TMD studies at JLab

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Jefferson Lab

"TMD workshop"

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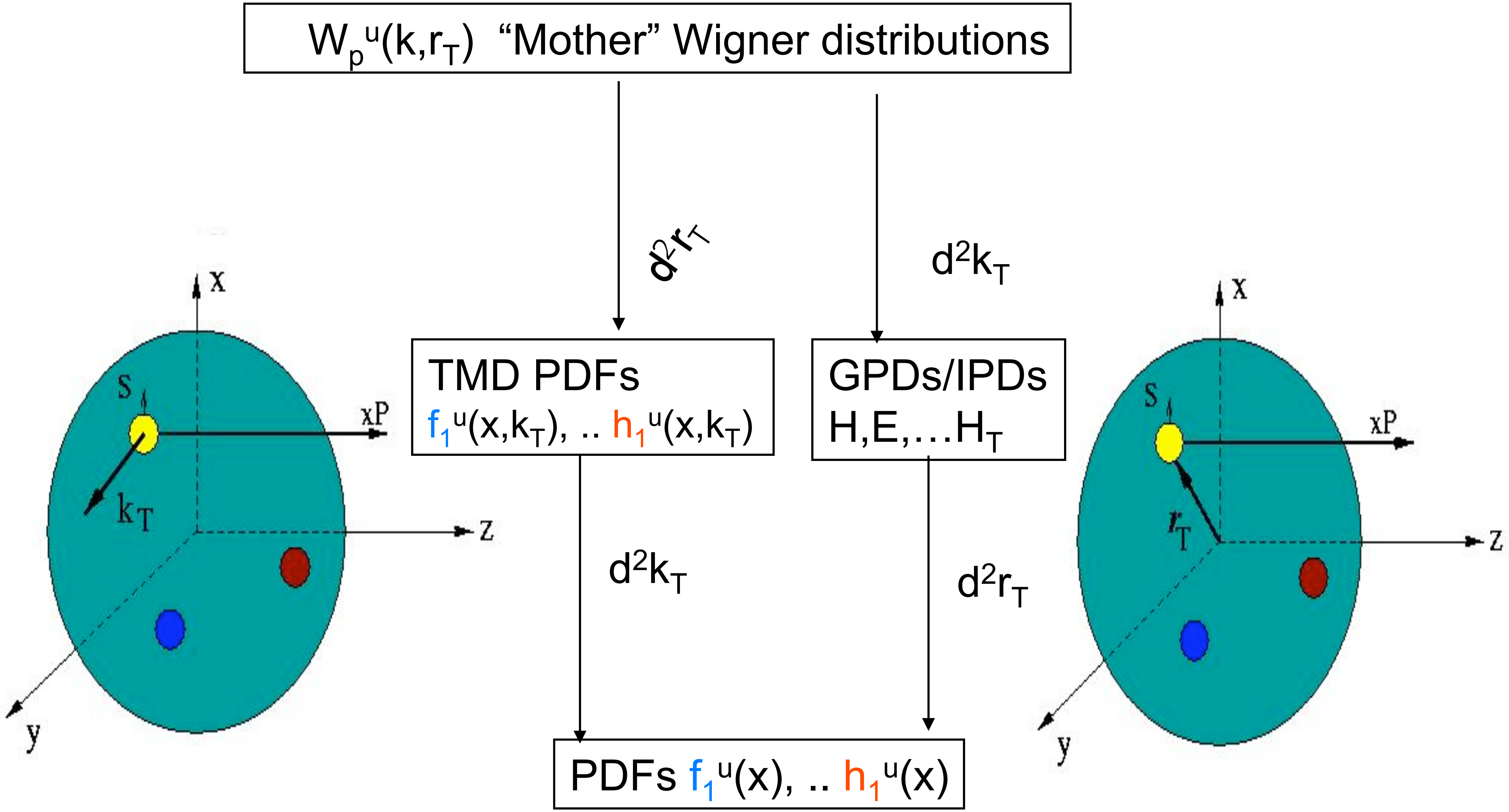
Outline

Transverse structure of the nucleon and partonic correlations

- Physics motivation
- k_T-effects with unpolarized and longitudinally polarized target data
  - Double spin asymmetries
  - Single Spin Asymmetries
- Physics with transversely polarized hadrons and quarks
  - k_T-effects and SSA in pion production
  - Hard exclusive processes and correlations between transverse degrees of freedom
- Studies of 3D PDFs at CLAS at 6 GeV and beyond
- Summary

Structure of the Nucleon



$W_p^u(k,r_T)$ “Mother” Wigner distributions

d^2r_T

d^2k_T

TMD PDFs
$f_1^u(x,k_T)$, .. $h_1^u(x,k_T)$

GPDs/IPDs
H,E,…H_T

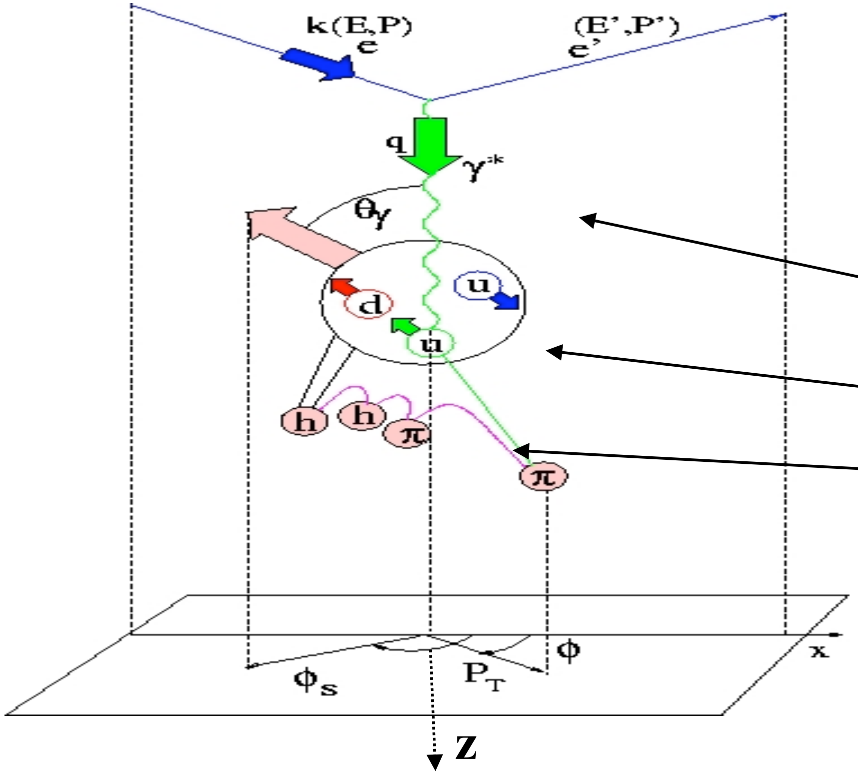
d^2k_T

d^2r_T

PDFs $f_1^u(x)$, .. $h_1^u(x)$

Analysis of SIDIS and DVMP are complementary

SIDIS kinematical plane and observables



Cross section is a function of scale variables ***x,y,z***

$$\nu = (qP)/M$$
$$Q^2 = (k-k')^2$$
$$y = (qP)/(kP)$$
$$x = Q^2/2(qP)$$
$$z = (qP_h)/(qP)$$

P_b, P_t

U unpolarized
L long.polarized
T trans.polarized

Target polarization

Beam polarization

$$\sigma = \sigma_{UU} + P_t \sigma_{UL} \sin 2\phi + P_b P_t \sigma_{LT} \cos(\phi - \phi_S) \ldots$$

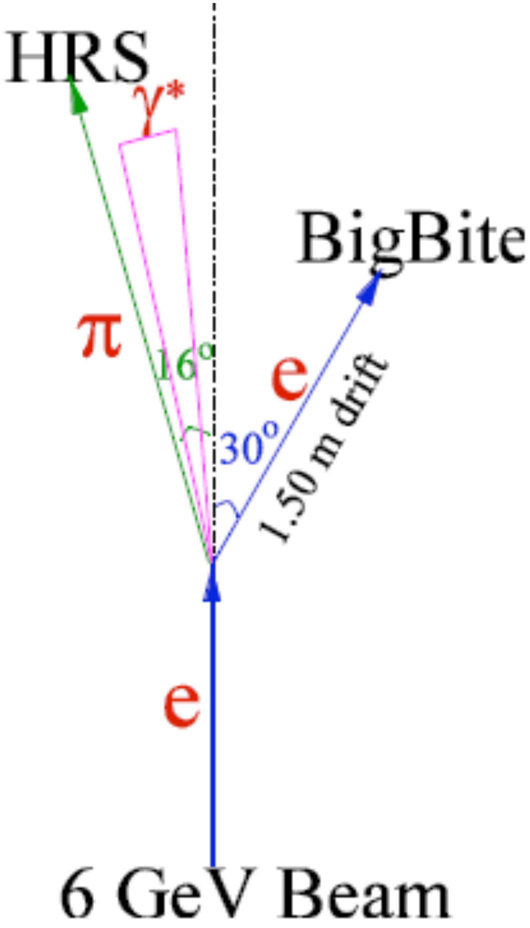
$$A_{UL}^{\sin 2\phi} = \frac{\sigma_{UL}}{\sigma_{UU}} \longrightarrow$$

sin2ϕ moment of the cross section for unpolarized beam and long. polarized target

E06-010:

Hall-A Transversity:

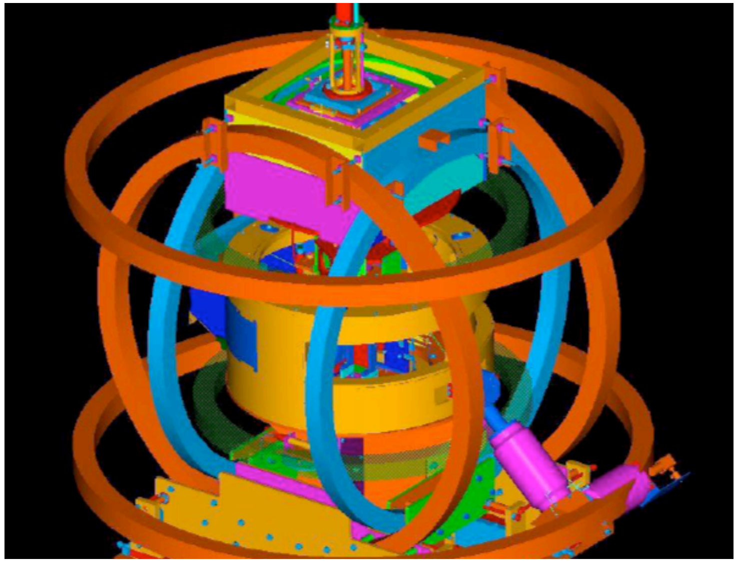
en→e'πX
en→e'KX



Polarized 3He: effective polarized neutron target

World highest polarized luminosity: 10^{36}

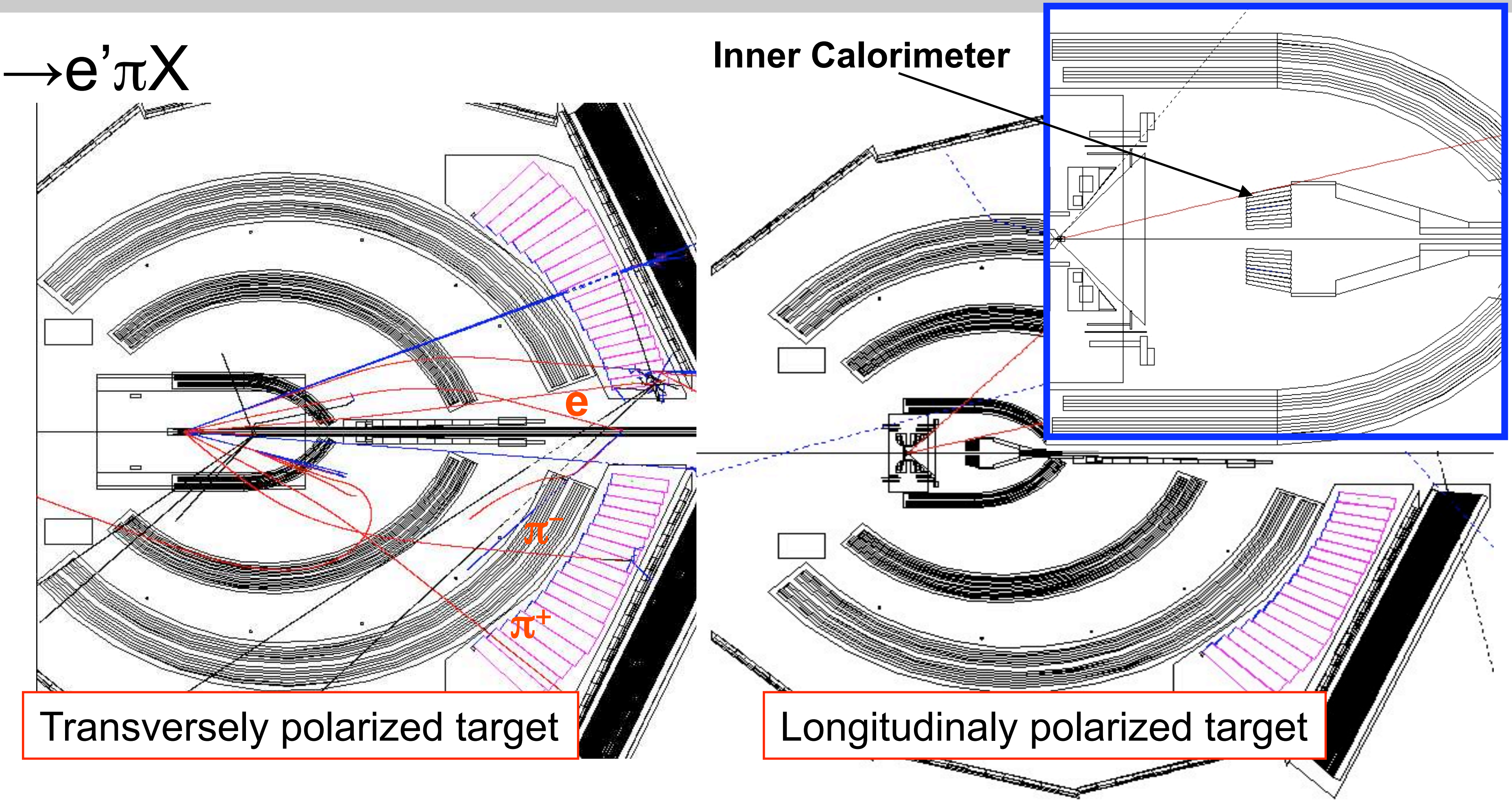
New record in polarization: >70% without beam
66% in beam and with spin-flip



HRSL for hadrons (p+- and K+-), new RICH commissioned
BigBite for electrons, 64 msr, detectors performing well

CLAS configurations

$ep\rightarrow e'\pi X$



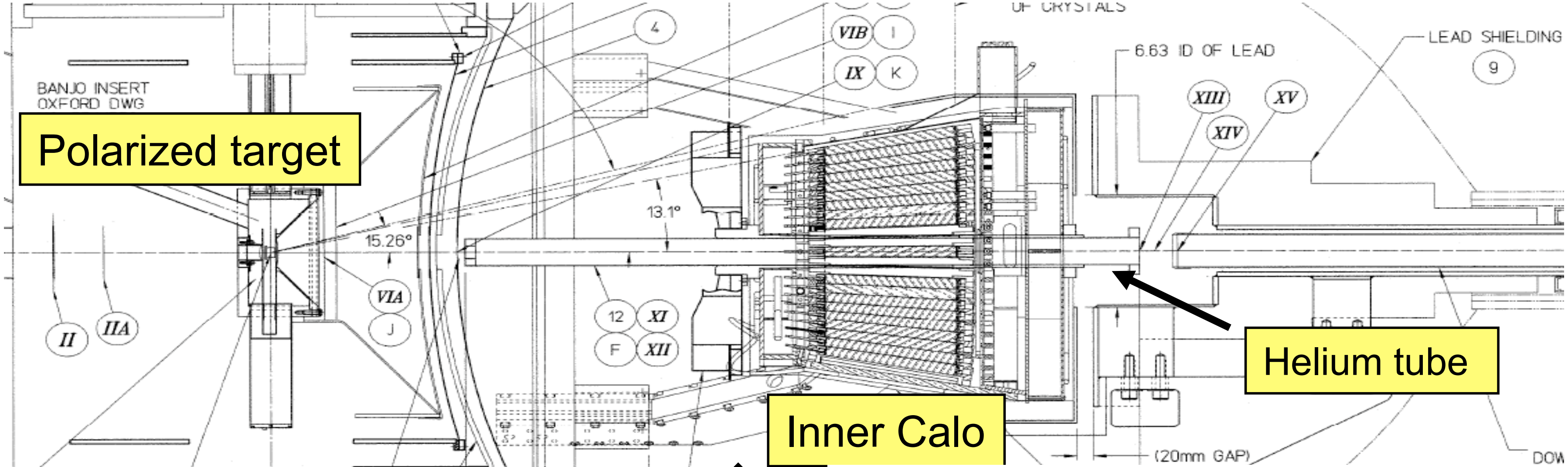
Transversely polarized target

Longitudinaly polarized target

1) Polarized NH3/ND3 (no IC, ~5 days)
2) Polarized NH3/ND3 with IC 60 days
3) Polarized HD-Ice (no IC, 25 days)

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

CLAS Longitudinally polarized target run (eg1-dvcs)

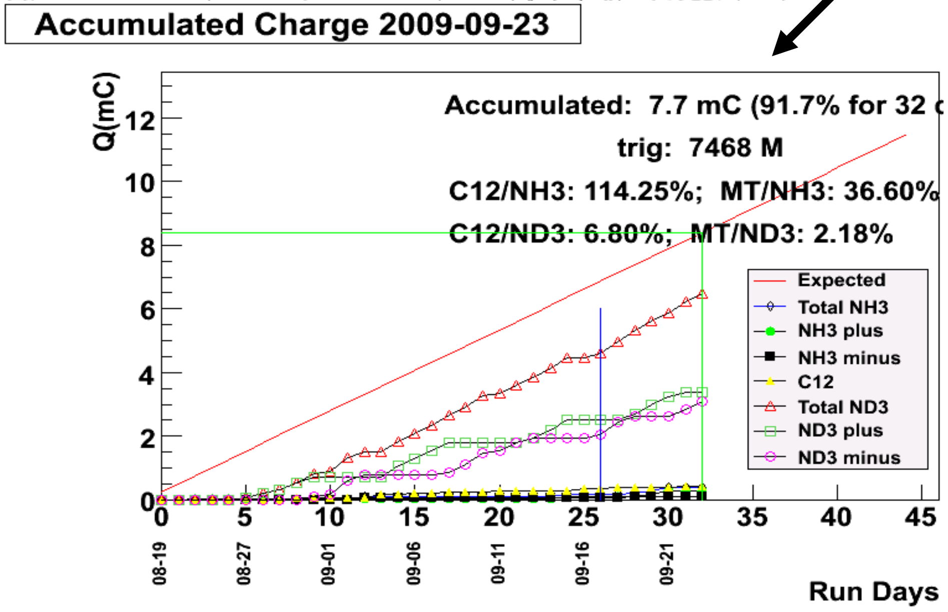


Polarized target

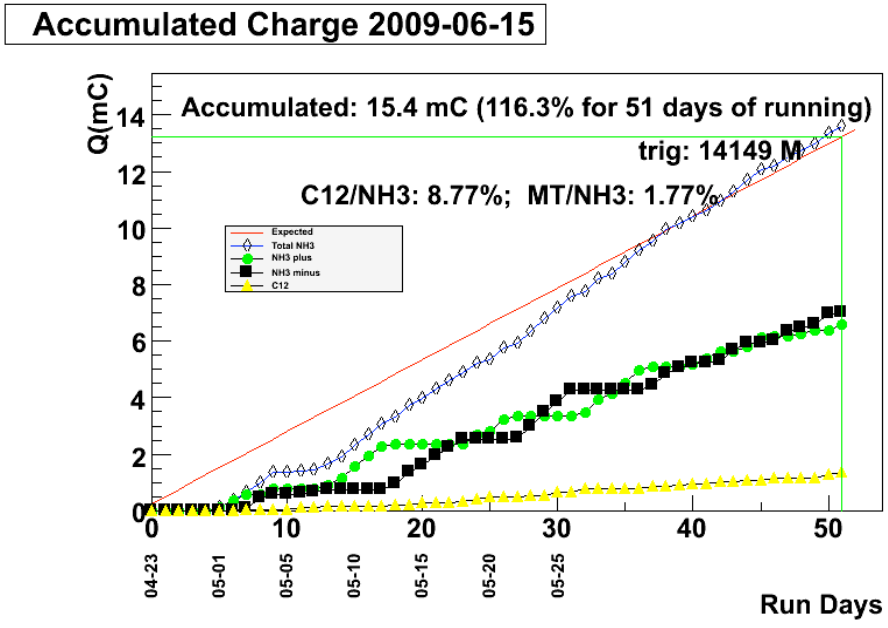
Helium tube

Inner Calo

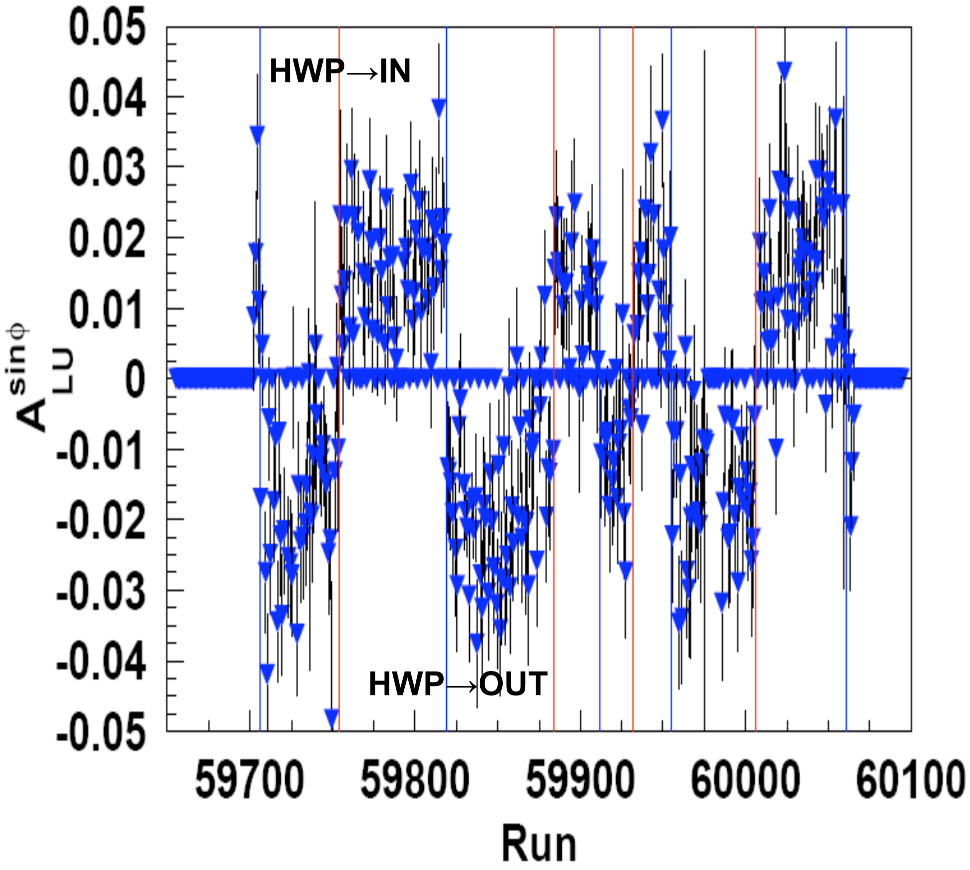
Accumulated Charge 2009-09-23

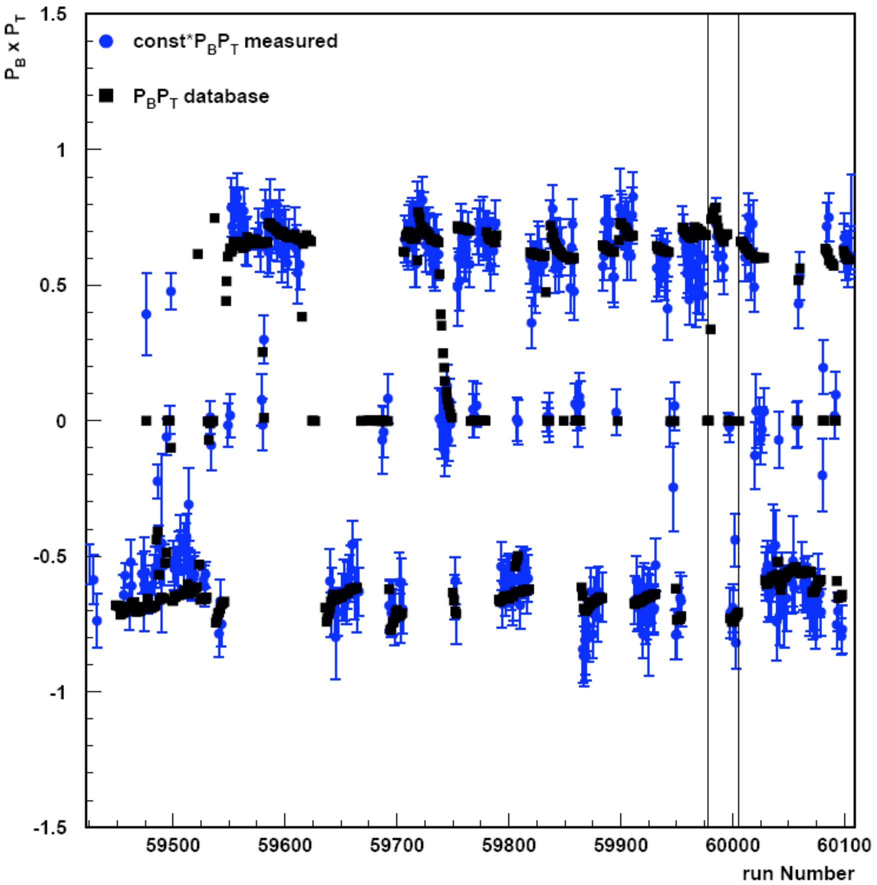


Accumulated Charge 2009-06-15



eg1-dvcs: Monitoring polarizations





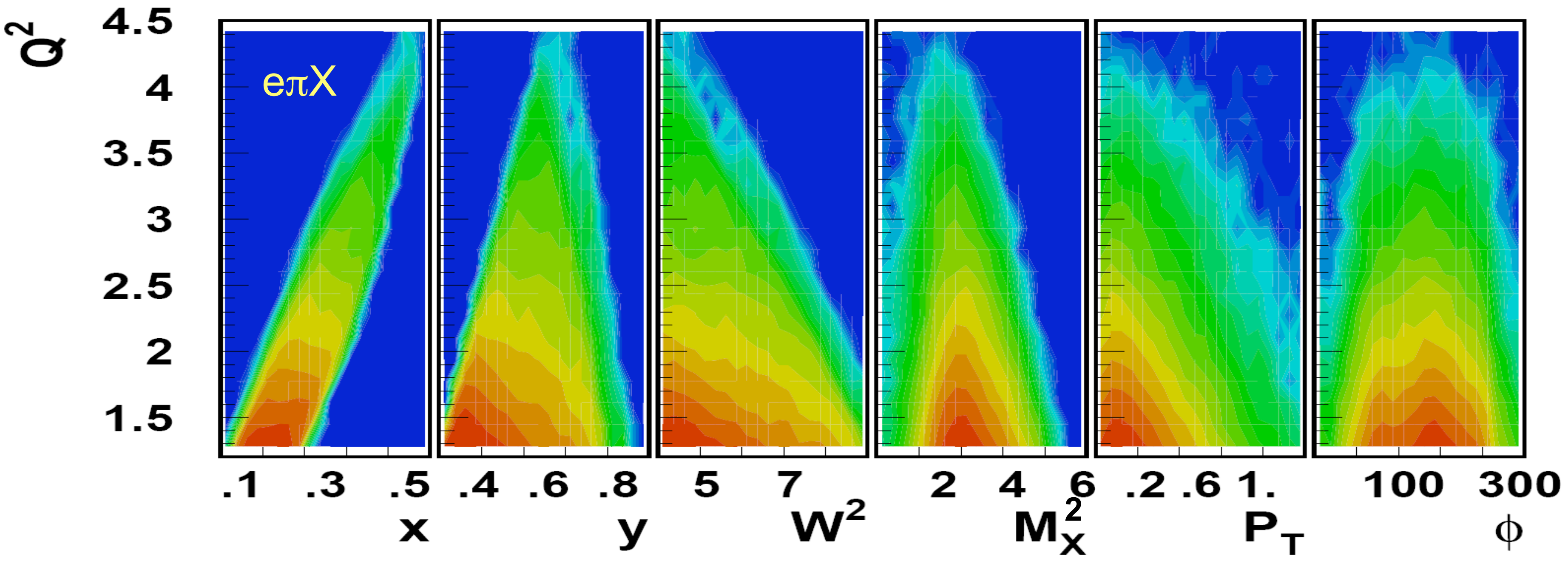
Monitoring the time dependence of the beam polarization using the single spin asymmetry in ep→e'πX

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

SIDIS with JLab at 6 GeV

Scattering of 5.7 GeV electrons off polarized proton and deuteron targets

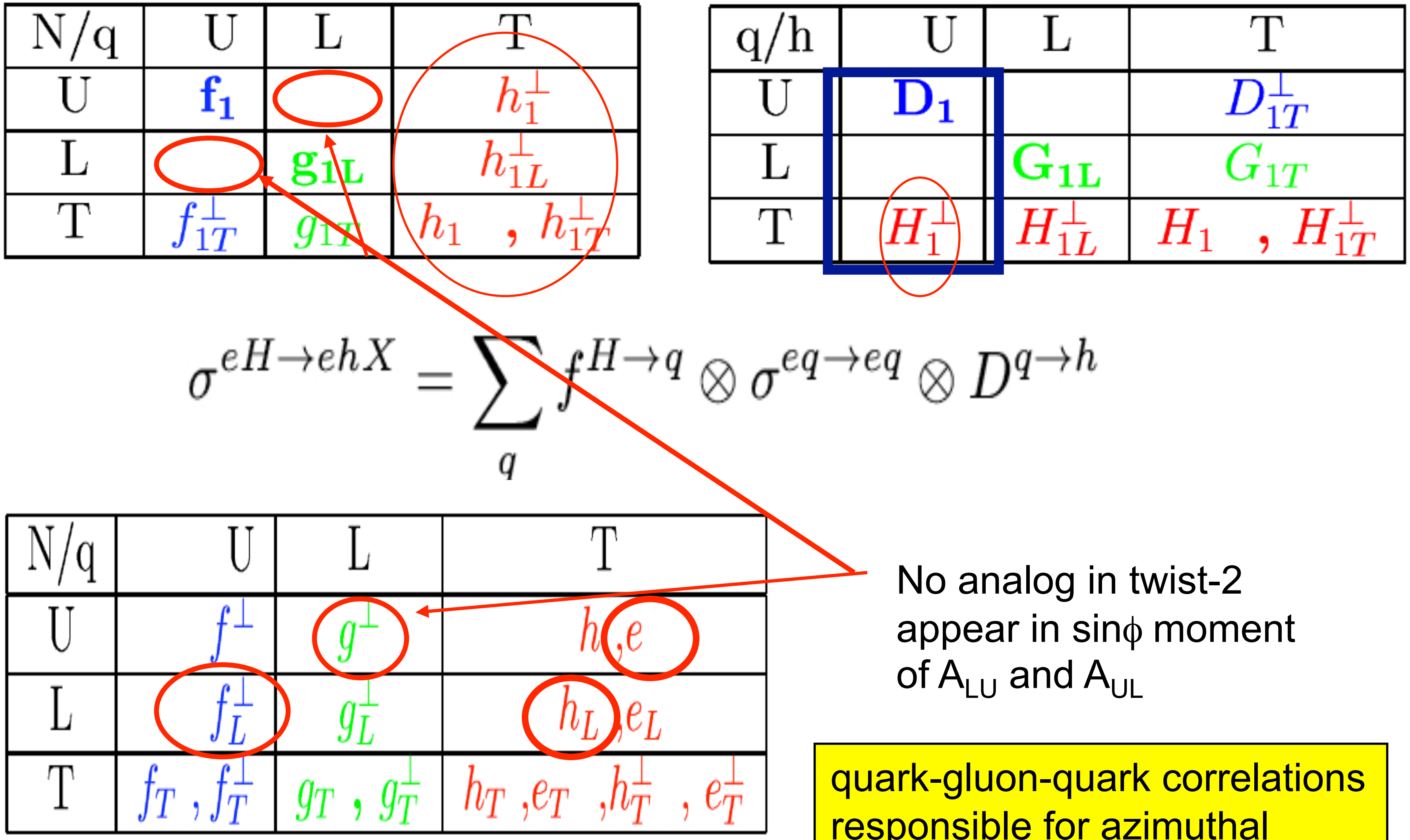
- **DIS kinematics,**
  Q^2>1 GeV^2, W^2>4 GeV^2, y<0.85
- **0.4>z>0.7, M_X^2>2 GeV^2**



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

k_T-dependent PDFs and FFs: "new testament"

Baccetta, Diehl, Goeke, Metz, Mulders, Schlegel EPJ-2007



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

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

$$\sigma^{eH\to ehX} = \sum_q f^{H\to q} \otimes \sigma^{eq\to eq} \otimes D^{q\to h}$$

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

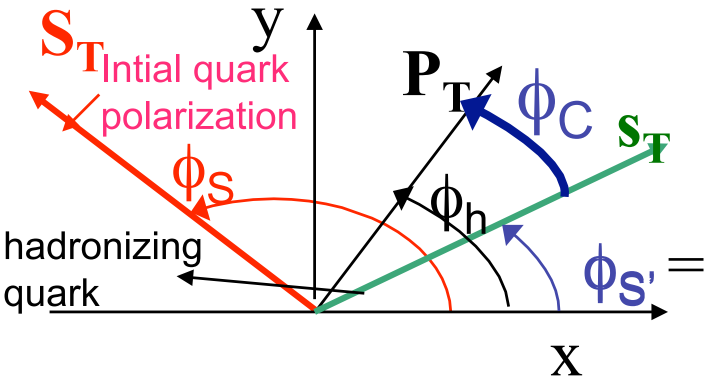
No analog in twist-2 appear in sinϕ moment of A_{LU} and A_{UL}

quark-gluon-quark correlations responsible for azimuthal moments in the cross section

Collins Effect: azimuthal modulation of the fragmentation function

$F_{UT} \propto h_1 H_1^{\perp}$

$s_T(q \times P_T) \leftrightarrow H_1^{\perp}$

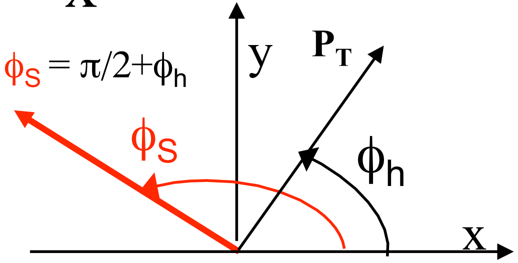


$$D(z,P_T)=D_1(z,P_T)+H_1^{\perp}(z,P_T)\,\sin(\overbrace{\phi_h-\phi_{S'}}^{\phi_C})$$

$\phi_{S'} = \pi - \phi_S$ ← spin of quark flips wrt y-axis

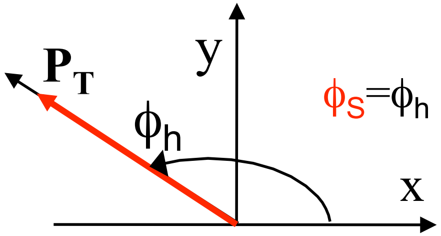
$\sin(\phi_h+\phi_S)$

$F_{UU}^{\cos 2\phi}$



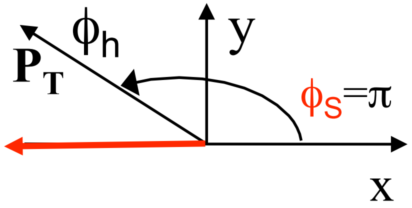
$h_1^{\perp} H_1^{\perp} \cos 2\phi_h$

$F_{UL}^{\sin 2\phi}$



$h_{1L}^{\perp} H_1^{\perp} \sin 2\phi_h$

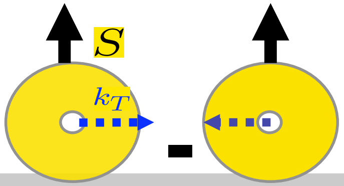
$F_{LU}^{\sin\phi}$ $F_{UL}^{\sin\phi}$

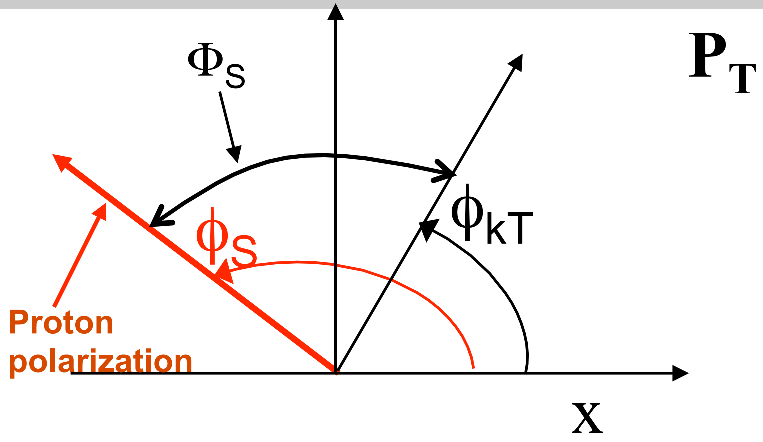


$eH_1^{\perp}$, $h_L H_1^{\perp}$ $\sin\phi_h$

HT function related to force on the quark. M.Burkardt (2008)

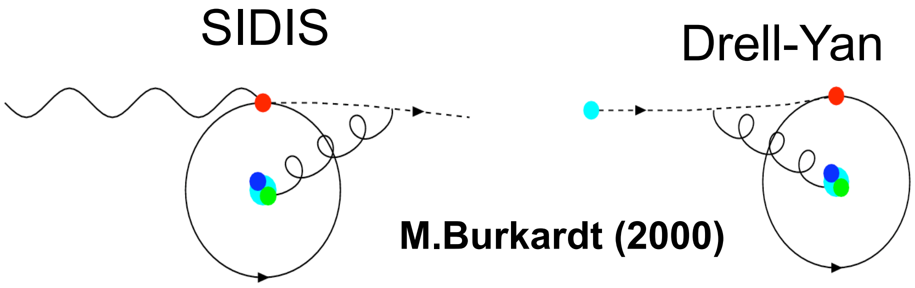
Sivers mechanisms for SSA





Correlation between quark transverse momentum and the proton spin

$$f_{q/p\uparrow}(x,k_T^2) \Rightarrow f_1^q(x,k_T^2) - f_{1T}^{\perp q}(x,k_T^2)\sin\Phi_S$$



M.Burkardt (2000)

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

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

$$F_{LU}^{\sin\phi} \propto g^{\perp q} D_1^q$$

$$F_{UL}^{\sin\phi} \propto f_L^{\perp q} D_1^q$$

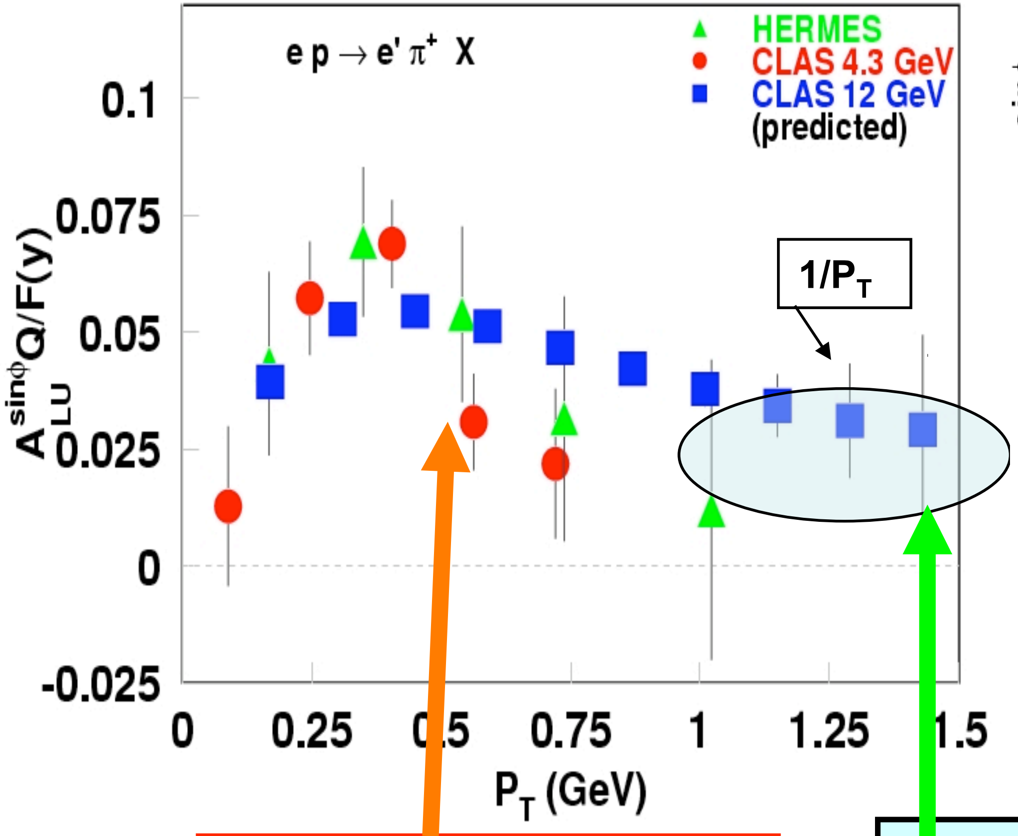
HT asymmetries (T-odd)

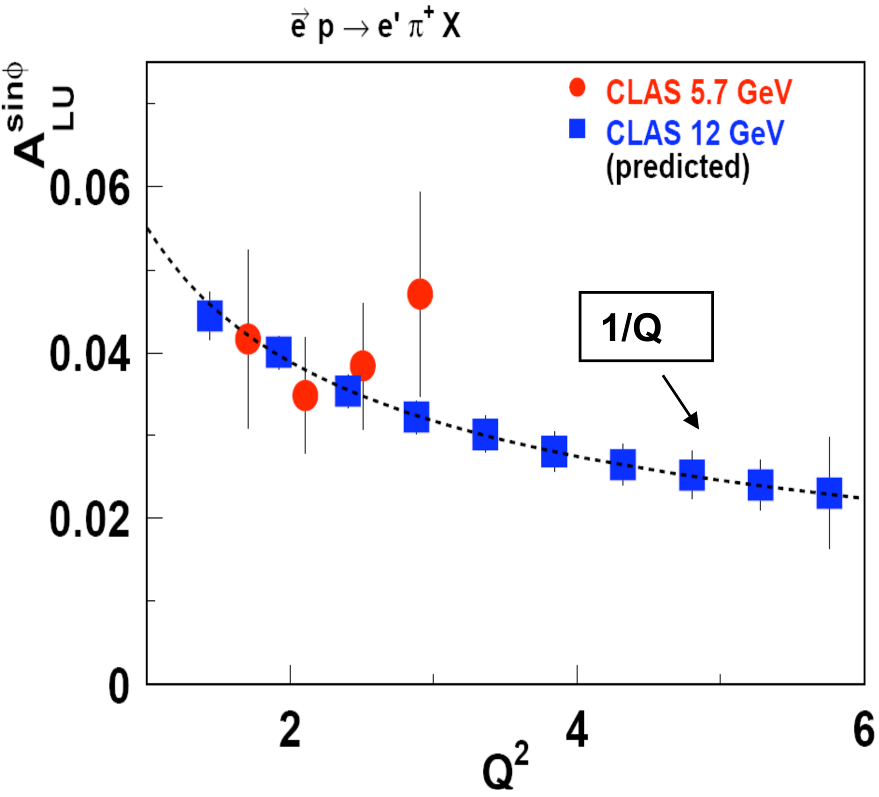
No leading twist, provide access to quark-gluon correlations

P_T-dependence of beam SSA

$\sigma^{\sin\phi}_{LU(UL)} \sim F_{LU(UL)} \sim 1/Q$ (Twist-3)

$$A_{LU} \propto g^{\perp}(x) D_1(z)$$





Nonperturbative TMD

Perturbative region

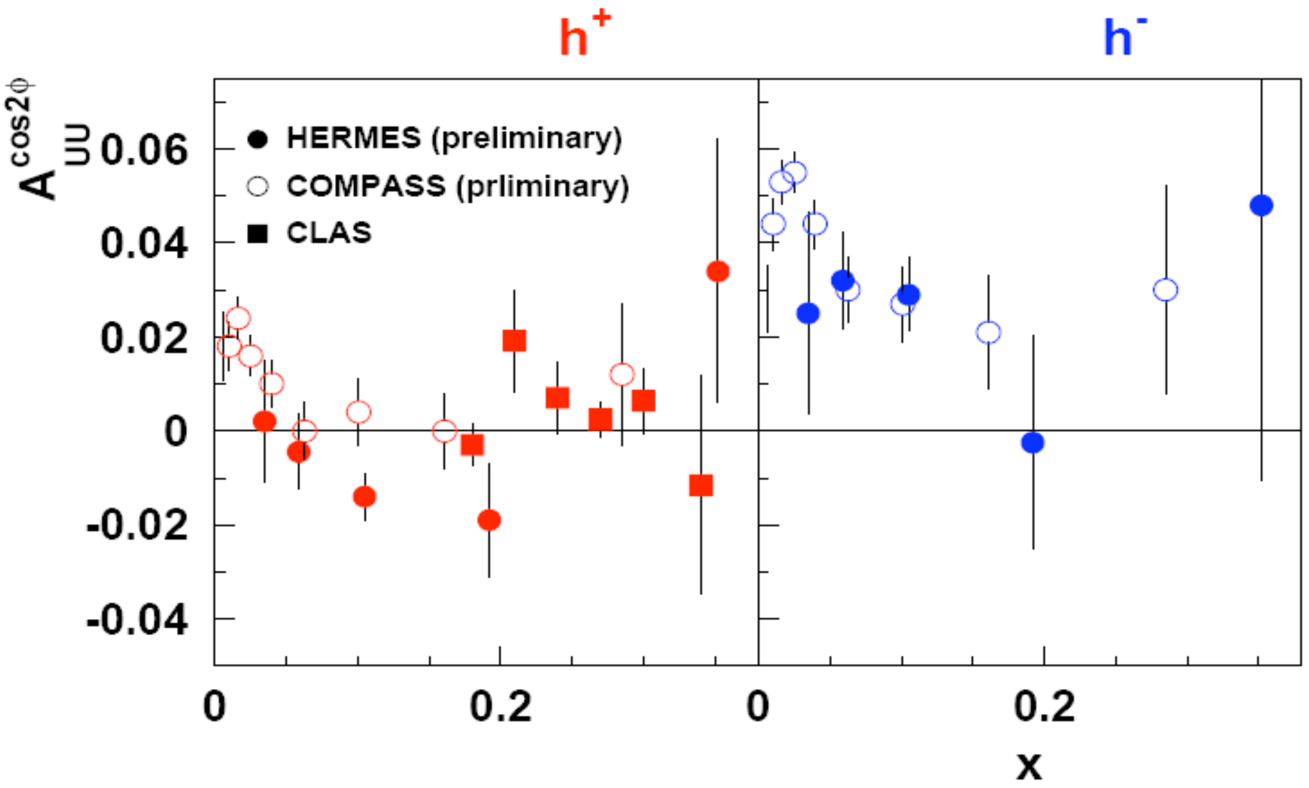
Check of the higher twist nature of observed SSA critical
SSA test transition from non-perturbative to perturbative region

SIDIS (γ*p->πX) x-section at leading twist

TMD PDFs

$$\frac{d\sigma}{dxdydzd^2\vec{P}_h} = \frac{4\pi\alpha^2 s}{Q^4}[x(1-y+y^2/2)F_{UU} \longrightarrow f_1 D_1$$

$$-x(1-y)\cos(2\phi)F_{UU}^{\cos 2\phi}] \longrightarrow h_1^{\perp} H_1^{\perp}$$

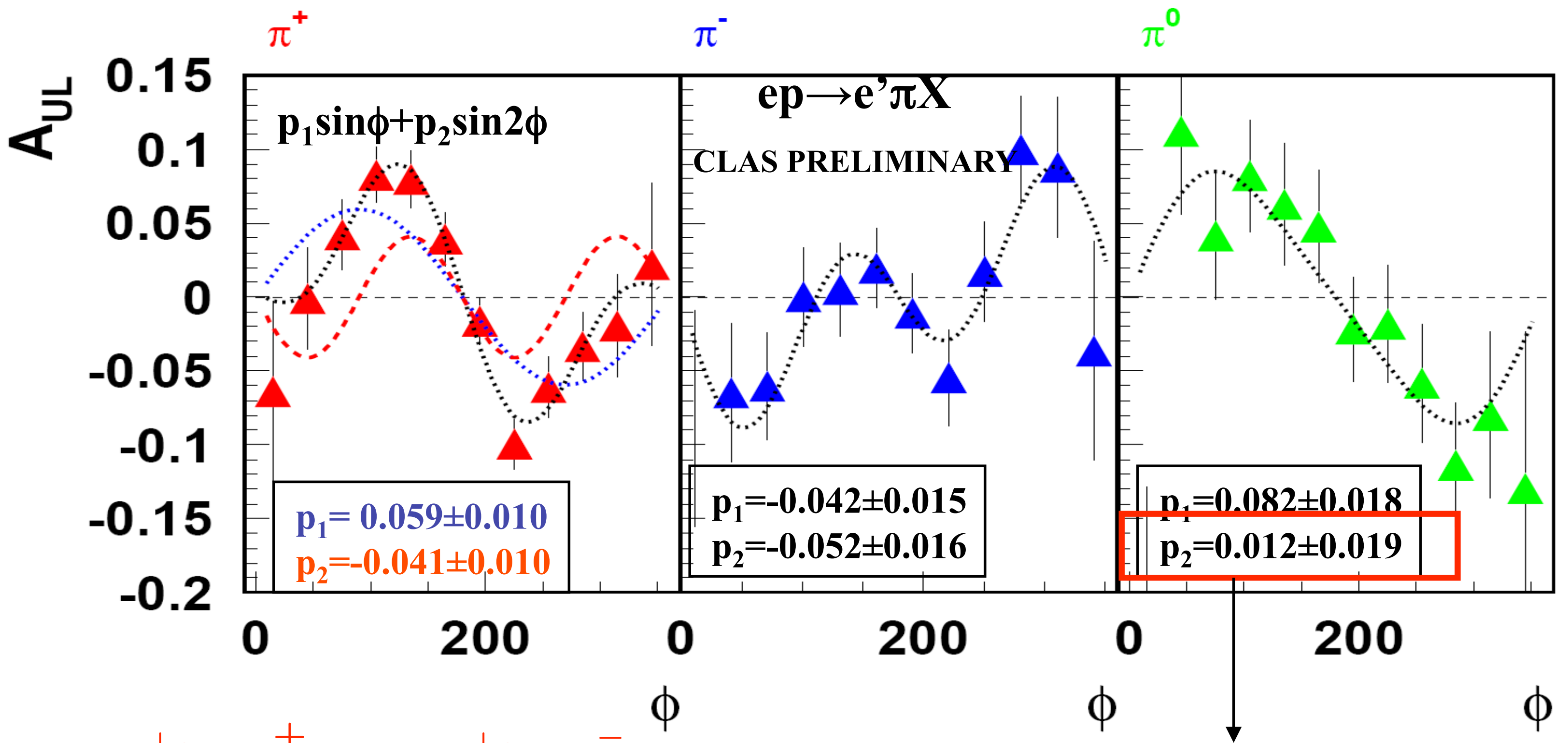


- Measure Boer-Mulders distribution functions and probe the polarized fragmentation function
- Measurements from different experiments consistent

Longitudinal Target SSA measurements at CLAS (E05-113)

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

- Complete azimuthal coverage crucial for separation of sinϕ, sin2ϕ moments



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

$0.4<z<0.7$
$M_X>1.4$ GeV

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

$$H_1^{\perp u\to\pi^+} \approx -H_1^{\perp u\to\pi^-}$$
$$\Downarrow$$
$$H_1^{\perp u\to\pi^0} \ll H_1^{\perp u\to\pi^+}$$

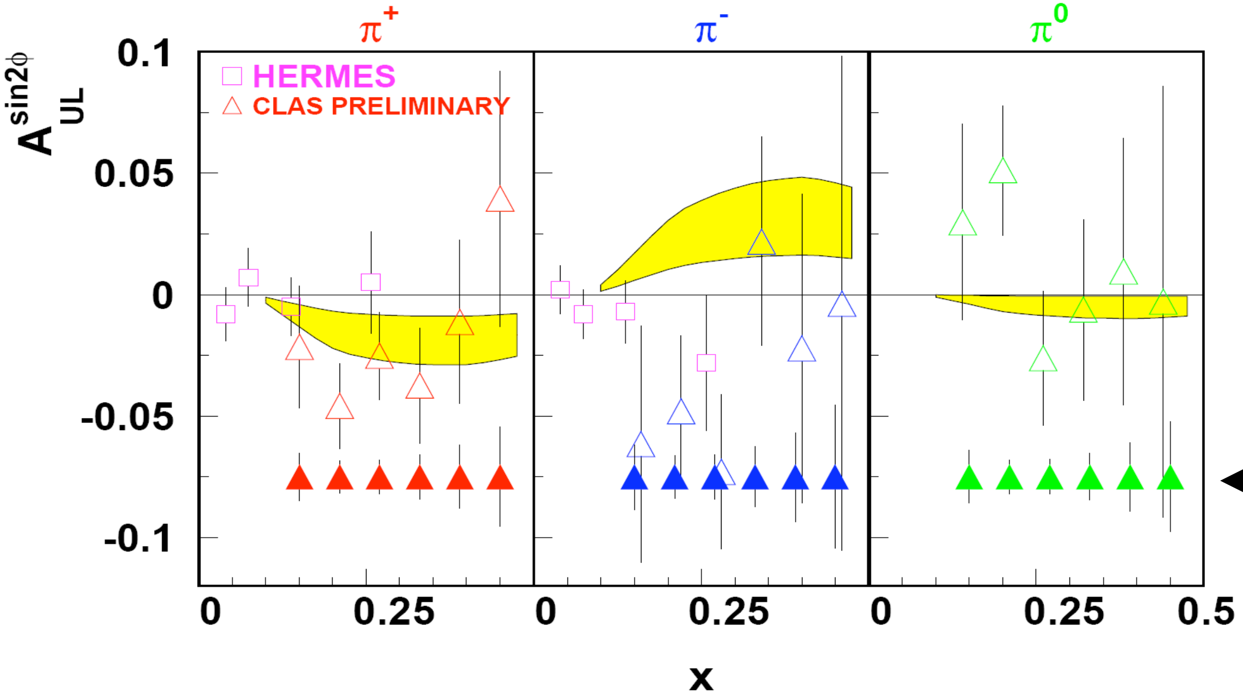
Large sinf for all pions and no indication of sin2ϕ for π^0s suggests Sivers dominance

Kotzinian-Mulders asymmetry

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 $h_{1T}^\perp$

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

Transversely polarized quarks in the longitudinally polarized nucleon

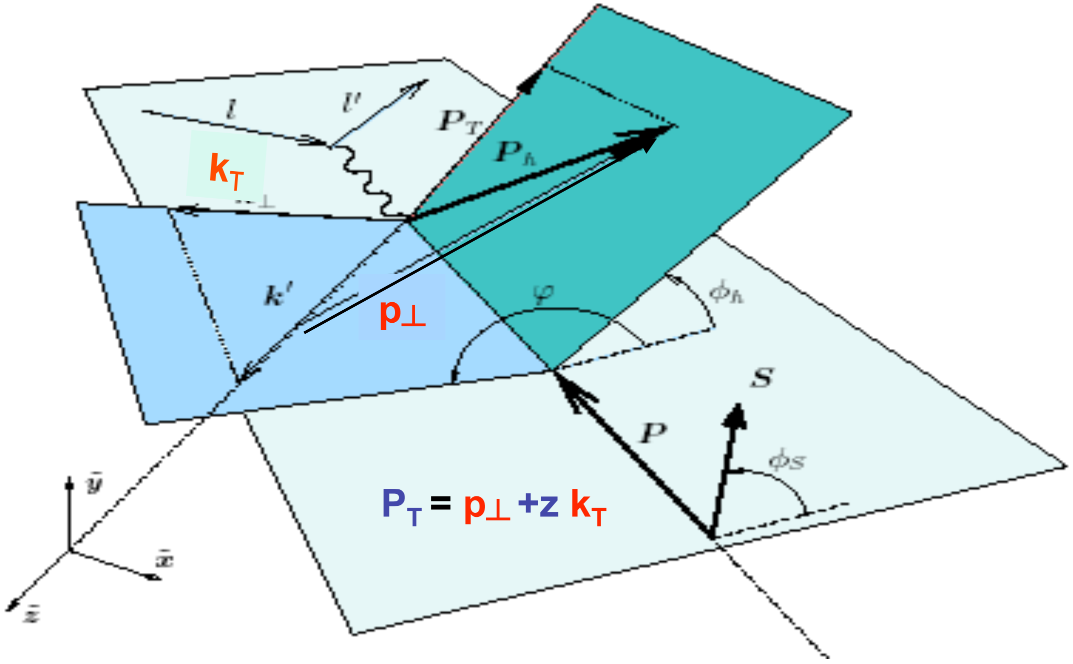


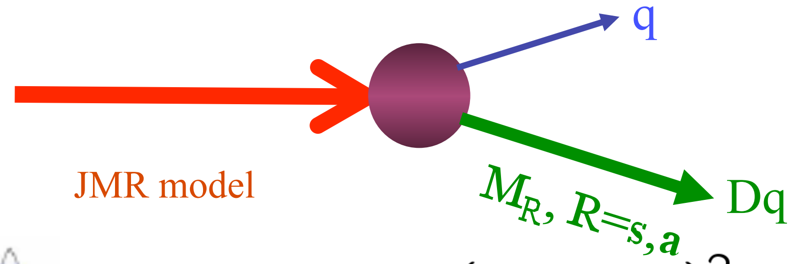
curves, χQSM from Efremov et al

CLAS 2009 (projected) L=1.5.10^{34}cm^{-2}s^{-1}

- **Provide measurement of SSA for all 3 pions, extract the RSMT TMD (Ralston-Soper (1979), Mulders-Tangerman (1995)**
- **Study Collins fragmentation with longitudinally polarized target**

SIDIS: partonic cross sections





JMR model

$$u^+(x,\mathbf{k}_T^2) \propto \frac{(xM+m)^2}{(\mathbf{k}_T^2+\lambda_R^2)^{2\alpha}},$$

$$u^-(x,\mathbf{k}_T^2) \propto \frac{\mathbf{k}_T^2}{(\mathbf{k}_T^2+\lambda_R^2)^{2\alpha}},$$

$$d\sigma^h \propto \sum f^{H\to q}(x,k_T) \otimes \mathbf{d}\sigma_q(y) \otimes D^{q\to h}(z,p_\perp)$$

$$\Big\downarrow$$

$$d\sigma^h \propto \sum f^{H\to q}(x)\mathbf{d}\sigma_q(y) D^{q\to h}(z)$$

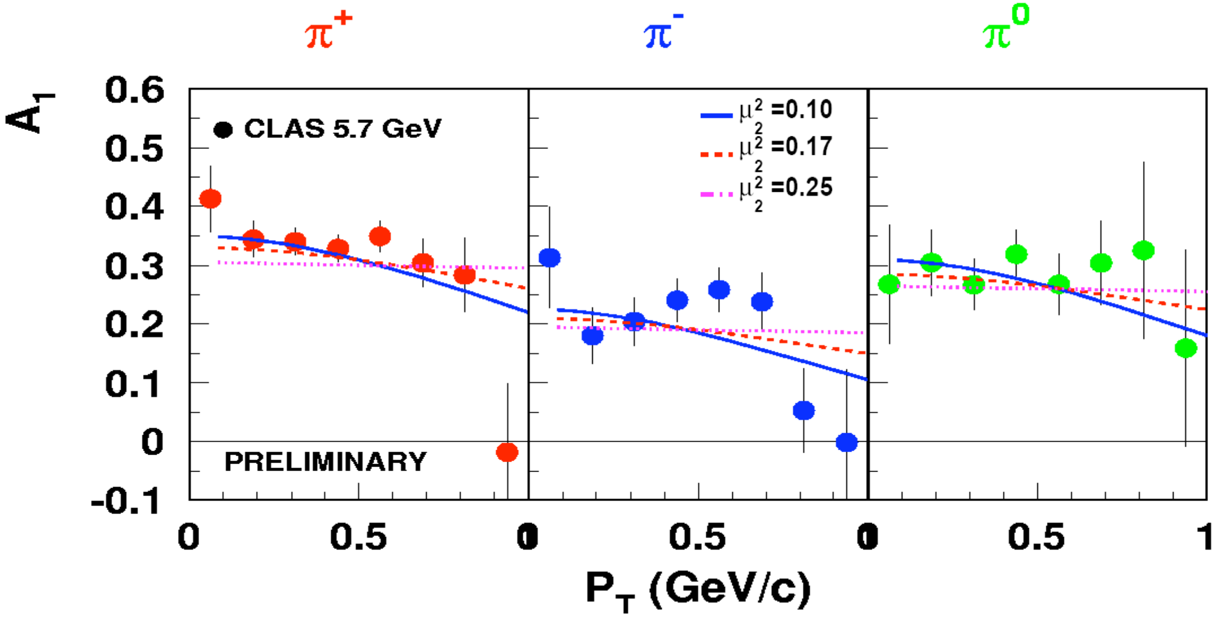
Do flavor decomposition using polarized proton and deuteron data in P_T bins

A_1 P_T-dependence in SIDIS

$$A_1(\pi) \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^{q\to\pi}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\pi}(z)}\; e^{-z^2 P_T^2 \frac{(\mu_0^2-\mu_2^2)}{(\mu_D^2+z^2\mu_0^2)(\mu_D^2+z^2\mu_2^2)}}$$

M.Anselmino et al

hep-ph/0608048



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

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

$$D_1^q(z,p_T) = D_1(z)\frac{1}{\pi\mu_D^2}\exp\left(-\frac{p_T^2}{\mu_D^2}\right)$$

μ_0^2=0.25GeV^2
μ_D^2=0.2GeV^2

x10 more data from eg1dvcs

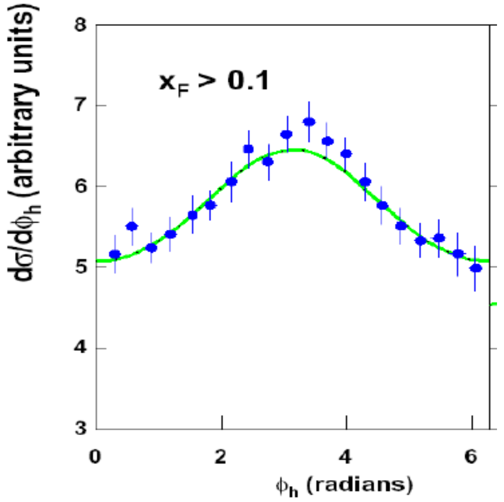
π+ A_{LL} can be explained in terms of broader k_T distributions for f_1 compared to g_1
π- A_{LL} may require non-Gaussian P_T-dependence for different helicities and flavors

Extracting widths from A_1

$A_1 \simeq F_{LL}/F_{UU}$ Assuming the widths of f_1/g_1 x,z and flavor independent

$$F_{LL}(x,z,P_T) = \sum_q e_q^2 x g_1^q(x) D_1^{q\to\pi}(z) \frac{\exp(-P_T^2/\langle P_T^{2,pol}\rangle)}{\pi\langle P_T^{2,pol}\rangle}$$

$$A_1(x,z,P_T) = A_1(x,z)\underbrace{\frac{\langle P_T^{2,unp}\rangle}{\langle P_T^{2,pol}\rangle}\exp(-P_T^2/\langle P_T^{2,pol}\rangle - P_T^2/\langle P_T^{2,unp}\rangle)}_{a_{LL}}$$



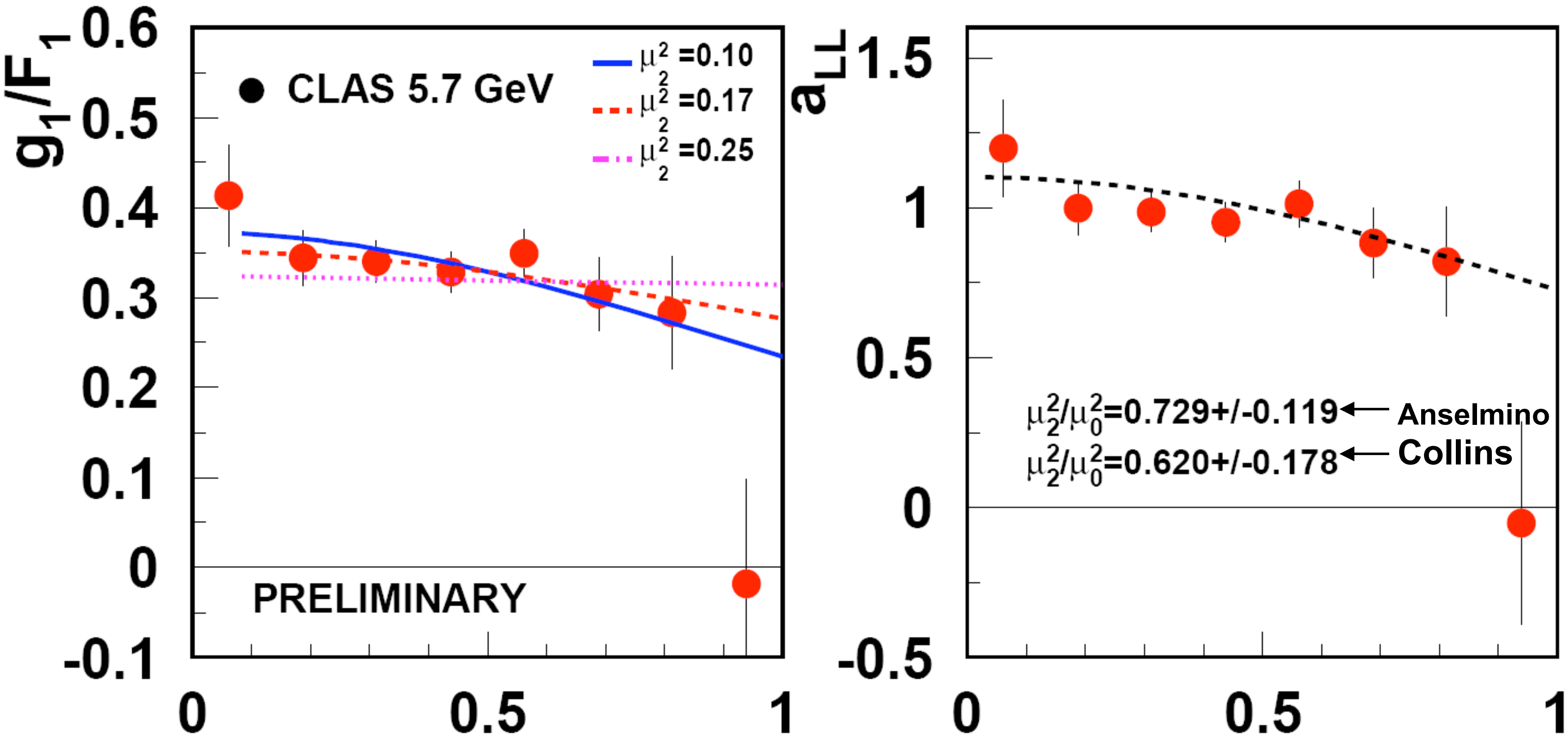
$$\boxed{\langle P_T^{2,pol}\rangle = \mu_D^2 + z^2\mu_2^2 \qquad \langle P_T^{2,unp}\rangle = \mu_D^2 + z^2\mu_0^2}$$

Fits to unpolarized data

$\langle k_T^2\rangle \equiv \mu_0^2 = 0.25\ \text{GeV}^2$ $\langle p_T^2\rangle \equiv \mu_D^2 = 0.2\ \text{GeV}^2$ Anselmino et al

$\mu_0^2 = 0.33\ \text{GeV}^2$ $\mu_D^2 = 0.16\ \text{GeV}^2$ Collins et al

A_1 P_T-dependence



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

What comes next

Hall-A Transversely polarized ^{3}He target measurement (E06-010/011)

Calibrating

Fixed bins in x/Q^2

- Sivers asymmetry
- Collins asymmetry with transverse (neutron) target

Hall-B Longitudinally polarized proton (NH_3) target measurement (E05-113)

Currently running

Hall-B Transversely polarized proton target measurement (E08-015)

September 2011

Wide kinematical coverage , multiple hadronic states

Hall-B Longitudinally polarized proton (NH_3) target:

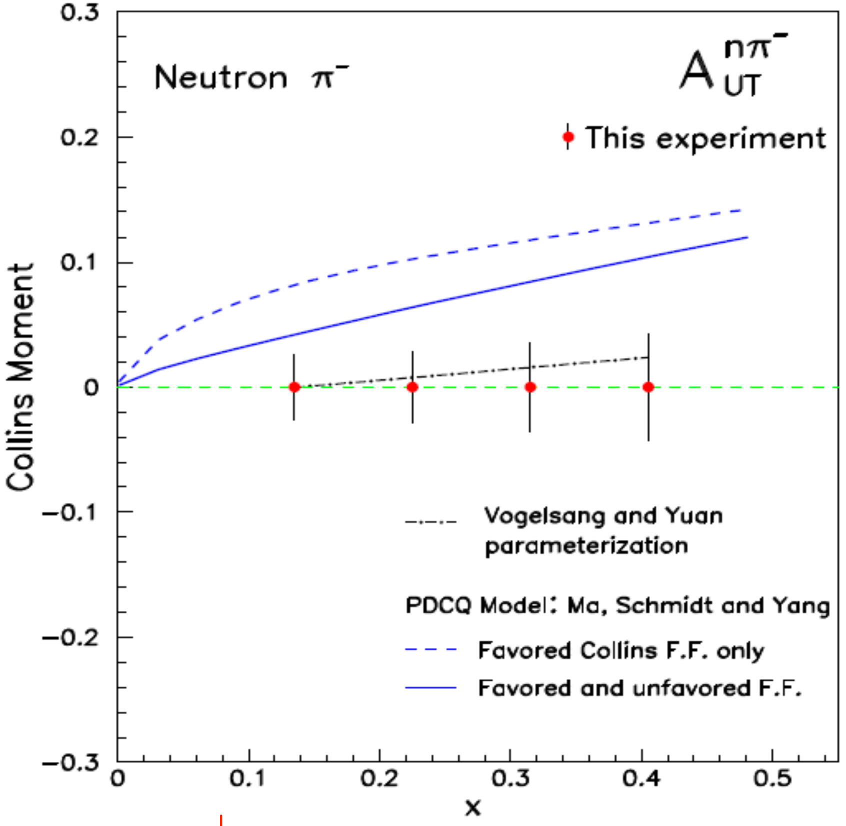
- Correlations of transverse and longitudinal momenta (P_T-dependences) in A_{LL}
- Collins asymmetry with longitudinally polarized (proton) target
- Exclusive asymmetries as background

Hall-B Transversely polarized proton target:

- Sivers asymmetry
- Collins asymmetry with transverse proton target
- Shape of proton studies
- Exclusive asymmetries as background

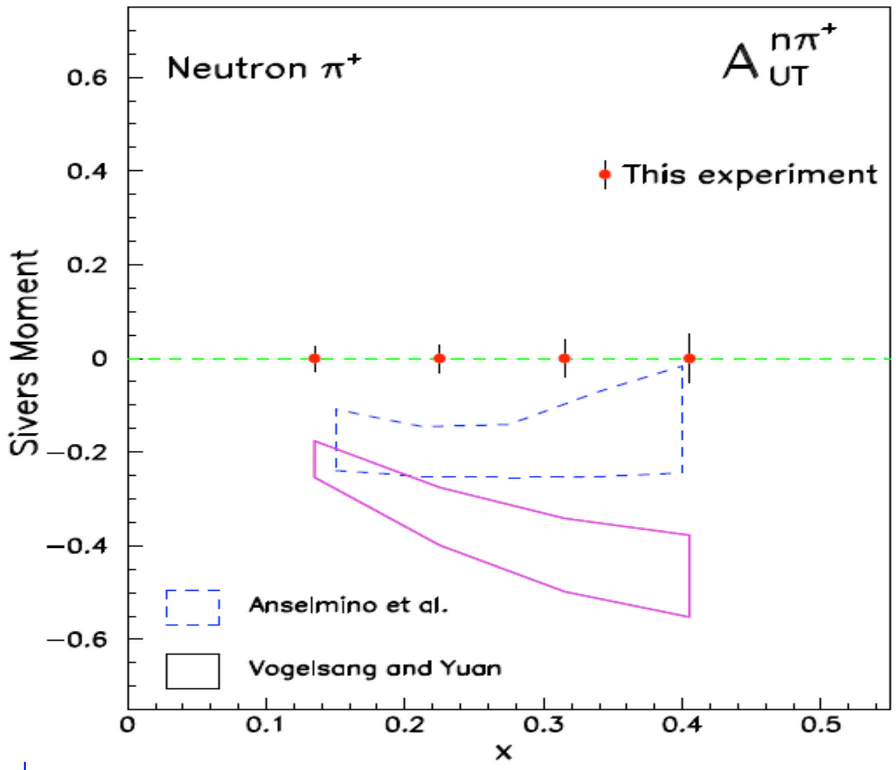
Hall A E06-010: Neutron (3He) Transversity

- **First JLab transverse SSA measurement**
- **First world neutron(^{3}He) measurement**



$h_1 H_1^{\perp}$

Collins: transversity



$f_{1T}^{\perp} D_1$

Sivers: Orbital Angular Momentum

A_{LL} P_T-dependence in SIDIS E05-113

$$A_{LL}(\pi) \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^{q\to\pi}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\pi}(z)}\, e^{-z^2P_T^2\frac{(\mu_0^2-\mu_2^2)}{(\mu_D^2+z^2\mu_0^2)(\mu_D^2+z^2\mu_2^2)}}$$

M.Anselmino et al

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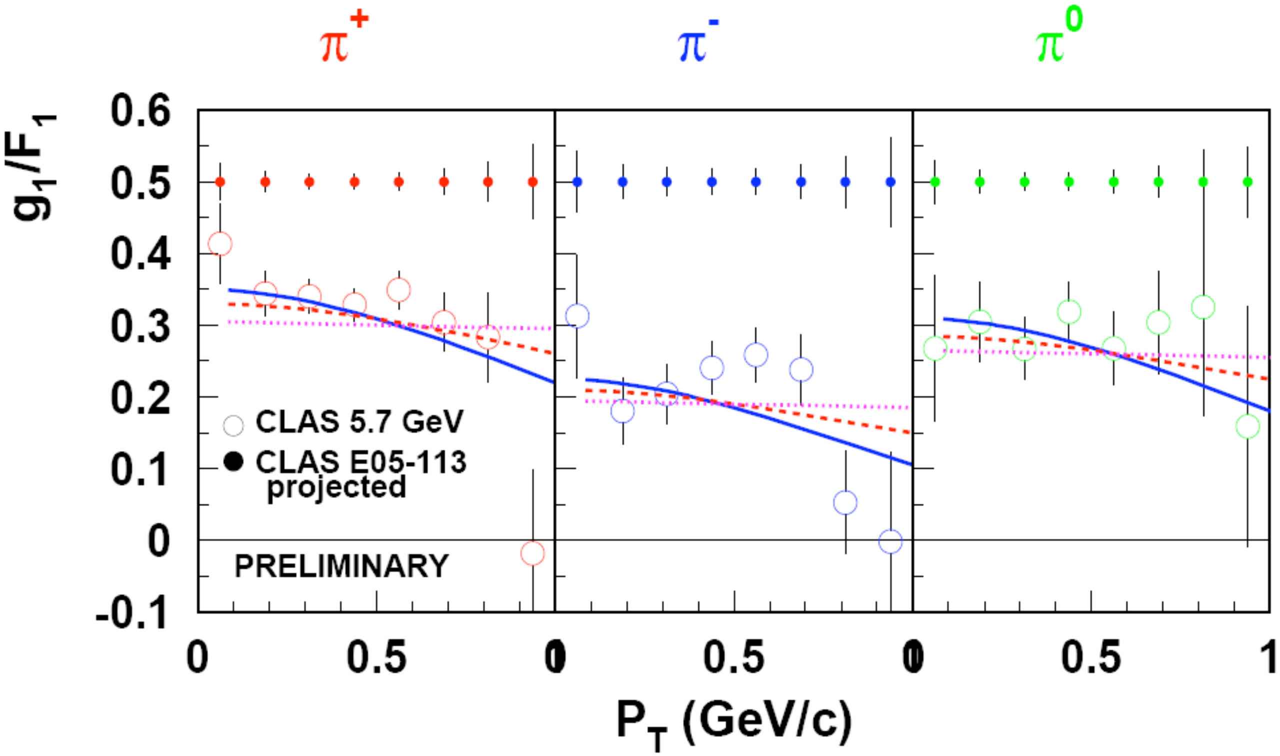


μ_2^2 =0.10

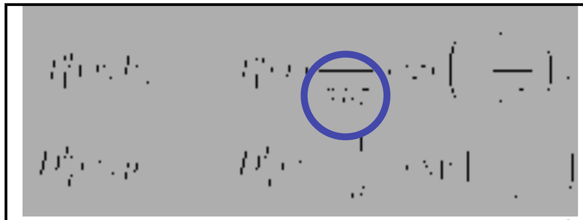
μ_2^2 =0.17

μ_2^2 =0.25

μ_0^2=0.25GeV^2

μ_D^2=0.2GeV^2

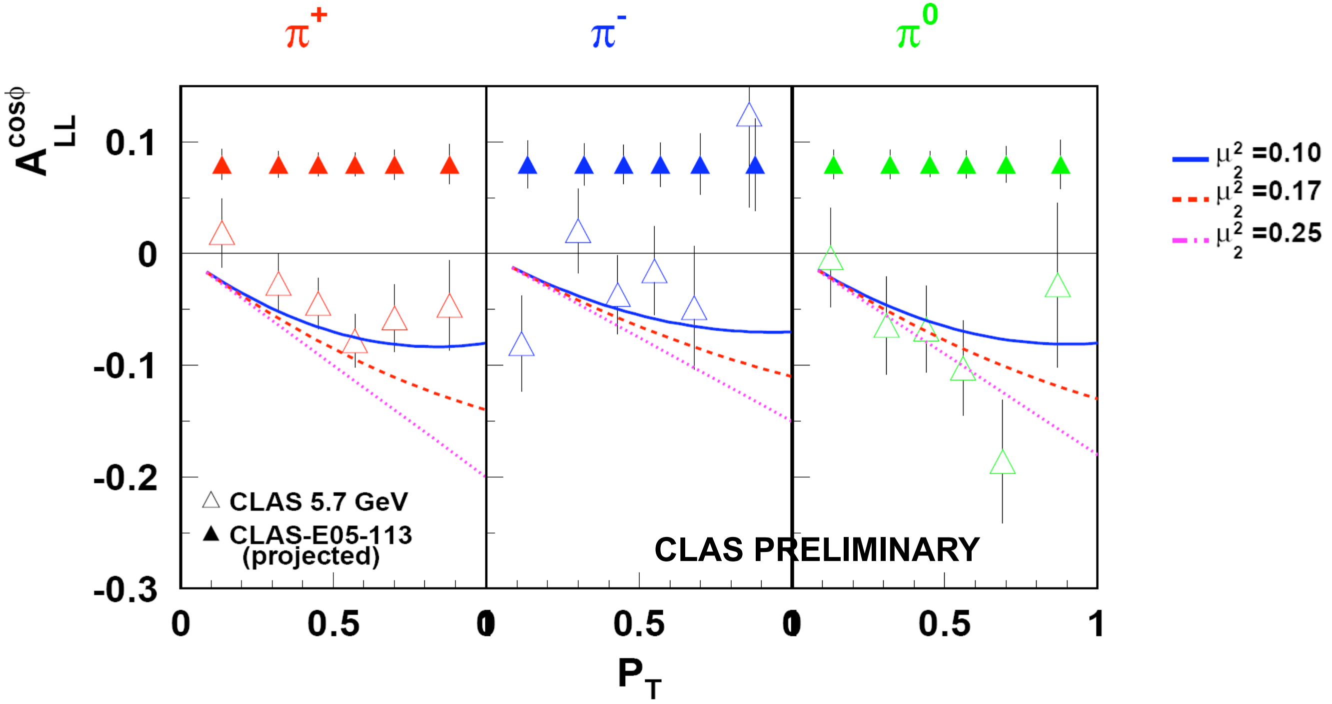
0.4<z<0.7



$$g_1^q(x,k_\perp) = g_1^q(x)\frac{1}{\pi\mu_2^2}exp(-\frac{k_\perp^2}{\mu_2^2})$$

- **New experiment with 10 times more data will study the P_T-dependence for different quark helicities and flavors for bins in x to check if $\mu_0 < \mu_2$**

cosϕ moment in A_{LL}-P_T-dependence



hep-ph/0608048

μ_0^2=0.25GeV^2

μ_D^2=0.2GeV^2

$$\sigma_0 = \frac{1+(1-y)^2}{xy^2}\,\frac{1}{\mu_D^2+z^2\mu_0^2}\exp\left(-\frac{P_{hT}^2}{\mu_D^2+z^2\mu_0^2}\right)\sum_q e_q^2\, f_1^q(x)\, D_q^h(z)$$

$$\Delta\sigma_{LL}^{\cos\phi_h} = -4\,\frac{\sqrt{1-y}}{xy}\,\frac{z\,\mu_2^2\,P_{hT}}{Q\,(\mu_D^2+z^2\mu_2^2)^2}\exp\left(-\frac{P_{hT}^2}{\mu_D^2+z^2\mu_2^2}\right)\sum_q e_q^2\, g_1^q(x)\, D_q^h(z)$$

$$A_{LL}^{\cos\phi} \sim e_L H_1^{\perp}$$

$$A_{LL}^{\cos\phi} \sim g_L^{\perp} D_1$$

P_T-dependence of cosϕ moment of double spin asymmetry is most sensitive to k_T-distributions of quarks with spin orientations along and opposite to the proton spin.

CLAS transversely polarized HD-Ice target

HD-Ice target vs std nuclear targets

Heat extraction is accomplished with thin aluminum wires running through the target (can operate at ***T~500-750mK***)

Material	gm/cm^2	mass fraction
HD	0.735	77%
Al	0.155	16%
CTFE (C_2ClF_3)	0.065	7 %

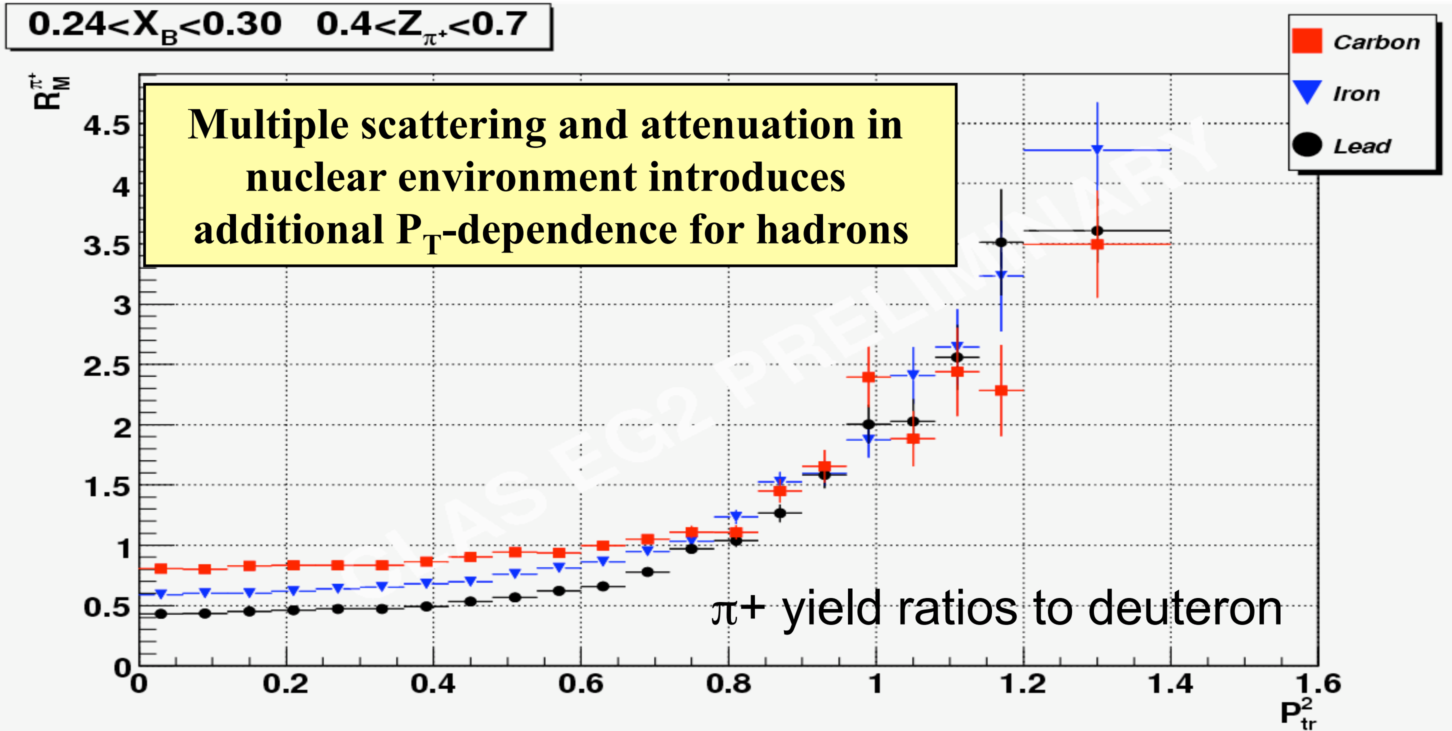
Pros

1. Small field ($\int Bdl \sim 0.0$
2. Small dilution (fract
3. Less radiation lengt
4. Less nuclear backgr
5. Wider acceptance

much better FOM, es

Cons

1. HD target is highly
   long polarizing time
2. Need to demonstrat
   electron beam wit
3. Additional shielding of Moller electrons necessary

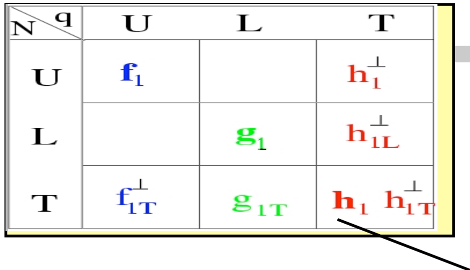


Multiple scattering and attenuation in nuclear environment introduces additional P_T-dependence for hadrons

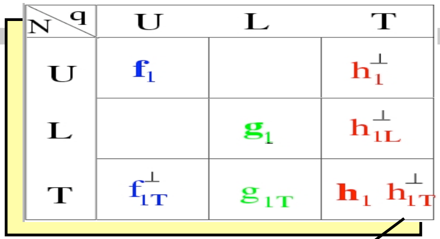
π+ yield ratios to deuteron

Collins SSAs

CLAS E08-015 (2011)



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 $h_{1T}^\perp$



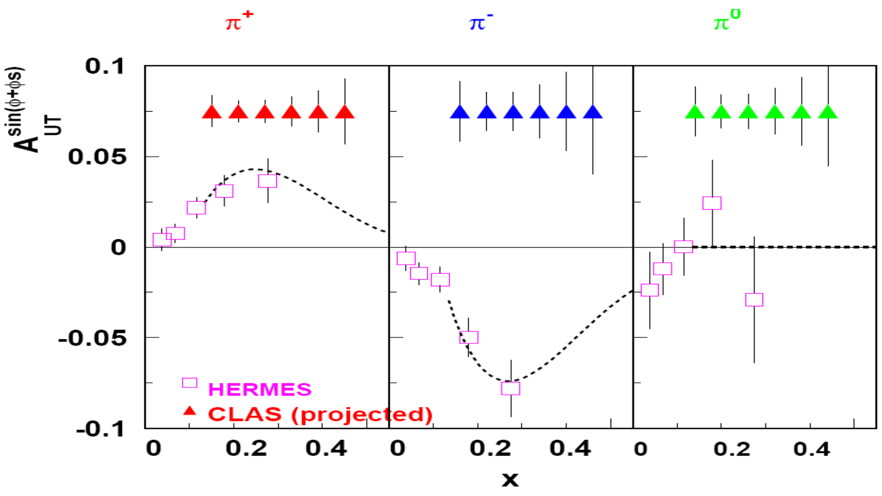
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

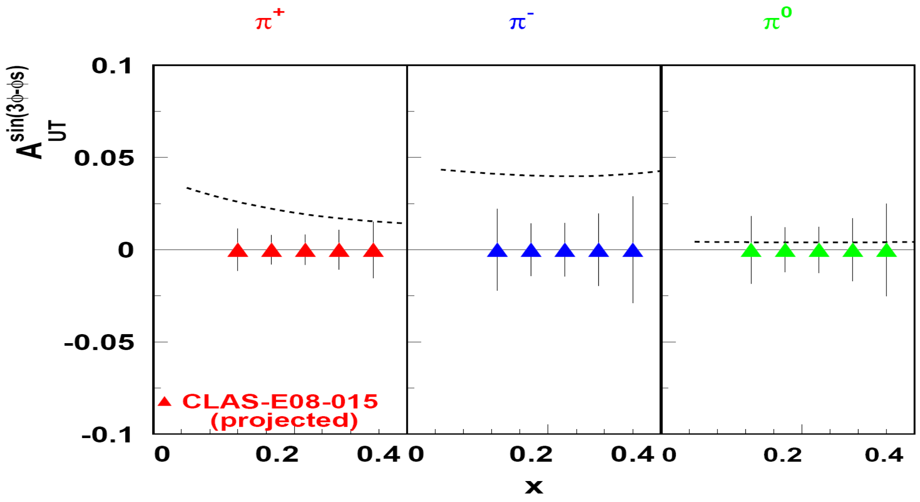
$$A_{UT}^{\sin(\phi+\phi_S)} \sim h_1 H_1^\perp$$

$$A_{UT}^{\sin(3\phi-\phi_S)} \sim h_{1T}^\perp H_1^\perp$$

$\sim (1-x)^5$

$\sim \frac{1}{P_T^5}$





Anselmino et al

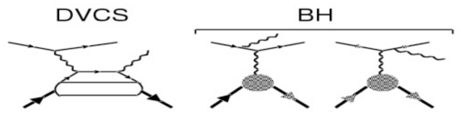
H.A.,A.Efremov,P.Schweitzer,F.Yuan

$$g_{1L}(x,k_T) - h_1(x,k_T) = \int \vec{k}_T^{\,2} h_{1T}^\perp(x,k_T) d^2\vec{k}_T$$

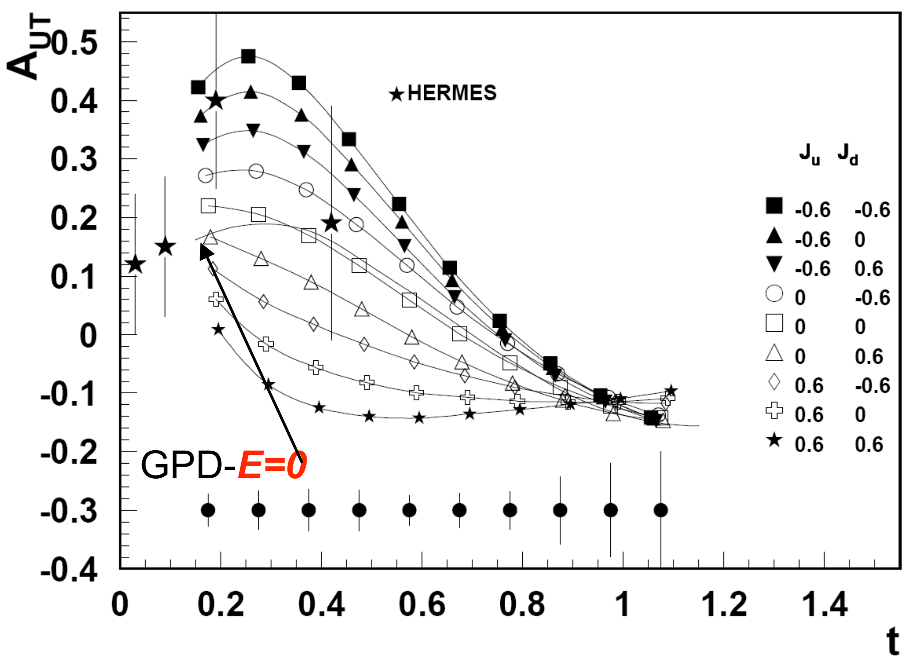
helicity-transversity=pretzelosity

CLAS with a transversely polarized target will allow measurements of transverse spin distributions and constrain Collins fragmentation function

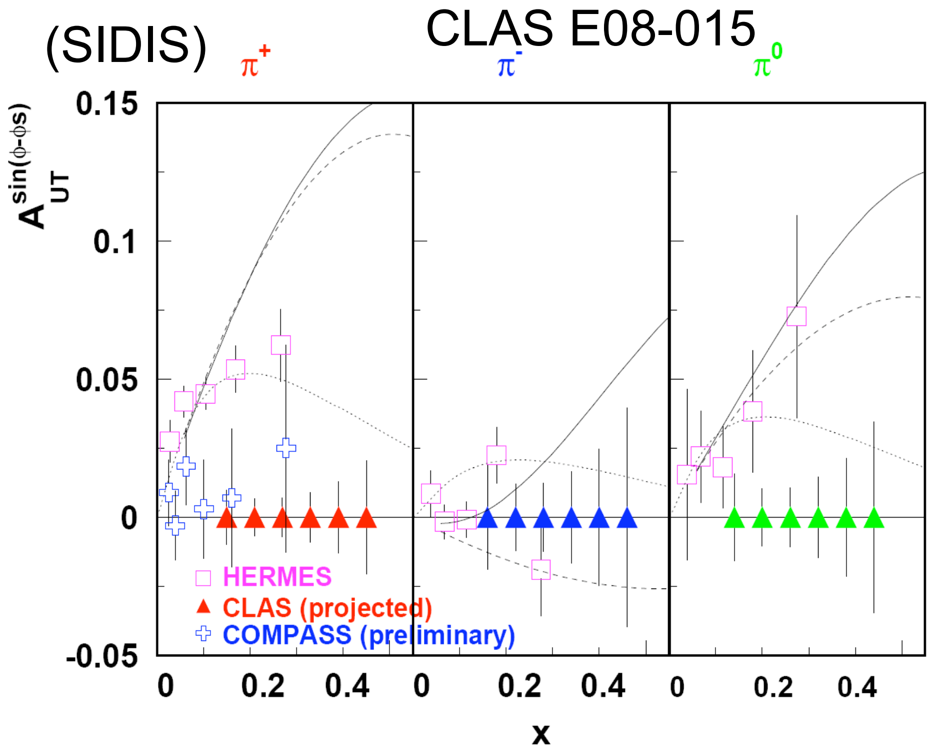
Measurement of Sivers function and GPD-E



(DVCS)



(SIDIS)

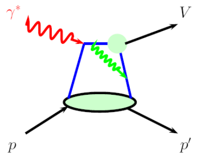


DVCS Transverse asymmetry (function of momentum transfer to proton) is large and has strong sensitivity to GPD-*E*

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

$$\int d^2\vec{k}_T \vec{k}_T^2 f_{1T}^{\perp}(x,\vec{k}_T^2) = -e_s e_q \frac{(1-x)}{4\pi} \int d^2\vec{b}_T \left(E(x,\vec{b}_T^2)\right)'$$

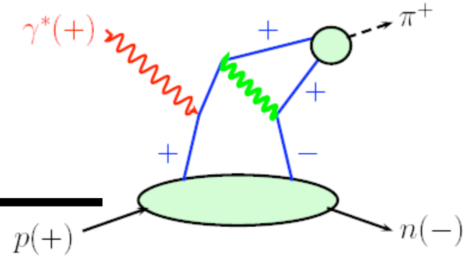
Meissner, Metz & Goeke (2007)



SSAs in exclusive pion production

Transverse photon matters

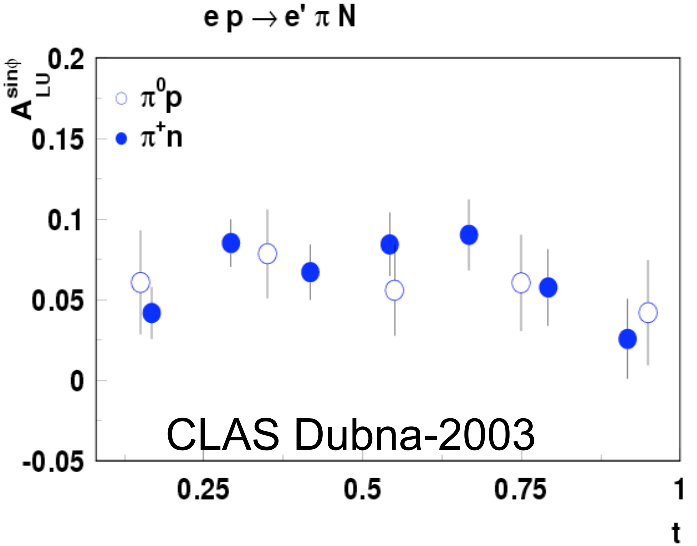
Ahmad,Liuti & Goldstein: arXiv:0805.3568
Gloskokov & Kroll : arXiv:0906.0460

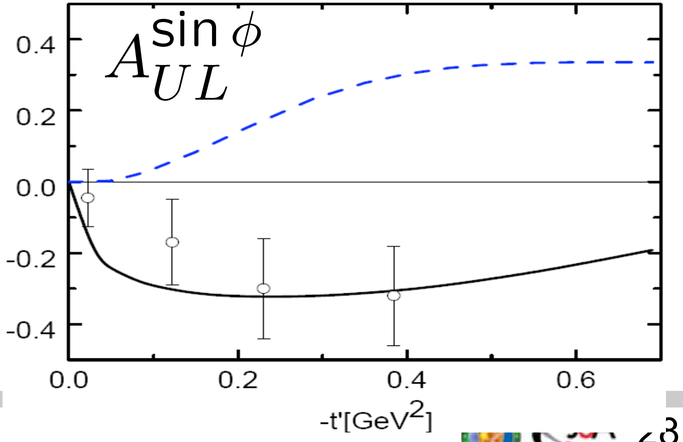


$$\mathcal{M}^{twist-3}_{0-,++} \approx e_0 \sqrt{1-\xi^2} \int_{-1}^{+1} d\bar{x} \mathcal{H}_{0-,++} [H_T^{(3)} + \ldots]$$

observable	dominant interf. term	amplitudes	low t' behavior
$A_{UT}^{\sin(\phi-\phi_s)}$	LL	$\mathrm{Im}[\mathcal{M}^*_{0-,0+}\mathcal{M}_{0+,0+}]$	$\propto \sqrt{-t'}$
$A_{UT}^{\sin(\phi+\phi_s)}$	TT	$\mathrm{Im}[\mathcal{M}^*_{0-,++}\mathcal{M}_{0+,++}]$	$\propto \sqrt{-t'}$
$A_{UT}^{\sin(3\phi-\phi_s)}$	TT	$\mathrm{Im}[\mathcal{M}^*_{0-,-+}\mathcal{M}_{0+,-+}]$	$\propto (-t')^{(3/2)}$
$A_{UT}^{\sin\phi_s}$	LT	$\mathrm{Im}[\mathcal{M}^*_{0-,++}\mathcal{M}_{0+,0+}]$	const.
$A_{UL}^{\sin\phi}$	LT	$\mathrm{Im}[\mathcal{M}^*_{0-,++}\mathcal{M}_{0-,0+}]$	$\propto \sqrt{-t'}$
$A_{LU}^{\sin\phi}$	LT	$\mathrm{Im}[\mathcal{M}^*_{0-,++}\mathcal{M}_{0-,0+}]$	$\propto \sqrt{-t'}$
$A_{LL}^{\cos\phi}$	LT	$\mathrm{Re}[\mathcal{M}^*_{0-,++}\mathcal{M}_{0-,0+}]$	$\propto \sqrt{-t'}$

$$A_{LU}^{\sin\phi}/A_{UL}^{\sin\phi} \approx \sqrt{(1-\epsilon)/(1+\epsilon)}$$





- HT SSAs are expected to be very significant
- CLAS12 can measure Q^2 dependence of HT SSAs

Summary

Measurements of azimuthal dependences of double and single spin asymmetries in SIDIS (TMDs) and hard exclusive processes (GPDs) indicate that there are significant correlations between spin and transverse distribution of quarks.

Sizable higher twist asymmetries measured both in SIDIS and Exclusive production indicate the quark-gluon correlations may be significant at moderate Q^2.

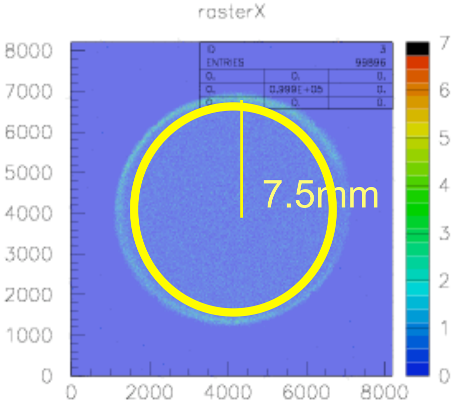
Upcoming JLab SIDIS experiments at 6 GeV will significantly improve the statistical precision of longitudinally polarized target data, and will provide new data on transversely polarized target, also allowing studies of correlations between longitudinal and transverse degrees of freedom

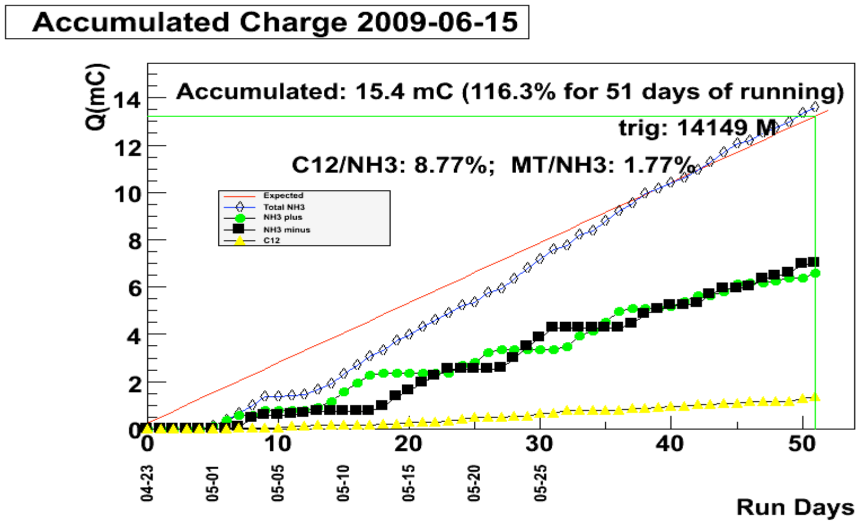
Measurements of TMDs at JLab in the valence region provide important input into the global analysis of Transverse Momentum Distributions (involving HERMES,COMPASS,RHIC,BELLE,BABAR+JPARC,GSI,EIC)

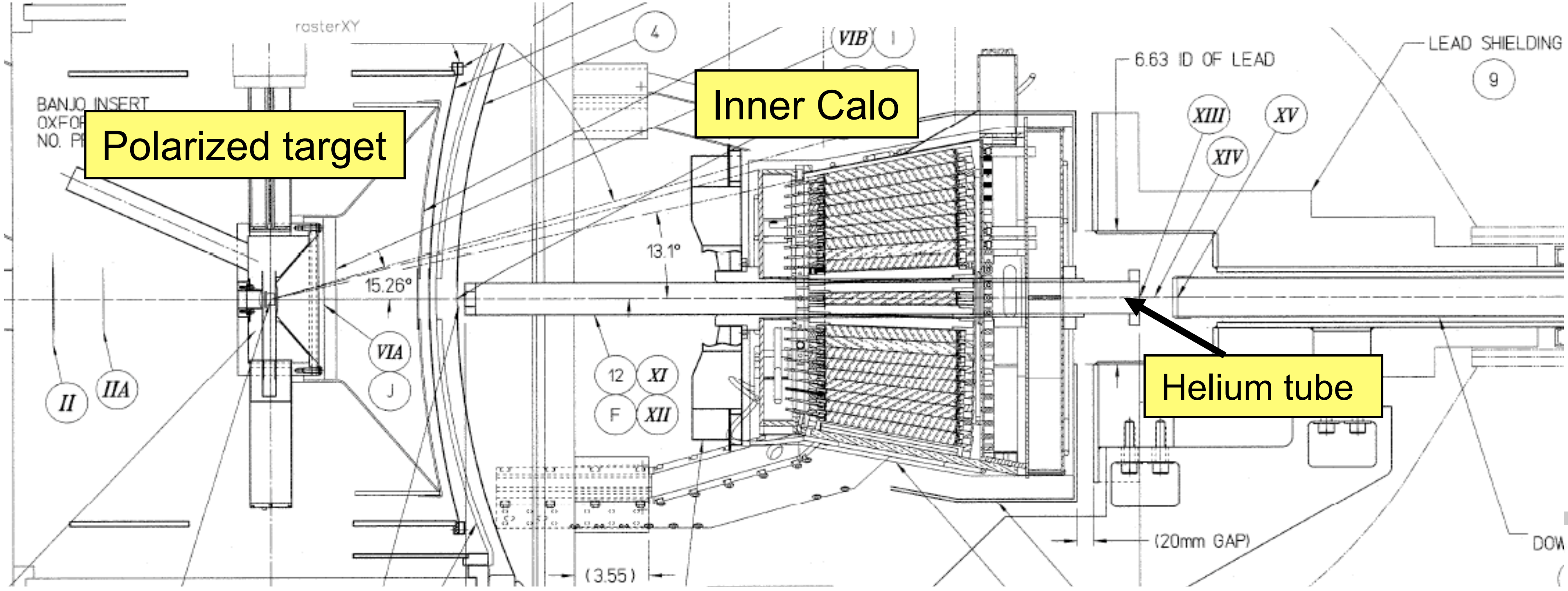
Support slides….

eg1-dvcs Run Conditions

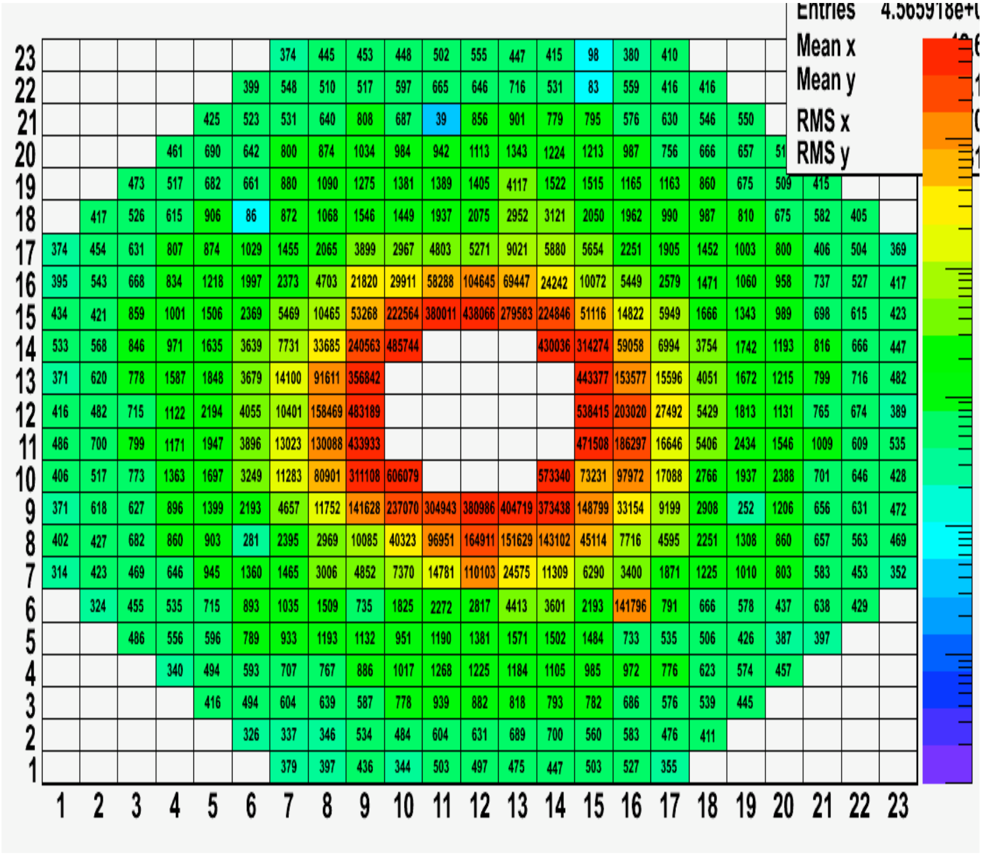
Beam polarization: >80%
Target polarization: >75%
Rastering: R=~7.mm







e1&eg1-dvcs: Monitoring and calibration



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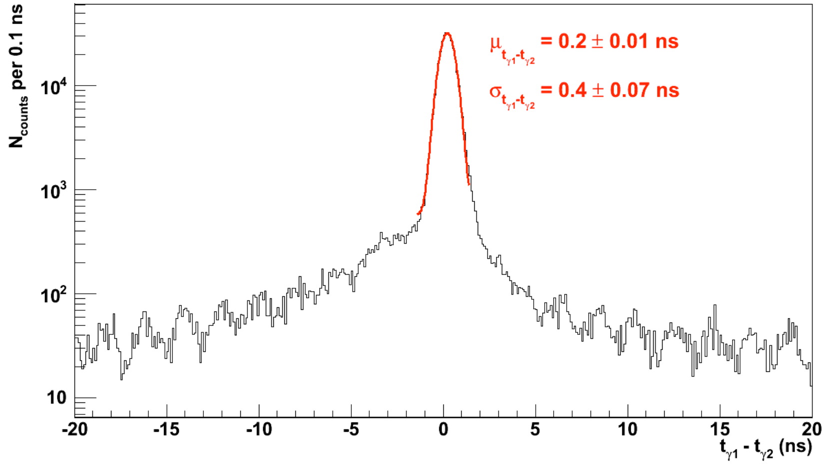
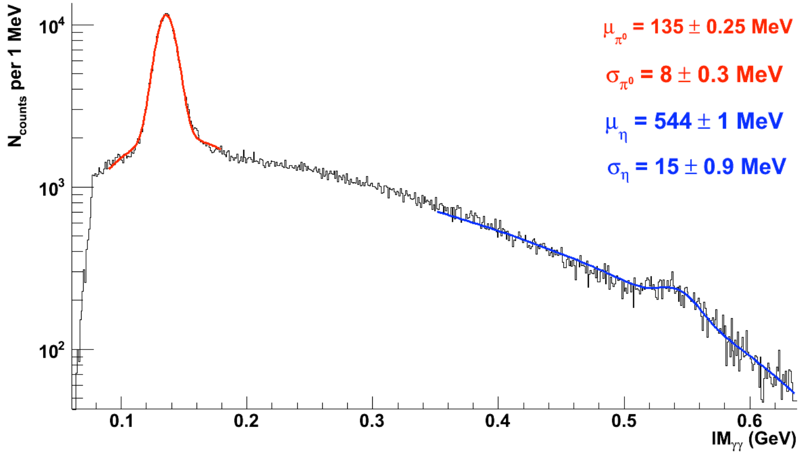
23							374	445	453	448	502	555	447	415	98	380	410						
22						399	548	510	517	597	665	646	716	531	83	559	416	416					
21					425	523	531	640	808	687	39	856	901	779	795	576	630	546	550				
20				461	690	642	800	874	1034	984	942	1113	1343	1224	1213	987	756	666	657	51			
19			473	517	682	661	880	1090	1275	1381	1389	1405	4117	1522	1515	1165	1163	860	675	509	415		
18		417	526	615	906	86	872	1068	1546	1449	1937	2075	2952	3121	2050	1962	990	987	810	675	582	405	
17	374	454	631	807	874	1029	1455	2065	3899	2967	4803	5271	9021	5880	5654	2251	1905	1452	1003	800	406	504	369
16	395	543	668	834	1218	1997	2373	4703	21820	29911	58288	104645	69447	24242	10072	5449	2579	1471	1060	958	737	527	417
15	434	421	859	1001	1506	2369	5469	10465	53268	222564	380011	438066	279583	224846	51116	14822	5949	1666	1343	989	698	615	423
14	533	568	846	971	1635	3639	7731	33685	240563	485744				430036	314274	59058	6994	3754	1742	1193	816	666	447
13	371	620	778	1587	1848	3679	14100	91611	356842						443377	153577	15596	4051	1672	1215	799	716	482
12	416	482	715	1122	2194	4055	10401	158469	483189						538415	203020	27492	5429	1813	1131	765	674	389
11	486	700	799	1171	1947	3896	13023	130088	433933						471508	186297	16646	5406	2434	1546	1009	609	535
10	406	517	773	1363	1697	3249	11283	80901	311108	606079				573340	73231	97972	17088	2766	1937	2388	701	646	428
9	371	618	627	896	1399	2193	4657	11752	141628	237070	304943	380986	404719	373438	148799	33154	9199	2908	252	1206	656	631	472
8	402	427	682	860	903	281	2395	2969	10085	40323	96951	164911	151629	143102	45114	7716	4595	2251	1308	860	657	563	469
7	314	423	469	646	945	1360	1465	3006	4852	7370	14781	110103	24575	11309	6290	3400	1871	1225	1010	803	583	453	352
6		324	455	535	715	893	1035	1509	735	1825	2272	2817	4413	3601	2193	141796	791	666	578	437	638	429	
5			486	556	596	789	933	1193	1132	951	1190	1381	1571	1502	1484	733	535	506	426	387	397		
4				340	494	593	707	767	886	1017	1268	1225	1184	1105	985	972	776	623	574	457			
3					416	494	604	639	587	778	939	882	818	793	782	686	576	539	445				
2						326	337	346	534	484	604	631	689	700	560	583	476	411					
1							379	397	436	344	503	497	475	447	503	527	355						



Tue Jun 30 00:20:09 2009

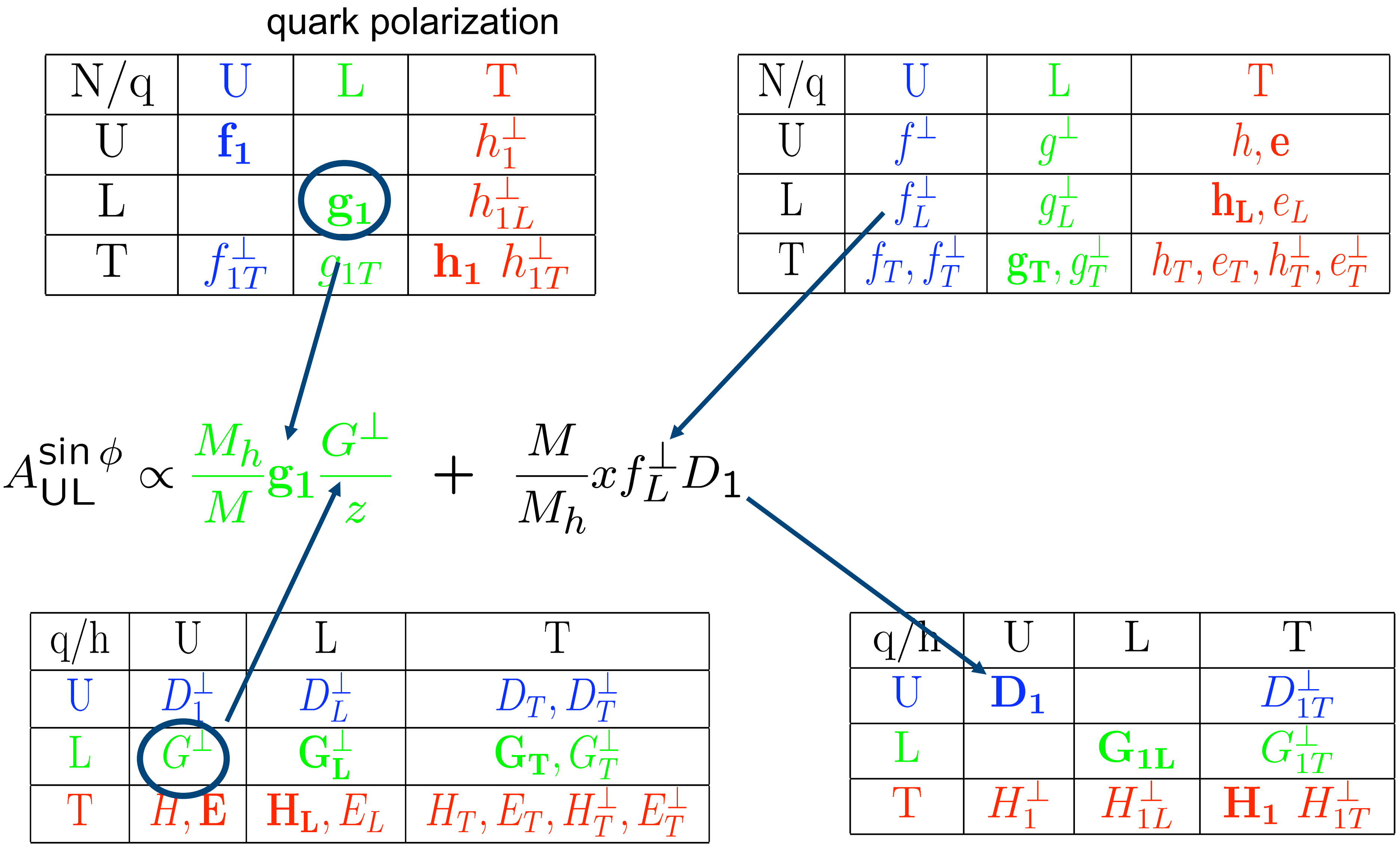


Tue Jun 30 00:05:50 2009

IC operating in high background was stable.

IC time and energy resolutions resolutions after calibration using 2 photon events.

SSA with long. polarized target



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}	$\mathbf{h_1}$ $h_{1T}^\perp$

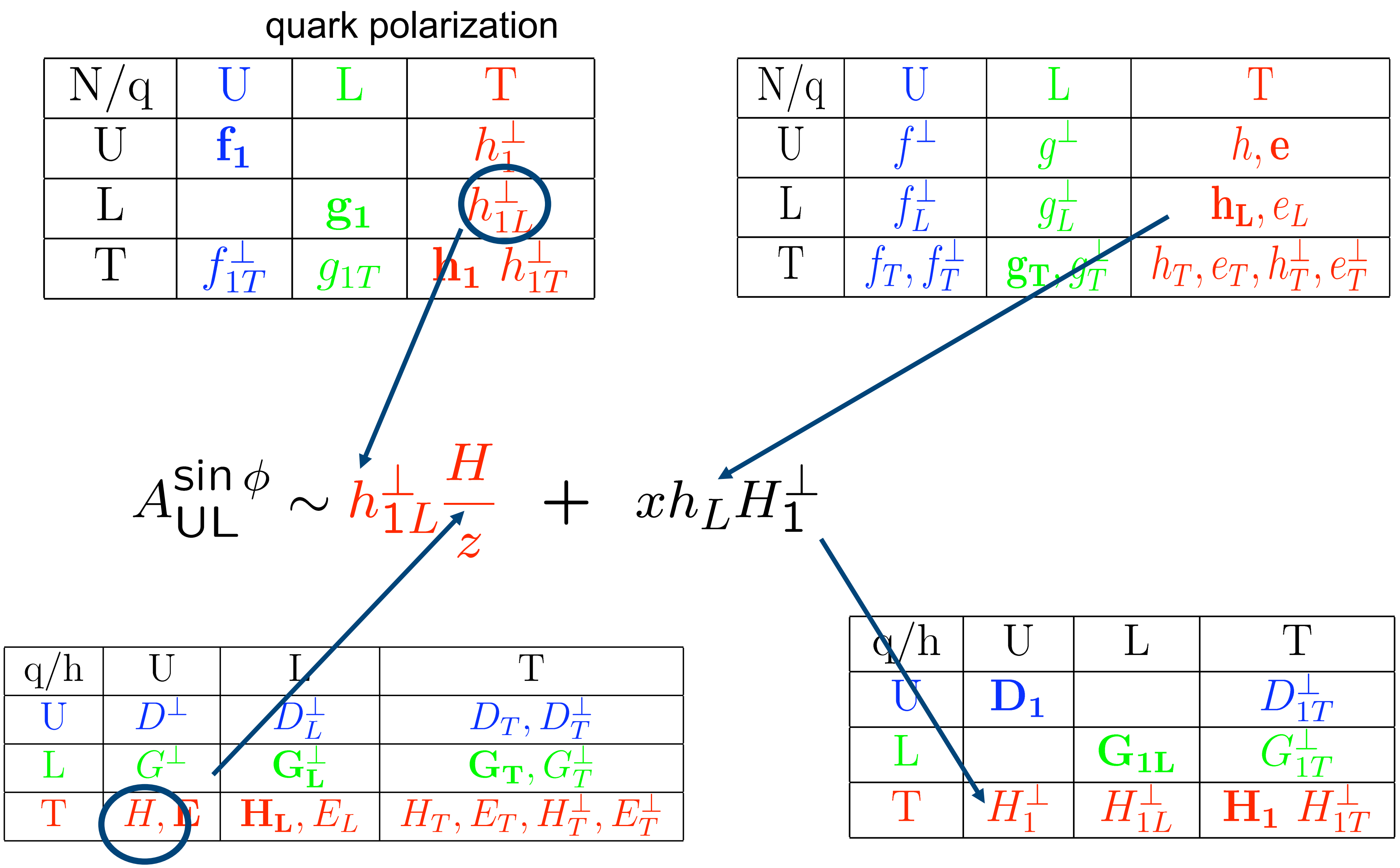
N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{\mathrm{UL}}^{\sin\phi} \propto \frac{M_h}{M}\mathbf{g_1}\frac{G^\perp}{z} + \frac{M}{M_h} x f_L^\perp D_1$$

q/h	U	L	T
U	$D_1^\perp$	$D_L^\perp$	$D_T, D_T^\perp$
L	$G^\perp$	$\mathbf{G_L^\perp}$	$\mathbf{G_T}, G_T^\perp$
T	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

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

SSA with long. polarized target



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}	$\mathbf{h_1}$ $h_{1T}^\perp$

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	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{\mathrm{UL}}^{\sin\phi} \sim h_{1L}^\perp \frac{H}{z} + x h_L H_1^\perp$$

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	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

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

SSA with unpolarized target

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}	$\mathbf{h_1}$ $h_{1T}^\perp$

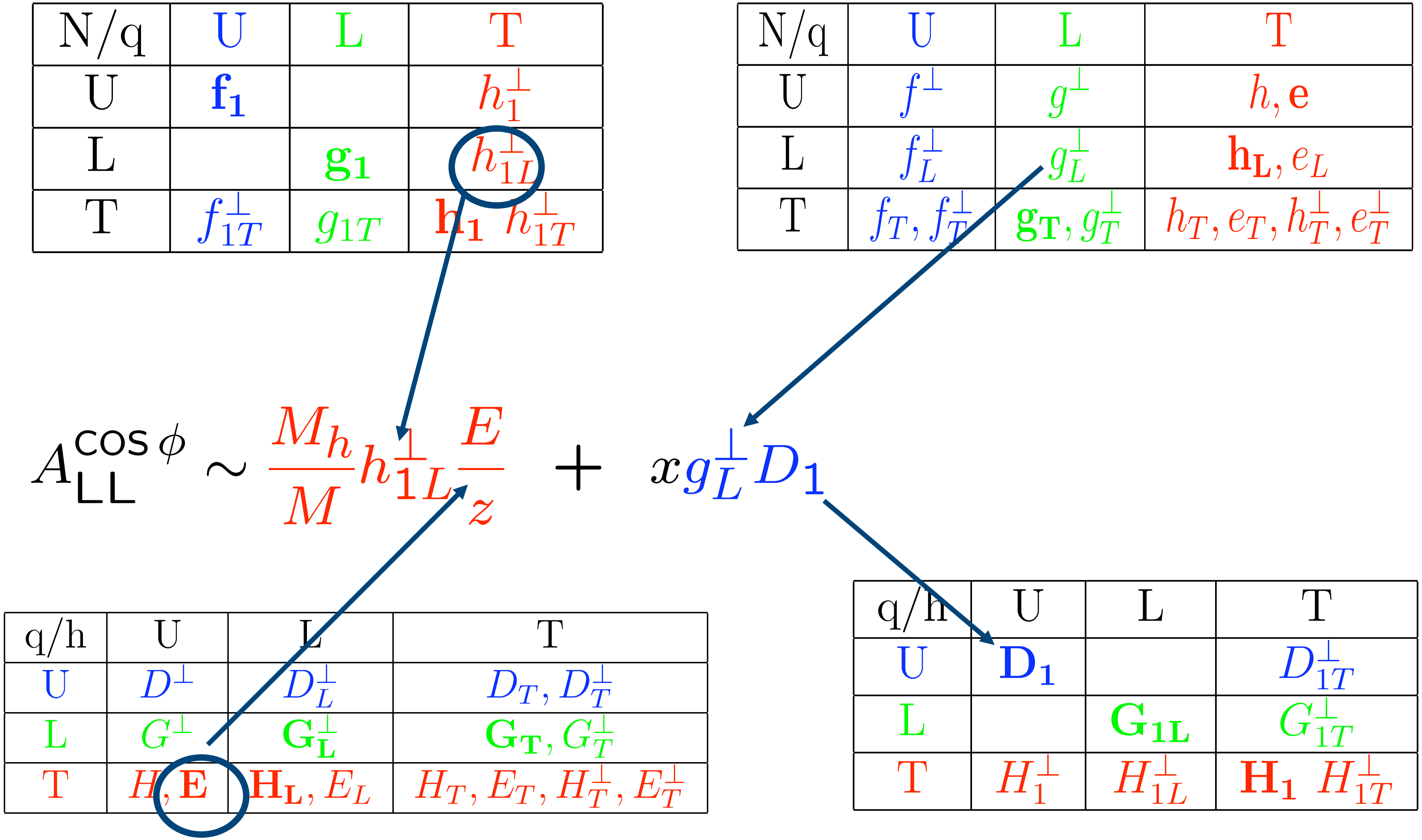
N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{\rm LL}^{\cos\phi} \sim \frac{M_h}{M} g_{1L} \frac{D^\perp}{z} \quad + \quad x e_L H_1^\perp$$

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	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

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

SSA with unpolarized target



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}	$\mathbf{h_1}$ $h_{1T}^\perp$

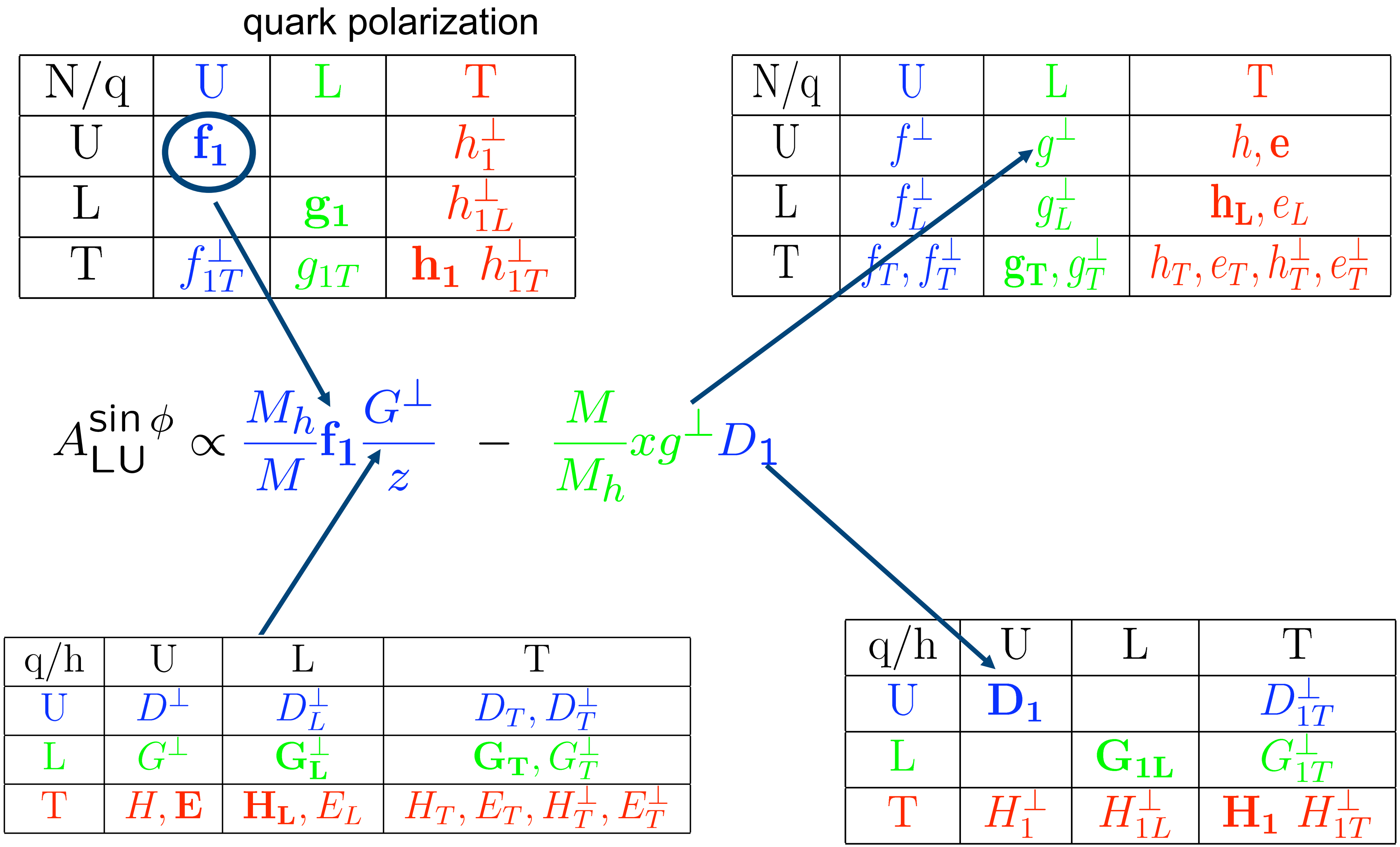
N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{LL}^{\cos\phi} \sim \frac{M_h}{M} h_{1L}^\perp \frac{E}{z} + x g_L^\perp D_1$$

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	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

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

SSA with unpolarized target



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}	$\mathbf{h_1}$ $h_{1T}^\perp$

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	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

$$A_{\mathrm{LU}}^{\sin\phi} \propto \frac{M_h}{M}\mathbf{f_1}\frac{G^\perp}{z} - \frac{M}{M_h} x g^\perp D_1$$

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	$H, \mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

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

SSA with unpolarized target

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}	$\mathbf{h_1}$ $h_{1T}^\perp$

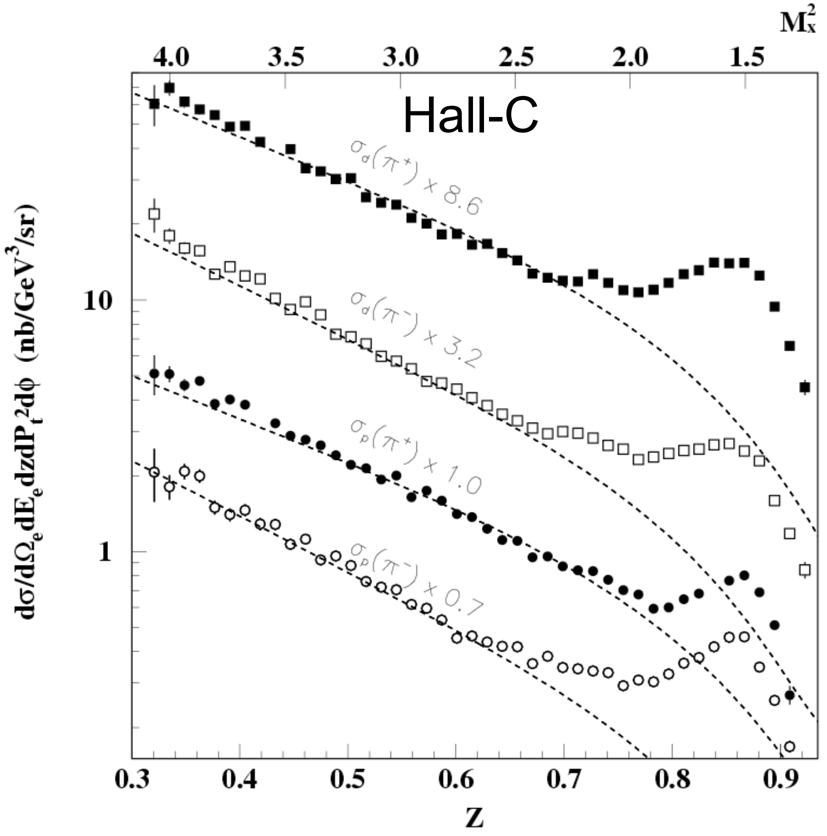
N/q	U	L	T
U	$f^\perp$	$g^\perp$	h, $\mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

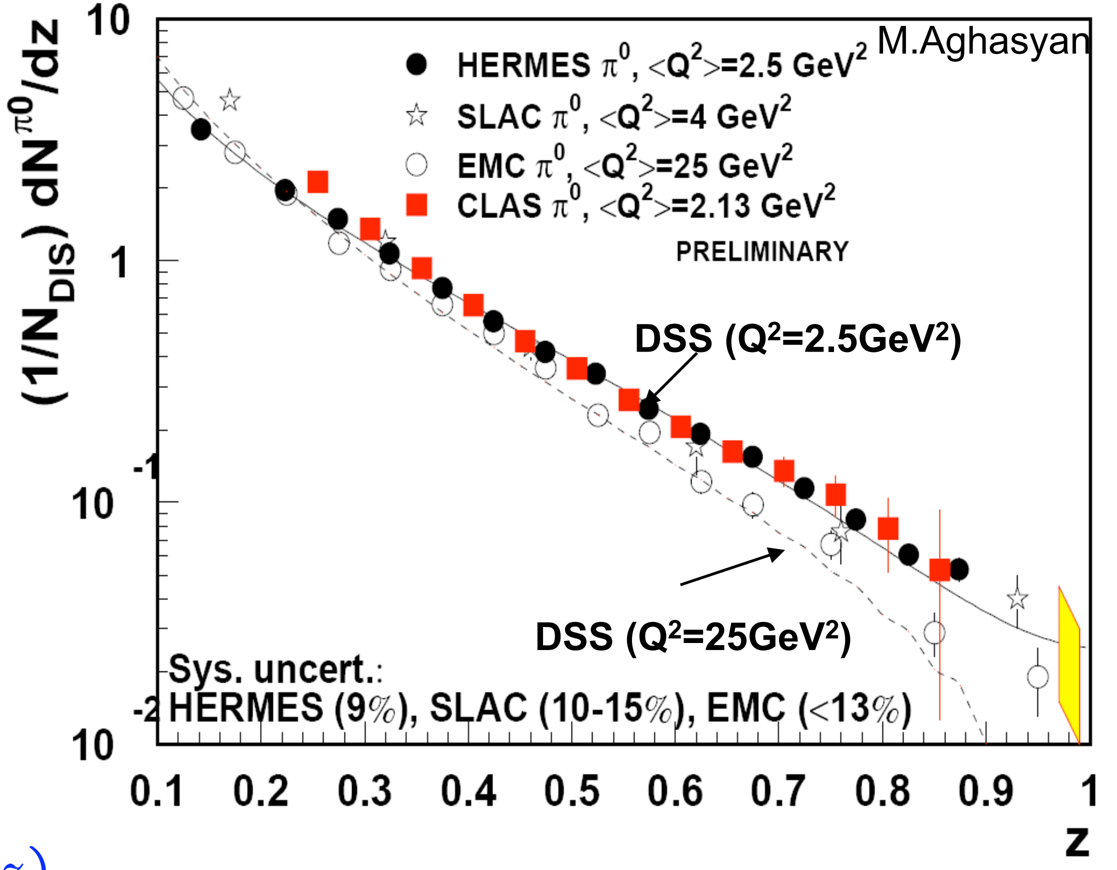
$$A_{\mathrm{LU}}^{\sin\phi} \sim h_1^\perp \frac{E}{z} + x e H_1^\perp$$

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, $\mathbf{E}$	$\mathbf{H_L}, E_L$	$H_T, E_T, H_T^\perp, E_T^\perp$

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

π multiplicities in SIDIS ep→e’πX





$$d\sigma^h \propto \sum f^{H\rightarrow q}(x)\,\mathrm{d}\sigma_q(y)\,D^{q\rightarrow h}(z)$$

$\pi^{+/-}$ multiplicities at large z diverge from SIDIS predictions

π^0 multiplicities less affected by higher twists

0.4<z<0.7 kinematical range, where higher twists are expected to be small

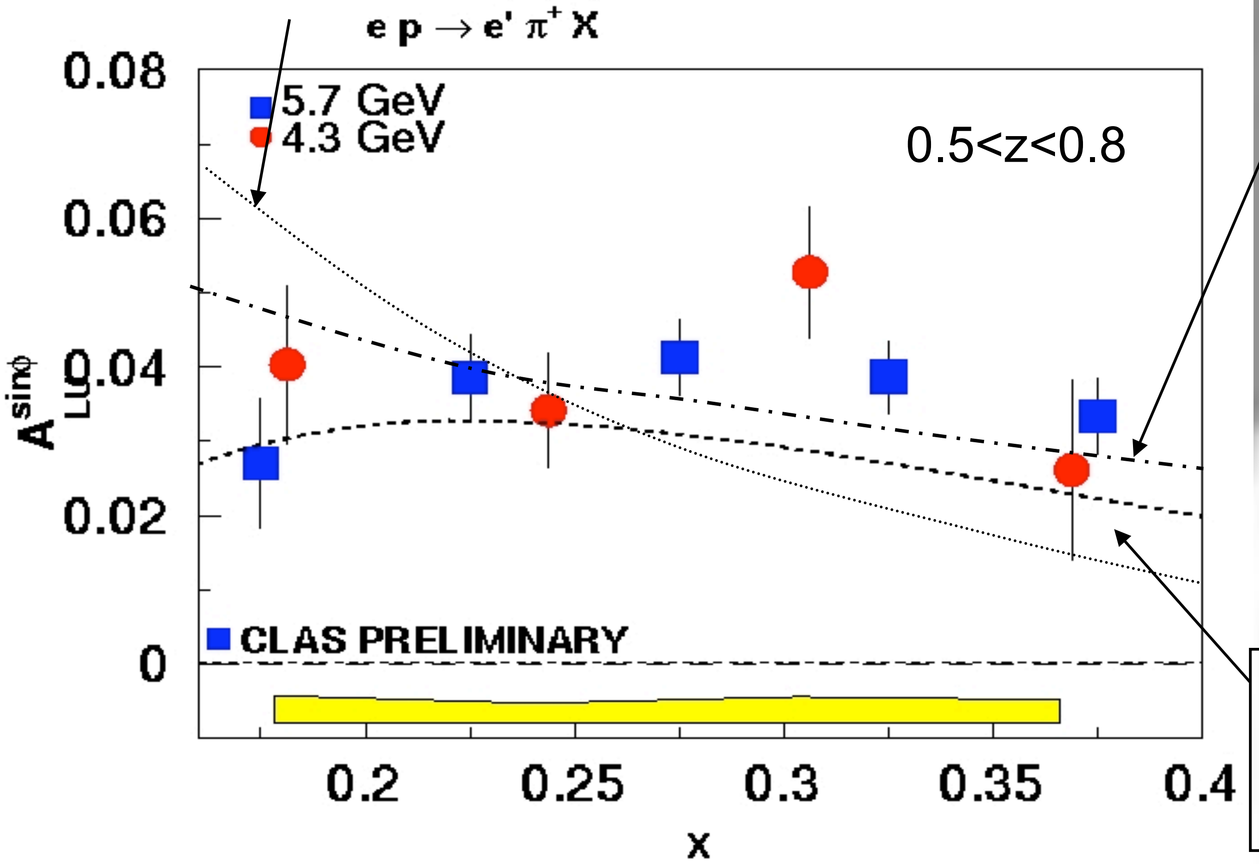
Beam SSA: A_{LU} from CLAS @ JLab

$$A_{UL}^{\sin\phi} \sim g^{\perp} D_1(z)$$

Photon Sivers Effect Afanasev & Carlson, Metz & Schlegel

$$A_{LU}^{\sin\phi} \sim h_1^{\perp}(x) E(z)$$

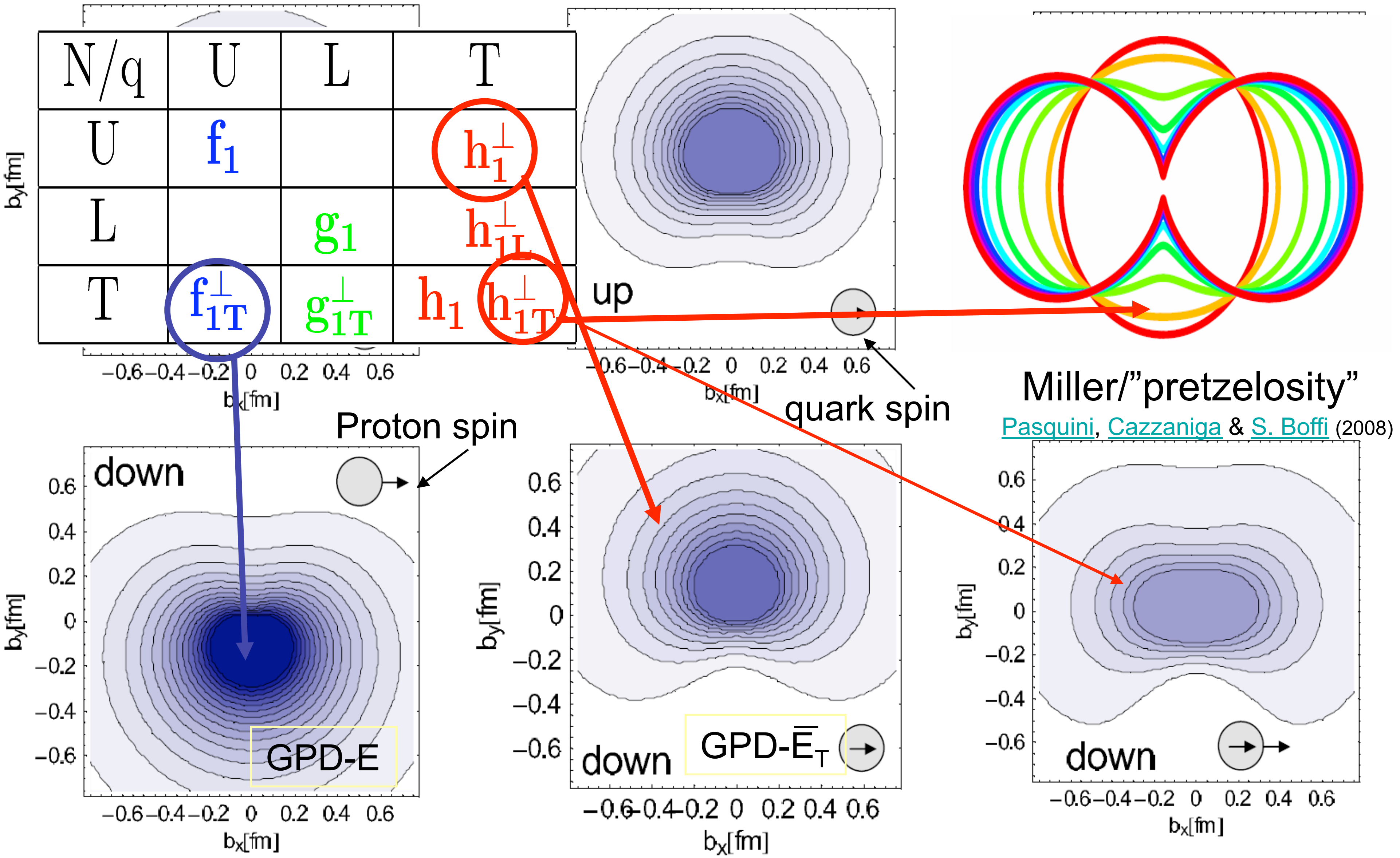
Beam SSA from initial distribution (Boer-Mulders TMD) F.Yuan using $h_1^{\perp}$ from MIT bag model



$$A_{LU}^{\sin\phi} \sim e(x) H_1^{\perp}(z)$$

Beam SSA from hadronization (Collins effect) by Schweitzer et al.

Spin densities from Lattice (QCDSF and UKQCD Collaborations)



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

Miller/"pretzelosity"

Pasquini, Cazzaniga & S. Boffi (2008)

$\vec{H}\cdot\dot{D}$ *as a potential target for electro-production experiments at JLab*

- ***$\gamma+\dot{H}\cdot\dot{D}$ spin-relaxation times: months –to- years at ~0.5^0K and 0.01 –to- 0.9 tesla***
  ⇔ 10 times higher temperature than conventional frozen-spin targets

- ***$e+\dot{H}\cdot\dot{D}$ depolarization mechanisms:***

  (i) beam heating: 5 nA of 10 GeV electrons ⇒ 5 mW heat in 2 cm of HD
  << heating than C_4H_9OH, due to lower Z
  - ample cooling power due to higher holding temperature

  ***(ii) spin-diffusion of paramagnetic centers*:**
  - e brem creates free radicals with randomly oriented nuclear spin;
  absolute number are small, but these can be sinks for polarization
  - spin-diffusion time measured at 2 K: ~ ♀ for $\dot{\boldsymbol{D}}$,
  ~ 1 d for $\dot{\boldsymbol{H}}$ at 2^0K; >> longer at lower T

- ***potential advantages:***
  ⇔ low fields ideal for transverse polarization experiments ⇔ beam not in detector
  ⇔ no dilution in a pure target, very low backgrounds
  ⇔ small bremsstrahlung background due to low Z

- ***$e+\dot{H}\cdot\dot{D}$ test scheduled for Spring, 2011, in CLAS at JLab***

HDice Timeline

HDice Lab – complete design of building modifications – Nov'08

Building construction – Feb – June'09

Install Cryogenic equipment into HDice Lab – beginning June'09

Polarize sets of targets for E06-101 – Mar-June'10; Aug-Dec'10

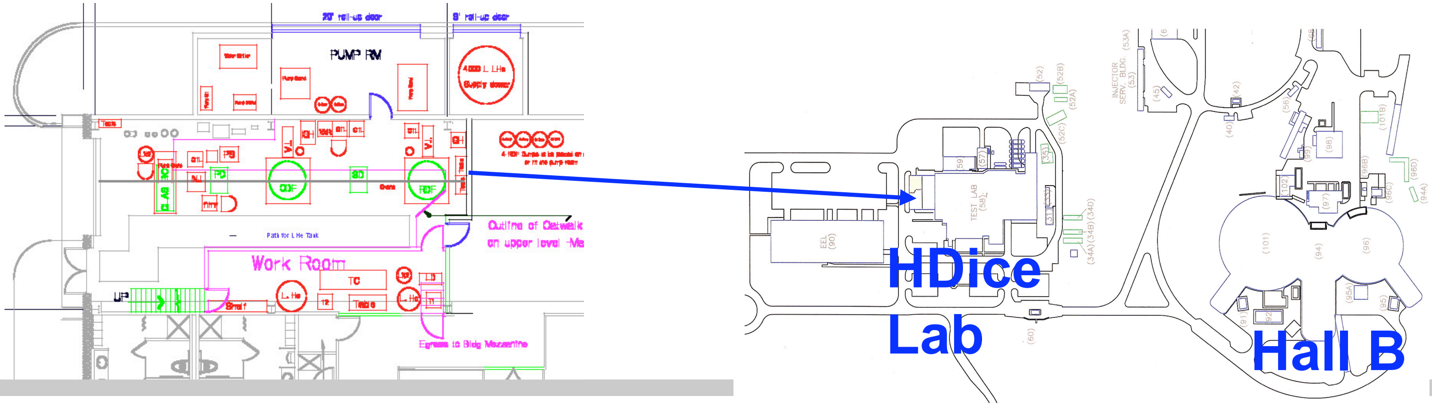
Design/construct new In-Beam Cryostat for CLAS – May'08-July'10

Installation in Hall B – July-Sept'10

E06-101 run: $\vec{\gamma} + \dot{H} \cdot \dot{D}$ **– Sept'10-April'11**

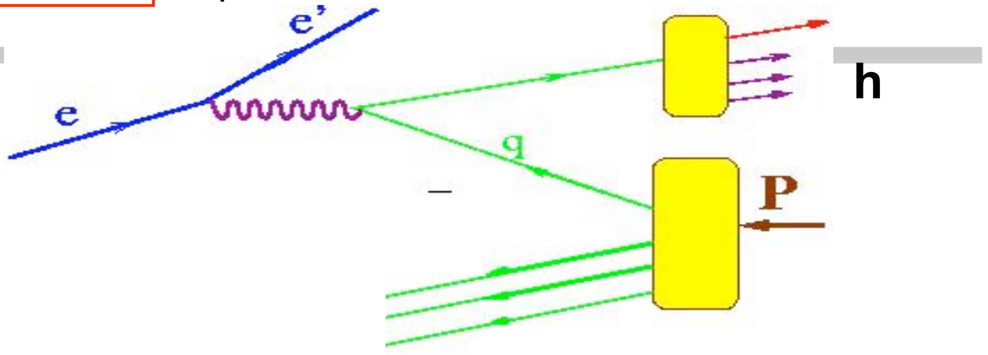
e+HD test – April'11
polarized targets for e+HD DVCS – June-Oct'11

E08-021 run: $\vec{e} + \dot{H} \cdot \dot{D}$ **– Nov-Dec'11**



Single hadron production in hard scattering

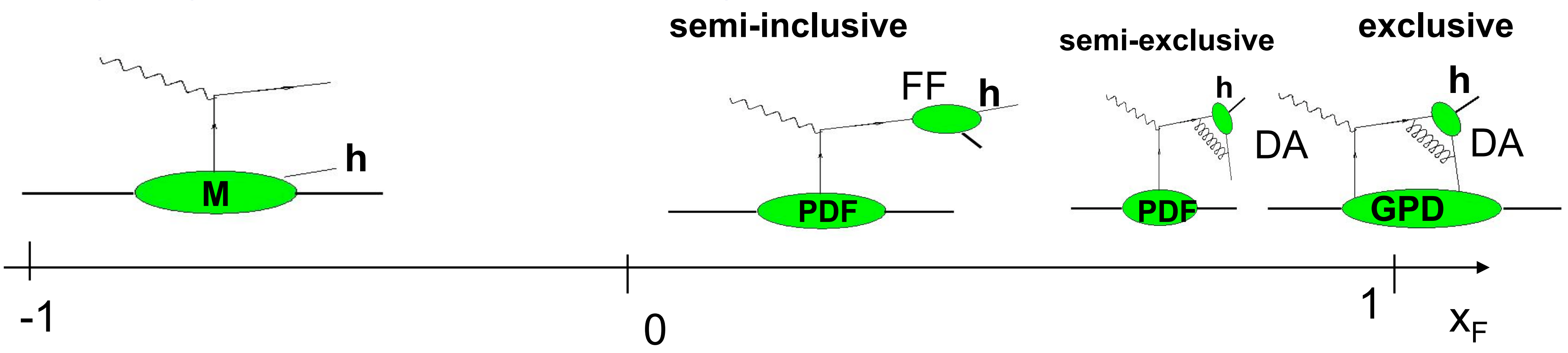
x_F>0 (current fragmentation)



x_F - momentum in the CM frame

Target fragmentation

Current fragmentation



Fracture Functions

k_T-dependent PDFs

Generalized PDFs

Wide kinematic coverage of large acceptance detectors allows studies of hadronization both in the target and current fragmentation regions

CLAS vs CLAS12?

- Existing inconsistencies between HERMES and COMPASS require new independent input. CLAS data will be crucial in developing global analysis of 3D parton distributions, TMDs GPDs and Wigner distributions.
- Study the Q2 dependence of different SSA at fixed Bjorken-x will require measurements with different beam energies, including 6 GeV.
- Virtual photon has some angle with beam direction, so measurements with longitudinal and transverse target are important for each other.
- Enables early understanding of higher order corrections and higher twist contributions.
- CLAS data at 6 GeV will be important to analyze future CLAS12 data (different systematics).
- Reaction asymmetries from events ray traced back to vertex gives tomographic decomposition of target polarization vs e running time.
  -> essential to optimize plans for 12 GeV experiments

Transverse force on the polarized quarks

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	$f_T, f_T^{\perp}$	$\mathbf{g_T}, g_T^{\perp}$	$h_T, e_T, h_T^{\perp}, e_T^{\perp}$

$$e_2 \equiv \int_0^1 dx x^2 \bar{e}(x)$$

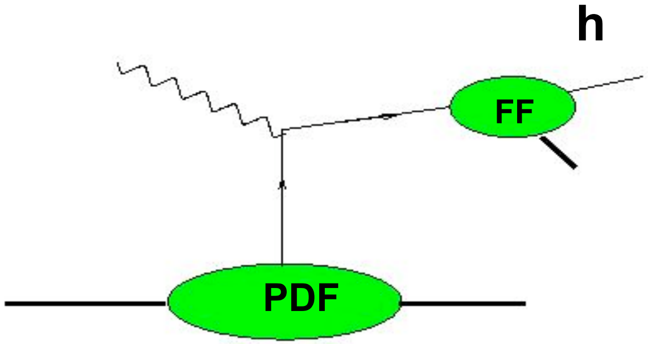
$$F^y(0) = \frac{M^2}{2} e_2$$

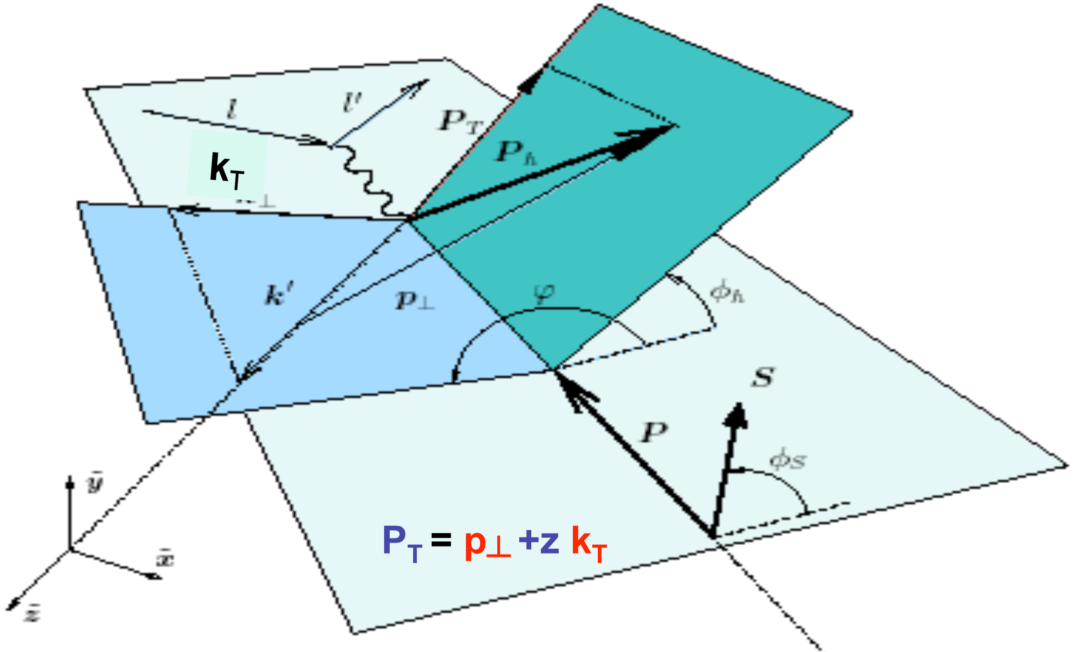
Quark polarized in the x-direction with k_T in the y-direction

Force on the active quark right after scattering (t=0)

Interpreting HT (quark-gluon-quark correlations) as force on the quarks (Burkardt hep-ph:0810.3589)

Transverse momentum of hadrons





$P_T = p_\perp + z\, k_T$

$$d\sigma^h \propto \sum q(x, k_T) \otimes \mathrm{d}\sigma_f(y) \otimes D^{q\to h}(z, p_\perp)$$

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

$$\sigma_{UU} = \frac{\pi}{xy^2}[1+(1-y)^2]\Sigma_q e_q^2 \int d^2\mathbf{k}_T^2\, f_1^q(x, \mathbf{k}_T) D_1^{q\to h}(z, \mathbf{P}_T - z\mathbf{k}_T)$$

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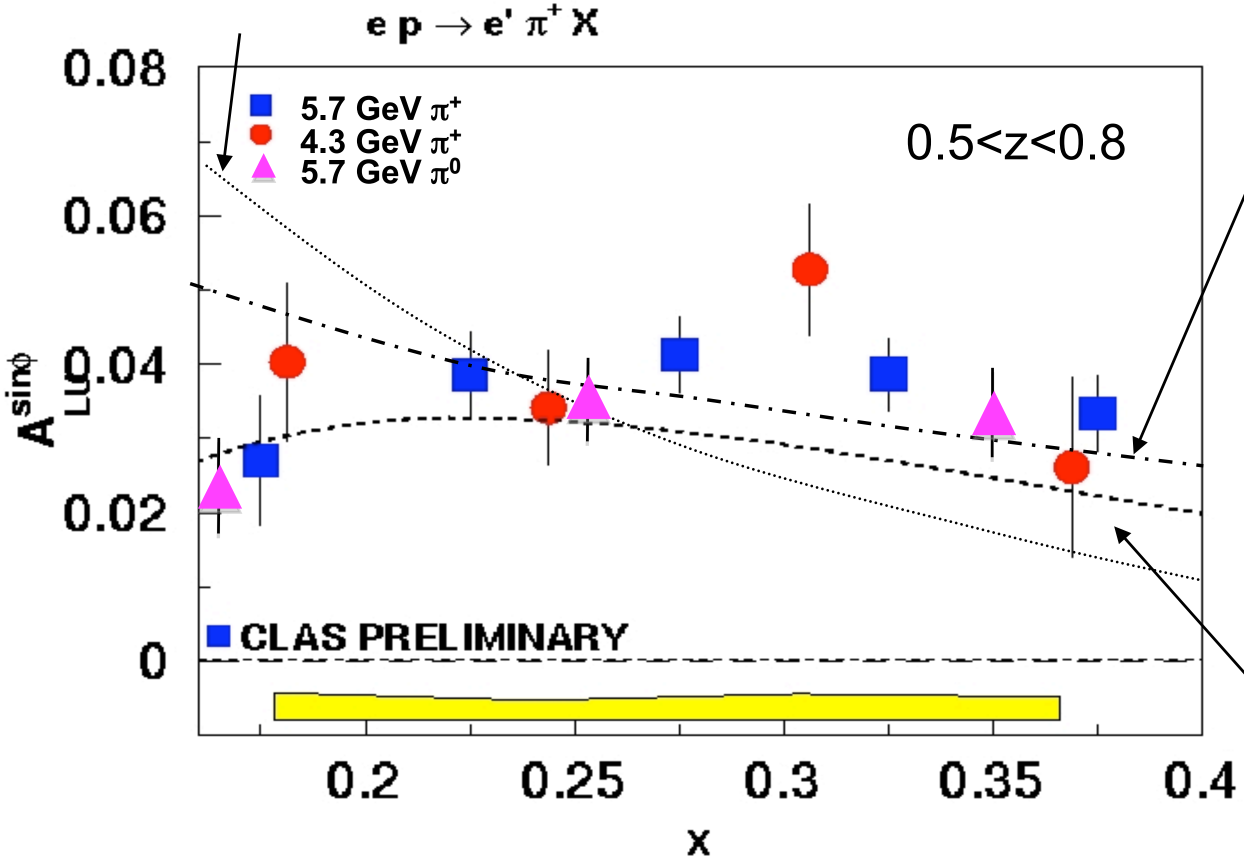
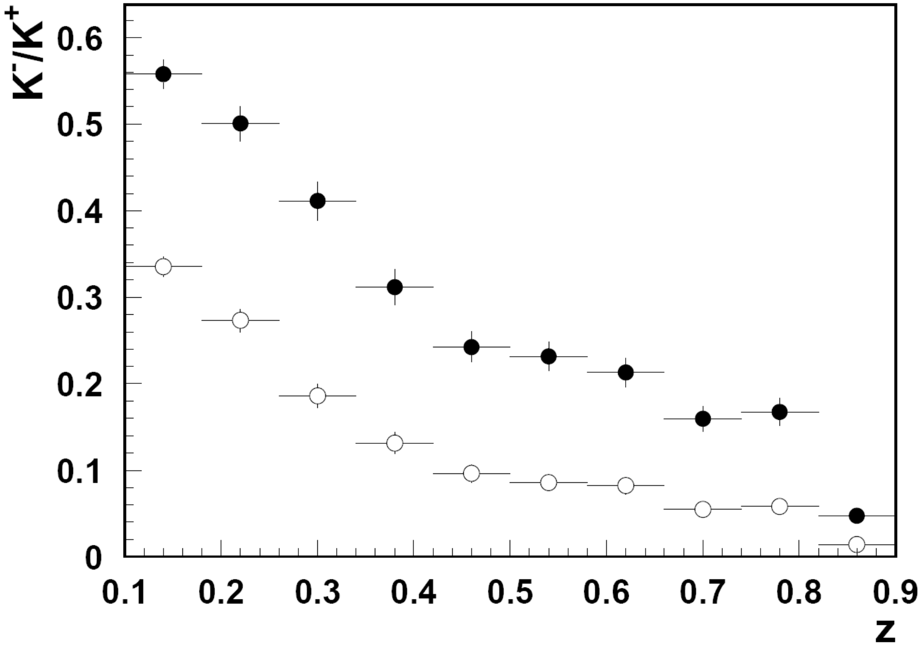


$$A_{LU}^{\sin\phi} \sim e(x) H_1^{\perp}(z)$$

Beam SSA from hadronization (Collins effect) by Schweitzer et al.

Beam SSA for π^0 and π^+ are comparable indicating small Collins type contributions

Inbendin/outbending configurations



Different polarities increase the acceptance of positive and negative hadrons.