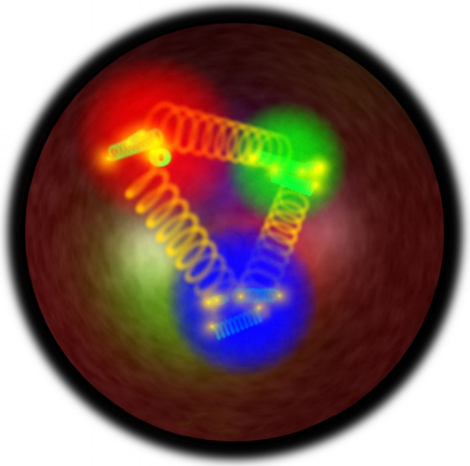
OLD DOMINION UNIVERSITY

# Exploring the 3D Partonic Structure of Neutron with BONuS12

M. Hattawy

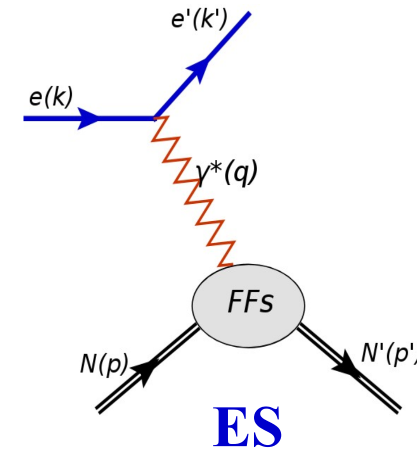
- Physics Motivations
- Recent Results.
- Proposed Measurements.



CLAS Collaboration Meeting, Jefferson Lab, June 18-21 2019

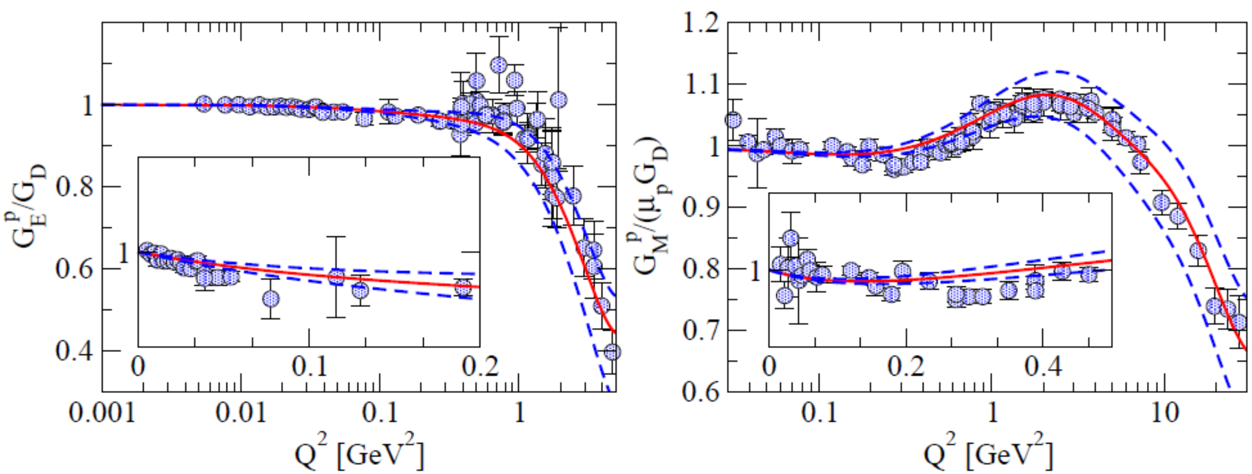
# Quick reminder about the Hadron Structure

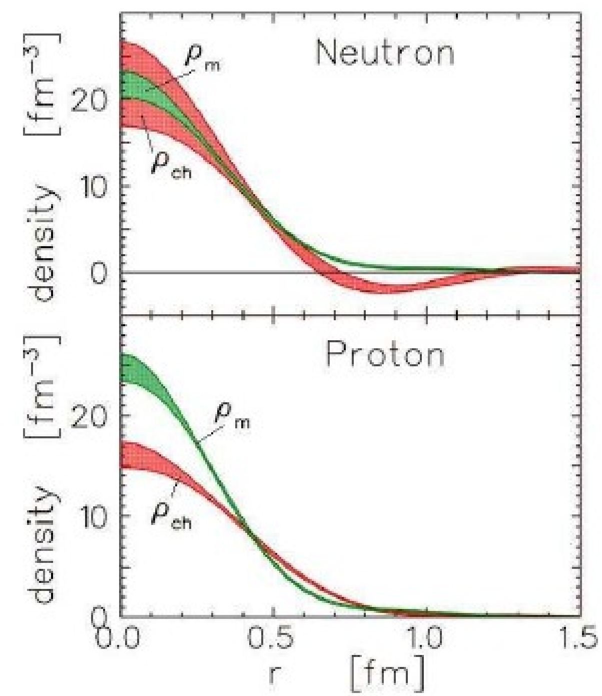
**Most of what we know today about hadrons' structure has come from the electromagnetic probes which give access to measure structure functions that quantify the properties of partons in hadrons.**




- **Form Factors (FFs)**
  - → Provide the charge and magnetization distributions inside a hadron.
  - → Accessible via Elastic Scattering (ES).

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{E'}{E}\left(\frac{G_E^2(Q^2)+\tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\left(\frac{\theta_e}{2}\right)\right)$$



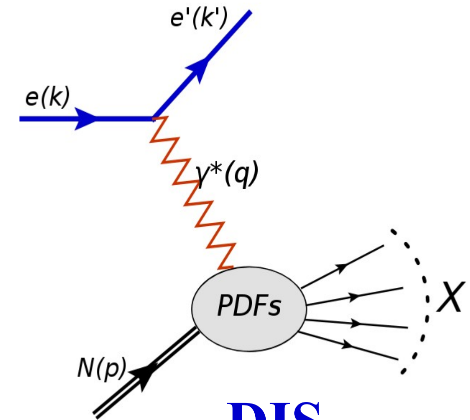




- C. F. Perdrisat, V. Punjabi and M. Vanderhaeghen, Prog. Part. Nucl. Phys. 59, 694-764 (2007)
- Kelly J. J., Phys. Rev. C 66, 065203 (2002)

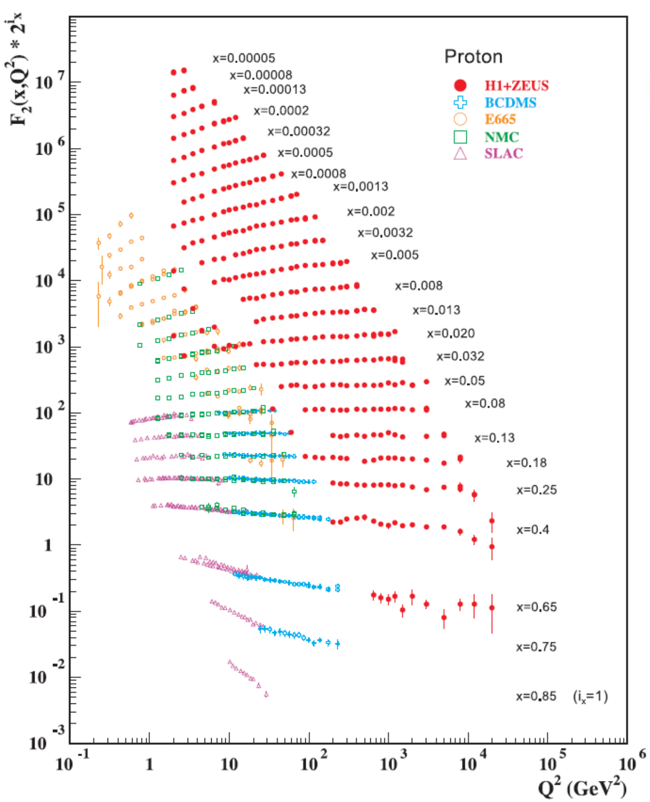
# Quick reminder about the Hadron Structure

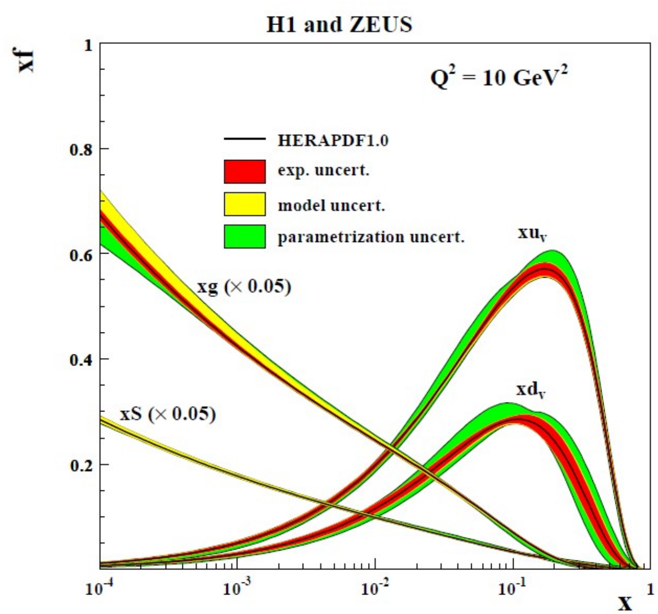
**Structure functions that quantify the properties of the partons in a hadron:**

- **Form Factors (FFs)**
- **Parton Distribution Functions (PDFs)**
  - → Provide partons longitudinal momentum distributions
  - → Measurable via Deep Inelastic Scattering (DIS).
    - \- For nucleons, the unpolarized DIS cross section is parametrized by two PDFs: $F_{1,2}(x)$, with $\mathcal{F}_1(x) = \frac{1}{2}\sum_q e_q^2 f_q(x)$ and $\mathcal{F}_2(x) = x\sum_q e_q^2 f_q(x)$




**DIS**




Proton structure:

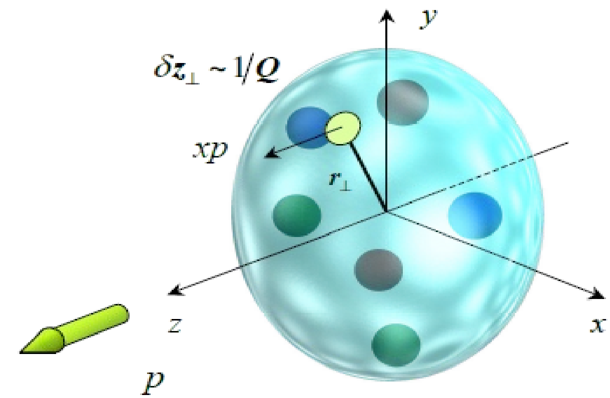
- → Large x, $u_v(x) \sim 2\, d_v(x)$
- → Low x, more gluons radiated and slpitting producing sea quarks


\- J. Beringer et al. (Particle Data Group), Phys. Rev. D 86, 010001, page241, 2012.
\- R. Placakyte et al. (H1 and ZEUS Collaborations), arXiv:1111.5452 [hep-ph], 2010.

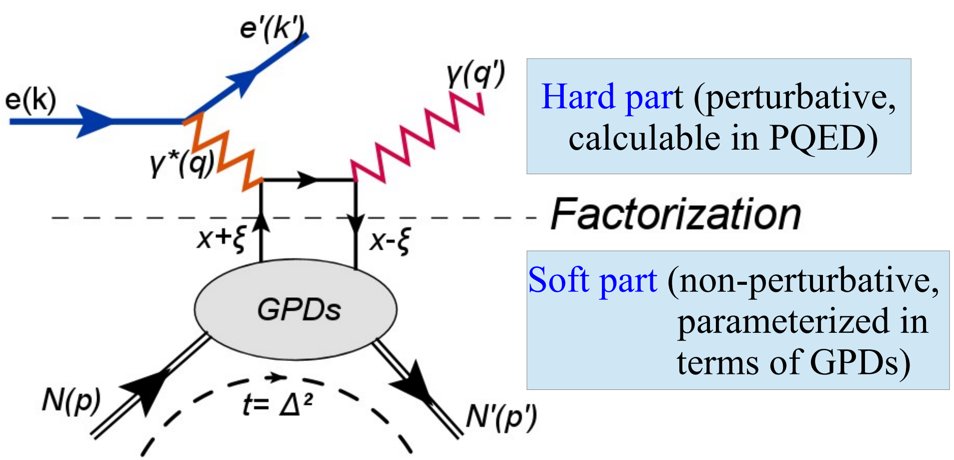
# Generalized Parton Distributions

**- Contain information on:**

→ Correlation between quarks and anti-quarks
→ Correlation between longitudinal momentum and transverse spatial position of partons




**- Can be accessed via hard exclusive processes such as deeply virtual Compton scattering (DVCS):**



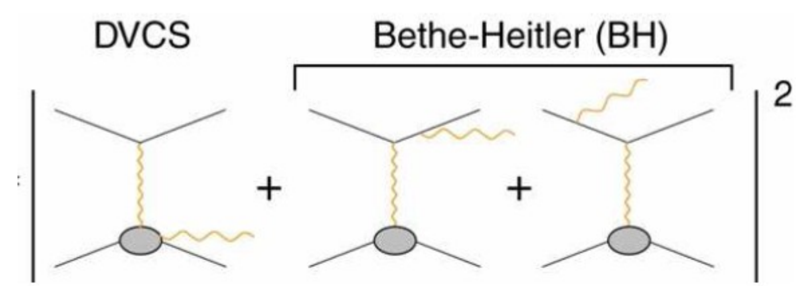

$$\xi \simeq x_B/(2-x_B) \qquad x_B = Q^2/2p.q$$

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

* At leading order in $1/Q^2$ (twist-2) and in the coupling constant of QCD ($\alpha_s$).

- **Experimentally,** the measured photon-electroproduction cross section ($ep \rightarrow ep\gamma$) is:

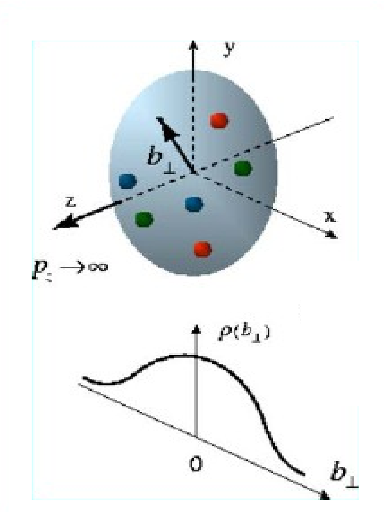
$$d\sigma \propto |\tau_{BH}|^2 + \underbrace{(\tau^*_{DVCS}\tau_{BH} + \tau^*_{BH}\tau_{DVCS})}_{\mathcal{I}} + |\tau_{DVCS}|^2$$

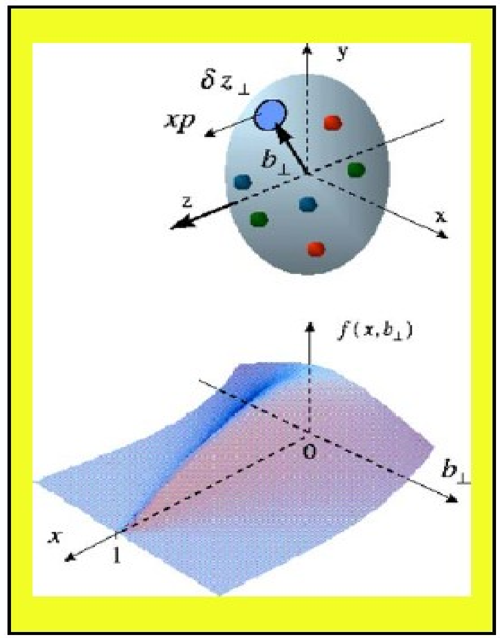


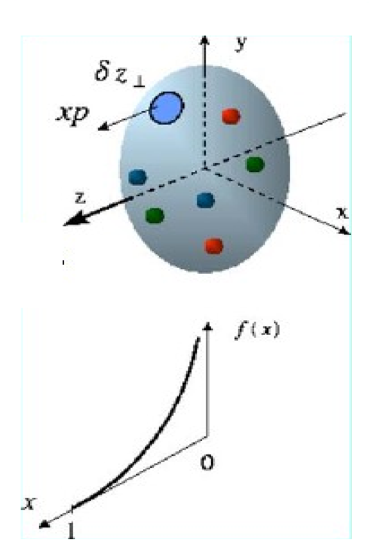

- The DVCS signal is enhanced by the interference with BH.

# GPDs links to FFs and PDFs

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

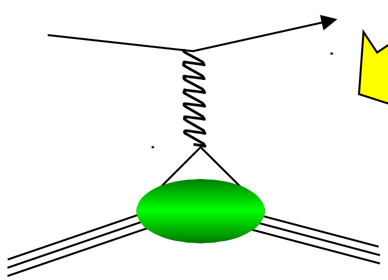


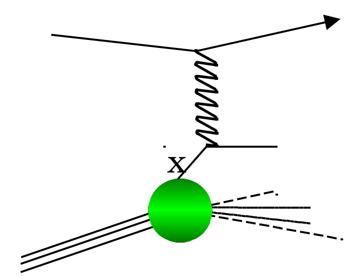




**Form factors:** **transverse quark distribution** in coordinate space

**Parton distributions:** **longitudinal quark distribution** in momentum space






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

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

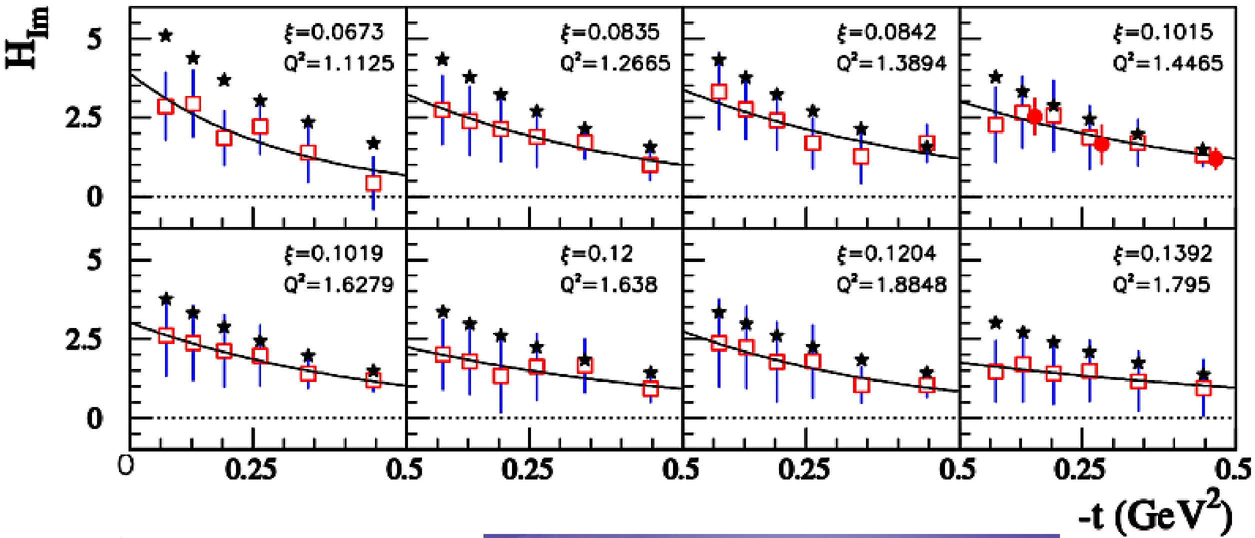
$H(x,0,0) = q(x)$,

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

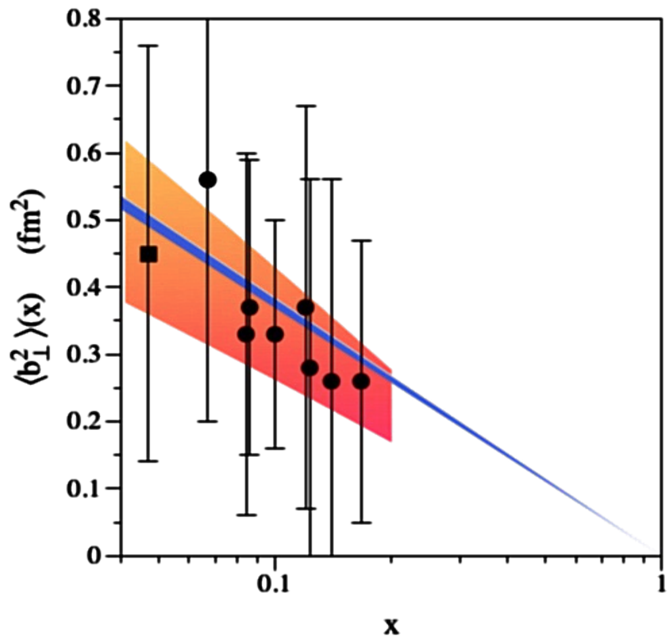
# Proton Tomography via DVCS

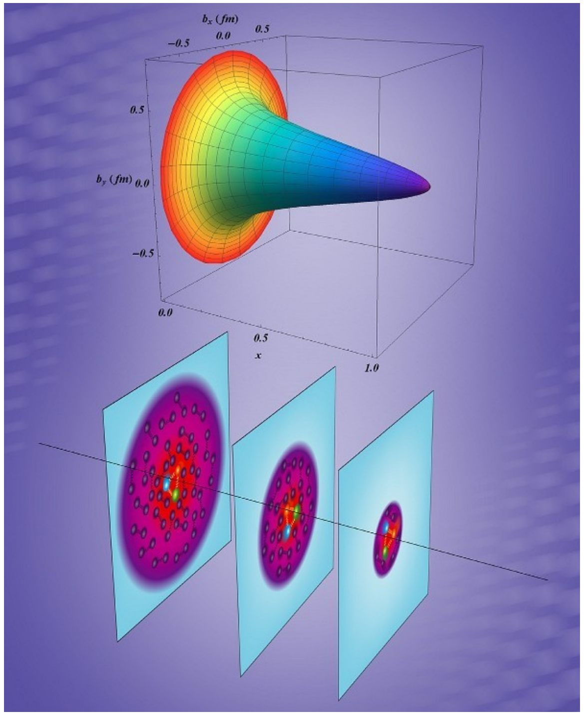
- Local fit of all the JLab data
  – Jlab Hall A (σ, Δσ)
  – CLAS (σ, Δσ, lTSA, DSA)

- Enough coverage to explore the t and $x_B$ (→ξ) dependence of $H_{Im}$.




- Obtaining the tomography of the proton
  – Represented is the mean square charge radius of the proton for slices of x.



- The nucleon size is shrinking with x.

[R. Dupré et al. Phys.Rev. D95 (2017) no.1, 011501]

# Why Do We Need to Measure Neutron GPDs

**- First free proton 3D tomography has been extracted within the GPDs frameowrk.**

**- Much less is known about the neutron structure, unavailability of free neutron target.**

**- First dedicated nDVCS measurment at CLAS12, E12-11-003**
**$\gamma^* + d \rightarrow n + \gamma + (p)$, looking for the flavor separation of GPDs:**

$$(H,E)_u(\xi,\xi,t) = \frac{9}{15}\left[4(H,E)_p(\xi,\xi,t) - (H,E)_n(\xi,\xi,t)\right]$$
$$(H,E)_d(\xi,\xi,t) = \frac{9}{15}\left[4(H,E)_n(\xi,\xi,t) - (H,E)_p(\xi,\xi,t)\right]$$

**What do we propose to measure here? Why? ...**

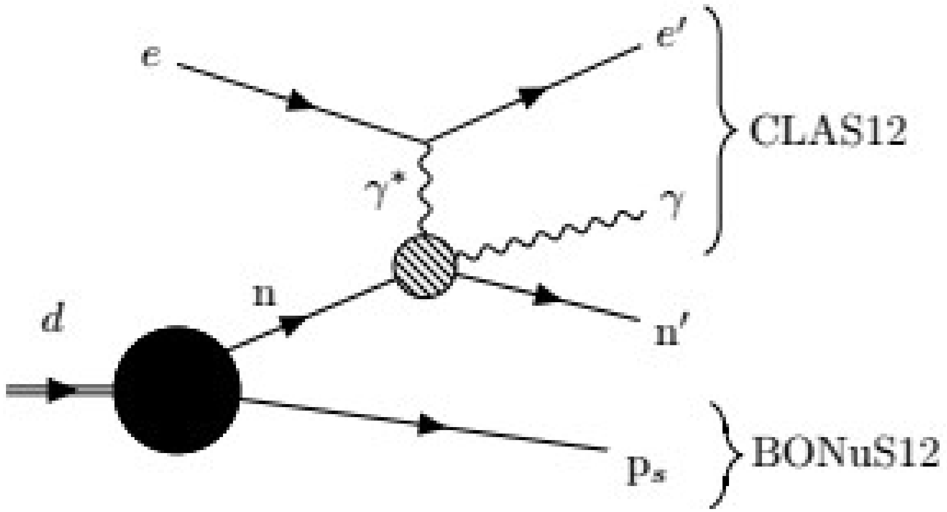
# nDVCS & GPDs

**<u>Two nDVCS channels are accessible with BONuS12:</u>**

◊ **Tagged-proton nDVCS: $e^- D \rightarrow e^- p \gamma (n)$**

→ Study the partonic structure of the neutron via measuring the $A_{LU}$

$$A_{LU} = \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-} = \frac{1}{P_B}\frac{N^+ - N^-}{N^+ + N^-}$$

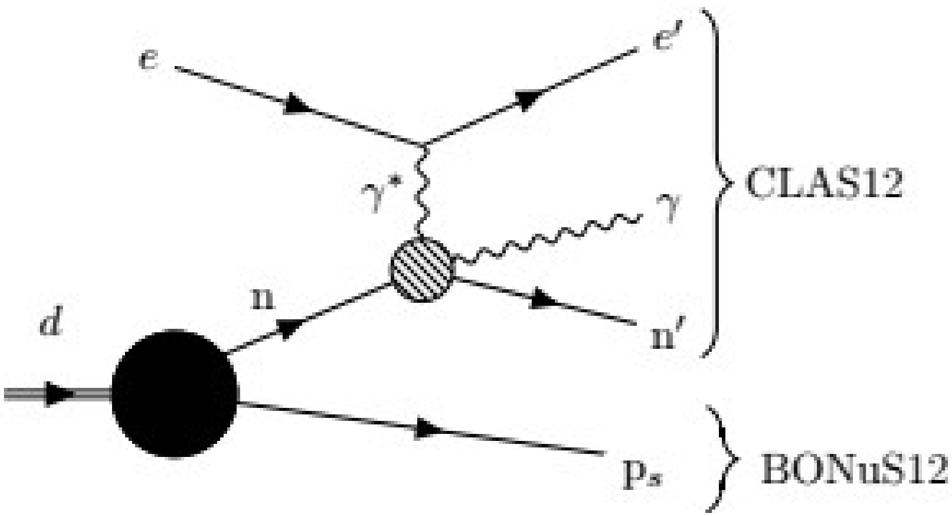



◊ **Fully exclusive nDVCS: $e^- D \rightarrow e^- n \gamma p$**

→ Study the Fermi motion effect on $A_{LU}$

→ Measure the size of the FSI on $A_{LU}$

→ Explore the size of the systematic uncert on RG-B measurement.



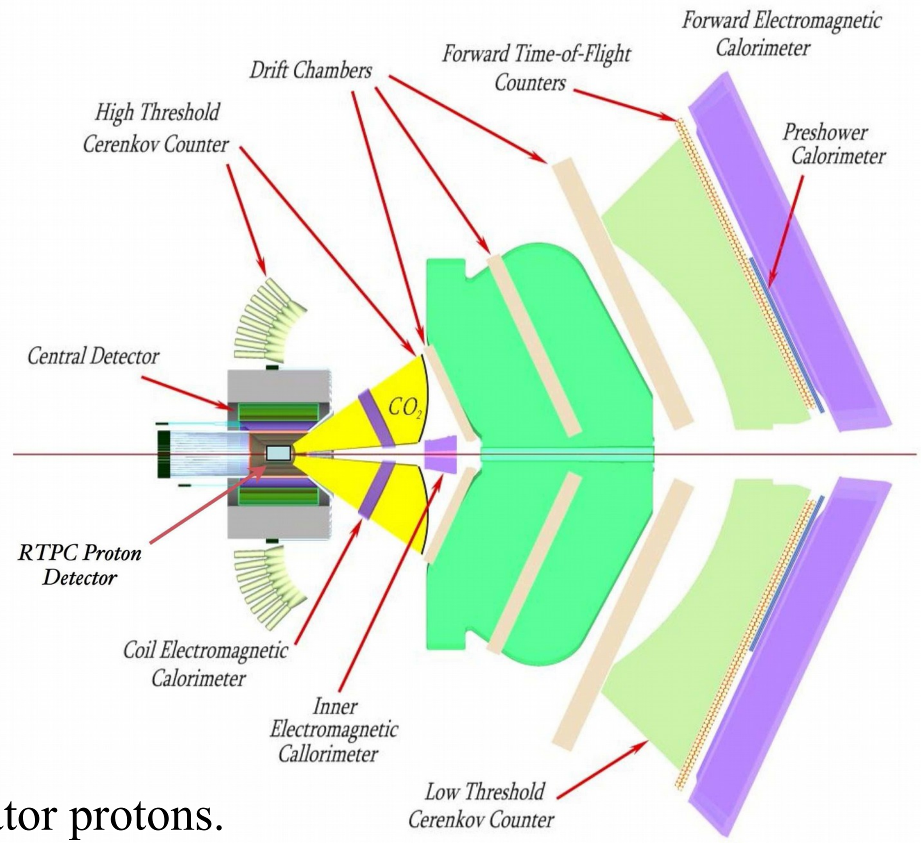
# RG-F Approved Experimental Setup

11 GeV

## $e^- D \rightarrow$ ……

**- CLAS12 Forward Detector:**

→ Superconducting Torus magnet.
→ 6 independent sectors:
  → HTCC: identifying $\pi^-$ (p >5.0 GeV/c).
  → 3 regions of DCs: tracking charged particles.
  → LTCC: $\pi^-$ identification (p >3.0 GeV/c).
  → FTOF Counters: identifying hadrons.
  → PCAL and Ecs: detecting $\gamma$, $e^-$ and n [5º,40º].
  → FT : detecting $\gamma$, $e^-$ [2.5º,4.5º]




**- Central Detector:**
- **Target:** D gas @ 7.5 atm, 293 K
- **BONuS12 RTPC:** Detects low energy spectator protons.
- **Solenoid:** - Shields the detectors from Møller electrons.
  - Enables tracking in the RTPC.
- **Additonal detectors to be used: CTOF, CND, and FMT**

35 days on D
5 days on $H_2$
with $L = 2 \cdot 10^{34}$ $cm^{-2}$ $sec^{-1}$

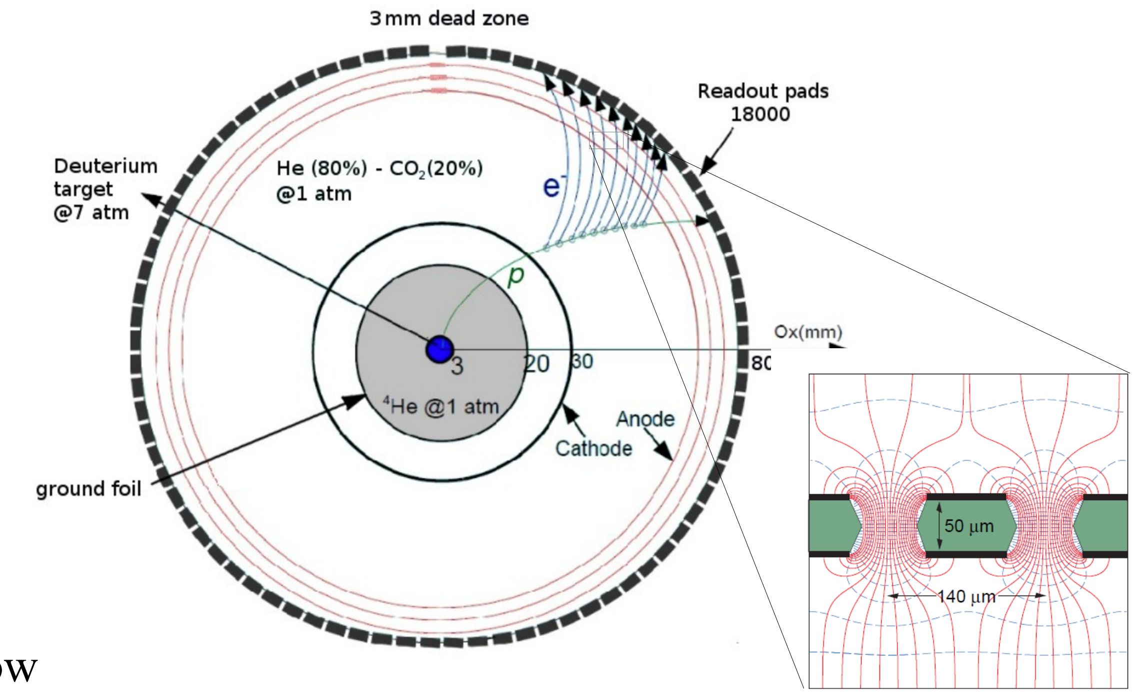
**We are asking for the electron beam to be highly polarized**

ODU

# BONuS12 RTPC

## - Design:

- ♦ 100% azimuthal coverage
- ♦ 400 mm long , 160 mm Ø
- ♦ 50 µm target's Kapton wall
- ♦ 4 µm cathode foil @ 4.3 kV
- ♦ 40 mm drift region, uniform $|\vec{E}|$ = 500 V/cm, $|\vec{B}|$ = 5 T
- ♦ 3 GEMs layers, gain of 1000/layer
- ♦ 17280 readout elements (2.7 mm x 3.9 mm).




## - Work principle:

Charged particle ionizes the gas atoms

→ Under EM field, released electrons follow their drift paths at a certain drift speed

→ Amplifications via the 3 GEM layers

→ Readout board, record electrons' charges (ADCs units) in time bins (TDCs units).

## - Offline reconstruction:

ADCs —Pads' gains ($G_i$)→ $\left\langle \frac{dE}{dX} \right\rangle = \frac{\sum_i \frac{ADC_i}{Gi}}{vtl}$

TDCs —Drift speed and paths→ Reconstructing chains of hits —Known $\vec{B}$→ p/q

→ **PID**

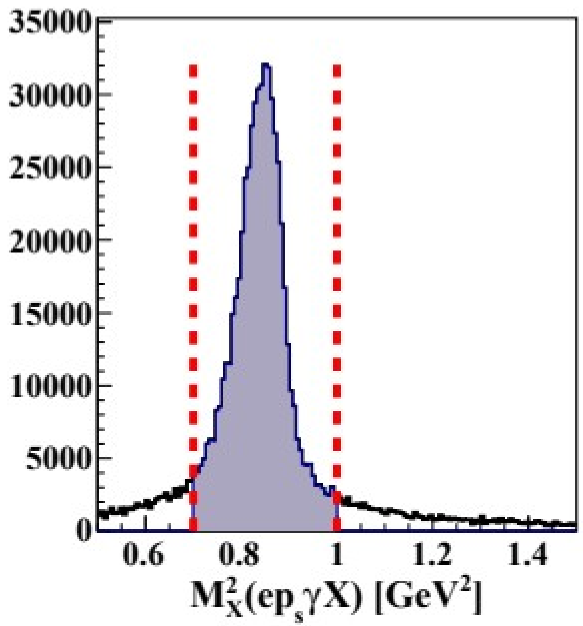
# nDVCS Generation, Simulation, & Reconstruction

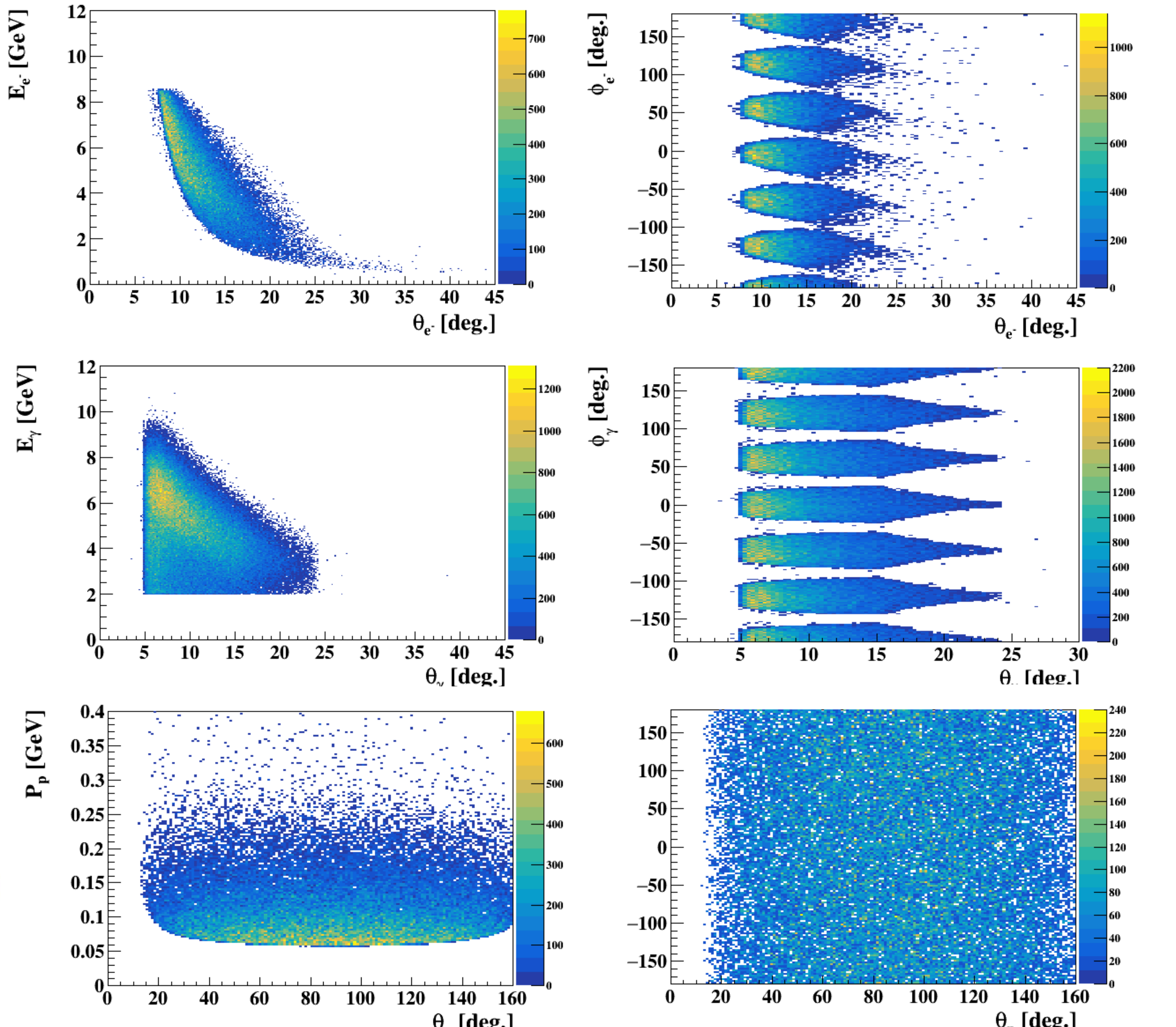
- nDVCS event generation: GENEPI DVCS/DVMP Generator
- Simulation: CLAS12 official simulation (GEMC 4.3.0)
- Reconstruction: COATJAVA 5b.7.4

# Tagged-proton nDVCS Events Selection

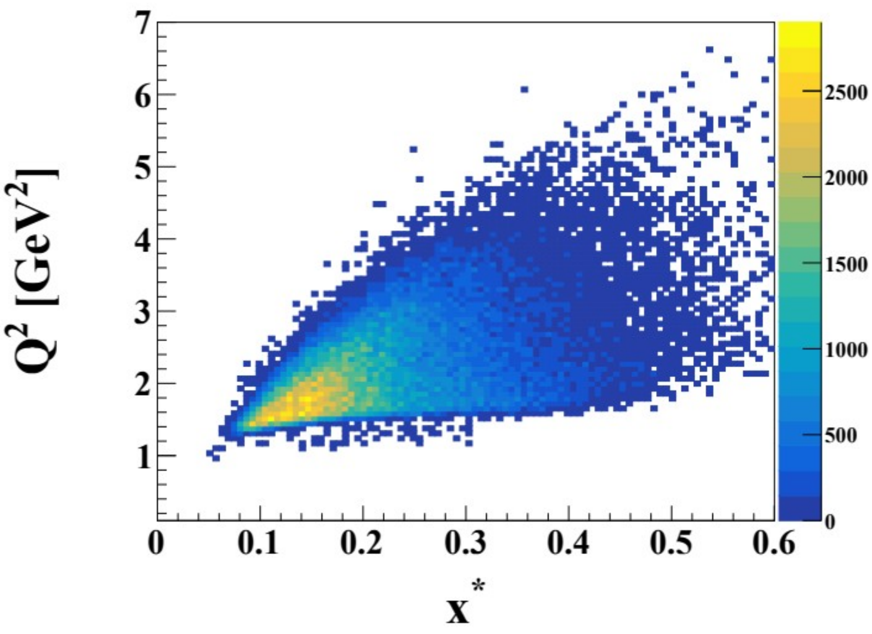
**Events which have:**

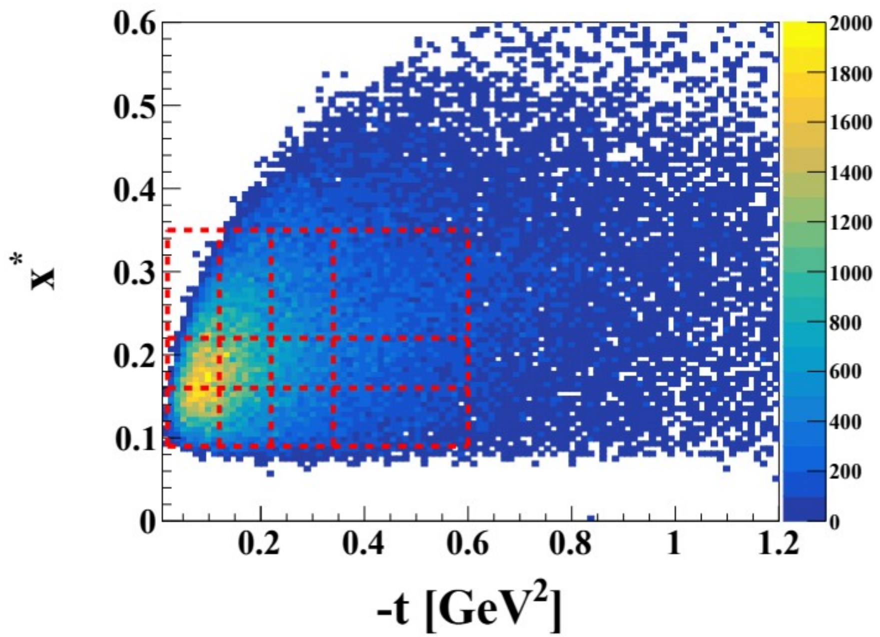
- ◊ Events with :
  - One good electron
  - One high-energy photon ($E\gamma > 2$ GeV)
  - One proton in BONuS12.
- ◊ $Q^2 > 1$ GeV² and W> 2 GeV/c²
- ◊ Exclusivity cuts.



# Tagged-proton nDVCS Phase-Space




$$A_{LU} = \frac{d^4\sigma^+ - d^4\sigma^-}{d^4\sigma^+ + d^4\sigma^-} = \frac{1}{P_B}\frac{N^+ - N^-}{N^+ + N^-}$$

$$x^* = \frac{Q^2}{2M_N E y(2-\alpha_{sp})} = \frac{x_B}{2-\alpha_{sp}},$$

3D bins : x* vs. t vs. phi

$$\alpha_{sp} = \frac{E_s - p_s^z}{M_N}$$

# Tagged-proton nDVCS $A_{LU}$ Projections

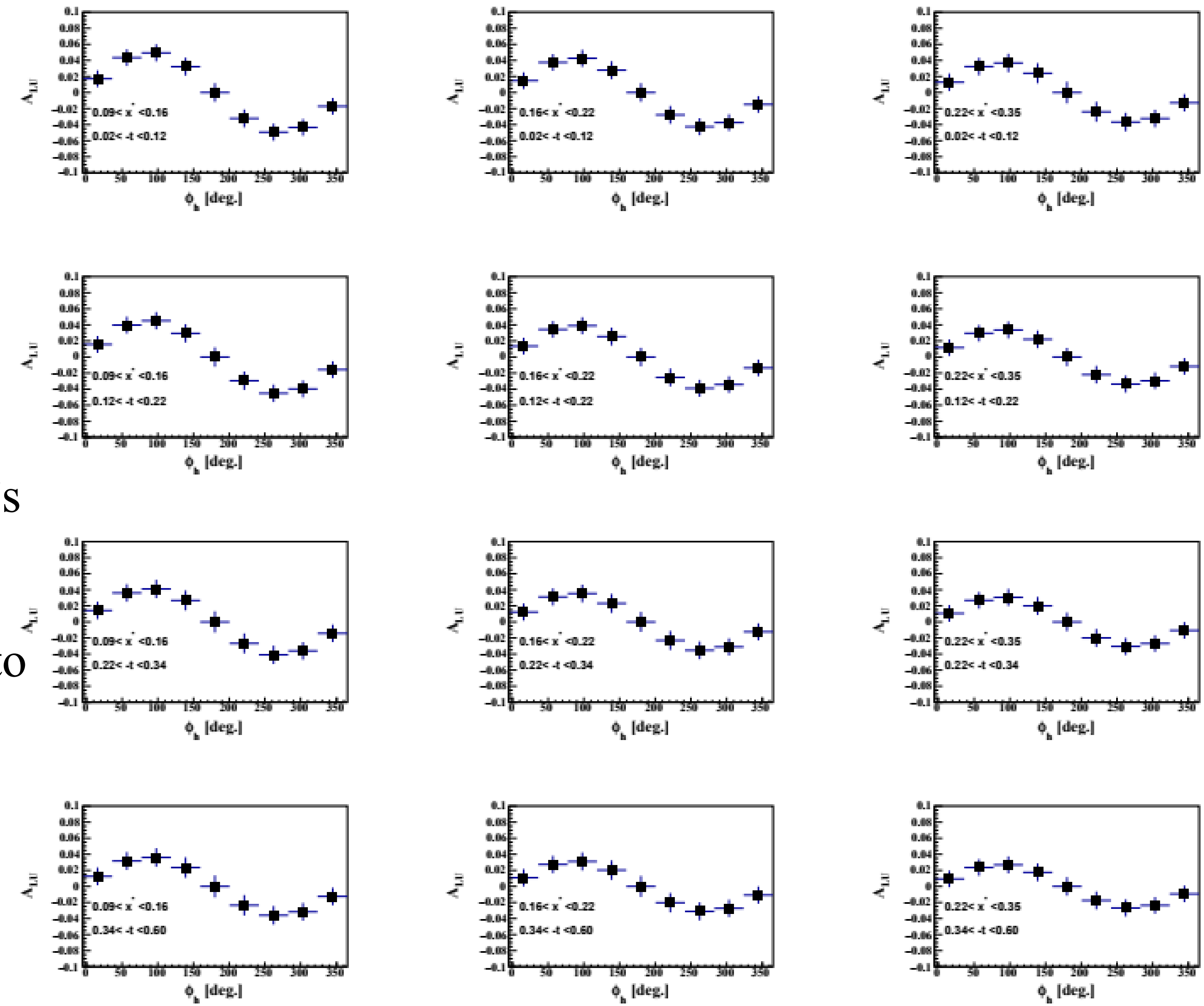
◊ 9M expected events.

◊ Total of 108 bins in x* vs. t vs. phi

◊ 20% conservative sys. Uncertainities.

◊ Exploring the neutron's CFF via the BSA.

◊ Compare the nDVCS to Free proton DVCS.



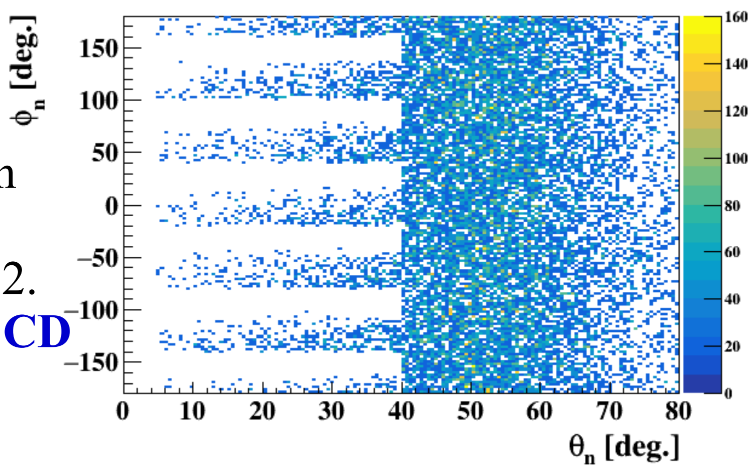
# Fully exclusive nDVCS Events Selection

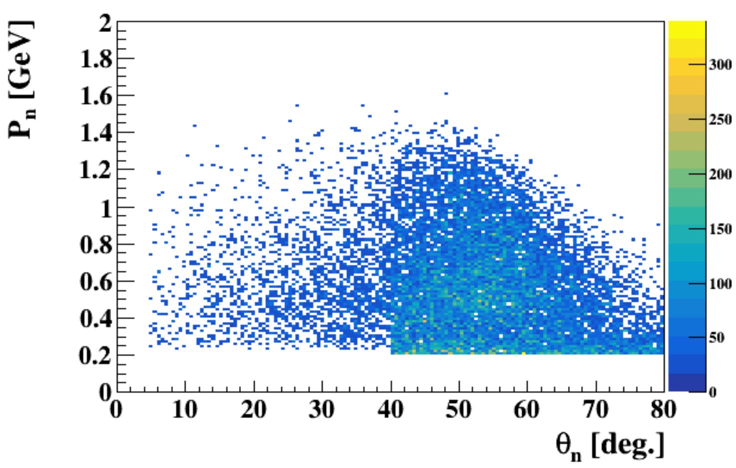
**Events which have:**

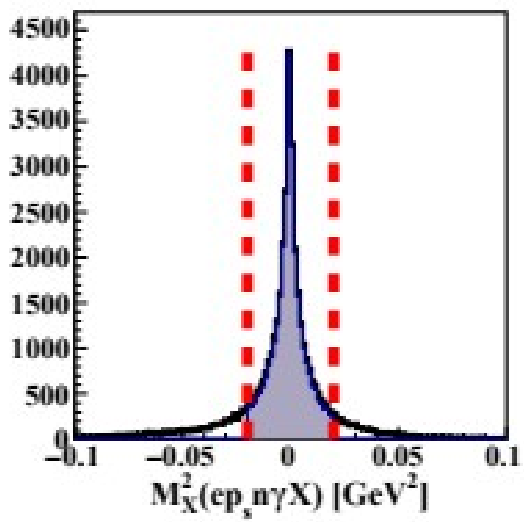
◊ Events with :
- One good electron
- One high-energy photon ($E\gamma$ > 2 GeV)
- One proton in BONuS12.
- **One neutron in FD or CD**

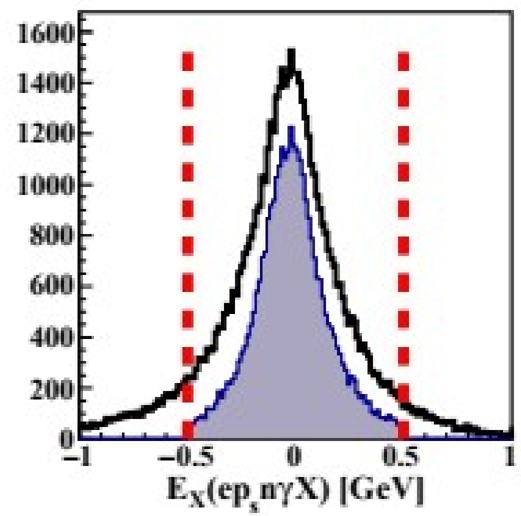
◊ $Q^2$ > 1 GeV² and W> 2 GeV/c²

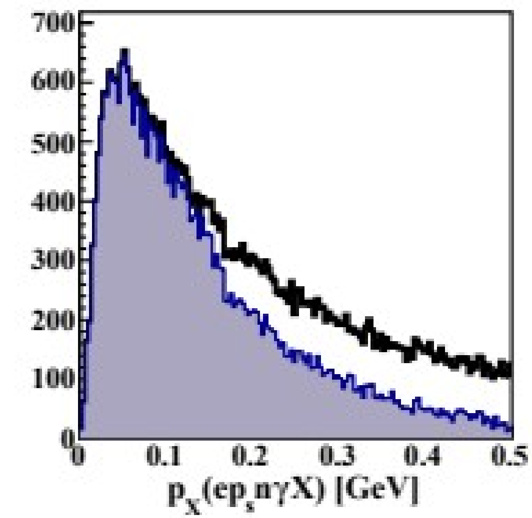
◊ Exclusivity cuts.



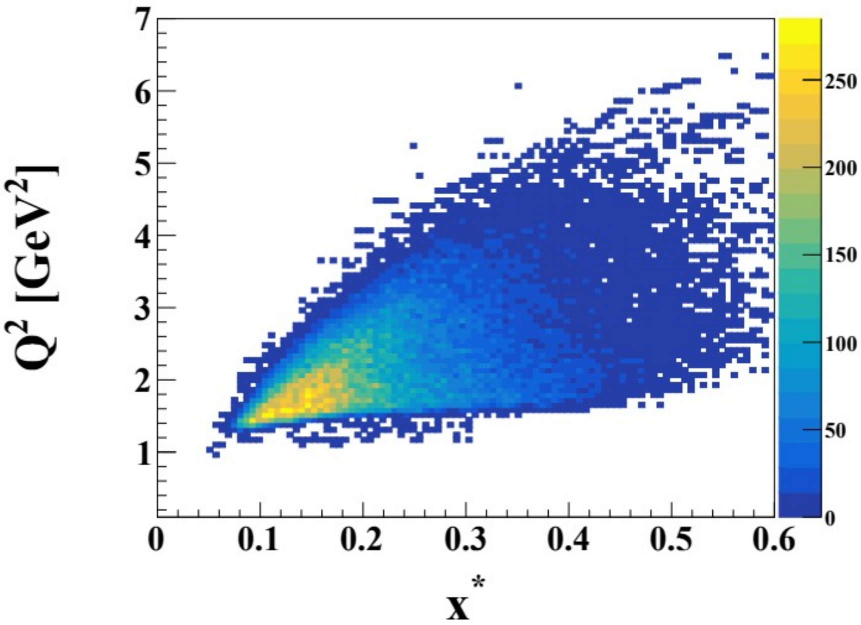



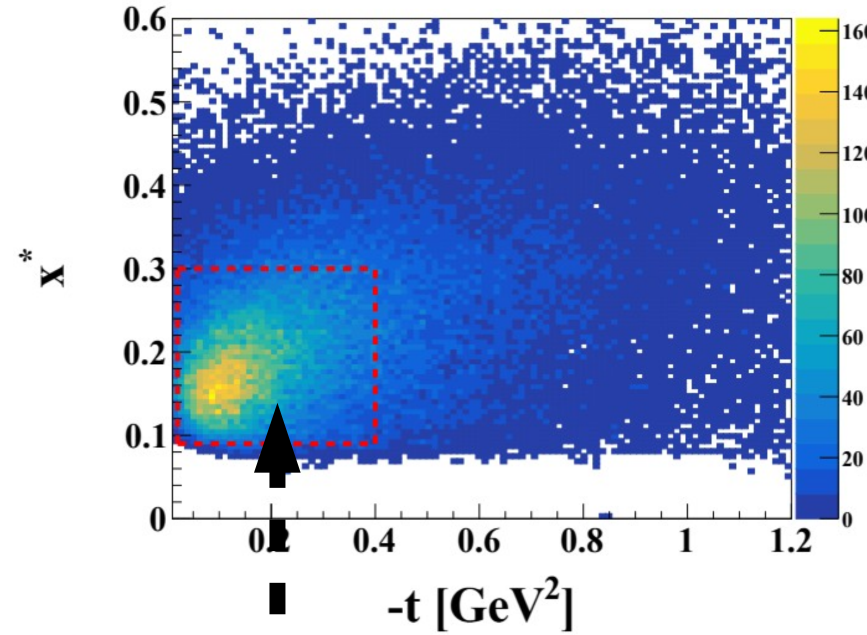



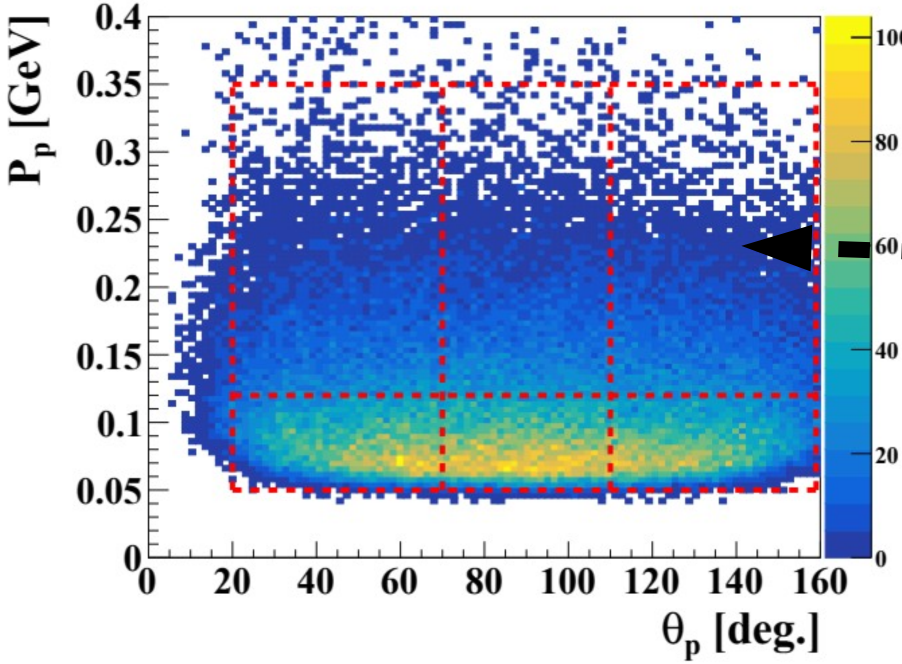



# Fully exclusive nDVCS Phase-Space & binning




**a. Initial bin in x* vs. t**

**b. 6 bins in the spectator proton p vs.θ**

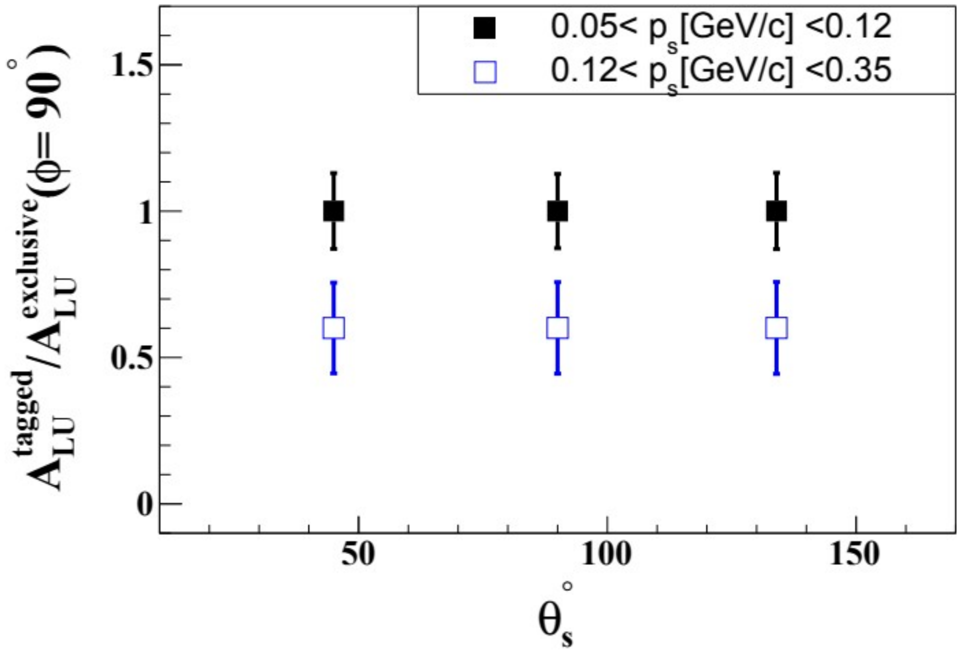
**c. Binning in φ**

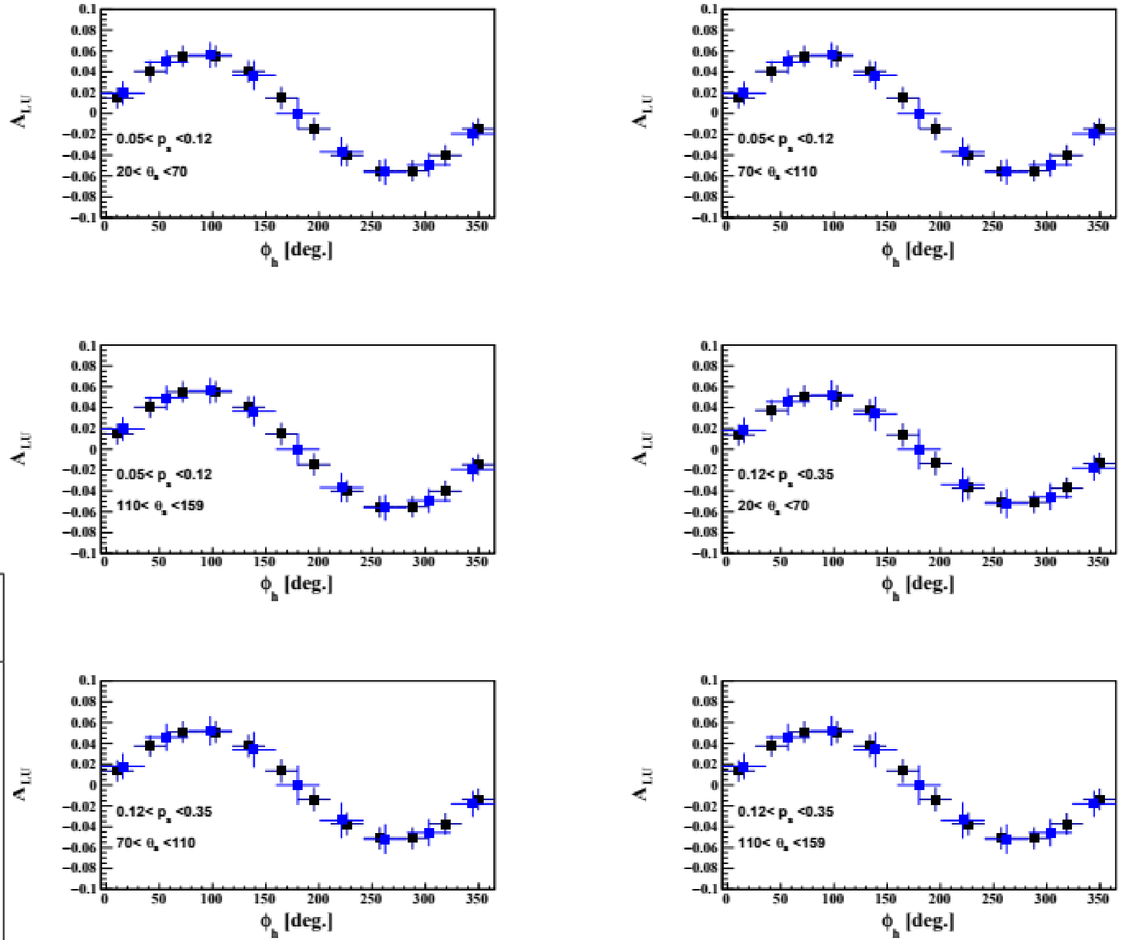
# Fully Exclusive nDVCS $A_{LU}$ Projections

◊ 9M tagged nDVCS events (**black**)
~ 0.8M fully exclusive nDVCS (**blue**).

◊ 20% conservative sys. uncertainities.

◊ Exploring the Fermi motion and FSI effects on BSA.



# Other Physics Opportunities

The proposed nDVCS measurments is only a fraction of the physics that can be achieved by successfully analyzing the polarized beam data from RG-F.

- $\pi^0$ production off D
  - Coherent and incoherent production.
  - Measure BSA, leading to chiral-odd CFFs.
  - Also as a DVCS background.
- Coherent DVCS off D
  - Access to new GPDs, $H_3$ , with relationships to dueteron charge form factors.
- Coherent DVMP off D
  - $\pi^0$ , φ, ω and ρ mesons.
- Semi-inclusive reaction p(e,e`p)X
  - Study the $\pi^0$ cloud of the proton.
- D(e, e\`pp$_S$ )X
  - Study the $\pi^-$ cloud of the neutron.
- Incoherent p DVCS & DVMP
- More Physics:
  - Transverse momentum distributions (TMDs) on the neutron (twist-3).
  - The medium modification of the transverse momentum dependent parton distributions.
  - Final state interactions through the 5 th structure function in D(e, e 0 p s )n.

# Summary

◊ **Polarizing the electron beam during the approved RG-F will allow us to investigate in a unique way many aspects of QCD within the GPD framework.**

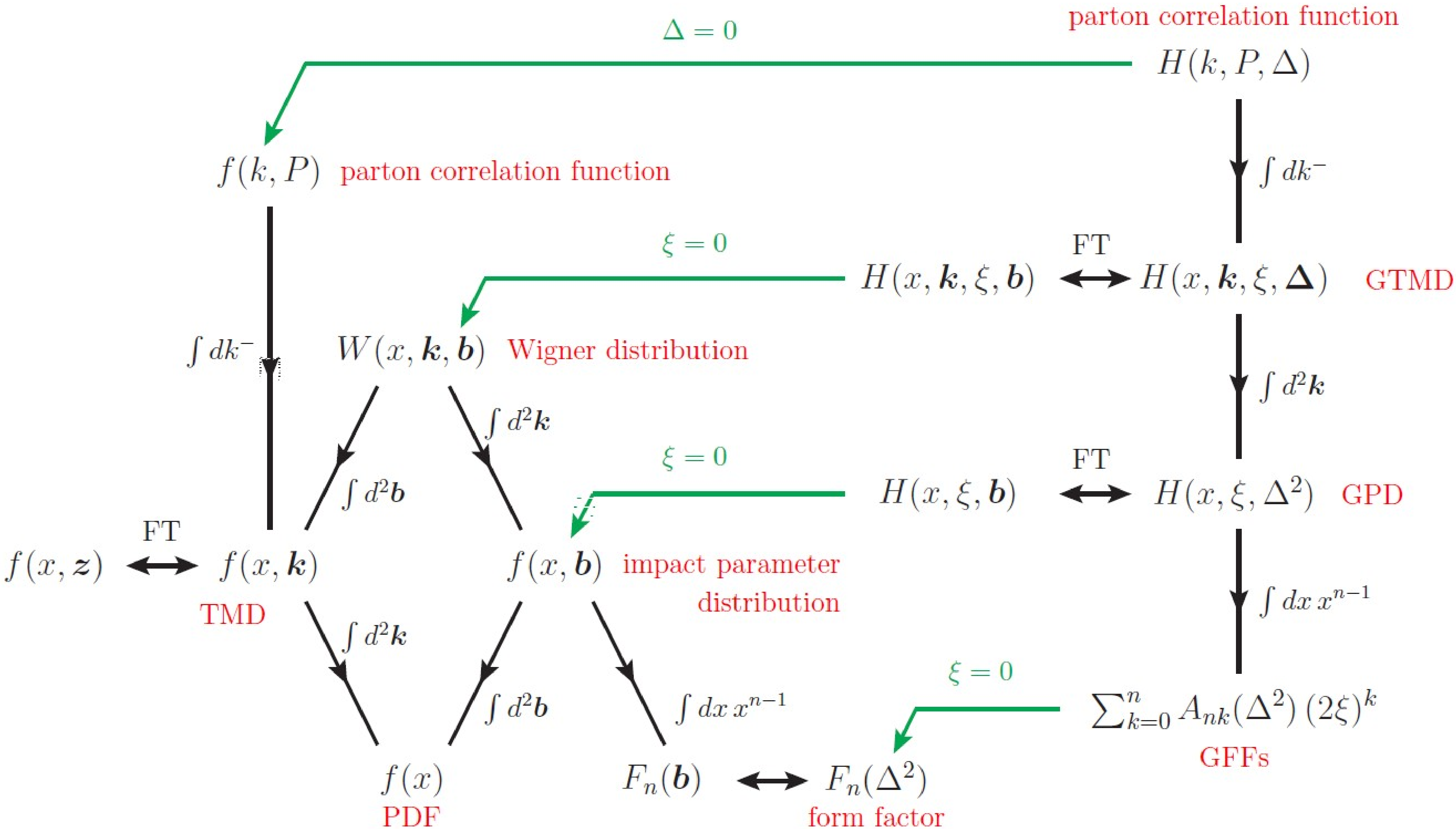
◊ **Complementary to the approved E12-11-003 experiment,**
**$\gamma^* + d \rightarrow n + \gamma + (p)$.**

◊ **We intend to measure the neutron DVCS beam-spin asymmetry by:**
**-> tagging the spectator slow-recoiling proton**
**-> measuring the fully exclusive neutron DVCS channel.**

◊ **Additional physics topics to be investigated, increasing the physics outcome of the approved beam time.**

# Hadronic Structure Functions

**Structure functions that quantify the properties of the partons in a hadron:**




[M. Diehl, arXiv:1512.01328v2 [hep-ph]]