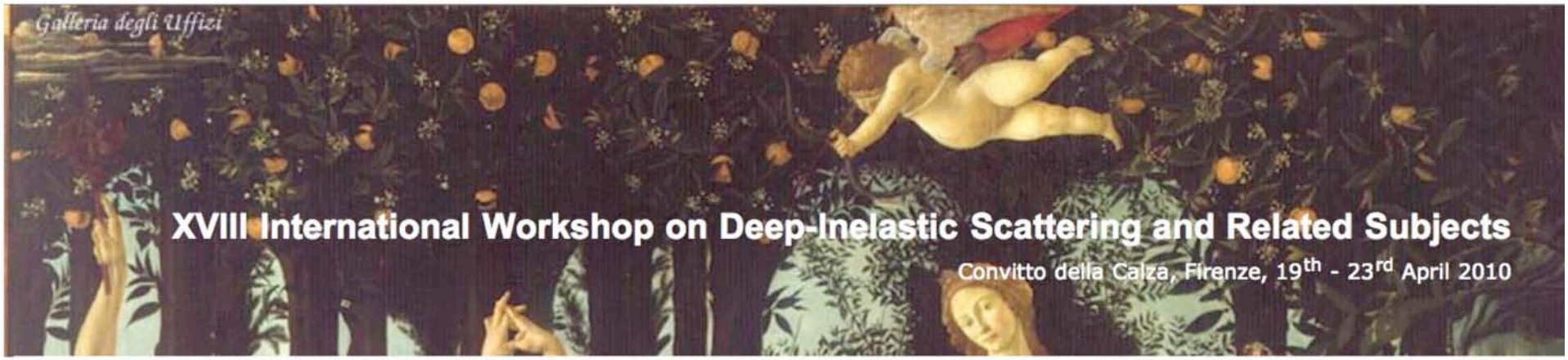
Transverse spin physics at Hall B

Patrizia Rossi - Laboratori Nazionali di Frascati, INFN

- TMDs and SIDIS
- Hall B results @ 6 GeV with longitudinal polarization
- Transversely polarized target
- Future experiments @ 12 GeV
- Conclusion



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The naïve quark model based on **collinear** approximation doesn't account for the complex structure of the nucleon for ex. it **doesn't account for all its spin**!

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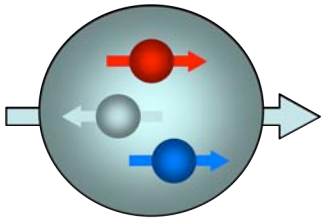

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$\Delta\Sigma = \Delta u_v + \Delta d_v = 1$

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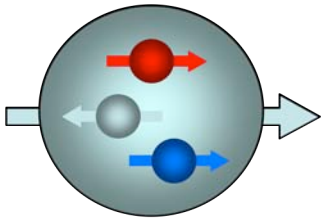

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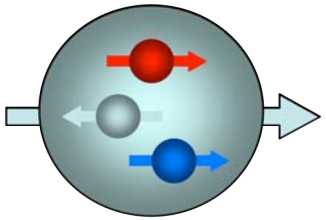

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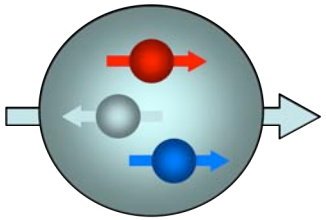

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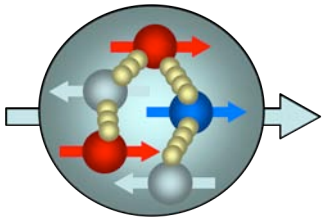

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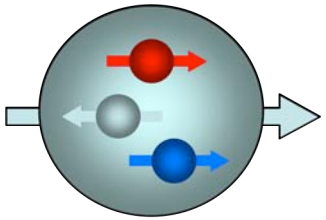

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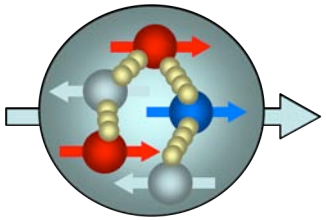

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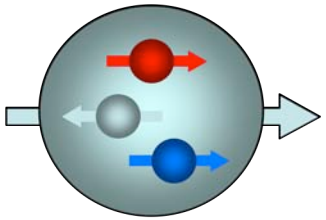

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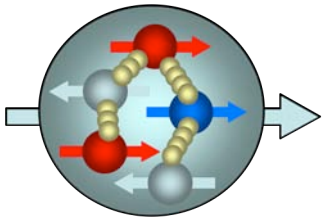

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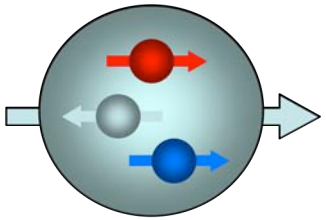

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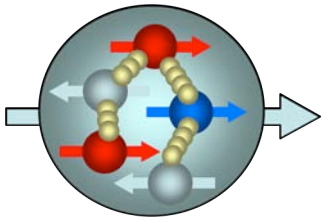

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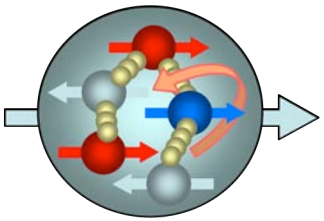

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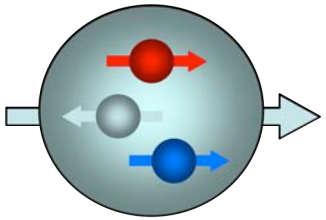

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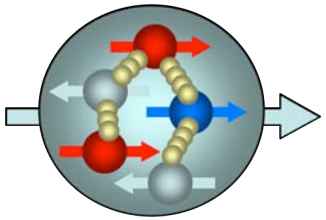

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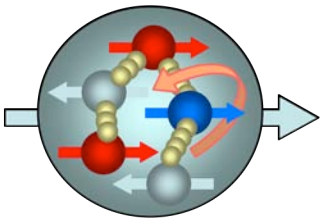

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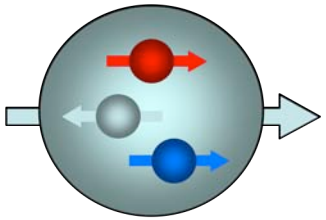

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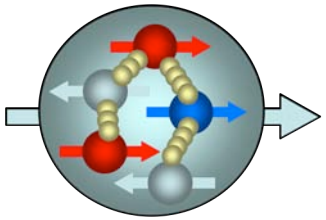

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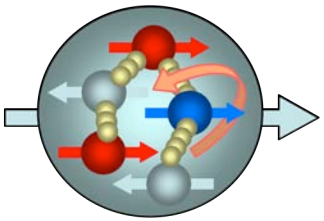

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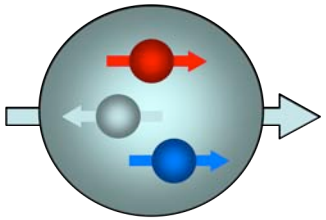

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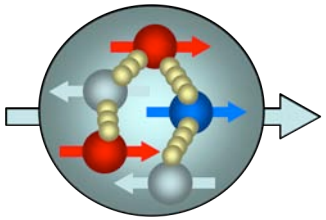

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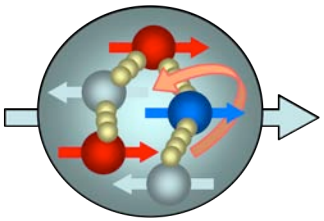

Orbital angular momenta ?

Longitudinal momentum space

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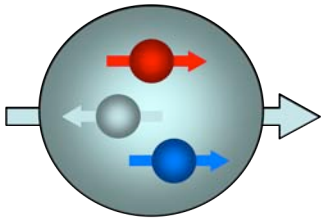

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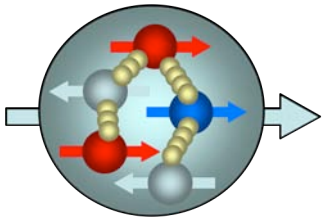

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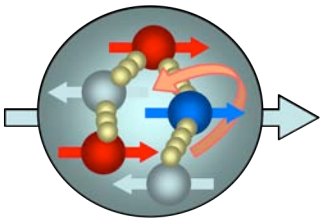


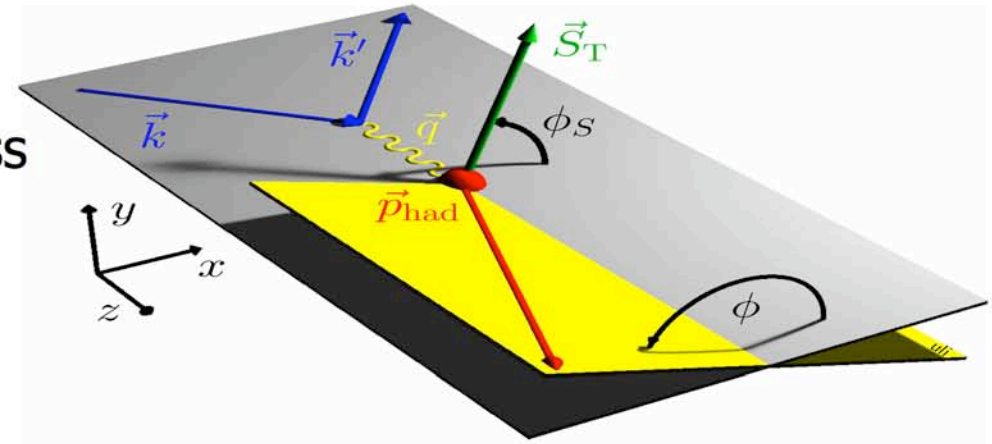
Orbital angular momenta ?

Longitudinal momentum space → **Transverse** momentum space

Observables

Non-zero transverse momenta of partons are accessible in measurements of azimuthal distributions of final state hadrons

Ex: SIDIS process



$$\nu = E - E'$$
$$Q^2 = (k - k')^2$$
$$y = \nu / E$$
$$x = Q^2 / 2M\nu$$
$$z = E_h / \nu$$

Observables: spin azimuthal asymmetries (SSA)

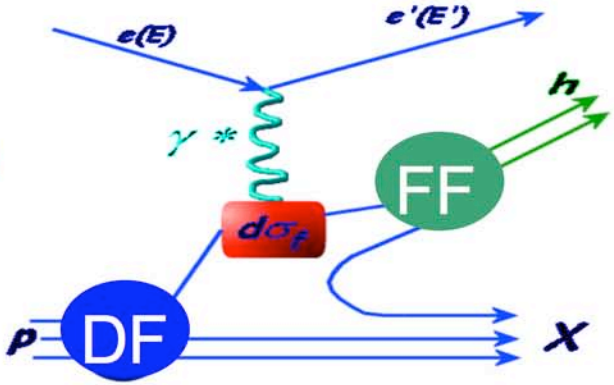
SSA are due to correlations between transverse momentum of quarks ($k_\perp$) and the spin of the quark/nucleon and appear as moments of ϕ

$$\sigma = \sigma_{UU} + P_B \sigma_{LU} \sin\phi + P_T \sigma_{UL} \sin 2\phi + ..$$

$$A_{UL}^{\sin 2\phi} = \frac{\sigma_{UL}}{\sigma_{UU}}$$

TMDs

$$d\sigma^h \propto \sum q_f(x) \otimes \mathrm{d}\sigma_f(y) \otimes D_f^{q\to h}(z)$$



Nucleon description at leading Twist

TMD		quark		
		U	L	T
nucleon	U	q		
	L		Δq -	
	T			$h_{1T}^{\perp}$ -

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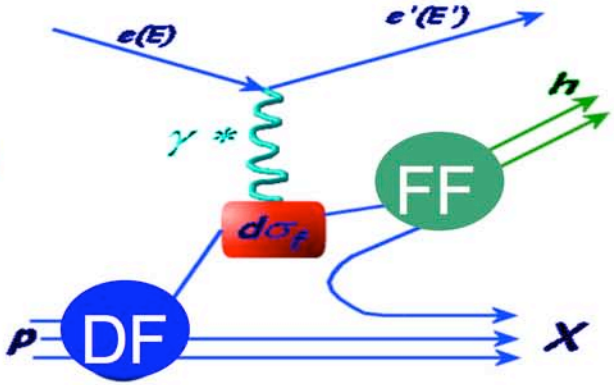
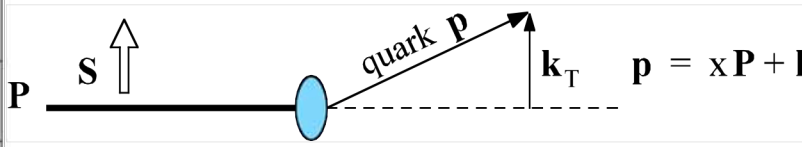


Nucleon description at leading Twist

TMD		quark U	quark L	quark T
nucleon	U	q		$h_1^\perp$
	L		Δq	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	δq, $h_{1T}^\perp$



Parton Distribution Functions generalized to contain information not only on longitudinal, but also on the transverse momentum distribution of partons

Jefferson Lab and CLAS

$e\,p \rightarrow e'\,h\,X$

1. high intensity beam with high polarization
2. polarized targets
3. high acceptance for the hadron

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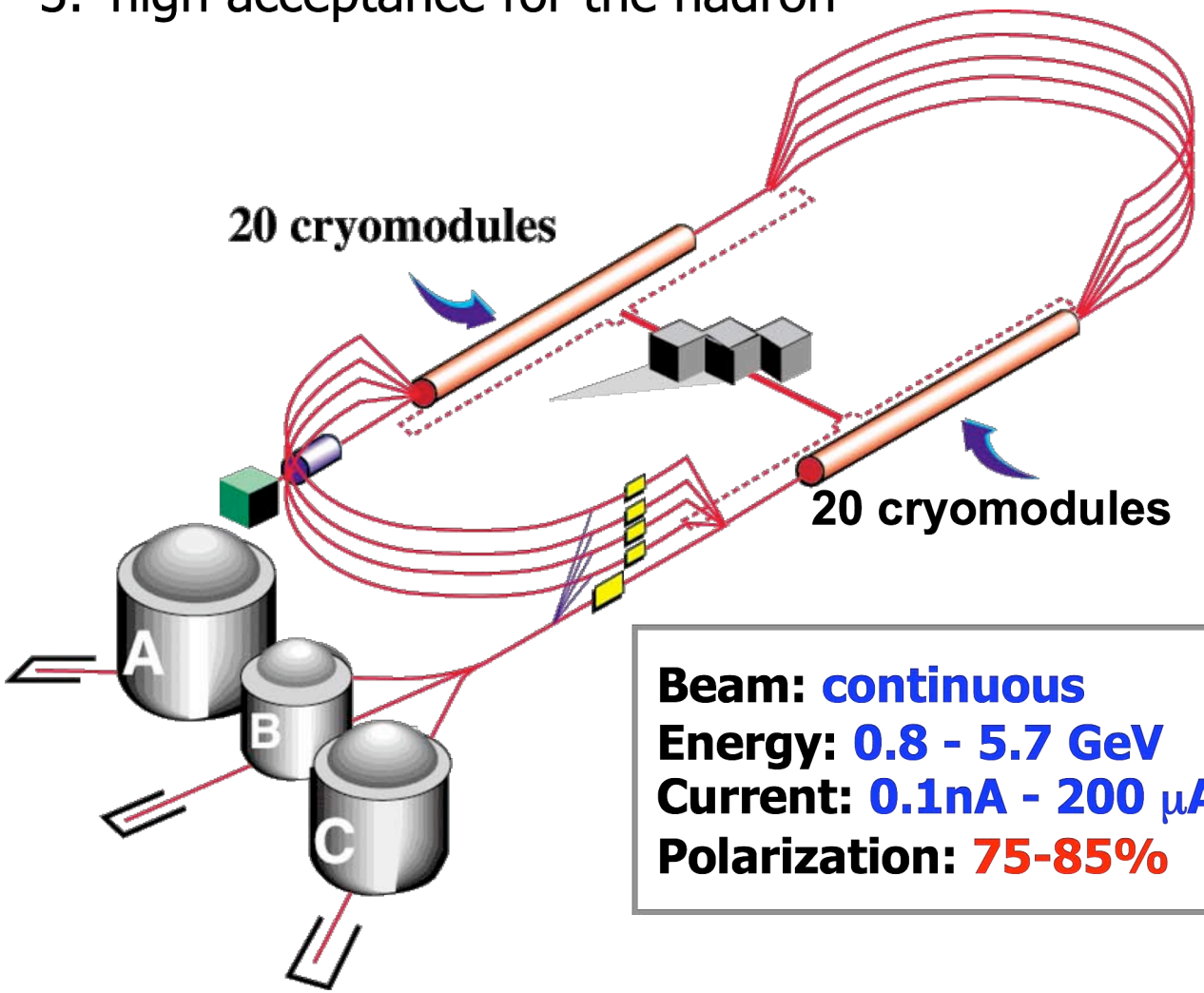
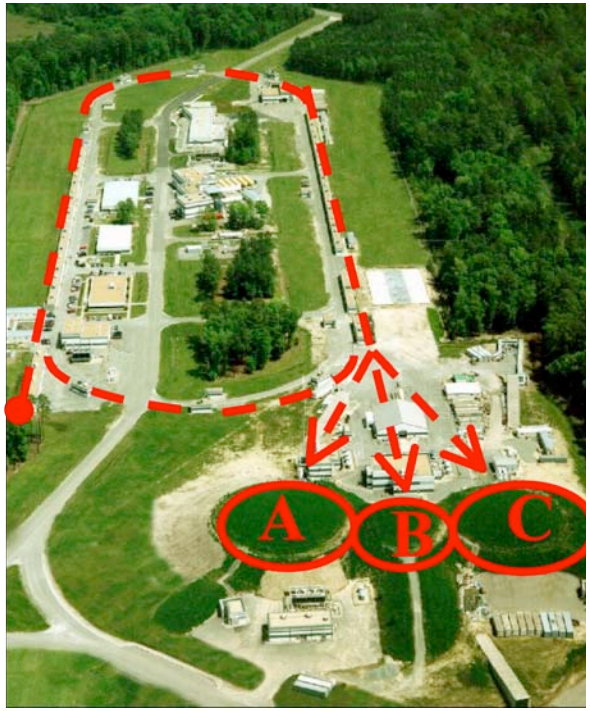


Beam: **continuous**
Energy: **0.8 - 5.7 GeV**
Current: **0.1nA - 200 μA**
Polarization: **75-85%**



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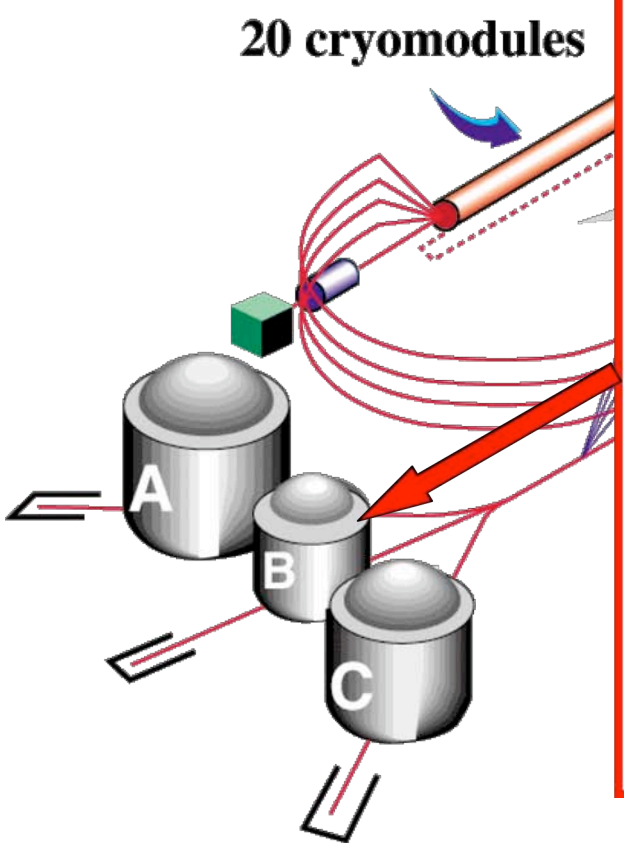

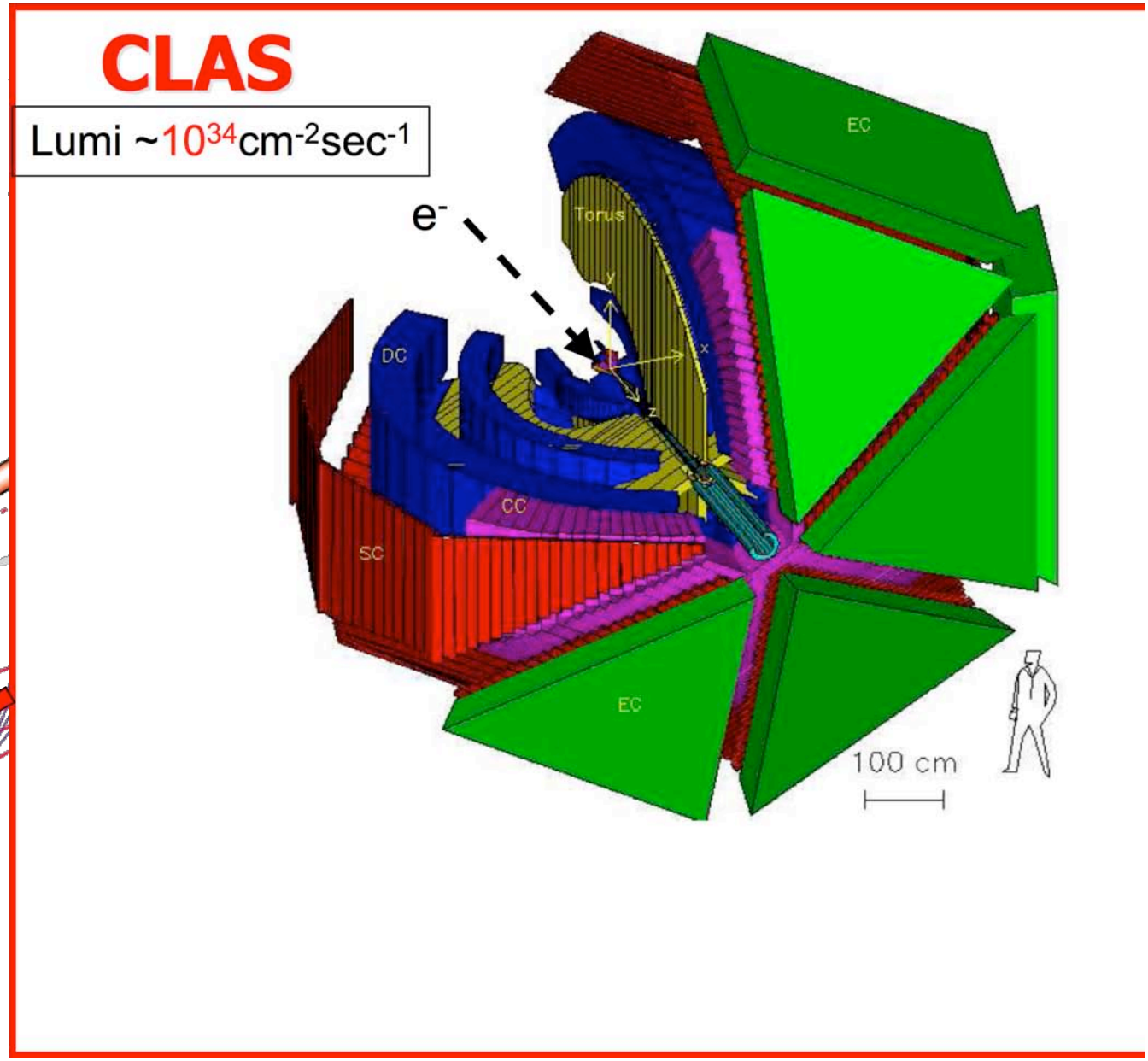

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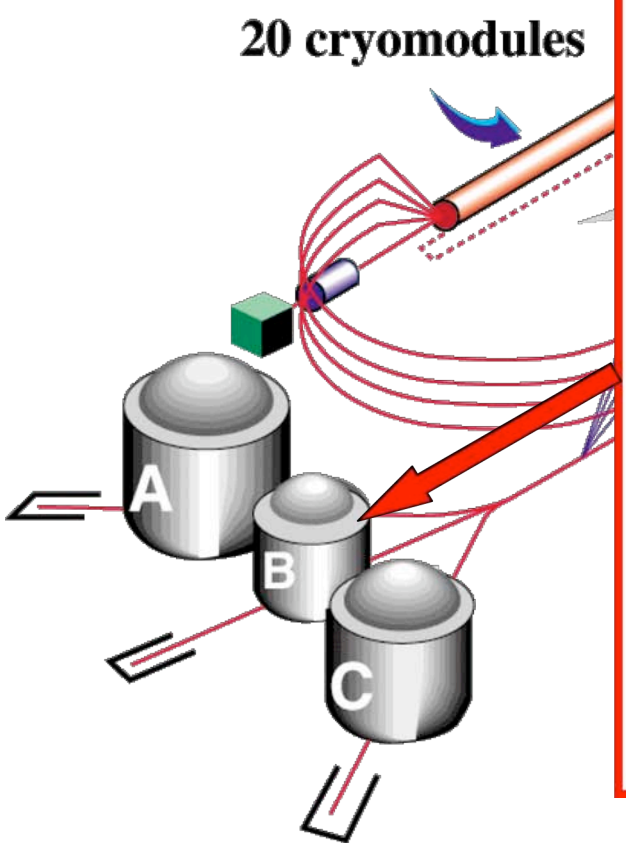
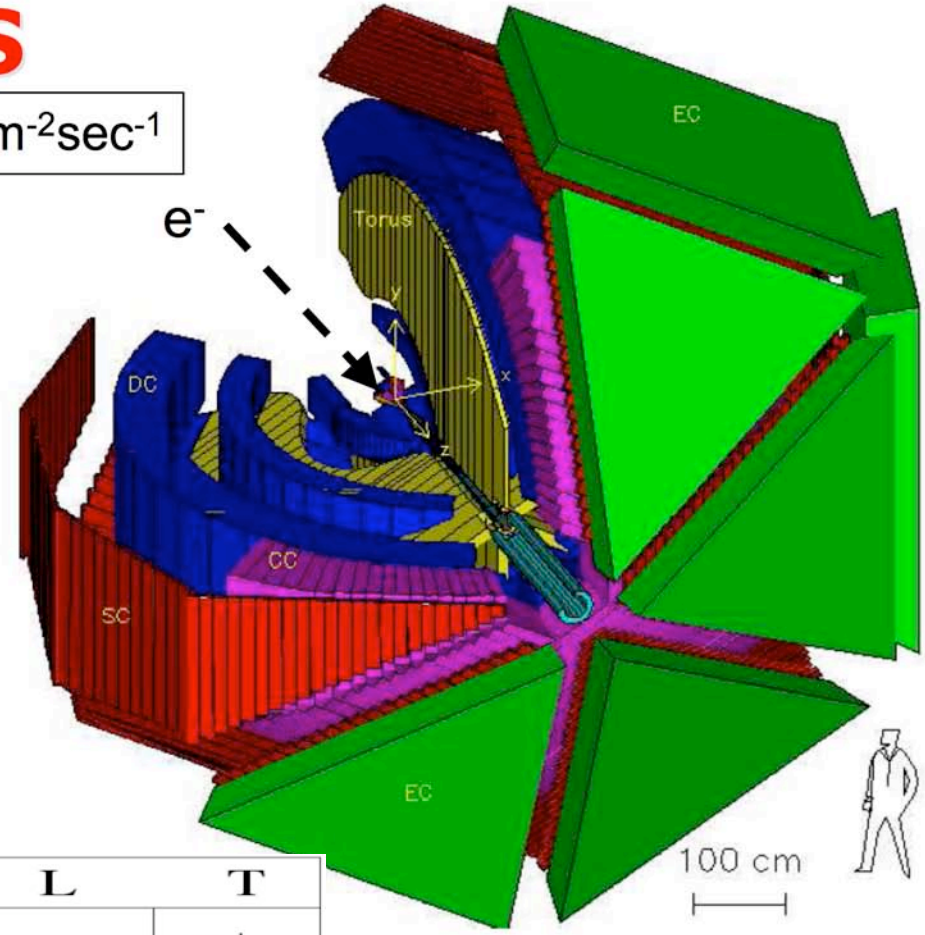


CLAS

Lumi ~10^{34}cm^{-2}sec^{-1}



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

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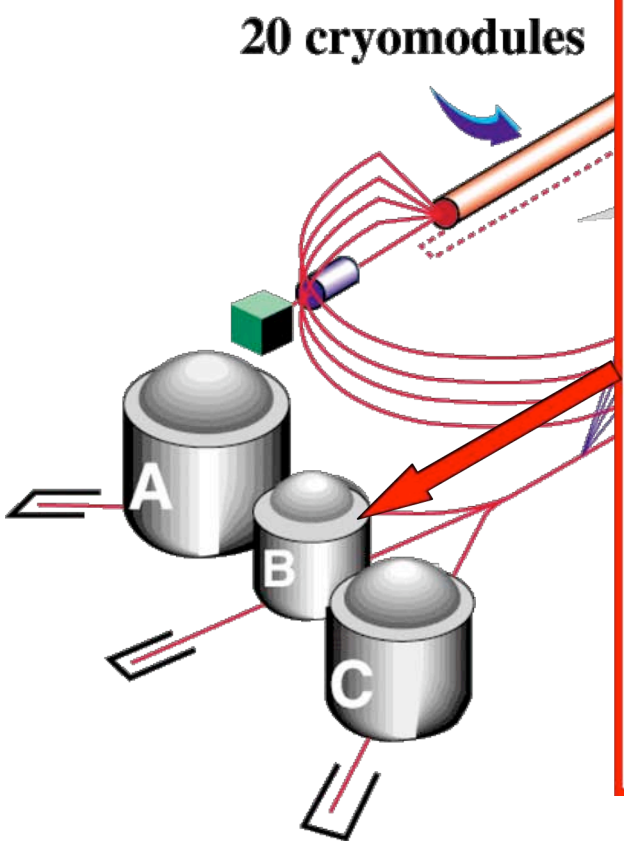

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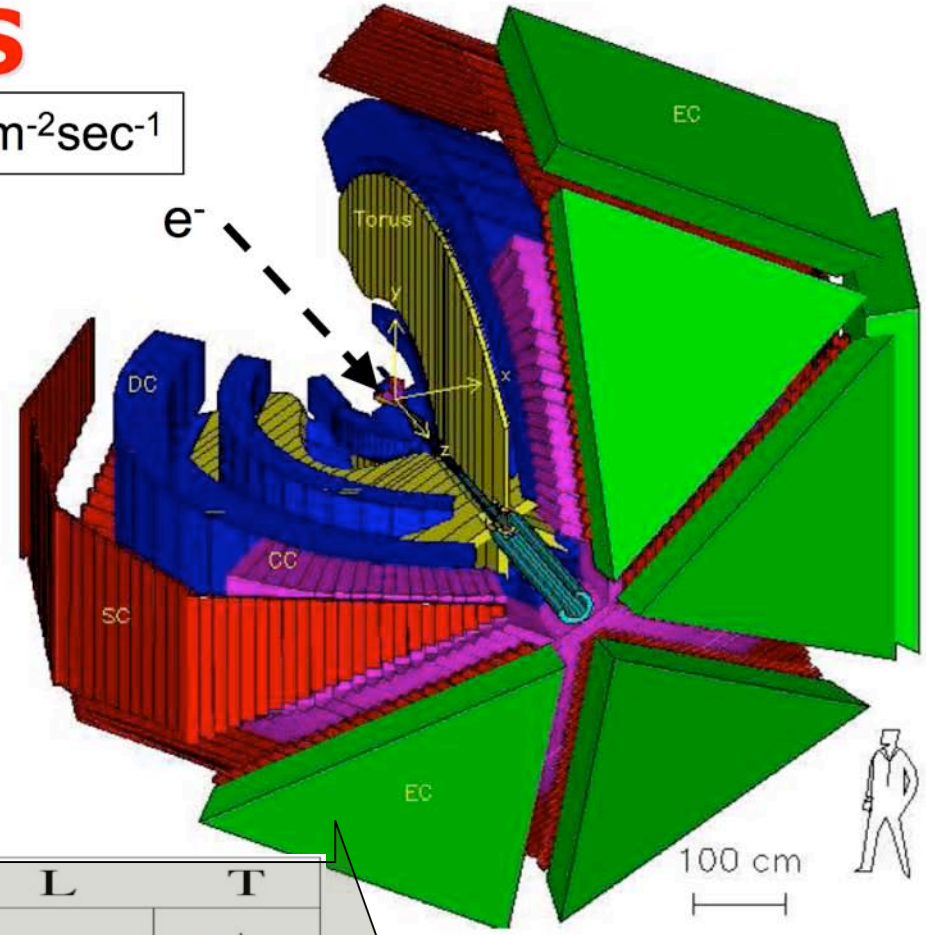

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Data taken in 2001/2005/2009

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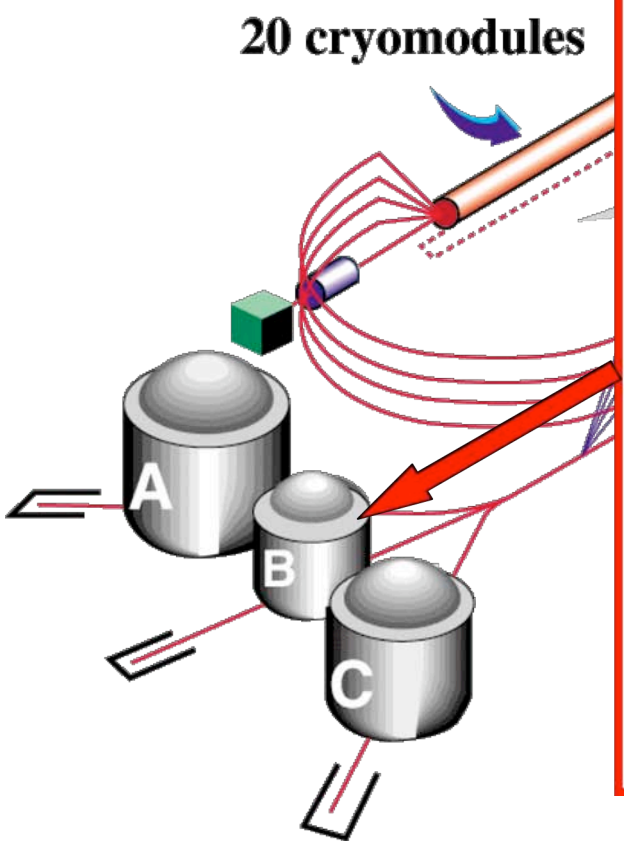

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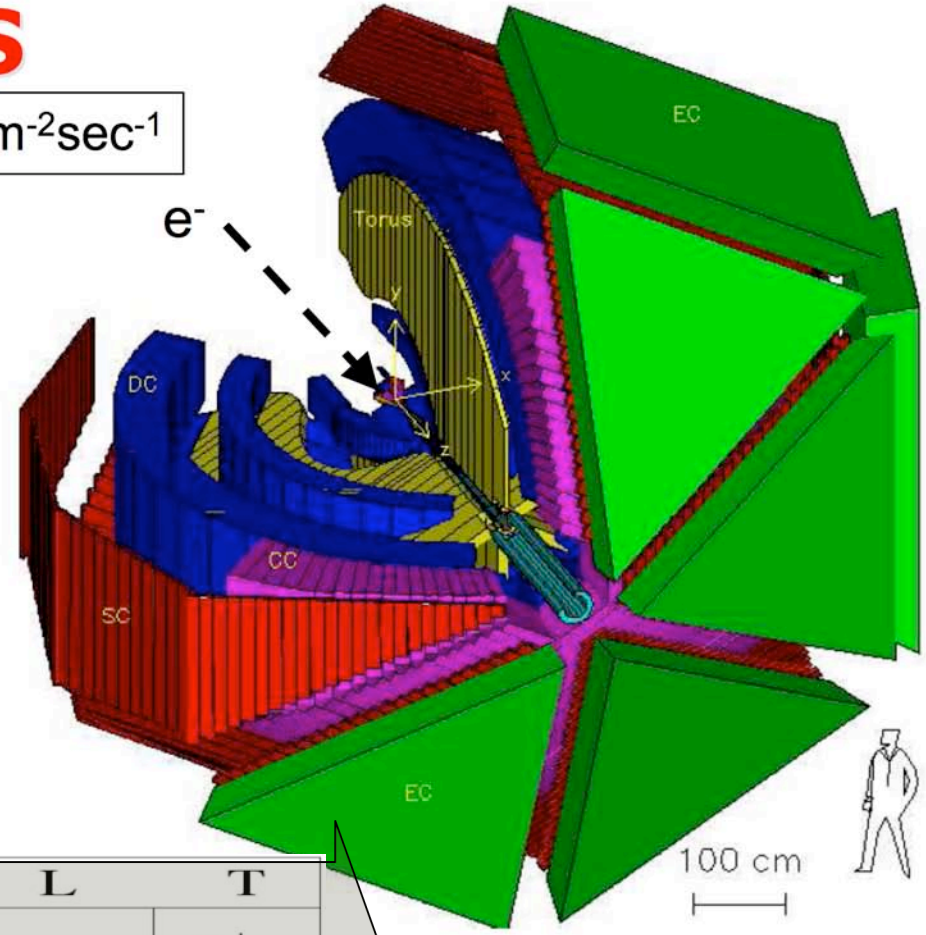

N \ q	U	L	T
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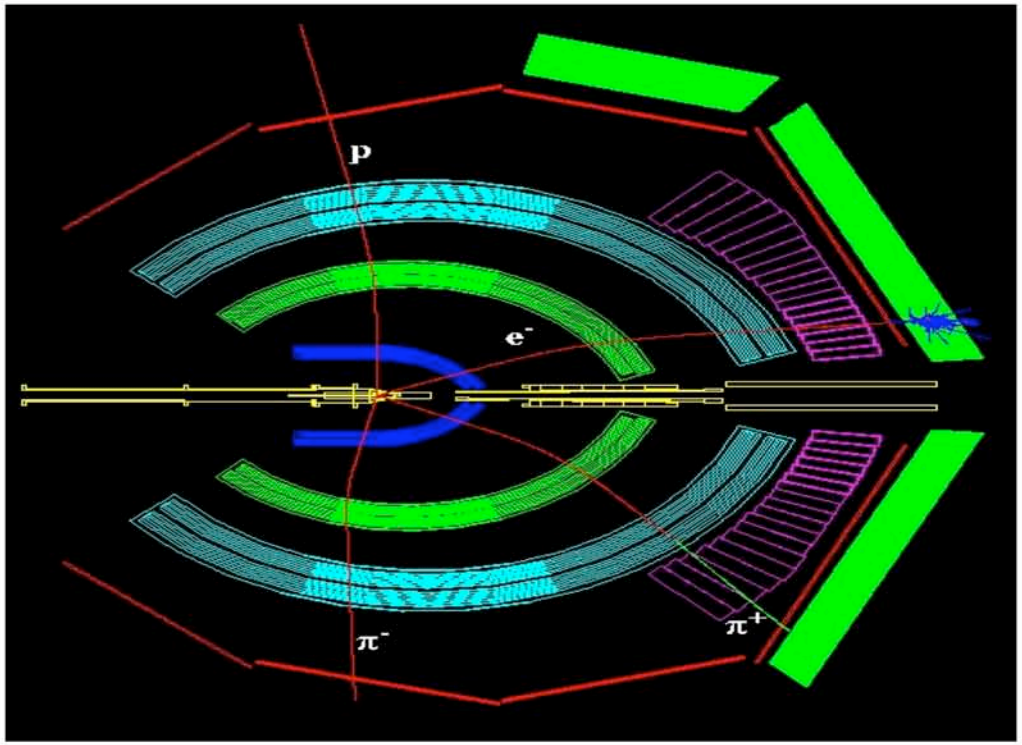
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Data taken in 2001/2005/2009

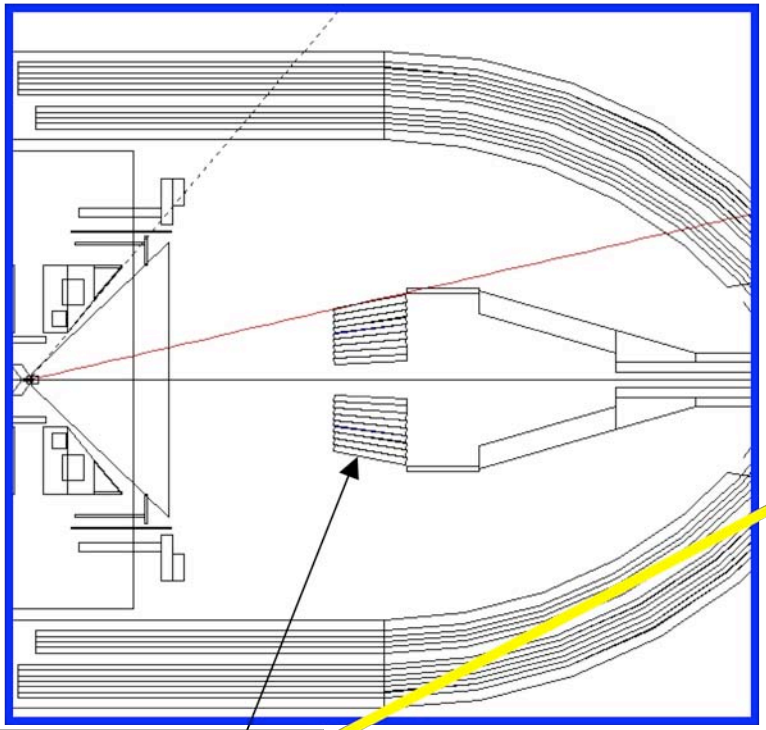
Data in 2011

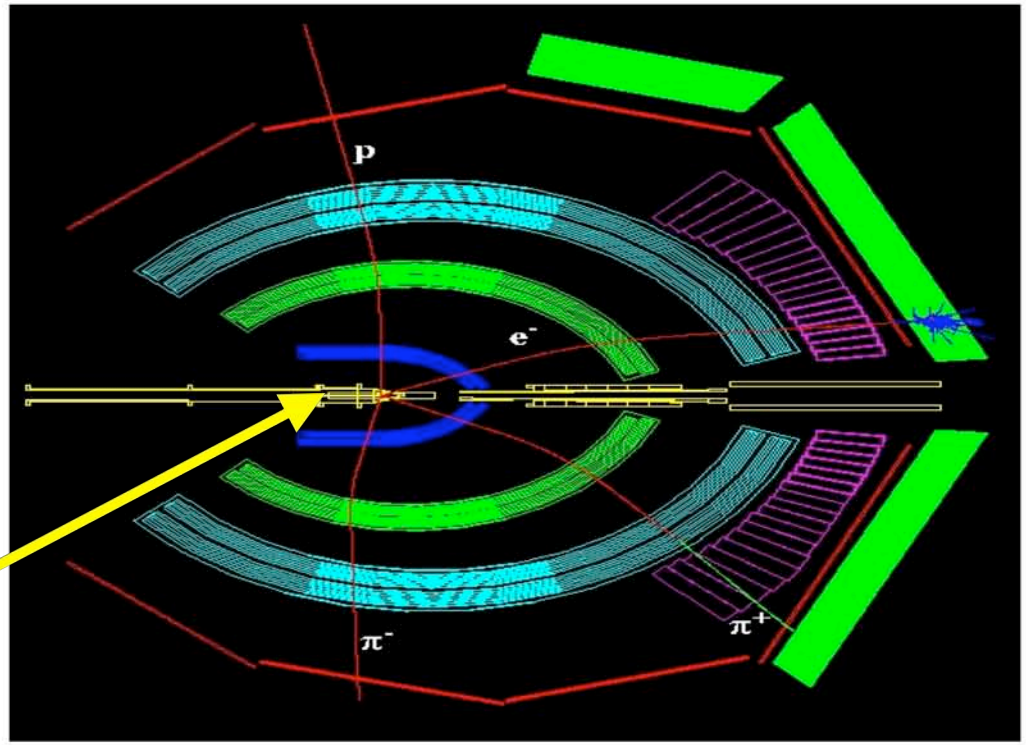
Experimental configuration

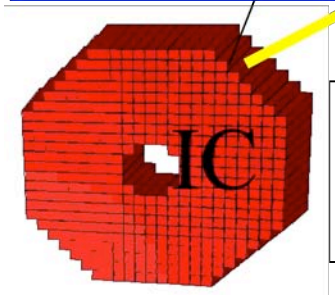


Experimental configuration for **unpolarized/long.polarized** target

Experimental configuration





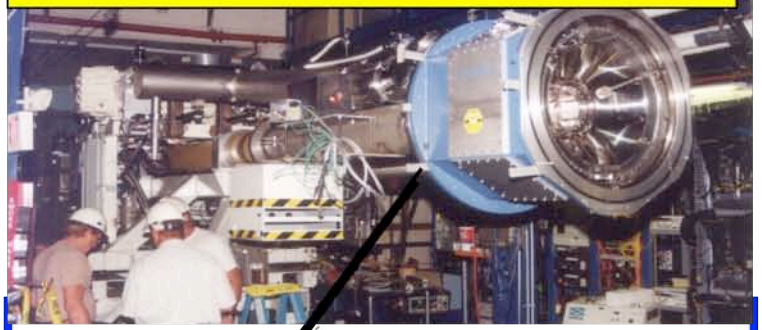


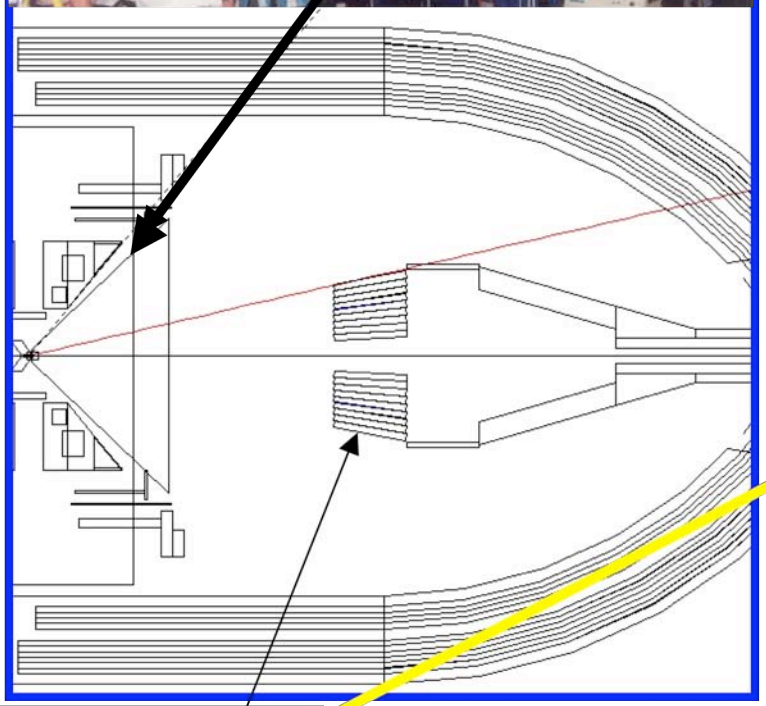
Inner Calorimeter (424 $PbWO_4$ crystals) to detect high energy photons at forward lab angles.

Experimental configuration for **unpolarized/long.polarized** target

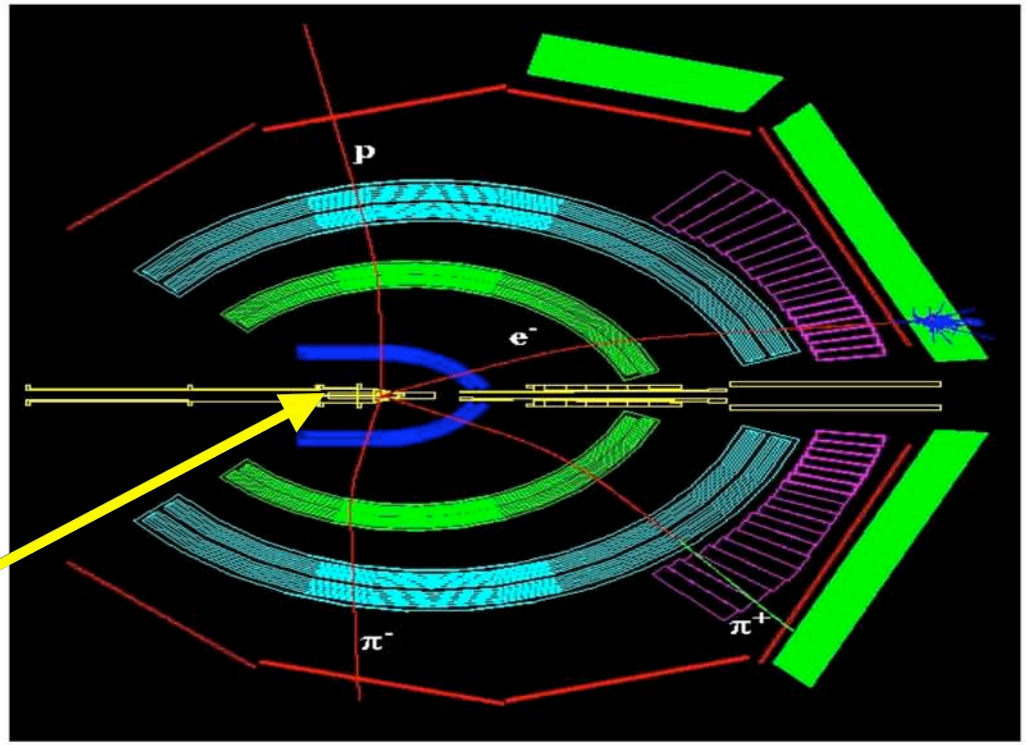
Experimental configuration

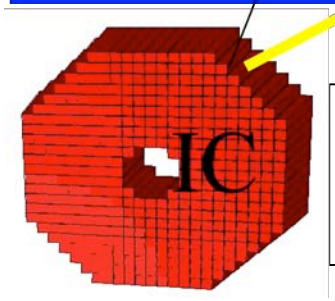
Polarized target (NH3/ND3)





Pol. $\vec{NH_3}$, $\vec{ND_3}$ targets $\langle P_H \rangle = 0.75$, $\langle P_D \rangle = 0.3$
Longitudinal polarization





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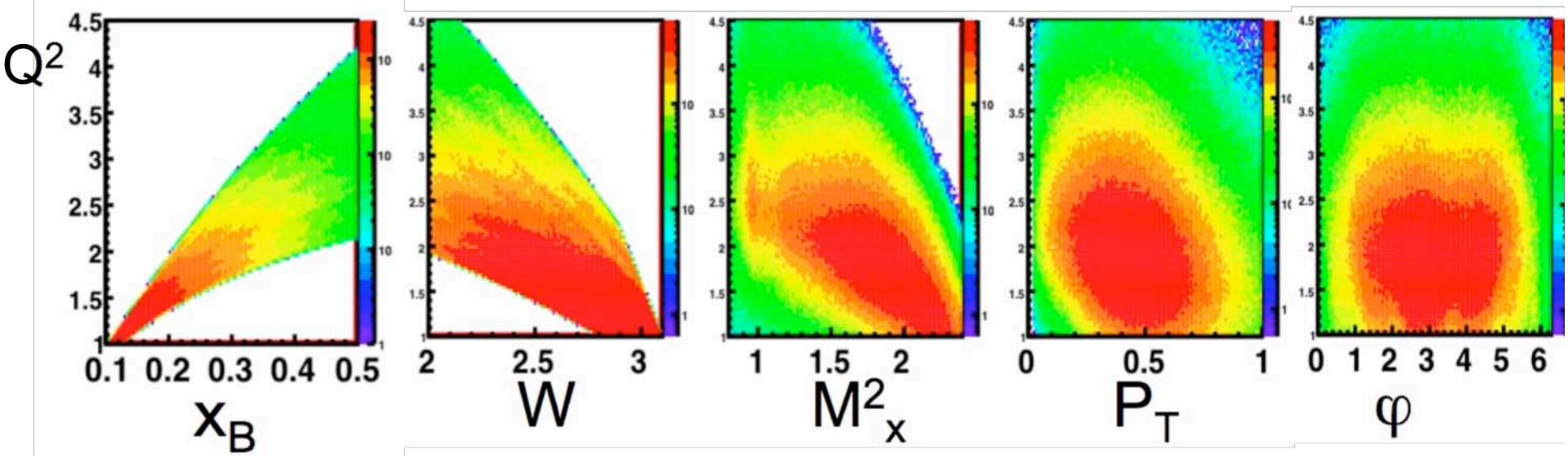
Experimental configuration for **unpolarized/long.polarized** target

SIDIS with CLAS @ 6 GeV

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

- **DIS kinematics:**
  $Q^2>1$ GeV^2, $W^2>4$ GeV^2, $y<0.85$



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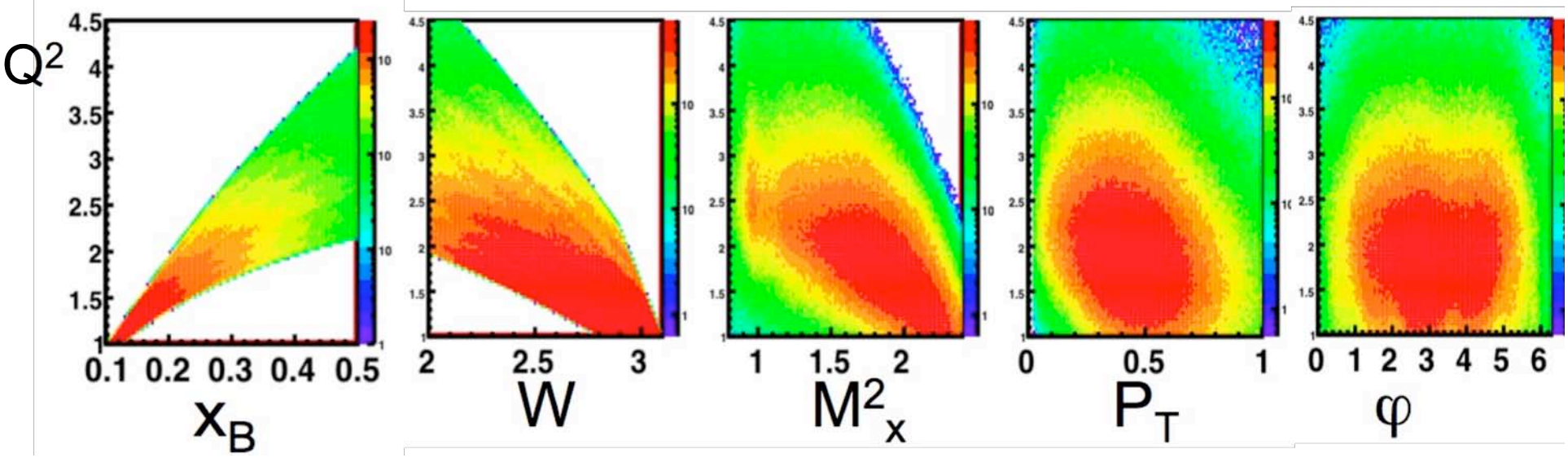

1) Longitudinally Polarized NH3/ND3 (no IC, ~5 days)	2001
2) Longitudinally Polarized NH3/ND3 with IC 60 days	2009
3) Unpolarized H with IC ~60 days	2005
4) Transversely Polarized HD-Ice (no IC, 25 days)	2011

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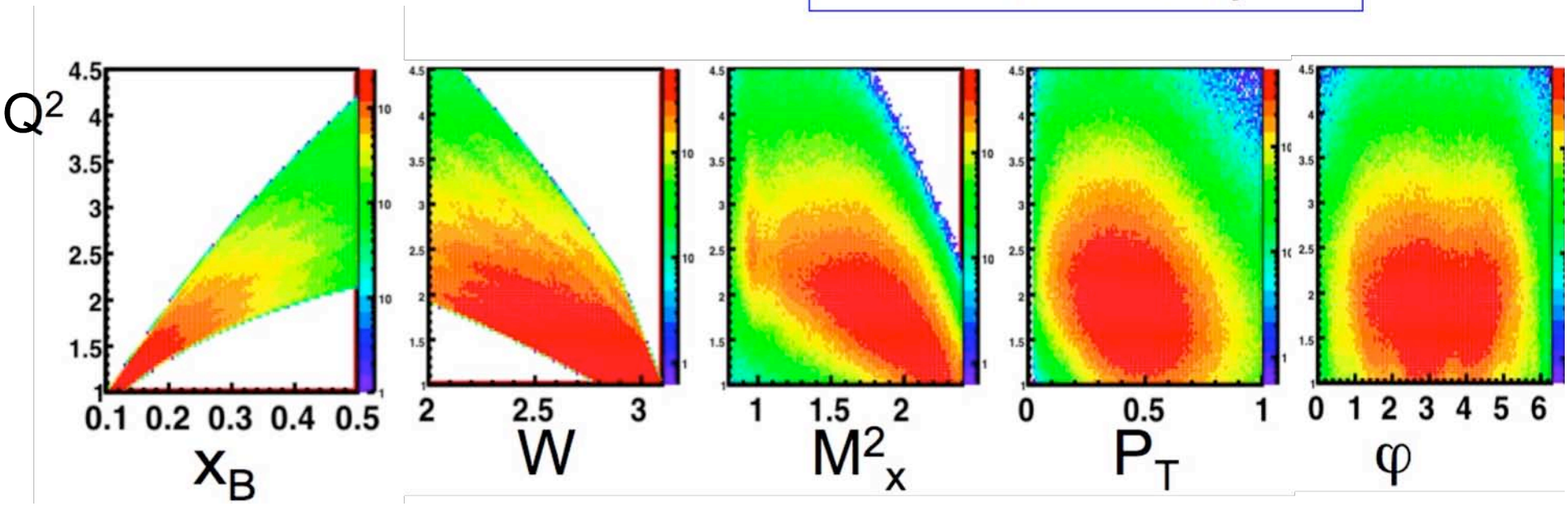

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A_{UL}, A_{LL}: **arXiv:1003.4549**
Submitted to PRL

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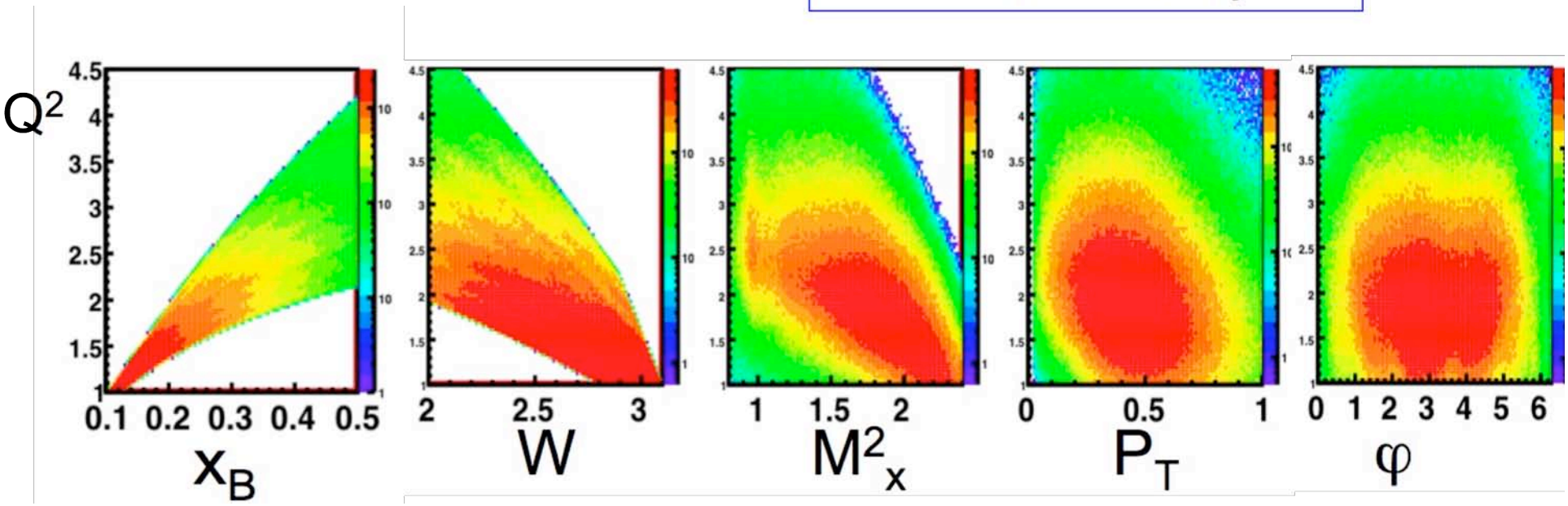

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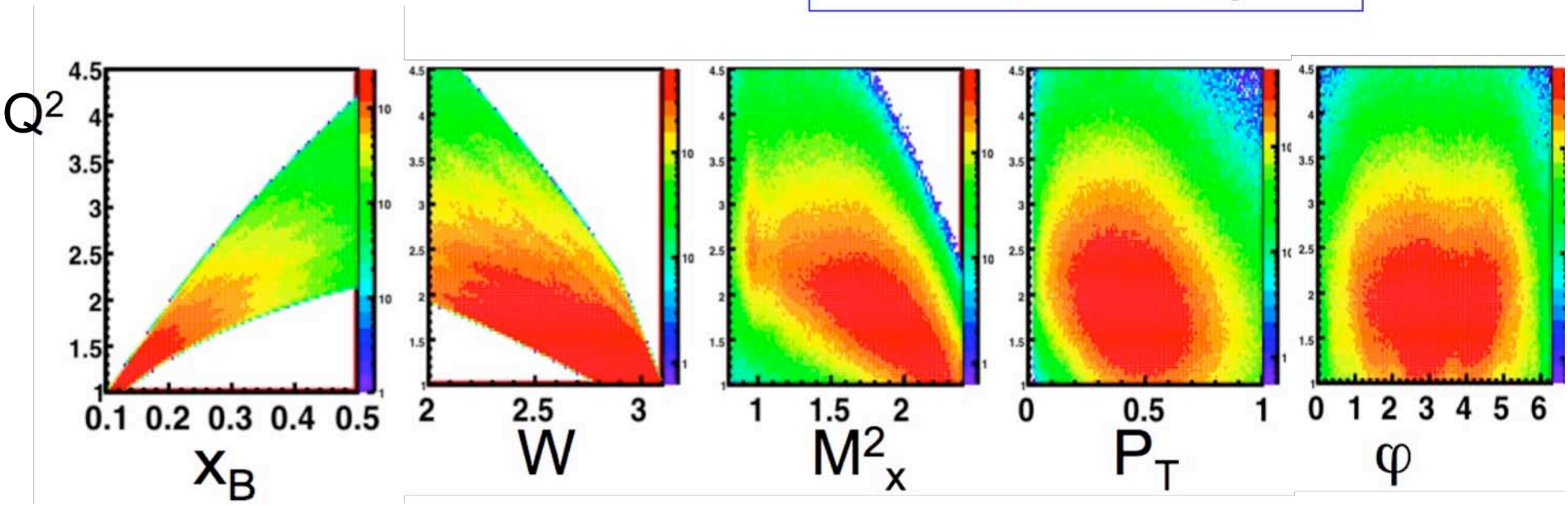

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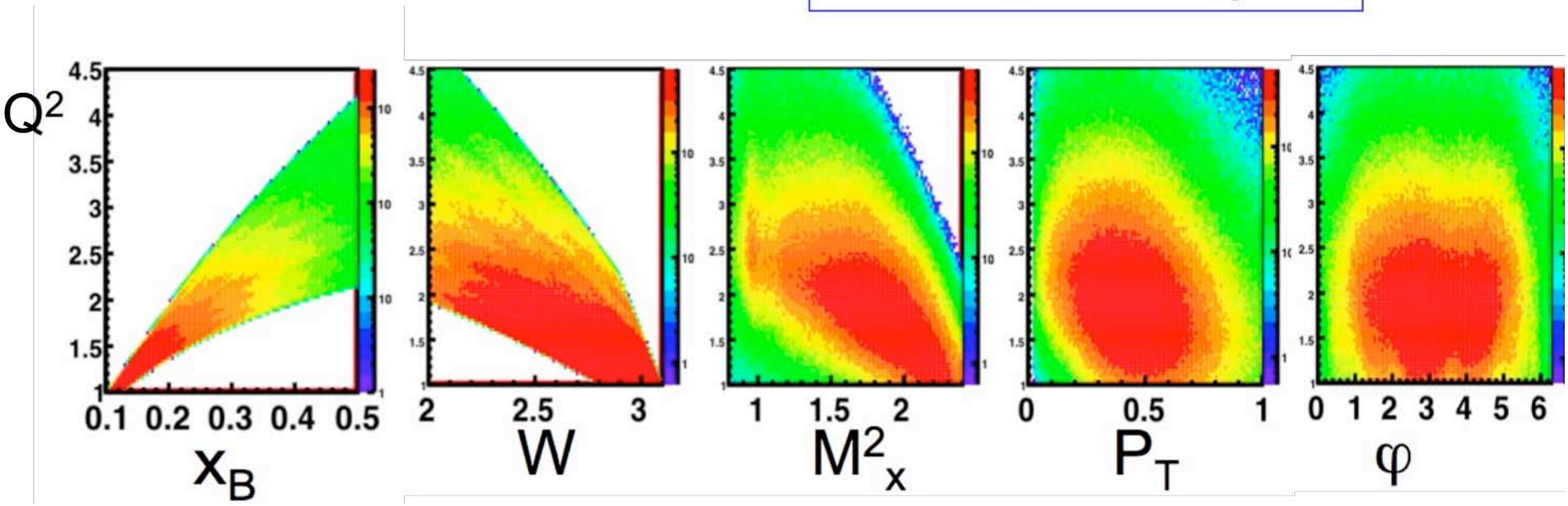

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Pion SSA with unpol./long. Polarized Target

- CLAS program: extraction of **leading twist** and **higher twist** TMDs
- **quark-gluon-quark correlations** responsible for azimuthal moments of **h.t.**

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LEADING TWIST

quark polarization

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

hadron polarization

q/h	U	L	T
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quark polarization nucleon polarization

HIGHER TWIST

quark polarization

N/q	U	L	T
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$$A_{LU}^{\sin(\phi)}$$

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Pion SSA with unpol./long. Polarized Target

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$$A_{UL}^{\sin(2\phi)}$$

$$A_{LU}^{\sin(\phi)}$$

π^0 BSA

LEADING TWIST

quark polarization

quark polarization nucleon polarization

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HIGHER TWIST

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$\pi^{0/+/-}$ TSA $A_{UL}^{\sin(2\phi)}$ A_{LL} $A_{LU}^{\sin(\phi)}$ π^0 BSA

LEADING TWIST

quark polarization

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

hadron polarization

q/h	U	L	T
U	$\mathbf{D_1}$		$D_{1T}^\perp$
L		$\mathbf{G_{1L}}$	$G_{1T}^\perp$
T	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

quark polarization nucleon polarization

HIGHER TWIST

quark polarization

N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

hadron polarization

q/h	U	L	T
U	$D^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G_L^\perp}$	$\mathbf{G_T}, G_T^\perp$
T	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

Pion SSA with unpol./long. Polarized Target

- CLAS program: extraction of **leading twist** and **higher twist** TMDs
- **quark-gluon-quark correlations** responsible for azimuthal moments of **h.t.**

$\pi^{0/+/-}$ TSA

$$A_{UL}^{\sin(2\phi)} \qquad A_{LL} \qquad A_{LU}^{\sin(\phi)}$$

π^0 BSA

P_T-dependence

LEADING TWIST

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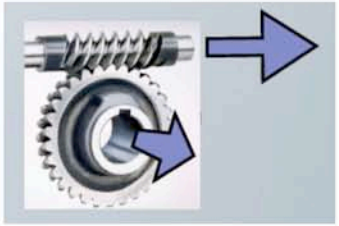
quark polarization nucleon polarization

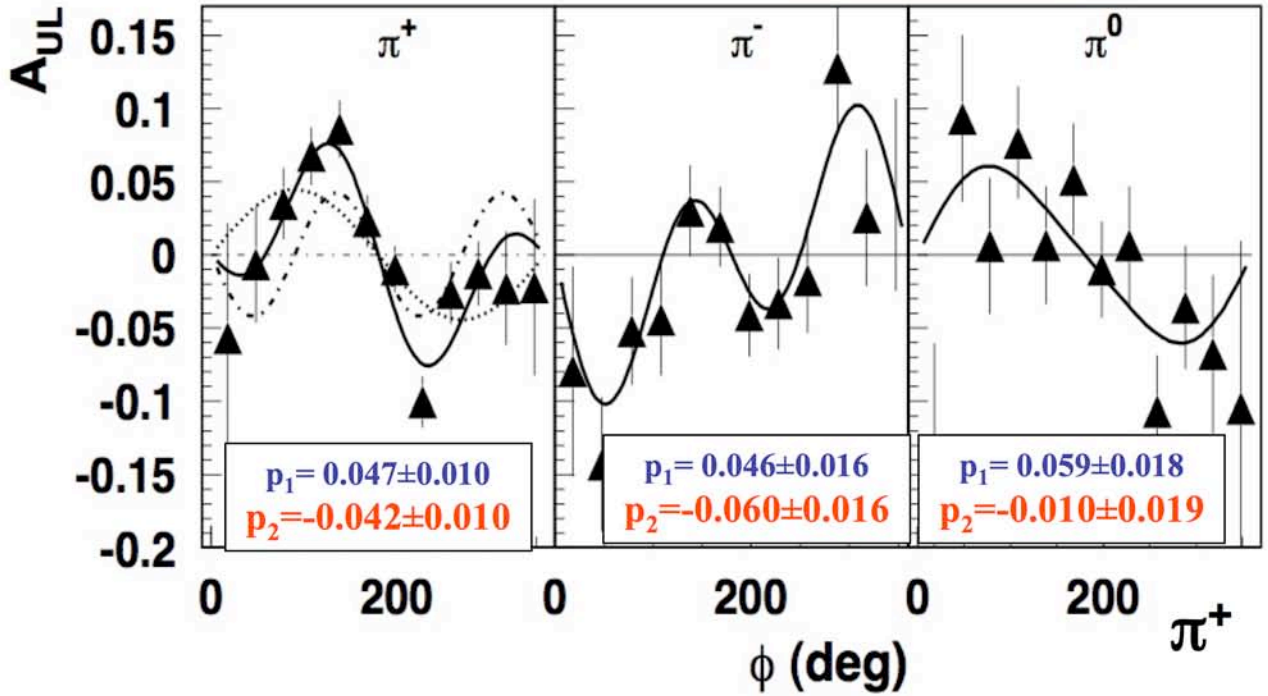
Longitudinal pol. target: Kotzinian-Mulders asymmetry

$e\,p \rightarrow e'\pi^{+/-/0}\,X$



Transversely polarized quarks in a longitudinally polarized nucleon

$$A_{UL}^{\sin 2\phi} \sim h_{1L}^{\perp} H_1^{\perp} \sin 2\phi$$



~5 days data taking

- A_{UL} $\int$ over the full kinematics
- Fitting function: $p_1 \sin\phi + p_2 \sin 2\phi$

H. Avakian et al. arXiv:1003.4549

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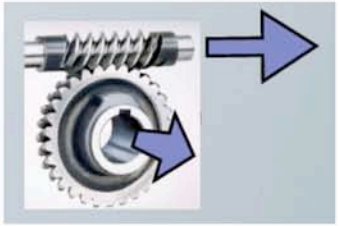

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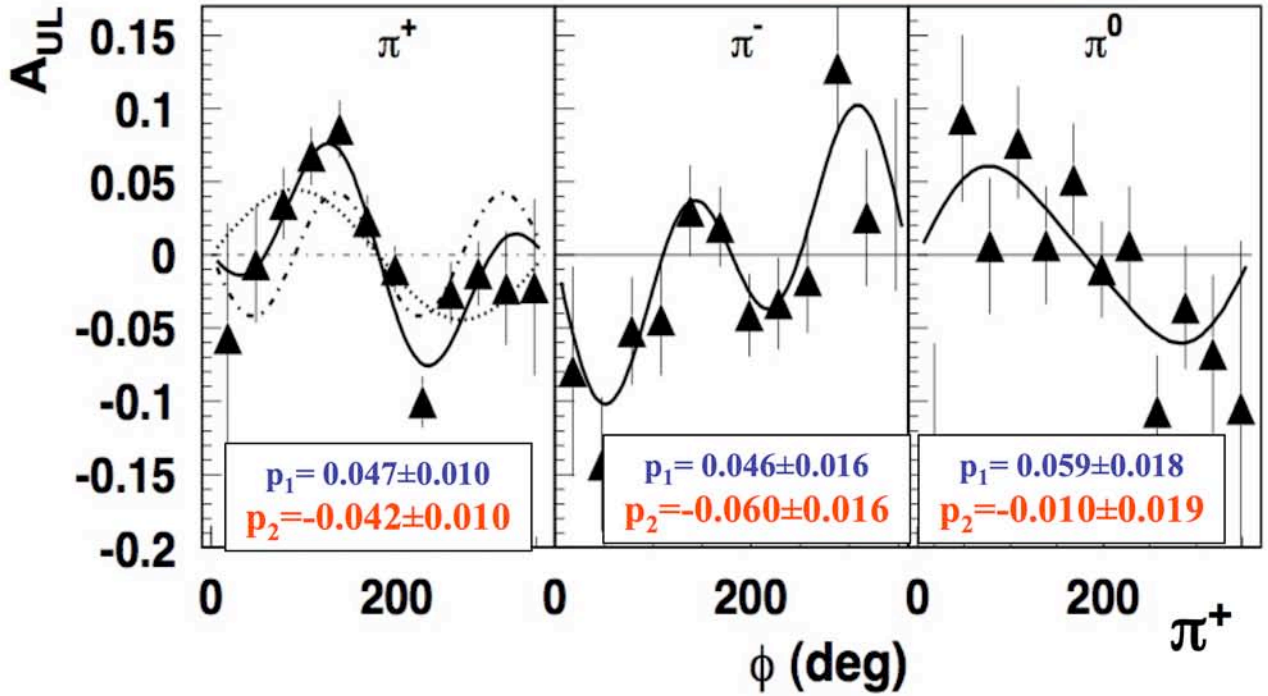

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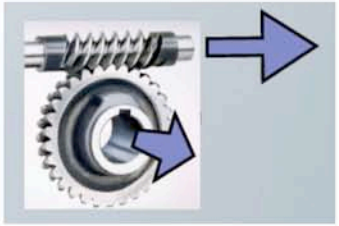

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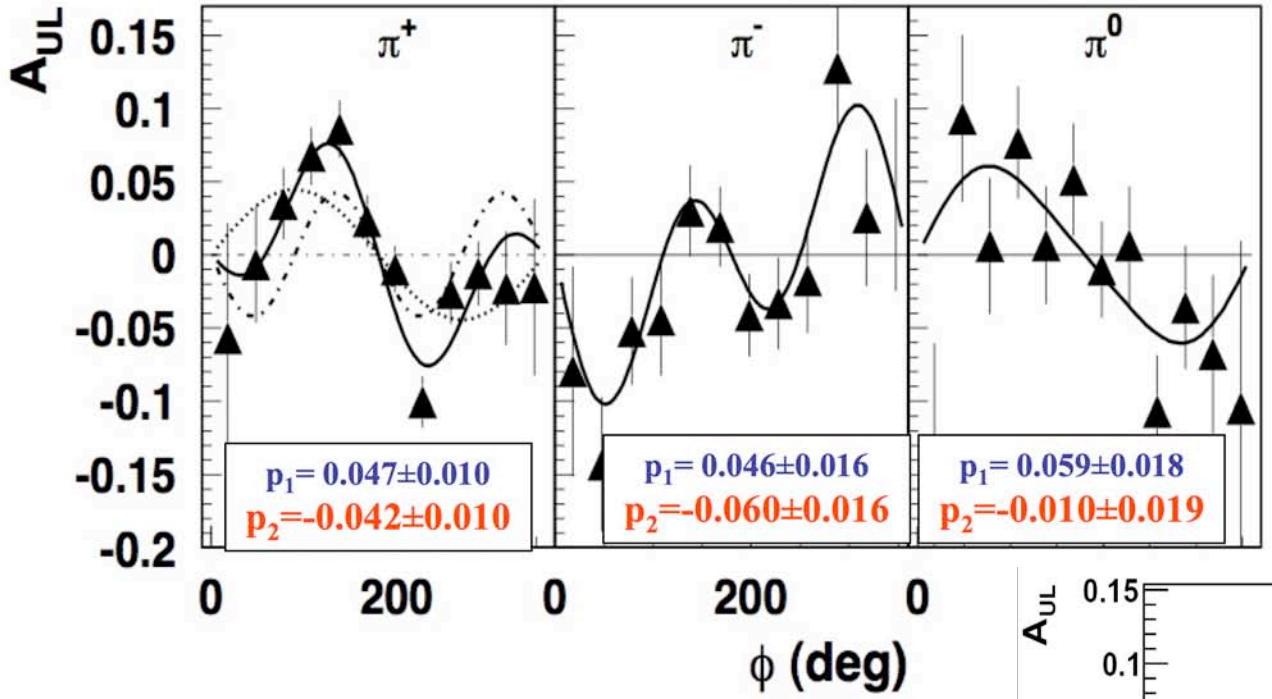

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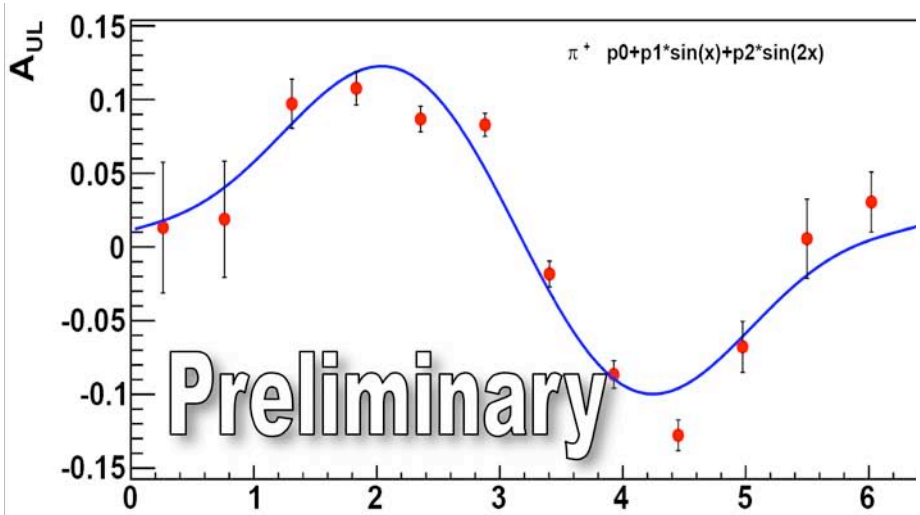
~10% of E05-113 data



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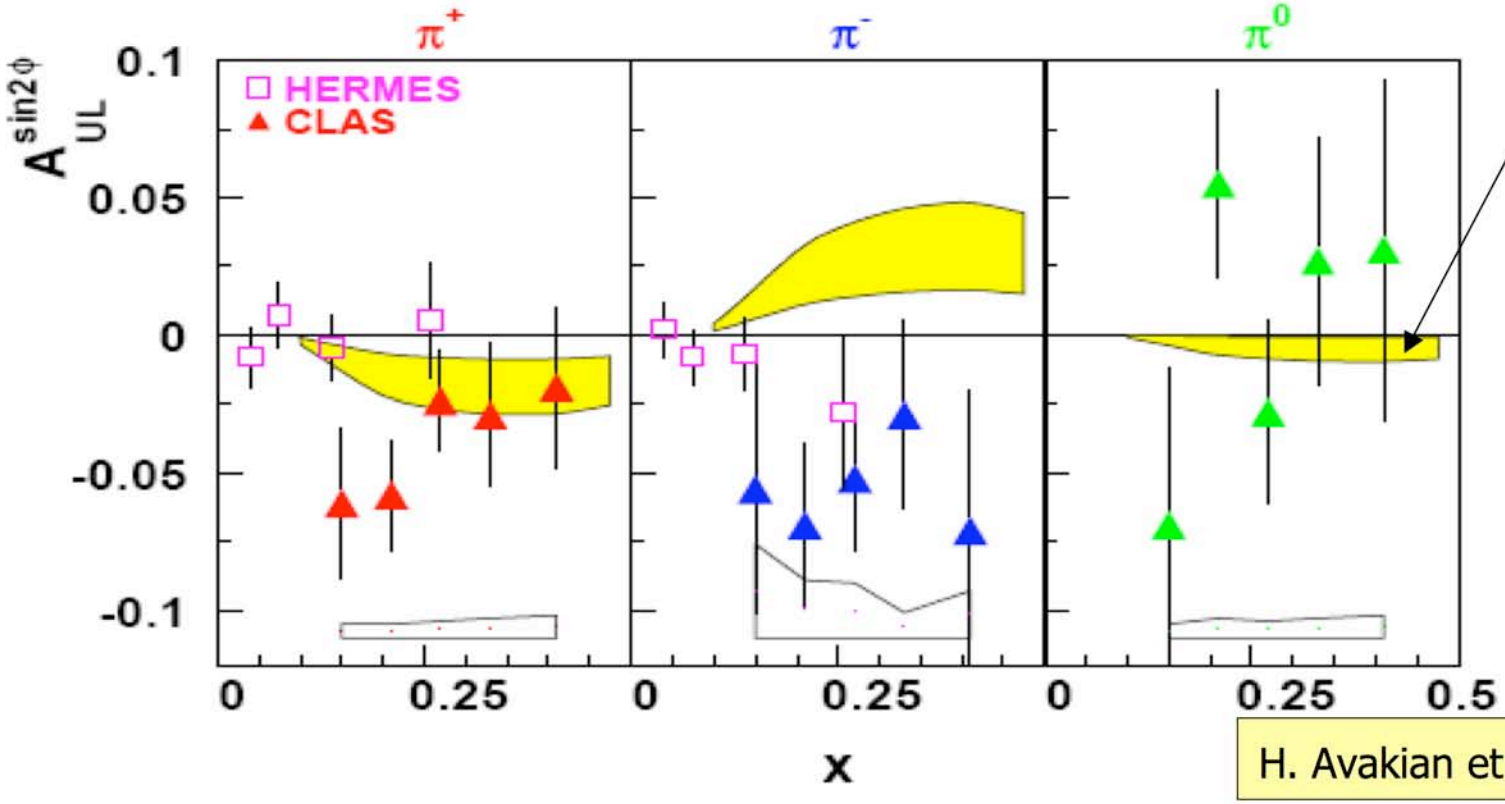

curves, χQSM from Efremov et al

H. Avakian et al. arXiv:1003.4549

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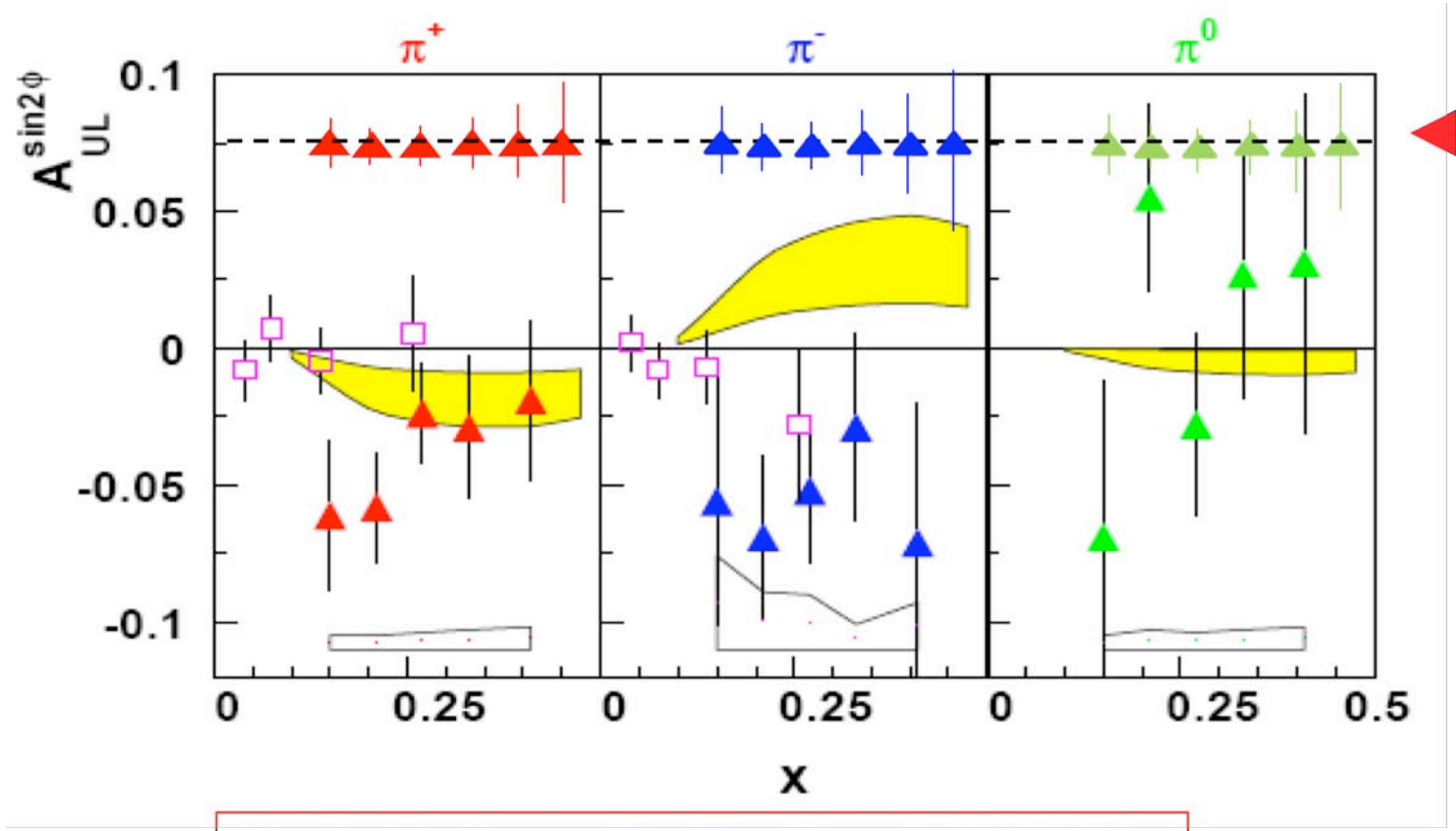
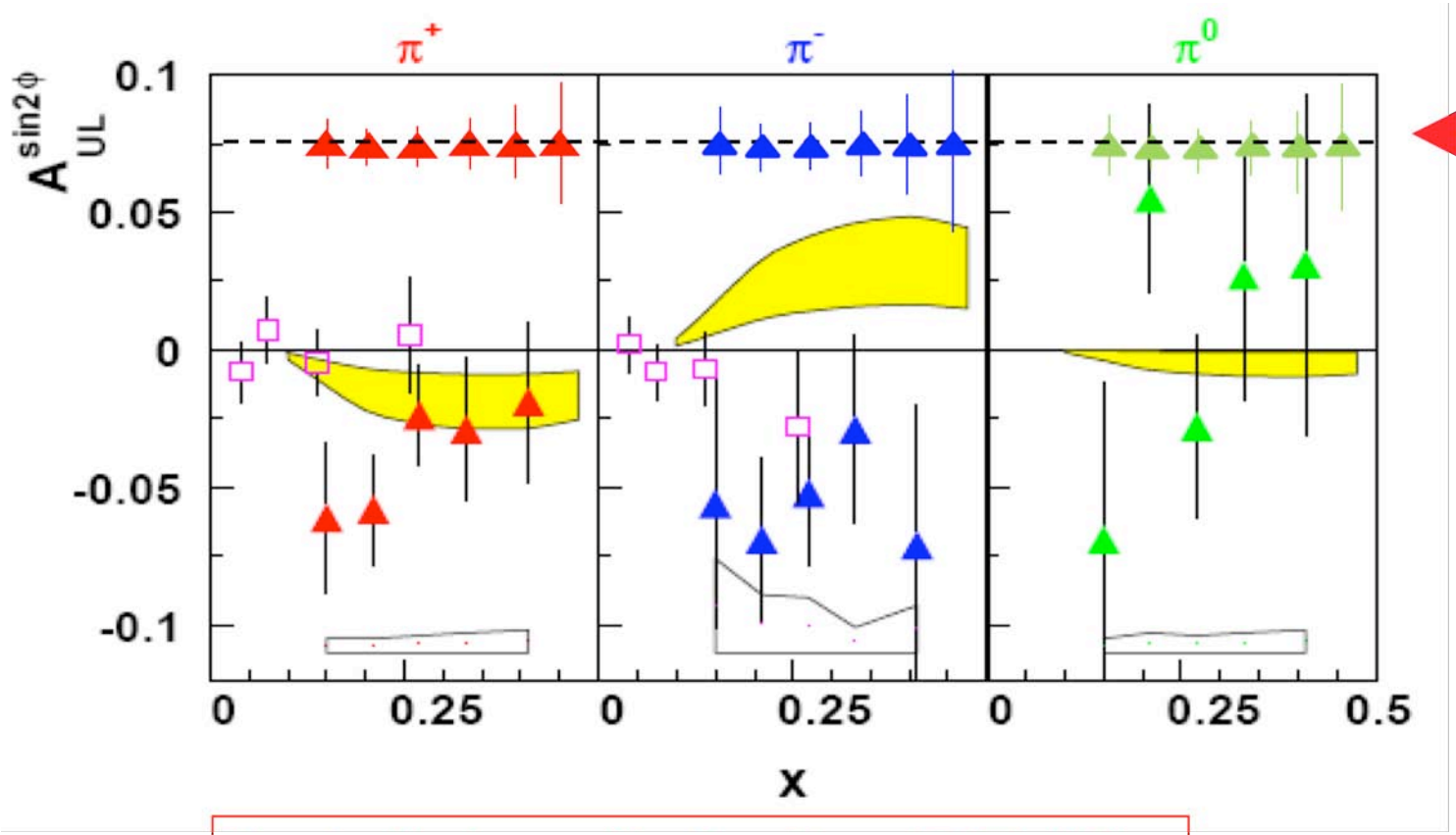


Projected results for Exp. E05-113

Longitudinal pol. target: Kotzinian-Mulders asymmetry

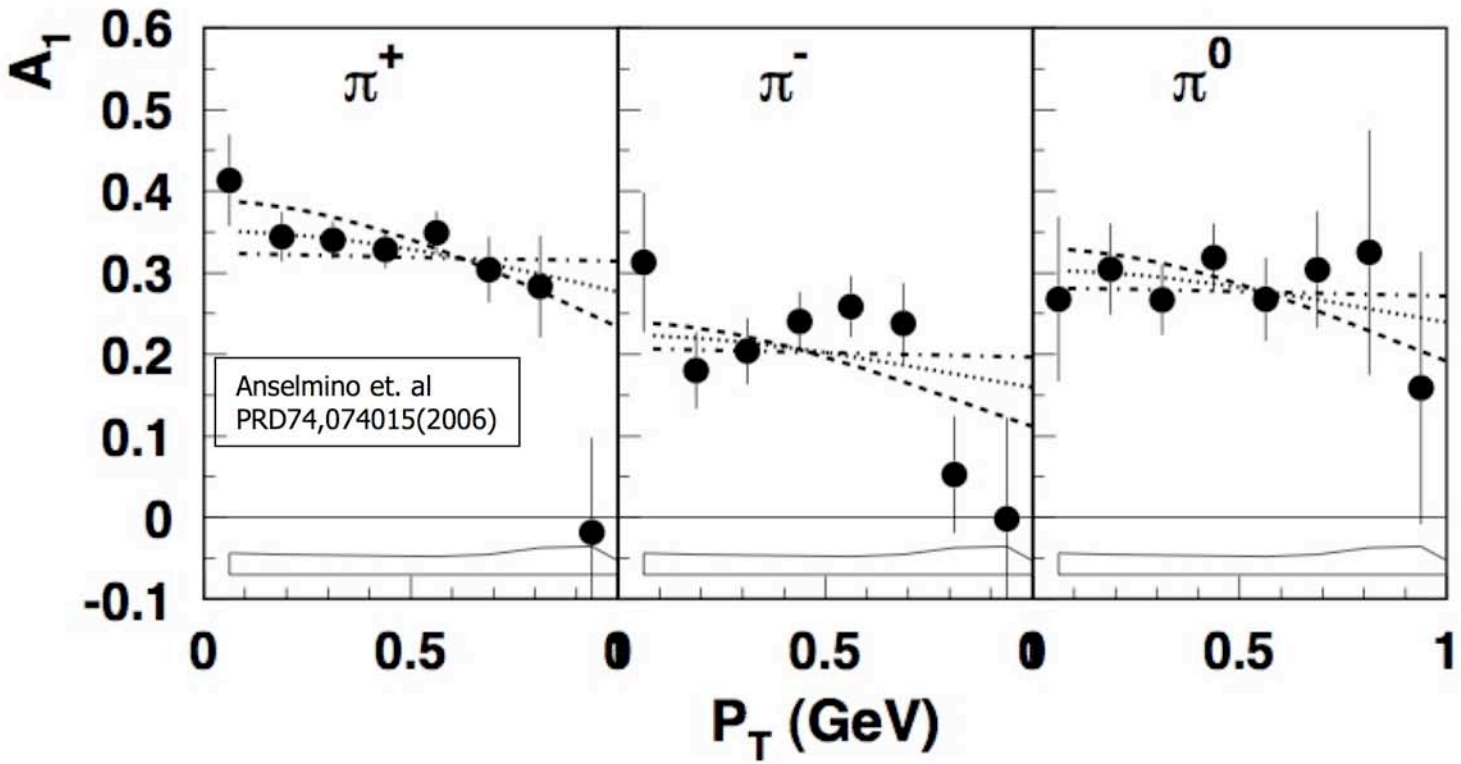


Projected results for Exp. E05-113

- Total good events accumulated with CLAS in 3 months ~ 10 times statistics accumulated by HERMES in 6 years

- Analysis Topics : $\pi^{+/-/0}$ $A_{UL}(\sin 2\phi)$, A_{LL}, $A_{LU}(\sin\phi)$
  $\rho^{+/-}$ $A_{UL}(\sin 2\phi)$

Longitudinal pol. target: A_1-P_T dependence



H. Avakian et al.
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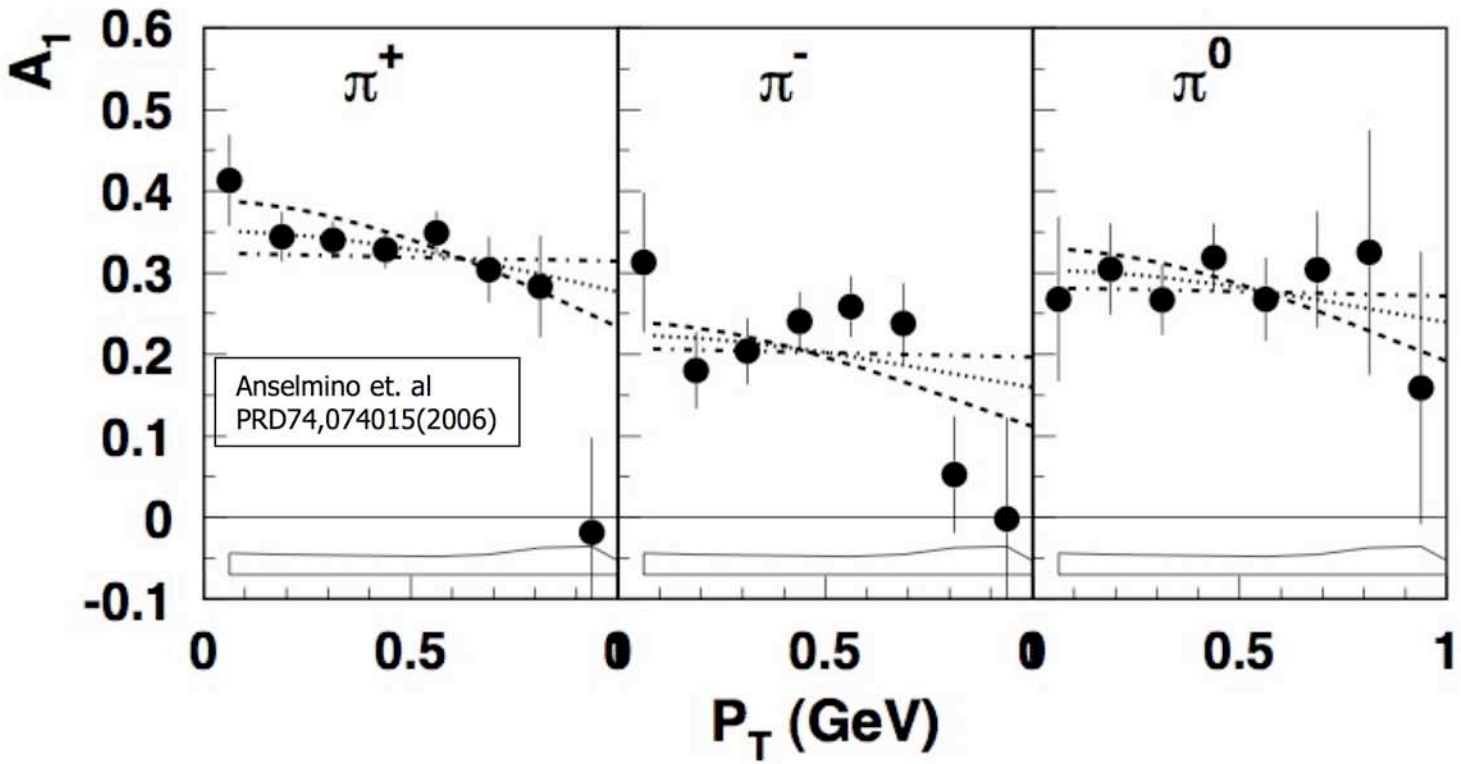

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Different width of TMDs of quarks with different flavor and polarizations

$$R = \frac{k_\perp width\, dist(g_1)}{k_\perp width\, dist(f_1)}$$

– – – R=0.40

..... R=0.68

– · – · R=1.0

f_1=0.25 GeV^2

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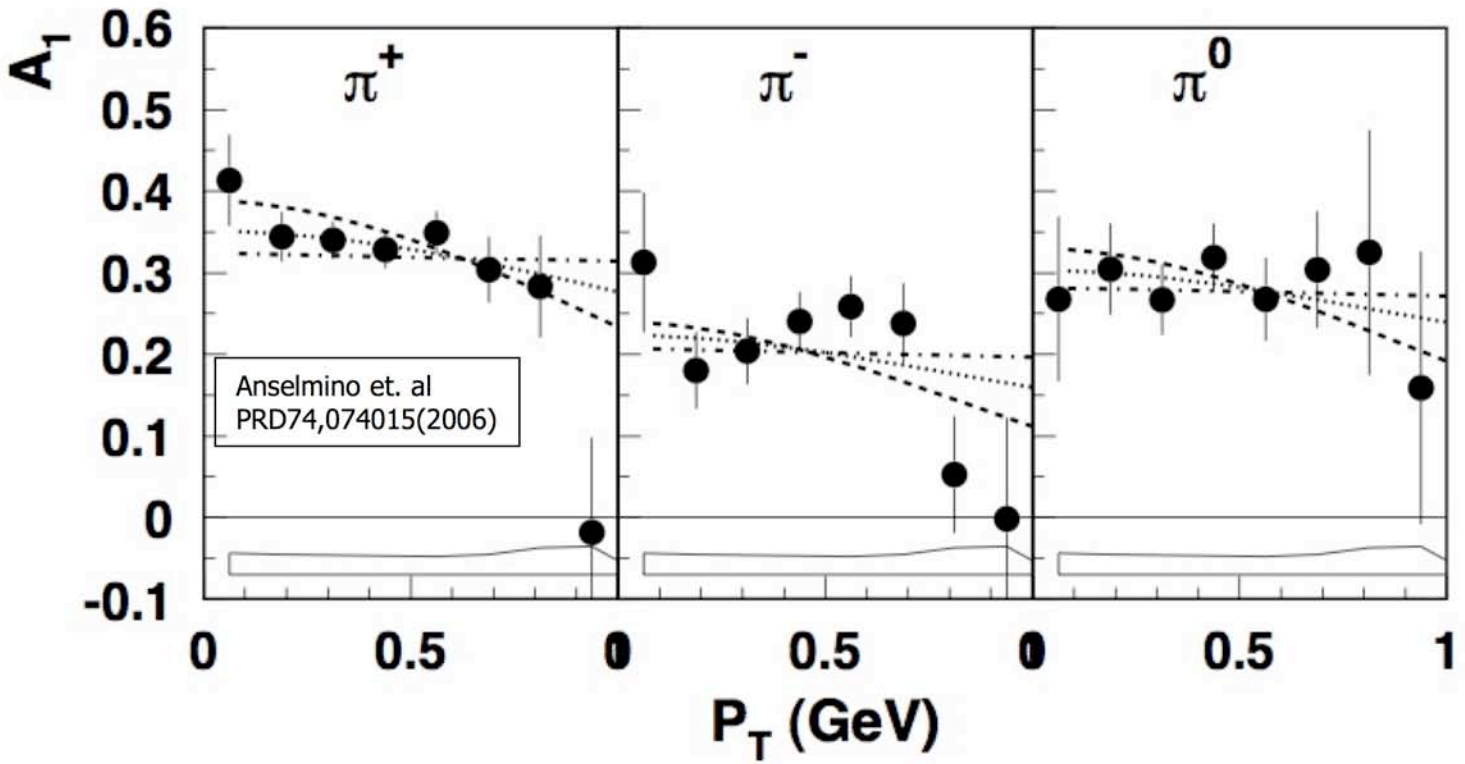

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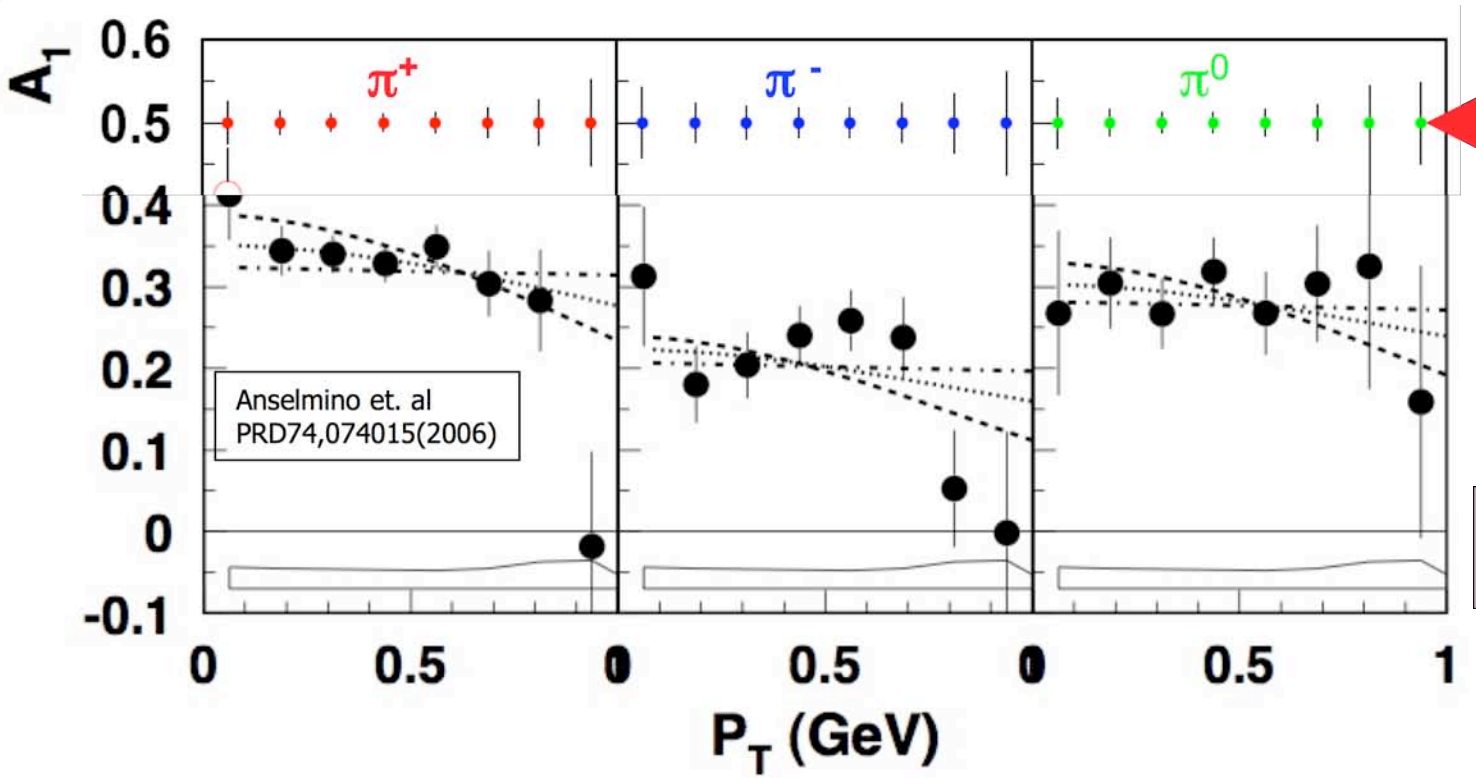

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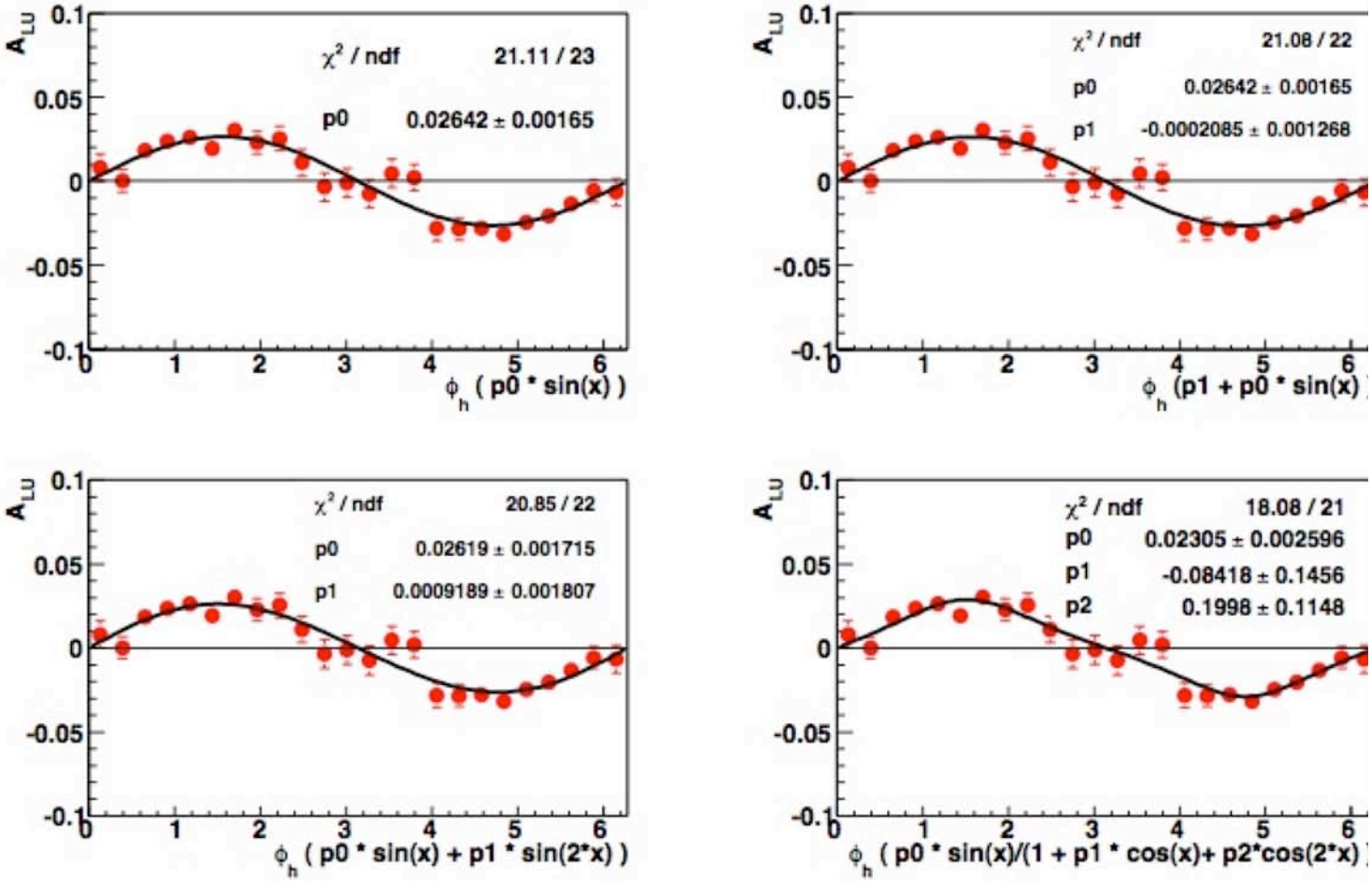
- Data shows slight preference for R< 1
- New experiment with 10 times more data will study the P_T-dependence for different quark helicities and flavors **for bins in x**

BSA: Asymmetry extraction and fitting for π^0

$e\,p \rightarrow e'\pi^0\,X$

$$A_{LU}^{\sin(\phi)}$$

$$A_{LU}(\phi) = \frac{1}{P}\frac{N^+ - N^-}{N^+ + N^-}$$



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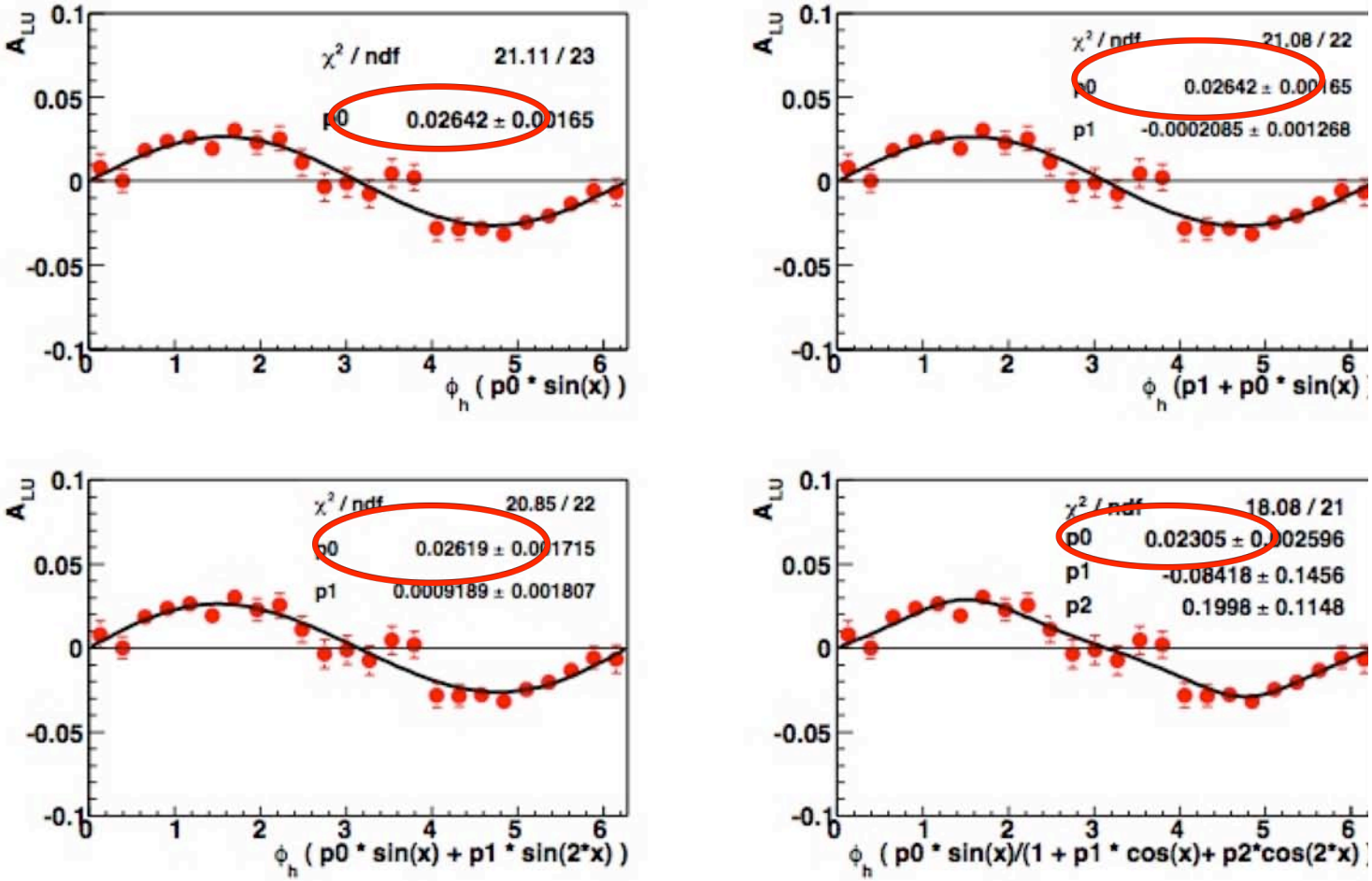
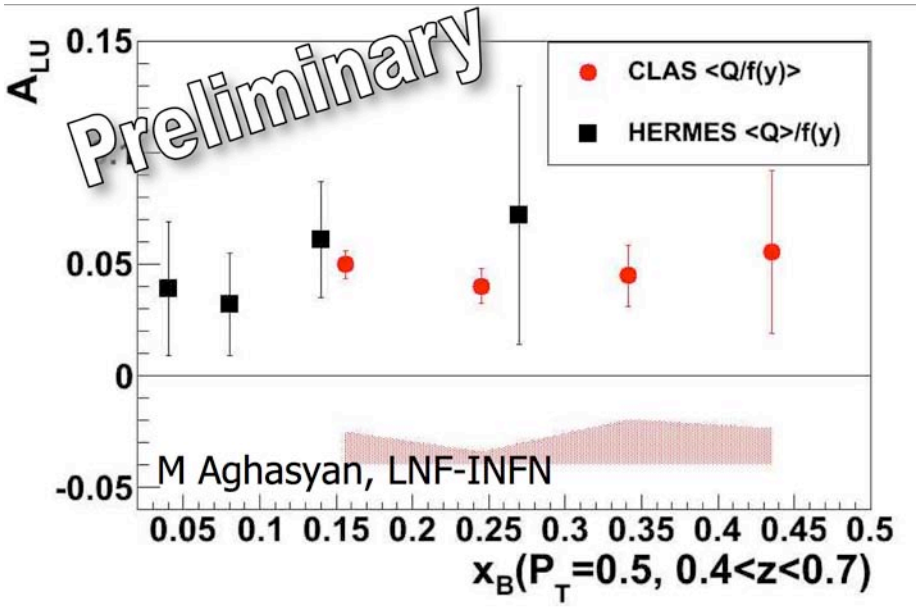
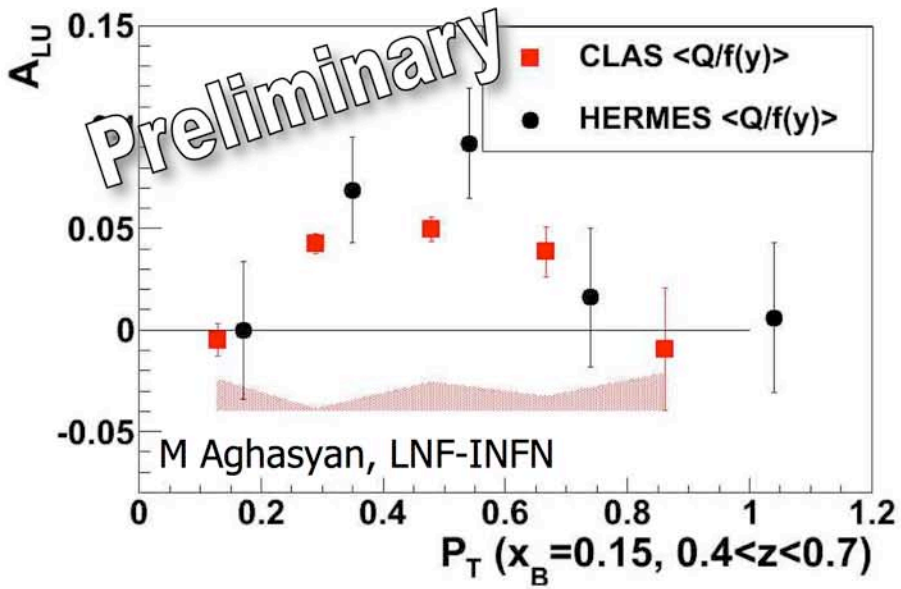
BSA ~ sinϕ
insensitive to
other harmonics



π^0 BSA Asymmetry results





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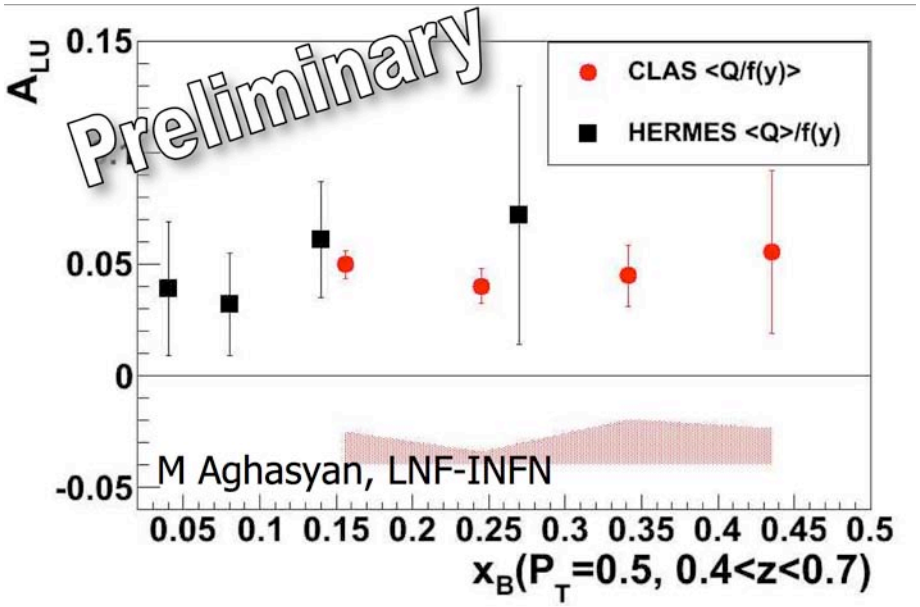

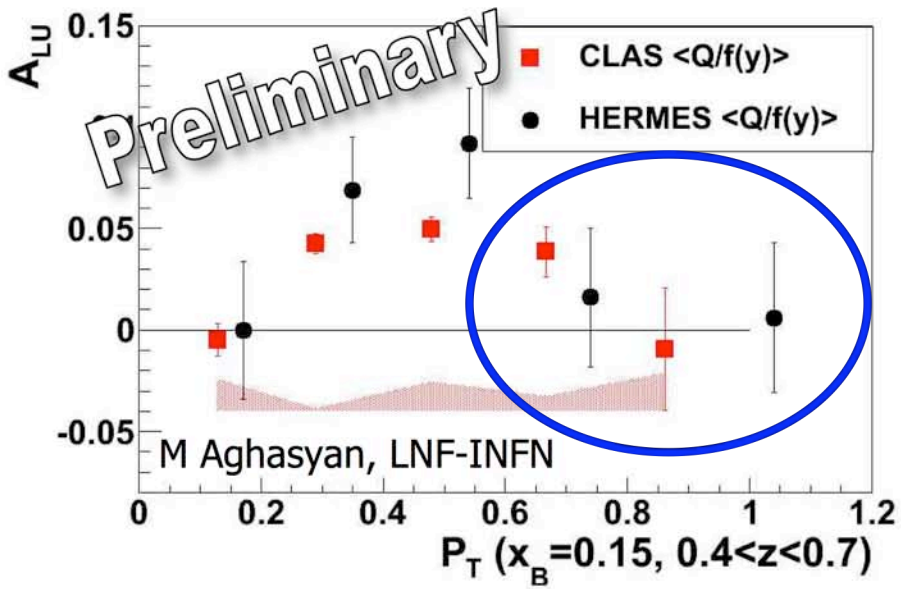

- Drop with P_T below 1 GeV/c

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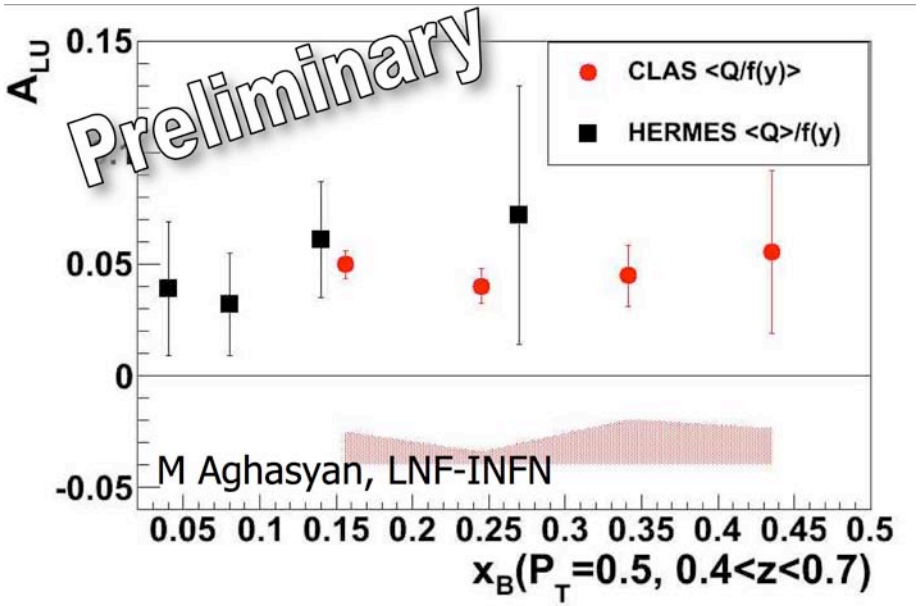

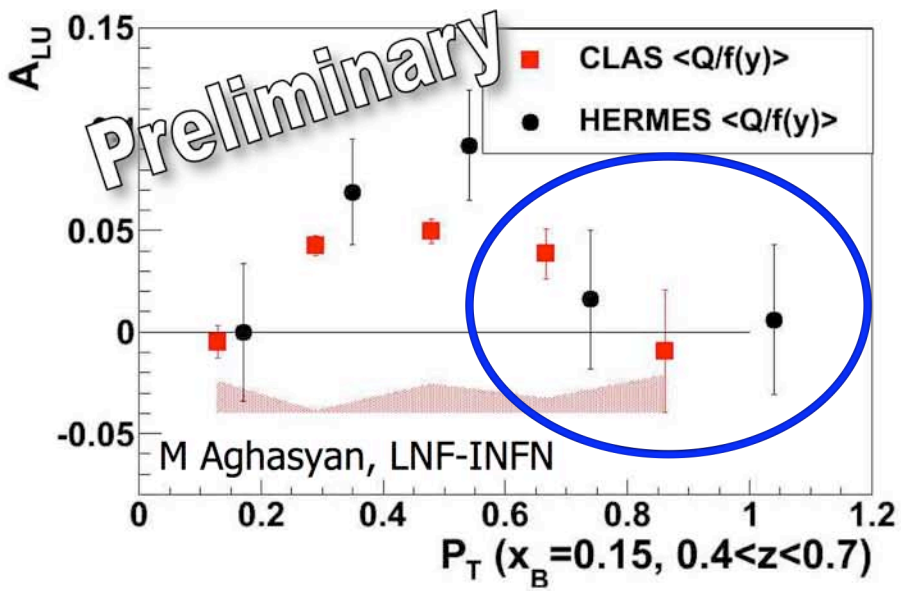

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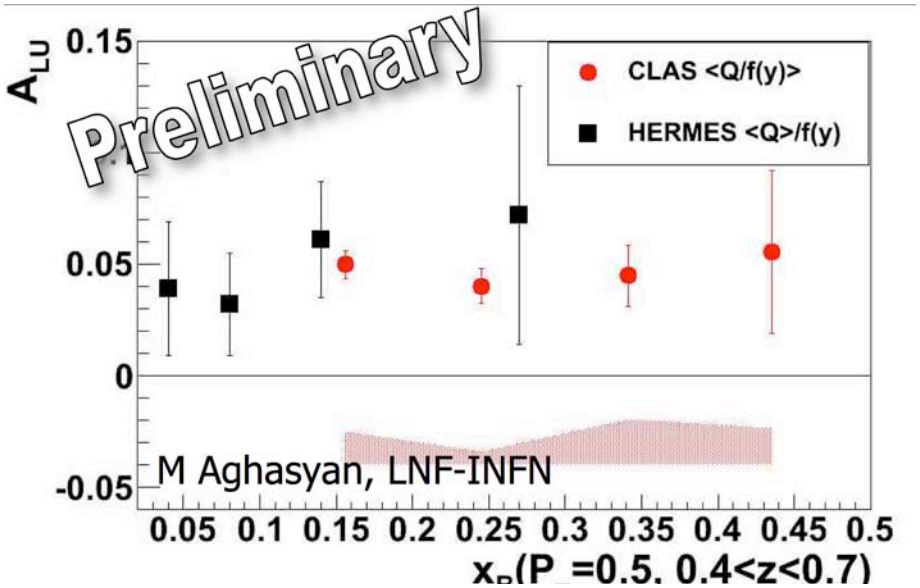

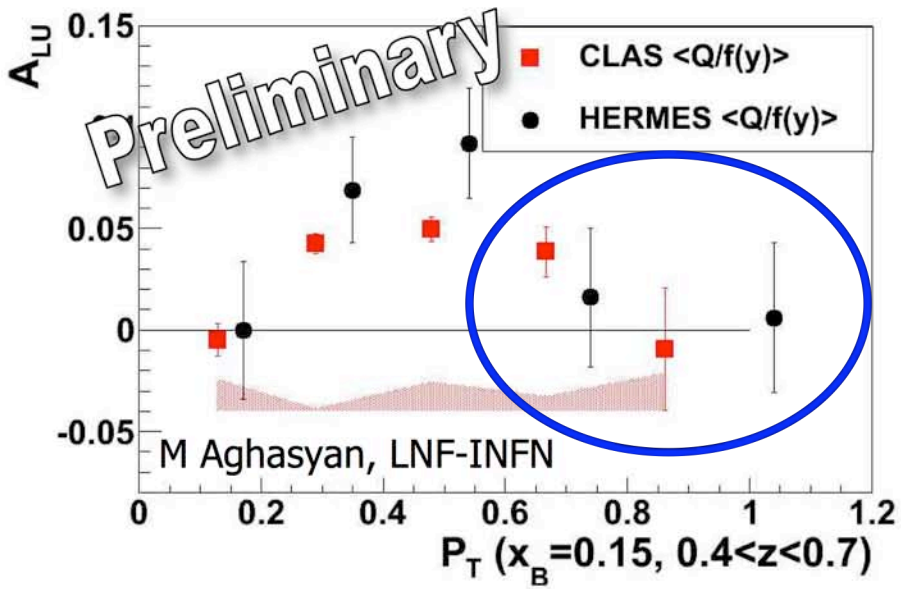

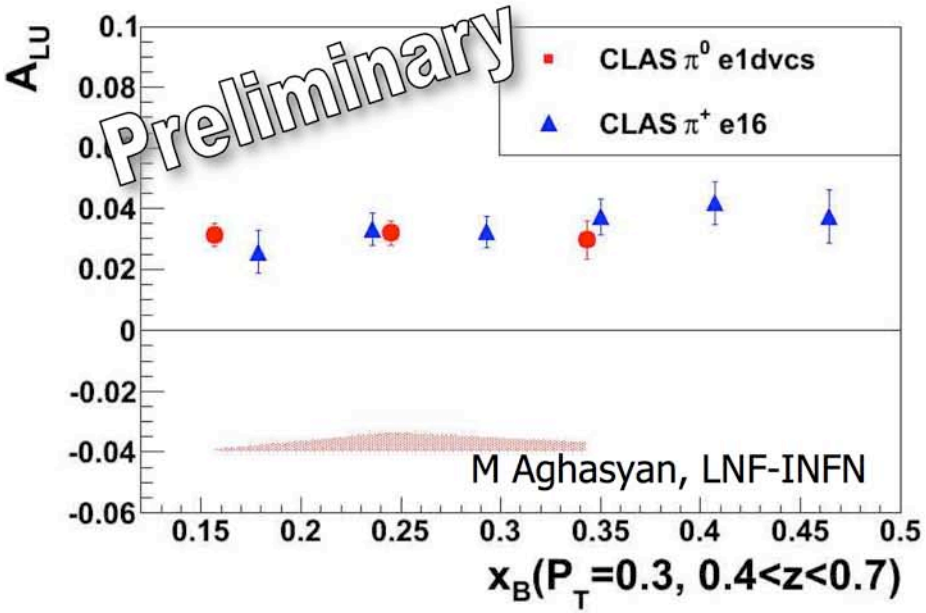

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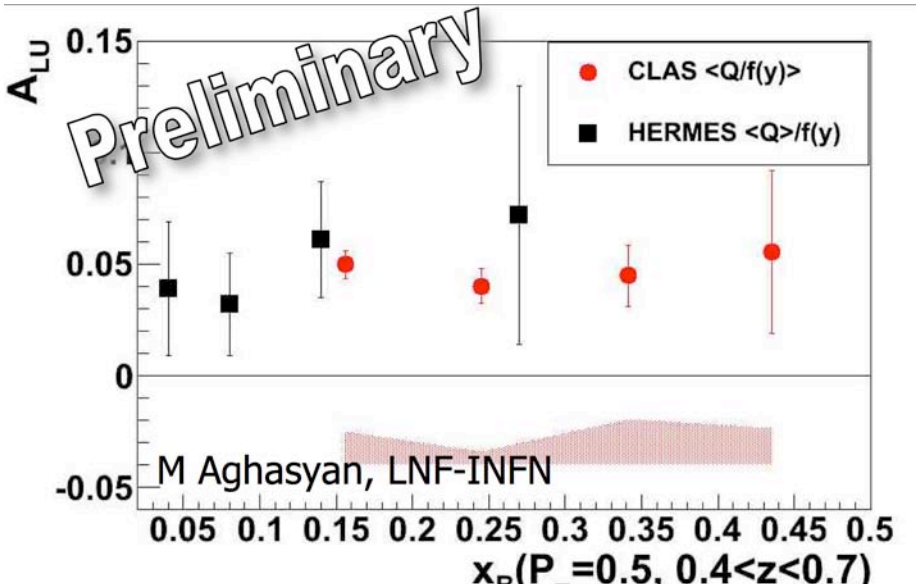
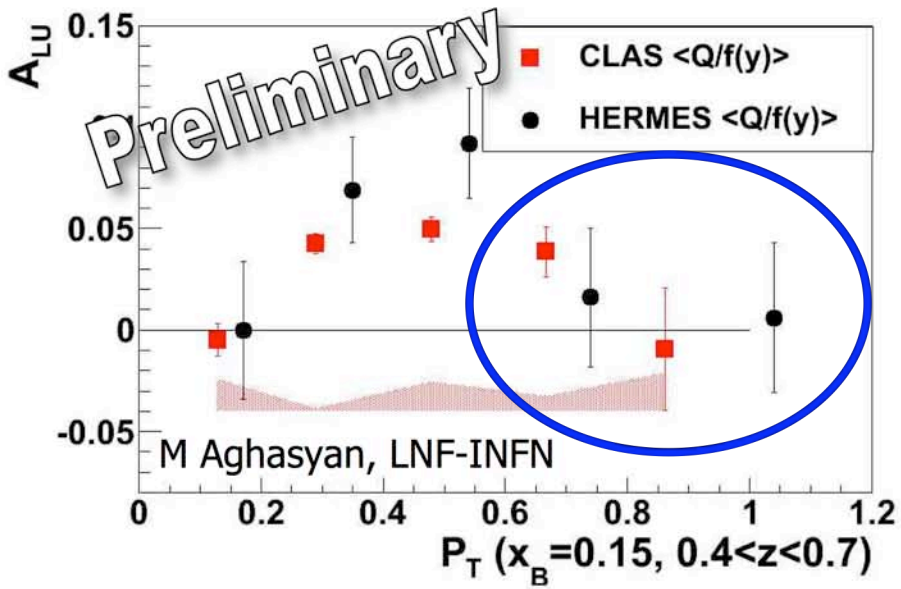
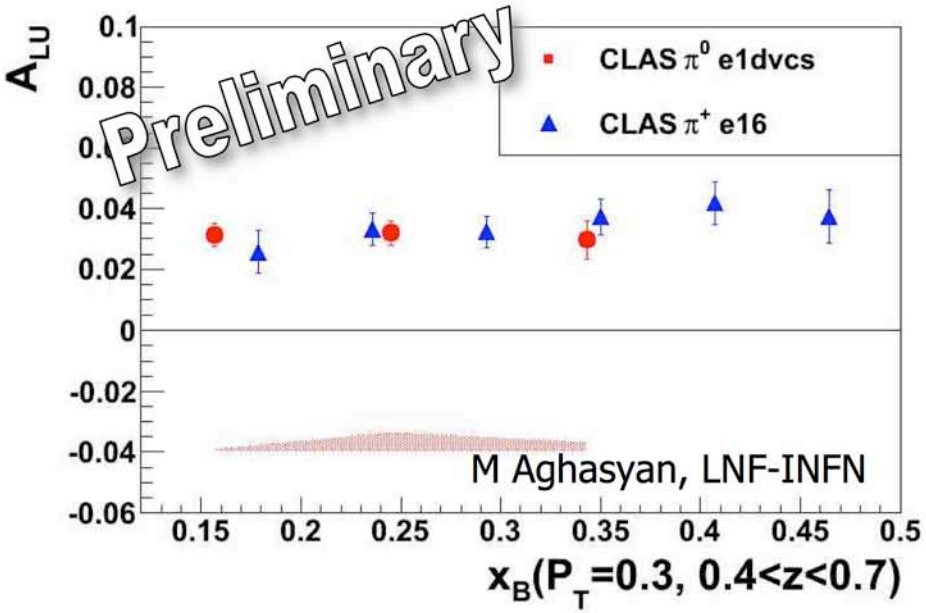
  Small Collins type contributions for π^+?

π^0 BSA Asymmetry results







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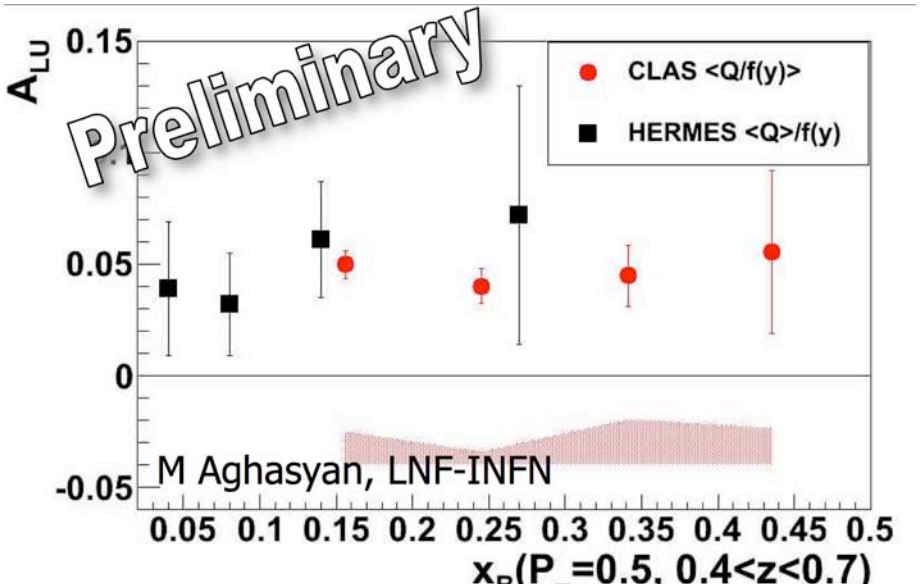

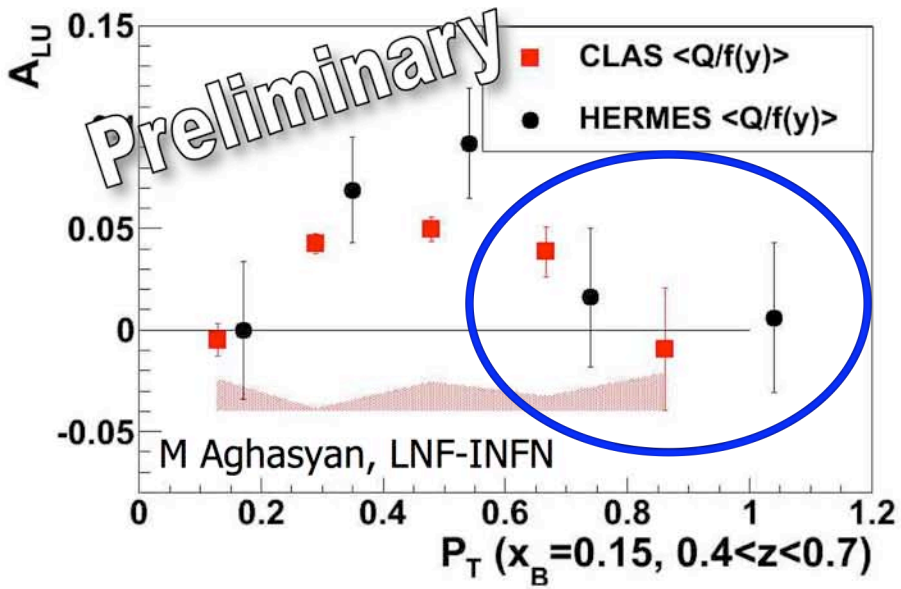

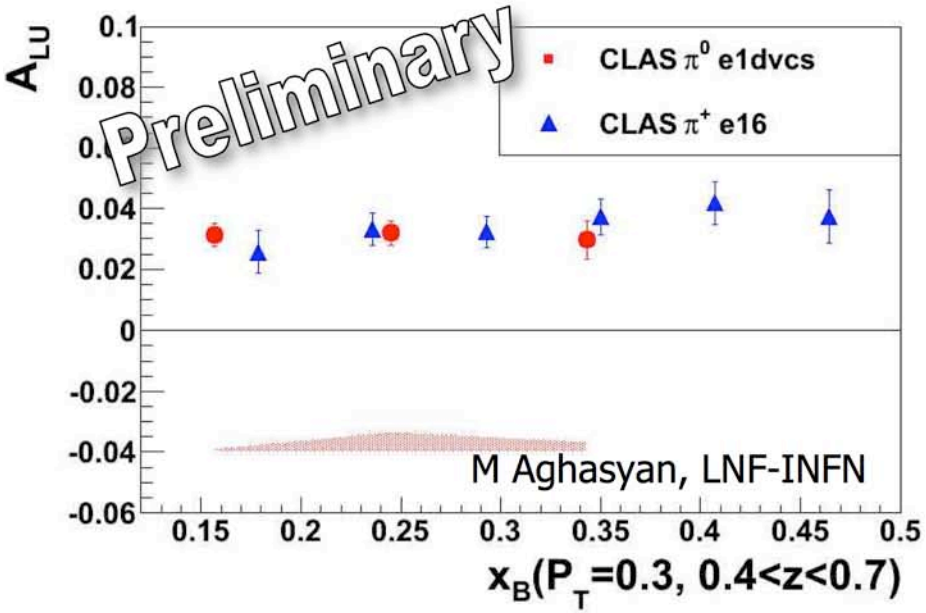

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Main contribution?

CLAS transversely polarized HD-Ice target

- **Target used by LEGS at BNL with photon beam**

Pros

- Small field ($\int Bdl \sim 0.005\text{-}0.05Tm$)
- Small dilution (fraction of events from polarized material)
- Less radiation length
- Less nuclear background
- Wider acceptance
- much better FOM, especially for deuteron

Cons

- HD target is highly complex and there is a need for redundancy due to the very long polarizing times (months).
- Need to demonstrate that the target can remain polarized for long periods with an electron beam with currents of order of 1-2 nA

- **The target is now at Jlab**

• polarization of targets	Mar-Jun 2010 / Aug-Dec 2010
• photon run with HD-ice	Sep 2010-Apr 2011
• test run with e-	Apr 2011
• physics run with e-	Nov./Dec 2011
• Expected luminosity L~ 5 10^{33}	

TMDs with Transverse Target

quark polarization

nucleon polarization

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

quark polarization

q/h	U	L	T
U	$\mathbf{D_1}$		$D_{1T}^\perp$
L		$\mathbf{G_{1L}}$	$G_{1T}^\perp$
T	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

$$F_{UT}^{(1)} \propto f_{1T}^\perp \otimes D_1 \sin(\phi - \phi_S)$$

$$F_{UT}^{(1)} \propto f_{1T}^\perp \otimes D_1$$

Sivers

Sivers TMD

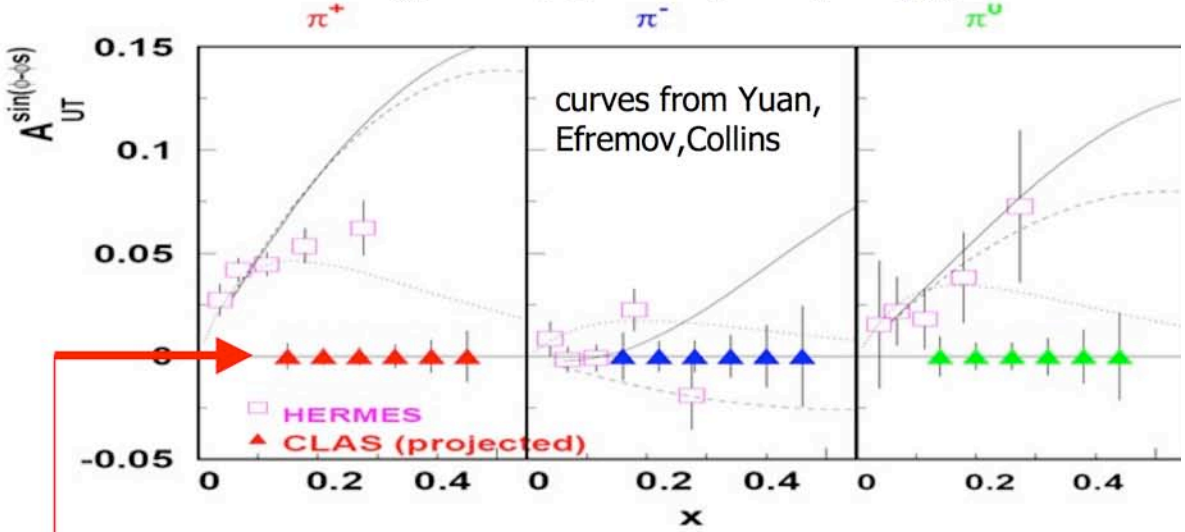
$$F_{UT}^{(2)} \propto h_1 \otimes H_1^\perp$$

Collins

transversity TMD **Collins FF**

$$F_{UT}^{(3)} \propto h_{1T}^\perp \otimes H_1^\perp$$

pretzelosity TMD **Collins FF**



Projected results for 30 days of CLAS at 6 GeV in 2011 (P_T=75% L=5.10^{33}cm^{-2}s^{-1})

CLAS will provide a superior measurements of Sivers asymmetry at **large x**, where the effect is large and models unconstrained by previous measurements.

The future

A new generation of experiments is necessary to fully exploit the properties of TMDs, with

- wide kinematic coverage
- high luminosity
- high polarization
- high capability of final hadron separation

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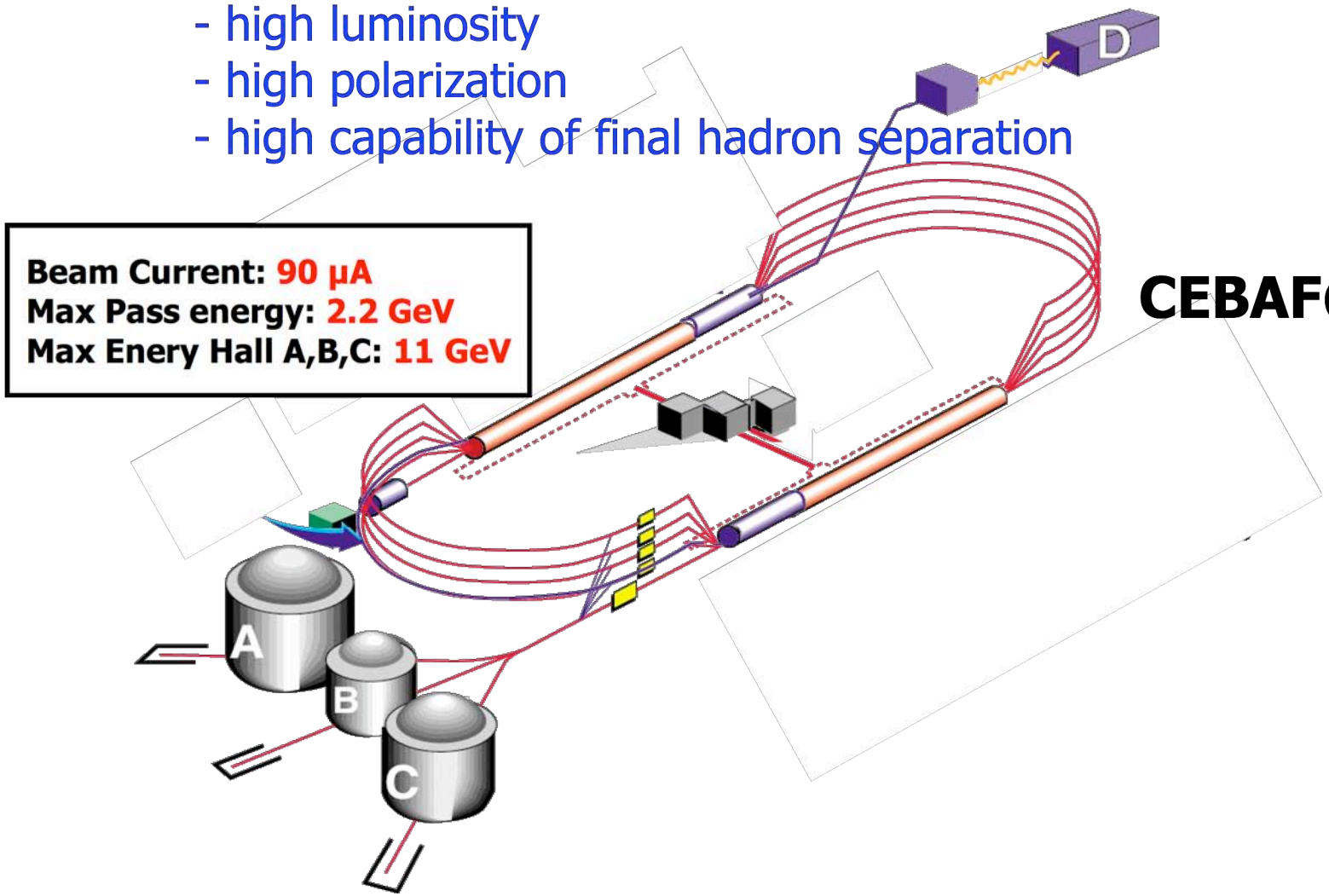

CEBAF@ 12 GeV

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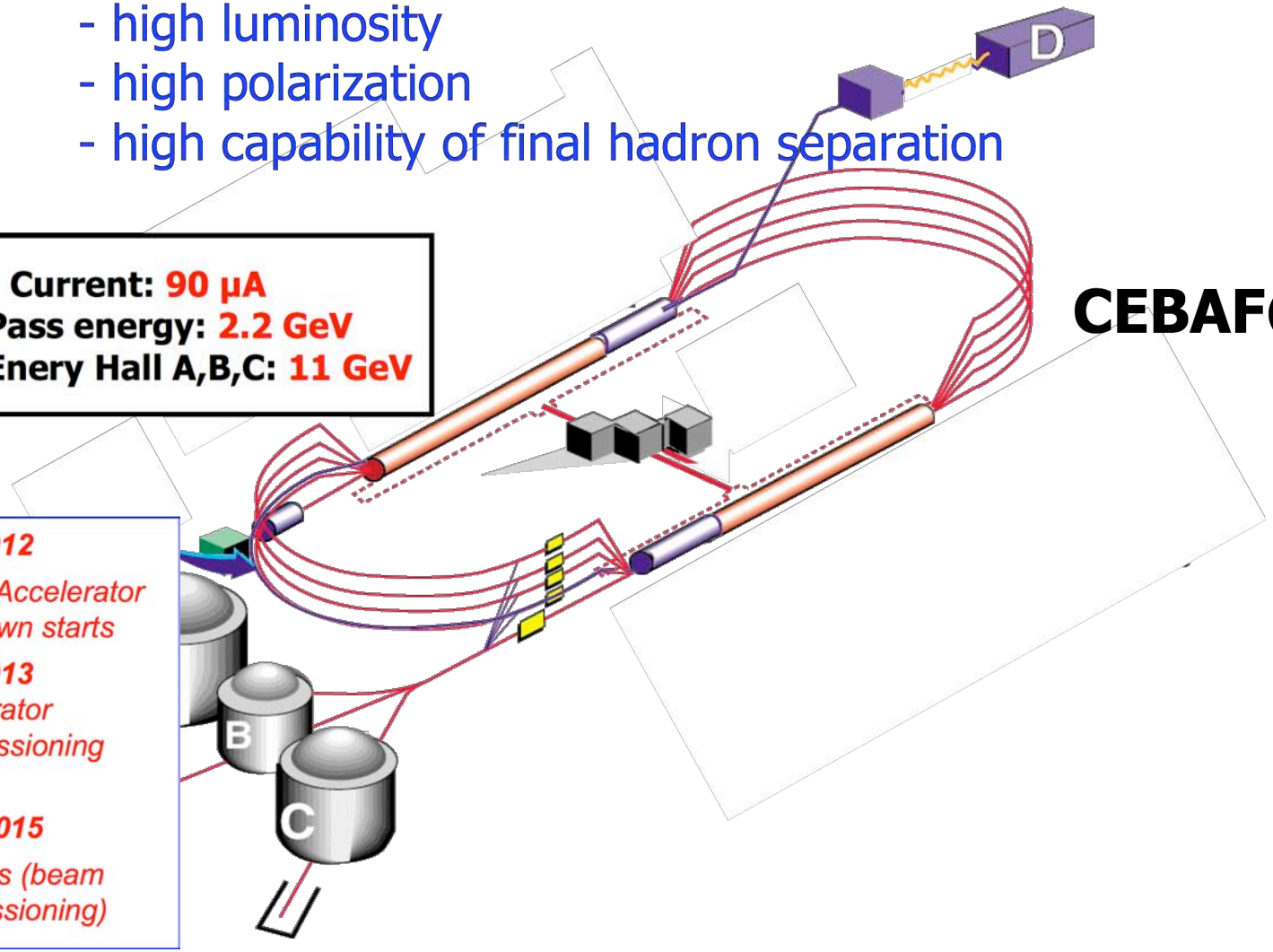

Beam Current: 90 μA
Max Pass energy: 2.2 GeV
Max Enery Hall A,B,C: 11 GeV

CEBAF@ 12 GeV

May 2012

6 GeV Accelerator Shutdown starts

May 2013

Accelerator Commissioning starts

2013-2015

Pre-Ops (beam commissioning)

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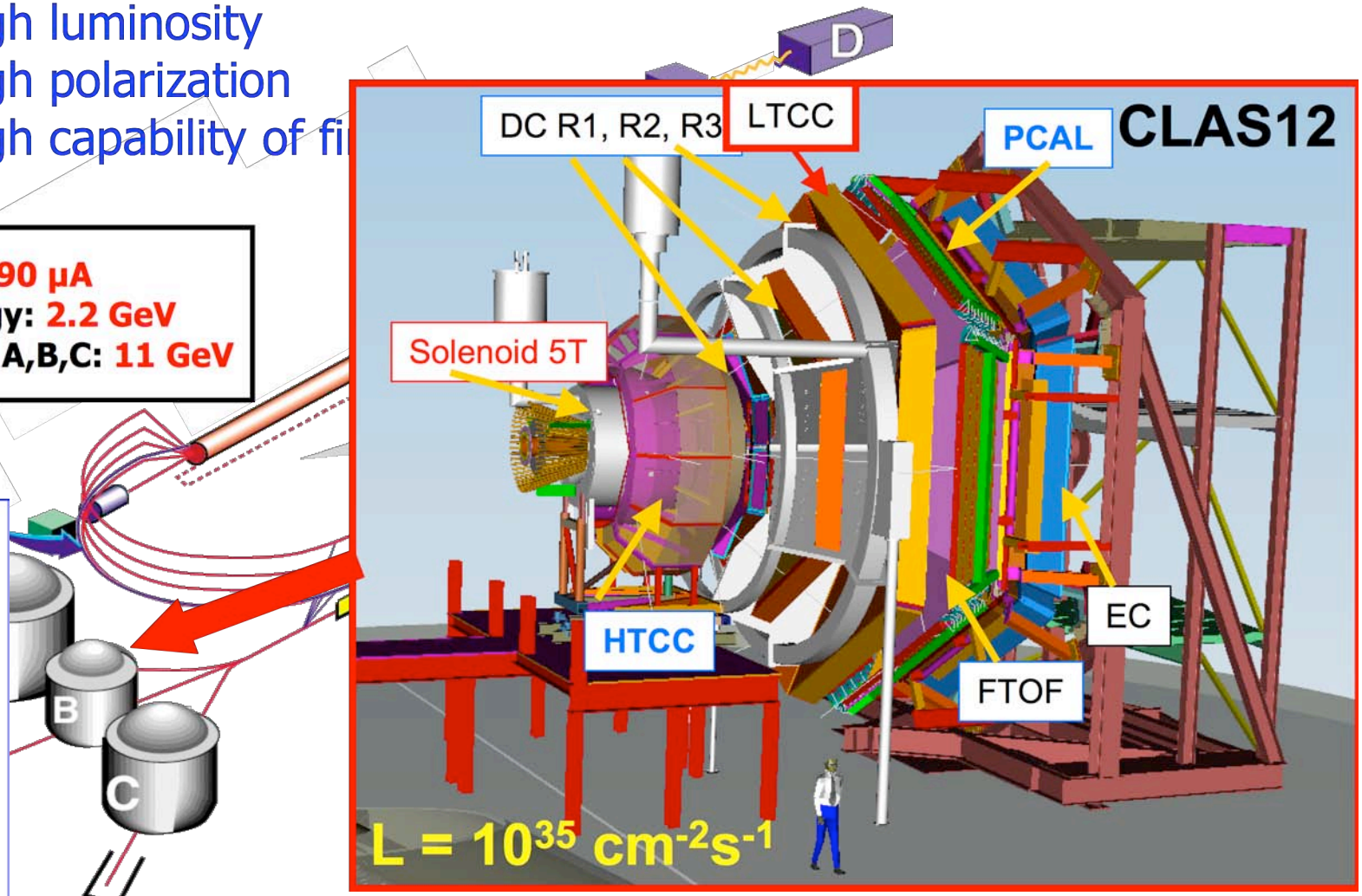
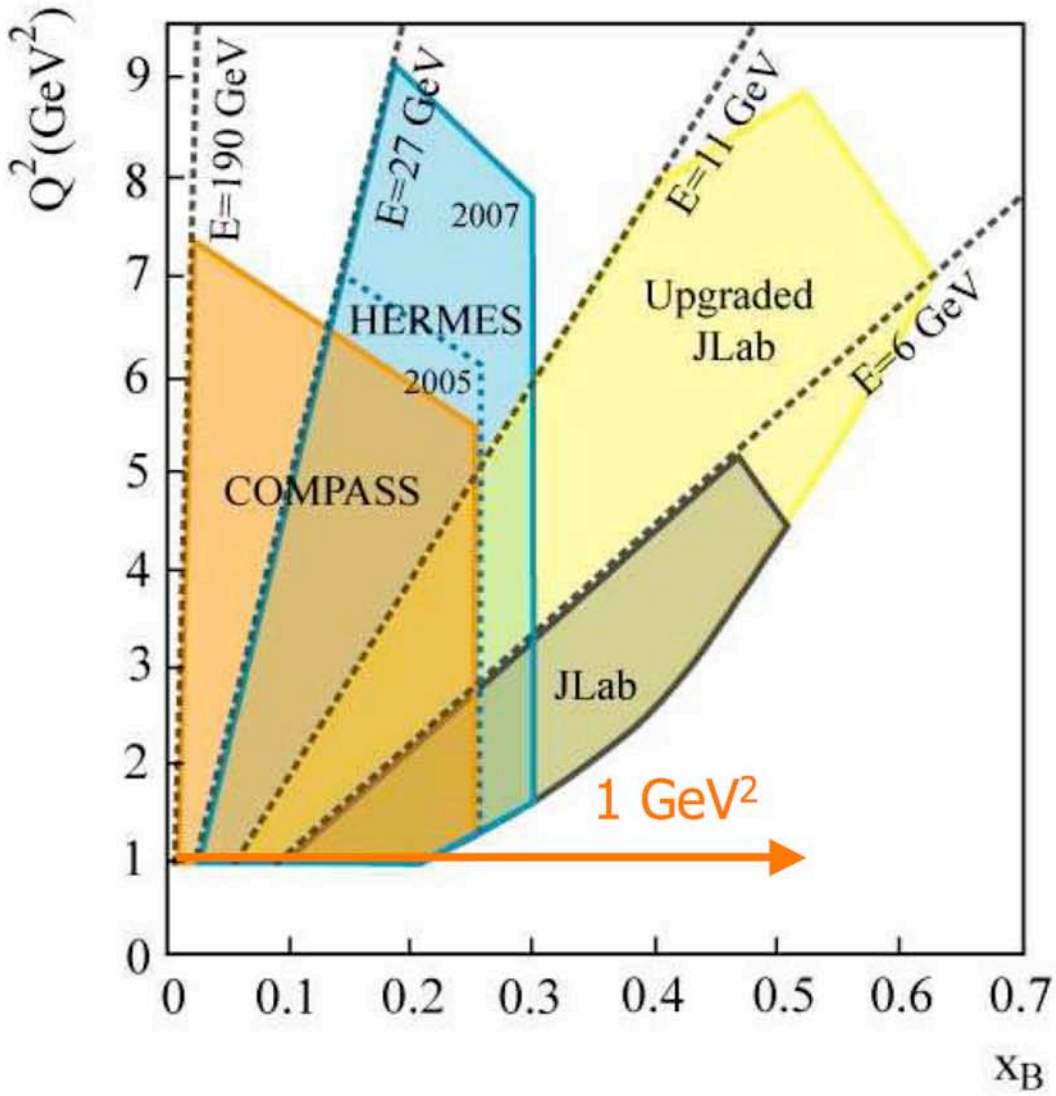
2013-2015

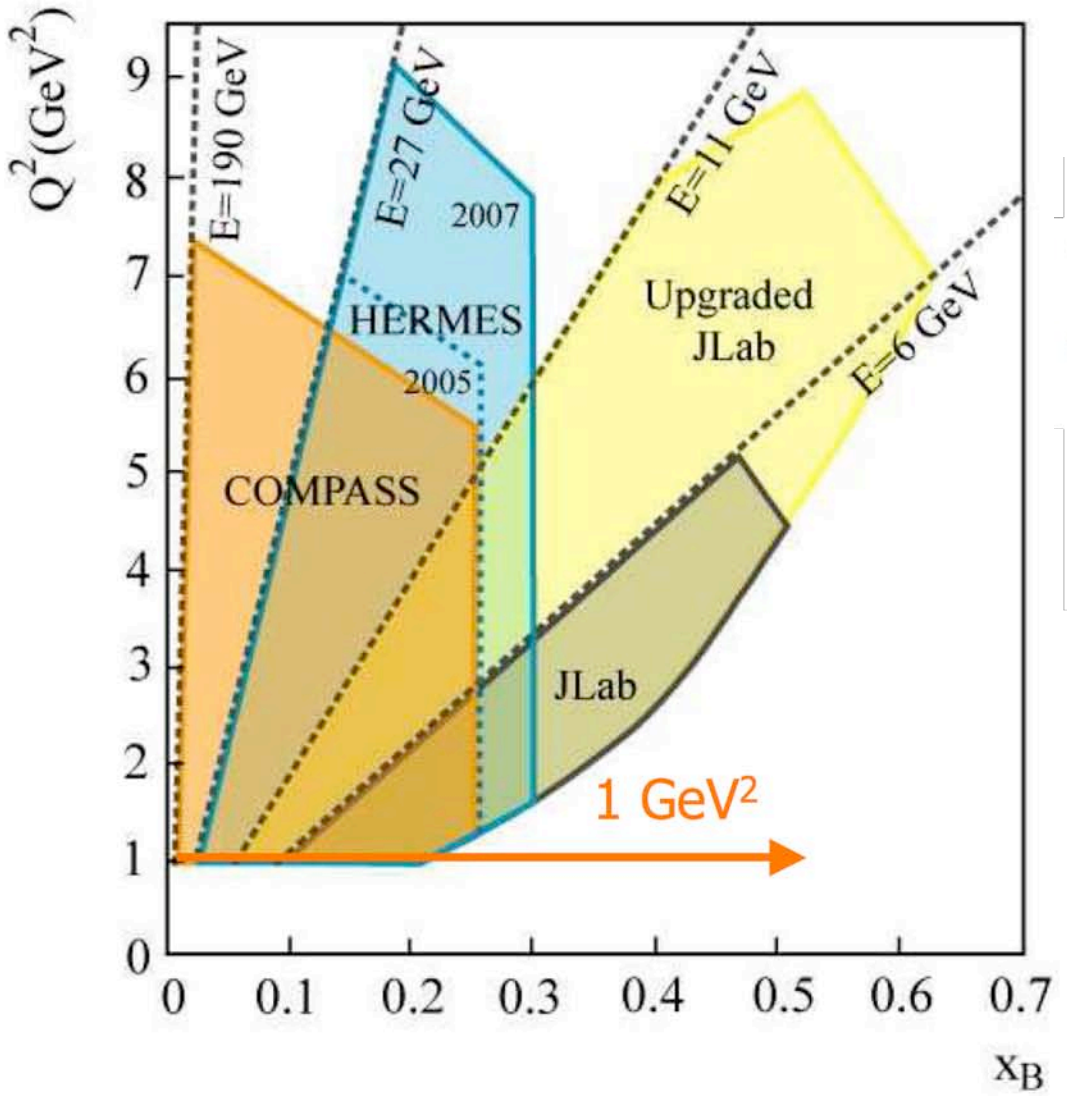
Pre-Ops (beam commissioning)



JLAB @12 GeV


$Q^2(GeV^2)$
E=190 GeV
E=27 GeV
2007
E=11 GeV
HERMES
2005
Upgraded
JLab
E=6 GeV
COMPASS
JLab
1 GeV²
0
1
2
3
4
5
6
7
8
9
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
x_B

JLAB @12 GeV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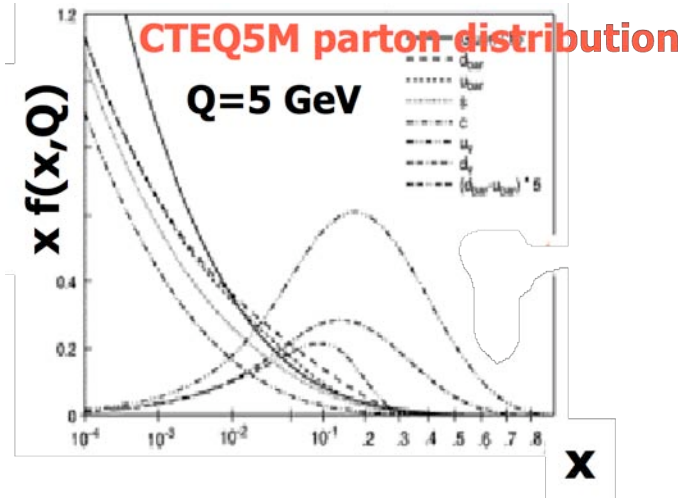
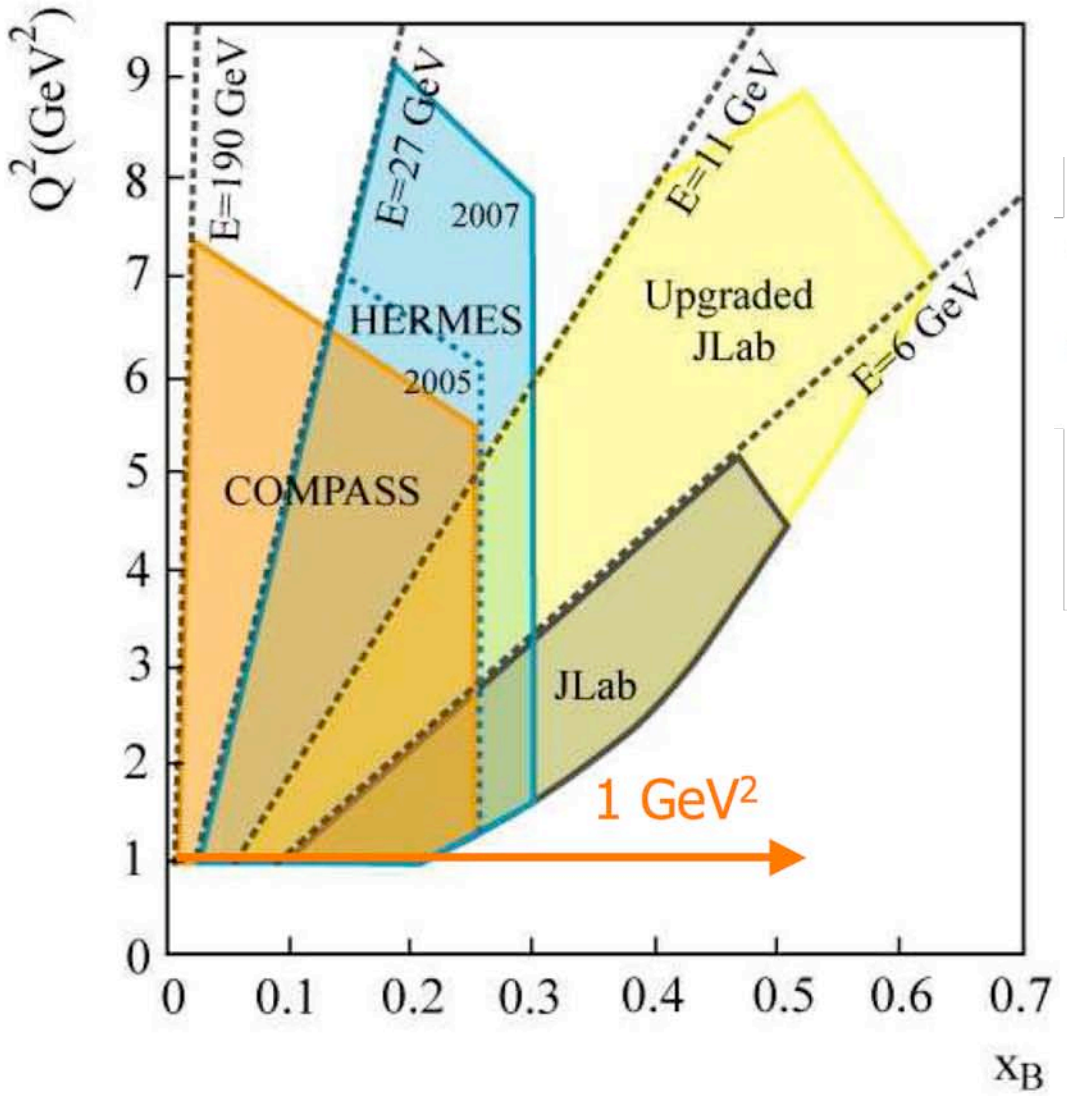
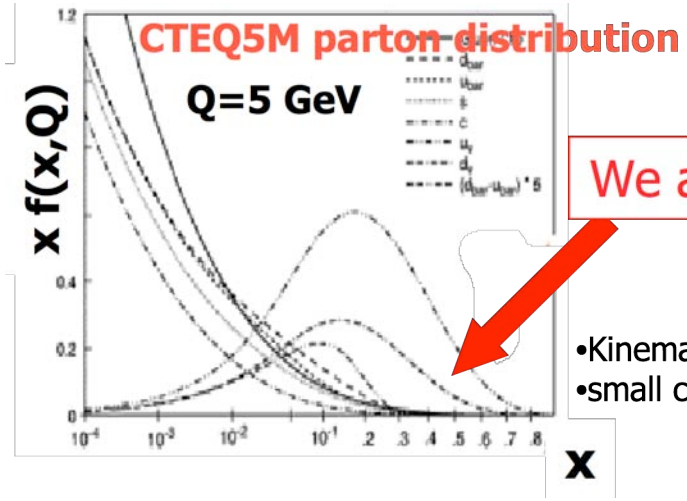

CTEQ5M parton distribution
Q=5 GeV
x f(x,Q)
x

JLAB @12 GeV

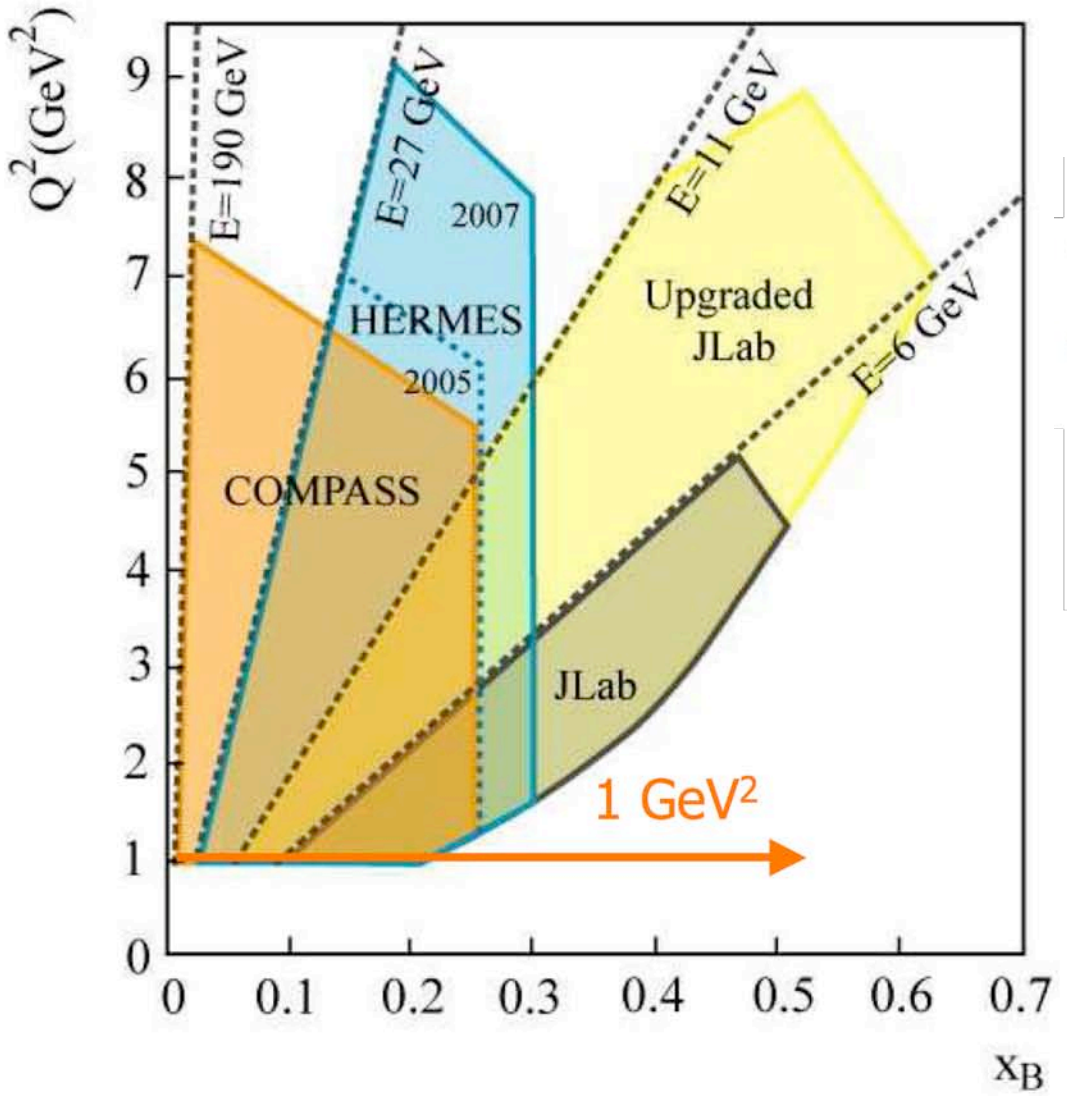


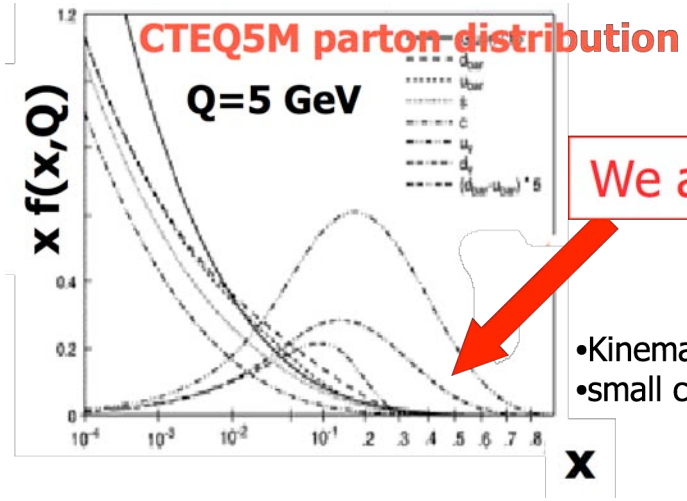


We are here!

•Kinematic suppressio
•small cross section

JLAB @12 GeV





We are here!

- Kinematic suppressio
- small cross section

Study of **high x_B** domain requires **high luminosity**

TMDs Program @ 12 GeV in Hall B

PAC approved experiments

E12-06-112: **Pion** SIDIS
E12-09-008: **Kaon** SIDIS

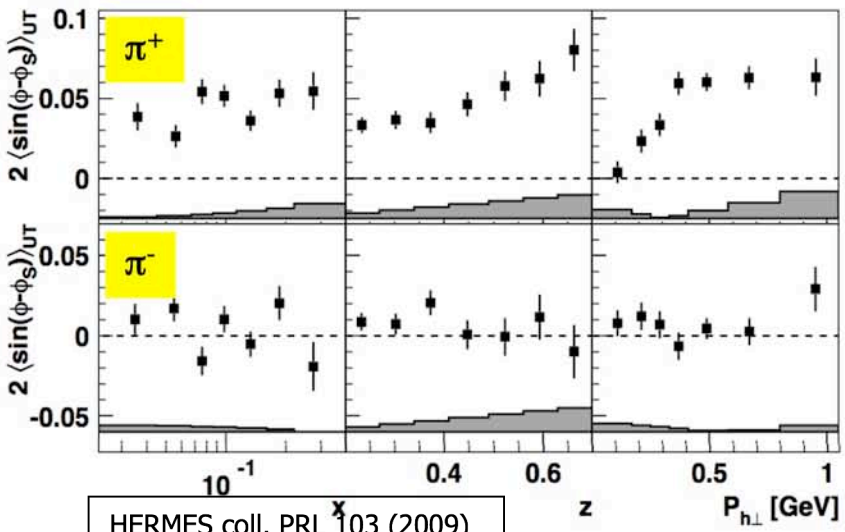
E12-07-107: **Pion** SIDIS
E12-09-009: **Kaon** SIDIS

LOI12-06-108: **Pion** SIDIS
LOI12-09-004: **Kaon** SIDIS

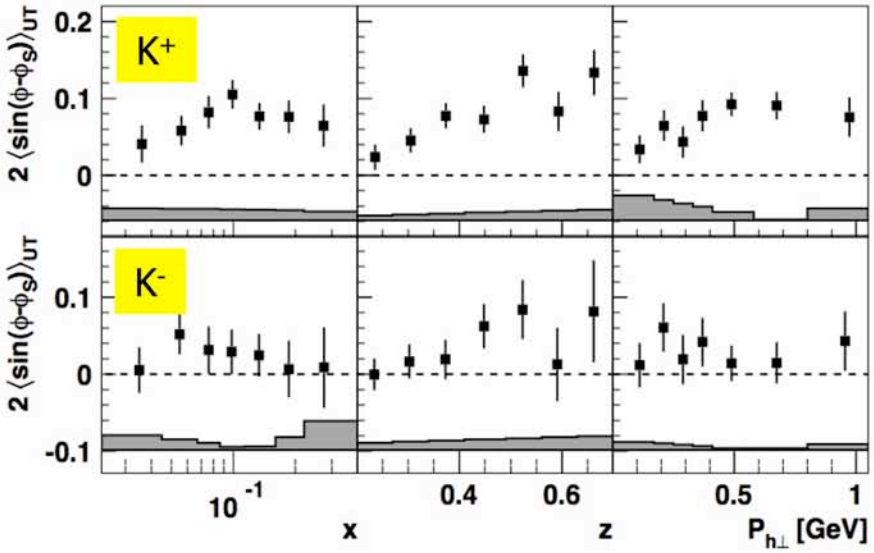
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

- Complete program of TMDs studies for pions and kaons
- Kaon measurements crucial for a better understanding of the TMDs "kaon puzzle"
- Kaon SIDIS program requires an upgrade of the CLAS12 detector PID ⇒ RICH detector to replace LTCC
  Project under development, major role played by INFN groups (LNF, FE, RMI/ISS, BA)

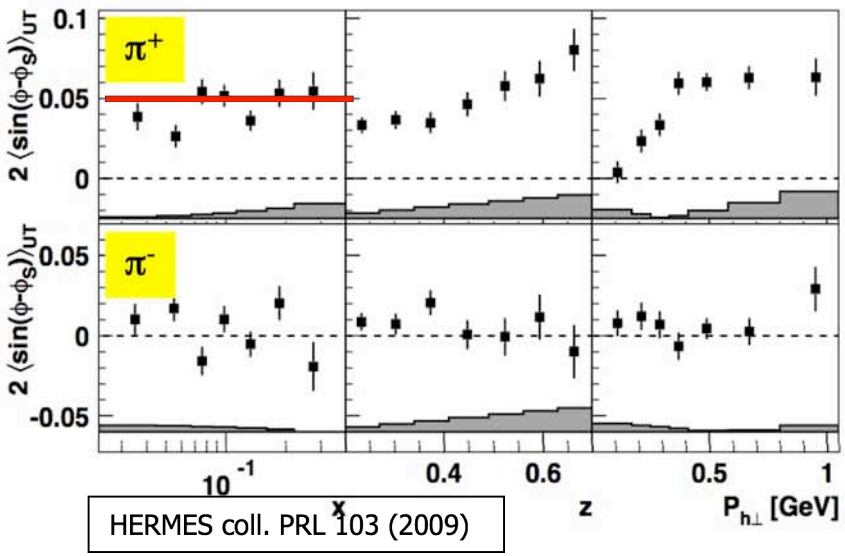
Kaon TMDs @ 12 GeV in Hall B



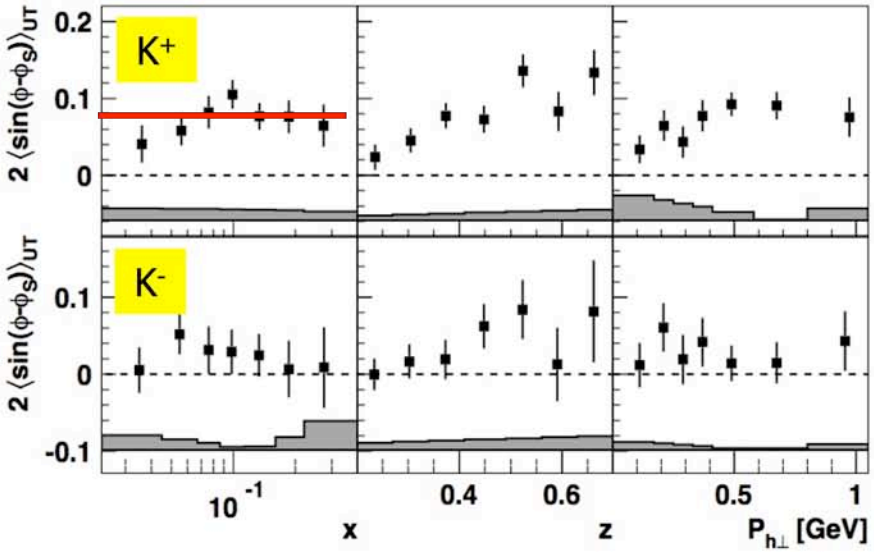
HERMES coll. PRL 103 (2009)



Kaon TMDs @ 12 GeV in Hall B



HERMES coll. PRL 103 (2009)

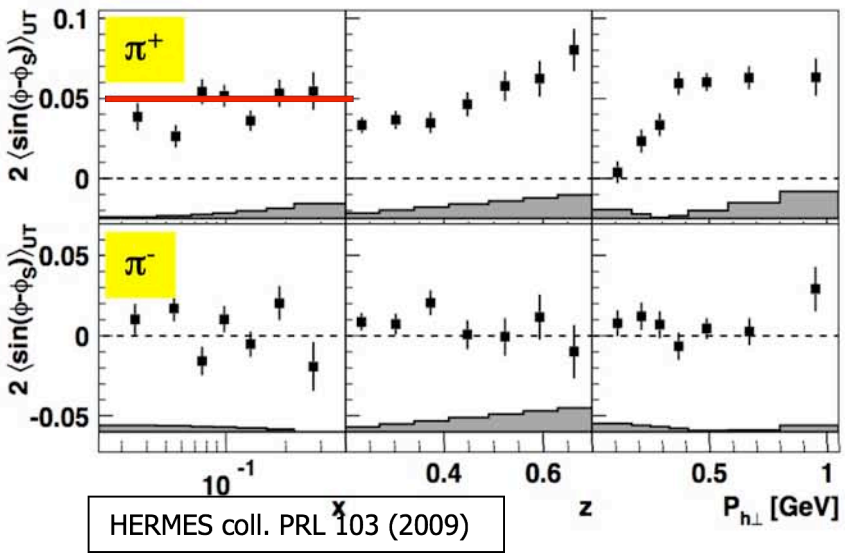


- K^+ ampl. > π^+ ampl.

Unespected from u-quark dominance!

- How large can the effect of s quarks be?

Kaon TMDs @ 12 GeV in Hall B



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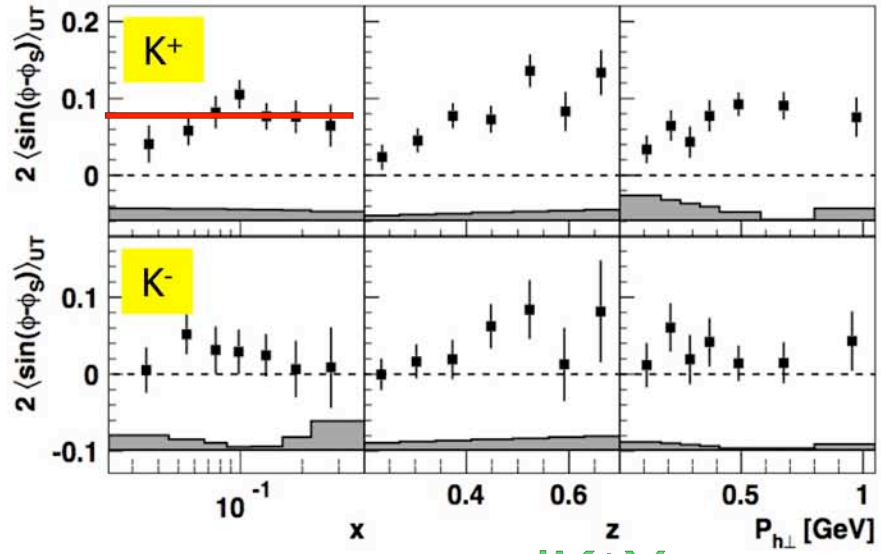
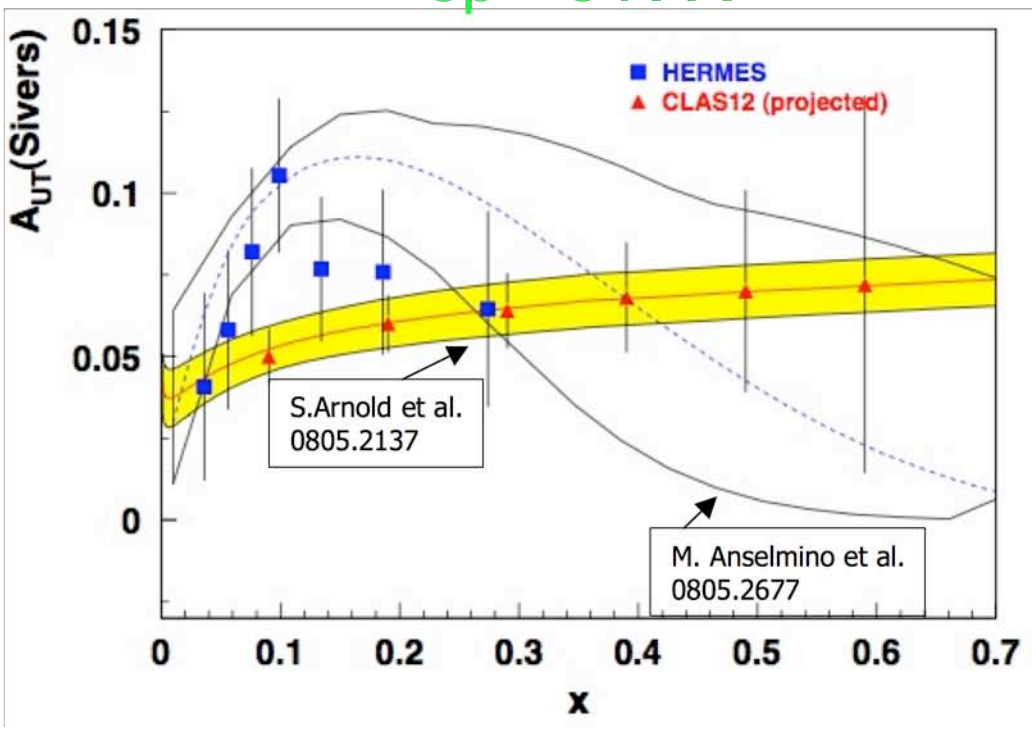


$ep \rightarrow e'K^+X$



- K^+ ampl. > π^+ ampl.

Unespected from u-quark dominance!

- How large can the effect of s quarks be?

π/K measurement @ CLAS12 will provide a more detailed knowledge of Sivers effect

Conclusion

- Correlation of spin and transverse momentum of partons is crucial in understanding of the nucleon structure in terms of quark and gluon degrees of freedom of QCD

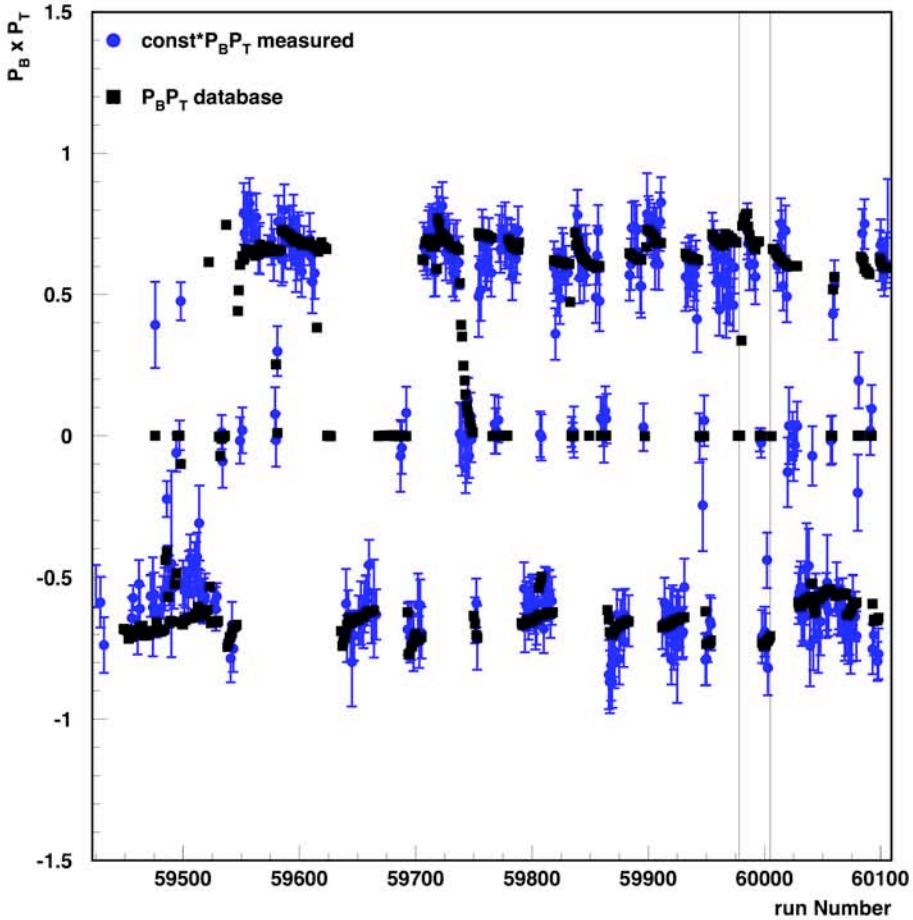
- CLAS in Hall B at Jlab is playing a major role in these studies

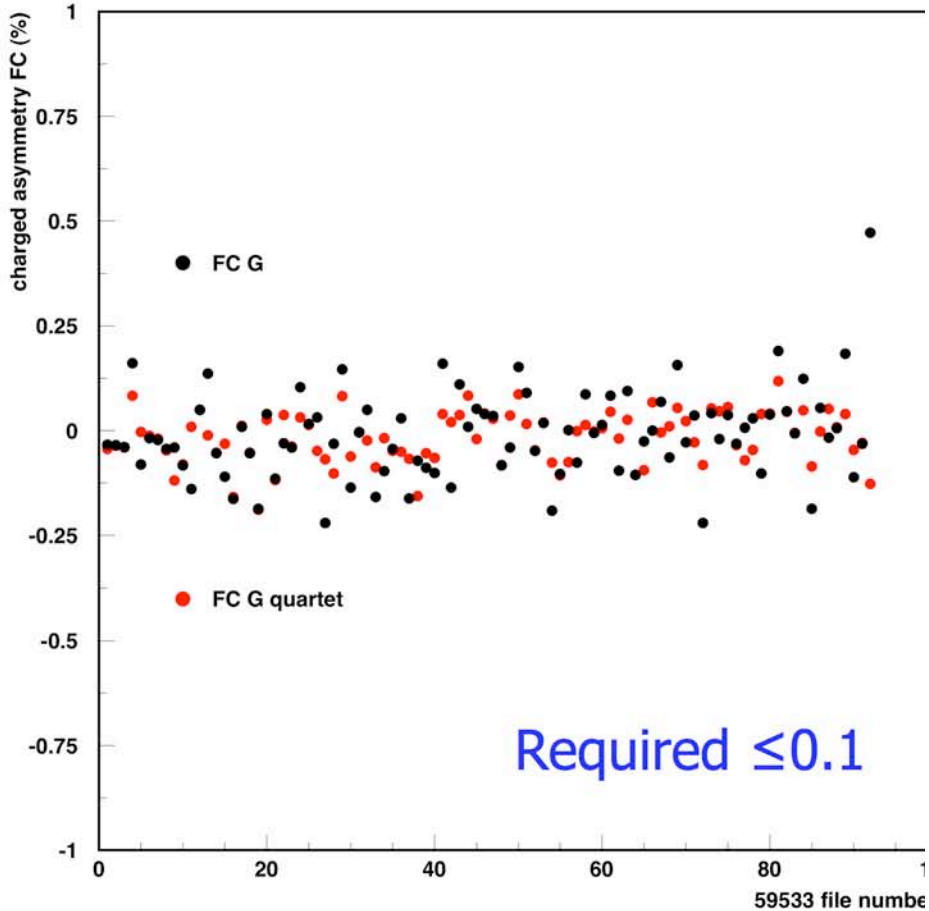
- The new CLAS experiment with longitudinally polarized NH3 and ND3 targets provides superior sample of events allowing multidimensional binning to study:
  - SSAs for π and ρ in SIDIS
  - Higher Twists and quark-gluon correlations
  - Double spin asymmetries and flavor decomposition of helicity dist.

- Studies of the spin-structure of the nucleon is one of the main driving forces behind the upgrade of Jefferson Lab

- JLab12 with wide kinematic coverage, high luminosity, high polarization is essential for high precision measurements of 3D PDFs in the valence region

Polarization monitoring: P_b*P_t - Charge Asymmetry





■ Database (Moller x NMR)

● Measured from elastic events

Monitoring the time dependence of the product of target and beam polarizations using the elastic asymmetry

$$\text{Charge Asymmetry} = \frac{(FC^{\uparrow} - FC^{\downarrow})}{(FC^{\uparrow} + FC^{\downarrow})}$$

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