# Results on DVCS

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# Generalized Parton Distributions

- **GPDs encode the non perturbative structure of the nucleon**

  D. Müller et al. Fortsch.Phys. 42 (1994) 101, X.-D. Ji Phys.Rev.Lett. 78 (1997) 610,

  A. Radyushkin Phys.Lett. B380 (1996) 417

  – 4 GPDs are needed to describe the nucleon, they depend on x, ξ and t
    - Can be flavored decomposed and extended to gluon

  – The GPDs H and E can be directly linked to the angular momentum

  – GPDs can be translated into a tomographic image of the proton

  *M. Burkardt Phys.Rev. D62 (2000) 071503*

- **They can be extracted from exclusive processes**

  – Factorization has been demonstrated

  – But these processes have small cross sections

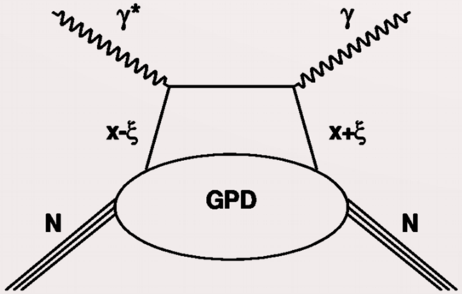
  – Deep Virtual Meson Production (DVMP)
    - Possible with many final states but with more theoretical issues

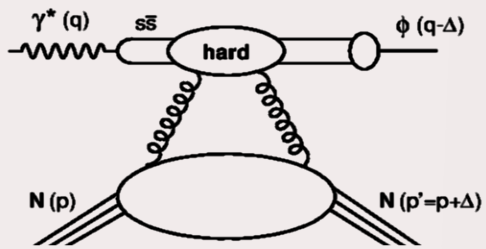
  – Deep Virtual Compton Scattering (DVCS)
    - Simplest process that interfere with Bethe-Heitler to give larger cross sections and spin asymmetries

- **Often these exclusive processes only give access to CFFs**

  – The 4 complex CFFs intervene as 8 free parameters in the calculation of the various observables

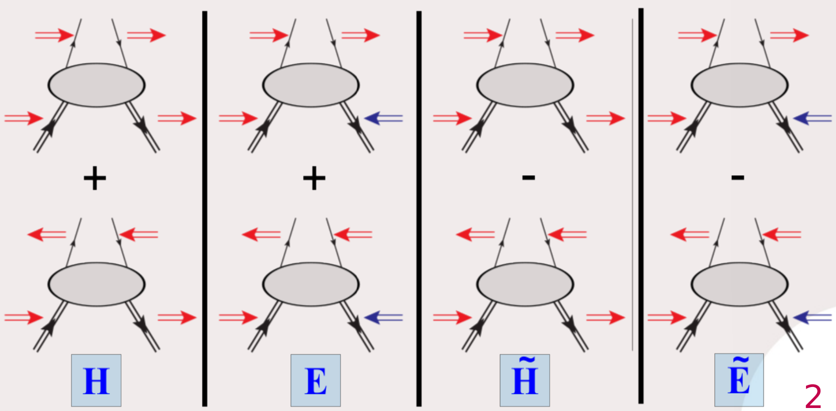
  *A. Belitsky et al. Nucl.Phys. B629 (2002) 323-392*




$$F_{Re}(\xi,t) = \mathcal{P}\int_{-1}^{1} dx \left[\frac{1}{x-\xi} \mp \frac{1}{x+\xi}\right] F(x,\xi,t),$$

$$F_{Im}(\xi,t) = F(\xi,\xi,t) \mp F(-\xi,\xi,t).$$



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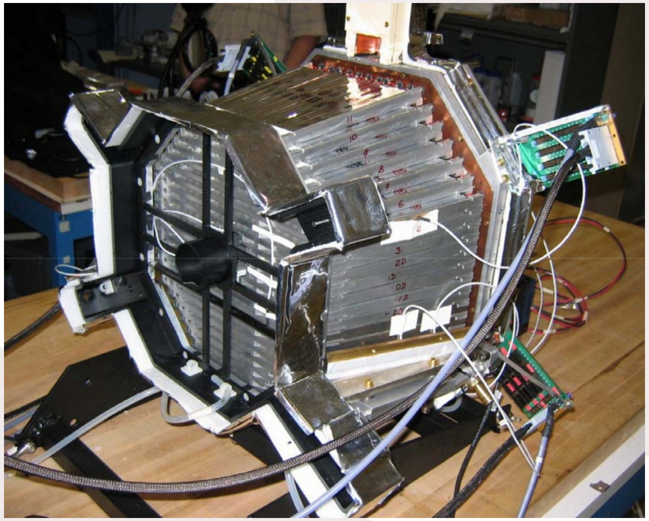
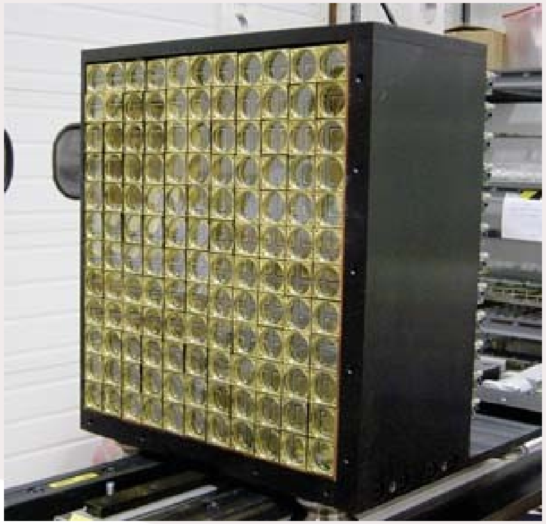
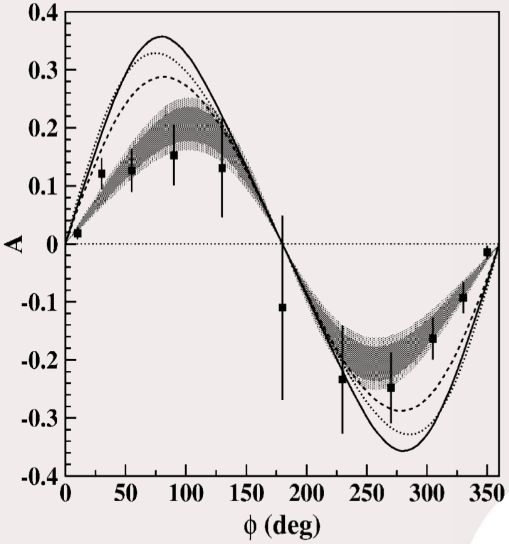
# First Measurement at JLab

- **First JLab DVCS Beam Spin Assymetries**
  - In Hall B by the CLAS collaboration
  - Using the existing setup only a very small phase space was accessible, but it provided the proof that strong asymmetries are accessible at JLab energies

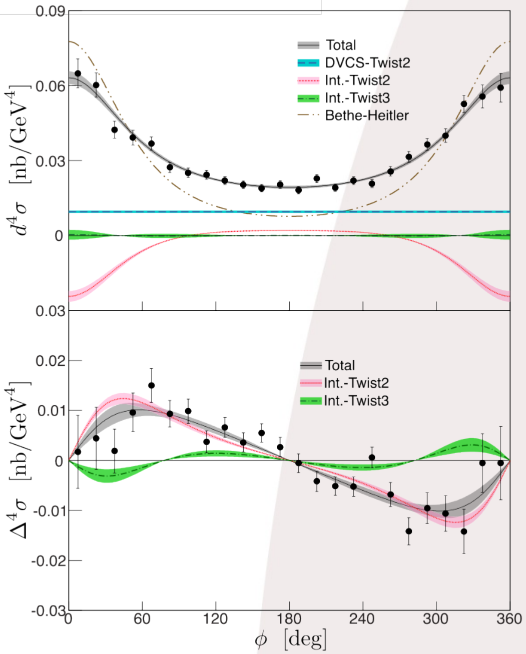
    *S. Stepanyan et al. (CLAS Coll.) PRL 87, 182002 (2001)*
- **Triggered important experimental efforts**
  - Construction of dedicated calorimeters for Hall A and B (CLAS)
  - Start of a large program to measure spin asymmetries and cross sections in both Hall-A and Hall-B (CLAS Coll.)







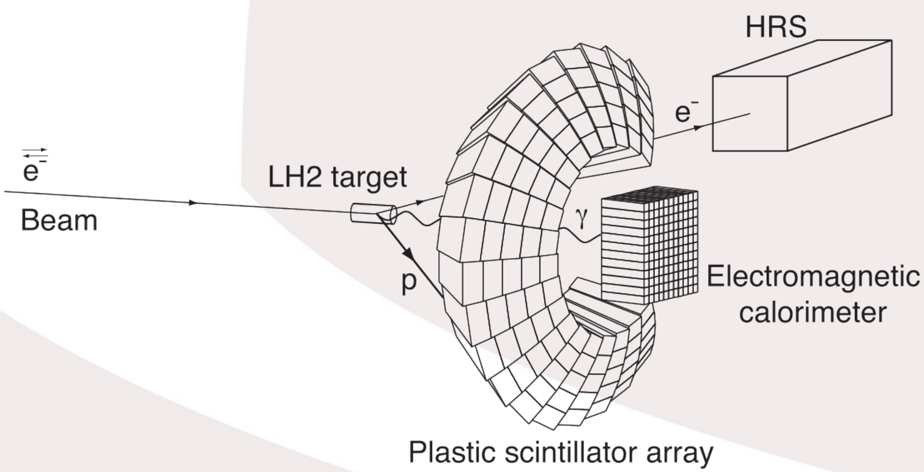
# DVCS in Hall A

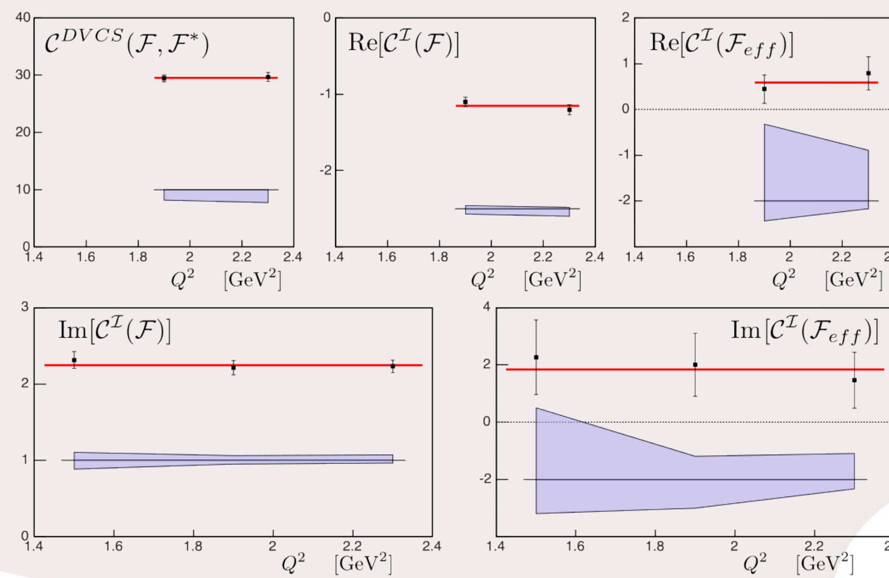



- **First measurement of absolute cross sections of DVCS**
  - Provided very high precision data in few bins

    *C. Muñoz Camacho et al., Phys.Rev.Lett. 97 (2006) 262002*
- **Tested the scaling behavior with $Q^2$**
  - Surprisingly enough it works well at JLab energy
  - Apparently, higher twist effects are not that strong
- **Final full results recently made available**
  - Solved some of the discrepancies between data sets

    *M. Defurne et al., Phys.Rev.C 92 (2015) 055202*



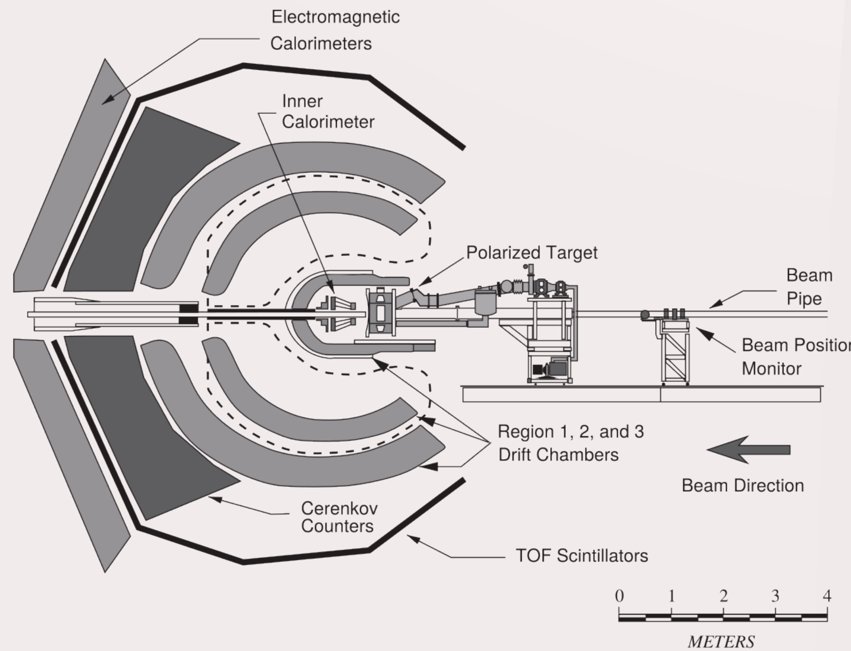
# DVCS in CLAS

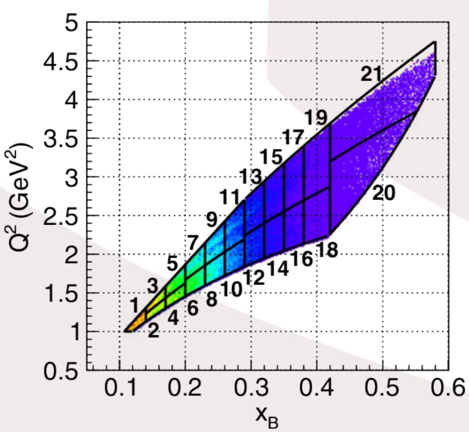
- **CLAS Published first Beam Spin Asymmetries**
  - Covers a much larger phase space

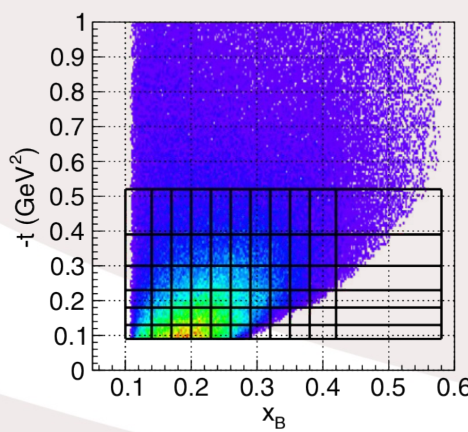
    *F.X. Girod et al (CLAS Coll.) Phys.Rev.Lett. 100 (2008) 162002*

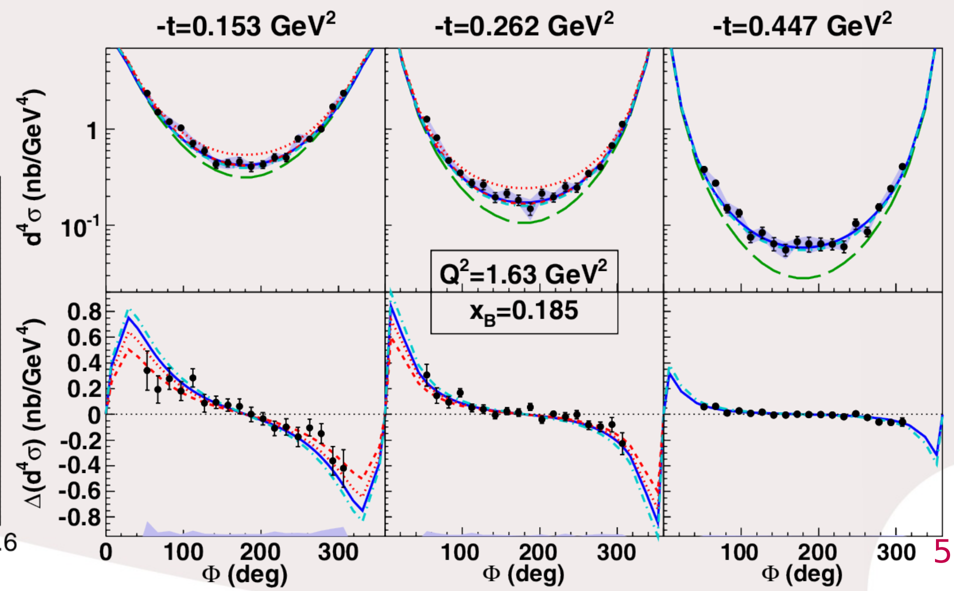
- **Now cross sections are also available**
  - Should allow the extraction of Im(H)
  - Amount of data reached the critical limit for extraction of proton tomography

    *H.S. Jo et al. (CLAS Coll.) Phys.Rev.Lett. 115 (2015) 21200*

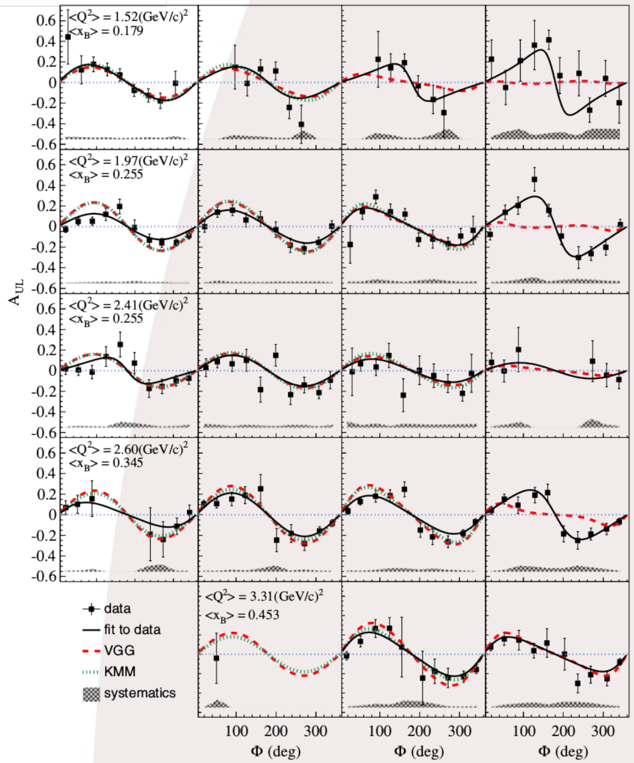


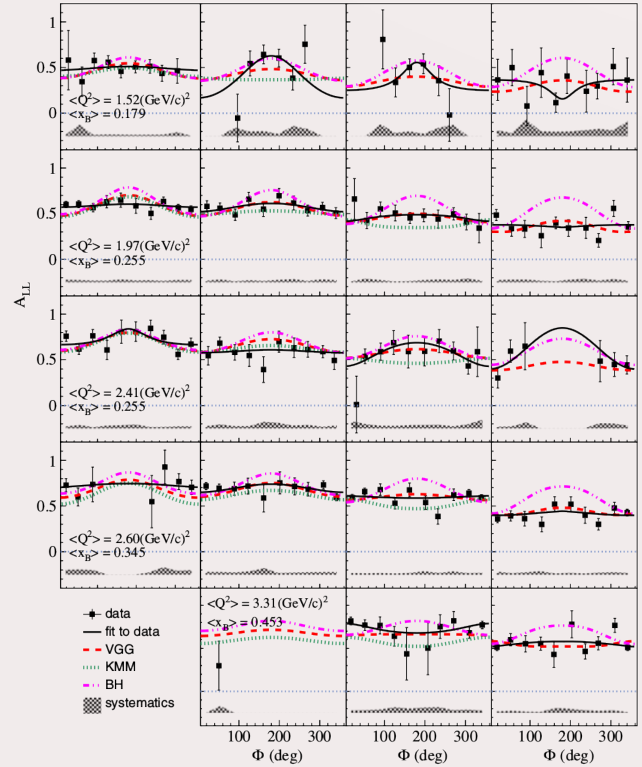



# DVCS in CLAS



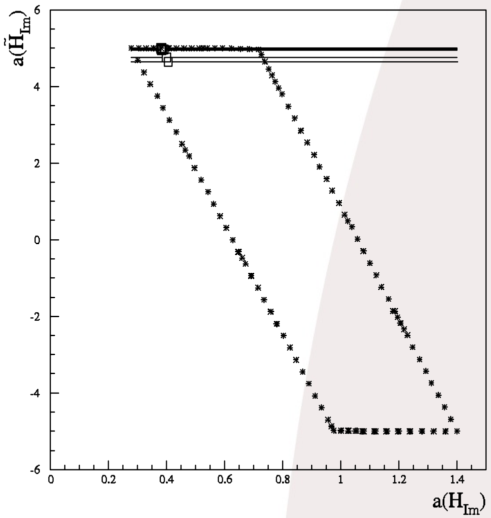




- **CLAS also measured DVCS on a longitudinally polarized target**
  - Measurement of the longitudinal Target Spin asymmetries (lTSA) and Double Spin Asymmetries (DSA)
  - Should give an insight into other CFFs → Im($\hat{H}$)
  - Reduce the number of unconstrained CFFs

*S. Pisano et al. (CLAS Coll.) Phys.Rev.D 91 (2015) 052014*

*E. Seder et al. (CLAS Coll.) Phys.Rev.Lett. 114 (2015) 032001*

# Extracting the 3D Map

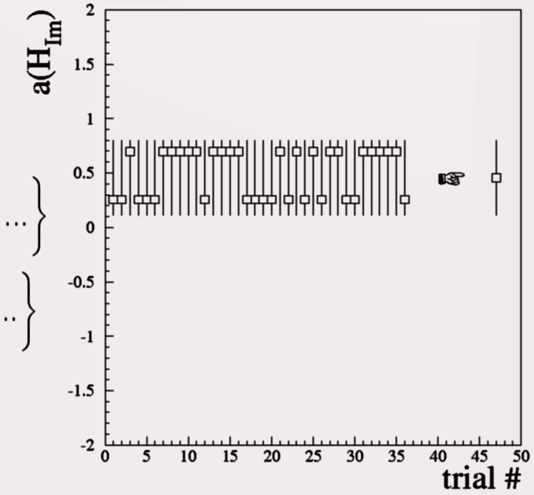


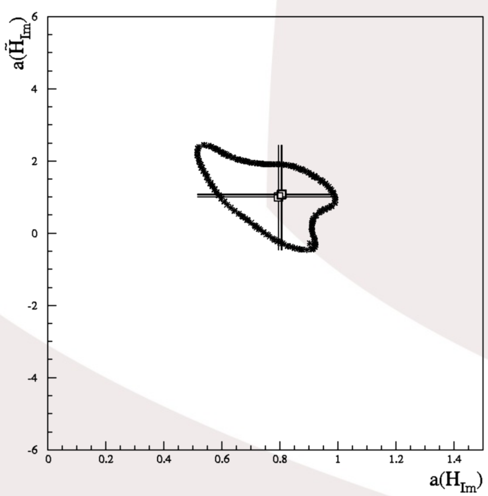

$$\Delta\sigma_{LU} \propto \sin\phi \;\; Im\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E} + ...\}$$

$$\Delta\sigma_{UL} \propto \sin\phi \;\; Im\left\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)\left(\tilde{\mathcal{H}} + \frac{x_B}{2}\mathcal{E}\right) - \xi k F_2\tilde{\mathcal{E}} + ...\right\}$$

$$\Delta\sigma_{LL} \propto (A + B\cos\phi) \;\; Re\left\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)\left(\mathcal{H} + \frac{x_B}{2}\mathcal{E}\right) + ...\right\}$$

$$\Delta\sigma_{Ux} \propto \sin\phi \;\; Im\{k(F_2\mathcal{H} - F_1\mathcal{E}) + ...\}$$




- **We performed a fit of all available data**
  - HERMES and JLab
- **With all the experimental effort the problem remains under-constrained**
  - We need some form of model input
  - Very lose bounds on the sub-leading CFF is enough
    - We use ± 5x the VGG model predictions
- **As expected adding target asymmetries constrains the Im(Ĥ)**
  - And incidentally it also constrains Im(H) !
- **However these data are not available for all kinematics**
  - More observables would be needed to constrain E and Ẽ
  - Transversely polarized target for example and charge asymmetries for the real parts

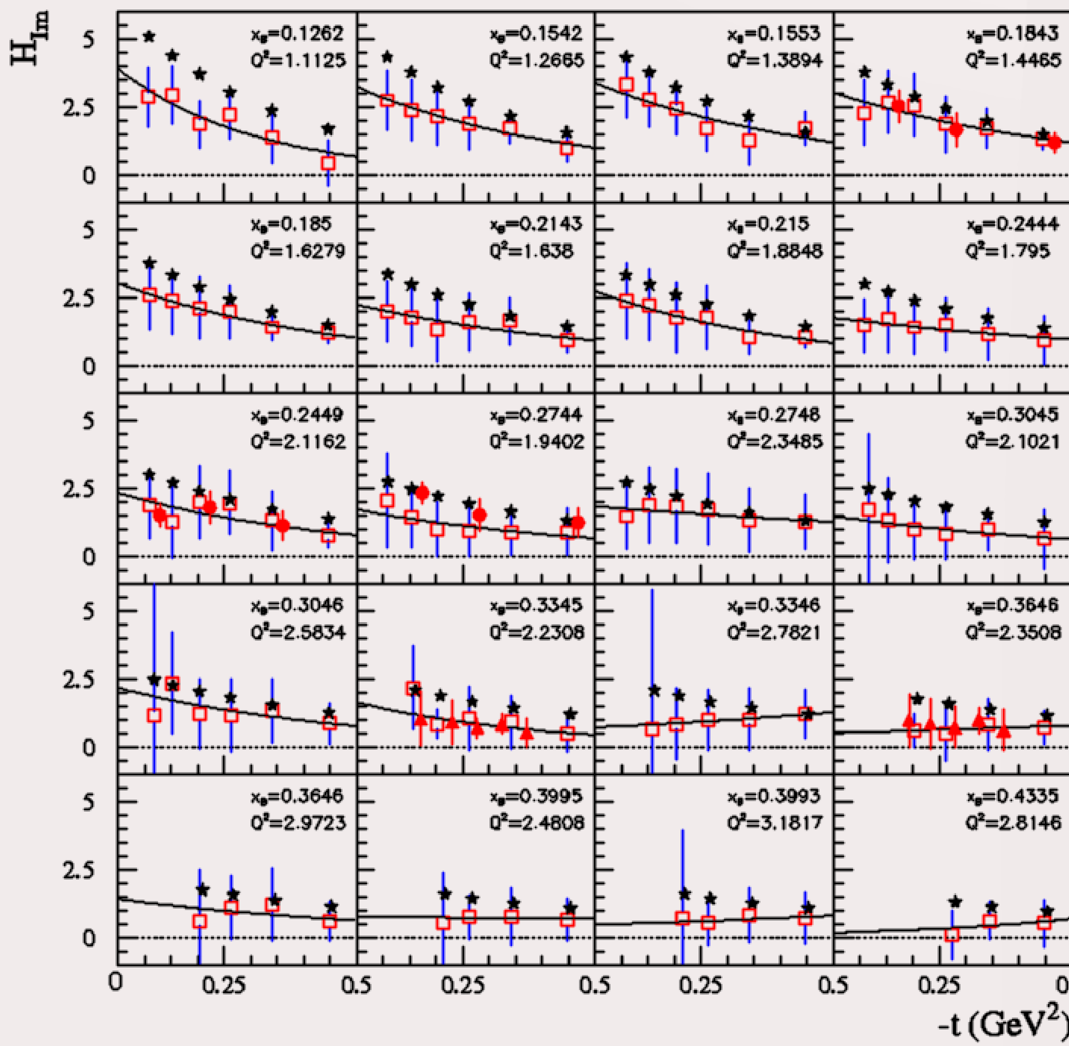
# Extraction of Im(H)

- **Applying the local fit method to all the JLab data**
  - Jlab Hall A (σ, Δσ)
  - CLAS (σ, Δσ, lTSA, DSA)

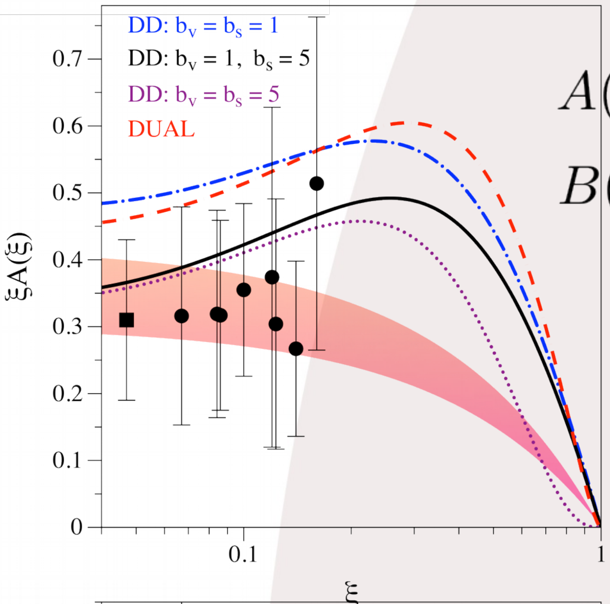
- **Gives enough coverage to explore the *t* and $x_B$ (→ ξ) dependence of Im(H)**
  - Can be fitted with an exponential form to extract the nucleon tomography

$$\mathcal{H}_{Im}(\xi,t) = A(\xi)e^{B(\xi)t}$$

- **Results are generally close slightly below VGG model**
  - Confirms that our limits based on VGG are very conservative

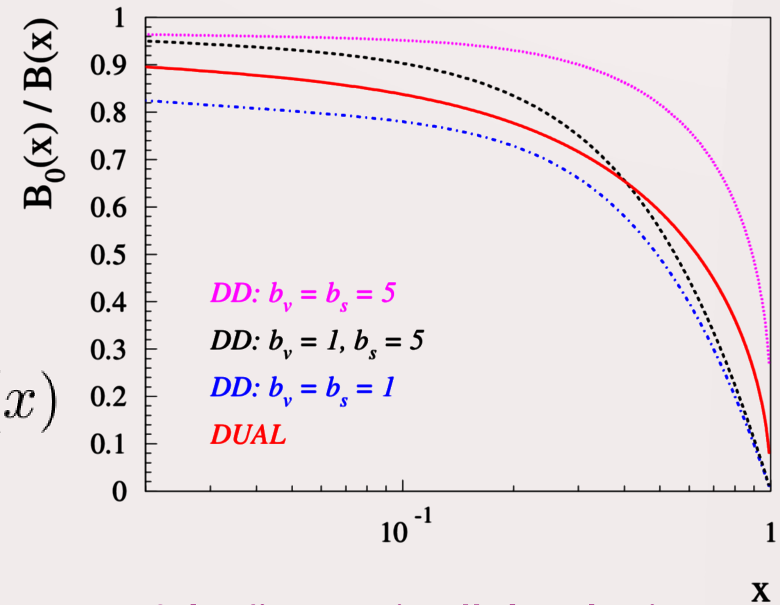


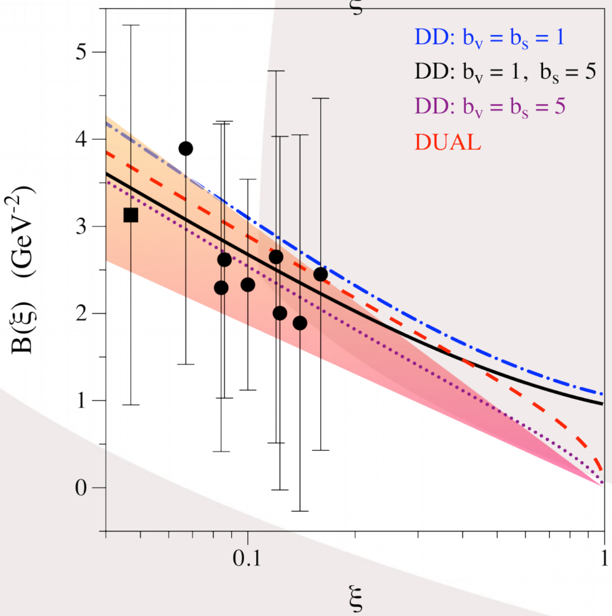
# Amplitude and Slope




$$A(\xi) \ = \ a_A(1-\xi)/\xi$$
$$B(\xi) \ = \ a_B \ln(1/\xi)$$

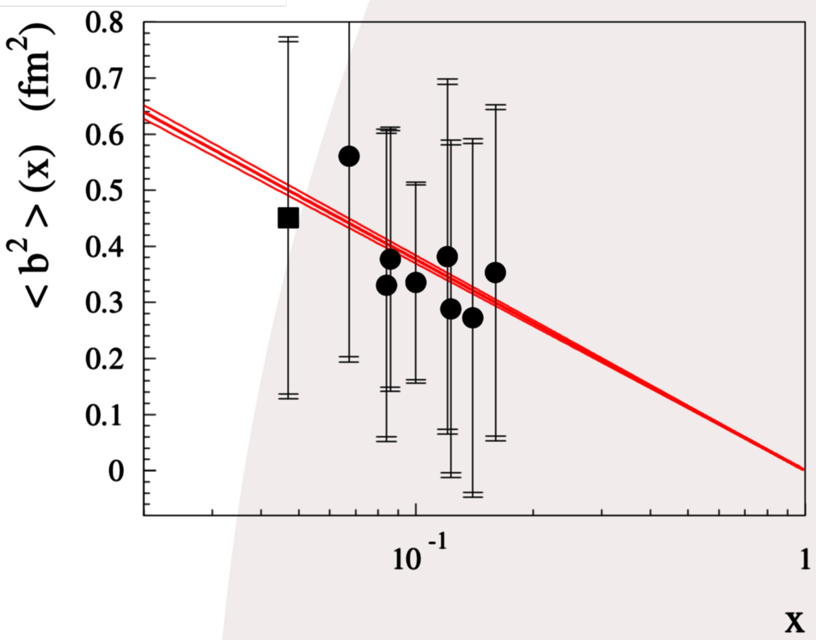
$$\langle b_\perp^2 \rangle^q(x) = 4B_0(x)$$

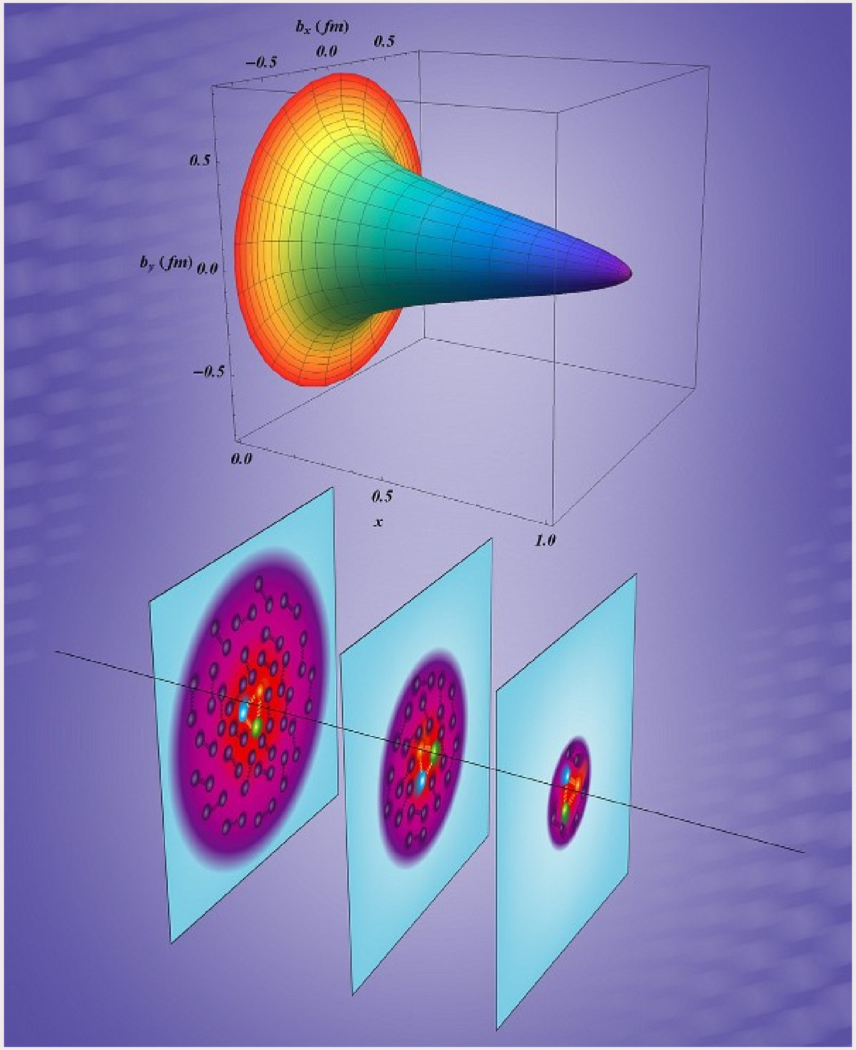



- **The A and B parameters of the fit contain all the physics**
  - They are linked to density and transverse size of the nucleon
- **Fitted using educated guess**
  - Asymptotic behavior expectations are similar to PDFs
  - In the future with larger amount of data, models can be directly tested at this level or used to perform global fits
- **The tomography of the nucleon**
  - We are not there yet! We need a ξ dependent correction to go from the singlet to the non-singlet distribution
  - We note that at low *x* the correction is small and similarly described by several models

# Proton Tomography



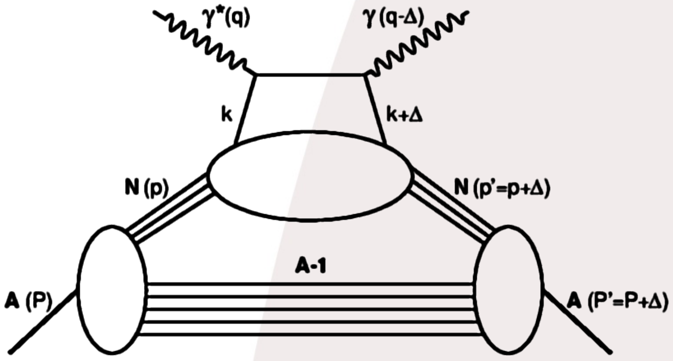



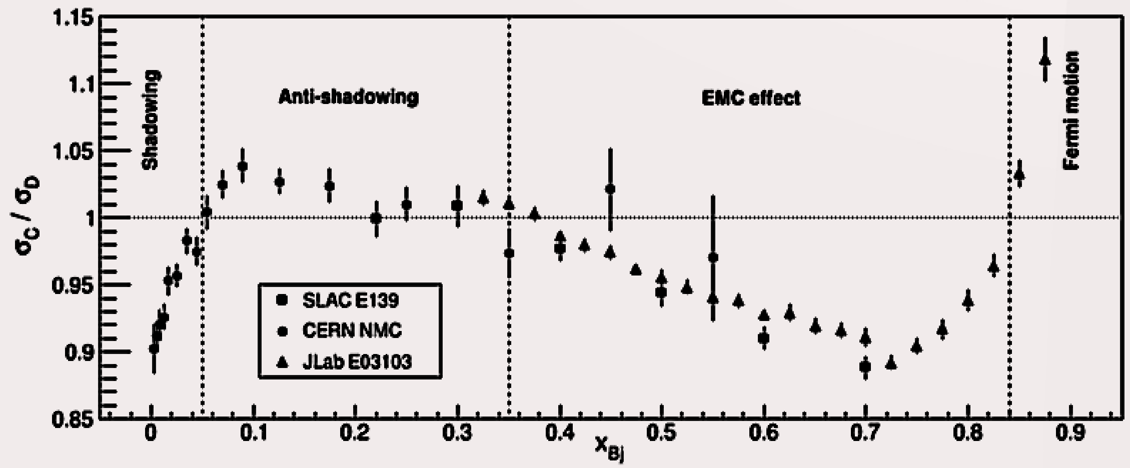

- **We then obtain the tomography of the proton**
  - Represented is the mean square charge radius of the proton for slices of *x*
  - Error bars reflect the unknown CFFs
    - To flatten this distribution, one would need a non constrained CFF with very strong opposite behavior

- **We observe the nucleon size shrinking with *x***

*RD, M. Guidal and M. Vanderhaeghen arXiv:1606.07821*

# Nuclear GPDs

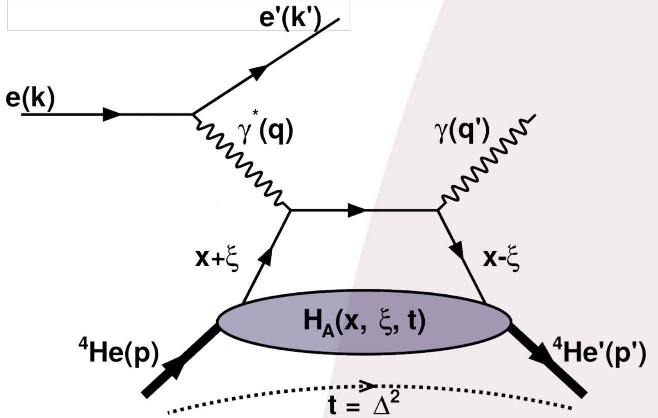


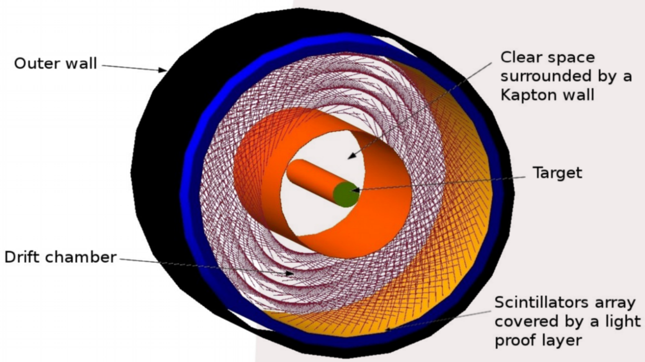



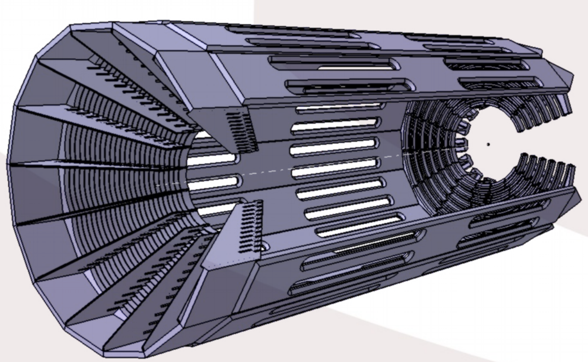

- **New view on nuclear effects**
  - GPDs offer a completely new point of view to understand the partonic structure of nuclei
- **Experimental access to completely new nuclear physics**
  - Non nucleonic degrees of freedom of the nuclei
  - Measurement of the pressure and forces in the nuclei
  - The EMC effect remain today a mystery, hadron tomography can help localize it in the nuclei

    *R.D. & S. Scopetta Eur.Phys.J. A52 (2016) no.6, 159*
- **Nuclei allow to play with the spin**
  - The use of helium 4 greatly simplifies the problem with only 1 GPD
    - The measurement of Beam Spin Asymmetry is enough to describe this nuclei
  - Use of helium 3 and deuterium can help to  understand the neutron and explore more complex spin dynamics in hadrons

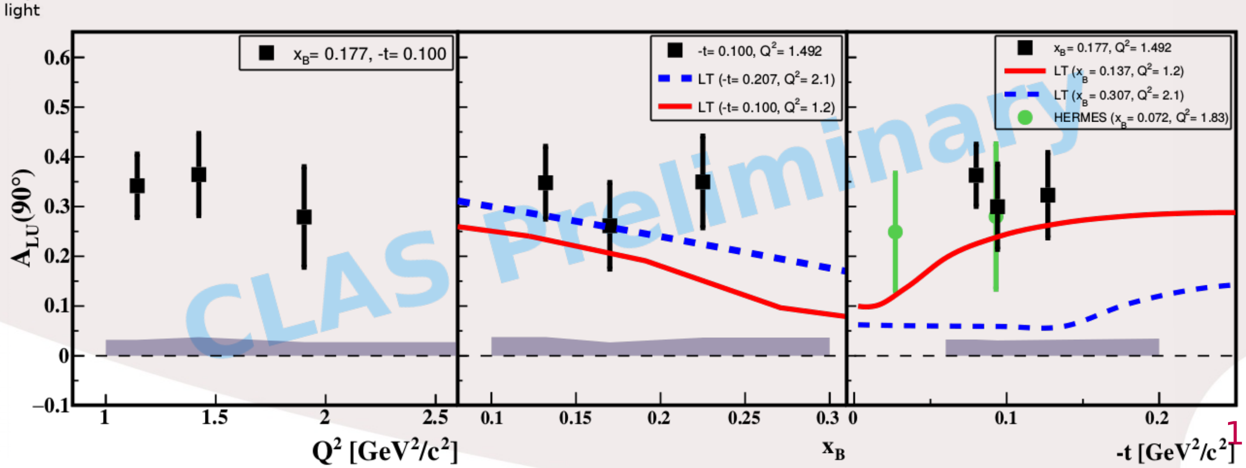
# DVCS on Nuclei



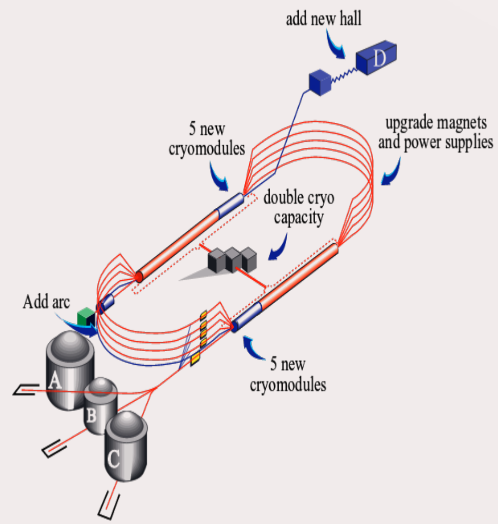



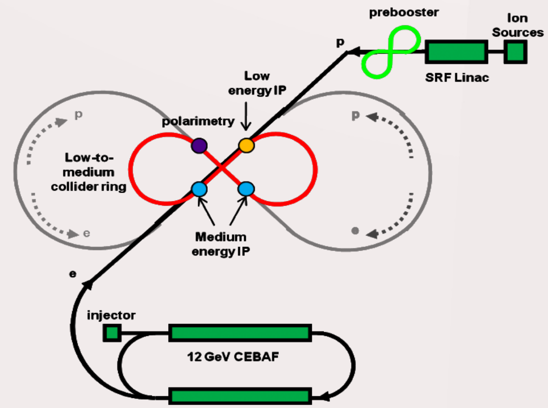
- **Already measured at JLab (CLAS)**
  - Coherent DVCS is cleanly measurable
    - Thanks to a low energy recoil detector (TPC)
  - Asymmetries are much larger than for the proton
    - Beam spin asymmetries of ~35%
  - Easy extraction of the H CFF directly from data
    - No model assumptions needed
- **The start of a new domain for GPD studies**
  - Already several studies on the theory side
    - In both valence and low x regions
- **Perspectives**
  - At 12 GeV, the higher $Q^2$ will make the situation much better on the theoretical side
  - More data can be taken in CLAS12 using the ALERT recoil detector
  - Approved by the JLab PAC in 2017

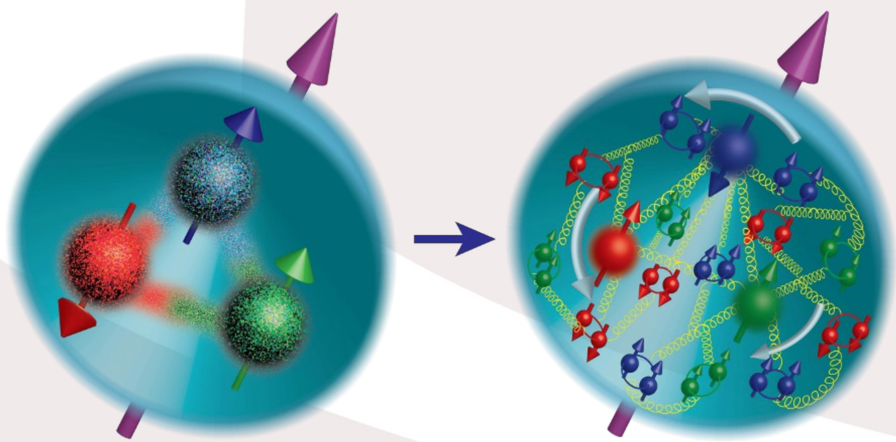


# Summary

- **In fifteen years of experiments at JLab, we have accumulated a wide array of data**
  - DVCS in particular can be interpreted in term of GPDs directly
  - DVMP appears more complicated but opens perspectives on transverse GPDs and gluon GPDs
- **We can now extract the tomography of the nucleon from these data**
  - Errors can be reduced by including more observables
    - Cross-sections, beam spin asymmetries, target asymmetries..
    - Transverse target, positron beam
  - Already the *x* dependence of the charge radius is visible



- **This will be completed in the near future**
  - In the sea region by COMPASS
  - In the valence region by JLab 12
  - We can go beyond in the sea region at an EIC
    - How wide the proton will get at low x?
- **What can we do to improve our picture?**
  - Measure many processes and observables
    - Double DVCS, Time-like CS…
    - Neutron DVCS, charge asymmetries, transverse polarized target…
- **This framework can be used to understand more complex hadron**
  - GPDs have also a word to say about the long standing questions of the partonic structure of the nuclei