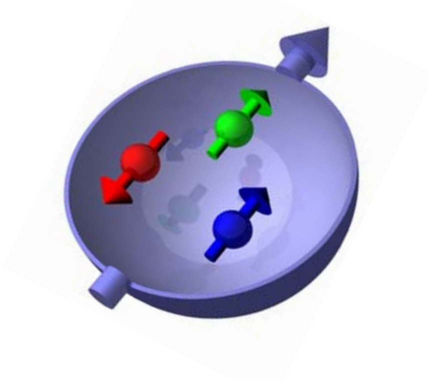

Hard exclusive reactions and General Parton Distributions at HERMES

Michael Düren

Universität Gießen

— New Trends in HERA Physics 2008, Ringberg Castle, Oct. 6, 2007 —

* Reuse of some transparencies from X. Ji, S. Yaschenko, and others

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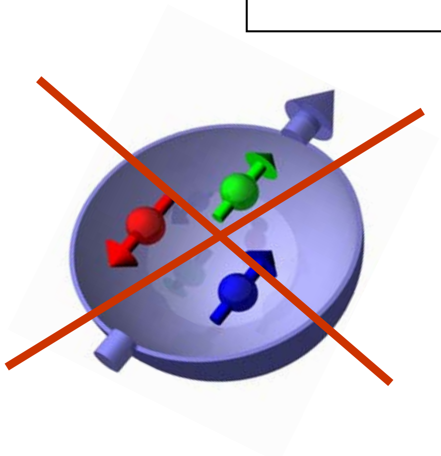
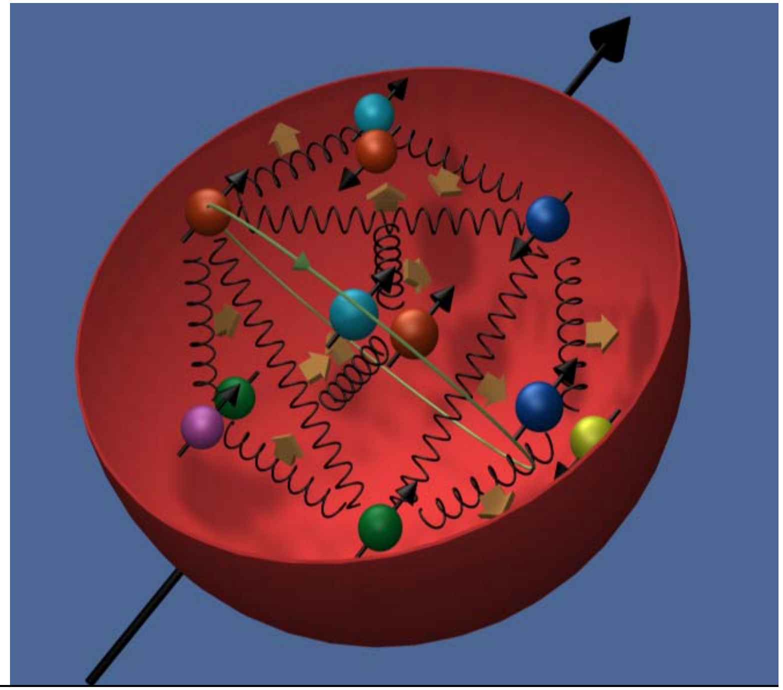
Proton spin structure



Only 1/3 of the proton spin comes the from quark spin



Helicity sum rule:

not gauge invariant

$$\underbrace{S_z}_{\substack{\text{proton}\\ \text{spin projection}}} = \tfrac{1}{2}\underbrace{(\Delta u + \Delta d + \Delta s)}_{\substack{\text{valence and sea}\\ \text{quark spin}}} + \underbrace{\Delta\hat{G}}_{\substack{\text{gluon}\\ \text{spin}}} + \underbrace{\Delta L_q + \Delta\hat{L}_g}_{\substack{\text{orbital angular}\\ \text{momentum}}}$$

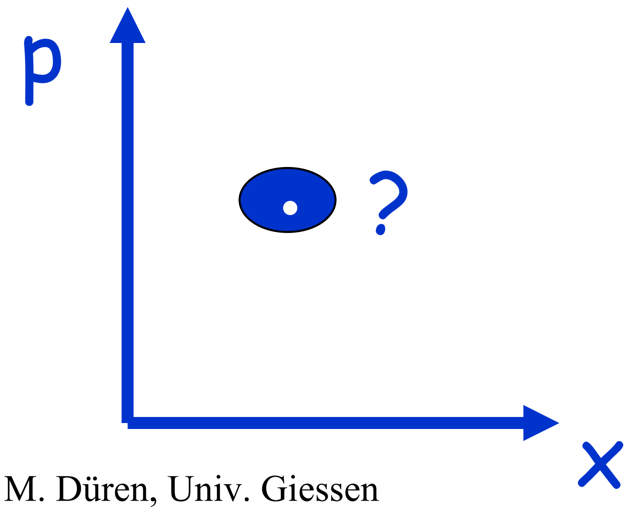
$$= \tfrac{1}{2} \qquad = \Delta\Sigma$$

Generalized Parton Distributions

Quantum phase-space „tomography"
of the nucleon

Wigner distribution in QM phase-space

- A classical particle is defined by its coordinate and momentum (x,p): **phase-space**
- A state of a classical identical particle system can be described by a **phase-space distribution f(x,p).** The time evolution of f(x,p) obeys the Boltzmann equation.
- In quantum mechanics, because of the uncertainty principle, the phase-space distributions seem useless, but…

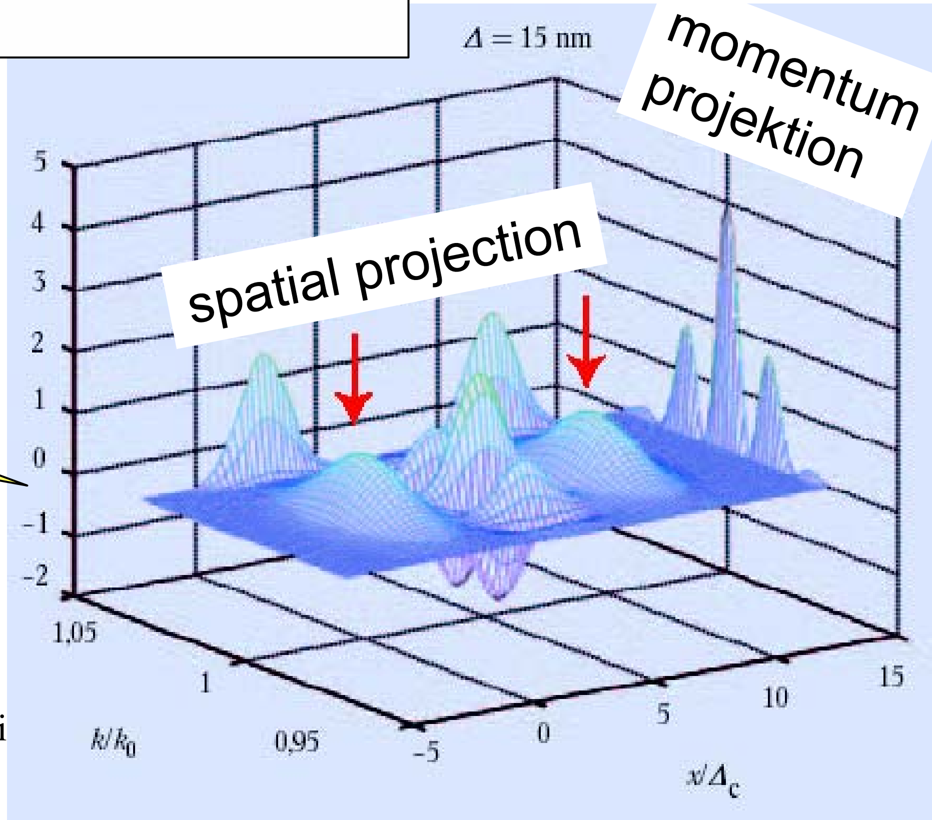


Wigner distribution in QM phase-space

- Wigner introduced the first phase-space distribution in quantum mechanics (1932)
- Wigner function:

$$W(x,p) = \int \psi^*(x-\eta/2)\psi(x+\eta/2)e^{ip\eta}d\eta \ ,$$

Example of a Wigner function (here: a particle passing an interferometer):



Wigner function

$$W(x,p) = \int \psi^*(x-\eta/2)\psi(x+\eta/2)e^{ip\eta}d\eta \ ,$$

- Integrating W(x,p) over x results in the momentum density.
- Integrating W(x,p) over p results in the probability density.
- Any dynamical variable can be calculated from it!

The Wigner function contains the *most complete (one-body) info* about a quantum system.

!

- In analogy, a Wigner operator can be defined that describes quarks in the nucleon
- The reduced Wigner distribution is related to *Generalized parton distributions* (GPDs)

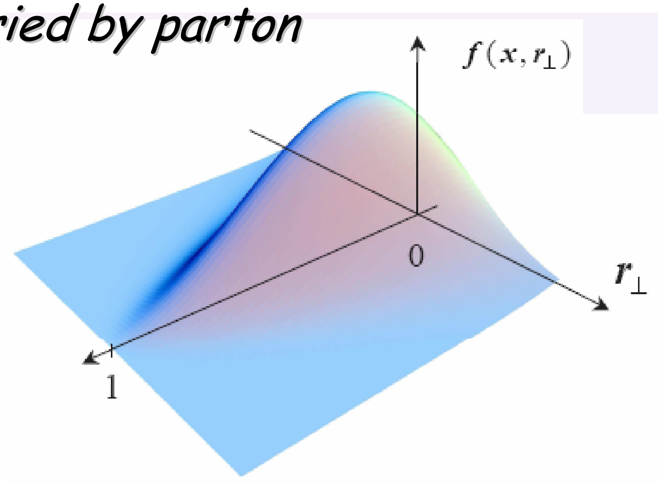
What is a GPD?

- A proton matrix element which is a hybrid of elastic form factor and Feynman distribution
- Depends on

  x: *fraction of the longitudinal momentum carried by parton*

  $t=q^2$: *t-channel momentum transfer squared*

  ξ: *skewness parameter*



There are 4 important GPDs (among others):

$$H^q(x,\xi,t), E^q(x,\xi,t), \tilde{H}^q(x,\xi,t), \tilde{E}^q(x,\xi,t)$$

Limiting cases:

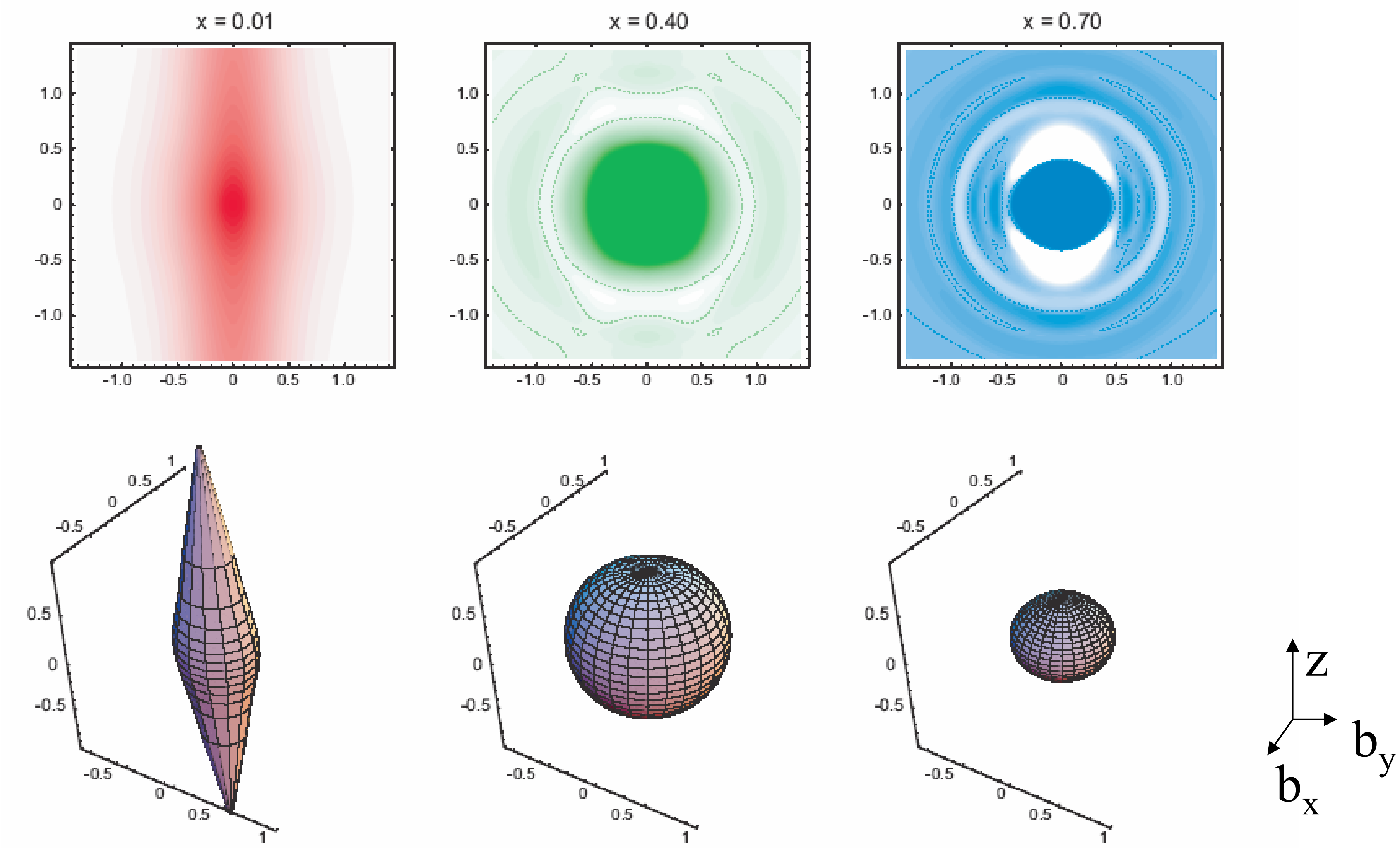
- t→0: Ignoring the impact parameters leads to ordinary **parton distributions**

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

- Integrating over x: Parton momentum information is lost, spatial distributions = **form factors** remain

$$F_1^q(t) = \int H^q(x,\xi,t)\, dx$$
$$F_2^q(t) = \int E^q(x,\xi,t)\, dx$$

3-D contours of quark distributions for various x



Fits to the known form factors and parton distributions
with additional theoretical constraints (e.g. polynomiality) and model assumptions

Quarks in quantum mechanical phase-space

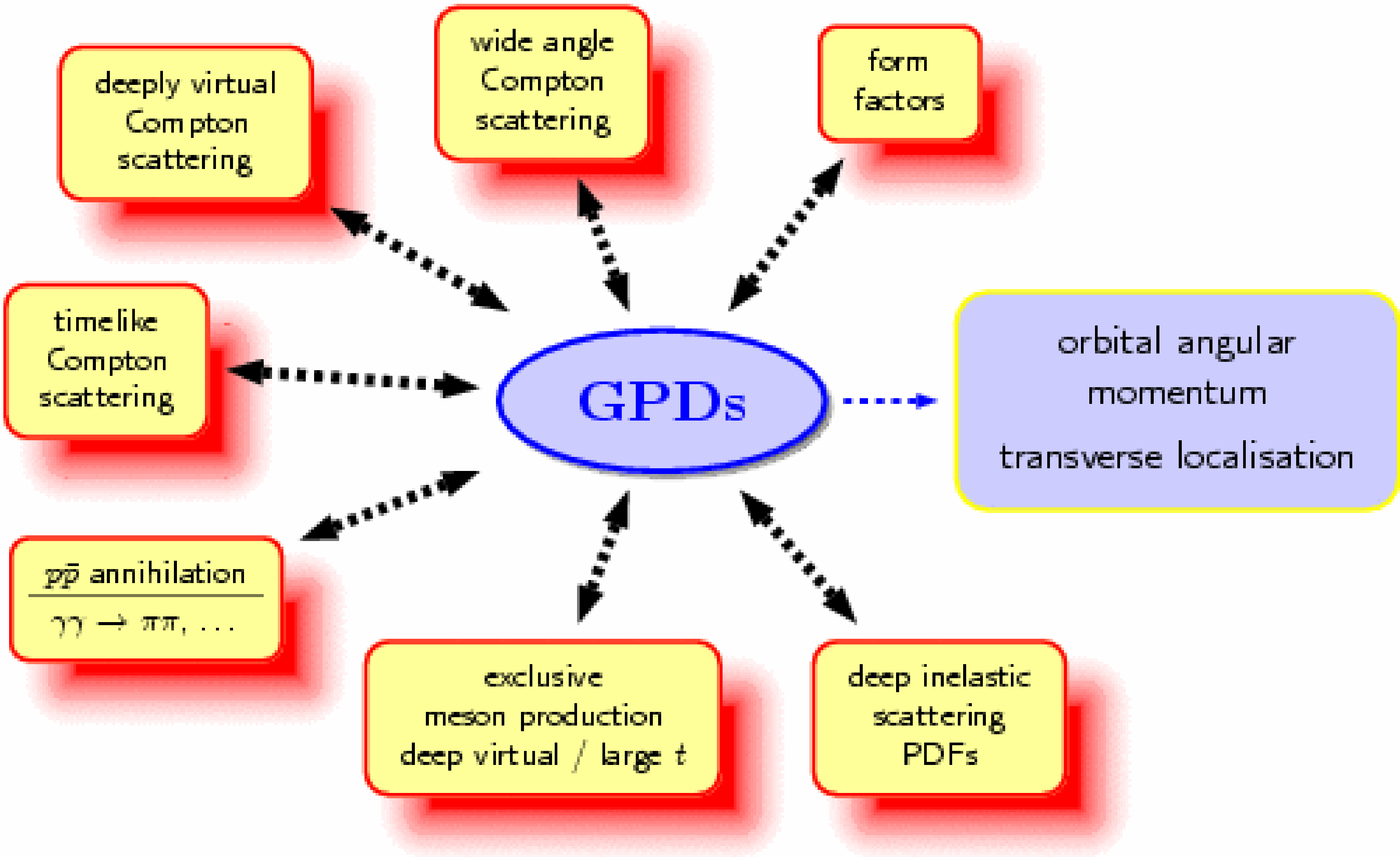
- Generalized parton distributions (GPDs) are reduced Wigner functions → correlation in phase-space → e.g. the orbital momentum of quarks: $L = r \times p$

- Angular momentum of quarks can be extracted from GPDs:

X. Ji relation: $$J^q = \lim_{t\to 0} \int_0^1 x dx \left[H^q(x,\xi,t) + E^q(x,\xi,t) \right]$$

- GPDs provide a unified theoretical framework for many experimental processes

Universality of GPDs

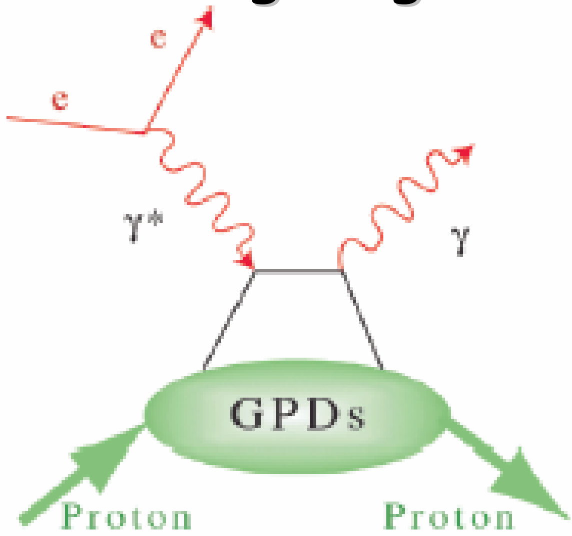


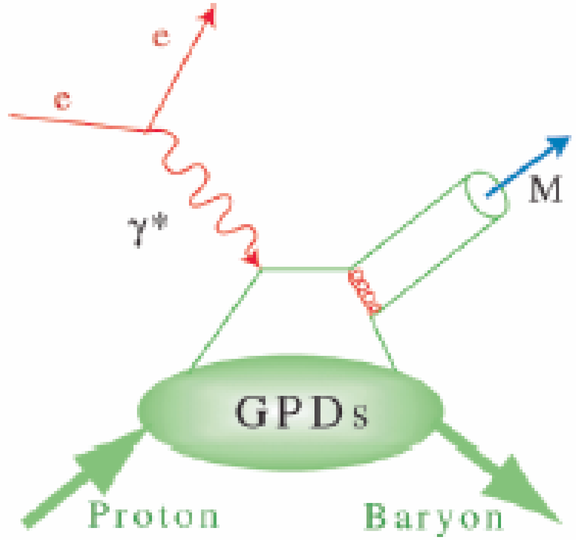
Hard exclusive reactions

Experimental access to GPDs

Hard exclusive reactions

QCD handbag diagram





Deeply virtual Compton scattering (DVCS)

Hard exclusive meson production (HEMP)

→ Quantum number of final state selects different GPDs:

Vector mesons (ρ, ω, ϕ): H E

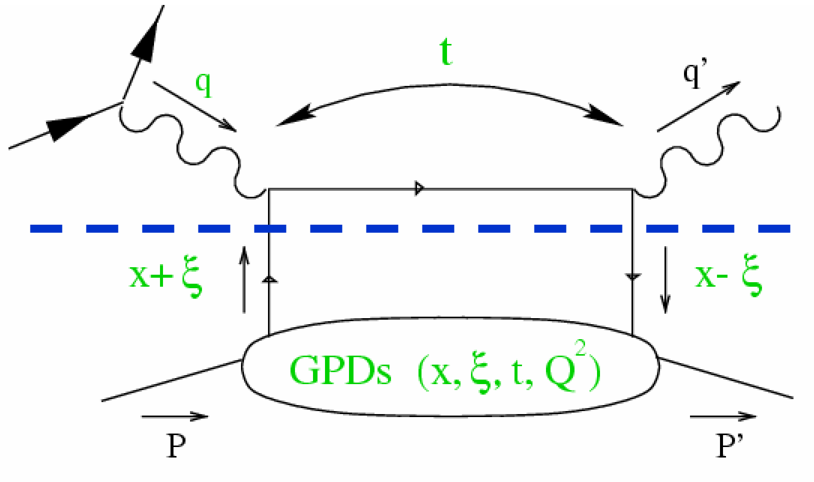
Pseudoscalar mesons (π, η): $\tilde{H}$ $\tilde{E}$

DVCS (γ) depends on H, E, $\tilde{H}$, $\tilde{E}$

Deeply virtual Compton scattering (DVCS)

- DVCS is the cleanest way to access GPDs: $\gamma^* N \rightarrow \gamma N$

Factorization theorem is proven!



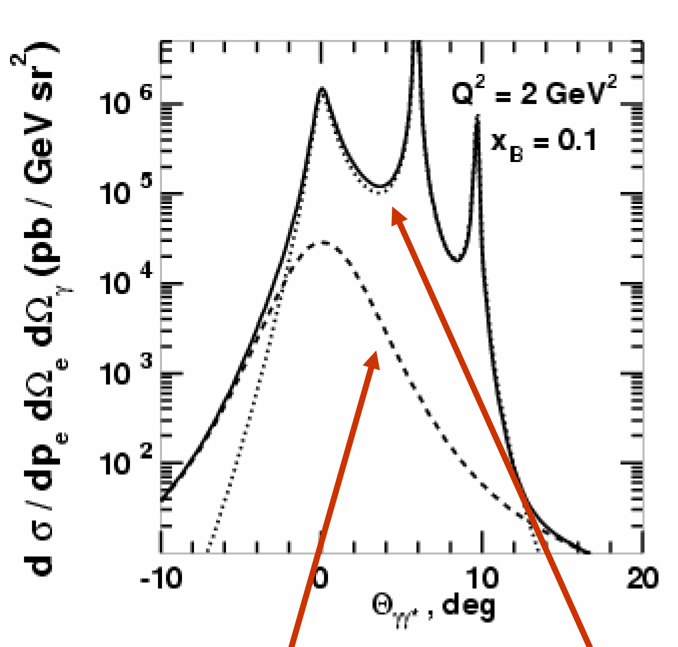
Handbag diagram separates

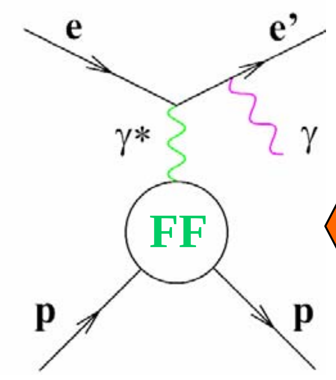
- hard scattering process (QED & QCD) and
- non-pertubative structure of the nucleon (GPDs)

GPDs = probability amplitude for a nucleon to emit a parton with ($x+\xi$) and to absorb it with momentum fraction ($x-\xi$)

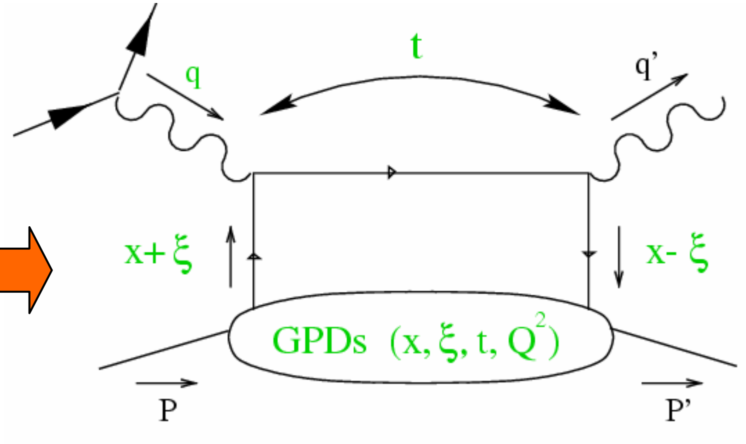
$$\xi \approx \frac{x_B}{2 - x_B}$$

DVCS and BH Interference ($ep \to e'\gamma p$)





Bethe-Heitler (BH)



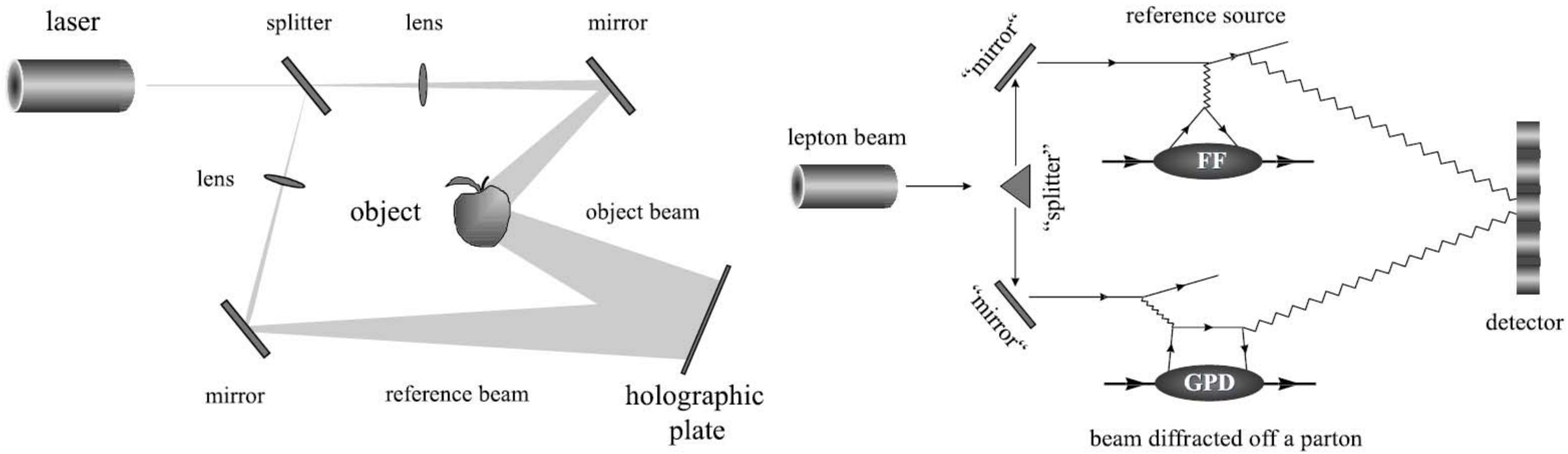
DVCS

$$d\sigma \propto |\tau_{DVCS}|^2 + |\tau_{BH}|^2 + (\tau^*_{BH}\tau_{DVCS} + \tau^*_{DVCS}\tau_{BH})$$

DVCS-BH interference I gives non-zero azimuthal asymmetry

Use BH as a vehicle to study DVCS.

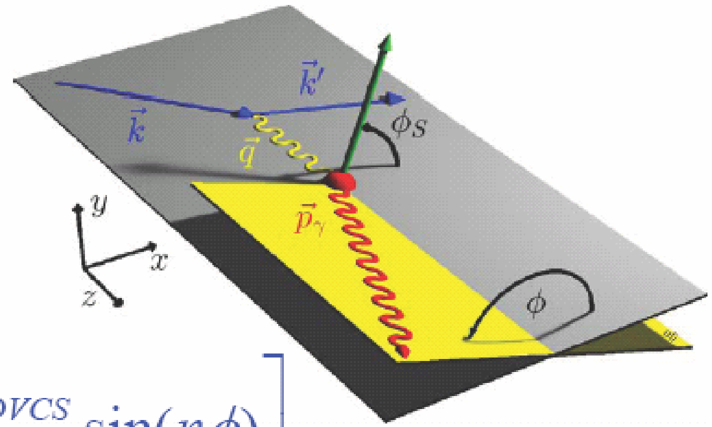
Laser and nucleon holography



(Belitsky/Mueller)

Azimuthal dependencies

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = \frac{y^2 x_B}{32(2\pi)^4 Q^4 \sqrt{1+\frac{4M^2 x_B^2}{Q^2}}} \left(|T_{DVCS}|^2 + |T_{BH}|^2 + I\right)$$



$$|T_{BH}|^2 = \frac{K_{BH}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{2} c_n^{BH} \cos(n\phi)$$

$$|T_{DVCS}|^2 = K_{DVCS}\left[\sum_{n=0}^{2} c_n^{DVCS} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{DVCS} \sin(n\phi)\right]$$

$$I = \frac{C_B K_I}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} K_{DVCS}\left[\sum_{n=0}^{3} c_n^{I} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{I} \sin(n\phi)\right]$$

Measured azimuthal asymmetries

- Cross Section

$$\sigma_{LU}(\phi; P_B, C_B) = \sigma_{UU}[1 + P_B A_{LU}^{DVCS} + C_B P_B A_{LU}^{I} + C_B A_C]$$

- Beam Spin Asymmetry

$$A_{LU}^{DVCS}(\phi) = \frac{1}{D(\phi)} \cdot \frac{x_B^2 t \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}{Q^2} s_1^{DVCS} \sin(\phi)$$

$$A_{LU}^{I}(\phi) = \frac{1}{D(\phi)} \cdot \frac{x_B^2}{Q^2}[s_1^I \sin(\phi) + s_2^I \sin(2\phi)]$$

- Beam Charge Asymmetry

$$A_C(\phi) = -\frac{1}{D(\phi)} \cdot \frac{x_B^2}{y}[c_0^I + c_1^I \cos(\phi) + c_2^I \cos(2\phi) + c_3^I \cos(3\phi)]$$

- Dilution factor through lepton propagators $\mathcal{P}_1(\phi), \mathcal{P}_2(\phi)$

$$D(\phi) = \frac{\sum_{n=0}^{2} c_n^{BH} \cos(n\phi)}{(1+\varepsilon^2)^2} + \frac{x_B^2 t \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}{Q^2} \sum_{n=0}^{2} c_n^{DVCS} \cos(n\phi)$$

Connection to GPDs

- Data with different beam charges and beam helicities were combined and fit simultaneously

- Connections to GPDs (leading contributions)

$$c_1^I \propto \frac{\sqrt{-t}}{Q} \Re e\left[F_1 \mathcal{H} + \xi (F_1 + F_2) \widetilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E} \right] \propto -\frac{Q}{\sqrt{-t}} c_0^I$$

$$s_1^I \propto \frac{\sqrt{-t}}{Q} \Im m\left[F_1 \mathcal{H} + \xi (F_1 + F_2) \widetilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E} \right]$$

where $\mathcal{H}, \widetilde{\mathcal{H}}, \mathcal{E}, \widetilde{\mathcal{E}}$ are Compton form factors - convolutions of hard scattering amplitude and twist-2 GPDs $H, \widetilde{H}, E, \widetilde{E}$

F_1, F_2 are Dirac and Pauli form factors of the nucleon

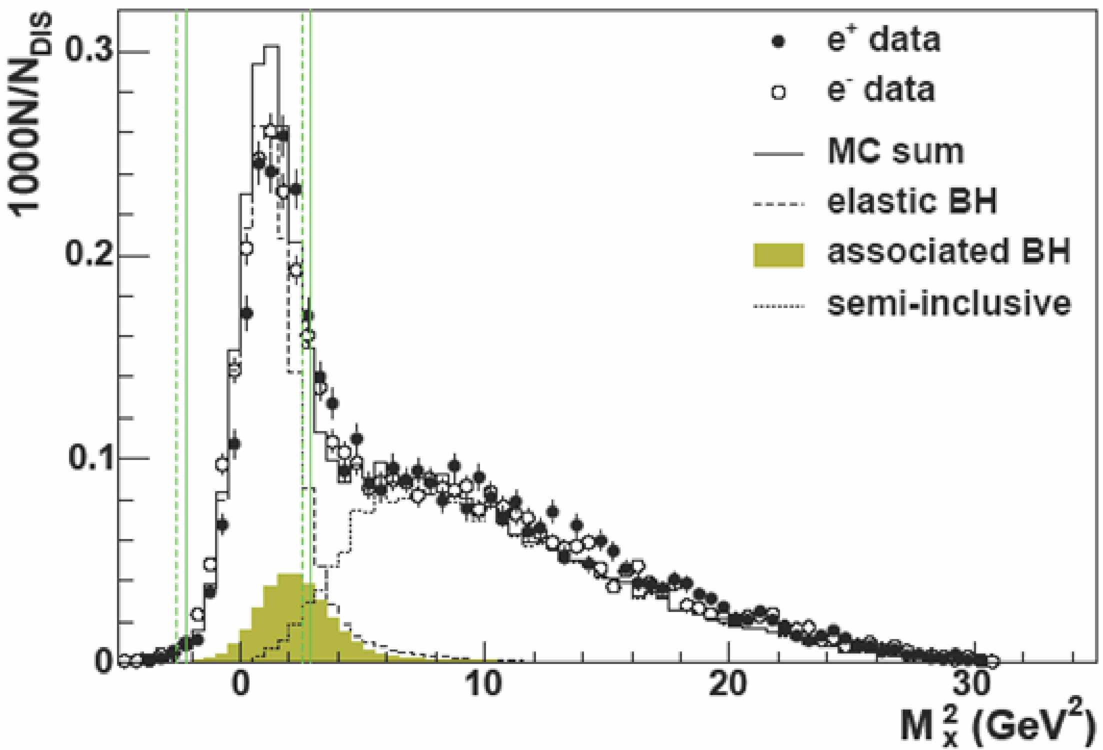
GPD Models

- VGG model (Vanderhaeghen, Guichon, Guidal 1999):
  - Based on double distributions
  - Includes a D-term to restore full polynomiality
  - Includes a Regge inspired and a factorized t-ansatz
  - Skewness depending on free parameters b_{val} and b_{sea}
  - Includes twist-3 contributions
- Dual model: (Guzey, Teckentrup 2006)
  - GPDs based on an infinite sum of t-channel resonances
  - Includes a Regge inspired and a factorized t-ansatz
  - Does not include twist-3

Experimental results

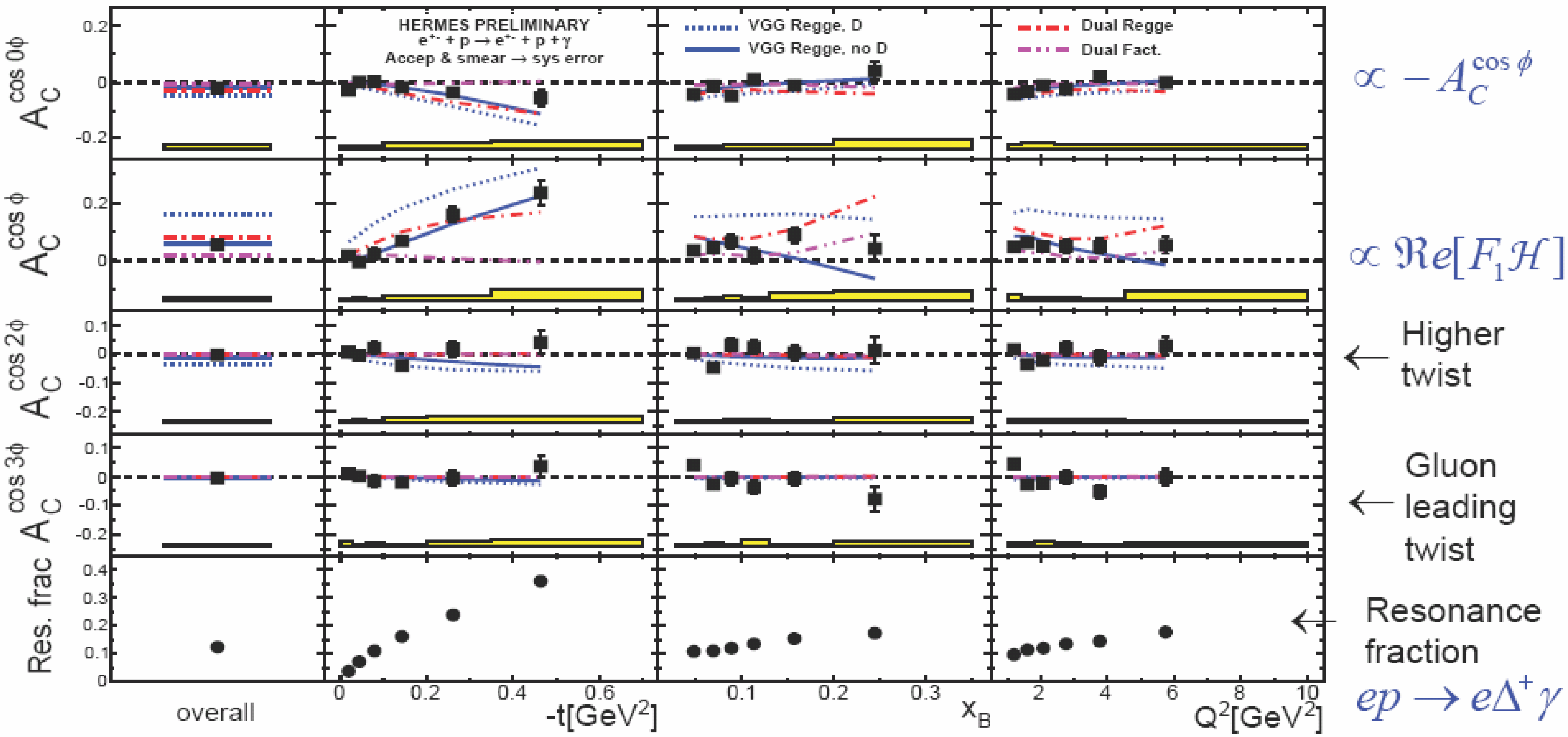
Asymmetries

DVCS: Selection of exclusive events



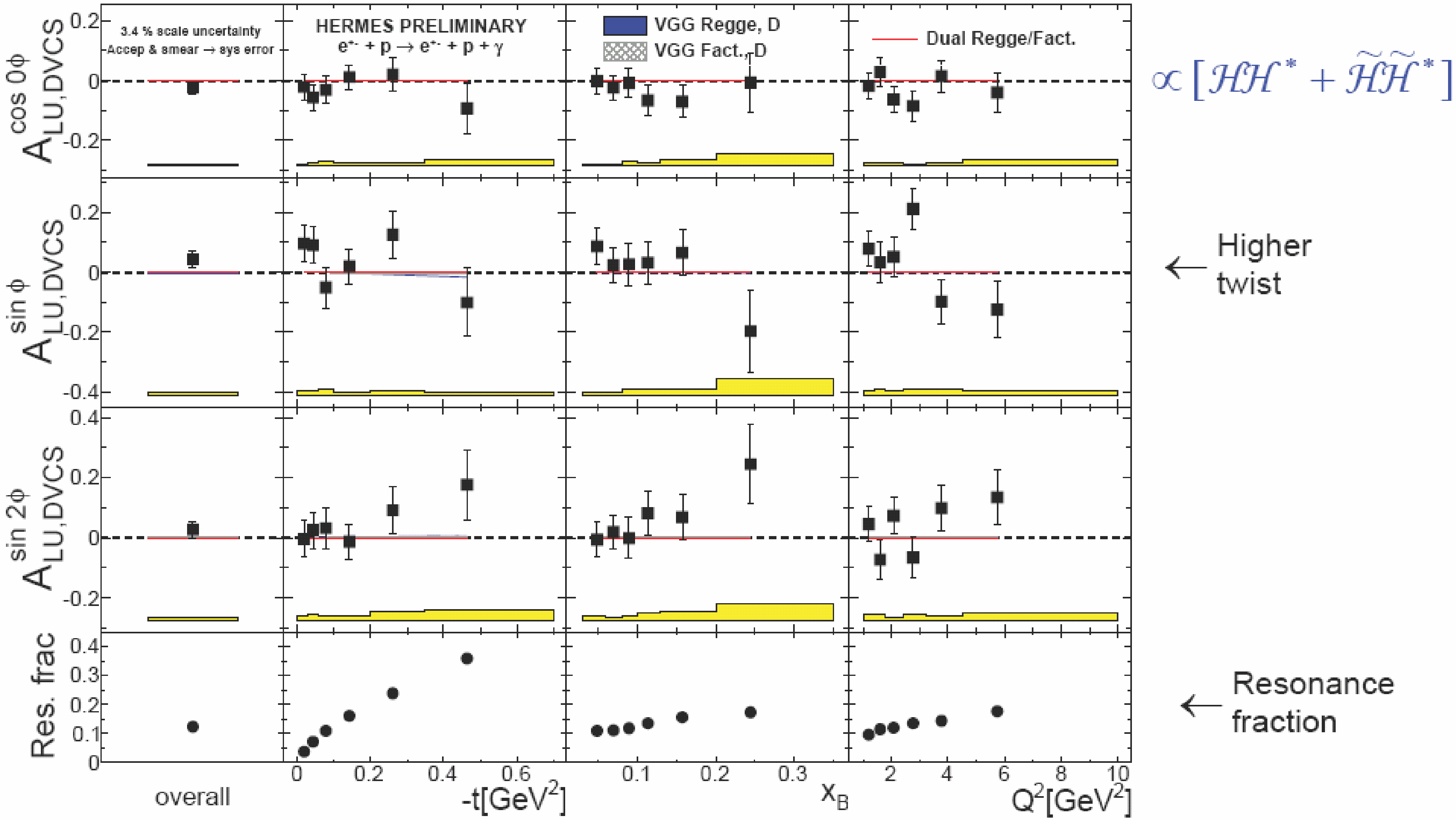
- Identification by missing mass technique ($ep \to e'\gamma X$)
- Associated Bethe-Heitler $ep \to e'\Delta^+\gamma$ ~12% stays part of the signal
- Semi-inclusive (mainly pion production) corrected as dilutions for charge dependent asymmetries. For pure DVCS term asymmetry extracted from π^0 ($z_\pi > 0.8$) data. Fractional contribution taken from Monte Carlo

Beam charge asymmetry (1996-2005)



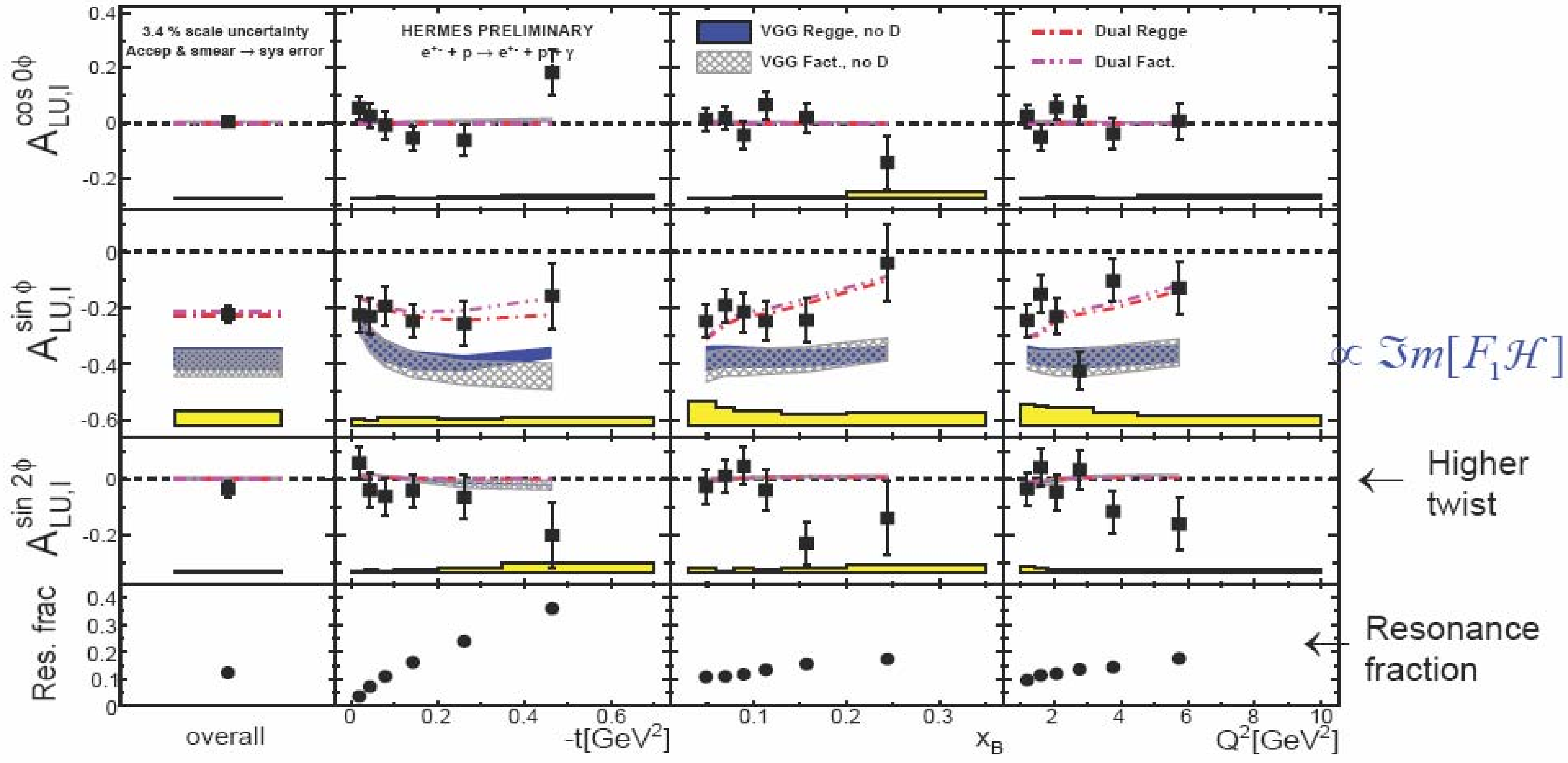
- The factorized ansatz and the VGG variant with the D-term are dis-favored by the beam charge asymmetry

Beam spin asymmetry (1996-2005)



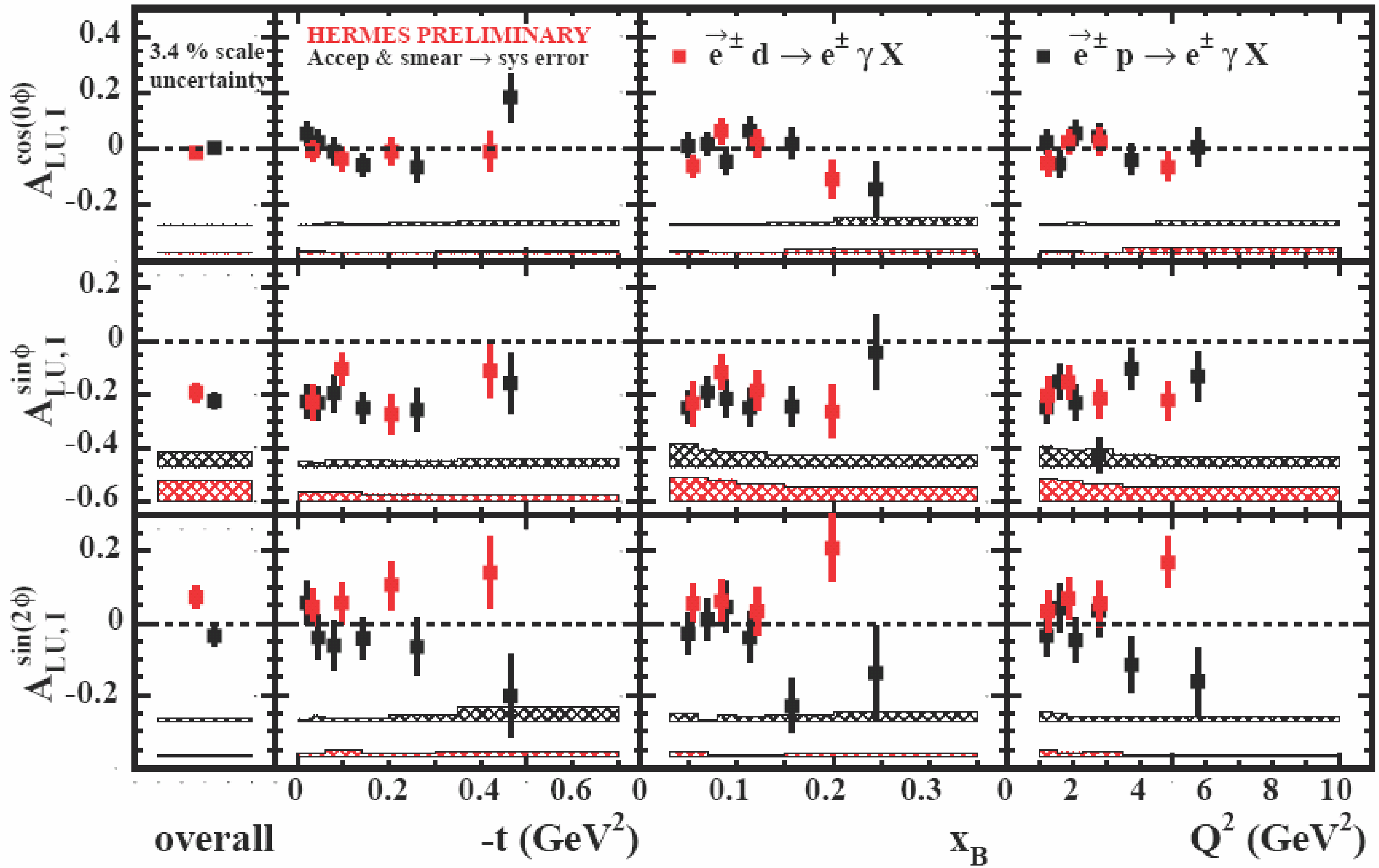
- Pure DVCS squared asymmetries are compatible with zero, in agreement with model assumptions

Beam spin asymmetry (1996-2005)



- Result agrees with Dual model predictions, but fractions of associated productions are not corrected for

Deuterium – Hydrogen comparison

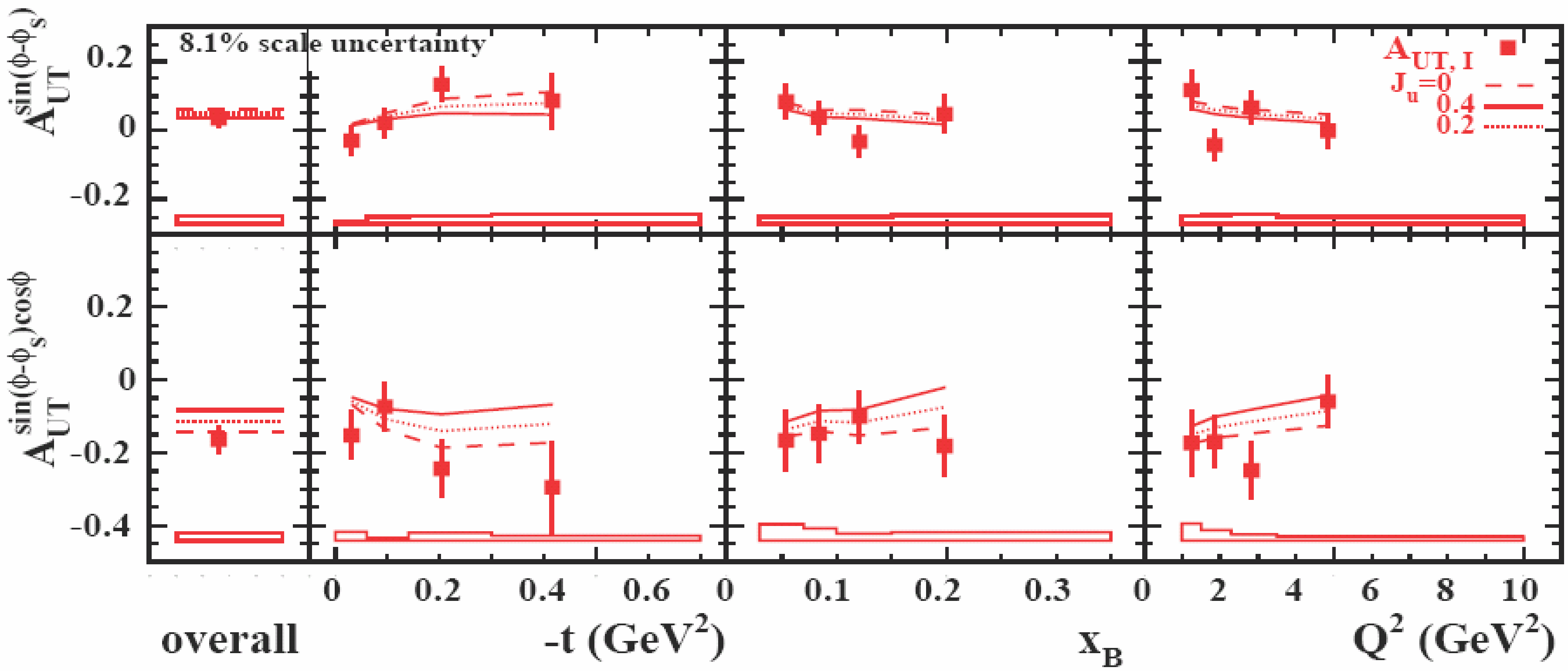


- Proton (black) and Deuteron (red) data are compatible for almost all amplitudes

Transverse target spin asymmetry (TTSA)

- Results on transverse target spin asymmetry are published [*A. Airapetian et al, JHEP 06 (2008) 066*]
- Data with Transversely Polarized Target (2002-2005)
- Access to GPD E
- Model-dependent constraints on J_u, J_d
  - Two GPD models (Double Distribution and Dual Parameterization)
- Comparison with JLAB data on neutron cross section data
- Comparison with lattice QCD calculations

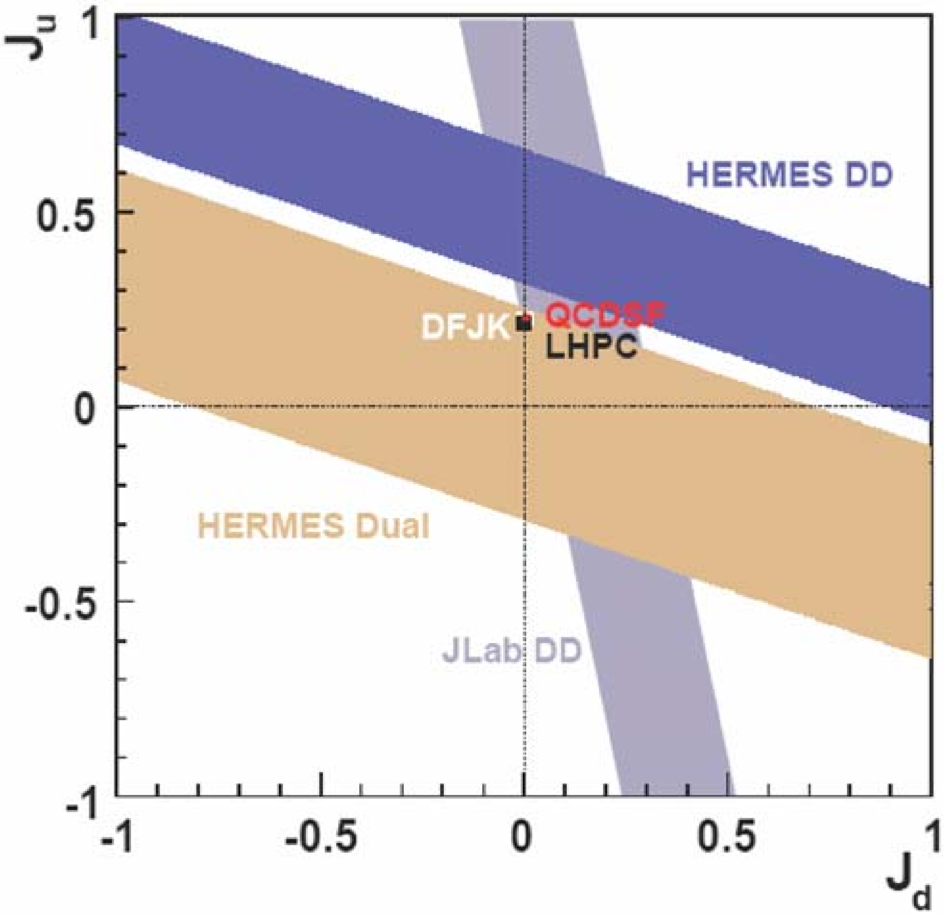
Transverse target spin asymmetry (TTSA)



Sensitivity of GPD model predictions to J_u at fixed J_d=0
[Phys. Rev. D74(2006) 054027]

Angular momentum: model dependent result

$$\chi^2(J_u,J_d) = \left(A_{UT,I}^{\sin(\varphi-\varphi_s)\cos n\varphi}\Big|_{exp} - A_{UT,I}^{\sin(\varphi-\varphi_s)\cos n\varphi}\Big|_{theo}(J_u,J_d) \right)^2 \Big/ \left(\delta A_{stat}^2 + \delta A_{syst}^2 \right)$$



- J_u, J_d are free parameters in GPD models
- Double Distribution (DD) [Phys.Rev.D 60 (1999) 094017, Prog. Part. Nucl. Phys. 47(2001)401]

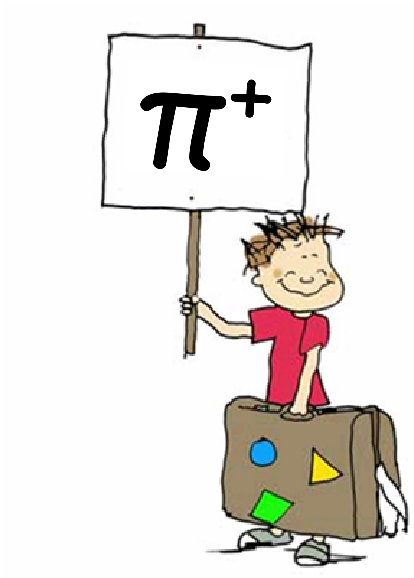
$$J_u + J_d/2.8 = 0.48 \pm 0.17$$

- Dual Parameterization (Dual) [hep-ph/0207153, Phys. Rev. D74(2006) 054027]

$$J_u + J_d/2.8 = -0.02 \pm 0.27$$

- Jlab DD (neutron cross section data) [Phys. Rev. Lett. 99(2007)242501]
- Lattice calculations QCDSF, LHPC

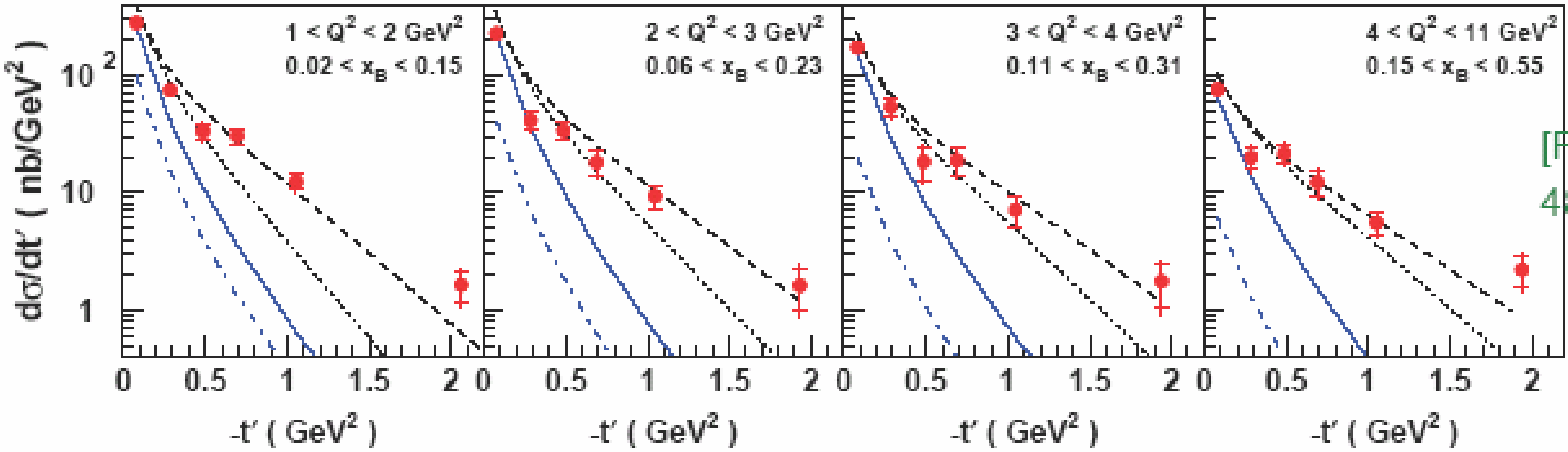
Experimental results



Many results
on exclusive meson production…

… here only one example

Exclusive π⁺ differential cross section



[PLB659, 486(2008)]

GPD model for $\frac{d\sigma_L}{dt'}$

[VGG PRD60(1999)094017]

– · – LO —— with power corr's

- $\widetilde{E}$ dominated by pion pole F_π
- $\widetilde{H}$ neglected
- Regge-inspired t dependence for $\widetilde{E}$
- power corrections due to intrinsic $k_\perp$ and soft-overlap contribution

⇒ Power corrections are needed! Fair agreement with data only at lower t'

Regge model

[J.M.Laget PRD70(2004)054023]

– – – – $\frac{d\sigma}{dt}$ · · · · · $\frac{d\sigma_L}{dt}$

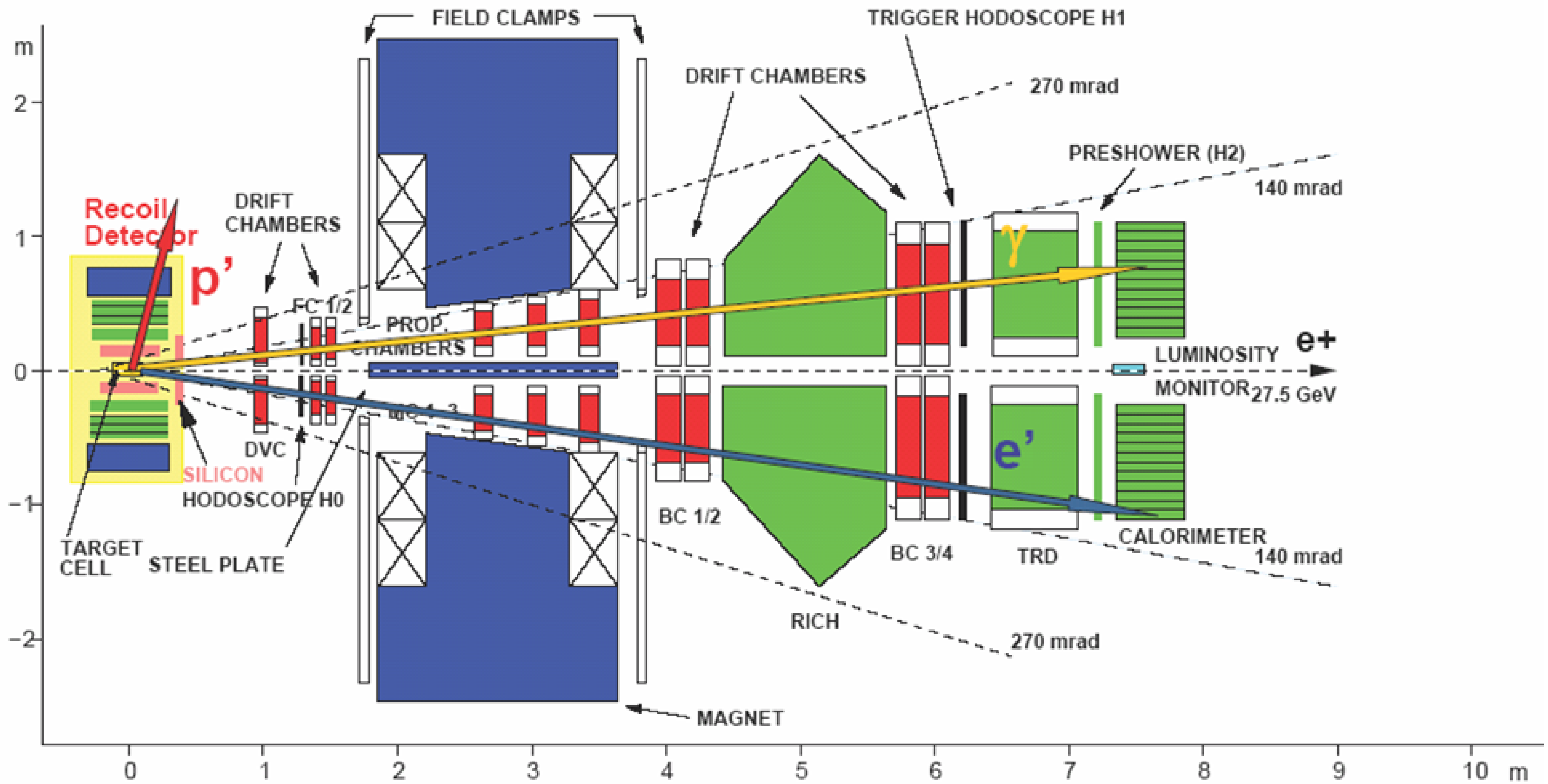
- π^+ production described by exchange of π and ρ Regge trajectories
- Q^2 and t' dep. FFs for $\pi\pi\gamma$ and $\pi\rho\gamma$
- σ_T predicted to be 15-25% of σ (about 6% at low t')

⇒ Good description of magnitude and $-t'$, Q^2 dependences of the data

HERMES recoil detector

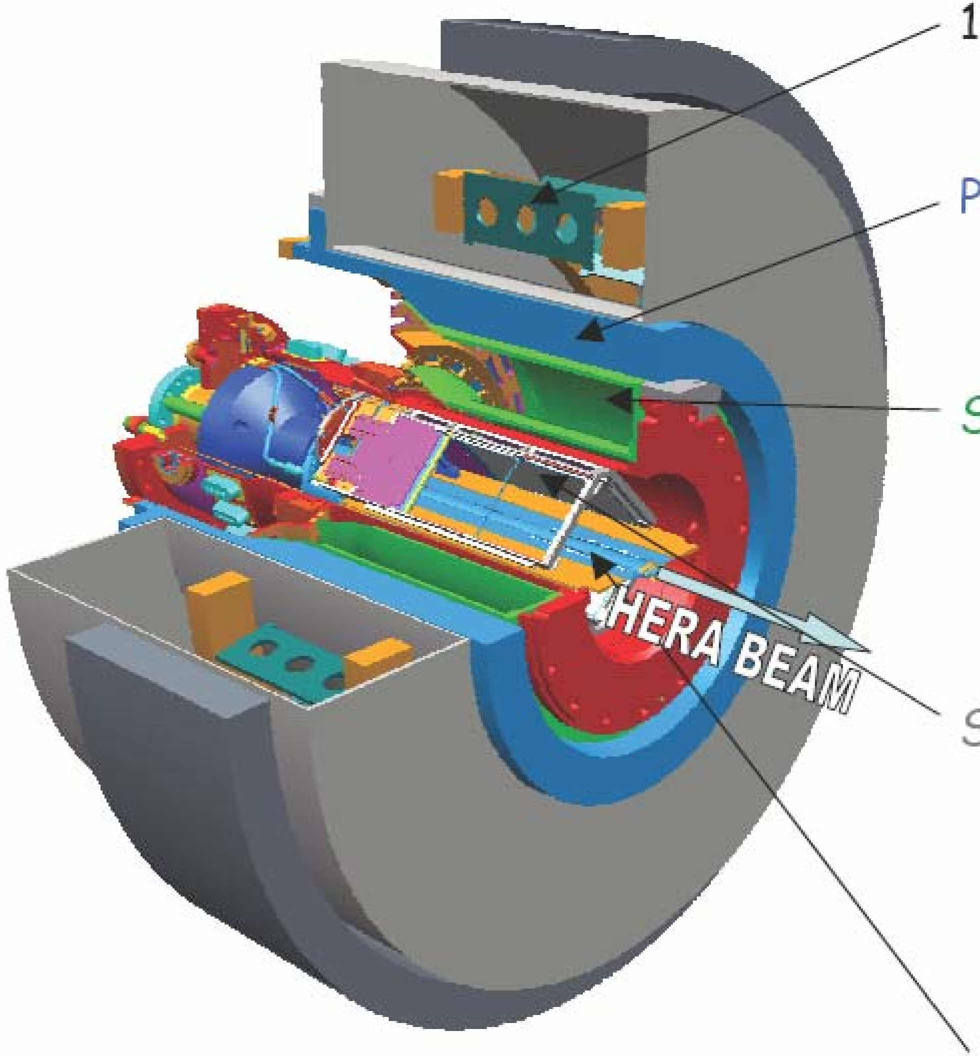
Hard exclusive scattering

Hermes with recoil detector



- Unpolarized hydrogen target: 38 Mio DIS (41.000 DVCS)
- Unpolarized deuterium target: 10 Mio DIS (7.500 DVCS)
- Two beam helicities, electron and positron beams

HERMES recoil detector



1 Tesla Superconducting Solenoid

Photon Detector (PD)

- 3 layers of tungsten-scintillator detect gammas, p/π PID

Scintillating Fiber Tracker (SFT)

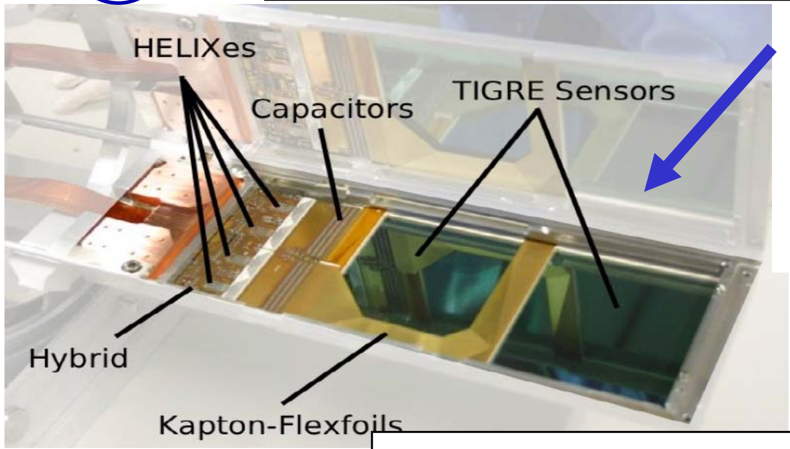
- 2 barrels of scintillation fibers with 2 parallel and 2 stereo layers
- Momentum reconstruction by bending in magnetic field

Silicon Strip Detector (SSD)

- Momentum reconstruction by energy deposit for low-momentum protons and deuterons
- Inside the HERA vacuum

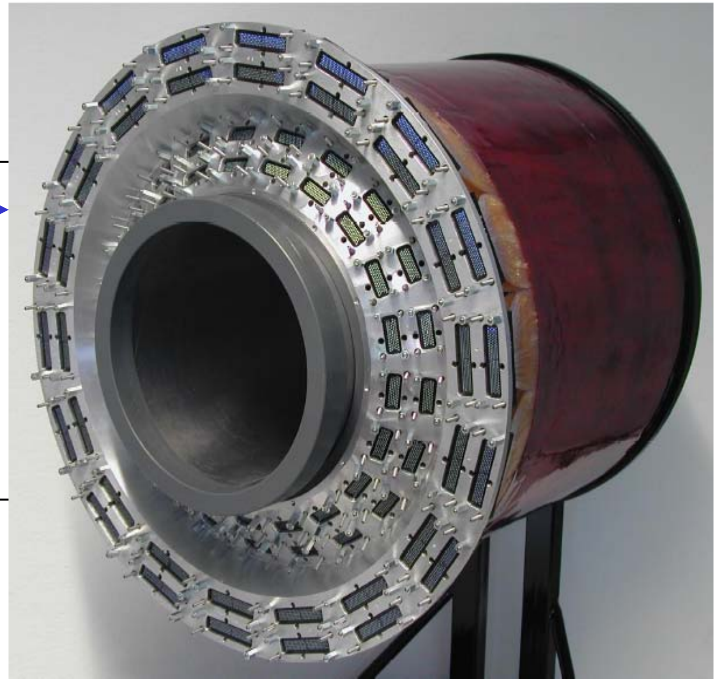
Target Cell of Unpolarized Target

Novel techniques: Recoil detector for exclusive physics



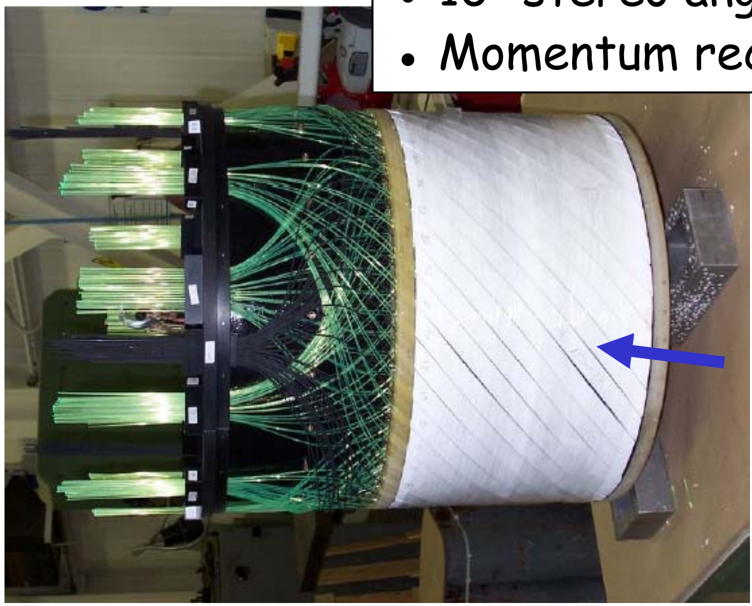
Silicon Detector

- Inside beam vacuum
- 16 double-sided sensors
- Momentum reconstruction & PID



Scintillating Fiber Detector

- 2 barrels
- 2x2 parallel and 2x2 stereo layers
- 10° stereo angle
- Momentum reconstruction & PID

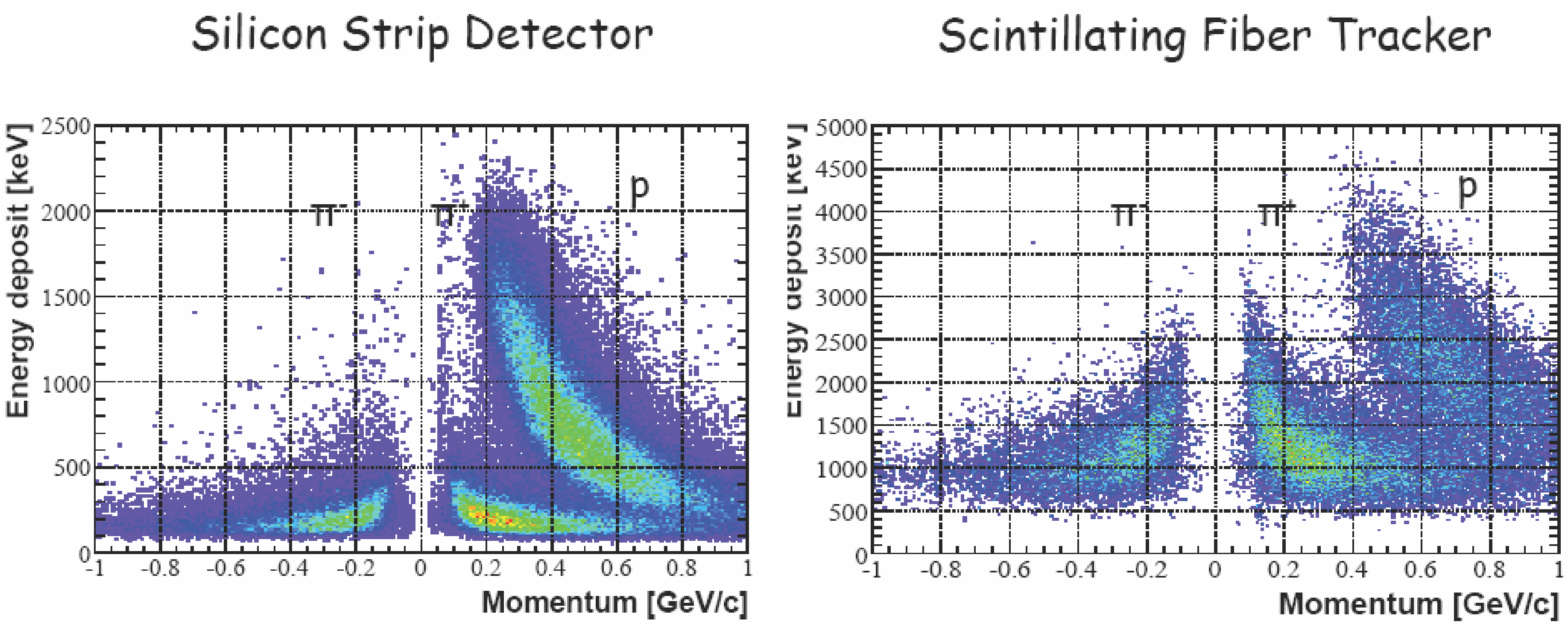


1 Tesla superconducting solenoid

Photon Detector

- 3 layers of tungsten/scintillator
- PID for higher momenta
- detects $\Delta^+ \rightarrow p\pi^0$

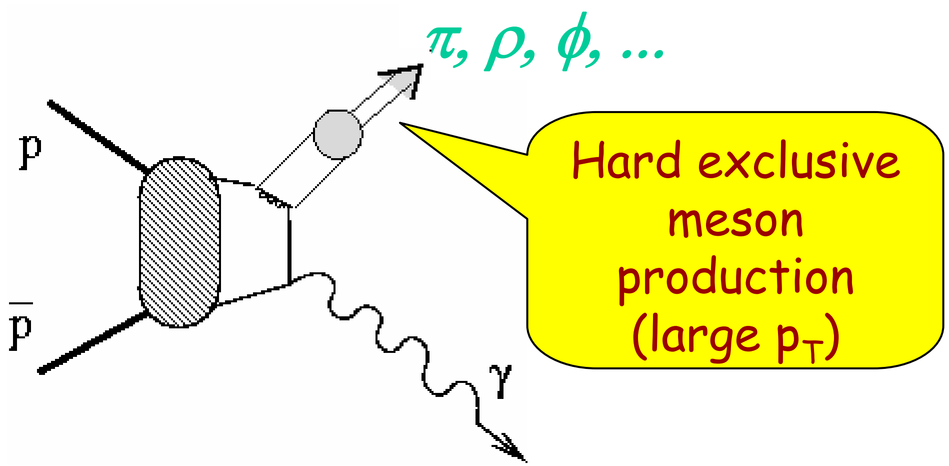
Recoil proton identification



Universality of the concept…

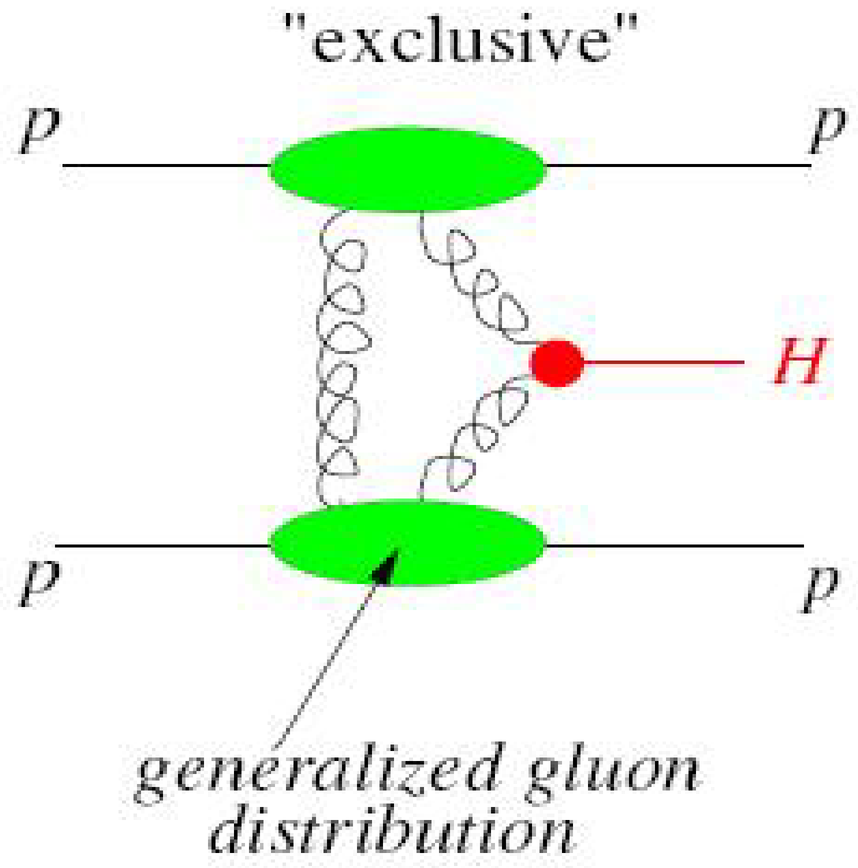
GPDs at FAIR

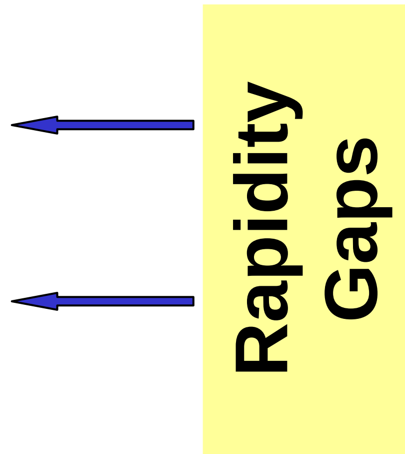
Handbag diagram at proton-antiproton annihilation
(e.g. PANDA/FAIR)
Generalized distribution amplitudes



GPDs at LHC

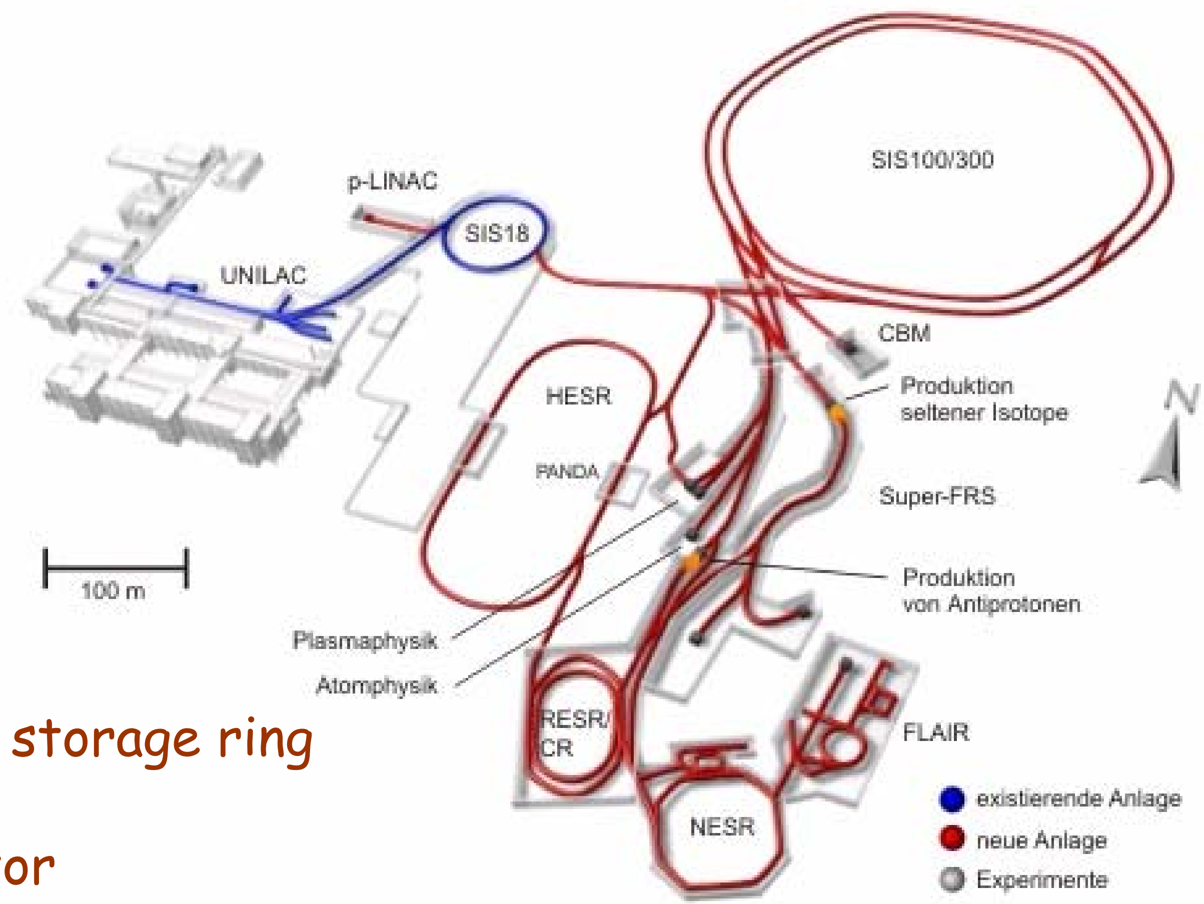
diffraktive Higgs produktion





Measure multidimensional GPDs in detail

Now as HERA has been retired, we need a new polarized high luminosity e-p collider



e.g. at FAIR:
using the HESR proton storage ring
(+ e.g. MAMI + ELSA)
and the PANDA detector

Conclusions and Outlook

- New concepts of GPDs, Double Distributions, etc. are used to describe hard exclusive reactions, especially DVCS asymmetries
- HERMES and JLab have done first explorative measurements of the orbital angular momentum of quarks in the proton
- Results are consistent with models of the nucleon and with lattice QCD calculations
- New exclusive data from HERMES using the recoil detector are being analyzed
- GPDs are also important for experiments at FAIR and LHC
- A precision mapping of GPDs requires a polarized high luminosity ep-collider, e.g. at FAIR