Cape Town EIC Workshop

Alexei Prokudin
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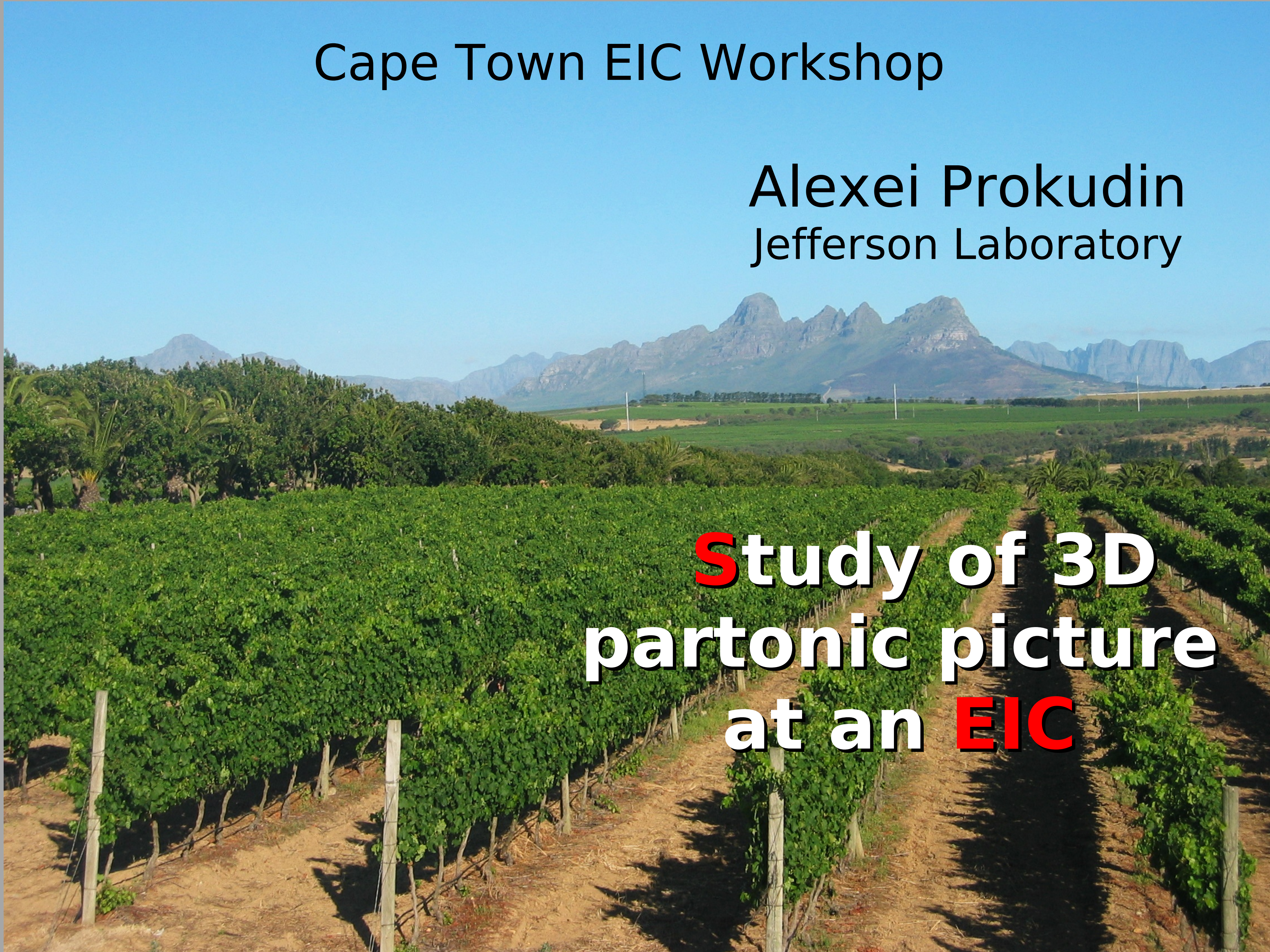
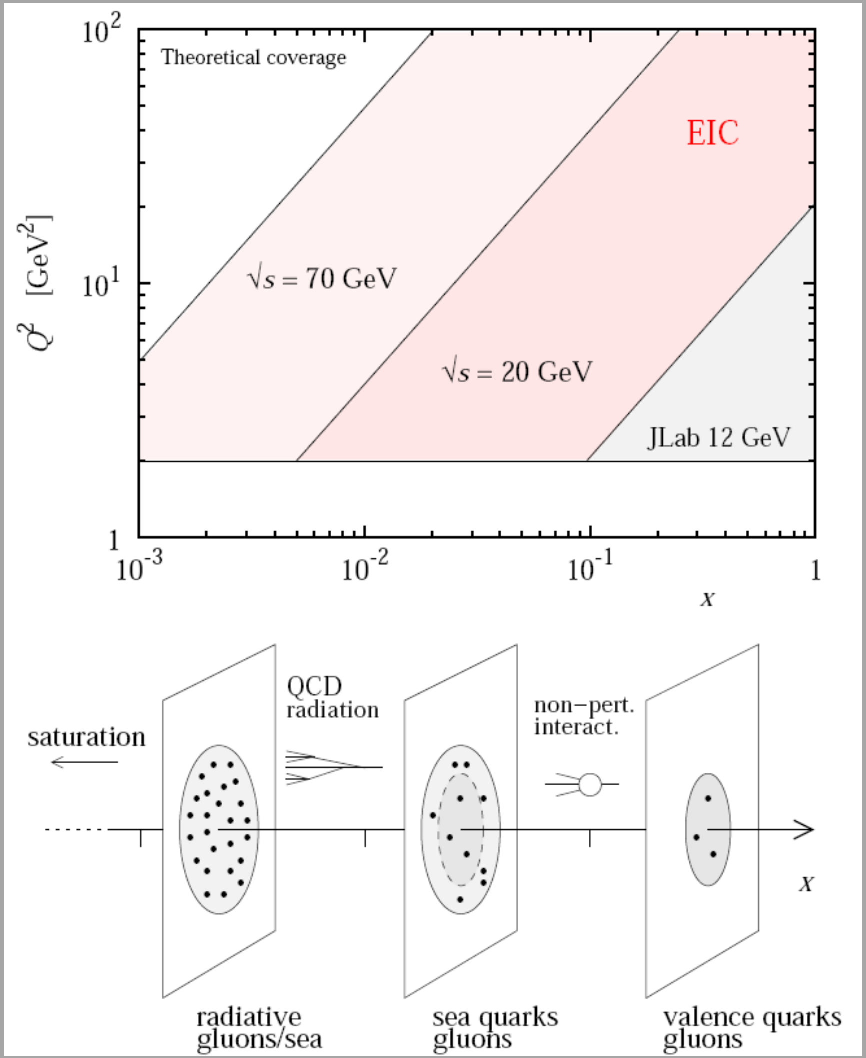
Study of 3D partonic picture at an EIC



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

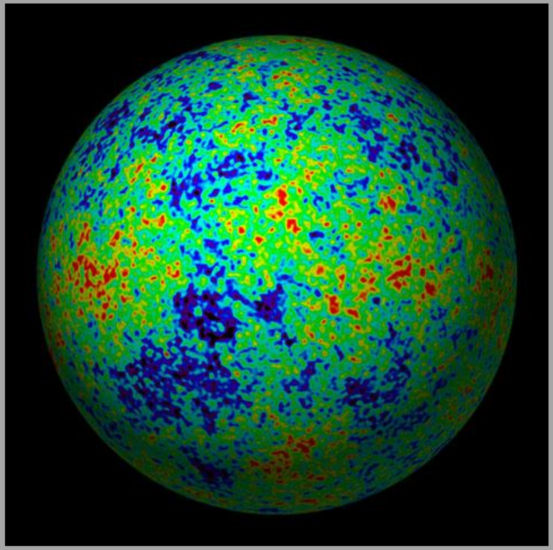
How partons move and how they are distributed in space is one of the future directions of development of nuclear physics

Technically such information is encoded into Generalised Parton Distributions

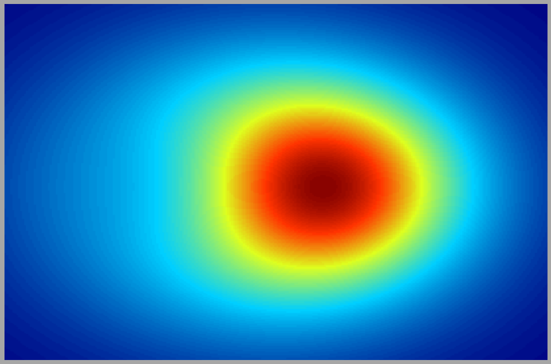
See talks by Markus Deihl and Matthias Burkadt

and Transverse Momentum Dependent distributions

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



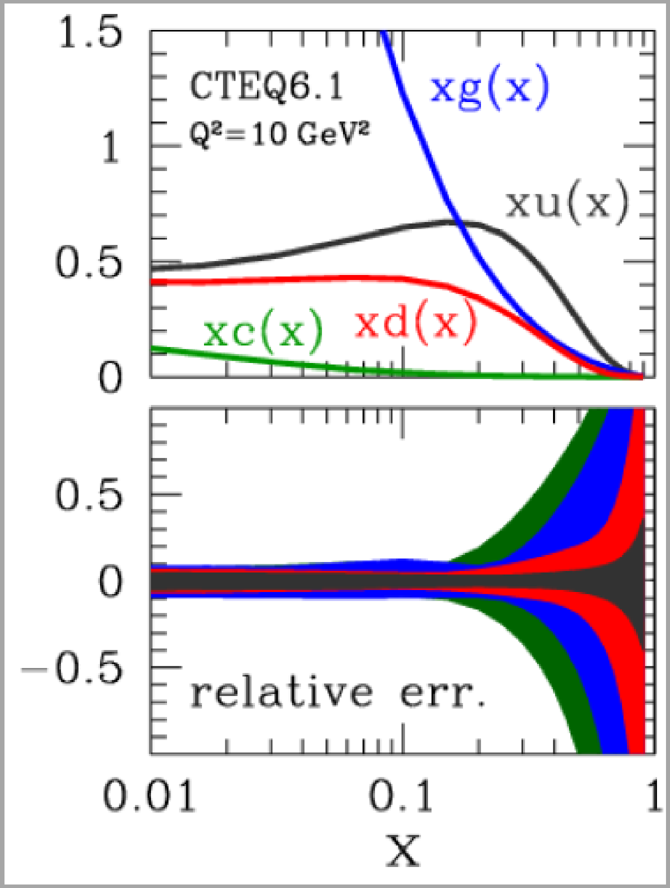
3 Dimensional partonic picture gives us insights on the dynamics of the confined system of quarks and gluons.

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



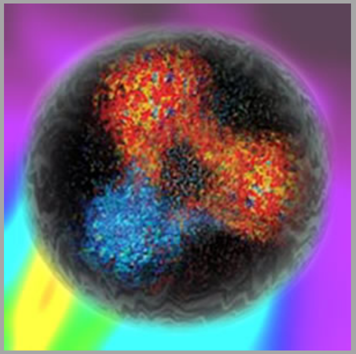
Good knowledge of
Parton
Distribution
Functions (PDFs)
is acquired at HERA

See talk by Voica Radescu

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

Wigner distribution

Our goal is to understand 3 dimensional distributions of partons,
How they move, there they are located inside a nucleon



Wigner distribution (1933) is a possibility

$$W(\mathbf{p},\mathbf{r}) = \int d^3\eta\, e^{i\,\mathbf{p}\eta}\psi^*(\mathbf{r}+\eta/\mathbf{2})\psi(\mathbf{r}-\eta/\mathbf{2})$$

It gives both position and momenta

Wigner distribution

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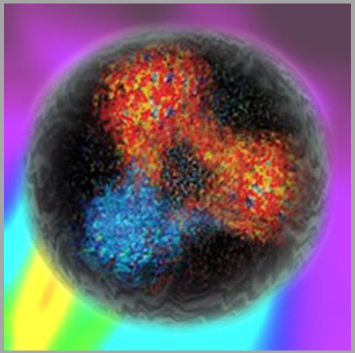

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Can it be measured?

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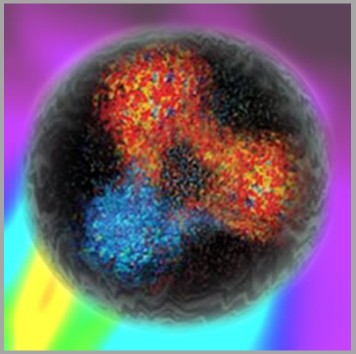

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It gives both position and momenta

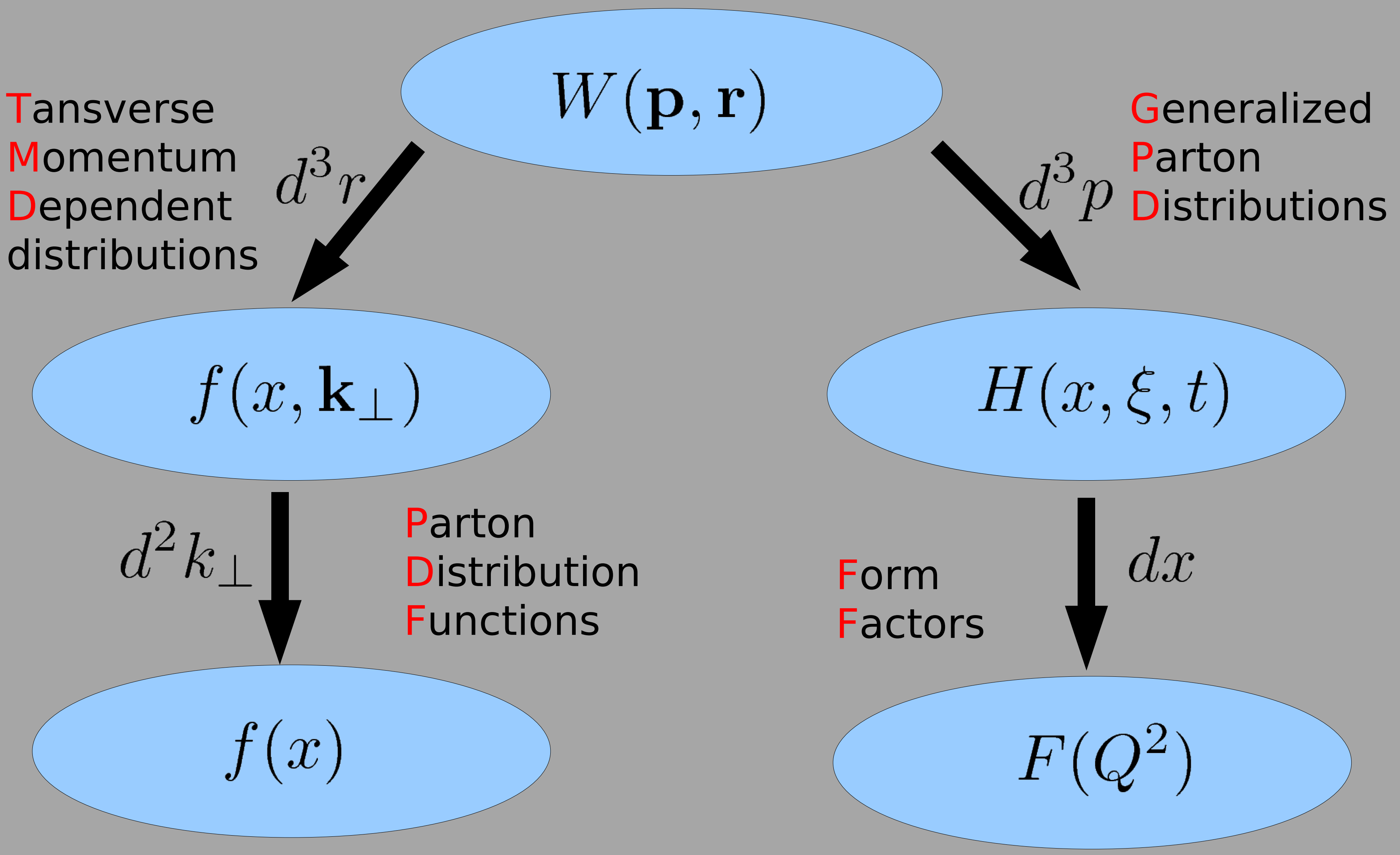
Can it be measured?

PROBABLY NOT!

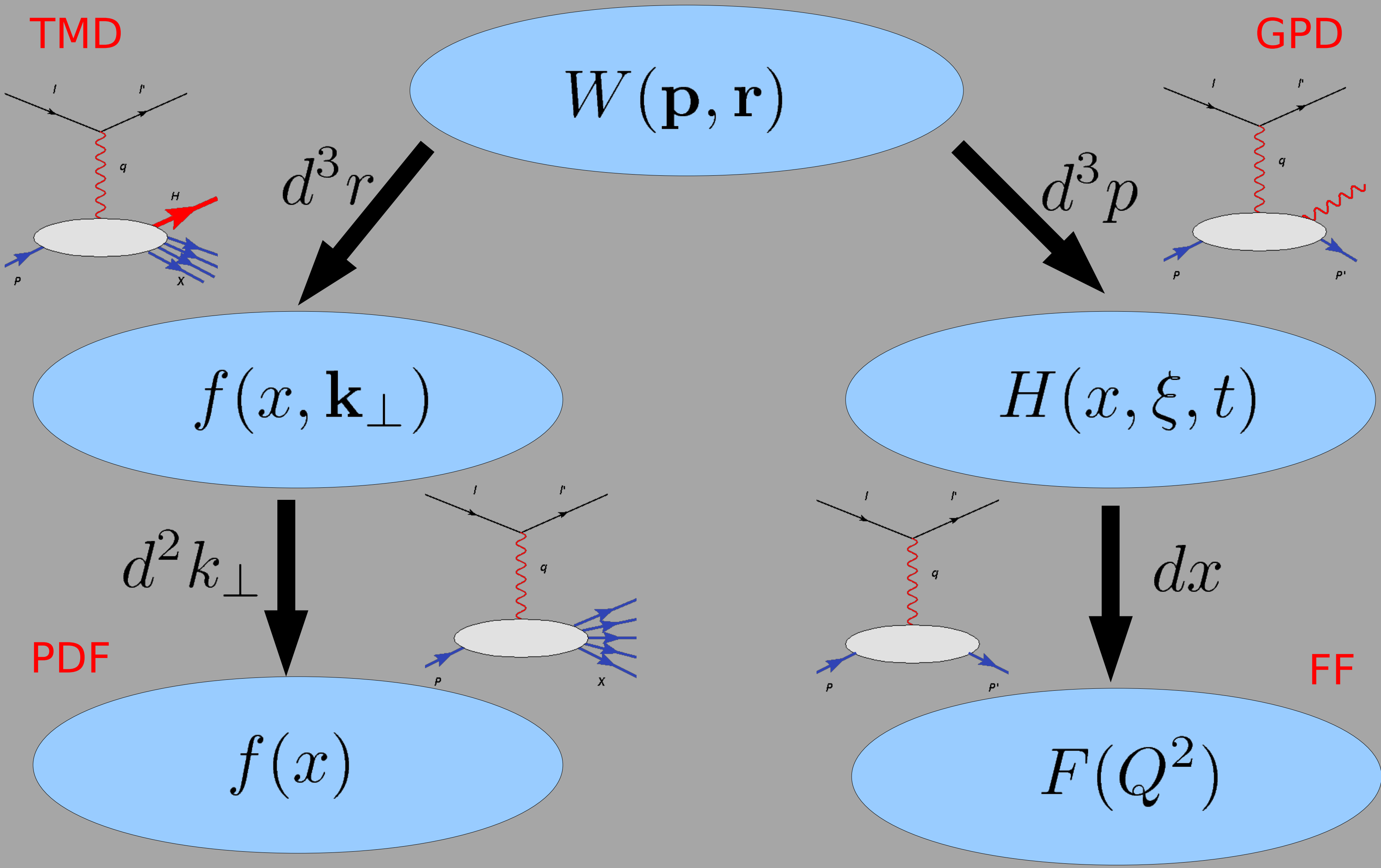
$$\Delta p \Delta r \geq \hbar/2$$

No simultaneous knowledge on position and momenta

Wigner distribution



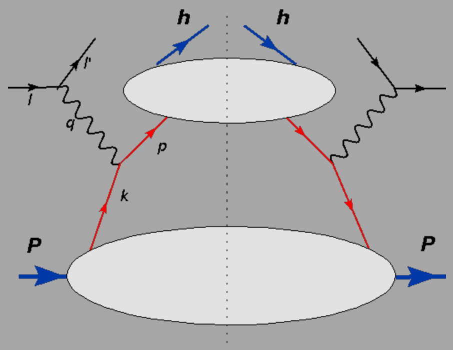
Wigner distribution



Alexei Prokudin

Transverse Momentum Dependent distributions

SIDIS



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

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)

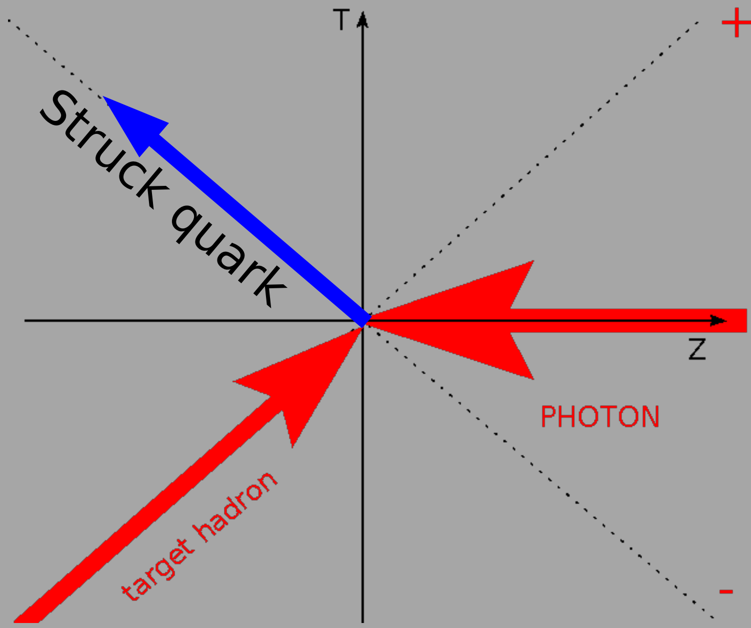
GAUGE INVARIANT

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

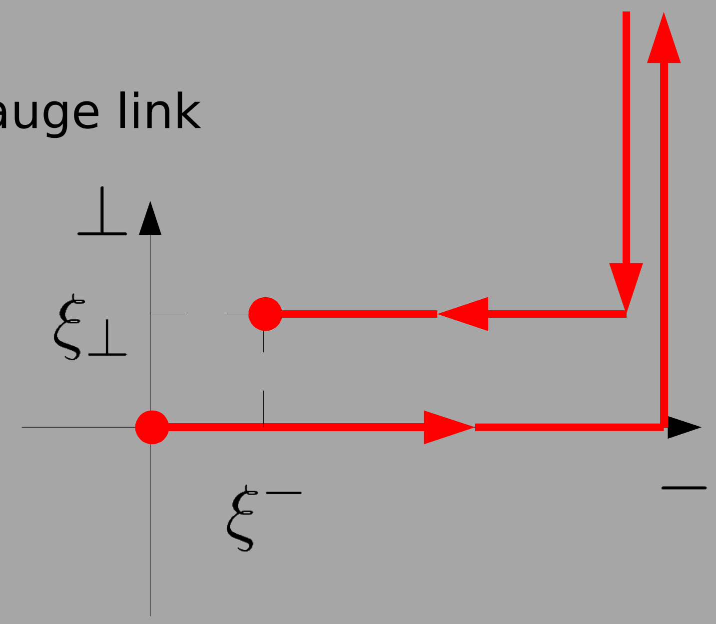
Transverse Momentum Dependent distributions

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

SIDIS in IMF:



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

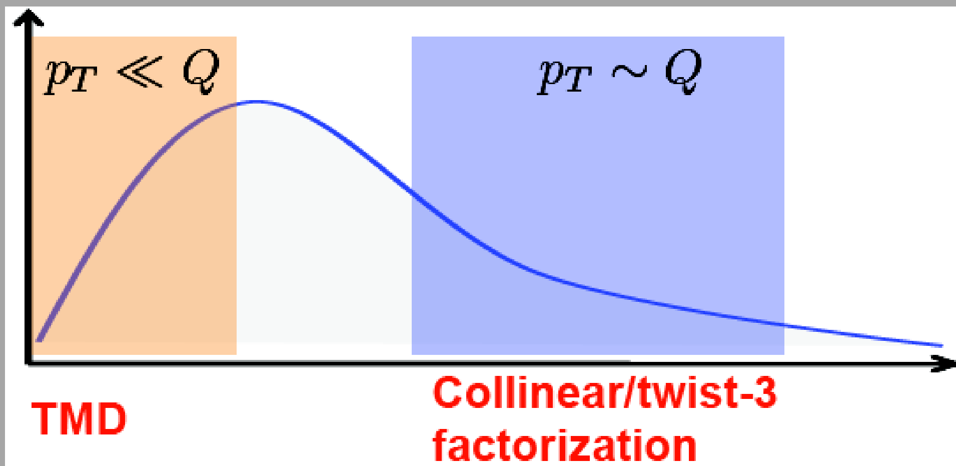
$$\Lambda^2_{QCD} \ll P^2_{h\perp}, Q^2$$

Sensitive to multy parton correlations.

Qui, Sterman, Efremov, Teryaev, Kanazava, Koike, etc

TMD and Collinear factorizations

Both factorizations are consistent in the overlap region



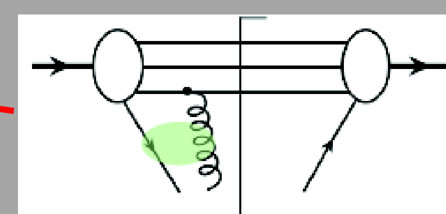
Collins, Mulders, Ji, Qui, Yuan, Bacchetta, Kang, Boer, Koike, Vogelsang, Yuan etc

Relation of multyparton correlations and moments of TMDs

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

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

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)

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

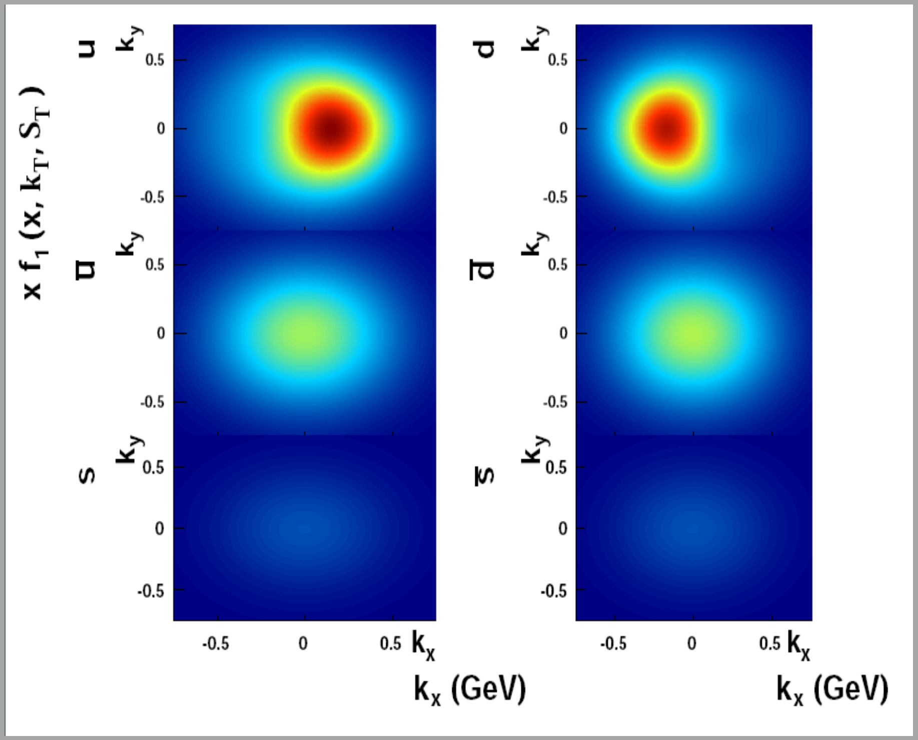
Physics of gauge links is represented

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

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



Dipole deformation

Sivers function from experimental data HERMES and COMPASS

Anselmino et al 2005

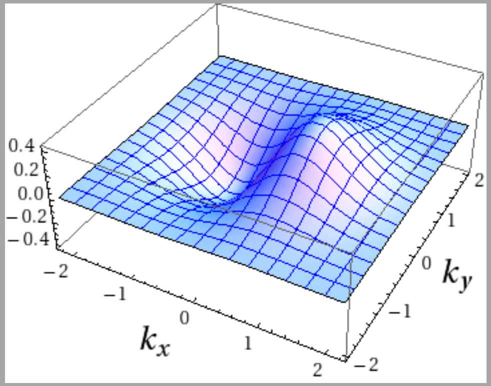
What do we learn from 3D distributions?

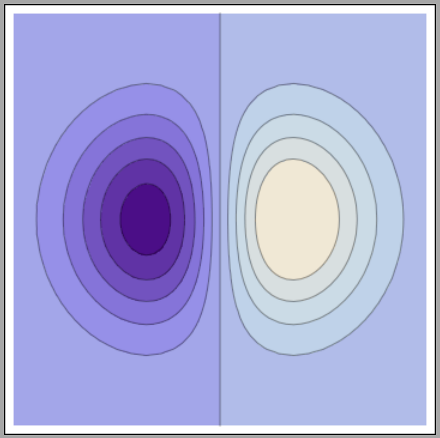
$$f(x, \mathbf{k_T}, \mathbf{S_T}) = f_1(x, \mathbf{k_T^2}) - f_{1T}^{\perp}(x, \mathbf{k_T^2}) \frac{\mathbf{k_x}}{M}$$

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 called "dipole" deformation.





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

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

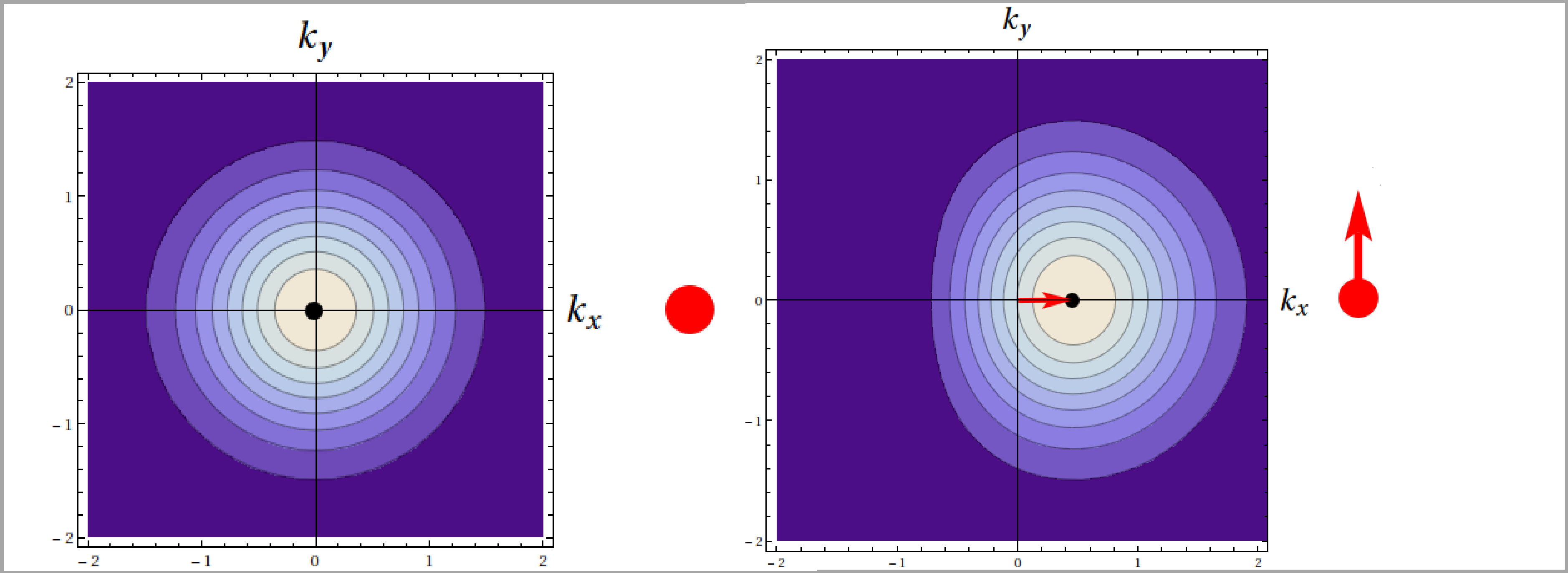
Average momentum shift is equal to the **first moment** of Sivers function

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: $S_y \Rightarrow \langle k_x \rangle$

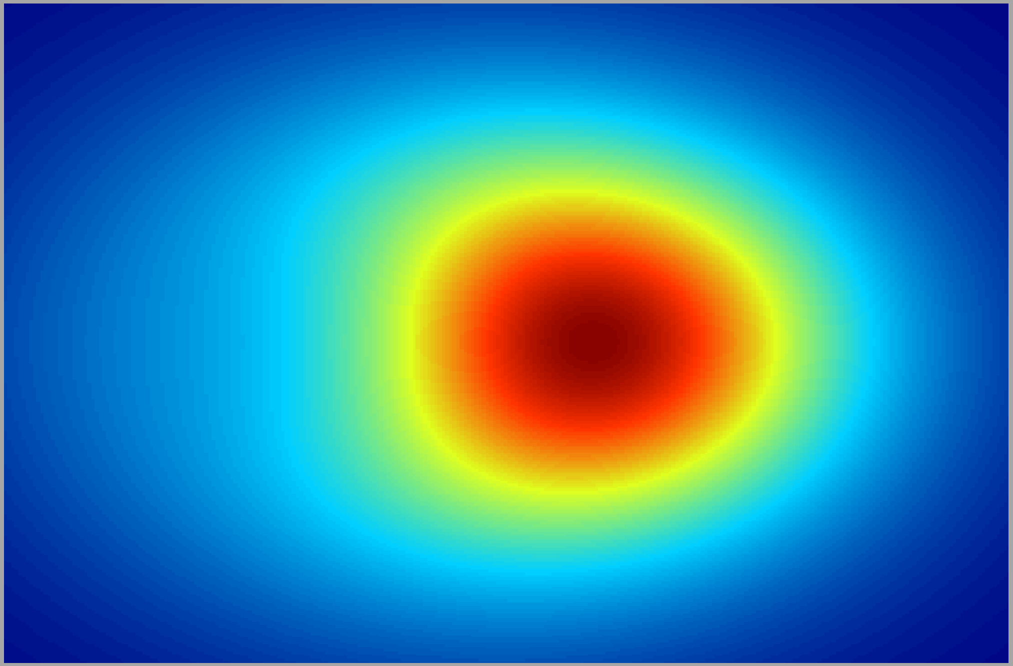


What do we learn from 3D distributions?

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

The same statement in figures:

This is what we know from exerimental data already:



How do we measure Sivers function?

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

$$\sigma^{\uparrow} - \sigma^{\downarrow} = -f_{1T}^{\perp} \otimes d\hat{\sigma} \otimes D_{h/q} \sin(\phi_h - \phi_S)$$

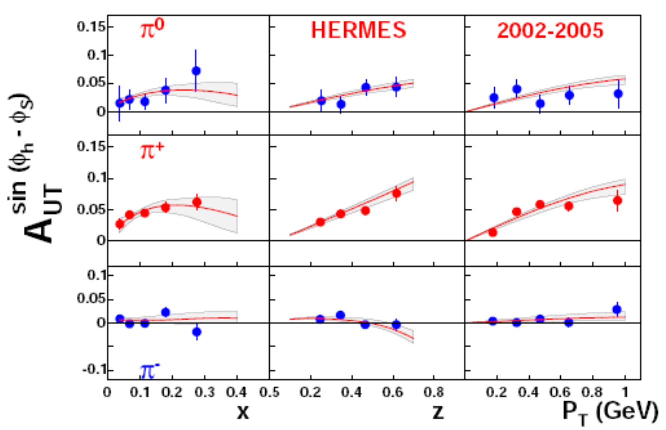
Unpolarised electron beam
Transversely polarised proton

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

See talk by Gunar Schnell

HERMES

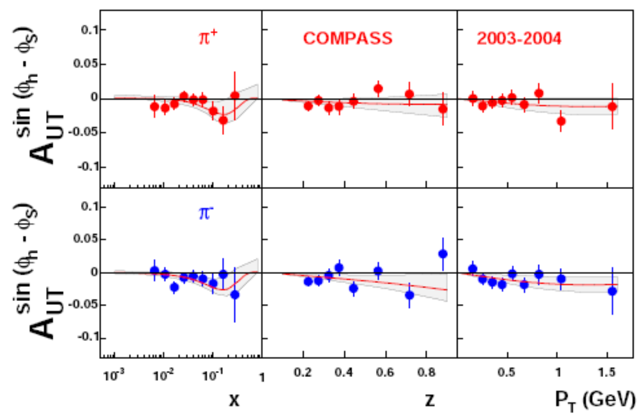
$ep \to e\pi X$, $p_{lab} = 27.57$ GeV.



Anselmino et al 2010

COMPASS

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



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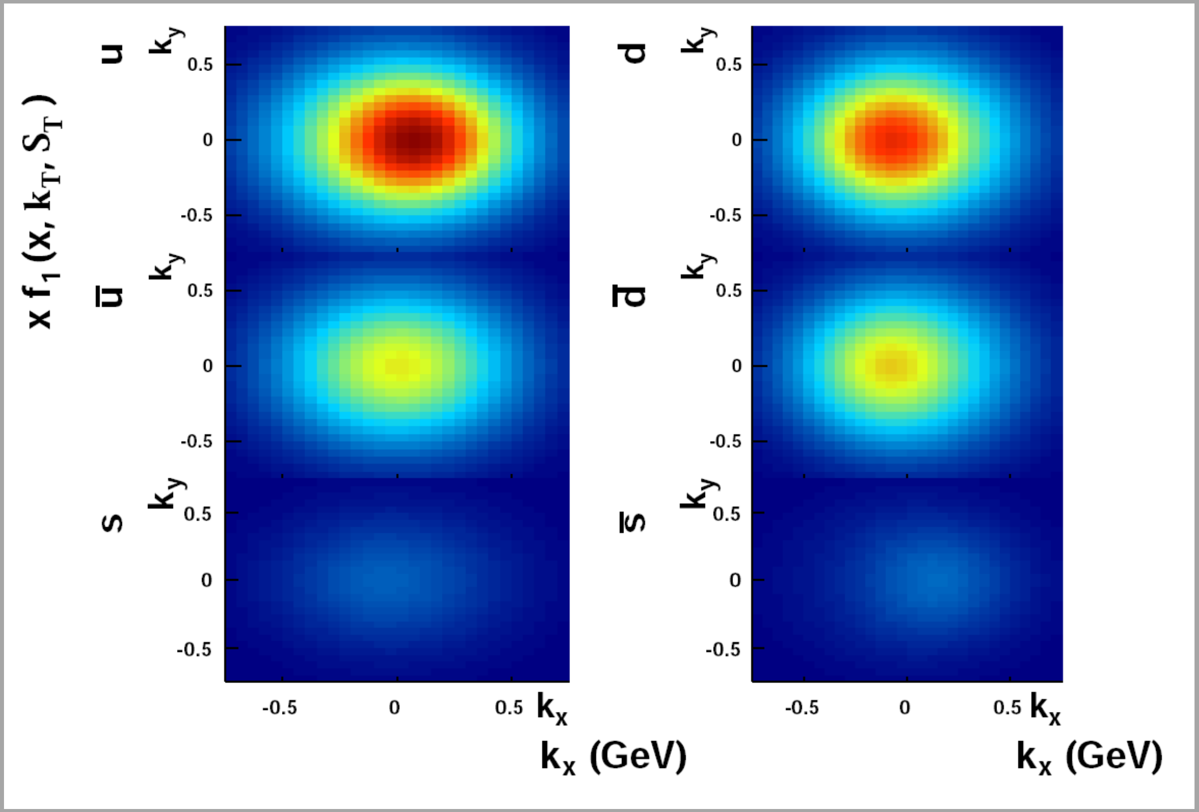


The slice is at:

$x = 0.1$

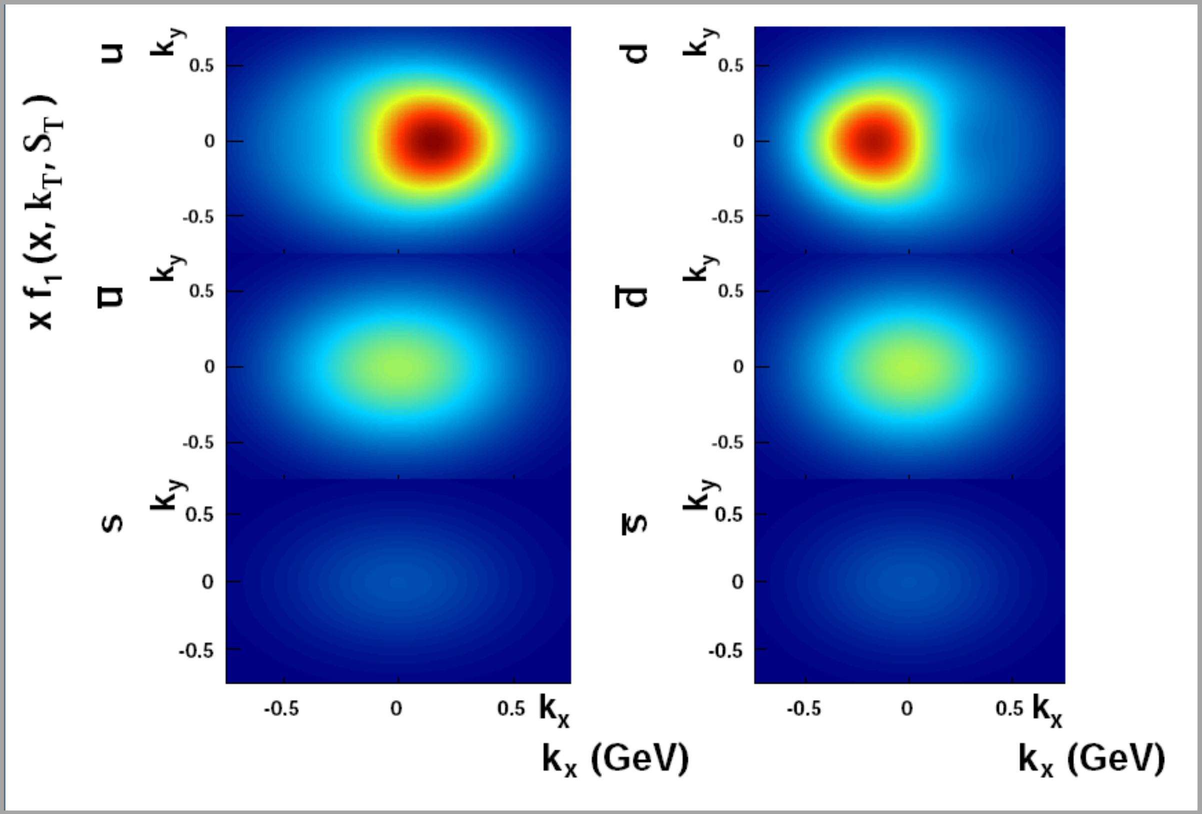
Low-x and high-x region is uncertain
JLab 12 and EIC will contribute

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:

$x = 0.1$

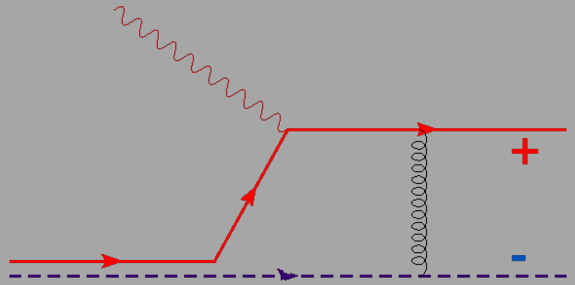
Low-x and high-x region is uncertain
JLab 12 and EIC will contribute

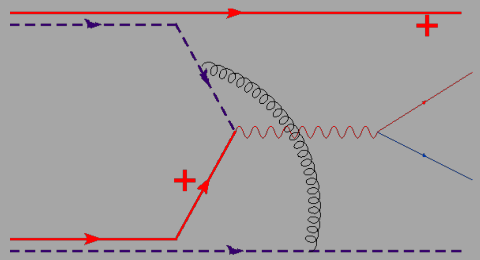
No information on sea quarks

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

TMD theoretical challenges

- Evolution and soft gluon resummation
- Global study at Next-to-Leading order
- Relation to Orbital Angular Momentum

Many more other questions

- What is the kt distributions of partons – gaussian, powerlike, sign changing?
- What is the difference of kt distributions of quarks and sea quarks?
- How to explore higher twist TMDs?
- How to explore distribution and fragmentation TMDs in a satisfactory way?
- etc

TMD evolution

Collins-Soper-Sterman factorization can be used

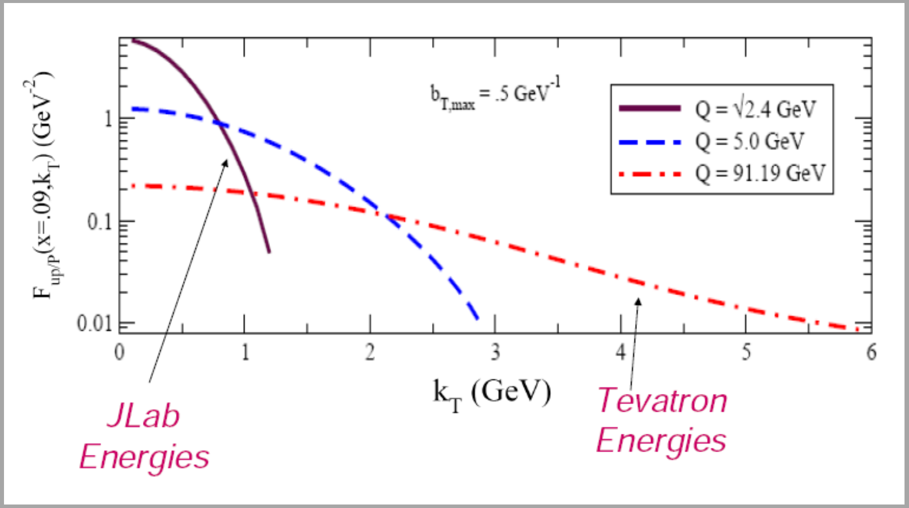
$$\frac{\partial \ln \tilde{F}(x, b_\perp, \mu, \zeta)}{\partial \ln \zeta} = \tilde{K}(b_\perp, \mu)$$

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

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

CS kernel in coordinate space

TMD:
Collins 2011
Rogers, Aybat 2011
Twist-3:
Kang, Xiao, Yuan 2011
Koike, Vogelsang 2011

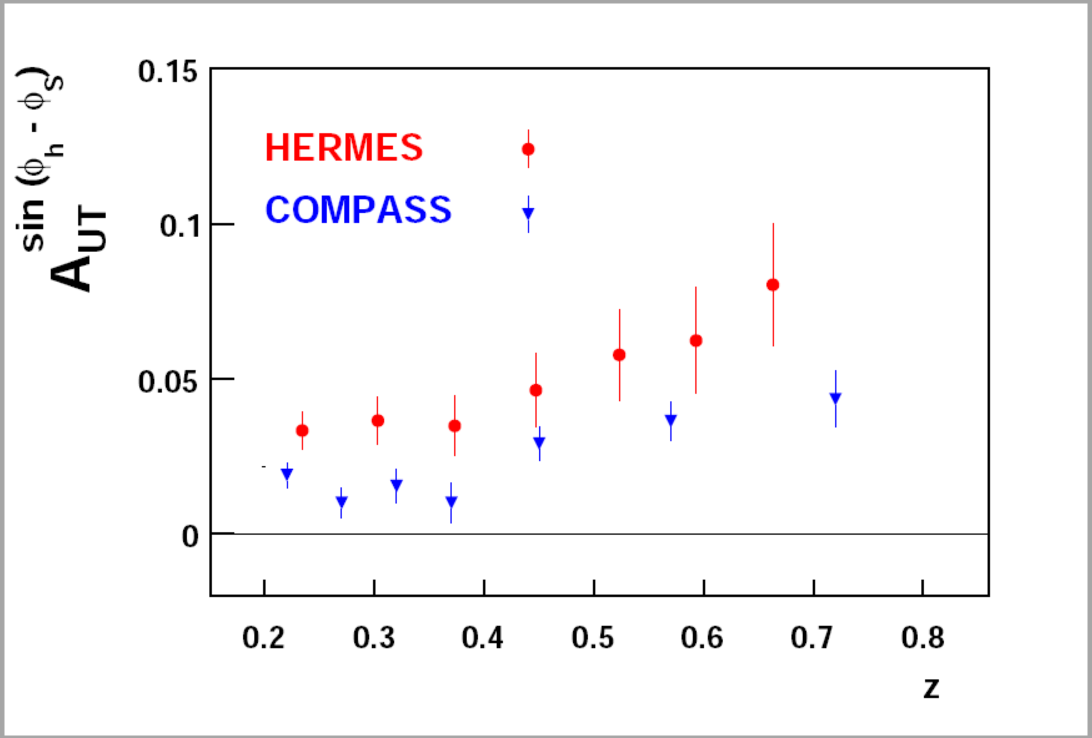


TMDs change with energy and resolution scale

Relevant to EIC

TMD evolution

Can we see signs of evolution in the experimental data?



Aybat, AP, Rogers 2011

COMPASS data is at

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

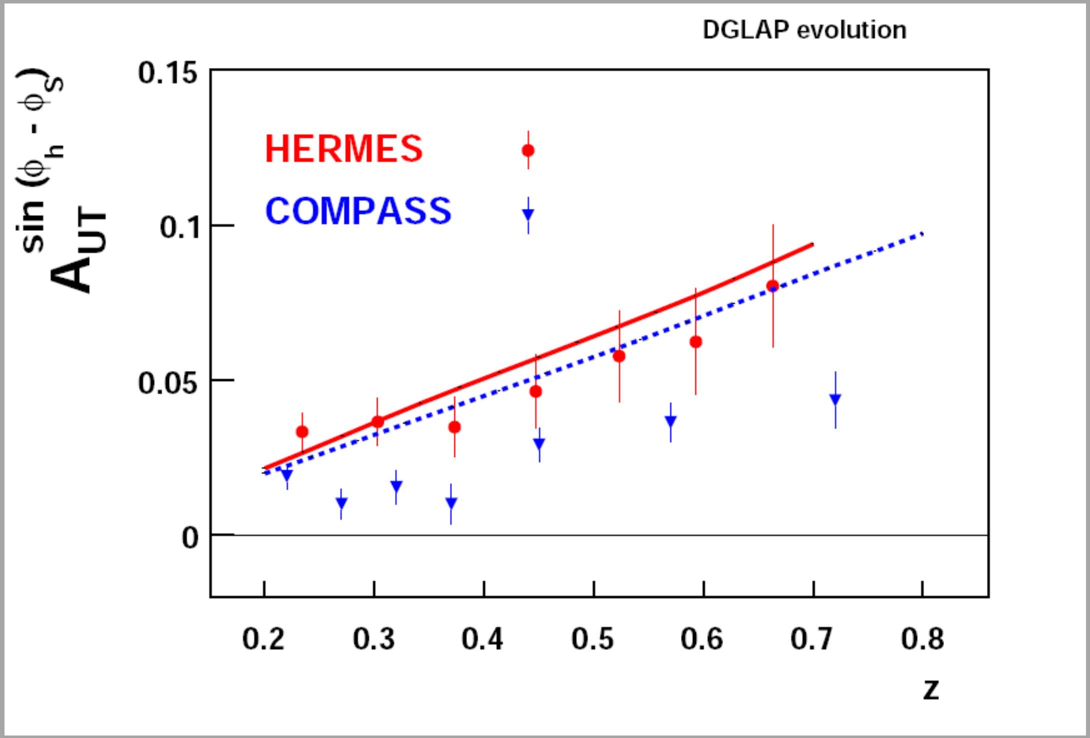
HERMES data is at

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

TMD evolution

Can we explain the experimental data?

Convention method is to apply DGLAP evolution only



Aybat, AP, Rogers 2011

COMPASS dashed line

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

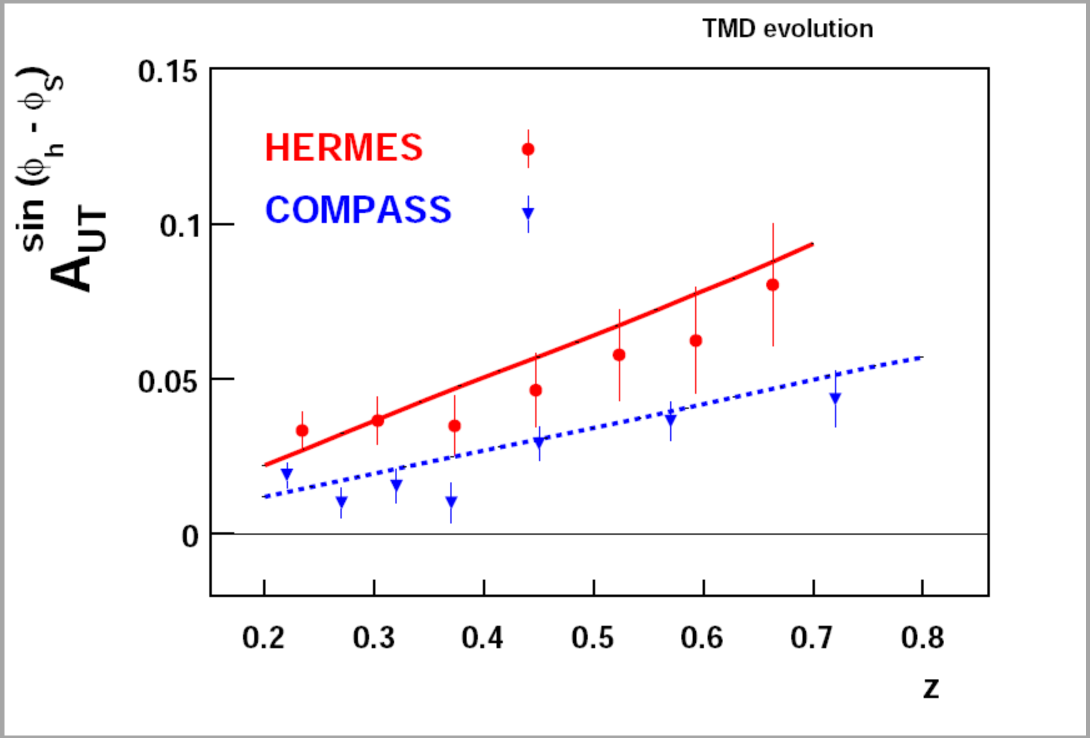
HERMES solid line

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

TMD evolution

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

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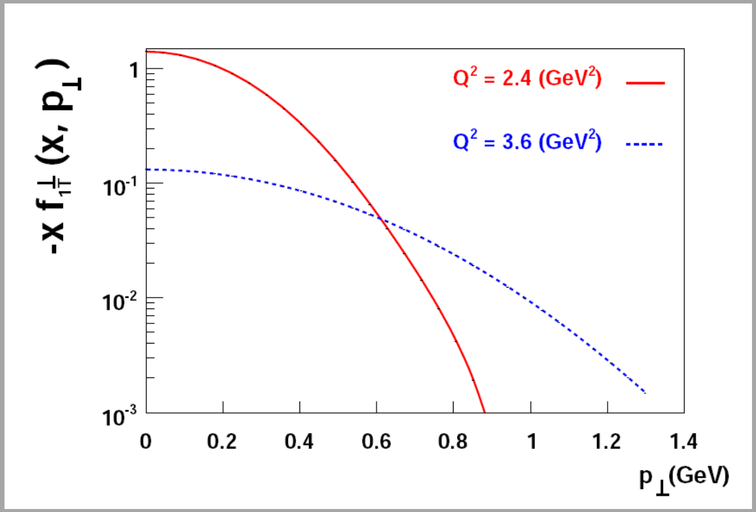
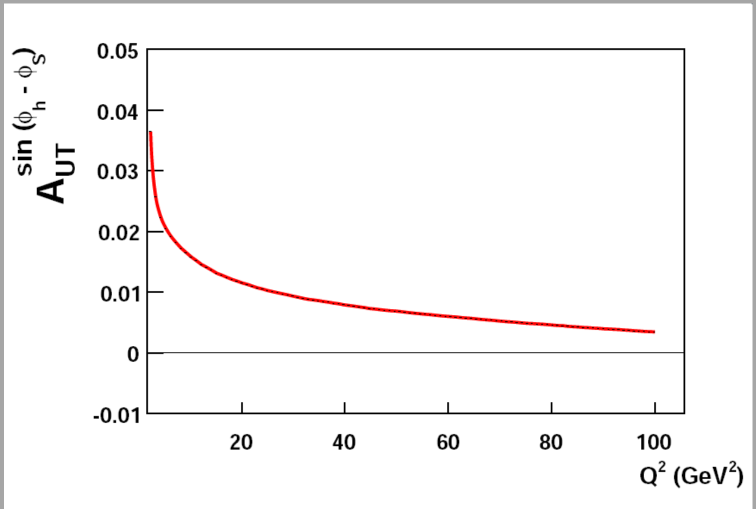
TMD evolution

This is the first implementation of TMD evolution for observables



Aybat, AP, Rogers 2011

Asymmetry changes with Q^2

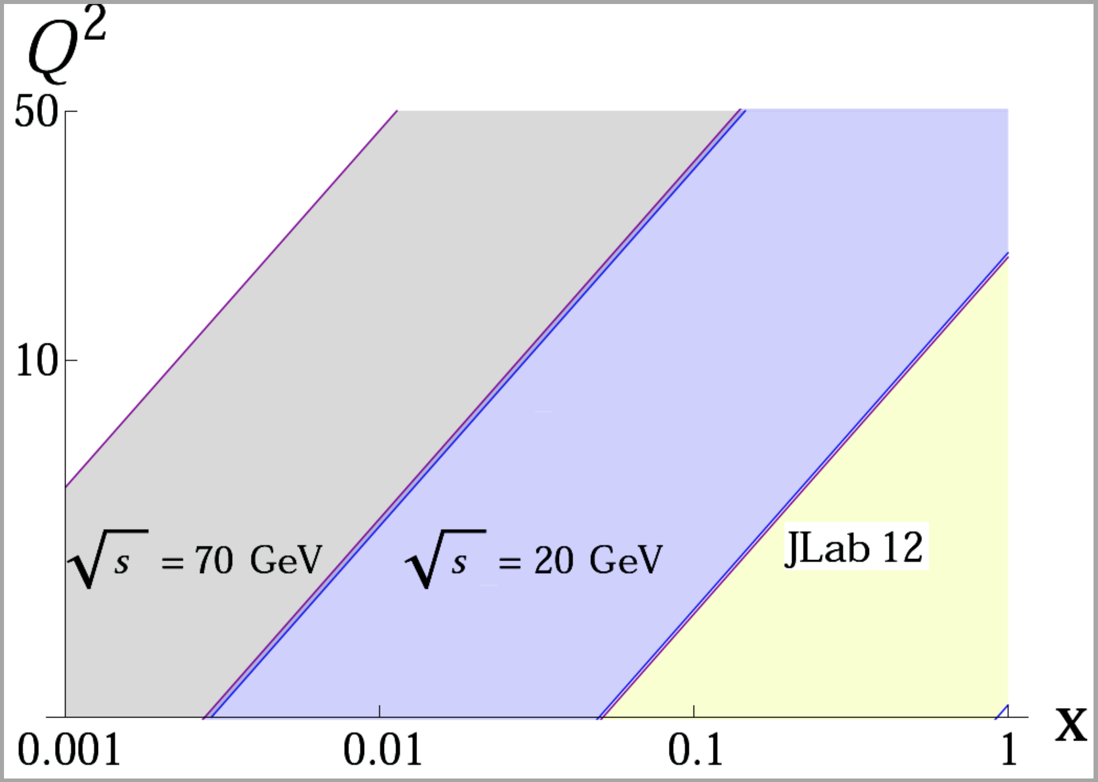


Functions change with energy

Phenomenological analysis with evolution is now possible

Kinematics

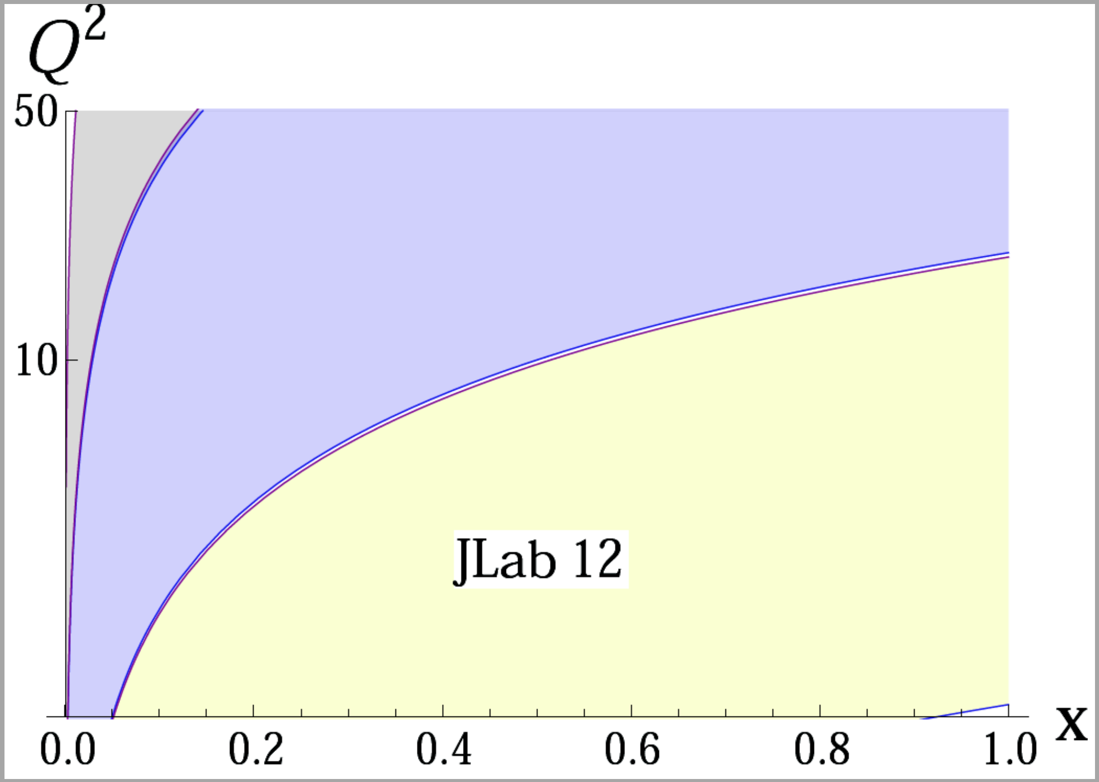
Kinematics $Q^2 \simeq sxy$



Jlab 12 and future Electron Ion Collider are complimentary

Kinematics

Kinematics $Q^2 \simeq sxy$

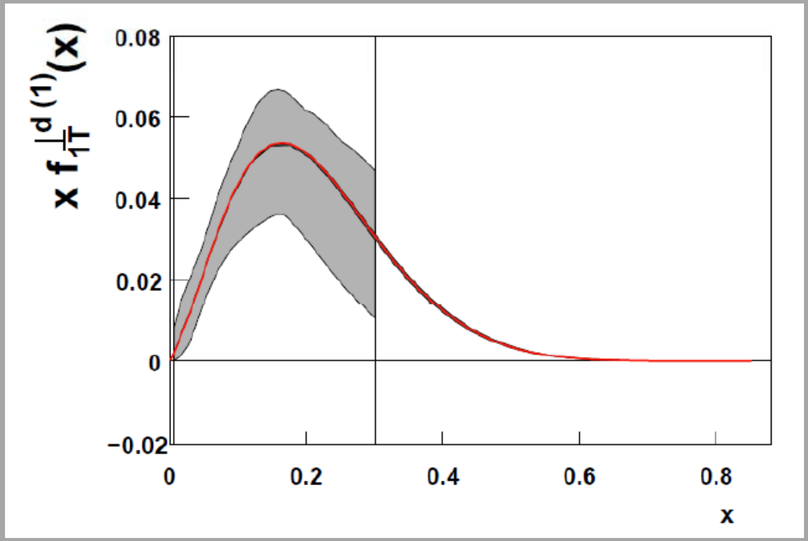


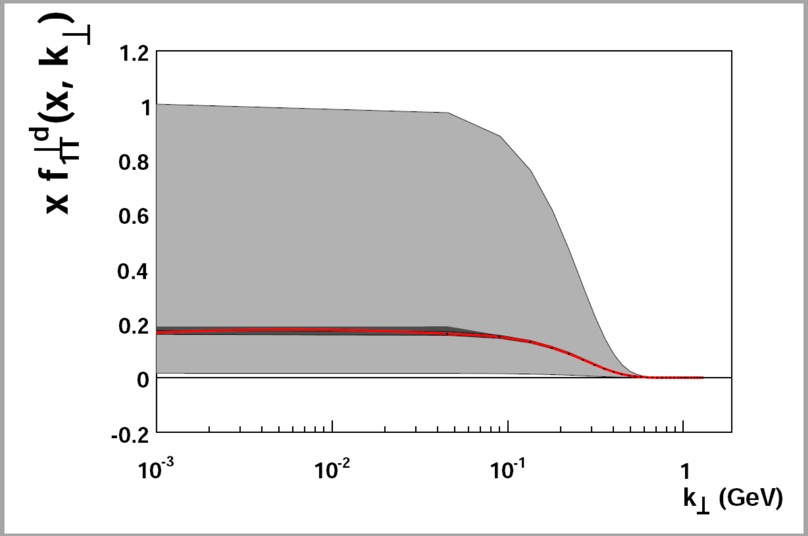
Jlab 12 and future Electron Ion Collider are complimentary

Jlab and EIC are going to provide fine 4D binning of the data.
Exact knowledge of evolution is crucial

Future improvement

What do we expect at JLab?



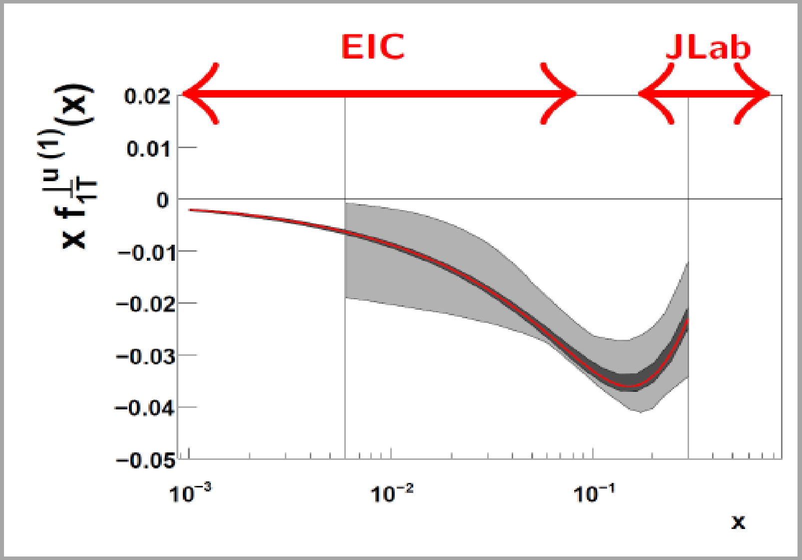


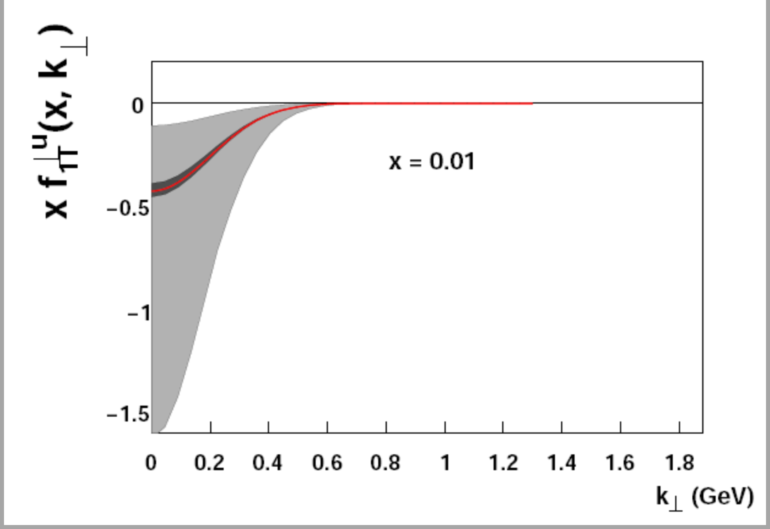
One example
TMD from Jlab
future data:
JLab 12 on 3HE target.

Very big improvement
in terms of our
knoweledge

Future improvement

What do we expect at EIC?





One example
TMD from EIC
future data

Very big improvement
in terms of our
knoweledge

Possible relations of TMDs and OAM

Bacchetta, Radici 2011 argue that

Inspired by model Relations, not full QCD

$$f_{1T}^{\perp(0)}(x) \simeq I(x)E(x,0,0)$$

So called “lensing” function
Burkardt, Metz, etc

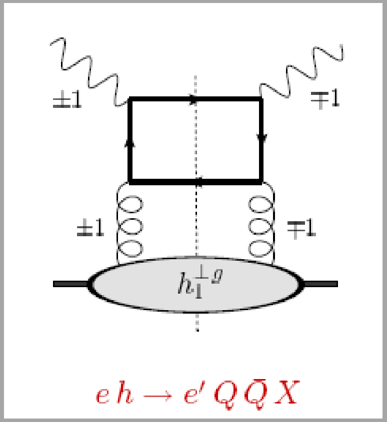
Making direct connection to total OAM from Ji's sum rule:

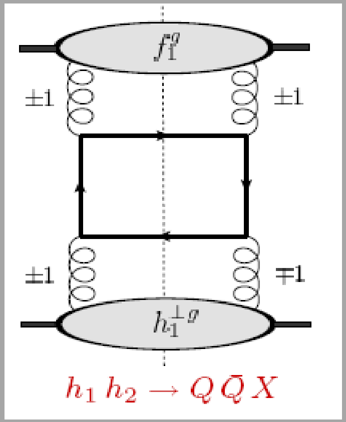
$$J_q = \frac{1}{2}\int_0^1 dx\, x(H_q(x,0,0) + E_q(x,0,0))$$

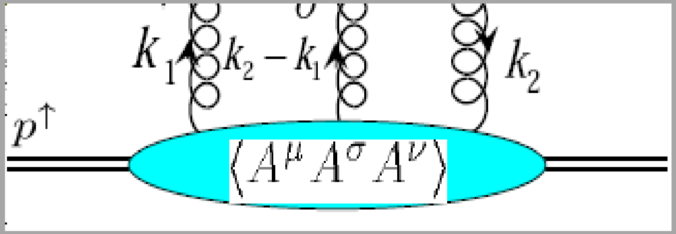
$J_u = 0.266, J_d = -0.012$ at $Q^2 = 1(GeV^2)$

Asumptions based on model calculations of course, but might be interesting.

Gluons distributions







- Gluon TMDs
- Linearly polarized gluons can be accessed in various channels
- Opportunities of studies at EIC, LHeC
- $h_1^{\perp,g}$ may contribute to Higgs production, resolve its parity

  Boer, Brodsky, Mulders, Pisano 2011

  Qiu, Vogelsang, Schlegel 2011

  Boer, den Dunnen, Pisano, Schlegel, Vogelsang 2011

- Tri-gluon correlations, Qiu-Sterman matrix elements, complete classification

  Koike, Tanaka

- TMD SSA in open charm

  Godbole, Misra, Mukherjee, Rawoot 2011

TMD experimental challenges

- 4D binning of observables $x, z, Q^2, P_{h\perp}$
- Different targets: proton, neutron, deuteron
- Different final state hadrons π, K
  open charm

All this helps to do correct flavour decomposition and correct analysis.

CONCLUSIONS

- Studies of 3D distributions represent big part of future of nuclear physics
- EIC is an ideal place to explore GPDs and TMDs
- Theory and phenomenology have made a lot of progress in recent years
- We are going to see more progress in future

CONCLUSIONS

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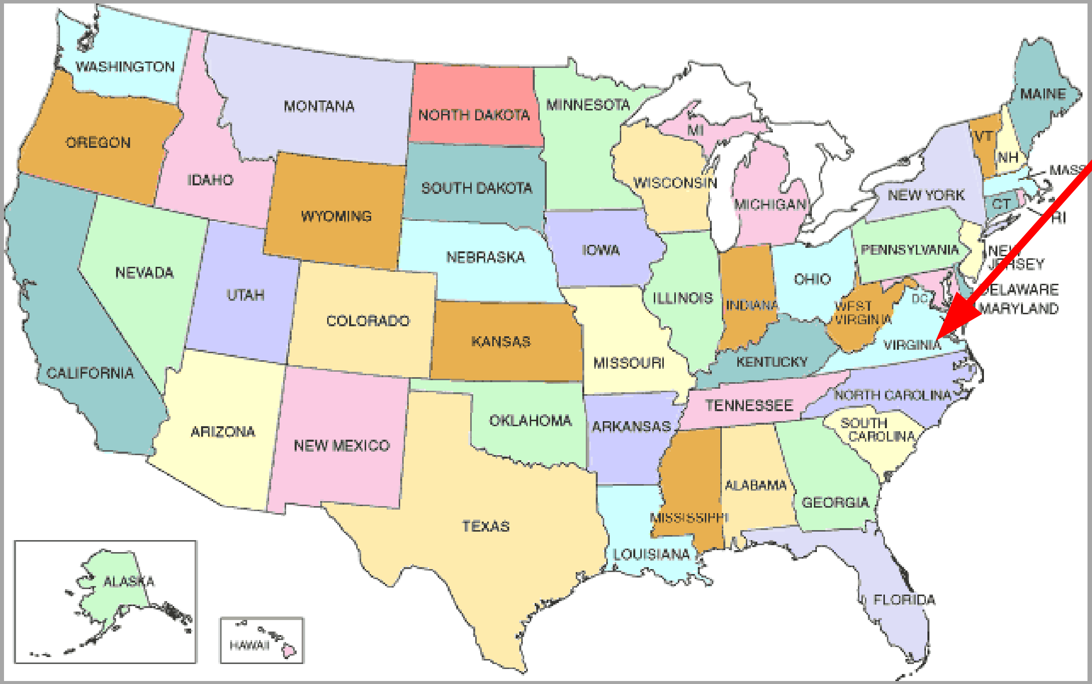
- **We are looking forward to EIC!**

QCD EVOLUTION 2012

http://www.jlab.org/conferences/qcd2012/



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Newport News,
Virginia, USA

Organizing committee:
Alexei Prokudin, Chair
Anatoly Radyushkin
Ian Balitsky
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Summer school: 27th Annual Hampton University Graduate Studies Program. Covers theoretical and experimental aspects of nuclear physics.

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June 4 - June 22, 2012

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The deadline for application submittal is April 2, 2012

HUGS 2012

Alexei Prokudin