Jefferson Lab

Nucleon tomography
Status and Prospect

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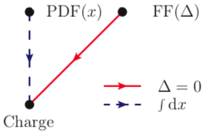
Overview

1. **Introduction**
2. **CLAS at 6 GeV**
3. **CLAS at 12 GeV**
4. **GPD extraction**
5. **Nucleon structure at collider(s)**
6. **Conclusion**

Introduction

Overview of the nucleon structure
Textbook description

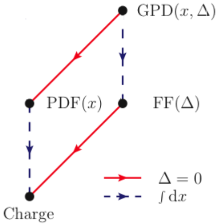
Parton Distribution Functions (PDF) and Form Factors (FF)



- PDF : measured in DIS
- Distribution in longitudinal momentum
- FF : measured in elastic
- (FT of) distribution in trasverse plane

Overview of the nucleon structure
GPD description

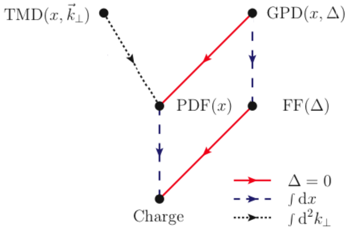
Generalized Parton Distributions (GPD)



- GPD : measured in exclusive processes
- Combines transverse plane and longitudinal momentum

Overview of the nucleon structure
TMD description

Transverse Momentum Dependend PDFs (TMD)

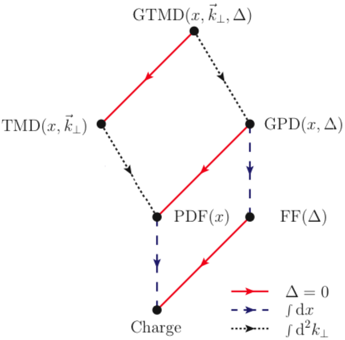


- TMD : measured in SIDIS
- 3D momentum description
- No model-independent relationship known with GPD

Overview of the nucleon structure

Most fundamental description

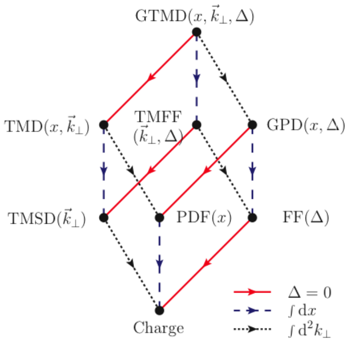
TMDs and GPDs are projections of the same Wigner function

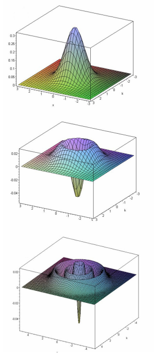


- Most general one-parton density matrix
- Not known how to measure
- Provides a unifying description
- Constraints for model building

Overview of the nucleon structure
Full picture

Inflation of acronyms





Unified framework for GPDs and TMDs within a 3Q LC picture of the nucleon

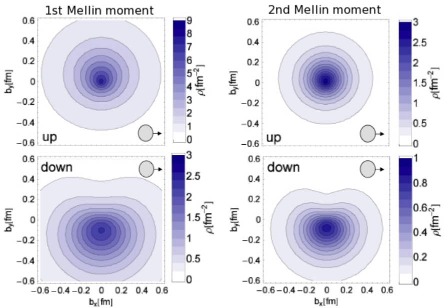
C. Lorce *et al*, arXiv:1102.4704 to appear in JHEP

Physical content of GPDs :

Momentum distributions in the transverse plane

$$q_X(x,\vec{b}_\perp) = \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} H(x,0,t) e^{-i\vec{\Delta}_\perp\cdot\vec{b}_\perp} - \frac{1}{2M}\frac{\partial}{\partial b_y}\int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} E(x,0,t) e^{-i\vec{\Delta}_\perp\cdot\vec{b}_\perp}$$

M. Burkardt, Phys. Rev. **D62**, (2000) 071503
$\xi \neq 0$ in M. Diehl, Eur. Phys. J. **C25** (2002) 223



QCDSF-UKQCD collaboration, Nucl. Phys. Proc. Suppl. **153** (2006) 146
($n = 1$ and 2 Mellin moment w.r.t. x of distributions)

u and *d* quarks have opposite orbital motions in a transversly polarized proton

Physical content of GPDs :

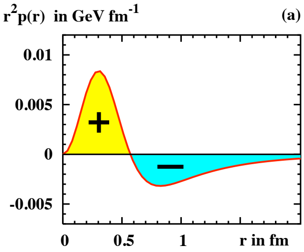
Energy-momentum tensor of q flavored quarks

$$\langle p_2 | \hat{T}^q_{\mu\nu} | p_1 \rangle = \bar{U}(p_2) \left[M_2^q(t) \frac{P_\mu P_\nu}{M} + J^q(t) \frac{\imath(P_\mu \sigma_{\nu\rho} + P_\nu \sigma_{\mu\rho})\Delta^\rho}{2M} + d_1^q(t) \frac{\Delta_\mu \Delta_\nu - g_{\mu\nu}\Delta^2}{5M} \right] U(p_1)$$

To measure gravitational FFs : graviton scattering or GPDs identities :

$$J^q(t) = \frac{1}{2} \int_{-1}^{1} \mathrm{d}x\, x \left[H^q(x,\xi,t) + E^q(x,\xi,t) \right] , \quad M_2^q(t) + \frac{4}{5} d_1(t) \xi^2 = \frac{1}{2} \int_{-1}^{1} \mathrm{d}x\, x H^q(x,\xi,t)$$

(Ji's sum rule)



$$\text{Stability} \Rightarrow \int_0^\infty \mathrm{d}r\, r^2 p(r) = 0$$

$r < 0.57$ fm $\Rightarrow p(r) > 0 \leftrightarrow$ repulsion (quark core)
$r > 0.57$ fm $\Rightarrow p(r) < 0 \leftrightarrow$ attraction (pion cloud)

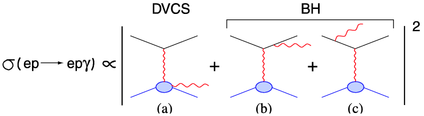
K.Goeke,*& al*, Phys. Rev. **D75** (2007) 094021

Access to GPDs : the DVCS process

Observables in the Bjorken limit

$$\gamma^* p \to \gamma p'$$

$$ep \to ep\gamma$$

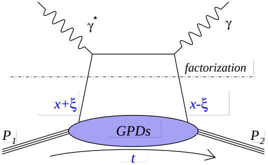


Bjorken regime :

$$Q^2 \to \infty,$$
$$\nu \to \infty,$$
$$x_B = Q^2/2M\nu \text{ fixed}$$
$$\left(\xi \to \frac{x_B}{2-x_B}\right)$$

Diehl, Gousset, Pire, Ralston (1997)

Belitsky, Müller, Kirchner (2002, 2010)

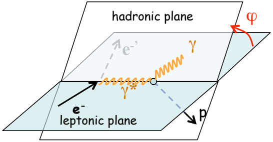


$$A_{LU} = \frac{d^4\sigma^{\rightarrow} - d^4\sigma^{\leftarrow}}{d^4\sigma^{\rightarrow} + d^4\sigma^{\leftarrow}} \overset{\text{twist-2}}{\approx} \frac{\alpha \sin\phi}{1 + \beta\cos\phi}$$

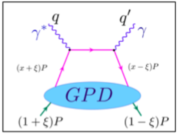
$$\alpha \propto \left(F_1 \mathcal{H} + \xi G_M \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E}\right)$$

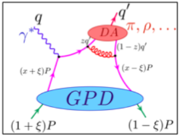
$$\mathcal{H}(\xi, t) = \pi \sum_q Q_q^2 \left[H^q(\xi, \xi, t) - H^q(-\xi, \xi, t)\right]$$

$$A_{UL} \propto \left(F_1 \tilde{\mathcal{H}} + \xi G_M \mathcal{H} + G_M \frac{\xi}{1+\xi} \mathcal{E} + \cdots\right) \sin\phi$$



Observables sensitivities to GPD





	$\mathcal{I}m$	$\mathcal{R}e$
$\mathcal{H}$	A_{LU}	σ , A_{LL}
$\tilde{\mathcal{H}}$	A_{UL}	
$\mathcal{E}$	A_{UT} , A_{LT}	

DVCS

	Meson	Flavor
$\tilde{\mathcal{H}}$,$\tilde{\mathcal{E}}$	π^+	$\Delta u - \Delta d$
	π^0	$2\Delta u + \Delta d$
	η	$2\Delta u - \Delta d + 2\Delta s$
$\mathcal{H}$,$\mathcal{E}$	ρ^+	$u - d$
	ρ^0	$2u + d$
	ω	$2u - d$
	ϕ	s

DVMP

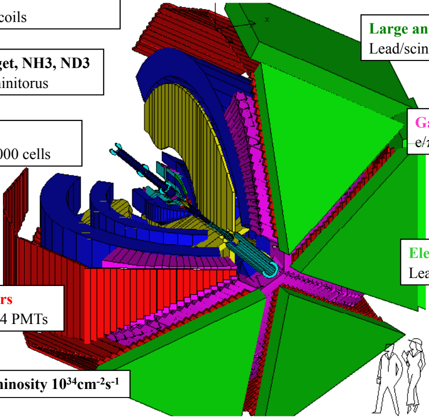
Only a global analysis of all observables can disentangle GPDs

Detector overview

Torus magnet
6 superconducting coils

Liquid D_2 (H_2)target, NH3, ND3
γ start counter; e^- minitorus

Drift chambers
argon/CO_2 gas, 35,000 cells



Large angle calorimeters
Lead/scintillator, 512 PMTs

Gas Cherenkov counters
e/π separation, 216 PMTs

Electromagnetic calorimeters
Lead/scintillator, 1296 PMTs

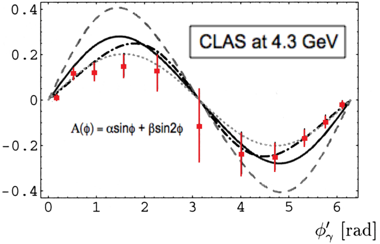
Time-of-flight counters
plastic scintillators, 684 PMTs

Operating luminosity 10^{34}cm^{-2}s^{-1}

Pioneering observations

First DVCS BSA and TSA observations

$A_{LU} \propto F_1\mathcal{H} + \xi G_M\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}$

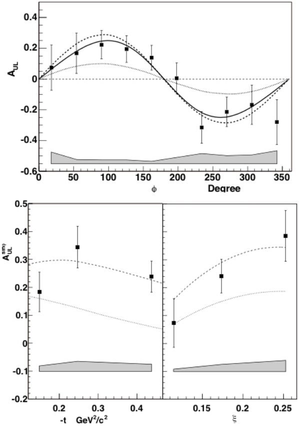


$Q^2 = 1.3$ GeV^2, $x_B = 0.2$, $-t = 0.2$ GeV^2

$$
\begin{aligned}
A(\phi) &= \alpha \sin\phi + \beta \cos(2\phi) \\
\alpha &= 0.202 \pm 0.028^{\text{stat}} \pm 0.013^{\text{syst}} \\
\beta &= -0.024 \pm 0.021^{\text{stat}} \pm 0.009^{\text{syst}}
\end{aligned}
$$

S. Stepanyan *at al.*,
PRL **87** (2001) 182002

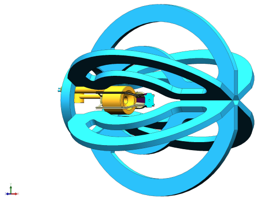
$A_{UL} \propto F_1\tilde{\mathcal{H}} + \xi G_M\left(\mathcal{H} + \frac{\xi}{1+\xi}\mathcal{E}\right) - \cdots$

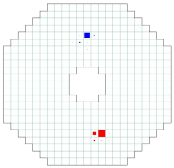


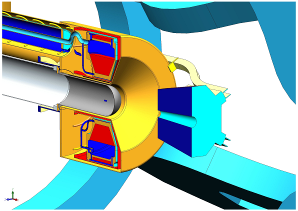
S. Chen *et al.*,
PRL **97** (2006) 072002

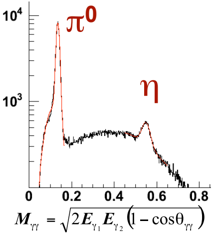
Solenoid and Inner Calorimeter

Hydrogen target, beam polarisation $\approx 80\%$, $\int \mathcal{L} \approx 45\ \mathrm{fb}^{-1}$

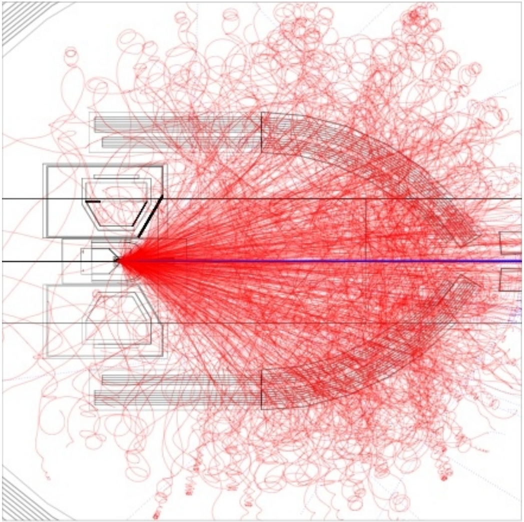




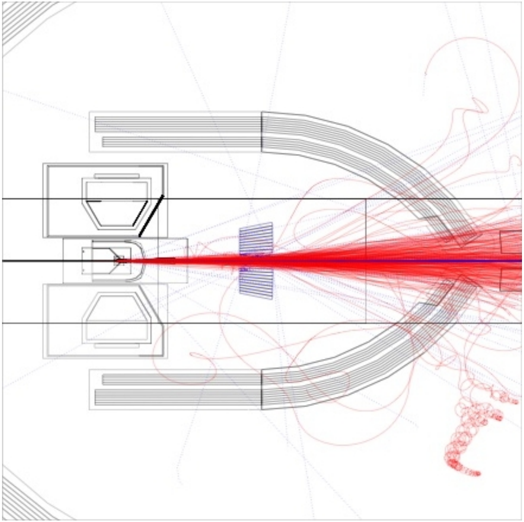




Solenoid and Inner Calorimeter

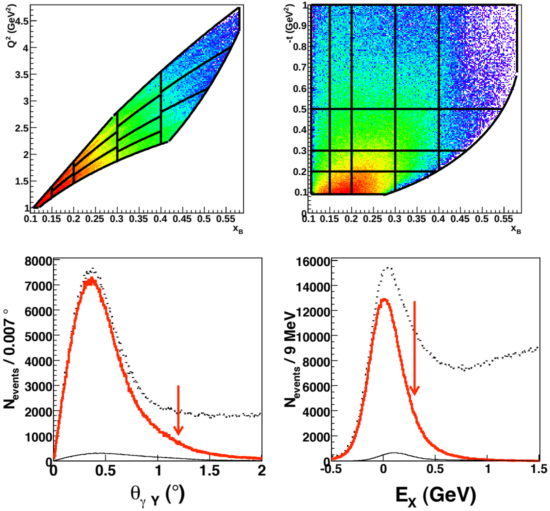


Solenoid and Inner Calorimeter



Flavor of analysis

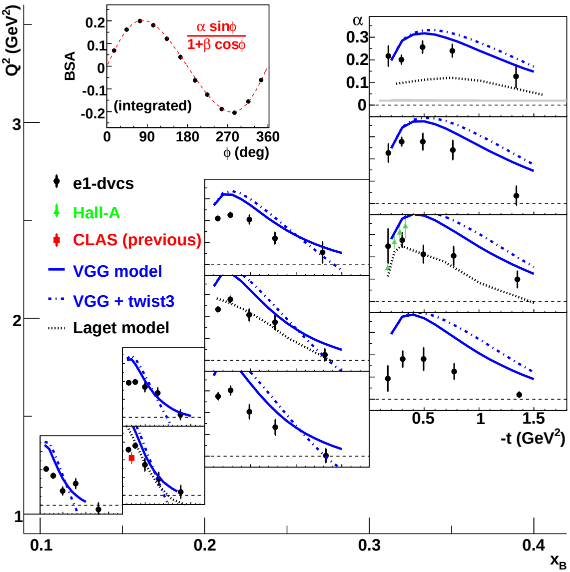
- kinematical coverage
- exclusivity cuts
- π^0 subtraction



Selected results

Proton BSA

$$F_1\mathcal{H} + \xi G_M\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}$$

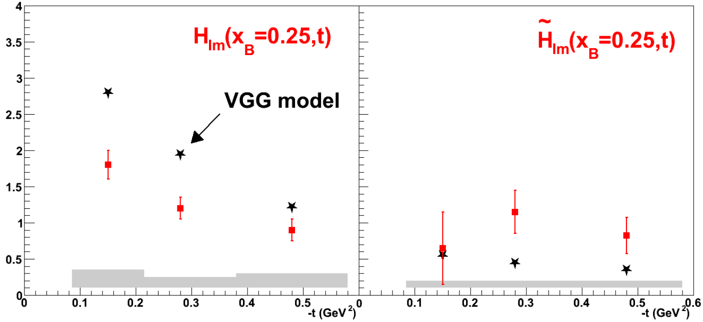


F.-X. G. *et al.*, PRL **100** (2008) 162002

Model independent extraction

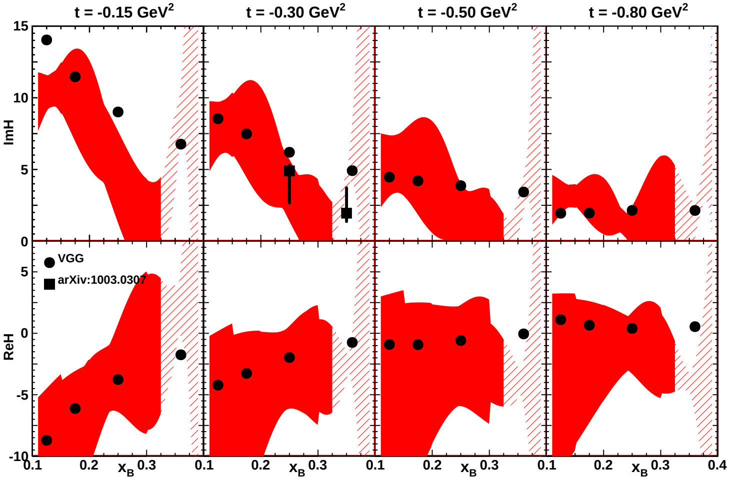
Using only A_{LU} and A_{UL} with sensitivity to $\mathcal{H}$ and $\tilde{\mathcal{H}}$

- CFFs varied within VGG model range
- Independence on Q^2
- $\tilde{\mathcal{H}}(t)$ more flat than $\mathcal{H}(t)$
- Stable results
- Large uncertainties



M. Guidal, arXiv:1003.0307

Global analysis of CFFs

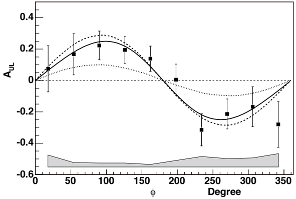


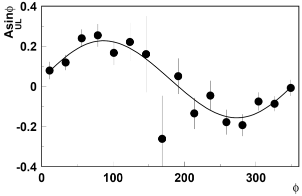
H. Moutarde, PR **D79** (2009) 094021

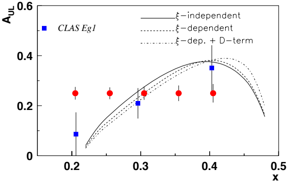
$A_{UL} \propto F_1 \tilde{\mathcal{H}}$

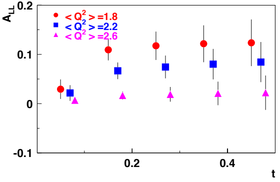
- Increase statistics with
  - better background conditions for σ and BSA
  - charged particle tagging in the Inner Calorimeter
- Dedicated experiment for $TSA_{||}$ with IC

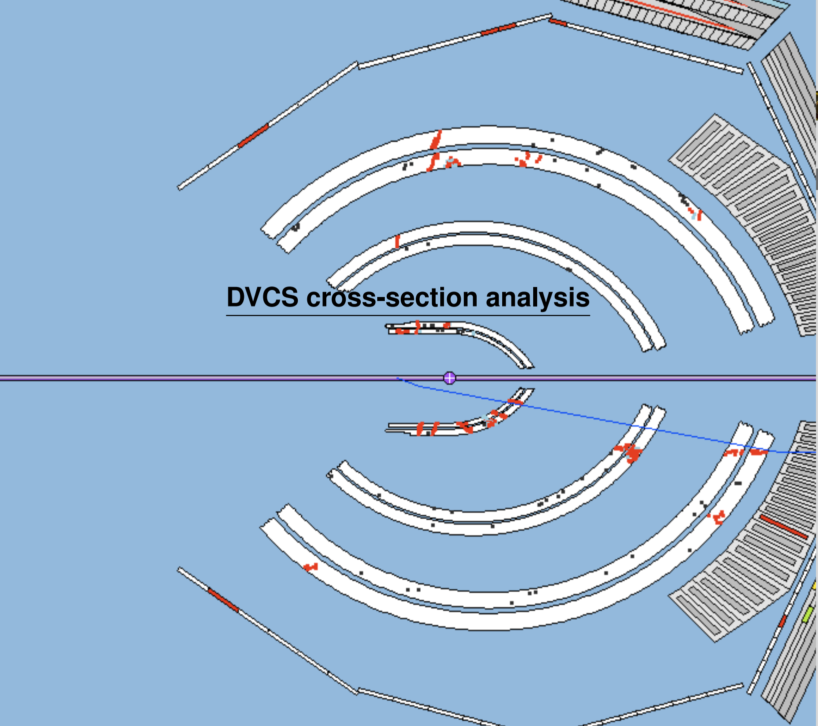
$$A_{UL} \propto F_1 \tilde{\mathcal{H}} + \xi G_M \left(\mathcal{H} + \frac{\xi}{1+\xi} \mathcal{E} \right) - \cdots$$







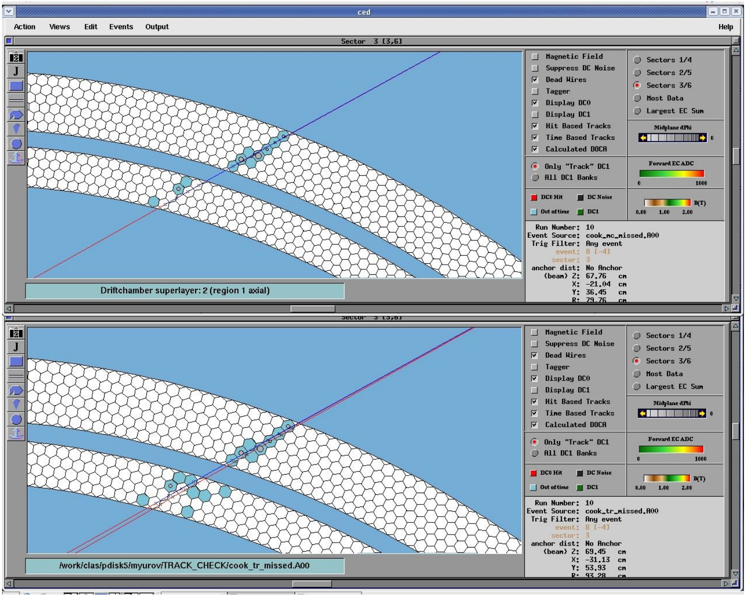




DVCS cross-section analysis

Random background and efficiencies

Illustration of lost electron track :



Random background and efficiencies

Quantitative conclusions :

Merging the background from data with simulation results in $\approx$ 30%

(1)	Not reconstructed	1.8%
(2)	stat[0]>0 cut	74.5%
(3)	ecsfr cut	0.9%
(4)	nphe>25 cut	4.7%
(5)	ficudial cut	0.9%
(6)	stat>0 (others)	14.4%
(7)	charge>0	1.8%
(8)	id==2212 cut	0.9%

Electron recovery procedure
Search for matching TB track with CC hit
Data : 9.4%
MC : 10.8%
remarquable test of consistency

Trigger recovery procedure
$\approx$ 5%

Final background correction $\approx$ 15%

First order radiative corrections
Another convenient factorization theorem

$$\left.\frac{d\sigma}{d\Omega}\right|_{\text{exp}} = \left.\frac{d\sigma}{d\Omega}\right|_{\text{Virtual }\gamma} + \left.\frac{d\sigma}{d\Omega}\right|_{\text{Real }\gamma}$$

$$= \left.\frac{d\sigma}{d\Omega}\right|_{\text{Born}} \left[1 + \delta_{\text{Vertex}} + \delta_{\text{Vacuum}} + \delta_{\text{Real}}(\Delta E)\right]$$

First order radiative corrections

Expressions for the virtual and real corrections

$$\delta_{\text{Vacuum}} = \frac{2\alpha}{3\pi}\left[\ln\left(\frac{Q^2}{m_e^2}\right) - \frac{5}{3}\right] + \infty$$

$$\delta_{\text{Vertex}} = \frac{\alpha}{\pi}\left[\frac{3}{2}\ln\left(\frac{Q^2}{m_e^2}\right) - 2 - \frac{1}{2}\ln^2\left(\frac{Q^2}{m_e^2}\right) + \frac{\pi^2}{6}\right] + \infty$$

$$\delta_{\text{Real}}(\Delta E) = \frac{\alpha}{\pi}\left\{2\ln\left(\frac{\Delta E}{\sqrt{EE'}}\right)\left[\ln\left(\frac{Q^2}{m_e^2}\right) - 1\right] - \frac{1}{2}\ln^2\frac{E}{E'} + \frac{1}{2}\ln^2\left(\frac{Q^2}{m_e^2}\right) - \frac{\pi^2}{3} + \mathrm{Sp}\left(\cos^2\frac{\theta_e}{2}\right)\right\} + \infty$$

$\delta_{\text{Vertex}} + \delta_{\text{Vacuum}} + \delta_{\text{Real}}(\Delta E)$ finite

All order resummation
Bloch & Nordsieck's magic

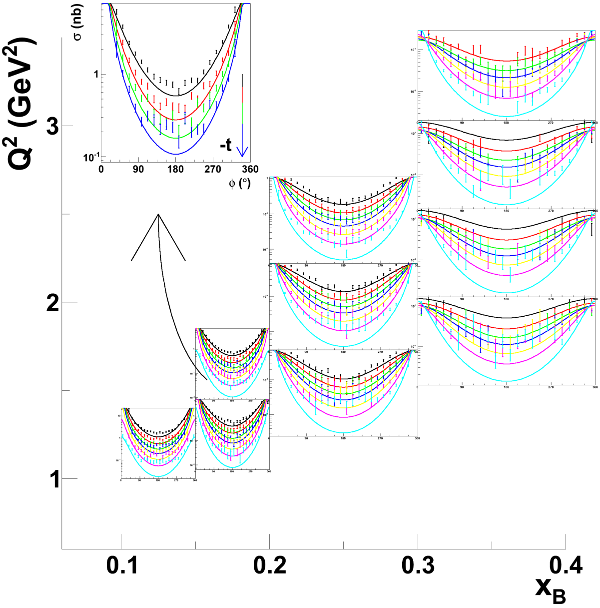
$$\left.\frac{d\sigma}{d\Omega}\right|_{\text{exp}} = \left.\frac{d\sigma}{d\Omega}\right|_{\text{Born}} \frac{e^{\delta_{\text{Vertex}}+\delta^0_{\text{Real}}}}{(1-\delta_{\text{Vacuum}}/2)^2} \left(\frac{\Delta E}{\sqrt{EE'}}\right)^{\delta_S}$$

$$\delta_S = \frac{2\alpha}{\pi}\left[\ln\left(\frac{Q^2}{m_e^2}\right)-1\right]$$

δ_S defining the radiative lineshape (soft-photon approximation) (soft-photon approximation) is integrated through fast-MC, in order to properly convolute with the 5-fold acceptance.

N.B.: This already is only justified in the peaking approximation

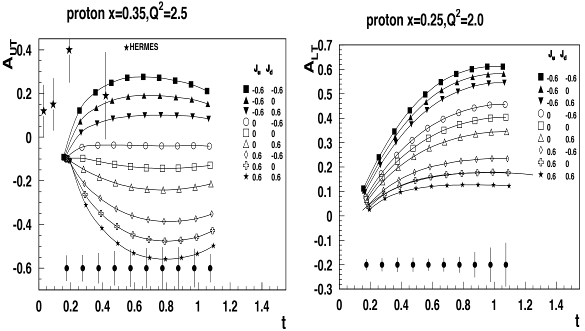
Proton cross-section (preliminary) $F_1\mathcal{H} + \xi G_M\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}$



A_{UT} and A_{LT}

Conditionally approved experiment with HD-Ice target (2012)

$\frac{t}{4M^2}\,(F_2\mathcal{H} - F_1\mathcal{E})$



Model-dependent extraction of J_u and J_d

Combined fit to all data will allow separation of $\mathcal{H}$, $\mathcal{E}$ and $\tilde{\mathcal{H}}$

BSA in π^0 SIDIS
Collins or Boer-Mulders ?

$$\frac{d\sigma_{\mathrm{LU}}}{dx_{\mathrm{B}}\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{\mathrm{T}}^2\,\mathrm{d}\phi_{\mathrm{h}}} = \frac{2\pi\alpha^2}{x_{\mathrm{B}}yQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x_{\mathrm{B}}}\right)\lambda_e\sqrt{2\epsilon(1+\epsilon)}\sin\phi_h F_{\mathrm{LU}}^{\sin\phi_h}$$

$$F_{\mathrm{LU}}^{\sin\phi_h} = \frac{2M}{Q}\int \mathrm{d}^2\mathbf{p}_T\mathrm{d}\mathbf{k}_T^2\delta^{(2)}(\mathbf{p}_T-\frac{P_T}{z}-\mathbf{k}_T)\times\hat{P}_T\cdot$$
$$\left\{\left[\frac{M_h}{M}h_1^{\perp}\frac{\tilde{E}}{z}+x_{\mathrm{B}}g^{\perp}D_1\right]\frac{\mathbf{p}_T}{M}-\left[\frac{M_h}{M}f_1\frac{\tilde{G}^{\perp}}{z}+x_{\mathrm{B}}eH_1^{\perp}\right]\frac{\mathbf{k}_T}{M_h}\right\}$$

P_T detected hadron

$\mathbf{p}_T$ active quark in Boer-Mulders DF $h_1^{\perp}$

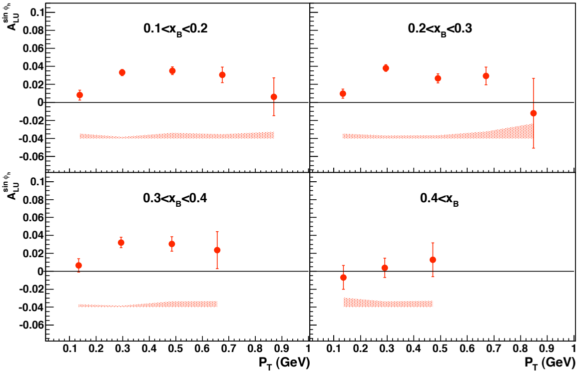
$\mathbf{k}_T$ active quark in Collins FF $H_1^{\perp}$

The calculations based on the Boer-Mulders part predicted a sizable BSA

Those based on the Collins mechanism predict a vanishing BSA for the π^0

BSA in π^0 SIDIS

Preliminary results

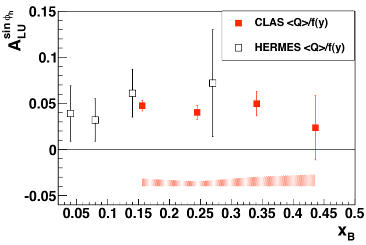


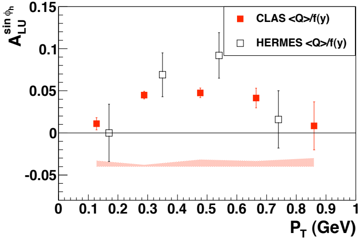
Without significant contribution from the Collins mechanism
this would be evidence for spin-orbit correlations, or another dynamical origin

BSA in π^0 SIDIS
Comparison with HERMES

The comparison includes a compensation for different kinematics

$$\sqrt{2\epsilon(1+\epsilon)} \quad \approx \quad f(y) = \frac{y\sqrt{1-y}}{1-y+y^2/2}$$





DVCS on a scalar nucleus

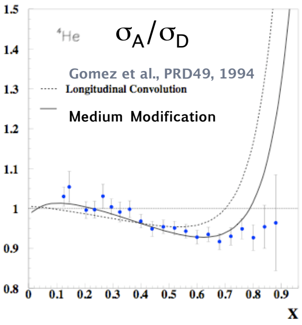
Only one twist-2 GPD, real and imaginary parts of the CFF can be fitted from the BSA simultaneously

EMC effect :

- Fermi motion ?
- Shadowing ?
- Off-shell effects ?
- $\cdots$?

Non-forward EMC effect provides additional constraints to the models

^{4}He is dense and simple enough for exact calculations at the proton and neutron level



DVCS on a scalar nucleus

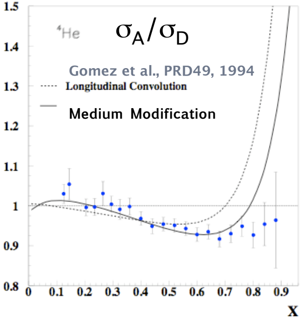
Only one twist-2 GPD, real and imaginary parts of the CFF can be fitted from the BSA simultaneously

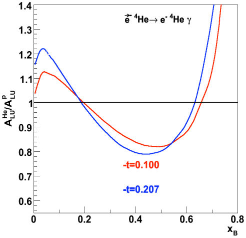
EMC effect :

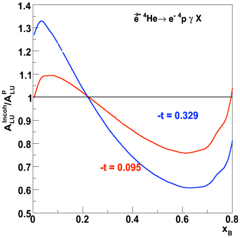
- Fermi motion ?
- Shadowing ?
- Off-shell effects ?
- . . . ?

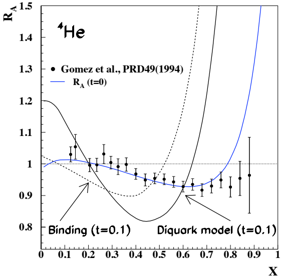
Non-forward EMC effect provides additional constraints to the models

^{4}He is dense and simple enough for exact calculations at the proton and neutron level

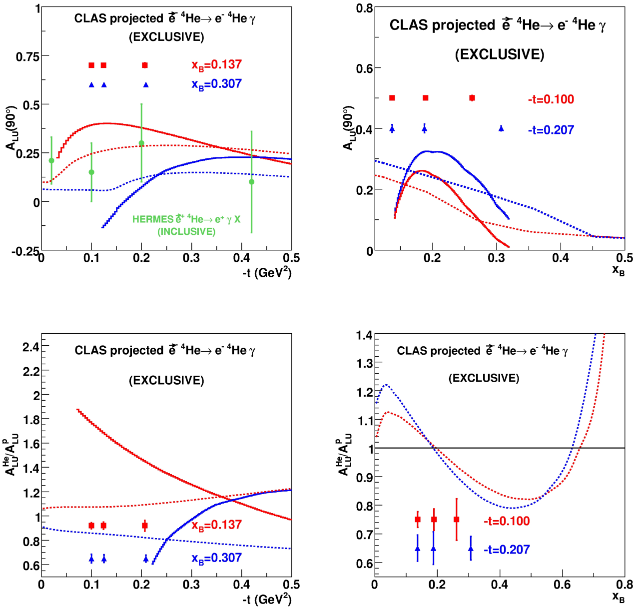




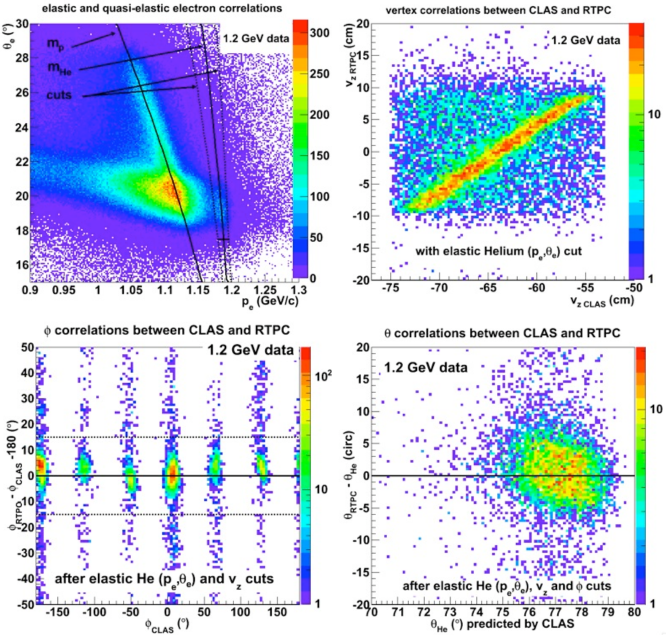




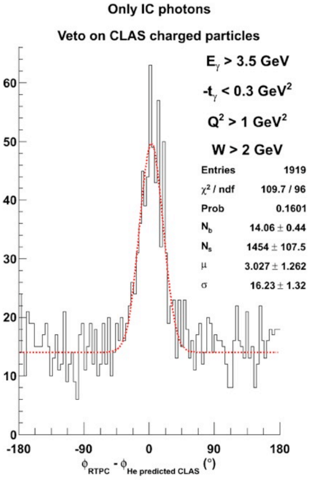
Projected results BSA and CFF



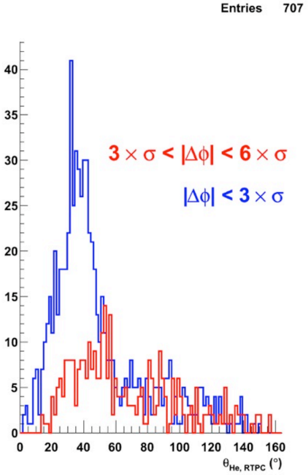
He elastic


elastic and quasi-elastic electron correlations
1.2 GeV data
m_p
m_{He}
cuts
θ_e (°)
p_e (GeV/c)
vertex correlations between CLAS and RTPC
1.2 GeV data
with elastic Helium (p_e,θ_e) cut
$v_{z\,RTPC}$ (cm)
$v_{z\,CLAS}$ (cm)
ϕ correlations between CLAS and RTPC
1.2 GeV data
after elastic He (p_e,θ_e) and v_z cuts
$\phi_{RTPC} - \phi_{CLAS}$ -180 (°)
ϕ_{CLAS} (°)
θ correlations between CLAS and RTPC
1.2 GeV data
after elastic He (p_e,θ_e), v_z and ϕ cuts
$\theta_{RTPC} - \theta_{He}$ (circ)
θ_{He} (°) predicted by CLAS

He DVCS ?



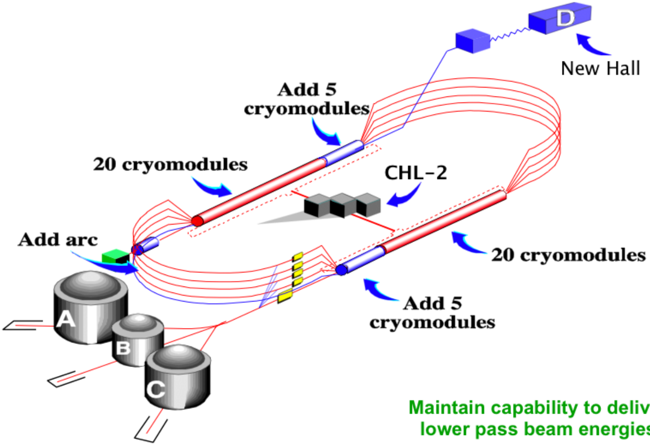
Only IC photons
Veto on CLAS charged particles
E_γ > 3.5 GeV
$-t_\gamma$ < 0.3 GeV^2
Q^2 > 1 GeV^2
W > 2 GeV
Entries 1919
χ^2 / ndf 109.7 / 96
Prob 0.1601
N_b 14.06 ± 0.44
N_s 1454 ± 107.5
μ 3.027 ± 1.262
σ 16.23 ± 1.32
$\phi_{RTPC} - \phi_{He\ predicted\ CLAS}$ (°)



Entries 707
$3 \times \sigma < |\Delta\phi| < 6 \times \sigma$
$|\Delta\phi| < 3 \times \sigma$
$\theta_{He,\ RTPC}$ (°)

12 GeV upgrade

JLab12

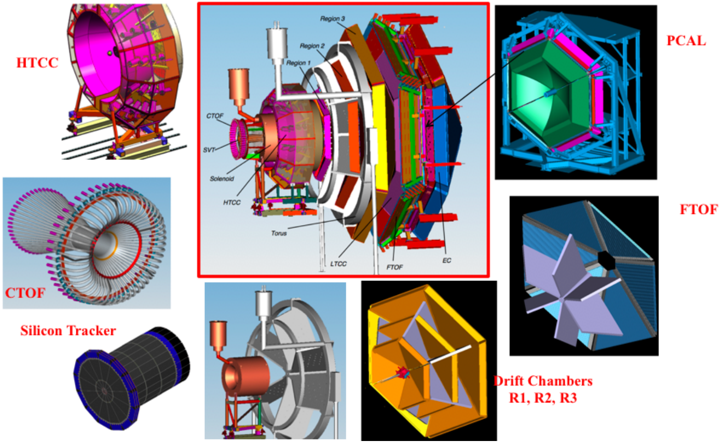


Enhanced capabilities in existing Halls

Maintain capability to deliver lower pass beam energies

Upgraded apparatus

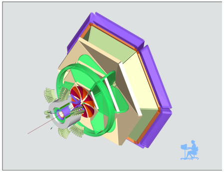
Higher energy, luminosity, hermiticity, analyzing power

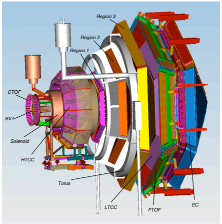


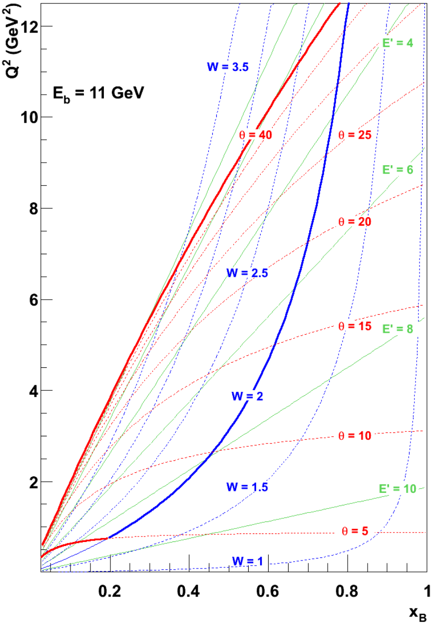
Upgraded apparatus

	Forward detector	Central detector
Angular range		
Tracks	$5 - 40^\circ$	$35 - 125^\circ$
Photons	$2.5 - 40^\circ$	n.a.
Resolution		
$\delta p/p$	< 1% @ 5 GeV/c	5% @ 1.5 GeV/c
$\delta\theta$	< 1 mr	< 10-20 mr
$\delta\phi$	< 3 mr	< 5 mr
Photon detection		
Energy	> 0.15 GeV	n.a.
$\delta\theta$	4 mr @ 1 GeV	n.a.
Neutron detection		
Efficiency	< 0.7	under dev.
Particle ID		
e/π	Full range	n.a.
π/p	Full range	< 1.25 GeV/c
π/K	Full range	< 0.65 GeV/c
K/p	< 4 GeV/c	< 1 GeV/c
$\pi \to \gamma\gamma$	Full range	n.a.
$\eta \to \gamma\gamma$	Full range	n.a.

Upgraded apparatus





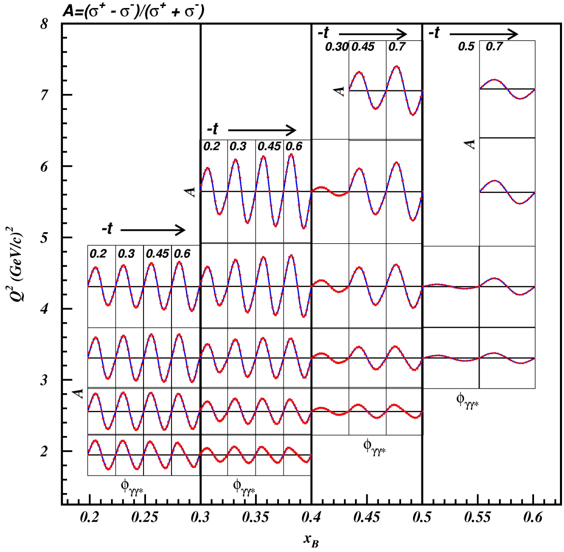


GPD program

Proton DVCS

Proton DVCS A_{LU}

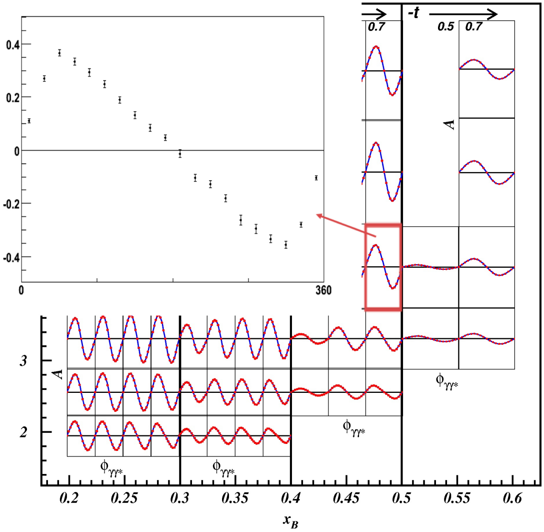
80 days @ $\mathcal{L} = 10^{35}$ cm^{-2}s^{-1} with 85% polarized beam



Statistical uncertainties from 1 % (low Q^2) to 10 % (high Q^2)

Proton DVCS A_{LU}

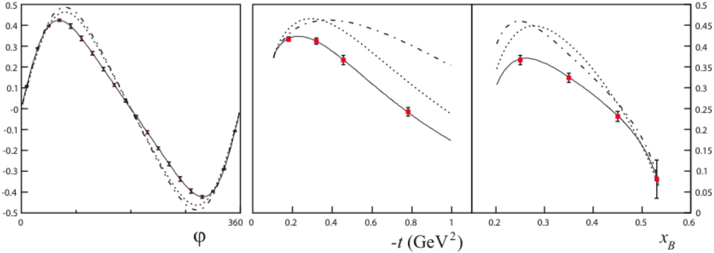
80 days @ $\mathcal{L} = 10^{35}$ cm^{-2}s^{-1} with 85% polarized beam



Statistical uncertainties from 1 % (low Q^2) to 10 % (high Q^2)

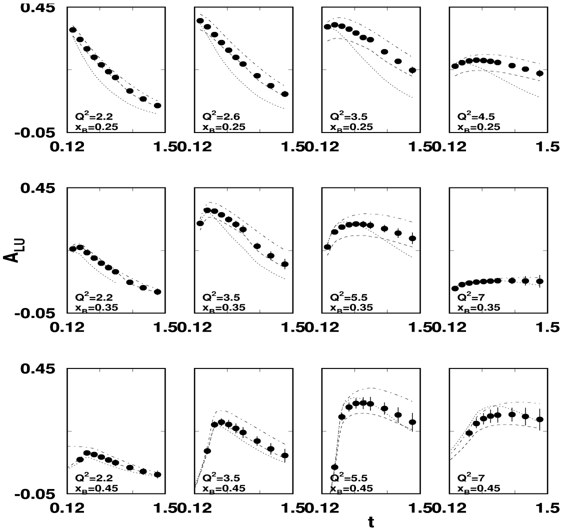
Proton DVCS A_{LU}

80 days @ $\mathcal{L} = 10^{35}$ cm^{-2}s^{-1} with 85% polarized beam



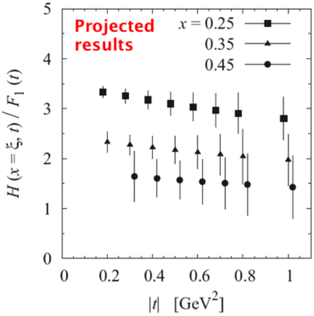
Dotted curve : no D-term, dashed-dotted : factorized t-dependence
$Q^2 = 3.3$ GeV^2, $x_B = 0.2$ (left and middle), $-t = 0.45$ GeV^2 (left and right)

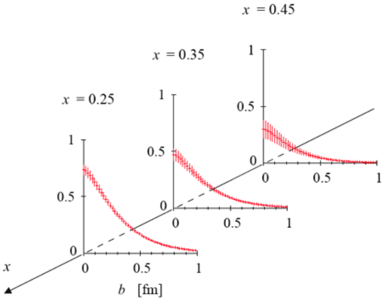
Proton DVCS A_{LU}



Proton DVCS A_{LU}

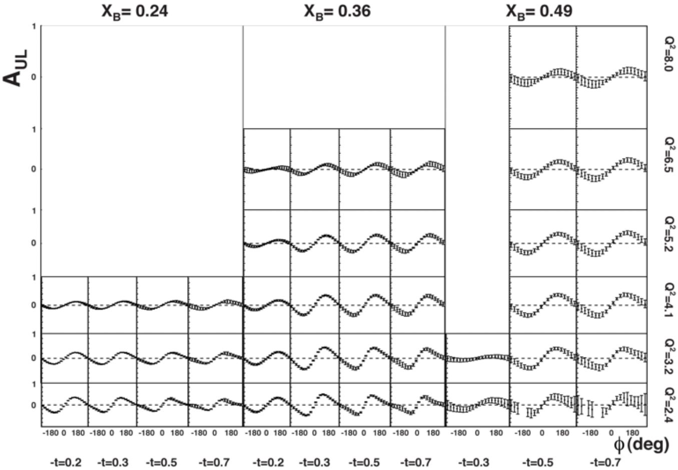
Extracted $H(\xi, \xi, t)$ and corresponding transverse profile





Proton DVCS TSA A_{UL}

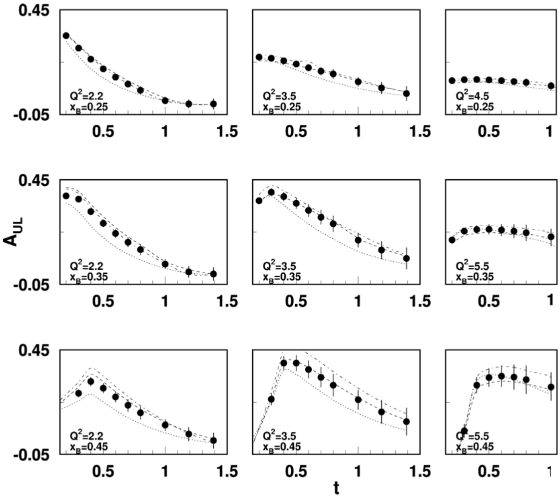
120 days @ $\mathcal{L} = 2 \times 10^{35}$ cm^{-2}s^{-1} with 80% polarized NH_3



Statistical uncertainties from 2 % (low Q^2) to 10 % (high Q^2)

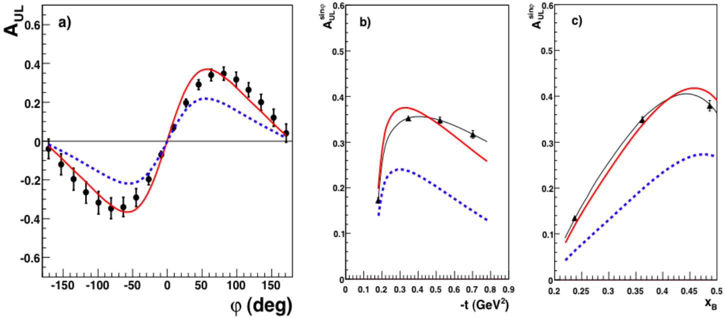
Proton DVCS TSA A_{UL}

120 days @ $\mathcal{L} = 2 \times 10^{35}$ cm^{-2}s^{-1} with 80% polarized NH_3



Proton DVCS TSA A_{UL}

120 days @ $\mathcal{L} = 2 \times 10^{35}$ cm^{-2}s^{-1} with 80% polarized NH_3



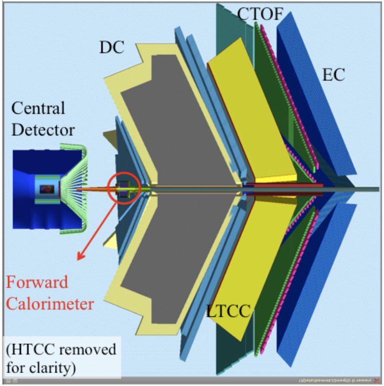
Red solid line : $E = \tilde{E} = 0$, blue dashed line : $\tilde{H} = 0$
$Q^2 = 4.1$ GeV^2, $x_B = 0.36$ (left and middle), $-t = 0.52$ GeV^2 (left and right)

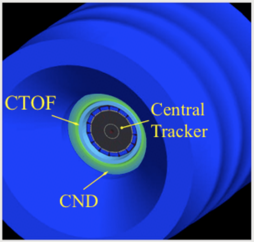
GPD program

Neutron DVCS

Neutron DVCS setup

For the detection of the scattered electron and of the DVCS photon: CLAS12 + Forward Calorimeter



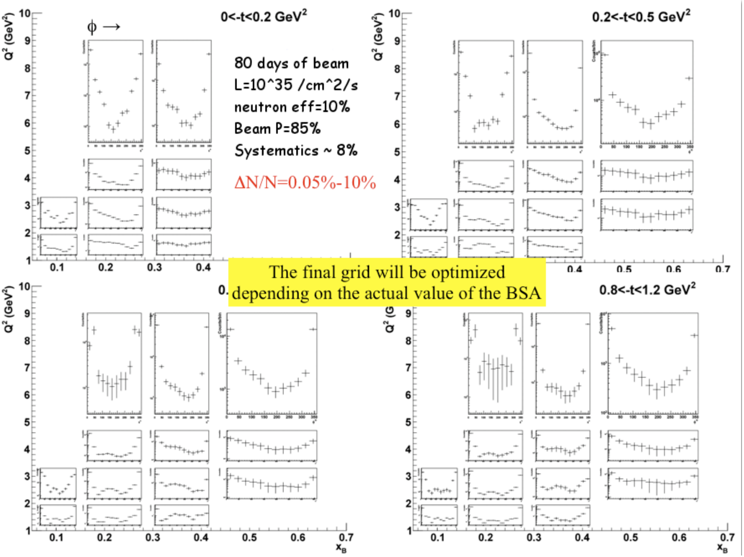


For the detection of the recoil neutron: Central Neutron Detector (CND)

Detection efficiency : 7 to 10 %

Acceptance for charged particles:
- **Central (CD), $40^{o}<\theta<135^{o}$**
- **Forward (FD), $5^{o}<\theta<40^{o}$**

Acceptance for photons:
- **FC $2.5^{o}<\theta< 5^{o}$**
- **EC, $5^{o}<\theta<40^{o}$**


0<-t<0.2 GeV²
0.2<-t<0.5 GeV²
0.8<-t<1.2 GeV²
ϕ →
80 days of beam
L=10^35 /cm^2/s
neutron eff=10%
Beam P=85%
Systematics ~ 8%
ΔN/N=0.05%-10%
The final grid will be optimized depending on the actual value of the BSA
Q² (GeV²)
x_B

GPD program

Other highlights

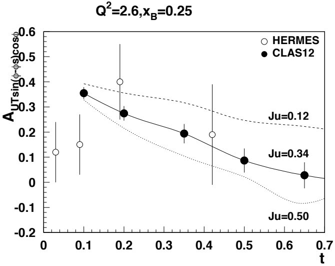
Transverse target asymmetries A_{UT}, DVCS & DVMP

More on angular momentum

DVCS with frozen HD-ice

$x_B \approx 0.25$

$Q^2 \approx 2.6$ GeV^2

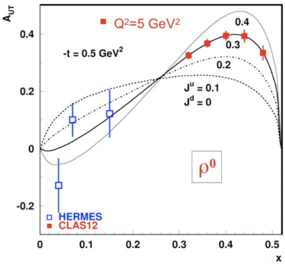


Exclusive ρ^0 production (hydrogen target)

$A_{UT} \sim \Delta_\perp \mathrm{Im} AB^*$

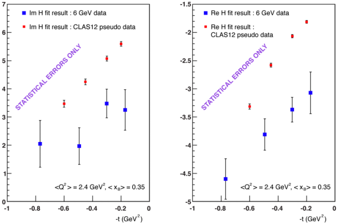
$A \sim 2H^u + H^d$

$B \sim 2E^u + E^d$

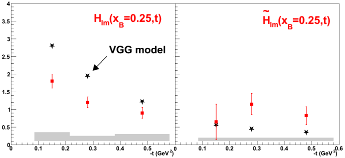


GPD Extraction

Efforts towards GPD extraction

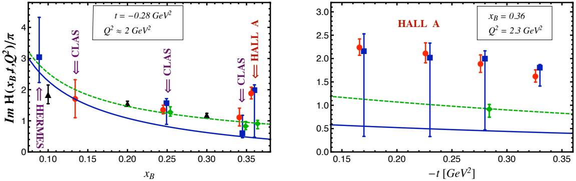


H. Moutarde, **PRD 79** (2009) 094021



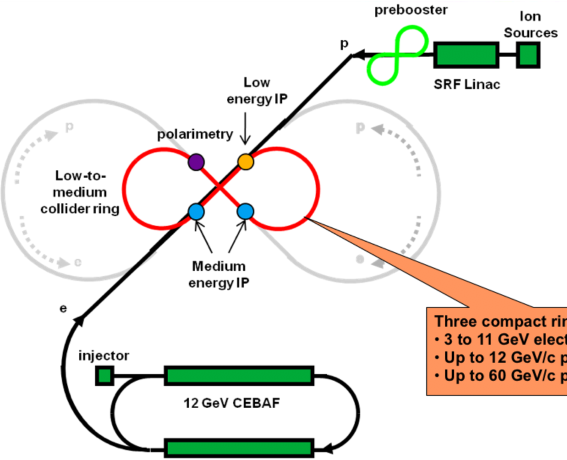
M. Guidal **PLB 689** (2010) 156

K. Kumericki & D. Mueller, arXiv:1008.2762



Medium energy Electron Ion Collider

JLab's design



Three compact rings:
- **3 to 11 GeV electron**
- **Up to 12 GeV/c proton (warm)**
- **Up to 60 GeV/c proton (cold)**

Interplay between spin and flavor decompositions

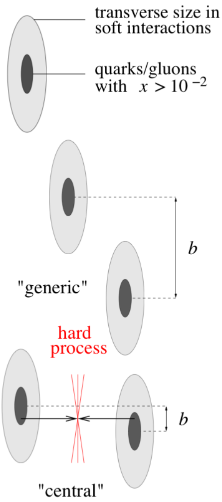
	Process	Flavor	$q/\bar{q}/g$	
$\mathcal{H}$,$\mathcal{E}$,$\tilde{\mathcal{H}}$,$\tilde{\mathcal{E}}$	pDVCS	$4u + d + s$	$q + \bar{q}\,,\, \alpha_S g$	
	nDVCS	$4d + u + s$	$q + \bar{q}\,,\, \alpha_S g$	(polarized) deuteron
$\mathcal{H}$,$\mathcal{E}$	ρ^+	$u - d$	$q + \bar{q}\,,\, g$	Im($\mathcal{H}E^*$) in A_{UT}
	ρ^0	$2u + d$	$q + \bar{q}\,,\, g$	
	ω	$2u - d$	$q + \bar{q}\,,\, g$	
	ϕ	s	$q + \bar{q}\,,\, g$	
	$J/\psi\,,\, \Upsilon$		g	
	$(\pi^+\pi^-)_{L=0}$	$2u - d$	$q - \bar{q}$	interfere with $(\pi^+\pi^-)_{L=1}$
	$K^{*0}\Sigma^+\,,\, K^{*+}\Sigma^0$	$d - s$	$2q - \bar{q}$	SU(3)
	$K^{*+}\Lambda$	$2u - d - s$	$2q - \bar{q}$	SU(3)
$\tilde{\mathcal{H}}$,$\tilde{\mathcal{E}}$	π^+	$\Delta u - \Delta d$	$2q - \bar{q}$	
	π^0	$2\Delta u + \Delta d$	$q - \bar{q}$	
	η	$2\Delta u - \Delta d + 2\Delta s$	$q - \bar{q}$	
	$K^{*0}\Sigma^+\,,\, K^{*+}\Sigma^0$	$d - s$	$2q + \bar{q}$	SU(3)
	$K^{*+}\Lambda$	$2u - d - s$	$2q + \bar{q}$	SU(3)

M. Diehl, "Which GPDs in which processes", INT workshop Nov. 10$^{\text{th}}$ 2010

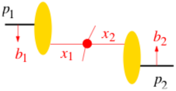
Interplay between spin and flavor decompositions

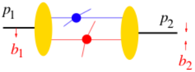
- Spin asymmetries have sensitivities to the imaginary parts of CFFs
- Real parts can be reconstructed from unitarity : long Q^2 lever arm
- Also : large acceptance, high luminosity
- Unpolarized cross-sections give access to real parts of CFFs
- Lepton charge asymmetries also give access to real parts of CFFs
- sensitivity to E from A_{UT} or from neutron

Nucleon structure for hadron-hadron colliders



- Multiple hard processes in *pp* indicate substantial correlations
- CDF 3 jet + γ consistent with $\rho \sim 0.3$ fm
- Forward dipion production at RHIC
- Crucial at LHC
- Very hard to tune MC generators (many parameters)
- Also underlying event physics





Summary

In the late 1970's, one could say "QED is 30 years old"
In 2002 we cannot but state that "QCD is 30 years young"

Yu.L. Dokshitzer, *QCD phenomenology*, Lectures at the CERN-Dubna School, Pylos, August 2002.

- Long program of extraction of GPDs and TMDs
- Flagship of NSAC long-range plan for both 12 GeV and (M)EIC
- Interplay between spin and flavor decompositions
- A positron option would be the most beneficial, polarization is essential
- Also crucial for QCD backgrounds at LHC and beyond