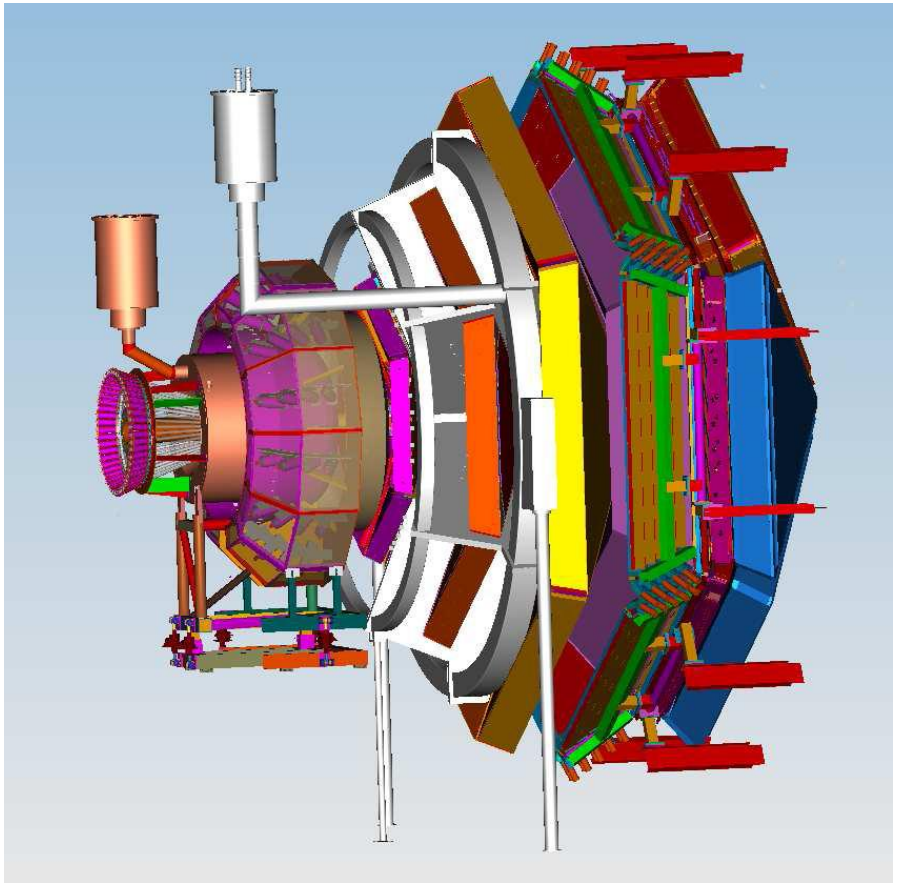
The physics program of CLAS12



Silvia Niccolai **for the CLAS Collaboration**

BEACH 2010

Perugia (Italia) - June 22nd 2010

The physics program of CLAS12

- **JLab@12 GeV and CLAS12**
- **CLAS12 initial scientific program**
- **GPDs & TMDs**
- **How to access GPDs experimentally**
- **Current status of GPD studies at JLab**
- **GPDs measurements planned at CLAS12**
- **SIDIS to access TMDs**
- **Planned SIDIS experiments with CLAS12**
- **Schedule of the upgrade**

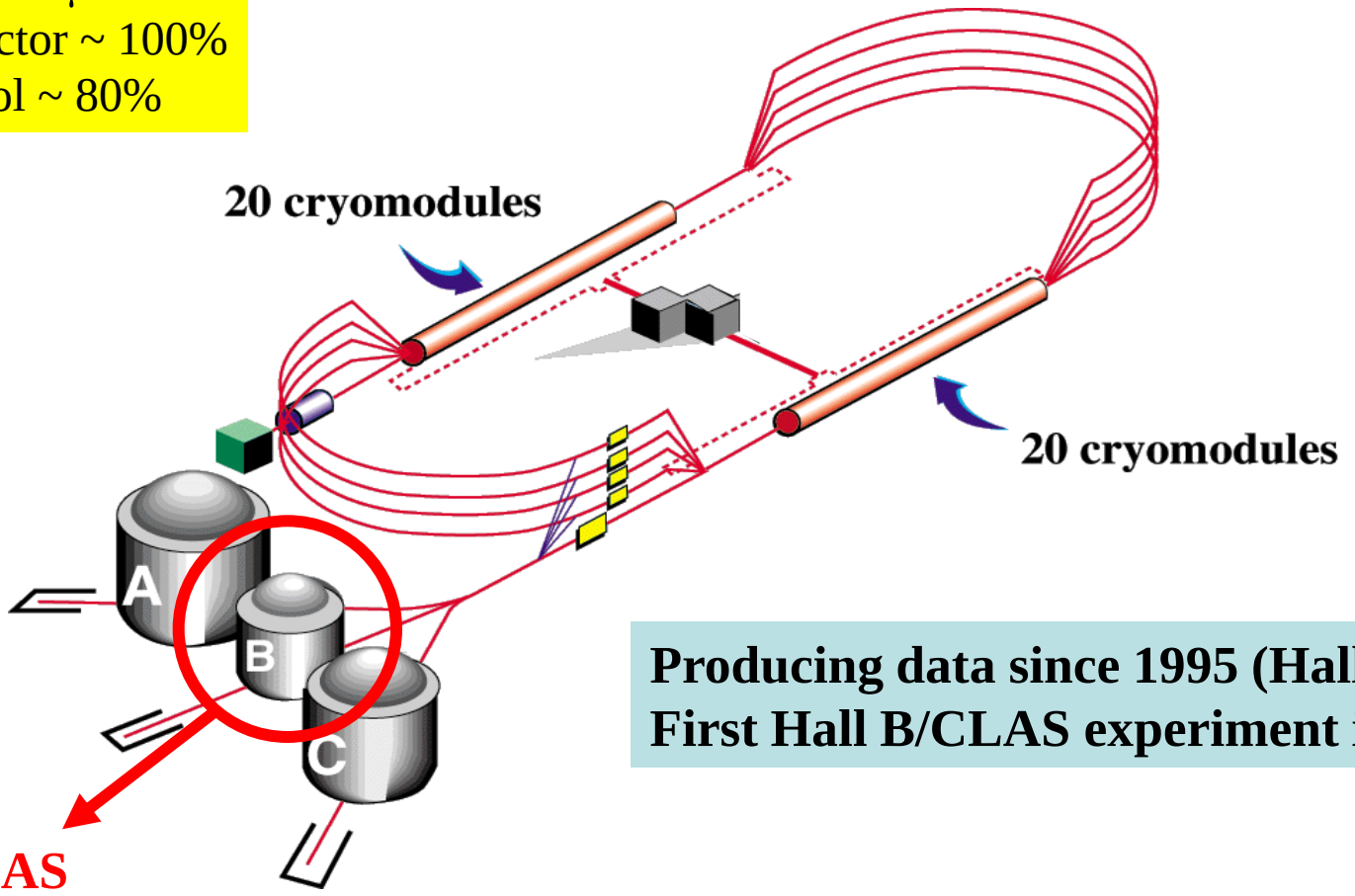
Silvia Niccolai  **for the CLAS Collaboration**

BEACH 2010
Perugia (Italia) - June 22nd 2010

JLab today

Continuous
Electron
Beam
Accelerator
Facility

2 LINACs
5 recirculating arcs
E_{max} = 6 GeV
I_{max} ~ 200 μA
Duty Factor ~ 100%
Beam Pol ~ 80%



Producing data since 1995 (Hall C)
First Hall B/CLAS experiment in 1997

Cebaf **L**arge **A**cceptance **S**pectrometer

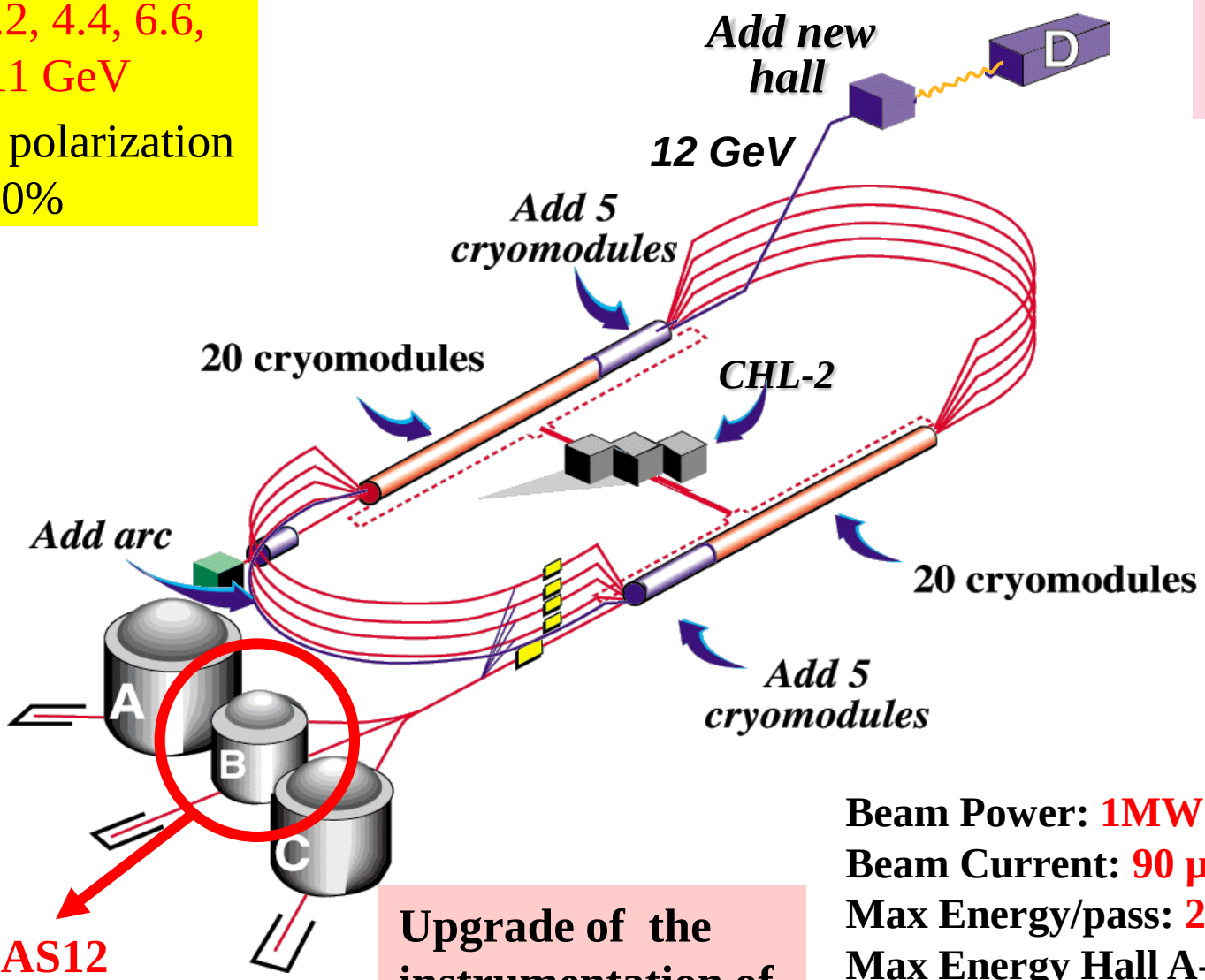
Newport News, VA (USA)

JLab upgraded to 12 GeV

Continuous Electron Beam Accelerator Facility

E= 2.2, 4.4, 6.6, 8.8, 11 GeV

Beam polarization $P_e > 80\%$



Upgrade of the instrumentation of the existing Halls

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

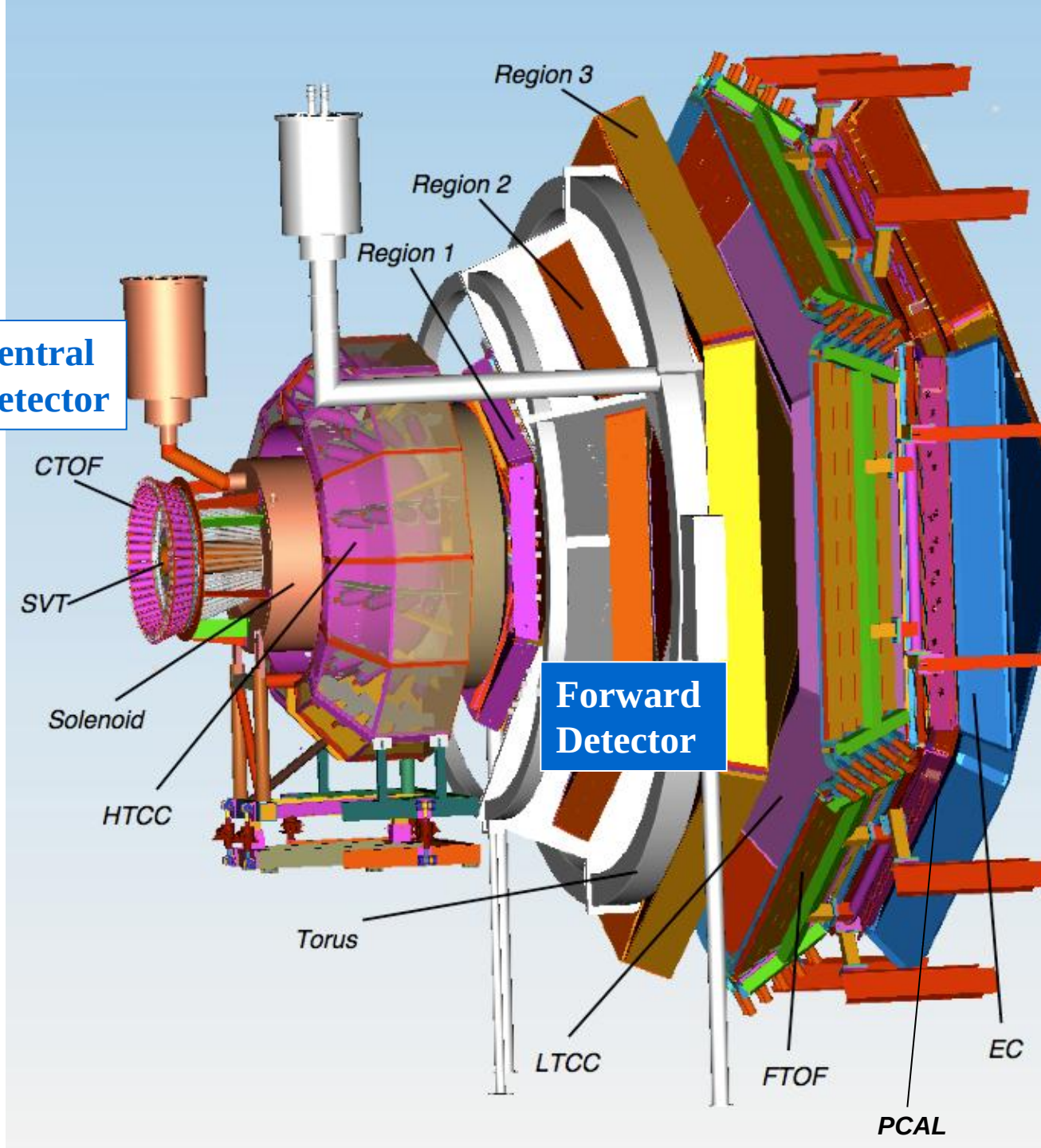
Hall B@12 GeV: CLAS12

Design luminosity
$L \sim 10^{35}$ cm^{-2}s^{-1}

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

Acceptance for photons:
- **IC $2^o<\theta<5^o$**
- **EC, $5^o<\theta<40^o$**

High luminosity & large acceptance:
Concurrent measurement of deeply virtual exclusive, semi-inclusive, and inclusive processes



Hall B@12 GeV: CLAS12

Forward Detector:

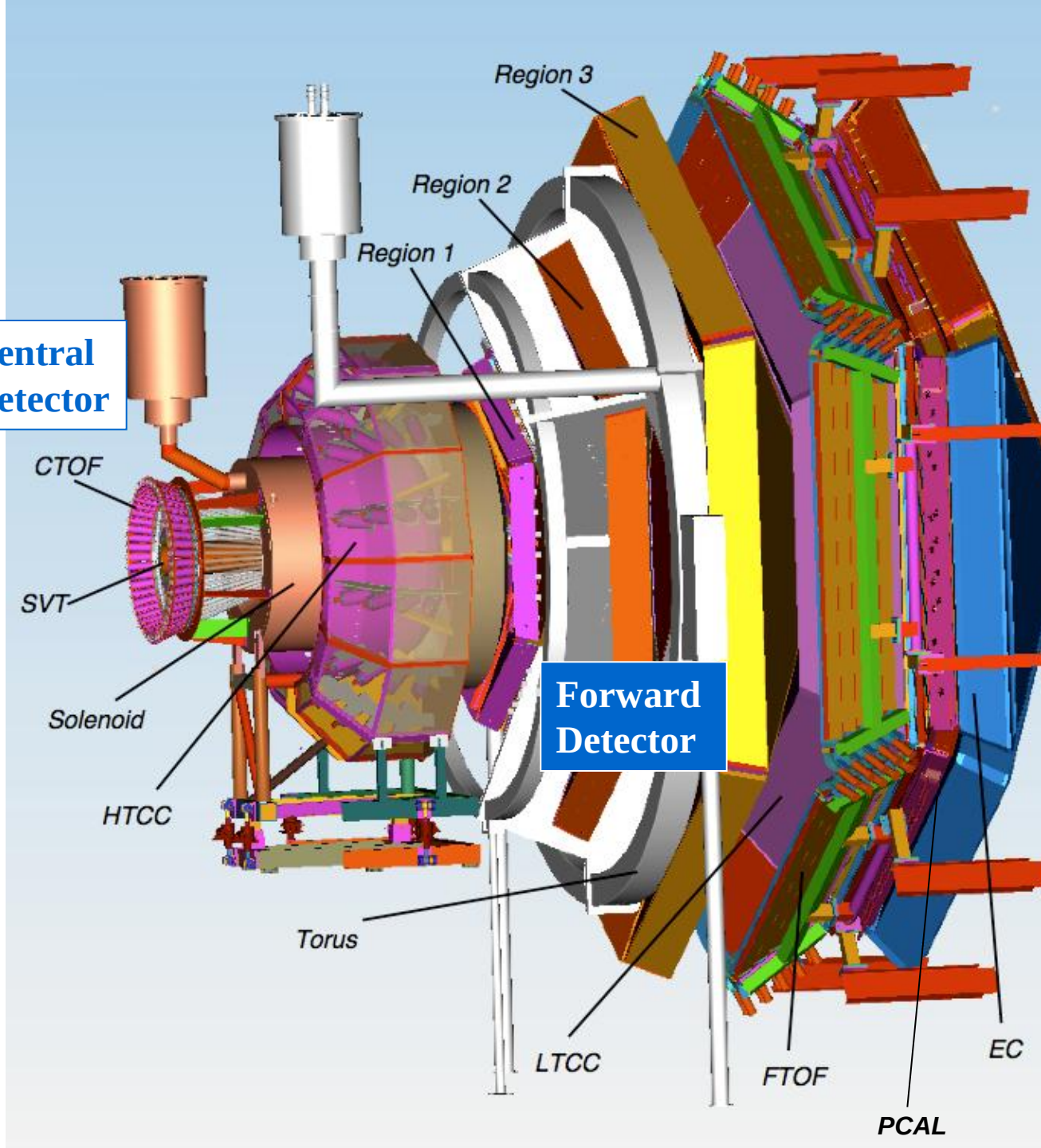
- TORUS magnet
- Forward tracker
  - HT Cherenkov Counter
  - Drift chambers (3 regions)
  - LT Cherenkov Counter
  - Forward ToF System
  - Preshower calorimeter
  - E.M. calorimeter (EC)
- Inner Calorimeter (IC, not shown)

Central Detector:

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

Proposed upgrades:

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



CLAS12: Initial Science Program

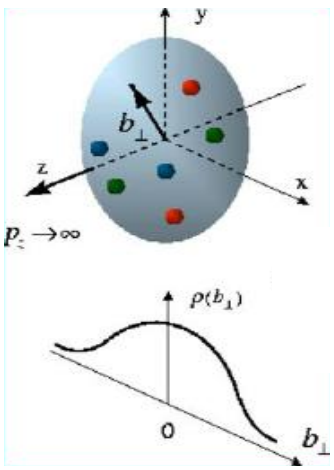
CLAS12: the optimal detector to study **nucleon structure** at **high x_B**

Physics Focus	Approved experiments	LOIs supported
GPD's & Exclusive Processes	3	1
SIDIS & TMDs	4	4
Parton Distribution Functions & DIS	2	1
Elastic & Resonance Form Factors	2	
Hadronization & Color Transparency	2	
Baryon Spectroscopy		1
Total	13	7

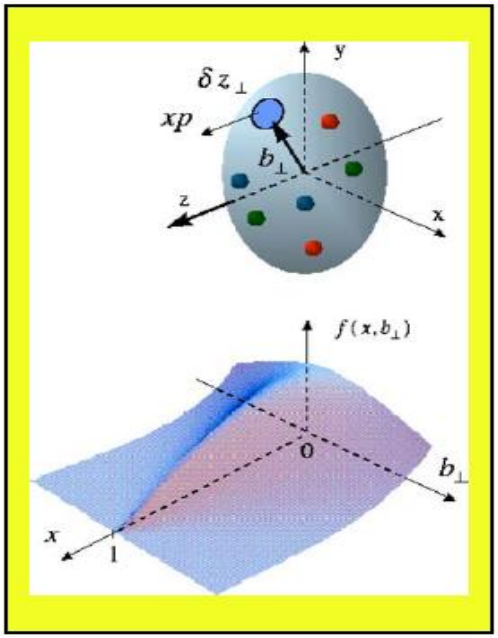
The approved experiments correspond to about 5 years of scheduled beam operation

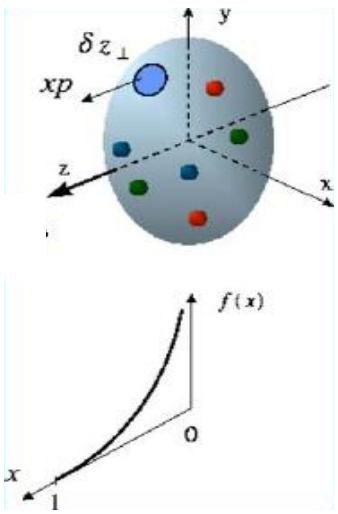
Generalized Parton Distributions

GPDs: H, E, $\tilde{H}$, $\tilde{E}$
Fully correlated quark distributions in both coordinate and momentum space

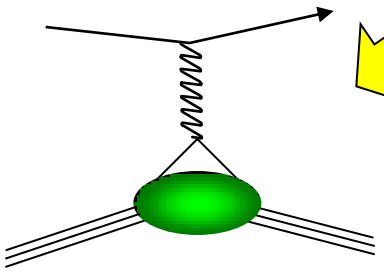


Form factors:
transverse quark distribution in coordinate space





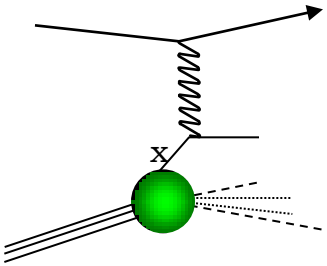
Parton distributions:
longitudinal quark distribution in momentum space



$\int H(x,\xi,t)dx = F_1(t)$ $(\forall\,\xi)$

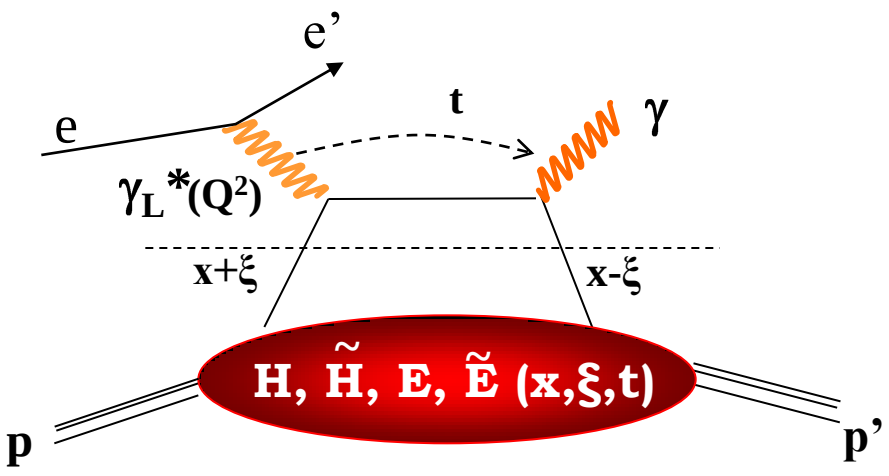
$\int E(x,\xi,t)dx = F_2(t)$ $(\forall\,\xi)$

Accessible in hard exclusive processes



$H(x,0,0) = q(x)$,
$\tilde{H}(x,0,0) = \Delta q(x)$

Deeply Virtual Compton Scattering and GPDs



- $Q^2 = -(e-e')^2$
- $x_B = Q^2/2M\nu$ $\nu = E_e - E_{e'}$

- $x+\xi$, $x-\xi$ longitudinal momentum fractions
- $t = (p-p')^2$
- $\xi \cong x_B/(2-x_B)$

« Handbag » factorization valid in the Bjorken regime: high Q^2 , ν (fixed x_B), $t \ll Q^2$

conserve nucleon helicity

Vector: $H(x,\xi,t)$ Axial-Vector: $\tilde{H}(x,\xi,t)$

Tensor: $E(x,\xi,t)$ Pseudoscalar: $\tilde{E}(x,\xi,t)$

flip nucleon helicity

Quark angular momentum (Ji's sum rule)

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

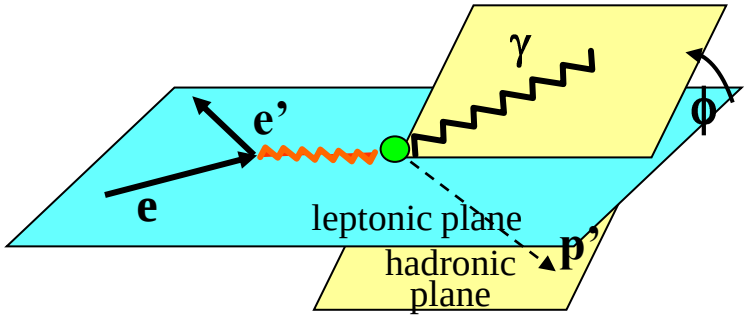
X. Ji, Phy.Rev.Lett.78,610(1997)

«3D» quark/gluon image of the nucleon

Extracting GPDs from DVCS spin observables

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

$\xi = x_B/(2-x_B)$
$k = -t/4M^2$



Polarized beam, unpolarized proton target:

$$\Delta\sigma_{LU} \sim \sin\phi\ \mathbf{Im}\{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}d\phi \rightarrow H_p, \tilde{H}_p, E_p$$

Kinematically suppressed

Unpolarized beam, longitudinal proton target:

$$\Delta\sigma_{UL} \sim \sin\phi\,\mathbf{Im}\{F_1\tilde{H} + \xi(F_1+F_2)(H + \ldots\}d\phi \rightarrow H_p, \tilde{H}_p$$

Unpolarized beam, transverse proton target:

$$\Delta\sigma_{UT} \sim \sin\phi\,\mathbf{Im}\{k(F_2 H - F_1 E) + \ldots..\}d\phi \rightarrow H_p, E_p$$

Polarized beam, unpolarized neutron target:

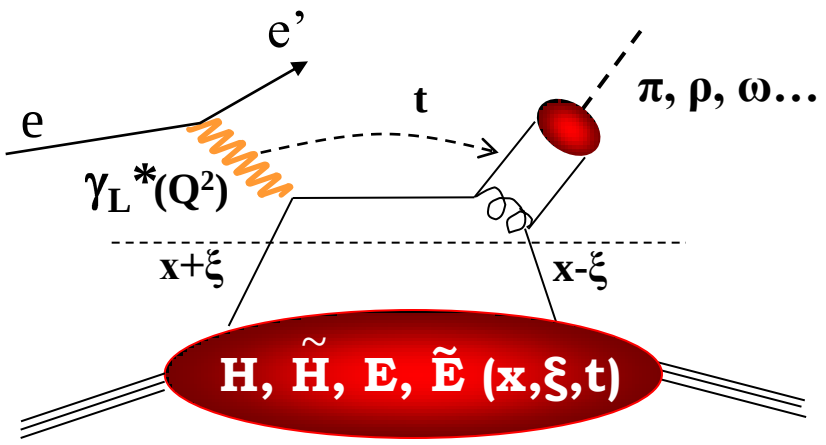
$$\Delta\sigma_{LU} \sim \sin\phi\ \mathbf{Im}\{F_1 H + \xi(F_1+F_2)\tilde{H} - kF_2 E\}d\phi \rightarrow H_n, \tilde{H}_n, E_n$$

Suppressed because $F_1(t)$ is small

Suppressed because of cancellation between PPD's of u and d quarks

$$H_p(\xi, \xi, t) = 4/9\ H_u(\xi, \xi, t) + 1/9\ H_d(\xi, \xi, t)$$
$$H_n(\xi, \xi, t) = 1/9\ H_u(\xi, \xi, t) + 4/9\ H_d(\xi, \xi, t)$$

Hard exclusive meson production and GPDs



Different mesons → different sensitivity to GPDs

H	E	$\tilde{H}$	$\tilde{E}$
↓		↓	
Vector mesons (ρ, ω, ϕ)		Pseudoscalar mesons (π, η)	

Factorization proven only for **longitudinally polarized** virtual photons and valid at **high Q^2** and **small t**

quark flavor decomposition accessible via meson production

π^0	$2\Delta u+\Delta d$
η	$2\Delta u-\Delta d$

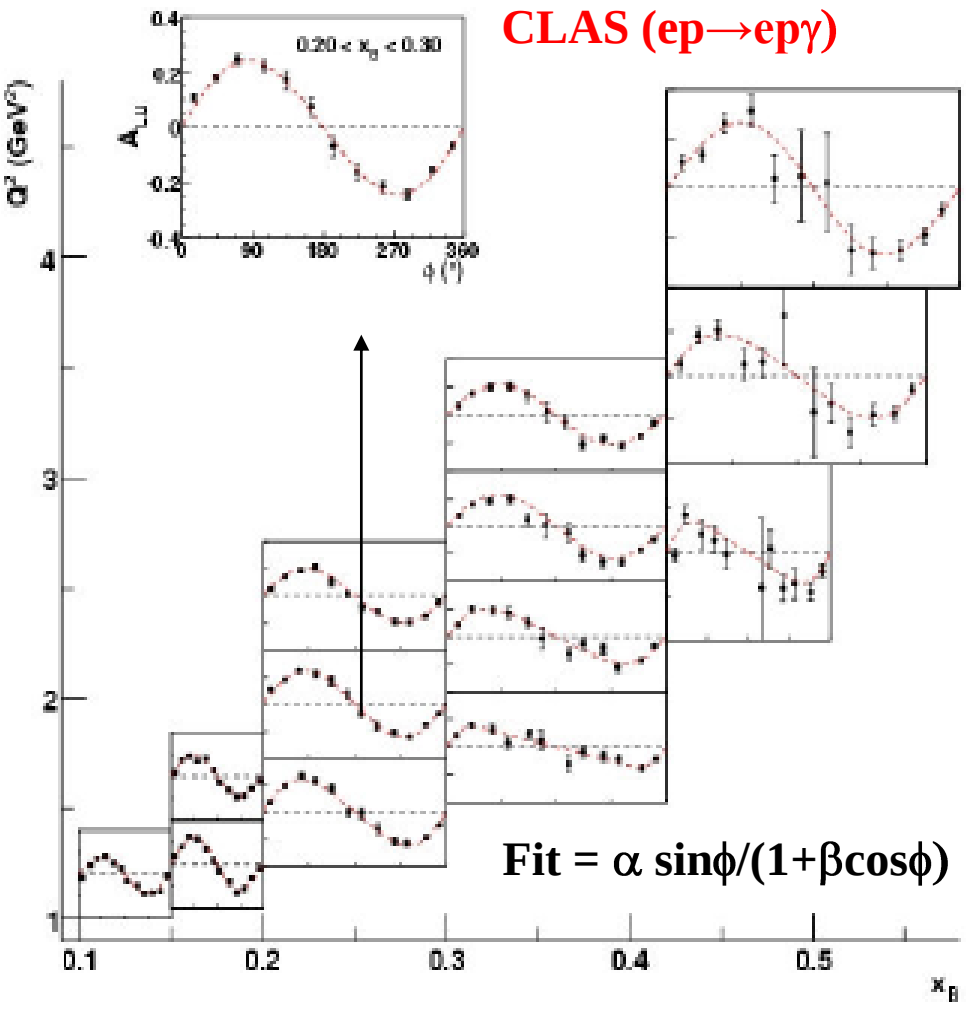
ρ^0	$2u+d$
ω	$2u-d$
ρ^+	$u-d$

$$\sigma_L(M) \sim \left| \int dx\, GPD(x,\xi,t) \right|^2$$

GPDs: where we stand, where we are going

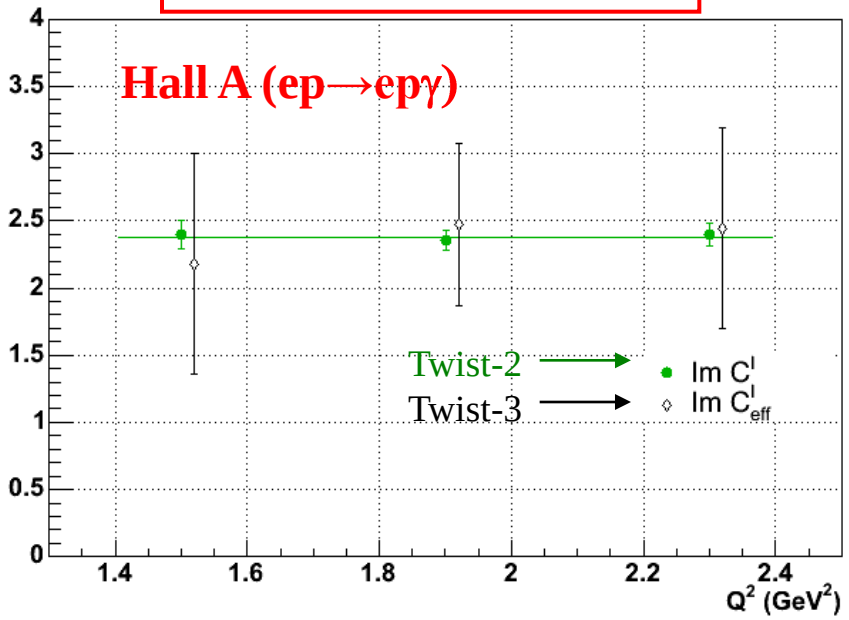
• Pioneering dedicated experiments on **DVCS** (Hall A, CLAS), show evidence for **handbag (twist-2) dominance** (asymmetry ~sinϕ) and **unexpected scaling** at $Q^2 \sim 2$ GeV^2 (Hall A)

CLAS (ep→epγ)



F. X. Girod et al., arXiv: 0711.4805, submitted to PRL

<-t>=0.26 GeV^2, <x_B>=0.36



$$C^I(F) = F_1 H + \frac{x_B}{2 - x_B}(F_1 + F_2)\tilde{H} - \frac{t}{4M^2}F_2 E$$

C. M. Camacho et al., PRL97, 262002 (2006)

Small Q^2 range (but small error bars)

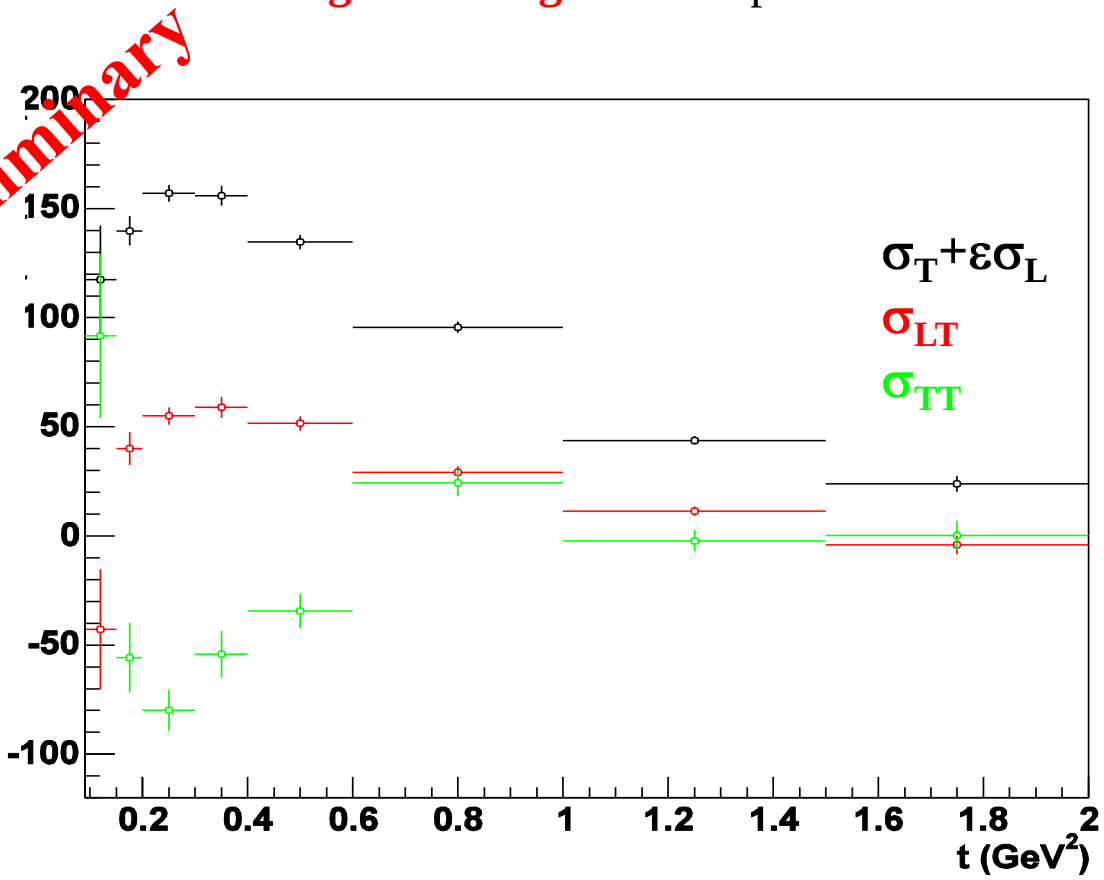
GPDs: where we stand, where we are going

• Pioneering dedicated experiments on **DVCS** (Hall A, CLAS), show evidence for **handbag (twist-2) dominance** (asymmetry ~sinϕ) and **unexpected scaling** at **$Q^2 \sim 2$ GeV^2** (Hall A)
• GPD models **fail** to reproduce consistently the **DVCS cross section and asymmetry** data
• **DVMP** experiments at CLAS (ρ, ω, π^0) and Hall A (π^0) hint that either **scaling cannot be reached** for Q^2 as low as for DVCS or **something is missing** in GPDs parameterizations

CLAS: $\gamma^* p \rightarrow p\pi^0$

Arbitrary units
Statistical errors only

Interference terms different from zero: transverse and longitudinal contributions



$Q^2 = 2.25$ (GeV/c)^2, $x_B = 0.34$

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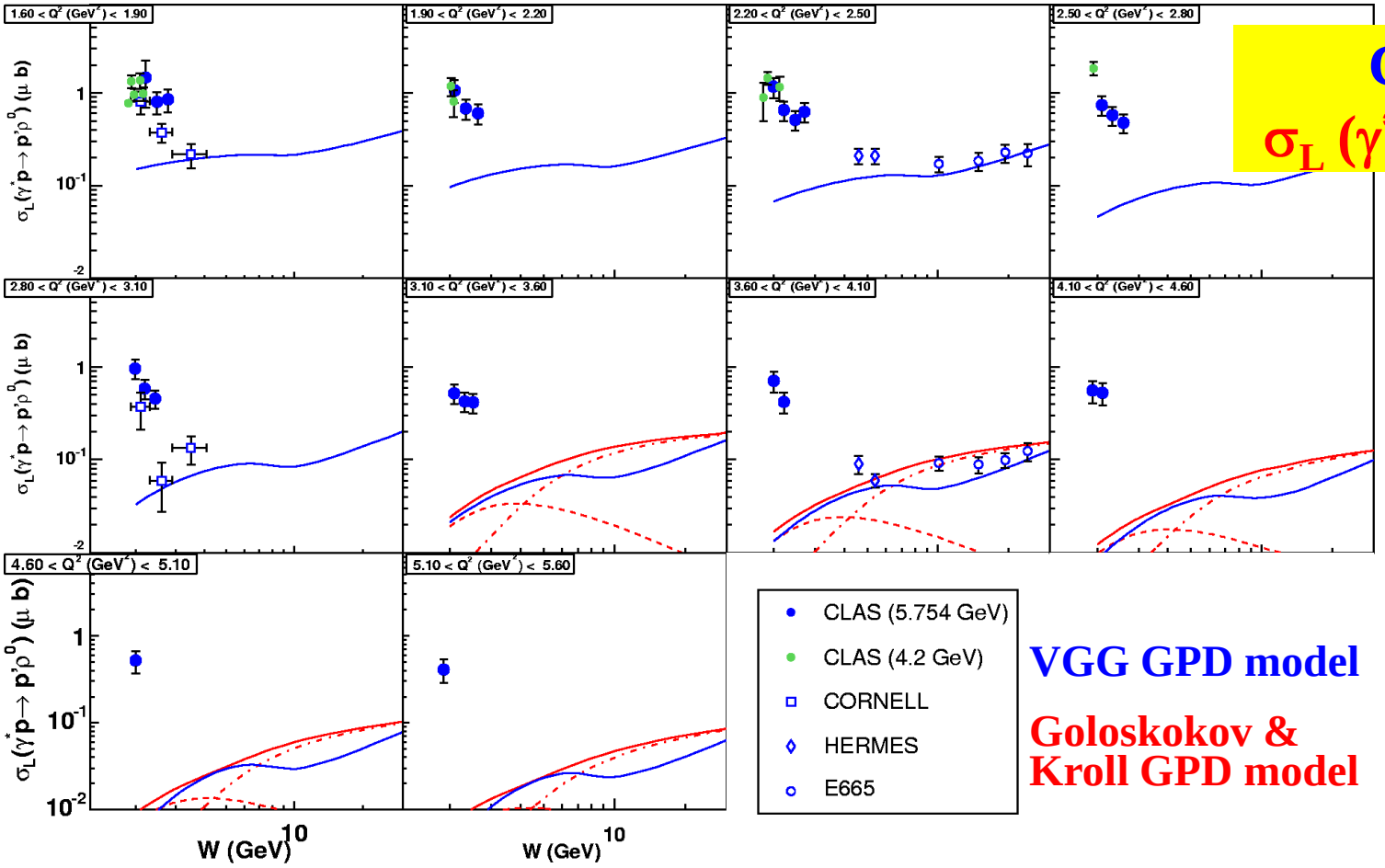

CLAS:
σ_L ($\gamma^*_L p \rightarrow p \rho^0_L$)

S. Morrow et al., Eur. Phys. J. A39:5, 2009

VGG GPD model

Goloskokov & Kroll GPD model

Models miss the data at low W (high x_B)

GPDs: where we stand, where we are going

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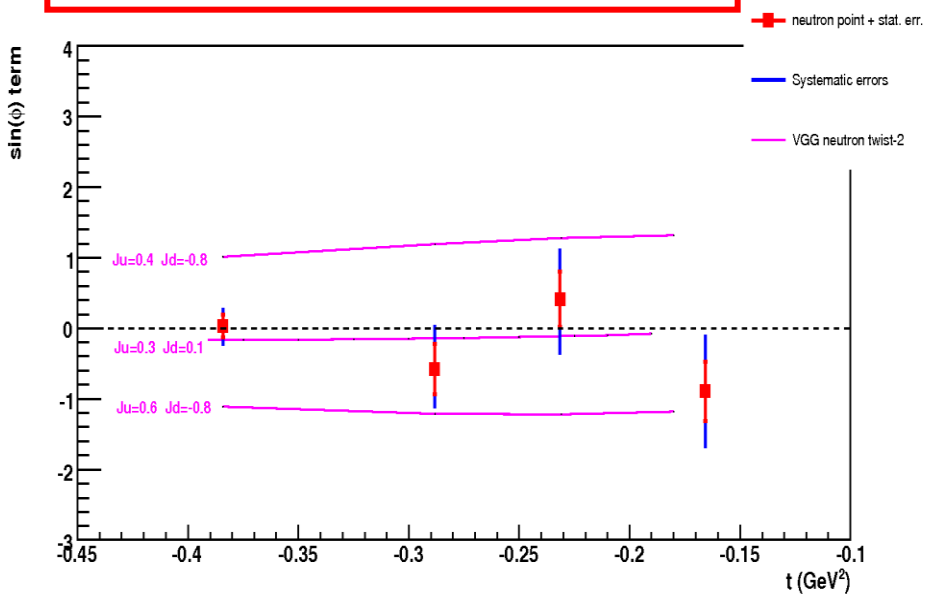
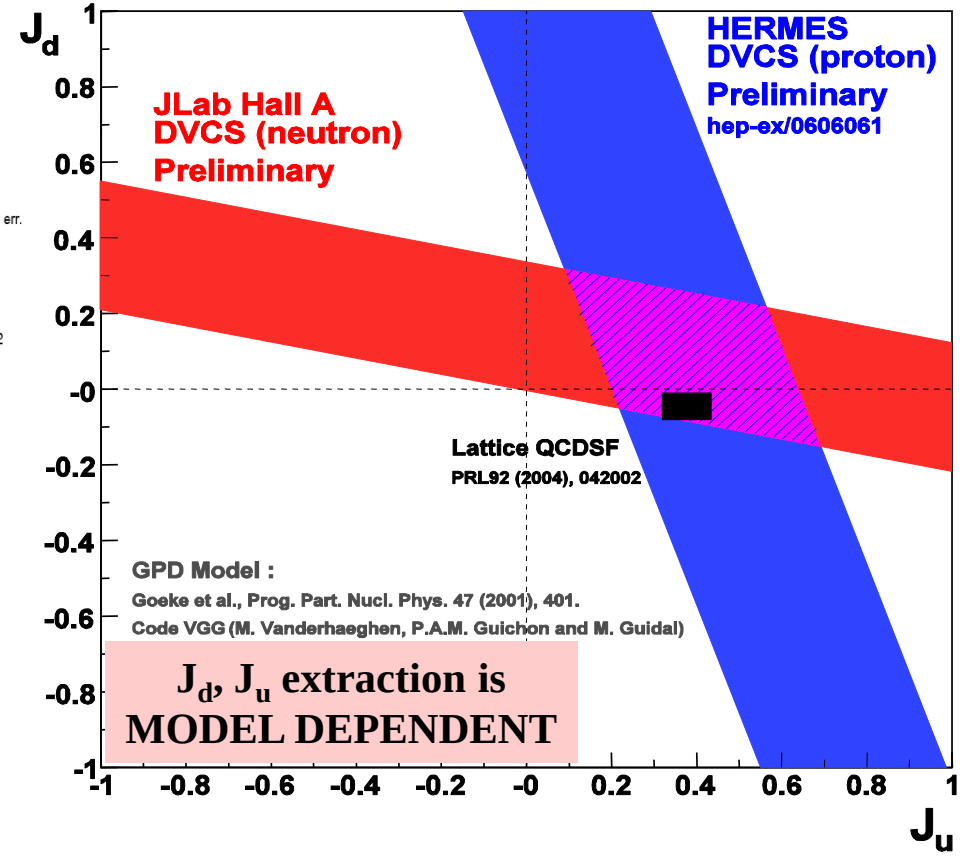
- Hall A's first attempt to measure **nDVCS** showed the importance of this channel for **Ji's sum rule** and the extraction of **J_q**

n-DVCS: access to E, the least known and constrained GPD





PhD thesis of M. Mazouz

GPDs: where we stand, where we are going

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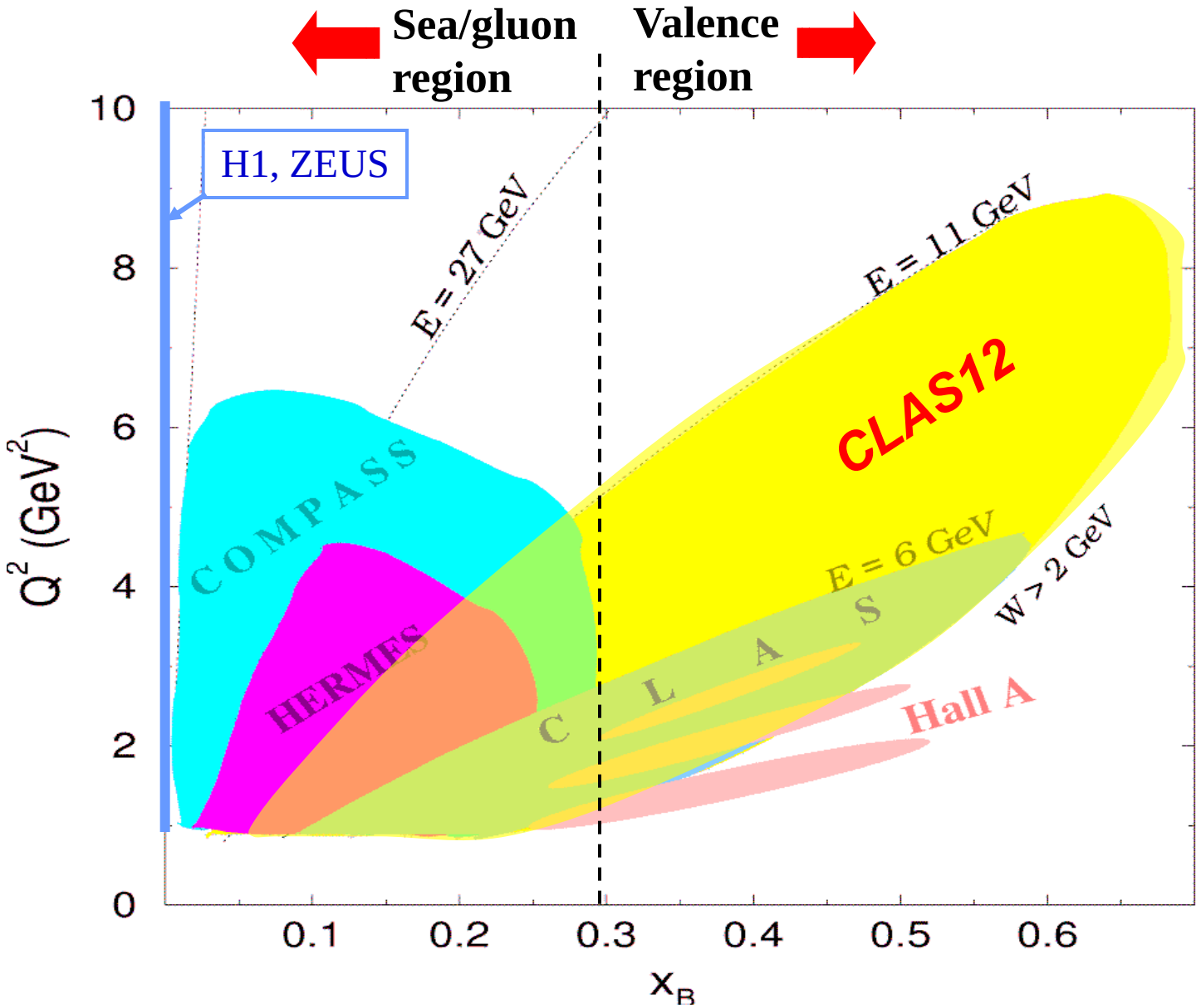
• Hall A's first attempt to measure **nDVCS** showed the importance of this channel for **Ji's sum rule** and the extraction of J_q

More data needed on DVCS and DVMP:

- **High Q^2 to verify scaling for DVCS on a wider Q^2 range, and to approach GPD validity regime for DVMP**
- **Wide x_B coverage**
- **High accuracy on measured observables to test models (high luminosity required)**
- **Measurements of spin-asymmetries and cross sections**

CLAS12 will be the optimal facility for these goals

Large phase space (ξ,t,Q^2) and high luminosity



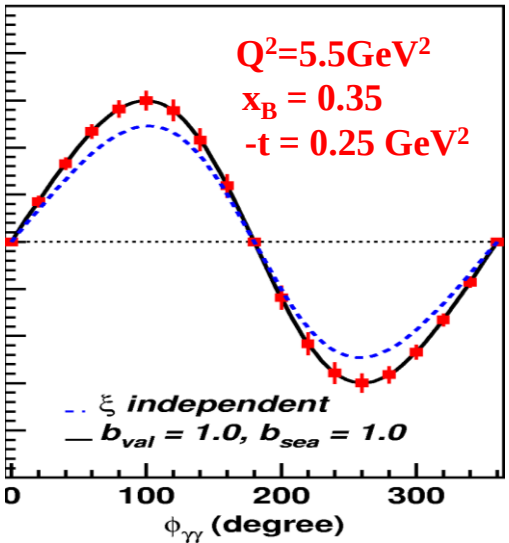
CLAS12: DVCS beam-spin asymmetry

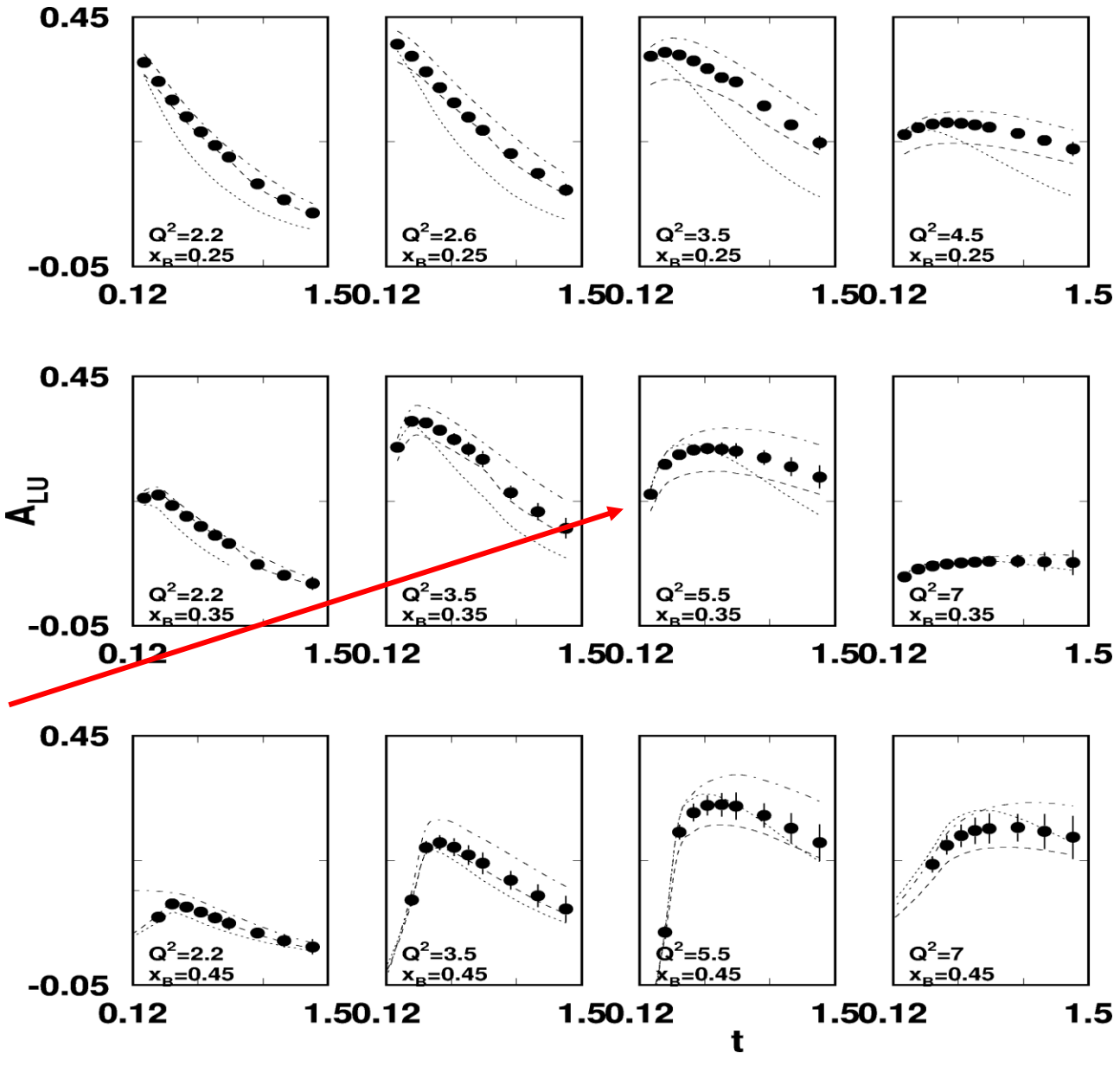
$\vec{e}\,p \longrightarrow ep\gamma$

E = 11 GeV

$\Delta\sigma_{LU} \sim \sin\phi\, \mathrm{Im}\{F_1 H + ..\}d\phi$

L = 1x10^{35}
T = 2000 hrs
ΔQ^2 = 1 GeV^2
Δx = 0.05





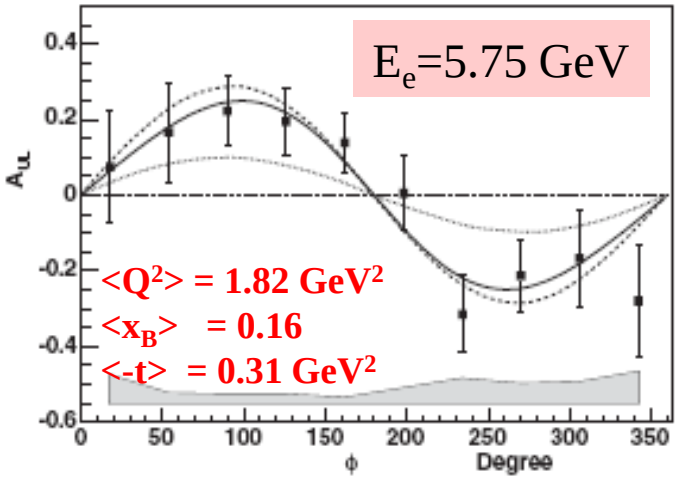
CLAS12: DVCS target-spin asymmetry

$e\vec{p} \longrightarrow ep\gamma$

Longitudinally polarized target

$\Delta\sigma_{UL} \sim \sin\phi\, \mathrm{Im}\{F_1\tilde{H} + \xi(F_1+F_2)H \ldots\}d\phi$

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

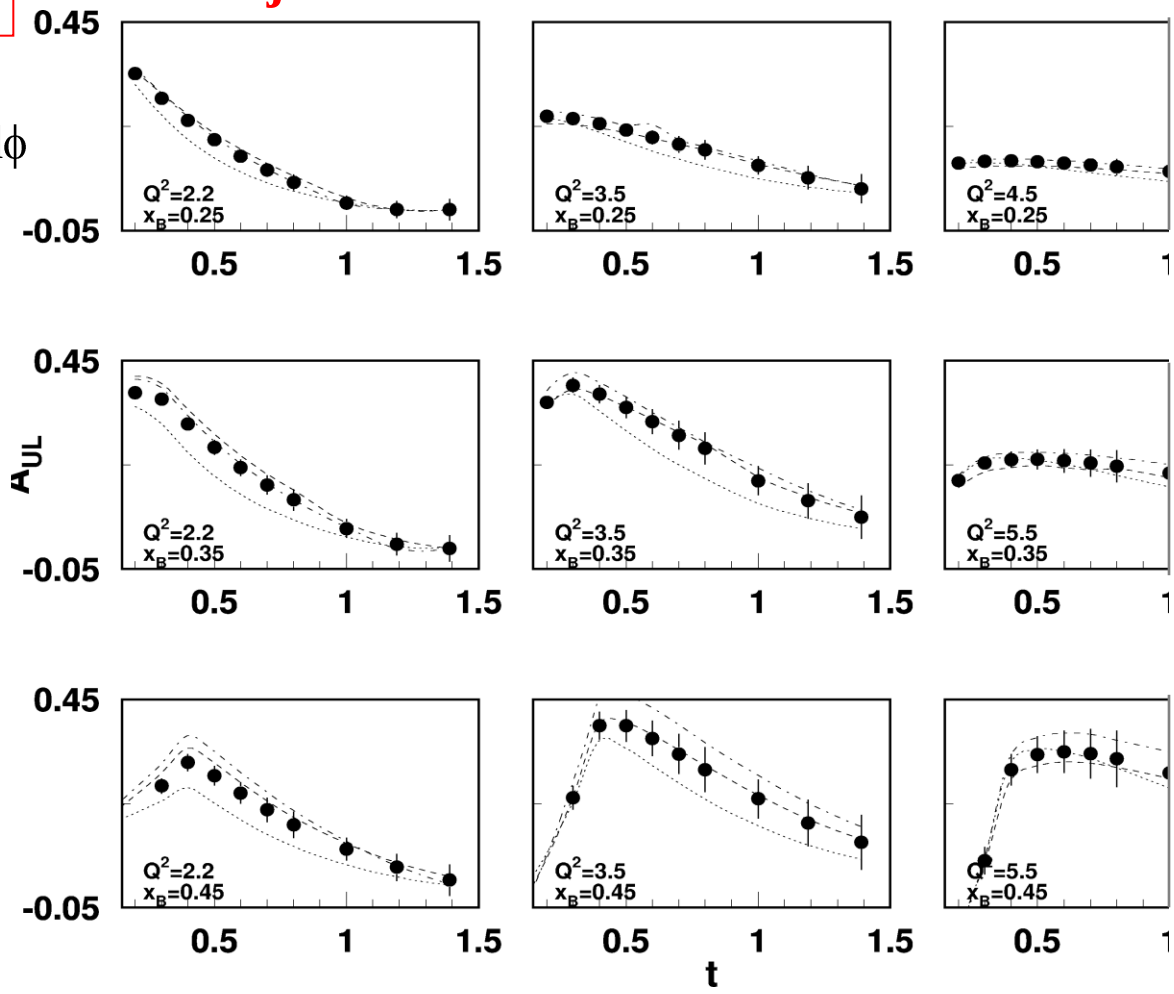


Dedicated experiment at 6 GeV ran in 2009 – analysis underway

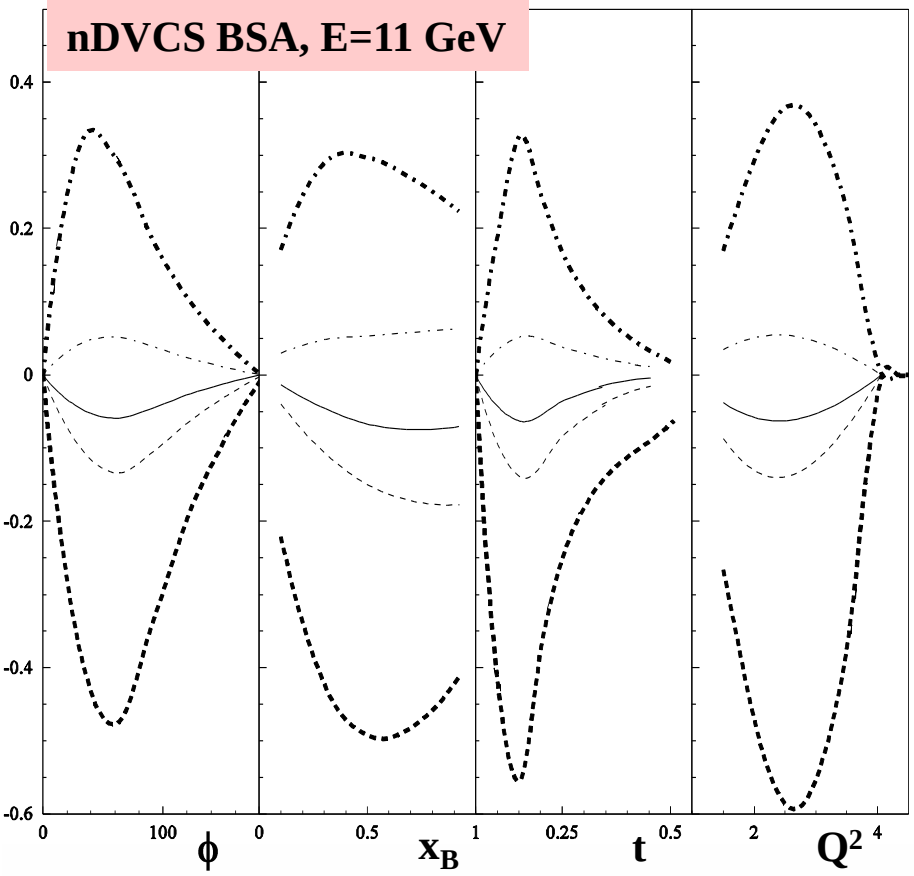
E = 11 GeV

Projected results

L = 2x10³⁵ cm⁻²s⁻¹
T = 1000 hrs
ΔQ^2 = 1GeV²
Δx = 0.05



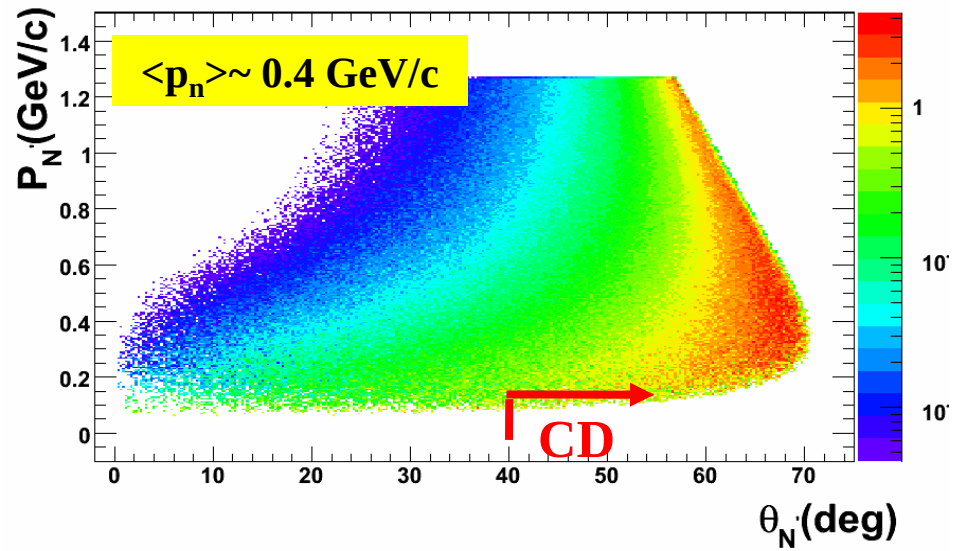
nDVCS with CLAS12



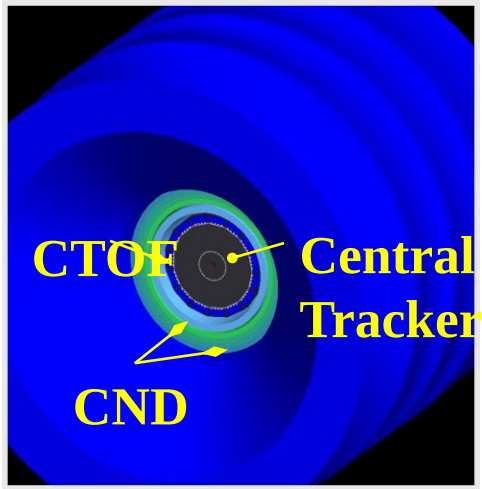
$\phi = 60°$
$x_B = 0.17$
$Q^2 = 2\ GeV^2$
$t = -0.4\ GeV^2$

VGG Model, for different combinations of J_u, J_d (M. Guidal)

n-DVCS BSA is:
- **very sensitive to J_u, J_d**
- **can be as strong as for the proton depending on the kinematics and J_u, J_d**



~ **80%** of neutrons from n-DVCS have θ>**40**
→ **neutron detector for central part of CLAS12 (CND)**



Challenges:
- **limited space**
- **high B field**

R&D ongoing
European joint effort
(Italia, France, UK)

CLAS12: DVCS *transverse* target-spin asymmetry

E = 11 GeV

$e\,p^{\uparrow} \longrightarrow ep\gamma$

Transversely polarized target

$\Delta\sigma \sim \sin\phi\,\mathrm{Im}\{k_1(F_2\mathbf{H} - F_1\mathbf{E}) + \ldots\}d\phi$

A_{UTx} Target polarization in scattering plane

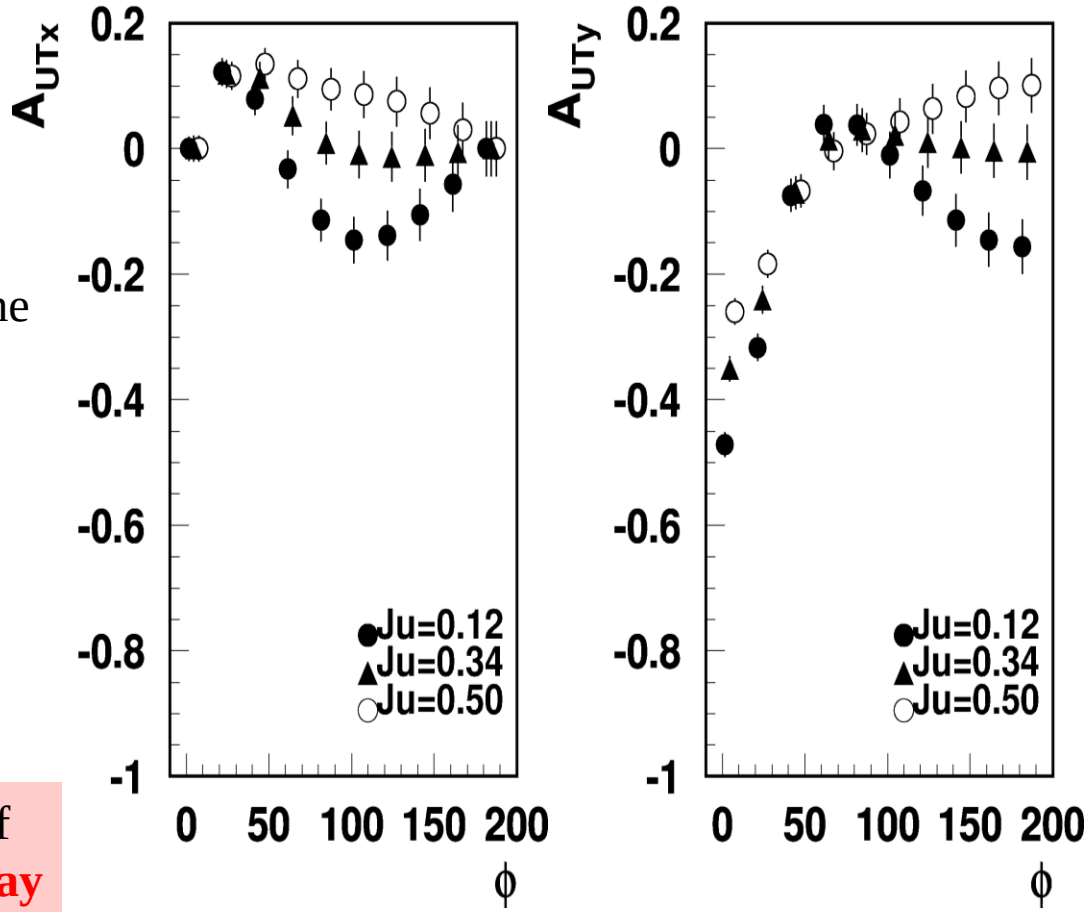
A_{UTy} Target polarization perpendicular to scattering plane

Transverse-target spin asymmetry is **highly sensitive** to the **u-quark contributions** to proton spin.

Transversely polarized target not part of CLAS12 base equipment. **R&D underway**

Projected results

Q^2=2.2 GeV^2, x_B = 0.25, -t = 0.5GeV^2



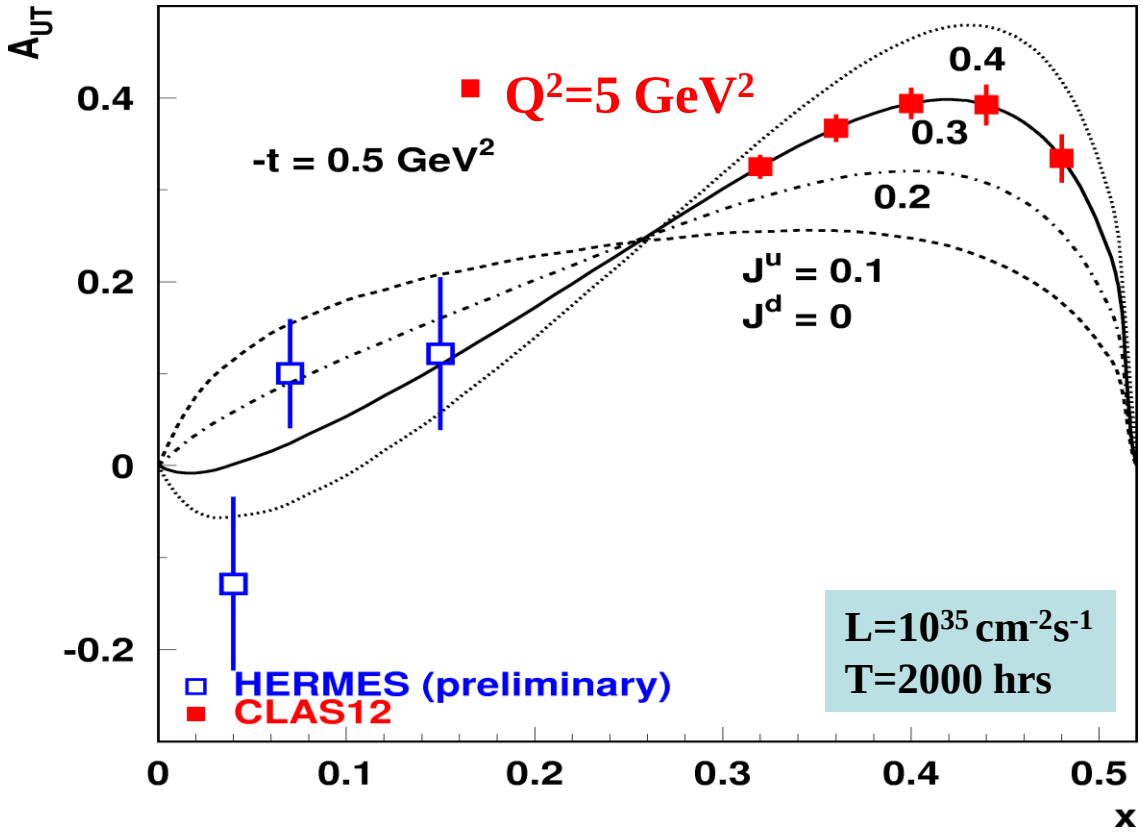
CLAS12: $ep^{\uparrow} \rightarrow ep\rho^0$

$$A_{UT} = - \frac{2\Delta_{\perp}(\mathrm{Im}(AB^*))/\pi}{|A|^2(1-\xi^2) - |B|^2(\xi^2+t/4m^2) - \mathrm{Re}(AB^*)2\xi^2}$$

ρ^0

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

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

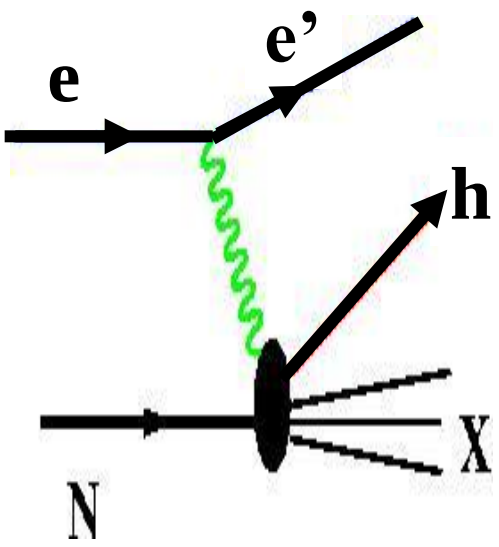


Asymmetry depends on the GPD E, necessary for Ji's sum rule

Goeke, Polyakov, Vanderhaegen (2001)

…and CLAS12 will allow us to measure also DVCS polarized and unpolarized cross sections, vector and pseudo-scalar meson electroproduction…

Semi-Inclusive DIS and TMDs



N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Boer-Mulders

Mulders

Sivers **transversity**

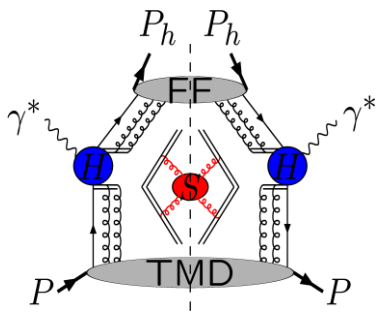
- TMDs describe transitions of an initial nucleon (N) with a given polarization to a final quark (q) with another polarization
- TMDs can be studied in **SIDIS** experiments measuring **azimuthal asymmetries** or **moments**
- TMDs are connected to **orbital angular momentum** (OAM) in the nucleon wave function

  TMD non-zero → OAM is present
- Different final state mesons → **flavor tagging**
- TMDs are **complementary to GPDs**, providing **3-D images** of the nucleon in ***momentum space***

SIDIS and DVMP are complementary

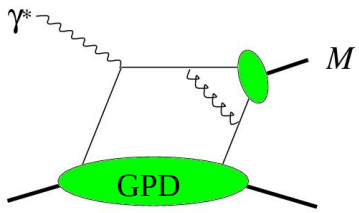
Probability to find a quark **u** in a nucleon **p** with a certain polarization in a position **r** with momentum **k**

$W_p^u(x,\mathbf{k},\mathbf{r})$ "Parent" Wigner distributions



d^3r

d^2k_T (FT)



TMD PDFs: $f_p^u(x,k_T)$,..

GPDs: $H_p^u(x,\xi,t)$, …

Measure **momentum transfer to quark** **k_T distributions also important for exclusive studies**

d^2k_T

$x=0,t=0$

$d\xi$

PDFs $f_p^u(x)$,…

FFs $F_{1p}^u(t)$,$F_{2p}^u(t)$..

Measure **momentum transfer to target** **Exclusive meson data important in understanding of SIDIS measurements**

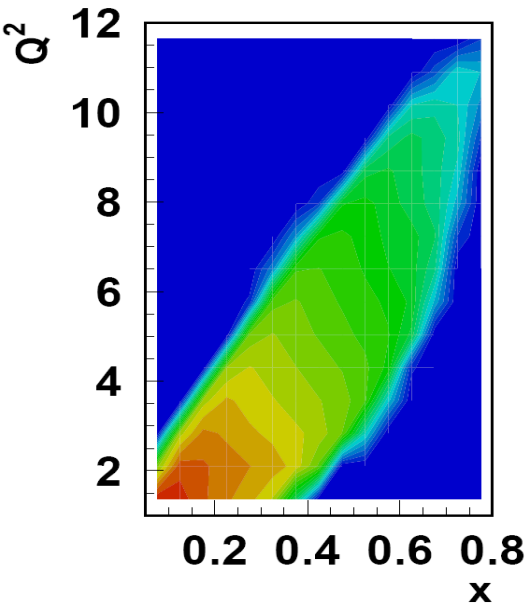
CLAS12: SIDIS on unpolarized protons

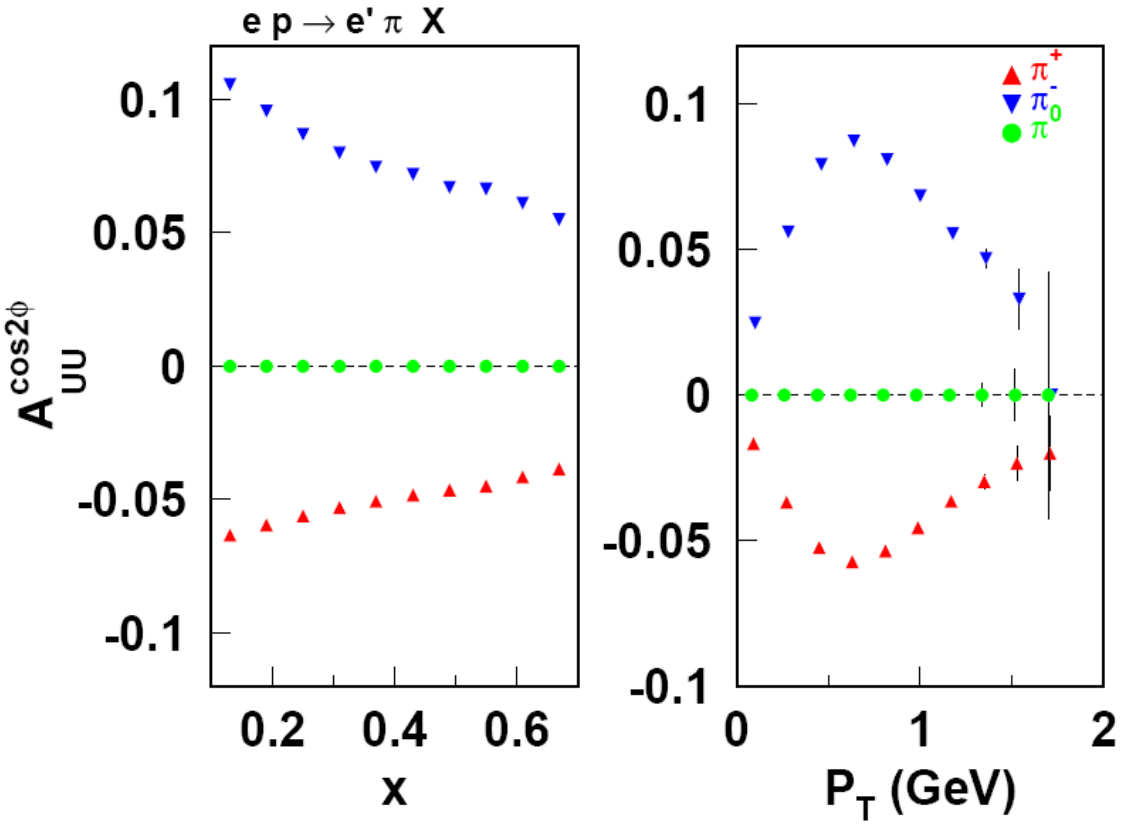
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

In **inclusive electroproduction of pions** the differential cross section has an **azimuthal modulation**

$$d\sigma/d\Omega = \sigma_T + \varepsilon\sigma_L + \varepsilon\sigma_{TT}\cos 2\phi + [\varepsilon(1+\varepsilon)]^{1/2}\,\sigma_{LT}\cos\phi$$

The **cos2ϕ moment** gives access to the **Boer-Mulders** function which measures the **momentum distribution** of **transversely polarized quarks** in unpolarized nucleons





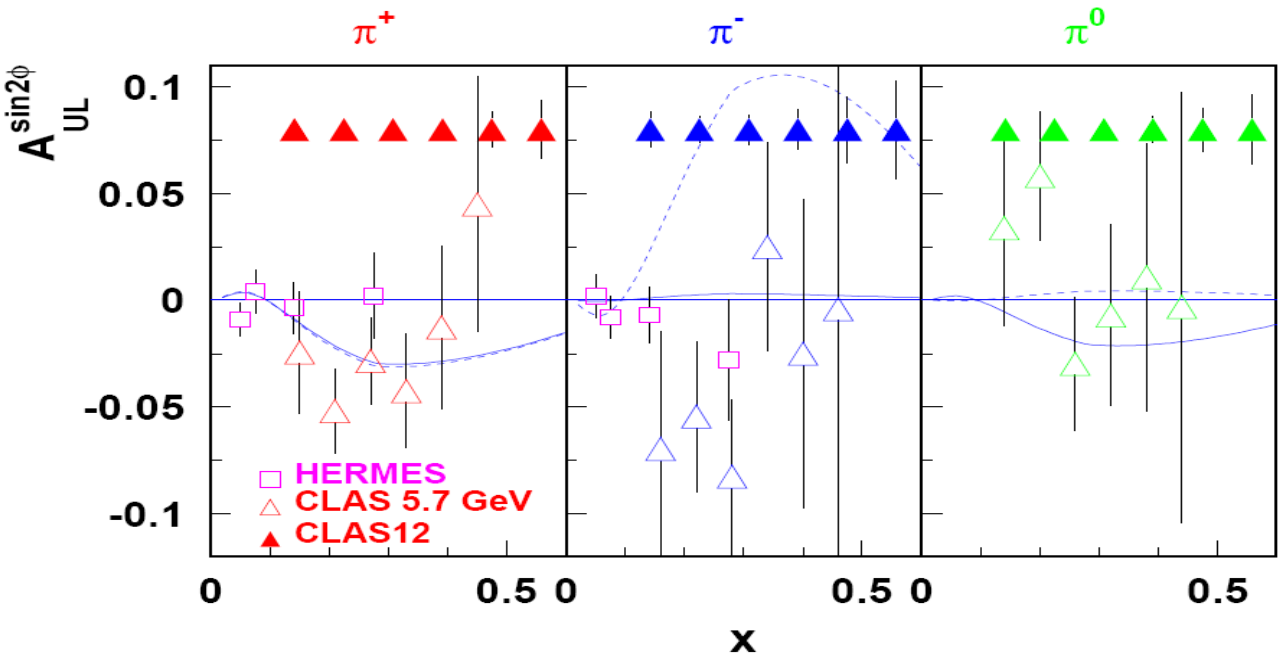
2000 hrs of running with CLAS12

CLAS12: SIDIS on longitudinally polarized target

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

The **sin2ϕ moment** of the **SSA** gives access to the **Kotzinian-Mulders function** which measures the momentum distribution of transversely polarized quarks in the longitudinally polarized nucleon.

The sin2ϕ moment is sensitive to **spin-orbit correlations**



Curves: Efremov, et al., J. Phys. 55 (2005) A189

2500 hrs of running with CLAS12

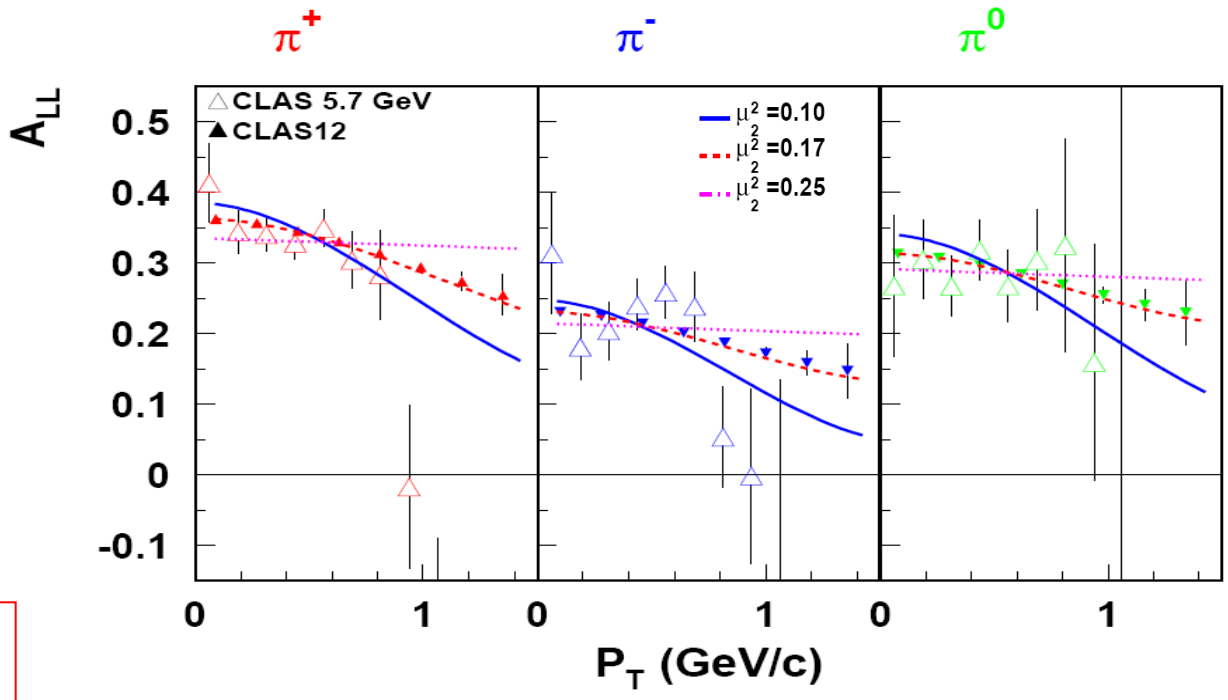
CLAS12: SIDIS in double polarization asymmetry

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Transverse momentum dependence of longitudinally polarized quarks in longitudinally polarized protons.

The **double polarization asymmetry** is sensitive to difference in the k_T **distribution** of quarks with spin orientation parallel and anti-parallel to proton spin.

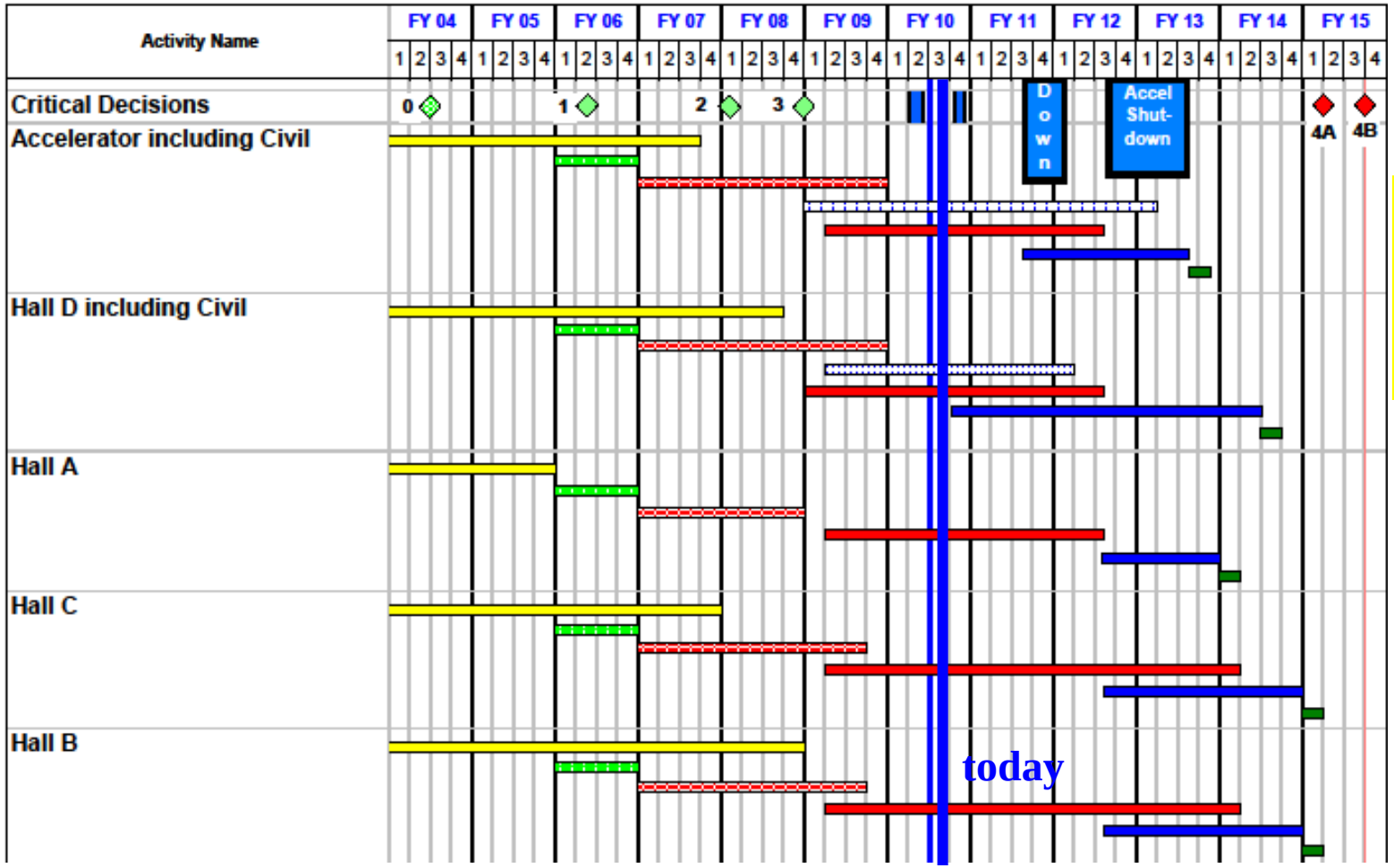
Curves: M.Anselmino et al Phys.Rev.D74:074015,2006



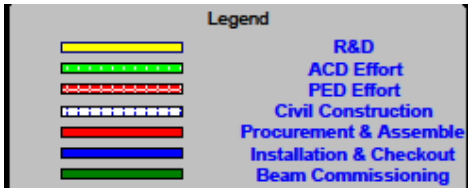
Also planned: SIDIS with kaon production → flavor-dependence of TMDs RICH detector for kaon ID will be added

- Current CLAS data are not sensitive enough to clearly identify the effect. CLAS12 has much more sensitivity and reaches higher P_T

Schedule of the upgrade



Construction started for **accelerator** and **Hall D**



- **6-months down for installation May-Oct 2011**
- **12-months down for installation May 2012-May 2013**
- **Hall A commissioning start October 2013**
- **Hall D commissioning start April 2014**
- **Halls B and C commissioning start October 2014**
- **Project Completion June 2015**

Summary

➢ The JLab 12 GeV upgrade is essential for the study of **3-D nucleon structure** in the **valence region** with high precision, allowing the measurement of:

- **deeply virtual exclusive processes** (to access GPDs)
- **semi-inclusive meson production** (TMDs)

with polarized beam and polarized targets

➢ **CLAS12** will be world wide **the only full acceptance**, general purpose detector for **high luminosity** electron scattering experiments, and it will be perfectly suited for the **GPD/TMD program**

➢ The experimental program of CLAS12 will provide new insight into

- quark orbital angular momentum contributions to the nucleon spin
- 3D structure of the nucleon's interior and correlations
- quark flavor polarization

➢ The first 11 GeV electron beam will hit the CLAS12 target at the **end of 2014**