

Exclusive Physics with the HERMES Recoil Detector

Erik Etzelmüller on behalf of the HERMES Collaboration

workshop on

“Exploring Hadron Structure with Tagged Structure Functions“

Thomas Jefferson National Accelerator Facility, 18.01.2014

- Motivation (GPDs - Generalized Parton Distributions)
- DVCS (Deeply Virtual Compton Scattering)
- The HERMES experiment and the Recoil detector
- Overview of the analysis and the results
- Associated DVCS/ Δ VCS ($ep \rightarrow e\gamma N\pi$)

Some milestones

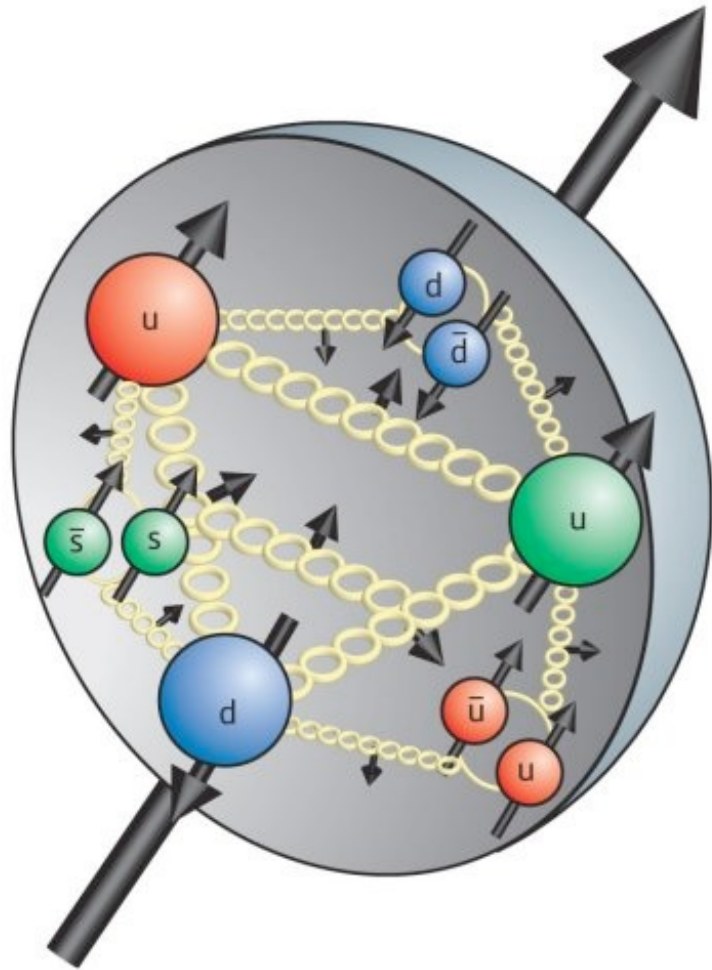
- 1988 EMC publication triggers “spin crisis”
- 1995 HERMES experiment at DESY starts data taking.
Mission: “spin puzzle”
- 1997 Ji finds a way to access the total angular momentum of a nucleon
- 2001 First HERMES DVCS paper published
- 2006 HERMES Recoil detector starts taking data

The proton spin puzzle

$$s_z = \frac{1}{2} = J_q + J_g$$

contribution from quarks lower than expected
from naive quark model

$$J_q = \frac{1}{2} \cdot \Delta\Sigma + L_q$$

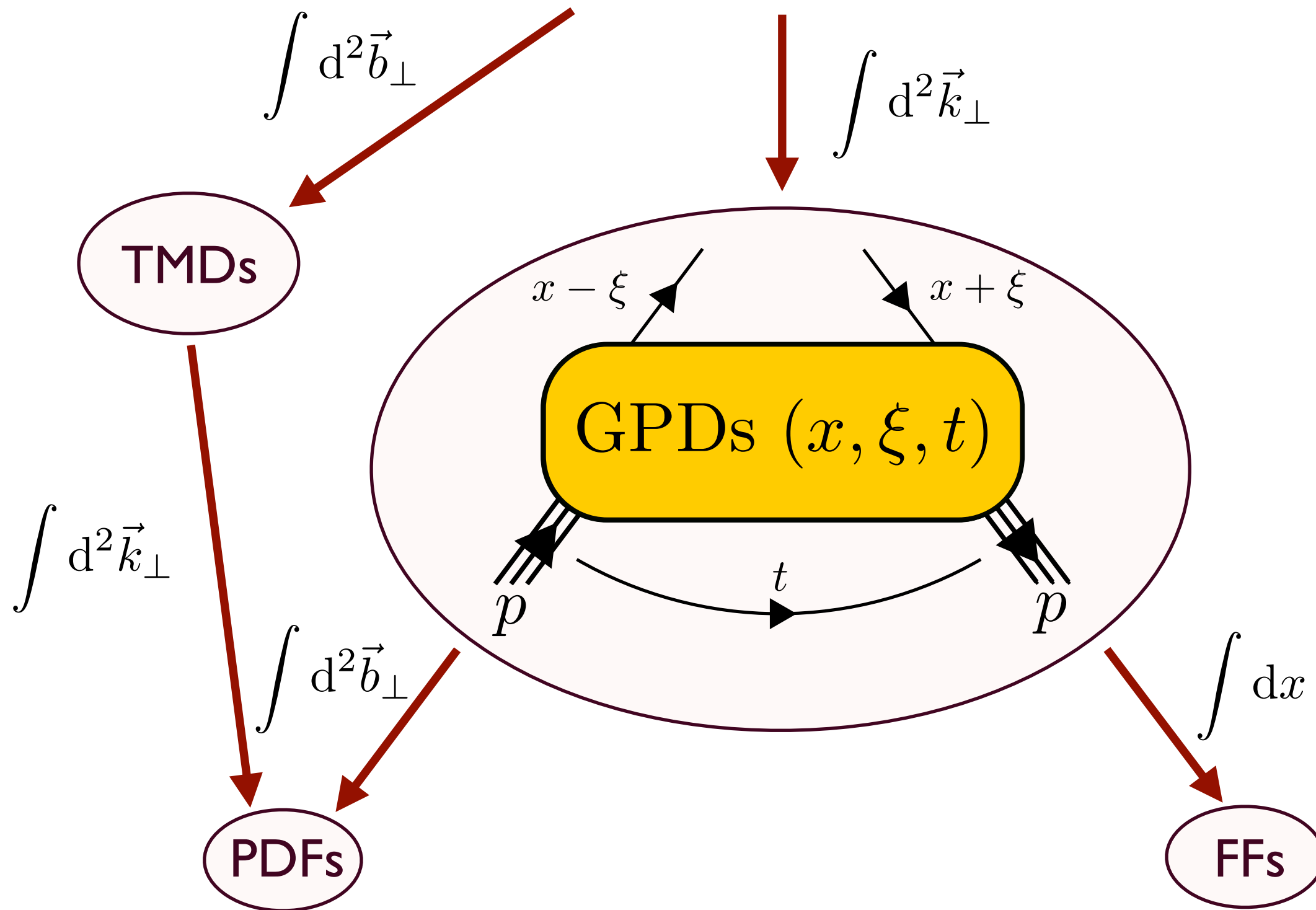


Ji found a way to access total angular momentum through GPDs [X. Ji, Phys. Rev. Lett. 78 (1997) 610]:

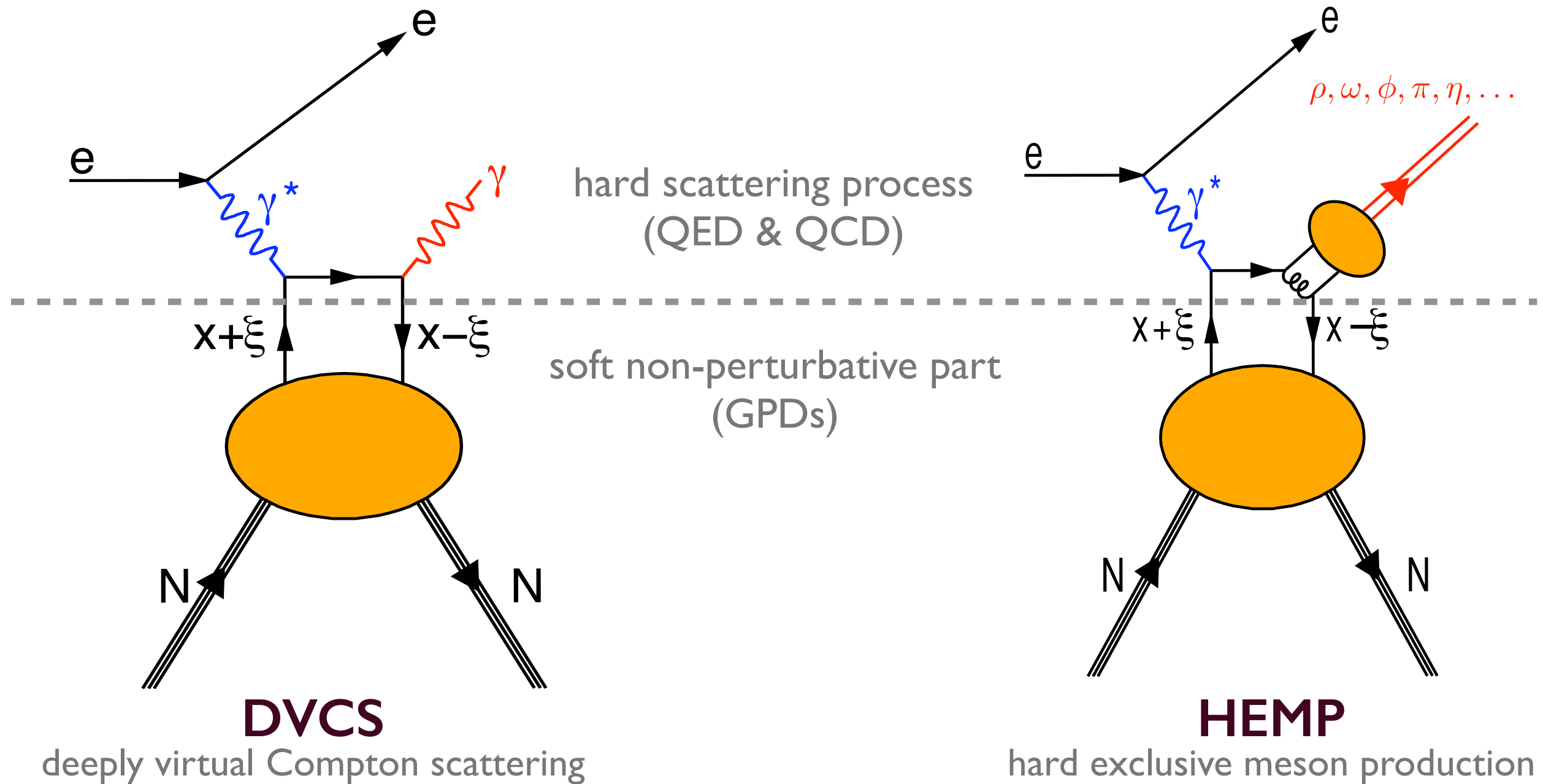
$$J_q = \frac{1}{2} \cdot \Delta\Sigma + L_q = \frac{1}{2} \int_{-1}^1 dx x [H_q(x, \xi, t=0) + E_q(x, \xi, t=0)]$$

GPDs

reduced Wigner distribution (GTMDs)

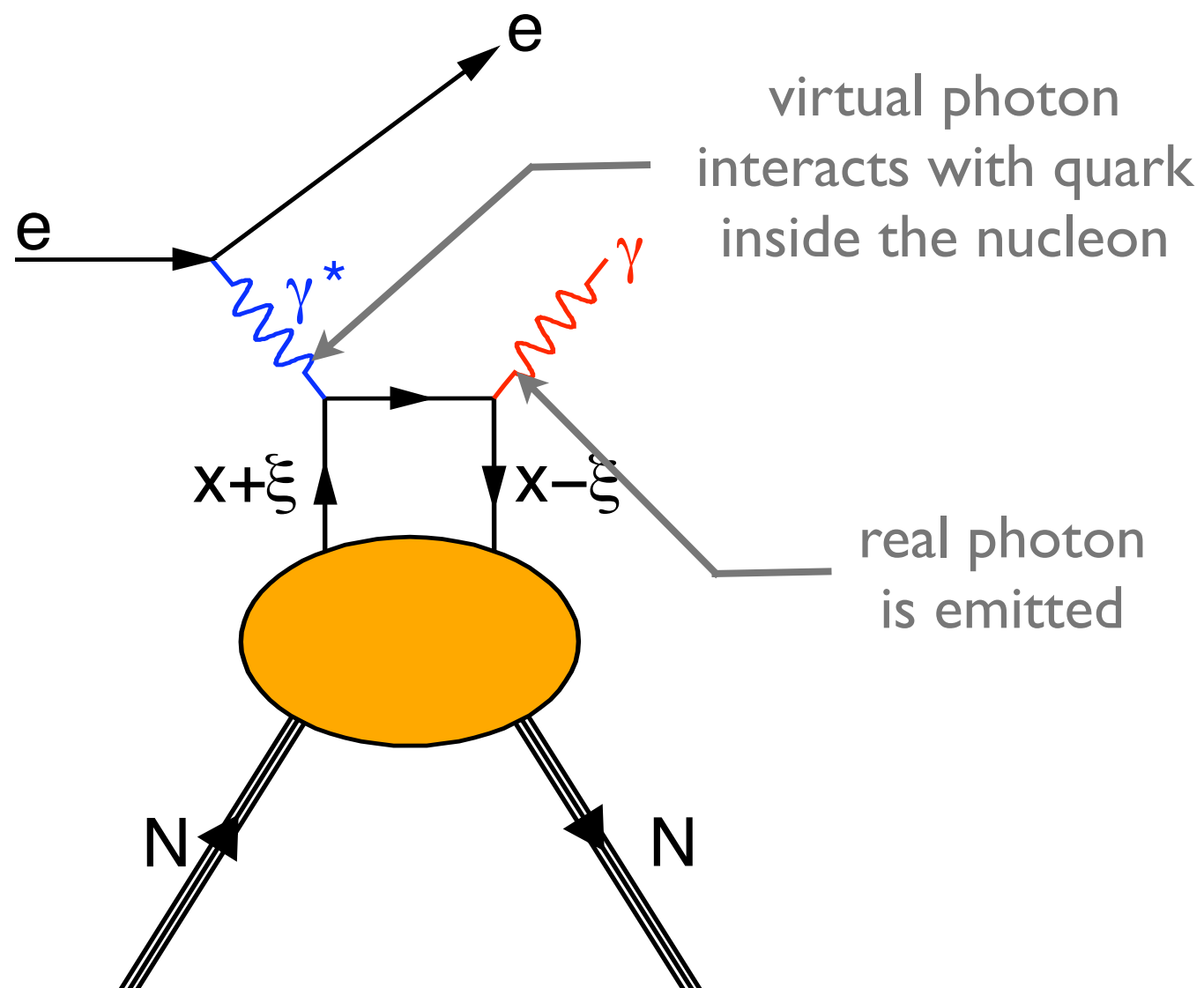


Experimentally GPDs can be accessed through measurements of hard exclusive lepton-nucleon scattering processes.

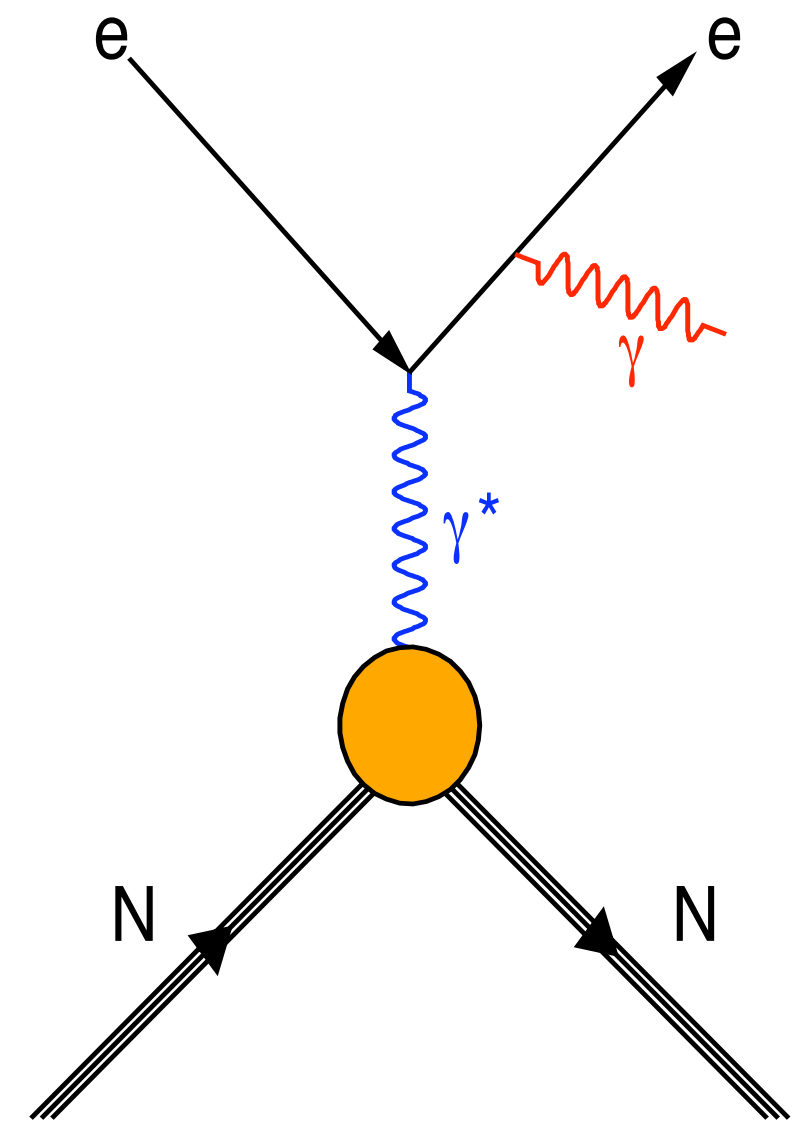


Theoretically cleanest access to GPDs through DVCS

But: final and initial state is equal to Bethe-Heitler scattering (BH)



DVCS

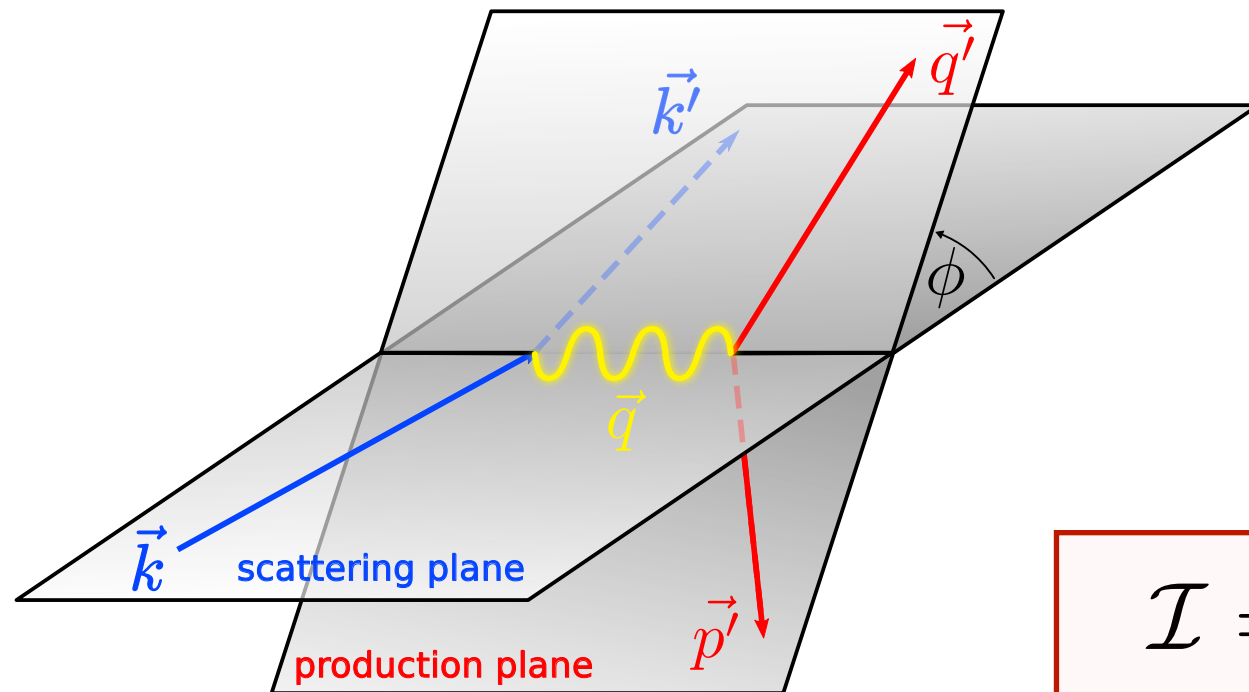


BH

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = \frac{x_B e^6}{32(2\pi)^4 Q^4 \sqrt{1 + \epsilon^2}} |\mathcal{T}_{ep \rightarrow ep\gamma}|^2$$

$$|\mathcal{T}_{ep \rightarrow ep\gamma}|^2 = |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \boxed{\mathcal{I}}$$

Amplitude of Bethe-Heitler scattering is dominant at HERMES kinematics



DVCS amplitude is amplified by BH in the interference term

$$\mathcal{I} = \mathcal{T}_{BH} \mathcal{T}_{DVCS}^* + \mathcal{T}_{DVCS} \mathcal{T}_{BH}^*$$

Access through the measurement of asymmetries:

$$\begin{aligned}
 \mathcal{A}_{\text{LU}}(\phi, e_l) &= \frac{\sigma_{\text{LU}}(\phi, e_l, \lambda = +1) - \sigma_{\text{LU}}(\phi, e_l, \lambda = -1)}{\sigma_{\text{LU}}(\phi, e_l, \lambda = +1) + \sigma_{\text{LU}}(\phi, e_l, \lambda = -1)} \\
 &= \frac{1}{\sigma_{\text{UU}}(\phi, e_l)} \left[K_{\text{DVCS}} s_1^{\text{DVCS}} \sin \phi - \frac{e_l K_{\mathcal{I}}}{\mathcal{P}_1(\phi) \mathcal{P}_2(\phi)} \sum_{n=1}^2 s_n^{\mathcal{I}} \sin(n\phi) \right]
 \end{aligned}$$

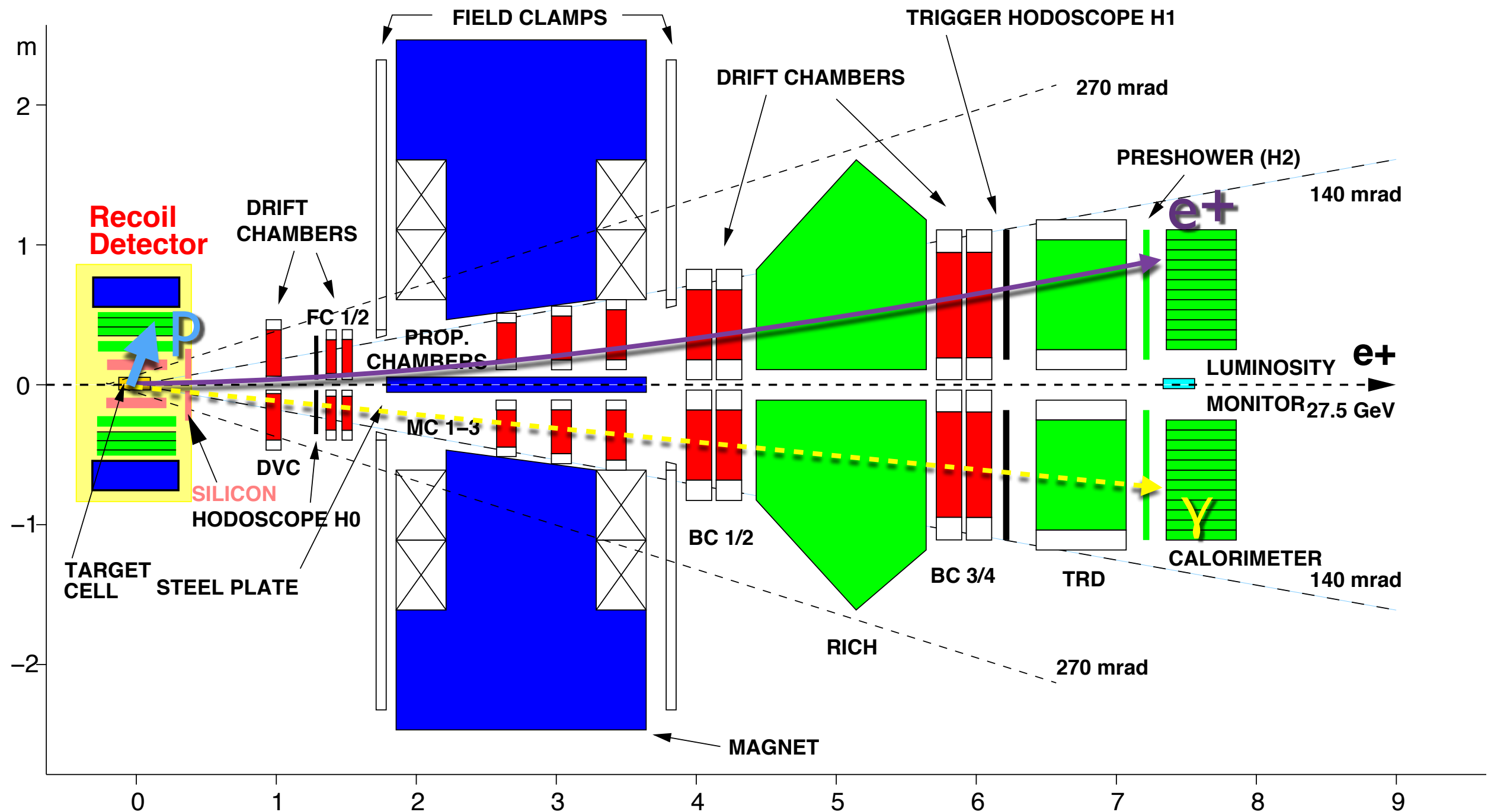
longitudinally polarized beam,
unpolarized target

Fourier coefficients comprise Compton-Form factors (CFFs) which are convolutions of the GPDs with the hard scattering kernel.

Example:

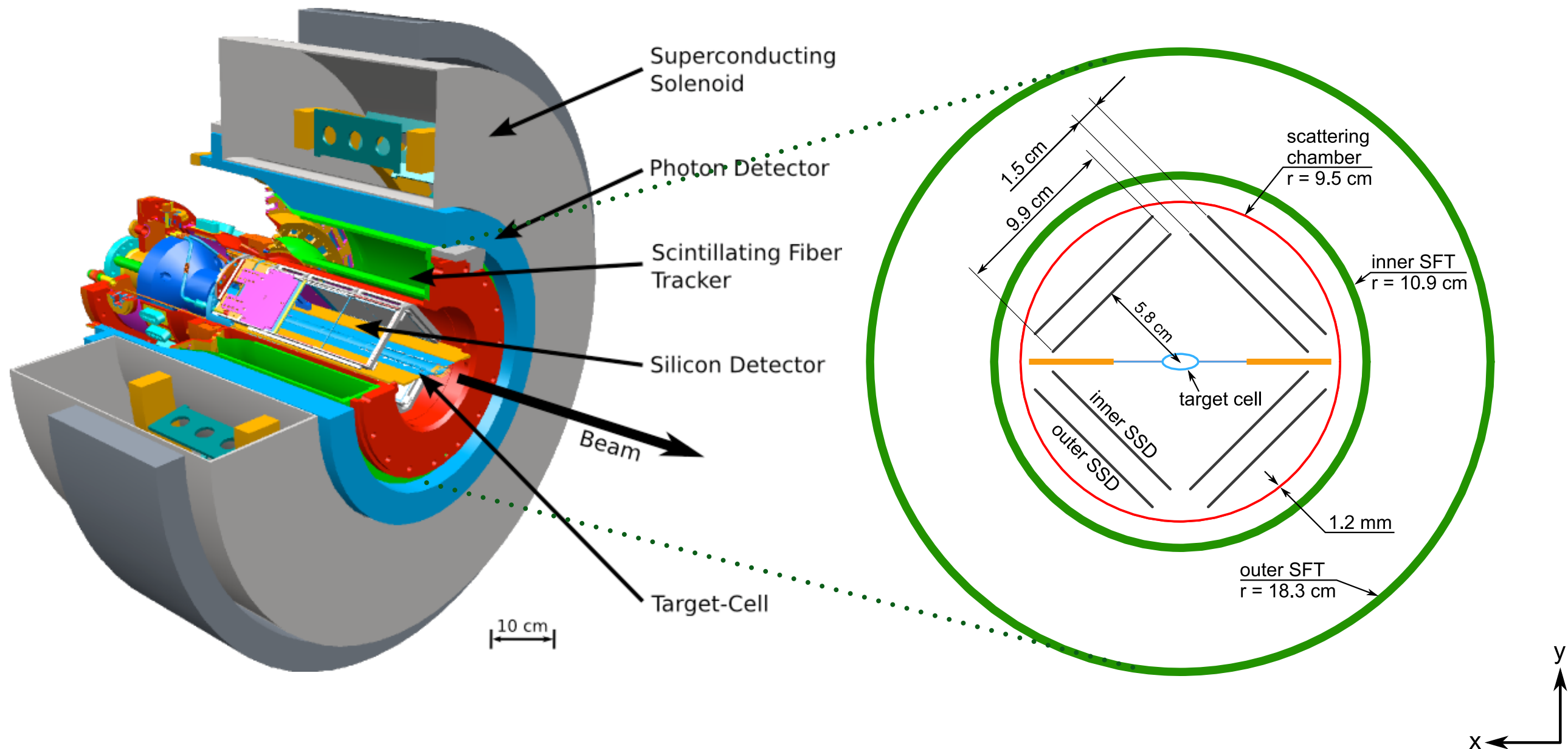
$$A_{\text{LU}}(\phi) \sim \pm \frac{x_B}{y} \frac{s_1^{\mathcal{I}}}{c_0^{\text{BH}}} \sin(\phi) \propto \Im \left\{ F_1 \mathcal{H} + \frac{x_B}{2 - x_B} (F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E} \right\} \sin(\phi)$$

The HERMES experiment



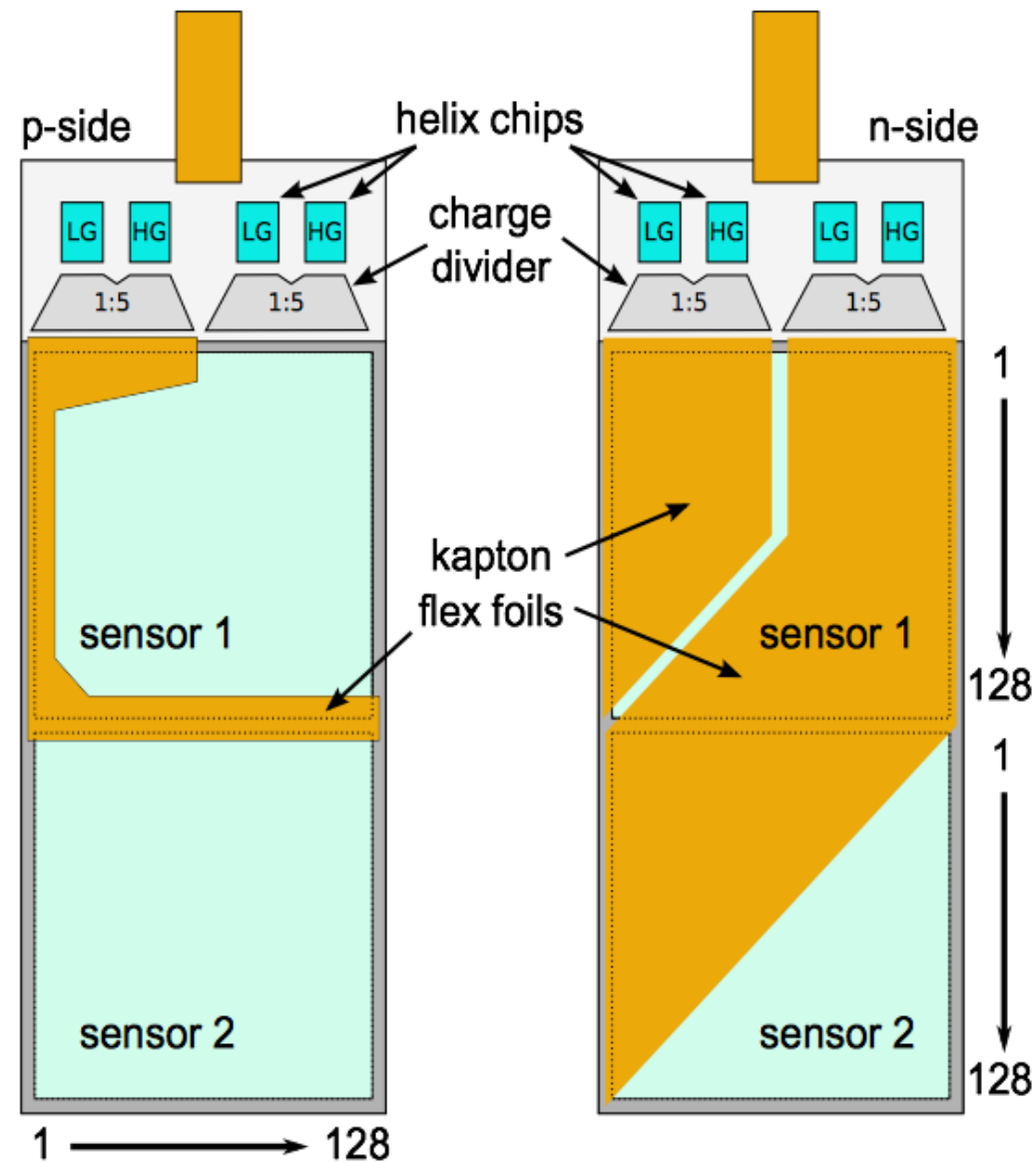
Recoil detector upgrade for 2006/2007 running

The HERMES Recoil detector

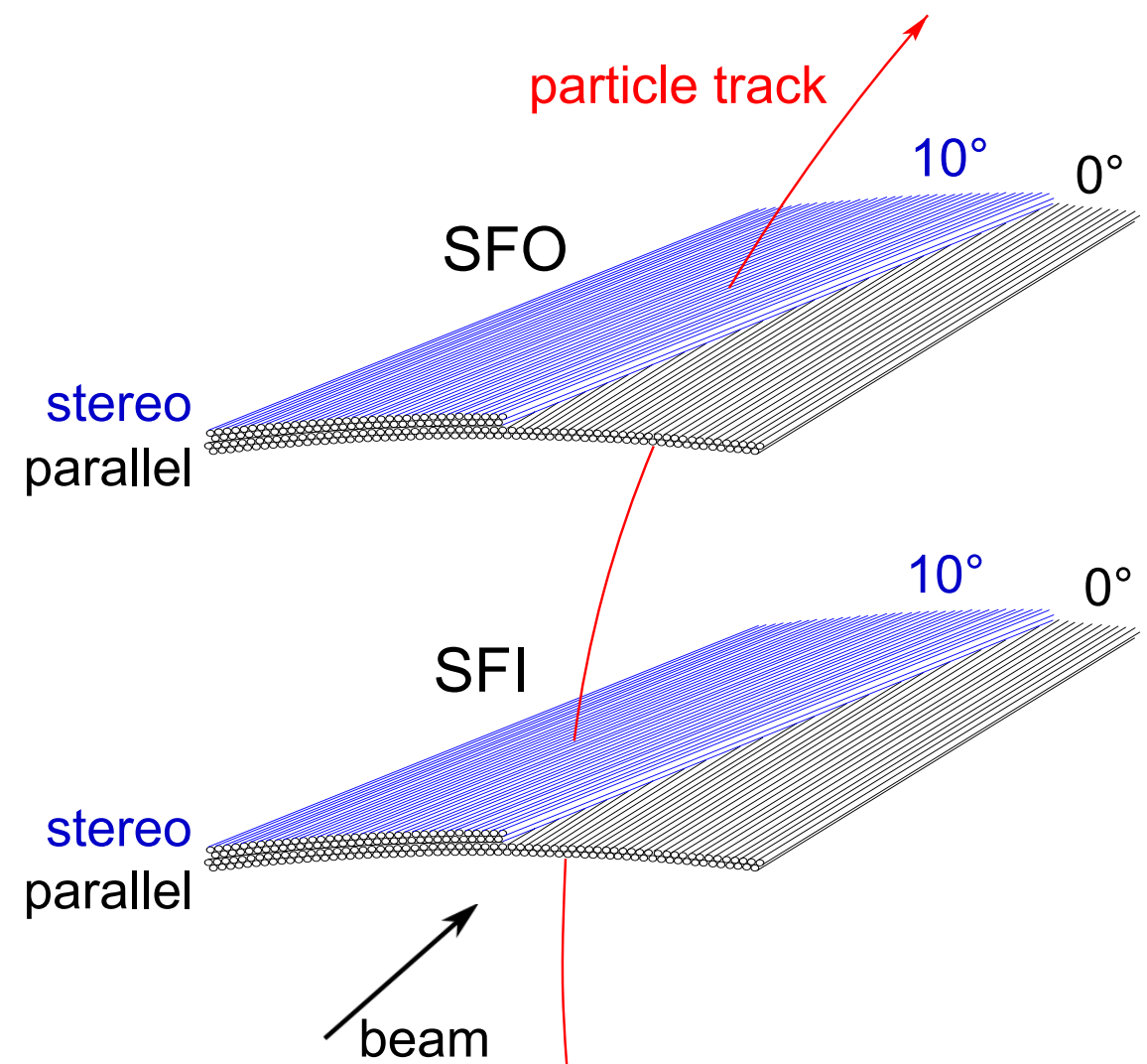


Enables the measurement of the recoiling charged particle and therefore full $ep \rightarrow ep\gamma$ event reconstruction

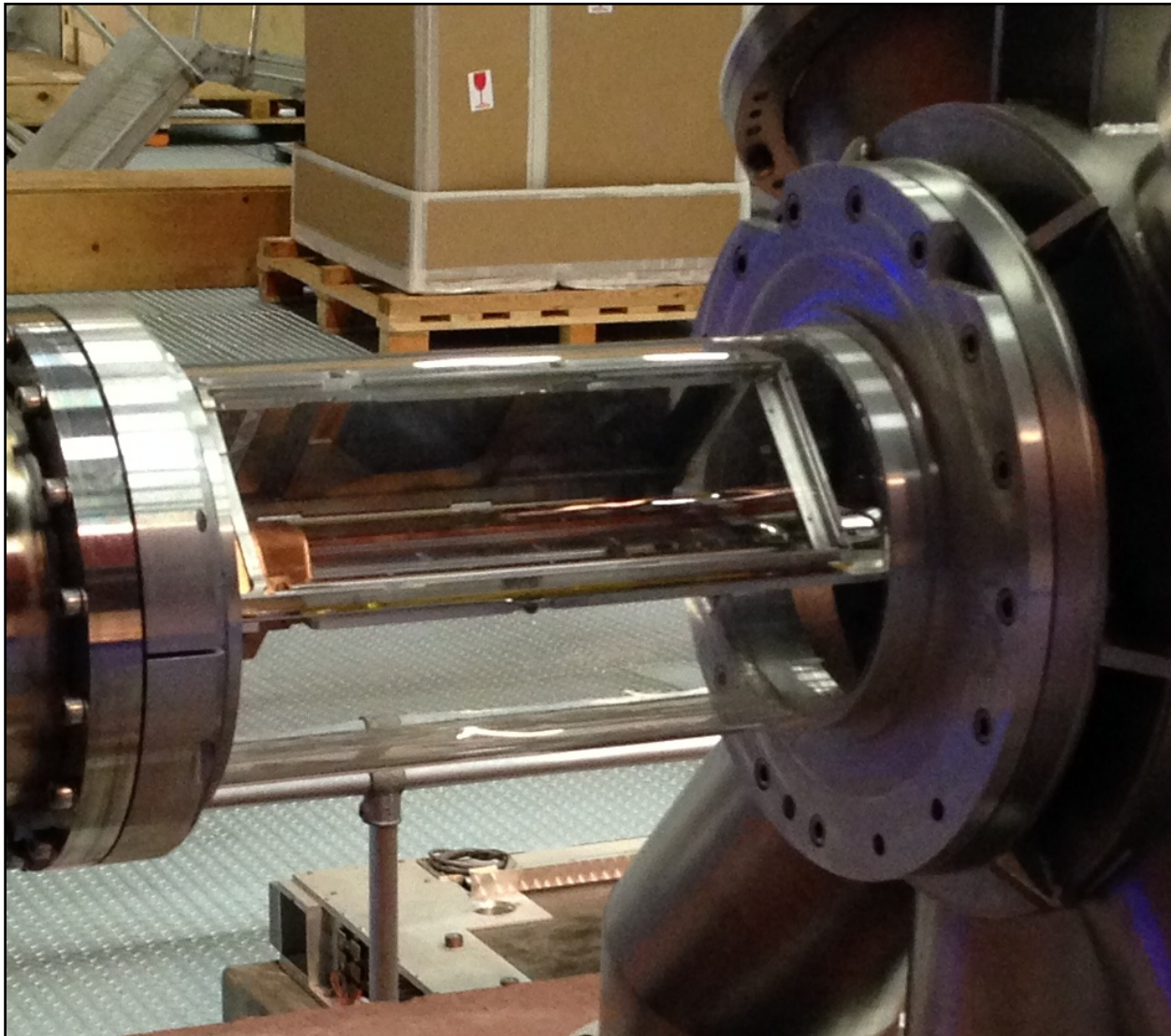
Sketch of front- and backside of a silicon strip detector module (SSD)



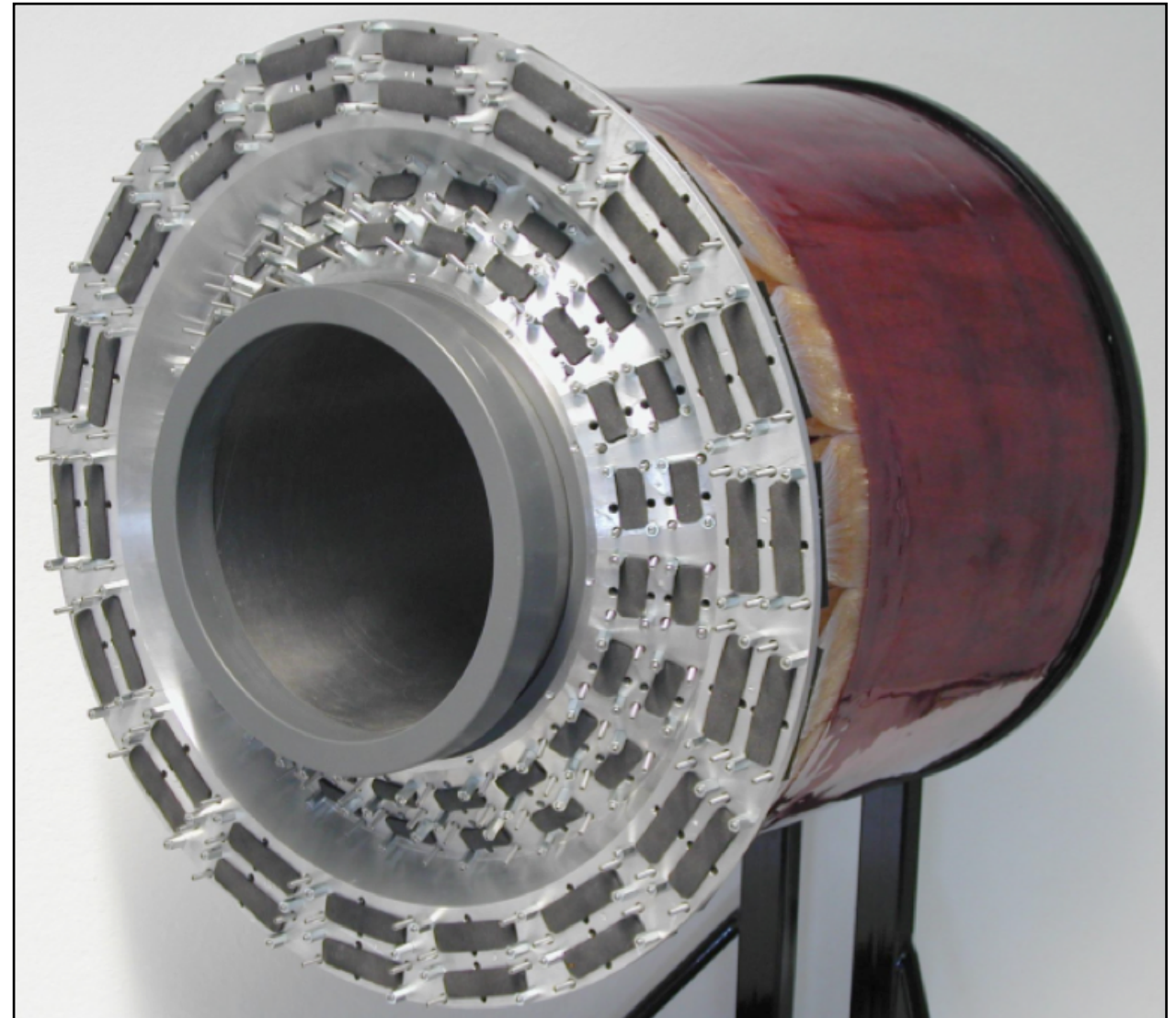
Schematic design of the scintillating fibre tracker (SFT)



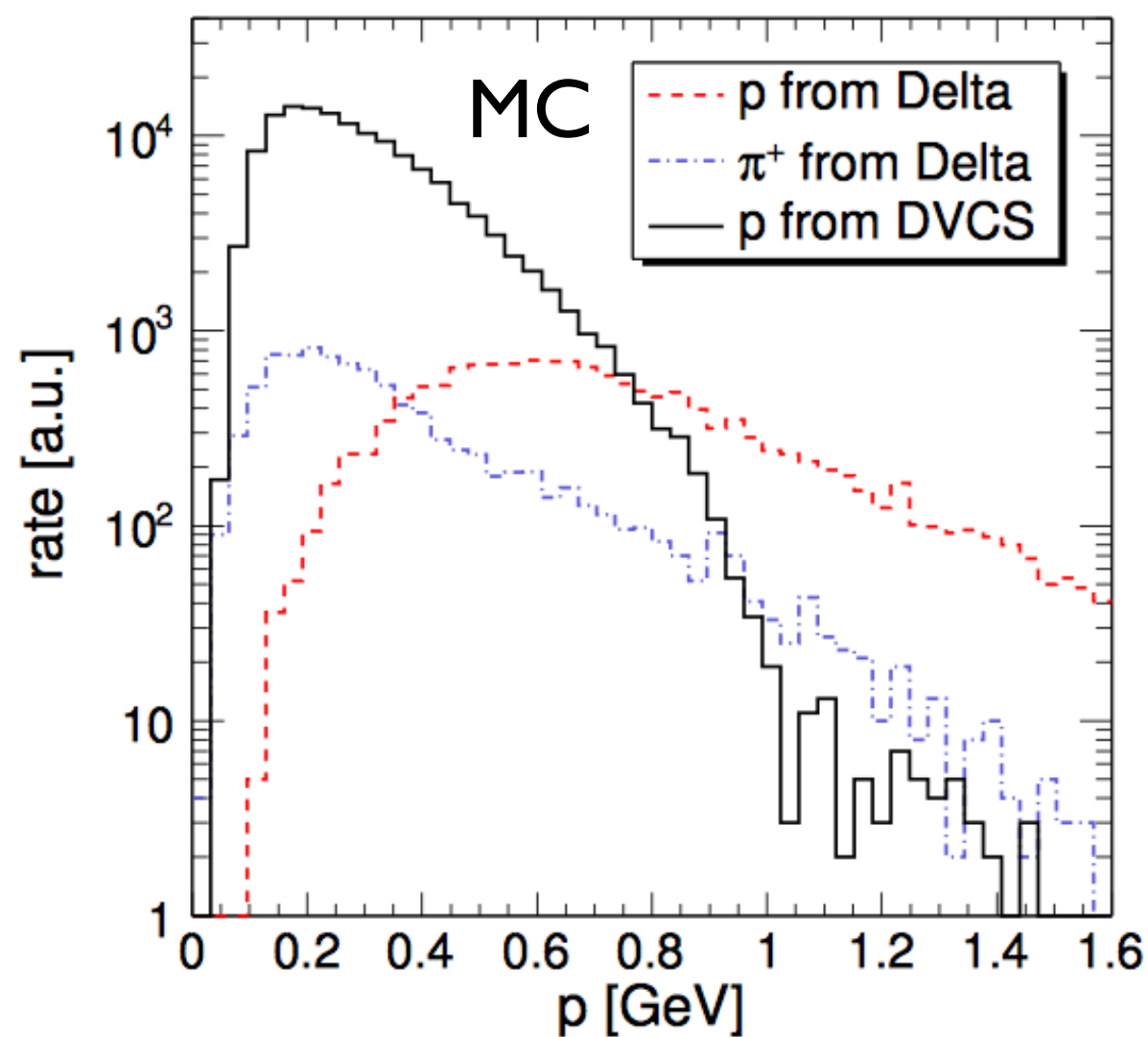
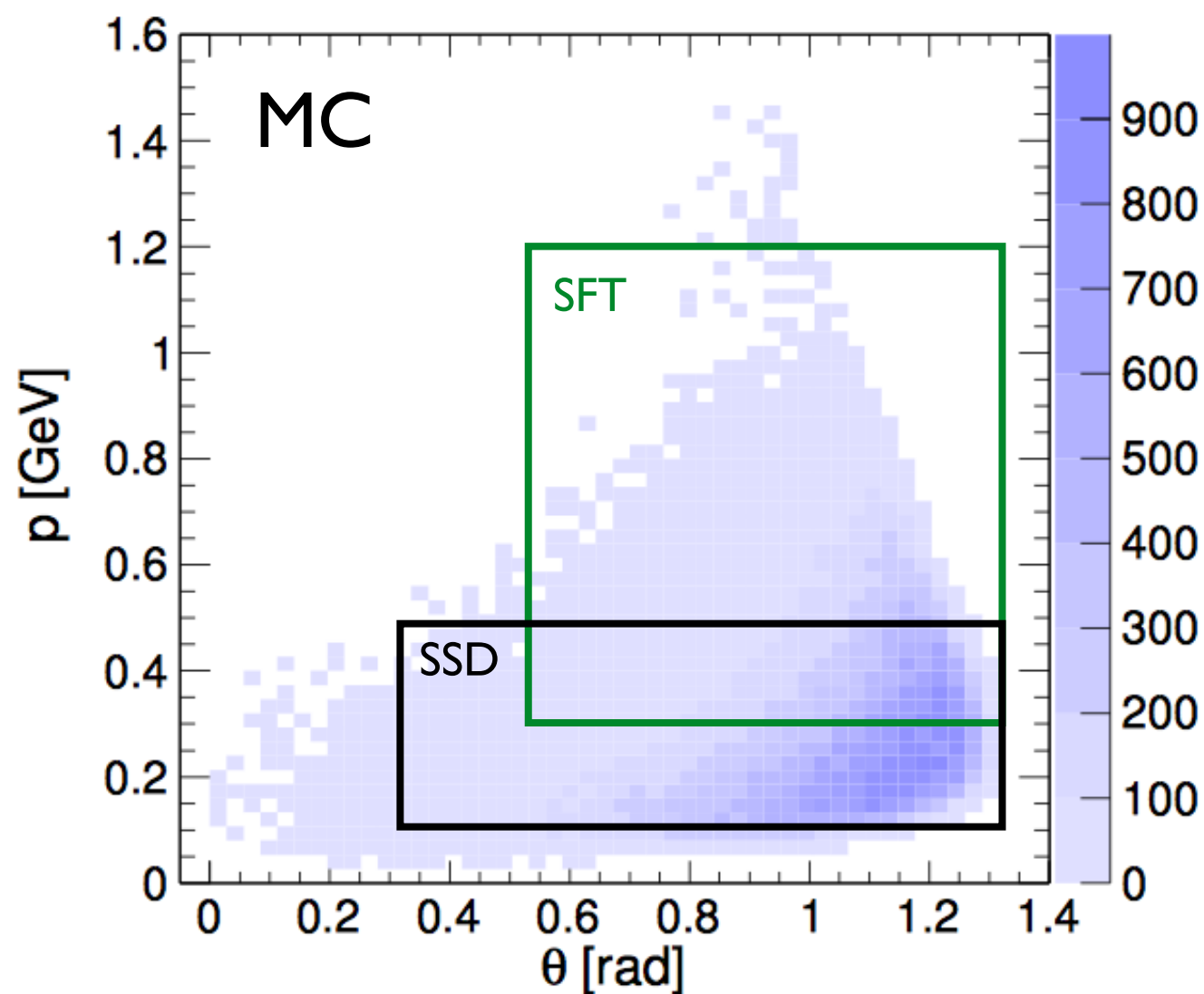
The silicon strip detector (SSD)



The scintillating fibre tracker (SFT)

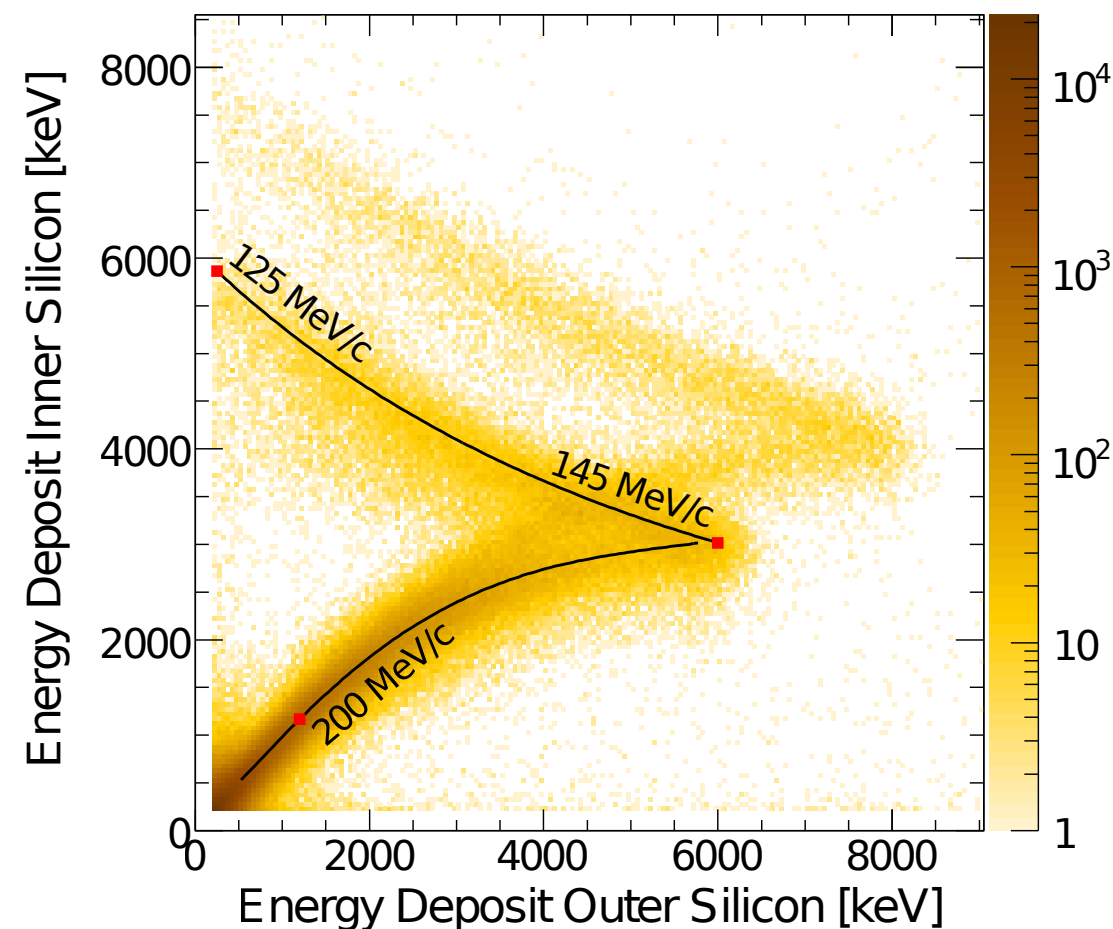
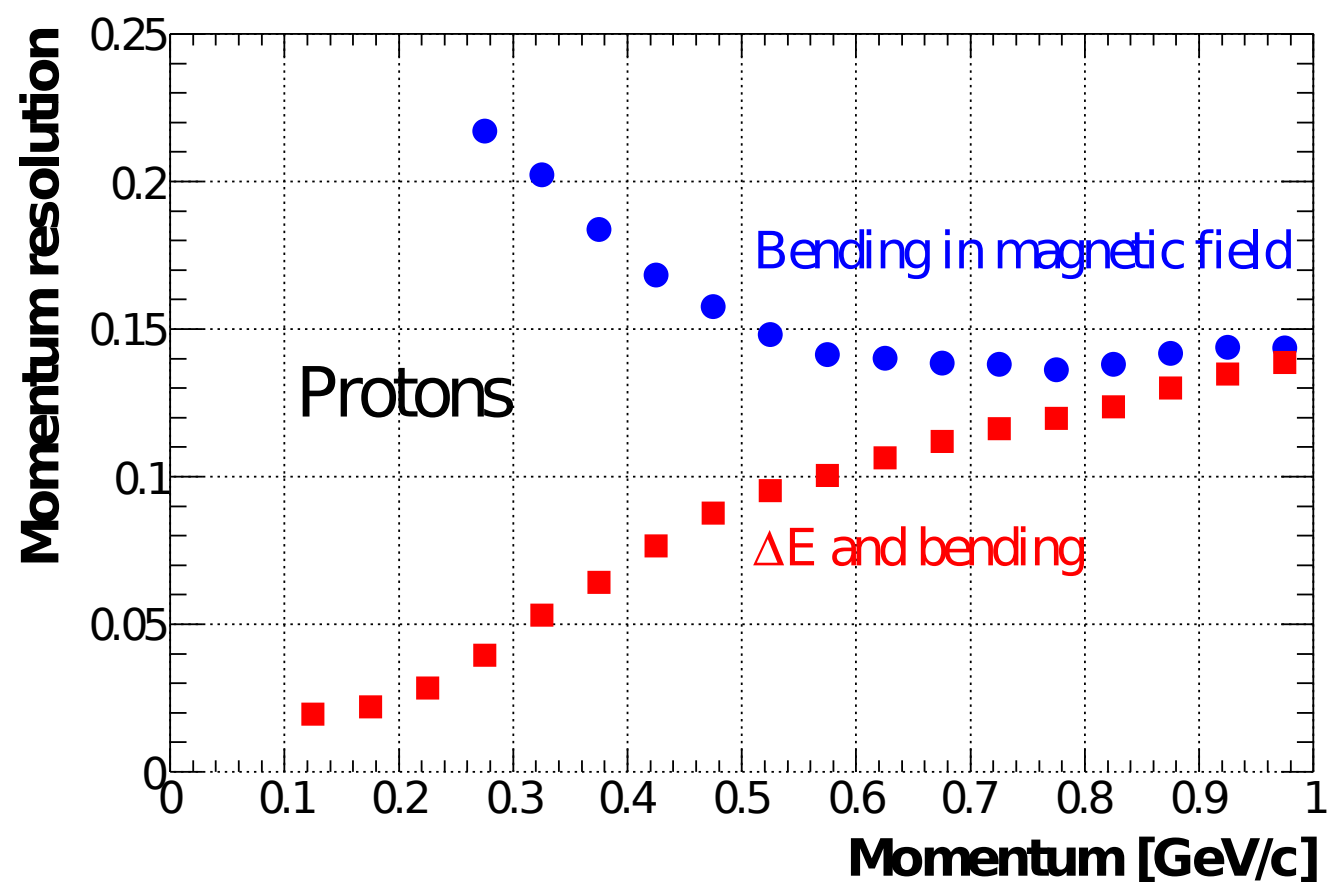


Kinematic coverage



Scintillating fibre tracker (SFT) and silicon strip detector (SSD)
complement each other

Recoil tracking



taking energy loss into account improves momentum resolution for low p

azimuthal-angle resolution: 4 mrad, polar-angle resolution: 10 mrad (for $p > 0.5$ GeV)

Improvement through the Recoil detector

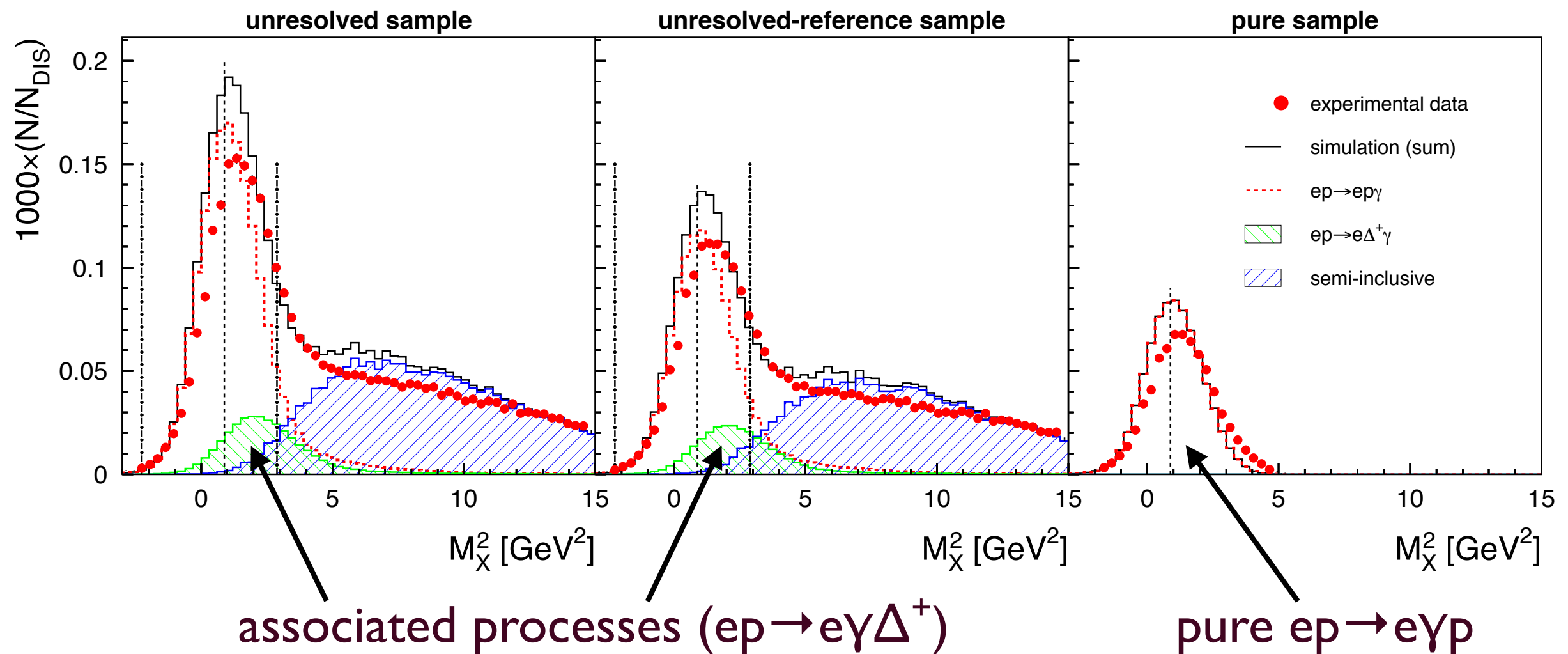
forward spectrometer only

similar background

measured

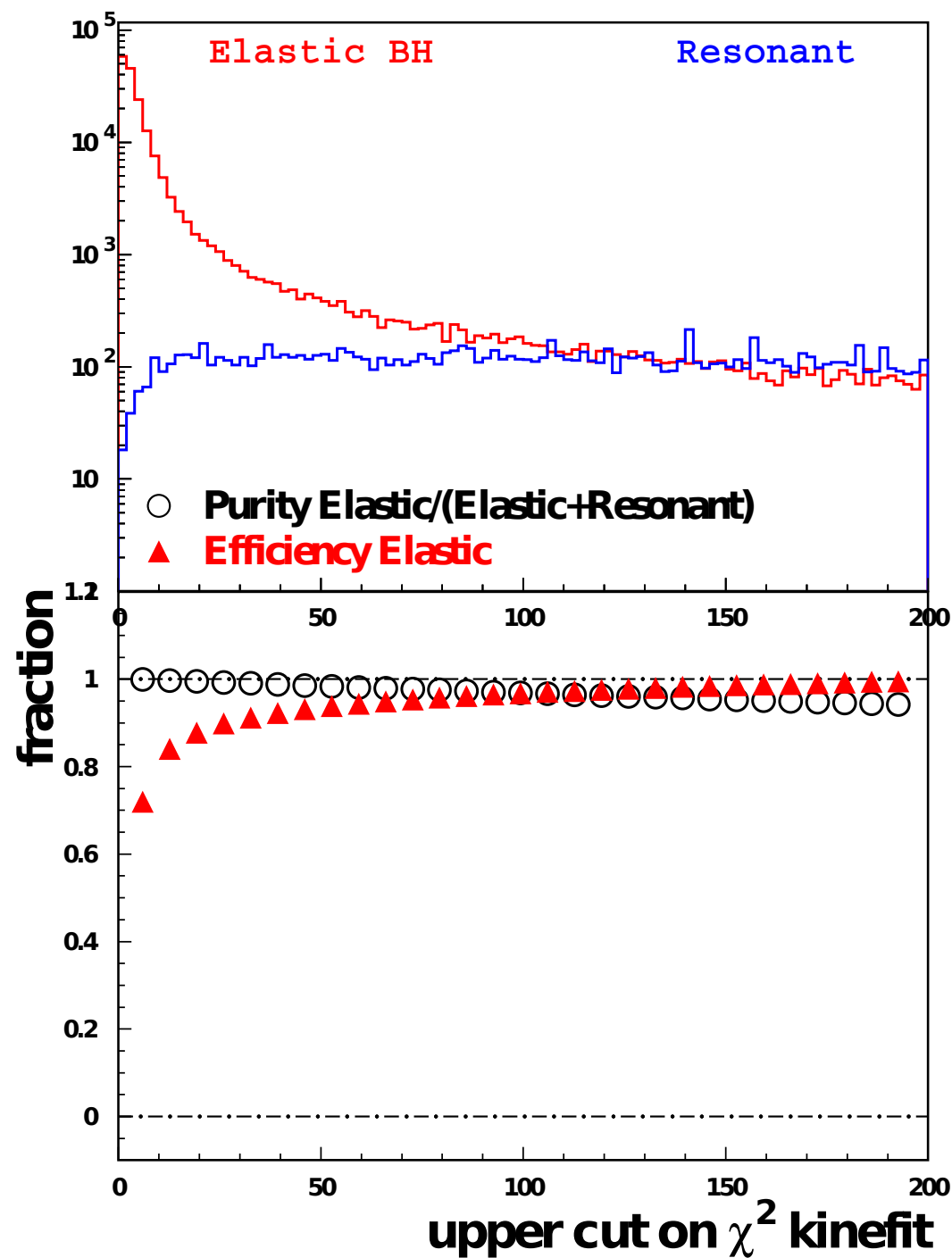
proton

same kinematic acceptance



Missing mass:

$$M_x^2 = (k - k' + P_0 - P_\gamma)^2 = M^2 + 2M(\nu - E_\gamma) + t$$

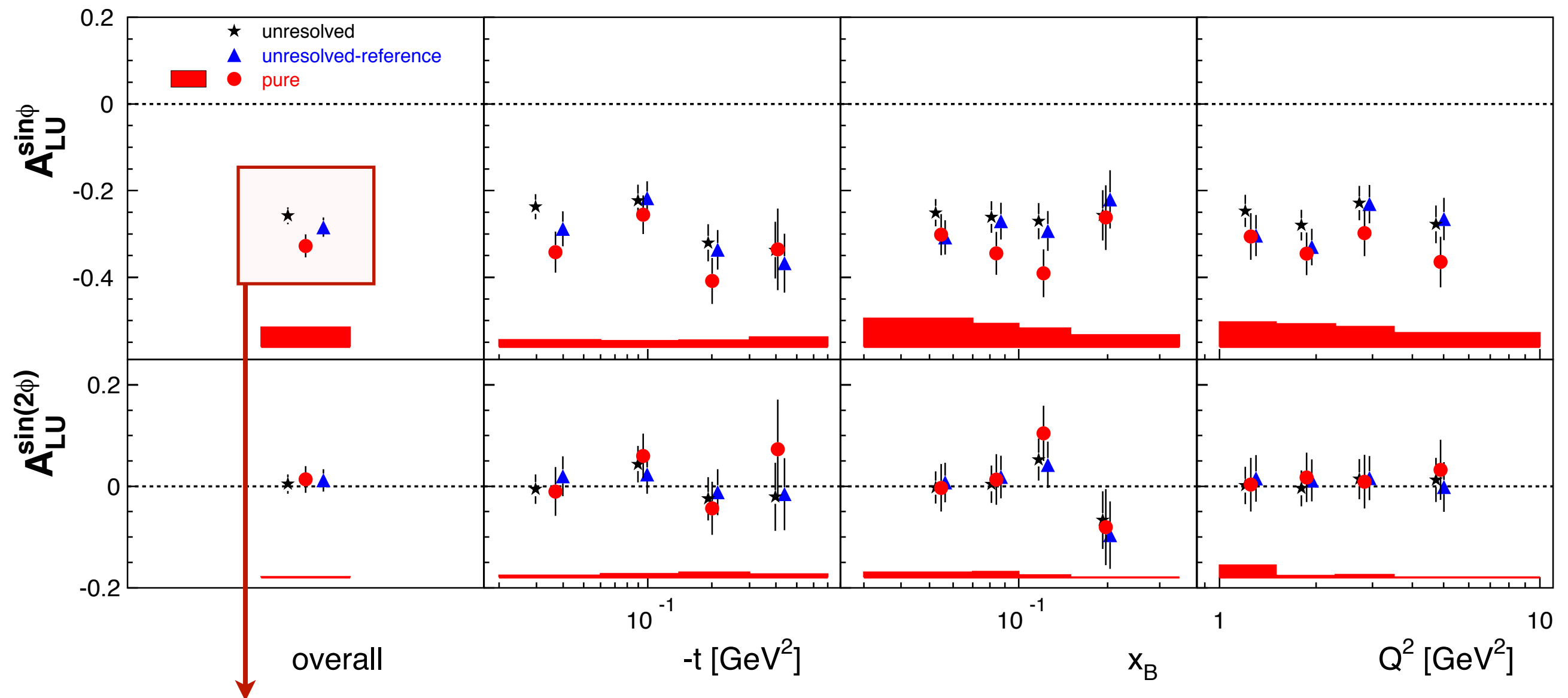


Kinematic event fitting:

$$\chi_{pen}^2 = \underbrace{\sum_{i=1}^9 \frac{(r_i^{fit} - r_i^{meas})^2}{\sigma_i^2}}_{\chi^2\text{-value of interest}} + \underbrace{T \cdot \sum_{j=1}^4 \frac{[f_j(r_1^{fit}, \dots, r_9^{fit})]^2}{(\sigma_j^f)^2}}_{\text{penalty term} + \text{constraints}}$$

- 4-momentum conservation as constraints
- lowest χ^2 -value in case of multiple recoil tracks per event
- minimum of 1 % fit probability required, which corresponds to $\chi^2 < 13.7$

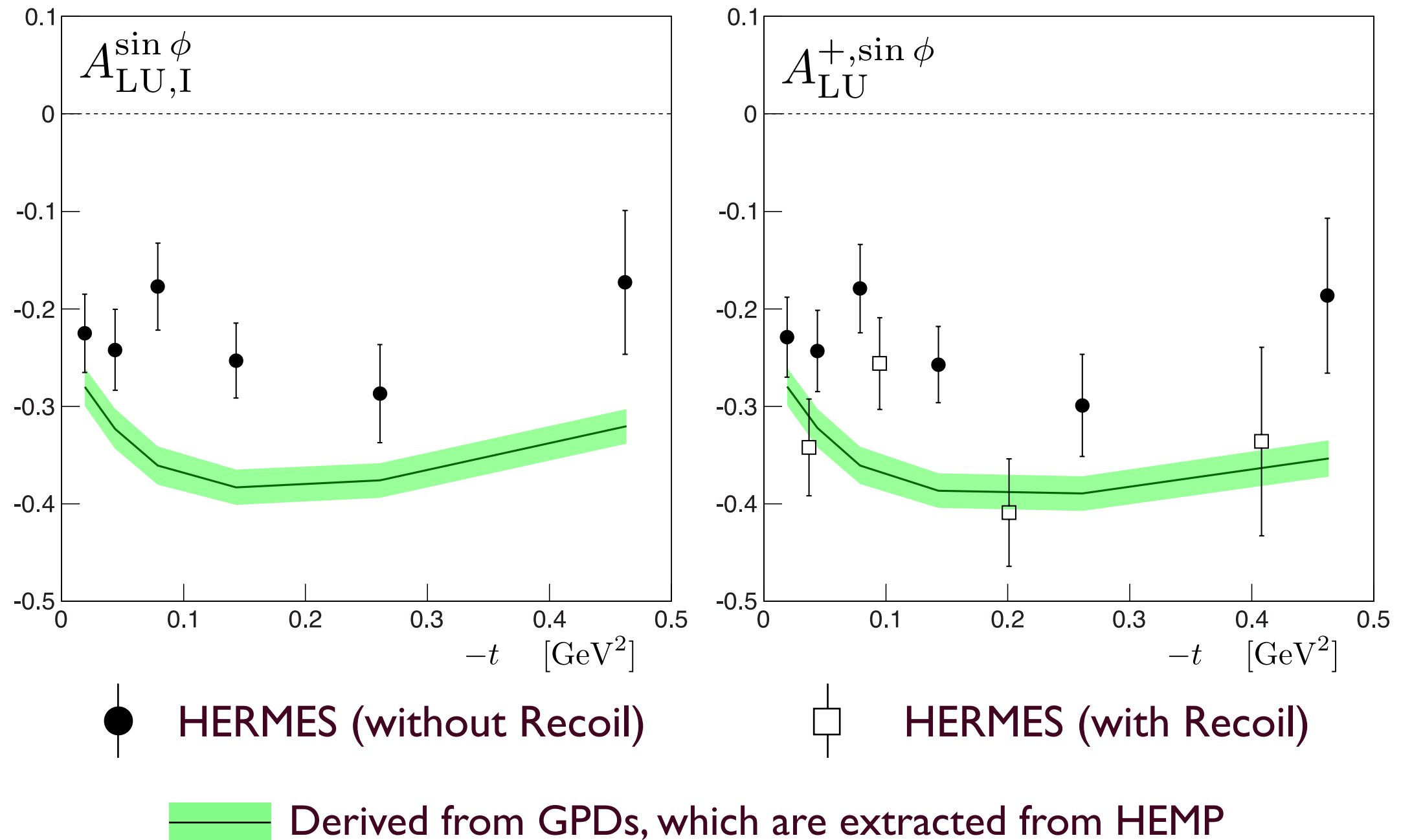
A. Airapetian et al, JHEP10 (2012) 042



Magnitude of the leading asymmetry has increased by 0.054 ± 0.016

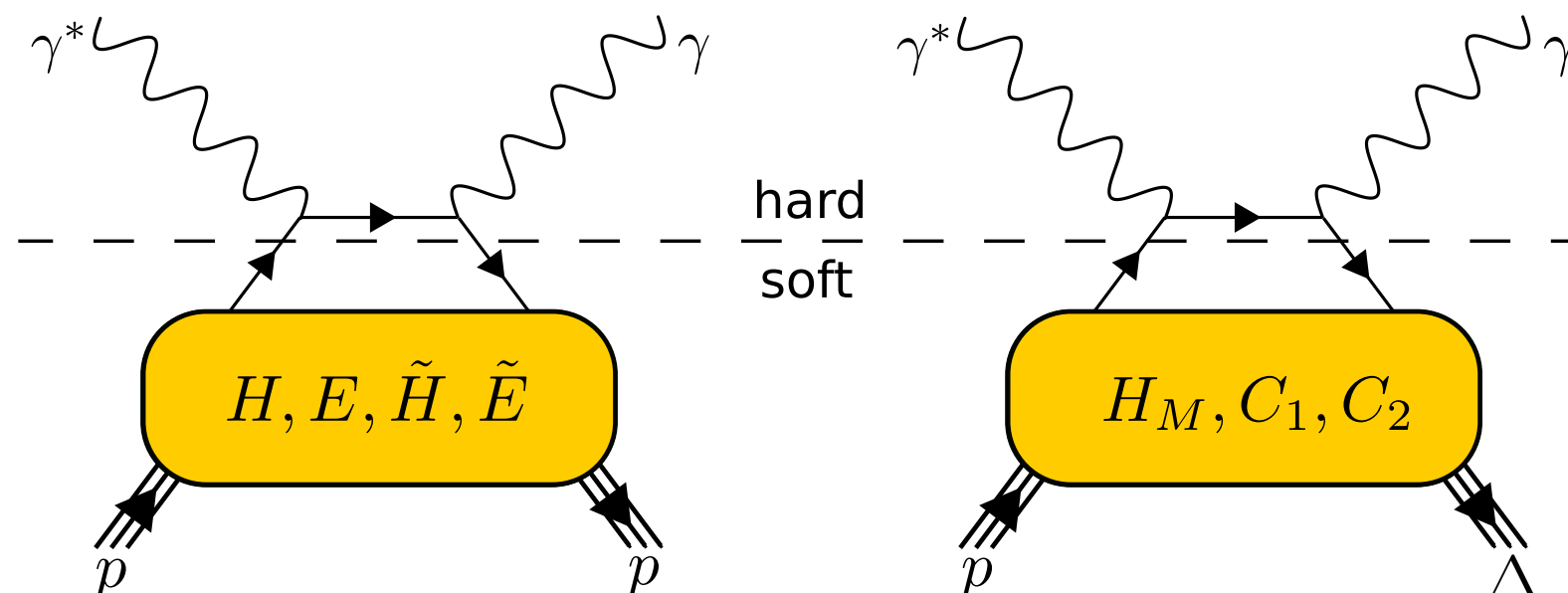
All sets are strongly correlated but the unresolved samples contain an average contribution of 12 -14 % of associated processes

P. Kroll, H. Moutarde, F. Sabatié, Eur. Phys. J. C (2013) 73:2278



Recoil data leads to a significantly better overlap with HEMP data

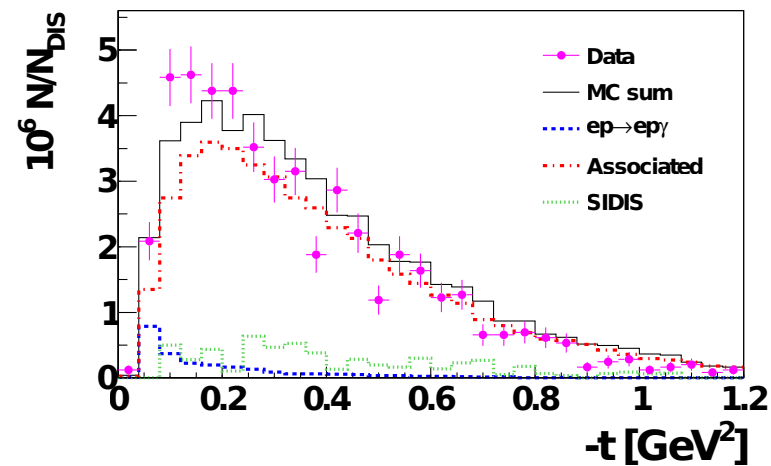
Besides a better understanding of the unresolved sample, associated DVCS in principle also allows further access to GPDs.



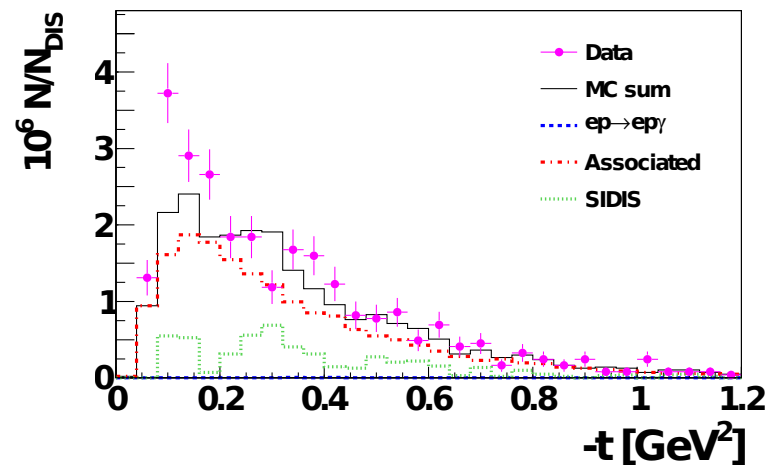
In the large N_c -limit the remaining $N \rightarrow \Delta$ GPDs can be related to the $N \rightarrow N$ isovector GPDs:

$$\begin{aligned}
 H_M(x, \xi, t) &= \frac{2}{\sqrt{3}} \left[E^u(x, \xi, t) - E^d(x, \xi, t) \right] , \\
 C_1(x, \xi, t) &= \sqrt{3} \left[\tilde{H}^u(x, \xi, t) - \tilde{H}^d(x, \xi, t) \right] , \\
 C_2(x, \xi, t) &= \frac{\sqrt{3}}{4} \left[\tilde{E}^u(x, \xi, t) - \tilde{E}^d(x, \xi, t) \right]
 \end{aligned}$$

$$ep \rightarrow e\gamma p\pi^0$$



$$ep \rightarrow e\gamma n\pi^+$$

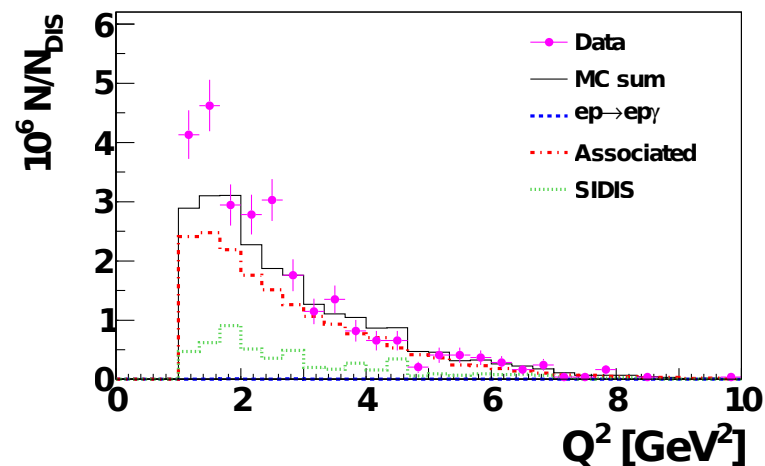
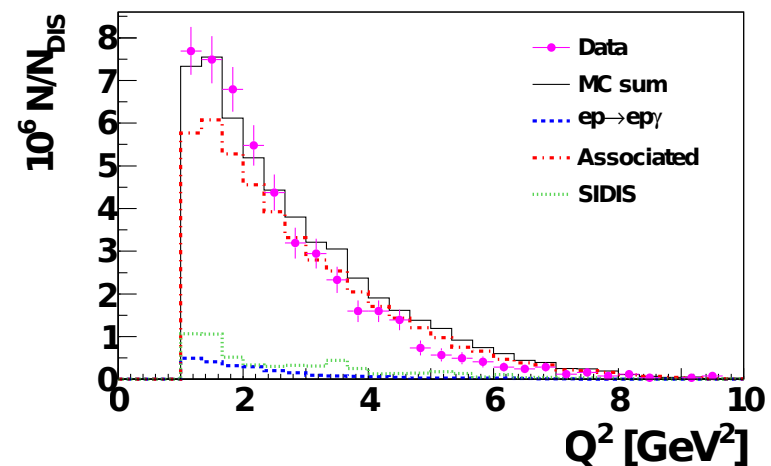
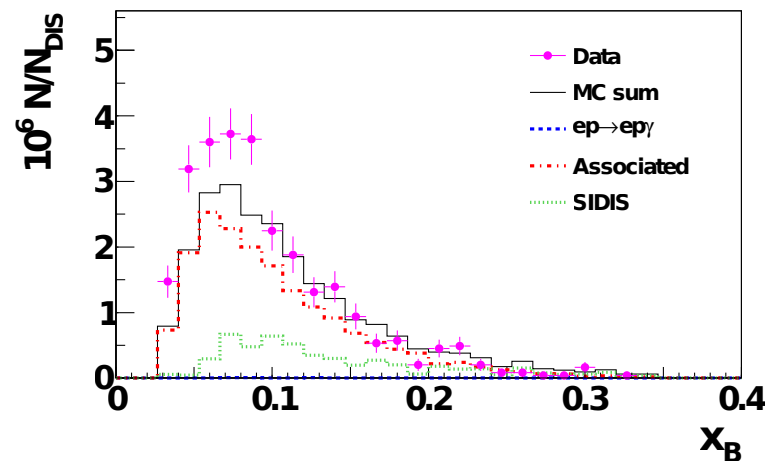
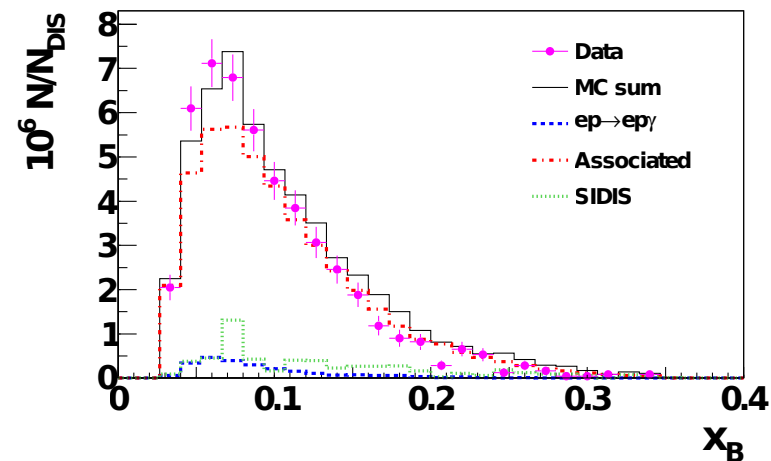


Uncharged particle remains undetected

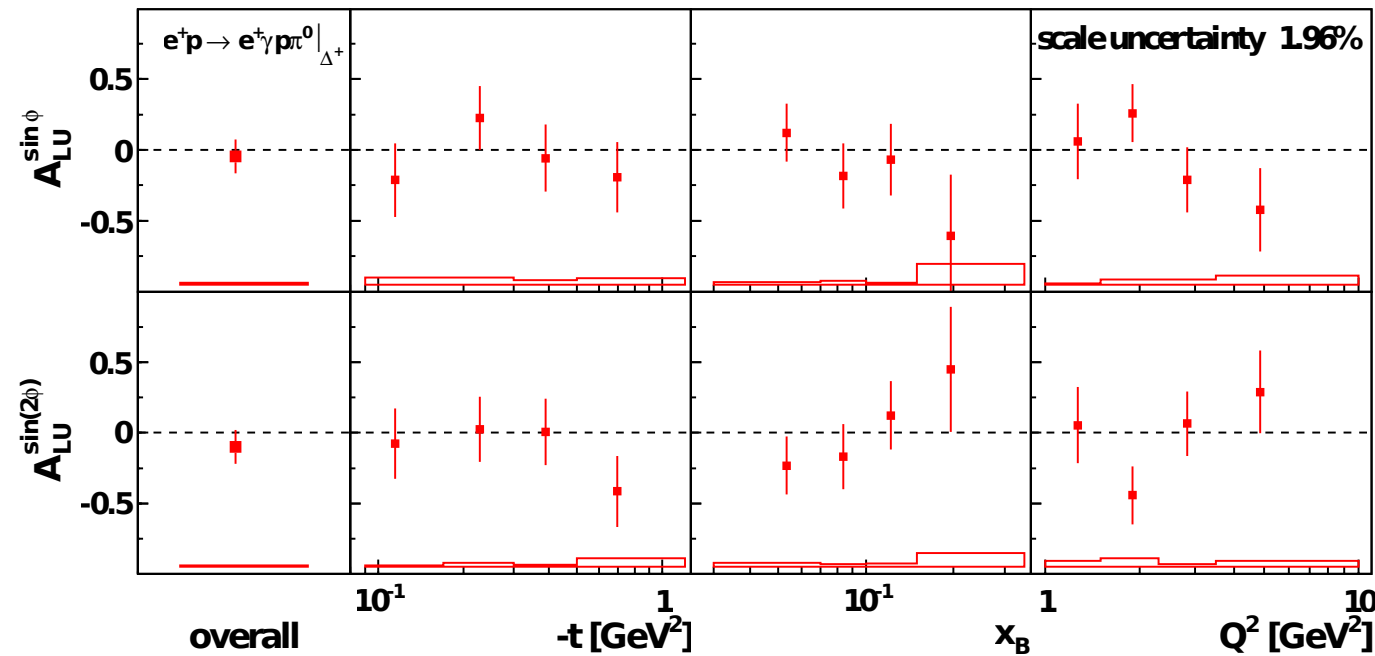
Kinematic fitting in case of $ep \rightarrow e\gamma N\pi$ hypothesis therefore not as strong

Additional selection criteria:

- Recoil PID information
- Lower-cut on $ep \rightarrow e\gamma p$ hypothesis



Beam-spin asymmetries $ep \rightarrow e\gamma p\pi^0$

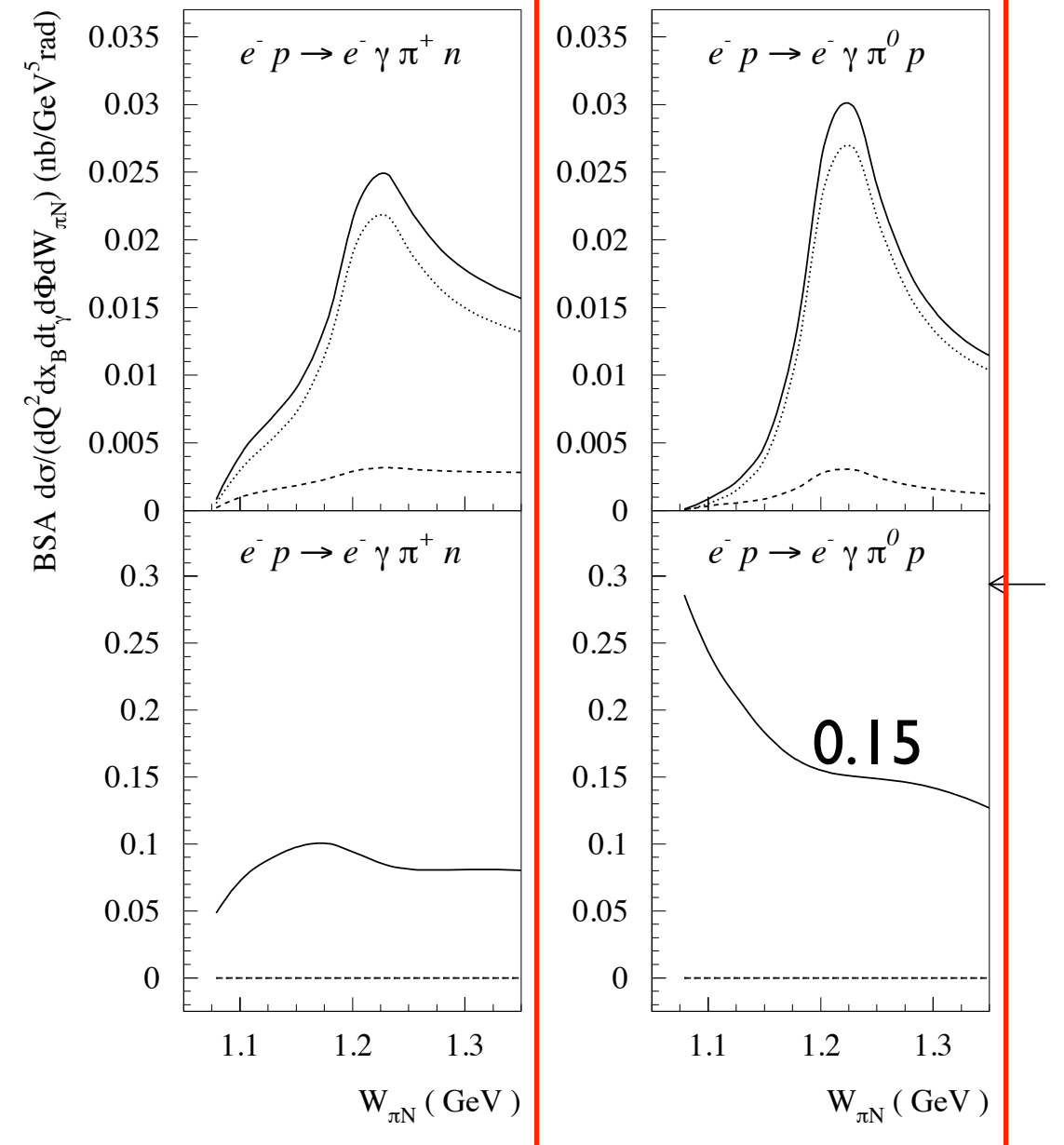


A. Airapetian et al, arXiv:1310.5081; JHEP 14 (in press)

Shown amplitudes are corrected for background
(only overall fractions are listed here):

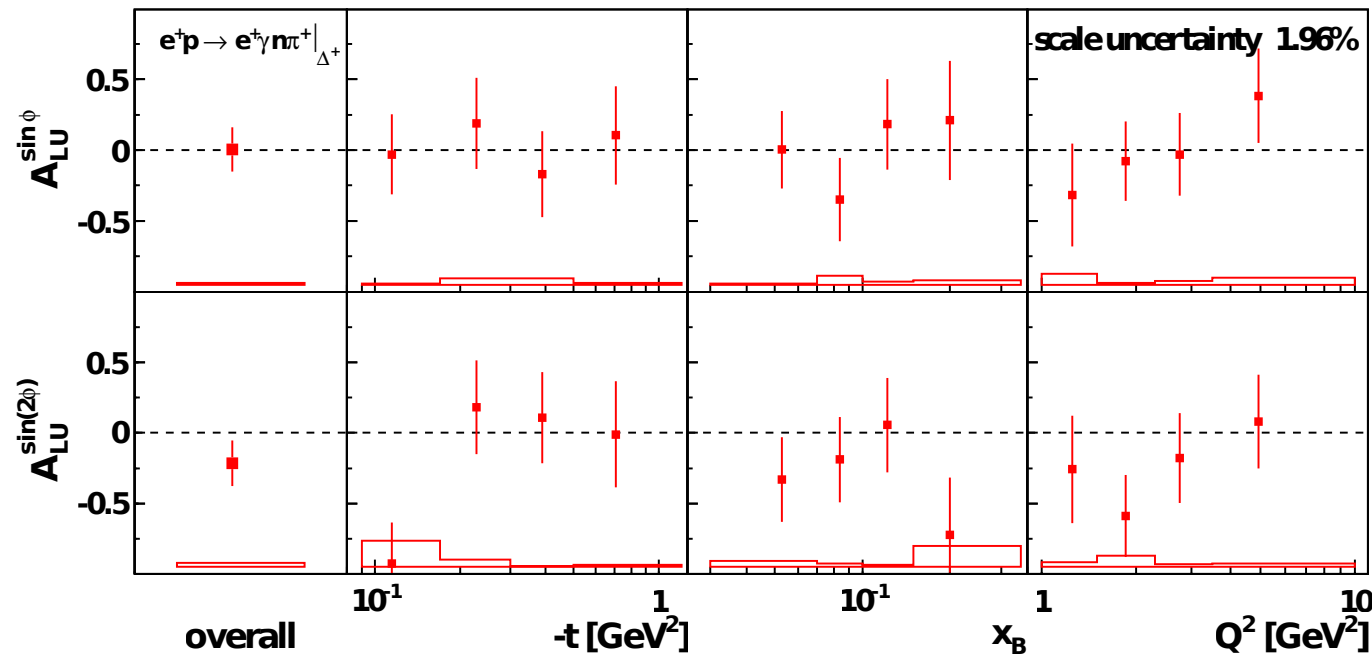
Associated DVCS/BH ($ep \rightarrow e\gamma p\pi^0$)	85 ± 1
Elastic DVCS/BH ($ep \rightarrow e\gamma p$)	4.6 ± 0.1
SIDIS ($ep \rightarrow eX\pi^0$)	11 ± 1

$E_e = 27 \text{ GeV}, Q^2 = 2.5 \text{ GeV}^2, x_B = 0.15, t_\gamma = -0.25 \text{ GeV}^2, \Phi = 90^\circ$



P.A. M. Guichon, L. Mossé, M. Vanderhaeghen,
Phys. Rev. D 68 (2003)

Beam-spin asymmetries $ep \rightarrow e\gamma n\pi^+$

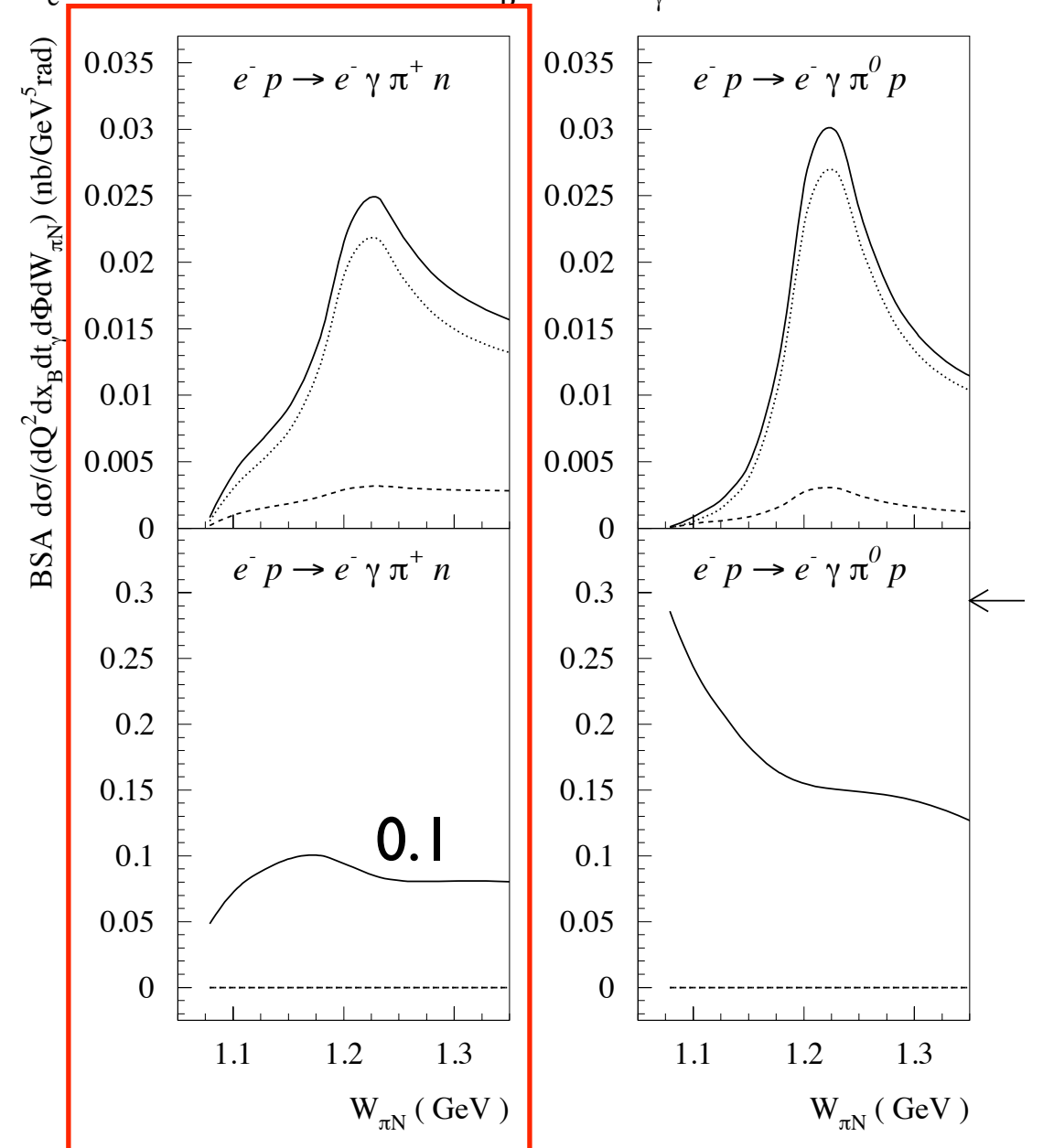


A. Airapetian et al, arXiv:1310.5081; JHEP 14 (in press)

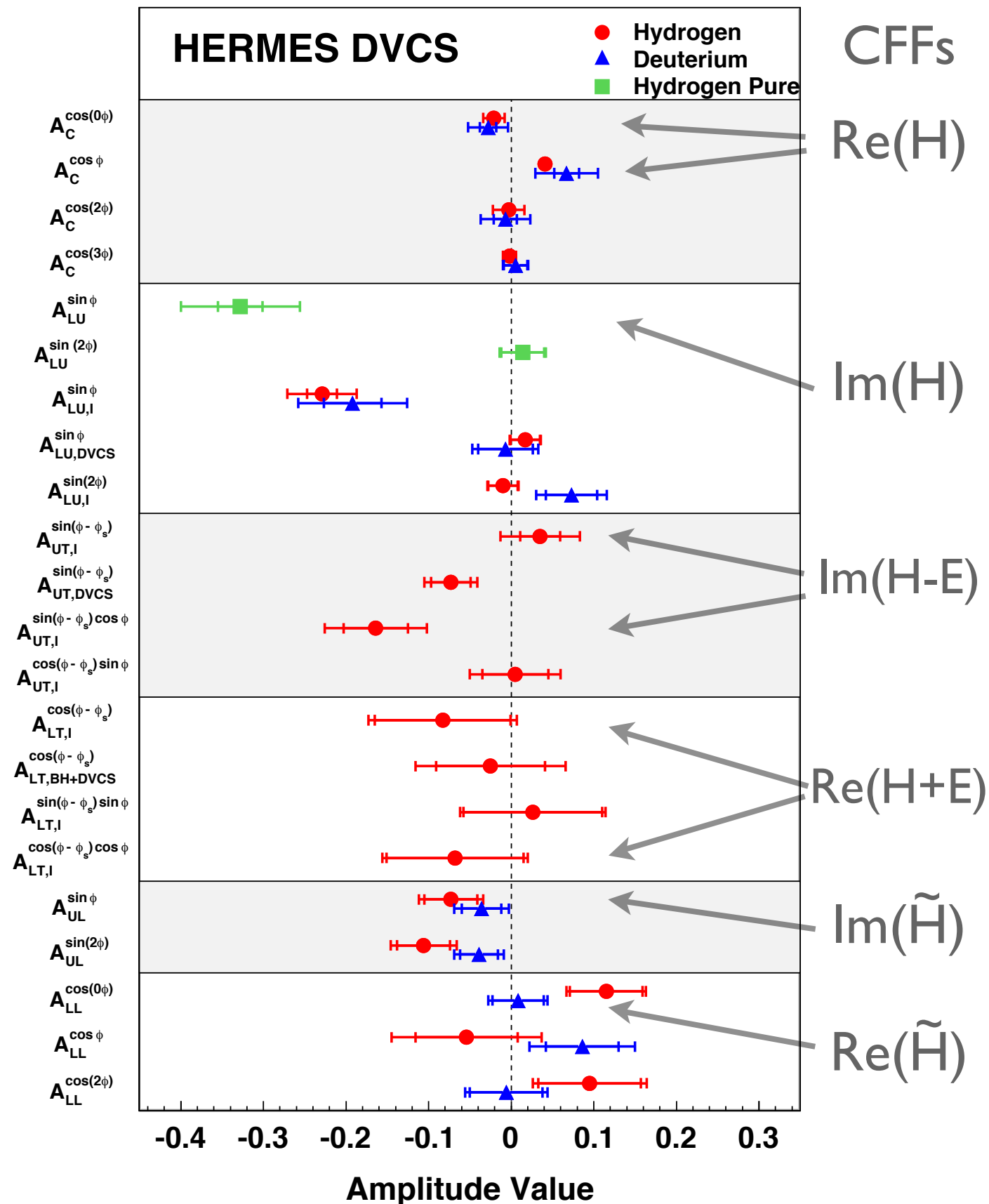
Shown amplitudes are corrected for background
(only overall fractions are listed here):

Associated DVCS/BH ($ep \rightarrow e\gamma n\pi^+$)	77 ± 2
Elastic DVCS/BH ($ep \rightarrow e\gamma p$)	0.2 ± 0.1
SIDIS ($ep \rightarrow eX\pi^0$)	23 ± 3

$E_e = 27 \text{ GeV}, Q^2 = 2.5 \text{ GeV}^2, x_B = 0.15, t_\gamma = -0.25 \text{ GeV}^2, \Phi = 90^\circ$



P.A. M. Guichon, L. Mossé, M. Vanderhaeghen,
Phys. Rev. D 68 (2003)

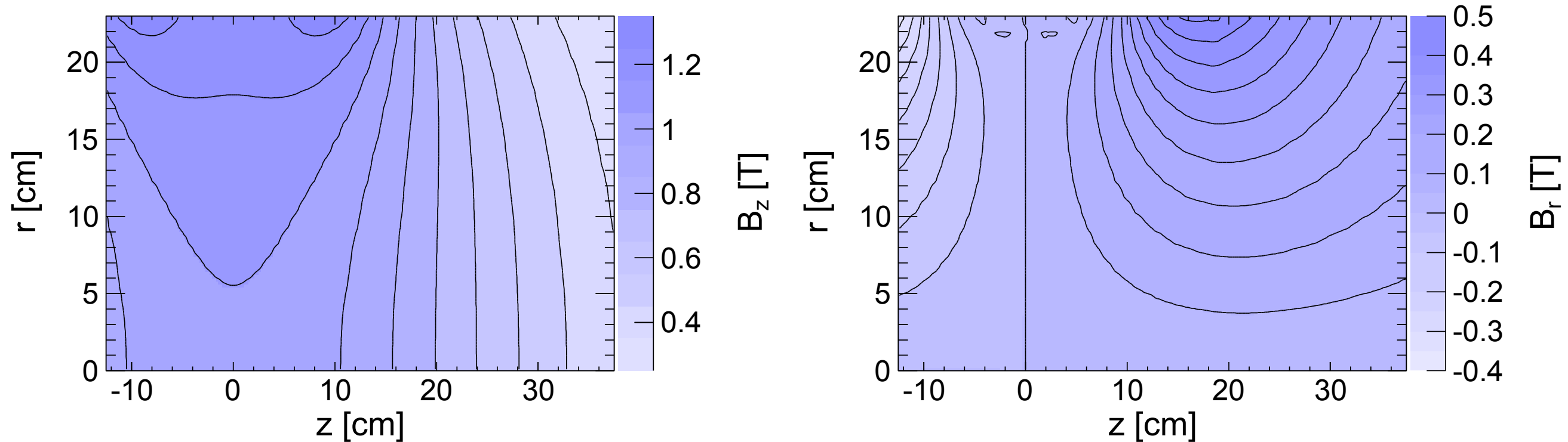


- The HERMES Recoil detector allows complete event reconstruction for $ep \rightarrow e\gamma p$ and reduces the resonant background to a negligible level
- First measurement of asymmetry amplitudes in associated DVCS ($ep \rightarrow e\gamma\pi N$)

A. Airapetian et al, JHEP 06 (2008) 066,
 Nucl. Phys. B 829 (2010) 1-27, JHEP 06 (2010) 019,
 Nucl. Phys. B 842 (2011) 265-298, JHEP 07 (2012) 032,
 Phys. Lett. B 704 (2011) 15-23, JHEP 10 (2012) 042,
 arXiv:1310.5081; JHEP 14 (in press),
 JINST 8 P05012 (2013)

Backup

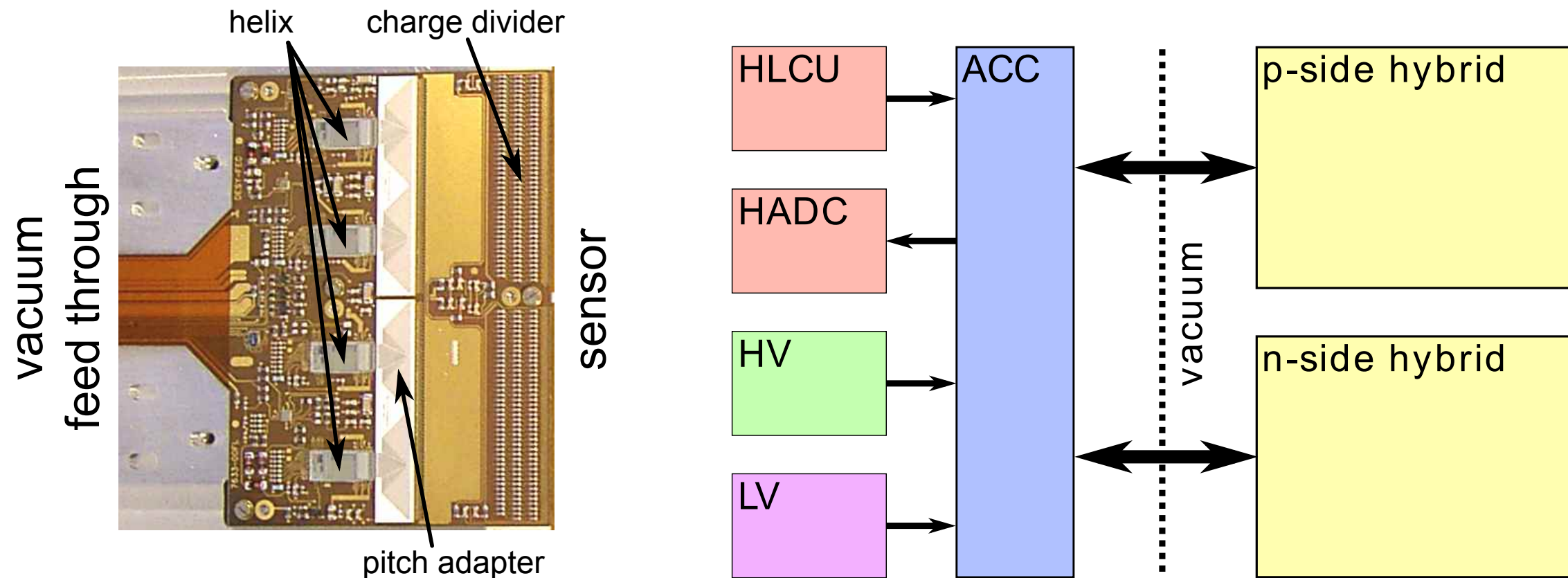
Recoil magnet



NbTi-wires with 0.85 mm diameter mounted on copper rings

166 A operating current $\rightarrow$ 1 T at center

SSD (silicon strip detector)

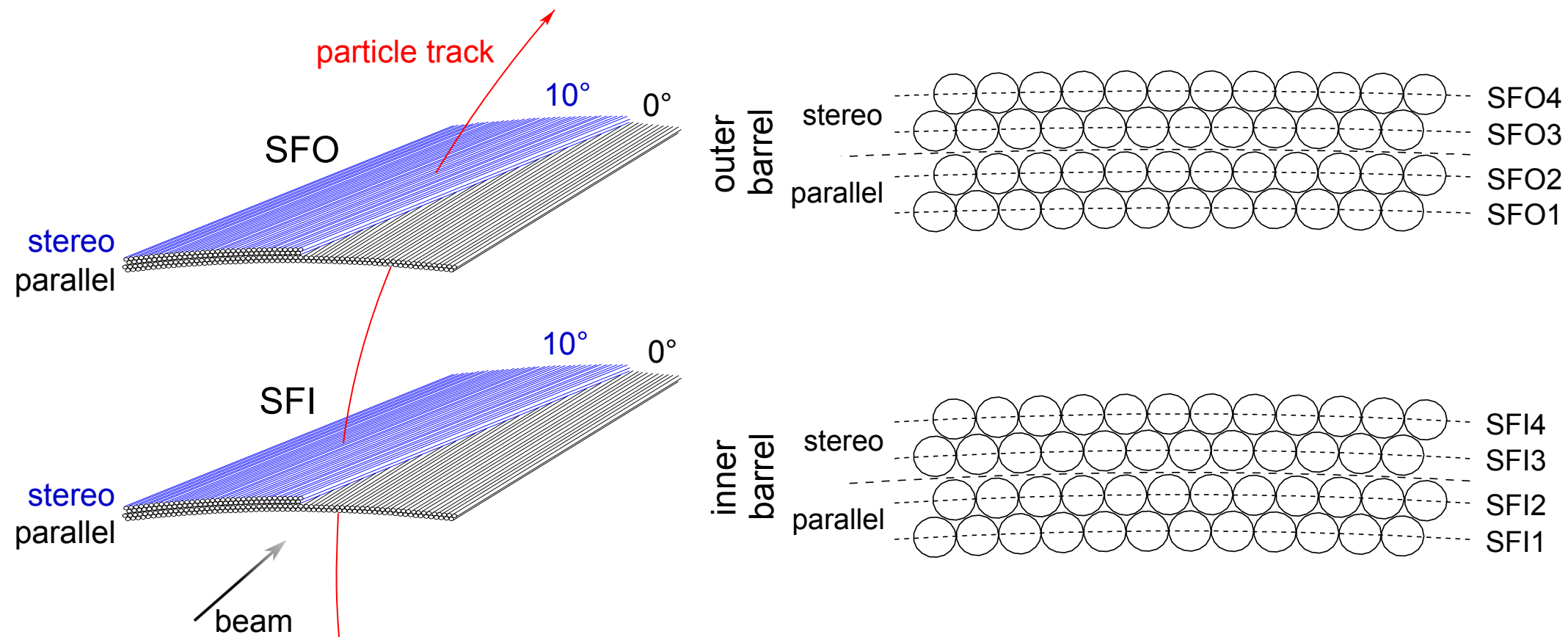


5.8 cm away from lepton beam, 1.5 cm gap

sensor thickness 295 μm - 315 μm

thickness of target cell 75 μm

SFT (scintillating fibre tracker)

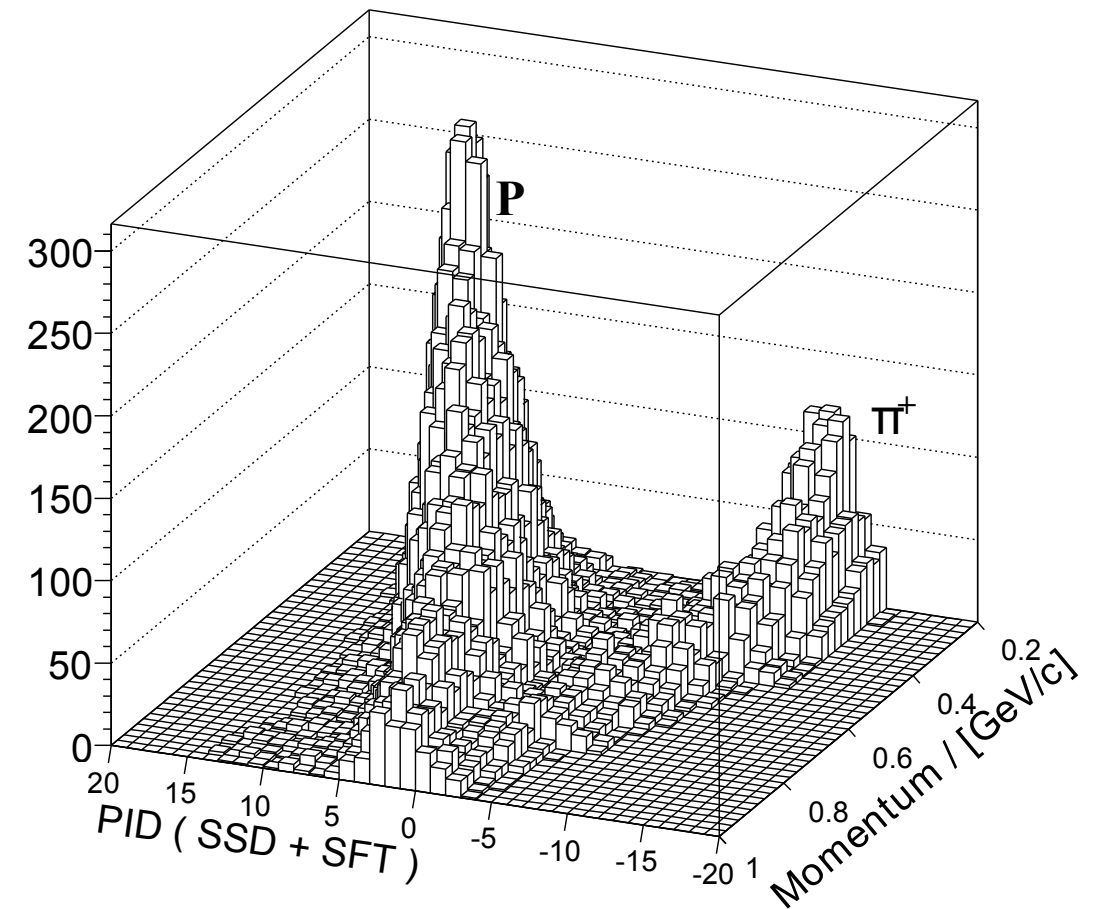
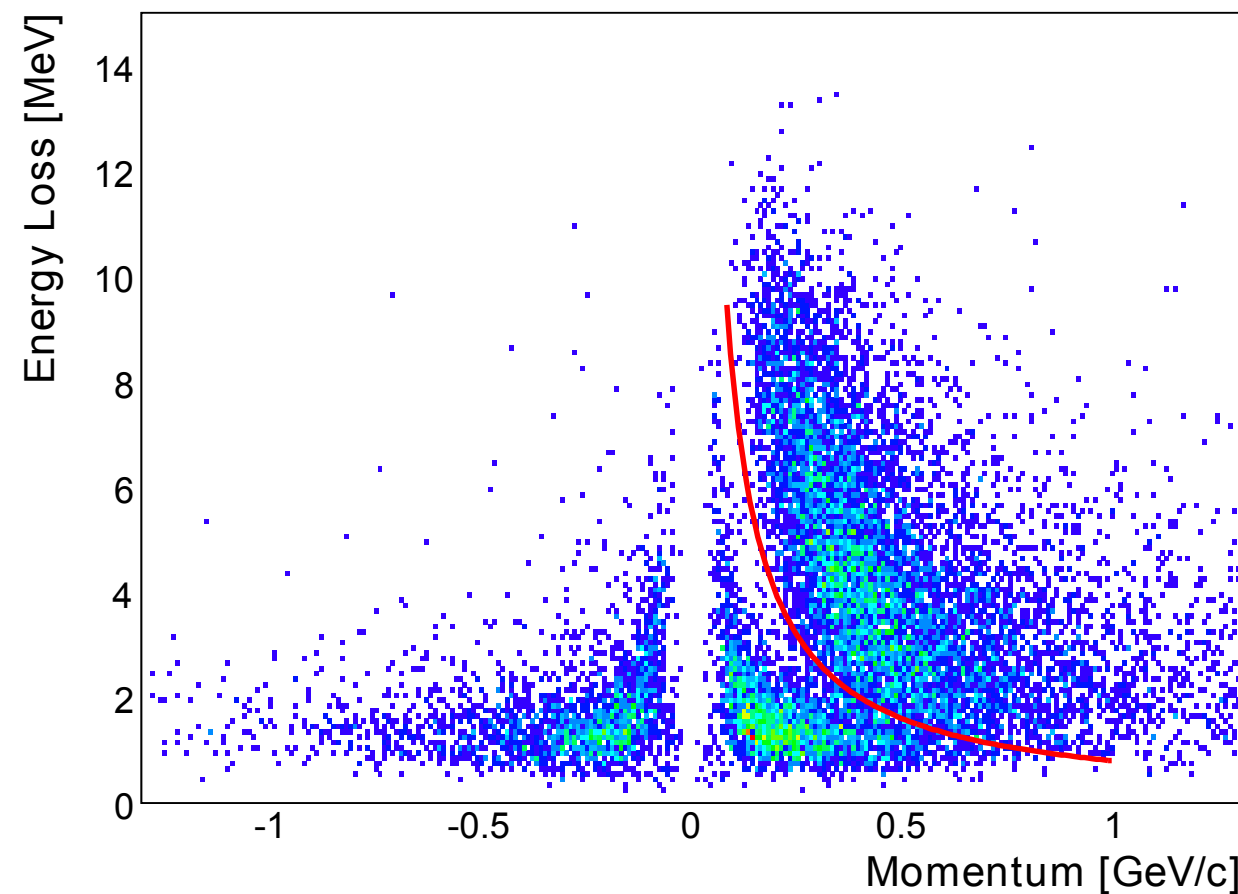


11.5 cm (18.5 cm) inner (outer) radius

1318+1320 (2198+2180) fibres with a diameter of 1 mm each

readout by 64-channel Hamamatsu H7546B MAPMTs

Recoil PID

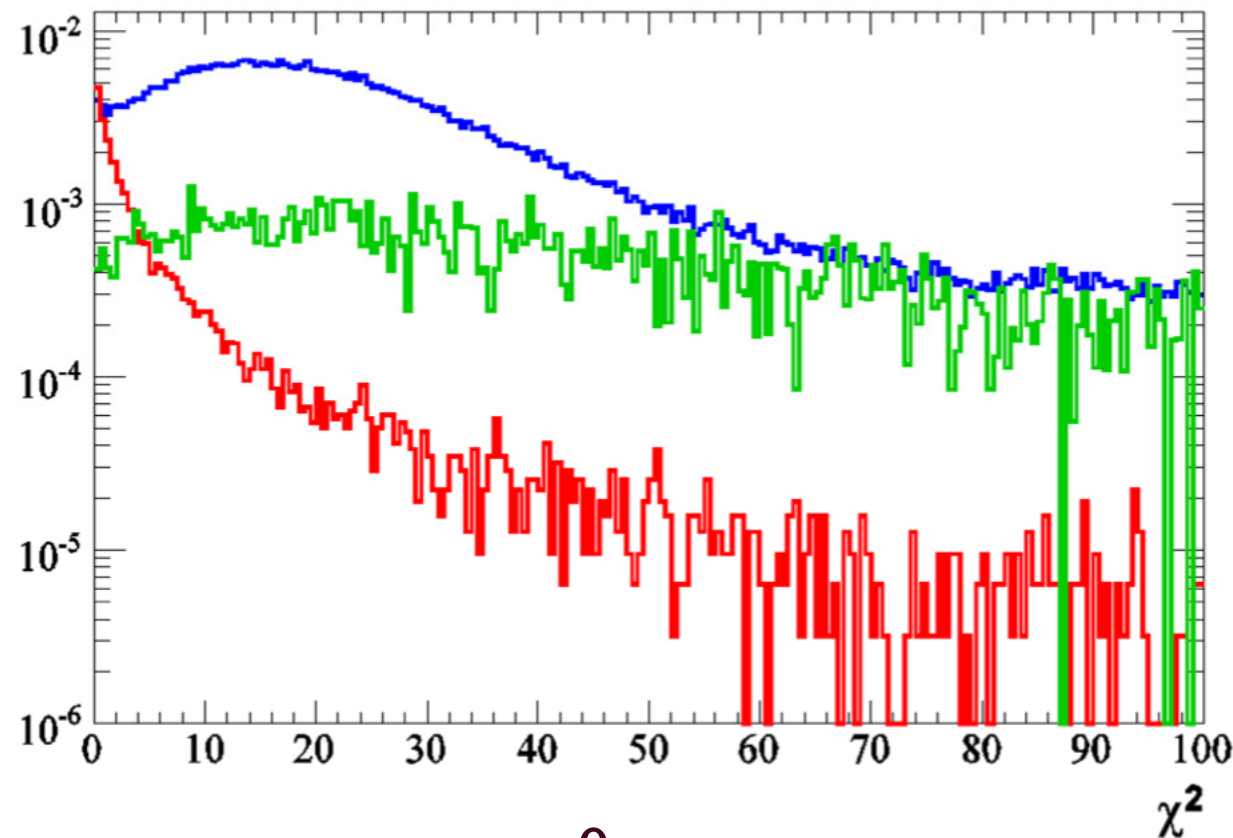


discrimination between protons and positively charged pions

parent distributions were crucial and determined experimentally

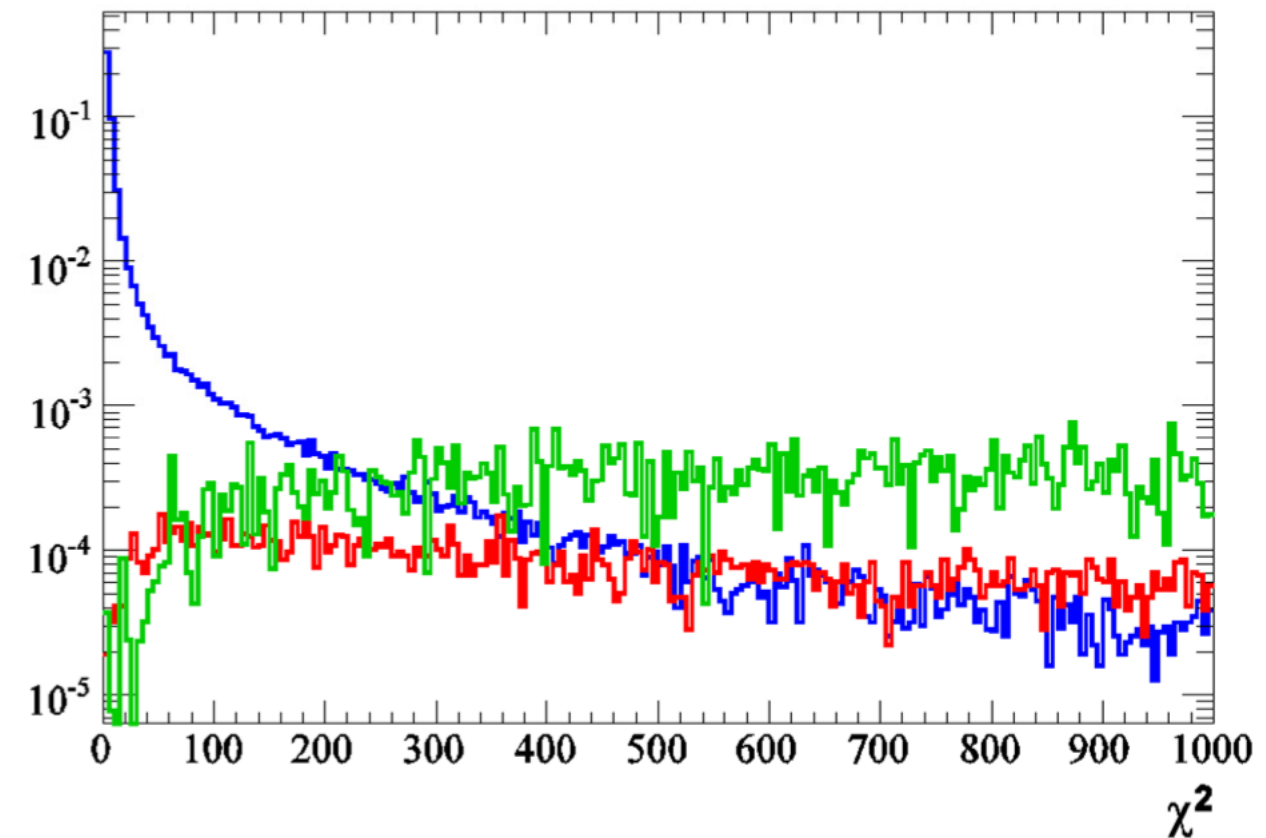
Kinematic fitting for $ep \rightarrow e\gamma p\pi^0$

$ep \rightarrow e\gamma p\pi^0$ $ep \rightarrow e\gamma p$ SIDIS



$ep \rightarrow e\gamma p\pi^0$ hypothesis

$$\chi^2_{ep \rightarrow e\gamma p\pi^0} < 4.6$$



$ep \rightarrow e\gamma p$ hypothesis

$$\chi^2_{ep \rightarrow e\gamma p} > 50$$

Using powerful kinematic fitting of $ep \rightarrow e\gamma p$ hypothesis
is crucial for the $ep \rightarrow e\gamma N\pi$ analysis