# From DVCS measurements to the tomography of the nucleon and the nucleus.

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# Generalized Parton Distributions

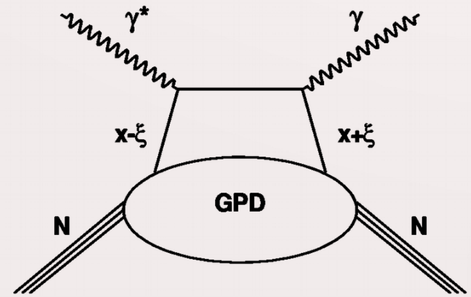
- **GPDs encode the non perturbative structure of the nucleon**

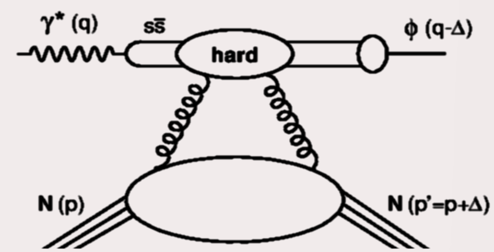
  D. Müller et al. Fortsch.Phys. 42 (1994) 101, X.-D. Ji Phys.Rev.Lett. 78 (1997) 610,

  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*



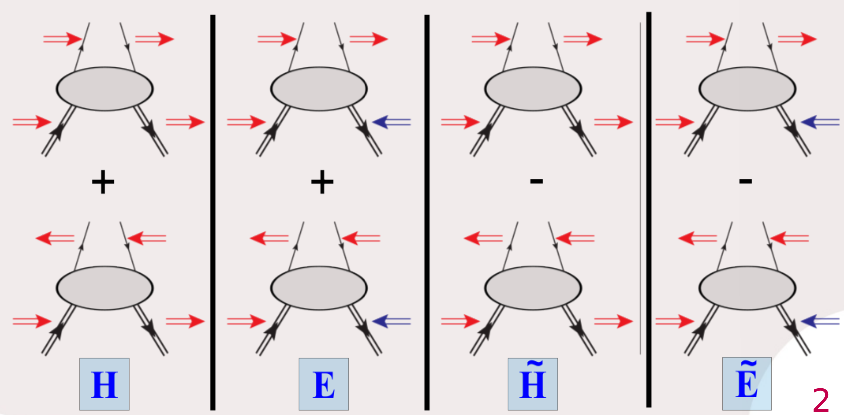

- **GPDs can be extracted from exclusive processes**
  - Factorization has been demonstrated
  - However, these processes have small cross sections
  - Deep Virtual Compton Scattering (DVCS)
    - Simplest process that interfere with Bethe-Heitler to give larger cross sections and spin asymmetries
 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

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

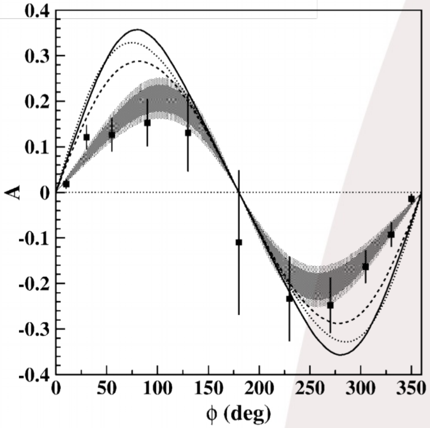
$$F_{Im}(\xi,t) = F(\xi,\xi,t) \mp F(-\xi,\xi,t).$$

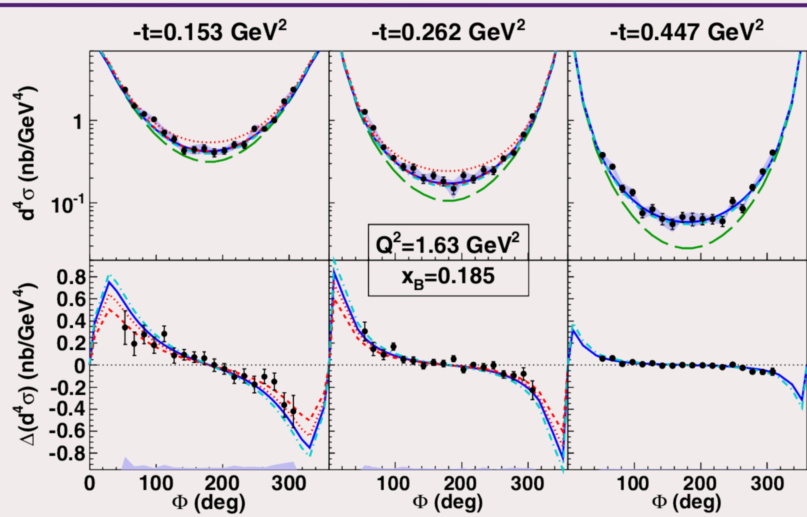
- **These exclusive processes only give access to CFFs**
  - The 4 complex CFFs intervene as 8 free parameters used to measure the original GPDs

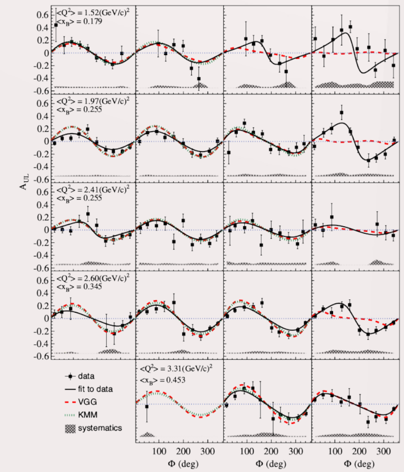
  *A. Belitsky et al. Nucl.Phys. B629 (2002) 323-392*



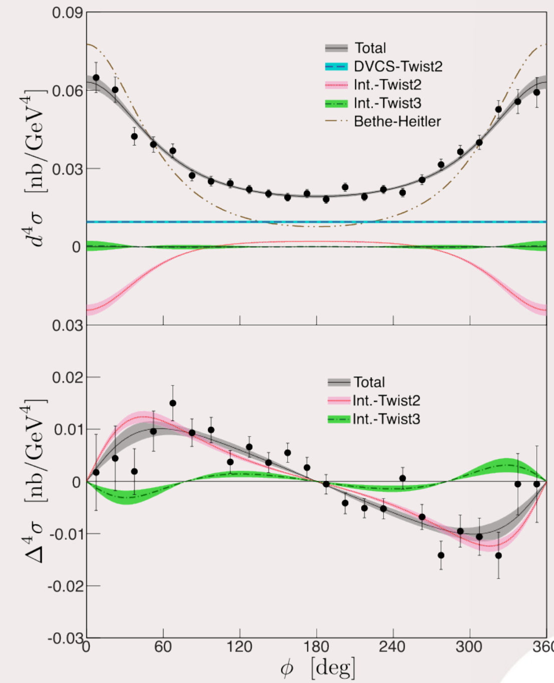
# DVCS Data and Promises



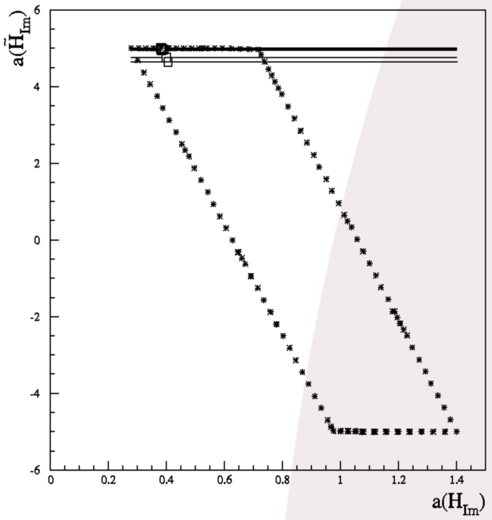



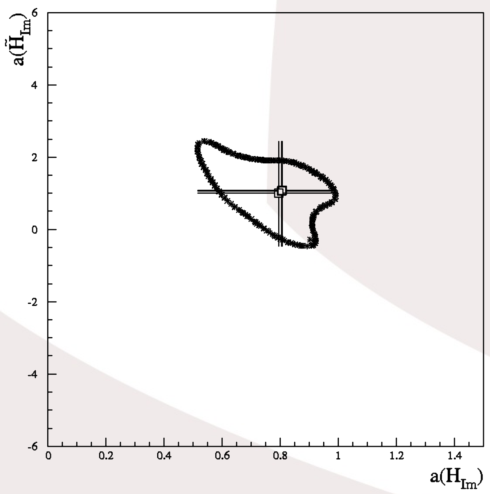




- **We made many measurements in the past two decades**
  - Both of DVCS and DVMP, in many experiments
    - DESY (HERA & HERMES), JLab (Hall A & CLAS) and soon CERN (COMPASS)
    - *See talk of S. Niccolai on the CLAS program*
- **These were often motivated based on two main arguments**
  - Measure the Ji sum rule to resolve the proton spin crisis
  - Make the tomography of the nucleon
    - This week topical focus
- **This talk will be about**
  - Delivering on the tomography of the nucleon
  - Extending these studies to the nulceus



# Extracting the 3D Map




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

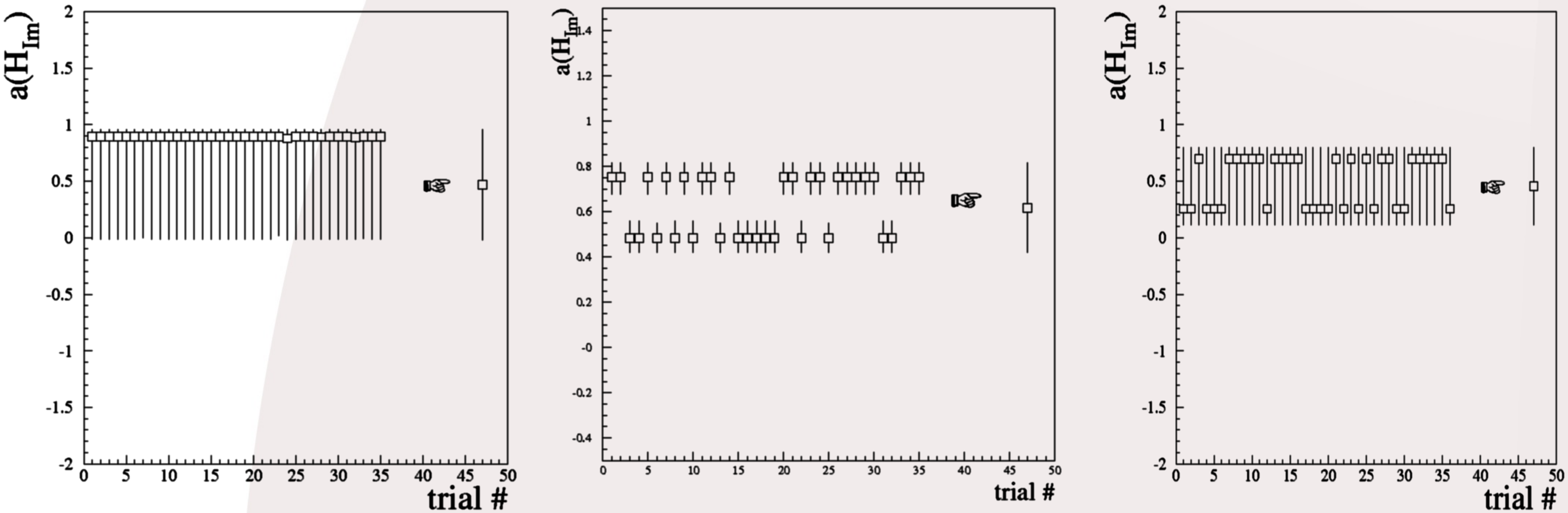
$$\Delta\sigma_{UL} \propto \sin\phi \;\; Im\left\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)\left(\tilde{\mathcal{H}} + \frac{x_B}{2}\mathcal{E}\right) - \xi k F_2\tilde{\mathcal{E}} + ...\right\}$$

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

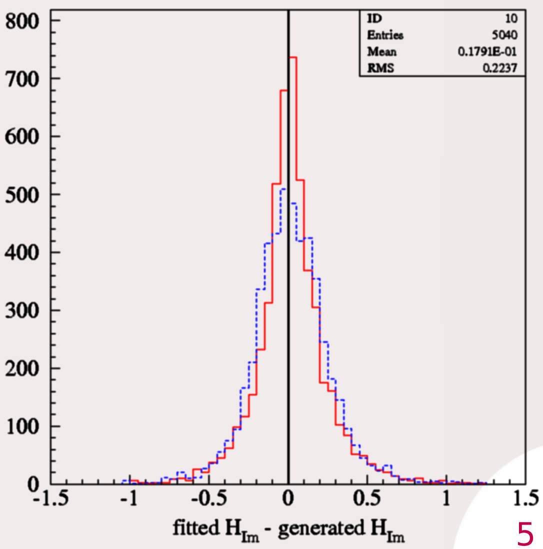
$$\Delta\sigma_{Ux} \propto \sin\phi \;\; Im\{k(F_2\mathcal{H} - F_1\mathcal{E}) + ...\}$$

- **We performed a fit of all available data from HERMES and JLab**
  - R. Dupré, M. Guidal, M. Vanderhaeghen, Phys.Rev. D95 (2017) no.1, 011501
  - R. Dupré, M. Guidal, S. Niccolai, M. Vanderhaeghen, Eur. Phys. J. A (2017) 53: 171
- **With all the experimental effort the problem remains under-constrained**
  - We need more observables to have a fully constrained fit
  - In the mean time, we need some form of model input
  - We chose to use very lose bounds on the sub-leading CFF
    - We use ± 5x the VGG model predictions
- **An illustration of this is the target asymmetry measurement effect on the Im(Ĥ)**
  - Which incidentally have a strong impact on Im(H) as well!
- **However these data are not available for all kinematics**
  - Moreover, we need more observables to constrain E and Ẽ
  - Transversely polarized target, double spin asymmetries, charge asymmetries…

# Using central values




- **In some cases the fit gives problematic results**
  - Explored with many independent pseudo-data sets and fit starting points
  - We often find highly asymmetric error bars
    - However, they do not reflect properly the $\chi^2$ profile
    - They are due to very flat $\chi^2$ valley
  - We also sometimes find double solutions
  - Both of these features are problematic to properly use these results
- **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
    - Taking the central value is equivalent to taking them at a value of 0
  - It was confirmed by simulation that central values give better results



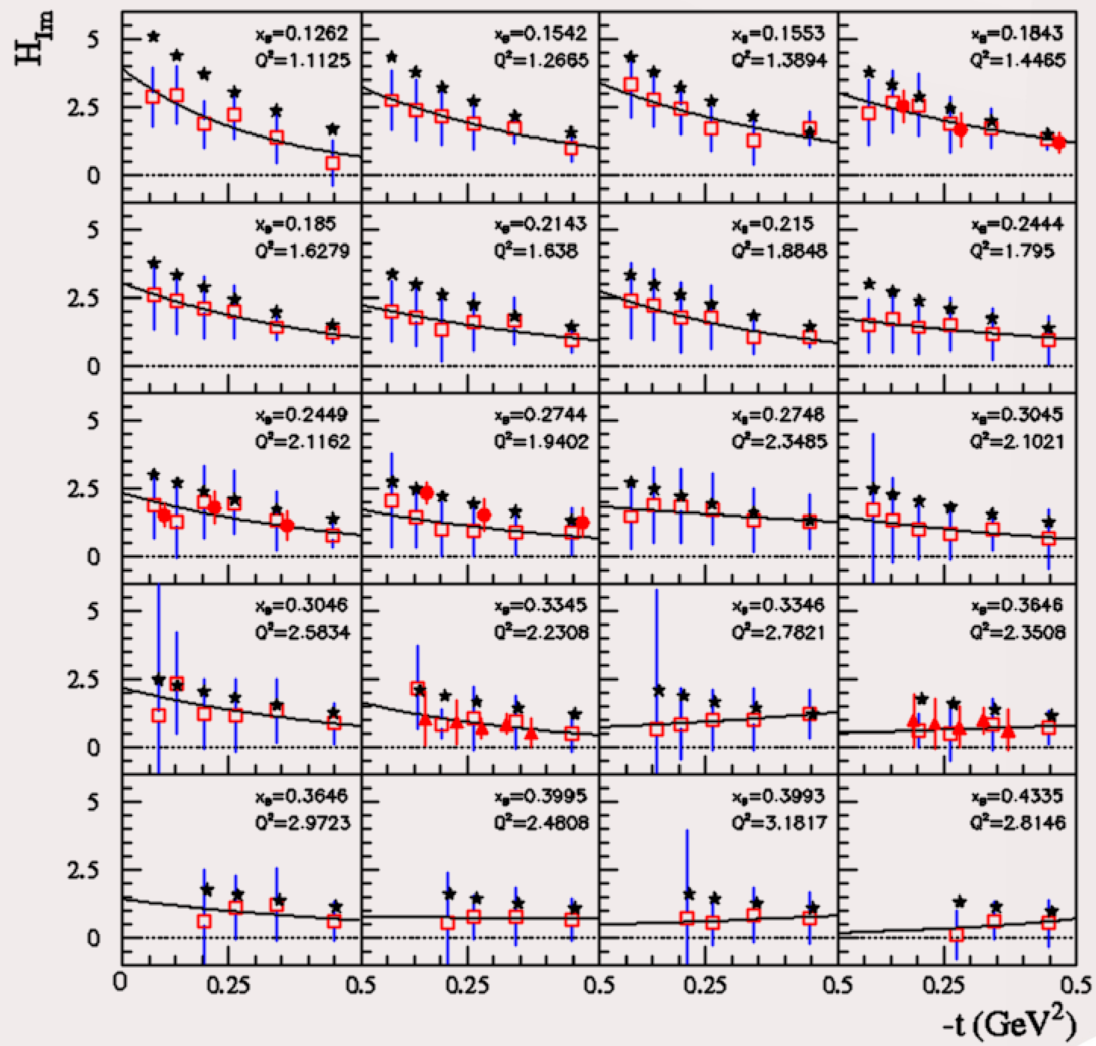
# Extraction of Im(H)

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

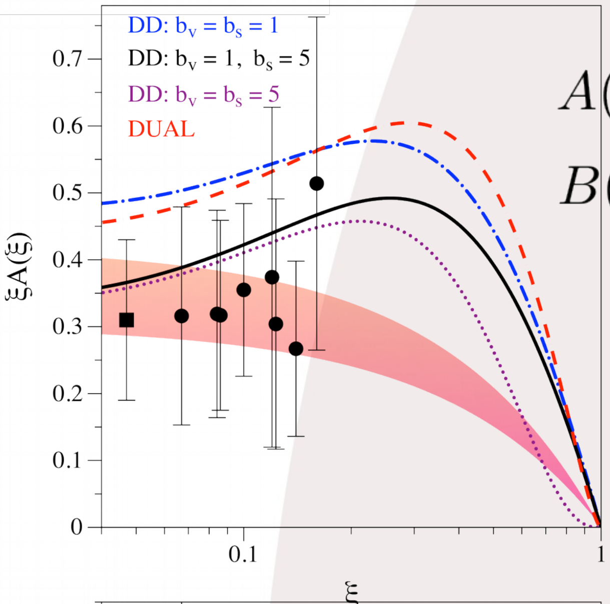
- **Gives enough coverage to explore the *t* and $x_B$ (→ ξ) dependence of Im(H)**
  - Can be fitted with an exponential form to extract the nucleon tomography

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

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

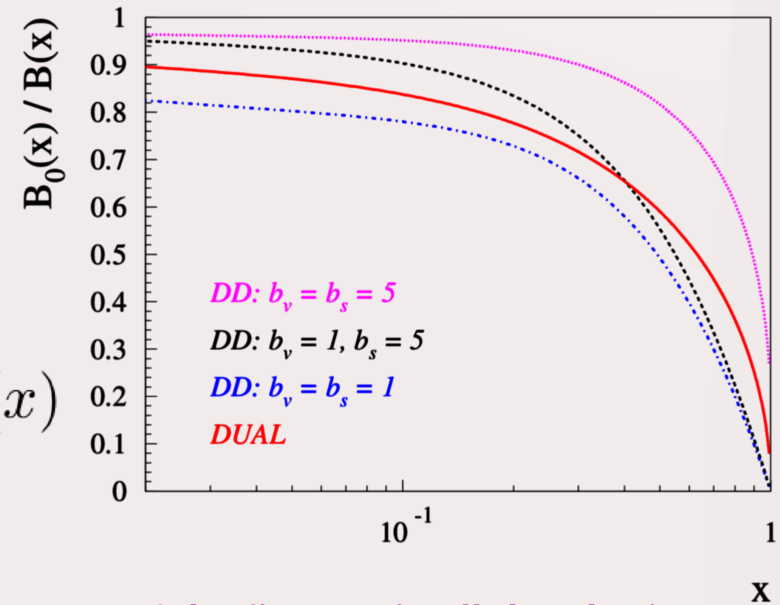


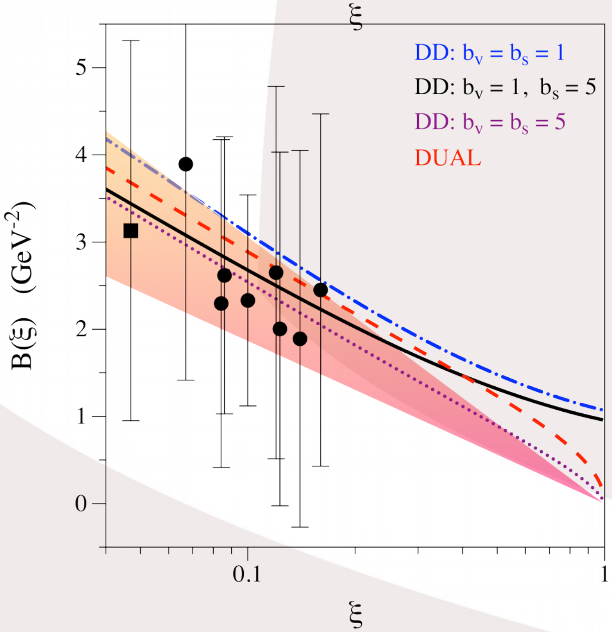
# Amplitude and Slope




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

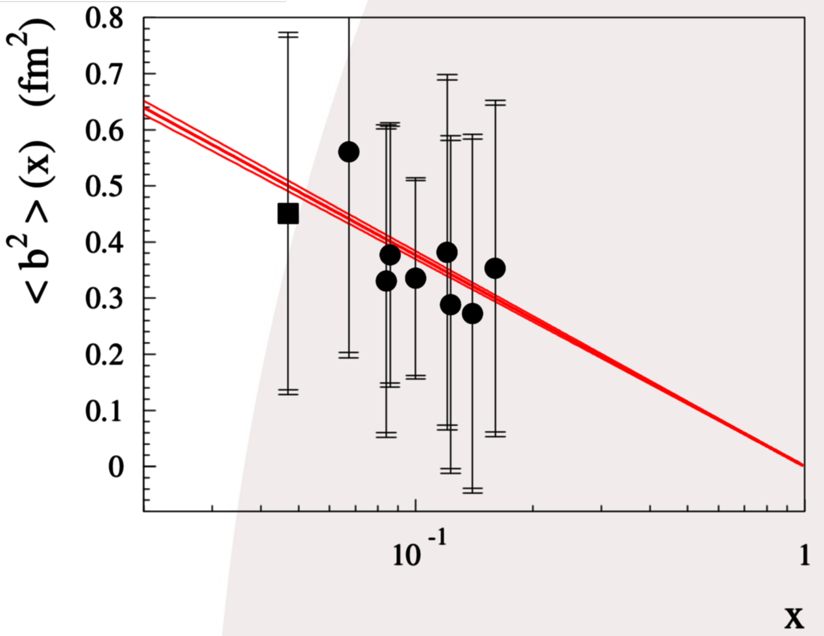
$$\langle b_\perp^2 \rangle^q(x) = 4B_0(x)$$

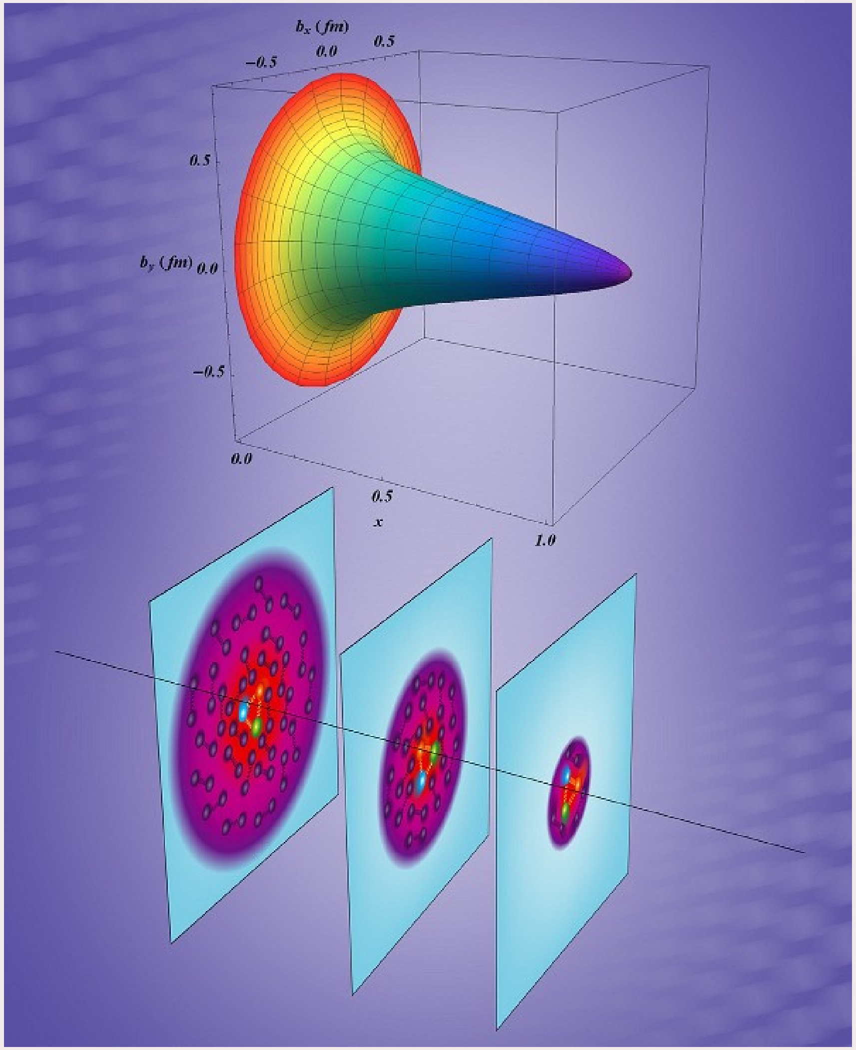



- **The A and B parameters of the fit contain all the physics**
  - They are linked to density and transverse size of the nucleon
- **Fitted using educated guess**
  - Asymptotic behavior expectations are similar to PDFs
  - In the future with larger amount of data, models can be directly tested at this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

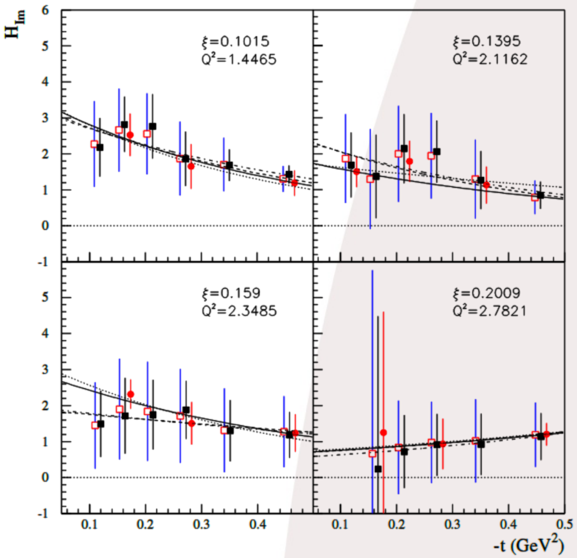


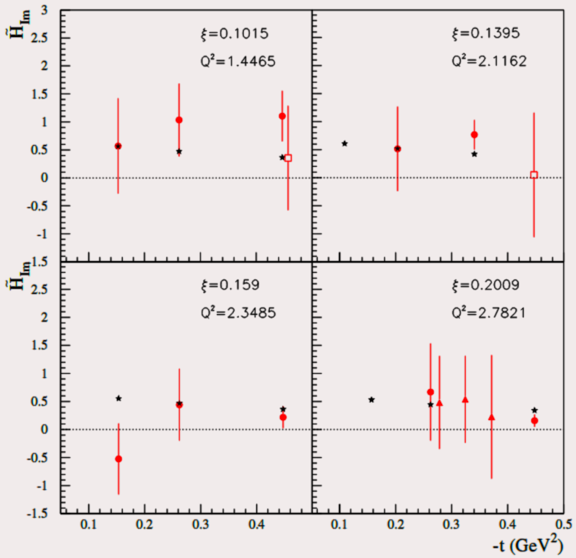



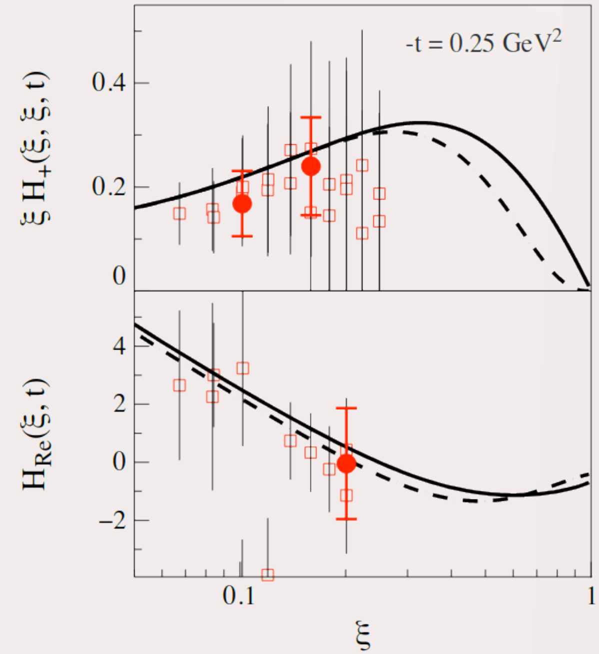

- **We then obtain the tomography of the proton**
  - Represented is the mean square charge radius of the proton for slices of *x*
  - Error bars reflect the unknown CFFs
    - To flatten this distribution, one would need a non constrained CFF with very strong opposite behavior

- **We observe the nucleon size shrinking with *x***
  - On a limited range, most of the phase space is extrapolated

# Access to other GPDs

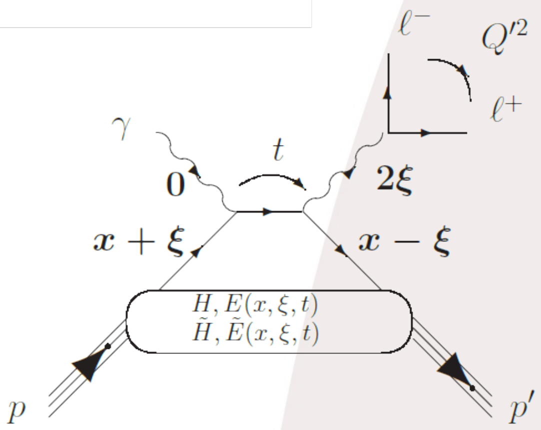


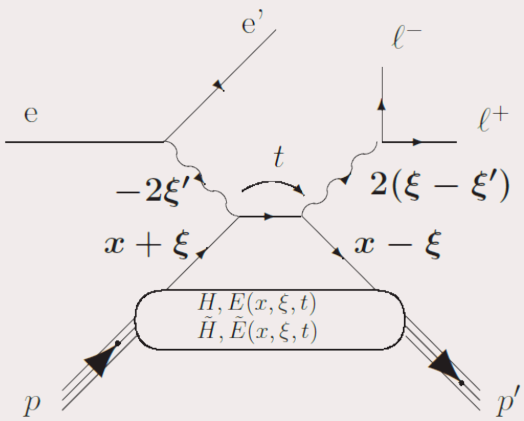



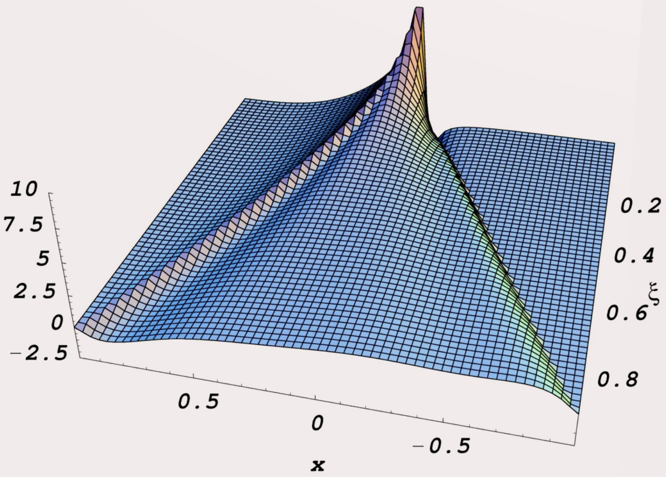




- **Target spin asymmetries give first insight in Im(Ĥ)**
  - Also reduce error bars significantly on Im(H)
  - We need more of these to efficiently reduce the error bars
  - This will hopefully be achieved with JLab 12 and other future programs
    - *See S. Niccolai talk on Tuesday*
- **Other theoretical inputs are possible from QCD**
  - Dispersion relations can help access the real parts of the CFFs
  - Global fits based on models can reduce the number of free parameters
    - At the cost of model dependencies

# Other Compton Scatterings



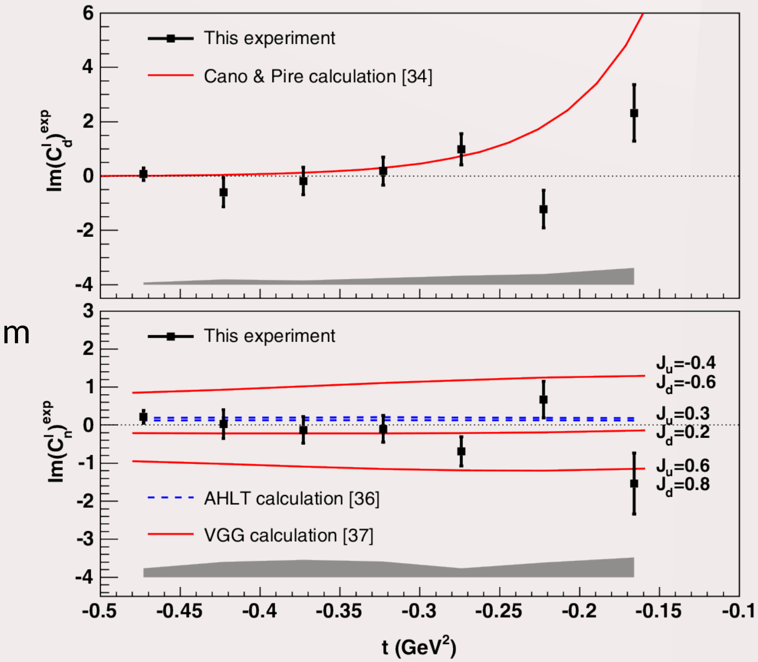



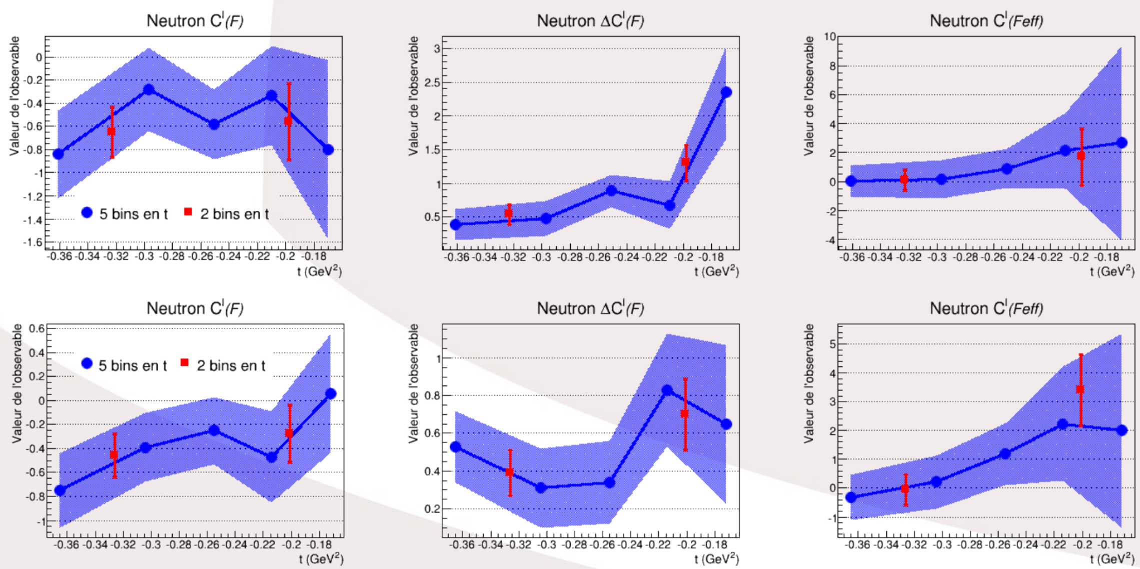

- **Time-like Compton scattering (TCS)**
  - Offers similar information as DVCS with smaller cross sections
  - Test the universality of the GPDs
  - Can experimentally facilitate the use of transversely polarized targets
- **Double DVCS**
  - Measure the off-diagonal ($x \neq \xi$) value of the GPDs
  - Unique measurement to test model extrapolations in this domain
- **Impact of these measurements is under investigation**
  - *See M. Boer talk on Friday*

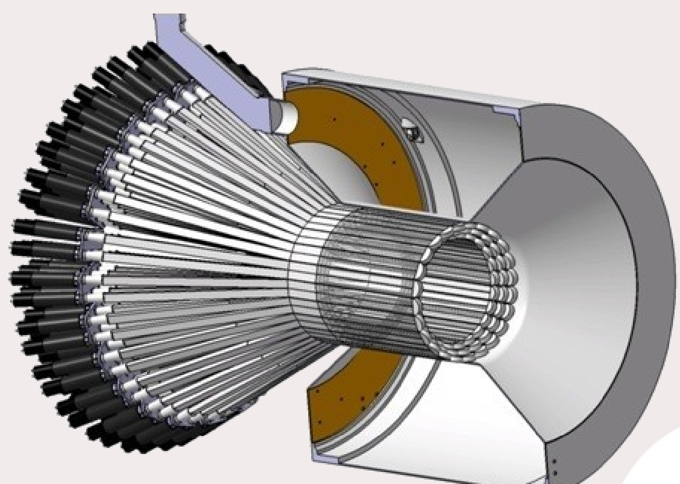
# Neutron DVCS

- **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 (Univ. Paris-Sud)*
- **CLAS12 perspectives**
  - Experiment proposed to solve this issue with the use of a neutron detector



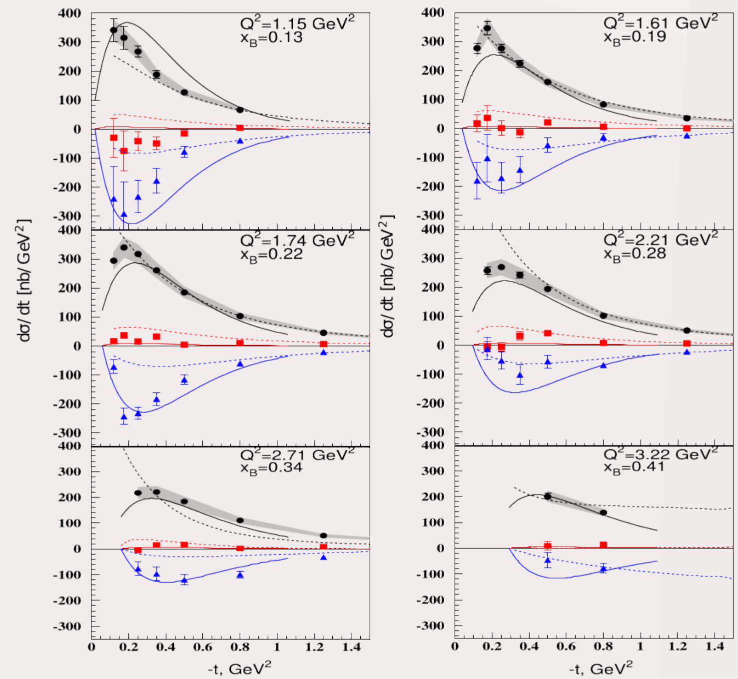



J. Bettane (IPN Orsay)

# Deep Virtual Meson Production

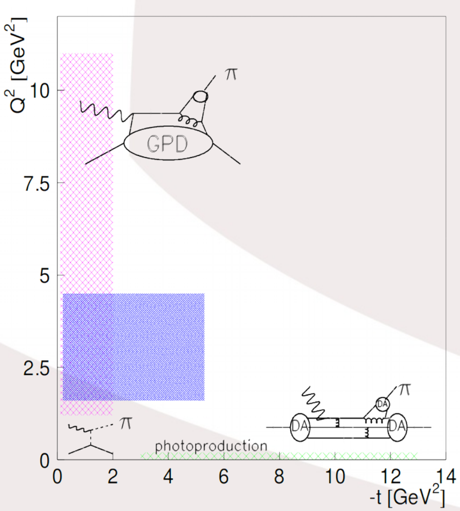
- **Exclusive $\pi^0$ production**
  - Comes for free with DVCS to which it is the main source of background
  - Dominated by its transverse component
    - Expected to give an insight into transverse GPDs

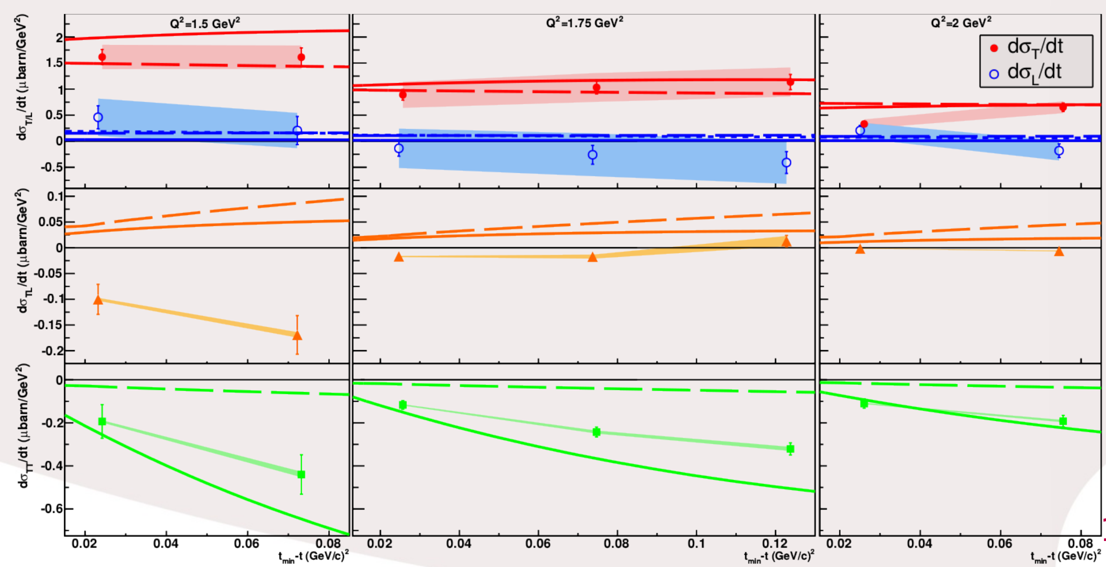
  *I. Bedlinskiy et al. (CLAS Coll.) Phys.Rev.Lett. 109 (2012) 112001, M. Defurne et al. (2016) arXiv:1608.01003*




- **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
- **In the future**
  - Higher energies will ease the data interpretation in term of GPDs
  - We will use vector mesons to access the gluon GPDs
  - Phi at CLAS12 and J/Psi at the future EIC

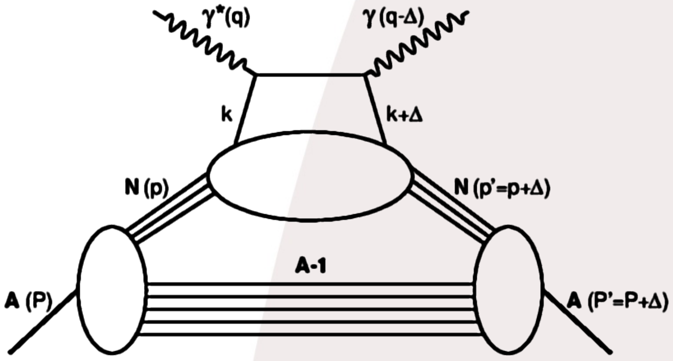


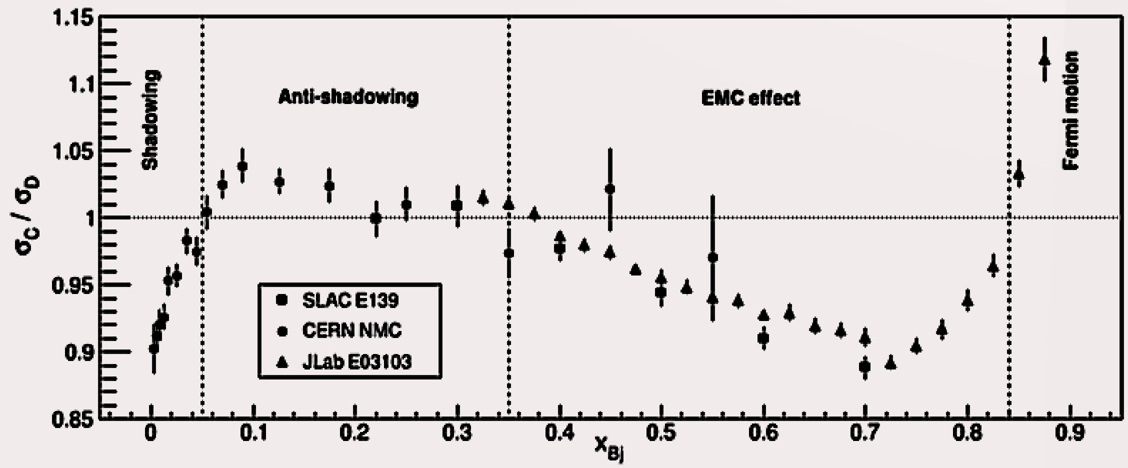



# Summary for the Nucleons

- **We are now able to go all the way from data to the tomography**
  - Thanks to the large amount of data produced in JLab in the past decade
    - Including the important polarized target results
- **Incremental progress will come with**
  - More data, from many observables, on a large phase space
    - We expect from JLab12 much more precision and coverage
    - We hope for many more observables as well (transversely polarized targets, Double DVCS, charge asymmetries…)
  - Theoretical progress to include meson production observables to the fits
- **Global fits can also help**
  - To include constraints from dispersion relations and correct behavior at the limits
  - Necessary to get to the second big promise of GPDs, the Ji sum rule

# Nuclear GPDs

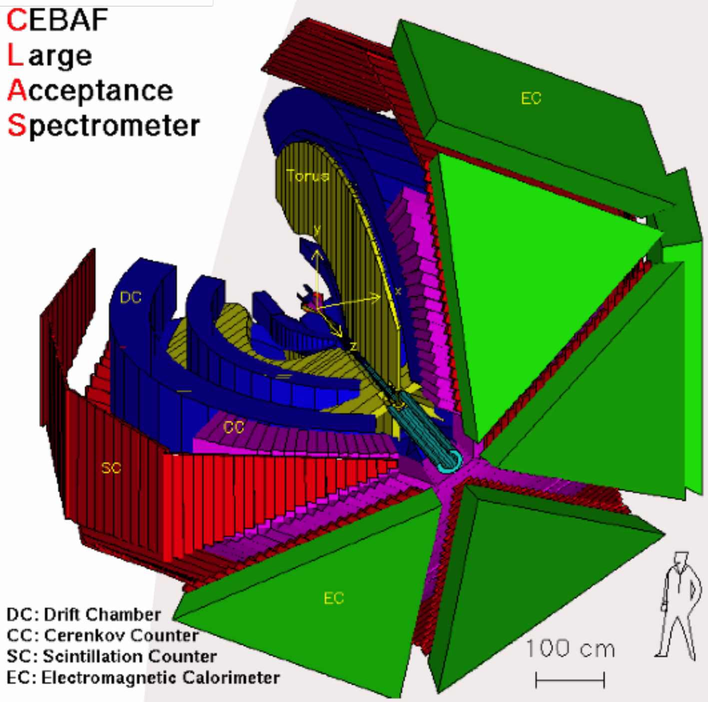


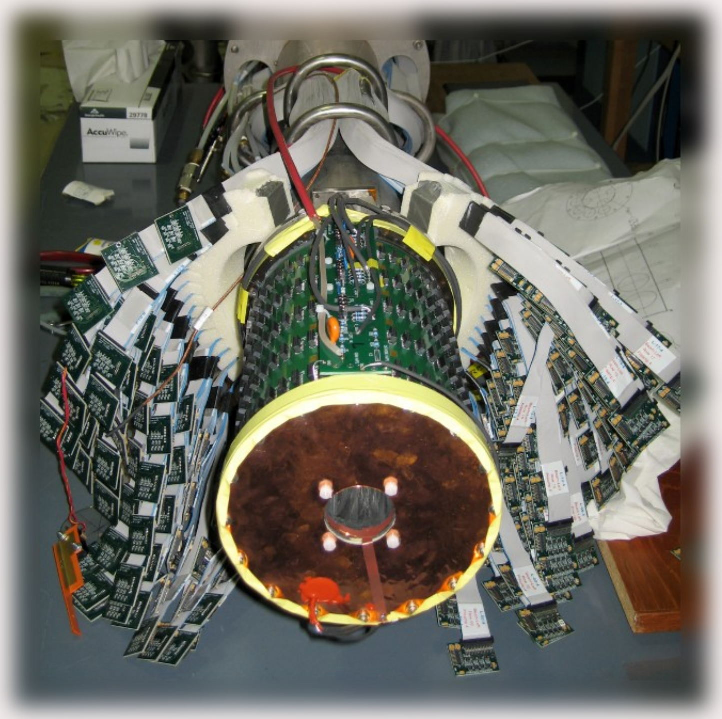



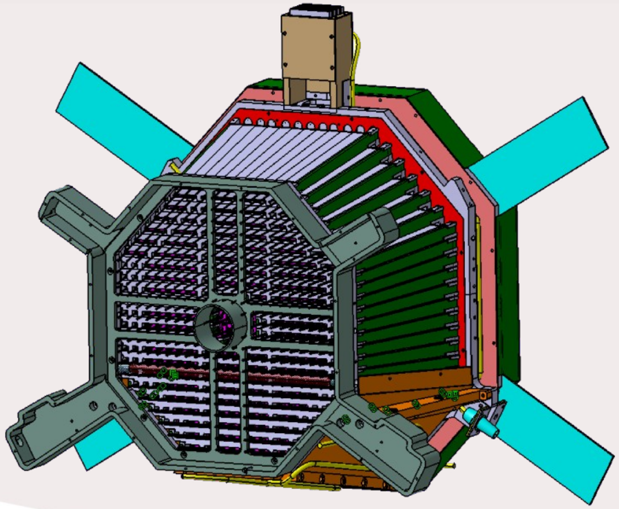

- **New view on nuclear effects**
  - GPDs offer a completely new point of view to understand the partonic structure of nuclei
- **Experimental access to completely new nuclear physics**
  - Non nucleonic degrees of freedom of the nuclei
  - Measurement of the pressure and forces in the nuclei
  - The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

    *R. Dupré & 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

# Experimental Apparatus

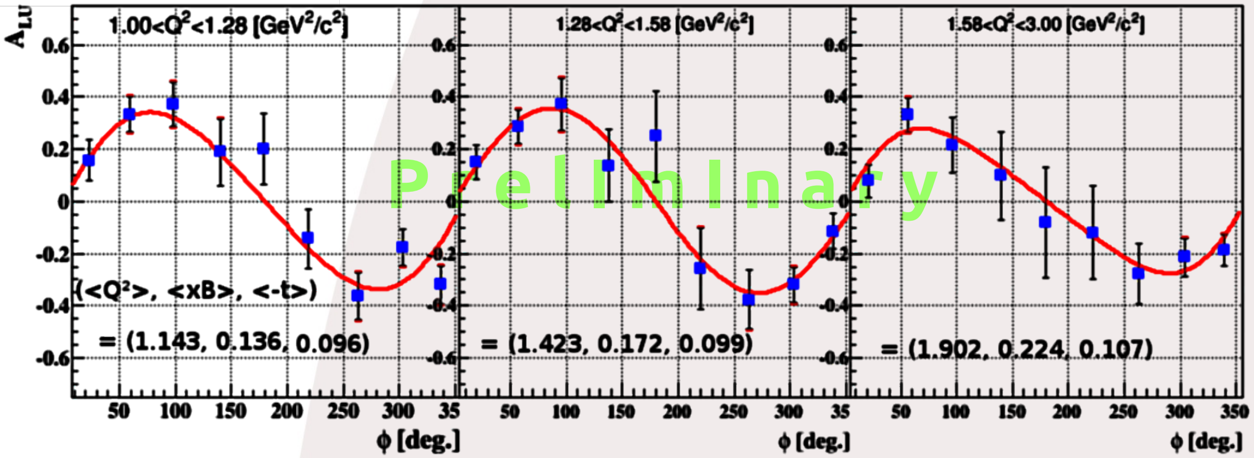


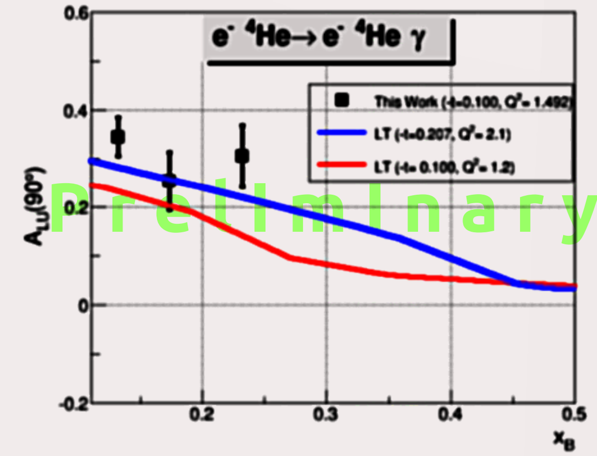



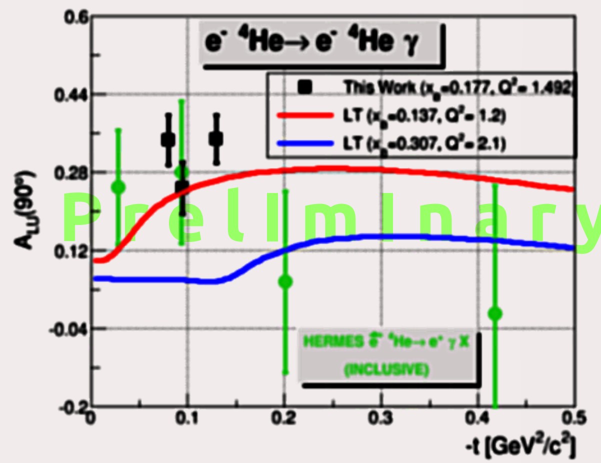


- **Experimental challenges**
  - Detecting very forward photons
  - Detecting very low energy alphas (7 MeV)
- **Radial Time Projection Chamber**
  - Small TPC placed around the target
- **Inner Calorimeter**
  - Very forward electromagnetic calorimeter

# The Coherent DVCS



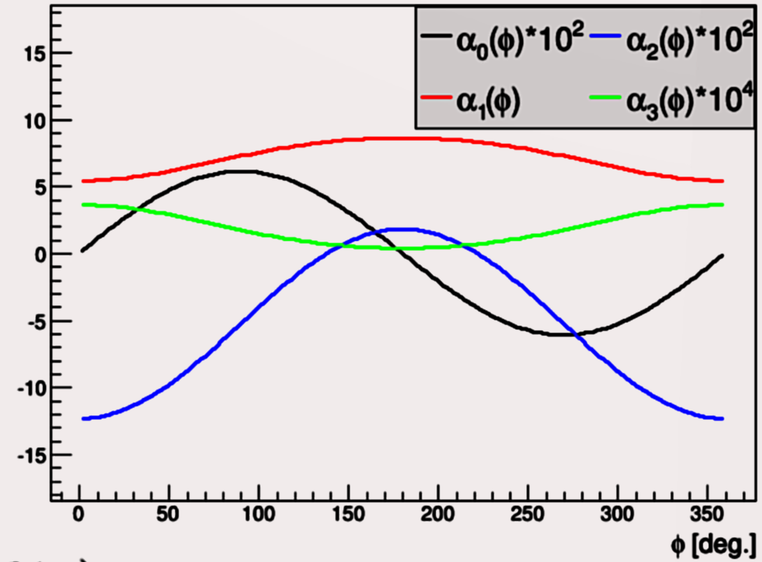




$$A_{LU} = \frac{d^5\sigma^+ - d^5\sigma^-}{d^5\sigma^+ + d^5\sigma^-} = \frac{1}{P_B}\frac{N^+ - N^-}{N^+ + N^-}$$

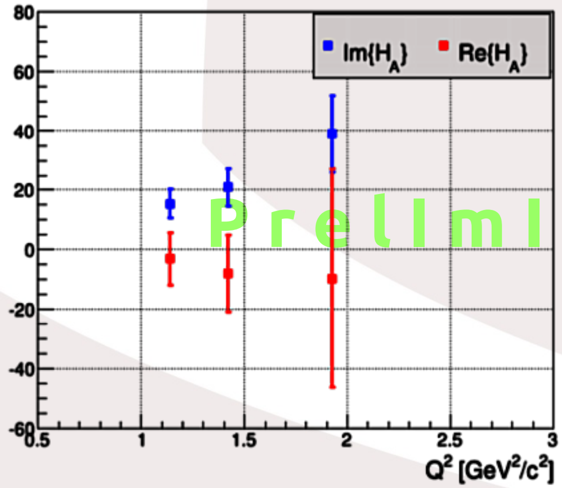
- **Coherent DVCS on helium**
  - Shows very strong beam spin asymmetry
  - Expected factor ~2 increase from PWIA prediction
- **Interpretation**
  - The very strong signal proves that we are indeed probing the nuclei as a whole
  - We see an even stronger signal than expected

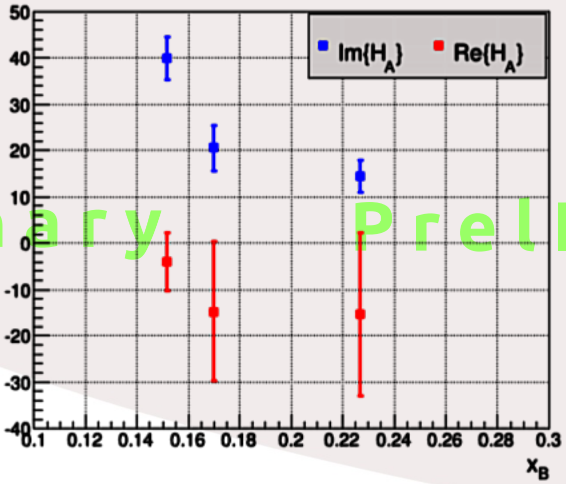
# Extraction of the CFF

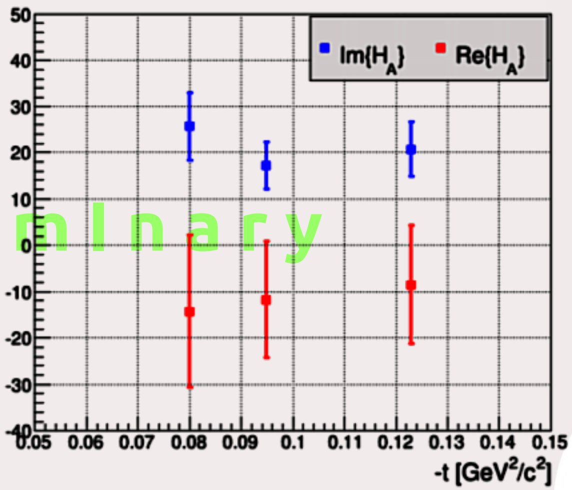
- **Simple extraction**
  - Spin-0 → 1 GPD → 2 CFF
  - Their different contributions in phi allows to separate their contributions
  - The different contributions are exactly calculable within perturbative QCD
  - We are mostly sensitive at the imaginary part
  - More precise measurement will be needed to extract the real part



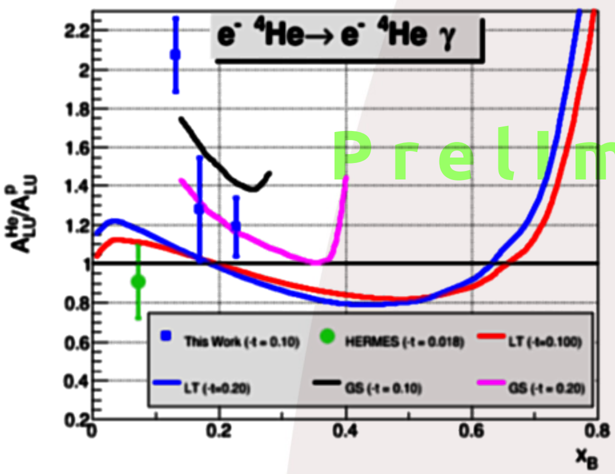

$$A_{LU}(\phi) = \frac{\alpha_0(\phi)\,\Im m(\mathcal{H}_A)}{\alpha_1(\phi) + \alpha_2(\phi)\,\Re e(\mathcal{H}_A) + \alpha_3(\phi)\left(\Re e(\mathcal{H}_A)^2 + \Im m(\mathcal{H}_A)^2\right)}$$

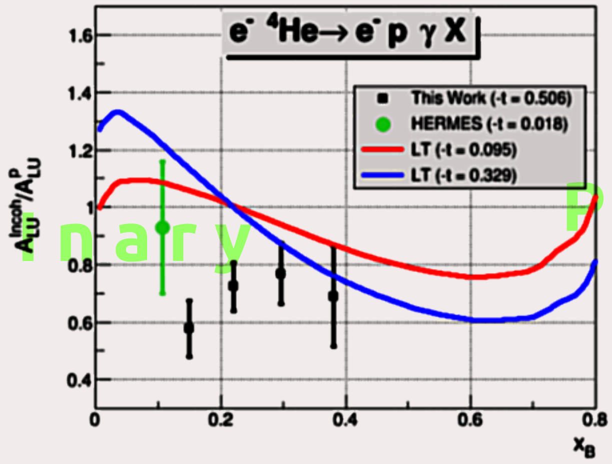


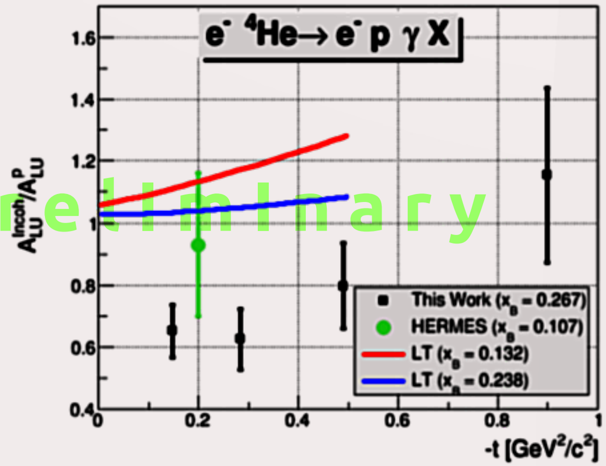



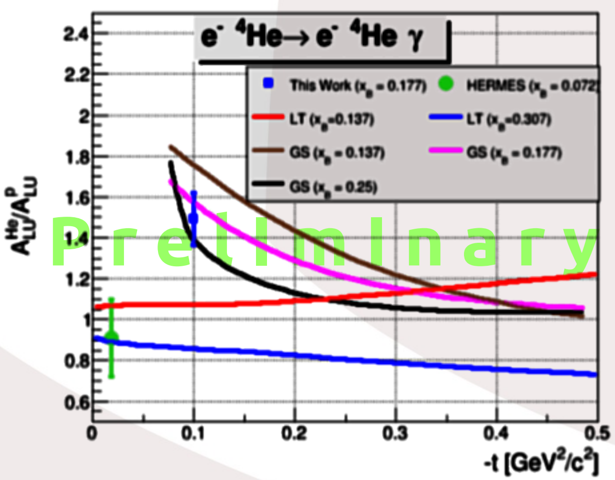



# The Generalized EMC Ratio




## Generalized EMC ratio

- Coherent/proton
  - The expected form factor slope is present

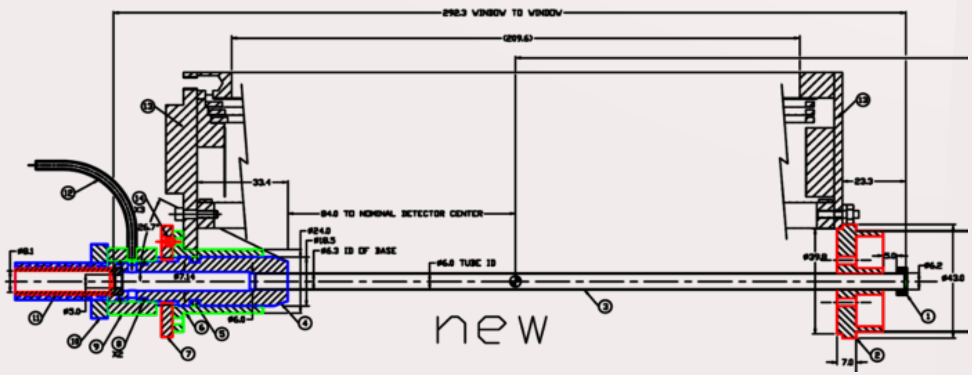
    *V. Guzey and M. Strikman Phys. Rev. C 68, 015204*
- Incoherent/proton
  - Suppressed compared to the binding model from

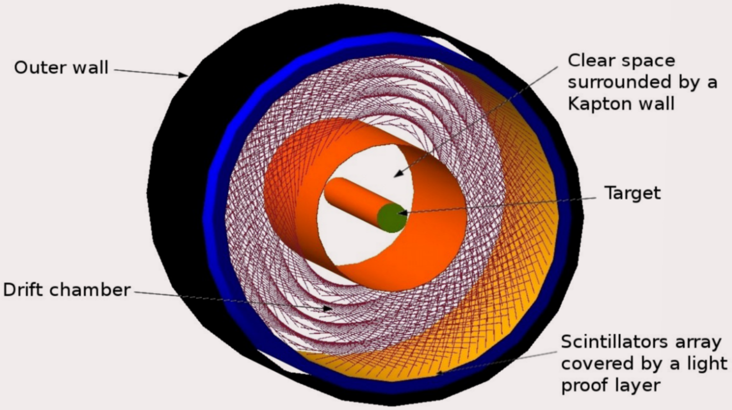
    *S. Liuti and S.K. Taneja Phys.Rev. C72 (2005) 032201*

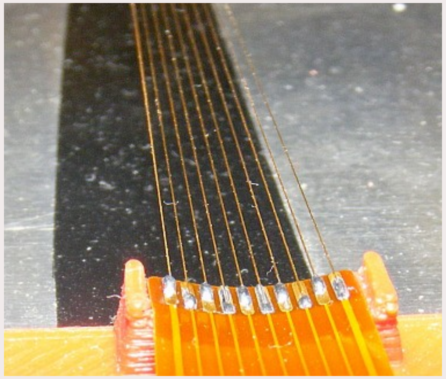
# The ALERT Detector for CLAS12

- **A Low Energy Recoil Tracker**
  - Replace the CLAS12 silicon vertex tracker (SVT) and the micromegas detectors
- **Hyperbolic drift chamber**
  - Stereo angles give the z-axis resolution
  - We tested electronic options
    - → first prototype tested with DREAM Front-End Board
- **Scintillators for TOF and total energy measurement**
  - GEANT4 simulations have been performed to estimate energy loss in different layers
  - Path of photons have been estimated to optimize tile sizes
- **Work in Progress**
  - Some technical choices are not final
    - We present a conservative version that we are confident we can build without problems
    - We are working with prototypes to optimize different parameters (exact gas mixture, wire materials and thickness…)

      *G. Charles et al. Nucl. Instrum. Meth., A855 (2017) 154*
  - Integration of electronics and other elements
    - We use the same electronics (DREAM), but with less channels, than the CLAS12 Micromegas, so we do not expect this to be a major challenge

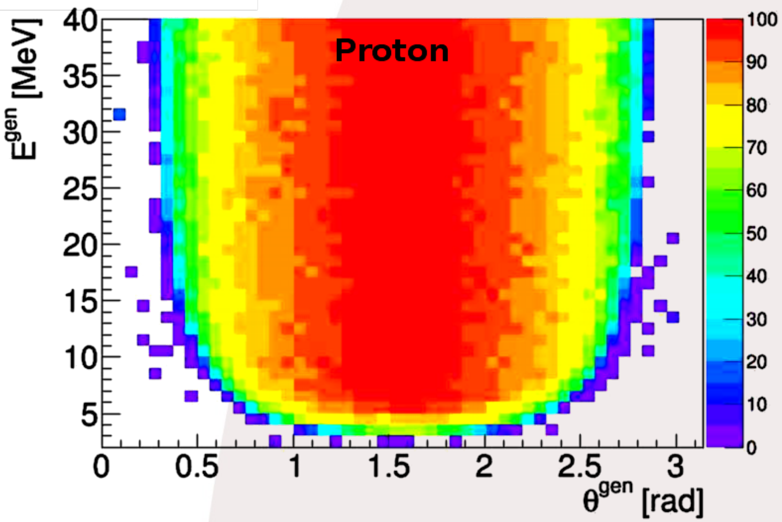


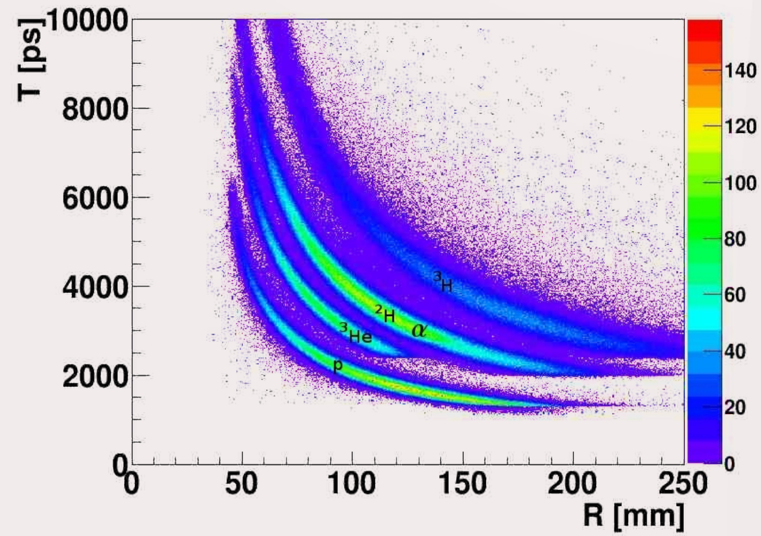



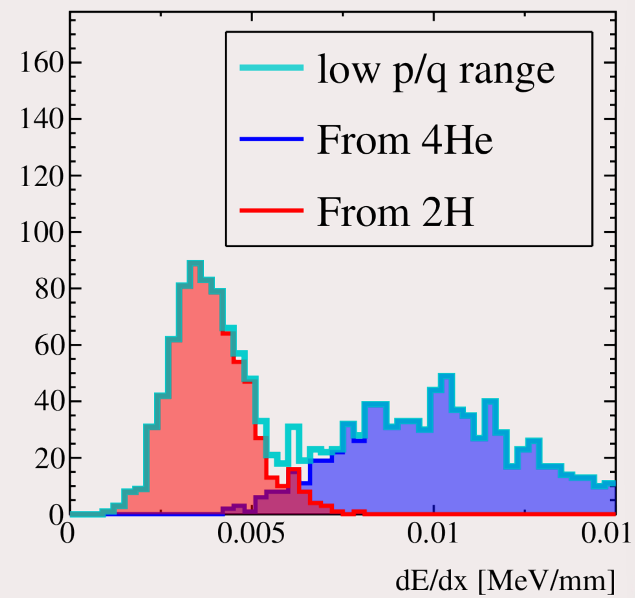
Soldering tests with a 2mm wire gap on a curved surface

# Expected Detector Performances

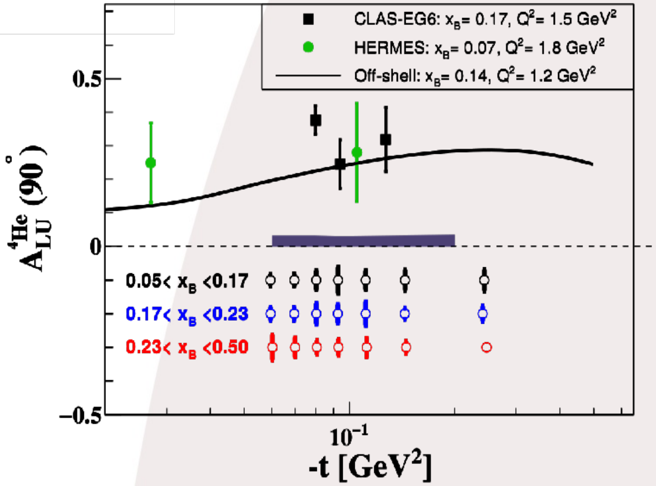


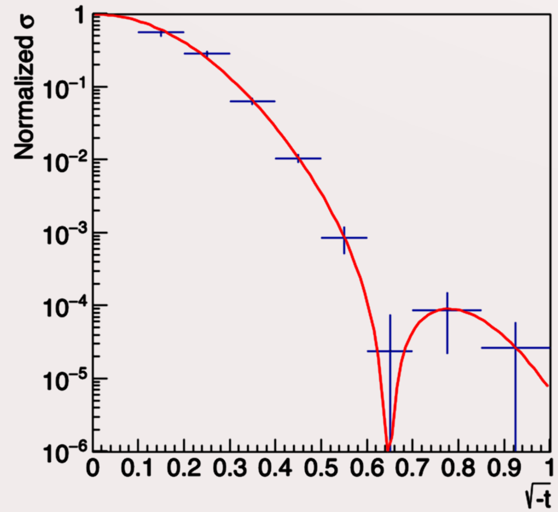



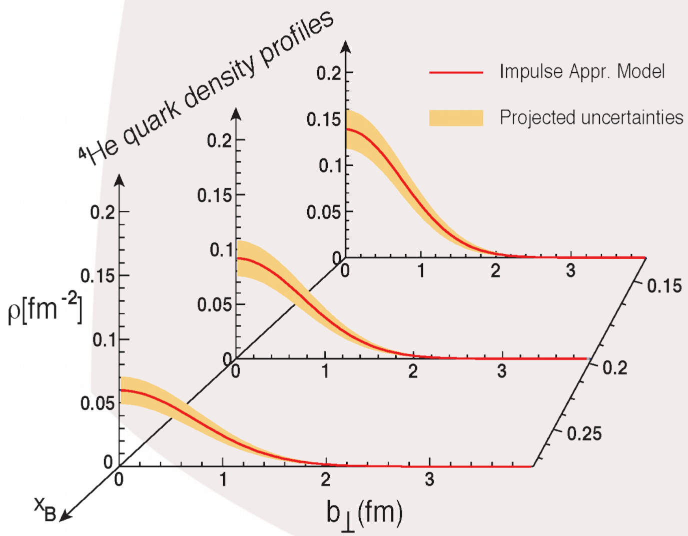

- **Capabilities for very low momentum detection**
  - As low as 70 MeV/c for protons and 240 MeV/c for $^4$He
  - Detection at large angles in forward and backward directions (25° from the beam)
  - Main limitations are due to recoils stopped in the target and are simulated with GEANT4
  - Target has 6 mm radius with 25 µm kapton walls and 3 atm pressure
- **Capabilities to handle high rates**
  - Small distance between wires leads to short drift time <250 ns (5 µs in a similar RTPC)
    - Based on MAGBOLTZ calculation
  - This translates into 20× less accidental hits
  - Allows to be integrated in the trigger for significantly reduced DAQ rate
- **Improved PID**
  - Like in the RTPC we get dE/dx
  - We have more resolution on the curvature due to the large pad size in previous RTPCs
  - We have new informations: TOF, total energy deposit…

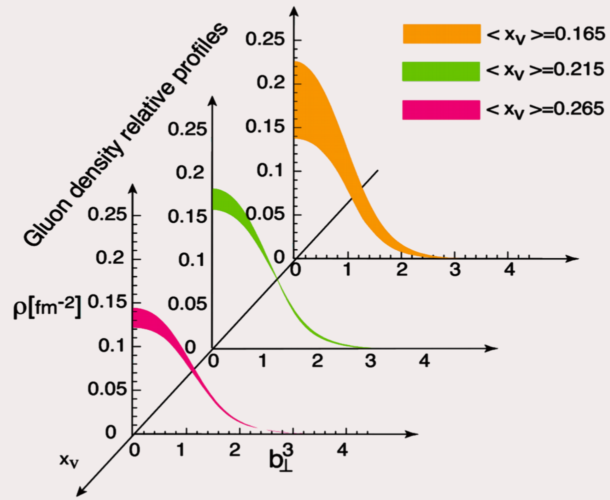


# Projections



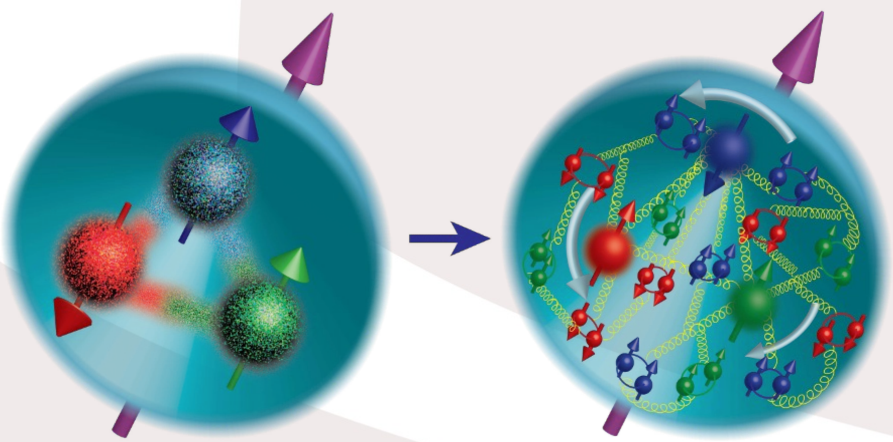



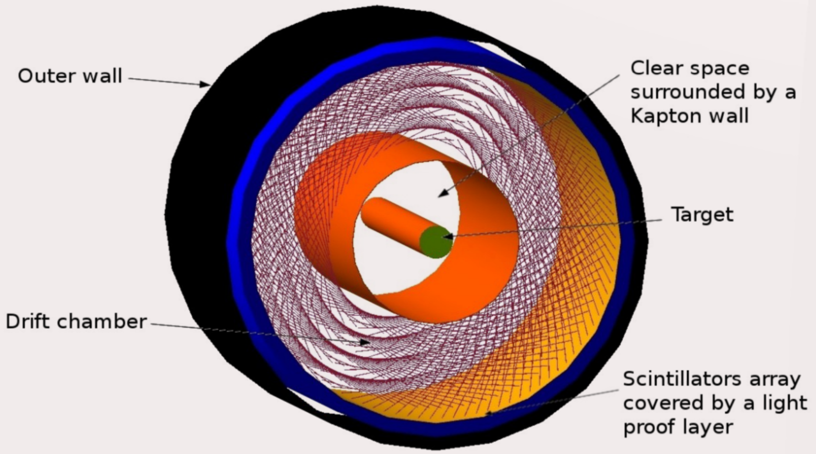




- **We will perform the tomography of the helium-4 nucleus both in term of quarks and gluons**
  - It will be a complete measurement of the leading order GPDs of helium
  - It is a unique opportunity to compare the quark and gluon distributions in the nucleus

# Summary

- **In fifteen years of experiments at JLab, we have accumulated a wide array of data**
  - DVCS in particular can already be interpreted directly in term of GPDs and 3D structure of the nucleon
  - 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 also go very low in the sea region at an EIC
    - How wide the proton will get at low x?
- **This framework can be used to understand more complex hadron**
  - GPDs have a word to say about the partonic structure of the nuclei
  - Give access to unique opportunities
- **First experimental results**
  - A first measurement of both coherent and incoherent DVCS on a nucleus has been made in CLAS
  - More is to come at JLab with the ALERT detector