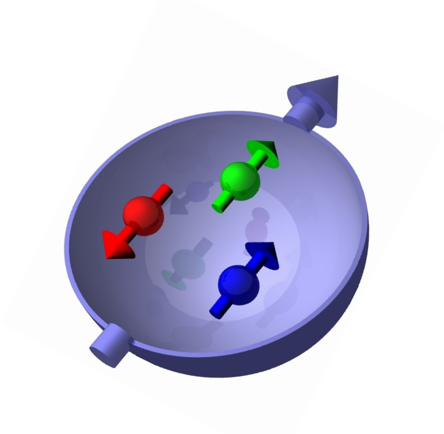

Are GPDs universal? Experimental Access at HERMES, PANDA and ATLAS

Michael Düren

Universität Gießen

— Int. School of nuclear physics, Erice, Sept. 17, 2011 —

PS: I was here last time in 1999 talking about HERMES…

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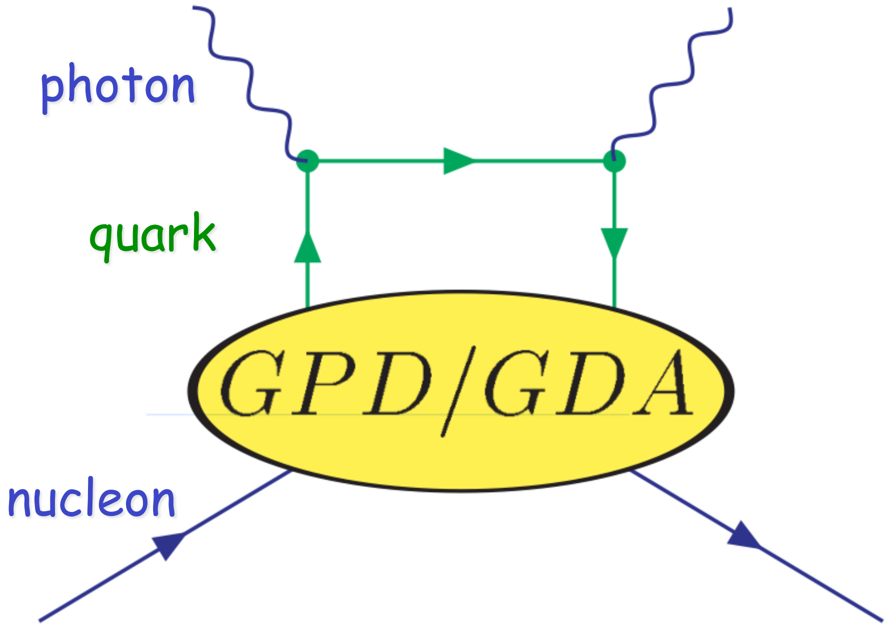
Generalized Parton Distributions

Quantum phase-space „tomography"
of the nucleon

Generalized Parton Distributions
and Generalized Distribution Amplitudes

GPDs and GDAs describe quarks and gluons in the nucleon

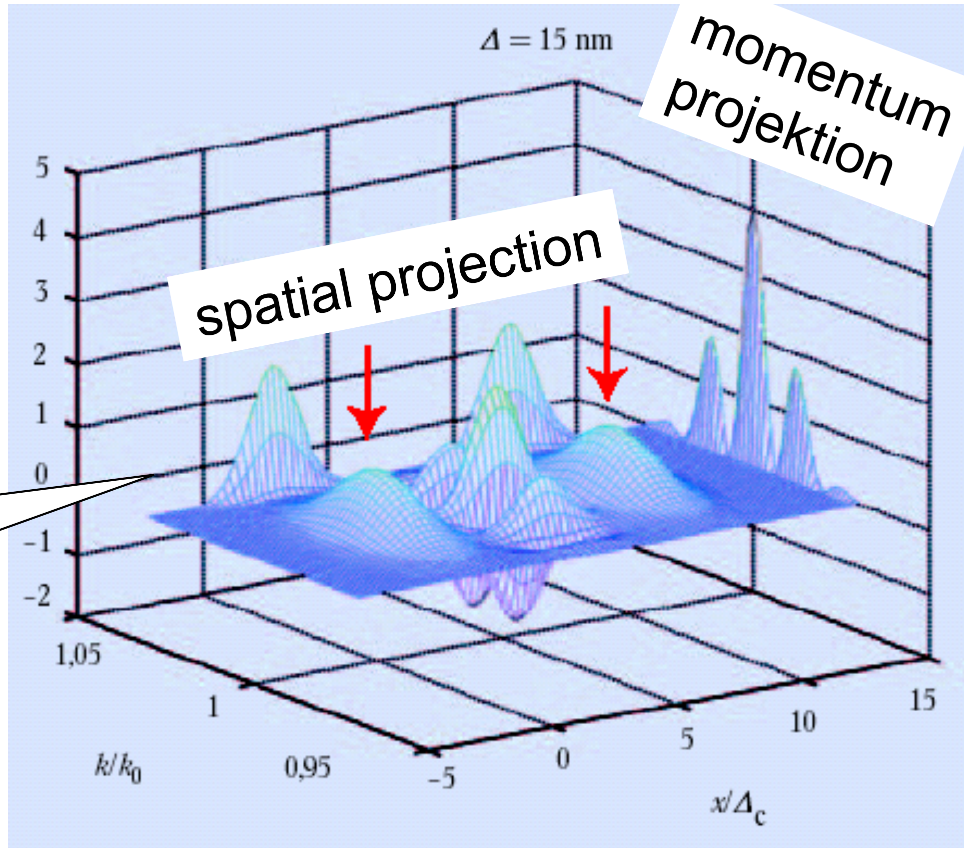


- spatial distributions (Form Factors)
- momentum distributions (Structure Functions)
- correlations in phase space (Wigner Distribution)
- spin and orbital angular momentum (Ji Sum Rule)

Wigner distribution in QM phase-space

- Wigner introduced the first well-defined phase-space distribution in quantum mechanics (1932)
  (despite of the uncertainty principle)
- Wigner function: $W(x,p) = \int \psi^*(x-\eta/2)\psi(x+\eta/2)e^{ip\eta}d\eta$

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



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

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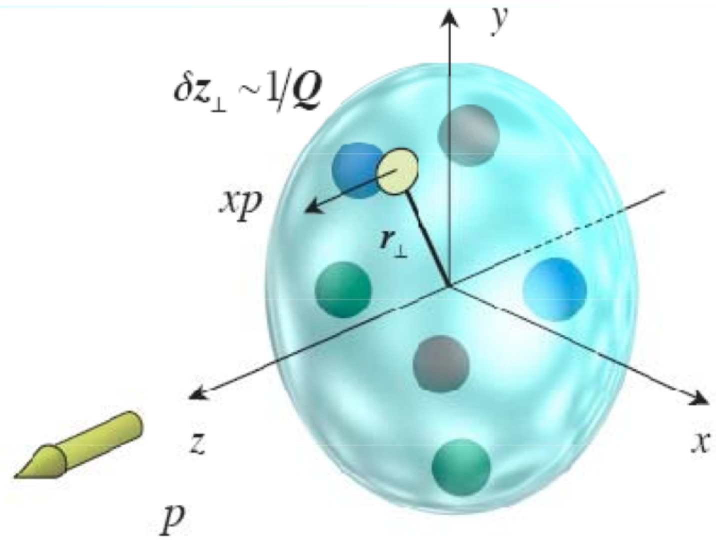
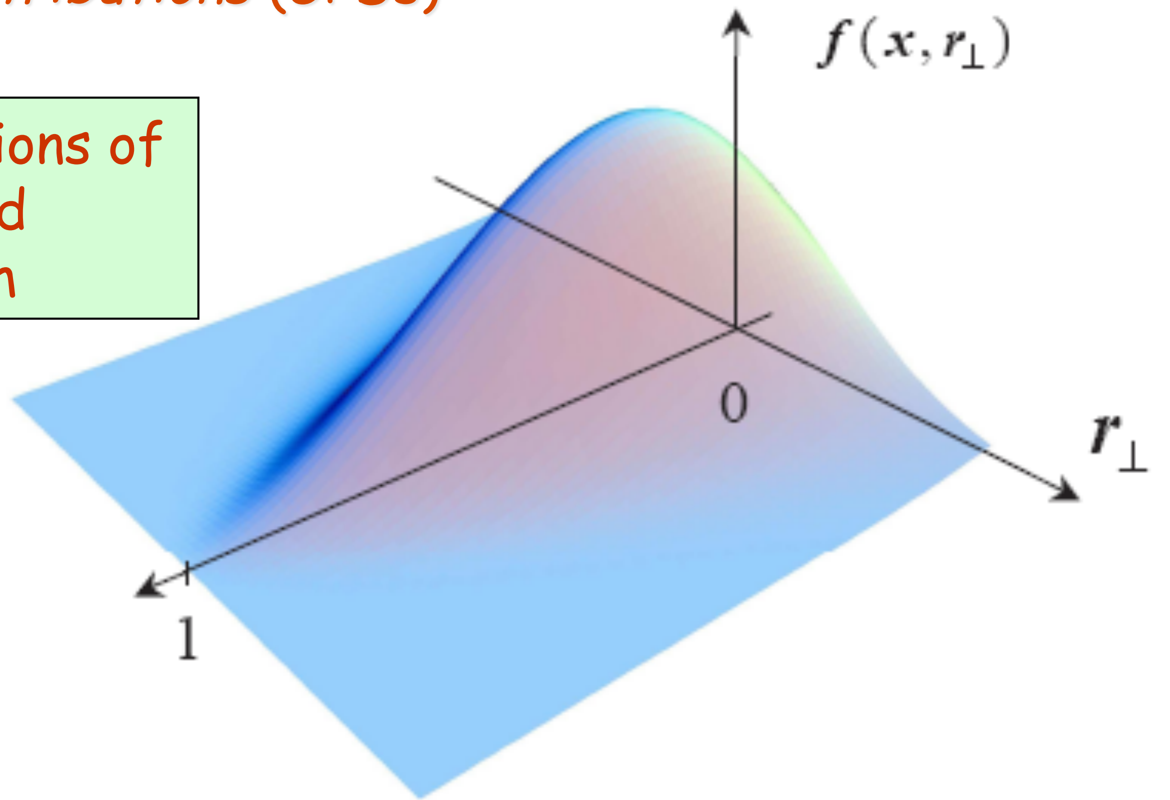
Generalized Parton Distribution

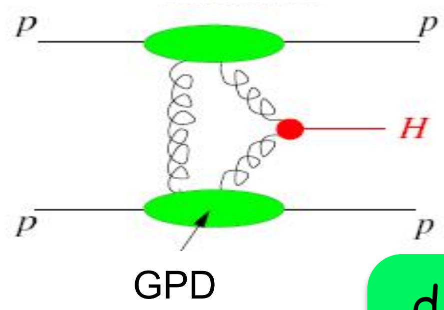
- A Wigner operator can be defined that describes quarks and gluons in the nucleon
- The reduced Wigner distribution is related to *Generalized Parton distributions* (GPDs)

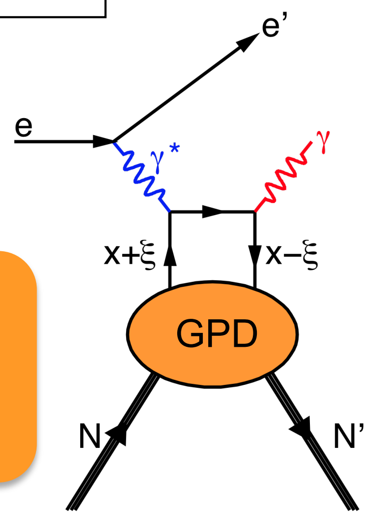
GPDs describe e.g. correlations of transverse position and longitudinal momentum





Are GPDs/GDAs universal?





deep inelastic scattering

diffractive higgs production

deeply virtual Compton scattering

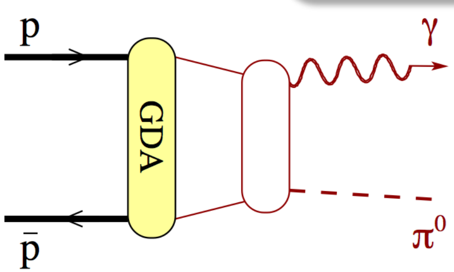
holographic picture of quarks in the nucleon

proton-antiproton annihilation

form factors

exclusive meson production

timelike Compton scattering



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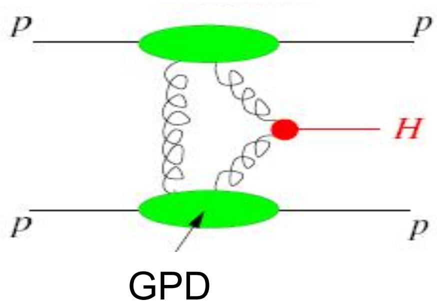
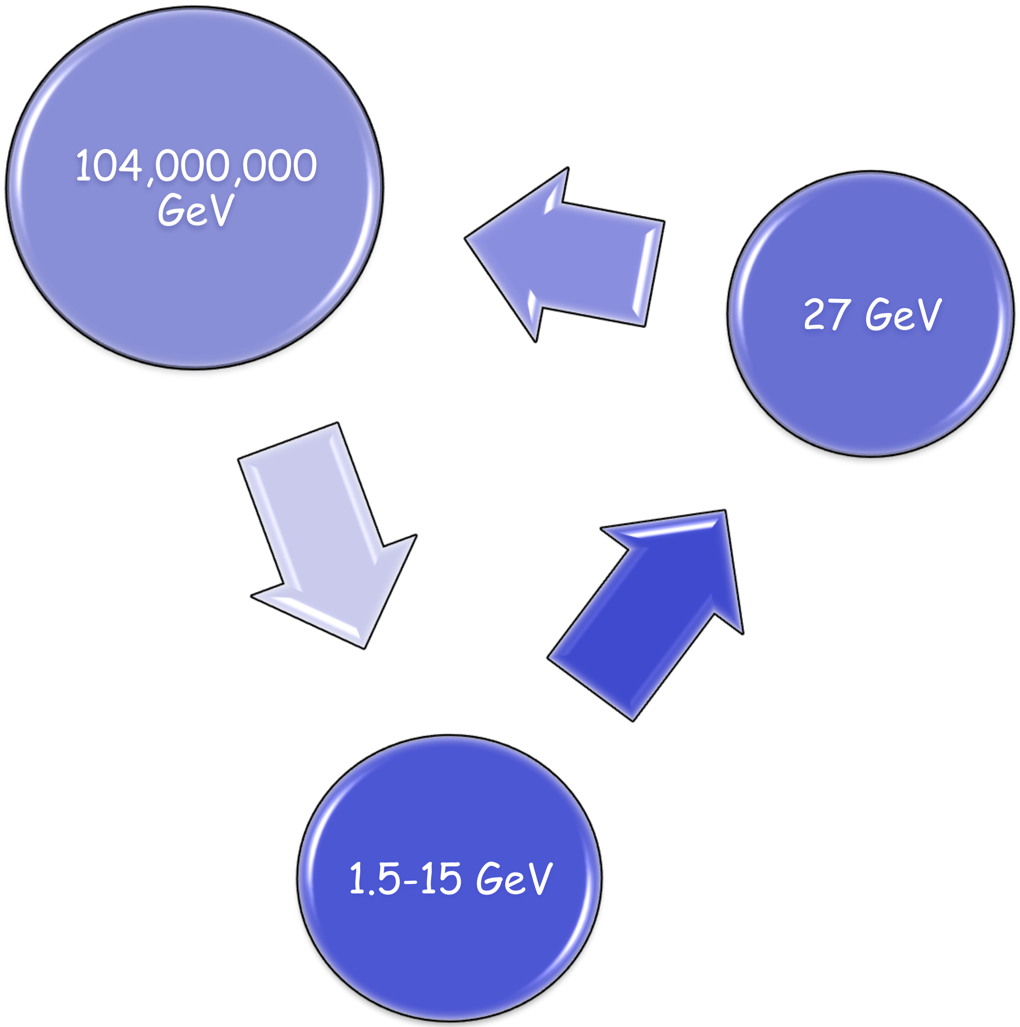
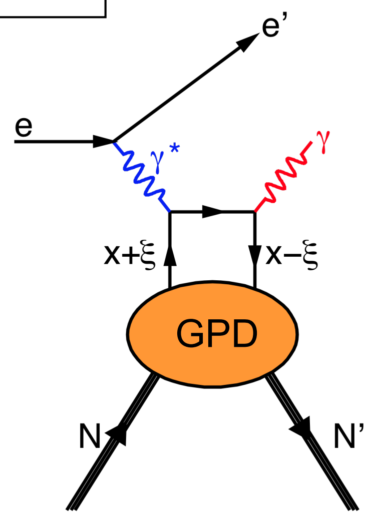
Are GPDs/GDAs universal?



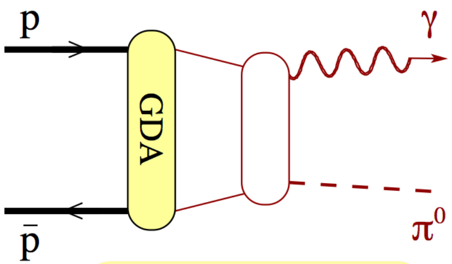
ATLAS/AFP
CERN



Energy of projectile
in proton rest frame



HERMES
DESY



PANDA
FAIR

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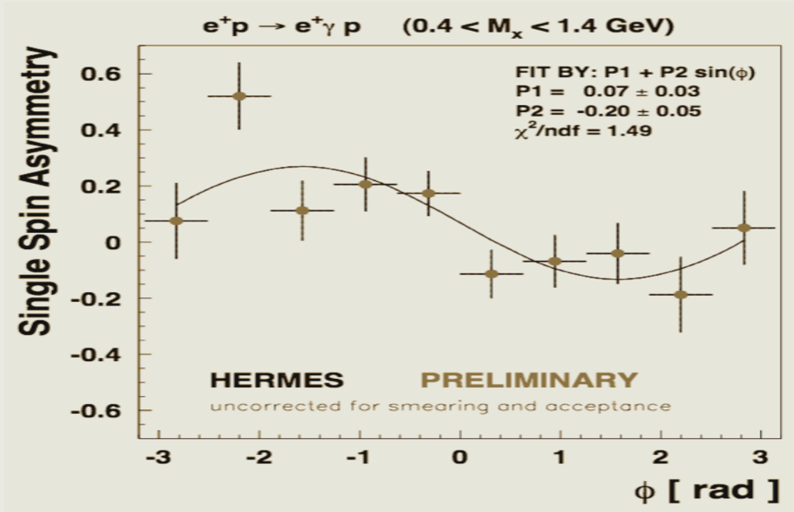
HERMES: a pioneering experiment

… from Ellis-Jaffe to Ji et al. …

The HERMES Experiment

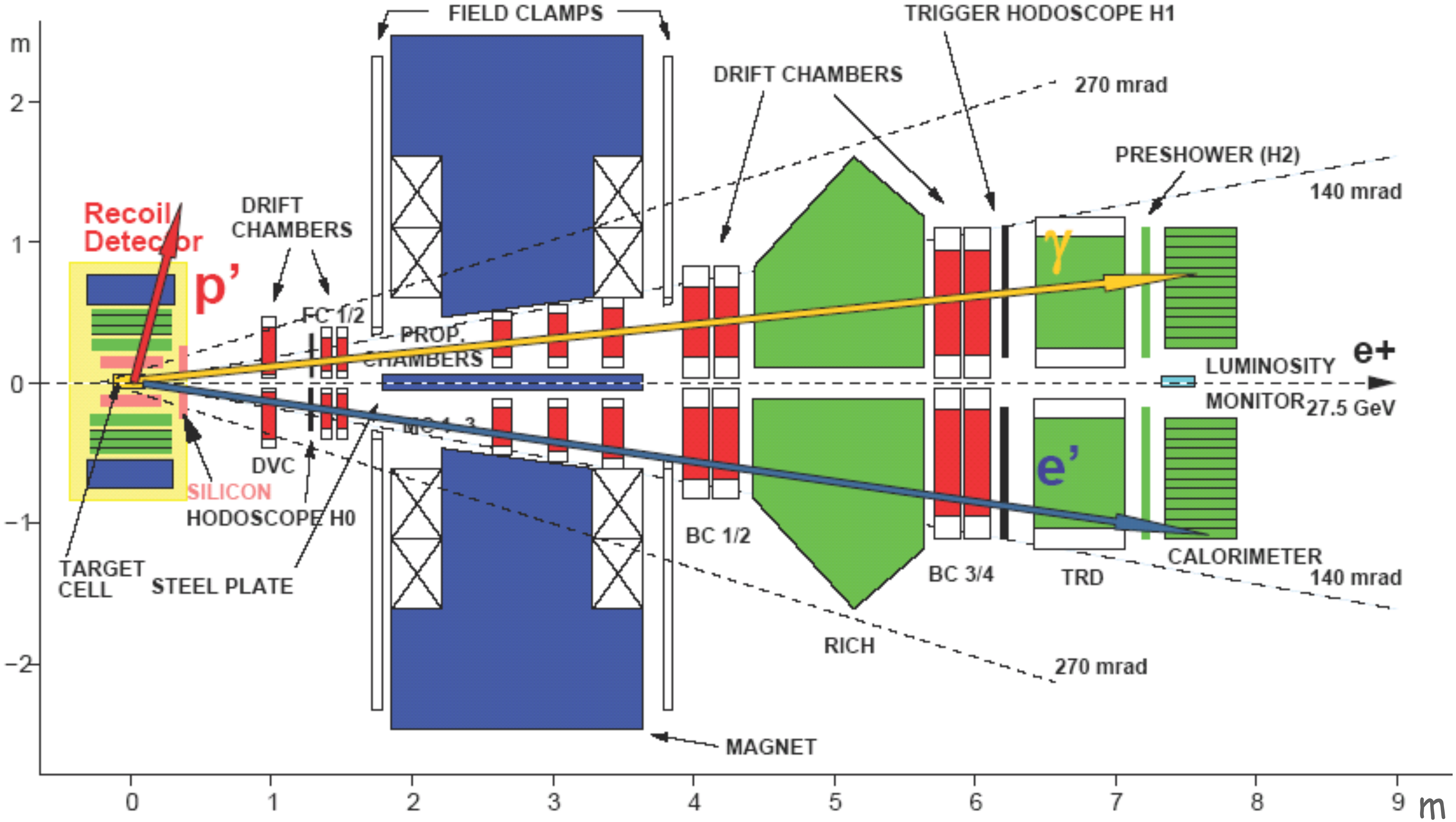
- Designed at times of the spin crisis
  - Ellis-Jaffe & Bjorken sum rule
  - strange quark polarization
- 12 years data taking 1995-2007
- Pioneering results of DVCS



First non-zero DVCS SSA (2000)

- Today: most complete experimental access:
  - charge reversal (e^+ and e^- beams)
  - beam spin reversal (both beam helicities)
  - target spin reversal (parallel, transverse, unpolarized)
  - target mass variation (H, D, He, N, Ne, Kr, Xe)
  - recoil and spectator proton detection
  - ...

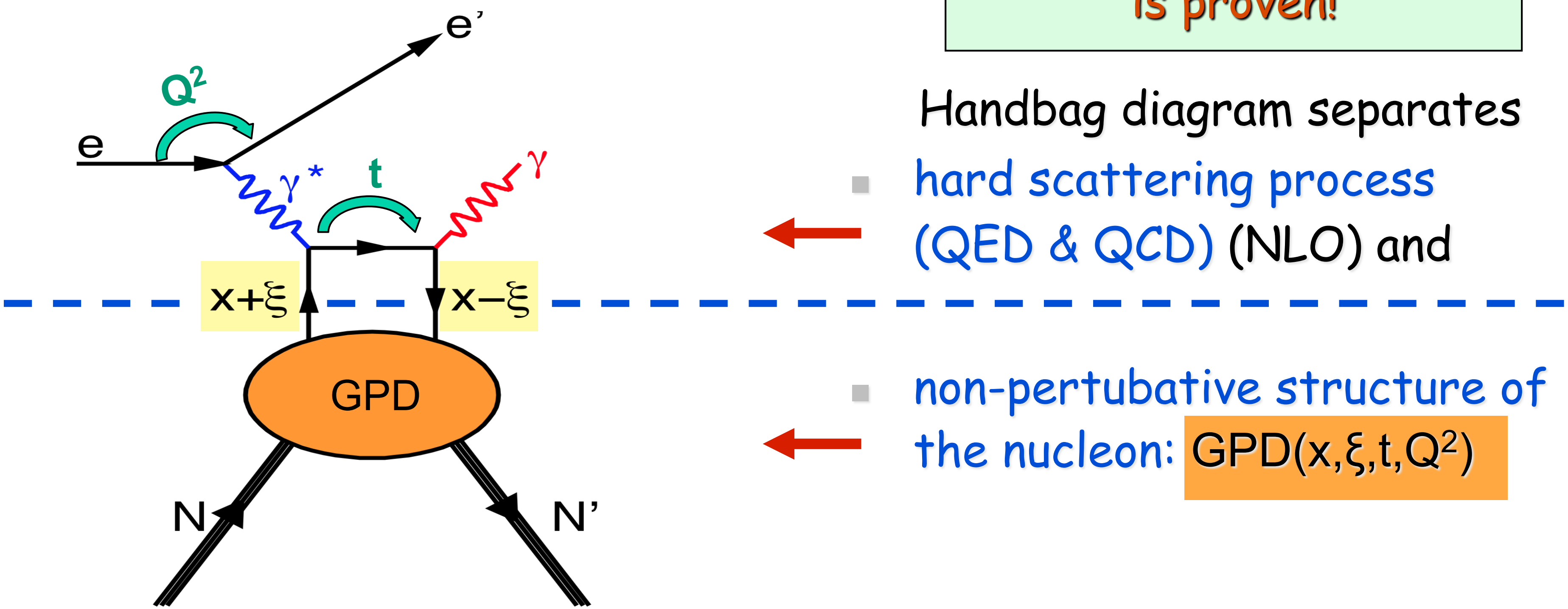
HERMES with recoil detection



Deeply Virtual Compton Scattering (DVCS)

DVCS is the cleanest way to access GPDs

Factorization theorem is proven!



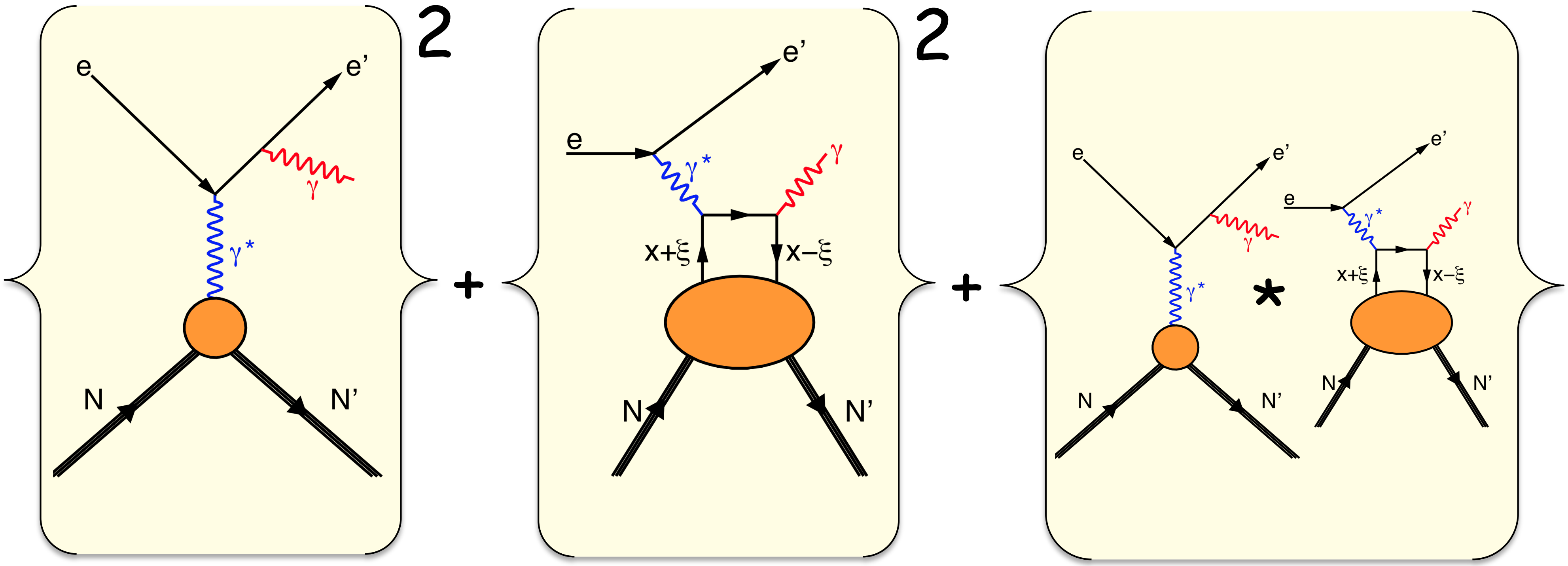
Handbag diagram separates

- hard scattering process (QED & QCD) (NLO) and
- non-pertubative structure of the nucleon: GPD(x,ξ,t,Q^2)

GPDs = probability amplitude for a nucleon to emit a parton with *x*+ξ and to absorb it with momentum fraction *x*-ξ

$$\xi \approx \frac{x_{Bj}}{2 - x_{Bj}}$$

Exclusive ep → epγ cross section at HERMES



BH: LARGE
+ known

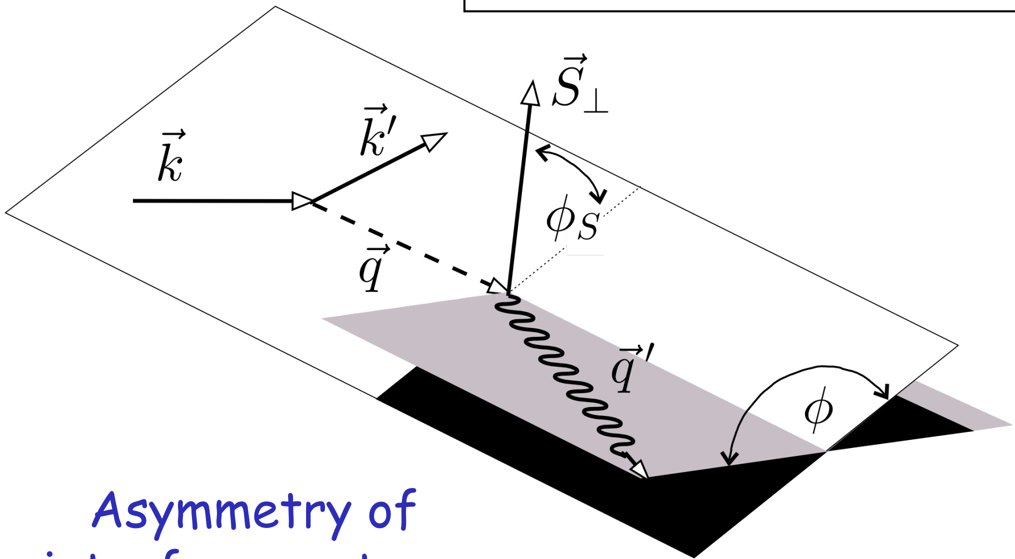
DVCS: small
+ unknown

Interference: medium
+ non-zero azimuthal
asymmetries

$$\frac{d\sigma}{dx_B\, dQ^2\, d|t|\, d\phi} = \frac{x_B\, e^6}{32\,(2\pi)^4\, Q^4\, \sqrt{1+\epsilon^2}} \left[|\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \overbrace{\tau_{DVCS}\, \tau_{BH}^* + \tau_{DVCS}^*\, \tau_{BH}}^{I} \right]$$

Direct access to DVCS matrix elements

Separation of amplitudes



- reversal of charge **and** spin

Asymmetry of interference term

$$\mathcal{A}_{\mathrm{LU}}^{\mathrm{I}}(\phi) \equiv \frac{(d\sigma^{+\rightarrow} - d\sigma^{+\leftarrow}) - (d\sigma^{-\rightarrow} - d\sigma^{-\leftarrow})}{(d\sigma^{+\rightarrow} + d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} + d\sigma^{-\leftarrow})}$$

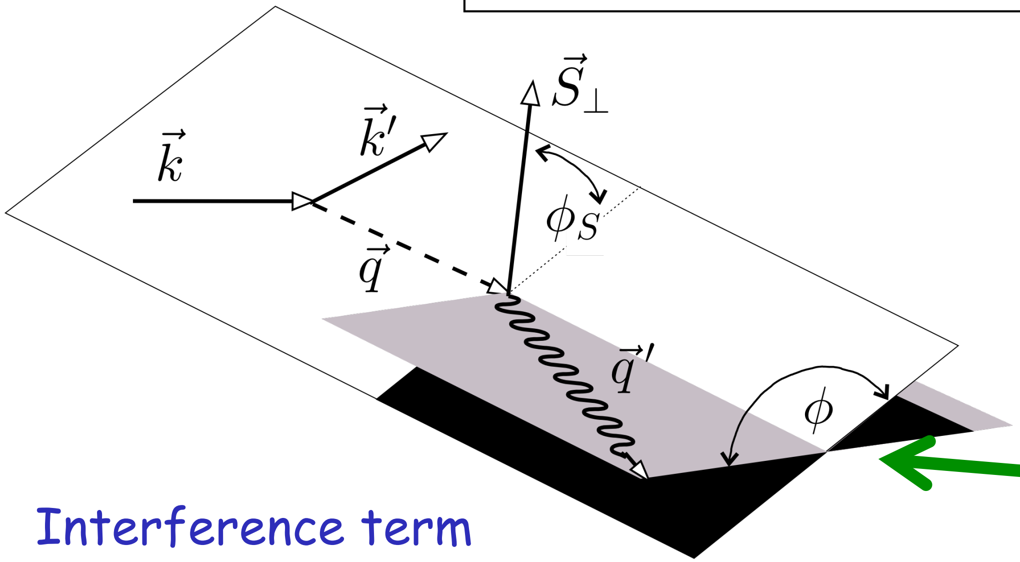
Asymmetry of DVCS

$$\mathcal{A}_{\mathrm{LU}}^{\mathrm{DVCS}}(\phi) \equiv \frac{(d\sigma^{+\rightarrow} - d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} - d\sigma^{-\leftarrow})}{(d\sigma^{+\rightarrow} + d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} + d\sigma^{-\leftarrow})}$$

longitudinal beam spin

unpolarized target spin

Separation of amplitudes



- reversal of charge **and** spin
- Fourier analysis of **azimuthal** modulation

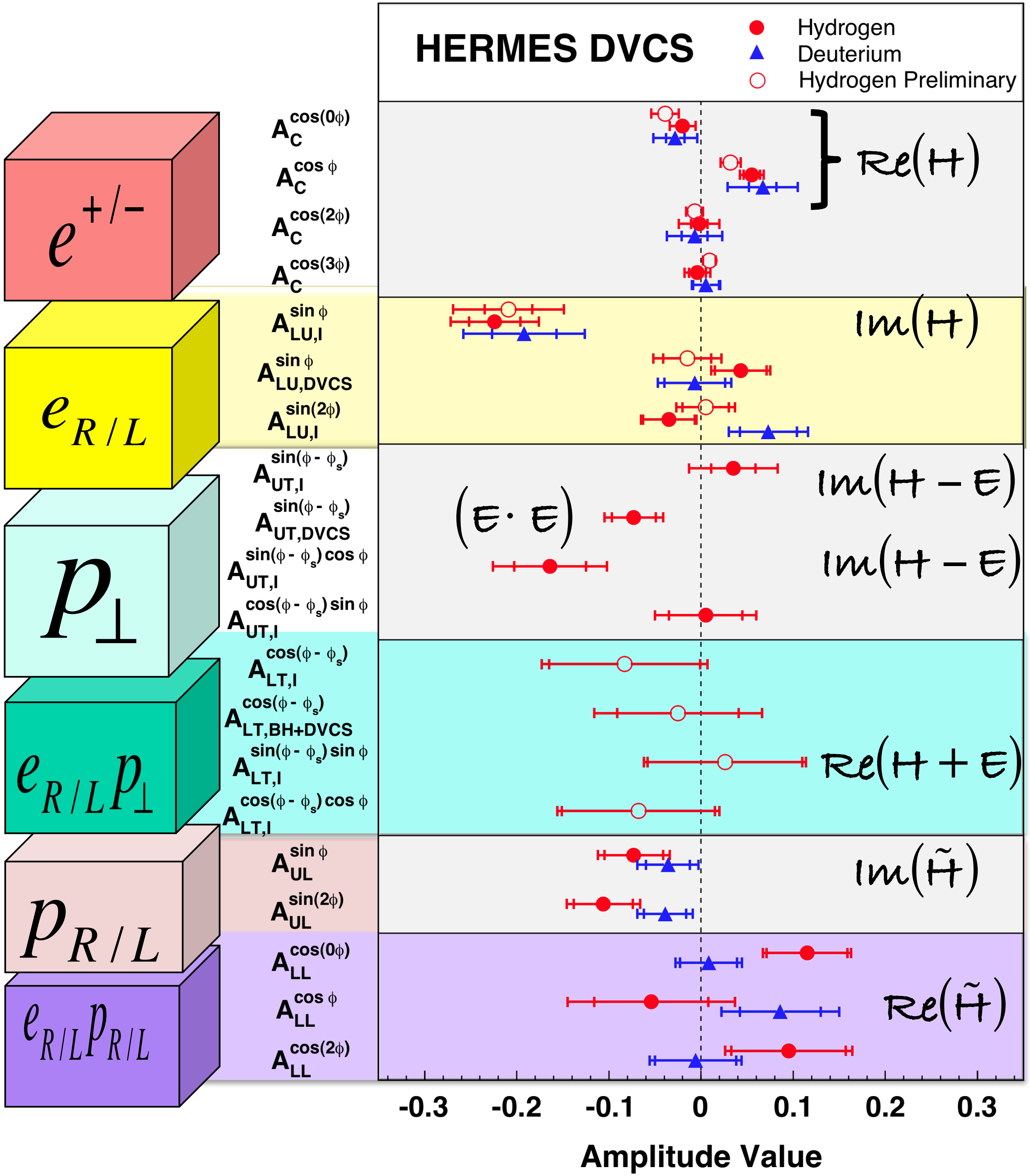
Interference term asymmetrie

$$\mathcal{A}^{\rm I}_{\rm LU}(\phi) \equiv \frac{(d\sigma^{+\rightarrow} - d\sigma^{+\leftarrow}) - (d\sigma^{-\rightarrow} - d\sigma^{-\leftarrow})}{(d\sigma^{+\rightarrow} + d\sigma^{+\leftarrow}) + (d\sigma^{-\rightarrow} + d\sigma^{-\leftarrow})}$$

$$= \frac{-\frac{K_{\rm I}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left[\sum_{n=1}^{2} s_n^{\rm I} \sin(n\phi)\right]}{\frac{K_{\rm BH}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\sum_{n=0}^{2} c_n^{\rm BH}\cos(n\phi) + \frac{1}{Q^2}\sum_{n=0}^{2} c_n^{\rm DVCS}\cos(n\phi)}$$

Fourier coefficients

Access to GPD H, $\tilde{H}$, E



- JHEP 11 (2009) 083
- Nucl. Phys. B829

sensitive to J_u

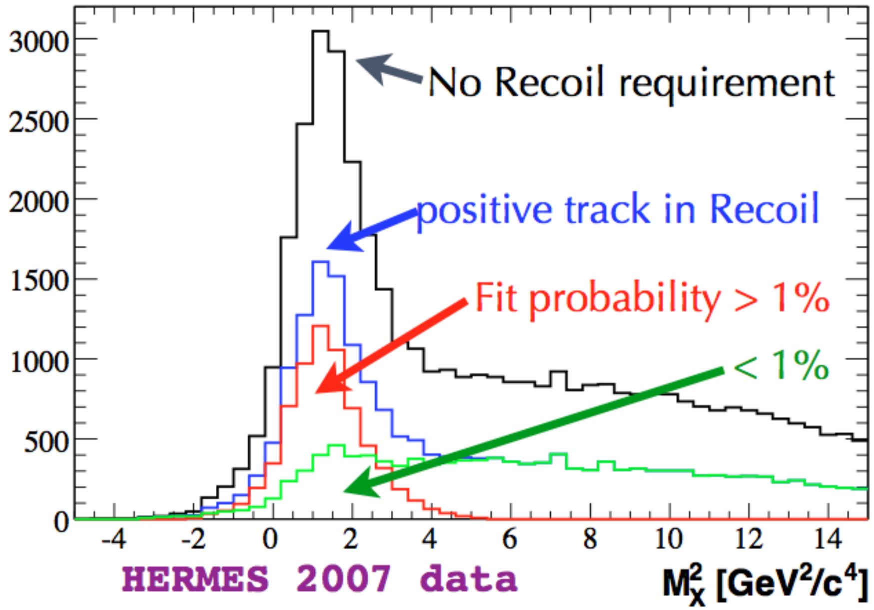
- JHEP 06 (2008) 066

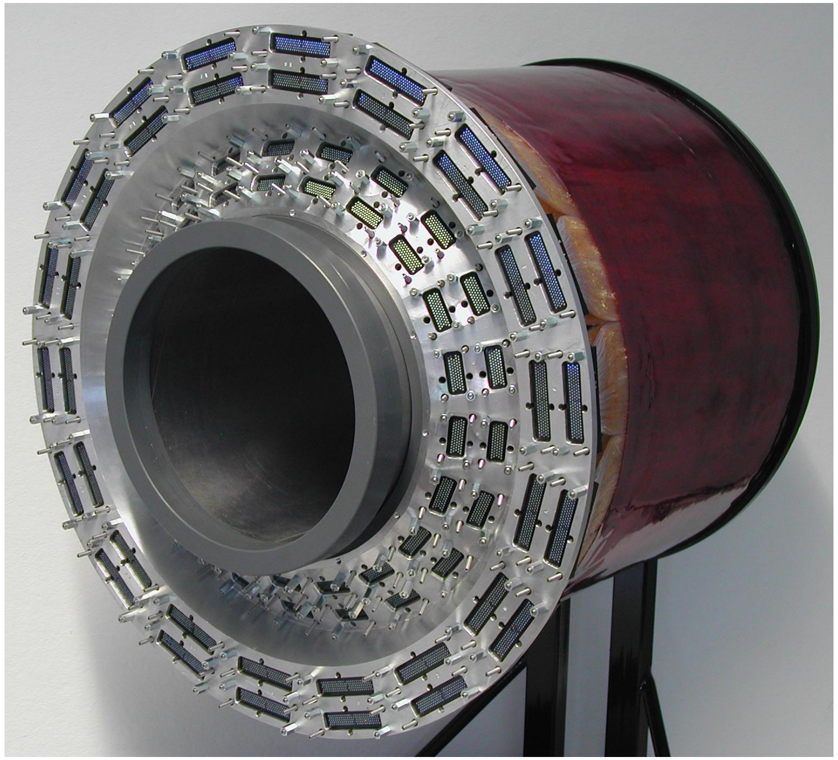
- Phys. Lett. B 704 Oct. 5, 2011

- JHEP 06 (2010) 019
- Nucl. Phys. B 842

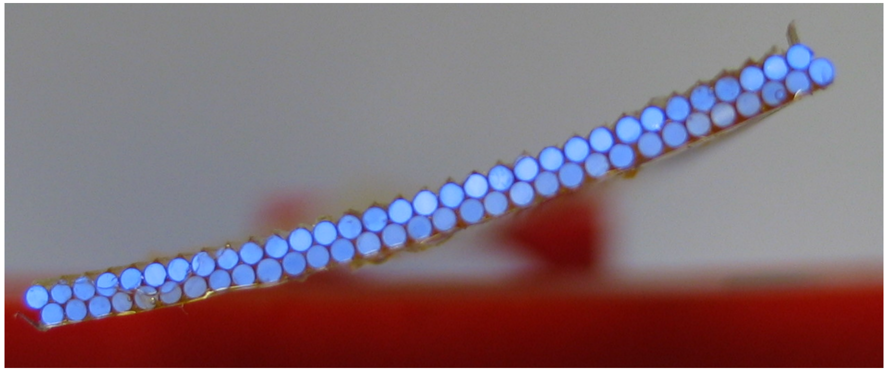
HERMES recoil detector

- Kinematic fit of complete DVCS event: $ep \rightarrow e'p'\gamma$
  - e': spectrometer
  - γ: calorimeter
  - p': recoil detector
- >99.9% purity





Recoil fibre detector made in Giessen



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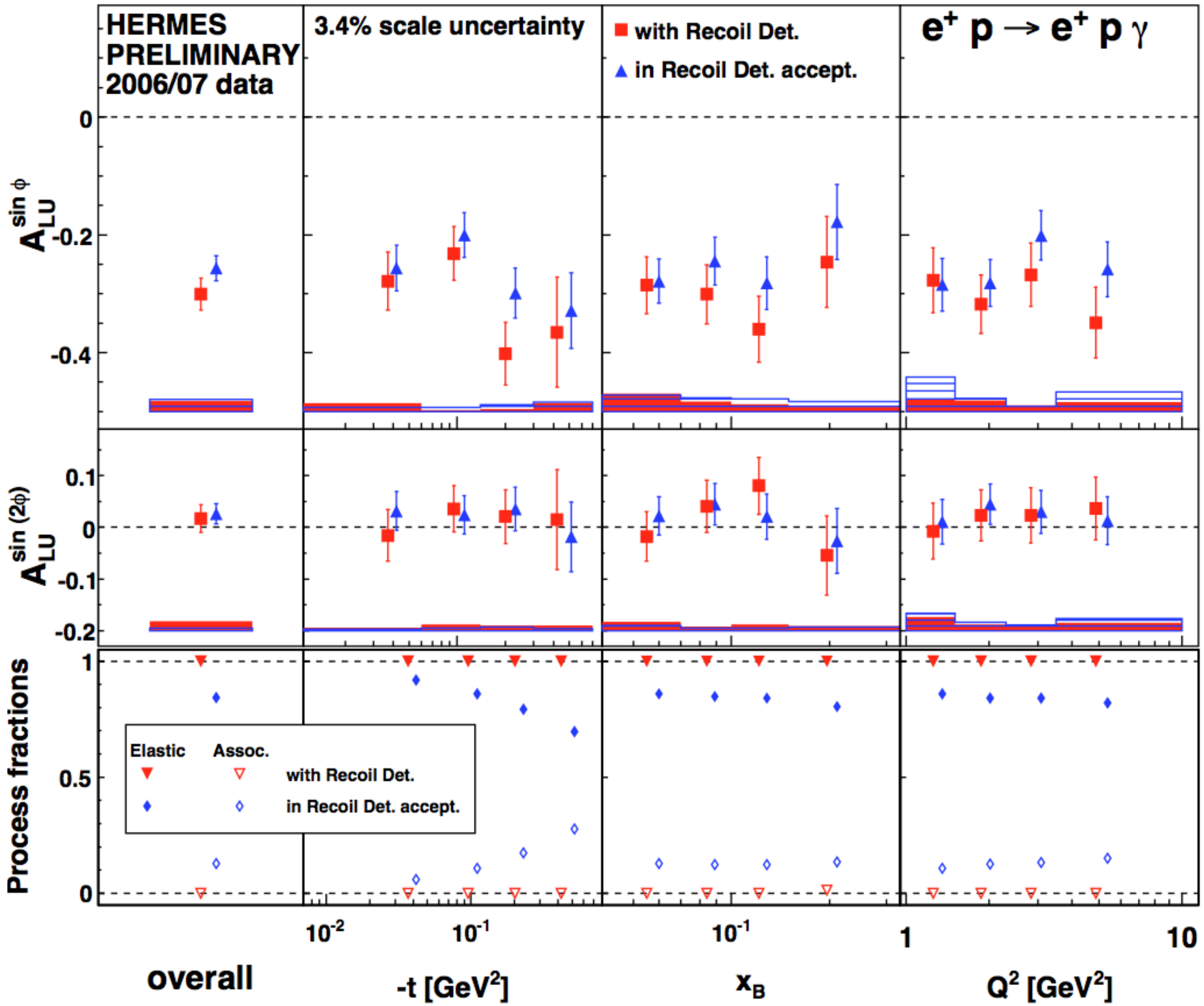
Beam helicity asymmetry with/without recoil detection



HERMES: $\langle Q^2 \rangle=2.46$ GeV², $\langle x_B \rangle=0.10$, $\langle -t \rangle=0.12$ GeV²

- Indication of A(ep→epγ) > A(no Recoil).
- Extraction of A(resonant) subject of an ongoing dedicated analysis.

fraction of
ep→ep γ

ep→eΔ γ

HERMES: Conclusion and Outlook

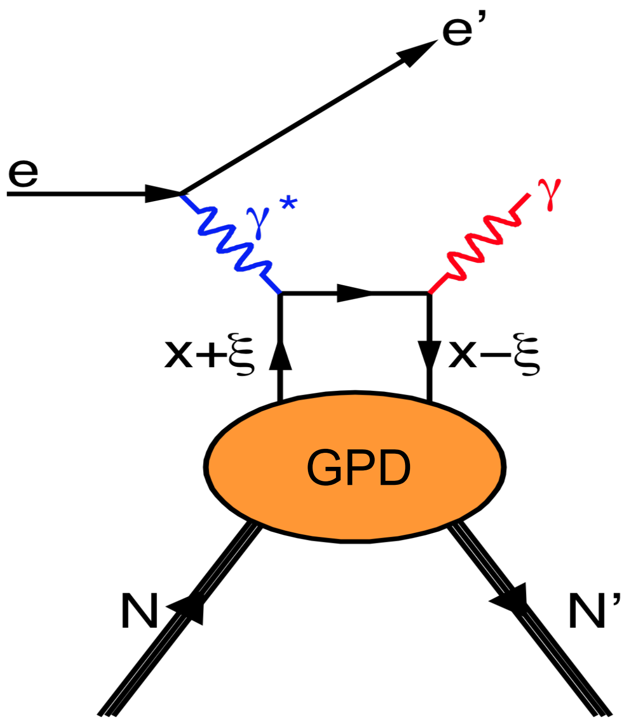
- GDPs are THE access to the nucleon structure
- HERMES is a pioneering experiment of DVCS
- Many more results from HERMES:
  - nuclear DVCS
  - exclusive meson production
  - …

PANDA: an experiment with time-reversed protons

… from spectroscopy to internal structure…

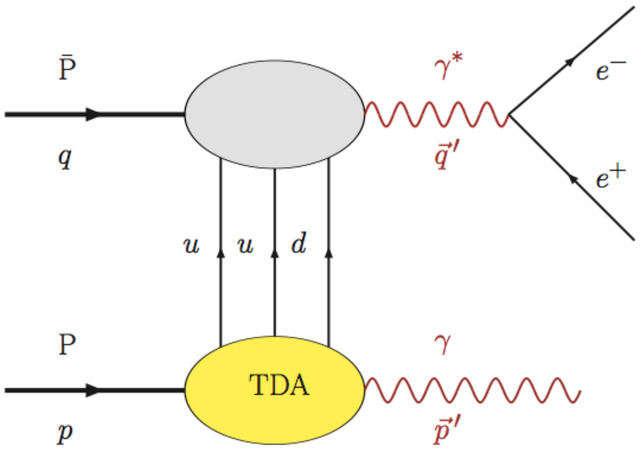
Time reversal / crossed diagrams

Scattering

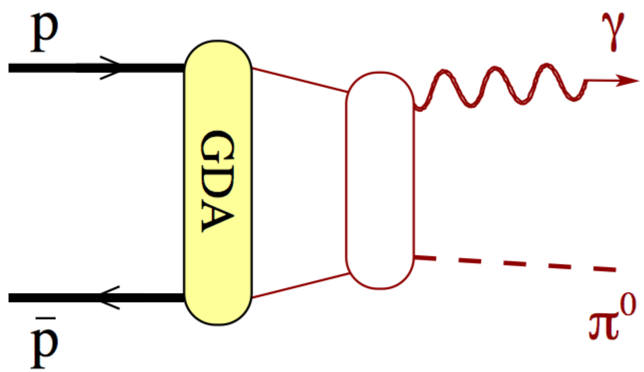


Generalized Parton Distributions

Annihilation

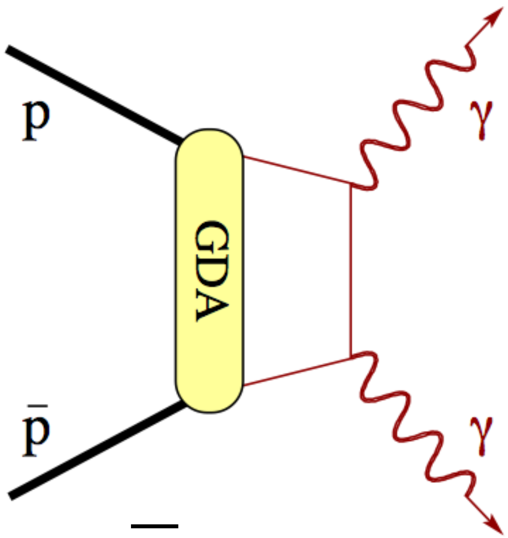


Transition Distribution Amplitudes



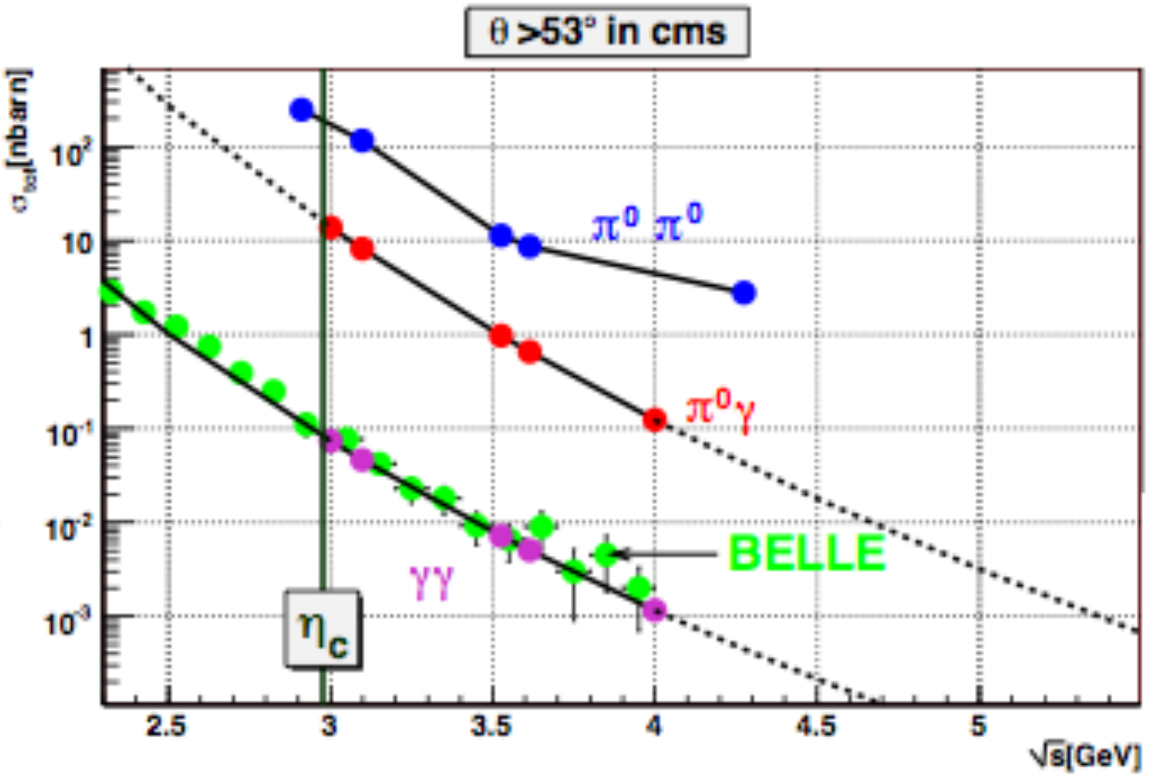
Generalized Distributions Amplitudes

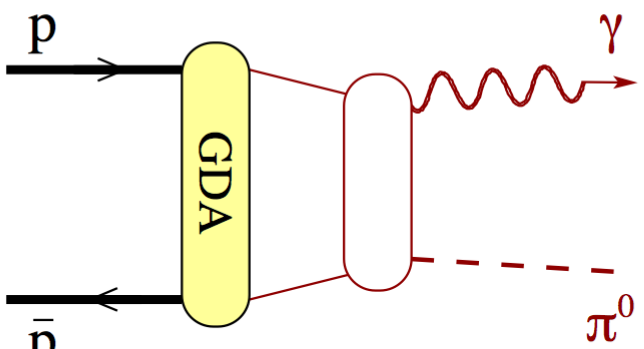
Measure GDAs at PANDA



$p\bar{p} \rightarrow \gamma\gamma$

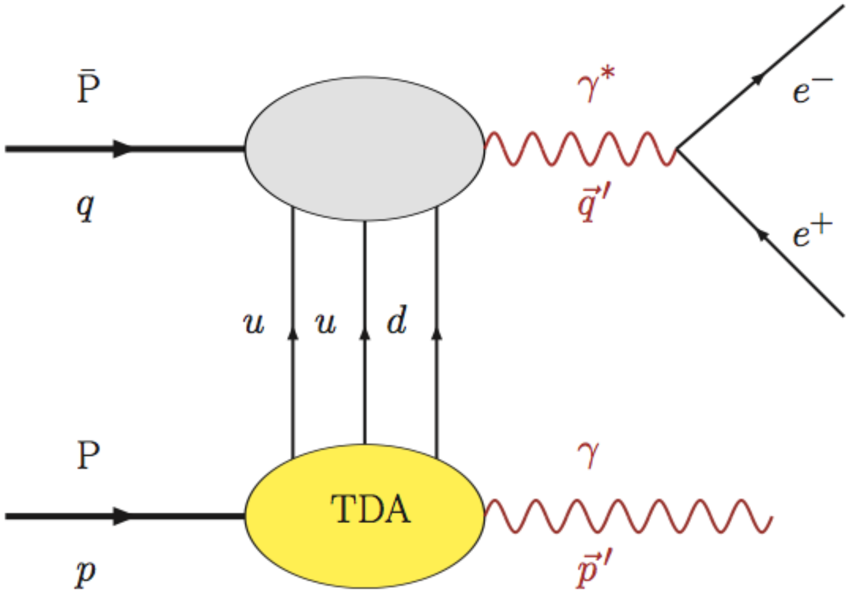
Predictions and simulations in the QCD handbag approach





$p\bar{p} \rightarrow \gamma\pi^0$

Another Ansatz: Transition Distribution Amplitudes (TDA)



$$p\bar{p} \rightarrow \gamma\gamma^* \rightarrow \gamma\, e^+e^-$$

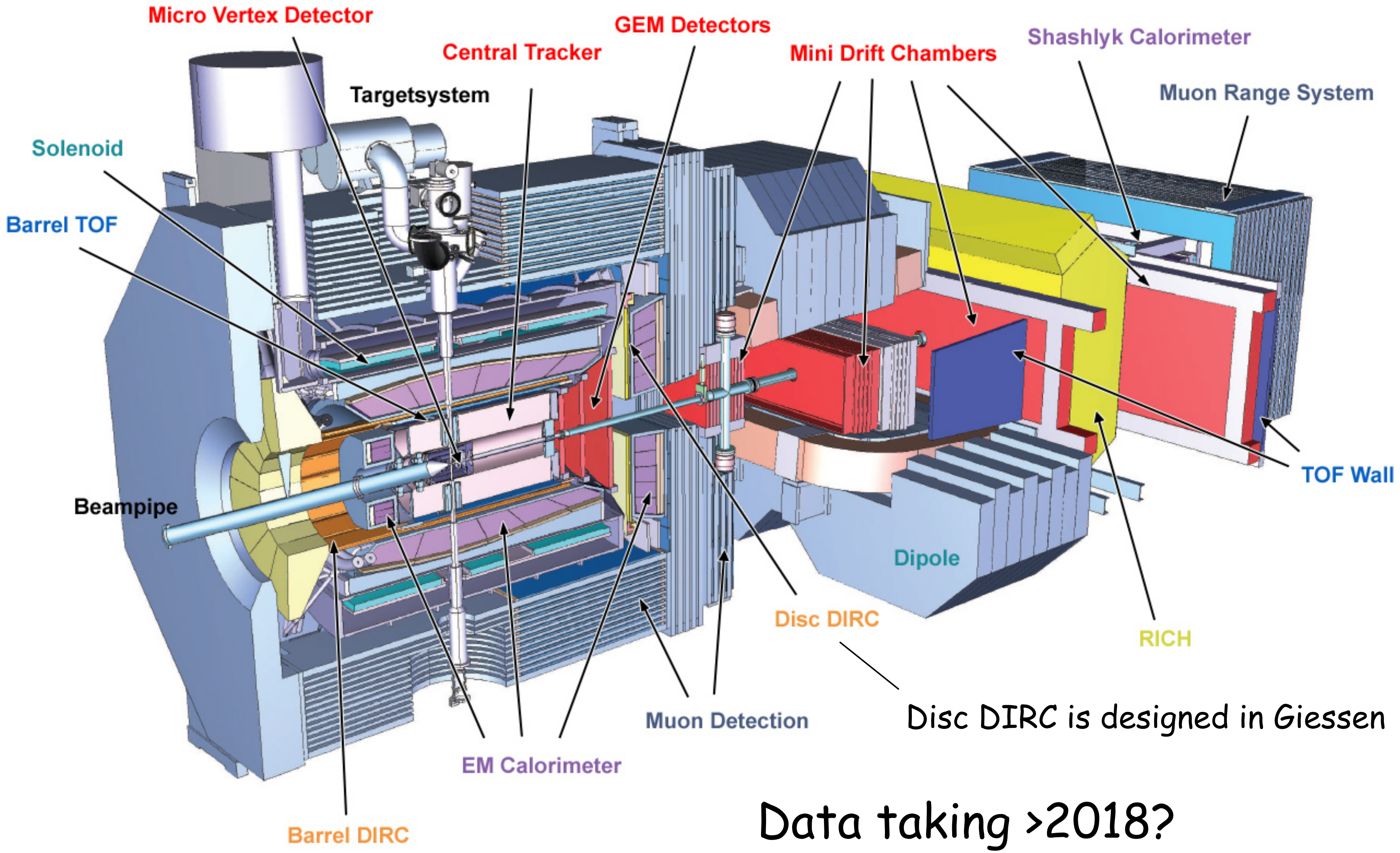
and

$$p\bar{p} \rightarrow \pi^0\gamma^* \rightarrow \pi^0\, e^+e^-$$

Whatever the theory is …

… PANDA should measure it

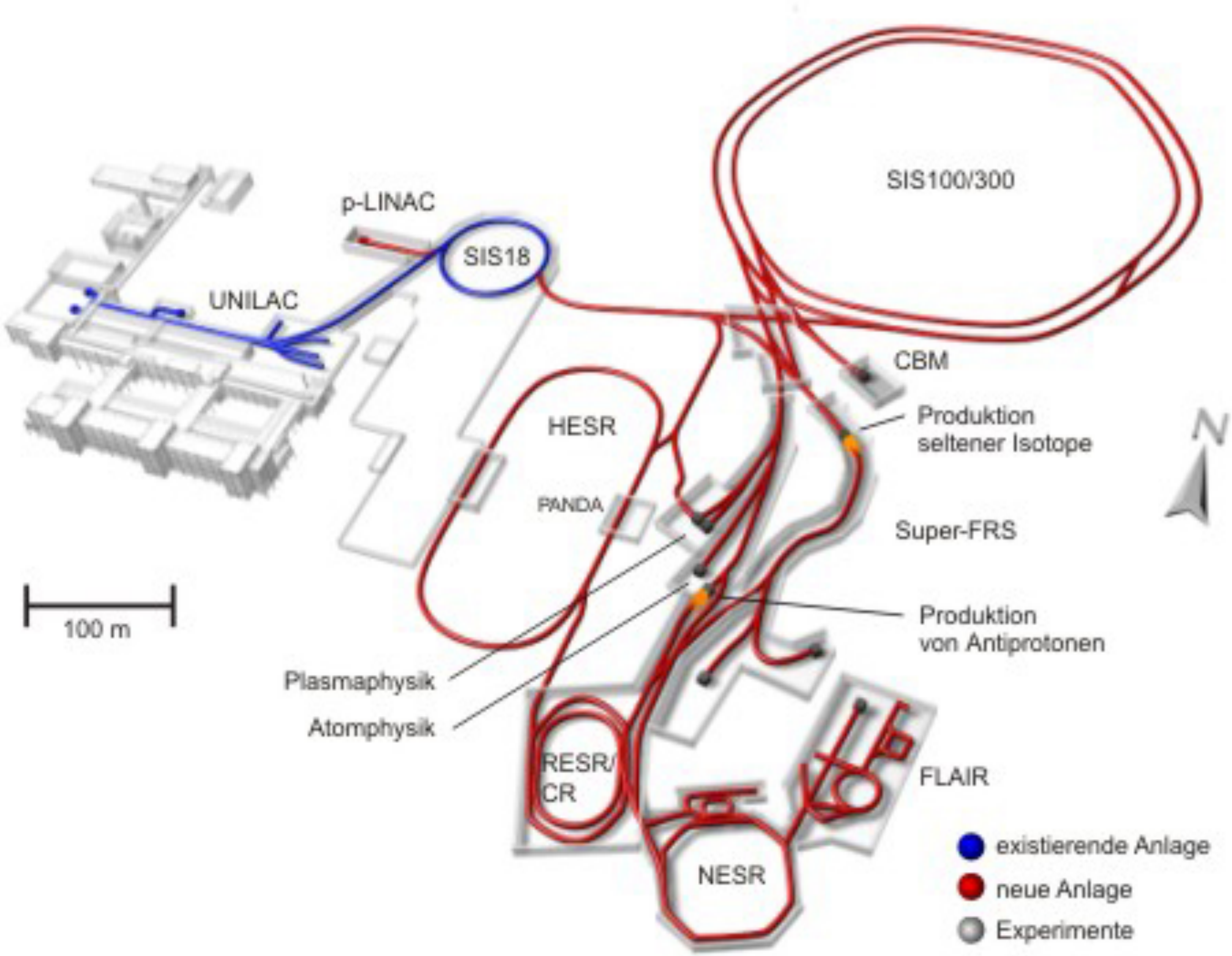
PANDA detector



Disc DIRC is designed in Giessen

Data taking >2018?

FAIR



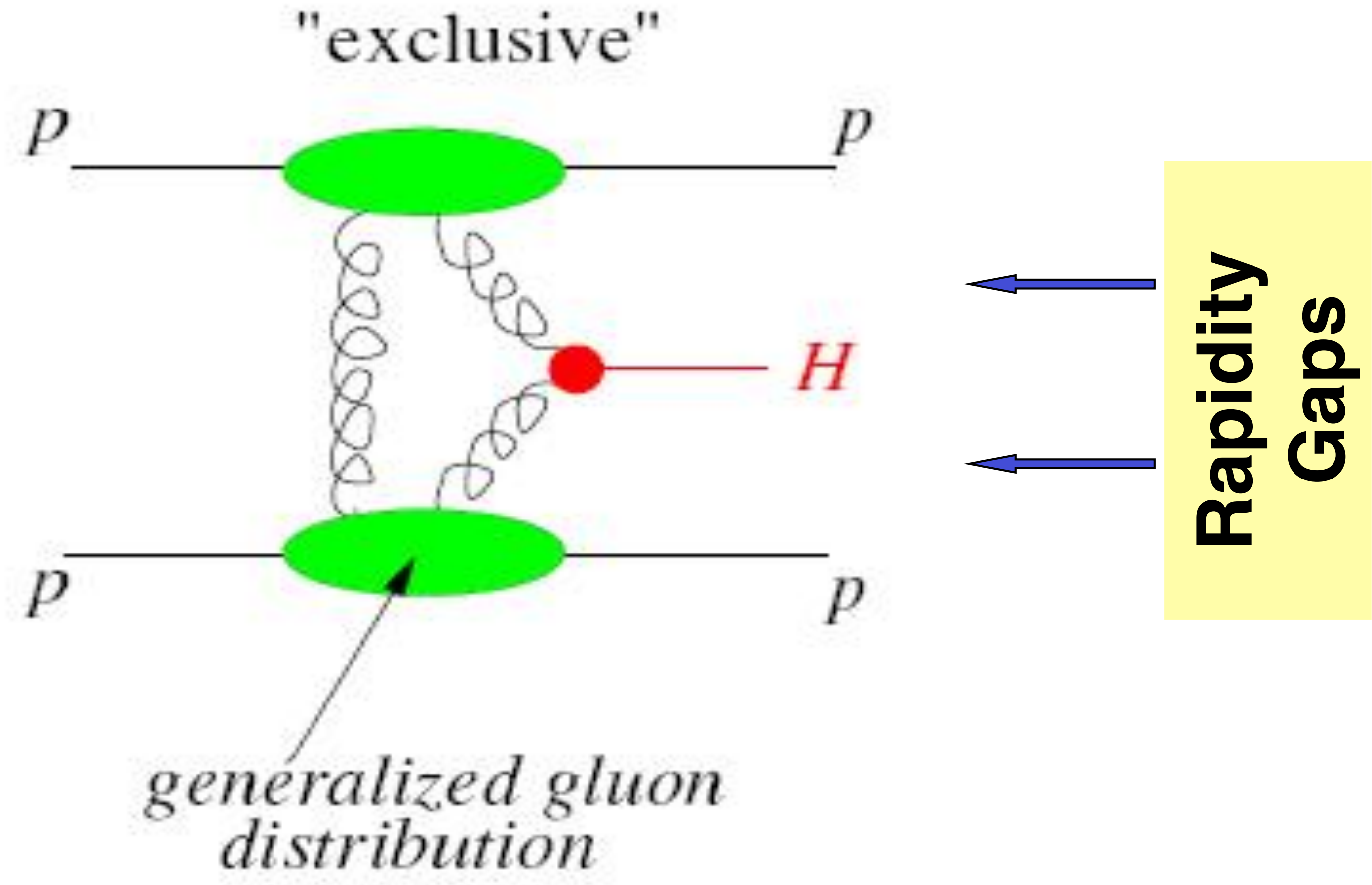
Highest luminosities needed for GDAs … not before … 202X

AFP at ATLAS

… ATLAS forward protons…

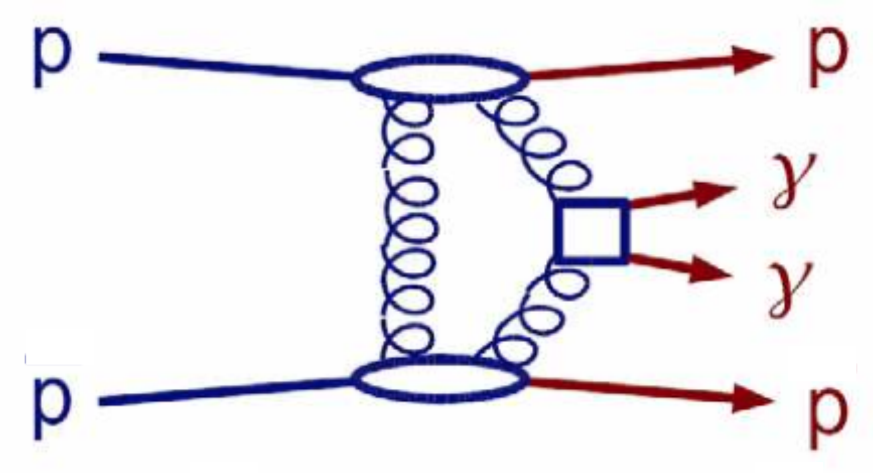
GPDs at LHC

diffractive Higgs production (~120-1200 GeV)



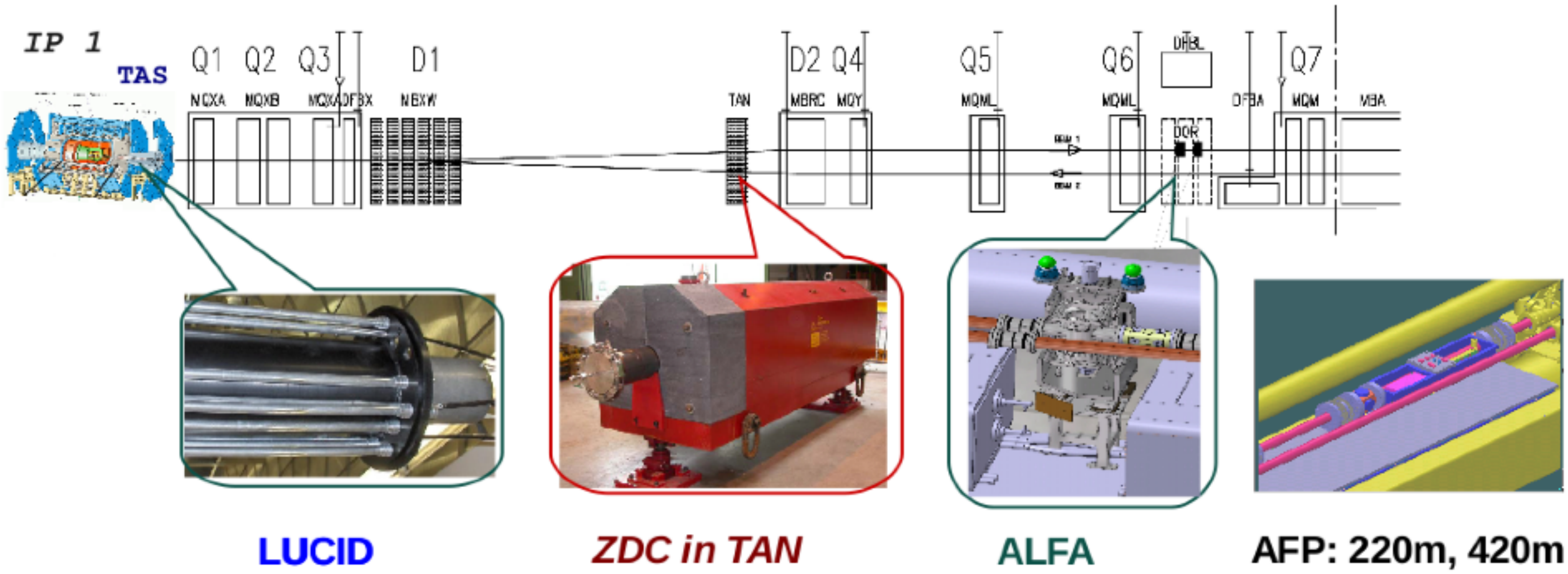
Diffractive Physics at LHC

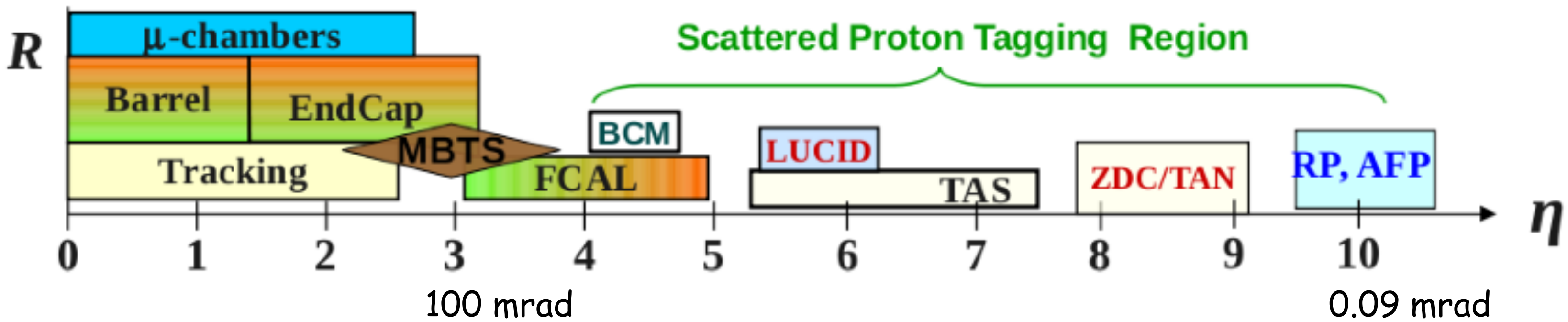
1/3 of events at LHC are diffractive: **rich physics**
– more effort is needed to understand it



$$pp \rightarrow p + \gamma\gamma + p$$

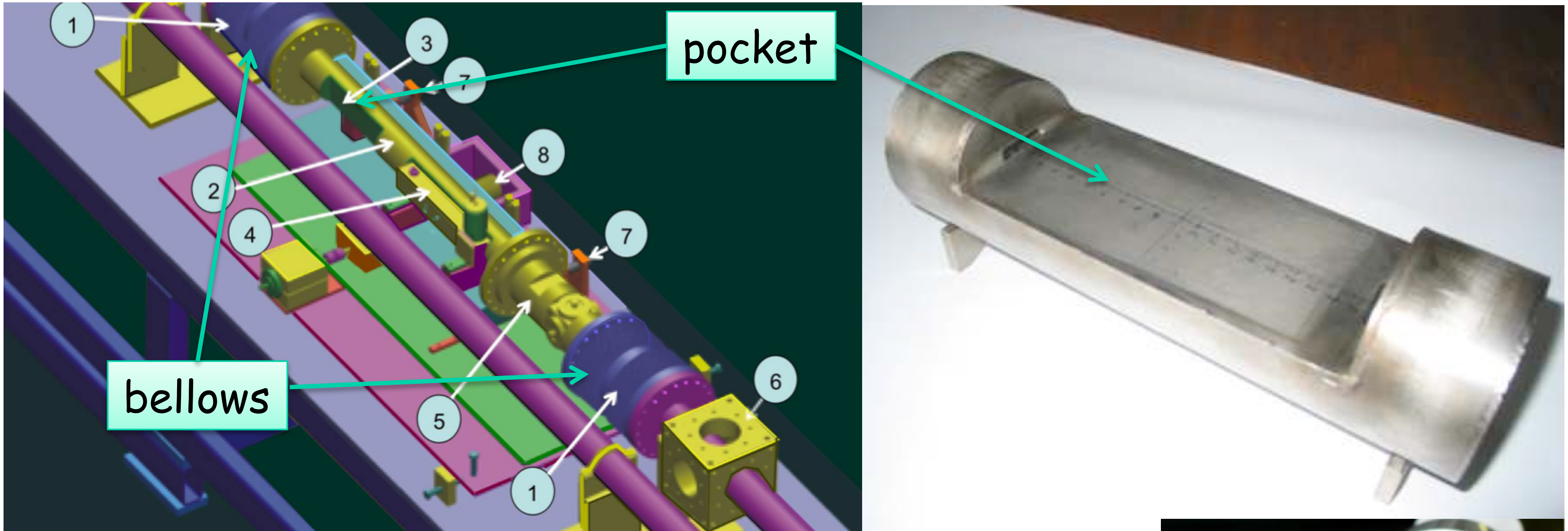
ATLAS Forward Detectors

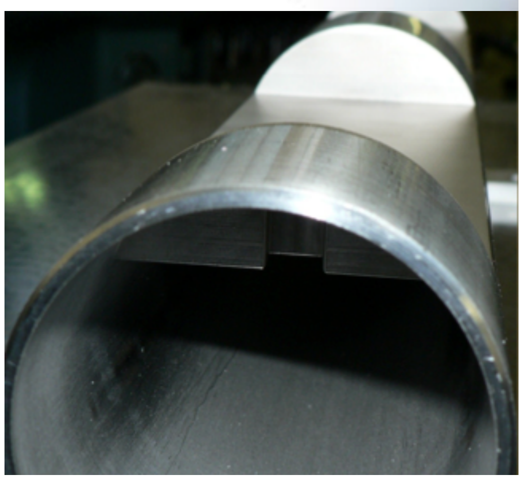




$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

Hamburg Beam Pipe





Moveable beam pipe with pockets
to replace "Roman Pots"

JINST 4 2009 t10001

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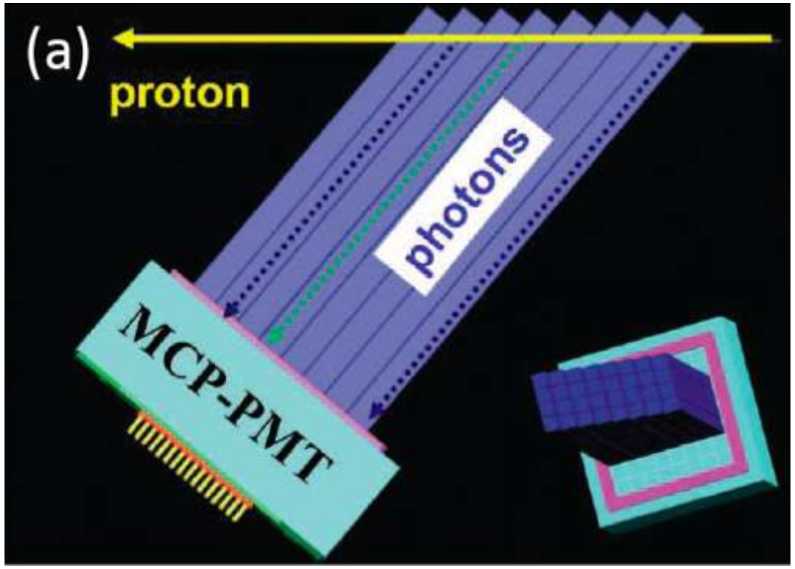
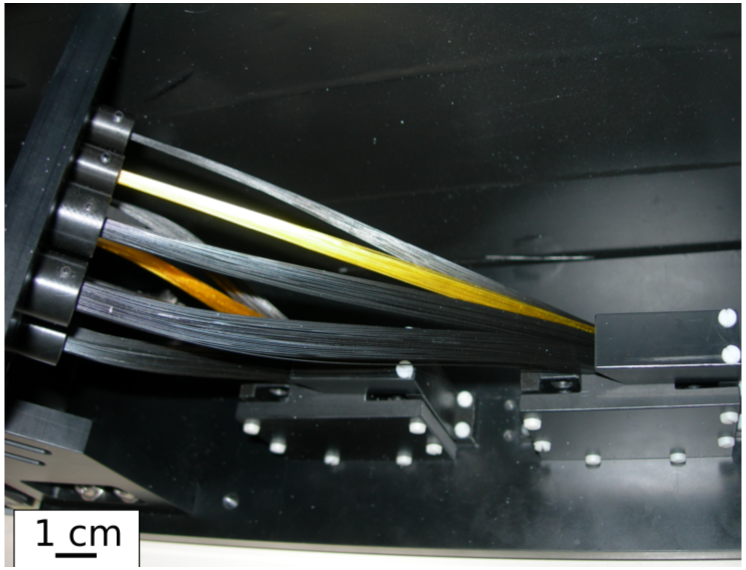
Cherenkov timing detectors



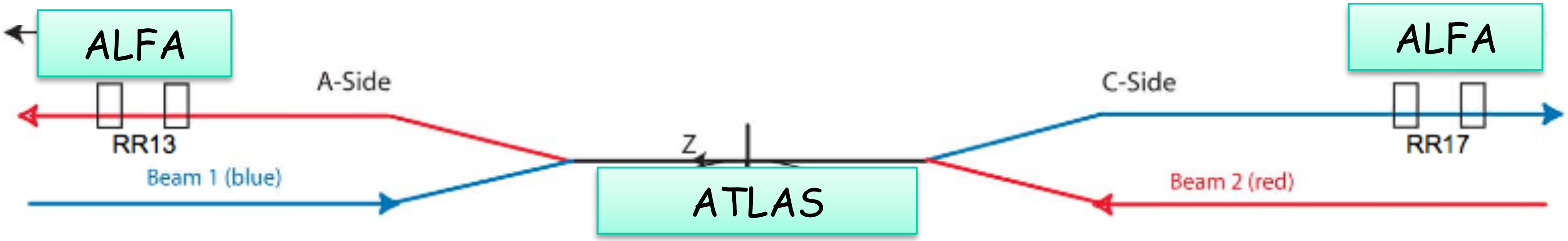
Quartz bars

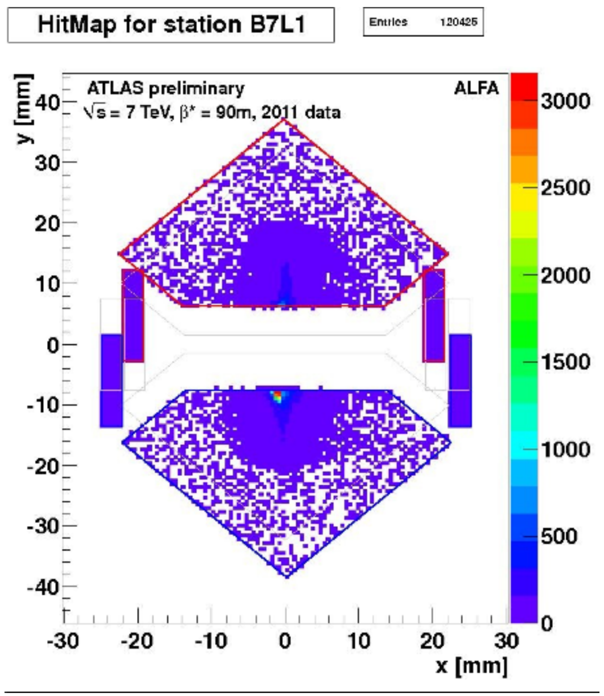


Quartz fibres
(Giessen)

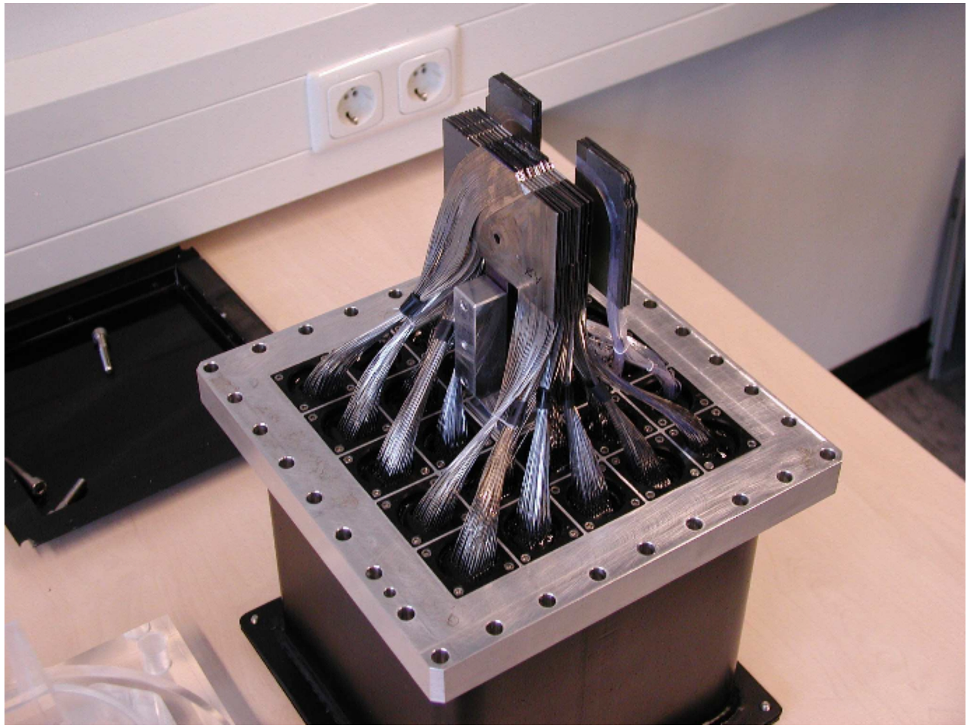
10 ps time resolution needed to reconstruct vertex position at ATLAS IP within 2 mm

ALFA detector at +/- 240 m from ATLAS





ALFA hit map y vs x
minimum bias trigger

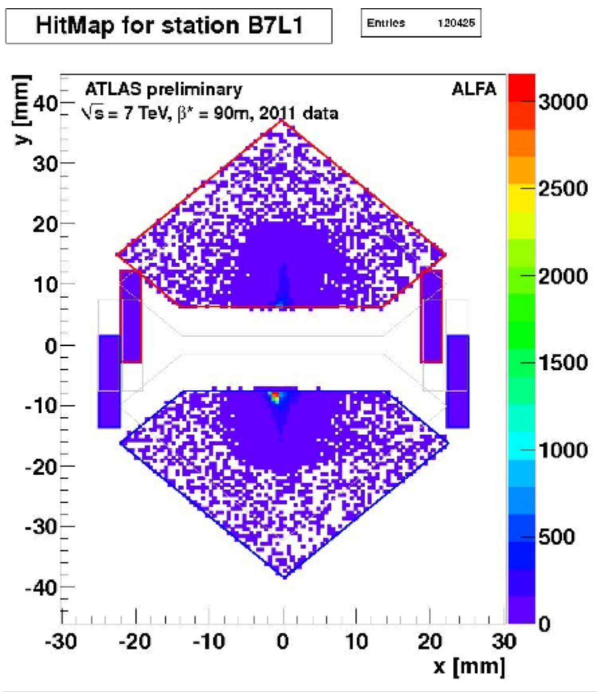


ALFA fibre detector made in Giessen

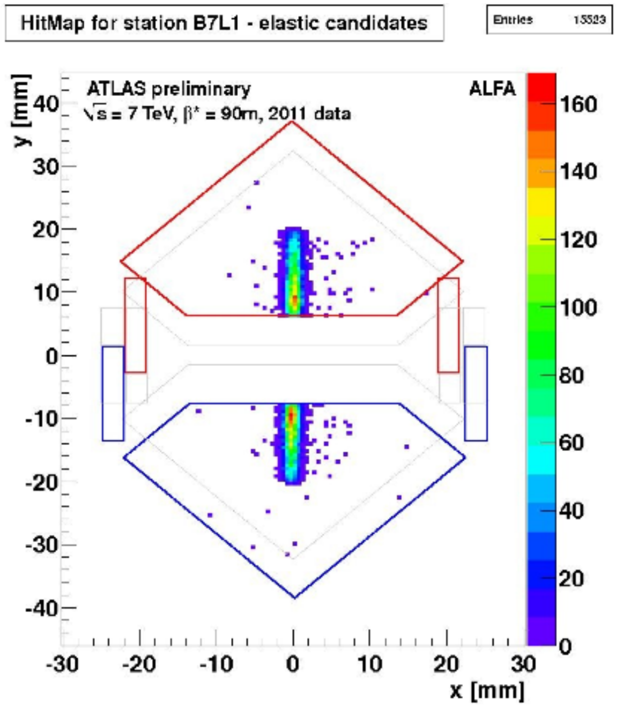
First elastic pp-data from the ALFA detector at ATLAS/LHC at E=7 TeV

ALFA hit maps y vs x

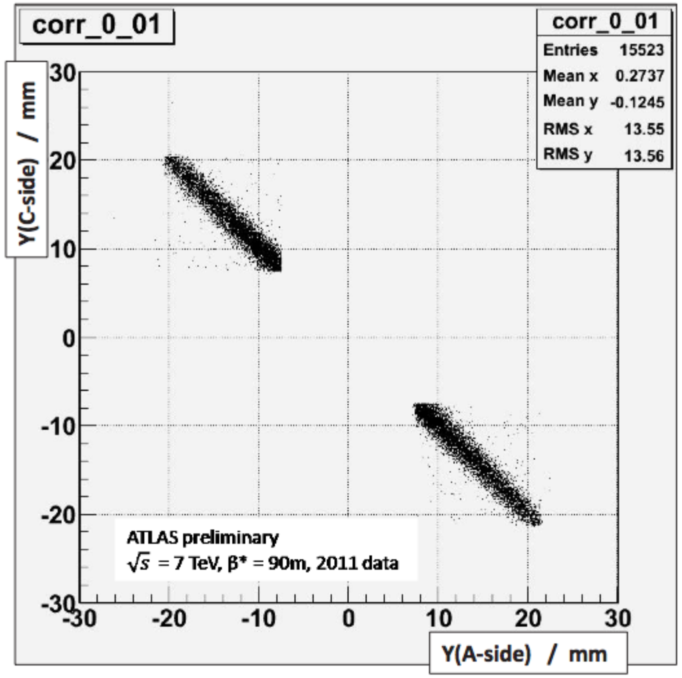
minimum bias trigger



coincidence trigger



ALFA y-postion
west vs east



beam optics: β*= 90m
June 28th, 2011

elastic proton scattering:
proton stays intact
after collision at 7 TeV

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
- GPDs are also important for experiments at FAIR and LHC
- PANDA will measure crossed processes
- ATLAS will measure hard diffractive processes
- A precision mapping of GPDs requires a polarized high luminosity ep-collider, EIC, e.g. at FAIR

Thanks to …

- my group in Giessen
- my collaborators at HERMES, PANDA, ATLAS
- especially thanks for plots and transparencies from Ji, I. Brodski, Riedl, Yaschenko, Stenzel, and others …
- and the organizers for inviting me here