A GPD overview: Current status and perspectives

M. Defurne

CEA Saclay - IRFU/SPhN

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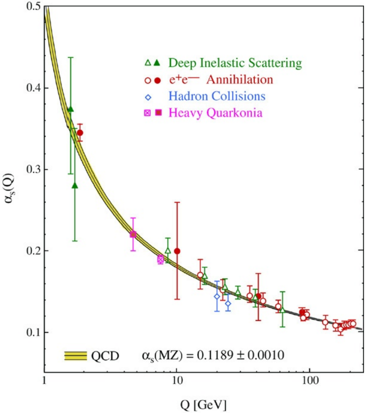
The nucleon: a formidable lab for QCD

- The nucleon is a dynamical object made of quarks and gluons.
- This dynamics is ruled by the strong interaction.
- A perturbative approach from first principles to unravel this dynamics is impossible due to the large size of the strong coupling constant.

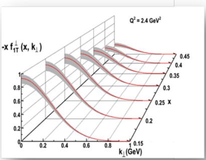


Although non-perturbative approaches (DSE, lattice QCD) starts making progress, the experimental approach remains more convenient to get complex information about this dynamics.

A set of distributions encoding the nucleon structure

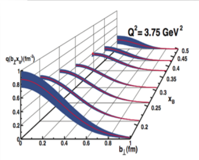
TMDs: Fraction of longitudinal momentum x et transverse momentum k

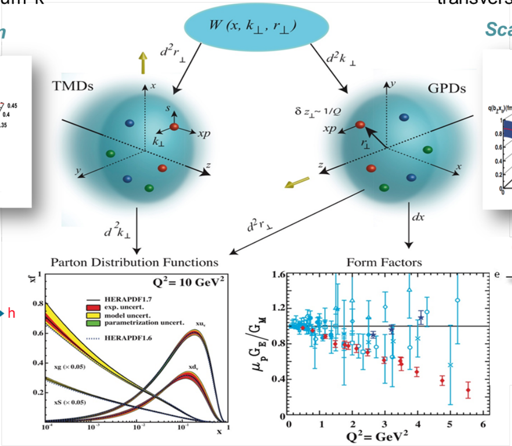
Scan in momentum

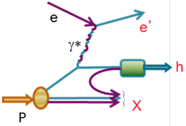


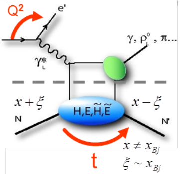
GPDs: Fraction of longitudinal momentum x et transverse position b

Scan in position



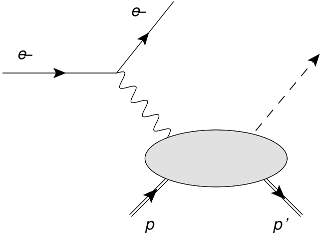






The deep exclusive processes

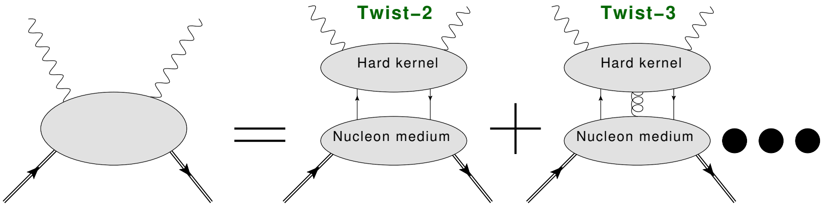
By measuring the cross section of deep exclusive processes, we get insights about the GPDs.

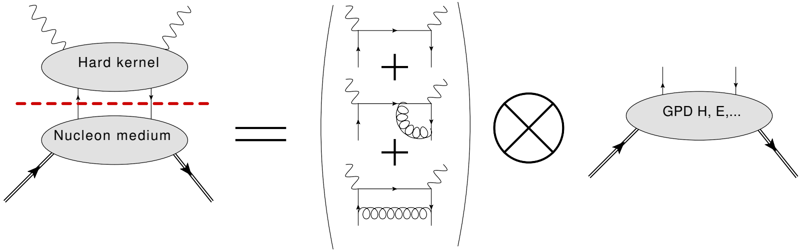


1. The electron interacts with the proton by exchanging a hard virtual photon.
2. The proton emits a particle (γ, π^0, ρ,...)

The link between these diagrams and the GPDs is guaranted by the factorization.

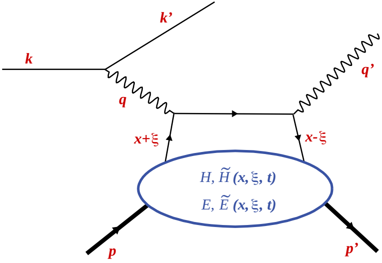
Factorization and GPDs





The amplitudes at twist-$(n+1)$ are suppressed by a factor $\frac{1}{Q}$ with respect to the twist-n amplitudes, with Q the virtuality of the photon.

DVCS and GPDs



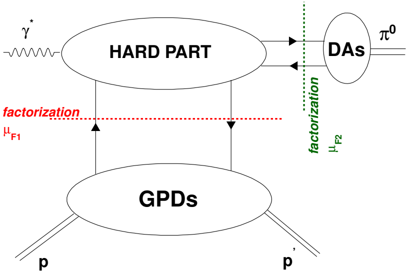
- $Q^2 = -q^2 = -(k - k')^2$.
- $x_B = \frac{Q^2}{2p \cdot q}$
- x longitudinal momentum fraction carried by the active quark.
- $\xi = \frac{x_B}{2 - x_B}$ the longitudinal momentum transfer.
- $t = (p - p')^2$ squared momentum transfer to the nucleon.

The GPDs enter the DVCS amplitude through a complex integral. This integral is called a *Compton form factor* (CFF).

$$\mathcal{H}_{++}(\xi, t) = \int_{-1}^{1} H(x, \xi, t) \left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right) dx \, .$$

DVMP and GPDs: just a few words about it

In DVMP, there is an additional non-perturbative structure: the meson.



The amplitude is given by the product of two twist-expansions:
There is a coupling between the GPDs and the DAs.

$$\mathcal{M} = GPDs(x, \xi, t, \mu_{F1}) \otimes HARD(x/\xi, z, \mu_{F1}, \mu_{F2}) \otimes DA(z, \mu_{F2})$$

But we can play with DAs to perform flavour separation or privilieged access to specific GPDs.

The generalized parton distributions and the nucleon

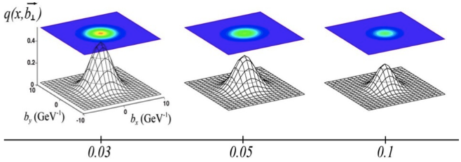
At leading twist there are 8 GPDs:

- 4 chiral-even GPDs: H, E, $\widetilde{H}$ and $\widetilde{E}$.
- 4 chiral-odd GPDs: H_T, E_T, $\widetilde{H}_T$ and $\widetilde{E}_T$.

Using the GPDs, we can determine the total angular momentum of quarks in the nucleon.

$$\int_{-1}^{1} x \left[H^f(x,\xi,0) + E^f(x,\xi,0) \right] \, dx = J^f \qquad \forall \xi \; .$$

By Fourier transform of the GPD H at ξ=0 (need extrapolation), we obtain the distribution in the transverse plane of the partons as a function of their longitudinal momentum.



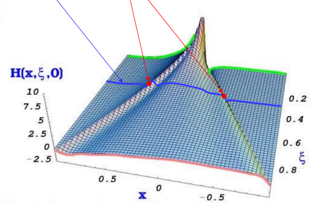
Modeling a Generalized parton distributions, a complex task

GPDs are well-constrained objects, making their modelisation challenging.

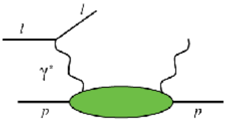
- Forward Limits: $H(x,0,0) \to q(x)$, $\widetilde{H}(x,0,0) \to \Delta q(x)$
- $\int_{-1}^{1} dx H^q(x,\xi,t) = F_1^q(t)$ and $\int_{-1}^{1} dx E^q(x,\xi,t) = F_2^q(t)$.
- Polynomiality: x^n Mellin moments of GPDs are polynomial in ξ with well-defined leading power.
- Positivity: Inequalities between a GPD and corresponding PDFs.

$$T^{DVCS} \approx \int_{-1}^{+1} \frac{H(x,\xi,t)}{x-\xi+i\varepsilon} dx \quad + \quad \cdots$$

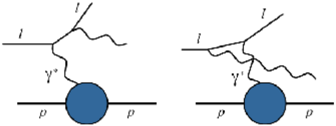
$$\approx P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x-\xi} dx \quad + \quad i\pi H(\xi,\xi,t) \quad + \quad \cdots$$



We use leptons beam to generate the γ^* in the initial state... not without consequences.
Indeed, experimentally we measure the cross section of the process $ep \to ep\gamma$ and not strictly $\gamma^* p \to \gamma p$.

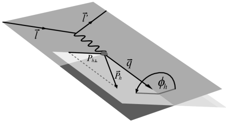


DVCS



Bethe-Heitler

$$\frac{d^4\sigma(\lambda,\pm e)}{dQ^2 dx_B dt d\phi} = \frac{d^2\sigma_0}{dQ^2 dx_B} \frac{2\pi}{e^6} \times \left[\left|\mathcal{T}^{BH}\right|^2 + \left|\mathcal{T}^{DVCS}\right|^2 \mp \mathcal{I} \right] ,$$



Photon electroproduction and GPDs (PART II)

The interference term allows to access the phase of the DVCS amplitude, *i.e* allows to isolate imaginary and real parts of CFFs.
A few examples of harmonic coefficients and their sensitivity to CFFs:

$$
\begin{aligned}
c_{0,UU}^{DVCS} &\propto 4(1-x_B)\left(\mathcal{H}\mathcal{H}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^*\right) + \cdots \\
c_{1,UU}^{\mathcal{I}} &\propto F_1\ Re\mathcal{H} + \xi(F_1+F_2)\ Re\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\ Re\mathcal{E}\,, \\
s_{1,LU}^{\mathcal{I}} &\propto F_1\ Im\mathcal{H} + \xi(F_1+F_2)\ Im\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\ Im\mathcal{E}\,, \\
s_{1,UL}^{\mathcal{I}} &\propto F_1\ \widetilde{\mathcal{H}} + \xi(F_1+F_2)\ \left(\mathcal{H} + \frac{x_B}{2}\mathcal{E}\right) - \xi\left(\frac{x_B}{2}F_1 + \frac{t}{4M^2}F_2\right)\ \widetilde{\mathcal{E}}\,,
\end{aligned}
\tag{1}
$$

At leading-order, the imaginary part of CFFs gives access to the GPD value on the diagonal x=ξ.

GPD hunter starter kit

If we want to really get the GPDs, we need to:

- Different regions in the proton need to be probed for a complete picture/reconstruction
  $\rightarrow$ Need different facilities.
- Disentangle the different GPD contributions
  $\rightarrow$ Plays with polarization of beam and targets for the different channels.
  $\rightarrow$ Switch to neutron also (described a few slides later).
- Separate the flavour contributions
  $\rightarrow$ Use DVMP data.

Different facilities to probe the nucleon

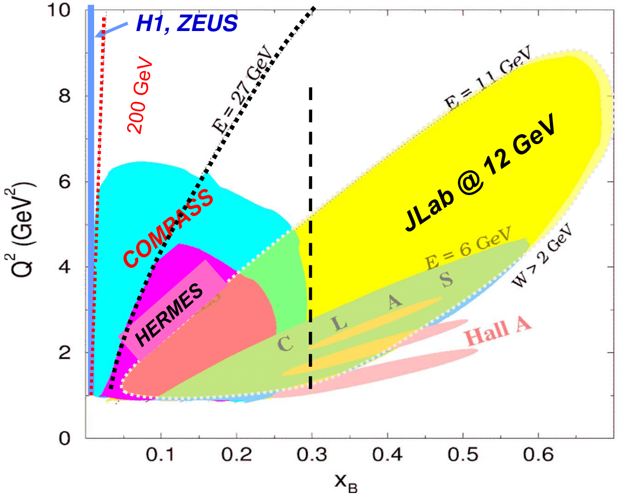
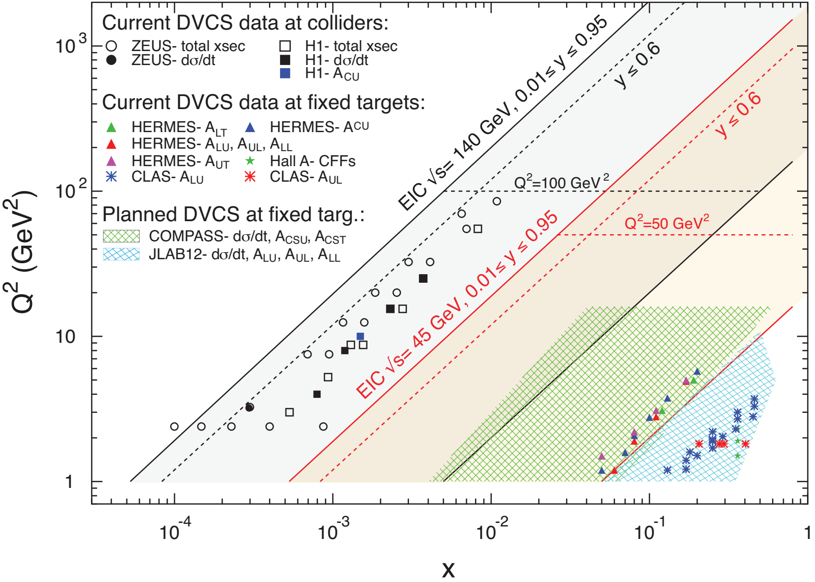


Figure: Partial overlap but different sensitivity to DVCS wrt BH.

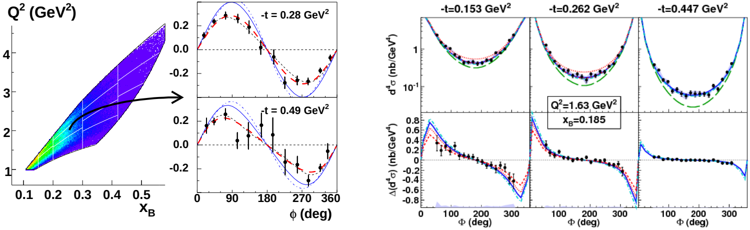
What have we collected so far? (DVCS only)



Unpolarized cross sections from CLAS

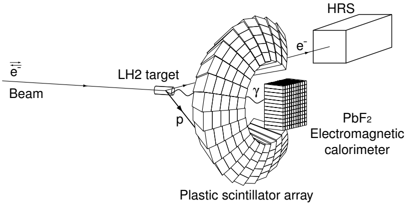
The CLAS collaboration has a impressive DVCS data set:

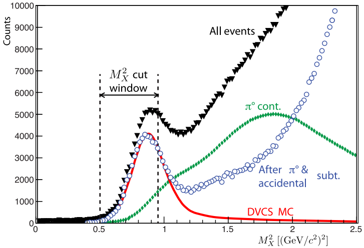
- With unpolarized cross sections.
- Target-spin asymmetries (A_{UL}).
- Double-spin asymmetries (A_{LL}).

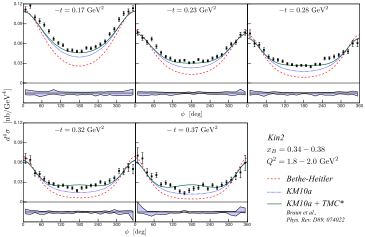


H.S. Jo *et al.*, CLAS collaboration, Phys.Rev.Lett. 115 (2015) no.21, 212003
E. Seder *et al.*, CLAS collaboration, Phys.Rev.Lett. 114 (2015) no.3, 032001
S. Pisano *et al.*, CLAS collaboration,Phys.Rev. D91 (2015) no.5, 052014

New analysis of Hall A data of 2004







- Beam-helicity dependent and independent cross section
- Significant deviation from KM10a
- Kinematical power corrections seems to explain the gap.

M. Defurne *et al.*, Hall A collaboration, Phys.Rev. C92 (2015) no.5, 055202

Last week: Rosenbluth separation of photon electroproduction cross section off proton

The ϕ-dependence is not enough to disentangle the contributions. Using the beam energy dependence, we can add constrains on the model (separation of DVCS and interference contribution)

Setting	E (GeV)	Q^2 (GeV^2)	x_B	W (GeV)
2004-Kin1	5.7572	1.5	0.36	1.9
2004-Kin2	5.7572	1.9	0.36	2.06
2004-Kin3	5.7572	2.3	0.36	2.23

Setting	E (GeV)	Q^2 (GeV^2)	x_B	W (GeV)
2010-Kin1	(3.355 ; 5.55)	1.5	0.36	1.9
2010-Kin2	(4.455 ; 5.55)	1.75	0.36	2
2010-Kin3	(4.455 ; 5.55)	2	0.36	2.1

Last week: A glimpse of gluons through DVCS

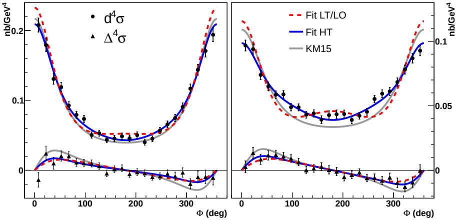
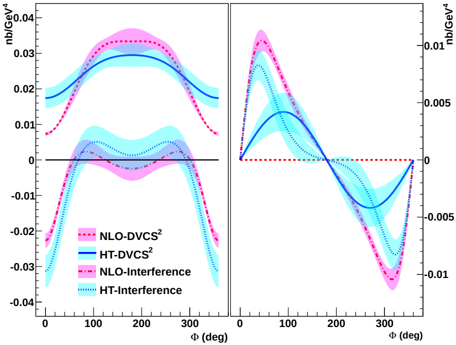


Figure: Q^2=1.75 GeV^2, -t=0.3 GeV^2. E=4.445 GeV (left) and E=5.55 GeV (right)



→ First data set at fixed kinematics but mutiple beam-energy.
→ First phenomenological analysis including kinematical power corrections.

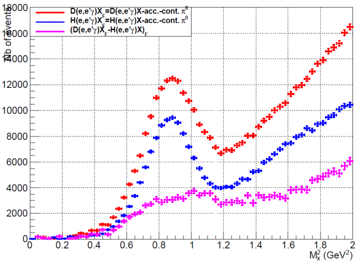
- NLO: Gluon transversity GPDs.
- HT: Q-G-Q correlations.

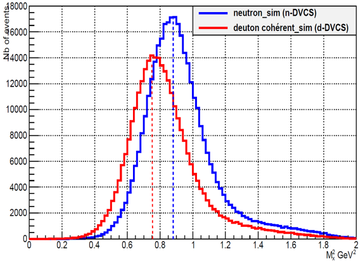
M. Defurne *et al.*, Hall A collaboration, arXiv:1703.0944

Near future: Rosenbluth off neutron

Data were also taken on Deuterium target to measure DVCS on neutron. Since $F_2^n \gg F_1^n$ (AN:1»0.03), we have an easier access to GPD E (alternative to transversely polarized target).

$$s^{\mathcal{I}}_{1,LU} \propto \quad F_1 \; Im\mathcal{H} + \xi(F_1 + F_2) \; Im\widetilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \; Im\mathcal{E} \,,$$



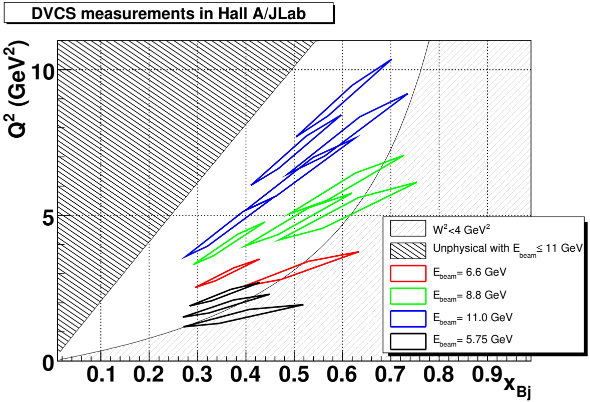


Stay tuned! (Courtesy Meriem Benali)

mid-term Future: Jefferson Lab 12 GeV program

Since 2014, it has started to take data in Hall A. DVCS experiment until late 2016 and extends the kinematical coverage of previous experiments to high x_B at higher Q^2.

In Hall C, HMS upgraded to Super-HMS, Rosenbluth separation of DVCS and π^0 electroproduction.

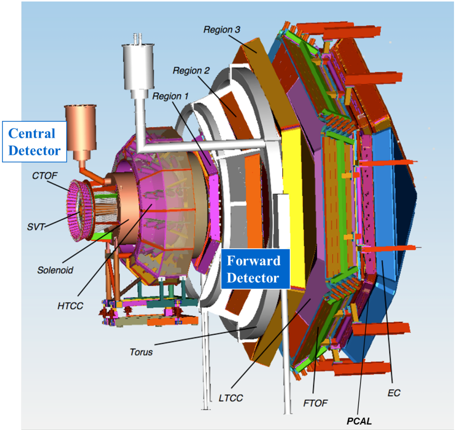


mid-term Future: Jefferson Lab 12 GeV program

It is an exciting time in Hall B since CLAS12 will be fully assemble this summer to receive beam this Fall.

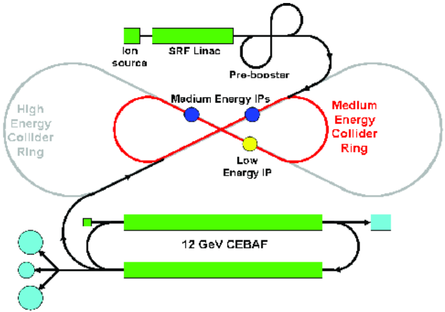
A complete GPD program will be covered:

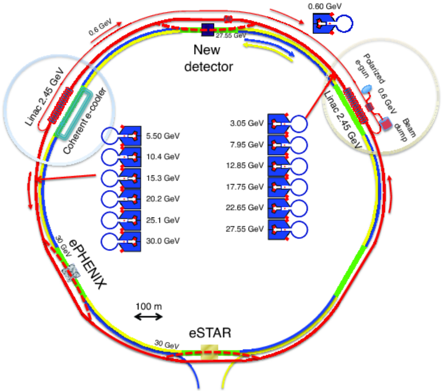
- longituinally polarized electron beam at multiple energy (6.6, 8.8, 11 GeV),
- proton and neutron target,
- unpolarized, longitudinally polarized, transversely polarized (HD-ice),
- to study DVCS and DVMP (π, ϕ, η).



Better than Christmas for the GPD business!

Long-term future: An electron-ion collider





Two designs at Jefferson Lab or at RHIC.

The Electron-Ion collider will complete the set of observables provided by the colliders and COMPASS. (polarizd beams, high luminosity)

Last but not least: The phenomenology

Many channels, many observables provided by different facilites and each of them holds a specific piece of the puzzle.
Need to work hand-by-hand with phenomenologists and theorists .

We will need to develop global analysis tools in order to:

- combine all data and thus strongly constrain fits or models.
- test systematically the impact of diverse assumptions:
  - LO, NLO, NNLO,...
  - the numbers of flavours,
  - the numbers of GPDs,

Kresimir has already shown on monday a global analysis of DVCS.
But I want to use this opportunity to make some advertisement for a project of major importance for me.

GPD Computing made simple.

Differential studies: physical models and numerical methods.

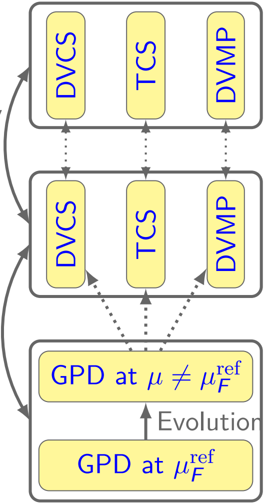
Phenomenology of Generalized Parton Distributions

PARTONS Project

Full processes
Experimental data and phenomenology

Small distance
Computation of amplitudes

Large distance
First principles and fundamental parameters



- Many observables.
- Kinematic reach.

- Perturbative approximations.
- Physical models.
- Fits.
- Numerical methods.
- Accuracy and speed.

H. Moutarde | Recent results | 2 / 4

Conclusion

- I have been unfair with DVMP because it is as interesting as DVCS.
- So far a lot of data have been collected, but high statistical data set startputting models and fit under pressure.
- The future data at 12 GeV, with an unprecedented statistical precision, will surely complete the proton profile in the valence region.
- COMPASS (Mathias'talk) will bring unique information about the sea quarks, and even add its touch to the low-valence region.
- Finaly, an EIC is needed to study the gluons at low-x by providing different observables with high statistics.

It is a great time to join the GPD adventure (Gotta catch'em all!)