SIDIS Measurements at JLab12

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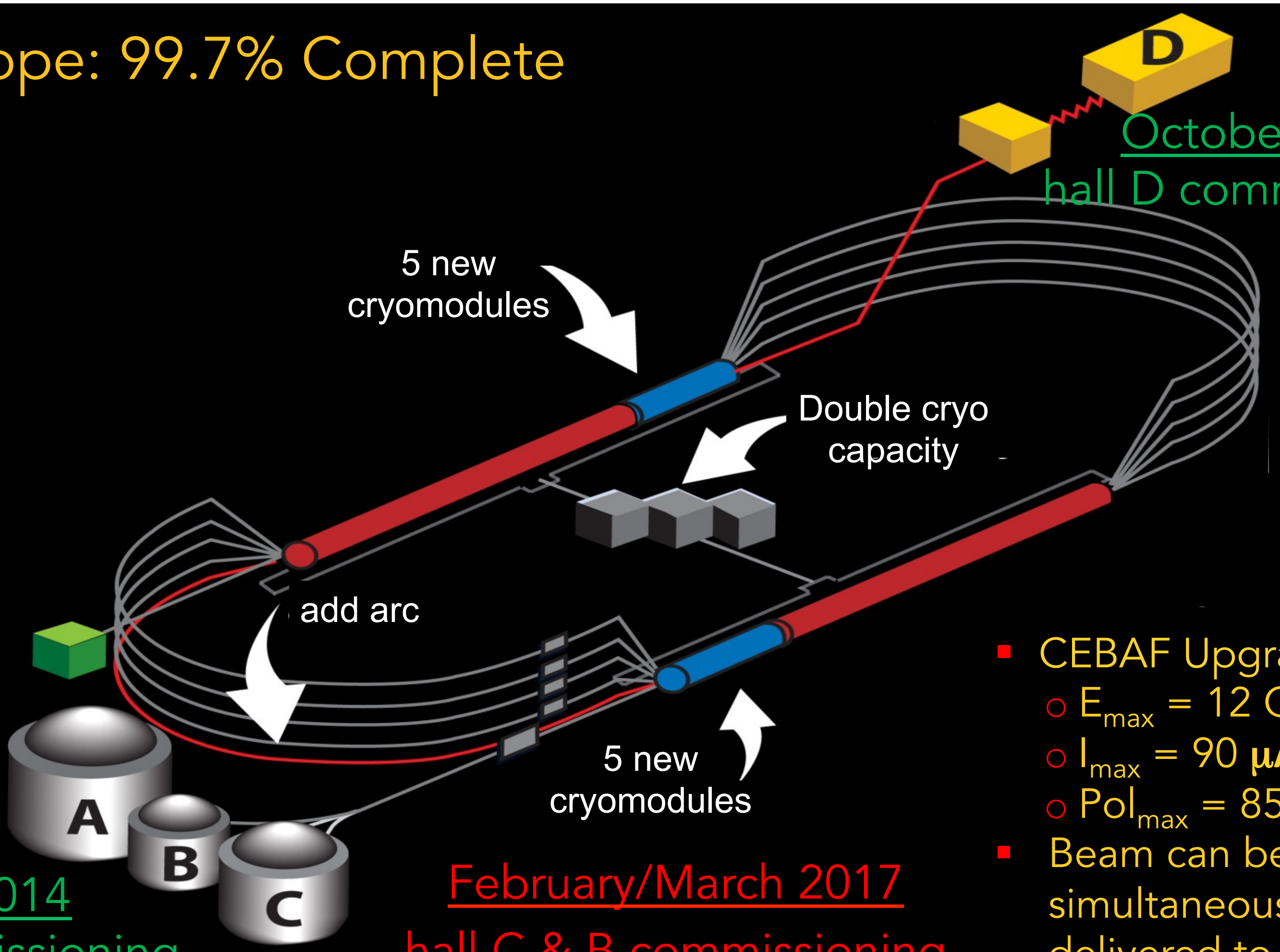
INT-17-3, Spatial and Momentum Tomography of Hadrons and Nuclei
Seattle, Washington - September 18, 2017

Outline

- The JLab SIDIS program at @ 12 GeV: some selected measurements
- Impact on existing and future measurements
  - **Investigation in the valence quark region**
    - Precise data in a wide phase space
    - Multi-dimensional mapping of 3D PDFs using CLAS12, SoLID
    - Different targets species with different polarization
    - Flavor tagging
- Nucleon structure: from measuring to understanding
- Conclusions

CEBAF @ 12 GeV

Project Scope: 99.7% Complete



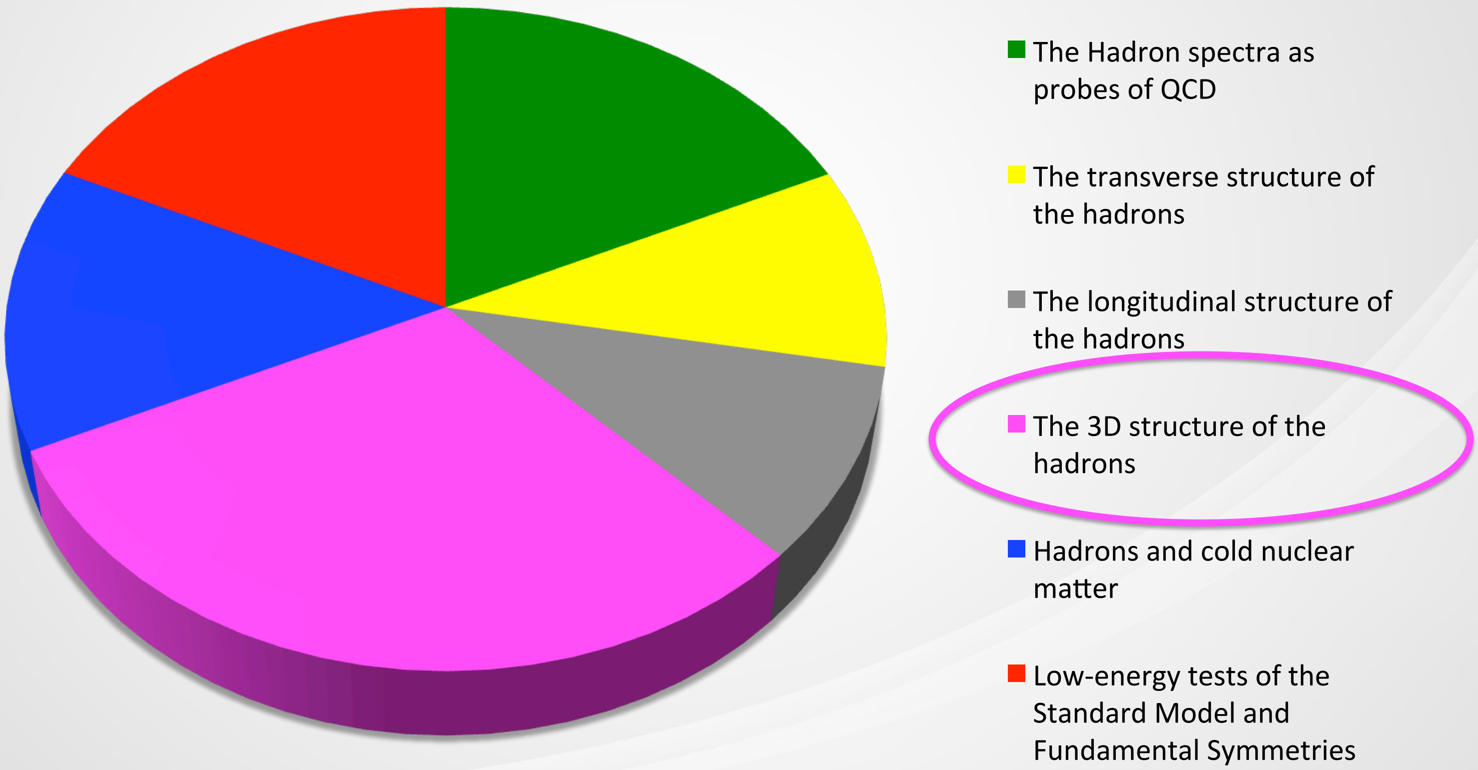
October 2014
hall D commissioning

April 2014
hall A commissioning

February/March 2017
hall C & B commissioning

- CEBAF Upgrade
  - E_{max} = 12 GeV
  - I_{max} = 90 μA
  - Pol_{max} = 85%
- Beam can be simultaneously delivered to 4 Exp. Halls

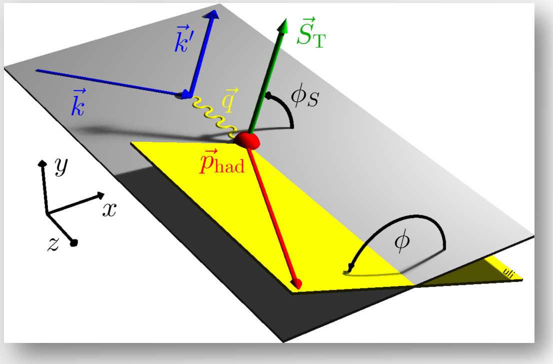
12 GeV Program: Approved PAC Days



A Decade of Experiments

Quark-parton Model Interpretation of SIDIS: Transverse Momentum Dependent PDFs (TMDs)

$l + N \rightarrow l' + h + X$



- Two scales
  - high Q - hard scale
  - Low p_T - sensitive to confining scale
- Two planes:
  - Lepton scattering plane and hadron production plane
  - The angular modulation allows TMD separation

Leading Order – Leading Twist

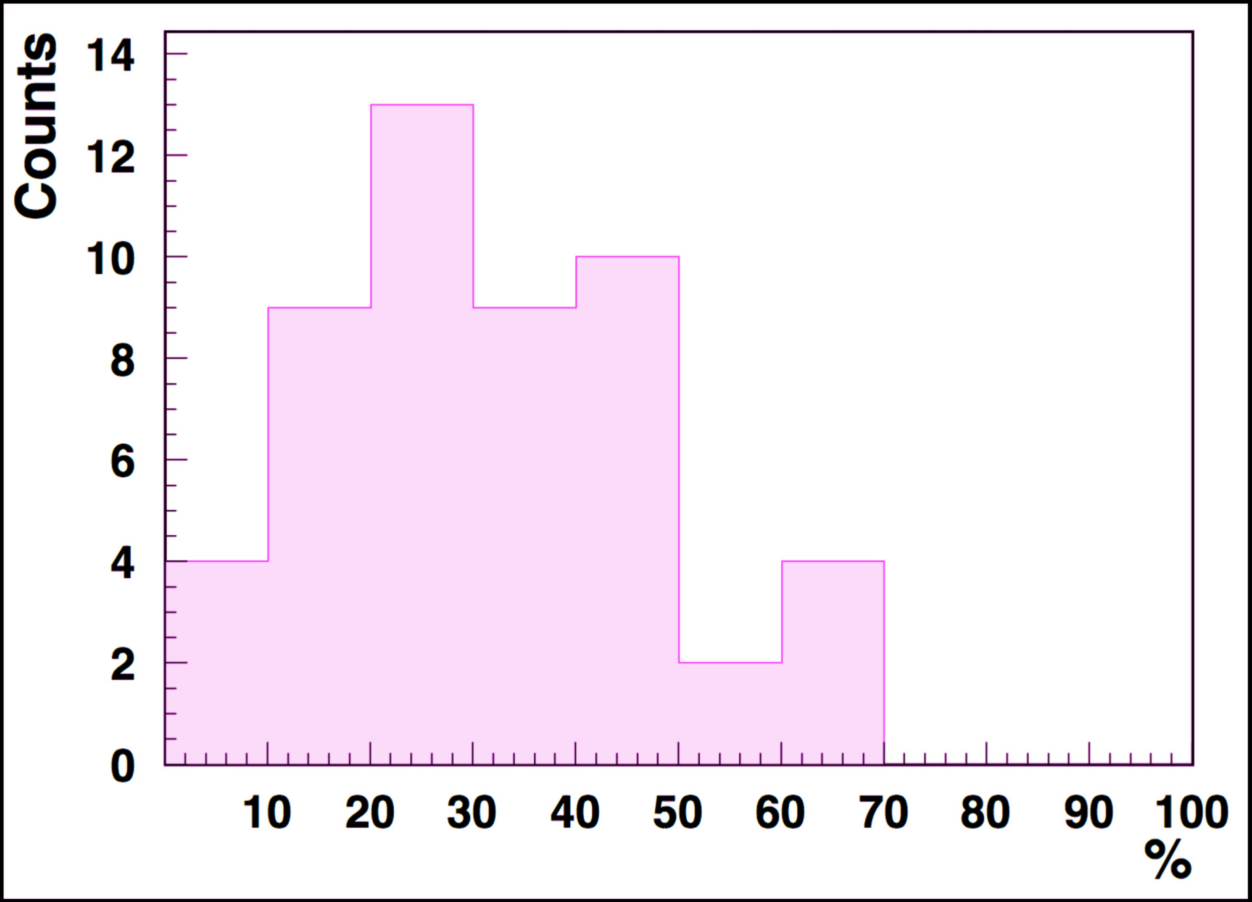
N/q	U	L	T
U	$\mathbf{f_1}$		$h_1^\perp$
L		$\mathbf{g_1}$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$\mathbf{h_1}$ $h_{1T}^\perp$

Higher Twist

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

The nucleon is a complex object!

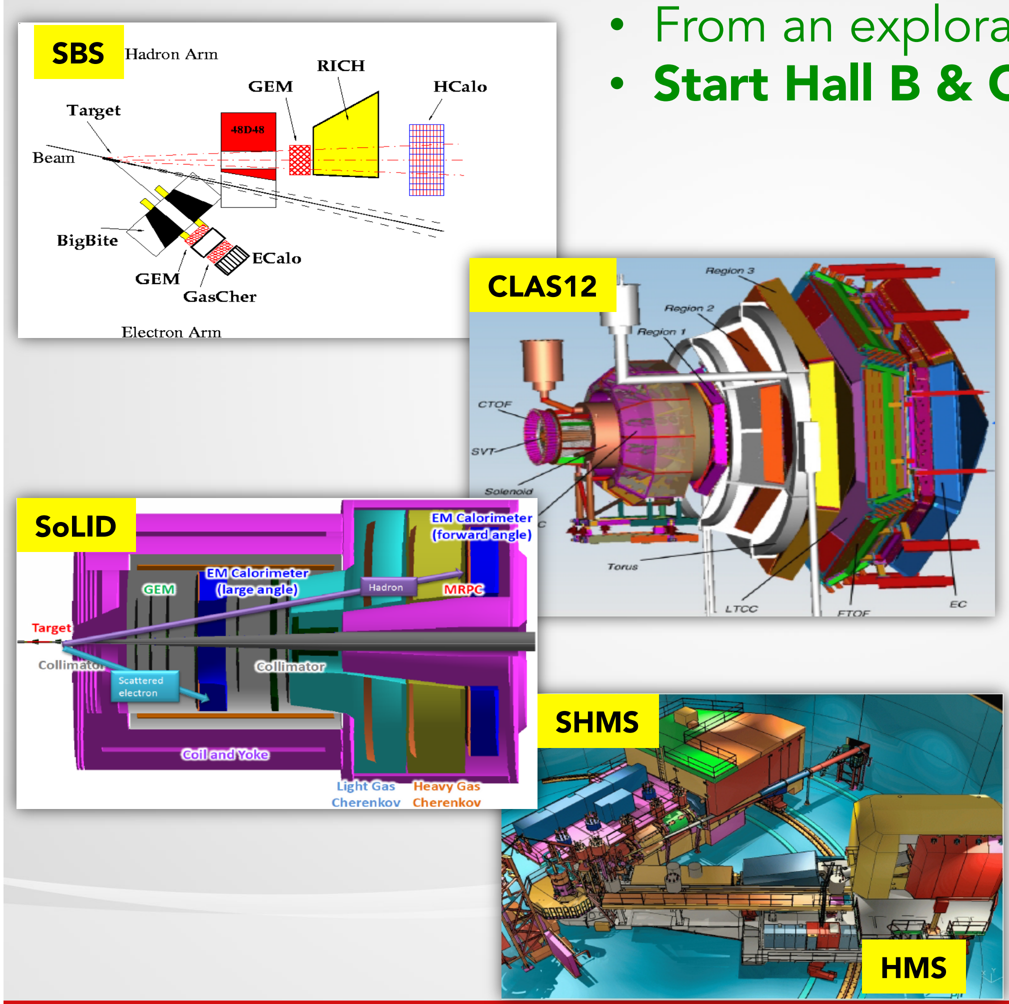
How much do we know about the structure of the nucleon?



P. Rossi's poll

A Multi-Hall SIDIS Program

- From an exploratory phase to a consolidation phase
- **Start Hall B & C: spring 2018**



Hall B: Large acceptance (CLAS12)

Unpolarized and polarized H & D targets

→ cross sections, single & double-spin asymmetries

→ start kaon SIDIS program with RICH detector

Hall C: SHMS + HMS

Unpolarized target

Precision magnetic-spectrometer setup, π and K, high luminosity,

→ L/T separations in SIDIS

→ precision cross sections and ratios of π^+ and π^- (and K^+, K^-)

Hall A: Solenoidal Large Intensity Device (SoLID) & SBS

Longitudinal & transversely polarized ^{3}He

→ Access to n structure at high-x and high-Q^2

→ pion & kaon run with BigBite and SBS

Unpolarized TMDs

- Unpolarized TMDs are not yet constrained in a satisfactory way

- They are present in all measurements
  → it is not sufficient to describe their qualitative features
  → precision is required

- Transverse momentum dependence of the **Multiplicities** provides leverage in the quest to unfold, from the transverse hadron momentum P_{hT} , the intrinsic quark p_T and fragmentation k_T
  - Access the shape of the unpolarized TMD
  - Constrain TMD models and calculations

Unpolarized SIDIS

$$\frac{d\sigma}{dx_B\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x_B y Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)\Big\{\overbrace{F_{UU,T}}^{f_1\otimes D_1} + \varepsilon\,\overbrace{F_{UU,L}}^{\text{HT}} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,\overbrace{F_{UU}^{\cos\phi_h}}^{\text{HT}}$$

$$+\,\varepsilon\cos(2\phi_h)\,\underbrace{F_{UU}^{\cos 2\phi_h}}_{h_1^\perp\otimes H_1^\perp} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,\underbrace{F_{LU}^{\sin\phi_h}}_{\text{HT}}\Big\},$$

- BM TMD describes correlation between the transverse momentum and transverse spin of quarks, requires FSI or ISI

$$\underbrace{F_{UU}^{cos\phi_h}\,cos\phi_h}_{\textbf{Cahn + BM}} \qquad \underbrace{F_{UU}^{cos2\phi_h}\,cos2\phi_h}_{\textbf{BM + h.t. Cahn}}$$

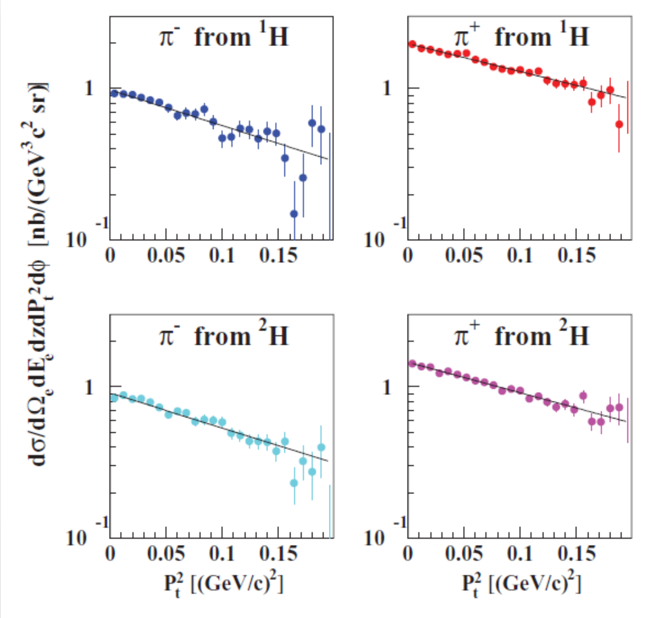
- Nontrivial modulations from the Cahn and Boer-Mulders effects

➔ under intensive studies worldwide, including experiments, model calculations, lattice simulations

Flavor dependence of k_T-distributions

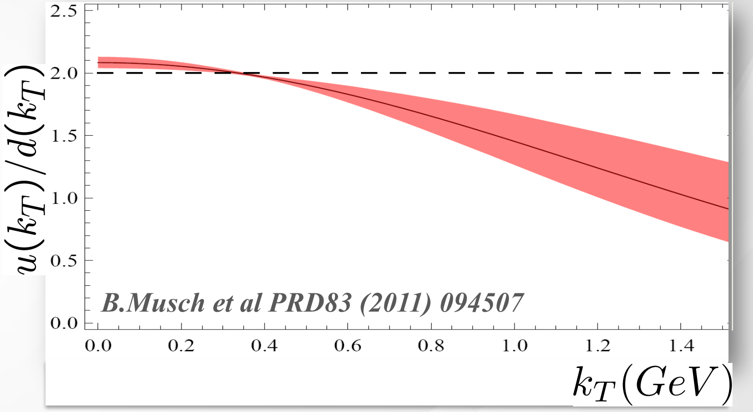
$$\langle P^2_{hT} \rangle = z^2 \langle k^2_T \rangle + \langle p^2_T \rangle$$

JLab 6 GeV Hall C



R. Asaturyan et al. PRC 85, 015202 (2012)

From the transverse hadron momentum P_{hT}
➔ information on the intrinsic k_T and the p_T generated during fragmentation



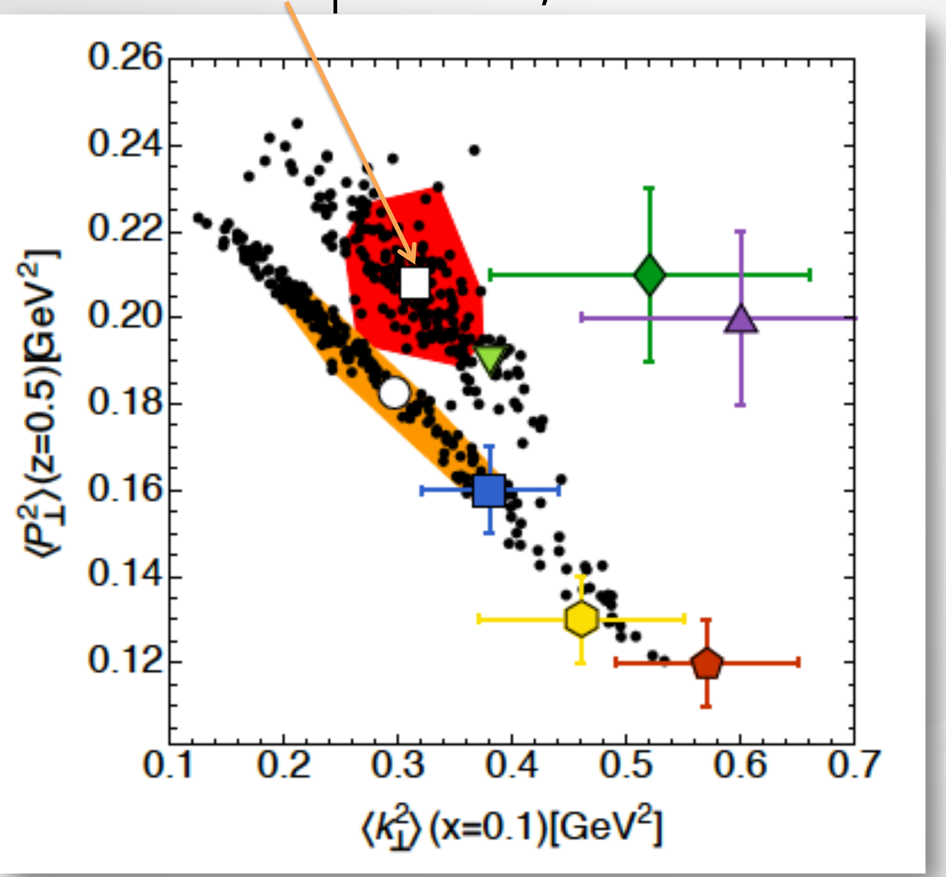
B.Musch et al PRD83 (2011) 094507

- Higher probability to find more d-quarks at large k_T
- Data (assuming only valence quarks) indicate that k_T-width of u-quarks is larger than for d-quarks

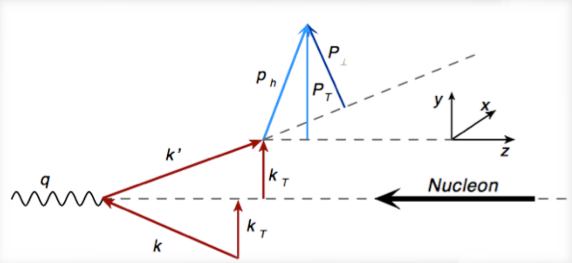
- Indications from both experimental data and theory (lattice, χCQM) of the k_T dependence of quark flavor distribution

Global analysis fitting

Pavia Group results, $Q^2 = 1$ GeV^2



arXiv:1703.10157v1



- Fit simultaneously SIDIS (HERMES, COMPASS), DY, and Z boson data
- Factorized functional form with **Gaussian dependence** on the intrinsic transverse momentum
- Flavor-indipendent TMDs
- TMD evolution at NLL

- More experimental data needed to extend the coverage in x , z , Q^2

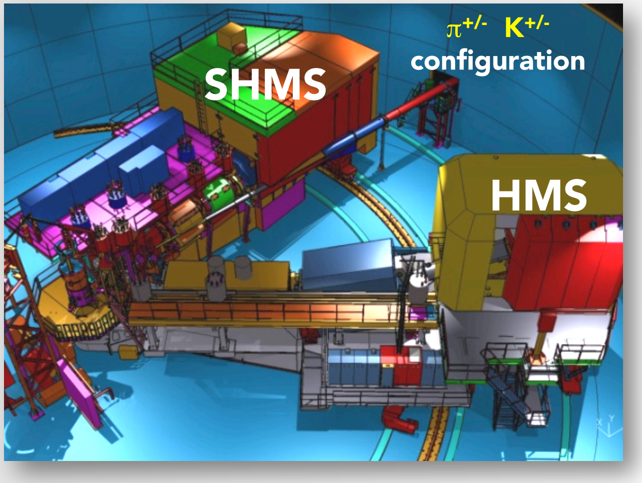
→The 12 GeV physics program at JLab will be very important to constrain TMD distributions at large x

- Multiplicities alone may not be enough to separate $<k_\perp>$ from $<p_\perp>$

Hall C: SHMS + HMS (+ NPS)

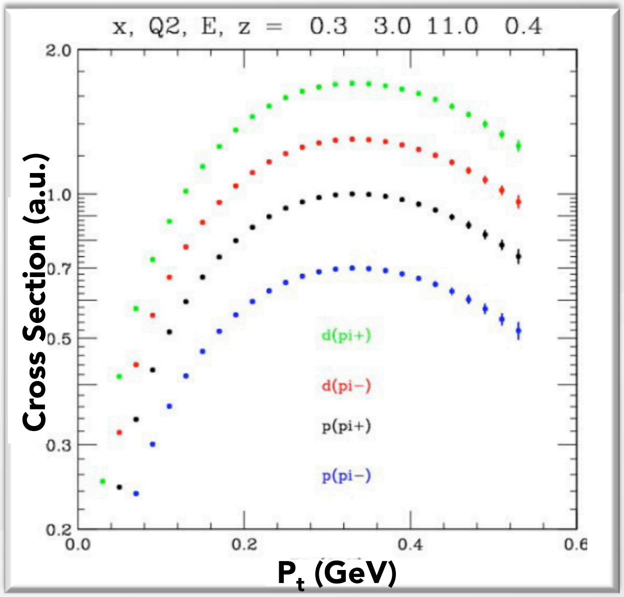
- Precise measurements of absolute cross-sections (O 1%) and p_T dependence $\pi^{+/-/0}$ and $K^{+/-}$ on p & d

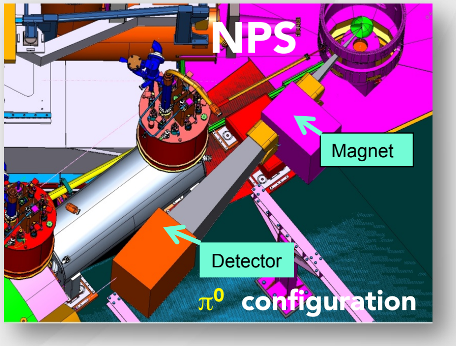
In the range: $0.2 < x < 0.5$, $2 < Q^2 < 5$ GeV^2 ,$0.3 < z < 0.5$, $P_t < 0.5$ GeV

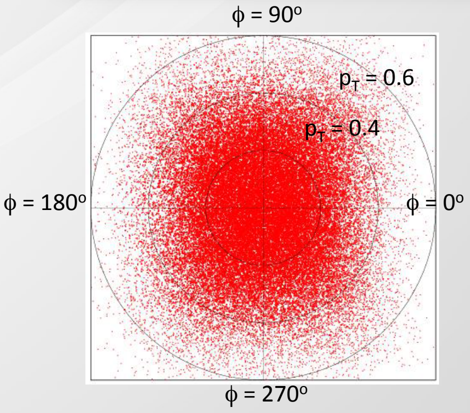


- High momentum capability & resolution
- Setup optimal for longitudinal-transverse separations and ratios of charged-meson cross sections (unique amongst the Hall experimental setups)

E12-09-017



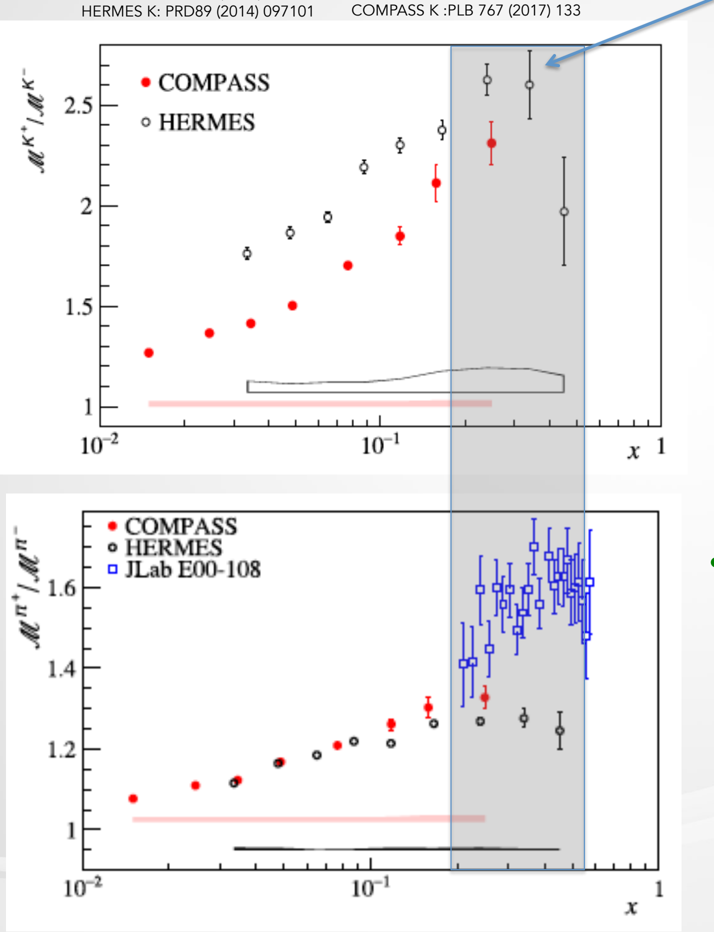




π^+/π^- & K^+/K^- Ratios

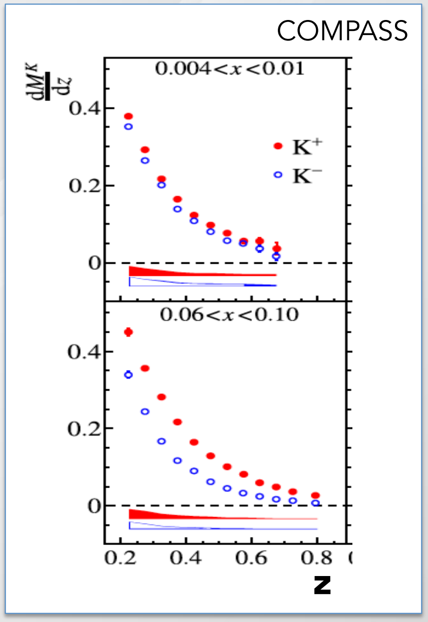
HERMES π : PRD87 (2013)_074029
HERMES K: PRD89 (2014) 097101

COMPASS π : PLB 764 (2017) 1
COMPASS K :PLB 767 (2017) 133



JLab data @ 12 GeV

- COMPASS and HERMES pion multiplicity ratios are found in good agreement
- COMPASS kaon results are systematically lower than those of HERMES.
- COMPASS & HERMES data integrated over z, JLab data (E00-108) at z=0.55



- High statistics and high precision Hall C data @ 12 GeV can be compared with HERMES and COMPASS data in the x overlapping points at the same averaged z and P_T to help understand the discrepancy for the k^+/k^- ratio

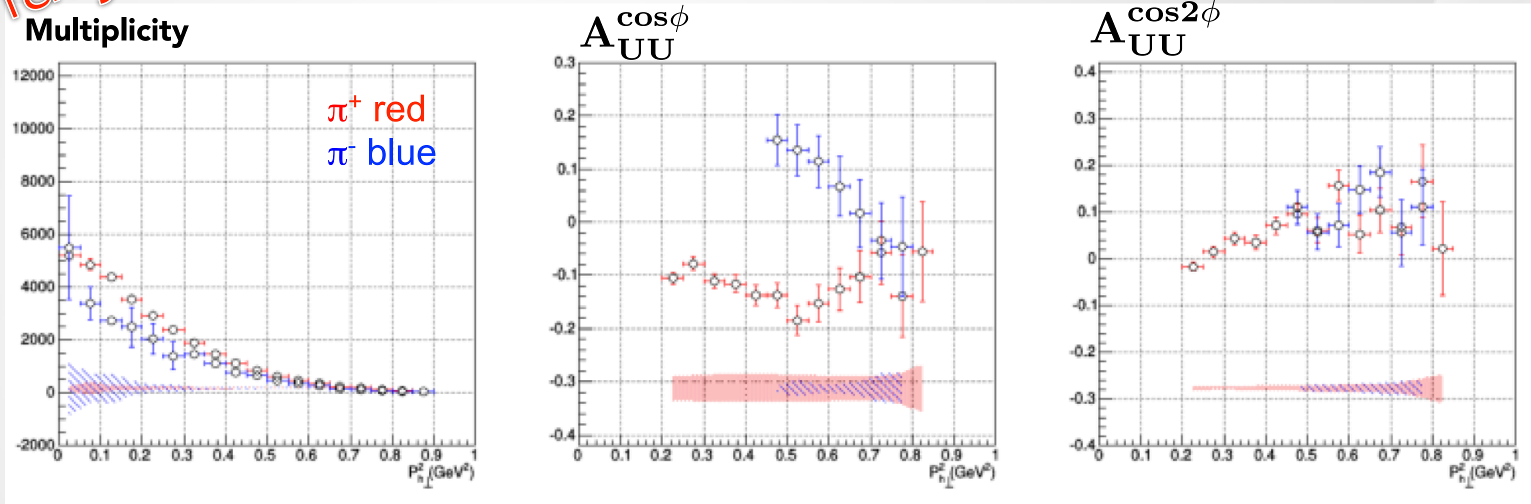
Unpolarized SIDIS x-section from CLAS @ 6 GeV

$$a(1 + b cos\phi_h + c cos2\phi_h)$$

N. Harrison

Preliminary

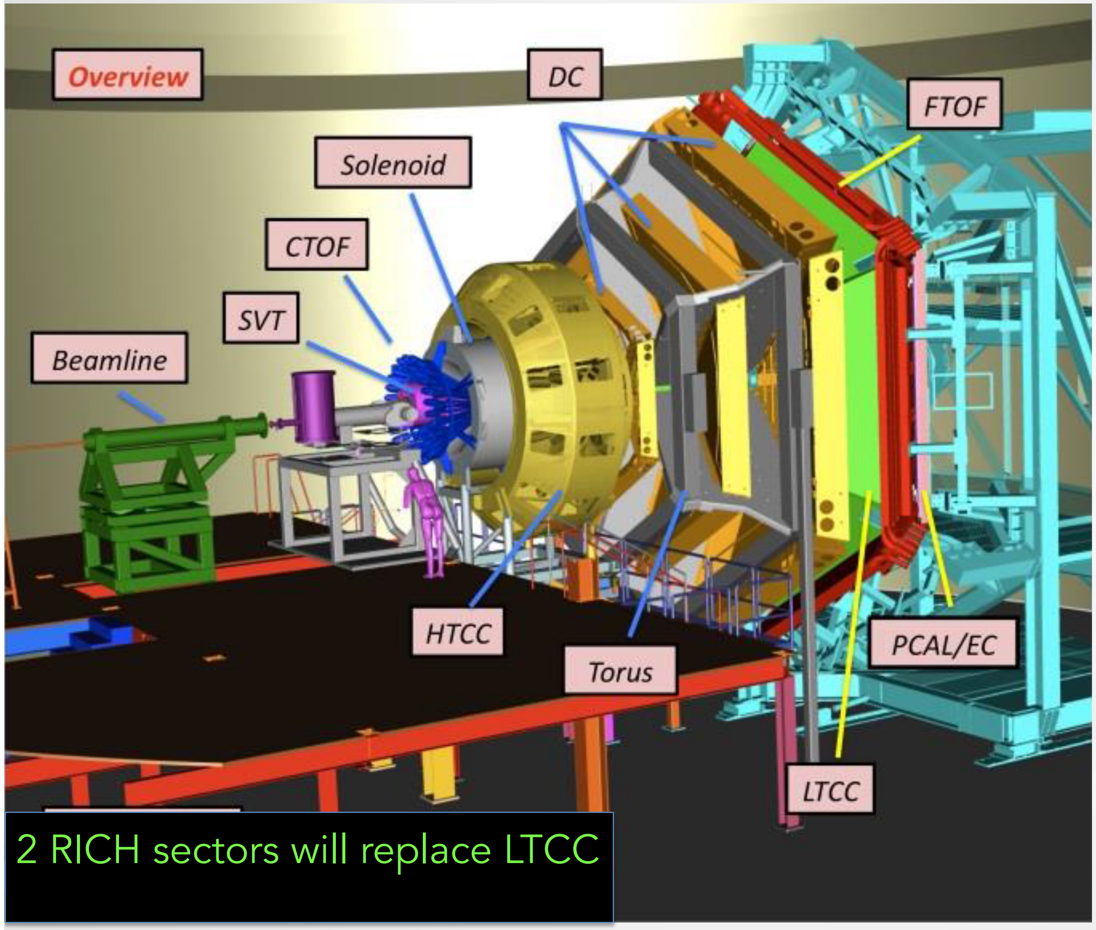
0.2 < x < 0.3
0.25 < Q² < 0.3
0.40 < x < 0.45



$$F_{UU}^{cos\phi_h} = \frac{2M}{Q} C[\frac{\hat{h}\cdot p_T}{zM_h}\frac{k_T^2}{M^2}h_1^\perp H_1^\perp - \frac{\hat{h}\cdot k_T}{M} z f_1 D_1]$$

- <cos ϕ> is more sensitive to the intrinsic k_T
- Symmetric behaviour indicates large BM contribution

Hall B: CLAS12



2 RICH sectors will replace LTCC

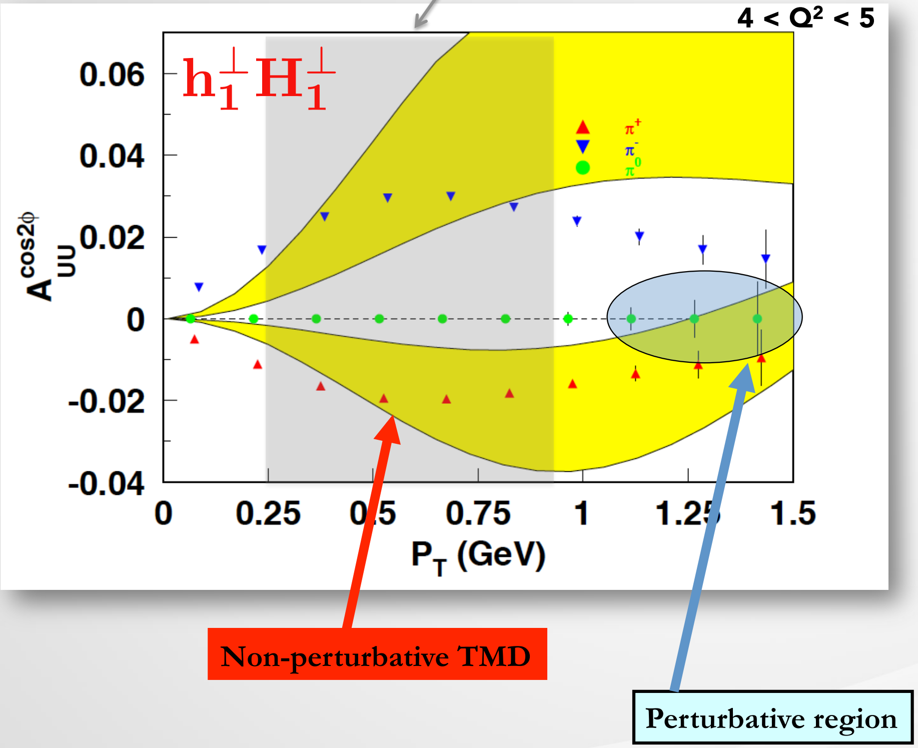
- Approved experiments @ 12 GeV will continue these studies in a wider Q^2 and P_T range.

- Very Large Acceptance
- Full PID
- Moderately high luminosity ($10^{35}cm^{-2}s^{-1}$)

Unpolarized SIDIS x-section with CLAS12

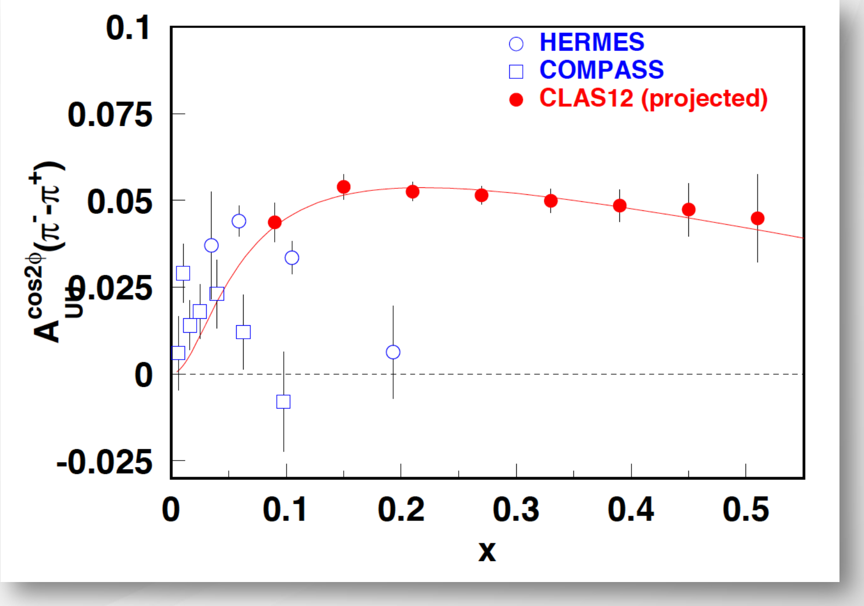
E12-06-112 : H_2 (e,e′π)

6 GeV coverage



Non-perturbative TMD

Perturbative region

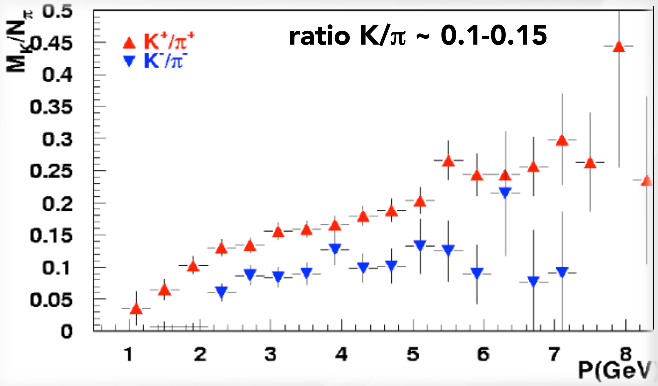


- P_T-dependence of BM asymmetry allows studies of transition from non-perturbative to perturbative description (Unified theory by Ji et al)
- Competing mechanisms (Cahn, Berger terms) and perturbative and radiative contributions to first order are expected to be "flavor blind" → in the first approximation, those effects cancel in the difference of the asymmetries for π^- and π^+

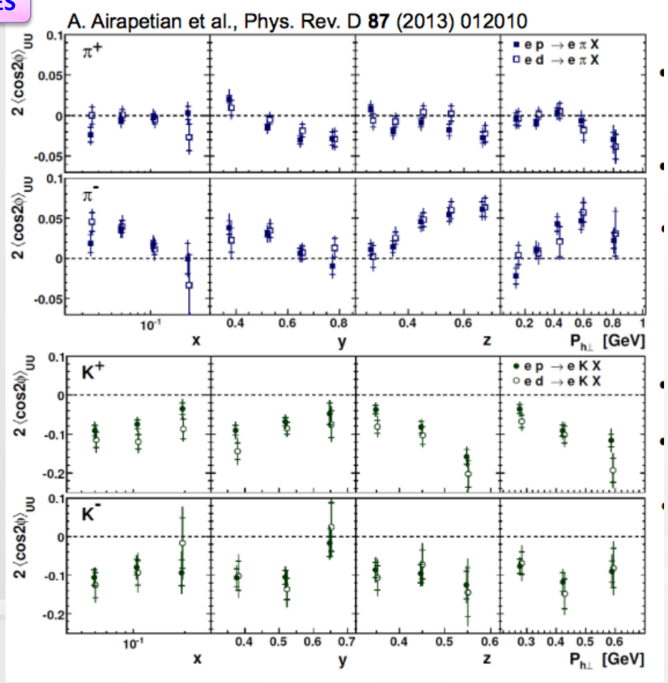
Spin-orbit Correlations of the Strange Quarks

- SIDIS with $K^{+/-}$ as leading particles, are of high interest.

- Kaon detection is generally challenged by the about one order of magnitude larger flux of pions → very little is known about the spin-orbit correlations related to the strange quark



HERMES


A. Airapetian et al., Phys. Rev. D **87** (2013) 012010

- HERMES and COMPASS results for Boer-Mulders asymmetries, despite the limited statistical accuracy, show surprising results
  - unexpectedly large Boer-Mulders asymmetries for kaons compared to pions
  - opposite signs for π^- and K^-

$u-dominance$

$K^+\{u\bar{s}\}$ $\quad$ $\pi^+\{u\bar{d}\}$

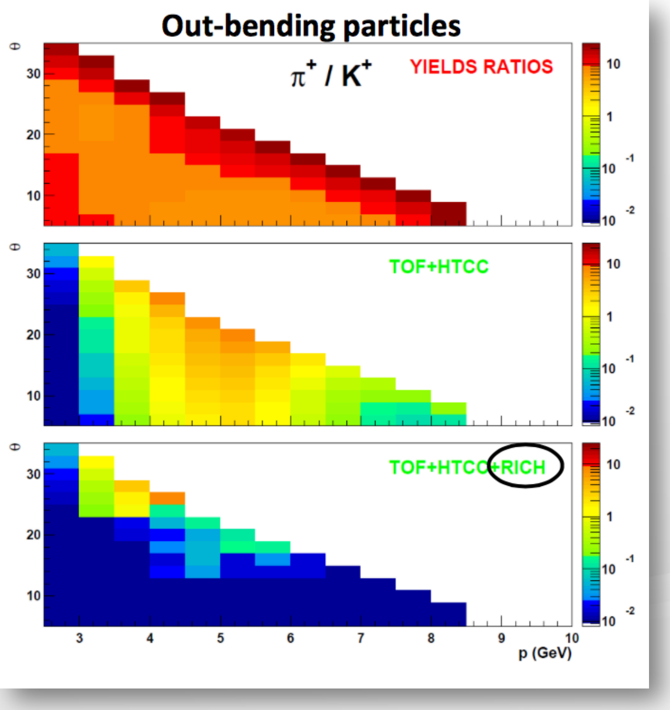
$$\xrightarrow{?} \frac{H_1^{\perp,u\to K^+}}{D_1^{u\to K^+}} > \frac{H_1^{\perp,u\to \pi^+}}{D_1^{u\to \pi^+}}$$

Relative sign $H_1^{\perp\ fav}$ / $H_1^{\perp\ unfav}$ for π and K inconstistent

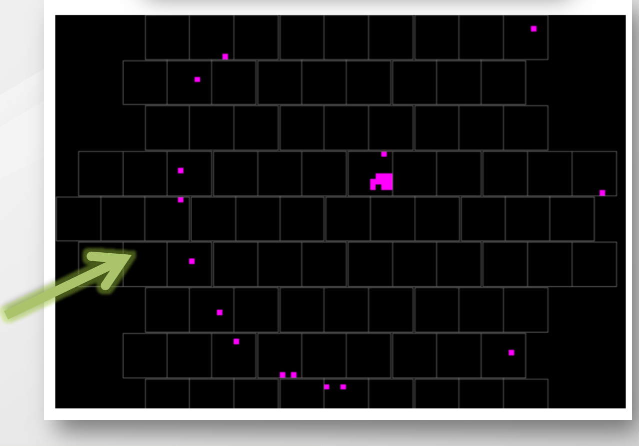
Kaon Identification with CLAS12

- These puzzling issues will be addressed with CLAS12 thanks to the improved PID obtained with the RICH detector

Hadron identification @ CLAS12



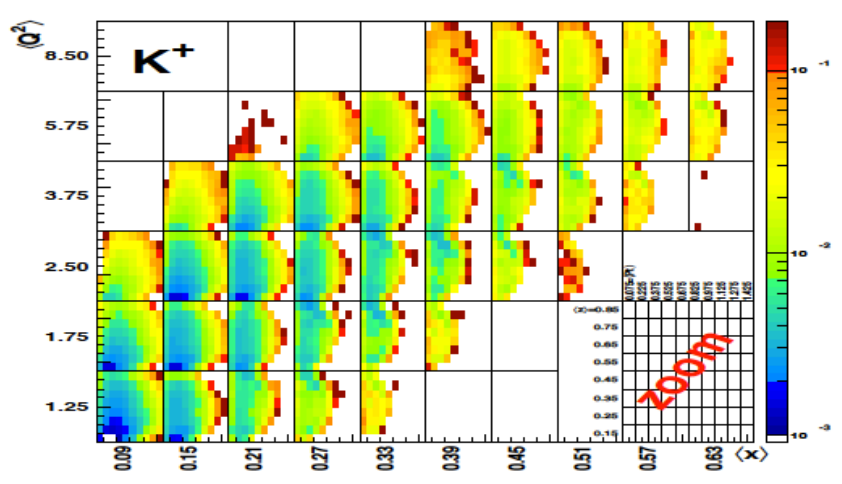
- Pion contamination in kaon sample from ×5-10 to ~$\mathbf{1\%}$ ⇒ $\mathbf{1:500}$ rejection factor ($\mathbf{4\sigma}$ separation) can be achived in full momentum range.
- Results confirmed at the CERN test beam with a RICH prototype (Eur. Phys. J. A (2016) 52: 23)
- Cherenkov ring at the cosmic test stand at Jefferson Lab



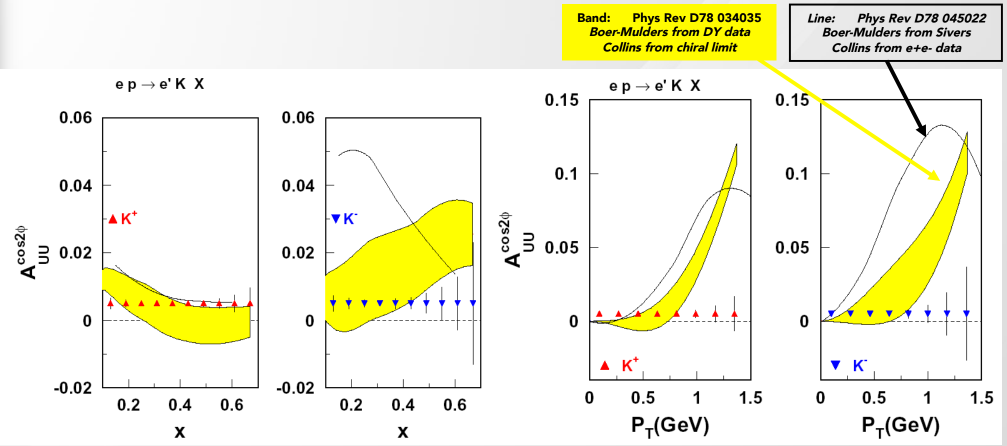
Boer – Mulders with CLAS12

E12-06-112 + E12-09-008

High precision data set on π and K azimuthal asymmetries in SIDIS with unpolarized hydrogen and deuterium targets in the region 0.06≤ x 0.8, 0≤ P_T≤1.5, 0.2≤ z ≤0.8



- Excellent precision vs model uncertainties



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

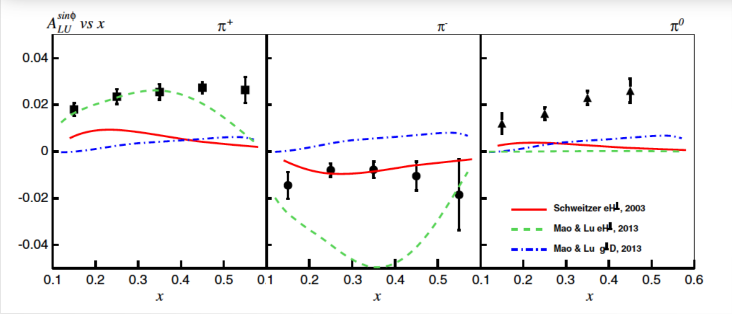
Line: *Phys Rev D78 045022*
Boer-Mulders from Sivers
Collins from e+e- data

- pions vs kaons
    - Different exclusive background
    - Different higher twist effects
    - Different hadronization effects

Higher Twist

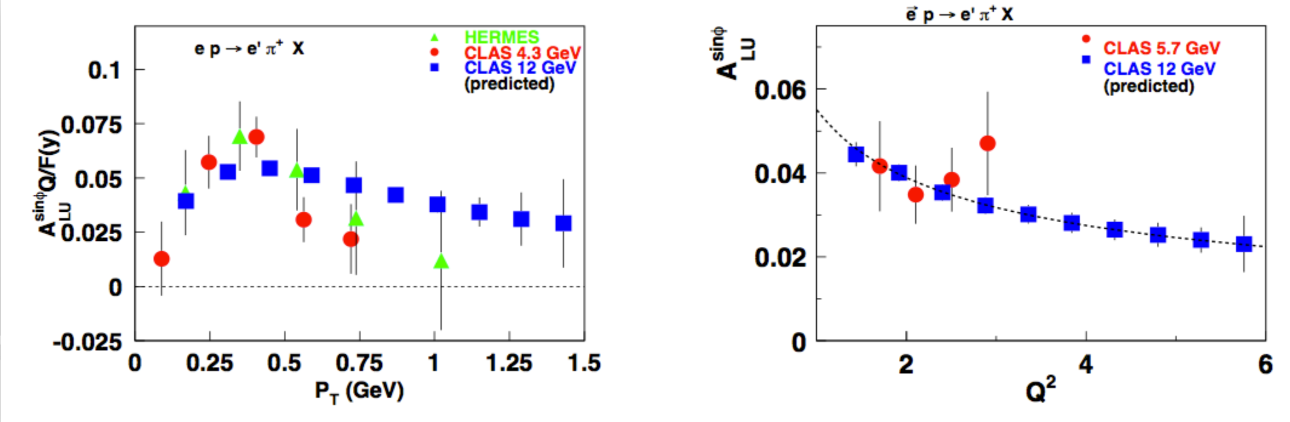
$$F_{LU}^{\sin\phi} \propto \frac{M}{Q}\sum_a e_a^2 (e^a H_{1|}^{\perp a} + f_1^a \tilde{G}^{\perp a} + g^{\perp a} D_1^a + h_1^{\perp a} \tilde{E}^a)$$

- SF related to quark-gluon-quark correlations
- Presently no satisfactory understanding of how much each function contributes



W. Gohn *et al.*, PRD89, 072011 (2014)

- A_{LU} measured with CLAS @ 5.5 GeV with better than 1% statistical precision over a large range of z, P_T, x_B, Q^2
  - permits comparison with several reaction models
  - the commonly used Wandzura-Wilczek approximation is not applicable as it would demand that the entire asymmetry be zero



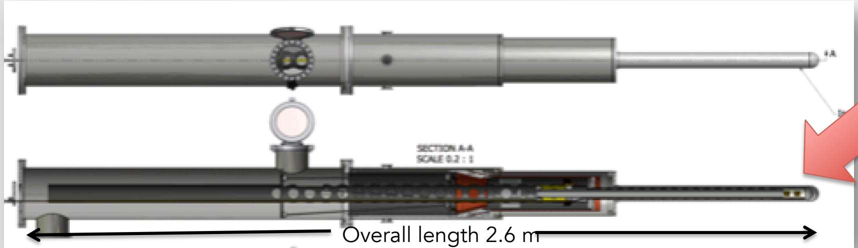
E12-06-112

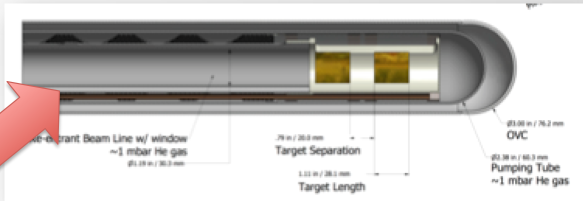
- A_{LU} vs P_T and Q^2 at fixed x_B and z with CLAS12

Measurements with Polarized Targets @ CLAS12

Longitudinally polarized proton (NH_3) and deuteron (ND_3)

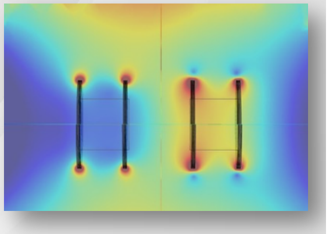
(Dynamic Nuclear Polarization)



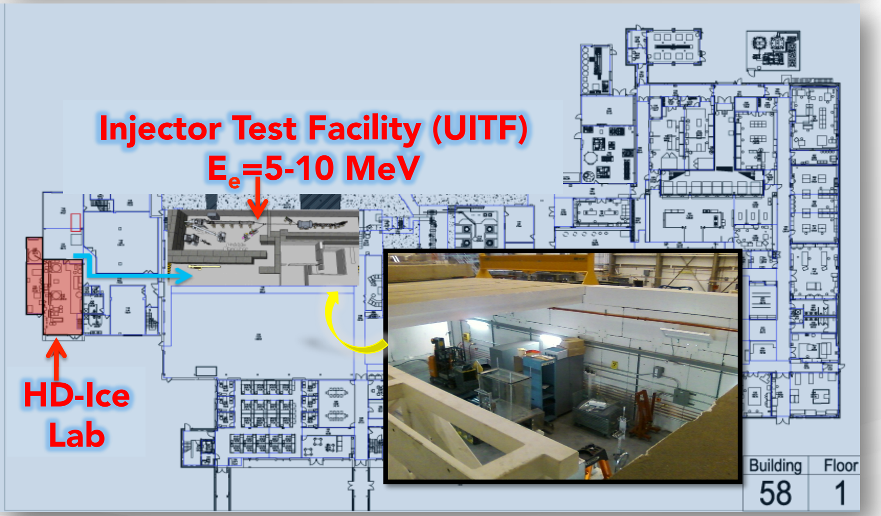


Improvement with respect to 6 GeV

- Can handle higher luminosity
- Double-cell target : Two target samples at opposing polarizations with a single μwave frequency → reduced systematic effects



- Estimated completion date: Dec. 2018



HD-Ice target

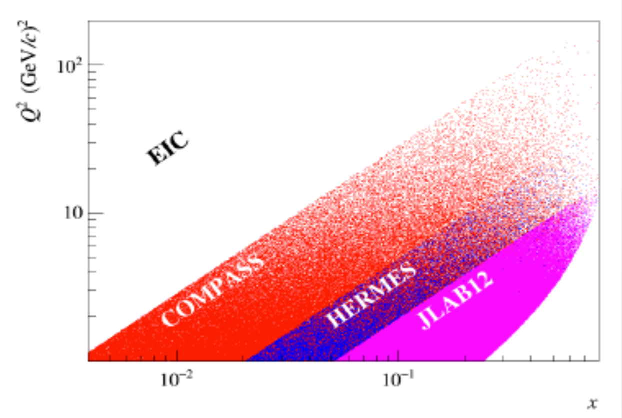
Solid HD material in a frozen spin state ➔requires only modest (~1 T)•short (~15 cm) field to hold spin in-beam

- Work in progress: 1) to test the target in the UITF 2) to operate it in transverse pol. mode in the CLAS12 Solenoid

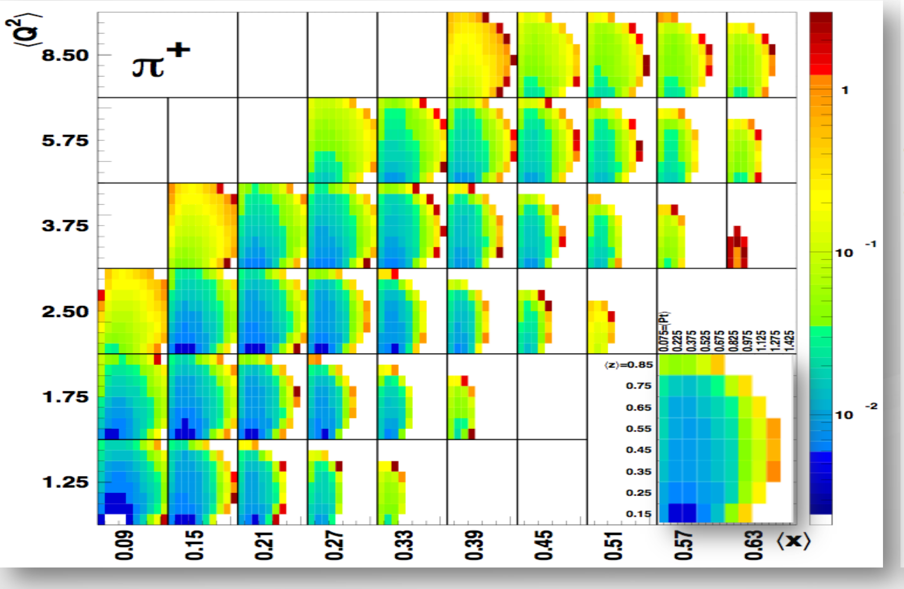
- Expected polarization: ≥ 90% (p); ≥ 40% (d)
- Electron beam current operation up to 30 nA.

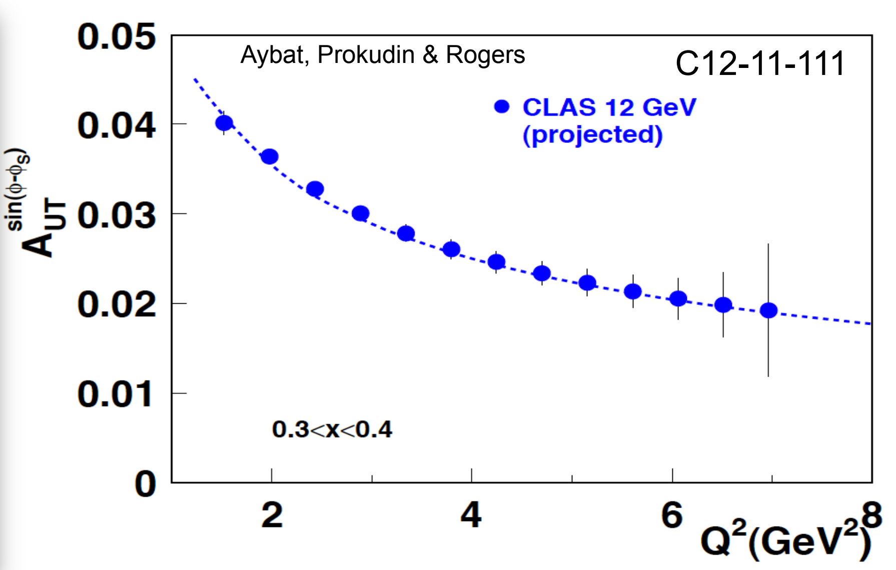
CLAS12: A_{UT} with Transverse Proton Target

- Large acceptance of CLAS12 allows studies of P_T and Q^2-dependence of SSAs in a wide kinematic range
- Comparison of JLab12 data with HERMES, COMPASS and EIC will pin down the Q^2 evolution of Sivers asymmetry



C12-11-111

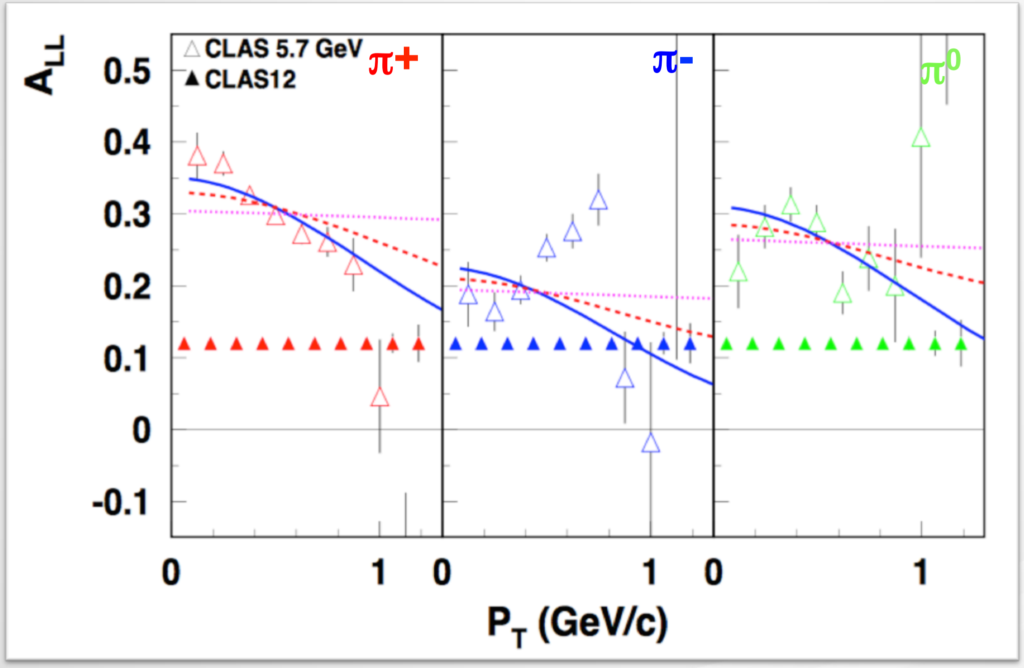




CLAS12: K$_T$ Helicity Dependence

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

E12-09-009



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

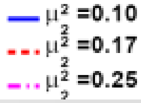
$$g_1^q(x,k_T) = g_1(x)\frac{1}{\pi\mu_2^2}e^{-\frac{k_T^2}{\mu_2^2}}$$

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

μ_0^2=0.25GeV^2
μ_D^2=0.2GeV^2

M.Anselmino et al hep-ph/0608048

Curves are calculated using different k$_T$ widths for helicity distributions

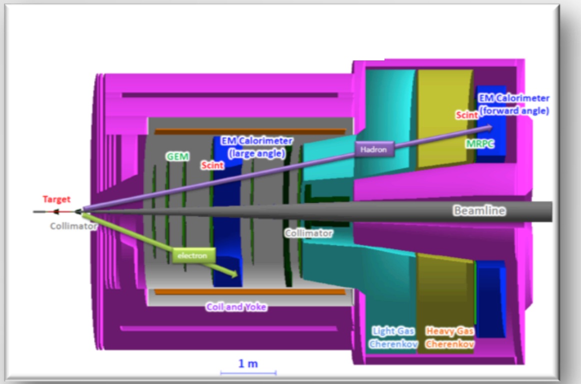


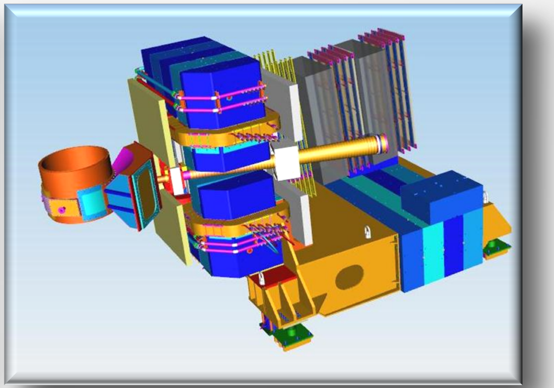
- A$_{LL}$ (π) sensitive to difference in k$_T$ distributions for f$_1$ and g$_1$
- Wide range in P$_T$ allows studies of transition to perturbative approach

Hall A: SoLID & SBS

SoLID: Long Term

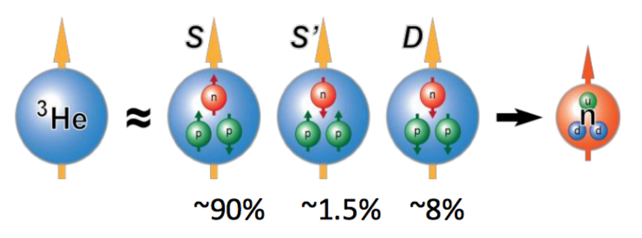
SBS: Near Term



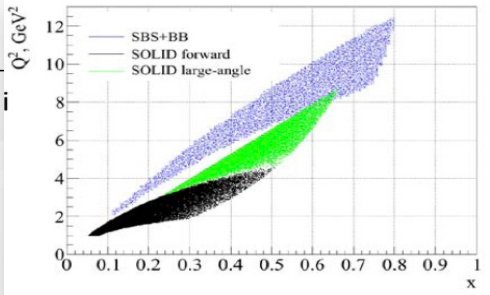


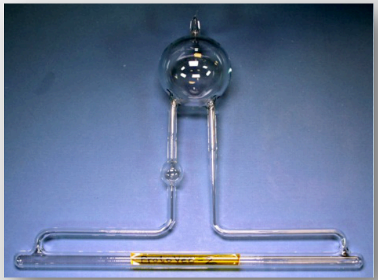
- Large acceptance (2π) - Moderately large P_T coverage - Quite high luminosity (10^{36} cm^{-2}s^{-1})	- Moderately large acceptance - Full PID (π and k)
(e e′ $\pi^{+/-}$) on Transversely Polarized **³He** (e e′ $\pi^{+/-}$) on Longitudinally Polarized **³He** (e e′ $\pi^{+/-}$) on Transversely polarized NH_3 Dihadron with Transversely Pol. **³He**	(e e′ $\pi^{+/-}$ & $K^{+/-}$) on Transversely Polarized **³He**
	Under Construction ; Physics > 2019
CLEO Solenoid at JLab ; Pre-CDR	

3He : effective polarized neutron target



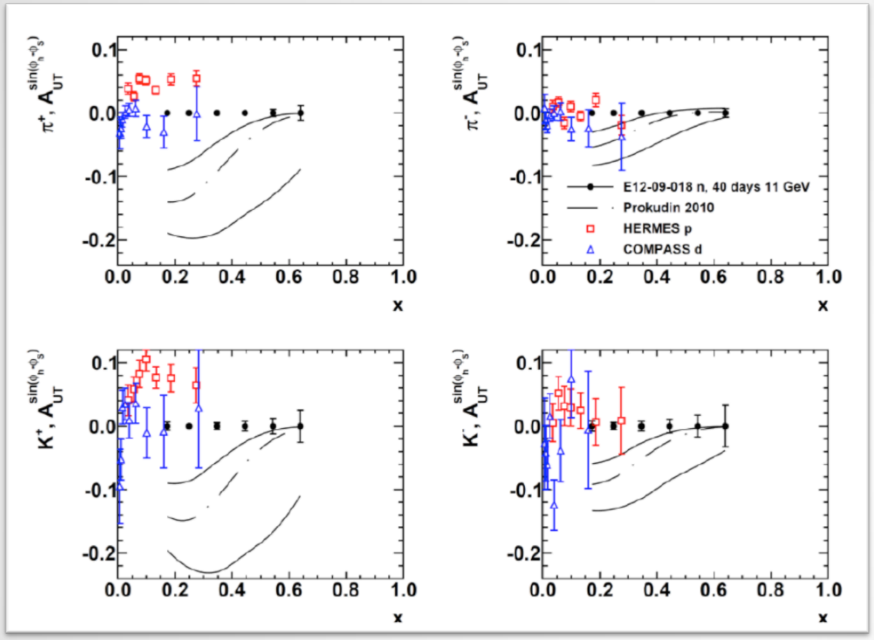
- 60 μA on 60 cm
- L ~ 6.6x10^{36} cm^{-2}s^{-1}
- Polarization ~60%





SoLID & SBS:
Complementary Kinematics

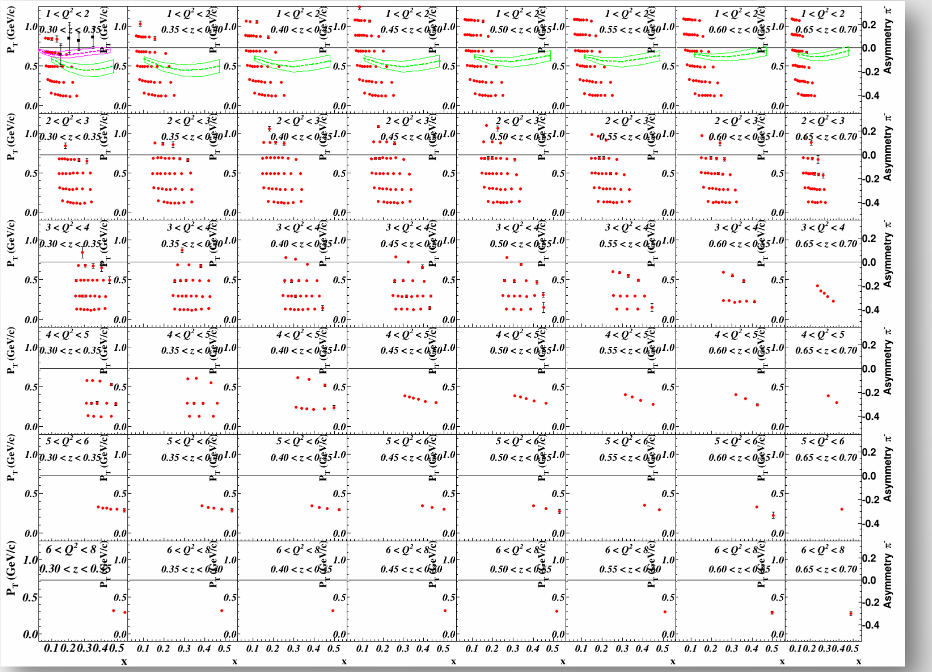
Sivers Asymmetry with SBS e SoLID



SBS

- will achieve statistical FOM for the neutron ~100X better than HERMES proton data and ~1000X better than JLab E06-010 neutron data
- Kaon and neutral pion data will aid flavor decomposition, and understanding of reaction-mechanism effects.

Power of **SoLID**



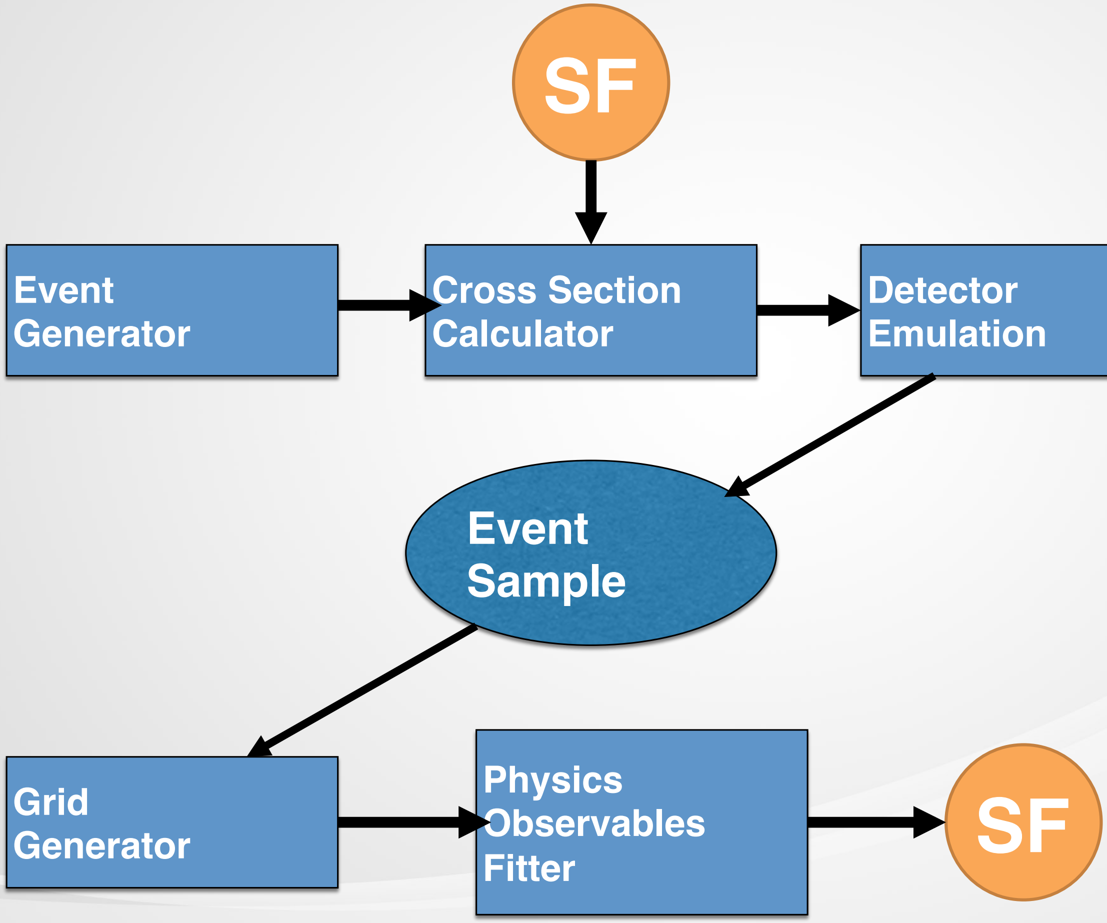
E12-10-006

Extraction and Validation framework

- The forthcoming years will be a time of unprecedented high precision and high volume data.
- Measurements from different experiments, different reactions at different energies will be soon available and the realization of a universal analysis framework to enable the **extraction** and the **interpretation** of the 3D PDFs, is mandatory.
  - The unambiguous interpretation of any SIDIS experiment (JLab in particular) in terms of leading twist TMDs requires:
    - understanding of evolution properties
    - control of various subleading $1/Q^2$ corrections
    - radiative corrections
    - knowledge of involved transverse momentum dependent FF
    - understanding of hadronic backgrounds not originating from current quarks
- This effort requires a comprehensive approach combining experimental, theoretical/ phenomenological and computational efforts.
- The analysis framework will be used to both extract the 3D PDFs from measure bles and from models of 3D PDFs to prediction of observables.
- The framework will allow testing different extraction procedures and estimating systematics related to different assumptions and models used in the extraction procedure.

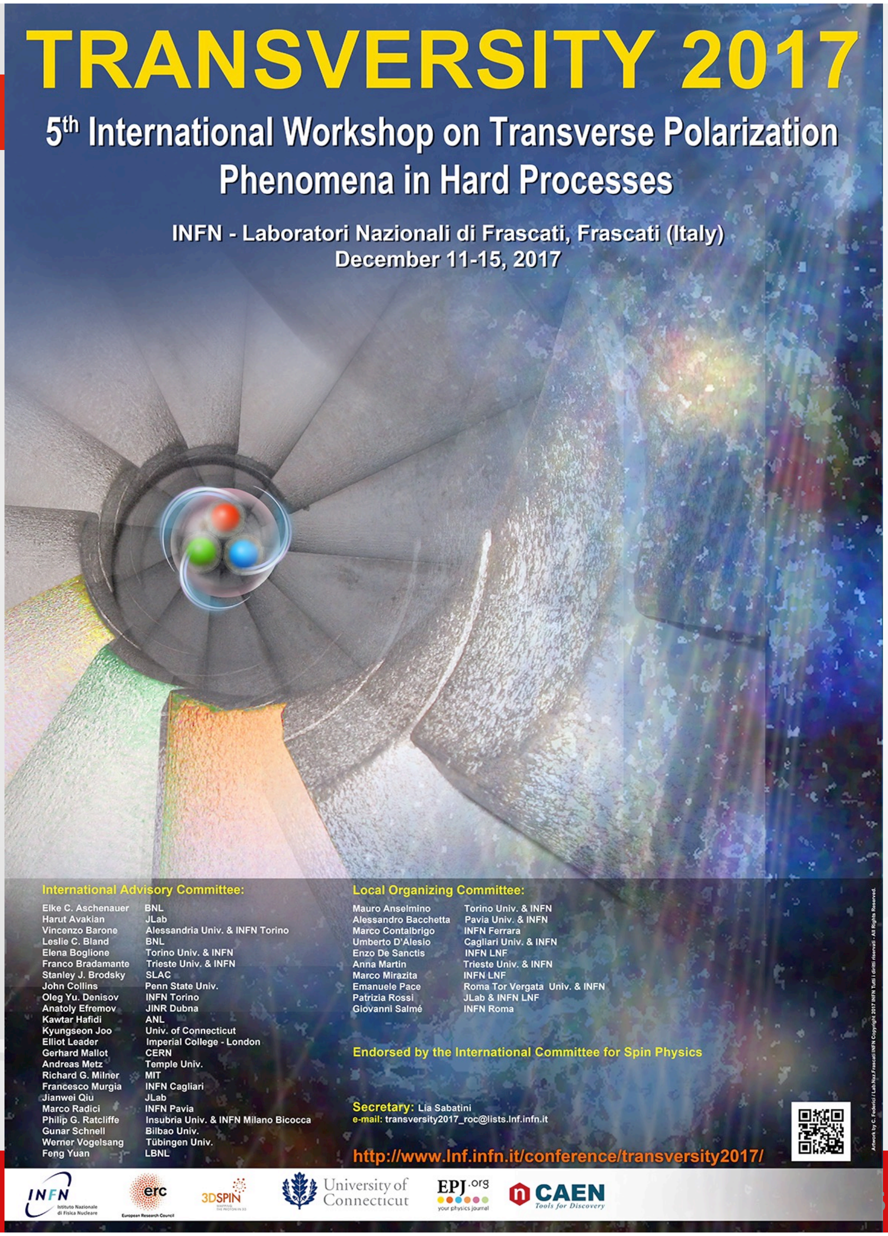
H. Avakian's talk

Framework (work flow)



- Framework is designed to have separate modules to tie together into functional code.
- Each part can be replaced by user implemented code.
- The pieces interact through data structures and take an input data.

Software developed by G. Gavalian



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5th International Workshop on Transverse Polarization Phenomena in Hard Processes

INFN - Laboratori Nazionali di Frascati, Frascati (Italy)
December 11-15, 2017

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Conclusions

- A comprehensive SIDIS program at 12 GeV is in place:
  - Wide kinematic coverage and large acceptance
  - Precise un-polarized cross-sections and their kinematic dependence
  - Study leading and sub-leading twist TMDs
  - Many modulations will be extracted in more than one experimental hall, equipped with complementary performing detectors

- Flavor separation will be performed analyzing asymmetries with different target/beam polarization combinations on both neutron and proton targets

- A consistent procedure for extraction of TMDs from data with controlled systematic errors has started.