# Exclusive Processes and GPDs at JLab


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# Generalized Parton Distributions

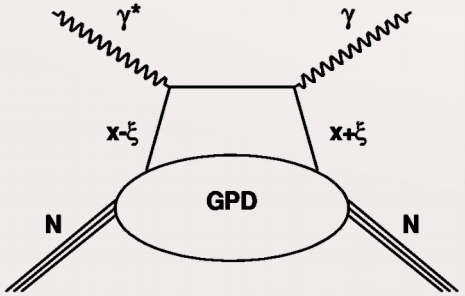
- **GPDs encode the non perturbative structure of the nucleon**

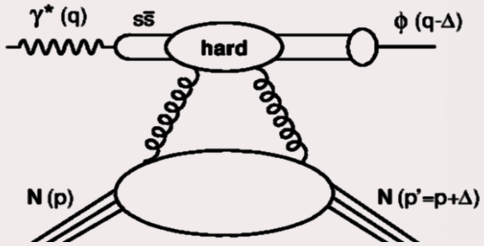
  D. Müller et al. Fortsch.Phys. 42 (1994) 101, X.-D. Ji Phys.Rev.Lett. 78 (1997) 610,

  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*



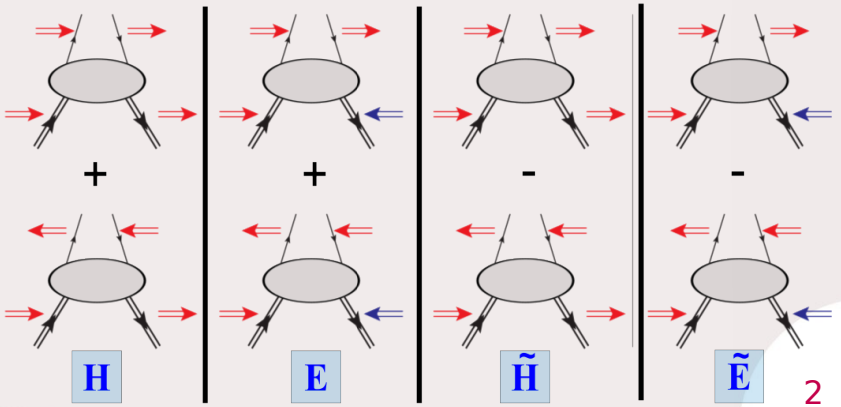

- **They can be extracted from exclusive processes**
  - Factorization has been demonstrated
  - But these processes have small cross sections
  - Deep Virtual Meson Production (DVMP)
    - Possible with many final states but with more theoretical issues
  - Deep Virtual Compton Scattering (DVCS)
    - Simplest process that interfere with Bethe-Heitler to give larger cross sections and spin asymmetries

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

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

- **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

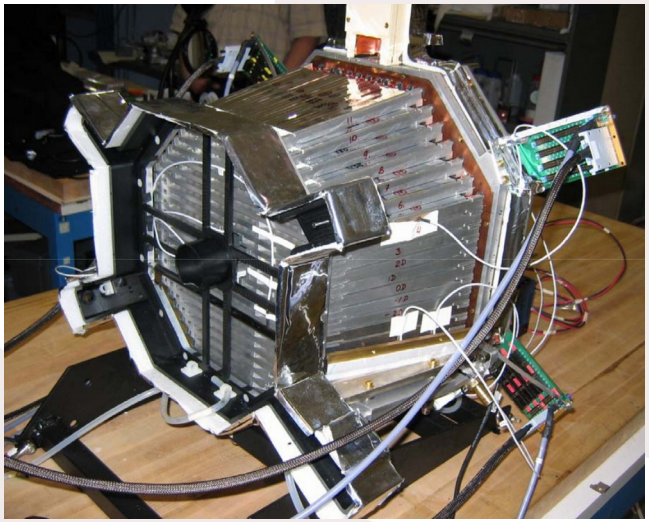
    *A. Belitsky et al. Nucl.Phys. B629 (2002) 323-392*

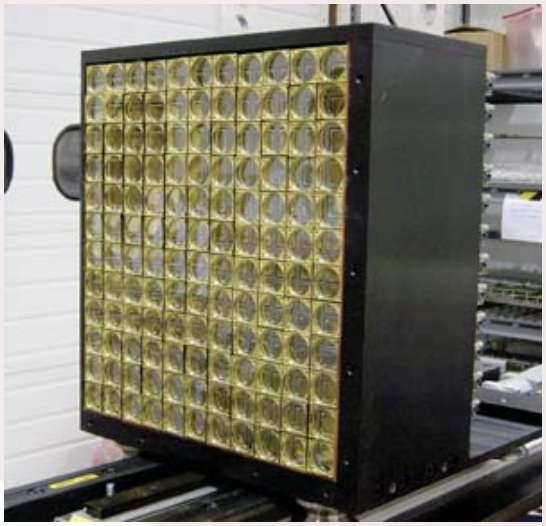


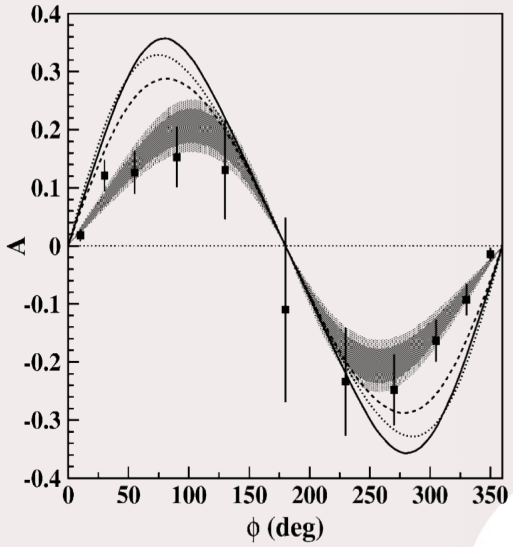
# First Measurement at JLab

- **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

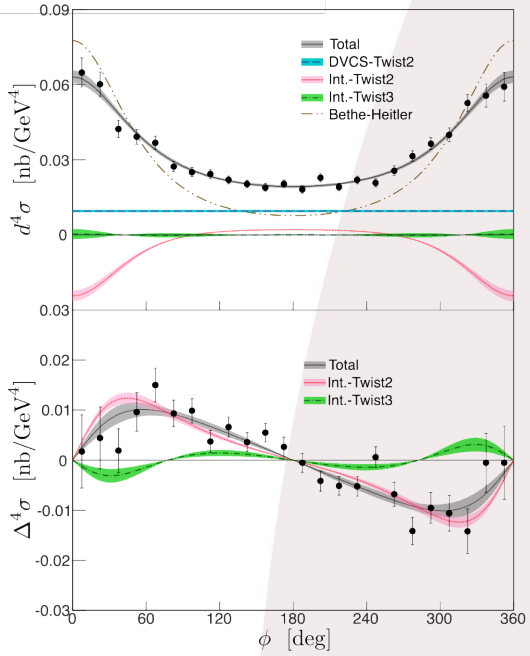
    *S. Stepanyan et al. (CLAS Coll.) PRL 87, 182002 (2001)*
- **Triggered important experimental efforts**
  - Construction of dedicated calorimeters for Hall A and B (CLAS)
  - Start of a large program to measure spin asymmetries and cross sections in both Hall-A and Hall-B (CLAS Coll.)







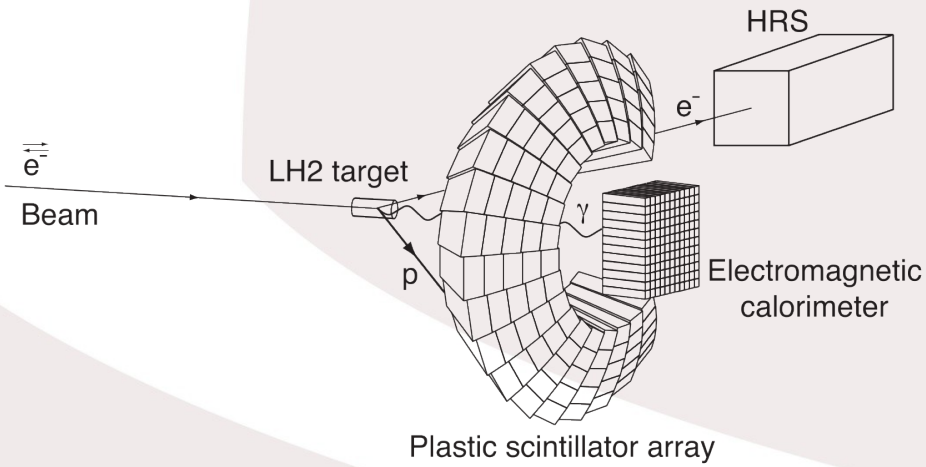
# DVCS in Hall A

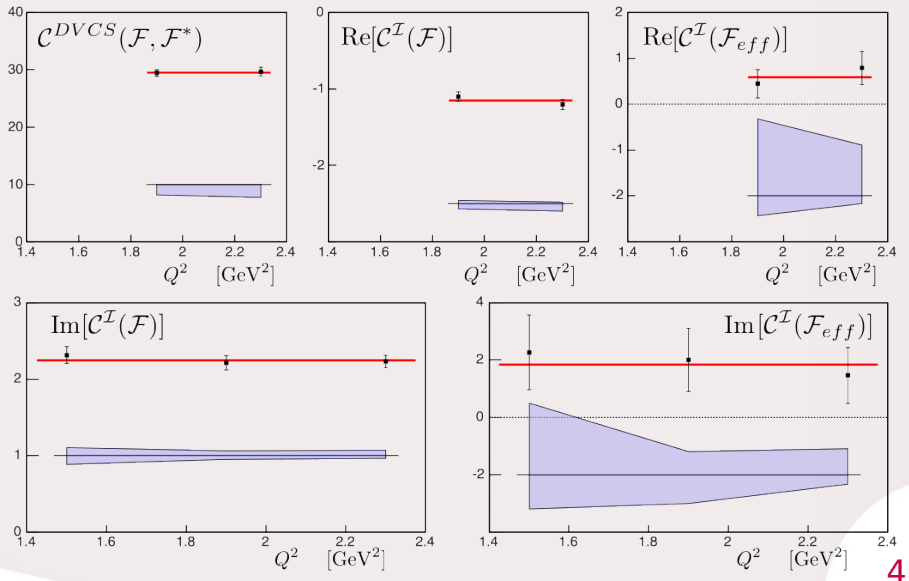



- **First measurement of absolute cross sections of DVCS**
  - Provided very high precision data in few bins

    *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*



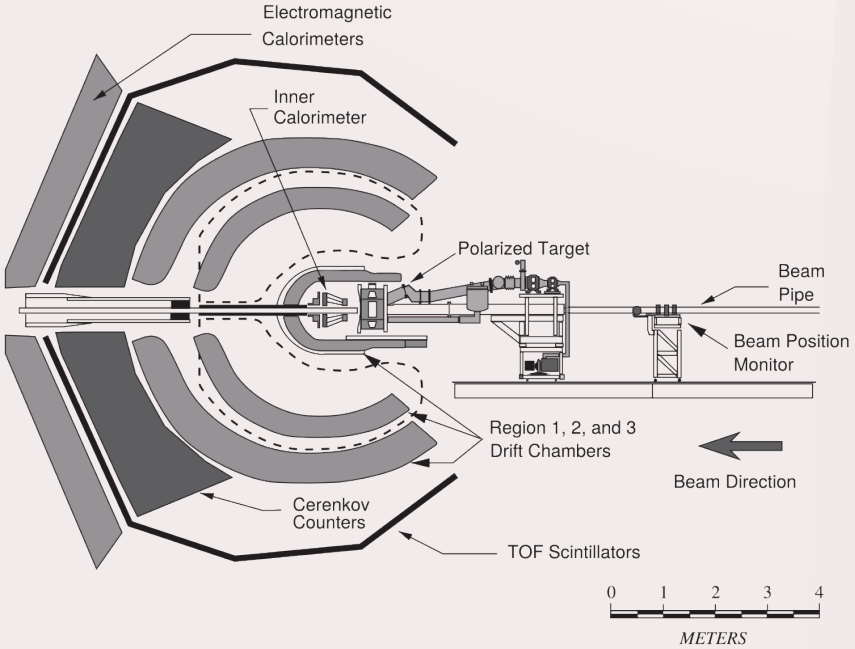
# DVCS in CLAS

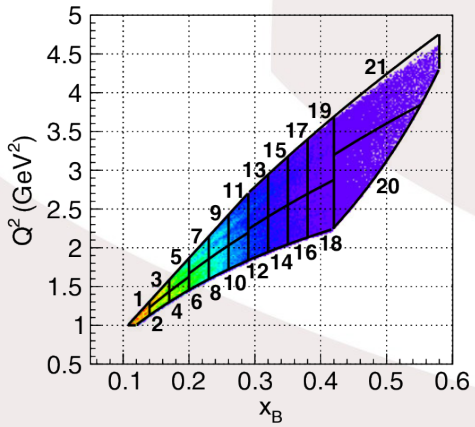
- **CLAS Published first Beam Spin Asymmetries**
  - Covers a much larger phase space

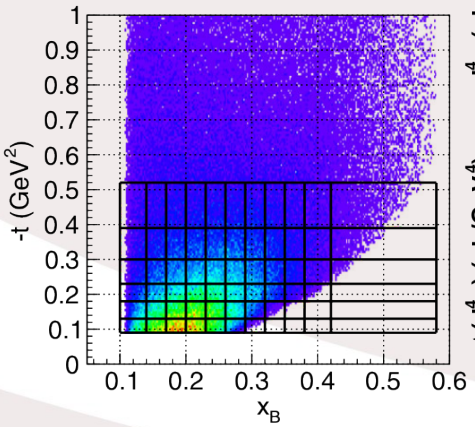
    *F.X. Girod et al (CLAS Coll.) Phys.Rev.Lett. 100 (2008) 162002*

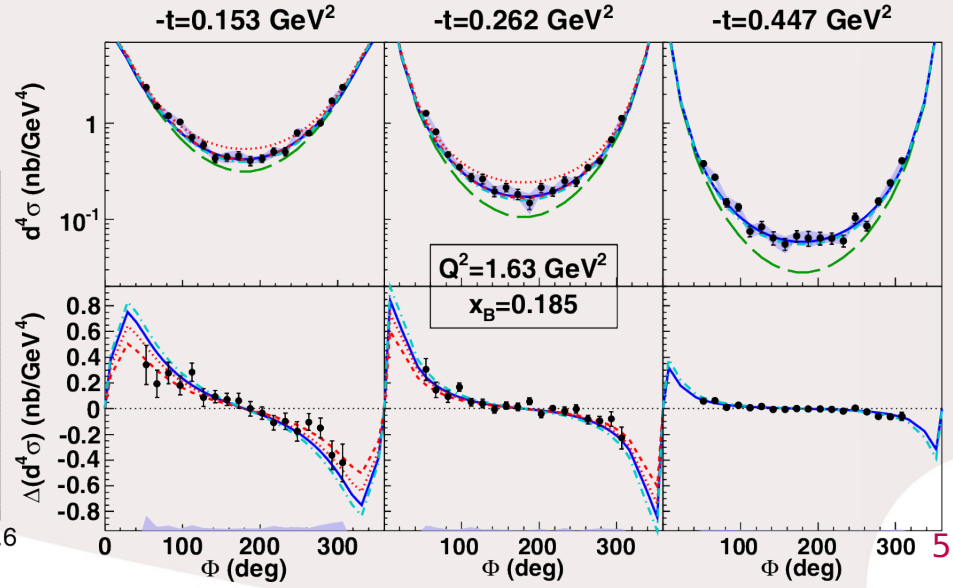
- **Now cross sections are also available**
  - Should allow the extraction of Im(H)
  - Amount of data reached the critical limit for extraction of proton tomography

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

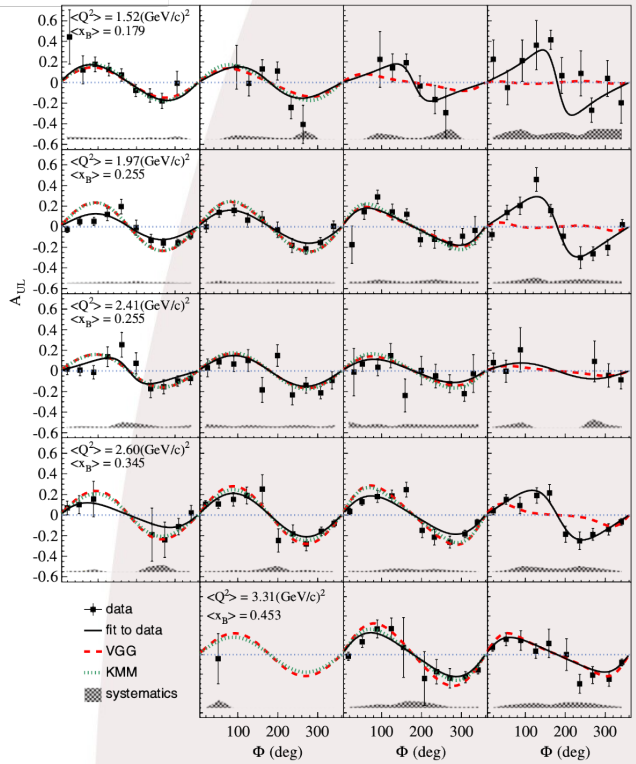


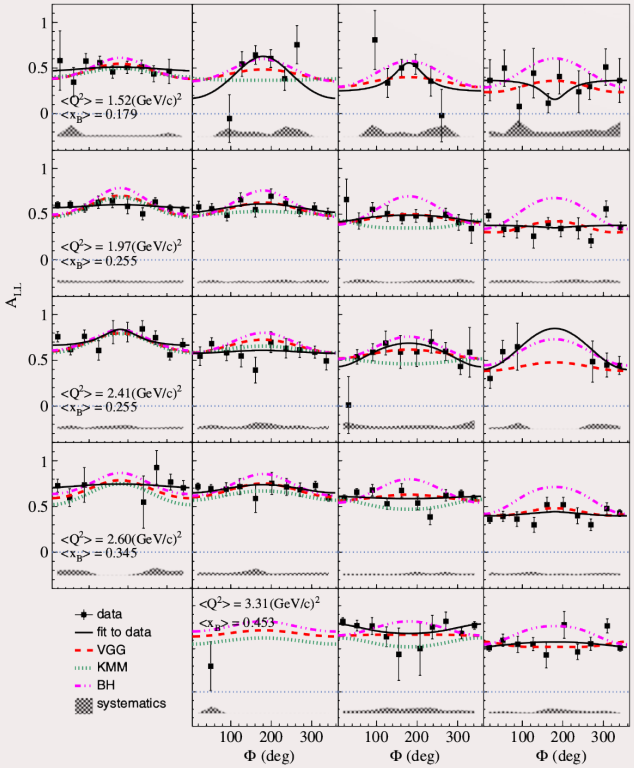



# DVCS in CLAS



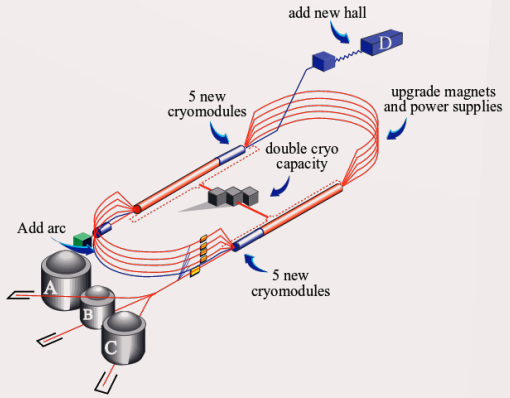

- **CLAS also measured DVCS on a longitudinally polarized target**
  - Measurement of the longitudinal Target Spin asymmetries (lTSA) and Double Spin Asymmetries (DSA)
  - Should give an insight into other CFFs → Im($\hat{H}$)
  - Reduce the number of unconstrained CFFs

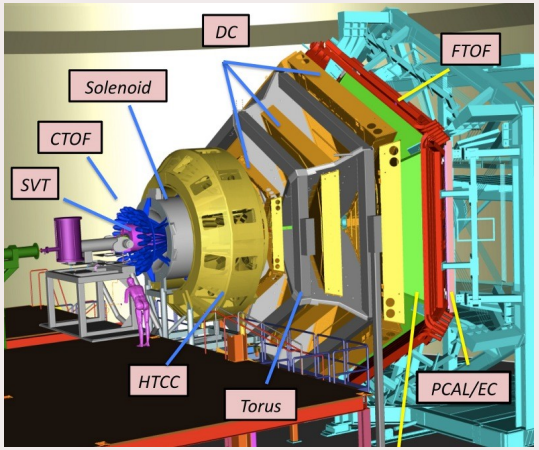
*S. Pisano et al. (CLAS Coll.) Phys.Rev.D 91 (2015) 052014*

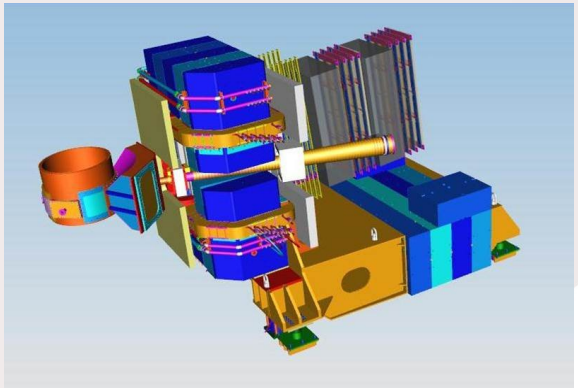
*E. Seder et al. (CLAS Coll.) Phys.Rev.Lett. 114 (2015) 032001*

# DVCS in JLab 12

- **This program is still on going**
  - Many proposals approved at JLab 12 GeV
- **Hall A**
  - An experiment is ongoing right now to cover a wide $Q^2$ range
  - To perform a Rosenbluth like extraction of the different contributions to the DVCS cross section
- **Hall B / CLAS12**
  - Experiments are approved to run on unpolarized proton target as well as longitudinally polarized target
  - High precision is expected over a very large phase space with the goal to extract a 3D map of the proton
    - Should provide data in higher $Q^2$ reducing possible higher twist contributions
  - Beam energy scan in CLAS now approved to obtain similar Rosenbluth extraction as Hall-A
  - Transversely polarized target measurement is also planned
    - Contingent to the HD Ice target
- **Hall A program to be extended in the Hall C**
  - $Q^2$ scan will be extended in Hall C



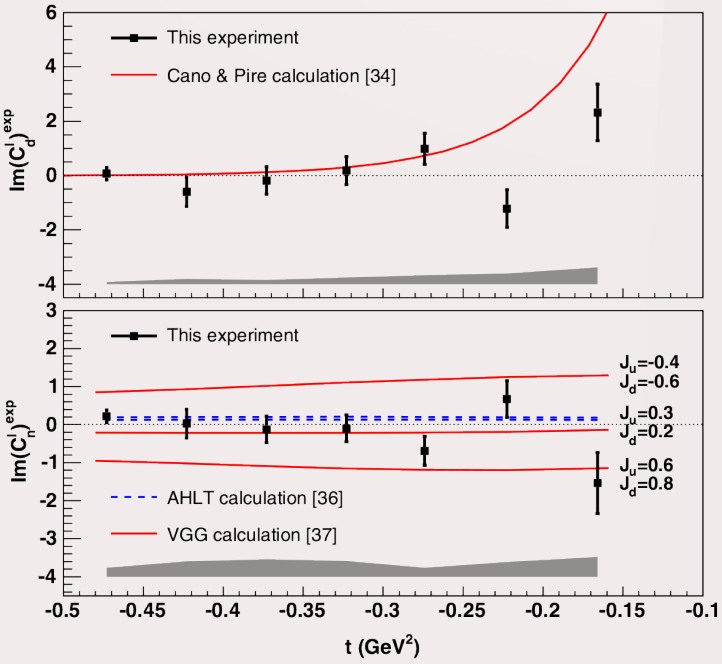



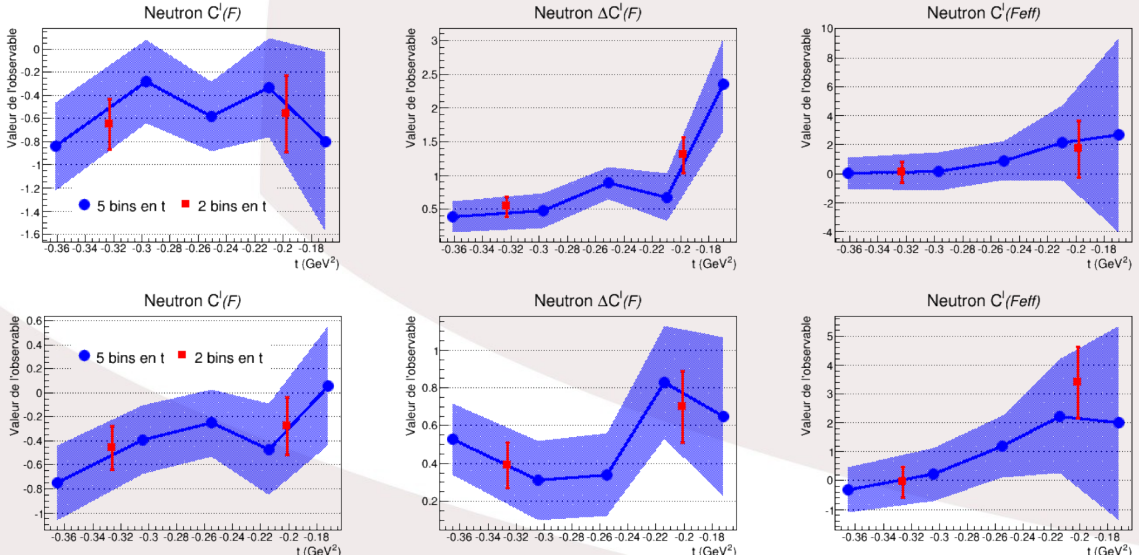



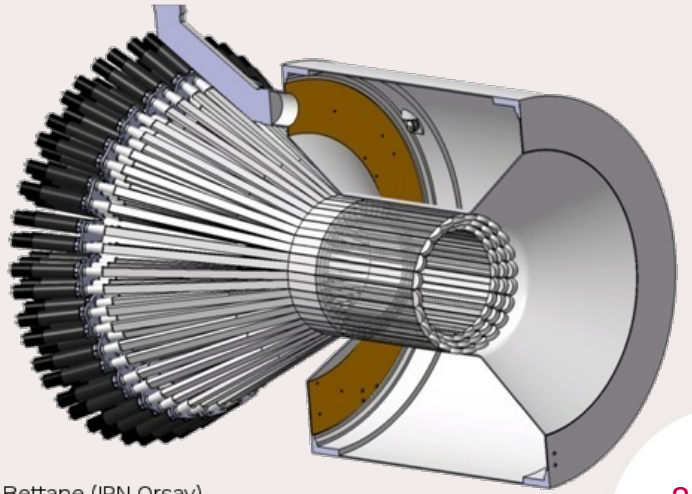
# Neutron DVCS

- **Why the neutron?**
  - Gives access to flavor decomposition of the GPDs
  - GPD H is suppressed giving a better access to the GPD E
    - Important GPD for the Ji sum rule
- **Hall A results**
  - Measurement was performed by subtracting proton to the deuterium
  - Asymmetries are found to be in line with expectations
  - But they are small and the subtraction is tricky

    *M. Mazouz et al. Phys.Rev.Lett. 99 (2007) 242501 / C. Desnault PhD Thesis*
- **CLAS12 perspectives**
  - Experiment proposed to solve this issue with the use of a neutron detector



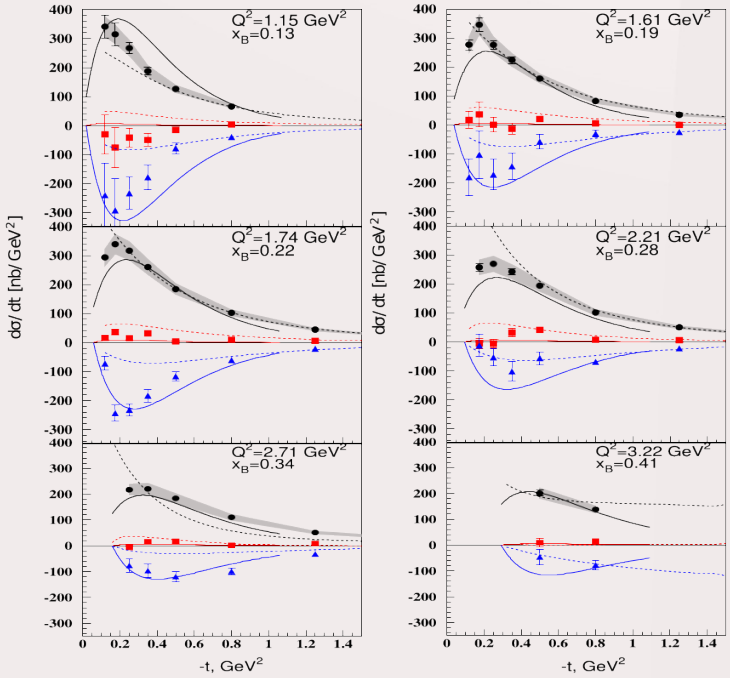
J. Bettane (IPN Orsay)

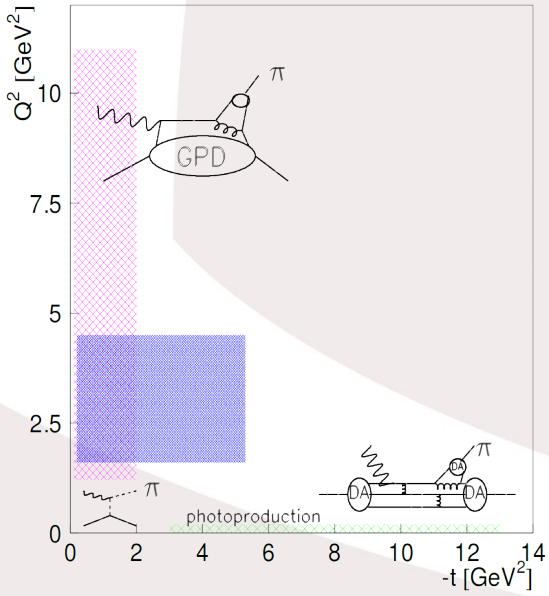
# Deep Virtual Meson Production

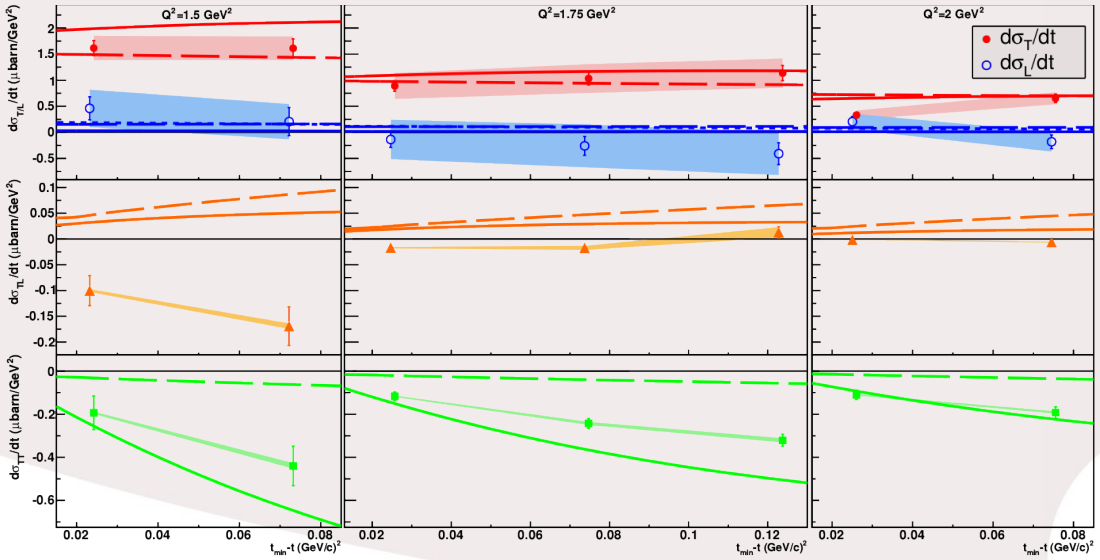
- **Exclusive $\pi^0$ production**
  - Comes for free with DVCS to which it is the main source of background
  - Dominated by its transverse component
    - Expected to give an insight into transverse GPDs

    *I. Bedlinskiy et al. (CLAS Coll.) Phys.Rev.Lett. 109 (2012) 112001, I. Bedlinskiy et al. (CLAS Coll.) Phys.Rev.C 90 (2014) 025205, M. Defurne et al. (2016) arXiv:1608.01003*
- **Other mesons**
  - $\pi^+$ production can also be interpreted in term of GPDs after subtracting contribution of single pion production

    *K. Park et al. (CLAS Coll.) Eur.Phys.J. A49 (2013) 16*
  - Several studies performed in CLAS but vector mesons appears not to be in the handbag diagram regime at JLab 6 GeV

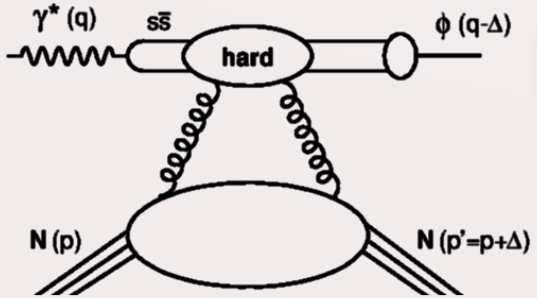


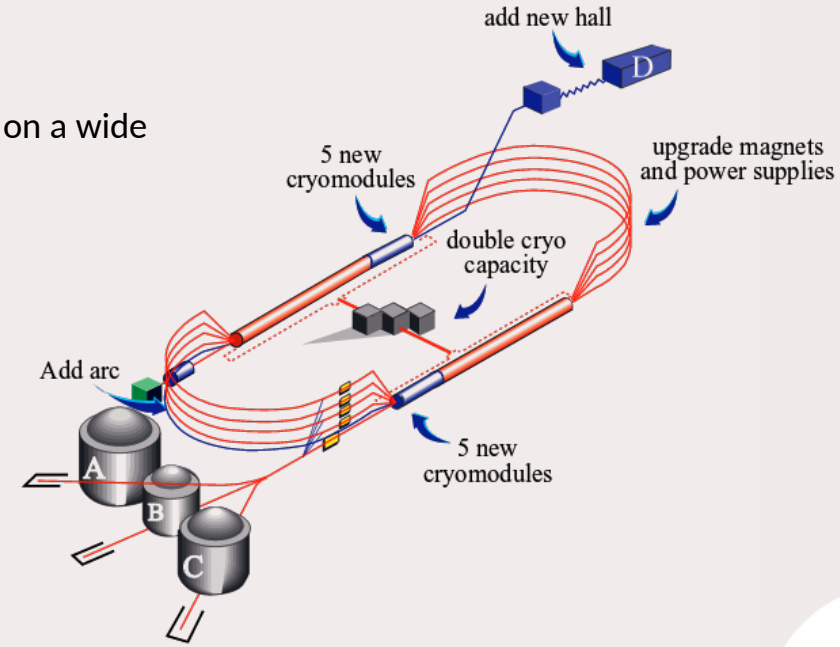



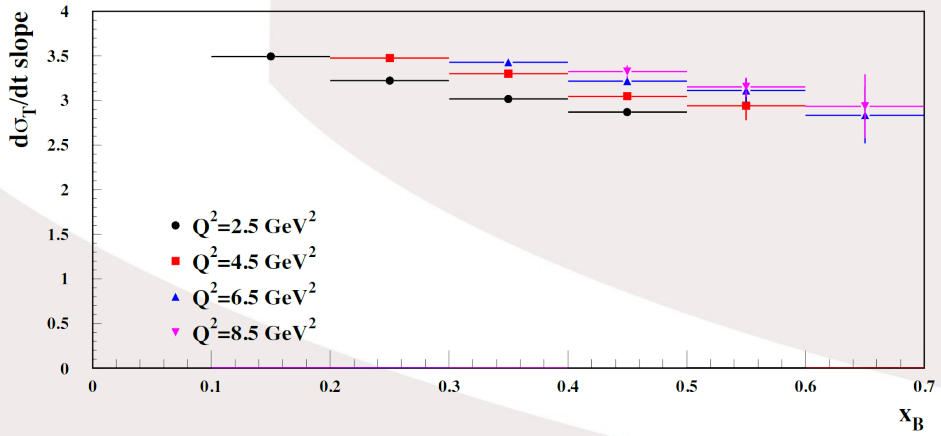
# Mesons at JLab12

- **DVMP measurements will be continued at JLab 12 GeV**
- **$\pi^0$ production is still coming for free with DVCS experiments**
  - We should be able to say something quantitative about transversity GPDs with 12 GeV data
- **Vector mesons should reach a regime where they can be interpreted in term of GPDs**
  - Will allow to control GPDs universality and help constrain CFF extraction
- **Particular interest is placed on $\phi$ production**
  - Should be sensitive to the gluon GPDs
  - We will be able to observe the gluon radius of the proton on a wide $x_B$ range in the valence region

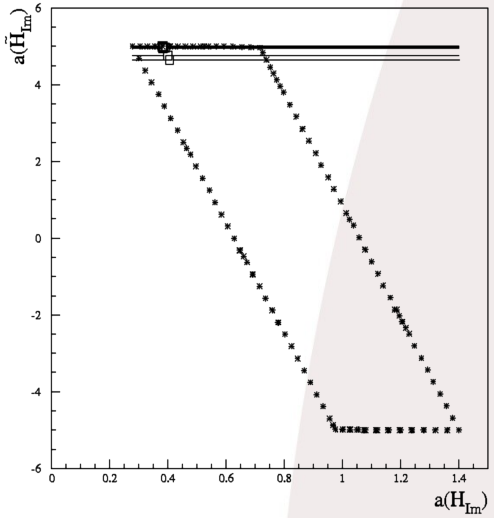


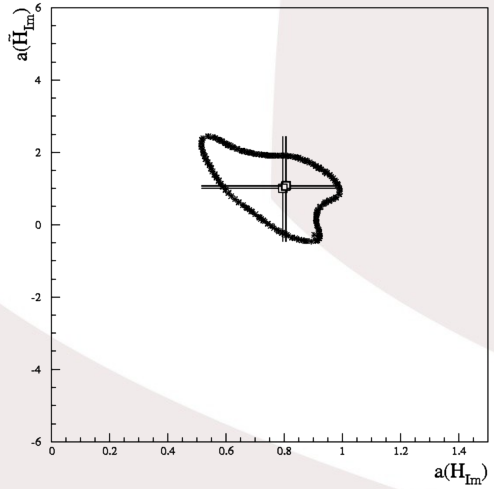




$d\sigma/dt\ (ep \rightarrow ep\phi)$



# Extracting the 3D Map



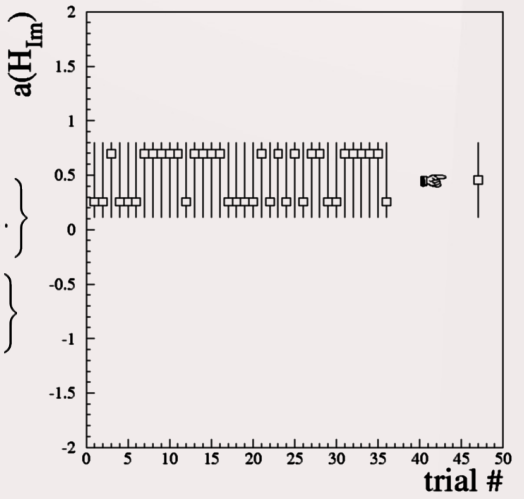




$$\Delta\sigma_{LU} \propto \sin\phi \;\; Im\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E} + ...\}$$

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

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

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



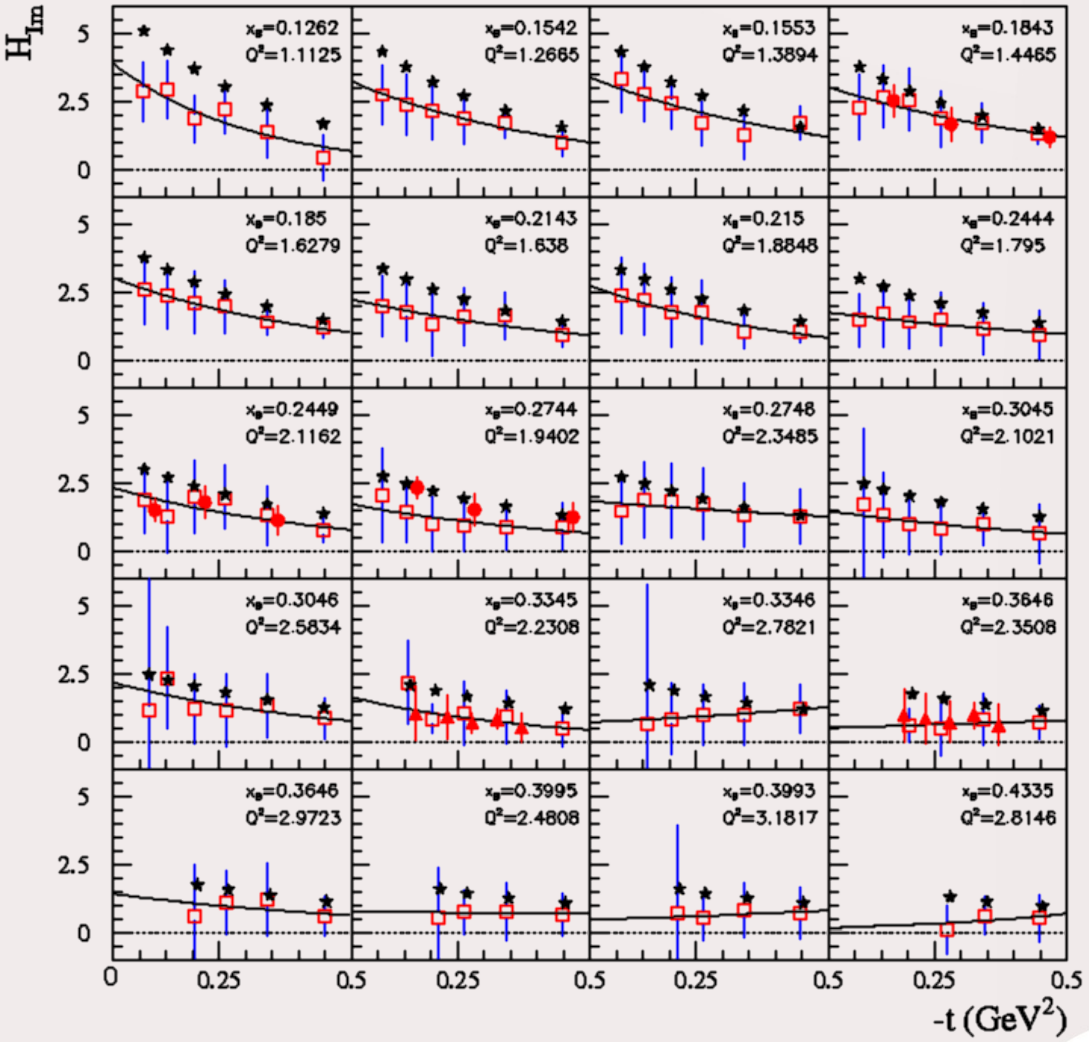

- **We performed a fit of all available data**
  - HERMES and JLab
- **With all the experimental effort the problem remains under-constrained**
  - We need some form of model input
  - Very lose bounds on the sub-leading CFF is enough
    - We use ± 5x the VGG model predictions
- **As expected adding 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)

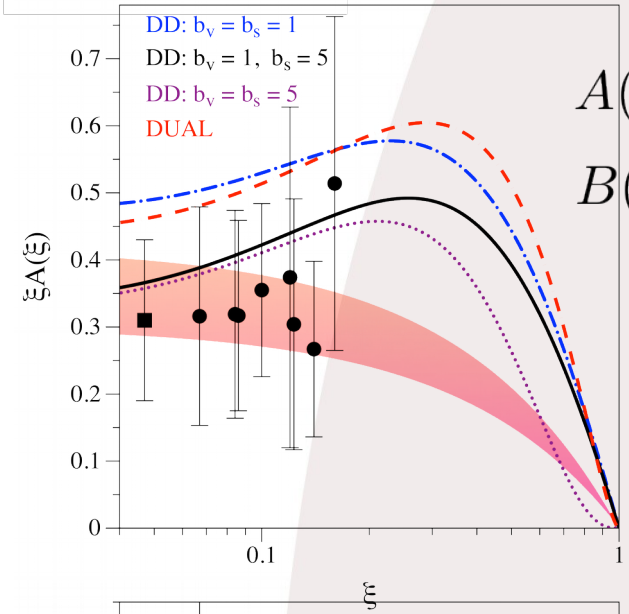
- **Applying the local fit method to all the JLab data**
  - Jlab Hall A (σ, Δσ)
  - CLAS (σ, Δσ, lTSA, DSA)
- **Gives enough coverage to explore the *t* and $x_B$ (→ ξ) dependence of Im(H)**
  - Can be fitted with an exponential form to extract the nucleon tomography

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

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



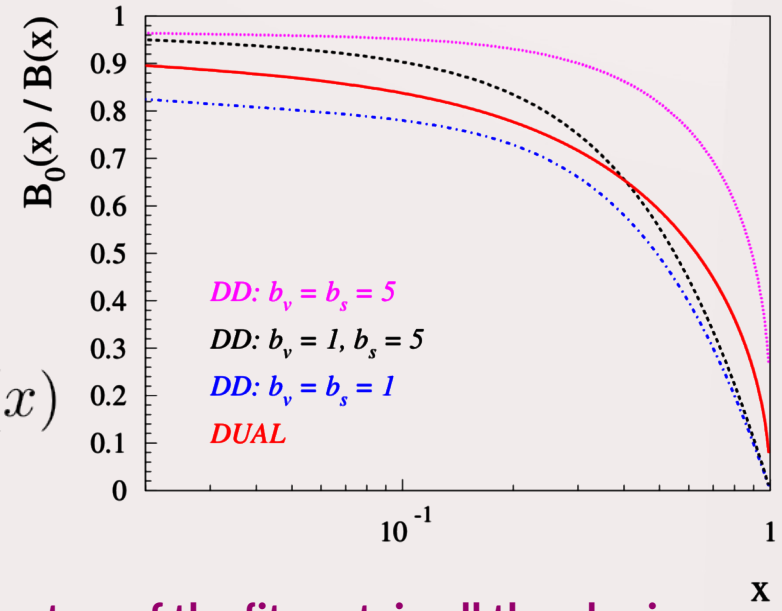
# Amplitude and Slope

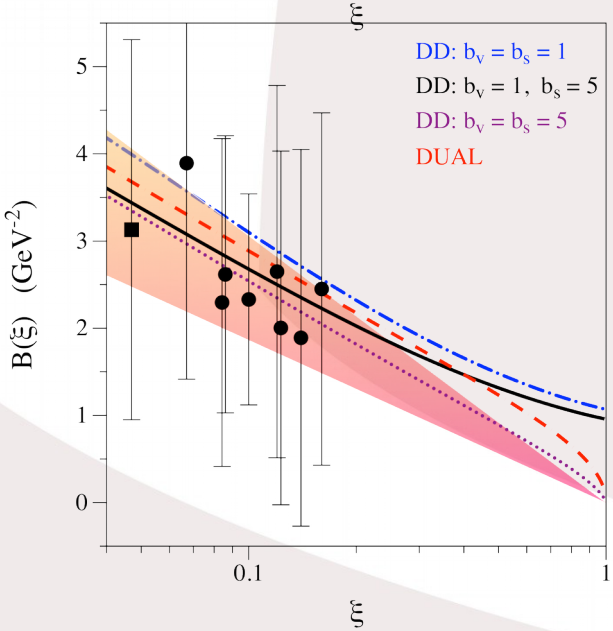



$$A(\xi) = a_A(1-\xi)/\xi$$

$$B(\xi) = a_B \ln(1/\xi)$$

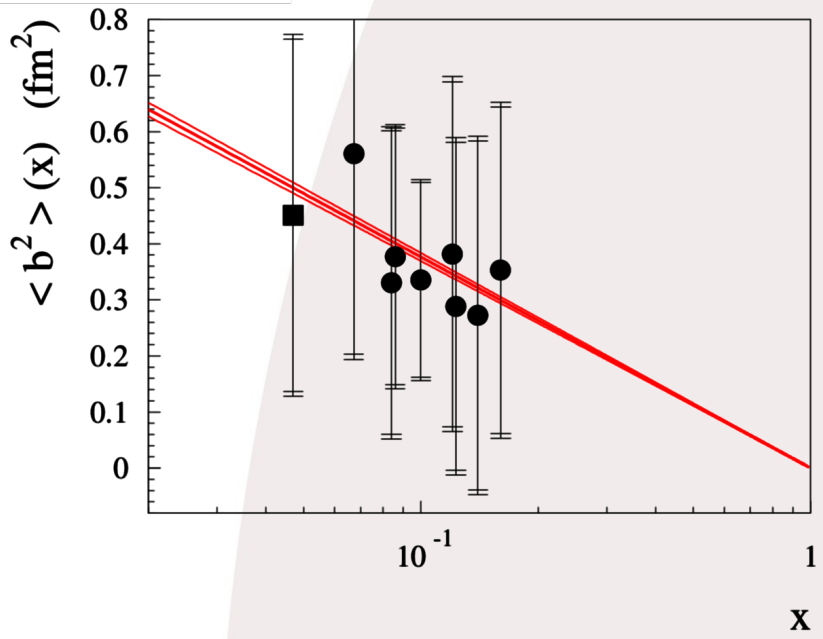
$$\langle b_\perp^2 \rangle^q(x) = 4B_0(x)$$

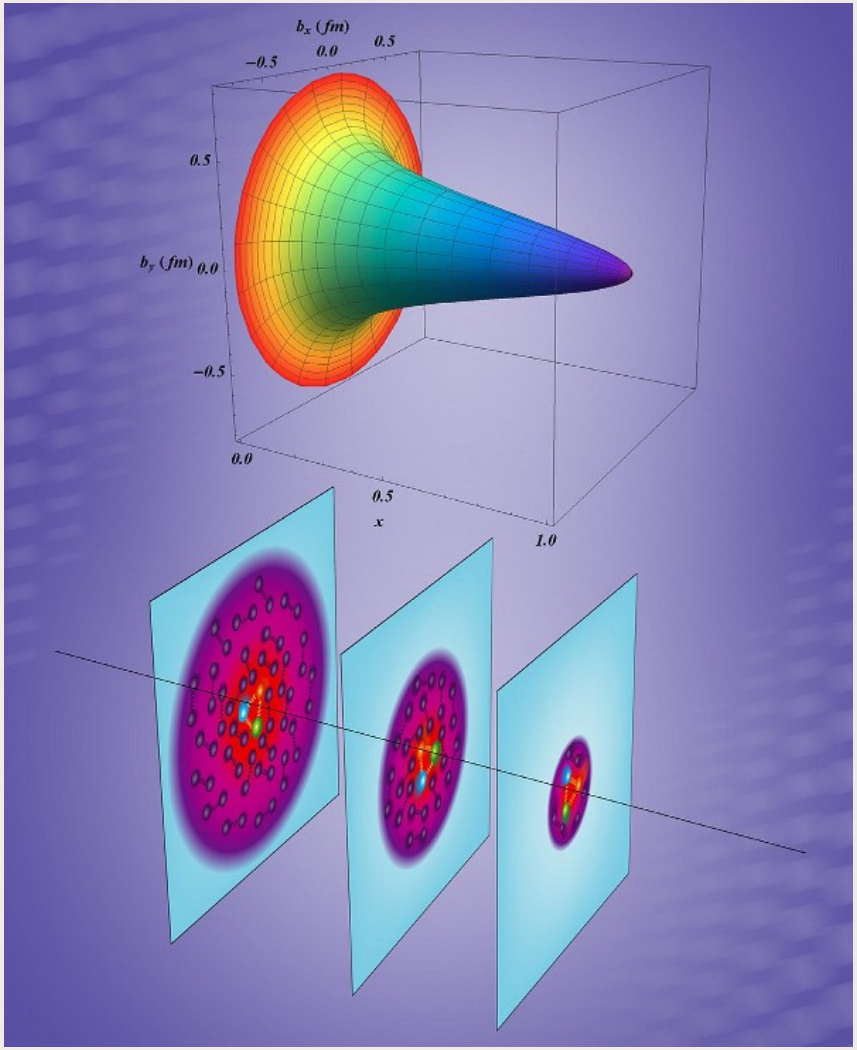



- **The A and B parameters of the fit contain all the physics**
  - They are linked to density and transverse size of the nucleon
- **Fitted using educated guess**
  - Asymptotic behavior expectations are similar to PDFs
  - In the future with larger amount of data, models can be directly tested at this 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



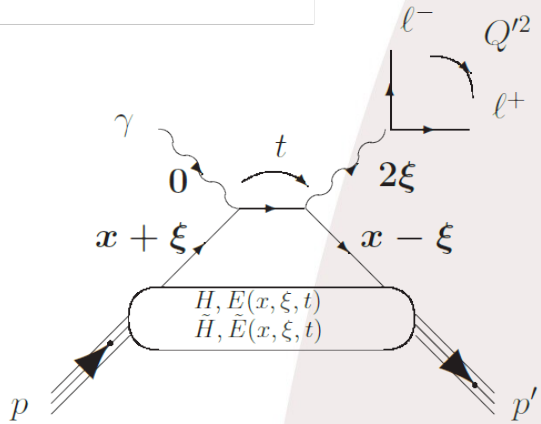



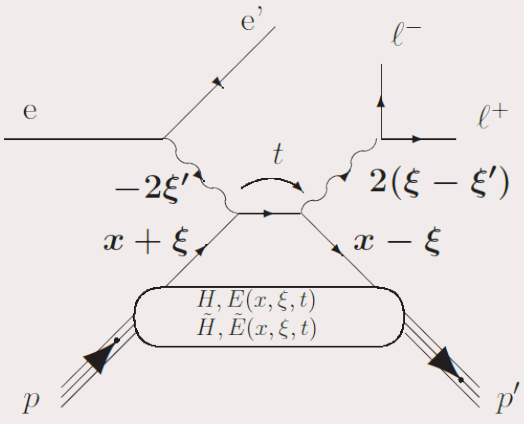

- **We then obtain the tomography of the proton**
  - Represented is the mean square charge radius of the proton for slices of *x*
  - Error bars reflect the unknown CFFs
    - To flatten this distribution, one would need a non constrained CFF with very strong opposite behavior

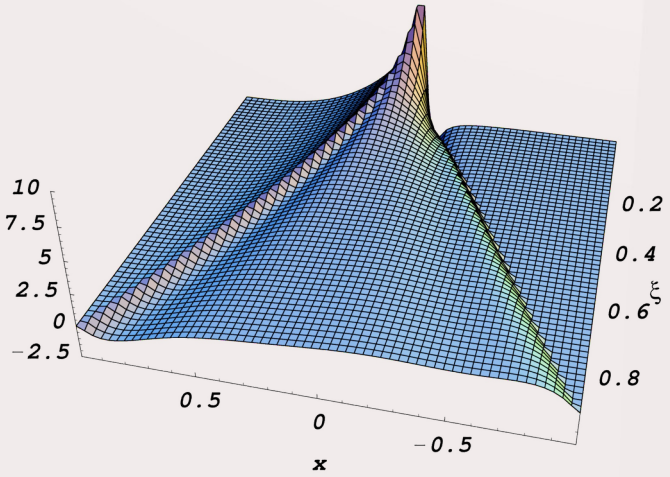
- **We observe the nucleon size shrinking with *x***

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

# Other Processes

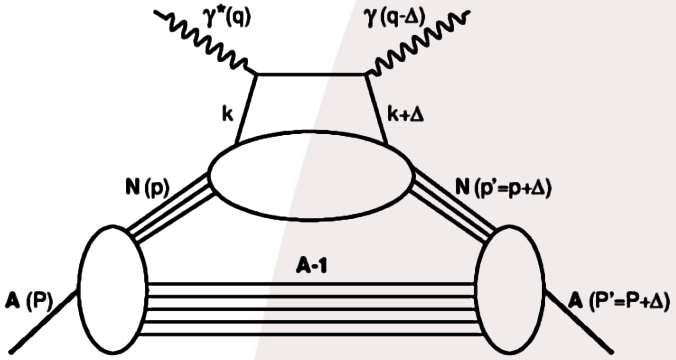


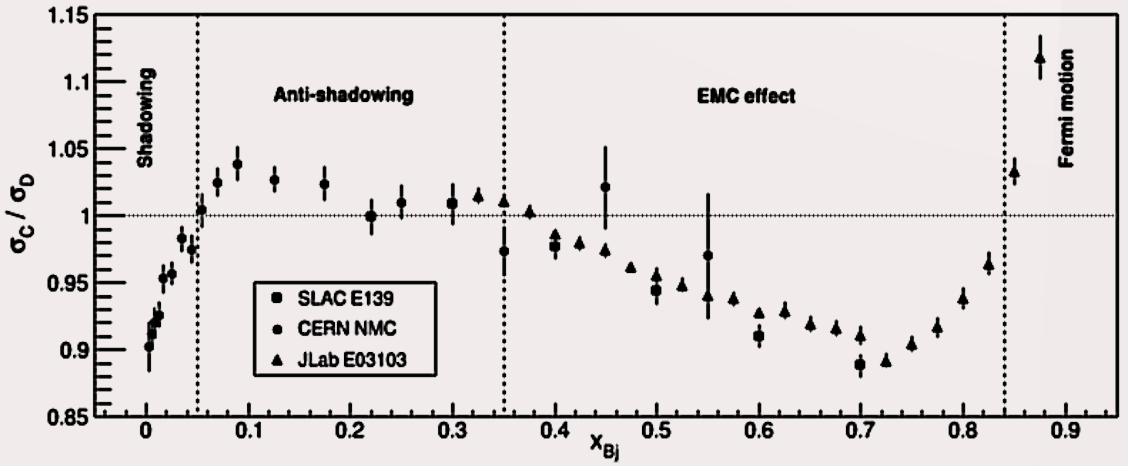




- **Time-like Compton scattering (TCS)**
  - Offers similar information as DVCS with smaller cross sections
  - Test the universality of the GPDs
  - Can experimentally facilitate the use of transversely polarized targets
- **Double DVCS**
  - Measure the off-diagonal (x ≠ ξ) value of the GPDs
  - Unique measurment to test model extrapolations in this domain
- **Impact of these measurements is still under investigation**
  - Specific TCS and DDVCS studies to come soon

# Nuclear GPDs

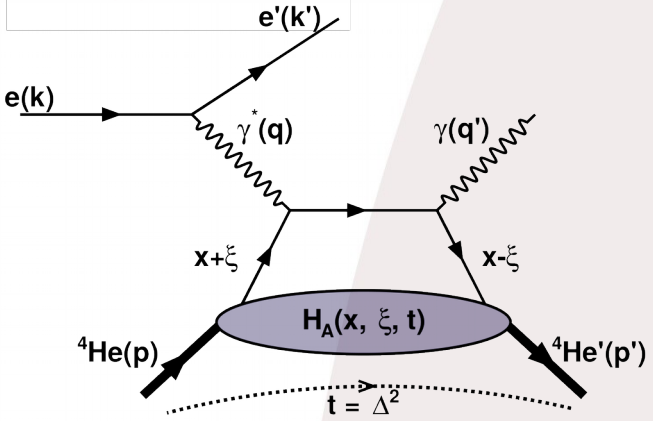


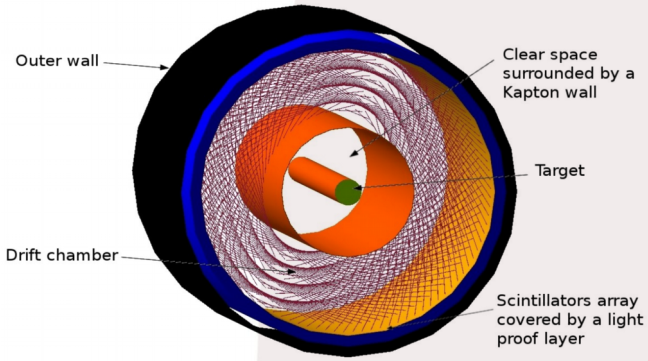



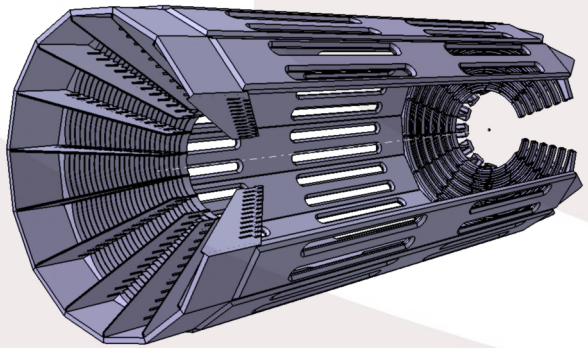

- **New view on nuclear effects**
  - GPDs offer a completely new point of view to understand the partonic structure of nuclei
- **Experimental access to completely new nuclear physics**
  - Non nucleonic degrees of freedom of the nuclei
  - Measurement of the pressure and forces in the nuclei
  - The 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

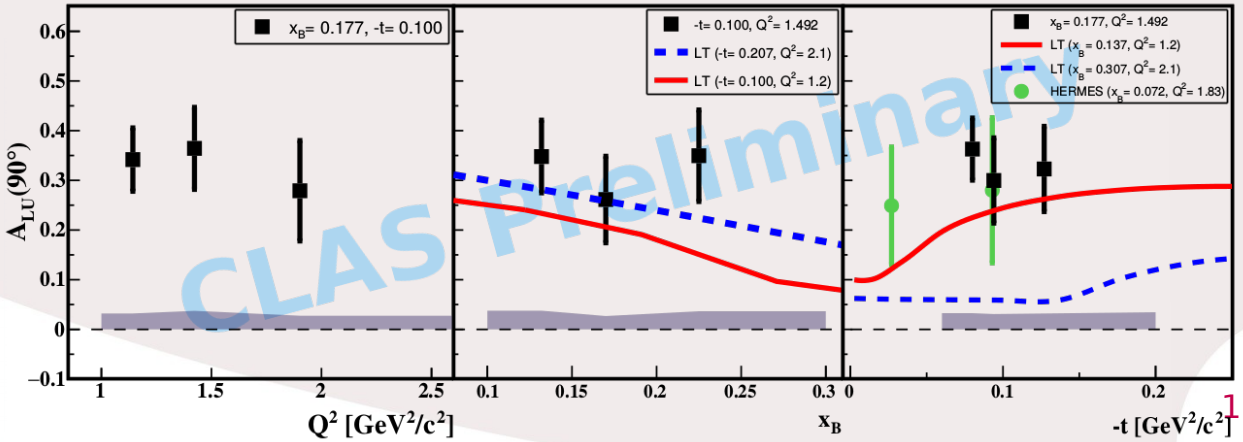
# DVCS on Nuclei



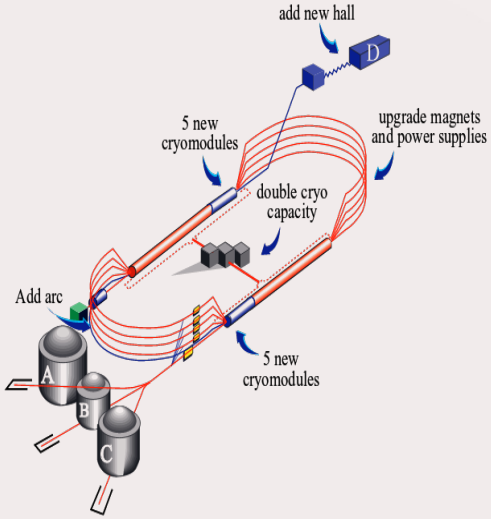



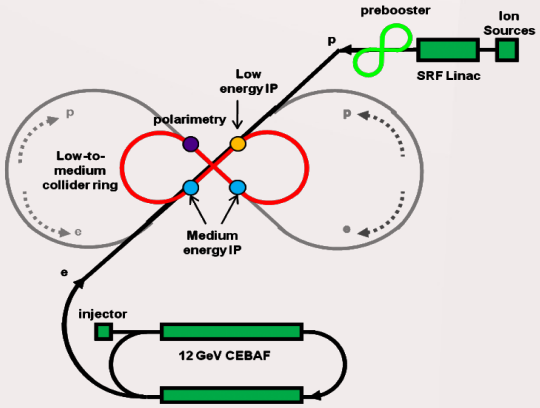
- **Already measured at JLab (CLAS)**
  - Coherent DVCS is cleanly measurable
    - Thanks to a low energy recoil detector (TPC)
  - Asymmetries are much larger than for the proton
    - Beam spin asymmetries of ~35%
  - Easy extraction of the H CFF directly from data
    - No model assumptions needed
- **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
  - JLab PAC has deferred the proposal, that will need some polishing

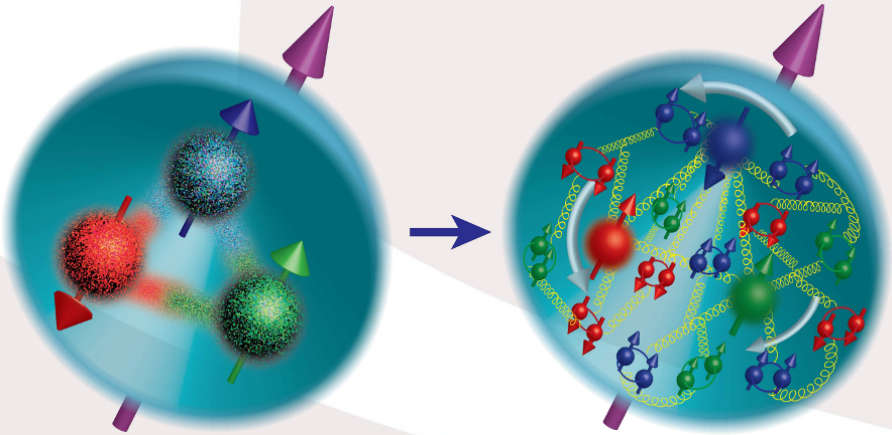


# Summary

- **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

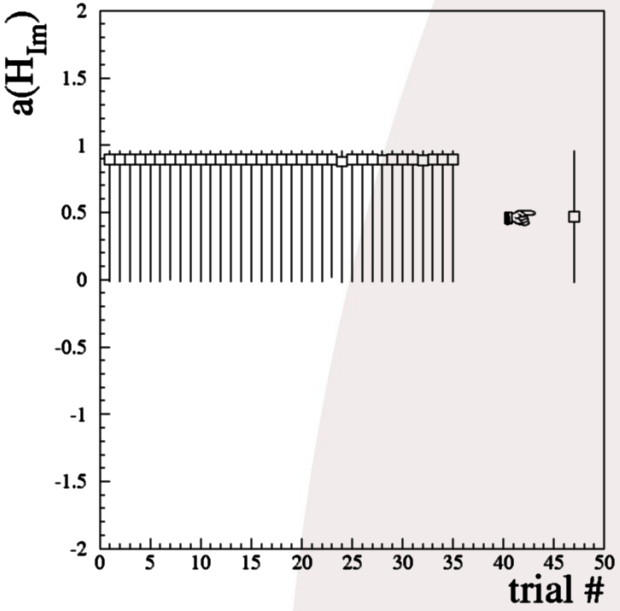


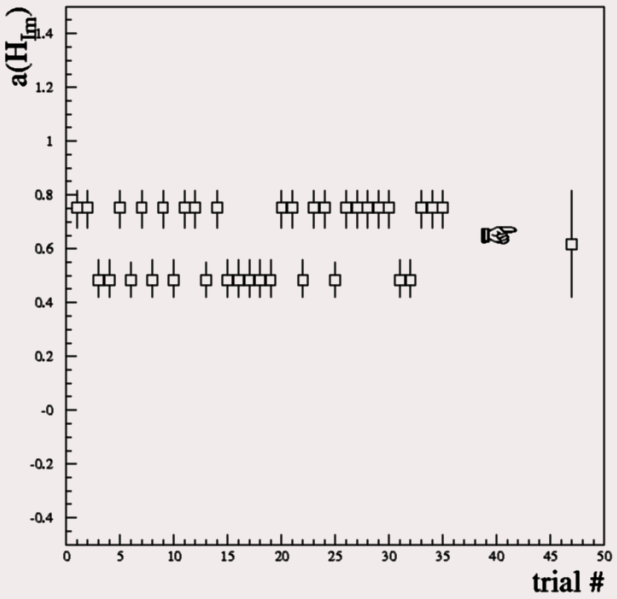



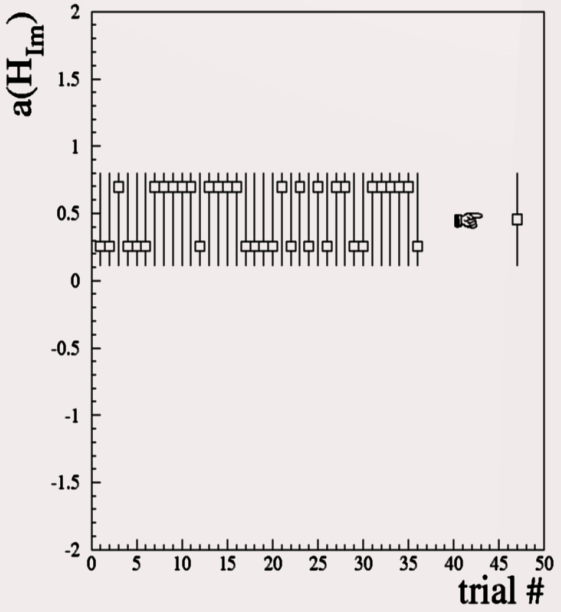



- **This will be completed in the near future**
  - In the sea region by COMPASS
  - In the valence region by JLab 12
  - We can go beyond in the sea region at an EIC
    - How wide the proton will get at low x?
- **What can we do to improve our picture?**
  - Measure many processes and observables
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

# Using central values




- **In some cases the fit gives problematic results**
  - Explored with many independent pseudo-data sets and fit starting points
  - Highly asymmetric error bars
    - Do not reflect properly the $\chi^2$ profile
    - They are due to very flat $\chi^2$ valley
  - Double solutions
  - Both these features are highly problematic for the coming global fit, which solution to use ?
- **We found that the central value of the error bars works best**
  - This is natural since subleading CFFs are in fact not constrained and the minimum $\chi^2$ in their range is most of the time not significant
  - It was confirmed by simulation that central values give better results