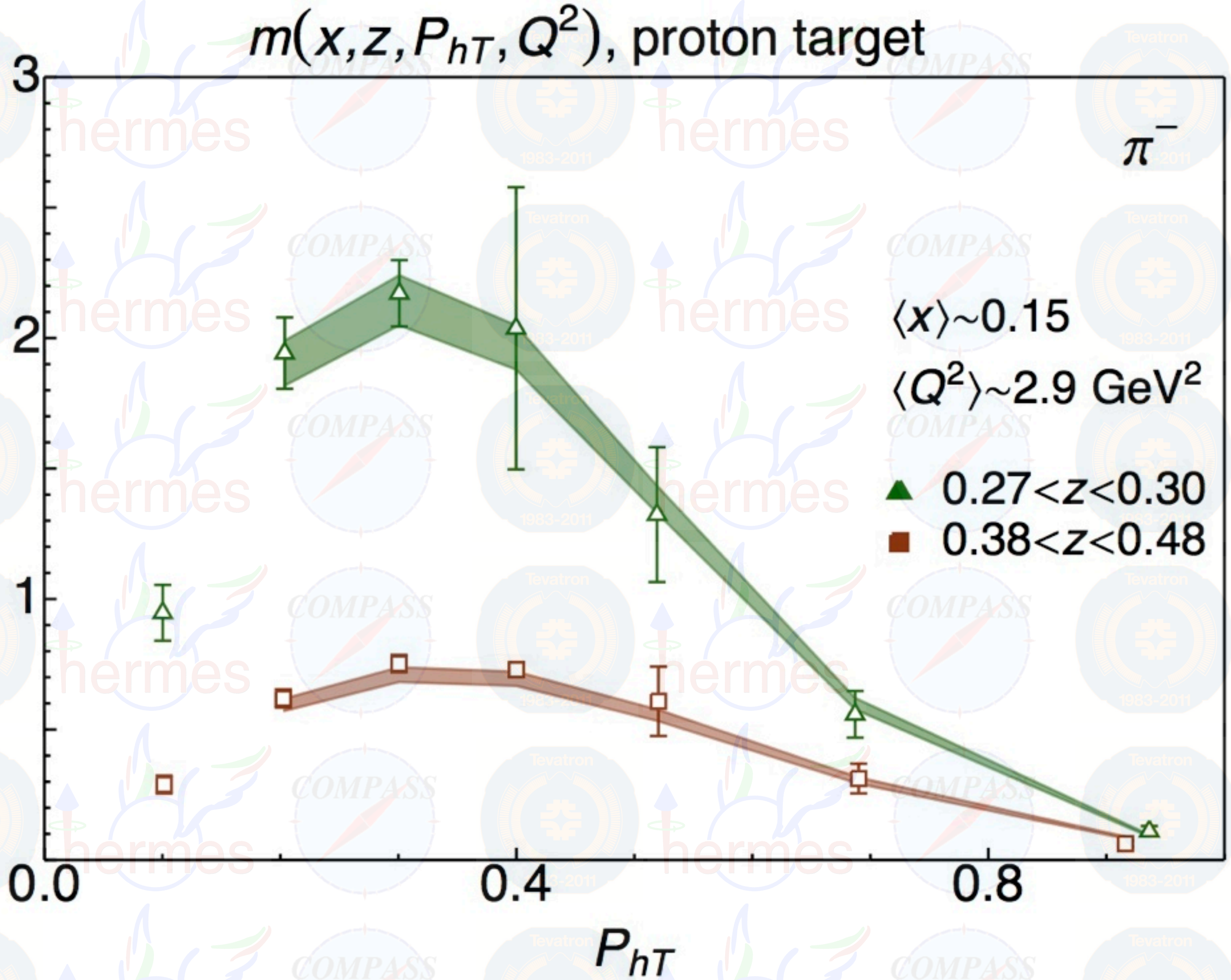
Fit of the replicated data

The replica method



Repeat the generation and the fit N times

The replica method



Obtain **distributions of best values** - calculate **68% CL bands**

Agreement data-theory

Flavor independent scenario

Flavor independent configuration | 11 parameters

Points	Parameters	χ^2	χ^2/d.o.f.
8059	11	12629 ± 363	1.55 ± 0.05

	HERMES $p \to \pi^+$	HERMES $p \to \pi^-$	HERMES $p \to K^+$	HERMES $p \to K^-$
Points	190	190	189	187
χ^2/points	4.83	2.47	0.91	0.82

Hermes P/D into π+:
problems at low z

	HERMES $D \to \pi^+$	HERMES $D \to \pi^-$	HERMES $D \to K^+$	HERMES $D \to K^-$	COMPASS $D \to h^+$	COMPASS $D \to h^-$
Points	190	190	189	189	3125	3127
χ^2/points	3.46	2.00	1.31	2.54	1.11	1.61

	E288 [200]	E288 [300]	E288 [400]	E605
Points	45	45	78	35
χ^2/points	0.99	0.84	0.32	1.12

	CDF Run I	D0 Run I	CDF Run II	D0 Run II
Points	31	14	37	8
χ^2/points	1.36	1.11	2.00	1.73

Hermes kaons better than pions:
larger uncertainties from FFs

Compass : better agreement due to
#points and normalization

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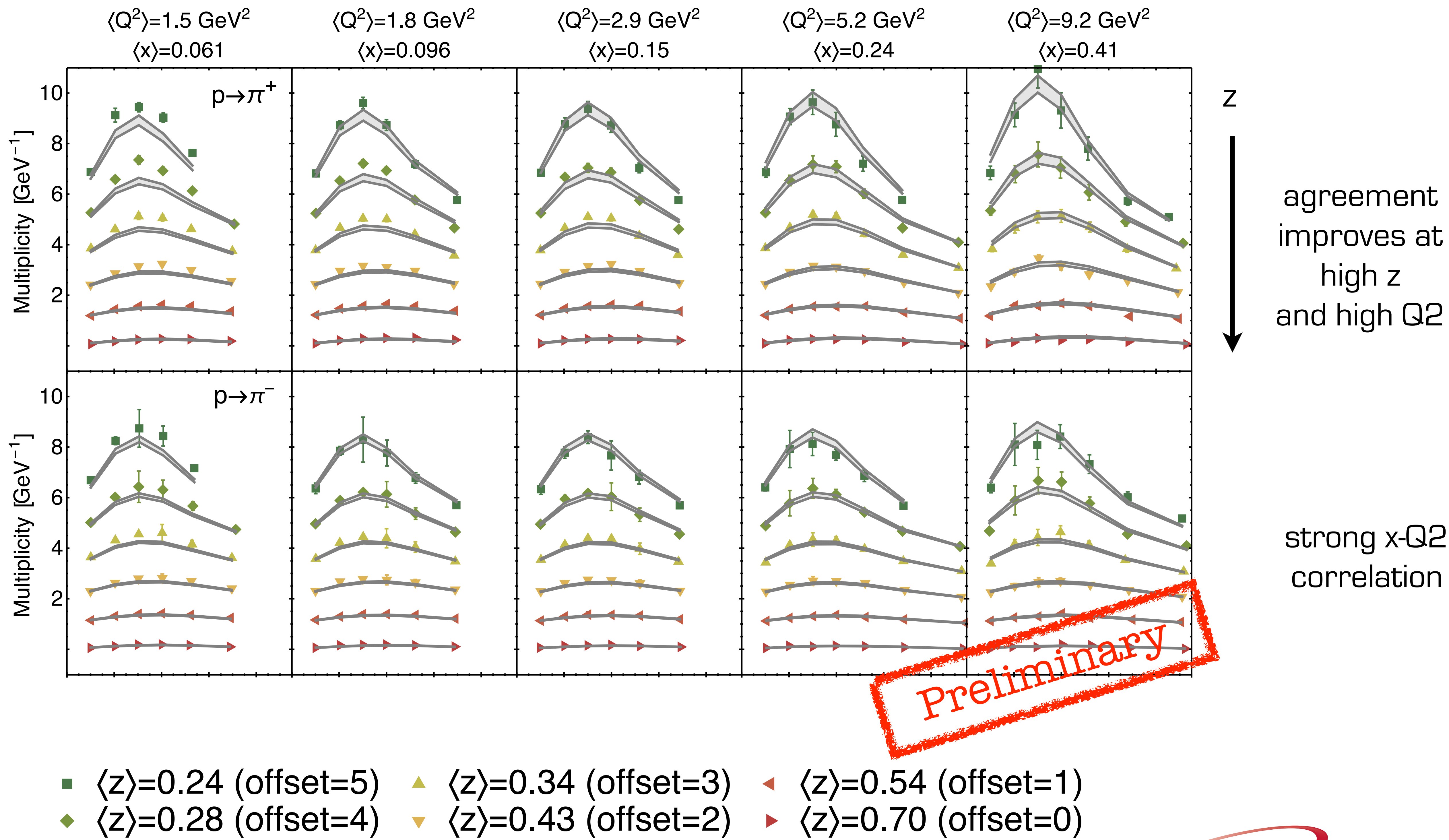
SIDIS @ Hermes

$\{P, \pi^{\pm}\}$



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SIDIS @ Compass

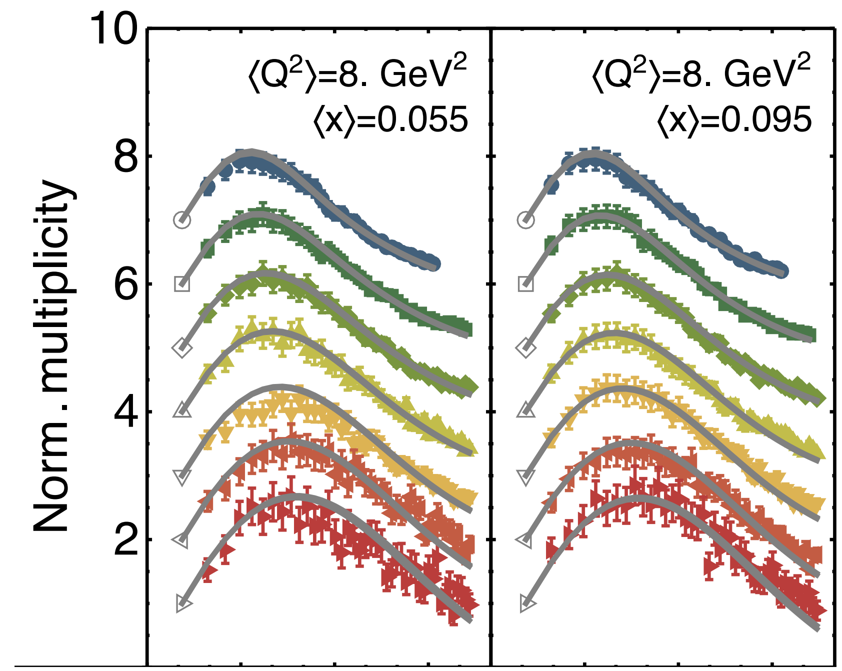
$\{D, h^{-}\}$

first data point used to **fix the normalization**, bin by bin (see Compass coll., Erratum)

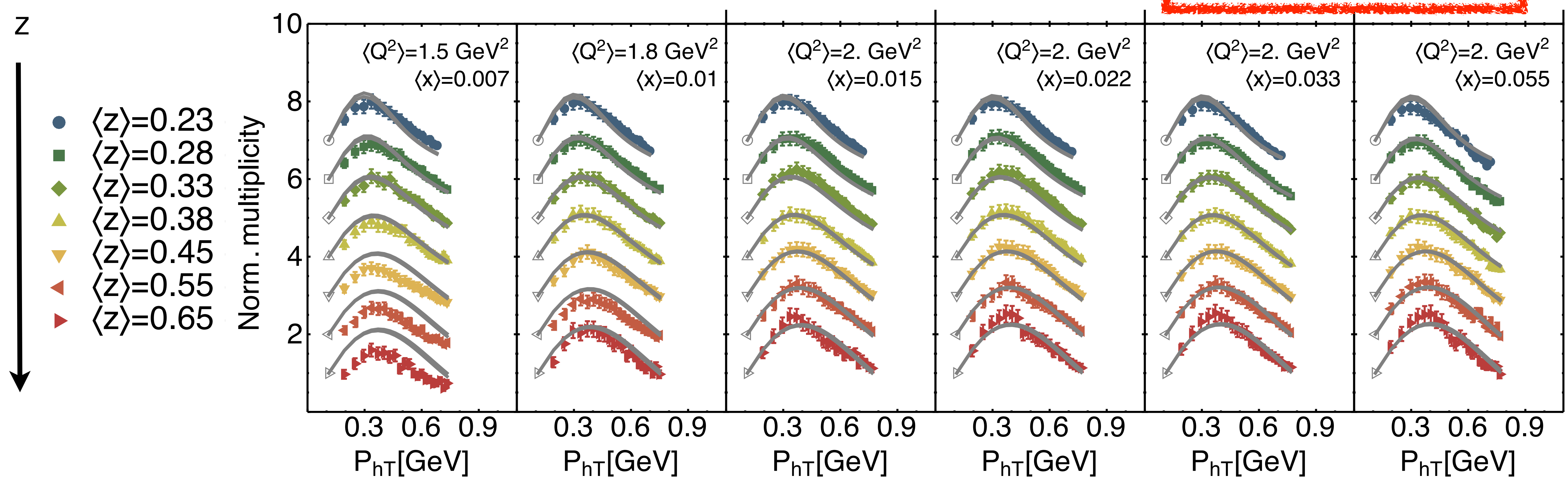
at high Q2 the agreement is good in all x,z bins

at low Q2 the agreement gets **worse at high z** (opposite behavior wrt Hermes)

at fixed Q2 and z the description improves increasing x

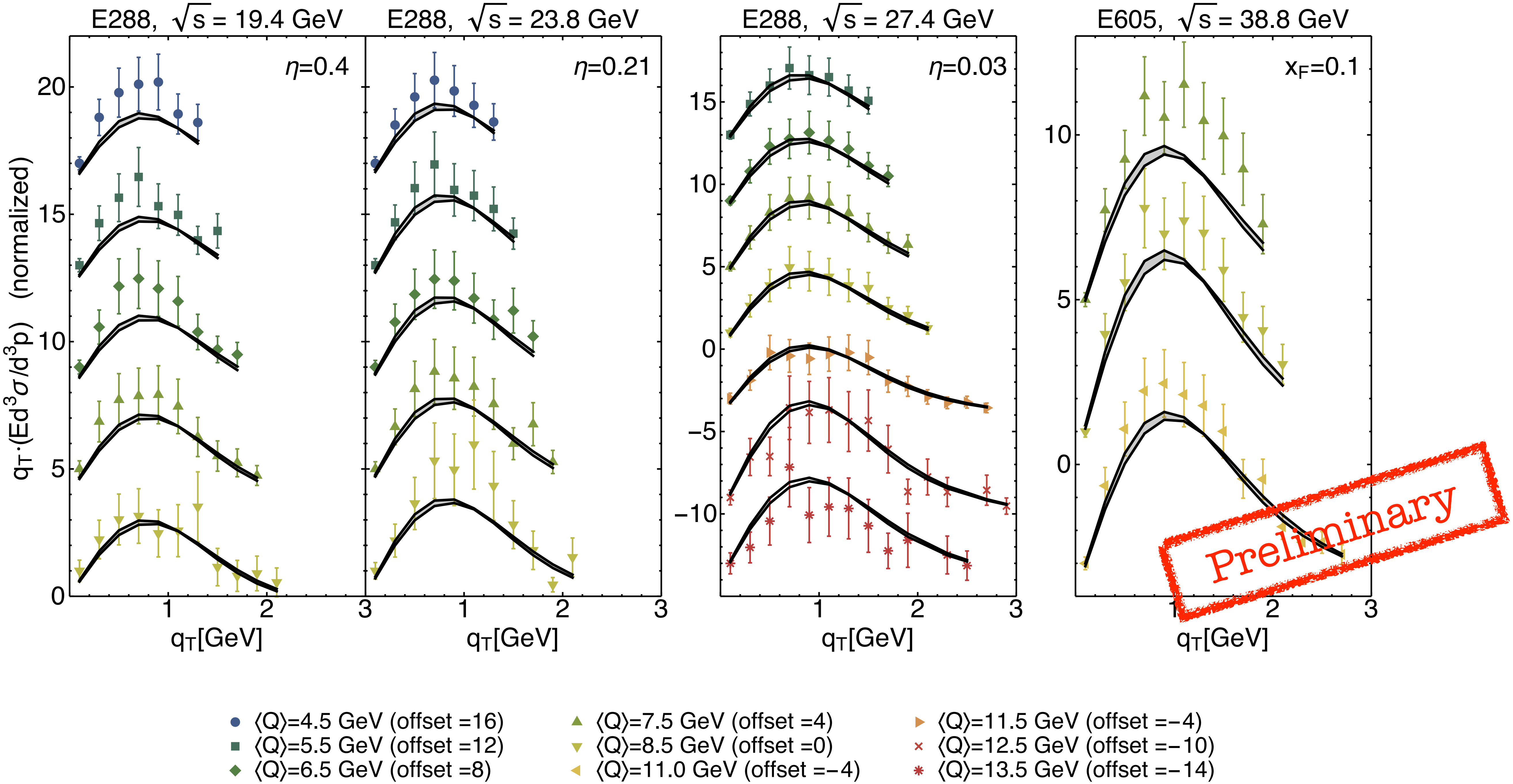


Preliminary



Drell-Yan @ Fermilab

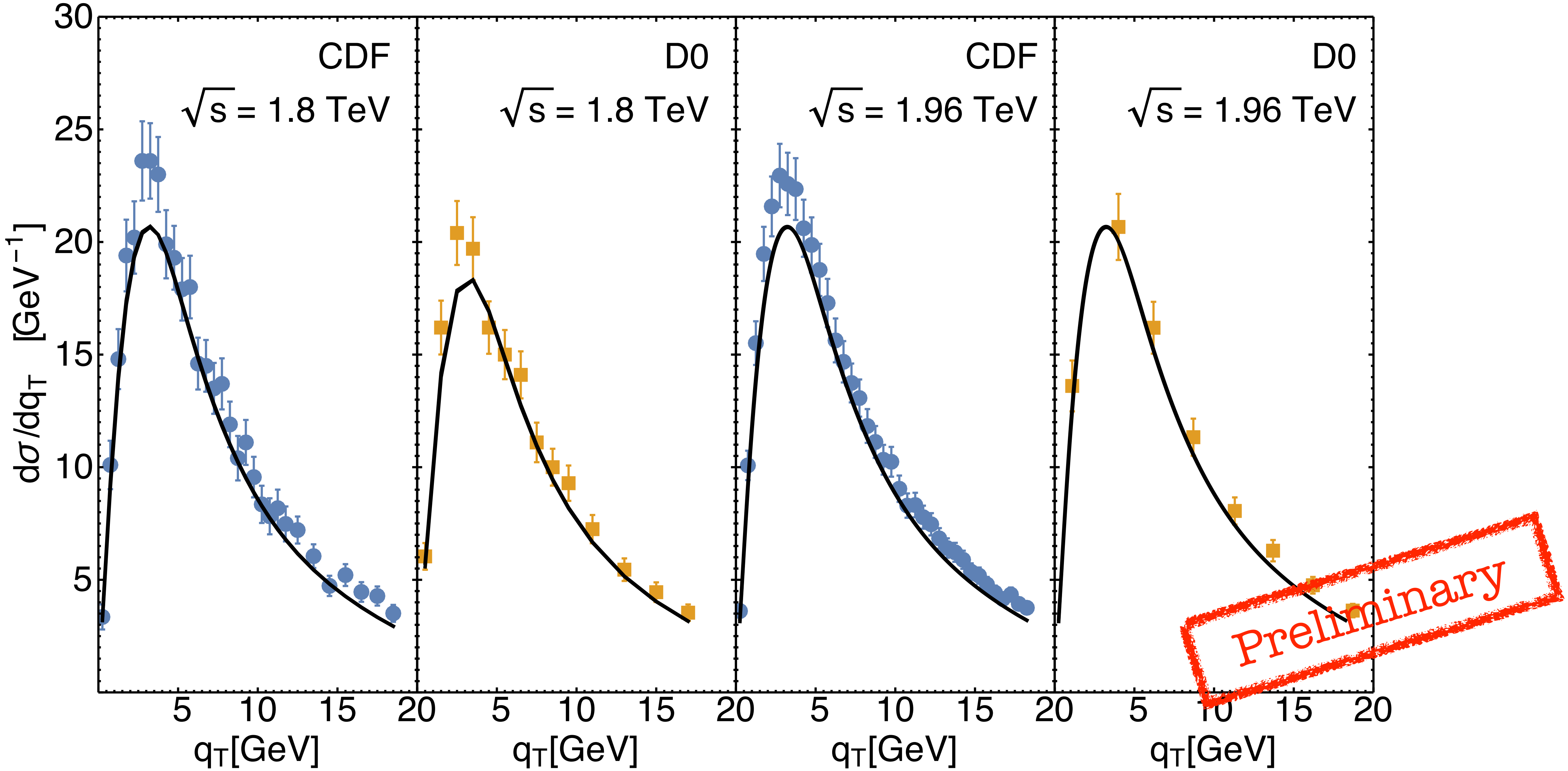
Evolution **shifts the peak** as Q increases



Z-boson @ Fermilab

Narrow bands, driven mainly by **g_2 values** (reduced sensitivity to intrinsic k_T)

Contributions to chi2 mainly from **normalization**, not shape



Best-fit values

TMD PDFs	$\langle \hat{\boldsymbol{k}}_\perp^2 \rangle$ [GeV^2]	α	σ		λ [GeV^{-2}]	
All replicas	0.28 ± 0.06	2.95 ± 0.05	0.17 ± 0.02		0.86 ± 0.78	
Replica 105	0.285	2.98	0.173		0.39	
TMD FFs	$\langle \hat{\boldsymbol{P}}_\perp^2 \rangle$ [GeV^2]	β	δ	γ	λ_F [GeV^{-2}]	$\langle \hat{\boldsymbol{P}}_\perp'^2 \rangle$ [GeV^2]
All replicas	0.21 ± 0.02	1.65 ± 0.49	2.28 ± 0.46	0.14 ± 0.07	5.50 ± 1.23	0.13 ± 0.01
Replica 105	0.212	2.10	2.52	0.094	5.29	0.135

TABLE XI: 68% confidence intervals of best-fit values for parametrizations of TMDs at $Q = 1$ GeV.

Flavor independent scenario:

$$\langle \hat{k}_\perp^2 \rangle = 0.28 \pm 0.06 \text{ GeV}^2$$

$$\langle \hat{P}_\perp^2 \rangle = 0.21 \pm 0.02 \text{ GeV}^2$$

$$\langle \hat{P}_\perp'^2 \rangle = 0.13 \pm 0.01 \text{ GeV}^2$$

$$g_2 = 0.13 \pm 0.01 \text{ GeV}^2$$

best value from 200 replicas

compatible with other extractions

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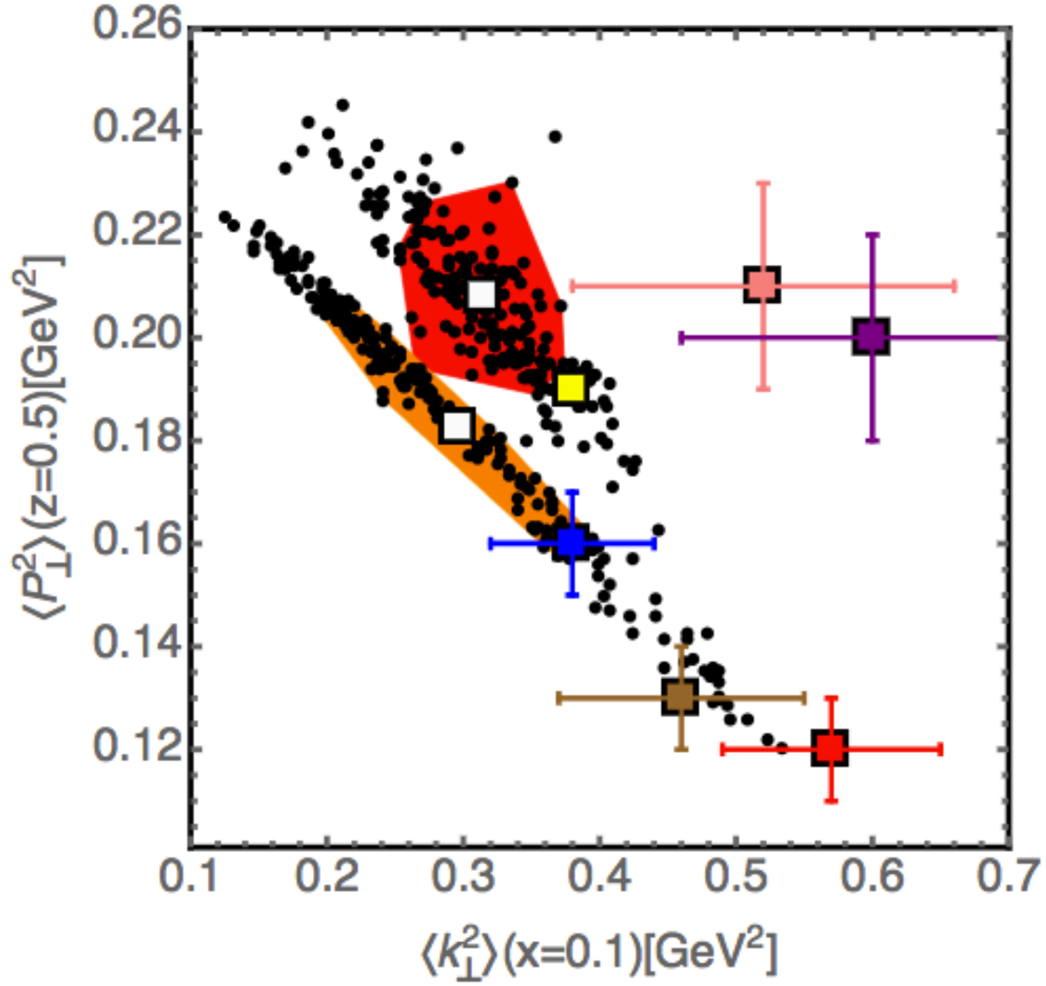
Best-fit values

Flavor independent scenario



- Bacchetta, Delcarro, Pisano, Radici, Signori, in preparation (Q = 1 GeV)
- Signori, Bacchetta, Radici, Schnell arXiv:1309.3507
- Schweitzer, Teckentrup, Metz, arXiv:1003.2190
- Anselmino et al. arXiv:1312.6261 [HERMES]
- Anselmino et al. arXiv:1312.6261 [HERMES, high z]
- Anselmino et al. arXiv:1312.6261 [COMPASS, norm.]
- Anselmino et al. arXiv:1312.6261 [COMPASS, high z, norm.]
- Echevarria, Idilbi, Kang, Vitev arXiv:1401.5078 (Q = 1.5 GeV)

Red/orange regions : **68% CL** from replica method

Inclusion of **DY/Z diminishes the correlation**

Inclusion of **Compass** increases the $\langle P_\perp^2 \rangle$ and reduces its spread

e+e- would further reduce the correlation

Caveat for comparisons :
NP effects (as the intrinsic momentum) always depend on the accuracy of the perturbative part ;

determined as observed - calculable

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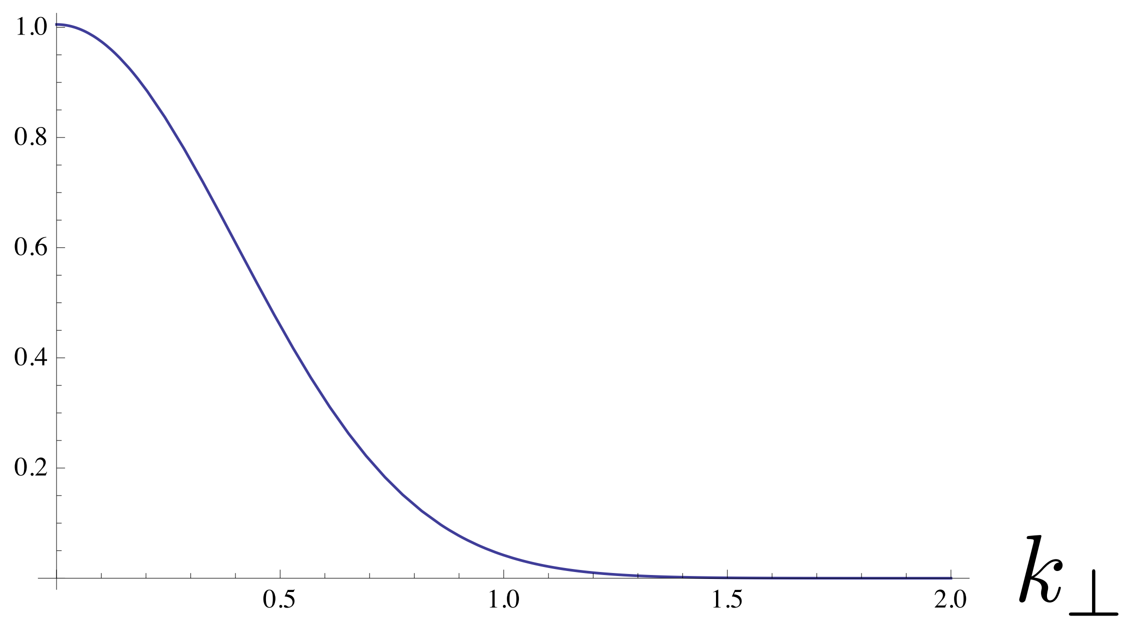
Test with replica 105

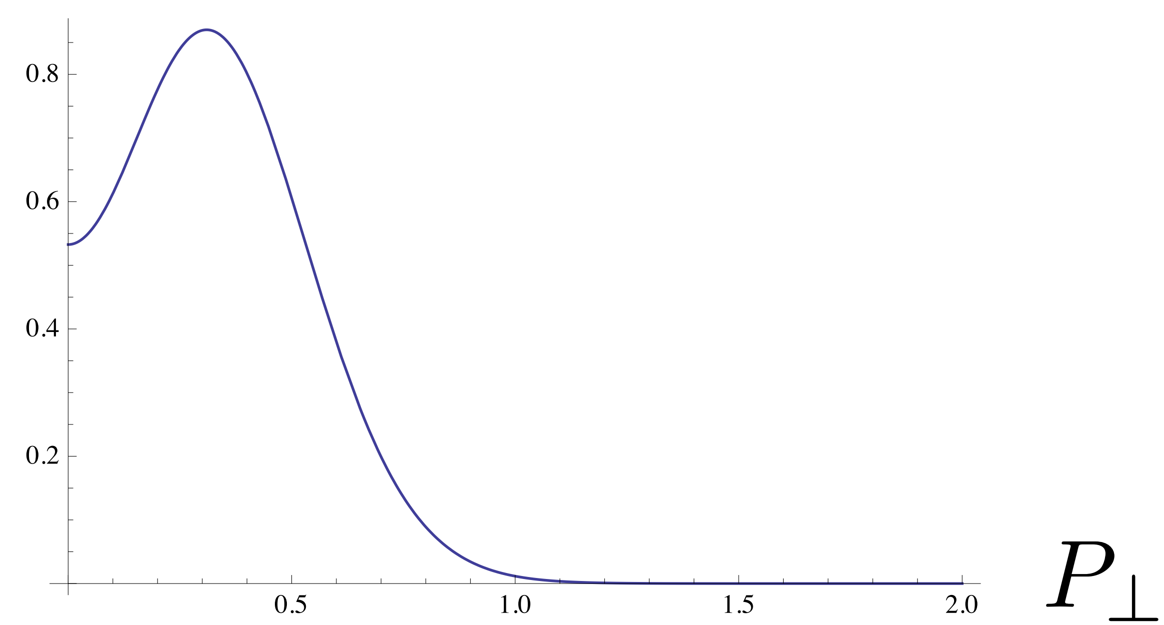
	$p \to \pi^+$	$p \to \pi^-$	$p \to K^+$	$p \to K^-$	$D \to \pi^+$	$D \to \pi^-$	$D \to K^+$	$D \to K^-$
Original	5.18	2.67	0.75	0.78	3.63	2.31	1.12	2.27
Normalized	1.94	1.13	0.57	0.29	1.59	0.80	0.47	0.97

Hermes data normalized to the first bin in transverse momentum :
the chi2 drops, confirming that **normalization effects are the main contribution to the chi2**

$f_{1NP}(x = 0.1, k_\perp^2)|_{r105}$



$D_{1NP}(z = 0.5, P_\perp^2)|_{r105}$



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Conclusions ...

In total: 8059 bins vs 11 parameters and
$$\chi^2/\text{d.o.f.} = 1.55 \pm 0.05$$

1) We demonstrated that it is possible to simultaneously fit TMDs on different data sets (universality), multidimensional and at different energy scales

2) we extracted TMD PDFs and FFs on > 8000 data points

3) this is the first step towards a global fit analysis of TMDs

4) once the analysis of unpolarized structures is solid, we can address the polarized structure functions

... questions ...

5) why is the description not good at low z for Hermes and high z for Compass ?

6) how can we relax the tension from the normalization of data ?

7) are there tensions between Hermes and Compass data ? (see the flavor decomposition) Waiting for JLab.

8) are we probing the "right" transverse momentum regions ?

9) can we find a clever way (theoretical and/or computational) to speed up the analysis procedure ?

10) is that all ..?

... and the next challenges

The goal is not only to fit data,
but to answer fundamental questions in QCD in the best possible way

11) identification of the current fragmentation region in SIDIS ?

12) rise the accuracy of transverse momentum resummation

13) match TMD and collinear factorization : fixed-order description of the high transverse momentum region and its matching to the low transverse momentum one

14) order the hadronic tensor in terms of definite rank

---

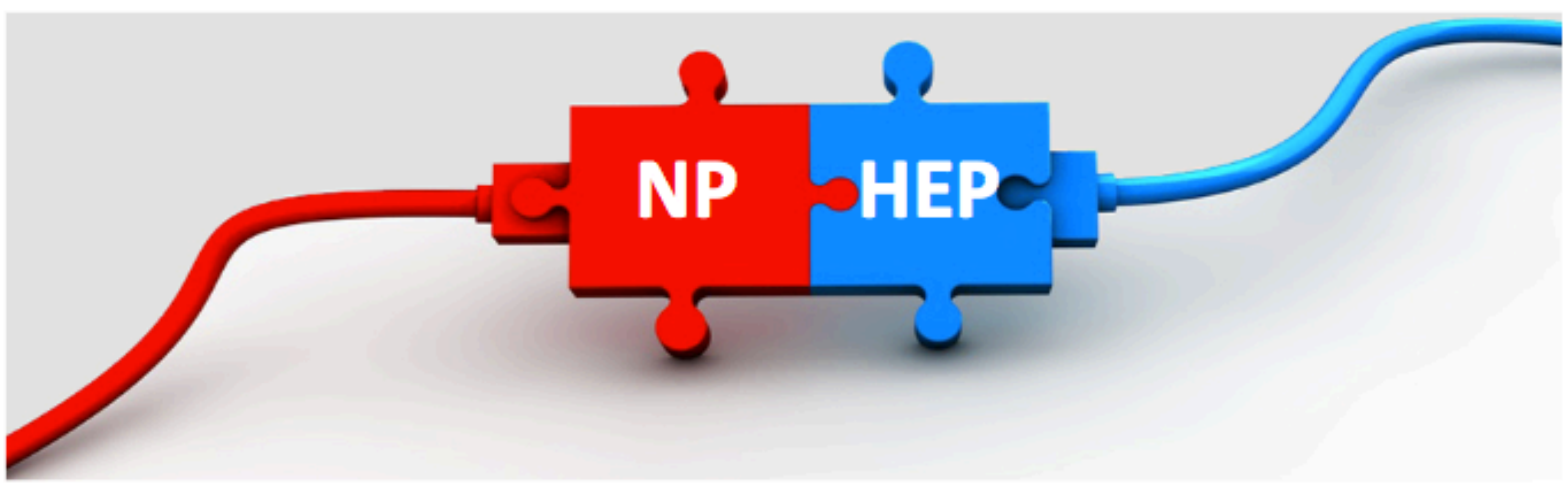
15) include electron-positron annihilation, LHC and JLab data
16) address the flavor decomposition in transverse momentum
17) address the polarized structure functions
18) Monte Carlo generators and TMDs
19) what about spin 1 targets ?

20) ...

Monte Carlo generators

LDRD

Mapping the hadronization description in the Pythia MCEG to the correlation functions of TMD factorization

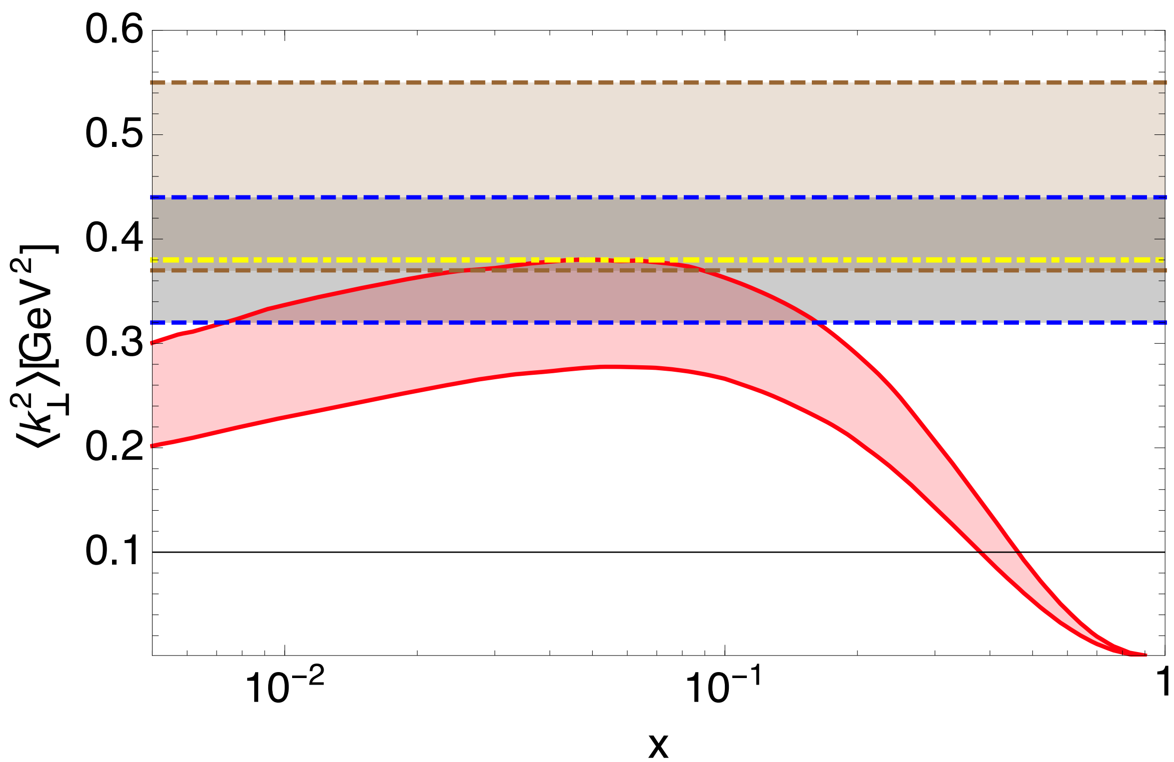


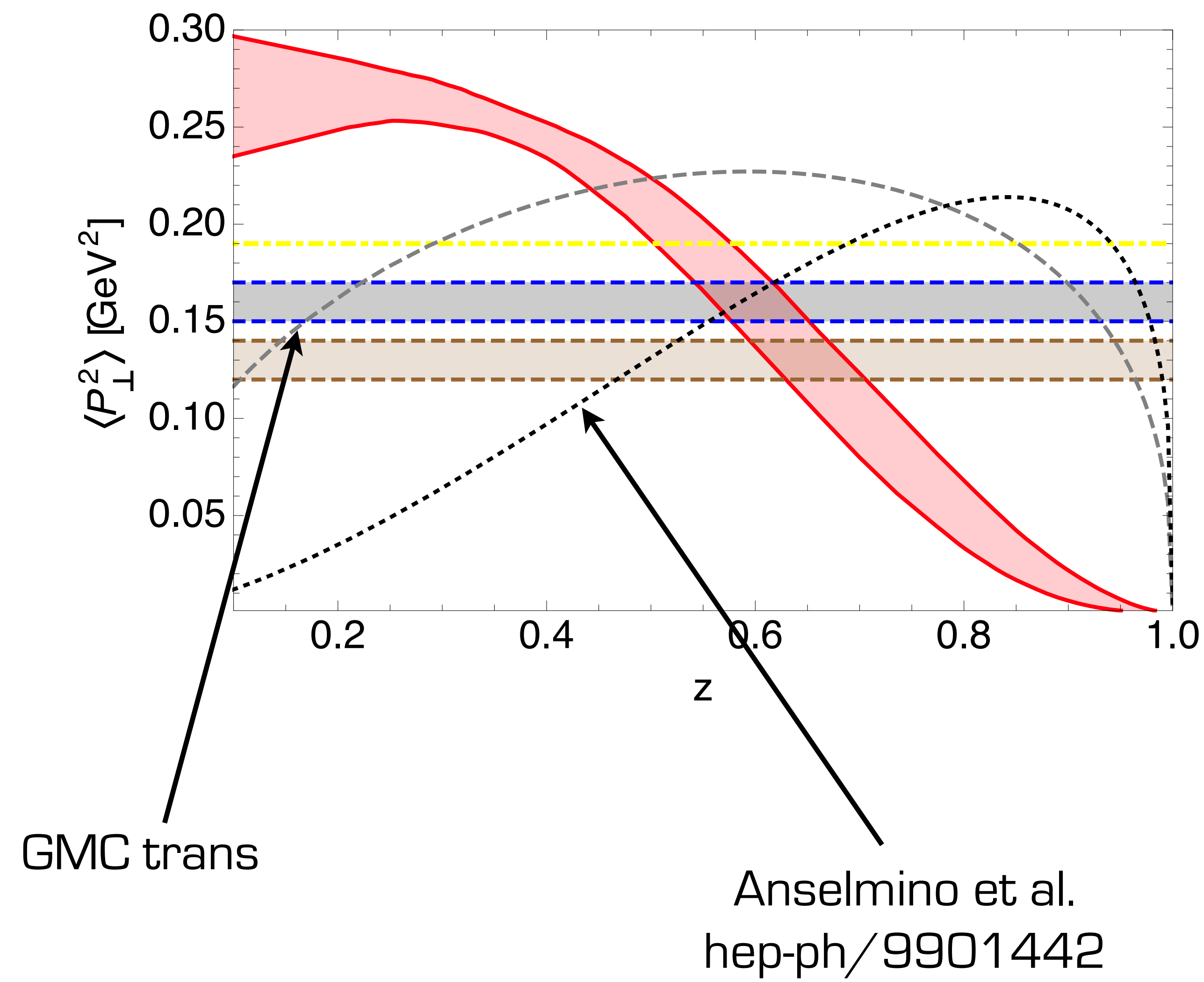
see the talk by M. Diefenthaler

Backup

Kinematic dependence

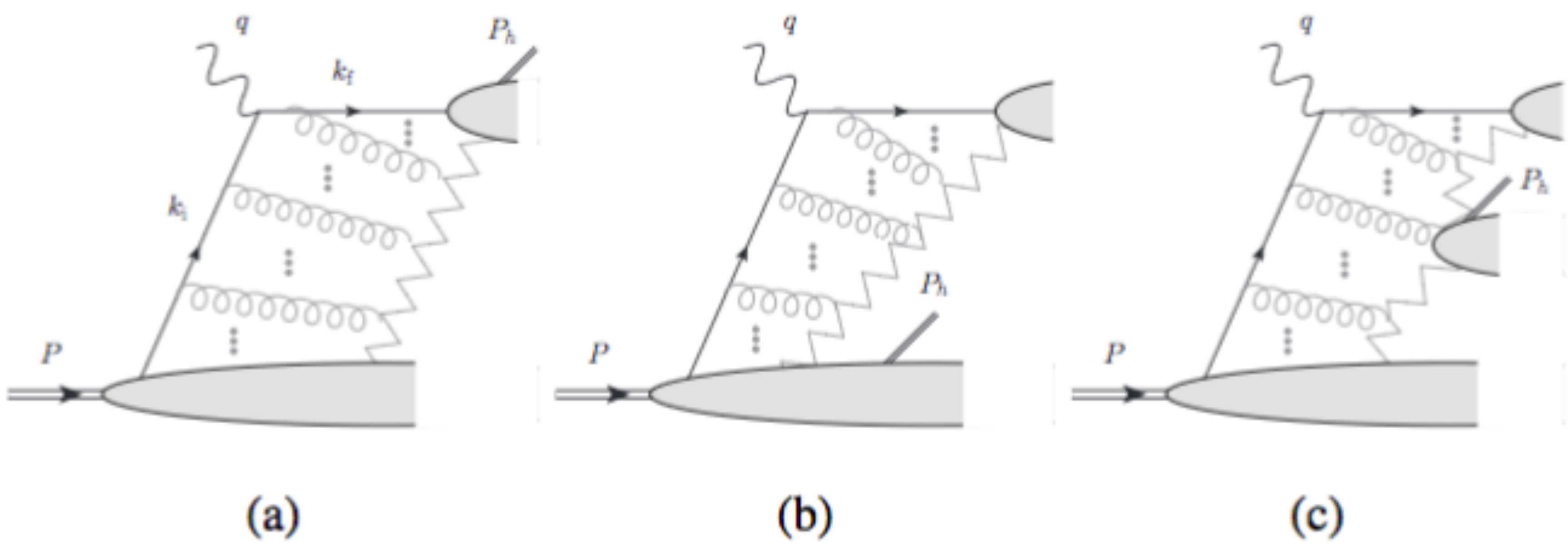
Comparison with other extractions :



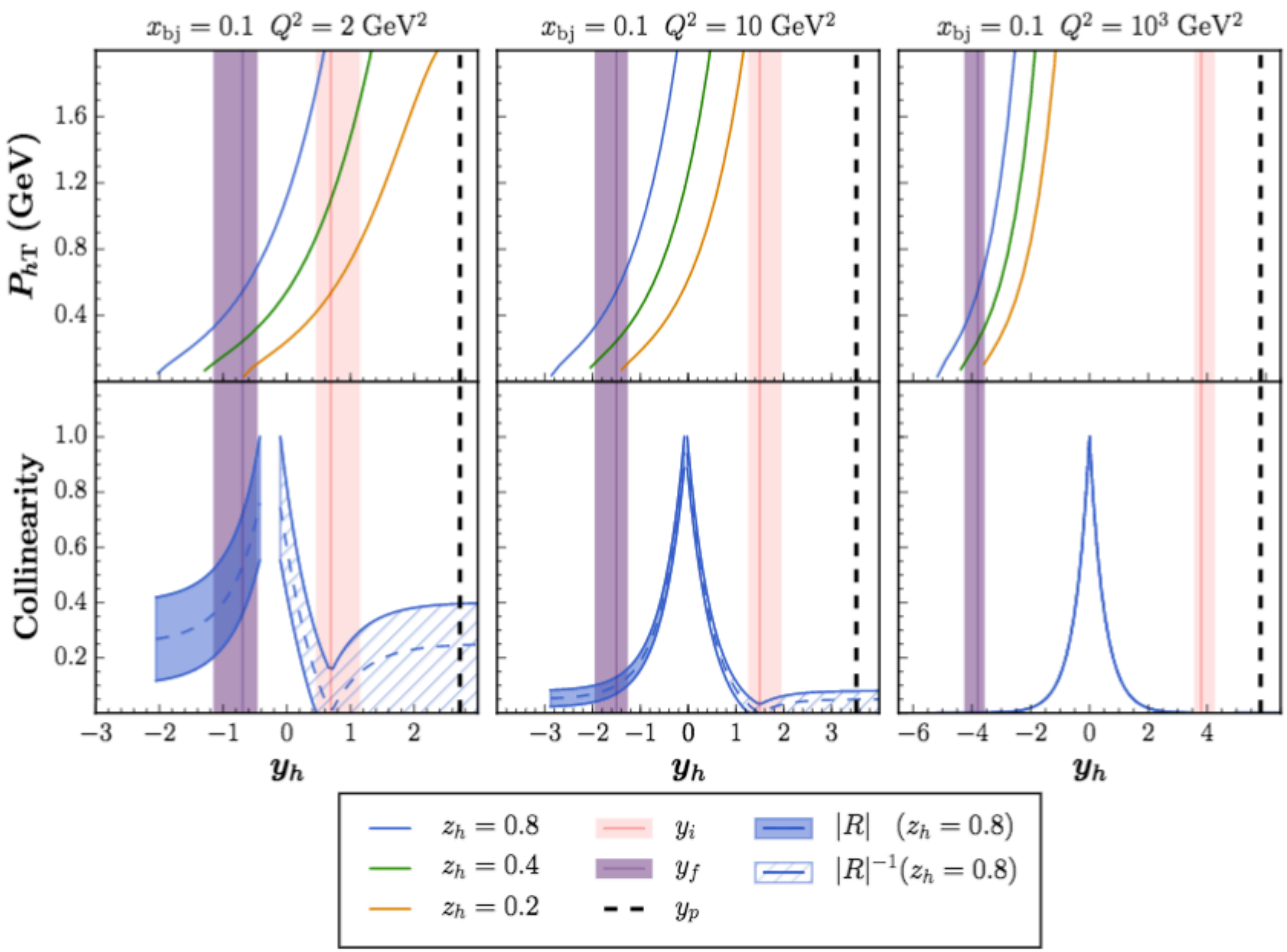


Color code : same as previous slide

Target vs current vs central regions



Target vs current vs central regions



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The polarized sector

The W+Y formalism needs to be built from scratch
 in the polarized sector
Apart from few cases, we have only results
based on a parton model description

W + Y for a polarized involves collinear higher twist!

Semi-inclusive deep inelastic scattering at small transverse momentum

Alessandro Bacchetta[a,*], Markus Diehl[a], Klaus Goeke[b], Andreas Metz[b], Piet J. Mulders[c], Marc Schlegel[b]

organize the hadronic tensor
in structures of definite rank
(several advantages)

Matches and mismatches in the descriptions of semi-inclusive processes at low and high transverse momentum

Alessandro Bacchetta[a*], Daniël Boer[b], Markus Diehl[a], Piet J. Mulders[b]

Look at the mismatches
between low and high
qT of some structure functions

what about the spin 1 case ..?

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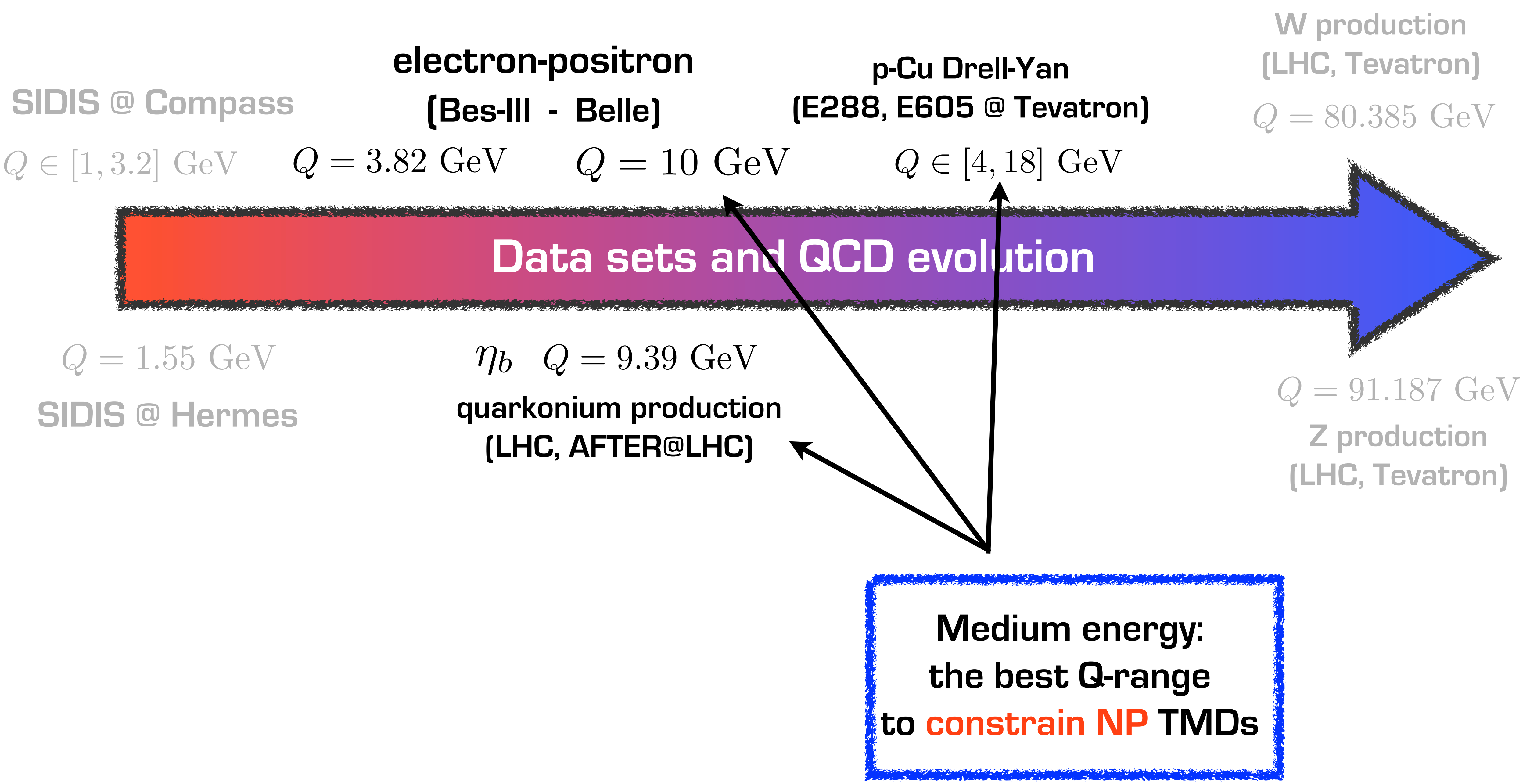
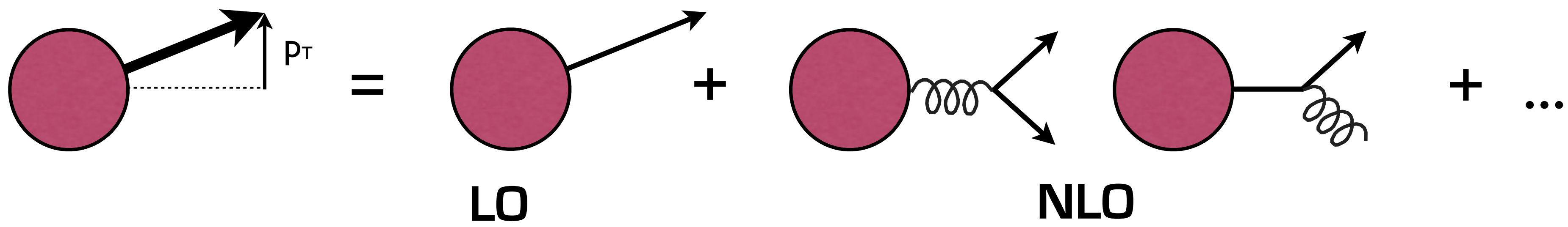
Evolution at work



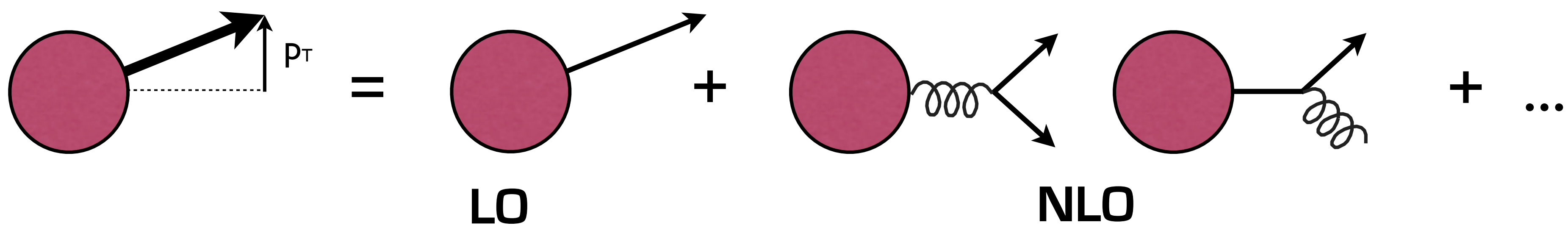
Perturbative accuracy

$C_{i/j}$ **Wilson coefficients** : expansion of the TMD distribution on a basis of collinear PDFs



Perturbative accuracy

$C_{i/j}$ **Wilson coefficients** : expansion of the TMD distribution on a basis of collinear PDFs



Anomalous dimension of the TMD and **logarithmic expansion**

$$\gamma_F[\alpha_s(\mu), \zeta/\mu^2] \sim \underbrace{\alpha_s L}_{\text{LL}} + \underbrace{(\alpha_s + \alpha_s^2 L)}_{\text{NLL}} + \underbrace{(\alpha_s^2 + \alpha_s^3 L)}_{\text{NNLL}} + \cdots$$

$$\sim \; 1 + \alpha_s + \alpha_s^2 + \cdots$$

$$L = \ln \frac{Q^2}{\mu} \, , \quad \alpha_s L \sim 1$$

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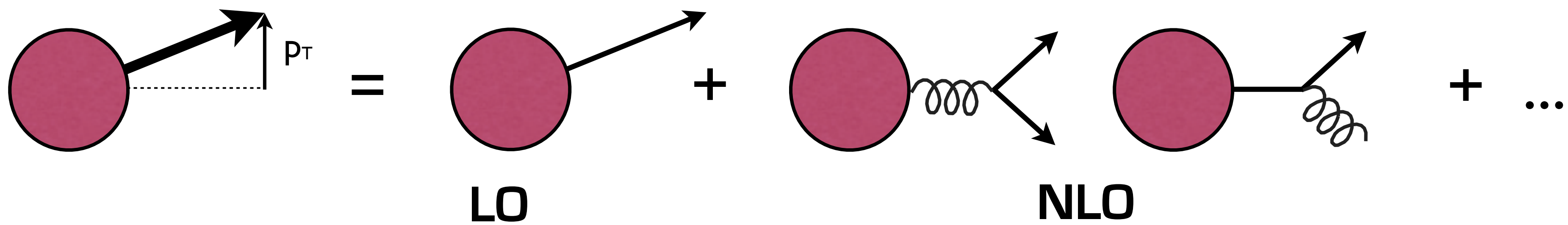
Perturbative accuracy

Overview of the terminology

$C_{i/j}$ **Wilson coefficients** : expansion of the TMD distribution on a basis of collinear PDFs



Anomalous dimension of the TMD and **logarithmic expansion**

$$\gamma_F[\alpha_s(\mu), \zeta/\mu^2] \sim \underbrace{\alpha_s L}_{\text{LL}} + \underbrace{(\alpha_s + \alpha_s^2 L)}_{\text{NLL}} + \underbrace{(\alpha_s^2 + \alpha_s^3 L)}_{\text{NNLL}} + \cdots$$

$$\sim \; 1 + \alpha_s + \alpha_s^2 + \cdots$$

$$L = \ln \frac{Q^2}{\mu} \; , \quad \alpha_s L \sim 1$$

Collins-Soper kernel : a power series in the coupling

$$K(b_T; \mu_b) \sim 1 + \alpha_s + \alpha_s^2 \cdots$$

accuracy chosen consistently
with Wilson coefficients
and anomalous dimension

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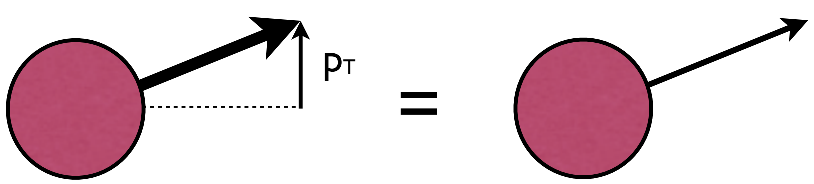
Perturbative accuracy

$C_{i/j}$ **Wilson coefficients** : expansion of the TMD distribution on a basis of collinear PDFs



LO

Anomalous dimension of the TMD and **logarithmic expansion** $\mu_{\hat{b}} = 2e^{-\gamma_E}/\bar{b}_\star$

$$\gamma_F[\alpha_s(\mu), \zeta/\mu^2] \sim \underbrace{\alpha_s L}_{\text{LL}} + \underbrace{(\alpha_s + \alpha_s^2 L)}_{\text{NLL}} + \cdots$$

$$\sim \; 1 + \alpha_s + \cdots$$

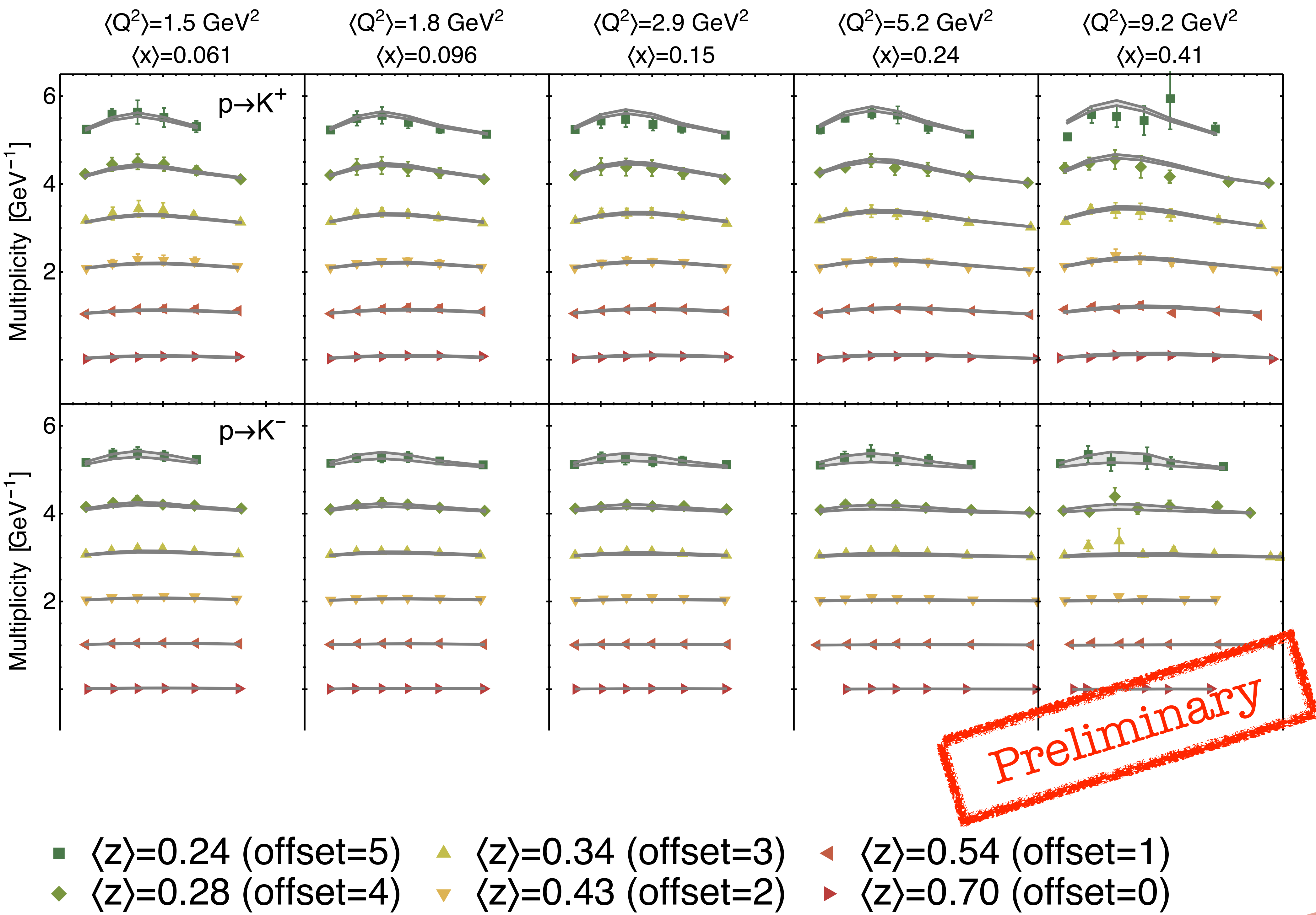
Collins-Soper kernel : a power series in the coupling

$$K(b_T; \mu_b) \sim 1 + \alpha_s + \cdots$$

$C_{i/j}$	$\gamma_{\rm nc}$	$\Gamma_{\rm cusp}$	K	*accuracy*
0	0	0	0	QPM
0	0	1	0	LO-LL
0	1	2	1	LO-NLL
0	2	3	2	LO-NNLL
1	1	2	1	NLO-NLL
1	2	3	2	NLO-NNLL
2	2	3	2	NNLO-NNLL

SIDIS @ Hermes

$\{P, K^{\pm}\}$



better agreement at low z wrt the pion case

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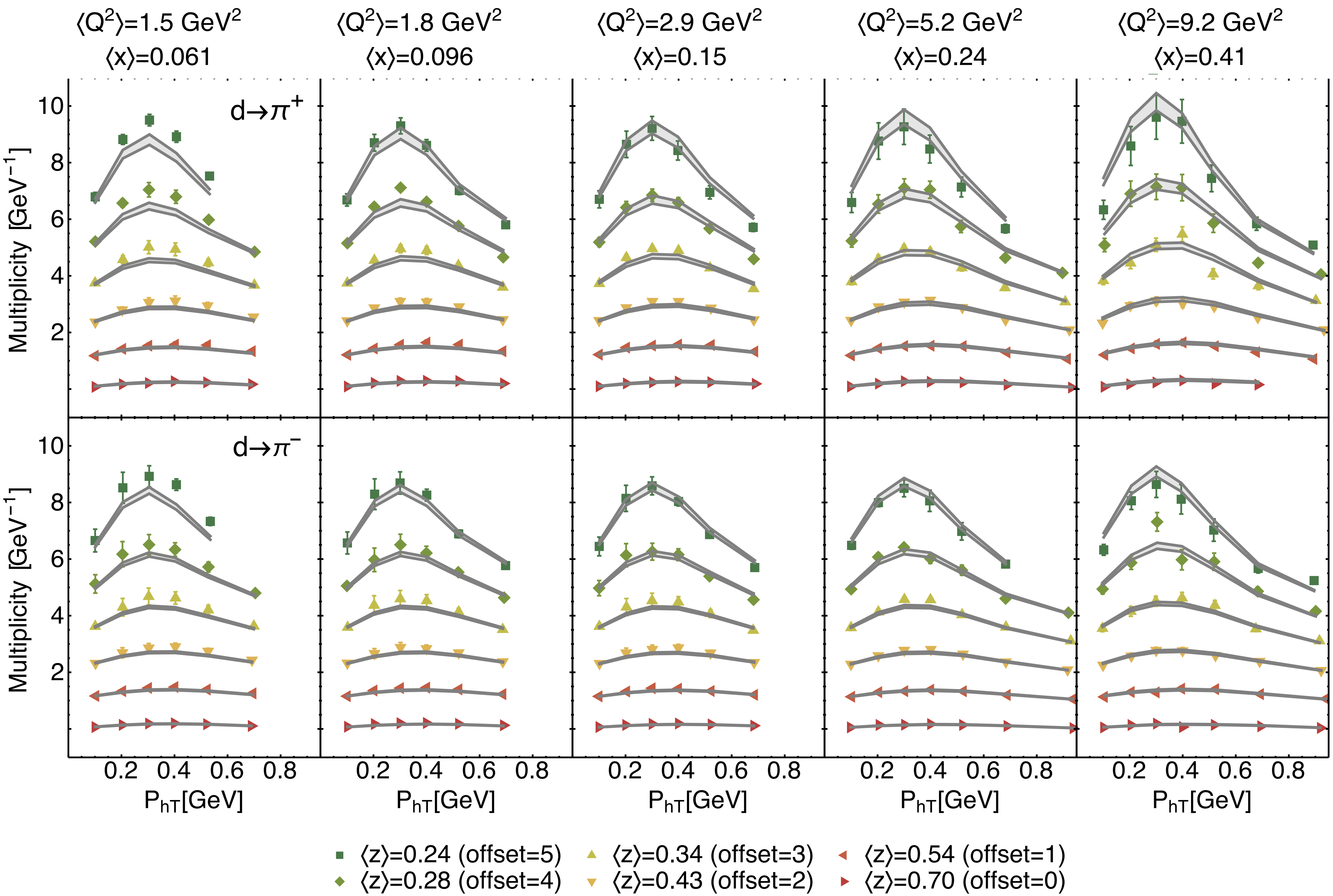
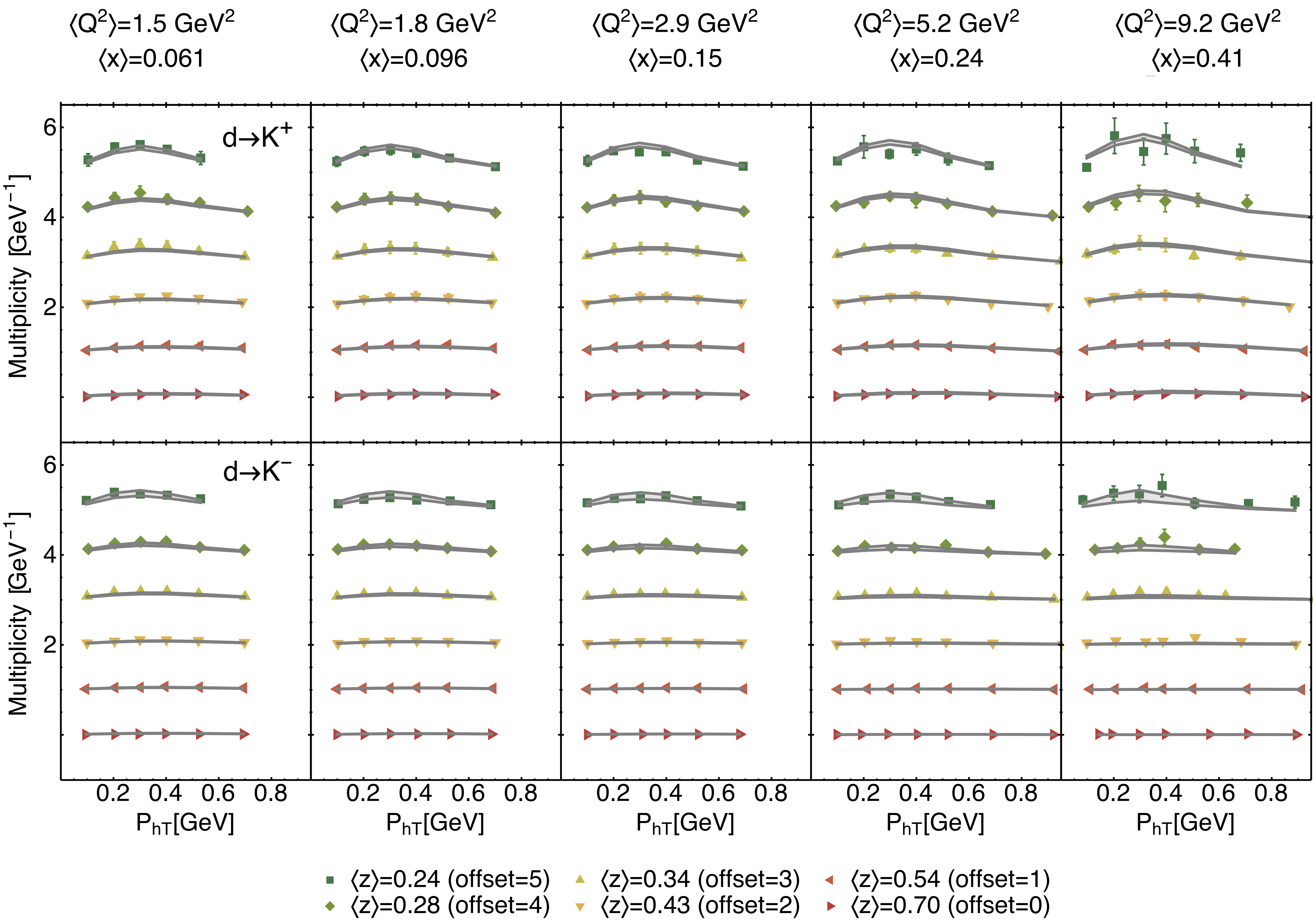
SIDIS @ Hermes



Lab

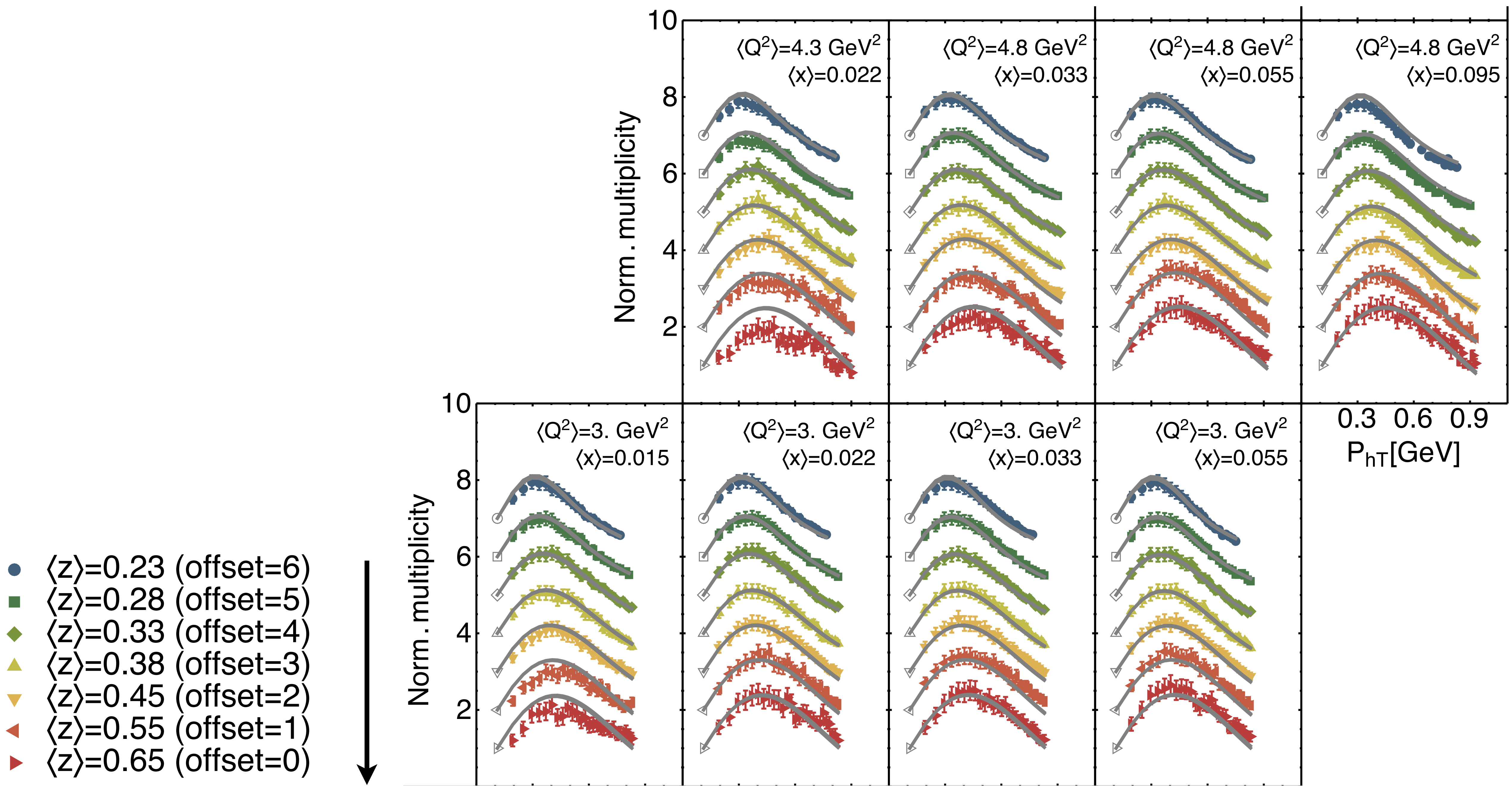
SIDIS @ Hermes



n Lab

SIDIS @ Compass

$\{D,\ h^+\}$



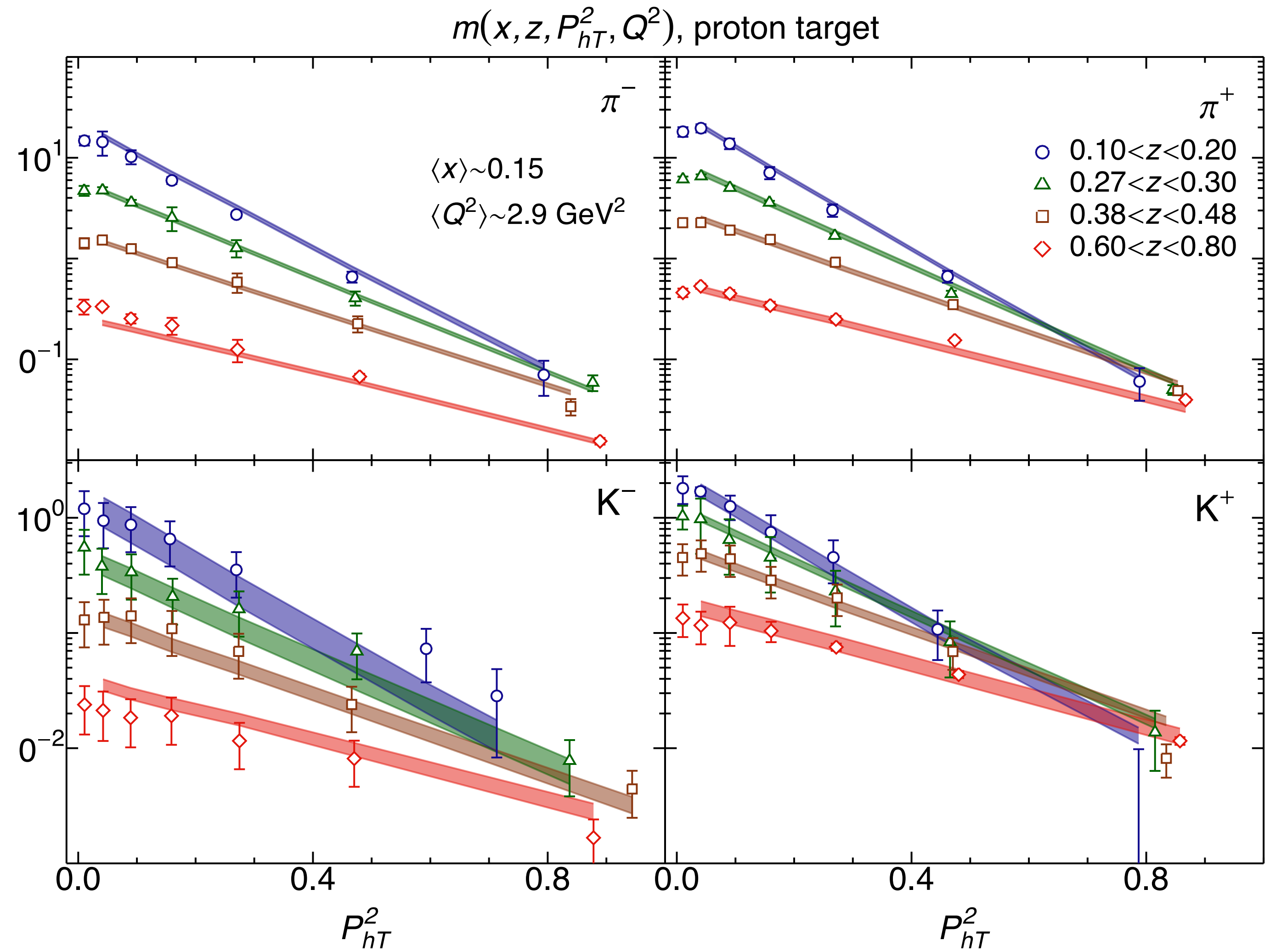
Pavia / Amsterdam / Bilbao 2013

proton target global χ^2 / d.o.f. = 1.63 ± 0.12

no flavor dep. 1.72 ± 0.11

π^-
1.80 ± 0.27
1.83 ± 0.25

K^-
0.78 ± 0.15
0.87 ± 0.16



π^+
2.64 ± 0.21
2.89 ± 0.23

K^+
0.46 ± 0.07
0.43 ± 0.07

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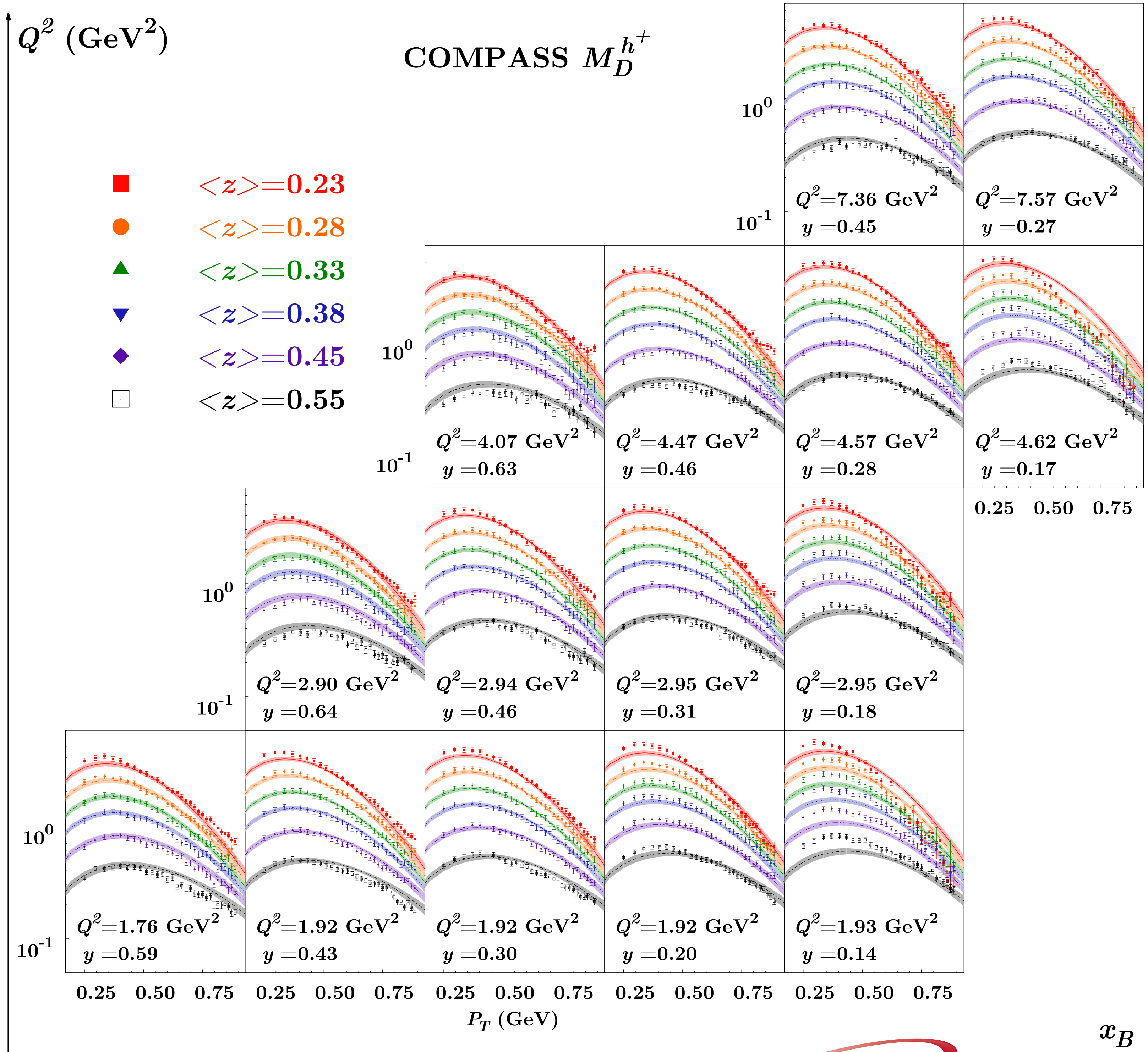
Torino / JLab 2014

COMPASS $M_D^{h^+}$

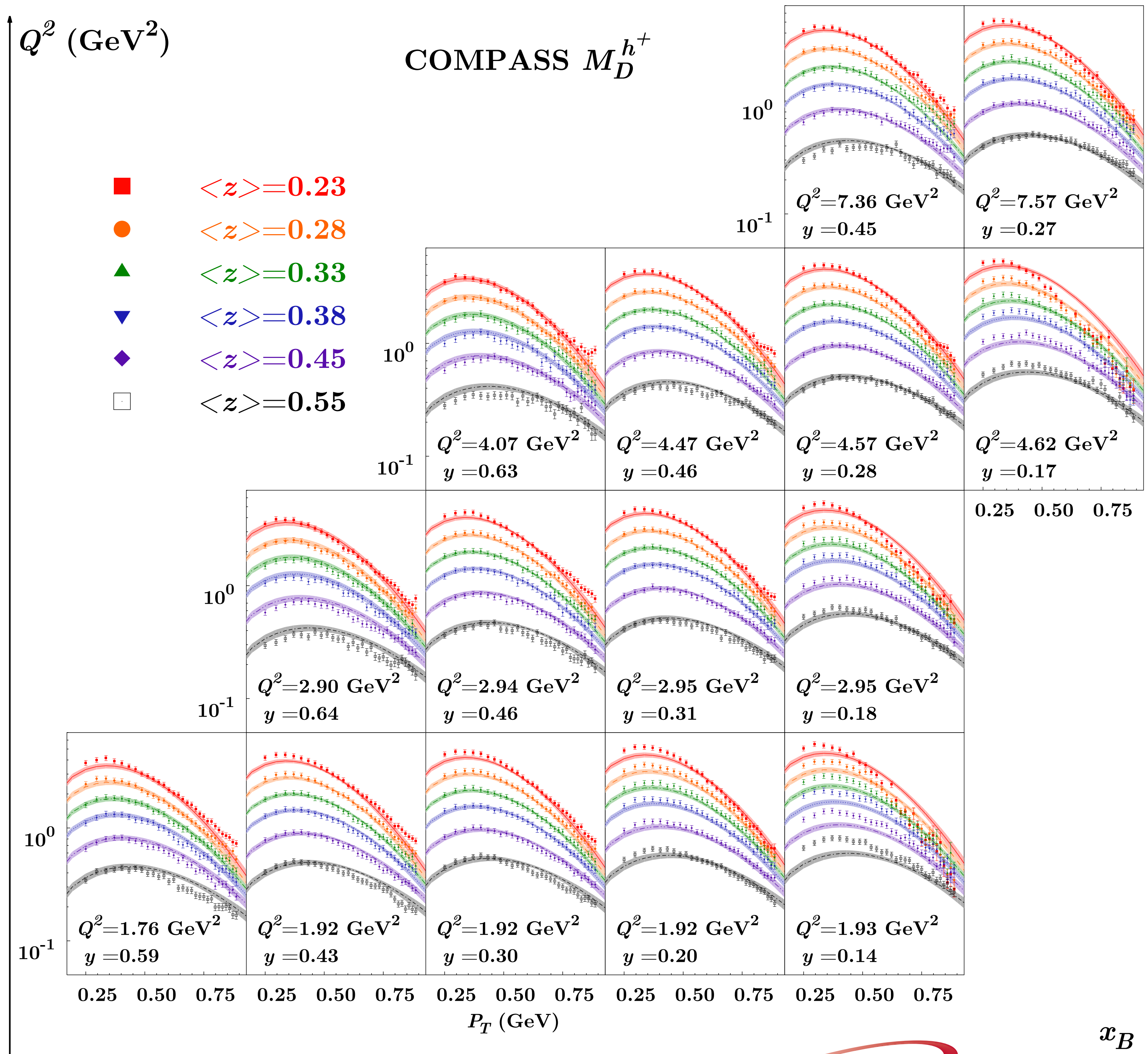


Anselmino, Boglione, Gonzalez, Melis, Prokudin, JHEP 1404 (14)

Torino / JLab 2014

COMPASS $M_D^{h^+}$

χ^2/dof = 3.79
with ad-hoc normalization



Anselmino, Boglione, Gonzalez, Melis, Prokudin, JHEP 1404 (14)

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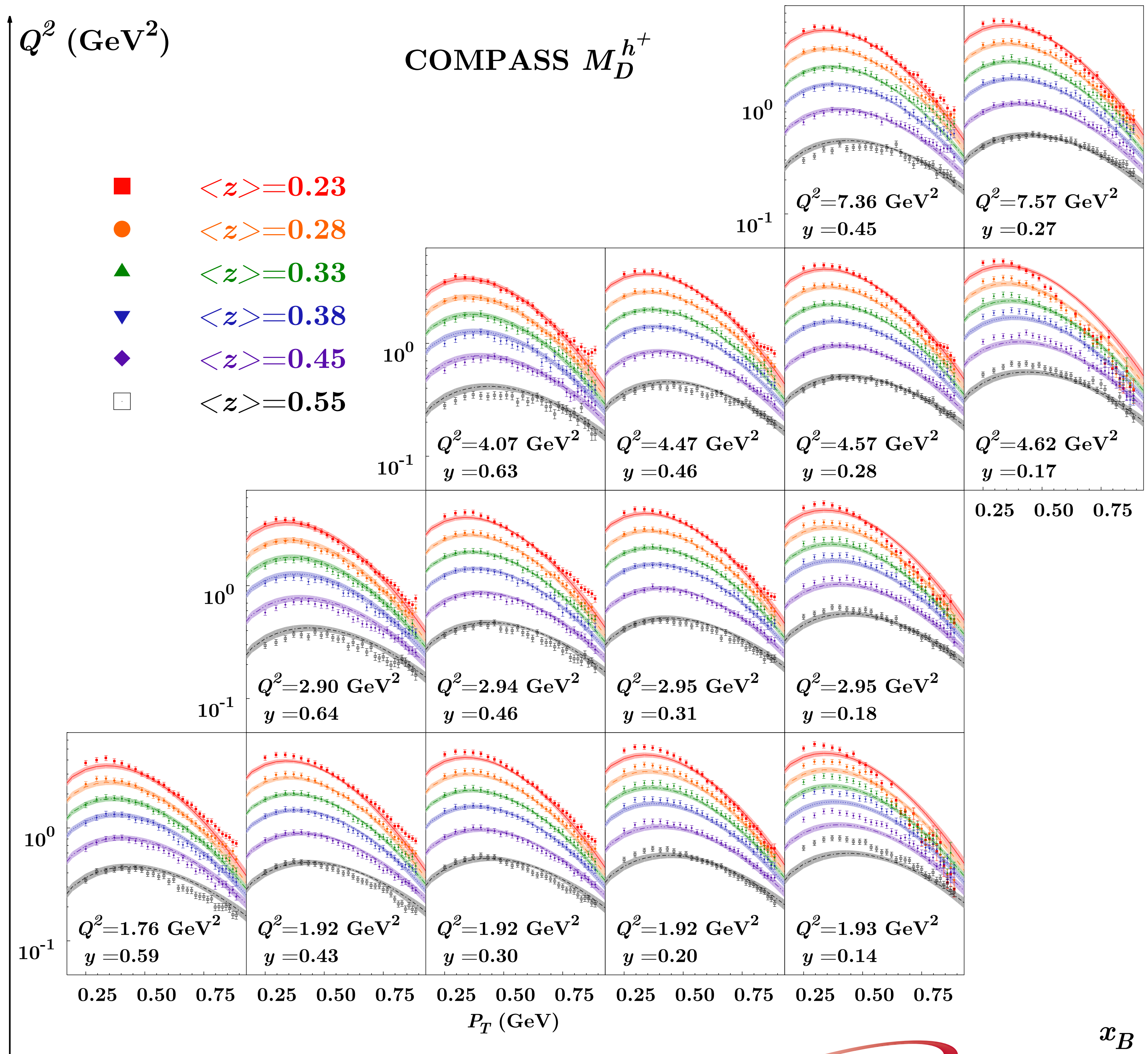
Torino / JLab 2014

COMPASS $M_D^{h^+}$



χ^2/dof = 3.79

with ad-hoc normalization

see Compass coll. Erratum

Anselmino, Boglione, Gonzalez, Melis, Prokudin, JHEP 1404 (14)

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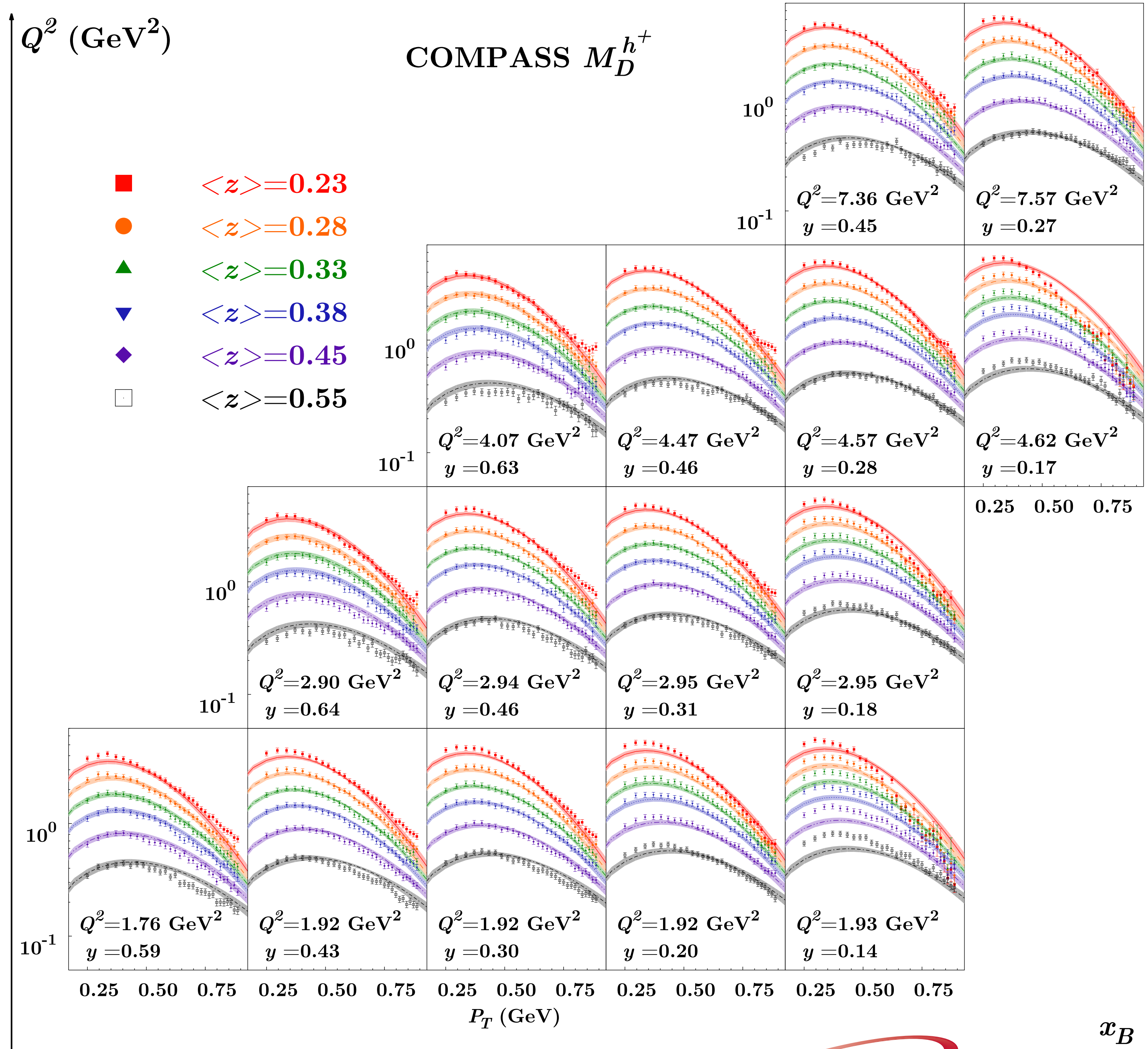
Torino / JLab 2014

COMPASS $M_D^{h^+}$

simple Gaussian ansatz

χ^2/dof = 3.79
with ad-hoc
normalization

see Compass coll.
Erratum



Anselmino, Boglione, Gonzalez, Melis, Prokudin, JHEP 1404 (14)

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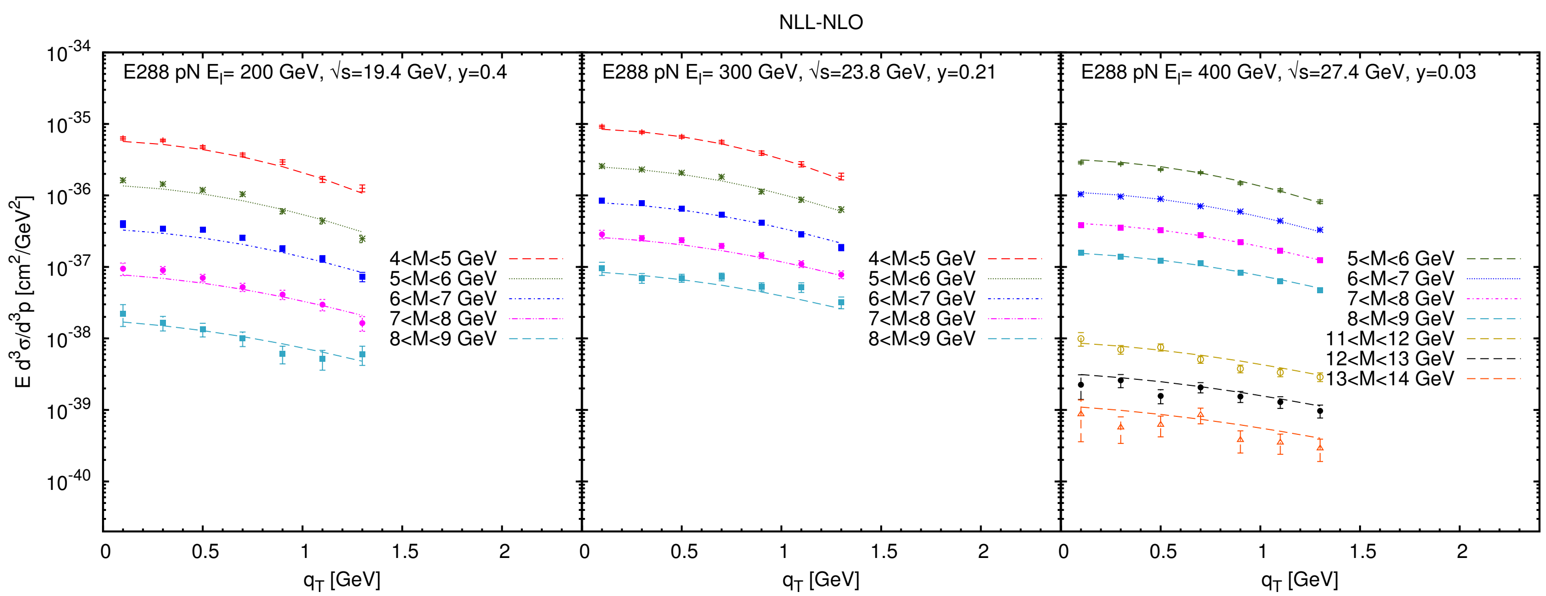
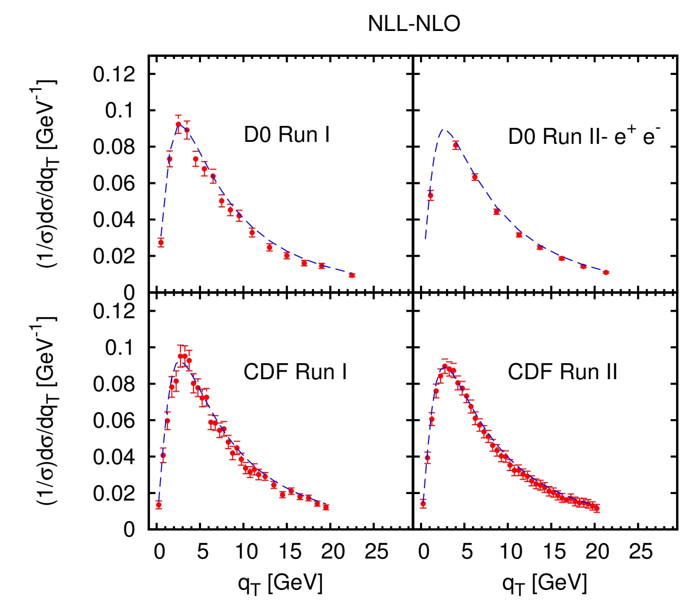
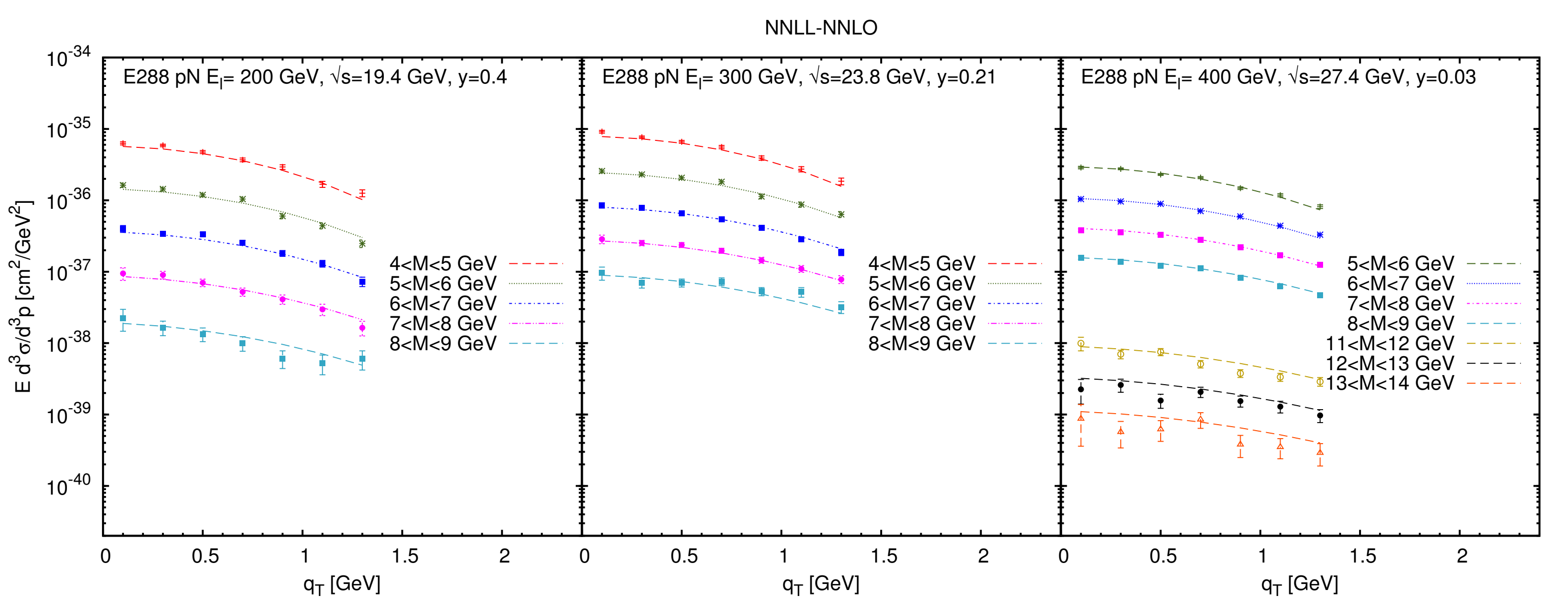
DEMS 2014

D'Alesio, Echevarria, Melis, Scimemi, JHEP 1411 (14)







NLO-NNLL analysis
with evaluation of
theoretical uncertainties

very good

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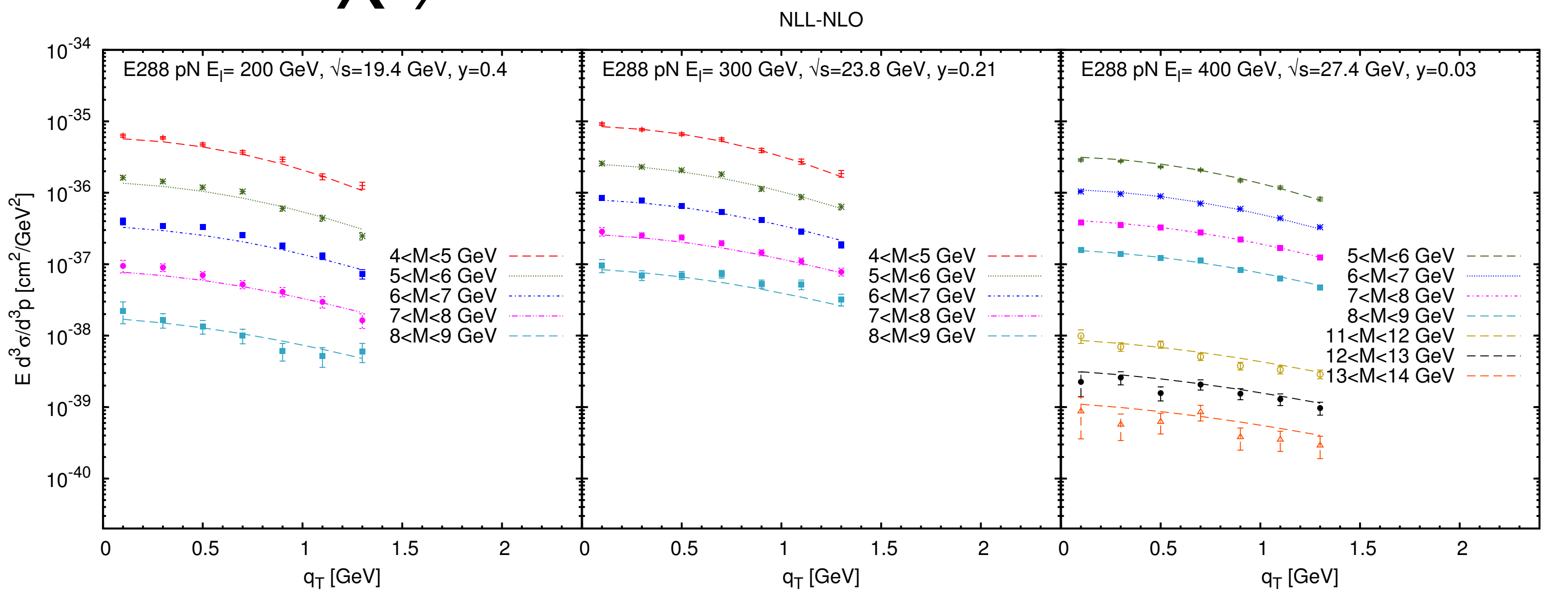
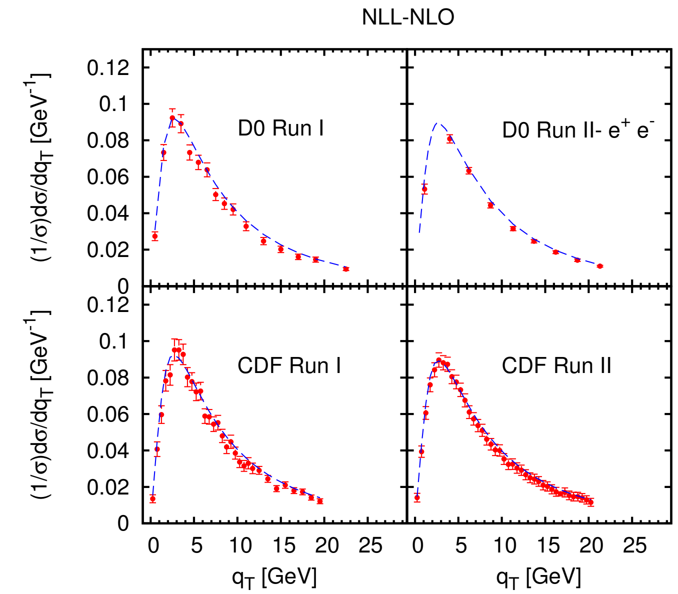
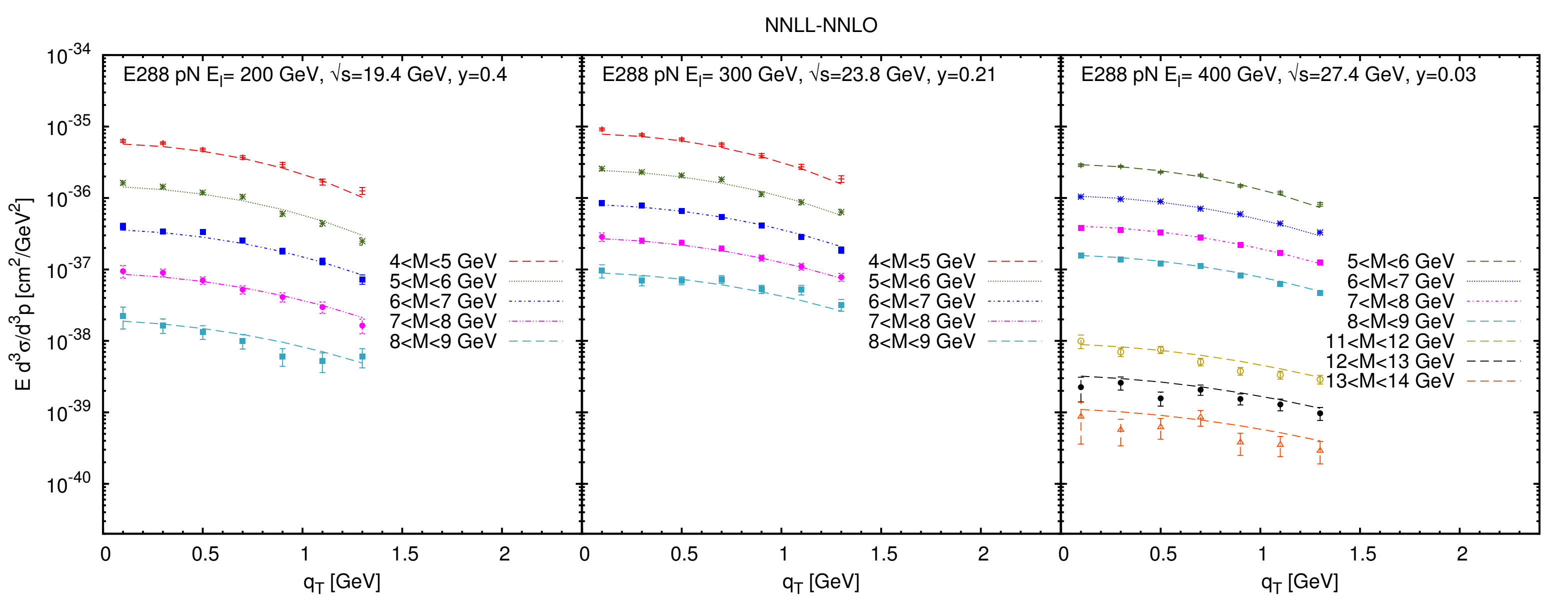
DEMS 2014

D'Alesio, Echevarria, Melis, Scimemi, JHEP 1411 (14)

$\chi^2/\text{dof} = 0.81$







NLO-NNLL analysis
with evaluation of
theoretical uncertainties

very good

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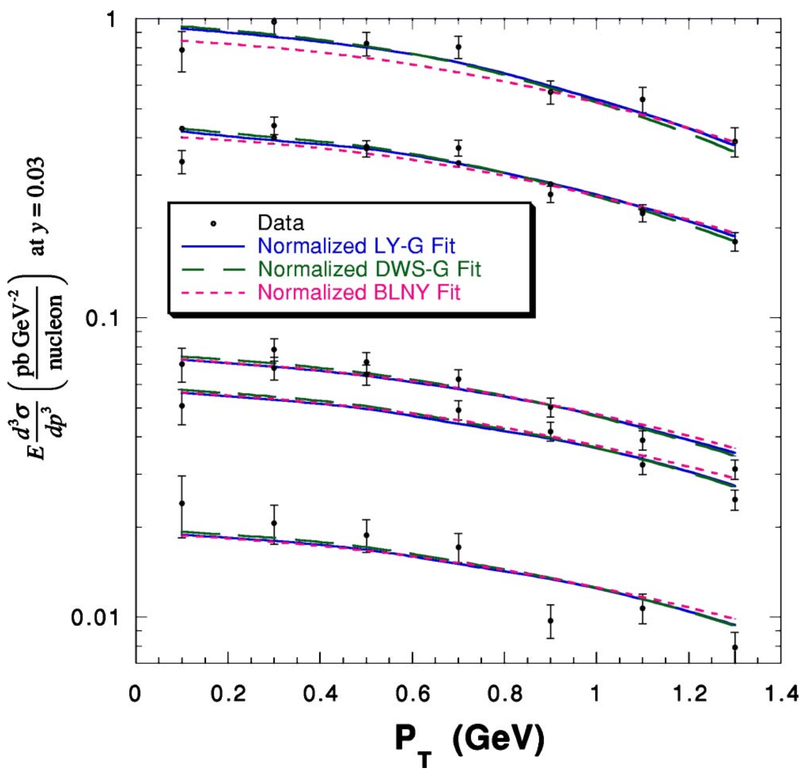
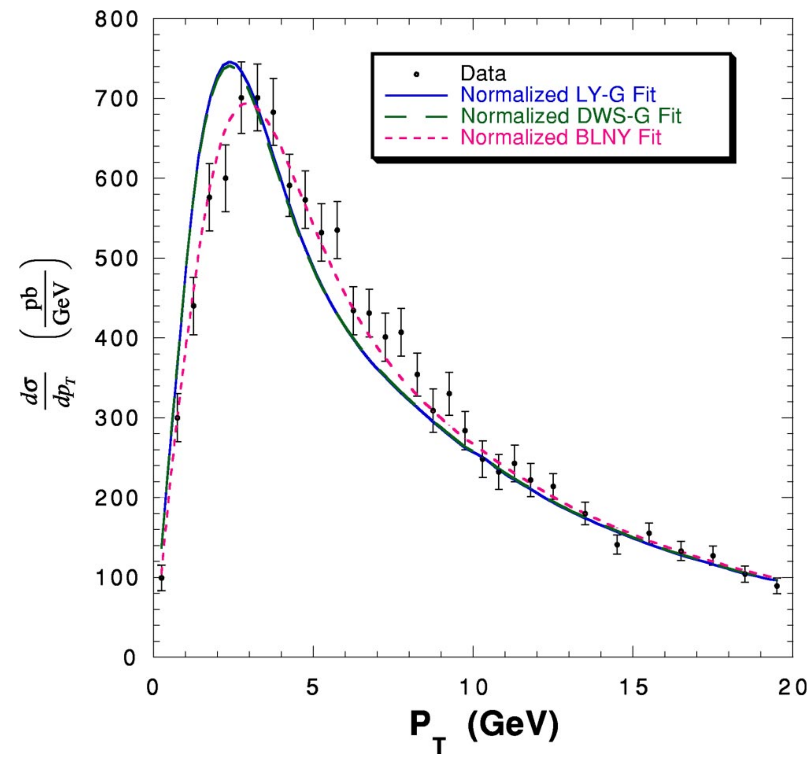
KN 2006

E605 Data



CDF Z Run 1



≈100 data points

$Q^2>4$ GeV

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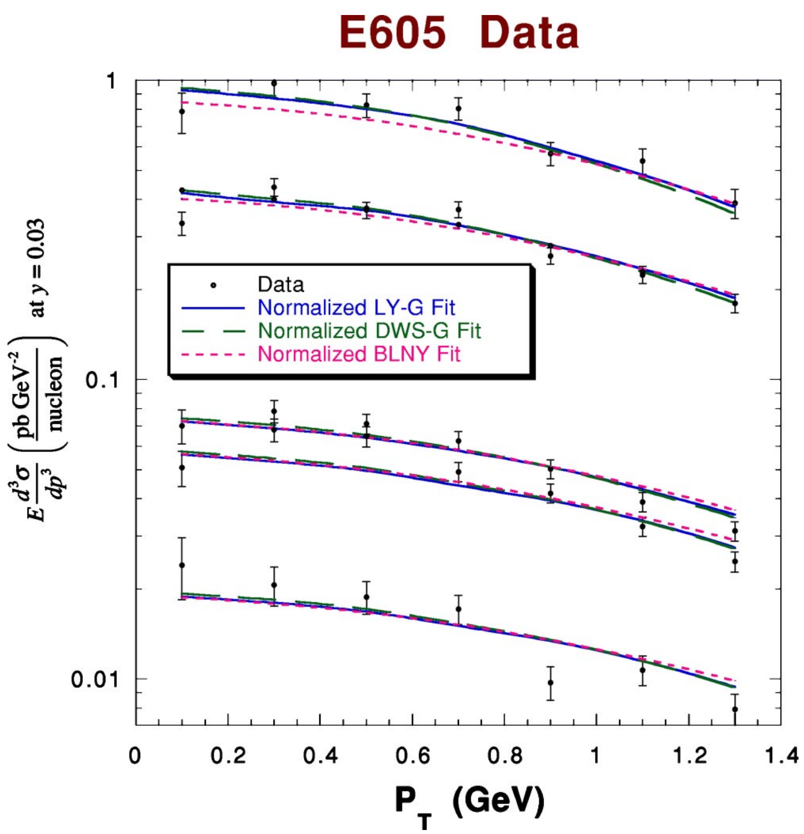
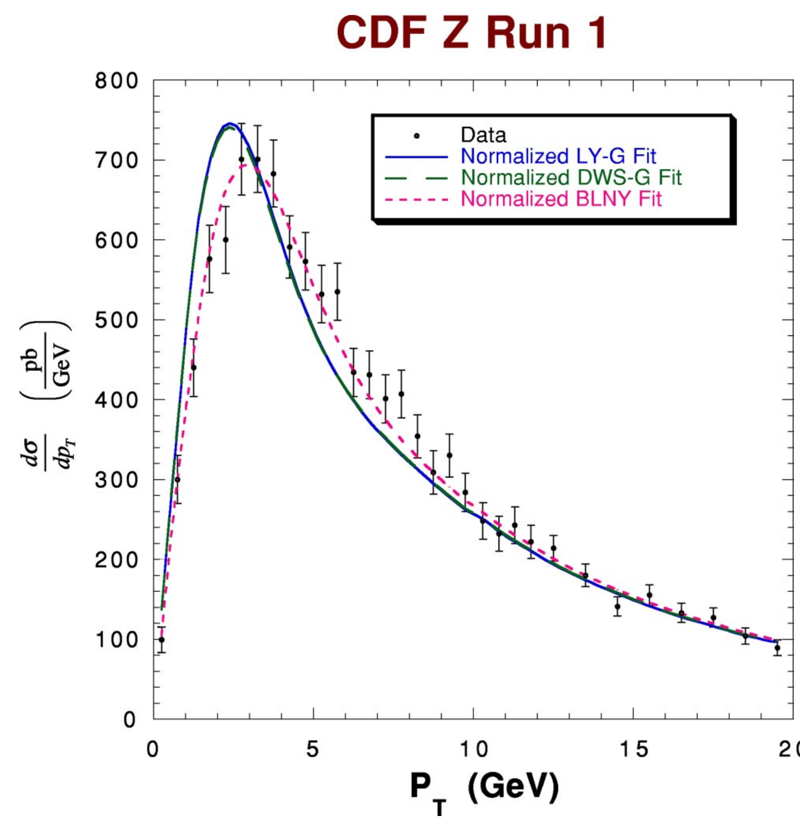
KN 2006





≈100 data points
$Q^2 > 4$ GeV

$$Q_0 = 3.2 \text{ GeV}$$

$$b_{\max} = 0.5 \text{ GeV}^{-1}$$

$$\frac{1}{\langle b_T^2 \rangle} = \frac{1}{2}\left(0.21 + 0.68 \log\left(\frac{Q}{2Q_0}\right) - 0.25 \log(10x)\right)$$

Brock, Landry, Nadolsky, Yuan, PRD67 (03)

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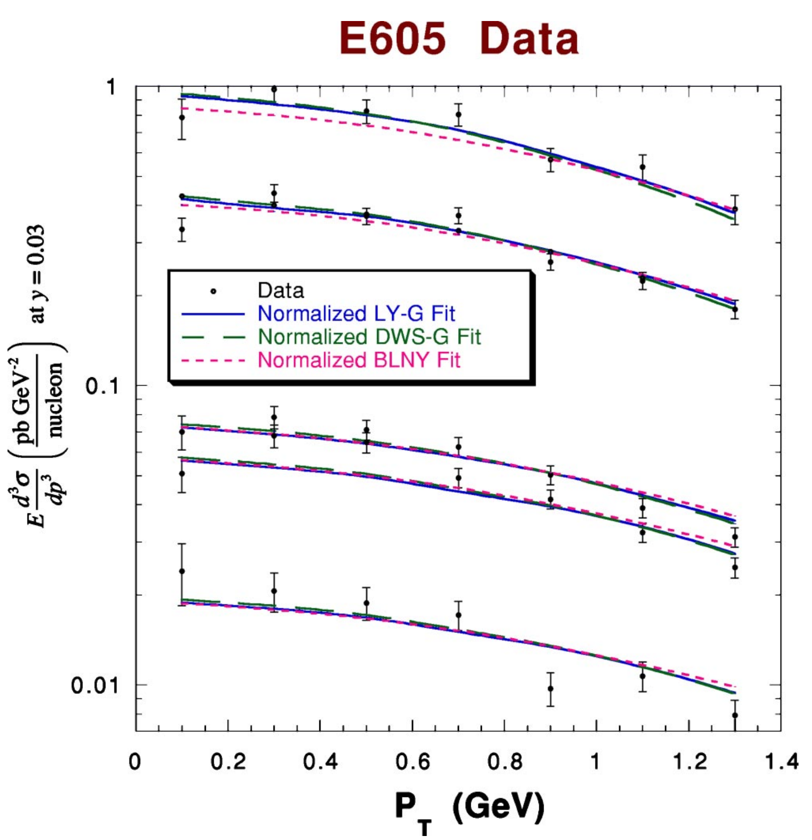
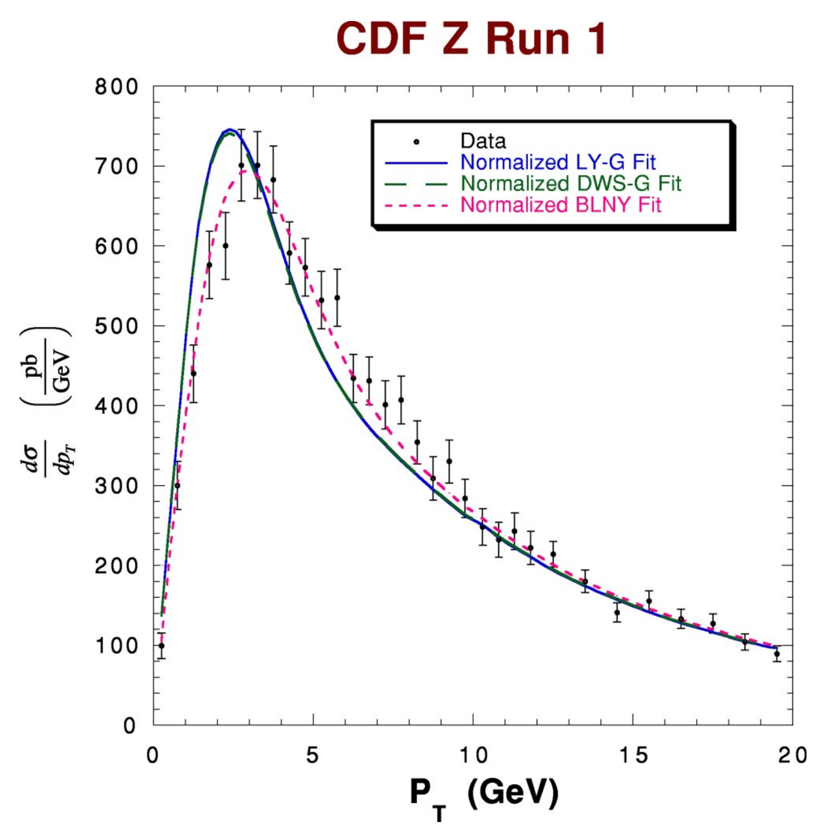
KN 2006





≈100 data points

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$b_{\max} = 0.5\ \mathrm{GeV}^{-1}$

Brock, Landry, Nadolsky, Yuan, PRD67 (03)

$$\frac{1}{\langle b_T^2 \rangle} = \frac{1}{2}\left(0.20 + 0.184 \log\left(\frac{Q}{2Q_0}\right) - 0.026 \log(10x)\right)$$

$b_{\max} = 1.5\ \mathrm{GeV}^{-1}$

EIKV 2014

Parametrizations for intrinsic momenta
and soft gluon emission :

$$F_{NP}(b_T, Q)^{\rm pdf} = \exp\left[-b_T^2\left(g_1^{\rm pdf} + \frac{g_2}{2}\ln(Q/Q_0)\right)\right]$$

$$F_{NP}(b_T, Q)^{\rm ff} = \exp\left[-b_T^2\left(g_1^{\rm ff} + \frac{g_2}{2}\ln(Q/Q_0)\right)\right]$$

Pros and Cons :

1) a global analysis of SIDIS and DY/Z/W data

2) TMD evolution at LO-NLL

3) multidimensionality not exploited

4) chi-square not provided

5) can't be considered as a "complete" fit

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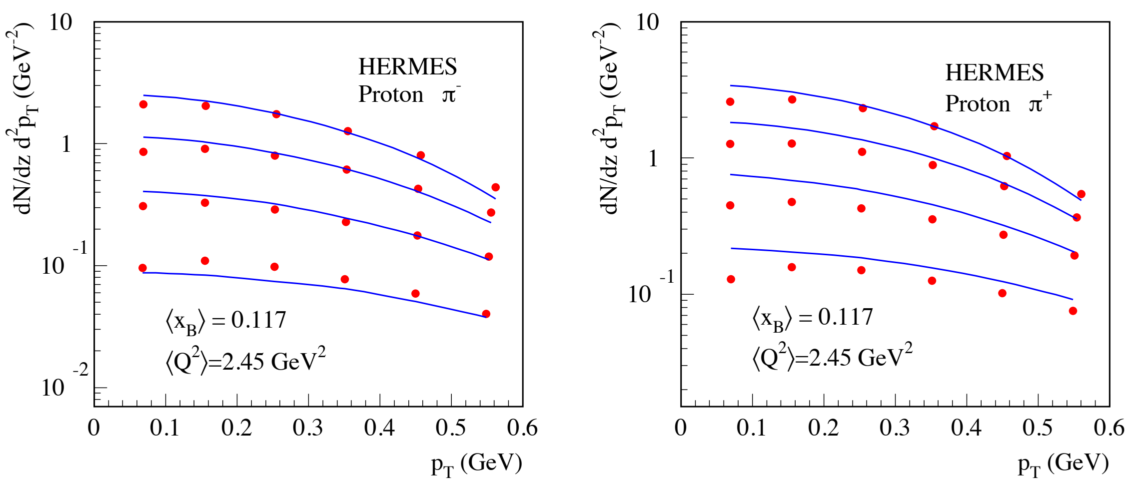
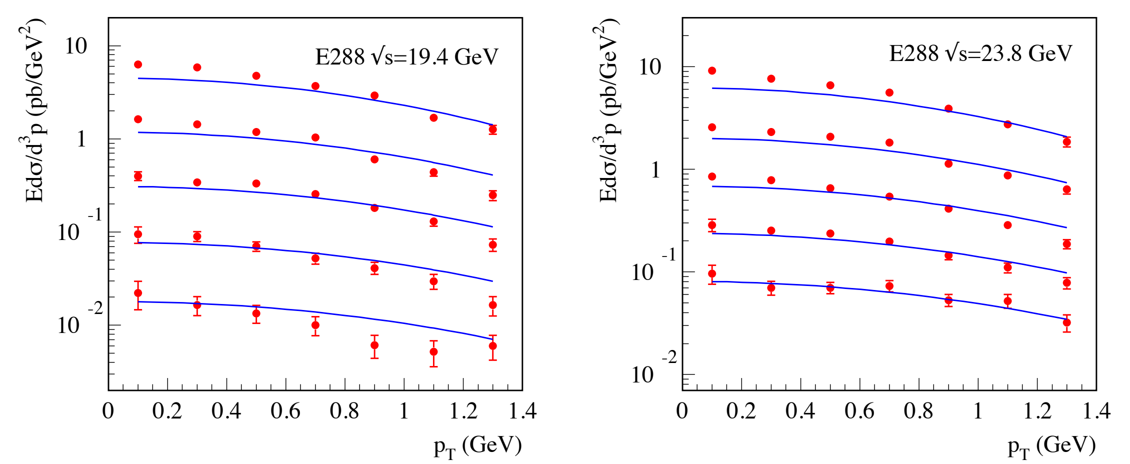
EIKV 2014

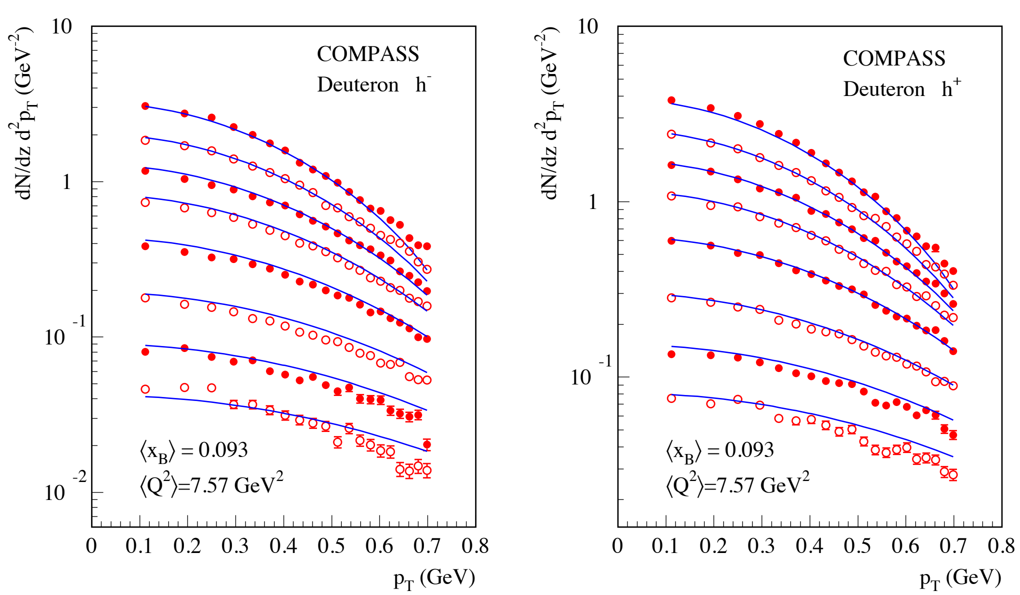
SIDIS



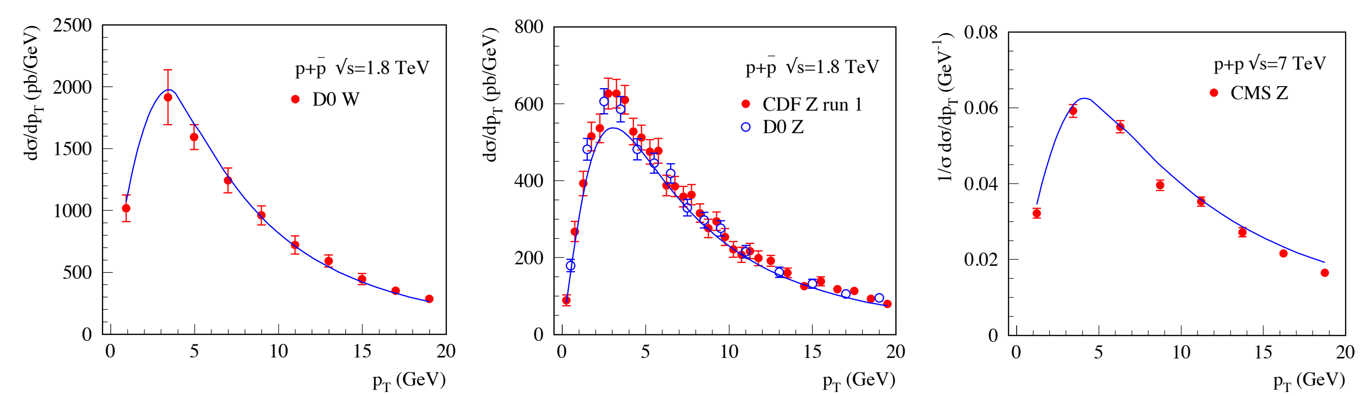
DRELL-YAN



SIDIS



W AND Z PRODUCTION



$$b_{\max} = 1.5 \text{ GeV}^{-1}$$

$$g_2 = 0.16$$

Echevarria et al. arXiv:1401.5078

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Other studies

CSS formalism on DY/Z/W data:

1) Davies-Webber-Stirling (DOI: 10.1016/0550-3213(85)90402-X)

2) Ladinsky-Yuan (DOI: 10.1103/PhysRevD.50.R4239)

3) BLNY (DOI: 10.1103/PhysRevD.63.013004)

4) Hirai, Kawamura, Tanaka (DOI: 10.3204/DESY-PROC-2012-02/136) - complex-b prescription

...

combined SIDIS/DY/W/Z :

5) Sun, Yuan (arXiv:1308.5003)

6) Isaacson, Sun, Yuan, Yuan (arXiv:1406.3073)

...