Recent Results on Structure Functions

Haiyan Gao

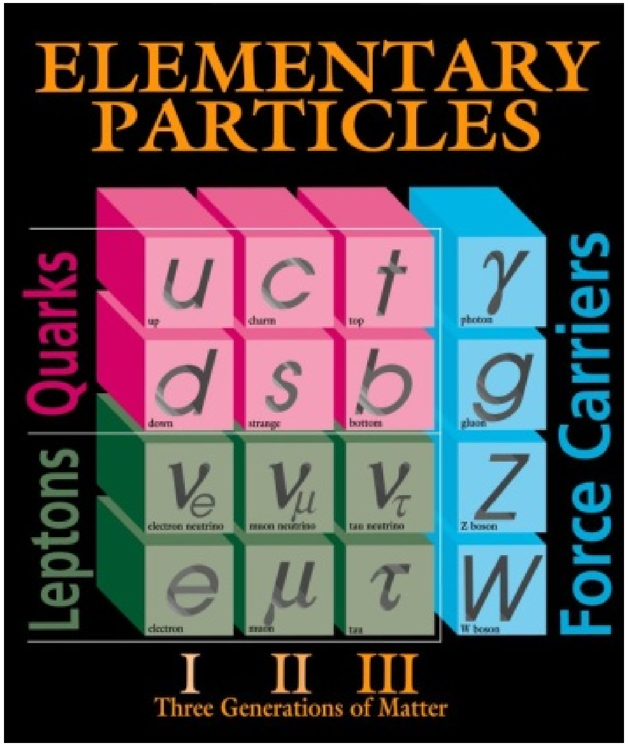
Duke University

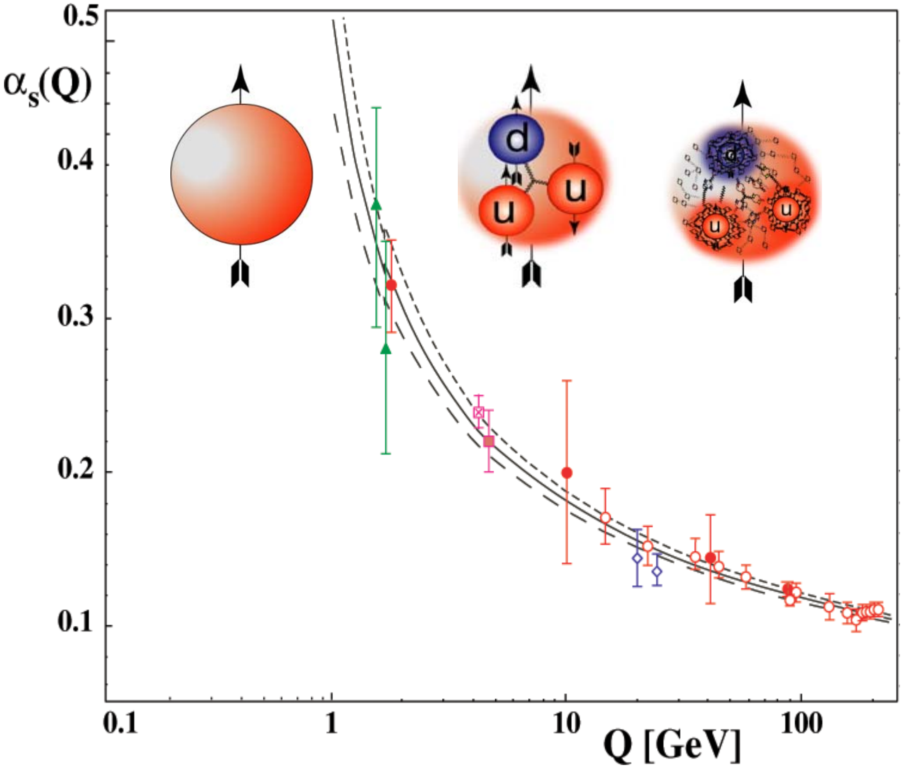
Durham, NC, U.S.A.

Outline

- Introduction
- Unpolarized nucleon structure
- Longitudinal (transverse) spin structure
- **3-dimensional Structure of nucleon**
  - **Transverse momentum dependent parton distributions (TMDs)**
  - **Generalized parton distributions (GPDs)**
- Summary and outlook

QCD: still unsolved in non-perturbative region

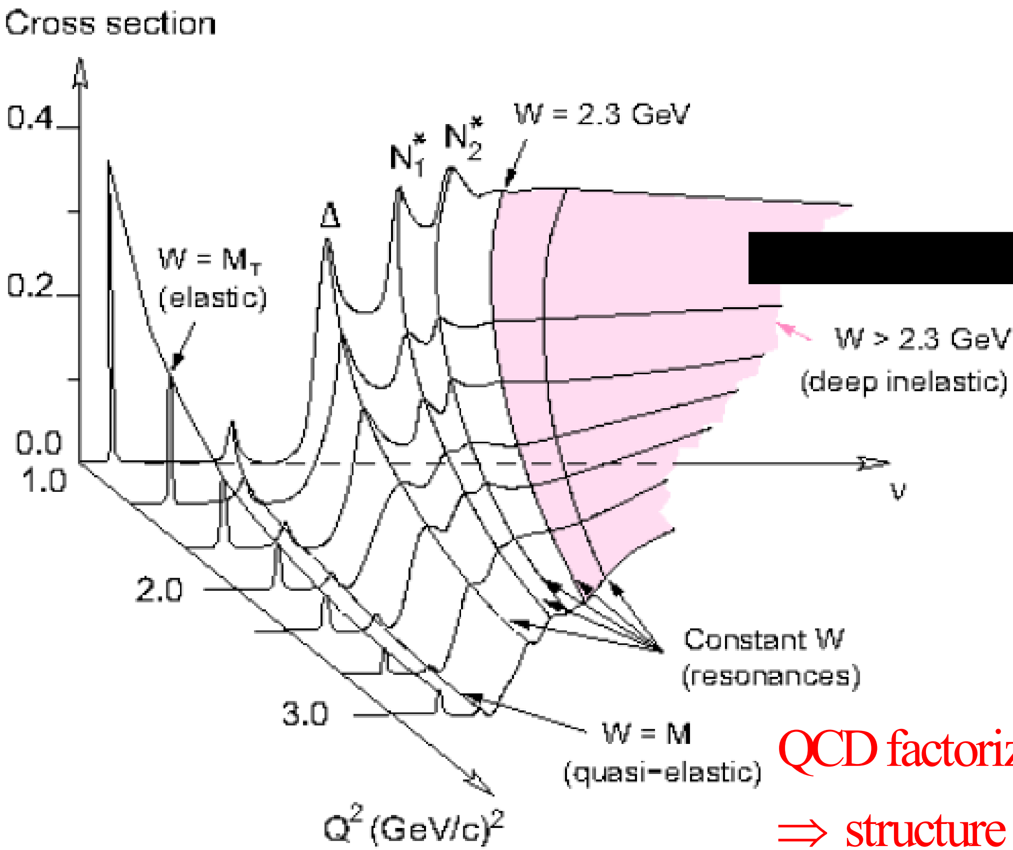


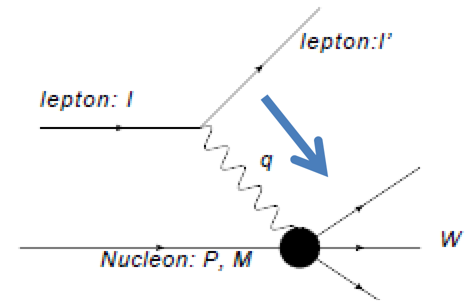


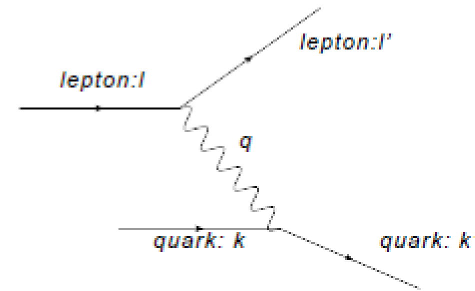
Gauge bosons: gluons (8)

- *2004 Nobel prize for ``asymptotic freedom''*
- *non-perturbative regime QCD ?????*
- *One of the top 10 challenges for physics!*
- *QCD: Important for discovering new physics beyond SM*
- *Nucleon structure is one of the most active areas*

Lepton Scattering ----- *A powerful tool*







QCD factorization

$\Rightarrow$ structure (non-perturbative) $\otimes$ hard part (pQCD)

$$Q^2 = -q^2 = -(l - l')^2$$

4-momentum transfer squared: resolution.

$$\nu = E_l - E_{l'}$$

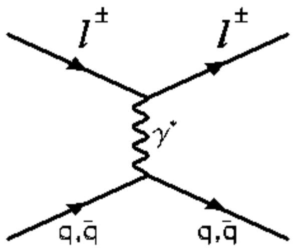
Energy transfer.

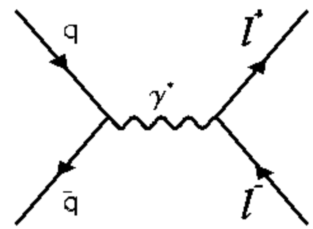
$$x_{Bjorken} = \frac{Q^2}{2m\nu}$$

Longitudinal momentum fraction of parton in the light cone frame.

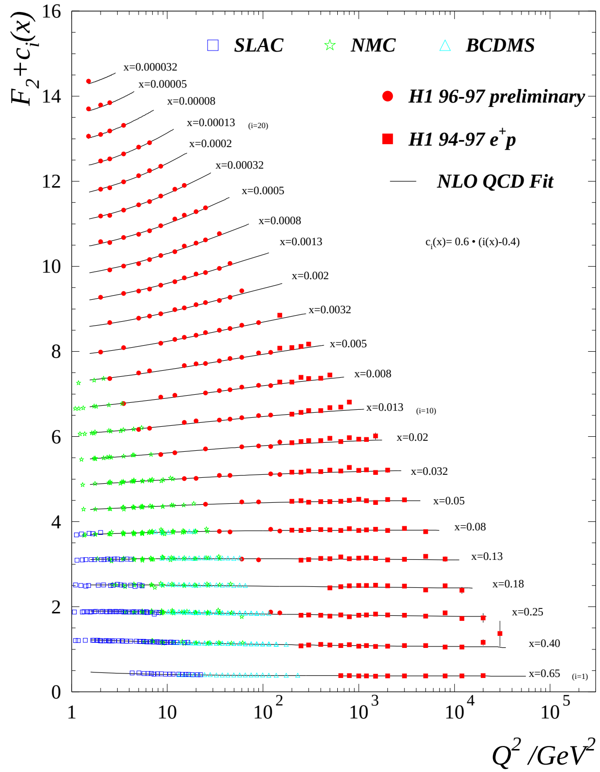
Universal Parton Distribution

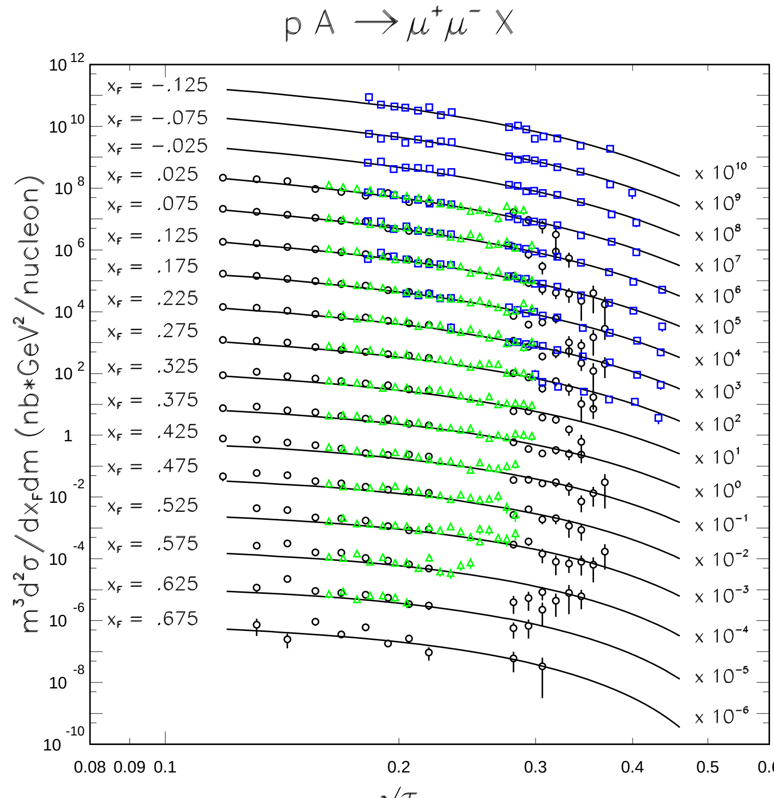
DIS





Drell-Yan





Drell-Yan and DIS cross sections are well described by Next-to-Leading Order QCD

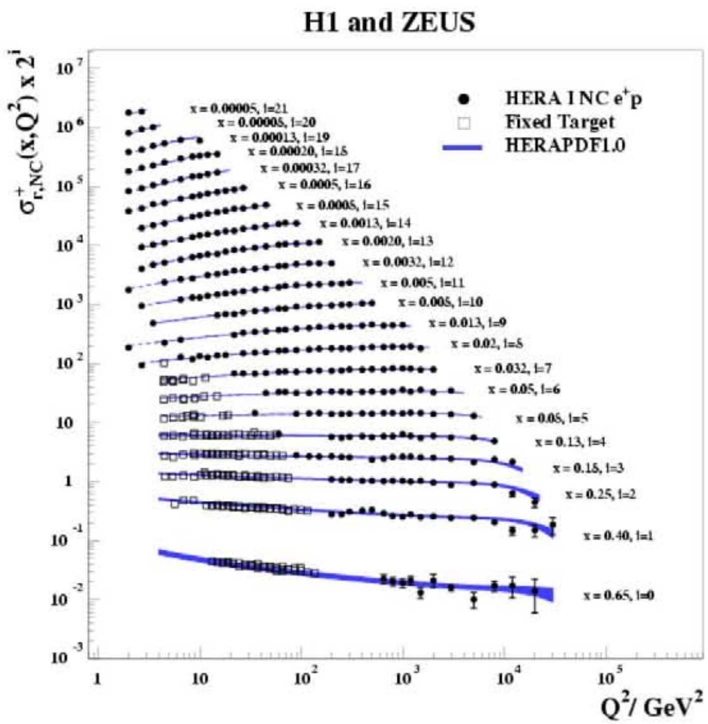
Incl. HERA I data and PDF fit

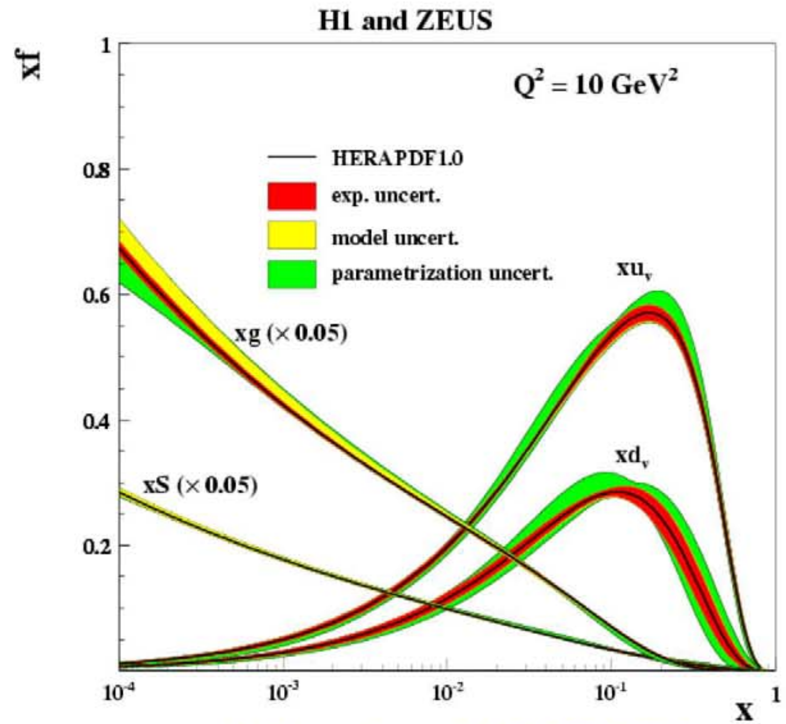
- complete HERA I combined incl. cross sections
- O(1%) precision for $10 < Q^2 < 100$ GeV^2
- sole input for HERAPDF1.0

→ precise PDFs in the region relevant for LHC

JHEP 1001:109,2010

→S. Habib [169]





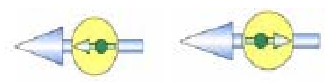
available since LHAPDF 5.8.1

Plenary talk by Emmanuel Sauvan, Tuedsday

Talk 1136 by V. Radescu

Nucleon Spin Structure

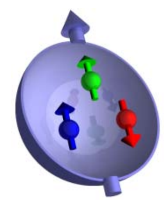
- Understand Nucleon Spin in terms of quarks and gluons (QCD).
  - **Nucleon spin is ½ at all energies.**

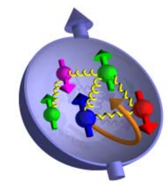


Nucleon's spin
Ji's Sum Rule

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

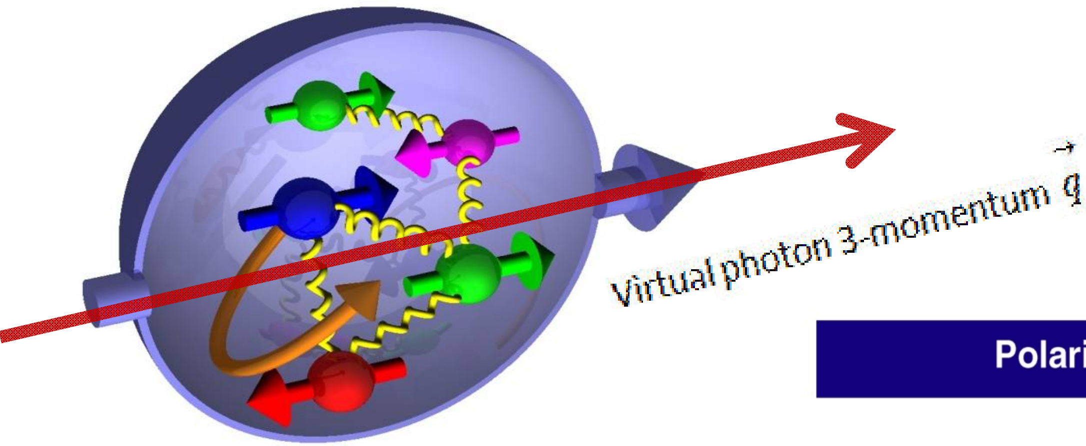
~30% from data
"spin crisis"





  - Small contribution from quarks and gluons' intrinsic spin
  - Orbital angular momentum of quarks and gluons is important
    - **Understanding of spin-orbit correlations.**

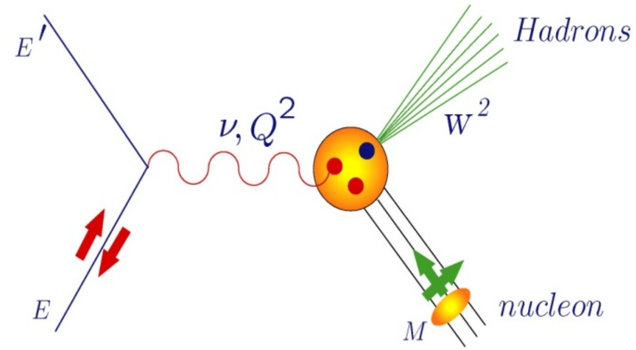
Longitudinal Spin Structure



g_{1L}

Probability for quark polarized in the nucleon spin direction

Polarized Deep Inelastic Electron Scattering



$x = \frac{Q^2}{2M\nu}$ Fraction of nucleon momentum carried by the struck quark

Q^2 = 4-momentum transfer of the virtual photon, ν = energy transfer, θ = scattering angle

- All information about the nucleon vertex is contained in

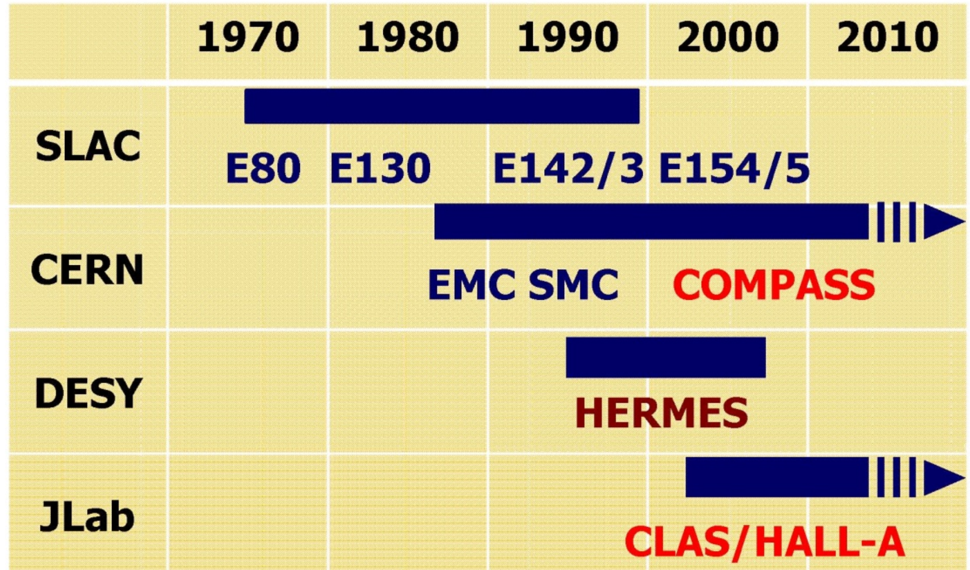
F_2 and F_1 the unpolarized (spin averaged) structure functions,

and

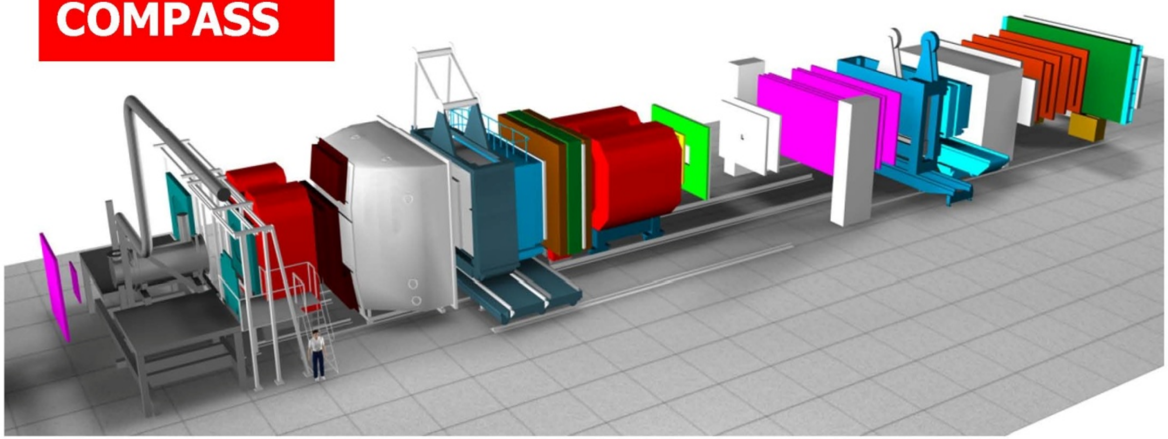
g_1 and g_2 the spin dependent structure functions

Experiments @Lepton facilities

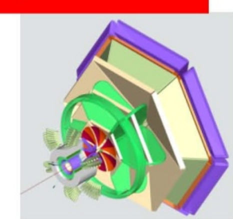
E80, E130	$\vec{\mathrm{e}}\ \vec{\mathrm{p}}$	≤ 20 GeV
EMC	$\vec{\mu}\ \vec{\mathrm{p}}$	100–200 GeV
E142, 143	$\vec{\mathrm{e}}\ \vec{\mathrm{p}}, \vec{\mathrm{n}}, \vec{\mathrm{d}}$	≤ 28 GeV
SMC	$\vec{\mu}\ \vec{\mathrm{p}}, \vec{\mathrm{d}}$	100, 190 GeV
E154, 155	$\vec{\mathrm{e}}\ \vec{\mathrm{p}}, \vec{\mathrm{n}}, \vec{\mathrm{d}}$	≤ 50 GeV
HERMES	$\vec{\mathrm{e}}\ \vec{\mathrm{p}}, \vec{\mathrm{n}}, \vec{\mathrm{d}}$	27.5 GeV
COMPASS	$\vec{\mu}\ \vec{\mathrm{p}}, \vec{\mathrm{d}}$	160 GeV
HALL A	$\vec{\mathrm{e}}\ \vec{\mathrm{n}}$	6 GeV
CLAS	$\vec{\mathrm{e}}\ \vec{\mathrm{p}}, \vec{\mathrm{d}}$	6 GeV

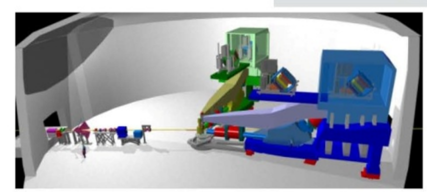


COMPASS

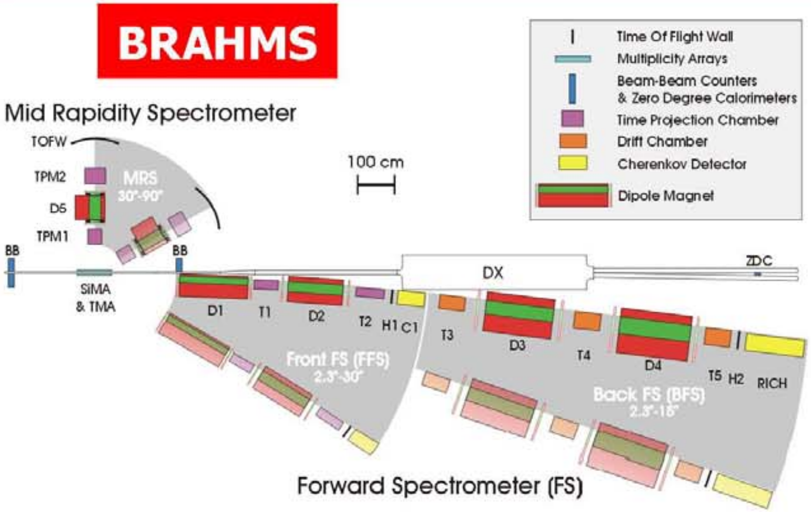


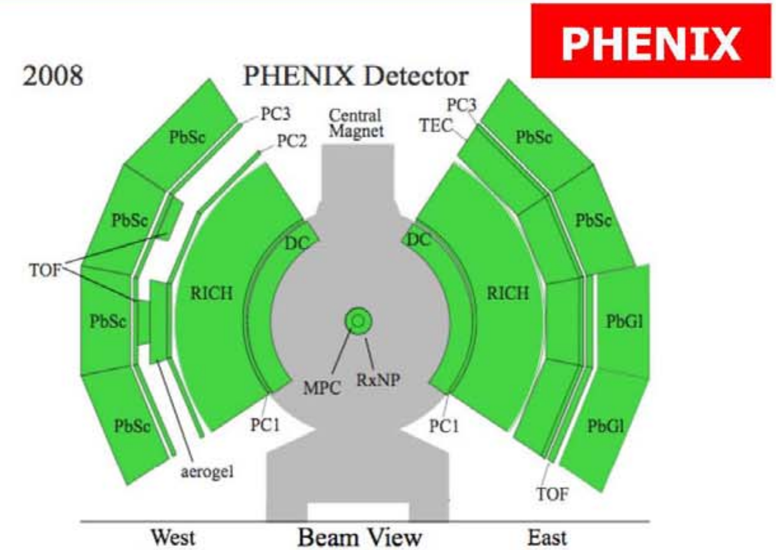
Jlab - CLAS, Hall A





Proton-Proton Scattering Experiments



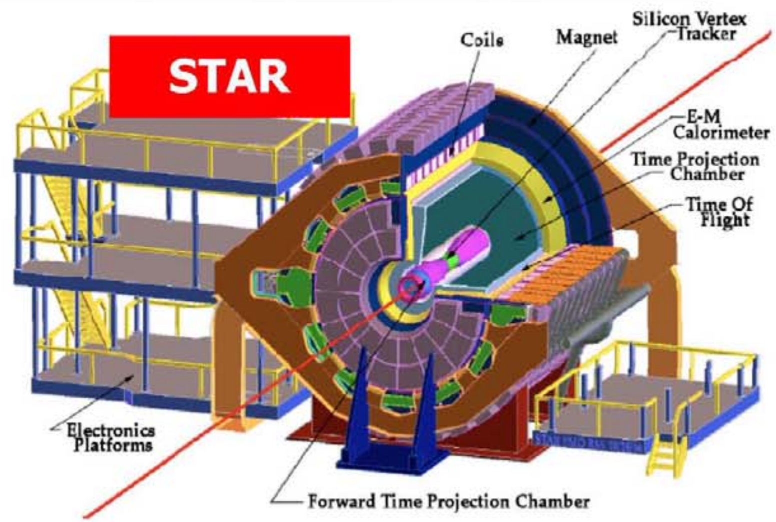


RHIC @ BNL: Proton-Proton

$\sqrt{s}$=200 /500 GeV

~50% polarization

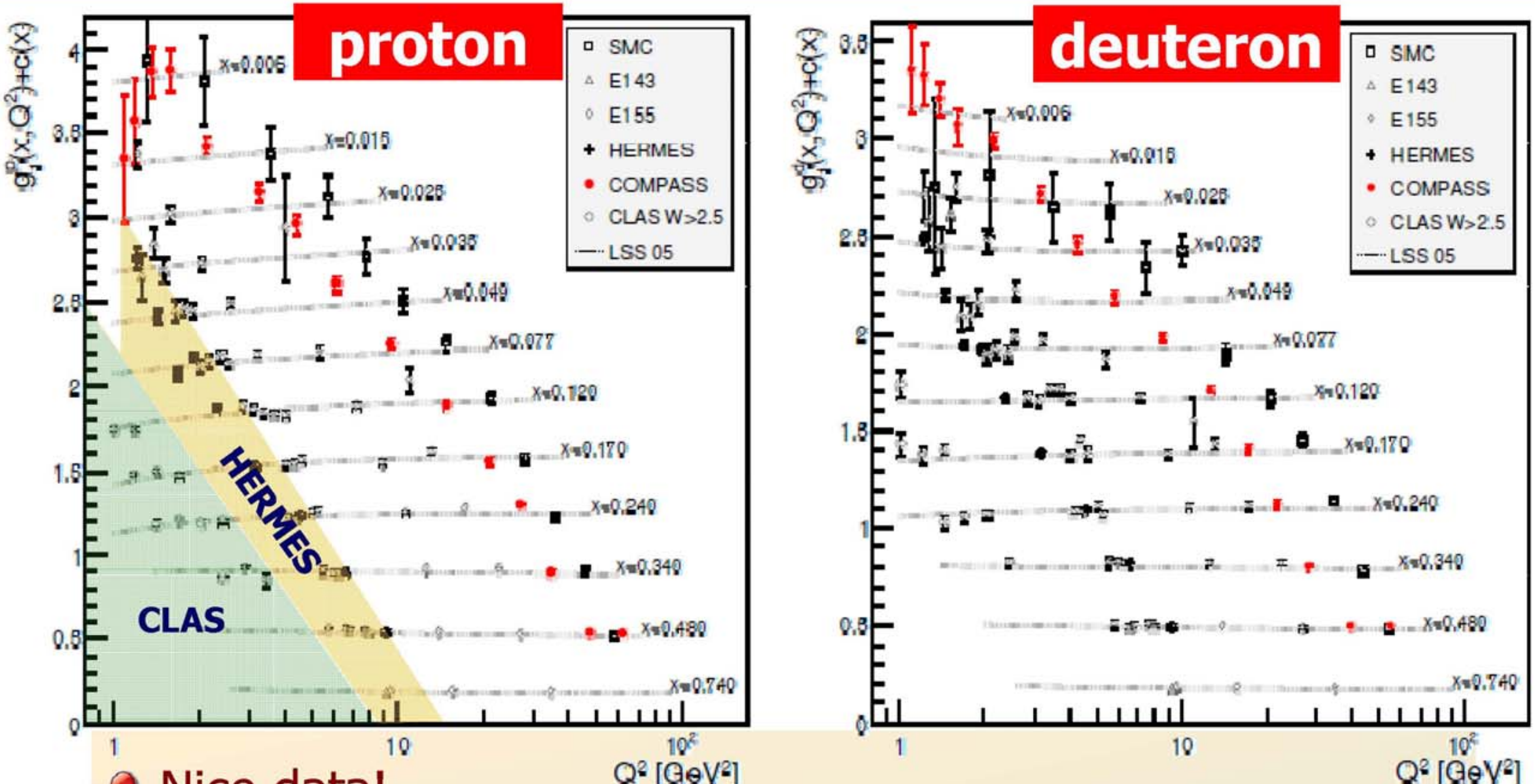
Lumi: L/T 48/18 pb^{-1}



Horst Fischer DIS2010

Talks by Surrow 636, Haggerty 1013

Global NLO QCD Analysis



- Nice data!
- Q^2 dependence of g_1 data described in QCD
- Limited kinematic range (c.f. Collider)

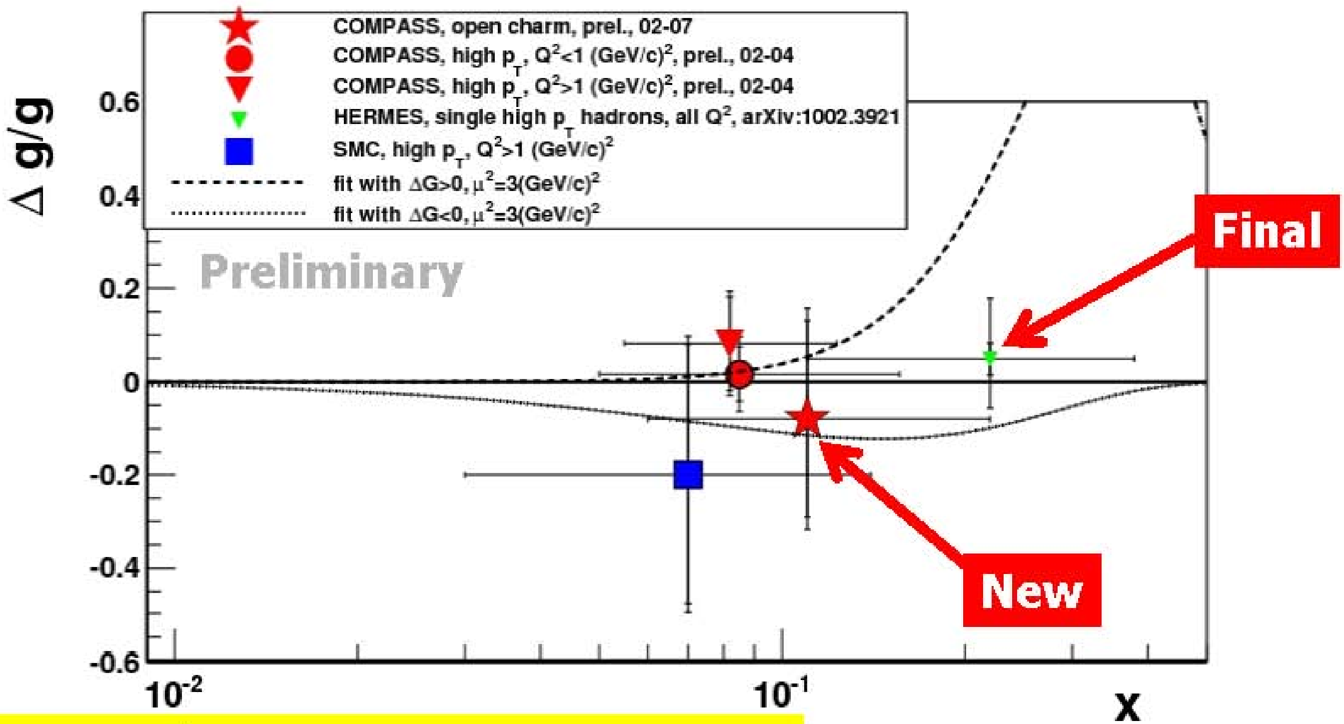
Horst Fischer DIS2010

SLAC and JLab ^{3}He data not shown

See Talk 1193 by F. Kunne

Summary Gluon Polarization

Presently all Analysis in LO only



COMPASS Open Charm:

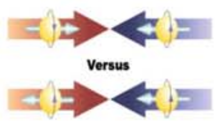
$\Delta G/G$=-0.08+- 0.21(stat) +- 0.11(sys.)
(Systematic error still under investigations)

(Value supersedes previous publication)

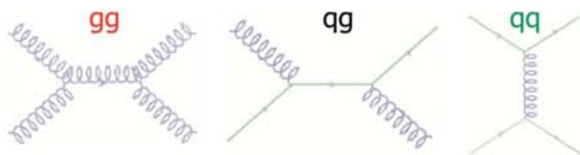
C.Franco

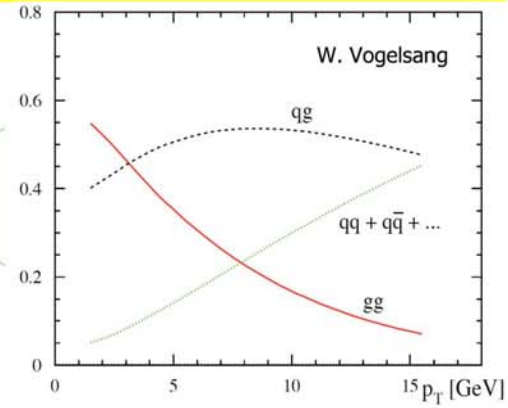
Gluon Polarization from RHIC

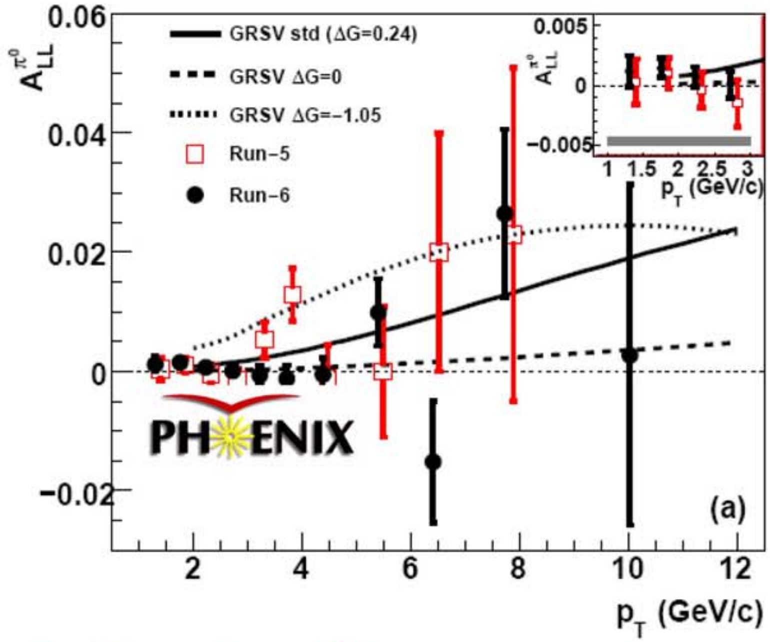
One example from PHENIX & STAR:

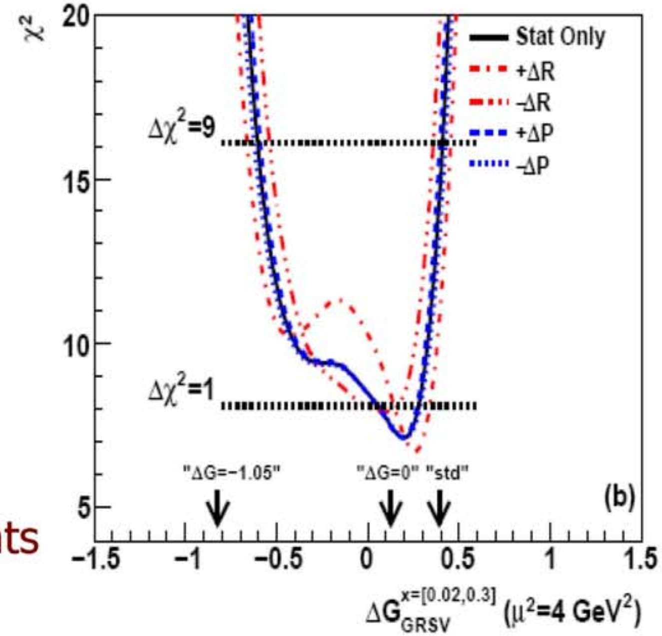


$$p^{\uparrow}p^{\uparrow} \rightarrow \pi^0 X$$







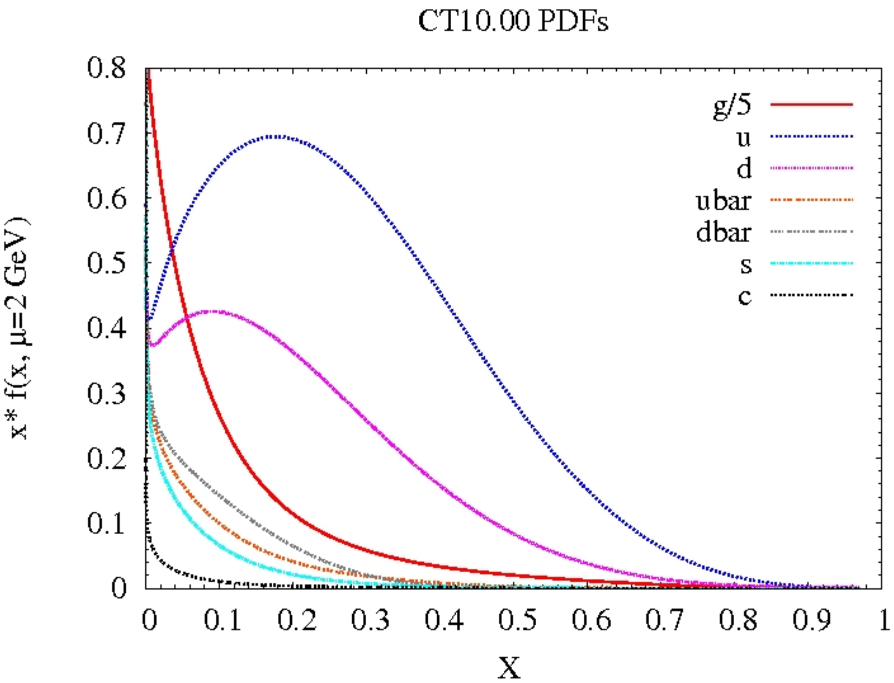


- Confirmation of lepton scattering experiments
- Impact on extraction of $\Delta g(x)$ in QCD-fits

STAR PV SSA results from W production (B. Surrow, Talk 636)

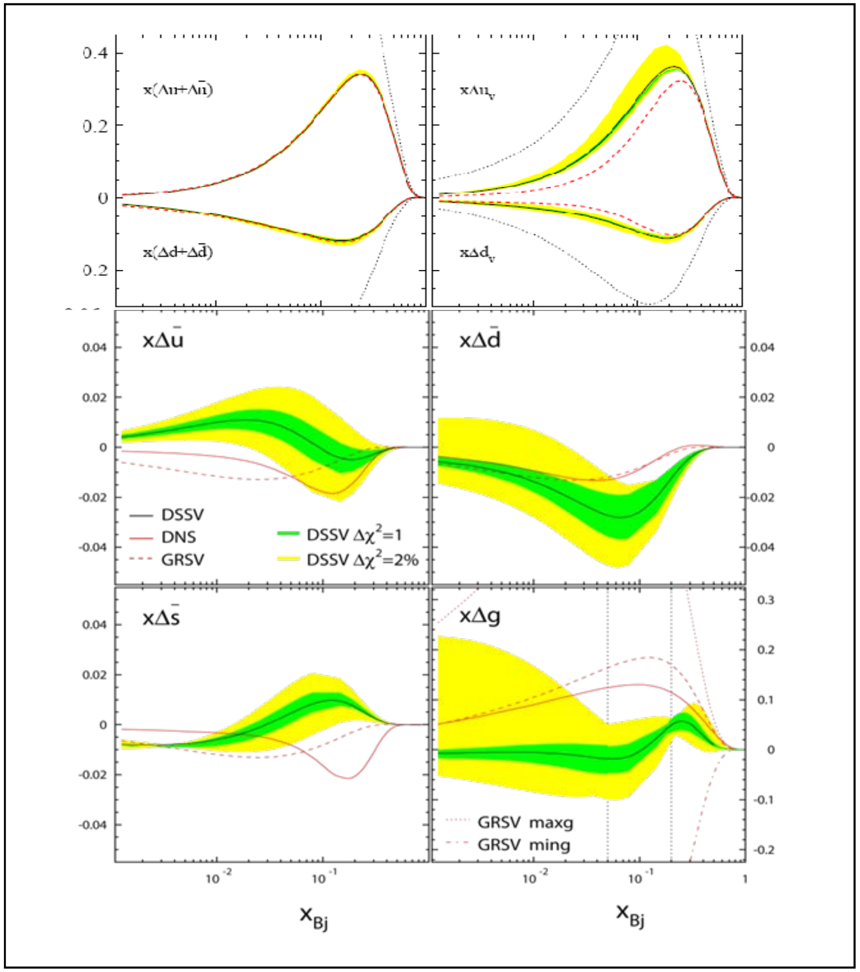
Parton Distributions (CTEQ and DSSV)

Unpolarized PDFs



CTEQ-TEA, H.L. Lai et al, arXiv:1007.2241

Polarized PDFs

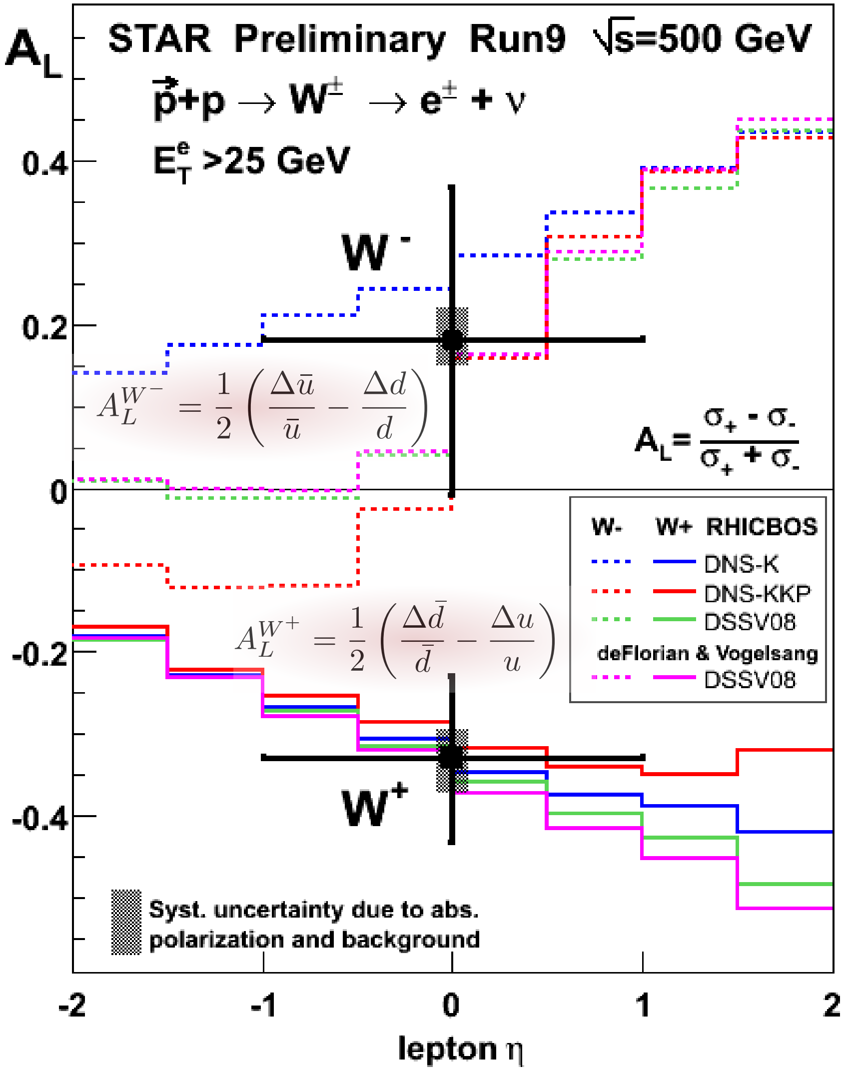


DSSV, PRL101, 072001 (2008)

Stefano Forte Talk 509

W production results: Asymmetry result

- Parity-violating single-spin asymmetry W^+/W^- A_L results



STAR Preliminary Run 9 (p+p √s=500 GeV)

$$A_L(W^+) = -0.33 \pm 0.10(\text{stat.}) \pm 0.04(\text{syst.})$$

$$A_L(W^-) = 0.18 \pm 0.19(\text{stat.}) \, {}^{+0.04}_{-0.03}(\text{syst.})$$

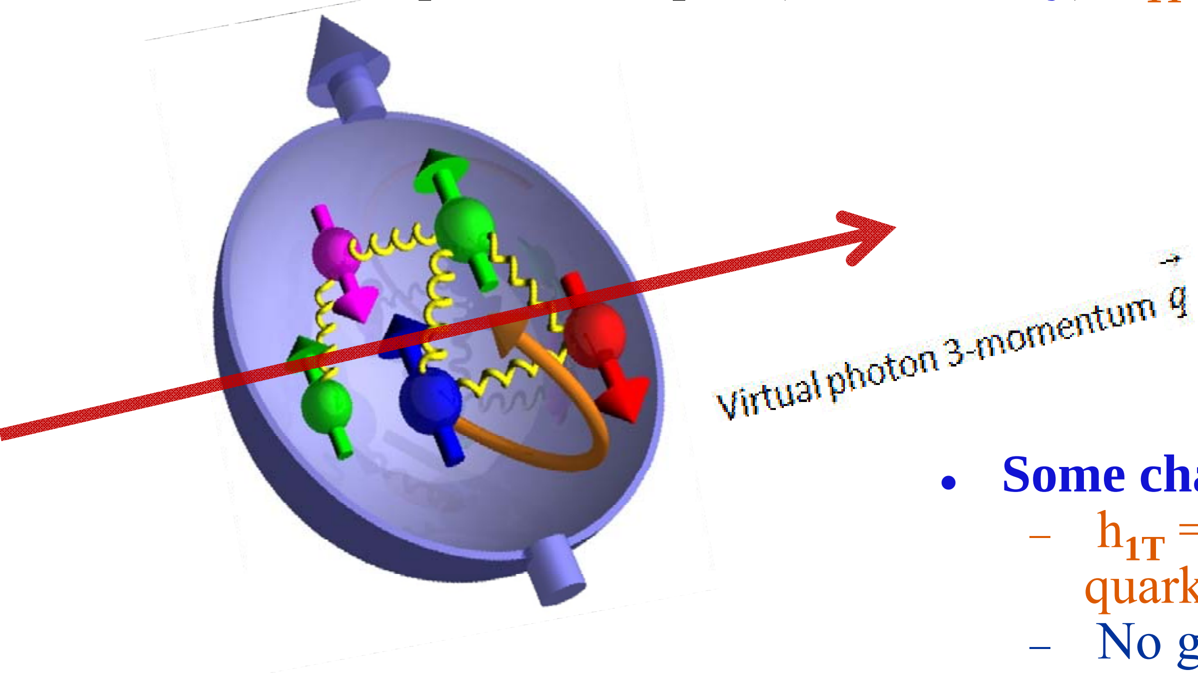
- $A_L(W^+)$ negative with a significance of 3.3σ
- $A_L(W^-)$ central value positive
- Systematic errors of A_L under control
- TPC charge separation works up to $p_T \sim$ 50GeV

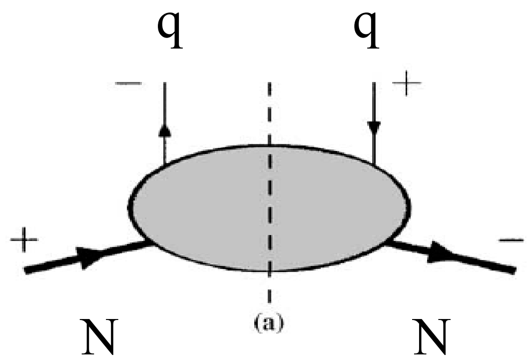
- Measured asymmetries are in agreement with theory evaluations using polarized pdf's (DSSV) constrained by polarized DIS data
  ⇒ Universality of helicity distribution functions!

Transverse Spin Structure

Longitudinal Spin structure function: g_{1L}

Its transverse spin counter part (**Transversity**): h_{1T}





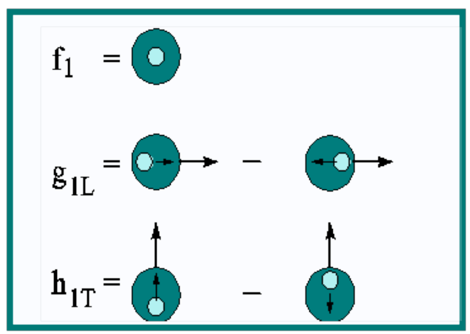
- **Some characteristics of transversity**
  - $h_{1T} = g_{1L}$ for non-relativistic quarks
  - No gluon transversity in nucleon
  - Chiral-odd → difficult to access in inclusive DIS
  - Soffer's bound
    - $|h_{1T}| <= (f_1+g_{1L})/2$

$$\text{Nucleon tensor charge} = \int_{-1}^{1} h_{1T}\,dx$$

Q: how about quark transverse momentum ?
3-D description in momentum space?

Transverse Momentum-dependent parton distributions (TMDs)

At leading twist 8 total, only 3 TMDs non vanishing upon integrating over transverse momentum of the quark



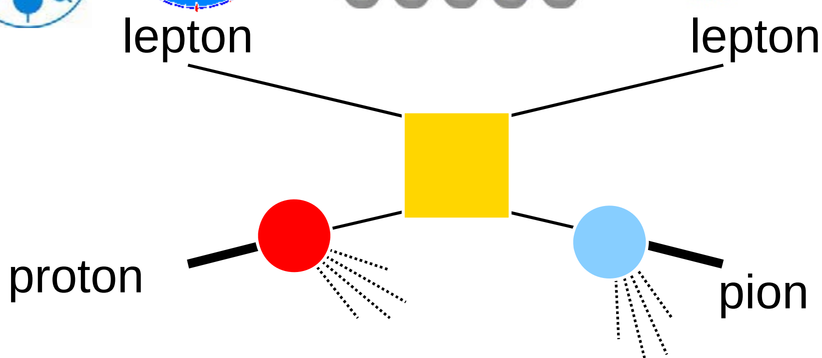
So how to study transversity and other TMDs experimentally?

All Leading Twist TMDs

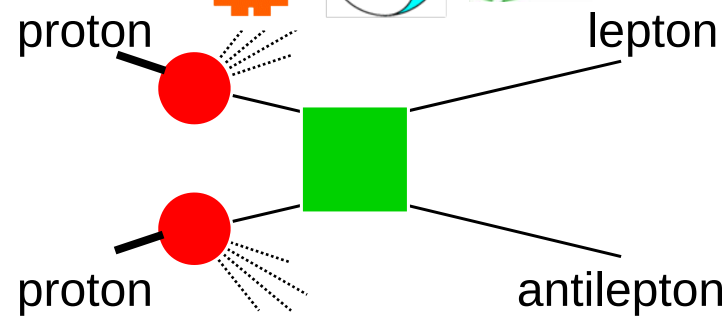
Nucleon
Quark Spin

		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

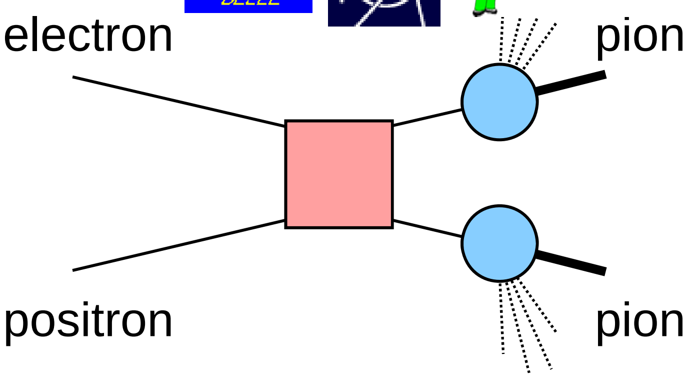
Access TMDs through Hard Processes



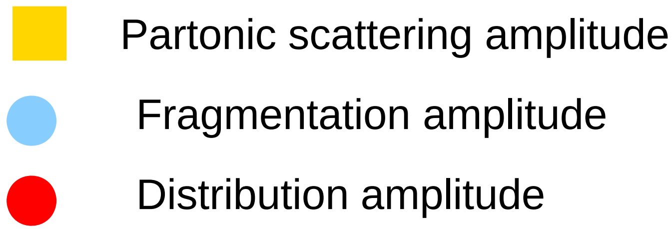
SIDIS



Drell-Yan



$e^{-}e^{+}$ to pions



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

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

Access Parton Distributions through Semi-Inclusive DIS

$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\cdot$$

$$\{F_{UU,T} + \ldots$$

$$+\varepsilon\cos(2\phi_h)\cdot F_{UU}^{\cos(2\phi_h)} + \ldots$$

Unpolarized

$$+S_L[\varepsilon\sin(2\phi_h)\cdot F_{UL}^{\sin(2\phi_h)} + \ldots]$$

$$+S_T[\varepsilon\sin(\phi_h+\phi_S)\cdot F_{UT}^{\sin(\phi_h+\phi_S)}$$

$$+\sin(\phi_h-\phi_S)\cdot(F_{UL}^{\sin(\phi_h-\phi_S)} + \ldots)$$

$$+\varepsilon\sin(3\phi_h-\phi_S)\cdot F_{UT}^{\sin(3\phi_h-\phi_S)} + \ldots]$$

Polarized Target

$$+S_L\lambda_e[\sqrt{1-\varepsilon^2}\cdot F_{LL} + \ldots]$$

$$+S_T\lambda_e[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\cdot F_{LT}^{\cos(\phi_h-\phi_S)} + \ldots]\}$$

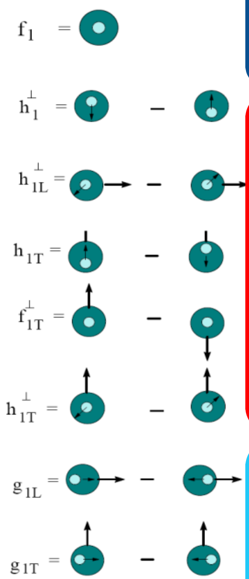
Polarized Beam and Target

Boer-Mulder

Transversity

Sivers

Pretzelosity



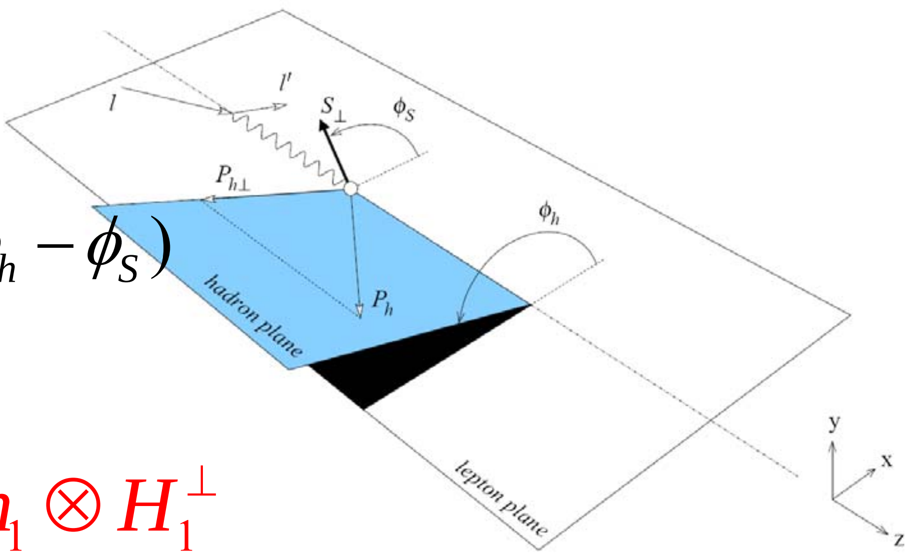
S_L, S_T: Target Polarization; λ_e: Beam Polarization

Separation of Collins, Sivers and pretzelocity effects through angular dependence

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

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

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



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

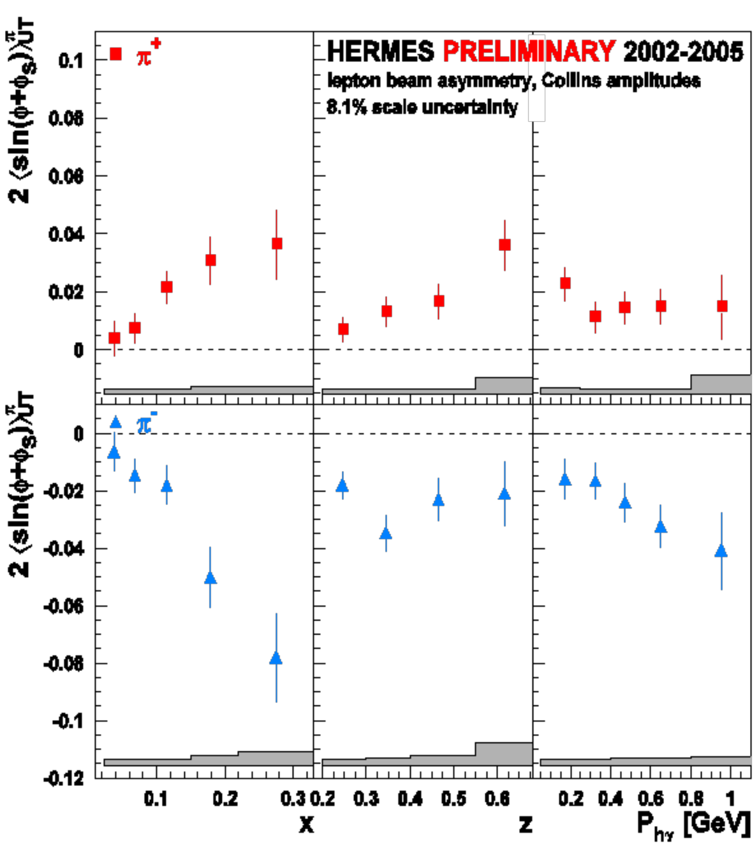
$$A_{UT}^{Sivers} \propto \left\langle \sin(\phi_h - \phi_S) \right\rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

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

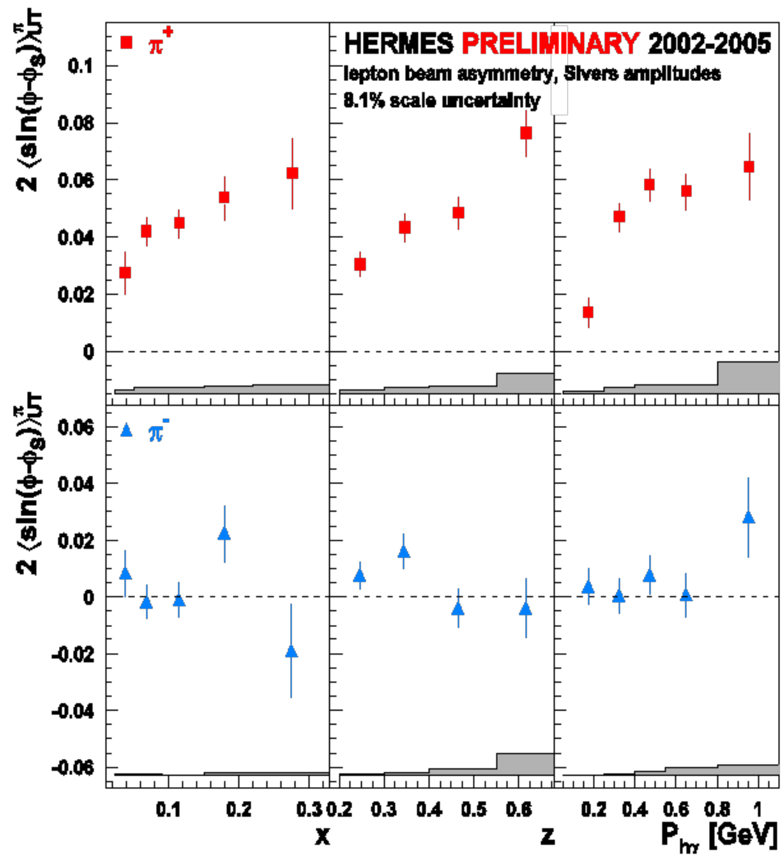
SIDIS SSAs depend on 4-D variables (x, Q^2, z and P_T)
Large angular coverage and precision measurement of asymmetries in 4-D phase space is essential.

$A_{UT}^{\sin(\phi)}$ from transv. pol. H target

`Collins' moments



`Sivers' moments



- Non-zero Collins asymmetry
- Assume $\delta q(x)$ from model, then

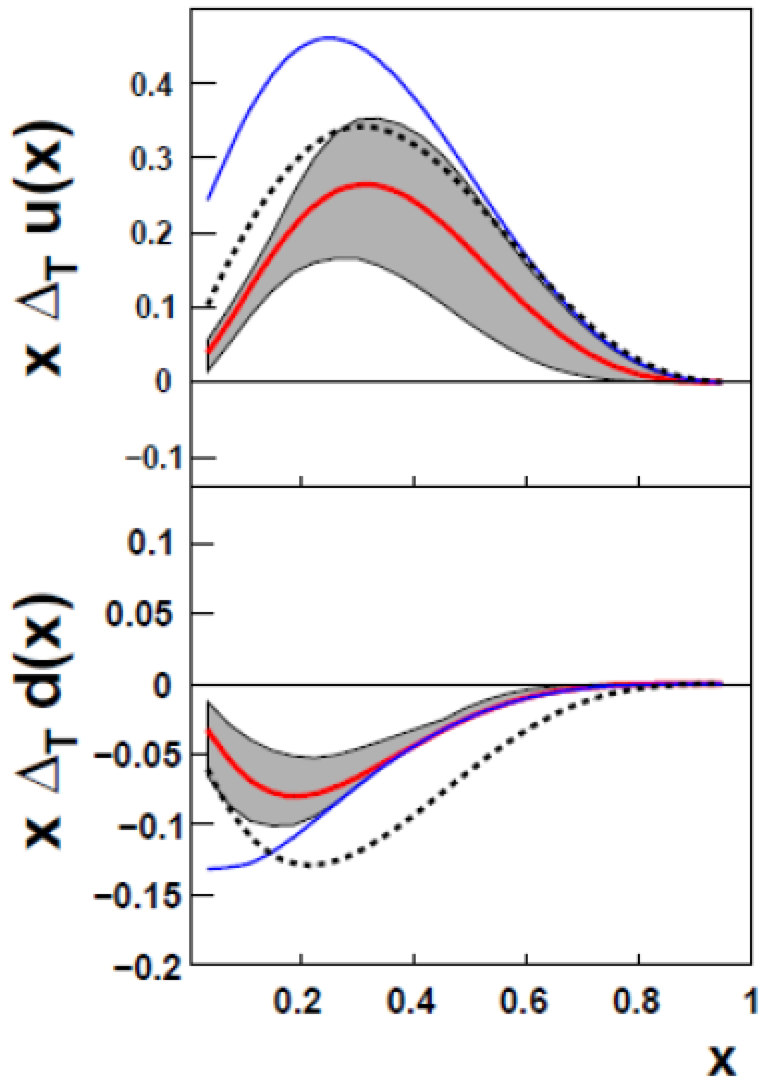
  H_1_unfav ~ -H_1_fav
- H_1 from Belle (arXiv:0805:2975)

- Sivers function nonzero (π^+)$\rightarrow$ orbital angular momentum of quarks
- Regular flagmentation functions

Klaus Rith , Talk 1194

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

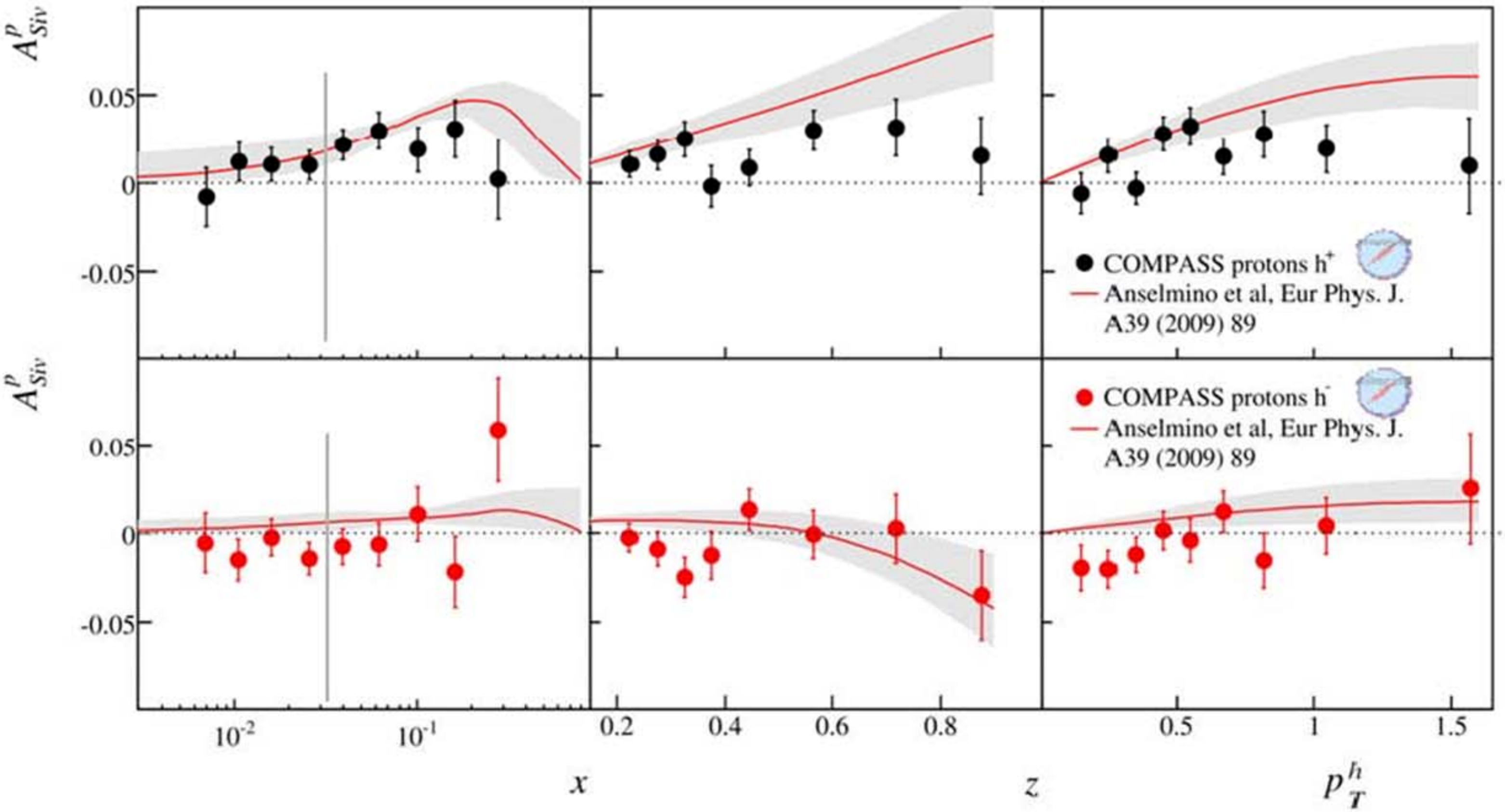
$$\Delta_T = h_{1T}$$

A. Prokudin, Talk 1059

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

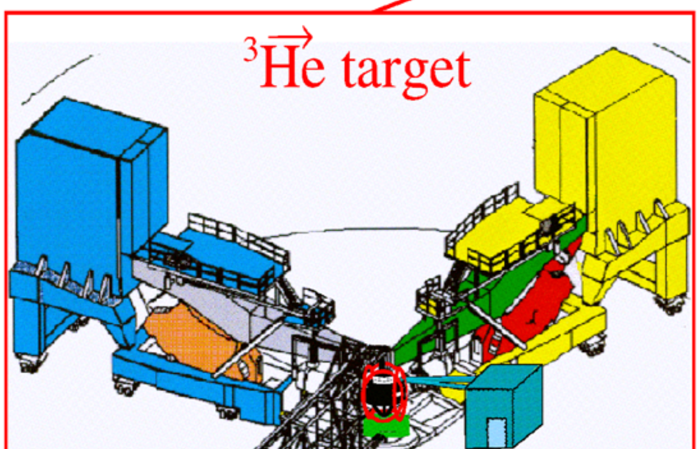


See Talk 1193 by F. Kunne

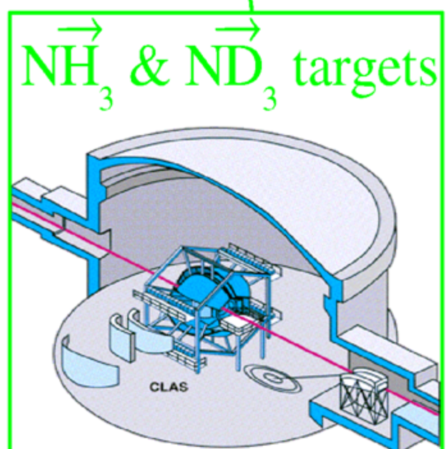
Jefferson Lab Experimental Halls

6 GeV polarized
CW electron beam
Pol=85%, 180μA

Will be upgraded to 12 GeV by ~2014 with a new Hall D



HallA: two HRS'

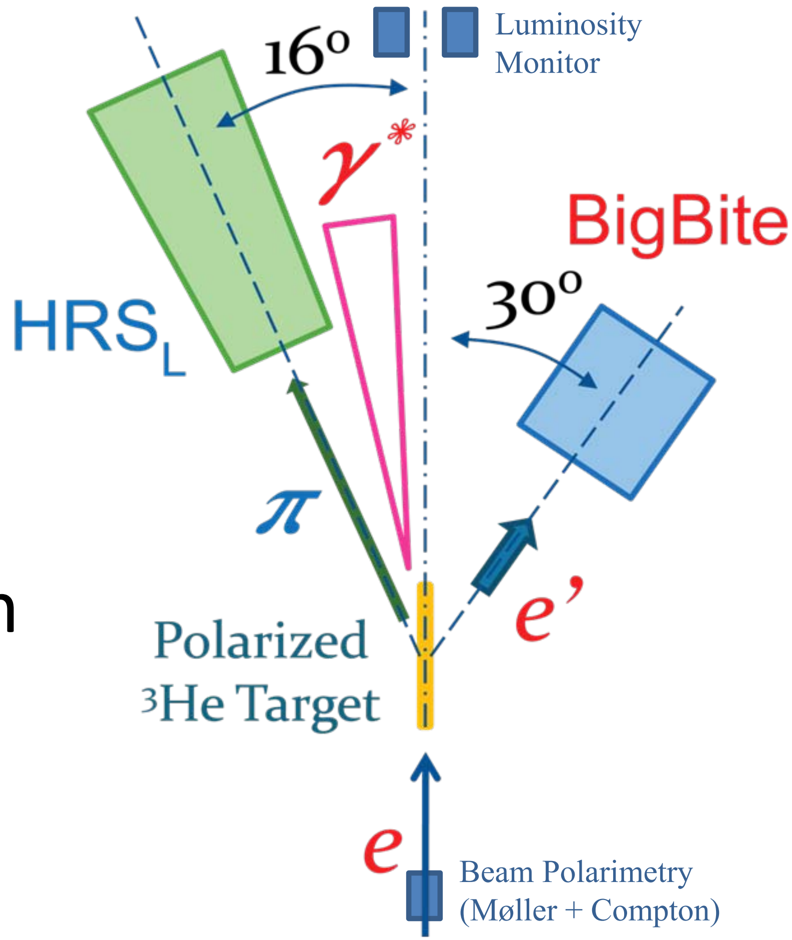


Hall B:CLAS

Hall C: HMS+SOS

JLab E06-010 Experiment

- Polarized ^{3}He Target, > 60% with beam, world record
- Polarized Electron Beam
  - ~80% Polarization
  - Fast Flipping at 30Hz
  - PPM Level Charge Asymmetry controlled by online feed back
- BigBite at 30º as Electron Arm
  - P_e = 0.7 ~ 2.2 GeV/c
- HRS_L at 16º as Hadron Arm
  - P_h = 2.35 GeV/c

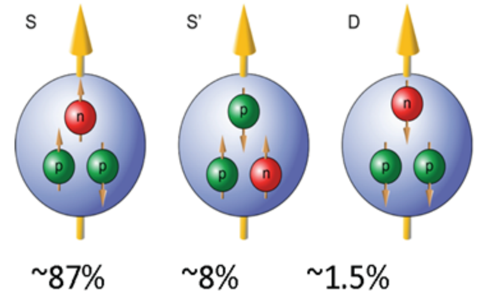


6 GeV Preliminary Results

^{3}He Target Single-Spin Asymmetry in SIDIS: JLab E06-010

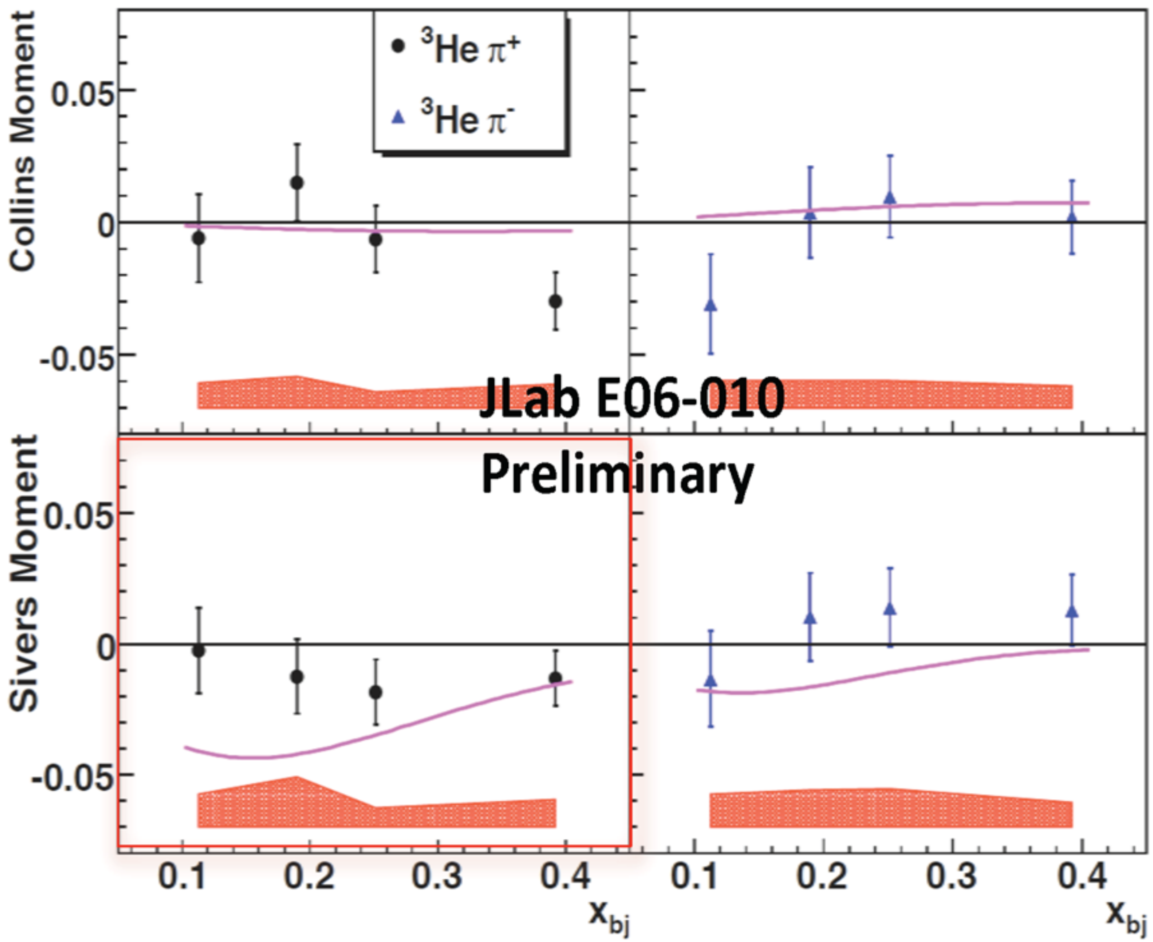
$$^3\mathrm{He}^{\uparrow}(e, e'h)$$

$$h = \pi^{+/-}, K^{+/-}$$



To extract information on neutron, one would assume:

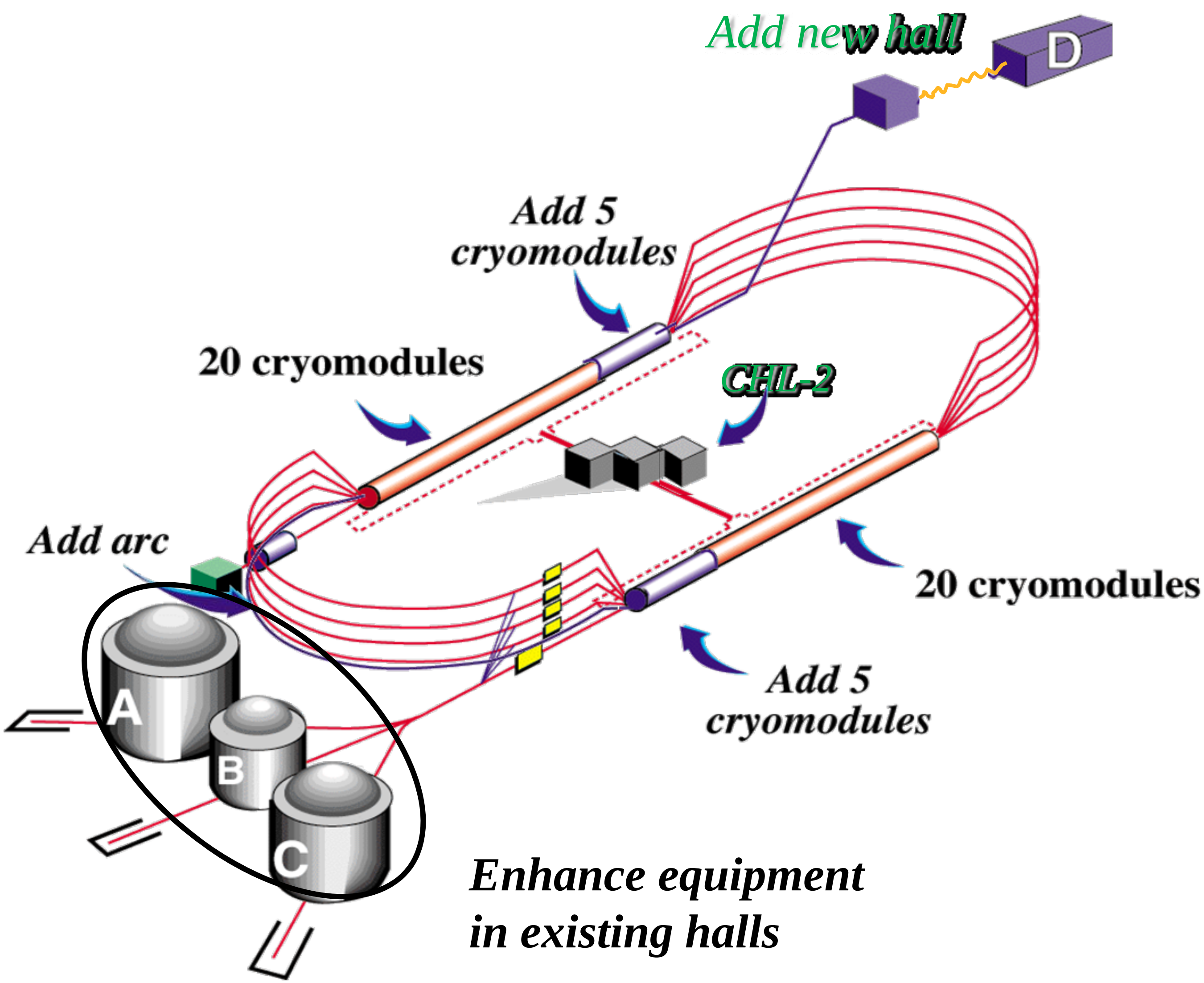
$$^3\mathrm{He}^{\uparrow} = 0.865 \cdot \mathrm{n}^{\uparrow} - 2 \times 0.028 \cdot \mathrm{p}^{\uparrow}$$



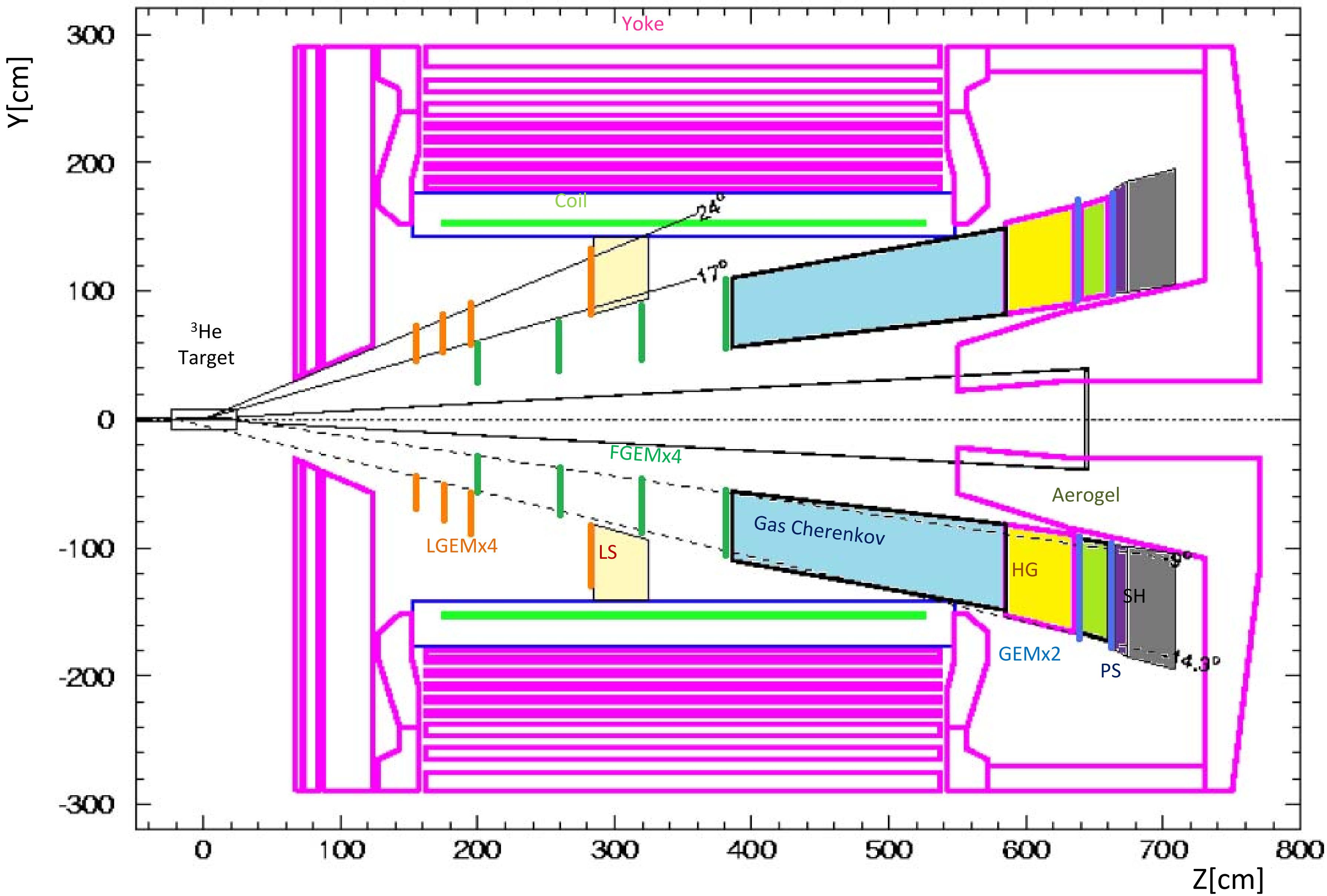
^{3}He Collins SSA are not large (as expected).

^{3}He Sivers SSA are smaller than expected (Vogelsong and Yuan 2006), follow the trend of Anselmino et al. 2009.

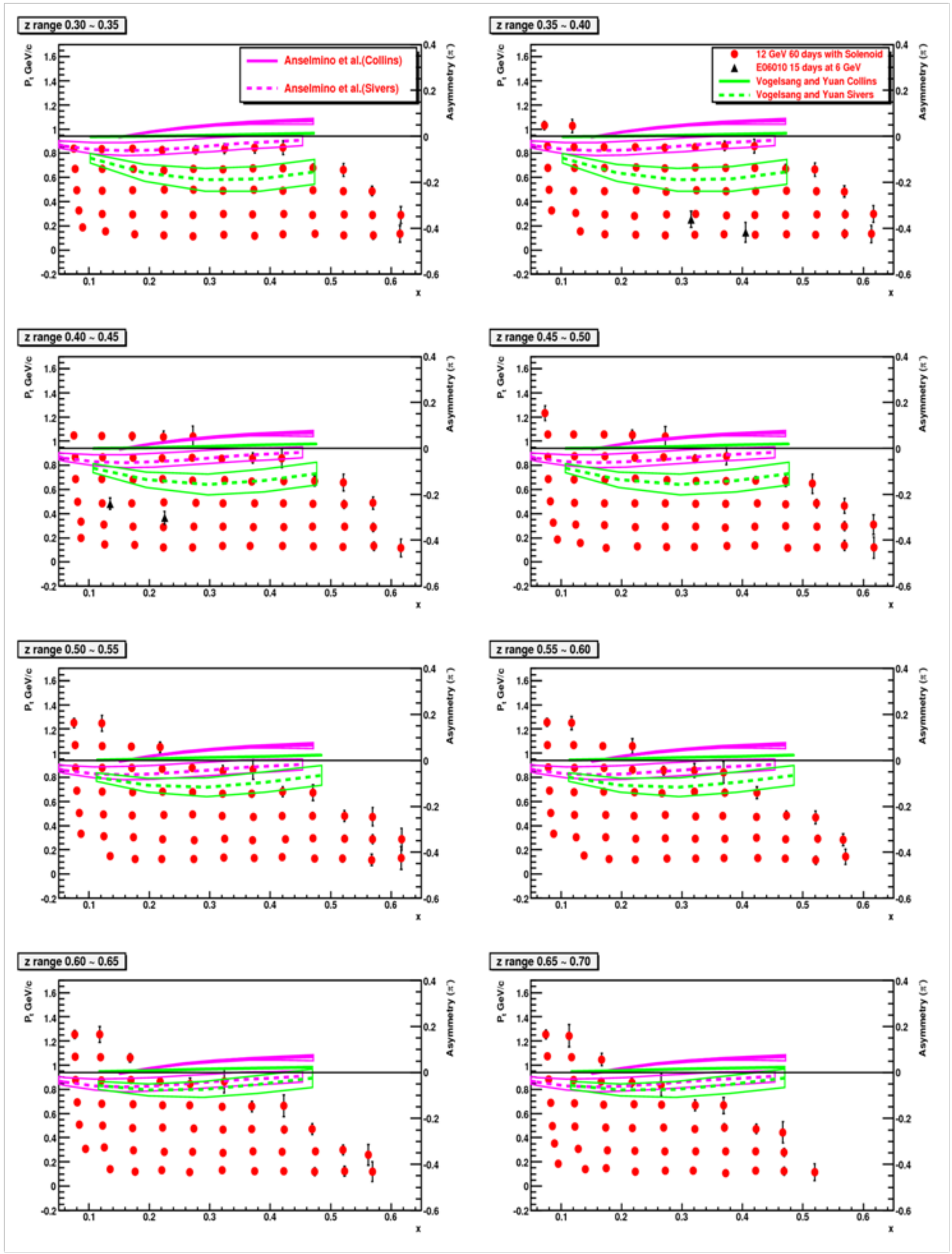
JLab Upgrade to 12 GeV

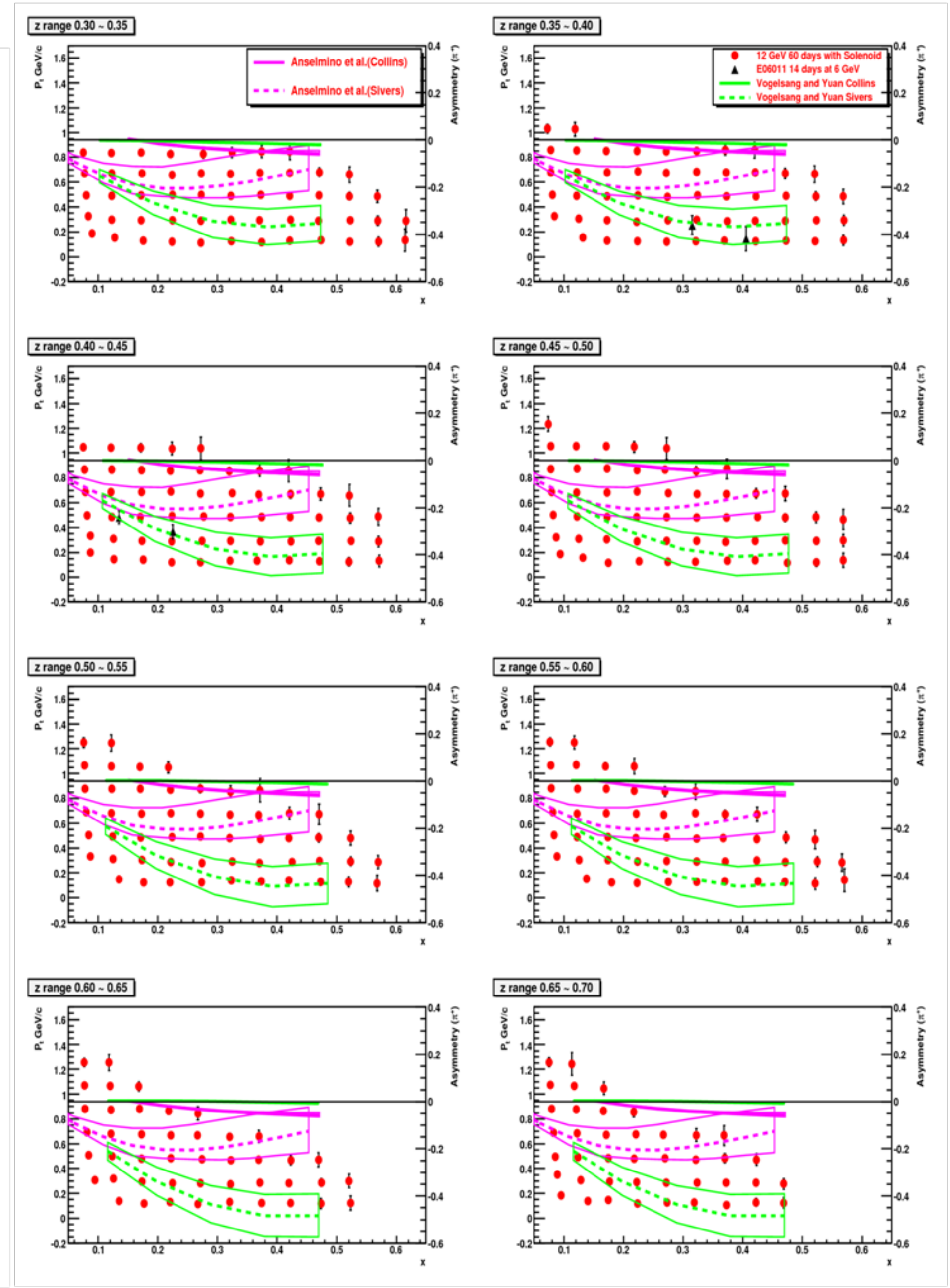


Solenoid detector for SIDIS at 11 GeV
Experiment E12-10-006



Power of SOLID

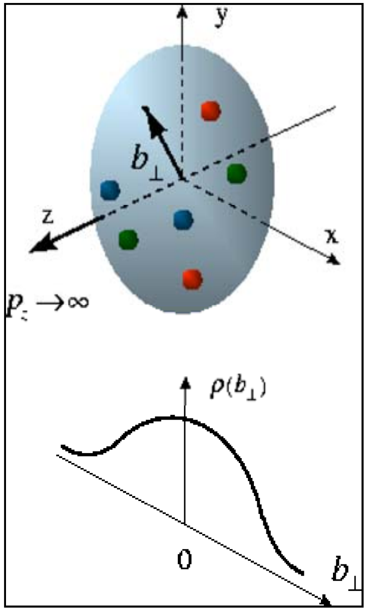




Generalized Parton Distributions (GPDs)

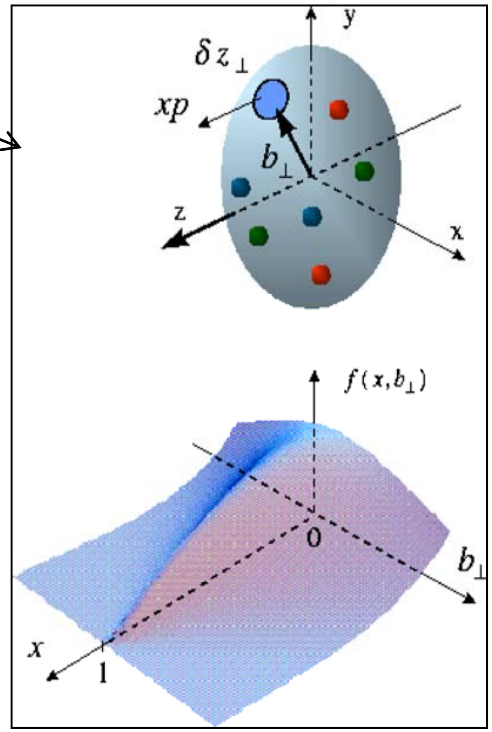
D. Mueller, X. Ji, A. Radyushkin, A. Belitsky,

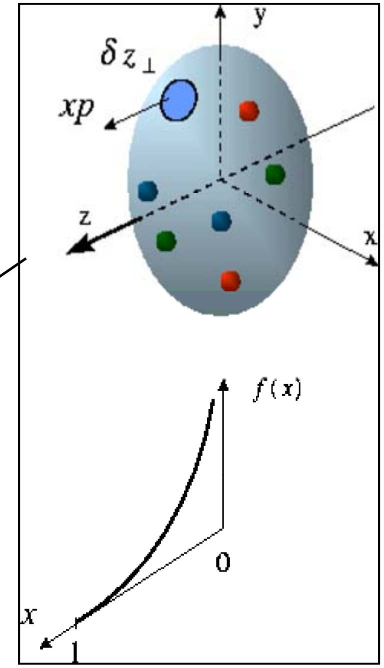
GPDs connect the charge and parton distribution



The size and structure of proton.
transverse

Nobel prize 1961- R. Hofstadter





Internal constituents of the nucleon
longitudinal

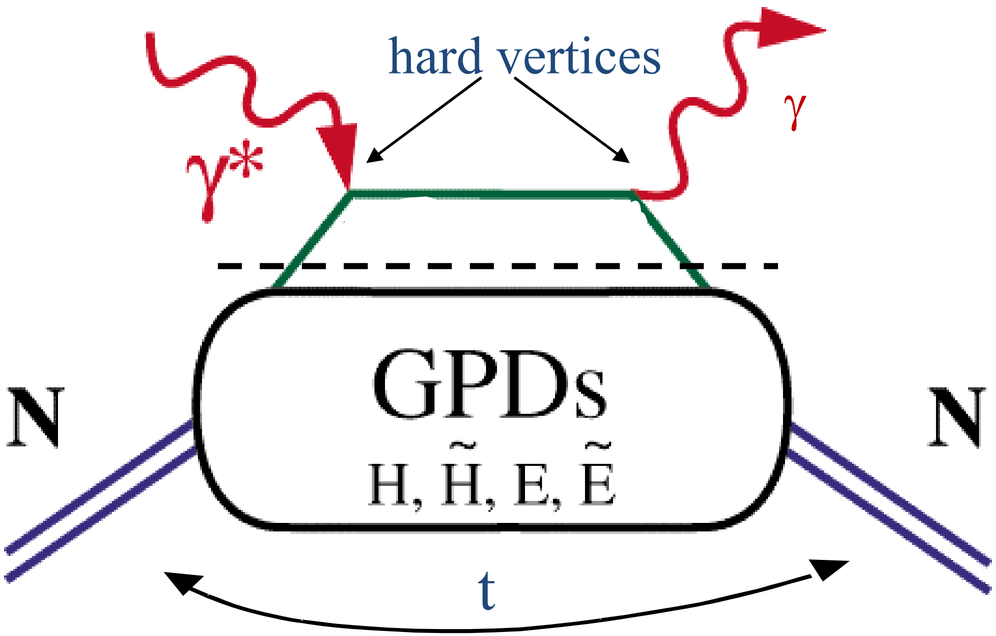
Nobel prize 1990 - J. Friedman, H. Kendall, R. Taylor

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

Next talk by Dieter Mueller, Talk 228 (M, Guidal), Talk 1116 (V. Kubarovsky)
K. Rith , Talk 1194 on HERMES GPD program

3 dimensional imaging of the nucleon

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



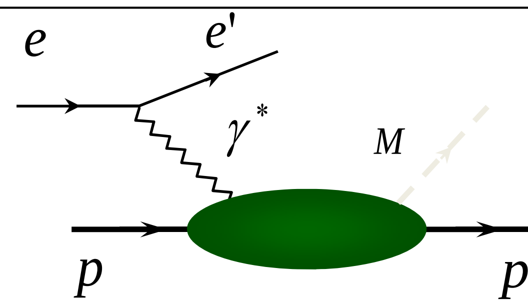
x – longitudinal quark momentum fraction

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.

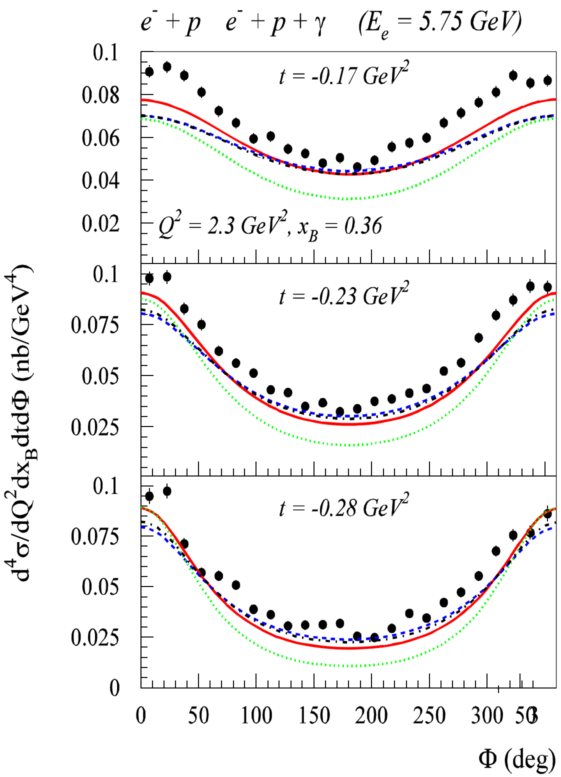
- **Hard exclusive meson productions (quark flavor filter) access GPDs**



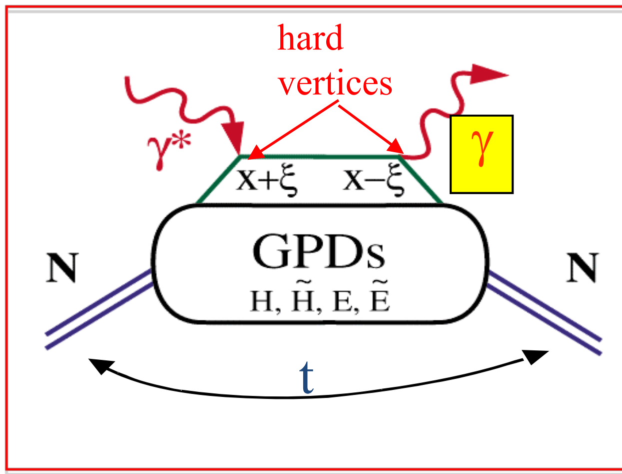
Deeply Virtual Compton Scattering & GPDs

Unprecedented set of Deeply Virtual Compton Scattering data accumulated in Hall A and with *CLAS in Hall B at JLab*

Hall A



Phys.Rev.Lett.97:262002,2006



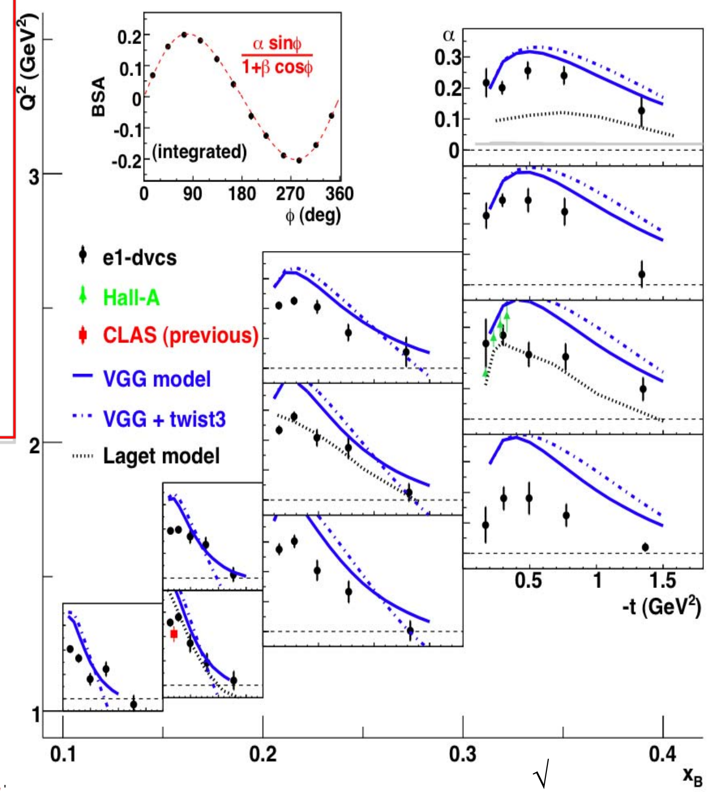
$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma_{LU}}{2\sigma}$$

Polarized beam, unpolarized target:

Kinematically suppressed

$$\Delta\sigma_{LU} \sim \sin\phi\{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}d\phi$$

CLAS

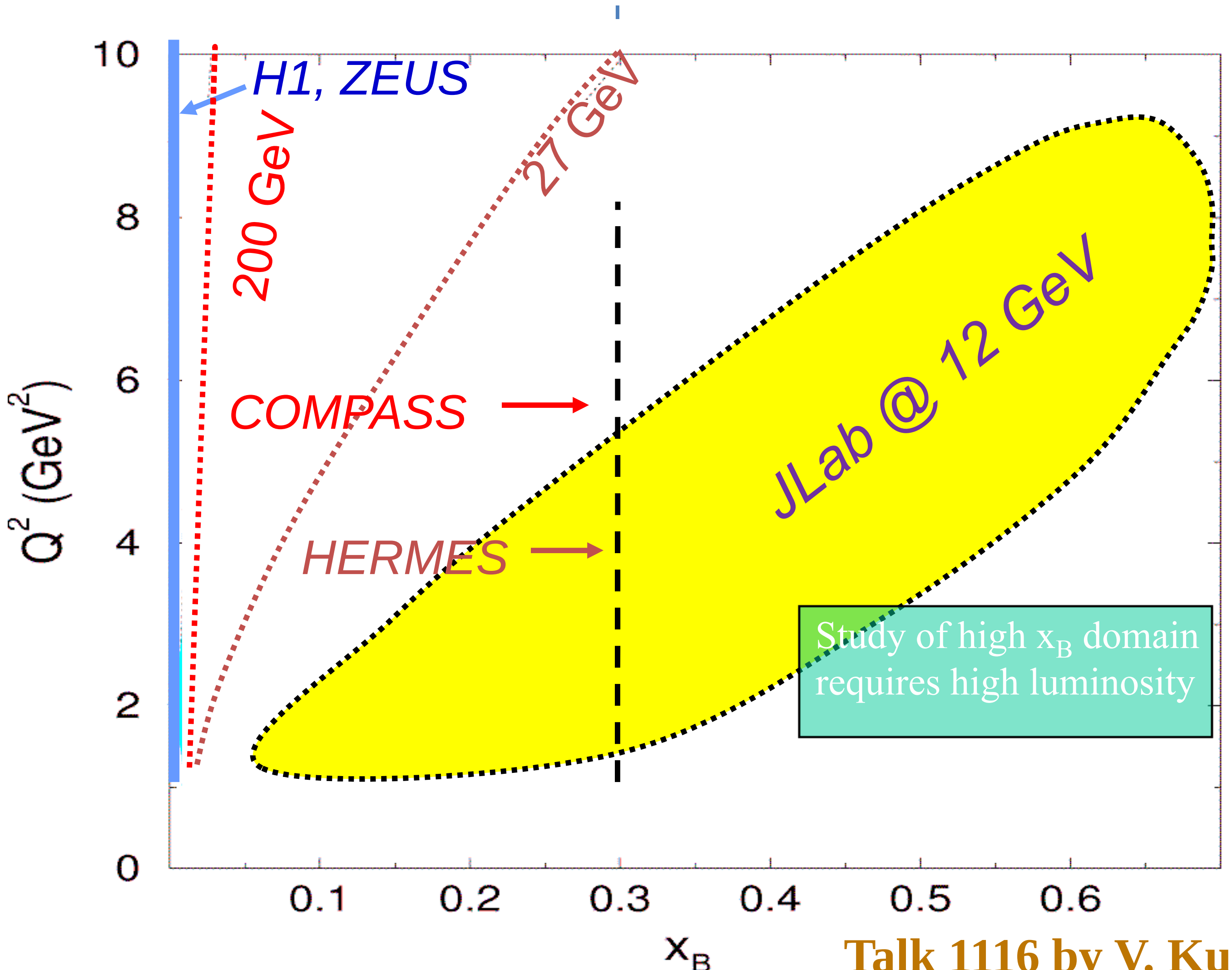


Phys.Rev.Lett.100:162002,2008

Model independent extraction of GPDs Talk 228: M. Guidal

Talk 1194 (K. Rith) on HERMES DVCS

Virtual Exclusive Processes - Kinematics Coverage of the 12 GeV Upgrade



Talk 1116 by V. Kubarovsky

At 12 GeV, CEBAF will be ideal for GPD studies using CLAS12

COMPASS II, Talk 1193 F. Kunne

Summary

- Major progress made in unpolarized and polarized structure functions
- Frontiers in nucleon structure go beyond colinear, 1-D picture
  - three-dimensional imaging of the nucleon through GPDs, revealing hidden aspects of its internal dynamics
  - TMDs
    - Direct link with orbital motion (orbital angular momentum)
    - Transverse motion: spin-orbit correlations, multi-parton correlations, dynamics of confinement and QCD
- JLab 12-GeV upgrade and COMPASS II will provide excellent opportunities to map out the 3-dimensional structure of the nucleon

Thanks to Jian-Ping Chen, Latifa Elouadrhiri, Horst Fischer, Achim Geiser, Michel Guidal, M, Huang, K. Krueger, Anna Martin, Dieter Mueller, X. Qian, Emmanuel Sauvan, Bernd Surrow, C.-P. Yuan,…

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