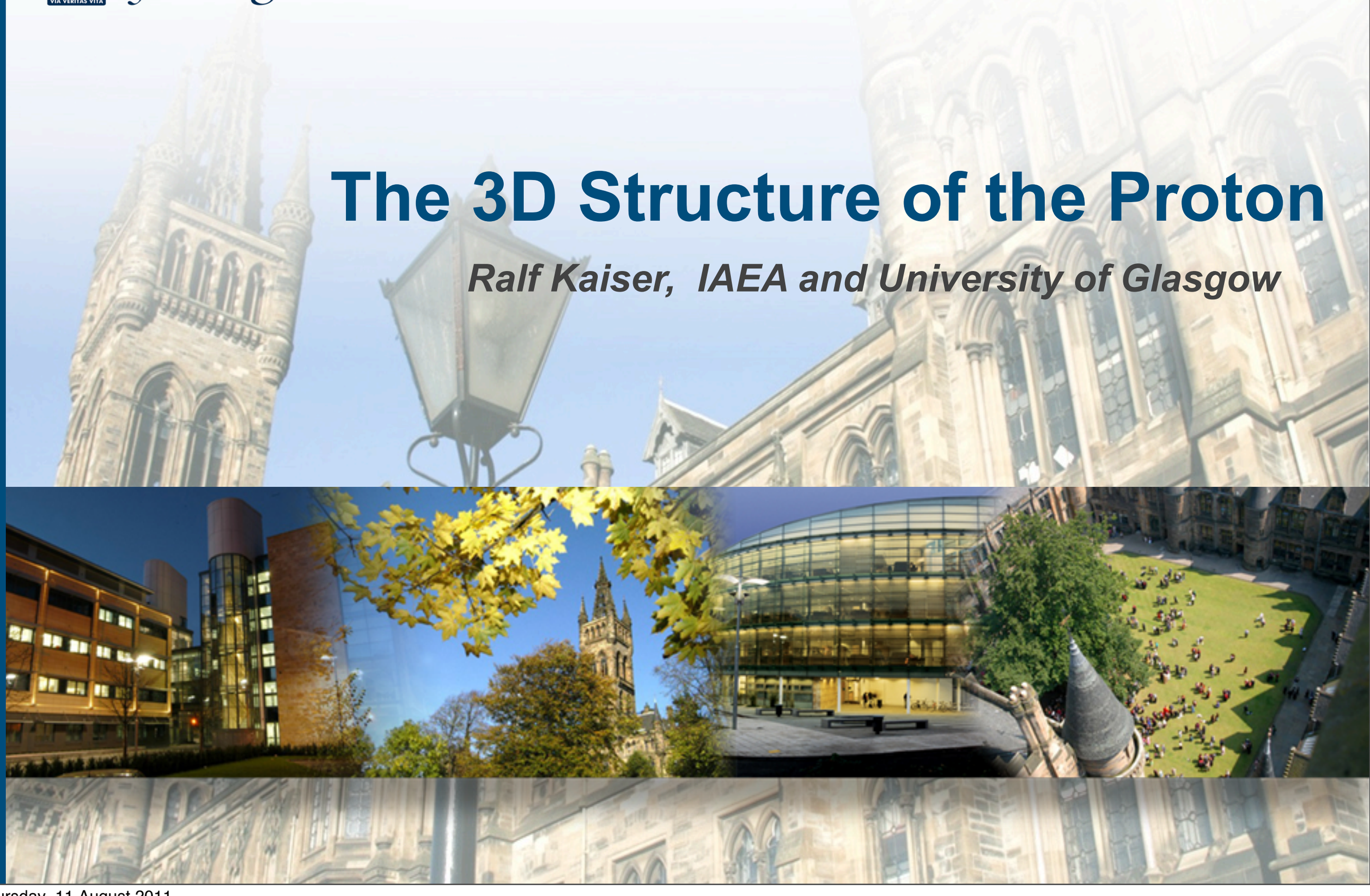
University of Glasgow

The 3D Structure of the Proton

Ralf Kaiser, IAEA and University of Glasgow



Topics

- From Rutherford Scattering to Deeply Virtual Compton Scattering (DVCS)
- Generalised Parton Distributions and the 3D Structure of the Proton
- Recent DVCS Results from HERMES
- Future Experiments in DVCS

Shotgun Pictures

Imagine you have a sand filled sack, and a cannon ball hidden somewhere inside. One way of figuring out where the cannon ball is, is shooting at it with a shotgun. You get a kind of picture and some of the bullets scatter back.

One (important) difference: Electron scattering off a proton, or alpha particles off a nucleus, is more like shooting individual bullets at lots of different (albeit supposedly identical) sacks. A combination of imaging and destructive testing....

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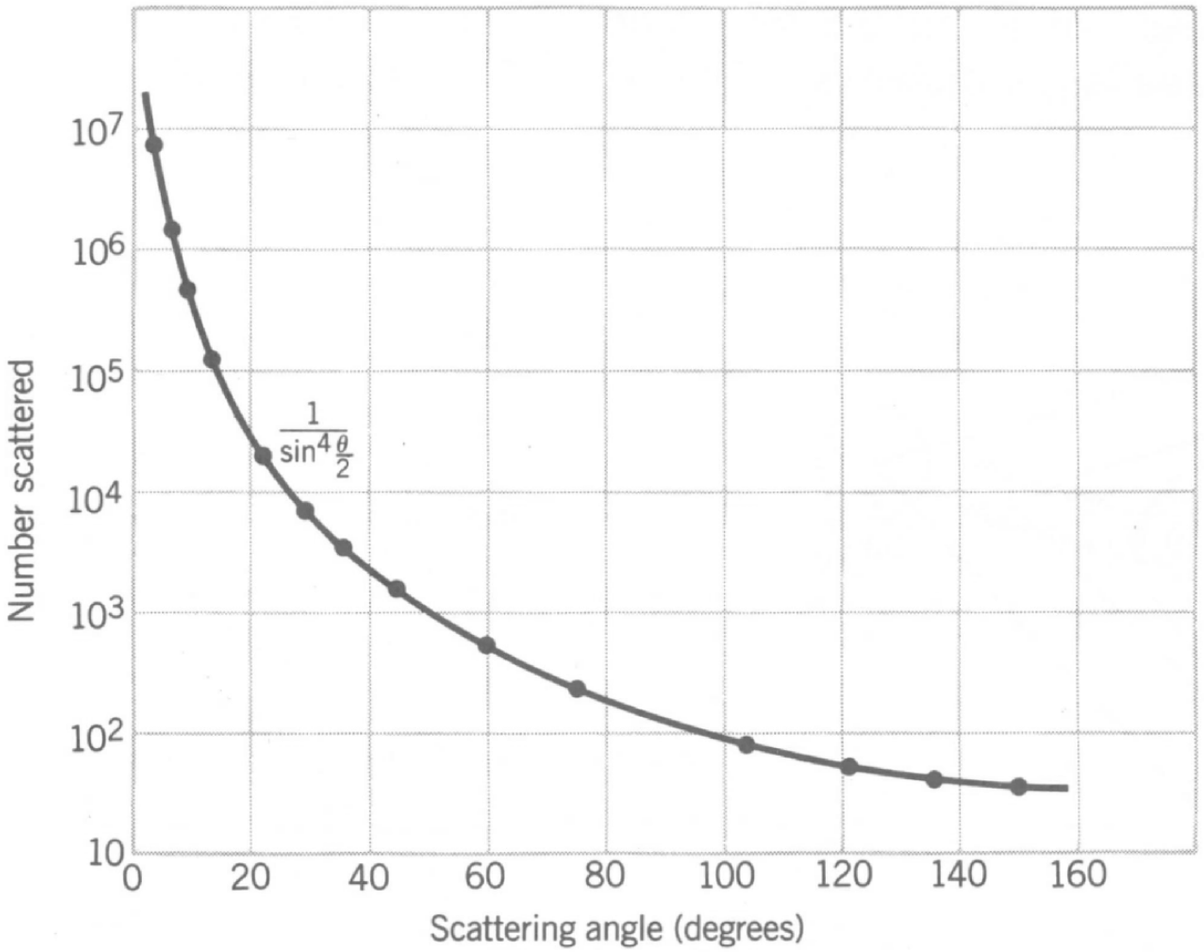
Rutherford Scattering Experiment

Rutherford Cross Section



Classical as well as quantum mechanical result under the assumption that

- target recoil can be neglected
- spin effects can be neglected
- the target is point-like

$$\left(\frac{\mathbf{d}\sigma}{\mathbf{d}\Omega}\right)_{\text{Rutherford}} = \frac{(\mathbf{Ze^2})^2}{(4\pi\epsilon_0)\cdot 4\mathbf{E^2}\sin^4\frac{\theta}{2}}$$

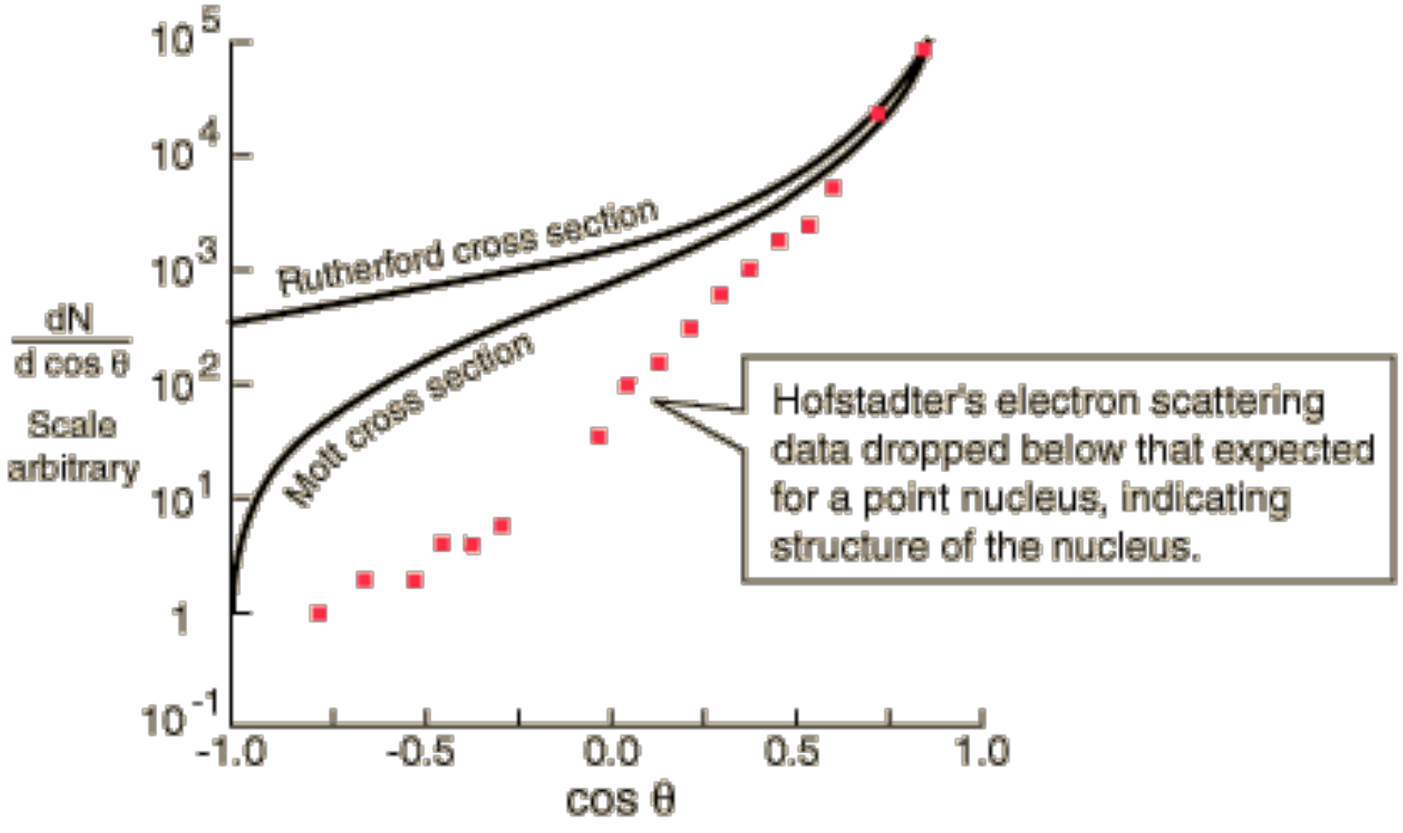
Mott Cross Section

$$\frac{d\sigma}{d\ \cos\theta} = \left(\frac{d\sigma}{d\ \cos\theta}\right)_R \frac{(1+\cos\theta)/2}{\left[1+\frac{(1-\cos\theta)KE}{Mc^2}\right]}$$

Electron Rutherford formula

Electron magnetic moment effect

Nuclear recoil effect



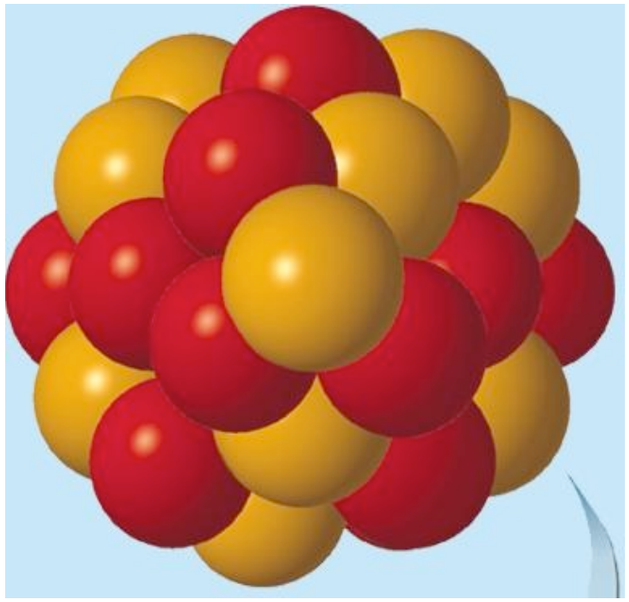
Taking target recoil and spin effects into account leads to the Mott cross section.

Any further deviation is therefore an indication that the target is not point-like.

This is the basic method to show that something has a substructure.

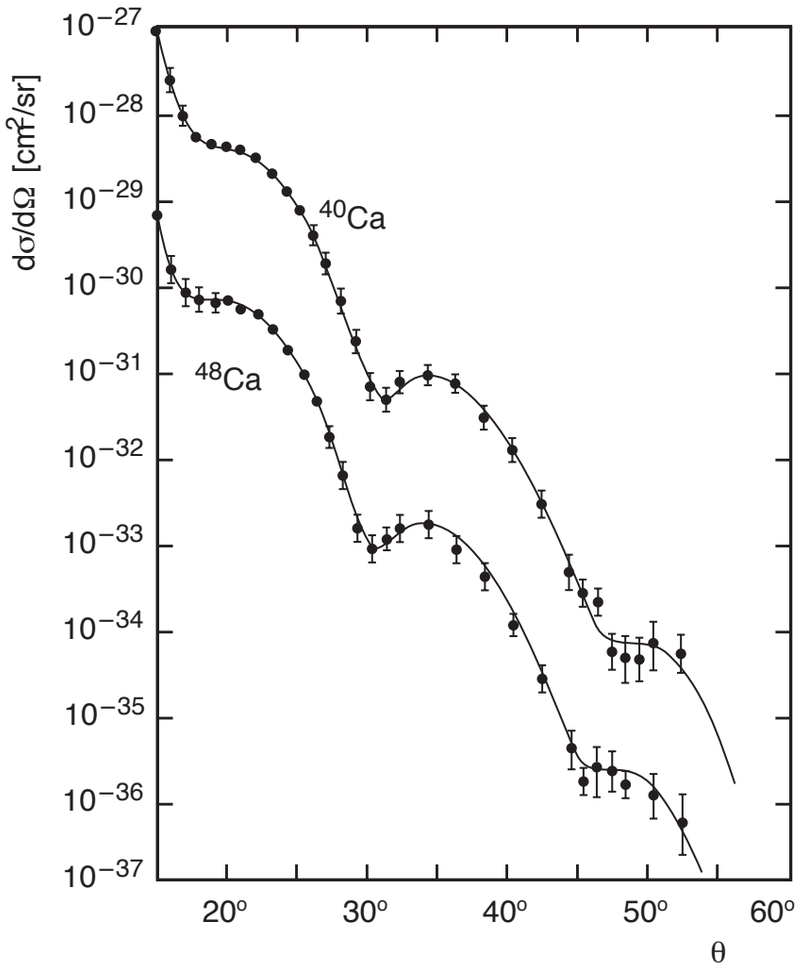
R.Hofstadter et al., Phys.Rev.92, 978 (1953)

Nuclear Form Factors

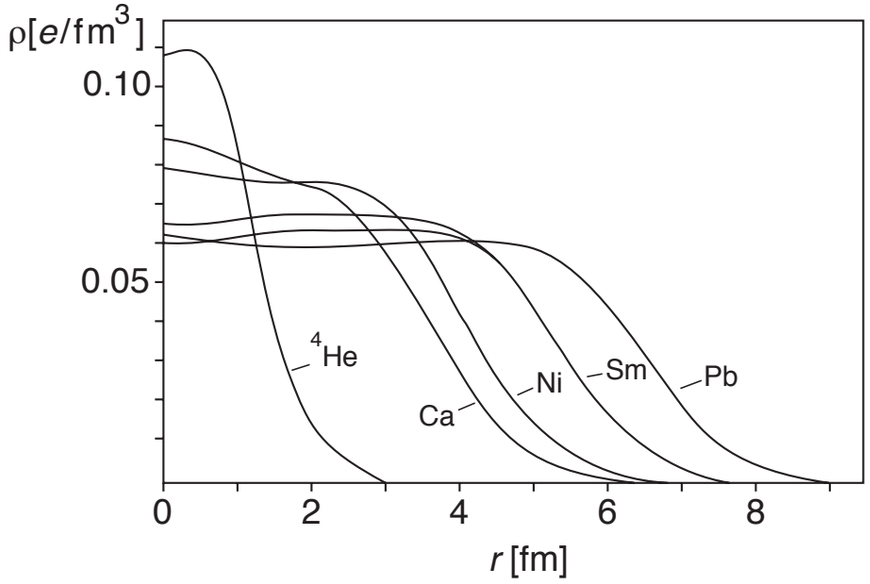


$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \cdot |F(q^2)|^2$$

Nuclear Form Factor: Ratio of measured elastic electron scattering cross section and theoretical cross section for a point-like particle.



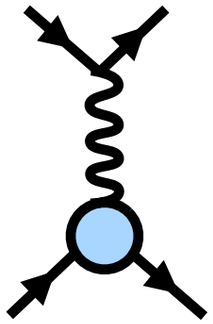
$$f(r) = \frac{1}{(2\pi)^3} \int F(q^2) e^{-iqx/\hbar}\, d^3q$$



Radial charge distribution from Fourier transformation.

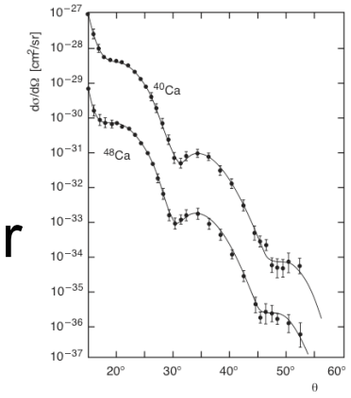
Structure and Rutherford Scattering

Elastic Scattering off a Nucleus



Deviation from Rutherford Scattering (point-like)

Nuclear Form Factor



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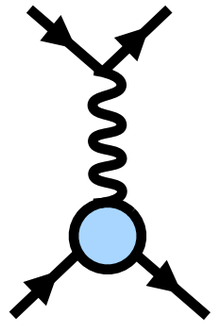

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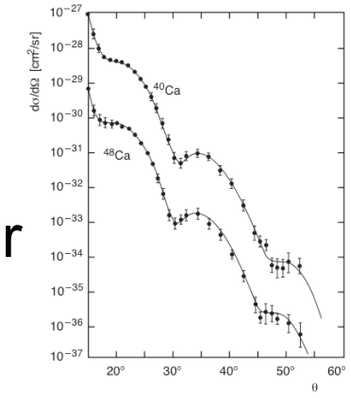
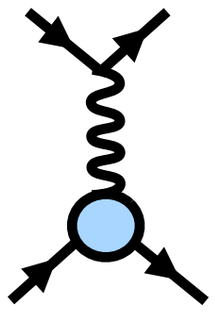


Elastic Scattering off a Nucleon



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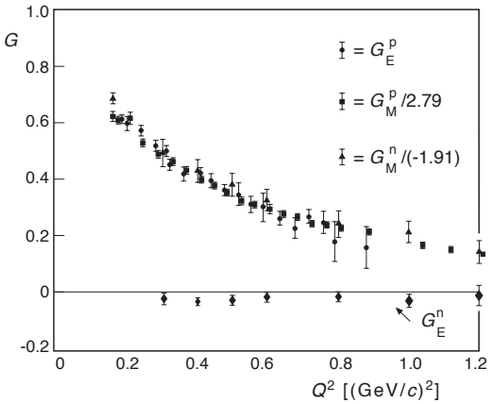
Nucleon Form Factors



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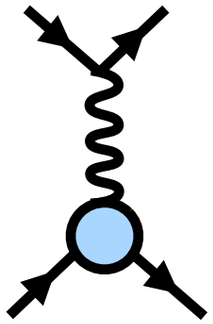

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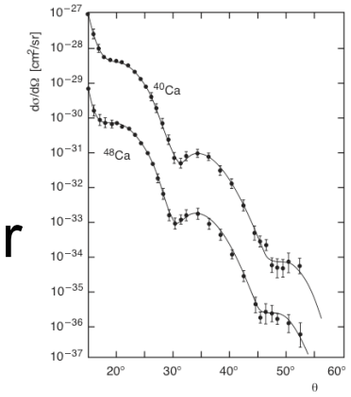
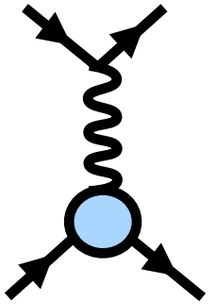


Elastic Scattering off a Nucleon



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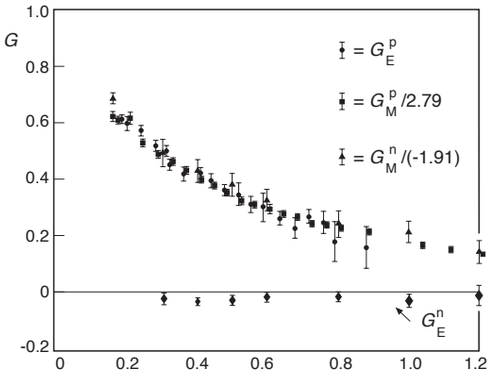
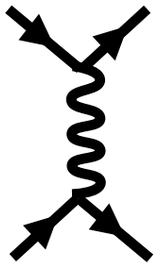
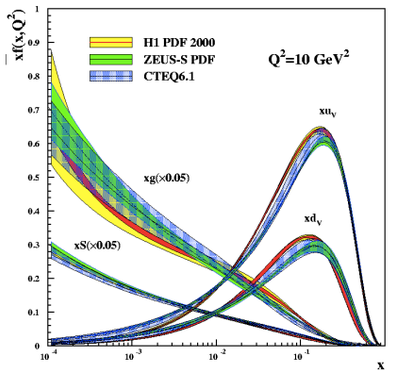


Elastic Scattering off a Quark/Parton i.e. DIS



Parameterisation of the Experimental Results →

Parton Distribution Functions



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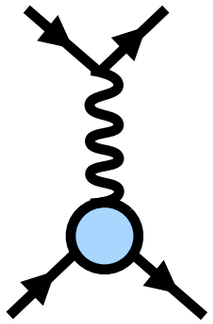

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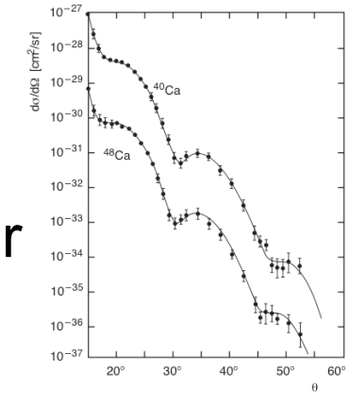

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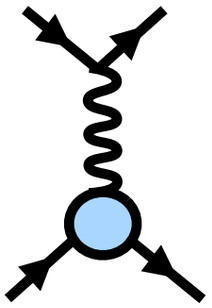

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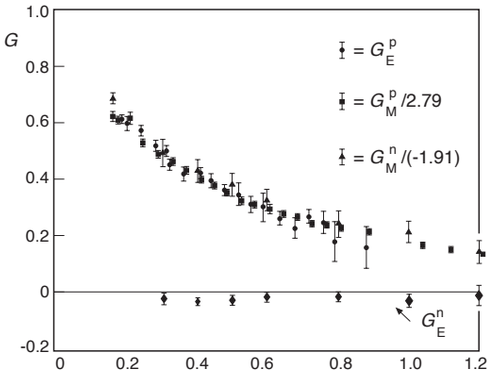

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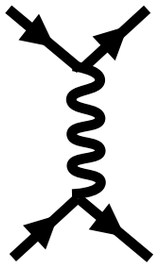

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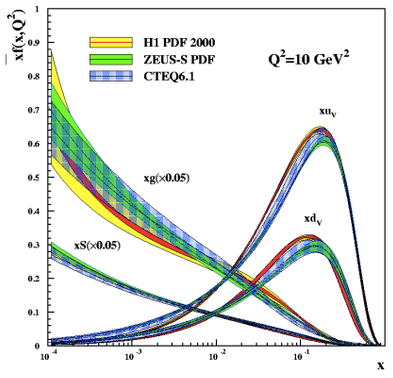
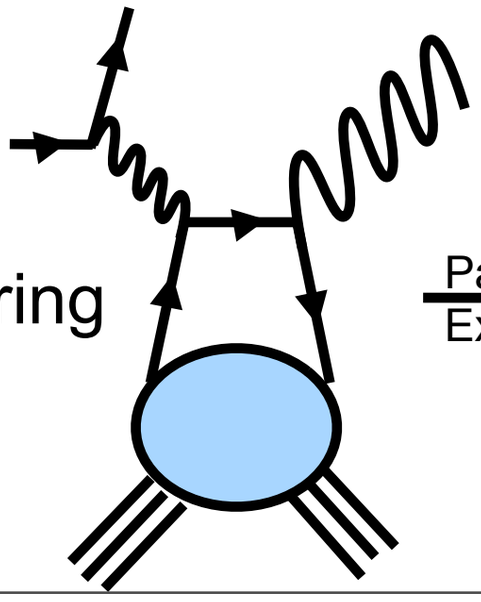


Deeply Virtual Compton Scattering i.e. DVCS



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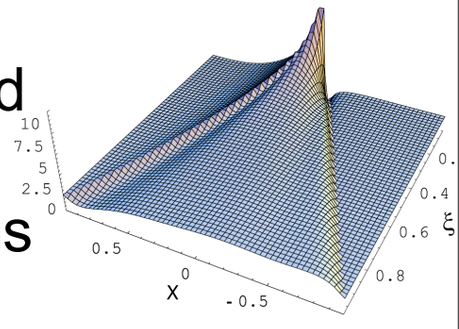

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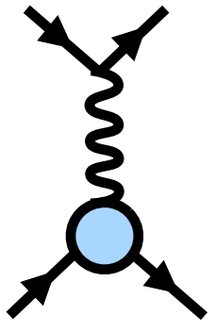

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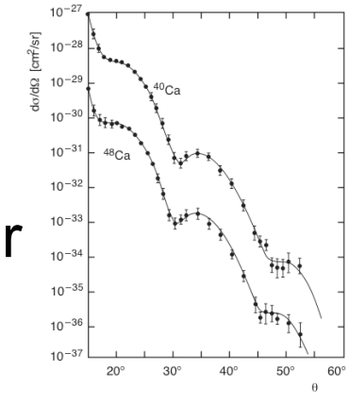

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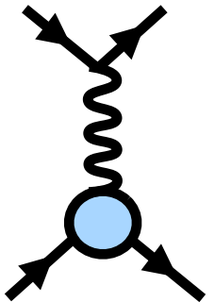

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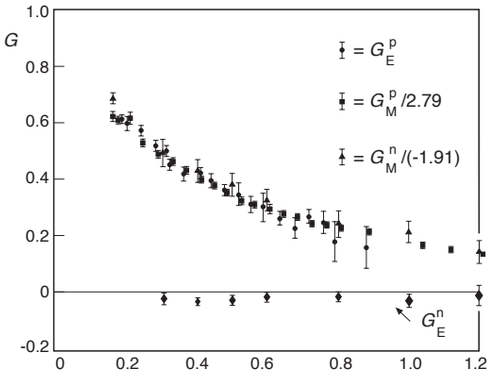

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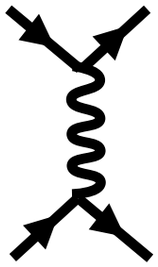

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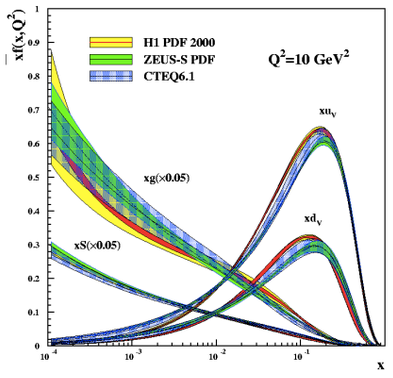

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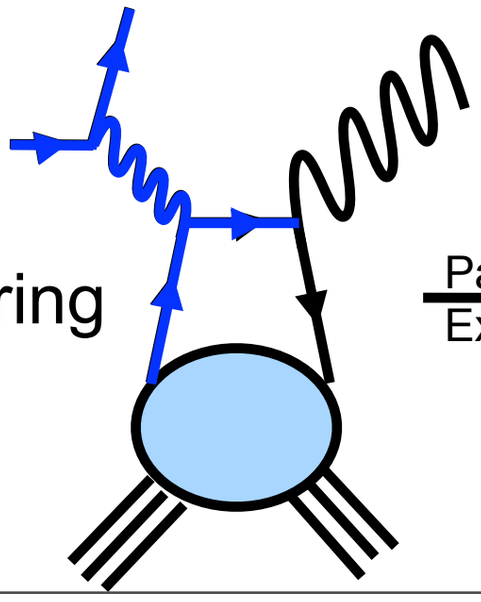

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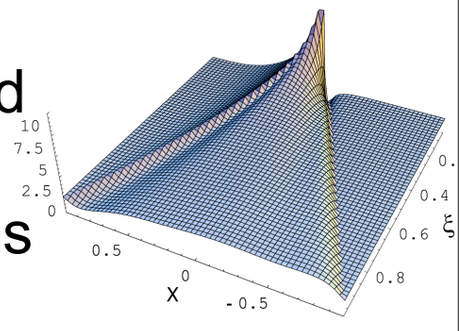
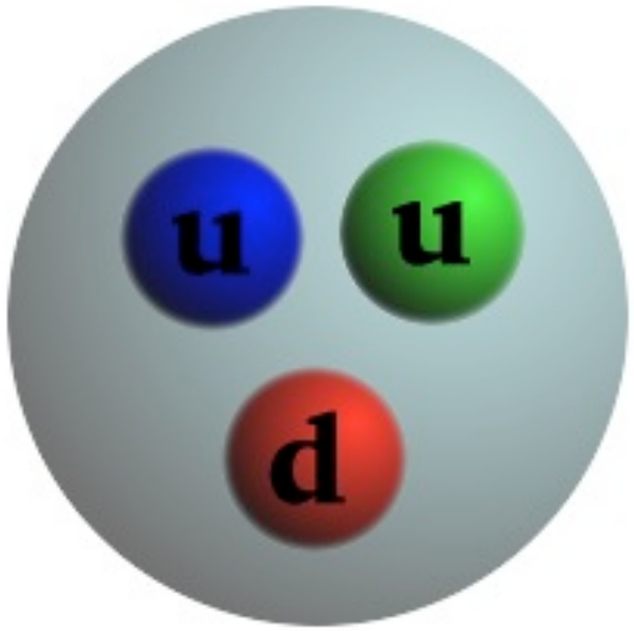
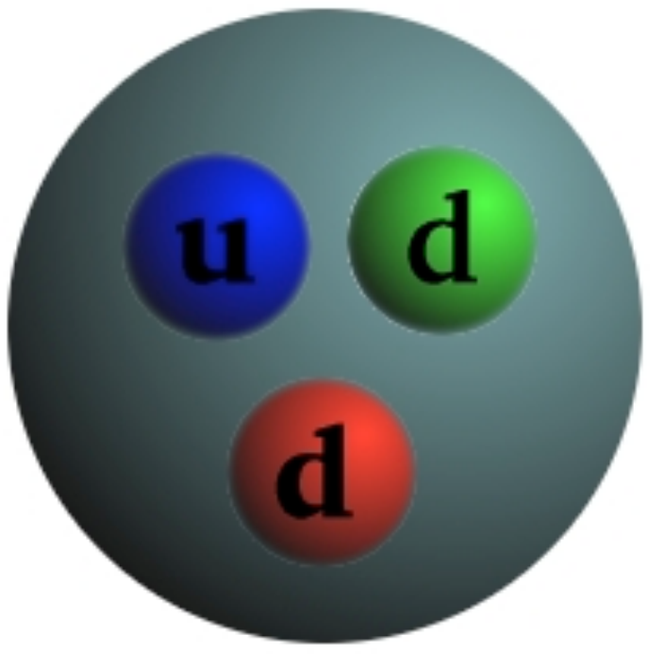


Proton and Neutron - The Basic Idea



Proton

3 quarks (uud)
Q= 2/3 + 2/3 -1/3 = 1
quarks in 3 colors

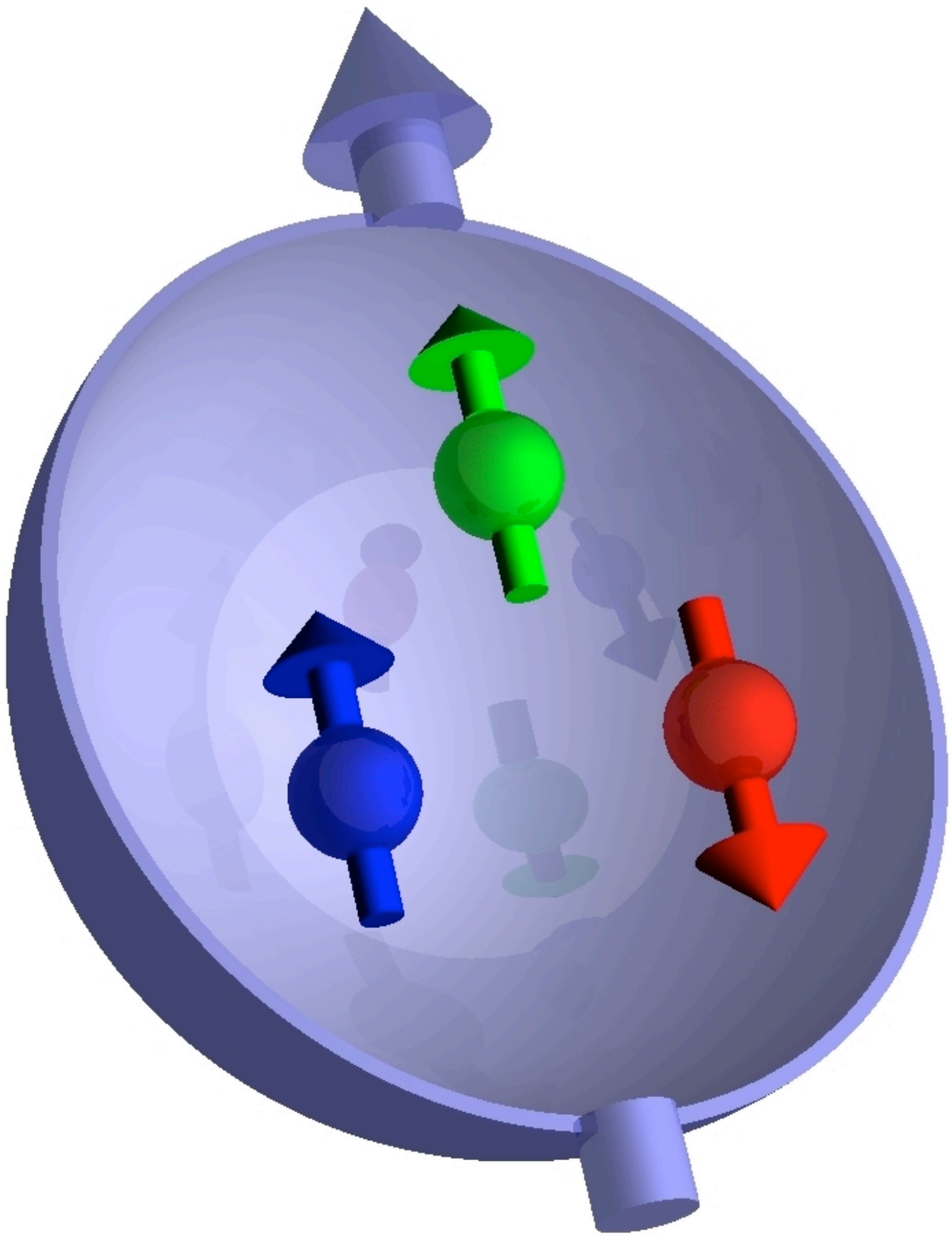


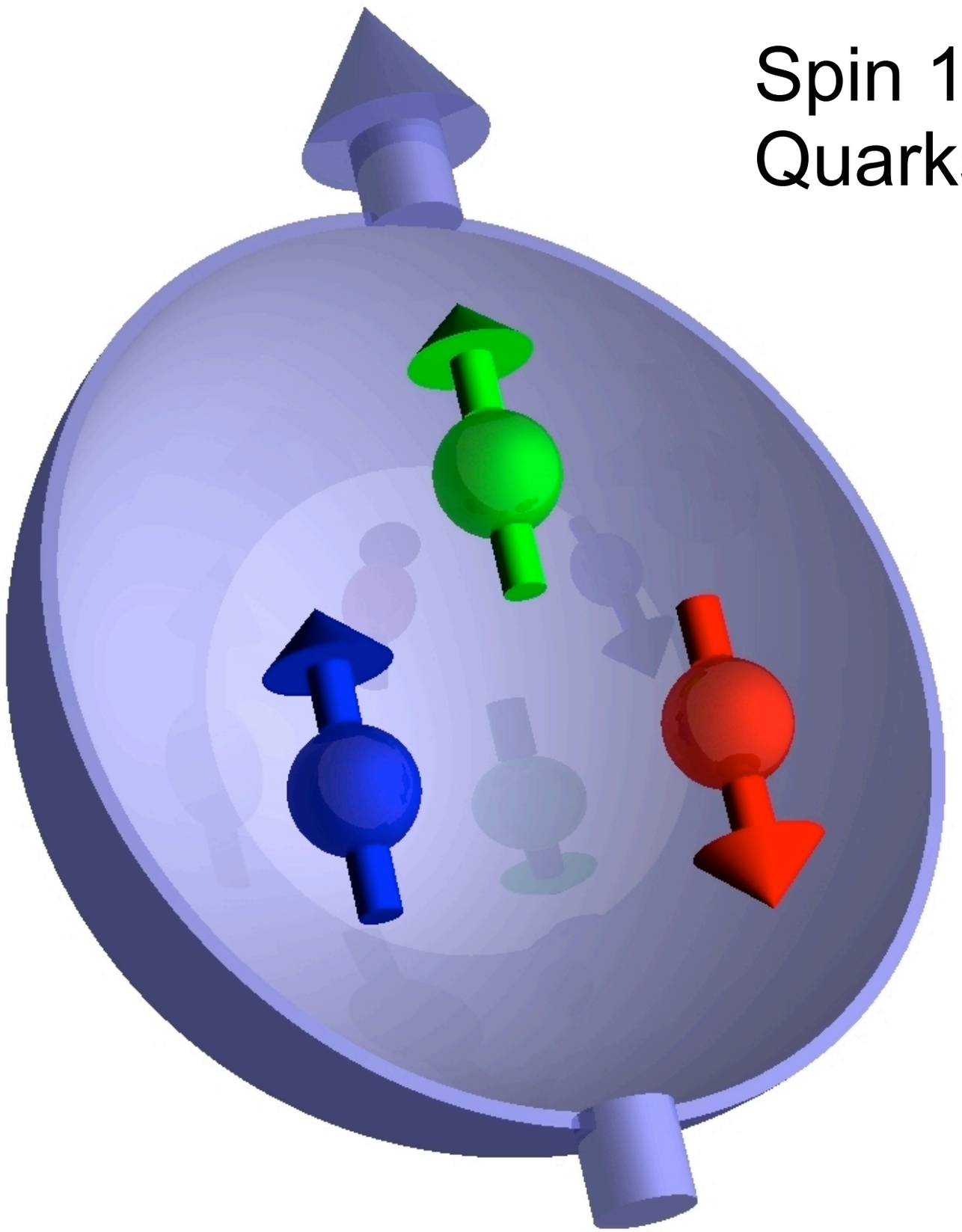
Neutron

3 quarks (udd)
Q= 2/3 - 1/3 -1/3 = 0
quarks in 3 colors

University of Glasgow

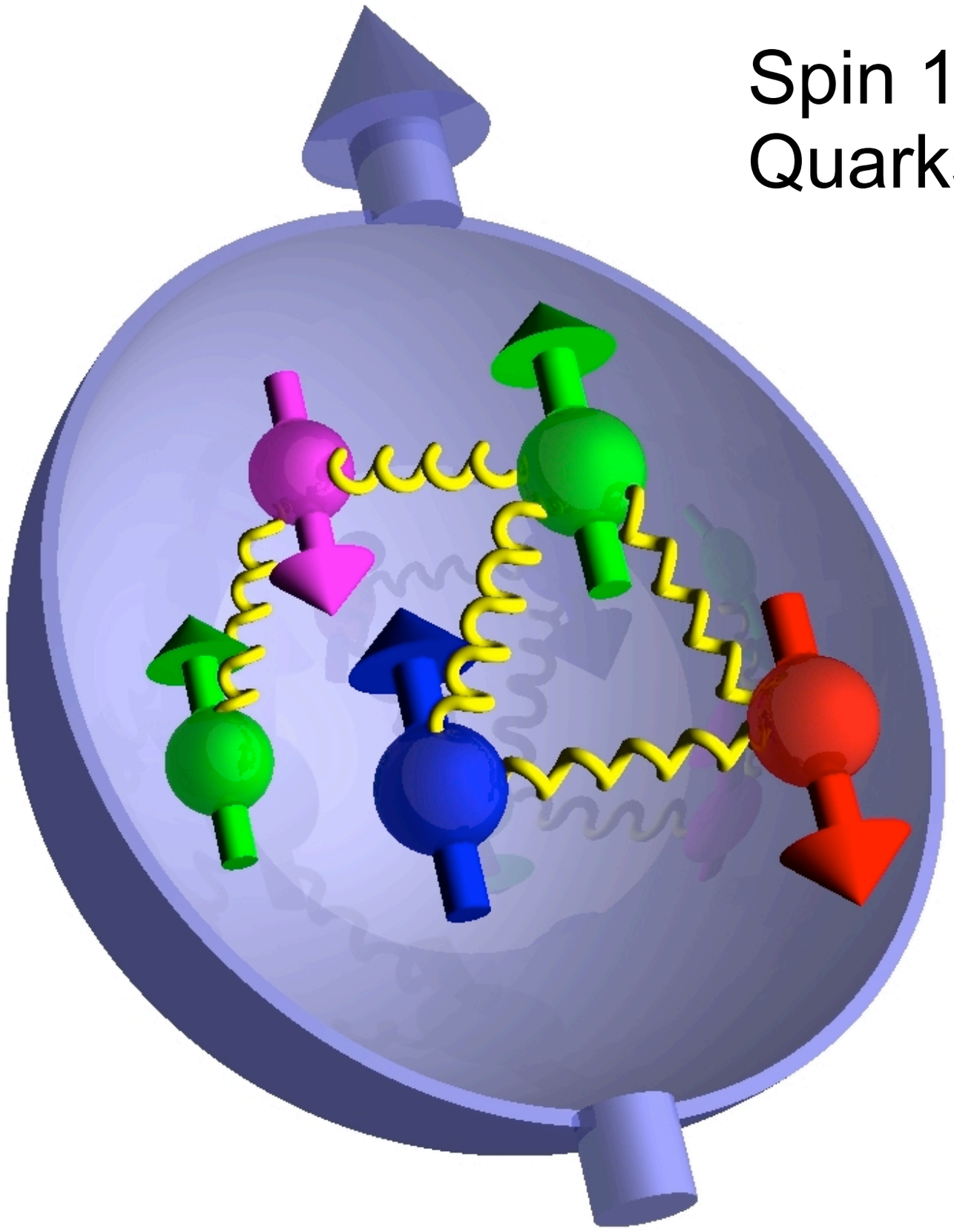
The Nucleon





Spin 1/2
Quarks also Spin 1/2

The Nucleon



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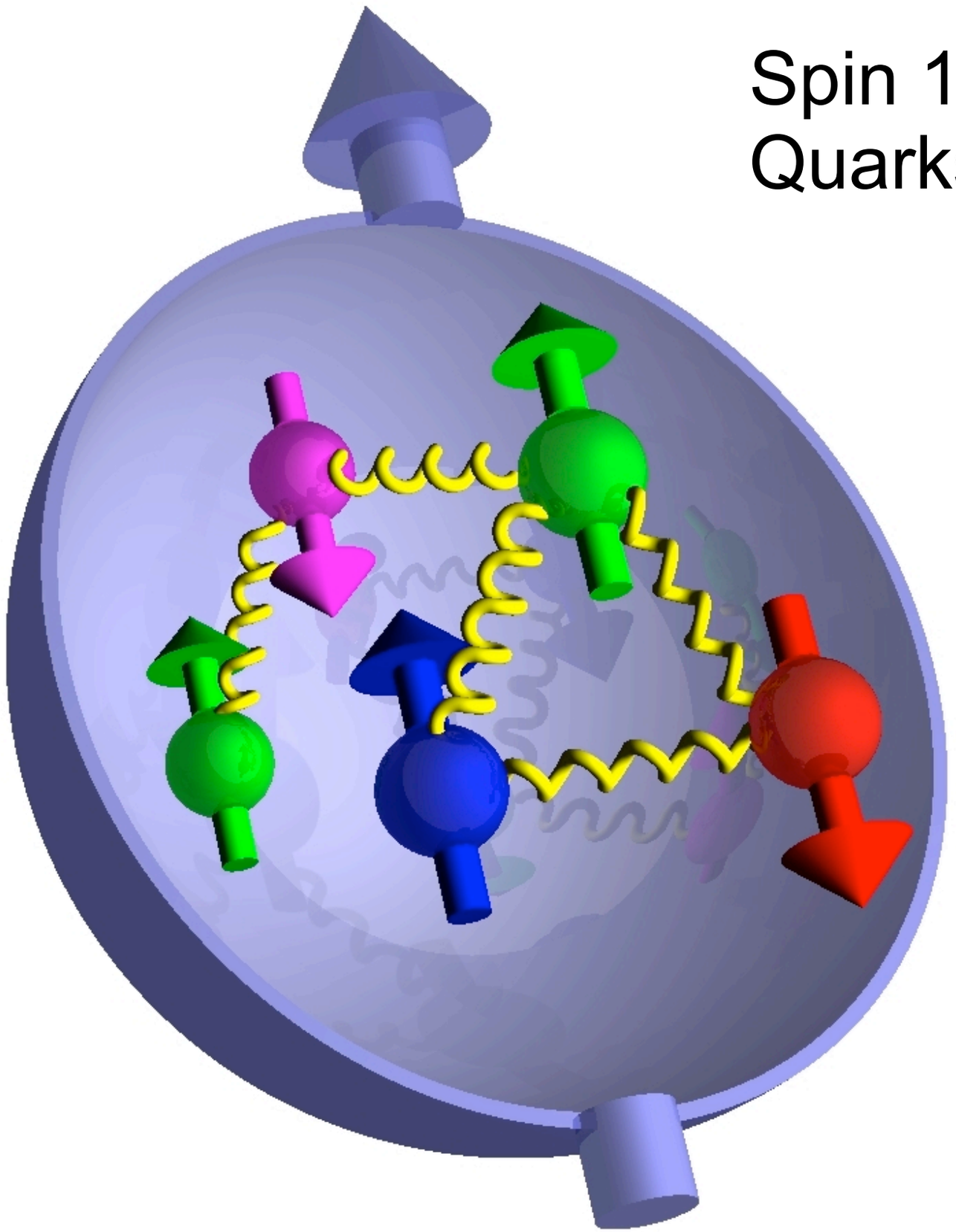
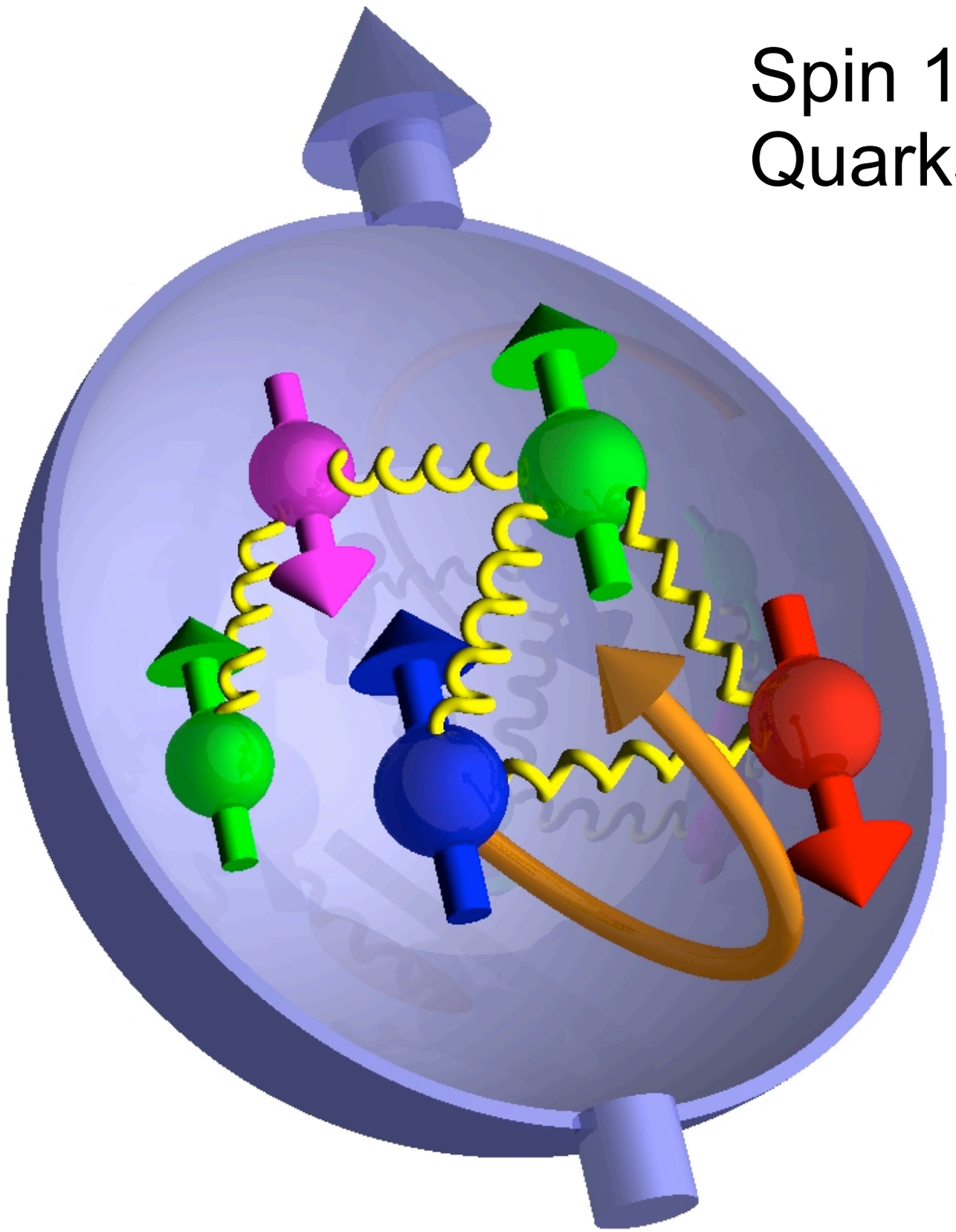


Spin 1/2
Quarks also Spin 1/2

Gluons &
Sea Quarks

The Nucleon



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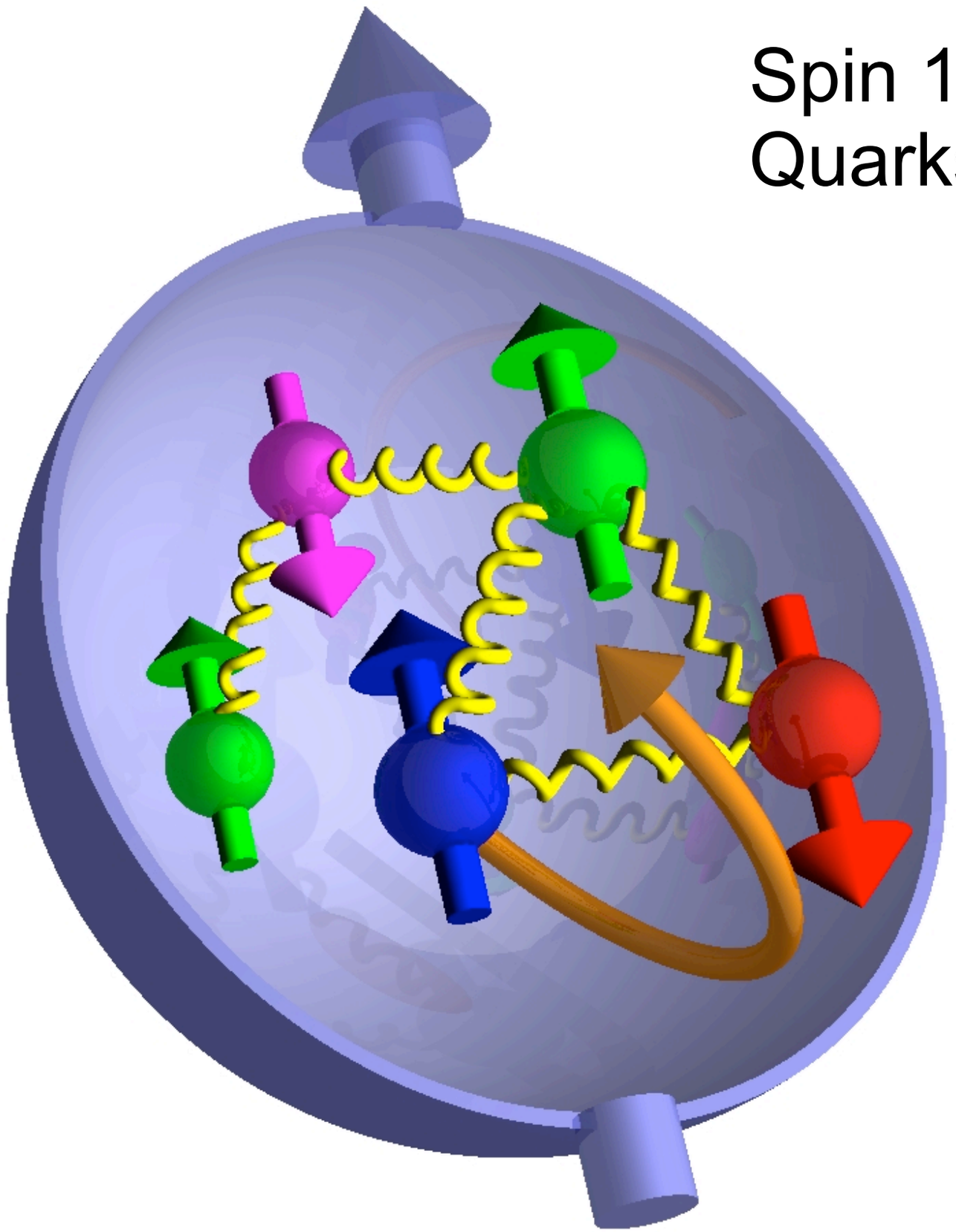
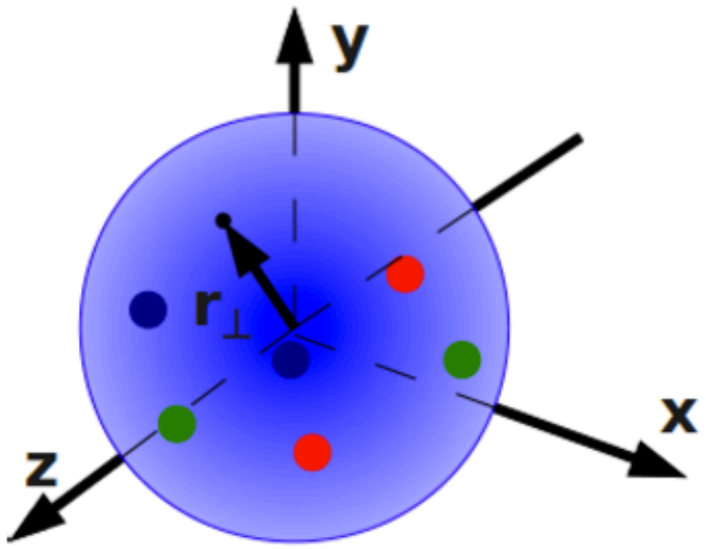


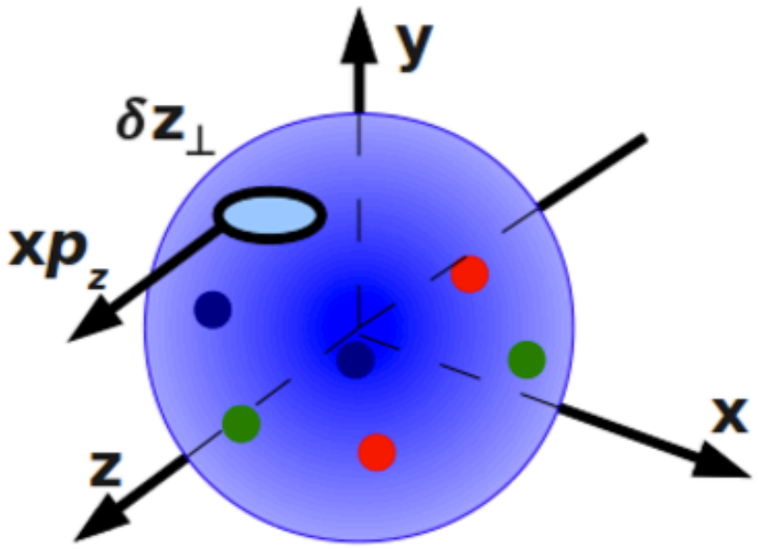
Spin 1/2
Quarks also Spin 1/2

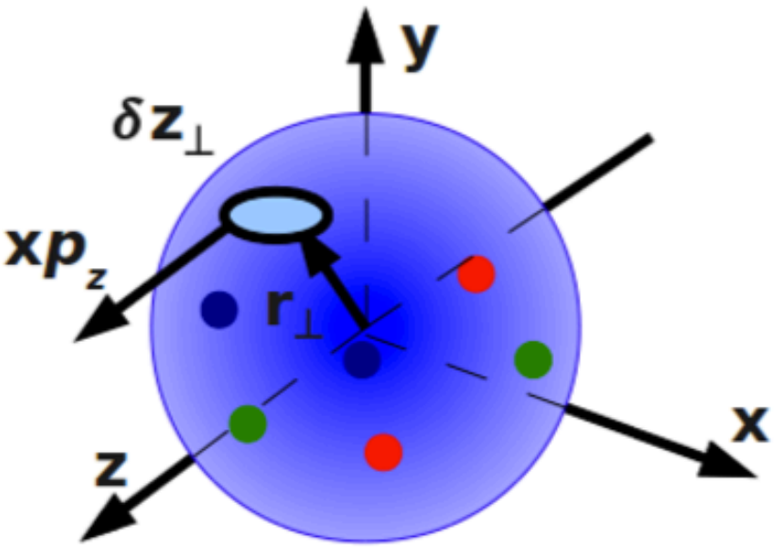
Gluons &
Sea Quarks

Orbital
Angular
Momentum

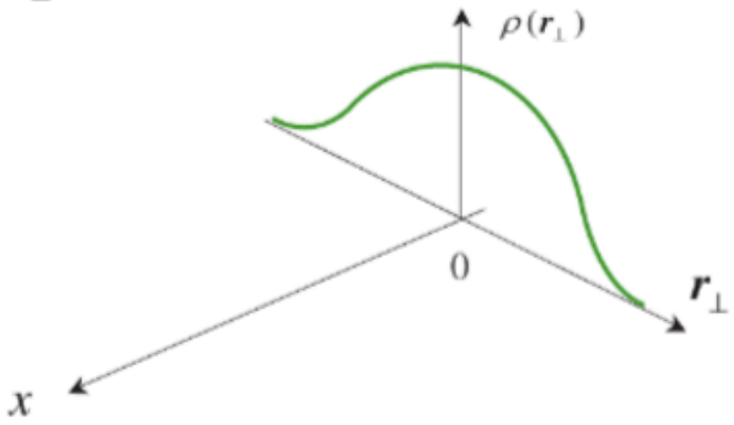
Generalised Parton Distributions

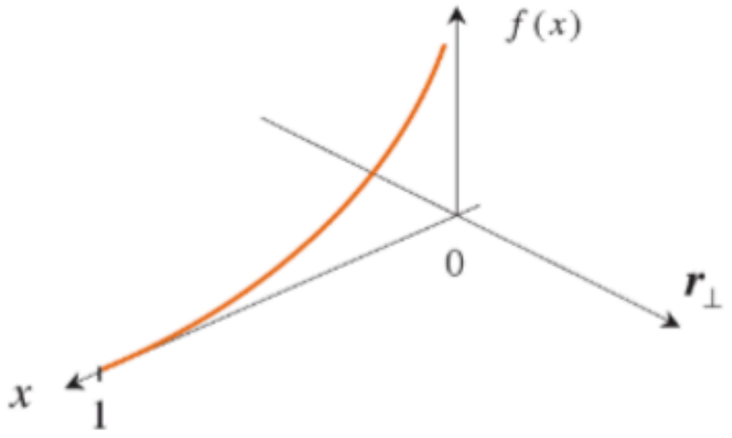


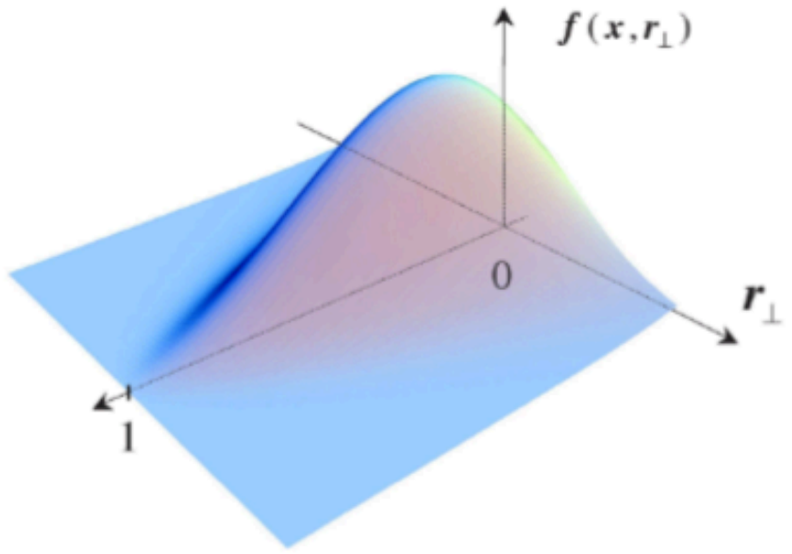




$p_z \to \infty$





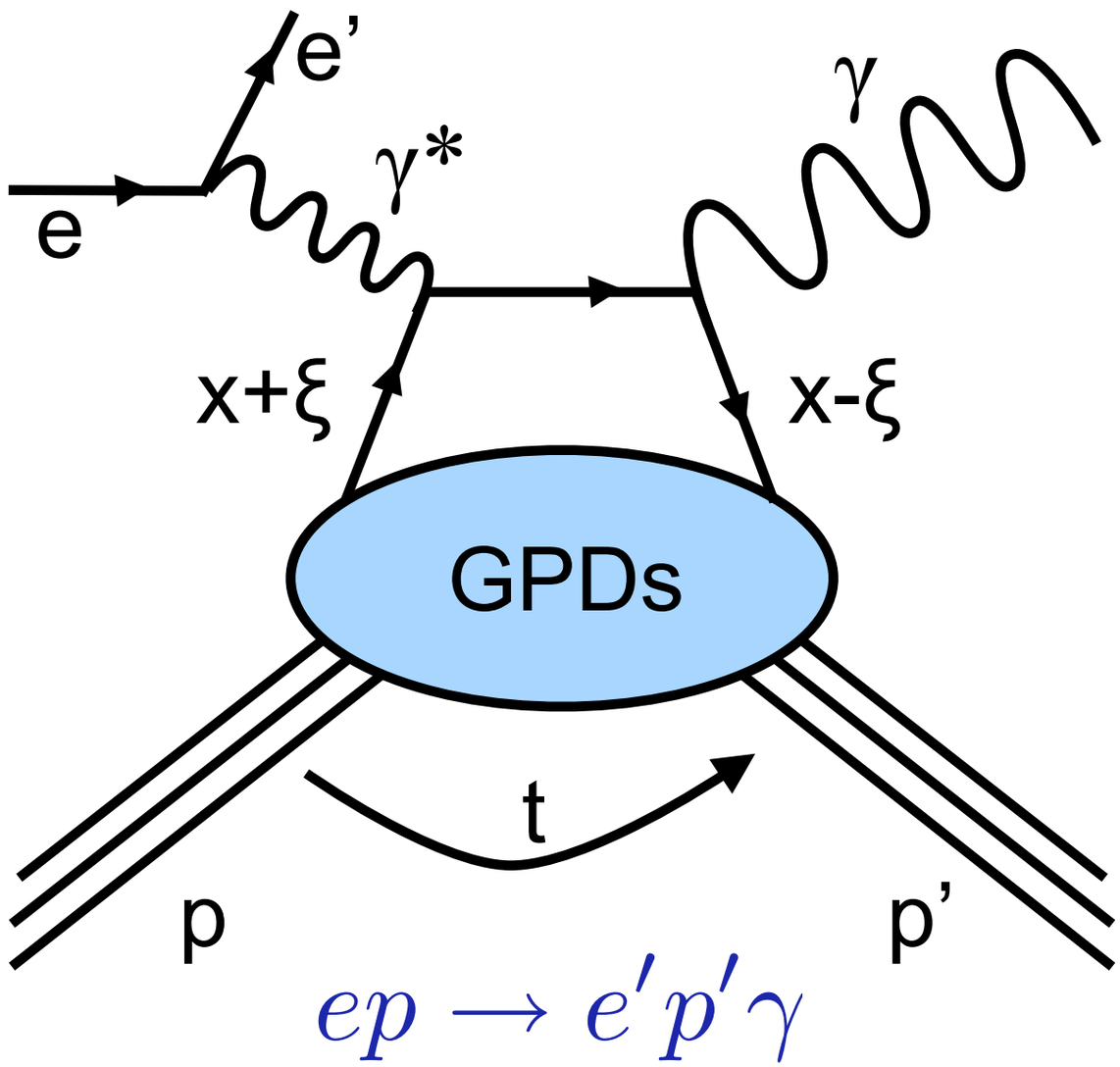


Form Factors (FFs)

Parton Distribution Functions (PDFs)

Generalised Parton Distributions (GPDs)

Generalised Parton Distributions

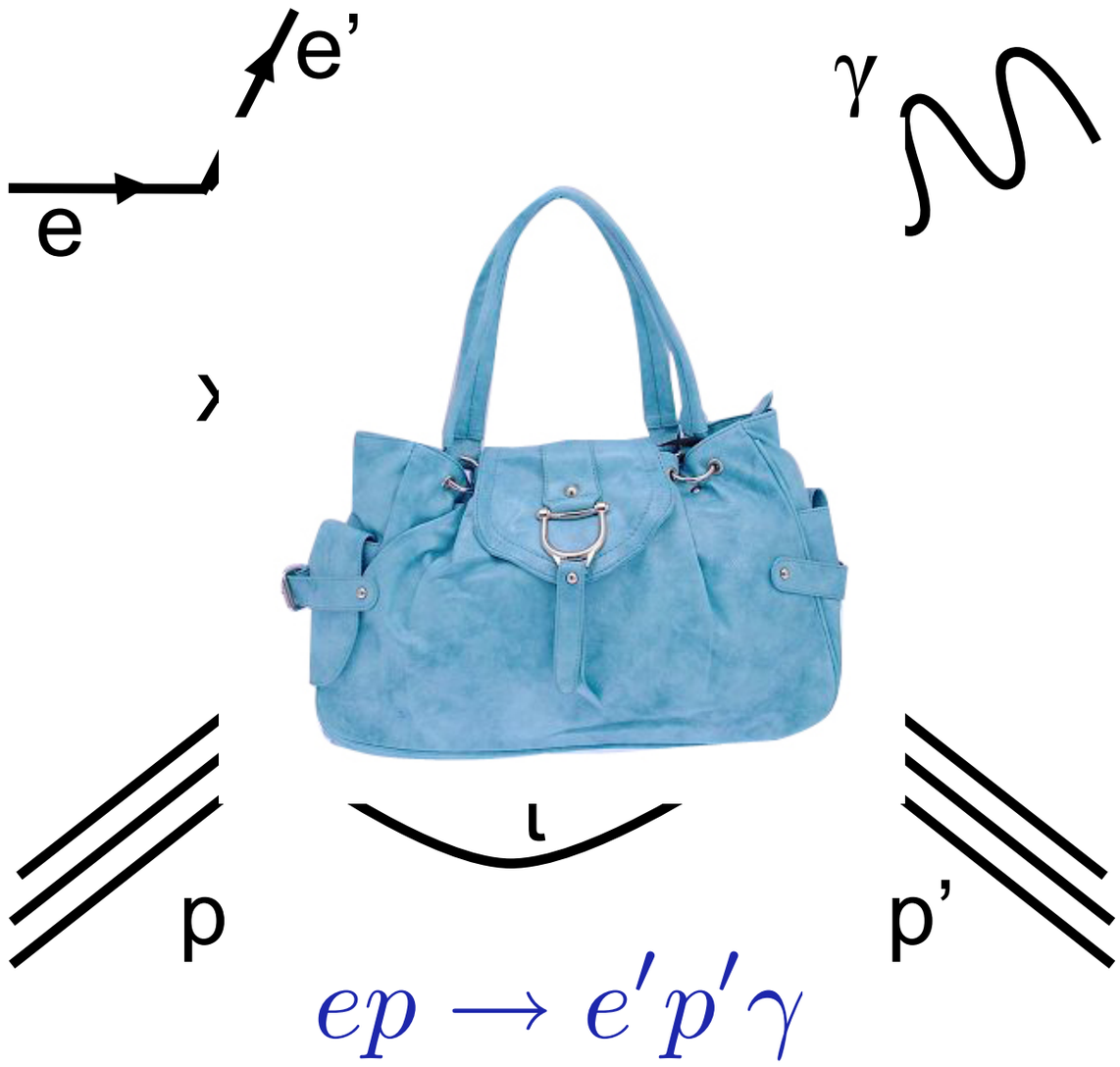


$$ep \to e'p'\gamma$$

- GPDs are functions of 3 variables: $H_q(x,\xi,t)$ as well as of Q^2.
- They include PDFs as limiting case: $q(x)=H_q(x,0,0)$
- Form factors are first moments of GPDs
- 4 quark GPDs: $H, \tilde{H}, E, \tilde{E}$

Often the so-called handbag diagram is used to illustrate GPDs. The simplest process to access GPDs is Deeply Virtual Compton Scattering (DVCS), shown in the diagram.

Generalised Parton Distributions



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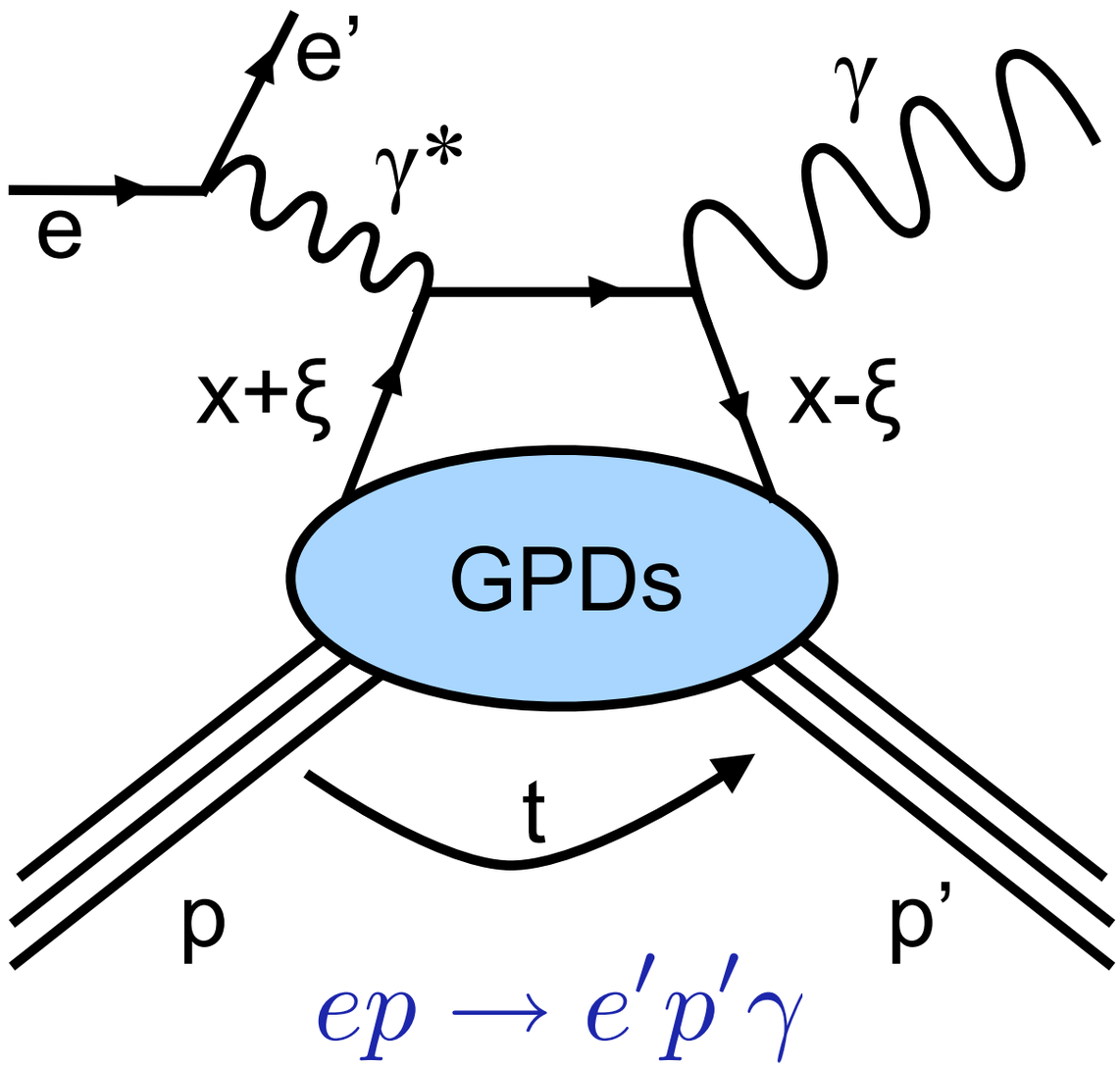

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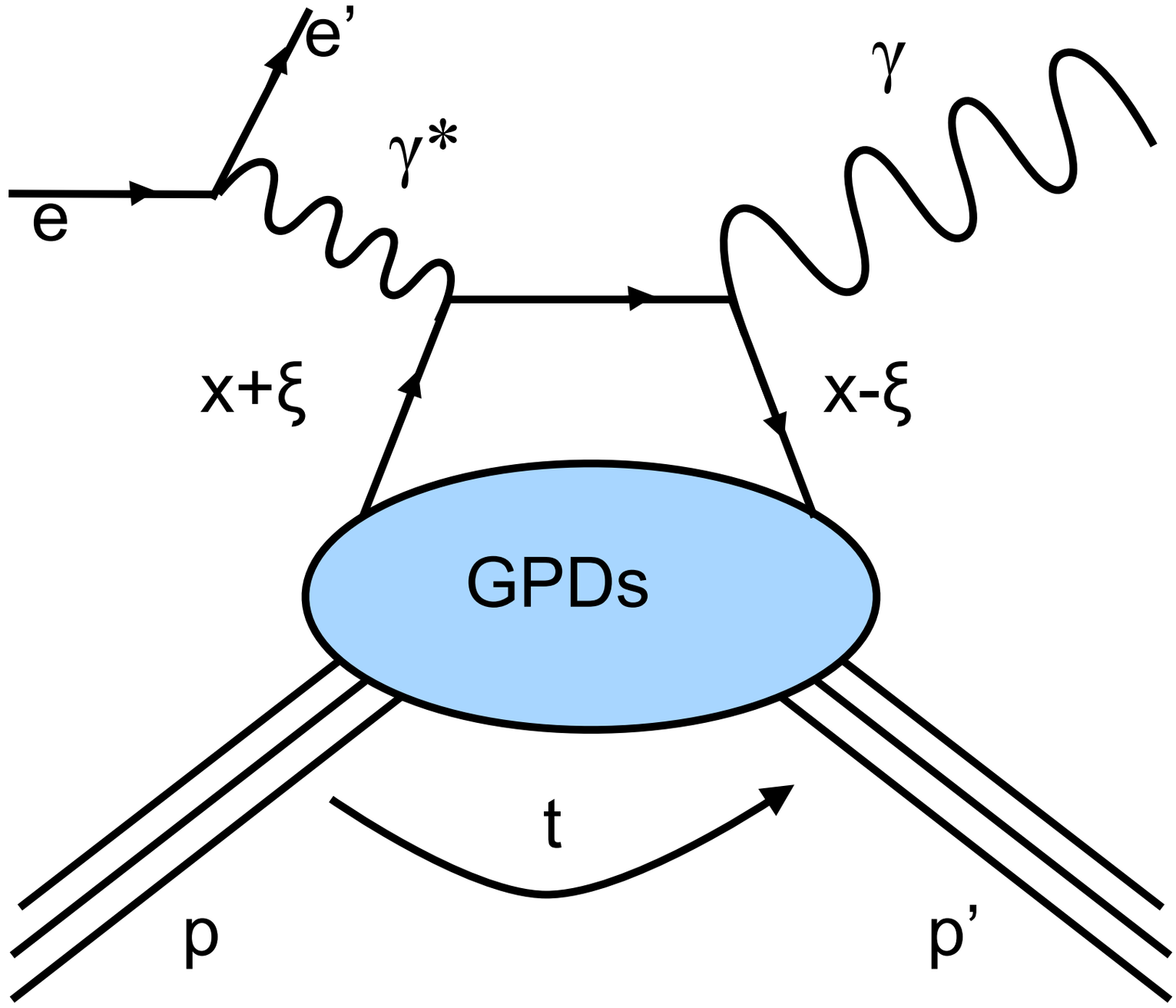
‘Reindeer Diagram’



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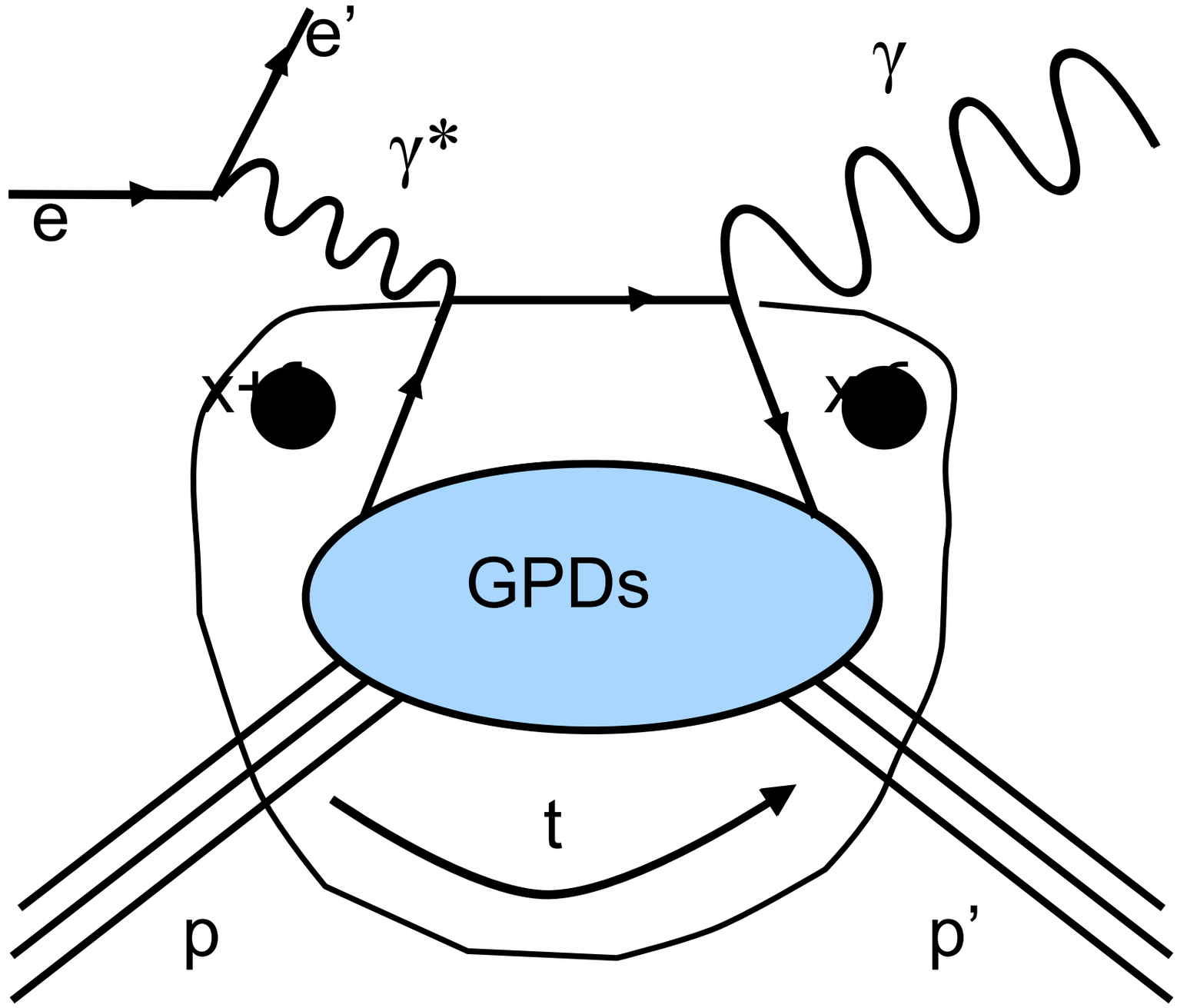
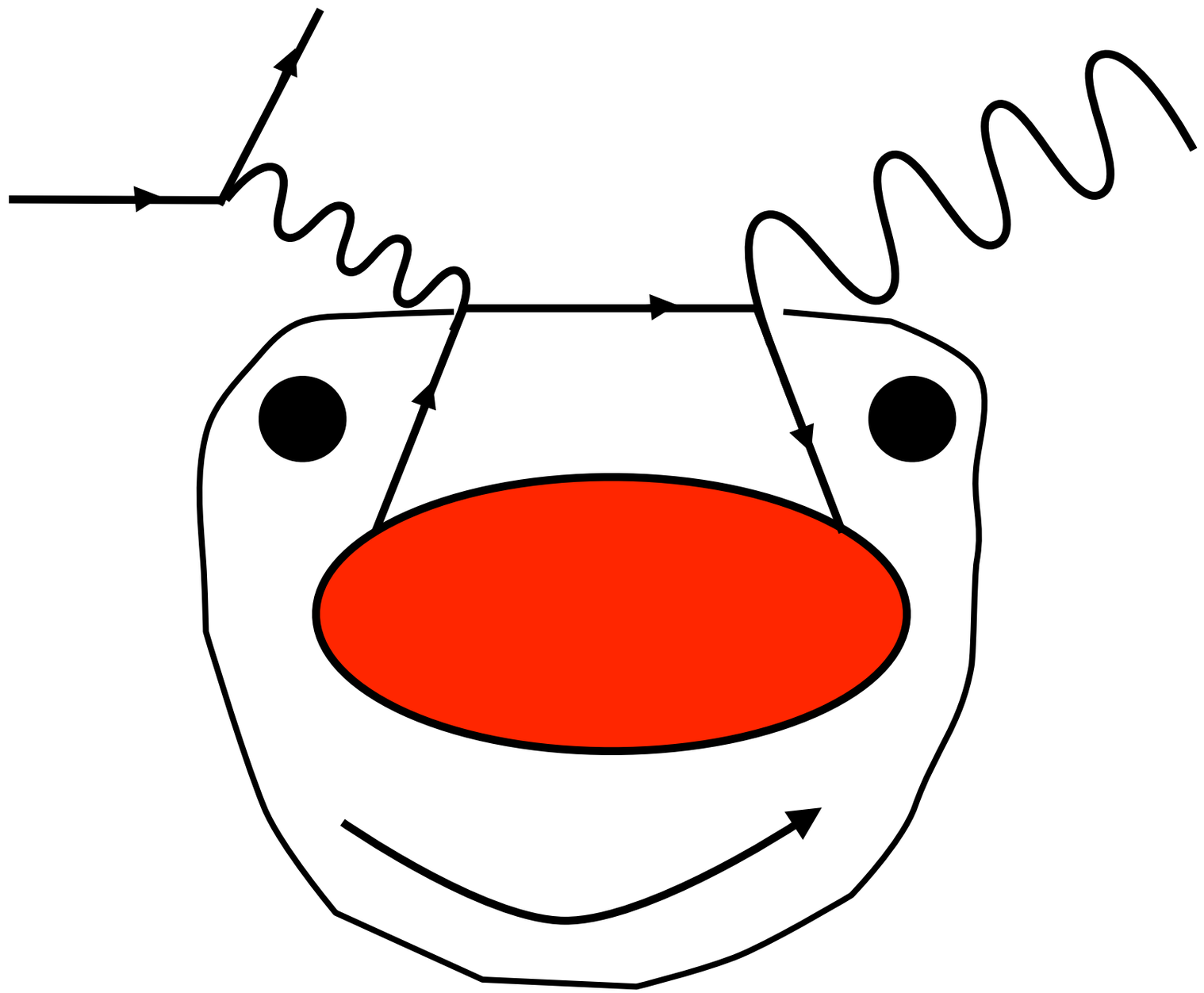


Rudolph

‘Reindeer Diagram’



Rudolph

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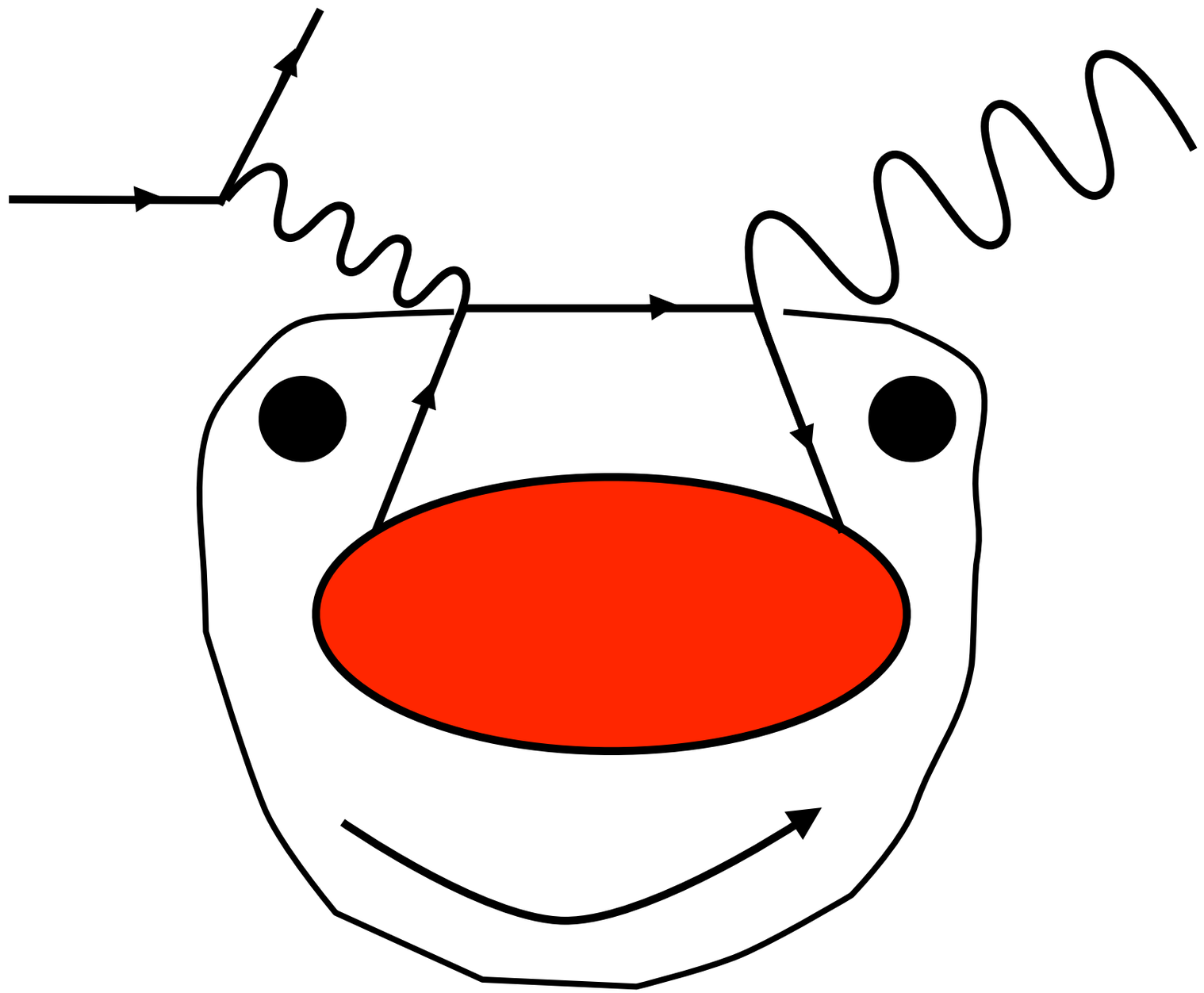


Rudolph

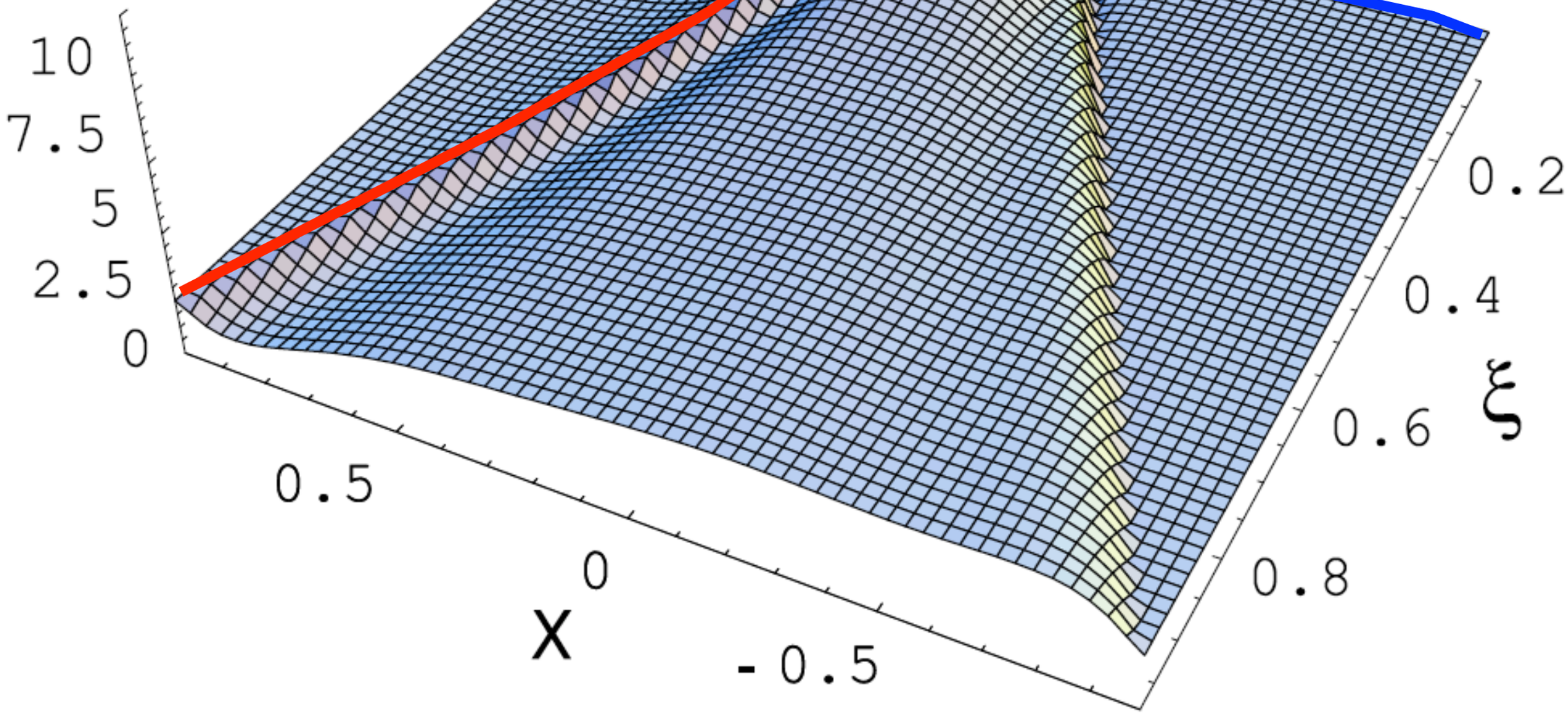
(c) Max Kaiser, 7 (now 9)

GPD H in VGG Model

PDF measured in DIS

H(x=ξ) measured in DVCS

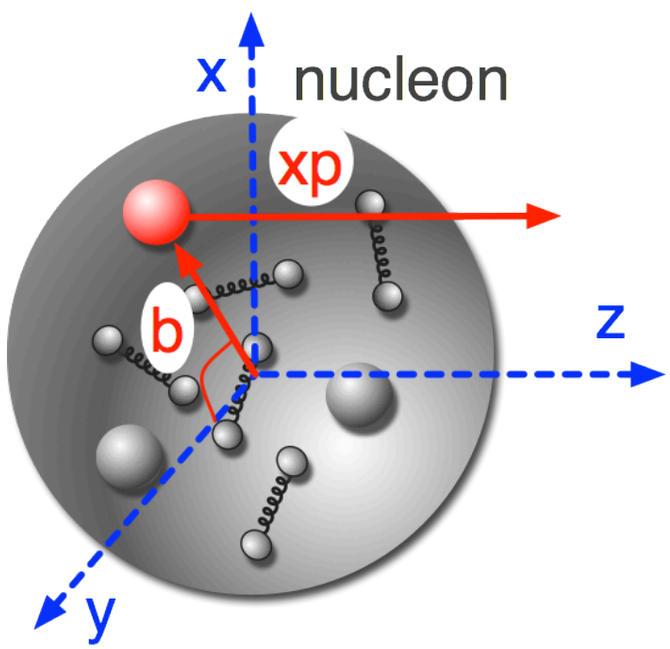
$$\mathbf{q}(-\mathbf{x}) = -\bar{\mathbf{q}}(\mathbf{x})$$

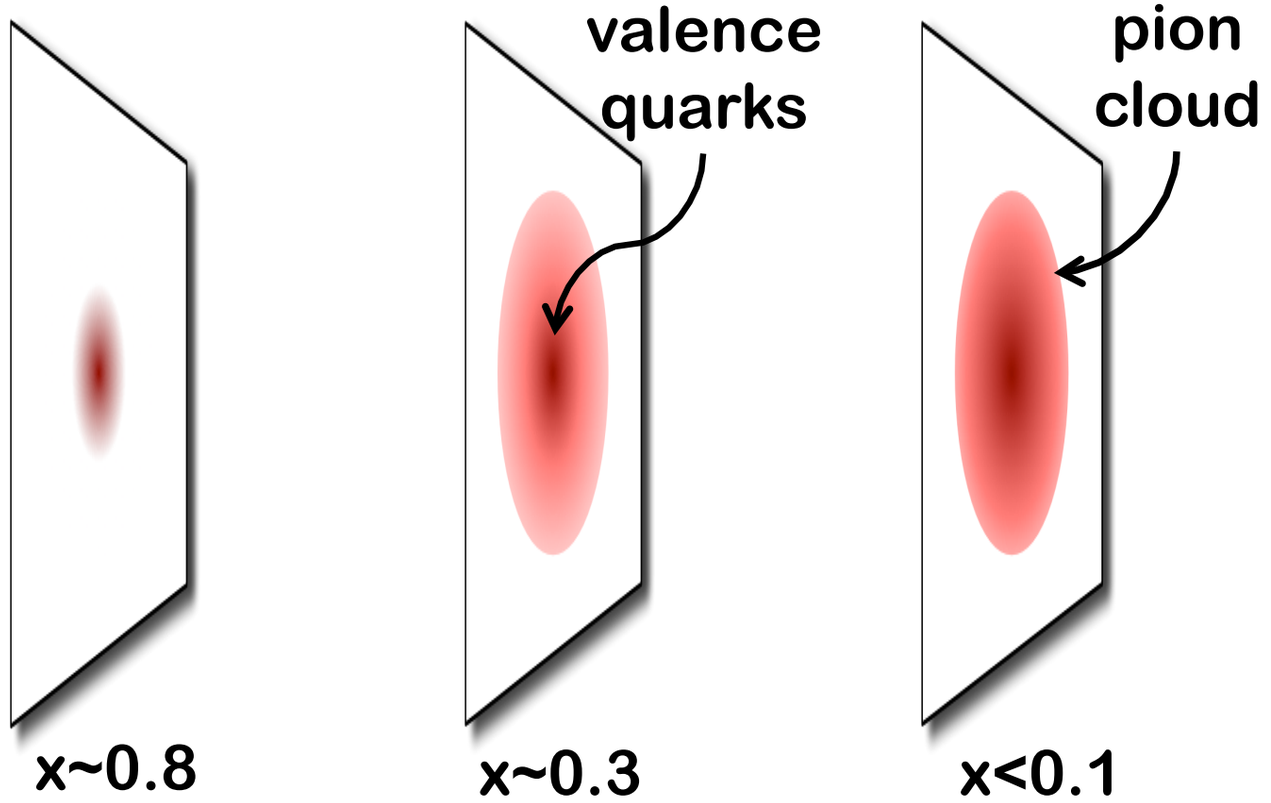


3D Picture of the Nucleon

Fourier transformation of GPDs at ξ=0 yields 2+1 dimensional picture of the nucleons, i.e. longitudinal in momentum fraction and transversal in impact parameter space

$$q(x, b_\perp) = \int \frac{d^2\Delta_\perp^2}{(2\pi)^2} H(x, 0, -\Delta_\perp^2) e^{-i\Delta_\perp \cdot b_\perp}$$





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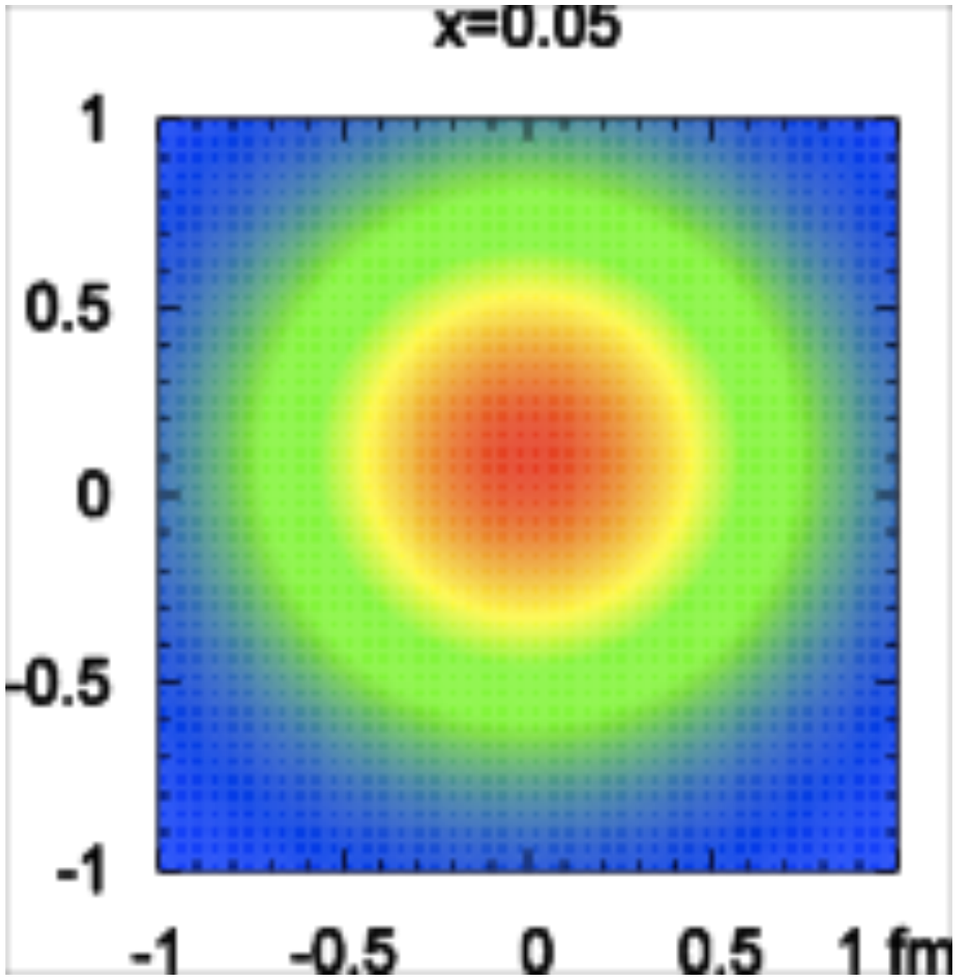
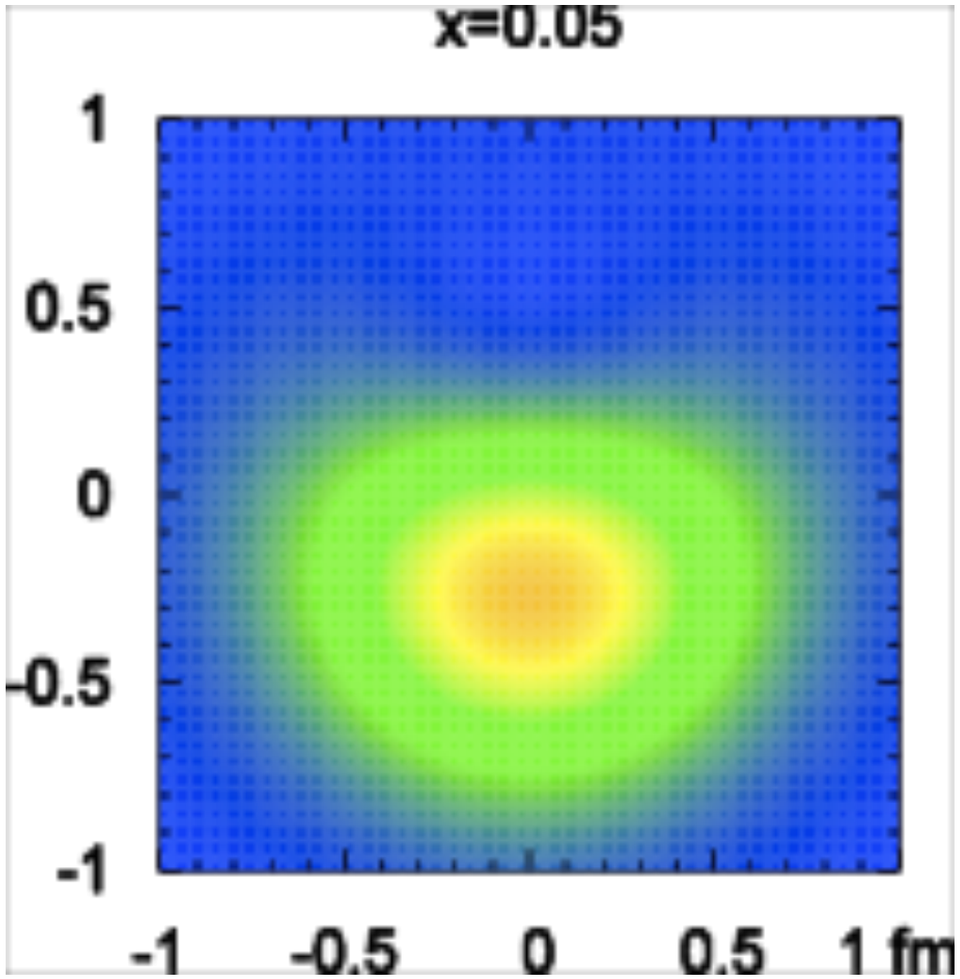
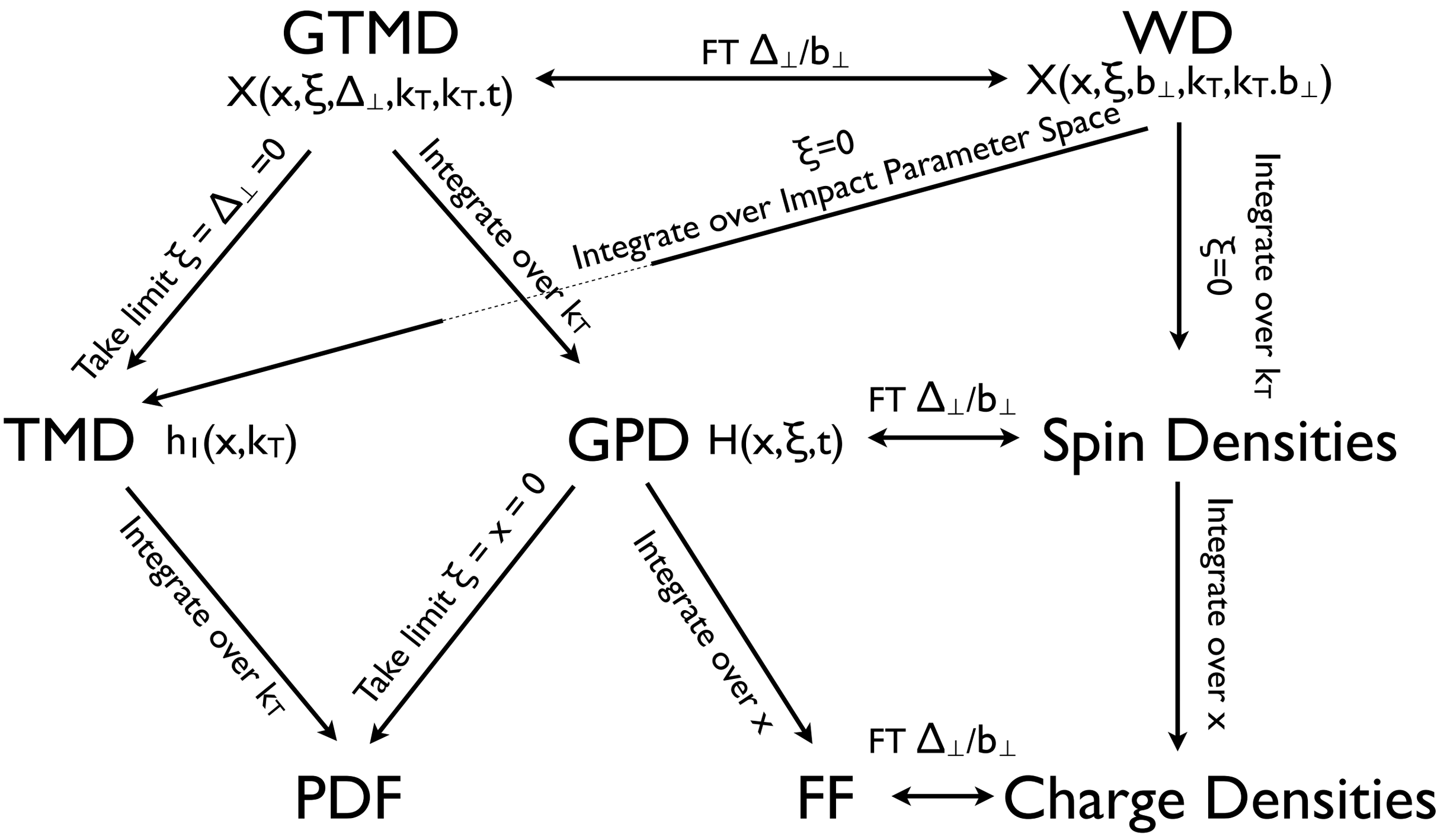




u-quark (left) and d-quark (right) density in impact parameter plane. Proton polarised in x-direction. GPD model fit based on existing form factor data.

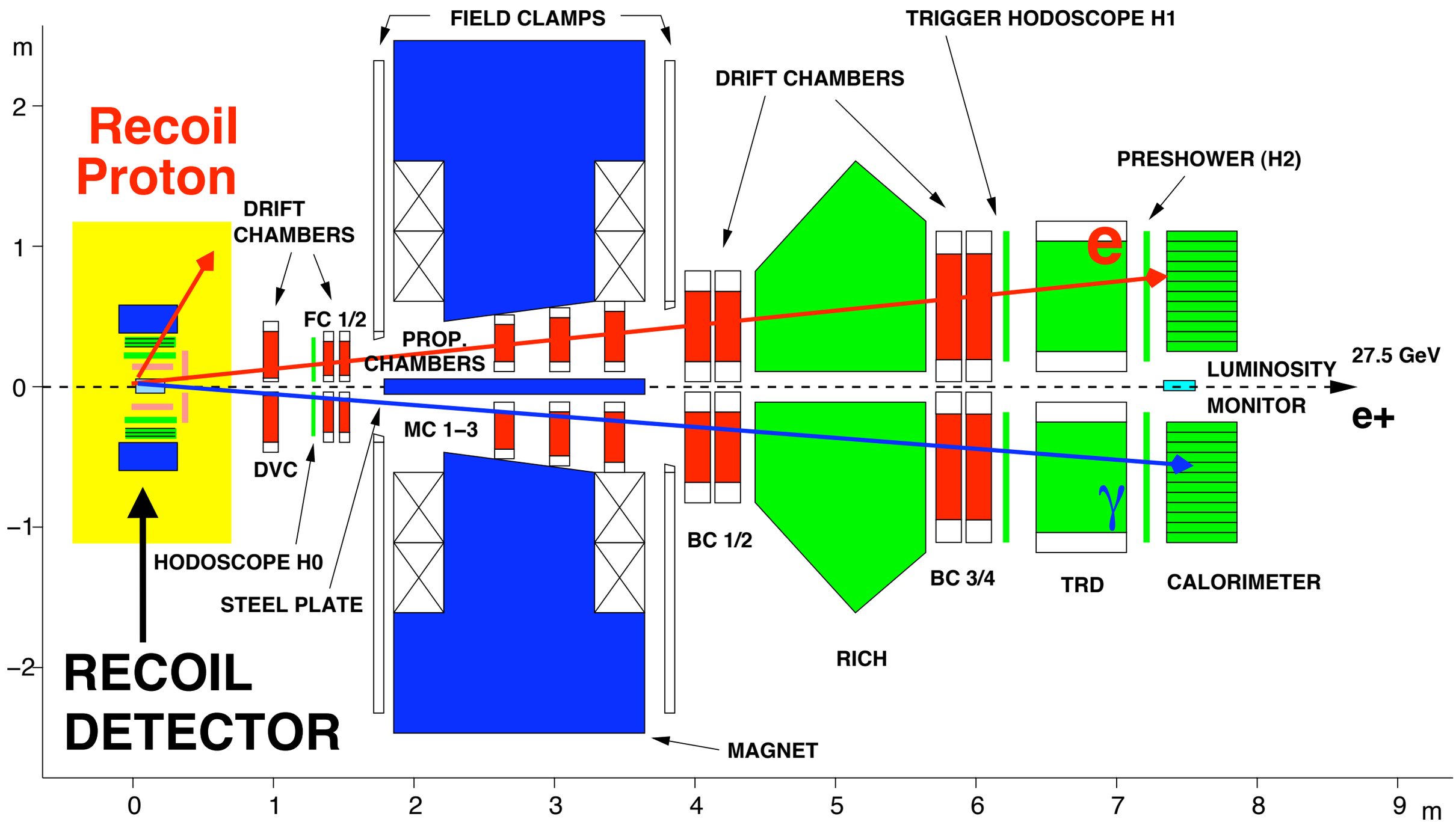
[P.Kroll, AIP Conf.Proc.904:76-86,2007]

Distribution Graph



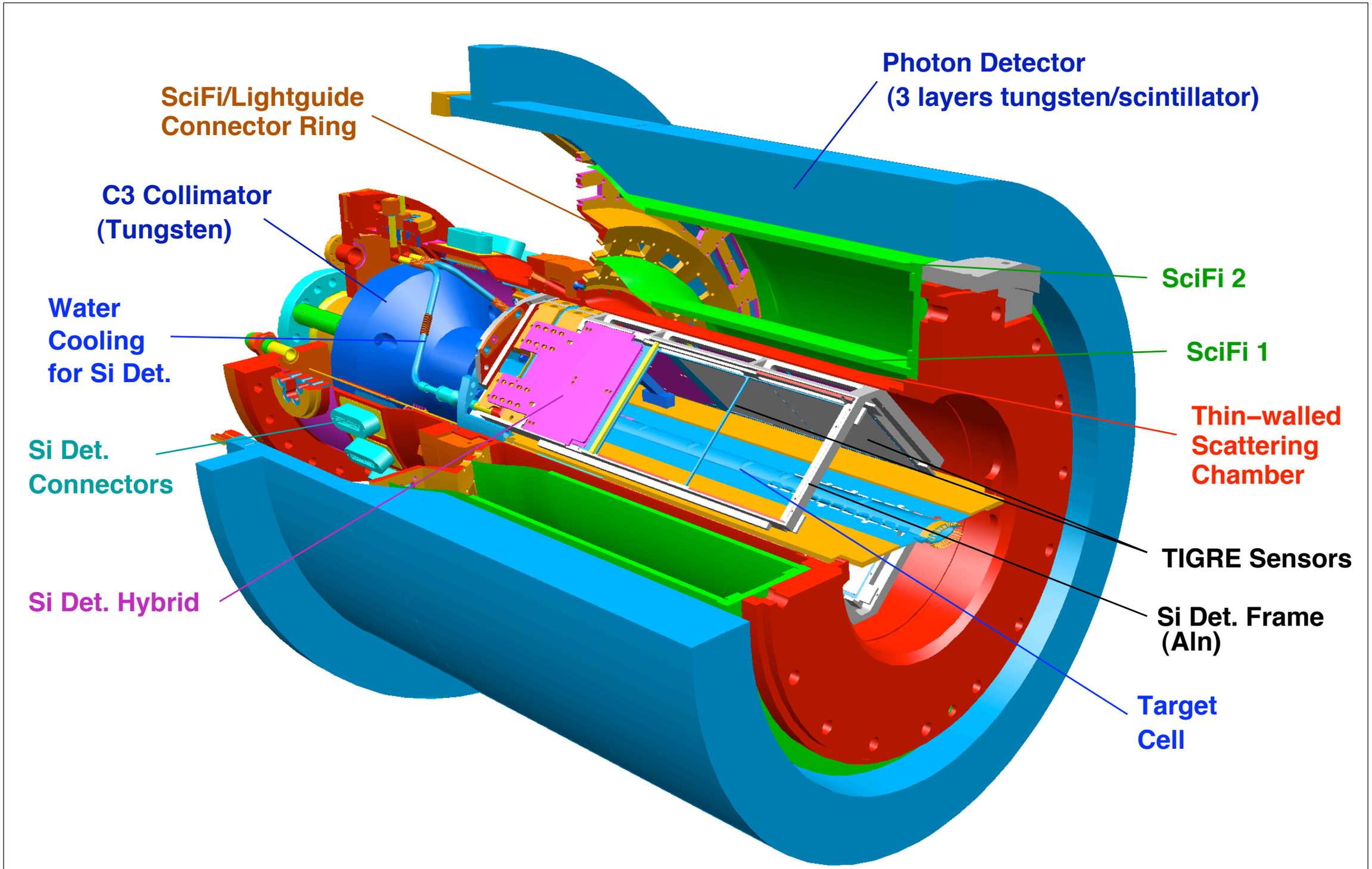
Courtesy M.Murray, Glasgow

HERMES @ DESY

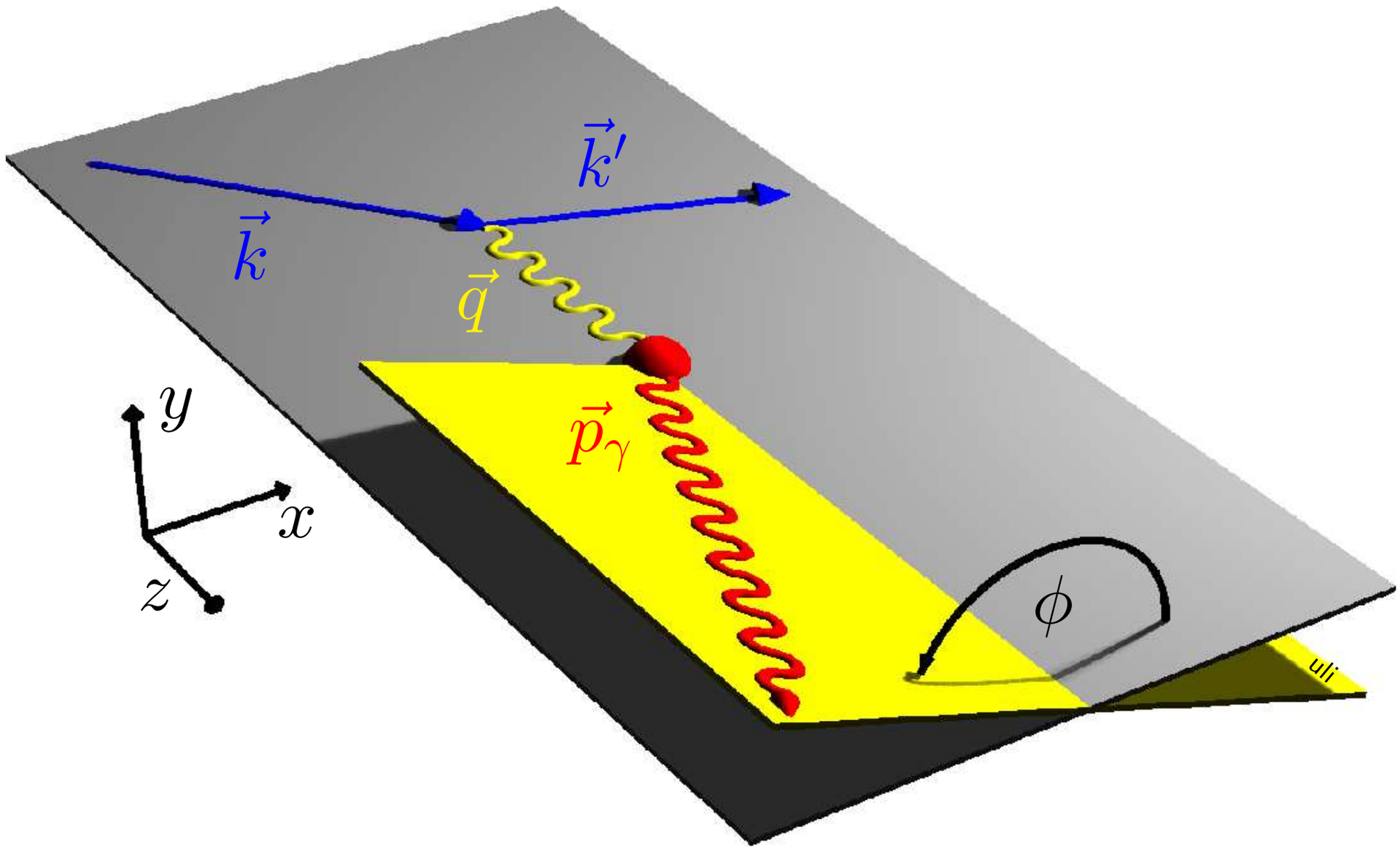


DVCS measurements with Recoil Detector in 2006/7 yielded about as much data as 1995-2005.

HERMES Recoil Detector



DVCS Asymmetries



DVCS Asymmetries

DVCS Asymmetries

$$\mathcal{A}_C(\phi) \equiv \frac{\mathrm{d}\sigma^+(\phi) - \mathrm{d}\sigma^-(\phi)}{\mathrm{d}\sigma^+(\phi) + \mathrm{d}\sigma^-(\phi)} \quad \widetilde{\propto} \quad \mathrm{Re}(\mathcal{H})$$

$$\mathcal{A}_{\mathrm{LU}}(\phi) \equiv \frac{[\sigma^{\rightarrow\Leftarrow}(\phi) + \sigma^{\rightarrow\Rightarrow}(\phi)] - [\sigma^{\leftarrow\Leftarrow}(\phi) + \sigma^{\leftarrow\Rightarrow}(\phi)]}{[\sigma^{\rightarrow\Leftarrow}(\phi) + \sigma^{\rightarrow\Rightarrow}(\phi)] + [\sigma^{\leftarrow\Leftarrow}(\phi) + \sigma^{\leftarrow\Rightarrow}(\phi)]} \quad \widetilde{\propto} \quad \mathrm{Im}(\mathcal{H})$$

$$\mathcal{A}_{\mathrm{UL}}(\phi) \equiv \frac{[\sigma^{\leftarrow\Rightarrow}(\phi) + \sigma^{\rightarrow\Rightarrow}(\phi)] - [\sigma^{\leftarrow\Leftarrow}(\phi) + \sigma^{\rightarrow\Leftarrow}(\phi)]}{[\sigma^{\leftarrow\Rightarrow}(\phi) + \sigma^{\rightarrow\Rightarrow}(\phi)] + [\sigma^{\leftarrow\Leftarrow}(\phi) + \sigma^{\rightarrow\Leftarrow}(\phi)]} \quad \widetilde{\propto} \quad \mathrm{Im}(\widetilde{\mathcal{H}})$$

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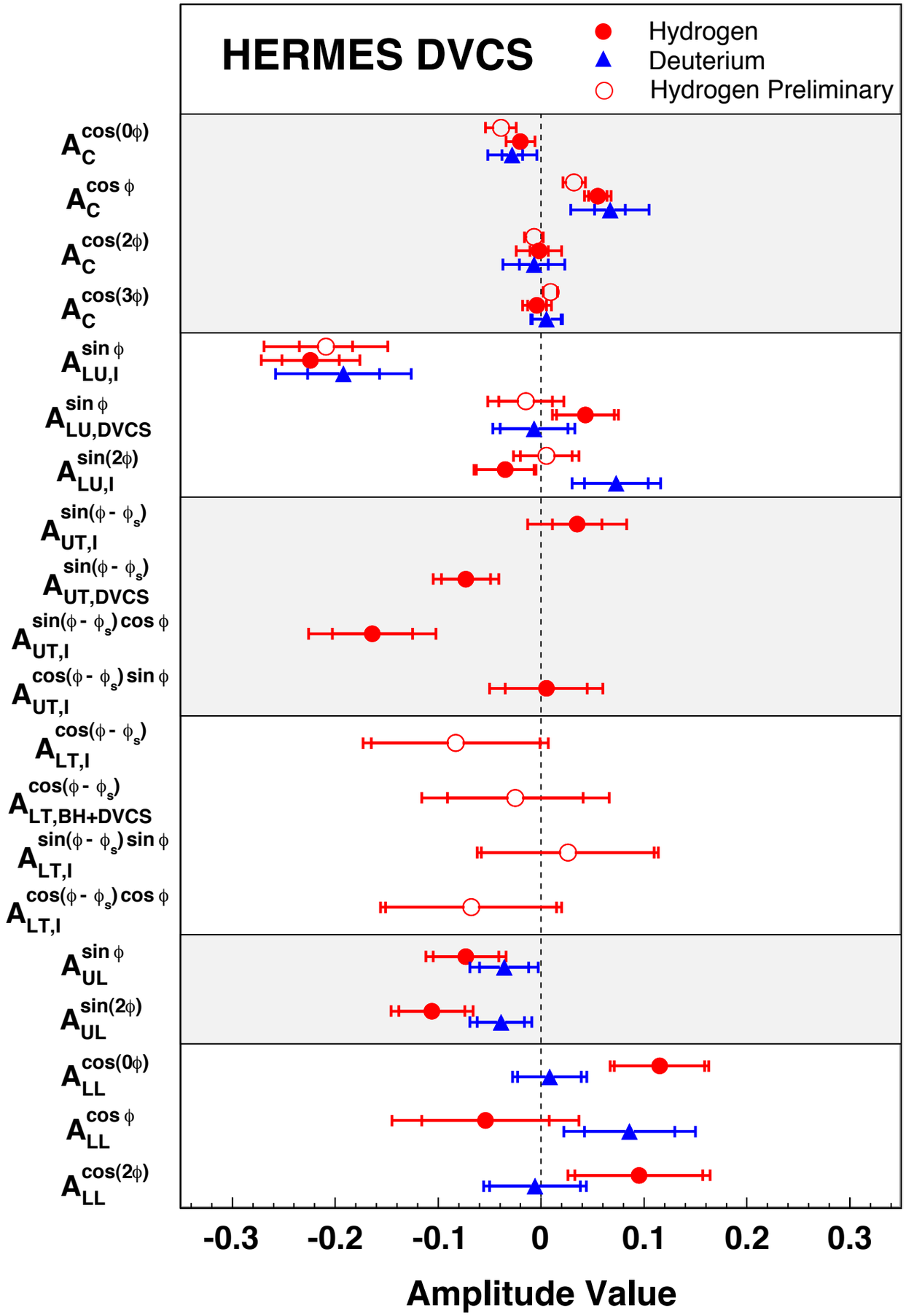
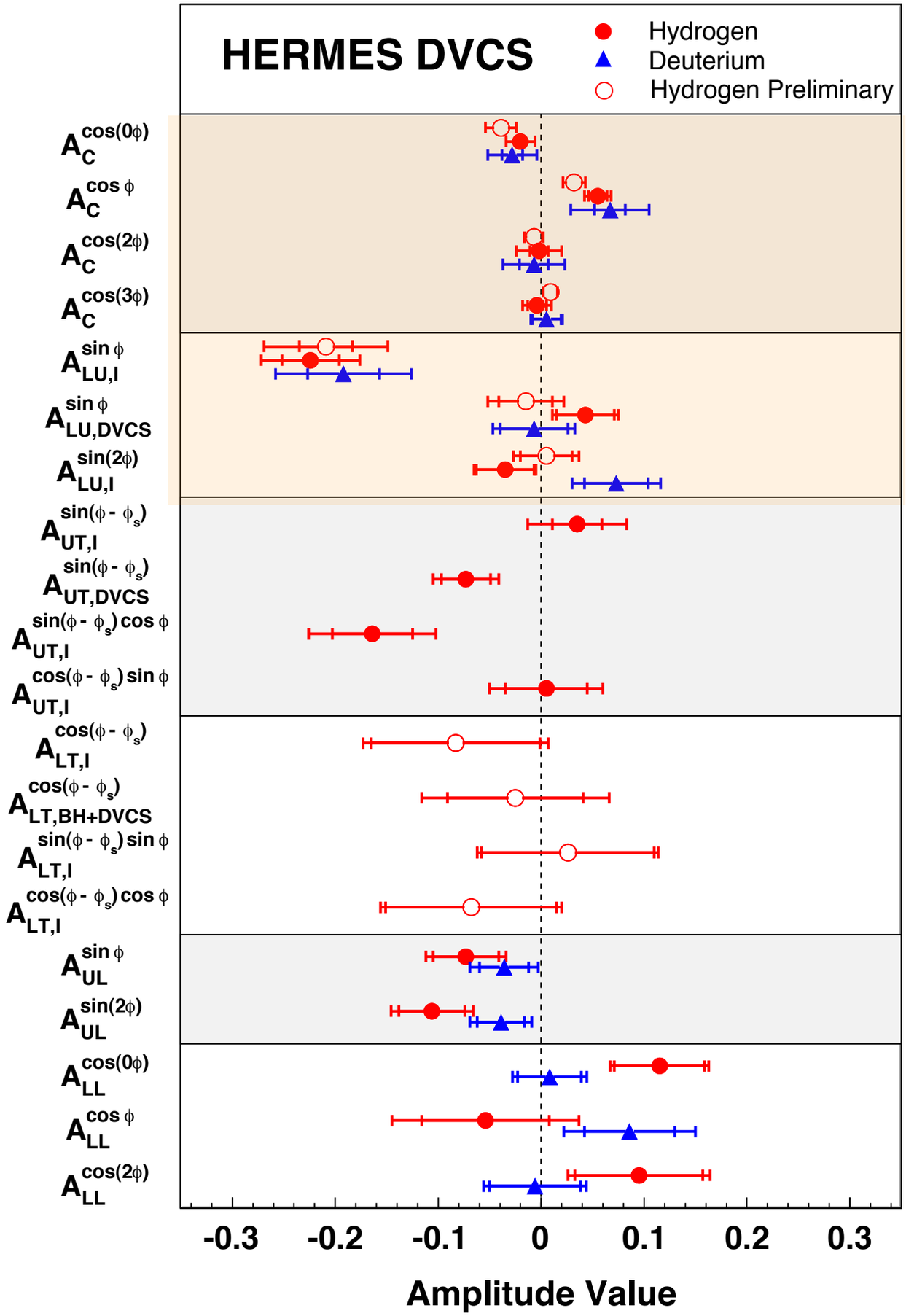
Statistics: Only 1 DVCS event for 1000 DIS events at HERMES kinematics !

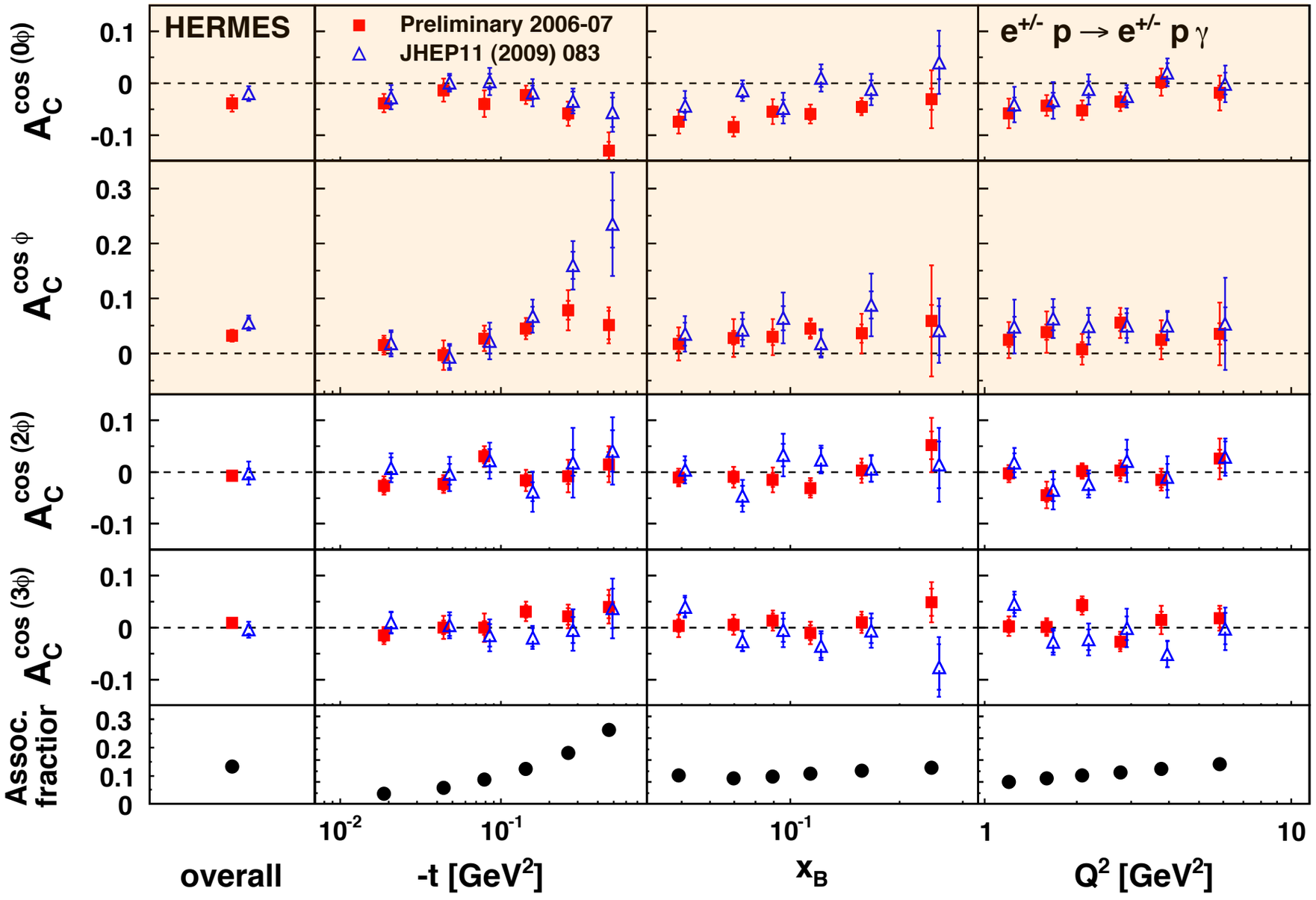
University of Glasgow



University of Glasgow



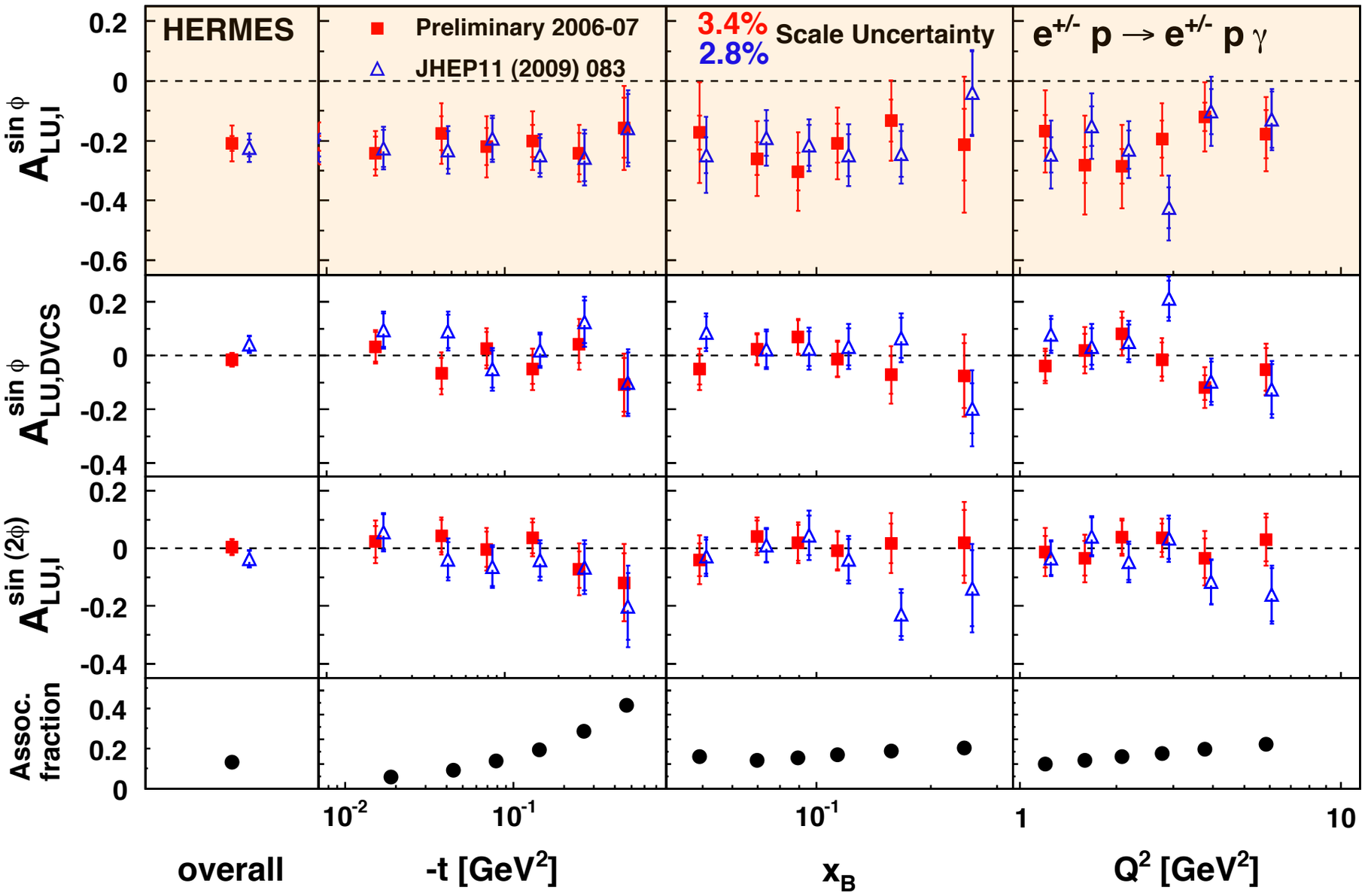
Beam Charge Asymmetry



Beam Charge Asymmetries access Re($\mathcal{H}$)

←Δ-resonance

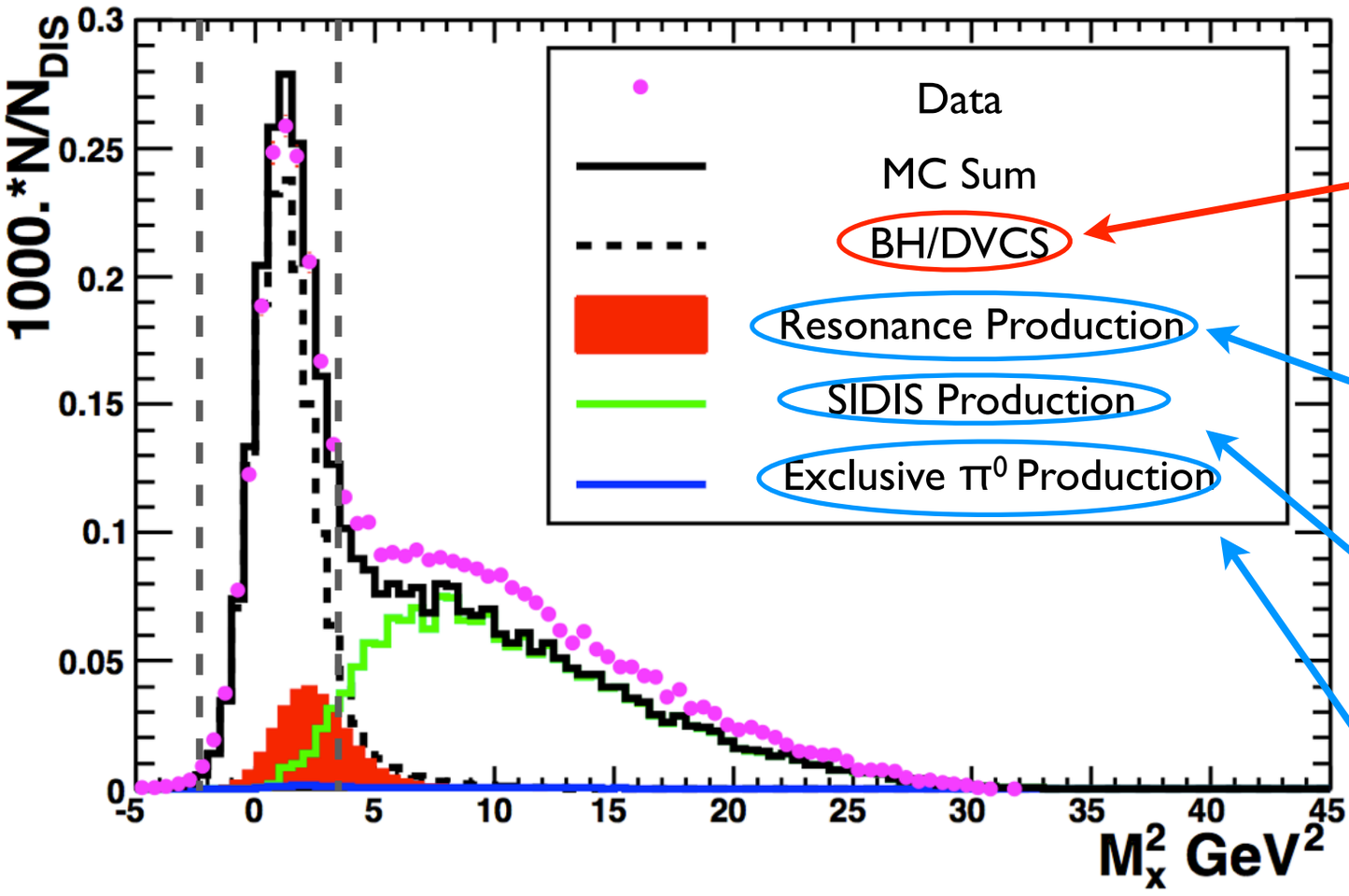
Beam Spin Asymmetry



Beam Spin Asymmetries access $\mathrm{Im}(\mathcal{H})$

Larger values for the BSA than BCA

DVCS Data at HERMES



Wanted

BH/DVCS from Δ, e.g

$e\,\Delta \rightarrow e\,\Delta\,\gamma \rightarrow e\,p\,\pi^0$

$e\,p \rightarrow e\,X$

$e\,p \rightarrow e\,p$

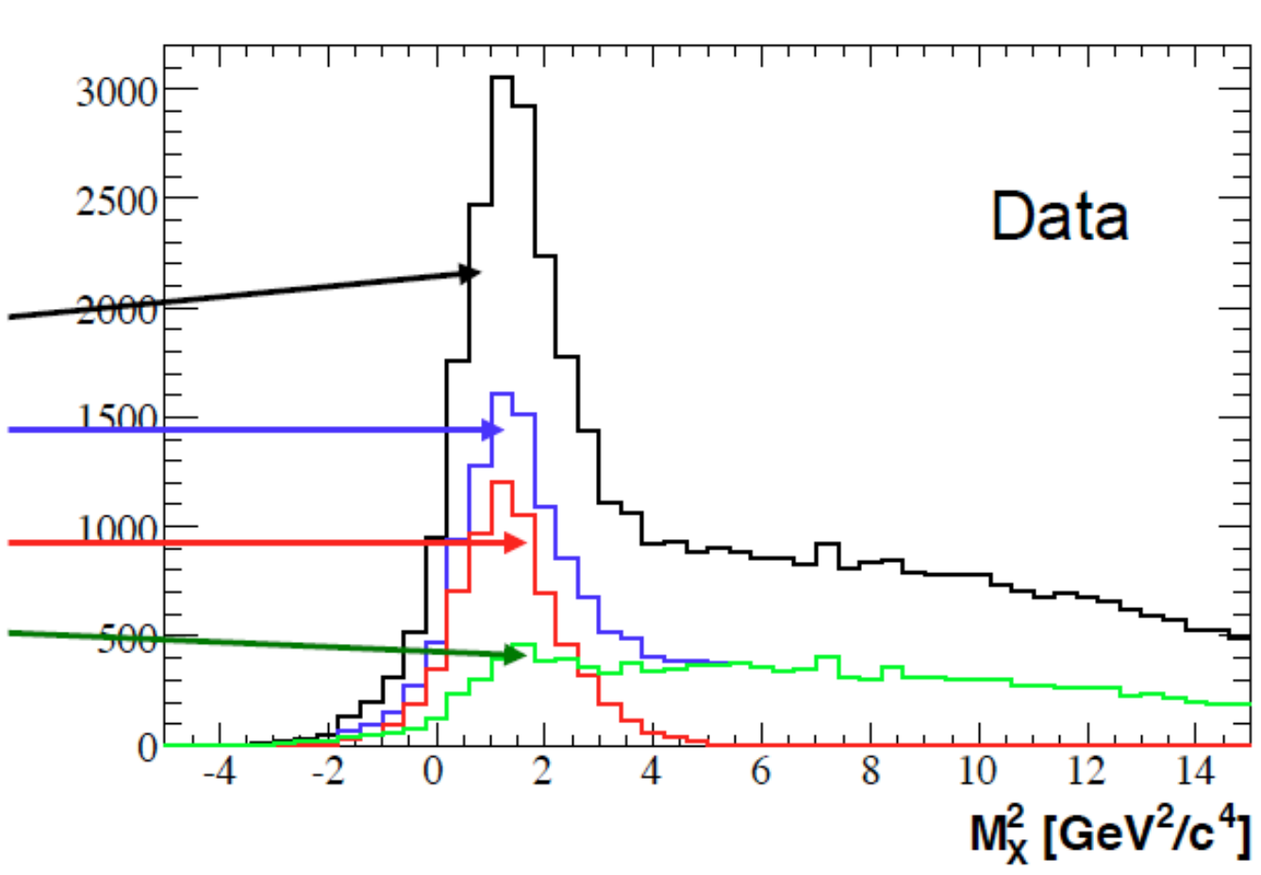
HERMES DVCS Event Selection

Kinematic event fitting technique

- All 3 particles in final state detected → 4 constraints from energy-momentum conservation
- Selection of elastic DVCS with high efficiency (~84%)
- Allows to suppress background from associated and semi-inclusive processes to a negligible level (~0.1%)

Missing mass distribution

- No requirement for Recoil
- Positively charged Recoil track
- Kinematic fit probability > 1%
- Kinematic fit probability < 1%



HERMES DVCS Event Samples

Without Recoil Detector

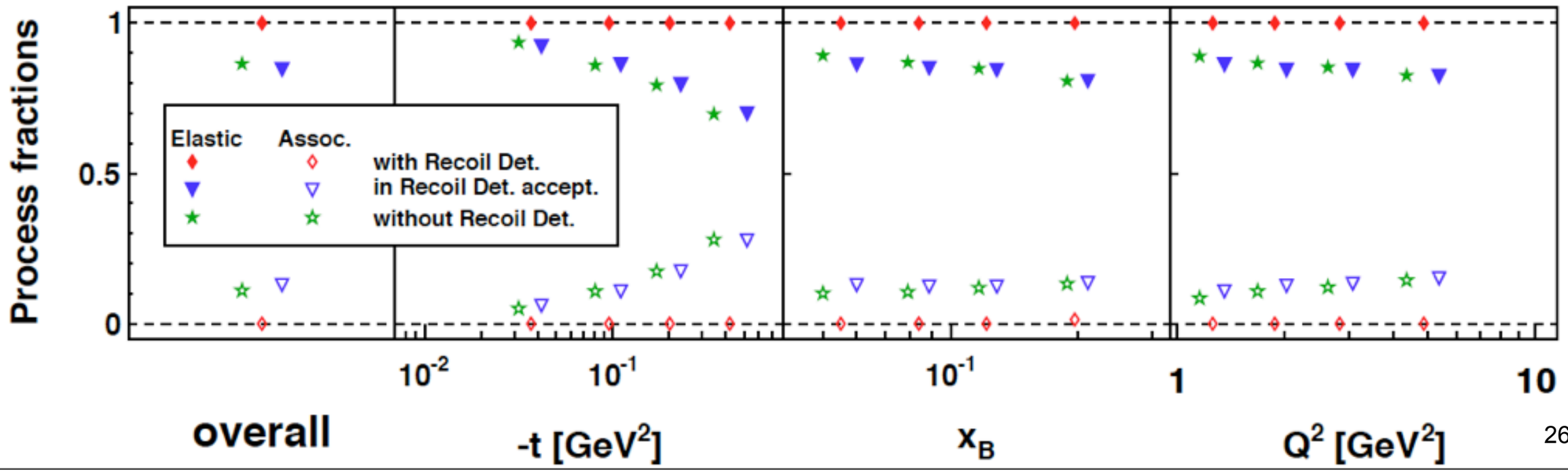
In Recoil Detector acceptance

With Recoil Detector

Similar background

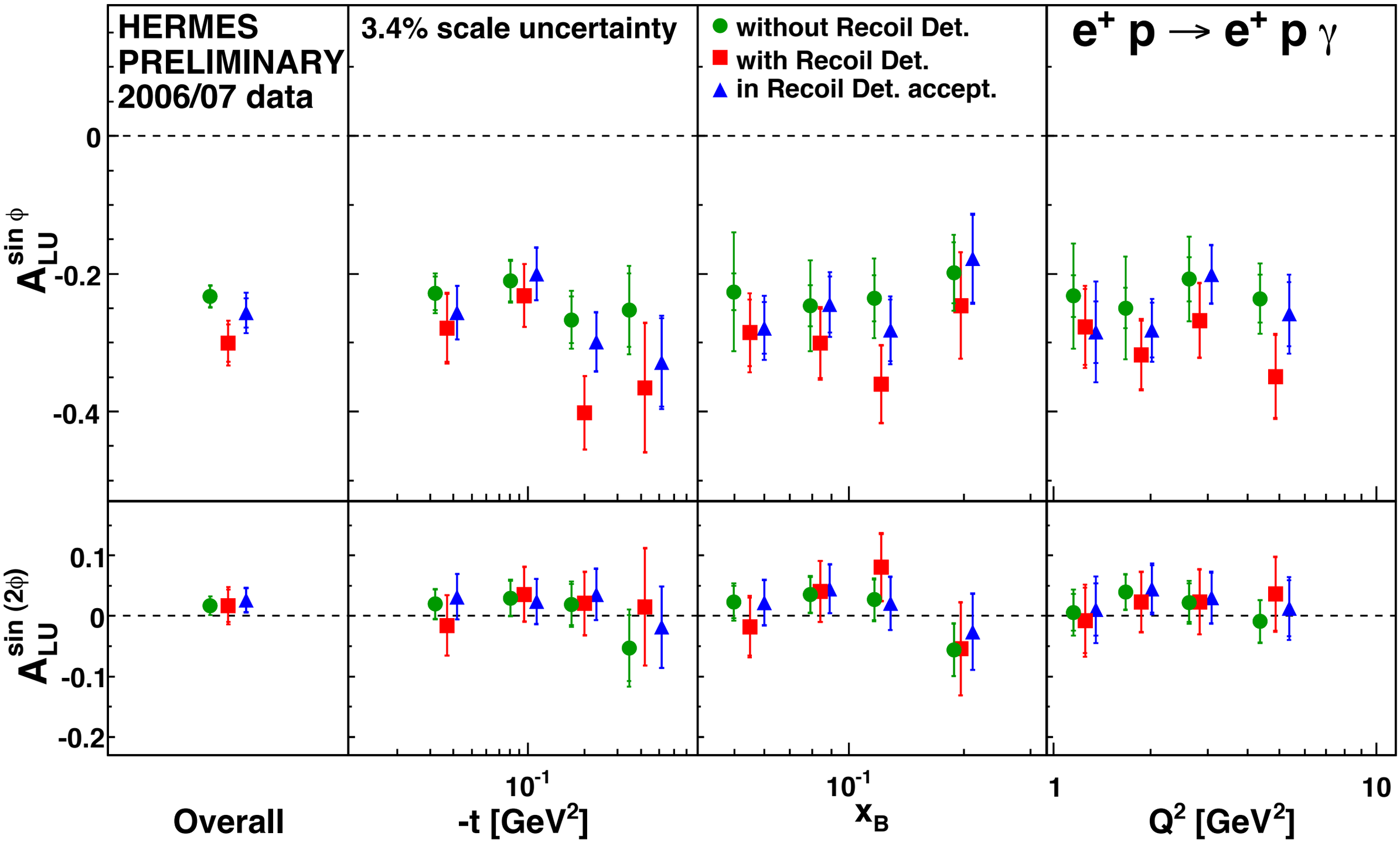
Background-free

Similar kinematics



HERMES DVCS BSA with Recoil Detector

University of Glasgow



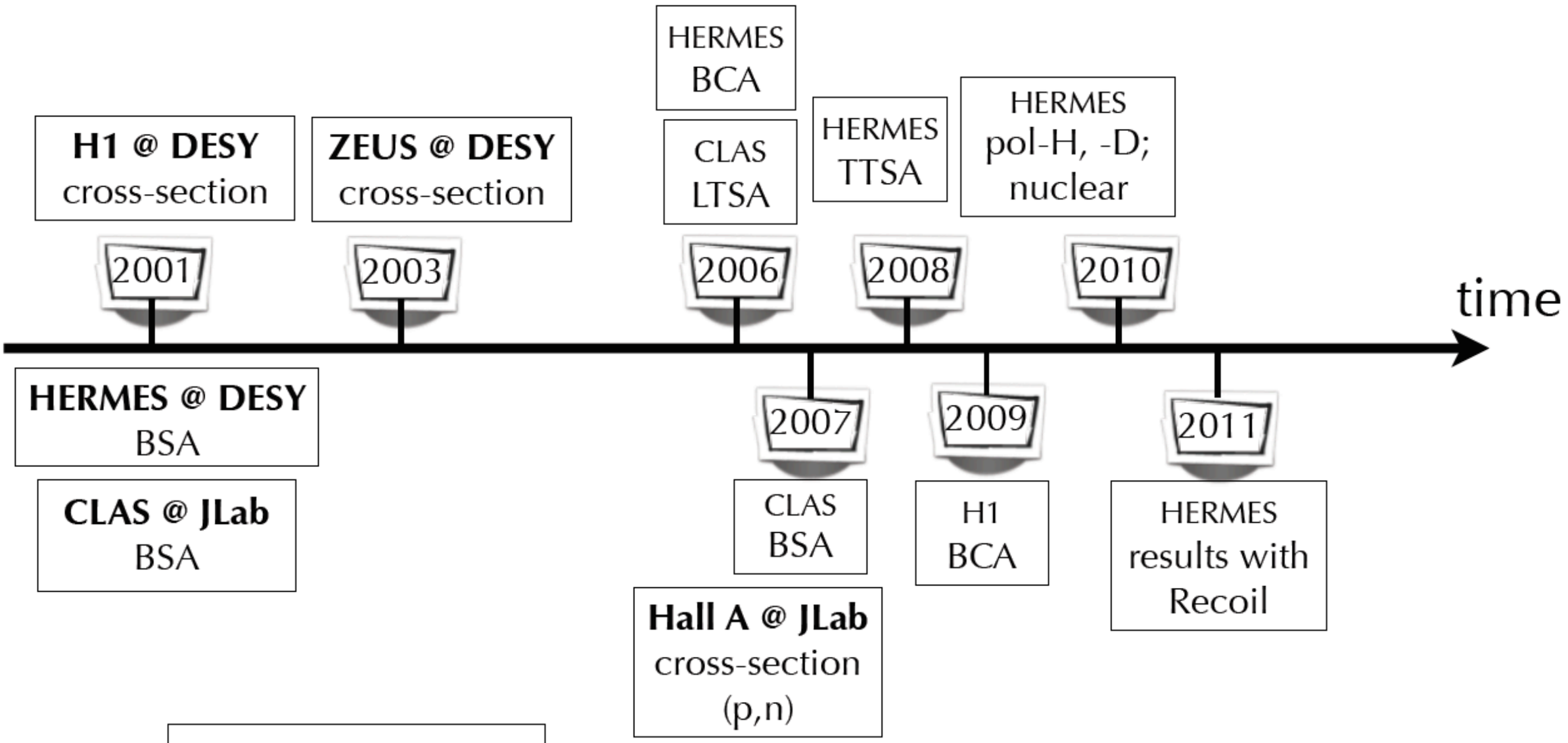
PhD Thesis Jennifer Bowles, Glasgow, in preparation

DVCS Measurements over the Years

List does not claim to be exhaustive.

Courtesy C.Riedl, DESY

DVCS Measurements over the Years



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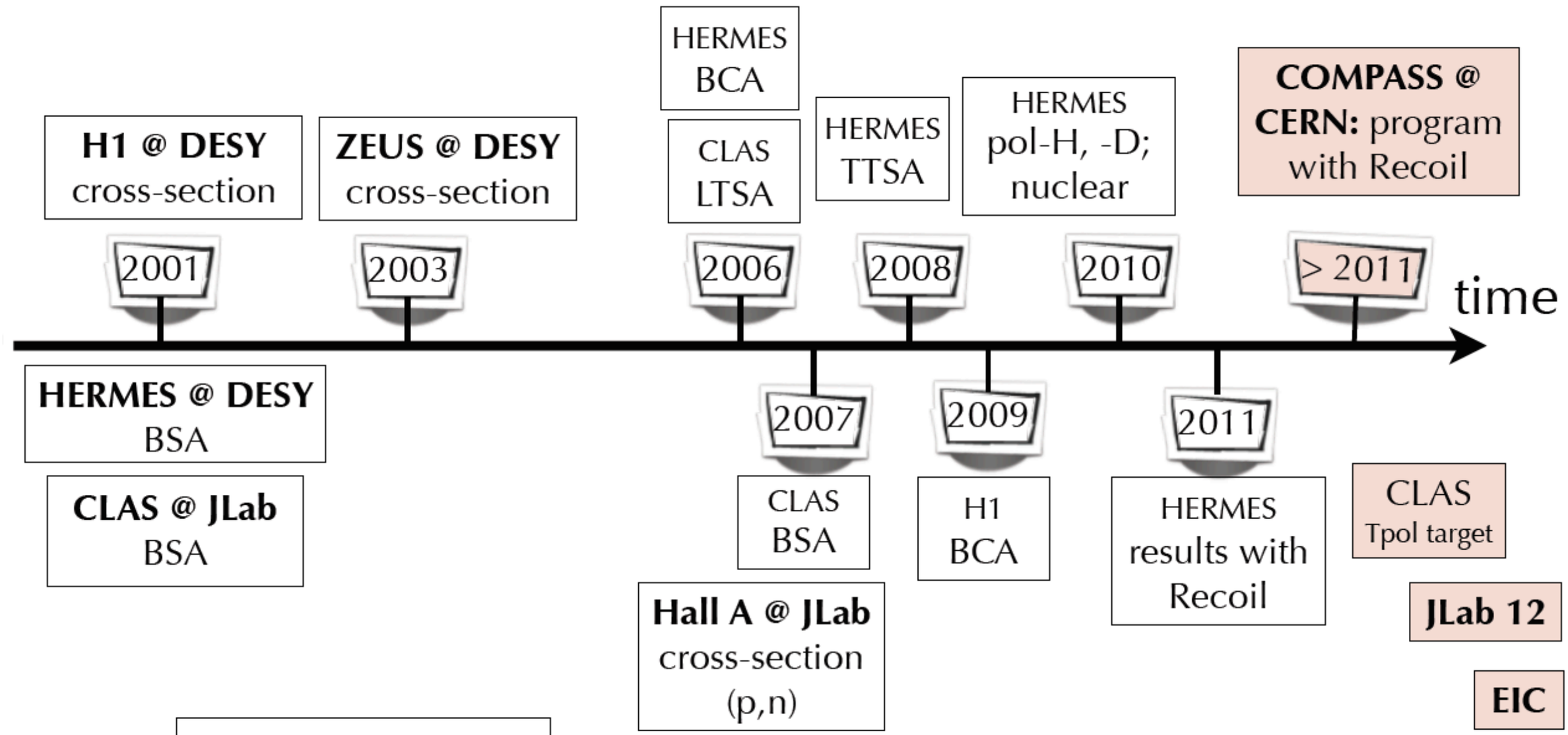
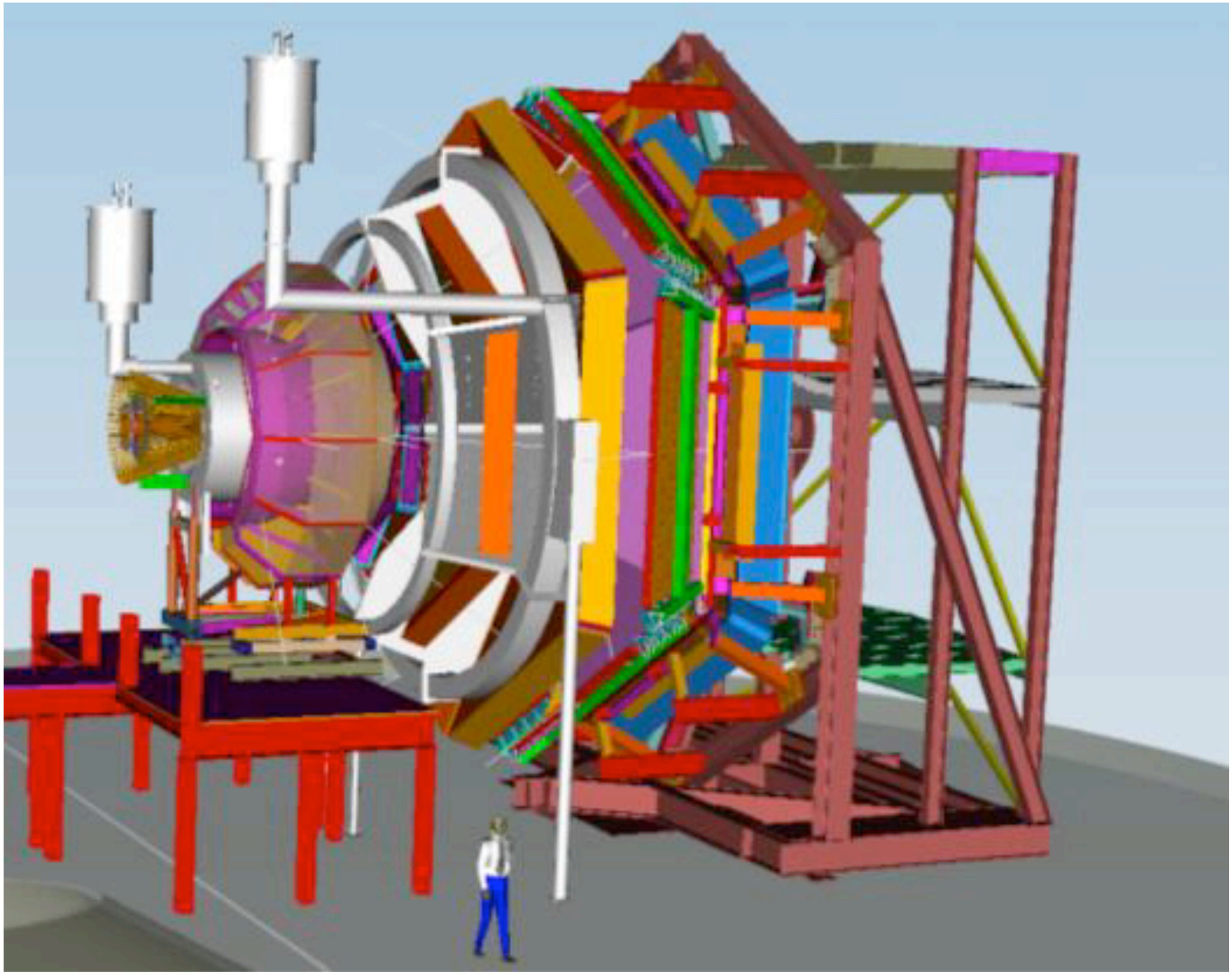
DVCS Measurements over the Years

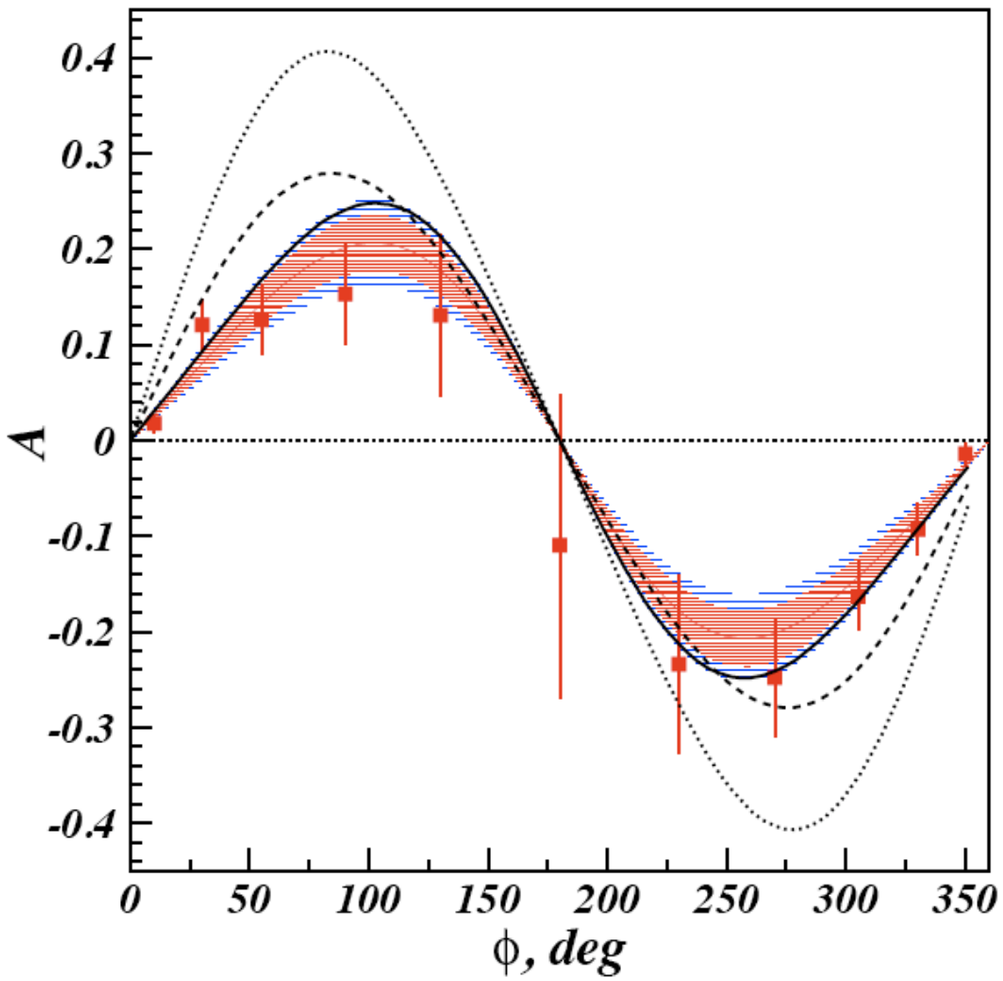


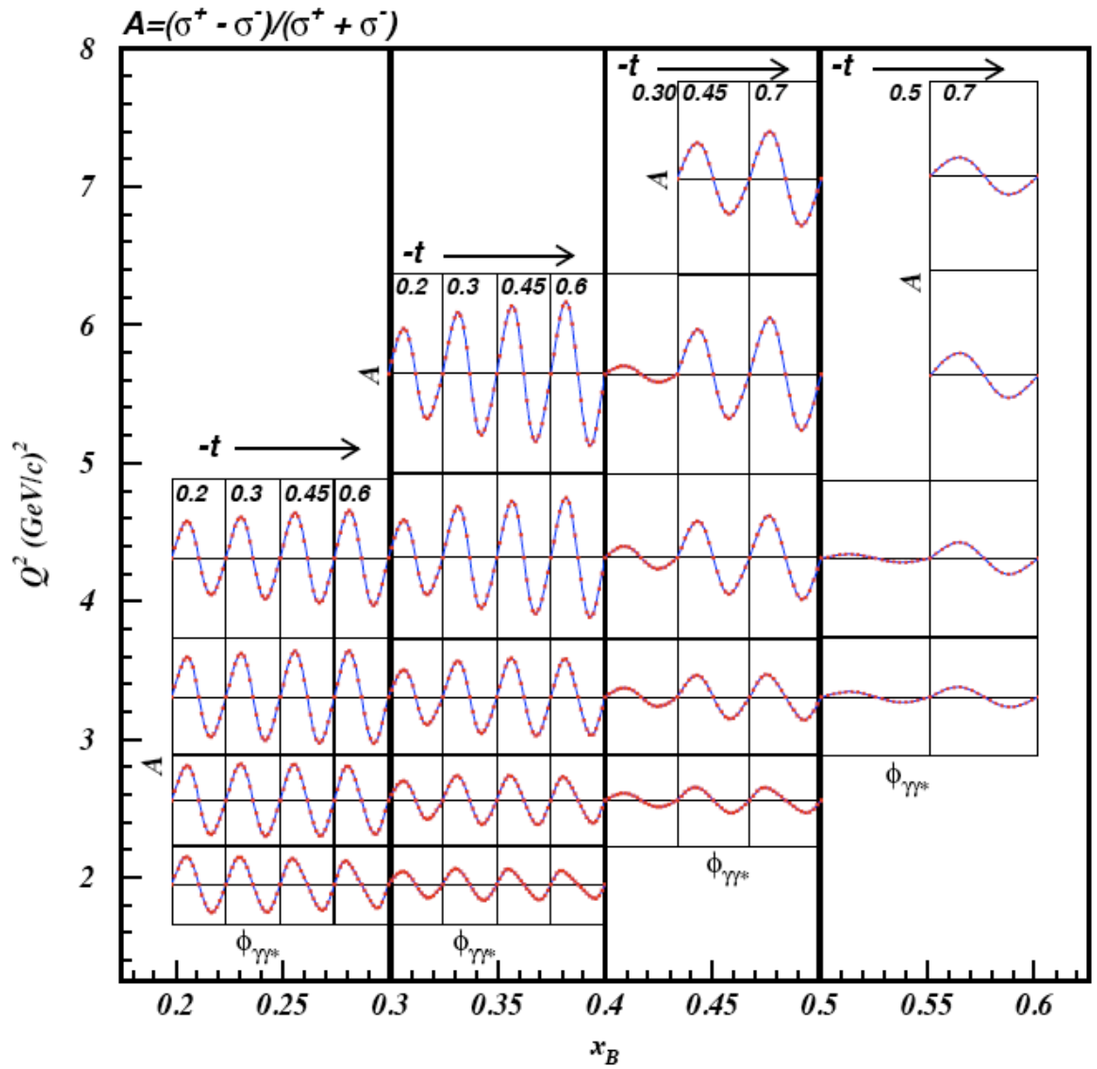
Courtesy C.Riedl, DESY

JLab Experiments: CLAS12 Detector



DVCS at CLAS12





CLAS
Phys.Rev.Lett.87:182002,2001.

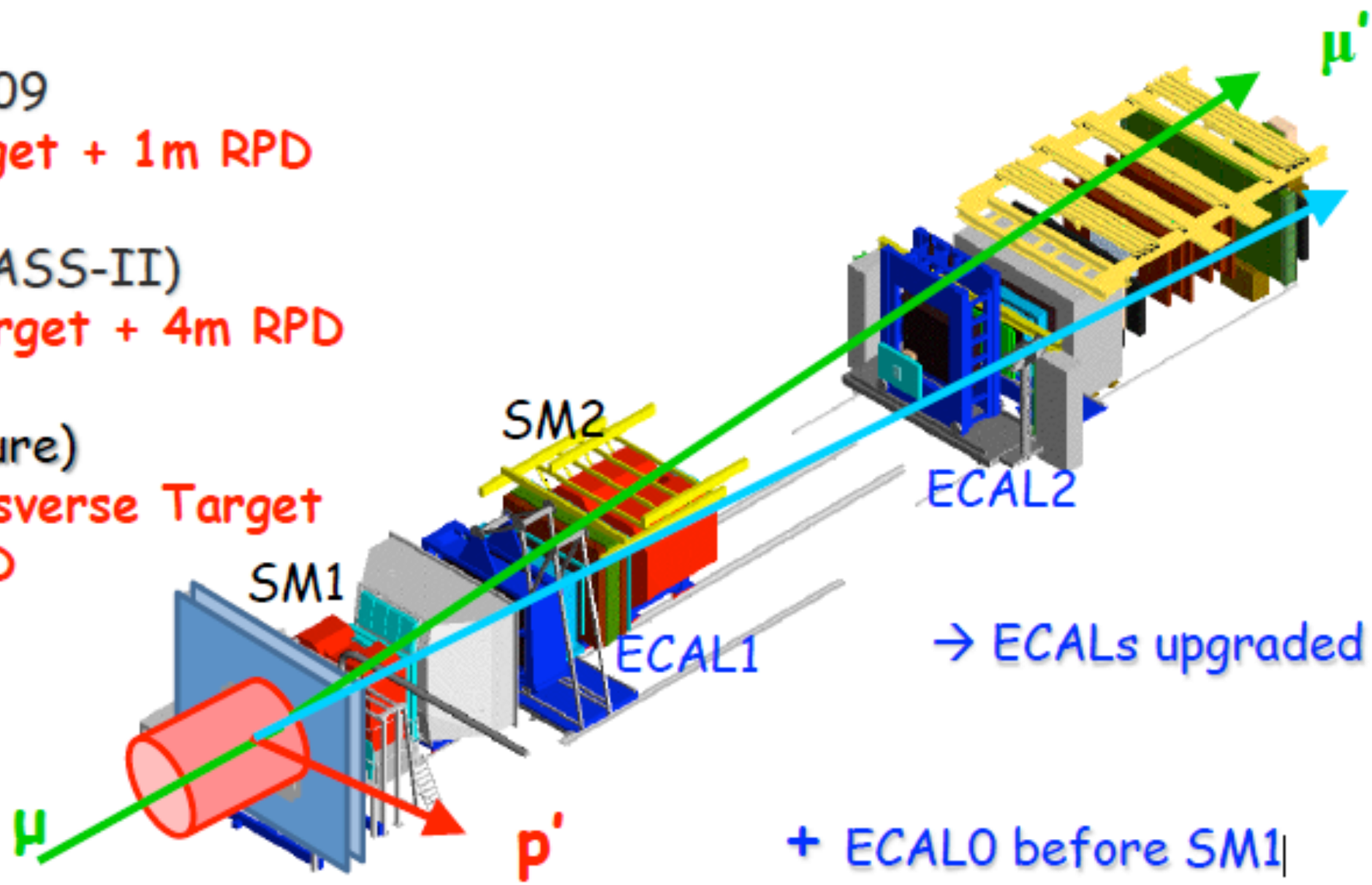
Projection for CLAS12
2000 hrs at $L=10^{35}\,cm^{-2}s^{-1}$

COMPASS Setup for DVCS Measurements

Tests in 2008-09
40cm LH2 target + 1m RPD

Phase 1 (COMPASS-II)
2.5 m LH2 target + 4m RPD

Phase 2 (in future)
Polarised Transverse Target
integrating RPD



→ ECALs upgraded

4.6 10^8 μ^+

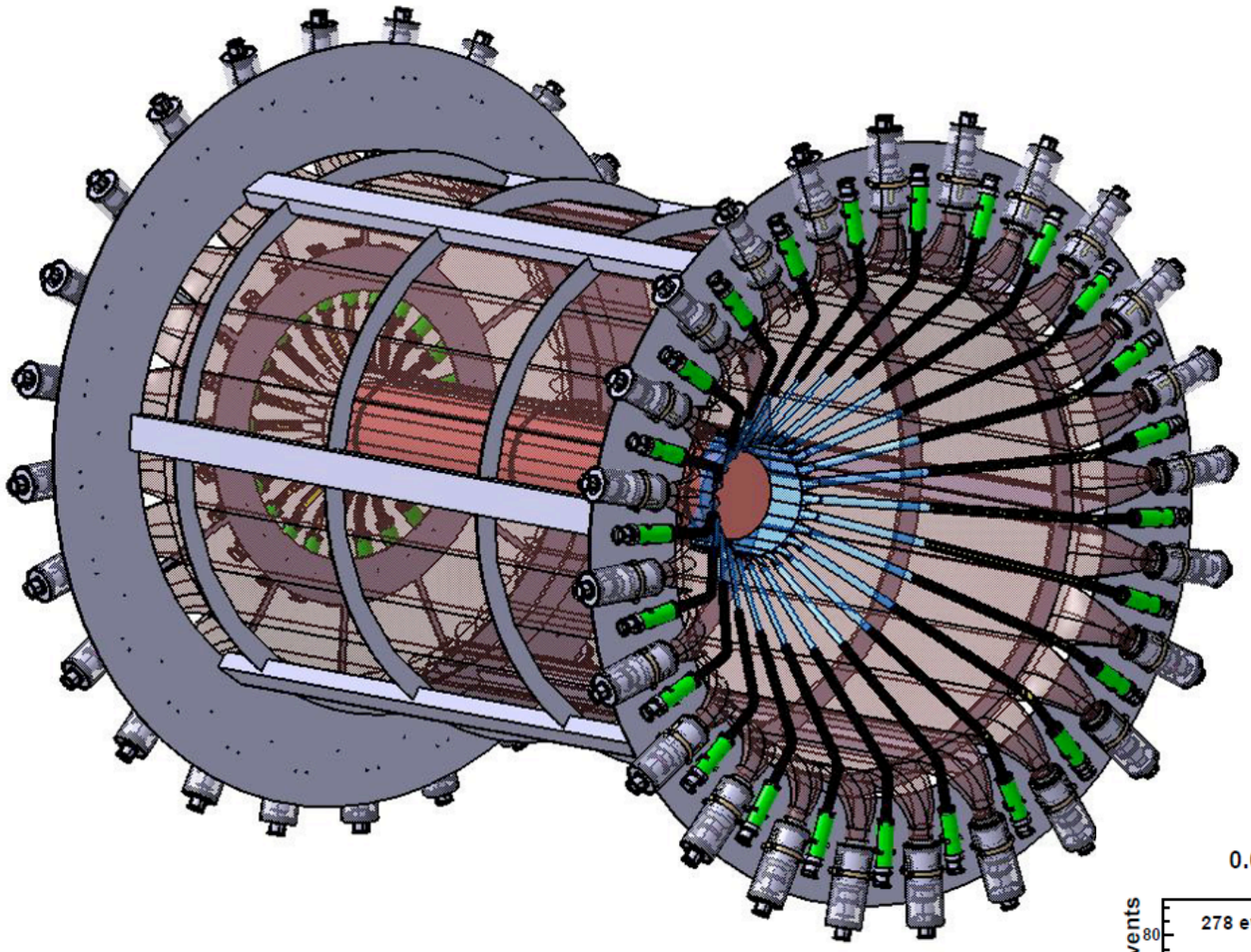
+ ECAL0 before SM1

for 2.7 10^{13} protons per SPS spill
(9.6s each 48 s)

→ Lumi= 10^{32} cm^{-2} s^{-1} with 2.5m LH2 target

Courtesy N.D'Hose

COMPASS Recoil Proton Detector

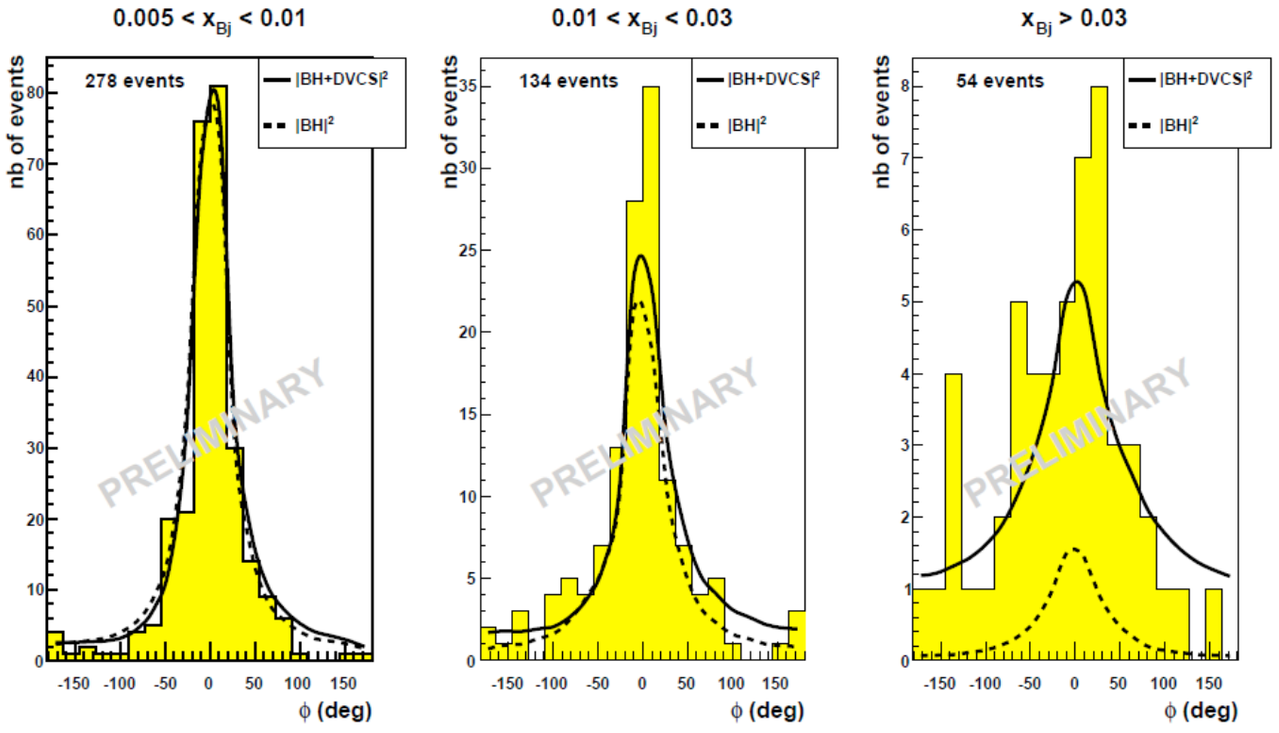


3.6 m long scintillator slabs
~ 300 ps timing resolution

Tests made with
- 2006: 4m sector prototype
- 2008-9: 1m long RPD

Observation of BH and DVCS events in 2009 data taken with 1 m RPD.

Courtesy N.D'Hose, Saclay

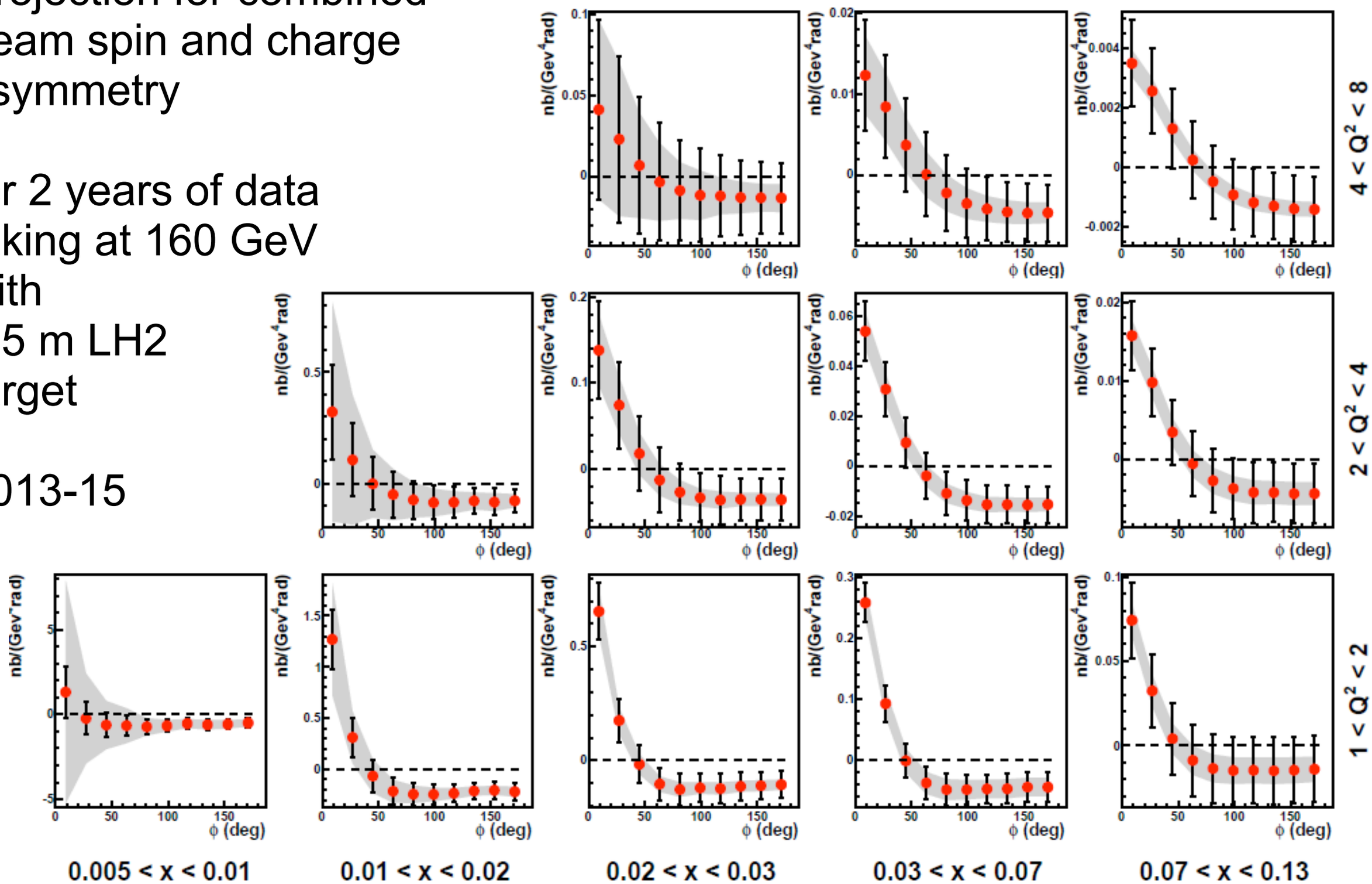


COMPASS Projection for BSCA

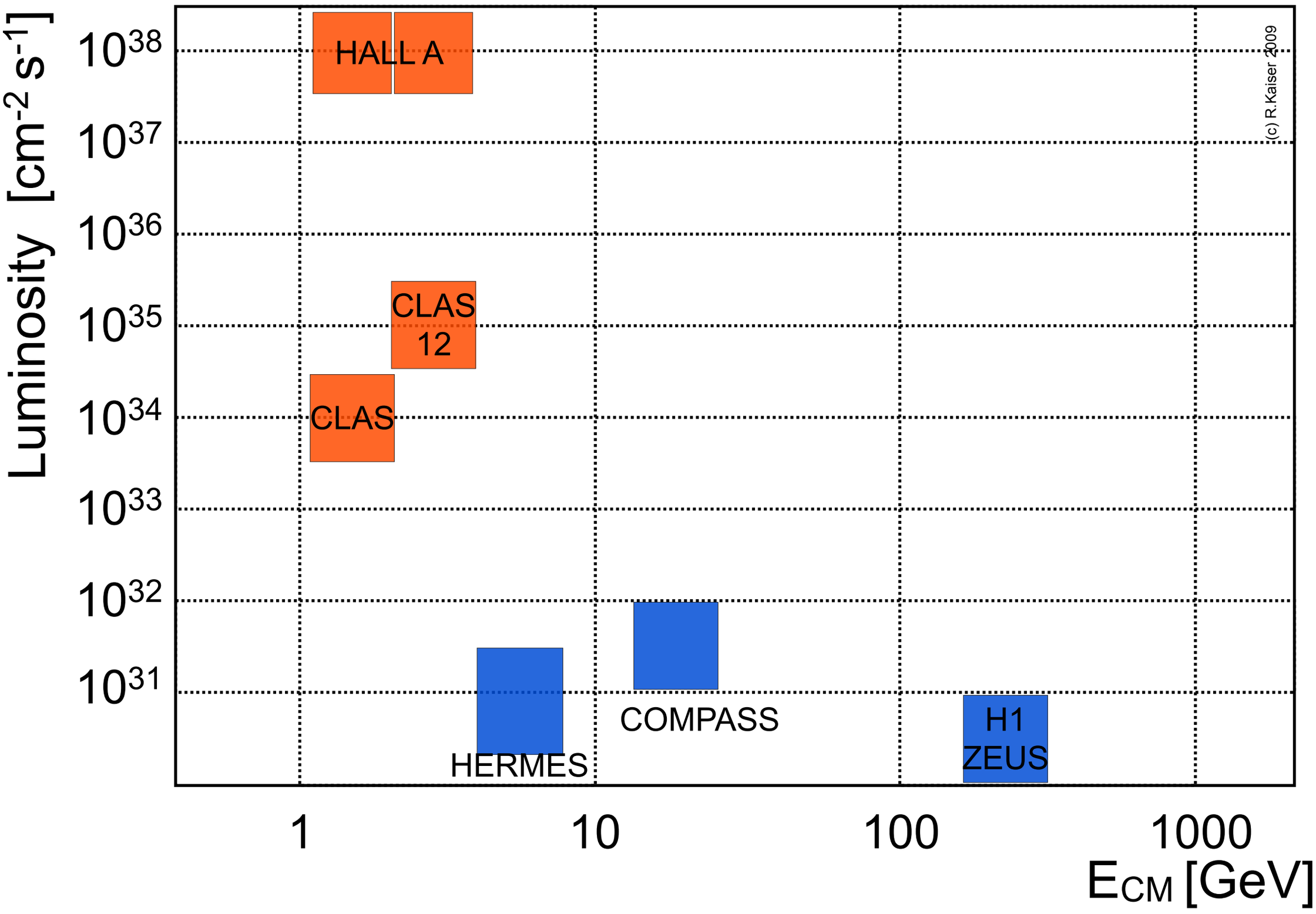
Projection for combined beam spin and charge asymmetry

for 2 years of data taking at 160 GeV with
2.5 m LH2 target

2013-15

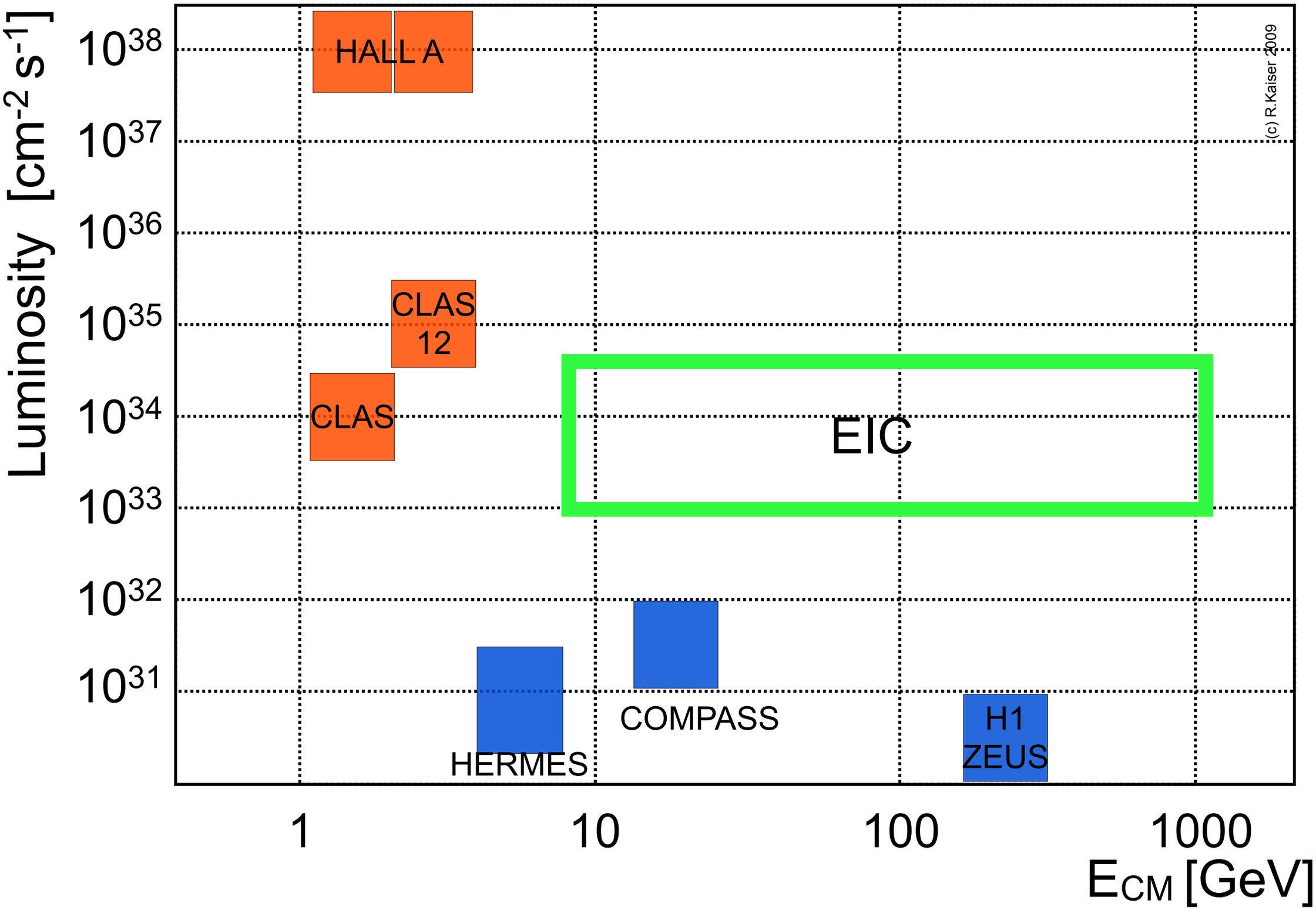


Present and Future ep-Facilities

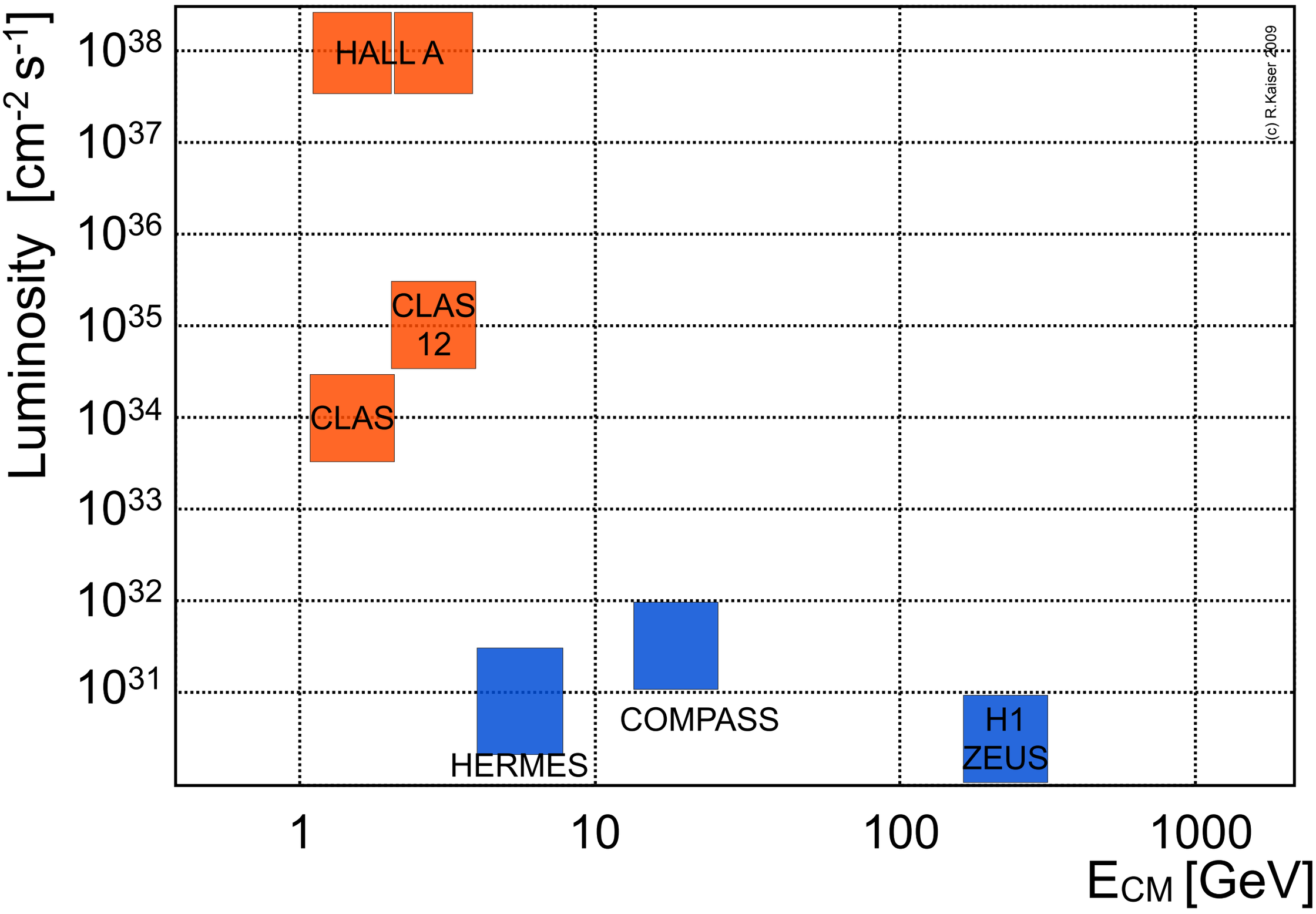


Present and Future ep-Facilities

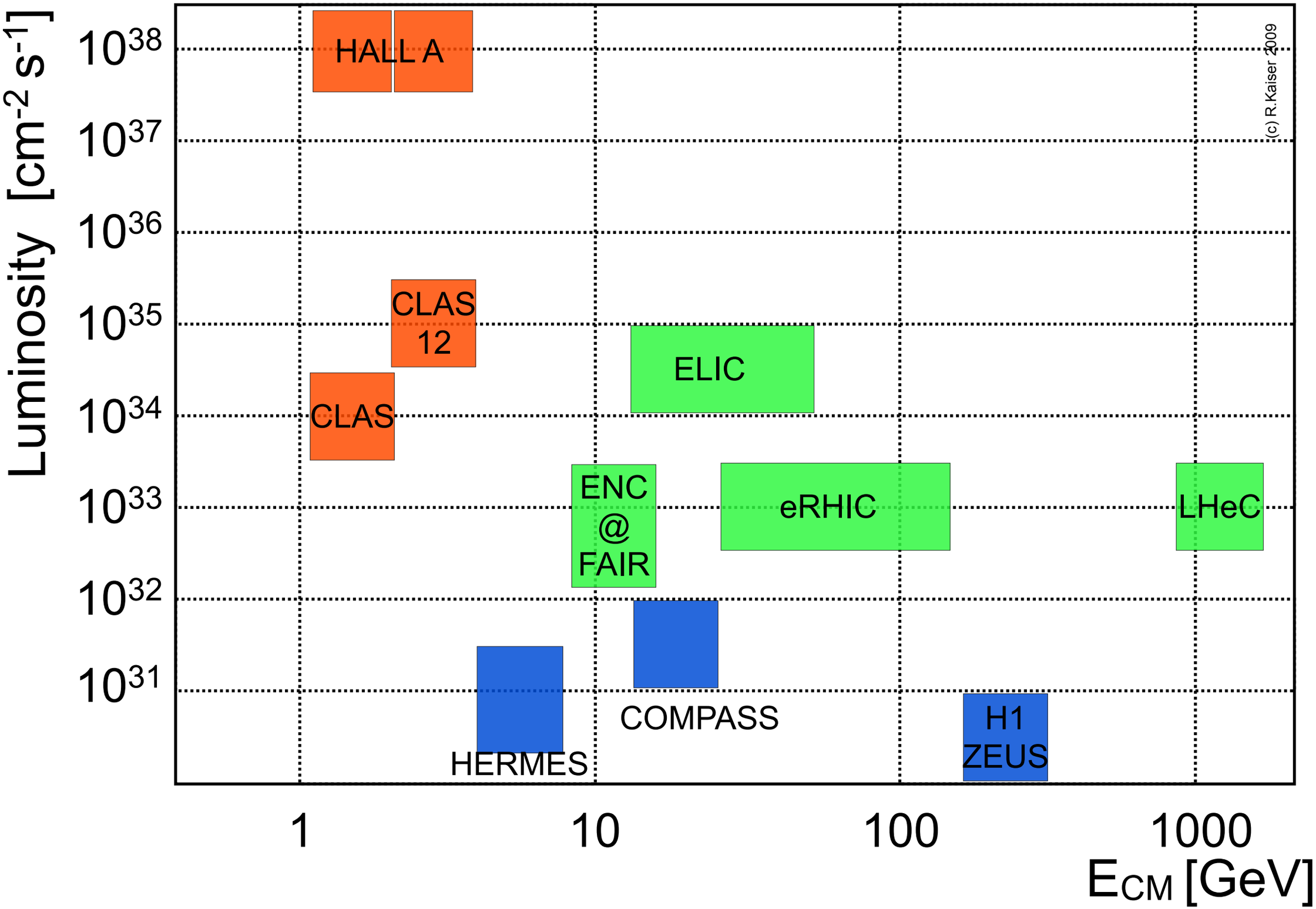
University of Glasgow



Present and Future ep-Facilities



Present and Future ep-Facilities



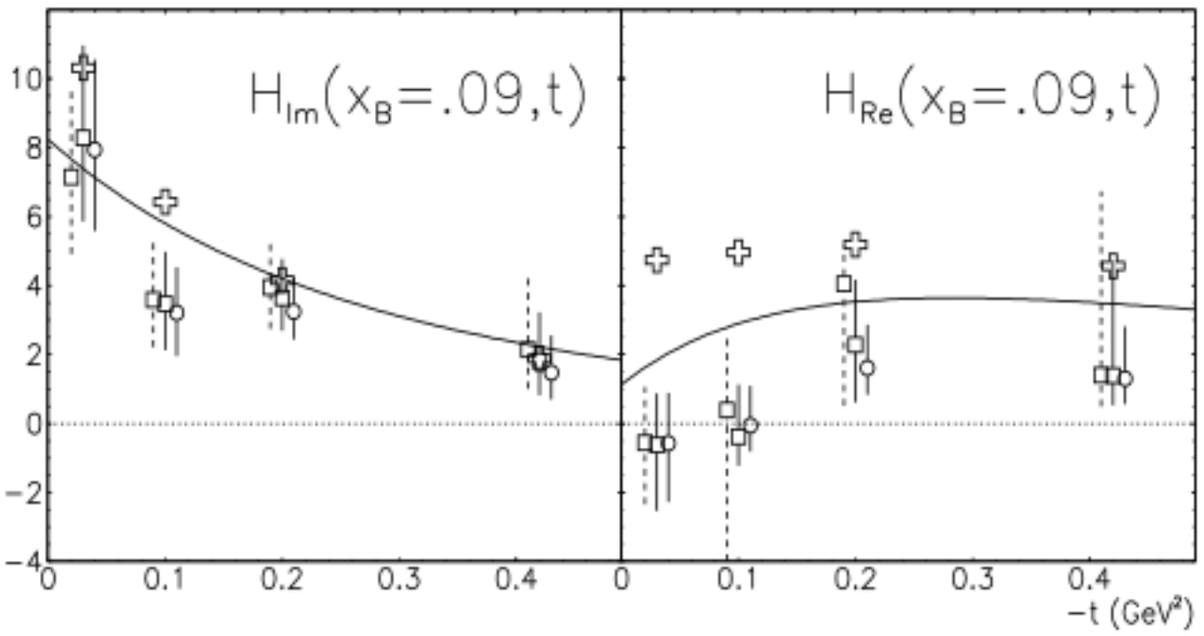
Summary and Outlook

- Generalised Parton Distributions are promising to revolutionise our knowledge about nucleon structure and will eventually deliver a 3D picture of the proton.
- Recent and present experiments at HERMES and JLab are playing a pioneering role in this field.
- Future experiments especially at JLab after the upgrade and at COMPASS will further complete the picture.
- Ultimately, a future ep-facility with high luminosity and an energy range up to higher energies will be required to finalise the picture. This could be EIC and/or ENC.
- All of this will only be successful in the combination of experiments, lattice calculations and GPD model fits to the data.

Thank you very much for your attention !

Additional Slides

GPD Model Fits to Data



http://arxiv.org/abs/1005.4922

M. Guidal

New CFF Fit Result incorporating A_{UL} moments

Postulate GPDs from first principle models

http://arxiv.org/abs/0904.0458

Kumerički and Müller

To appear in Nucl. Phys. B