Spin Physics at JLab

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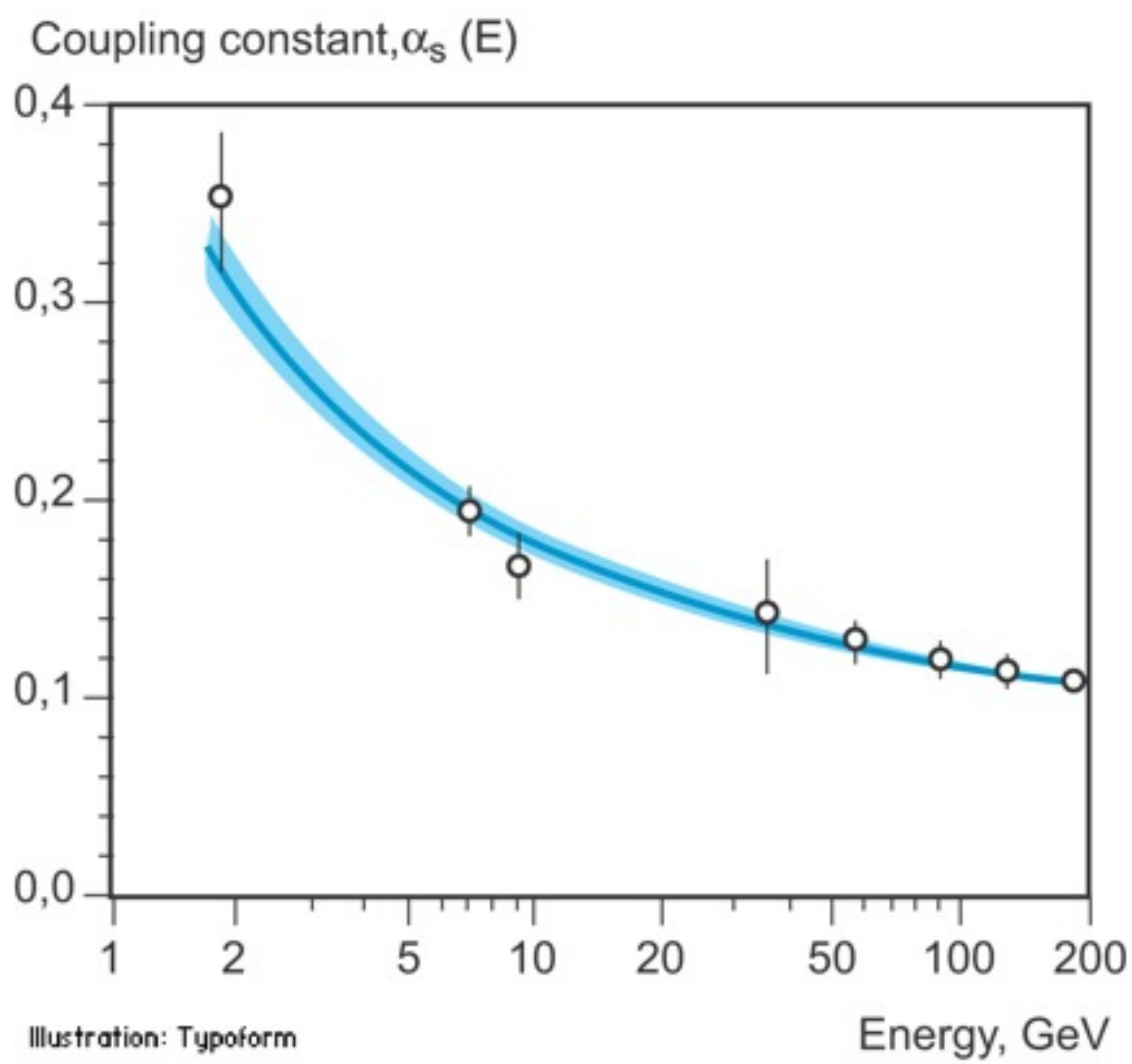
PacSPIN 2011 Cairns, Australia

Contents

Quarks, Gluons & QCD



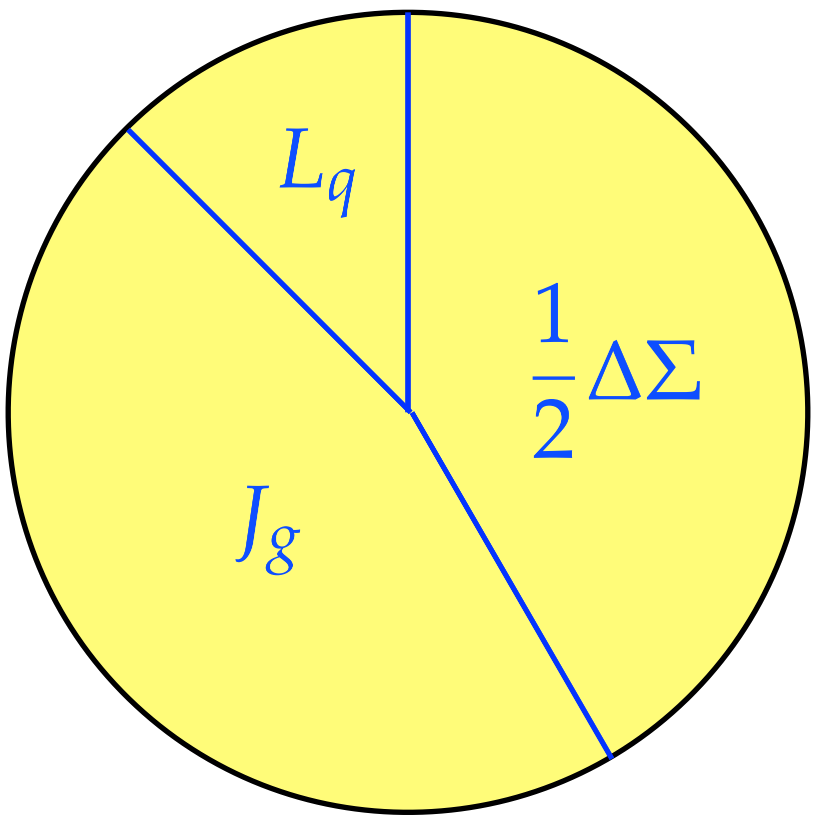
- Asymptotic freedom to Non-perturbative region
- One of the major challenges in current nuclear physics
- Spin structure is one of important tests.

Nucleon Spin Structure

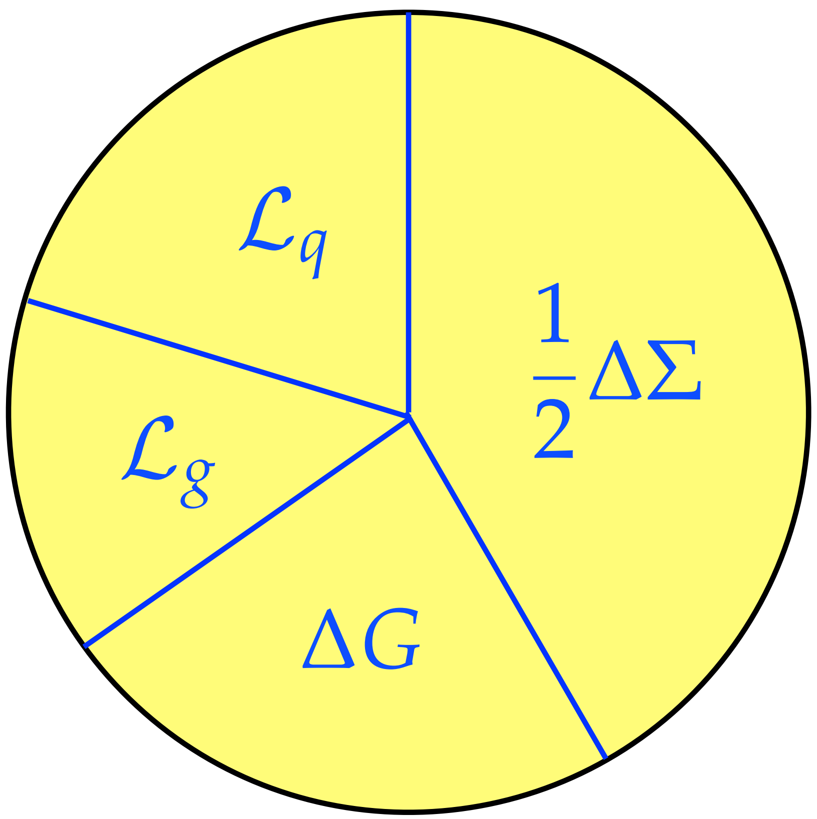
- Explaining nucleon spin in terms of quarks and gluons (QCD)
  - Nucleon spin is 1/2
    - De-composition is not trivial

Nucleon Spin Pizza

Ji



Jaffe & Manohar



Only $\frac{1}{2}\Delta\Sigma = \frac{1}{2}\sum_q \Delta q$ common to both decompositions!

More on the decomposition, Cho's Talk Today 11:40

Nucleon Spin Structure

- Explaining nucleon spin in terms of quarks and gluons (QCD)
  - Nucleon spin is 1/2
    - De-composition is not trivial
    - ~30% from quark spins
    - Little or no polarized gluons

Solving the Puzzle

- Spin structure functions g_1 and g_2
  - Electron scattering on polarized targets (p, d, ^{3}He)
- Gluon polarization
  - Direct measurement from polarized pp scattering (PHENIX, STAR)
  - QCD evolution from spin structure functions
- Orbital Angular Momentum (OAM)
  - Partly from Generalized Parton Distributions

Related Talks

- Fields (Next talk) OAM at RHIC
- Okada (11:00) Delta G at PHENIX
- Wakamatsu (12:20) OAM extraction

Polarized DIS

- Deep Inelastic Scattering
  - with polarized electron beams
  - and polarized targets
- Probes spin states of the quarks
- Spin structure functions, g_1 and g_2
  - 2 different target polarization directions

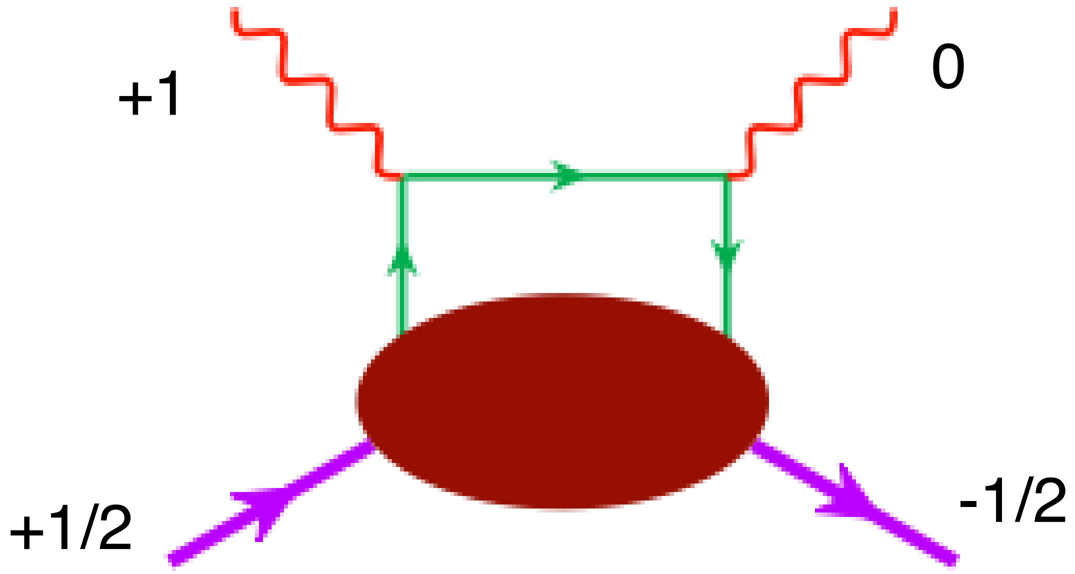
Spin Structure Functions

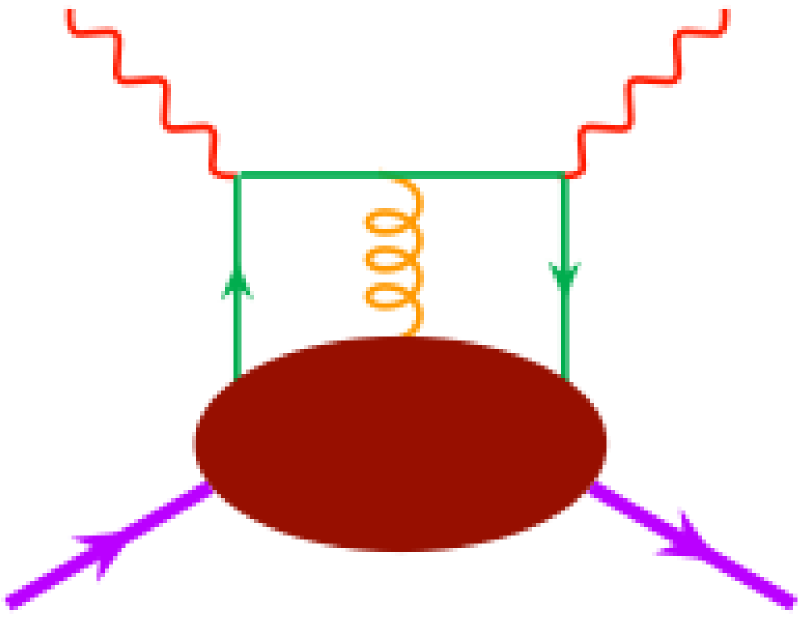
- g_1 : easy to understand, relatively easy to measure
$$g_1(x,Q^2) = \frac{1}{2}\sum_i e_i^2 \left[q_i^{\uparrow}(x,Q^2) - q_i^{\downarrow}(x,Q^2)\right]$$
- g_2 : more complex
  - $g_2 = 0$ in naive quark model
  - sensitivity with target polarization perpendicular to beam polarization

g_2 and Higher Twists

- Decomposition of g_2

$$g_2(x, Q^2) = g_2^{WW}(x, Q^2) + \bar{g}_2(x, Q^2)$$





g_2 and quark-gluon correlations

- a twist-2 term (Wandzura-Wilcek)

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 g_1(x,Q^2)\,dx$$

- a twist-3 term with a suppressed twist-2 piece

$$\bar{g}_2(x,Q^2) = -\int_x^1 \frac{\partial}{\partial y}\left[\frac{m_q}{M}\boxed{h_T(y,Q^2)} + \boxed{\xi(y,Q^2)}\right]\frac{dy}{y}$$

Transversity

qg correlations

Color Polarizability d_2

- 2^{nd} moment of g_2-g_2^{WW}

  d_2: twist-3 matrix element

$$d_2(Q^2) = 3\int_0^1 x^2[g_2(x,Q^2) - g_2^{WW}(x,Q^2)]dx$$

$$= \int_0^1 x^2[2g_1(x,Q^2) + 3g_2(x,Q^2)]dx$$

d_2 and g_2-g_2^{WW}: clean access of higher twist (twist-3) effect: q-g correlations

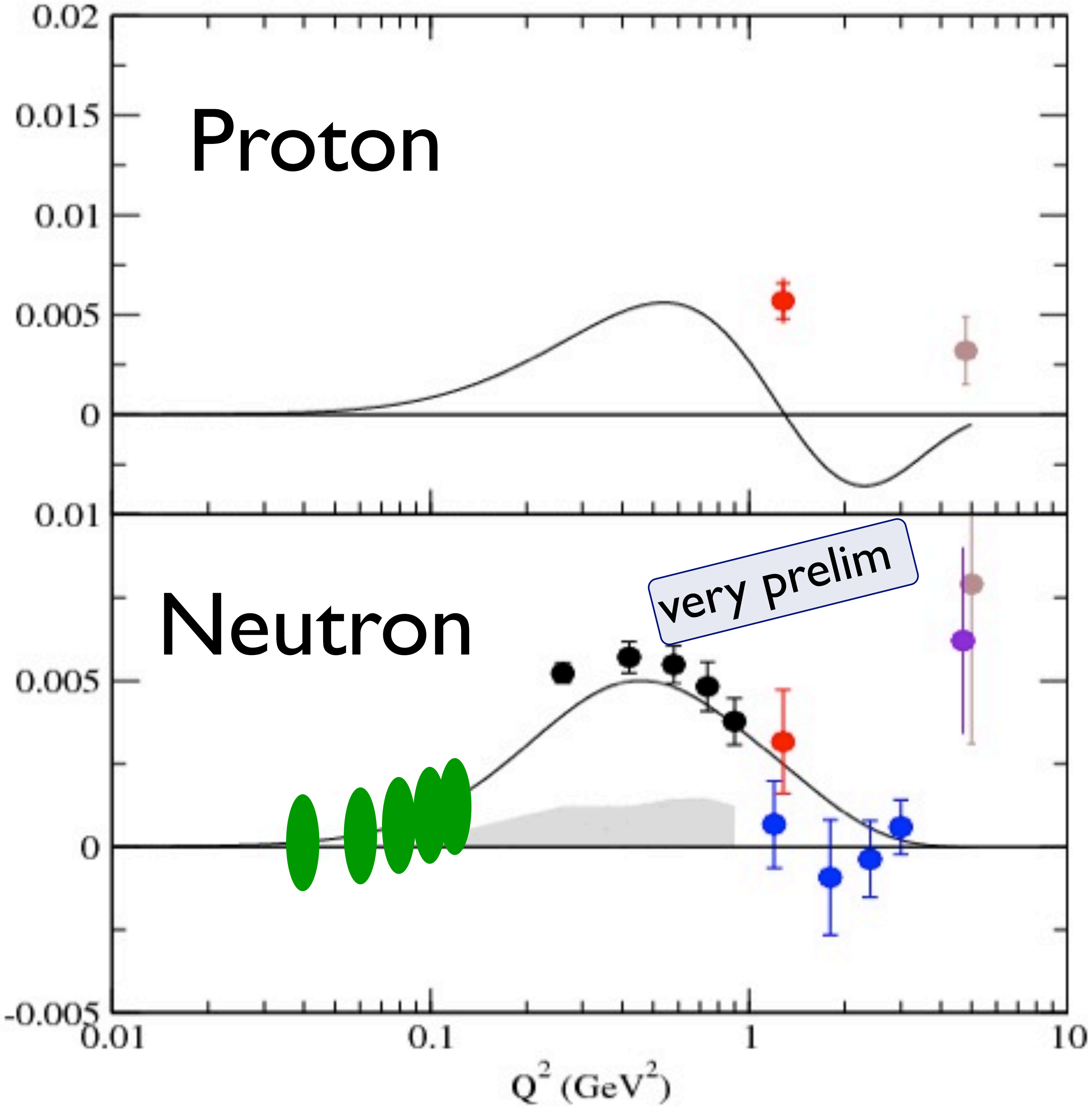
Color polarizabilities χ_E,χ_B are linear combination of d_2 and f_2

Provide a benchmark test of Lattice QCD at high Q^2

Avoid issue of low-x extrapolation

Relation to Sivers and other TMDs?

$d_2(Q^2)$



RED : RSS. (Hall C, NH_3,ND_3)

BLUE: E01-012. (Hall A, ^3He)

GREEN: E97-110. (Hall A, ^3He)

"d2n" completed in Hall A, more details in Chen's talk

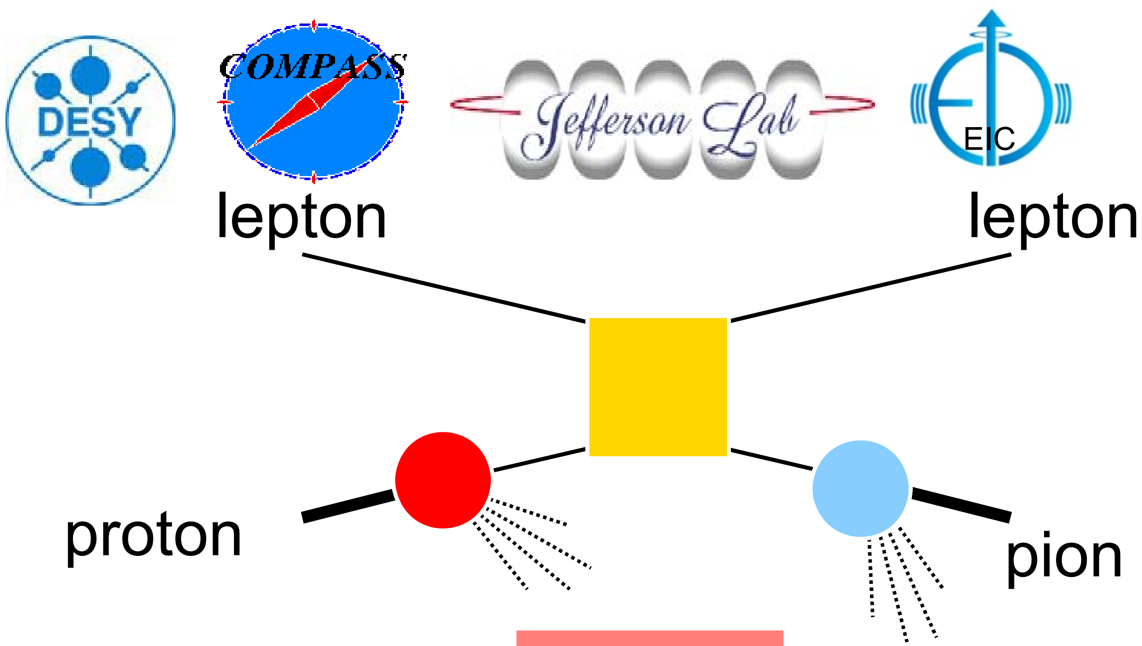
3-D Description in Momentum Space

- Transverse Momentum-dependent parton Distributions (TMD's)

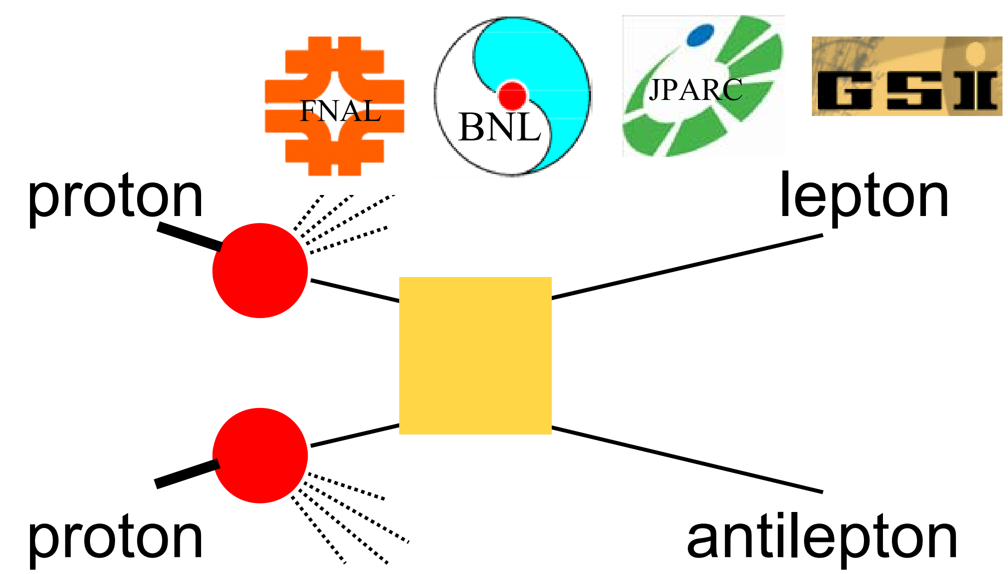
→ Nucleon
→ Quark Spin

		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

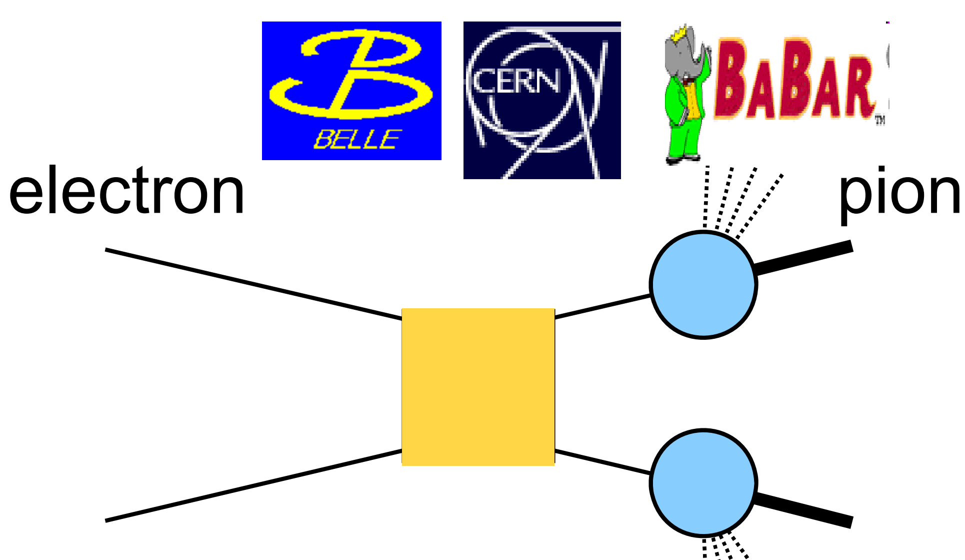
Accessing TMD's



SIDIS



Drell-Yan



e^+e^-

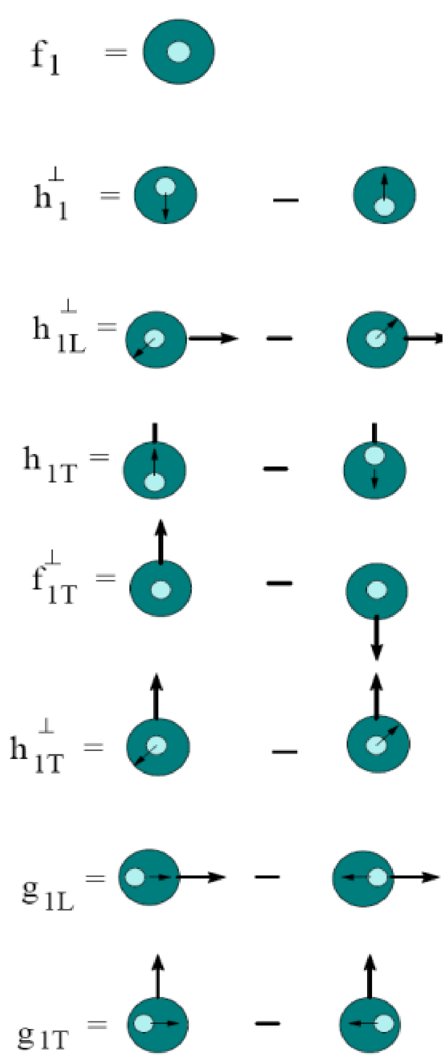
- Partonic scattering amplitude
- Fragmentation amplitude
- Distribution amplitude

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

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

SIDIS

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



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

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

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

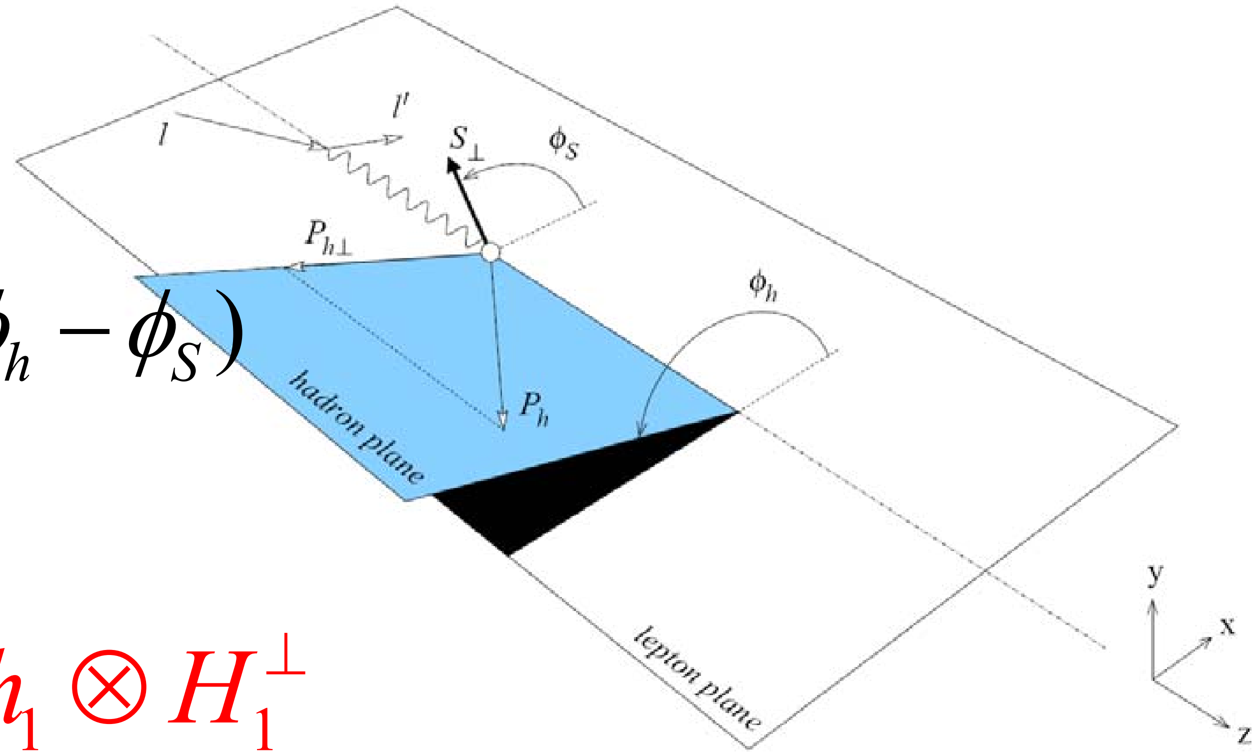
S_L, S_T: Target Polarization; λ_e: Beam Polarization

Separation via Angular Dependence

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

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

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

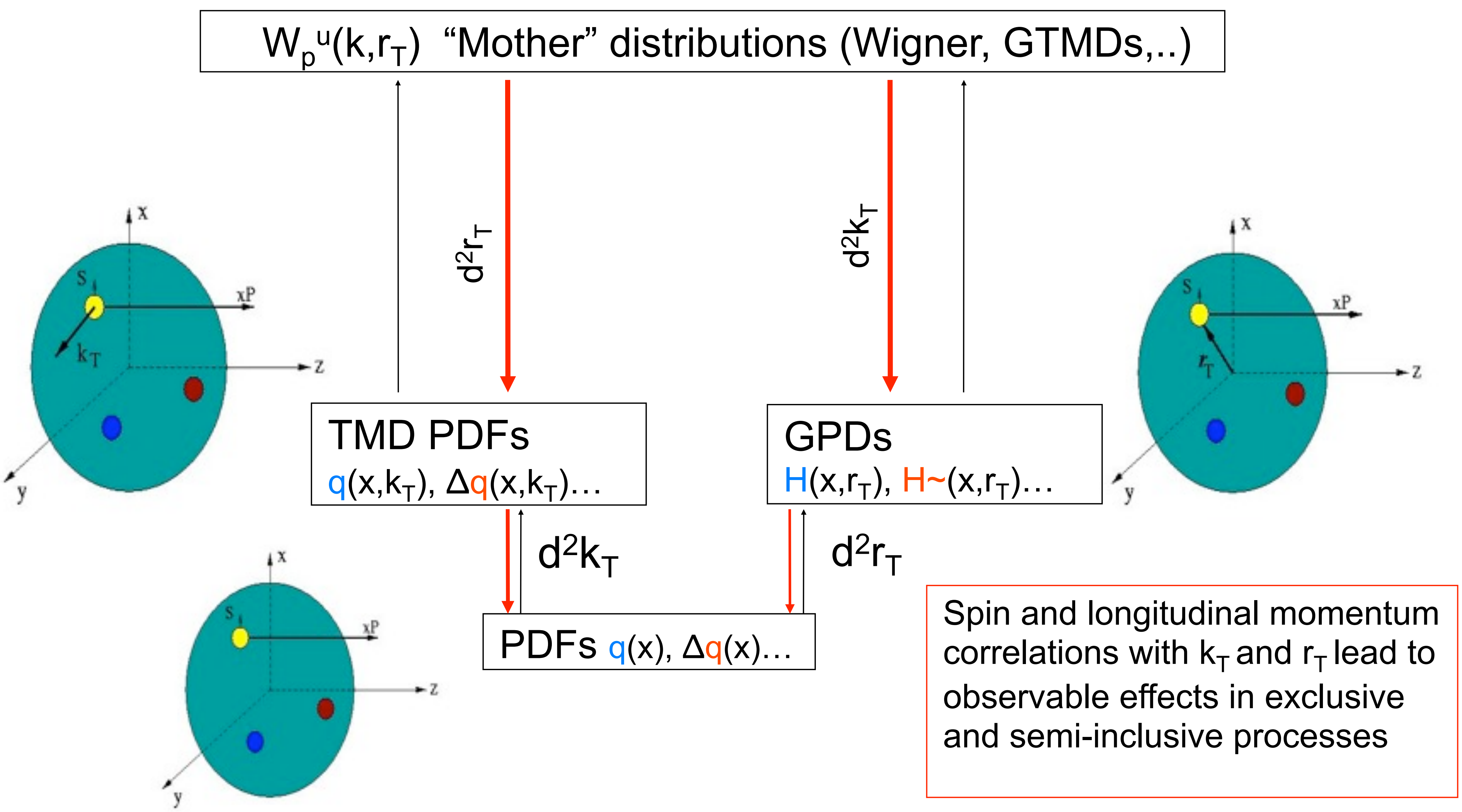


$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^\perp$$

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

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

Structure of the Nucleon

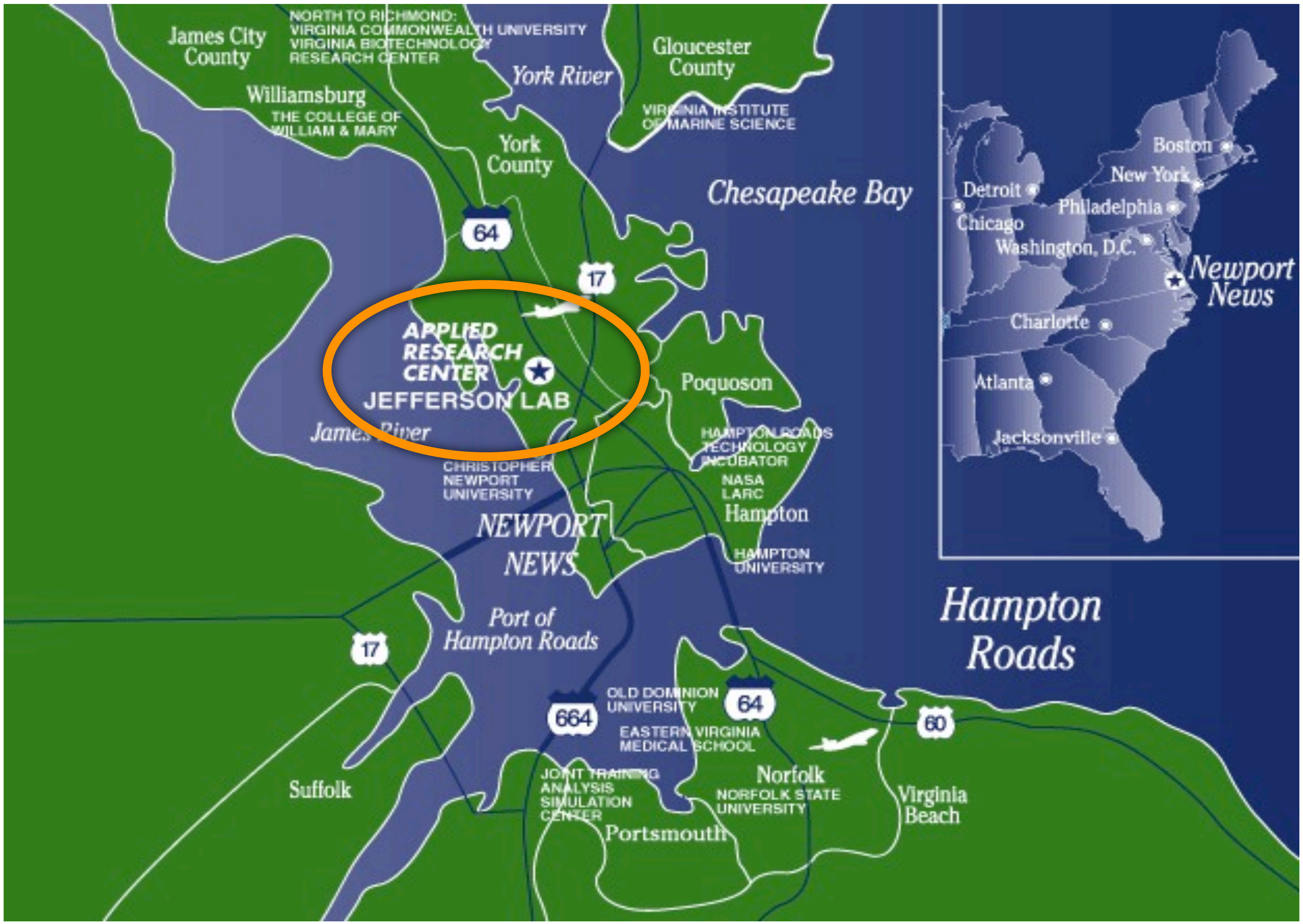


The Machine

Jefferson Lab at a Glance

- Electron linear accelerator
  - Beam energy up to ~ 6 GeV
    - 12 GeV upgrade in progress
  - Beam polarization over 80%
  - 100% duty cycle, continuous beam
  - 3 Experimental Halls: A, B and C

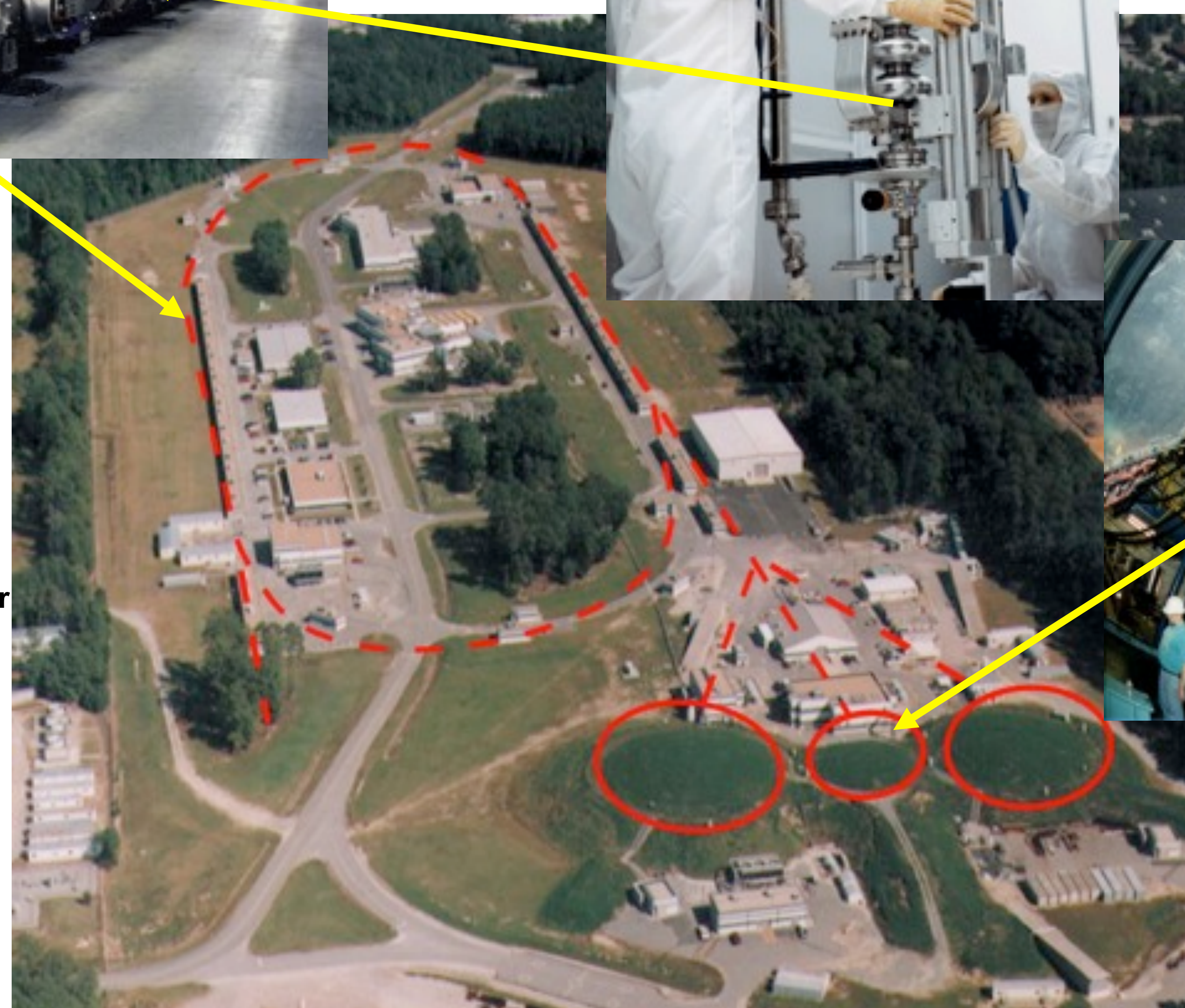
Jefferson Lab



Jefferson Lab

Superconducting radiofrequency (SRF) cavities undergo vertical testing.

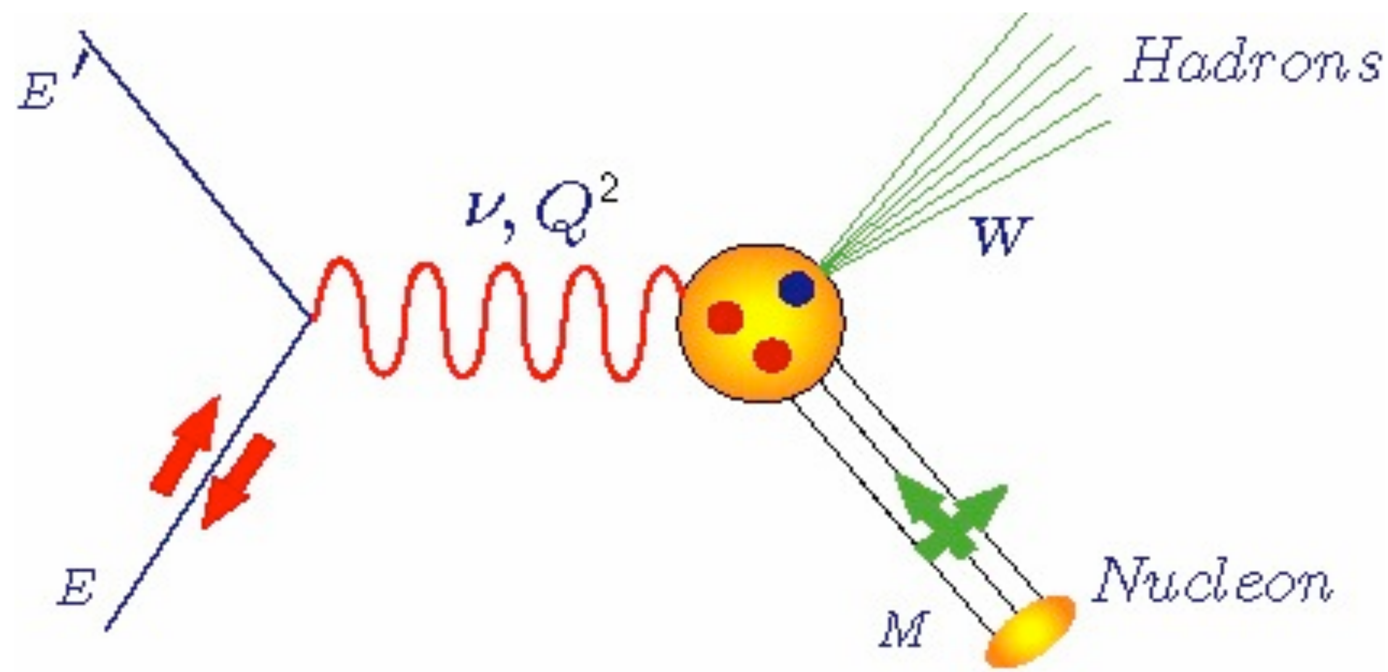
Cryomodules in the accelerator tunnel



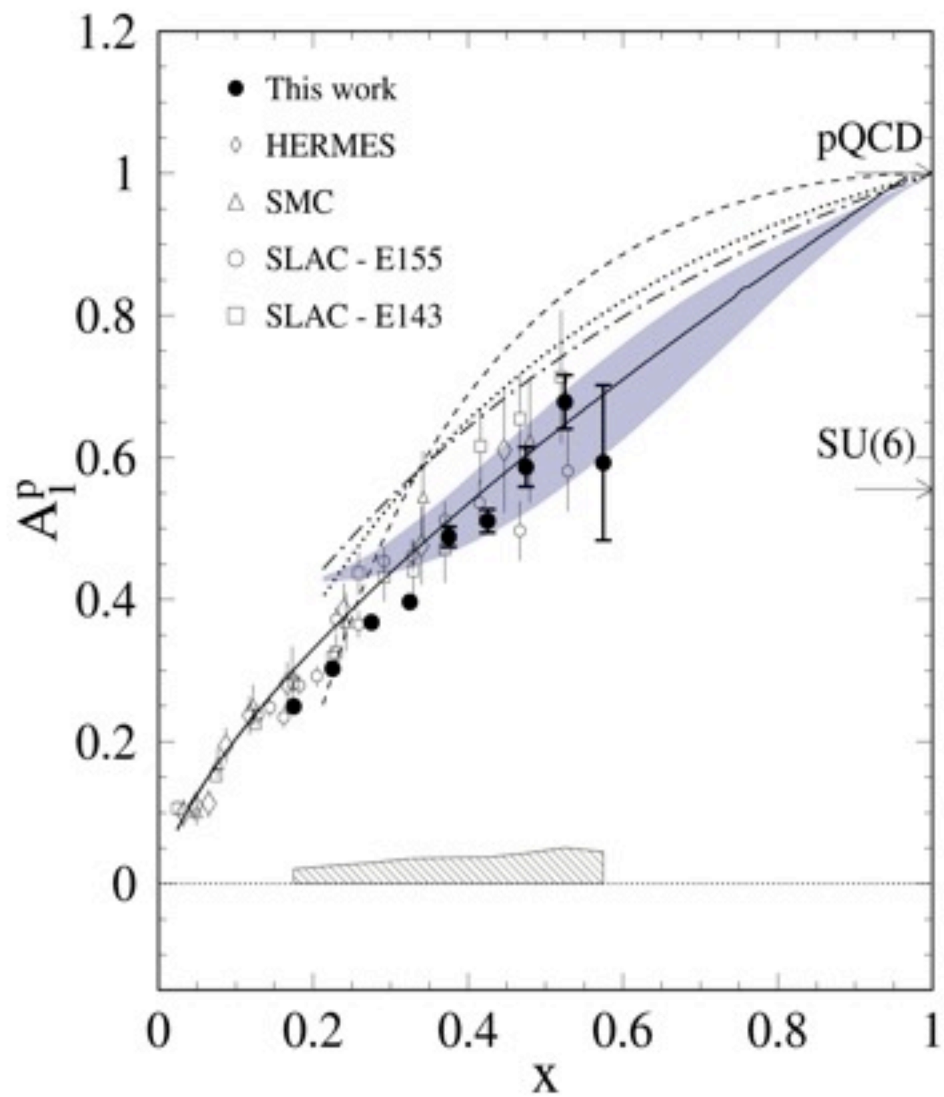
An aerial view of the recirculating linear accelerator and 3 experimental halls.

CEBAF Large Acceptance Spectrometer (CLAS) in Hall B

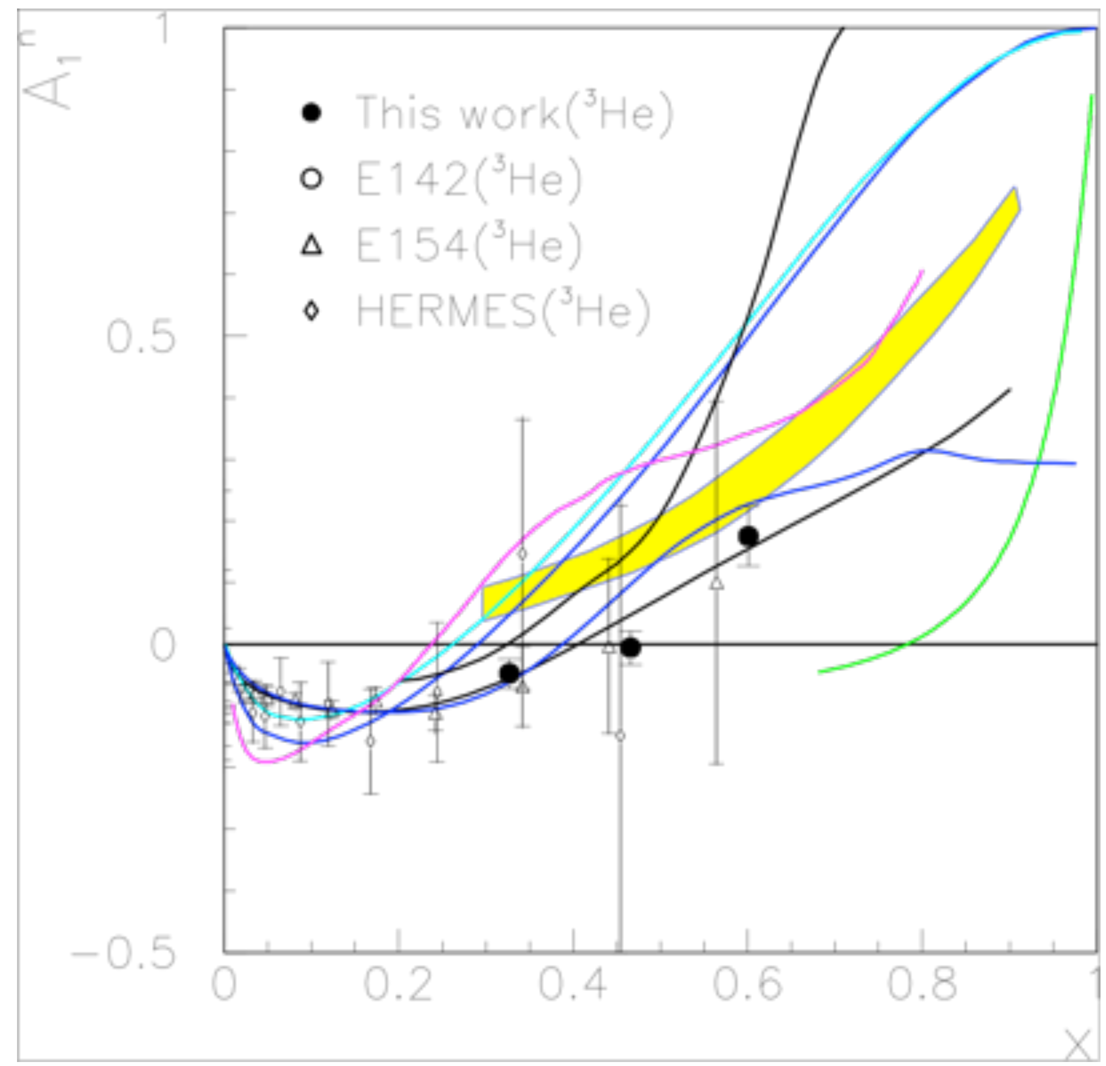
Inclusive DIS at JLab



Valence A_1^p and A_1^n

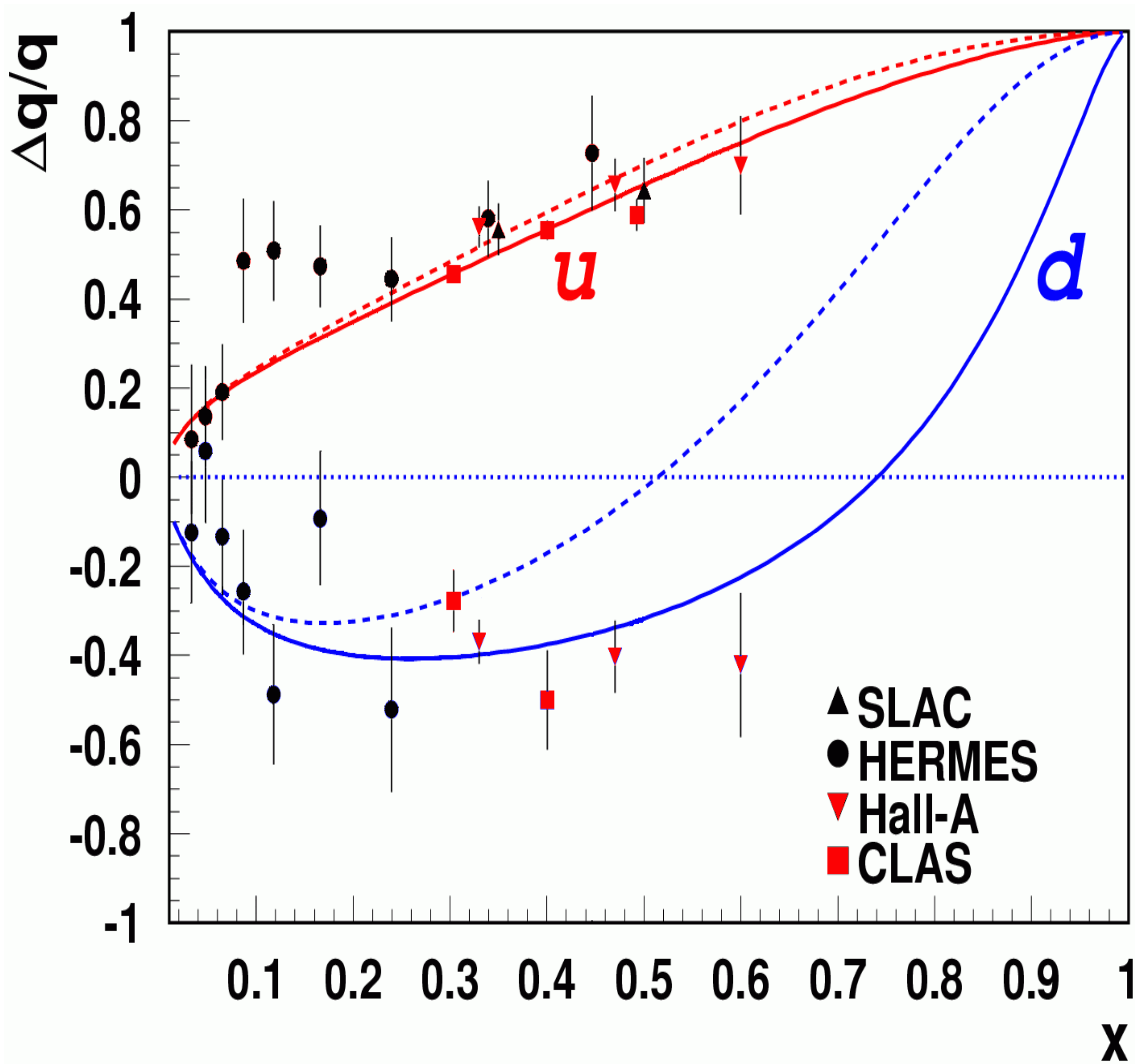


Hall B CLAS, Phys.Lett. B641 (2006) 11



Hall A E99-117, PRL 92, 012004 (2004)
PRC 70, 065207 (2004)

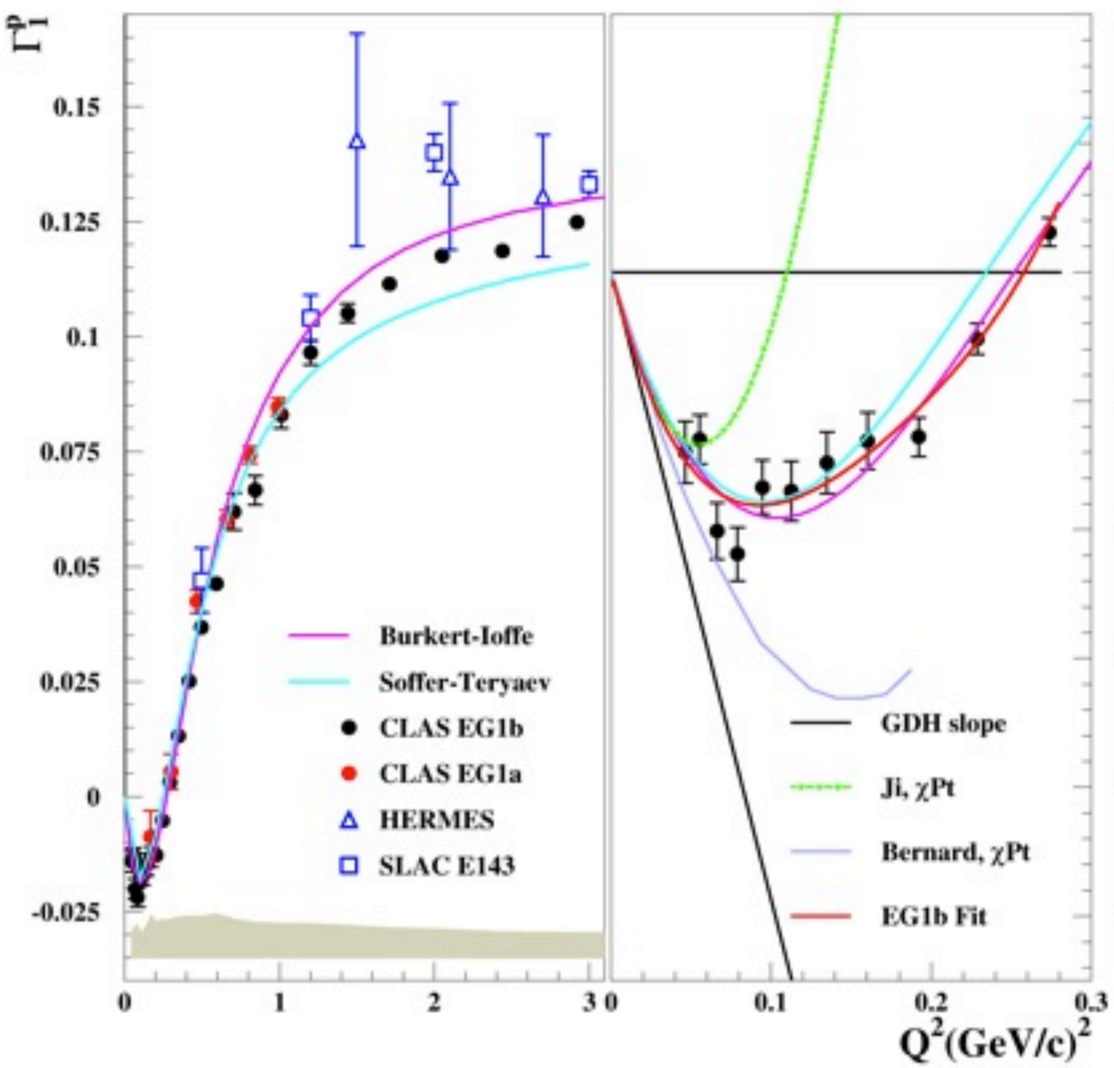
Effect of OAM

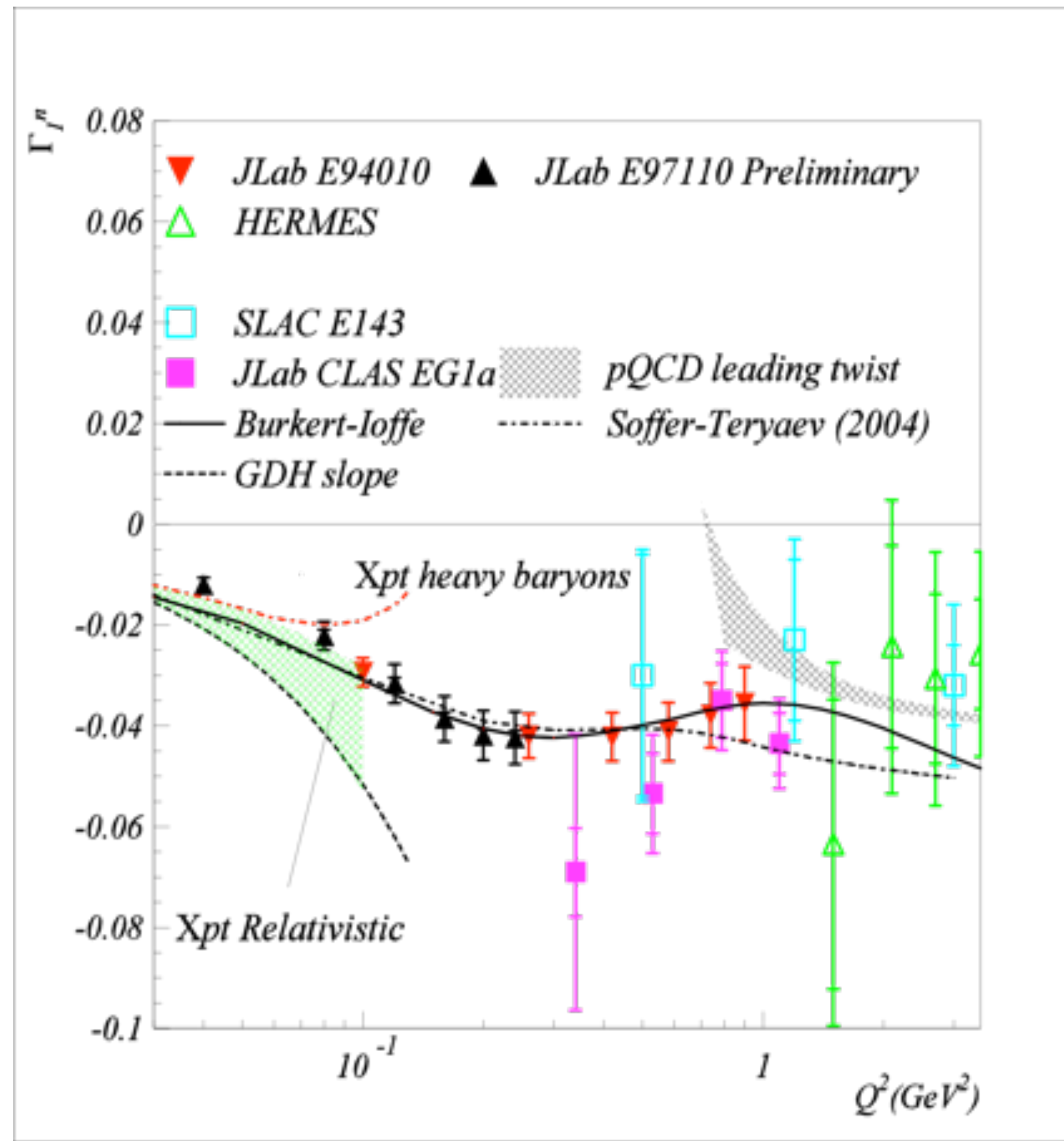


First Moments of g_1^p and g_1^n

Test fundamental understanding

ChPT at low Q^2, Twist expansion at high Q^2, Future Lattice QCD

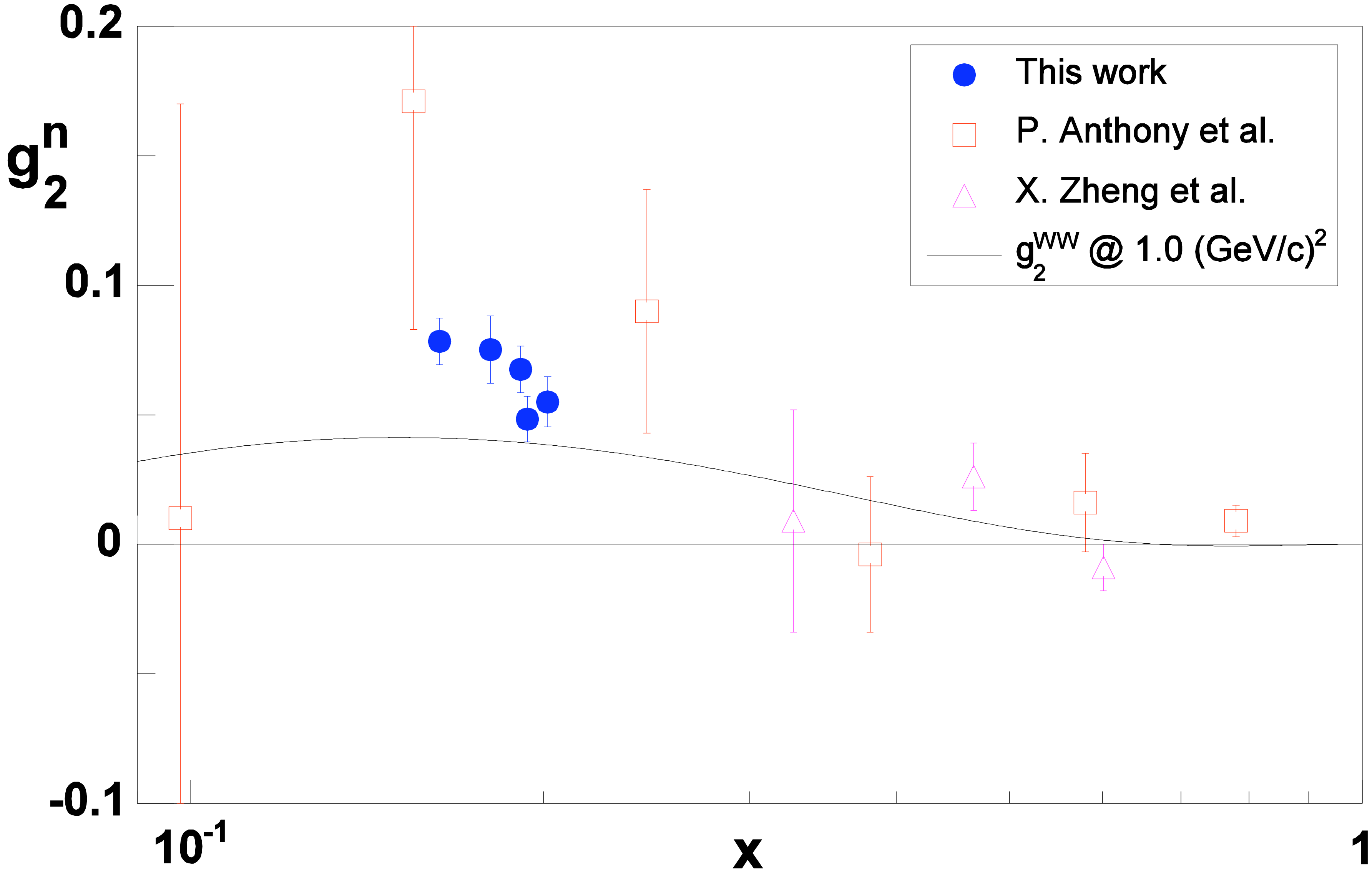




EG1b, arXiv:0802.2232
EG1a, PRL 91, 222002 (2003)

E94-010, from ^3He, PRL 92 (2004) 022301
E97-110, from ^3He, EG1a, from d-p

Precision Measurement of g_2^n

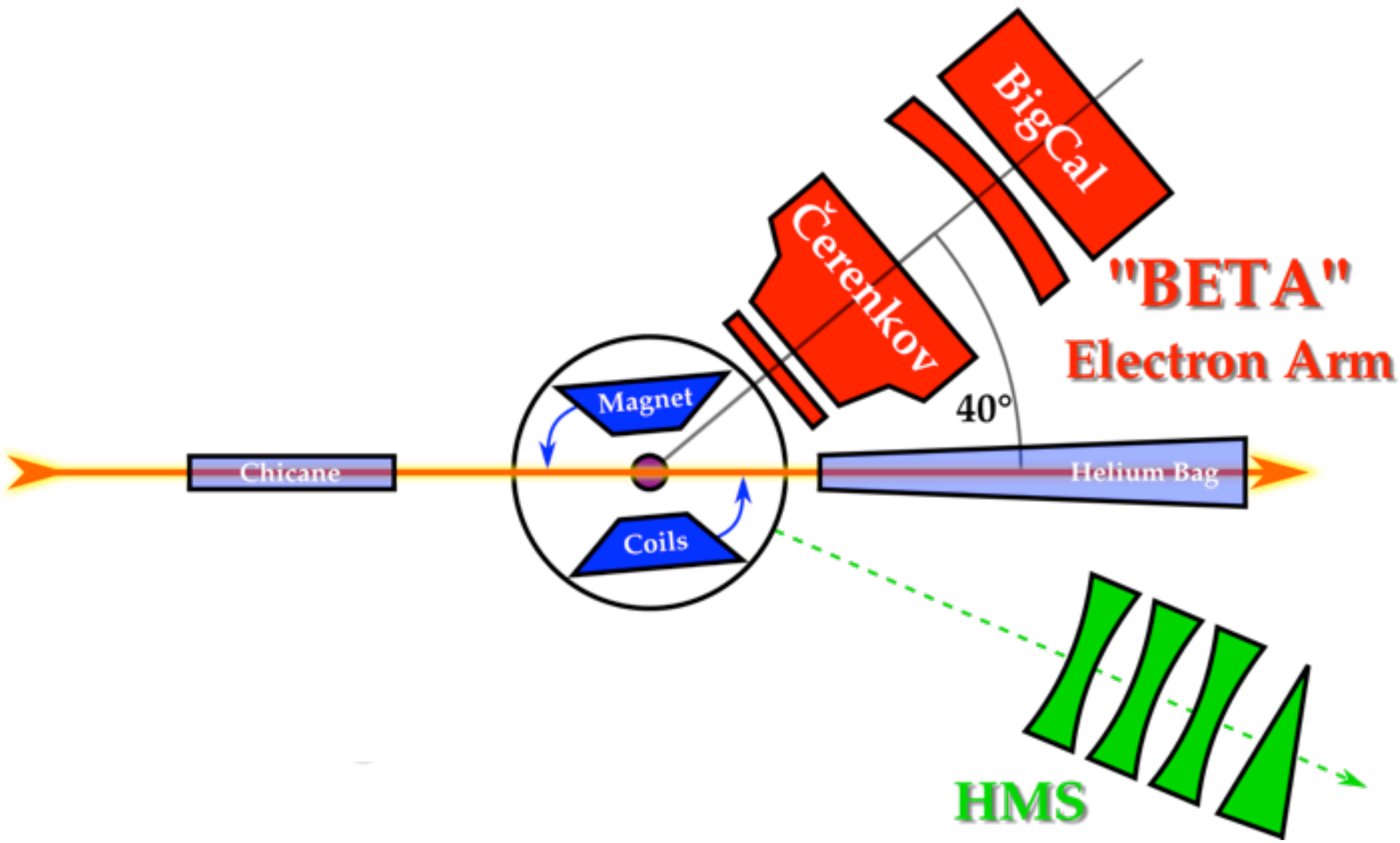


- Measure higher twist → quark-gluon correlations.
- Hall A Collaboration, K. Kramer et al., PRL 95, 142002 (2005)

SANE at Hall-C

- **Beam**: polarized electron beam (Jefferson Lab) at **4.7** and **5.9** GeV
- **Target**: Polarized NH_3 target
  - Polarization: ~67%
  - Orientation: parallel (0°) or "**perpendicular**" (80°)
- Scattering angle: 40°
- **Detectors**: **BETA** and HMS of Hall-C

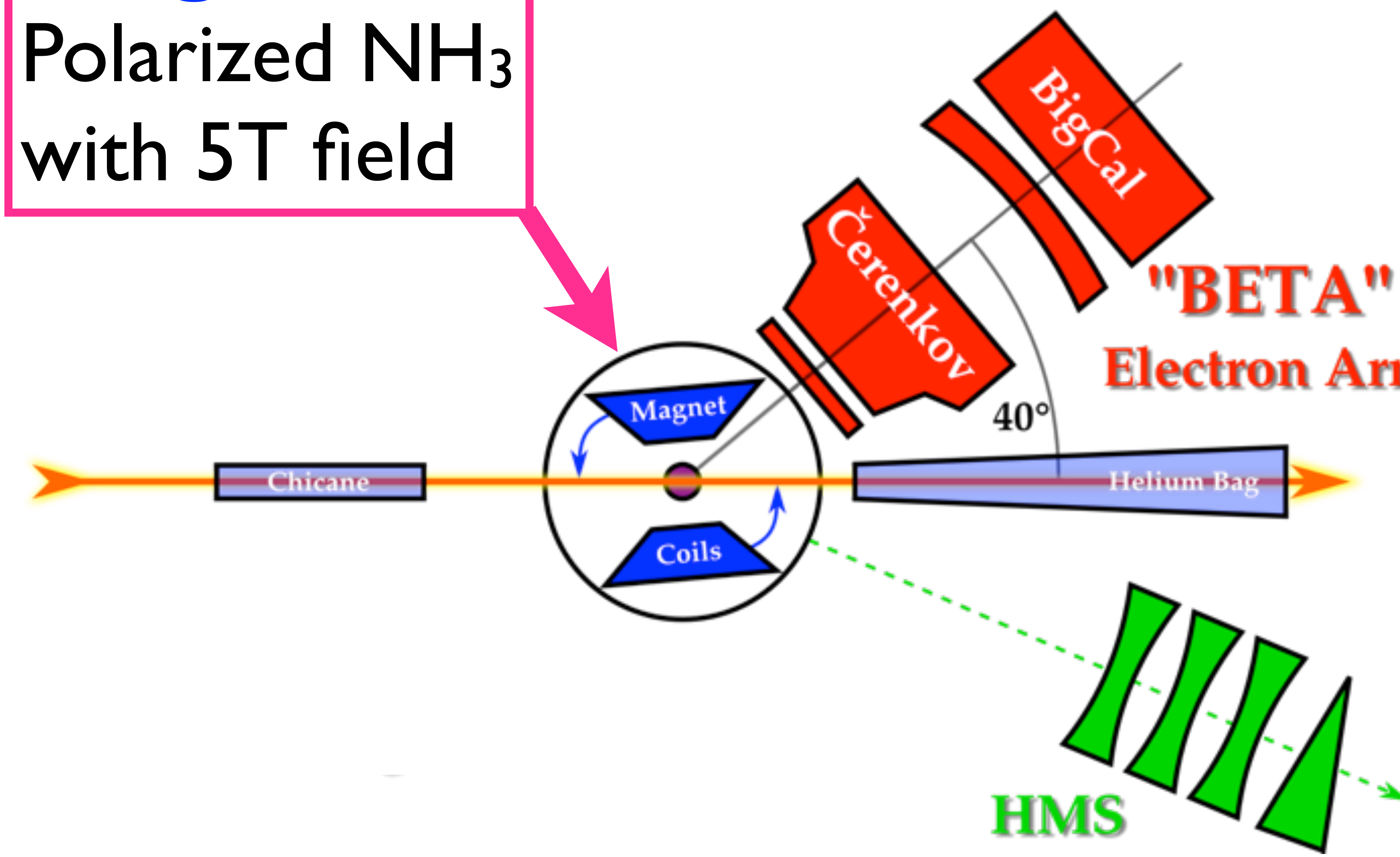
Setup



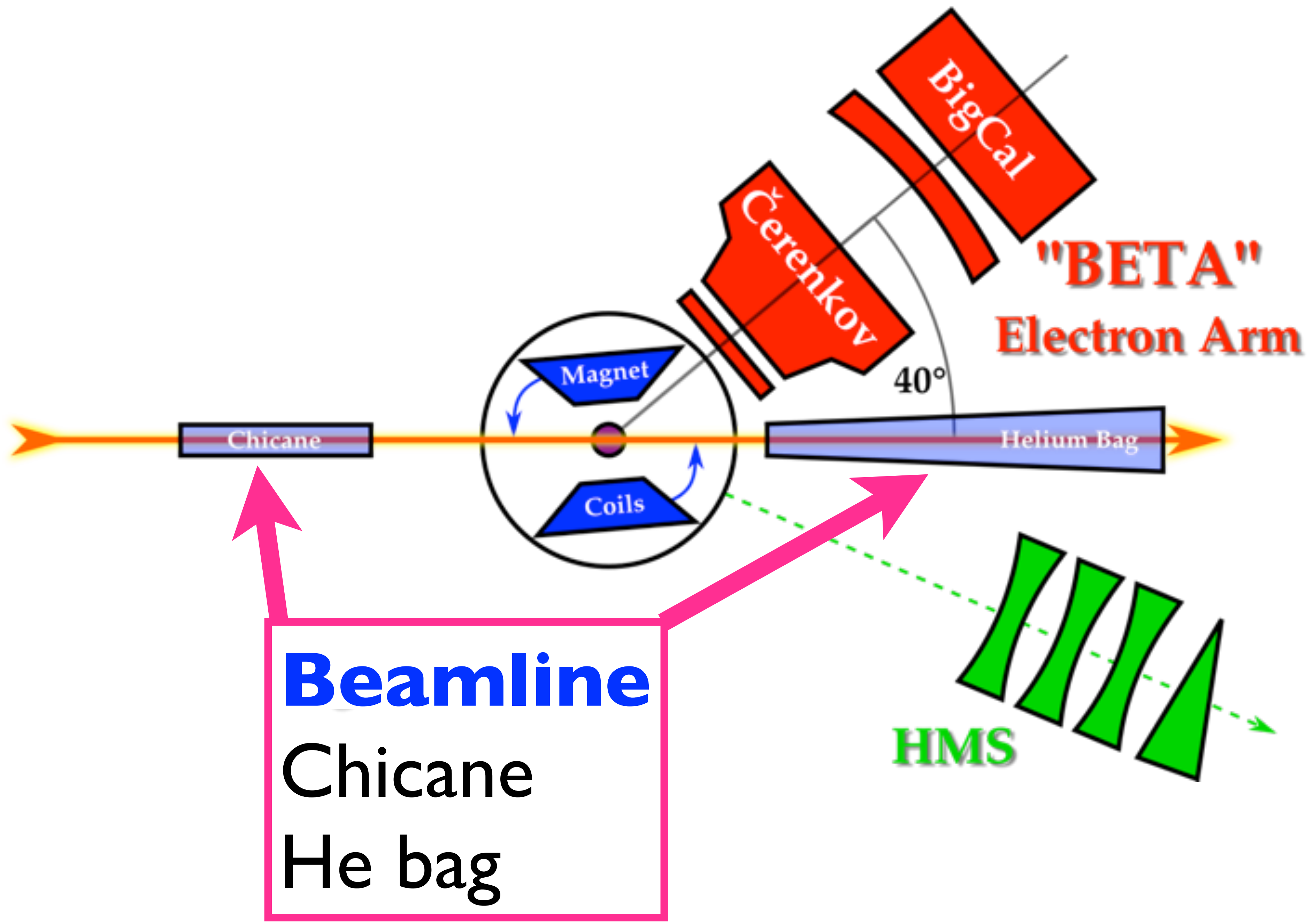
BigCal
Čerenkov
"BETA"
Electron Arm
40°
Magnet
Chicane
Helium Bag
Coils
HMS

Setup

Target
Polarized NH_3
with 5T field

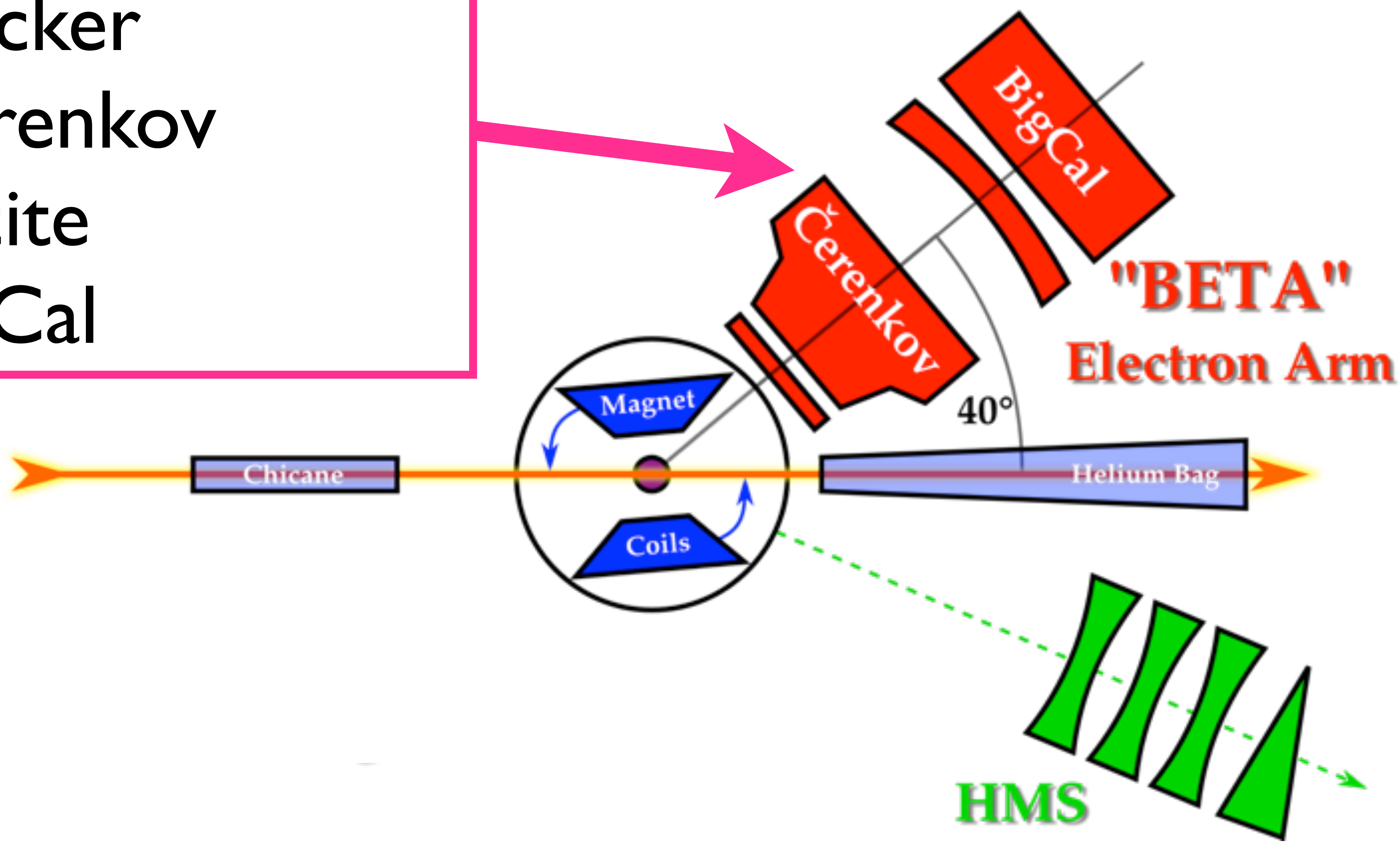


Setup

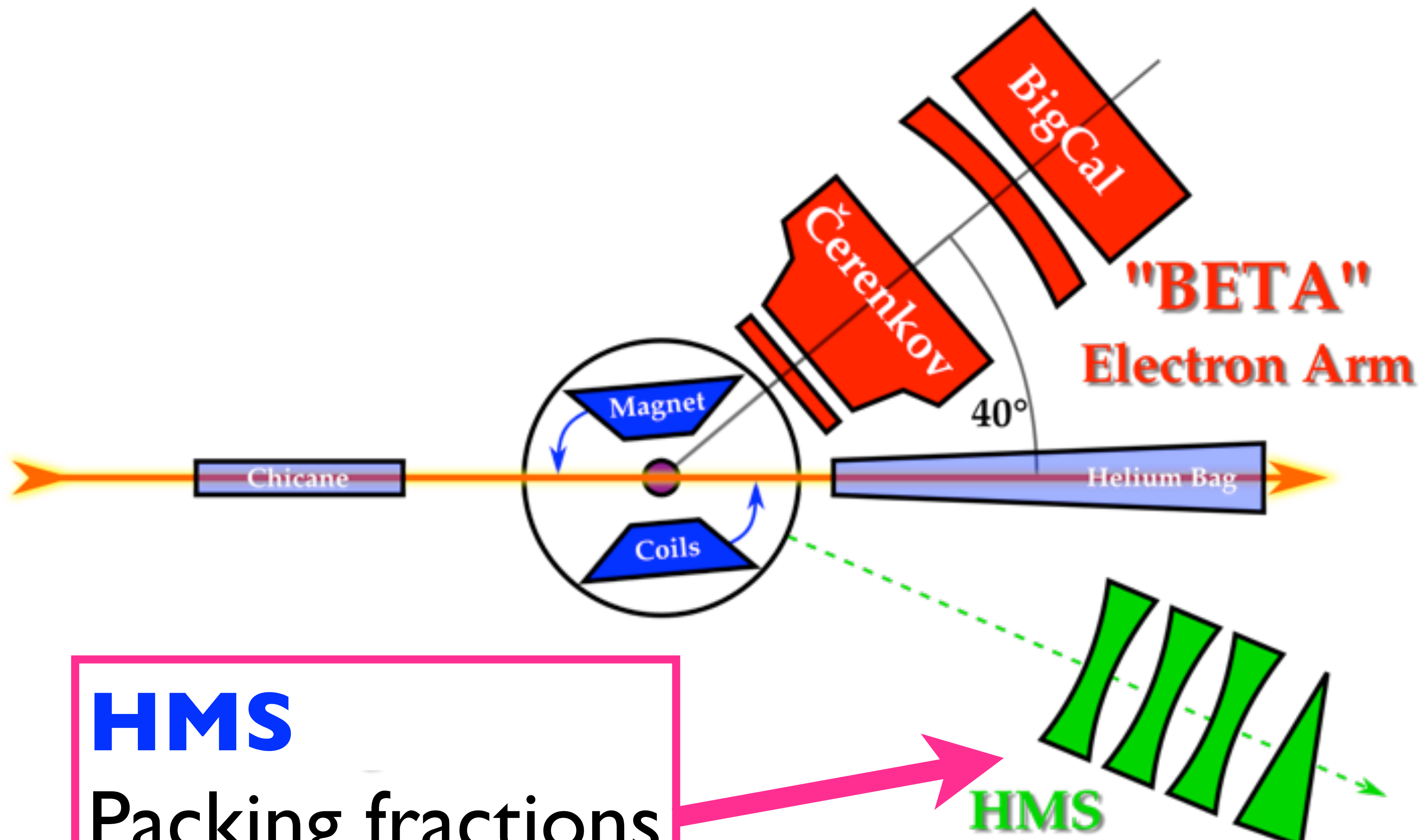

BigCal
Čerenkov
"BETA"
Electron Arm
40°
Magnet
Coils
Chicane
Helium Bag
HMS
Beamline
Chicane
He bag

Setup

Electron Arm
Tracker
Cerenkov
Lucite
BigCal



Setup

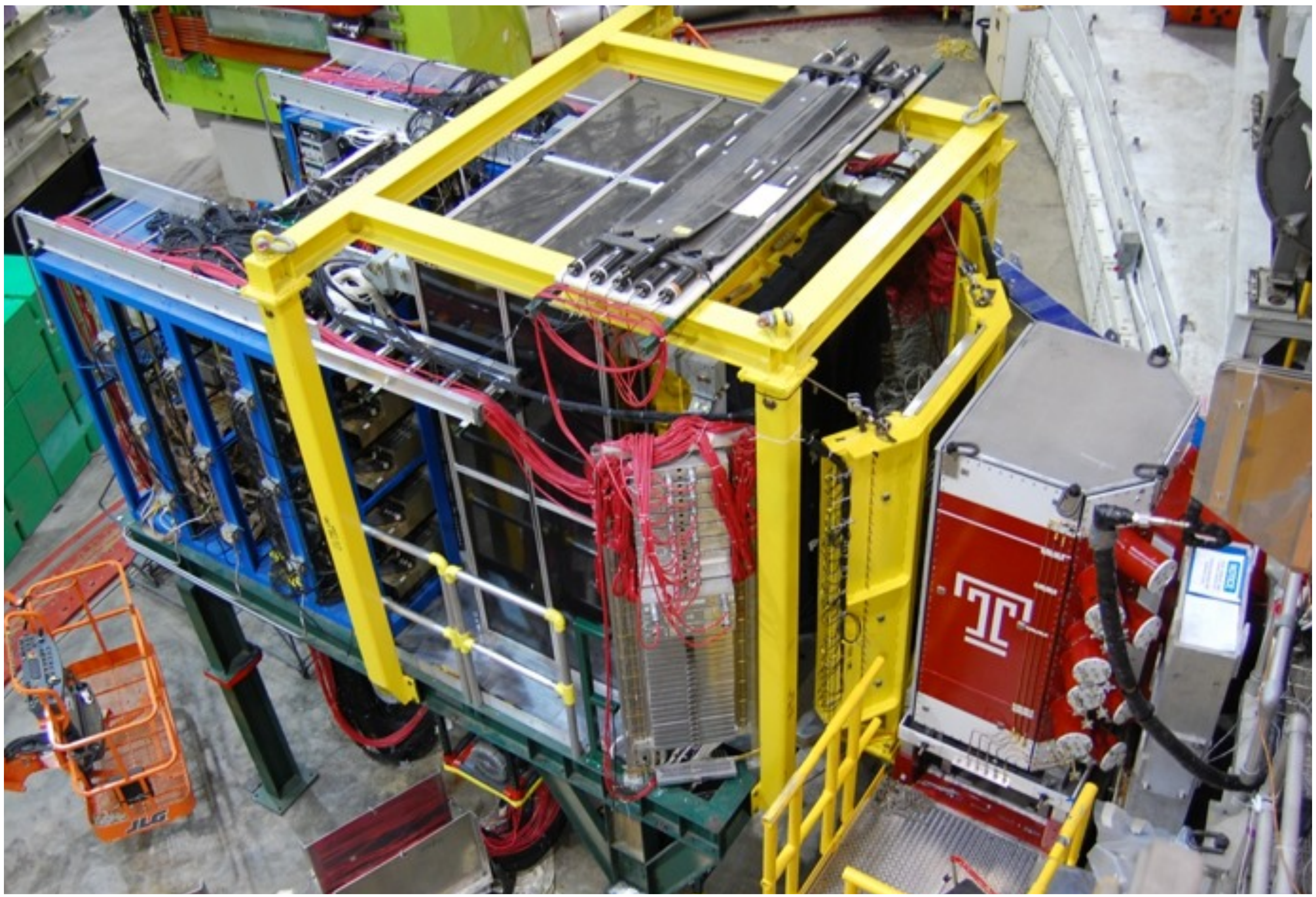


HMS

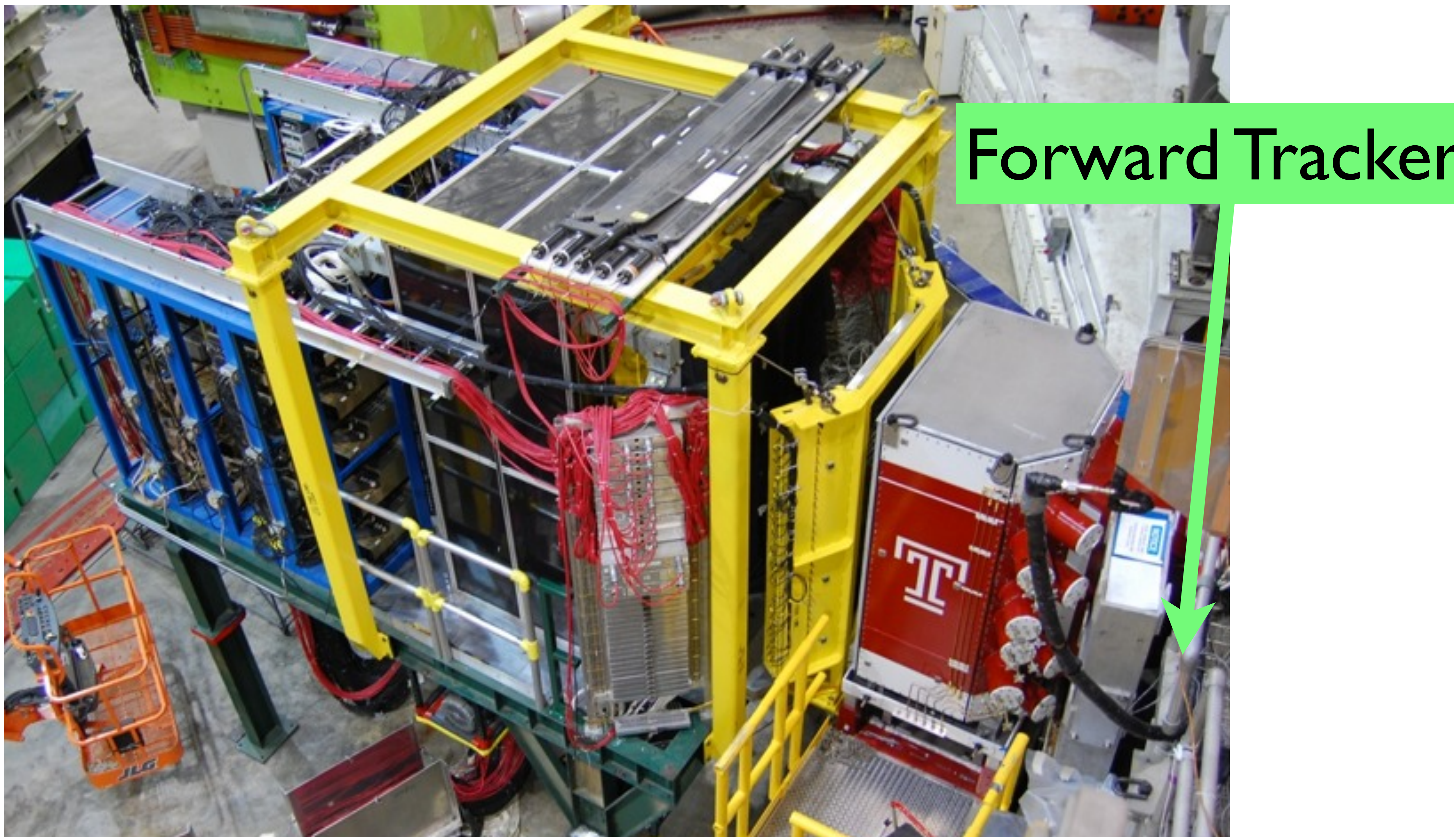
Packing fractions

Monitoring

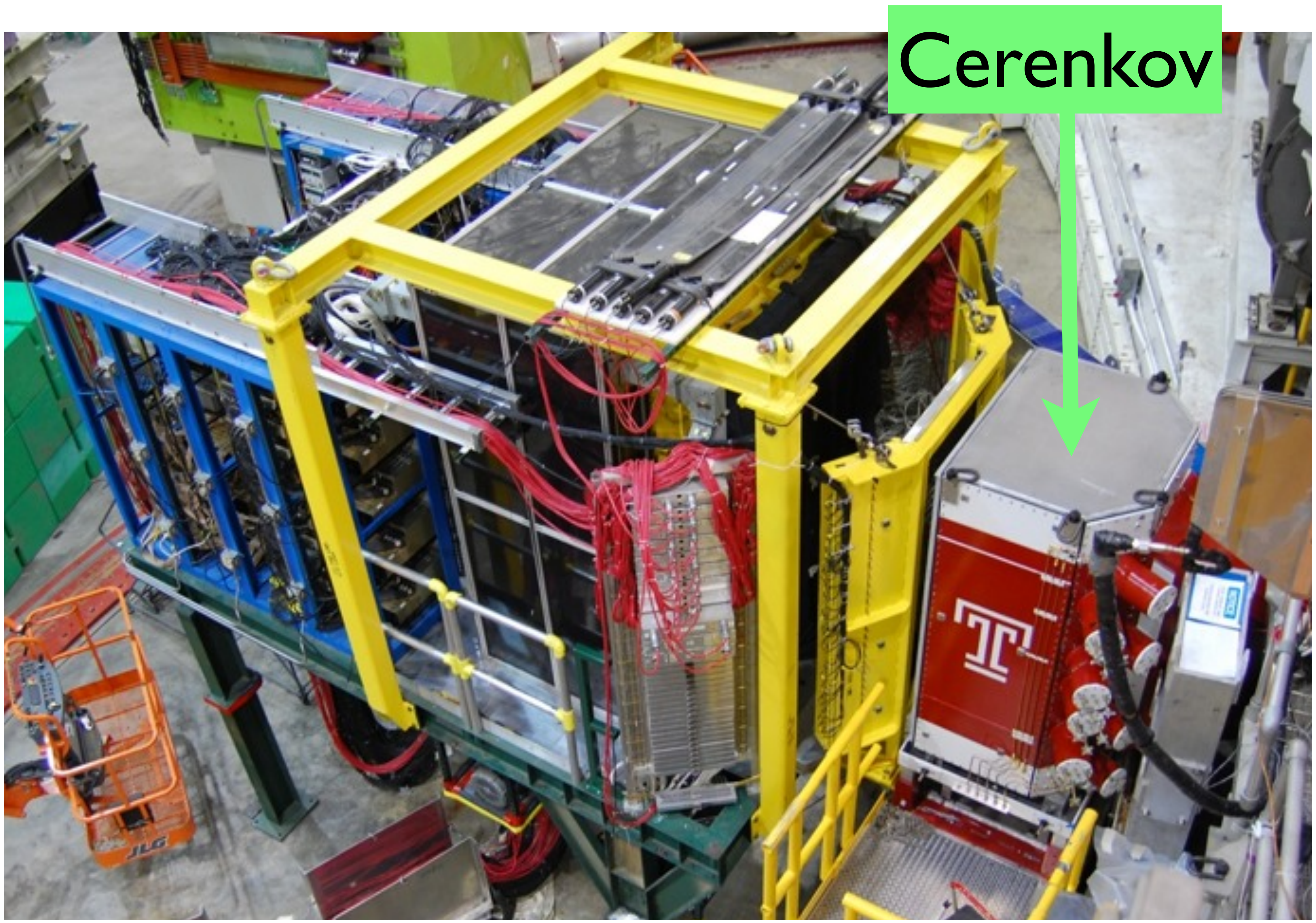
Big Electron Telescope Array



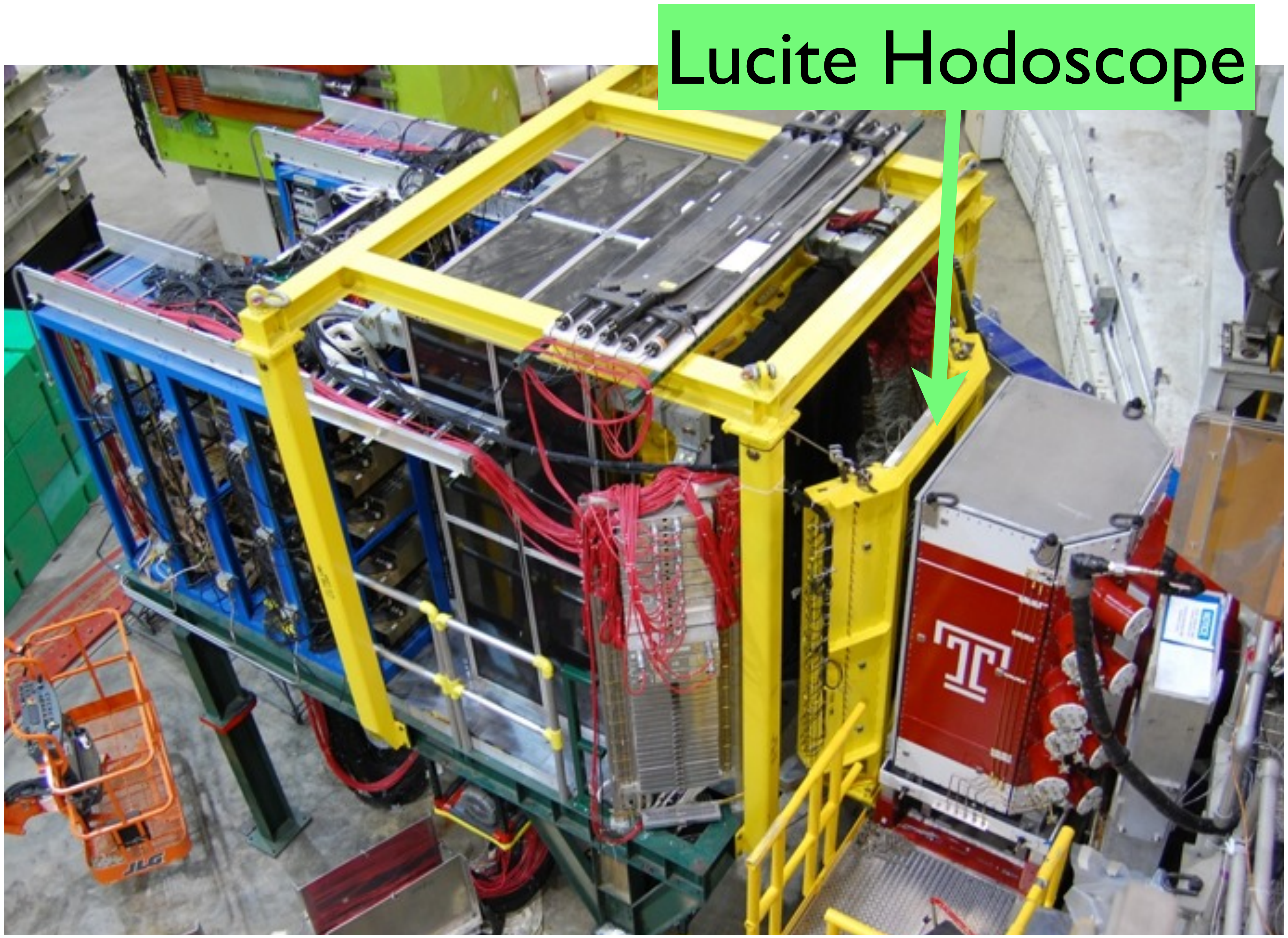
Big Electron Telescope Array



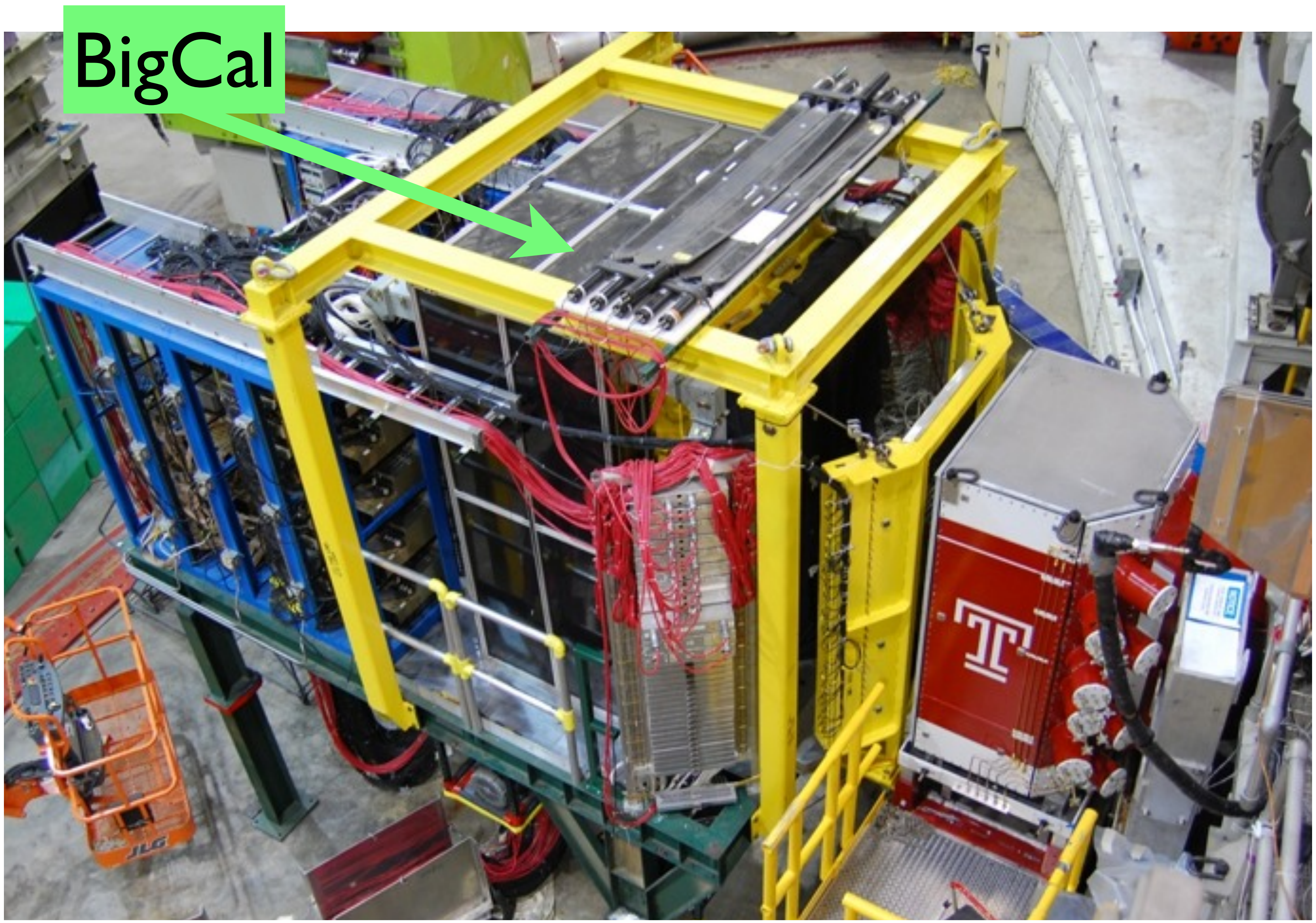
Big Electron Telescope Array



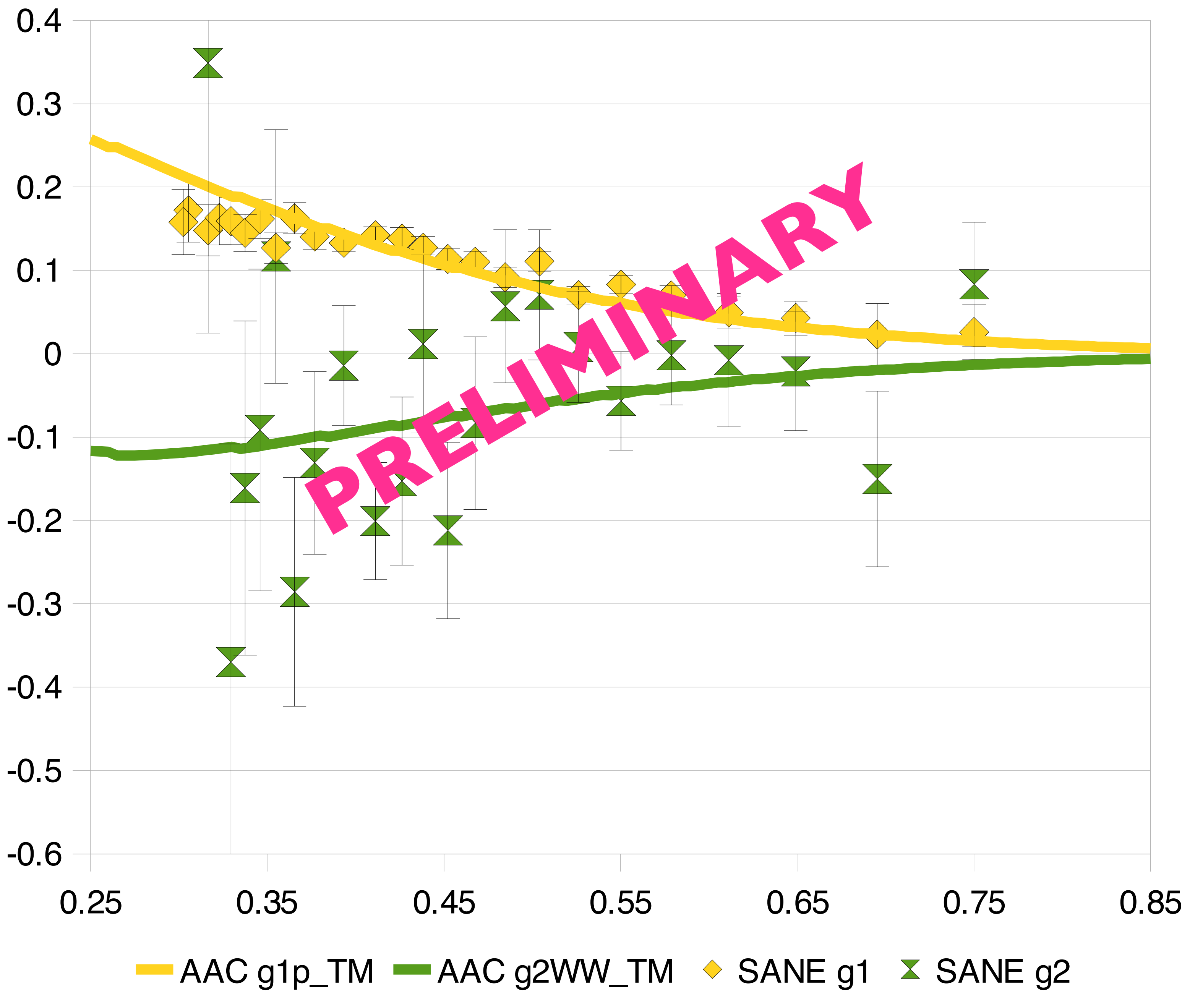
Big Electron Telescope Array



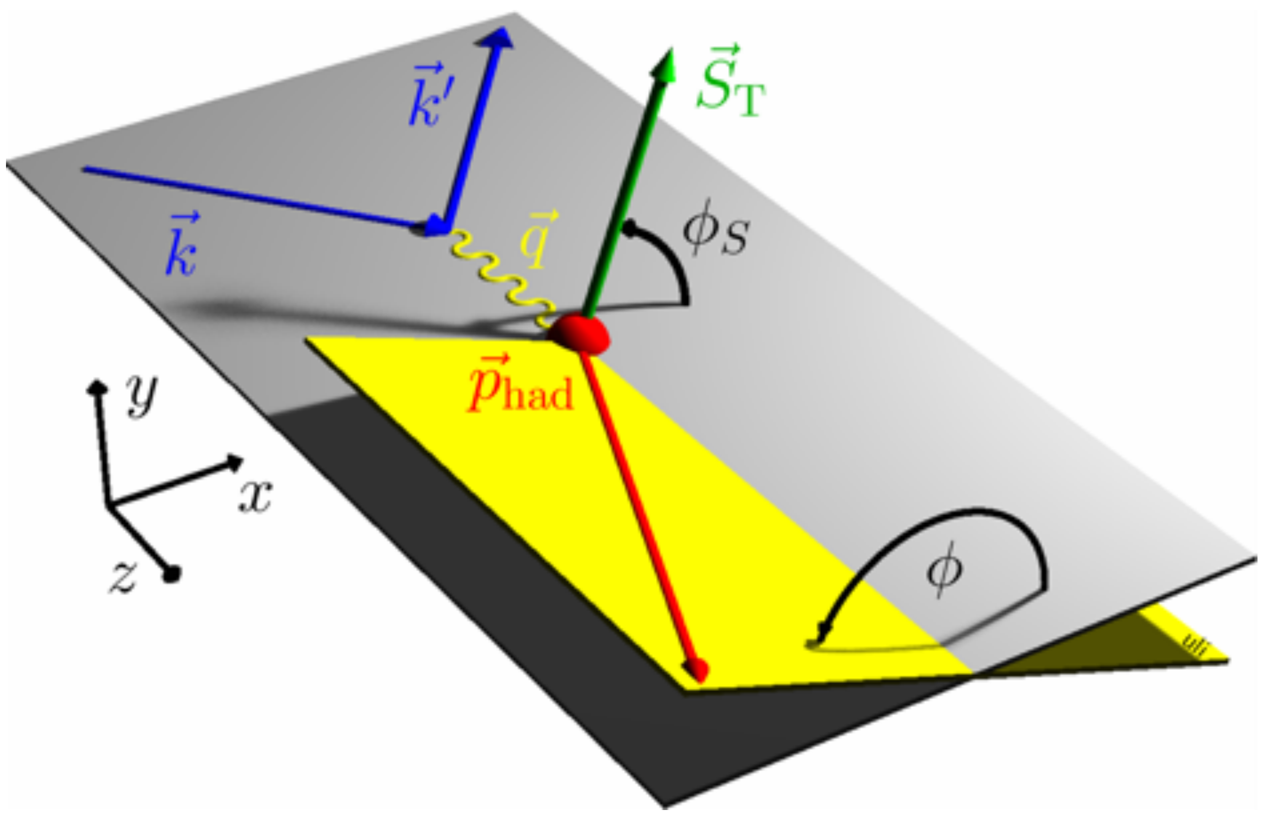
Big Electron Telescope Array



Analysis in Progress

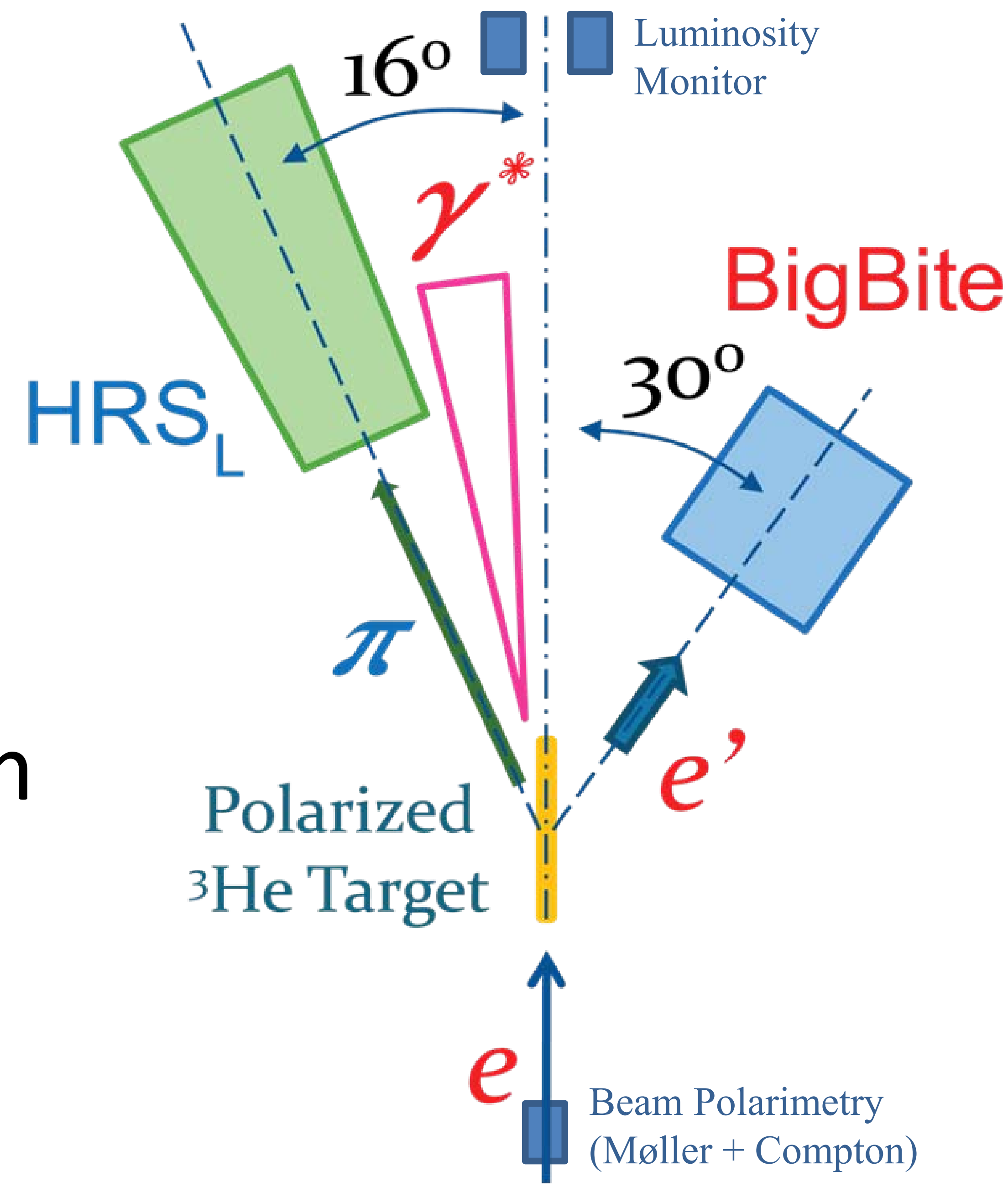


SIDIS at JLab

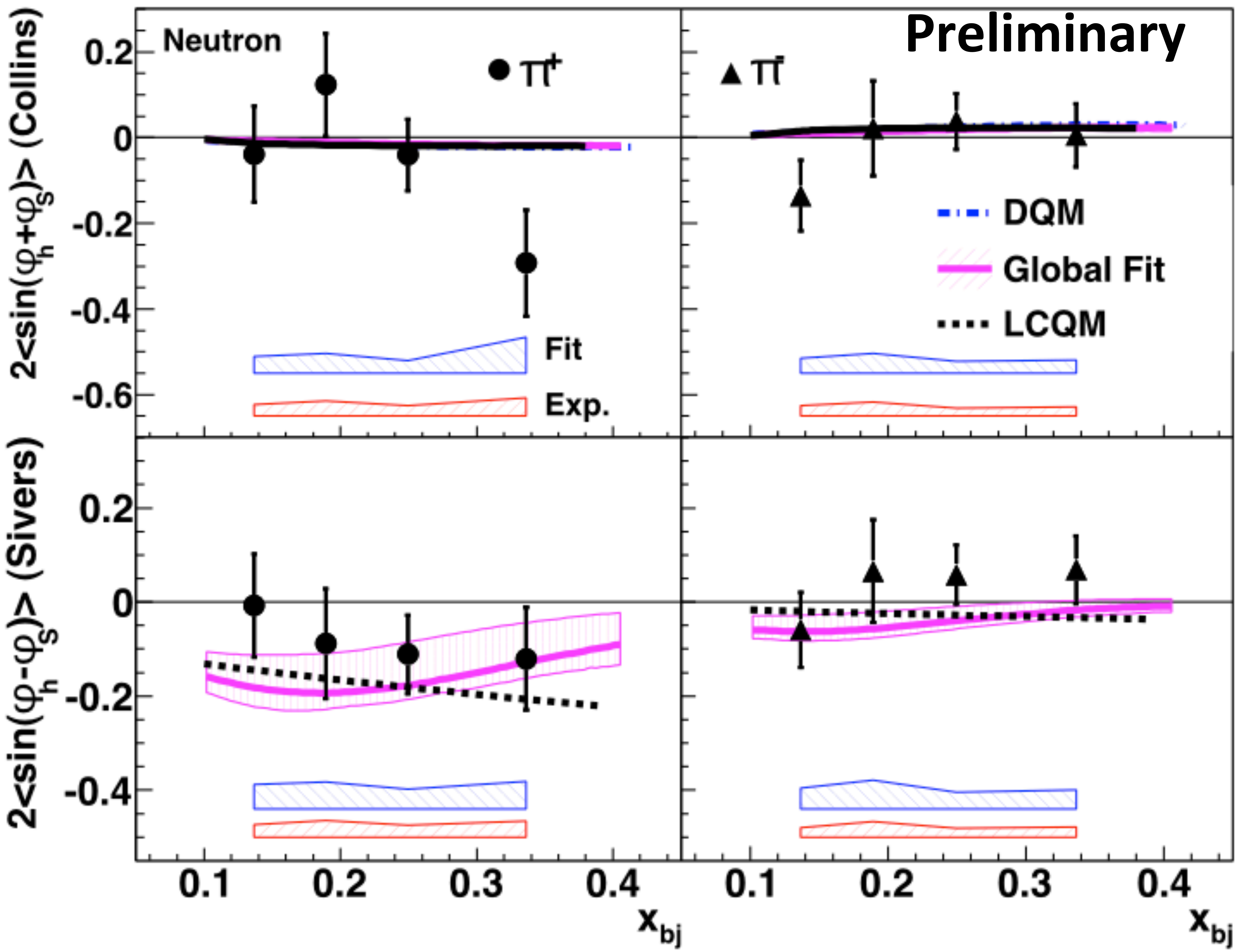


SIDIS at Hall-A

- 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



Neutron Single-Spin Asymmetry



$\pi^+ (u\bar{d})$

Collins

asymmetries are not large, except at x=0.34

Sivers

agree with global fit, and light-cone quark model.

$\pi^+ (u\bar{d})$ favors negative.

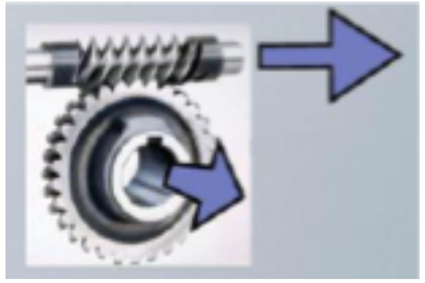
u-quark in neutron favors negative.

by SU(2):

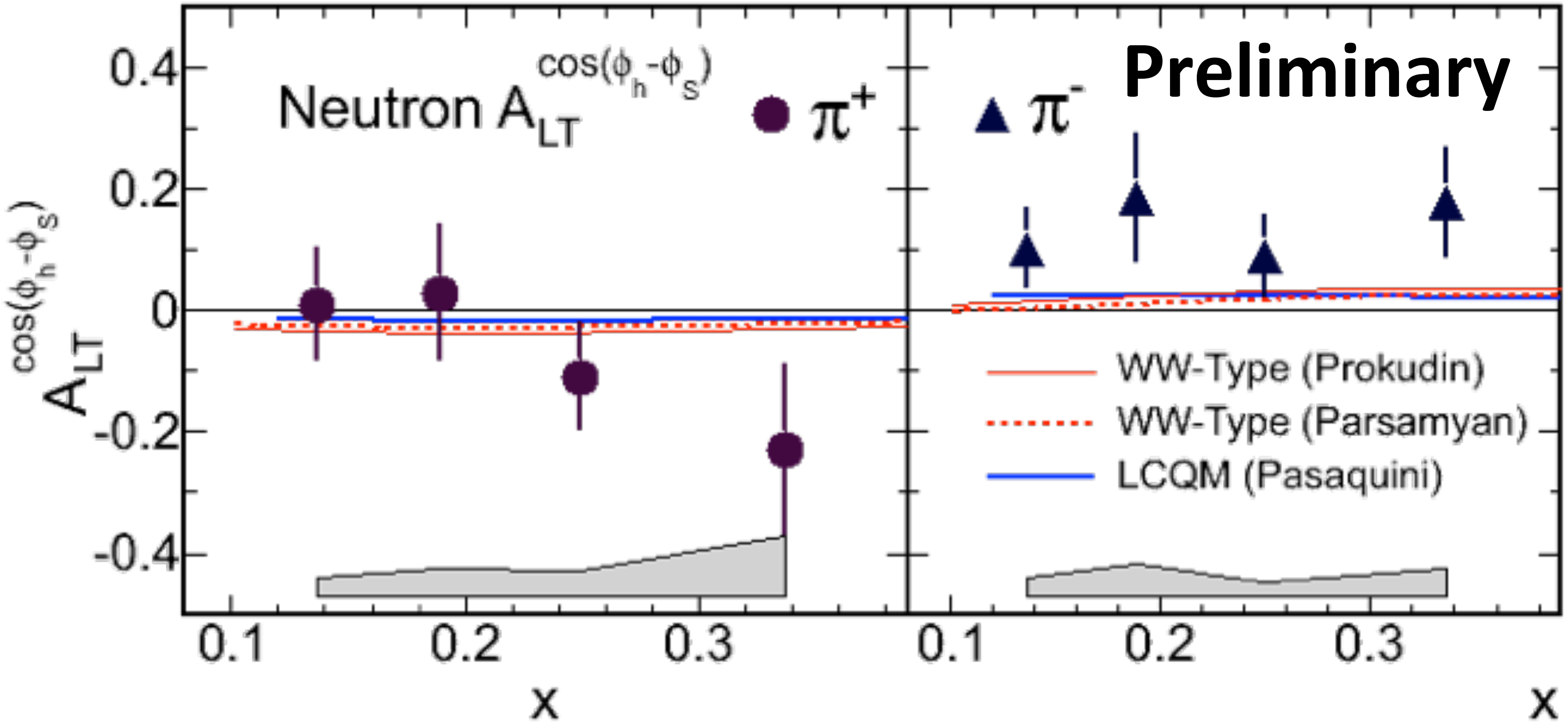
d-quark in proton favors negative.

Neutron Double-Spin Asymmetry A_{LT}

- Worm-gear TMD, $g_{1T} \otimes D_1$
  - –Dominated by L=0 (S) and L=1 (P) interference.

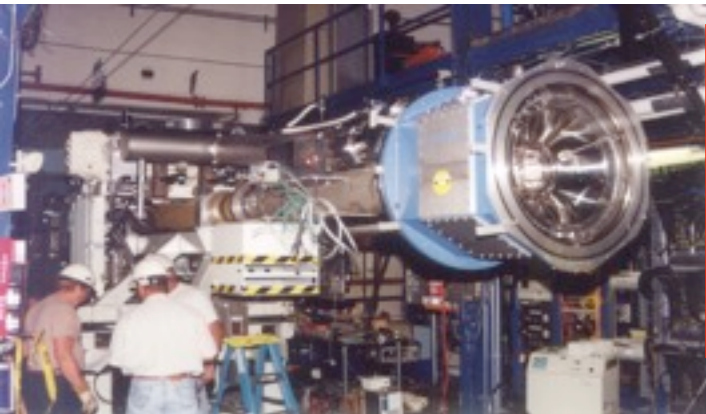


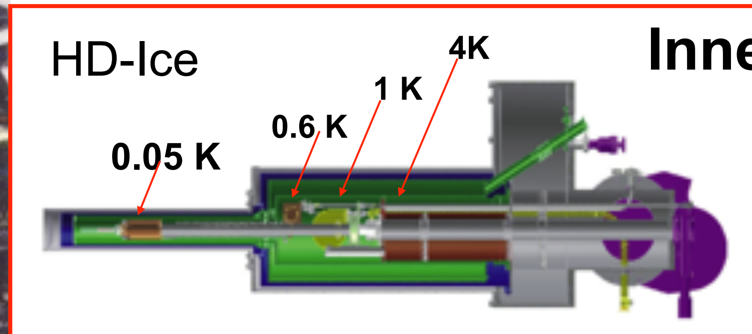
- Consist with model in sign.
  suggest a larger asymmetry.

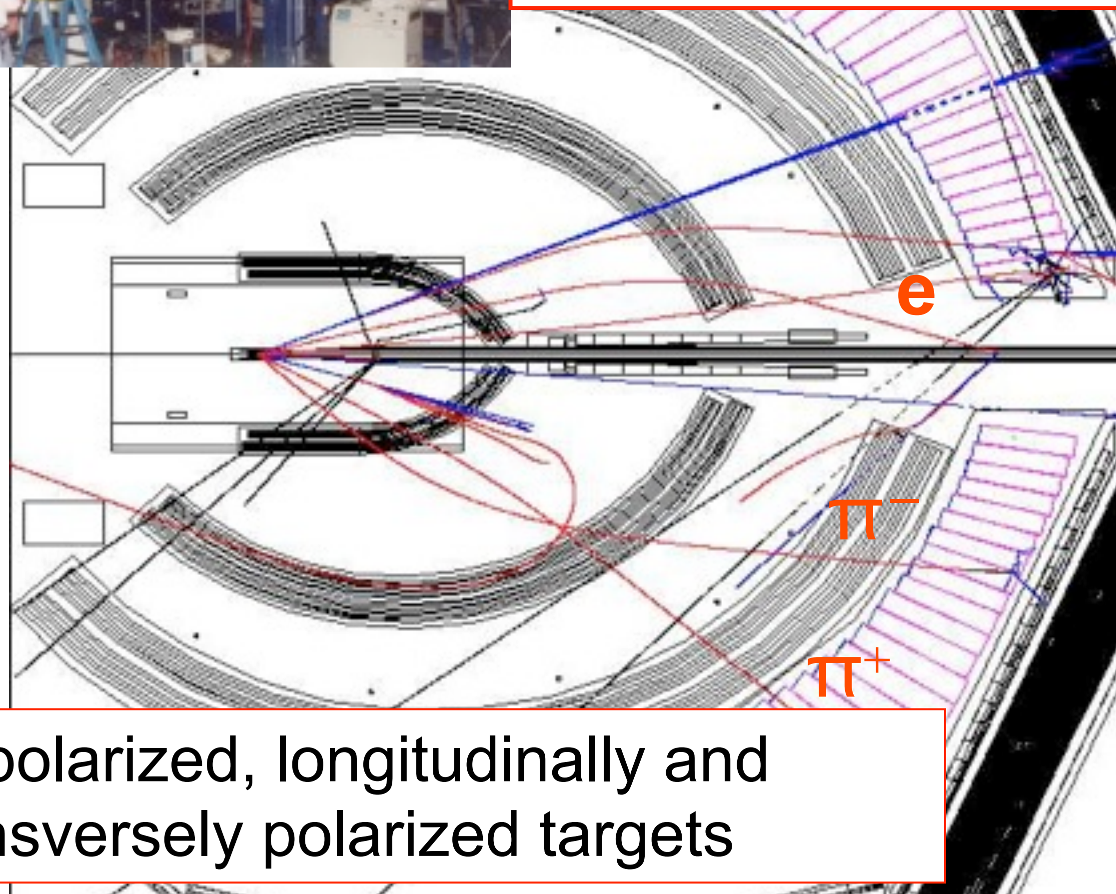


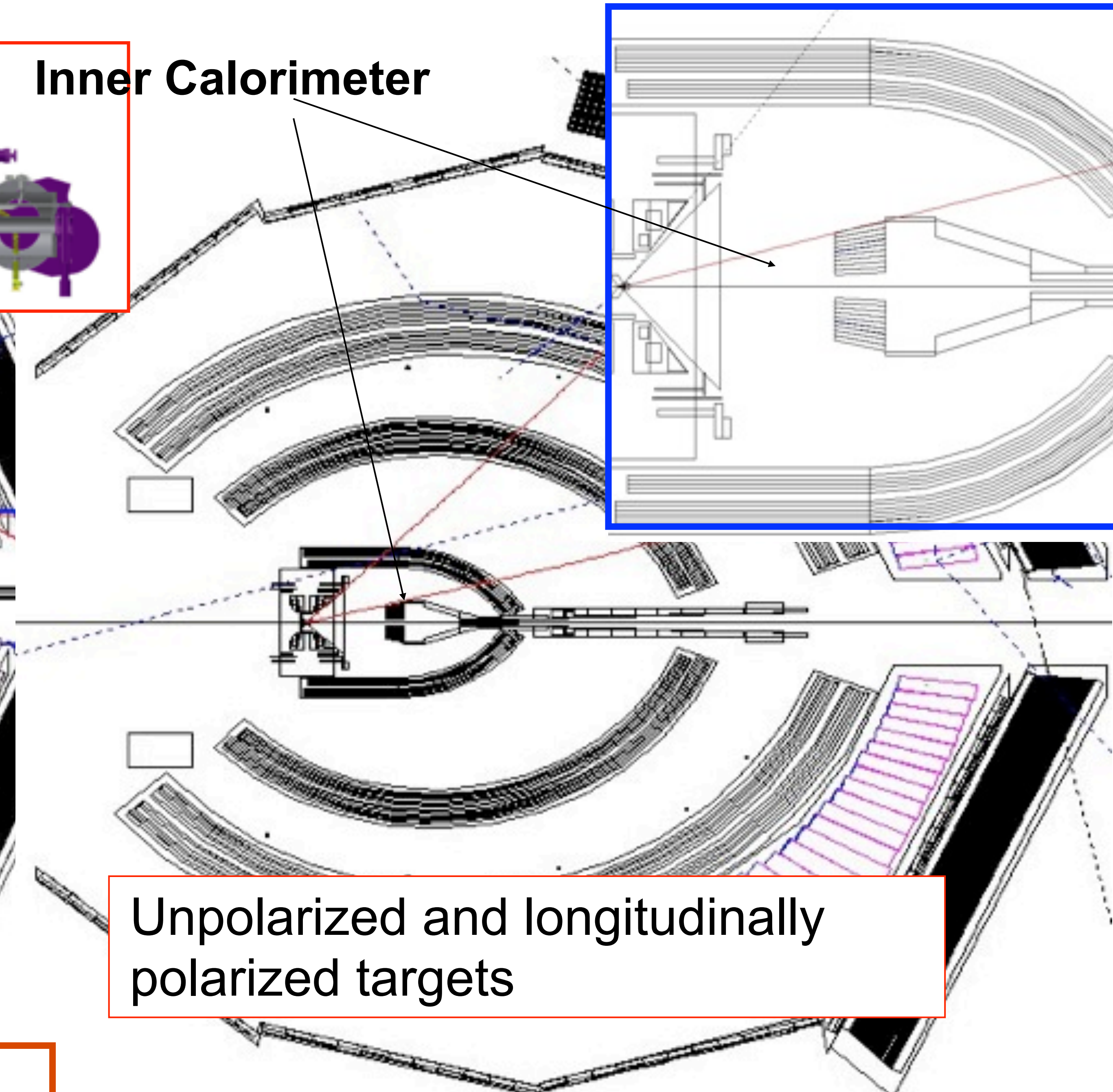
More details on Spin Physics
from Hall-A
Chen's Talk
Thursday 16:20

$ep \rightarrow e'\pi X$ CLAS configurations









Unpolarized, longitudinally and transversely polarized targets

Unpolarized and longitudinally polarized targets

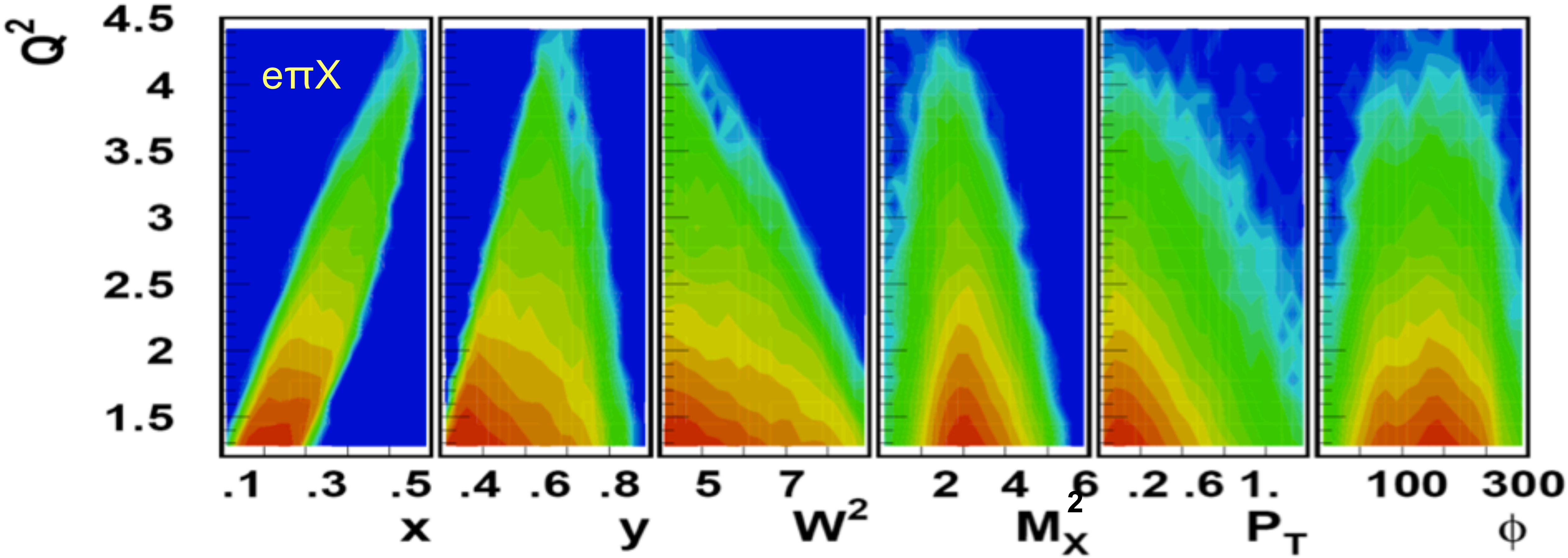
1) Polarized NH3/ND3 (no IC, ~5 days)
2) Unpolarized H (with IC ~ 60 days)
3) Polarized NH3/ND3 with IC 60 days
   10% of data on carbon
4) Polarized HD-Ice (no IC, 25 days)

- **Polarizations:**
- **Beam: ~80%**
- **NH3 proton 80%,ND3 ~30%**
- **HD (H-75%,D-25%)**

SIDIS with JLab at 6 GeV

Scattering of 5.7 GeV electrons off polarized proton and deuteron targets

- **DIS kinematics,** **$Q^2>1$ GeV^2, $W^2>4$ GeV^2, $y<0.85$**
- **$0.4>z>0.7$, $M_X^2>2$ GeV^2**



Large P_T range and full coverage in azimuthal angle φ crucial for studies

A_1 P_T-dependence in SIDIS

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 $h_{1T}^\perp$

$$A_1(\pi) \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^{q\to\pi}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\pi}(z)}$$

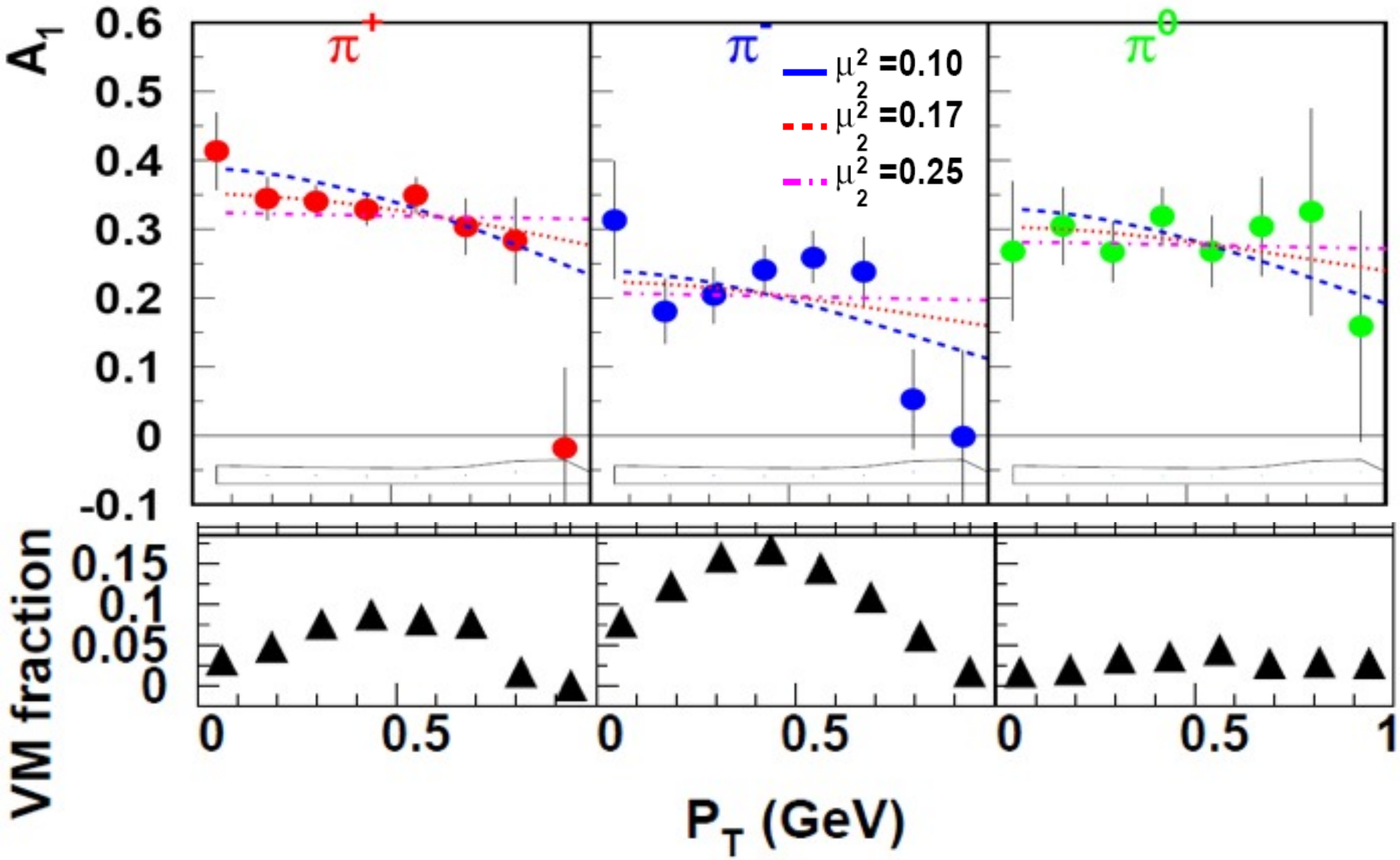
arXiv:1003.4549

0.4<z<0.7

M.Anselmino et al hep-ph/0608048

μ_0^2=0.25GeV^2

μ_D^2=0.2GeV^2



$$f_1^q(x,k_T) = f_1(x)\frac{1}{\pi\mu_0^2}\exp\left(-\frac{k_T^2}{\mu_0^2}\right)$$

$$g_1^q(x,k_T) = g_1(x)\frac{1}{\pi\mu_2^2}\exp\left(-\frac{k_T^2}{\mu_2^2}\right)$$

$$\langle P_T^2(z)\rangle = z^2\mu_0^2 + \mu_D^2$$

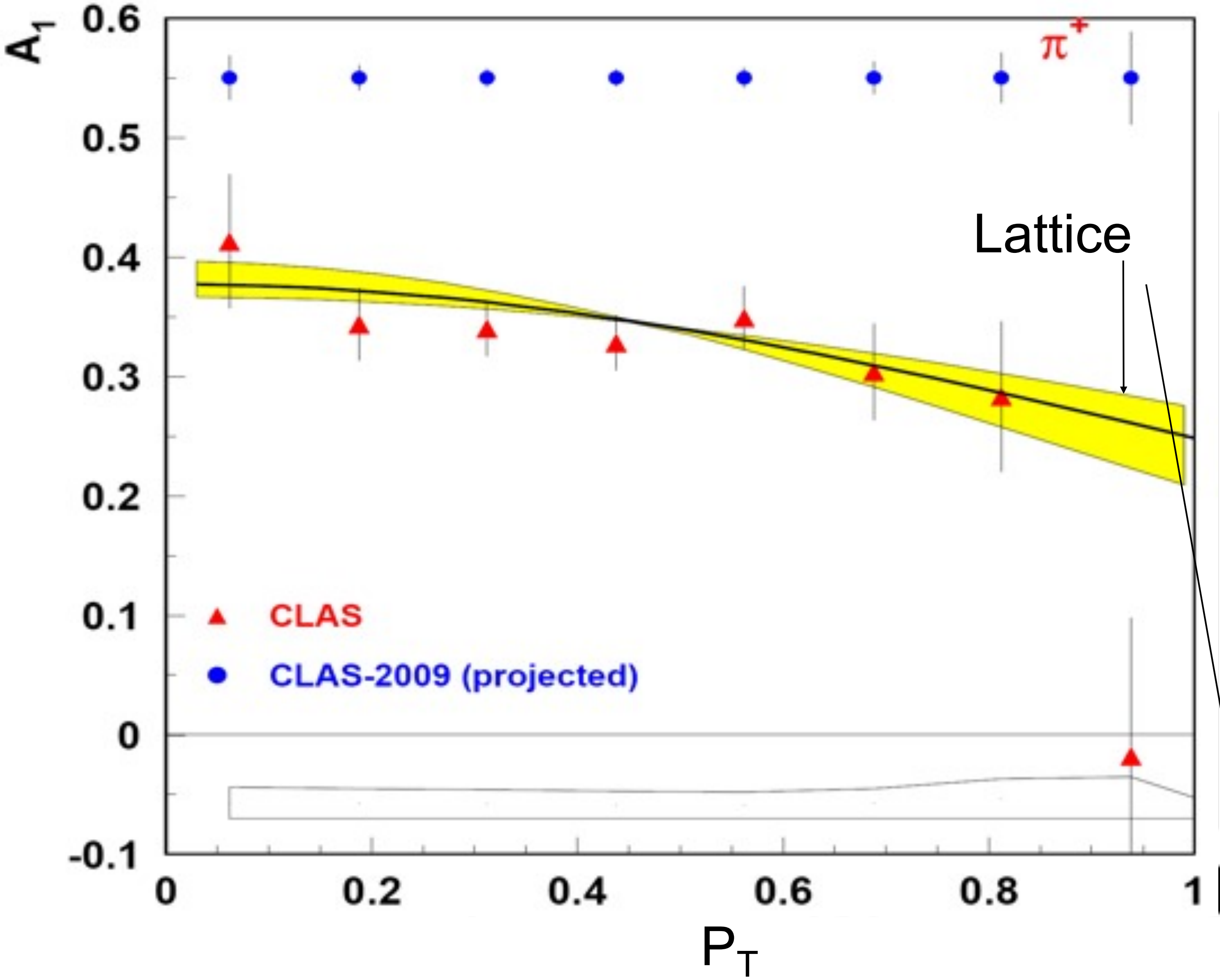
π+ A_1 suggests broader k_T distributions for f_1 than for g_1

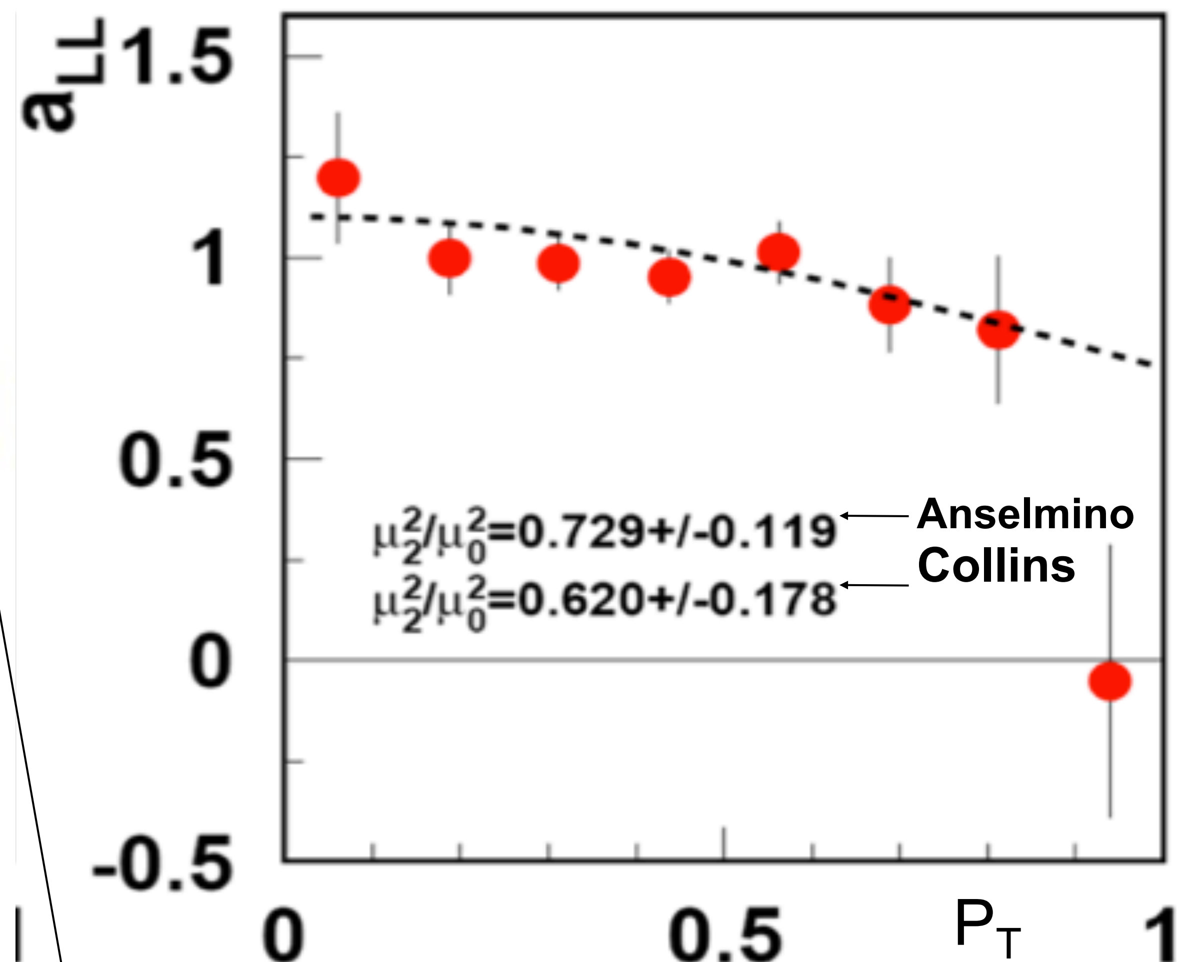
π- A_1 may require non-Gaussian k_T-dependence for different helicities and/or flavors

A_1 P_T-dependence

arXiv:1003.4549

$$A_1(\pi) \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^{q\to\pi}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\pi}(z)} \longrightarrow A_1(x,z,P_T) = A_1(x,z)\underbrace{\frac{\langle P_T^{2,unp}\rangle}{\langle P_T^{2,pol}\rangle}\exp(-P_T^2/\langle P_T^{2,pol}\rangle - P_T^2/\langle P_T^{2,unp}\rangle)}_{a_{LL}}$$





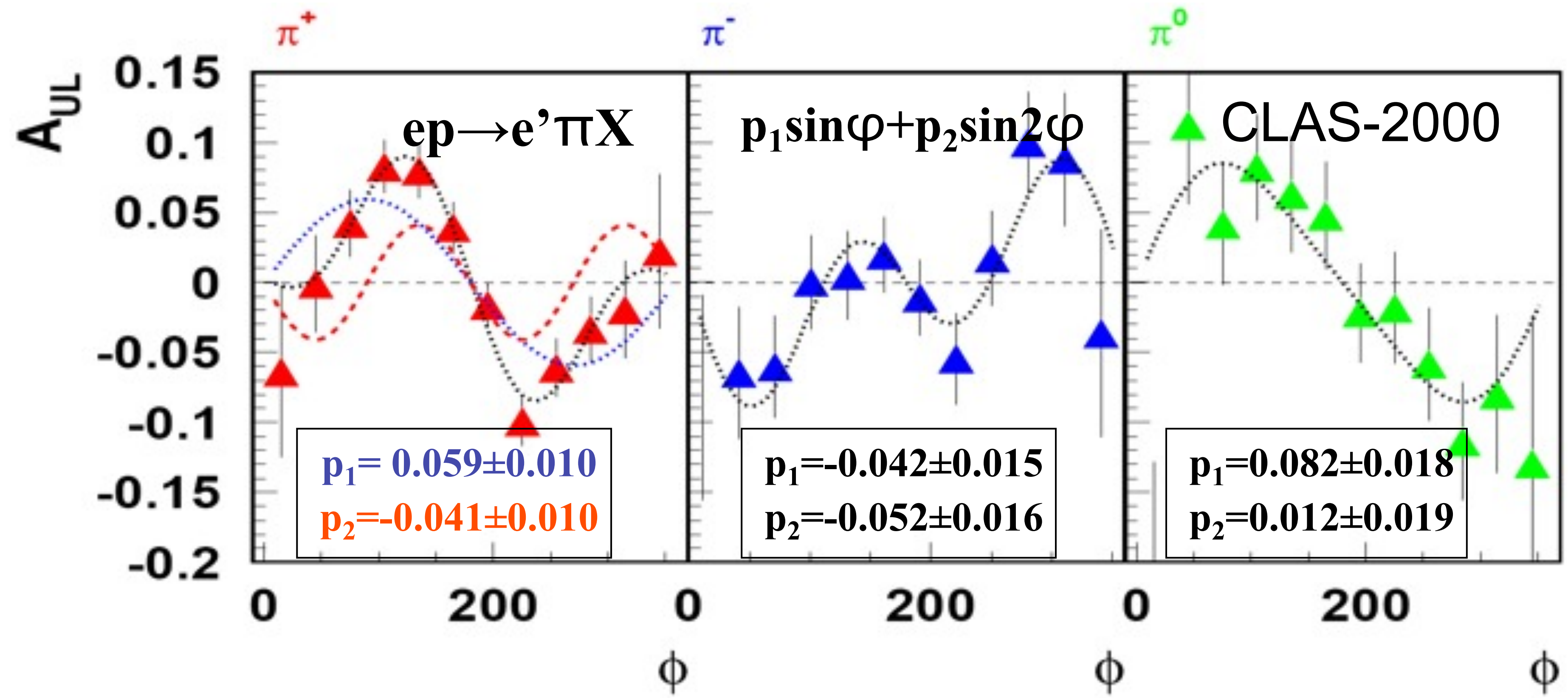
$$\mu_2^2/\mu_0^2 = 0.692 \pm 0.039 \pm 0.045$$

CLAS data suggests that width of g_1 is less than the width of f_1

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 $h_{1T}^\perp$

Longitudinal Target SSA measurements at CLAS

$$A_{UL}(\phi) = \frac{1}{P_t}\frac{N^+ - N^-}{N^+ + N^-}$$



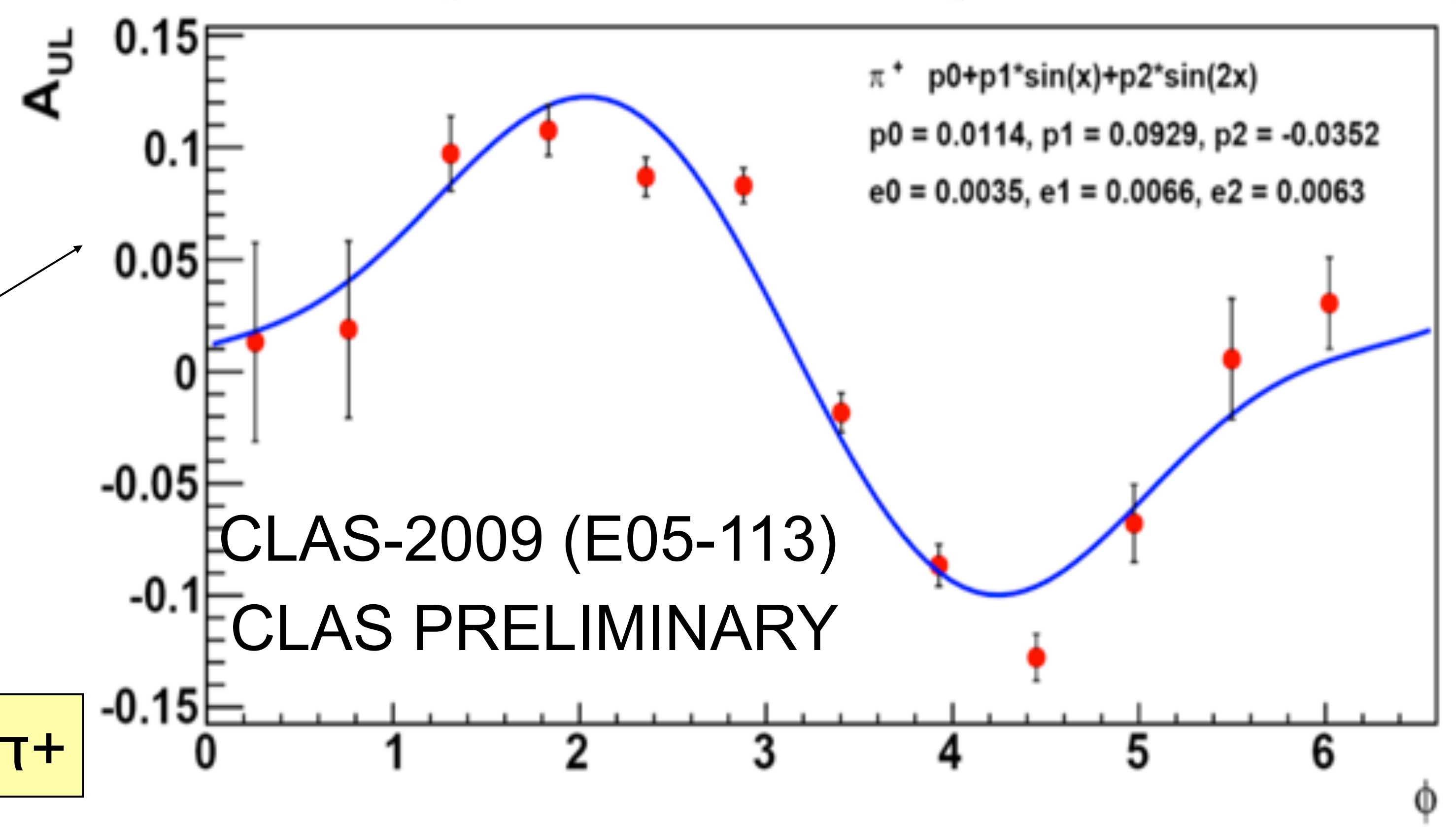
$W^2>4$ GeV^2
$Q^2>1.1$ GeV^2
$y<0.85$

$M_X>1.4$ GeV

$P_T<1$ GeV
$0.12<x<0.48$

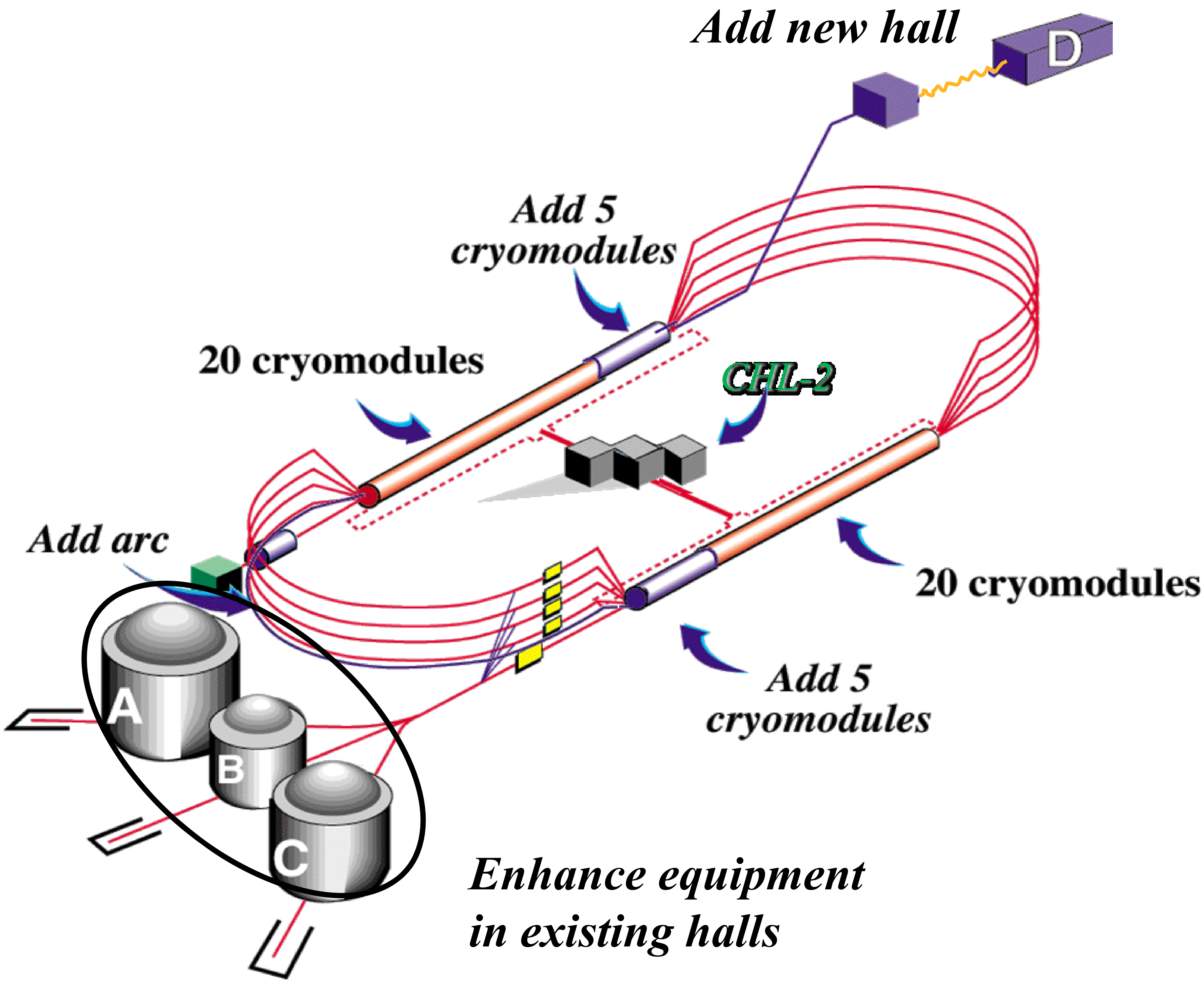
$0.4<z<0.7$

~10% of E05-113 data



Data consistent with negative sin2φ for π+

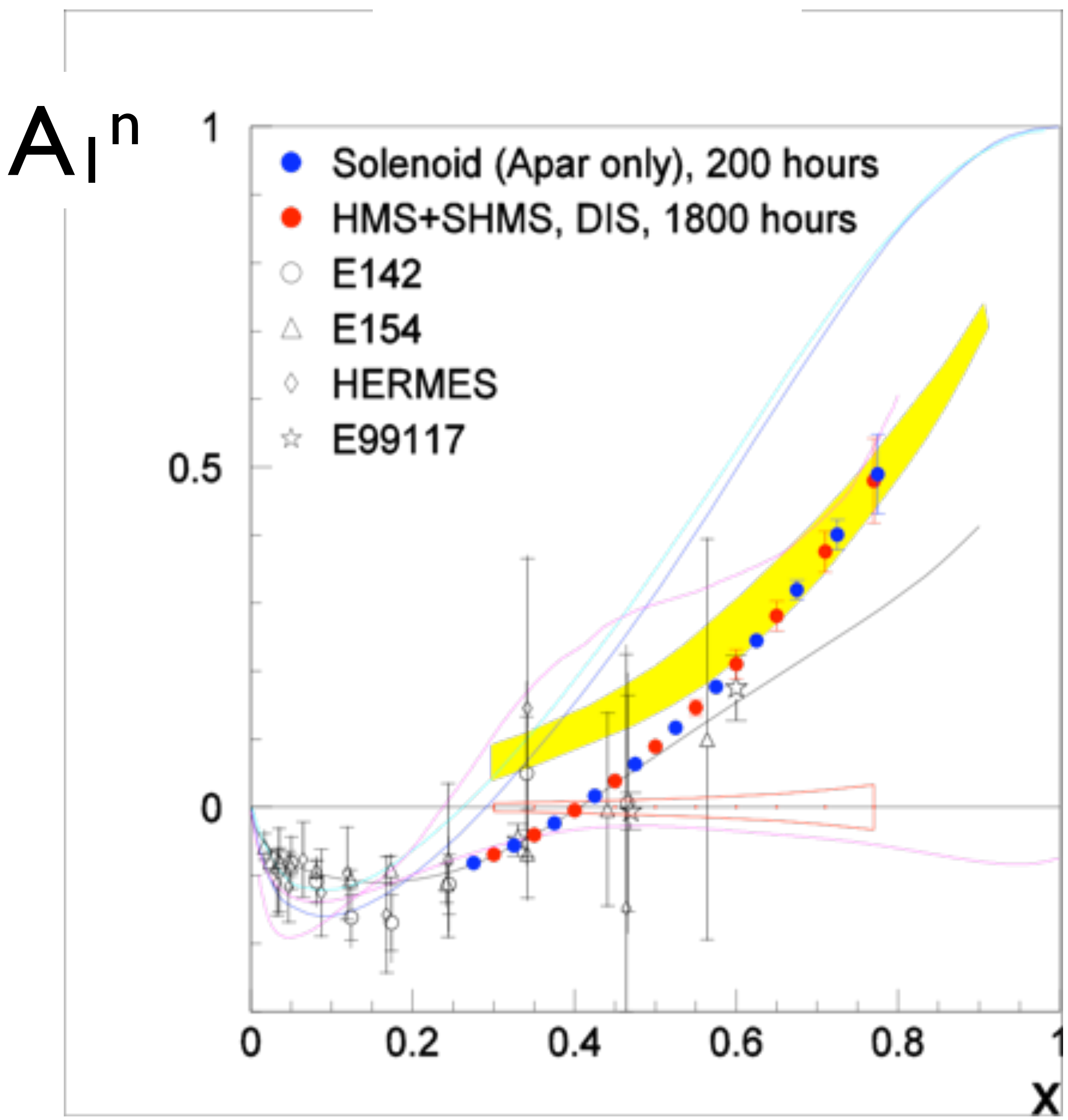
JLab 12GeV Upgrade

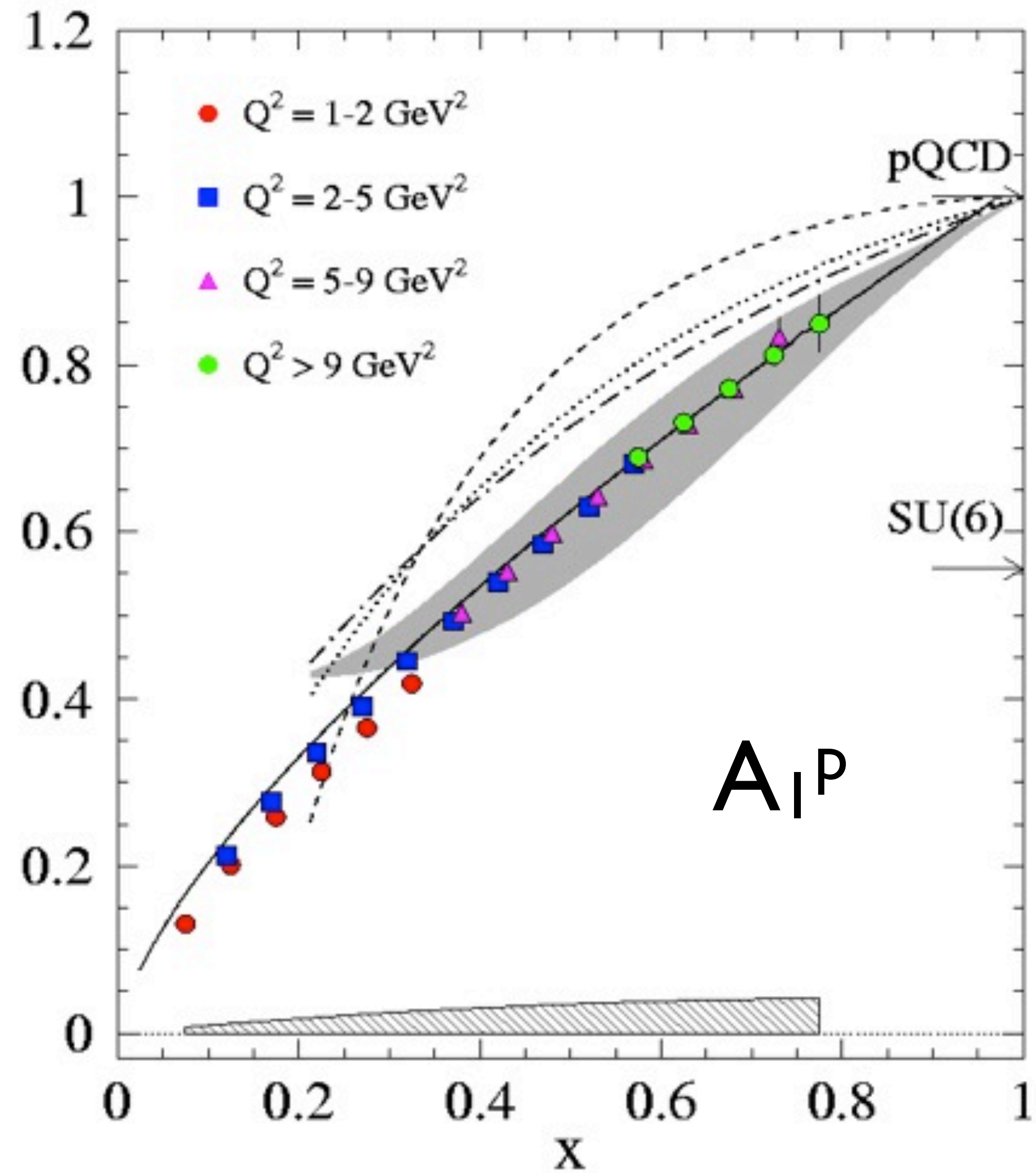


12 GeV Science Program

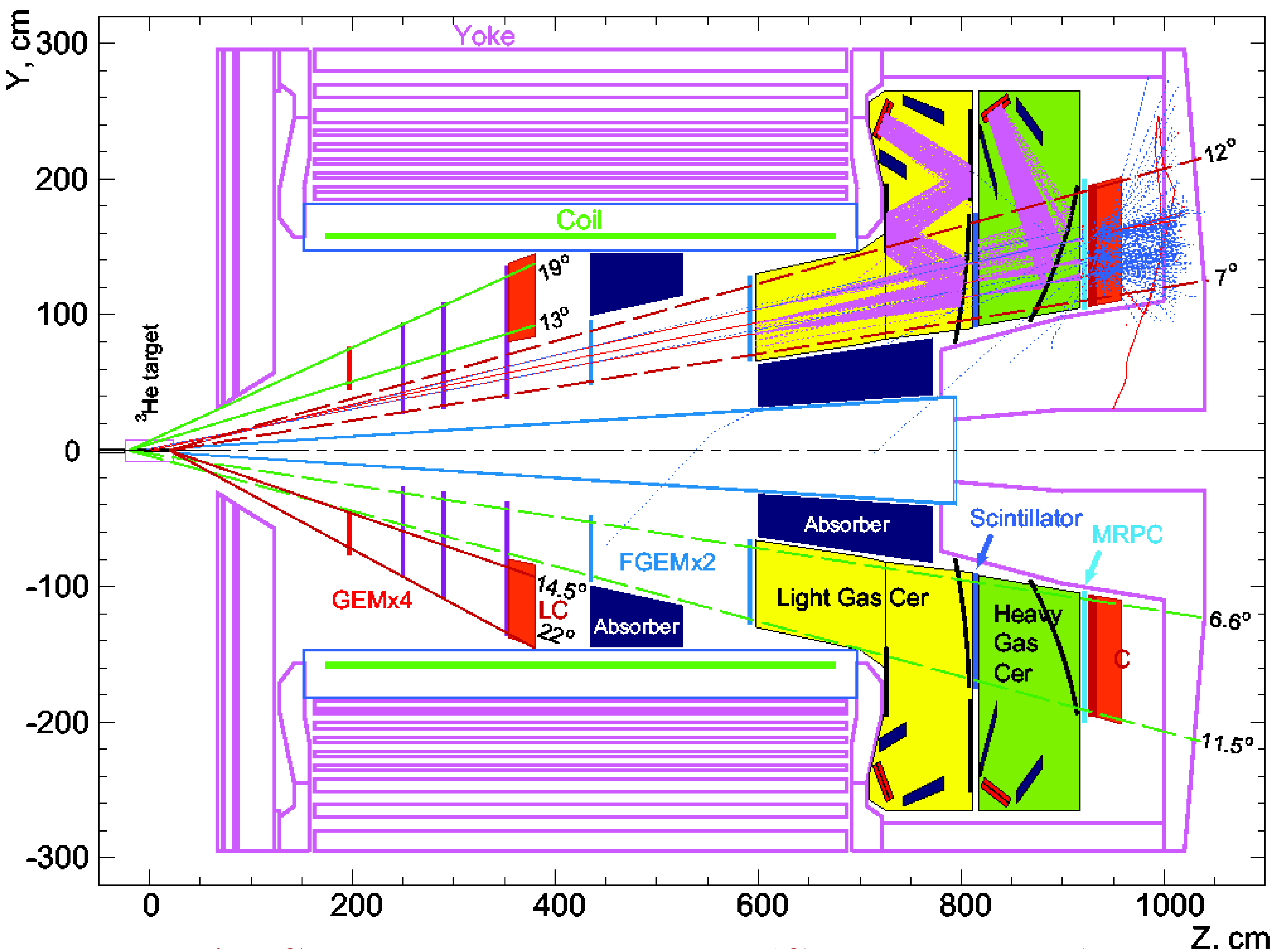
- The physical origins of quark confinement (GlueX, meson and baryon spectroscopy)
- The spin and flavor structure of the proton and neutron (PDF's, GPD's, TMD's)
- The quark structure of nuclei
- Probe potential new physics through high precision tests of the Standard Model

Projections for JLab at 12 GeV



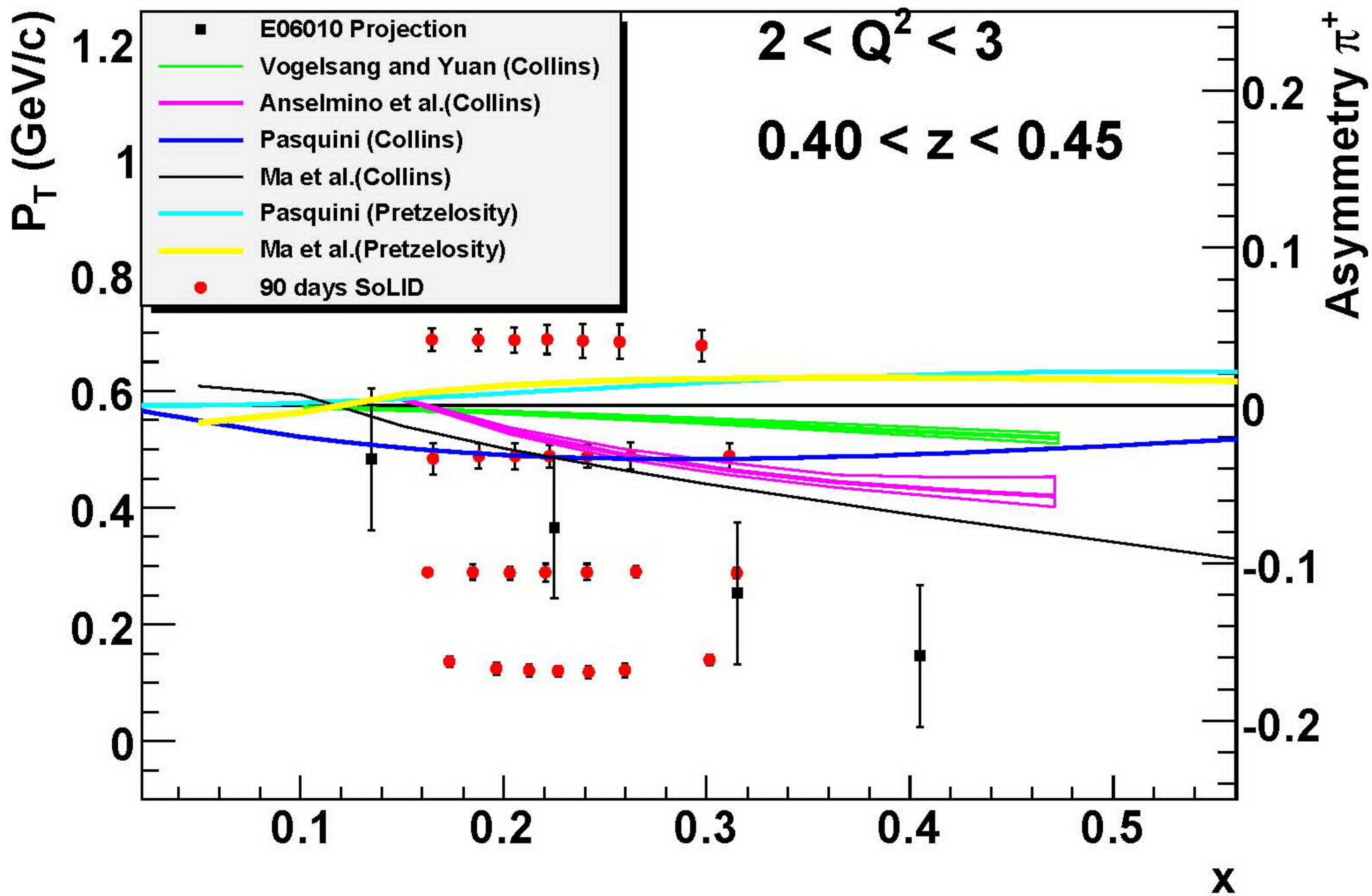


Solenoidal Detector for SIDIS (Hall-A)



Projected Data

- **Total 1400 bins in x, Pt and z for 11/8.8 GeV beam.**
- **z ranges from 0.3 ~ 0.7, only a sub-range of 11/8.8 GeV shown here.**



For more details,
Meziani's Talk
Thursday 17:00

Summary

- Polarized DIS
  - Extensive measurements for non-perturbative region
    - longitudinal target: Halls A, B and C
    - transverse target: Halls A and C
- SIDIS
  - Start of the program at 6 GeV
  - More to come after 12 GeV upgrade
- GPD's
  - Towards full understanding of nucleon structure
- EIC will be an ideal upgrade to the next frontier of QCD