Probing the nucleon structure with SIDIS at Jefferson Lab.

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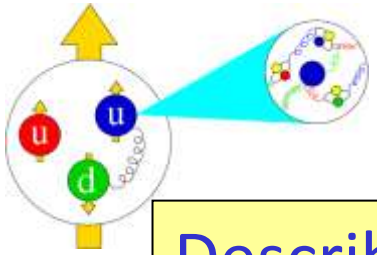
INFN – Frascati

(for the CLAS collaboration)



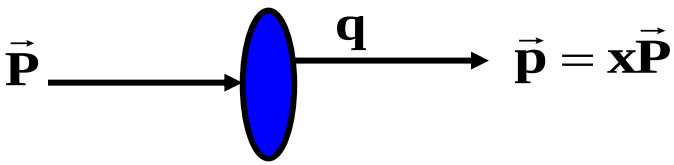
Physics Motivation

Describe the complex nucleon structure in terms of partonic degrees of freedom of QCD

- Our knowledge on the universal parton distribution functions (PDFs) and fragmentation functions (FFs), which connect the partonic dynamics to the observed hadrons, has been improved in recent years,
- As a probability density to find a parton (quark or gluon) inside a hadron with the parton carrying the hadron's longitudinal momentum fraction *x,* the PDFs have provided us information about the partonic structure of a hadron.
- Partonic structure of hadrons has been investigated beyond the PDFs by exploring the parton's motion and its spatial distribution in the direction perpendicular to the parent hadron's momentum.

The nucleon parton model and TMDs

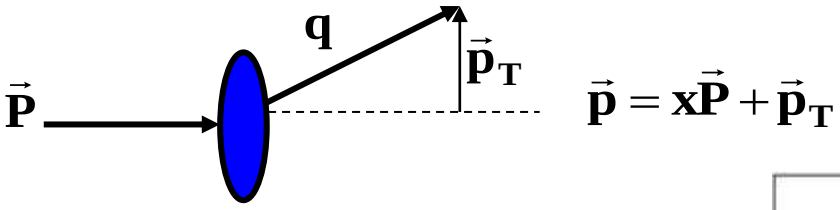
In the collinear approximation:



DIS distribution functions

$$f_1(x), g_1(x), h_1(x)$$

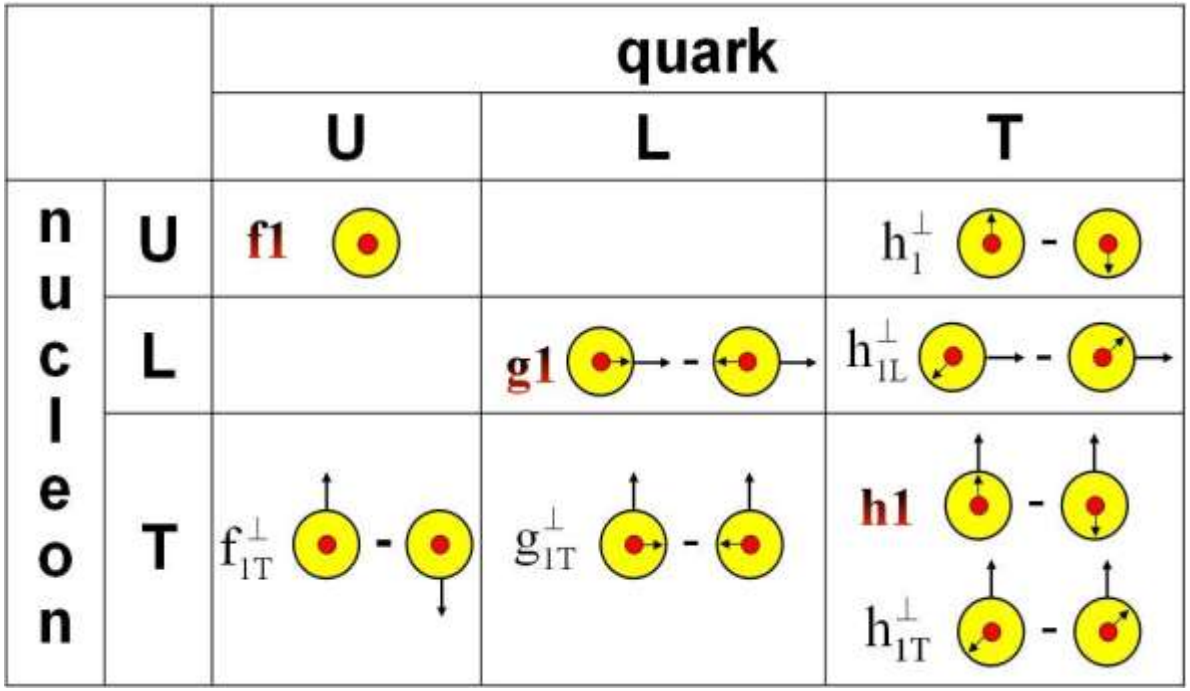
Parton transverse momentum



more complex dist. functions

$$f_1(x, \vec{p}_T), g_1(x, \vec{p}_T), h_1(x, \vec{p}_T)$$

Transverse Momentum Distributions (TMDs) of partons describe the distribution of quarks and gluons in a nucleon with respect to x and the intrinsic transverse momentum p_T carried by the quarks



The nucleon parton model and TMDs

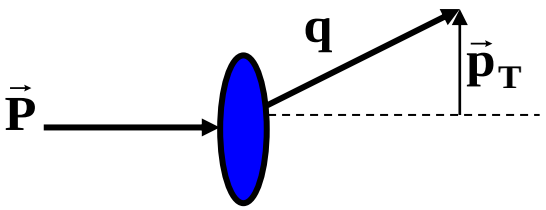
In the collinear approximation:

TMDs are <u>universal</u> objects, i.e. the same functions can be found in SIDIS, e^+e^-, DY, etc

distribution functions

$f_1(x), g_1(x), h_1(x)$

Parton transverse momentum

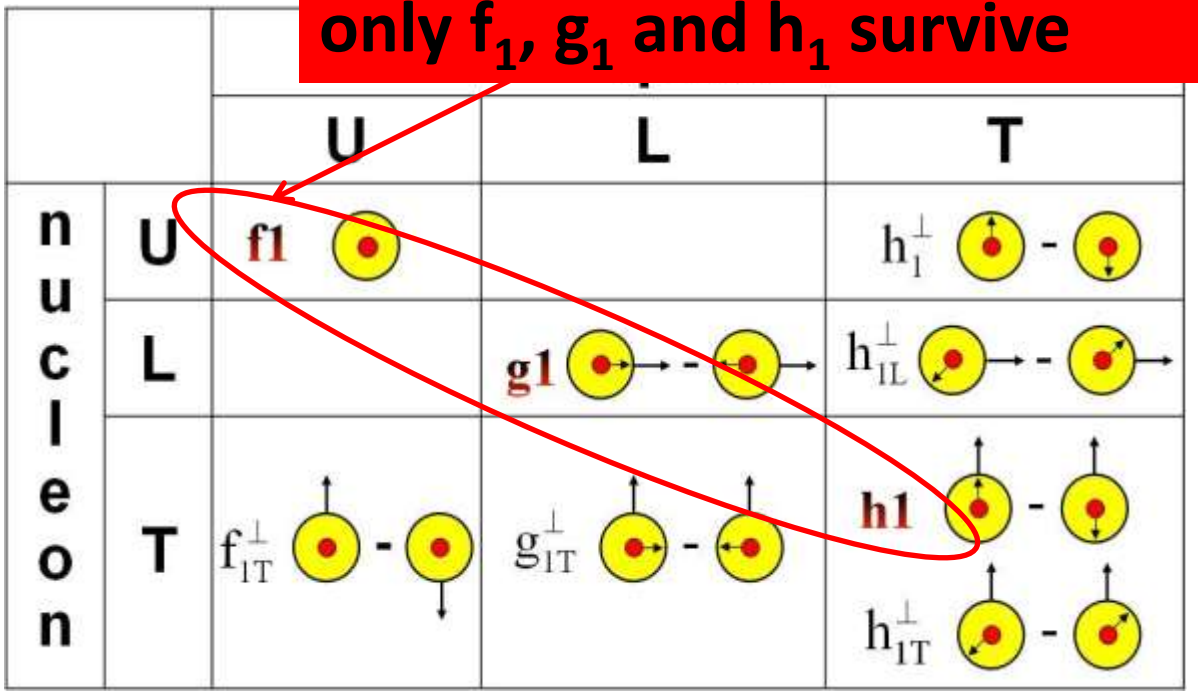


$\vec{p} = x\vec{P} + \vec{p}_T$

f_1

after quark transverse momentum (p_T) integration only f_1, g_1 and h_1 survive

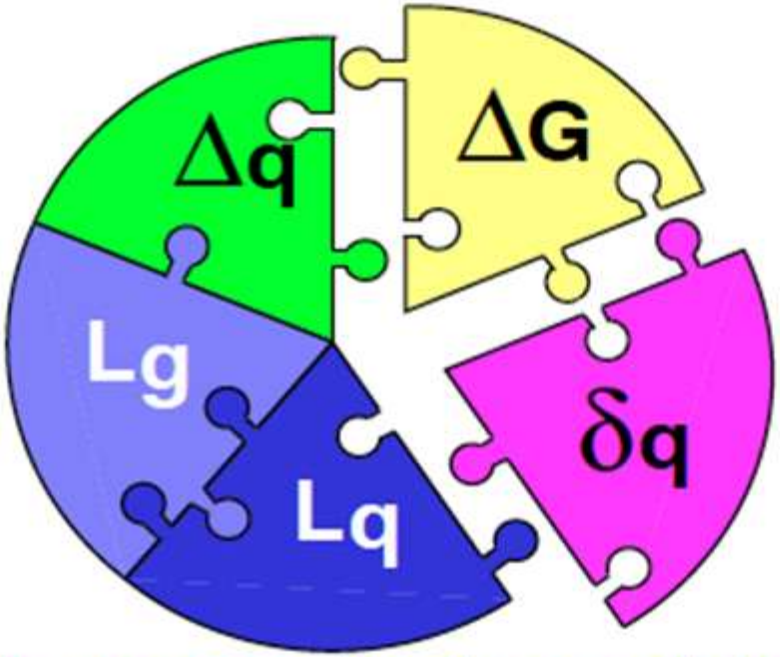
Transverse Momentum Distributions (TMDs) of partons describe the distribution of quarks and gluons in a nucleon with respect to x and the intrinsic transverse momentum p_T carried by the quarks



The Spin Structure of the Proton

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

- From NLO-QCD analysis of DIS measurements
  - $\Delta\Sigma \approx 0.2$
  - $\Delta G = 1.0 \pm 1.2$ → probably small?
- quark polarization $\Delta q(x)$
  - →first 5-flavor separation from HERMES
- transversity $\delta q(x)$
  - →a new window on quark spin
  - →azimuthal asymmetries from HERMES and JLab
  - →future: flavor decomposition
- gluon polarization $\Delta G(x)$
  - →RHIC-spin and COMPASS started providing answers!
- orbital angular momentum L
  - →how to determine?
  - → GPD's and TMD's



We want to solve this puzzle! → need large range in x and Q^2 and high luminosity for precision!

TMD measurements with CLAS at JLab

TMDs are studied at JLab through SIDIS on nucleons (and nuclei) with different experimental equipments

- measuring transverse momentum of final state hadrons in SIDIS gives access to the transverse momentum distributions (TMDs) of partons

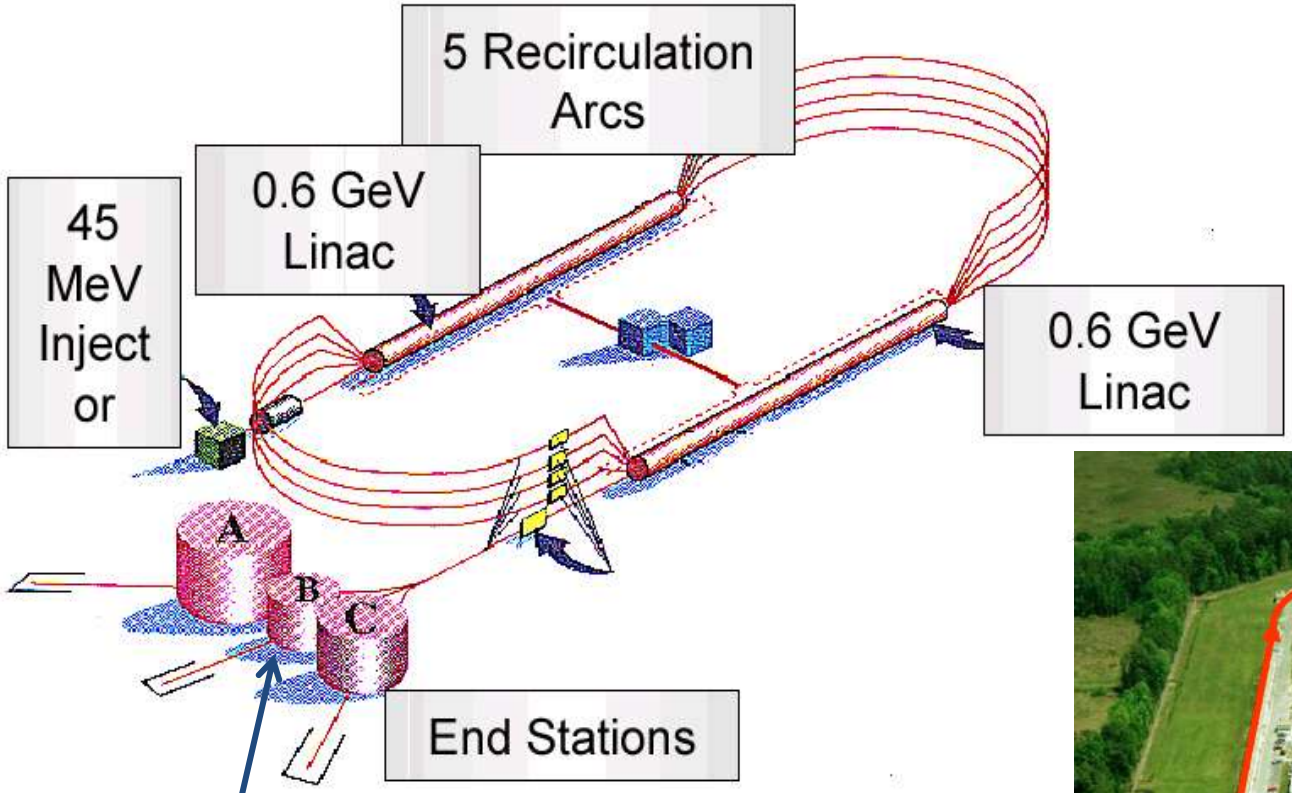
- spin asymmetries measurements give us access to different TMDs, providing information on how quarks are confined in hadrons

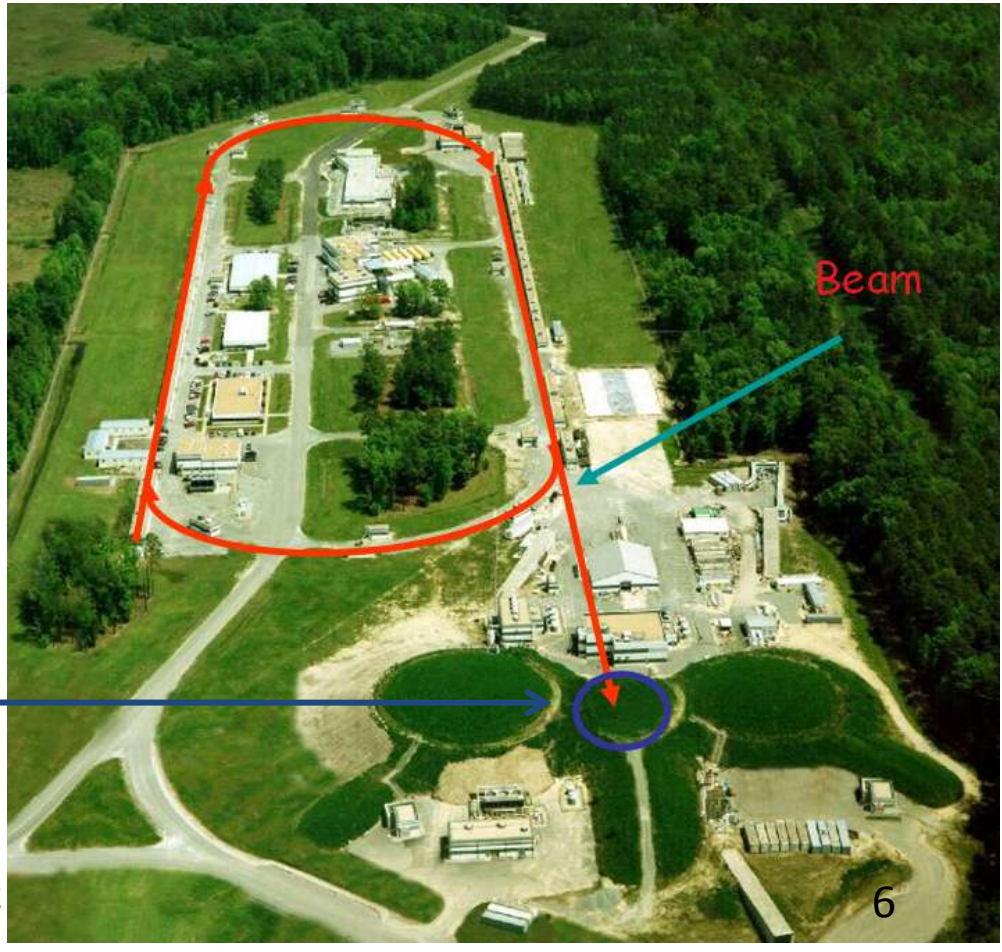
(here we will concentrate on CLAS detector and linearly polarized target results)

CLAS @ Hall B

- large acceptance spectrometer with good resolution
- luminosity ≈ 10^{34} cm^{-2} s^{-1}
- asymmetry measurements over a broad kinematical range
- polarized electron beam
- polarized solid NH3 and ND3 targets

JLab Accelerator CEBAF

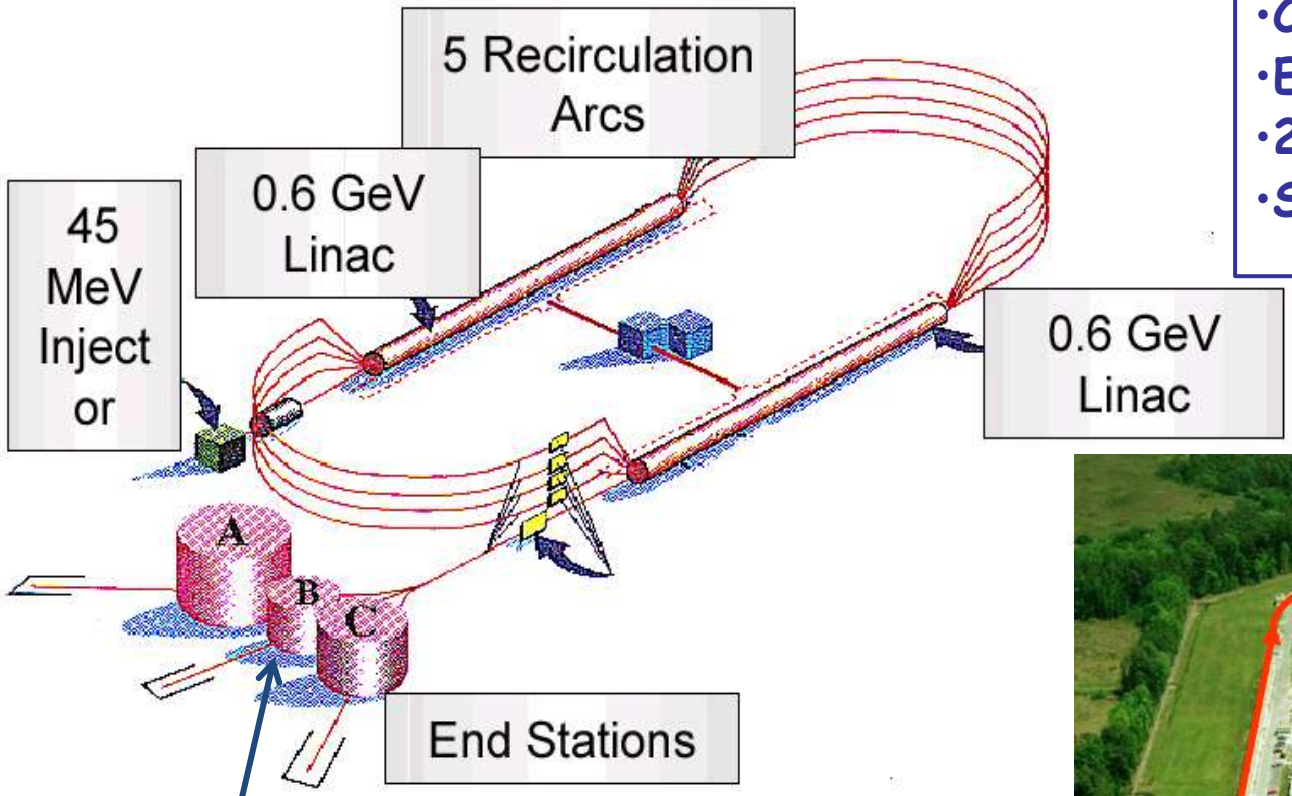


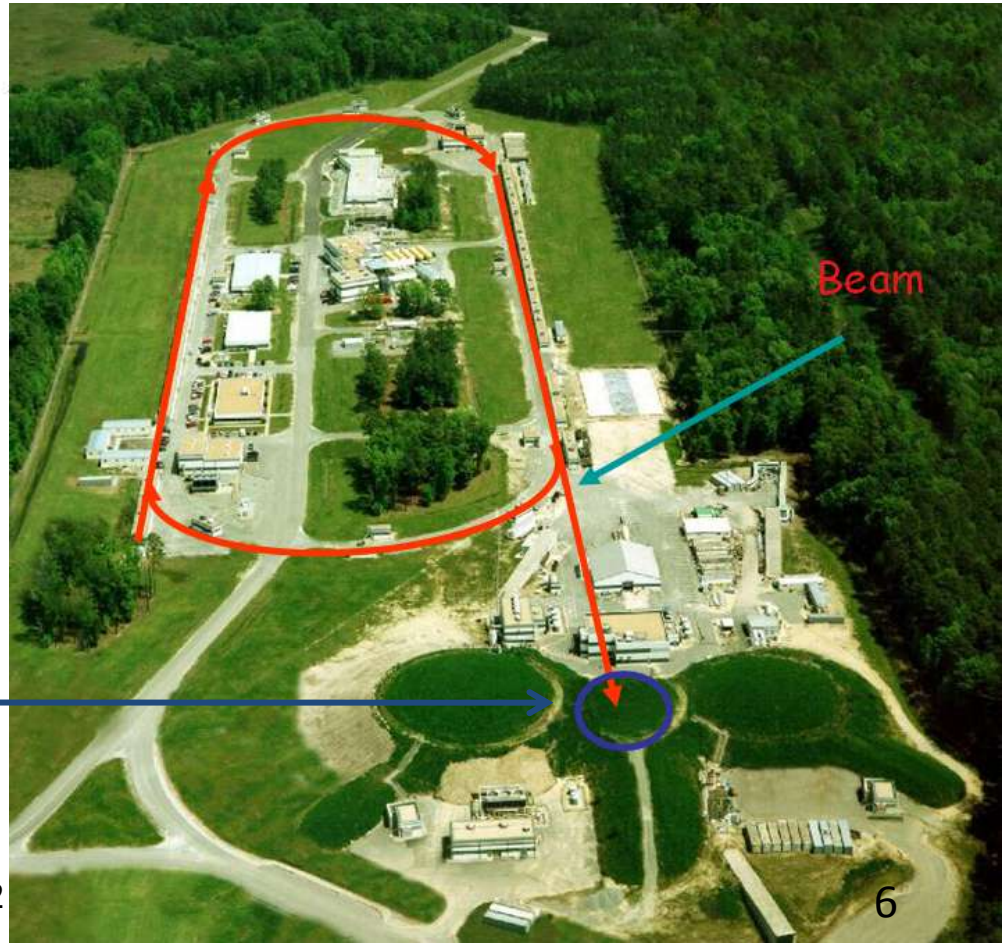


CLAS

JLab Accelerator CEBAF

- Continuous Electron Beam
- Energy 0.8-5.7 GeV
- 200μA, polarization 85%
- Simultaneous delivery to 3Halls





CLAS

Hall B: Cebaf Large Acceptance Spectrometer

beam

Torus magnet

6 superconducting coils

Electromagnetic calorimeters

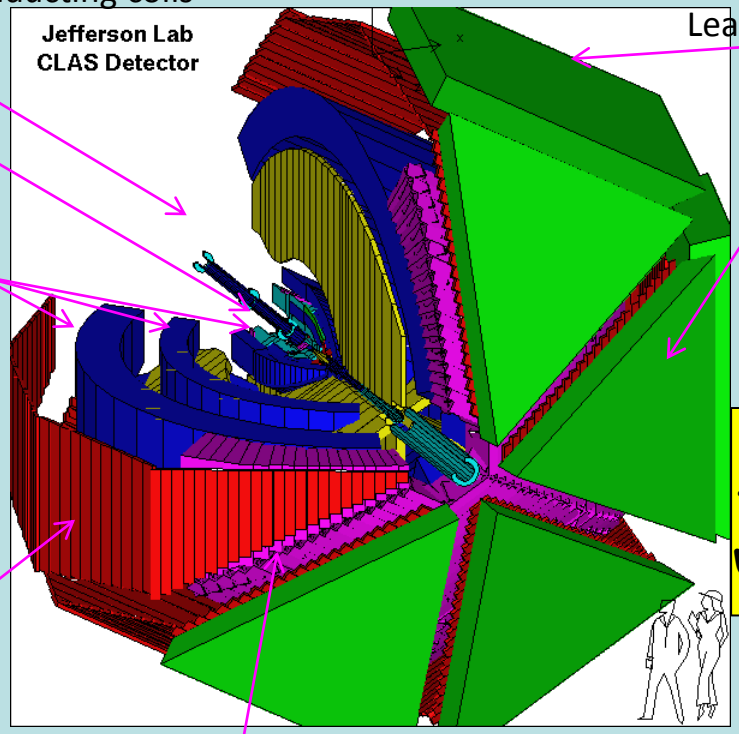
Lead/scintillator, 1296 photomultipliers

Liquid D_2 (H_2)target +

□ start counter; e minitorus

Drift chambers

argon/CO_2 gas, 35,000 cells



- Broad angular coverage (**8° - 140°** in LAB frame)
- Charged particle momentum resolution **~0.5%** forward dir

CLAS is designed to measure exclusive reactions with multi-particle final states

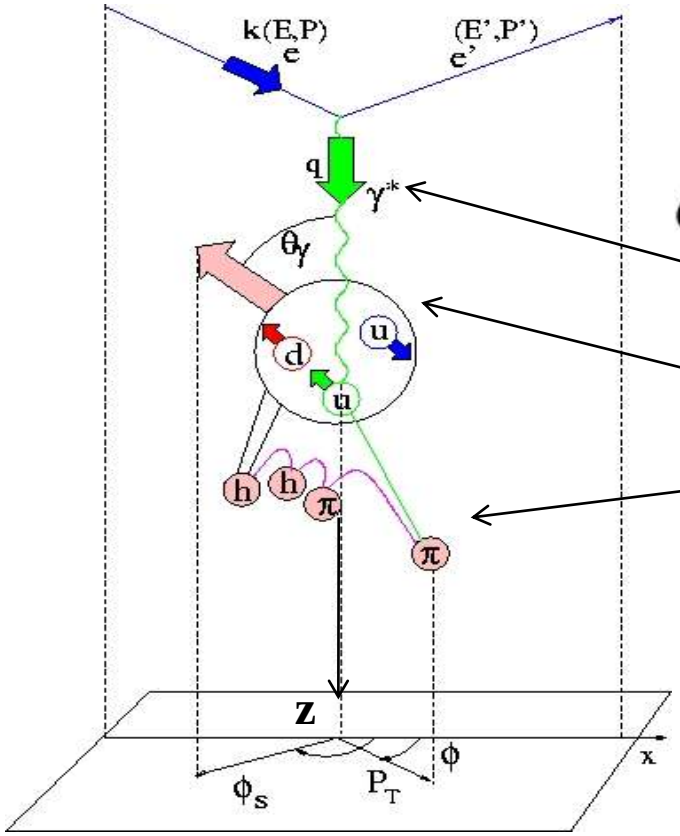
Time-of-flight counters

plastic scintillators, 684 photomultipliers

Gas Cherenkov counters

e/□ separation, 216 PMTs

SIDIS kinematical plane and observables



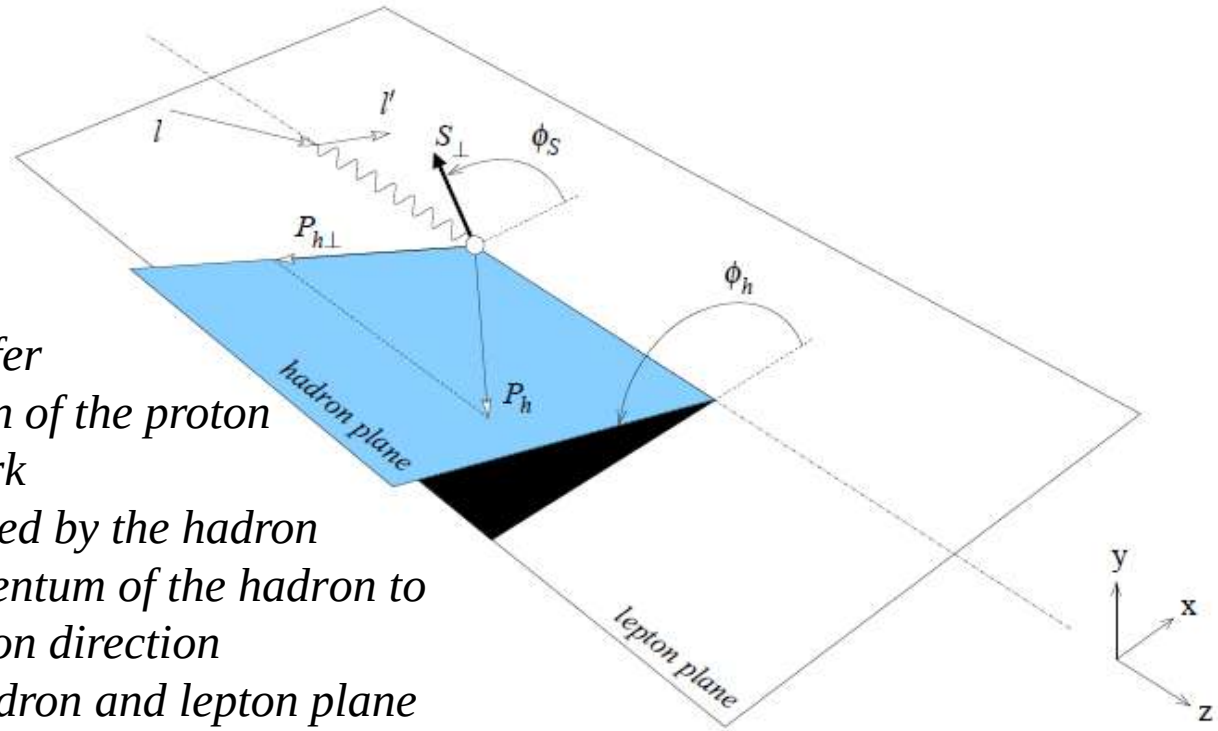
$$\nu = E - E'$$

$$Q^2 = (k - k')^2$$

$$y = \nu / E$$

$$x = Q^2 / 2M\nu$$

$$z = E_h / \nu$$



Q^2 = momentum transfer

x = momentum fraction of the proton carried by the quark

z = quark energy carried by the hadron

$P_{h\perp}$ = transverse momentum of the hadron to the virtual photon direction

ϕ_h = angle between hadron and lepton plane

SIDIS cross section

$$\frac{d\sigma}{y\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

$$+\,S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]$$

$$+\,S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]$$

$$+\,|\boldsymbol{S}_\perp|\Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

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

$$+\,\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg]$$

$$+\,|\boldsymbol{S}_\perp|\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

$$+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\},$$

Bacchetta et al., JHEP 0702:093,2007

SIDIS cross section

$$\frac{d\sigma}{y\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

$$+\,S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]$$

$$+\,S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]$$

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

$$+\,\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg]$$

$$+\,|\boldsymbol{S}_\perp|\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

$$+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\},$$

18 structure functions

Leading Twist

Bacchetta et al., JHEP 0702:093,2007

SIDIS cross section

$$\frac{d\sigma}{y\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h}$$

$$+\varepsilon\cos(2\phi_h)F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}$$

$$+S_\parallel\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)F_{UL}^{\sin 2\phi_h}\right]$$

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

$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg]$$

$$+|S_\perp|\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}$$

$$+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\},$$

18 structure functions

Leading Twist

Sub-Leading Twist

where each structure function now depends also on transverse hadron momentum $P_{h\perp}$

Bacchetta et al., JHEP 0702:093,2007

SIDIS cross section

$$\frac{d\sigma}{y\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{F_{UU,T} + \varepsilon\, F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\, F_{UU}^{\cos\phi_h}$$

$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

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

$$+\,\sqrt{2\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} + \sqrt{2\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg]$$

$$+\,|\boldsymbol{S}_\perp|\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

$$+\,\sqrt{2\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\},$$

$f_1 \otimes D_1$

$g_1 \otimes D_1$

18 structure functions

Leading Twist

ist

Structure functions decomposition

$$F \propto DF \otimes FF$$

where each structure function now depends also on transverse hadron momentum $P_{h\perp}$

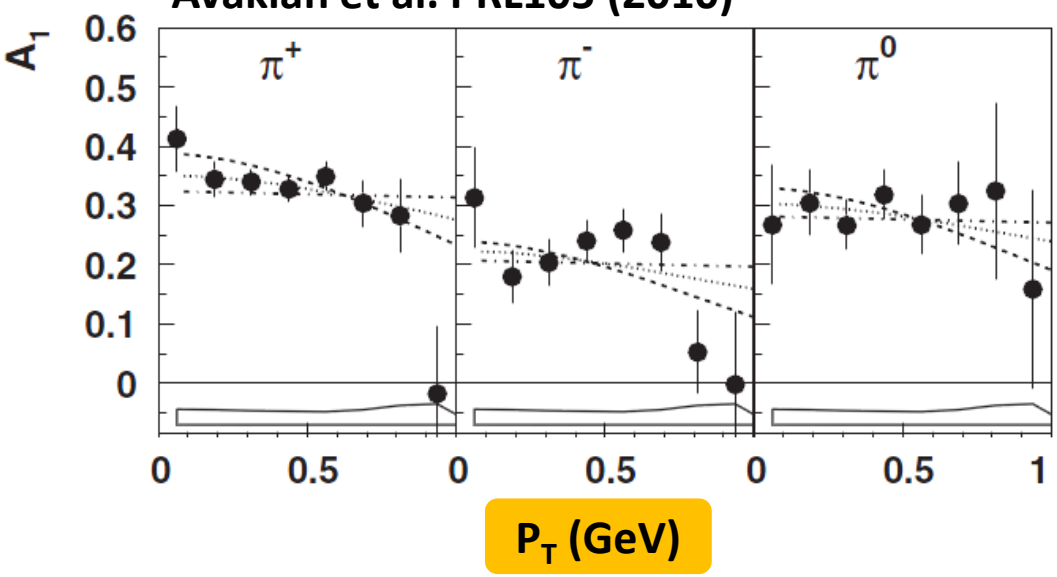
Bacchetta et al., JHEP 0702:093,2007

Double spin asymmetry

$$\vec{e}\,\vec{p} \rightarrow e'\pi X$$

$$A_{LL} = \frac{1}{fD(y)P_B P_t}\frac{N^+ - N^-}{N^+ + N^-} \propto \frac{g_1(x, P_T)}{f_1(x, P_T)}$$

Avakian et al. PRL105 (2010)



$\langle k_T^2 \rangle_g / \langle k_T^2 \rangle_f$

1.0

0.68

0.4

Calculations using gaussian ansatz

$$f_1(x, \vec{k_T}) = f_1(x) e^{-\frac{k_T^2}{\langle k_T^2 \rangle_f}}$$

$$g_1(x, \vec{k_T}) = g_1(x) e^{-\frac{k_T^2}{\langle k_T^2 \rangle_g}}$$

Double spin asymmetry

$$\vec{e}\,\vec{p} \rightarrow e'\pi X$$

$$A_{LL} = \frac{1}{fD(y)P_B P_t}\frac{N^+ - N^-}{N^+ + N^-} \propto \frac{g_1(x, P_T)}{f_1(x, P_T)}$$

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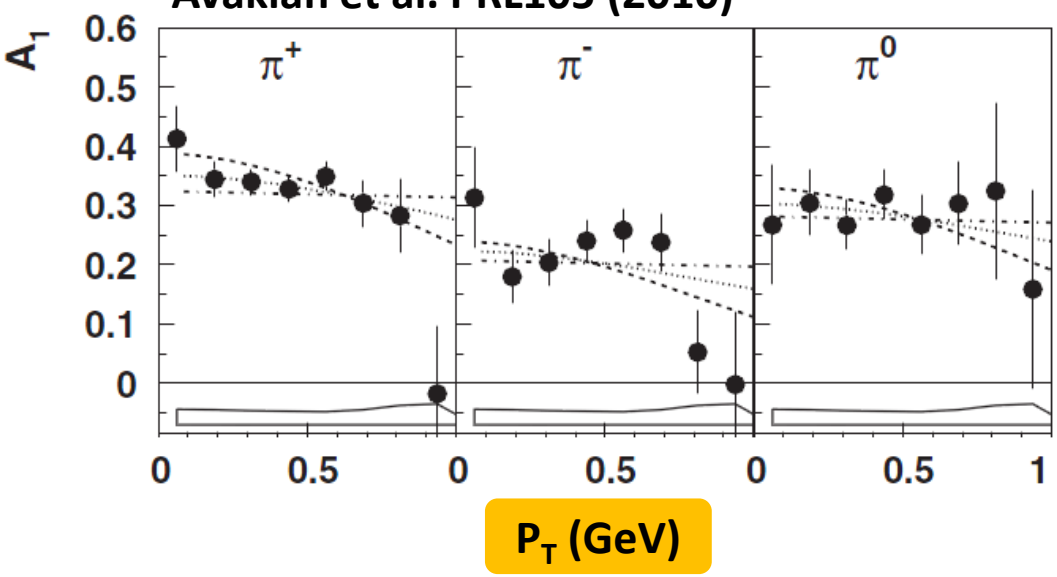

$\langle k_T^2 \rangle_g / \langle k_T^2 \rangle_f$

1.0

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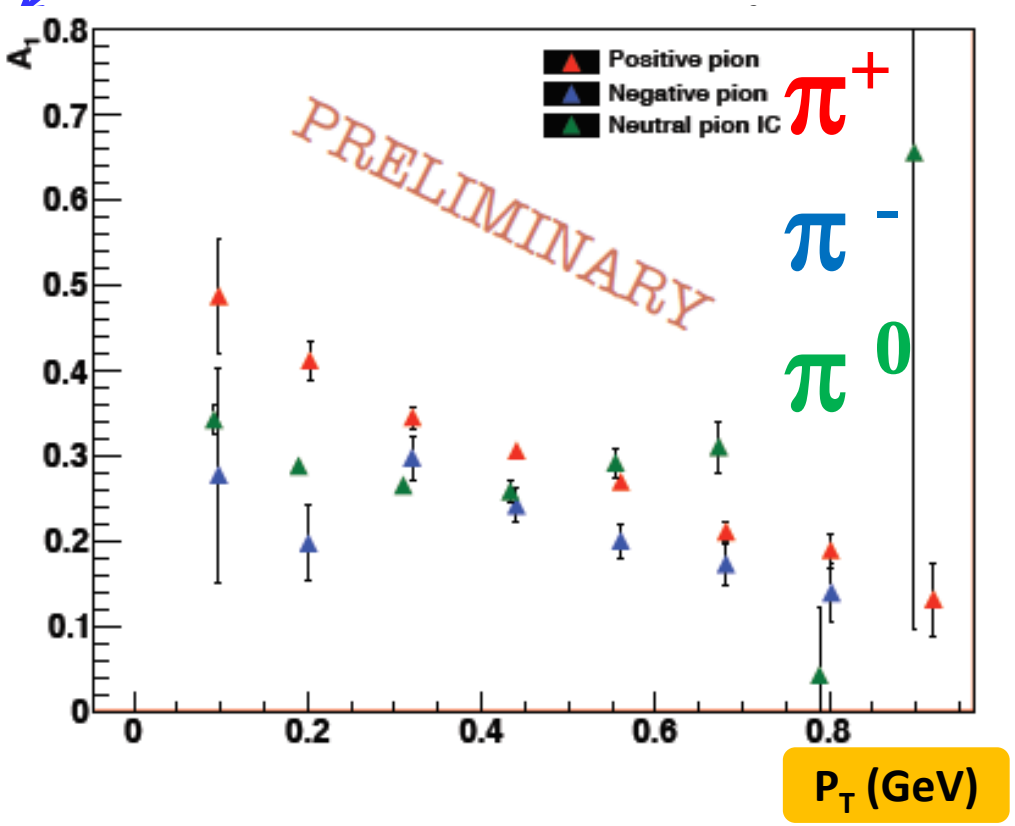


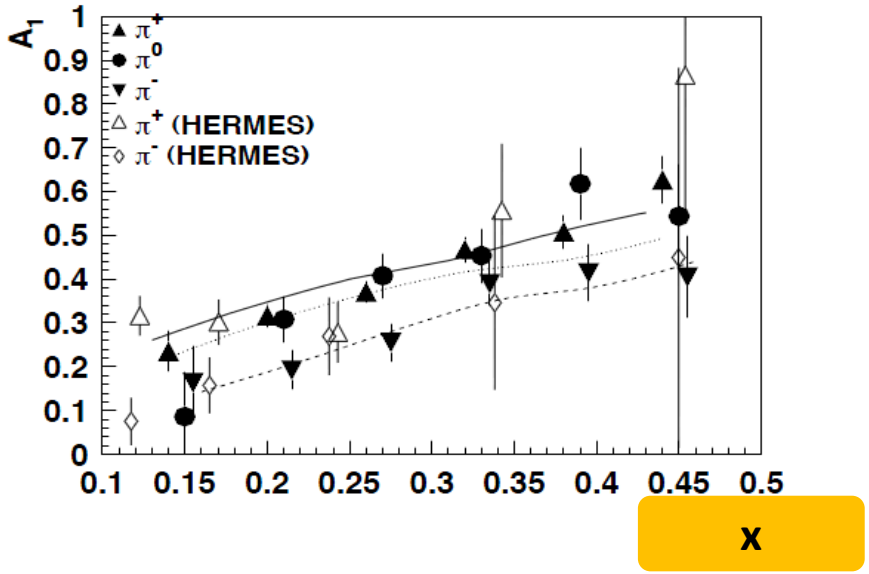
new CLAS results

Double spin asymmetry

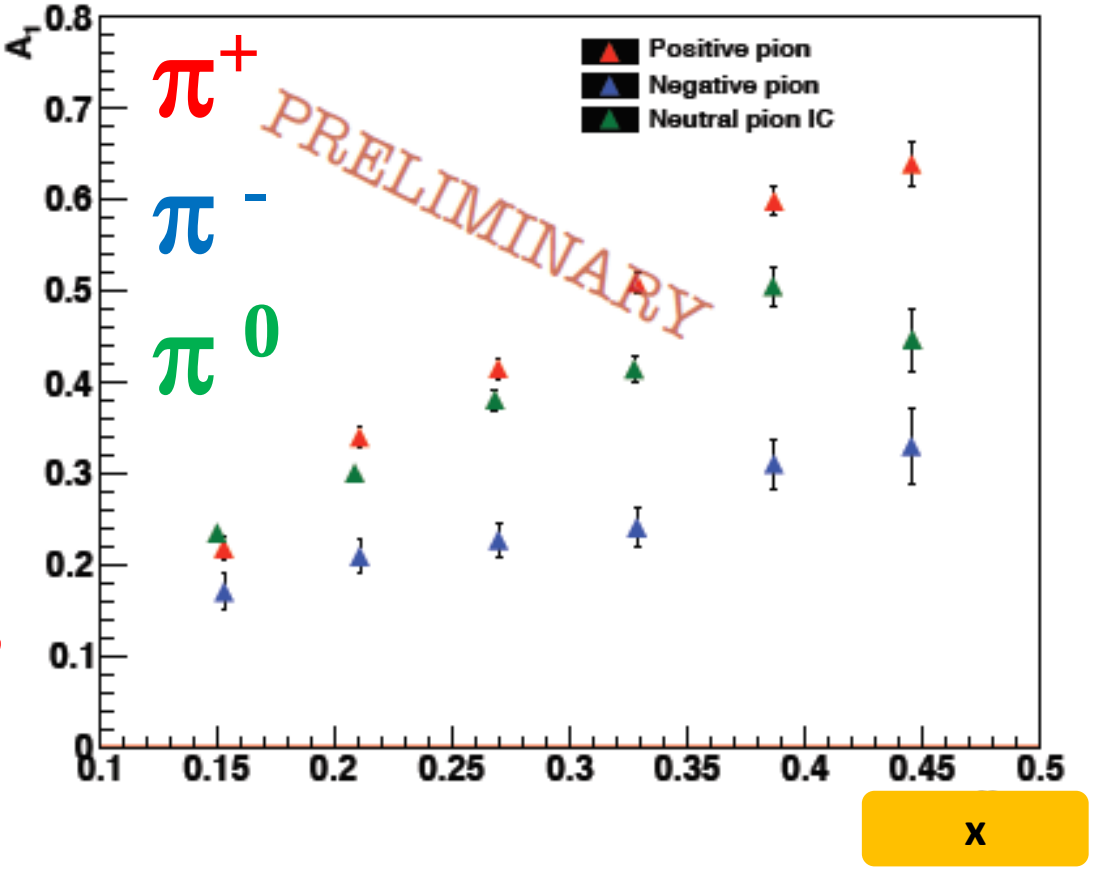
$$\vec{e}\,\vec{p} \rightarrow e'\pi X$$

$$A_{LL} = \frac{1}{fD(y)P_B P_t}\frac{N^+ - N^-}{N^+ + N^-} \propto \frac{g_1(x, P_T)}{f_1(x, P_T)}$$

Avakian et al. PRL105 (2010)



new CLAS results



Target single spin asymmetry

$$\vec{e}p \rightarrow e'\pi X$$

$$A_{UL} = \frac{1}{fP_t}\frac{N^+ - N^-}{N^+ + N^-}$$

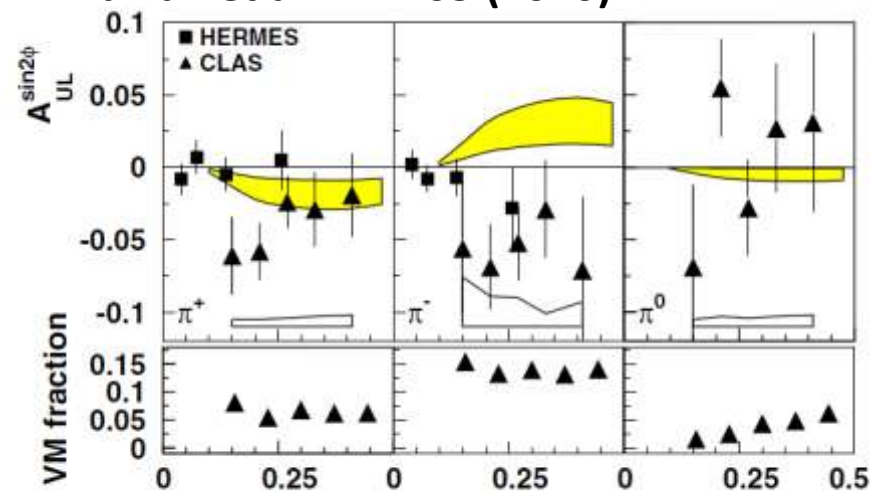
$$\sigma_{UL} \propto F_{UL}^{\sin 2\phi} \sin 2\phi + F_{UL}^{\sin\phi} \sin\phi$$

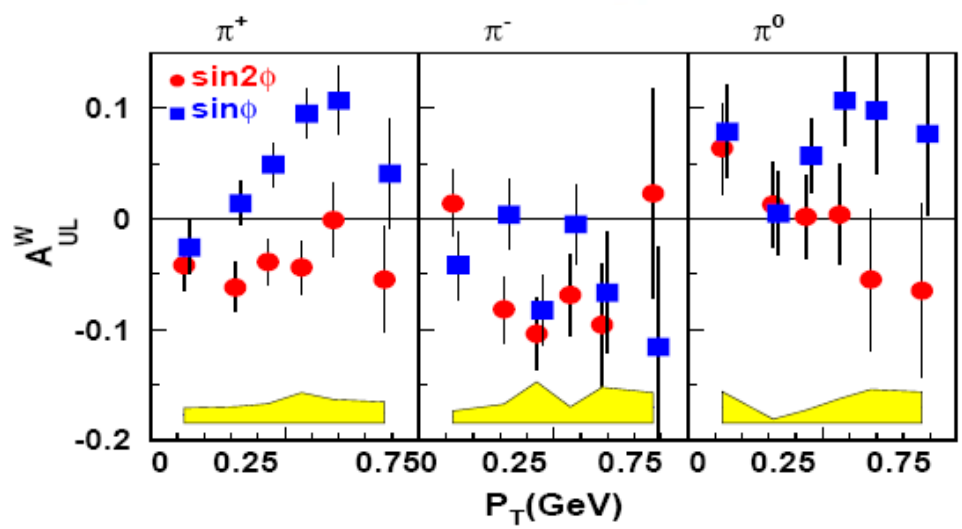
leading term

higher twist

$$F_{UL}^{\sin 2\varphi} \propto h_{1L}^{\perp} \otimes H_1^{\perp}$$

Avakian et al. PRL105 (2010)





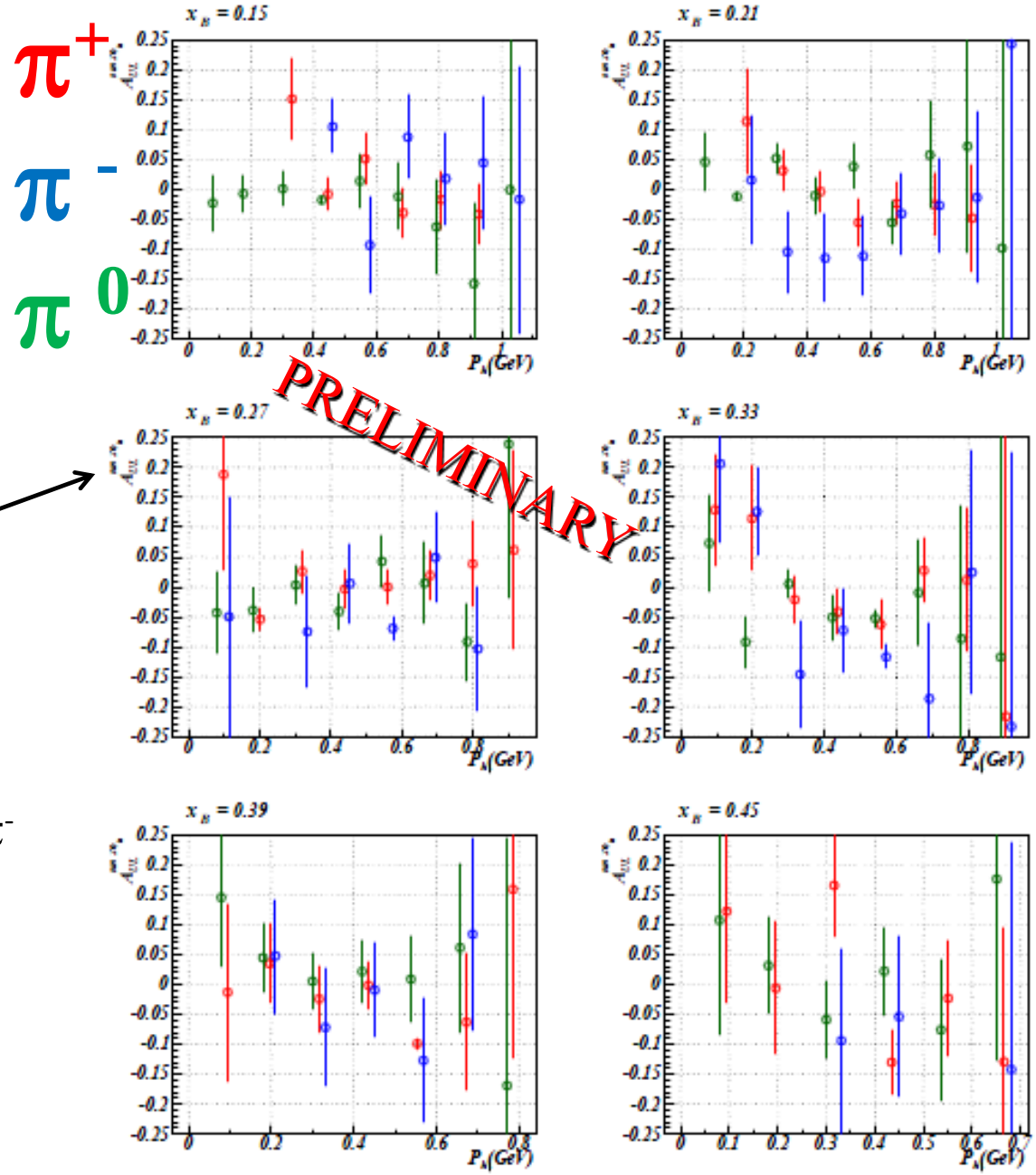
$H_1^{\perp}$:
Collins FF of transverse polarized quark in unpol. hadron

$h_{1L}^{\perp}$:
correlation between transverse spin of quarks and longitudinal spin of nucleon

HT terms are important at JLab

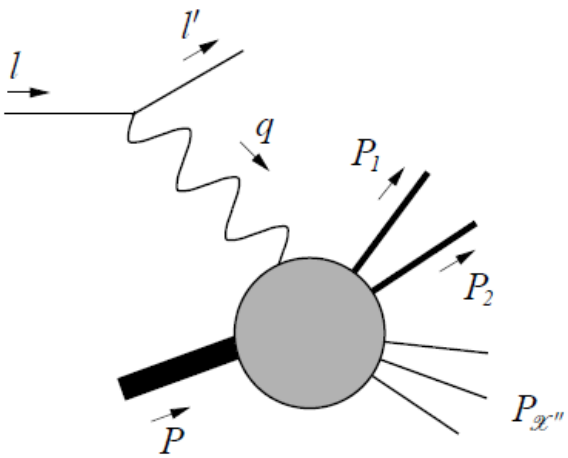
Target single spin asymmetry

$$F_{UL}^{\sin 2\varphi} \propto h_{1L}^{\perp} \otimes H_1^{\perp}$$



- $A_{UL}^{\sin 2\phi}$ (leading twist) is small suggesting that the Collins π^+ and π^- FF are nearly equal and opposite

Dihadron analysis



factorization:

$$\sigma_{SIDIS}^{hh} \propto \Sigma_f \hat{\sigma} \otimes pdf_f(x) \otimes frag^{f \to hh}(z)$$

In the dihadron channel, different FFs appear but it also brings a very useful advantage:

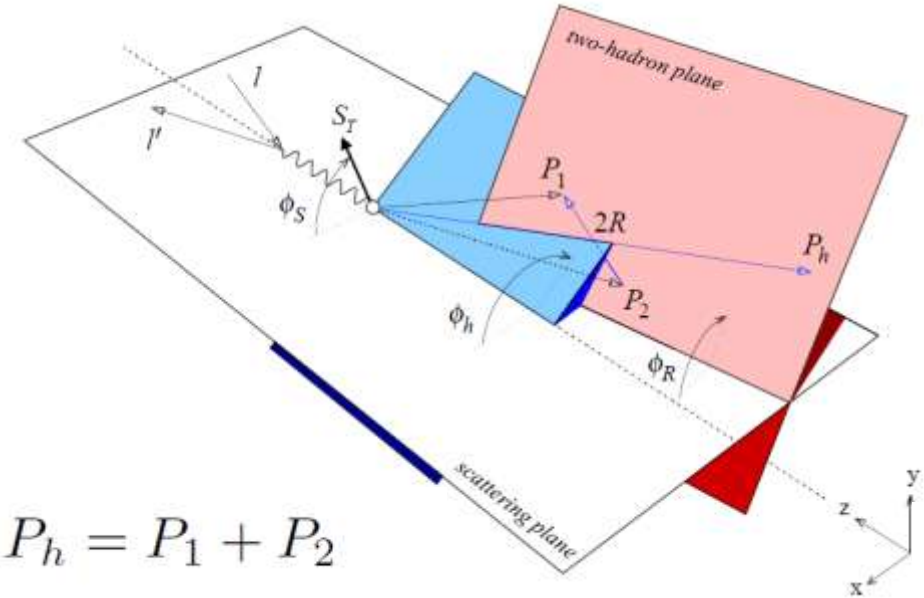
in single hadron production,
the observables are convolution
of TMDs

single hadron

$$F_{LU}^{\sin 2\varphi} \propto h_{1L}^{\perp} \otimes H_1^{\perp}$$

in double hadron production, observables are **product** of TMDs

CLAS dihadron beam spin asymmetries

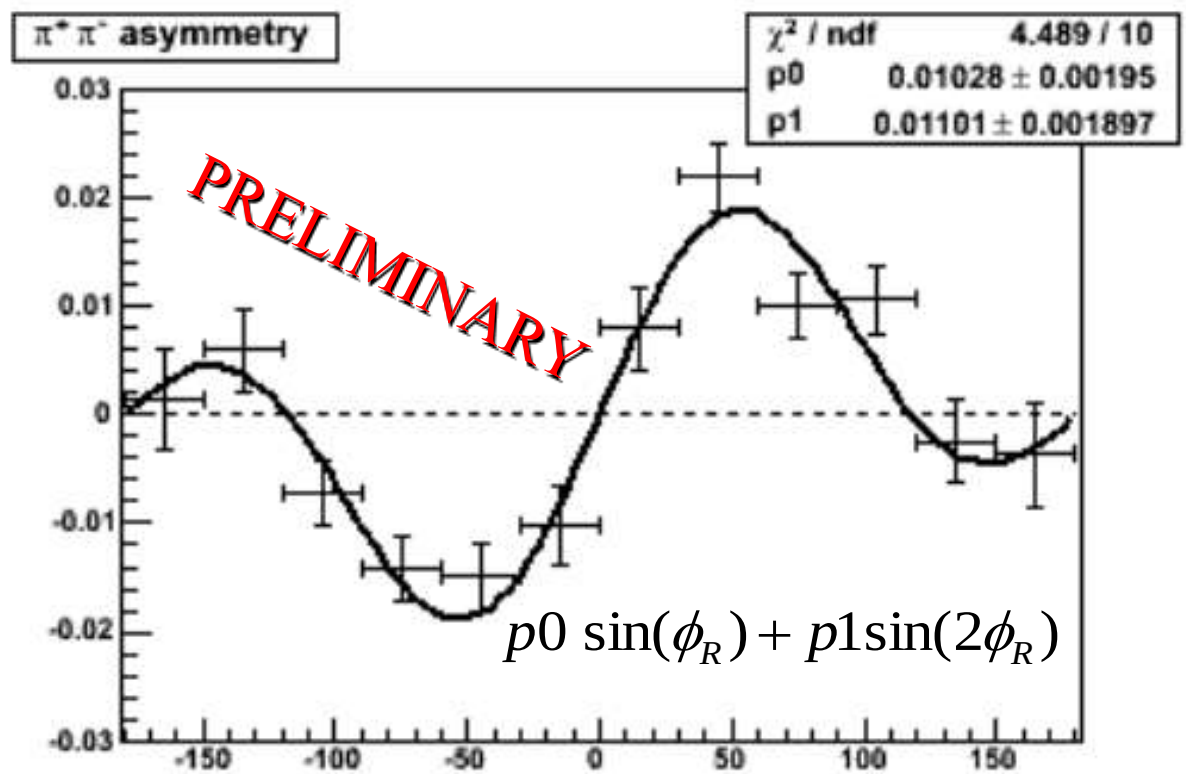


$$P_h = P_1 + P_2$$

$$R = (P_1 - P_2)/2$$

$$A_{LU} = \frac{1}{P_{beam}} \frac{N^+ - N^-}{N^+ + N^-}$$

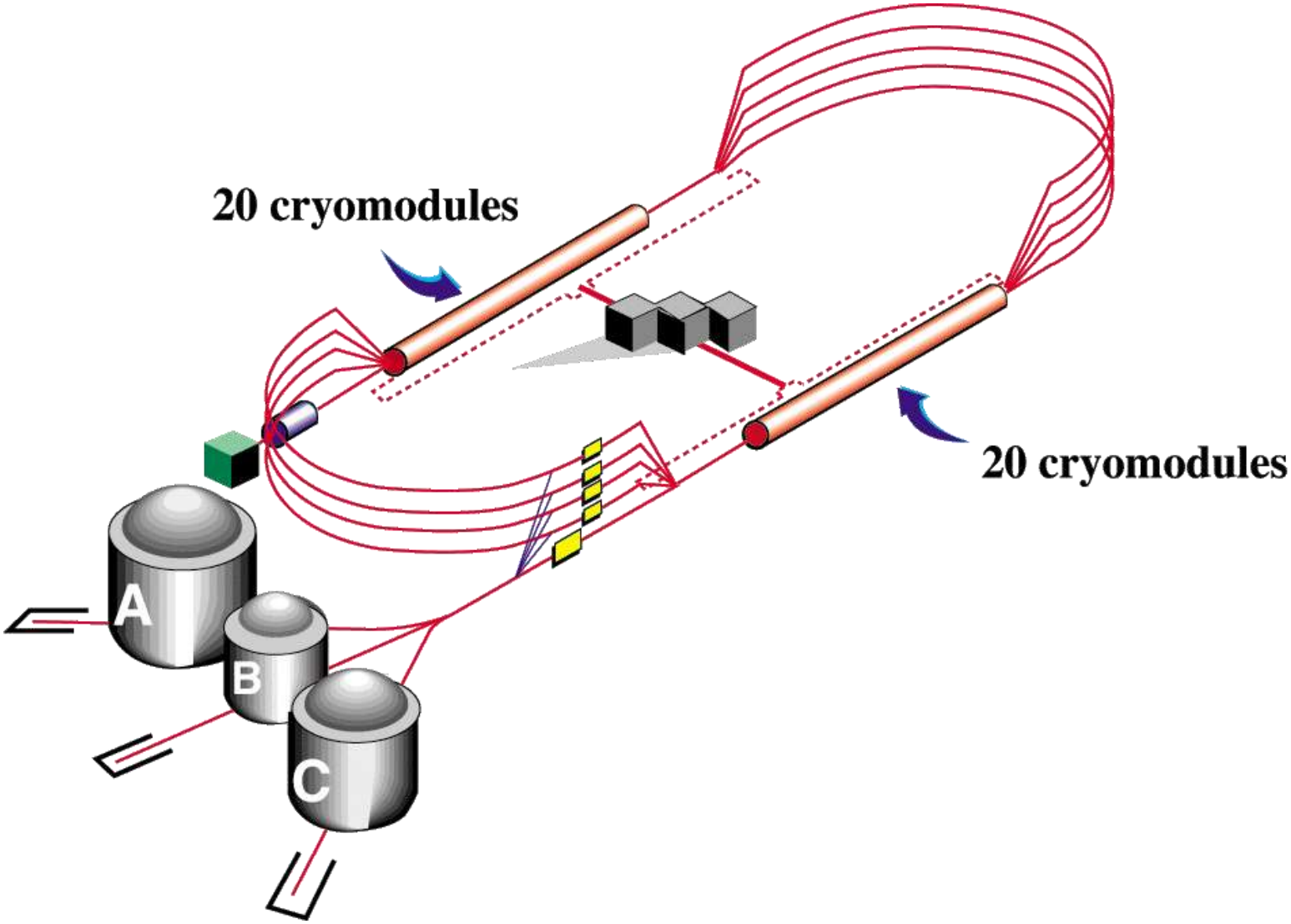
$$\vec{e}\vec{p} \rightarrow e' \pi^+ \pi^- X$$



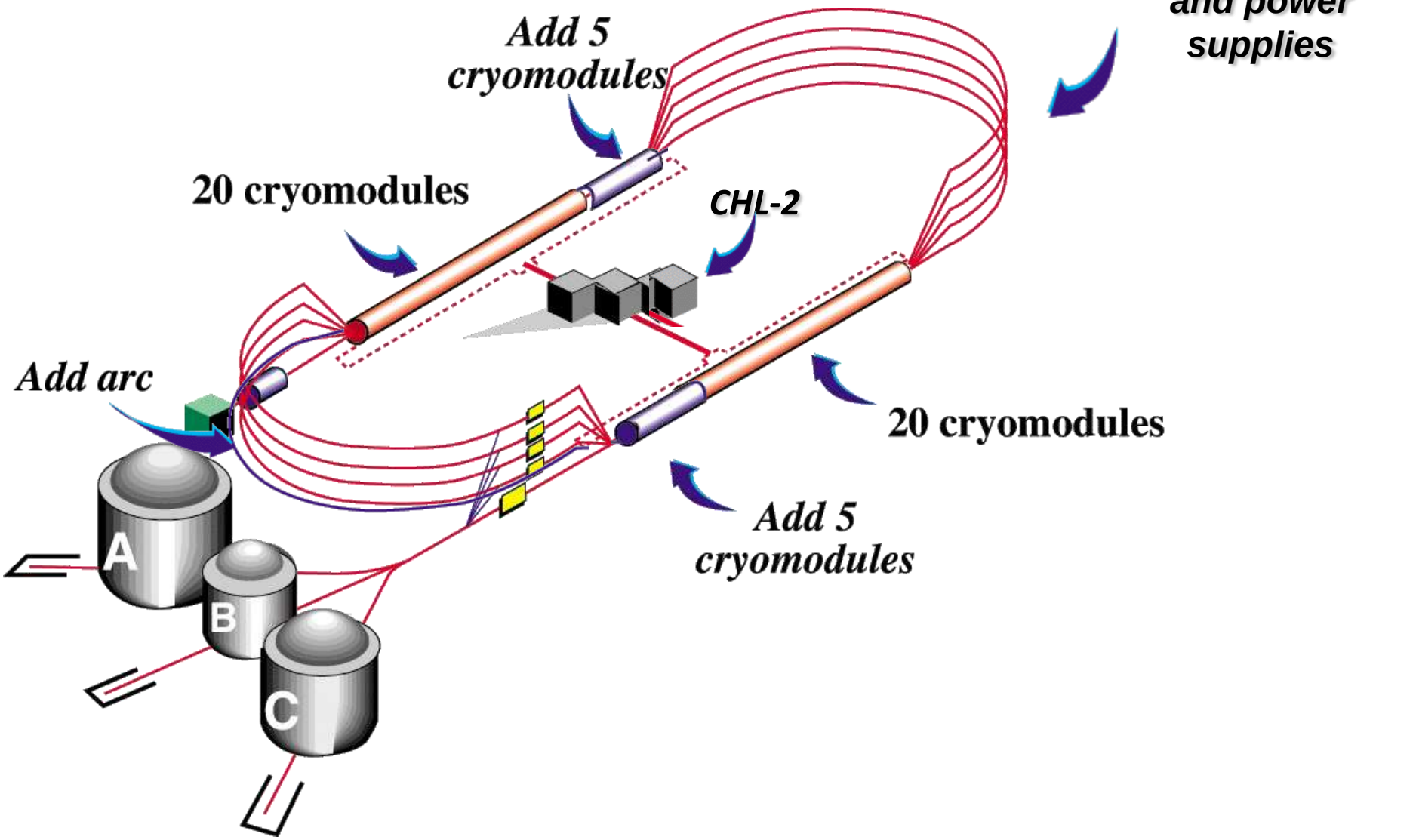
$$F_{LU}^{\sin\phi_R} \propto h_L^q\ H_1^{<q}$$

6 GeV CEBAF

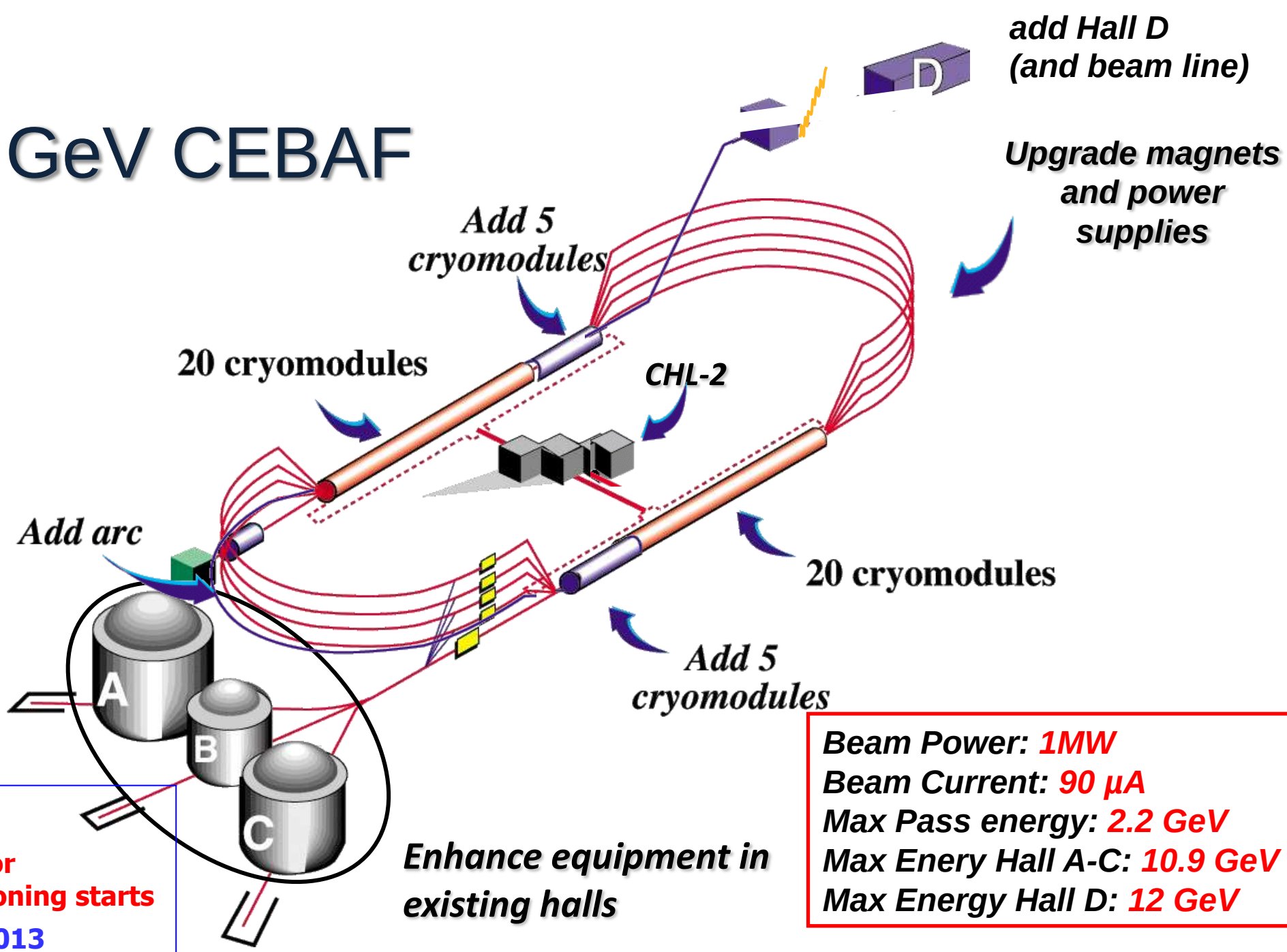
End physics program @ 6 GeV in 2012



12 GeV CEBAF


Upgrade magnets and power supplies
Add 5 cryomodules
20 cryomodules
CHL-2
Add arc
20 cryomodules
Add 5 cryomodules
A
B
C

12 GeV CEBAF



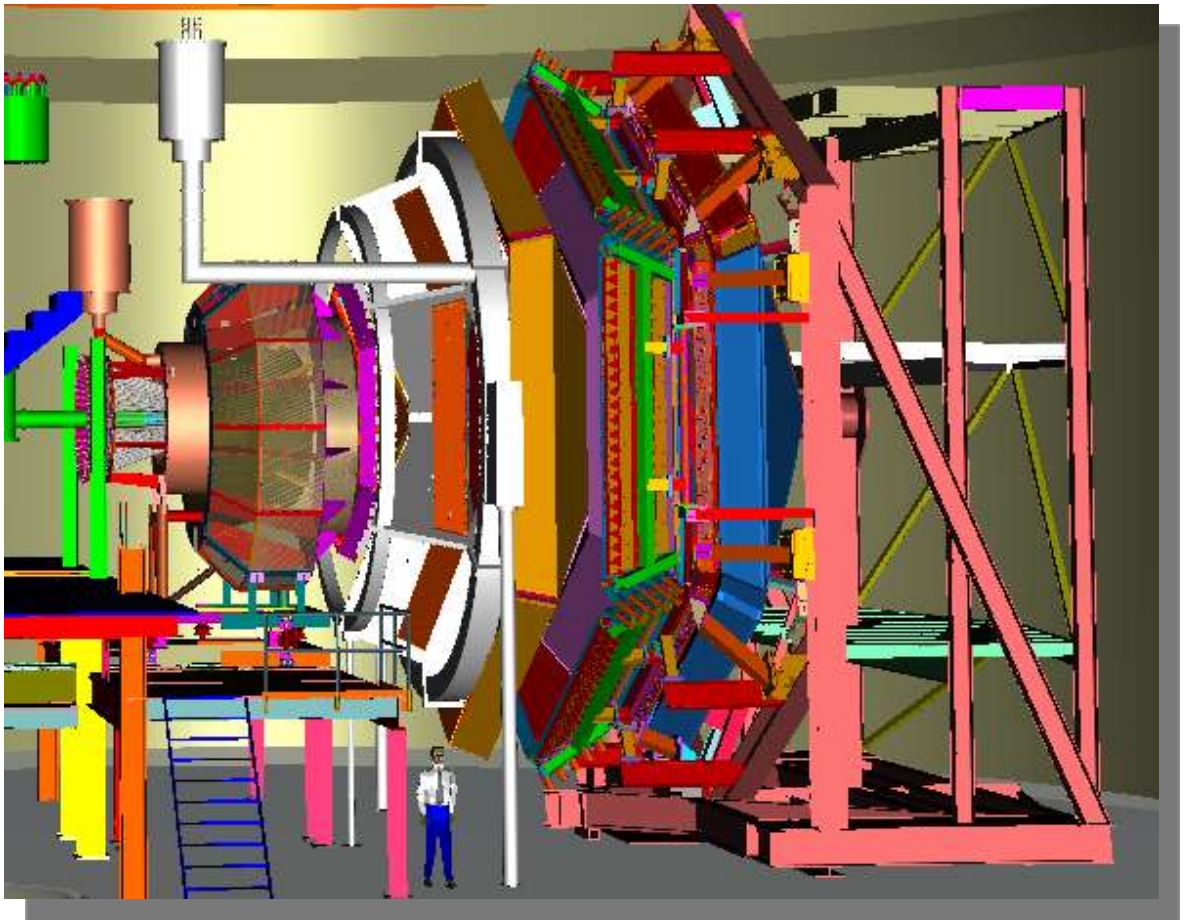
Enhance equipment in existing halls

Beam Power: 1MW
Beam Current: 90 μA
Max Pass energy: 2.2 GeV
Max Enery Hall A-C: 10.9 GeV
Max Energy Hall D: 12 GeV

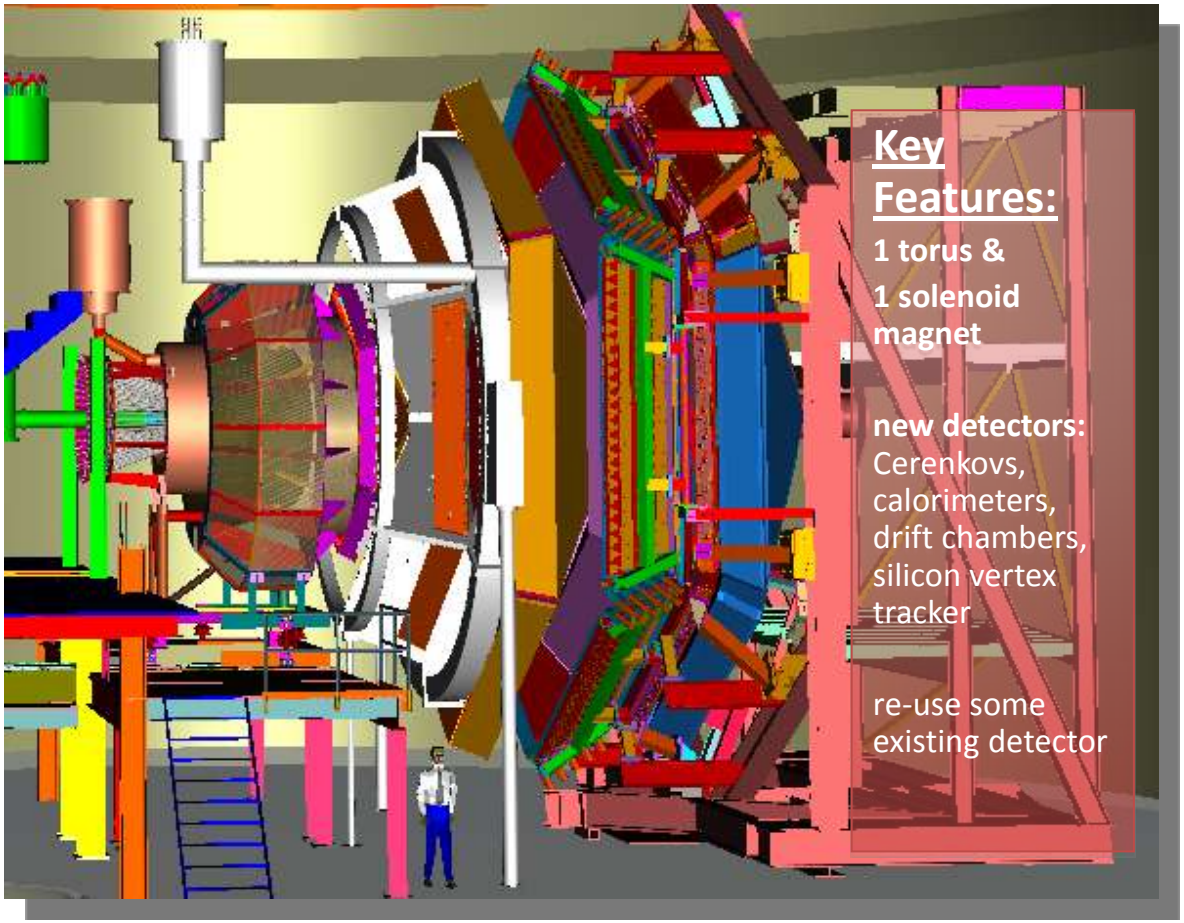
May 2013
Accelerator Commissioning starts

October 2013
Hall Commissioning starts

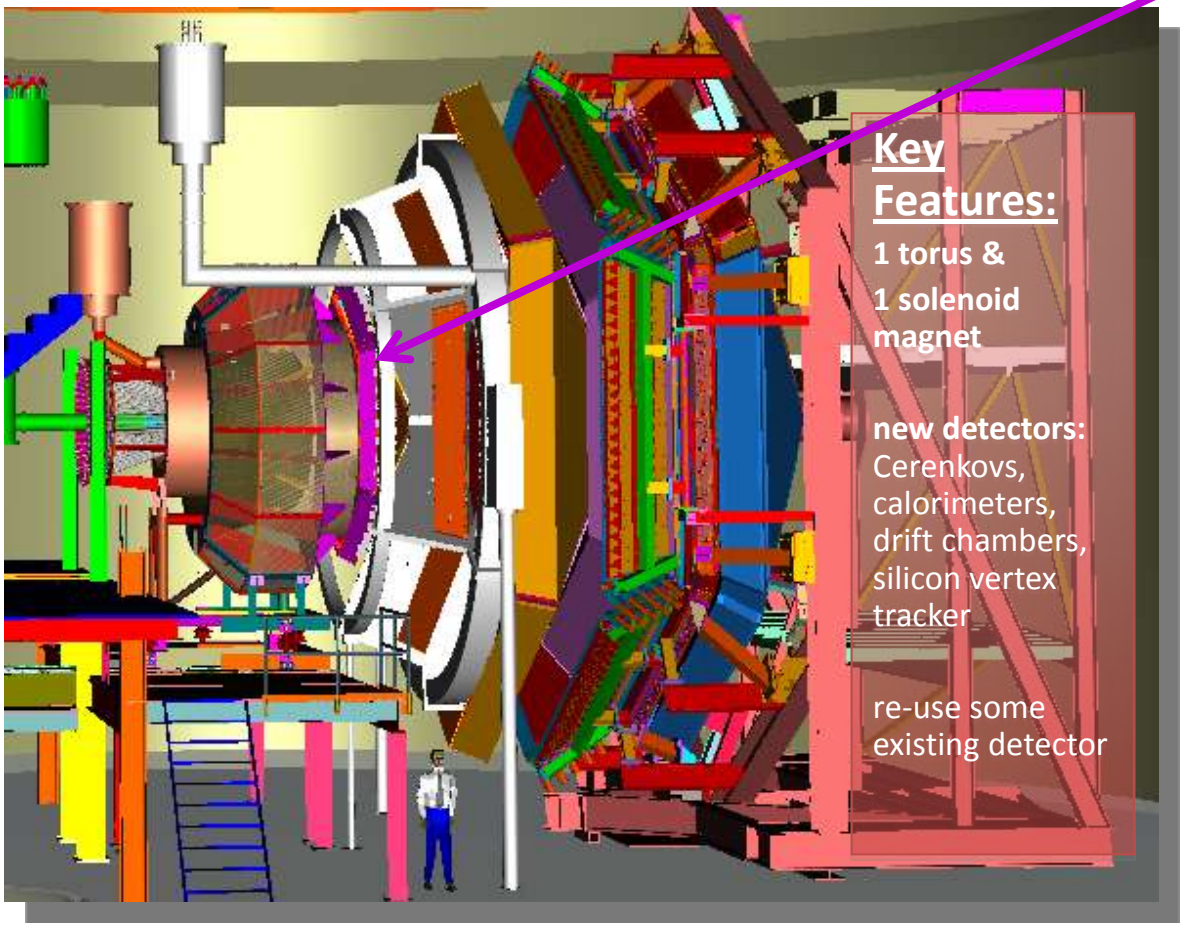
Hall B - CLAS12 Highlights



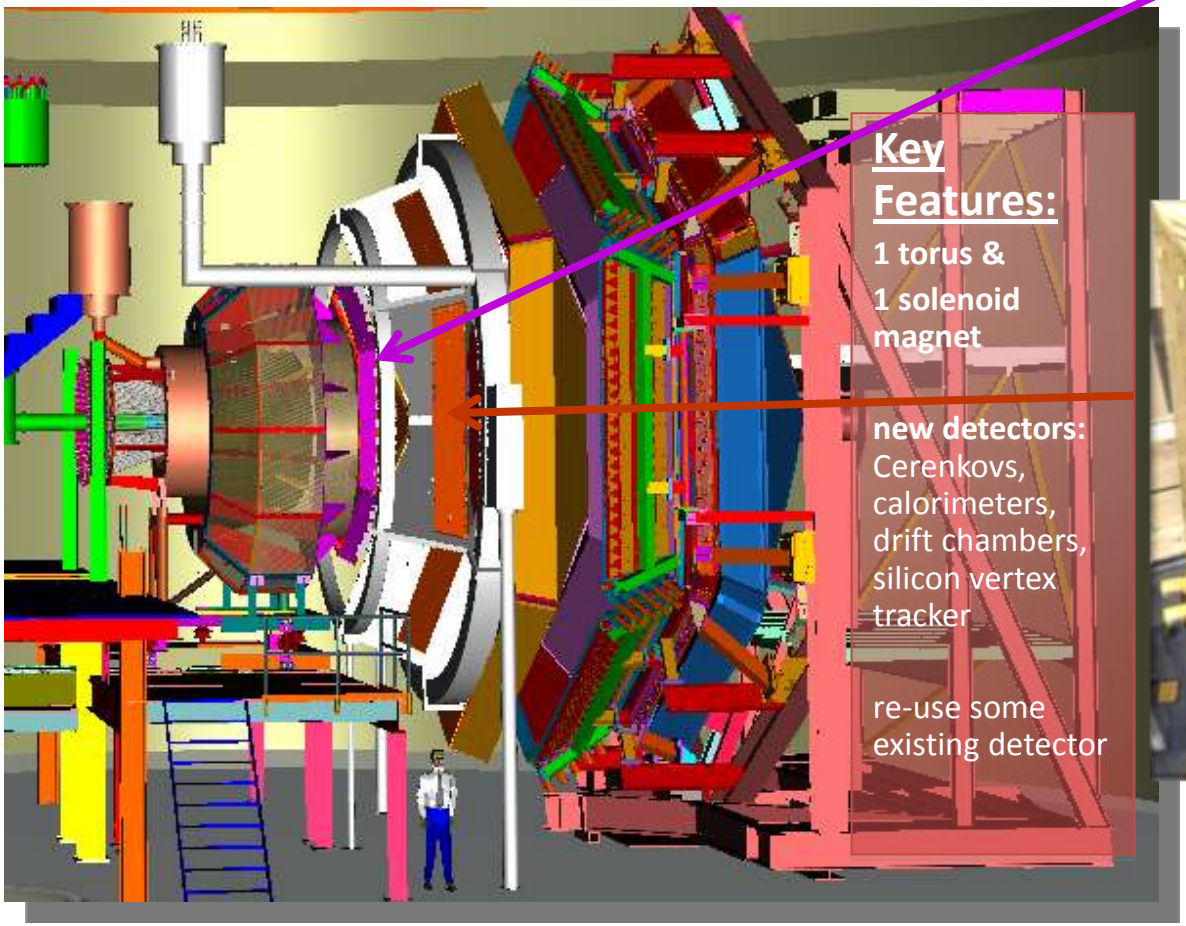
Hall B - CLAS12 Highlights

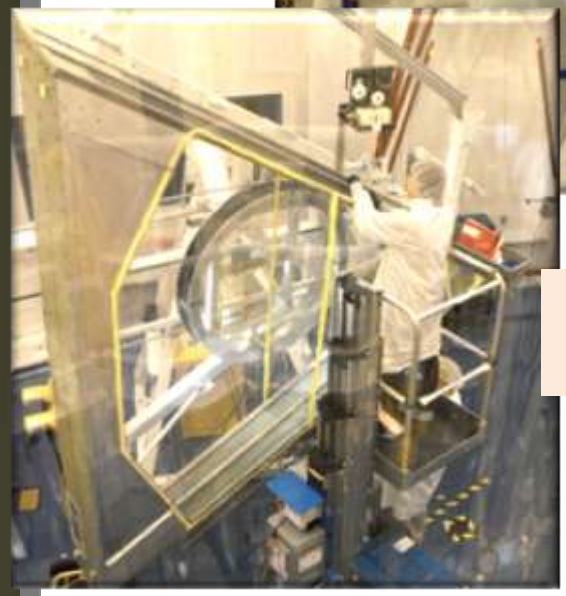


Hall B - CLAS12 High

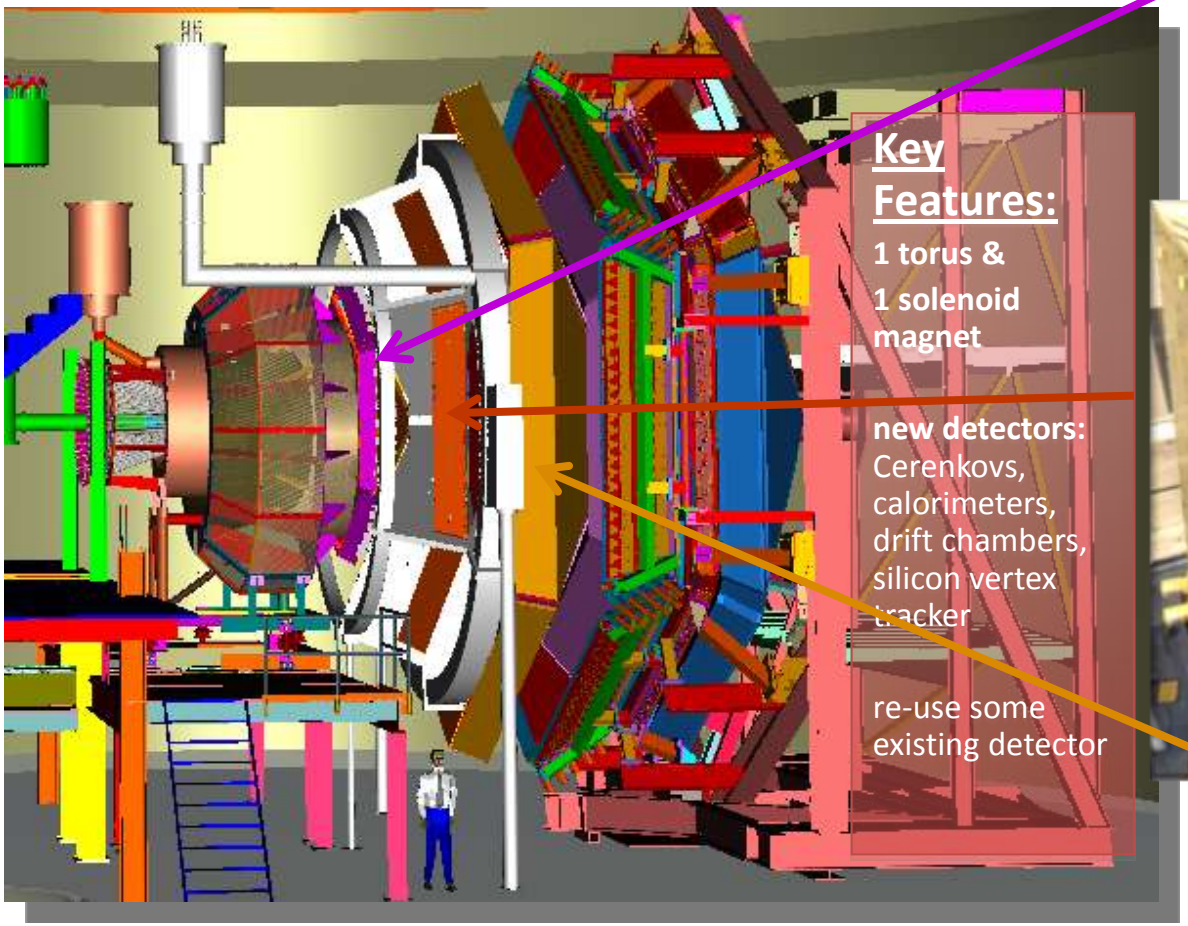


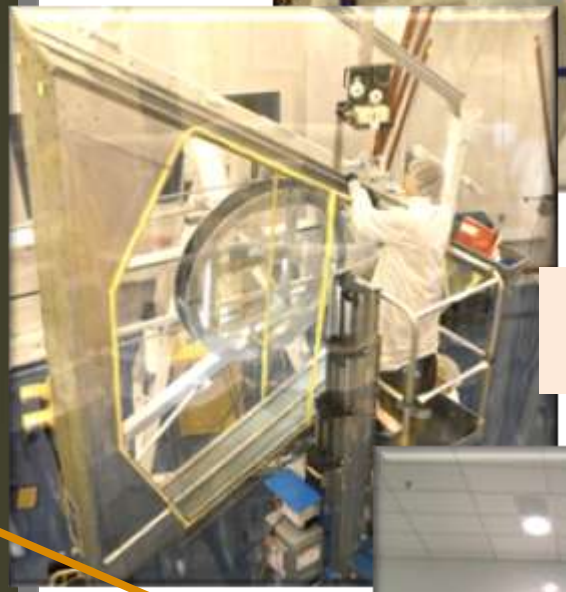
Hall B - CLAS12 High

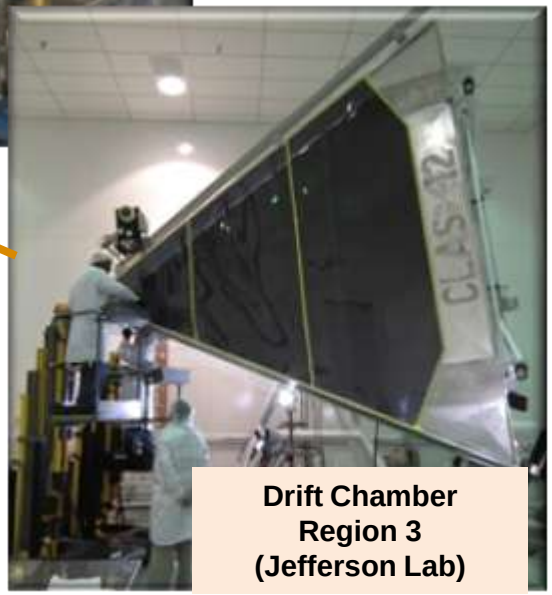




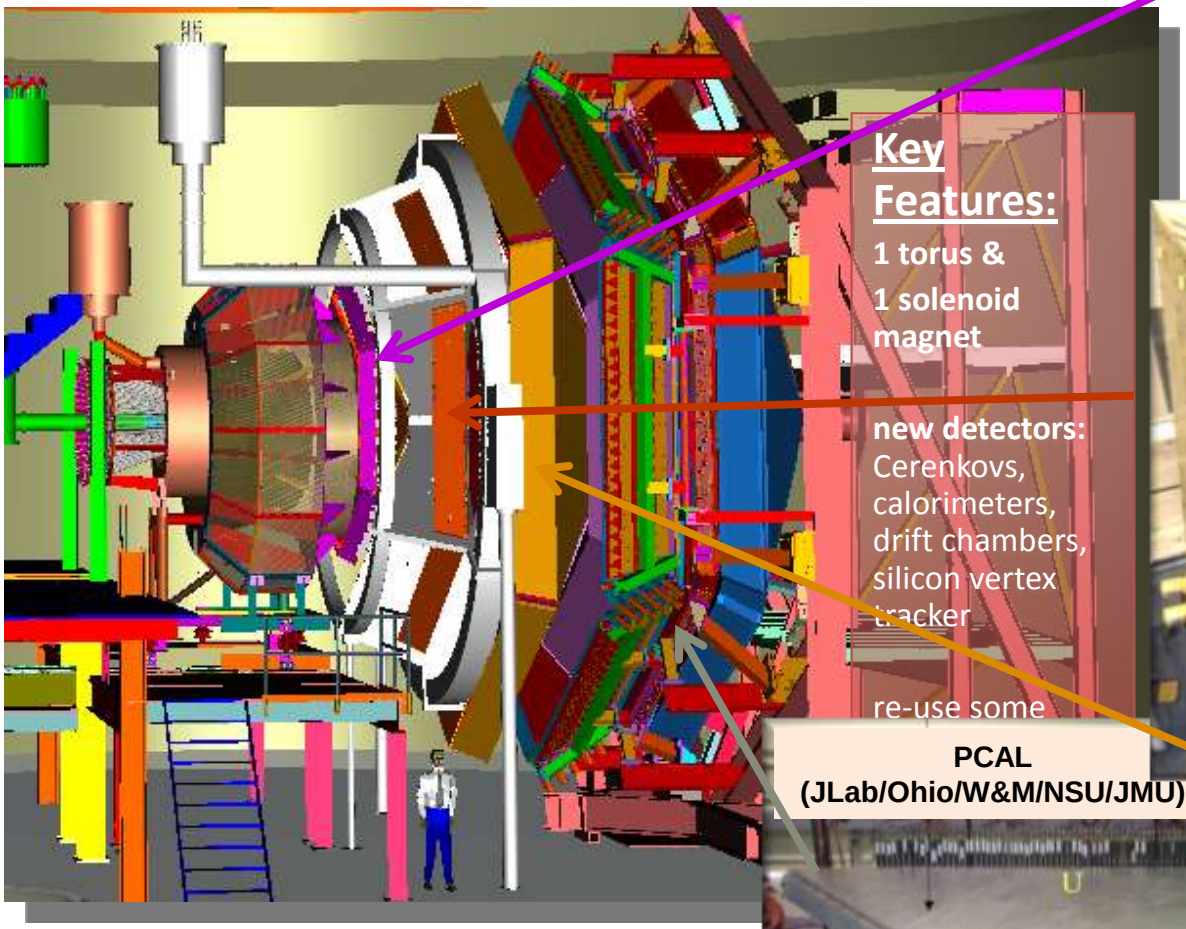
Hall B - CLAS12 High







Hall B - CLAS12 High



Key Features:

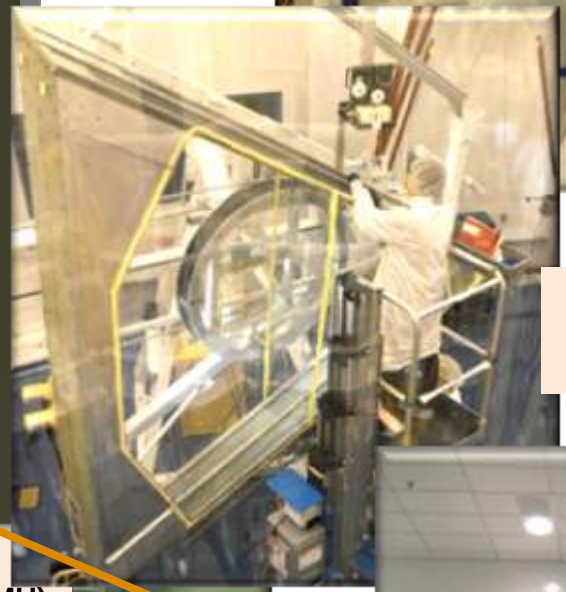
1 torus &

1 solenoid magnet

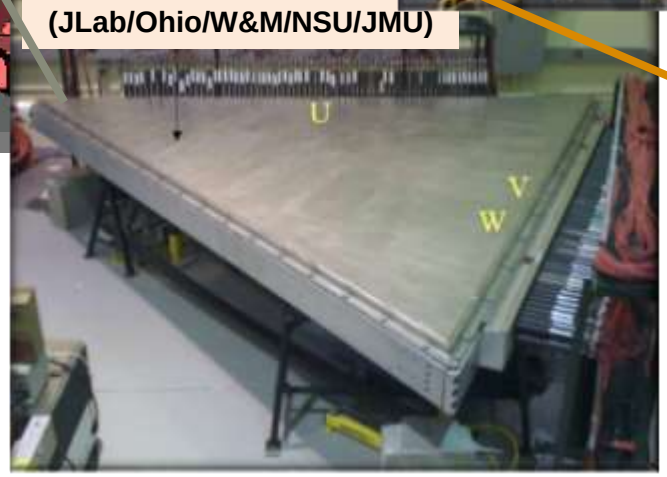
new detectors:
Cerenkovs, calorimeters, drift chambers, silicon vertex tracker

re-use some

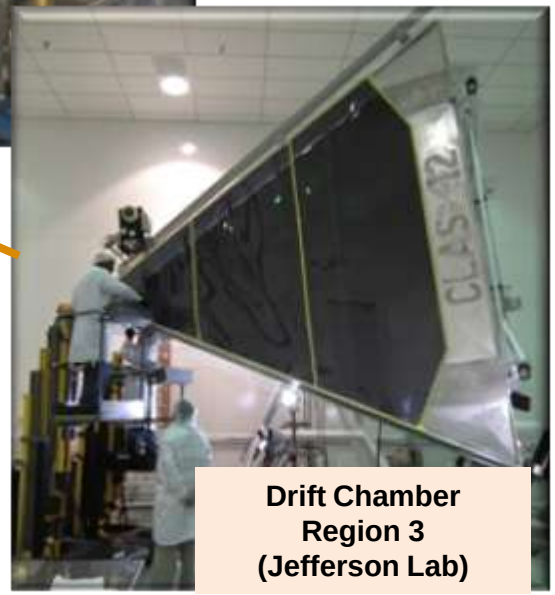
Drift Chamber Region 1 (Idaho State U)



Drift Chamber Region 2 (Old Dominion U)

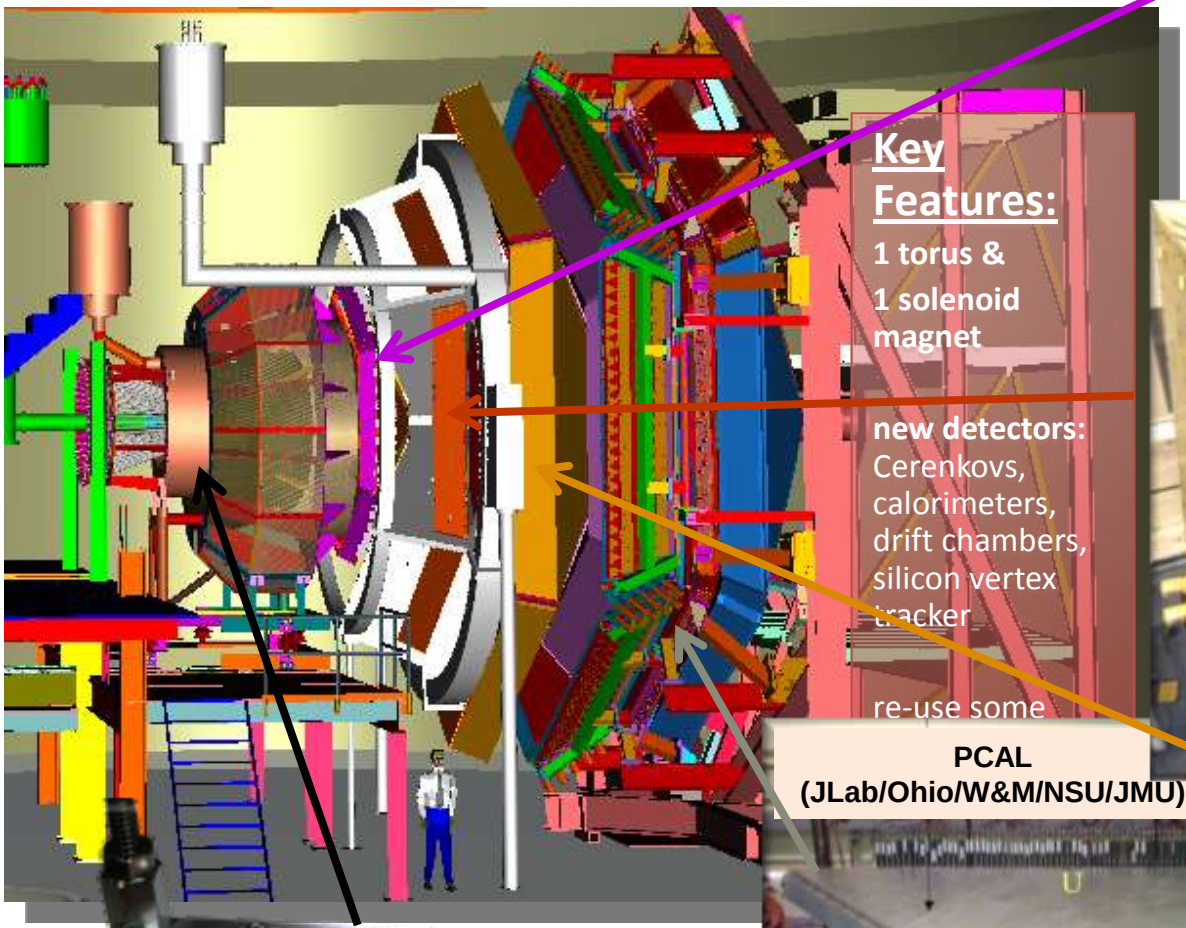


PCAL (JLab/Ohio/W&M/NSU/JMU)



Drift Chamber Region 3 (Jefferson Lab)

Hall B - CLAS12 High



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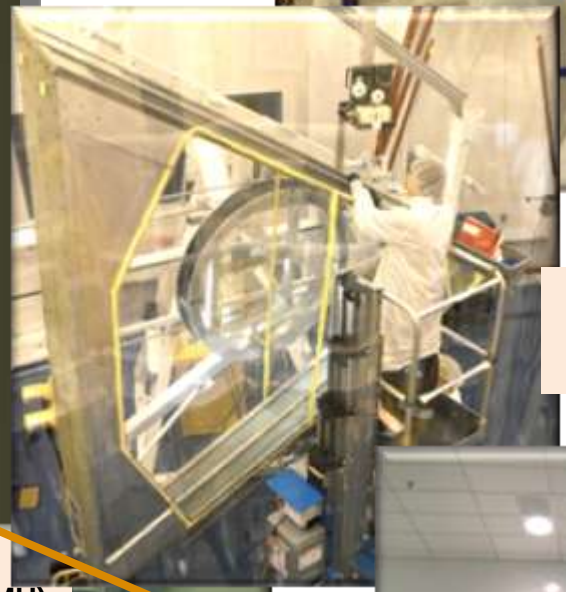
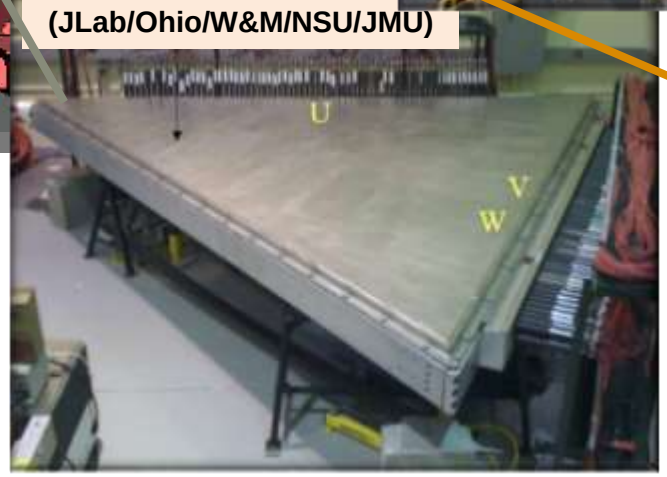
Drift Chamber Region 1 (Idaho State U)



Drift Chamber Region 2 (Old Dominion U)



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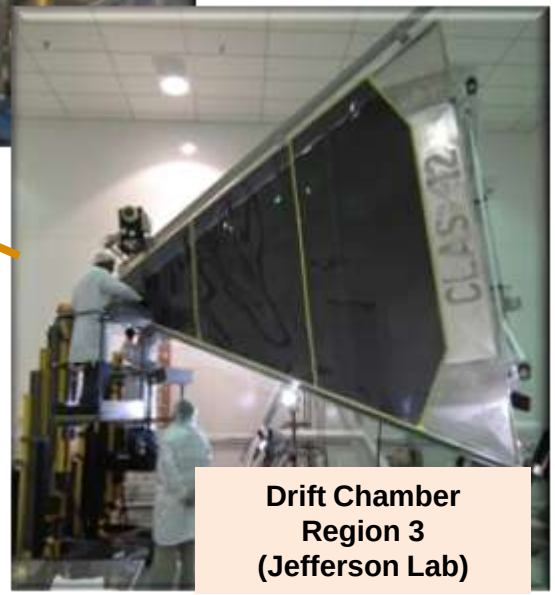
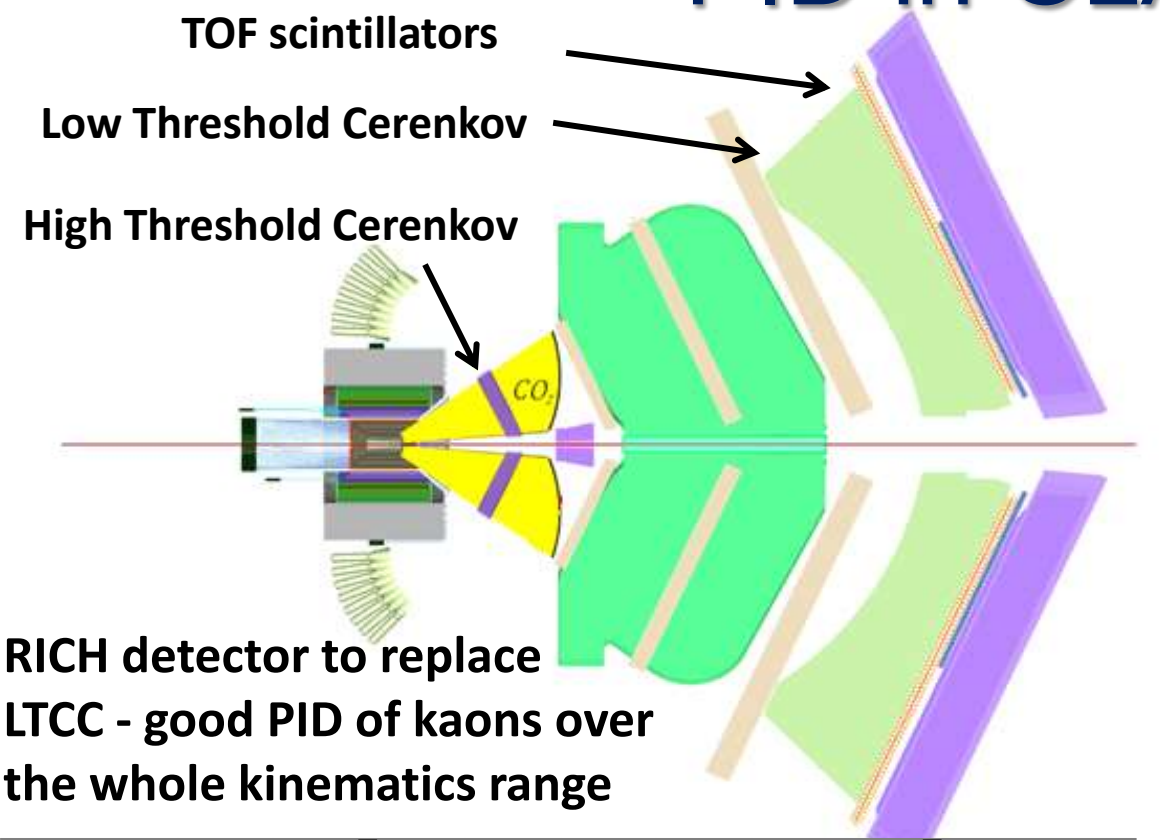


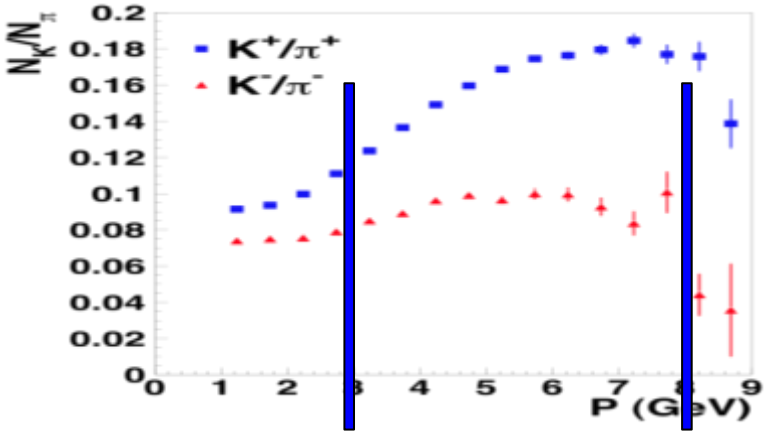
Drift Chamber Region 3 (Jefferson Lab)

Silicon Vertex Tracker (JLab/FNAL/UNH)

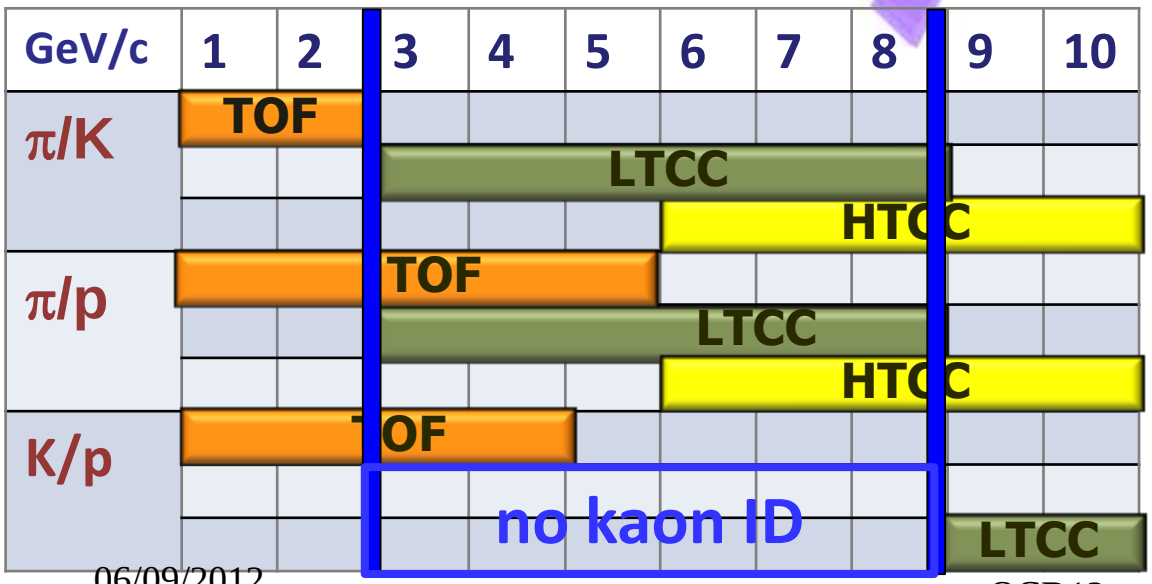
PID in CLAS12



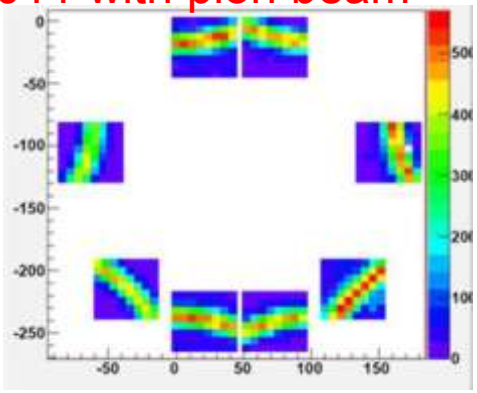
- Kaon ID necessary for TMD flavor separation
- Rejection factor >1000 because of relative π/K production rate



RICH detector to replace LTCC - good PID of kaons over the whole kinematics range



First RICH prototype test at CERN in summer 2011 with pion beam



- Cherenkov rings for pions with 10 GeV/c momentum, measured with 8 H8500
- A new prototype is under construction and will be tested in summer 2012

Physics program with CLAS12

Proposal	Contact Person	Physics	Energy (GeV)	PAC days	Parallel Running	Run Group	Comment
PR-09-103	Gothe, Mokeev	N* at high Q^2	11	60	80	120	
E12-06-119a	Sabatie	DVCS pol. beam	11	80			
E12-06-112	Avakian	$ep \rightarrow e\pi^{+/-/0}X$	11	60			
E12-06-108	Stoler	DVMP in π^0, η prod	11	80			
		L/T separation	8.8	20	20		
			6.6	20	20		
E12-06-119b	Sabatie	DVCS pol. target	11	120	120	175	Assume polarized experiments run 50% of time w/ reversed field
E12-06-109	Kuhn	Long. Spin Str.	11	82	50		
E12-07-107	Avakian	TMD SSA	11	103	5		
PR-09-007(b)	Hafidi	Partonic SIDIS	11	103			
PR-09-009	Avakian	Spin-Orbit Corr.	11	103			
E12-06-106	Hafidi	Color Trans. ρ^0	11	40	40	40	
E12-06-117	Brooks	Quark Hadronizat.	11	60	60	60	
E12-06-113	Bültman	Neutron Str. Fn.	11	40	40	40	cond. appr.
E12-07-104	Gilfoyle	Neutron mag. FF	11	56	56	82	007/008 need 26d reversed field
PR-09-007(a)	Hafidi	Partonic SIDIS	11	56	26		
PR-09-008	Contalbrigo	Boer-Mulders w/ Kaons	11	56			
Total				**1139**		**517**	

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PR-09-00							
PR-09-0							
E12-06-							
E12-06-							
E12-06-113	Bültman	Neutron Str. Fn.	11	40	40	40	cond. appr.
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Total				**1139**		**517**	

Experiments for the first 5 years of data taking already approved

Conclusions

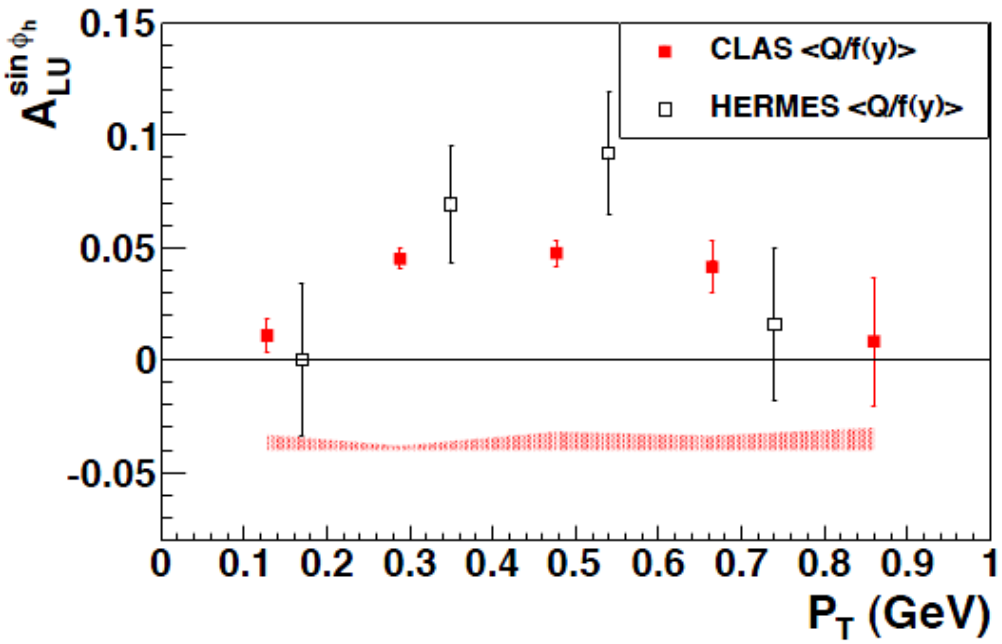
- **TMDs are needed to understand nucleon spin**
- **They provide a deep insight into the nucleon structure**
- **Study of TMDs is one of the main items in the JLab physics program**
- **The 6GeV generation of experiments have shown evidence of sizeable effects due to TMDs but also open questions**
- **Azimuthal moments can be extracted in multidimensional analysis with high statistics.**
- **A new 12GeV generation of experiments is in preparation at JLab with higher luminosity and improved detectors to test fundamental properties of TMDs.**

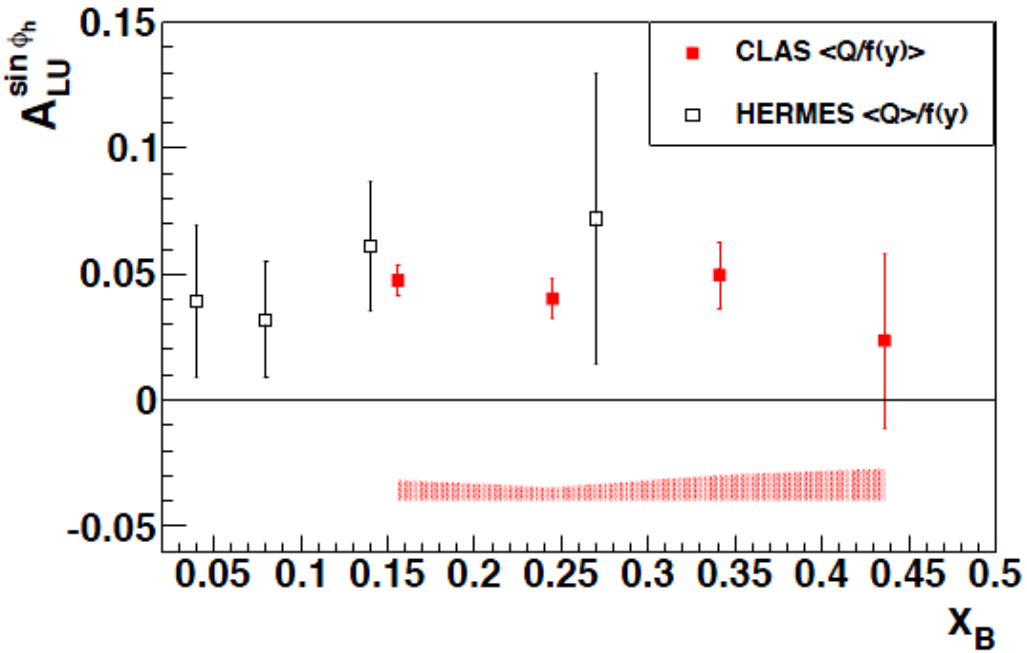
BACKUP SLIDES

CLAS asymmetries – A_{LU}

Aghasyan et al PLB704 (2011)

- CLAS data for $A_{LU}\pi^{\circ}$
- Unpolarized liquid hydrogen target
- Beam energy of 5.776 GeV
- Q2>1; 0.4 < z < 0.7





For the first time A_{LU} two dimensional mapping for 0.4<z<0.7