Study of the structure of hadrons using beam and target polarization observables with CLAS

AKA Overview of the eg1-dvcs results

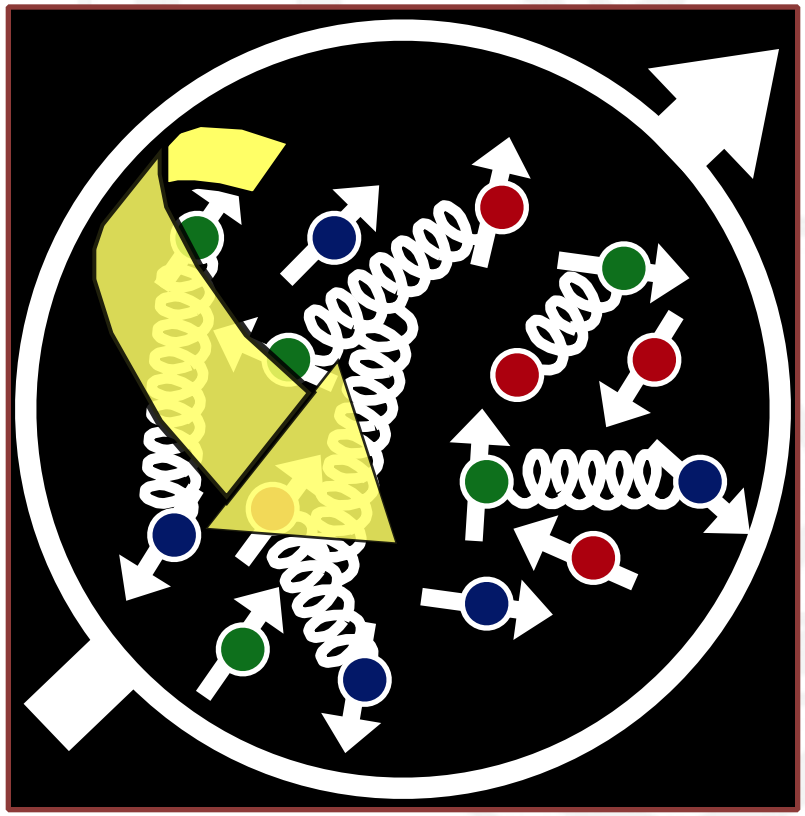
Angela Biselli

CLAS2015 the 4th European CLAS workshop

Catania, Italy, February 17-20 2015

Some open questions on hadronic structure

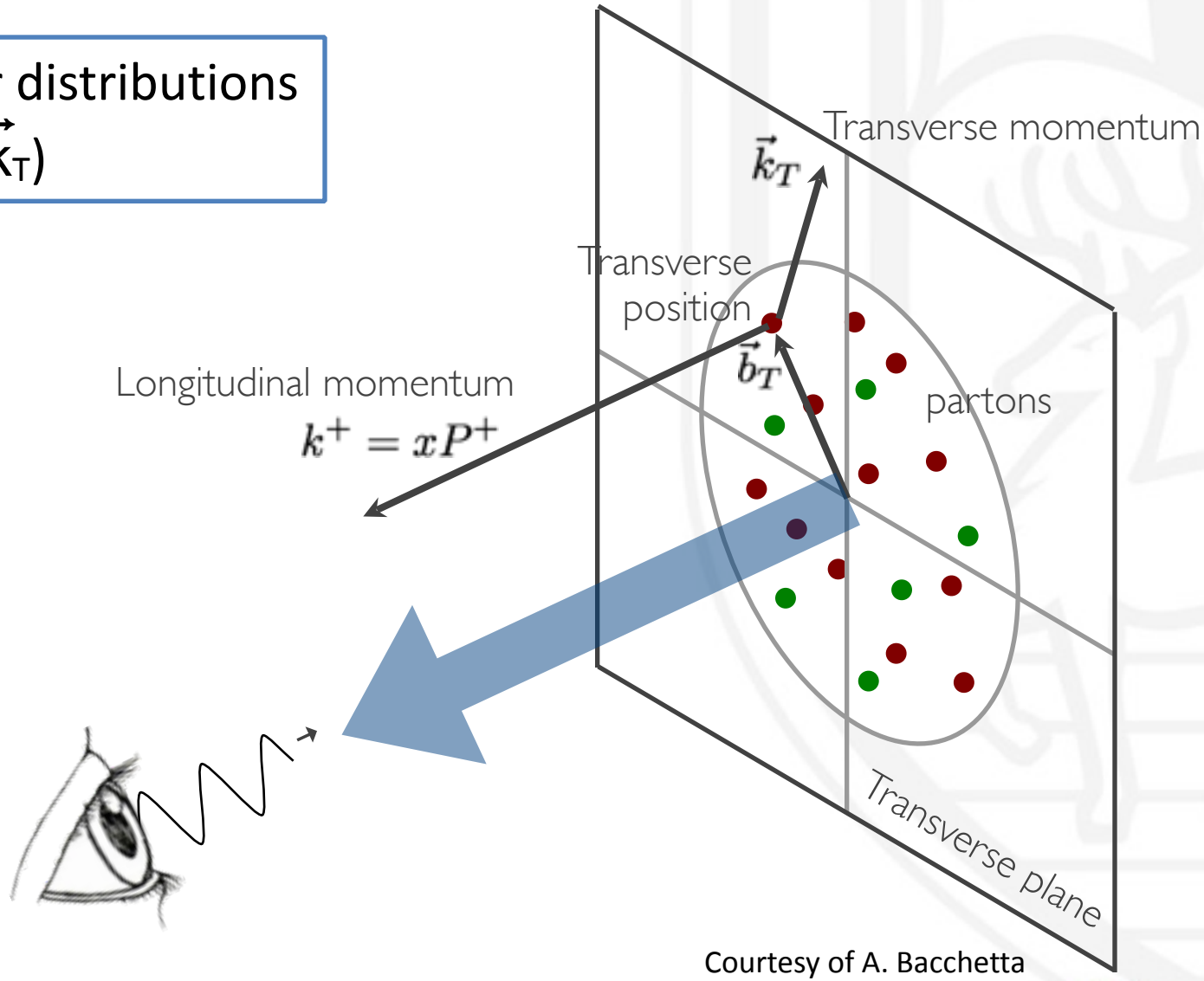
- Can we describe nucleons in terms of its constituents
- Where does the spin of the nucleon come from?



Courtesy of A. Bacchetta

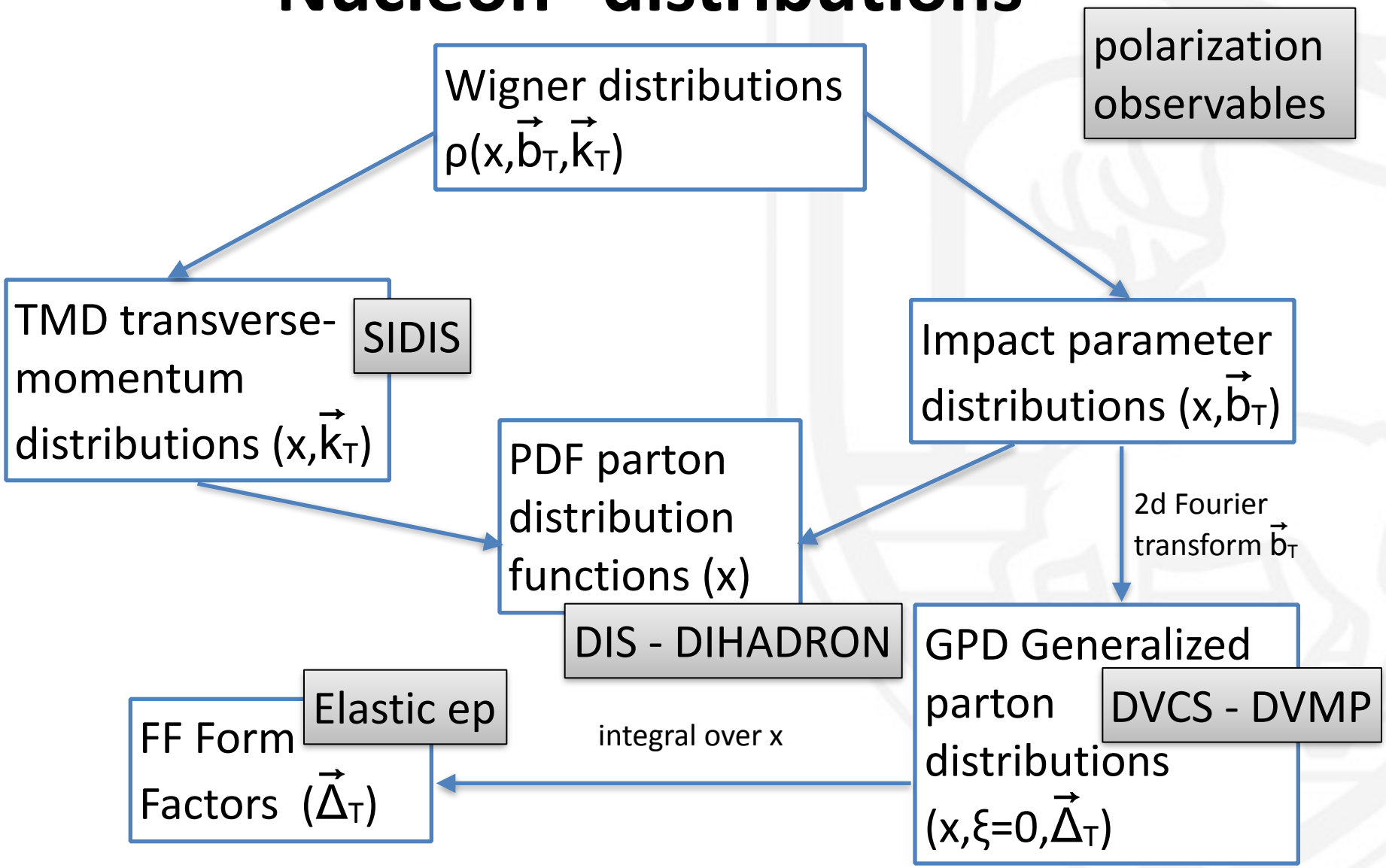
5 Dimensional Structure of the nucleon

Wigner distributions
$\rho(x,\vec{b}_T,\vec{k}_T)$



Courtesy of A. Bacchetta

Nucleon "distributions"

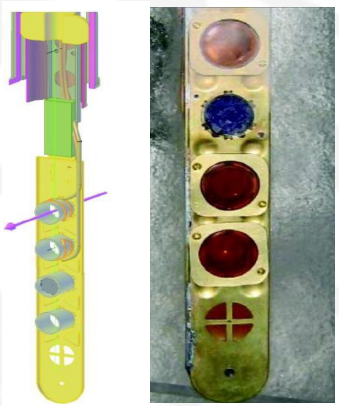


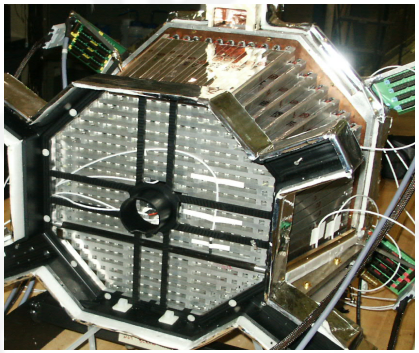
Courtesy of A. Bacchetta

Fairfield UNIVERSITY

eg1-dvcs run

- Polarized electron beam ~85%
- Polarized target
  - NH3 ~80%
  - ND3 ~40%
- CLAS+ Inner calorimeter (IC)





Part A (Feb.-Mar. 2009)	Part B (Apr.-Jun. 2009)	*Part C (Aug.-Sep. 2009)*
Hydrogen target NH_3	Hydrogen target NH_3	Deuteron target ND_3
Beam energy: 5.892 & 4.735 GeV	Beam energy: 5.967 GeV	***Beam energy: 5.764 GeV***
Luminosity: 22.7 fb^{-1}	Luminosity: 50.7 fb^{-1}	Luminosity: 25.3 fb^{-1}
Target position: -57.95 cm	Target position: -67.97 cm	***Target position: -68.18 cm***

Summary of eg1-dvcs analyses and status

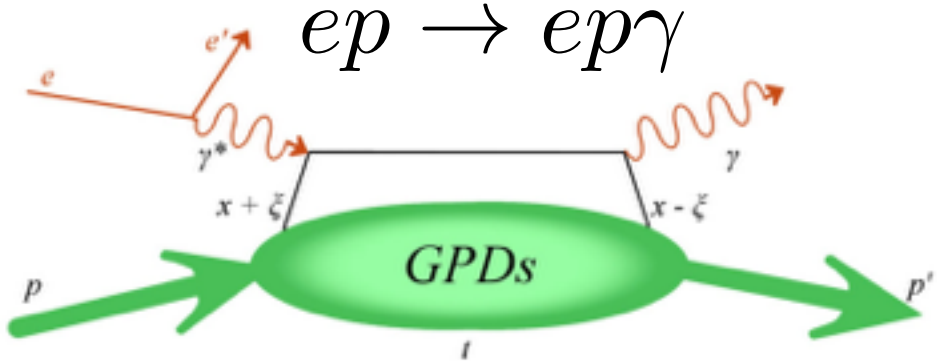
Analysis	*Authors*	*Status*
Single and double spin asymmetries for Deeply Virtual Compton Scattering on Longitudinally Polarized Proton Target	Biselli, Niccolai, Pisano, Seder	E. Seder et al Phys. Rev. Lett. 114 (2015) 032001 PRD: S. Pisano et al arXiv: 1501.07052 - ACCEPTED
Single and Double Spin Asymmetries for Deeply Virtual Exclusive π^0 Production on Longitudinally Polarized Proton Target	A. Kim	Ad Hoc review
Measurement of Single and Double Spin Asymmetries in Semi-Inclusive Deep Inelastic Scattering on Proton and Deuteron	S Koirala	Analysis note review
Target and beam spin asymmetries for di-hadron production $ep \rightarrow e'\pi^+\pi^-X$	S. Anefalos Pereira	In progress
DVCS beam and target spin asymmetries on the neutron target	D. Sokhan	In progress
Spin Asymmetries in exclusive π^+, π^0, η, and π^- electro-production from the eg1-DVCS experiment	P. Bosted	Analysis note approved
Precision measurements of g_1 of the proton and the deuteron with 6 GeV electrons	Y. Prok	Y. Prok et al Phys.Rev. C90 (2014) 2, 025212

Single and double spin asymmetries for DVCS on proton target

$GPDs$ "F"

$H, \tilde{H}, E, \tilde{E}$

$ep \rightarrow ep\gamma$



$F(x, \xi, t)$

- x longitudinal quark momentum fraction
- 2ξ longitudinal momentum transfer to the struck quark
- t momentum transfer to the nucleon

$$\xi = x_B \frac{1 + \frac{t}{Q^2}}{2 - x_B + x_B \frac{t}{Q^2}}$$

$$t = (p - p')^2$$

Compton Form Factors: 8 GPDs related quantities

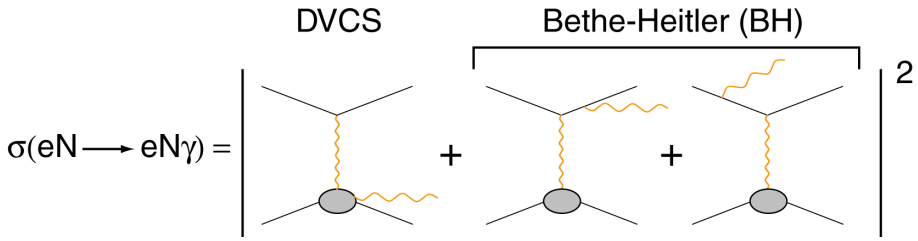
$$\Re\mathrm{e}\mathcal{F} = \mathcal{P} \int_{-1}^{1} dx \left[\frac{1}{x - \xi} \mp \frac{1}{x + \xi} \right] F(x, \xi, t)$$

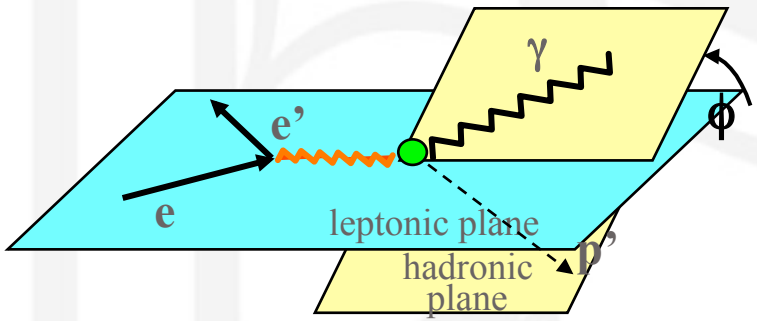
$$\Im\mathrm{m}\mathcal{F} = \pi \left[F(\xi, \xi, t) \mp F(-\xi, \xi, t) \right]$$

Fairfield UNIVERSITY

DVCS Polarization observables

Asymmetries ∝ interference BH & DVCS





Beam Spin Asymmetry A_{LU}

$$A_{\mathrm{LU}}(\phi) \propto \Im\mathrm{m}[F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}]\sin\phi$$

Target Spin Asymmetry A_{UL}

$$A_{\mathrm{UL}}(\phi) \propto \Im\mathrm{m}[F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + \frac{x_B}{2}\mathcal{E}) - \xi(\frac{x_B}{2}F_1 + \frac{t}{4M^2}F_2)\widetilde{\mathcal{E}}]\sin\phi$$

Double Spin Asymmetry A_{LL}

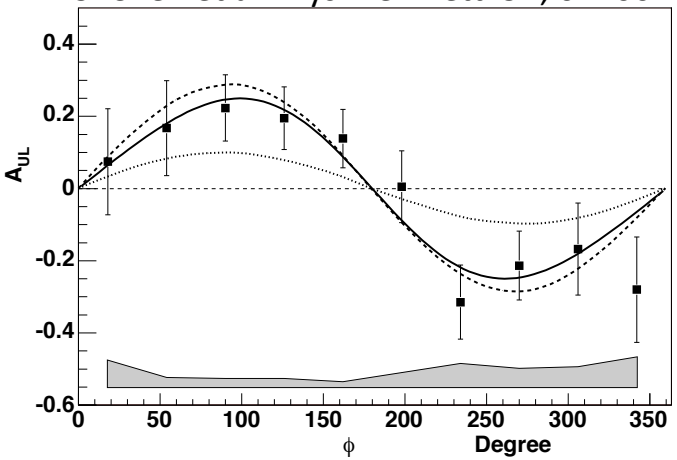
$$A_{\mathrm{LL}}(\phi) \propto \Re\mathrm{e}[F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + \frac{x_B}{2}\mathcal{E}) - \xi(\frac{x_B}{2}F_1 + \frac{t}{4M^2}F_2)\widetilde{\mathcal{E}}](A + B\cos\phi)$$

Fairfield UNIVERSITY

eg1-DVCS highlights

- **High statistics**, improvement of a factor 10 over previous target asymmetry measurement (S. Chen et al)
- Complete detection of the final state ->small nuclear background
- Large kinematic range
- **Simultaneous measurement of all three Beam, Target, and Double spin asymmetries in the same kinematic range**
  - simultaneous fit
  - Compton Form Factors

S. Chen et al Phys. Rev. Lett. 97, 072002

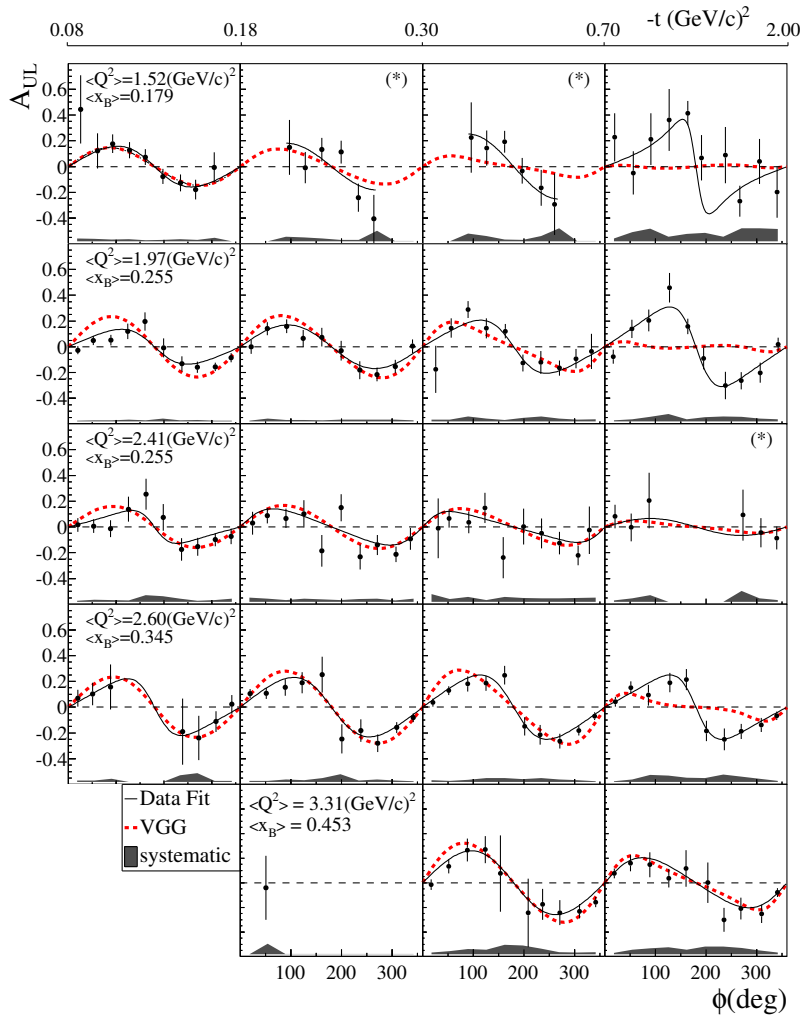


Observable	*Sensitivity to CFFs*	*Experiment*	*Notes*
$\Delta\sigma_{beam}(p)$	Im $\mathcal{H}_p$	Hall A	High statistics, limited coverage, 4 dimensional
$A_{LU}(p)$	Im $\mathcal{H}_p$	HERMES CLAS	High statistics and coverage, 4 dimensional
$\Delta\sigma_{beam}(n)$	Im $\mathcal{E}_n$	Hall A	One (Q^2,x_b) bin, 7 -t bins, low statistics, high
$A_{UL}(p)$	Im $\tilde{\mathcal{H}}_p$,Im $\mathcal{H}_p$	HERMES CLAS	Low statistics integrated over 3/4 variables
$A_{LL}(p)$	Re $\tilde{\mathcal{H}}_p$,Re $\mathcal{H}_p$	HERMES	Low statistics integrated over 3/4 variables
$A_{UT}(p)$	Im $\mathcal{H}_p$,Im $\mathcal{E}_p$	HERMES	Low statistics integrated over 3/4 variables

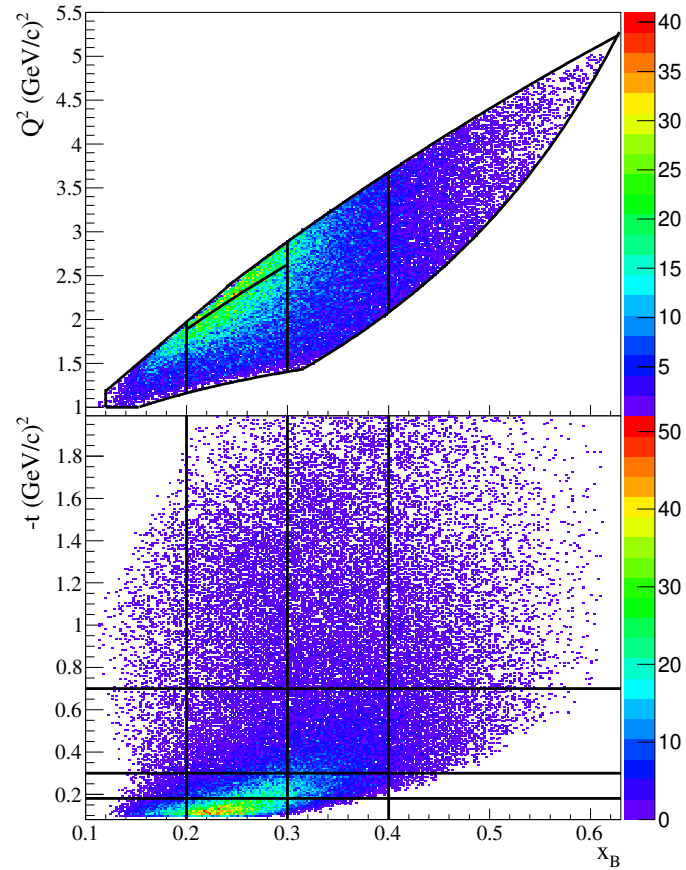
Fairfield UNIVERSITY

Target Spin Asymmetries for DVCS

E. Seder et al Phys. Rev. Lett. 114 (2015) 032001



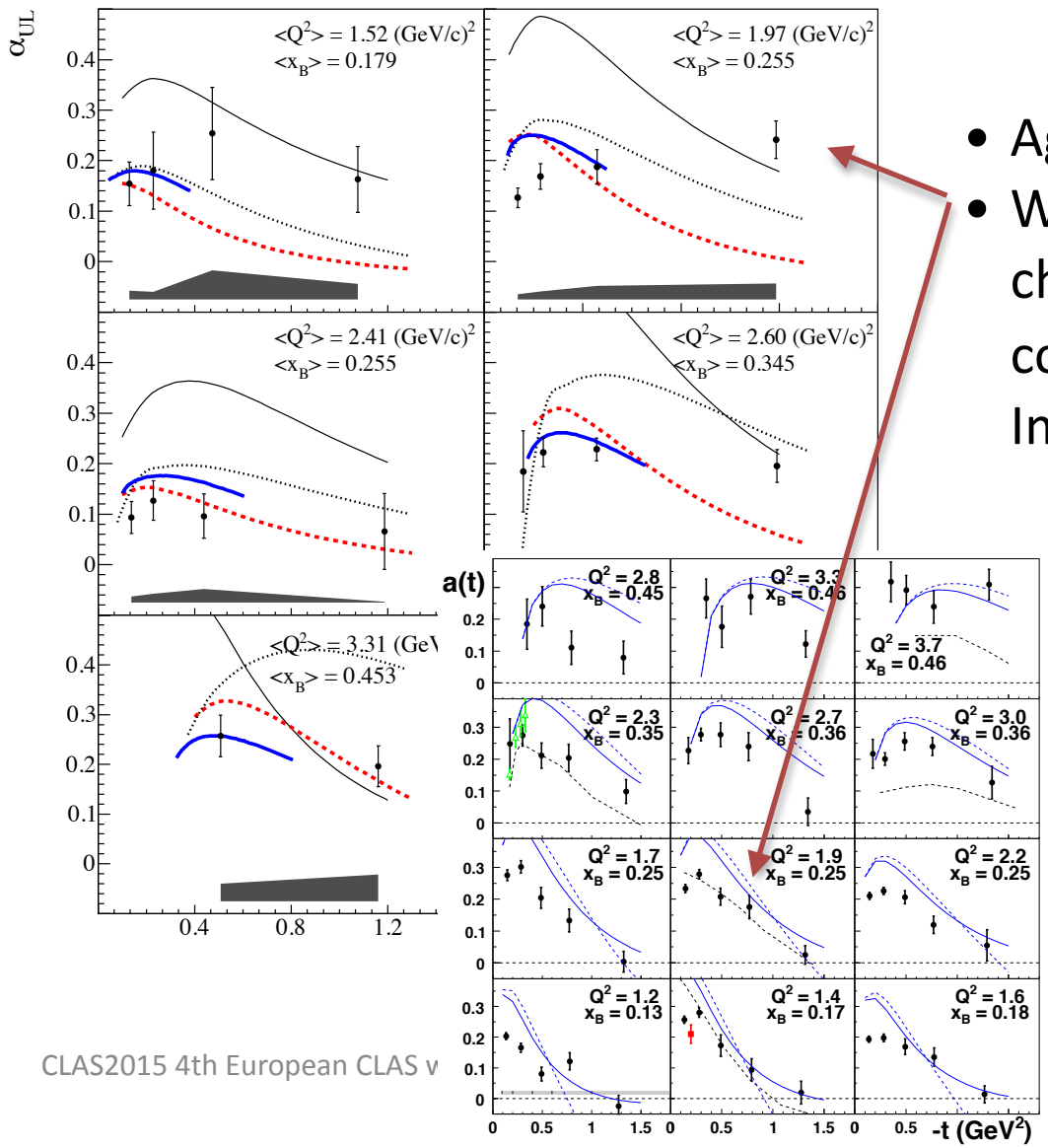
5 (Q^2,x_b) bins x 4 -t bins



Fairfield UNIVERSITY

Target Spin Asymmetries for DVCS

E. Seder et al Phys. Rev. Lett. 114 (2015) 032001



$$A_{UL} = \frac{\alpha_{UL} \sin\phi}{1 + \beta \cos\phi}$$

- Agreement with Hermes & CLAS
- Weaker drop in -t than A_{UL} ⇨Axial charge Im$\tilde{\mathcal{H}}$ ⇔ A_{LU} is more concentrated than electric charge Im$\mathcal{H}$ ⇔ A_{LU}
  - Qualitative agreement VGG & GK low t
  - Good agreement KMM12 but $t<Q^2/4$

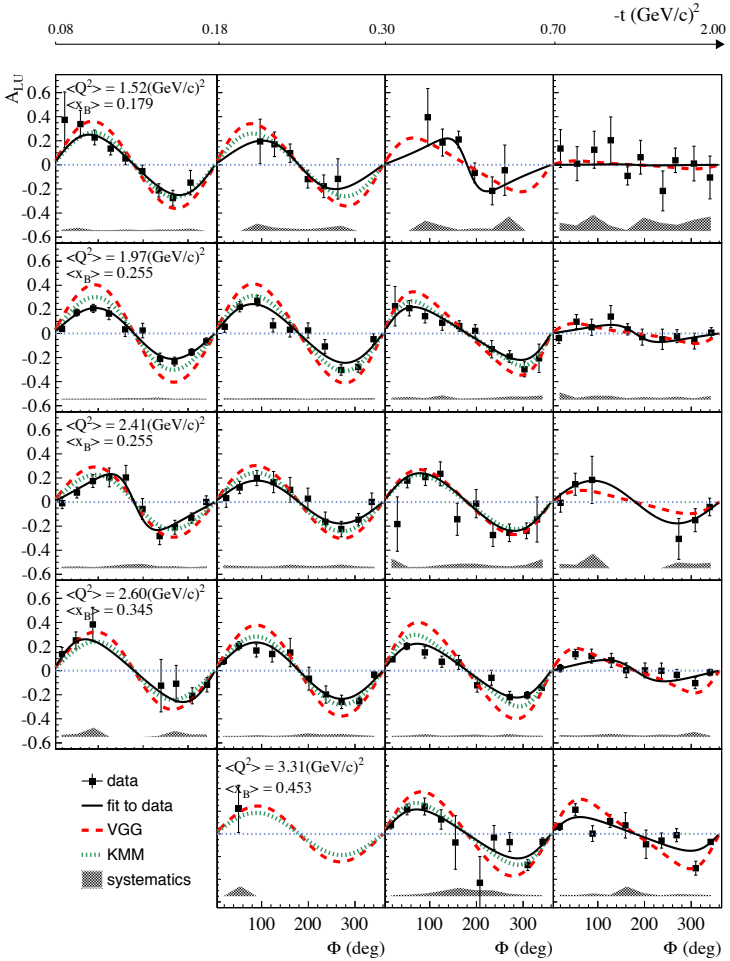
Models

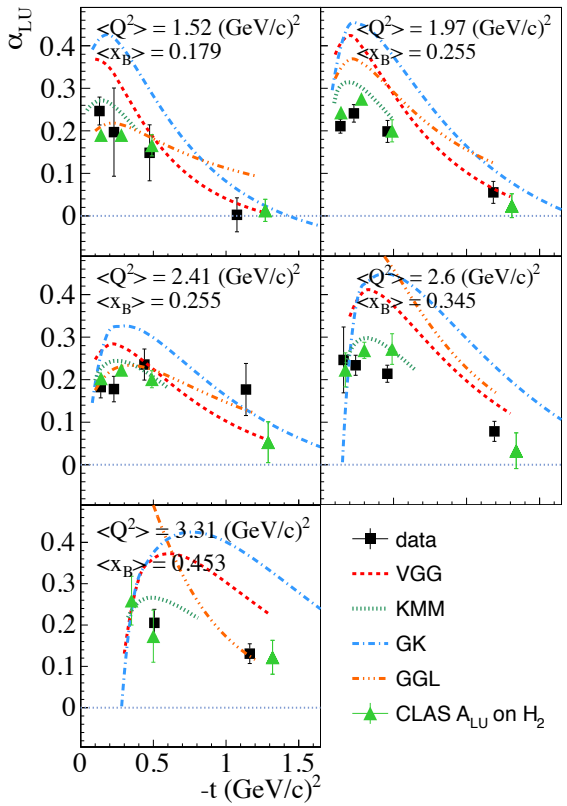
- - - VGG Vanderhaeghen, Guidal, Guichon
- .... GK Goloskokov, Kroll
- — KMM12 Kumericki, Müller, Murray
- — GGL Gonzalez, Goldstein, Liuti

Fairfield UNIVERSITY

Beam Spin Asymmetries for DVCS

S. Pisano *et al* arXiv:1501.07052 - PRD Accepted





- Agreement with CLAS on H_2
- No sensitivity to nuclear effects
- Sensitivity to Im $\mathcal{H}_p$
- Fast drop in -t
- Good agreement KMM12 but $t<Q^2/4$
- Good agreement GL in some bins
- VGG & GK overestimate

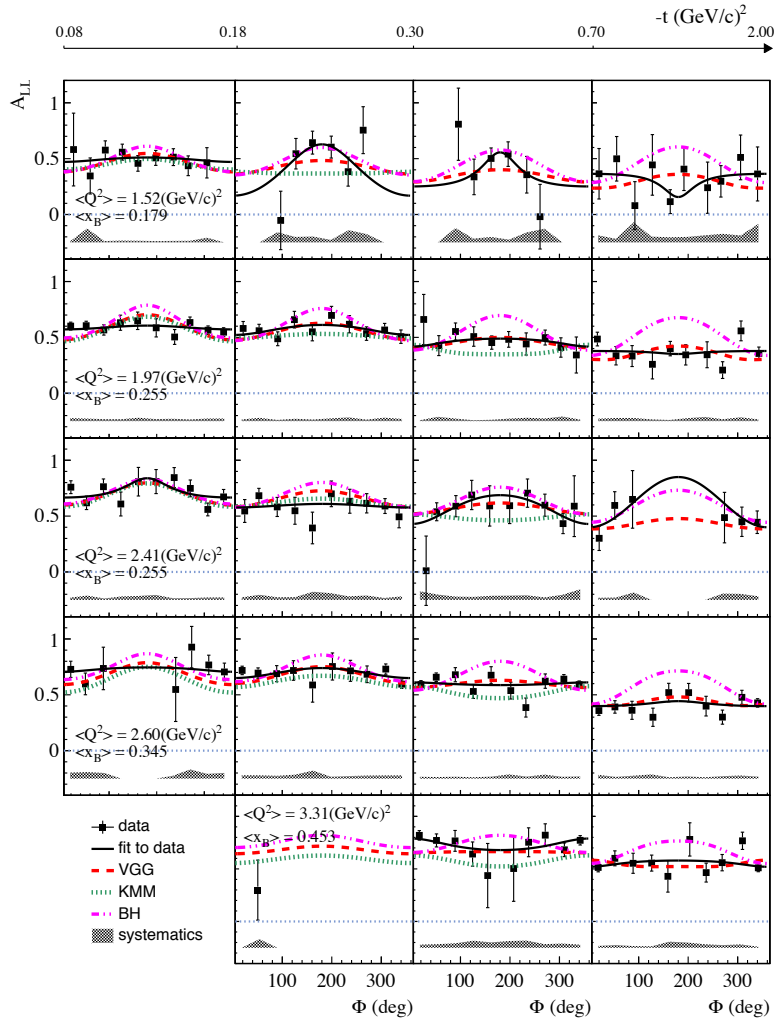
$$A_{LU} = \frac{\alpha_{LU} \sin\phi}{1 + \beta\cos\phi}$$

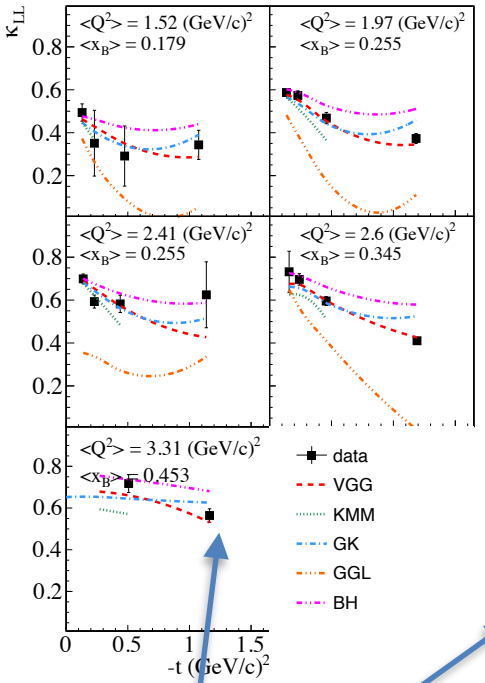
Fairfield UNIVERSITY

Double Spin Asymmetries for DVCS

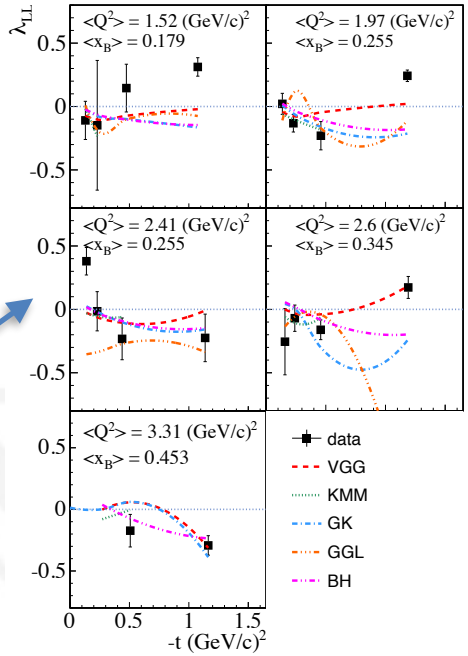
S. Pisano *et al* arXiv:1501.07052 - PRD Accepted

- Constant term dominated by BH
- cosϕ term small and dominated by BH
- Agreement with VGG, GK, KMM



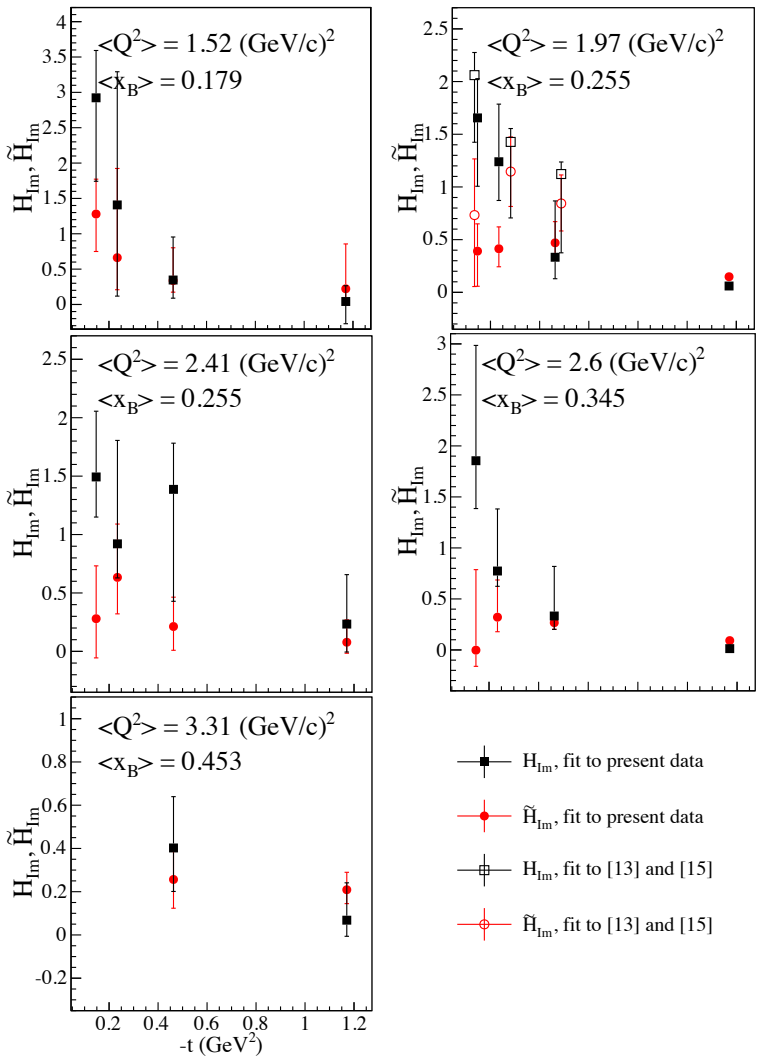


$$A_{LL} = \frac{k_{LL} + \lambda_{LL}\cos\phi}{1 + \beta\cos\phi}$$



Compton Form Factors

S. Pisano *et al* arXiv:1501.07052 - PRD Accepted



- M. Guidal, Eur. Phys. J. A 37, 319 (2008)
- Local fitting at each experimental Q^2,x_B,t
- Quasi model-independent: bounding the domains of variation of the CFFs (5xVGG)
- 8 unknowns, non linear problem, strong correlations

- Mostly sensitive to Im$\tilde{\mathcal{H}}$
- Im$\mathcal{H}$ has a steeper slope than Im$\tilde{\mathcal{H}}$ - axial charge more concentrated?
- Slope of Im$\mathcal{H}$ decreasing as x_b increases - fast quarks (valence) more concentrated in the nucleon's center, slow quarks (sea) more spread out
- Not enough A_{LL} statistical precision to extract real parts Re$\tilde{\mathcal{H}}$ Re$\tilde{\mathcal{E}}$

Fairfield UNIVERSITY

DVCS Beam and Target spin asymmetries on the neutron target

D. Sokhan

$$en \rightarrow en\gamma$$

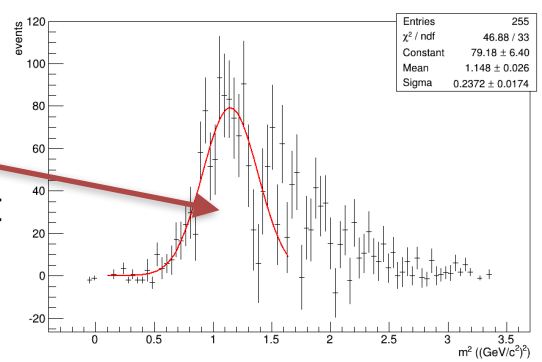
- Pioneering CLAS measurement
- nDVCS important for flavor separation

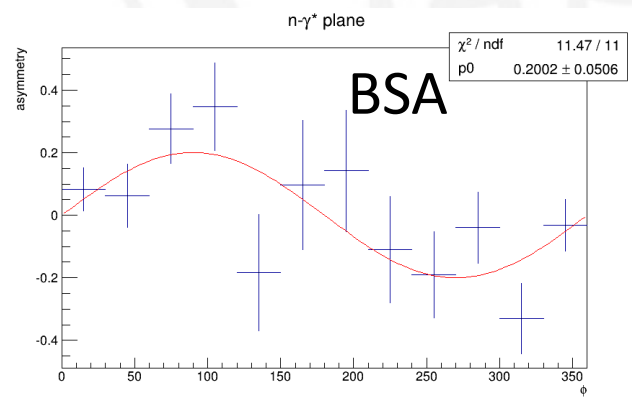
$$(H,E)_u(\xi,\xi,t) = 9/15[4(H,E)_p(\xi,\xi,t) - (H,E)_n(\xi,\xi,t)]$$
$$(H,E)_d(\xi,\xi,t) = 9/15[4(H,E)_n(\xi,\xi,t) - (H,E)_p(\xi,\xi,t)]$$

- A_{LU} on neutron needed to constrain E_n, together with E_p (from A_{UT}) and $H_{p,n}$ we can extract the quark angular momentum (Ji's sum rule)

$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^{+1} xdx[H^q(x,\xi,0) + E^q(x,\xi,0)]$$

nDVCS selection cut



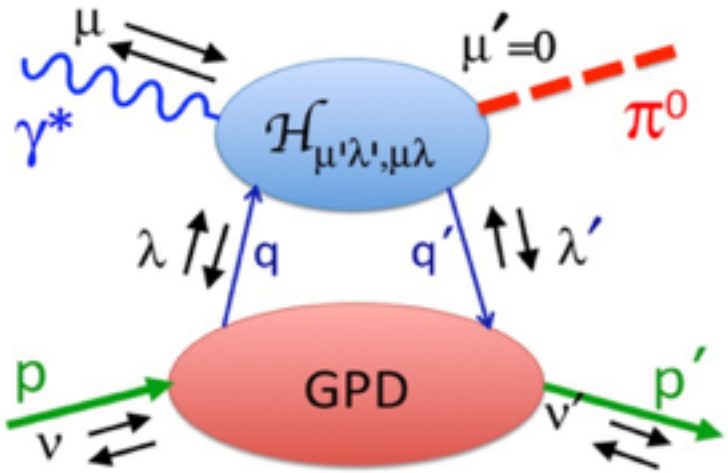


Fairfield UNIVERSITY

Single and Double Spin Asymmetries for Deeply Virtual Exclusive π^0

A. Kim

$$ep \rightarrow ep\pi^0$$



$8\ GPDs$ "F"

$H^q, \tilde{H}^q, E^q, \tilde{E}^q$ parton helicity-conserving (chiral- even)

$H^q_T, \tilde{H}^q_T, E^q_T, \tilde{E}^q_T$ parton helicity-flip (chiral-odd)

For the π^0

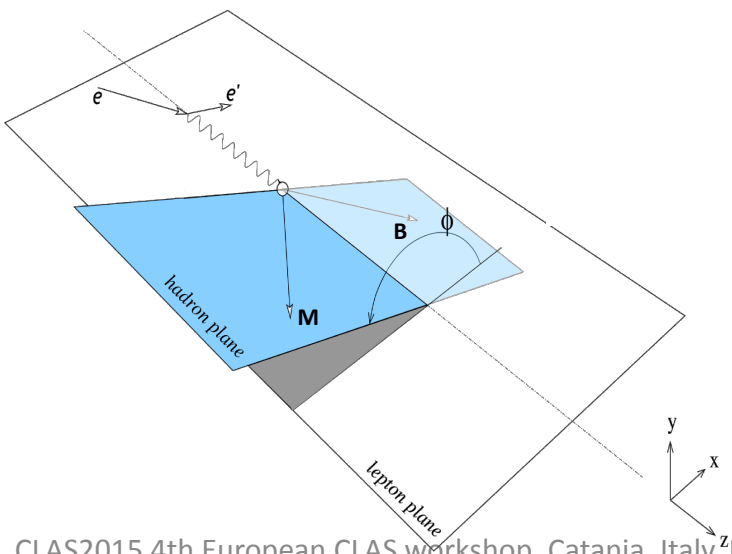
$$F_i^{\pi^0} = (e_u F_i^u - e_d F_i^d)/\sqrt{2}$$

Fairfield UNIVERSITY

Single and Double Spin Asymmetries for Deeply Virtual Exclusive π^0

A. Kim

$$\frac{2\pi}{\Gamma}\frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} = \sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT}\cos 2\phi + \sqrt{\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi$$
$$+P_b\sqrt{\epsilon(1-\epsilon)}\sigma_{LT'}\sin\phi$$
$$+P_t(\sqrt{\epsilon(1+\epsilon)}\sigma_{UL}^{\sin\phi}\sin\phi + \epsilon\sigma_{UL}^{\sin 2\phi}\sin 2\phi)$$
$$+P_b P_t(\sqrt{1-\epsilon^2}\sigma_{LL} + \sqrt{\epsilon(1-\epsilon)}\sigma_{LL}^{\cos\phi}\cos\phi)$$

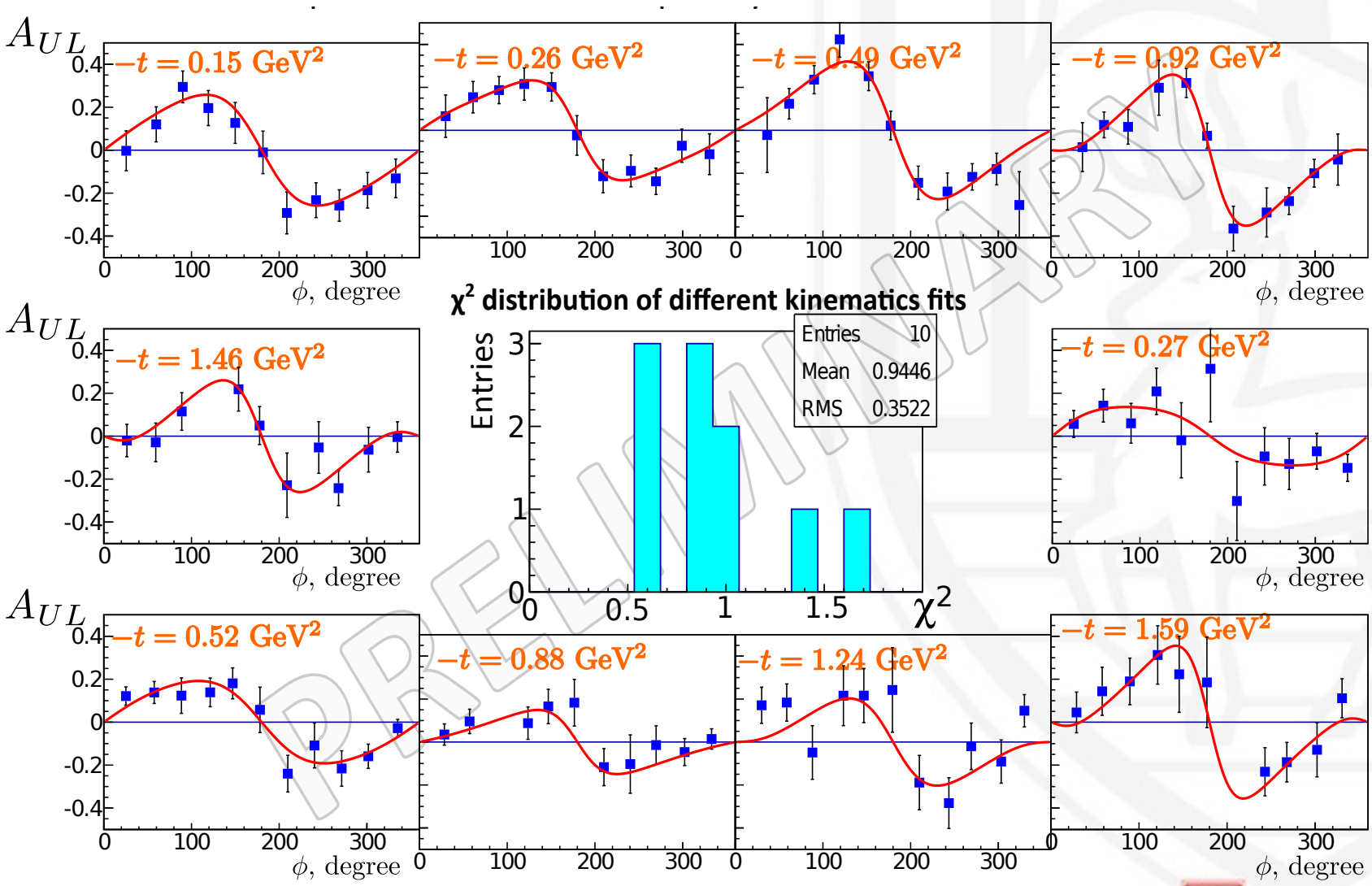


$$\langle F\rangle = \sum_\lambda \int_{-1}^{1} dx \mathcal{H}_{0\lambda,\mu\lambda}(x,\xi,Q^2,t)F(x,\xi,t)$$

$$A_{LU}^{\sin\phi}\sigma_0 \sim \mathrm{Im}[\langle H_T\rangle * \langle\tilde{E}\rangle]$$
$$A_{UL}^{\sin\phi}\sigma_0 \sim \mathrm{Im}[\langle\bar{E}_T\rangle * \langle\tilde{H}\rangle + \xi\langle H_T\rangle * \langle\tilde{E}\rangle]$$
$$A_{LL}^{const}\sigma_0 \sim |\langle\bar{H}_T\rangle|^2$$
$$A_{LL}^{\cos\phi}\sigma_0 \sim \mathrm{Re}[\langle\bar{E}_T\rangle * \langle\tilde{H}\rangle + \xi\langle H_T\rangle * \langle\tilde{E}\rangle]$$

Target Spin Asymmetries for ep->epπ^0

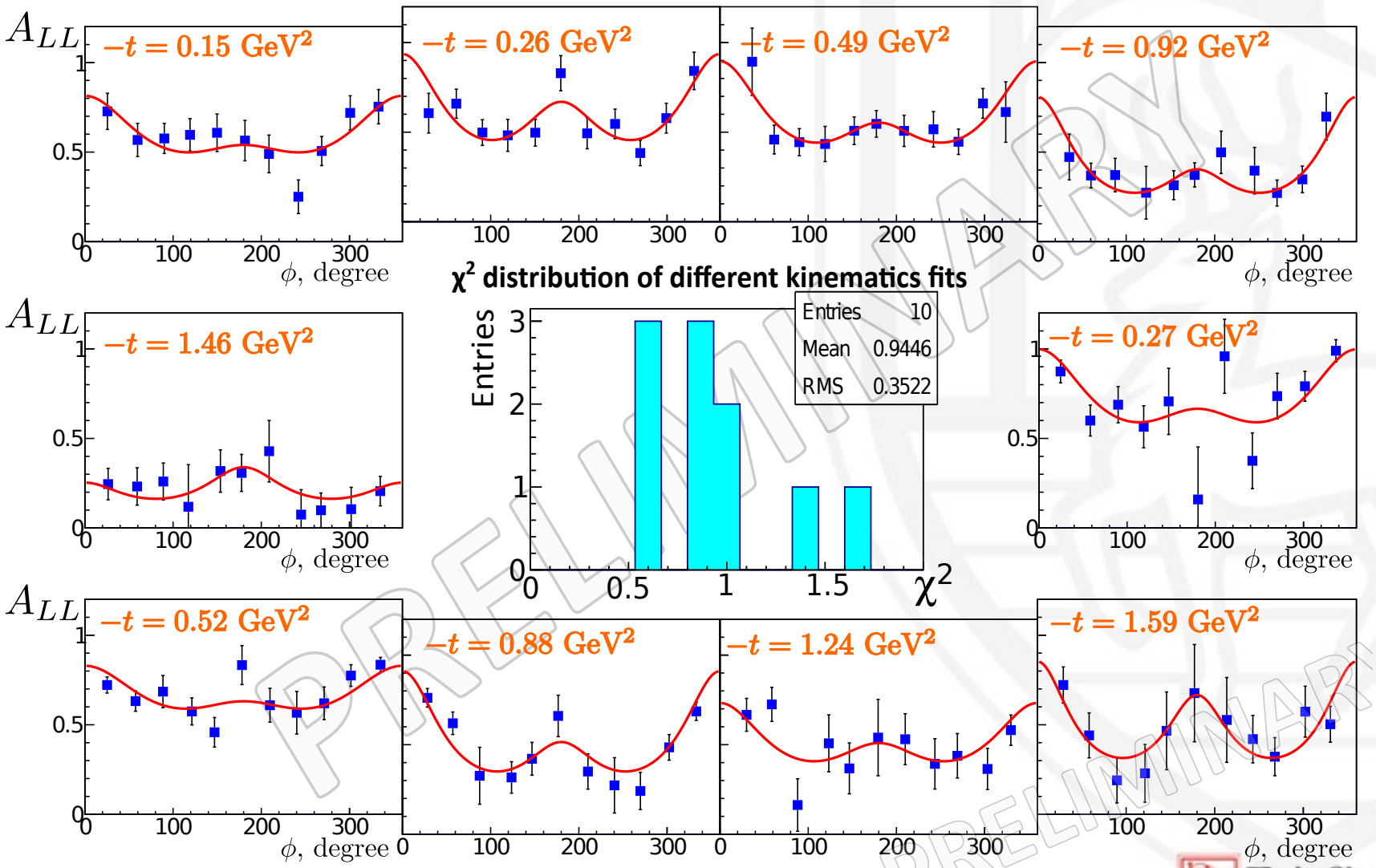
A. Kim



Fairfield UNIVERSITY

Double Spin Asymmetries for ep->epπ^0

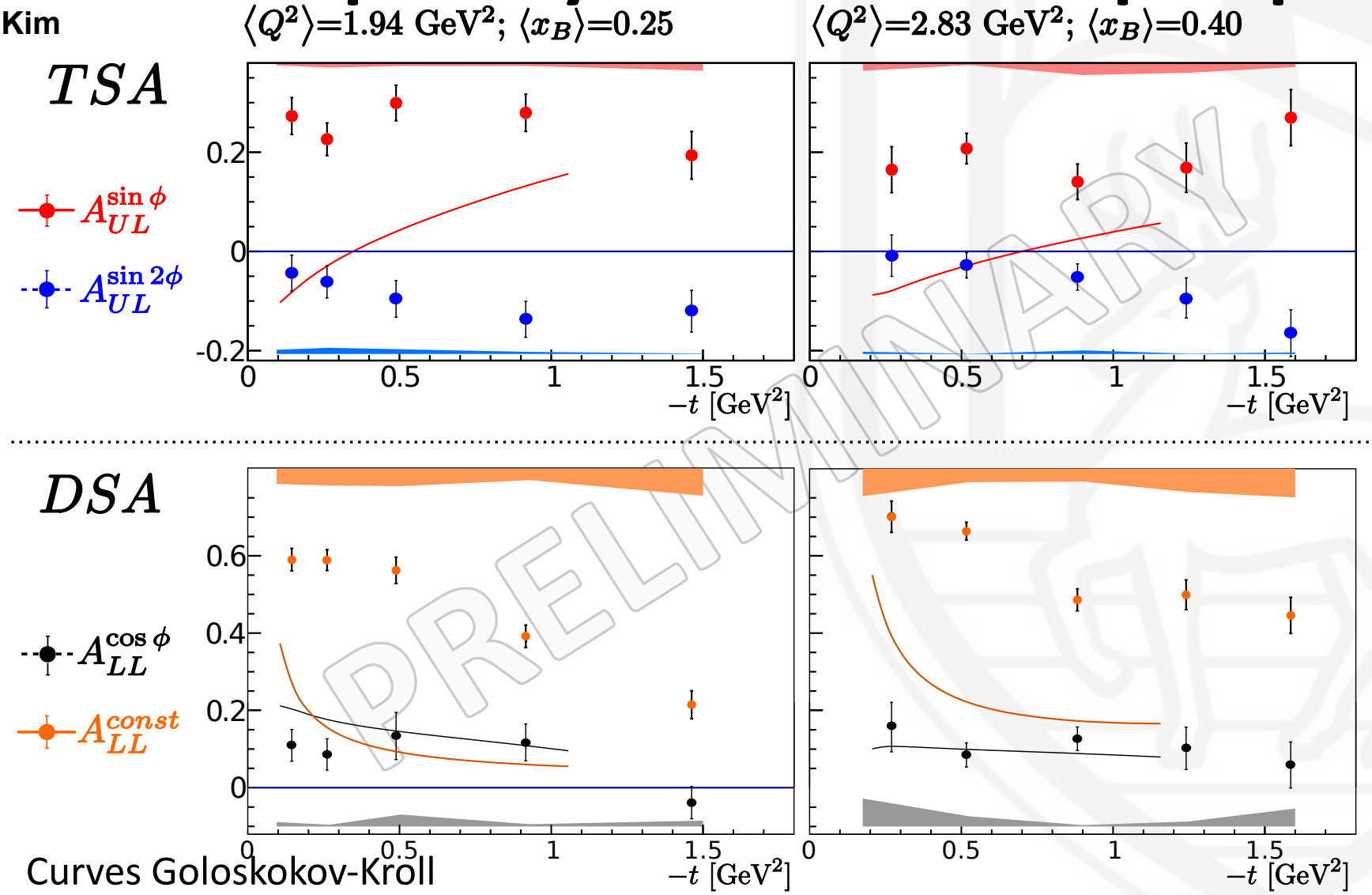
A. Kim



Fairfield UNIVERSITY

Double Spin Asymmetries for ep->epπ^0

A. Kim



Curves Goloskokov-Kroll

Fairfield UNIVERSITY

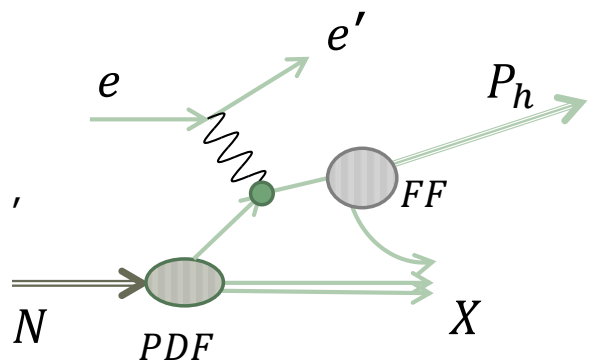
Measurement of Single and Double Spin Asymmetries in Semi-Inclusive DIS

S. Koirala

$$eN \rightarrow e\pi X$$

Leading twist TMD

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



FF

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

$$A_{UL} = \frac{1}{fP_t}\frac{N^+ - N^-}{N^+ + N^-} \propto A_{UL}^{\sin\phi}\sin\phi + A_{UL}^{\sin 2\phi}\sin 2\phi$$

$$A_{LL} = \frac{1}{fD'(y)P_bP_t}\frac{N^+ - N^-}{N^+ + N^-} \propto \frac{g_1 \otimes D_1}{f_1 \otimes D_1}$$

g_1 well known from the collinear case (DIS), its $P_{h\perp}$ dependence only recently explored

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

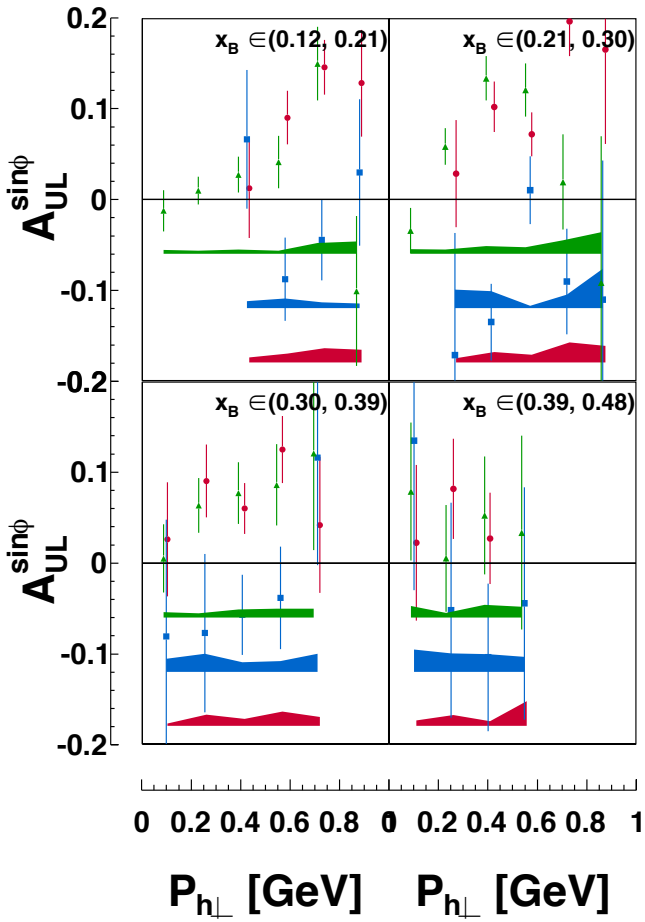
- only term at LEADING ORDER
- involves $h_{1L}^{\perp} \otimes H_1^{\perp}$
- @ Hermes ~ zero
- related to transverse polarization of quarks in the longitudinal target
- Non-zero in CLAS (Avakian PRL 105, 262002 (2010)

Fairfield UNIVERSITY

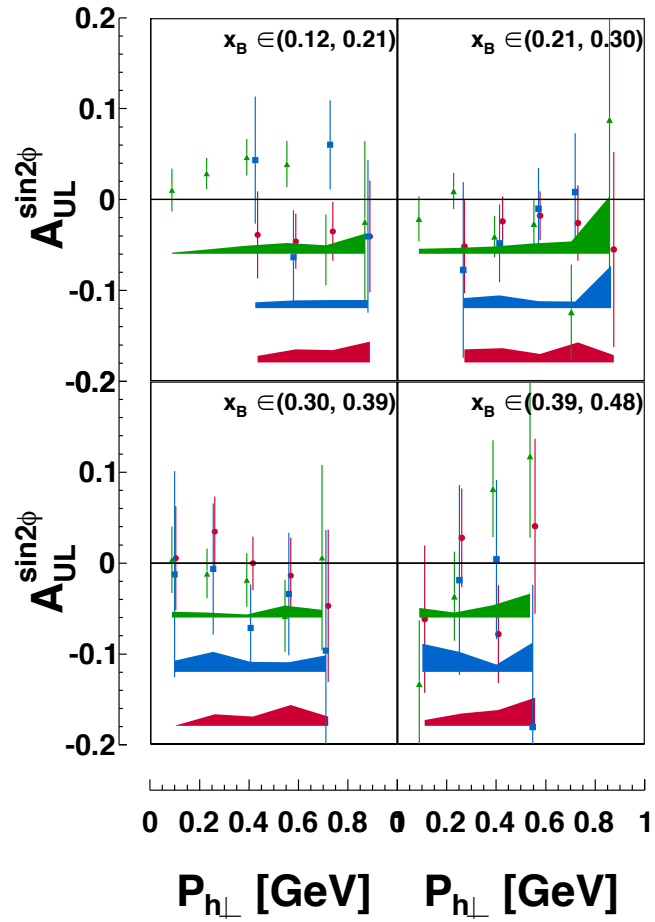
Target Spin Asymmetries for ep->eπX

S. Koirala

$\pi^+ \pi^- \pi^0$



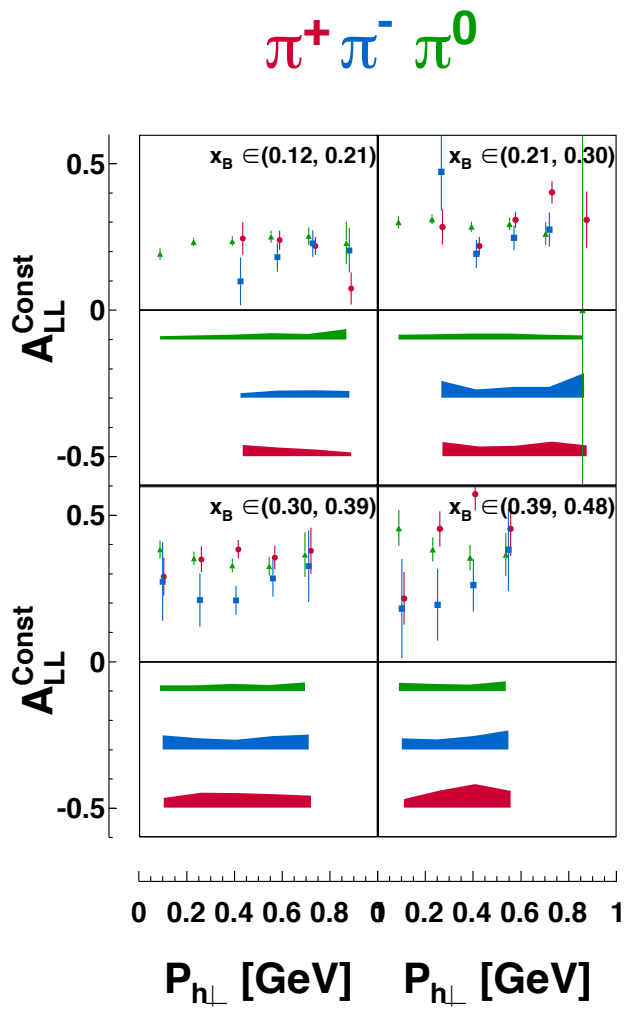
$\pi^+ \pi^- \pi^0$

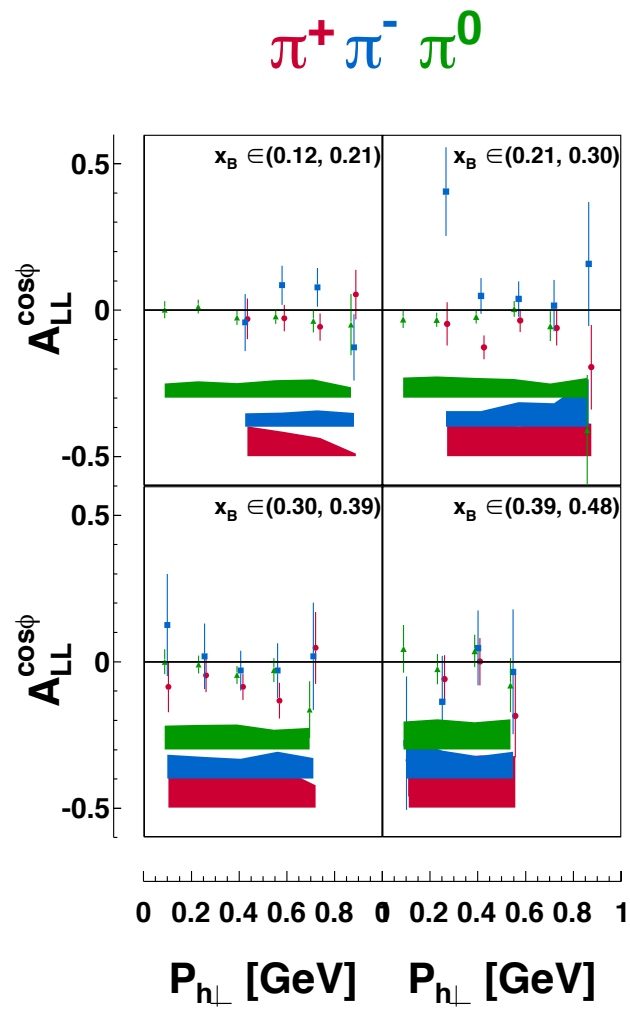


Fairfield UNIVERSITY

Double Spin Asymmetries for ep->eπX

S. Koirala





Fairfield UNIVERSITY

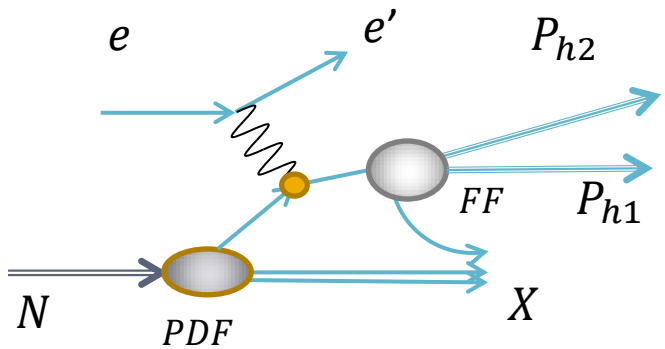
Target and beam spin asymmetries for di-hadron production

S Anefalos Pereira

Higher-twist PDF

q/H	U	L	T
U	$f_1(x)$		$e(x)$
L		$g_1(x)$	$h_L(x)$
T		$g_T(x)$	$h_1(x)$

$$ep \rightarrow e\pi^+\pi^- X$$



DiFF

$\tilde{H}_1^{\sphericalangle q}$ chiral-odd interference fragmentation function

extracted by the Belle Collaboration from e^+/e^- data PRD 85, 114023 (2012)

Experimental status

- $f_1(x)$,$g_1(x)$, and $g_T(x)$ measured through DIS
- $h_1(x)$: transversity distribution - chiral odd. Can be accessed only with Semi-Inclusive DIS
- $e(x)$, and $h_L(x)$ still unknown

Fairfield UNIVERSITY

Target and beam spin asymmetries for di-hadron production

S Anefalos Pereira

$$ep \to e\pi^+\pi^- X$$

Accessing higher twist PDFs with polarization experiments

$$F_{UU,T} = x f_1^q(x) D_1^q(z, \cos\theta, M_h)$$

$$F_{UU}^{\cos\phi_R} = -x \frac{|\mathbf{R}| \sin\theta}{Q} \frac{1}{z} f_1^q(x) \tilde{D}^{\sphericalangle q}(z, \cos\theta, M_h)$$

$$F_{LU}^{\sin\phi_R} = -x \frac{|\mathbf{R}| \sin\theta}{Q} \left[\frac{M}{M_h} x e^q(x) \tilde{H}_1^{\sphericalangle q}(z, \cos\theta, M_h) + \frac{1}{z} f_1^q(x) \tilde{G}^{\sphericalangle q}(z, \cos\theta, M_h) \right]$$

$$F_{UL}^{\sin\phi_R} = -x \frac{|\mathbf{R}| \sin\theta}{Q} \left[\frac{M}{M_h} x h_L^q(x) \tilde{H}_1^{\sphericalangle q}(z, \cos\theta, M_h) + \frac{1}{z} g_1^q(x) \tilde{G}^{\sphericalangle q}(z, \cos\theta, M_h) \right]$$

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

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

~0 in the Wandzura-Wilczek approx

Beam Asymmetry

Target Asymmetry

Double Spin Asymmetry

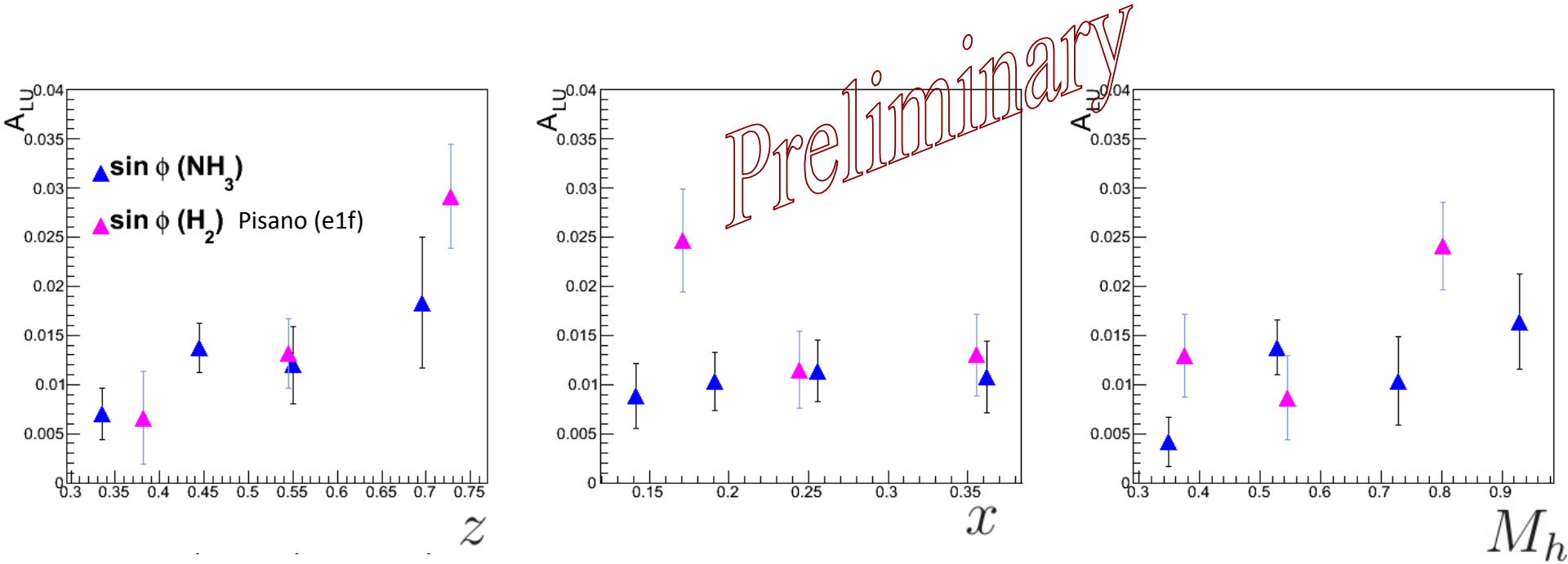
e(x) and $h_L(x)$

- related to quark-gluon correlations
- e(x) x-integral related to scalar-charge of the nucleon
- $h_L(x)$ x-integral related to the nucleon tensor charge

Fairfield UNIVERSITY

Results beam asymmetry for ep->eπ⁺π⁻X

S Anefalos Pereira



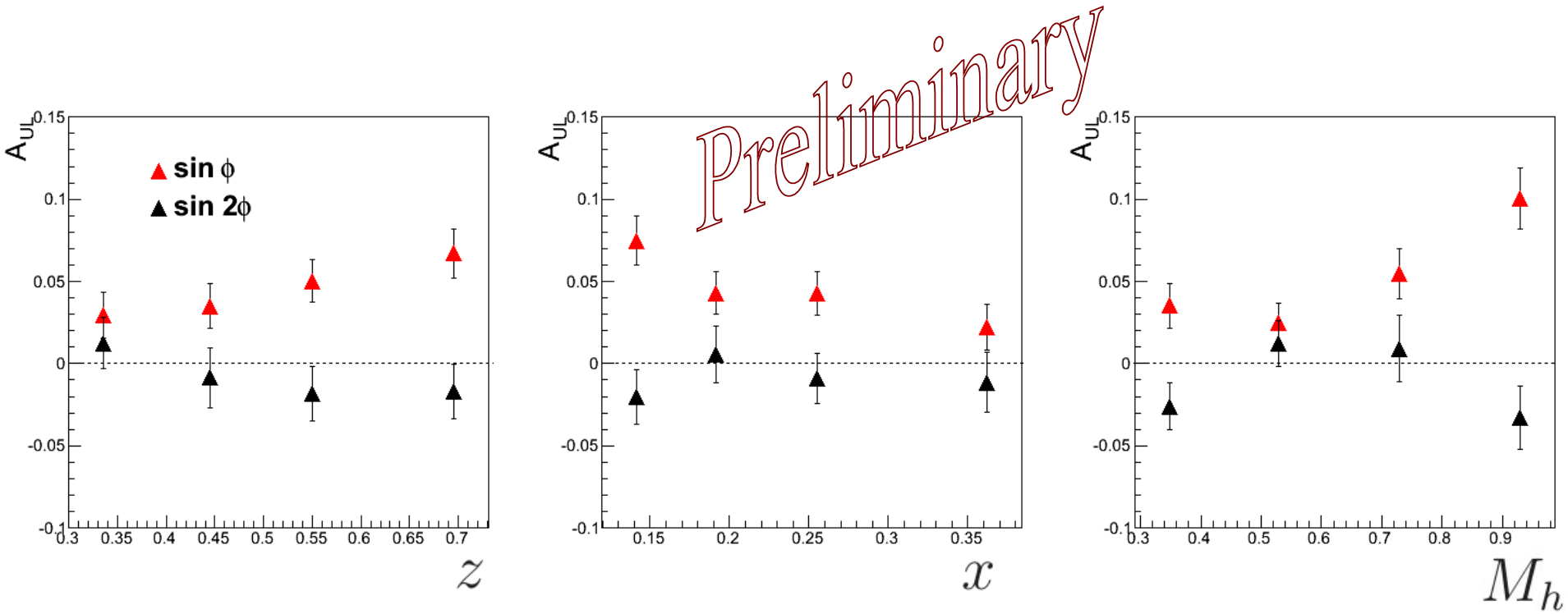
- Significant non-zero asymmetry
- Agreement with e1f analysis (Pisano)

$$A_{LU} \propto e^q(x)\tilde{H}_1^{\sphericalangle q}(z, \cos\theta, M_h)$$

Fairfield UNIVERSITY

Results target asymmetry for ep->eπ⁺π⁻X

S Anefalos Pereira



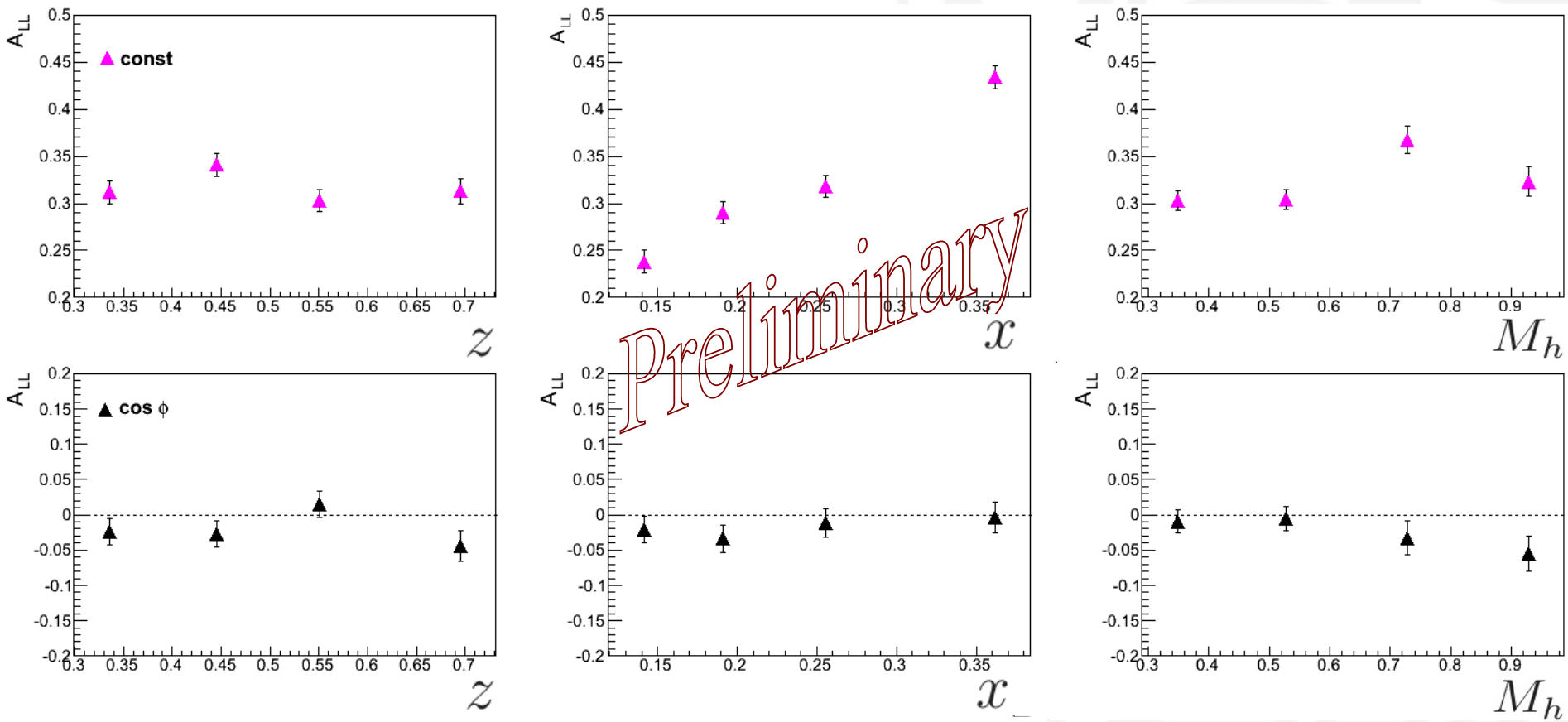
- Non zero sinϕ
- sin 2ϕ compatible with zero

$$A_{UL} \propto h_L^q(x)\tilde{H}_1^{\sphericalangle q}(z, \cos\theta, M_h)$$

Fairfield UNIVERSITY

Results double spin asymmetry for ep->eπ⁺π⁻X

S Anefalos Pereira



- Non zero const term

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

$$A_{LL}^{\cos\phi_R} \propto g_1^q(x) \tilde{D}_1{}^{\sphericalangle q}(z, \cos\theta, M_h)$$

Fairfield UNIVERSITY

Precision measurements of g_1 of the proton and the deuteron with 6 GeV

Y. Prok et al Phys.Rev. C90 (2014) 2, 025212

$$eN \rightarrow eX$$

$$\frac{d\sigma^{\uparrow\Downarrow/\uparrow\Uparrow}}{d\Omega dE'} = \sigma_M \left[\frac{F_2}{\nu} + 2\tan^2\frac{\theta}{2}\frac{F_1}{M} \pm 2\tan^2\frac{\theta}{2}\left(\frac{E_0 + E'\cos\theta}{M\nu} g_1 - \frac{Q^2}{M\nu^2} g_2\right)\right]$$

F_1, F_2 unpolarized structure functions

g_1, g_2 polarized structure functions

$$A_{||}(\nu, Q^2, y) = \frac{d\sigma^{\uparrow\Downarrow} - d\sigma^{\uparrow\Uparrow}}{d\sigma^{\uparrow\Downarrow} + d\sigma^{\uparrow\Uparrow}}$$

$$\frac{g_1}{F_1} = \frac{A_{||}}{D'} C_{g_2}$$

$g_1 \Leftrightarrow$ quark Δq, antiquark $\Delta\bar{q}$ and gluon ΔG

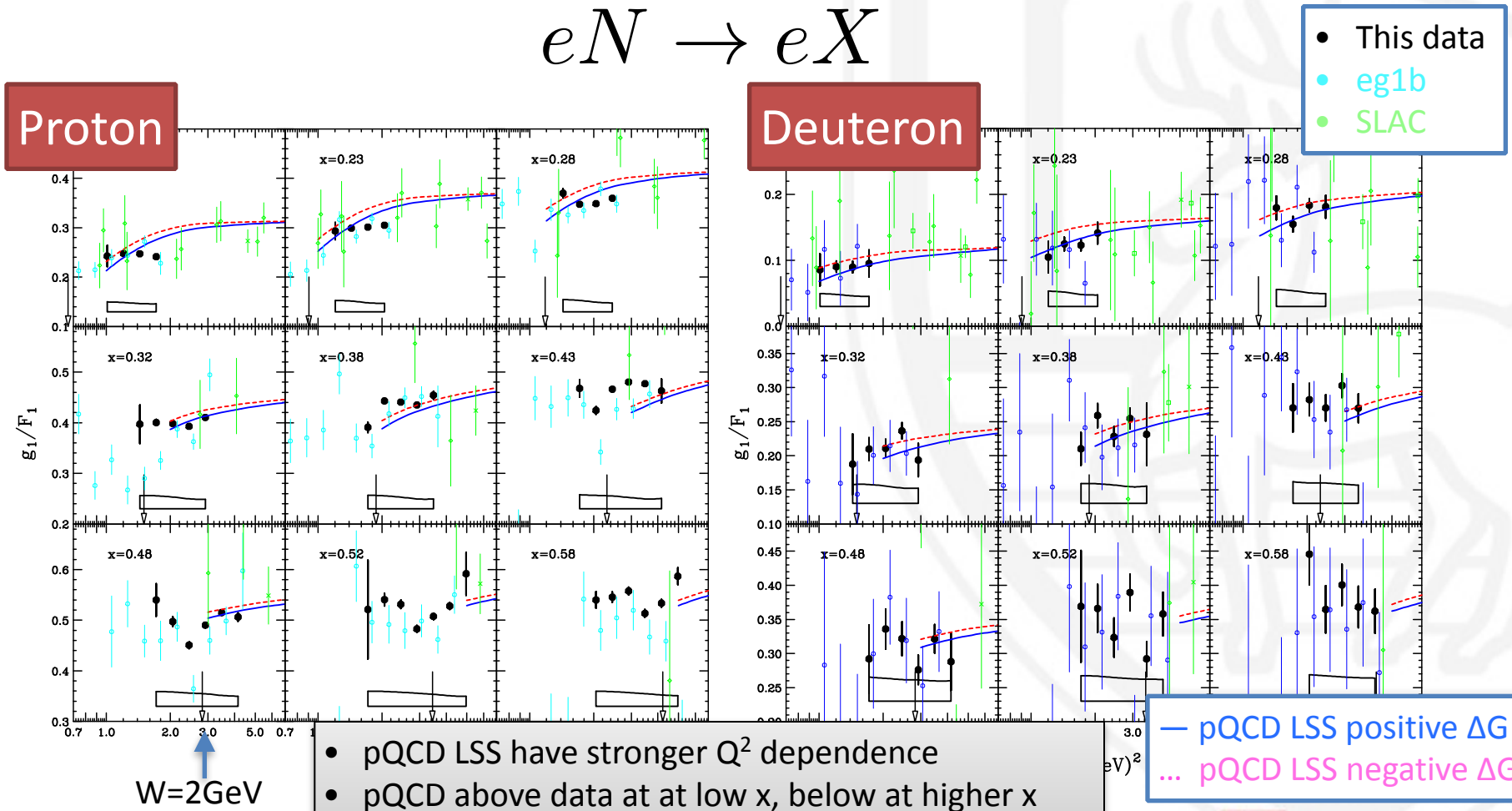
$$g_1(x, Q^2)_{pQCD} = \frac{1}{2}\sum e_q^2 \left[(\Delta q + \Delta\bar{q}) \otimes \left(1 + \frac{\alpha_s(Q^2)}{2\pi}\delta C_q\right) + \frac{\alpha_s(Q^2)}{2\pi}\Delta G \otimes \frac{\delta C_G}{N_f}\right]$$

Fairfield UNIVERSITY

Precision measurements of g_1 of the proton and the deuteron with 6 GeV

Y. Prok et al Phys.Rev. C90 (2014) 2, 025212

$$eN \rightarrow eX$$



- pQCD LSS have stronger Q^2 dependence
- pQCD above data at at low x, below at higher x
- new global fit will constrain higher twist correction and improve ΔG

Fairfield UNIVERSITY

Spin Asymmetries in exclusive π^+, π^0, η, and π^- electro-production

P. Bosted

topology	final state particles
$ep \to e\pi^+ n$	electron, π^+, neutron
$ep \to e\gamma\gamma(\pi^0)p$	electron, two photons, proton
$ep \to e\gamma\gamma(\eta)p$	electron, two photons, proton
$en \to e\pi^- p$	electron, π^-, proton
$ep \to e\pi^+(n)$	electron, π^+
$ep \to e\gamma(\pi^0)p$	electron, one photon, proton
$ep \to e\gamma(\eta)p$	electron, one photon, proton
$en \to e\pi^-(p)$	electron, π^-
$ep \to e\gamma\gamma(\pi^0)(p)$	electron, two photons
$ep \to e\gamma\gamma(\eta)(p)$	electron, two photons

- Comprehensive study of exclusive meson production
- Resonance region
- Main motivation: global fit for radiative to semi-inclusive meson production
- Topologies combined to maximize statistics
- Kinematic range:
  - 1.1 < W <3 GeV
  - 1 < Q^2< 6 GeV^2

$$\sigma = \sigma_0(1 + P_b A_{LU} + P_t A_{UL} + P_b P_t A_{LL})$$

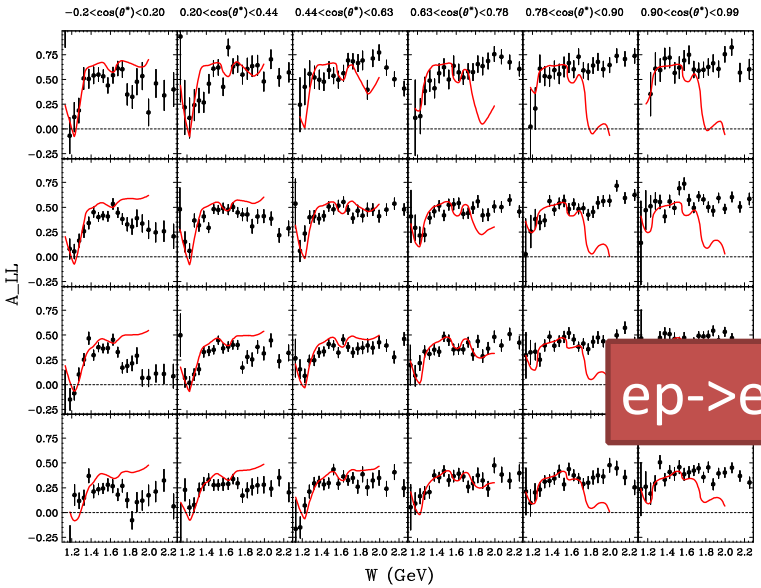
Fairfield UNIVERSITY

Double Spin Asymmetry results

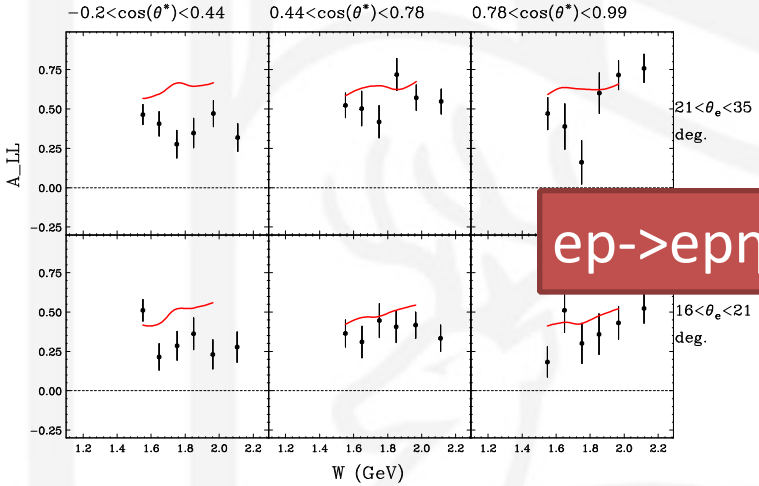
Averaged over ϕ^*

P. Bosted

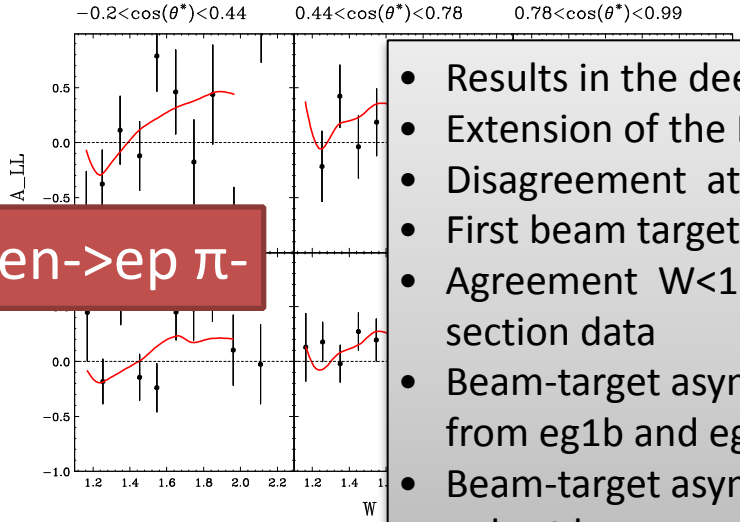
—Maid 2007



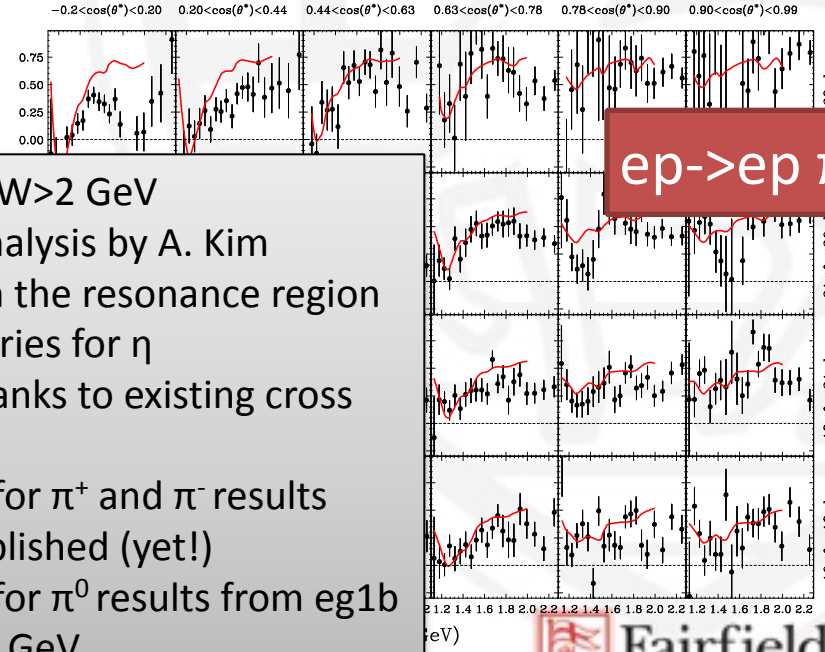
ep->en π^+



ep->epη



en->ep π-



ep->ep π^0

- Results in the deep region W>2 GeV
- Extension of the DV π^0 P analysis by A. Kim
- Disagreement at high W in the resonance region
- First beam target asymmetries for η
- Agreement W<1.5 GeV thanks to existing cross section data
- Beam-target asymmetries for π^+ and π^- results from eg1b and eg4 not published (yet!)
- Beam-target asymmetries for π^0 results from eg1b only at beam energy of 1.6 GeV

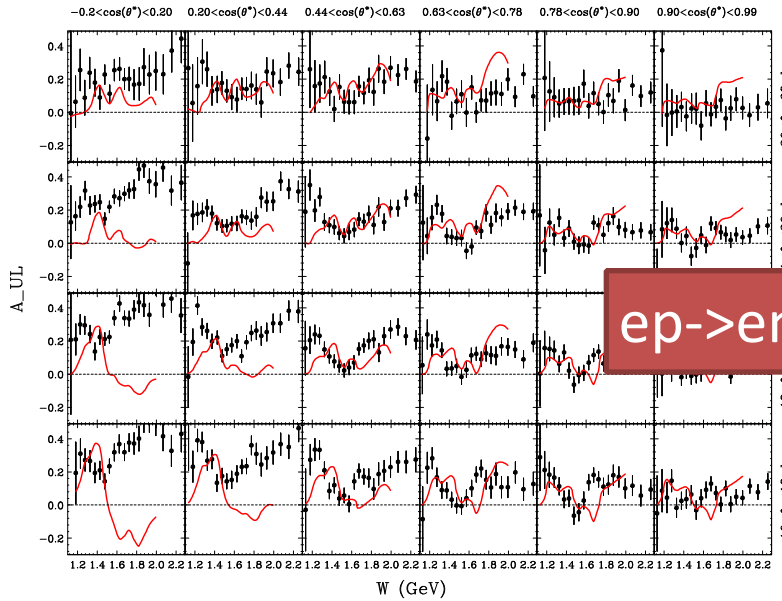
Fairfield UNIVERSITY

Target Asymmetry results

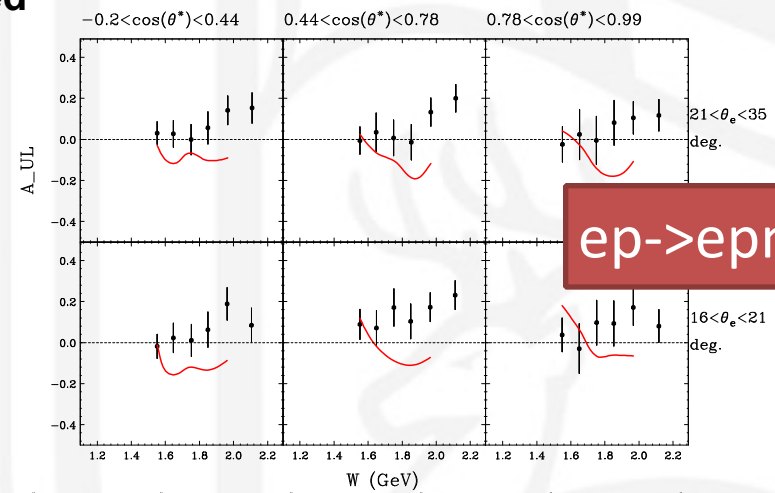
Averaged over ϕ^*

P. Bosted

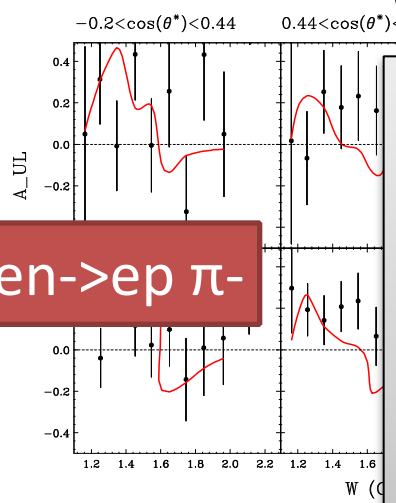
—Maid 2007



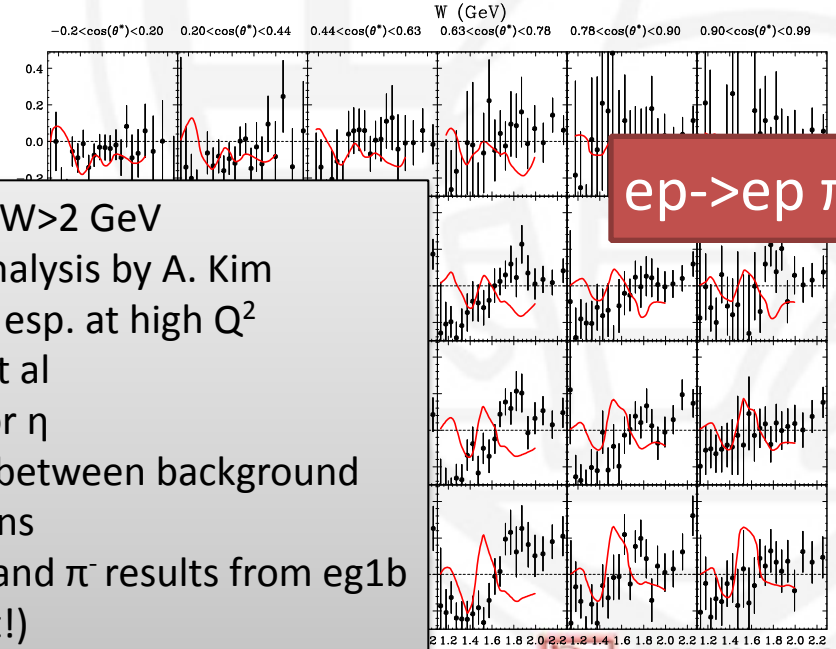
ep->en π^+



ep->epη



en->ep π-



ep->ep π^0

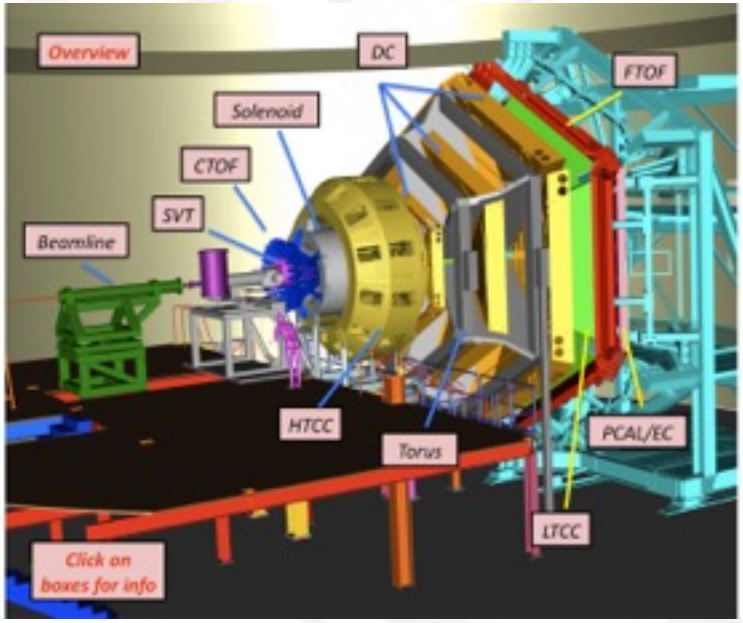
- Results in the deep region W>2 GeV
- Extension of the DV π^0 P analysis by A. Kim
- Disagreement with MAID, esp. at high Q^2 Consistent with π^0 Biselli et al
- First target asymmetries for η
- Sensitivity to interference between background and resonance contributions
- target asymmetries for π^+ and π^- results from eg1b and eg4 not published (yet!)
- Beam-target asymmetries for π^0 results from eg1b only at beam energy of 1.6 GeV

Fairfield UNIVERSITY

Conclusions

- Both single and double polarization observables
- Inclusive, semi-inclusive and exclusive channels
- Large kinetic range in x,Q2, W, t
- Enough precision to extract some quantities (e.g. CFF) and to distinguish different models
- More data to come in CLAS12

CLAS experiment	*physics*
E12-06-112	SIDIS
E12-06-112	DVCS
E12-11-109 a	di-hadron
E12-11-003	nDVCS
E12-06-109	DIS
E12-06-119	pol target DVCS
PR12-11-109	pol target di-hadron



Fairfield UNIVERSITY

Thank you.

Thank you to the organizers for the invitation

Thank you to S. Anefalos Pereira , A. Bacchetta, P. Bosted, A. Kim, , S. Koirala, S. Niccolai, S. Pisano, Y. Prok, E. Seder, D. Sokhan