Transverse Spin Physics at Electron Ion Collider

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Electron Ion Collider

Future facility Electron Ion Collider is proposed by EIC Collaboration – more than 100 physicists from over 20 laboratories and universities

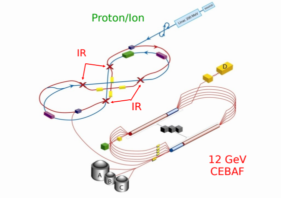
Two working groups in JLab, USA and BNL, USA

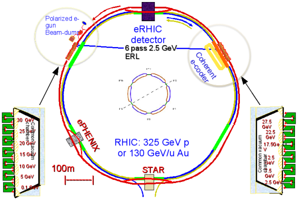
http://web.mit.edu/eicc/index.html

Electron – Ion Collider at medium – high energy of $\sqrt{s} \sim 10 \div 200$ GeV will allow high precision measurements with polarised proton and D, He^3, and unpolarised ion beams, Li, Ca, Au, Pb. Luminosity up to $\mathcal{L} \simeq 10^{34}$ cm^{-2}s^{-1}.

JLAB: hadron part should be added to existing facility CEBAF.

RHIC: electron part should be added to existing facility RHIC.



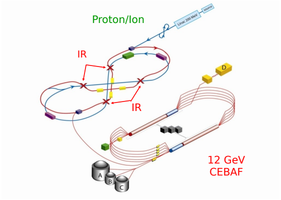


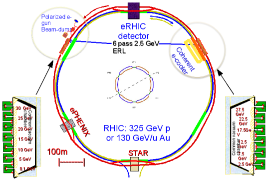
Colliders: from particle to nuclear physics

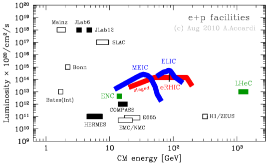
		$\sqrt{s}$ GeV	http://pdg.lbl.gov/
e^+e^-	DAΦNE	1.4	Φ meson
	VEPP	2	
	KEK B	11	B meson
	PEPII	11	
	LEP	200	W, Z bosons
$\bar{p}p$	Tevatron	2000	t quark
pp	LHC	14000	Higgs, SUSY
AA	RHIC	200	QGP
	LHC	5500	
$\vec{p}\vec{p}$	RHIC	500	Nucleon spin
ep	HERA	330	small-x gluons, diffraction...
$\vec{e}\vec{p}$	EIC	10-200	precision nucleon structure in QCD
eA	EIC		QCD in nuclei

- EIC: dedicated high-luminosity $\vec{e}\vec{p}/eA$ collider for study and exploration of QCD.
  No such collider was built before.
  Physics expectations are different than that of JLab 12, RHIC, HERA etc
- Advantages of a collider
  High energy: $s = 4E_e E_p$ vs. $2E_e M_p$
  Energy-efficient: beams collide multiple times
  Detection: Variable scattering angles, prtoton/nucleous recoil, target fragmentation region
- Challenges:
  High luminosity requires particular beam optics
  Integration of detectors and accelerator elements

EIC designs



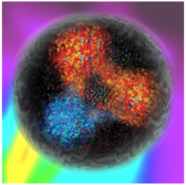




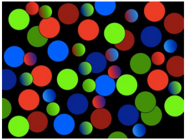
- JLab ring-ring desing MEIC/ELIC:
  11 GeV CEBAF as injector
  Medium energy: 1 km ring, 3-11 on 60/96 GeV
  High energy: 2.5 km ring, 3-11 on 250 GeV
  Luminosity $\sim 10^{34}$ cm^{-2}s^{-1} over wide s range
  Figure-8 for polarization transport, up to 4 IPs
- BNL linac-ring design eRHIC
  RHIC proton/ion beam up to 325 GeV
  5-20 (30) GeV electrons from linac in the RHIC tunnel
  Luminosity $\sim 10^{34}(10^{33})$ over wide s range
  Re-use of RHIC detectors: eRHIC
- Related proposals:
  CERN LHeC: 20-150 GeV on 7 TeV unpolarised
  Luminosity $\sim 10^{33}$
  GSI ENC: 3.3 GeV on 15 GeV polarised
  PANDA detector

EIC Physics: Golden Topics

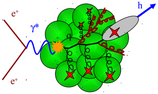
- **3D quark/gluon structure of the nucleon**
  - Gluon and sea quark polarization
  - Transvese spatial distributions (GPDs)
  - Orbital motion of quarks and gluons (TMDs) and its role in nucleon spin
  - Parton correlations



- **Dynamics of color fields in nuclei**
  - Nuclear gluon density
  - Color transparency for small-size probes
  - Coherent nuclear effects in shadowing/diffraction
  - Strong gluon fields and saturation



- **Emergence of hadrons from color charge**
  - Quark/gluon fragmentation
  - Hadron breakup
  - Interaction of color charge with matter: radiation, energy loss



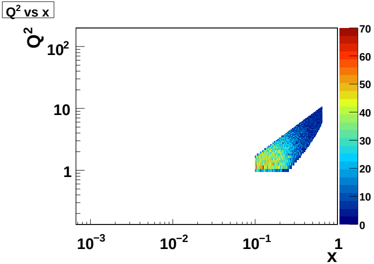
EIC past, present and future

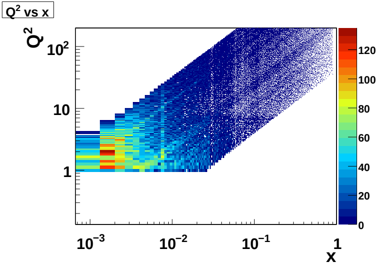
- **Late 90's** EIC physics discussions/workshops; first designs
- **2007** EIC as "unnumbered" recommendation of Nuclear Science Advisory Committee long range plan
- **2008** EIC collaboration http://web.mit.edu/eicc/
  BNL and JLab create joint advisory committee
- **2009** Concept of medium-energy high-luminosity collider at JLab.
  BNL develops EIC desing, BNL task force, dedicated resources
- **2010** JLab Users Workshops dedicated to EIC, increasing interest
  10-week INT Program to formulate scientific case and prepare White Paper.
- **2012** Aim for full recommendation in NSAC Long Range Plan
- **2020** EIC construction starts
- **2025** Operation of EIC

Why JLab 12 and EIC are needed together?

JLab 12 $\sqrt{s} = 4.63$ GeV

EIC $\sqrt{s} = 65$ GeV





- JLab 12 will extend owr knowledge of distributions at high-x region.
- EIC will explore low-x region.
- Q^2 range of EIC (from ~ 1 to ~ 100 GeV^2) will allow to study *evolution* of observables.
- P_{hT} range of EIC (up to ~ 4 GeV) will allow to study interplay of TMD and collinear factorization schemes.

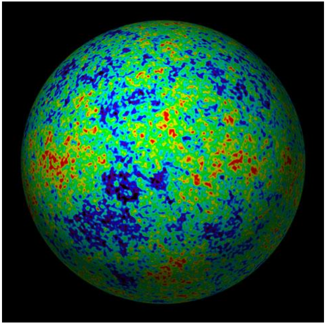
EIC Golden Topic

Map the spin and spatial quark-gluon structure of nucleons

- Image the 3D spatial distributions of gluons and sea quarks through Generalized Parton Distributions, exclusive observables: J/Ψ exclusive production, Deep Virtual Compton Scattering and exclusive meson production. $\rightarrow$ 3D imaging of quarks and gluons in the nucleon in the coordinate space.
- Measure ΔG, and the polarization of the sea quarks through Semi Inclusive Deep Inelastic Scattering, DIS, and open charm production. $\rightarrow$ collinear parton distributions and spin.
- Establish the orbital motion of quarks and gluons through Transverse Momentum Dependent distributions, inclusive observables: Semi Inclusive Deep Inelastic Scattering and jet production. $\rightarrow$ 3D imaging of quarks and gluons in the nucleon in the momentum space, non collinear partons.

EIC Golden Topic

Image of Cosmic Microwave Background (CMB) radiation.



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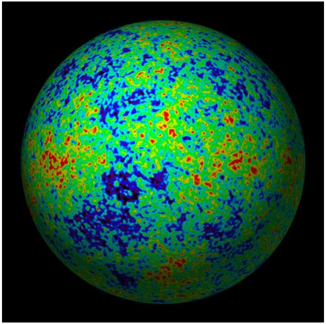
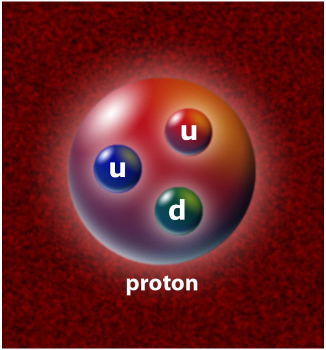


Cartoon of the proton 3D distribution.



Deep Inelastic Scattering and jet production. $\rightarrow$ 3D imaging of quarks and gluons in the nucleon in the momentum space, non collinear partons.

Wigner distribution and 3D partonic structure

Wigner distribution

$W(x, \mathbf{b_T}, \mathbf{k_T})$

not measurable due to uncertainty principle

GPDs $\int d^2\mathbf{k_T} W = f(x, \mathbf{b_T})$ **TMDs** $\int d^2\mathbf{b_T} W = f(x, \mathbf{k_T})$.

Probabilistic distribution functions

GPDs require exclusive processes to be measured ($\langle P|\bar{\psi}(x)\mathcal{U}[x,0]\psi(0)|P'\rangle$ hadron states $|P\rangle \neq |P'\rangle$)

TMDs are measured in inclusive processes ($\langle P|\bar{\psi}(x)\mathcal{U}[x,0]\psi(0)|P\rangle$ hadron states are the same $|P\rangle$)

There is no model indipendent relation of TMDs and GPDs

We can relate variables by Fourier transform:

quark fileds $\tilde{\psi}(k_T, x^-) = \int d^2x_T e^{ix_T k_T}\psi(x_T, x^-)$, $x^- = x_0 - x_3$

proton states $|p^+, b_T\rangle = \int d^2p_T e^{-ib_T p_T}|p^+, p_T\rangle$, $p^+ = p_0 + p_3$.

On the level of squared amplitudes we have:

$\bar{\tilde{\psi}}(k_T, x^-)\tilde{\psi}(l_T, y^-) = \int d^2x_T d^2y_T e^{-i(x_T k_T - y_T l_T)}\bar{\psi}(x_T, x^-)\psi(y_T, y^-)$

$x_T k_T - y_T l_T = \frac{1}{2}(x_T - y_T)(k_T + l_T) + \frac{1}{2}(x_T + y_T)(k_T - l_T)$

"average" transverse momentum $k_T + l_T$ *corresponds to* position difference $x_T - y_T$

transverse momentum transfer $k_T - l_T$ *corresponds to* "average" position $x_T + y_T$

Proton Spin Sum Rule

Jaffe, Manohar

$$\frac{1}{2} = \langle P; \tfrac{1}{2} | J_z | P; \tfrac{1}{2} \rangle = \frac{1}{2} \sum_q \Delta q + \Delta G + \sum_q L_q^z + L_g^z$$

$\frac{1}{2} \sum_q \Delta q = \frac{1}{2} \Delta\Sigma$ total contribution oquarks.
ΔG gluon contribution.
$\sum_q L_q^z + L_g^z$ Orbital Angular Momentum of quarks and gluons.

Quark model of the proton:

$$|p^\uparrow\rangle = \frac{1}{\sqrt{18}} (-2 | u^\uparrow u^\uparrow d^\downarrow \rangle + | u^\uparrow u^\downarrow d^\uparrow \rangle + | u^\downarrow u^\uparrow d^\uparrow \rangle)$$

$$\left.\begin{array}{l} \Delta u = \langle p^\uparrow | \hat{N}_{u^\uparrow} | p^\uparrow \rangle - \langle p^\uparrow | \hat{N}_{u^\downarrow} | p^\uparrow \rangle = \dfrac{4}{3} \\[2em] \Delta d = \langle p^\uparrow | \hat{N}_{d^\uparrow} | p^\uparrow \rangle - \langle p^\uparrow | \hat{N}_{d^\downarrow} | p^\uparrow \rangle = -\dfrac{1}{3} \end{array}\right\} \Delta\Sigma = \Delta u + \Delta d = 1$$

the expectation $\frac{1}{2} = \frac{1}{2} \Delta\Sigma$

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EMC result on $\Delta\Sigma = \sum_{q,\bar{q}} \Delta q \simeq 0.3$ triggered so called "Spin crisis" – only 30% of the spin of the proton is carried by quarks.
Leader, Anselmino ''A Crisis In The Parton Model: Where, Oh Where Is The Proton's Spin?'' Z.Phys.C41:239,1988

- Role of gluon polarization ΔG?
- Role of OAM $\sum_q L_q^z + L_g^z$?

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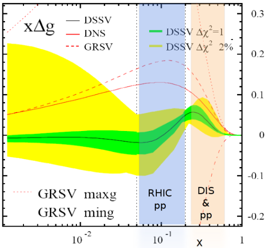
The latest extraction from experimental data DSSV global fit de Florian, Sassot, Stratmann, Vogelsang:
$\Delta G \simeq \int_{0.05}^{0.2} dx \Delta g(x) \simeq 0$
The existing data still have big uncertainties in low-x region for extraction of ΔG $\rightarrow$ need of **EIC**.
The data indicate that OAM contribution is not negligible, thus quark transverse motion is important $\rightarrow$ **TMDs**.

What can be achieved for Δg?

see talk of Marco Stratmann @ INT workshop

DSSV global fit de Florian, Sassot, Stratmann, Vogelsang



- low-x behavior unconstrained
- no reliable error estimate for 1^{st} moment $\int_0^1 dx \Delta g(x, Q^2)$ (entering spin sum rule)
- find $\int_{0.05}^{0.2} dx \Delta g(x, Q^2) \simeq 0$

What can be achieved for Δg?

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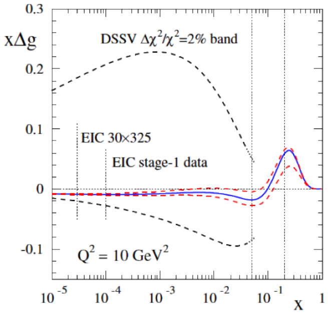
Sassot, Stratmann



- strategy to quantify impact: global QCD fit with realistic pseudo-data
- DIS data sets produced for EIC 5x50, 5x100, 5x250, 5x325 and 20x250, 30x325.
- even with flexible DSSV x-shape we can now determine $\int_0^1 dx \Delta g(x, Q^2)$ up to ± 0.07.

Transverse Momentum Dependent distributions

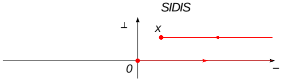
Spin structure of spin-1/2 nucleon is described by 8 TMDs. Each of them depend on two indipendent variables x and $\mathbf{p}_\perp$.

$$\Phi_{ij}(p,P,S) = \int \frac{d^4\xi}{(2\pi)^4} e^{ik\cdot\xi} \langle P,S|\bar{\psi}_j(0)\mathcal{W}(0,\xi|n^-)\psi_i(\xi)|P,S\rangle$$

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 $h_{1T}^\perp$

time-reversal odd

Plot courtesy of B. Musch



Kotzinian 1995;
Mulders, Tangerman 1995;
Boer and Mulders 1997;
Anselmino et al 2006,
Bacchetta et al 2007

T-odd TMD FFs survive due to Final State Interactions.

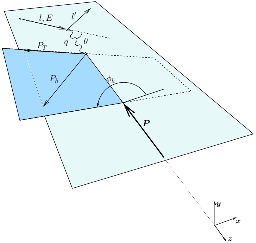
Polarised Semi Inclusive Deep Inelastic Scattering

Asymmetry in $\gamma^* p$ cm frame of $\ell p^\uparrow \to \ell' h X$

TMD functions can be studied in asymmetries

$$A_{UT} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$

Unpolarised electron beam, Transversely polarised proton. Azimuthal dependence on ϕ_h and ϕ_S singles out different combinations.



Contributions at leading twist

$$d\sigma^\uparrow - d\sigma^\downarrow \propto \underbrace{f_{1T}^\perp \otimes D_1 \sin(\phi_h - \phi_S)}_{\text{Sivers effect}} + \underbrace{h_1 \otimes H_1^\perp \sin(\phi_h + \phi_S)}_{\text{Collins effect}} + \ldots$$

$$d\sigma^\uparrow + d\sigma^\downarrow \propto f_1 \otimes D_1 \equiv F_{UU}$$

Kotzinian 1995; Mulders, Tangerman 1995; Boer and Mulders 1997; Bacchetta et al 2007

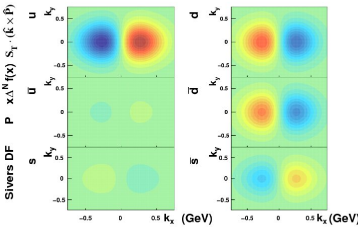
Sivers function

Sivers function is a distribution of unpolarised quarks in a transversely polarised nucleon

$$\mathbf{f_{q/P^\uparrow}(x, p_\perp, S) = f_1(x, p_\perp^2) - \frac{S\cdot(\hat{P}\times p_\perp)}{M} f_{1T}^\perp(x, p_\perp^2)}$$

Sivers function for quarks and gluons is a candidate for **GOLDEN EXPERIMENT** at **EIC**

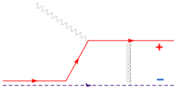
- This function gives access to 3D imaging
- Spin-orbit correlation
- Physics of gauge links is represented
- Requires Orbital Angular Momentum



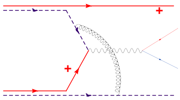
Physics of gauge links

- Colored objects are surrounded by gluons, profound consequence of gauge invariance technically implemented by Wilson lines - gauge links.
- Sivers function has opposite sign when gluon couple after quark scatters (SIDIS) or before quark annihilates (DY)

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



SIDIS - attractive

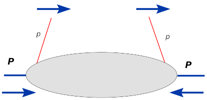


DY - repulsive

- Sivers function would be zero if gluons were absent

Orbital Angular Momentum

- Sivers function requires proton helicity flip $\langle\uparrow|\mathcal{O}|\downarrow\rangle$



Interference of configurations with L_z and $L'_z = L_z \pm 1$.

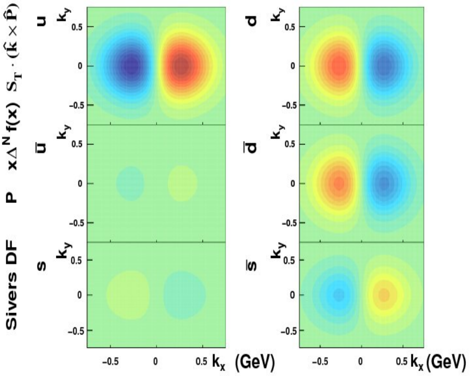
- Chromodynamic lensing (M. Burkardt)

Transverse shift in p_T described by $f_{1T}^{\perp}$

- Sivers function exist for both quarks and gluons.

THE GOAL: THREE DIMENSIONAL PICTURE OF THE PROTON

The proton moves along $-Z$ direction (into the screen) and S_T is along Y.



Red color – more quarks. Blue color – less quarks. Sivers functions is a left – right asymmetry of quark distribution.
$x = 0.01$
Electron Ion Collider and JLab will contribute.

Typical ingredients used in TMD phenomenology

We start from TMD factorization Ji, Ma, Yuan 05

$$F_{UU} = \int d^2\mathbf{p_T} d^2\mathbf{K_T} d^2\mathbf{l_T} \delta^{(2)}(z\mathbf{p_T}+\mathbf{K_T}+\mathbf{l_T}-\mathbf{P_{h\perp}}) f_1(x,\mathbf{p_T}^2)\, D_1(z,\mathbf{K_T}^2)\, U(\mathbf{l_T})$$

Soft factor $U(\mathbf{l_T})$ is not included
Gaussian parametrization of TMDs

$$f_1(x,\mathbf{p_T}) = f_1(x)\,\frac{1}{\pi\langle p_\perp^2\rangle} e^{-\mathbf{p_T}^2/\langle p_\perp^2\rangle}, \quad \int d^2\mathbf{p_T} f_1(x,\mathbf{p_T}) \equiv f_1(x)$$

$$D_1(z,\mathbf{K_T}) = f_1(x)\,\frac{1}{\pi\langle K_\perp^2\rangle} e^{-\mathbf{K_T}^2/\langle K_\perp^2\rangle}, \quad \int d^2\mathbf{K_T} D_1(x,\mathbf{K_T}) \equiv D_1(x)$$

Justified by lattice QCD studies Musch et al, 2008 and phenomenology Metz, Teckentrup, Schweitzer, 2010

TMDs are parametrized in such a way that positivity constraints Bacchetta, Boglione, Henneman, Mulders, 2000 are taken into account. Usually $\propto x^\alpha(1-x)^\beta$. Evolution in Q^2 is taken for moments of TMDs and usually is supposed to be the same as for collinear distributions. *Kang, Qiu, Zhou, Yuan evolution to be implemented*

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Typical ingredients used in TMD phenomenology

We start from TMD factorization Ji, Ma, Yuan 05

$$F_{UU} = \int d^2\mathbf{p_T} d^2\mathbf{K_T} d^2\mathbf{l_T} \delta^{(2)}(z\mathbf{p_T}+\mathbf{K_T}+\mathbf{l_T}-\mathbf{P_{h\perp}}) f_1(x,\mathbf{p_T}^2)\, D_1(z,\mathbf{K_T}^2)\, U(\mathbf{l_T})$$

Soft factor $U(\mathbf{l_T})$ is not included

Gaussian parametrization of TMDs

$$f_1(x,\mathbf{p_T}) = f_1(x)\,\frac{1}{\pi\langle p_\perp^2\rangle} e^{-\mathbf{p_T}^2/\langle p_\perp^2\rangle}, \quad \int d^2\mathbf{p_T} f_1(x,\mathbf{p_T}) \equiv f_1(x)$$

$$D_1(z,\mathbf{K_T}) = f_1(x)\,\frac{1}{\pi\langle K_\perp^2\rangle} e^{-\mathbf{K_T}^2/\langle K_\perp^2\rangle}, \quad \int d^2\mathbf{K_T} D_1(x,\mathbf{K_T}) \equiv D_1(x)$$

Justified by lattice QCD studies Musch et al, 2008 and phenomenology Metz, Teckentrup, Schweitzer, 2010

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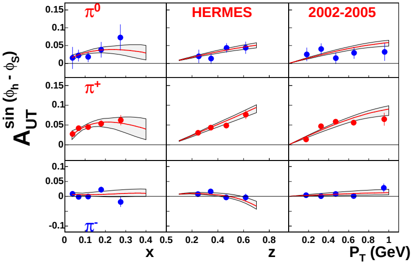
EXPERIMENTAL DATA

HERMES

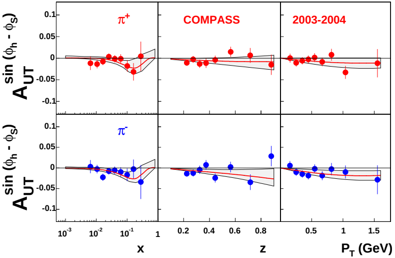
$ep \rightarrow e\pi X$, $p_{lab} = 27.57$ GeV.



Anselmino et al 2010 in preparation

COMPASS

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



Anselmino et al 2010 in preparation

$lp^{\uparrow} \rightarrow l\pi^+ X \simeq -f_{1T}^{\perp u} \otimes D_{u/\pi^+} > 0$ thus $f_{1T}^{\perp u} < 0$

$lD^{\uparrow} \rightarrow l\pi^+ X \simeq -(f_{1T}^{\perp u} + f_{1T}^{\perp d}) \otimes D_{u/\pi^+} \simeq 0$ thus $f_{1T}^{\perp u} \sim -f_{1T}^{\perp d}$ in accordance with large N_C predictions Pobylitsa hep-ph/0301236

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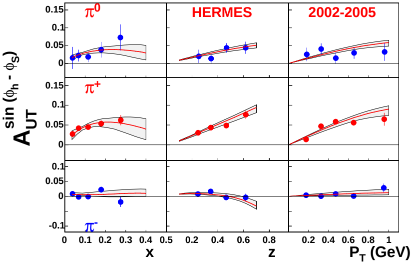

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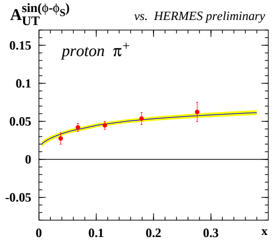

Arnold et al 2008

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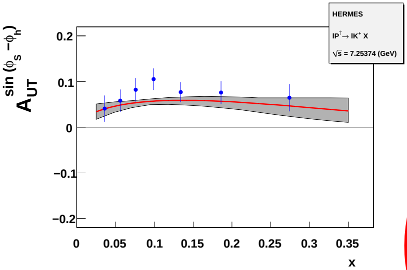
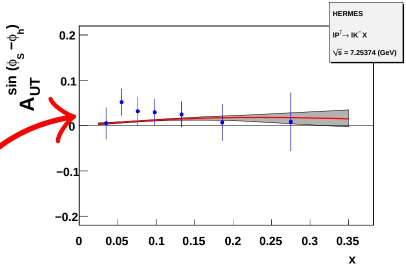
How do we "see" sea quarks in the data?

$K^+(u\bar{s})$



HERMES no sea contributions

$K^-(\bar{u}s)$



HERMES no sea contributions

$f_{1T}^{\perp\bar{u}} = 0$

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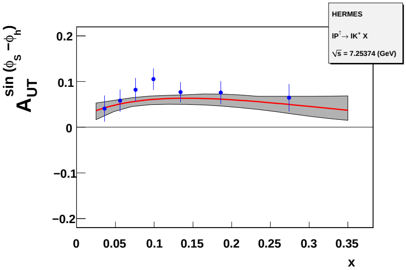
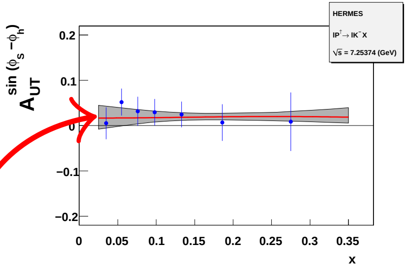


HERMES with sea contributions

$K^-(\bar{u}s)$



HERMES with sea contributions

$-f_{1T}^{\perp\bar{u}} > 0$

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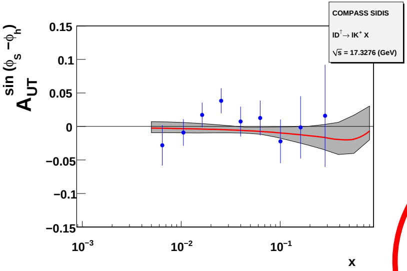
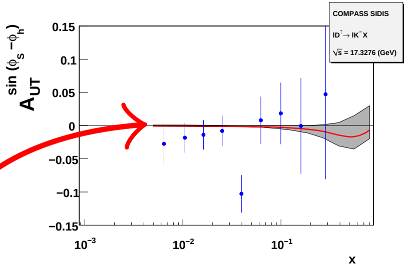


COMPASS no sea contributions

$K^-(\bar{u}s)$



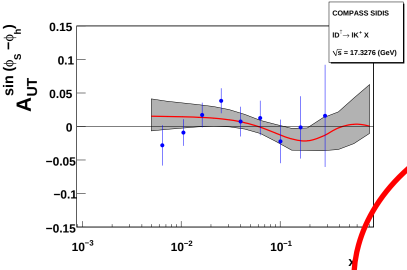
COMPASS no sea contributions

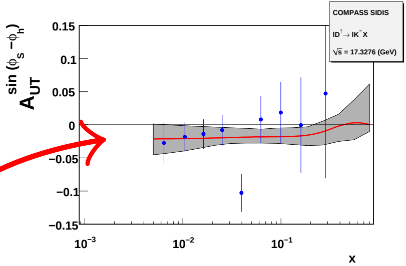
$$f_{1T}^{\perp\bar{u}} + f_{1T}^{\perp\bar{d}} = 0$$

How do we “see” sea quarks in the data?

$K^-(\bar{u}s)$

$K^+(u\bar{s})$





COMPASS with sea contributions

COMPASS with sea contributions

$-(f_{1T}^{\perp\bar{u}} + f_{1T}^{\perp\bar{d}}) < 0$

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

Jefferson Lab

Sivers function comparison with models

There is a number of model calculations of Sivers function

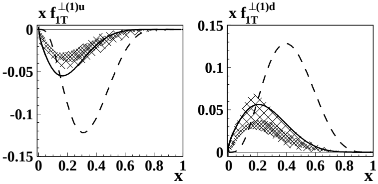
Light-cone quark model Barbara Pasquini and Feng Yuan 2010

Diquark model Alessandro Bacchetta et al 2010, Leonard Gamberg, Gary Goldstein, and Marc Schlegel 2008 etc

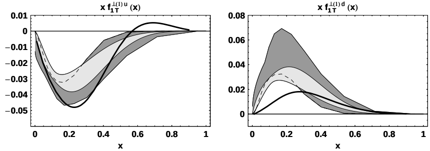
MIT bag model Feng Yuan 2003, H. Avakian, A.V. Efremov, P. Schweitzer, F. Yuan 2010 etc

Pasquini and Yuan 2010

Alessandro Bacchetta et al 2010



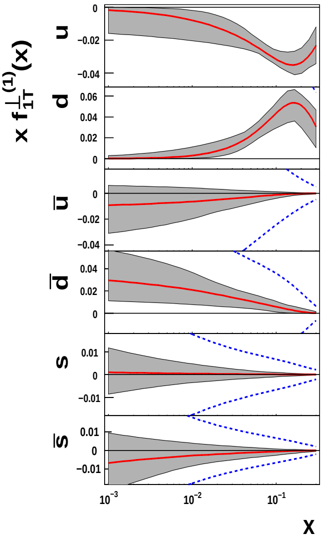
Pasquini and Yuan arXiv:1001.5398



Bacchetta et al arXiv:1003.1328

Reasonable agreement of the extracted Sivers functions Anselmino et al 2009 and Collins et al 2005 and model calculations.

What can be achieved for $f_{1T}^{\perp}$?

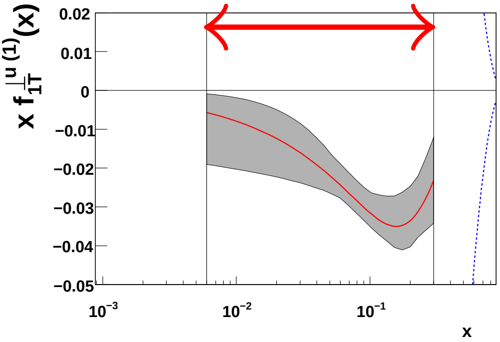


Global fit Anselmino et al 2010 in preparation.

- low-x behavior unconstrained
- $f_{1T}^{\perp u} < 0$, $f_{1T}^{\perp d} > 0$, hints on nonzero sea quark Sivers functions.
- Sea quark functions may grow at low x. $f_{1T}^{\perp sea} \propto x^0 f_1^{sea}$

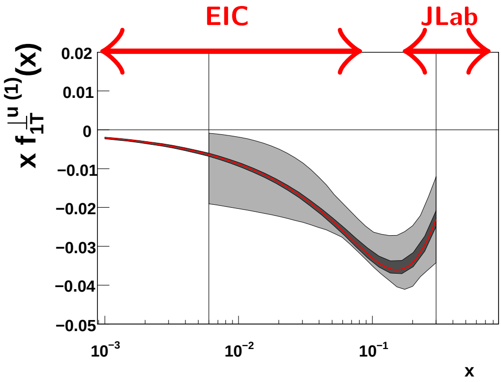
What can be achieved for $f_{1T}^{\perp}$?

COMPASS, HERMES



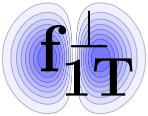
- strategy to quantify impact: global fit with realistic pseudo-data
- SIDIS data sets produced for EIC 11x60 (Min Huang)
- Incredible precision data allows extraction of $f_{1T}^{\perp}$

What can be achieved for $f_{1T}^{\perp}$?

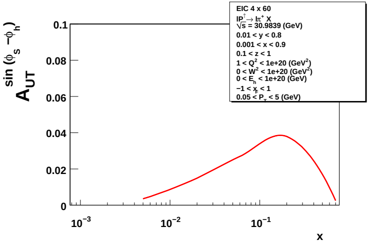


- strategy to quantify impact: global fit with realistic pseudo-data
- SIDIS data sets produced for EIC 11x60 (Min Huang, JLab)
- Incredible precision data allows extraction of $f_{1T}^{\perp}$
- JLab 12 and EIC are complementary.

SIVERS FUNCTION FUTURE



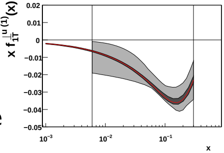
- Scale dependence of asymmetries $\mathbf{A_{UT}(Q^2)}$
- Gluon and sea quark Sivers functions $\mathbf{f_{1T}^{\perp \bar{u}, \bar{d}, s, \bar{s}}}$. D meson production will help.
- Low to high $P_{h\perp}$ and Sivers function versus Qiu-Sterman matrix elements $\mathbf{f_{1T}^{\perp(1)}} \propto \mathbf{T_F(x,x)}$.
- Interplay of TMD and collinear factorization
- Q^2 evolution of Siver function
- Different hadron production $\pi^{\pm}$, $K^{\pm}$, D etc
- Weighted asymmetries, etc

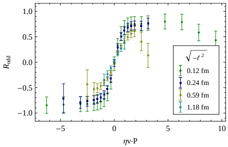


Jefferson Lab

Effort at Jefferson Laboratory towards EIC

- JLab together with colleagues from other laboratories performs error estimate of extraction of TMDs from the future EIC data.
  JLab: AP, Min Huang, Jian-Ping Chen, Harut Avakian, Berni Musch
  BNL: Tom Burton, Elke Aschenauer
  Caltech: Xin Qian
  Duke University: Haian Gao
  INFN Frascatti: Delia Hasch
  et al





- Effort to extarct TMDs on lattice
  JLab: Berni Musch, AP et al
- Talks during conferences and proceedings in 2010:
  1. AP, EIC COLLABORATION MEETING, Stony Brook University, USA
  2. AP, DUKE UNIVERSITY WORKSHOP, Duke, USA
  3. AP, MENU 2010, The Colledge of William & Mary, USA
  4. AP, EXCLUSIVE REACTIONS 2010, JLAB, USA
  5. AP, DIS 2010, Florence, Italy
  6. AP, ICHEP 2010, Paris, France
  7. AP, DIFFRACTION 2010, Otranto, Italy
  8. AP, INT 2010 workshop, INT Seattle, USA

  many more contributions by others

CONCLUSIONS

- EIC will be a powerful tool to study parton dynamics and TMDs.
- High Q^2 range will allow to study twist-2 functions and higher twist content of the nucleon.
- Range of P_T will allow to study intermediate region where both TMD and collinear factorizations are applicable.
- Q^2 range at some fixed x will provide information on Q^2 behavior of the asymmetries and Q^2 evolution of TMDs.
- Range of P_T will allow for measurements of weighted asymmetries at EIC, so that moments of TMDs could be extracted from the data.
- Full flavor and spin decomposition of TMDs can be attempted at EIC.

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THANK YOU!

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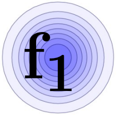
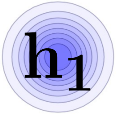
EXTRA SLIDES

f_1 FUTURE PROSPECTIVES

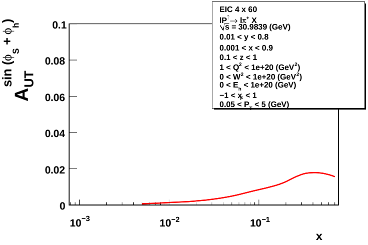


- Gluon TMD $g(x, k_T)$
- From large to low x, from quarks to sea quarks and gluons
- Scale dependence and energy studies $\mathbf{f_1(x, k_T)}$ and its width $\langle p_\perp^2 \rangle (Q^2, s)$
- Flavour dependence studies of width $\langle p_\perp^2 \rangle_{u,d,\bar{u},\bar{d}}$
  Gluon and quark distributions may have different widths (phenomenology and models).
- Gaussian vs non gaussian shape studies
- $P_{h\perp}$ range of **EIC** will allow us to study interplay of TMD and collinear factorizations
- Etc

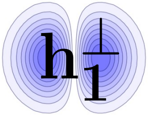
TRANSVERSITY FUTURE



- Transversity is one of the three fundamental colliear PDFs
- Scale dependence is known up to NLO, study of $\mathbf{A_{UT}(Q^2)}$ is important
- Tensor charge is not measured with a good precision
- Sea quark transversity $\mathbf{h_1^{\bar{u},\bar{d},s,\bar{s}}}$
- Weighted asymmetries
- Extraction of transversity with dihadron IFF
  talk by Marco Radici



BOER-MULDERS FUNCTION FUTURE



- Scale dependence of asymmetries $\mathbf{A_{UU}^{\cos(2\phi_h)}(Q^2)}$ will allow us to distinguish twist-2 from twist-3 contribution
- Sea quark Boer-Mulders functions $\mathbf{h_1^{\perp \bar{u}, \bar{d}, s, \bar{s}}}$
- Low to high P_T and Boer-Mulders function versus Qiu-Sterman matrix elements $\mathbf{h_1^{\perp(1)}} \propto \mathbf{T_F^{\sigma}(x, x)}$
- Different hadron production $\pi^{\pm}$, $K^{\pm}$ etc

OTHER TMD DISTRIBUTIONS

- Non trivial width of $\mathbf{g_1}$ with respect to $\mathbf{f_1}$
- Wandzura-Wilcek relations for $\mathbf{g_{1T}^{\perp}}$ and $\mathbf{h_{1L}^{\perp}}$. Some models predict $\mathbf{g_{1T}^{\perp(1)}} = -\mathbf{h_{1L}^{\perp(1)}}$. Numerically feasable in WW approximation.
- $\mathbf{h_{1T}^{\perp}}$ is quadrupole deformation in $\mathbf{k_T}$ thus more involved structure. Some models predict $\mathbf{h_{1T}^{\perp}} = \mathbf{h_1} - \mathbf{g_1}$, connection to $\mathbf{L^q}$.
- *P. S.* Once we measure azimuthal modulations we can measure **all** TMDs. Each of them represent different physics. NO STAMP COLLECTION.