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Nucleon Structure in Time and Space Like Dimensions

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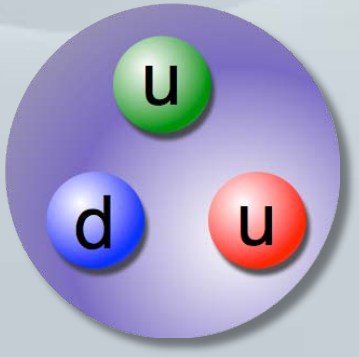
Recent Results in Nuclear Physics
9th June 2010, UWS Paisley

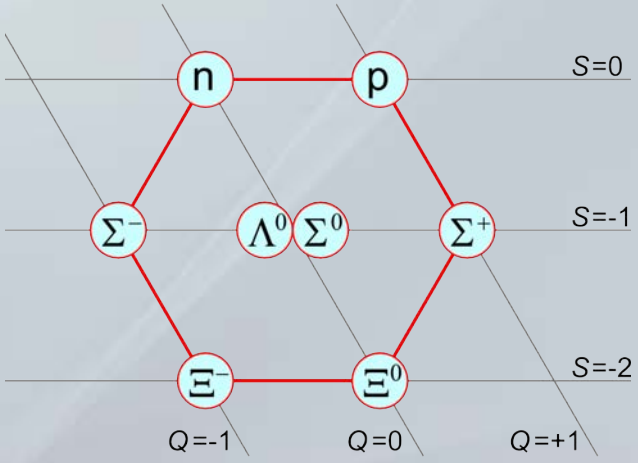
Open Questions

- Form factors not yet fully understood
  - G_E/G_M discrepancy, addressed at OLYMPUS(DESY)
- Generalised Parton Distributions
  - powerful tool
  - first results from HERMES(DESY)
  - future CLAS12(JLab)
- Spin structure
  - main contribution unexplained
  - results from HERMES(DESY) and HallA(JLab)
- Time like structure functions
  - largely uncharted territory
  - future PANDA(FAIR)

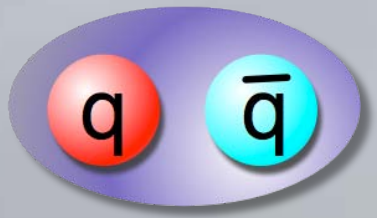
Naive Picture of the Hadron

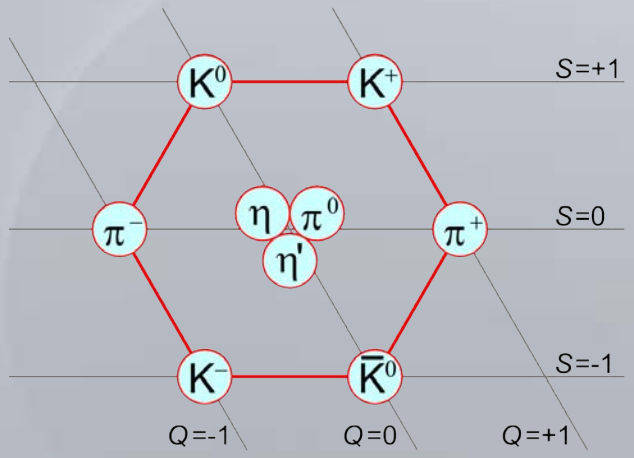
- Baryons
  - e.g. proton, neutron
  - 3 quarks
  - half integer spin





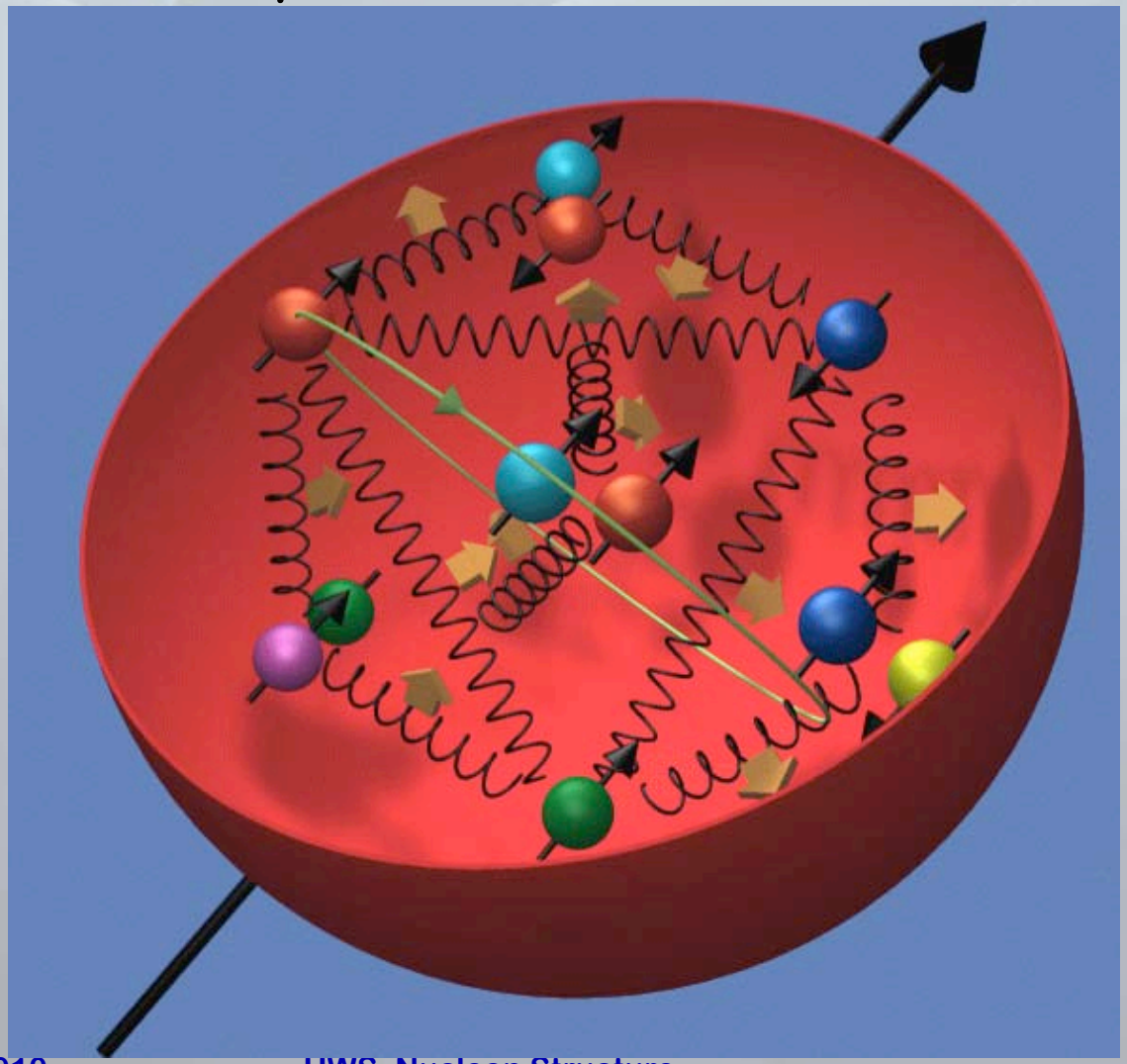
- Mesons
  - e.g. pion
  - quark-antiquark
  - integer spin





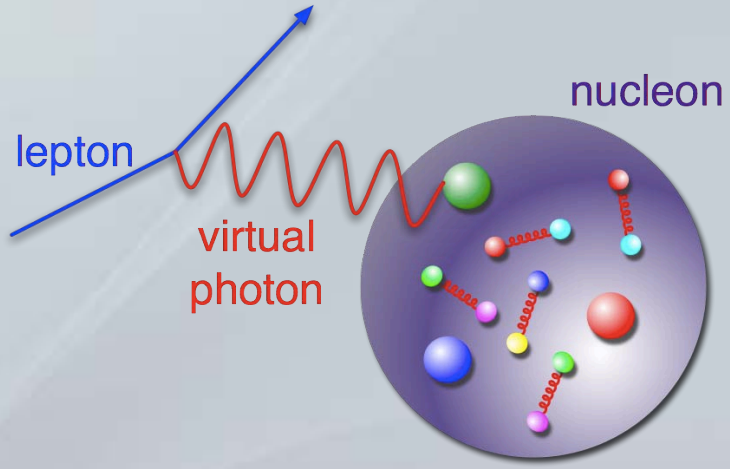
Closer Look

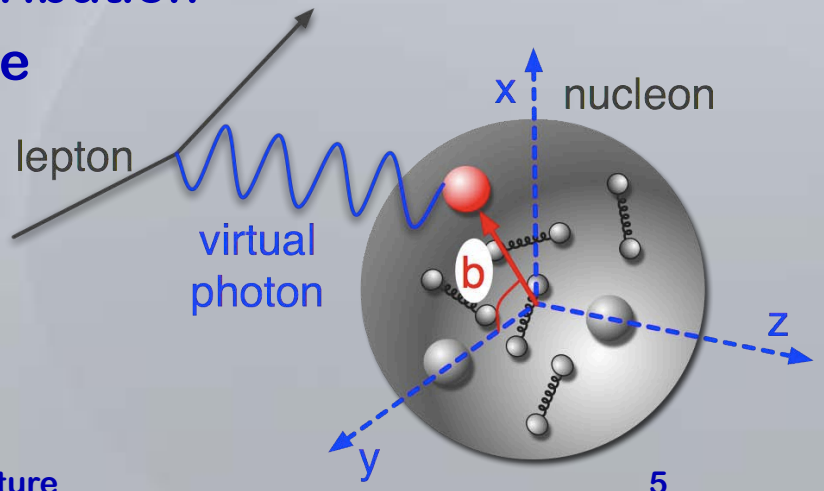
- Reality is more complicated



Experimental Approach

- Perform scattering experiments
- Measure
  - differential cross sections
  - asymmetries
- Form factors (Sachs)
  - G_M – magnetic
  - G_E – electric
  - Fourier transform density distribution
  - probe impact parameter space



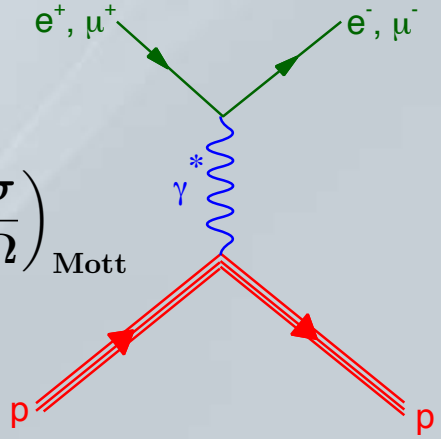


Experimental Approach

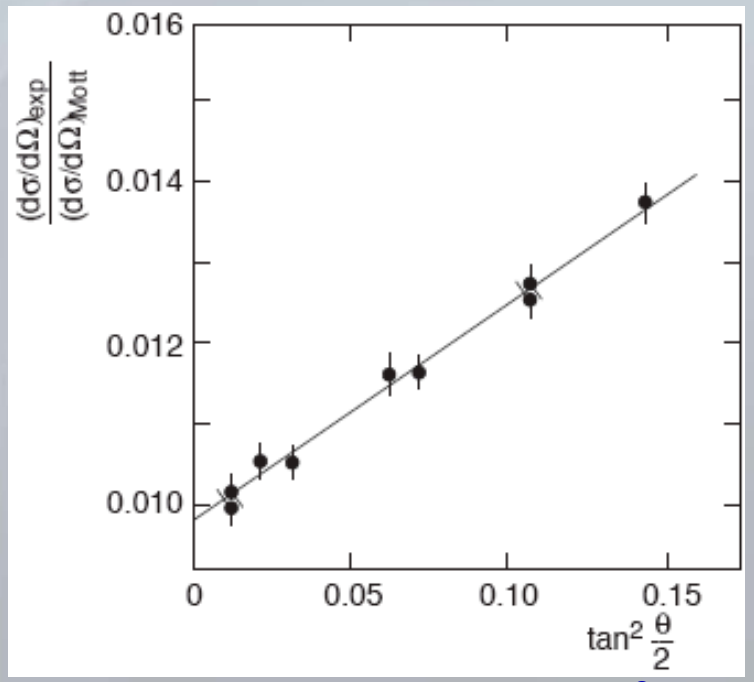
- Rosenbluth cross section
  - assuming single photon exchange

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Rosenbluth}} = \left[\frac{|G_E|^2 + \tau|G_M|^2}{1+\tau} + 2\tau|G_M|^2 \tan^2\frac{\theta}{2}\right] \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}}$$

$$\tau = \frac{Q^2}{4M_p^2} \qquad \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{\alpha^2}{4E^2} \frac{\cos^2\frac{\theta}{2}}{\sin^4\frac{\theta}{2}} \frac{E'}{E}$$

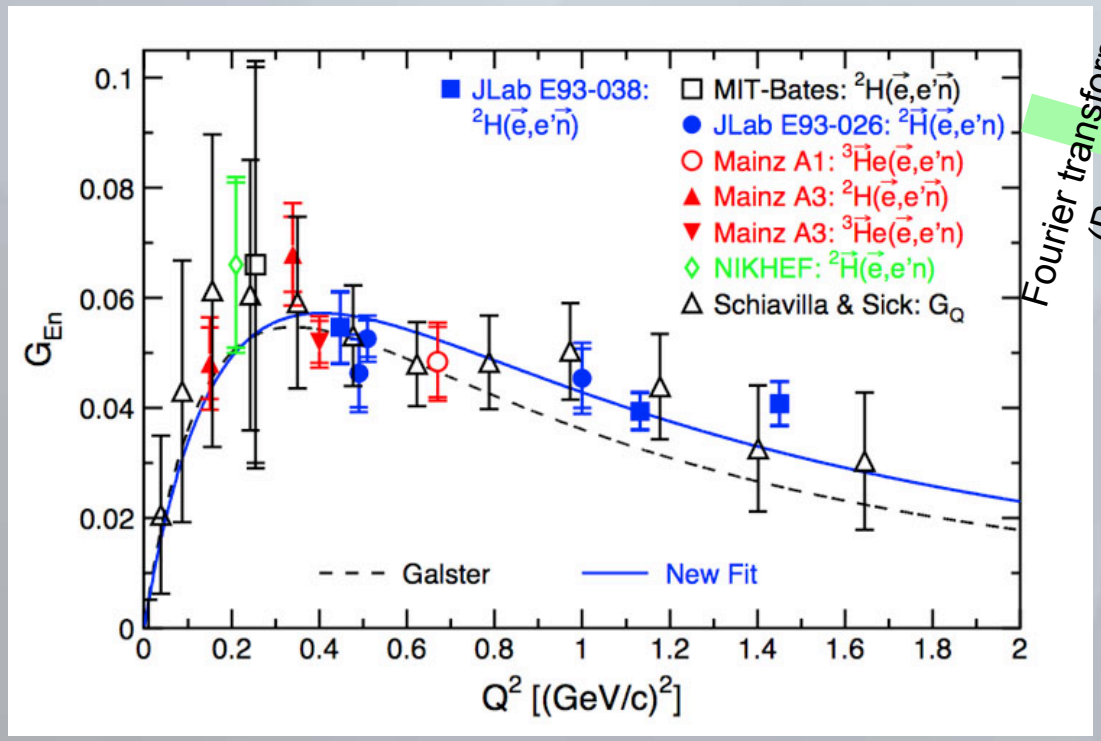


- Extract G_E and G_M
  - slope determines G_M
  - offset allows to access G_E

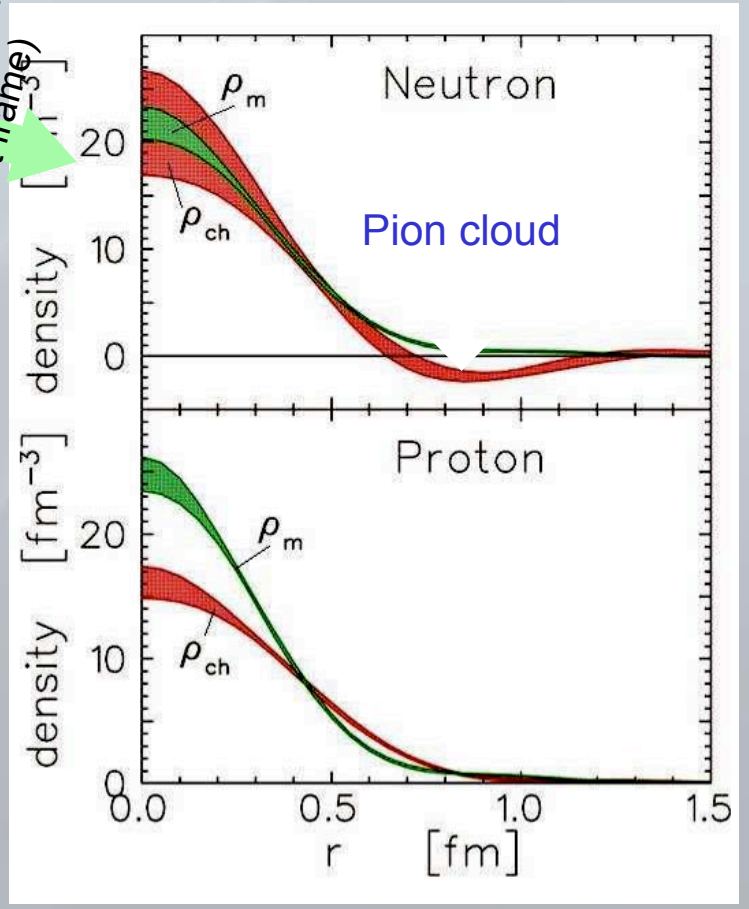


Radial EM Distribution

- Series of space like form factor measurements
  - access to radial charge and magnetic distributions

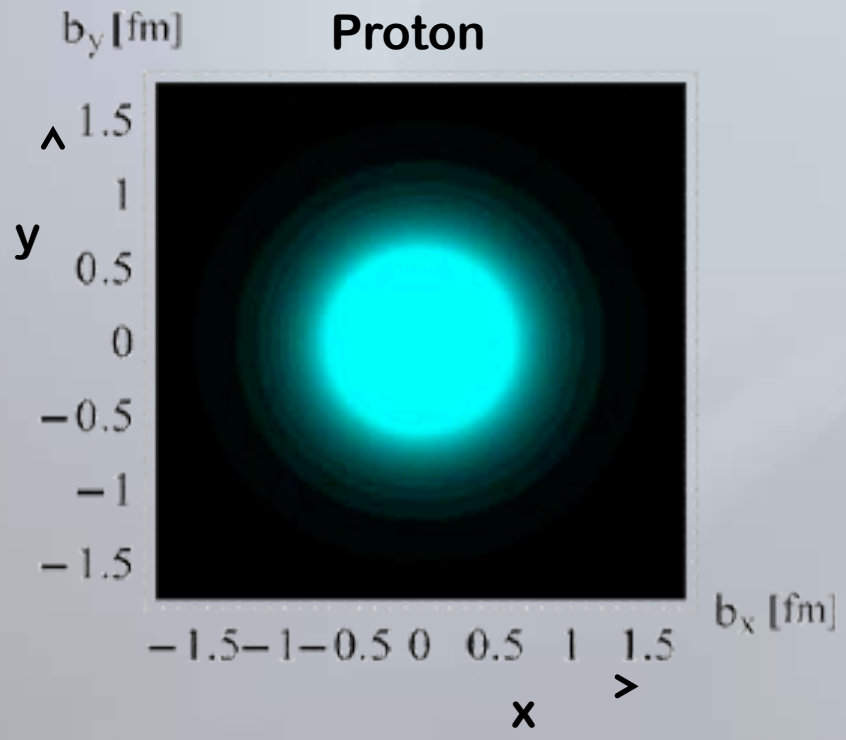


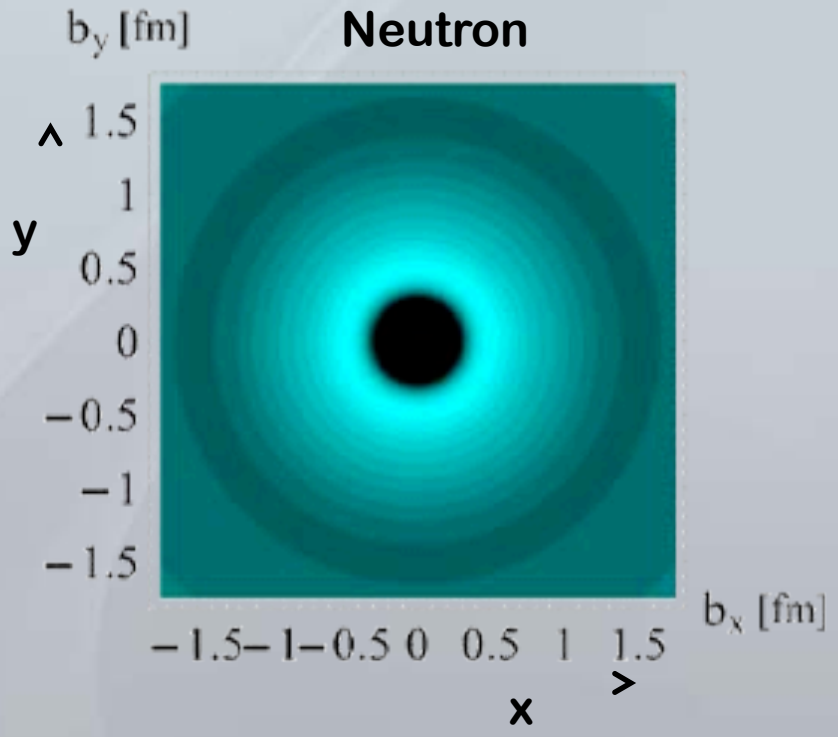
Fourier transformation (Breit frame)



Recent Calculations

- New refined results (infinite momentum frame)
  - from experimental form factors, unpolarised:

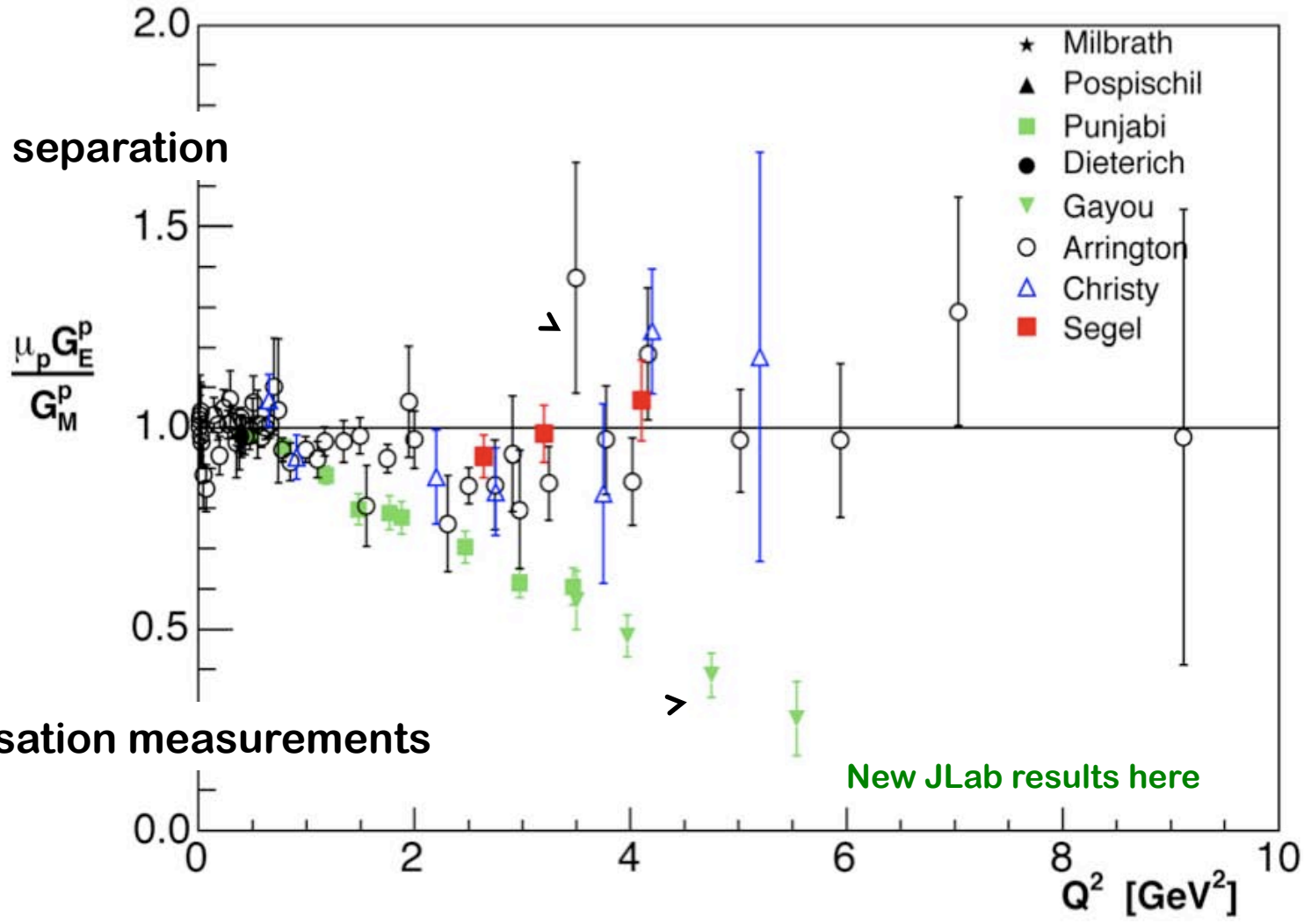




C.E. Carlson and M. Vanderhaeghen, Phys. Rev. Lett. 100, 032004 (2008)

Recent Puzzle in G_E/G_M

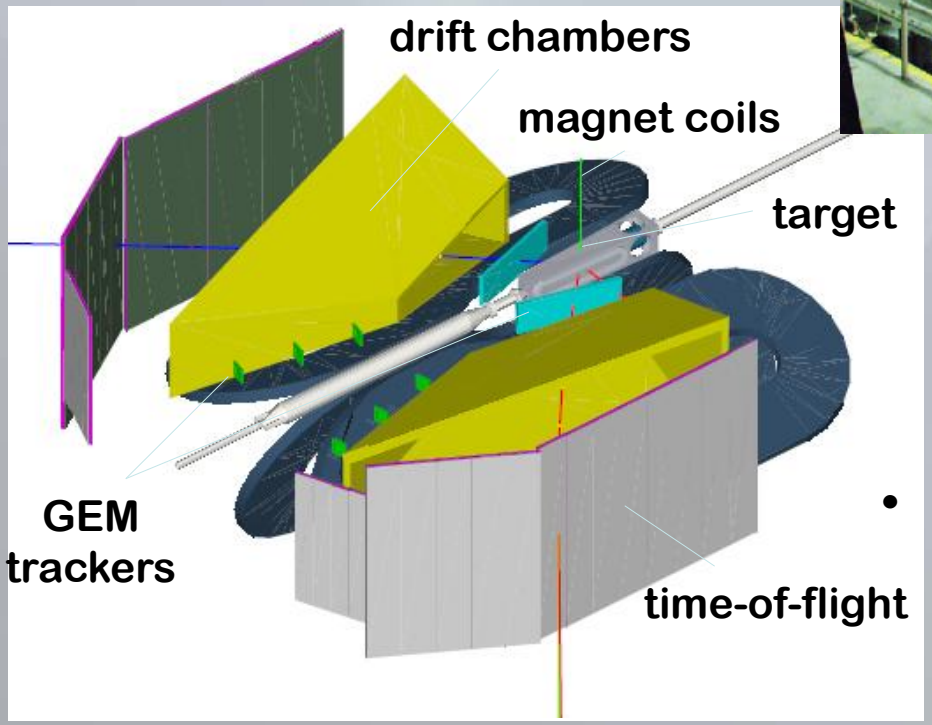
Rosenbluth separation



Double polarisation measurements

OLYMPUS (DESY)

BLAST at BATES...



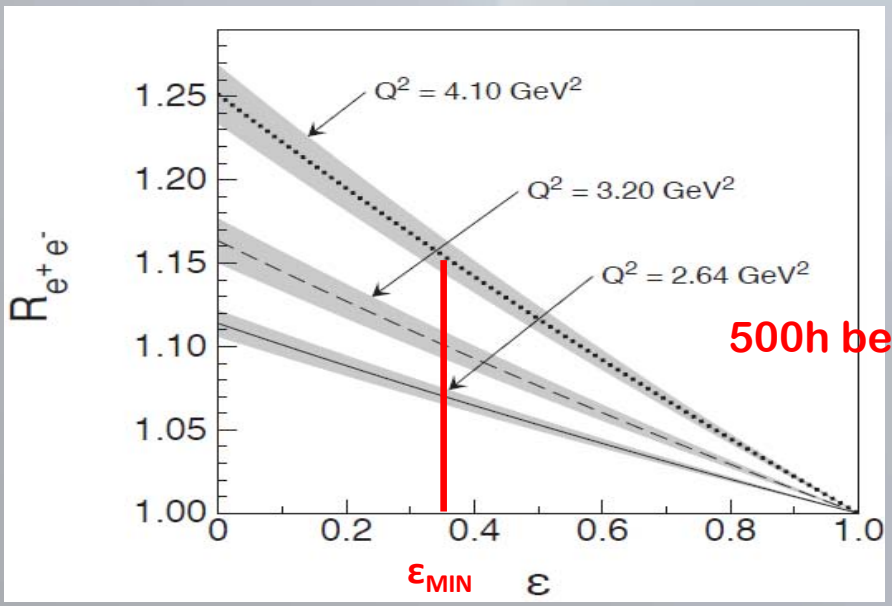
...moved to former ARGUS position at DORIS, DESY

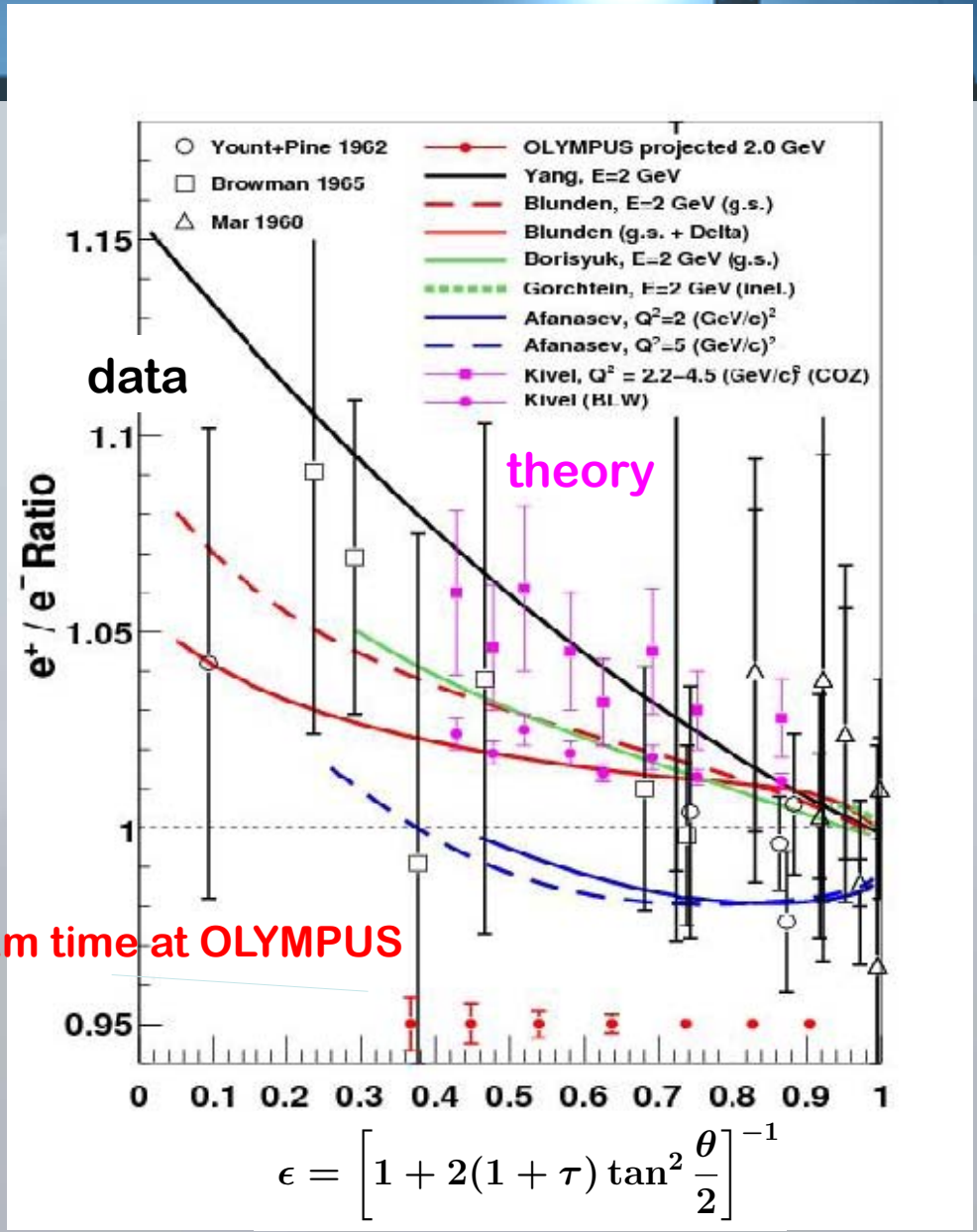
- Measurement
  - e^+/e^- at $Q^2 = 0.6\text{-}2.4(4.1)$ $(GeV/c)^2$
  - data taking in 2012

OLYMPUS (DESY)

- Decisive experiment
- Theory predictions vary significantly

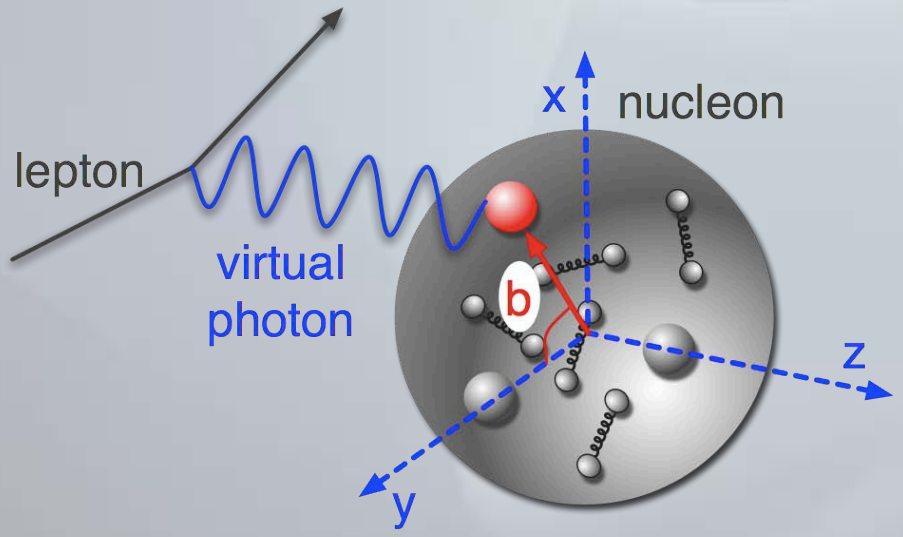
Empirical extraction by M. Vanderhaeghen





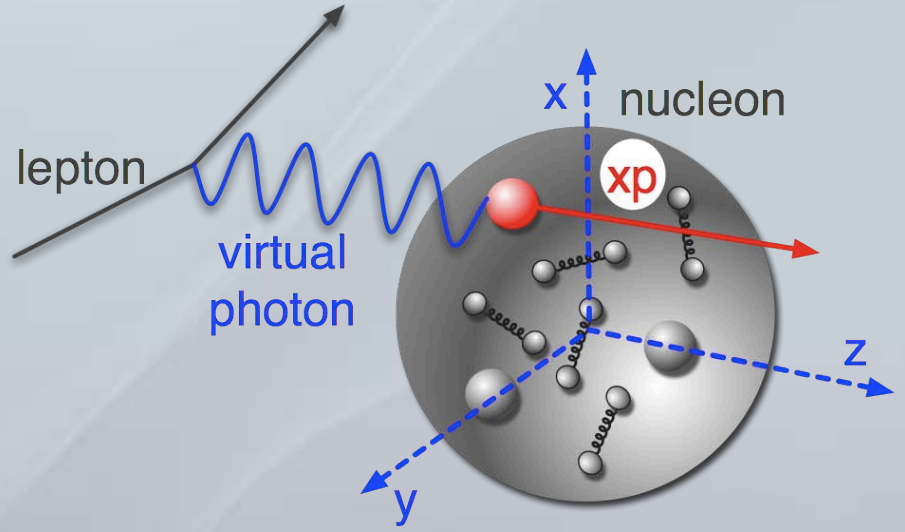
Comparison

Form Factors



Density in transverse impact parameter space

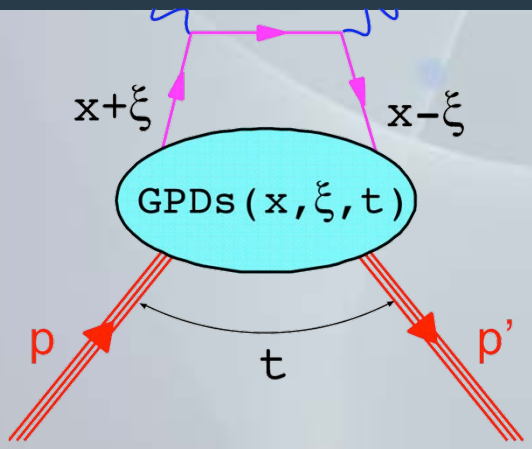
Parton Distribution Functions

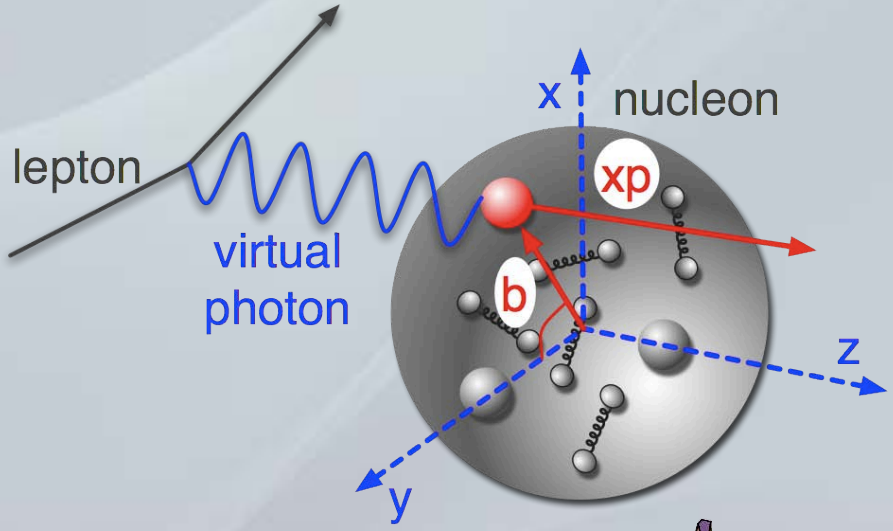


Momentum fraction in longitudinal space

- **Combined approach…**

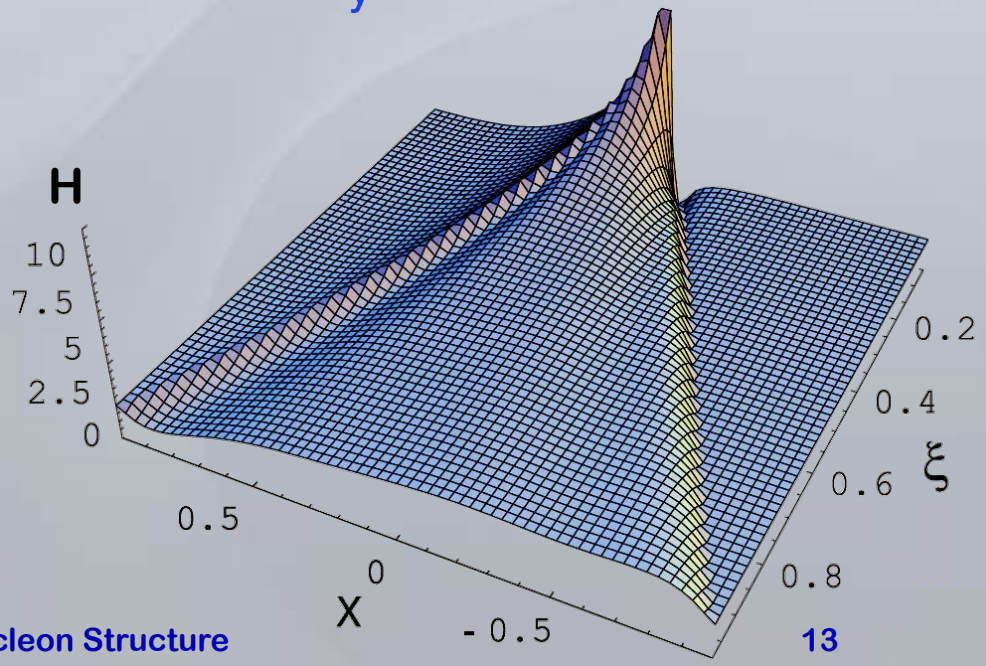
Generalised Parton Distributions





- Functions of 3 variables
  - parton momentum fraction x
  - skewedness ξ
  - p momentum transfer t
- 4 (chirality conserving) quark GPDs

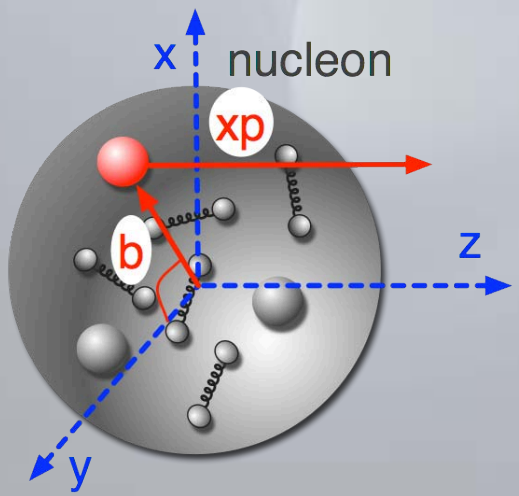
$$H(x,\xi,t), E(x,\xi,t),$$
$$\widetilde{H}(x,\xi,t), \widetilde{E}(x,\xi,t)$$

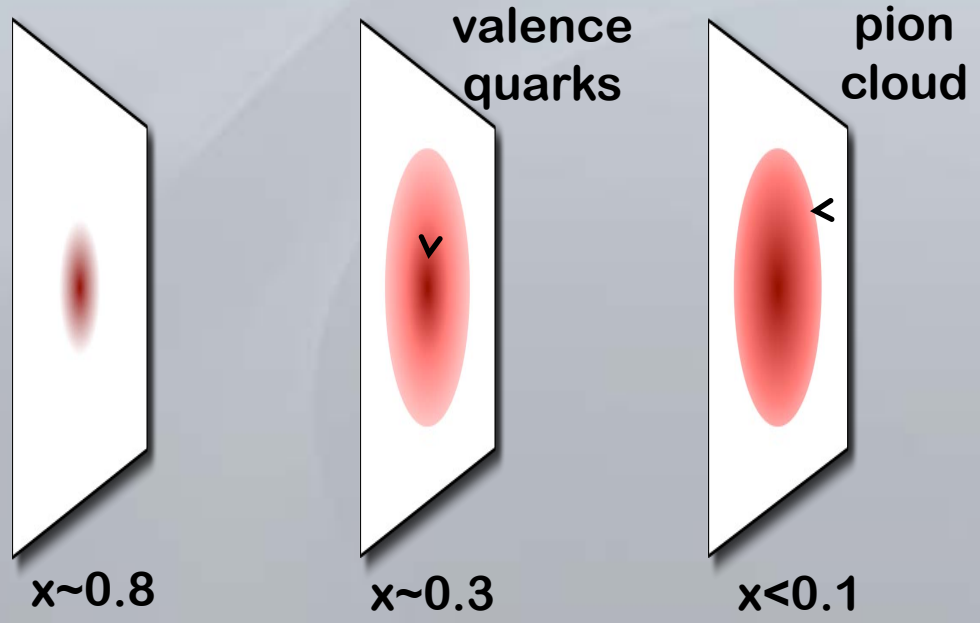


Interpretation of GPDs

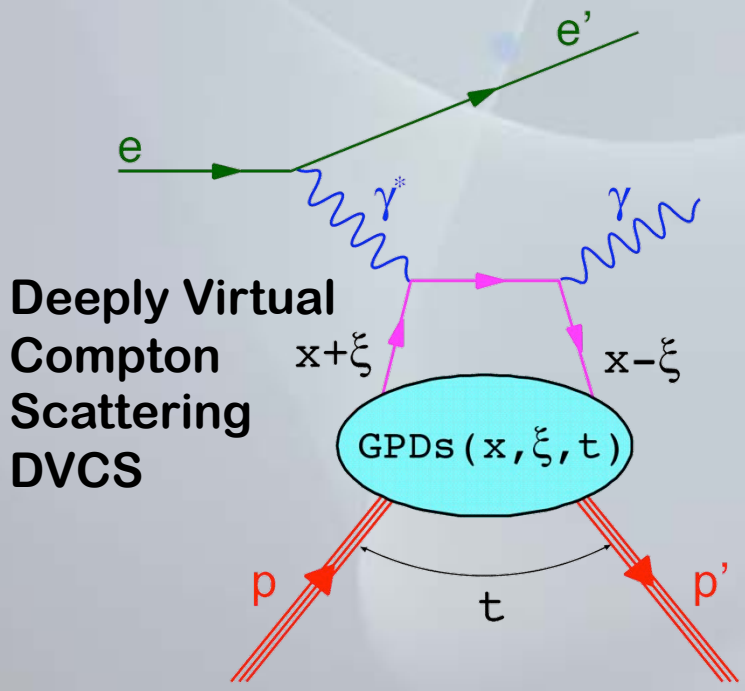
- Fourier transformation of GPDs at $\xi=0$ yields 2+1 dimensional picture of the nucleons
  - i.e. longitudinal in momentum fraction and transversal in impact parameter space

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



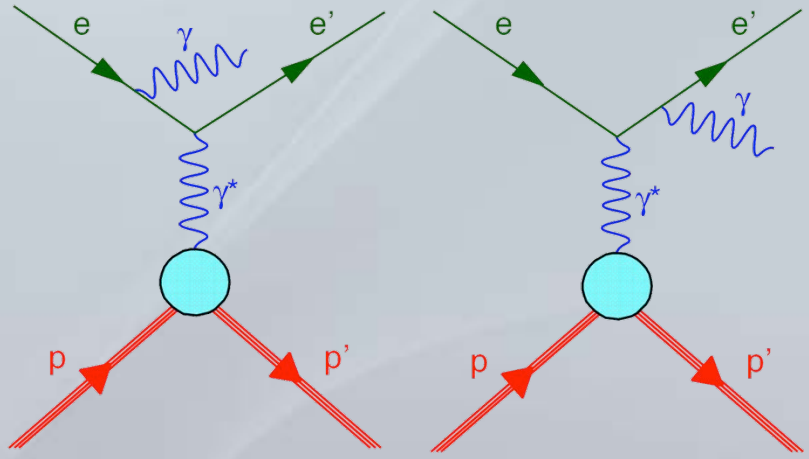


How to Access GPDs → DVCS



Deeply Virtual Compton Scattering DVCS

Bethe-Heitler Scattering BH



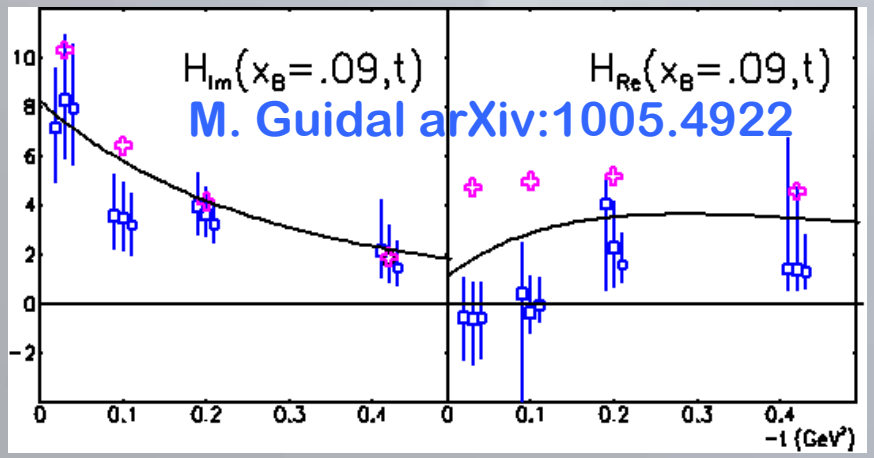
- Indistinguishable and cross section dominated by BH
  - extraction using interference term

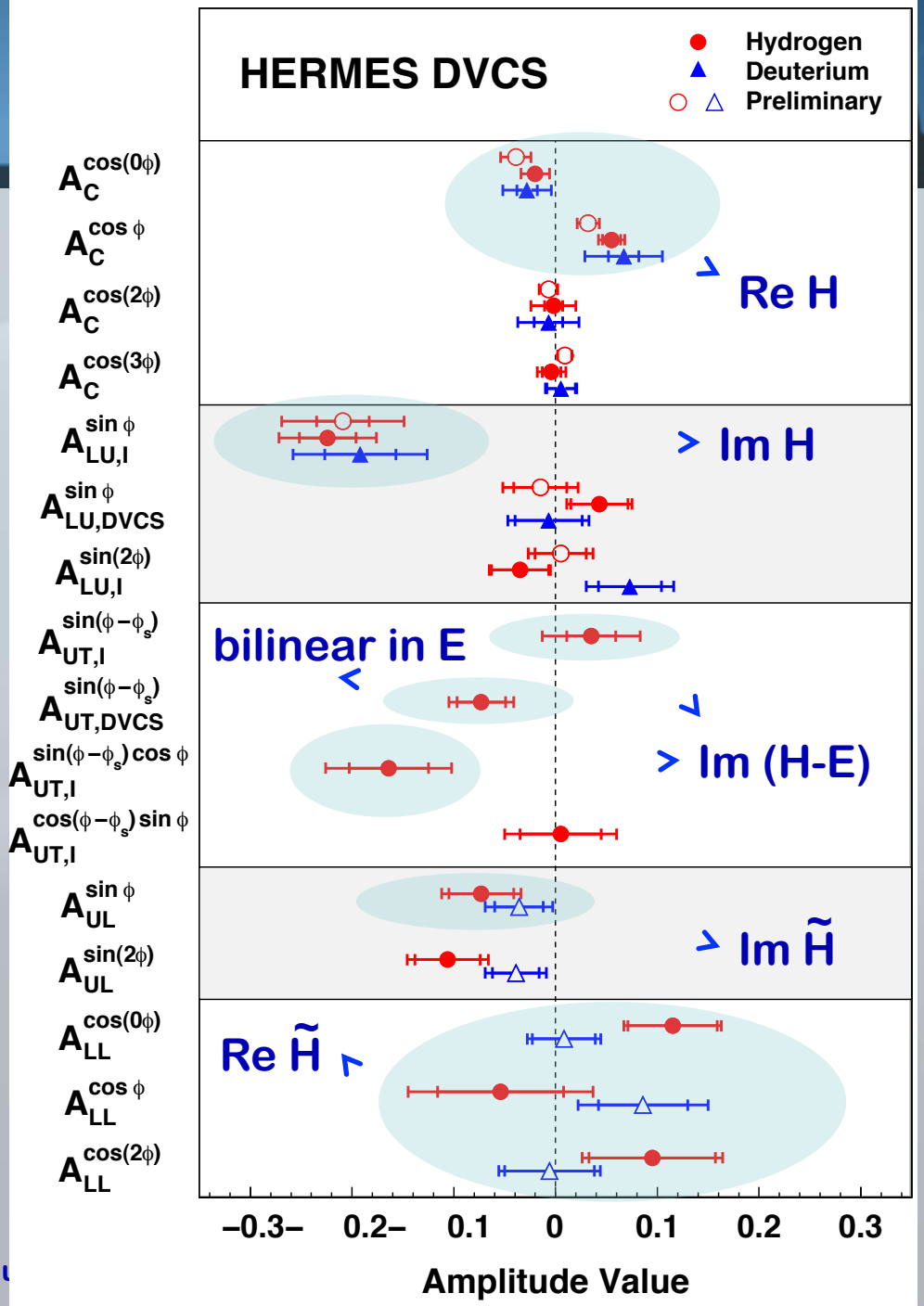
$$d\sigma(eN \to eN\gamma) \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \mathcal{T}_{BH}\mathcal{T}^*_{DVCS} + \mathcal{T}^*_{BH}\mathcal{T}_{DVCS}$$

BH: precisely known from QED DVCS: access to the GPDs

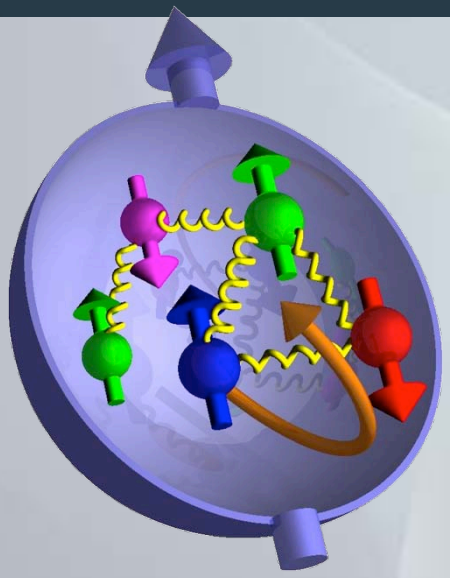
HERMES (DESY)

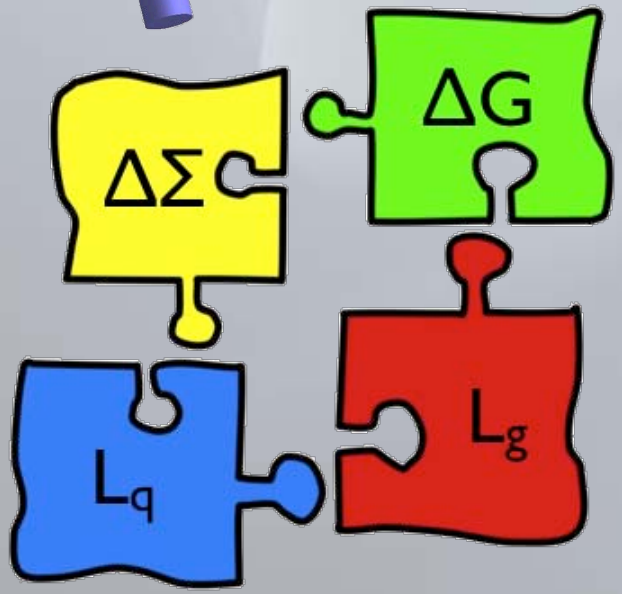
- Asymmetries from DVCS measurements at HERMES
  - Relation to real and imaginary parts of Compton form factors, which directly relate to respective GPDs





Spin Structure





- Proton spin

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

- $\Delta\Sigma$: quark spin
  - fraction about 1/3
- ΔG : gluon spin
  - first results
- L_q : quark angular momentum
  - unknown
- L_g : gluon angular momentum
  - unknown

Spin Structure

- Ji sum rule:

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

GPDs

- Proton spin

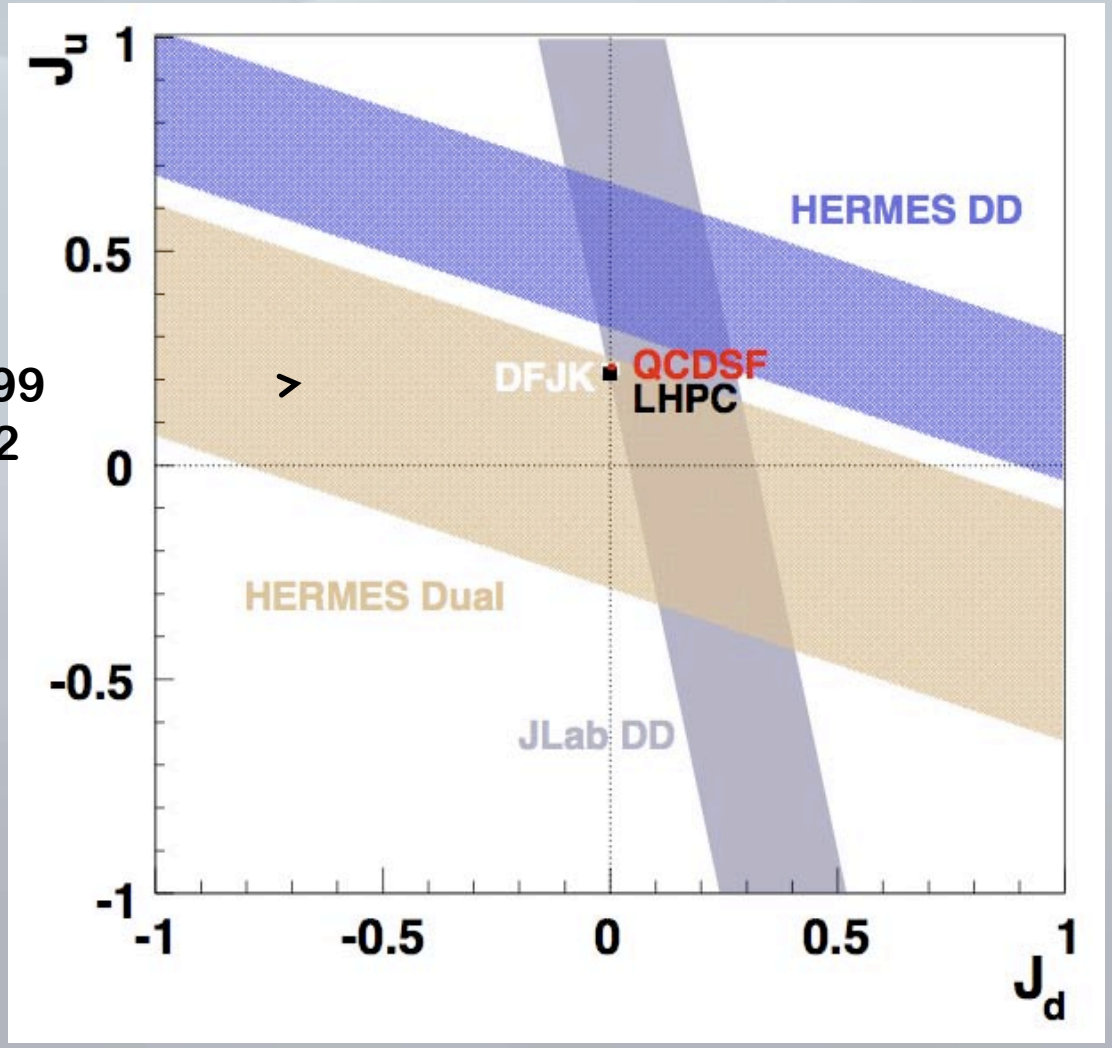
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

- $\Delta\Sigma$: quark spin
  - fraction about 1/3
- ΔG : gluon spin
  - first results
- L_q : quark angular momentum
  - unknown
- L_g : gluon angular momentum
  - unknown

HERMES/JLab Constraint on J_u/J_d

- In result quark angular momenta can be constraint

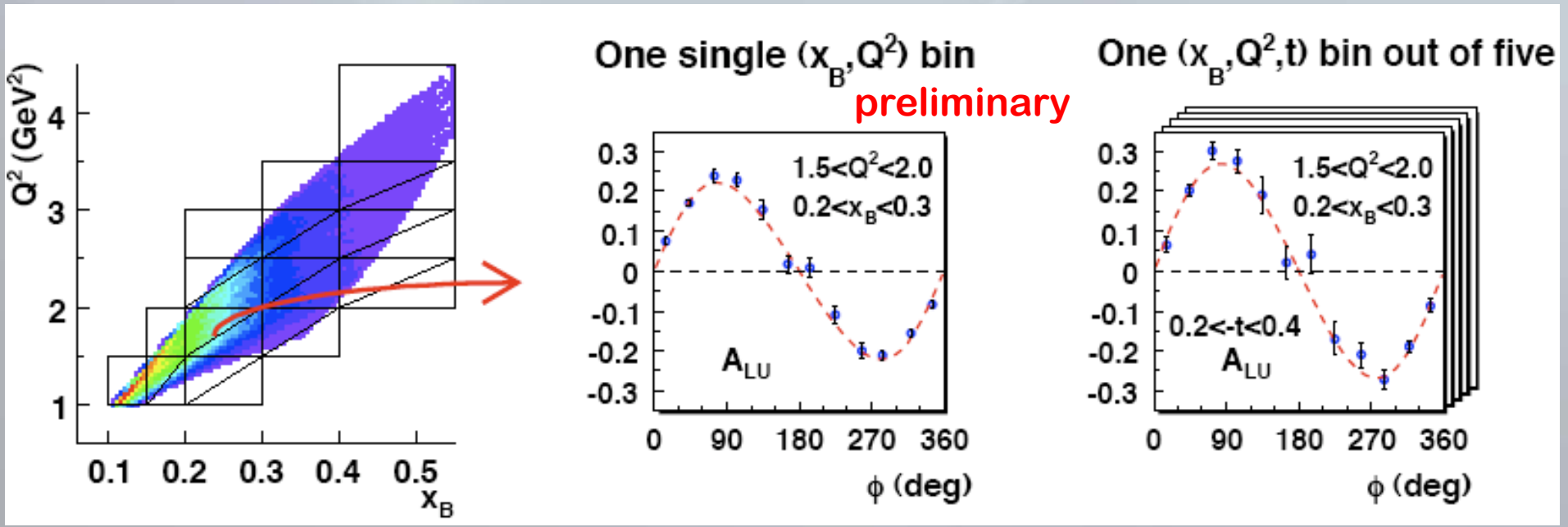
JHEP 0806:066,2008



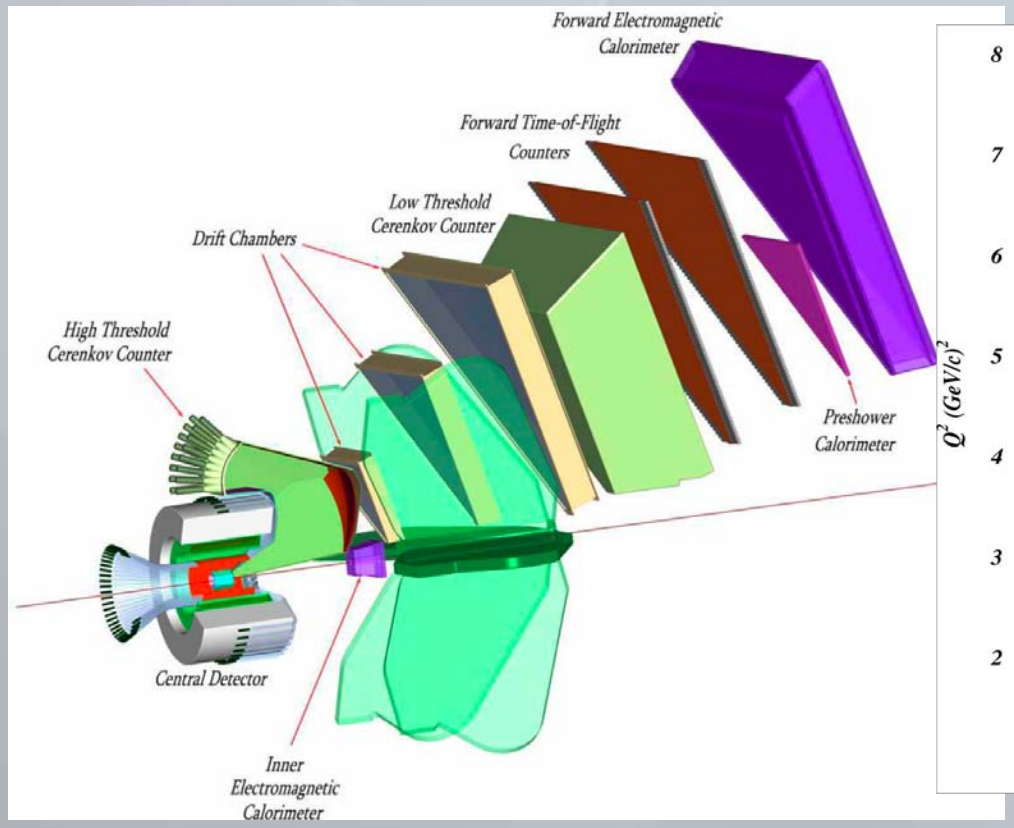
Erratum: arXiv:0810.3899
Model error: factor 1.5-2

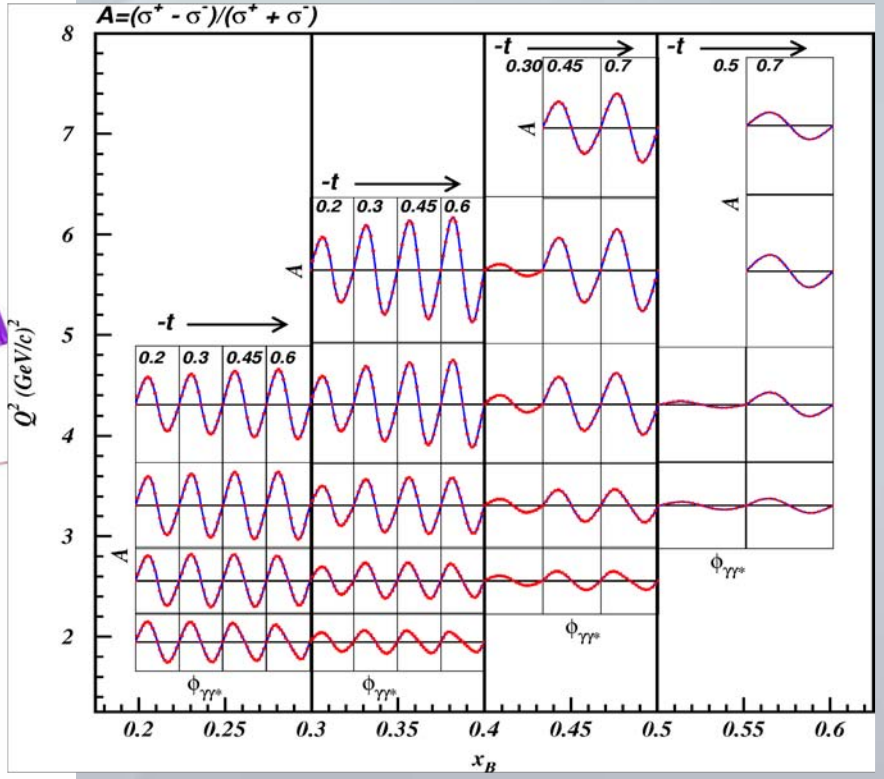
CLAS(JLab) Beam Spin Asymmetry

- 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



Future CLAS12 at JLab

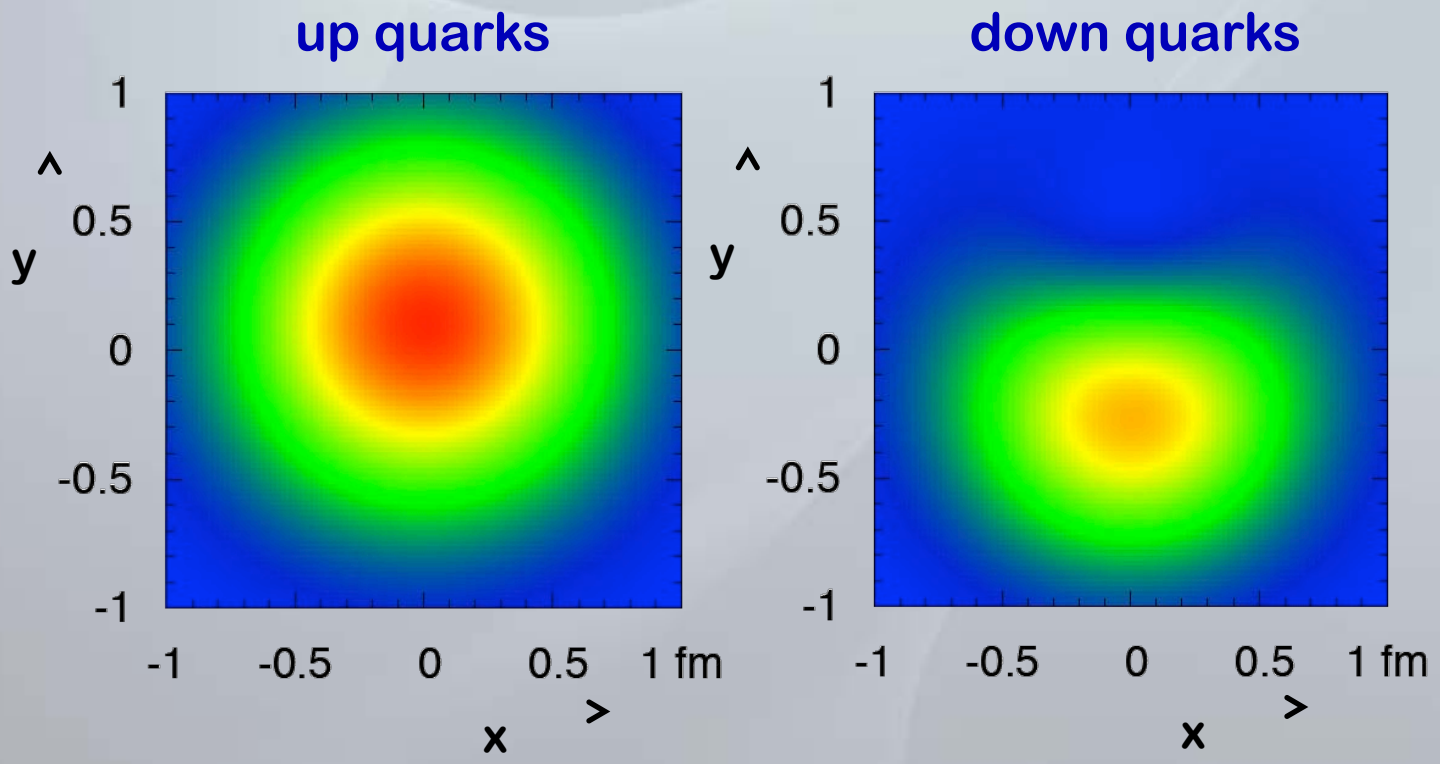




- High statistics measurements at 11 GeV with upgraded CLAS12 detector
- Constrain GPD H from BSA

Model Calculations

- GPD model, constrained by experimental form-factor data

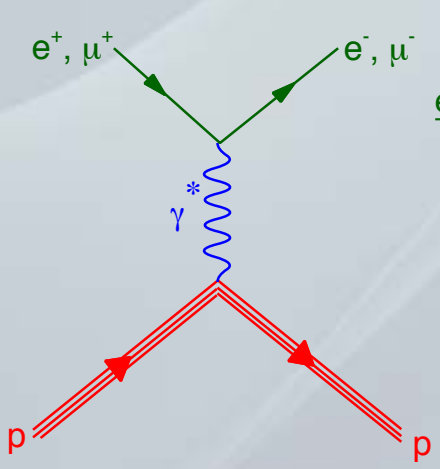


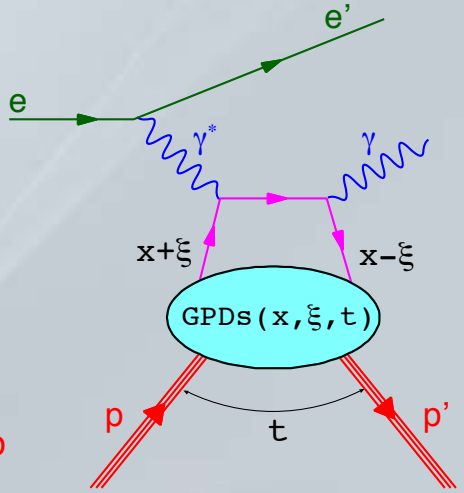
- Density distribution in impact parameter plane for quarks. Proton transv. polarised along x axis.

[P.Kroll, AIP Conf.Proc.904:76-86,2007]

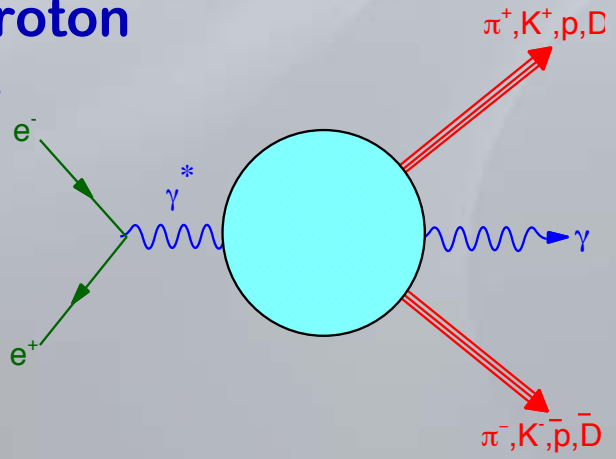
Space and Time Like Processes

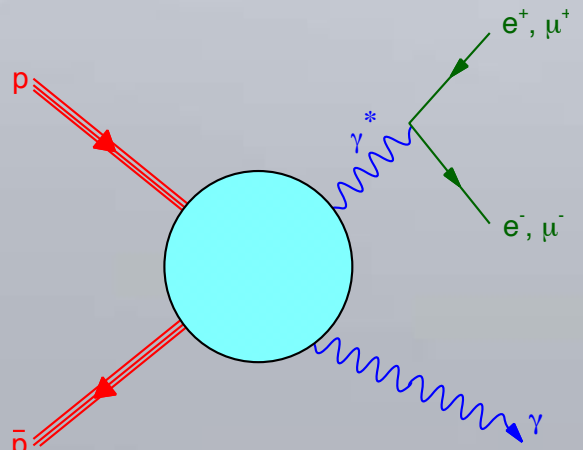
- Space like
  - elastic lepton scattering
  - deep virtual Compton scattering





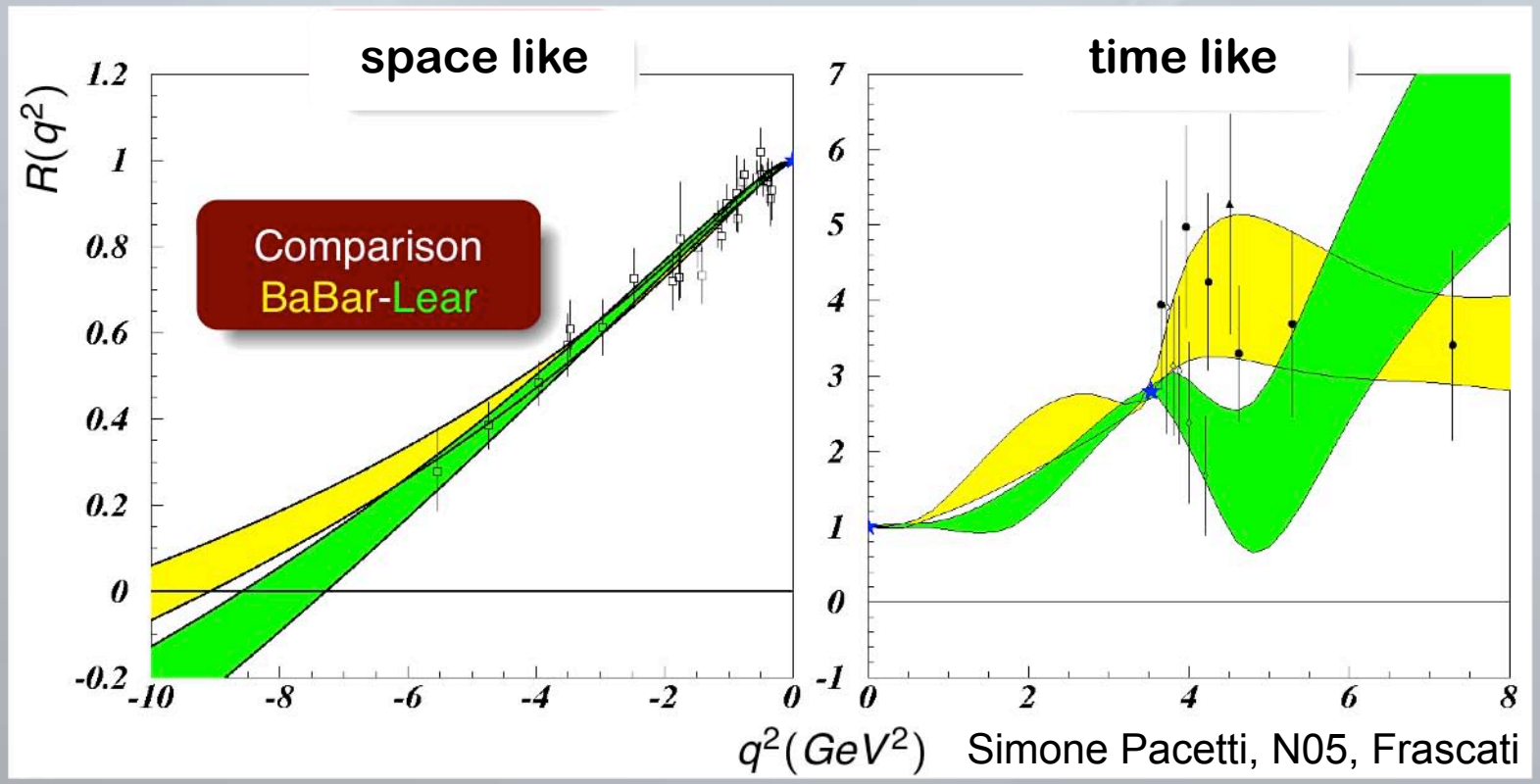
- Time like
  - electron-positron collisions
  - proton-antiproton annihilations





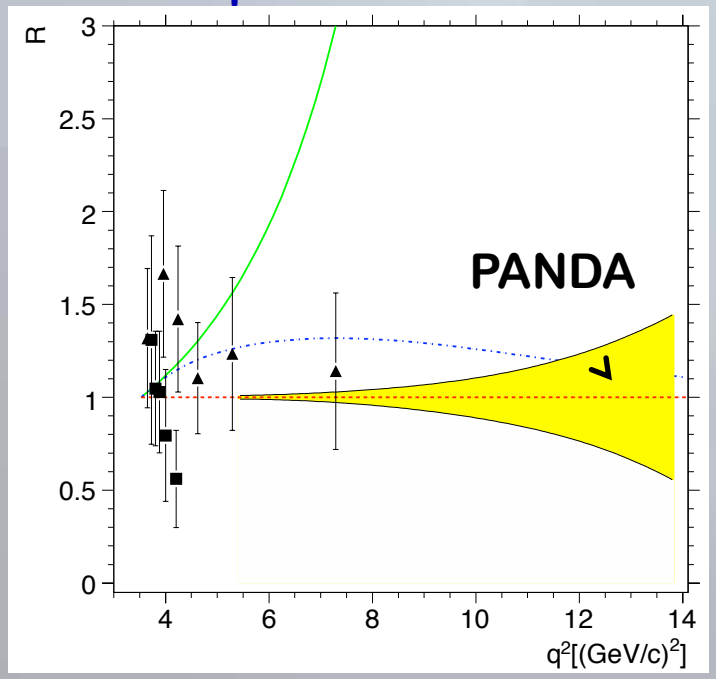
Relation between regions

- R = $\mu_p G_E/G_M$ Using Dispersion Relation
  - fit only to double polarisation measurements in space like region
  - scarce data in time like region

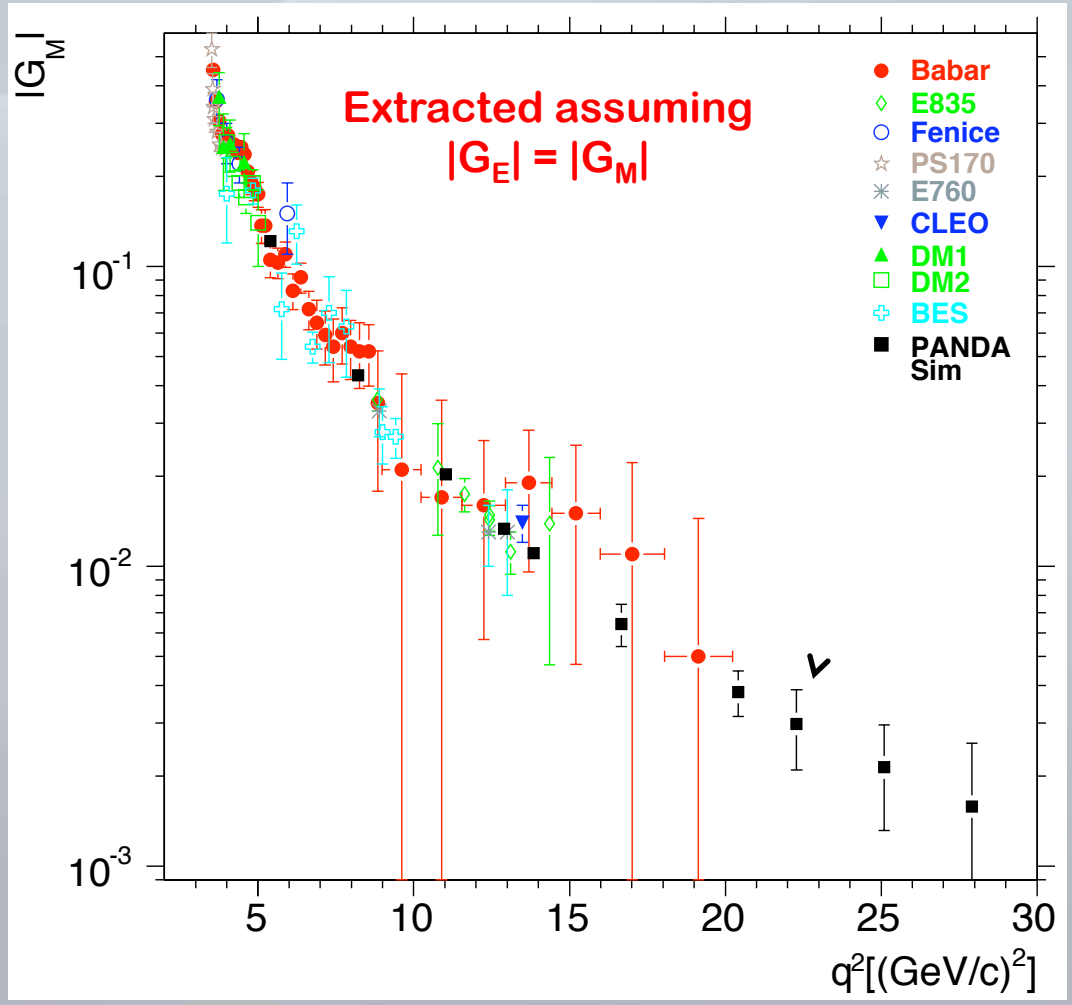


Time Like Form Factors

- PANDA (FAIR)
  - R = $\mu_p G_E/G_M$ with unprecedented precision



  - absolute value of $|G_M|$ up to 30(GeV/c)^2



PANDA Physics Performance Report: arXiv:0903.3905

Conclusions

- Structure of the nucleon still not well understood
- Space like form factors
  - were believed to be understood…
  - discrepancy in G_E/G_M needs resolution – OLYMPUS
- Space like GPDs
  - first constraints achieved – HERMES
  - more precise data required – CLAS 12GeV
- Spin structure
  - progress by HERMES and JLab
- Time like information
  - scarce to date
  - precise G_M and G_E/G_M – PANDA
- Goal
  - 3D map of the nucleon