Transverse Spin Physics with CLAS12

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Workshop on Partonic Transverse Momentum in Hadrons:
Quark Spin-Orbit Correlations and Quark-Gluon Interactions

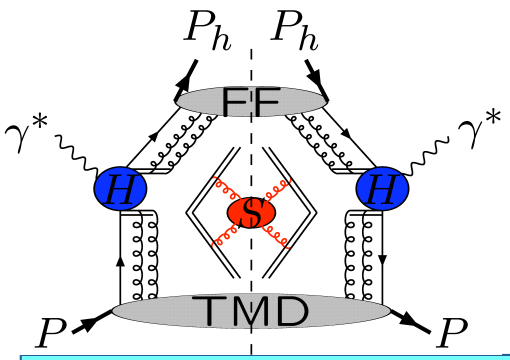
March 12-13, 2010 Duke University

Partonic Transverse Momentum

Quantum Phase-Space Distributions of Quarks

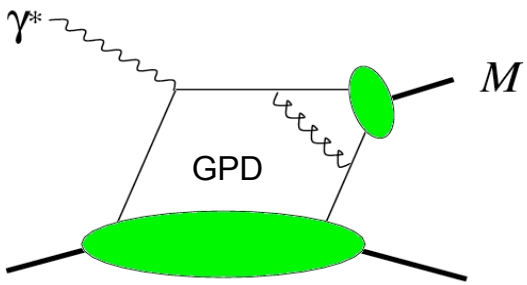
$W_p^u(x,k_T,r)$ "Mother" Wigner distributions

Probability to find a quark u in a nucleon P with a certain polarization in a position r & momentum k



d^3r

d^2k_T (FT)



TMD PDFs: $f_p^u(x,k_T)$,…

GPDs: $H_p^u(x,\xi,t)$, …

$f_1^q(x,\mathbf{k}_\perp)$ g_1^q $f_{1T}^{\perp q}$ g_{1T}^q
h_1^q $h_{1T}^{\perp q}$ $h_{1L}^{\perp q}$ $h_1^{\perp q}$

d^2k_T

$\xi=0,t=0$

dx

$H^q(x,\xi,t)$ $\tilde{H}^q$ E^q $\tilde{E}^q$
H_T^q $\tilde{H}_T^q$ E_T^q $\tilde{E}_T^q$

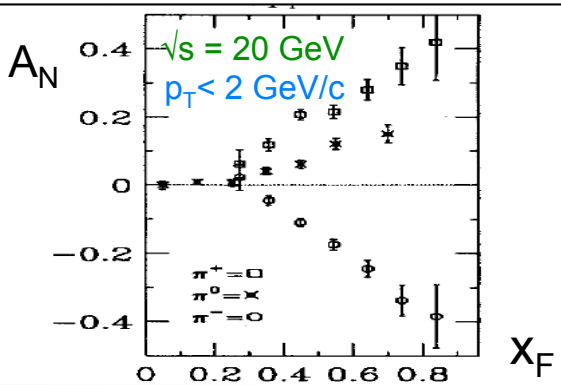
Form Factors
$F_{1p}^u(t)$,$F_{2p}^u(t)$..

Measure momentum transfer to quark
Direct info about momentum distributions

Measure momentum transfer to target
Direct info about spatial distributions

PDFs $f_p^u(x)$,…

SSA



Proton spin puzzle

$$\frac{1}{2} = \frac{1}{2}\sum_f (q_f^+ - q_f^-) + L_q + \Delta G + L_g$$

TMD correlators

Distribution Functions (DF)				
		quark		
		U	L	T
nucleon	U	q		$h_1^\perp$
	L		g_{1L}	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1 $h_{1T}^\perp$

Off-diagonal elements are important objects:

Interference between wave functions with different angular momenta: contains infos about parton orbital angular momenta

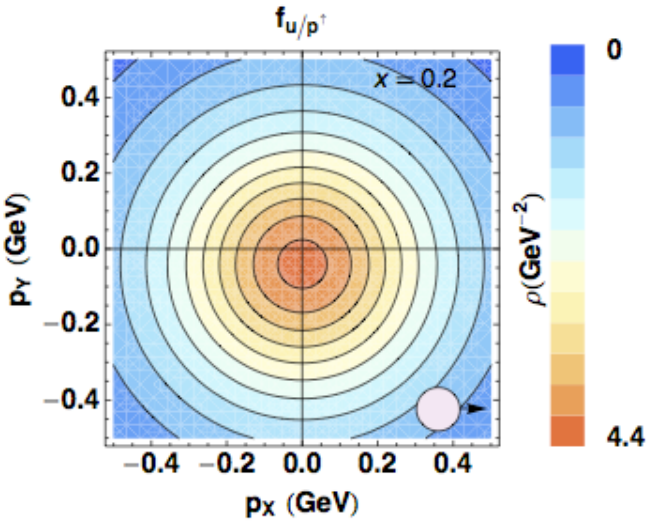
Testing QCD at the amplitude level

→ sign change between DY and SIDIS
- universality of TMDs

Fundamental prediction of QCD !

3D description in momentum space

PRD 78 (2008) 074010



Fragmentation Functions (FF)				
		quark		
		U	L	T
nucleon	U	D_1		$H_1^\perp$
	L		G_{1L}	$H_{1L}^\perp$
	T	$D_{1T}^\perp$	G_{1T}	H_1 $H_{1T}^\perp$

The 3D description of the nucleon

Distribution Functions (DF)				
		quark		
		U	L	T
nucleon	U	q		$h_1^\perp$
	L		Δq	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	δq, $h_{1T}^\perp$

BOER-MULDERS

Spin orbit effect

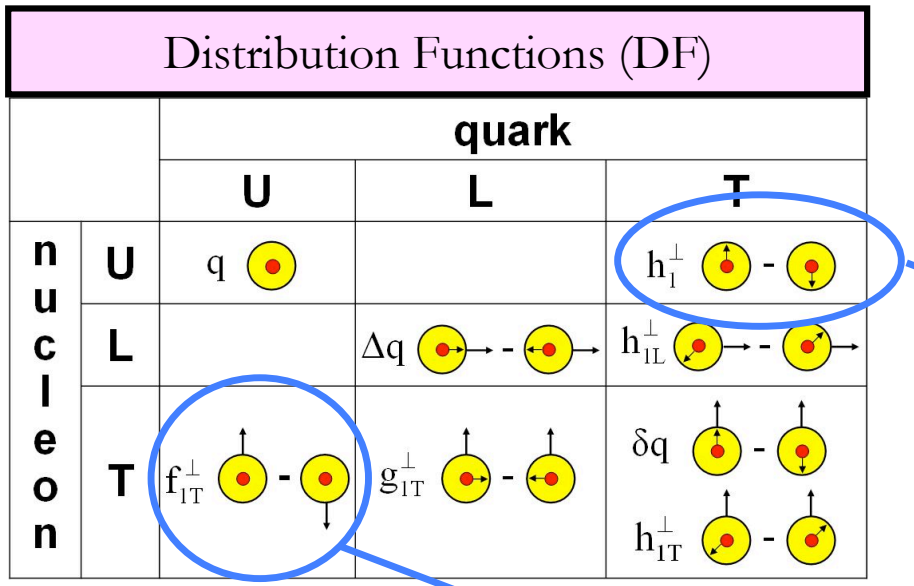
SIVERS

Quark orbital angular momentum

Impact parameter space

3-momentum space

The 3D description of the nucleon



BOER-MULDERS

Spin orbit effect

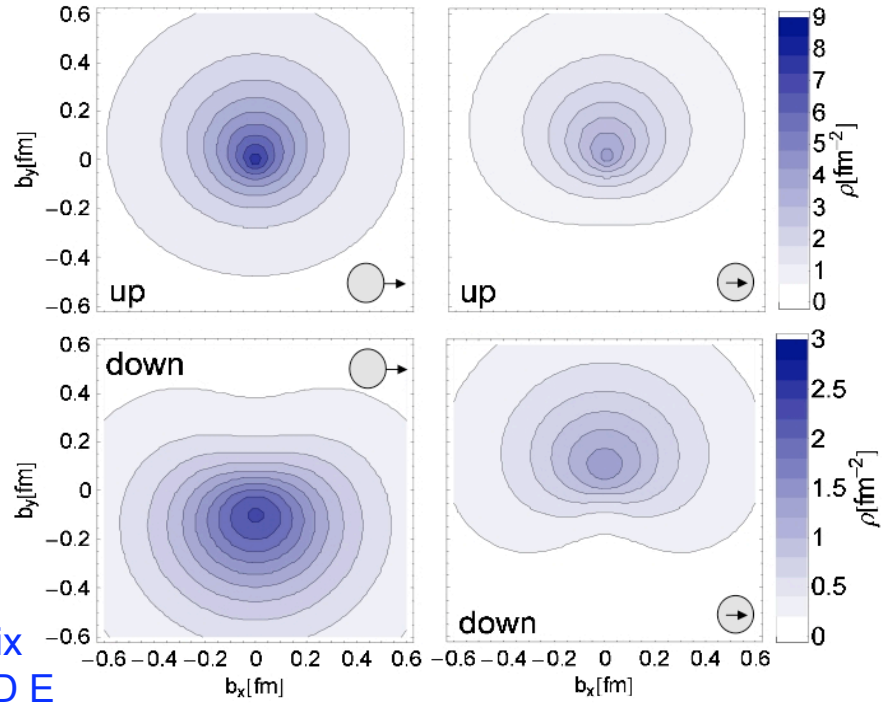
$$h_1^{\perp q} \sim -\kappa_T^q$$

Impact parameter space

Deformations by

GPD E

GPD $E_T+2\tilde{H}_T$

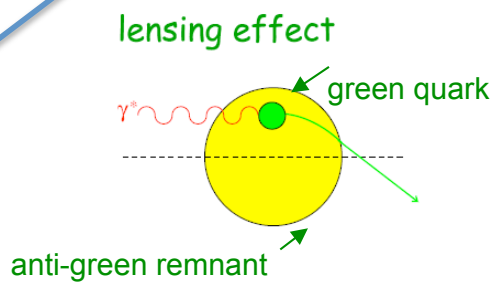


SIVERS

Quark orbital angular momentum

$$f_{1T}^{\perp q} \sim -\kappa^q$$

3-momentum space



i.e. Sivers: spin-orbit correlations with same matrix element of anomalus magnetic moment, and GPD E

Correlation Functions and SIDIS

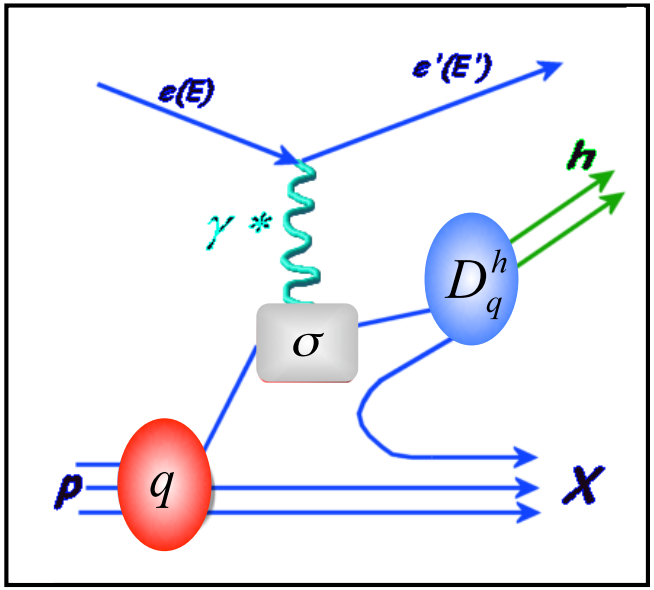
Distribution Functions (DF)

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

Fragmentation Functions (FF)

		quark		
		U	L	T
nucleon	U	D_1		$H_1^\perp$

$$\Lambda_{QCD} \sim P_T \ll Q$$



$$\sigma^{ep\to ehX} = \sum_q q(x) \otimes \sigma^{eq\to eq} \otimes D_q^h(z)$$

Rich phenomenology but rather involved observables

Target type and hadron ID provide flavor tagging !!

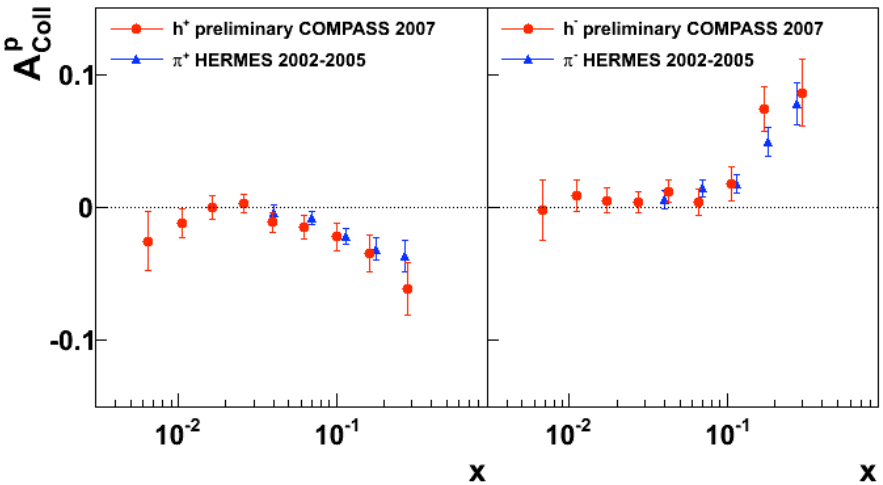
→ constrain valence and sea

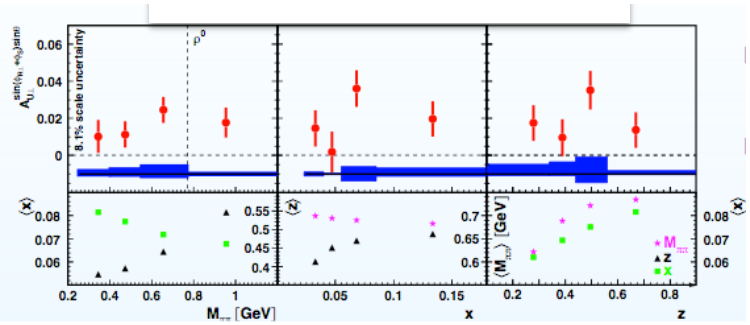
Multidimensional analysis resolves kinematic correlations !!

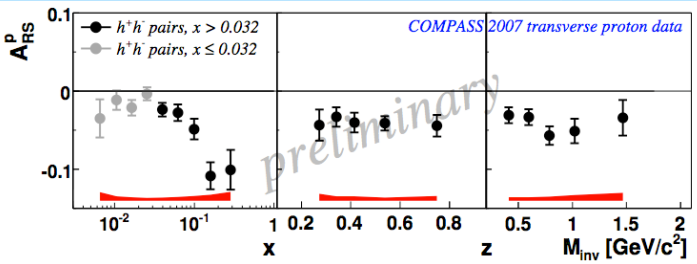
→ disentangle distribution and fragmentation functions (test factorization, HT)

Several observables already measured… with matches and mismatches

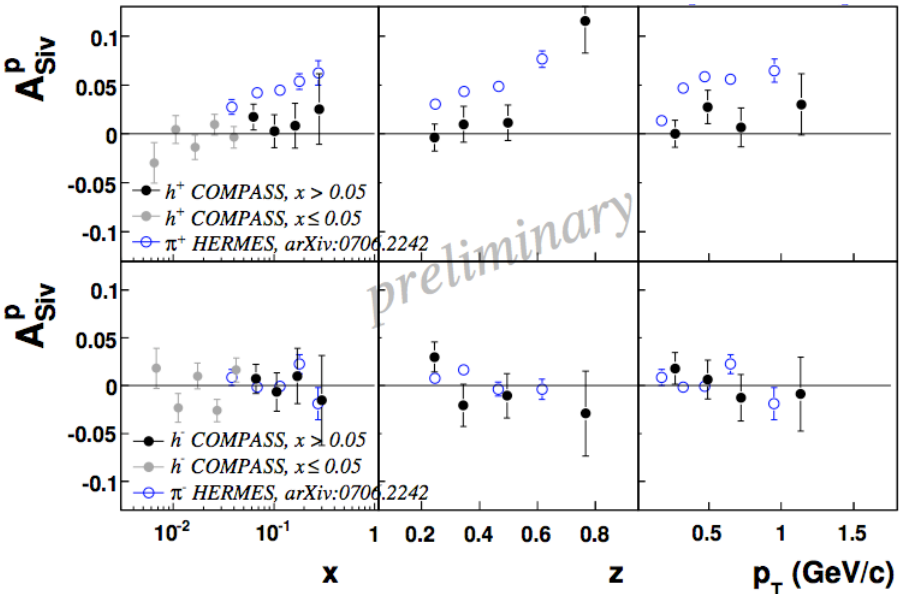
Collins



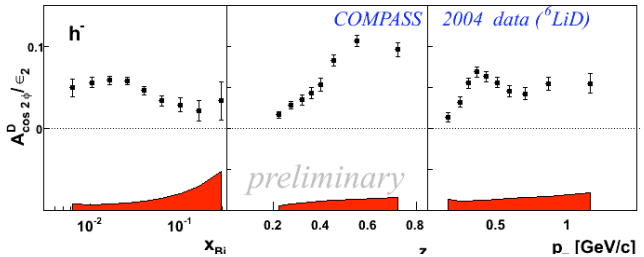


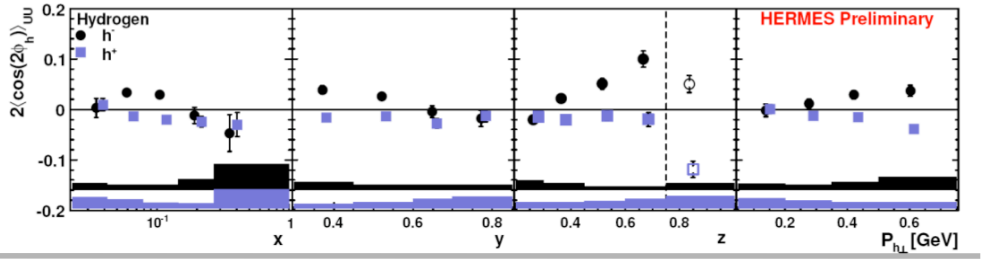


Sivers



Boer-Mulders





Executive summary

TMDs are a new class of phenomena
providing novel insights into the rich nuclear structure

Non-zero results from DIS experiments
provide promises but also open questions

Limited knowledge on transverse momentum dependences

Flavor decomposition often missing

Evolution properties to be defined

Role of the higher twist to be quantified

Universality ⟷ Fundamental test of QCD

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Universality ⟷ Fundamental test of QCD

Still incomplete phenomenology is asking for new inputs

Crucial: completeness
flavor tagging and five-fold differential
extraction in all variables
(x,z,Q^2,P_T) to have
all dependencies resolved

JLAB 12

NSAC 2007 Long Range Plan

Reccomendation 1

We recommend the completion of the 12 GeV Upgrade at Jefferson Lab.

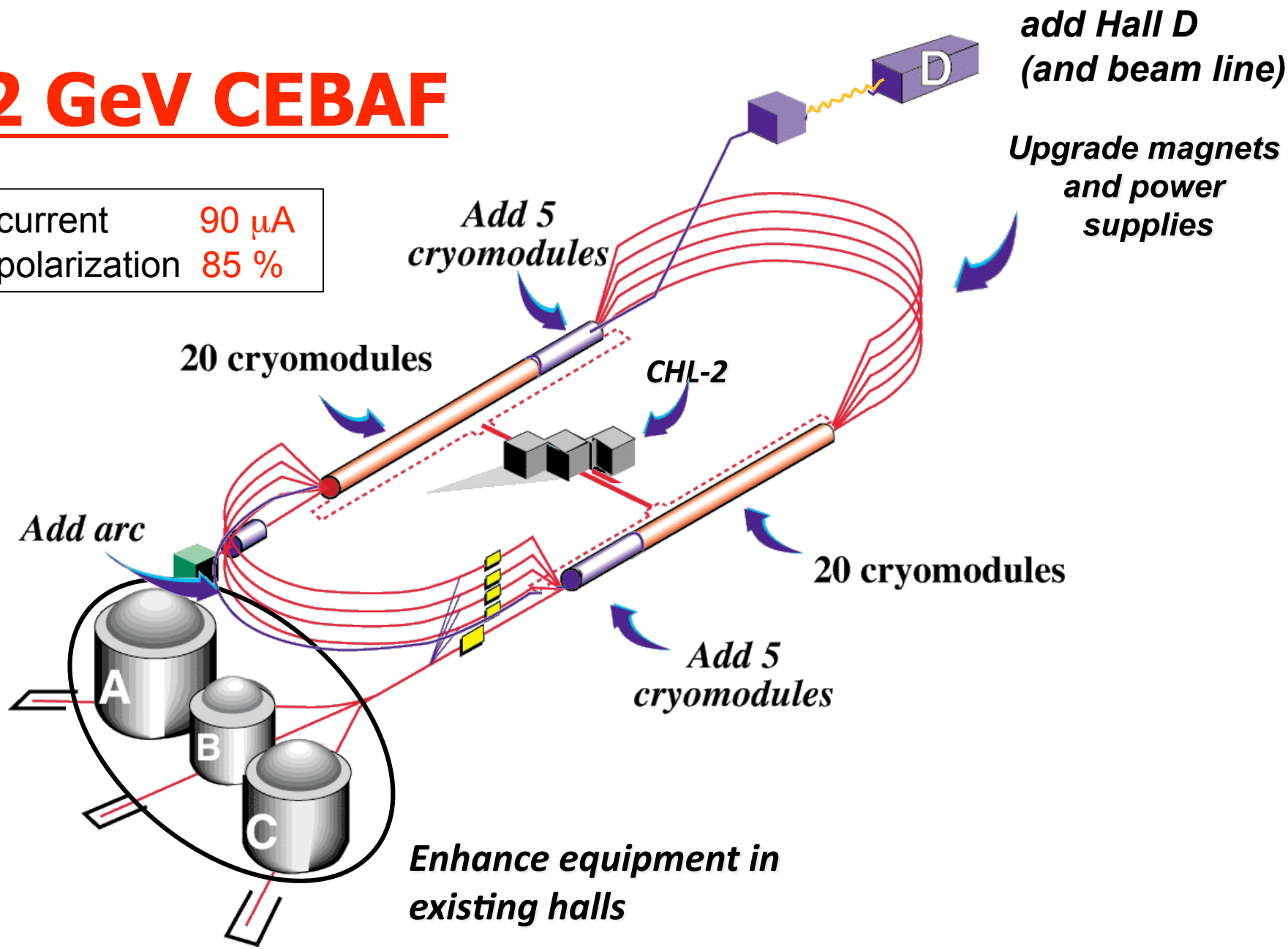
- It will enable three-dimensional imaging of the nucleon, revealing hidden aspects of its internal dynamics.

- It will complete our understanding of the transition between the hadronic and the quark/gluon descriptions of nuclei.

- …

12 GeV CEBAF

Beam current	90 μA
Beam polarization	85 %



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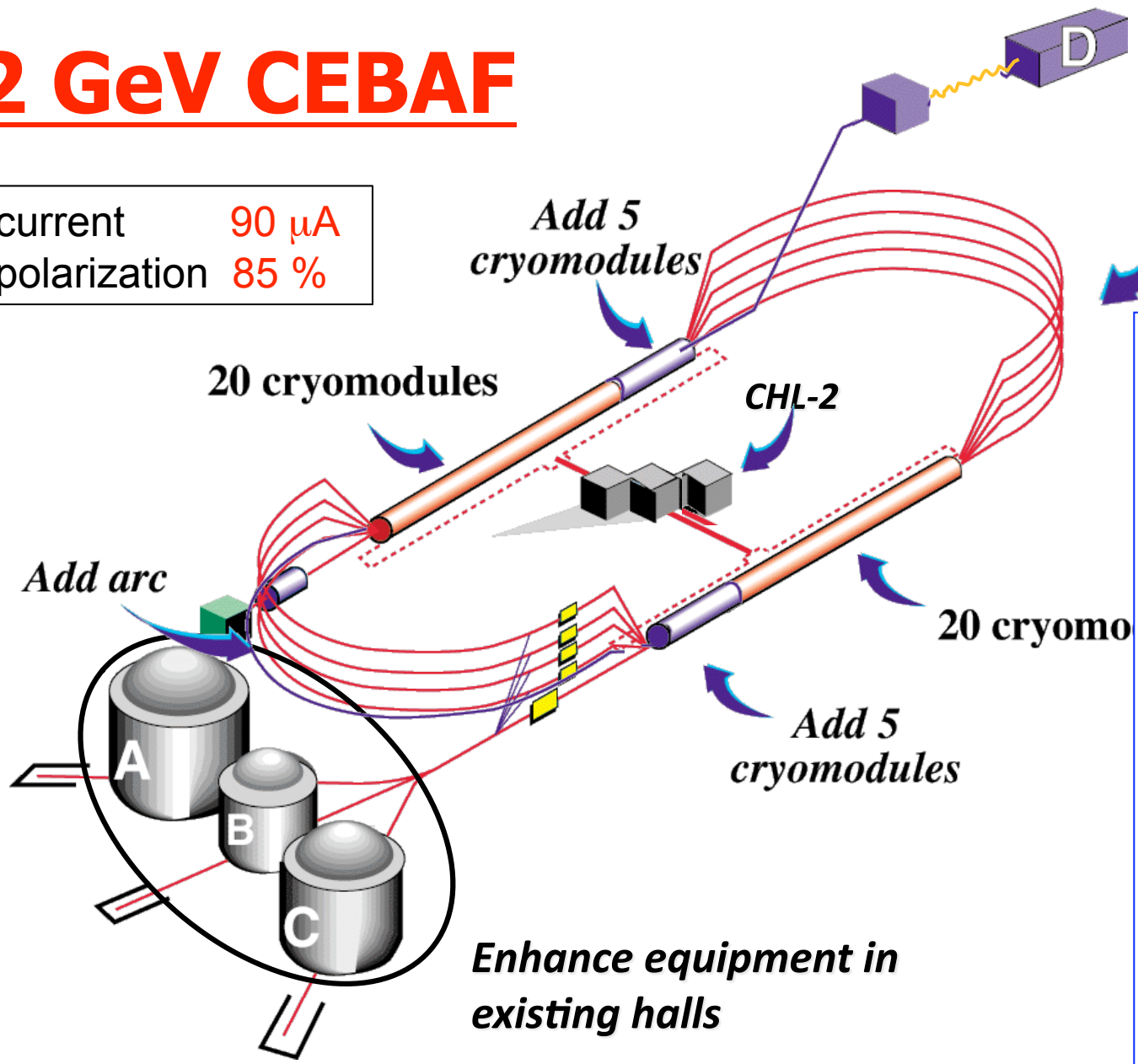


add Hall D (and beam line)

Upgrade magnets and power supplies

Enhance equipment in existing halls

2008-2014:
Construction ***(funded at 99%)***

May 2012
6 GeV Accelerator Shutdown starts

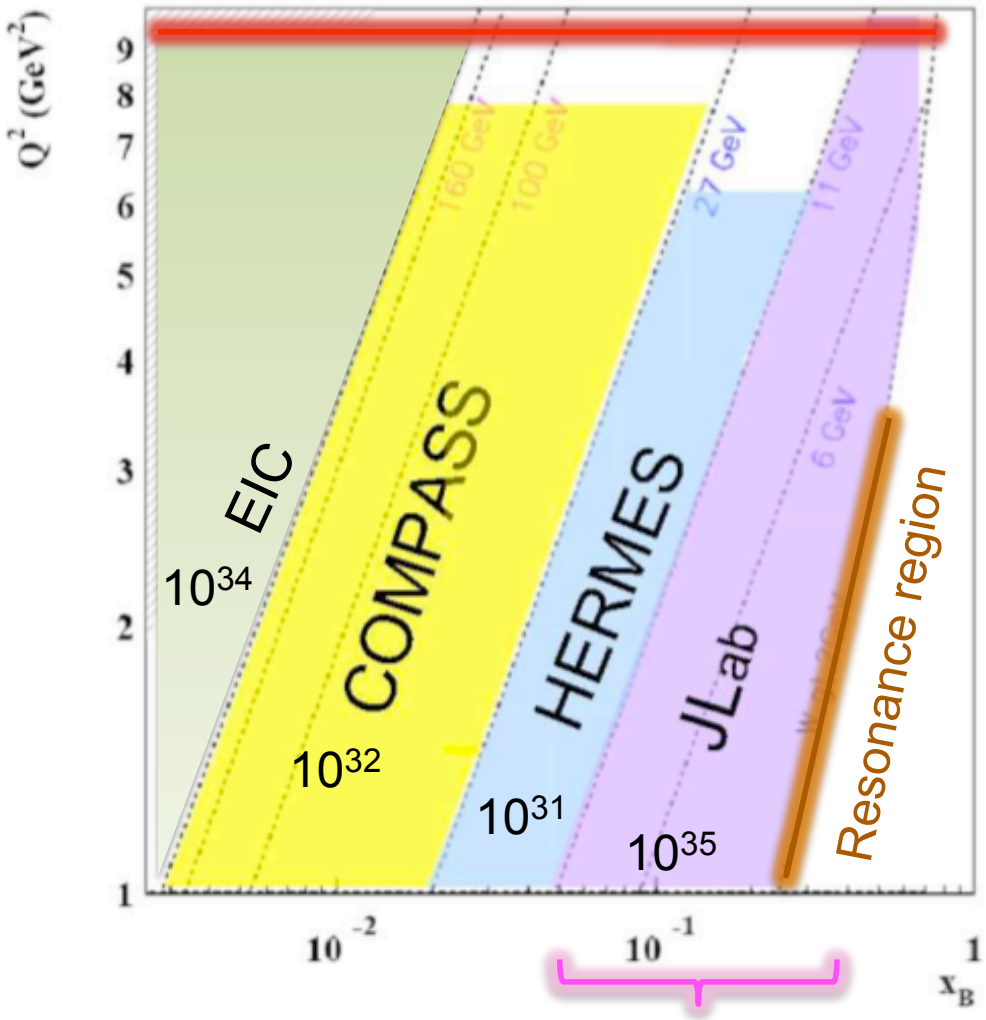
May 2013
Accelerator Commissioning starts

October 2013
Hall Commissioning starts

2013-2015
Pre-Ops (beam commissioning)

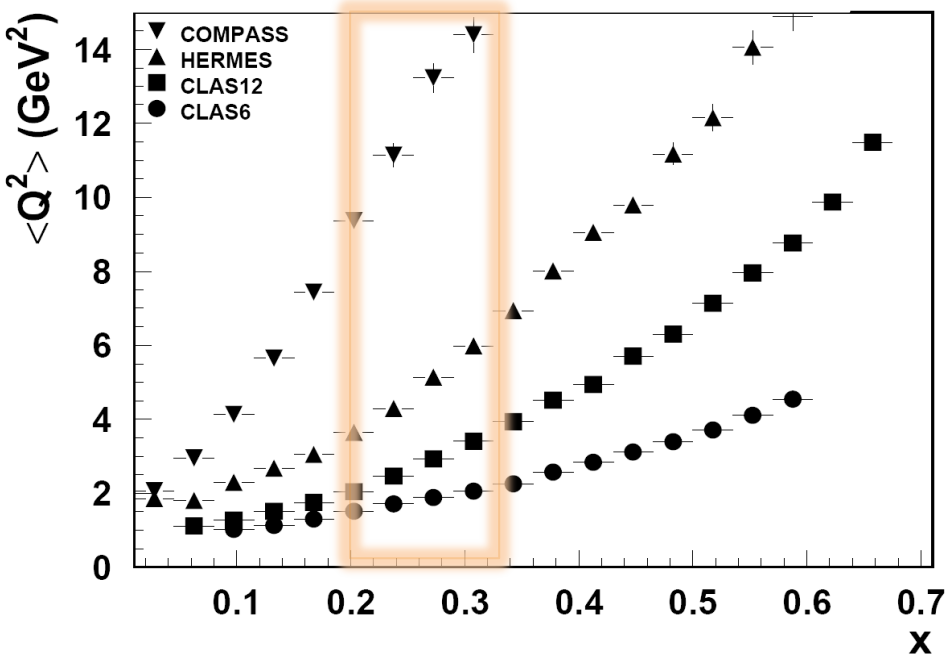
The SIDIS landscape

Limit defined by luminosity



Matches valence

Different Q2 for same x range



Complementary experiments

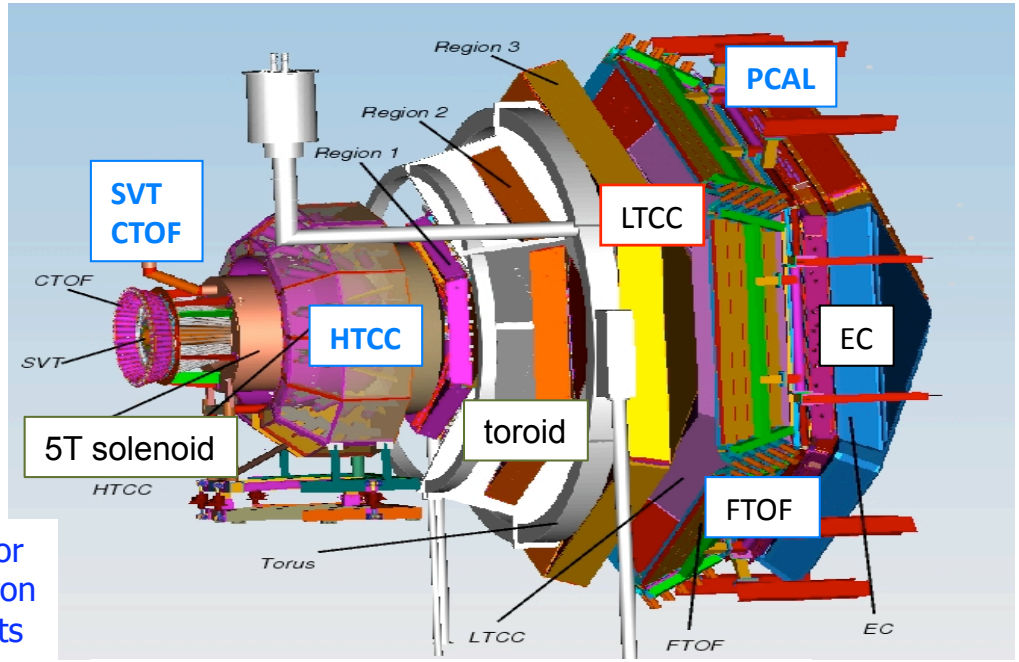
CLAS12

$L \sim 10^{35}\ cm^{-2}s^{-1}$

10 nA electron beam
85% beam polariz

NH_3 ND_3 target
85 % polarization

multi-purpose detector for fixed target electron scattering experiments



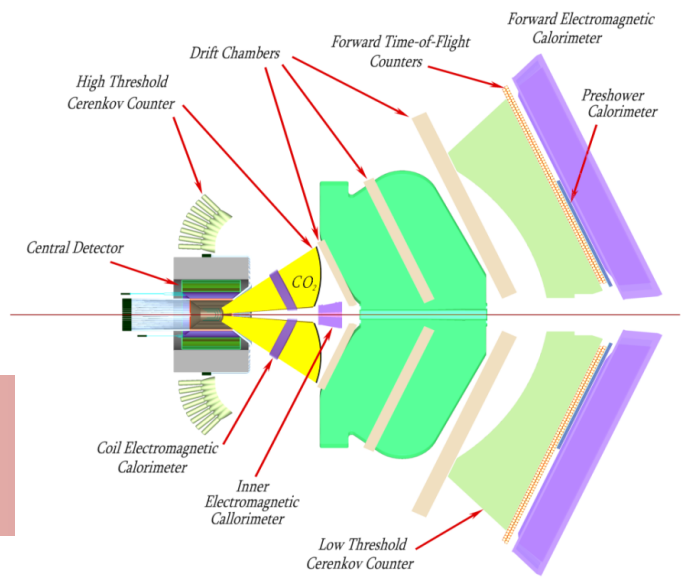
large luminosity

H and D targets

broad kinematical range

Pion and kaon, …. SSA

$Q^2>1GeV^2$
$W^2>4\ GeV^2$
$y<0.85$
$M_X>2GeV$



Wide detector acceptance allows current & target fragmentation measur.

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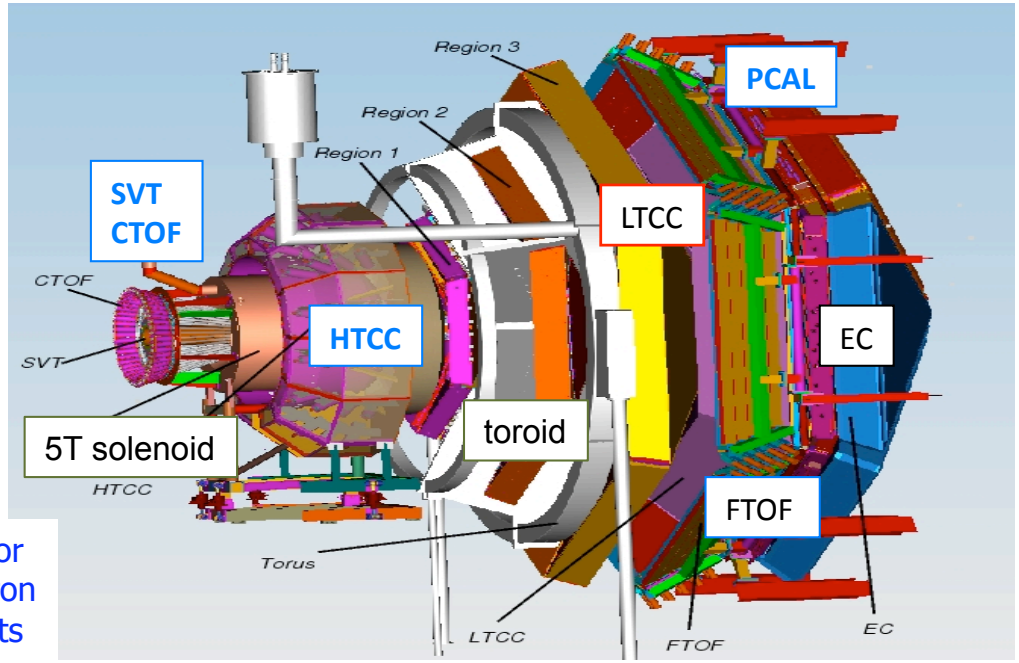

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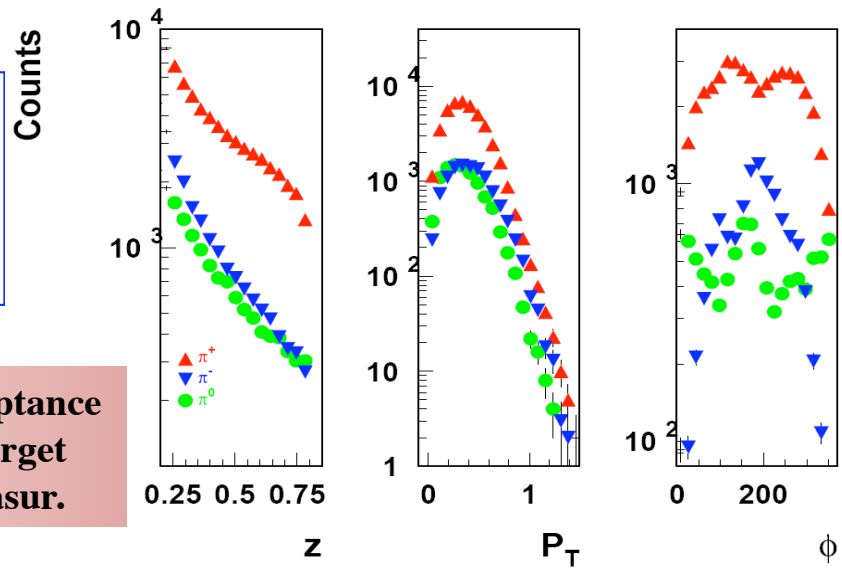


Wide detector acceptance allows current & target fragmentation measur.

Large kinematic ranges accessible with CLAS12 are important for separation of
- Valence region
- Higher Twist contributions (Q^2)
- Perturbative regime ($P_T \geq 1$)

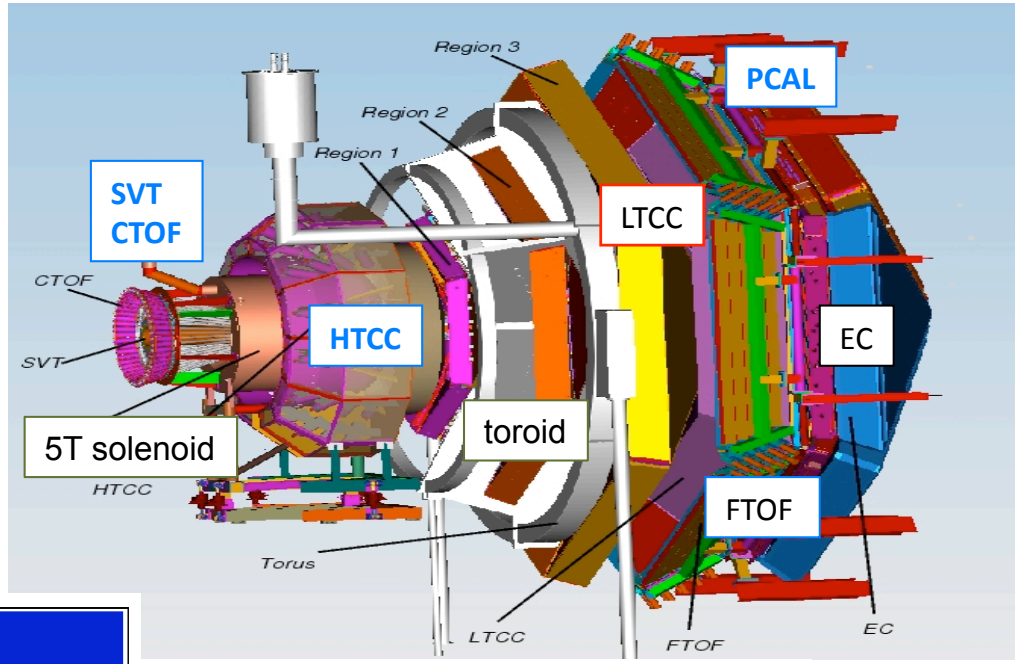
High luminosity important for
- Multidimensional analysis
- Test factorization
- Reduce systematic

CLAS12

$L \sim 10^{35}\ cm^{-2}s^{-1}$

10 nA electron beam
85 % polarization

NH_3 ND_3 target
85 % polarization



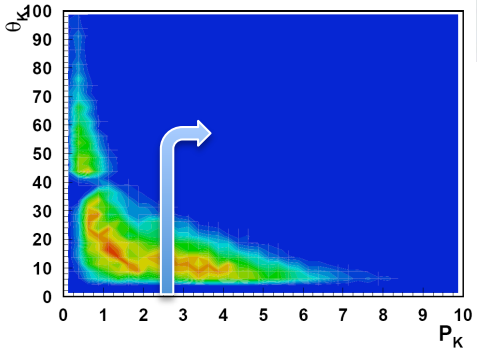
large luminosity

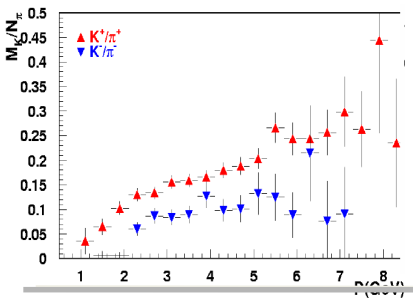
H and D targets

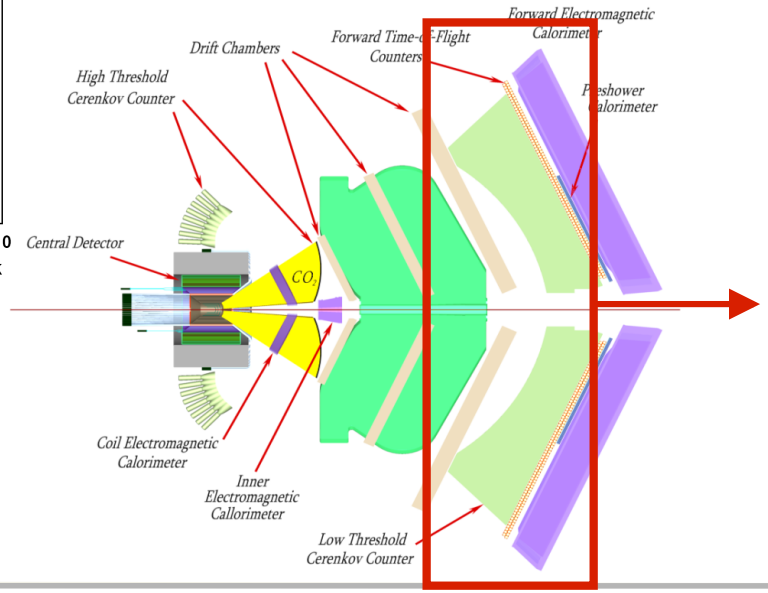
broad kinematical range

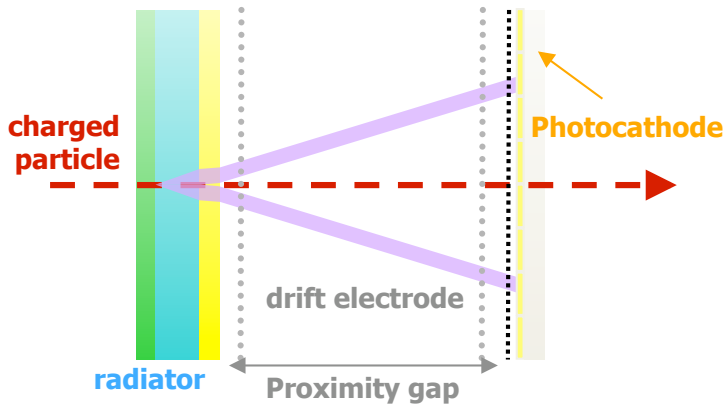
Pion and kaon, …. SSA

Replace 2 sectors of LTCC with a proximity RICH detector to identify Kaons approved by JLab PAC34









TMDs with Unpolarized Targets

TMD correlators

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}$$

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

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

$$+|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)+\varepsilon\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

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

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

Distribution Functions (DF)

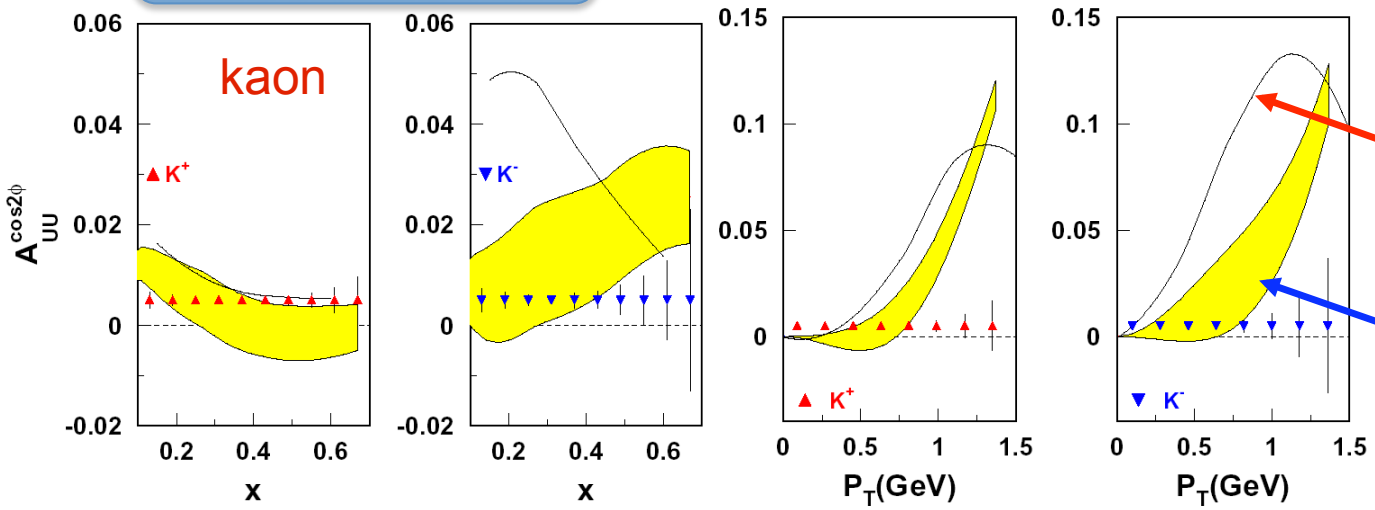
		quark		
		U	L	T
nucleon	U	q		$h_1^\perp$
	L		g_{1L}	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

Unpolarized target @ CLAS12

$$F_{UU}^{\cos 2\phi} \propto h_1^{\perp} H_1^{\perp}$$

Boer-Mulders spin-orbit effect

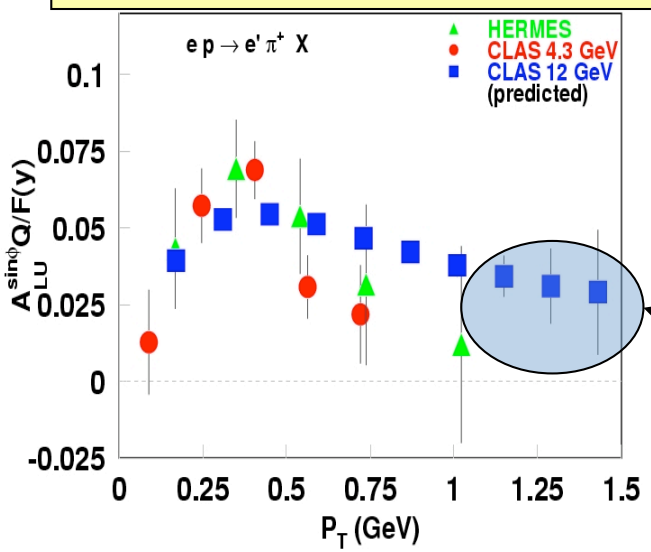
56 d @ 10^{35} $s^{-1}cm^{-2}$
LH_2 LD_2 targets



Line: Phys Rev D78 045022
Boer-Mulders from Sivers
Collins from e+e- data

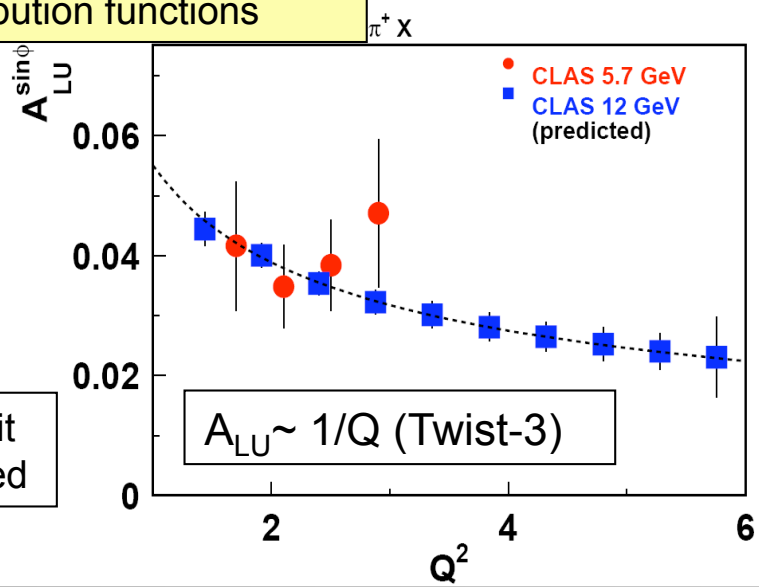
Band: Phys Rev D78 034035
Boer-Mulders from DY data
Collins from chiral limit

Measurements of kinematic (x, Q^2, z, P_T) will probe HT distribution functions



P_{beam} = 85 %

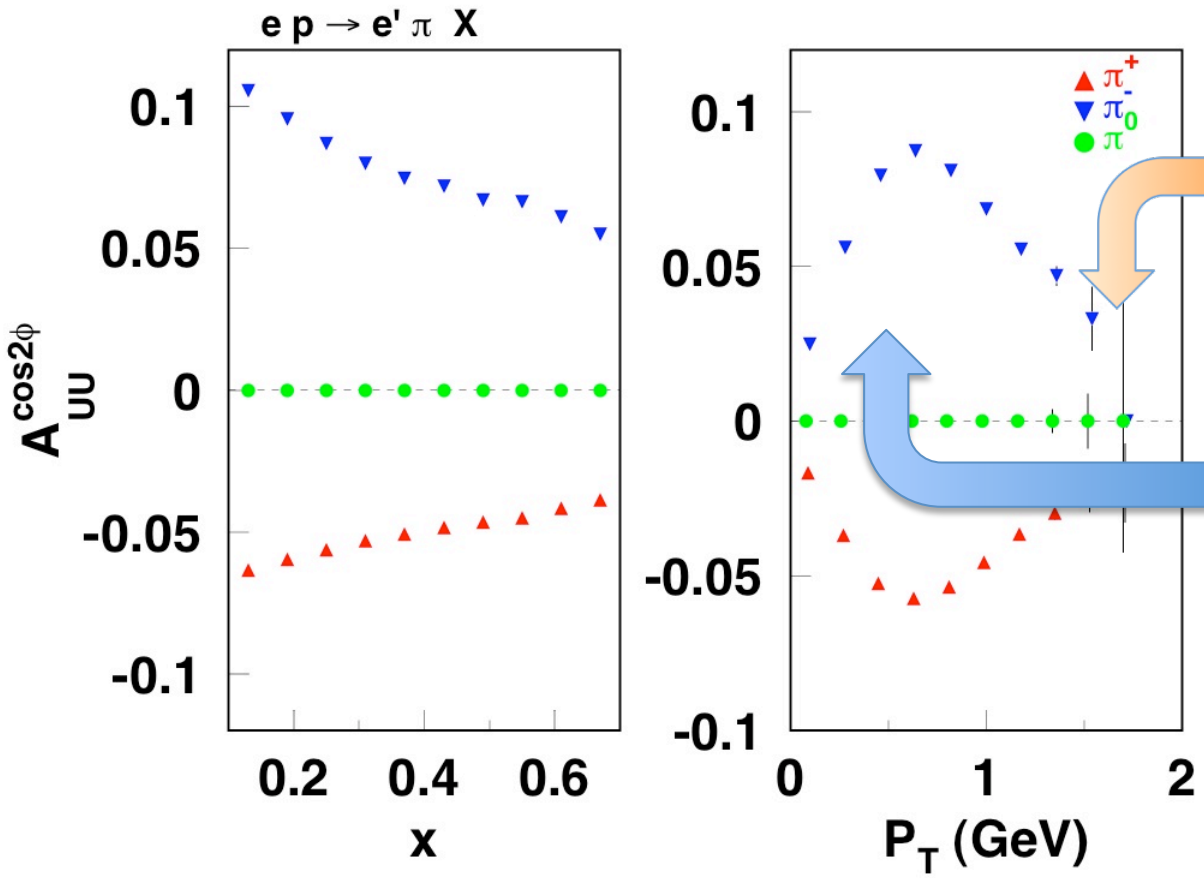
In the perturbative limit
$1/P_T$ behavior expected



Unpolarized target @ CLAS12

PT-dependence of azimuthal moments allows studies of transition from non-perturbative to perturbative description
(Unified theory by Ji et al, P_T matches and mismatches by Bacchetta et al).

$$F_{UU}^{\cos 2\phi} \propto h_1^{\perp} H_1^{\perp}$$



In the perturbative limit $1/P_T^2$ behavior expected

Perturbative region

$\Lambda_{QCD} \ll P_T \ll Q$

$4<Q^2<5$ GeV^2

Non-perturbative TMD

$$H_1^{\perp u \to \pi^+} = -H_1^{\perp u \to \pi^-}$$

2000h @ 10^{35} s^{-1}cm^{-2}
LH_2 target

TMDs with Longitudinal Polarized Targets

TMD correlators

$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{ & F_{UU,T} + \varepsilon F_{UU,L} \\
& + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\, F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\, F_{LU}^{\sin\phi_h} \\
& + S_\parallel\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h\, F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\, F_{UL}^{\sin 2\phi_h}\right] + S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\, F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h\, F_{LL}^{\cos\phi_h}\right] \\
& + |\boldsymbol{S}_\perp|\Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) + \varepsilon\sin(\phi_h+\phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\sin(3\phi_h-\phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)} \\
& \qquad + \sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] \\
& + |\boldsymbol{S}_\perp|\lambda_e\left[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S\, F_{LT}^{\cos\phi_S} + \sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)\, F_{LT}^{\cos(2\phi_h-\phi_S)}\right]\Bigg\}
\end{aligned}
$$

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nucleon	**U**	q		$h_1^\perp$
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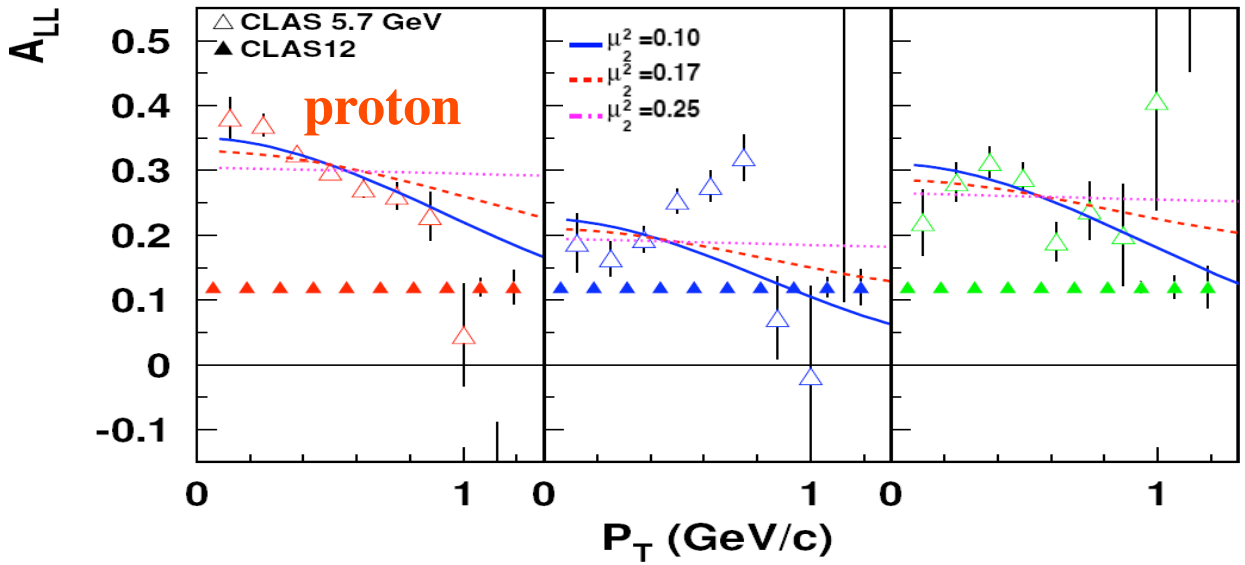
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

Longitudinal Target Spin @ CLAS12

$$F_{LL} \propto g_{1L} D_1$$

2000h @ 10^{35} $s^{-1}cm^{-2}$
NH_3 and ND_3 target



Constituent quark model (Pasquini et al).

TMD	$\frac{\langle k_T^2 \rangle}{\mu_0^2}$
f_1	1.00
g_1	0.74
h_1	0.79
$g_{1T}^{\perp}$	2.20
$h_{1L}^{\perp}$	2.20
$h_{1T}^{\perp}$	0.63

M.Anselmino et al hep-ph/0608048
Phys.Rev.D74:074015,2006

$$f_1^q(x,k_\perp) = f_1^q(x)\frac{1}{\pi\mu_0^2}exp(-\frac{k_\perp^2}{\mu_0^2})$$

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

μ_0^2=0.25GeV² μ_D^2=0.2GeV²

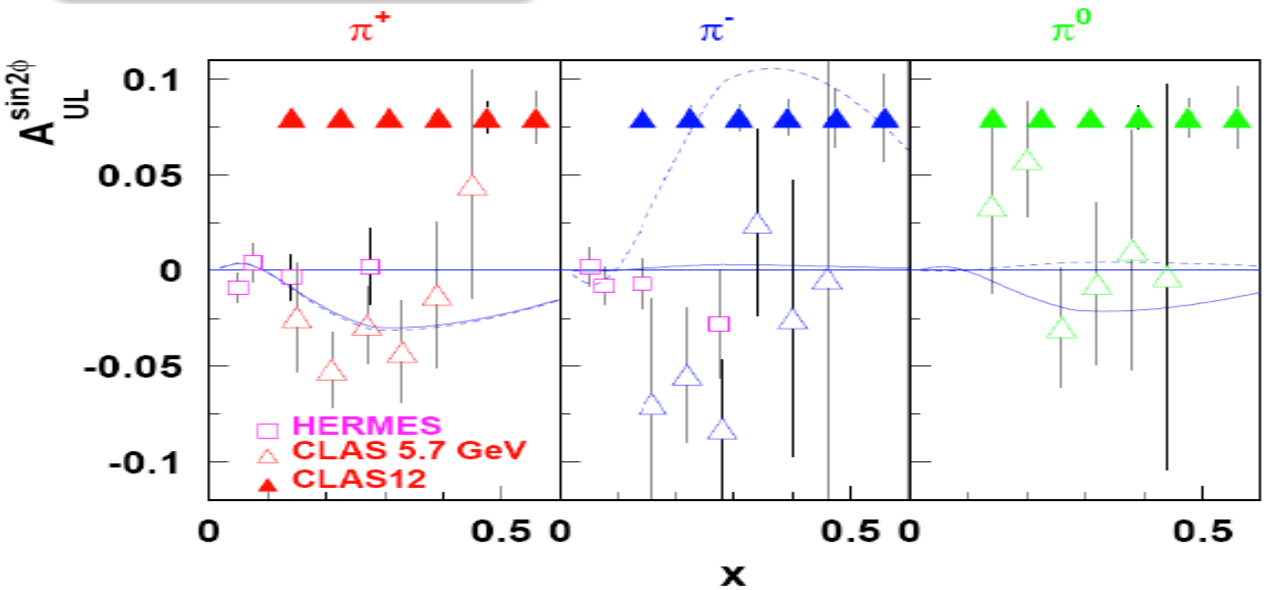
Helicity dependence of k_T-distribution of quarks

$$A_{LL} \propto \frac{\mu_D^2 + z^2\mu_0^2}{\mu_D^2 + z^2\mu_2^2}\exp\left(-z^2 P_{hT}^2 \frac{(\mu_0^2 - \mu_2^2)}{(\mu_D^2 + z^2\mu_0^2)(\mu_D^2 + z^2\mu_2^2)}\right)\frac{\sum e_q^2 g_1^q D_q^h}{\sum e_q^2 f_1^q D_q^h}$$

Longitudinal Target Spin @ CLAS12

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

Transversely polarized quarks in long polarized nucleon
Leading twist, sensitive to spin-orbit correlations



Curves, χQSM, Efremov et al, Czech J Phys 55 (2005) A189

$$H_1^{\perp u \to \pi^+} / H_1^{\perp u \to \pi^-} = 0, -1, -5$$

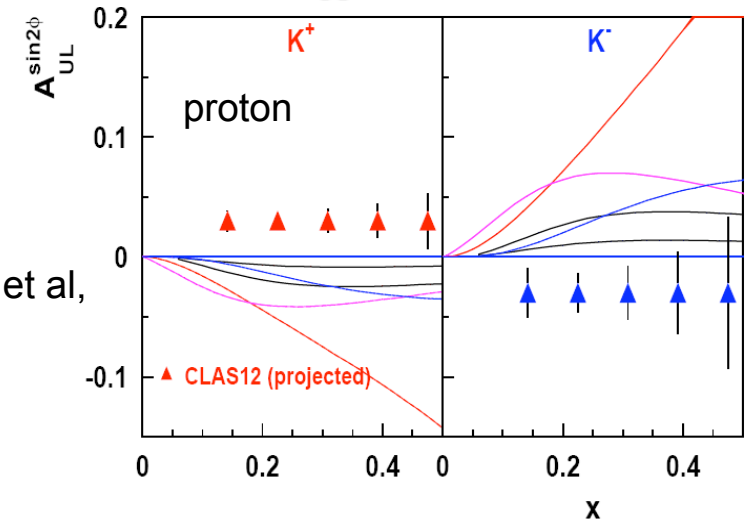
$$H_1^{\perp d \to \pi^+} = 0$$

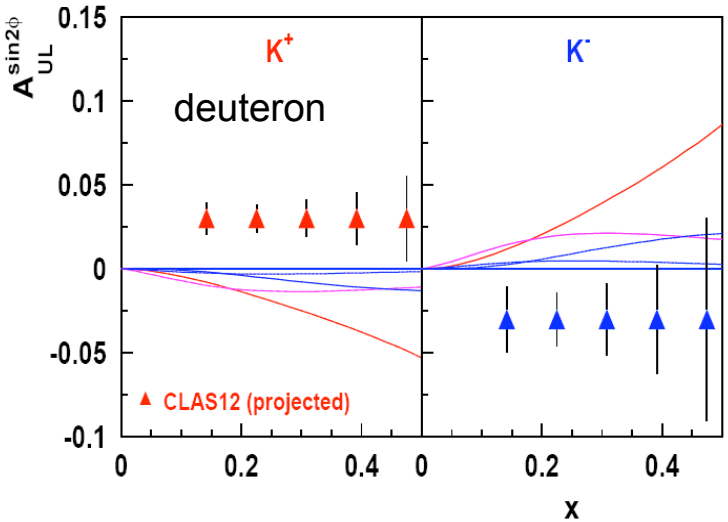
2000h @ 10^{35} $s^{-1}cm^{-2}$
NH_3 and ND_3 target

Curves

colored: CQM, Pasquini et al, PRD78 (2008) 034025

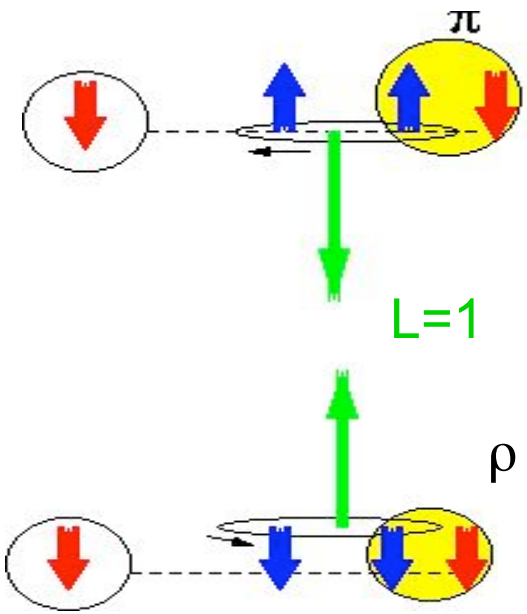
black: Avakian et al, PRD77 (2008) 014012





Collins effect

Simple string fragmentation (Artru model)



Sub-leading pion opposite to leading (into page)

$$h_1 H_1^{\perp u \to \pi}$$

ρ production may produce an opposite sign A_{UT}

Leading ρ opposite to leading π(into page)

$$H_1^{\perp u \to \rho} \sim -\frac{1}{3} H_1^{\perp u \to \pi}$$

hep-ph/9606390

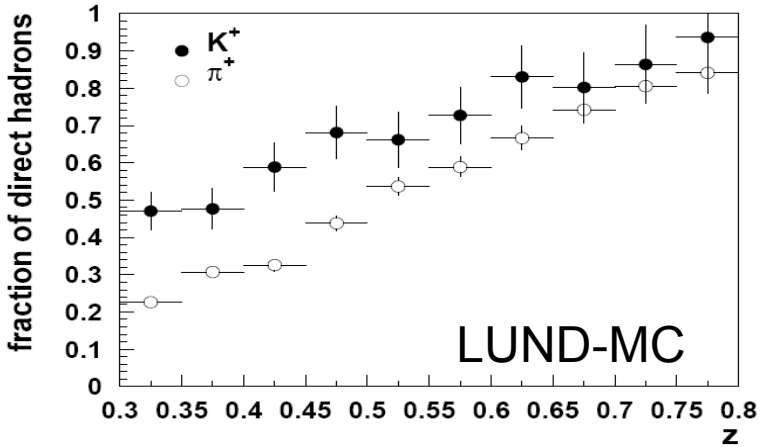
Collins function:

extracted from e+e- collider data (BELLE)

→ at much higher scale than SIDIS
to be investigate at SIDIS scale too
- evolution of TMDs

only for pions
→ unknown for kaons
- strange vacuum
- strangeness in the nucleon

→ unknown for vector mesons



Fraction of direct kaons may be higher than the fraction of direct pions.

TMDs with Transversely Polarized Targets

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 %

P= 95 % H , 70 % D

Pros

1. **Small field (*∫Bdl~0.005-0.05Tm*)**
2. **Small dilution (fraction of events from polarized material)**
3. **Less radiation length**
4. **Less nuclear background (no nuclear attenuation)**
5. **Wider acceptance much better FOM, especially for deuteron**
6. **H and D may be independently polarized**

HD-Ice target at ~ 1-2nA
NH_3 at ~ 5-10 nA

Cons

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

TMD correlators

$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{ & F_{UU,T} + \varepsilon F_{UU,L} \\
& + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\, F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\, F_{LU}^{\sin\phi_h} \\
& + S_\parallel\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h\, F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\, F_{UL}^{\sin 2\phi_h}\right] + S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\, F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h\, F_{LL}^{\cos\phi_h}\right] \\
& + |\boldsymbol{S}_\perp|\Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) + \varepsilon\sin(\phi_h+\phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\sin(3\phi_h-\phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)} \\
& \qquad + \sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] \\
& + |\boldsymbol{S}_\perp|\lambda_e\left[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S\, F_{LT}^{\cos} + \sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)\, F_{LT}^{\cos(2\phi_h-\phi_S)}\right]\Bigg\}
\end{aligned}
$$

Distribution Functions (DF)

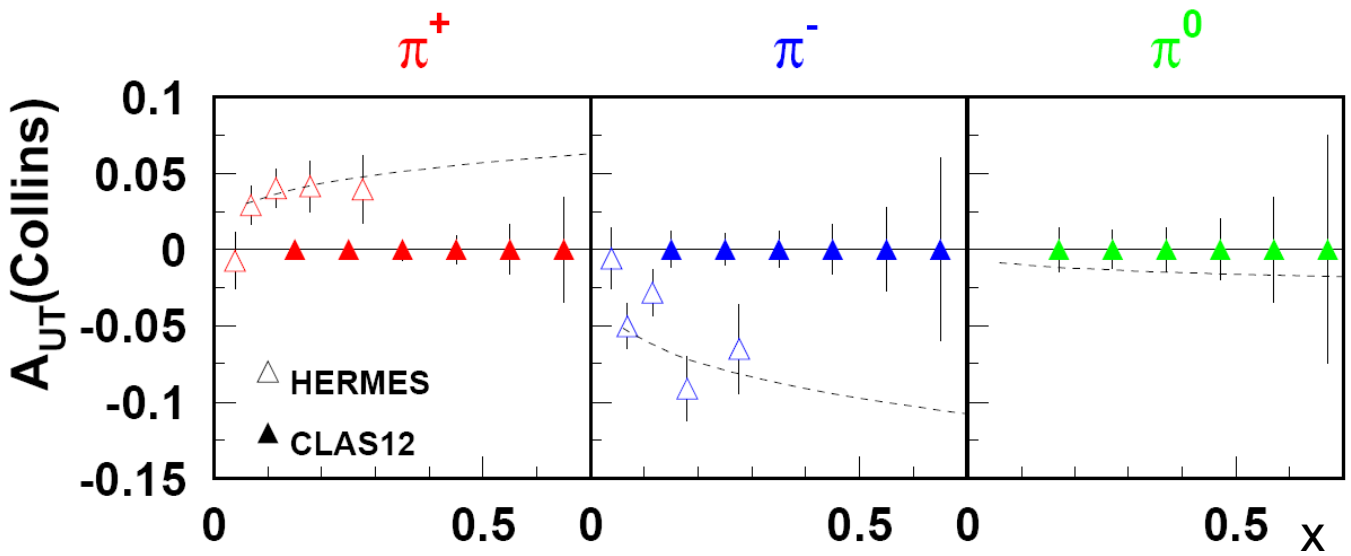
		quark		
		U	L	T
nucleon	U	q		$h_1^\perp$
	L		g_{1L}	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1 $h_{1T}^\perp$

Collins asymmetry @ CLAS12

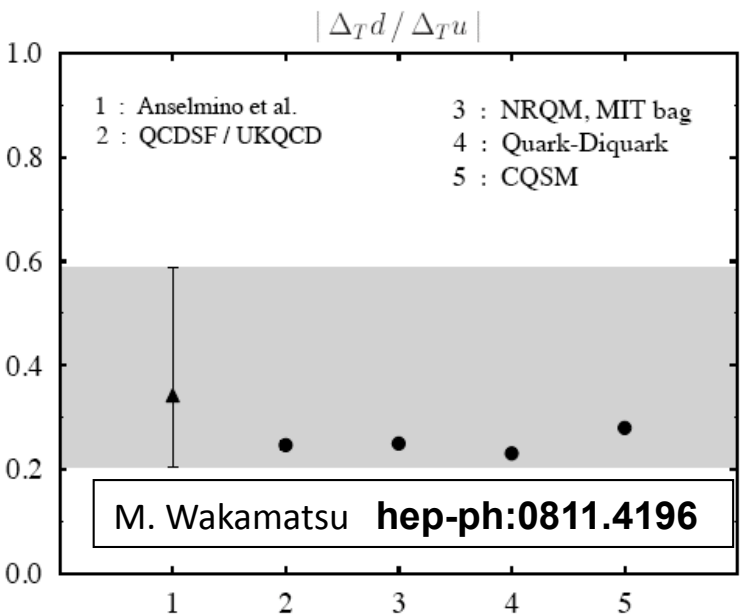
$$F_{UT}^{\sin(\phi+\phi_S)} \propto h_1 H_1^{\perp}$$

2000h @ 10^{34} $s^{-1}cm^{-2}$
HD-ice (P=85%)

Curves fom A.V. Efremov et al
PRD76:094025,2006



Study A_{UT} at large x (valence) where models are mostly unconstrined



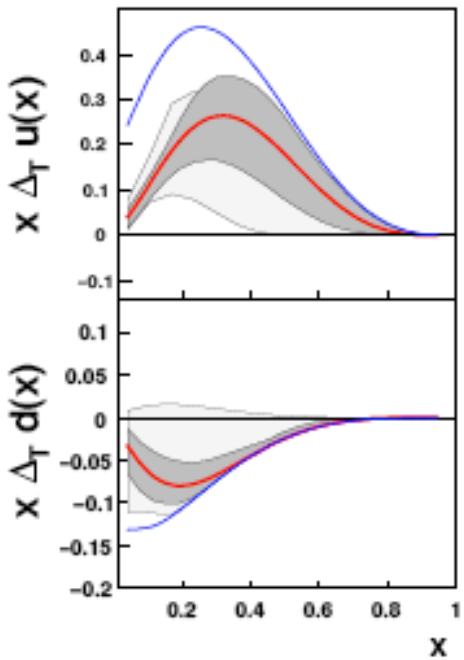
M. Wakamatsu **hep-ph:0811.4196**

Tensor charge

$$\delta u = 0.54^{+0.09}_{-0.22}$$

$$\delta d = -0.23^{+0.09}_{-0.16}$$

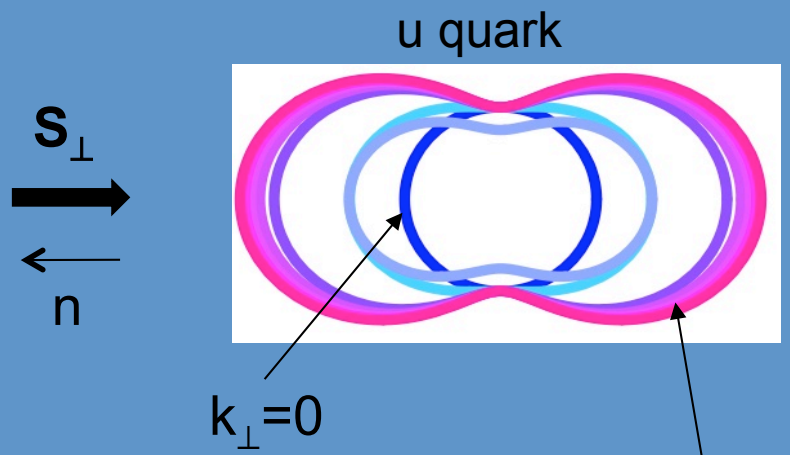
M. Anselmino et al
hep-ph:0812.4366



Pretzelosity @ CLAS12

unpolarized beam, transv. target

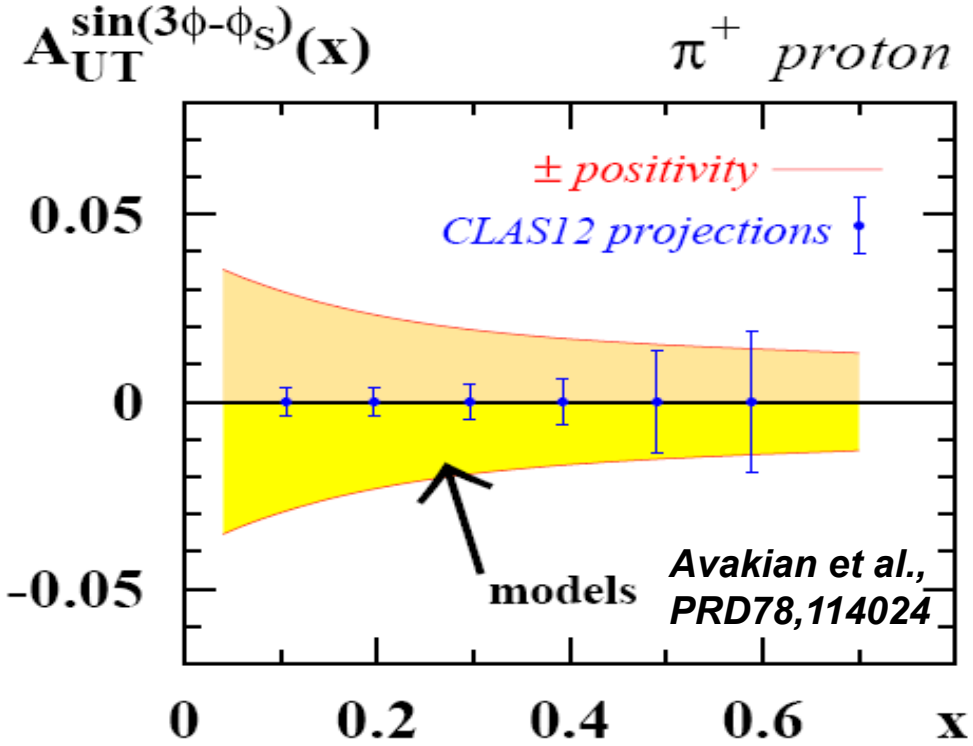
non spherical shape of the nucleon



B. Pasquini et al. arXiv:0806.2298

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

2000h @ 10^{34} $s^{-1}cm^{-2}$
HD-ice (P=85%)



Relation in no-gluon models:
(in bag & spectator model)

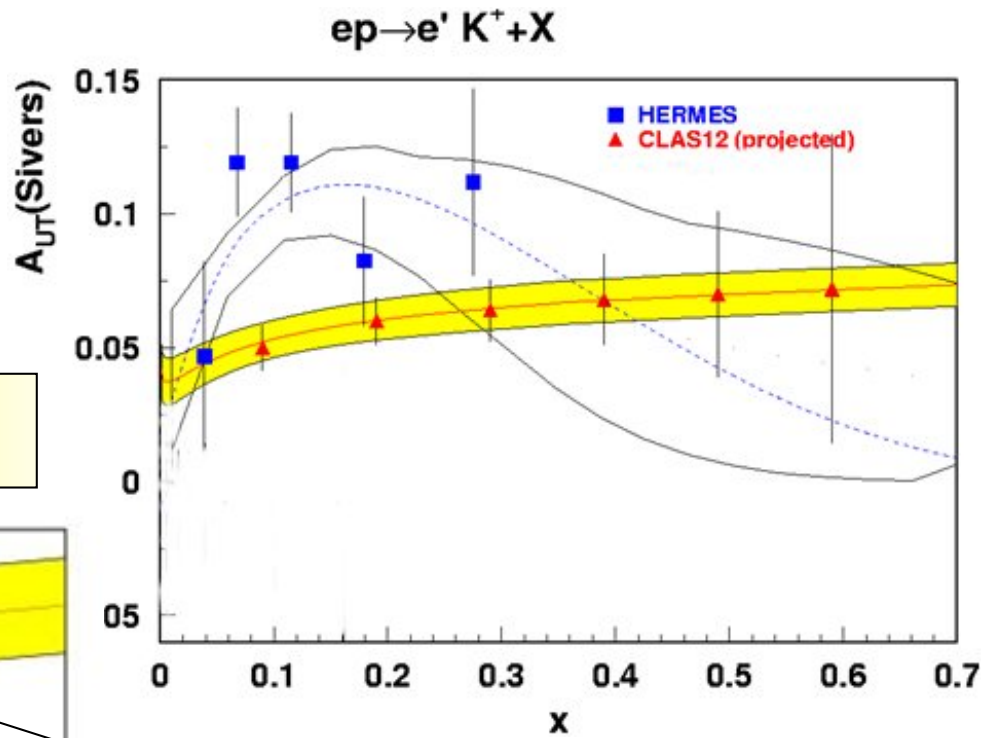
$$g_1^q(x) - h_1^q(x) = h_{1T}^{q(1)}(x)$$

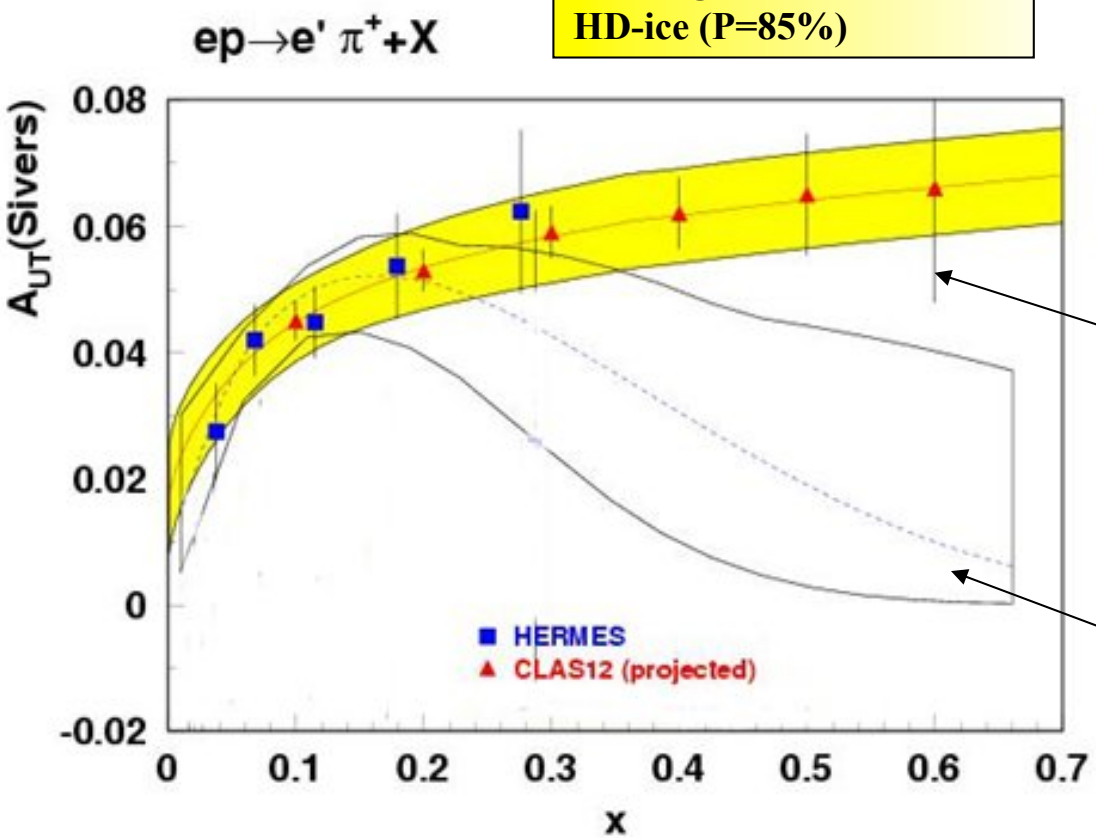
Sivers effect @ CLAS12

unpolarized beam, transverse target

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

2000h @ 10^{34} $s^{-1}cm^{-2}$
HD-ice (P=85%)



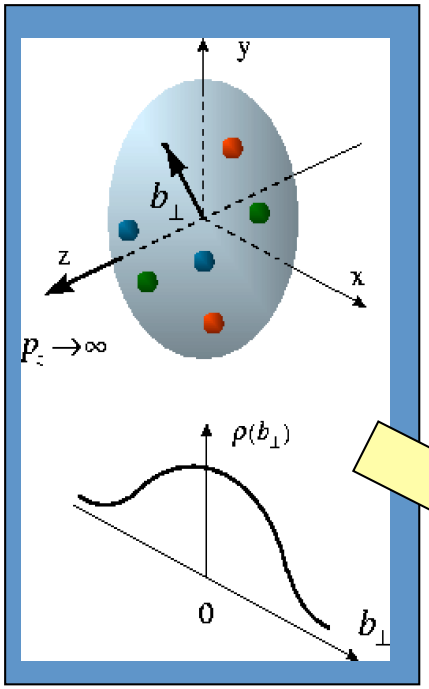


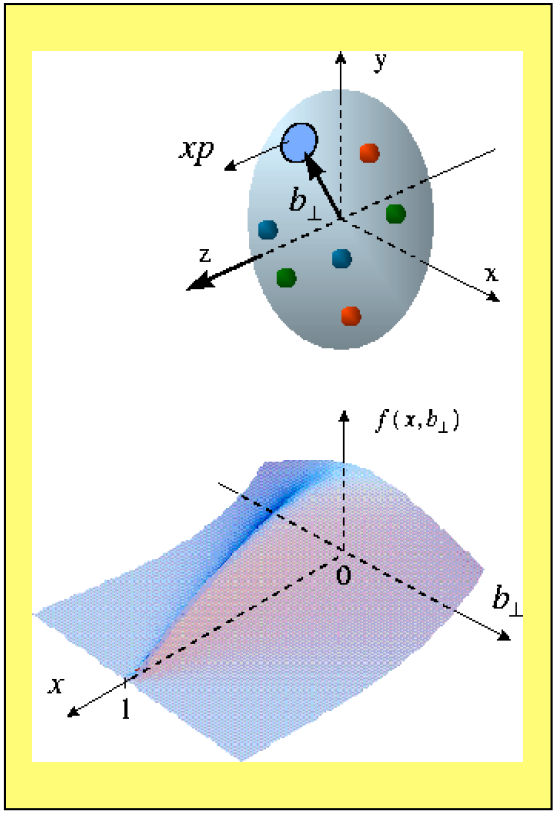
S. Arnold et al
arXiv:0805.2137

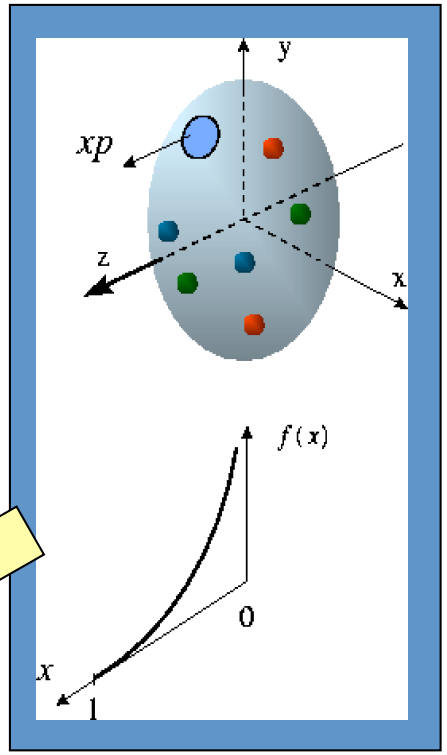
M. Anselmino et al
arXiv:0805.2677
Eur.Phys.J.A39:89-100,2009

GPDs @ CLAS12

D. Mueller, X. Ji, A. Radyushkin, A. Belitsky, …
M. Burkardt, … Interpretation in impact parameter space







Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

DVCS @ CLAS12

$e\, p^{\uparrow} \longrightarrow e\, p\, \gamma$

$\Delta\sigma \sim \sin\phi \, \mathrm{Im}\{k_1(F_2 H - F_1 E) + \ldots\} d\phi$

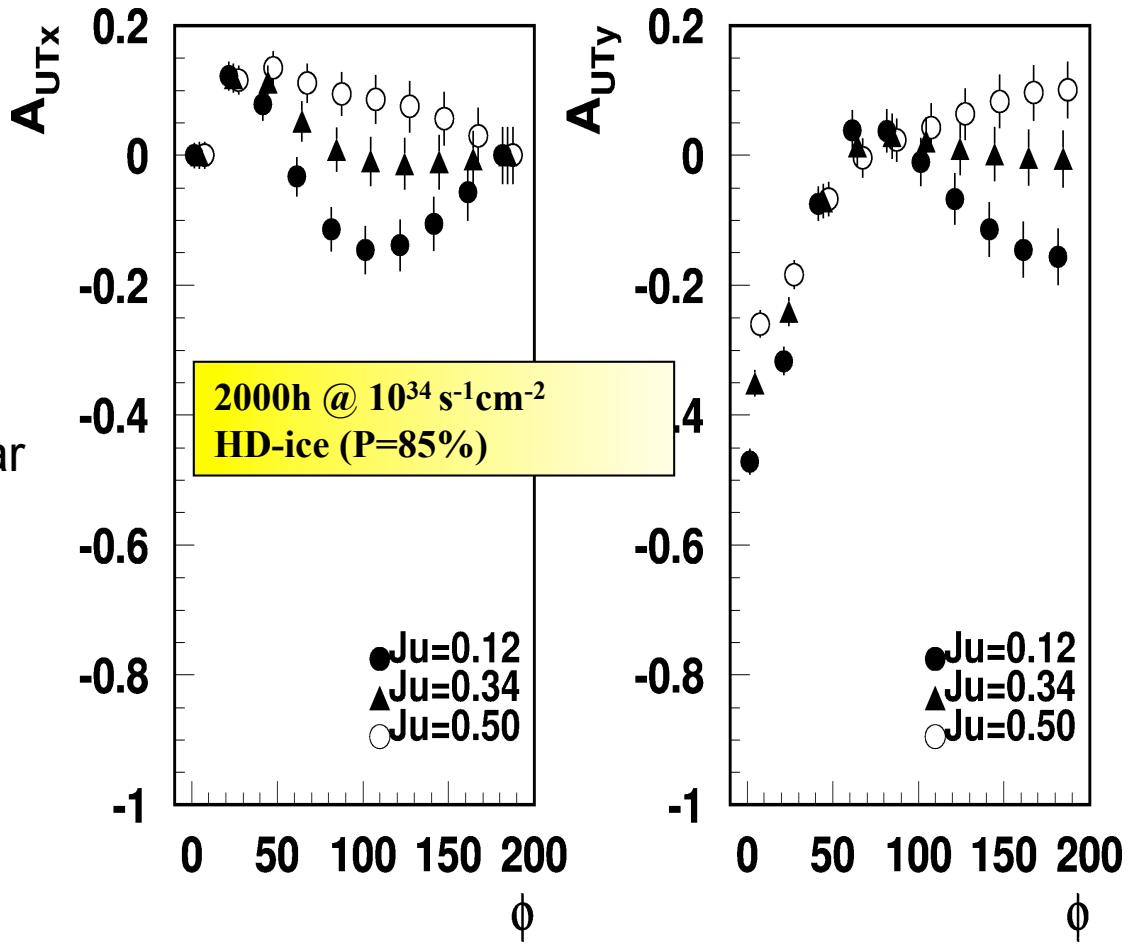
A_{UTx} Target polarization in the scattering plane

A_{UTy} Target polarization perpendicular to the scattering plane

- Asymmetries highly sensitive to the u-quark contributions to the proton spin.

Sample kinematics

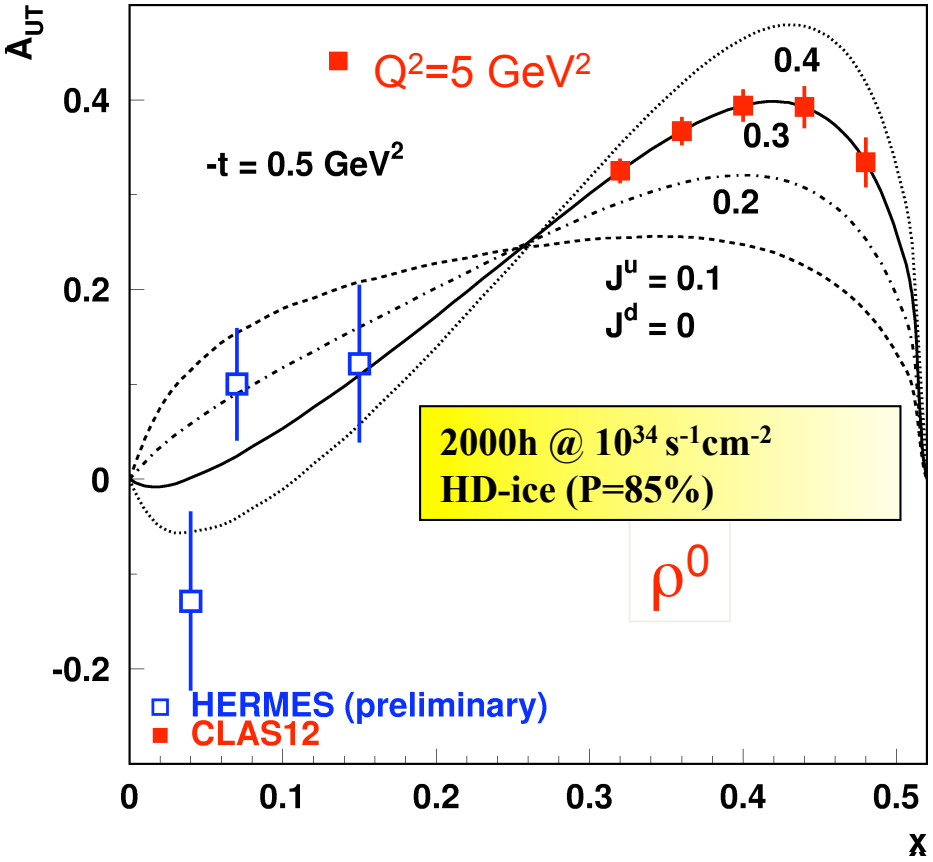
Q^2=2.2 GeV^2, x_B = 0.25, -t = 0.5GeV^2



Exclusive ρ^0 production @ CLAS12

$$A_{UT} \sim 2\Delta_{\perp}(\mathrm{Im}(AB^*))$$

E^u, E^d allow to map the *orbital motion of quarks*.



K. Goeke, M.V. Polyakov, M. Vanderhaeghen, 2001

ρ^0	$A \sim 2H^u - H^d$ $B \sim 2E^u - E^d$
ρ^+	$A \sim H^d - H^u$ $B \sim E^d - E^u$
ω^0	$A \sim 2H^u + H^d$ $B \sim 2E^u + E^d$

Possible flavor decomposition

Conclusions

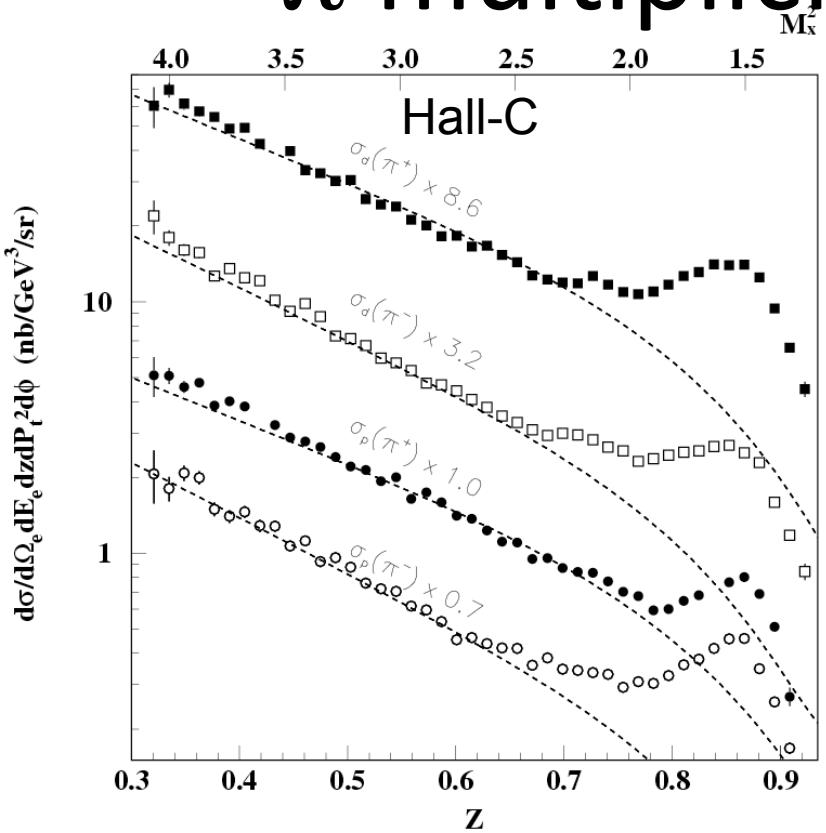
CLAS12: a wide-acceptance high-luminosity high-polarization experiment for a comprehensive study of the partonic transverse degree of freedoms in the nucleon

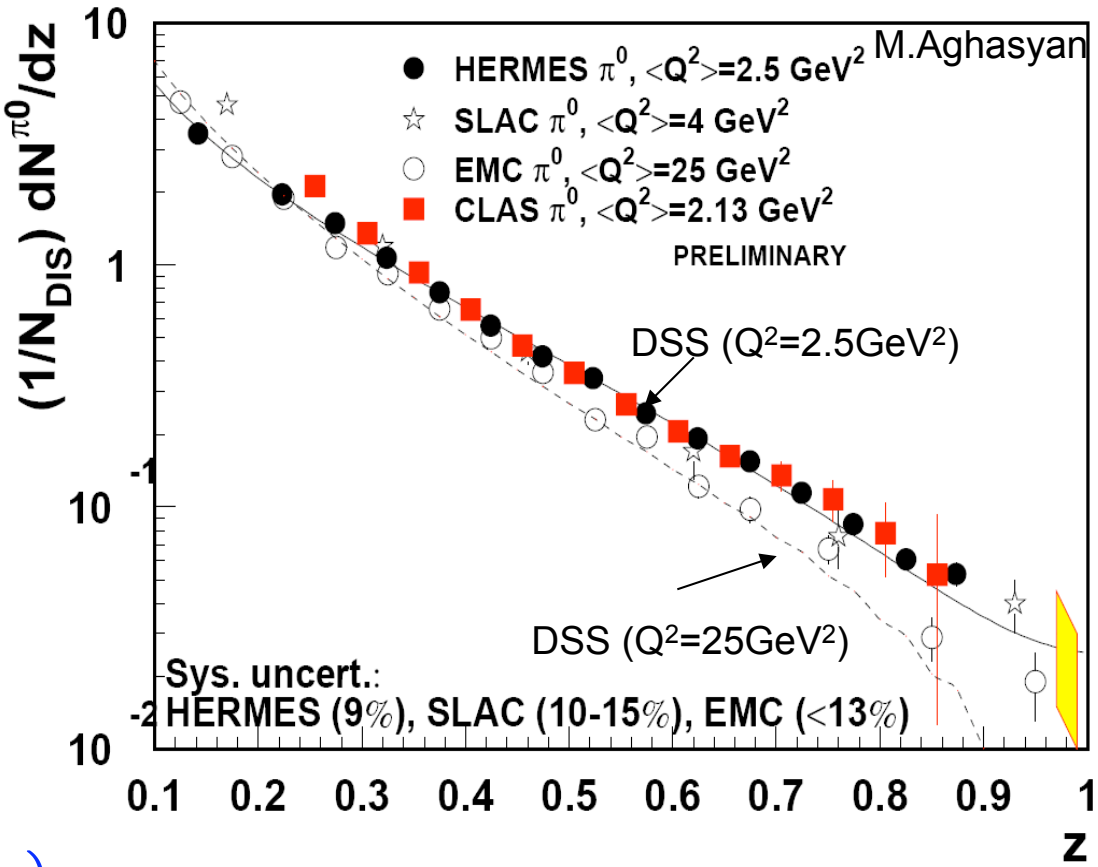
Precise mapping of TMDs (pdf & FF) and GPDs in a multi-D approach

- Constrain models in the valence region
- Test factorization
- Study higher twist effects
- Investigate non-perturbative to perturbative transition (along P_T)
- Test of QCD: universality SIDIS vs Drell-Yan
- Test of Lattice QCD calculations: tensor charge
- Access to OAM

π multiplicities in SIDIS

ep→e'πX





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

$\pi^{+/-}$ 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

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

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

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	$H_1^\perp$	$H_{1L}^\perp$	$\mathbf{H_1}$ $H_{1T}^\perp$

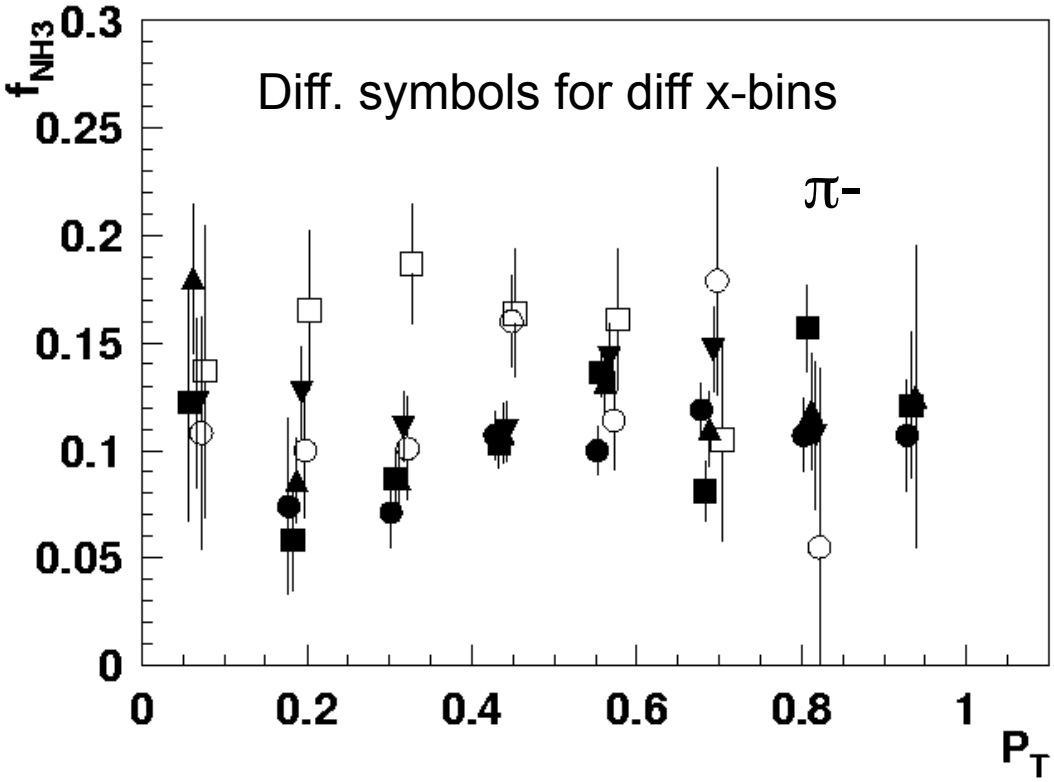
Dilution factor in SIDIS

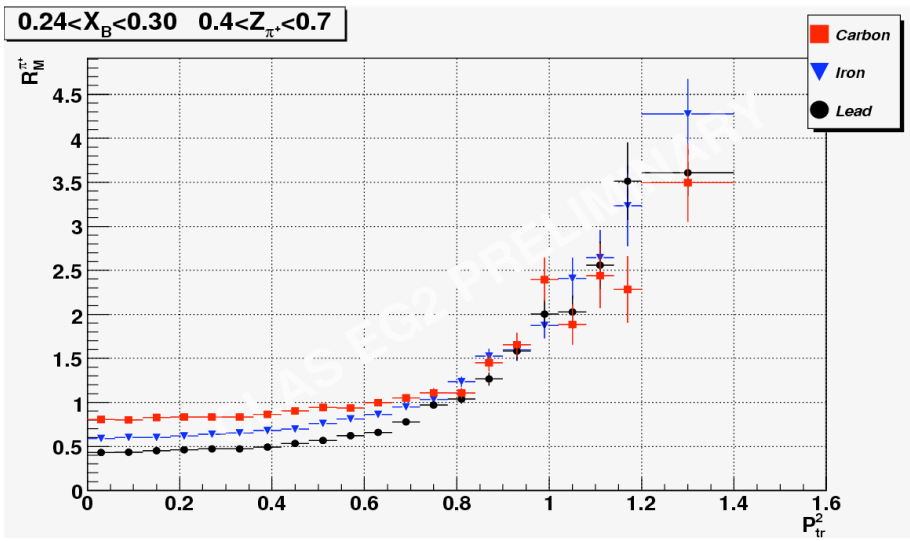
Fraction of events from polarized hydrogen in NH3

$$f(x, Q^2, z, p_t, \phi) = 1 - (N_u/N_p)(\rho_p/\rho_u)C_n(x, Q^2, z)$$

N_u,N_p -total counts from NH3 and carbon normalized by lumi

ρ_u, ρ_p -total areal thickness of hydrogen (in NH3), and carbon target





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

Uncertainties

Table 5: Uncertainties for asymmetry measurements.

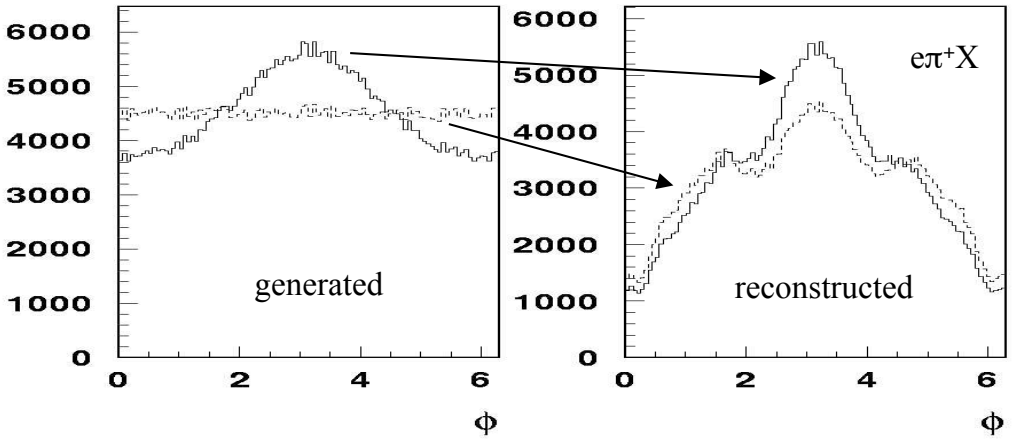
Item	A_1^p	$A_{UL}^{\sin\phi}$	$A_{UL}^{\sin 2\phi}$
beam x target polarization	2%	-	-
target polarization	-	3%	3%
depolarization and R	4%	-	-
dilution factor	3%	3%	3%
radiative corrections	3%	3%	3%
fitting procedure	-	4%	5%
transverse (to γ^*) spin effects	3%	3%	-%

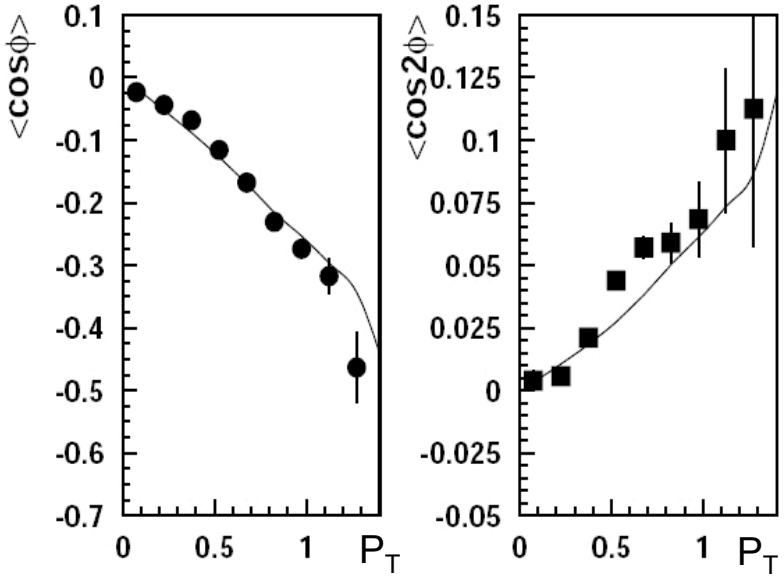
CLAS12 Acceptance MC studies

$$\langle \cos n\phi \rangle(\omega) = \frac{\iint \sigma(\omega,\phi)\varepsilon_{acc}(\omega,\phi)\varepsilon_{RAD}(\omega,\phi)L\cos(n\phi)\ d\omega d\phi}{\iint \sigma(\omega,\phi)\varepsilon_{acc}(\omega,\phi)\varepsilon_{RAD}(\omega,\phi)L\ d\omega d\phi}$$

$$\omega = (x, y, z, P_{h\perp})$$

CLAS12 SIDIS MC (LUND-PEPSI) used to study azimuthal moments from acceptance and radiative corrections for different pions.





After acceptance correction
the generated azimuthal moments are
recovered with an error < 10%
(dominant contribution to systematics)

Even better results expected with a fully-differential analysis

Uncertainties

Table 5: Uncertainties for asymmetry measurements.

Item	$A_{UU}^{\cos 2\phi}$	$A_{UU}^{\cos \phi}$	$A_{LU}^{\sin \phi}$
beam polarization	-	-	3%
acceptance corrections	4%	4%	2%
radiative corrections	3%	3%	3%
fitting procedure	4%	4%	3%

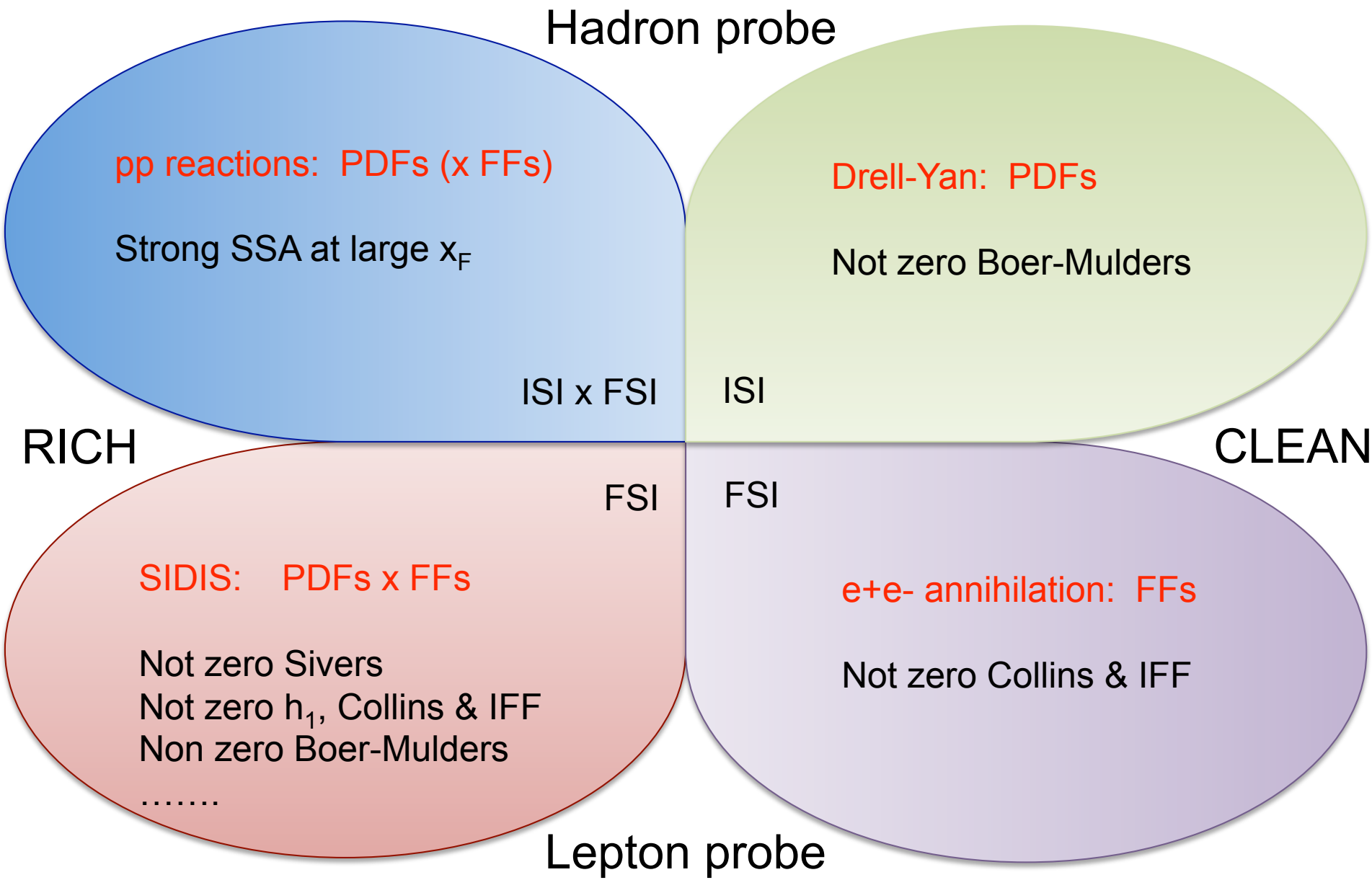
Systematics

Source	Size	relative	Comment
Beam/Target polarization	2-4 %	relative	
Dilution factor Nuclear effects	2-4 %	relative	HD-ice to suppress these effects
Detector performance	1-2 %	absolute	RICH to improve hadron ID
Acceptance effects Fitting procedure	3-4 %	absolute	Statistical origin Multidimensional approach
Radiative corrections	1-2 %	relative	

TMDS PHYSICS WITH SIDIS

Experiment	Reactions	√s (GeV)	Planned	Status	Remarks
HERMES @ DESY	e⇧p⇧	7.5	< 2012	Data-taking is over	Completing analyses
COMPASS @ CERN	μ⇧p⇧, μ⇧d⇧	17-20	> 2009	Proposal	Improved statistics
Hall-A,B,C @ JLaB	ep⇧,ed⇧, en⇧	5	> 2013	Approved	Detector upgrades HD-ice polarized target
EIC	e⇧p⇧	30-100	> 2017 ?	Under study	NSAC Long Range plan 2012
eN @FAIR	e⇧p⇧	12	> 2020 ?	Under study	
LHeC @ CERN	ep	1400	> 2020 ?	Under study	Conceptual Design Report in 2010

TMD palette


Hadron probe
pp reactions: PDFs (x FFs)
Strong SSA at large x_F
Drell-Yan: PDFs
Not zero Boer-Mulders
ISI x FSI
ISI
RICH
CLEAN
FSI
FSI
SIDIS: PDFs x FFs
Not zero Sivers
Not zero h_1, Collins & IFF
Non zero Boer-Mulders
…….
e+e- annihilation: FFs
Not zero Collins & IFF
Lepton probe