Experimental results on quark-gluon correlations

Anselm Vossen

Thanks for helpful discussions and slides to

- Daniel Pitonyak
- Andreas Metz
- Chris Dilks

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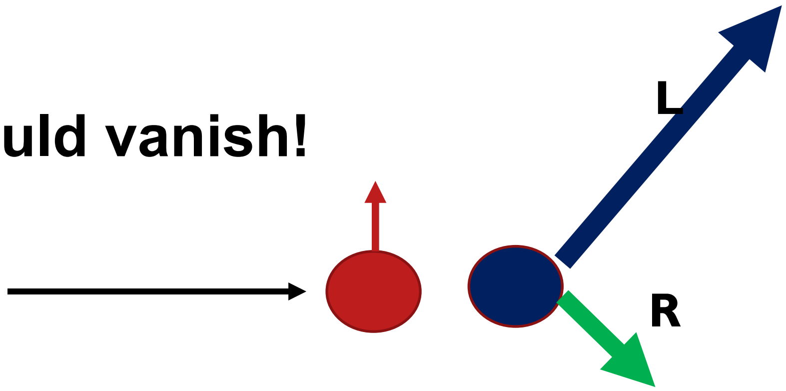
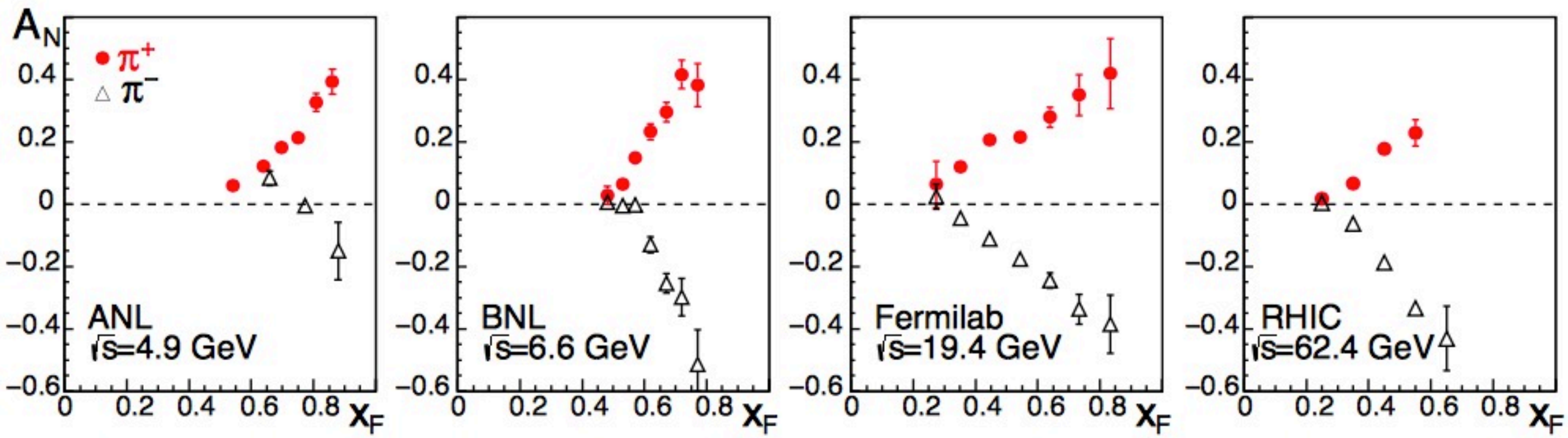
Outline

- Motivation: transverse spin phenomena in hard scattering
- Recent theoretical progress in unifying twist3 functions and connections to TMD framework
- Recent results in single hadron channels
- **Toward better specificity → Di-hadron channels**
- Recent results and plans at CLAS12 to access twist3 PDFs

- Since 40+ years
- P, T- invariance→ **TSSAs should vanish!**



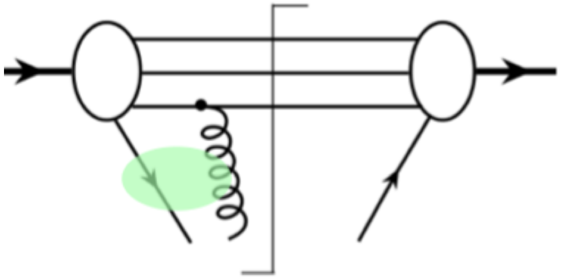
$A_N\,(pp \to \pi X)$



1976 →

Interference of QCD amplitudes

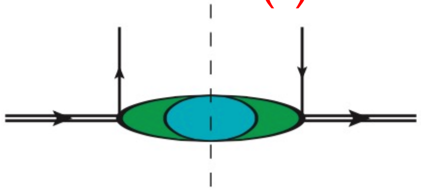
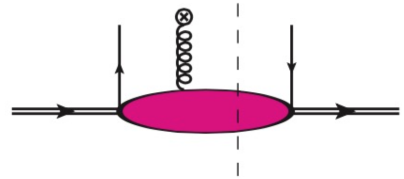
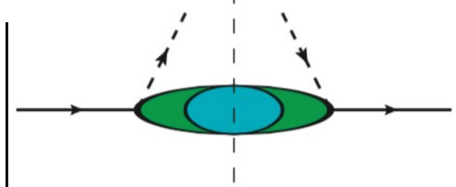
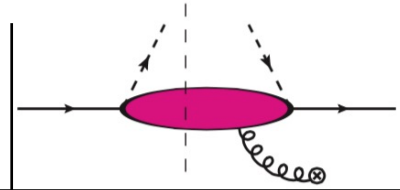
$F_{FT} \propto$



Qiu, Sterman, 1991, ...

- Explanation: Phase shifts due to interference on the QCD amplitude level
- Qiu, Sterman 1991: (Colinear) Twist3: measurement of direct QCD quantum interference
  - Single scale process $Q^2, p_T \gg \Lambda_{QCD}$

Slide from D. Pitonyak

Hadron Pol.	CT3 PDF (x)		CT3 PDF (x, x_1)	CT3 FF (z)		CT3 FF (z, z_1)
						
	intrinsic	kinematical	dynamical	intrinsic	kinematical	dynamical
U	e	$h_1^{\perp(1)}$	H_{FU}	E, H	$H_1^{\perp(1)}$	$\hat{H}_{FU}^{\mathfrak{R},\mathfrak{S}}$
L	h_L	$h_{1L}^{\perp(1)}$	H_{FL}	H_L, E_L	$H_{1L}^{\perp(1)}$	$\hat{H}_{FL}^{\mathfrak{R},\mathfrak{S}}$
T	g_T	$f_{1T}^{\perp(1)}$, $g_{1T}^{\perp(1)}$	F_{FT}, G_{FT}	D_T, G_T	$D_{1T}^{\perp(1)}$, $G_{1T}^{\perp(1)}$	$\hat{D}_{FT}^{\mathfrak{R},\mathfrak{S}}, \hat{G}_{FT}^{\mathfrak{R},\mathfrak{S}}$

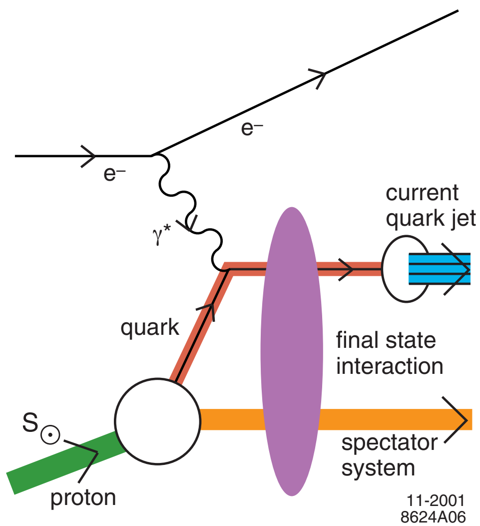
Slide from D. Pitonyak

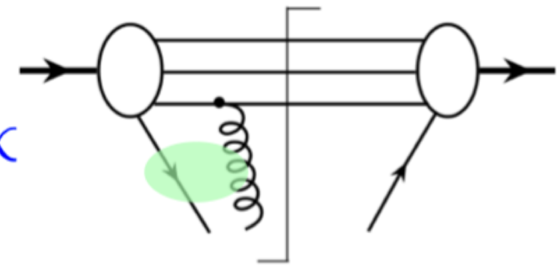
Hadron Pol.	PDF (x): intrinsic	PDF (x): kinematical	PDF (x, x_1): dynamical	FF (z): intrinsic	FF (z): kinematical	FF (z, z_1): dynamical
U	~~e~~	~~$h_1^{\perp(1)}$~~	H_{FU}	~~E~~, ~~H~~	~~$H_1^{\perp(1)}$~~	$\hat{H}_{FU}^{\Re,\Im}$
L	~~h_L~~	~~$h_{1L}^{\perp(1)}$~~	H_{FL}	~~E_L~~, ~~H_L~~	~~$H_{1L}^{\perp(1)}$~~	$\hat{H}_{FL}^{\Re,\Im}$
T	~~g_T~~	~~$f_{1T}^{\perp(1)}$~~, ~~$g_{1T}^{(1)}$~~	F_{FT}, G_{FT}	~~D_T~~, ~~G_T~~	~~$D_{1T}^{\perp(1)}$~~, ~~$G_{1T}^{(1)}$~~	$\hat{D}_{FT}^{\Re,\Im}, \hat{G}_{FT}^{\Re,\Im}$

All kinematical and intrinsic functions can be written in terms of dynamical functions (multi-parton correlators)!

(Kanazawa, Koike, Metz, Pitonyak, Schlegel, PRD **93** (2016))

Interference of QCD amplitudes



$T^{(3)}(x,x) \propto$ 

Qiu, Sterman, 1991, ...

From Brodsky, Schmidt, Hwang

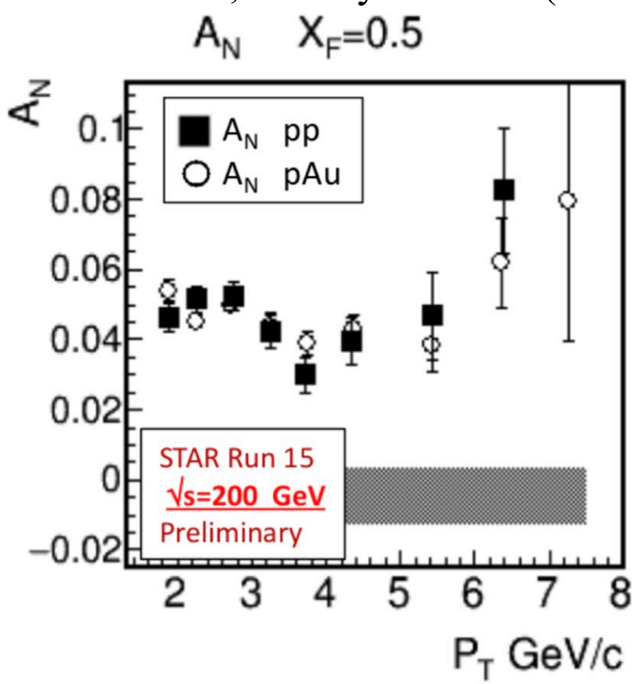
- Explanation: Phase shifts due to interference on the QCD amplitude level
- Qiu, Sterman 1991: (Colinear) Twist3: measurement of direct QCD quantum interference
  - Single scale process $Q^2, p_T \gg \Lambda_{QCD}$
- TMD picture, Sivers (1990), Collins (1992), (e.g. model calculations by Brodsky, Schmidt, Hwang (2002)
  - Two scale process: $Q^2 \gg k_T \approx \Lambda_{QCD}$
- **Recent Developments: Strong relation between TMD and Twist3 picture→can be treated in same framework on same footing**
- **All transverse spin phenomena are driven my multi-parton correlations!**

What can we learn from Twist3 PDFs/FFs (non-exhaustive list)

- **Fundamentally the result of quark gluon correlations**
- **Interference between single and two parton amplitude**
- OPE: Fundamental to study Proton Wave function
- Connection to TMD framework via EoMR and LIR→On same footing as TMDs!
- Interpretation in terms of forces of the gluon fields on the struck quark → See M. Burkardt's talk
- Twist3 FF E→Connection to hadronic mass generated in fragmentation (Accardi, Signori **arXiv:1903.04458)**
- …
- **Last but not least: Large effects! (see A_N)**

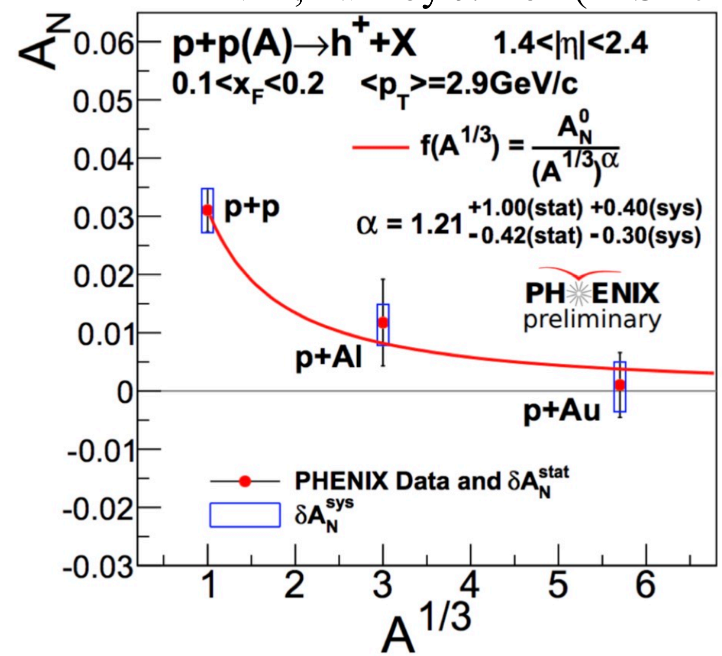
The 'classic' $pp \to \pi X$

STAR, Talk by C. Dilks (DIS 2016)



STAR shows *no* suppression with *A*
(neutral pions, larger x_F region)

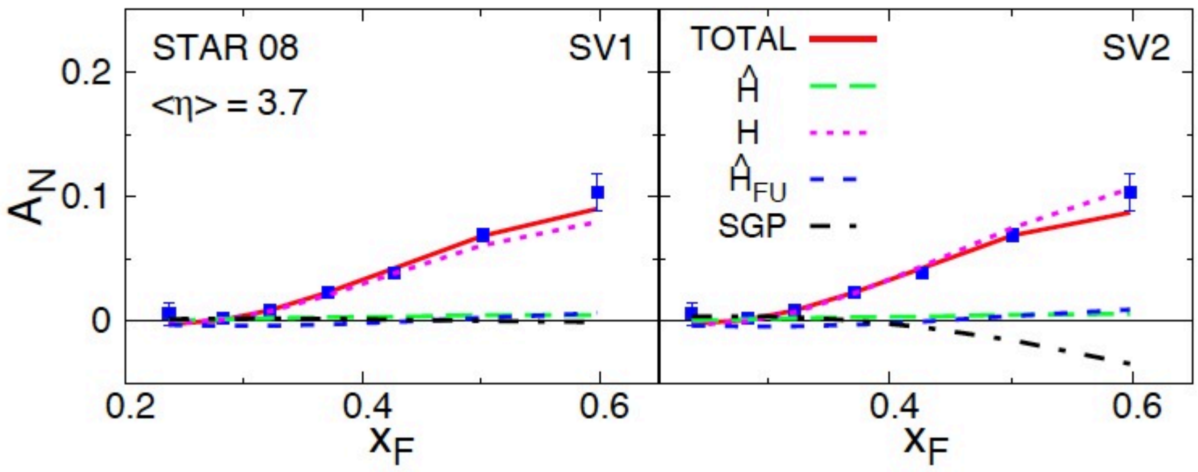
PHENIX, Talk by J. Bok (DIS 2018)



PHENIX shows $A^{1/3}$ suppression
(charged hadrons, smaller x_F region)

Sensitive to F_{FT} and $H_{FU}^{I,R}$

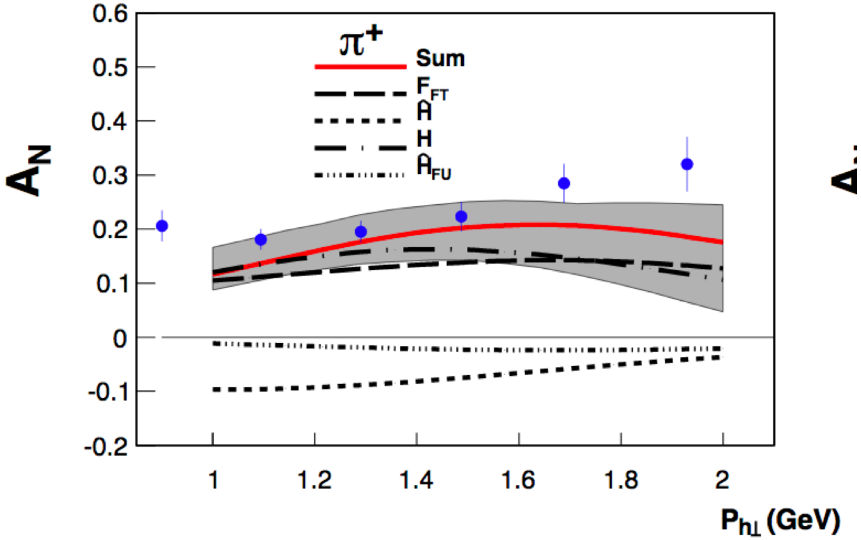
Fit shows leading contribution by FF piece

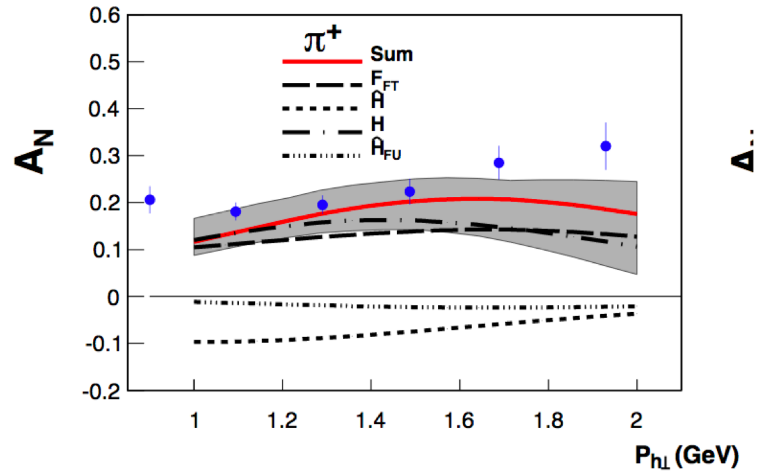


(Kanazawa, Koike, Metz, Pitonyak,PRD **89**(RC) (2014))

STAR Data at $\sqrt{s} = 200\ GeV$ from :Phys. Rev. D86, 051101 (2012)

A_N in $ep \to \pi X$





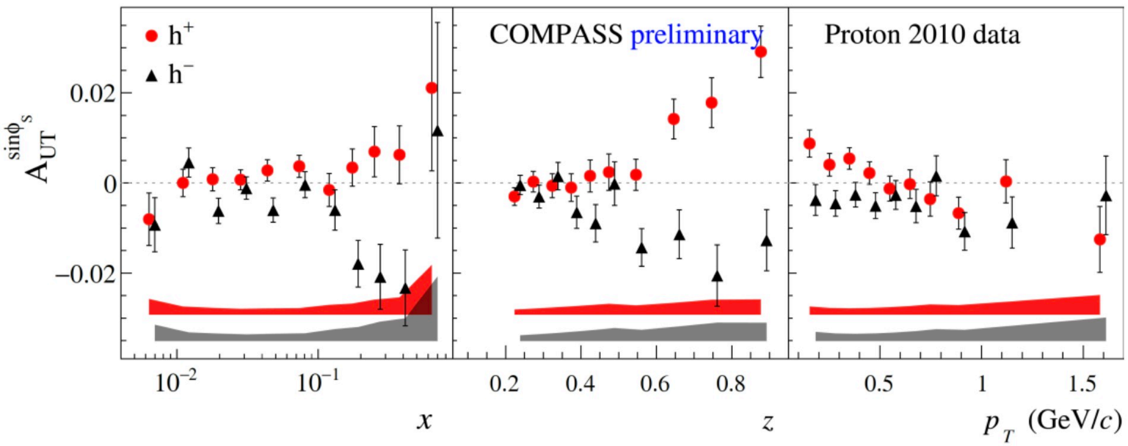
From PRD **90** (2014))

Hermes data from PLB 728 183 (2014)

- HERMES A_N
- Sensitive to F_{FT} and $H_{FU}^{I,R}$

$F_{UT}^{sin\phi_S}$ in SIDIS: Access to $\tilde{H}$

- Compass $sin\phi_S$ modulation

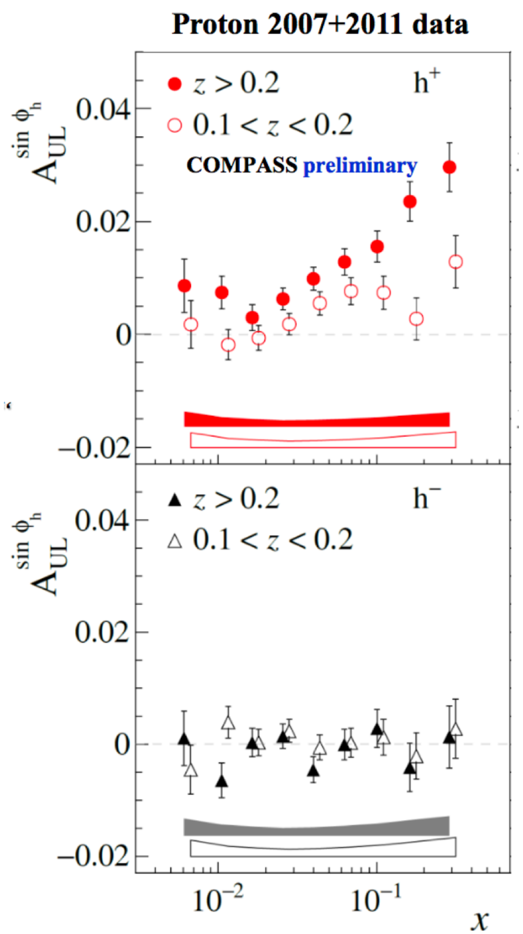


$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q} C\left\{\left(x f_T^q D_{1q}^h - \frac{M_h}{M} h_1^q \frac{\tilde{H}_q^h}{z}\right) - \frac{\boldsymbol{p_T}\cdot\boldsymbol{k_T}}{2MM_h}\left[\left(x h_T^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1T}^q \frac{\tilde{G}_q^{\perp h}}{z}\right) - \left(x h_T^{\perp q} H_{1q}^{\perp h} - \frac{M_h}{M} f_{1T}^{\perp q} \frac{\tilde{D}_q^{\perp h}}{z}\right)\right]\right\}$$

$$F_{UT}^{\sin\phi_S} \propto \sum_a e_a^2 \frac{2M_h}{Q} h_1^a(x) \frac{\tilde{H}^a(z)}{z}$$

See Mulders, Tangerman **Nucl.Phys. B461 (1996) 197-237,** Erratum: **Nucl.Phys. B484 (1997) 538-540**

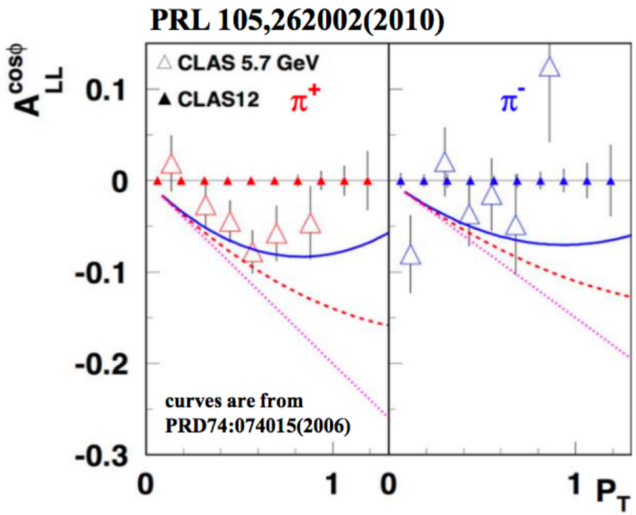
$F_{UL}^{sin\phi_h}$ in SIDIS: Mix of Twist2/Twist3 PDF, FFs

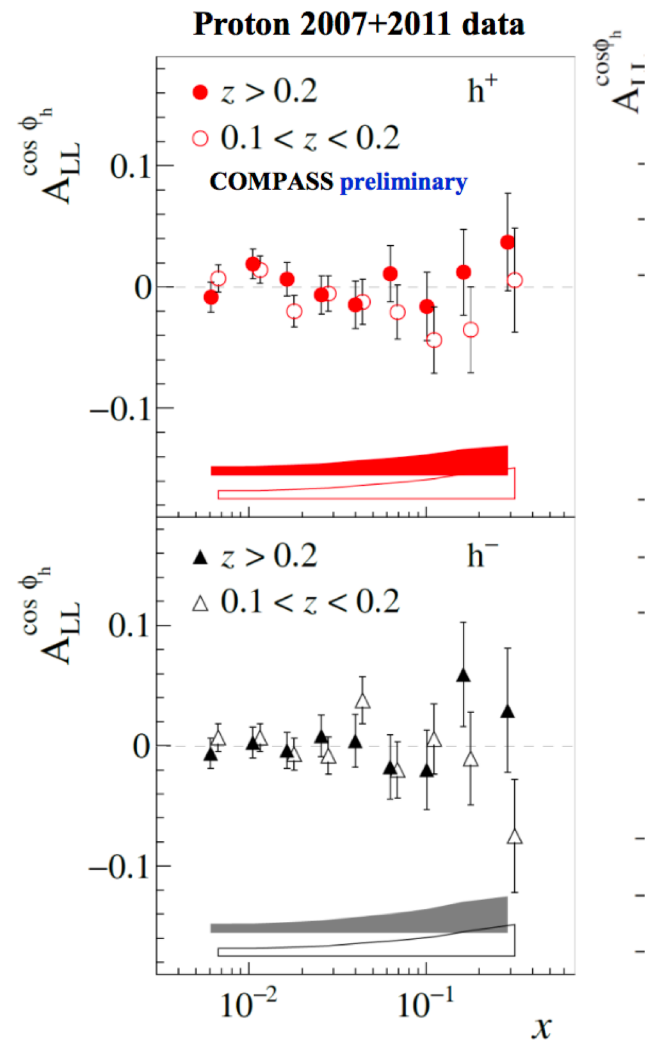


$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h}\left(xh_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{G}_q^{\perp h}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}\left(xf_L^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1L}^{\perp q}\frac{\tilde{H}_q^h}{z}\right)\right\}$$

From B Parsamyan at DIS 2018

$F_{LL}^{\cos\phi_h}$ in SIDIS: Mix of Twist2/Twist3 PDF, FFs

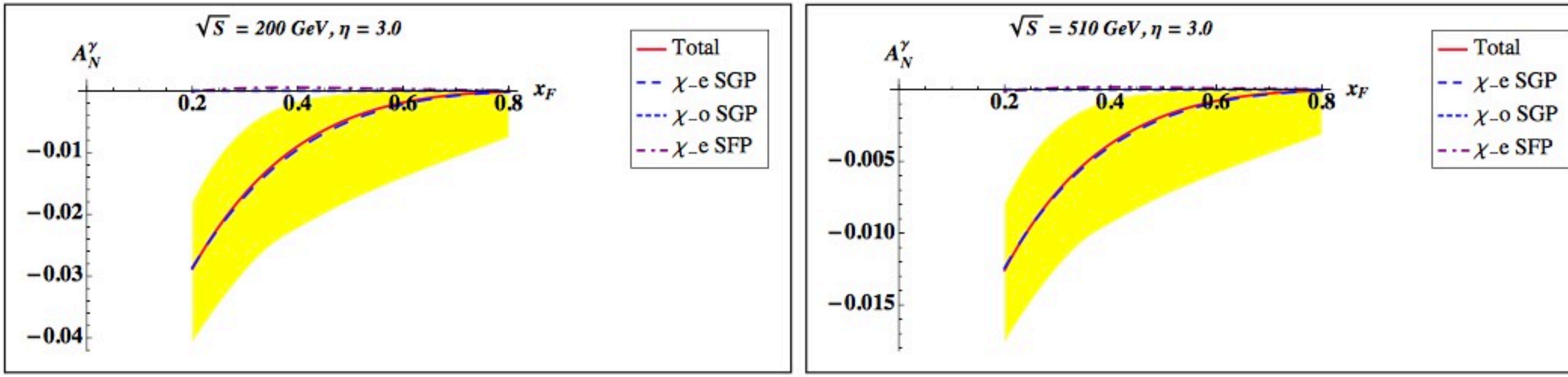




$$F_{LL}^{\cos\phi_h} = \frac{2M}{Q}\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h}\left(x e_L^q H_{1q}^{\perp h} + \frac{M_h}{M} g_{1L}^q \frac{\tilde{D}_q^{\perp h}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M}\left(x g_L^{\perp q} D_{1q}^h - \frac{M_h}{M} h_{1L}^{\perp q} \frac{\tilde{E}_q^h}{z}\right)\right\}$$

From B Parsamyan at DIS 2018

Planned at STAR: A_N for direct γ

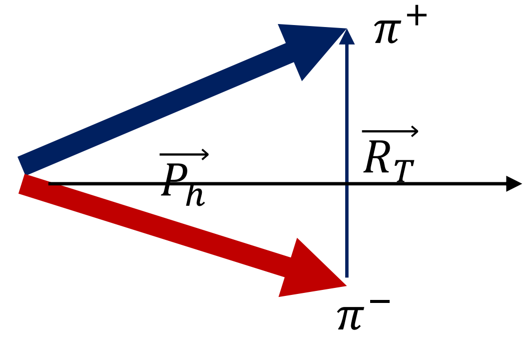


(Gamberg, Kang, Prokudin (2013), Kanazawa, Koike, Metz, Pitonyak (2015))

$$d\Delta\sigma^{\pi} \sim H \otimes f_1 \otimes \boldsymbol{F_{FT}(x,x)}$$

So.. That sounds interesting, what are the experimental challenges?

- **Single scale observable**→Less degrees of freedom in typical inclusive π production measurement
  - $lp \to \pi X$
  - $pp \to \pi X$
- **Solution:** Use more final states with more degrees of freedom
  - **Di-hadrons (here)**
  - Polarized Λ → See M. Schlegel's talk



- (or processes with only PDFs, or only FFs)
  - E.g. $A_N(pp \to \gamma X)$ (not discussed here)
  - Unclear how to access twist3 FFs in e^+e^-
- OTOH: Inclusive observables can have twist3 contributions, e.g. g_2→See W. Armstrong's talk

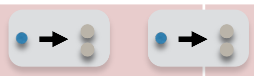
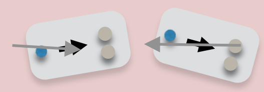
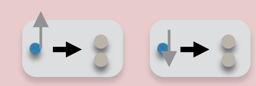
Di-hadron fragmentation Functions

<u>Additional Observable:</u>

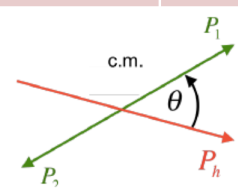
$\vec{R} = \vec{P_1} - \vec{P_2}$:

The relative momentum of the hadron pair is an additional degree of freedom:

<u>the orientation of the two hadrons w.r.t. each other and the jet direction can be an indicator of the quark transverse spin</u>

Parton polarization → Hadron Polarization ↓	Spin averaged	longitudinal	transverse
spin averaged	$D_1^{h/q}(z,M)$ 		
longitudinal			
Transverse	Type equation here.	**$G_1^{\perp}(z,M,P_h,\theta)$=** T-odd, chiral-even →jet handedness QCD vaccum strucuture 	**$H_1^{\sphericalangle}(z,M)$=** T-odd, chiral-odd Colinear 

- Relative momentum of hadrons can carry away angular momentum
  - Partial wave decomposition in θ
  - Relative and total angular momentum →In principle endless tower of FFs



Dihadron Production in SIDIS

$$\ell(l) + N(P) \to \ell(l') + h_1(P_1) + h_2(P_2) + X$$

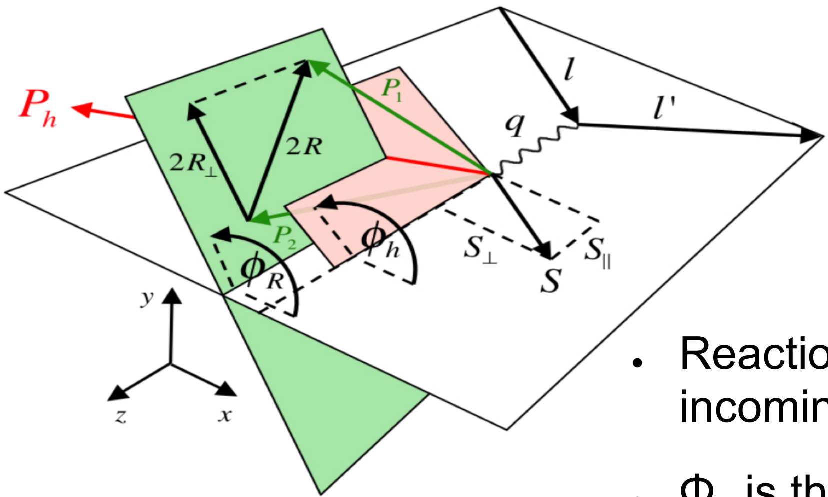


Figure from arXiv:1702.07317

- Dihadron degrees of freedom:

$$P_h = P_1 + P_2$$

$$R = \frac{1}{2}(P_1 - P_2)$$

- Reaction plane is spanned by q and the incoming/outgoing lepton momenta
- Φ_h is the angle between the reaction plane and **plane spanned by P_h and q**
- Φ_R is the angle between the reaction plane and the **plane spanned by R and q**
- M_h denotes dihadron invariant mass

Dihadron Spin asymmetries depend on momentum combinations P_h and R
Modulations in Φ_h and Φ_R are sensitive to different fragmentation and parton distributions

Accessing Twist-3 PDFs via SIDIS Dihadrons in Longitudinal Beam/Target Spin Asymmetries

Beam Spin Asymmetry

$$F_{LU}^{\sin\phi_R} = -x\frac{|\boldsymbol{R}|\sin\theta}{Q}\left[\frac{M}{M_h}\, x\, e^q(x)\, H_1^{\sphericalangle q}(z,\cos\theta,M_h) + \frac{1}{z} f_1^q(x)\, \widetilde{G}^{\sphericalangle q}(z,\cos\theta,M_h)\right]$$

Target Spin Asymmetry

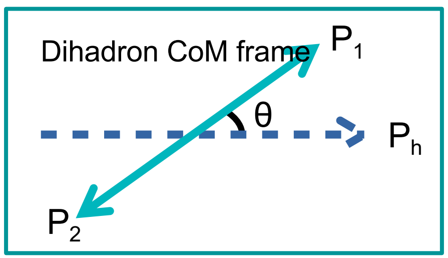
$$F_{UL}^{\sin\phi_R} = -x\frac{|\boldsymbol{R}|\sin\theta}{Q}\left[\frac{M}{M_h}\, x\, h_L^q(x)\, H_1^{\sphericalangle q}(z,\cos\theta,M_h) + \frac{1}{z} g_1^q(x)\, \widetilde{G}^{\sphericalangle q}(z,\cos\theta,M_h)\right]$$

Twist-3 PDFs

IFF

PDFs

Twist-3 DiFFs
(likely small)



Twist-3 PDFs are accessible in the sin(Φ_R) modulation in longitudinal single spin asymmetries

Pereira, PoS (DIS2014) 231
Bacchetta and Radici, Phys.Rev. D67 (2003) 094002
Bacchetta and Radici, Phys.Rev. D69 (2004) 074026

Twist-3 PDF Interpretations

e(x)

Collinear PDFs
– Twist-2
– Twist-3

Nucleon Polarization

	U	L	T
U	f_1		e
L		g_1	h_L
T		g_T	h_1

Quark Polarization

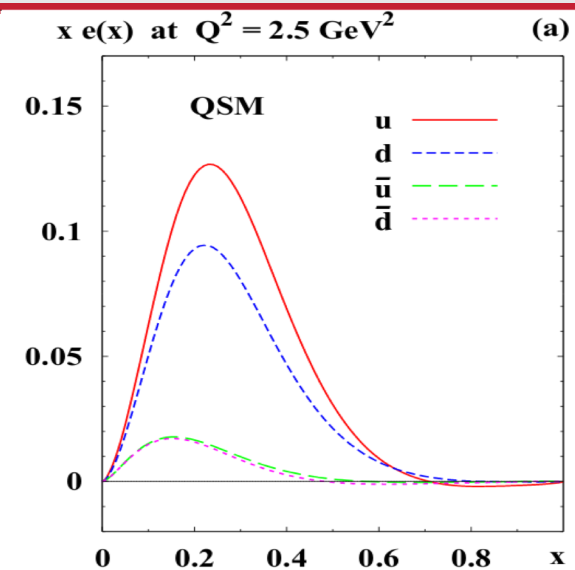
- Decomposable in terms of:
  - Unpolarized PDF $f_1(x)$ [twist-2]
  - Pure twist-3 part
- 1st moment → pion-nucleon σ term, representing the contribution to the nucleon mass from the finite quark masses
- 2nd moment → proportional to quark mass and number of valence quarks
- 3rd moment → transverse polarization dependence of the transverse color-Lorentz force experienced by a struck quark, in an unpolarized nucleon

$h_L(x)$

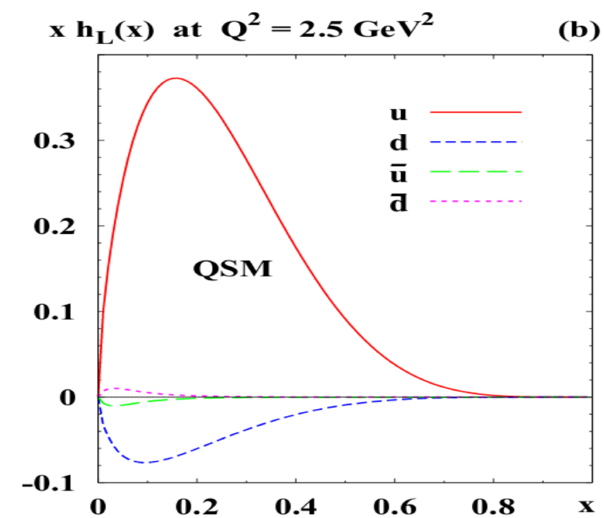
- Decomposable in terms of:
  - Helicity PDF $g_1(x)$ [twist-2]
  - Wormgear TMD moment $h_{1L}^{\perp(1)}$ [twist-2]
  - Pure twist 3 part
- Related to the distribution of transversely polarized quarks in a longitudinally polarized nucleon

e(x) and h_L(x) Predictions

- Chiral Quark Soliton Model
- Similar
  - Light Front Const. Quark. Mod. (Lorcé , Pasquini, Schweitzer, JHEP 1501 (2015) 103)
  - Bag Model (Jaffe and Ji, Nucl.Phys. B375 (1992) 527-560)
  - Spectator Model (Jakob, Mulders, and Rodrigues, Nucl.Phys. A626 (1997) 937-965)



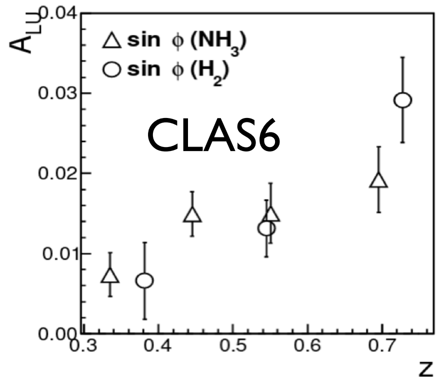
Cebulla et al., Acta Phys.Polon. B39 (2008) 609-640



Dihadron Asymmetries from CLAS and COMPASS

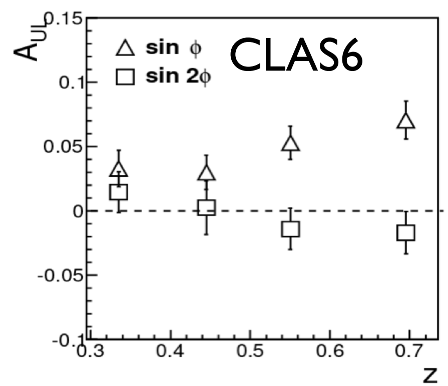
Beam Spin Asymmetries A_{LU}

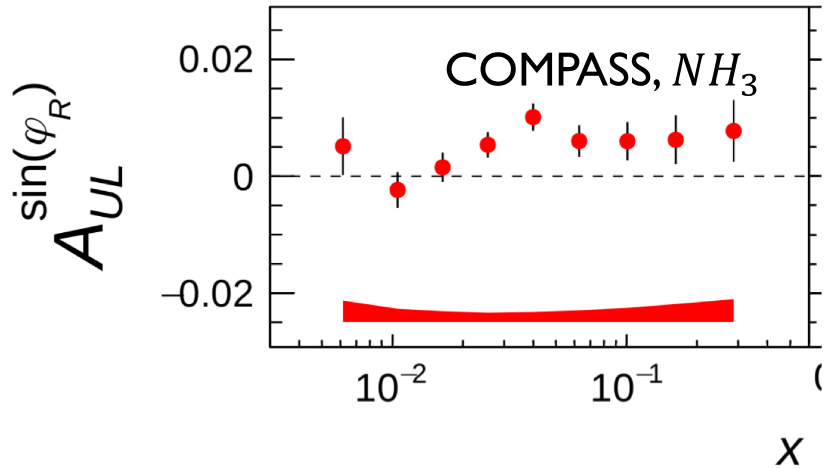
•[e $H_1^{<}$]



Target Spin Asymmetries A_{UL}

•[h_L $H_1^{<}$]





Pereira, PoS(DIS2014

- 5.5 GeV electrons scattered on:
- Longitudinally Polarized solid NH_3 (compared to BSAs with H_2 target)
- 85% beam polarization, 80% target polarization

- SinΦ_R modulation, sensitive to e(x)
- (see aforementioned extraction)

CLAS12

Forward Detector:

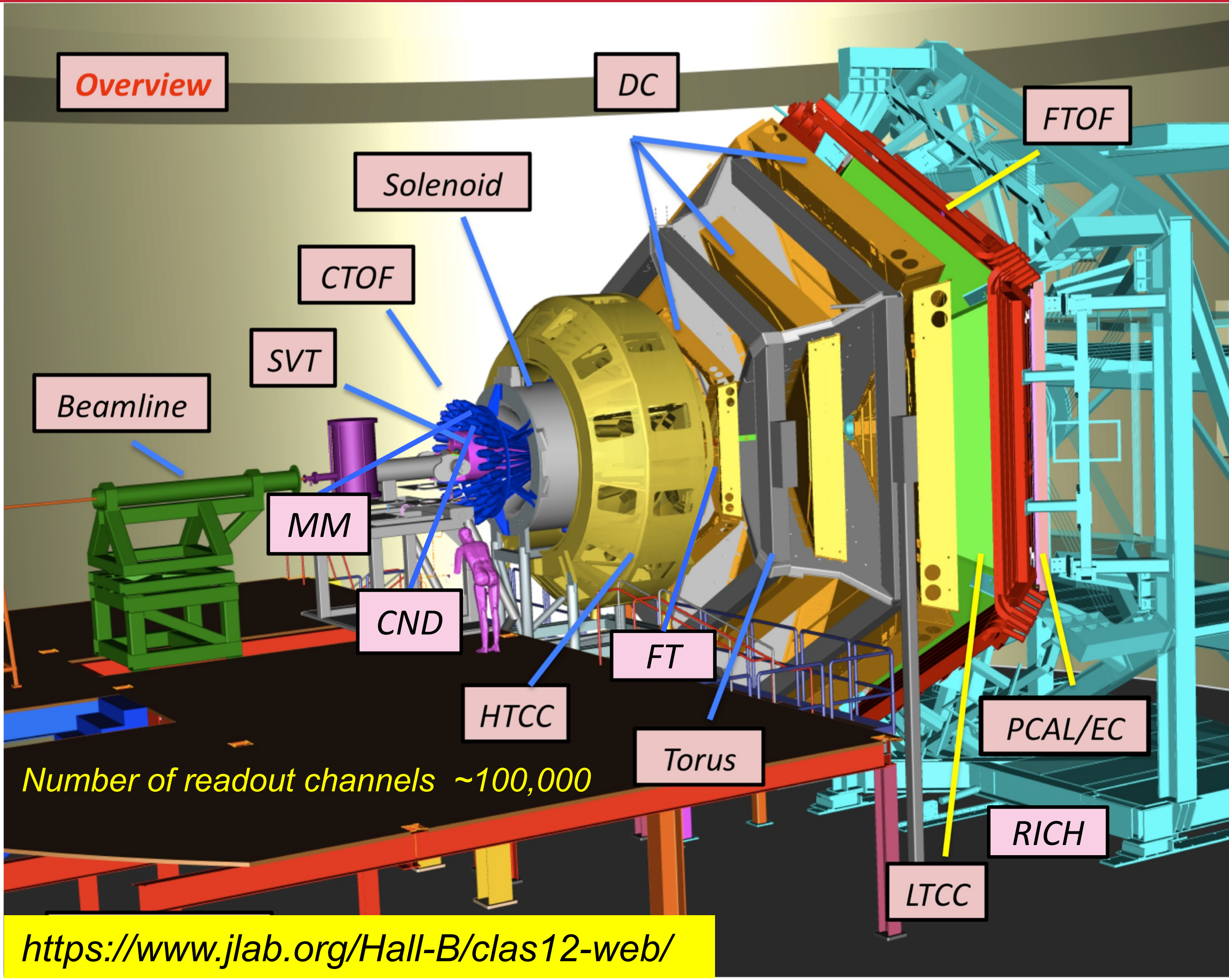
- *TORUS magnet*
- *HT Cherenkov Counter*
- *Drift chamber system*
- *LT Cherenkov Counter*
- *Forward ToF System*
- *Preshower calorimeter*
- *E.M. calorimeter (EC)*

Central Detector:

- *SOLENOID magnet*
- *Barrel Silicon Tracker*
- *Central Time-of-Flight*

Implemented Upgrades:

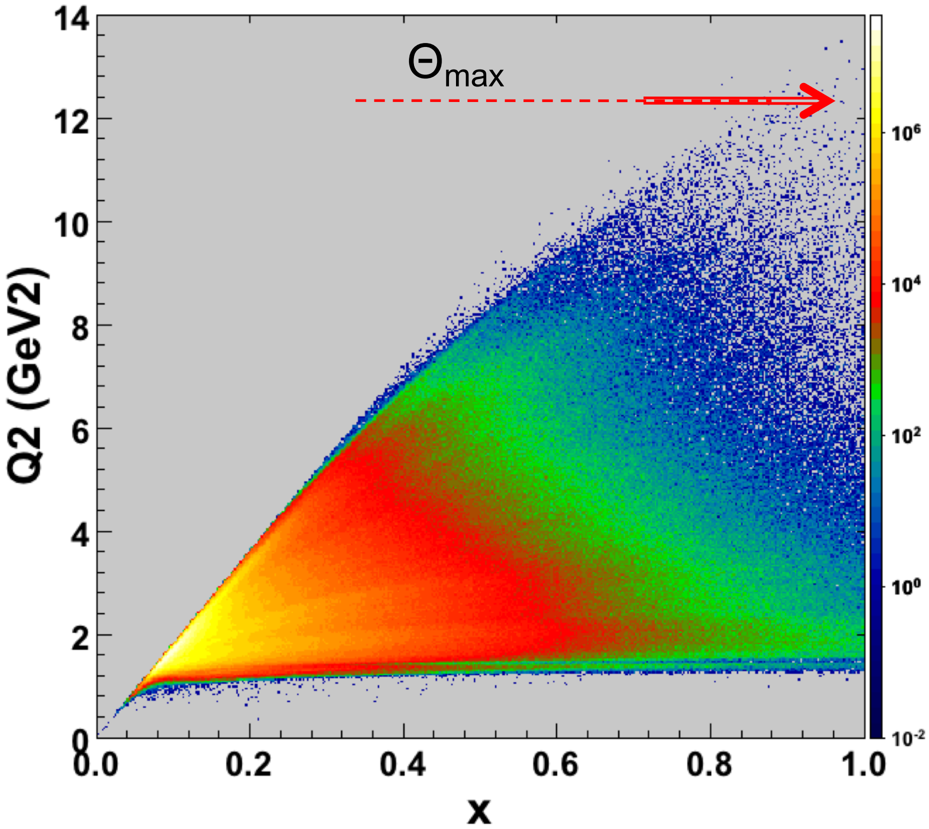
- *Micromegas (CD)*
- *Neutron detector (CD)*
- *RICH detector (FD)*
- *Forward Tagger (FD)*

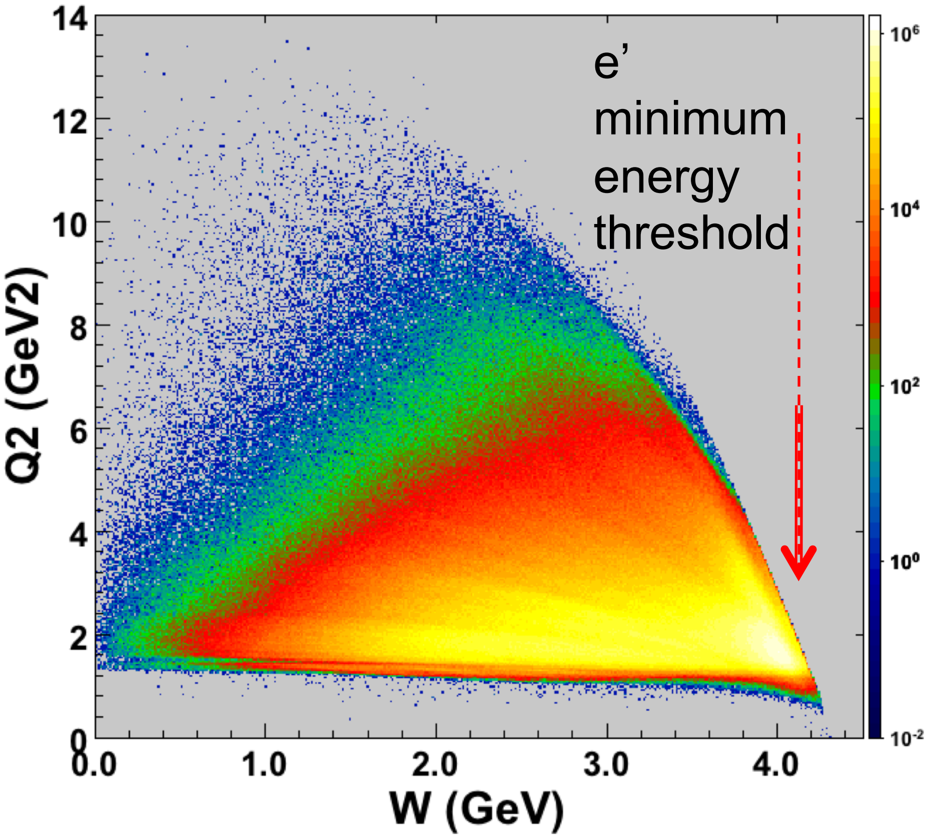


CLAS12 Kinematic Reach

Beam energy at 10.6 GeV Torus current 3770 A, electrons in-bending, Solenoid magnet at 2416 A.

p(e,e')X





CLAS12 Data Acquisition Status

Run Group	Target	Period	Observable	Sensitivity
A	Liquid H_2 (Unpolarized)	Spring 2018 Autumn 2018 Spring 2019	A_{LU}	$e(x)$, $G_1^{\perp}$
B	Liquid D_2 (Unpolarized)	Spring 2019 Autumn 2019	A_{LU}	$e(x)$, $G_1^{\perp}$
C	Solid NH_3 Solid ND_3 Longitudinal Polarization	Possibly Autumn 2020 or later	A_{UL} (and A_{LU}, A_{LL})	$h_L(x)$, $G_1^{\perp}$ (and $e(x)$, also twist-3 DiFFs)

First results on di-hadron correlations

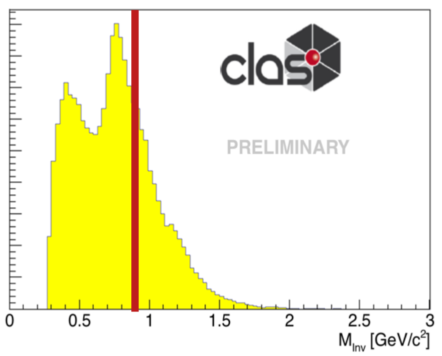
- Use about 10% of spring run (~3% of approved running time)
- Select $ep \rightarrow \pi^+\pi^- + X$
- Calculate ϕ_R, ϕ_h angles of hadron pair

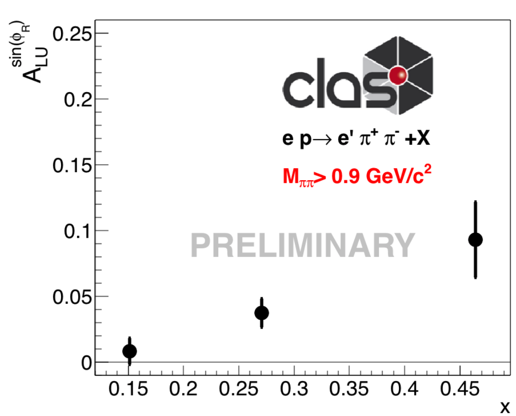
$$\overrightarrow{P_h} = \overrightarrow{P_\pi^+} + \overrightarrow{P_\pi^-}, \qquad \vec{R} = \overrightarrow{P_\pi^+} - \overrightarrow{P_\pi^-}$$

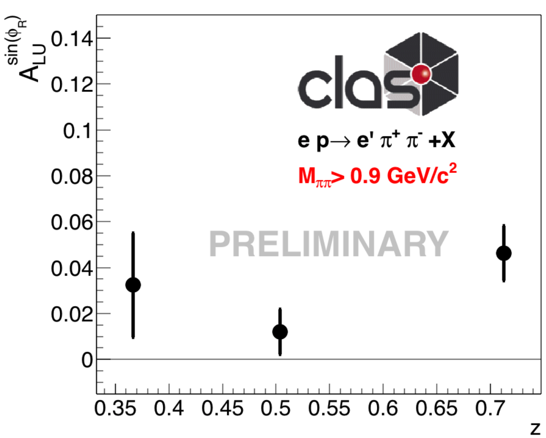
- 2D fit to asymmetries $\frac{N^+ + N^-}{N^+ + N^-}(\phi_R, \phi_h) \rightarrow A_{LU}^{sin\phi_R}$
- Correct with kinematic factor and P_{beam}~86%

Particle selection

- Q^2>1.0 GeV^2
- W>2.0 GeV/c^2
- z_i>0.1
- z<0.95
- M_{miss}>2.05 GeV/c^2
- x_F>0
- y<0.8
- $p_{\pi i}$>1 GeV/c

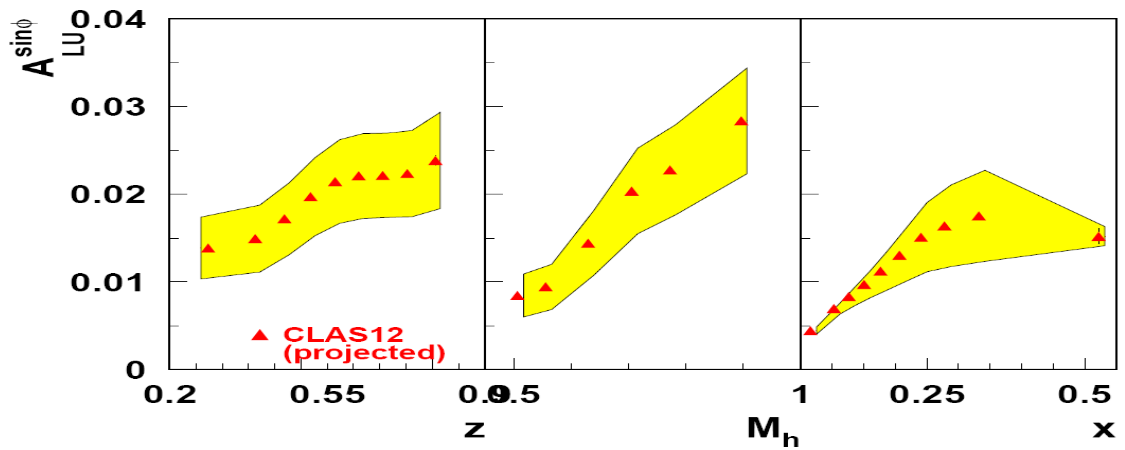






Projections for $e(x)$ sensitive di-hadron correlations at CLAS12

- 120/30 days of running are approved with unpolarized liquid H2/liquid D2 targets **(underway!)**
- 120 + 50 days of running are approved with longitudinally polarized NH3/ND3 targets (targets ready ~2020)



Projections using 54 days of unpolarized proton

Summary

- Twist3 functions encapsulate fundamental quark-gluon correlations in the nucleon
- Integration of Twist3 picture and TMD picture exciting!
  - Global fits on the horizon
- Di-hadron observables are a great tool to isolate twist3 PDFs
- Exciting program at CLAS12 ahead

BACKUP

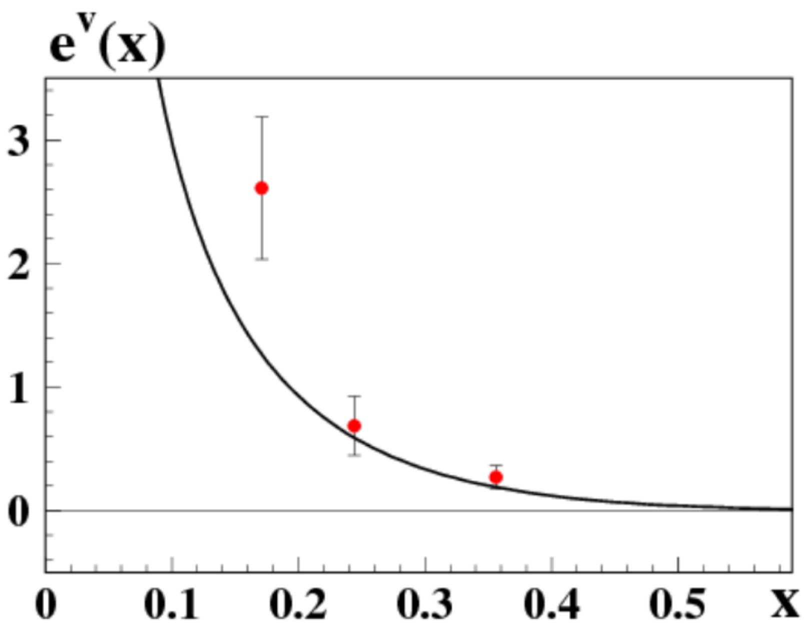
Flavor Separation

Flavor separation can be achieved with different targets:

Proton Target: $$A_{LU,p}^{\sin\phi_R \sin\theta}(z, m_{\pi\pi}, x; Q, y) = -\frac{W(y)}{A(y)} \frac{M}{Q} \frac{|\boldsymbol{R}|}{m_{\pi\pi}} \frac{\boxed{\left(4\, x e^{u_V}(x) - x e^{d_V}(x)\right)}\, H_{1,sp}^{\sphericalangle,u}(z, m_{\pi\pi})}{\left(4\ f_1^{u_V}(x) +\ f_1^{d_V}(x)\right) D_1^u(z, m_{\pi\pi})}$$

Deuteron Target: $$A_{LU,d}^{\sin\phi_R \sin\theta}(z, m_{\pi\pi}, x; Q, y) = -\frac{W(y)}{A(y)} \frac{M}{Q} \frac{|\boldsymbol{R}|}{m_{\pi\pi}} \frac{3\, \boxed{\left(x e^{u_V}(x) + x e^{d_V}(x)\right)}\, H_{1,sp}^{\sphericalangle,u}(z, m_{\pi\pi})}{5\ \left(f_1^{u_V}(x) +\ f_1^{d_V}(x)\right) D_1^u(z, m_{\pi\pi})}$$

e(x) extraction



$$e^V(x) = \frac{4}{9} e^{u_V}(x) - \frac{1}{9} e^{d_V}(x)$$

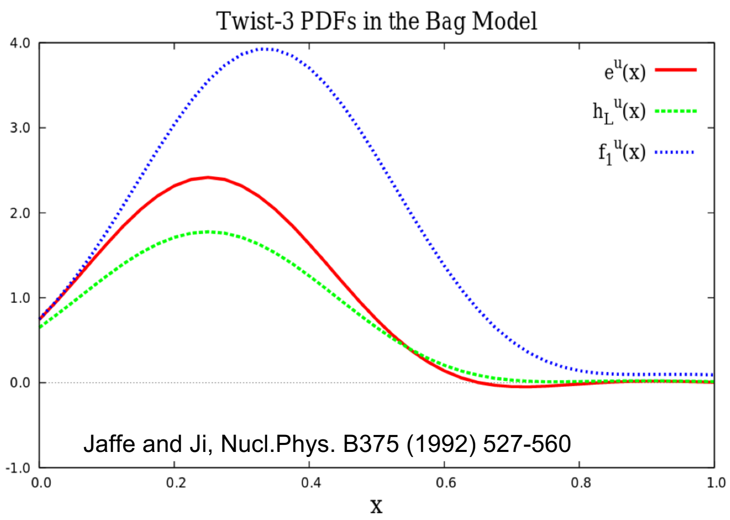
Extracted from CLAS6 preliminary A_{LU} and A_{UL}

Consistent with LFCQM model prediction (black curve)

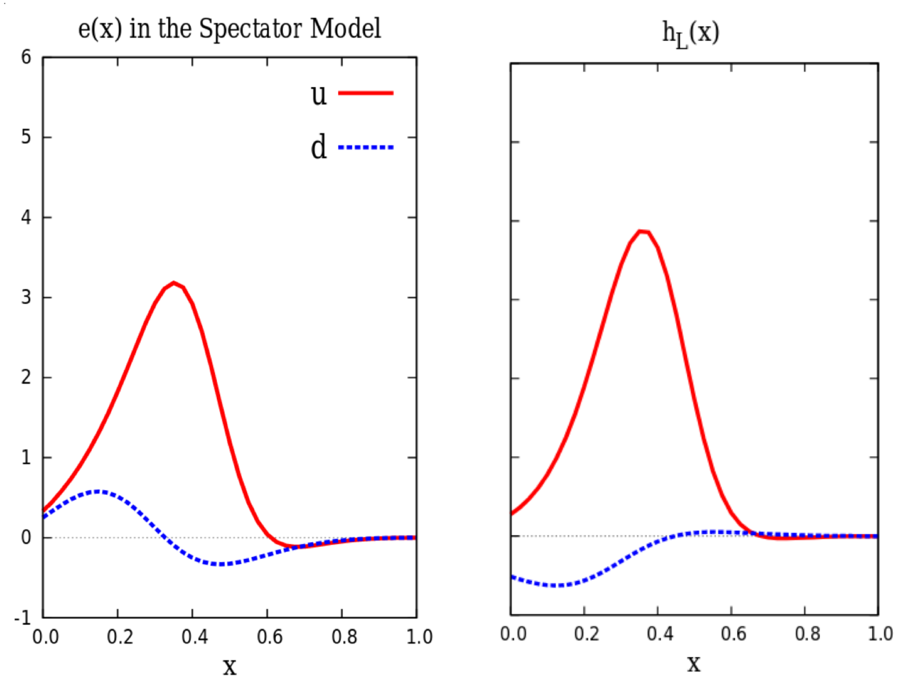
Extraction: Courtoy, arXiv:1405.7659
LFCQM Model: Lorcé , Pasquini, Schweitzer, JHEP 1501 (2015) 103
[figure from Pisano, Radici, Eur.Phys.J. A52 (2016) no.6, 155]

e(x) and h_L(x) Predictions

Bag Model



Spectator Model



Jakob, Mulders, and Rodrigues, Nucl.Phys. A626 (1997) 937-965

Figures from JLab Proposal E12-06-112B/E12-09-008B

Twist-3 Dihadron Fragmentation Function

$$F_{LU}^{\sin\phi_R} = -\sum_q e_q^2 \, x \frac{|R|\sin\theta}{Q}\left[\frac{M}{m_{hh}}\, x\, e^q(x)\, H_1^{\sphericalangle q}(z,\cos\theta, m_{hh}) + \frac{1}{z} f_1^q(x)\, \widetilde{G}^{\sphericalangle q}(z,\cos\theta,m_{hh})\right]$$

Extracting e(x) and $h_L(x)$ involves

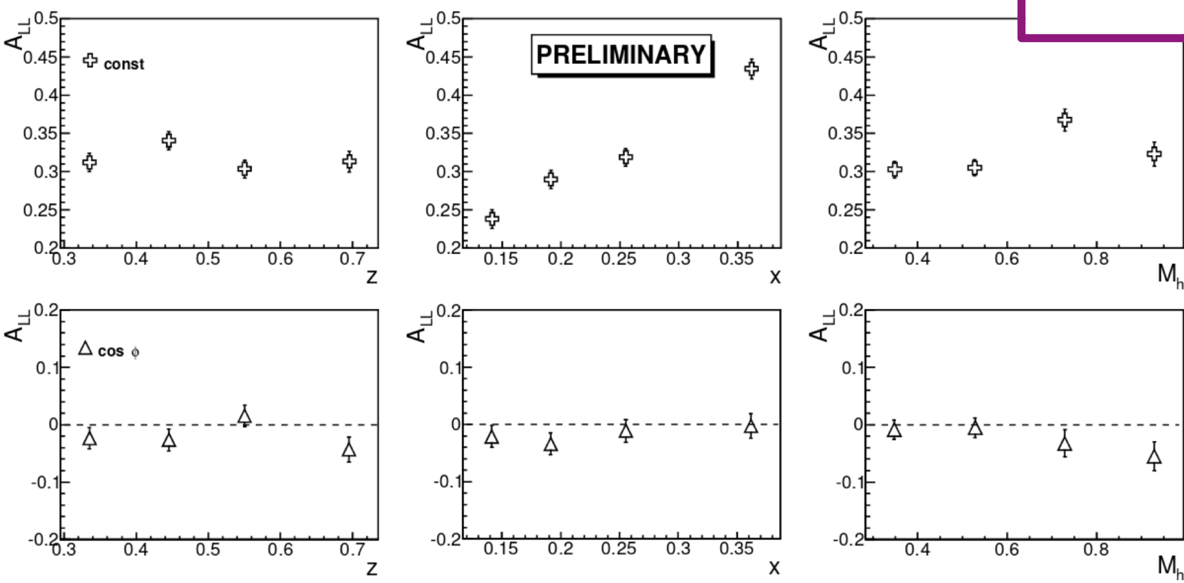
$\widetilde{G}^{\sphericalangle q}$ – a pure twist-3 DiFF

~0 under Wandzura-Wilzcek approximation
What can we learn from data?

Double spin asymmetries can help:

$$F_{LL}^{const} = x g_1^q(x)\, D_1^q(z,\cos\theta, M_h),$$

$$F_{LL}^{\cos\phi_R} = -x\frac{|\boldsymbol{R}|\sin\theta}{Q}\frac{1}{z} g_1^q(x)\, \widetilde{D}^{\sphericalangle q}(z,\cos\theta,M_h)$$



$\widetilde{D}^{\sphericalangle q}$ is expected to be larger than $\widetilde{G}^{\sphericalangle q}$

$\widetilde{D}^{\sphericalangle q}$ is very small, since $\cos\Phi_R$ a

$\widetilde{G}^{\sphericalangle q}$ is also likely very small

Pereira, PoS(DIS2014)231

Twist-3 Dihadron Fragmentation Function

$$A^{\mathrm{LU}}_{\mathrm{SIDIS}}(x,z,M_h;Q) = -\frac{W(y)}{A(y)}\frac{M}{Q}\frac{|\boldsymbol{R}|}{M_h}\frac{\sum_q e_q^2\left[x\,e^q(x)\,H_{1\,sp}^{\sphericalangle\,q}(z,M_h^2) + \frac{M_h}{zM}\,f_1^q(x)\,\tilde{G}_{sp}^{\sphericalangle\,q}(z,M_h^2)\right]}{\sum_q e_q^2\,f_1^q(x)\,D_1^q(z,M_h^2)}$$

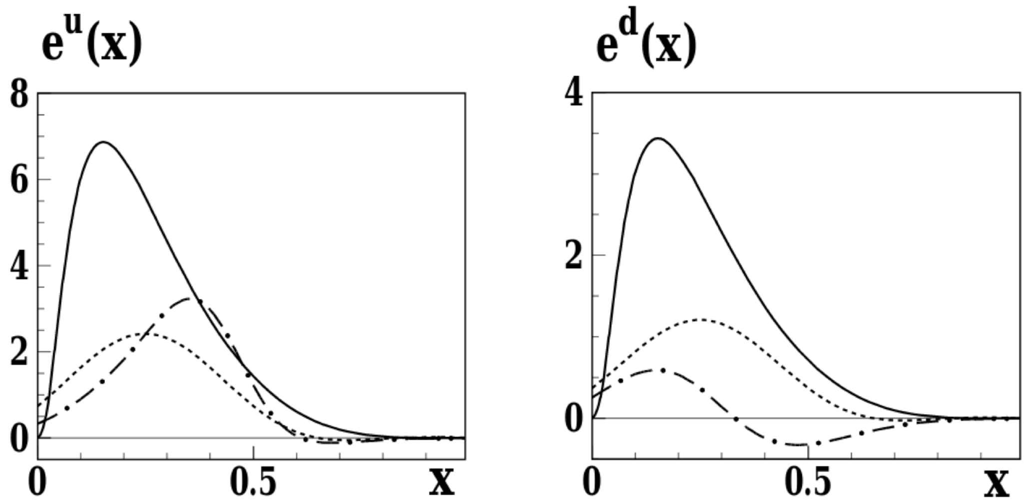
$$A^{\mathrm{UL}}_{\mathrm{SIDIS}}(x,z,M_h;Q) = -\frac{V(y)}{A(y)}\frac{M}{Q}\frac{|\boldsymbol{R}|}{M_h}\frac{\sum_q e_q^2\left[x\,h_L^q(x)\,H_{1\,sp}^{\sphericalangle\,q}(z,M_h^2) + \frac{M_h}{zM}\,g_1^q(x)\,\tilde{G}_{sp}^{\sphericalangle\,q}(z,M_h^2)\right]}{\sum_q e_q^2\,f_1^q(x)\,D_1^q(z,M_h^2)}$$

$\frac{A_{LU}}{A_{UL}}$ should not depend on (z, M_h) if $\tilde{G}^{\sphericalangle}$ is negligible

- Extraction of e(x) is more difficult if this is not the case
- Higher-precision data from CLAS12 will help address this

e(x) and h_L(x) Predictions

Light Front Constituent Quark Model

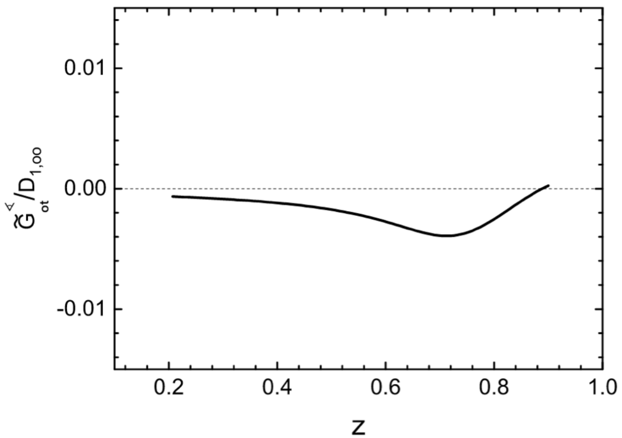


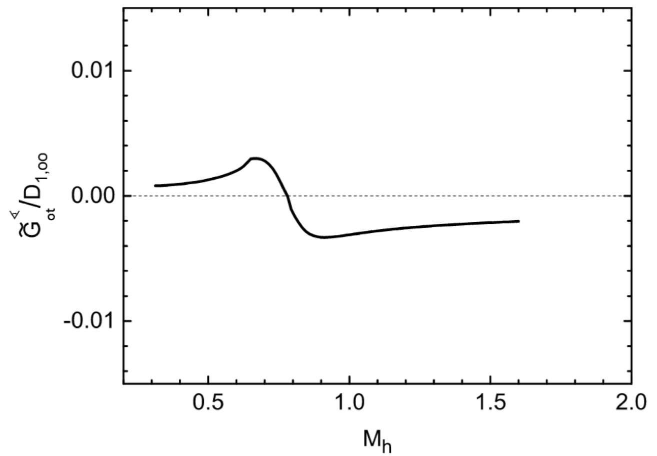
Lorcé , Pasquini, Schweitzer, JHEP 1501 (2015) 103

Solid: LFCQM model
Dot-Dashed: spectator model
Dashed: bag model

- Relatively larger magnitude partly

Twist-3 Dihadron Fragmentation Function





Spectator Model Calculation:

Leading order term of $\tilde{G}^{\sphericalangle}$ is <0.5% of that of the leading-twist DiFF D_1

Partial Wave Expansions

$$\widetilde{G}^{\sphericalangle}(z,\cos\theta,M_h^2) = \boxed{\widetilde{G}^{\sphericalangle}_{ot}(z,M_h^2)} + \widetilde{G}^{\sphericalangle}_{lt}(z,M_h^2)\cos\theta$$

$$D_1^a(z,\cos\theta,M_h^2) = \boxed{D_{1,oo}^a(z,M_h^2)} + D_{1,ol}^a(z,M_h^2)\cos\theta + D_{1,ll}^a(z,M_h^2)(3\cos^2\theta - 1)$$

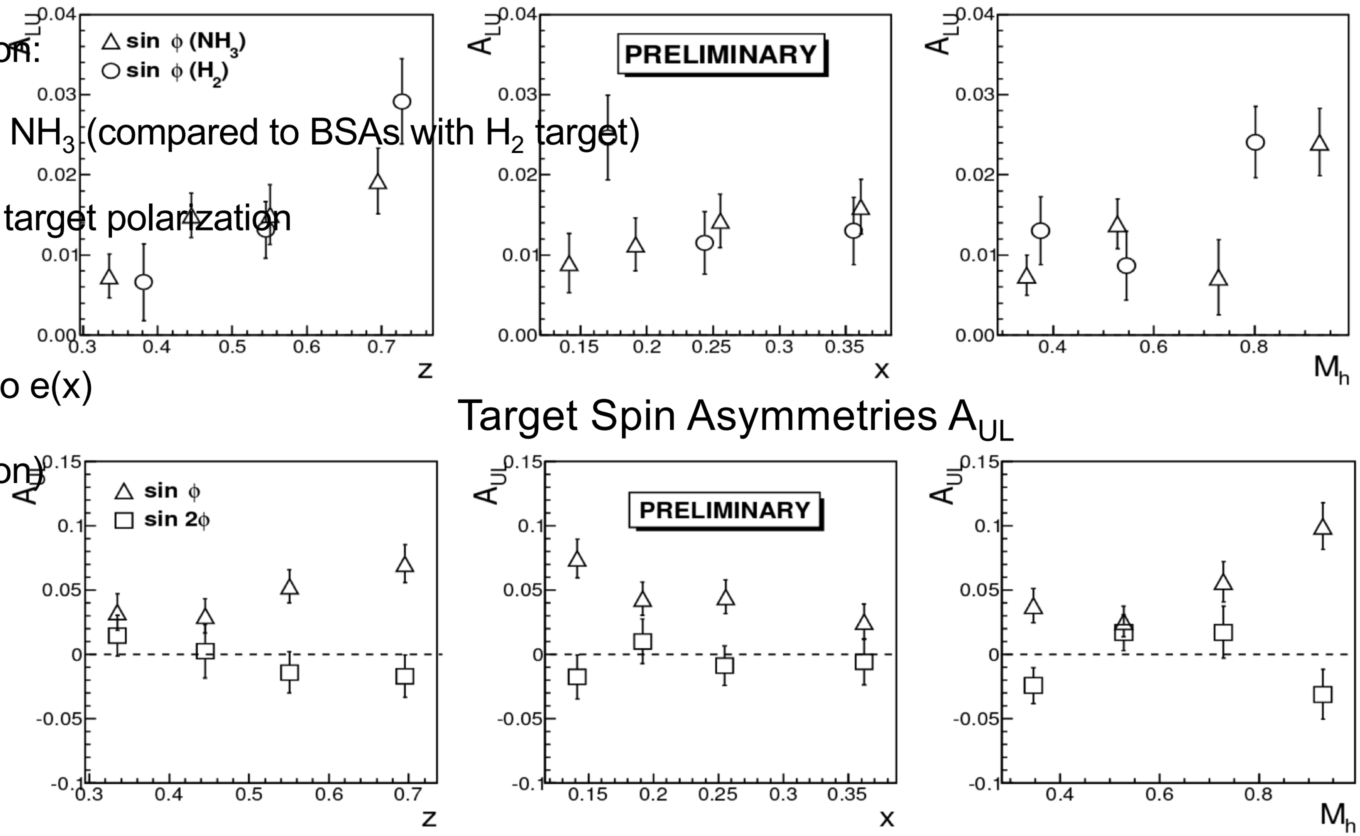
W. Yang , X. Wang, Y. Yang, Z. Lu
Phys.Rev. D99 (2019) no.5, 054003

Dihadron Asymmetries from CLAS6

- 5.5 GeV electrons scattered on:
- Longitudinally Polarized solid NH_3 (compared to BSAs with H_2 target)
- 85% beam polarization, 80% target polarization
- $1 < Q^2 < 6$ GeV^2
- $\sin\Phi_R$ modulation, sensitive to e(x)
- (see aforementioned extraction)

Beam Spin Asymmetries A_{LU}

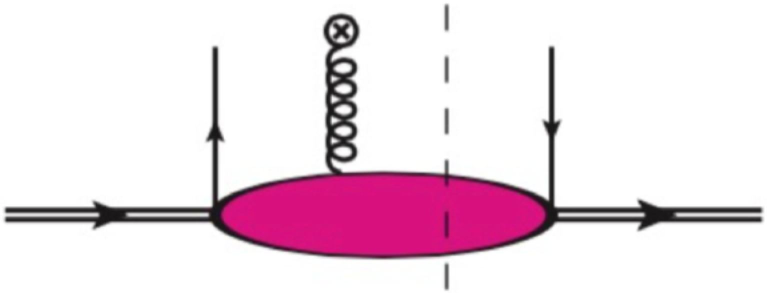
Target Spin Asymmetries A_{UL}

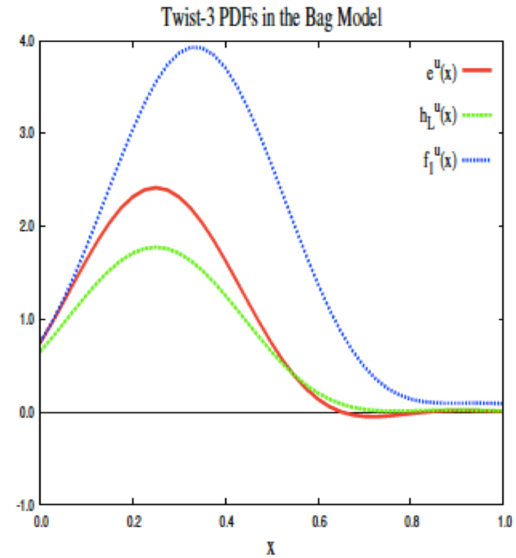


Pereira, PoS(DIS2014)231

Access of e(x) in SIDIS x-section

- One of only three colinear twist-3 parton distribution functions in the nucleon
- Interference of quark-gluon with quark amplitude
- $\int x^2 e(x) dx$ →⊥ force on ⊥ polarized quarks in an unpolarized nucleon, "Boer-Mulders force" (Burkardt)
- Sizable model predictions



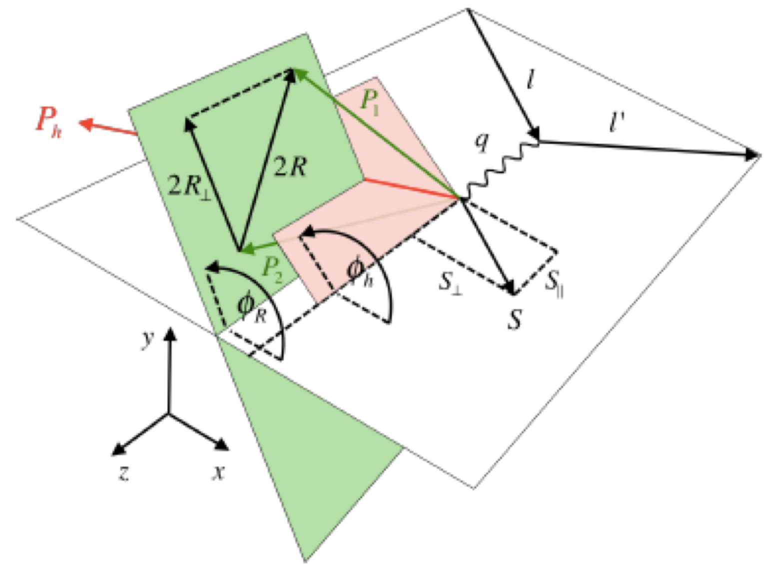


Jaffe, Ji, Nucl. Phys. **B**375, 527-560 (1992).

$BSA\ ep \rightarrow \pi^+\pi^- + X$: Clean access to e(x)

- See e.g. Aurore Courtoy, arXiv:1405.7659

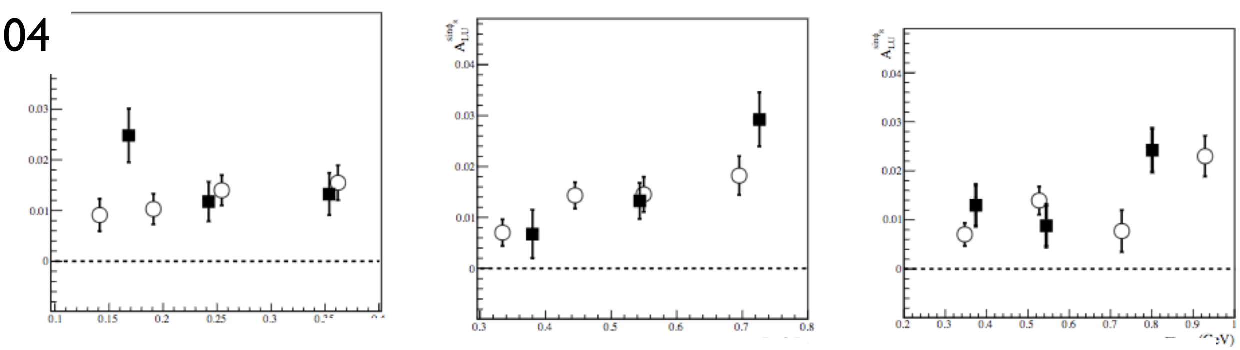
$$F_{LU}^{\sin\phi_R} = -x\frac{|\boldsymbol{R}|\sin\theta}{Q}\left[\frac{M}{m_{hh}}\, x\, e^q(x)\, H_1^{\sphericalangle q}(z,\cos\theta,m_{hh}) + \frac{1}{z} f_1^q(x)\, \widetilde{G}^{\sphericalangle q}(z,\cos\theta,m_{hh})\right],$$



- Evidence for non-zero BSA $A_{LU}^{sin\phi_R} = \frac{F_{LU}^{\sin\phi_R}}{F_{UU}}$ from CLAS6:

$$\overrightarrow{P_h} = \overrightarrow{P_\pi^+} + \overrightarrow{P_\pi^-}, \qquad \vec{R} = \overrightarrow{P_\pi^+} - \overrightarrow{P_\pi^-}$$

0.04



Solid: points hydrogen E.P.J. Web of Conf. 73(2014) 02008
Open points: NH_3 PoS DIS2014 (2014) 231

CLAS12

Forward Detector:

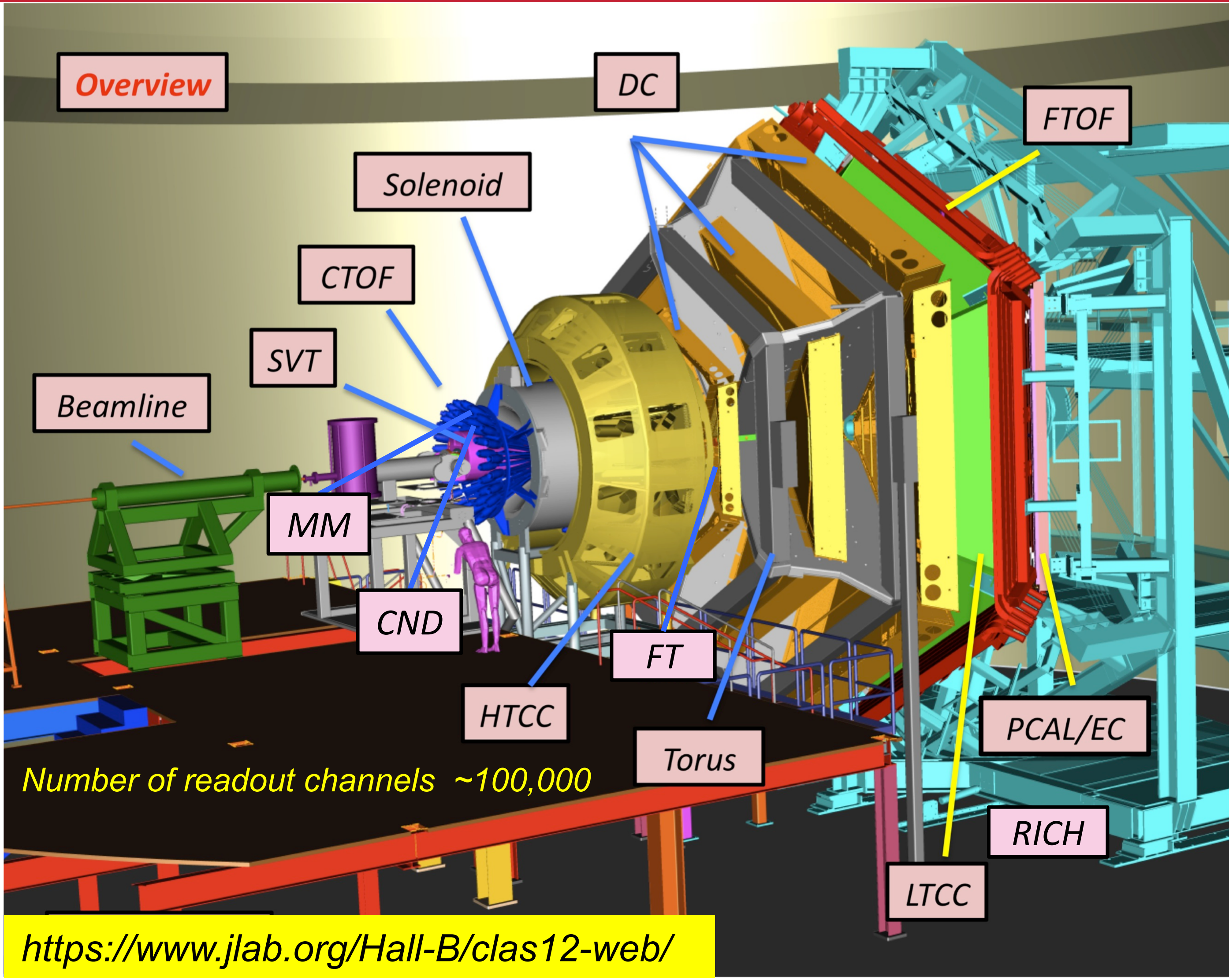
- *TORUS magnet*
- *HT Cherenkov Counter*
- *Drift chamber system*
- *LT Cherenkov Counter*
- *Forward ToF System*
- *Preshower calorimeter*
- *E.M. calorimeter (EC)*

Central Detector:

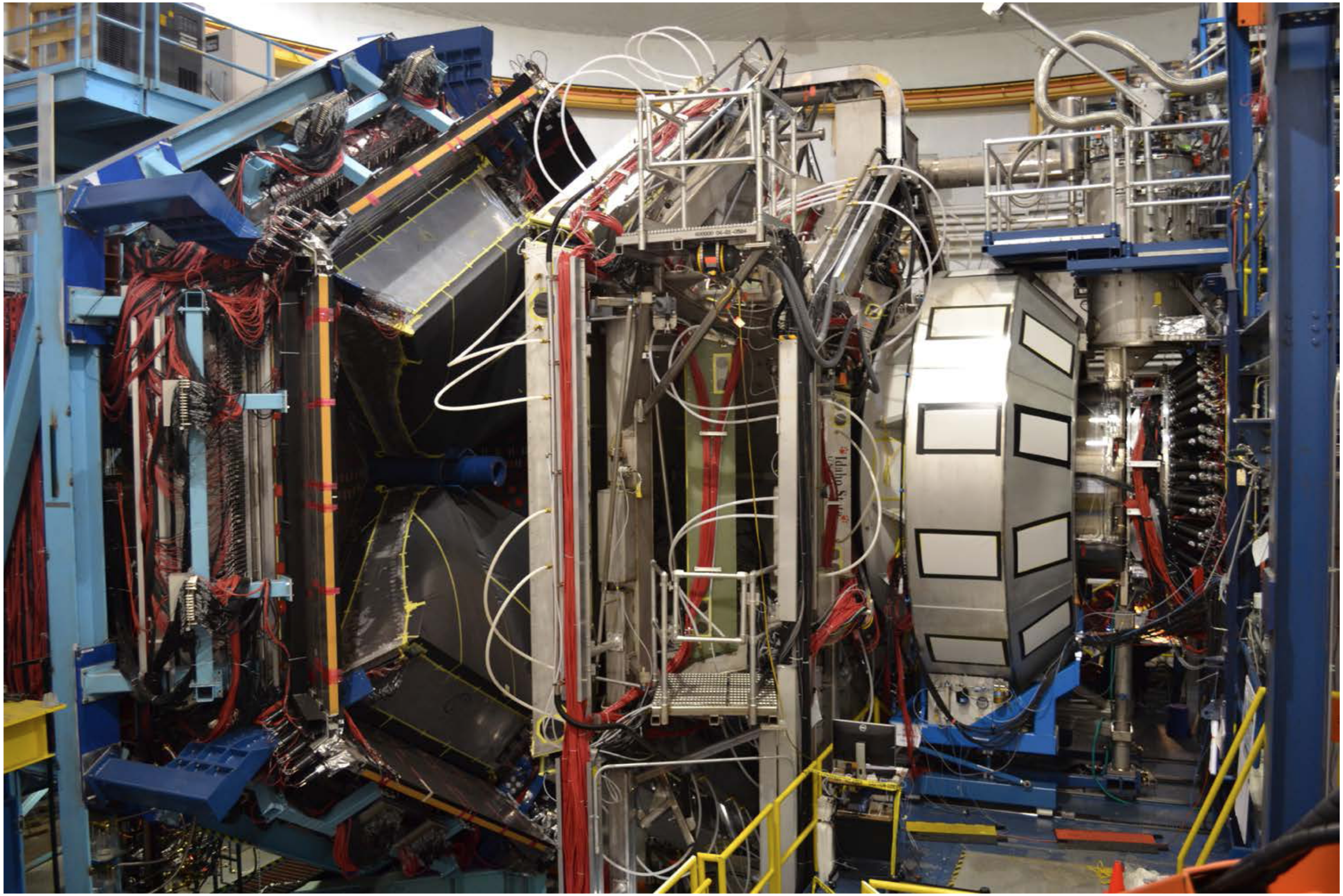
- *SOLENOID magnet*
- *Barrel Silicon Tracker*
- *Central Time-of-Flight*

Implemented Upgrades:

- *Micromegas (CD)*
- *Neutron detector (CD)*
- *RICH detector (FD)*
- *Forward Tagger (FD)*



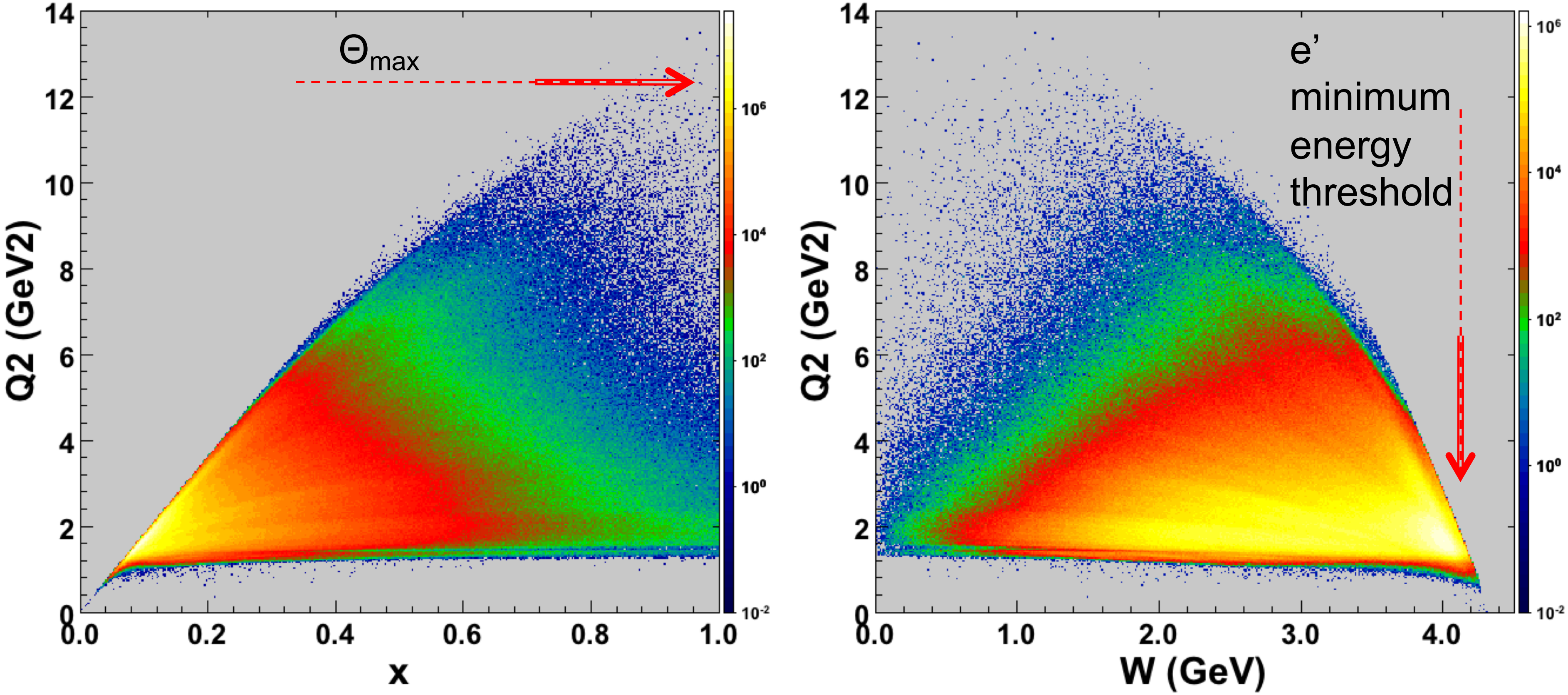
Spring 2018: CLAS12 installation complete for first run with H2 target



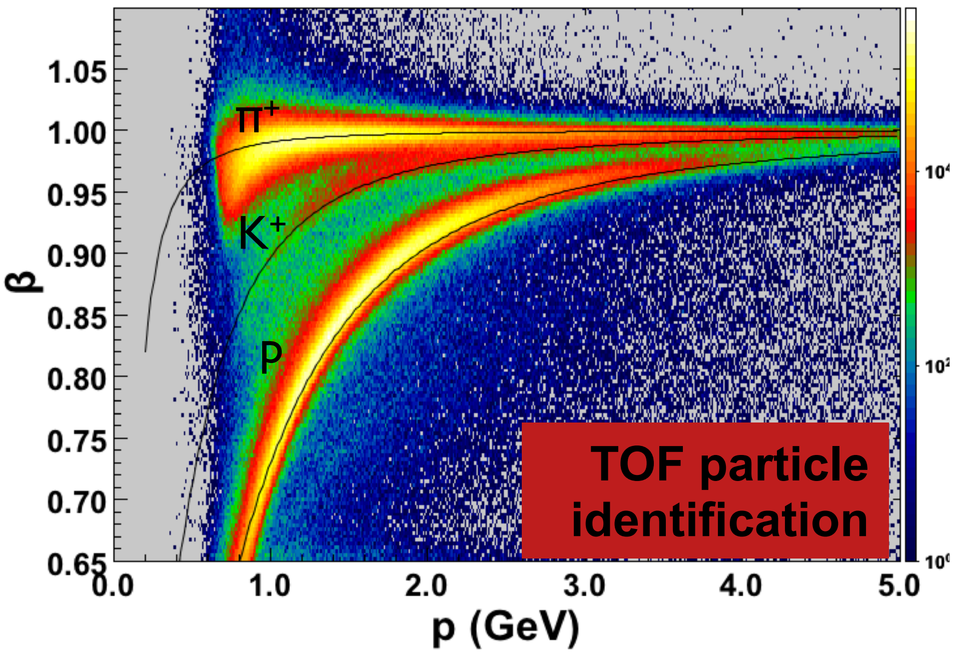
CLAS12 Kinematic Reach

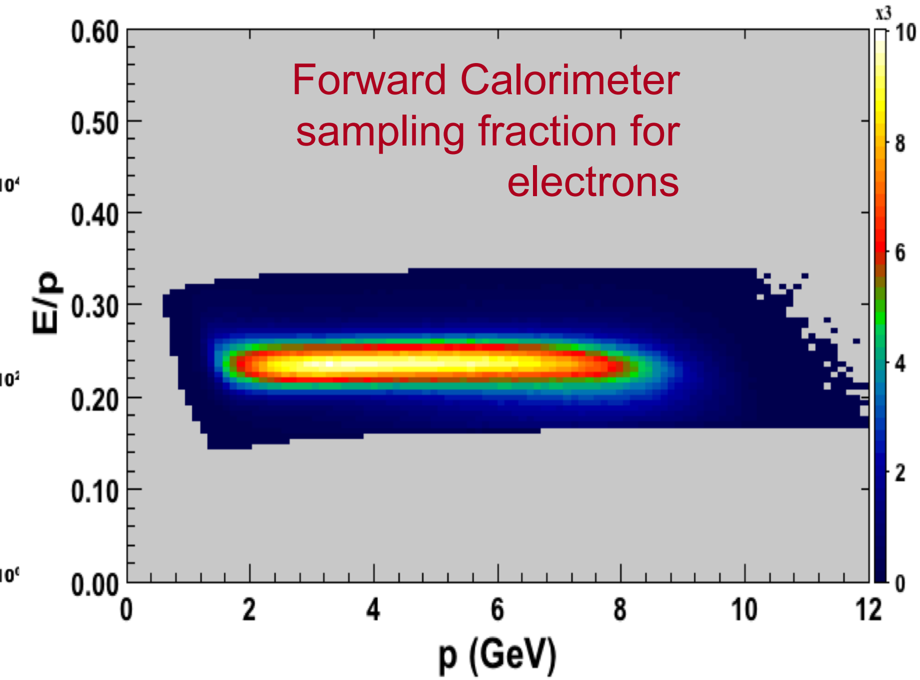
Beam energy at 10.6 GeV Torus current 3770 A, electrons in-bending, Solenoid magnet at 2416 A.

p(e,e')X



Performance plots





First results on di-hadron correlations

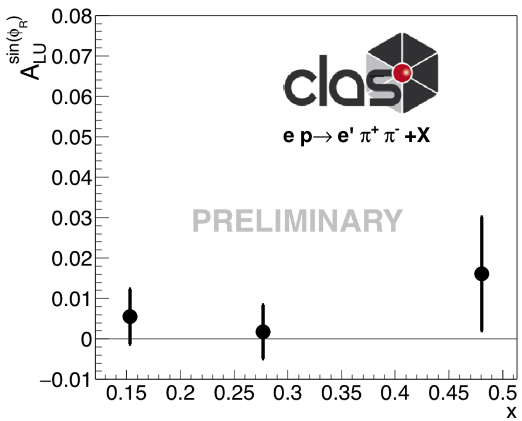
- Use about 10% of spring run (~3% of approved running time)
- Select $ep \rightarrow \pi^+\pi^- + X$
- Calculate ϕ_R, ϕ_h angles of hadron pair

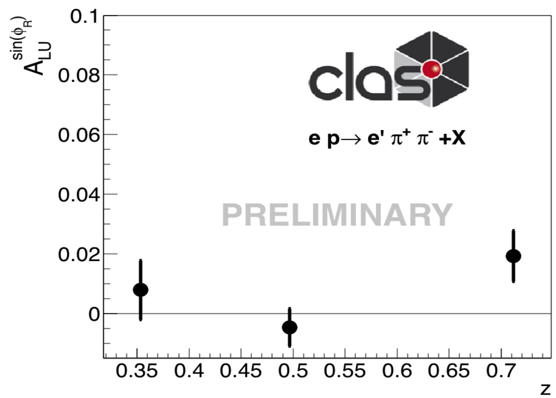
$$\overrightarrow{P_h} = \overrightarrow{P_\pi^+} + \overrightarrow{P_\pi^-}, \qquad \vec{R} = \overrightarrow{P_\pi^+} - \overrightarrow{P_\pi^-}$$

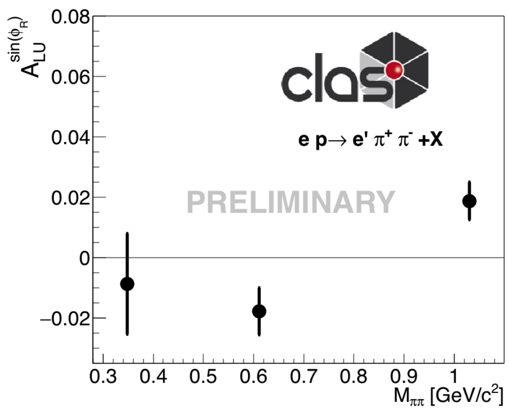
- 2D fit to asymmetries $\frac{N^+ + N^-}{N^+ + N^-}(\phi_R, \phi_h) \rightarrow A_{LU}^{sin\phi_R}$
- Correct with kinematic factor and P_{beam}~86%

Particle selection

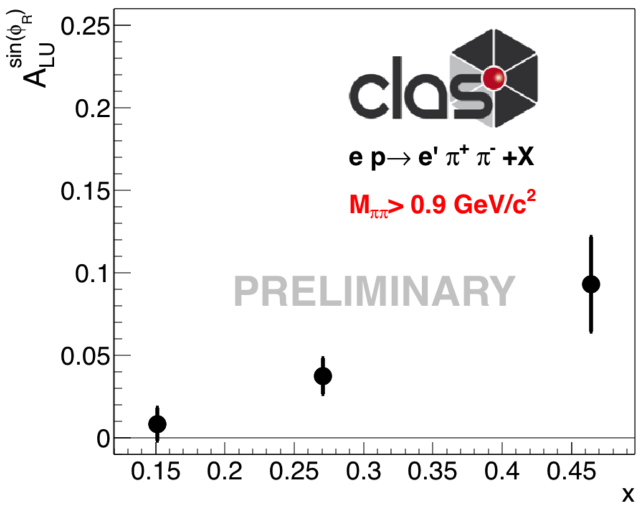
- $Q^2 > 1.0$ GeV^2
- $W > 2.0$ GeV/c^2
- $z_i > 0.1$
- $z < 0.95$
- $M_{miss} > 2.05$ GeV/c^2
- $x_F > 0$
- $y < 0.8$
- $p_{\pi i} > 1$ GeV/c

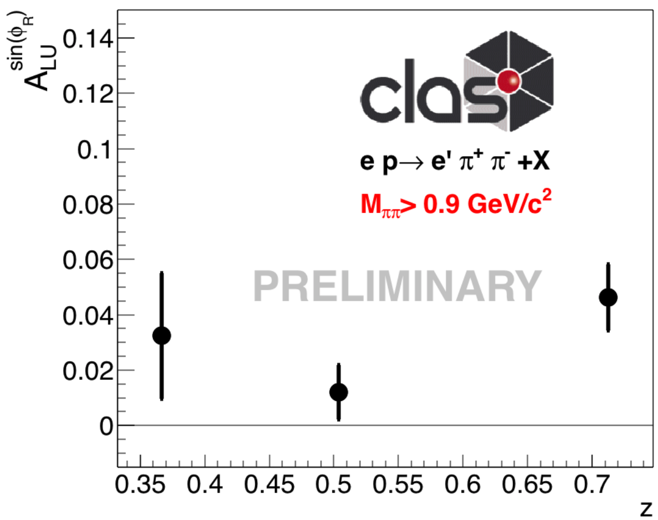


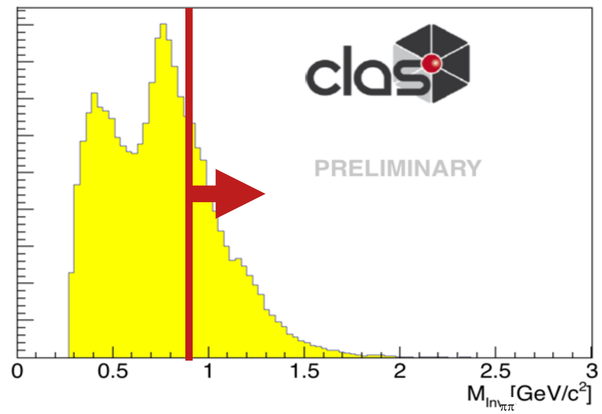




Using only pairs with $M_{\pi\pi}$> 0.9 GeV/c²



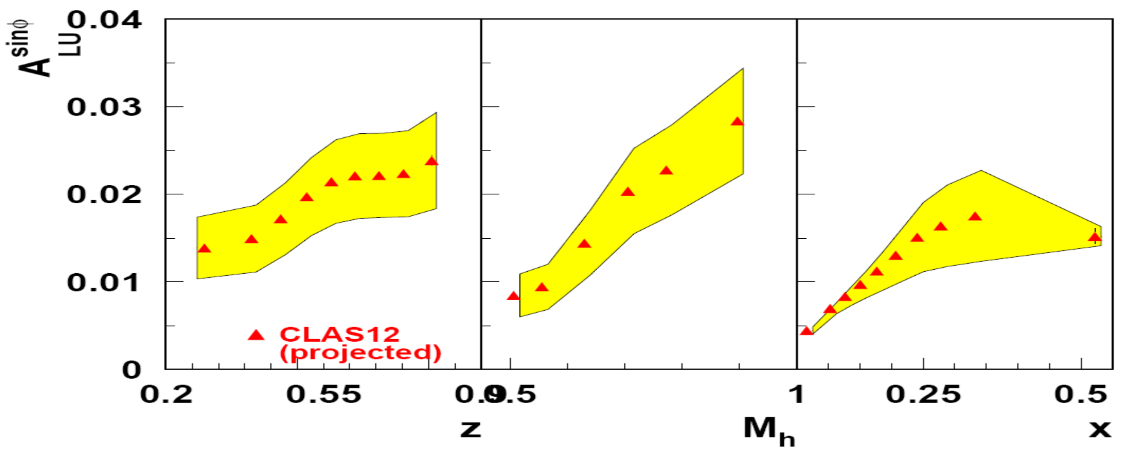




- Enhanced asymmetries
- Rise with *x*

Summary

- First Beam Spin Asymmetries of Di-hadrons shown
- Indications of signal consistent with previous measurement
- 120/30 days of running are approved with unpolarized liquid H2/liquid D2 targets **(underway!)**
- 120 + 50 days of running are approved with longitudinally polarized NH3/ND3 targets (targets ready ~2020)



Projections using 54 days of unpolarized proton

What can we learn?

$$\sum_{h,\,S_h} \int dz M_h$$

Jet / quark mass as the
average of the masses
of the produced hadrons weighted by
the chiral-odd E FF

WW approximation

$$M_j = m_q$$

s

Dynamical mass!

Full QCD

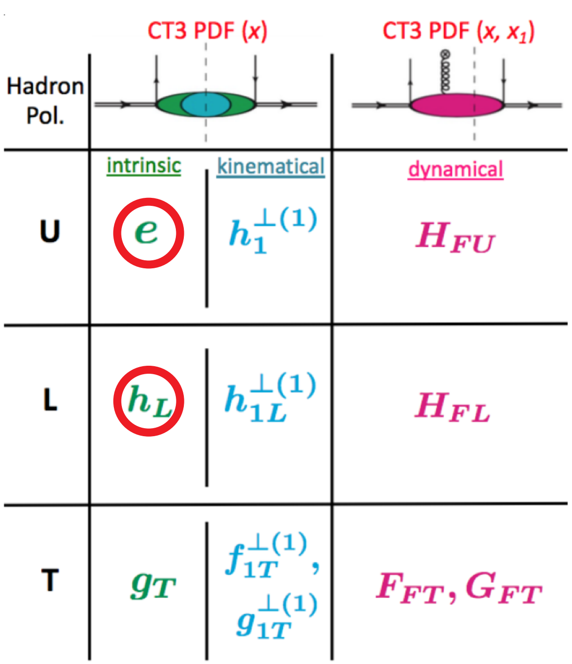
$$M_j = m_q + m_q^{corr}$$

Andrea Signori at FF2019

Twist-3 Parton Distribution Functions

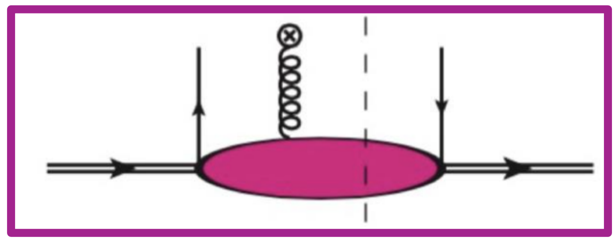
e sin(Φ_R) modulation of A_{LU} and A_{UL} in dihadrons is sensitive to Twist-3 PDFs: e(x) ar

Twist-3 PDFs



Hadron Pol.	CT3 PDF (x) intrinsic	CT3 PDF (x) kinematical	CT3 PDF (x, x_1) dynamical
U	e	$h_1^{\perp(1)}$	H_{FU}
L	h_L	$h_{1L}^{\perp(1)}$	H_{FL}
T	g_T	$f_{1T}^{\perp(1)}$, $g_{1T}^{\perp(1)}$	F_{FT}, G_{FT}

Image from Gamberg, FF2019 Workshop



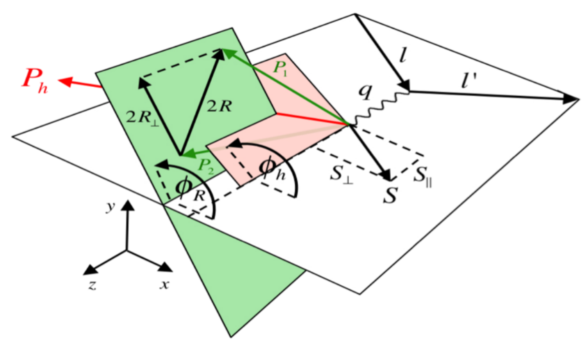
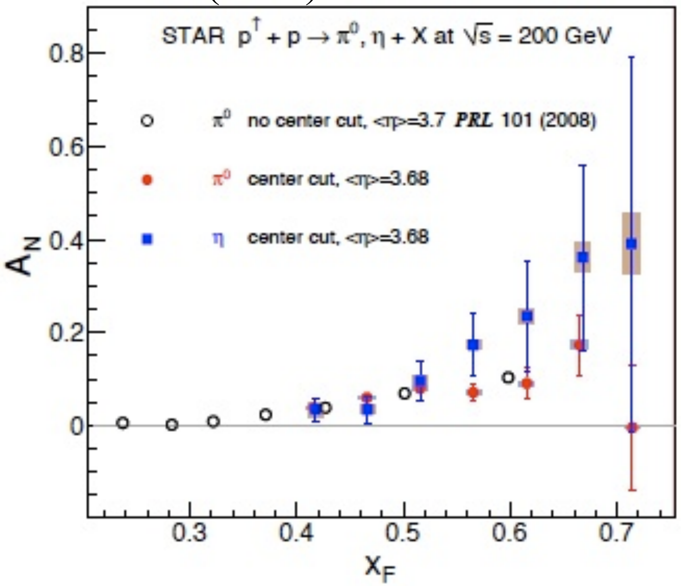


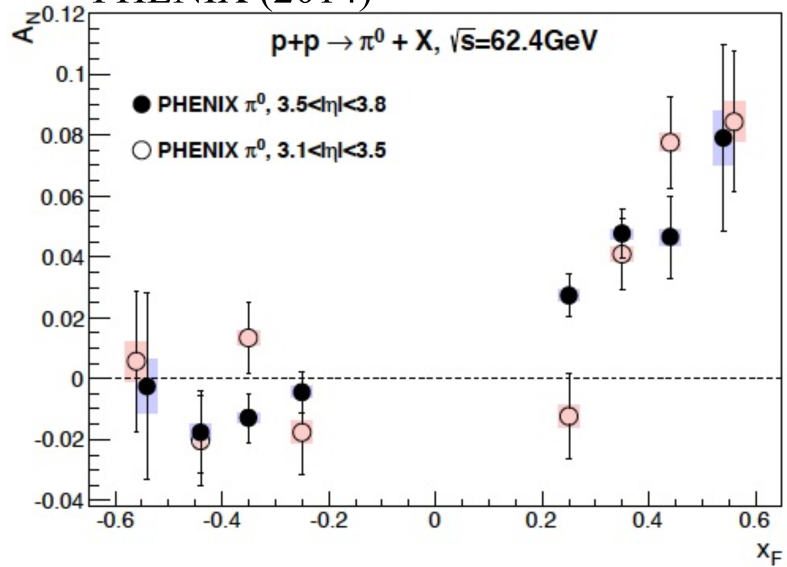
Figure from arXiv:1702.07317

A_N in $pp \to \pi X$ – PUZZLE FOR 40+ YEARS!

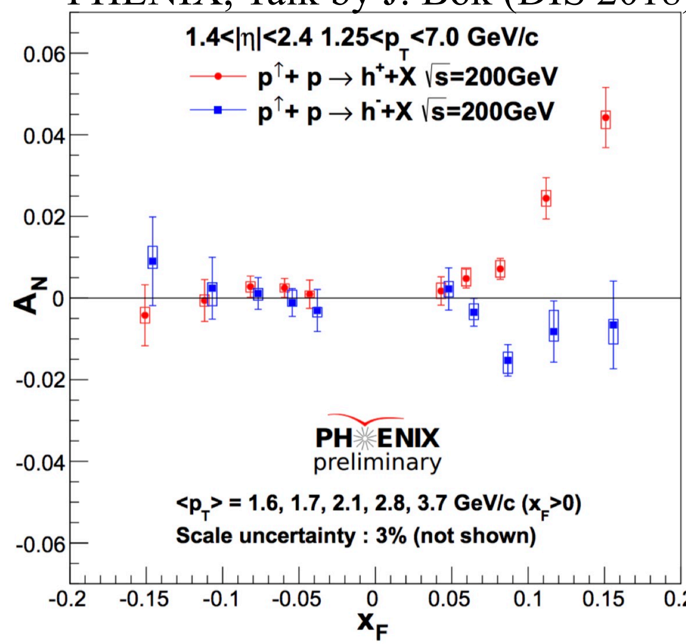
STAR (2012)



PHENIX (2014)



PHENIX, Talk by J. Bok (DIS 2018)



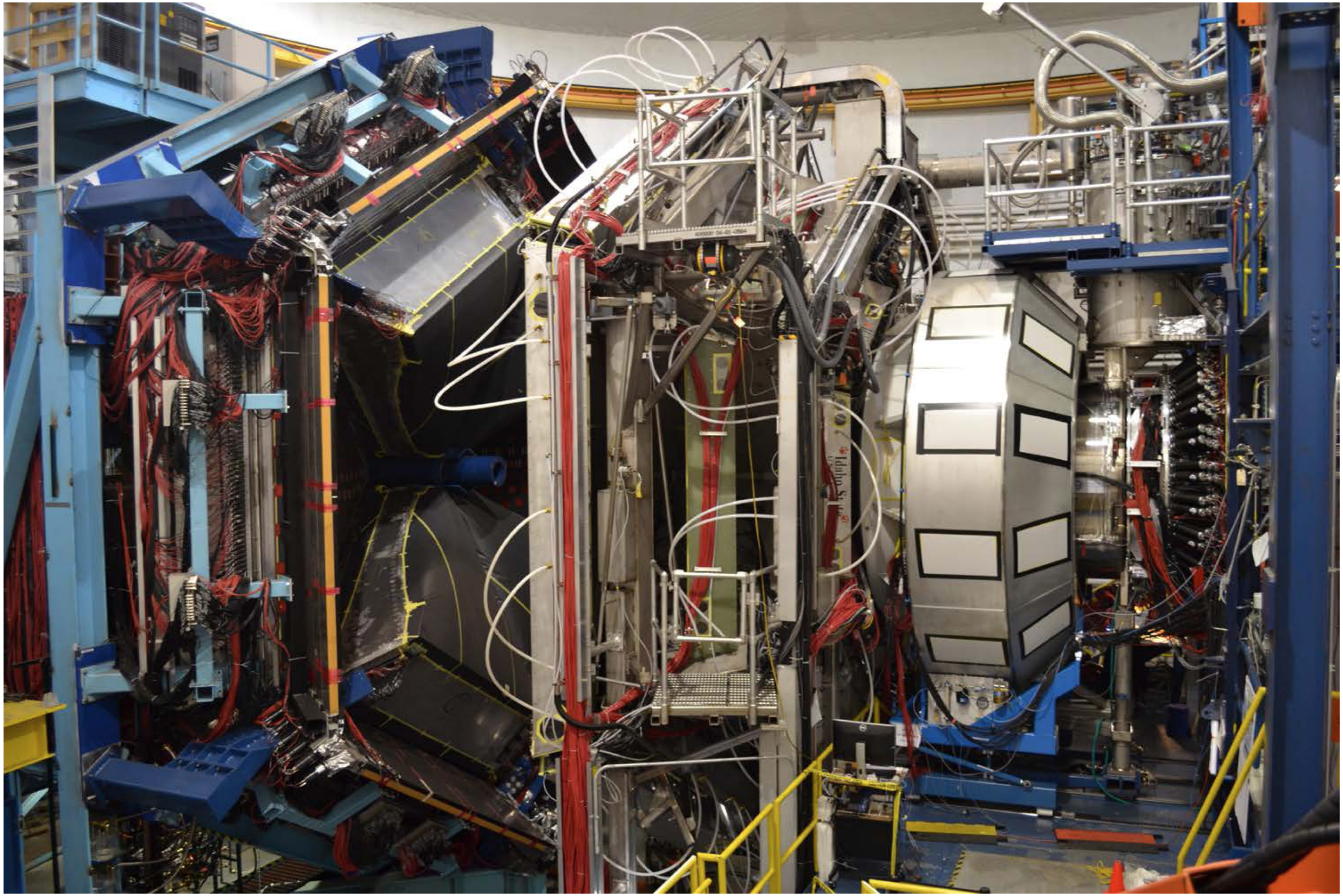
- Fds $xe(x) = \frac{m_q}{M} f_1(x) - 2\mathcal{P}\int_{-1}^{1} \frac{dx' H_{FU}(x,x')}{x-x'}$
- $\frac{x}{2} h_L = \frac{m}{M} g_1(x) - h_{1L}^{\perp(1)}(x) - 2\mathcal{P}\int_{-1}^{1} \frac{dx' H_{FL}(x,x')}{x-x'}$
-

$$h_L^q(x) = 2x \int_x^{\epsilon(x)} dx_1 \frac{h_1^q(x_1)}{x_1^2} + \frac{m_q}{M}\left(\frac{g_1^q(x)}{x} - 2x \int_x^{\epsilon(x)} dx_1 \frac{g_1^q(x_1)}{x_1^3}\right) + 4x \int_x^{\epsilon(x)} \frac{dx_1}{x_1^3} \times \mathcal{P}\int_{-1}^{1} dx_2 \frac{(x_1/2)(x_2 - x_1)\delta(x_1 - x) +}{(x_1 - x_2)^2}$$

$$h_{1L}^{\perp(1),q}(x) = x^2 \int_x^{\epsilon(x)} dx_1 \frac{h_1^q(x_1)}{x_1^2} - \frac{m_q}{M} x^2 \int_x^{\epsilon(x)} dx_1 \frac{g_1^q(x_1)}{x_1^3} + 2x^2 \int_x^{\epsilon(x)} \frac{dx_1}{x_1^3} \mathcal{P}\int_{-1}^{1} dx_2 \frac{2x_1 - x_2}{(x_1 - x_2)^2} H_{FL}^q(x_1, x_2).$$

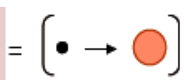
From: **Phys.Rev. D93 (2016) no.5, 054024**

Spring 2018: CLAS12 installation complete for first run with H2 target

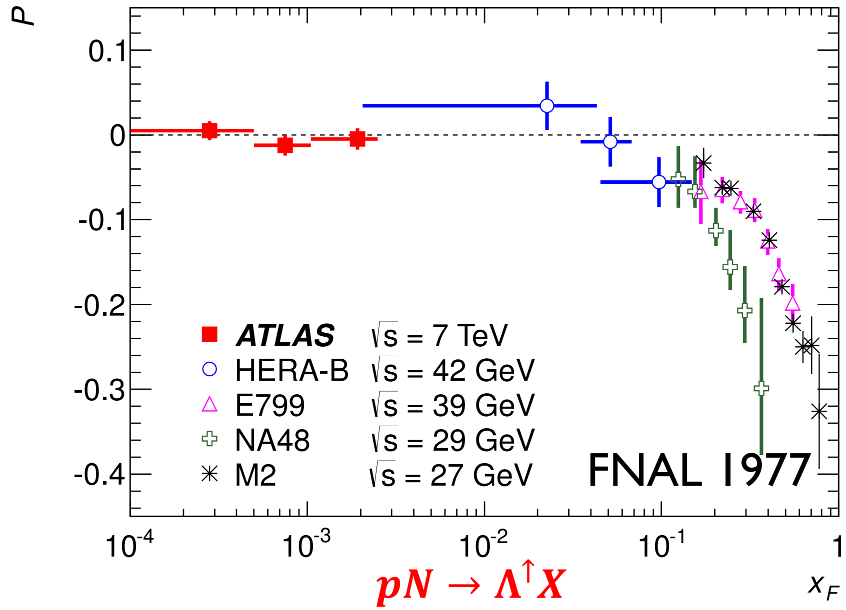


Enter polarization in the final States

<u>Observables:</u>
z: fractional energy of the quark carried by the hadron
$p_{h,T}$: transverse momentum of the hadron wrt the quark direction: **TMD FFs**

Parton polarization → **Hadron Polarization ↓**	**Spin averaged**	**longitudinal**	**transverse**
spin averaged	$D_1^{h/q}(z, p_T)$ = 		$H_1^{\perp h/q}(z, p_T)$ = 
longitudinal			
Transverse (here Λ)	$\boldsymbol{D_{1T}^{\perp \Lambda/q}(z, p_T)}$ = 		

- Analogue →similar to PDFs encoding spin/orbit correlations
- Determining final state polarization needs self analyzing decay (Λ)
- Gluon FFs similar but with circular/linear polarization (not as relevant for e+e-)



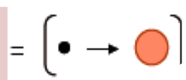
Phys.Rev. D91 (2015) no.3, 032004

- Similar: A_N in SIDIS ...
- Since 40+ years
- P, T- invariance→ TSSAs should vanish!

Enter polarization in the final States

See M. Schlegel's talk

<u>Observables:</u>
z: fractional energy of the quark carried by the hadron
$p_{h,T}$: transverse momentum of the hadron wrt the quark direction: **TMD FFs**

Parton polarization → Hadron Polarization ↓	Spin averaged	longitudi	ansverse
spin averaged	$D_1^{h/q}(z,p_T)$ 		$H_1^{\perp h/q}(z,p_T)$ 
longitudinal			
Transverse (here Λ)	$D_{1T}^{\perp\Lambda/q}(z,p_T)$		

- Analogue →si… …ıg spin/orbit correlations
- Determining final … …ation needs self analyzing decay (Λ)
- Gluon FFs similar b… …ı circular/linear polarization (not as relevant for e+e-)

Flavor Separation

Flavor separation can be achieved with different targets:

Proton Target:

$$A_{LU,p}^{\sin\phi_R \sin\theta}(z, m_{\pi\pi}, x; Q, y) = -\frac{W(y)}{A(y)} \frac{M}{Q} \frac{|\boldsymbol{R}|}{m_{\pi\pi}} \frac{\boxed{\left(4\, x e^{u_V}(x) - x e^{d_V}(x)\right)} H_{1,sp}^{\sphericalangle,u}(z, m_{\pi\pi})}{\left(4\, f_1^{u_V}(x) + f_1^{d_V}(x)\right) D_1^u(z, m_{\pi\pi})}$$

Deuteron Target:

$$A_{LU,d}^{\sin\phi_R \sin\theta}(z, m_{\pi\pi}, x; Q, y) = -\frac{W(y)}{A(y)} \frac{M}{Q} \frac{|\boldsymbol{R}|}{m_{\pi\pi}} \frac{3\, \boxed{\left(x e^{u_V}(x) + x e^{d_V}(x)\right)} H_{1,sp}^{\sphericalangle,u}(z, m_{\pi\pi})}{5\, \left(f_1^{u_V}(x) + f_1^{d_V}(x)\right) D_1^u(z, m_{\pi\pi})}$$

Extras