Experimental Overview of e+p Physics at an EIC

DIS2011, Newport News, VA, U.S.A.
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Outline

- **Introduction**
- **e-p physics with EIC: selected examples**
  - **Spin structure of the nucleon (gluon)**
  - **Imaging of nucleons in 3-dimensions**
  - ***Generalized parton distributions***
  - ***Transverse momentum dependent parton distributions***
  - **Electroweak physics (very brief)**
- **Summary**

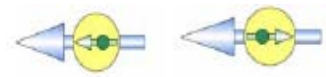
INT-10-03: http:/www.int.washington.edu/PROGRAMS/programs_all.html
Duke workshop: http:// michael.tunl.duke.edu/workshop
Rutgers workshop: http://www.physics.rutgers.edu/np/2010rueic-home.html

Talks by Min Huang, Tanja Horn, Tom Burton in this session

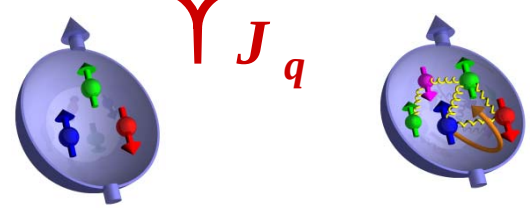
Nucleon Spin Structure

- Understand Nucleon Spin in terms of quarks and gluons (QCD).
  - **Nucleon spin is ½ at all energies, how to divide non trivial (recent developments by Chen *et al.*, Wakamatsu)**

Nucleon's spin
Ji's Sum Rule
(example)



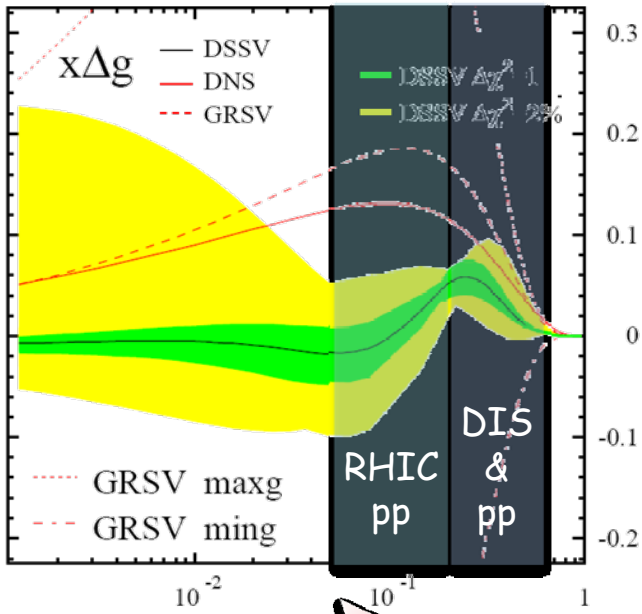
$$\frac{1}{2} = \underbrace{\frac{1}{2}\sum_f (q_f^+ - q_f^-) + L_q}_{J_q} + J_g$$



~30% from quark spin by EMC
1/3 confirmed by more precise data
Gluon intrinsic spin contribution not large (x from ~0.05 to ~0.2)

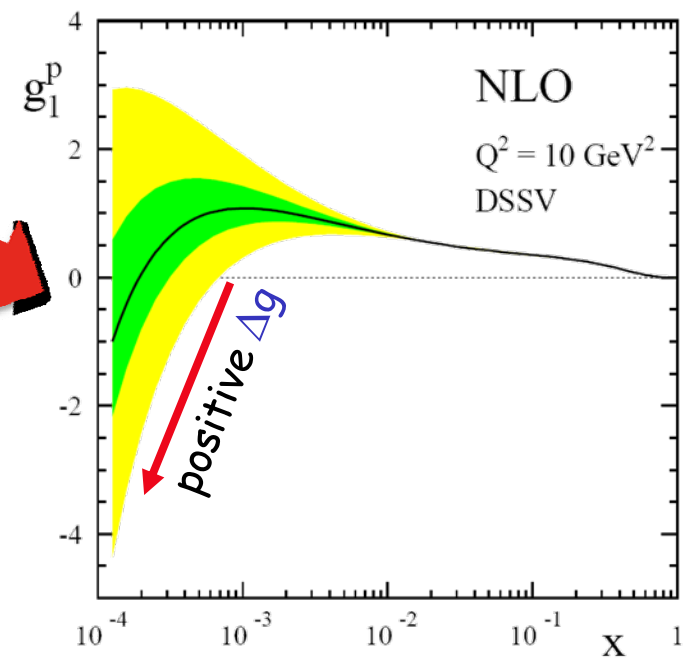
  - Small contribution from quarks and gluons' intrinsic spin
  - Orbital angular momentum of quarks and gluons is important
  - Gluon spin contribution in very small *x* region?

what can be achieved for Δg?



DSSV global fit
de Florian, Sassot, MS, Vogelsang

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



pQCD scaling violations

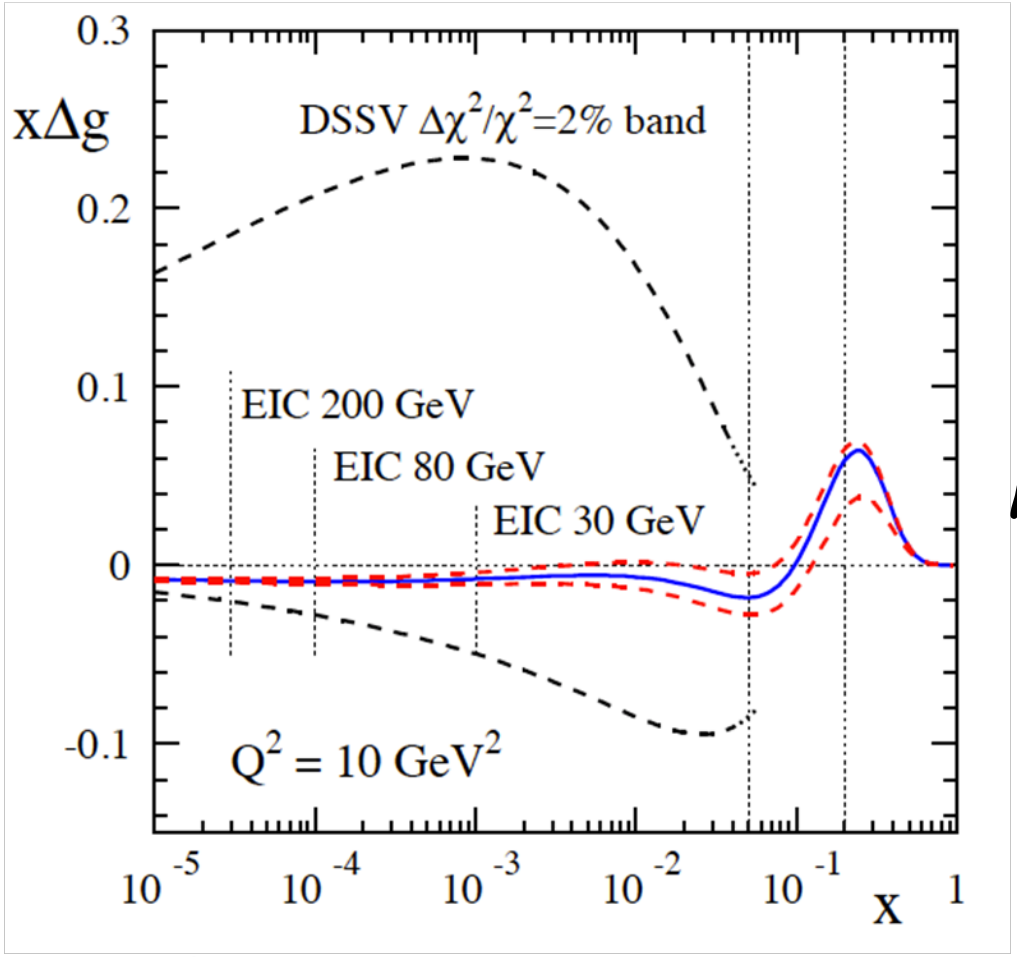
$$\frac{dg_1}{d\log(Q^2)} \propto -\Delta g(x, Q^2)$$

Marco Stratmann @ EIC advisory committee meeting, April 10, 2011

what can be achieved for Δg? – cont'd

what about the uncertainties on the x-shape …

Sassot, MS



golden measurement

- ✓ unique
- ✓ feasible
- ✓ relevant

Marco Stratmann @ EIC advisory committee meeting, April 10, 2011

Tom Burton's talk

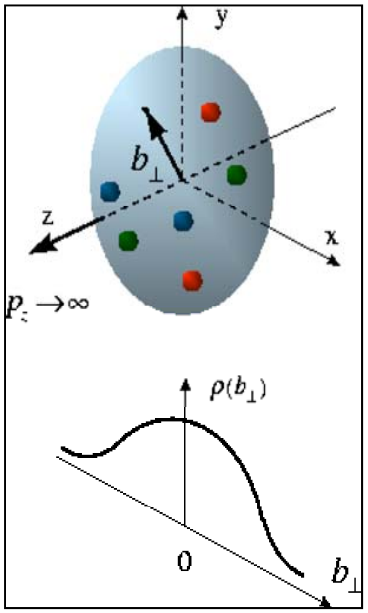
- expect to determine $\int_0^1 dx\, \Delta g(x, Q^2)$ at about 10% level (or better – more studies needed)

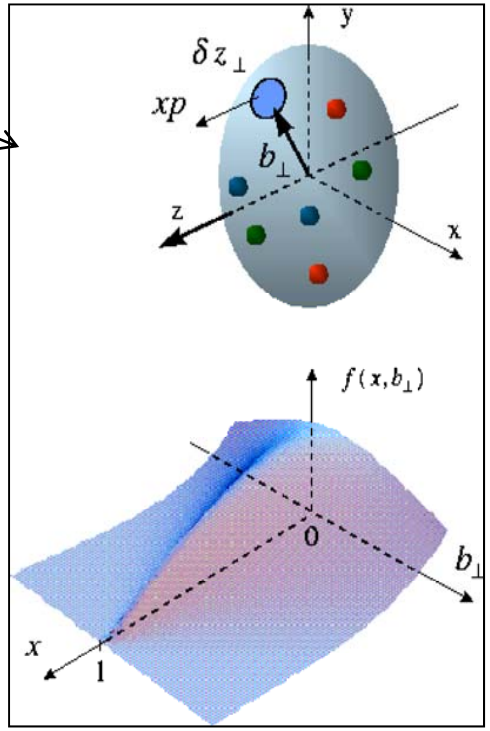
kinematic reach down to x = 10^{-4} essential to determine integral

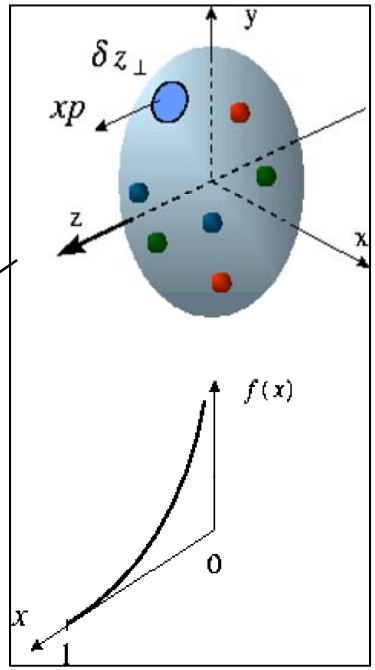
Generalized Parton Distributions (GPDs)

D. Mueller, X. Ji, A. Radyushkin, A. Belitsky,

GPDs connect the charge and parton distribution







The size and structure of proton.
transverse

Nobel prize 1961- R. Hofstadter

Internal constituents of the nucleon
longitudinal

Nobel prize 1990 - J. Friedman, H. Kendall, R. Taylor

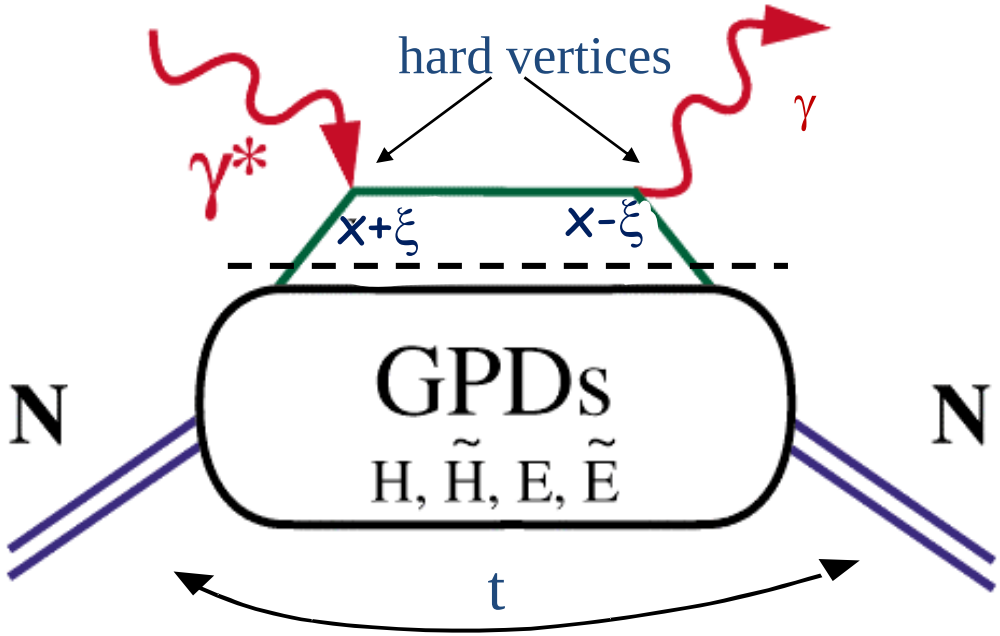
Extend longitudinal quark momentum & helicity distributions to transverse momentum distributions - TMDs

Allow access to the orbital angular momentum of quarks

Tanja Horn's talk

3 dimensional imaging of the nucleon

Deeply Virtual Compton Scattering (DVCS) (clean probe, flavor blind)



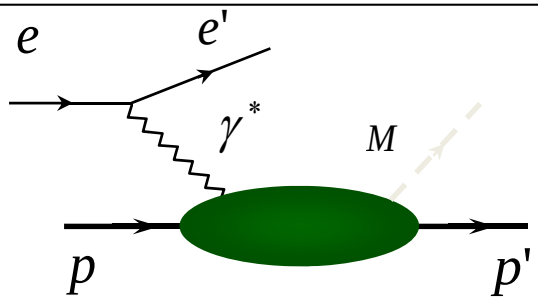
x – longitudinal quark momentum fraction

2ξ – longitudinal momentum transfer

$\sqrt{-t}$ – Fourier conjugate to transverse impact parameter

GPDs depend on 3 variables, e.g. $H(x, \xi, t)$. They describe the internal nucleon dynamics.

- **Hard exclusive meson productions (quark flavor filter) access GPDs**



Link to DIS and Elastic Form Factors

DIS at $\xi = t = 0$

$$H^q(x,0,0) = q(x)$$

$$\tilde{H}^q(x,0,0) = \Delta q(x)$$

Form factors (sum rules)

$$\int_{-1}^{1} dx \sum_q \left[H^q(x,\xi,t) \right] = F_1(t) \quad \text{Dirac f.f.}$$

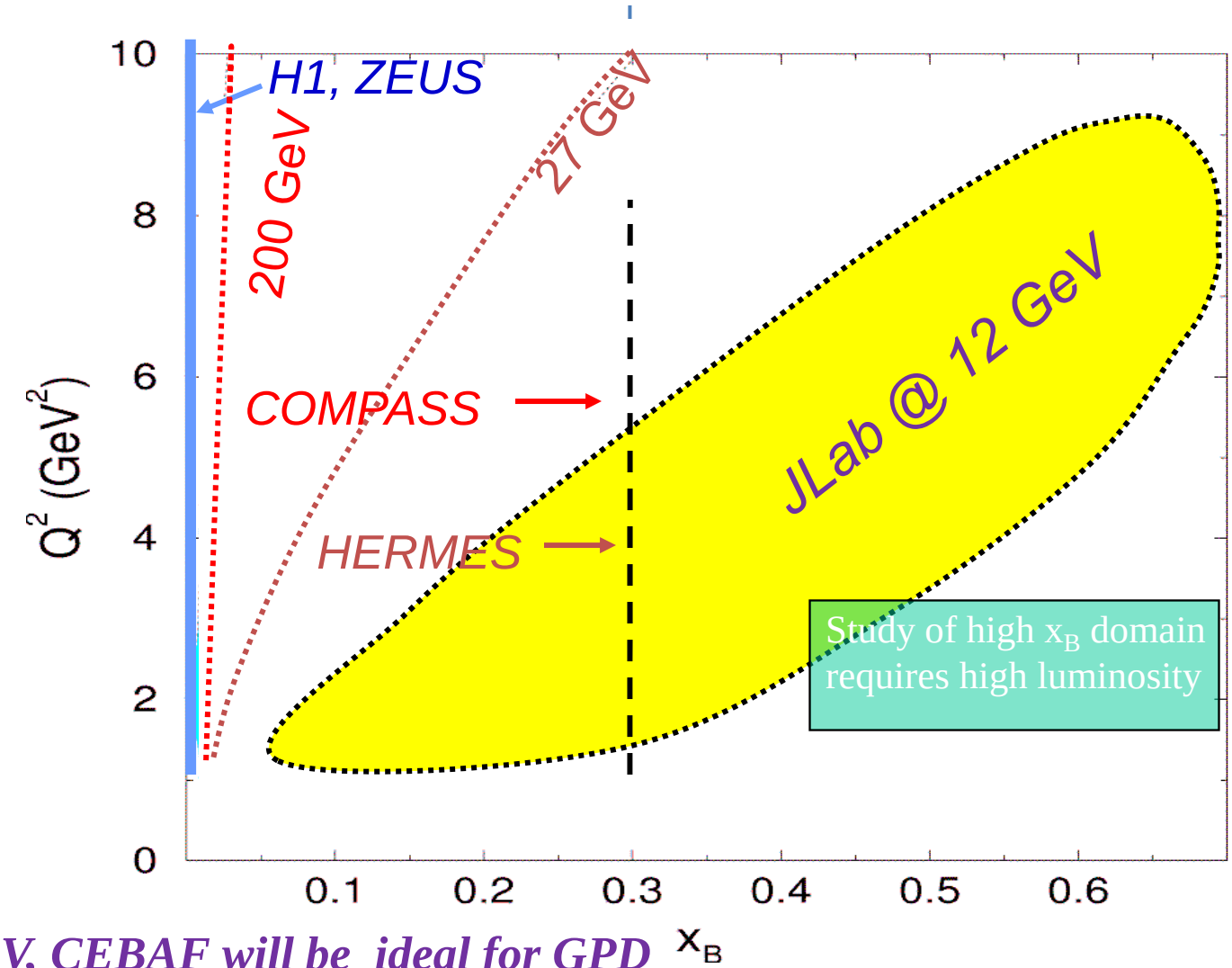
$$\int_{-1}^{1} dx \sum_q \left[E^q(x,\xi,t) \right] = F_2(t) \quad \text{Pauli f.f.}$$

$$\int_{-1}^{1} dx\, \tilde{H}^q(x,\xi,t) = G_{A,q}(t), \quad \int_{-1}^{1} dx\, \tilde{E}^q(x,\xi,t) = G_{P,q}(t)$$

$$H^q, E^q, \tilde{H}^q, \tilde{E}^q(x,\xi,t)$$

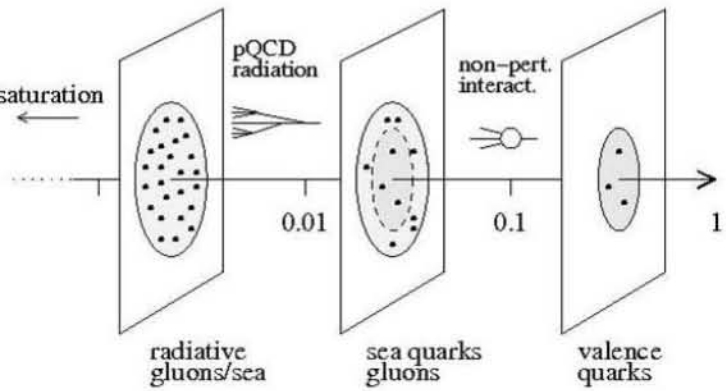
$$J^q = \frac{1}{2} - J^G = \frac{1}{2} \int_{-1}^{1} x dx \left[H^q(x,\xi,0) + E^q(x,\xi,0) \right]$$

Virtual Exclusive Processes - Kinematics Coverage of the 12 GeV Upgrade



At 12 GeV, CEBAF will be ideal for GPD studies using CLAS12 in the valence quark region

Kinematic coverage at EIC and accessing sea quarks and gluons

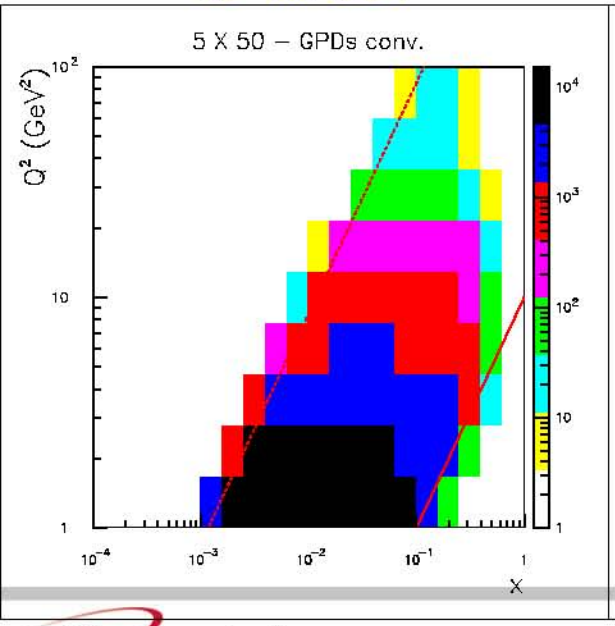


- Nucleon/nucleus is a many-body system
- Deep inelastic scattering (DIS) probes different parton (quark and gluon) components of wave function

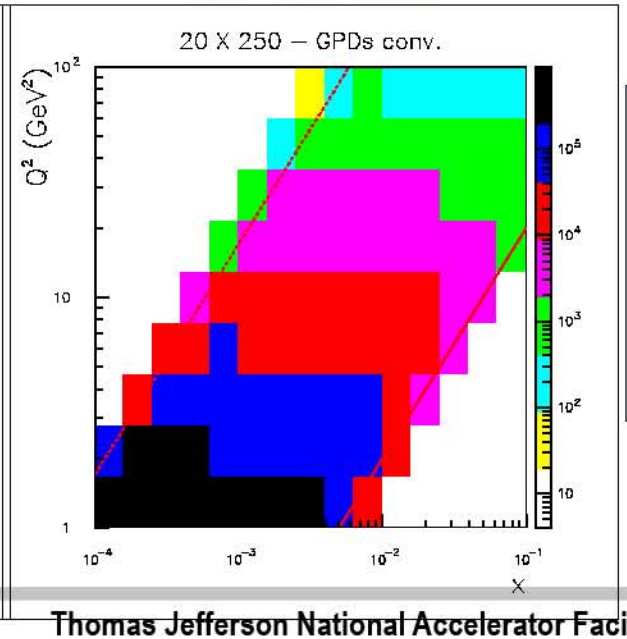
Figure due to C. Weiss

V. Guzey @ EIC advisory Committee meeting, April 10, 2011

$\sqrt{s} \approx 30$ GeV



$\sqrt{s} \approx 140$ GeV

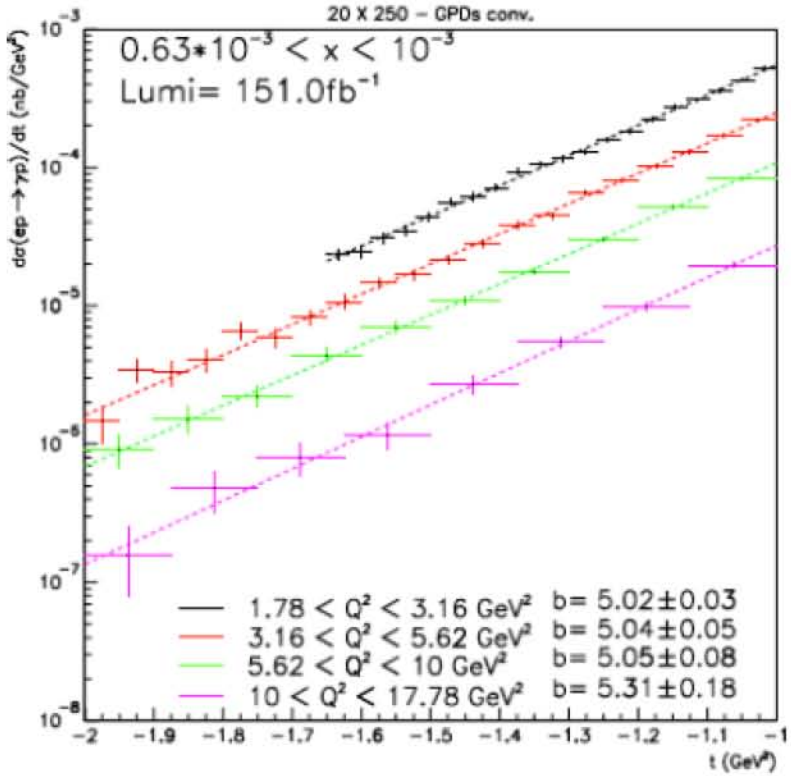


EIC is the machine to study the sea quark and gluon structure of protons/nuclei !

S. Fazio,
INT 10-03 program write-up

Example 1: Simulation of DVCS cross section for EIC

Simulated DVCS cross section
(150 fb^{-1})

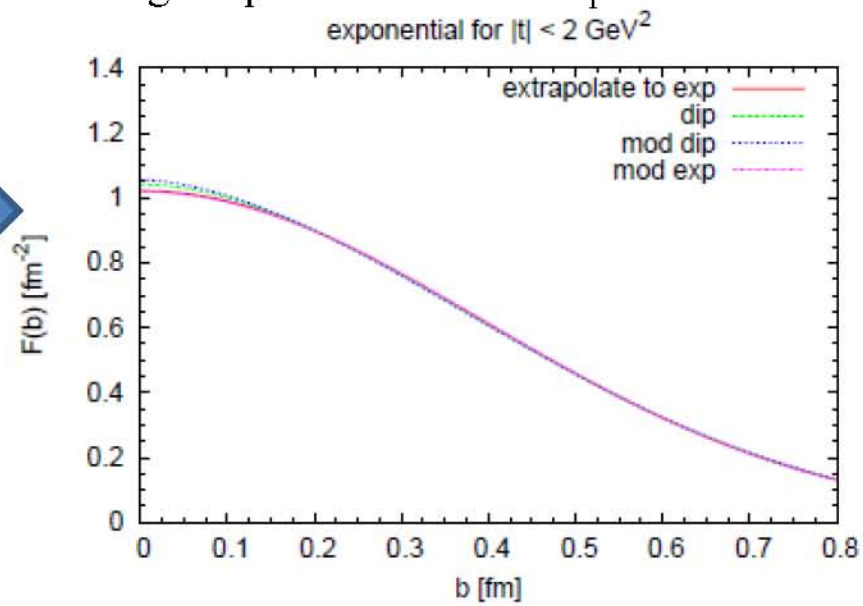


S. Fazio

F.T.

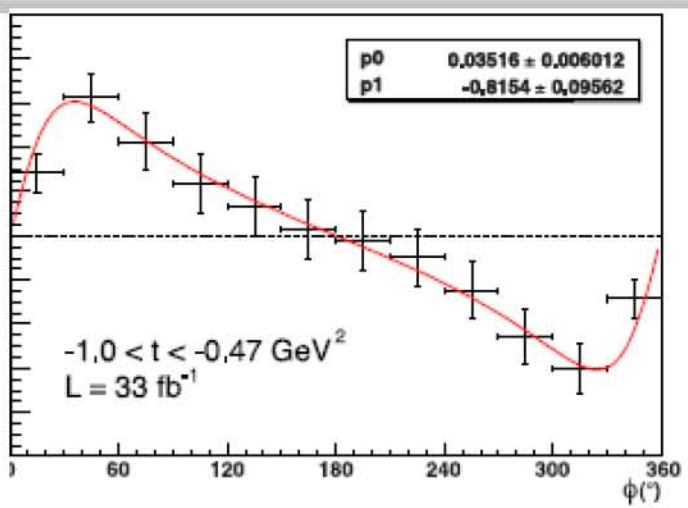
- The slope of the t dependence can be extracted with 1% accuracy due to high luminosity!
(compare to ~10% accuracy at HERA)

- Extracted transverse distribution of "singlet quarks" down to $b_T \approx 0.05$ fm



E. Aschenauer, M. Diehl, S. Fazio
(from the write-up of the INT10-03 program)

Example 2: Simulated DVCS beam-spin asymmetry



$$A_{LU} = \frac{d\sigma^{\leftarrow} - d\sigma^{\rightarrow}}{d\sigma^{\leftarrow} + d\sigma^{\rightarrow}}$$

20x250 GeV

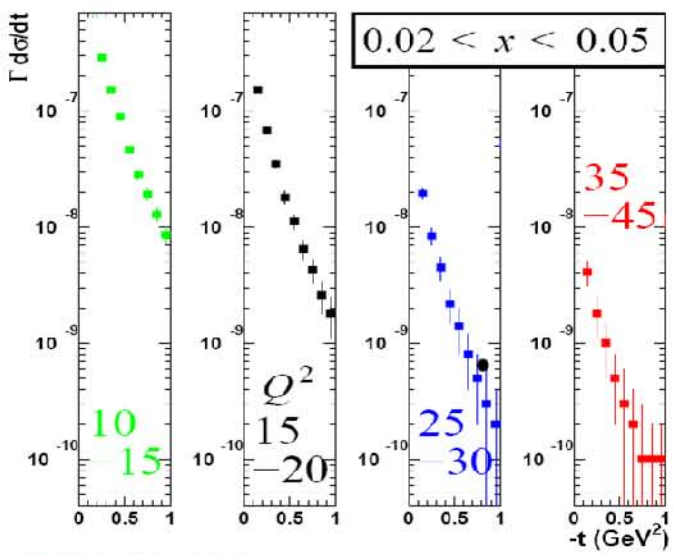
- in typical kinematic bin $1.6\times10^{-3} < x < 2.5\times10^{-2}$ and $3.2 < Q^2 < 5.6$
- 3 months with 50% efficiency at $L = 10^{34}$ will provide 10-15% accuracy on Im H for singlet quarks
- using L and T polarized hadron beam, will access other GPDs

R. Geraud, H. Moutarde, F. Sabatie, INT write-up

Example 3: Production of π^+

$ep \rightarrow e'\pi^+ n$

5x50 GeV



- probes polarized quark GPDs Htilde and Etilde
- flavor structure u-d
- replacing π^+ by K^+ → will probe 2u-d-s
- requires luminosity and L/T separation, but does not need high energy

T. Horn, INT write-up

V. Guzey @ EIC advisory

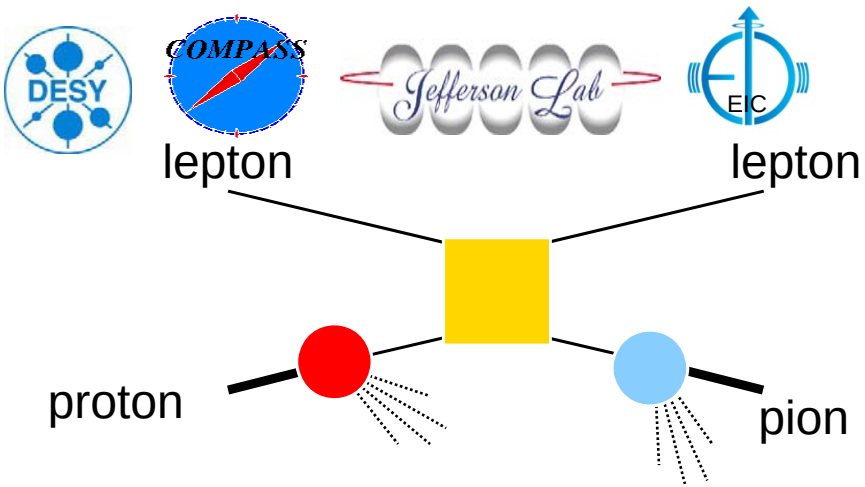
Transverse Momentum-dependent parton distributions (TMDs)

Leading Twist eight TMDs

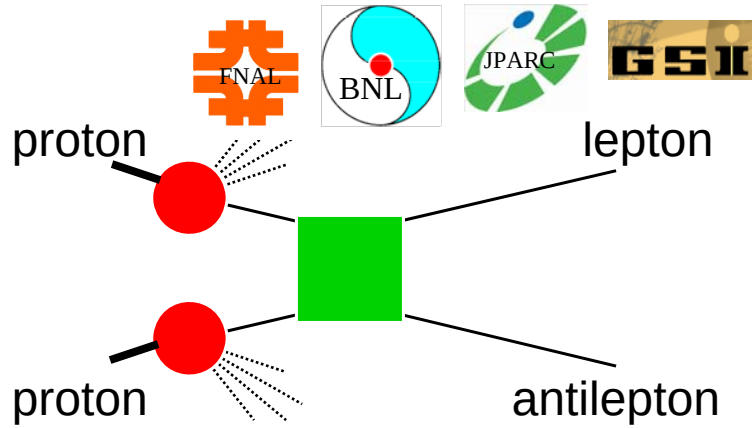
→ Nucleon
→ Quark Spin

		Quark polarization		
		Un-Polarized	Longitudinally Polarized	Transversely Polarized
Nucleon Polarization	U	f_1 =		$h_1^\perp$ = – Boer-Mulder
	L		g_1 = – Helicity	$h_{1L}^\perp$ = –
	T	$f_{1T}^\perp$ = – Sivers	$g_{1T}^\perp$ = –	h_{1T} = – Transversity $h_{1T}^\perp$ = – Pretzelosity

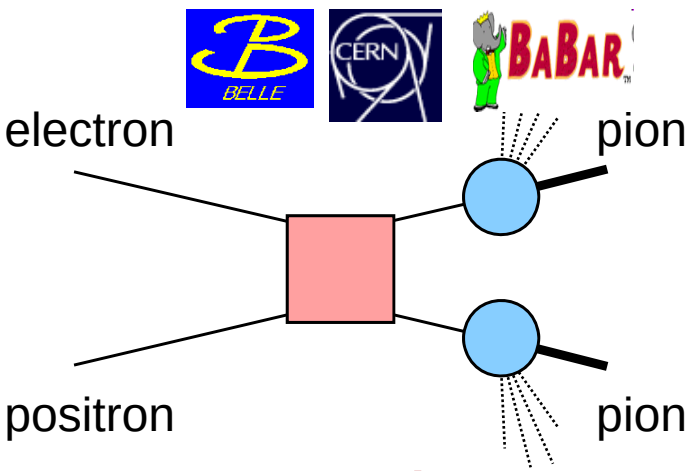
Access TMDs through Hard Processes



SIDIS



Drell-Yan



e^-e^+ to pions

Partonic scattering amplitude

Fragmentation amplitude

Distribution amplitude

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

$$h_1^{\perp}(\mathrm{SIDIS}) = -h_1^{\perp}(\mathrm{DY})$$

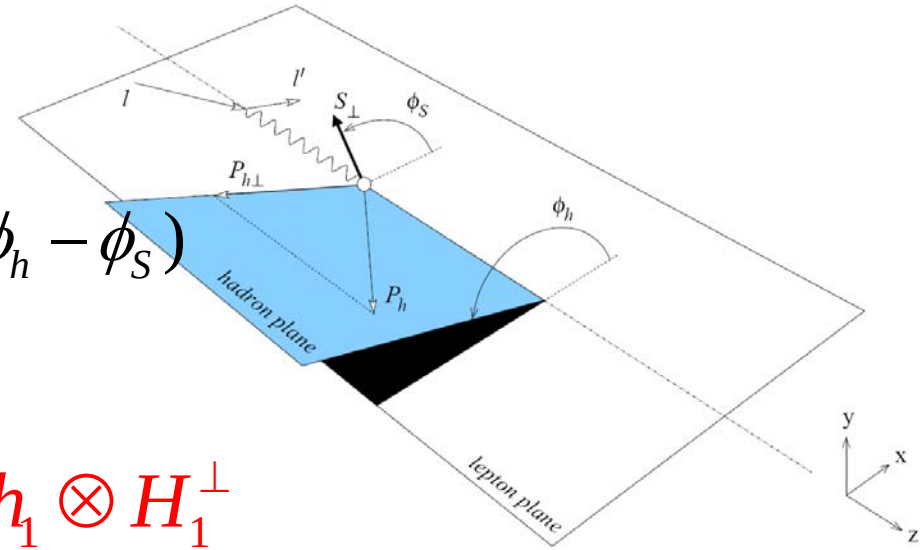
lattice talk by Bernhard Musch

Separation of Collins, Sivers and pretzelocity effects through angular dependence

$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

$$= A_{UT}^{Collins} \sin(\phi_h + \phi_S) + A_{UT}^{Sivers} \sin(\phi_h - \phi_S)$$

$$+ A_{UT}^{Pretzelosity} \sin(3\phi_h - \phi_S)$$



$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$

$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

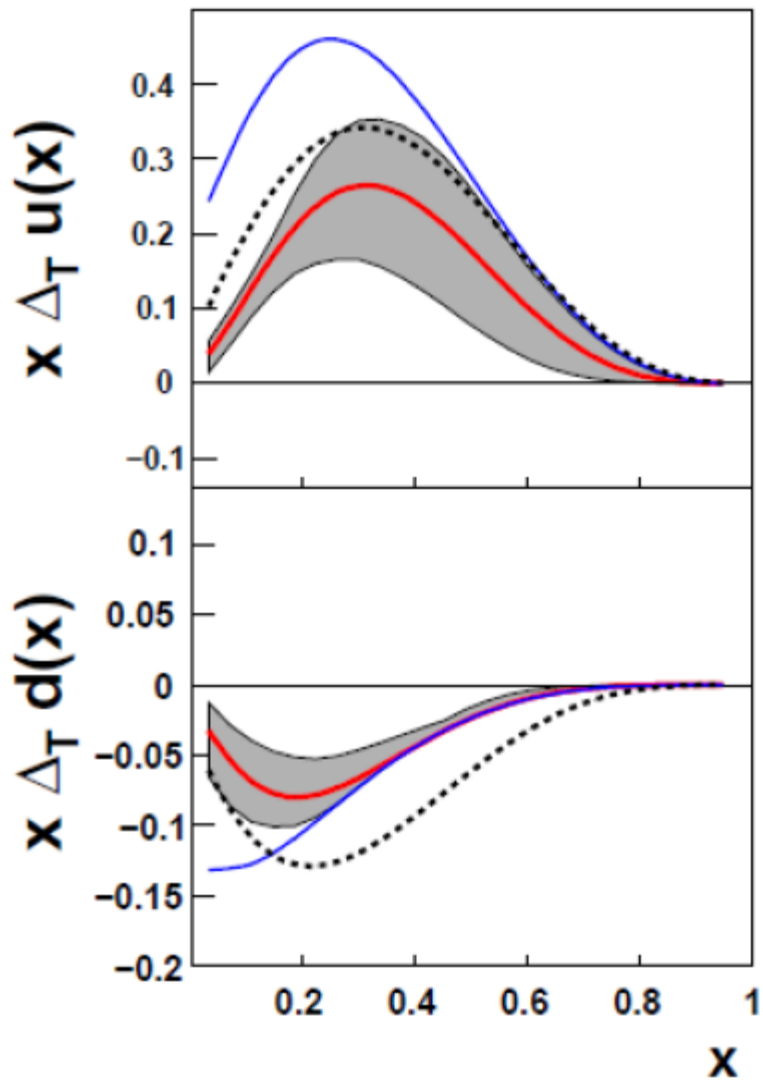
$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

SIDIS SSAs depend on 4-D variables (x, Q^2, z and P_T)

Large angular coverage and precision measurement of asymmetries in 4-D phase space is essential.

Transversity Distributions

A global fit to the HERMES p, COMPASS d and BELLE e+e- data by the Torino group, Anselmino et al., arXiv:0812.4366



Solid red line : transversity distribution, analysis at Q^2=2.4 $(GeV/c)^2$

Solid blue line: Soffer bound
$|h_{1T}| <= (f_1+g_{1L})/2$
GRV98LO + GRSV98LO

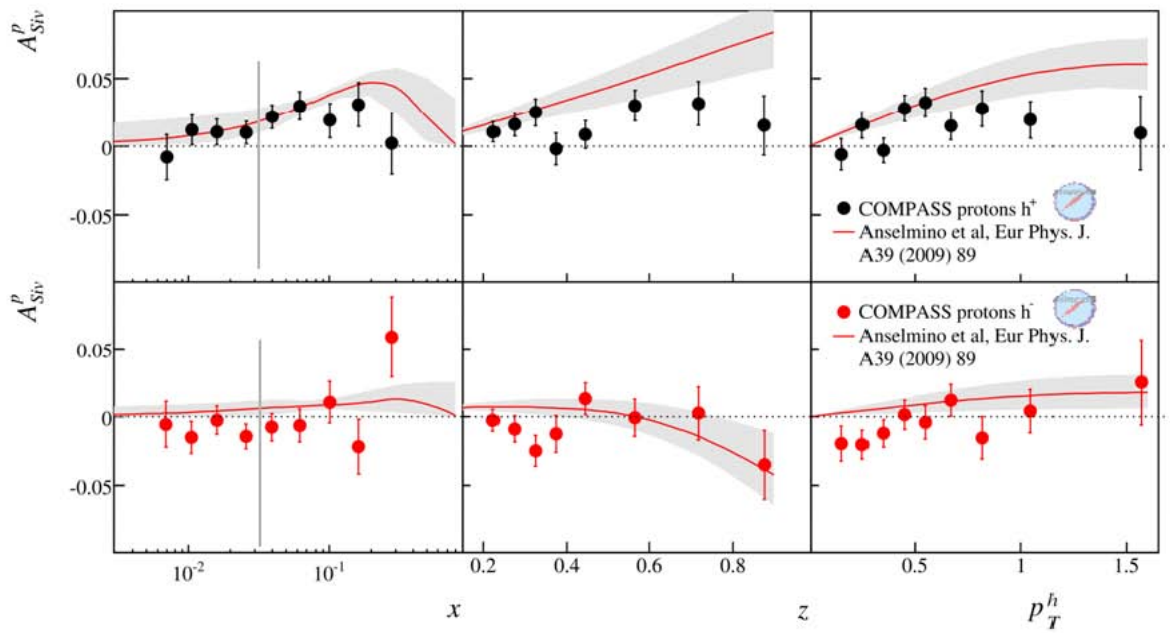
Dashed line: helicity distribution g_{1L}, GRSV98LO

$$\Delta_T = h_{1T}$$

Sivers asymmetry - proton

comparison with theory

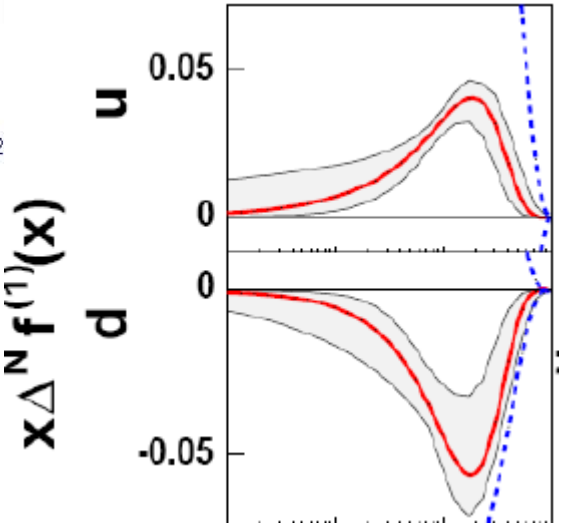
… most recent predictions from *M. Anselmino et al.*
based on the fit of HERMES proton and COMPASS deuteron data



Anna Martin

June 22

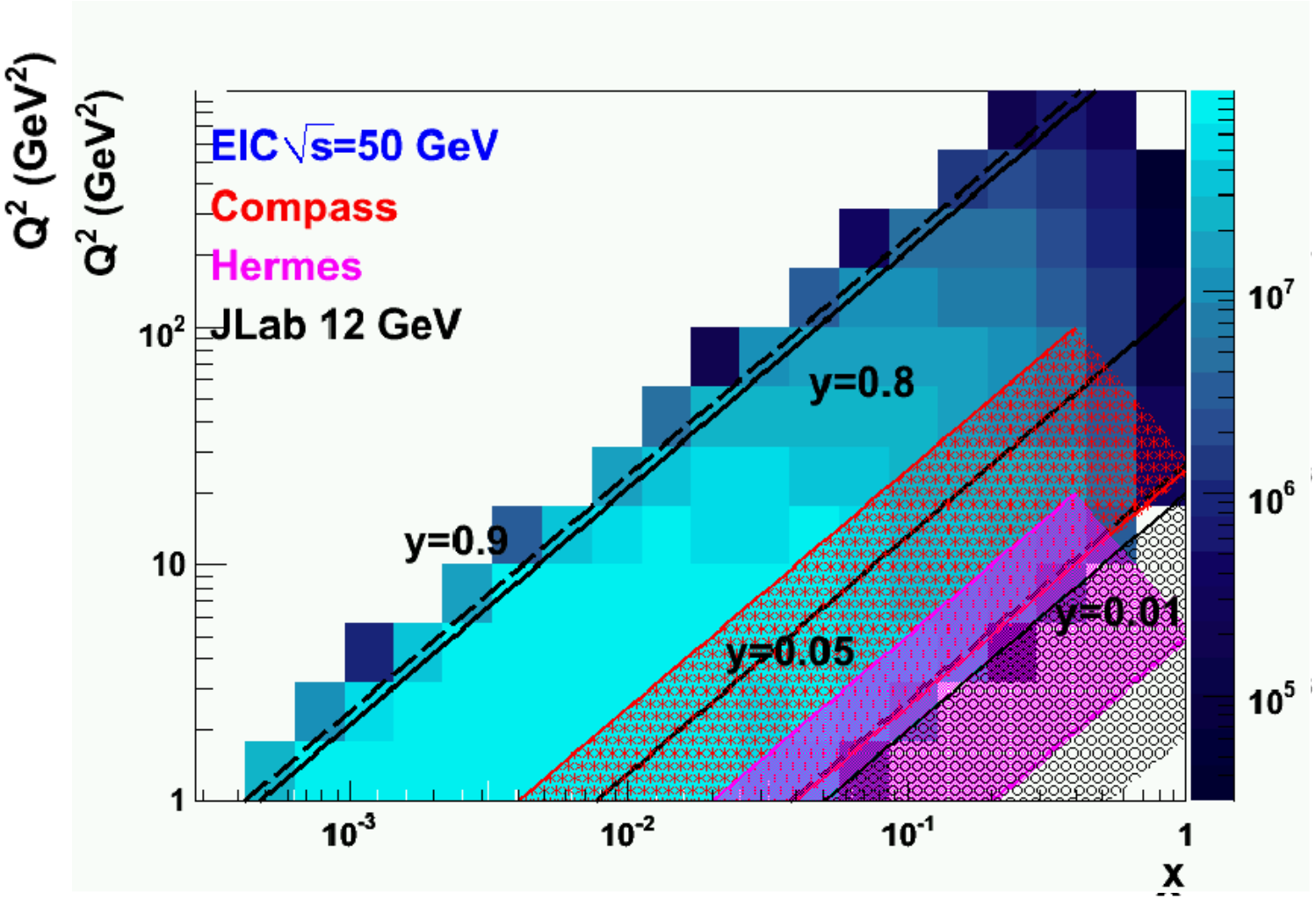
Extraction of Sivers fcn (HERMES p, COMPASS d)



Ext: M. Anselmino *et al.*, arXiv:0812.4366

Lattice talk by Bernhard Musch

Phase Space Coverage



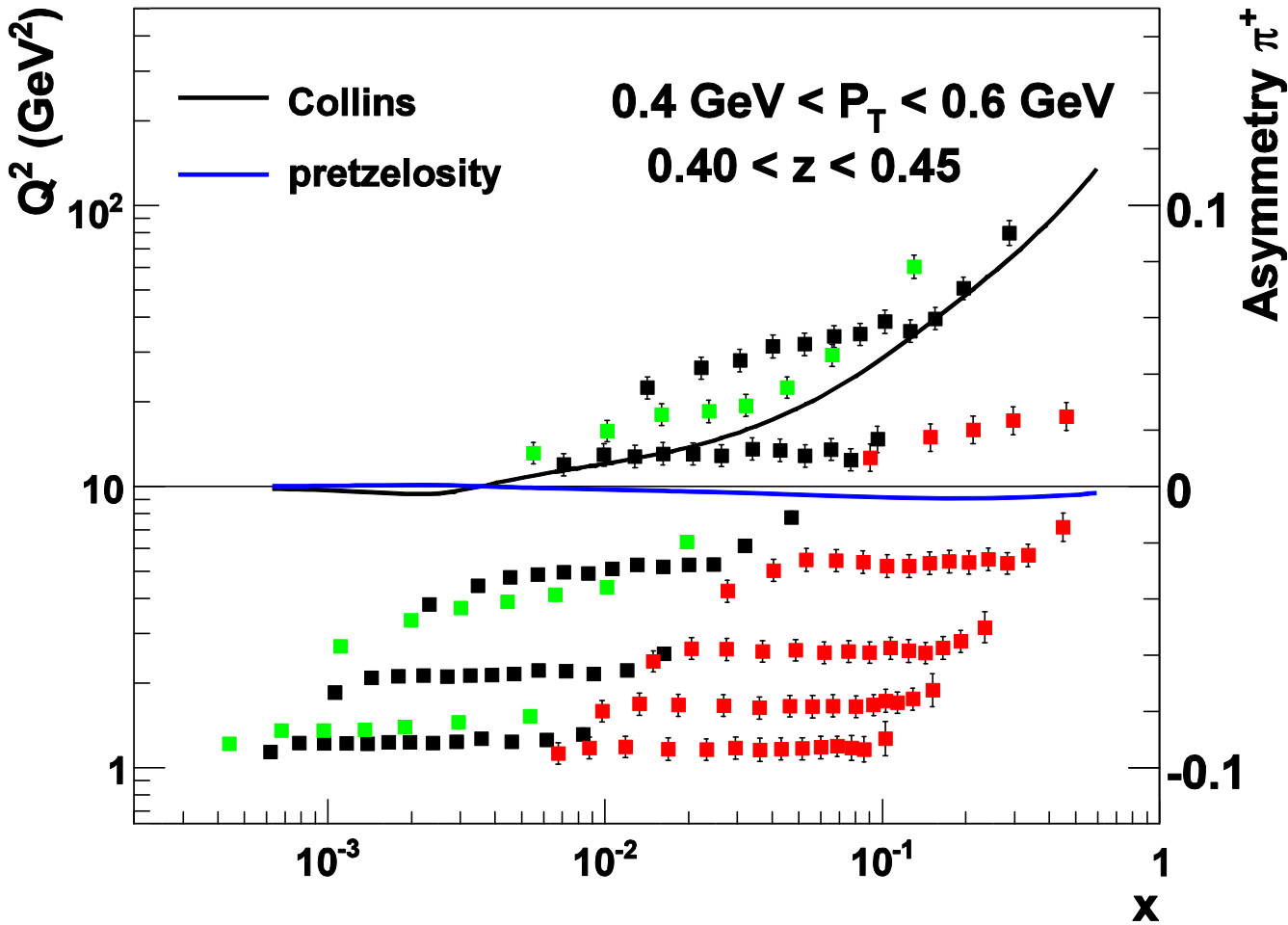
Note that the coverage of Compass Hermes & Jlab 12 may not be able to do 4D mapping

Min Huang's talk

Projections with Proton (Collins)

- **11 + 60 GeV**
  36 days
  L = 3×10^{34} /cm^2/s
- **11 + 100 GeV**
  36 days
  L = 1×10^{34}/cm^2/s

  2×10^{-3} , $Q^2<10$ GeV^2
  4×10^{-3} , $Q^2>10$ GeV^2
- **3 + 20 GeV**
  36 days
  L = 1×10^{34}/cm^2/s
  4×10^{-3} , $Q^2<10$ GeV^2
  5×10^{-3} , $Q^2>10$ GeV^2



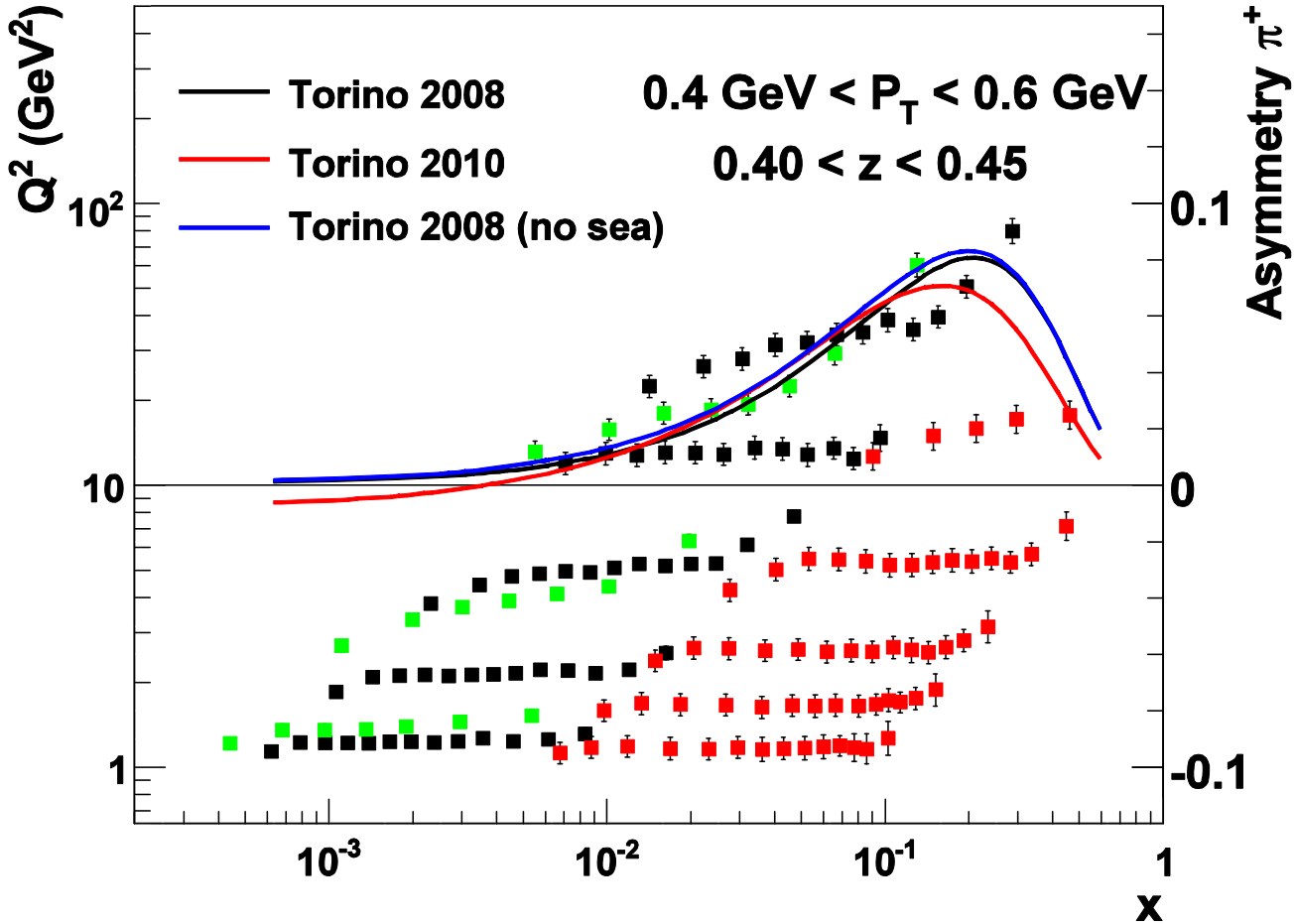
Results on kaons also

Min Huang's talk

Projections with Proton (Sivers)

Polarization 70%
Overall efficiency 50%

z: 12 bins 0.2 - 0.8
P_T: 5 bins 0-1 GeV
Also π^-



Results on kaons also

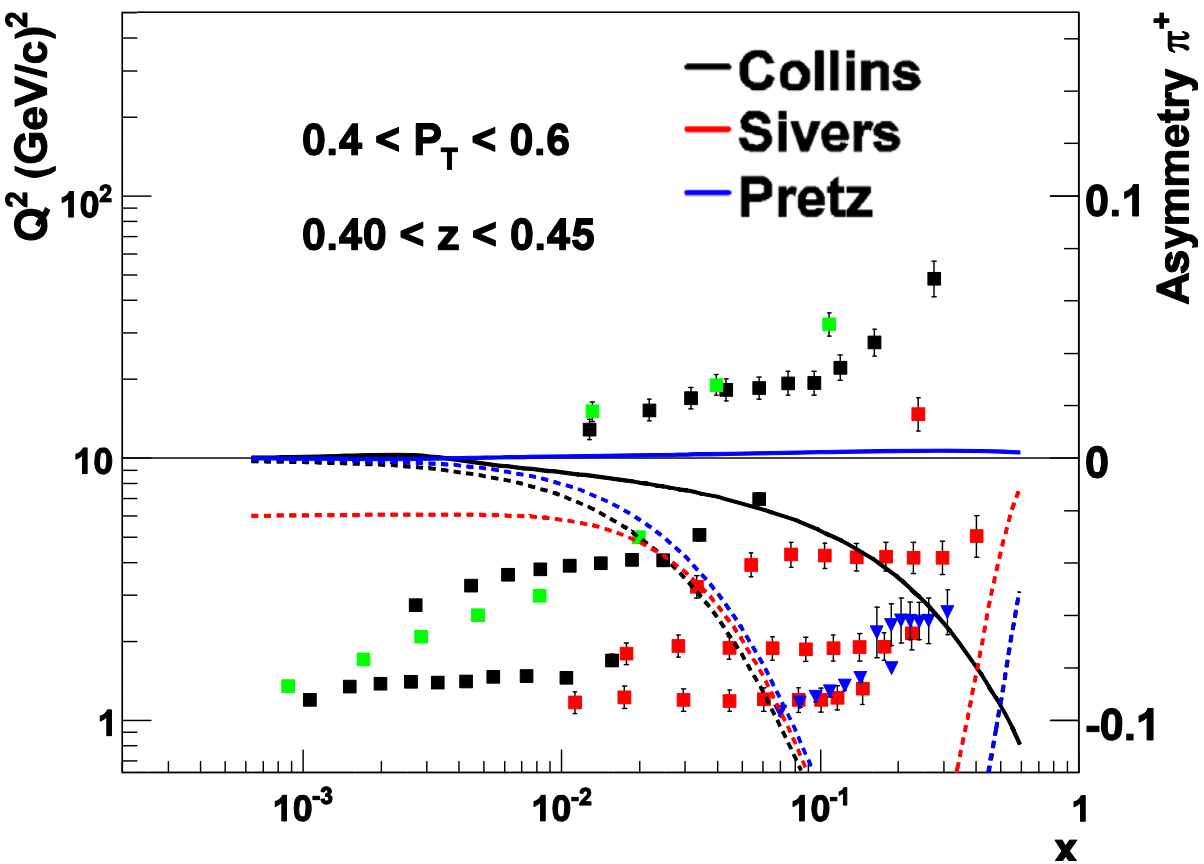
Min Huang's talk

Projections with ^{3}He (neutron)

- 11 + 60 GeV
  72 days
- 11 + 100 GeV
  72 days
- 12 GeV SoLid

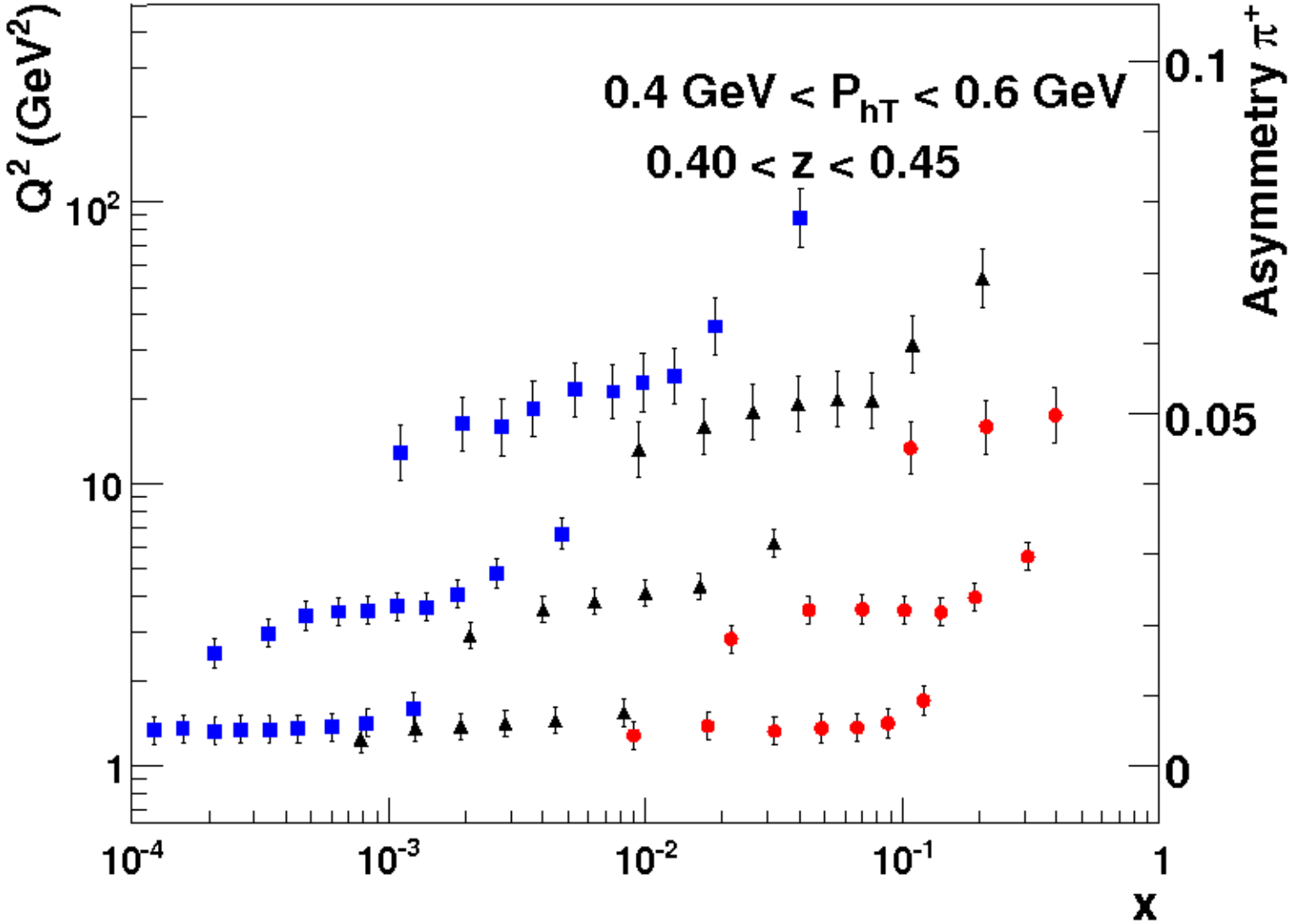
^{3}He: 87% effective polarization

Equal stat. for proton and neutron (combine ^{3}He and D)



	11 + 60 GeV	11 + 100 GeV	3+20 GeV
P	36 d (3×10^{34}/cm^2/s)	36 d (1×10^{34}/cm^2/s)	36 d (1×10^{34}/cm^2/s)
D	72 d	72 d	72 d
^{3}He	72 d	72 d	72 d

Higher center-of-mass energies



blue: 140 GeV, black 50 GeV, red 15 GeV, integrated lumi: 30 fb^{-1}

what about the gluon *Sivers* ?

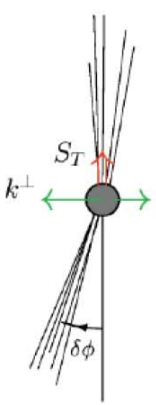
essentially nothing known → might be (very) large:

- positivity bound: $f_{1T}^{\perp,g}(x,p_T^2)\frac{p_T}{M_p} \le f_1^g(x,p_T^2)$

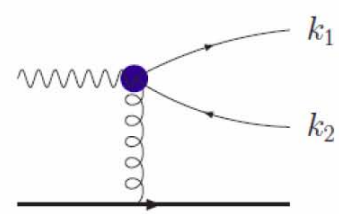
  as for quark Sivers, further bounds might be derived

- Burkardt-SR: $\sum_{a=q,\bar{q},g}\langle p_T^a\rangle = 0 \rightarrow \sum_{a=q,\bar{q},g}\int dx\, f_{1T}^{\perp(1),a}(x) = 0$

ways to measure the gluon *Sivers* :



- DIS dijet (dihadron): $\gamma_T^* A \rightarrow q(k_1) + \bar{q}(k_2) + X$



- heavy quark / quarkonium production (J/Ψ, D):
  imbalance between q and q-bar probes gluon TMDs

  [talk by C. Pisano: week-2, W. Xiao: week-5]

→ *inclusive* heavy flavour prod. probes the integrated gluon distr. or gluon correlation (twist-3)

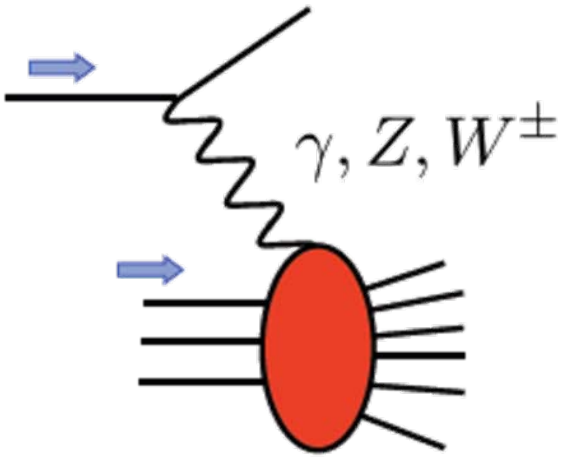
[talk by K. Tanaka: week-9]

Tom Burton's talk, Min Huang's talk

Delia Hasch talk @ INT

electroweak probes: why interesting

Deshpande, Kumar, Ringer, Riordan, Taneja, Vogelsang



high enough Q^2 electroweak probes become relevant

- **neutral currents** (γ, Z exchange, γZ interference)
- **charged currents** (W exchange)

parameterized by new structure functions which probe combinations of PDFs different from photon exchange

flavor decomposition without SIDIS, e-w couplings

hadron-spin averaged case: studied to some extent at HERA (limited statist

hadron-spin difference:

contains e-w propagators and couplings

Wray; Derman; Weber, MS, Vogelsang; Anselmino, Gambino, Kalinowski; Blumlein, Kochelev; Forte, Mangano, Ridolfi; …

$$\frac{d\Delta\sigma^{e^{\mp},i}}{dxdy} = \frac{4\pi\alpha^2}{xyQ^2}\left[\pm y(2-y)x\hat{g}_1^i - (1-y)\hat{g}_4^i - y^2 x\hat{g}_5^i\right] \quad \mathrm{i} = \mathrm{NC}, \mathrm{CC}$$

unexplored so far – unique opportunity for the EIC

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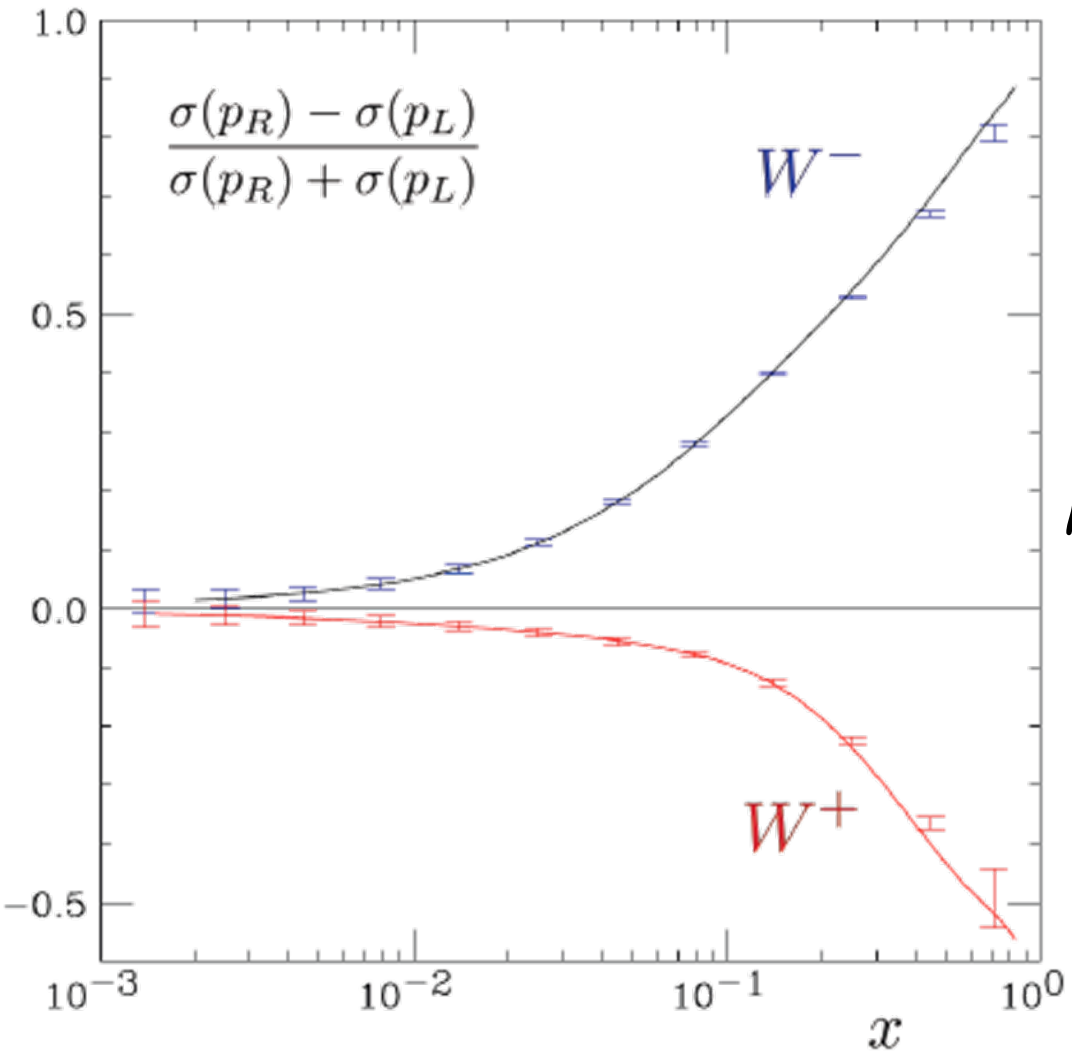
most promising: CC DIS



20 × 250 GeV

$Q^2 > 1$ GeV^2

$0.1 < y < 0.9$

10 fb^{-1}

DSSV PDFs

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need to be able to reconstruct x, Q^2 from hadronic final-state

separate up-type and down-type PDF combinations by varying y

$$A^{W^-} = \frac{(\Delta u + \Delta c) - (1-y)^2(\Delta \bar{d} + \Delta \bar{s})}{(u+c) + (1-y)^2(\bar{d} + \bar{s})} \quad A^{W^+} = \frac{(1-y)^2(\Delta d + \Delta s) - (\Delta \bar{u} + \Delta \bar{c})}{(1-y)^2(d+s) + (\bar{u} + \bar{c})}$$

Summary

Some of the
NSAC LRP Overarching QCD questions
(December 2007)

- What is the internal spin and flavor landscape of hadrons?
- What is the role of gluons and gluons self interactions in nucleon and nuclei?
- What governs the transition of quarks and gluons into pions and nucleons?

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