Hard Exclusive Processes at HERMES and Future Prospects

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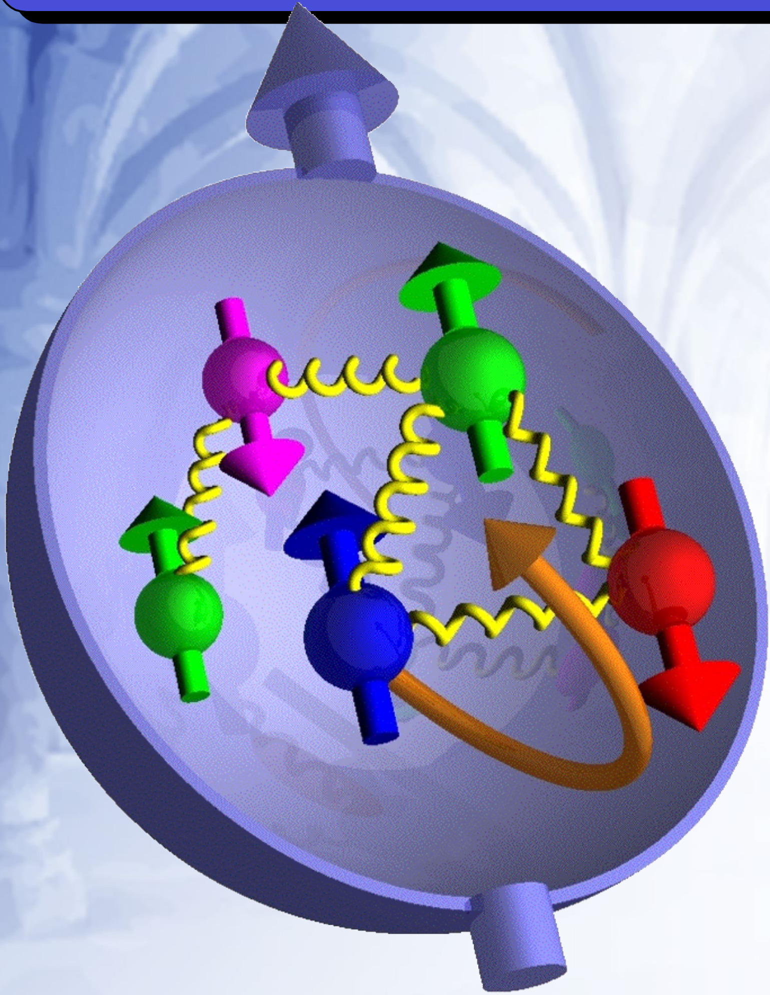
UNIVERSITY *of* GLASGOW

Table of Contents

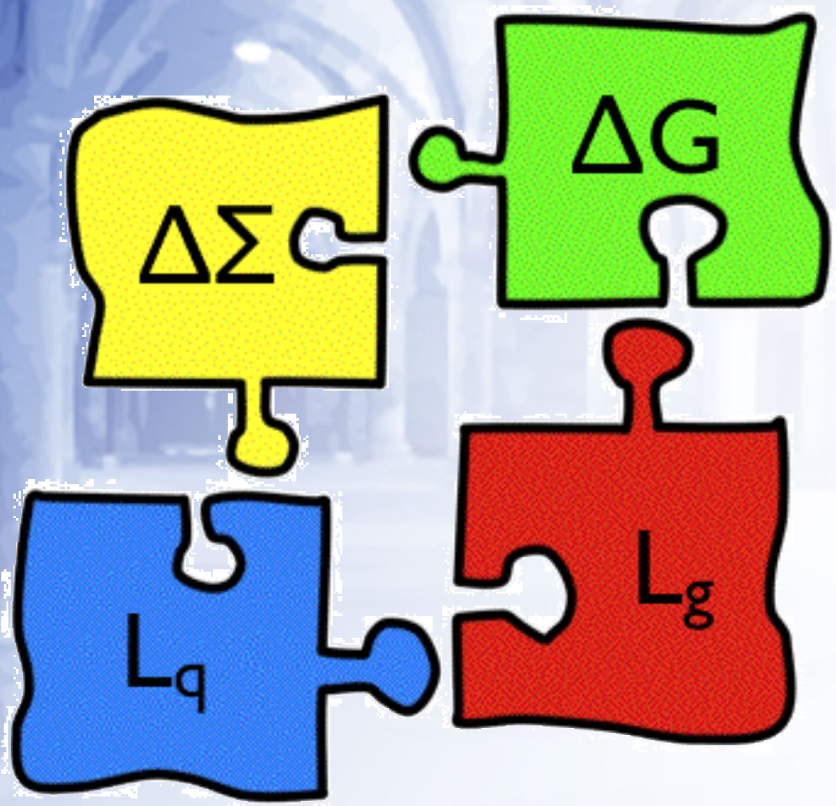
A short History...



- Proton consists of 3 quarks (Gell-Mann, Zweig 1964)
- ... and gluons and sea quarks (QCD)
- Partons (Feynman/Bjorken) identified with quarks and gluons and verified in scattering experiments
- Proton has spin 1/2, and so do the quarks
- 2004 Nobel Prize for Gross, Wilczek, Politzer

- How is the spin distributed?

Nucleon Spin Structure



- Proton spin (naive)

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

- $\Delta\Sigma$: quark spin
  - highest precision measurement by HERMES

$$\Delta\Sigma = 0.330 \pm 0.011(\text{theo.}) \pm 0.025(\text{exp.}) \pm 0.028(\text{evol.})$$

A. Airapetian et al, Phys. Rev. D75(2007)012007

- ΔG : gluon spin
  - first measurements
- L_q : quark ang. momentum
  - unknown
- L_g : gluon ang. momentum
  - unknown

Nucleon Spin Structure

- Ji Sum Rule:

$$J_q \underset{t\to 0}{=} \frac{1}{2}\int_{-1}^{1} x\,dx\,[H_q + E_q]$$

GPDs

- Knowing of GPDs H_q, E_q:
  - access L_q !

- Proton spin (naive)

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

- $\Delta\Sigma$: quark spin
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- ΔG : gluon spin
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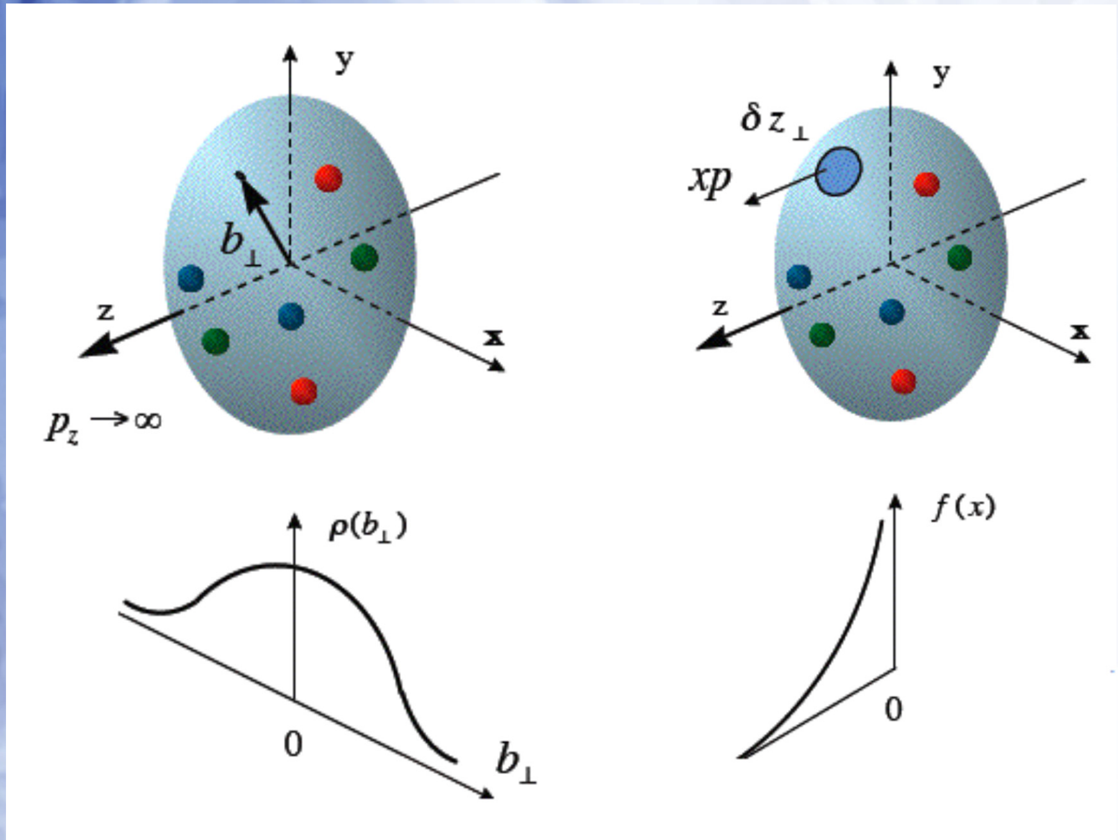
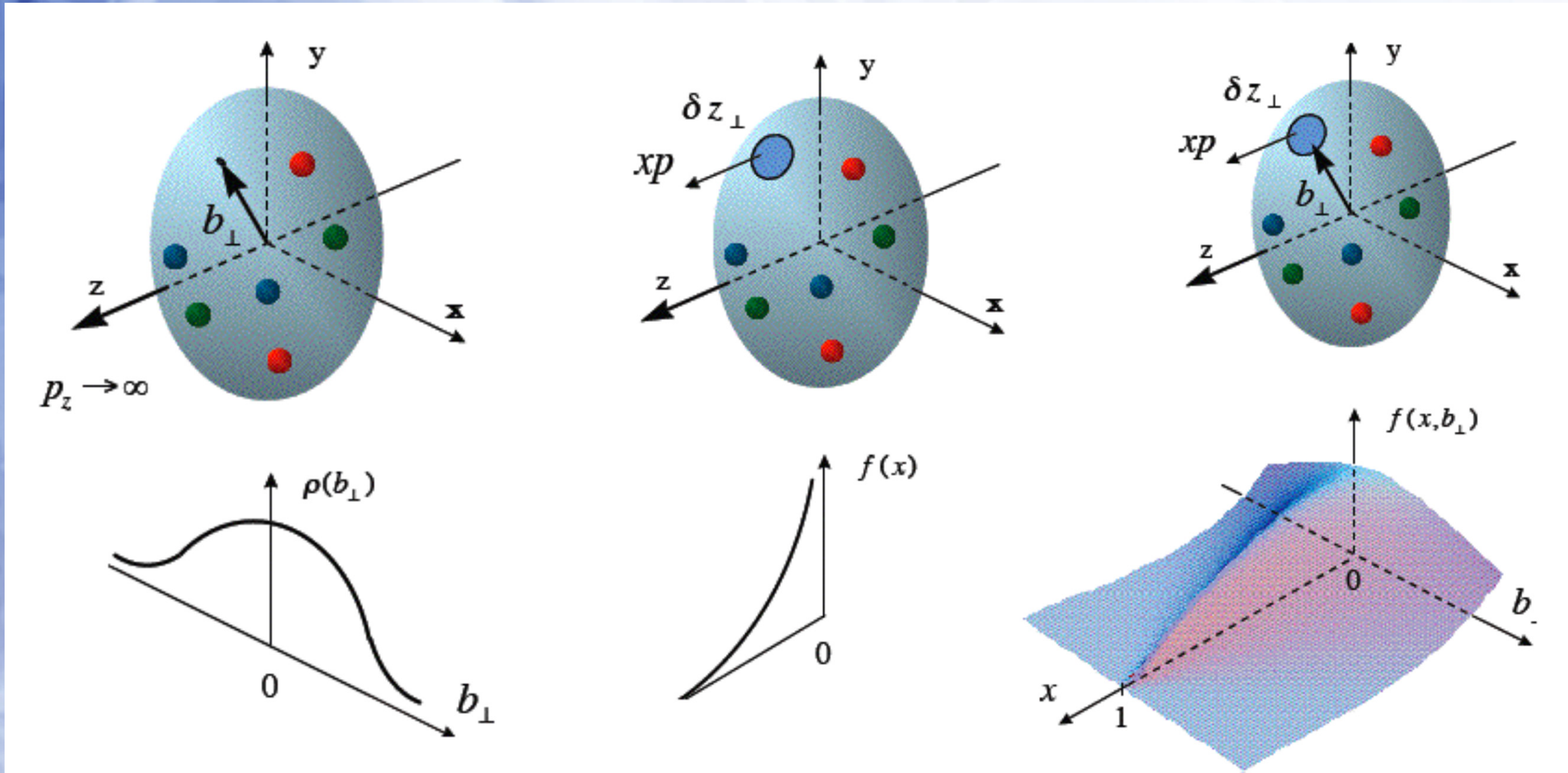
What are GPDs?



Form Factor

Parton Distribution Function

Generalised Parton Distributions

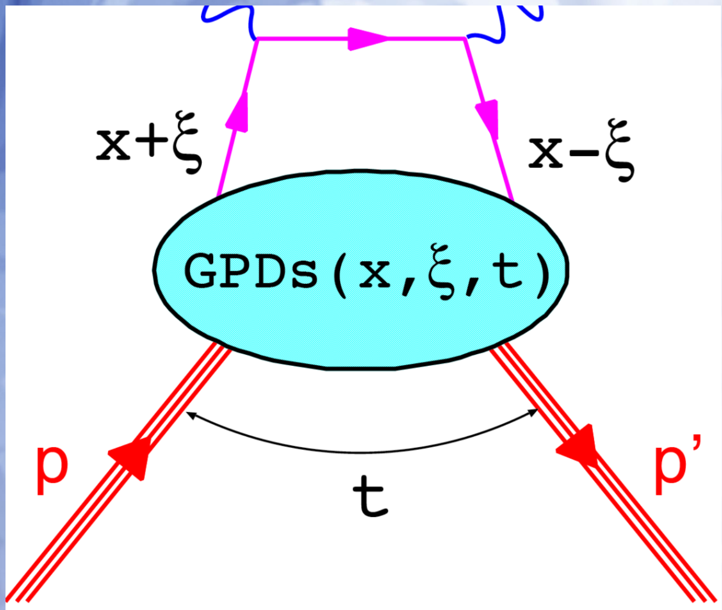


Form Factor

Parton Distribution Function

Generalised Parton Distribution

Generalised Parton Distributions GPDs



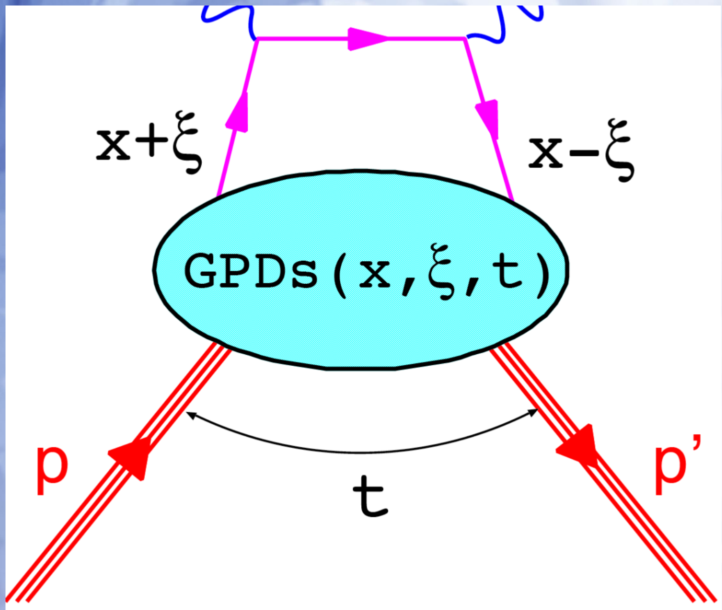
- **Functions of 3 variables**
  - parton momentum fraction x
  - skewedness ξ
  - p momentum transfer t
- **4 (chirality conserving) quark GPDs**
  - unpolarised

    $H(x,\xi,t), E(x,\xi,t),$
  - polarised

    $\widetilde{H}(x,\xi,t), \widetilde{E}(x,\xi,t)$

spin even　　spin odd

Generalised Parton Distributions GPDs



- **Limits of GPDs:**
  - Parton Distribution Functions

$$q(x) = H_q(x,0,0)$$
$$\Delta q(x) = \tilde{H}_q(x,0,0)$$

  - Form factors

$$F_1^q(t) = \int_{-1}^{1} dx H^q(x,\xi,t)$$
$$F_2^q(t) = \int_{-1}^{1} dx E^q(x,\xi,t)$$
$$g_a^q(t) = \int_{-1}^{1} dx \tilde{H}^q(x,\xi,t)$$
$$h_a^q(t) = \int_{-1}^{1} dx \tilde{E}^q(x,\xi,t)$$

The Role of GPDs

Deeply Virtual Compton Scattering

Crossed Compton Scattering

Wide Angle Compton Scattering

exclusive meson production

GPDs

$\bar{p}p$ annihilation

PDF in DIS

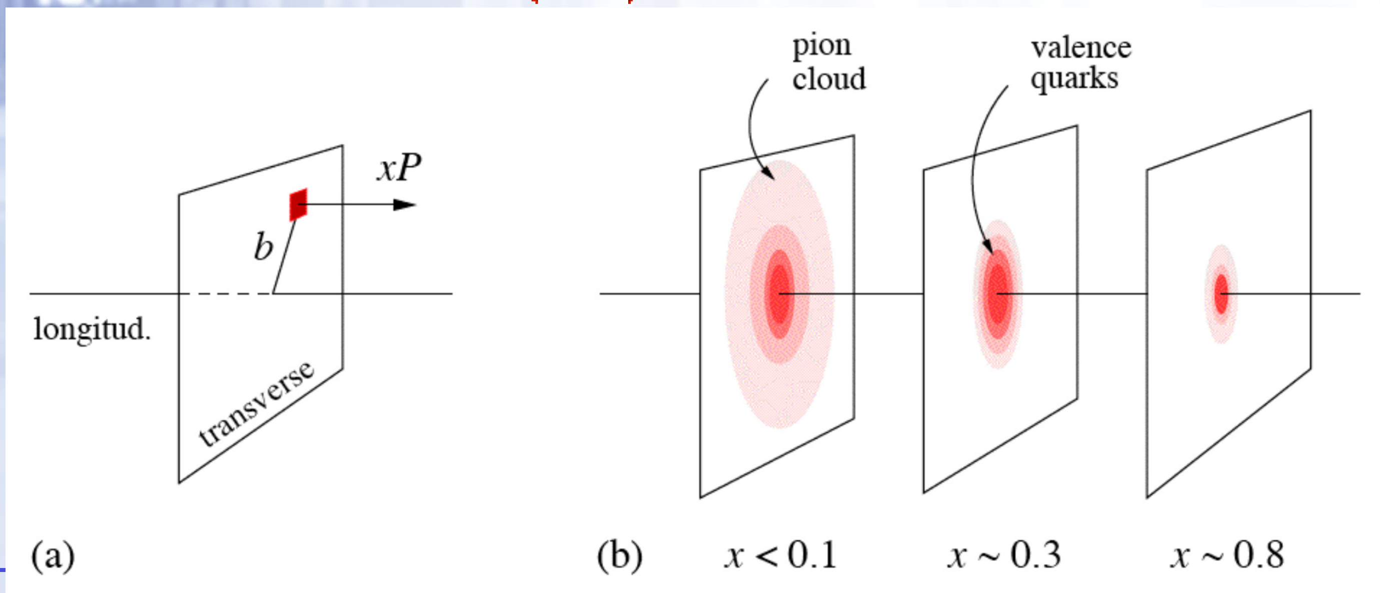
Form Factors

orbital angular momentum
"hadron tomography"

Interpretation of GPDs

- **The Fourier transform of GPDs at $\xi=0$ leads to a 2+1 dimensional picture of the nucleon:**
  - longitudinal momentum fraction and transverse impact parameter space.

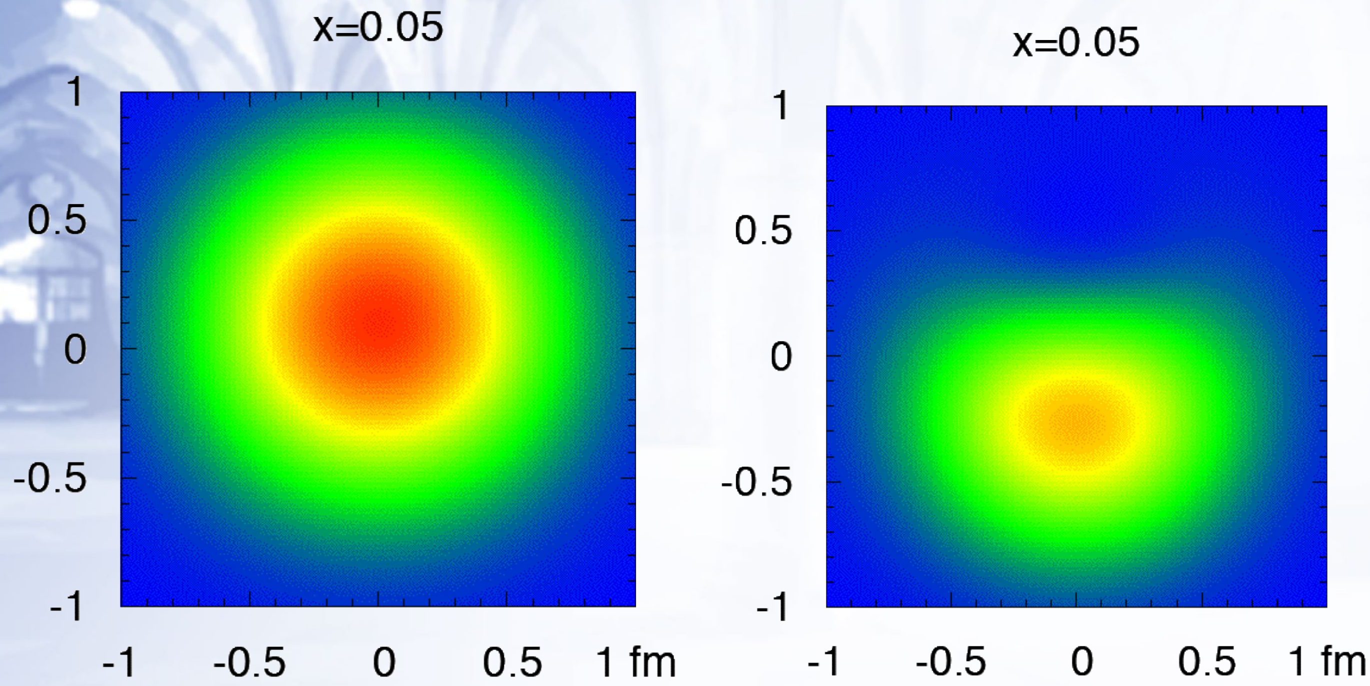
$$q(x,b_\perp) = \int \frac{d^2\Delta_\perp^2}{(2\pi)^2} H(x,0,-\Delta_\perp^2) e^{-i\Delta_\perp \cdot b_\perp}$$



Model Prediction

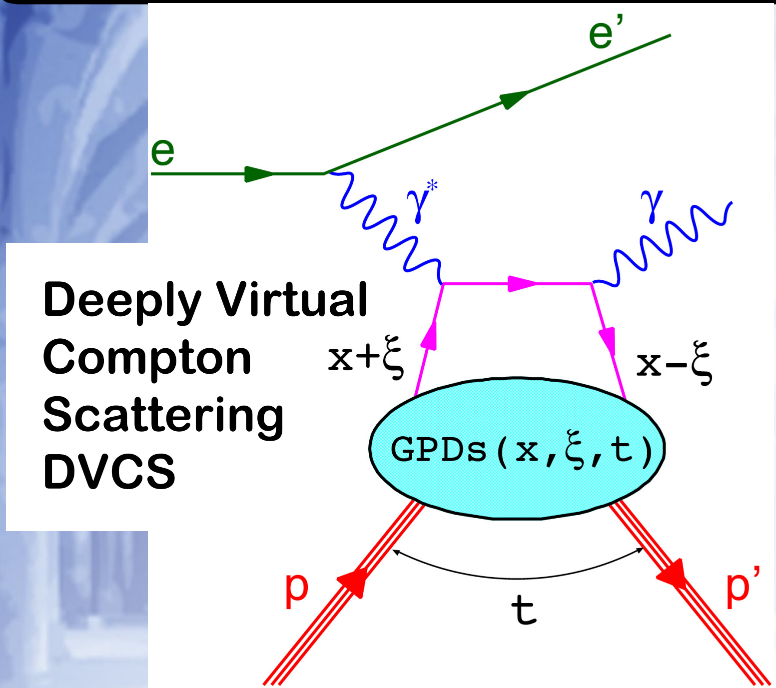
- **GPD Model restricted by form factor data exists:**

  [P.Kroll, hep-ph/0612026, 4.Dec.2006]

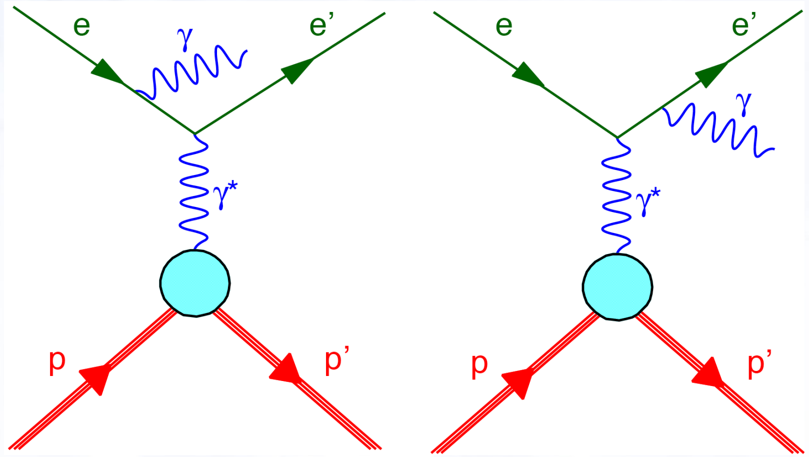


- **u-quark (left) and d-quark (right) density in impact parameter plane. Proton polarised in x-direction**

How to Measure GPDs → DVCS



Bethe-Heitler Scattering BH



- **Indistinguishable and cross section dominated by BH**
  - extraction using interference term

$$d\sigma(eN \to eN\gamma) \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \mathcal{T}_{BH}\mathcal{T}^*_{DVCS} + \mathcal{T}^*_{BH}\mathcal{T}_{DVCS}$$

BH: precisely known from QED **DVCS: access to the GPDs**

Measure Asymmetries

- **Beam Spin Asymmetry**

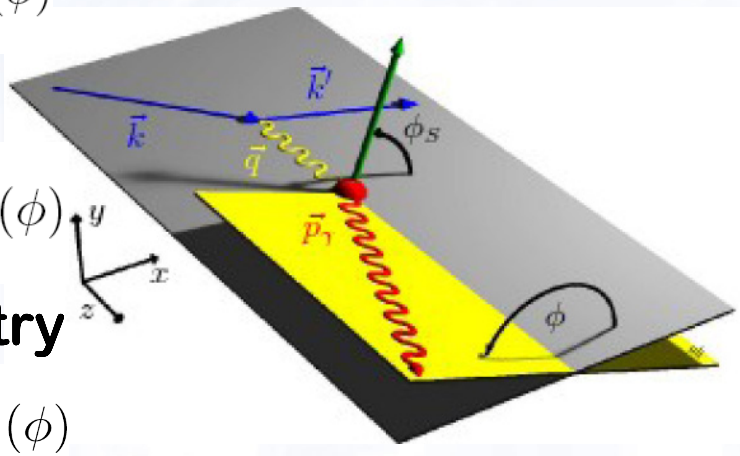
$$A_{LU} = \frac{d\sigma(\boldsymbol{e}^{\rightarrow},\phi) - d\sigma(\boldsymbol{e}^{\leftarrow},\phi)}{d\sigma(\boldsymbol{e}^{\rightarrow},\phi) + d\sigma(\boldsymbol{e}^{\leftarrow},\phi)} \propto \Im m(\mathcal{H}) \sin(\phi)$$

- **Beam Charge Asymmetry**

$$A_{C} = \frac{d\sigma(\boldsymbol{e}^{+},\phi) - d\sigma(\boldsymbol{e}^{-},\phi)}{d\sigma(\boldsymbol{e}^{+},\phi) + d\sigma(\boldsymbol{e}^{-},\phi)} \propto \Re e(\mathcal{H}) \cos(\phi)$$

- **Longitudinal-Target Spin Asymmetry**

$$A_{UL} = \frac{d\sigma(\boldsymbol{p}^{\rightarrow},\phi) - d\sigma(\boldsymbol{p}^{\leftarrow},\phi)}{d\sigma(\boldsymbol{p}^{\rightarrow},\phi) + d\sigma(\boldsymbol{p}^{\leftarrow},\phi)} \propto \Im m(\widetilde{\mathcal{H}}) \sin(\phi)$$



- **Transverse-Target Spin Asymmetry**

$$A_{UT} = \frac{d\sigma(\boldsymbol{p}^{\uparrow},\phi) - d\sigma(\boldsymbol{p}^{\downarrow},\phi)}{d\sigma(\boldsymbol{p}^{\uparrow},\phi) + d\sigma(\boldsymbol{p}^{\downarrow},\phi)} \propto f(\mathcal{H},\mathcal{E},\widetilde{\mathcal{H}},\widetilde{\mathcal{E}},\phi,\phi_S)$$

  - Imaginary and real parts of $\mathcal{H},\mathcal{E},\widetilde{\mathcal{H}},\widetilde{\mathcal{E}}$ are directly related to GPDs $H(x,\xi,t), E(x,\xi,t), \widetilde{H}(x,\xi,t), \widetilde{E}(x,\xi,t)$

Kinematical Coverage of DVCS Experiments

- **HERA collider experiments H1 and ZEUS have small skewedness**

$$x_B < 0.01 \quad Q^2 : 5 ... 100\, GeV^2$$

- **Fixed target experiments are crucial to explore GPDs !**

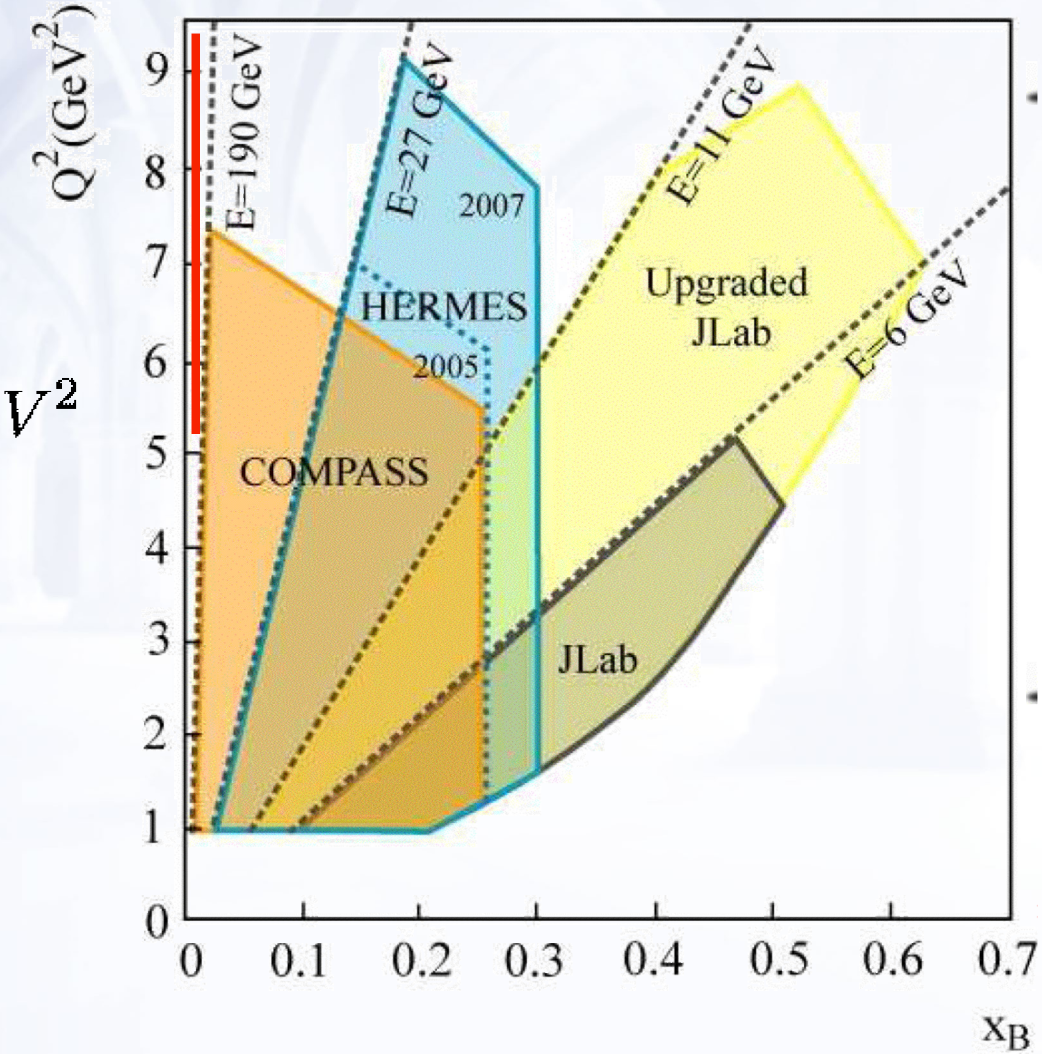
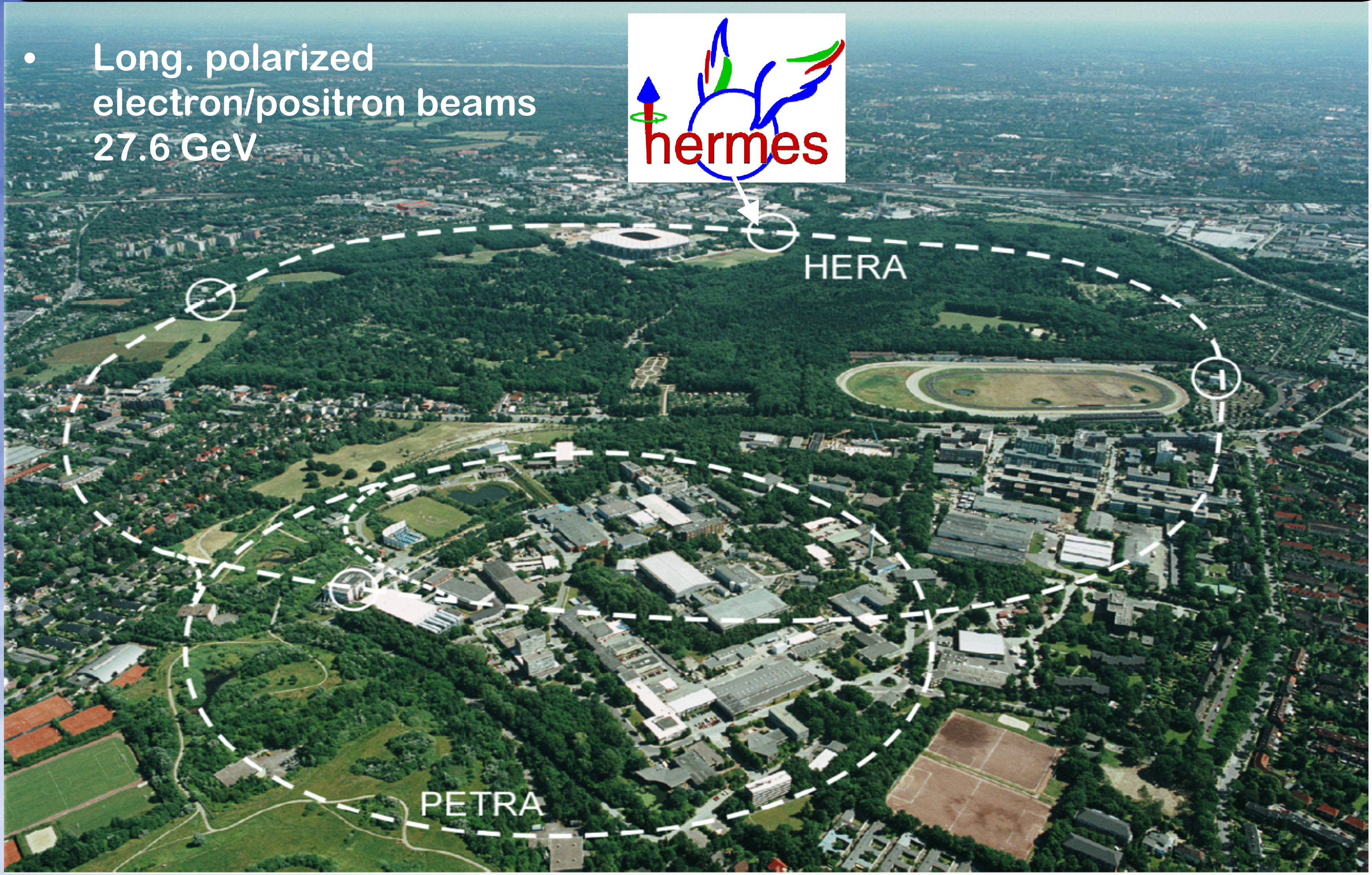


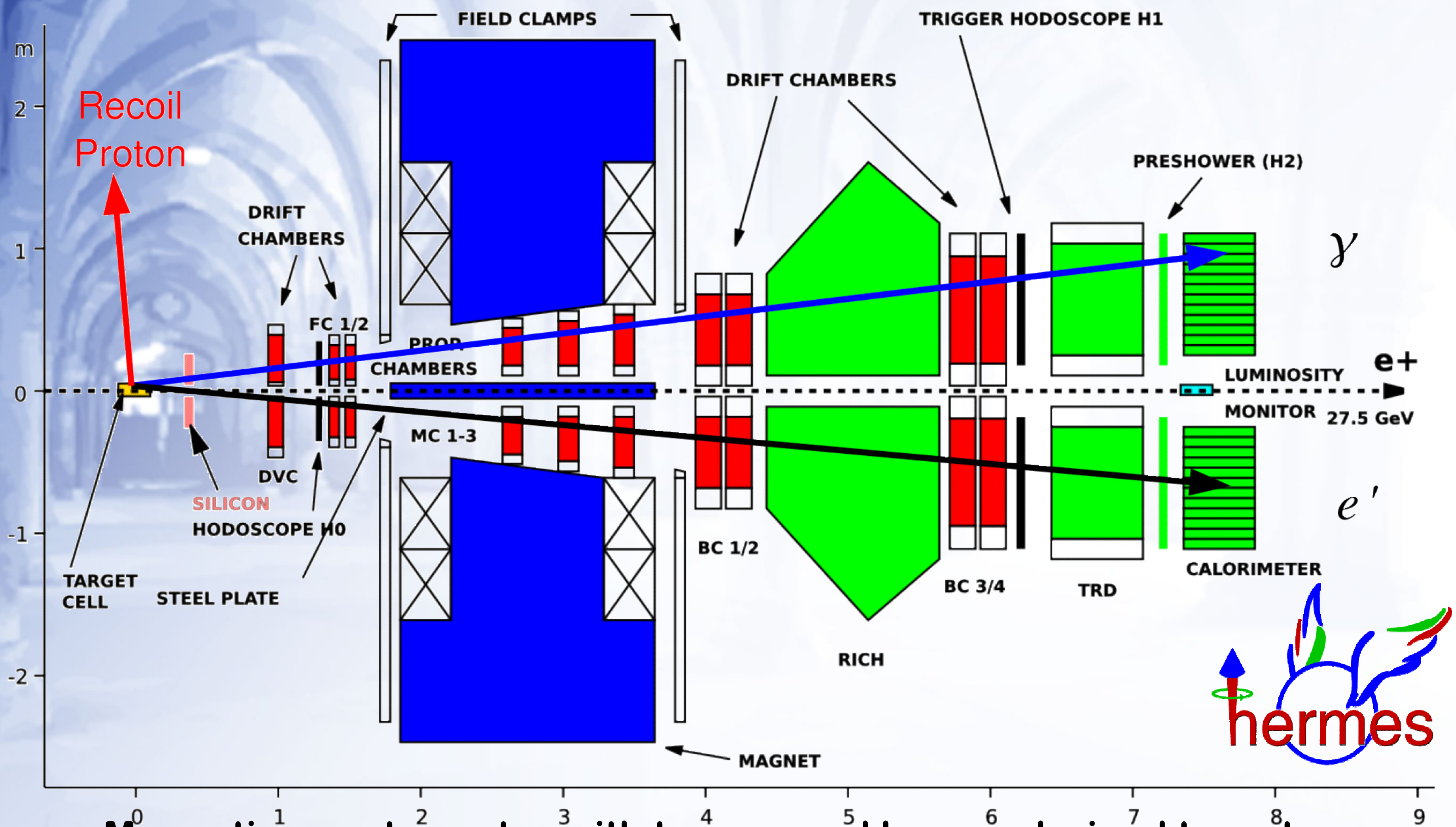
Table of Contents

HERMES at HERA, DESY

- Long. polarized electron/positron beams 27.6 GeV



HERMES at HERA, DESY

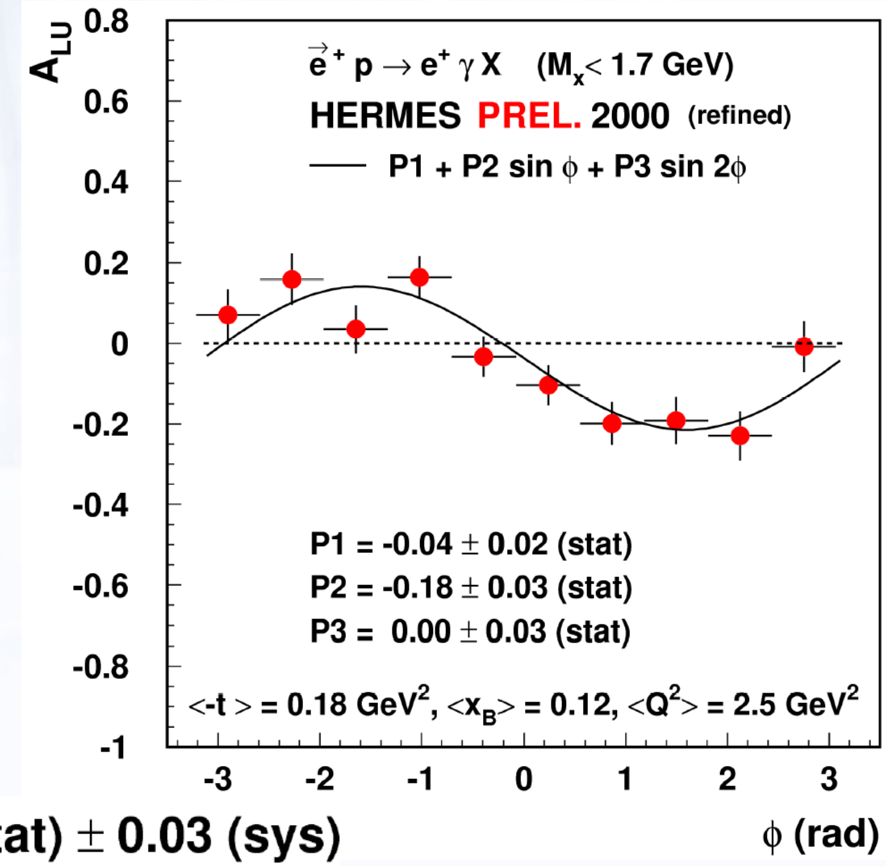


Magnetic spectrometer with transv. and long. polarised targets

DVCS Asymmetries: Beam Spin

$$A_{LU} = \frac{d\sigma(e^{\rightarrow},\phi) - d\sigma(e^{\leftarrow},\phi)}{d\sigma(e^{\rightarrow},\phi) + d\sigma(e^{\leftarrow},\phi)} \propto \Im m(\mathcal{H}) \sin(\phi)$$

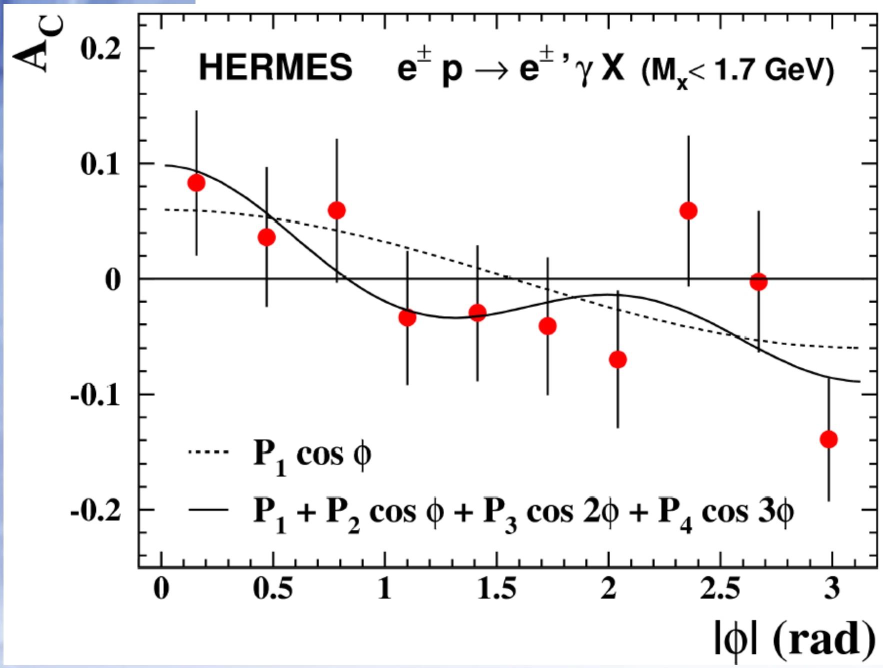
- First measurements of DVCS asymmetries:
  - Beam-spin asymmetry by HERMES and CLAS, both published in PRL87(2001).
- Refined analysis:
  - consistent result
- Constrains the GPD H

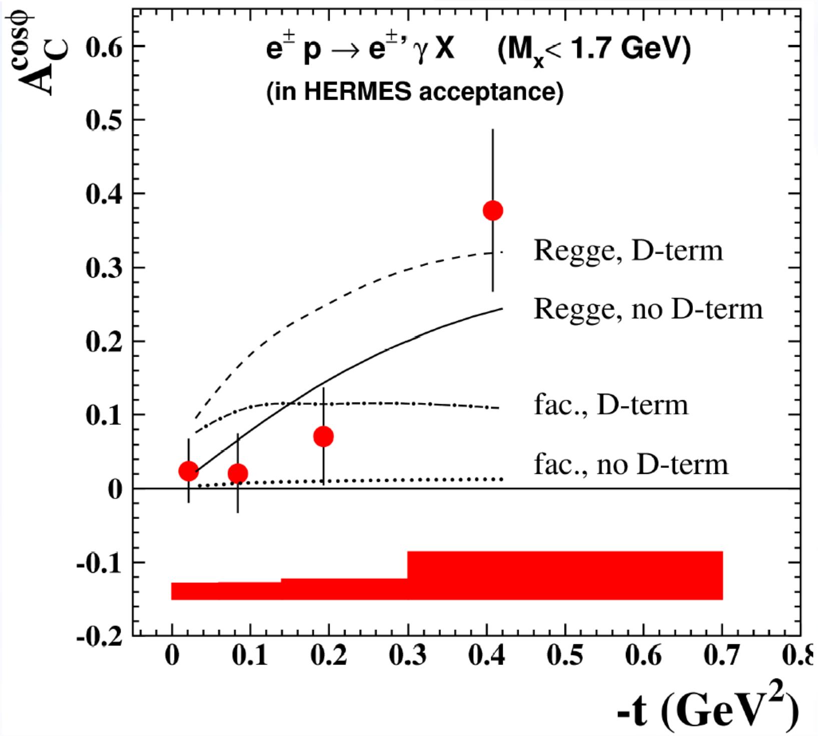


$$A_{LU}^{\sin\phi}\Big|_{M_x < 1.7\,\text{GeV}} = -0.18 \pm 0.03\,(\text{stat}) \pm 0.03\,(\text{sys})$$

DVCS Asymmetries: Beam Charge

$$A_C = \frac{d\sigma(e^+,\phi) - d\sigma(e^-,\phi)}{d\sigma(e^+,\phi) + d\sigma(e^-,\phi)} \propto \Re e(\mathcal{H}) \cos(\phi)$$



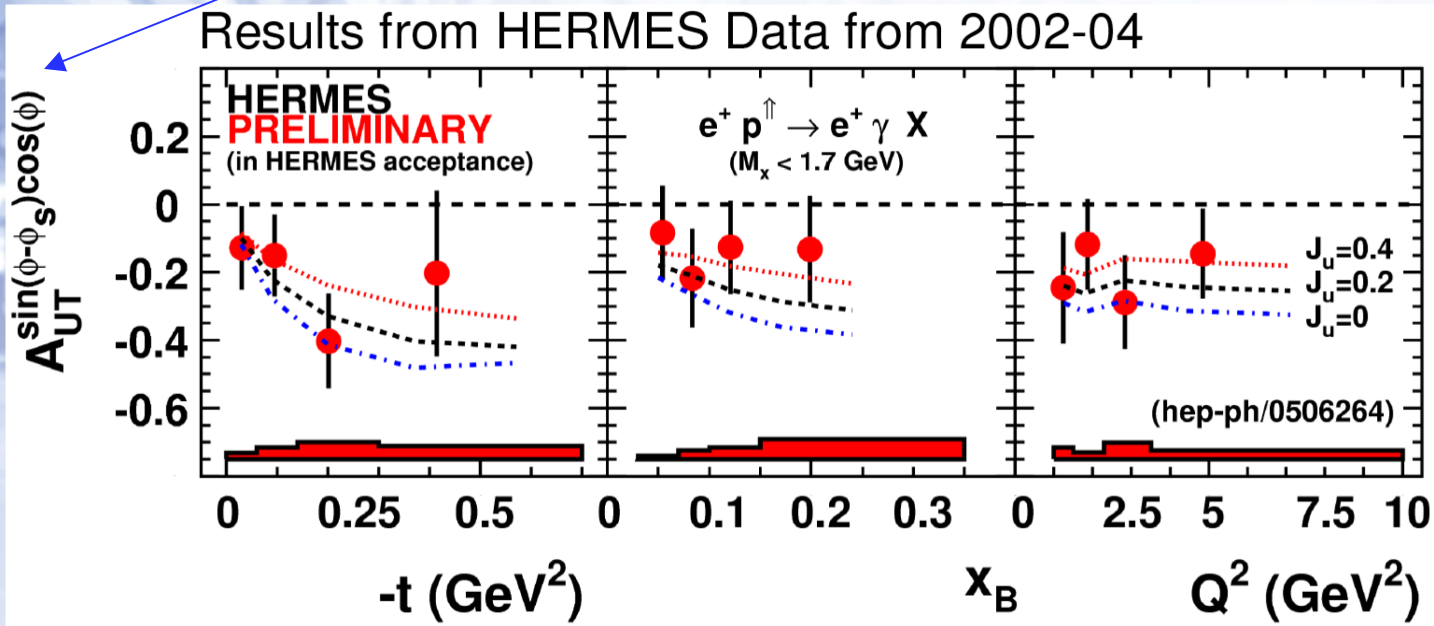


$$A_C^{\cos\phi} = 0.063 \pm 0.029(stat.) \pm 0.026(sys.)$$

- Constrains the GPD H
- t-dependence constrains models

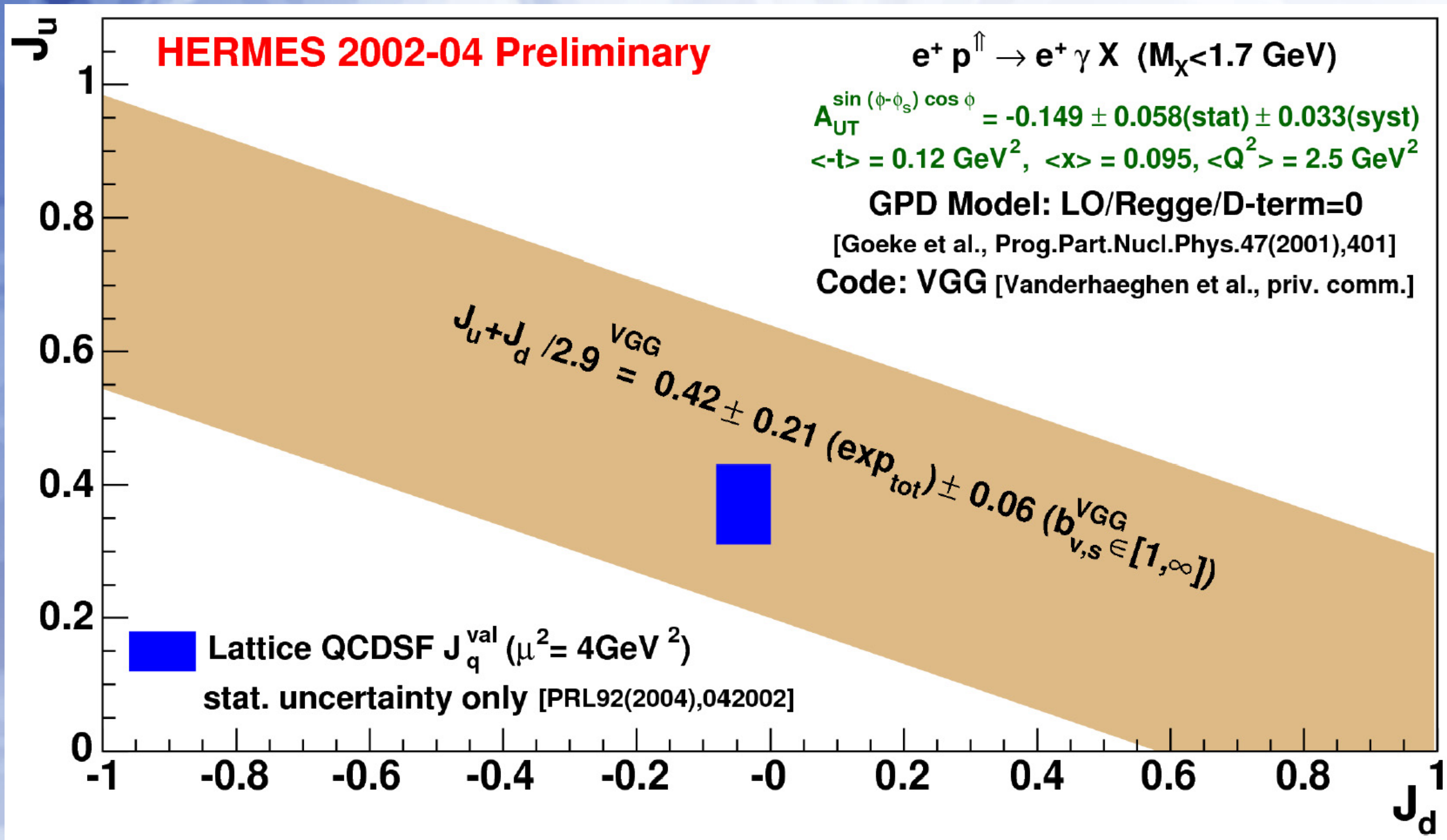
DVCS Asymmetries: Transverse Target

$$A_{UT} = \frac{d\sigma(p^{\uparrow}, \phi) - d\sigma(p^{\downarrow}, \phi)}{d\sigma(p^{\uparrow}, \phi) + d\sigma(p^{\downarrow}, \phi)} \propto Im[F_2\mathcal{H} - F_1\mathcal{E}] \cdot \sin(\phi - \phi_S) \cdot \cos\phi + Im[F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}] \cdot \cos(\phi - \phi_S) \cdot \sin\phi$$



- Here E is not suppressed
- Sensitive to variation in quark angular momentum J_q

DVCS Asymmetries: Constrain J_u/J_d



- Large 2005 data sample not yet included

Analysis: J_u/J_d from the Neutron

- **At HERMES we measure ALU:**

$$A_{LU} = \frac{d\sigma(\mathbf{e}^{\rightarrow},\phi) - d\sigma(\mathbf{e}^{\leftarrow},\phi)}{d\sigma(\mathbf{e}^{\rightarrow},\phi) + d\sigma(\mathbf{e}^{\leftarrow},\phi)}$$

$$A_{LU}^{\sin\phi} \propto \Im C^{I}_{\mathrm{unpol}} = F_1^n(t)\,\Im\mathcal{H}^n(\xi,t,Q^2) + \frac{x_B}{2-x_B}\left(F_1^n(t)+F_2^n(t)\right)\,\Im\tilde{\mathcal{H}}^n(\xi,t,Q^2) - \frac{t}{4m^2}F_2^n(t)\,\Im\mathcal{E}^n(\xi,t,Q^2)$$

Dominant on the proton

Dominant on the neutron

$$\Im\mathcal{F}(\xi,t,Q^2) = \pi\sum_q e_q^2\left[F^q(\xi,\xi,t,Q^2) \mp F^q(-\xi,\xi,t,Q^2)\right]$$

Sensitive on the quark angular momentum J_q

DVCS Asymmetries: Constrain J_u/J_d

New HallA result on the neutron:
M. Mazouz et al.
arXiv:0709.0450 [nucl-ex]

New lattice point:
Ju , Jd = 0.214(16) , 0.001(16)
Ph. Haegler et al.
arXiv:0705.4295 [hep-lat]

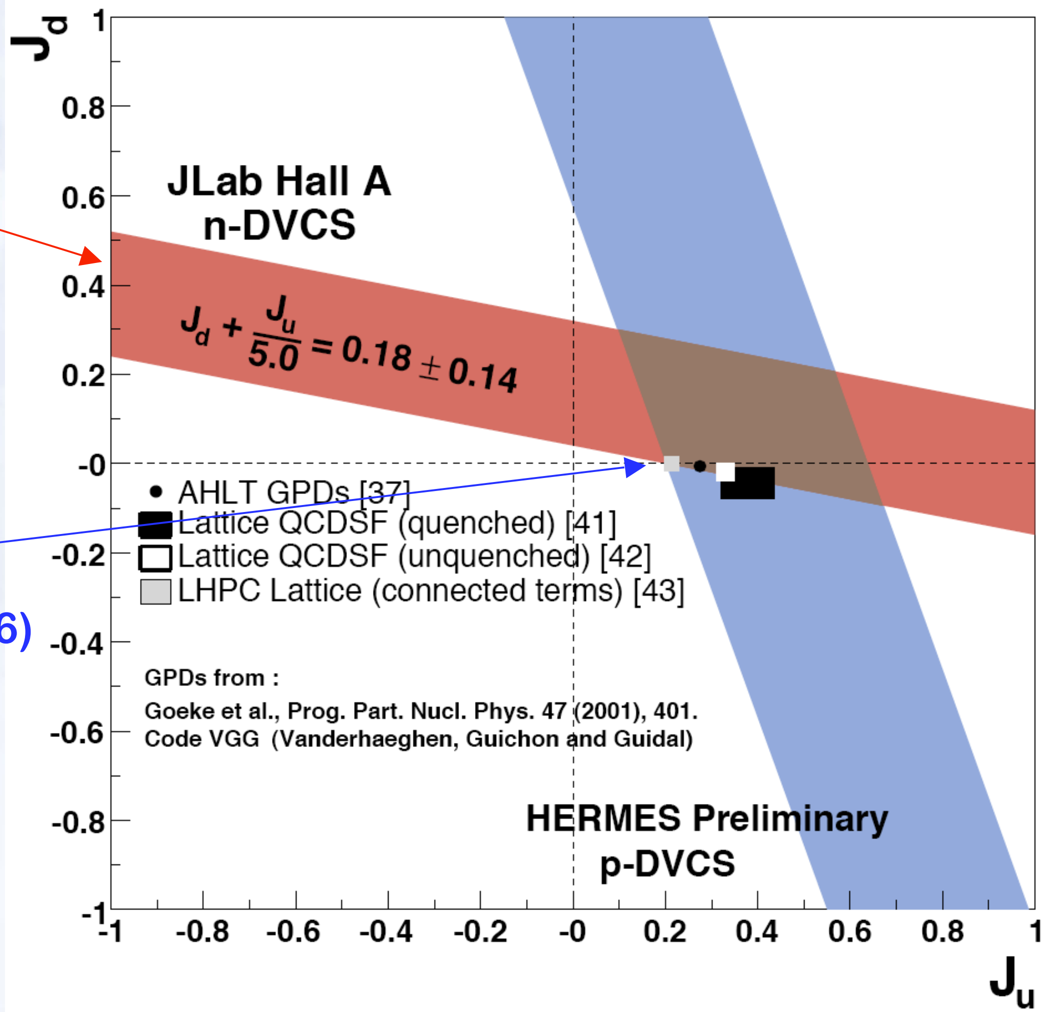
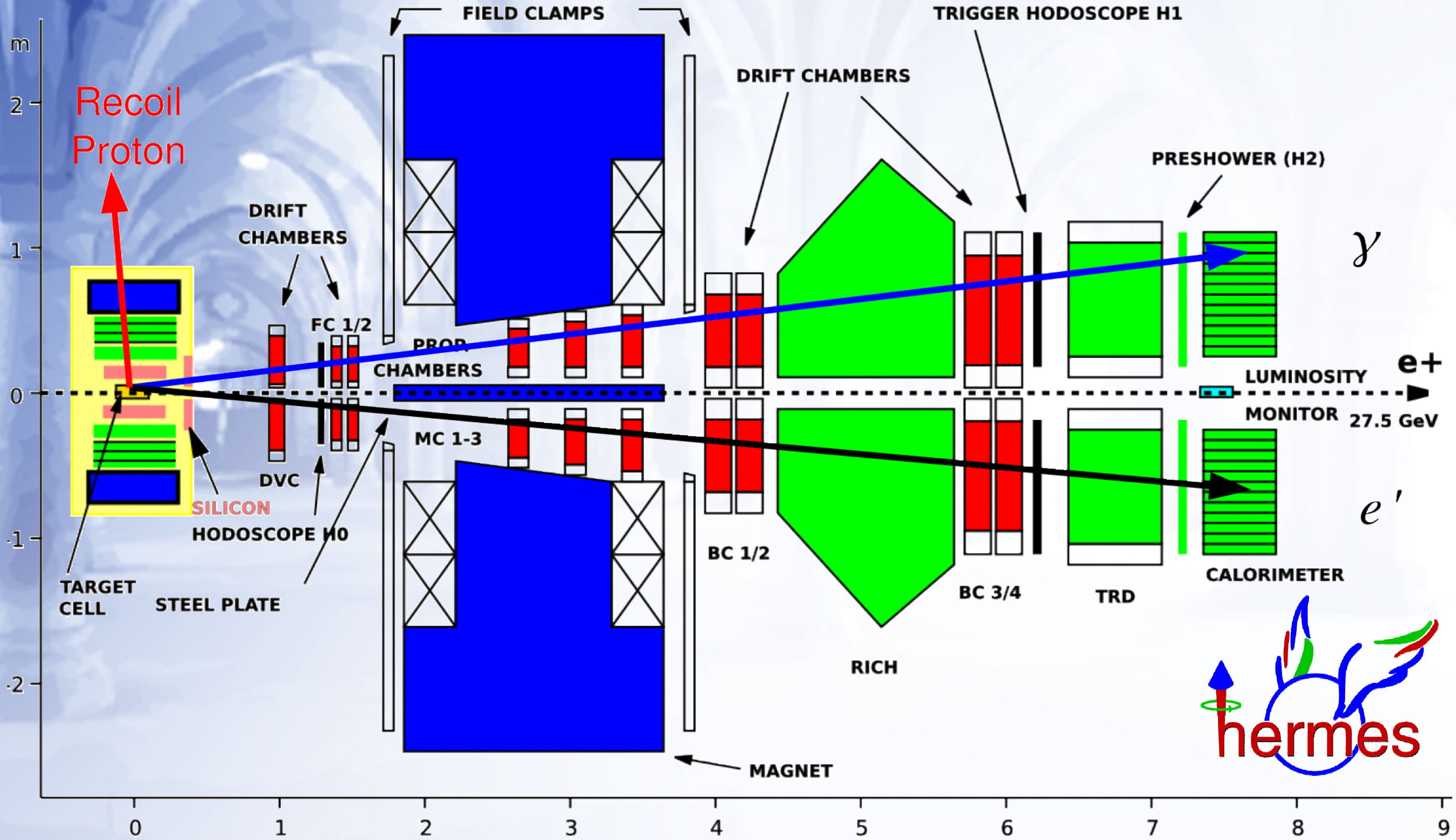


Table of Contents

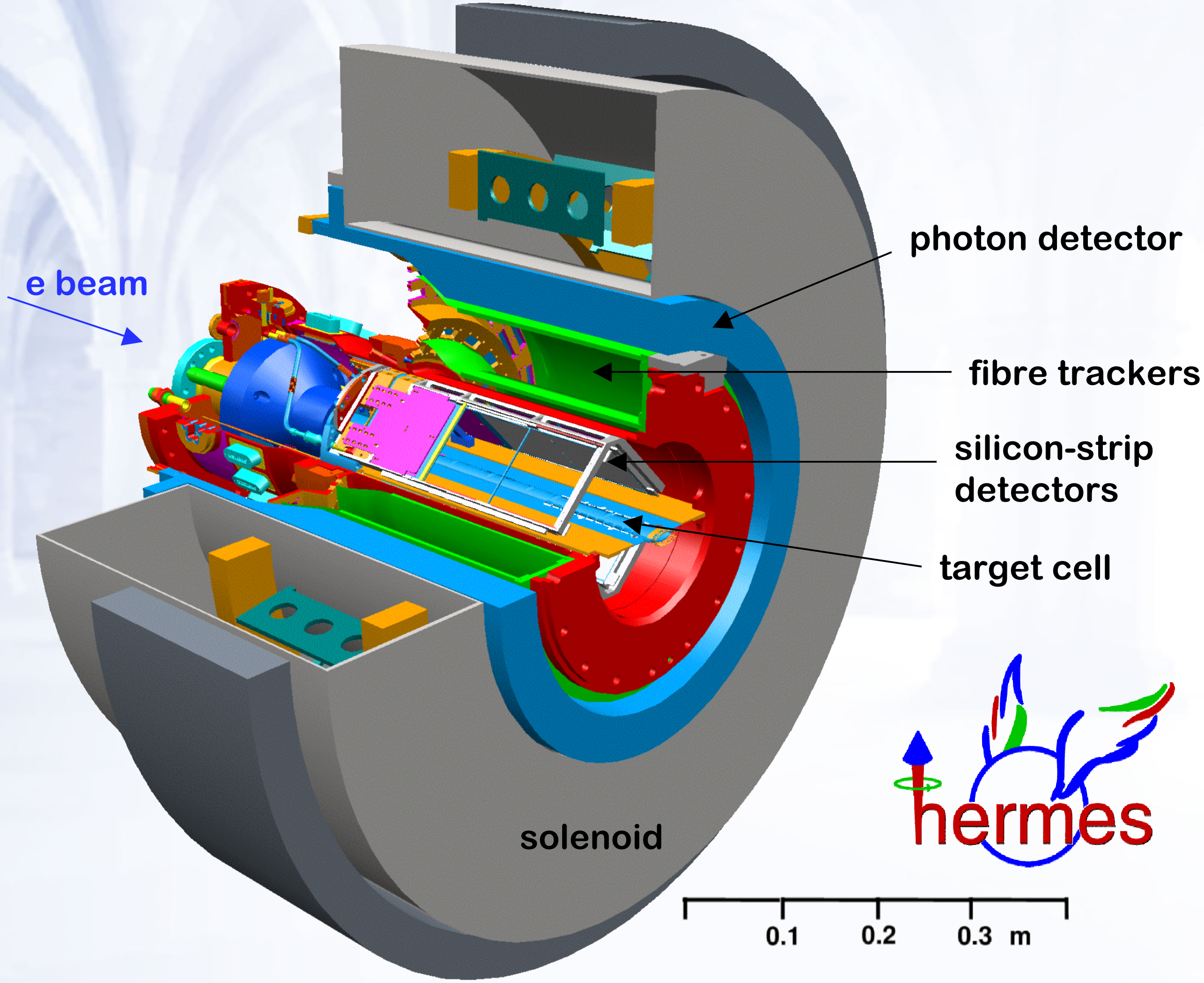
- Glimpse on Physics
- Results from HERMES
- Recoil at HERMES
- Future Prospects
- Summary

HERMES with Recoil Detector



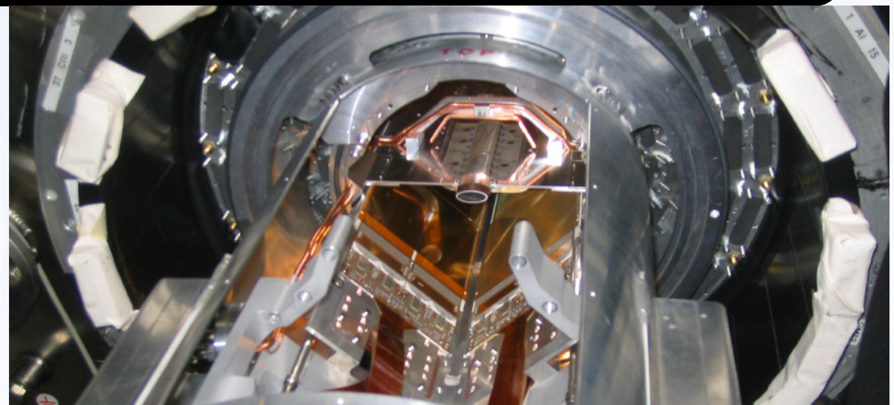
HERMES Recoil Detector

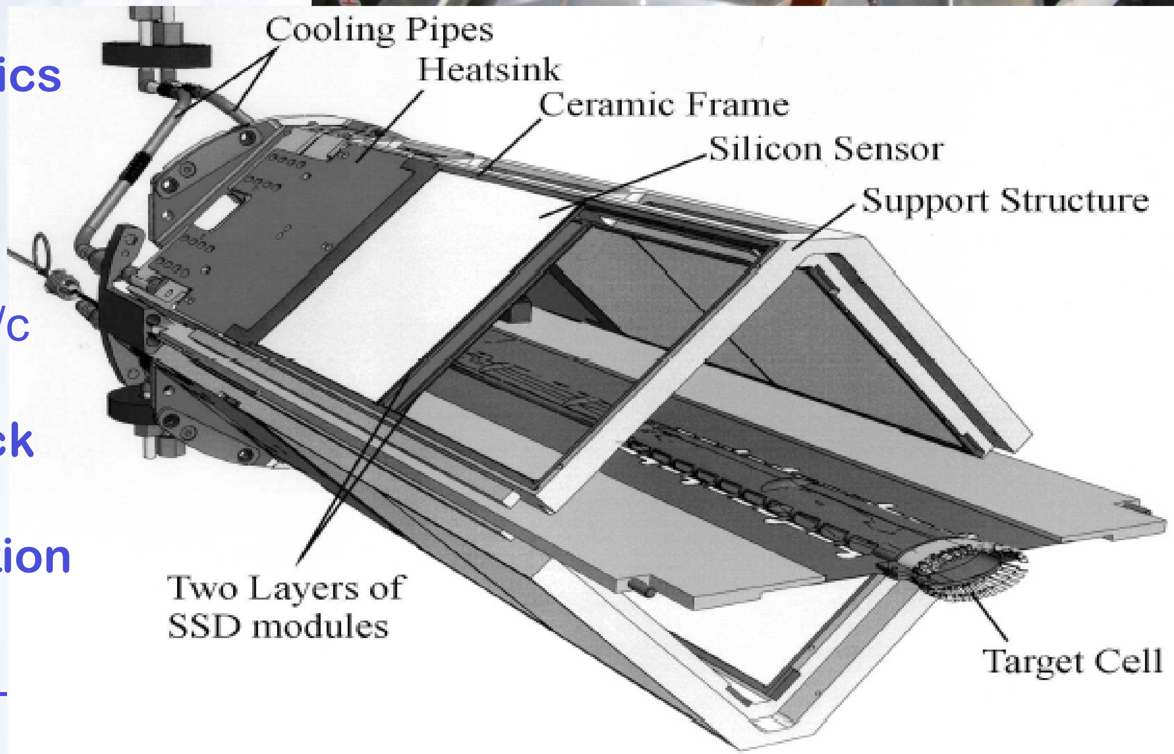
- Unpolarised gas targets
- Challenging detectors



Silicon Strip Detector

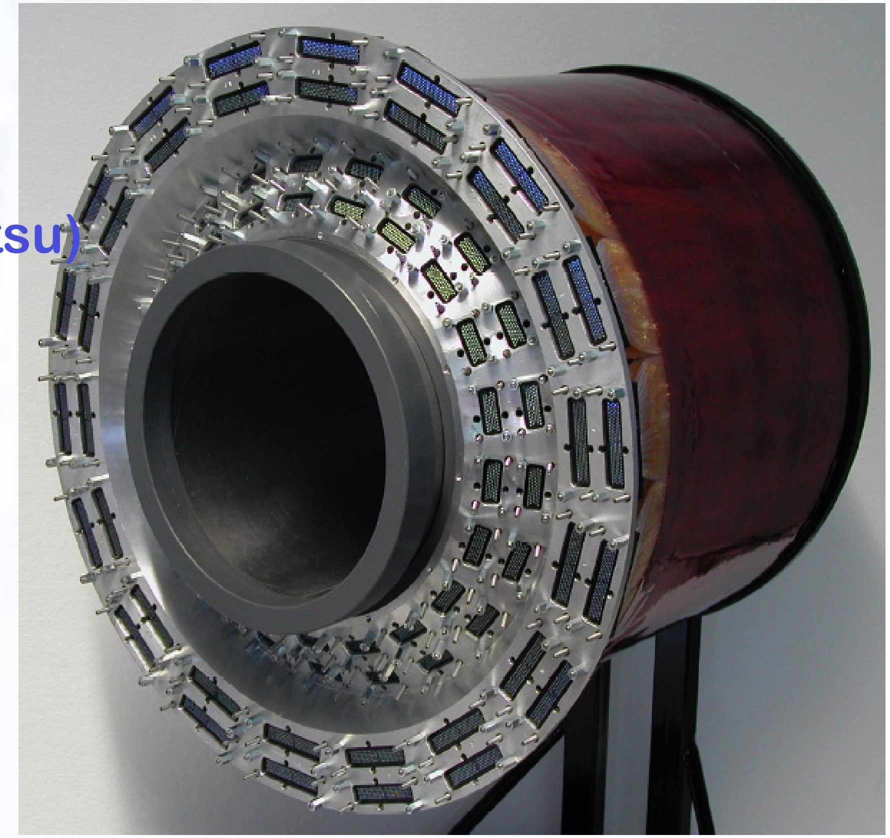
- 16 silicon sensors:
  - 10 x 10 cm^2 area
  - 300um thickness
  - double-sided strips
- Arranged in 2 layers
- Challenge
  - Detector + electronics close to e beam
  - Inside vacuum
- Purpose
  - detect 135-500 MeV/c protons
  - Momentum and track reconstruction
  - Particle Identificantion





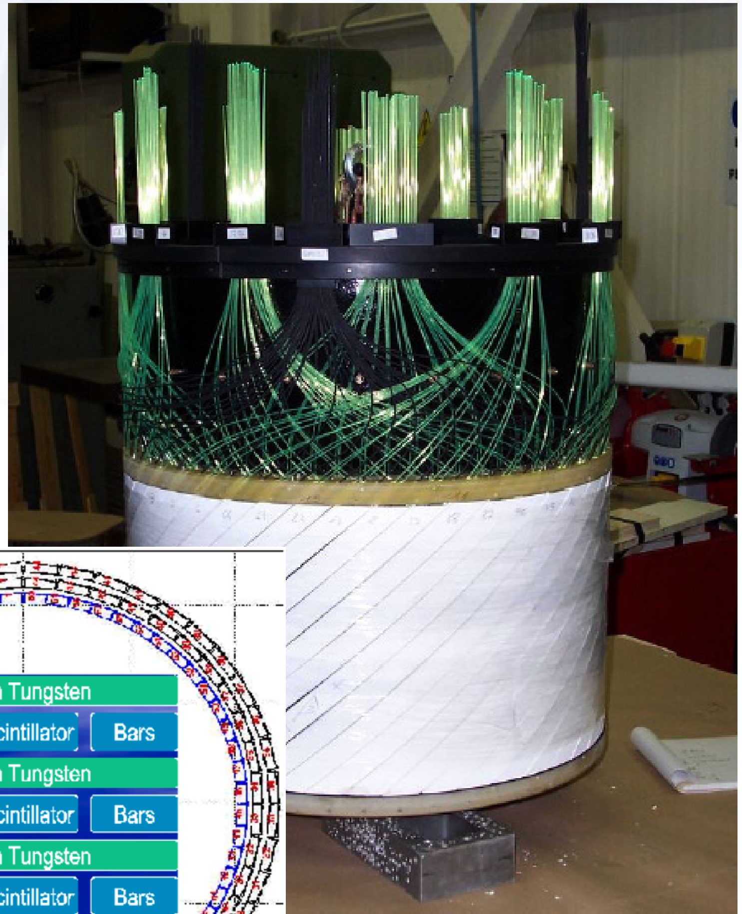
Scintillating Fibre Detector

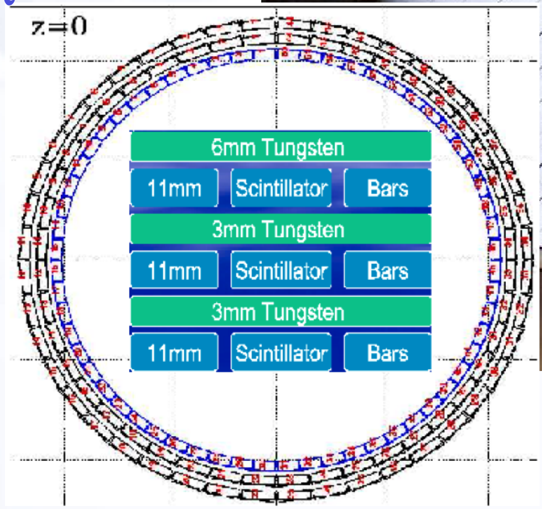
- **2 barrels with each:**
  - **2 layers parallel with resp. to beam**
  - **2 layers 10° stereo angle**
- **Readout:**
  - **64 channels PMT (Hamamatsu)**
  - **totally 5120 channels**
- **Purpose**
  - **Momentum and track reconstruction**
  - **Particle Identification**
  - **Range:** p_p = 250-1200 MeV/c



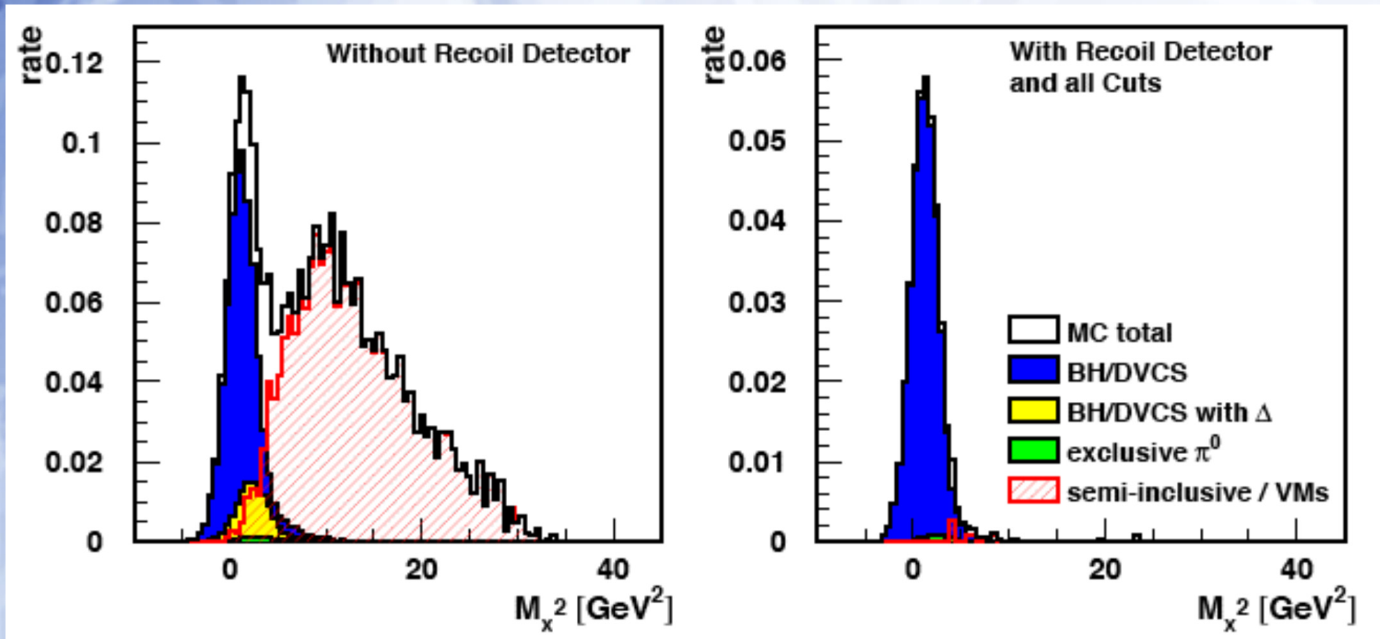
Photon Detector

- 3 layers of tungsten and scintillator
  - 1st layer parallel to beam
  - 2nd layer +45° resp. to beam
  - 3rd layer -45° resp. to beam
- Purposes
  - Photon detection from π^0 decays ($\Delta^+ \rightarrow p\, \pi^0$)
  - Particle Identification
  - Background reduction





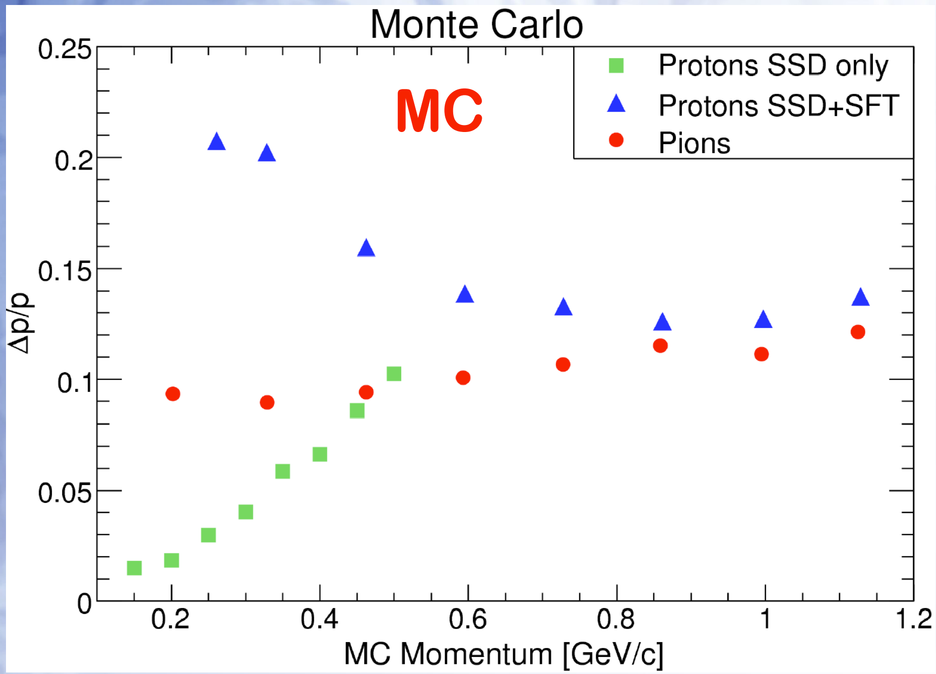
Advantages of the Recoil Detector



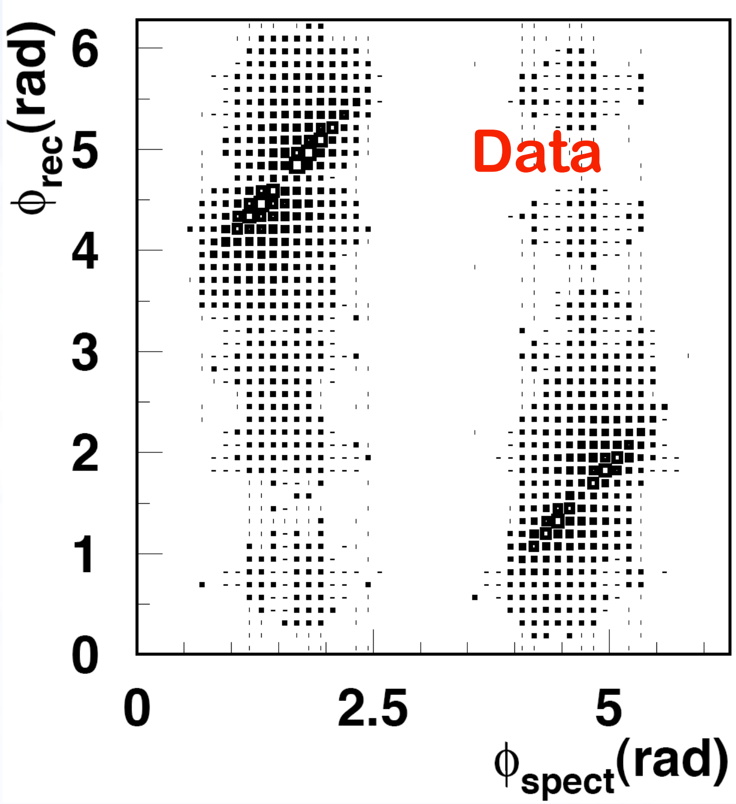
- **Remove background from associated BH/DVCS with intermediate Δ-production and from semi-inclusive processes**
  - Reduction from 17% to about 1%
- **Improve t-resolution at small t (with Si-detector)**
- **High luminosity with unpolarised target**

First Results From the Recoil Detector

Momentum resolution:
$\Delta p/p$ = 1-15% for protons

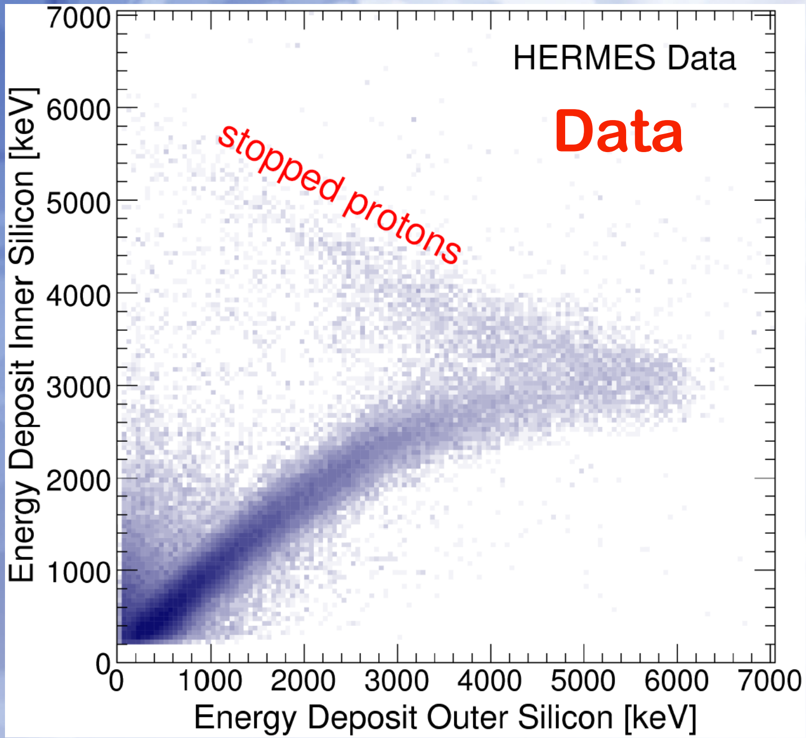


Elastic scattering:
e and p back-to-back

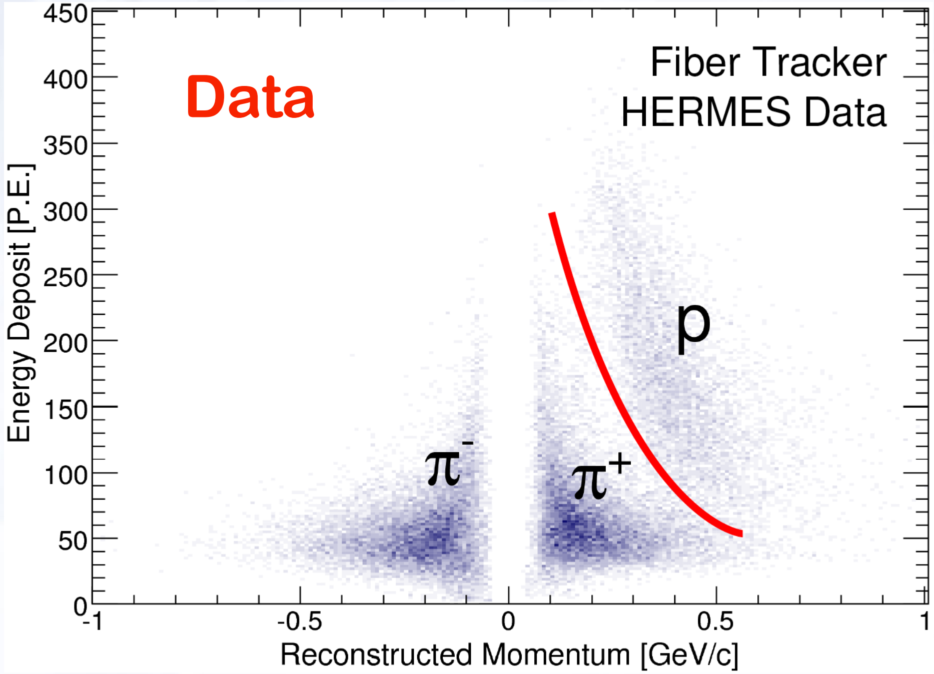


First Results From the Recoil Detector

Energy Deposit in Silicon Detectors



Track Reconstruction Through Curvature

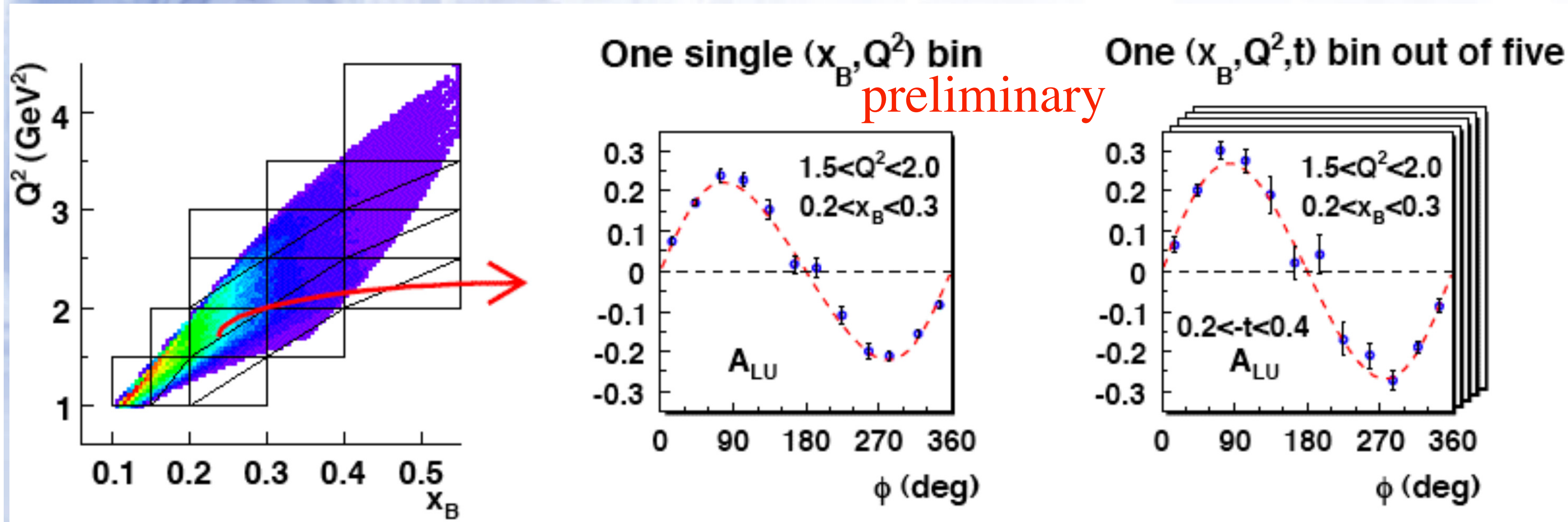


- **Detectors operational:**
  - **Momentum reconstruction**
  - **Particle identification: pions, protons, photons, ...**

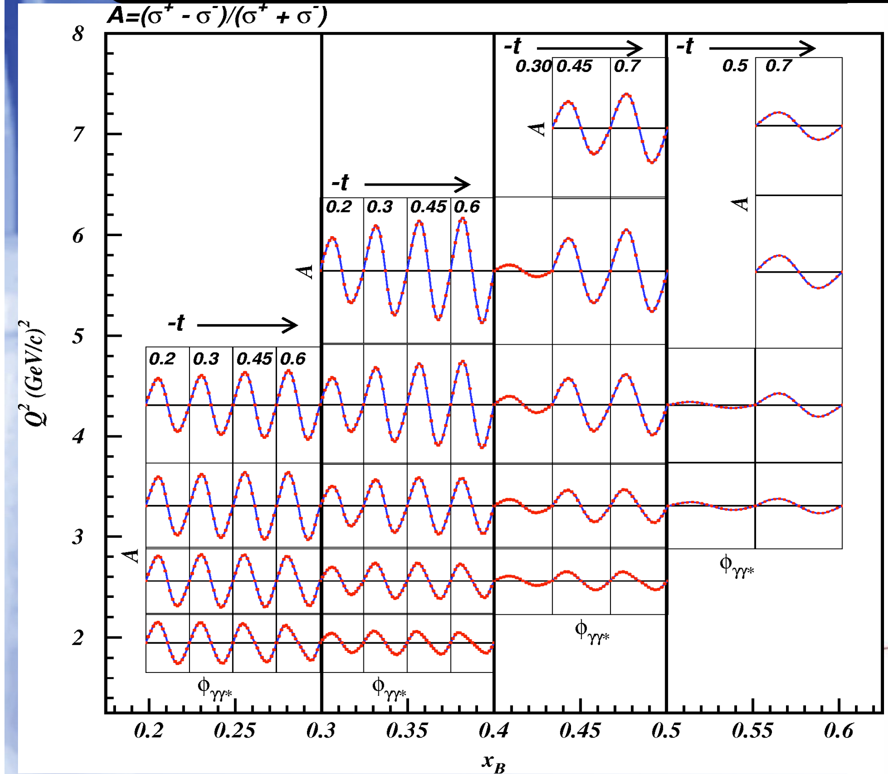
Table of Contents

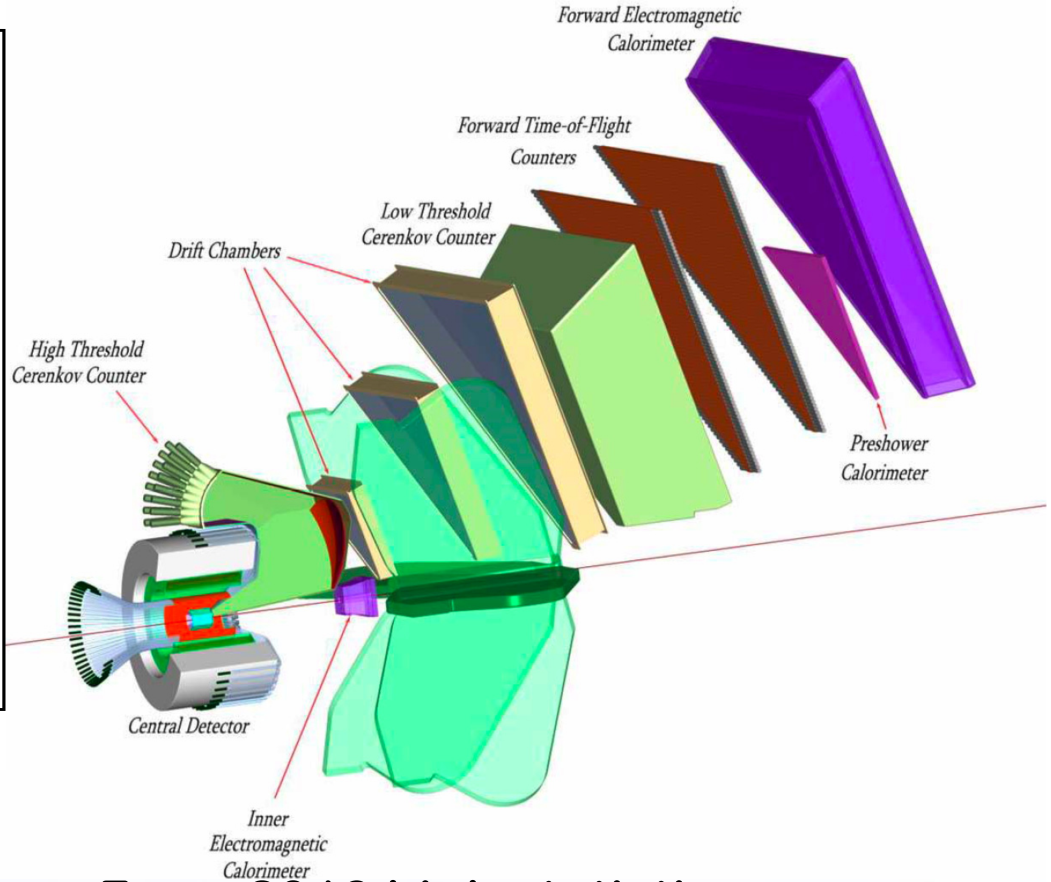
CLAS : High Statistics Beam Spin Asymmetry

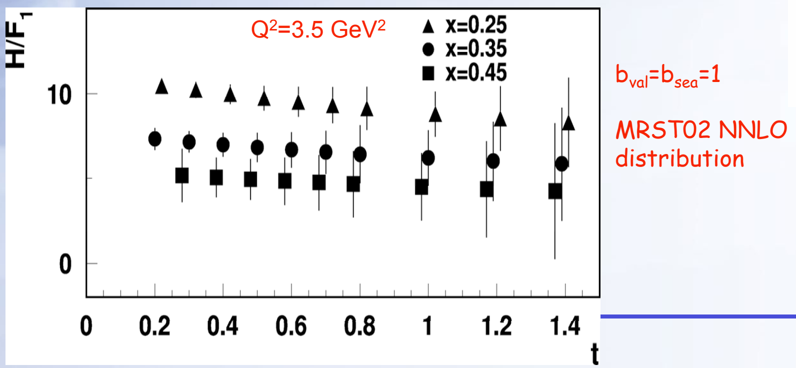
- Experiment E01 - 113, preliminary data, still unpublished
- All three final state particles (electron, photon, proton) detected
- Statistics allows 3-d binning in x, Q^2 and t
- First glimpse at what future JLab experiments will be able to do



CLAS12 at JLAB



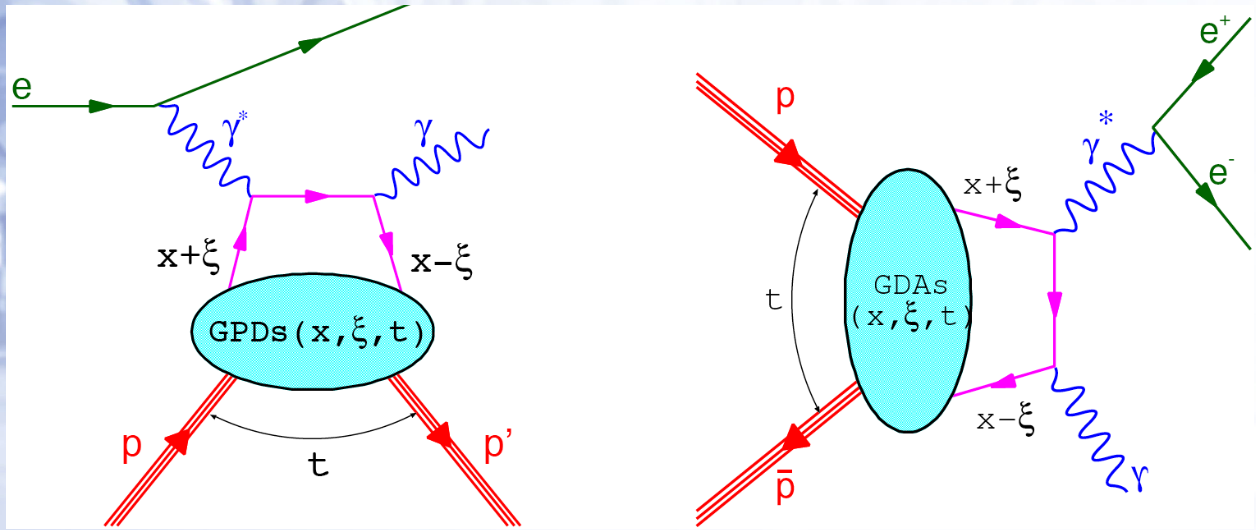




- **From 2013 high statistics measurements at 11 GeV with upgraded CLAS12 detector**
- **Extraction of GPD H from BSA**
  - Other kinematics measured concurrently

Antiproton Annihilations → PANDA

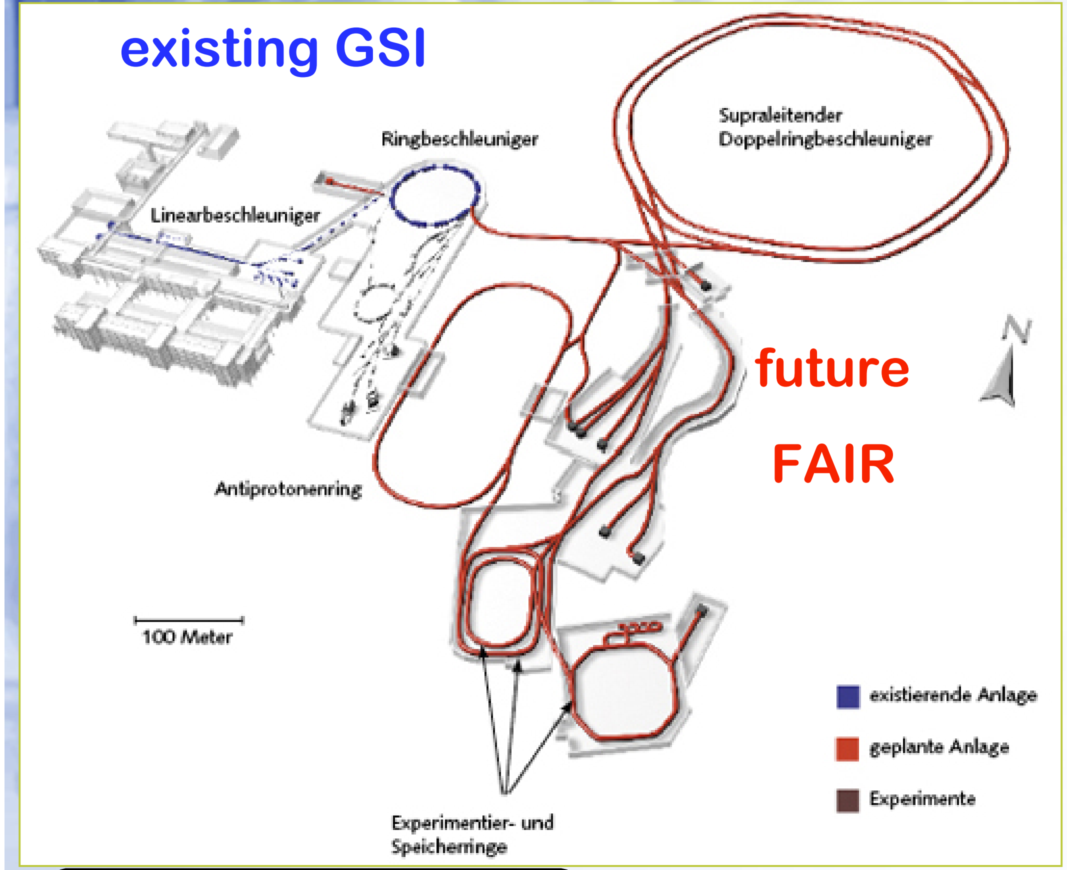
- 'Cross channel' or 'time-like' version of DVCS complementary:
  - Generalised Distribution Amplitudes or
  - Transition Distribution Amplitudes



- Time-like form factors
  - Measure GE and GM separately
- Putting data together (with DIS)
  - First 3-dimensional picture of the nucleon

FAIR at Darmstadt

Facility for Antiproton and Ion Research



Primary Beams

- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
- 10^{10}/s $^{238}U^{73+}$ up to 35 GeV/u
- 3×10^{13}/s 30 GeV protons

Secondary Beams

- broad range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 higher in intensity than presently
- antiprotons 3 - 30 GeV

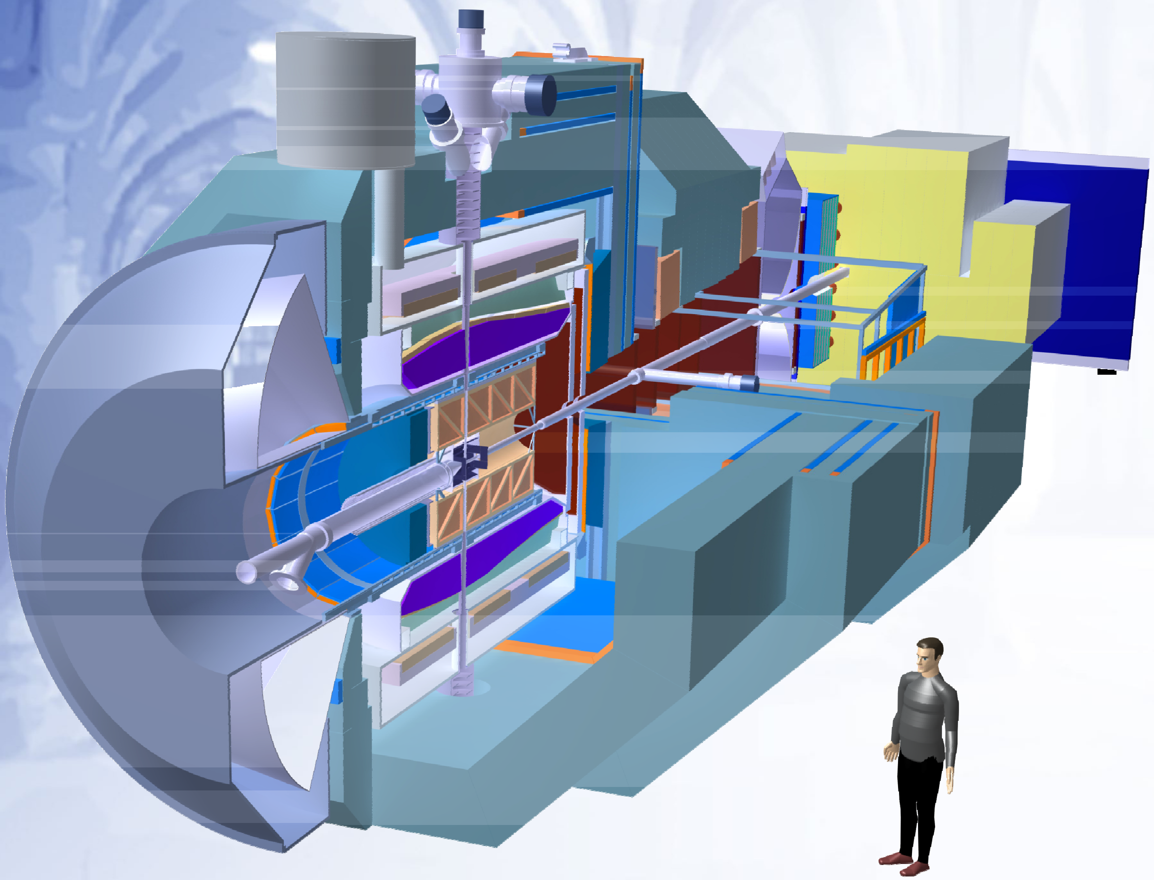
Storage and Cooler Rings

- radioactive beams
- 10^{11} antiprotons 1 - 15 GeV/c, stored and cooled

Technical Challenges

- cooled beams, rapid cycling superconducting magnets

PANDA at FAIR



- **Properties**
  - Fixed target
  - Antiproton beam
    p= 1.5 - 15 GeV/c
  - $\Delta p/p = 10^{-5}$
  - 4π detector charged + neutral
  - High luminosity
- **Main physics topics**
  - Charmonium spectroscopy
  - Gluonic excitations (hybrids, glueballs)
  - Open and hidden charm in nuclei
  - γ-ray spectroscopy of hypernuclei
  - Structure of the nucleon

Summary and Outlook

- **Hard exclusive reactions**
  - Potential to picture the nucleon GPDs, GDAs
- **HERMES is contributing a lot**
  - Many results were not shown
  - Much more data is on tape
  - Data with Recoil Detector have large potential
- **This subject will become more important**
  - Currently: (HERMES), CLAS, COMPASS
  - Future: CLAS12, PANDA, ...
- **Glasgow is strongly engaged**
  - Coordinate EU FP6 Network http://gpd.gla.ac.uk
  - New EU FP7 in preparation