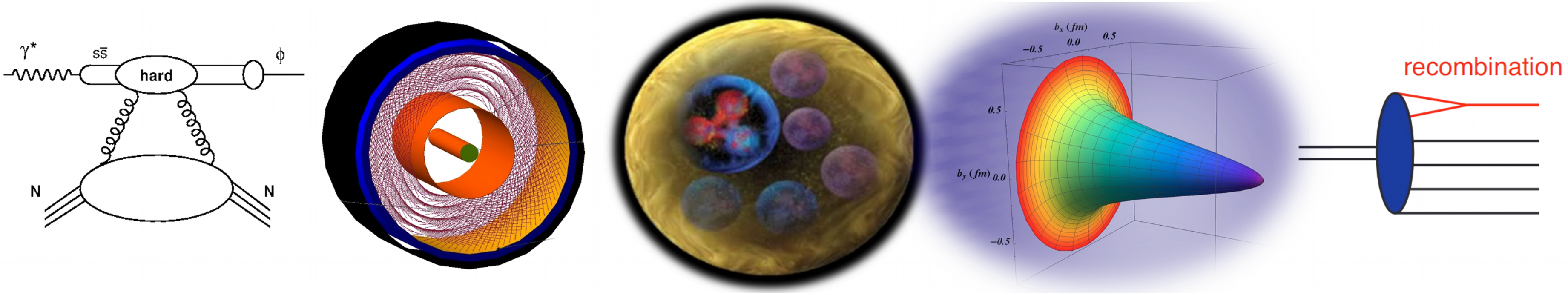
Lessons from Lepton-Nucleon and Lepton-Nuclei Interactions



Probing the structure of the atomic nucleus

Raphaël Dupré

INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

université PARIS-SACLAY

Disclaimer

This will be only a selection of topics

- Like any review of a field
- I encourage you to go read some of the ref.

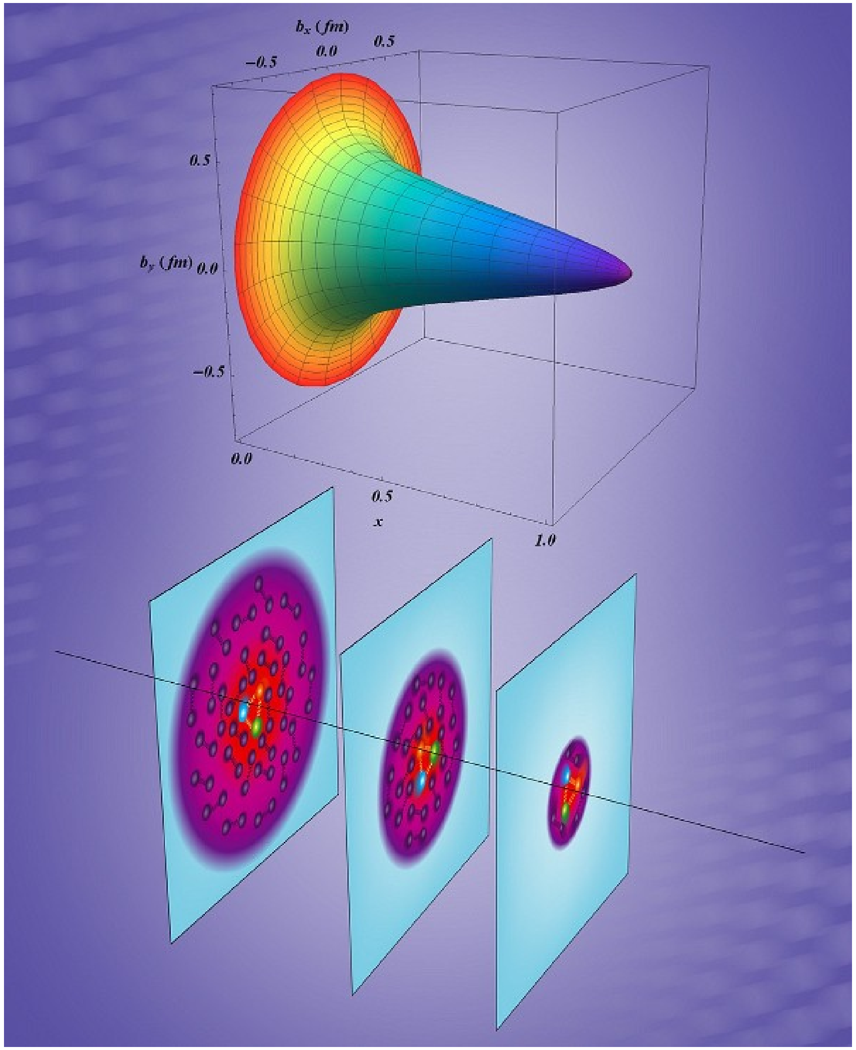
Speaking of references

- I will only give references to (some) reviews, which I highly recommend to read
- Original papers are often outdated or overly technical and not very helpful

Please ask questions or clarifications

- Let me know if you want more details on a topic

Table of Content



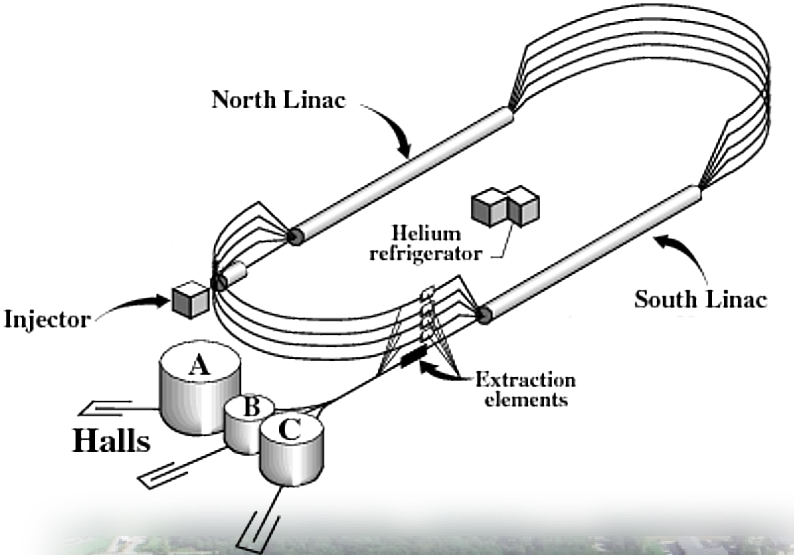
Presentation JLab

Jefferson Laboratory

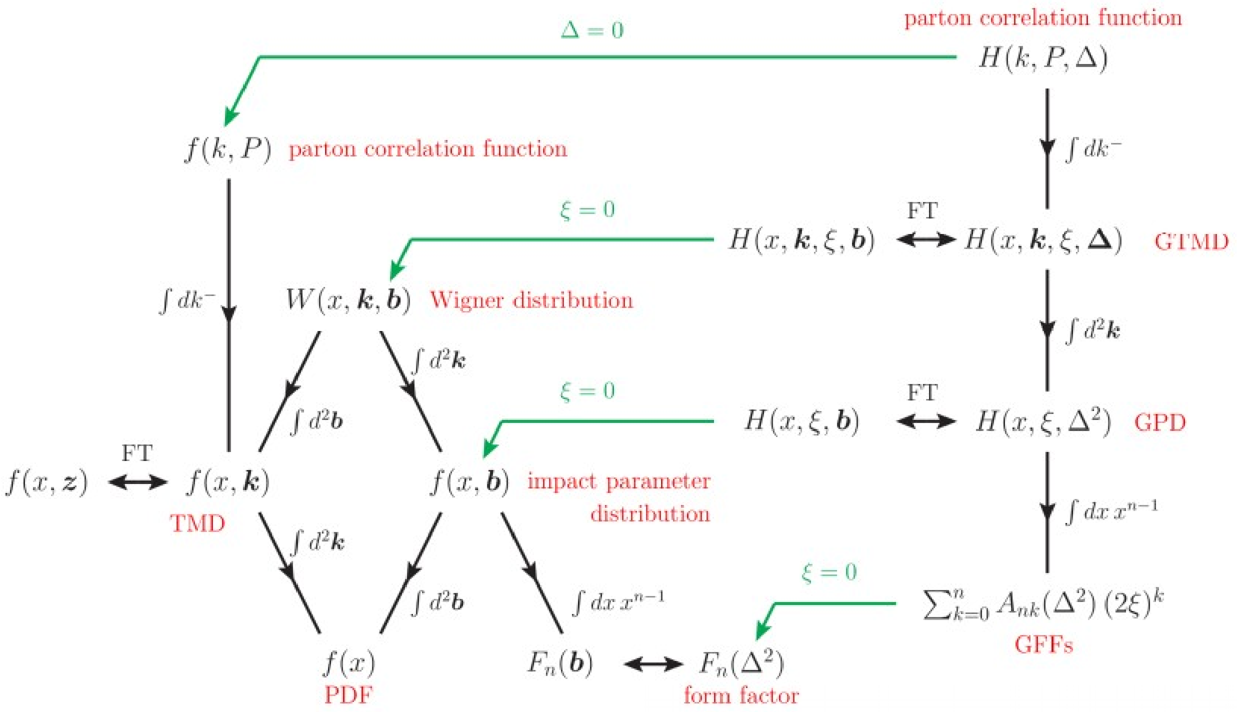
- **Provides a 6 GeV electron beam (now up to 12 GeV)**
- **High quality beam**
  - *Beam size ~150µm*
- **100% duty factor**
- **Intensity up to 100 µA**

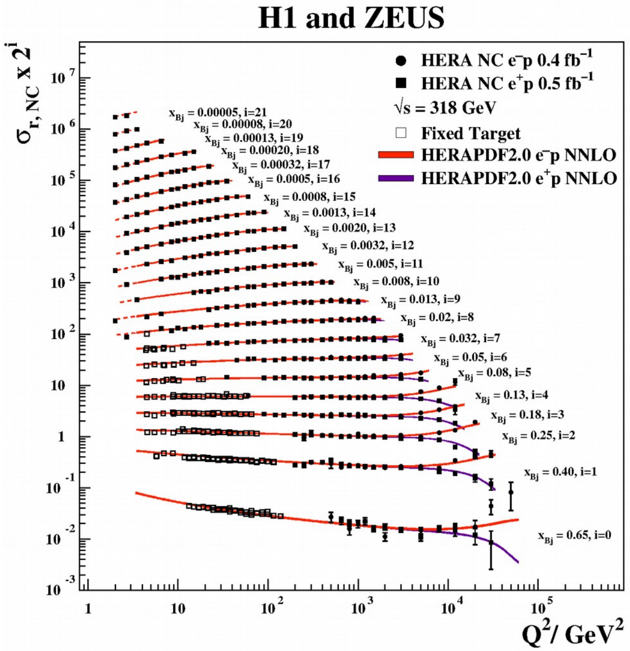
Four experimental Halls

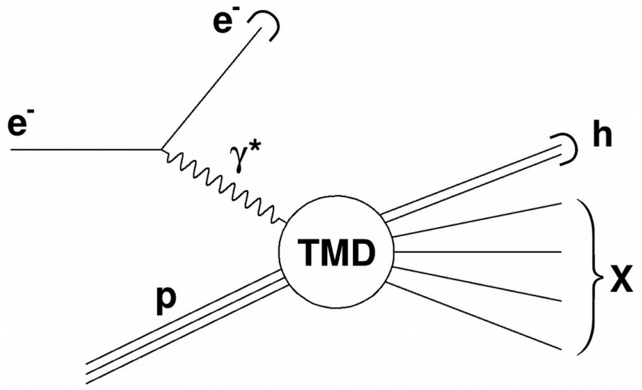
- **Hall A & C with arm spectrometers**
- **Hall B with a large acceptance spectrometer**
- **Hall D with a photon beam**

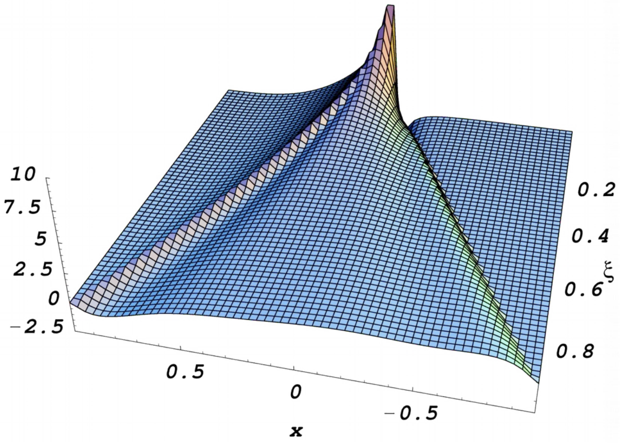


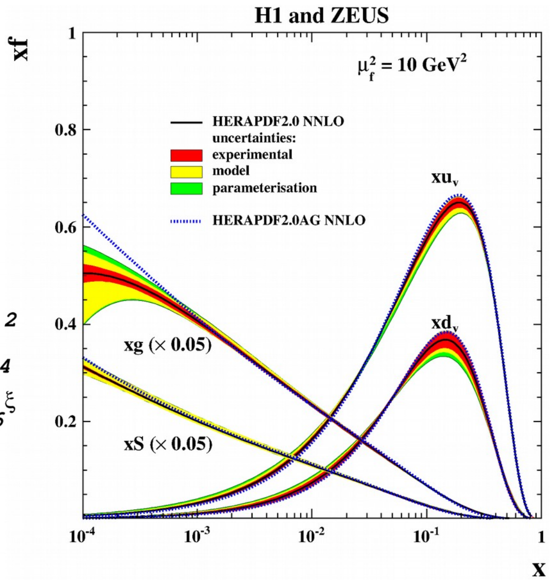
Part 1: Lepton-Nucleon



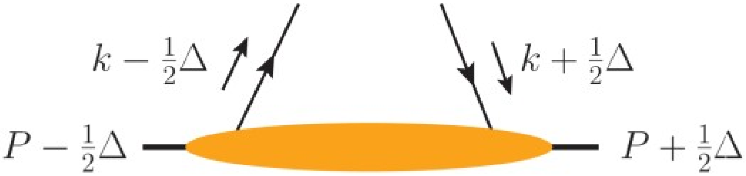


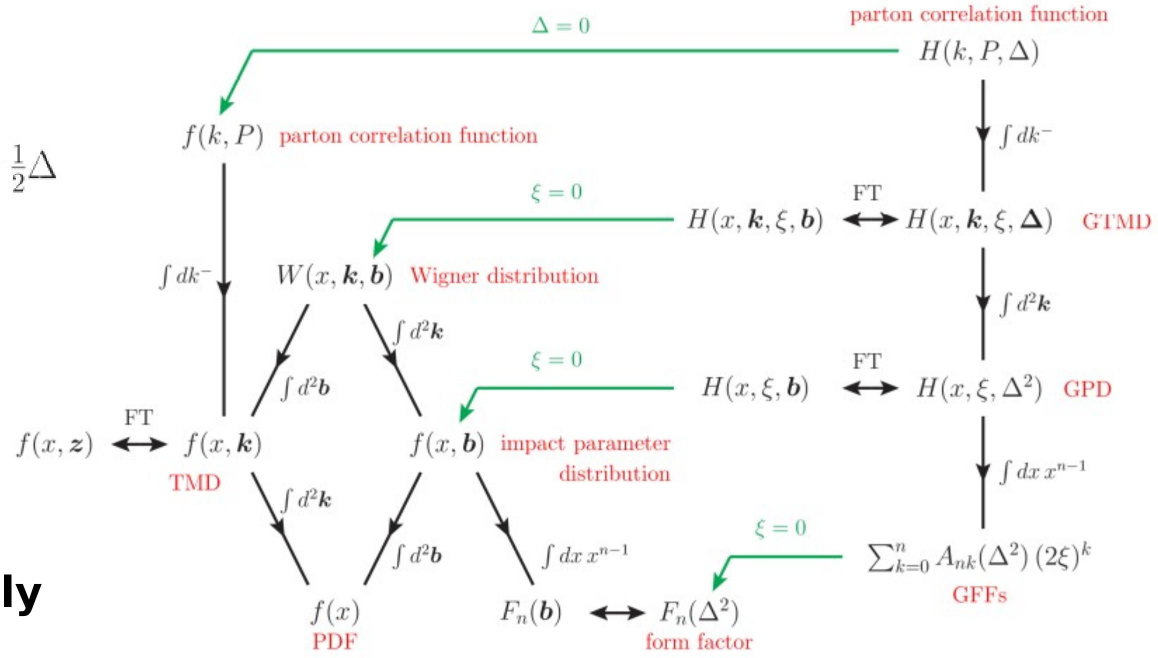






Structure Functions





They parametrize the unknown

- In QCD we have very little information on them
- Their knowledge is mostly based on experiment
- Calculations and models lead to sum rules and behavior at the limits

They are carefully defined

- To understand the structure of the target hadron
- They are universal, i.e. not process dependent
- See M. Diehl QCD lecture for details

M. Diehl, Eur. Phys. J. A (2016) 52: 149

All fundamentally parton correlation functions

From experiment to structure functions

What process for what structure function?

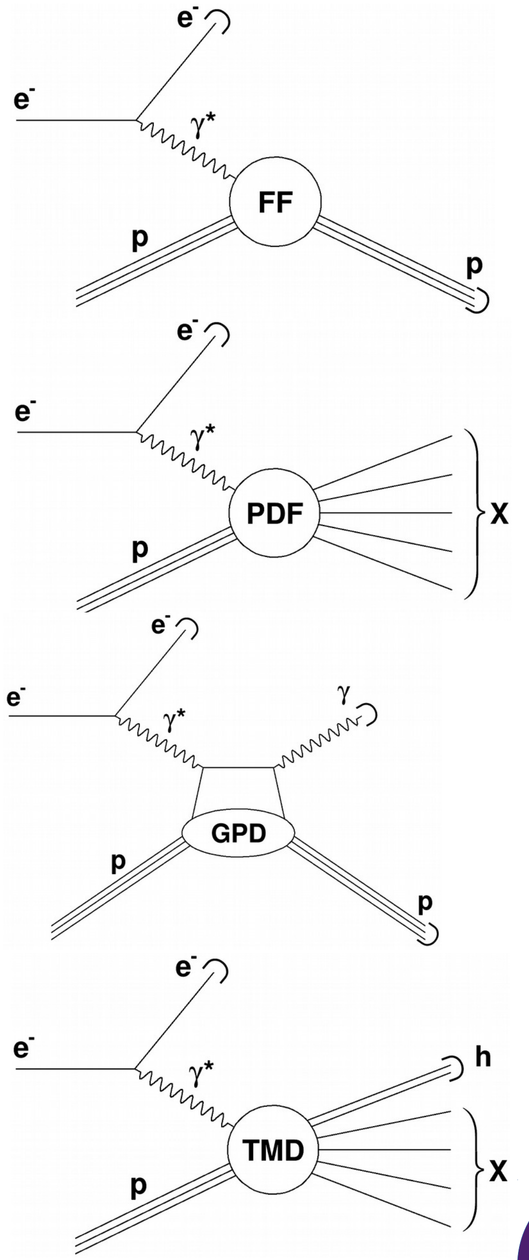
R. Brock et al. Rev.Mod.Phys. 67 (1995) 157-248

Simplest structure goes with simpler processes

- **Form factors are obtained from elastic scattering**
- **Parton distribution functions from deeply inelastic scattering (DIS)**

More complex structure is unraveled through complex processes

- **Exclusive processes like DVCS give generalized parton distributions**
- **Semi-inclusive DIS are linked to TMDs**



Evolution

Disclaimer

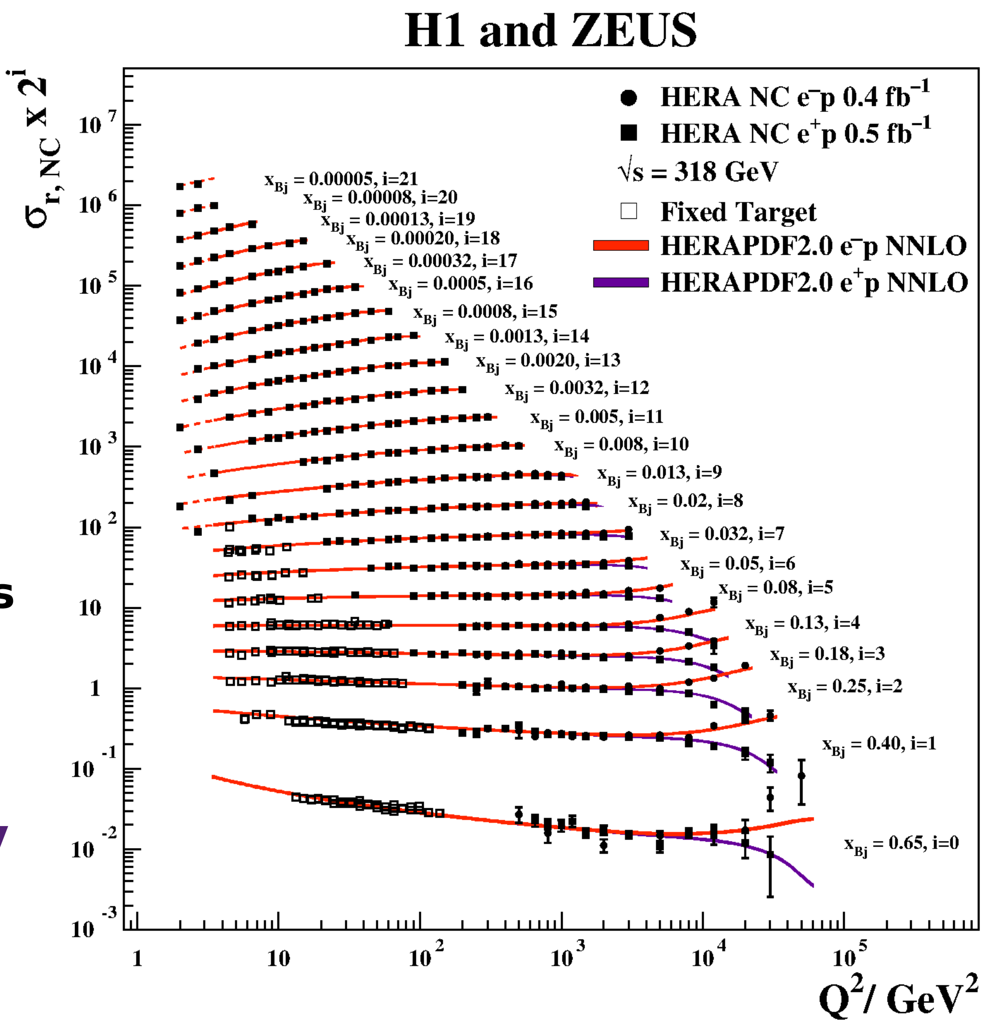
- In this lecture, Q^2 will be mostly ignored
  - *Except for FF*
- However, evolution applies to most structure functions
  - *PDFs, GPDs, TMDs...*

What is evolution?

- It is the effect of changing the virtuality of the probe
- Given by DGLAP formulas in PDFs for this lecture
- Their are other regimes
  - *See lecture on CGC*

It works very well over many orders of magnitude

- And similarly in fragmentation functions
- A very strong case for QCD



Factorization and Universality

A not so straight forward property

- The dynamic in the target can be separated from the probe
- It gives their predictive power to the structure functions

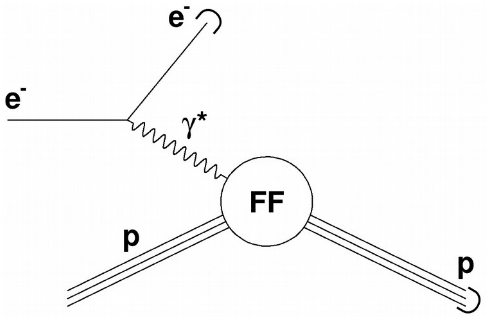
Mathematically even less straight forward

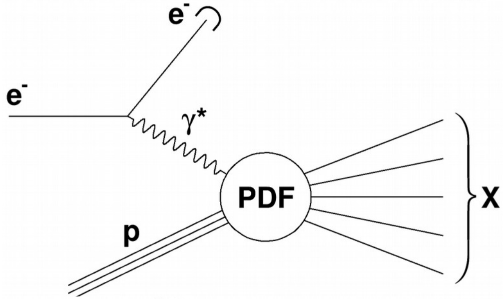
- Proven now for all processes discussed here in nucleon-lepton
- Not so clear for some processes on nuclear targets

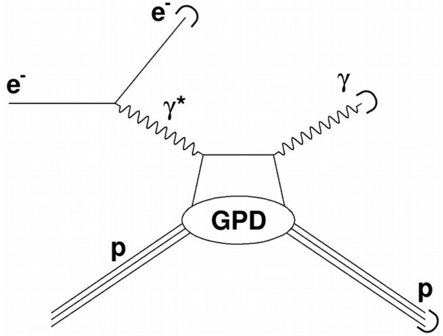
Key to universality

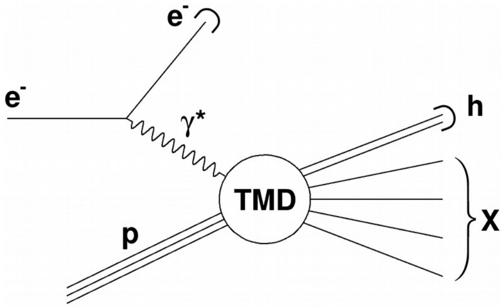
- Allows to use these functions in other processes
  - *Any lepton beam*
  - *Hadron collisions*
  - *Neutrino interactions*

J. Collins, Camb.Monogr.Part.Phys.Nucl.Phys.Cosmol. 32 (2011) 1-624









Measuring Form Factors

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e} = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{\mathrm{Mott}} \frac{E_e}{E_{\mathrm{beam}}} \frac{1}{1+\tau} \left(G_E^2 + \frac{\tau}{\epsilon} G_M^2\right),$$

Form Factors

- Two of them for spin ½ nucleon
- Encode the charge and magnetic distributions
- Mean squared radius is given by their slope at $Q^2 \to 0$

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_{\mathrm{Mott}} = \frac{\alpha^2 \cos^2\frac{\theta}{2}}{4E_{\mathrm{beam}}^2 \sin^4\frac{\theta}{2}}.$$

$$\epsilon = \frac{1}{1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}}.$$

$$\tau = Q^2/4M^2.$$

Cross section measurements

- Most common and easiest method
- The Rosenbluth extraction
- Problematic for very small or large Q^2

$$A_{\mathrm{perp}} = \frac{-2\sqrt{\tau(1+\tau)}\tan\frac{\theta_e}{2}\frac{G_E}{G_M}}{\left(\frac{G_E}{G_M}\right)^2 + \frac{\tau}{\epsilon}}.$$

Double polarization experiments

- Necessitates a polarized target
- And measuring the polarized scattered nucleon
- Experimentally much more complex
- Gives better accuracy at high momentum

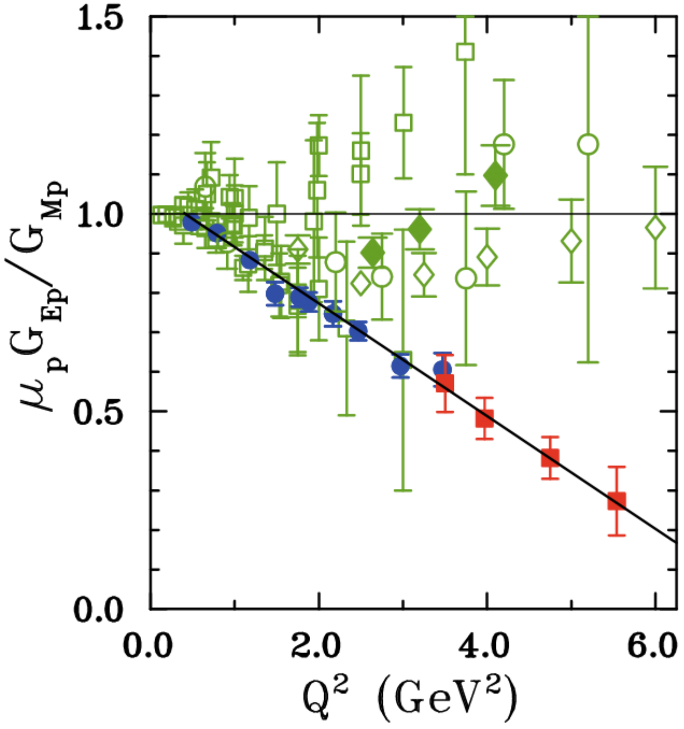
$$\frac{G_E}{G_M} = -\frac{P_t}{P_\ell}\frac{(E_{\mathrm{beam}} + E_e)}{2M}\tan\frac{\theta_e}{2}.$$

V. Punjabi et al. Eur.Phys.J. A51 (2015) 79

Discrepancies between methods

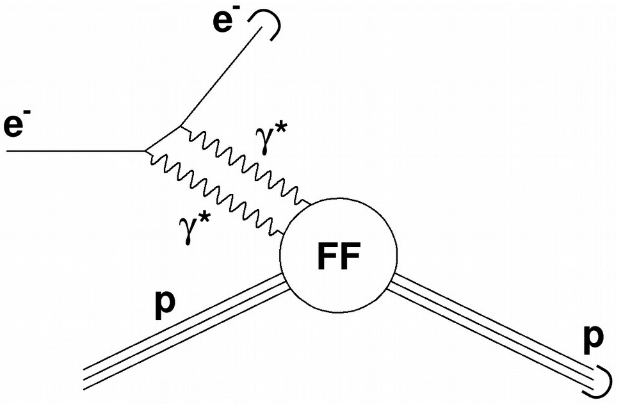
Using the two methods, we found conflicting results

- **Two different behaviors between Rosenbluth and polarization measurements**
- **Gets larger at high momentum transfer**
- **Which is correct? What is going on?**



We neglected too much

- **Two photon exchange becomes relevant in this situation**
- **Neglecting higher order diagrams can be problematic**
  - *Often when getting in extreme kinematics*



Corrections are model dependent

- **Polarization measurements are better in this regard**

The Proton Charge Radius

On the opposite end of the Q^2 spectrum

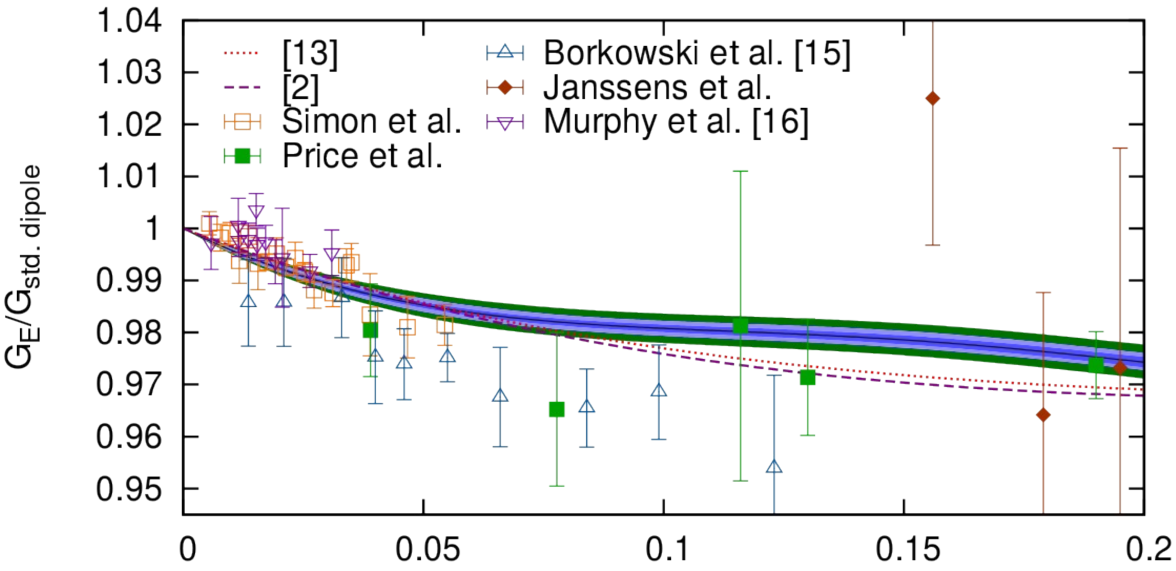
- Important focus to measure the proton radius

Two conflicting constraints

- Measuring lower values give less lever arm
- Higher values are sensitive to other features

Highlights the importance of statistical analysis

- Fitting of form factors (and all structure functions) is very controversial and discussed in an important literature



The Proton Radius Puzzle

The proton radius is also subject to controversy

- Here most electron scattering measurement agrees

Atomic Physics measurements however…

- It is possible to access the proton radius independently through atomic physics
- Certain level splits are directly sensitive to the proton radius

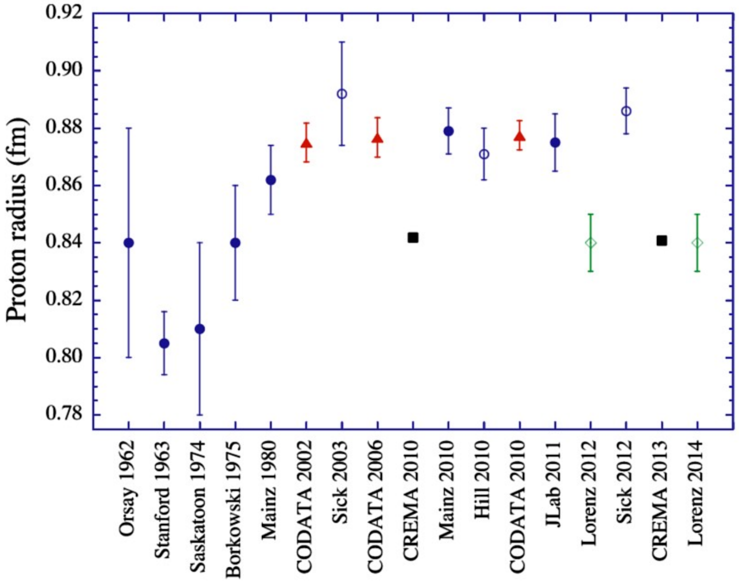
Discrepency between electronic and muonic atoms

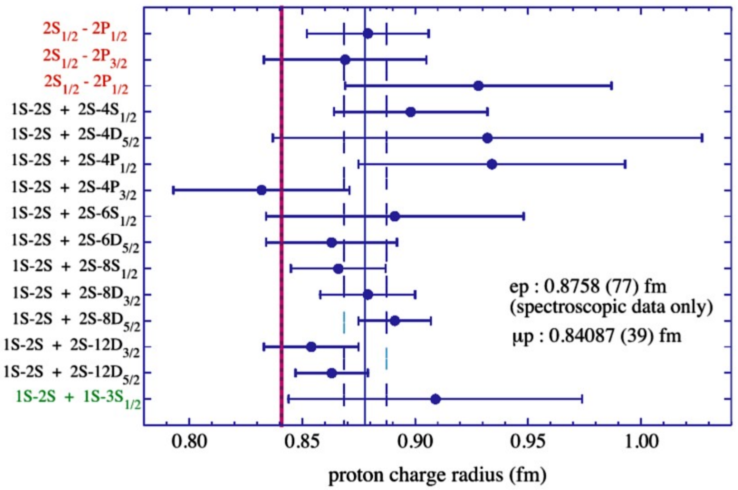
- The electronic hydrogen measurements are in line with scattering
- The muonic hydrogen measurement is an order of magnitude more precise but 5 sigma away

This puzzle remains an open question to this day

R. Pohl et al. Ann.Rev.Nucl.Part.Sci. 63 (2013) 175-204

C. Carlson, Prog.Part.Nucl.Phys. 82 (2015) 59-77





Interpretation of FFs

The interpretation of the FFs is not so simple

- One can make a three dimensional Fourier transform to get an image of the proton
- While natural this method raises many issues
- Mainly boost invariance

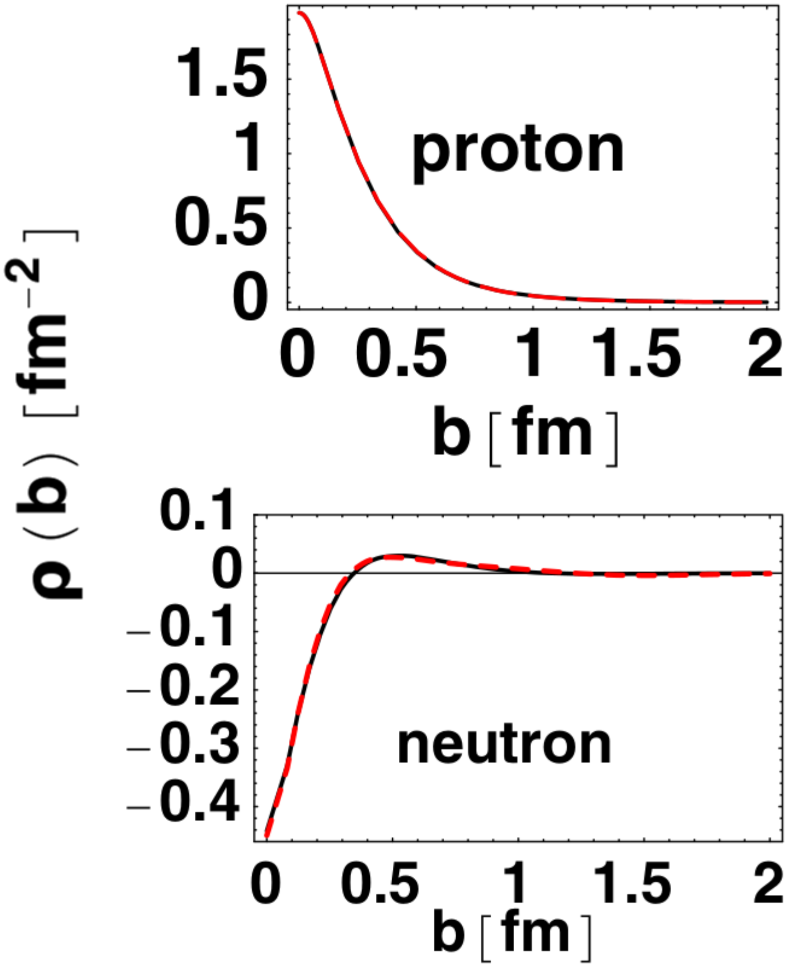
On the light front

- Based on modern GPD interpretations
- Only a two dimensional Fourier transform
- Gives a clean image of the nucleon

Be aware of the limitations

- Higher order contributions
- Nucleons might not be spherical

C. Alexandrou et al. Rev.Mod.Phys. 84 (2012) 1231



Flavor Separation of FFs

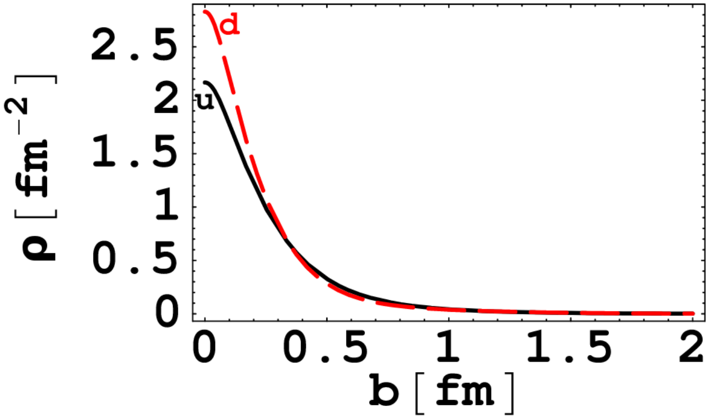
Using isospin symmetry

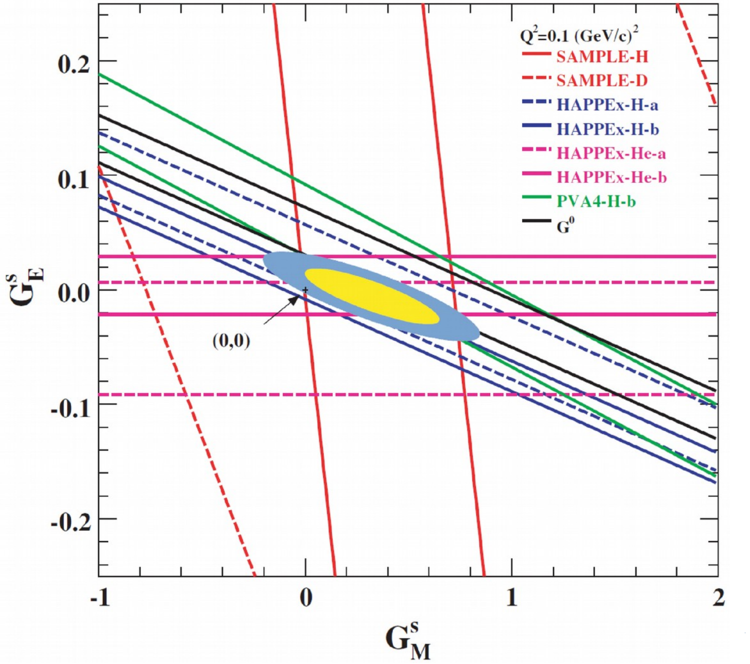
- We can separate the u and d quark profiles in the nucleon

Parity violating scattering

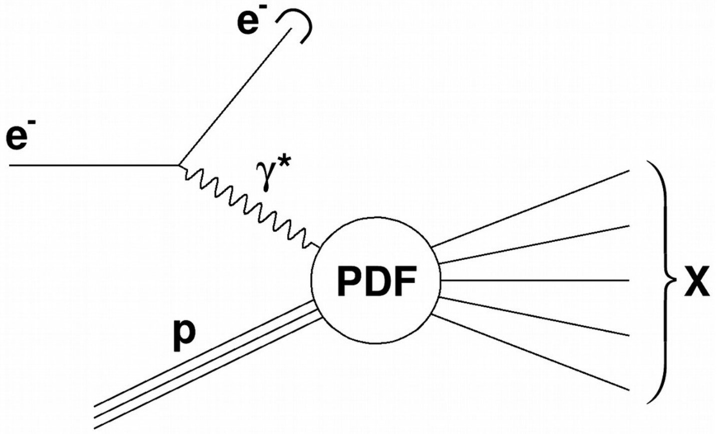
- Give access to the weak charge of the nucleon
- Leads to the strange form factor
- Present measurement indicates that it is non 0

D. Armstrong and R. McKeown
Ann.Rev.Nucl.Part.Sci. 62 (2012) 337-359





Deeply Inelastic Scattering and PDFs



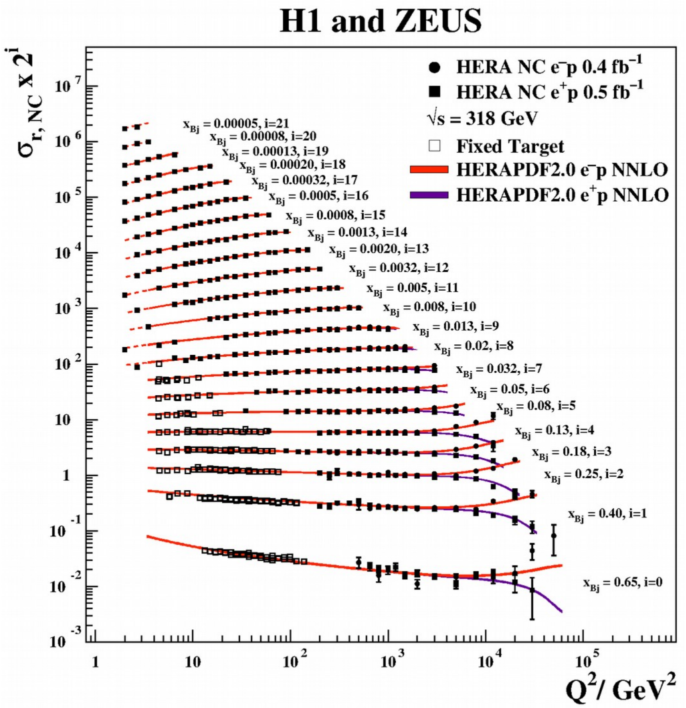
Extracting PDFs

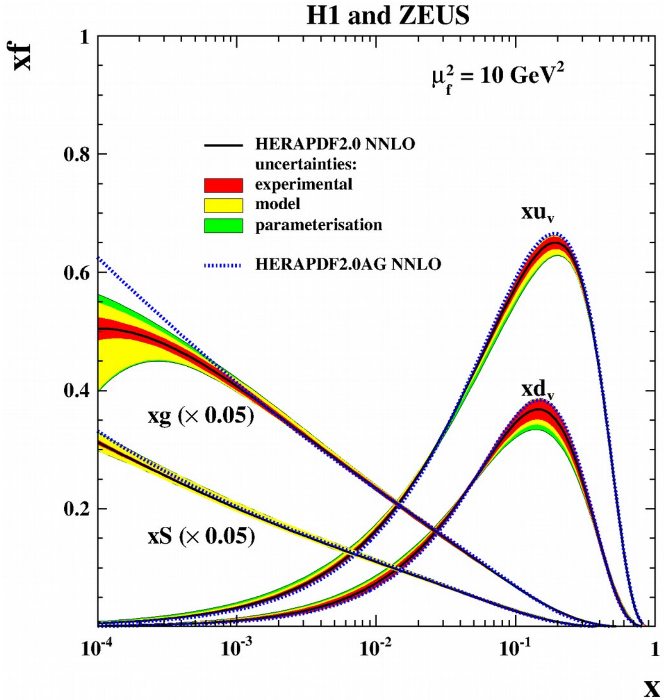
- **Mostly using DIS**
  - *HERA with H1 and Zeus*
- **Now with more and more processes**

Now most extractions are made using NNLO calculations

- **We see a very good fit using only a x dependence of the PDF**

A. Accardi et al. Eur.Phys.J. C76 (2016) no.8, 471



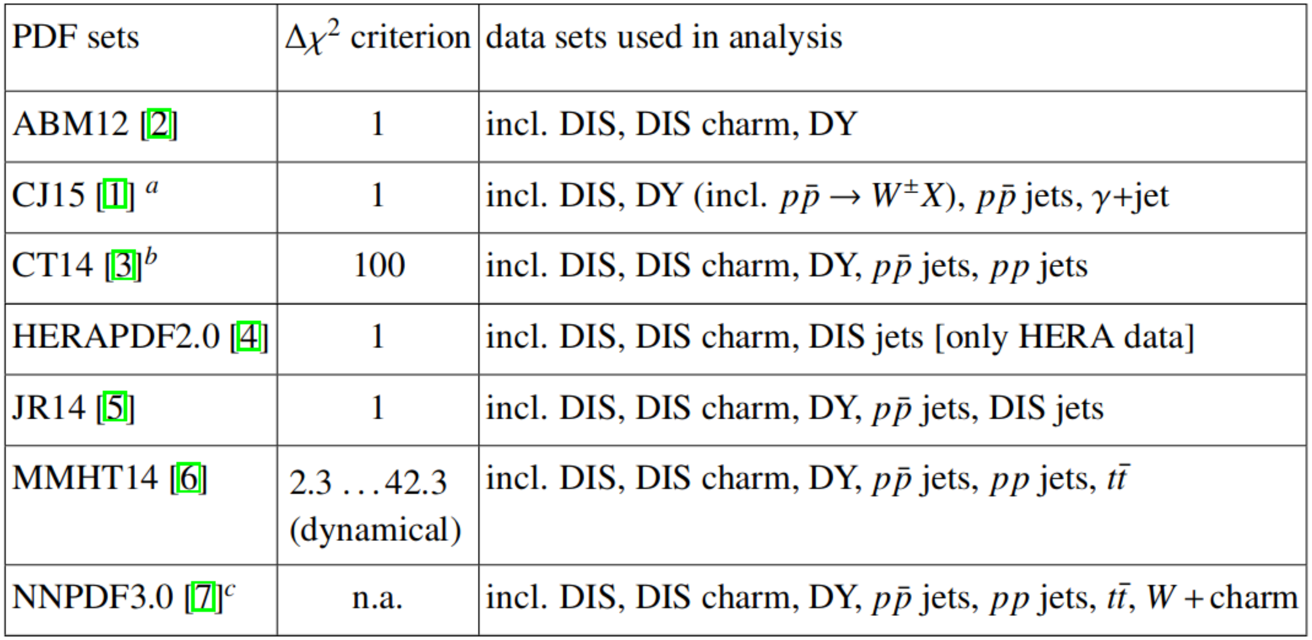


The Main Fit Collaborations

There are many fitting collaborations

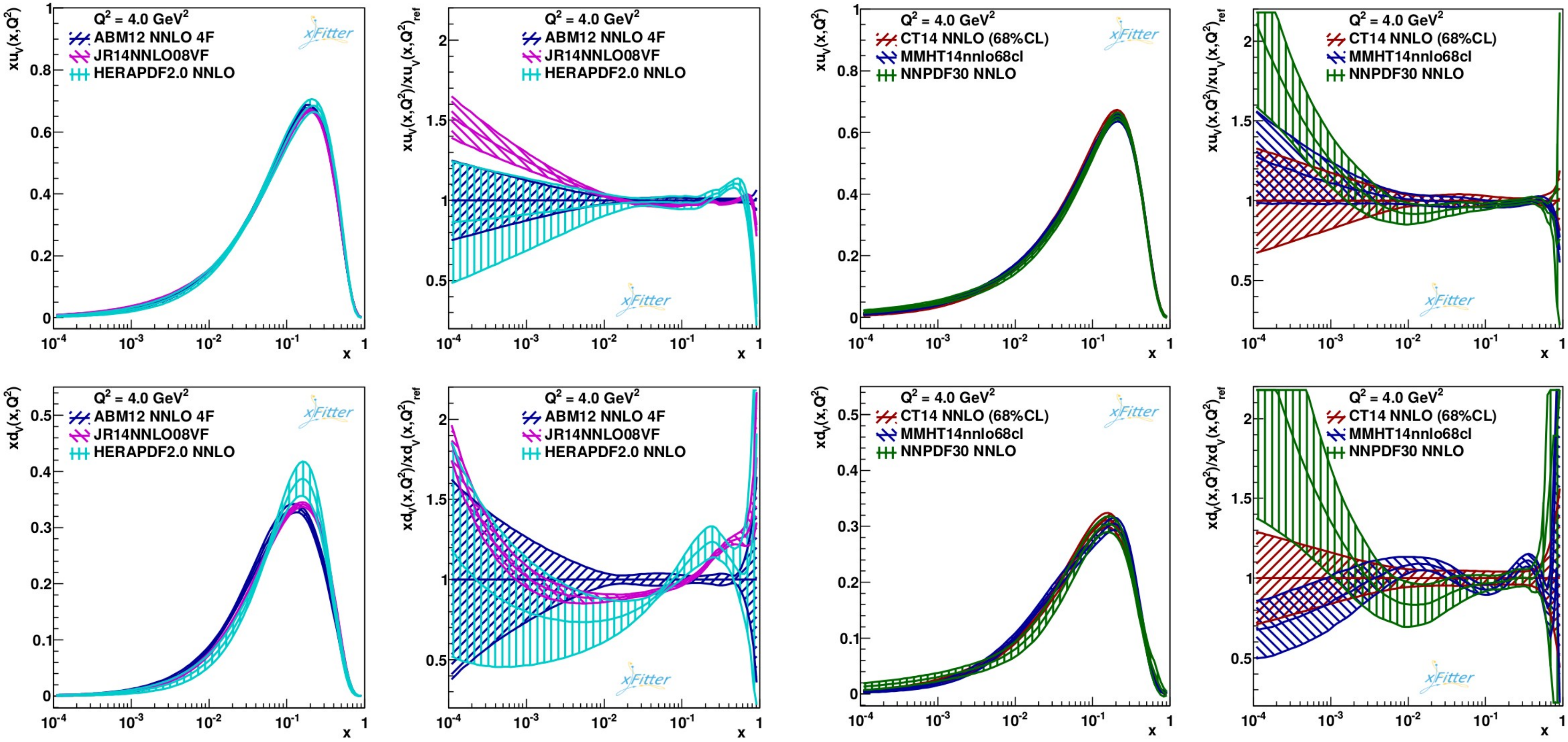
- **They use different orders**
  - *When using them one needs to be careful with consistency*
- **They include different processes**
  - *Especially important for flavor decomposition*
- **They apply different cuts for DIS (Q^2 & W)**
- **They use different data sets**
- **They use different parametrizations**

→ Therefore they give rather different results



PDF sets	$\Delta\chi^2$ criterion	data sets used in analysis
ABM12 [2]	1	incl. DIS, DIS charm, DY
CJ15 [1] [a]	1	incl. DIS, DY (incl. $p\bar{p} \to W^{\pm}X$), $p\bar{p}$ jets, γ+jet
CT14 [3] [b]	100	incl. DIS, DIS charm, DY, $p\bar{p}$ jets, pp jets
HERAPDF2.0 [4]	1	incl. DIS, DIS charm, DIS jets [only HERA data]
JR14 [5]	1	incl. DIS, DIS charm, DY, $p\bar{p}$ jets, DIS jets
MMHT14 [6]	2.3 . . . 42.3 (dynamical)	incl. DIS, DIS charm, DY, $p\bar{p}$ jets, pp jets, $t\bar{t}$
NNPDF3.0 [7] [c]	n.a.	incl. DIS, DIS charm, DY, $p\bar{p}$ jets, pp jets, $t\bar{t}$, W + charm

Valence PDFs



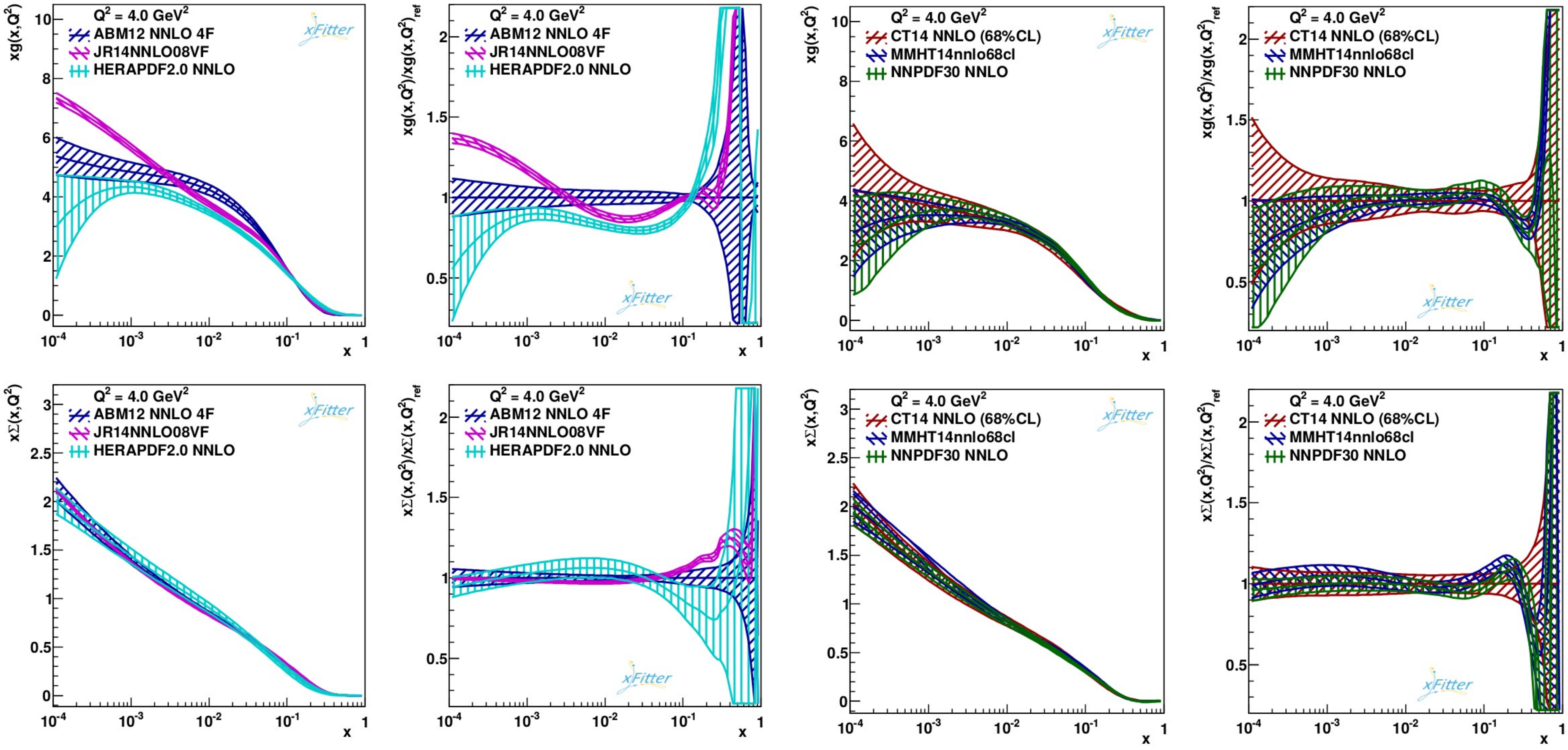
Valence quarks

- Defined as u-bar(u)
- Rather well known from x of 5.10^{-3} to 0.4

High x region remains problematic

- High x and high W is difficult to obtain

Sea & Gluon PDFs



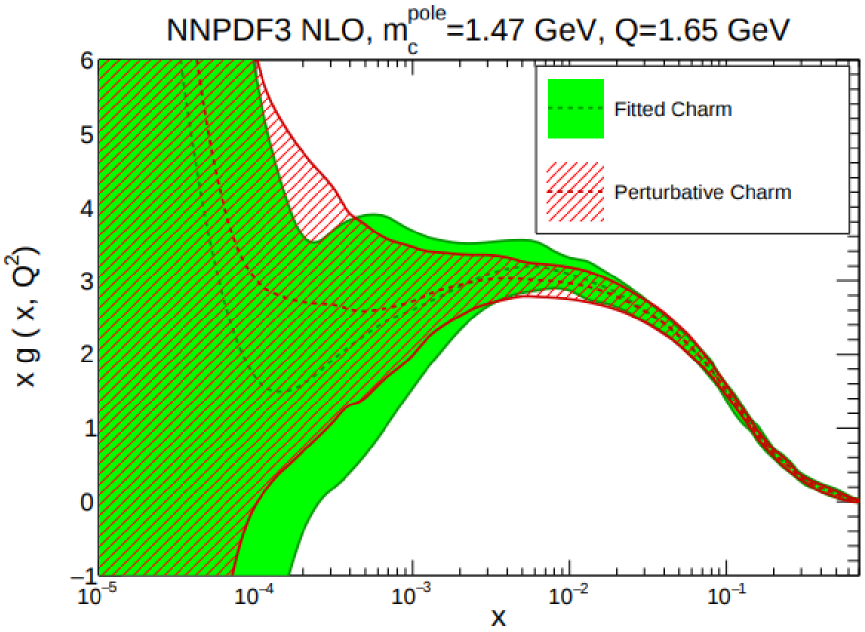
Sea Quarks

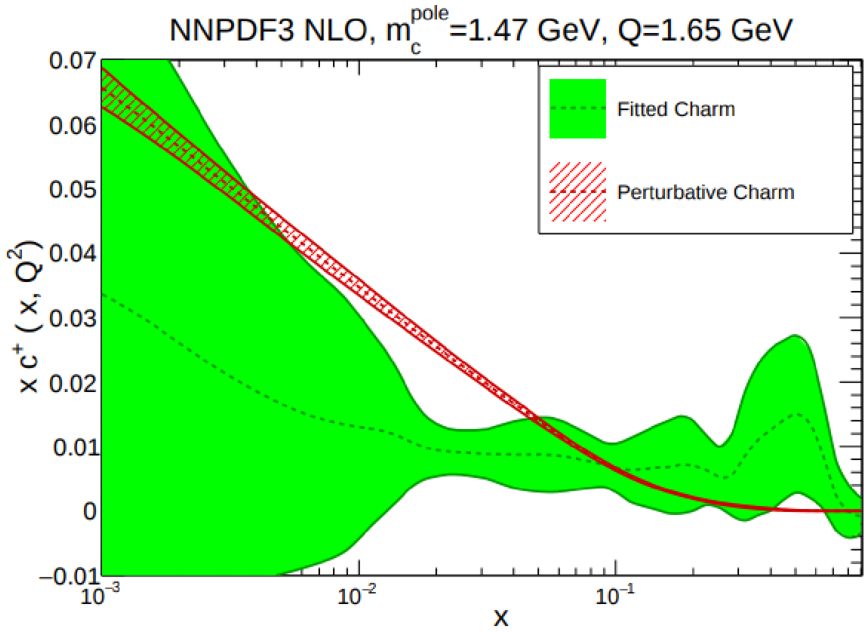
- Very well known down to small x
- Dominated by perturbative contributions

Gluons are least known

- They are mostly constrained by hadron-hadron collisions

Heavy Quarks in PDFs





Separating perturbative from intrinsic

- Try to resolve the part of sea quark purely generated through evolution
- To isolate the part present in the nucleon before the high energy interaction

This remains undecided for charm

- None the less charm perturbative contribution is particularly useful to constrain gluon PDFs

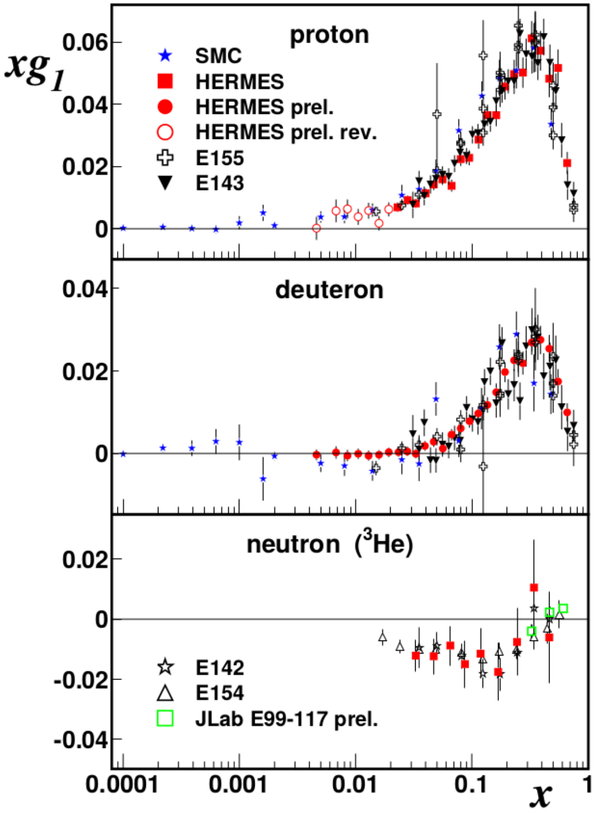
Polarized PDFs

Polarization gives access to new structure

$$F_1(x) = \frac{1}{2x}F_2(x) = \frac{1}{2}\sum_q e_q^2\{q+\bar{q}\}(x)$$

$$g_1(x) = \frac{1}{2}\sum_q e_q^2 \Delta q(x).$$

- At the root of the proton spin crisis
- We find surprisingly small contribution from the quarks to the proton spin
- Yet they follow their sum rules

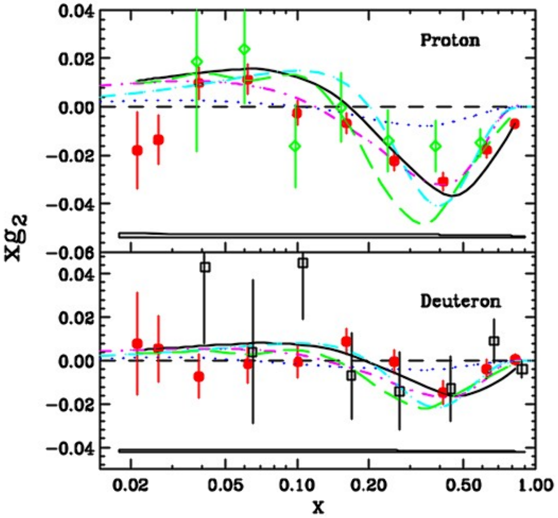


Important input from other experimental sources

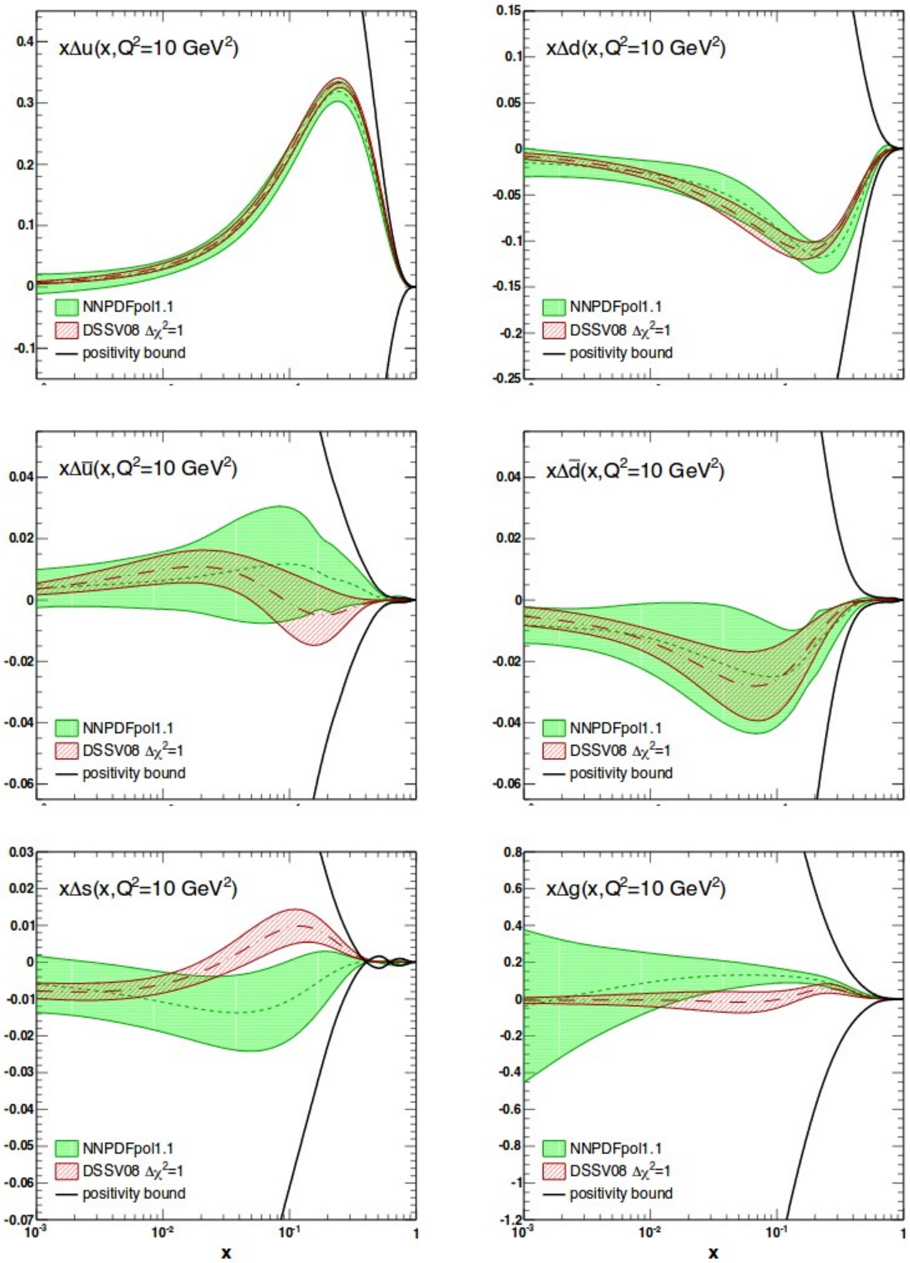
- Beta decay of bosons

S. Bass, Rev.Mod.Phys. 77 (2005) 1257-1302

C. Aidala et al. Rev.Mod.Phys. 85 (2013) 655-691



Polarized PDFs



Only a few extractions of the polarized PDFs

- u and d have opposite contributions
- Indications that the s contribution is negative

Polarization of gluons remains elusive

- Focus of important experimental programs
- Use polarized p-p collisions

Other sources of spin

- Orbital angular momentum is the main motivation to measure GPDs

Open Questions

Many problems remain open:

What is the radius of the proton?

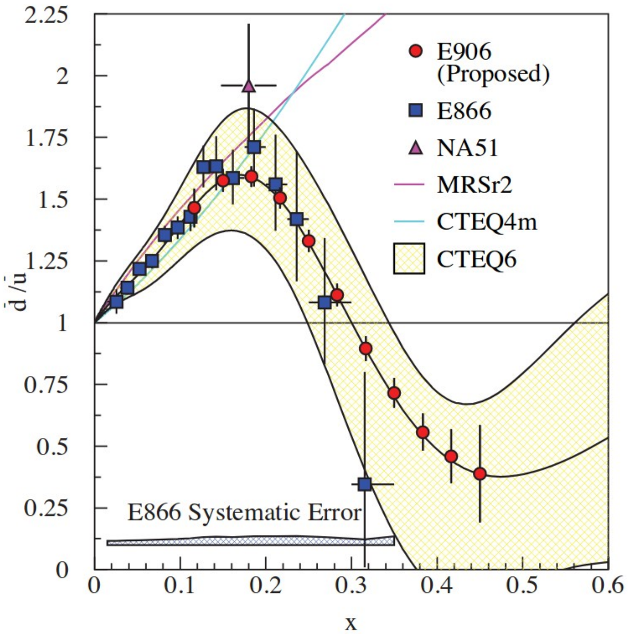
- Muon scattering measurements are ongoing

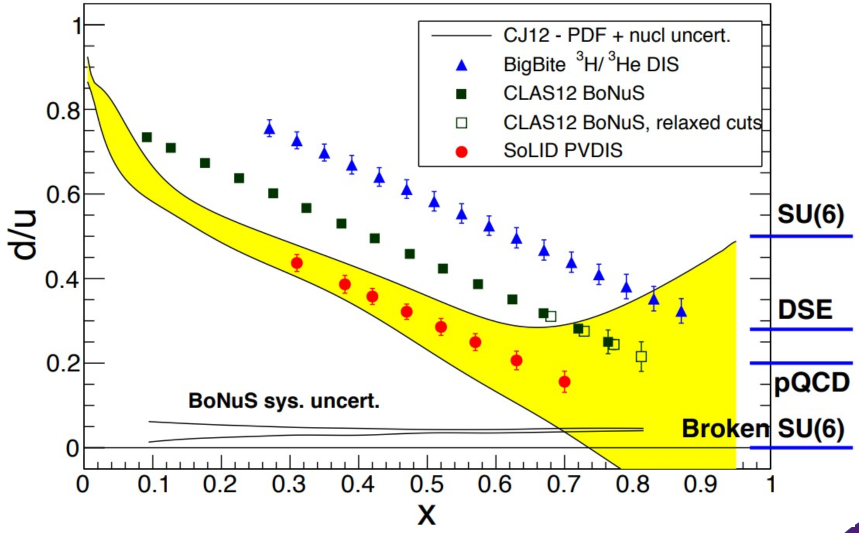
Understanding high x behaviors

- Drell-Yan measurements are used to look for flavor asymmetries in the sea
- Measurements are trying to better understand the neutron

Proton spin crisis

- Better understanding of the spin contributions
- Higher precision determination of sum rules

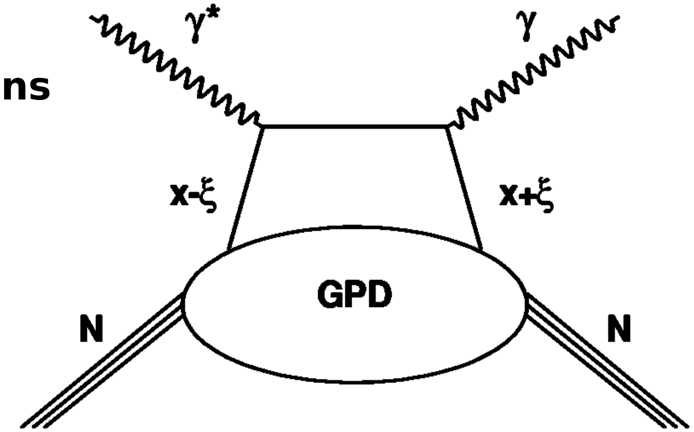




GPD Theory Basics

Generalizing the parton distributions

- Three dimensional (x, ξ and t) structure functions
- Accessible through exclusive processes
  - *DVCS, DVMP, TCS, DDVCS…*



Deeply virtual Compton scattering

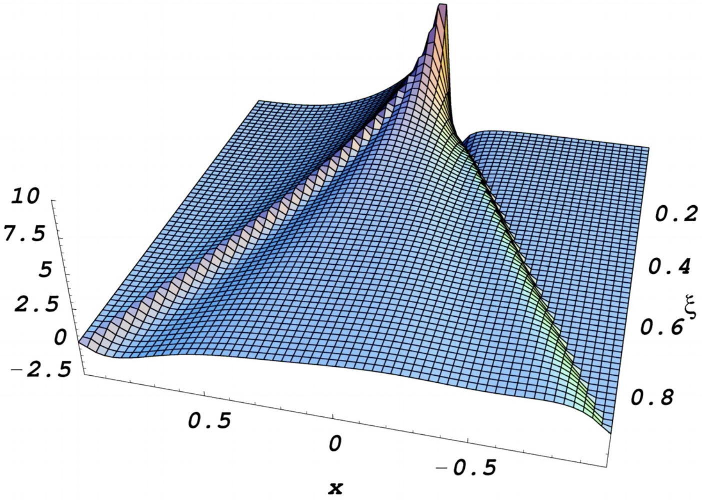
- The exclusive electro-production of a photon
- The simplest access to GPDs

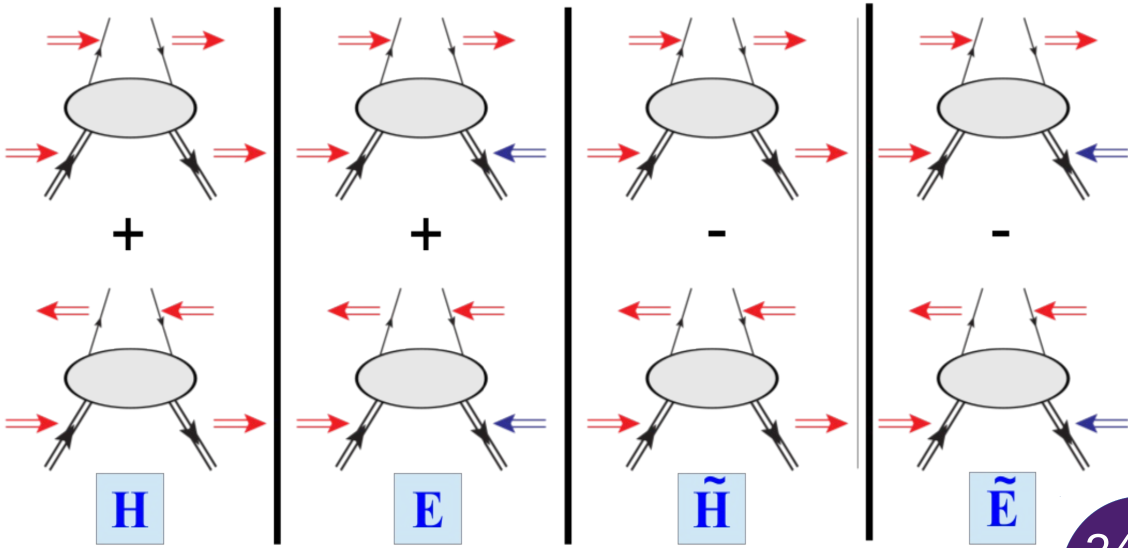
Ji Sum Rule

- Links directly GPDs to the orbital angular momentum of quarks

$$J_q = \frac{1}{2}\int_{-1}^{+1} dx\, x\, [H^q(x,\xi,t=0) + E^q(x,\xi,t=0)]$$

M. Diehl, Phys.Rept. 388 (2003) 41-277





GPD Phenomenology Summary

DVCS is not the only process to produce photons exclusively

- Photons can be emitted by the lepton (Bethe-Heitler)
- Generates asymmetries through its interference with DVCS

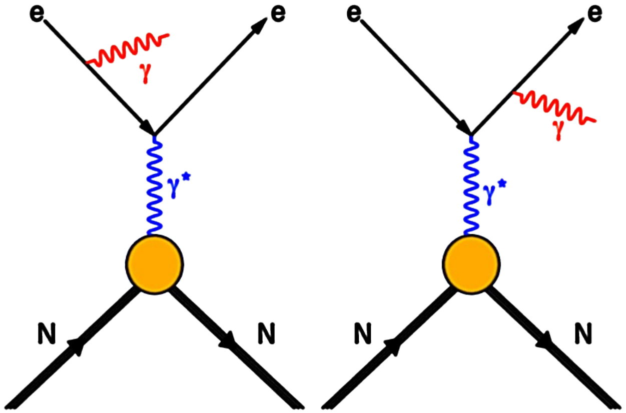
DVCS does not give access to all three variables

- We measure Compton form factors (CFFs)

Gives many interesting observables

- Absolute cross sections
- Spin asymmetries (beam and target)
- Charge asymmetries

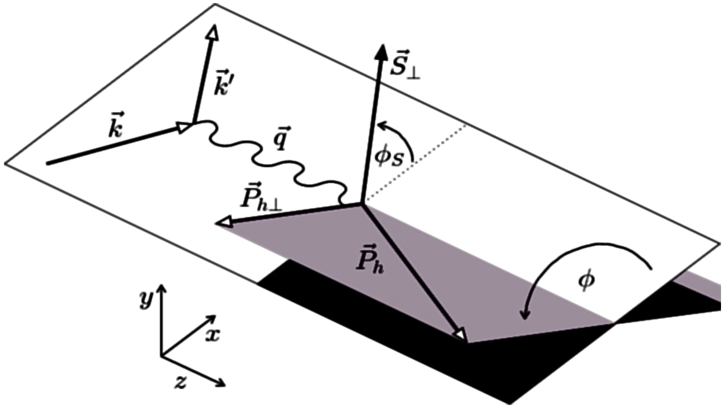
M. Guidal et al. Rept.Prog.Phys. 76 (2013) 066202



$$d\sigma \propto |\tau_{\mathrm{BH}}|^2 + \underbrace{\left(\tau^*_{\mathrm{DVCS}}\tau_{\mathrm{BH}} + \tau^*_{\mathrm{BH}}\tau_{\mathrm{DVCS}}\right)}_{\mathcal{I}} + |\tau_{\mathrm{DVCS}}|^2$$

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

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



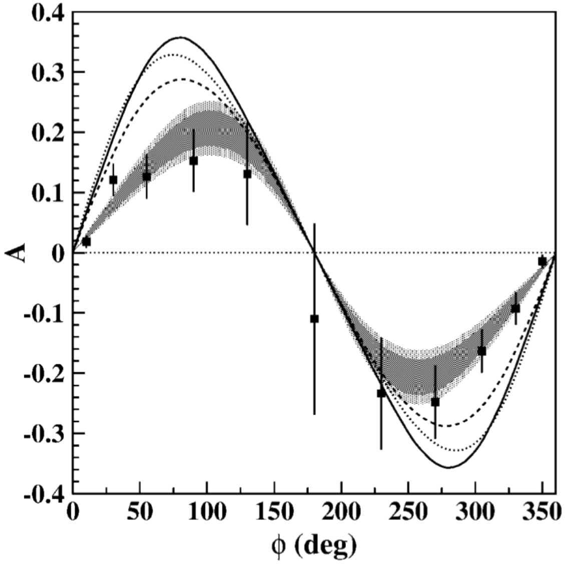
Actually Measuring GPDs

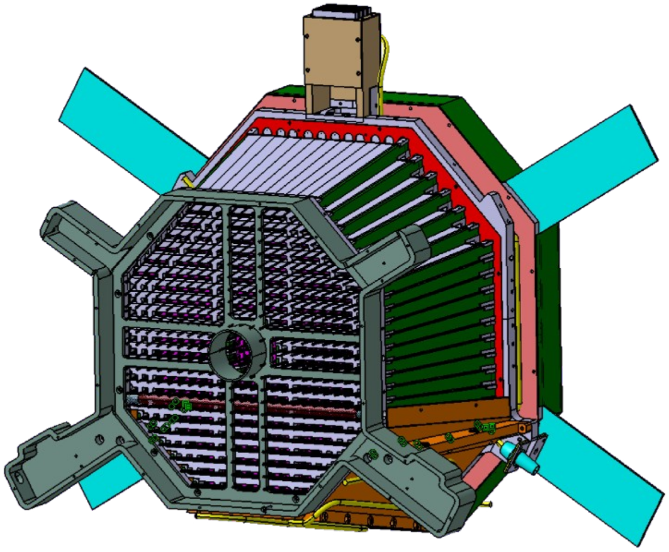
Theory triggered lots of DVCS measurements

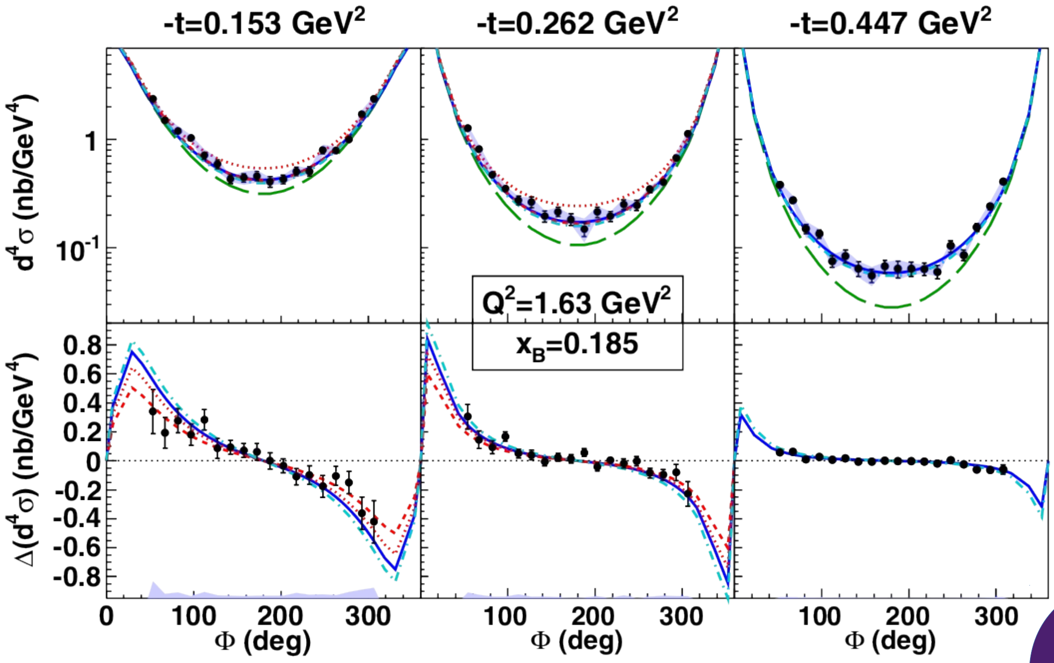
- First by HERMES and CLAS
- Then with new dedicated equipment

Allows to extract the complex CFFs

- A complete set of measurement is possible
    - *Need positron beam and transversely polarized target*
- Only achieved by HERMES







The Fits and the Caveats

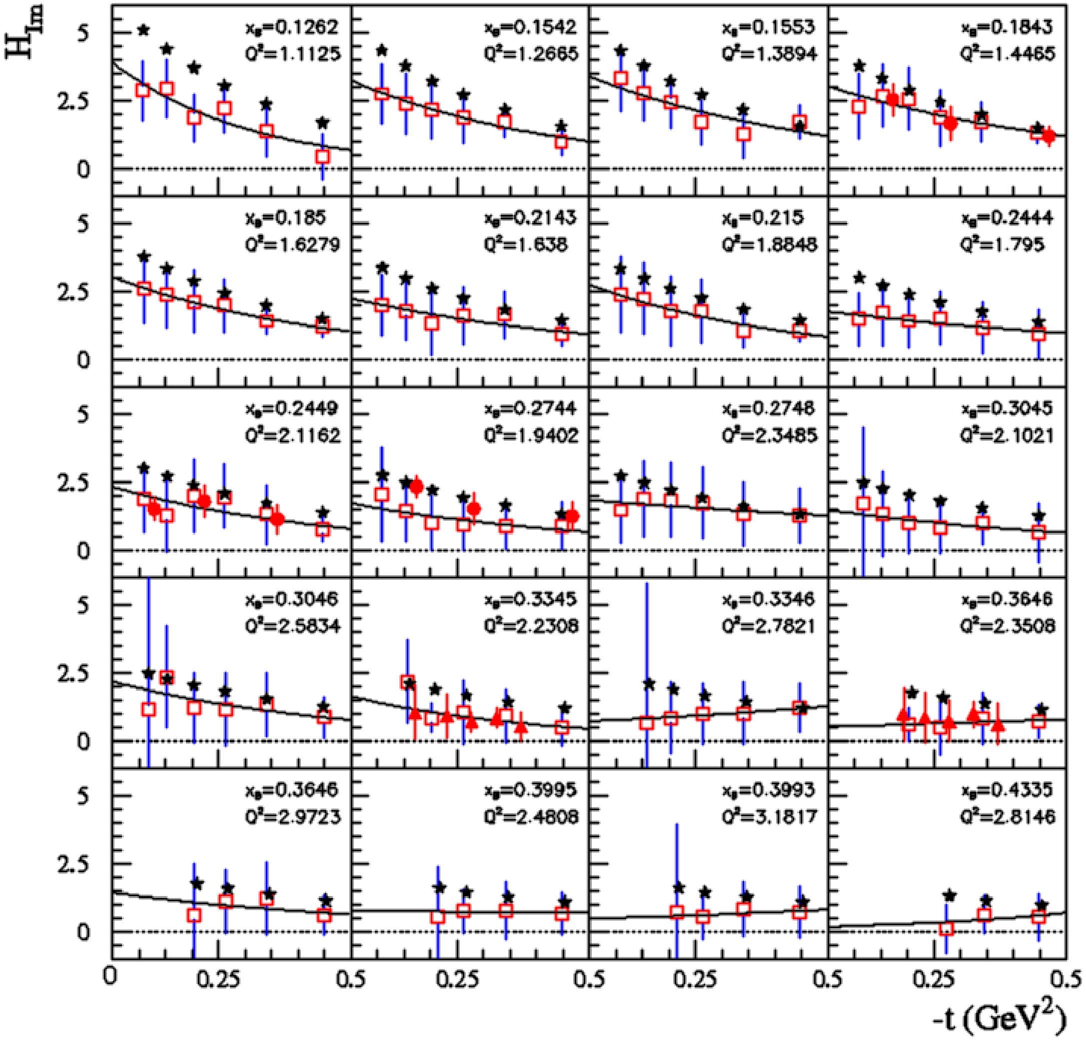
Fitting procedures

- Fits get more complex with more dimensions
- Very small data set available at this point

How to make an underconstrained fit?

- Insert some model dependence
- With boundaries or model assumptions
- Here error bars reflect a factor 5 of the model

Or take more data...



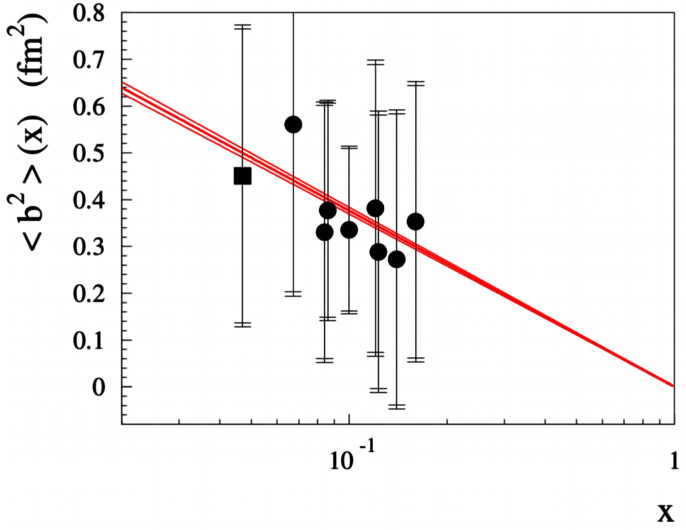
Tomography

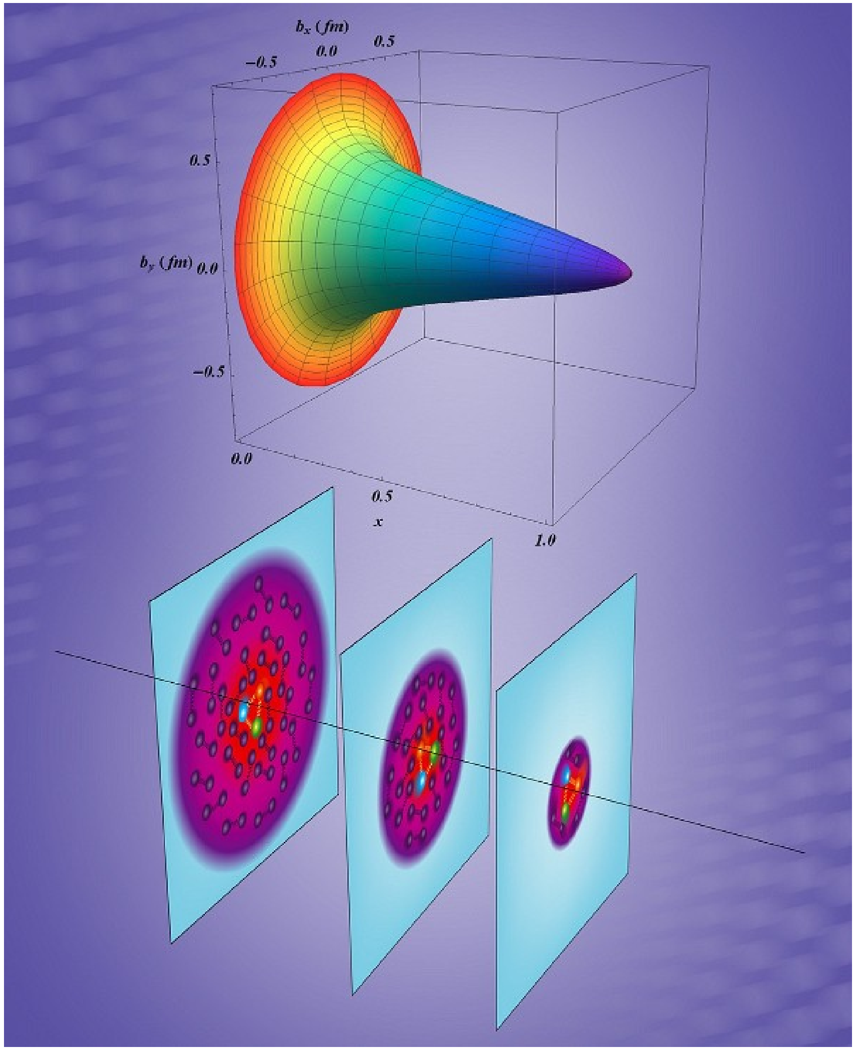
CFFs are directly linked to the tomography of the proton

- The mean square charge radius of the proton for slices of x
- Error bars reflect a factor 5 of the model for unconstrained CFFs

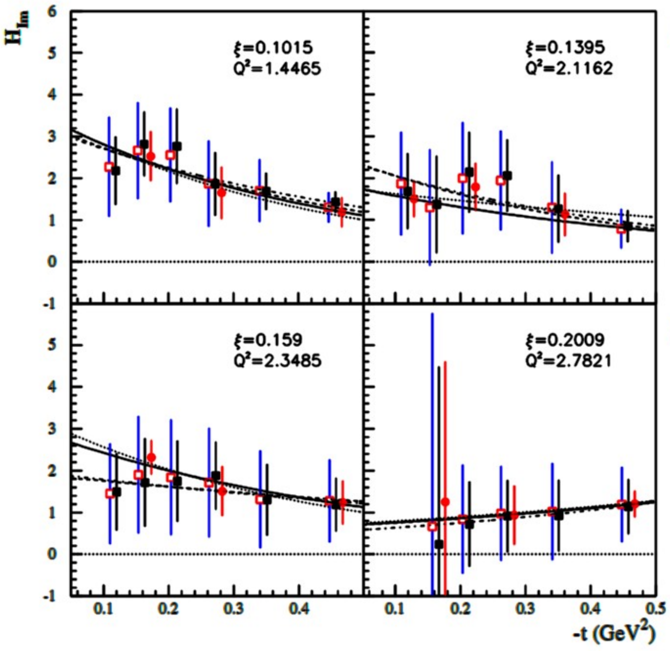
We observe the nucleon size shrinking with x

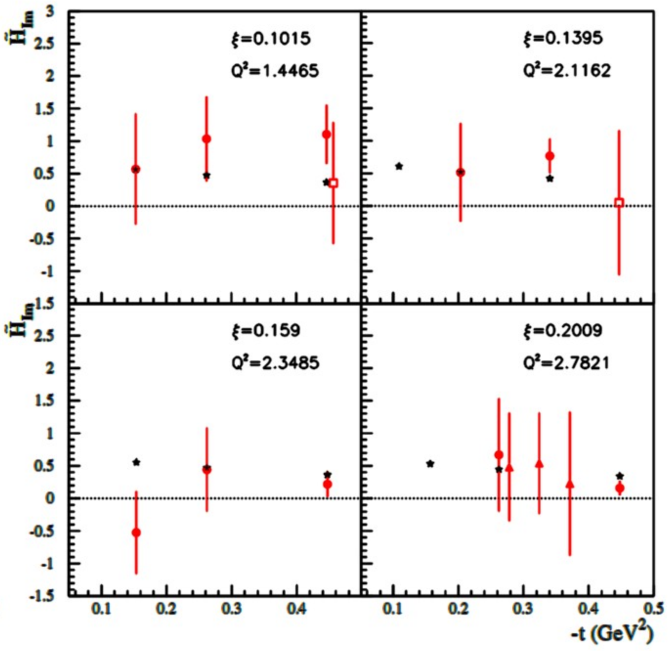
- Expected behavior
- In the future, we want to access the shape of the GPD

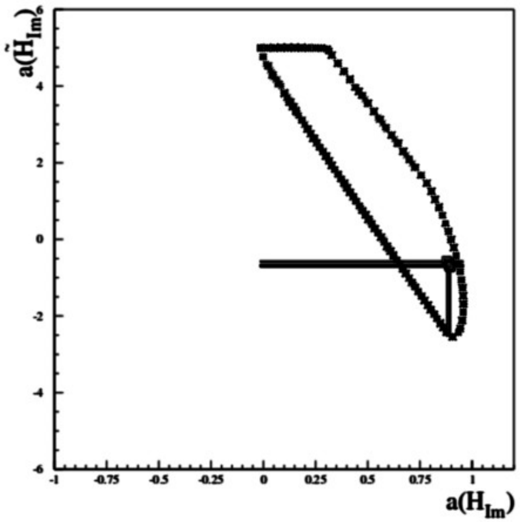


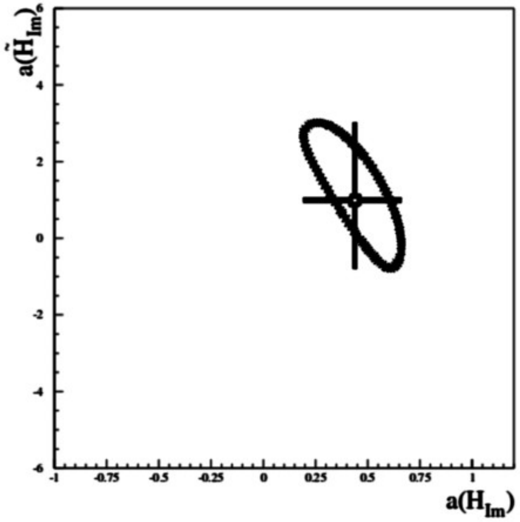


The Coming Challenges









Multiply observables

- New observables help the most to reduce the model errors

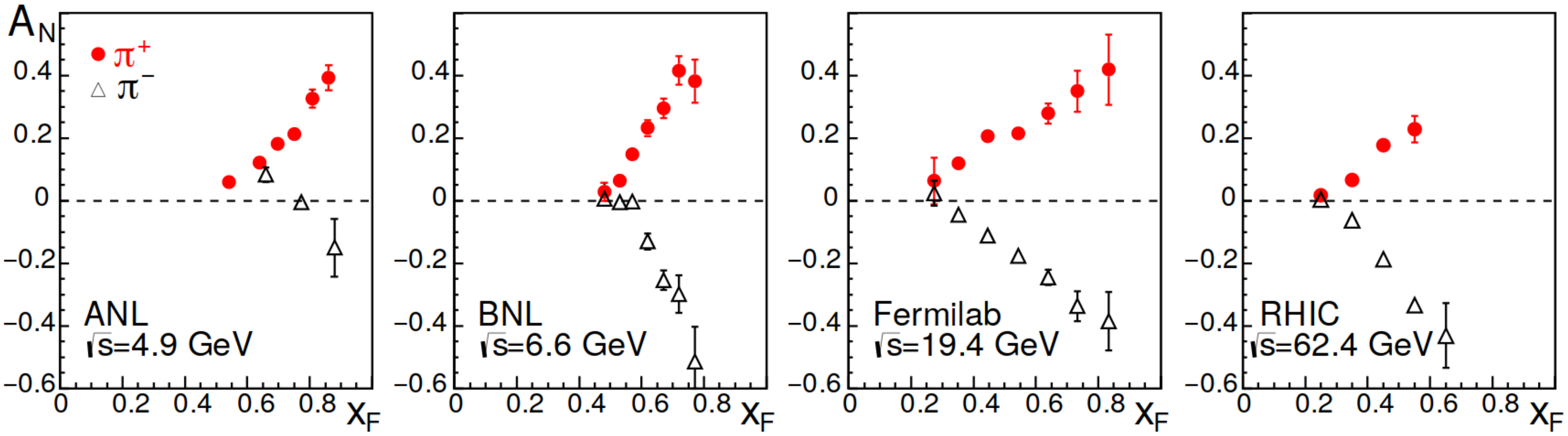
Use global fits

- Introduce more model dependence
- Allows to implement all theoretical constraints

Understand better GPDs

- There is more than tomography

Transverse Momentum Dependent PDFs



Most proeminent in Hadron-hadron

- Experimentally observed more than 40 years ago
- It took a long time for theory to catch up

N \ q	U	L	T
U	$\mathbf{f_1}$		$h_1^\perp$
L		$\mathbf{g_1}$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$\mathbf{h_1}$ $h_{1T}^\perp$

The basic theory

- TMD PDFs are convoluted with fragmentation functions (beyond the scope of this lecture)
- Works well for lepton scattering

Extracting Signal of the TMDs

TMD extraction is simple, in principle

- Each function has a different modulation
- Experimentally, it is a bit more complicated

Experimental needs

- Polarized targets
    - *Preferably long. and tr.*
- High acceptance
- High resolution

$$
\begin{aligned}
\frac{d\sigma}{dx_B\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} &= \frac{\alpha^2}{x_B y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)} \\
\times \Big\{ & F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
& + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
& + S_\parallel\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big] \\
& + S_\parallel\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big] \\
& + |S_\perp|\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) \\
& \quad + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
& \quad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] \\
& + |S_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
& \quad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}.
\end{aligned}
$$

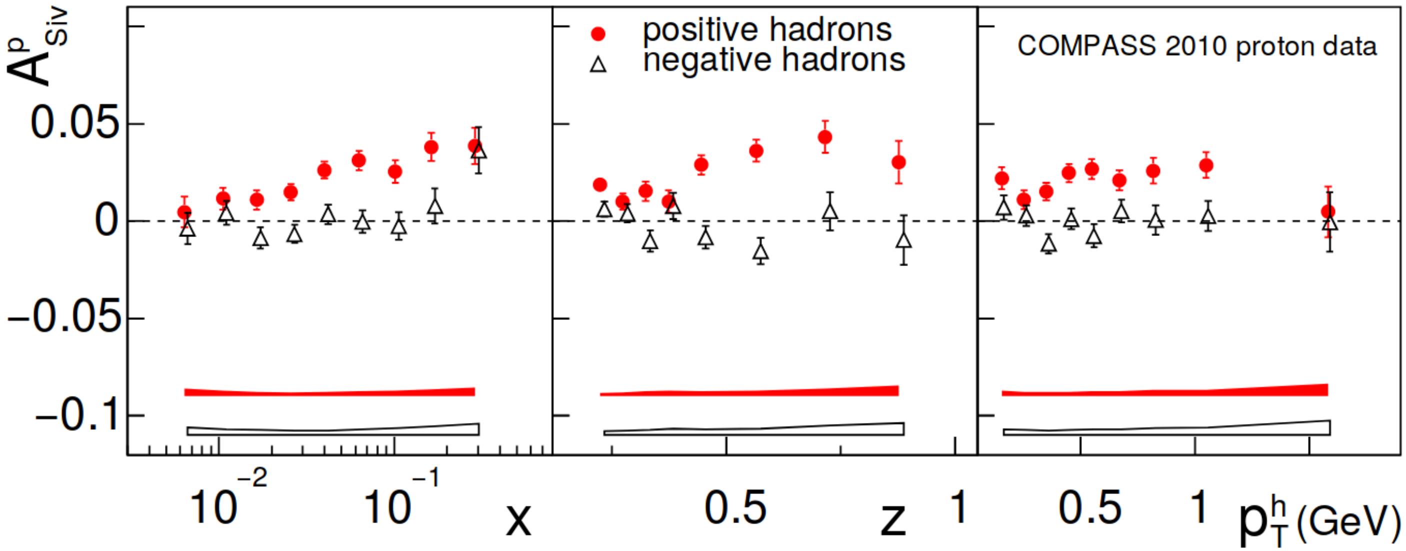
The Sivers Distribution

Correlate target spin and hadron direction

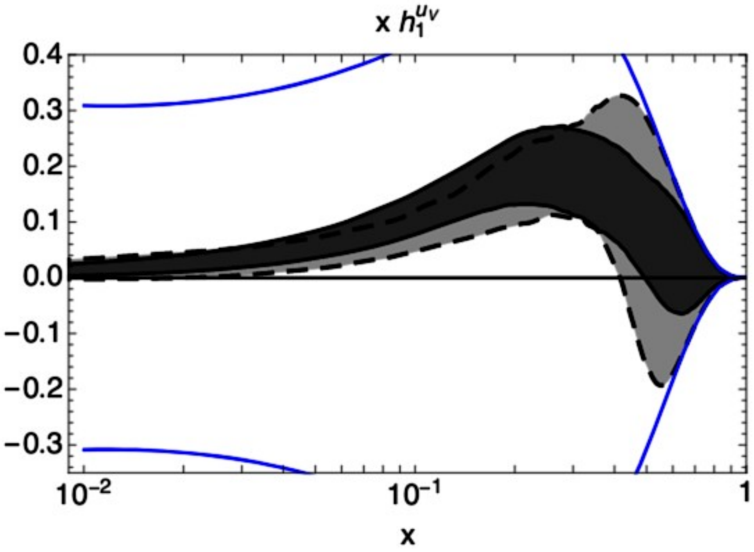
- Indicates the presence of orbital angular momentum (OAM)
- Positive and negative hadrons as well as proton and deuterium targets
- u and d quarks seem to contribute in opposite directions

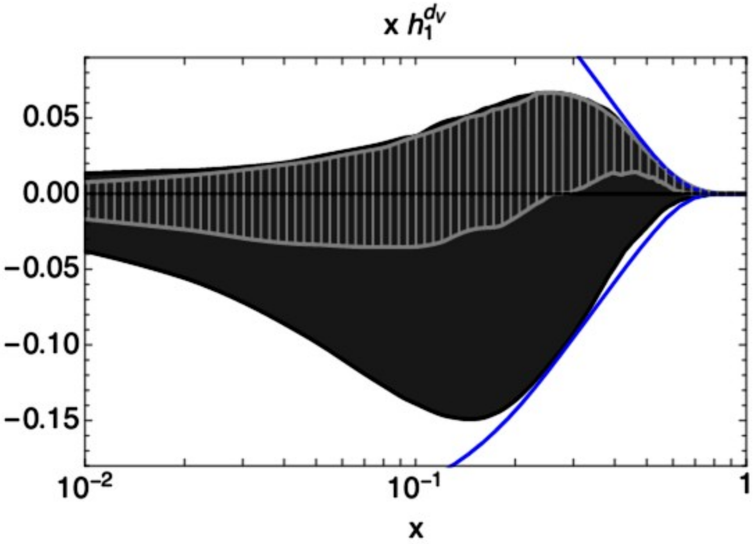
No quantitative link with OAM

- Possible only using model dependent assumptions



TMD Fits





Fits of TMDs are just starting

- Includes lepton-proton and proton-proton
- Allows to separate u and d

Shows the “hints” from data are to be taken carefully

Necessitate di-hadron fragmentation functions

- Not well studied in the past
- Renewed interest due to TMDs phenomenology

What is coming?

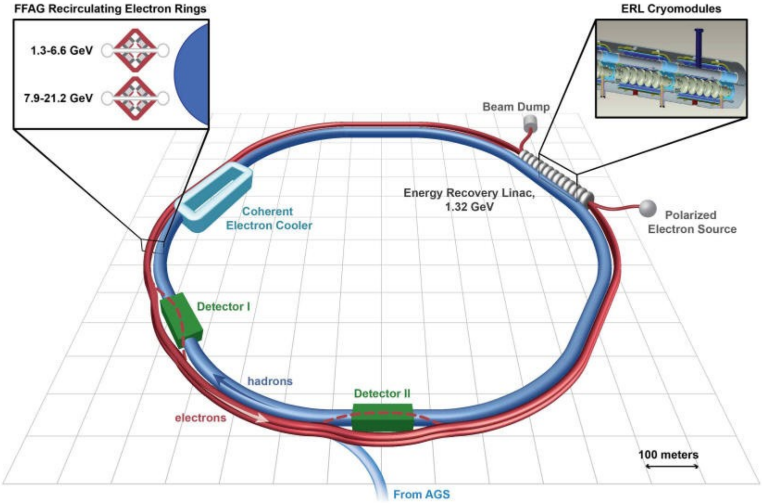
Jefferson Lab and COMPASS@CERN

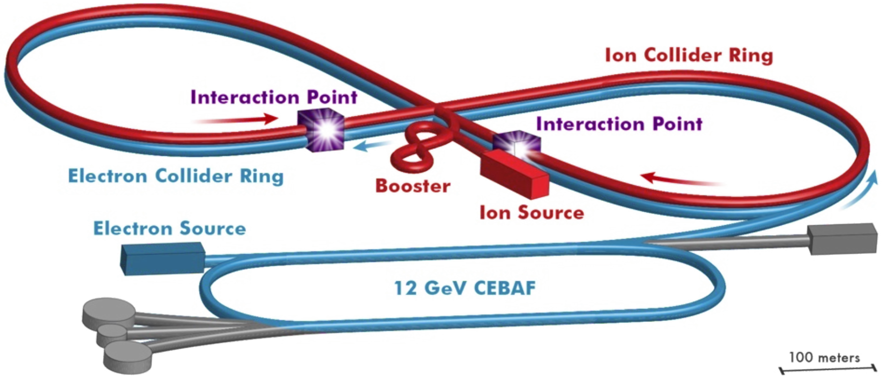
- **They are running many more experiments**
- **Precision will progress a lot, as well as covered phase space**

Farther in the future is the EIC

- **Billion dollars large scale accelerator**
- **Will run at energies larger than COMPASS with luminosity comparable to Jefferson Lab**
- **All spin configurations will be available**

See lecture at the end of the week from T. Ullrich





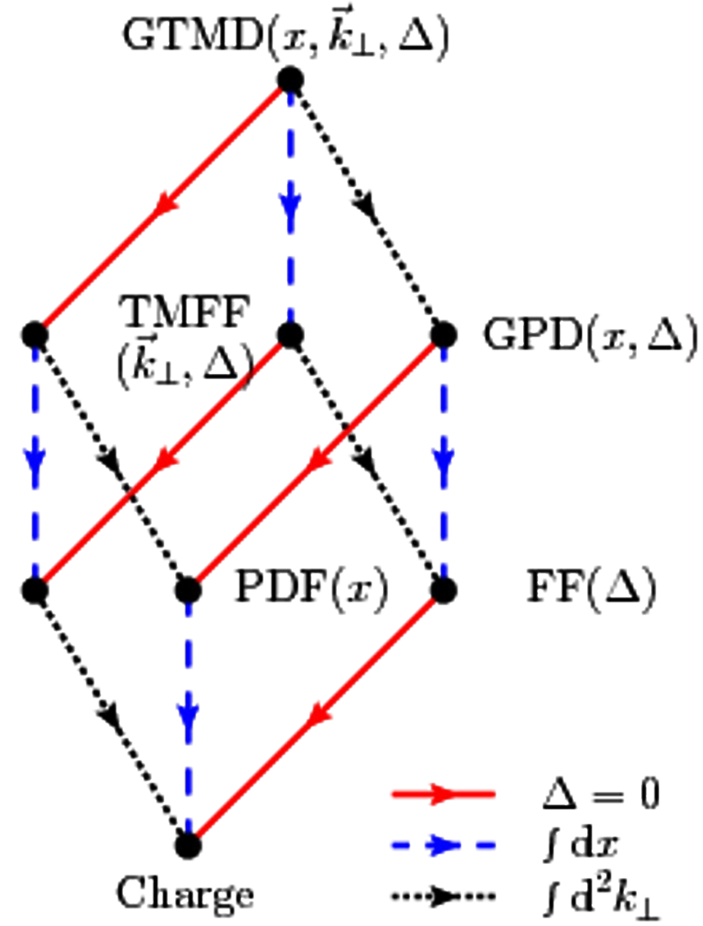
One Function to Unify Them All

Eventually, we would like to unify all of this

- **Wigner distributions are the tool of choice**
- **They are five dimensional**
- **Include uncertainty principle**

How to measure them?

- **Ideas are only starting to be proposed**
- **16 complex GTMDs for the proton**
- **Needless to say, there is still some serious work in front of us**



Summary

Nucleon structure

- Characterized by a zoo of functions
- Understood using electron scattering and many other processes

Some outstanding issues remain with older structure functions (FFs and PDFs)

- Proton radius, large x structure, origin of the proton spin...

Many new opportunities present themselves with the 3D structure of the nucleon unravelling

- Starting to build a 3D image of the nucleon
- Understanding the dynamic of the quarks
- Correlations of quarks and more...