The Jefferson Lab TMD Studies at 12 GeV

Patrizia Rossi

Correlations in Partonic and Hadronic Interactions - 2020 (CPHI-2020)

3 - 7 February, 2020 CERN, Geneva (Switzerland)

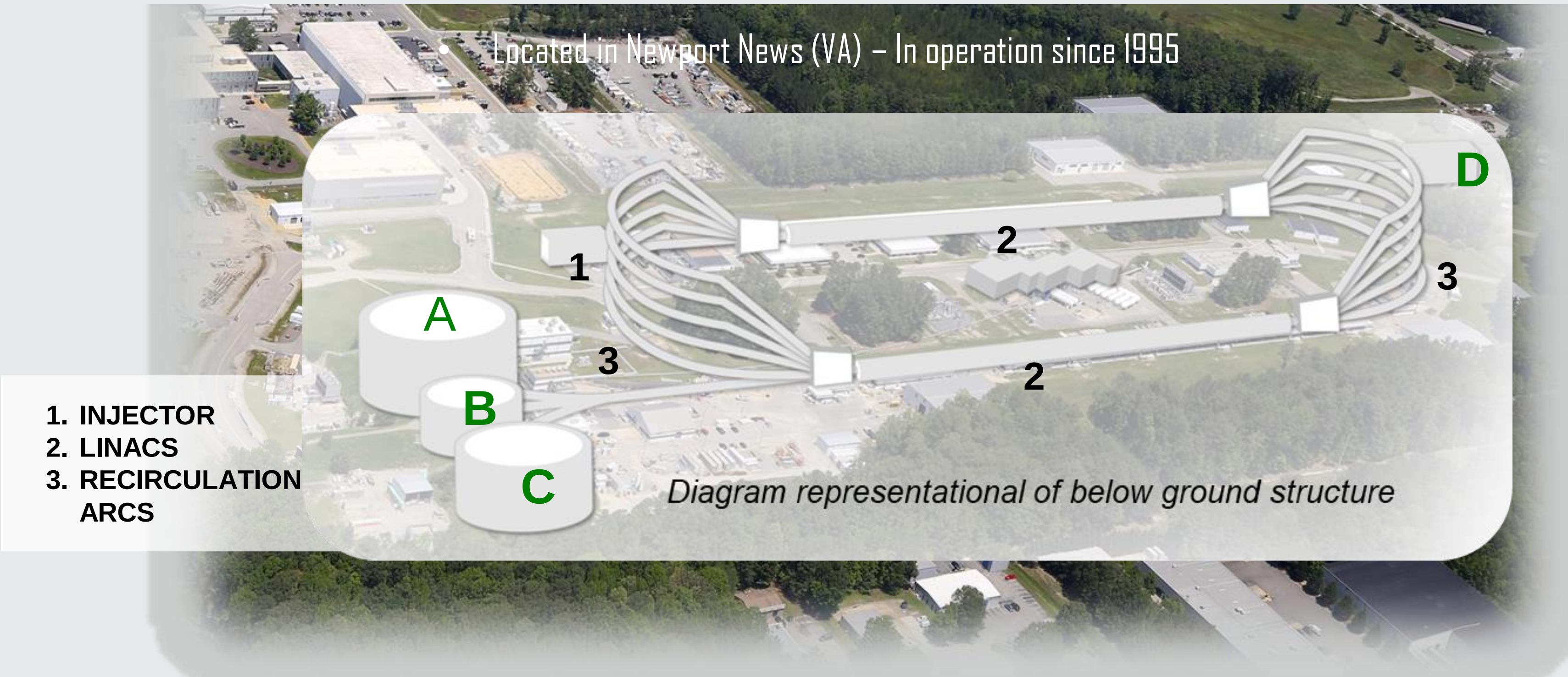
Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

Jefferson Lab and CEBAF

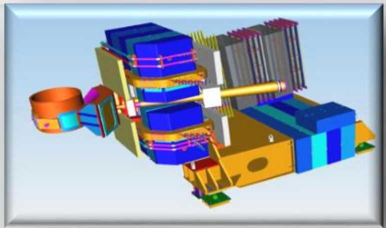
- Explore the fundamental nature of confined states of quarks and gluons → Non-perturbative regime of QCD
- Discover evidence for physics beyond the standard model

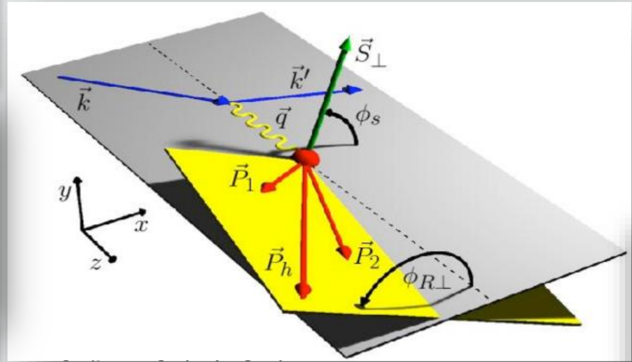


- CW electron beam
  12 GeV max Energy; high polarization (∼ 90%); high current (up to 90 μA)
- Beam delivered simultaneously to 4 exp. halls at ≠ energy & current
- Exps up to 10^{39} e-n cm^{-2} s^{-1}

A Multi-Halls SIDIS Program

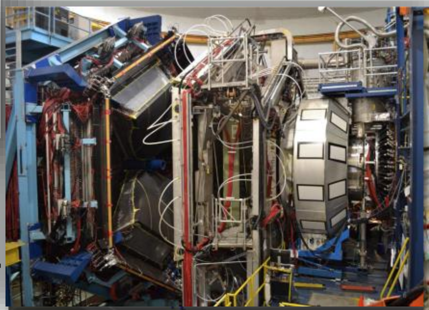
Hall A/SBS
High x - Q^2, 2-3D



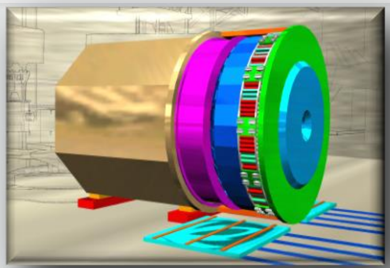


Hall B/CLAS12
Large Acceptance, medium luminosity

Hall C/HMS- SHMS
L-T studies, π^+/π^- ratios



Hall A/SoLID
High Lumi and acceptance – 4D



E12-07-007: π^+,π^-

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 $h_{1T}^\perp$

E12-06-112: π^+,π^-,π^0
E12-09-008: k^+, k^-, k^0

E12-06-112B / E12-09-008B: Higher-twist collinear structure of the nucleon through di-hadron SIDIS on unpolarized hydrogen and deuterium

E12-07-107: π^+,π^-,π^0
E12-09-009: k^+, k^-, k^0

E12-11-111: π^+,π^-, π^0, K^+,K^-
E12-12-009: di-hadron

E12-09-017: π^+,π^- K+K-
E12-06-104: π^+,π^-
E12-09-002: π^+,π^-
E12-13-007: π^0

E12-09-018: π^+,π^- K^+,K^-
E12-10-006: π^+,π^-
E12-11-108: π^+,π^-
E12-10-006A: di-hadron
E12-10-006/: inclusive A_y
E12-11-108A

^3He, NH_3

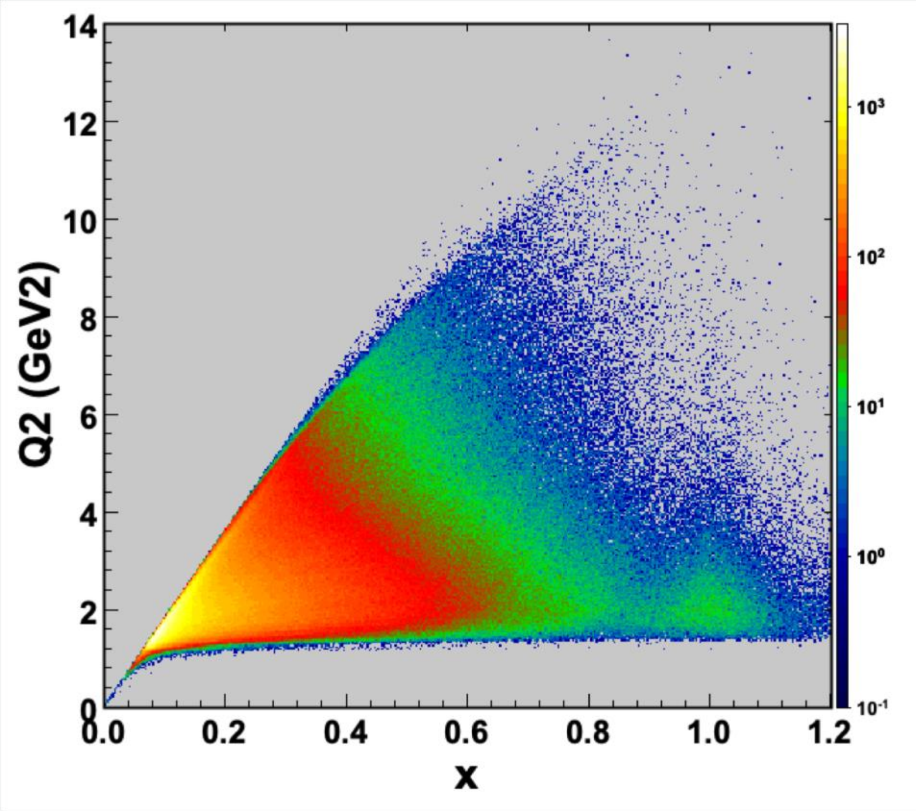
H_2 NH_3 D_2 ND_3,HD

H_2 D_2

Leading and Higher-Twist Structure Functions

TMD Studies at JLab

- Combination of high resolution measurements from spectrometers with large acceptance data from CLAS12 and SoLID, with different targets and polarization would allow to pin down all TMDs in the valence region



- The low Q^2 range of Jefferson Lab is ideal for extraction of twist-3 TMDs
- Sub-leading twists are important:
  - carry information on quark-gluon correlation functions
  - they may affect significantly the extraction of leading-twist moments
- No factorization proof for TMD observables at twist-3 is available, but steps in this direction have recently been taken (A. Bacchetta arXiv:1906.07037v1)

Unpolarized SIDIS

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

$\mathbf{f_1 \otimes D_1}$

HT

HT

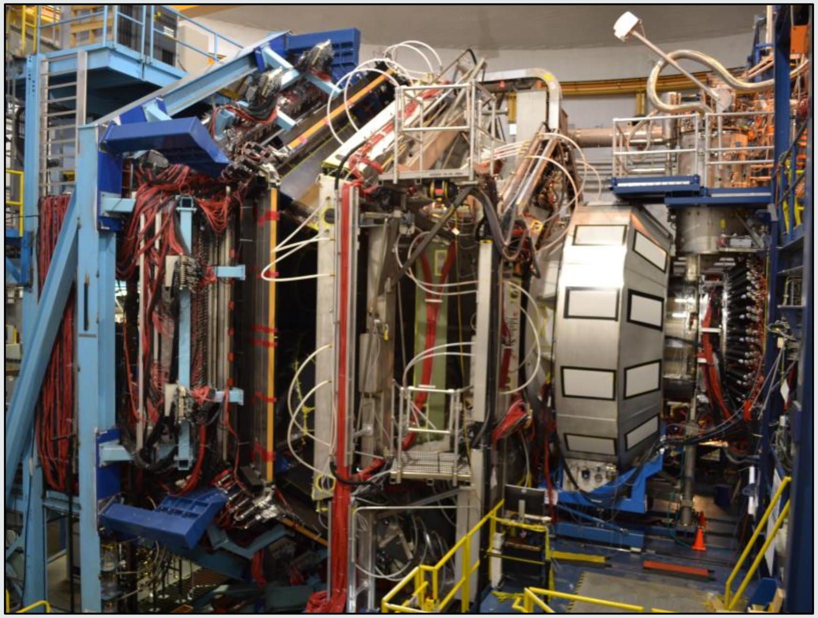
$\mathbf{h_1^\perp \otimes H_1^\perp}$

HT

- Data taken with CLAS12 (Hall B) and SHMS+HMS (Hall C) with LH_2 and LD_2
- Hall C data taking completed for charged π, K
- Preliminary results for:
  - Multiplicities (Hall B and C)
  - $F_{LU}^{sin\phi_h}$ (Hall B) single hadron & di-hadron

Jefferson Lab

CLAS12 Data Taking

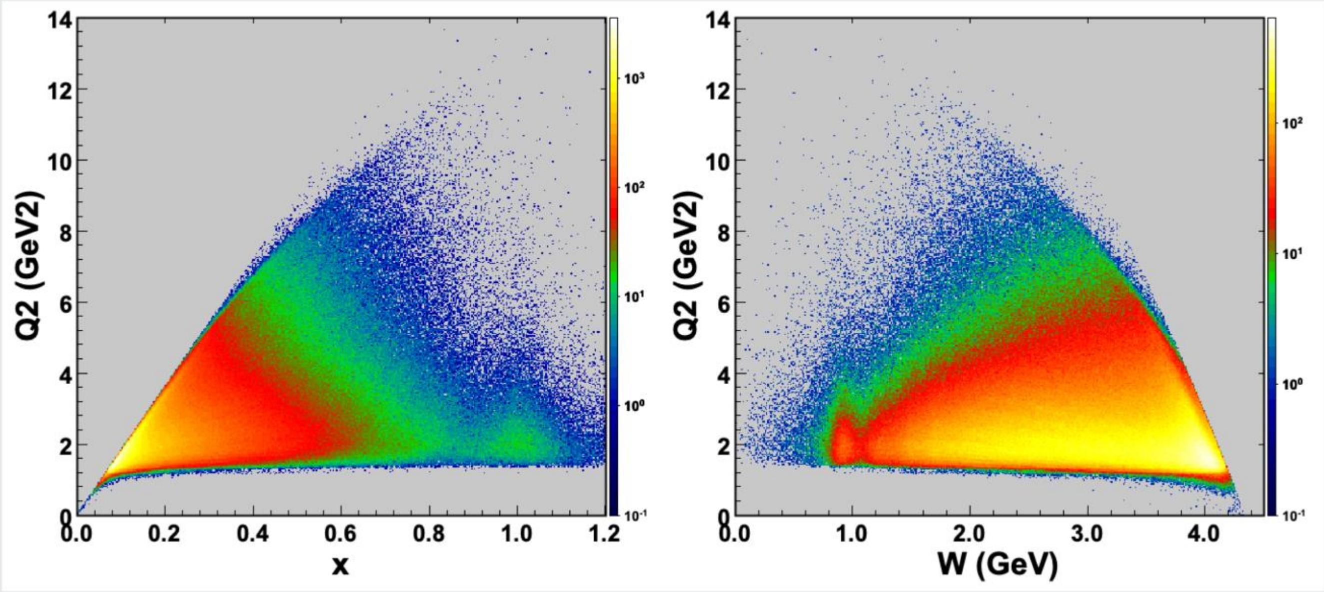


- Run Group A:

- 13 experiments
- 10.2-10.6 GeV polarized e-
- Liquid-hydrogen target
- ~50% of approved beam time

- Run Group B:

- 7 experiments
- 10.2-10.5 GeV polarized e- Liquid-deuterium target
- ~50% of approved beam time

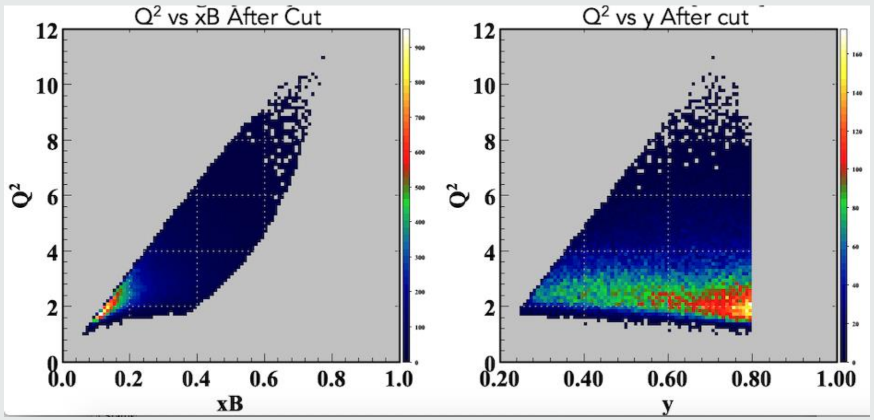


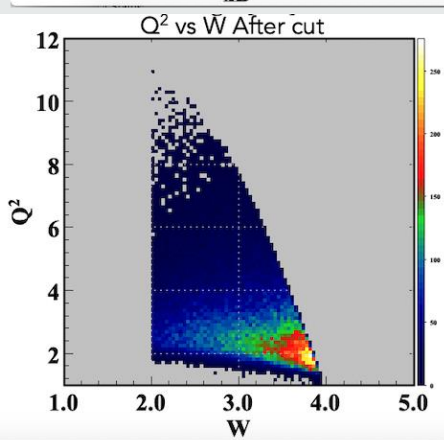
- The large kinematic acceptance and sample size allows for a multidimensional analysis in Q^2, x, z, P_T

π Multiplicities with CLAS12

$$m^h(x, z, dP_{hT}^2, Q^2) = \frac{d\sigma_{SIDIS}^h / dx dz dP_{hT}^2 dQ^2}{d\sigma_{DIS} / dx dQ^2}$$

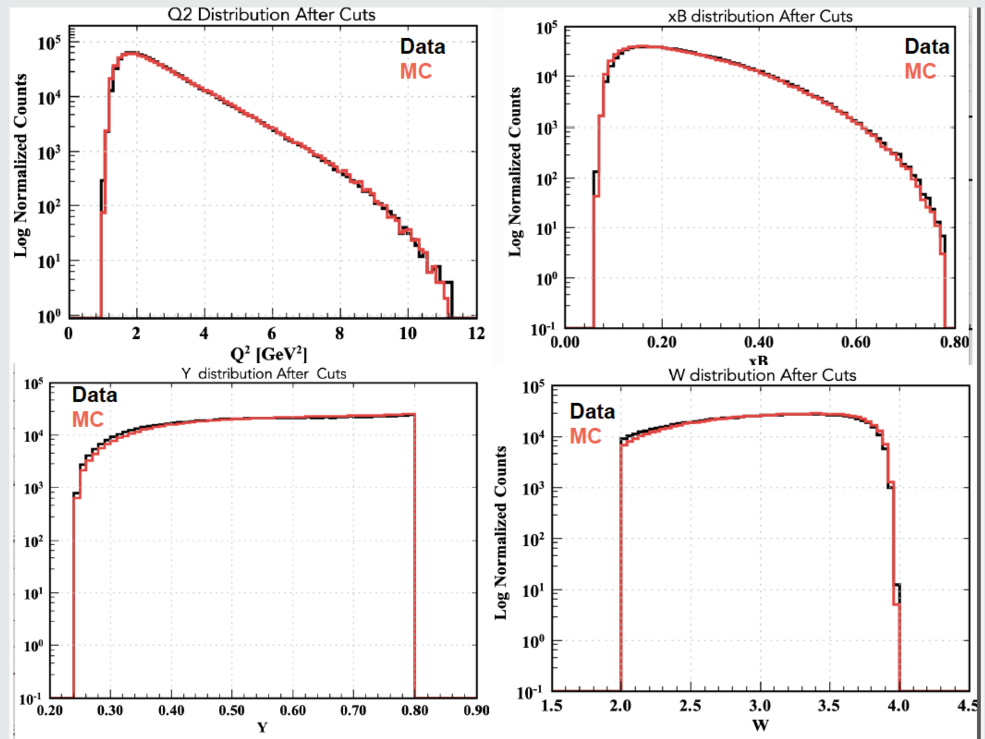
- E_e = 10.6 GeV kinematical
- Target = LH_2
- e' kin. cats: Q> 1 GeV, W > 2 GeV y<0.80



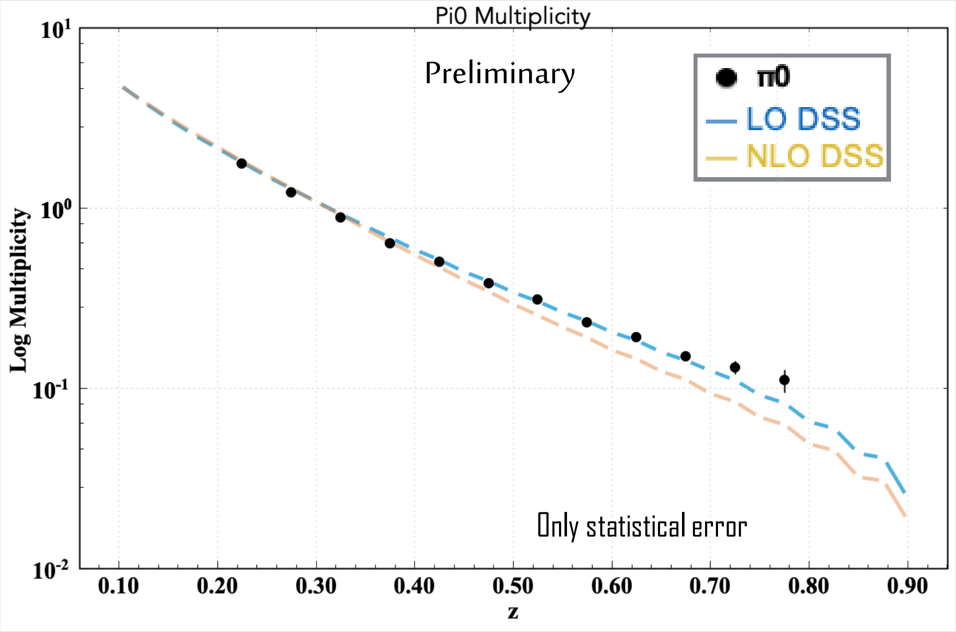


- π^0: $E\gamma$ > 400 MeV, $\vartheta\gamma e'$ > 4deg
- Data corrected for efficiency/acceptance

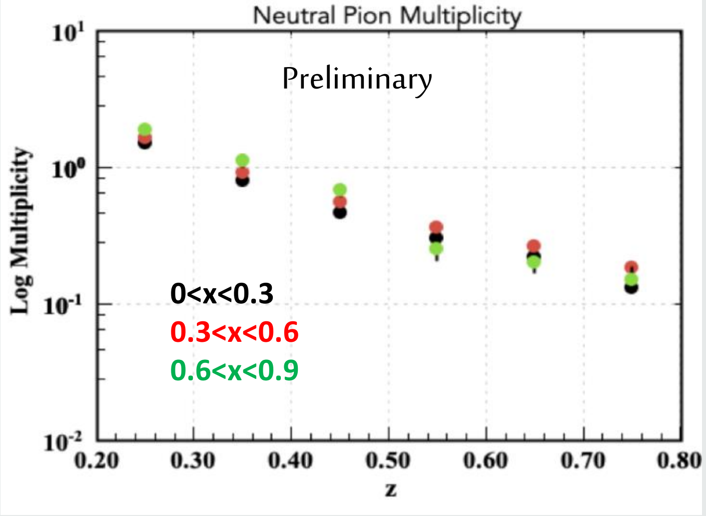
- Comparison Data - MC

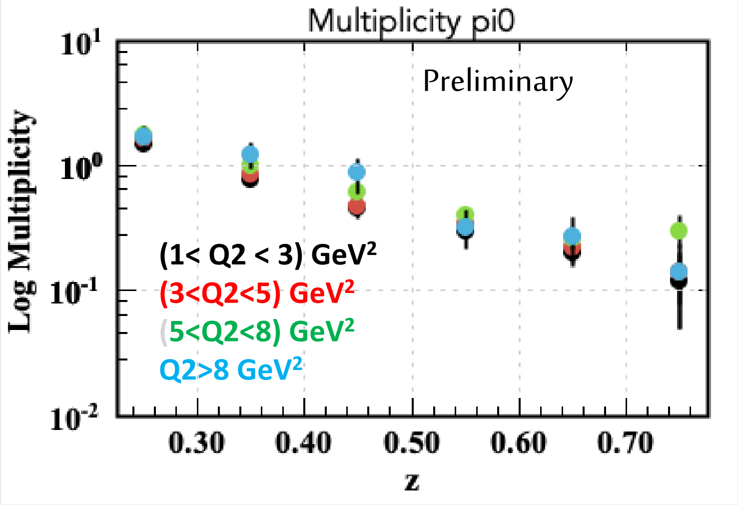


π^0 Multiplicities with CLAS12



- Plots based on ~4% of the approved beam time
- Extracted preliminary multiplicity is in good agreement with models of the unpolarized fragmentation function
- CLAS12 statistics will allow for binning in P_T, Q^2, x_B, z

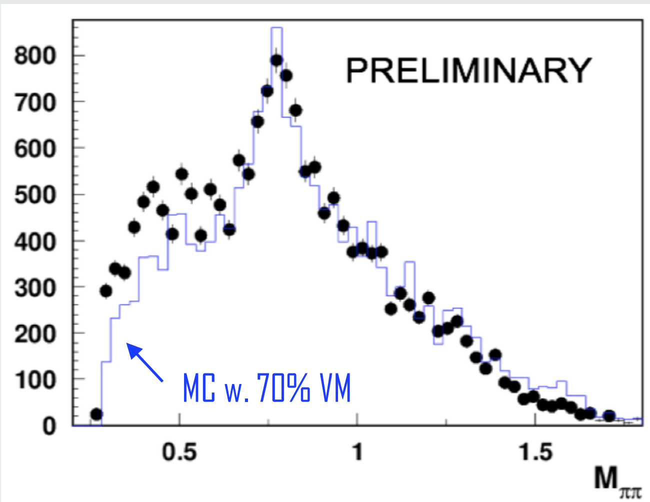




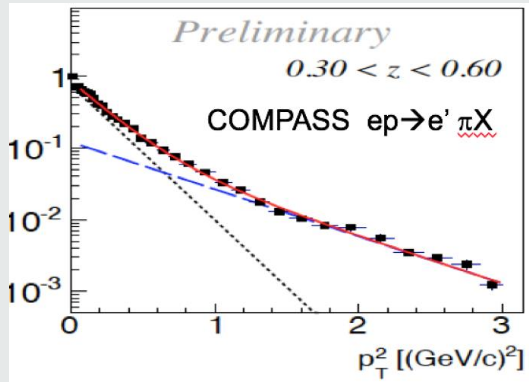
Courtesy of G. Angelini

2h Multiplicity with CLAS12: $ep \rightarrow e'\pi^+\pi^-X$

- Production of correlated hadron pairs can plays an important role in the interpretation of hadronization process of quarks

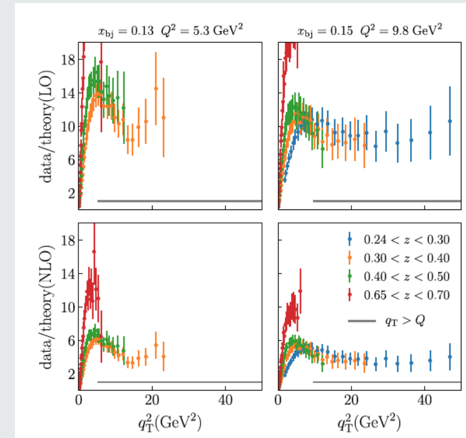


- Clarify double Gauss structures in P_T

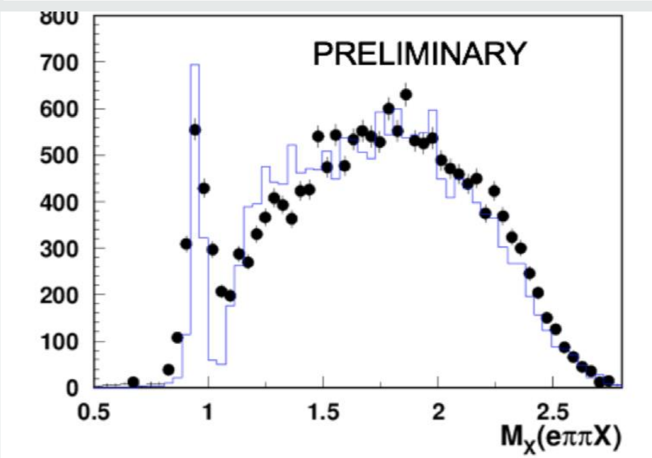


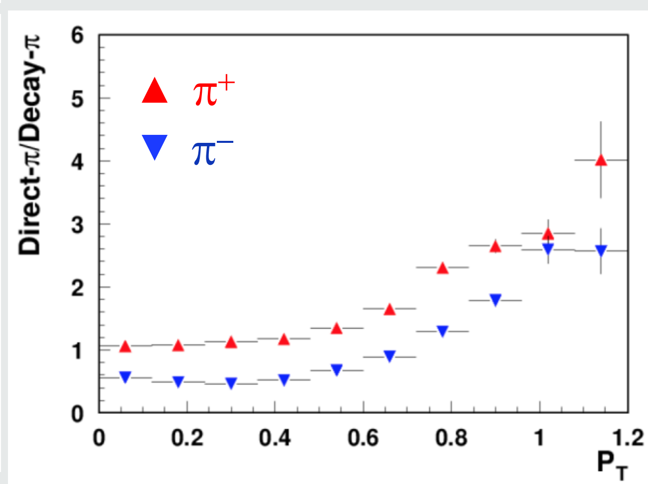
Gonzalez et al., Phys. Rev.D982018

- Provide possible expl. of this large discrepancies



Comparison data/MC (based on Lund fragm) indicates there is a very significant fraction of π from VM decays



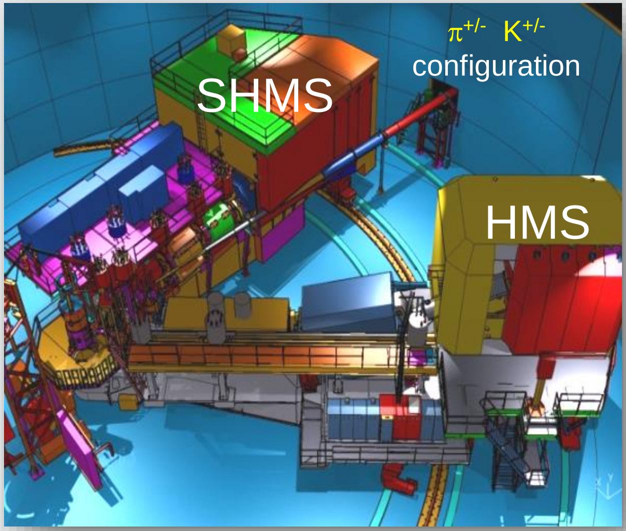


- May pions from rho decay be easily related to quark PDF, in particular how to calculate correctly the $q_T=P_T/z_\pi$ distribution?
- Large acceptance detectors are needed to detect > 1h in the f.s.

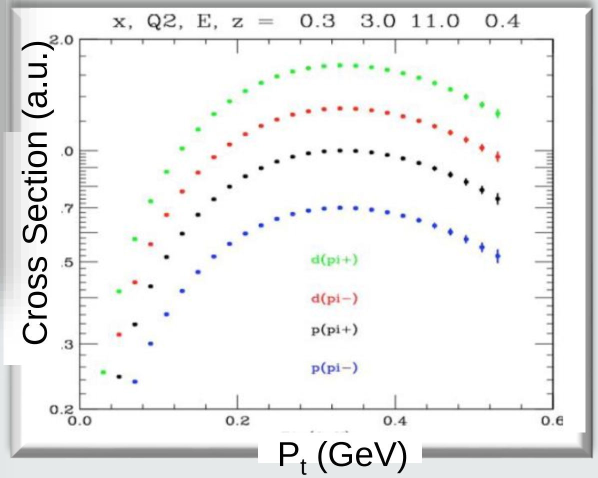
Courtesy of H. Avakian

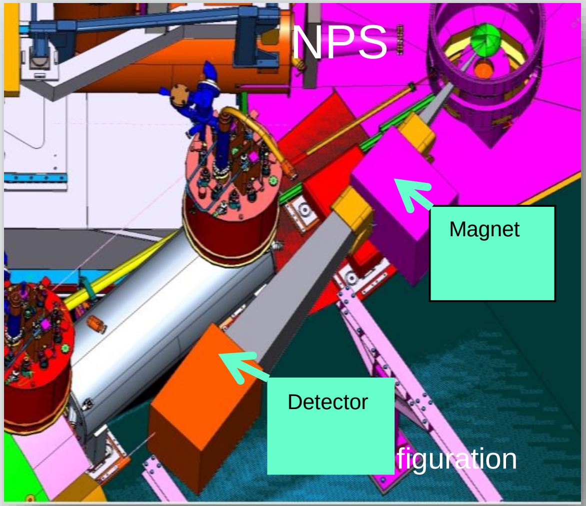
Hall C: SHMS + HMS (+ NPS)

Precision magnetic-spectrometer setup for high luminosity measurements



- Precise measurements of absolute cross-sections and p_T dependence $\pi^{+/-/0}$ & $K^{+/-}$ on p & d $0.2 < x < 0.5$, $2 < Q^2 < 5$ GeV^2, $0.3 < z < 0.5$, $P_t < 0.5$ GeV
- L/T separations in SIDIS





- Data taking for charged hadrons: 100% complete
- Data taking for neutral pion foreseen for 2022

Analysis Status

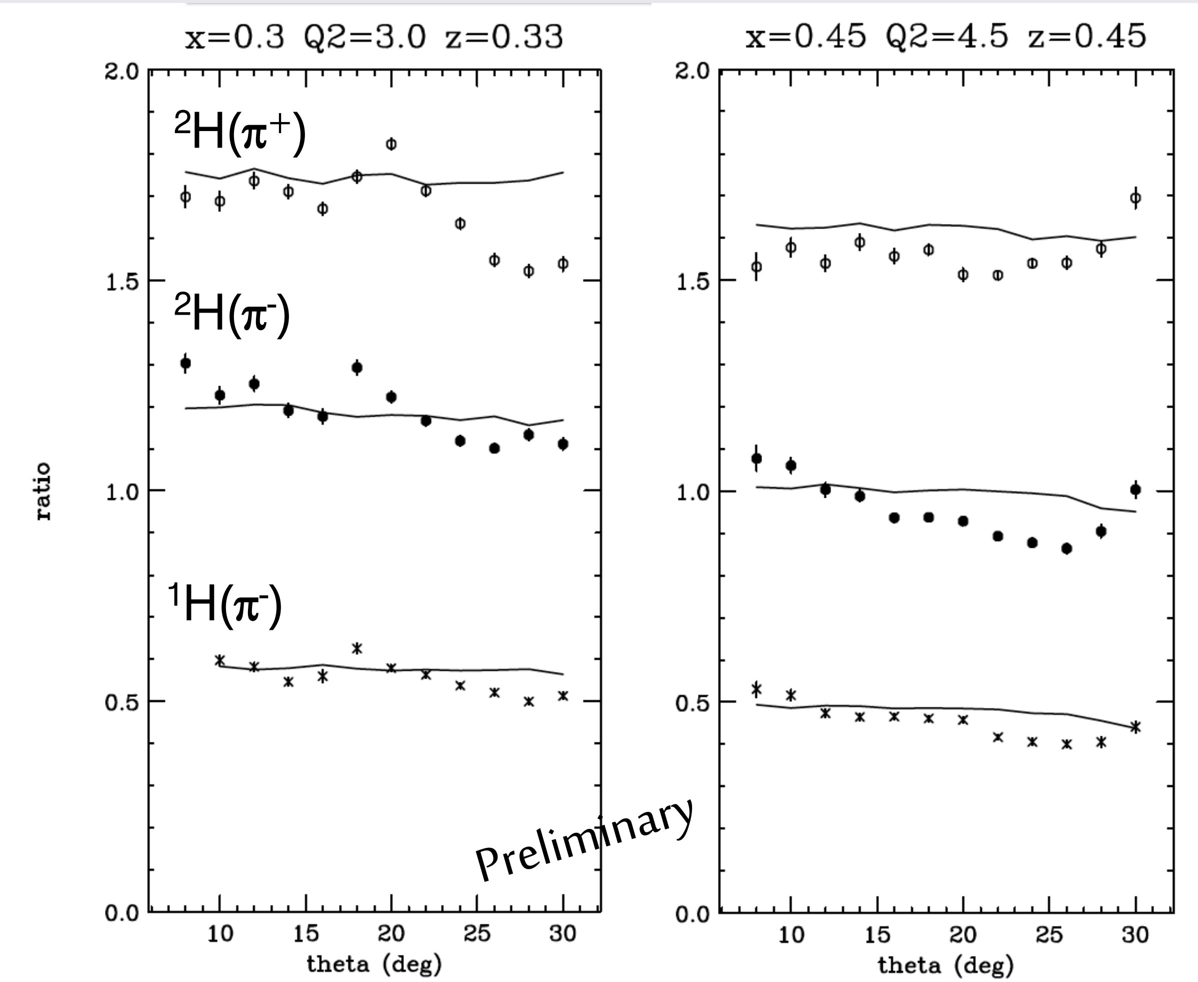
- All detector calibrations done
- In process of adjusting SIDIS model in SIMC to agree better with data

Ratios to Hydrogen π^+

x	Q^2	z
0.3	3	0.33
0.3	3	0.45

x	Q^2	z
0.3	4.1	0.33
0.3	4.1	0.45

x	Q^2	z
0.45	4.5	0.35
0.45	4.5	0.45



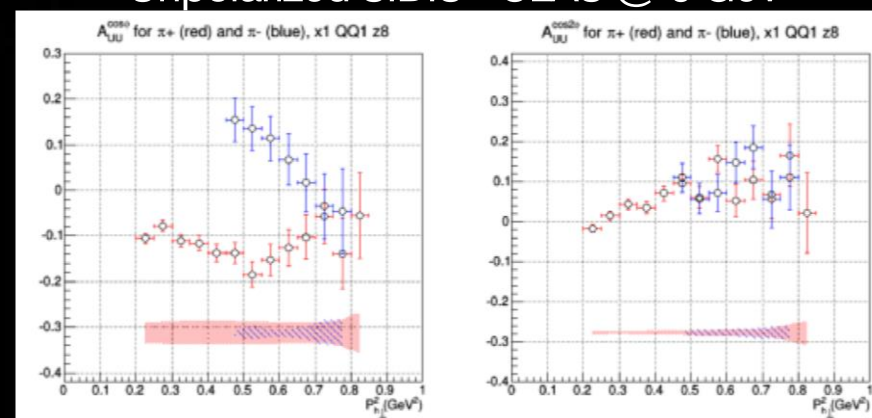
- Overall, magnitude of the data ratios is in reasonable agreement with SIMC ratios.
- There is a slight trend for the ratios to be smaller than SIMC at larger SHMS angles (larger pt).
- Difference from SIMC could be due to a combination of pt-dependence and phi* dependence for pi+/pi+ and/or p/d
- Also contribution from exclusive pion tail is being investigated

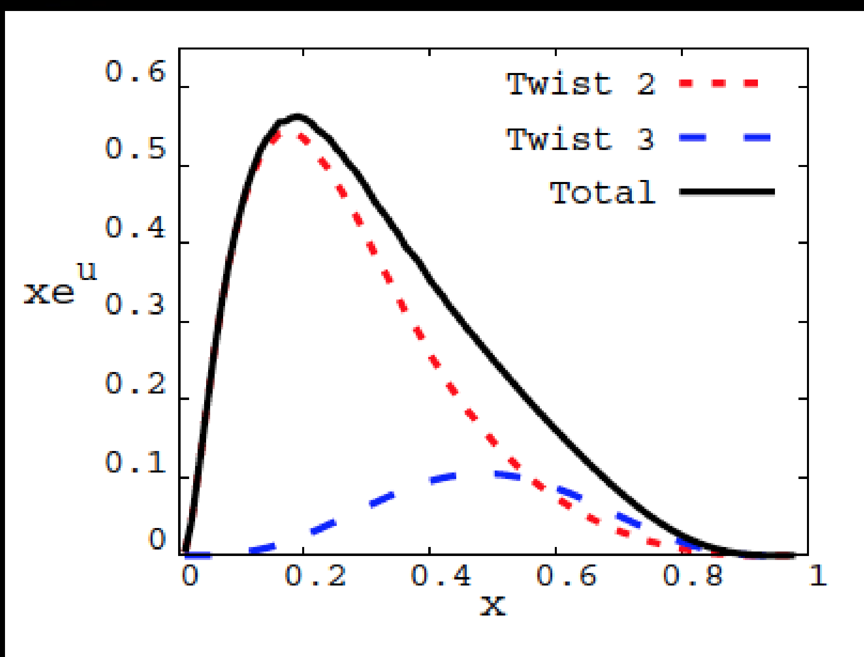
Higher Twist Structure Functions

It is a popular assumption that twist-3 terms are small but ….

$$A_{UU}^{\cos\phi} \simeq A_{UU}^{\cos 2\phi}$$

Unpolarized SIDIS - CLAS @ 6 GeV





$e(x,k_T) \rightarrow F_{LU}^{\sin\phi}$

Calculations using light-front wavefunctions indicate the pure twist-3 contributions can be very signicant in certain kinematics.

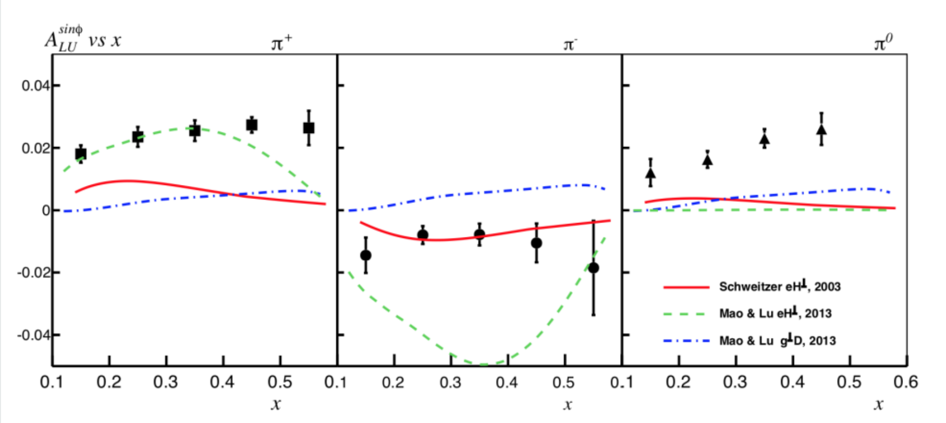
B. Pasquini, S. Rodini PLB788 (2019) 414

Higher Twist: F_{LU} sinϕ

$$F_{LU}^{sin\phi} \propto \frac{M}{Q}\sum_a e_a^2 (e^a H_1^{\perp a} + f_1^a \tilde{G}^{\perp a} + g^{\perp a} D_1^a + h_1^{\perp a} \tilde{E}^a)$$

- No satisfactory understanding of contribution from each function
- Large difference between different models
- **e(x)** (q-g-q correlations) as **force on the quarks** (Burkardt PRD88 (2013) 114502)

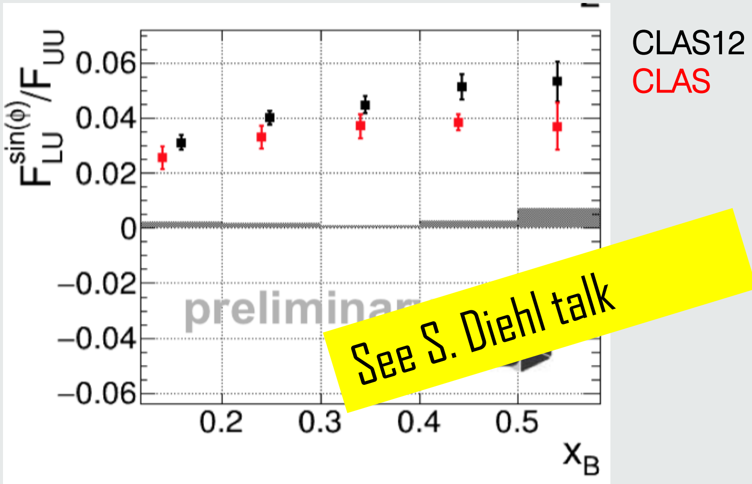
CLAS @ 5.5 GeV



W. Gohn et al. PRD 89, 072011 (2014)

CLAS12 @ 10.6 GeV

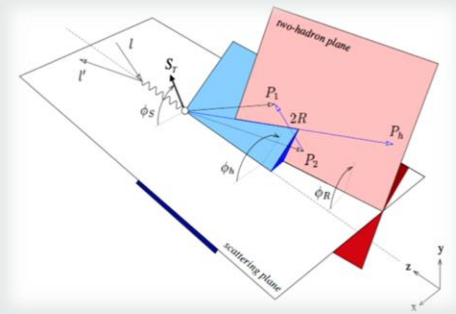
Analyzed data ~3% of approved beam time



- The large data sample provided by CLAS12 in a large kinematic acceptance will allow a multidimensional analysis (Q^2, x, z, P_T) for a better comparison with different reaction models

Jefferson Lab

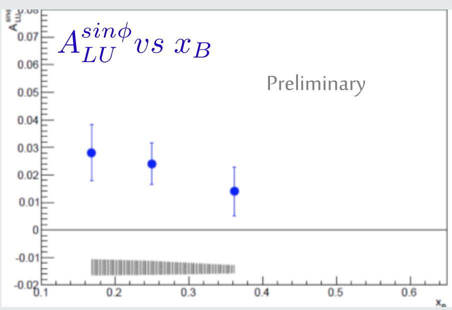
Unpolarized SIDIS: di-hadron



$$F_{LU}^{sin\phi_R} = -x\frac{|\vec{R}|sin\theta}{Q}\left[\frac{M}{M_{\pi\pi}}xe^a(x)H_1^{\measuredangle a}(z,cos\theta,M_{\pi\pi}) + \frac{1}{z}f_1^a(x)\tilde{G}(z,cos\theta,M_{\pi\pi})\right]$$

- Easier extraction of twist-3 PDF from di-hadron SF: the process can be analyzed in the collinear factorization framework
- Unique tool to study the higher- twist effects in sin ϕ modulations of the BSA

$$\mathbf{BSA} \propto \sin\phi_R \left[\frac{eH_1 \sin\theta}{f_1 D_1}\right]$$

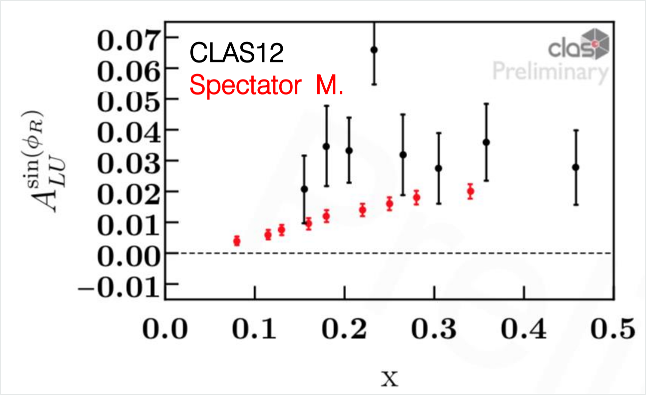


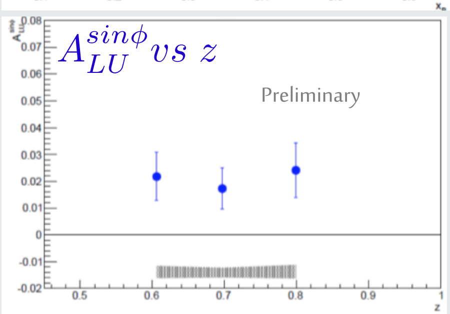
CLAS @ 5.5 GeV

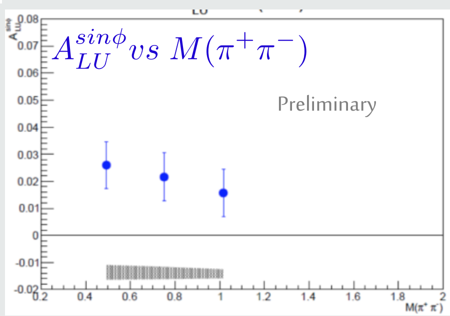
- Asymmetry amplitudes ~ 2%
- Small kinematic dependence

CLAS12 @ 10.6 GeV

Analyzed data ~3% of approved beam time







Courtesy of M. Mirazita

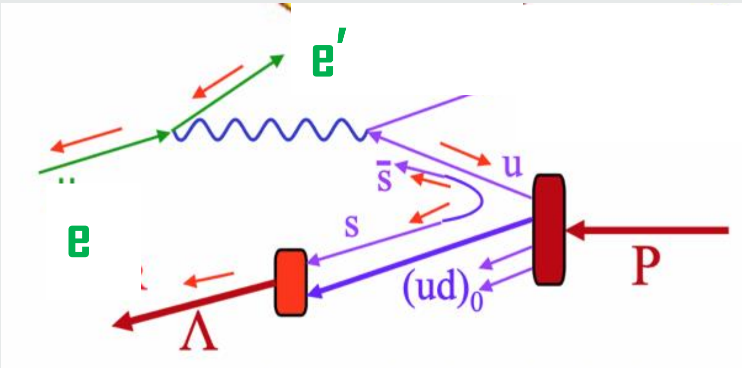
- Access the Helicity Dependent di-hadron FF $G_1^{\perp}$

$$\mathbf{BSA} \propto \sin(\phi_h - \phi_R)\left[\frac{f_1 G_1^{\perp}}{f_1 D_1}\right]$$

H. Matevosyan, A. Kotzinian, A. Thomas PRL 120, 252001 (2018), PRD 96, 074010 (2017)

See T. Hayward talk

Λ production in SIDIS in the TFR



ep → e′ΛX

Gain insight into

- The non-perturbative strange sea
- How the diquark-like remnant system becomes a hadron and how this process is correlated with the spin of the target or/and the produced particles

Fracture Functions: encode the information on the interacting quark and on the fragmentation of the spectator system

Classification of all the LT Fracture Function → M. Anselmino, V. Barone, A. Kotzinian PLB 699, 108 (2011), PLB 706, 46 (2011), PLB 713, 317 (2012).

Unpolarized target

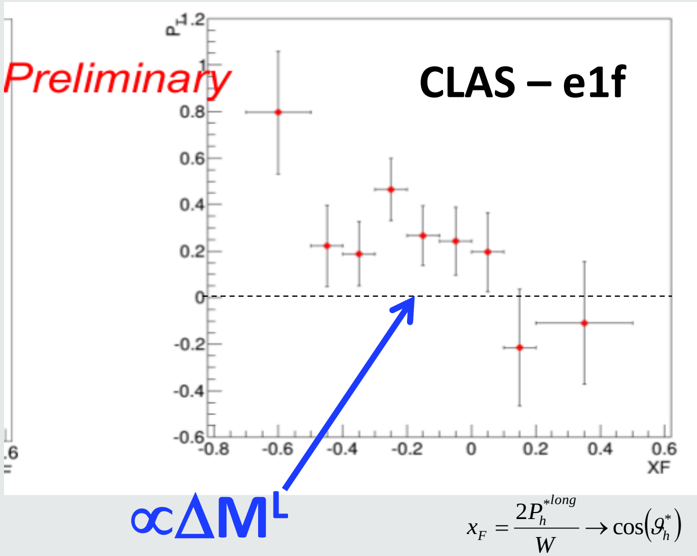
$$\frac{d\sigma^{TFR}}{dx_B\,dy\,d\zeta\,d\phi_S\,d\phi} = \frac{\alpha_{em}^2}{\pi Q^2 y}\sum_a e_a^2 \times$$

$$\left\{\left(1-y+\frac{y^2}{2}\right)\left[M(x_B,\zeta) + S_{N\parallel}S_{\parallel}M_L^L(x_B,\zeta) + |\mathbf{S}_{N\perp}|\,|\mathbf{S}_{\perp}|\,M_T^T(x_B,\zeta)\cos(\phi-\phi_S)\right]\right.$$

$$+hy\left(1-\frac{y}{2}\right)\left[S_{N\parallel}\Delta M_L(x_B,\zeta) + S_{\parallel}\Delta M^L(x_B,\zeta)+\right.$$

$$\left.\left. + |\mathbf{S}_{N\perp}|\,|\mathbf{S}_{\perp}|\,\Delta M_T^T(x_B,\zeta)\sin(\phi-\phi_S)\right]\right\}$$

Λ Polarization transfer in Hall B



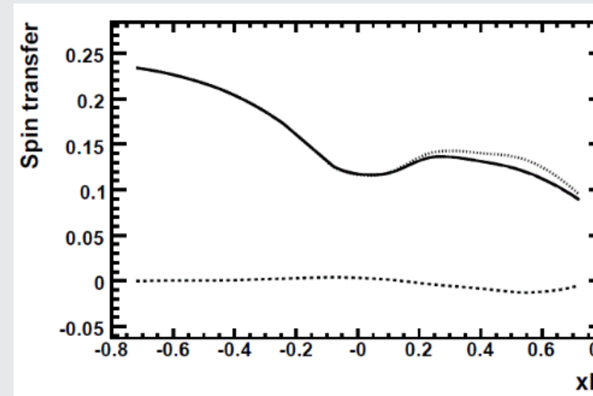
Courtesy of M. Mirazita

$$x_F = \frac{2P_h^{*long}}{W} \to \cos(\vartheta_h^*)$$

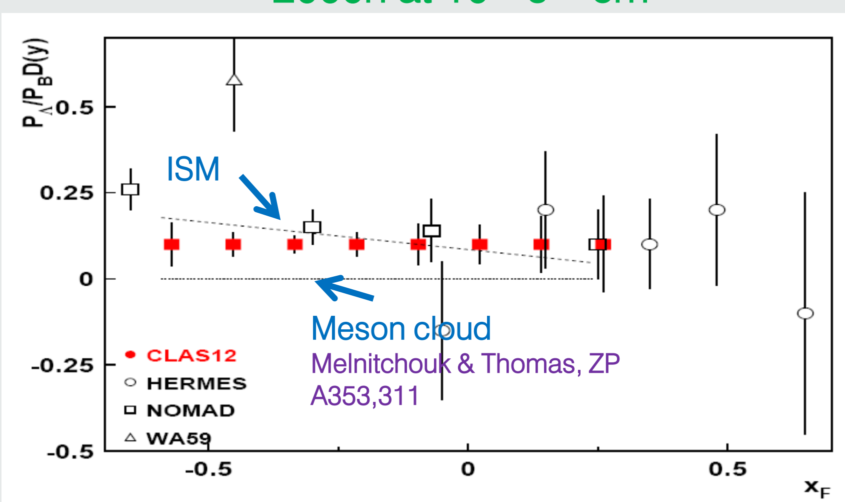
$$\frac{dN_p}{d\cos\vartheta_p^*} \propto 1 + \alpha P_\Lambda \cos\vartheta_p^*$$

- $x_F < 0$ $P_\Lambda^{measured} \sim 0.3$
- CLAS data in agreement with ISM model in TFR

- Intrinsic Strangeness Model (ISM) Ellis, Kotzinian, et al EPJ. C 52 283 (2007)



- Projections for CLAS12
  - 2000h at 10^{35} s^{-1} cm^{-2}



- In the ISM at JLab energy the spin transfer to Λ is dominated by the spin transfer of the intrinsic polarised-strangeness in the remnant nucleon

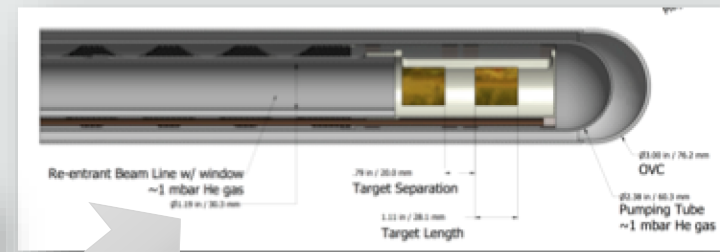
CLAS12 data analysis just started

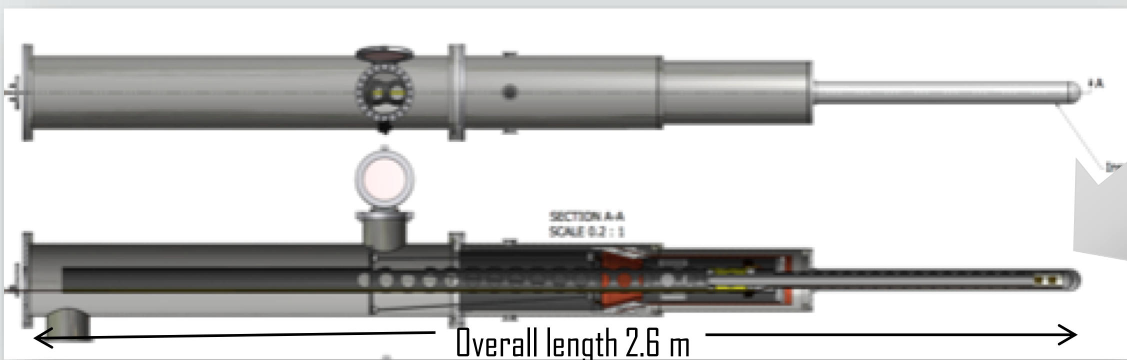
SIDIS with Longitudinally Polarized Target

Hall B in 2022

Longitudinally polarized proton (NH_3) and deuteron (ND_3)

(Dynamic Nuclear Polarization)





Improvement with respect to 6 GeV

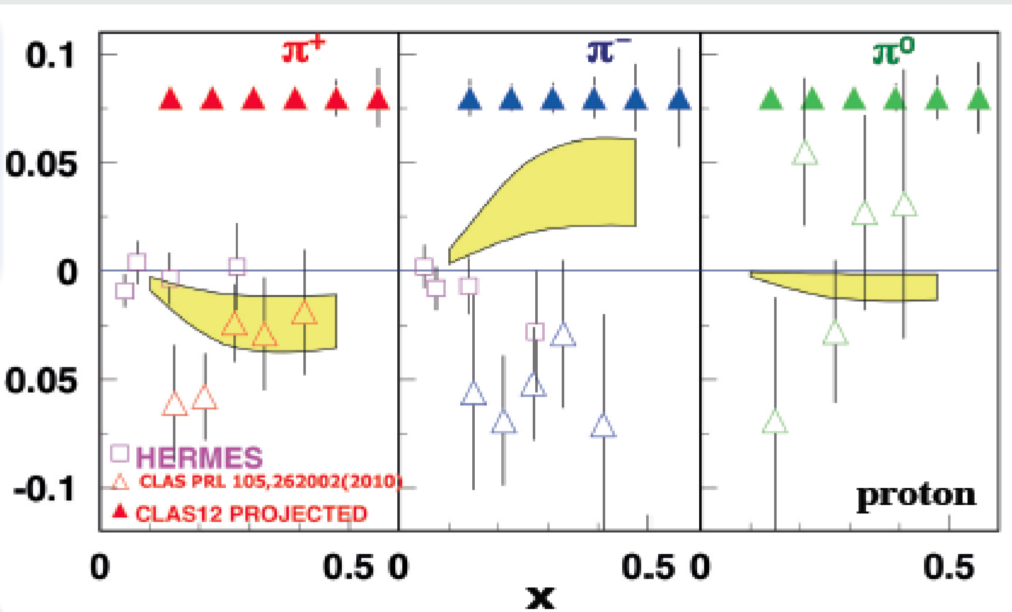
- Can handle higher luminosity
- Double-cell target : Two target samples at opposing polarizations with a single μwave frequency → reduced systematic effects

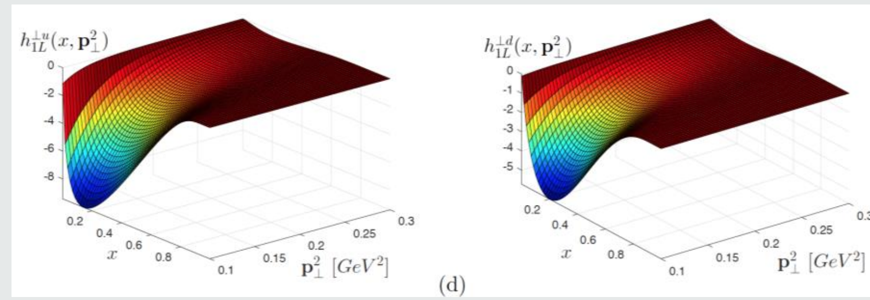
The Kotzinian-Mulders TMD $h_{1L}^{\perp}$

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

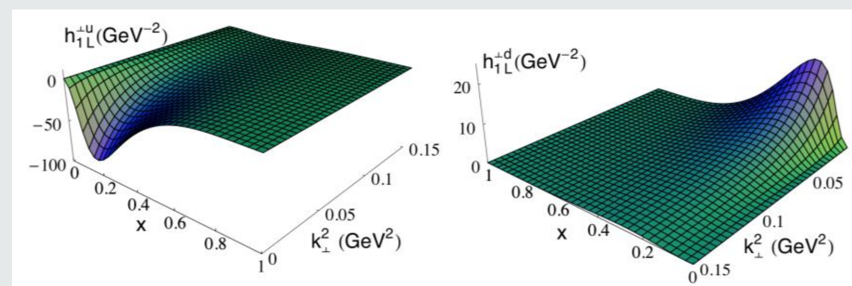
$$\frac{d\sigma}{dx\,dy\,d\phi_S\,d\phi_h\,dP_{h\perp}^2} \propto S_L\left[\sqrt{2\epsilon(1+\epsilon)}\sin\phi_h F_{UL}^{\sin\phi_h} + \epsilon \sin(2\phi_h) F_{UL}^{\sin(2\phi_h)}\right] + S_L\lambda_e\left[\sqrt{1-\epsilon^2}F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos(\phi_h)F_{LL}^{\cos(\phi_h)}\right]$$

h.t. ; $h_{1L}^{\perp} \otimes H_1^{\perp}$; $g_{1L} \otimes D_1$; h.t.





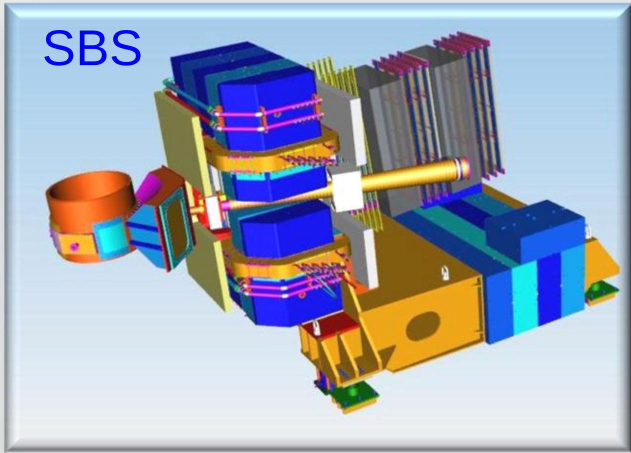
Light-Front Quark-Diquark M. (LFQDM)
T. Maji, D.Chakrabarti, PRD94,094020(2016)



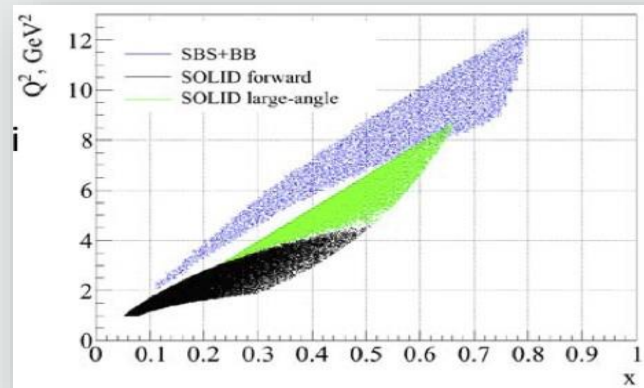
Light-Cone Constituent Quark M. (LCCQM)
B. Pasquini, et al Phys.Rev.D78:034025,2008

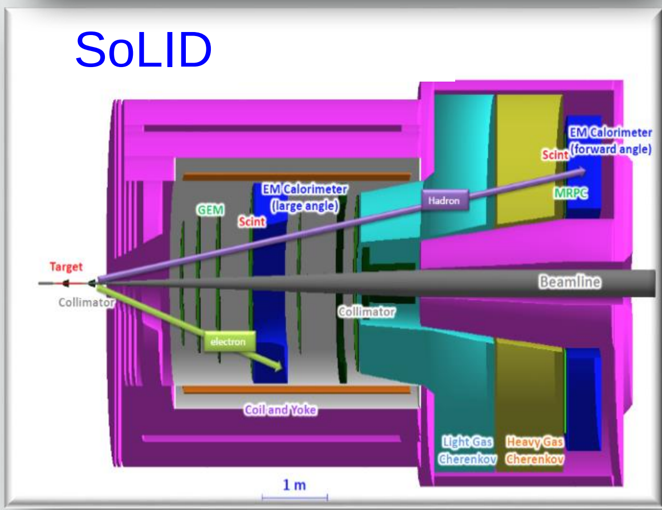
Polarized p and d data will allow flavor separation needed to check against different models

The Future SIDIS Experiments in Hall A



- Moderately large acceptance
- Full PID (π and k)
- (e e' $\pi^{+/-}$ & $K^{+/-}$) on Transversely Polarized ^{3}He
- SBS Installation this year





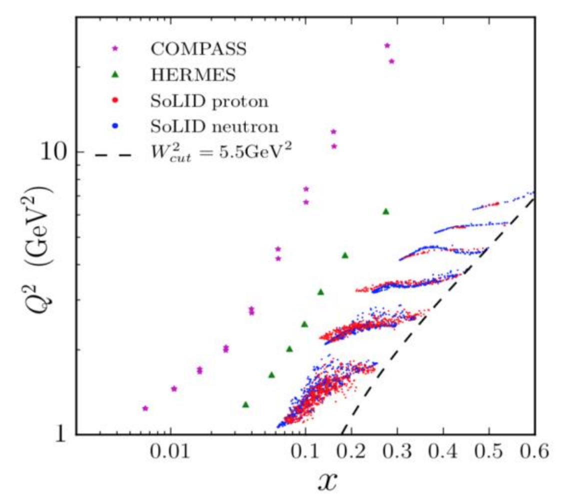
- Large acceptance (2π)
- Moderately large P_T coverage
- Quite high luminosity (10^{36} $cm^{-2}s^{-1}$)
- (e e' $\pi^{+/-}$) on Transversely Polarized ^{3}He
- (e e' $\pi^{+/-}$) on Longitudinally Polarized ^{3}He
- (e e' $\pi^{+/-}$) on Transversely polarized NH_3
- Dihadron with Transversely Pol. ^{3}He
- CLEO Solenoid at JLab ; Pre-CDR

SIDIS exps. with ^{3}He at high luminosity: L ~ 6.6×10^{36} $cm^{-2}s^{-1}$

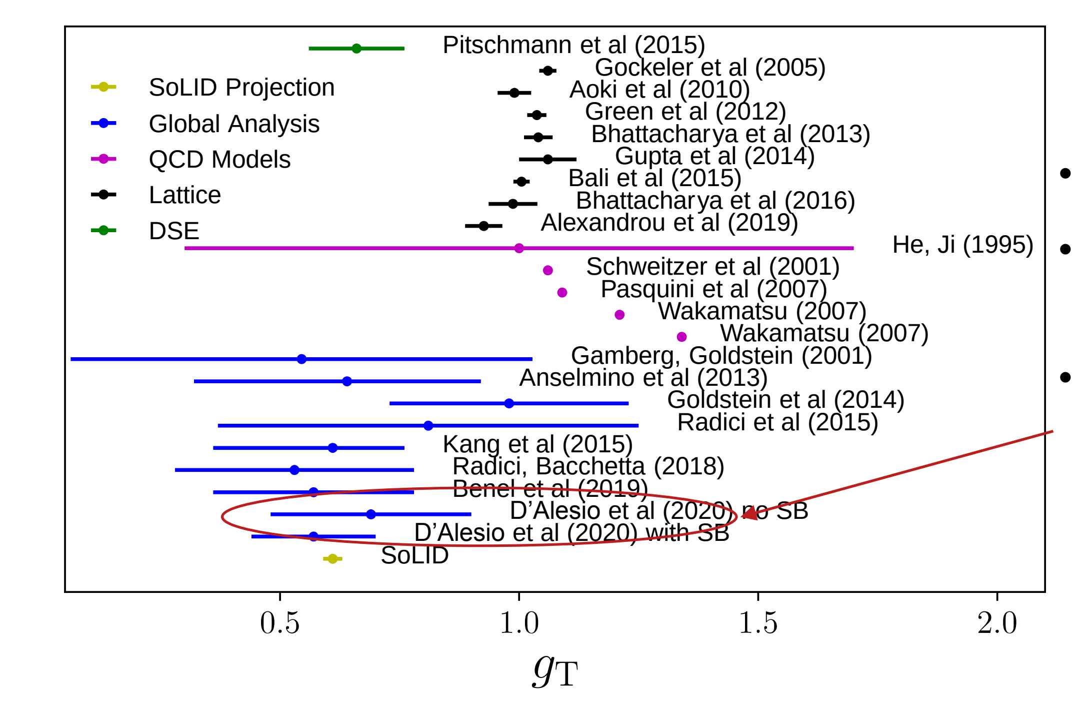
SoLID impact on Tensor Charge

$$\delta_{Tq} = \int_0^1 [h_1^q(x) - h_1^{\bar{q}(x)}]dx$$

- **A fundamental QCD quantity: matrix element of local operators**
- **Calculable in lattice QCD**



Phys. Lett. B767 (2017) 91-98



- **Improvement up to one order of magnitude with SoLID**
- Caveat: model dependent assumptions on the shape of underlying TMD distributions
- Study role of some assumptions adopted in phenomenological parametrizations (D'Alesio Fiore, Prokudin arXiv:2001.01573v1)

Jefferson Lab

The Critical Extraction Process

- Large sets of high precision data are on the horizon:
  - statistical errors will not be the main limiting factor in the TMD extraction procedure
  - Main role will be played by the uncertainties due to input parametrizations and the role of the underlying assumptions

- A consistent procedure for extraction of TMDs from data with controlled systematic errors is needed.

- ExtractionVAlidation framework (EVA)

  Main goal: assist extraction of 3D PDFs, by testing different extraction procedures and estimating systematics related to different assumptions and models used in the extraction procedure.

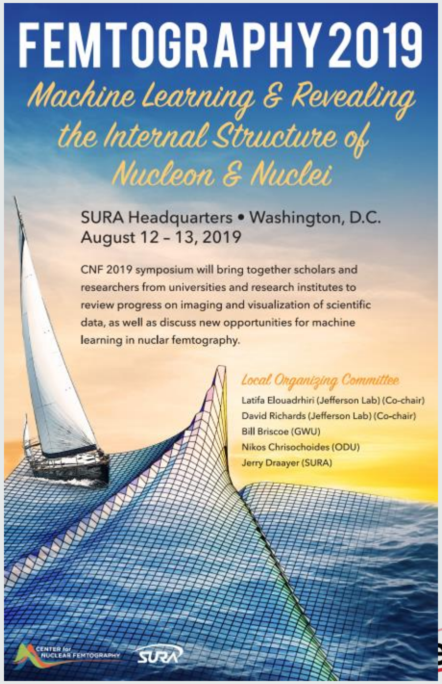
Virginia Center for Nuclear Femtography

CENTER for NUCLEAR FEMTOGRAPHY

- Funded by Commonwealth to "…..to facilitate the application of modern developments in data science to the problem of imaging and visualization of sub-femtometer scale structure of protons, neutrons, and atomic nuclei"
- Multi-disciplinary, bringing together nuclear theorists and experimentalists, mathematicians, computer scientists,… … and architects and artists!
- Seven joint lab/university initiatives funded by the Commonwealth of VA

- 1st Workshop at University of Virginia in Dec 2018
- Symposium at SURA Headquarters in Aug 2019
  - Review, share, and capitalize on progress made so far.
  - Explore new avenues and ideas - e.g machine learning
  - Specific goals:
    - Development of next round of activities
    - Securing long-term future of effort

Note: Increased funding ($1.25M/yr) in VA Governor's budget for FY20.

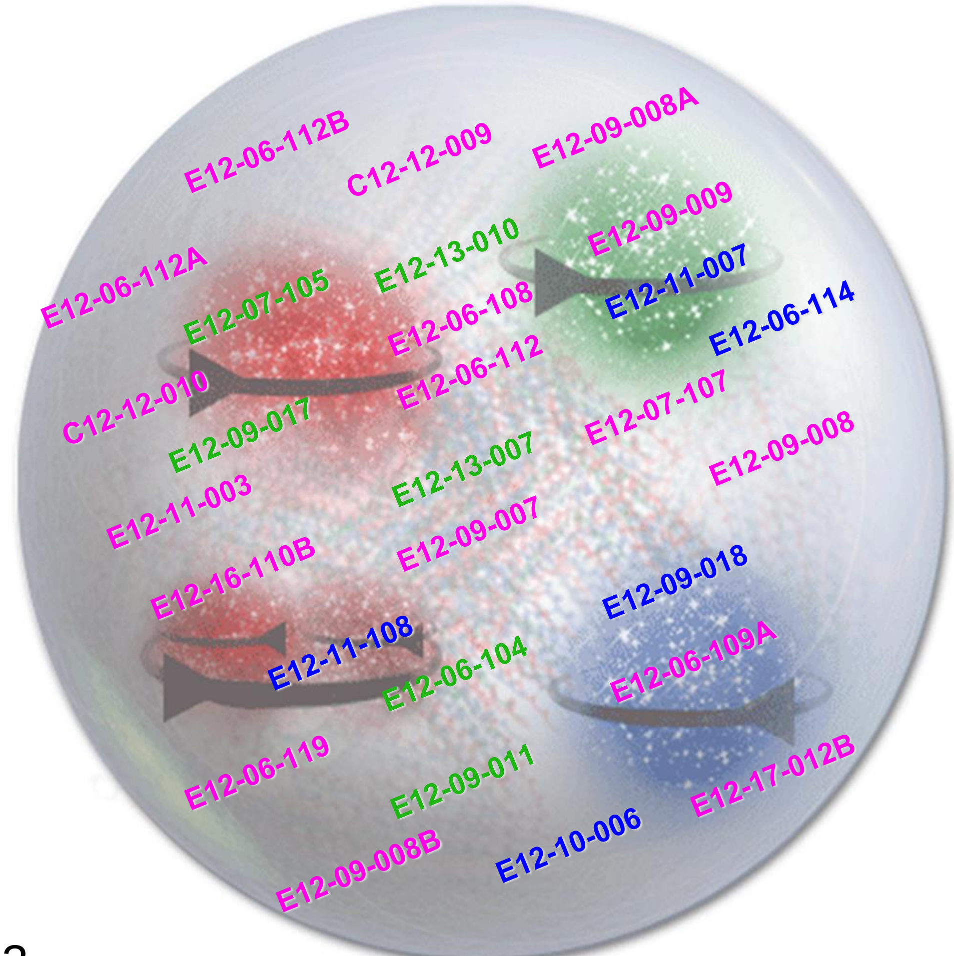


Conclusions and Outlook

❖ The nucleon 3D partonic structure is rich and complex. Each TMD PDF/FF contains information on different aspects of the nucleon

❖ TMD @ Jefferson Lab:
- Multi-Halls SIDIS program to study leading and sub-leading twist TMDs
- Precision multi-dimensional mapping in the valence region
- Training field for the EIC
  - ~75% EIC White Paper is the continuation at higher energies of Jlab program

❖ The forthcoming years will be a time of unprecedented high precision and high volume data → a multi-dimensional effort is required for the extraction and interpretation of 3D PDFs



...and to conclude

Happy

Birthday!

...and thank you for your invaluable and inspiring work and your dedication to dig into the mysteries of the nature