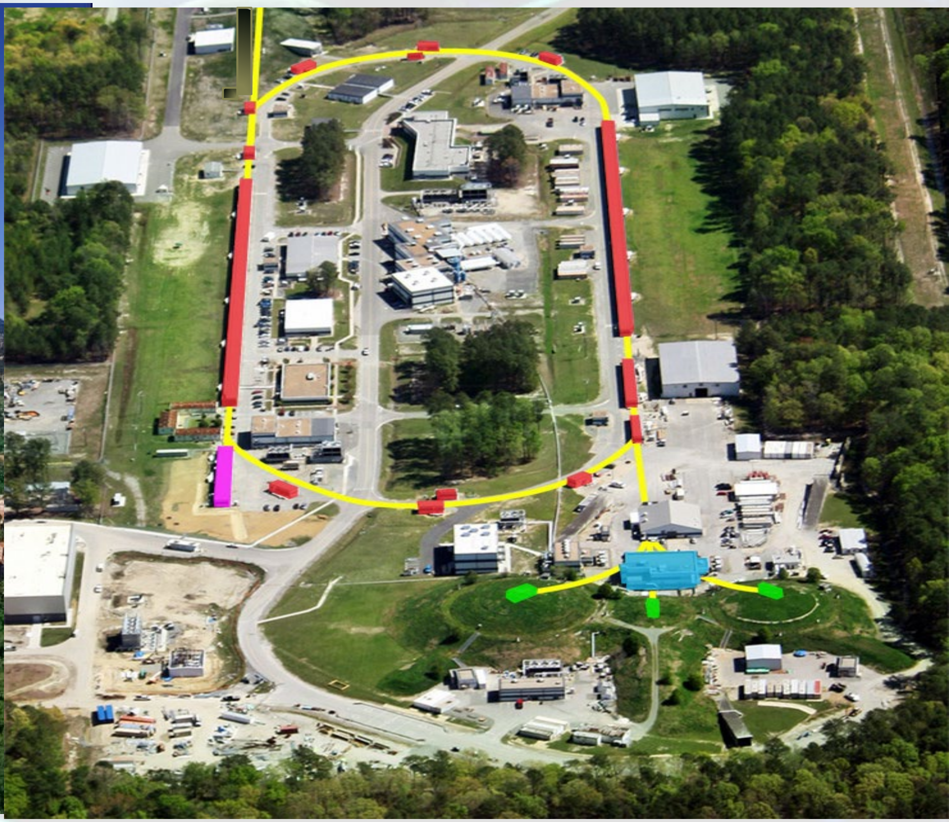
Nuclear Physics at Jefferson Lab - III

Thia Keppel

National Nuclear Physics Summer School



University of Colorado at Boulder

July 2017

Jefferson Lab

Thomas Jefferson National Accelerator Facility

Lecture Scheme

DAYS 1 - 2

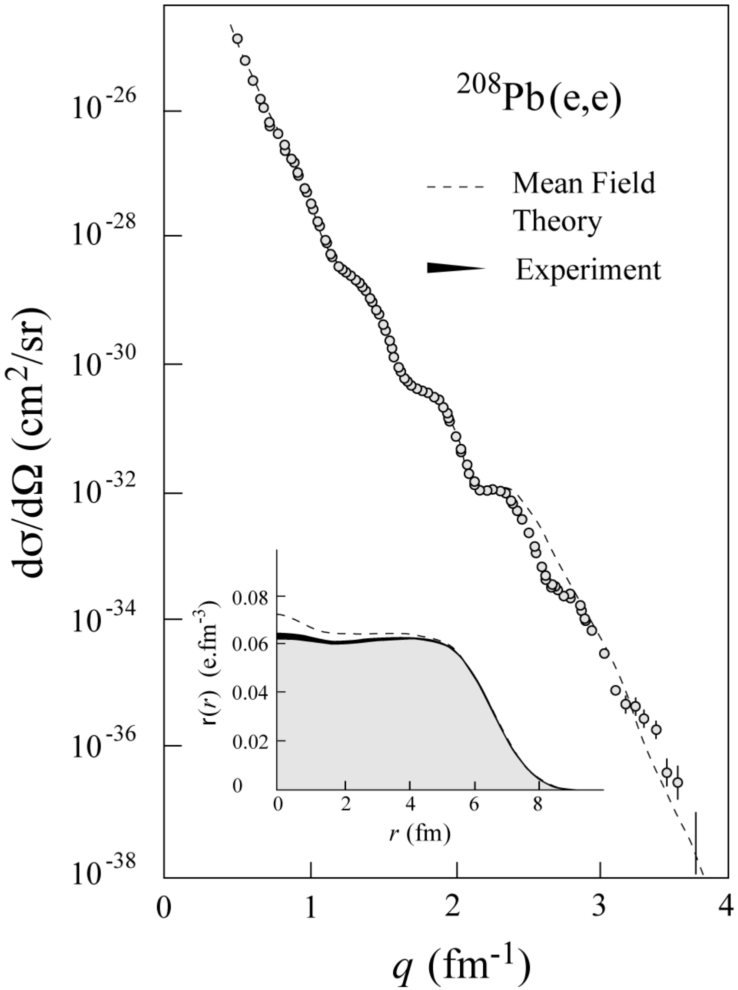
- ✓ History and Basics of Electron Scattering
  - *Form Factors*
  - *Structure Functions*
  - *Parton Distribution Functions*
- ✓ Jefferson Lab
- ✓ 1D Nucleon Structure

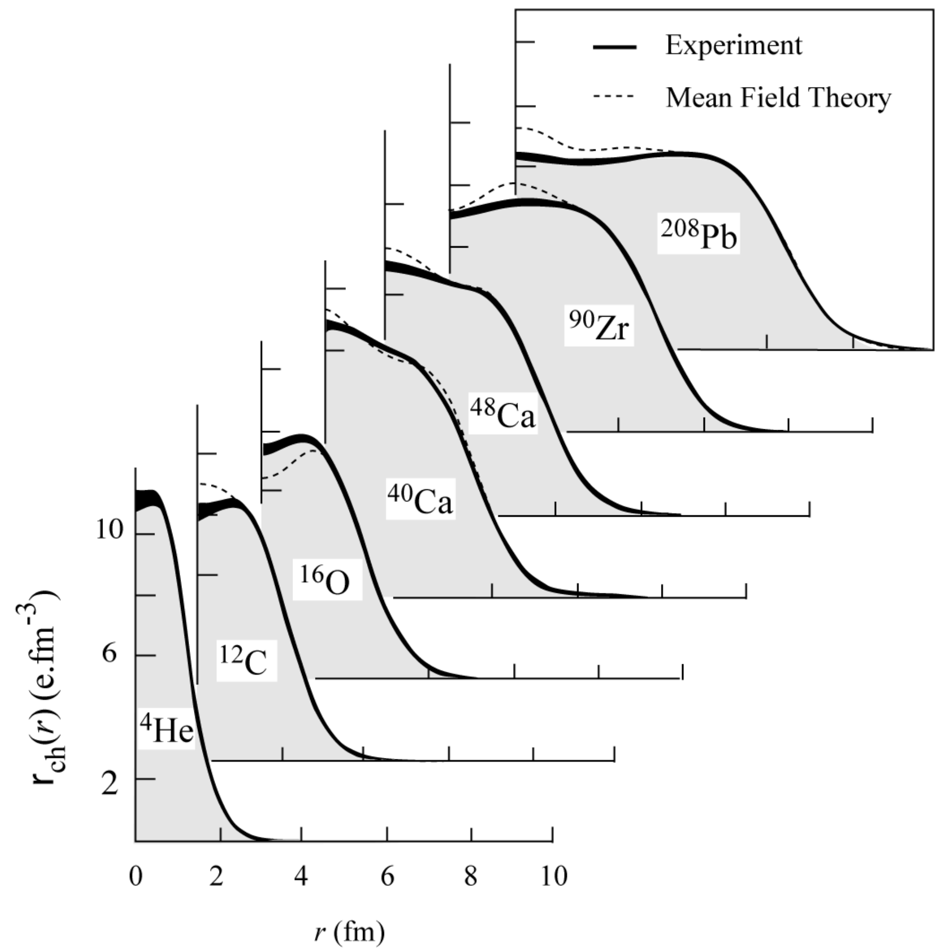
DAYS 2 - 3

- Nucleons in the Nuclear Medium
- 3D Nucleon Structure
- *Other topics*
  - *Polarization*
  - *Meson Photoproduction*
  - *Parity Violating Electron Scattering*

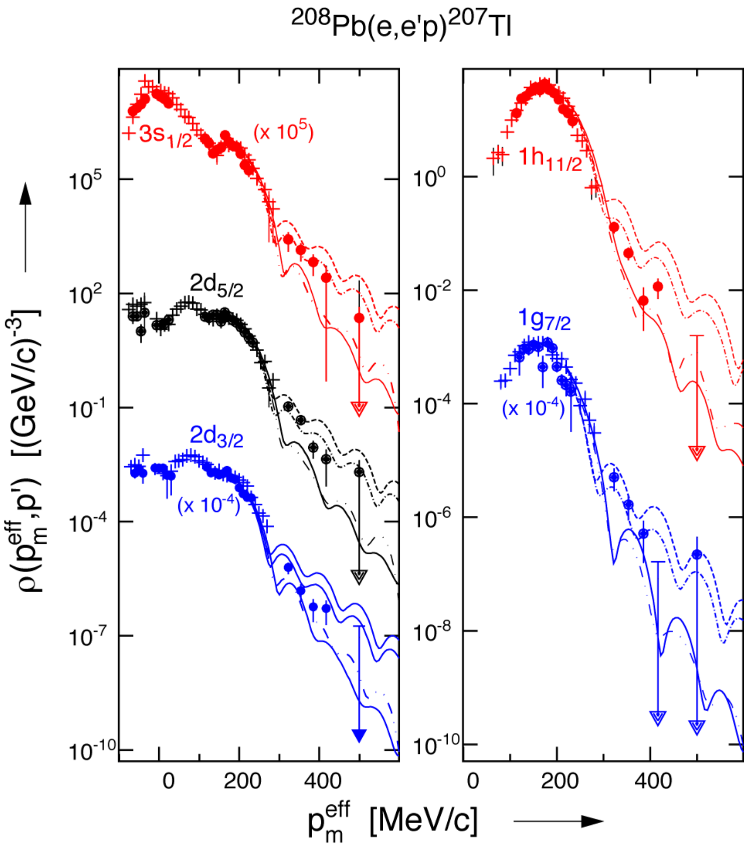
Electron Scattering – historical example

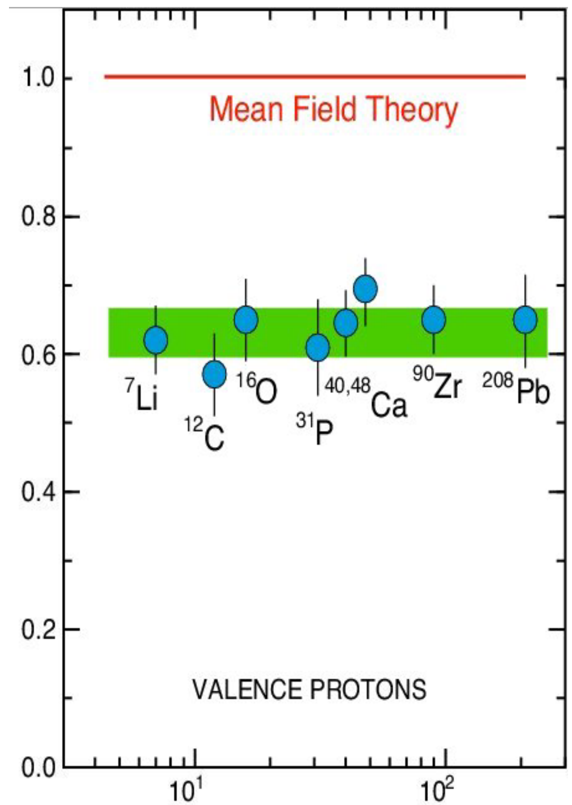
Elastic Scattering → Charge Distributions





The Classic A(e,e'p)A-1 Problem



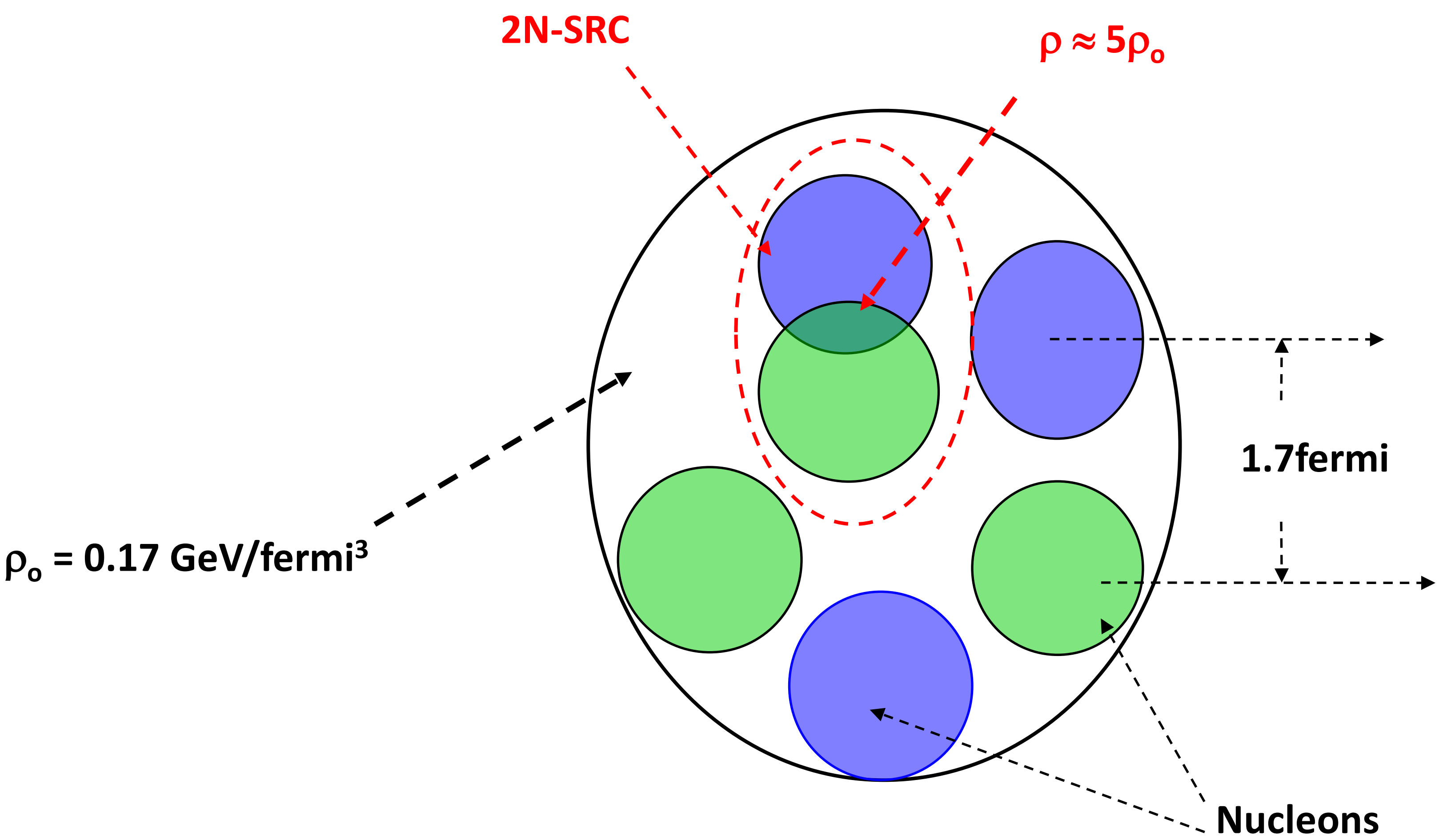


Target Mass

Independent-Particle Shell-Model is based upon the assumption that each nucleon moves independently in an average potential (mean field) induced by the surrounding nucleons

The (e,e'p) data for knockout of valence and deeply bound orbits in nuclei gives spectroscopic factors that are 60 – 70% of the mean field prediction.

Possible Answer: *Short-Range Correlations*



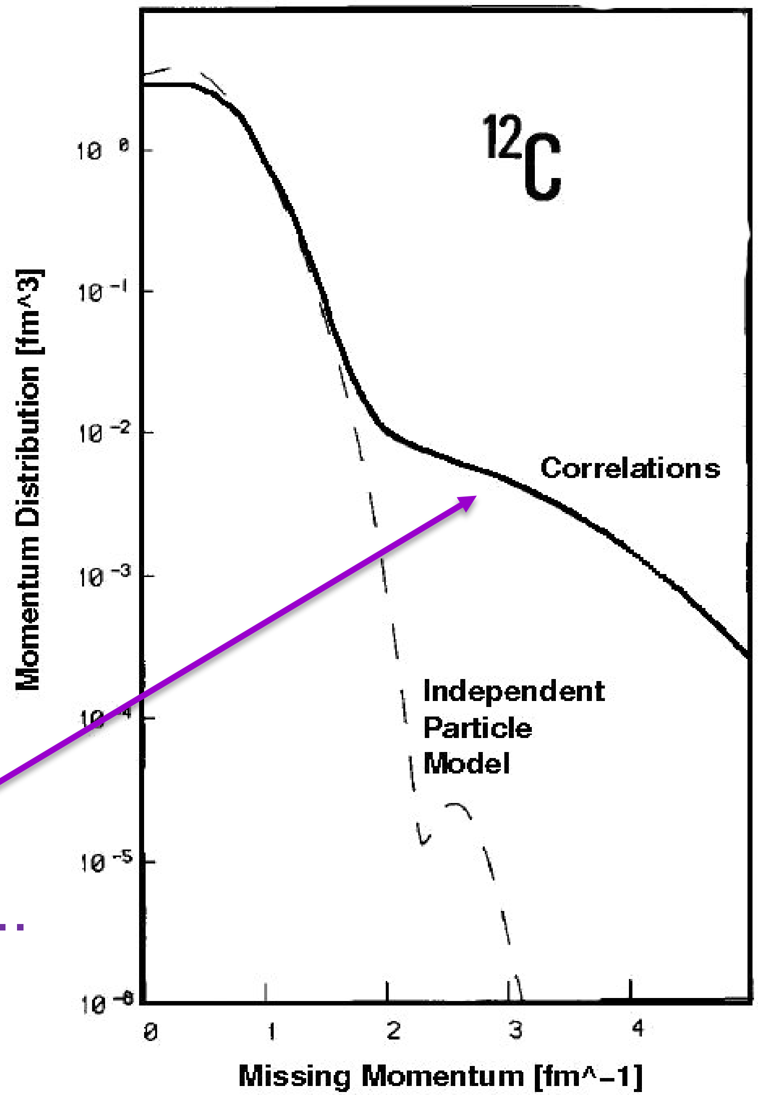
Nucleons are made up of Quarks, so does NOT violate Pauli exclusion principle

If Correct Raises More Questions

- What fraction of the momentum distribution is due to 2N-SRC?
- What is the relative momentum between the nucleons in the pair?
- What is the ratio of pp to pn pairs?
- Are these nucleons different from free nucleons (e.g. size)?

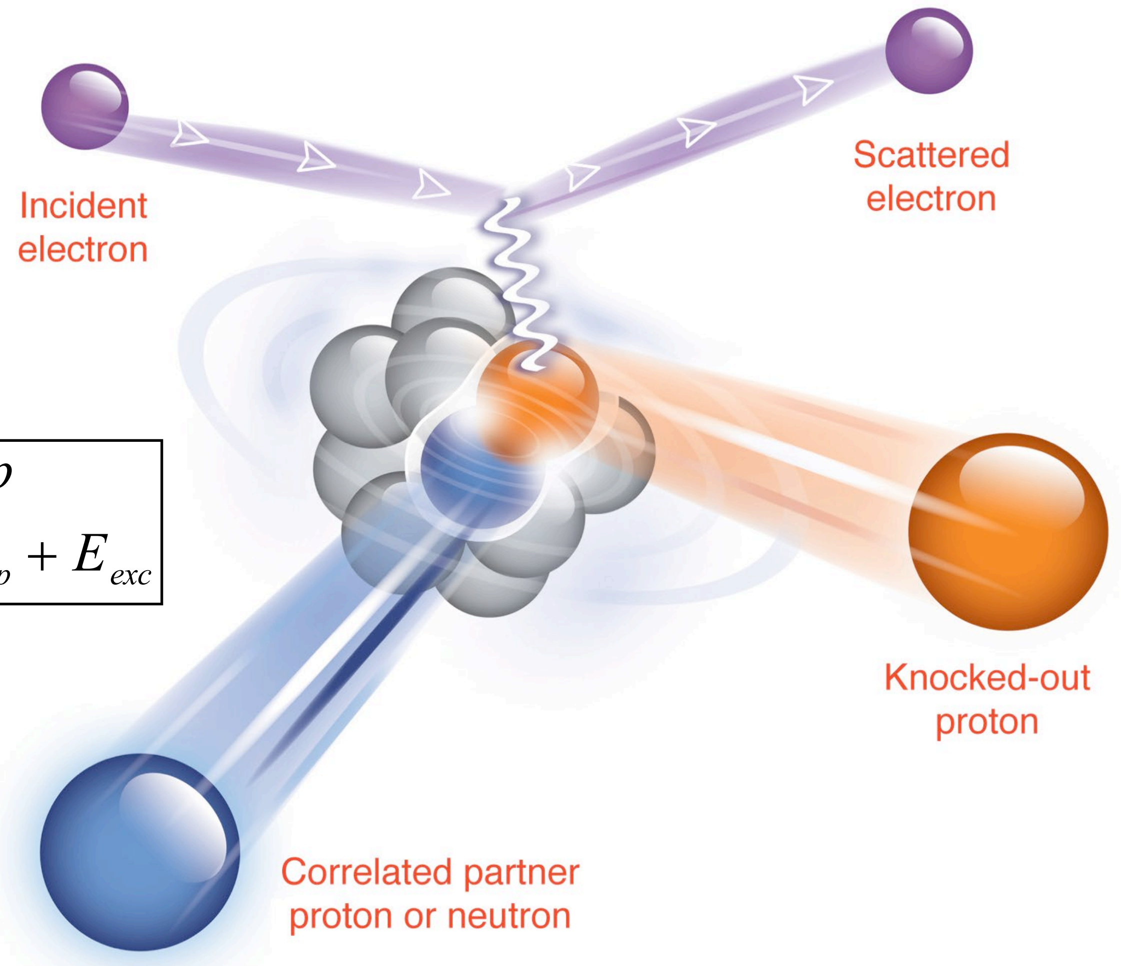
Measure out here…!...

Benhar et al., Phys. Lett. **B** 177 (1986) 135.



Coincidence (e,e'pN) Measurement

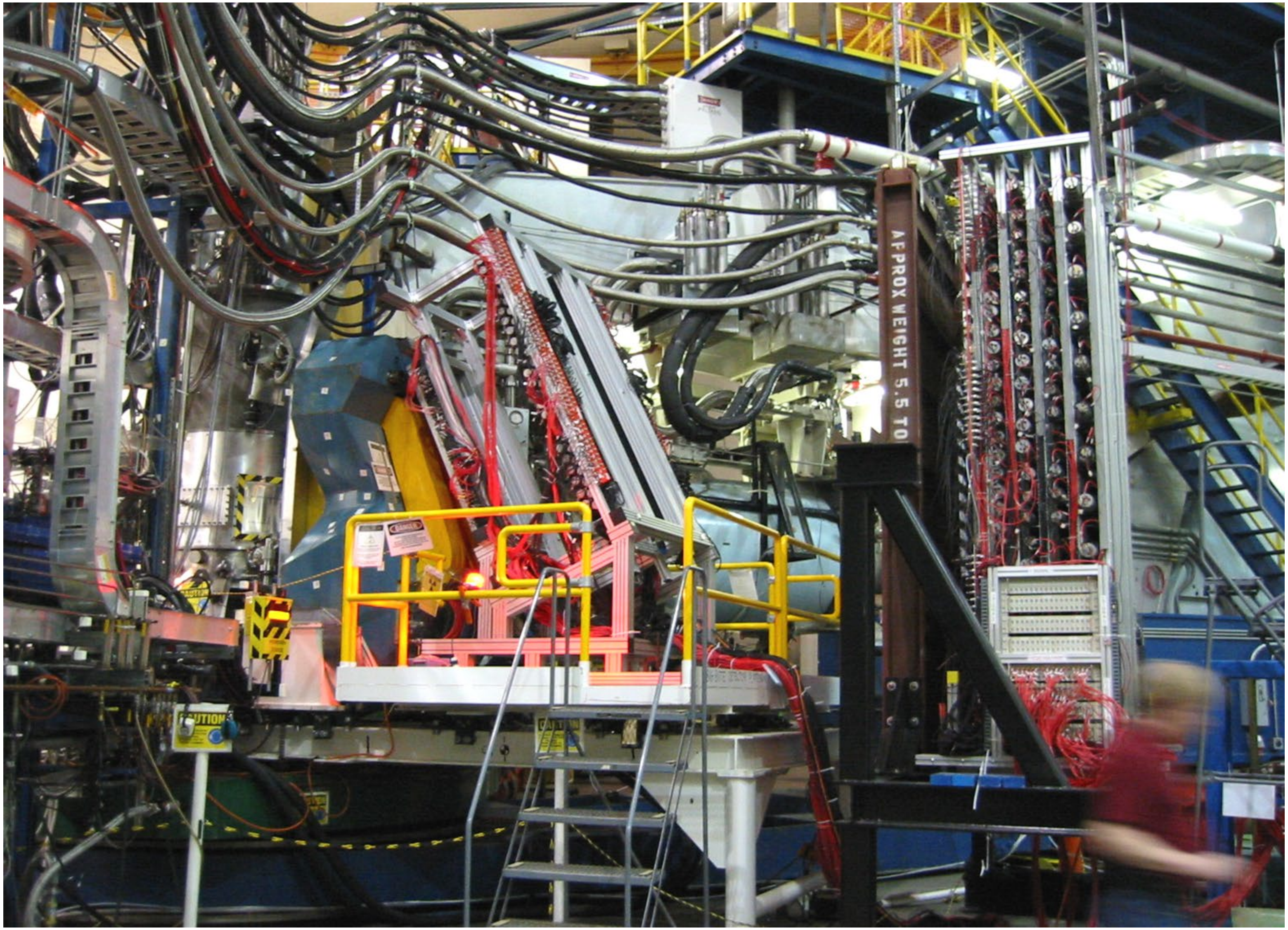
Study nucleon pairs and the fraction that contribute to momentum tail.



$$p_m = E_e - E_{e'} - p = q - p$$
$$E_m = \omega - T_p - T_{A-1} = E_{sep} + E_{exc}$$

x > 1 , $Q^2 = 1.5\ [\mathrm{GeV}/c]^2$ and missing momentum of 500 MeV/c

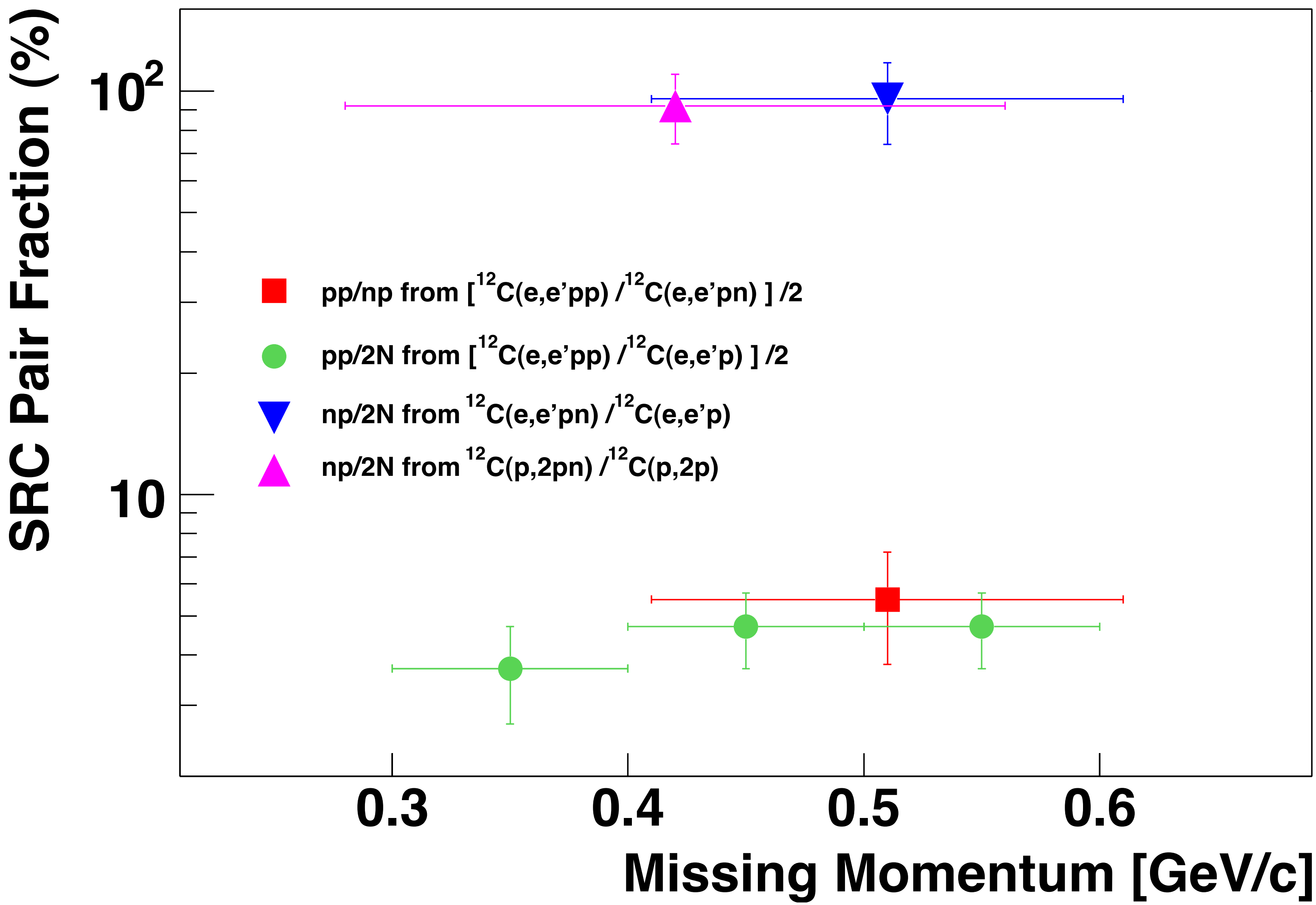
BigBite and Neutron Detector in Hall A



First step along the way to many successful high luminosity, large acceptance measurements.

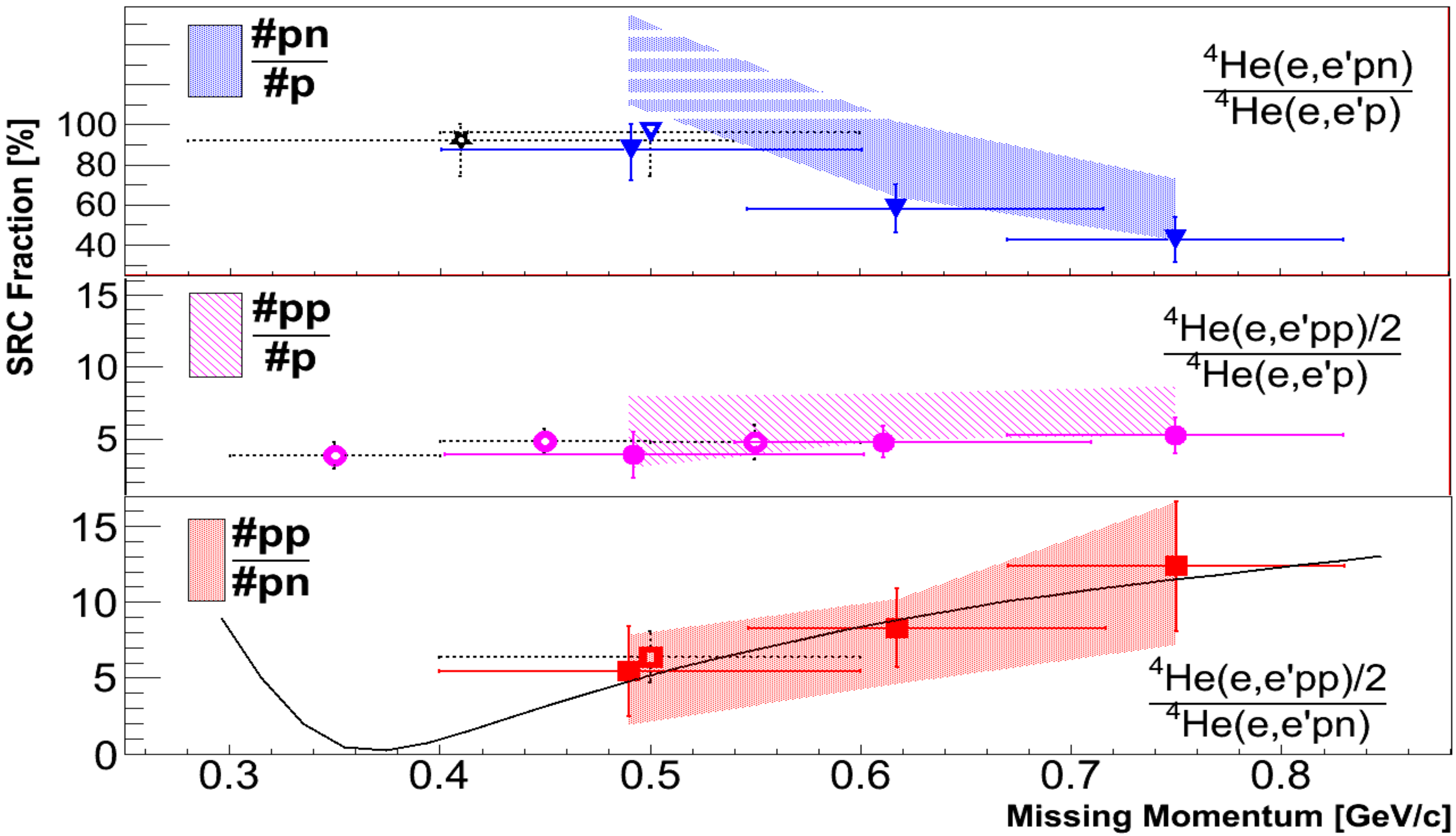
High p_m (e,e'p) events have recoiling neutrons.

R. Subedi *et al.*, Science **320** (2008) 1476.



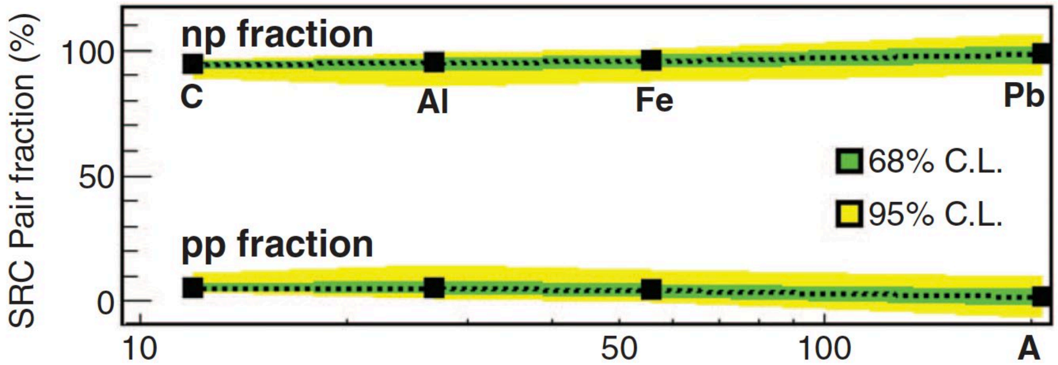
2nd Generation $^{4}He(e,e'pN)$ Results

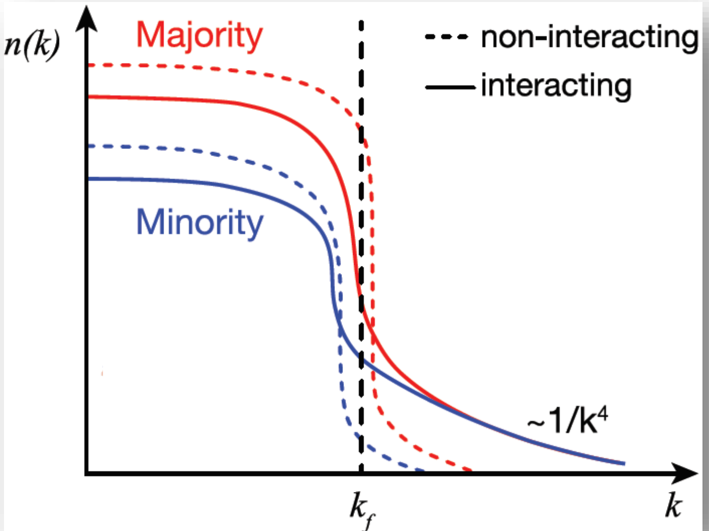
I. Korover *et al.*, Phys. Rev. Lett. **113** (2014) 022501.

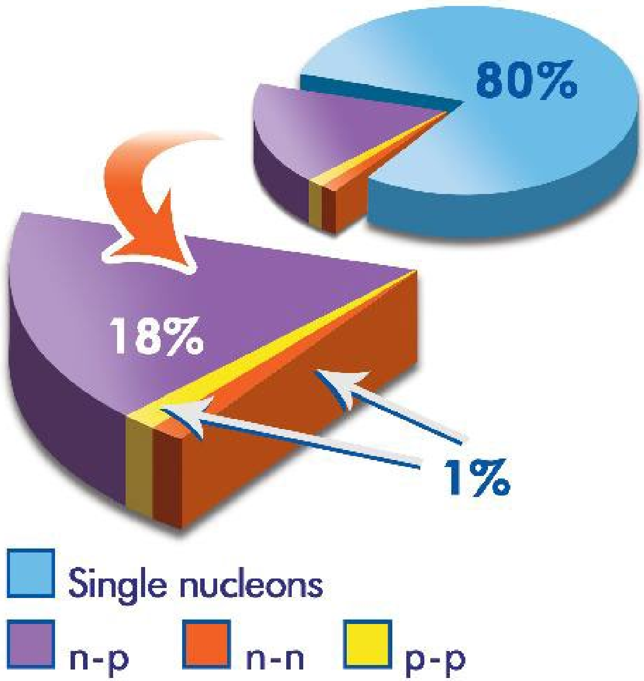


Proton-Neutron Pairing In All Nuclei

Or Hen *et al.* (Jefferson Lab CLAS Collaboration) Science 346 (2014) 614.



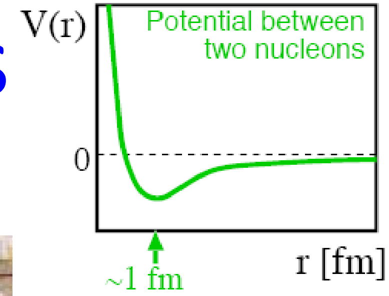




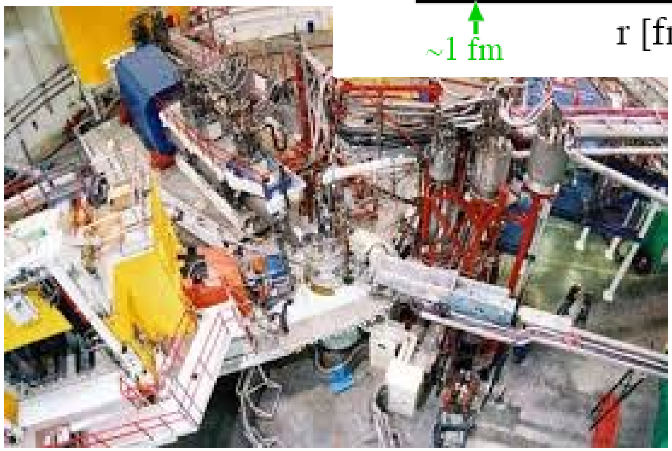
The minority particle will have a higher average kinetic energy then the majority particle.

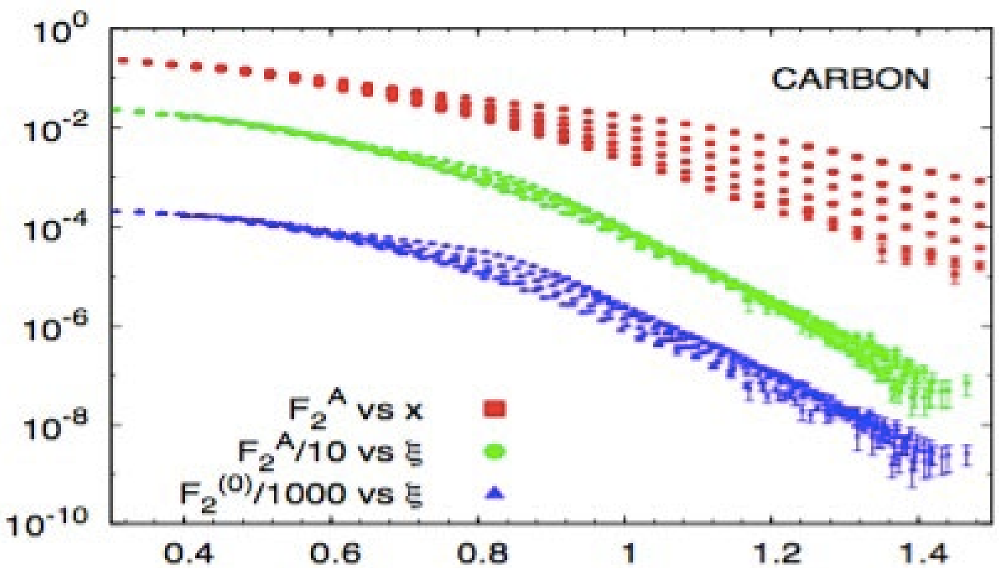
Precision (e,e') x>1 Cross Sections

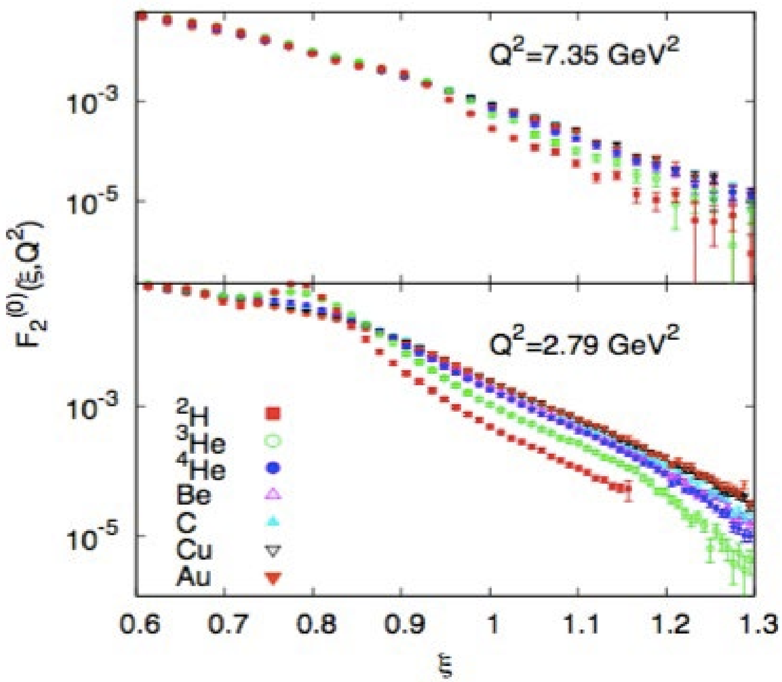
N. Fomin *et al.*, Phys. Rev. Lett. **105** (2010) 212502 – JLab Hall C

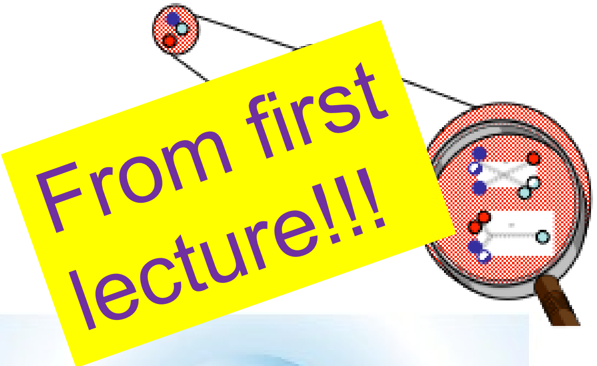


- Electron-nucleus scattering allows for F_2 structure functions above $x = 1$
- Nucleons are close together and interact via the (poorly-constrained) repulsive core of the N–N interaction, yielding high momentum nucleons.
- Deuteron limited to $x < 2$, etc.
- Deep inelastic probe of very high momentum "superfast" quarks

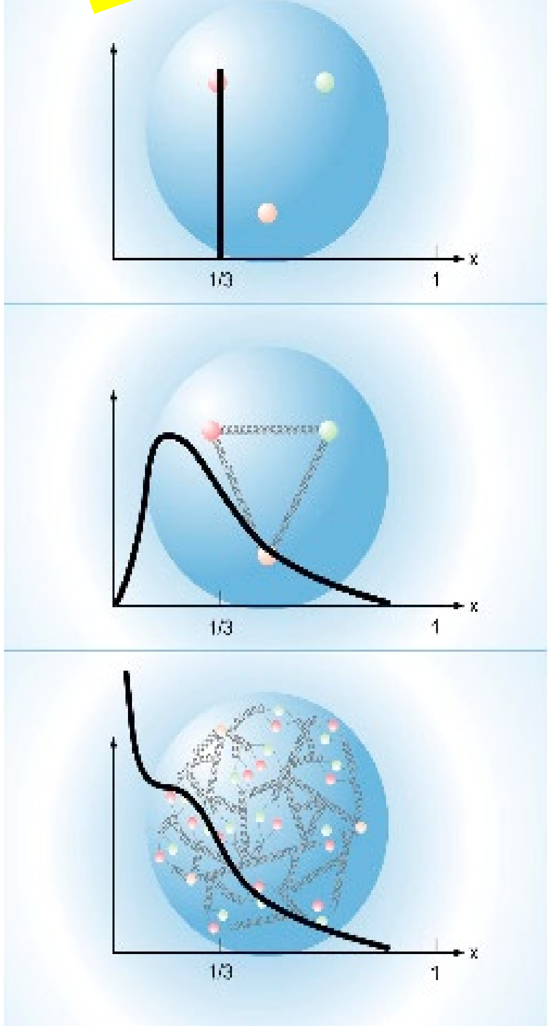


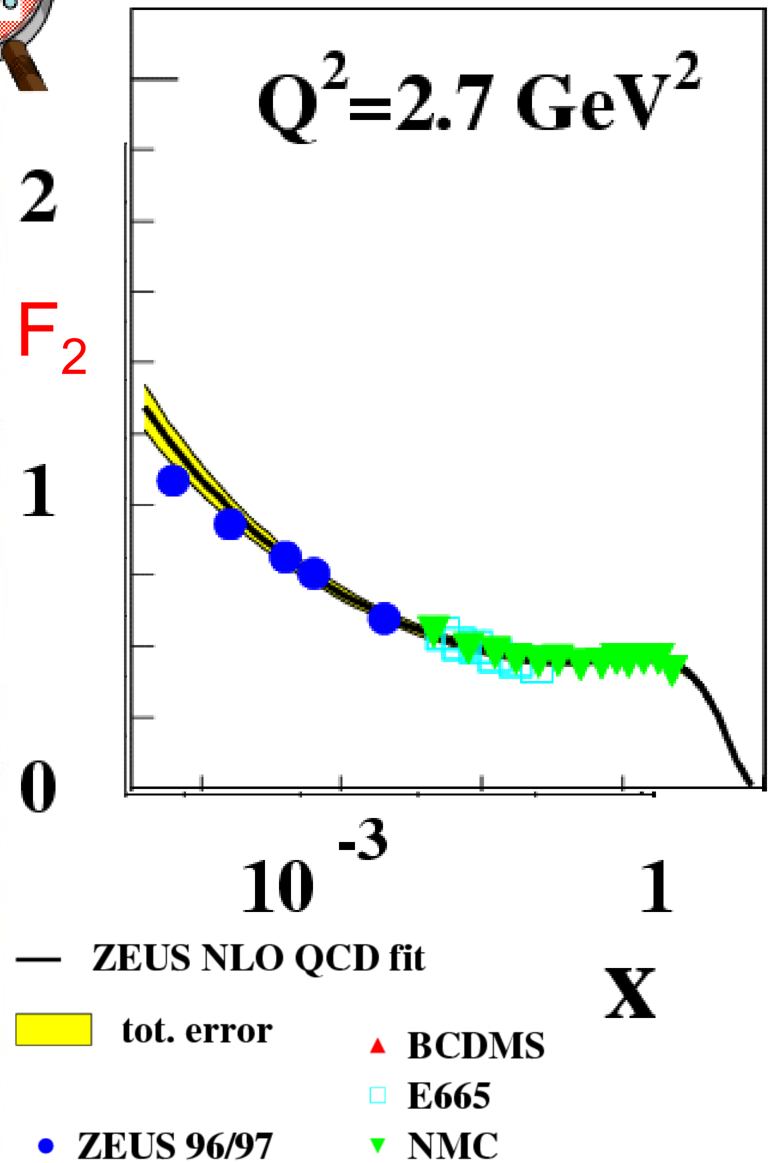






Proton Structure Function F_2





Q^2 dependence described by the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations

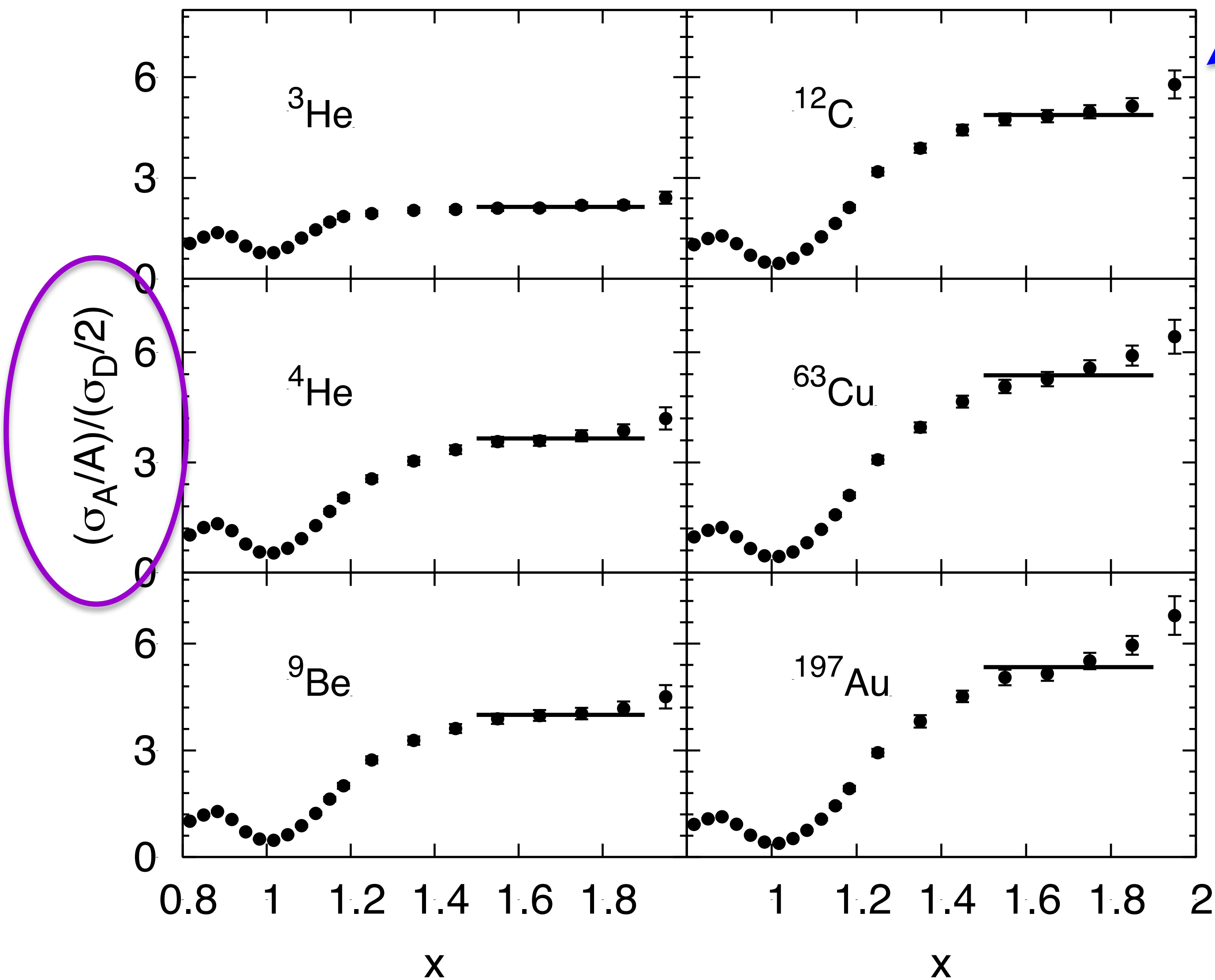
Increasing Q^2:

- High x decrease
- Low x increase

Allows extraction of Parton Distribution Functions $f(x,Q^2)$ through Q^2 evolution From high x, low Q to high Q, low x

Precision (e,e') x>1 Cross Section Ratios

N. Fomin *et al*., Phys. Rev. Lett. **108** (2012) 092502.



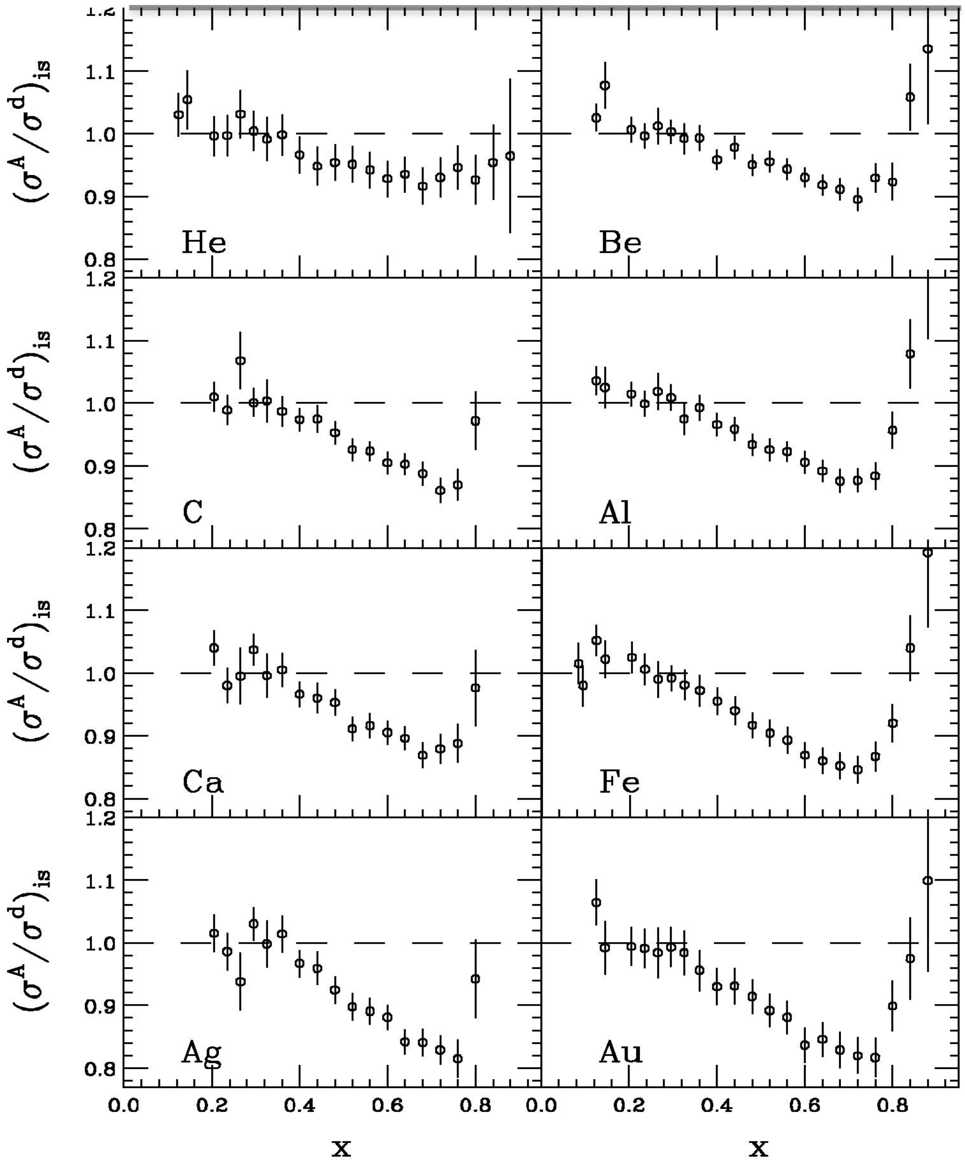
Plateaus seen in the ratio $(\sigma_A/A)/(\sigma_D/2)$

Roughly A independent

Understood as evidence for 2N short range correlations

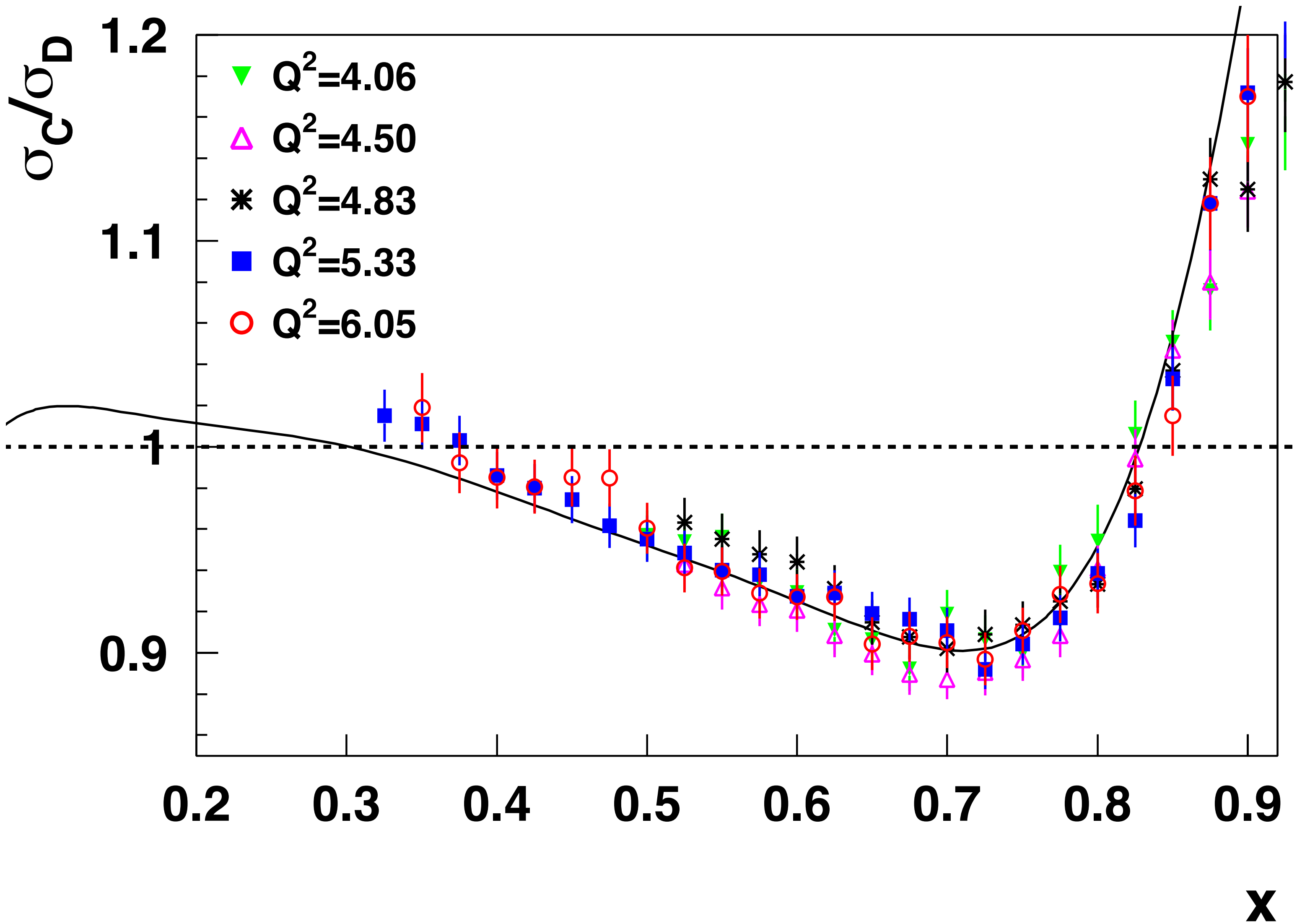
The Deep Inelastic EMC Effect

- **The EMC effect is the observation that the ratio of nuclear DIS cross sections to deuterium is not one**
  - EMC paper: J.J. Aubert et al. PLB 123 (1983) 275
  - Simple Parton Counting Expects One
  - ***<u>MANY Explanations, multiple experiments</u>***
- **Behavior**
  - Q^2-independent
  - Universal x-dependence (shape)
  - Magnitude varies with A ***– a density effect?....***



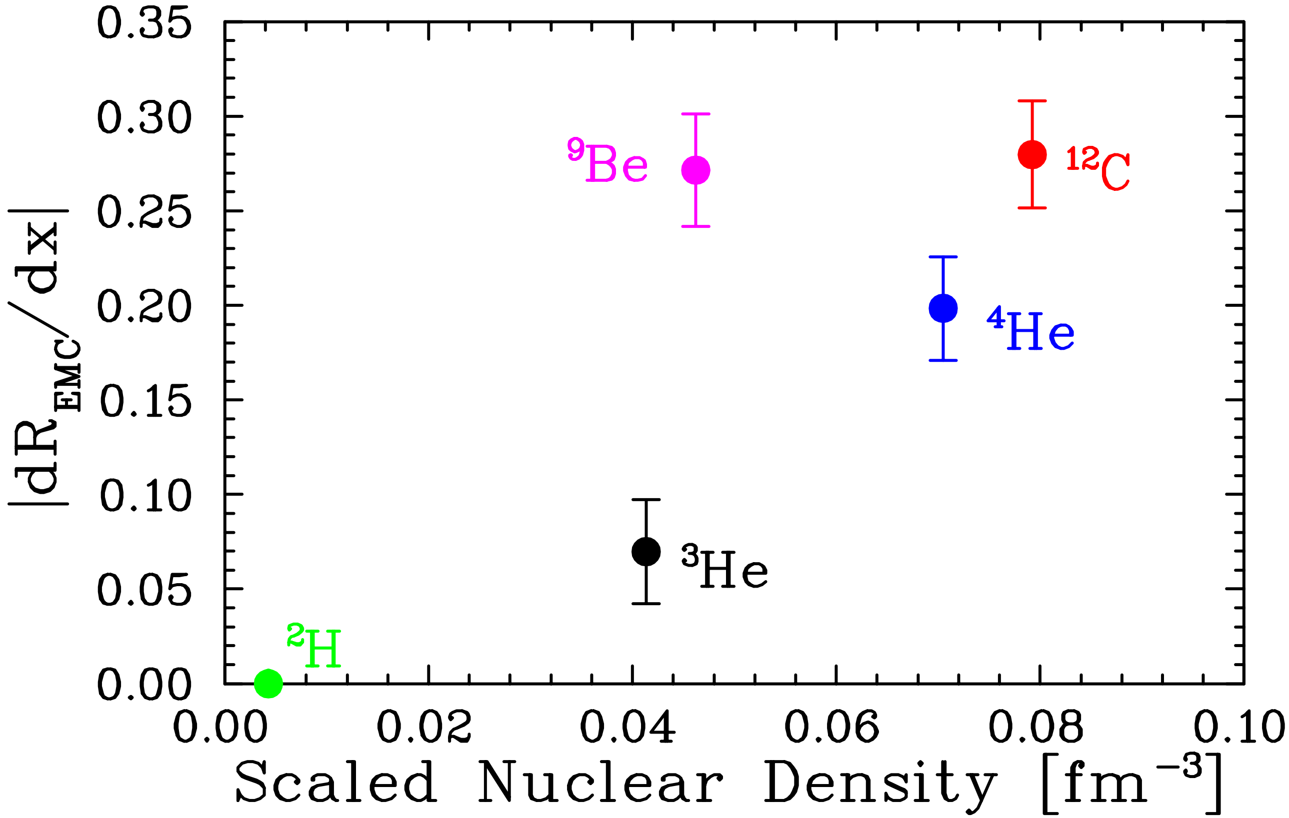
Jefferson Lab EMC Effect Data

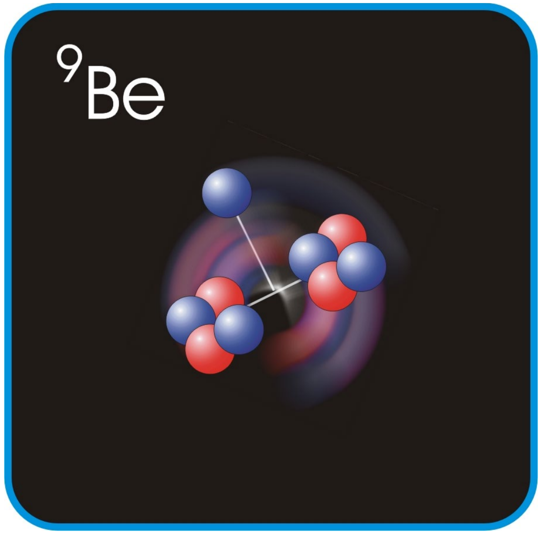
J. Seely *et al.*, Phys, Rev. Lett. **103** (2009) 202301.



Jefferson Lab EMC Effect Data

J. Seely *et al.*, Phys, Rev. Lett. **103** (2009) 202301.

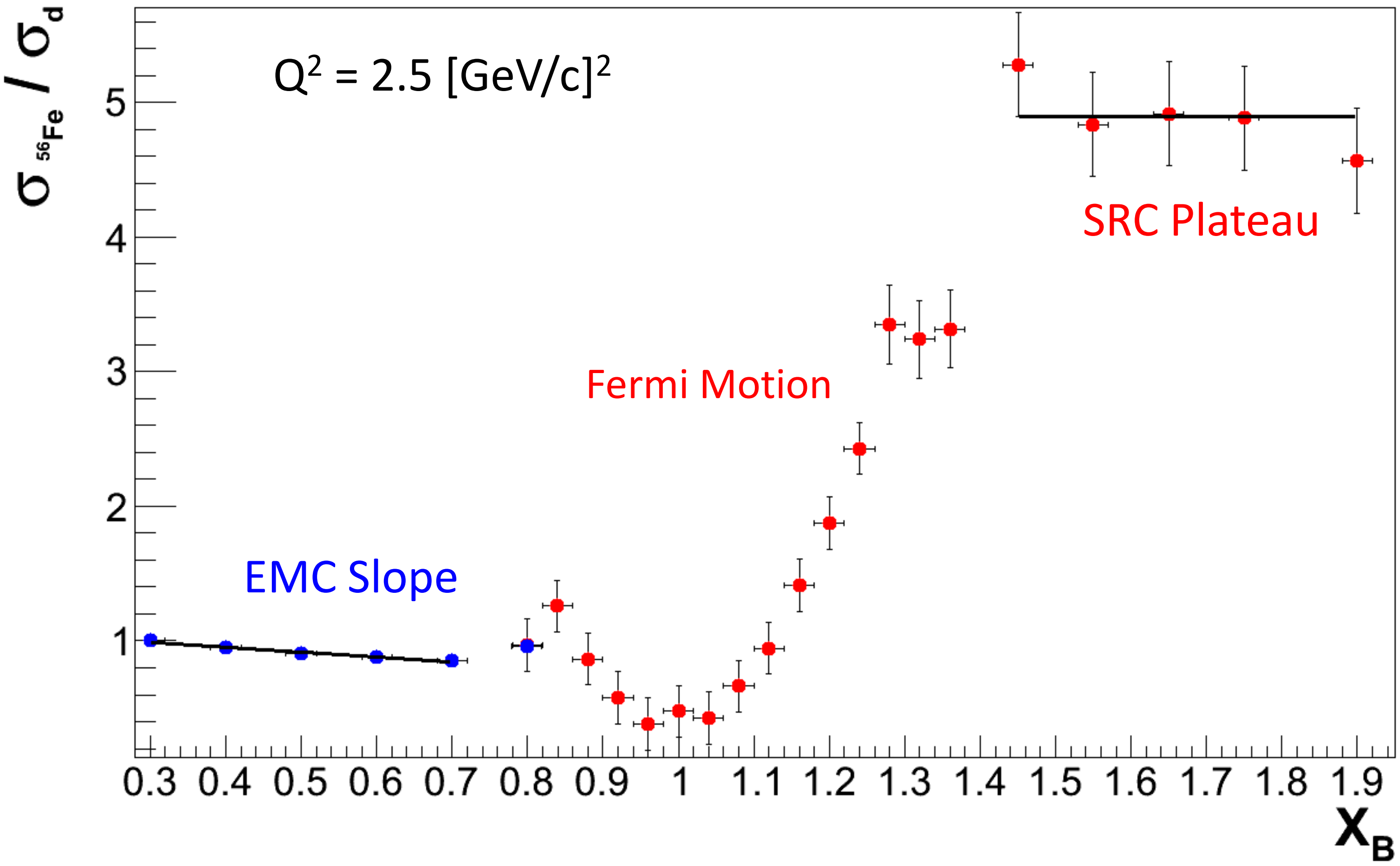




- Plot shows slope of ratio σ_A/σ_D at EMC region.
- EMC effect correlated with **local densit**y not average density.

Holistic View of inclusive EMC & SRC Data

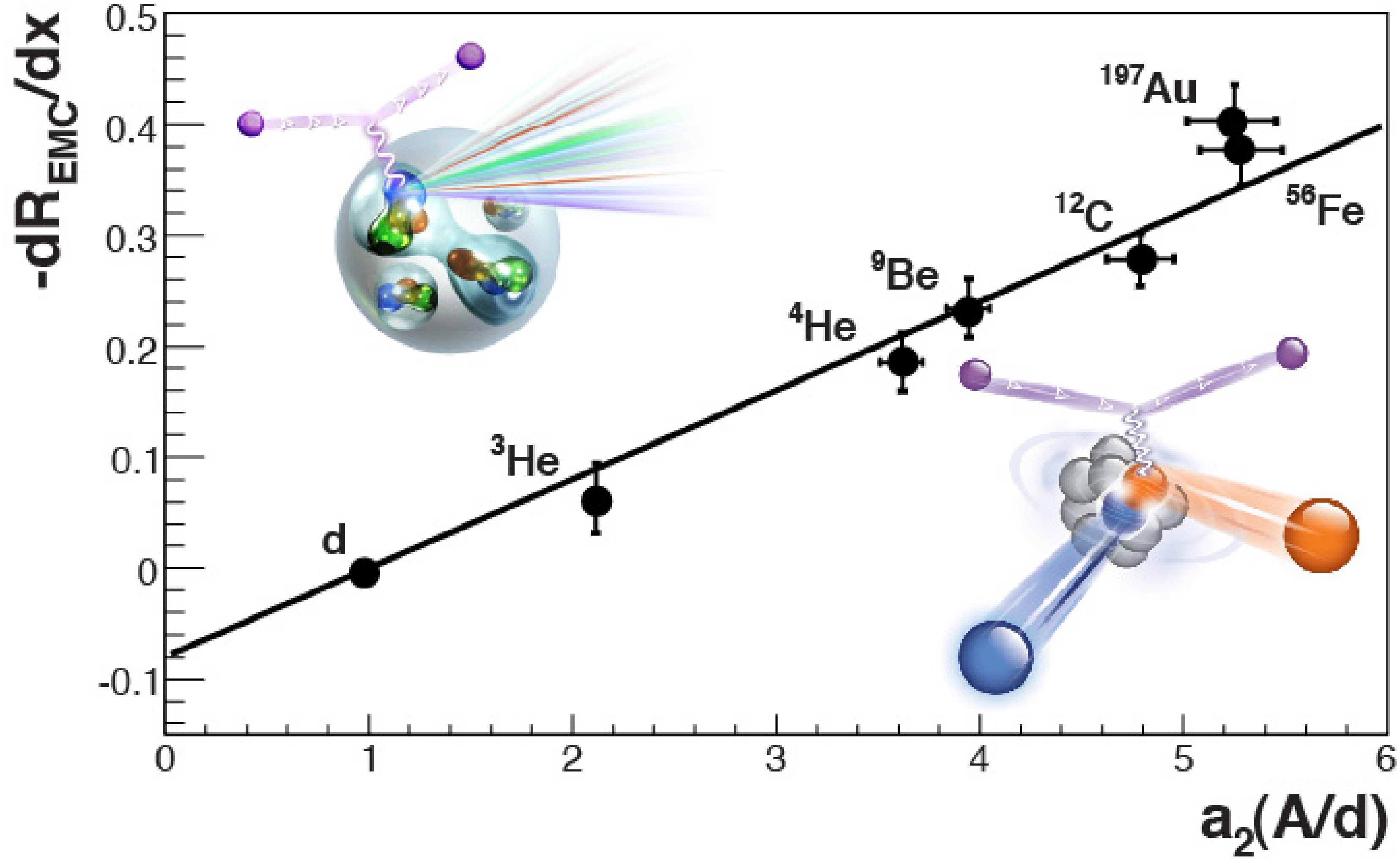
S. Malace, D. Gaskell, D.H., I. Cloet, Int. J. Mod. Phys. E **23** (2014) 1430013



- Scaling plateaus are likely due to proton-nucleon **local density** correlations
- So could the **EMC** slopes (x_B<0.7) and **SRC plateaus** (x_B>1.5) correlated?!

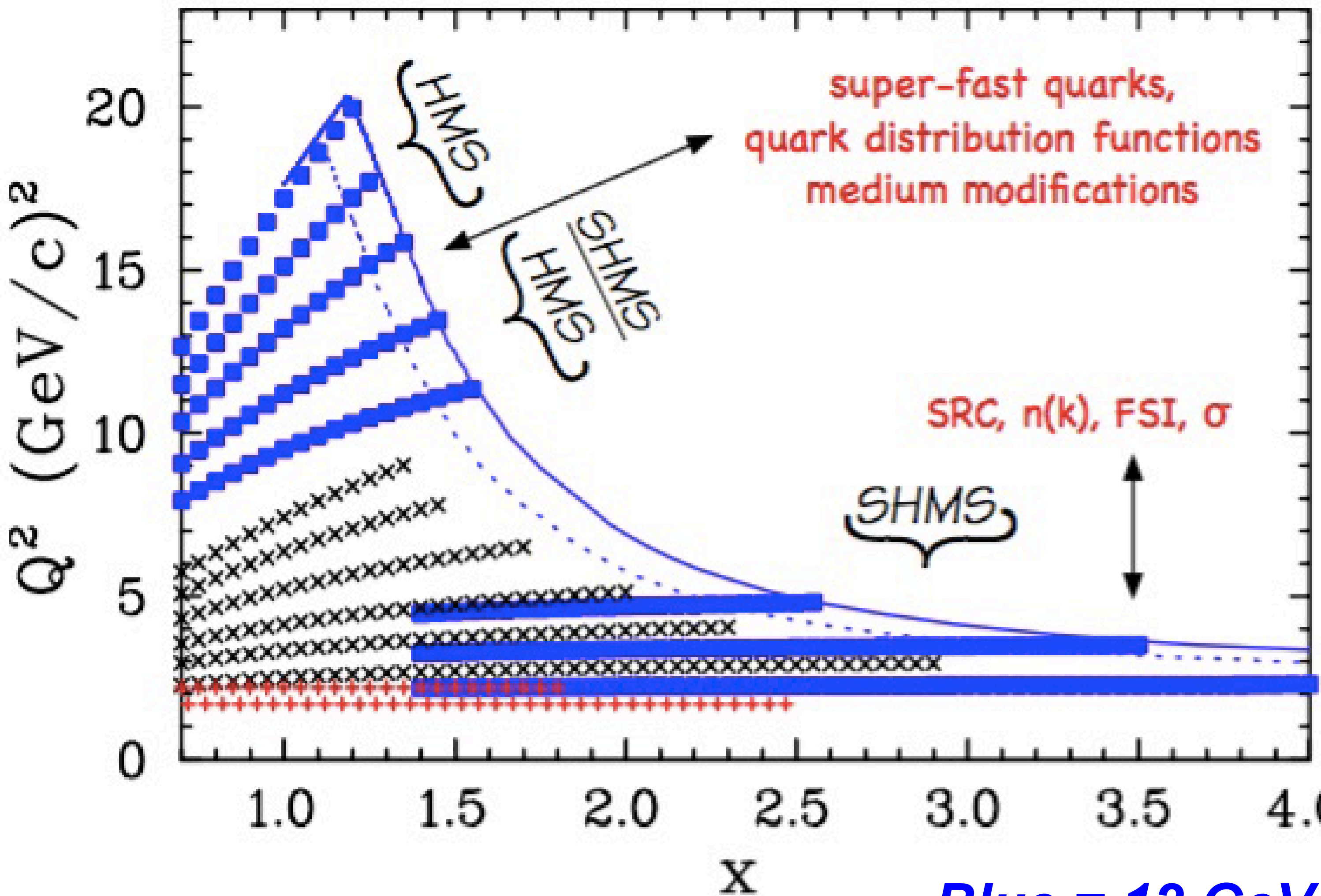
x>1 Ratios and EMC Slope Correlation

L. Weinstein, E. Piasetzky, DH, J. Gomez, O. Hen, and R. Shneor, Phys. Rev. Lett. 106 (2011) 052301.



Origin of the EMC effect? Not a smoking gun, but highly suggestive….

EMC, x>1 experiments to run in Jlab Hall C this Fall!



3N plateau?

Also ^3H, ^3He (e,e'p) in Hall A

More!

Black = 6 GeV Hall C

Red = 6 GeV Hall B

Blue = 12 GeV Hall C!!

(push up in x, Q^2, range of A)

Hmmm… nuclear medium modifications are interesting...

But, let's check out polarized partons….

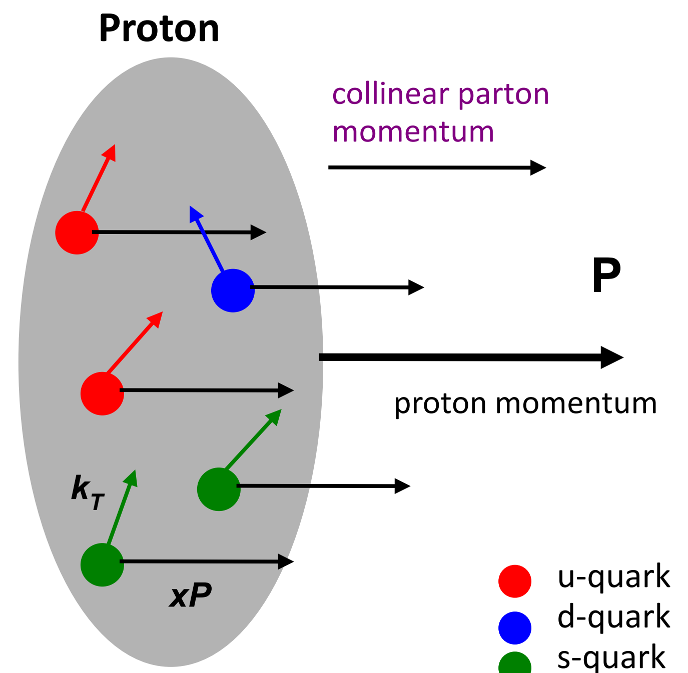
Collinear Parton Distribution Functions

In DIS nucleon structure is described by three collinear PDFs:

Momentum distribution – $q(x, Q^2)$

Helicity distribution - $\Delta q(x, Q^2)$

Transversity distribution - $h(x, Q^2)$

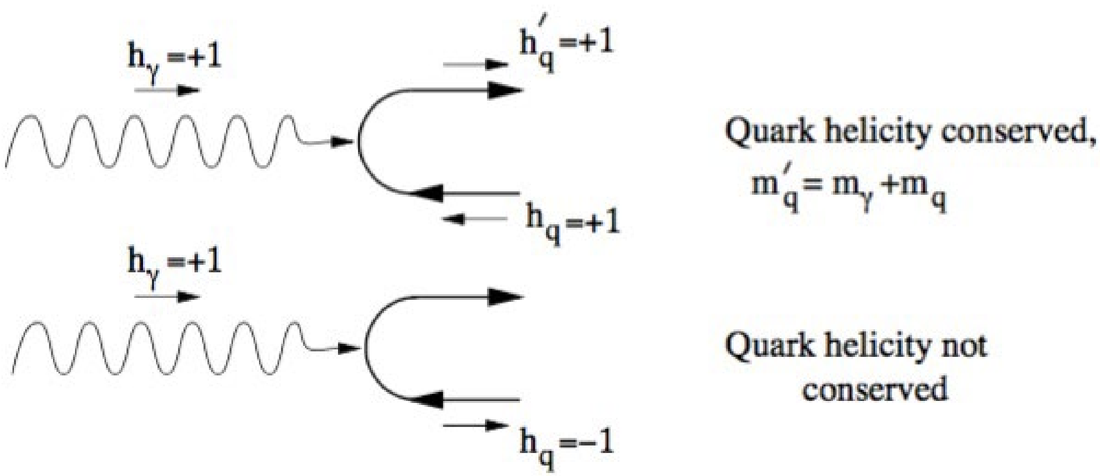


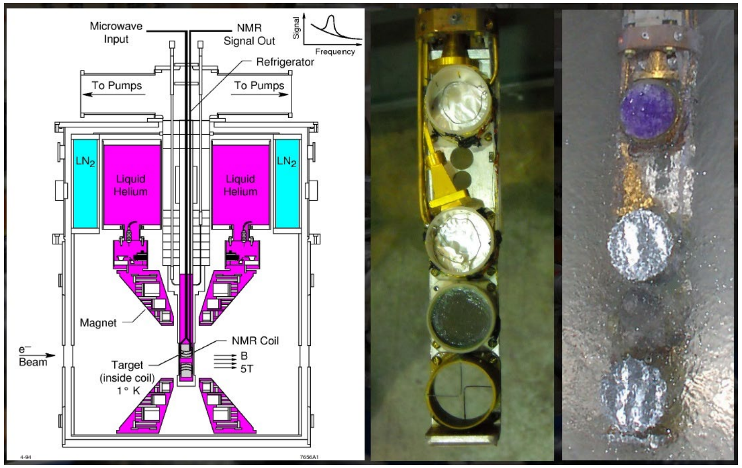
- The helicity dependent parton distributions ("spin-dependent PDFs") describe the number density of partons with given longitudinal momentum x and given polarization in a hadron polarized longitudinally with respect to its motion.

- The transverse momentum distributions ("TMDs") describe the number density of partons with given transverse momentum x in a hadron. *We'll come back to this….*

Polarized DIS

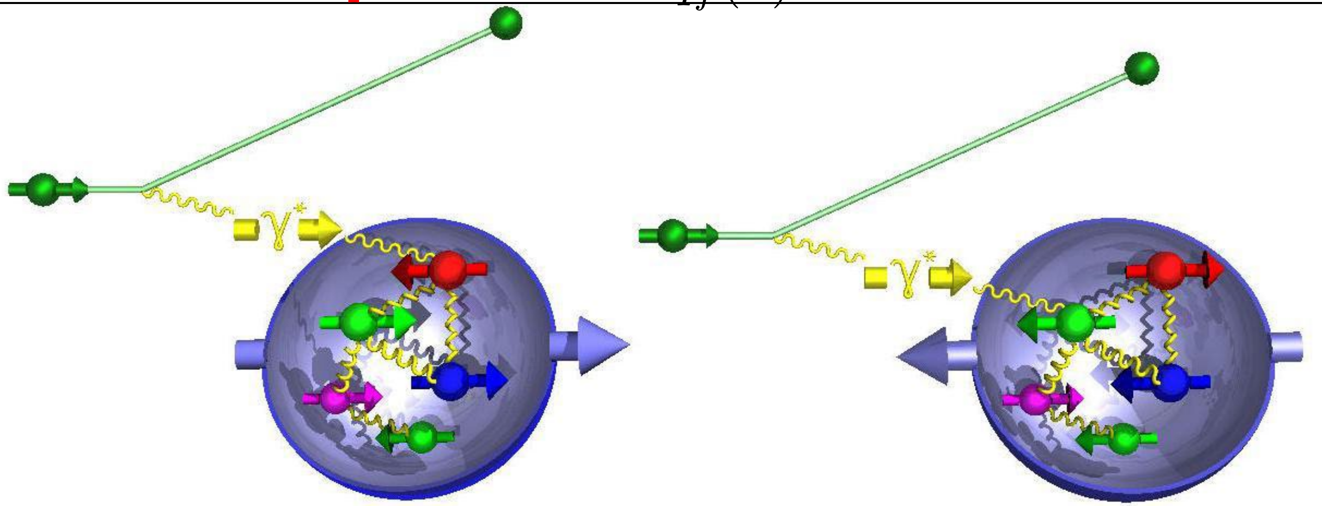
- Consider the case when the beam electron and target nucleon are both polarized along the scattering axis….
- Helicity conservation - the virtual γ inherits some of the incident lepton helicity
- The electromagnetic interaction will conserve helicity. So…
- A + (-) helicity quark can only absorb a + (-) helicity photon.
- Study the difference under reversal of electron/photon helicity (or equivalently reversing the target spin)….
- Determine the probability that the struck quark has the same helicity as the incident lepton for a fixed spin orientation of the proton.





The Polarized Structure Functions

$$\mathbf{g_1(x) = \frac{1}{2}\sum_i e_i^2 \underbrace{[\Delta q_i(x) + \Delta \bar{q}_i(x)]}_{\Delta q_f(x)}} \qquad \Delta q_i(x) = q_i^+ - q_i^-$$



Polarized deep inelastic electron scattering

Parallel electron & quark spins

Anti-parallel electron & quark spins

Measure yield asymmetry:

$$A_1 = \frac{1}{DP_T P_B}\frac{N_{\uparrow\downarrow} - N_{\uparrow\uparrow}}{N_{\uparrow\downarrow} + N_{\uparrow\uparrow}}$$

In the Quark-Parton Model:

$$A_1 \approx \frac{g_1(x)}{F_1(x)} = \frac{1}{F_1(x)}\sum_f e_f^2 \Delta q_f(x)$$

Spin-dependent Structure Function

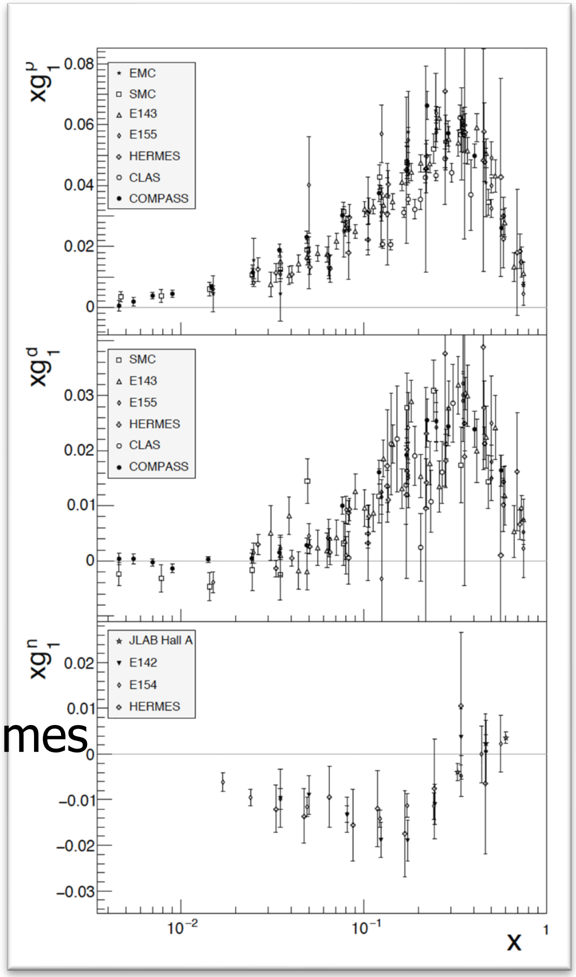
Polarized Parton Distributions

$$\Gamma_1^{p,n} \equiv \int_0^1 g_1^{p,n}(x_B)dx_B = \frac{1}{2}\sum_f e_f^2(\Delta q_f^{p,n} + \Delta\bar{q}_f^{p,n})$$

$$\Delta\Sigma \equiv (\Delta u(x) + \Delta\bar{u}(x)) + (\Delta d(x) + \Delta\bar{d}(x)) + (\Delta s(x) + \Delta\bar{s}(x))$$

$$\Gamma_1 \equiv \int_0^1 g_1(x_B)dx_B = \underbrace{\frac{1}{6}F + \frac{1}{18}D}_{\text{From hyperon decays}} + \frac{1}{9}\Delta\Sigma$$

- Mesurement of Γ_1^p, Γ_1^n
- Constraint based on neutron and hyperon beta decay lifetimes
- Assumption of SU(3) flavor symmetry
- Global fit with DGLAP Q^2 evolution

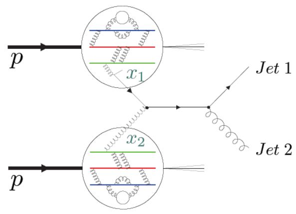


arX:1209.2803

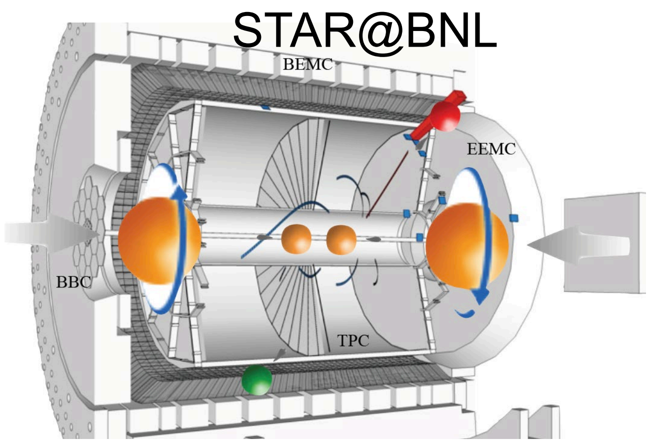
$$\rightarrow \Delta\Sigma \approx 0.25$$

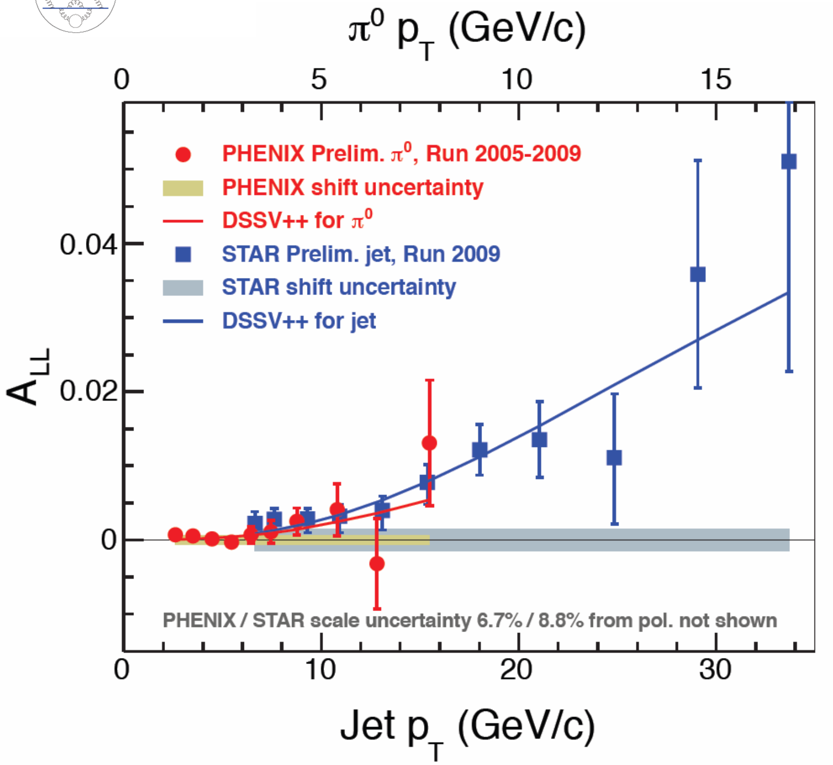
Only small fraction of the proton spin is carried by the quarks & antiquarks!!

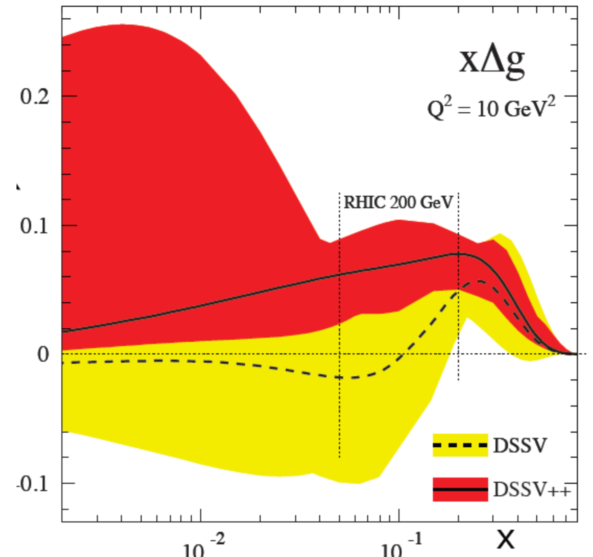
Gluon Helicity



$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P_1 P_2} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$$







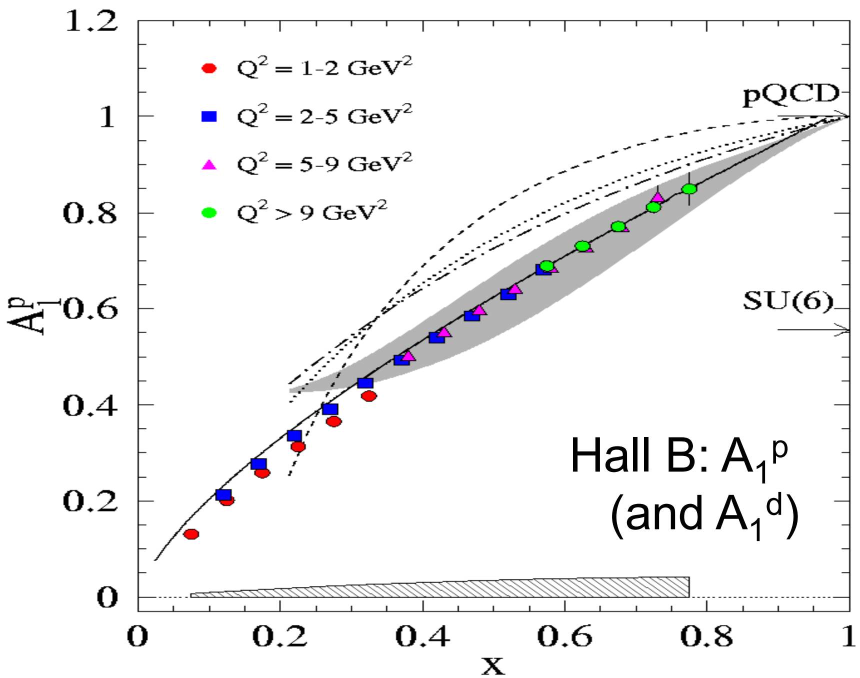
Indication of small, but non-0 Δg from RHIC data, in particular STAR jet results

$$\int_{0.05}^{0.2} \Delta g(x)\,dx = 0.1 \pm^{0.06}_{0.07}$$

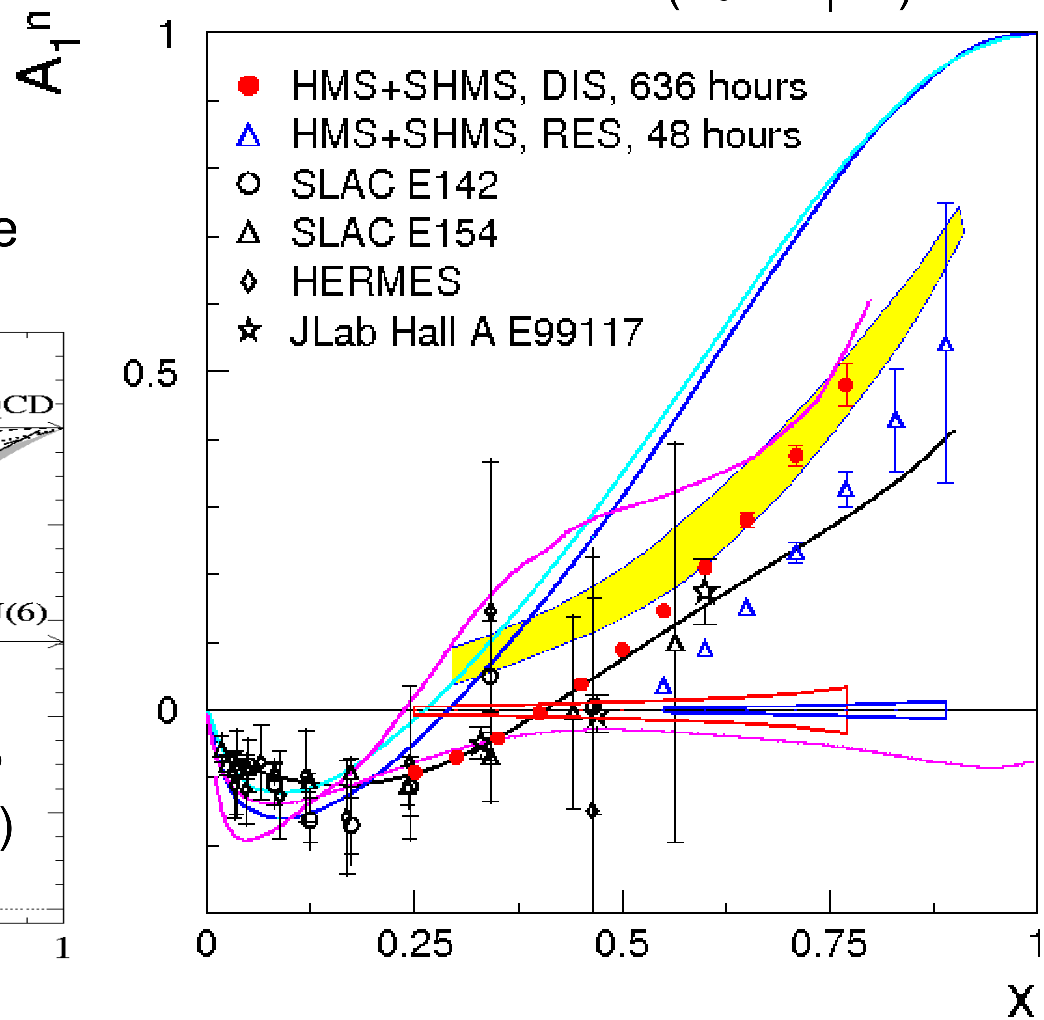
12 GeV Era Polarized Structure Functions

REQUIRES:

- High beam polarization
- High electron current
- High target polarization
- Large solid angle spectromete

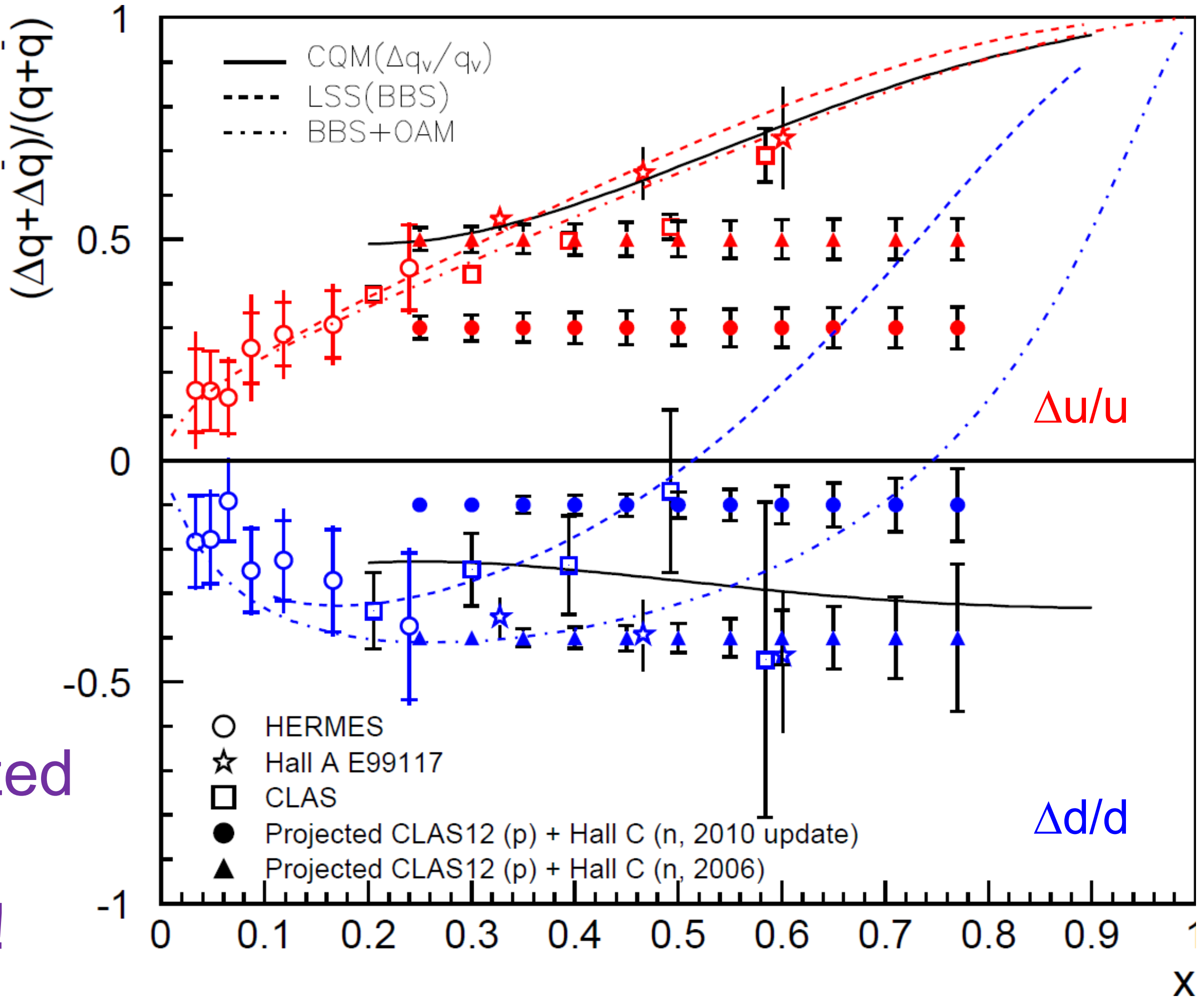


Hall C: A_1^n (from A_1^{3He})



12 GeV Era Polarized PDFs

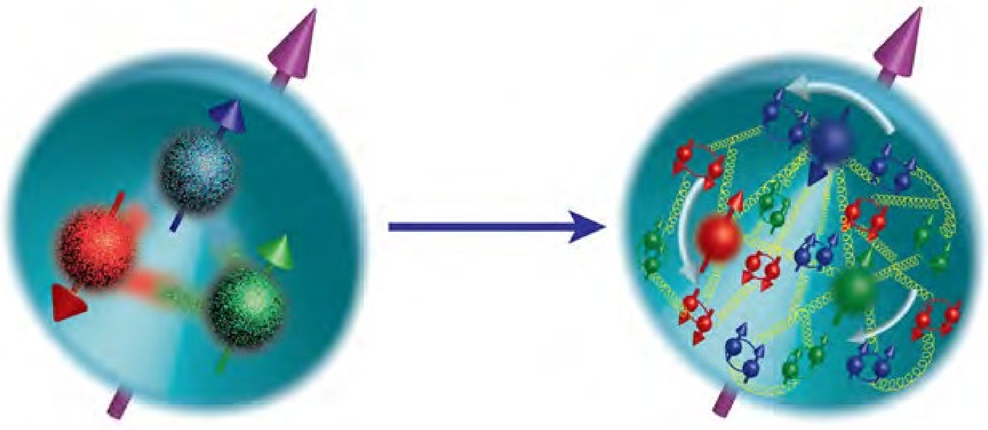
Combine Hall B A_1^p and Hall C A_1^n
→ extract $\Delta u/u$ and $\Delta d/d$



12 GeV will access the regime (x > ~0.3) where valence quarks dominate

Polarized ^{3}He critical!

The Incomplete Nucleon: Spin Puzzle

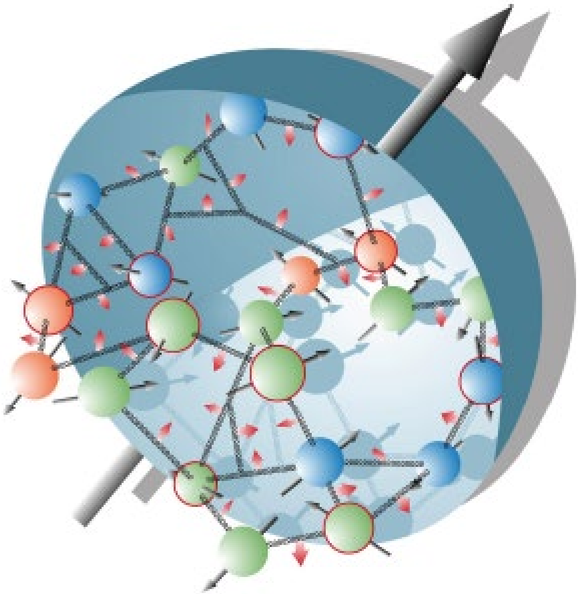


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$

- $\Delta\Sigma \sim 0.25$ (world DIS)
- ΔG small ~ 0.1 (RHIC+DIS)
- L_q??

<u>*Note:*</u>
The constituent quarks considered in the quark models of the nucleon are massive (~ $M_P/3$) objects with the same spin, charge, and magnetic properties of the massless objects that we observe in deep inelastic scattering. While these quark model objects might be related to the degrees of freedom observed in deep inelastic scattering, they are not identical and this confuses the "proton spin crisis".

The Incomplete Nucleon: Spin Puzzle



- Proton has spin-1/2
- Proton is a composite system consisting of spin-1/2 quarks and spin-1 gluons

This implies that the sum of angular momentum of quarks and gluons together must amount to 1/2. Can be due to:

Quark spin	Quark orbital momentum
Gluon spin	Gluon orbital momentum

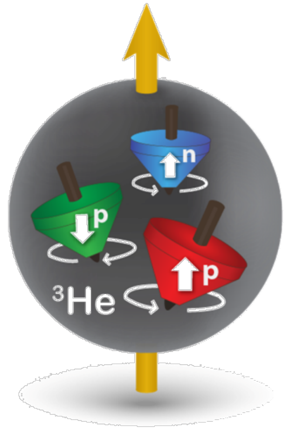
Classical: ~ $\mathbf{r} \times \mathbf{p}$

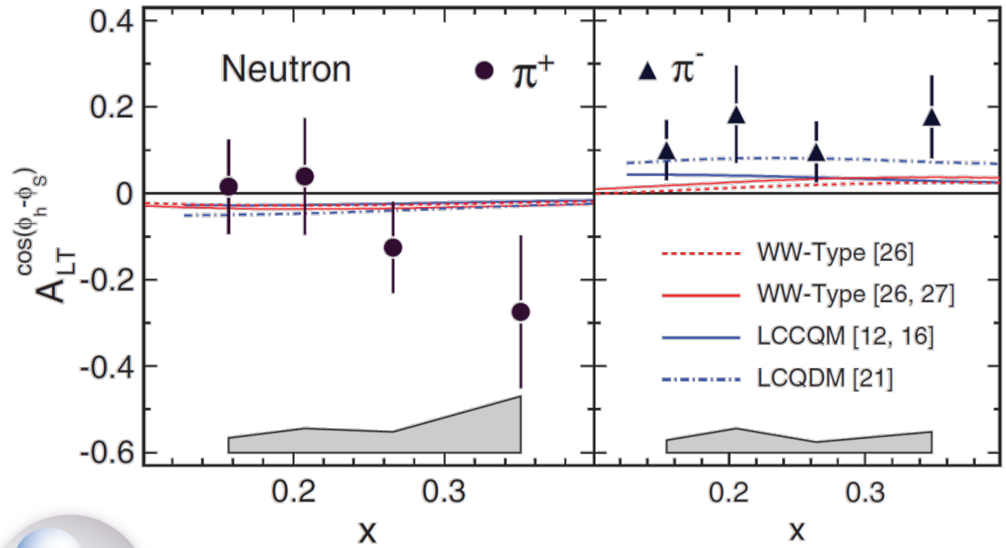
Needs a cross-product or something three-dimensional….

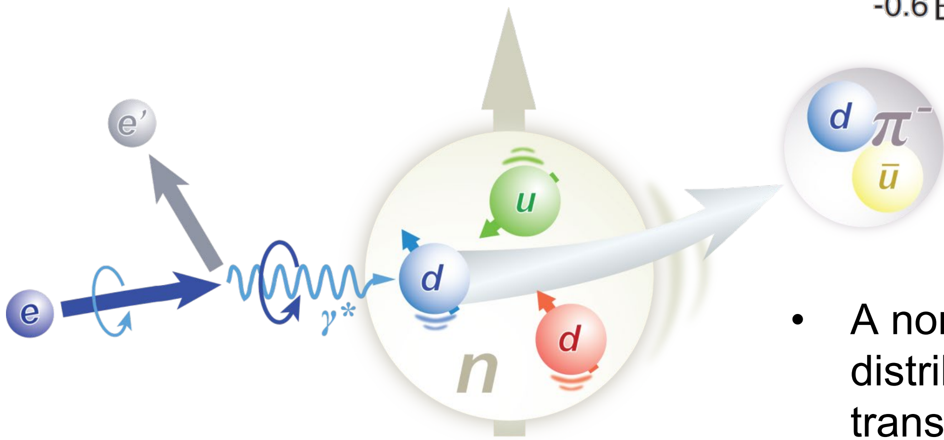
New Observable Reveals Interesting Behavior of Quarks

Huang, *et. al.* PRL. 108, 052001 (2012)

Target:
transversely
polarized ^{3}He ~ polarized neutron







1st measurement of A_{LT}

beam-target double-spin asymmetry

- A non-vanishing quark "transversal helicity" distribution, reveals alignment of quark spin transverse to neutron spin direction

Also 1st measurements of ^{3}He (neutron) single-spin asymmetries
X. Qian *et al.,* PRL 107, 072003 (2011)

Volume 57B, number 1 PHYSICS LETTERS 9 June 1975

SPIN EFFECTS IN THE INCLUSIVE REACTIONS $\pi^{\pm} + p(\uparrow) \rightarrow \pi^{\pm}$ + ANYTHING AT 8 GeV/c

L. DICK, A. GONIDEC, A. GSPONER and M. WERLEN
CERN, Geneva, Switzerland

C. CAVERZASIO, K. KURODA, A. MICHALOWICZ a
IPN, Orsay, France

and

D. ASCHMAN, K. GREEN, P. PHIZACKLEA and G.
Oxford University, Oxford, England

The asymmetry in inclusive reactions of the type $a + p(\uparrow) \rightarrow a$ + anything at 8
measured at the CERN Proton Synchrotron using a polarized proton target. In th
range of p_T ($0.17 \leq p_T \leq 0.36$) GeV/c the results indicate i) an asymmetry for x
symmetric for the π^+ and π^- reactions; ii) an asymmetry compatible with zero fc

Transverse SSA

Phys. Lett. B 57, 93 (1975)

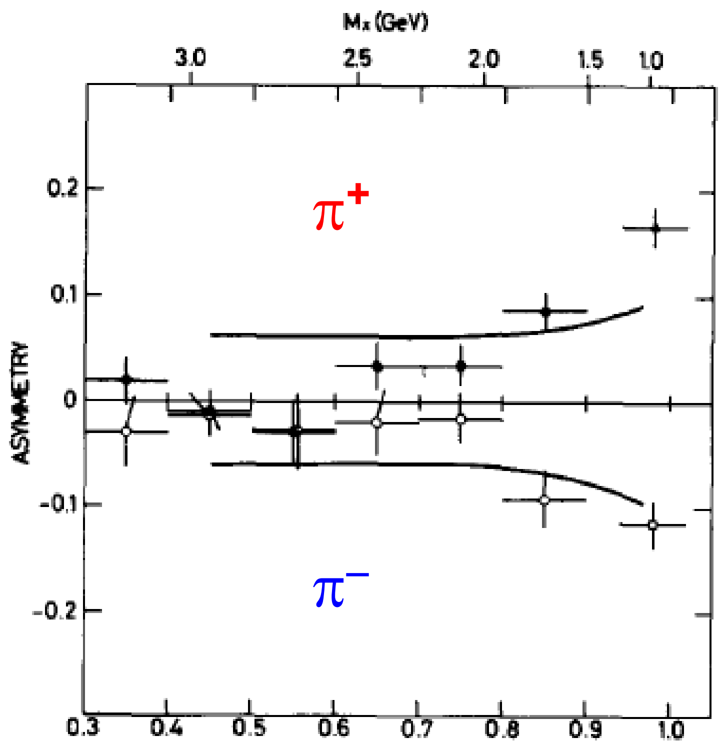
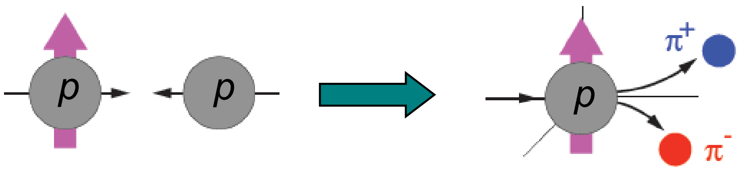
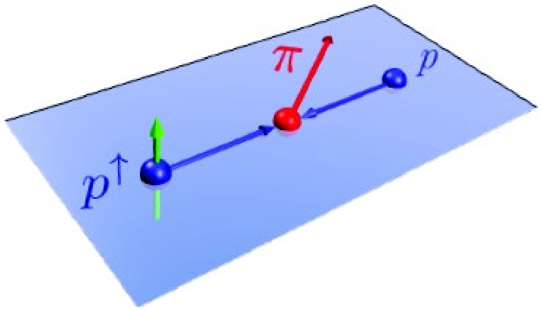


Fig. 3. Asymmetry data from this experiment. (●): $\pi^+ p \rightarrow \pi^+$; (○): $\pi^- p \rightarrow \pi^-$; (▲) and (□) "elastic points" in π^+, π^-.

Transverse SSA in Proton-Proton Reactions

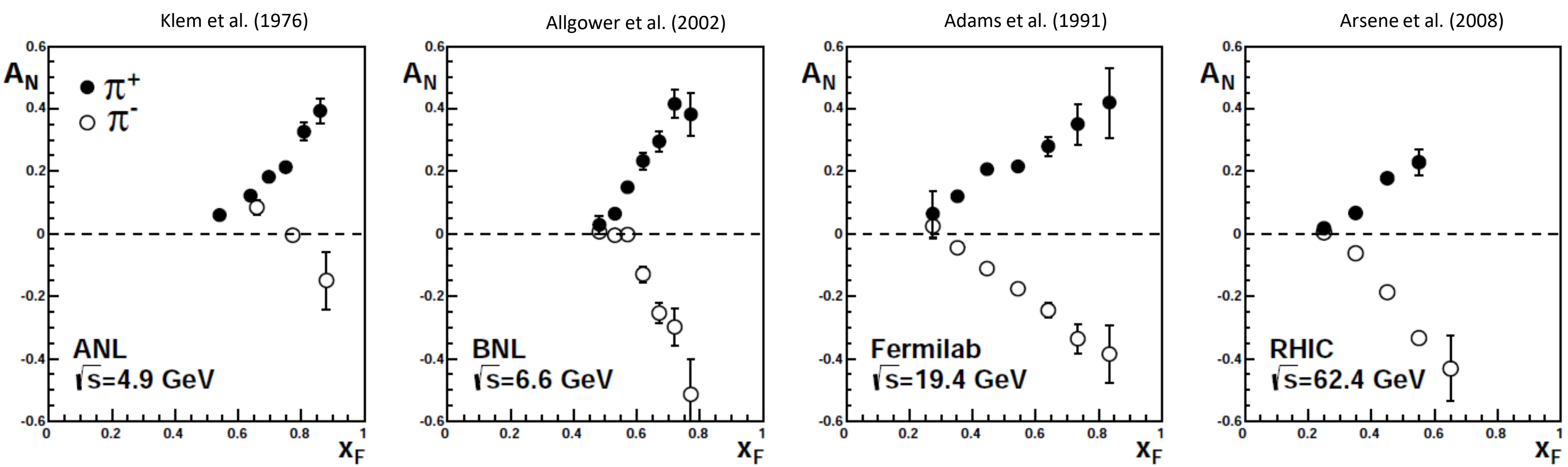




$$A_N = \frac{1}{P_{\text{beam}}} \frac{N^\pi_{\text{left}} - N^\pi_{\text{right}}}{N^\pi_{\text{left}} + N^\pi_{\text{right}}}$$

In collinear picture, the QCD predict small SSAs with transversely polarized protons colliding at high energies

$$A_N \sim \alpha_s m_q / P_{h\perp}$$

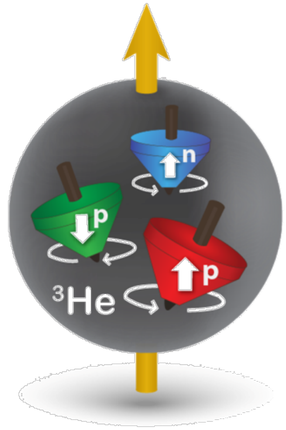


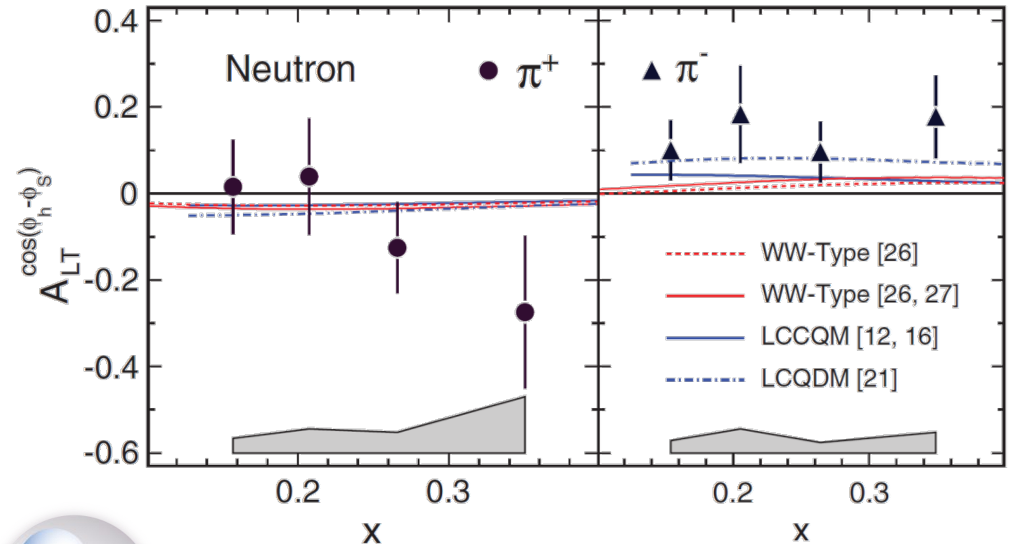
C. Aidala et al., Rev. Mod. Phys. 85, 655

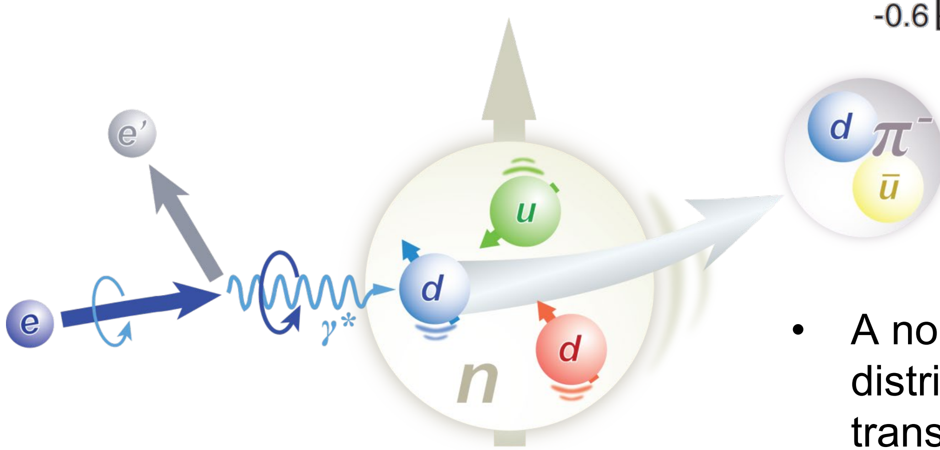
New Observable Reveals Interesting Behavior of Quarks

Huang, *et. al.* PRL. 108, 052001 (2012)

Target: transversely polarized ^{3}He ~ polarized neutron







1st measurement of A_{LT}

beam-target double-spin asymmetry

- A non-vanishing quark "transversal helicity" distribution, reveals alignment of quark spin transverse to neutron spin direction
- **Indicative of quark orbital motion**
- Foundation for future mapping in four kinematic dimensions (x, Q^2, z, p_T) of transverse-momentum dependent parton distributions

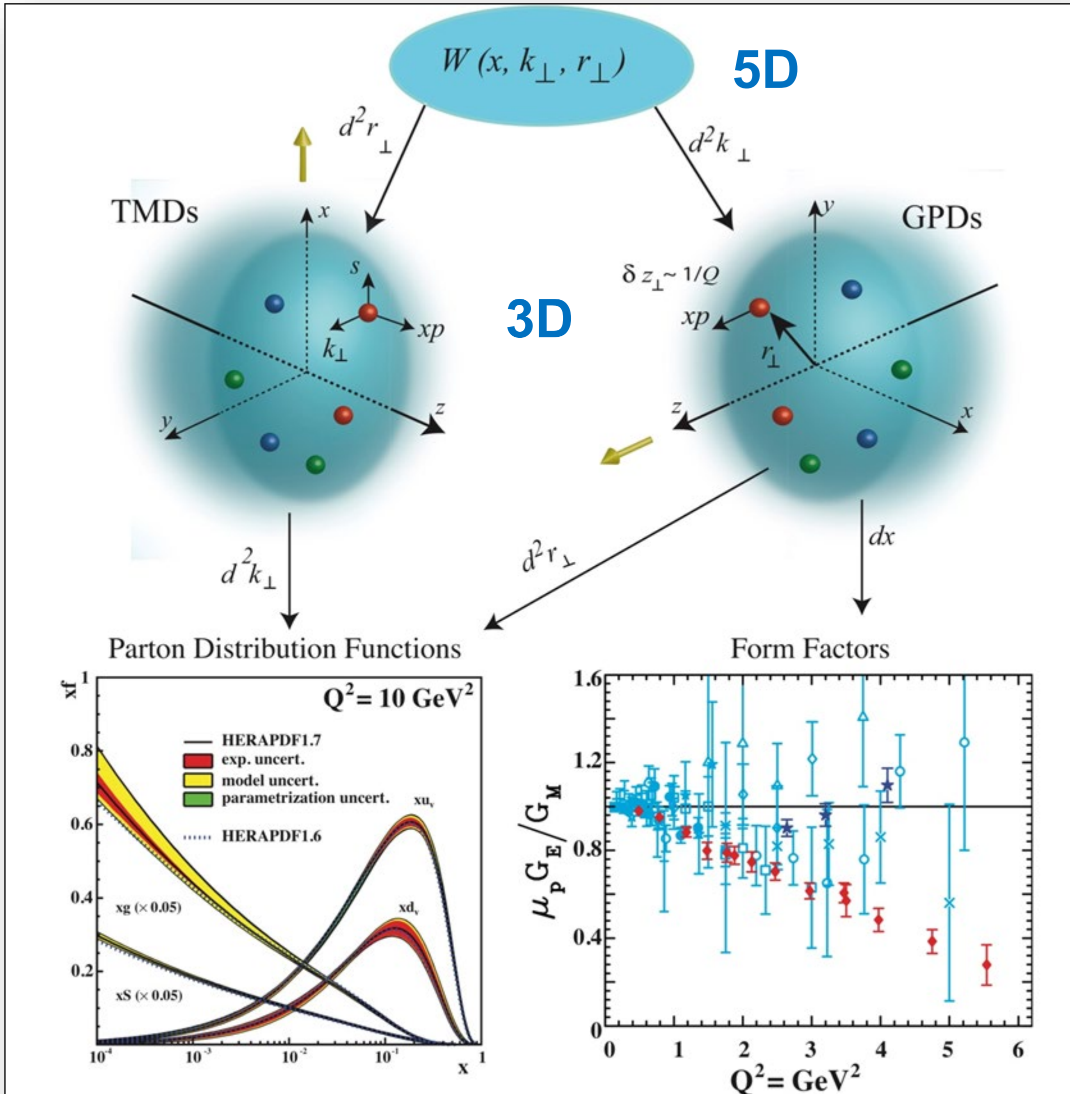
Also 1st measurements of ^{3}He (neutron) single-spin asymmetries

X. Qian *et al.*, PRL 107, 072003 (2011)

What? Multi-dimensional parton distributions? Let’s check it out….

- In general, parton distributions are 6 dimensional (*Wigner distributions*)
- 3D structure = GPDs in impact parameter space
- 3 dim. in coordinate space (GPDs) • 3 dim. in momentum space (TMDs)
- *X. Ji, PRL 91 (03)*
- *Collins, Rogers, Stasto, PRD77 (08)*

New Paradigm for Nucleon Structure



- TMDs
  - Confined motion in a nucleon (semi-inclusive DIS)
- GPDs
  - Spatial imaging (exclusive DIS)
- Requires
  - High luminosity
  - Polarized beams and targets

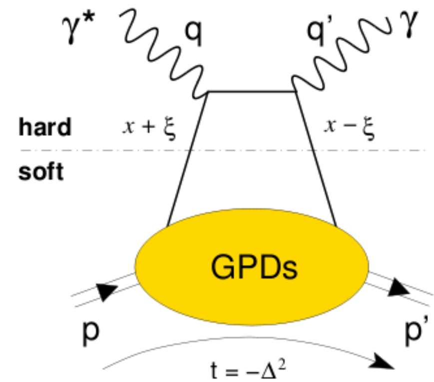
➡ Major new capability with JLab12

Nucleon Structure: the 3D World

- Generalized Parton Distributions: form factors of only those quarks in the nucleon carrying a certain fixed momentum fraction x

Deeply Virtual Compton Scattering (**DVCS**):

→ **GPDs** -- amplitude for "kicking out" a parton of the fast moving nucleon by the virtual photon and "putting it back" with a different momentum after radiating a real photon



$$P = \frac{p+p'}{2}$$

$$\Delta = p - p'$$

$$x = \frac{k^+}{P^+}$$

$$\xi = -\frac{\Delta^+}{2P^+}$$

→ **4 GPDs** defined through matrix elements of quark and gluon operators:

$$\boldsymbol{H(x,\xi,t)} \quad \boldsymbol{E(x,\xi,t)} \quad \boldsymbol{\widetilde{H}(x,\xi,t)} \quad \boldsymbol{\widetilde{E}(x,\xi,t)}$$

→ Pauli, Dirac form factors lowest x-moments of H and E: $\boldsymbol{F_1} = \int dx\, H(x,\xi,t)$ $\boldsymbol{F_2} = \int dx\, E(x,\xi,t)$

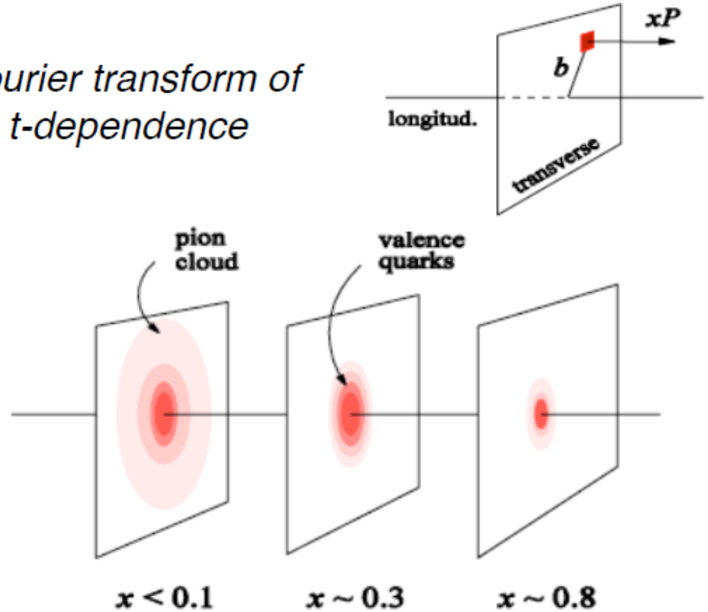
→ In the limit of p = p' H become the usual PDF: $H_q(x,\xi=0,t=0) = q(x) = \frac{1}{2}(\boldsymbol{q\uparrow(x) + q\downarrow(x)})$

$$\widetilde{H}_q(x,\xi=0,t=0) = \Delta q(x) = \frac{1}{2}(\boldsymbol{q\uparrow(x) - q\downarrow(x)})$$

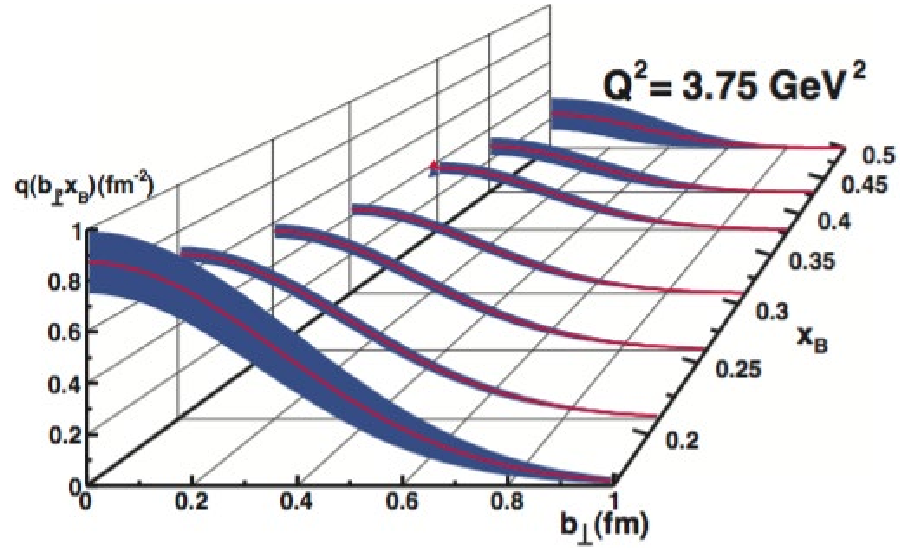
Hard Exclusive Processes → GPDs

Goal 1: Transverse Imaging of Nucleon

Fourier transform of t-dependence



The proton's transverse profile as function of the impact parameter b



Goal 2: Orbital Angular Momentum

Ji's Sum Rule for $J^q = \frac{1}{2}\Delta\Sigma + L^q$

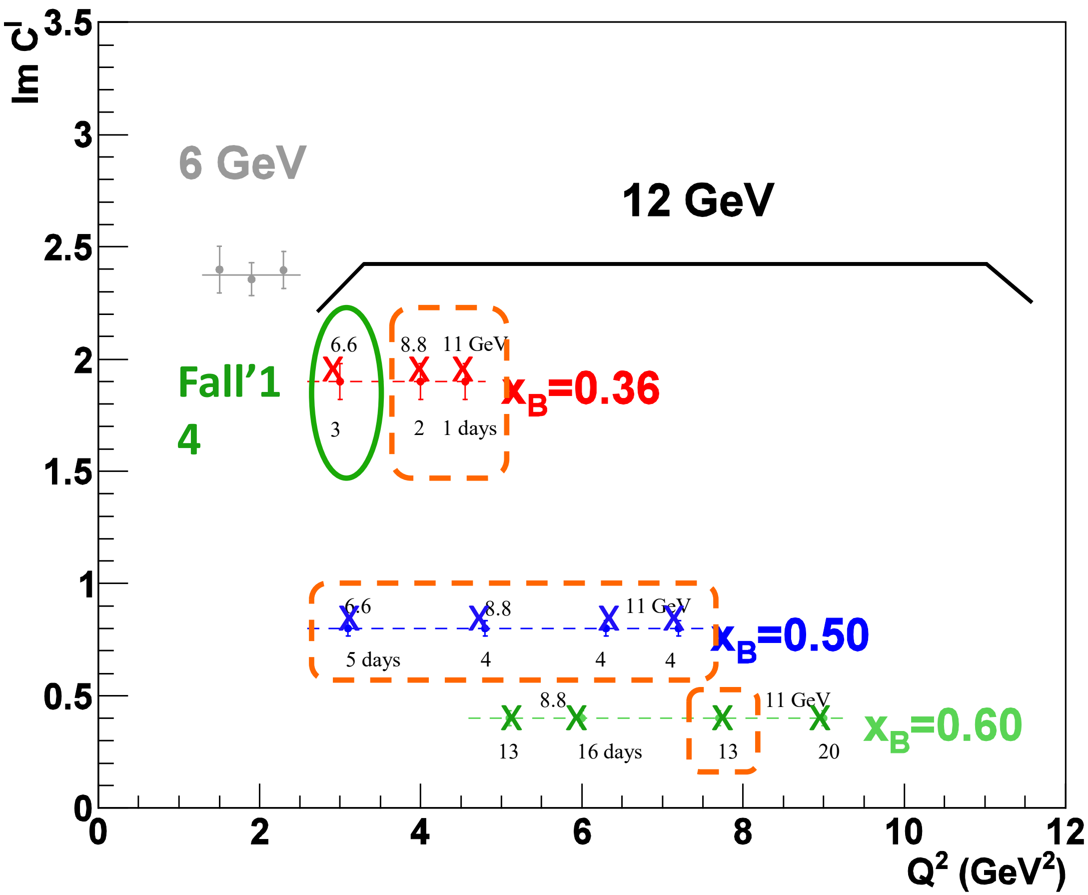
$$J^q = \frac{1}{2}\int_{-1}^{1} x\,dx\,[H^q(x,\xi,t=0) + E^q(x,\xi,t=0)]$$

CLAS12 with help from Halls A & C

DVCS-I and G_M^p: Concurrent Experiments in Hall A at 11 GeV

The 12 GeV era begins!

Original projections for 10 calendar weeks in Spring'16

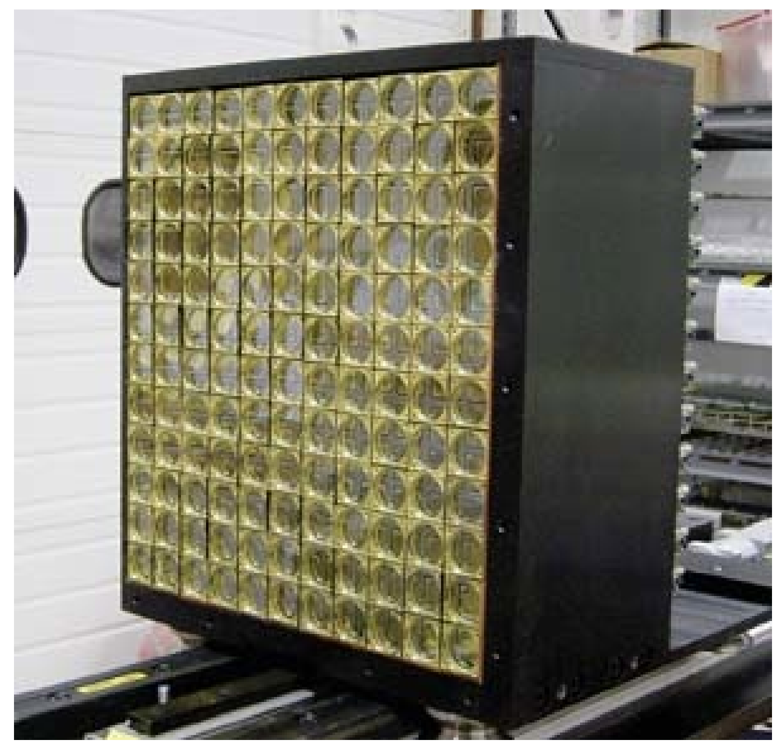


High impact experiment for 3D nucleon imaging

Deeply Virtual Compton Scattering (DVCS) provides access to Generalized Parton Distributions (GPDs)

Will provide highest available Q^2 measurement of the DVCS cross section

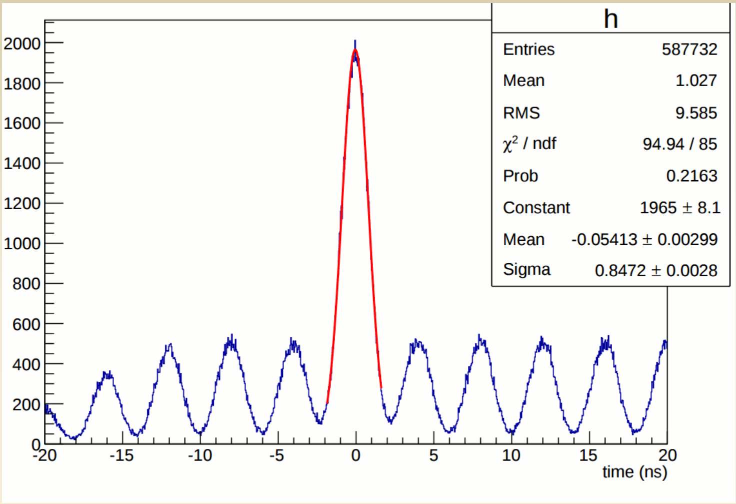
Demonstration of scaling critical to full JLab 12 GeV GPD program

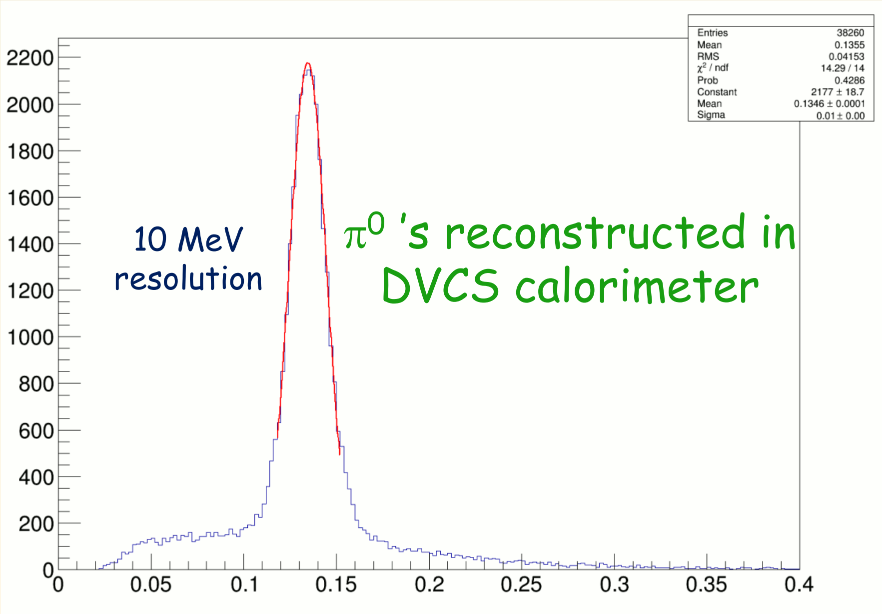


E12-06-114 DVCS/Hall A Experiment at 11 GeV

- **High impact experiment for nucleon 3D imaging program**
- High precision scaling tests of the DVCS cross section at constant x_B
- CEBAF12 will allow to explore for the first time the high x_B region

Excellent coincident time resolution:
250 MHz beam structure





Analysis path:

- **Jun'17:** Report at JLab Summer Meeting.
- **Jan'18:** Preliminary results on π^0 at x_B=0.36
- **Apr'18:** Preliminary results on DVCS
- **Jul'18 :** Short paper submitted to PRL on π^0
- **Jan'19:** Letter to PRL on DVCS
- **Jul'19:** Long paper to PRC (DVCS & pi0)

Transverse Momentum Structure of Nucleon – TMDs

(Quantum phase-space quark distribution in the nucleon)

5D

$$W_\Gamma(\mathbf{r},k) = \frac{1}{2M_N}\int \frac{d^3\mathbf{q}}{(2\pi)^3} e^{-i\mathbf{q}\cdot\mathbf{r}} \left\langle \mathbf{q}/2 \left| \hat{\mathcal{W}}_\Gamma(0,k) \right| -\mathbf{q}/2 \right\rangle$$

$$W_\Gamma(\mathbf{r},\mathbf{k}) = \int \frac{dk^-}{(2\pi)^2} W_\Gamma(\mathbf{r},k)$$

Integrate over *spatial* dimensions

Transverse Momentum-dependent Distributions (TMD)

3D 3D imaging of the nucleon in momentum space

Quark spin polarization

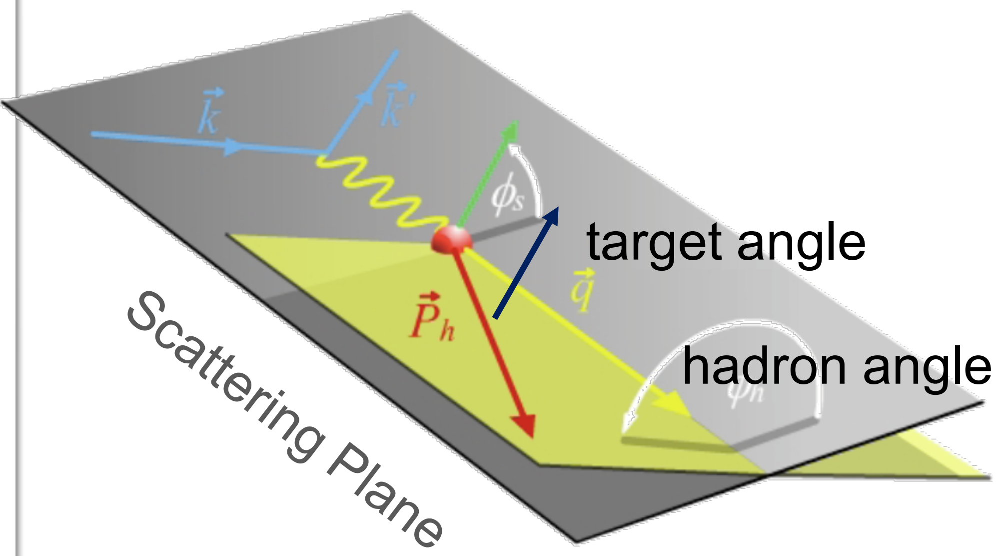
Nucleon polarization

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 $h_{1T}^\perp$

JLab has planned a complete SIDIS program with π/K to access quark TMDs

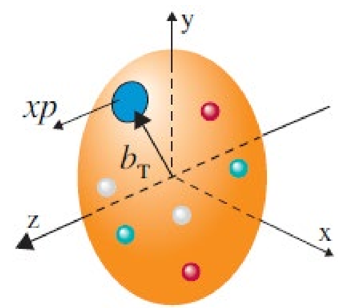
TMDs Accessible through Semi-Inclusive Physics

- Separate Sivers and Collins effects



Naturally, two scales:
- High Q: localized probe to "see" quarks and gluons
- Low P_T: sensitive to confining scale to "see" their confined motion

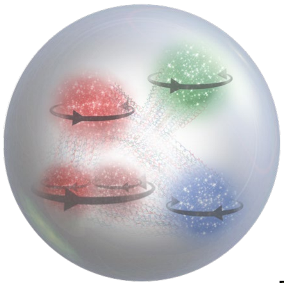
+ Theory input: TMD QCD factorization
TMD QCD evolution



- **Sivers** angle, effect in distribution function: $(\phi_h - \phi_s)$

  Or other combinations: Pretzelosity: $(3\phi_h - \phi_s)$
- **Collins** angle, effect in fragmentation function: $(\phi_h + \phi_s)$

Features of 3D Distributions/TMDs



$f^a(x, k_T^2; Q^2)$

Ex. TMD PDF for a given combination of parton and nucleon spins

$$\sigma = \sum_q e_q^2 f(x) \otimes D(z)$$

$$f^a(x, k_T^2; Q^2)$$

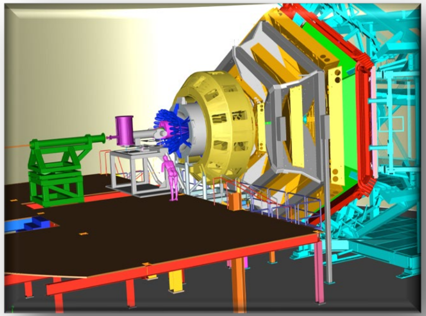
nucleon polarization \ quark polarization	U	L	T
U	f_1		$h_1^\perp$ Boer-Mulders
L		g_1 helicity	$h_{1L}^\perp$ worm-gear
T	$f_{1T}^\perp$ Sivers	g_{1T} worm-gear	h_1 transversity, $h_{1T}^\perp$ pretzelosity

- transverse position and momentum of partons are correlated with the spin orientations of the parent hadron and the spin of the parton itself
- transverse position and momentum of partons depend on their flavor
- transverse position and momentum of partons are correlated with their longitudinal momentum
- spin and momentum of struck quarks are correlated with remnant
- quark-gluon interaction play a crucial role in kinematical distributions of final state hadrons, both in semi-inclusive and exclusive processes

Together stronger: SIDIS Studies with 12 GeV

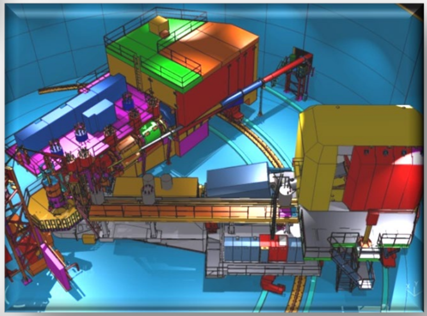
- **CLAS12 in Hall B**

  General survey, medium lumi



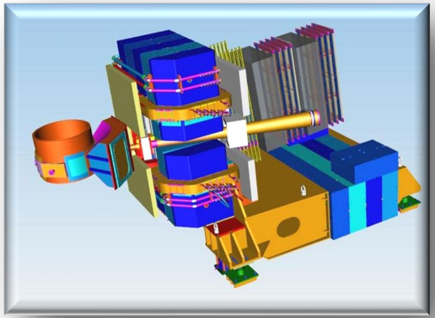
- **SHMS, HMS, NPS in Hall C**

  L-T studies, precise $\pi^+/\pi^-/\pi^0$ ratios



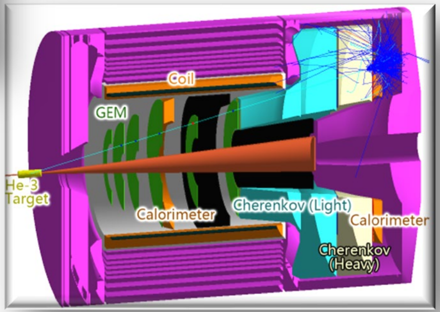
- **SBS in Hall A**

  High x, High Q^2, 2-3D



- **SOLID in Hall A**

  High lumi and acceptance – 4D



Hall C SIDIS Program (typ. $x/Q^2 \sim$ constant)

HMS + SHMS (or NPS) Accessible Phase Space for SIDIS; w. typical z range 0.3-0.65

Accurate cross sections for validation of SIDIS factorization framework and for L/T separations

E12-13-007

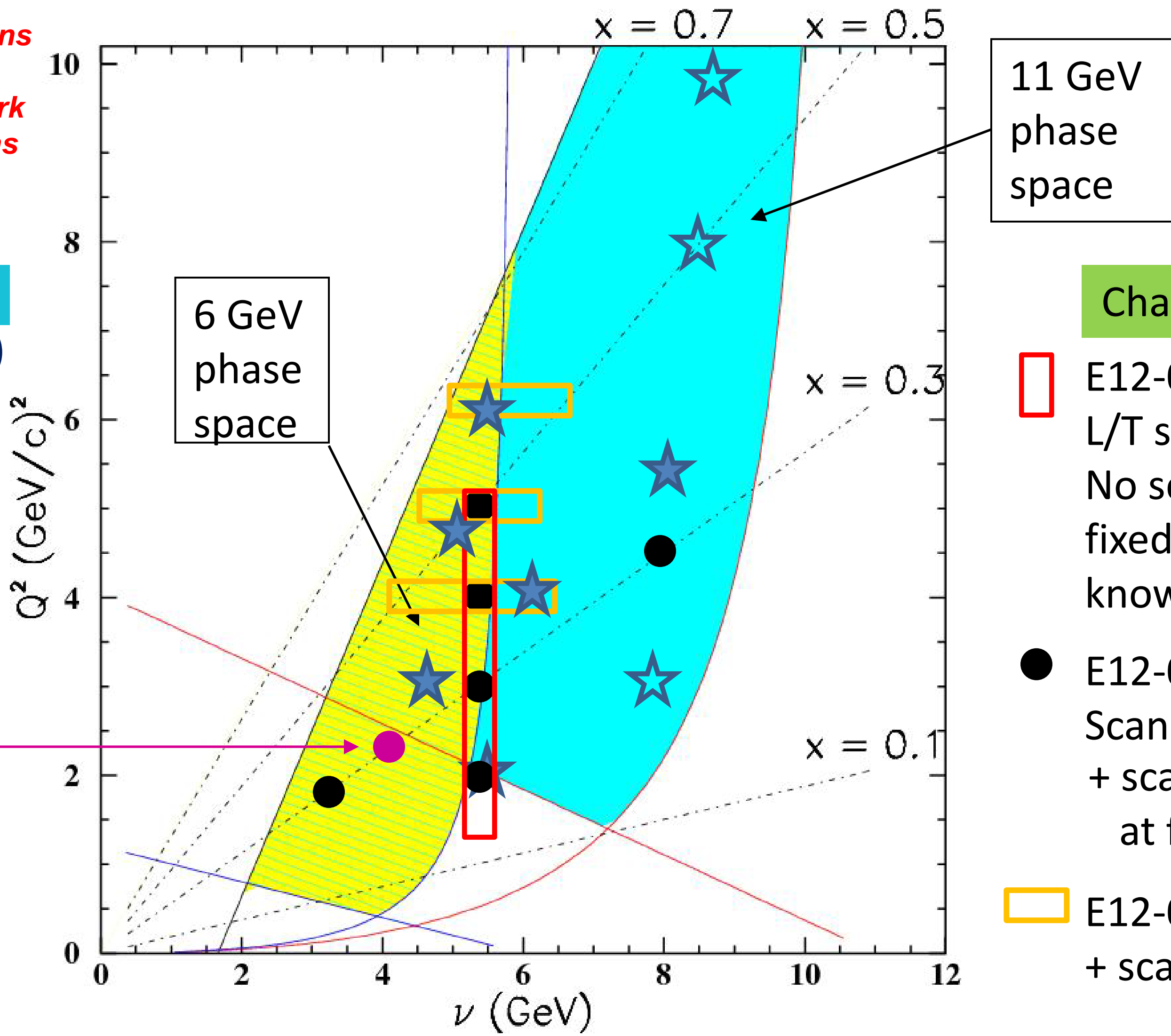
★ Neutral pions:

Scan in (x,z,P_T)

Overlap with E12-09-017 & E12-09-002

☆ Parasitic with E12-13-010

E00-108 (6 GeV)



Charged pions:

E12-06-104

L/T scan in (z,P_T)

No scan in Q^2 at fixed x: $R_{DIS}(Q^2)$ known

E12-09-017

Scan in (x,z,P_T)

+ scan in Q^2 at fixed x

E12-09-002

+ scans in z

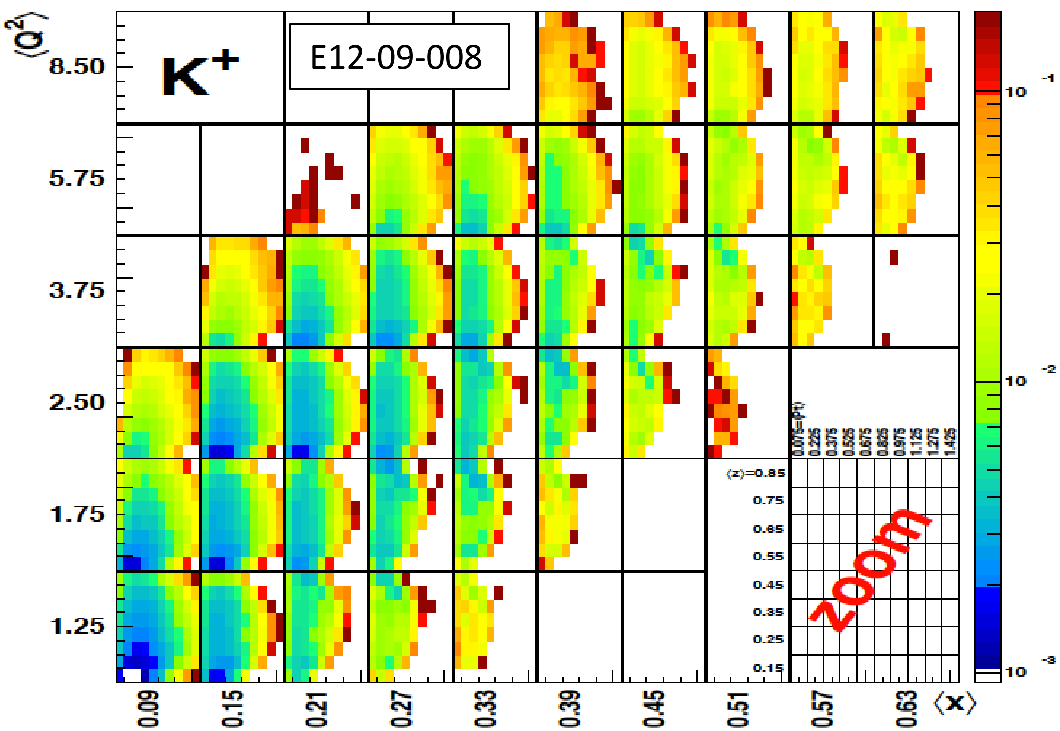
SIDIS π/K on unpolarized protons/deuterons

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 $h_{1T}^\perp$

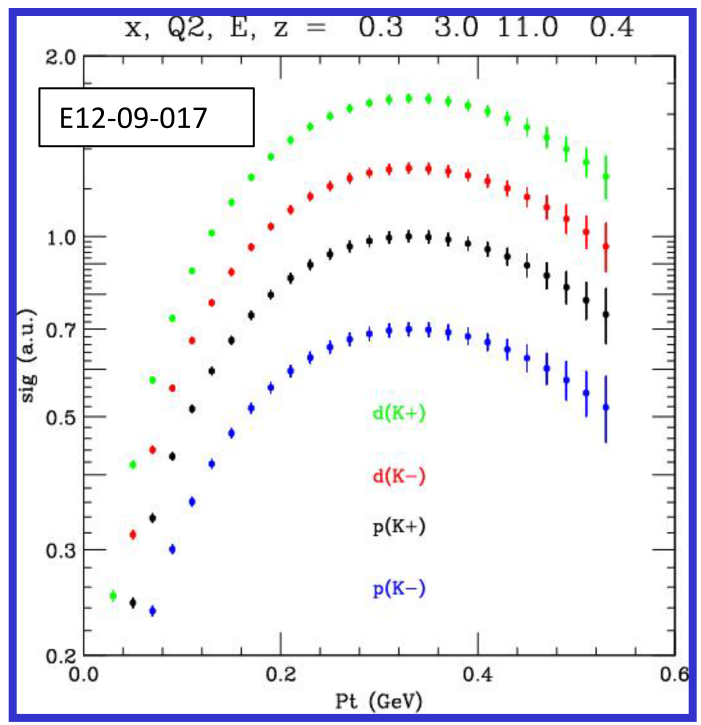
E12-06-112

$$\frac{d\sigma}{dx_B\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\,F_{LU}^{\sin\phi_h}\Big\},$$

Kaons

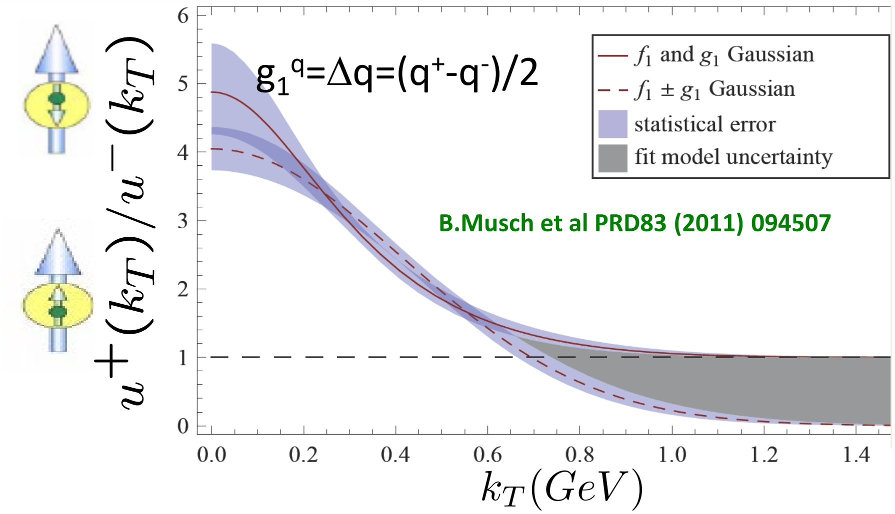


(CLAS12)



(Hall C, Kinematics II, z = 0.4 bin only)

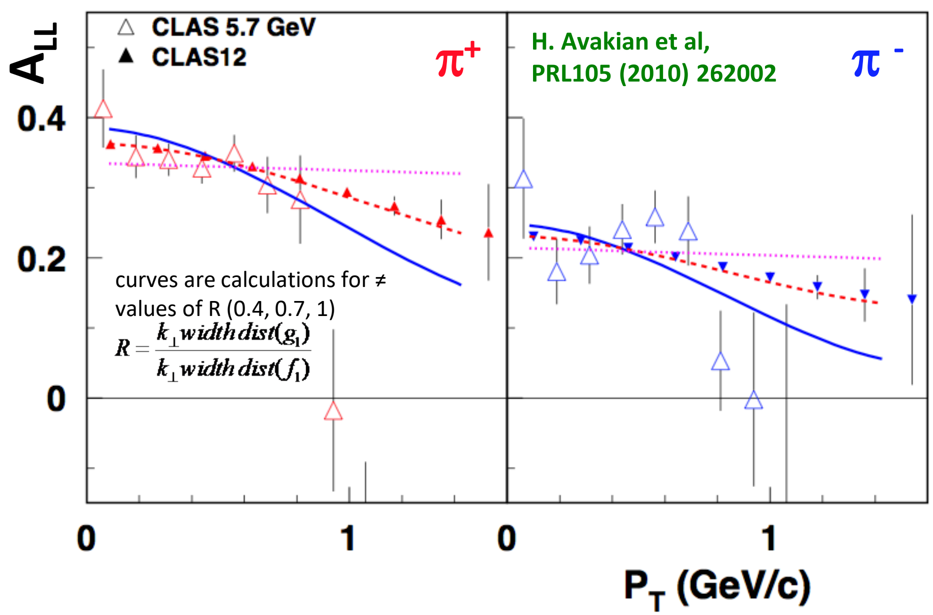
CLAS12: K_T Helicity Dependence



- Higher probability to find a quark anti-aligned with proton spin at **large k_T**
- Important to have q^+ and q^- **k_T** dependent distribution separately
- q^- sensitive to orbital motion:

$$q^-_{L=1} \sim (1-x)^5 log^2(1-x)$$

H. Avakian et al. PRL 99 (2007) 082001



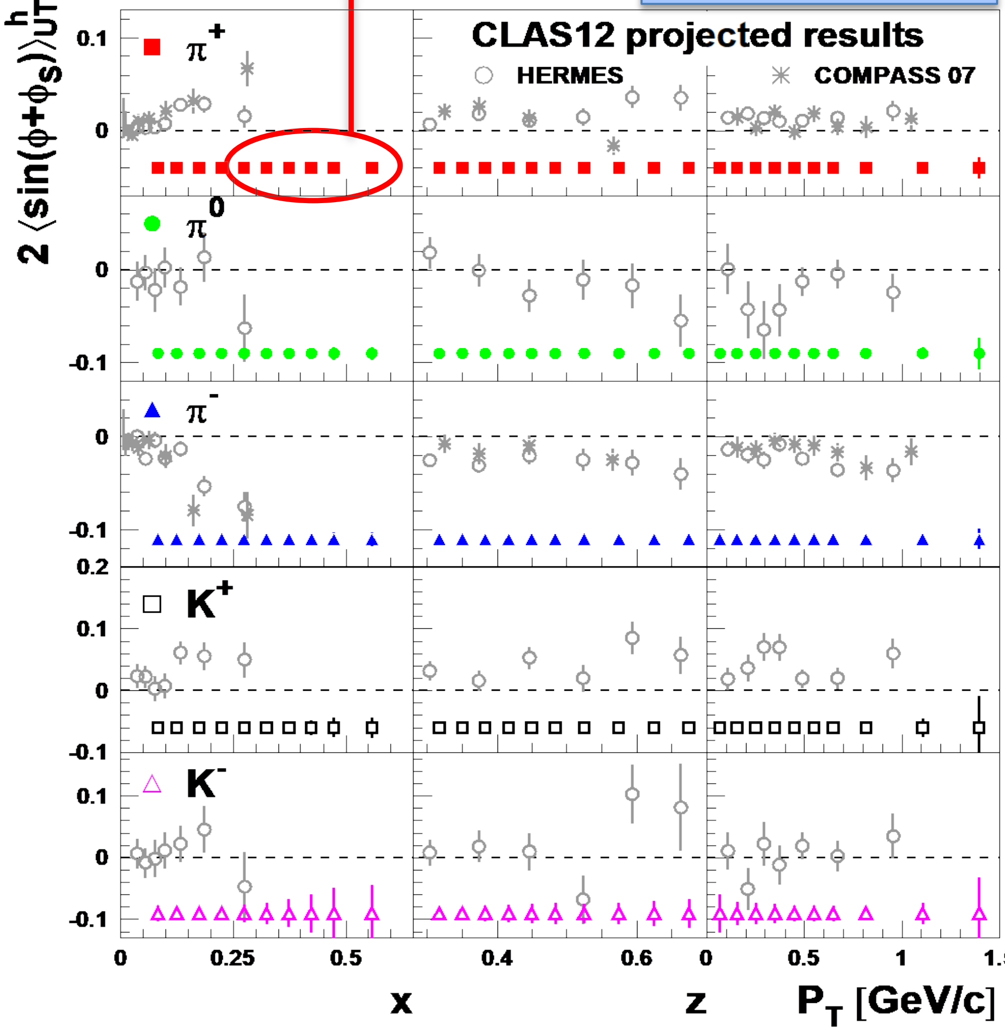
- Double spin asymmetries from CLAS@JLab consistent with wider **k_T** distributions for f_1 than for g_1
- **Wider range in P_T from CLAS12 is crucial !**

Measurements of the P_T-dependence of A_{LL} ($\propto g_1/f_1$) provide access to transverse momentum distributions of quarks anti-aligned with the proton spin.

Transversity with CLAS12

Large x important to constrain the tensor charge

Single Hadron

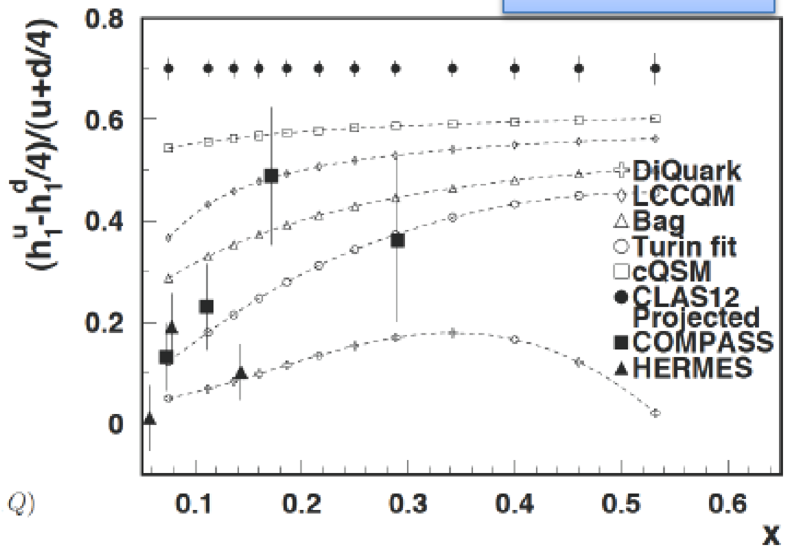


High Impact Exp. From PAC41 (C12-11-111 + C12-12-009)

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

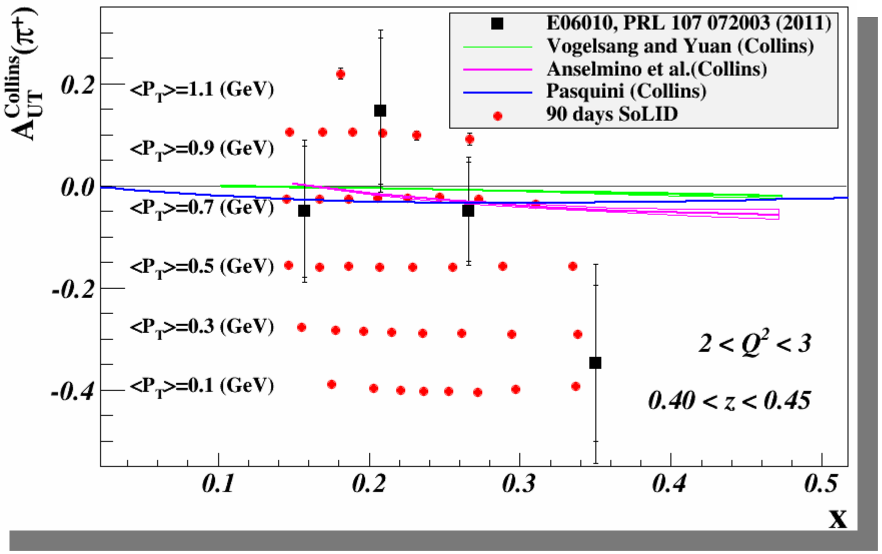
- HD-transversely polarized target and CLAS12

Di-hadron

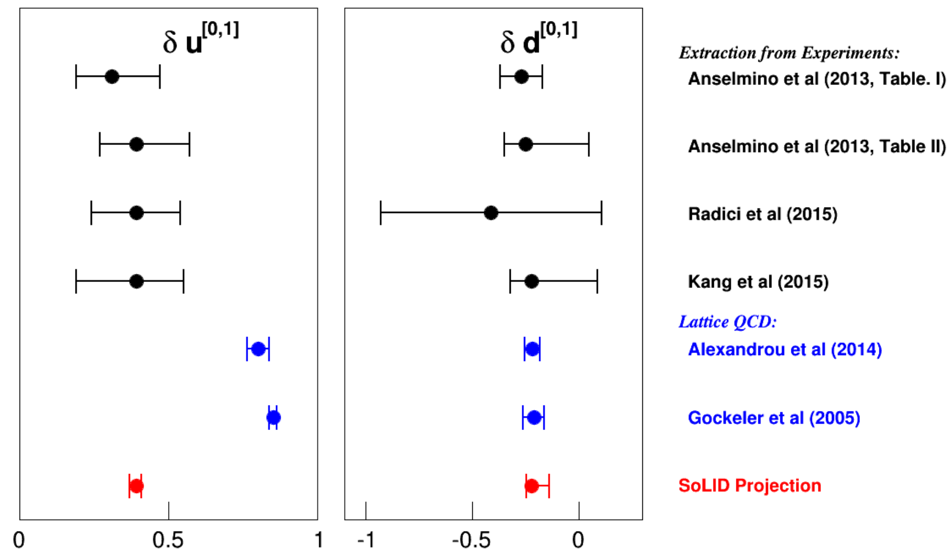


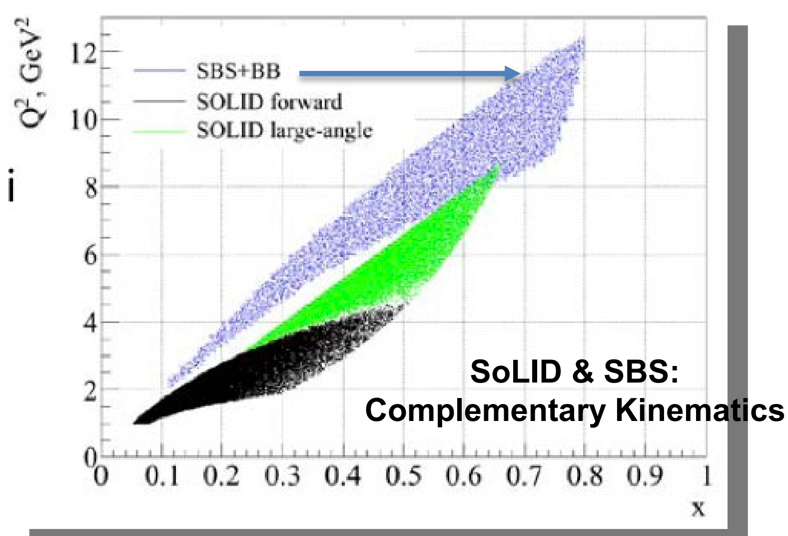
TMD Program in Hall A with SoLID & SBS

(match large acceptance devices at high luminosity to anticipated polarized 3He target performance)



Tensor Charges



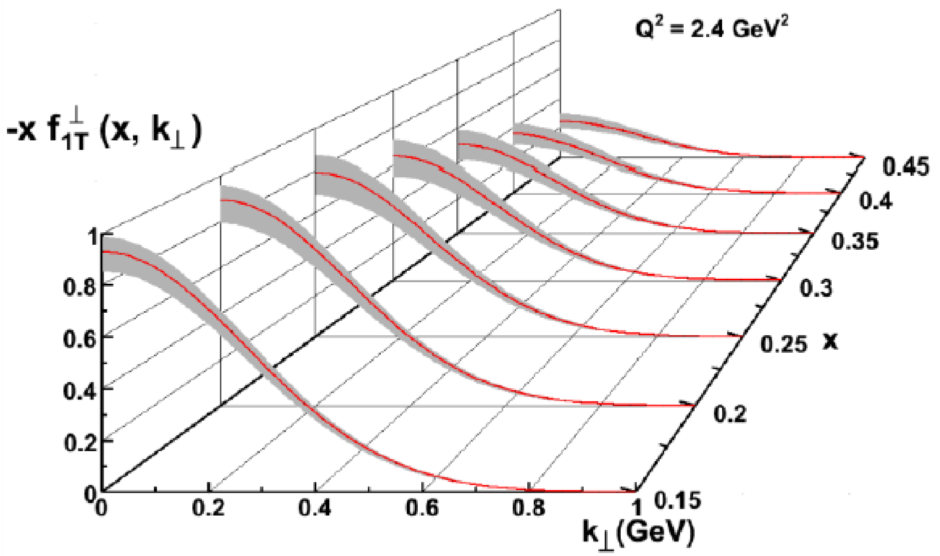


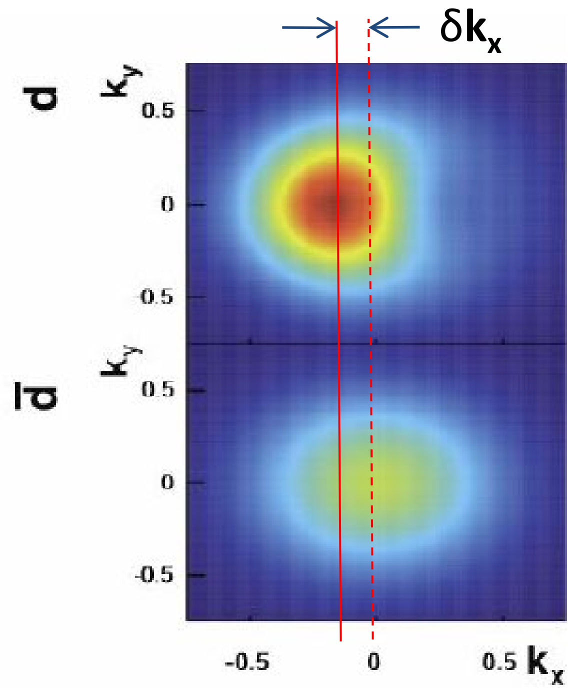
SoLID projection extraction by A. Prokudin using **only** statistical errors and based on:

- a set of data with a limited range of x values
- the assumption of a negligible contribution from sea quarks
- assumption on Q^2 evolution
- model dependent assumptions on the shape of underlying TMD distributions

Momentum Tomography with TMDs

Sivers function for d-quarks extracted from model simulations with a transverse polarized ^{3}He target.



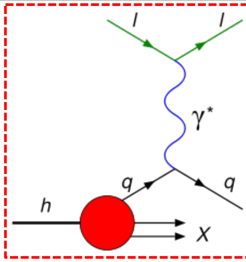


- Requires global fitting effort
- Access to orbital angular momentum

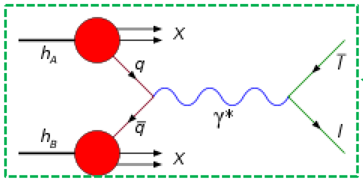
d-quark momentum tomography for Sivers function. The d-quark momentum density shows a distortion and shift in $\mathbf{k_x}$. A non-zero $\delta\mathbf{k_x}$ value requires a non-zero orbital angular momentum.

Much Data = Parton Distributions Functions

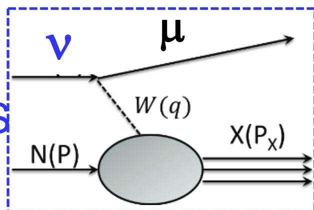
charged lepton DIS: CERN, SLAC, JLab



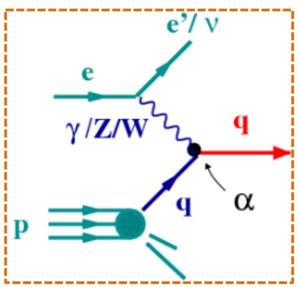
Drell-Yan: Fermi Lab



neutrino DIS

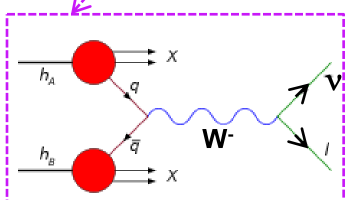


charged lepton DIS, high energy: HERA



Example of global data set used to extract nucleon's unpolarized, 1D PDFs (The NNPDFs Collaboration)

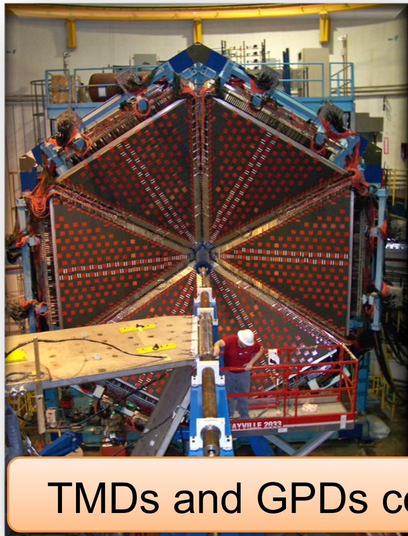
	Process	Partons	x range
fixed target	$\ell^\pm \{p,n\} \to \ell^\pm X$	$q, \bar{q}, g$	$x \gtrsim 0.01$
	$\ell^\pm n/p \to \ell^\pm X$	d/u	$x \gtrsim 0.01$
	$pp \to \mu^+\mu^- X$	$\bar{q}$	$0.015 \lesssim x \lesssim 0.35$
	$pn/pp \to \mu^+\mu^- X$	$\bar{d}/\bar{u}$	$0.015 \lesssim x \lesssim 0.35$
	$\nu(\bar{\nu}) N \to \mu^-(\mu^+) X$	$q, \bar{q}$	$0.01 \lesssim x \lesssim 0.5$
	$\nu N \to \mu^-\mu^+ X$	s	$0.01 \lesssim x \lesssim 0.2$
	$\bar{\nu} N \to \mu^+\mu^- X$	$\bar{s}$	$0.01 \lesssim x \lesssim 0.2$
collider	$e^\pm p \to e^\pm X$	$g, q, \bar{q}$	$0.0001 \lesssim x \lesssim 0.1$
	$e^+ p \to \bar{\nu} X$	d, s	$x \gtrsim 0.01$
	$e^\pm p \to e^\pm c\bar{c} X$	c, g	$0.0001 \lesssim x \lesssim 0.01$
	$e^\pm p \to \text{jet} + X$	g	$0.01 \lesssim x \lesssim 0.1$
	$p\bar{p} \to \text{jet} + X$	g, q	$0.01 \lesssim x \lesssim 0.5$
	$p\bar{p} \to (W^\pm \to \ell^\pm \nu) X$	$u, d, \bar{u}, \bar{d}$	$x \gtrsim 0.05$
	$p\bar{p} \to (Z \to \ell^+\ell^-) X$	d	$x \gtrsim 0.05$

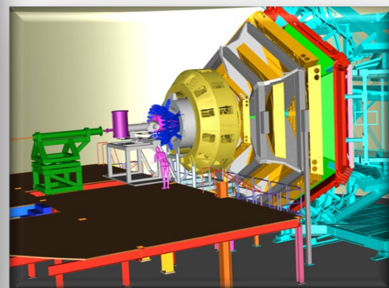


Fermi Lab Tevatron

12 GeV (GPD/TMD) Scientific Capabilities

Hall B **– understanding nucleon structure via generalized parton distributions**

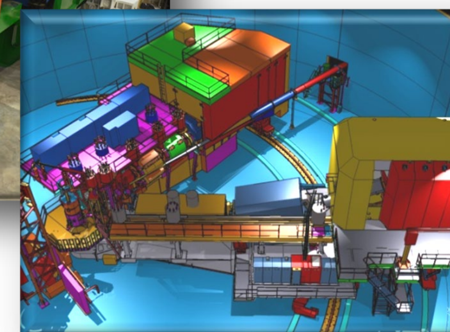




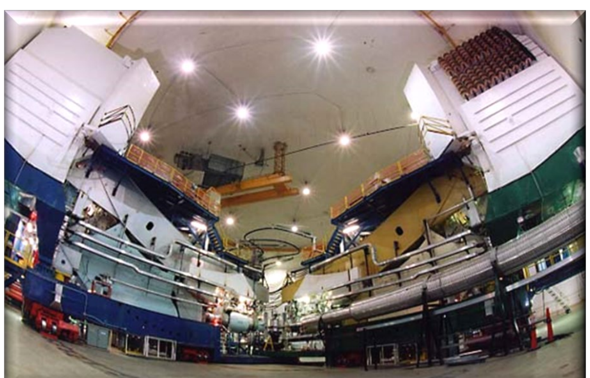
TMDs and GPDs comprehensive study

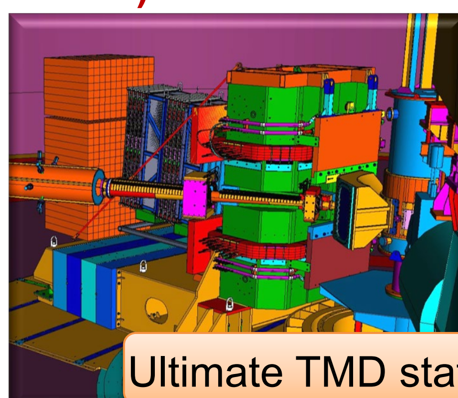
Hall C **– precision determination of valence quark properties in nucleons/nuclei**

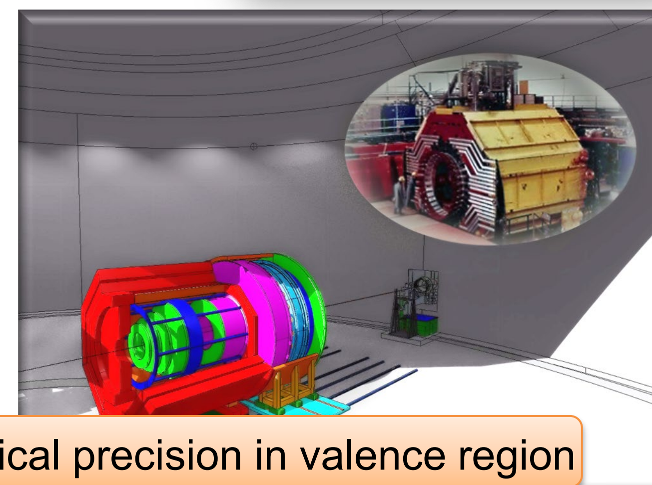
SIDIS/DES cross-section factorization tests



Hall A **– polarized 3He, future new experiments (e.g., SBS, MOLLER and SoLID)**







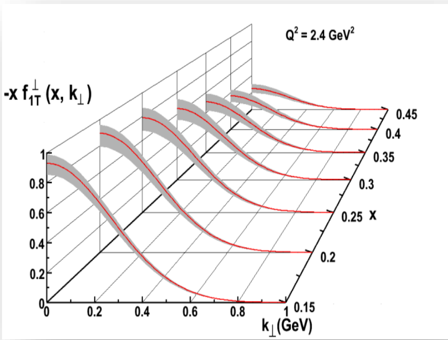
Ultimate TMD statistical precision in valence region

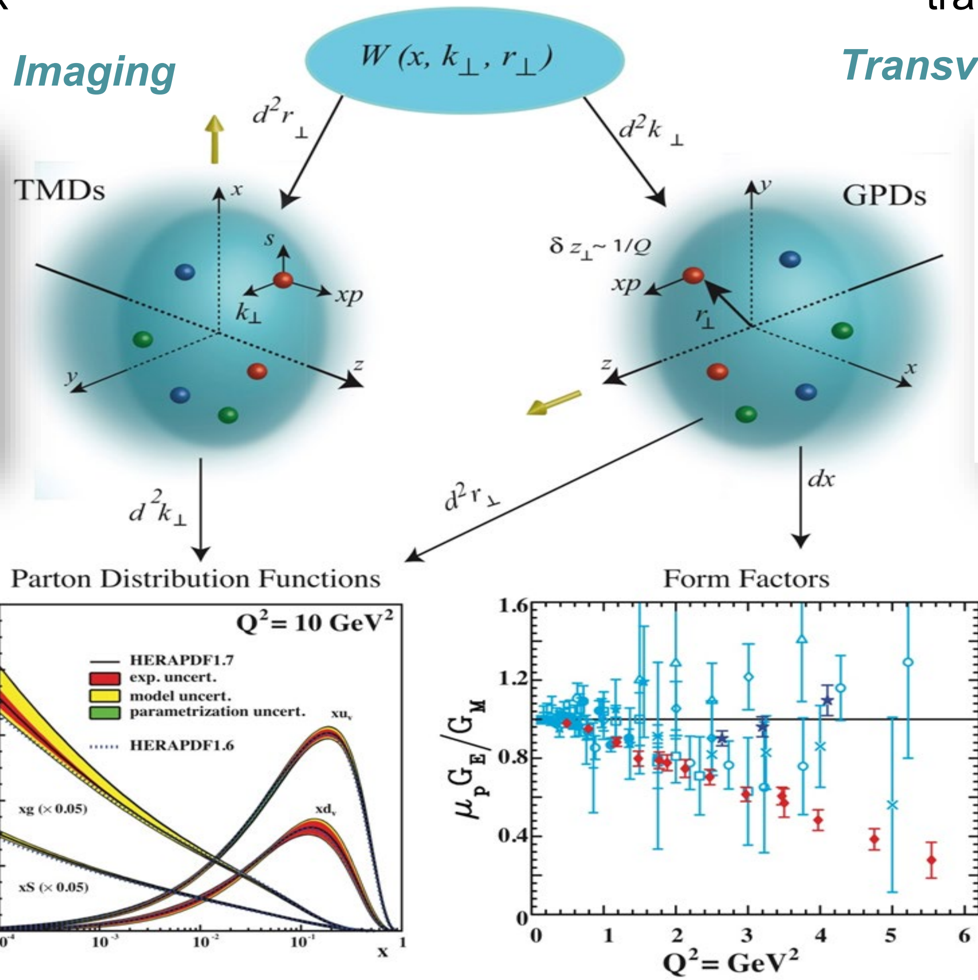
3D Mapping of the Nucleon

TMDs: Longitudinal momentum fraction x and transverse momentum k

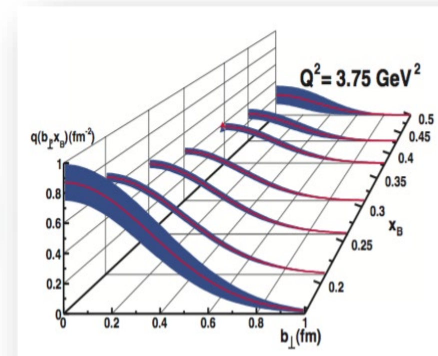
GPDs: Longitudinal momentum fraction x at transverse location b

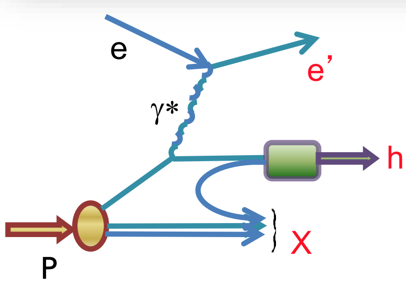
Transverse Momentum Imaging

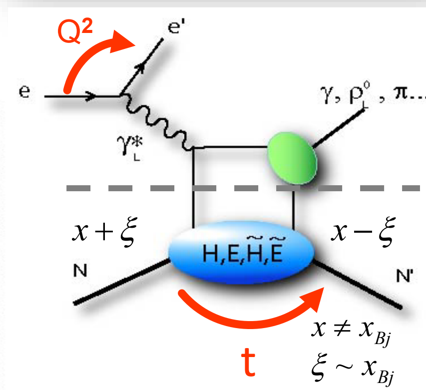




Transverse Spatial Imaging

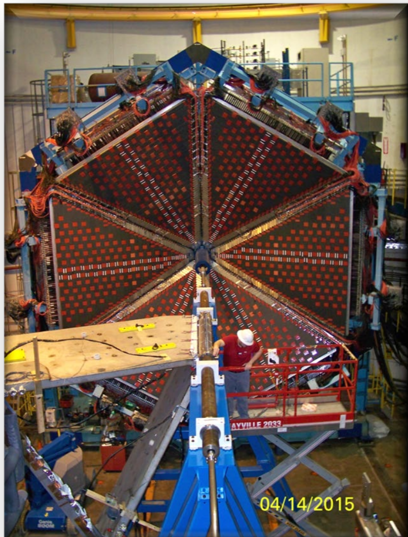


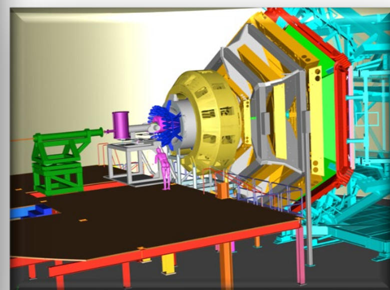




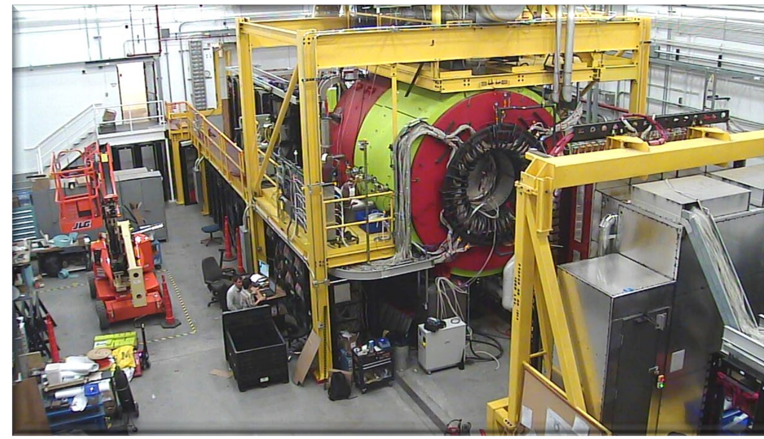
Numerous 12 GeV Scientific Capabilities *– many undiscussed*

Hall B – understanding nucleon structure via generalized parton distributions

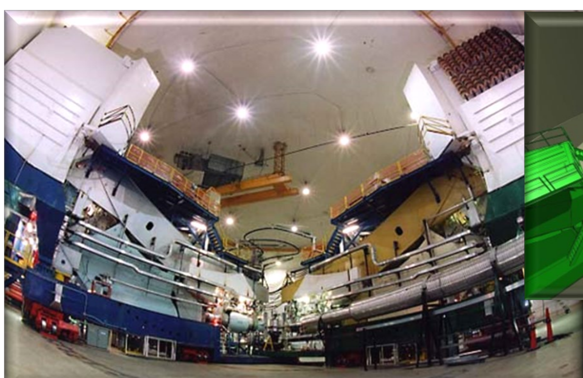


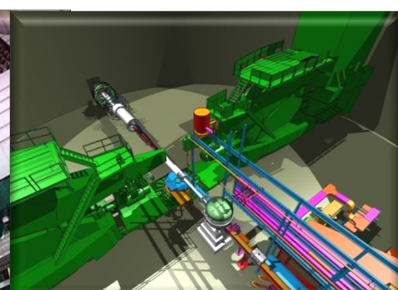


Hall D – exploring origin of confinement by studying exotic mesons

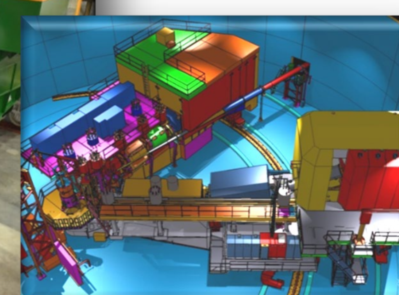


Hall A – form factors, future new experiments (e.g., SoLID and MOLLER)





Hall C – precision determination of valence quark properties in nucleons/nuclei



Hall D: Gluonic Excitations and the Mechanism for Confinement

QCD predicts a rich spectrum of as yet to be discovered gluonic excitations - whose experimental verification is crucial for our understanding of QCD in the confinement regime.

With the upgraded CEBAF, a linearly polarized photon beam, and the **GlueX detector**, Jefferson Lab will be uniquely poised to: - discover these states

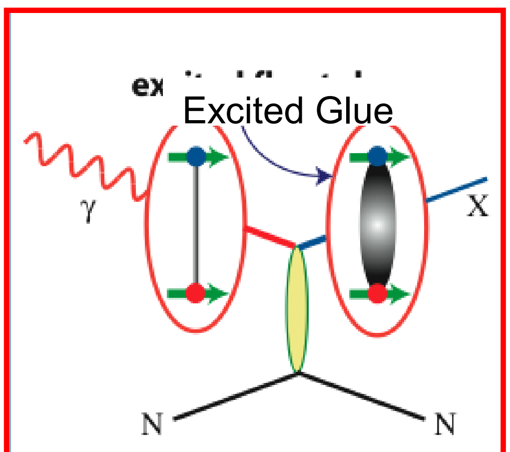
- map out their spectrum
- measure their properties

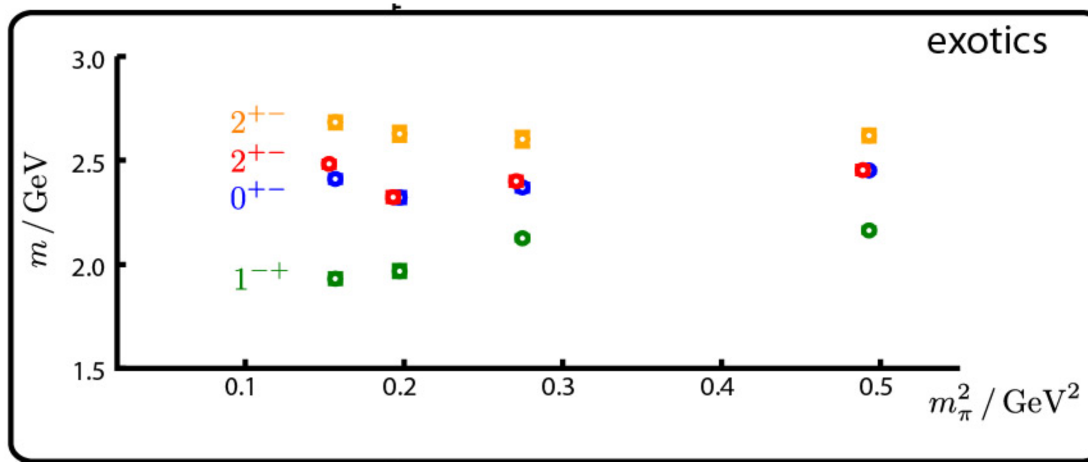
12 GeV electrons

States with Exotic Quantum Numbers

Dudek et al.

γ beam

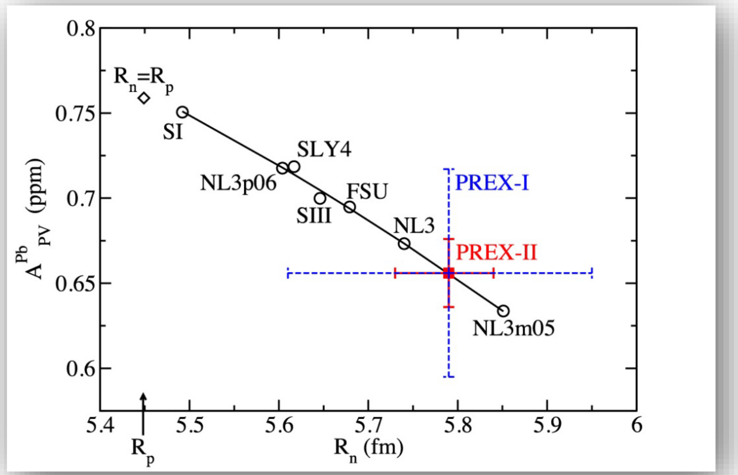




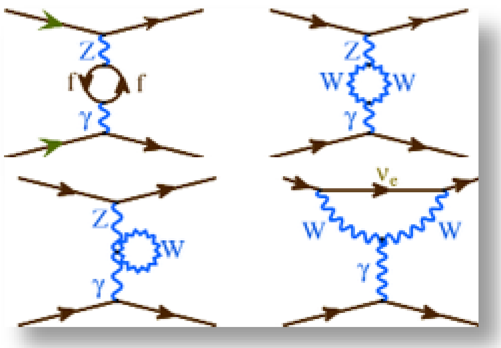
Parity Violation Program at JLab

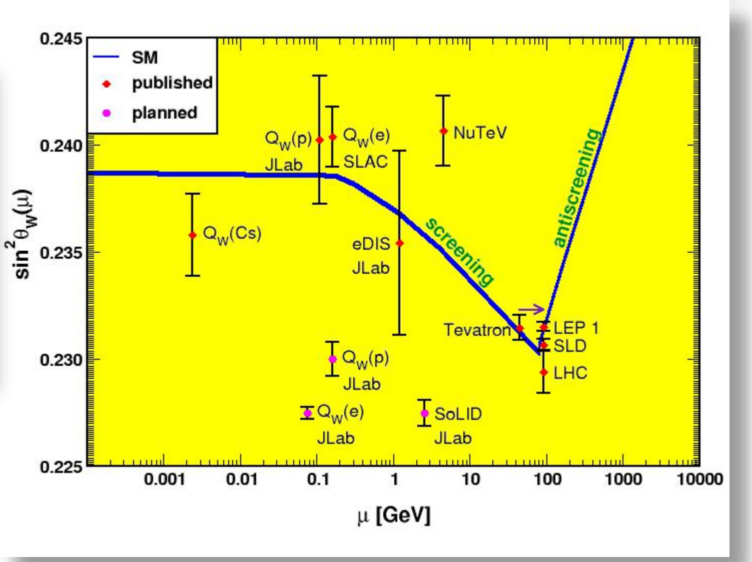
- Strangeness Form Factors (complete)
  - HAPPEX (Hall A)
  - G0 (Hall C)

Luminosity, polarization



- PREX neutron skin
  - first PREX (^{208}Pb) experiment completed
  - PREX-II and CREX (^{48}Ca) preparation ongoing
- Qweak (to be released)
  - proton weak charge
  - lepto-quark couplings

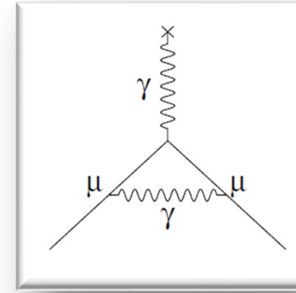


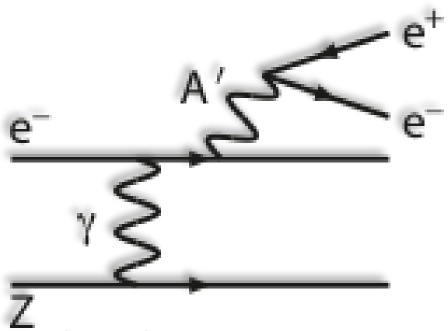


- MOLLER
  - electron weak charge
  - purely leptonic
- SoLID
  - lepto-quark couplings
  - lepto-phobic Z'
  - d/u, higher-twist

New Opportunity: Searches for A’ at Jefferson Lab

- BNL “g-2” expt: $\Delta a_\mu(\text{expt-thy}) = (295 \pm 88) \times 10^{-11}$ (3.4 σ)
- No evidence for SUSY at LHC (yet)
- Another solution: A’, a massive neutral vector boson

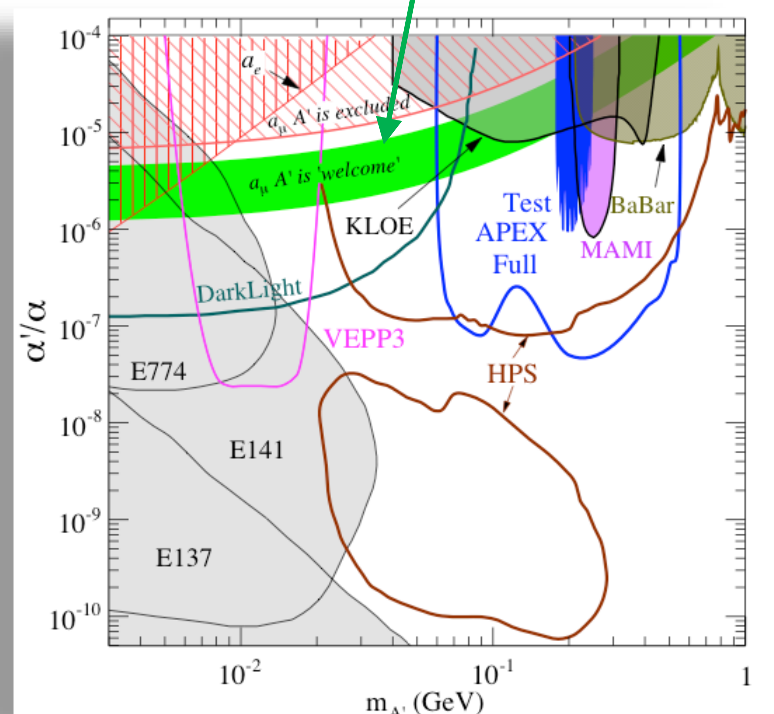




  - also useful for dark matter models

- 3 Jefferson Lab proposals:
  - APEX test run (Hall A) – published
  - HPS test run (Hall B) – complete
    HPS engineering/1st physics run – complete
  - DarkLight test run (FEL) – complete

g – 2 preferred!



Questions?....