Neutron GPD fixed-target measurements at JLab

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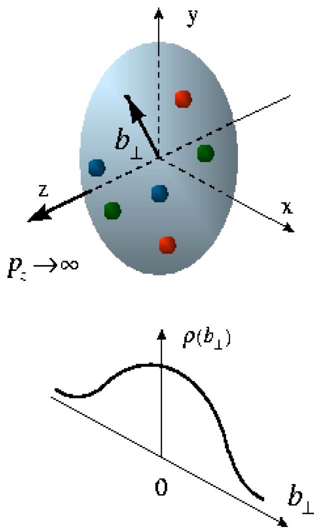
Fairfield, CT, USA

Exploring QCD with light nuclei at EIC
Stony Brook University, Stony Brook, January 21-24 2020

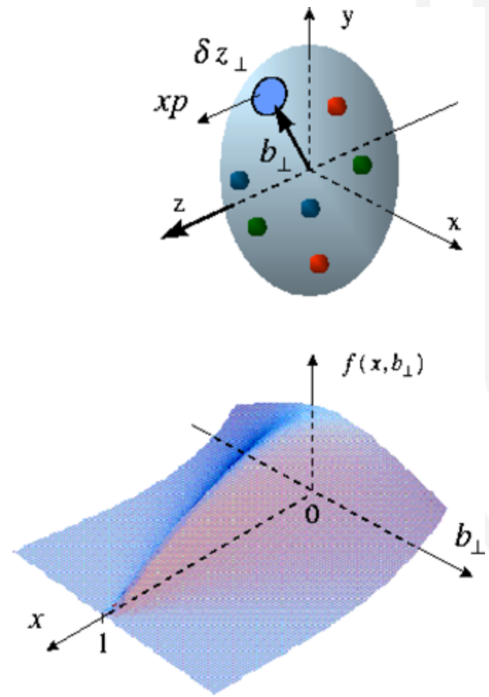
Generalized Parton Distributions

3-dimensional quark structure of nucleon



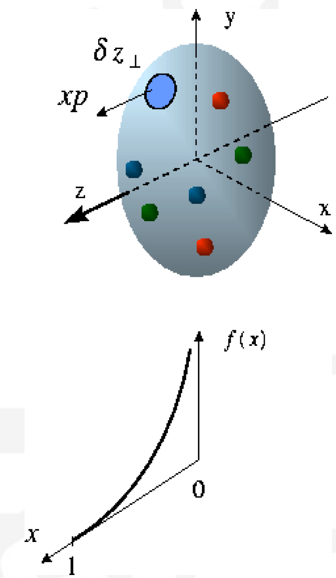
Elastic Scattering

Transverse quark distributions in coordinate space



Deeply exclusive scattering GPDs

Fully-correlated quark distribution in both coordinate and momentum space -



Deep inelastic scattering

Longitudinal quark distributions in momentum space

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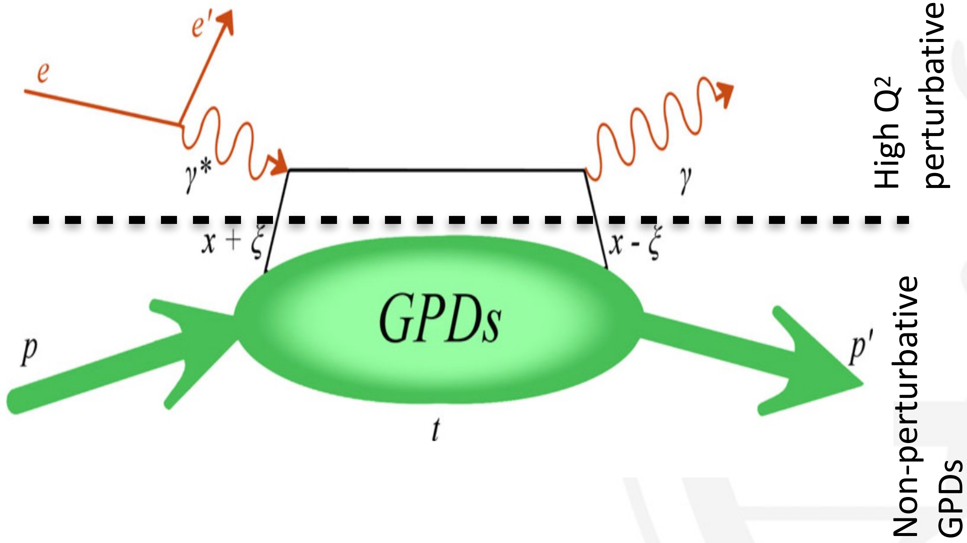
Deeply Virtual Compton Scattering and GPDs

$$eN \rightarrow e\gamma N$$

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

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



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

Large Q^2, $t \ll Q^2$ and fixed x_B :

- factorization
- soft part: 4 chiral even GPDs at LO

$$GPDs \text{ “}F\text{” } : H, \tilde{H}, E, \tilde{E}$$

$$F(x, \xi, t)$$

4 GPDs for each quark flavor

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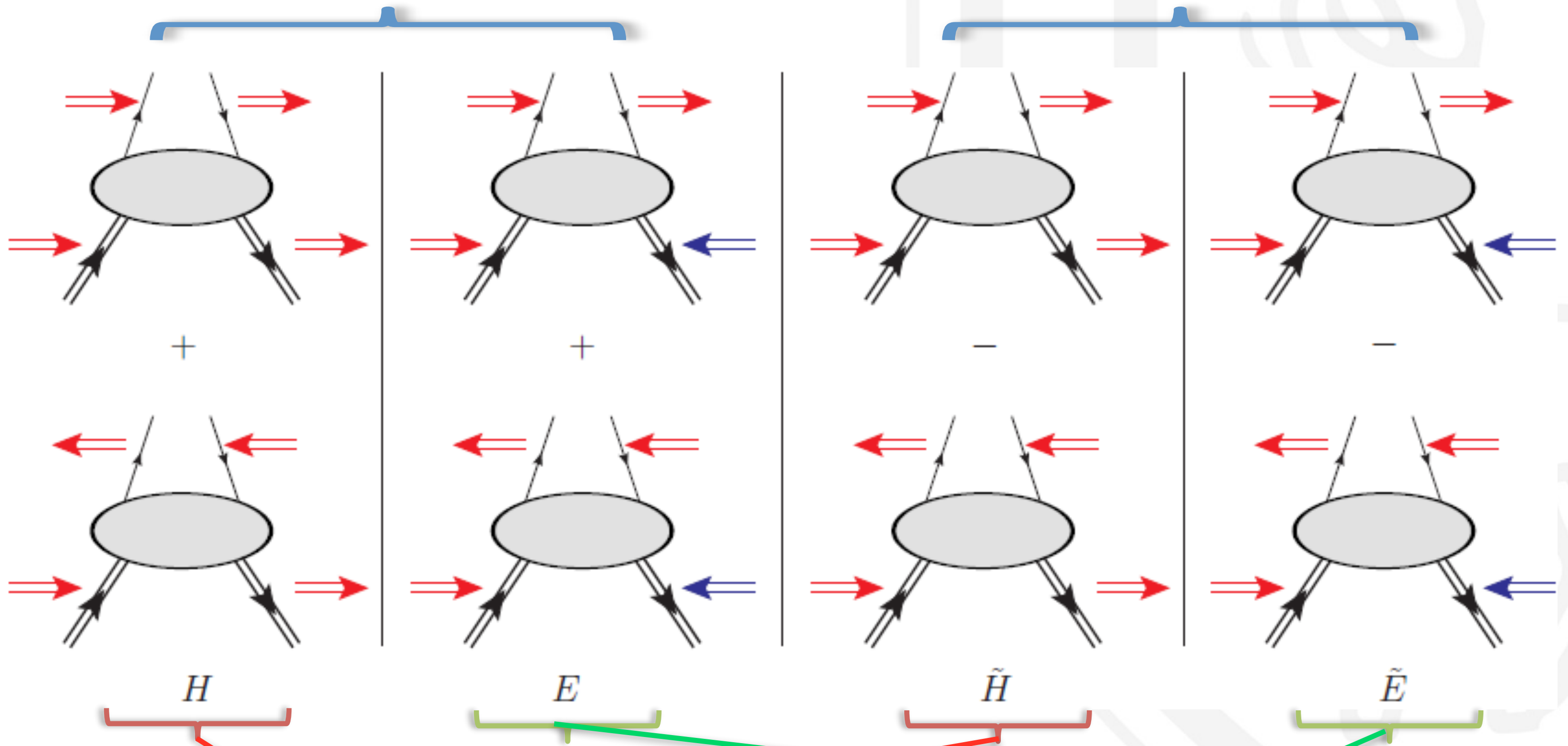
Deeply Virtual Compton Scattering and GPDs

Average over quark helicity
unpolarized GPDs

Difference of quark helicity
polarized GPDs



Hs conserve nucleon spin

Es flip nucleon spin

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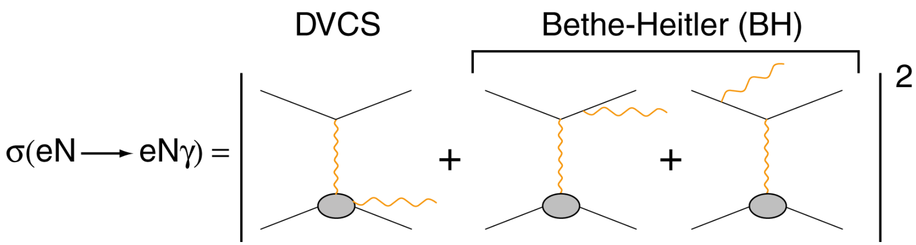
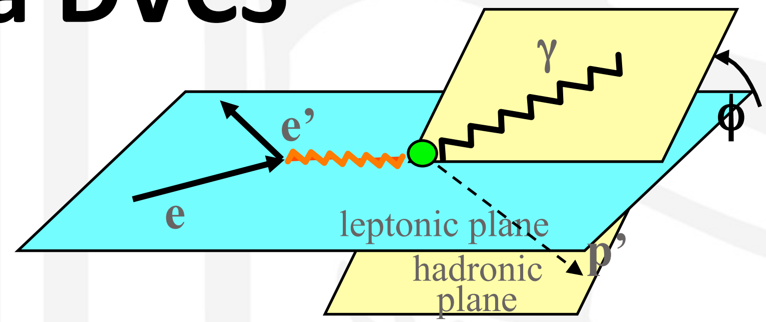
Chiral even: Quark helicity is conserved

Accessing GPDs via DVCS





Bethe Heitler experimentally indistinguishable from DVCS

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \propto |T_{\rm DVCS} + T_{\rm BH}|^2 = |T_{\rm DVCS}|^2| + |T_{\rm BH}|^2 + I$$

- Cross section measurement
- Polarization measurements: asymmetries and cross-section differences ⇒ $\sigma^+ - \sigma^- \propto I = T_{\rm DVCS} T^*_{\rm BH} + T^*_{\rm DVCS} T_{\rm BH}$

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \propto \frac{I}{|T_{\rm DVCS}|^2 + |T_{\rm BH}|^2 + I}$$

$$T_{\rm DVCS} \propto \mathcal{P} \int_{-1}^{1} dx \left[\frac{1}{x-\xi} \mp \frac{1}{x+\xi} \right] F(x,\xi,t) - i\pi [F(\xi,\xi,t) \mp F(-\xi,\xi,t)]$$

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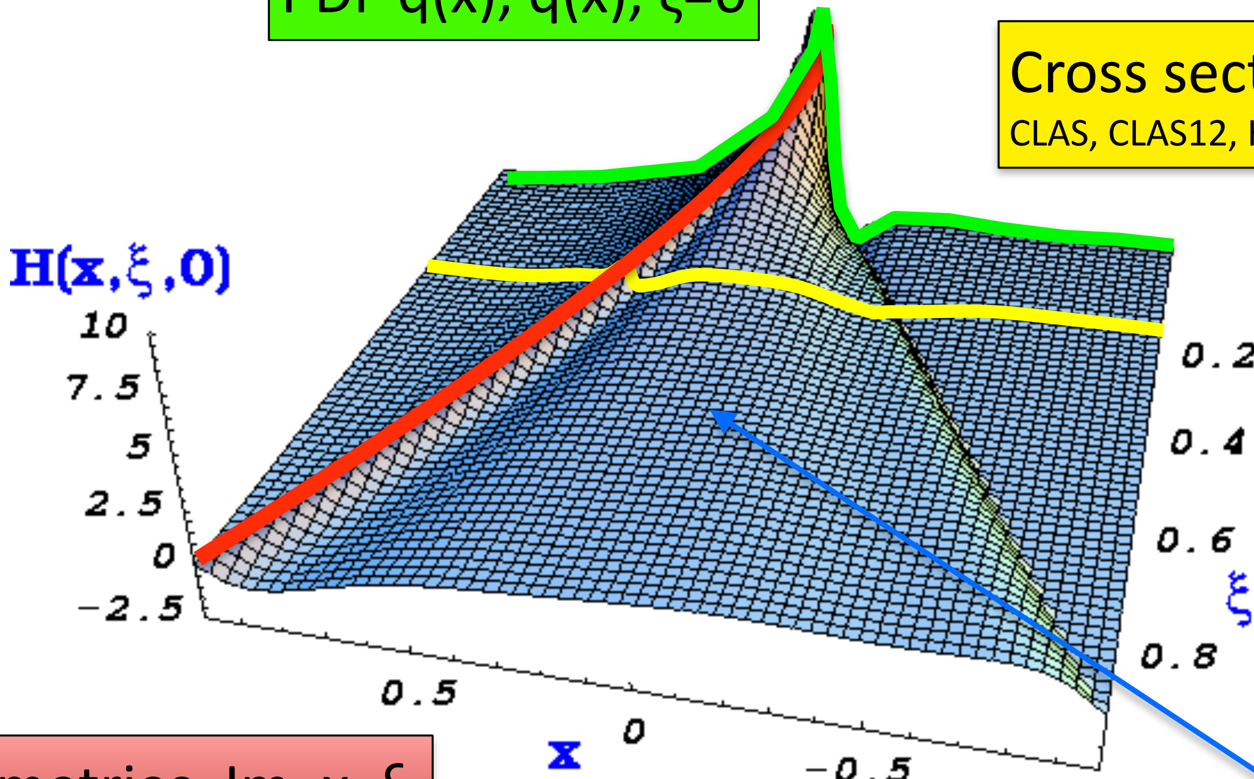
Accessing GPDs experimentally

BCA, Re
HERMES,COMPASS

TCS, Re

PDF q(x), q̄(x), ξ=0

Cross section, |Re|²
CLAS, CLAS12, Hall A,COMPASS, H1



Spin Asymmetries, Im, x=ξ
HERMES, CLAS, CLAS12, Hall A,COMPASS

TCS, Im

DDVCS, Im, x≠ξ

GPDs sensitivity of DVCS spin observables

Compton Form Factors: 8 GPD-related quantities

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

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

Observable	*Proton*	*Neutron*
Beam Spin Asymmetry A_{LU}		
$A_{\rm LU}(\phi) \propto \Im m[F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}]\sin\phi$		
Target Spin Asymmetry A_{UL}		
$A_{\rm UL}(\phi) \propto \Im m[F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + \frac{x_B}{2}\mathcal{E}) - \xi(\frac{x_B}{2}F_1 + \frac{t}{4M^2}F_2)\widetilde{\mathcal{E}}]\sin\phi$		
Double Spin Asymmetry A_{LL}		
$A_{\rm LL}(\phi) \propto \Re e[F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + \frac{x_B}{2}\mathcal{E}) - \xi(\frac{x_B}{2}F_1 + \frac{t}{4M^2}F_2)\widetilde{\mathcal{E}}](A + B\cos\phi)$		
Transverse Target Spin Asymmetry A_{UT}		
$A_{\rm UT}(\phi) \propto \Im m[k(F_2\mathcal{H} - F_1\mathcal{E}) + ...]\sin\phi$		

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

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Target Spin Asymmetry A_{UL}		
$A_{UL}(\phi) \propto \Im\mathrm{m}[F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + \frac{x_B}{2}\mathcal{E}) - \xi(\frac{x_B}{2}F_1 + \frac{t}{4M^2}F_2)\widetilde{\mathcal{E}}]\sin\phi$	$\Im\mathrm{m}\{\mathcal{H}_p, \widetilde{\mathcal{H}}_p\}$	
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Observable	*Proton*	*Neutron*
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Transverse Target Spin Asymmetry A_{UT}		
$A_{\mathrm{UT}}(\phi) \propto \Im\mathrm{m}[k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots]\sin\phi$	$\Im\mathrm{m}\{\mathcal{H}_p, \mathcal{E}_p\}$	$\Im\mathrm{m}\{\mathcal{H}_n\}$

DVCS on the neutron

- We can extract GPDs for proton or neutron but we want GPDs for quark flavors

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

- H,E for both proton and neutron are needed
  - E_n BSA on neutron
  - E_p TTSA on proton
  - H_n TSA on neutron
  - H_p BSA on proton

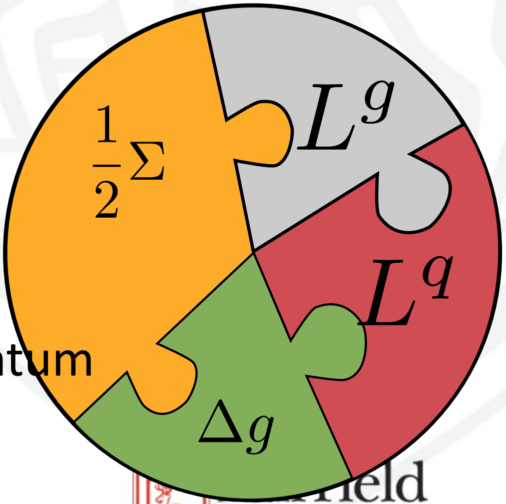
nDVCS important for flavor separation

- with H_q,E_q can extract the quark angular momentum (Ji's sum rule)

$$J_N = \frac{1}{2} = J^q + J^g = \frac{1}{2}\Sigma + L^q + \Delta g + L^g$$

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

information on quark orbital angular momentum



Hall A: DVCS neutron E03-106 (2004)

M. Mazouz et al., PRL 99,242501 (2007)

LD_2 & LH_2 $\quad D(\vec{e},e',\gamma)X \quad H(\vec{e},e',\gamma)X$

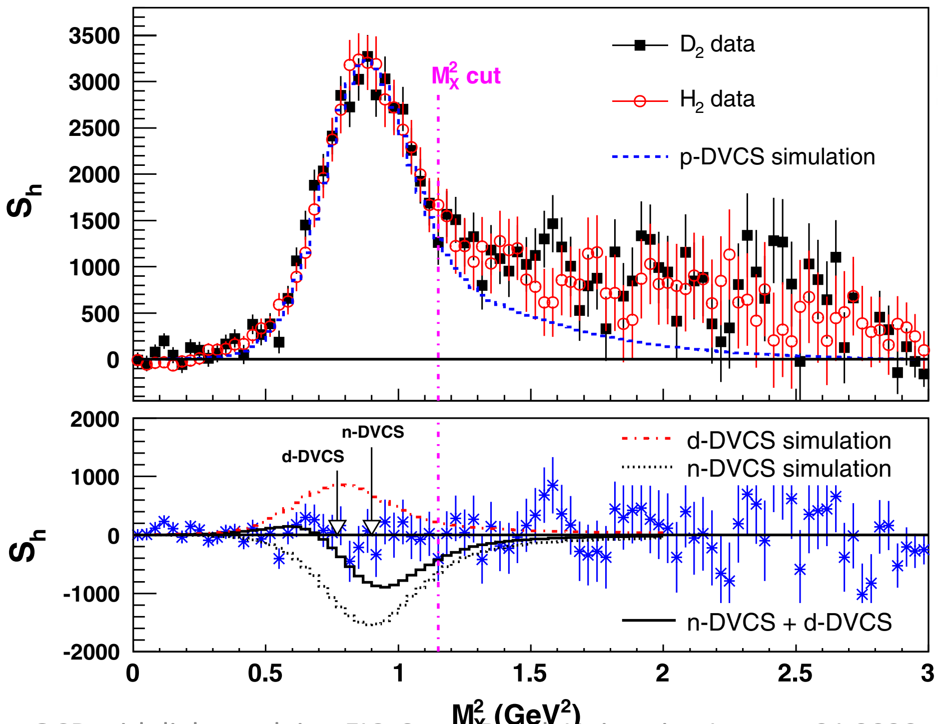
Impulse approximation:

$$D(\vec{e},e',\gamma)X - H(\vec{e},e',\gamma)X = d(\vec{e},e',\gamma)d + n(\vec{e},e',\gamma)n + p(\vec{e},e',\gamma)p - p(\vec{e},e',\gamma)p + \ldots$$

$\langle Q^2 \rangle$=1.9 GeV^2

$\langle x_B \rangle$=0.36

-t=0.1-0.5 GeV^2



Cross sections diff

Helicity signal

$$S_h = \int_0^{\pi} (N^+ - N-) d^5\Phi - \int_{\pi}^{2\pi} (N^+ - N-) d^5\Phi$$

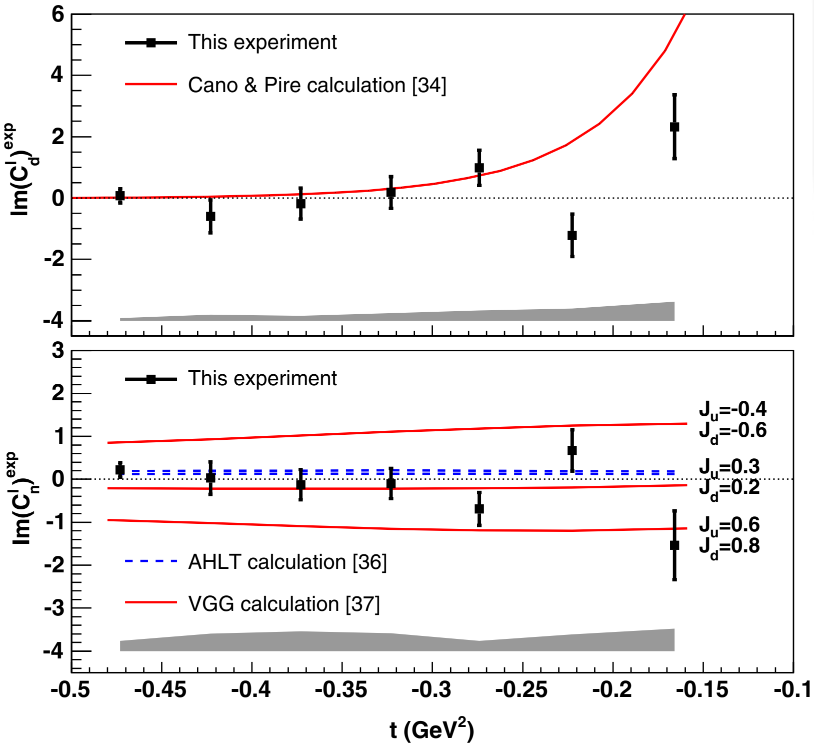
$$d^5\Phi = dQ^2 dx_B dt d\phi_e d\phi_{\gamma\gamma}$$

Hall A: DVCS neutron E03-106 (2004)

M. Mazouz et al., PRL 99,242501 (2007)

$$\frac{d^5\Sigma_{D-H}}{d^5\Phi} = \frac{1}{2}\left(\frac{d^5\sigma^+}{d^5\Phi} - \frac{d^5\sigma^-}{d^5\Phi}\right) = \left(\Gamma_d^{\mathcal{I}}\mathcal{I}m[\mathcal{C}_d^I]^{exp} + \Gamma_n^{\mathcal{I}}\mathcal{I}m[\mathcal{C}_n^I]^{exp}\right)\sin(\phi_{\gamma\gamma})$$

Fit of 2520 bins in M_x, t and $\phi_{\gamma\gamma}$ to extract CFFs



Sensitivity to Im{E}

Sensitivity to quark angular momentum J_u J_d

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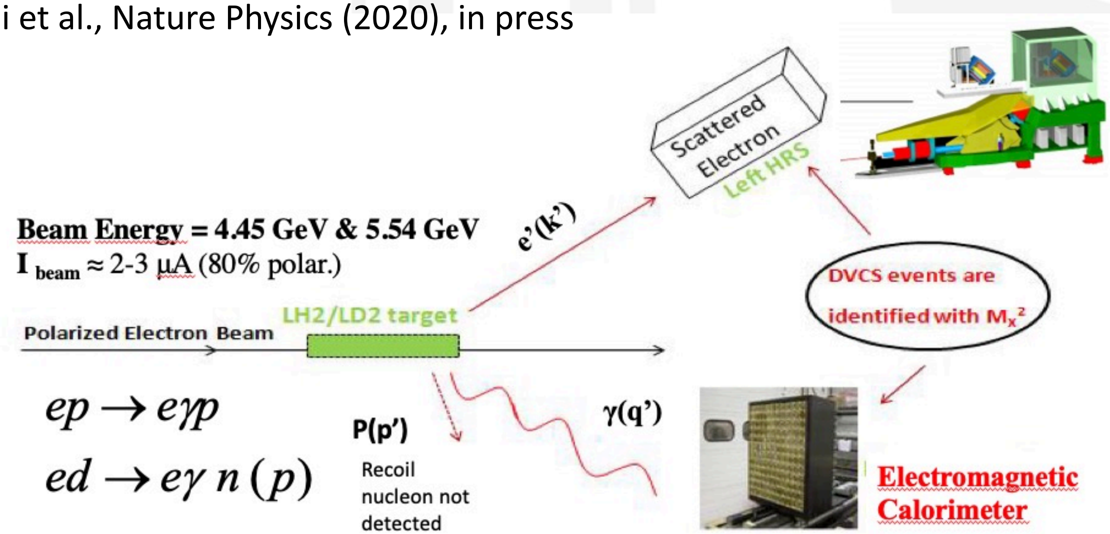
Hall A: DVCS neutron E08-025 (2010)

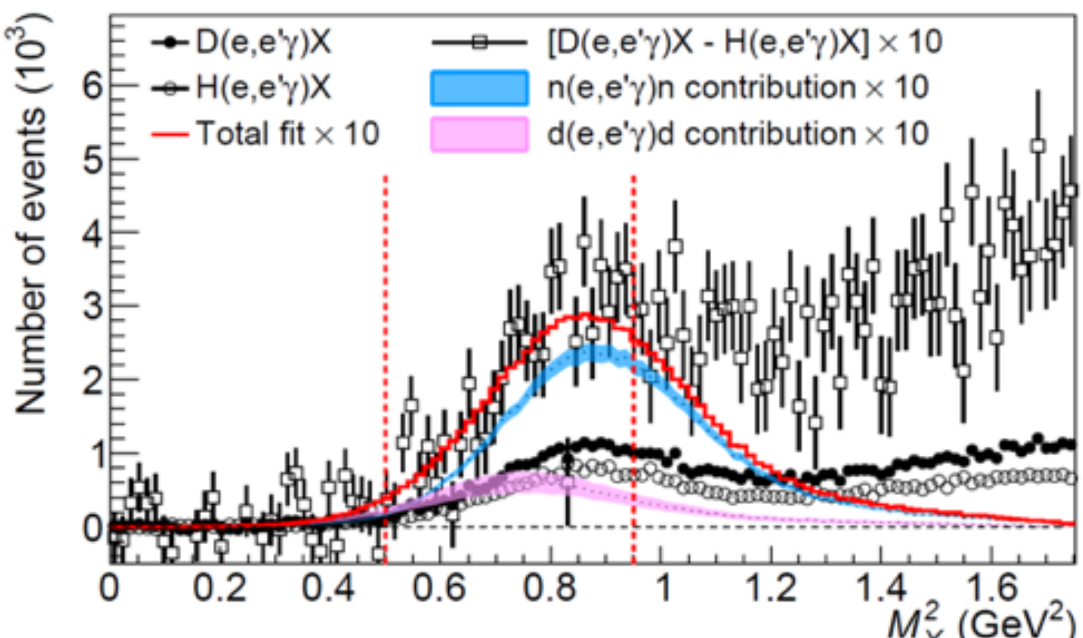
M. Benali et al., Nature Physics (2020), in press

LD_2 & LH_2

$$D(\vec{e}, e', \gamma)X$$

$$H(\vec{e}, e', \gamma)X$$





- Frequent swaps LH2, LD2
  - Better proton subtraction
- New calorimeter
  - Better π^0 subtraction

- Cross sections
- Different beam energies
  - Rosenbluth separation

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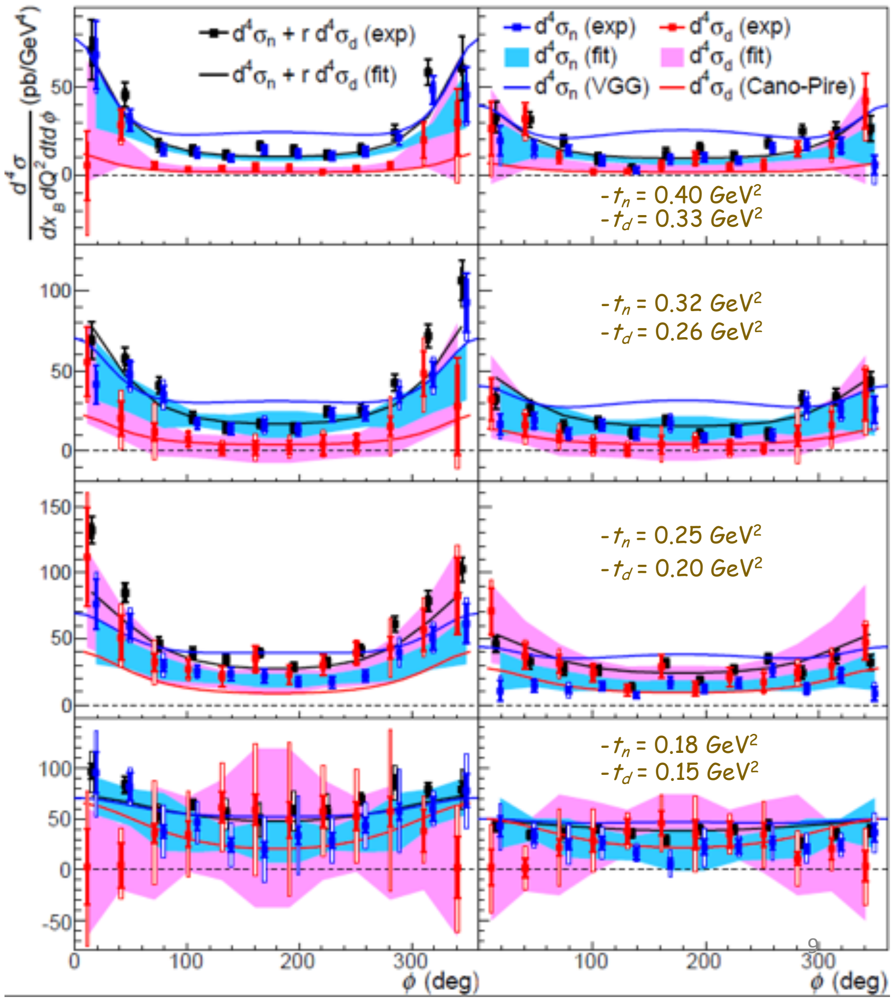
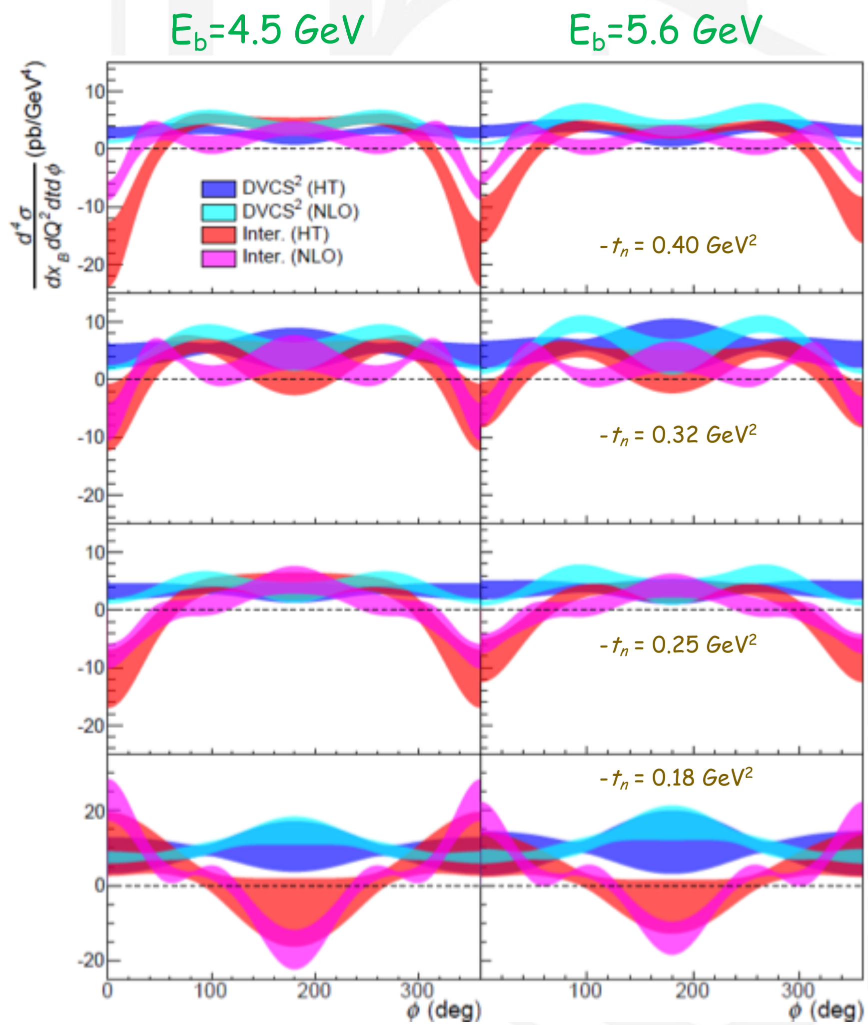
Hall A: DVCS neutron E08-025 (2010)

Cross sections



DVCS² & Int

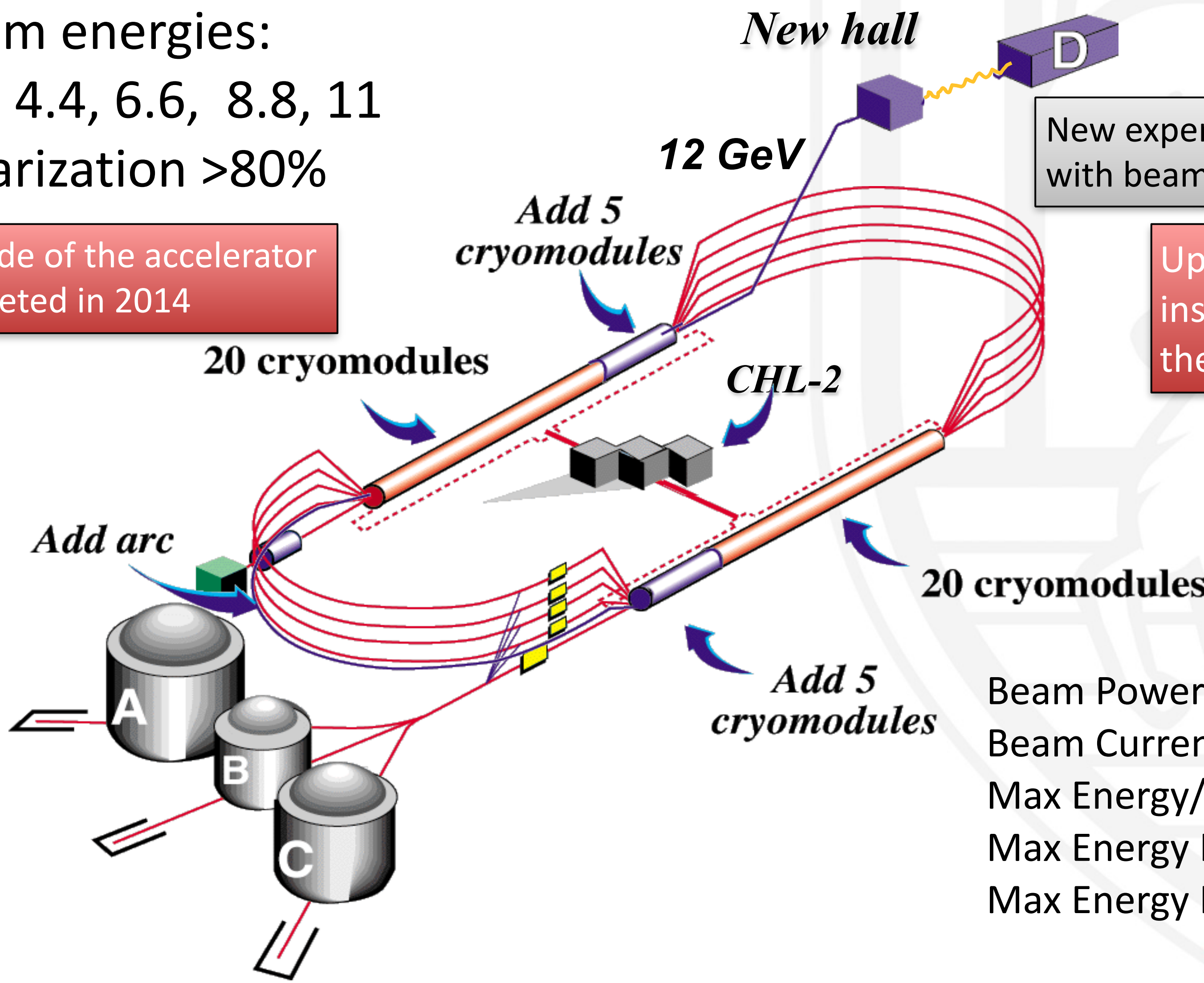


- Higher twist (HT) fit
- Next-to-leading (NLO) fit

12GeV @ Jefferson Lab

Beam energies:
2.2, 4.4, 6.6, 8.8, 11
Polarization >80%

Upgrade of the accelerator completed in 2014



New experimental hall, Hall D with beam energy up to 12GeV

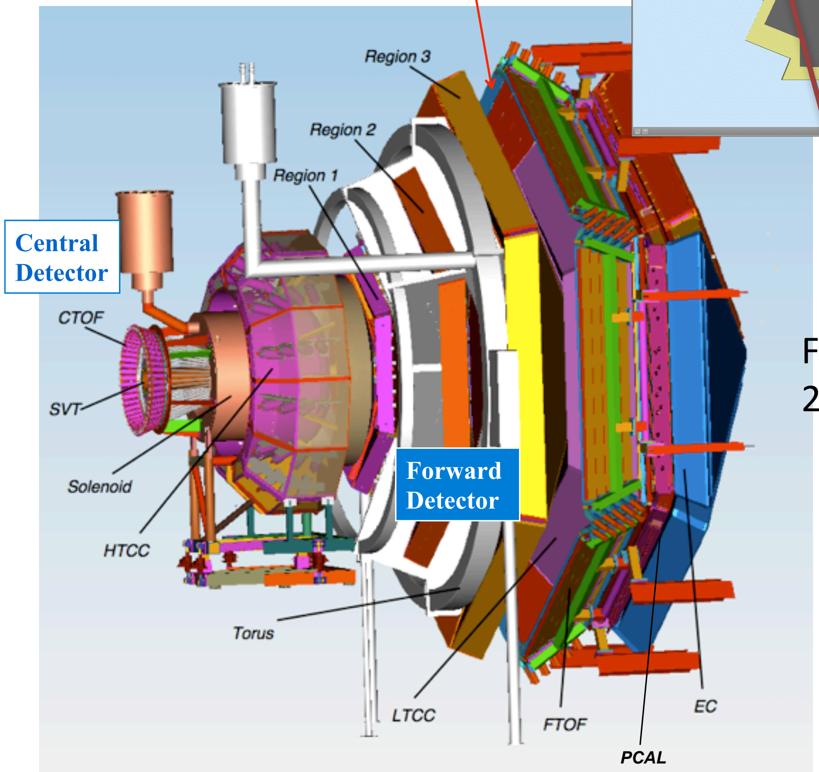
Upgrade of the instrumentation in the three Halls

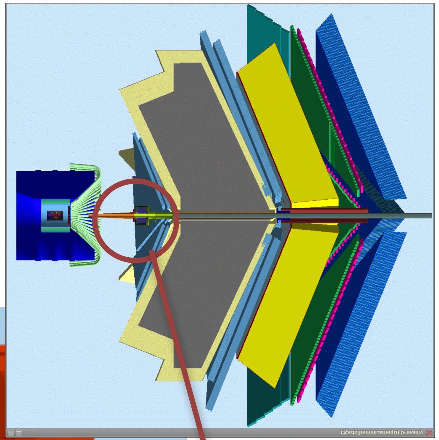
Beam Power: 1MW
Beam Current: 90 μA
Max Energy/pass: 2.2 GeV
Max Energy Hall A-B-C: 11 GeV
Max Energy Hall D: 12 GeV

CLAS12 DVCS experiments

CLAS12,FT,CND,NH3,HDIce

- Large kinematic coverage
- BSA, TSA, DSA, tTSA
- cross-section
- CFF extraction

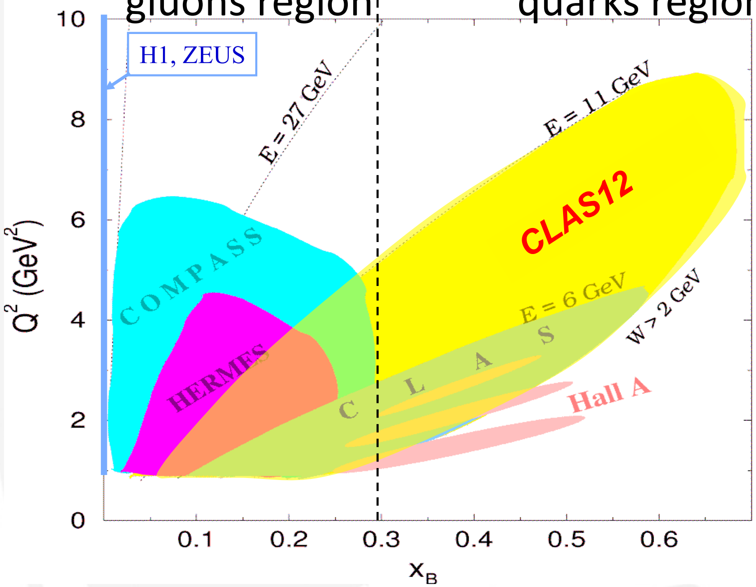




Forward Tagger
2.5-5 deg photons

sea quarks, gluons region

valence quarks region



CLAS exper.	*physics*
E12-06-112	pDVCS BSA TSA
E12-11-003	nDVCS BSA
E12-06-119	pol target nDVCS
E12-12-010	pDVCS transverse TSA
E12-12-001	Timelike DVCS
E12-16-113A	nDVCS with tagged p

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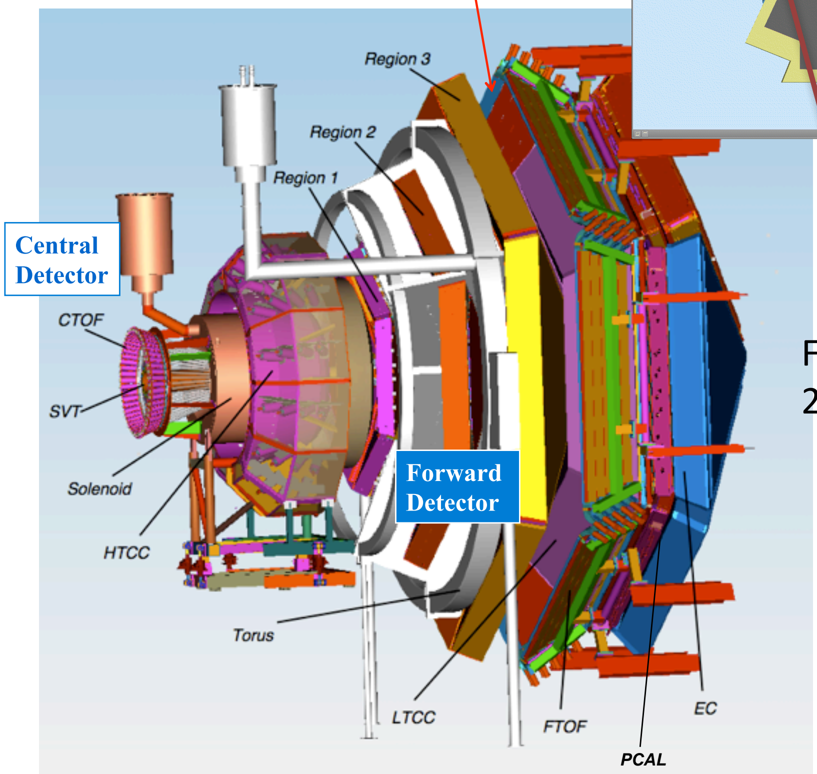

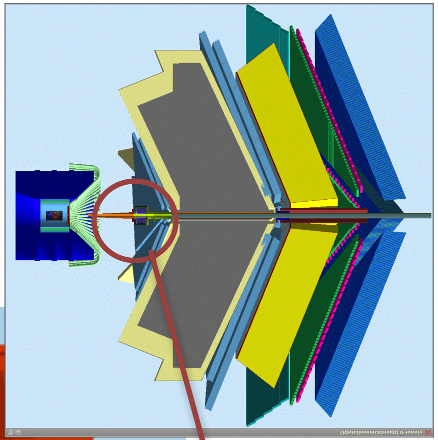

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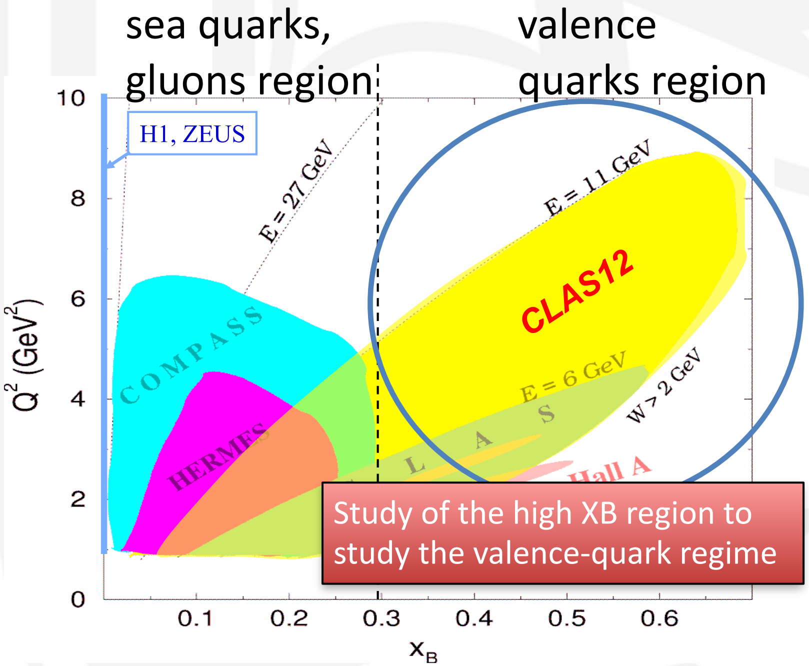

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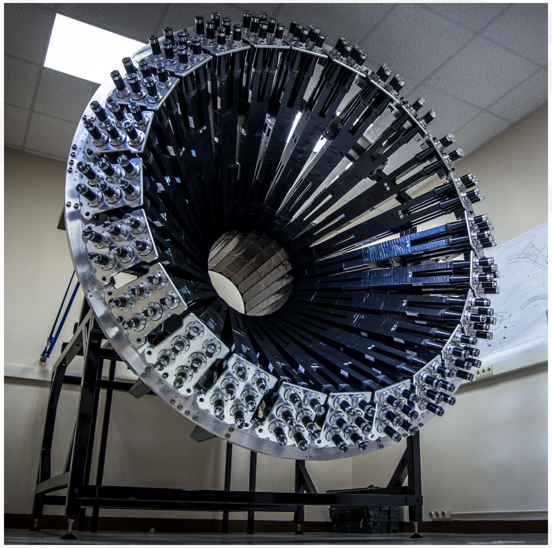
E12-16-113A	nDVCS with tagged p

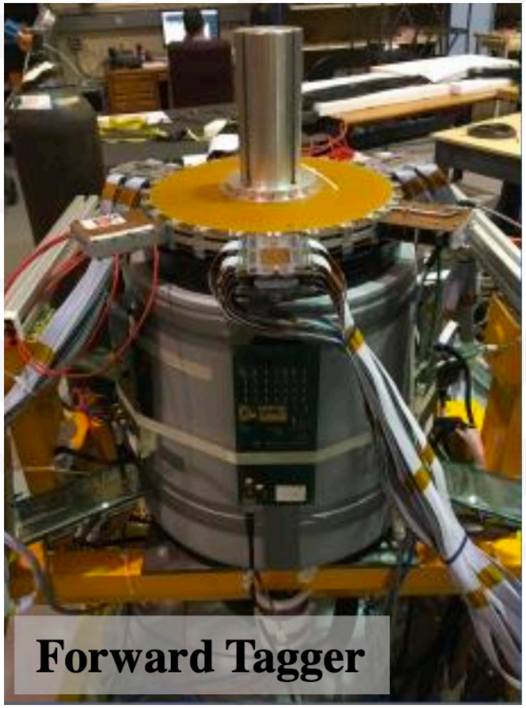
Electron scattering off unpolarized deuteron a.k.a. **Run Group B**

- Approved for 90 PAC days
- CLAS12+CND+FT+BAND+RICH
- Ran in Feb 8, 2019 to March 19 2019 (45 PAC days)
- **Currently** running Nov 2019-Jan 2020

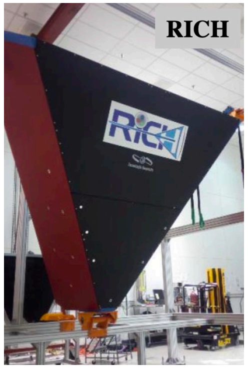
- deuteron target: ρ = 0.163 g/cm^3 (23.6 K, 1200 mbar), unpolarized LD_2 L = 5 cm, d = 2 cm
- Polarized beam - beam pol 85-87%
- Beam energy 10.6 and 10.2 GeV
- $L=10^{35}$ $cm^{-2}s^{-1}$/nucleon



Winter 2019-2020 run
- 35-45nA current
- 10.4 GeV energy
- On-going



Spring 2019 run
237 production runs (35 nA, 50 nA)
- low-current runs, empty-target runs
- 9.7 B events at 10.6 GeV, 11.7 B events at 10.2 GeV

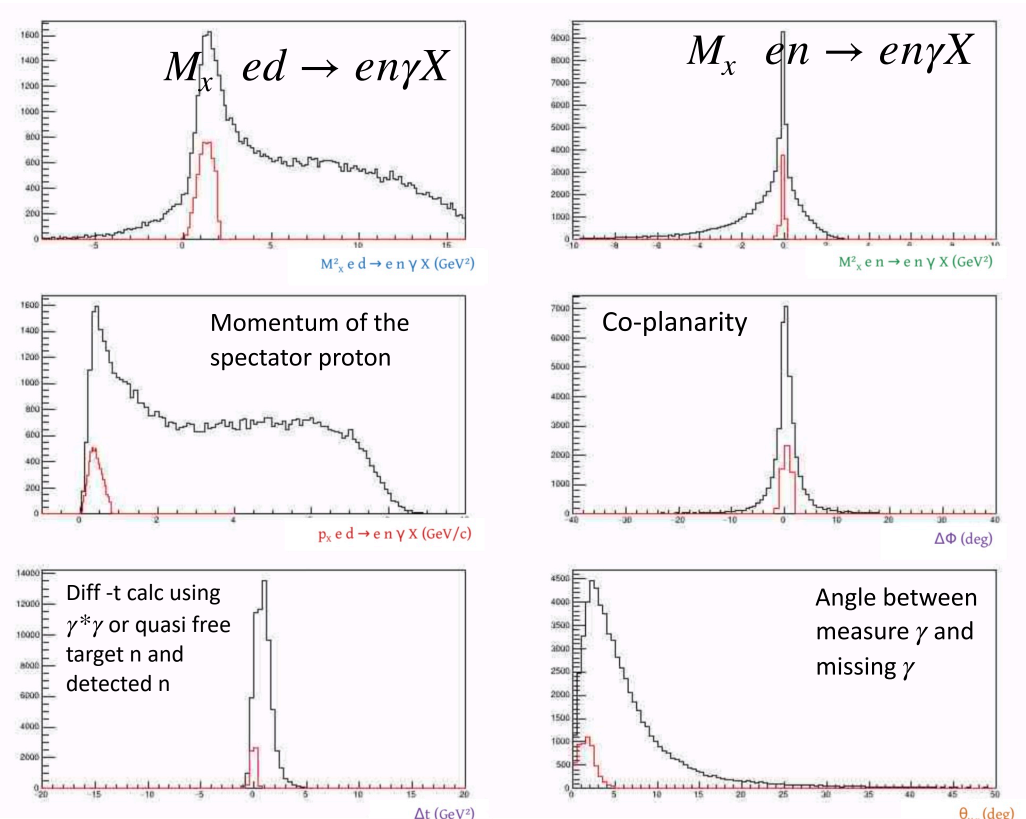


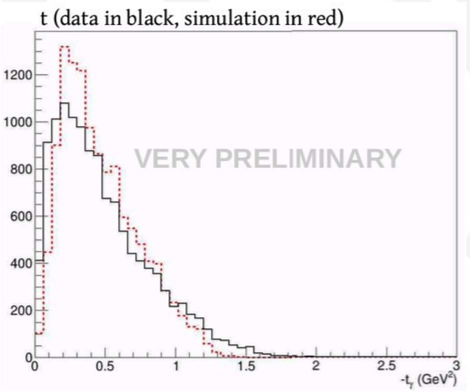
nDVCS with RGB data first look

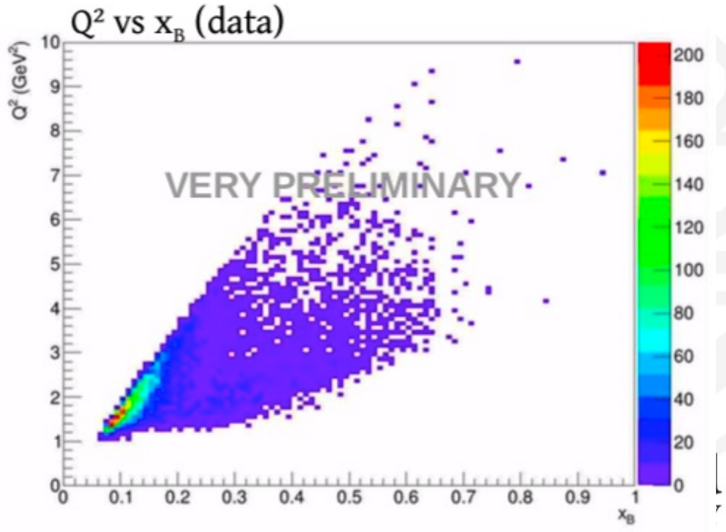
Work done by Kitty Price

Analysis strategy

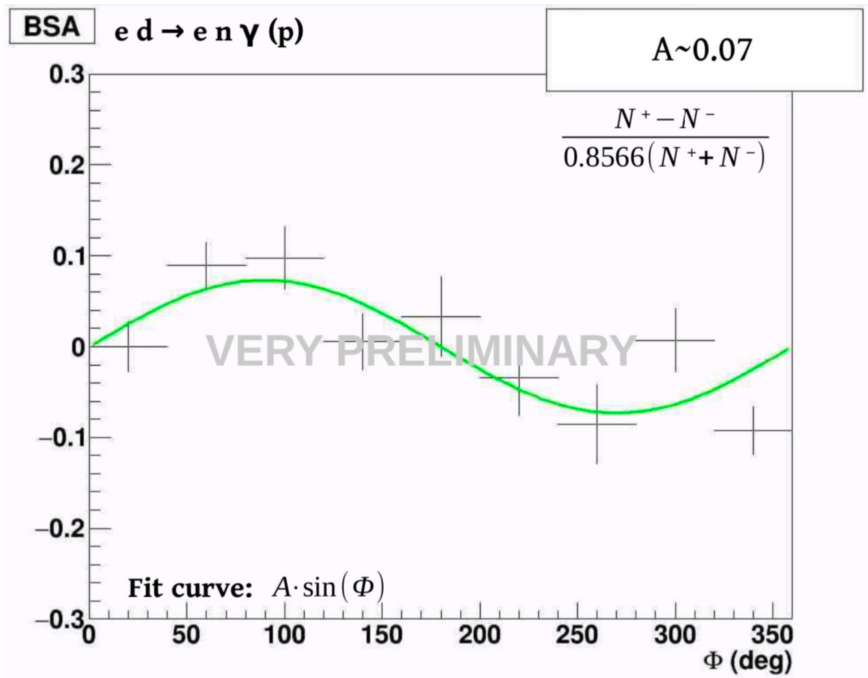
- Fully exclusive: detect n in the final state
- Leverage exclusivity by looking at $eD \rightarrow en\gamma$ and $en \rightarrow en\gamma$ kinematic variables







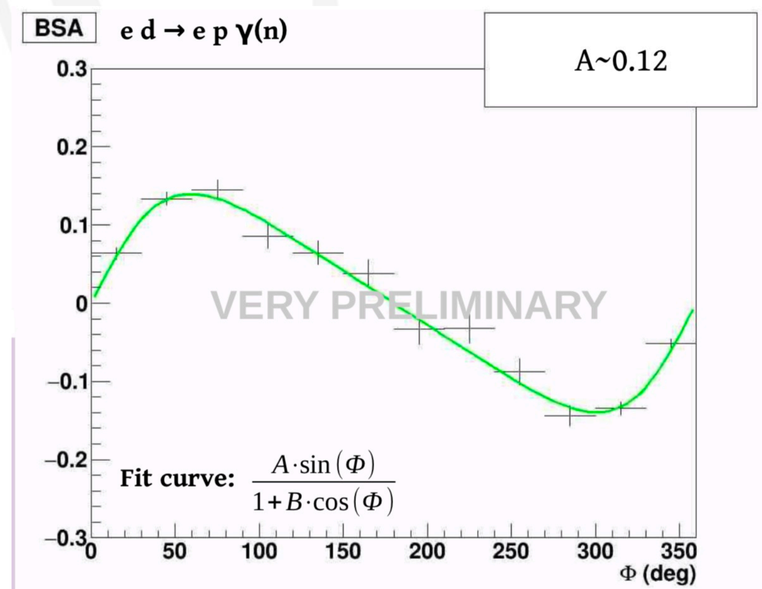
nDVCS with RGB data first look



Very preliminary nDVCS BSA

- No π^0 background subtraction
- Consistent with sin expectation
- 10% of the Spring 2019 data

Extraction of pDVCS BSA using RGB data to check the analysis

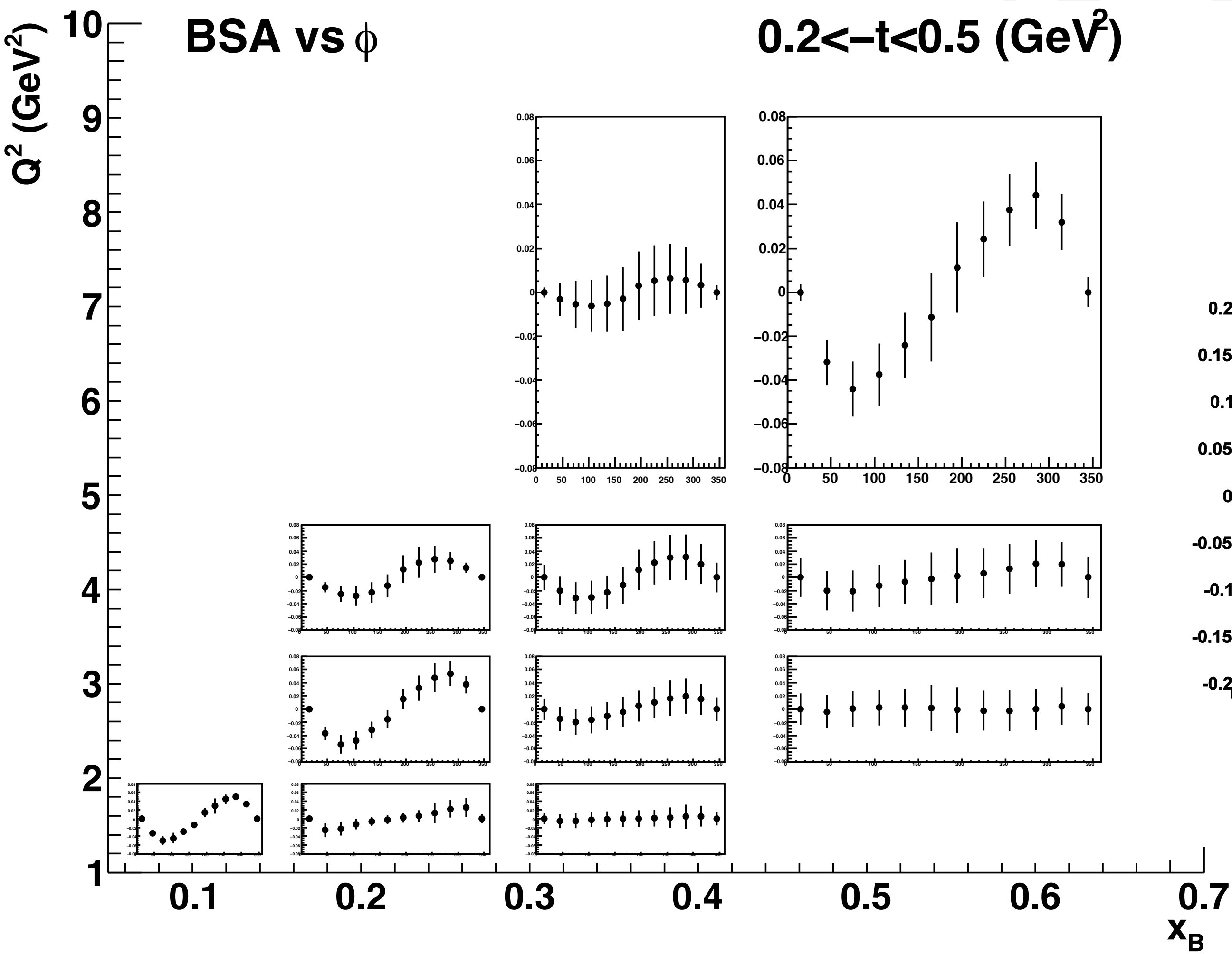


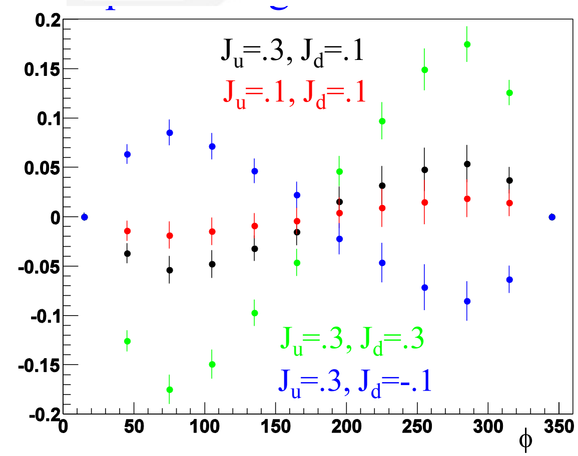
Projected results for RGB

- BSA
- ~90 PAC days

Sensitivity to:

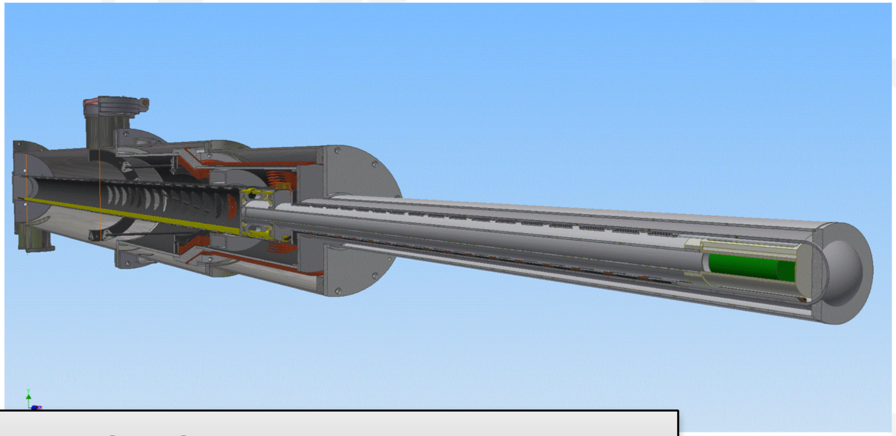
- ImE





Experiment E12-06-119 TSA DSA nDVCS a.k.a Run Group C

- TSA and DSA
- ~65 PAC days (together with DIS)
- CLAS12+CND+pol target+(FT?)



The APOLLO target
(Ammonia POlarized LOngitudinally)

- ND3
- beam pol 85%
- target pol 40%
- e d -> e(p) n g
- $L=10^{35}$ $cm^{-2}s^{-1}$/nucleon
- $1<Q^2<10$ GeV^2 $0.1<x_B<0.7$
- $-t_{min}<-t<1.2$ GeV^2

Planning to run in 2021-2022
First part of the run no FT

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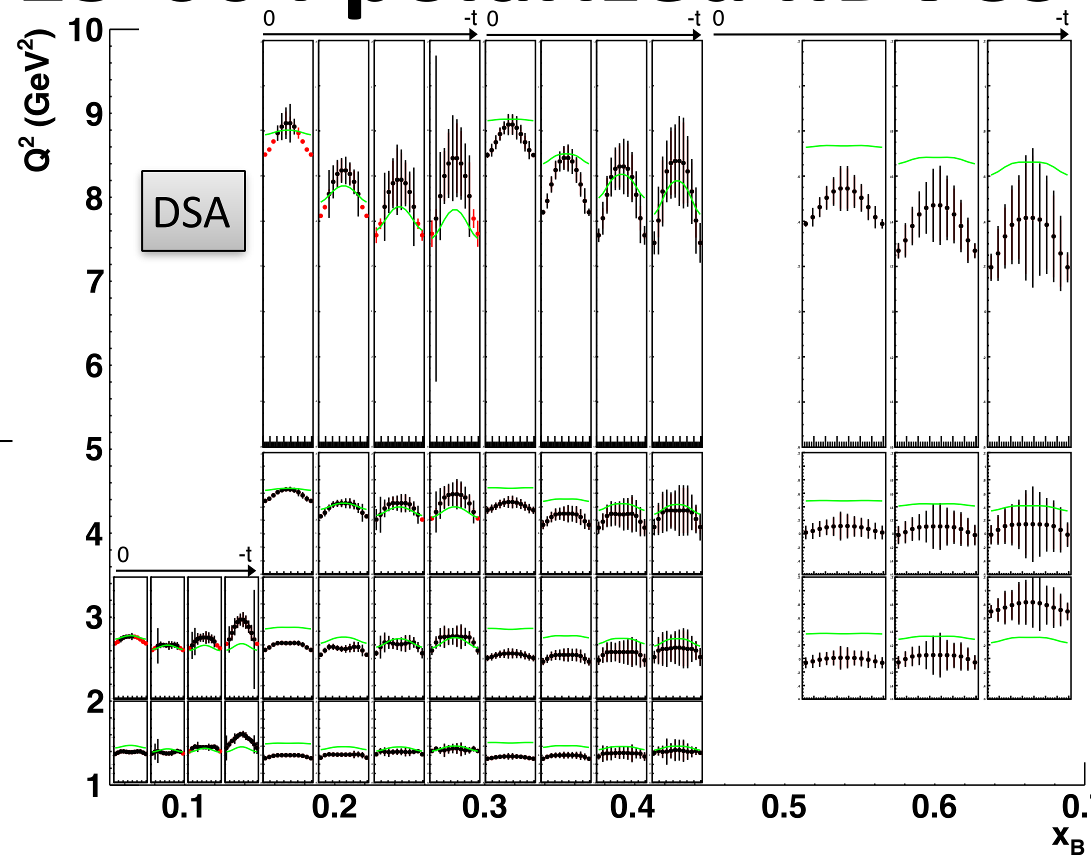
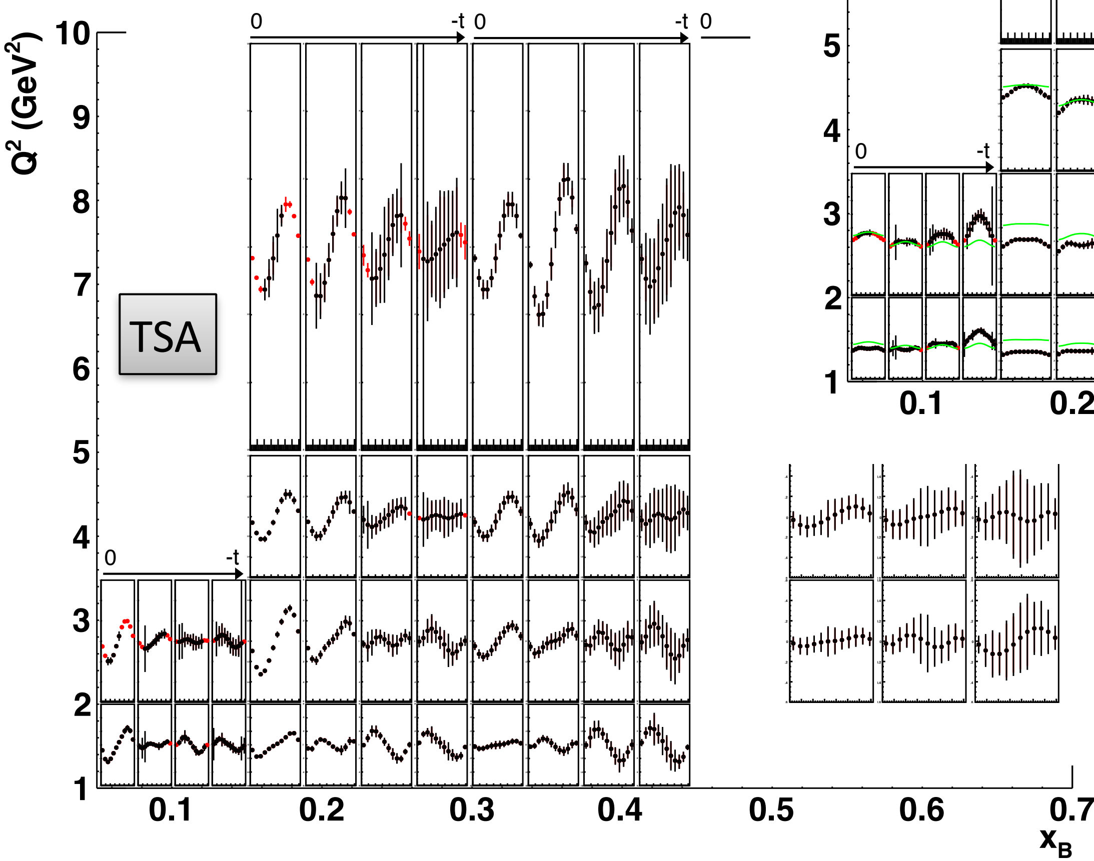
Experiment E12-15-004 polarized nDVCS





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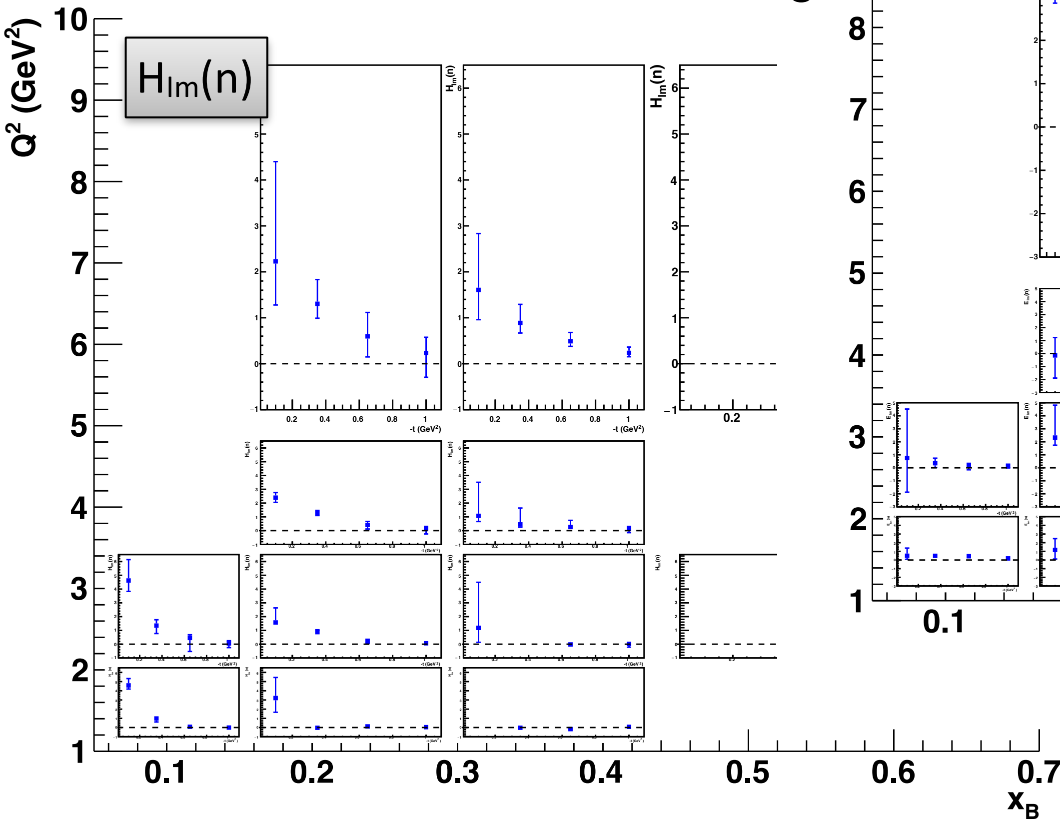
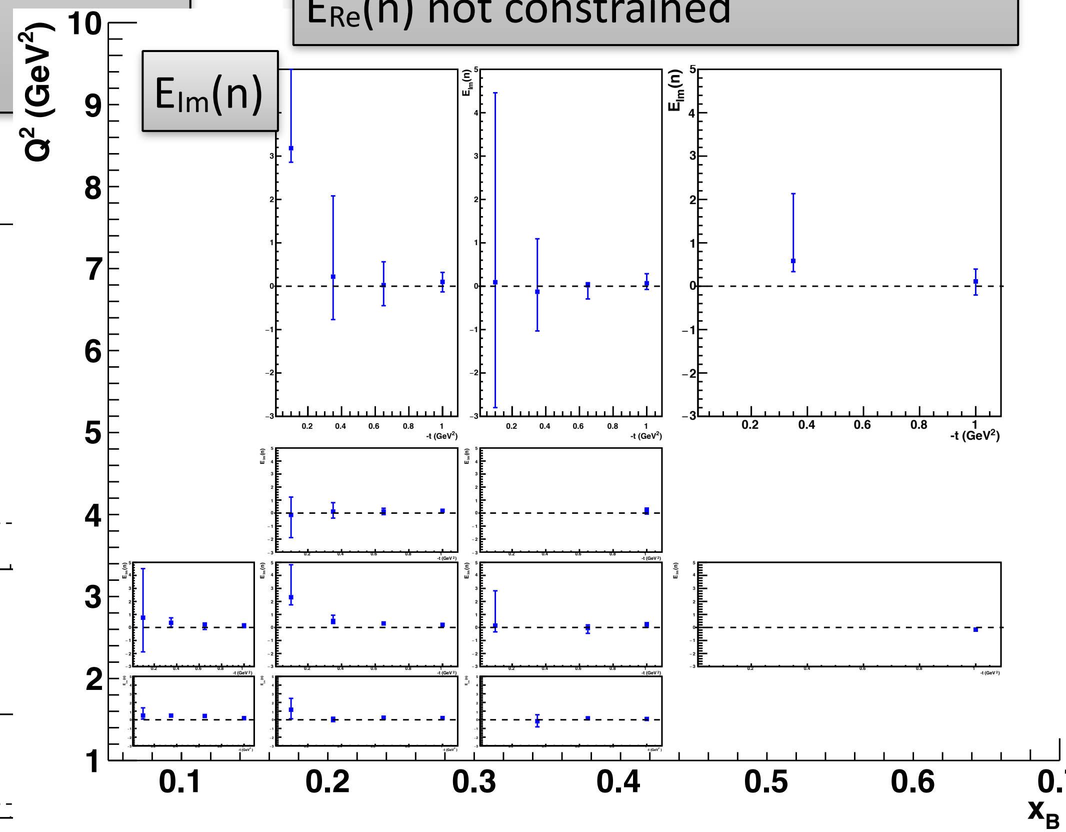
Experiment E12-15-004 polarized nDVCS

- Combining results of neutron experiments
- Fit of BSA, TSA, DSA to extract CFF for the neutron
- Assumption $\tilde{E}$ purely real: $\tilde{E}_{Im}(n)=0$
- 7 CFF to be fitted
- limit +/- 5VGG prediction

$E_{Im}(n)$, $H_{Im}(n)$ best constrained
$\tilde{E}_{Re}(n)$, good sensitivity
$\tilde{H}_{Im}(n)$, $H_{Re}(n)$ constrained low Q^2-x_B
$\tilde{H}_{Re}(n)$ very limited
$E_{Re}(n)$ not constrained





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Flavor separation with CLAS12

- Flavor separation by combining results pDVCS and nDVCS experiments

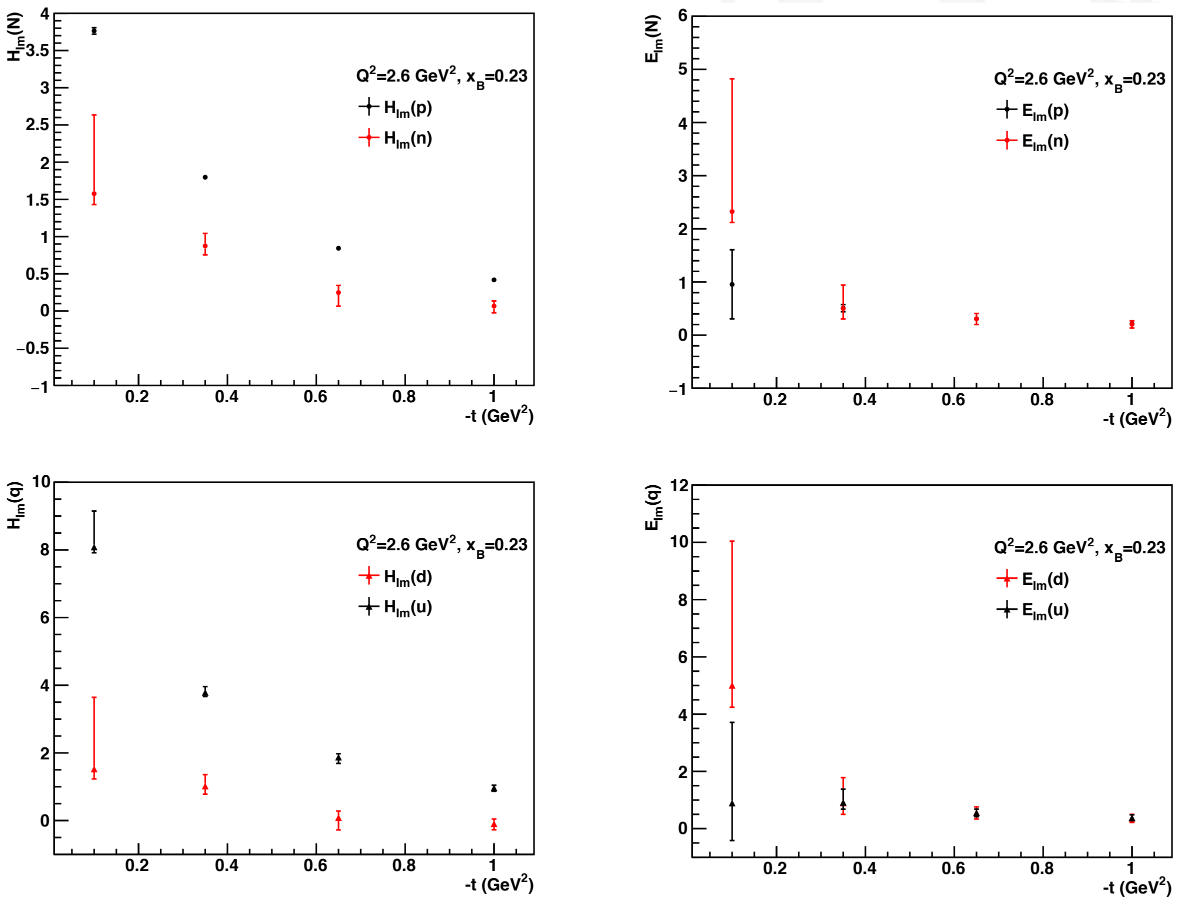
$$(H,E)_u(\xi,\xi,t) = 9/15[4(H,E)_p(\xi,\xi,t) - (H,E)_n(\xi,\xi,t)]$$
$$(H,E)_d(\xi,\xi,t) = 9/15[4(H,E)_n(\xi,\xi,t) - (H,E)_p(\xi,\xi,t)]$$

$H_{Im}(N)$

$E_{Im}(N)$

$H_{Im}(q)$

$E_{Im}(q)$



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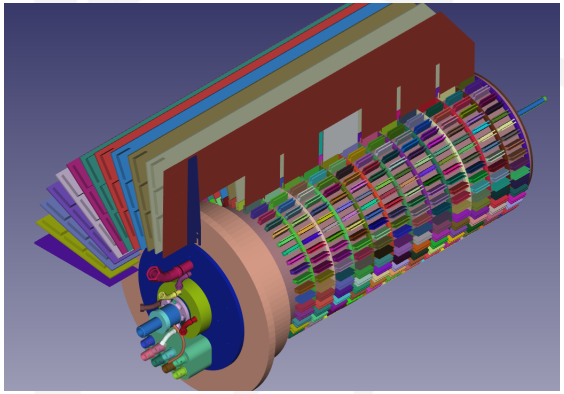
Experiment E12-06-119 nDVCS BSA a.k.a Bonus12

BONuS12 RTPC



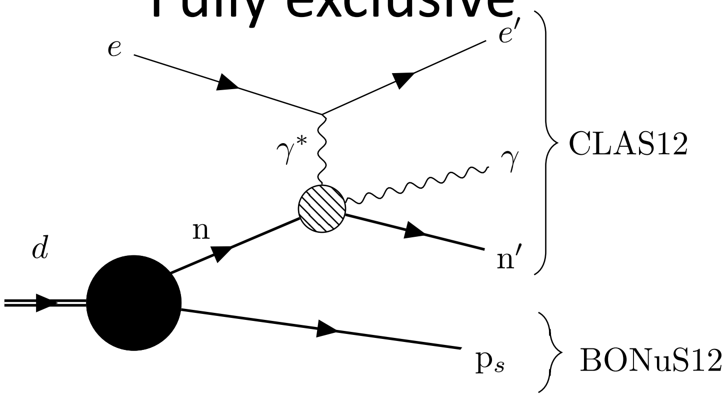
Extension of E12-06-113 : Bonus12 + polarized beam

Bonus Radial TPC →Tagged proton spectator

Scheduled to run Spring 2020 (soon)

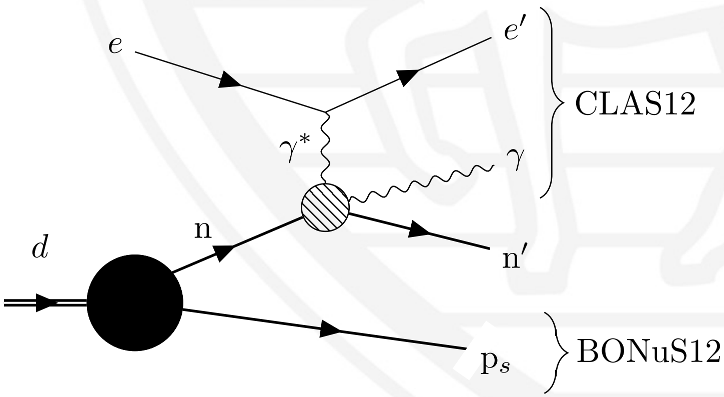
Two ways of measuring the asymmetry :

Fully exclusive



- Very limited statistics
- Can be used for cross checks and systematics studies

Neutron tagged



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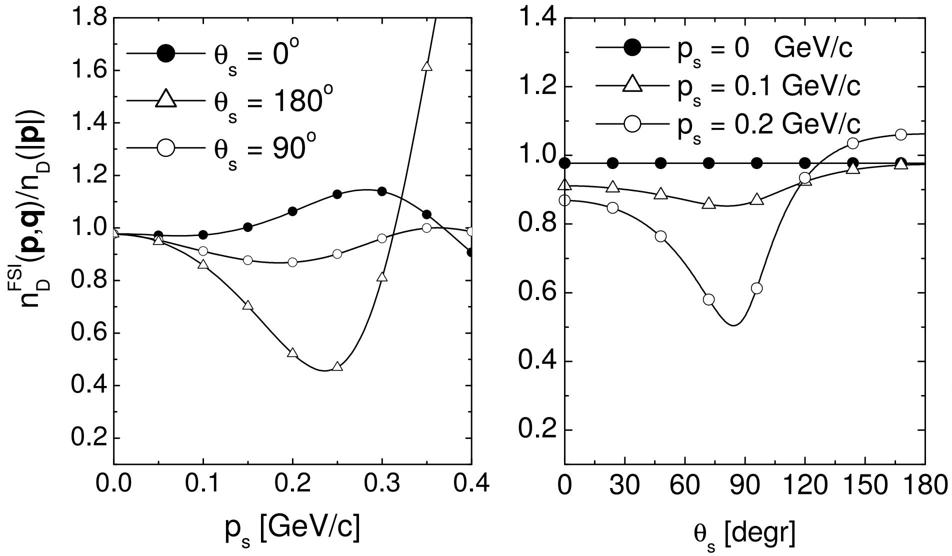
nDVCS BSA BoNUS12

Possible sensitivity to the initial state and break of the deuterium



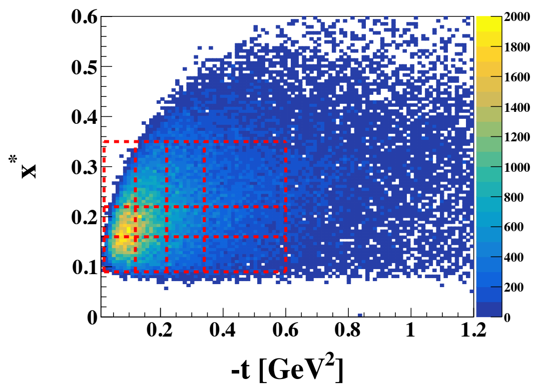
Ratio FSI model to PWIA

p_s spectator momentum

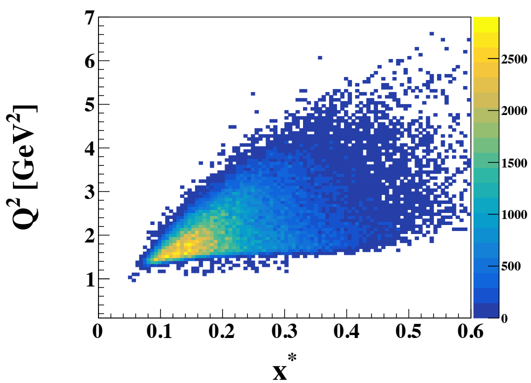
θ_s spectator angle

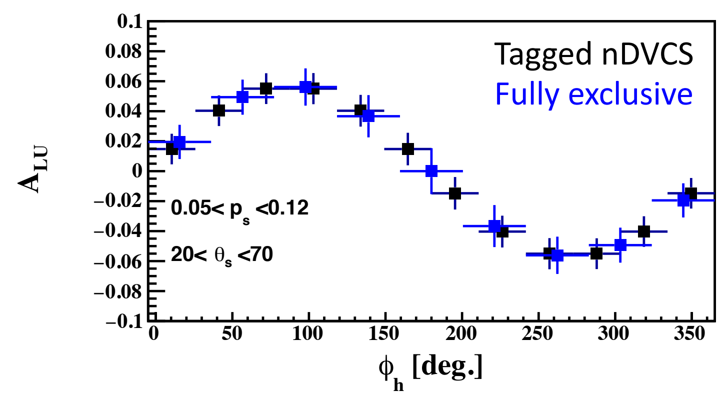
We can select regions with high/small FSI

x^* vs -t



Q^2 vs x^*





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More opportunities with deuteron target

Deeply Virtual Compton on nuclei

Deeply Virtual Compton on nuclei

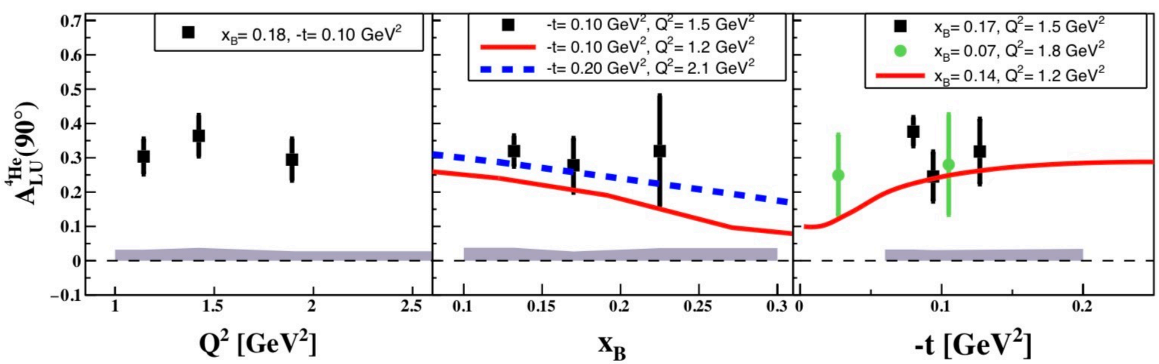
Measure of coherent DVCS

$$\vec{e}A \rightarrow e'A'\gamma$$

- Different spins: additional structure functions
- Three dimensional picture of nuclei
- Study of the modification of quark and gluon distributions in nuclei

Helium measurement - clas6 ^{4}He spin 0, only one GPD at twist-2 in DVCS BSA

eg6 run
CLAS+IC+RTCP
^{4}He target
Beam: 6GeV
M. Hattawy



Deeply Virtual Compton on Deuteron

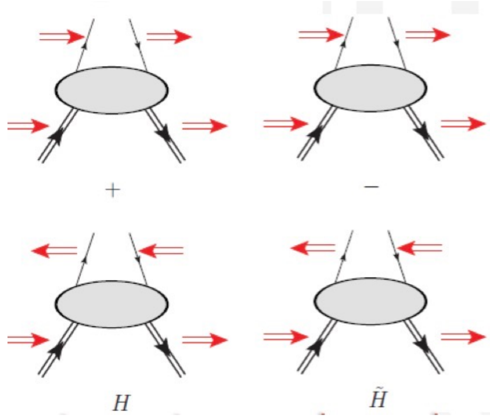
Spin 1 9 GPDs at LO

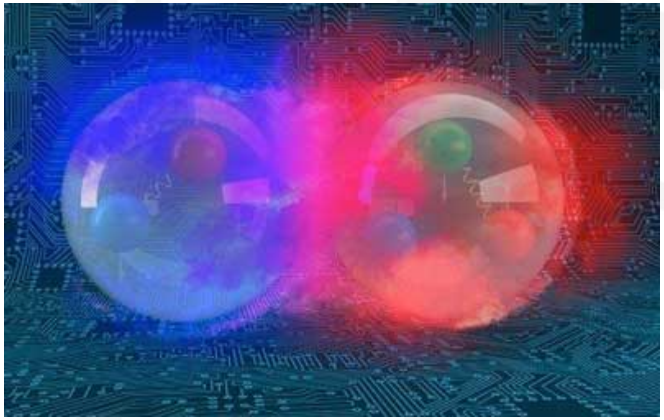
5 vector (unpolarized)

$$H_1^i, H_2^i, H_3^i, H_4^i, H_5^i$$

4 axial (polarized)

$$\tilde{H}_1^i, \tilde{H}_2^i, \tilde{H}_3^i, \tilde{H}_4^i$$





Related to the form factors

$$\int_{-1}^{1} H_i(x,\xi,t)dx = G_i(t) \quad i = 1,2,3$$

$$\int_{-1}^{1} \tilde{H}_i(x,\xi,t)dx = \tilde{G}_i(t) \quad i = 1,2$$

$$G_1(t) = G_C(t) - \frac{2}{3}\eta G_Q(t)$$

$$G_2(t) = G_M(t)$$

$$(1+\eta)G_3(t) = G_M(t) - G_C(t) + (1+\frac{2}{3}\eta)G_Q(t)$$

$$G_C(0) = 1, \quad G_M(0) = \mu_d = 1.74, \quad G_Q(0) = Q_d = 25.83$$

Sum rule

$$J_{q,g} = \frac{1}{2}\int dx x H_2^{q,g}(x,0,0)$$

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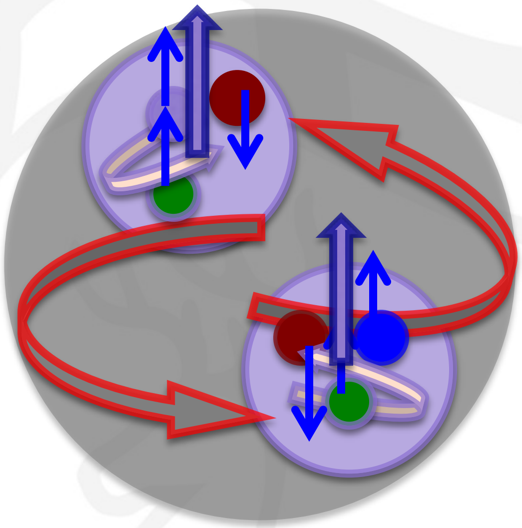
Deuteron BSA

$$A_{LU}(\phi) = \frac{x_A(2-y)\sqrt{\frac{-\Delta^2(1-y)}{Q^2}}}{2-2y+y^2}$$
$$\times \Im m \frac{2G_1\mathcal{H}_1 + (G_1 - 2\tau G_3)(\mathcal{H}_1 - 2\tau\mathcal{H}_3) + \frac{2}{3}\tau G_3 \mathcal{H}_5}{2G_1^2 + (G_1 - 2\tau G_3)^2}$$
$$\times sin(\phi)$$



Here $\mathcal{H}$s are the Compton form factor and they are related to GPDs by

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

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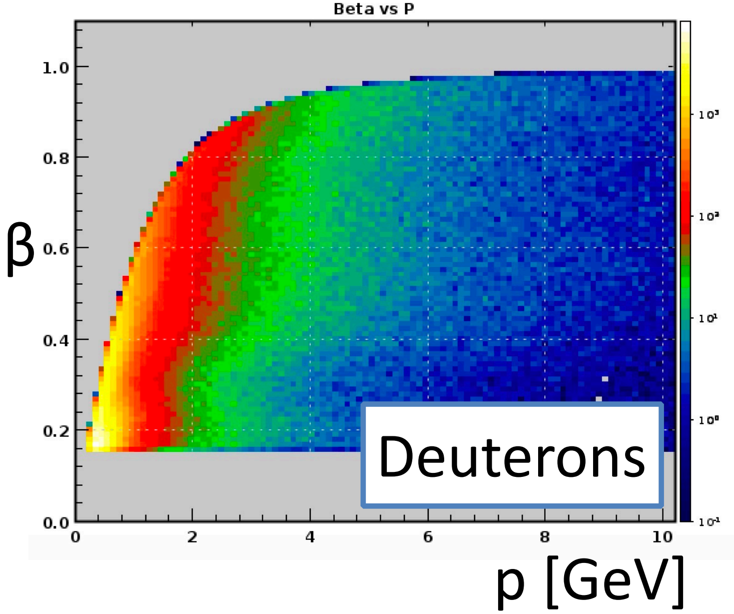
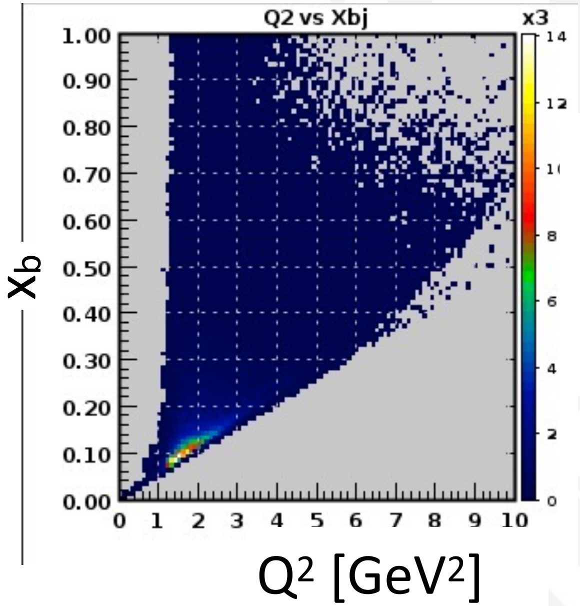
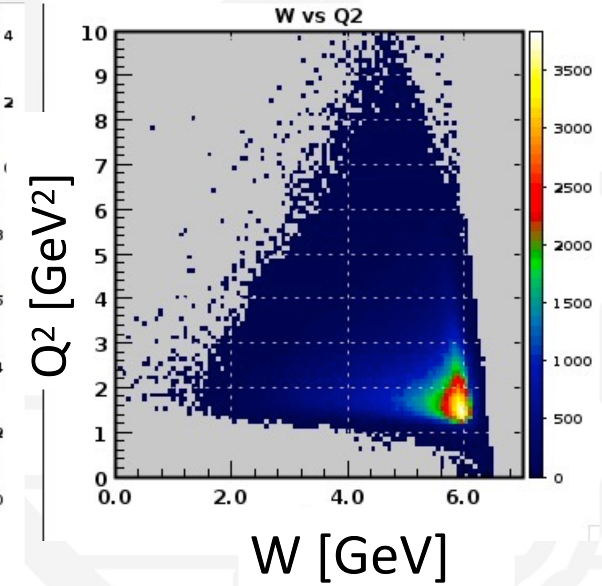
Coherent deuteron DVCS selection

Select events with:

- at least 1 electron, 1 deuteron and 1 gamma
- Electron: FD, Deuteron CD, gamma FT
- Deuterons: beta>0.16, minimum energy CTOF dE/dx>5







DVCS events:

- Q^2>2 GeV^2
- W>1 GeV
- E_g>2GeV
- p_D<2 GeV

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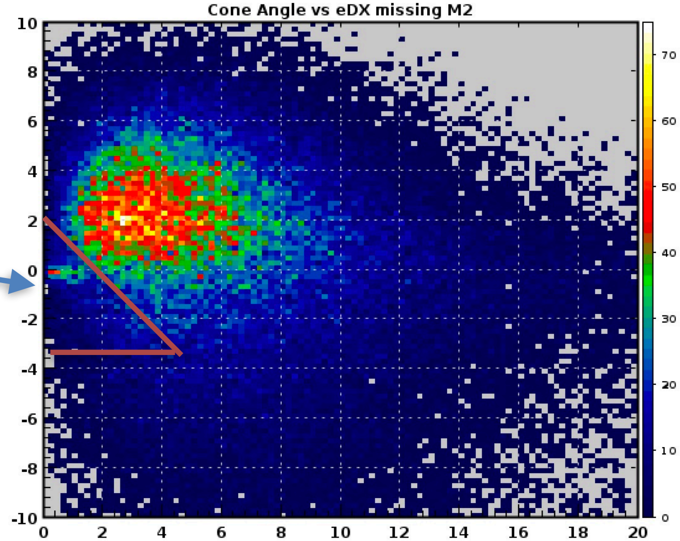
Coherent deuteron DVCS selection

Use the full exclusive channel to apply tight kinematic cuts to select coherent DVCS

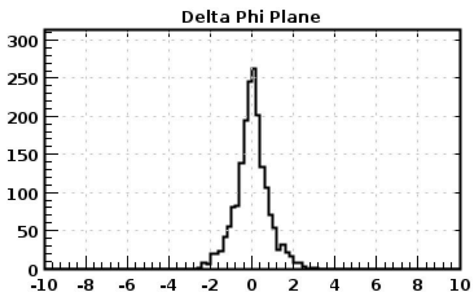
Coherent DVCS Candidates

M^2_{eDX} [GeV^2]



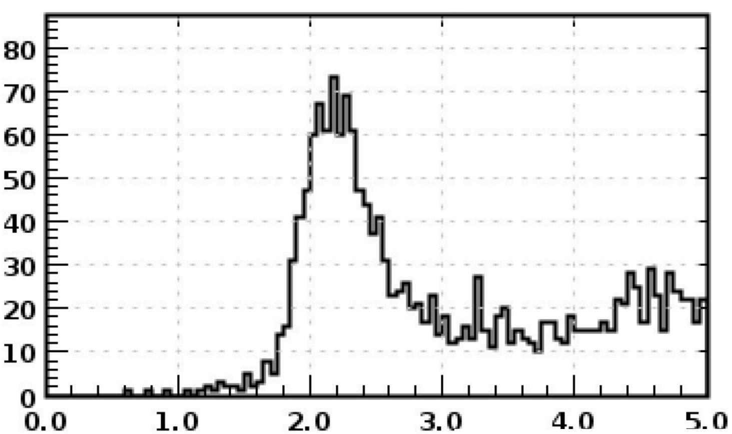
Cone angle

Cone angle:
angle between detected photon and missing eDX vectors

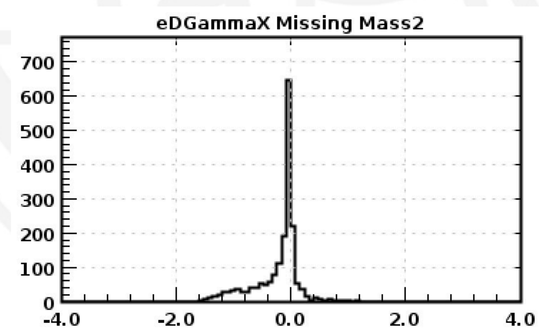


$\Delta\phi$ [deg]

All particles are co-planar



$M_{e\gamma X}$ [GeV]



$M^2_{eD\gamma X}$ [GeV^2]

No other particles missing

Conclusions

- GPD are a powerful and unique tool explore the structure of the nucleon
- GPDs are fully-correlated quark distributions in both coordinate and momentum space -> 3D imaging
- Complex extraction from data
  - 4 GPD for each quark flavor
  - GPDs depend on 3 variables but only two are experimentally accessible. Need models to map the x dependence
  - Cross sections depend on integrals of GPDs
- Neutron data essential for flavor separation
- Successful analyses of 6 GeV data in Hall A
- Preliminary results from RGB data
- Several upcoming experiments on neutron targets

nDVCS at EIC?

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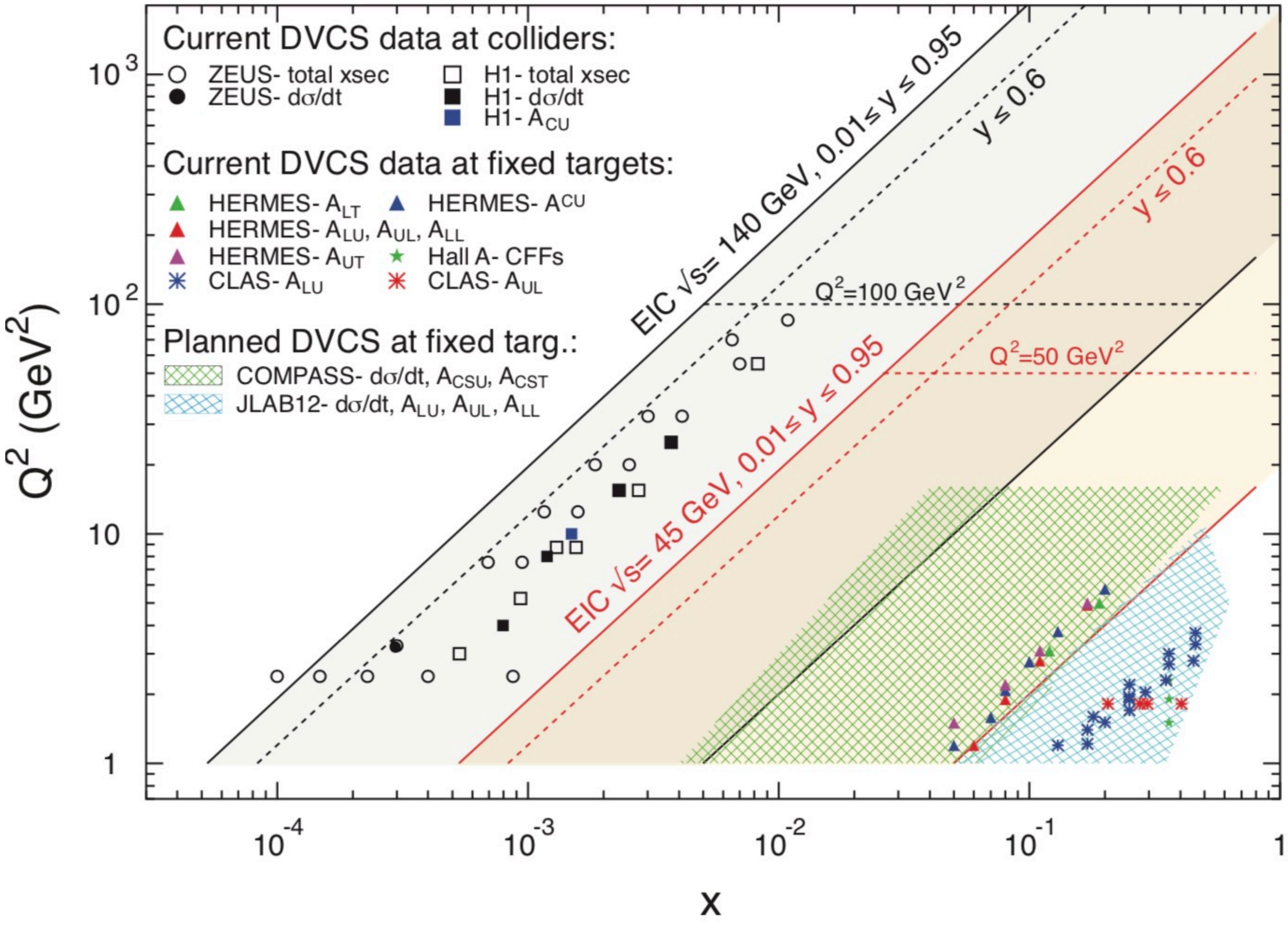
Thank you for the invitation.



DVCS summary

Observable	*Sensitivity to CFFs*	*Completed Experiments*	*12GeV experiments*
$\Delta\sigma_{beam}(p)$	Im $\mathcal{H}_p$	Hall A, CLAS	Hall A, CLAS12, Hall C
A_{LU} (p)	Im $\mathcal{H}_p$	HERMES CLAS	CLAS12
A_{UL} (p)	Im $\tilde{\mathcal{H}}_p$,Im $\mathcal{H}_p$	HERMES CLAS	CLAS12
A_{LL} (p)	Re $\tilde{\mathcal{H}}_p$,Re $\mathcal{H}_p$	HERMES, CLAS	CLAS12
A_{UT} (p)	Im $\mathcal{H}_p$,Im $\mathcal{E}_p$	HERMES	CLAS12
$\Delta\sigma_{beam}(n)$	Im $\mathcal{E}_n$	Hall A	
A_{LU} (n)	Im $\mathcal{E}_n$		CLAS12
A_{UL} (n)	Im $\mathcal{H}_n$		CLAS12
A_{LL} (n)	Re $\mathcal{H}_n$		CLAS12
TCS	Re $\mathcal{H}_n$ Im $\mathcal{H}_n$	CLAS (no published)	CLAS12

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CLAS12 schedule

Run Group	Days	2015	2016	2017	2018	2019	2020	2021	Remain
All Run Groups	**936**		CND	FT RICH MM			Trans. PT	**525**	**411**
HPS	180*	2-3	7 ?						
PRad	15*		10 ?						---
CLAS12 KPP				**15**					
RG-A (proton)	139*			20 **50**					69*
RG-F (BoNuS)	42*				**40**				2
RG-B (deut.)	90*				**45**				45*
RG-C (NH_3)	120				**15**	**45**			60
RG-C-b (ND_3)	65					**35**			30
RG-E (Hadr.)	60					**20**	**15**		25
RG-G (TT)	110*						**55**		55
RG-D (CT)	60						**30**		30
RG-K (LiD)	55							**55**	---

pDVCS BSA

nDVCS BSA

pDVCS TSA DSA

nDVCS TSA DSA

pDVCS tTSA

CLAS: DVCS neutron

$$e + \vec{d} \rightarrow e' + \gamma + n + (p_s)$$

Work by D. Sokhan

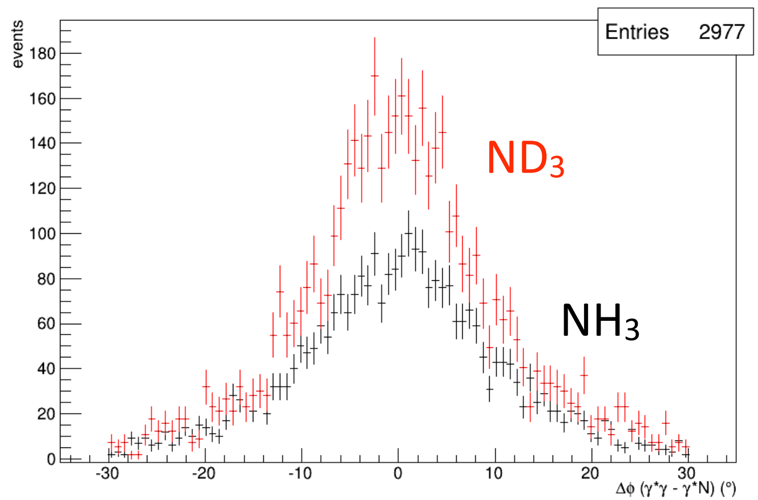
eg1-dvcs run
CLAS+IC

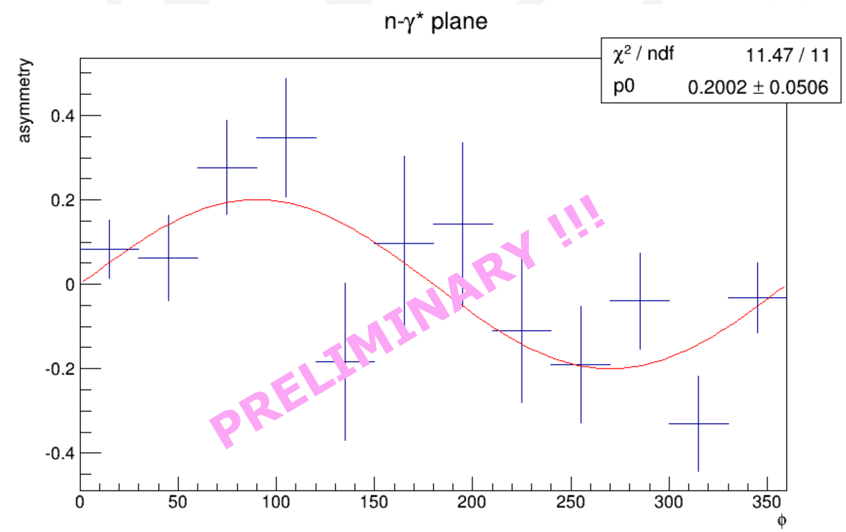
- NH3 95 days
- ND3 33 days

Analysis underway

E_b=6 GeV
beam pol=80%
neutron pol 30%

Non-zero BSA





Use NH_3 to subtract nuclear background

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