# Confinement in Nstar and DIS Physics

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# Introduction

QCD Mystery: Color confinement & its origin?

- ”Paradox : Quarks are Born Free but Everywhere they are in Chains(*)”.
- Quarks behave independently when they’re close, but they can’t be pulled apart: CONFINEMENT!

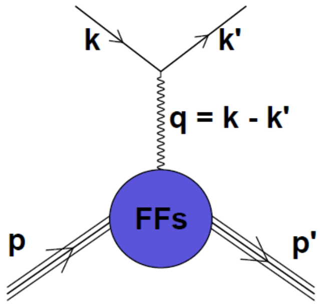
**The understanding of color confinement and how do strong forces balance to produce stability, is central question to nuclear and particle physics**

(*) F-Wilczek, Lecture given in acceptance of the Nobel Prize, Dec 2004

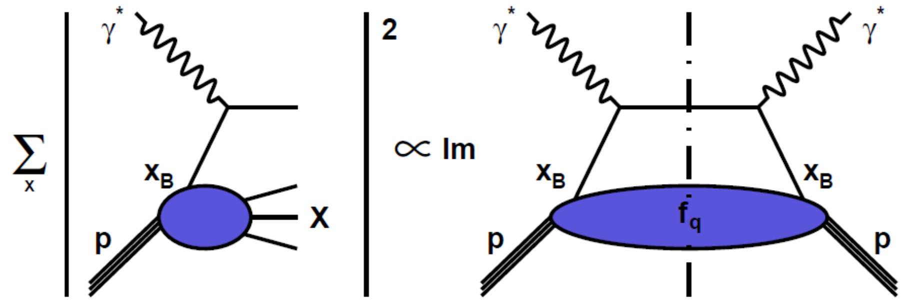
**Electron scattering is a superb experimental tool to study the internal structure of nucleons at differing distance scales, as the resolving power of the probe can be varied.**

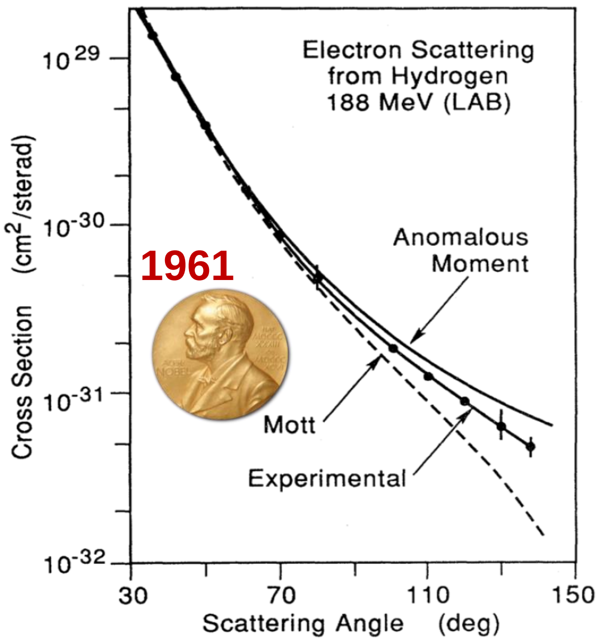
# Elastic and Deep Inelastic Scattering

## Form Factors



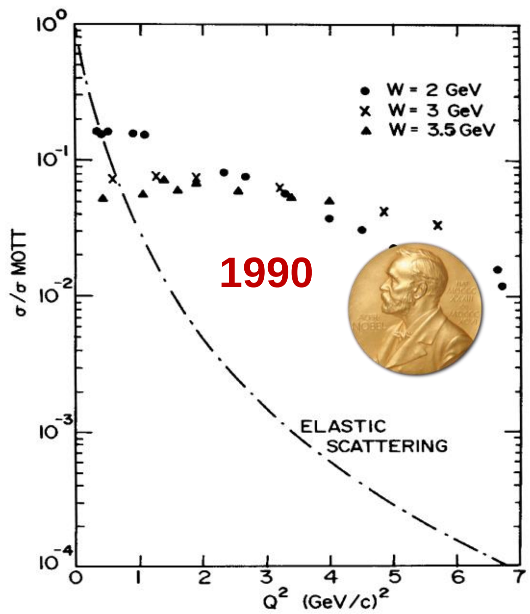

## Parton Distributions




**2 D Imaging in transverse impact parameter**

**??**




**1D distribution in longitudinal momentum space**

# Asymptotic Freedom: Nobel Prize of 2004

**David J. Gross**

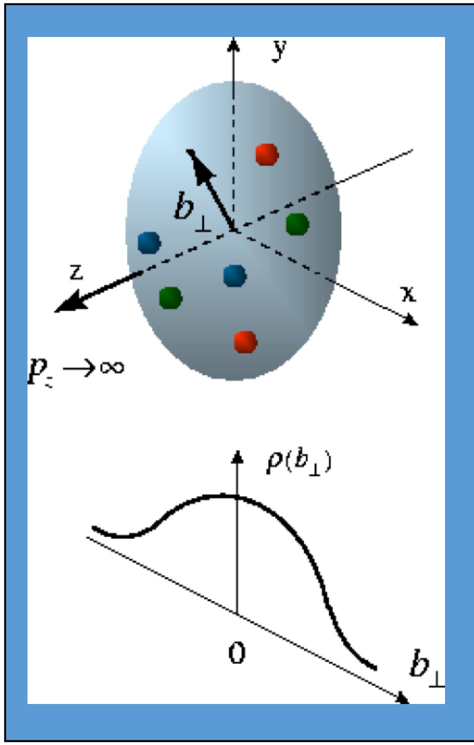
**H. David Politzer**

**Frank Wilczek**

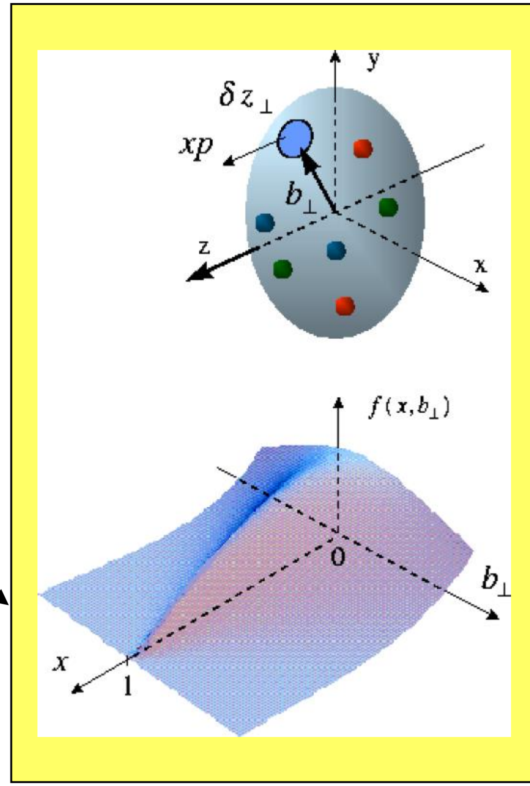
**The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek *"for the discovery of asymptotic freedom in the theory of the strong interaction"*.**

# 3D Imaging of the Nucleon and GPDs

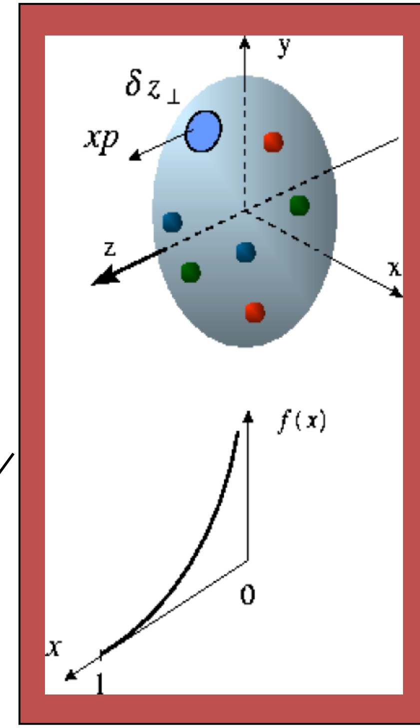
Last 60 years




Last 20 years




Last 45 years




Elastic form factors → Transverse charge & current densities $F_1(t)$, $F_2(t)$.

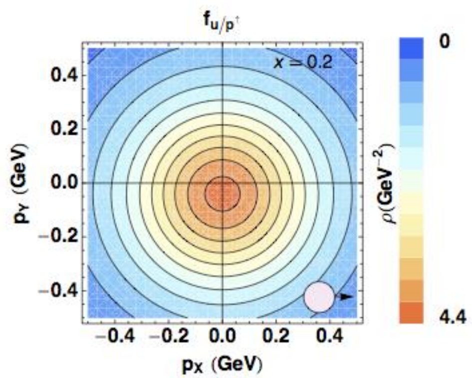
Deeply exclusive processes → GPD's and (2+1)D images in transverse space and longitudinal momentum.
4 GPDs H, $\tilde{E}$, $\tilde{H}$, E (x,ξ,t)

DIS structure functions → Longitudinal parton momentum & helicity densities, $F_2(x)$, $g_1(x)$.

# Quantum phase-space distributions of quarks

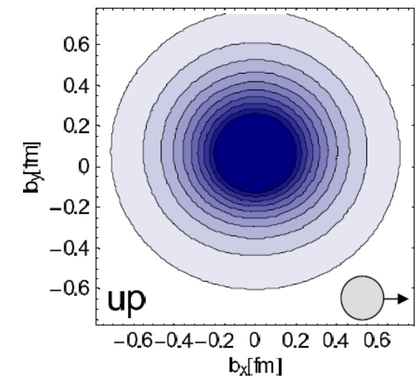
$W_p^q(x,k_T,r)$ Wigner distributions

Probability to find a quark q in a nucleon P with a certain polarization in a position r & momentum k




$d^3r$

$d^2k_T$




[Wigner (1932)] QM
[Belitsky, Ji, Yuan (04)] QFT (Breit frame)
[Lorce', BP (11)] QFT (light cone)

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

GPDs: $H_p^u(x,x,t), \ldots$

Semi-inclusive measurements
Momentum transfer to quark
Direct info about momentum distribution

$d^2k_T$

$\xi=0, t=0$

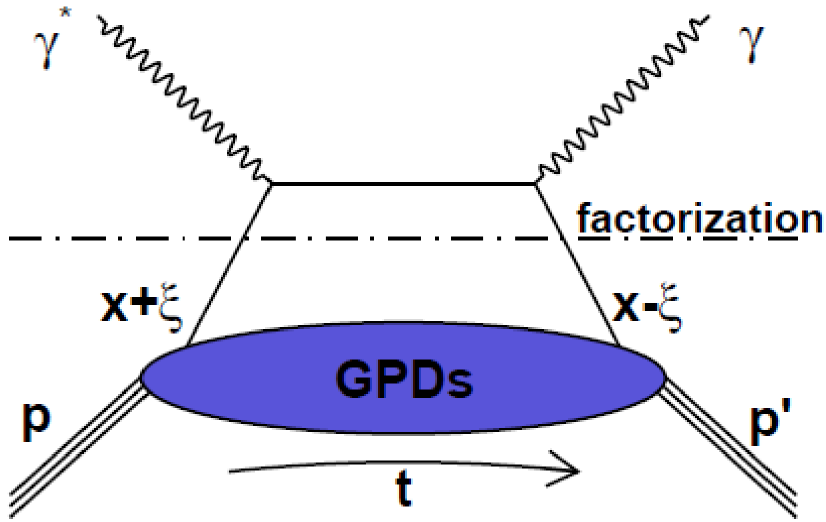
Exclusive Measurements
Momentum transfer to target
Direct info about spatial distribution

PDFs $f_p^u(x),\ldots$

$$J_q = \frac{1}{2}\mathrm{DS} + L_q = \lim_{t\to 0}\int_{-1}^{1} dx\, x\, \left[H(x,z,t)+E(x,z,t)\right]$$

# Deeply Virtual Compton Scattering (DVCS)

DVCS and Generalized Parton Distributions




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

Bjorken regime :
$Q^2 \to \infty$, $x_B$ fixed

$t$ fixed $\ll Q^2$ , $\xi \to \frac{x_B}{2-x_B}$

$$\frac{P^+}{2\pi} \int dy^- \, e^{ixP^+y^-} \langle p' | \bar{\psi}_q(0) \gamma^+ (1+\gamma^5) \psi(y) | p \rangle$$

$$= \bar{N}(p') \left[ H^q(x,\xi,t)\gamma^+ + E^q(x,\xi,t) i\sigma^{+\nu} \frac{\Delta_\nu}{2M} + \tilde{H}^q(x,\xi,t)\gamma^+\gamma^5 + \tilde{E}^q(x,\xi,t)\gamma^5 \frac{\Delta^+}{2M} \right] N(p)$$

x: average fraction of quark longitudinal momentum

$\xi$ fraction of longitudinal momentum transfer

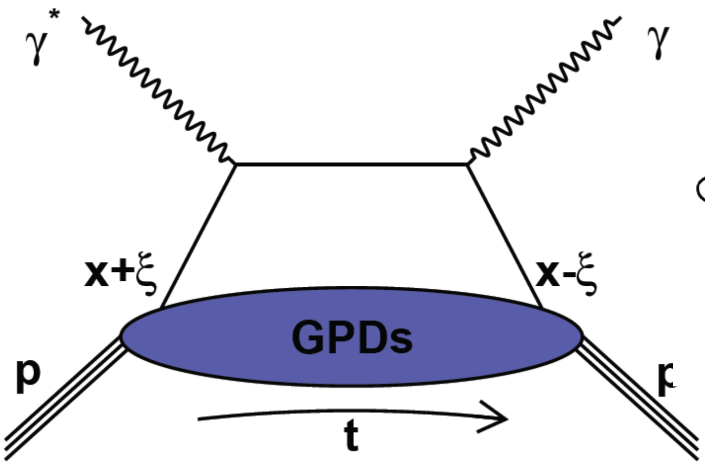
*H, E, $\tilde{H}$, $\tilde{E}$* : **G**eneralized **P**arton **Di**stributions (**GPDs**)

**3-D Imaging conjointly in transverse impact parameter and longitudinal momentum**

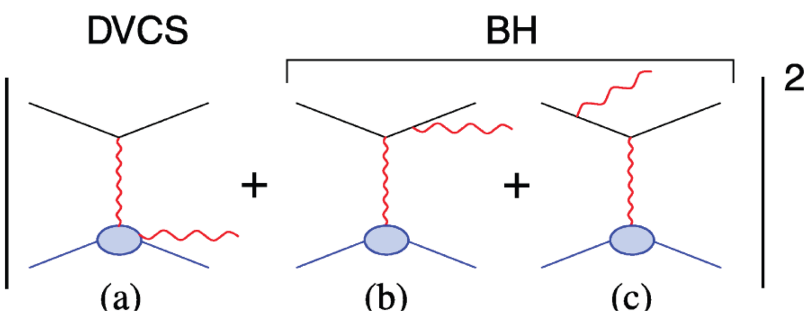
# Deeply Virtual Compton Scattering (DVCS)

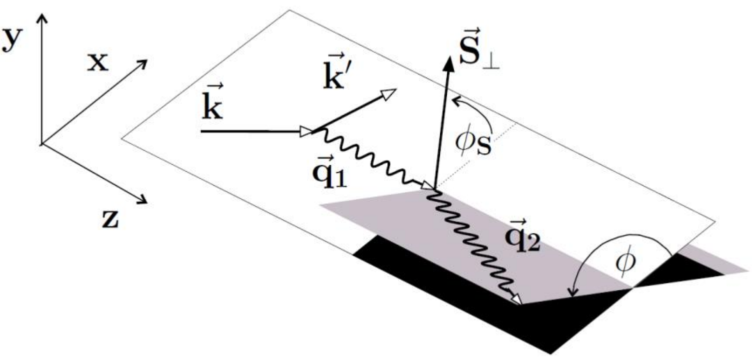
## The cleanest probe at low medium energies

$$ep \rightarrow ep\gamma$$




$\sigma(ep \rightarrow ep\gamma) \propto$




$$A_{UT} = \frac{d^4\sigma^{U\uparrow}(\phi_S - \phi) - d^4\sigma^{U\downarrow}(\phi_S - \phi + \pi)}{d^4\sigma^{U\uparrow}(\phi_S - \phi) + d^4\sigma^{U\downarrow}(\phi_S - \phi + \pi)}$$

$$\overset{\text{twist-2}}{\propto} A_{UT}^{\sin(\phi_S-\phi)\cos\phi}\sin(\phi_S-\phi)\cos\phi + A_{UT}^{\cos(\phi_S-\phi)\sin\phi}\cos(\phi_S-\phi)\sin\phi$$

$$A_{UT}^{\sin(\phi_S-\phi)\cos\phi} = \frac{1}{\pi}\int_0^{2\pi} d\phi\cos(\phi) A_{UT}^{\sin(\phi_S-\phi)}$$

$$A_{UT}^{\sin(\phi_S-\phi)} \propto \frac{1-x}{2-x}\frac{t}{Q^2}F_2\mathcal{H} + \frac{t}{4M^2}(2-x)F_1\mathcal{E}$$

# Unraveling Confinement Forces in Proton

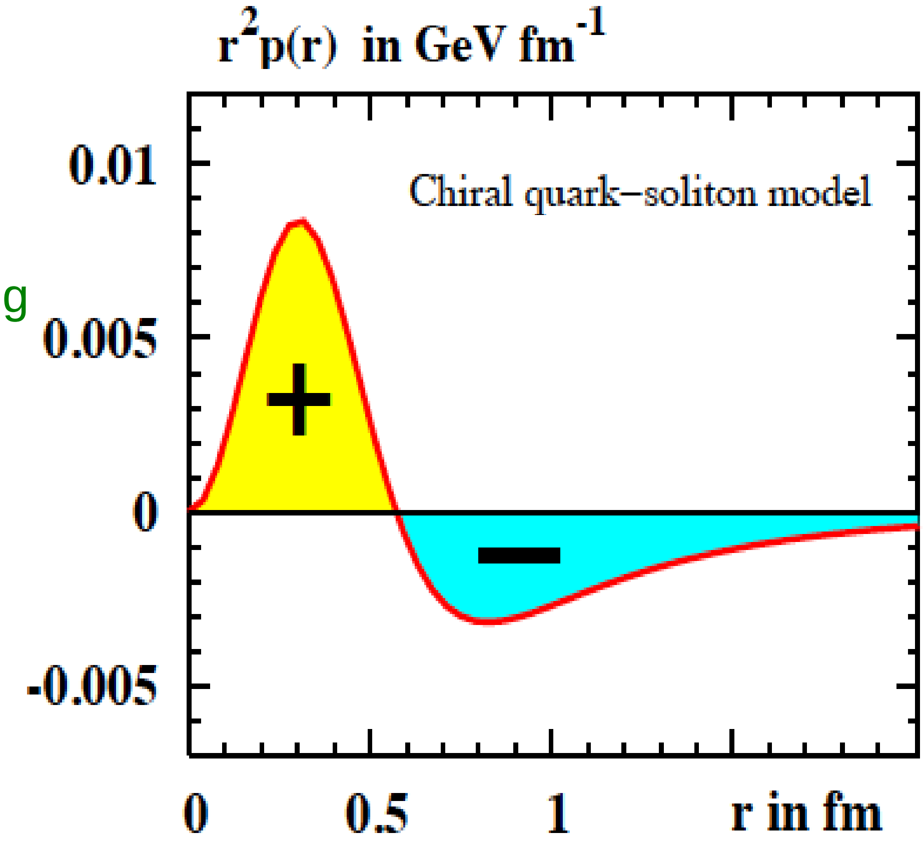
Nucleon matrix element of Energy Momentum Tensor (EMT) contains:

$M_2(t)$ : Mass distribution inside the nucleon
$J(t)$ : Angular momentum distribution
$d_1(t)$ : **Shear forces and pressure distribution**

Measure directly in graviton-proton scattering

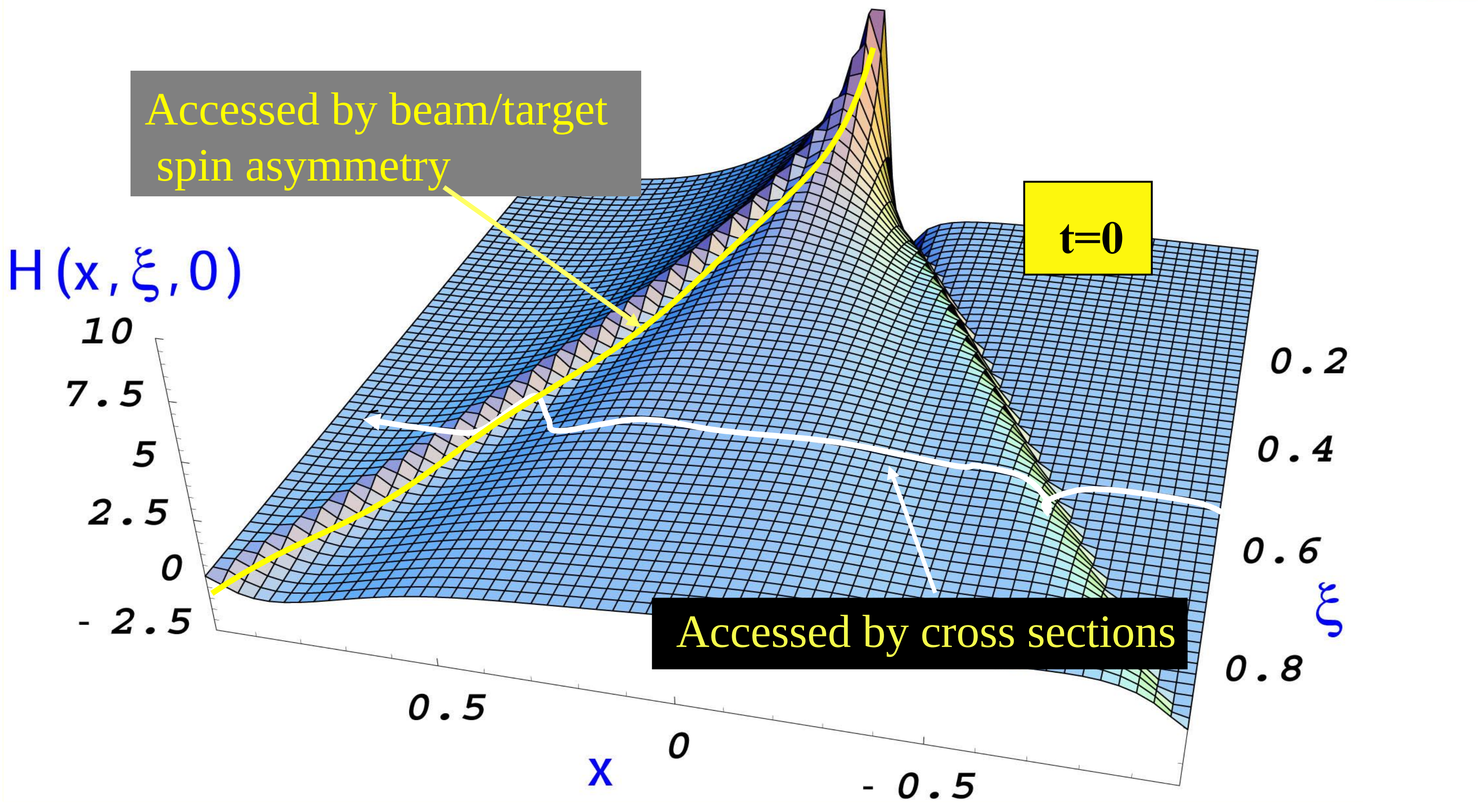
$$\int dx\, x H(x,\xi,t) = M_2(t) + \frac{4}{5}\xi^2 d_1(t)$$

$$\mathrm{Re}\mathcal{H}(\xi,t) \stackrel{\mathrm{LO}}{=} D(\xi,t) + \mathcal{P}\int_{-1}^{1} dx \left(\frac{1}{\xi-x} - \frac{1}{\xi+x}\right) \mathrm{Im}\mathcal{H}(\xi,t)$$

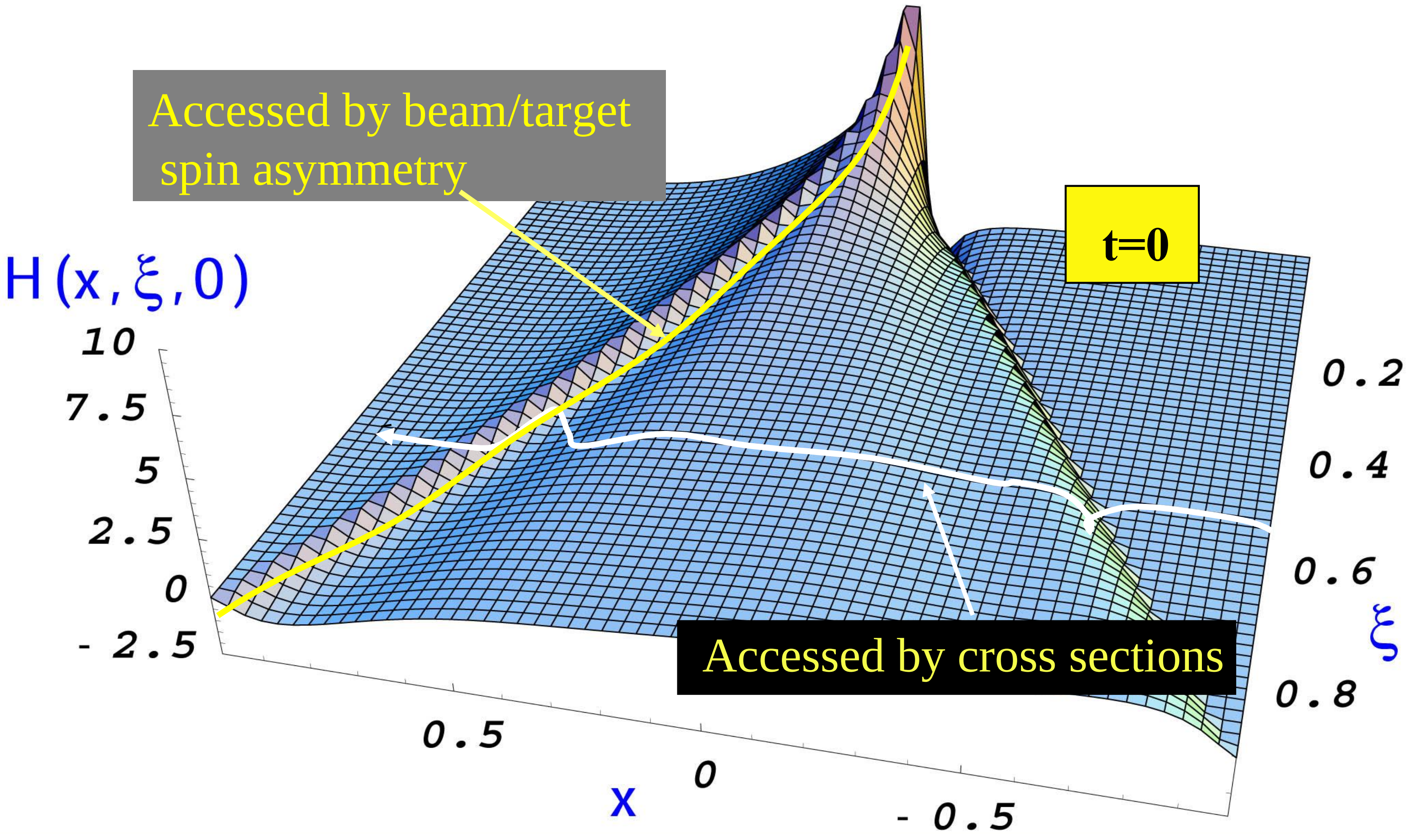



From measurement of D(t), we learn about confinement forces in the proton.

# GPDs Kinematics



# GPDs Kinematics

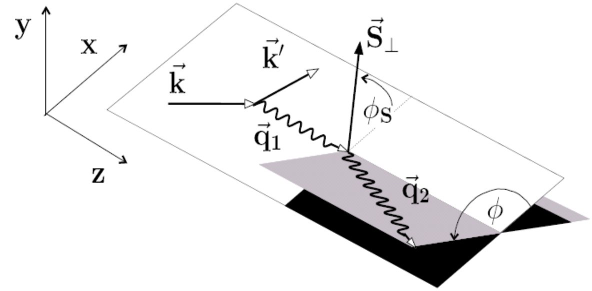



**Mapping GPDs requires large kinematical coverage**

# A path towards extracting GPDs

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

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




Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\phi\ \{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}d\phi$$

→ $H(\xi,t)$

Unpolarized beam, longitudinal target:

$$\Delta\sigma_{UL} \sim \sin\phi\ \{F_1\tilde{H} + \xi(F_1+F_2)(H + \xi/(1+\xi)E)\}d\phi$$

→ $\tilde{H}(\xi,t)$

Unpolarized beam, transverse target:

$$\Delta\sigma_{UT} \sim \cos\phi \sin(\phi_s-\phi)\{k(F_2 H - F_1 E)\}d\phi$$

→ $E(\xi,t)$

Unpolarized total cross section:

Separates h.t. contributions to DVCS

→ $\mathcal{R}e(T^{DVCS})$

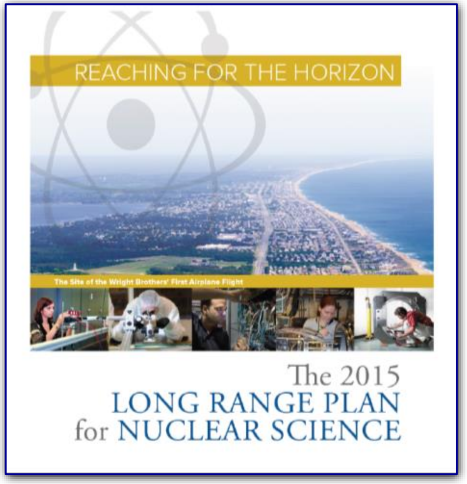
**The Generalized Parton Distributions (GPDs) provide the theoretical framework to interpret the experimental data**

**Breakthrough in theory of QCD (1990s): developing DVCS as a tool to characterize the structure of the nucleon within QCD and showing how its properties can be probed through experiments.**

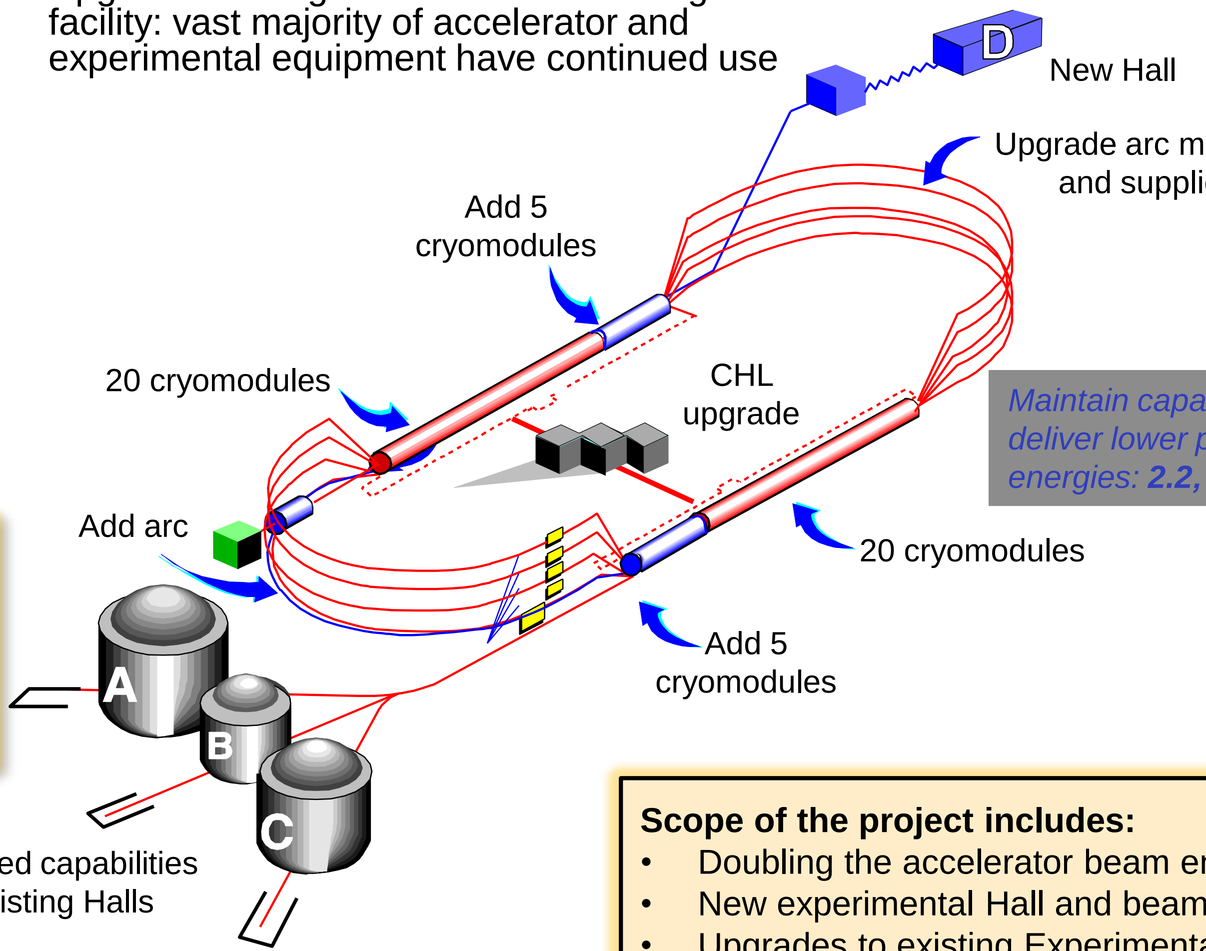
*D. Mueller (1994), X.Ji (1996), A.Radyushkin (1996)*

(2015 JSA Prize award to X. Ji and A. Radyushkin & 2016 APS Feshbach Prize award to X. Ji )

# 12 GeV Upgrade Project




Upgrade is designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use




*Maintain capability to deliver lower pass beam energies: **2.2, 4.4, 6.6….***

The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 & 2015 NSAC Long Range Plan.

**Scope of the project includes:**

- Doubling the accelerator beam energy
- New experimental Hall and beamline
- Upgrades to existing Experimental Halls

# THE CLAS12 DETECTOR

Baseline equipments

Forward Detector (FD)

- TORUS magnet (6 coils)
- HT Cherenkov Counter
- Drift chamber system
- LT Cherenkov Counter
- Forward ToF System
- Pre-shower calorimeter
- E.M. calorimeter

Central Detector (CD)

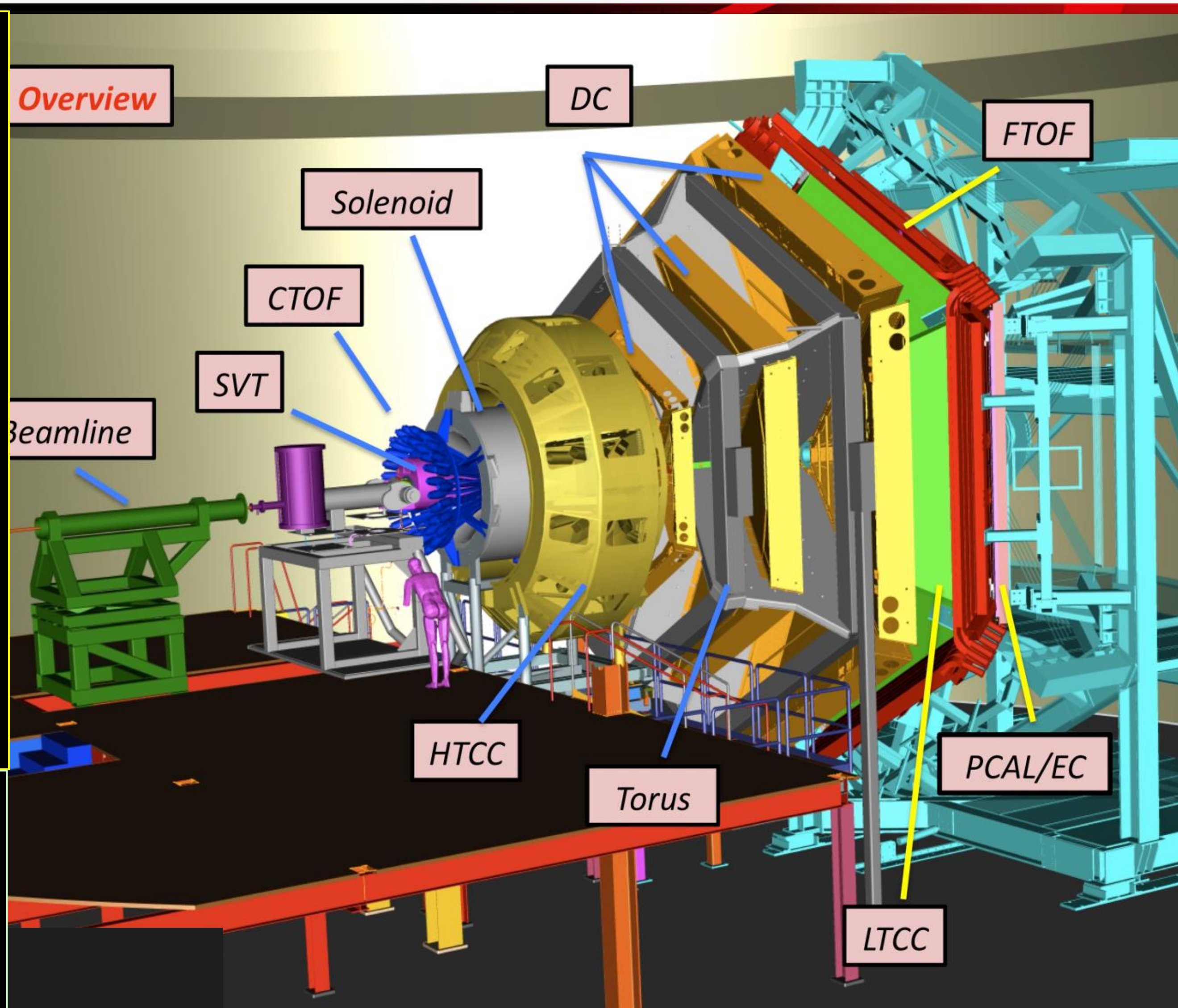
- SOLENOID magnet
- Barrel Silicon Tracker
- Central Time-of-Flight

Beamline

- Polarized target (transv.)
- Moller polarimeter
- Photon Tagger

Upgrades to the baseline & under construction

- RICH detector (FD)
- Forward Tagger (FD)
- Neutron detector (CD)
- Micromegas (CD)
- Polarized target (long.)




Number of readout channels : 111, 832

# CLAS12-Demonstarted the Key Performance Parameter February 2107!

## Data taking with the full detector readout:

- **8 hr data taking Feb 3$^{rd}$ - 4$^{th}$**

**- 5 nA electron beam**
**- 0.5 mm carbon wire**
**- ECAL total energy trigger**
**- Torus on**


- **All CLAS12 baseline detectors installed**
- **No solenoid magnet**
- **CTOF counters mounted on solenoid mockup**

# International Collaboration

CEBAF Large Acceptance Spectrometer

**Armenia:**
- Yerevan Physics Institute, Yerevan

**Chile:**
- Universidad Tecnica Federico Santa Maria, Valparaiso

**France:**
- CEA Saclay, IRFU, Paris
- Orsay University, IN2P3, Paris

**Germany:**
- Institut f. Kernphysik, Jülich
- Justus-Liebig-University Giessen, Giessen

**Italy:**
- INFN - LNF, Frascati, Roma
- Università di Genova,INFN, Genova
- Università di Ferrara, Ferrara
- INFN - Pavia, Universita di Pavia
- INFN - University di Roma Tor Vergata, Roma
- INFN - Sezione.di Torino, University di Torino

**Republic of Korea:**
- Kyungpook National University, Daegu

**Russian Federation:**
- MSU, Skobeltsin Institute for Nuclear Physics, Moscow
- Lomonsov Moscow State University, Moscow
- Institute for Theoretical and Experimental Physics, Moscow

**Spain:**
- University of the Basque Country, Bilbao

**United Kingdom:**
- Edinburgh University, Edinburgh
- Glasgow University, Glasgow

**United States of America:**
- Argonne National Laboratory, Argonne, Il
- California State University, Dominguez Hills, CA
- Canisius College, Buffalo, New York
- College of William and Mary, Williamsburg, VA
- Christopher Newport University, Newport News, VA
- Duquesne University, Pittsburgh, PA
- Fairfield University, Fairfield, CT
- Florida International University, Miami, FL
- Florida State University, Tallahassee, FL
- George Washington University, Washington, DC
- Idaho State University, Pocatella, ID
- James Madison University, Harrisionburg, VA
- Massachusetts Institute of Technology , MA
- Mississippi State University, Starkville, MS
- Norfolk State University, Norfolk, VA
- Ohio University, Athens, OH
- Old Dominion University, Norfolk, VA
- Rensselaer Polytechnic Institute, Troy, NY
- Temple University, Philadelphia, PA
- Thomas Jefferson National Facility, Newport News, VA
- University of Connecticut, Storrs, CT
- University of New Hampshire, Durham, NH
- University, of Richmond, Richmond, VA
- University of South Carolina, Columbia, SC
- University of Virginia, Charlottesville, VA
- Virginia Polytechnic Institute and State University, Blacksburg, VA

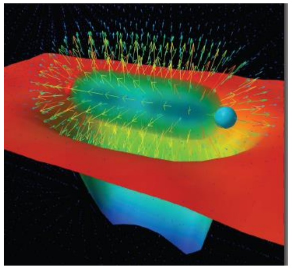
**45 Institutions**

# 12 GeV Approved Experiments by PAC Days

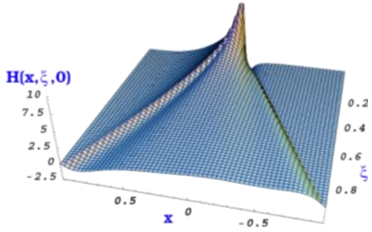
| Topic | Hall A | Hall B | Hall C | Hall D | Other | Total |
|---|---|---|---|---|---|---|
| The Hadron spectra as probes of QCD | | 219 | 11 | 540 | | **770** |
| The transverse structure of the hadrons | 145.5 | 185 | 110 | 25 | | **465.5** |
| The longitudinal structure of the hadrons | 65 | 230 | 165 | | | **460** |
| The 3D structure of the hadrons | 409 | 972 | 212 | | | **1593** |
| Hadrons and cold nuclear matter | 208 | 175 | 201 | | 14 | **598** |
| Low-energy tests of the Standard Model and Fundamental Symmetries | 547 | 180 | | 79 | 60 | **866** |
| **Total Days** | **1374.5** | **1961** | **699** | **644** | **74** | **4752.5** |
| **Total Days – Without MIE Days** | **725.5** | **1961** | **699** | **644** | **28** | **4057.5** |
| **Total Approved Run Group Days (includes MIE)** | **1374.5** | **926** | **656** | **424** | **74** | **3454.5** |
| **Total Approved Run Group Days (without MIE)** | **556.5** | **926** | **656** | **424** | **28** | **2590.5** |
| **Total Days Completed** | **20** | **30** | **0** | **25** | **0** | **75** |

# CLAS12 Science Program

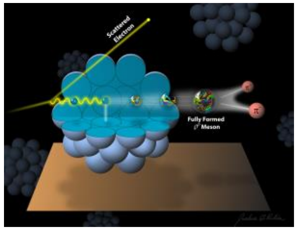
- Quark confinement and the role of the glue in hadron spectroscopy



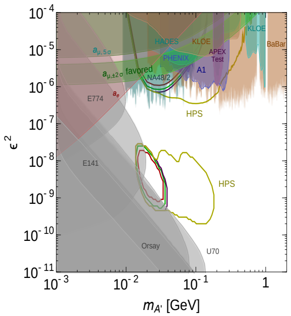
- Unraveling confinement forces in the proton, studying Nucleon and Nsar




- The strong interaction in nuclei – evolution of quark hadronization, nuclear transparency of hadrons

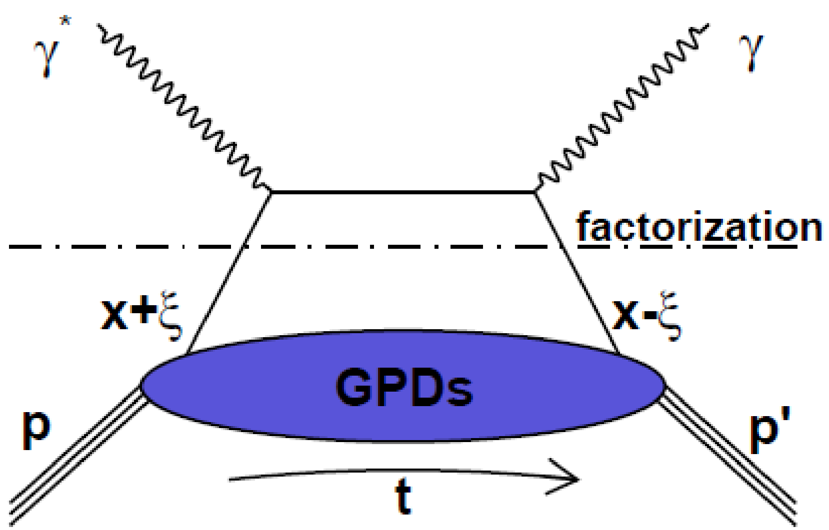


- Search for science beyond the Standard Model – precision and intensity frontiers



# Deeply Virtual Compton Scattering (DVCS)

## DVCS and Generalized Parton Distributions




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

Bjorken regime :
$Q^2 \to \infty$, $x_B$ fixed

$$t \text{ fixed} \ll Q^2 \;,\; \xi \to \frac{x_B}{2-x_B}$$

$$\frac{P^+}{2\pi}\int dy^- \, e^{ixP^+y^-} \langle p' | \bar{\psi}_q(0)\gamma^+(1+\gamma^5)\psi(y)|p\rangle$$

$$= \bar{N}(p')\left[ H^q(x,\xi,t)\gamma^+ + E^q(x,\xi,t) i\sigma^{+\nu}\frac{\Delta_\nu}{2M} + \tilde{H}^q(x,\xi,t)\gamma^+\gamma^5 + \tilde{E}^q(x,\xi,t)\gamma^5\frac{\Delta^+}{2M}\right] N(p)$$

x: average fraction of quark longitudinal momentum

$\xi$ fraction of longitudinal momentum transfer

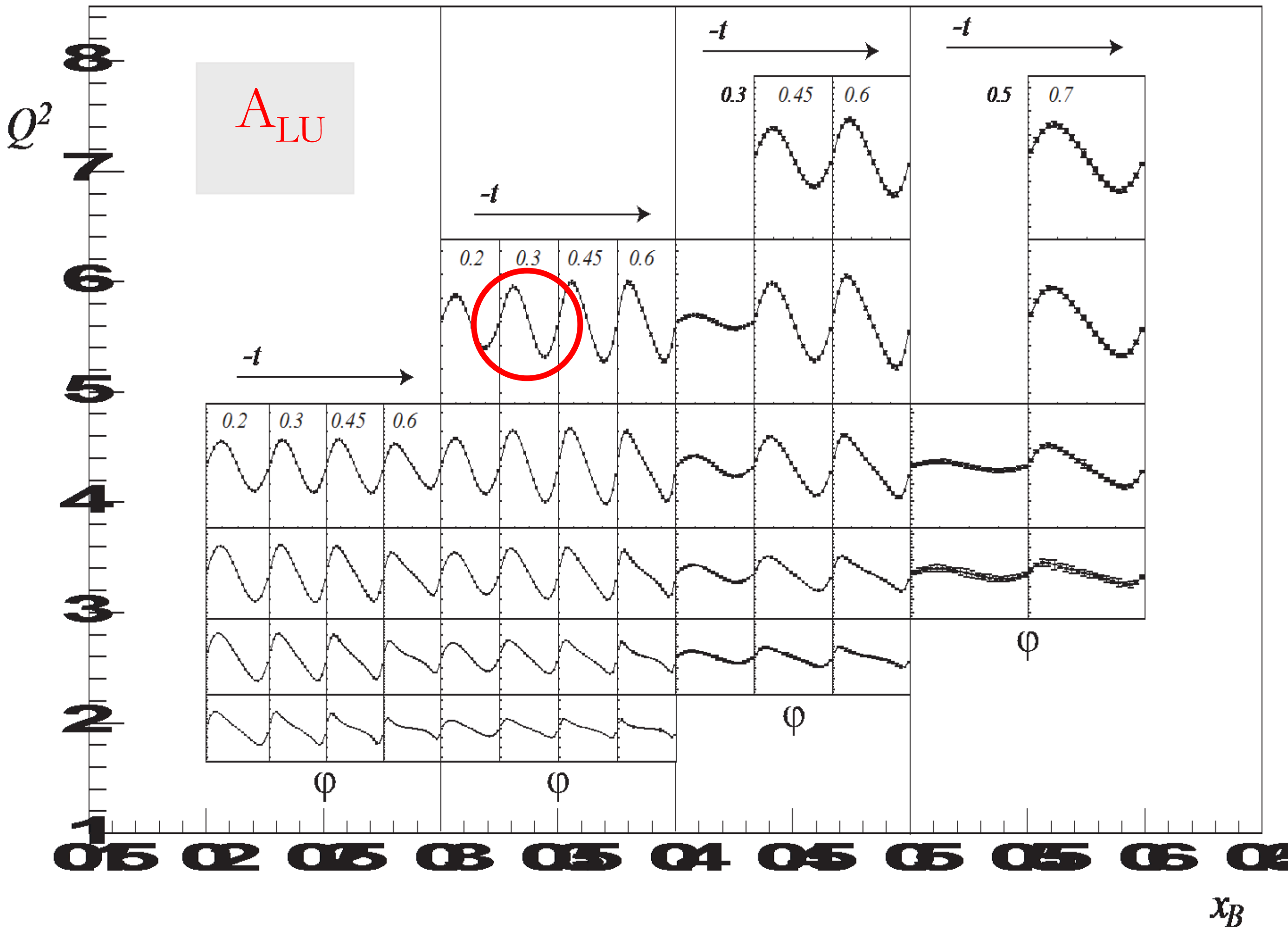
*H, E, $\tilde{H}$, $\tilde{E}$* : **G**eneralized **P**arton **Di**stributions (**GPDs**)

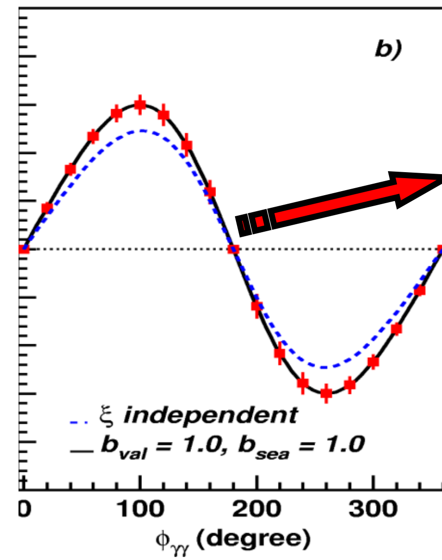
**3-D Imaging conjointly in transverse impact parameter and longitudinal momentum**

# $A_{LU}$ Projections for 12GeV

$\Delta\sigma_{LU} \sim \sin\phi\ \{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} + kF_2\mathcal{E}\}d\phi$

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

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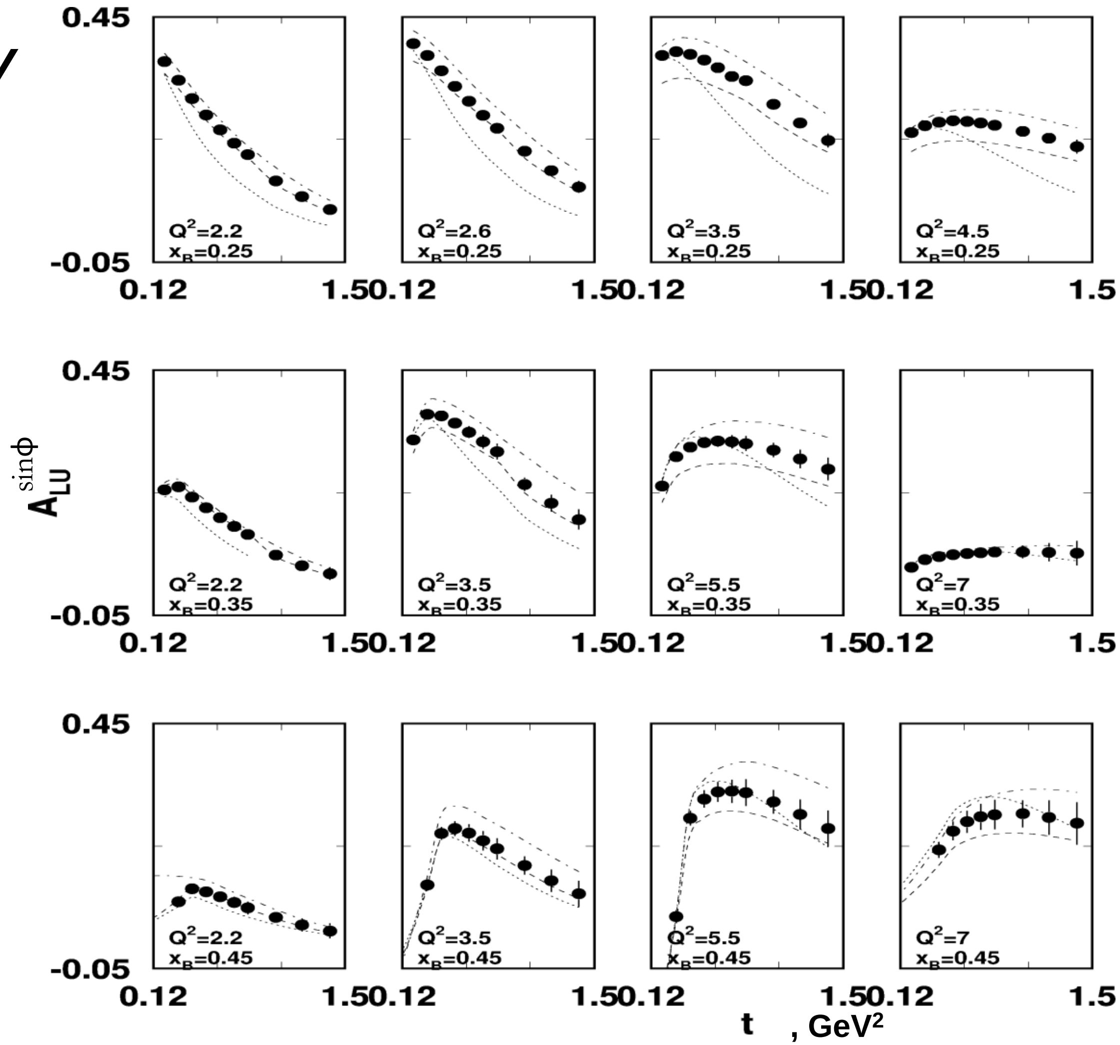
# $A_{LU}$ - Projections for protons

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

$\Delta\sigma_{LU} \sim \sin\phi \{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}d\phi$

$E_e$=11GeV

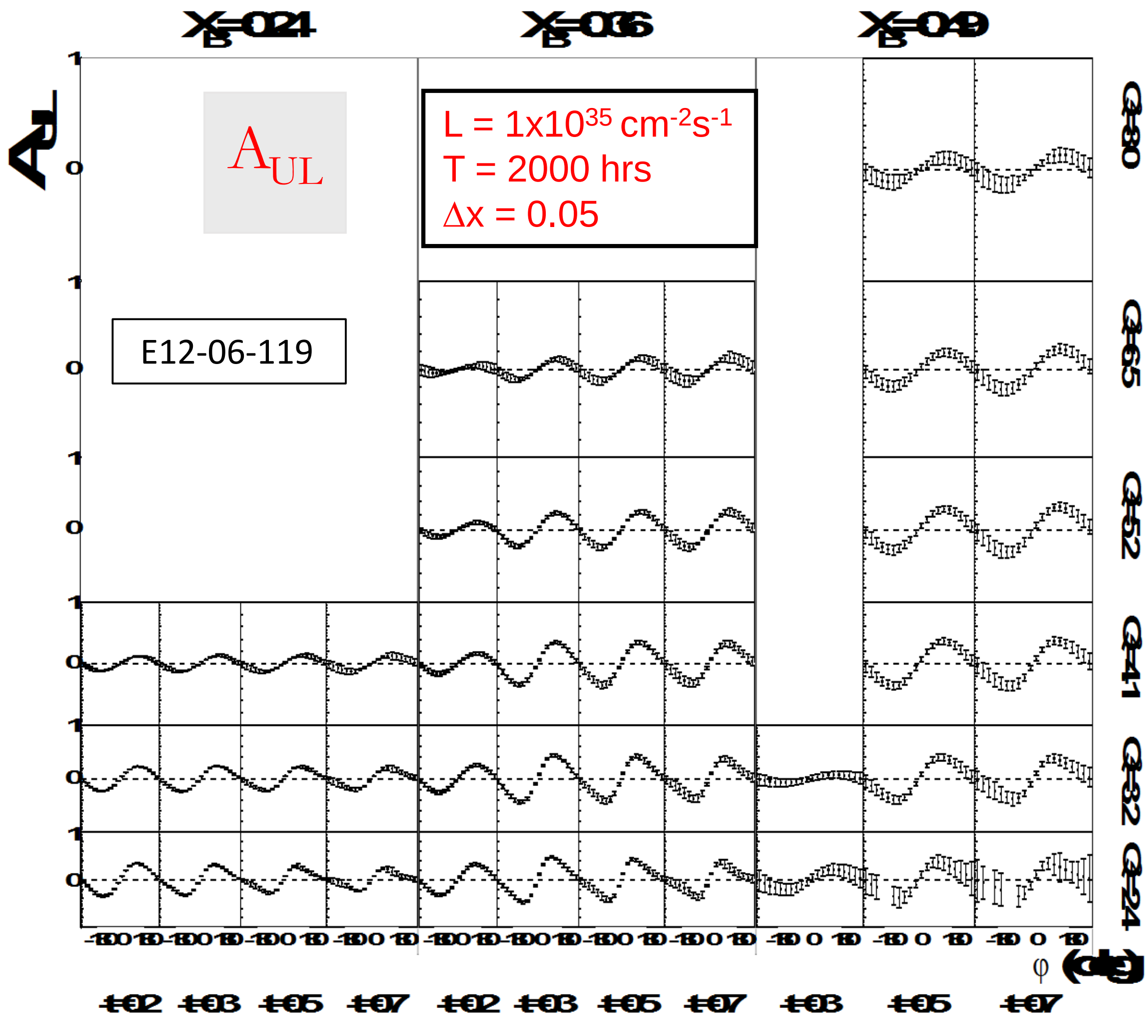


# $A_{UL}$ Projections for polarized protons

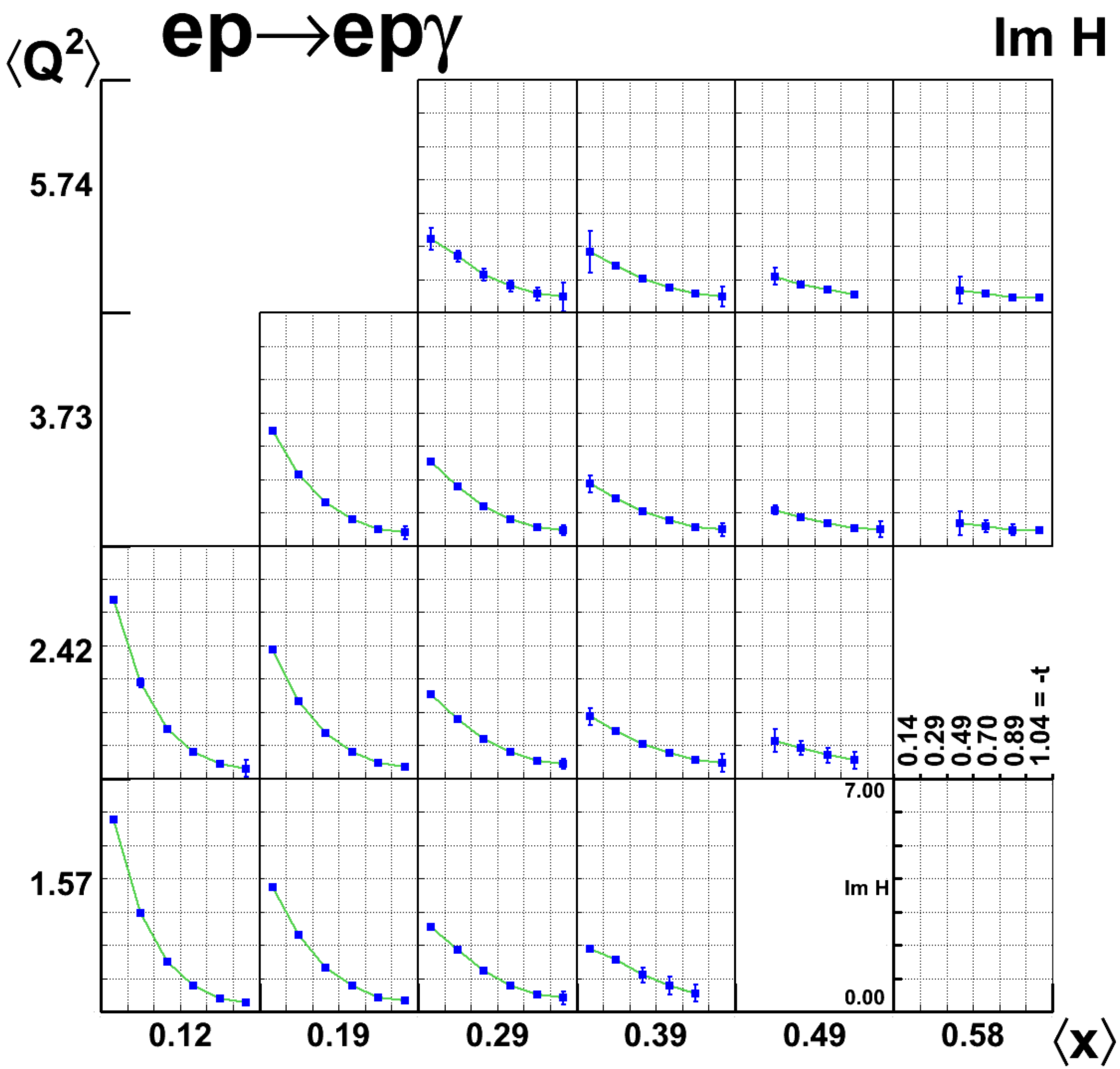
$e\,\vec{p} \rightarrow ep\gamma$

$\Delta\sigma_{UL} \sim \sin\phi\ \{F_1\tilde{H} + \xi(F_1+F_2)(H + \xi/(1+\xi)E)\}d\phi$

Dynamically polarized target $NH_3$, $ND_3$

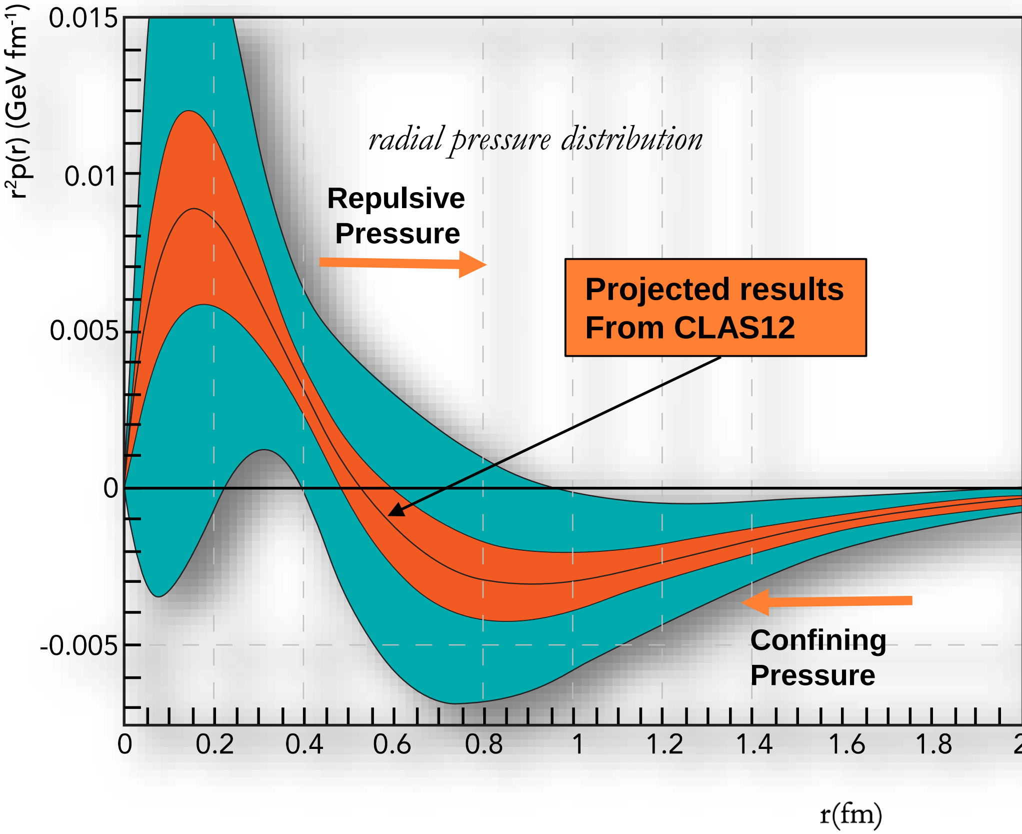


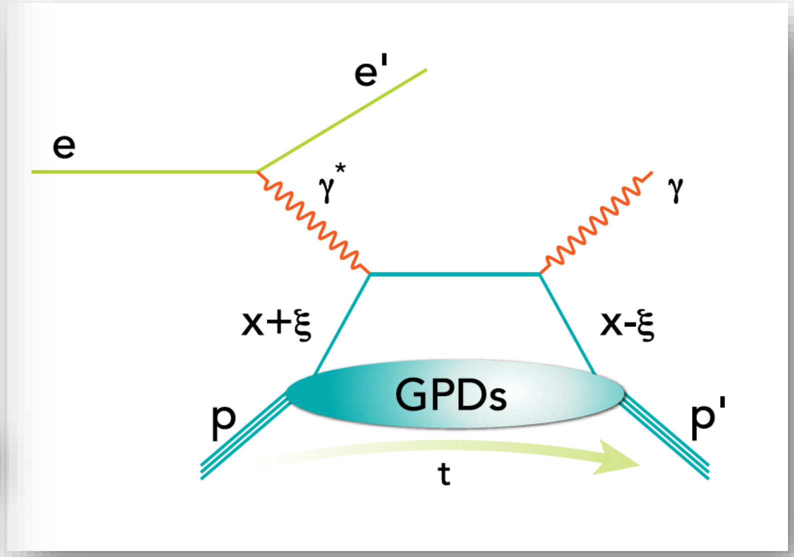
# GPD Extraction – Im H




Model-independent fit, at fixed $x_B$, t and $Q^2$,of DVCS observables

# Unraveling Quark Confinement in the Proton



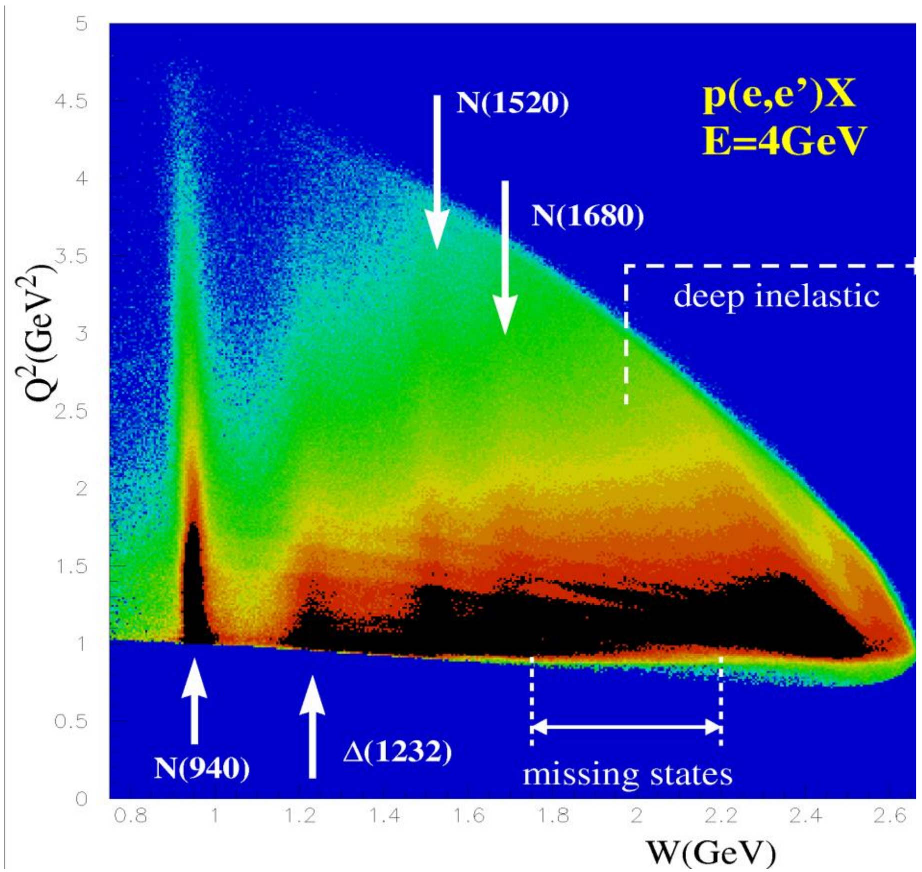

*Extract the confinement form factor and through a Fourier transform the radial shear force and pressure distribution.*

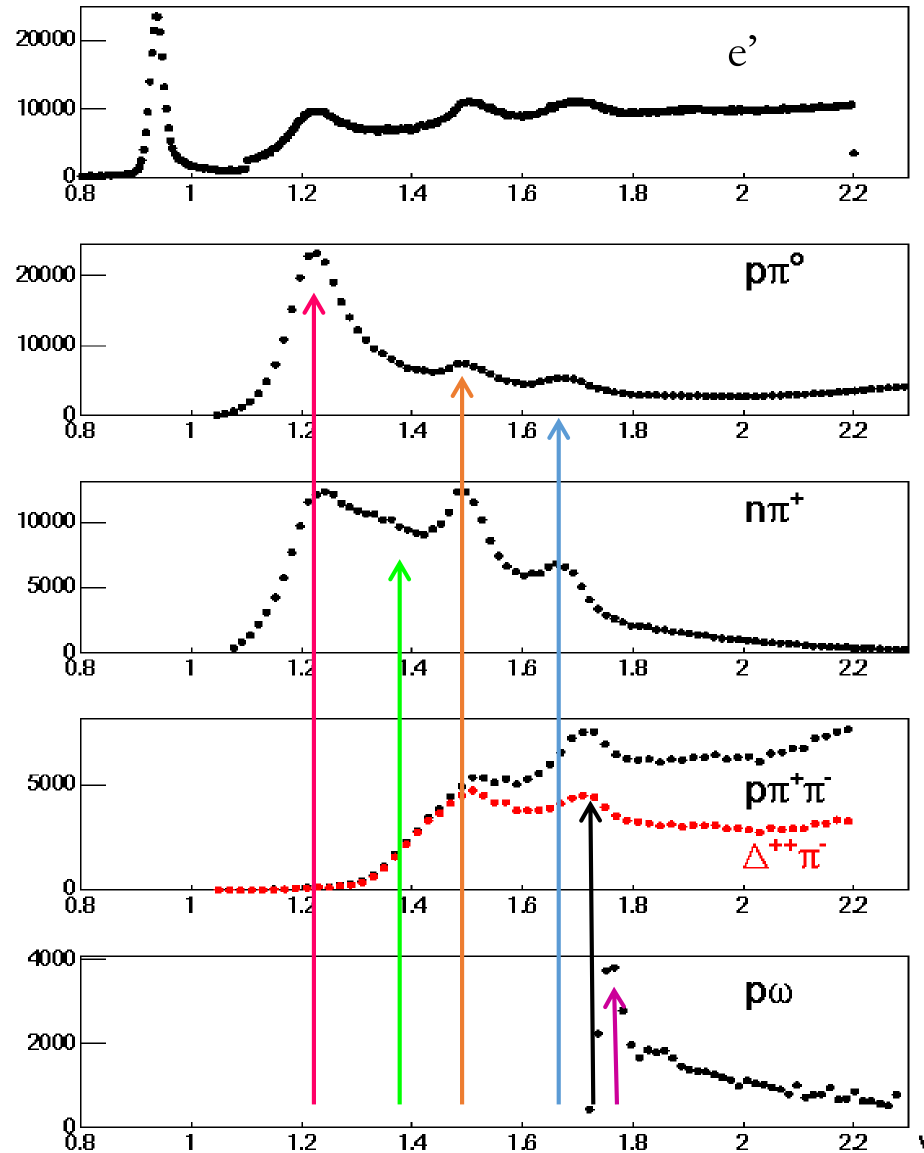
DVCS with CLAS12 will address one of the most fundamental unresolved problems in physics: How is quark confinement and the stability of visible matter in the universe realized?

*We address this by direct measurement of the confinement forces built from strong QCD.*

# Electron Scattering ep→e'X

$Q^2=-(e-e')^2; \quad W^2 = M_X^2=(e-e'+p)^2$




Resonances cannot be uniquely separated in inclusive scattering → exclusive processes

# From 2D to 3D imaging of NN* transitions

- Charge transition densities are 2D projections in ($b_x$, $b_y$) space.

- In order to get complete 3(2+1)D image of NN* transition in transverse impact parameter space and longitudinal momentum space we need a second scale beyond $Q^2$.

- Go from s-channel excitation of N* (where $Q^2 = t$) to t-channel excitation with $Q^2$ and t independently variable and $Q^2 >> t$.

- Experimentally this is achieved in N*DVCS. Probes quark contributions directly, avoids coupling to meson cloud for $Q^2 > 2\text{-}3\ GeV^2$, while $t/Q^2 << 1$.

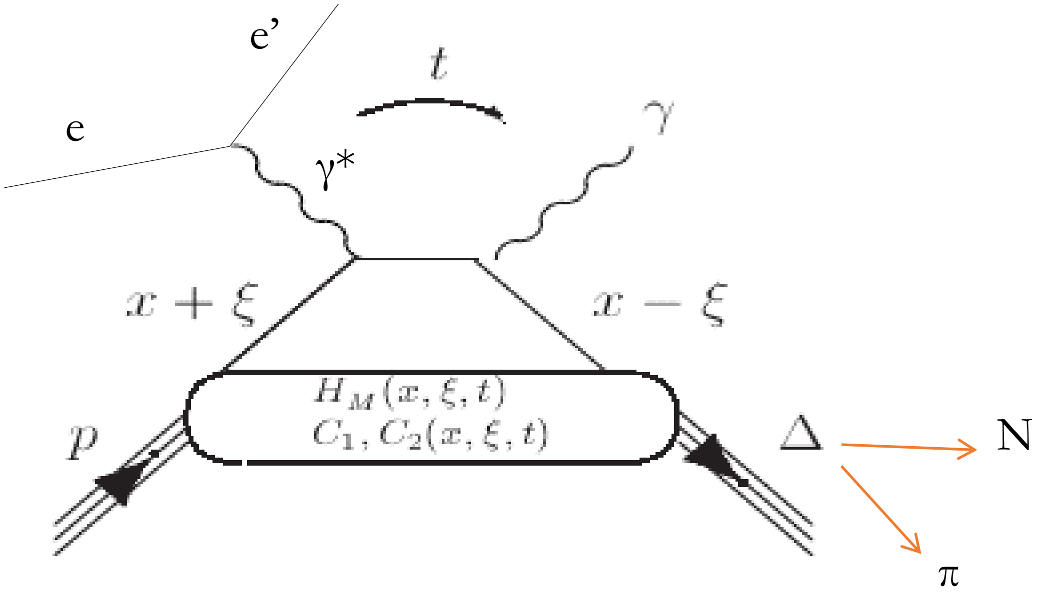
# ΔDVCS

Understand the physics of NΔ transition at the partonic level.

At leading twist in QCD: 3 vector N-Δ GPDs and 4 axial-vector N-Δ GPDs.

Expectation is that 3 GPDs dominate at small t.

## ΔVCS




$$H_M(x,\xi,t) = \frac{2}{\sqrt{3}}\left[E^u(x,\xi,t) - E^d(x,\xi,t)\right] ,$$

$$C_1(x,\xi,t) = \sqrt{3}\left[\tilde{H}^u(x,\xi,t) - \tilde{H}^d(x,\xi,t)\right] ,$$

$$C_2(x,\xi,t) = \frac{\sqrt{3}}{4}\left[\tilde{E}^u(x,\xi,t) - \tilde{E}^d(x,\xi,t)\right] .$$

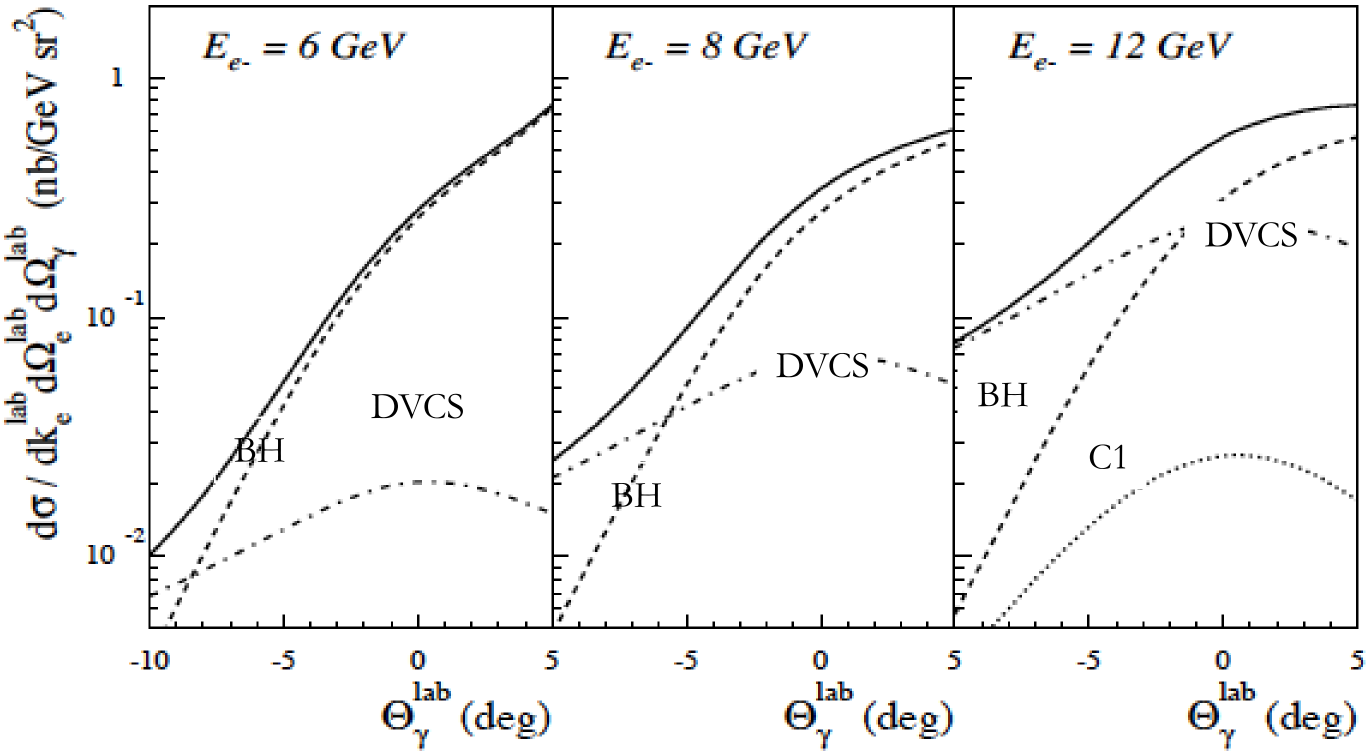
# ΔDVCS & BH cross section

K. Goeke,
M.V. Polyakov,
M. Vanderhaeghen,
Prog. Part. Nucl.
Phys. 47, 401
(2001).

## Example: Access NΔ GPDs in ΔVCS

$$e^- + p \rightarrow e^- + \Delta^+ + \gamma \;\; (\Phi = 0^\circ)$$

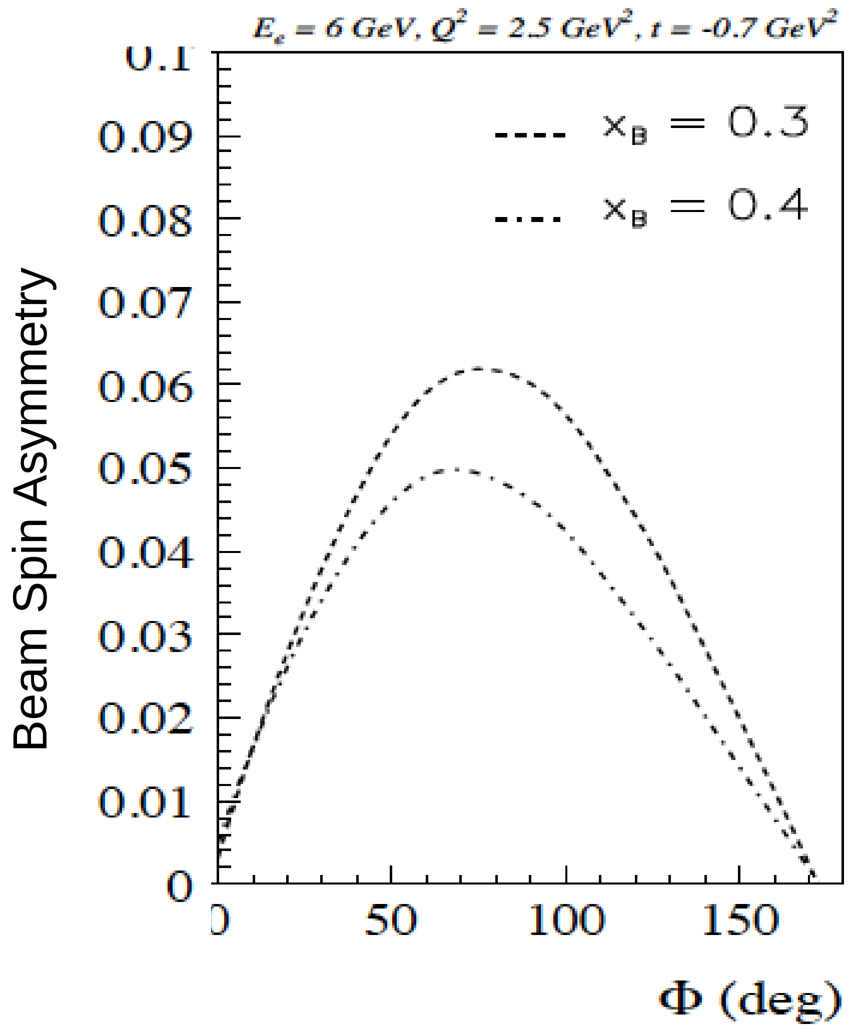
$$Q^2 = 2.5\ GeV^2,\ x_B = 0.3$$



# Beam Spin Asymmetry in ΔDVCS

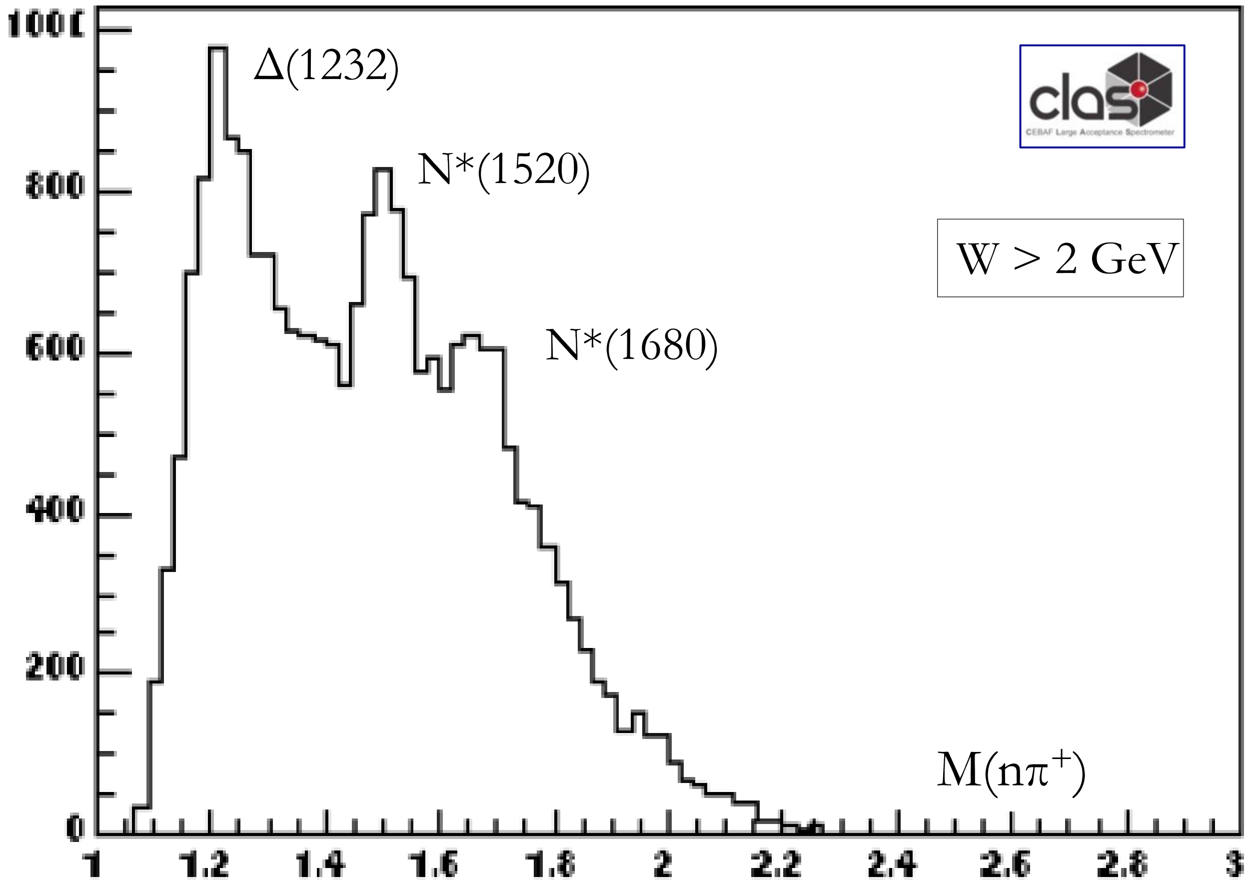
Similar to elastic DVCS+BH ΔVCS + BH have a beam spin asymmetry.

In large $N_c$ limit beam spin asymmetry can be computed using magnetic transition form factor $G_M^{\Delta}$ of NΔ as input.



# Experimental Aspects

ep --> enπ$^+$(γ)  $E_e$=4.2GeV, $Q^2$ ~ 1GeV$^2$




CLAS12 can access, $Q^2$< 10 GeV$^2$, $x_B$<0.8

N-N*(J=1/2, T=1/2) GPDs should have simpler structure than N-Δ (J=3/2, T=3/2) GPDs.

M. Guidal, et al. Nucl. Phys. A, 721, C327, 2003.

# Incorporate NN* GPDs in general framework?

- Need to develop transition GPD formalism for NN* transitions in N*DVCS.

- Channels of interest for experiments p(e,e'γpπ$^0$), p(e,e'γpη), p(e,e'γnπ$^+$), n(e,e'γpπ$^-$) for low mass states, and p(e,e'γ pπ$^+$π$^-$) for high mass states.

- Experiment schedule – data taking 2017/2018

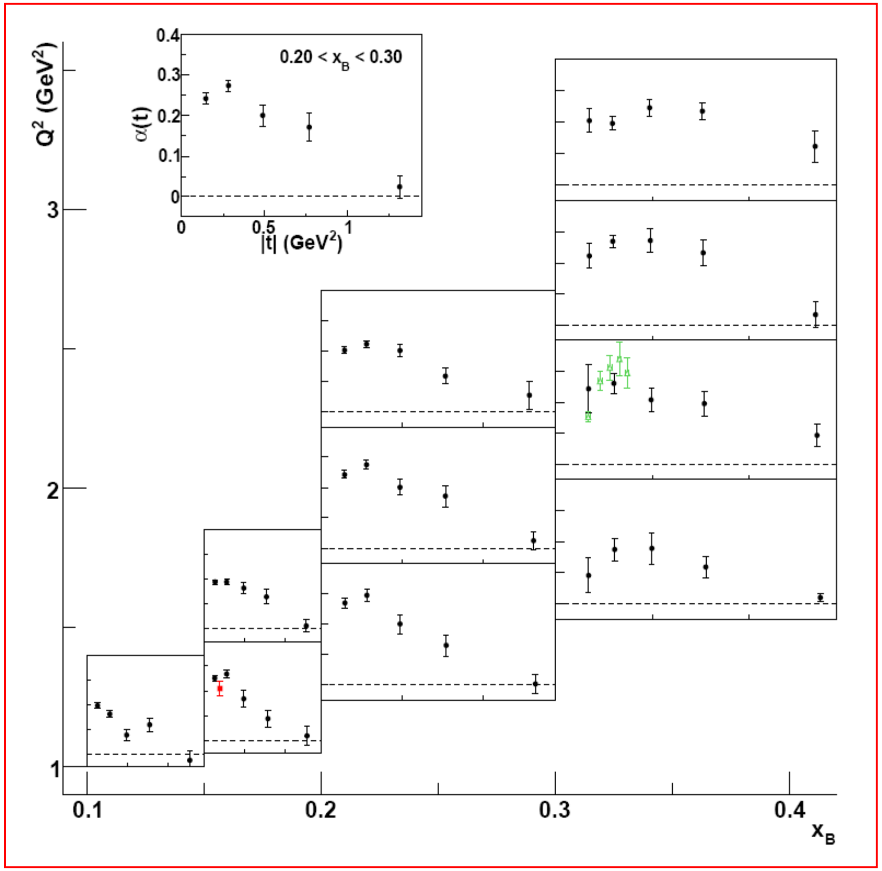
# Summary

Study of the Nucleon ground state and Nstar to understand color confinement is a central question to the CLAS12 science program.

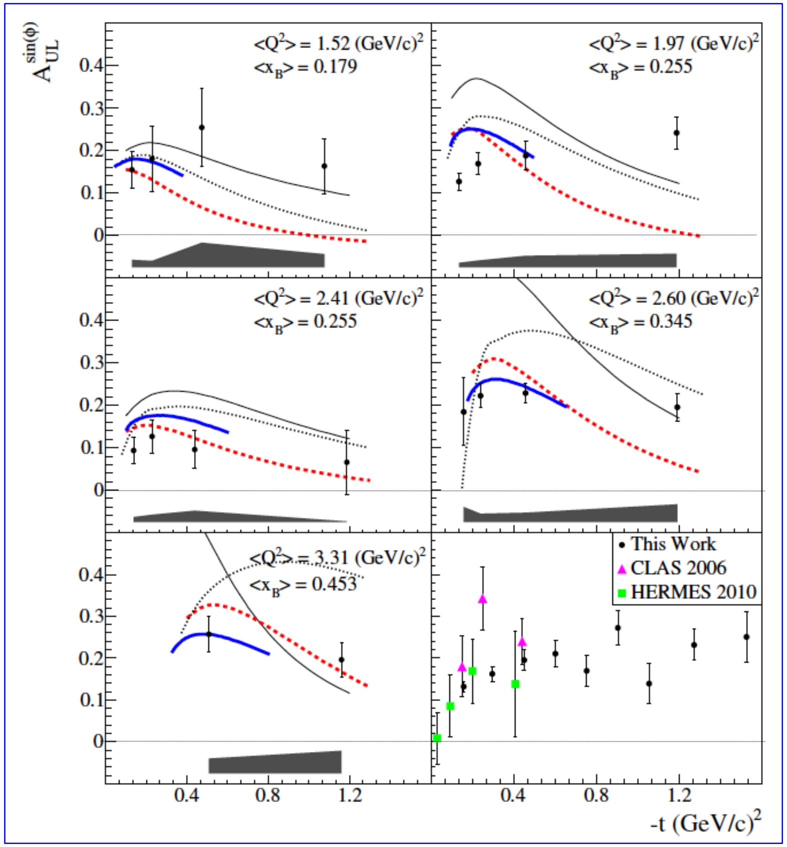
**CLAS12 Ready for Science!**

# DVCS measurements at 6 GeV $H$, $\widetilde{H}$ at 6 GeV

## Beam asymmetry




## Target asymmetry




Asymmetries are large!

*F.X. Girod et al. (CLAS), Phys.Rev.Lett100:162002,2008*

*E. Seder, et al. (CLAS), arXiv:1410.6615, 2014*

# 12 GeV Approved Experiments by PAC Days

| Topic | Hall A | Hall B | Hall C | Hall D | Other | Total |
|---|---|---|---|---|---|---|
| The Hadron spectra as probes of QCD | | 219 | 11 | 540 | | **770** |
| The transverse structure of the hadrons | 145.5 | 185 | 110 | 25 | | **465.5** |
| The longitudinal structure of the hadrons | 65 | 230 | 165 | | | **460** |
| The 3D structure of the hadrons | 409 | 972 | 212 | | | **1593** |
| Hadrons and cold nuclear matter | 208 | 175 | 201 | | 14 | **598** |
| Low-energy tests of the Standard Model and Fundamental Symmetries | 547 | 180 | | 79 | 60 | **866** |
| **Total Days** | **1374.5** | **1961** | **699** | **644** | **74** | **4752.5** |
| **Total Days – Without MIE Days** | **725.5** | **1961** | **699** | **644** | **28** | **4057.5** |
| **Total Approved Run Group Days (includes MIE)** | **1374.5** | **926** | **656** | **424** | **74** | **3454.5** |
| **Total Approved Run Group Days (without MIE)** | **556.5** | **926** | **656** | **424** | **28** | **2590.5** |
| **Total Days Completed** | **20** | **30** | **0** | **25** | **0** | **75** |

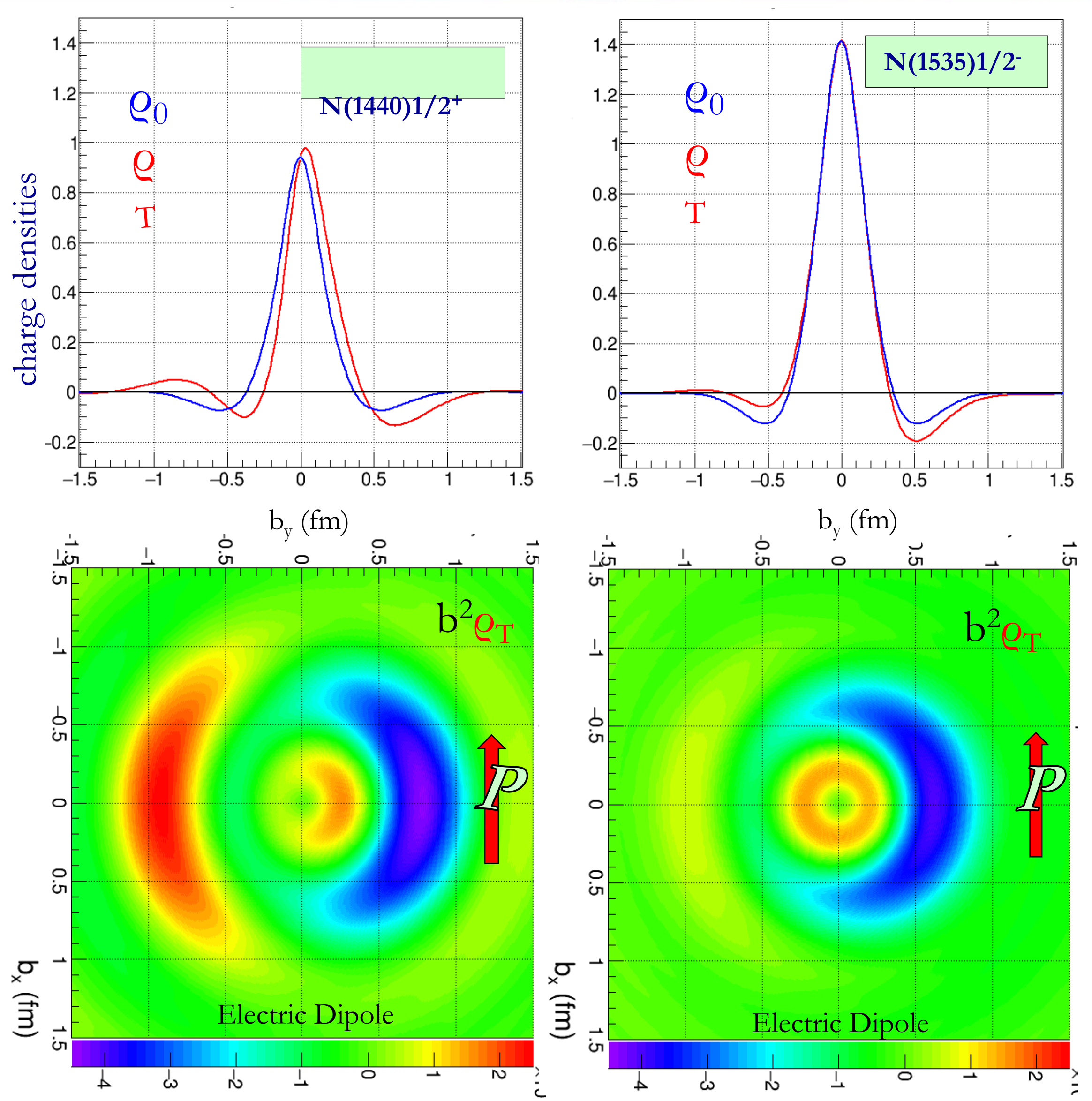
# Light Front γpN* transition charge densities

**Fourier transform in $Q^2$ of transition form factors result in the IMF in transition charge densities from the proton to the two states.**

**The N(1440) exhibits a softer core and wider clouds than N(1535)**

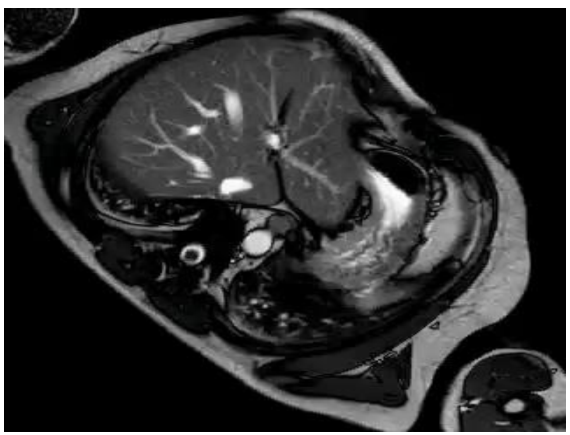
FT involves integral in $Q^2 \rightarrow \infty$
**=> need data at higher $Q^2$**

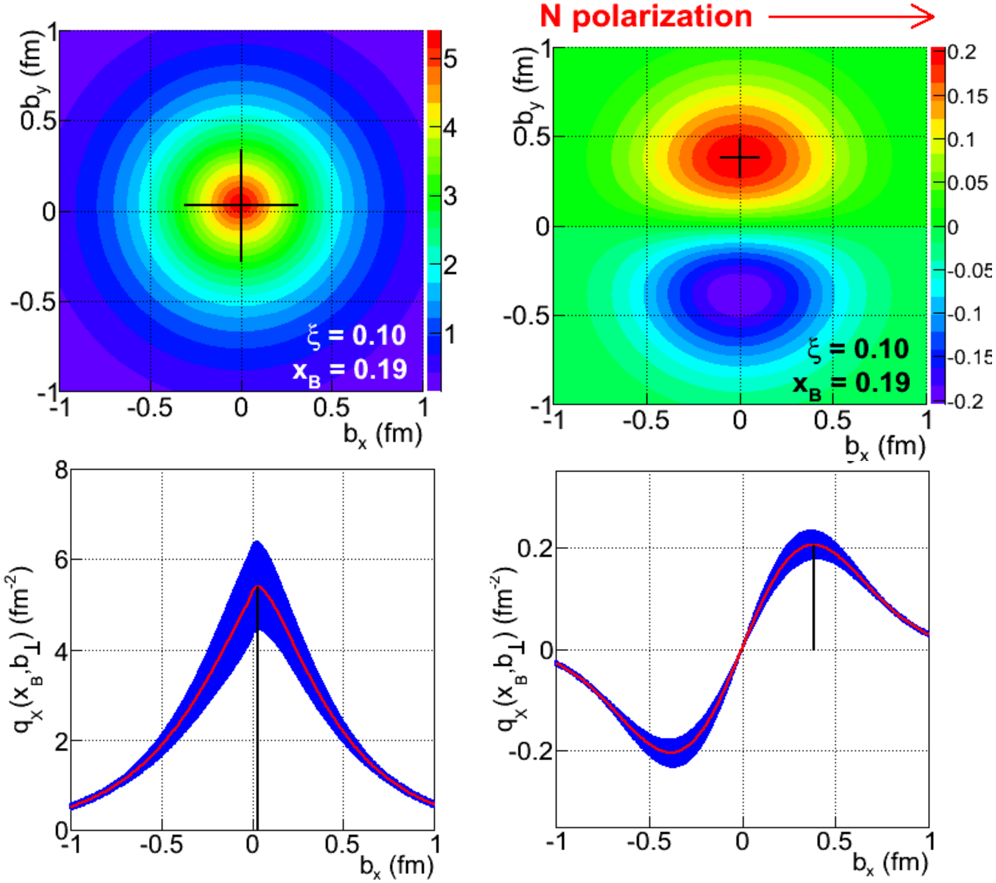
**With N*DVCS we get similar $(b_x, b_y)$ slices but at fixed $x_B$.**



# From GPDs to **spatial imaging** of the proton

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






Contribution of $H+E$ Contribution of $E$