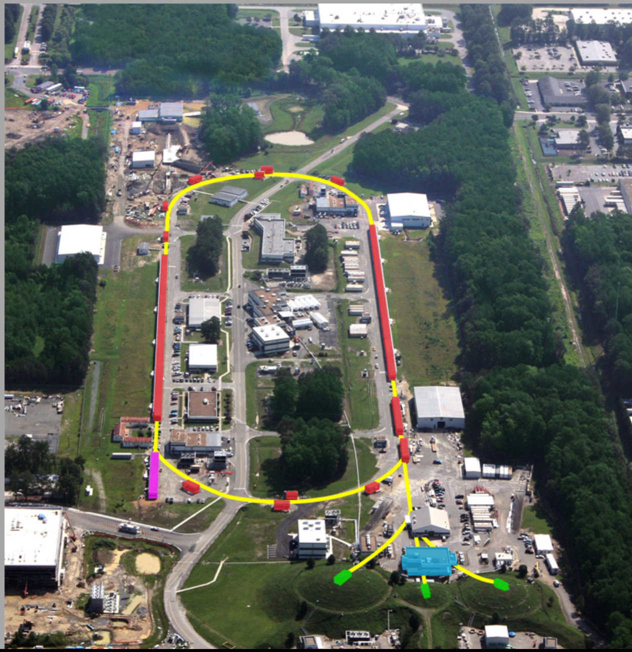
BROOKHAVEN NATIONAL LABORATORY

Brookhaven National Laboratory
April 9, 2012

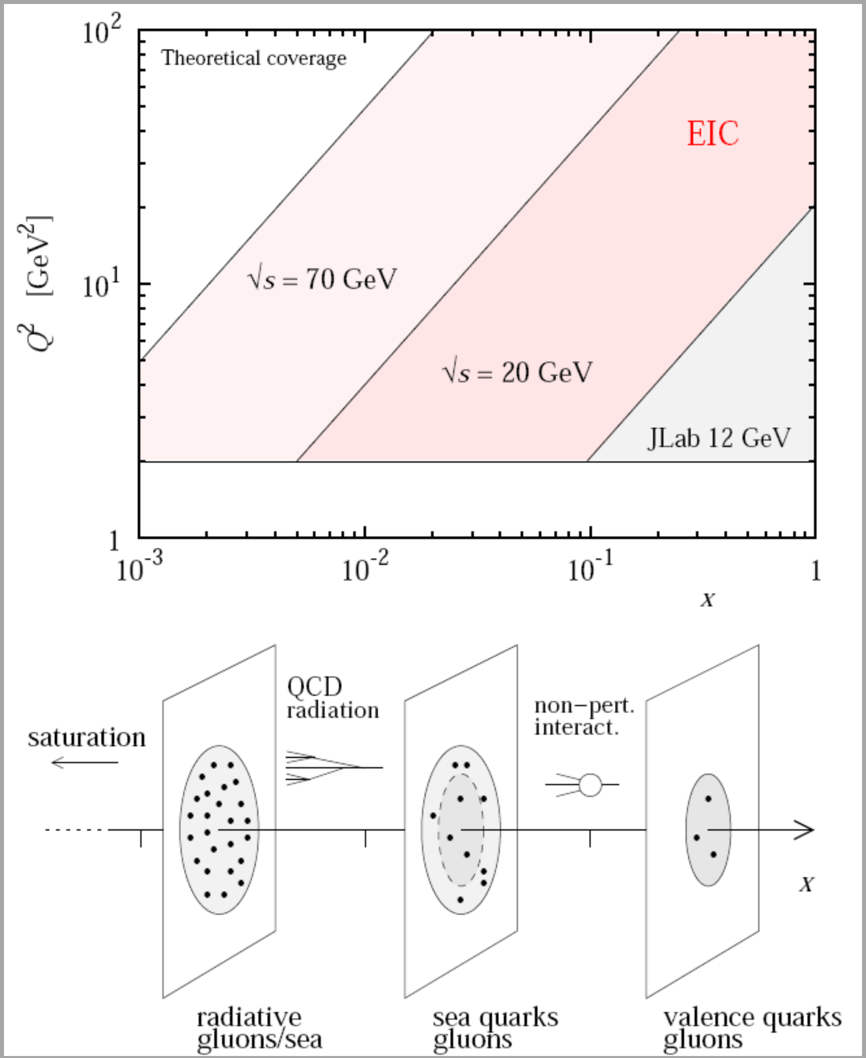
Evolution of Transverse Momentum Dependent distributions and experimental data

Alexei Prokudin
Jefferson Lab



Jefferson Lab

Nucleon landscape



Plot courtesy of Christian Weiss

Nucleon is a many body dynamical system of quarks and gluons

Changing x we probe different aspects of nucleon wave function

How partons move and how they are distributed in space is one of the future directions of development of nuclear physics

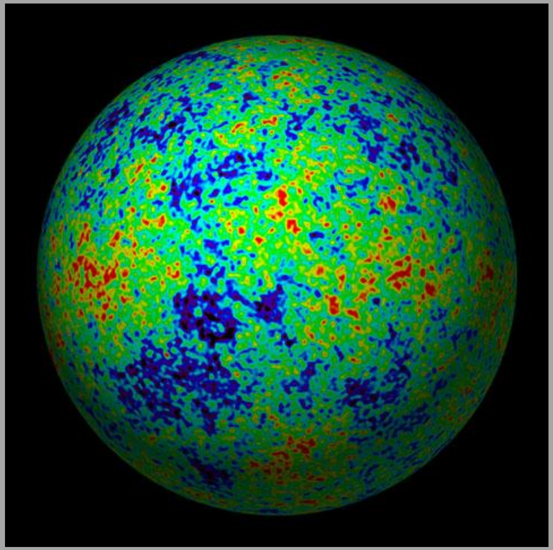
Technically such information is encoded into Generalised Parton Distributions

Markus Diehl (2003)
Matthias Burkardt (2003)

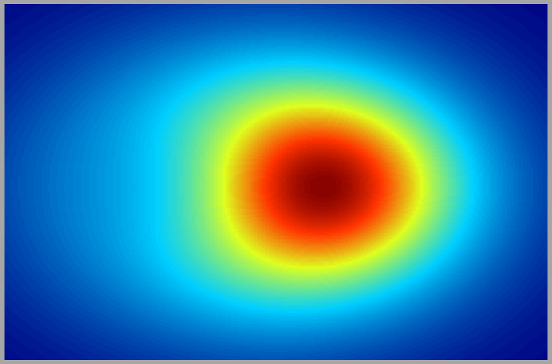
and Transverse Momentum Dependent distributions

EIC report, Boer, Diehl, Milner, Venugopalan, Vogelsang et al , 2011

Fundamental knowledge from 3D distributions



Cosmic Microwave Background is the source of information on history of our universe, inflation, distribution of matter, dark matter etc



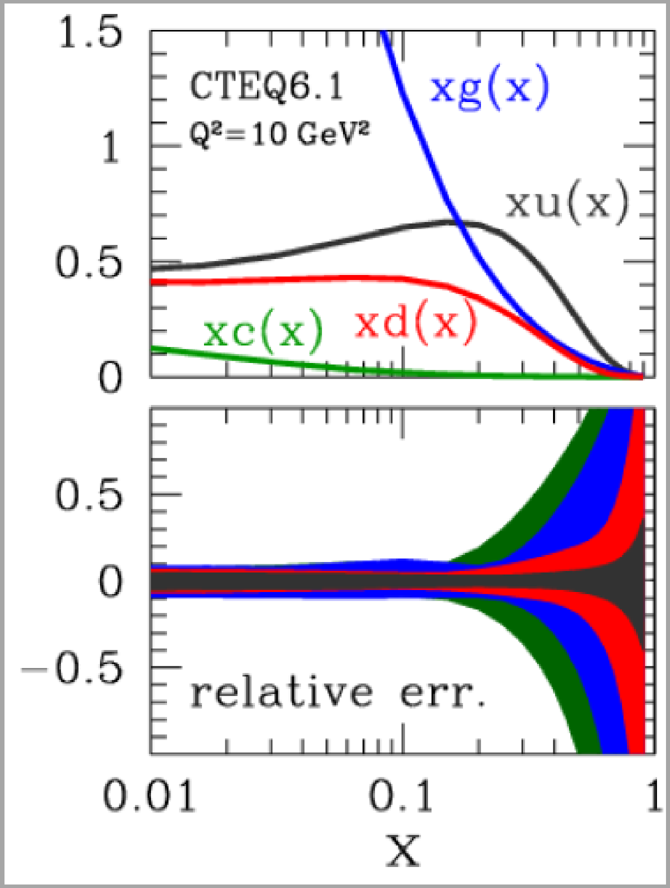
3 Dimensional partonic picture gives us insights on the dynamics of the confined system of quarks and gluons.

It also gives information on fundamental properties of the nucleon

Spin is one of these properties

Hadron tomography

Conventional inclusive processes are sensitive to longitudinal momentum fraction of hadron momenta, they give no information on spatial or momentum 3D distribution of partons



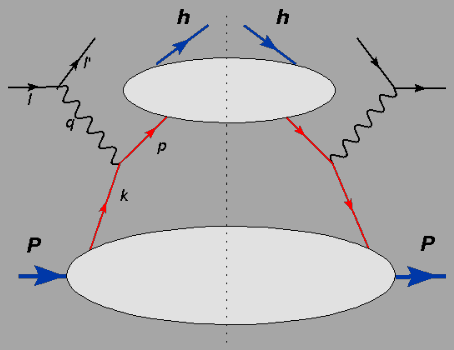
Good knowledge of
Parton
Distribution
Functions (PDFs)
is acquired at HERA

See Forte (2010)

However large-x behavior has still large uncertainties
Data from Jlab 12 will be important

Transverse Momentum Dependent distributions

SIDIS



$$\mathbf{l} + \mathbf{P} \rightarrow \mathbf{l}' + \mathbf{h} + \mathbf{X}$$

If produced hadron has low transverse momentum

$$P_{hT} \sim \Lambda_{QCD} << Q$$

it will be sensitive to quark transverse momentum $k_\perp$

TMD factorization

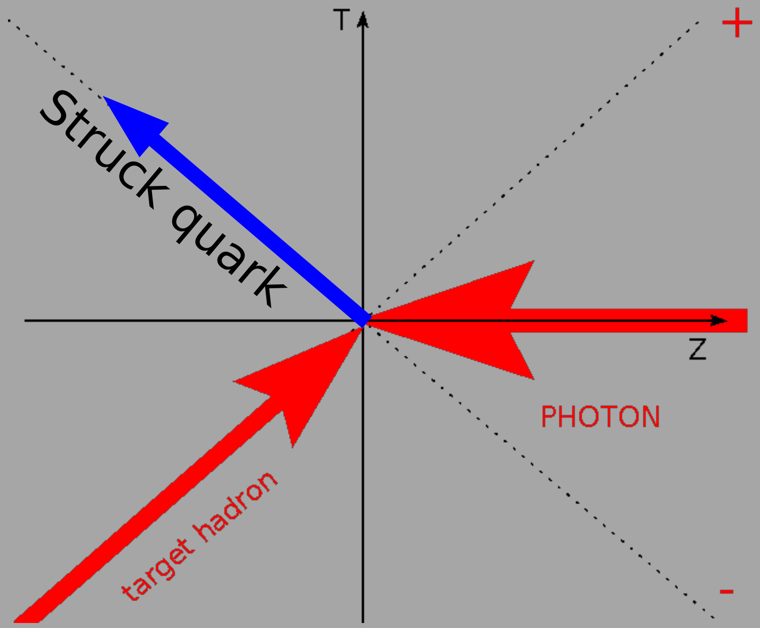
Ji, Ma, Yuan (2002)
Collins(2011)

$$\Phi_{ij}(x, \mathbf{k}_\perp) = \int \frac{d\xi^-}{(2\pi)} \frac{d^2\xi_\perp}{(2\pi)^2} e^{ixP^+\xi^- - i\mathbf{k}_\perp \xi_\perp} \langle P, S_P | \bar{\psi}_j(0) \mathcal{U}(\mathbf{0}, \xi) \psi_i(\xi) | P, S_P \rangle$$

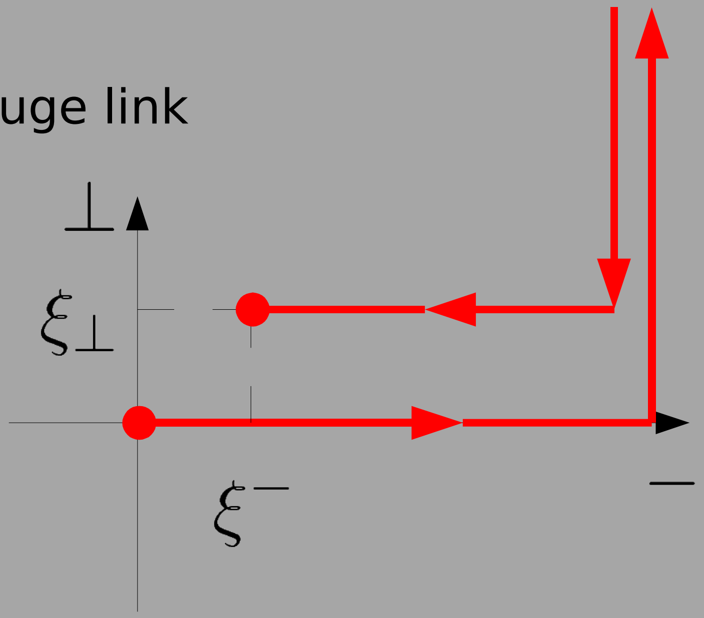
Transverse Momentum Dependent distributions

$$\Phi_{ij}(x,\mathbf{k}_\perp) = \int \frac{d\xi^-}{(2\pi)} \frac{d^2\xi_\perp}{(2\pi)^2}\, e^{ixP^+\xi^- - i\mathbf{k}_\perp\xi_\perp} \langle P, S_P|\bar{\psi}_j(0)\mathcal{U}(\mathbf{0},\xi)\psi_i(\xi)|P,S_P\rangle|_{\xi^+=0}$$

SIDIS in Infinite Momentum Frame:



Gauge link



Transverse separation is due to presence of transverse parton momentum

Struck quark propagates in the gauge field of the remnant and forms gauge link

Factorization theorems

- Related: Factorization Theorems:
  - Semi-Inclusive deep inelastic scattering. ✓
  - Drell-Yan. ✓
  - e^+/e^- annihilation. ✓
  - ~~p + p → $h_1 + h_2 + X$~~ !!

- TMD factorization

$$\Lambda^2_{QCD} < P^2_{h\perp} \ll Q^2$$

Sensitive to parton transverse motion.

Ji, Ma, Yuan, Collins, Metz, Rogers, Mulders, etc

- Related: Factorization Theorems:
  - Semi-Inclusive deep inelastic scattering. ✓
  - Drell-Yan. ✓
  - e^+/e^- annihilation. ✓
  - p + p → $h_1 + h_2 + X$ ✓

- Collinear factorization

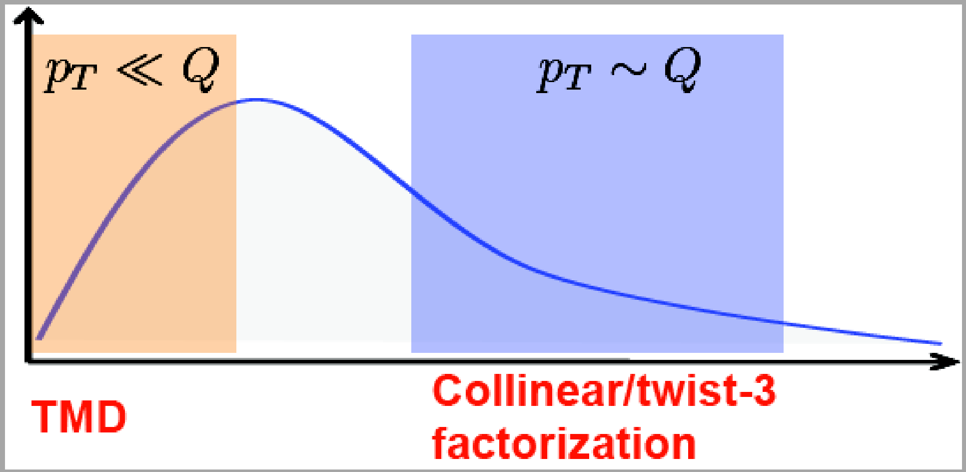
$$\Lambda^2_{QCD} \ll P^2_{h\perp}, Q^2$$

Sensitive to multy parton correlations.

Qiu, Sterman, Efremov, Teryaev, Kanazava, Koike, etc

TMD and Collinear factorizations

Both factorizations are consistent in the overlap region

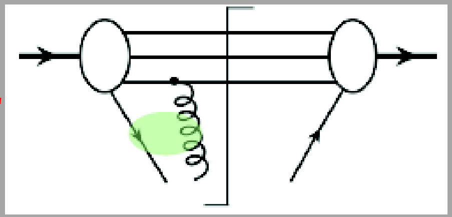


Collins, Mulders, Ji, Qiu, Yuan, Bacchetta, Metz, Kang, Boer, Koike, Vogelsang, Yuan etc

Relation of multyparton correlations and moments of TMDs

$$\int d^2k_T \frac{k_T^2}{M} f_{1T}^{\perp}(x, k_T^2) + UVCT(\mu^2) = T_F(x, x, \mu^2) \qquad f_{1T}^{\perp(1)} \equiv \int d^2k_T \frac{k_T^2}{2M^2} f_{1T}^{\perp}(x, k_T^2)$$

Sivers function



TMDs

N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

8 functions in total (at leading twist)

Each represents different aspects of partonic structure

Each function is to be studied

Mulders, Tangerman (1995), Boer, Mulders (1998)

Sivers function

Let's consider unpolarised quarks inside transversely polarised nucleon

DISTRIBUTION

$$f(x, \mathbf{k}_T, S) = f_1(x, \mathbf{k}_T^2) - \frac{[\mathbf{k}_T \times \hat{P}] \cdot S_T}{M} f_{1T}^{\perp}(x, \mathbf{k}_T^2)$$

Usual unpolarised distribution

This one is called SIVERS function
Correlation of transverse motion and transverse spin
Sivers (1990) Boer, Mulders (1998)

Sivers function

$$f(x,\mathbf{k}_T,S) = f_1(x,\mathbf{k}_T^2) - \frac{[\mathbf{k}_T \times \hat{P}]\cdot S_T}{M} f_{1T}^{\perp}(x,\mathbf{k}_T^2)$$

This function gives access to 3D imaging

Spin-orbit correlation

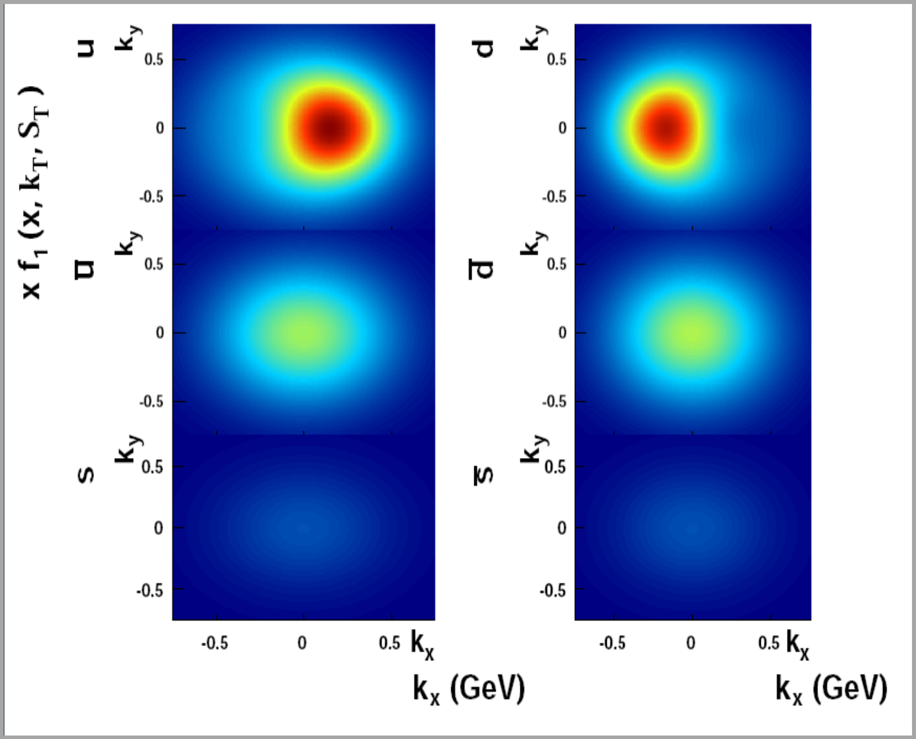
Physics of gauge links is represented

Requires Orbital Angular Momentum

EIC report, Boer, Diehl, Milner, Venugopalan,
Vogelsang et al , 2011;
Duke workshop report: Anselmino et al Eur.Phys.J.A47:35,2011

Access to 3D imaging

$$f(x, \mathbf{k}_T, S) = f_1(x, \mathbf{k}_T^2) - \frac{[\mathbf{k}_T \times \hat{P}] \cdot S_T}{M} f_{1T}^{\perp}(x, \mathbf{k}_T^2)$$



Sivers function from experimental data HERMES and COMPASS

Anselmino et al 2005

Dipole deformation

What do we learn from 3D distributions?

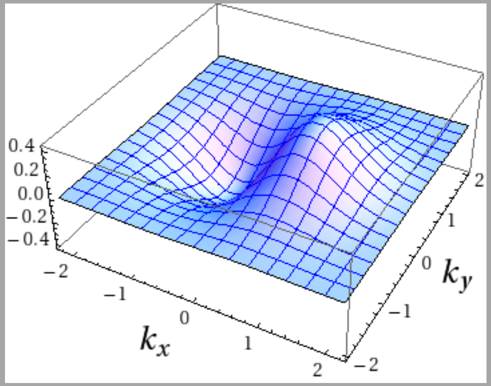
$$f(x, \mathbf{k_T}, \mathbf{S_T}) = f_1(x, \mathbf{k_T^2}) - f_{1T}^{\perp}(x, \mathbf{k_T^2}) \frac{\mathbf{k_x}}{M}$$

Suppose the spin is along Y direction: $S_T = (0, 1)$

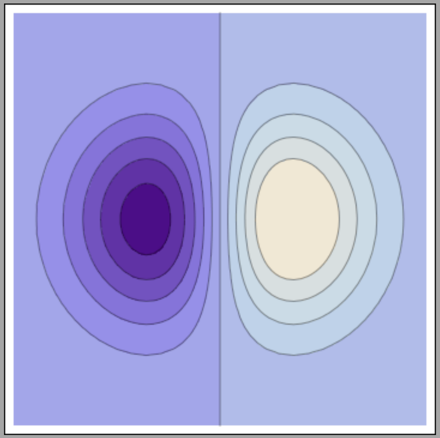
Deformation in momentum space is: $k_x \cdot f(k_x^2 + k_y^2)$

This is so-called “dipole” deformation.

3D picture:



Tomography:



What do we learn from 3D distributions?

$$f(x, \mathbf{k_T}, \mathbf{S_T}) = f_1(x, \mathbf{k_T^2}) - f_{1T}^{\perp}(x, \mathbf{k_T^2}) \frac{\mathbf{k_x}}{M}$$

We calculate now average shift: $\langle k_x \rangle$

$$\langle k_x \rangle = \int d^2 k_T \frac{\mathbf{k_T^2}}{2M} f_{1T}^{\perp}(x, \mathbf{k_T^2}) \equiv f_{1T}^{\perp(1)}(x) M$$

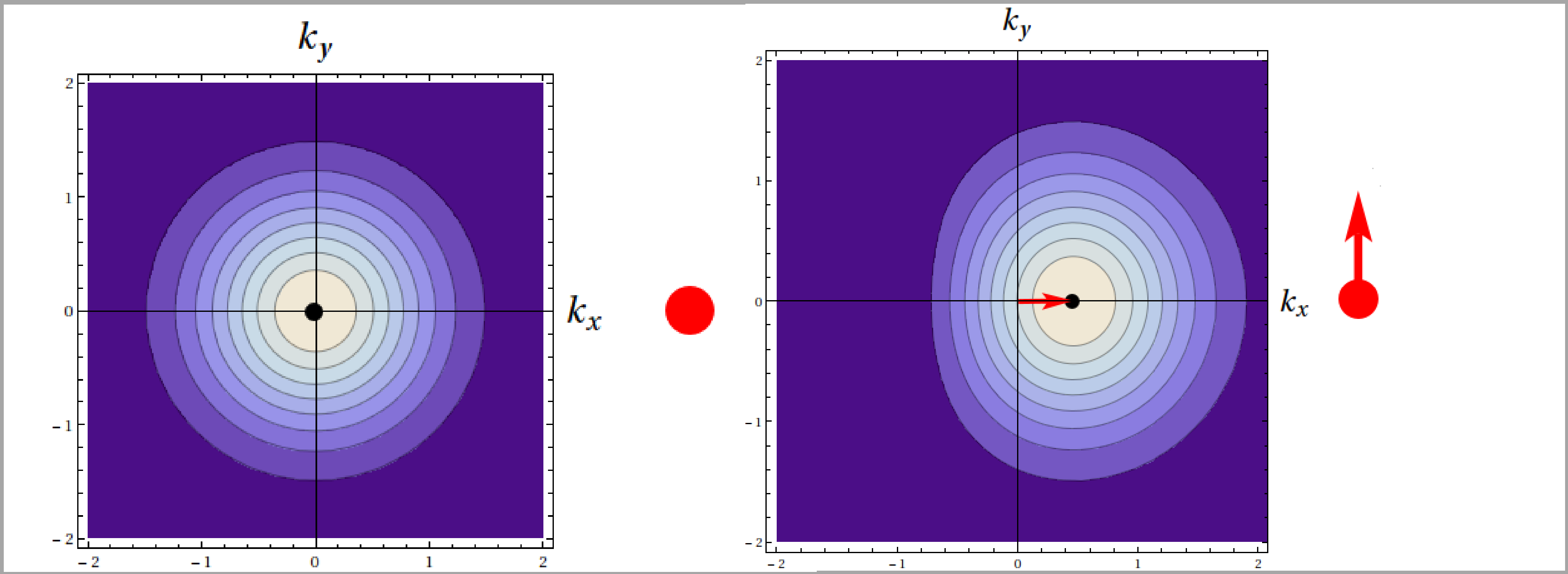
Average momentum shift is proportional to the **first moment** of Sivers function

What do we learn from 3D distributions?

$$f(x, \mathbf{k_T}, \mathbf{S_T}) = f_1(x, \mathbf{k_T^2}) - f_{1T}^{\perp}(x, \mathbf{k_T^2}) \frac{\mathbf{k_x}}{M}$$

The same statement in figures:

No polarisation: Polarisation: $S_y \Rightarrow \langle k_x \rangle$

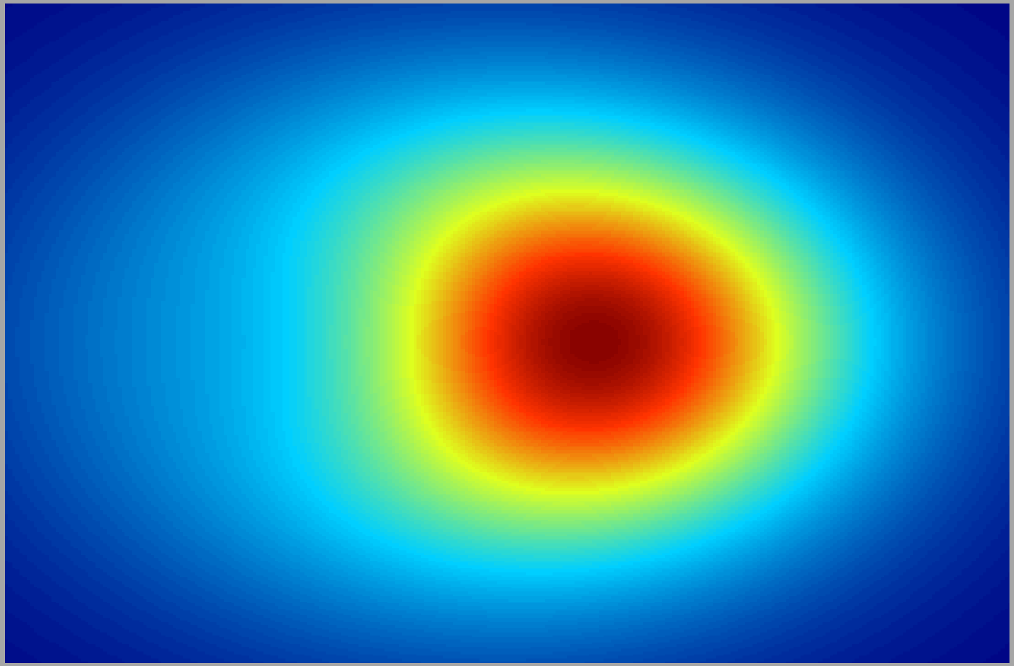


What do we learn from 3D distributions?

$$f(x, \mathbf{k_T}, \mathbf{S_T}) = f_1(x, \mathbf{k_T^2}) - f_{1T}^{\perp}(x, \mathbf{k_T^2}) \frac{\mathbf{k_{T1}}}{M}$$

The same statement in figures:

This is what we know from exerimental data already:



How do we measure Sivers function?

$$A_{UT}^{\sin(\Phi_h-\Phi_S)} = 2\frac{\int d\phi_h(\sigma^{\uparrow}-\sigma^{\downarrow})\sin(\Phi_h-\Phi_S)}{\int d\phi_h(\sigma^{\uparrow}+\sigma^{\downarrow})}$$

Unpolarised electron beam
Transversely polarised proton

$$A_{UT}^{\sin(\Phi_h-\Phi_S)} = -\frac{\sum_q e_q^2 f_{1T}^{\perp} \otimes d\hat{\sigma} \otimes D_{h/q}}{\sum_q e_q^2 f_1 \otimes d\hat{\sigma} \otimes D_{h/q}}$$

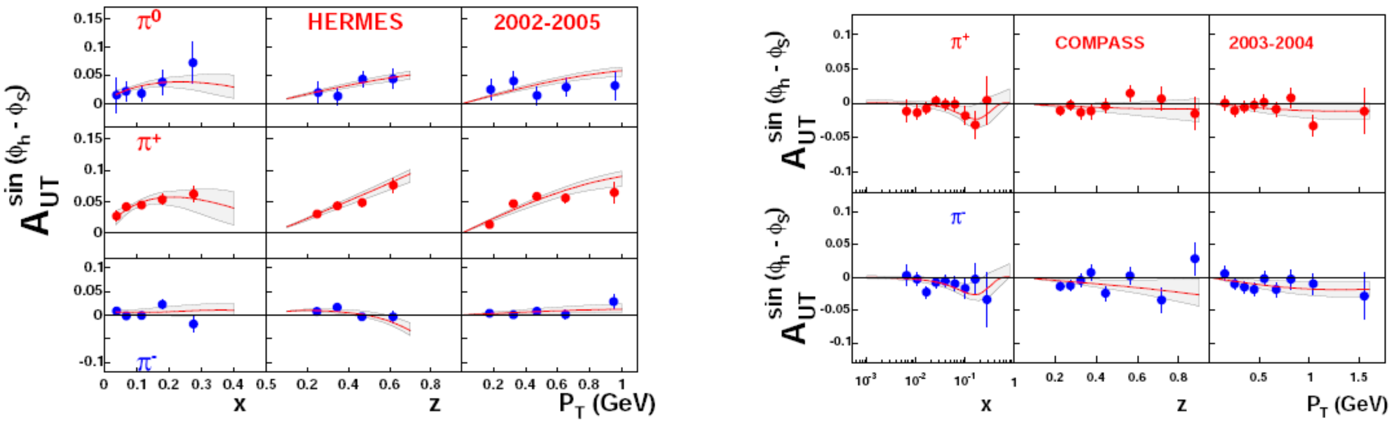
Bacchetta, Diehl, Goeke, Metz, Mulders, Schlegel (2006)

HERMES

$ep \to e\pi X$, $p_{lab} = 27.57$ GeV.

COMPASS

$\mu D \to \mu\pi X$, $p_{lab} = 160$ GeV.



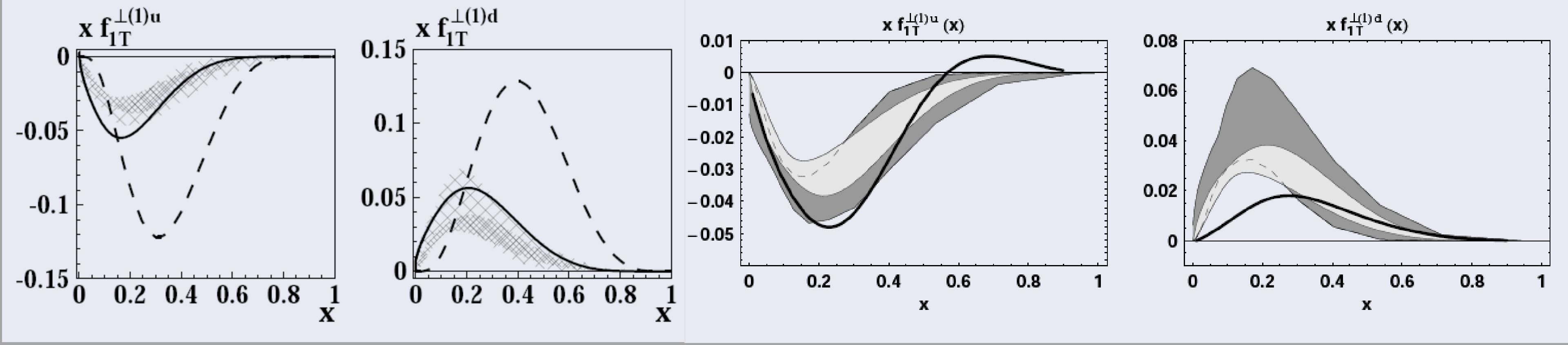
Anselmino et al 2010

Anselmino et al 2010

Comparison with models

Light cone wf model Pasquini, Yuan (2011),
Quark-diquark models Bacchetta et al (2010),
Gamberg, Goldstein, Schlegel (2010)
Bag models Yuan (2003), Avakian, Efremov, Schweitzer, Yuan (2010)

Pasquini, Yuan (2011) Bacchetta et al (2010)

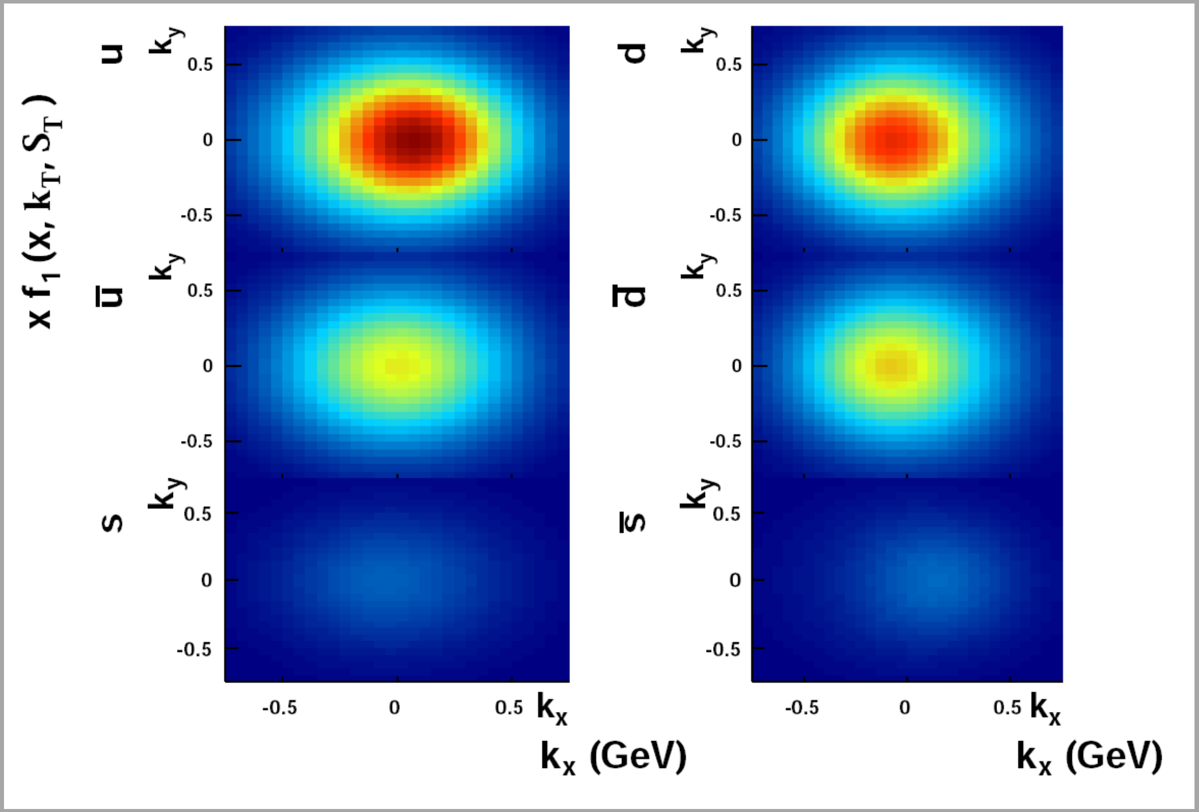


$f_{1T}^{\perp u} < 0$ $f_{1T}^{\perp d} > 0$

Good agreement.

What do we learn from 3D distributions?

$$f(x,\mathbf{k_T},\mathbf{S_T}) = f_1(x,\mathbf{k_T^2}) - f_{1T}^{\perp}(x,\mathbf{k_T^2})\frac{\mathbf{k_{T1}}}{M}$$



The slice is at:

$x = 0.1$

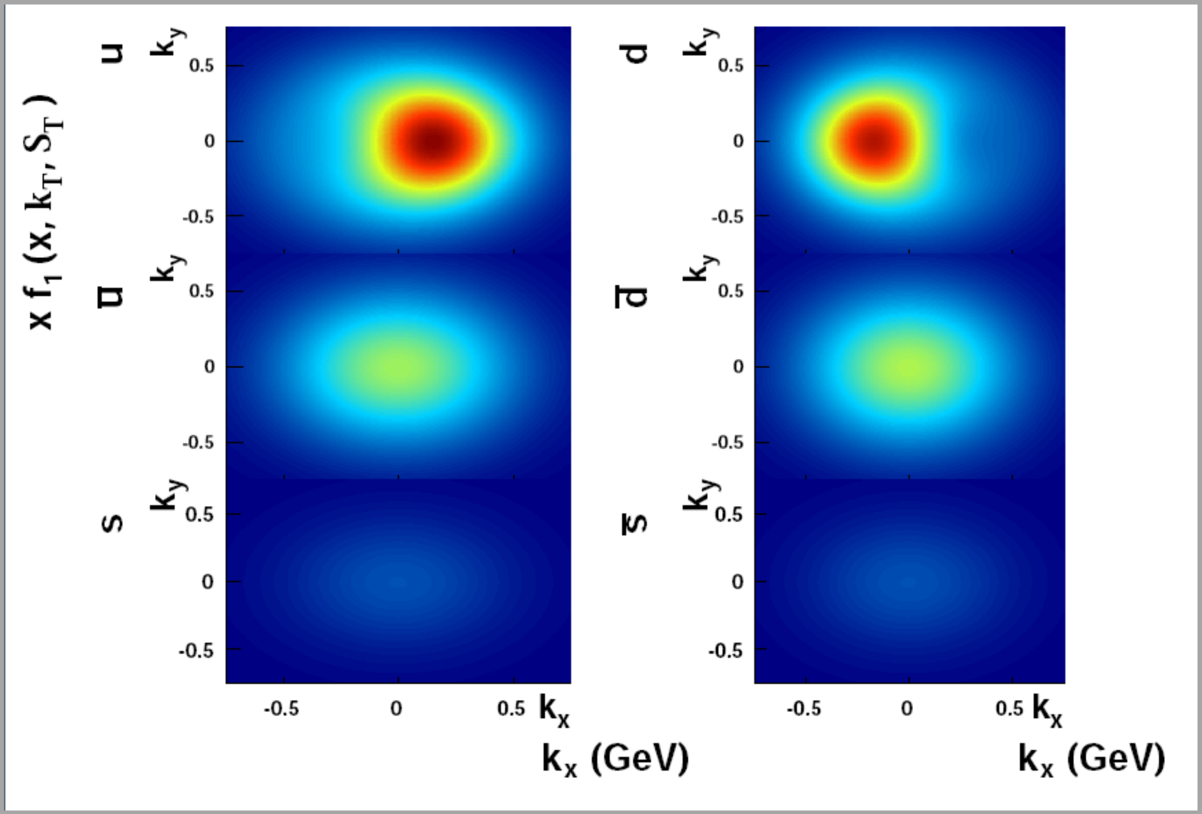
Low-x and high-x region is uncertain
JLab 12 and EIC will contribute

No information on sea quarks

Picture is still quite uncertain

What do we learn from 3D distributions?

$$f(x,\mathbf{k_T},\mathbf{S_T}) = f_1(x,\mathbf{k_T^2}) - f_{1T}^{\perp}(x,\mathbf{k_T^2})\frac{\mathbf{k_{T1}}}{M}$$



The slice is at:

$x = 0.1$

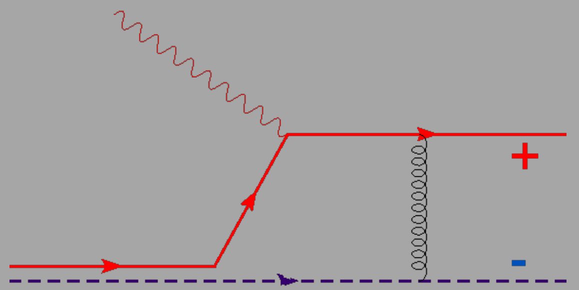
Low-x and high-x region is uncertain
JLab 12 and EIC will contribute

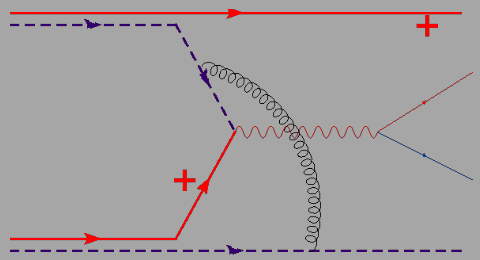
No information on sea quarks

In future we will obtain much clearer picture

Physics of gauge links

Colored objects are surrounded by gluons, profound consequence of gauge invariance.
 Sivers function has opposite sign when gluon couple after quark scatters (SIDIS) or before quark annihilates (Drell-Yan)





Brodsky,Hwang, Schmidt
Belitsky,Ji,Yuan
Collins
Boer,Mulders,Pijlman,
etc

$$f_{1T}^{\perp SIDIS} = -f_{1T}^{\perp DY}$$

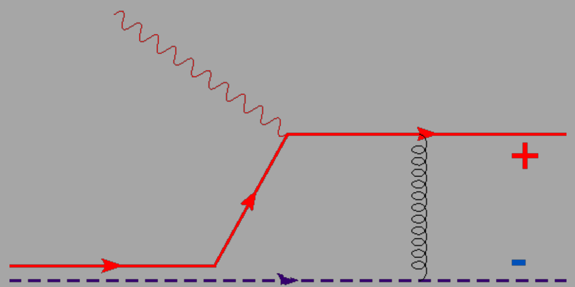
One of the main goals is to verify this relation.
It goes beyond “just” check of TMD factorization.
Motivates Drell-Yan experiments

AnDY, COMPASS, JPARC, PAX etc
Barone et al., Anselmino et al., Yuan,Vogelsang, Schlegel et al., Kang,Qiu, Metz,Zhou

Physics of gauge links

Colored objects are surrounded by gluons, profound consequence of gauge invariance.

Sivers function has opposite sign when gluon couple after quark scatters (SIDIS) or before quark annihilates (Drell-Yan)



man,

$$f_{1T}^{\perp SIDIS} = -$$

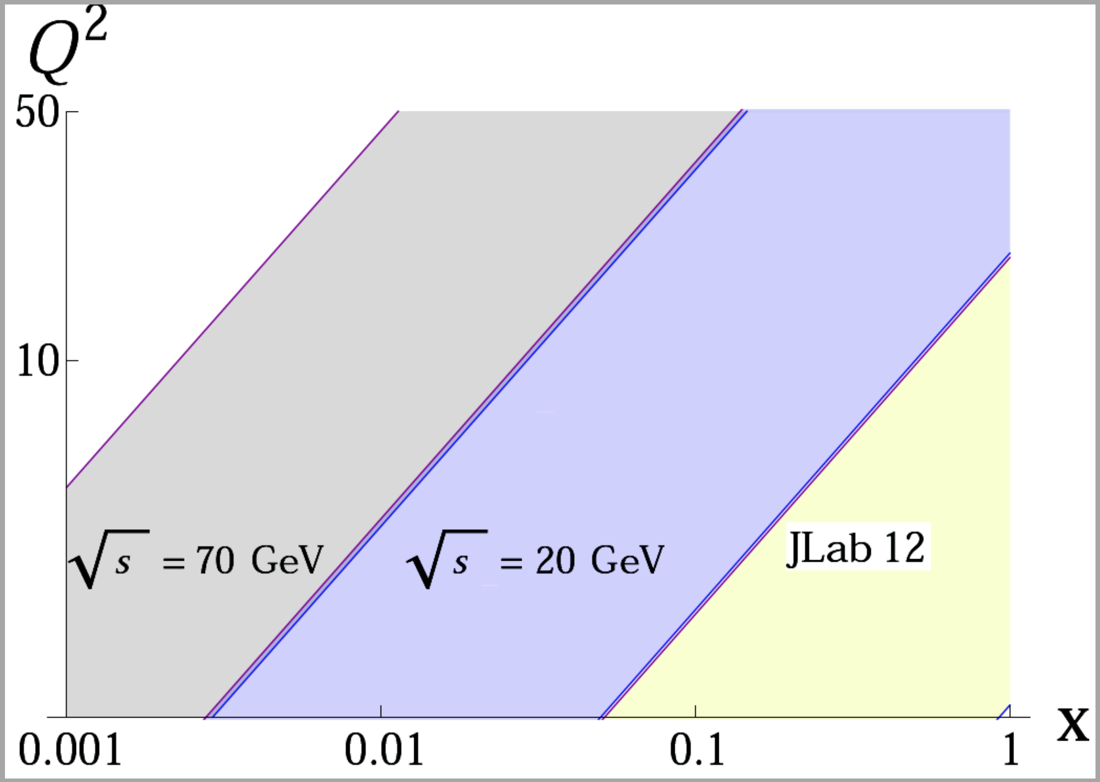
Drell-Yan is at much different resolution scale Q.
EIC will operate at higher Q.
What do we know about evolution of TMDs?

One of the main goals is to verify ution.
It goes beyond "just" check of TMD ctorization.
Motivates Drell-Yan experiments

AnDY, COMPASS, JPARC, PAX etc
Barone et al., Anselmino et al., Yuan,Vogelsang, Schlegel et al., Kang,Qiu, Metz,Zhou

Kinematics

Kinematics $Q^2 \simeq sxy$



Electron Ion Collider reaches higher Q

Jlab 12 and future Electron Ion Collider are complimentary

Evolution of TMDs

One needs a unique definition of TMDs

Foundations of perturbative QCD
Collins 2011

$$W^{\mu\nu} = \sum_f |H_f(Q^2, \mu|^{\mu\nu}$$
$$\times \int d^2\mathbf{k}_{1T} d^2\mathbf{k}_{2T} F_{f/P_1}(x_1, \mathbf{k}_{1T}; \mu, \zeta_F) F_{\bar{f}/P_1}(x_2, \mathbf{k}_{2T}; \mu, \zeta_F)$$
$$\times \delta^{(2)}(\mathbf{k}_{1T} + \mathbf{k}_{2T} - \mathbf{q}_T) + Y(\mathbf{q}_T, Q)$$

$F_{f/P_1}(x_1, \mathbf{k}_{1T}; \mu, \zeta_F)$ **TMD distribution of partons in hadron**

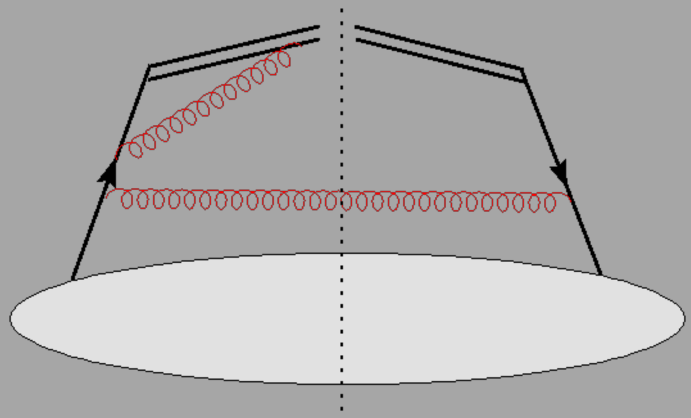
Rapidity divergence regulator

Renorm group (RG) renormalization

Evolution of TMDs

One needs a unique definition of TMDs

Foundations of perturbative QCD
Collins 2011



Infinite rapidity of the gluon creates so called rapidity divergence

In collinear PDFs this divergence is cancelled between virtual and real gluon diagrams

It is not the case for TMDs
Thus new regulator ζ_F is needed

$$F_{f/P_1}(x_1, \mathbf{k}_{1T}; \mu, \zeta_F)$$

Rapidity divergence regulator

Renorm group (RG) renormalization

Evolution of TMDs

Evolution of TMDs is done in coordinate space $\mathbf{b}_T$

$$F_{f/P}(x, \mathbf{k}_T; \mu, \zeta_F) = \frac{1}{(2\pi)^2} \int d^2\mathbf{b}_T e^{i\mathbf{k}_T \cdot \mathbf{b}_T} \tilde{F}_{f/P}(x, \mathbf{b}_T; \mu, \zeta_F)$$

Colins Soper 1982
Foundations of perturbative QCD Collins 2011

Why coordinate space?

Convolutions become simple products:

Collins, Soper 1982
Collins, Soper, Sterman 1985
Idilbi, Ji, Ma, Yuan 2004
Boer, Gamberg, Musch, AP 2011

$$\tilde{W}^{\mu\nu} = \sum_f |H_f(Q^2, \mu|^{\mu\nu} \times \int d^2\mathbf{b}_T e^{i\mathbf{b}_T \mathbf{q}_T} \tilde{F}_{f/P_1}(x_1, \mathbf{b}_T; \mu, \zeta_F) \tilde{F}_{\bar{f}/P_1}(x_2, \mathbf{b}_T; \mu, \zeta_F)$$

In principle experimental study of functions in coordinate space
Is possible

Boer, Gamberg, Musch, AP 2011

Evolution of TMDs

Evolution of TMDs is done in coordinate space $\mathbf{b}_T$

$$F_{f/P}(x, \mathbf{k}_T; \mu, \zeta_F) = \frac{1}{(2\pi)^2} \int d^2\mathbf{b}_T e^{i\mathbf{k}_T\cdot\mathbf{b}_T} \tilde{F}_{f/P}(x, \mathbf{b}_T; \mu, \zeta_F)$$

Colins Soper 1982
Foundations of perturbative QCD Collins 2011

Complicated in case of Sivers function

Aybat, Collins, Qiu, Rogers 2012

$$F_{f/P^\uparrow}(x, \mathbf{k}_T, \mathbf{S}_T; \mu, \zeta_F) = F_{f/P}(x, \mathbf{k}_T; \mu, \zeta_F) - F_{1T}^{\perp f}(x, \mathbf{k}_T; \mu, \zeta_F) \frac{\epsilon_{ij} k_T^i S^j}{M_p}$$

Unpolarised part:

$$\tilde{F}_{f/P}(x, b_T; \mu, \zeta_F) = (2\pi) \int_0^\infty dk_T k_T J_0(k_T b_T) F_{f/P}(x, k_T; \mu, \zeta_F)$$

Sivers function:

$$\tilde{F}_{1T}^{\prime\perp f}(x, b_T; \mu, \zeta_F) = -(2\pi) \int_0^\infty dk_T k_T^2 J_1(k_T b_T) F_{1T}^{\perp f}(x, k_T; \mu, \zeta_F)$$

TMD evolution

Energy evolution

$$\frac{\partial \ln \tilde{F}(x, b_\perp, \mu, \zeta)}{\partial \ln \sqrt{\zeta}} = \tilde{K}(b_\perp, \mu)$$

→ Collins-Soper kernel in coordinate space

TMD:
Collins 2011
Rogers, Aybat 2011
Aybat, Collins, Qiu, Rogers 2011

Renormalization group equations

$$\frac{d\tilde{K}(b_\perp, \mu)}{d \ln \mu} = -\gamma_K(g(\mu))$$

$$\frac{d \ln \tilde{F}(x, b_\perp, \mu, \zeta)}{d \ln \mu} = -\gamma_F(g(\mu), \zeta)$$

TMD evolution

Energy evolution

$$\frac{\partial \ln \tilde{F}(x, b_\perp, \mu, \zeta)}{\partial \ln \sqrt{\zeta}} = \tilde{K}(b_\perp, \mu)$$

→ Collins-Soper kernel in coordinate space

At small $\mathbf{b}_T$ perturbative treatment is possible

TMD:
Collins 2011
Rogers, Aybat 2011
Aybat, Collins, Qiu, Rogers 2011

$$\tilde{K}(b_T, \mu) = -\frac{\alpha_s C_F}{\pi}\left(\ln(\mu^2 b_T^2) - \ln 4 + 2\gamma_E\right) + \mathcal{O}(\alpha_s^2)$$

Large $\mathbf{b}_T$ nonperturbative – matching via $\mathbf{b}_*$ Collins Soper 1982

$$b_*(b_T) = \frac{b_T}{\sqrt{1 + b_T^2/b_{max}^2}}$$

TMD evolution

Energy evolution

$$\frac{\partial \ln \tilde{F}(x, b_\perp, \mu, \zeta)}{\partial \ln \sqrt{\zeta}} = \tilde{K}(b_\perp, \mu)$$

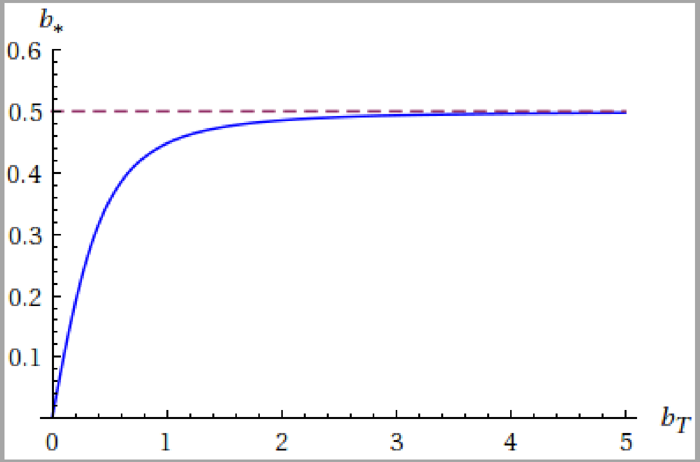
→ Collins-Soper kernel in coordinate space

Large $\mathbf{b}_T$ nonperturbative – matching via $\mathbf{b}_*$ Collins Soper 1982

$$b_*(b_T) = \frac{b_T}{\sqrt{1 + b_T^2/b_{max}^2}}$$

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

Brock, Landry, Nadolsky, Yuan 2003



TMD evolution

Energy evolution

$$\frac{\partial \ln \tilde{F}(x, b_\perp, \mu, \zeta)}{\partial \ln \sqrt{\zeta}} = \tilde{K}(b_\perp, \mu)$$

Collins-Soper kernel in coordinate space

Large $\mathbf{b}_T$ nonperturbative – matching via $\mathbf{b}_*$ Collins Soper 1982

$$\tilde{K}(b_T, \mu) = \tilde{K}(b_*, \mu) - g_K(b_T)$$

Always perturbative

Non perturbative

$$g_K(b_T) = \frac{1}{2} g_2 b_T^2$$

$$g_2 \simeq 0.68 \; (GeV^2)$$

This function is universal for different partons!

Brock, Landry, Nadolsky, Yuan 2003

TMD evolution

Relation to collinear treatment:

$$\tilde{F}_f(x, b_T, \mu, \zeta) = \sum_j \int_x^1 \frac{d\hat{x}}{\hat{x}} \tilde{C}_{j/f}\left(\frac{x}{\hat{x}}, b_T, \mu, \zeta\right) f_j(\hat{x}, \mu) + \mathcal{O}(\Lambda_{QCD} b_T)$$

Collins Soper 1982

Valid at small $\mathbf{b}_T$, lowest order:

$$\tilde{C}_{j/f}(\frac{x}{\hat{x}}, b_T, \mu, \zeta) = \delta_{jf} \delta\left(\frac{x}{\hat{x}} - 1\right) + \mathcal{O}(\alpha_s)$$

Higher order for TMD PDFs

Aybat Rogers 2011

Higher order for Sivers function

Kang, Xiao, Yuan 2011

TMD evolution

Solution Rogers, Aybat 2011
Aybat, Collins, Qiu, Rogers 2011

$$\tilde{F}_{f/P}(x, b_T; Q, \zeta_F) = \tilde{F}_{f/P}(x, b_T; Q_0, Q_0^2)$$
$$\times \exp\Big[-g_K(b_T) \ln \frac{Q}{Q_0} \Big]$$

Non perturbative

$$\times \exp\Big[\ln \frac{Q}{Q_0} \tilde{K}(b_*; \mu_b) + \int_{Q_0}^{Q} \frac{d\mu'}{\mu'} \Big[\gamma_F(g(\mu'); 1) - \ln \frac{Q}{\mu'} \gamma_K(g(\mu')) \Big]$$
$$+ \int_{Q_0}^{\mu_b} \frac{d\mu'}{\mu'} \ln \frac{Q}{Q_0} \gamma_K(g(\mu')) \Big]$$

Perturbative

Typically for TMDs:

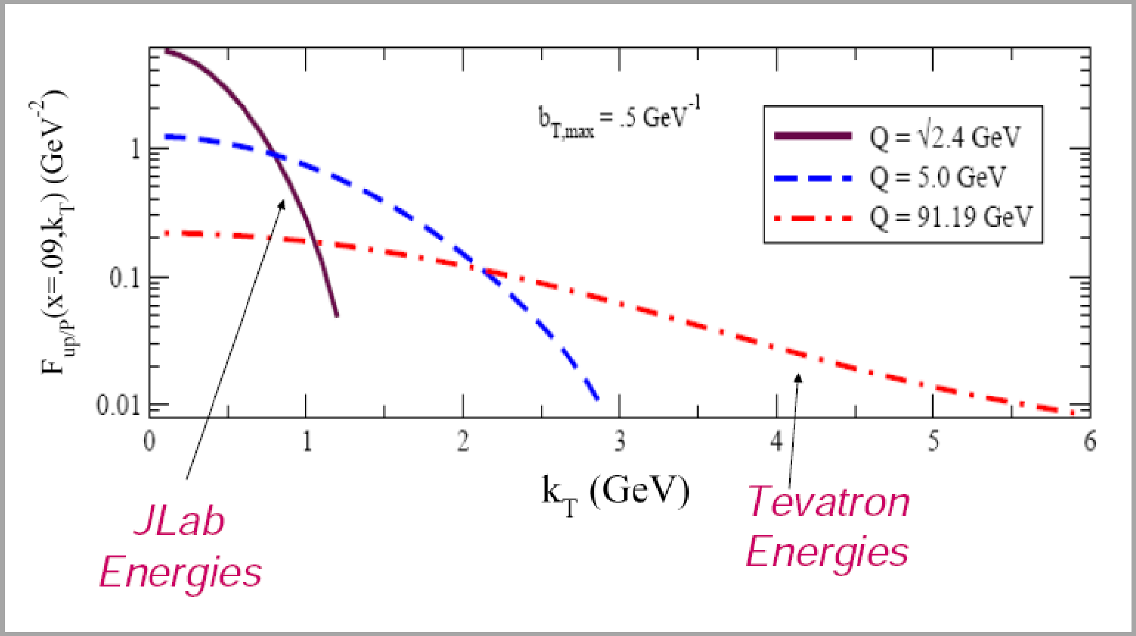
$$\tilde{F}_{f/P}(x, b_T; Q_0, Q_0^2) = F_{f/P}(x; Q_0) \exp\Big(-\frac{\langle k_T^2 \rangle}{4} b_T^2 \Big)$$

TMD evolution

Solution Rogers, Aybat 2011
Aybat, Collins, Qiu, Rogers 2011

$$\tilde{F}_{f/P}(x, b_T; Q, \zeta_F) = F_{f/P}(x; Q_0) \exp\Big(- \Big[\frac{\langle k_T^2 \rangle}{4} + \frac{g_2}{2} \ln \frac{Q}{Q_0}\Big] b_T^2 \Big)$$

Non perturbative

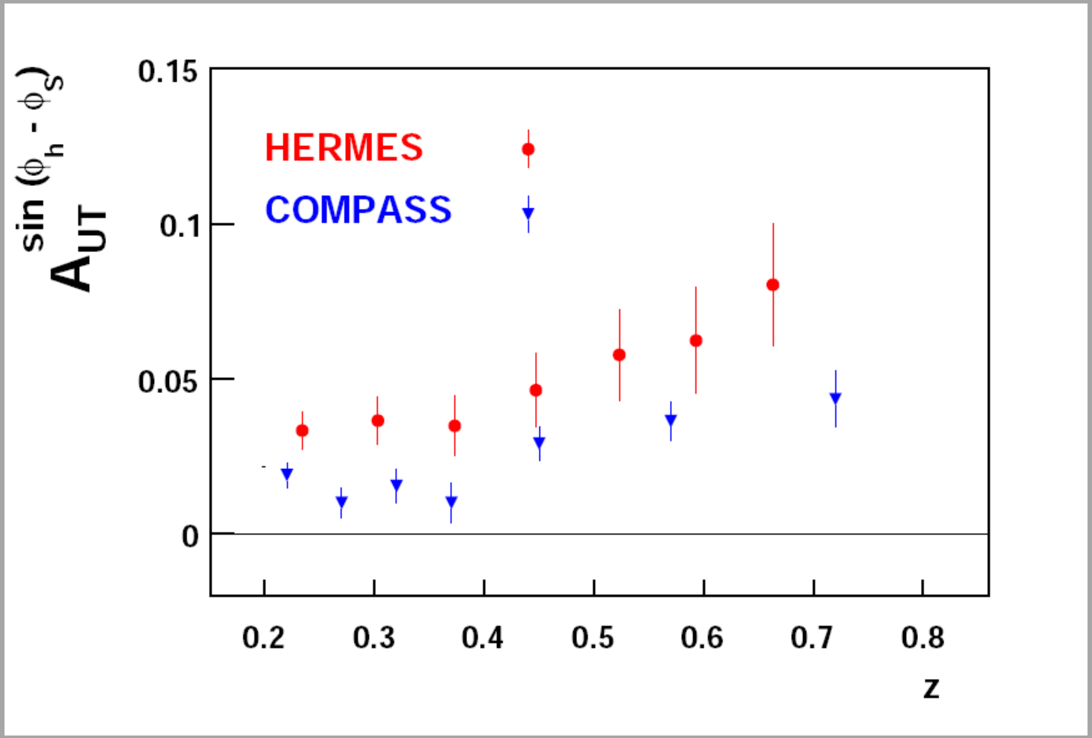


Gaussian behaviour is appropriate only in a limited range

TMDs change with energy and resolution scale

TMD evolution

Can we see signs of evolution in the experimental data?



Aybat, AP, Rogers 2011

COMPASS data is at

$$\langle Q^2 \rangle \simeq 3.6\ (GeV^2)$$

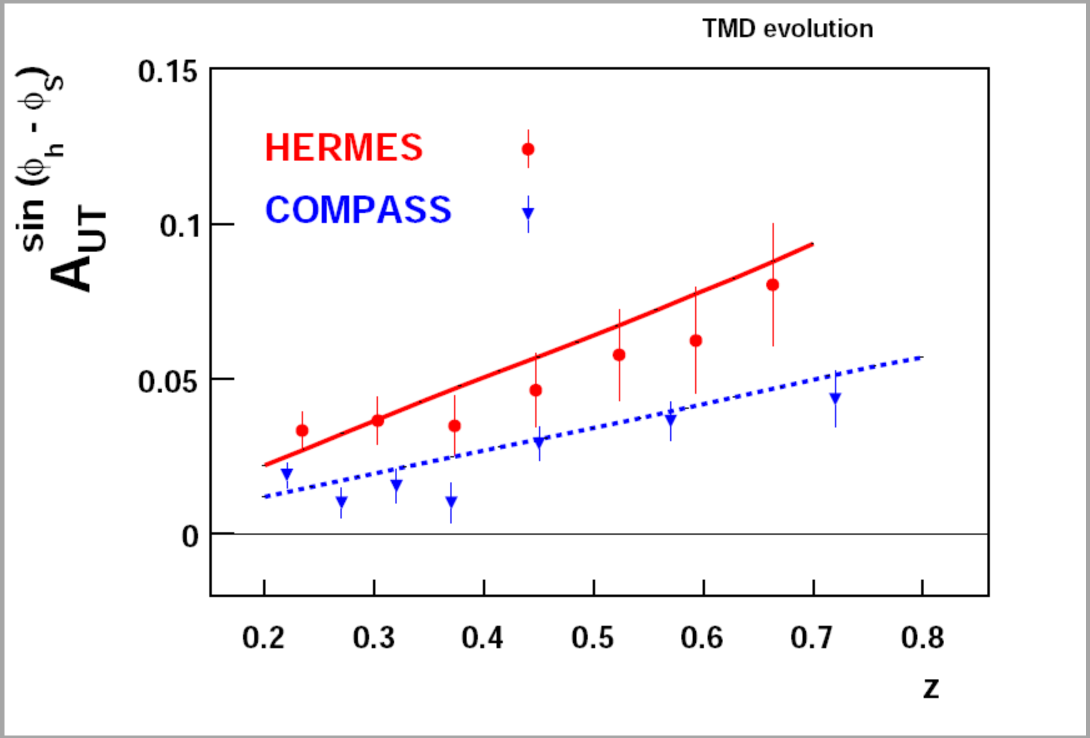
HERMES data is at

$$\langle Q^2 \rangle \simeq 2.4\ (GeV^2)$$

TMD evolution

Can we explain the experimental data?

Full TMD evolution is needed!



Aybat, AP, Rogers 2011

COMPASS dashed line

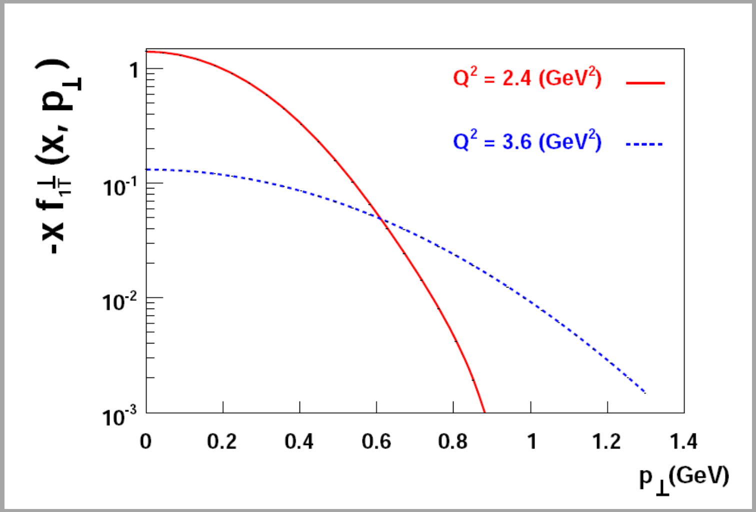
$$\langle Q^2 \rangle \simeq 3.6 \ (GeV^2)$$

HERMES solid line

$$\langle Q^2 \rangle \simeq 2.4 \ (GeV^2)$$

TMD evolution

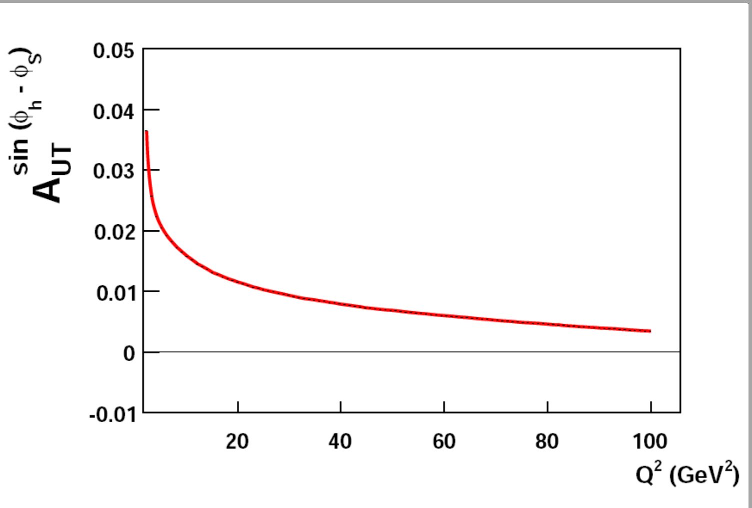
This is the first implementation of TMD evolution for observables



Aybat, AP, Rogers 2011

Asymmetry changes with Q^2

Functions change with energy



Phenomenological analysis with evolution is now possible

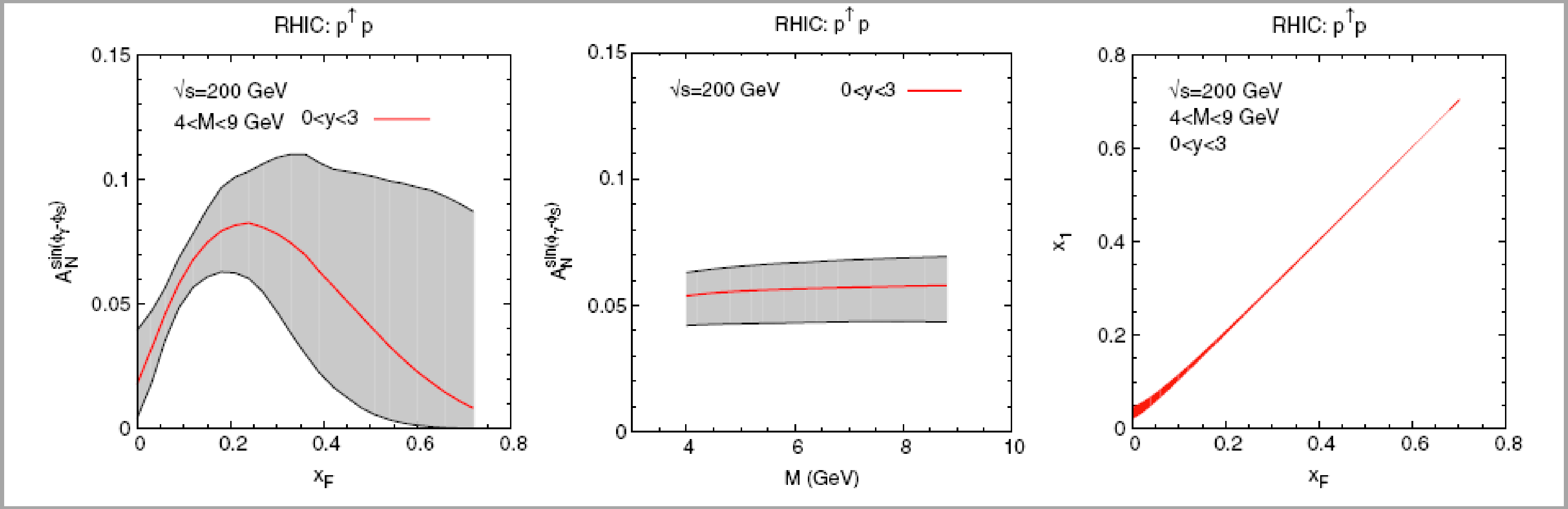
Drell Yan

$$\mathbf{A_N = \frac{\sum_q f_{1T}^{\perp q}(x_1, p_T) \otimes f_1^{\bar{q}}(x_1, p_T)\sigma_{q\bar{q}}}{\sum_q f_1^{q}(x_1, p_T) \otimes f_1^{\bar{q}}(x_1, p_T)\sigma_{q\bar{q}}}}$$

Analysis at LO in hadronic cm frame
Anselmino et al (2009)

$$\mathbf{x_1 = \frac{x_F + \sqrt{x_F^2 + 4M^2/s}}{2} \approx x_F}$$

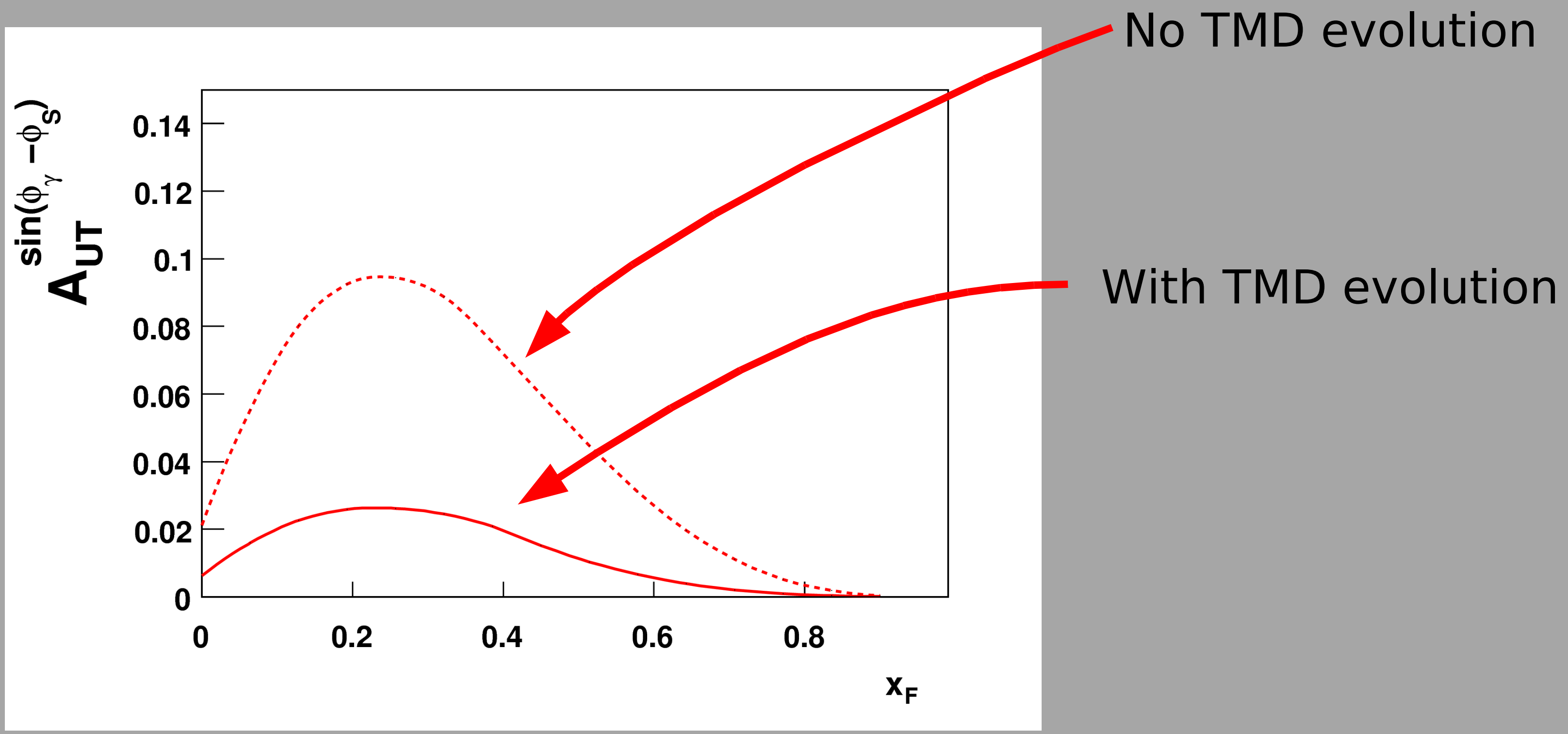
In DY we probe Sivers function at $\mathbf{x_F}$
Anselmino et al (2009)



Drell Yan

$$A_N = \frac{\sum_q f_{1T}^{\perp q}(x_1, p_T) \otimes f_1^{\bar{q}}(x_1, p_T)\sigma_{q\bar{q}}}{\sum_q f_1^q(x_1, p_T) \otimes f_1^{\bar{q}}(x_1, p_T)\sigma_{q\bar{q}}}$$

Analysis in hadronic cm frame



Asymmetry is suppesed with respect to LO analysis

CONCLUSIONS

- Three dimensional parton picture is achievable with GPD and TMD measurements
- TMD phenomenology is possible with evolution
- HERMES and COMPASS data are compatible with TMD evolution
- Future measurements at Electron Ion Collider and Drell-Yan experiments are important for both confirmation of sign change of function and TMD evolution effects.

QCD EVOLUTION 2012

Deadline registration April 13th! Register soon!