The Quark Structure of the Nucleon

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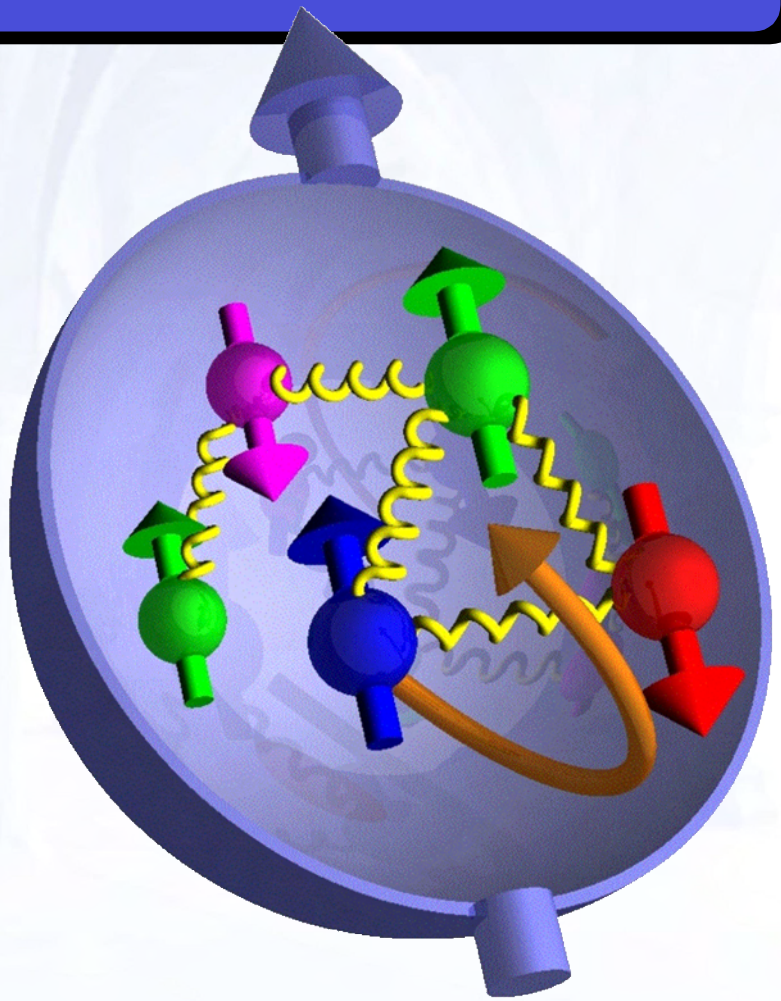
Cosener's House Meeting
23/05/2007

- Nucleon Structure
- Generalised Parton Distributions
  - What are GPDs?
  - Deeply Virtual Compton Scattering
- GPD Experiments
  - HERMES at DESY
  - CLAS at JLAB
  - PANDA at FAIR

UNIVERSITY of GLASGOW

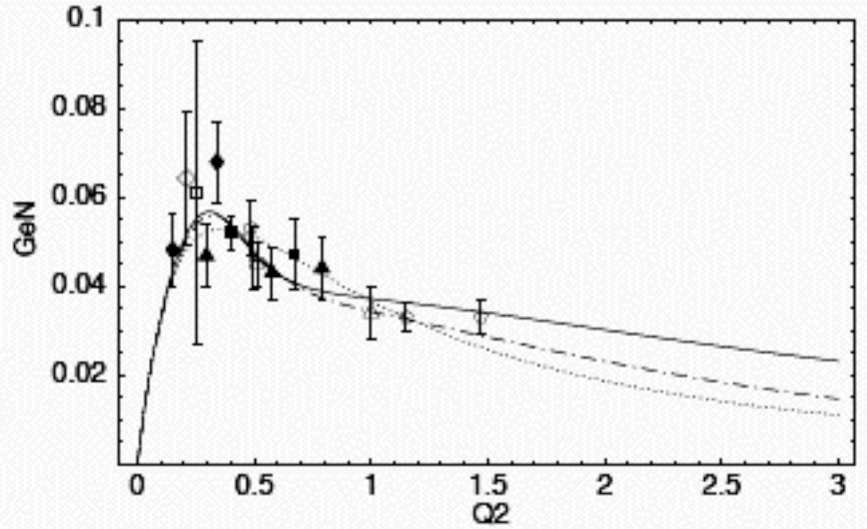
Nucleon Structure

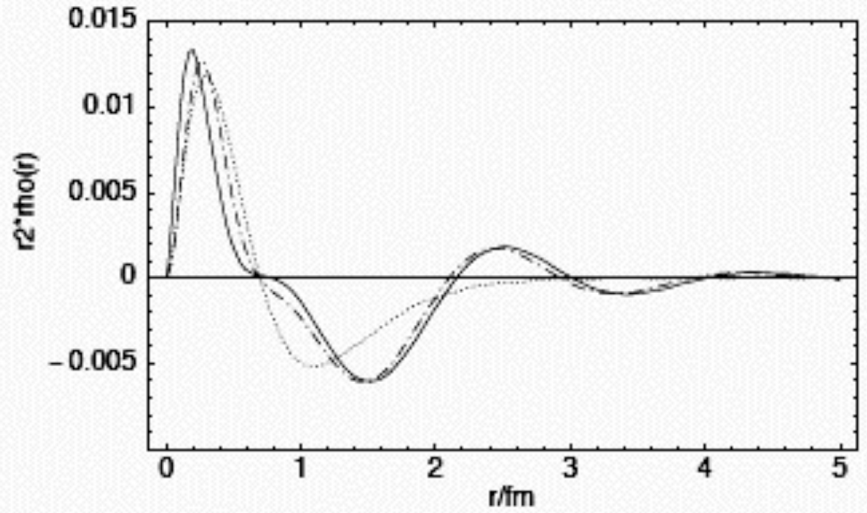
- Proton consists of 3 quarks (Gell-Mann, Zweig 1964)
- … and gluons and sea quarks (QCD)
- Partons (Feynman/Bjorken) identified with quarks and gluons and verified in scattering experiments
- Proton has spin 1/2, and so do the quarks
- 2004 Nobel Prize for Gross, Wilczek, Politzer



Form Factors

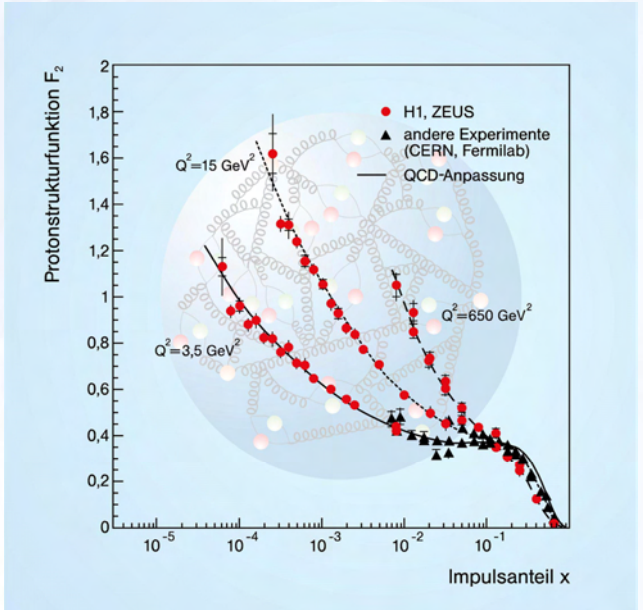
- Form Factors are measured in elastic scattering experiments
- Transverse Structure of the proton
- Fourier Transform of the form factor gives charge distribution
- Example:
  - Electric form factor of the neutron G_E^n . Result shows evidence for pion cloud.
- Glasgow:
  - Form factor measurements at MAMI and JLAB

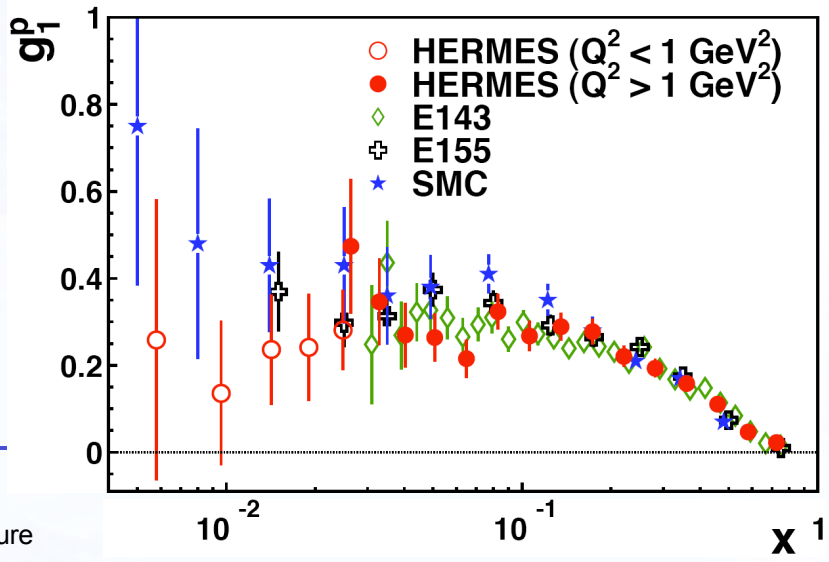




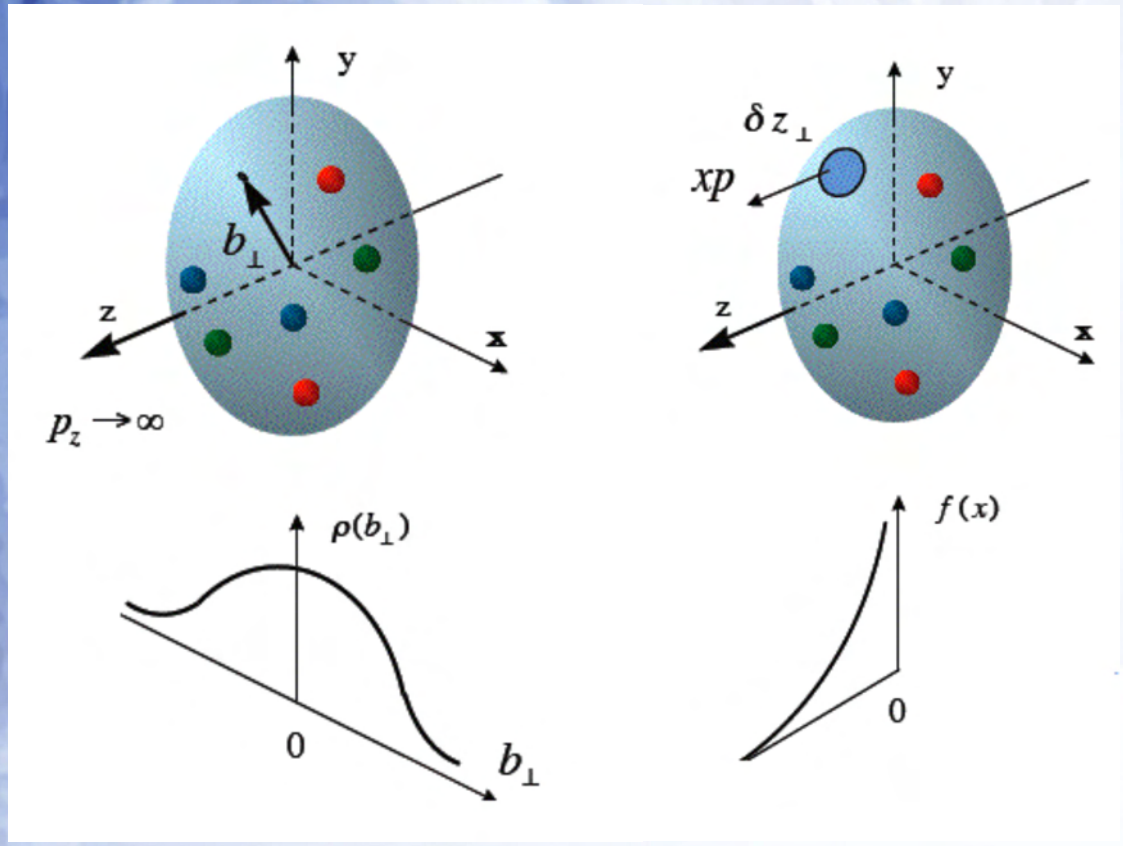
Parton Distribution Functions

- Structure functions and parton distribution functions are measured in deep inelastic scattering
- Longitudinal Structure of the proton
- Example: Measurement of Structure Function F2 from H1 and ZEUS at DESY.
  - The number of quarks and gluons seen increases dramatically for small momentum fraction x.
- Glasgow:
  - Polarised quark distributions with HERMES at DESY.





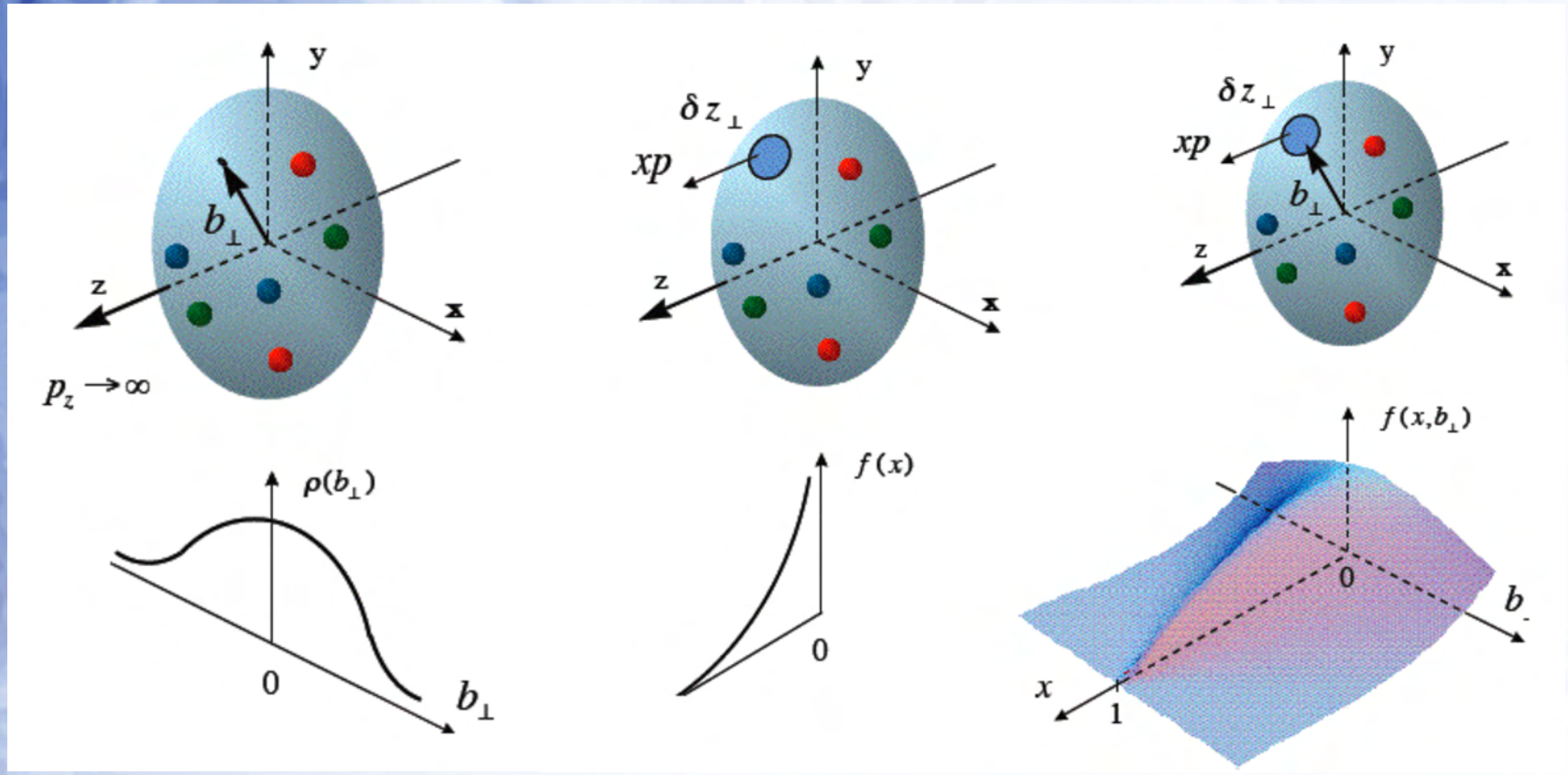
Comparison



Form Factor

Parton Distribution Function

Generalised Parton Distributions

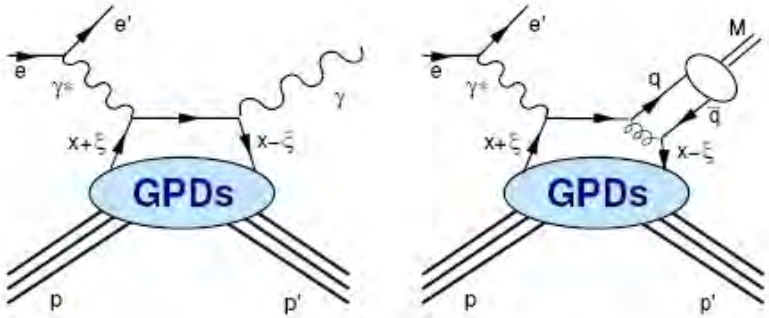


Form Factor

Parton Distribution Function

Generalised Parton Distribution

Generalised Parton Distributions



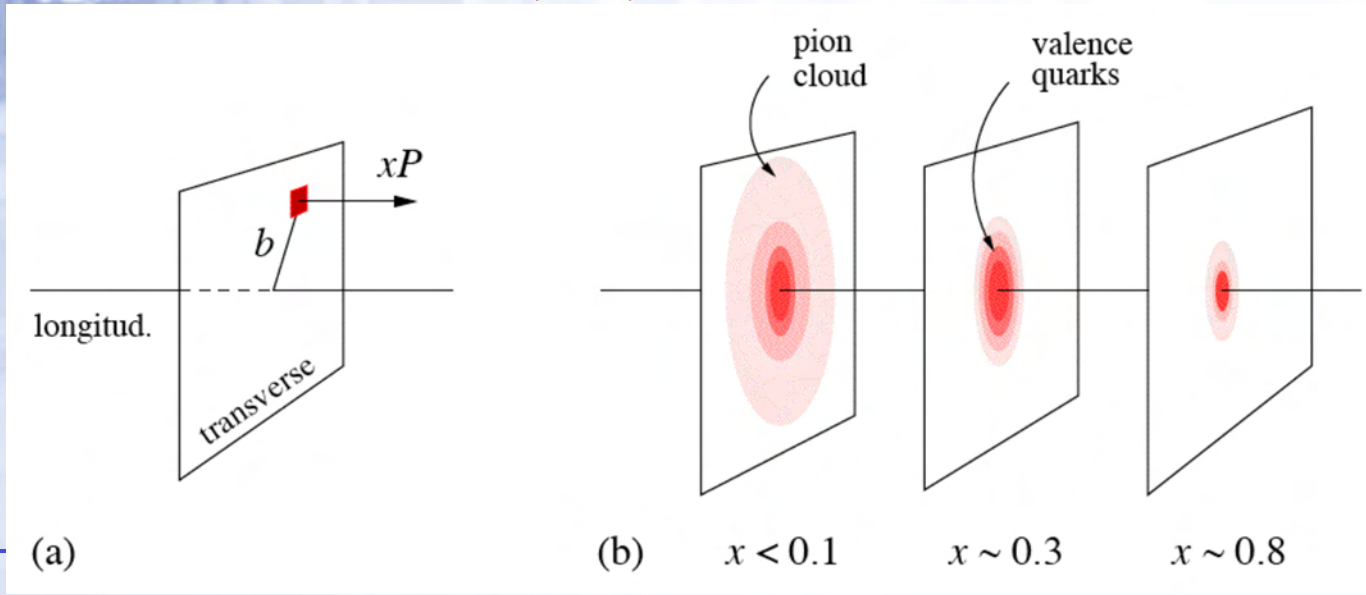
- functions of three variables: x, ξ, t
- H_q: nucleon spin preserved, E_q: nucleon spin flipped
- H_q: unpolarised $\tilde{H}_q$: polarised
- 4 (chirality conserving) quark GPDs: $H_q(x,\xi,t)$, $\tilde{H}_q(x,\xi,t)$, $E_q(x,\xi,t)$, $\tilde{E}_q(x,\xi,t)$

- parton distribution functions
  $q(x) = H_q(x,0,0)$
  $\Delta q(x) = \tilde{H}_q(x,0,0)$
- $q(-x) = -\bar{q}(x)$
  $\Delta q(-x) = \Delta\bar{q}(x)$
- form factors
  $F_1^q(t) = \int_{-1}^{1} dx H^q(x,\xi,t)$
  $F_2^q(t) = \int_{-1}^{1} dx E^q(x,\xi,t)$
  $g_a^q(t) = \int_{-1}^{1} dx \tilde{H}^q(x,\xi,t)$
  $h_a^q(t) = \int_{-1}^{1} dx \tilde{E}^q(x,\xi,t)$
- quark orbital angular momentum
  $J_q = \frac{1}{2}\int_{-1}^{1} x\, dx[H_q + E_q]$
  $= \frac{1}{2}\Delta\Sigma + L_q$ [X.Ji 1997]

Hadron Tomography

- **The Fourier transform of GPDs at ξ=0 leads to a 3-dimensional picture of the nucleon:**
  - **longitudinal momentum fraction and transverse impact parameter space.**

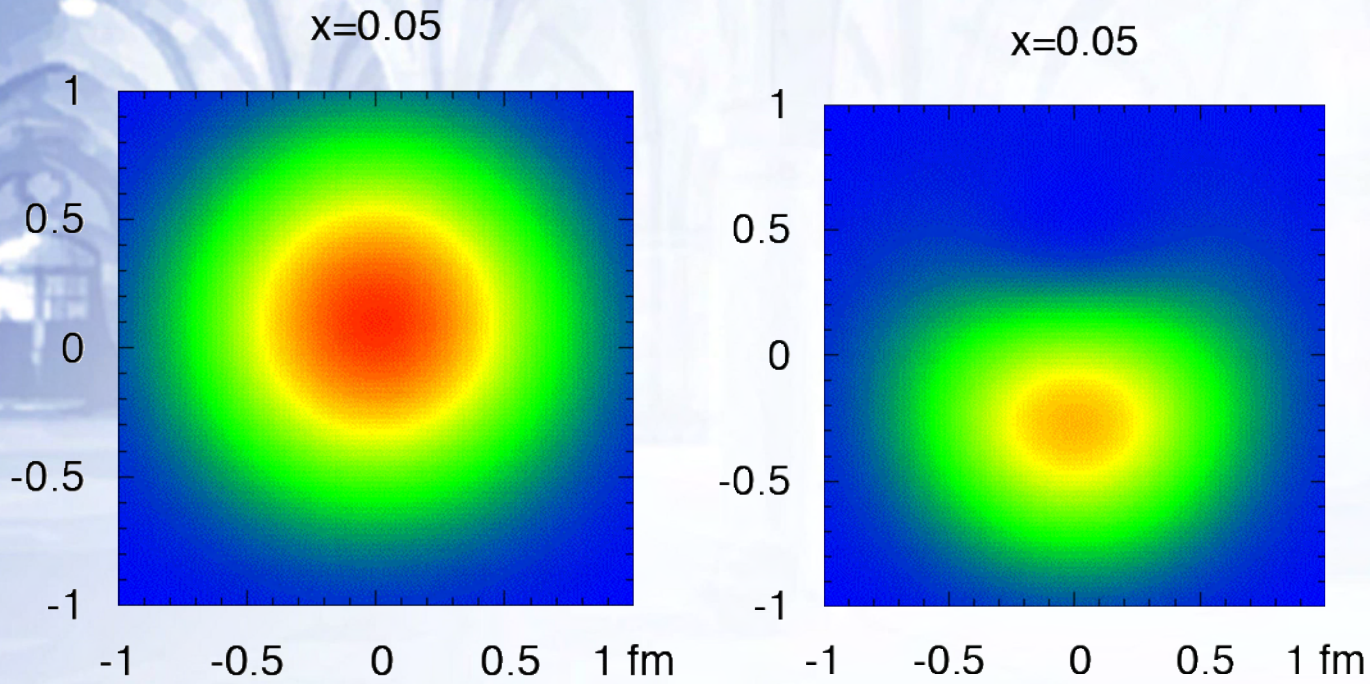
$$q(x, b_\perp) = \int \frac{d^2\Delta_\perp^2}{(2\pi)^2} H(x, 0, -\Delta_\perp^2) e^{-i\Delta_\perp \cdot b_\perp}$$



Hadron Tomography

- **GPD Model restricted by form factor data exists:**

  [P.Kroll, hep-ph/0612026, 4.Dec.2006]



- **u-quark (left) and d-quark (right) density in impact parameter plane. Proton polarised in x-direction**

GPDs and the Spin Puzzle

$$S_z = \frac{1}{2} = J_q + J_g = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

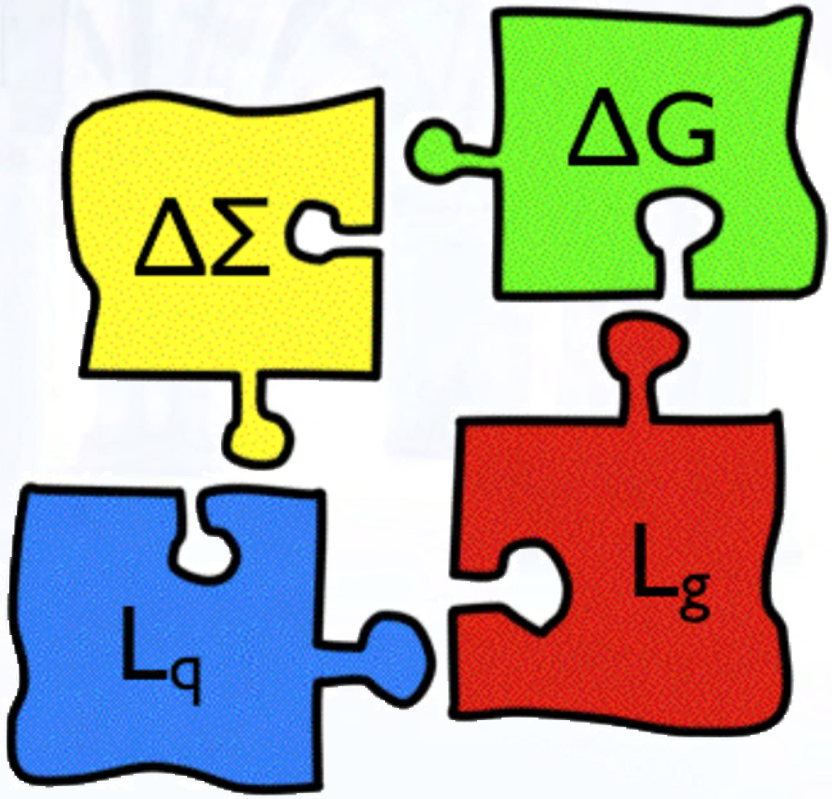
$$\Delta\Sigma = \Sigma\Delta q \sim 0.3$$

Ji Sum Rule:

$$J_q = \frac{1}{2}\int_{-1}^{1} x\,dx\,[H_q + E_q]$$

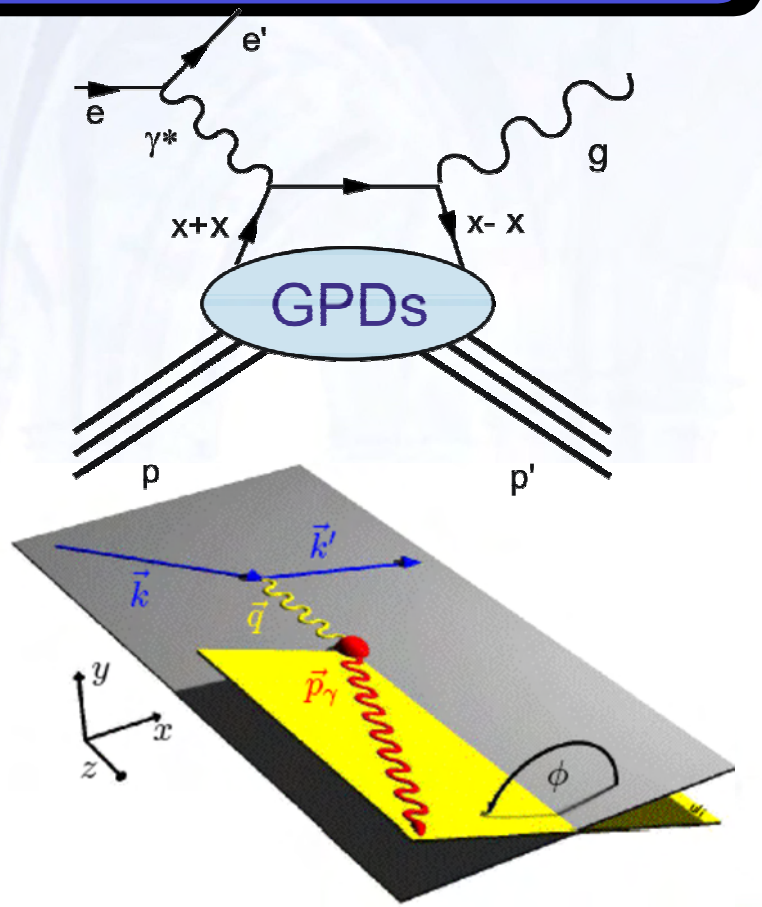
$$= \frac{1}{2}\Delta\Sigma + L_q$$

Measure GPDs to determine L_q !



How to Measure GPDs → DVCS

- Deeply Virtual Compton Scattering DVCS: cleanest process to measure GPDs
- Experimentally:
  - Measurements of several asymmetries
- Main current and future experiments:
  - HERMES and JLAB, especially with 12 GeV upgrade, perhaps COMPASS



Beam Spin $$A_{LU}(\phi) = \frac{d\sigma^{\uparrow}(\phi) - d\sigma^{\downarrow}(\phi)}{d\sigma^{\uparrow}(\phi) + d\sigma^{\downarrow}(\phi)} \propto \sin\phi \Rightarrow \Im\mathrm{m}(H)$$

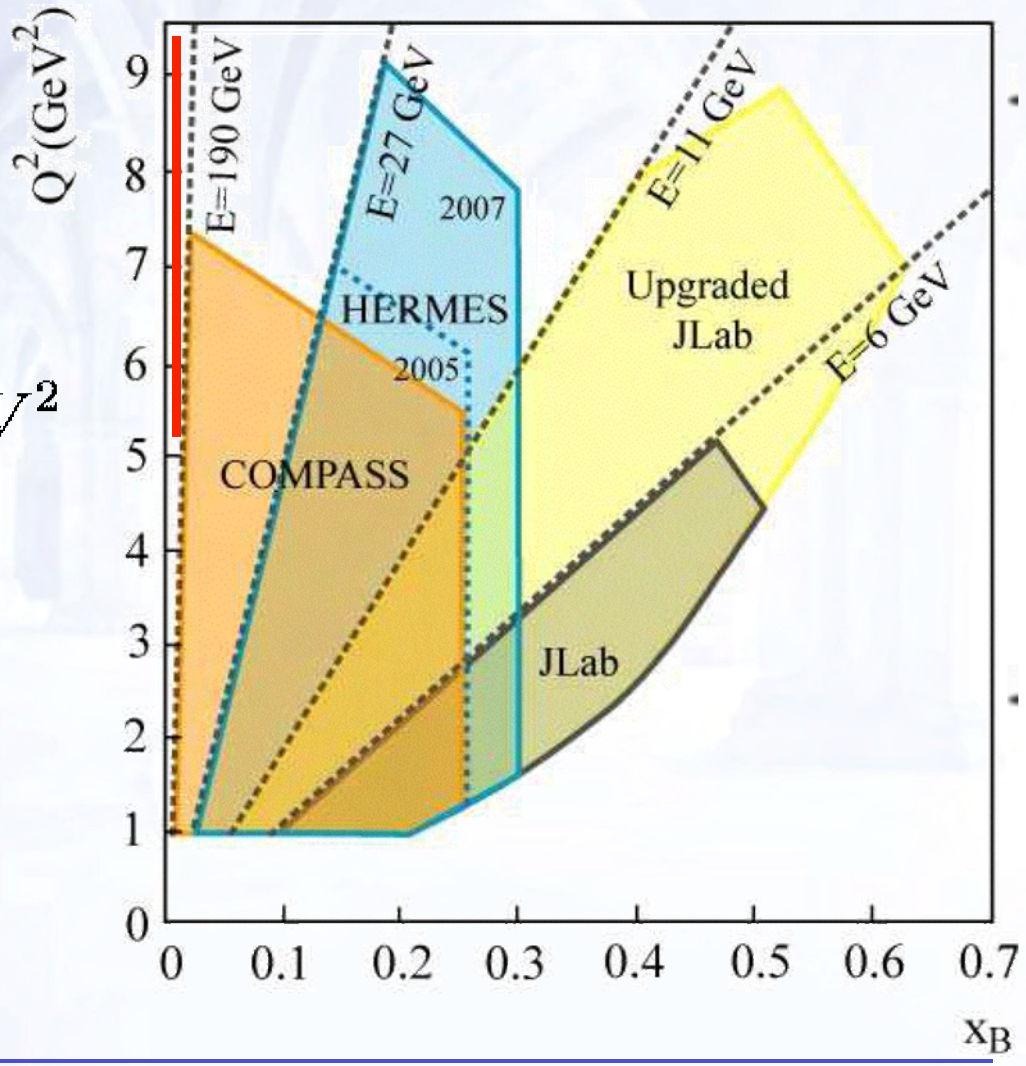
Beam Charge $$A_{ch}(\phi) = \frac{d\sigma^{+}(\phi) - d\sigma^{-}(\phi)}{d\sigma^{+}(\phi) + d\sigma^{-}(\phi)} \propto \cos\phi \Rightarrow \Re\mathrm{e}(H)$$

Kinematical Coverage of DVCS Experiments

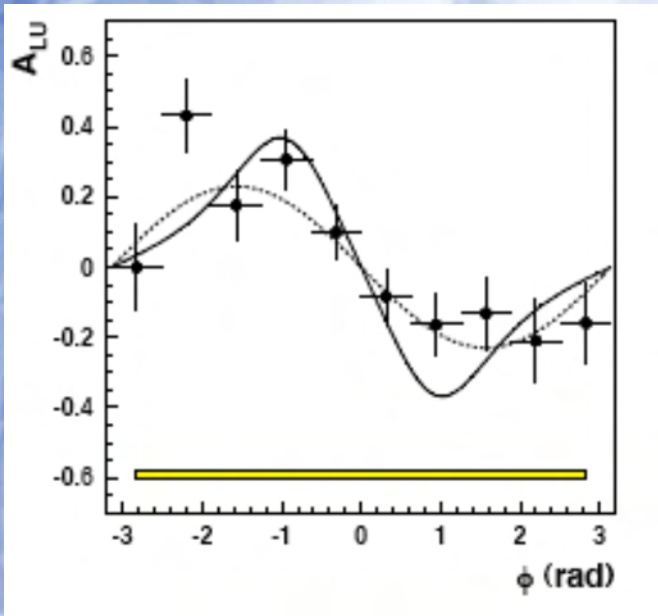
- HERA collider experiments H1 and ZEUS have small skewedness

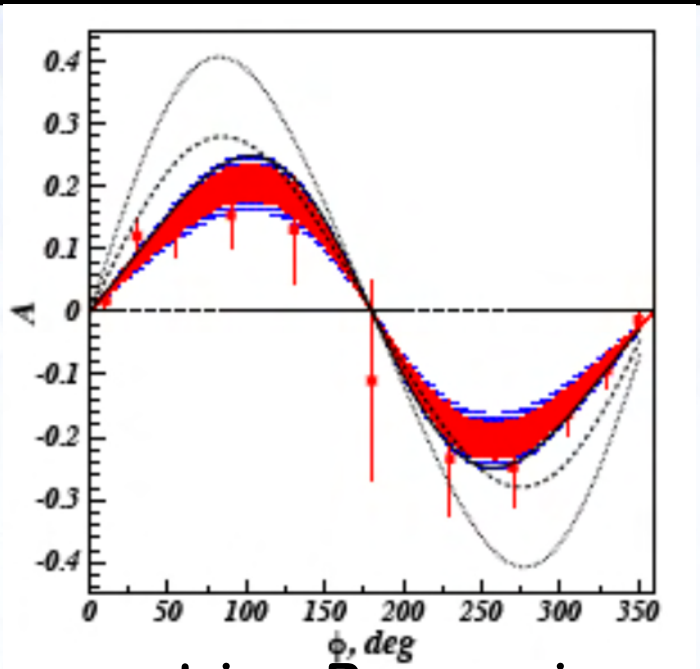
$$x_B < 0.01 \quad Q^2 : 5...100\, GeV^2$$

- Fixed target experiments are crucial to explore GPDs !



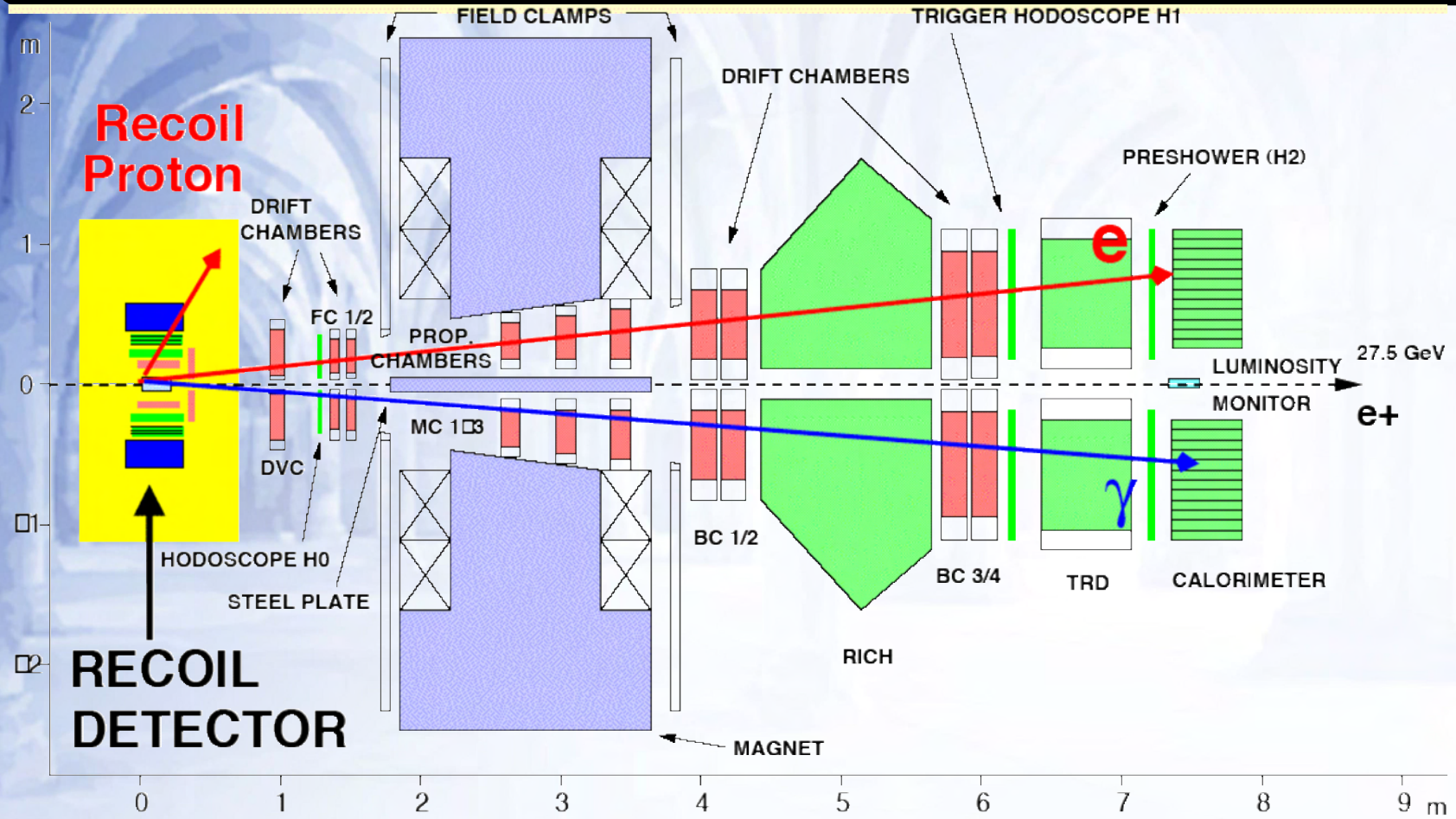
DVCS Asymmetries - First Measurements





- First measurements of DVCS asymmetries: Beam-spin asymmetry by HERMES and CLAS, both published in PRL87(2001). Glasgow group involved in both of them.
- HERMES 27.5 GeV, beam polarisation ~55%, recoil proton not detected
- CLAS (JLab Hall B) 4.25 GeV, beam polarisation ~70%, produced photon not detected

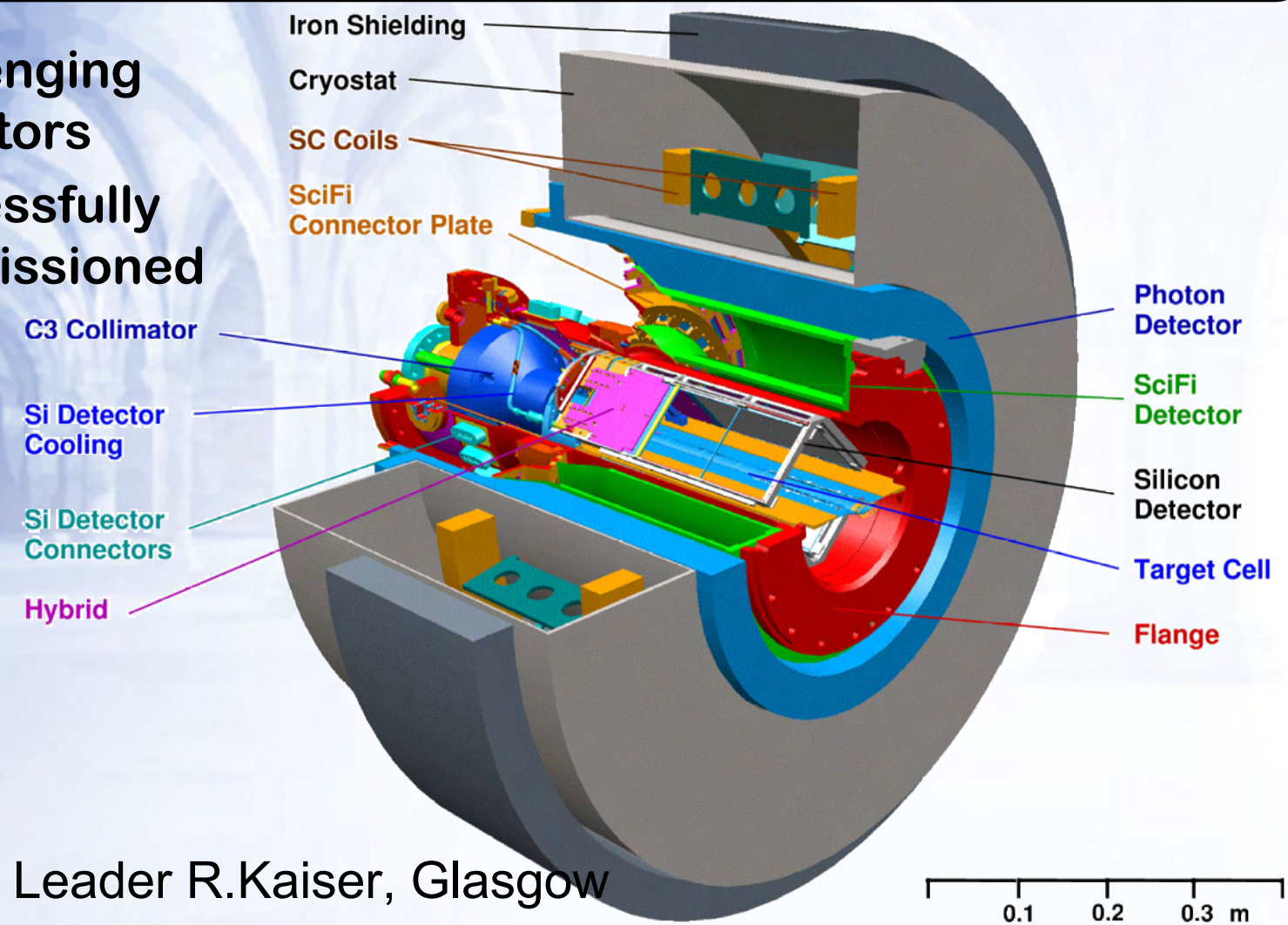
HERMES at DESY



Exclusive measurements (e.g. DVCS) with Forward Spectrometer and Recoil Detector since 2006

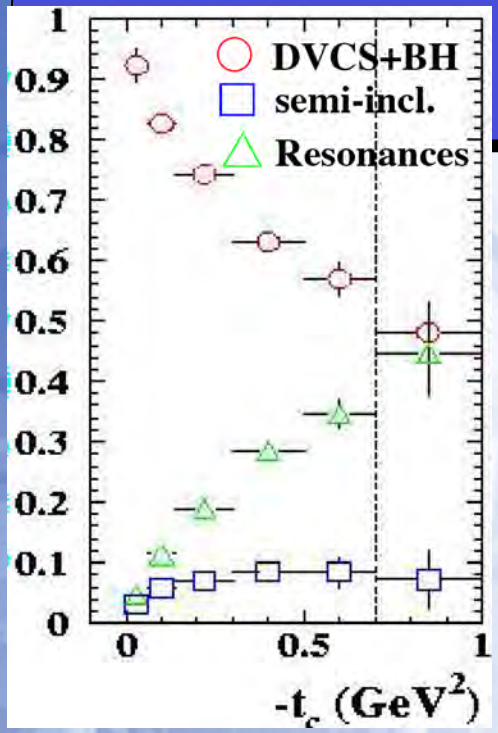
HERMES Recoil Detector

- Challenging Detectors
- Successfully commissioned

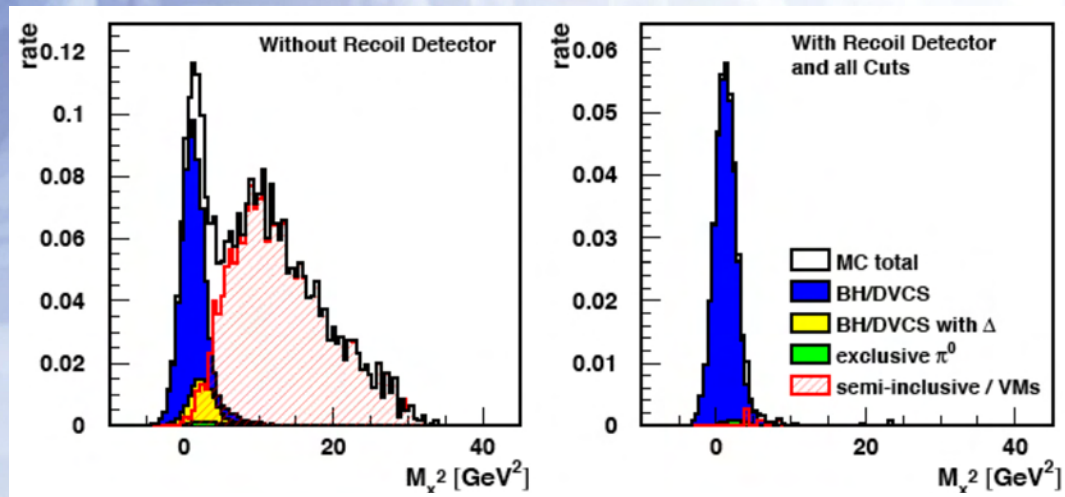


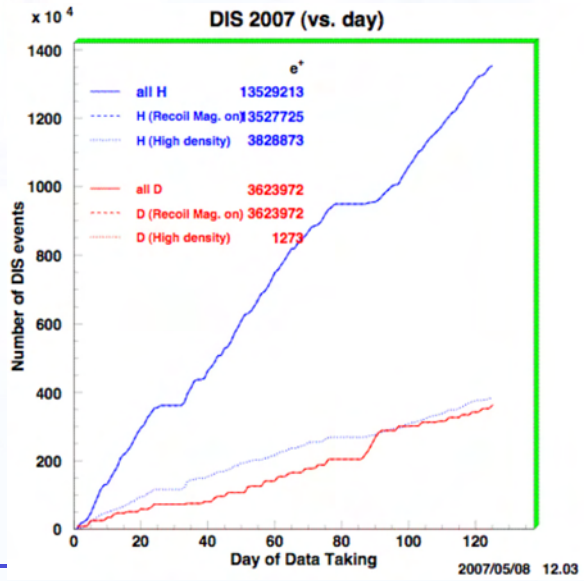
Project Leader R.Kaiser, Glasgow

HERMES with Recoil Detector



- Remove background from associated BH/DVCS with intermediate Δ-production and from semi-inclusive processes
- improve t-resolution at small t (with Si-detector)
- About the same statistics in 1 year as in the 10 years before

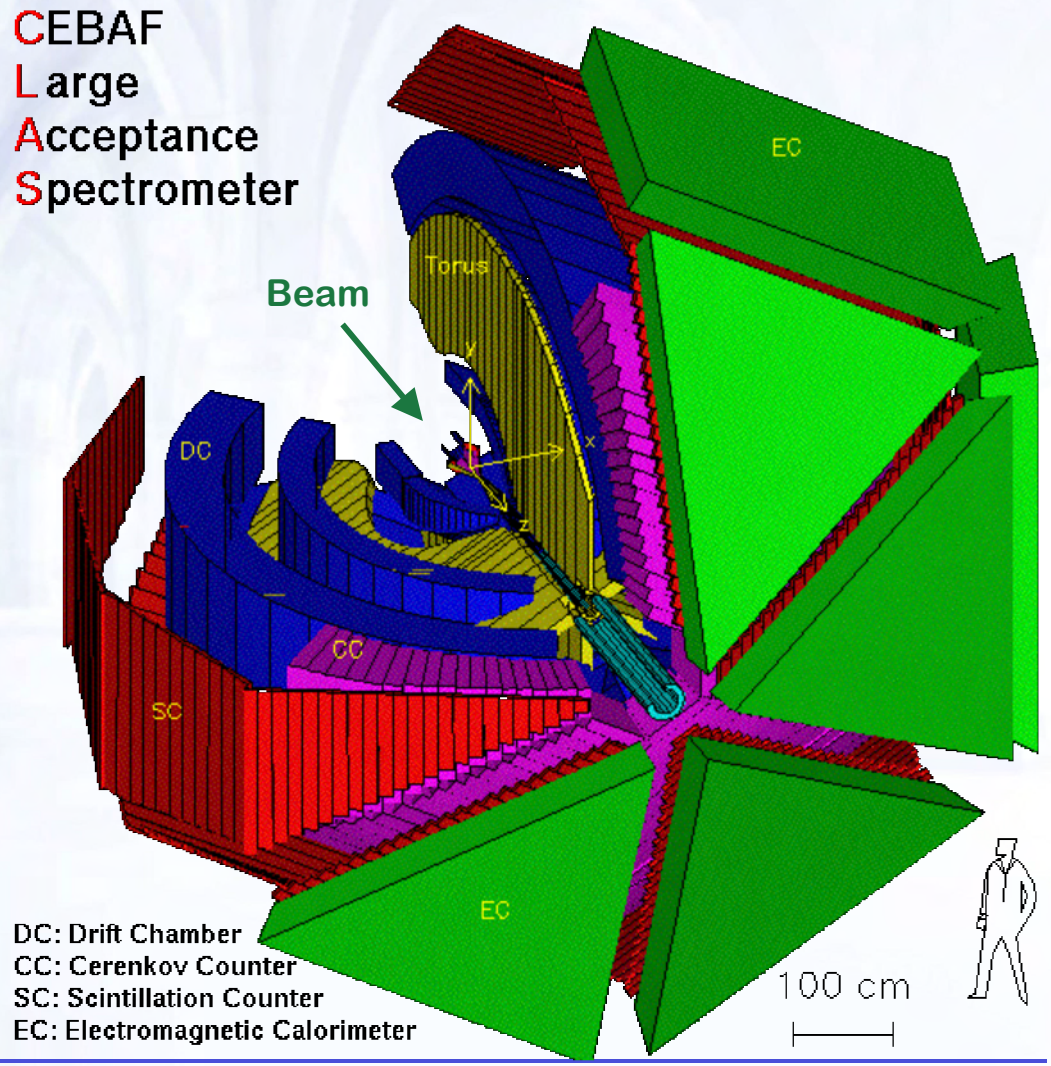




Background Reduction from 17% to ~2%

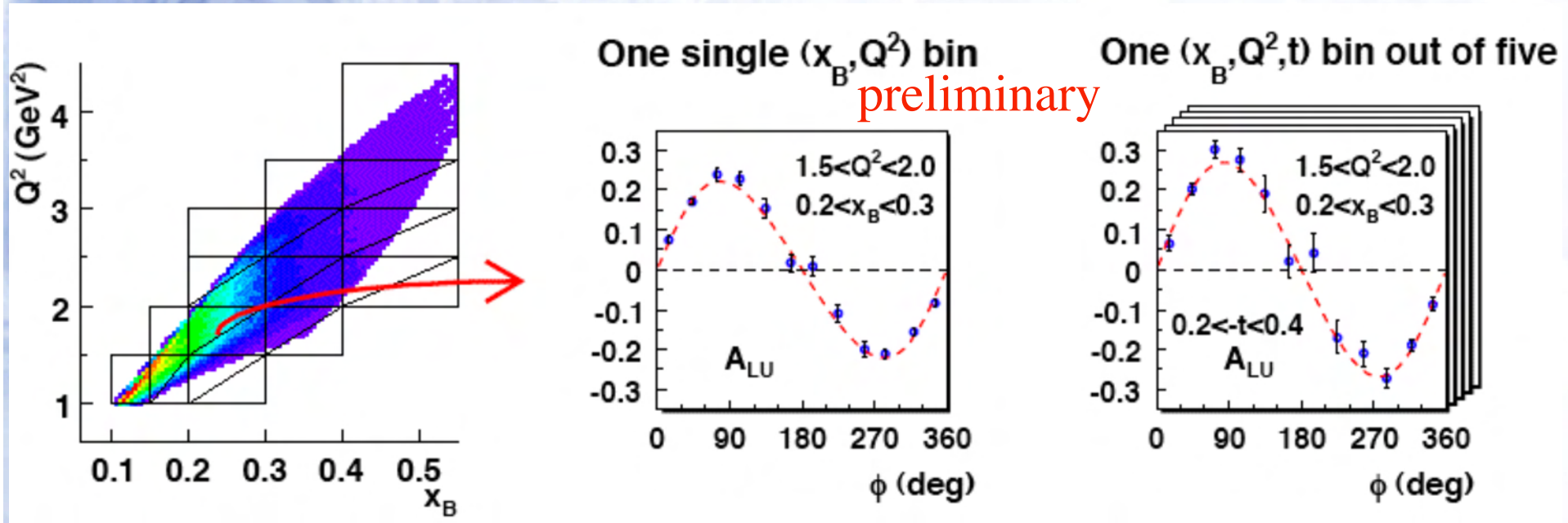
CLAS at JLAB

- CEBAF Large Acceptance Spectrometer at JLab in Hall B
- Toroidal Magnet
- Electron and tagged real photon beams
- Large collaboration of almost 200 members



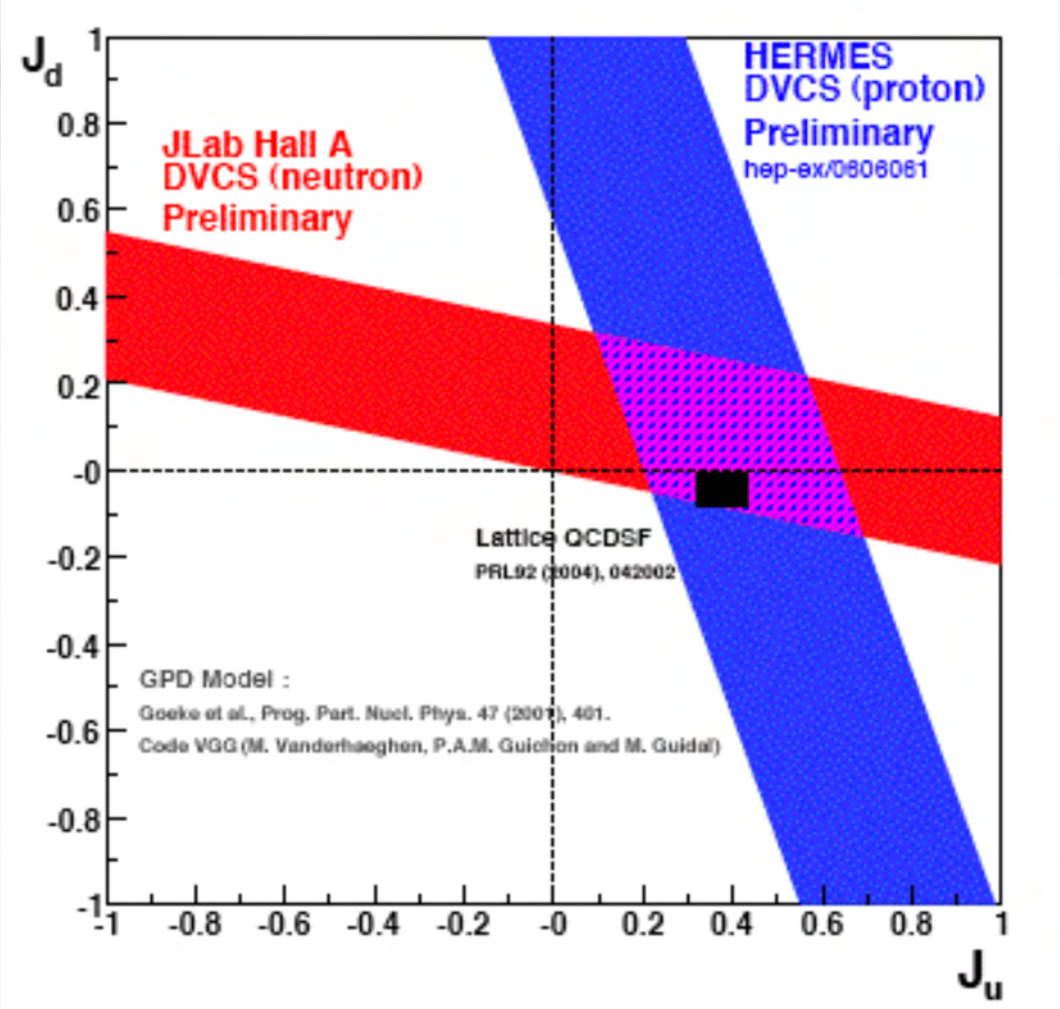
CLAS : High Statistics Beam Spin Asymmetry

- Experiment E01 - 113, preliminary data, still unpublished
- All three final state particles (electron, photon, proton) detected
- Statistics allows 3-d binning in x, Q^2 and t
- First glimpse at what future JLab experiments will be able to do

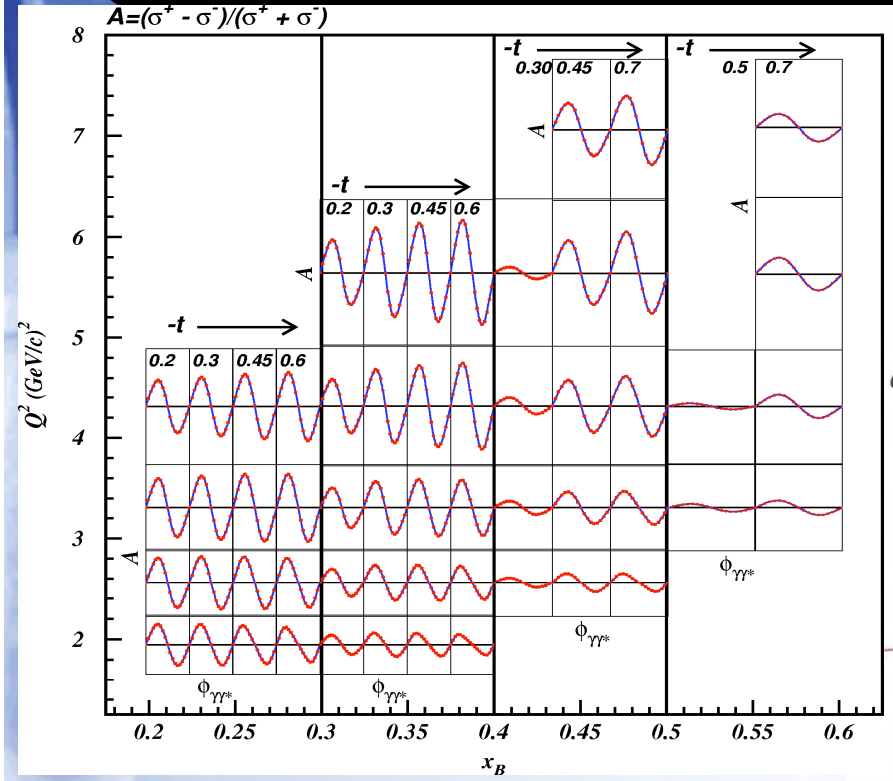


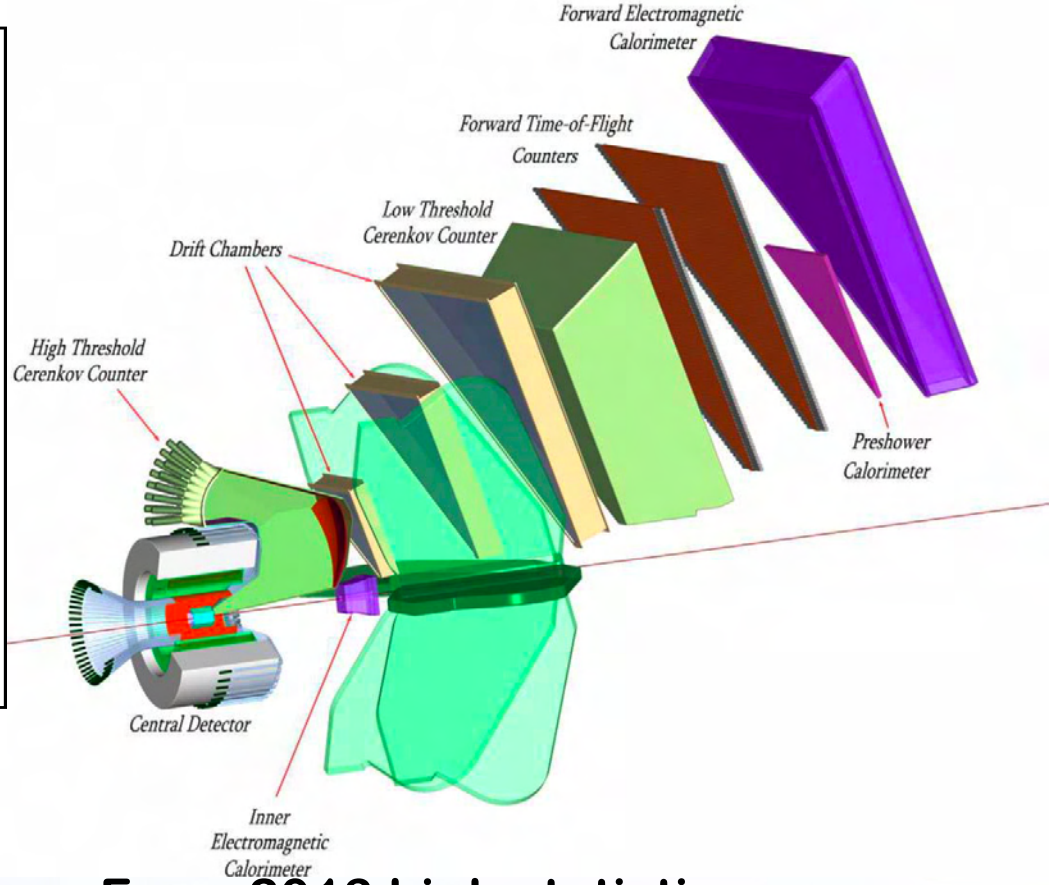
$J_u + J_d$ Limits from HERMES and JLab

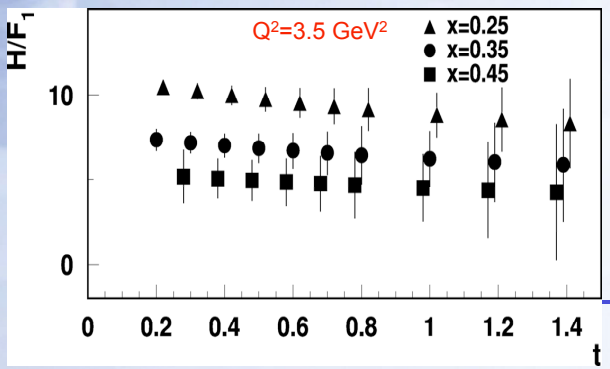
- JLab Hall A E03-106 neutron beam-spin asymmetry using unpolarised LD_2 target
- HERMES transverse target spin asymmetry on proton target
- Combination gives (model-dependent) constraint on J_u+J_d



CLAS12 at JLAB







$b_{val}=b_{sea}=1$

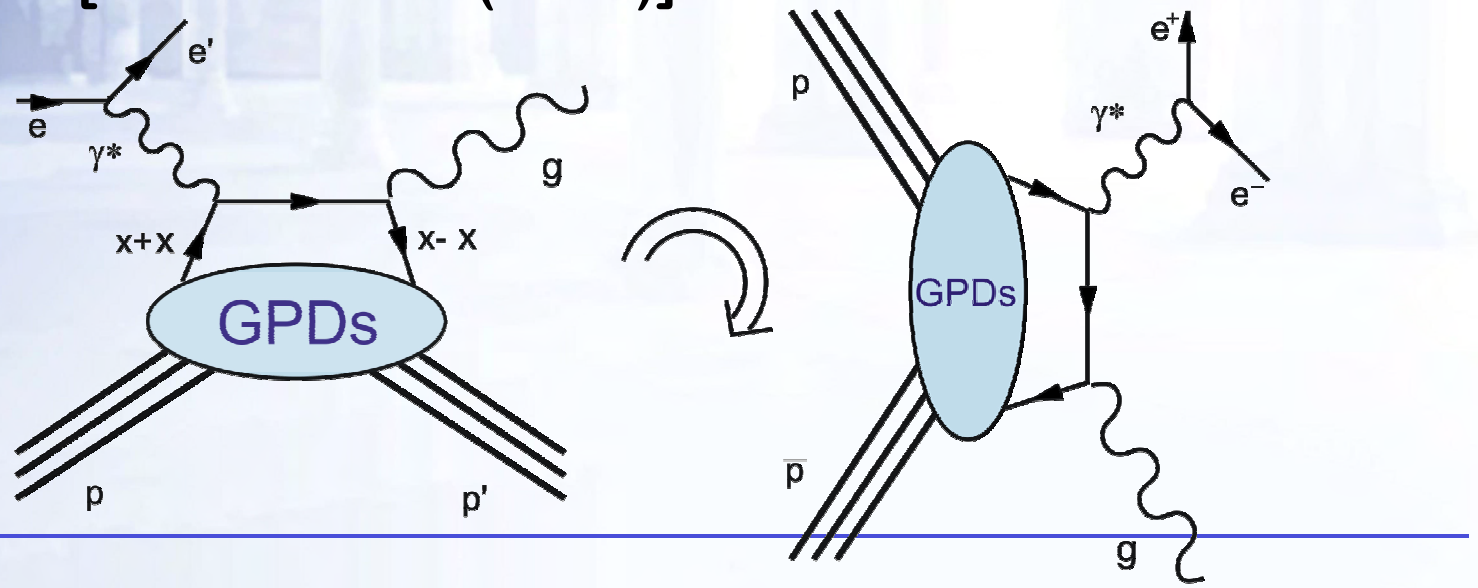
MRST02 NNLO distribution

- From 2013 high statistics measurements at 11 GeV with upgraded CLAS12 detector
- Extraction of GPD H from BSA

I. Lehmann & R. Kaiser
- Other kinematics measured concurrently

DVCS at PANDA at FAIR

- PANDA will have a 15 GeV anti-proton beam on a proton target. It therefore can measure the ‘cross channel’ or ‘time-like’ version of the DVCS process, that depends on the same GPDs
- More precisely on Generalised Distribution Amplitudes, introduced by M.Diehl et.al. to describe the inverse process [PRL.81:1782 (1998)].



Outlook

- Current measurements by CLAS and HERMES:
  - Lots of data is coming; analysis work still do be done
- Future experiments at JLAB and FAIR:
  - Hall A, CLAS12 and PANDA, respectively
- The Glasgow NP group is unique in its access to all key GPD data worldwide and is playing a leading role in Europe in coordinating GPD research
- Framework 6 Joint Research Activity coordinated by R.Kaiser, Glasgow (gpd.gla.ac.uk)
- Framework 7 Network in preparation, global fit to all existing data (R.Kaiser)