A first extraction of quark TMDs from a global analysis of *ep* and *pp* data

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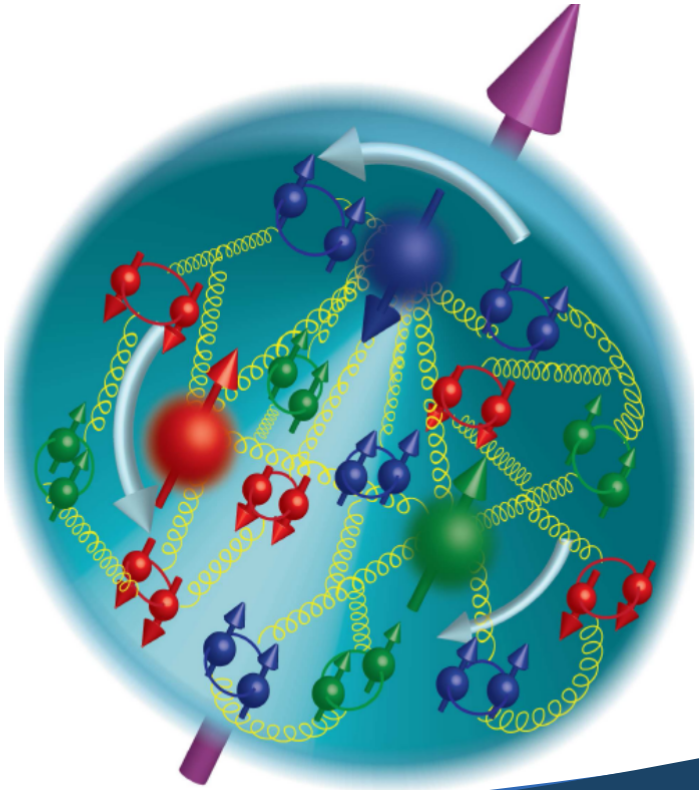
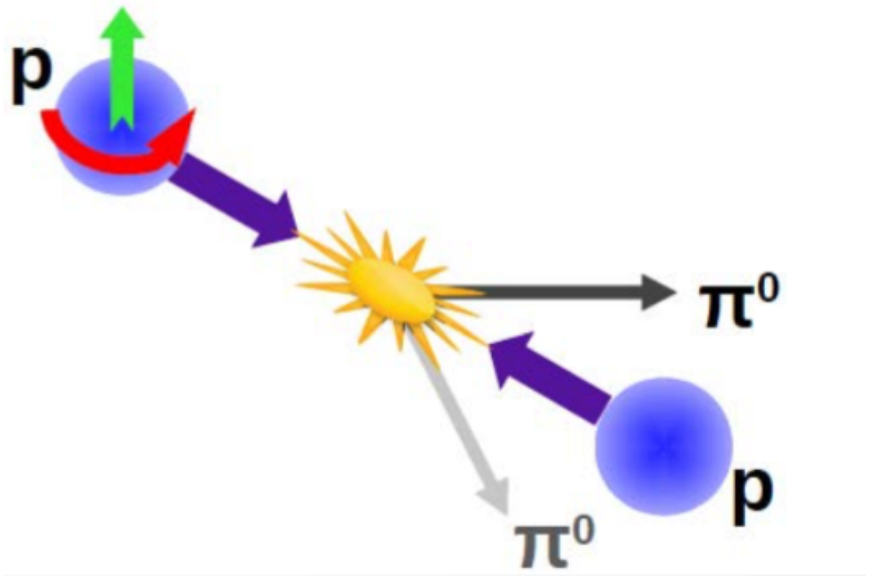
IPN Orsay (France), 22 March 2018



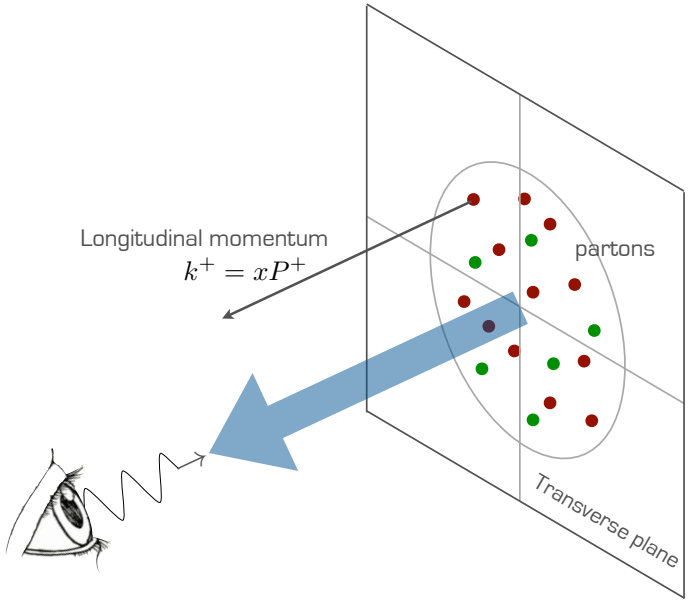
Scattering processes at high energy scales $Q \gg M_p$ (proton mass) provide important information on the internal structure of hadrons

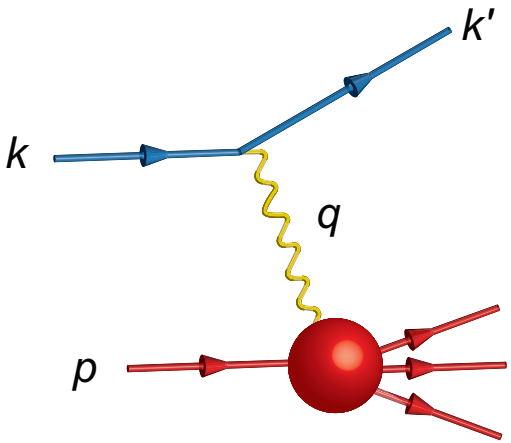


Partons are usually taken to be collinear to their parent hadrons

The probe defines a longitudinal direction

1D-Parton Distribution Functions are universal

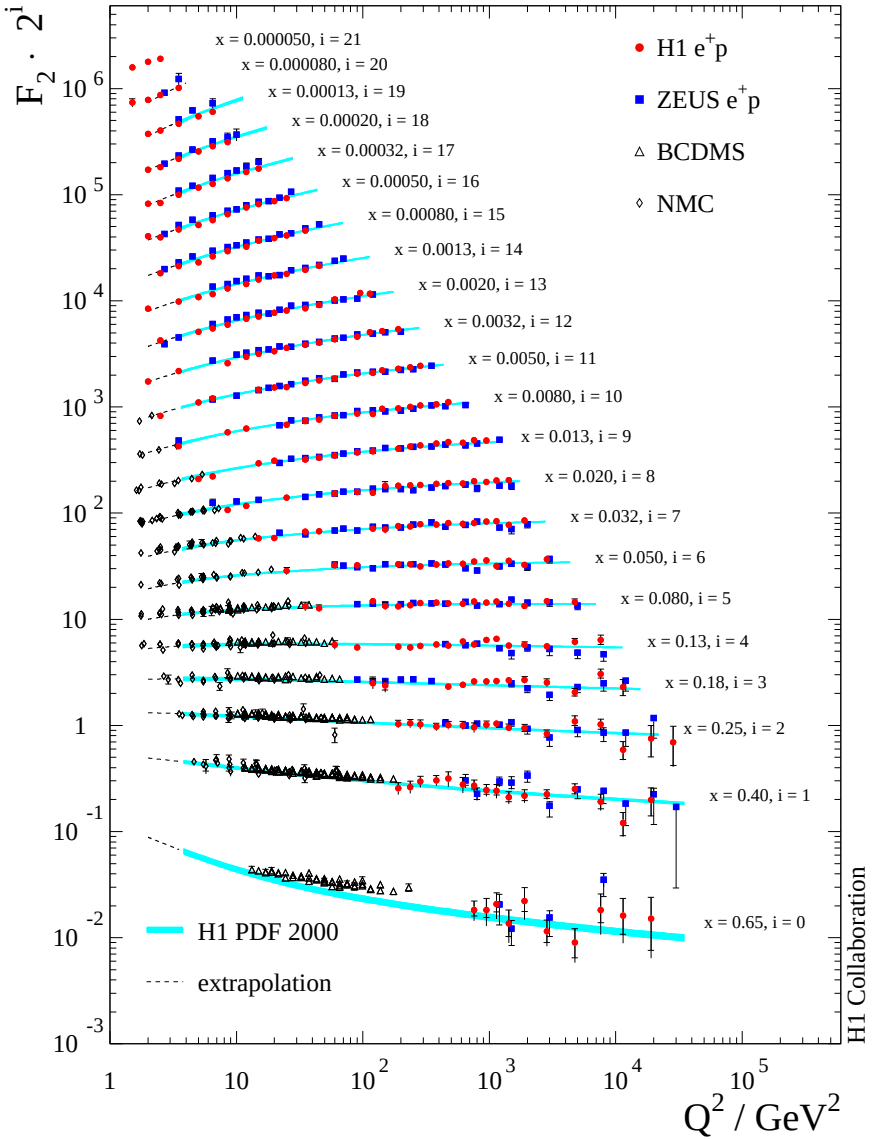




x: fraction of proton's momentum carried by the struck quark

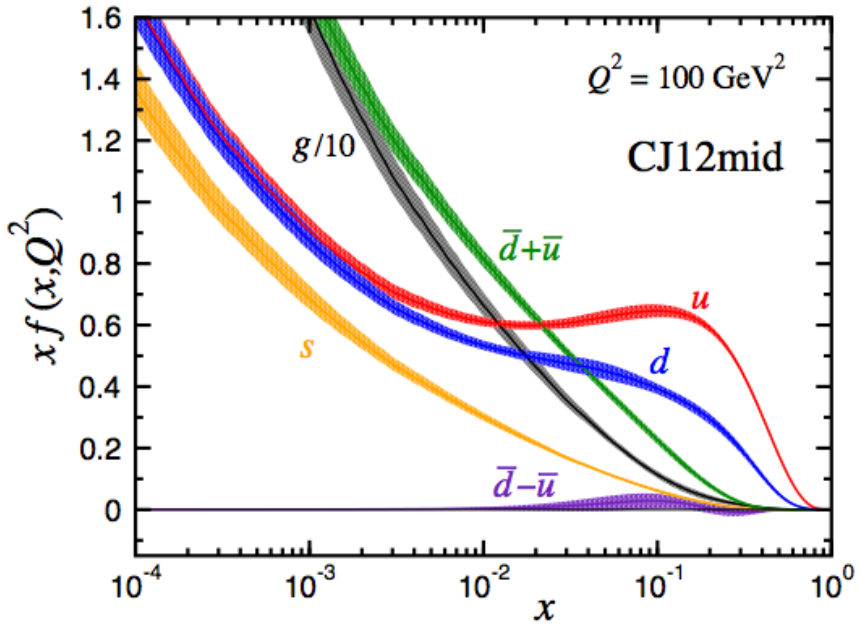
$Q^2 \equiv -q^2$: defines the resolution of the measurement

Structure Function F_2



$$F_2(x, Q^2) = x \sum_q e_q^2 \, f_1^q(x, Q^2)$$

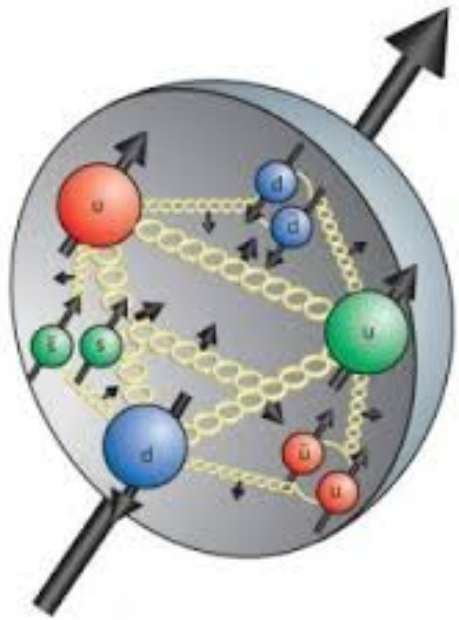
1D collinear parton distributions



CTEQ-JLAB Collaboration, PRD 87 (2013)

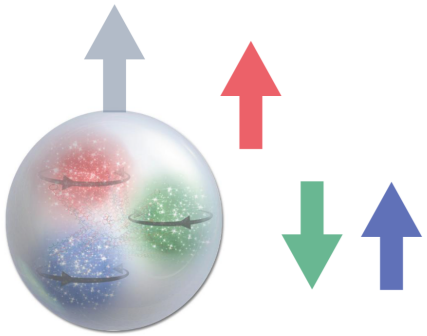
Scaling violations: great success of QCD evolution!

The one-dimensional picture of the proton is not always satisfactory: a more complete description is nedeed



Spin: fundamental quantum degree of freedom, a tool to study the inner structure of a composite system like the nucleon

The proton has spin 1/2, the three *valence* quarks have also spin 1/2, we expect:



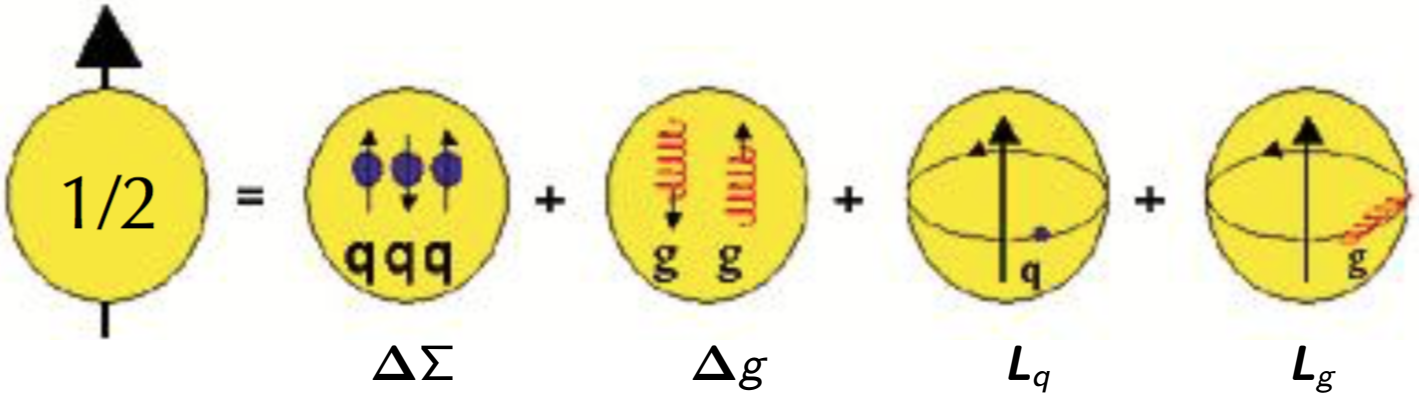
However: only 30% of the spin of the proton comes from the spin of the quarks

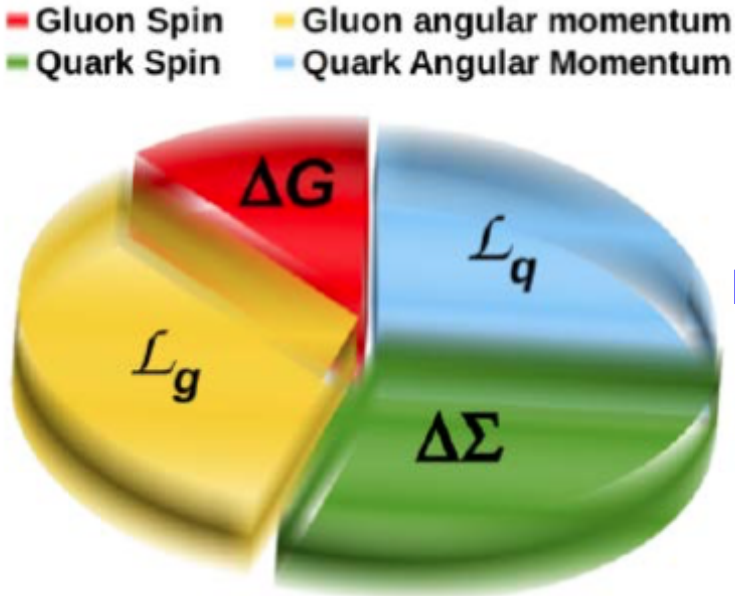
First measurement by the European Muon Collaboration (EMC, CERN 1987)

$$\vec{\mu}\vec{p} \to \mu X \qquad\qquad A = \frac{(\vec{\mu}\vec{p}) - (\vec{\mu}\,\overleftarrow{p})}{(\vec{\mu}\,\vec{p}) + (\vec{\mu}\,\overleftarrow{p})}$$

Spin asymmetry in longitudinally polarized muon-proton scattering

One needs to take into account the partonic orbital angular momentum



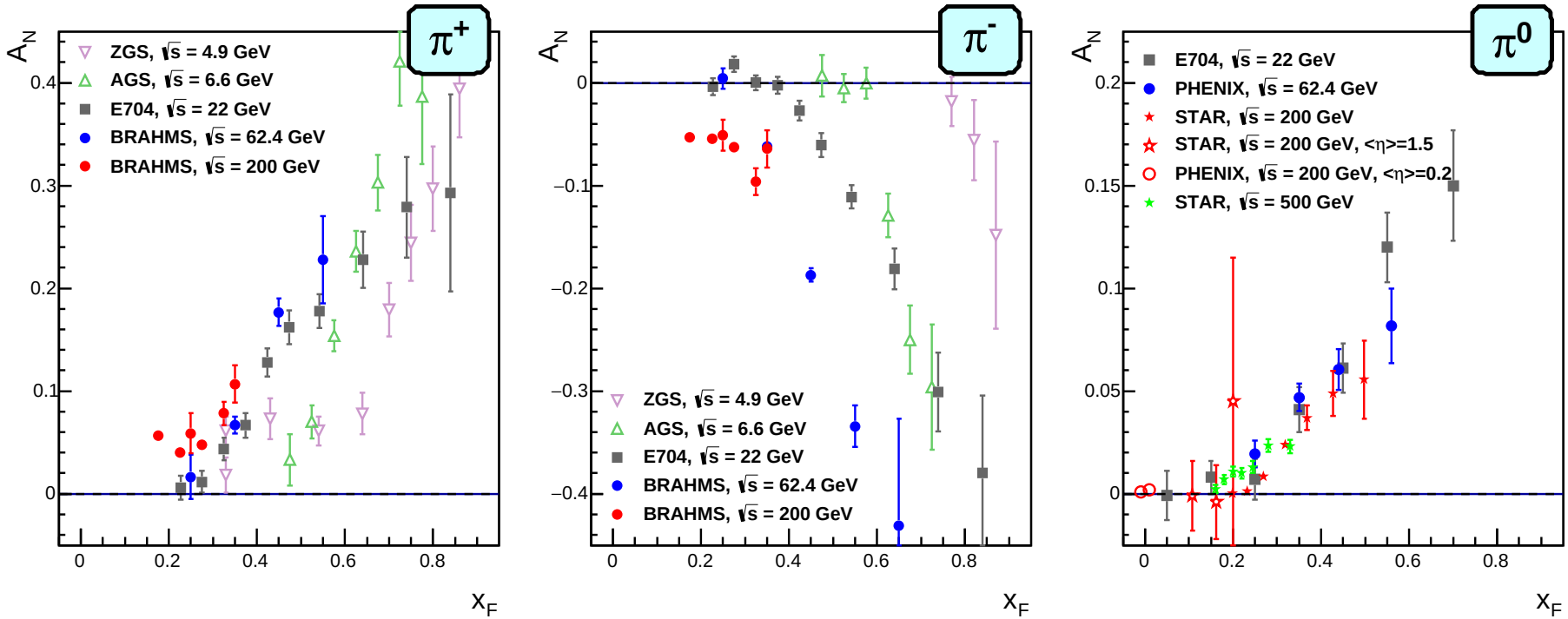


Different definitions of orbital angular momentum:
the decomposition is highly non trivial

Leader, Lorcé, Phys Rept 541 (2014)

A_N in $p^\uparrow p \to \pi X$ is a long standing puzzle, only a few % in twist-2 collinear QCD

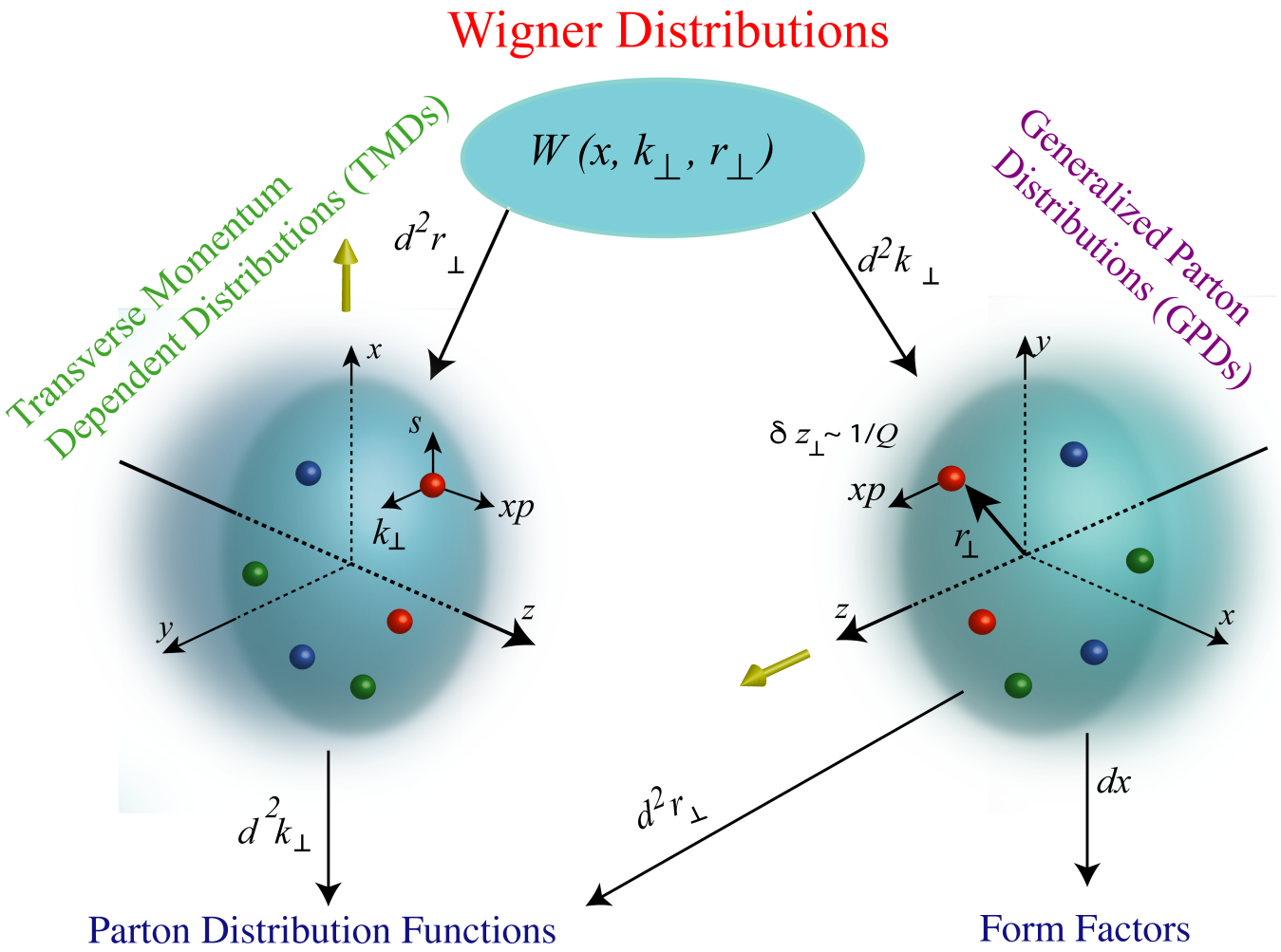
$$A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \qquad x_F = \frac{2p_L}{\sqrt{2}}$$



Aschenauer, D'Alesio, Murgia, EPJA52 (2016)

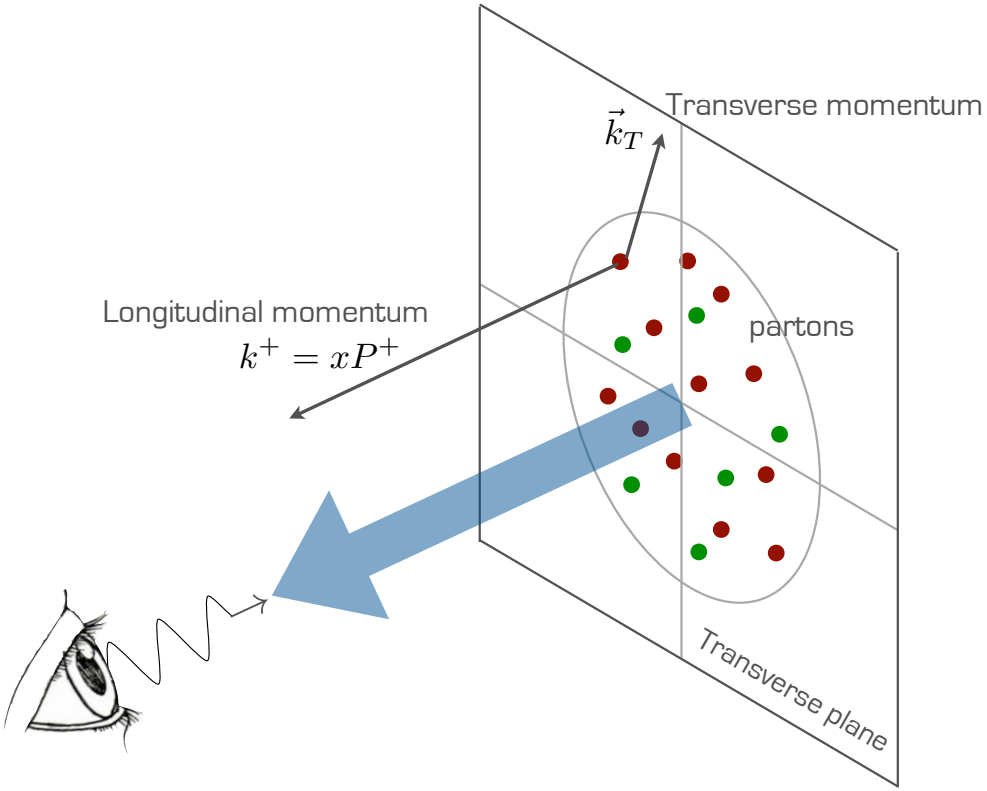
Almost energy independent

Proton's image in 3D: in momentum (TMDs) and in configuration space (GPDs)



Transverse momentum dependent parton distributions

Three-dimensional distributions: provide information on the partonic longitudinal momentum and the two-dimensional transverse momentum



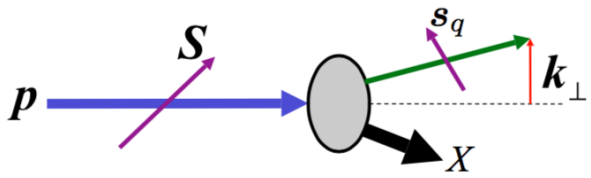
The are eight TMDs for quarks (many more than collinear PDFs!):

More detailed information on the structure of the proton

Leading Twist TMDs

Nucleon Polarization	Quark Polarization: Un-Polarized (U)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: Transversely Polarized (T)
U	f_1 =		$h_1^\perp$ = — Boer-Mulders
L		g_{1L} = — Helicity	$h_{1L}^\perp$ = —
T	$f_{1T}^\perp$ = — Sivers	$g_{1T}^\perp$ = —	h_1 = — Transversity $h_{1T}^\perp$ = —

Beyond the unpolarized f_1, helicity g_{1L} and transversity h_1 surving the collinear limit, we have five more. In particular the Sivers ($f_{1T}^{\perp}$) and Boer-Mulders ($h_1^{\perp}$):



$\boldsymbol{S} \cdot (\boldsymbol{p} \times \boldsymbol{k}_\perp)$
Sivers effect

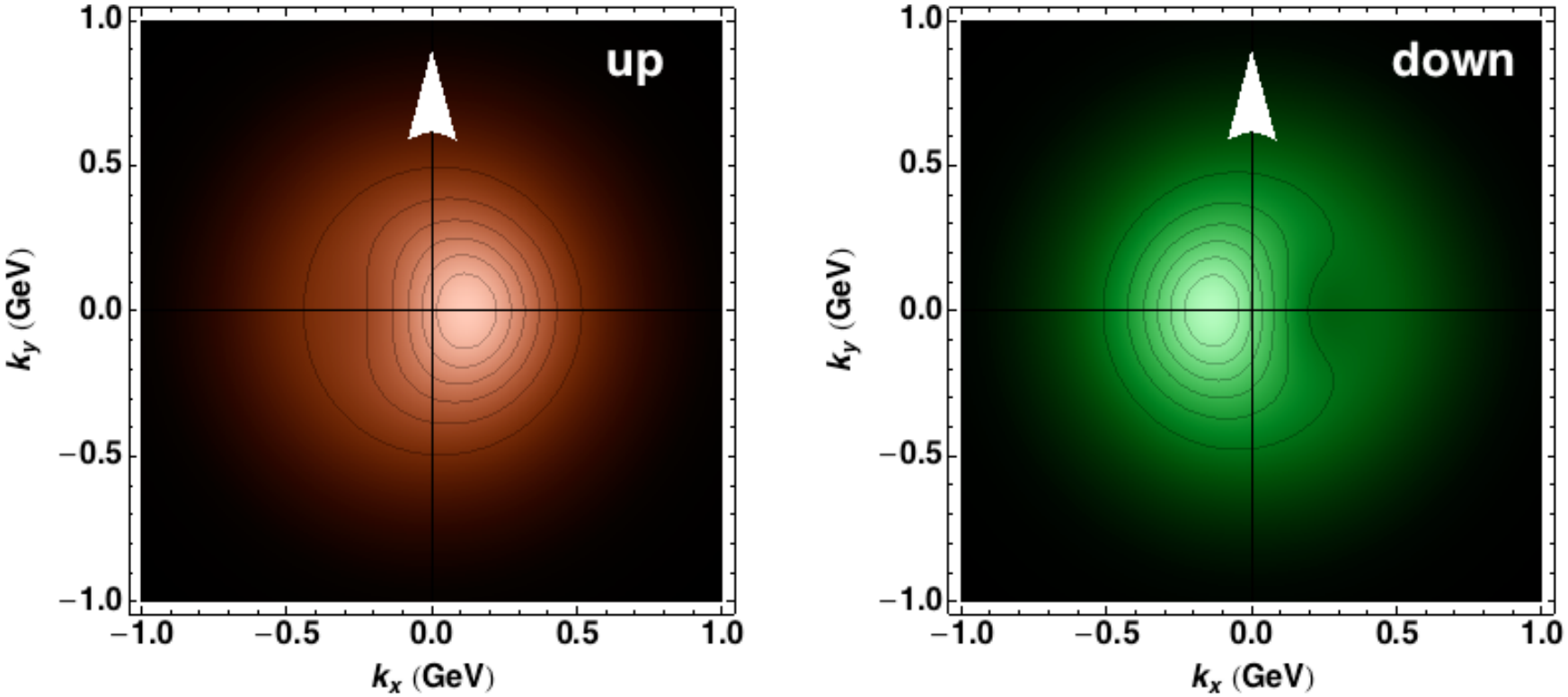
$\boldsymbol{s}_q \cdot (\boldsymbol{p} \times \boldsymbol{k}_\perp)$
Boer-Mulders effect

Correlations between (proton or quark) spin and quark transverse momentum

The Sivers effect is expected to give rise to transverse single spin asymmetries

Sivers (1989)

Distorsion in the transverse plane

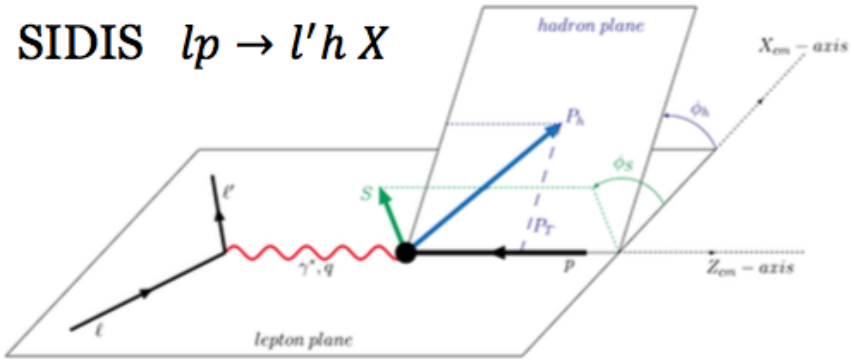


Bacchetta, Contalbrigo (2012)

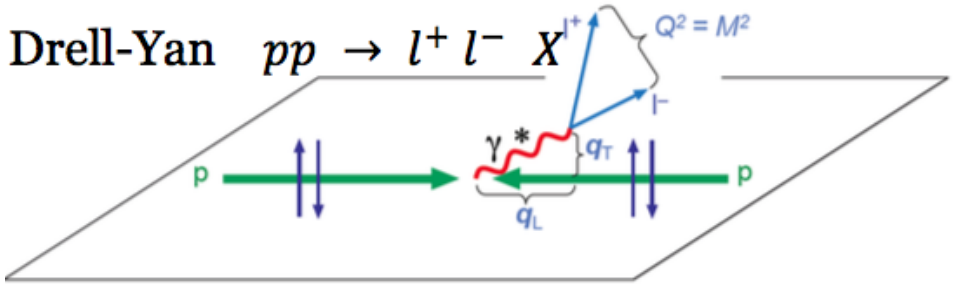
Non zero Sivers effect related to parton orbital angular momentum

Two scale processes $Q^2 \gg p_T^2$

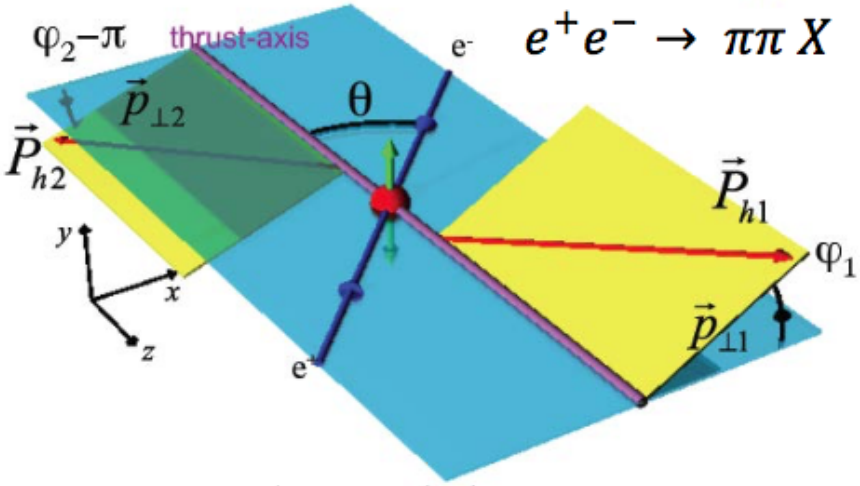
SIDIS $lp \to l'h\,X$



Drell-Yan $pp \to l^+ l^- X$



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



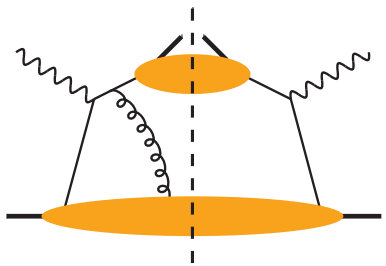
Factorization proven

TMD distributions are affected by initial (ISI) and final (FSI) state interactions

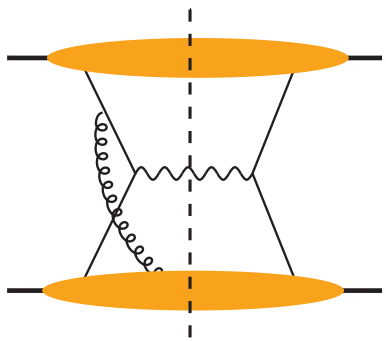
Encoded in the *Wilson lines*, needed to have a gauge invariant definition of TMDs

Fundamental test of TMD theory

$$f_{1T}^{\perp\,[DY]}(x, \boldsymbol{k}_\perp^2) = -f_{1T}^{\perp\,[SIDIS]}(x, \boldsymbol{k}_\perp^2) \qquad h_1^{\perp\,[DY]}(x, \boldsymbol{k}_\perp^2) = -h_1^{\perp\,[SIDIS]}(x, \boldsymbol{k}_\perp^2)$$



FSI in SIDIS

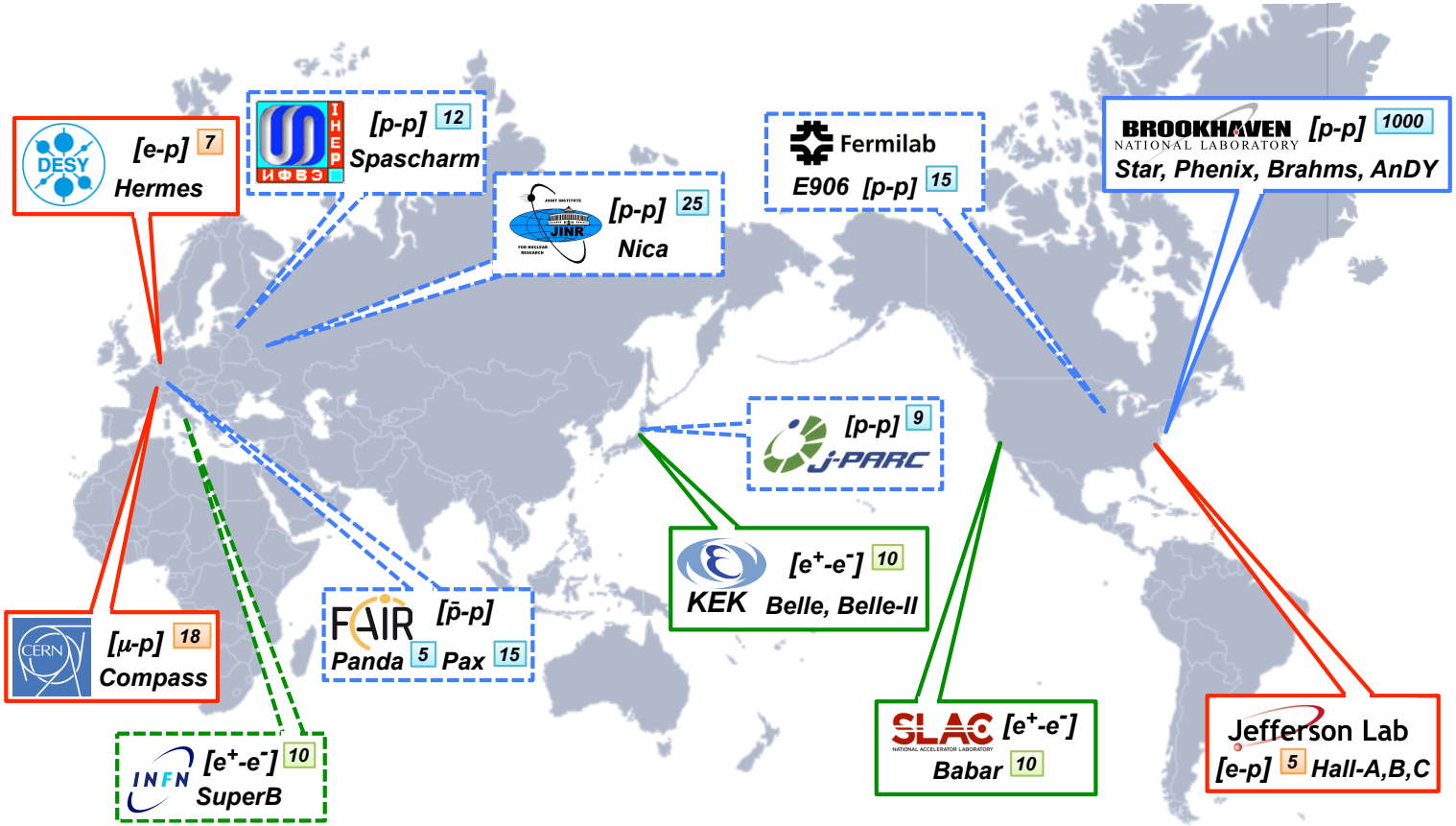


ISI in DY

ISI/FSI lead to process dependence of TMDs, could even break factorization

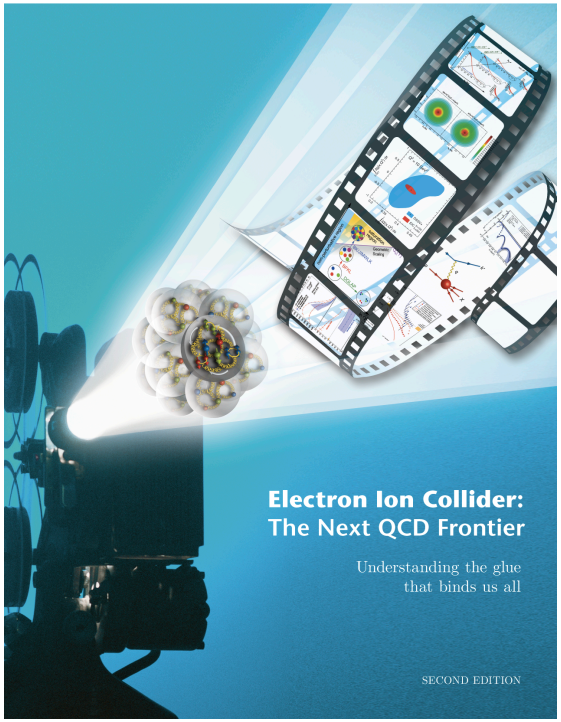
Rogers, Mulders, PRD81 (2010)

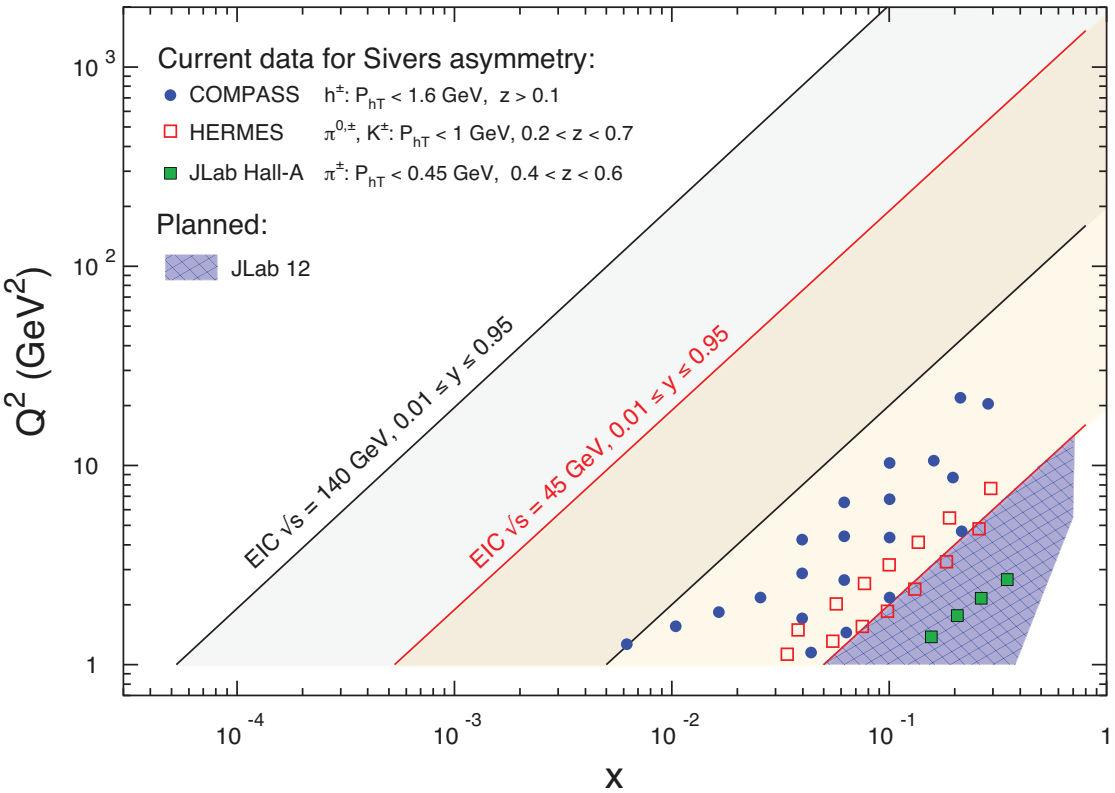
TMDs are, or will be, under experimental investigation all over the world



Bacchetta, Contalbrigo (2012)

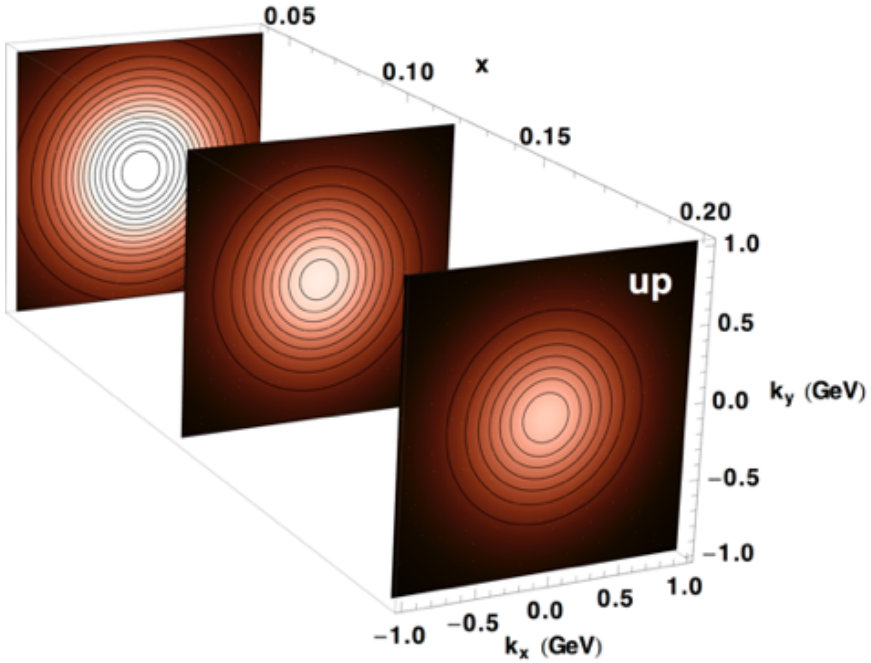
The future Electron Ion Collider





- Access to small-x domain
- Space, momentum and spin distributions of gluon and sea quarks
- Missing and complementary information on TMDs and GPDs

Extraction of unpolarized quark distributions

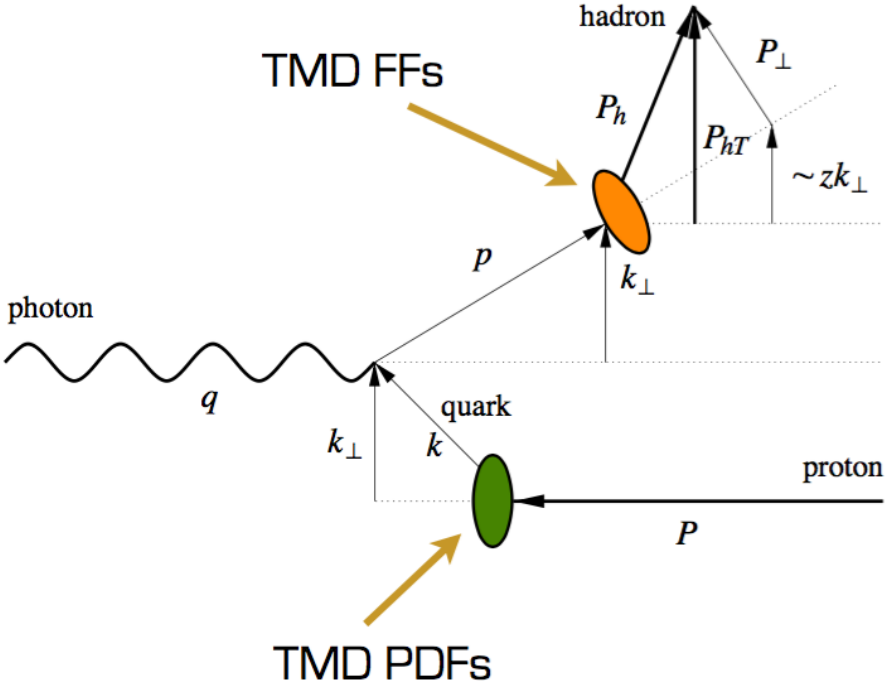


- Are unpolarized quark TMDs universal?
- Does TMD evolution allow for a description of the data at different Q^2?
- How wide is the transverse momentum distribution? Is it wider at low x?

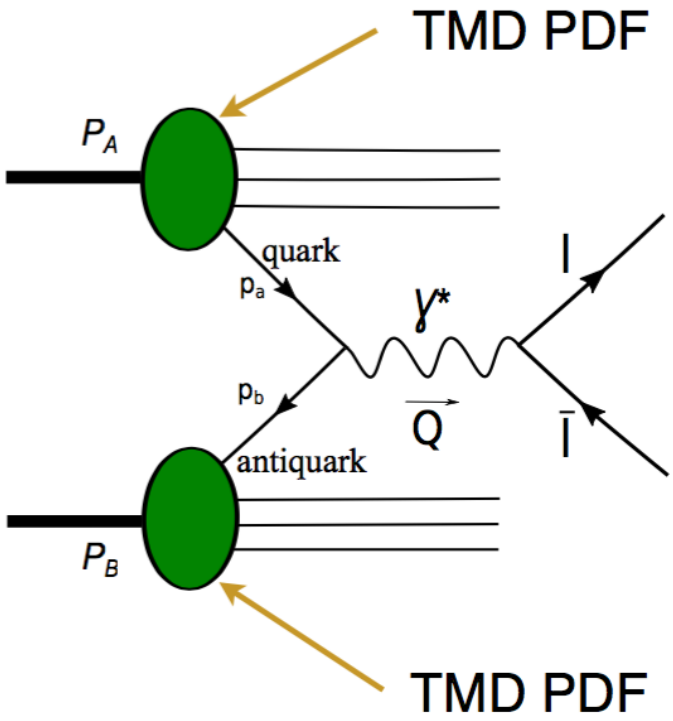
Bacchetta, Delcarro, CP, Radici, Signori, JHEP 1706 (2017)

Semi-inclusive DIS vs DY

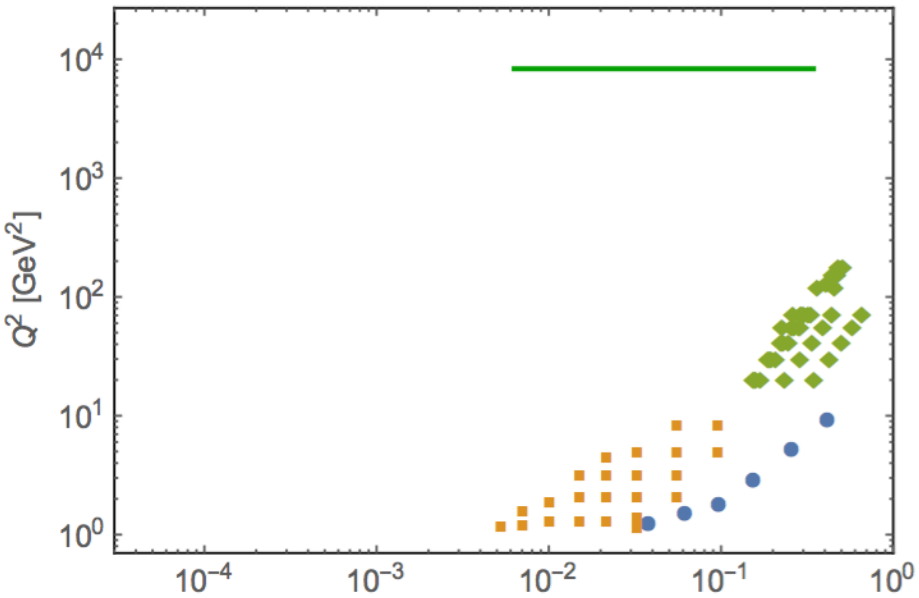
$$l(\ell) + N(\mathcal{P}) \to l(\ell') + h(\mathcal{P}_h) + X$$



$$A + B \to \gamma^* \to l^+ l^-$$
$$A + B \to Z \to l^+ l^-$$



Experiments



Z production@ Fermilab

Abbot et al. hep-ex/9909020
Affolder et al. hep-ex/0001021
Abazov et al. arXiv:0712.0803

Drell-Yan@ Fermilab

Ito et al., PRD93 (81)
Moreno et al. PRD 43 (91)
Antreyan et al. PRL47 (81)

SIDIS@ hermes

Airapetian et al., PRD87 (2013)

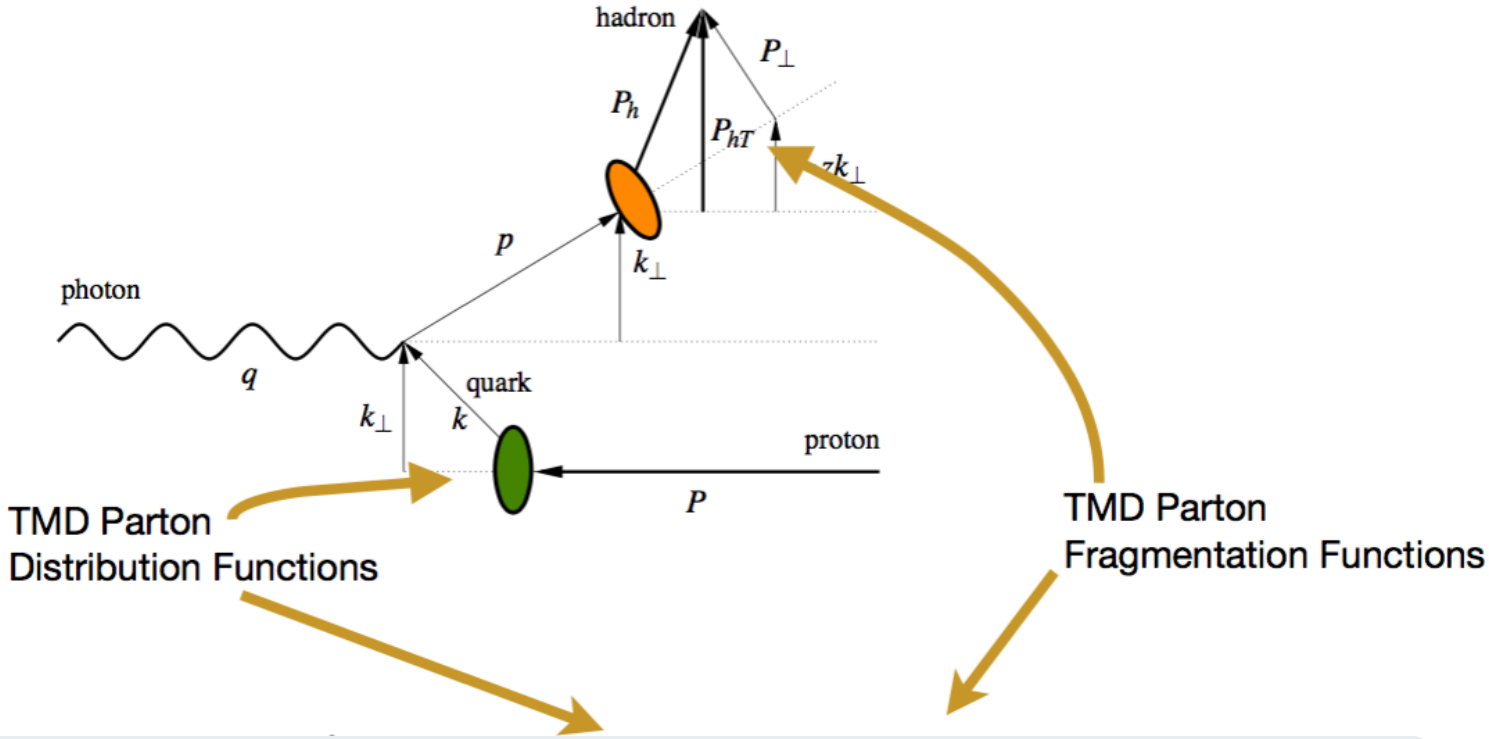
SIDIS@ COMPASS

Adolph et al., EPJ C73 (13)

Extraction of unpolarized quark TMDs
State of the art

	Framework	HERMES	COMPASS	DY	Z production	N of points
KN 2006 hep-ph/0506225	NLL/ NLO	✘	✘	✔	✔	98
Pavia 2013 arXiv:1309.3507	No evo	✔	✘	✘	✘	1538
Torino 2014 arXiv:1312.6261	No evo	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
DEMS 2014 arXiv:1407.3311	NNLL/ NLO	✘	✘	✔	✔	223
EIKV 2014 arXiv:1401.5078	NLL/ LO	1 (x,Q^2) bin	1 (x,Q^2) bin	✔	✔	500 (?)
Pavia 2016 arXiv:1703.10157	NLL/ LO	✔	✔	✔	✔	8059
SV 2017 arXiv:1706.01473	NNLL/ NNLO	✘	✘	✔	✔	309

SIDIS structure function



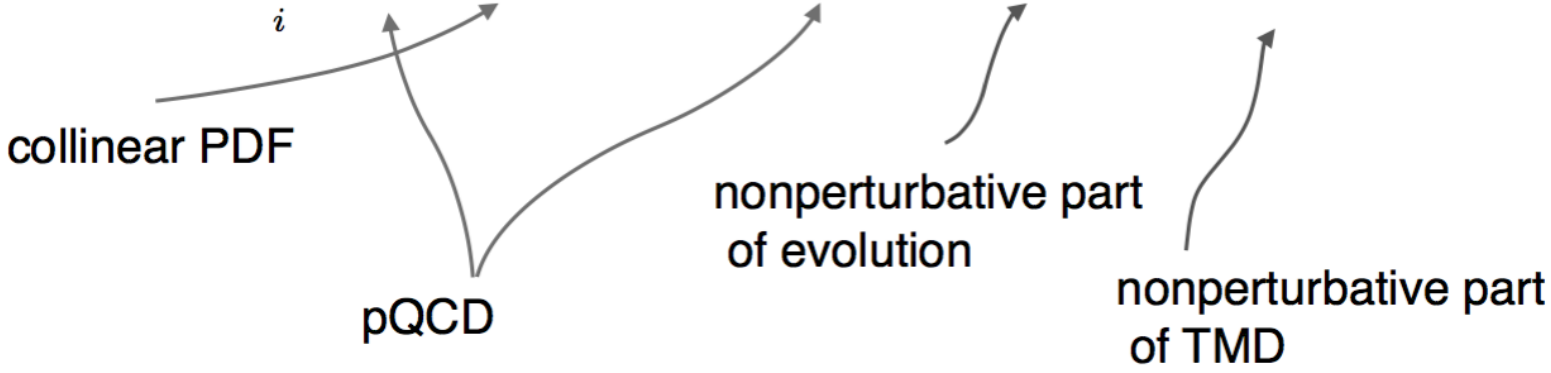
$$F_{UU,T}(x,z,P_{hT}^2,Q^2) = \sum_a \mathcal{H}^a_{UU,T}(Q^2;\mu^2) \int d^2\boldsymbol{k}_T\, d^2\boldsymbol{P}_T\, f_1^a(x,\boldsymbol{k}_T^2;\mu^2)\, D_1^{h/a}(z,\boldsymbol{P}_T^2;\mu^2)\, \delta^2(z\boldsymbol{k}_T - \boldsymbol{P}_{hT} + \boldsymbol{P}_T)$$
$$+ Y_{UU,T}(Q^2,\boldsymbol{P}_{hT}^2) + \mathcal{O}(M^2/Q^2)$$

$\mathcal{H}^a_{UU,T} \approx \mathcal{O}(\alpha_S^0)$, $Y_{UU,T}(Q^2,\boldsymbol{P}_{hT}^2) \approx 0$ in Pavia 2016

Multiplicities: $m_N^h(x,z,\boldsymbol{P}_{hT}^2,Q^2) = \dfrac{\mathrm{d}\sigma_N^h/\mathrm{d}x\,\mathrm{d}z\,\mathrm{d}\boldsymbol{P}_{hT}^2\,\mathrm{d}Q^2}{\mathrm{d}\sigma_{\mathrm{DIS}}/\mathrm{d}x\,\mathrm{d}Q^2} \approx \dfrac{2\pi|\boldsymbol{P}_{hT}|F_{UU,T}(x,z,\boldsymbol{P}_{hT}^2,Q^2)}{F_T(x,Q^2)}$

$$f_1^a(x, k_\perp; \mu^2) = \frac{1}{2\pi} \int d^2 b_\perp e^{-i b_\perp \cdot k_\perp} \widetilde{f}_1^a(x, b_\perp; \mu^2)$$

$$\widetilde{f}_1^a(x, b_T; \mu^2) = \sum_i (\tilde{C}_{a/i} \otimes f_1^i)(x, b_*; \mu_b) e^{\tilde{S}(b_*; \mu_b, \mu)} e^{g_K(b_T) \ln \frac{\mu}{\mu_0}} \hat{f}_{\rm NP}^a(x, b_T)$$



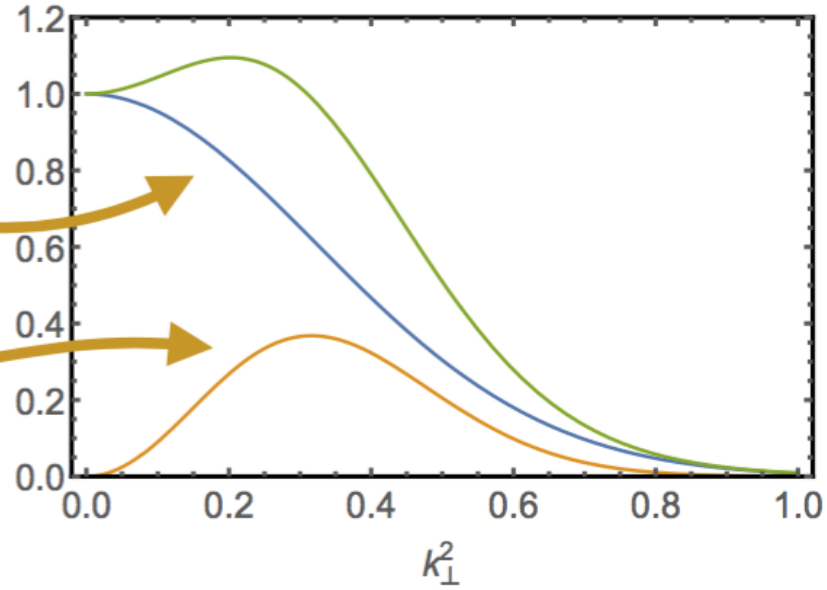
Rogers, Aybat, PRD 83 (11)
Collins, *Foundations of Perturbative QCD* (11)

Different schemes have been suggested

Collins, Soper, Sterman, NPB 250 (85)
Laenen, Sterman, Vogelsang, PRL 84 (00)
Echevarria, Idilbi, Schaefer, Scimemi, EPJ C73 (13)

Assumption for nonperturbative evolution: $g_K = -g_2 \frac{b_T^2}{4}$

$$\hat{f}^a_{\rm NP} = \text{F.T. of } \left(e^{-\frac{k_\perp^2}{\langle k_{\perp,a}^2 \rangle}} + \lambda k_\perp^2 e^{-\frac{k_\perp^2}{\langle k_{\perp,a}^2 \rangle'}} \right)$$



x-dependent width:

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

where

$$\langle \hat{\boldsymbol{k}}_{Ta}^2 \rangle \equiv \langle \boldsymbol{k}_{Ta}^2 \rangle(\hat{x}) \qquad \text{with} \qquad \hat{x} = 0.1$$

α, σ, $\langle \hat{\boldsymbol{k}}_{Ta}^2 \rangle$, λ: free parameters (4 for TMD PDFs, 6 for TMD FFs)

$Q^2 > 1.4$ GeV^2

$0.2 < z < 0.7$

P_{hT}, $q_T < \mathrm{Min}[0.2Q, 0.7Qz] + 0.5$ GeV

Problems in separating the fragmentation regions in SIDIS at low Q^2

Boglione, Collins, Gamberg, Gonzalez-Hernandez, Rogers, Sato, PLB 766 (2017)

Fit of 200 replicas of the data

Summary of the results

Total number of data points: 8059

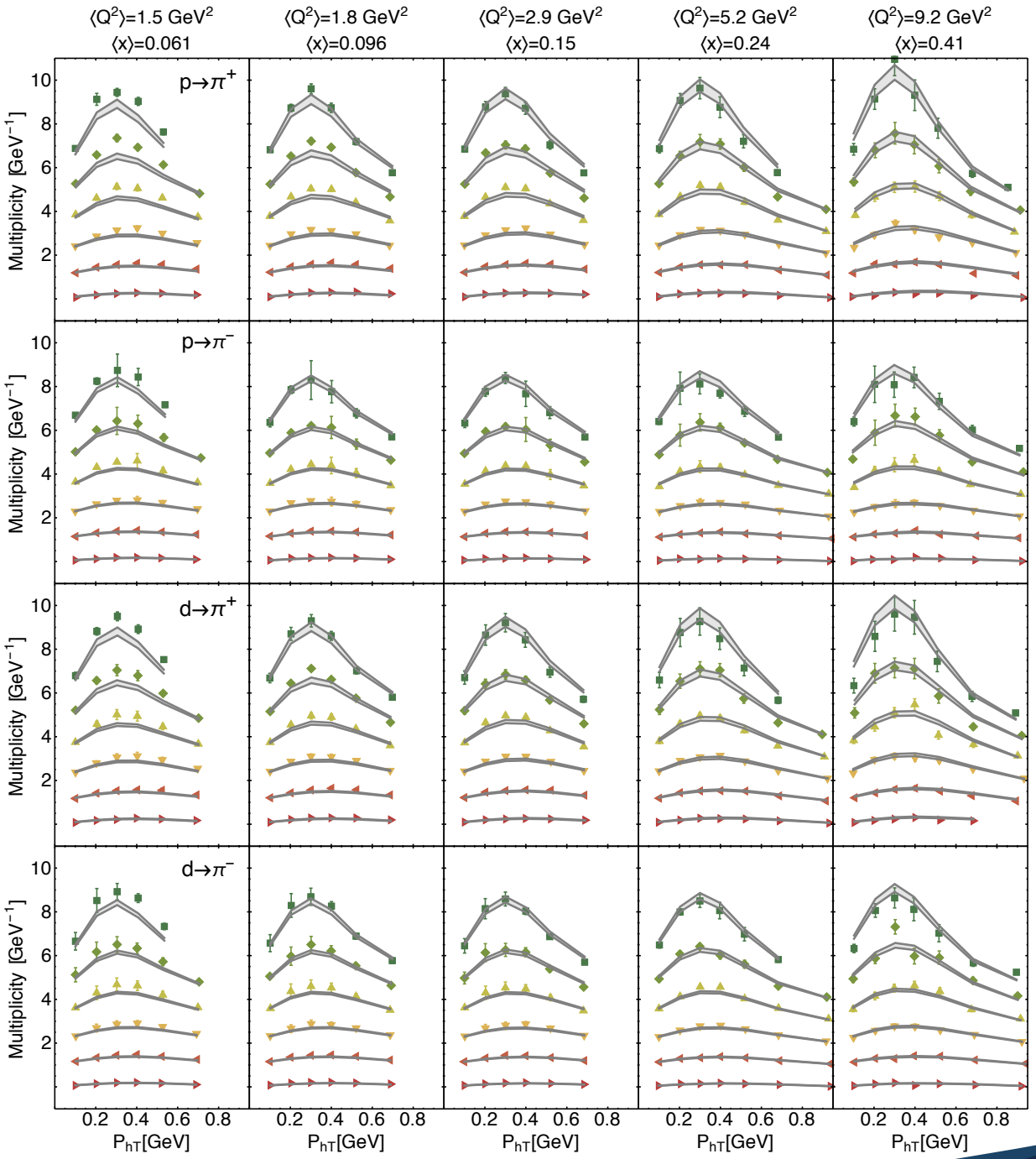
Total number of free parameters: 11

- 4 for TMD PDFs
- 6 for TMD FFs
- 1 for TMD evolution

Total $\chi^2/\text{dof} = 1.55 \pm 0.05$

Fit of 200 replicas of the data

HERMES data
Pion production



χ^2/dof

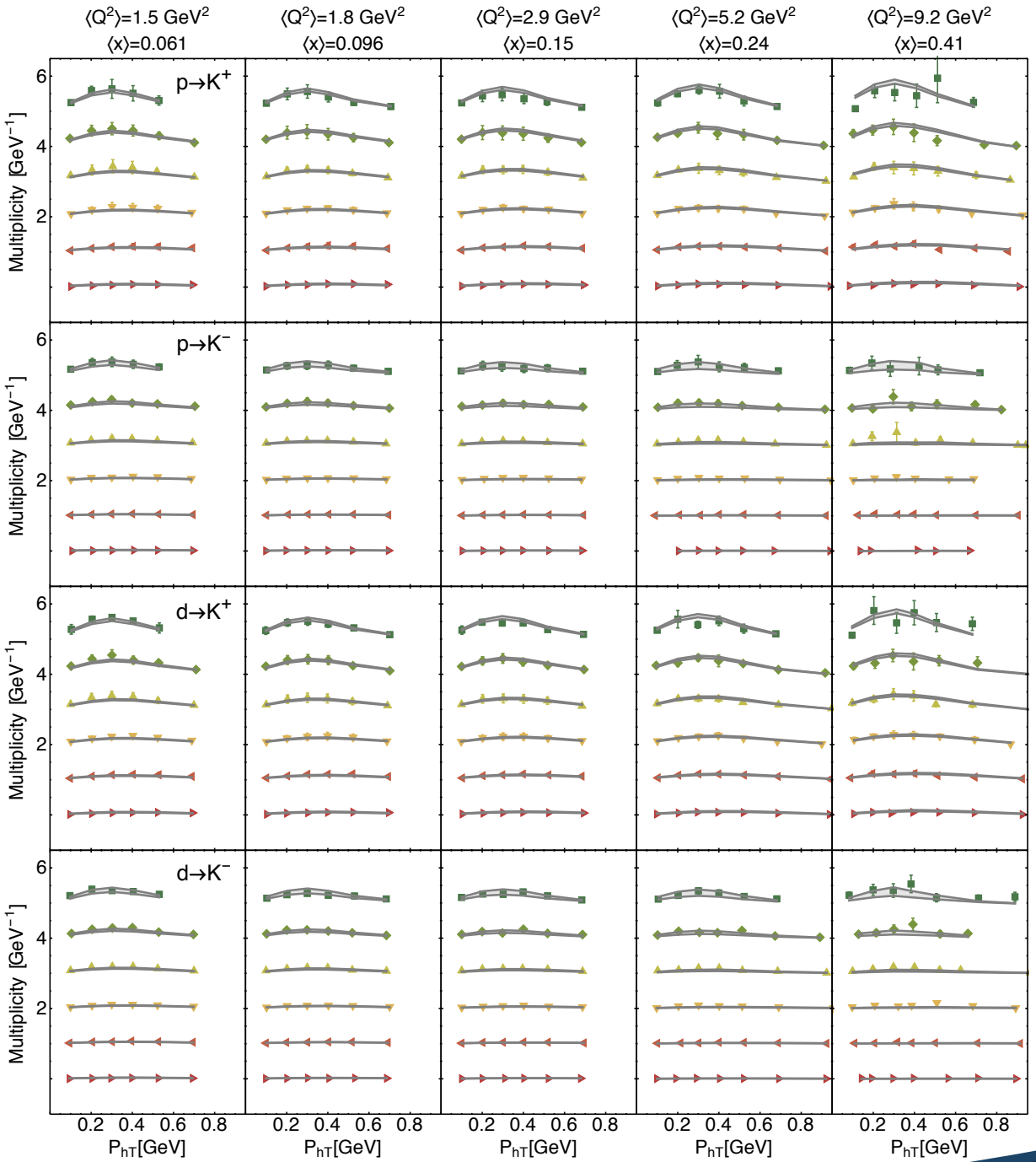
4.83

2.47

3.46

2.00

HERMES data
Kaon production



χ^2/dof

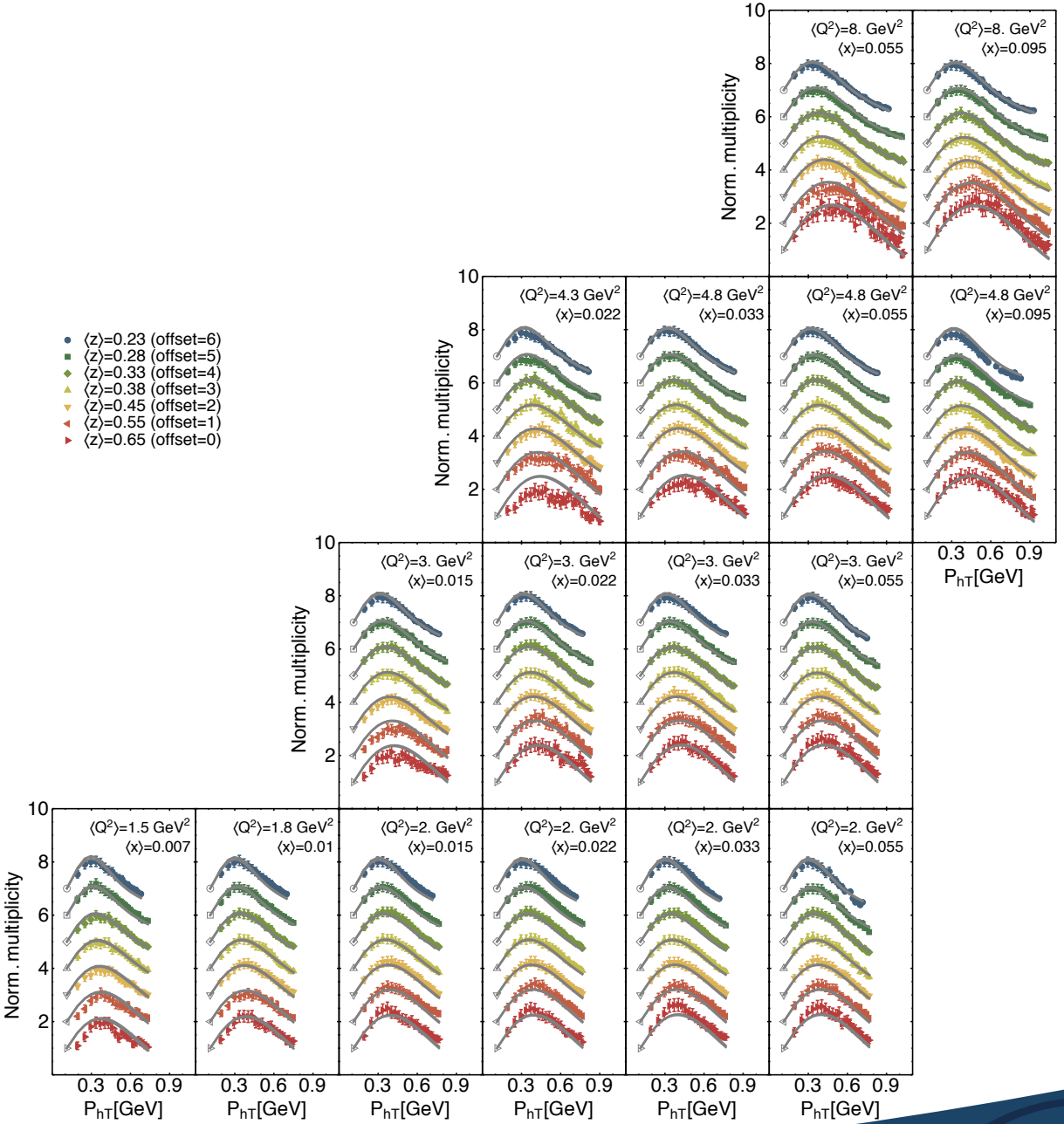
0.91

0.82

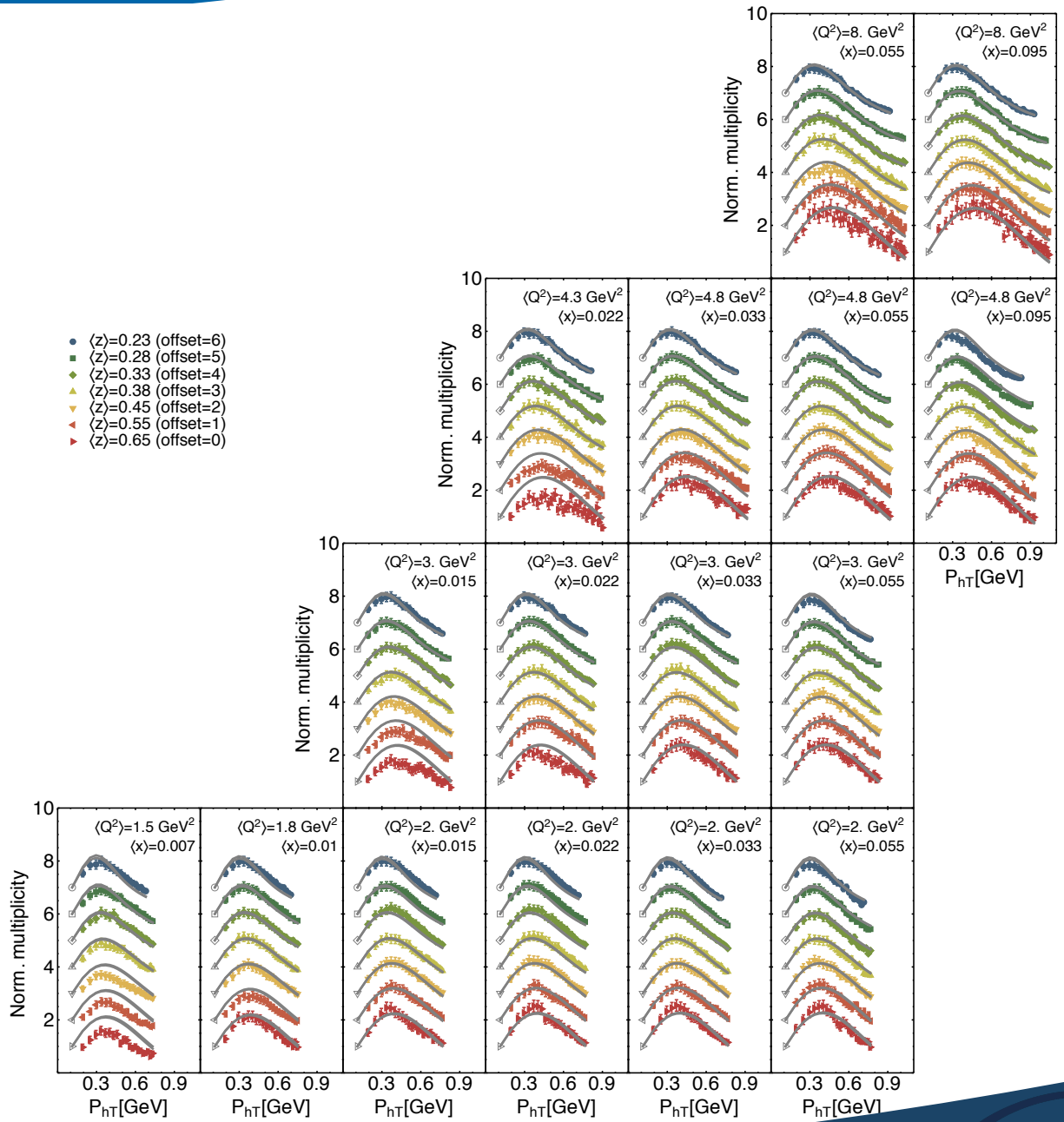
1.31

2.54

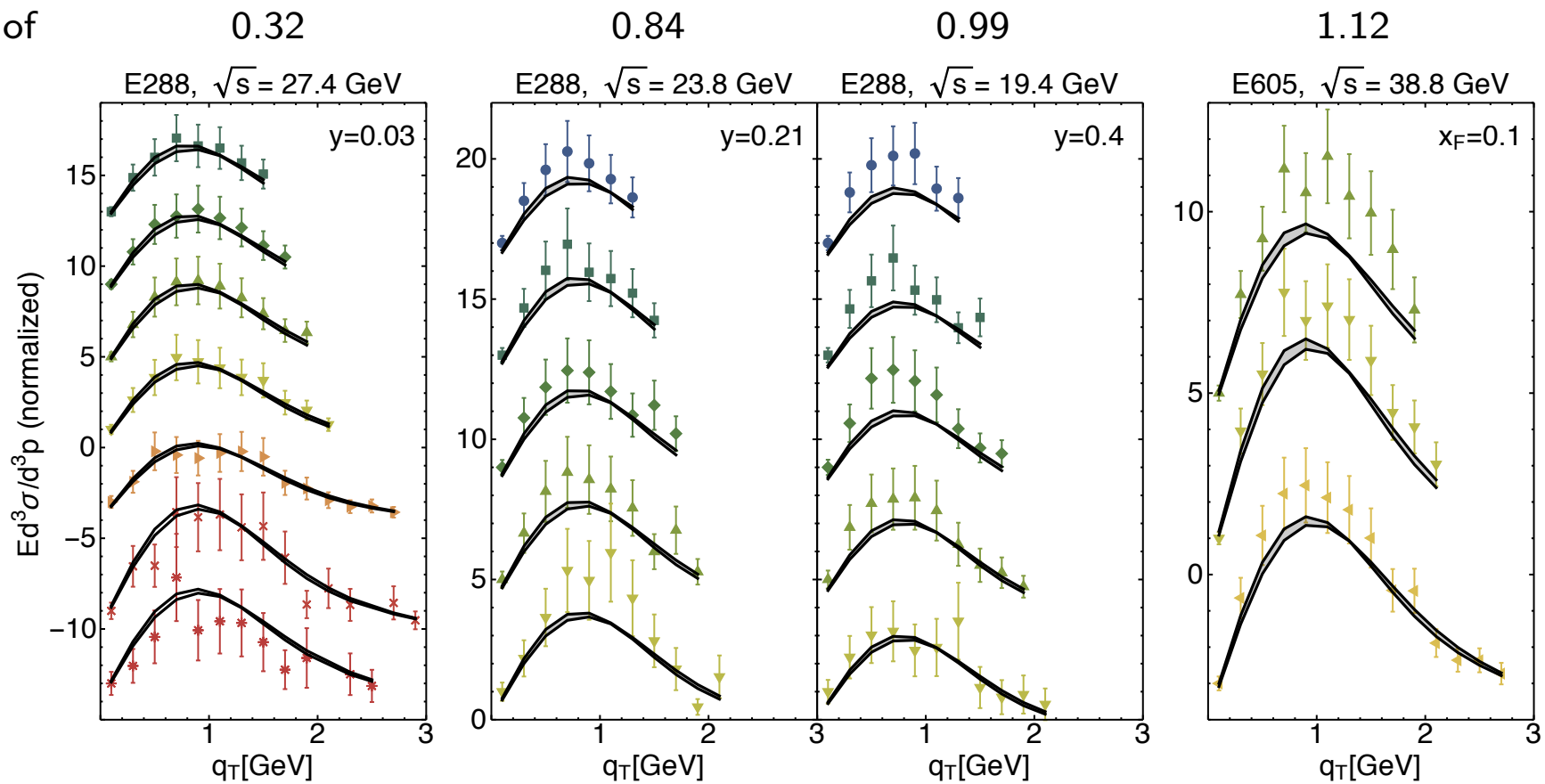
$$\chi^2/\text{dof} = 1.01$$



$\chi^2/\text{dof} = 1.61$



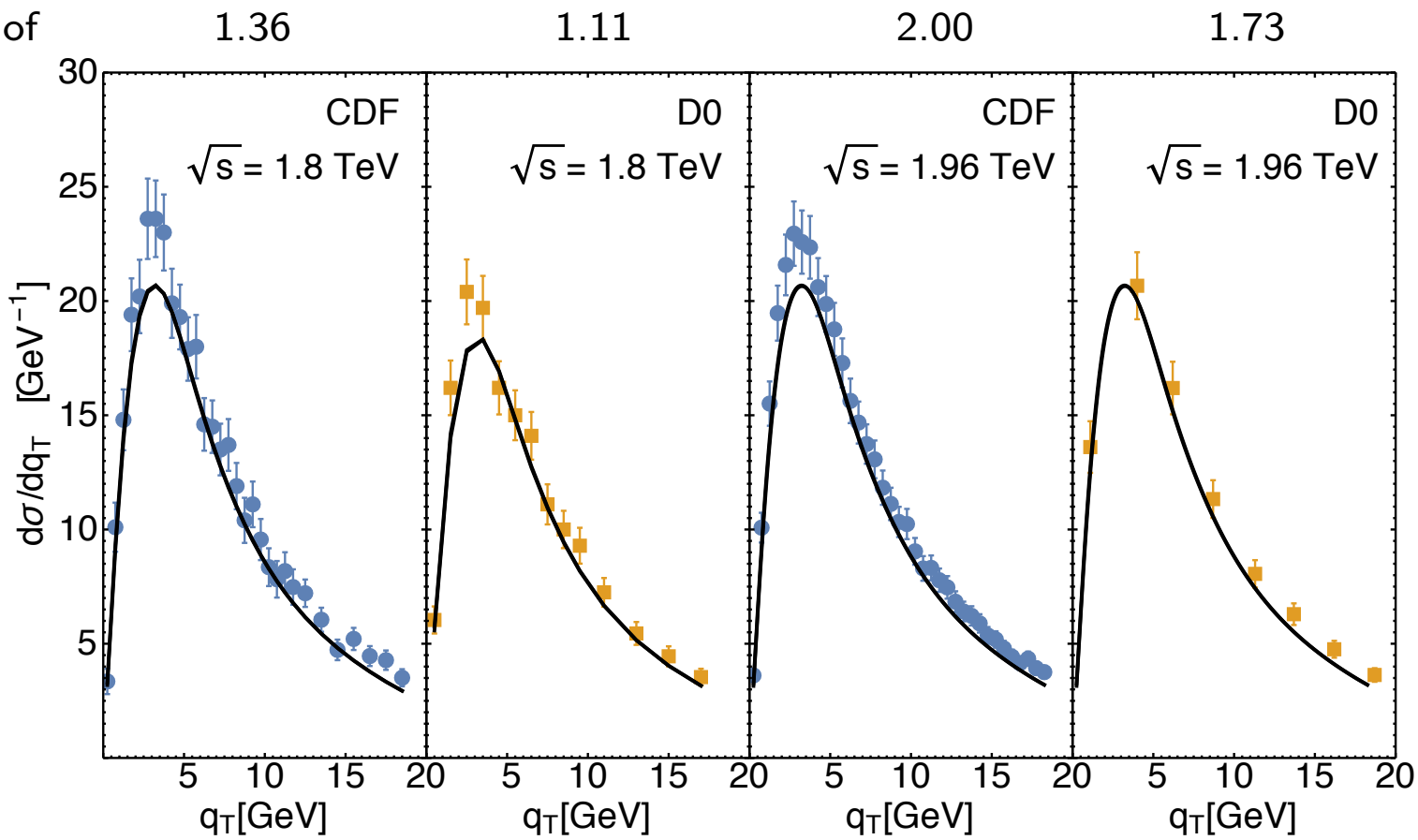
Drell-Yan data



Fermilab

The peak is now at about 1 GeV, it was at 0.4 GeV

Z-boson production



- The peak is now at 4 GeV
- Most of the χ^2 is due to normalization

TMD evolution is not uniquely determined by pQCD calculations

Different schemes may behave differently

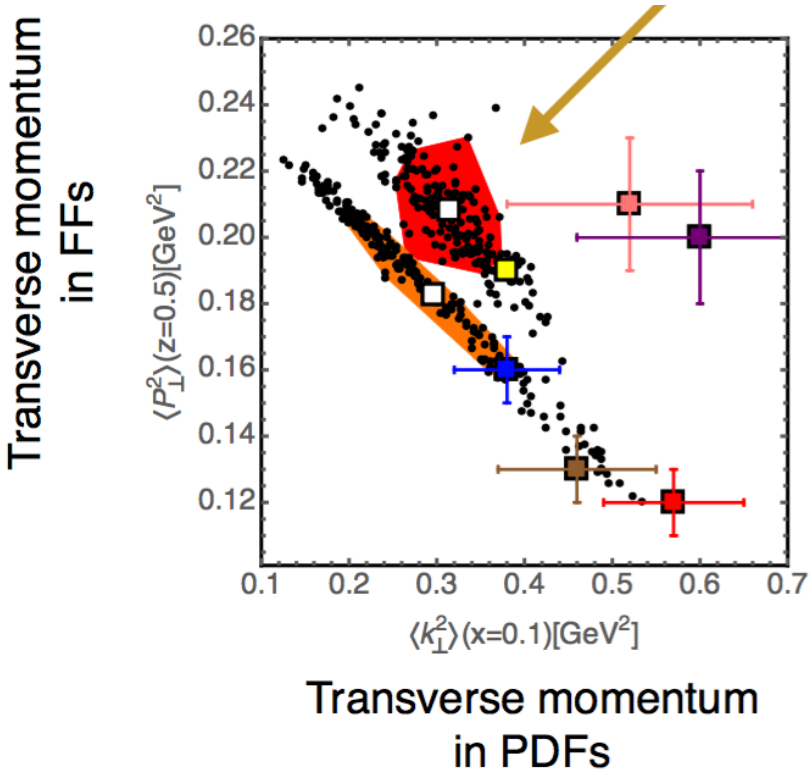
Nonperturbative input is needed to determine evolution precisely

	g_2 (GeV^2)	b_{max}(GeV^{-1})
BLNY 2003	0.68 ± 0.02	0.5
KN 2006	0.184 ± 0.018	1.5
EIKV 2014	0.18	1.5
Pavia 2016	0.13 ± 0.01	1.123

Faster evolution: transverse momentum increases faster due to gluon radiation

Slower evolution: the effect of gluon radiation is weaker

Pavia 2016 results

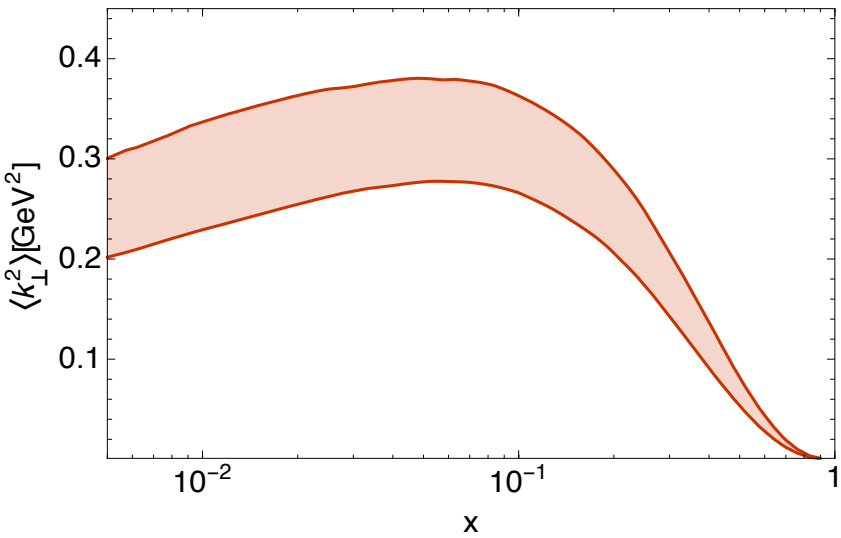


- Bacchetta, Delcarro, Pisano, Radici, Signori (Q = 1 GeV)
- Signori, Bacchetta, Radici, Schnell arXiv:1309.3507
- Schweitzer, Teckentrup, Metz, arXiv:1003.2190
- Anselmino et al. arXiv:1312.6261 [HERMES]
- Anselmino et al. arXiv:1312.6261 [HERMES, high z]
- Anselmino et al. arXiv:1312.6261 [COMPASS,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

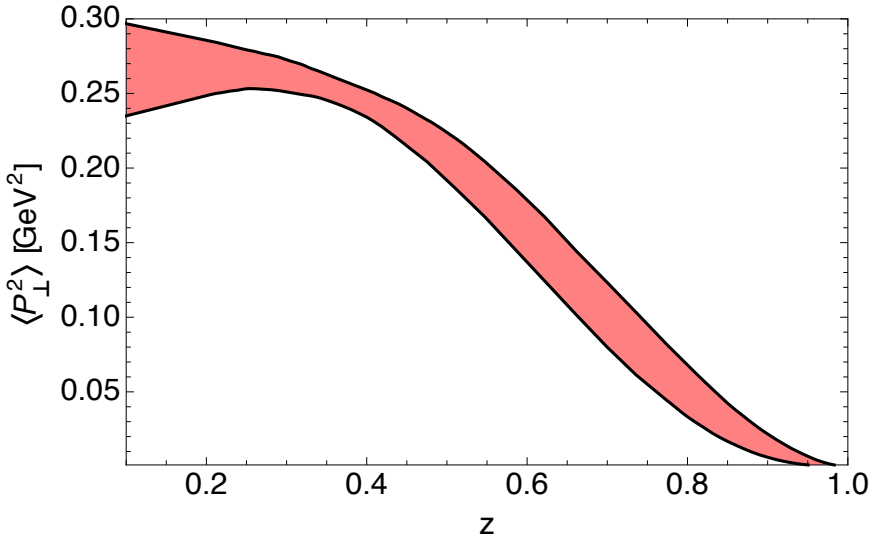
Anticorrelation between transverse momentum in TMD PDFs and in TMD FFs

Mean transverse momentum
$Q^2 = 1$ GeV^2

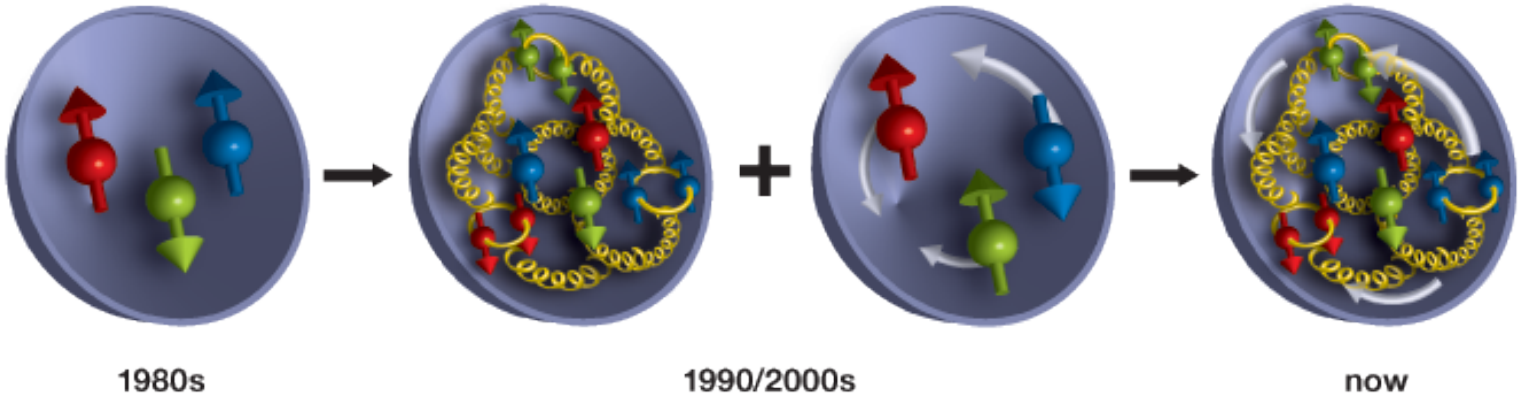
In TMD distribution functions



In TMD fragmentation functions



Conclusions



- Much progress in our understanding of the nucleon, however it still remains a mysterious and fascinating object. Evidence for going beyond 1D picture
- Transverse momentum distributions provide a 3D description of the partonic structure of the nucleon; interplay between theory and experiment
- Unpolarized quark TMDs extracted from several hundred data points
- Waiting for new data from COMPASS, JLAB-12, RHIC, LHC and EIC
- Phenomenology and theory issues:
  factorization breaking, TMD evolution, nonperturbative inputs