Latest News on DVCS from HERMES

Caroline Riedl

EIC Meeting at BNL

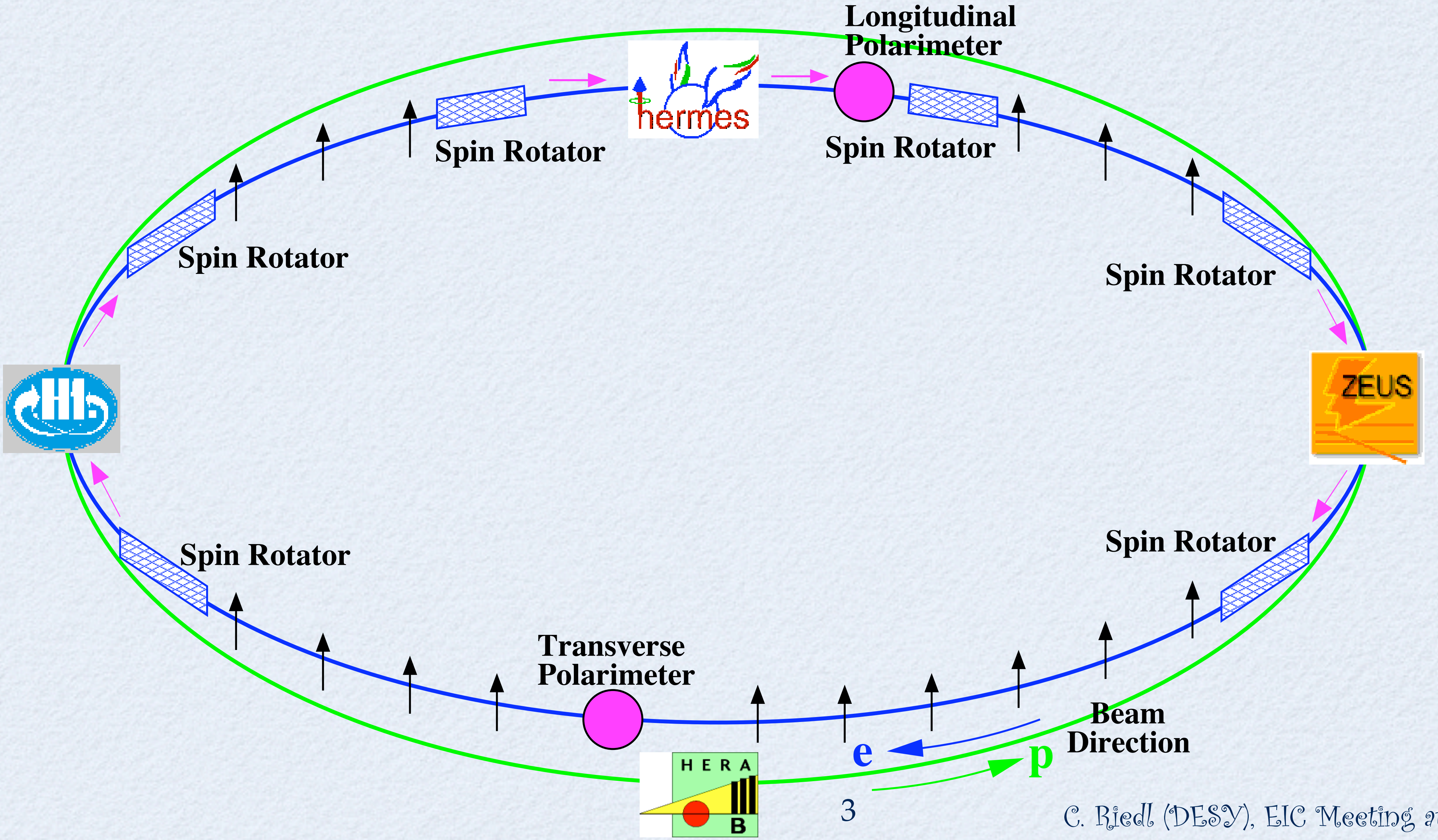
August 25, 2009

Latest News on DVCS from HERMES

- Appetizer: HERA and HERMES
- Motivation: Generalized Parton Distributions, orbital angular momentum and 3-dimensional nucleon structure
- Measurements of azimuthal asymmetries in DVCS
  - Beam helicity and charge asymmetries on hydrogen and nuclear targets
  - Transverse target spin asymmetry on hydrogen
- A Recoil Detector for HERMES

HERA @ DESY in Hamburg, Germany

- Polarized electron/positron beam of 27.6 GeV and 40mA
- Beam polarization 30...65%, 2 beam helicities
- Proton beam of 920 GeV / 90 mA



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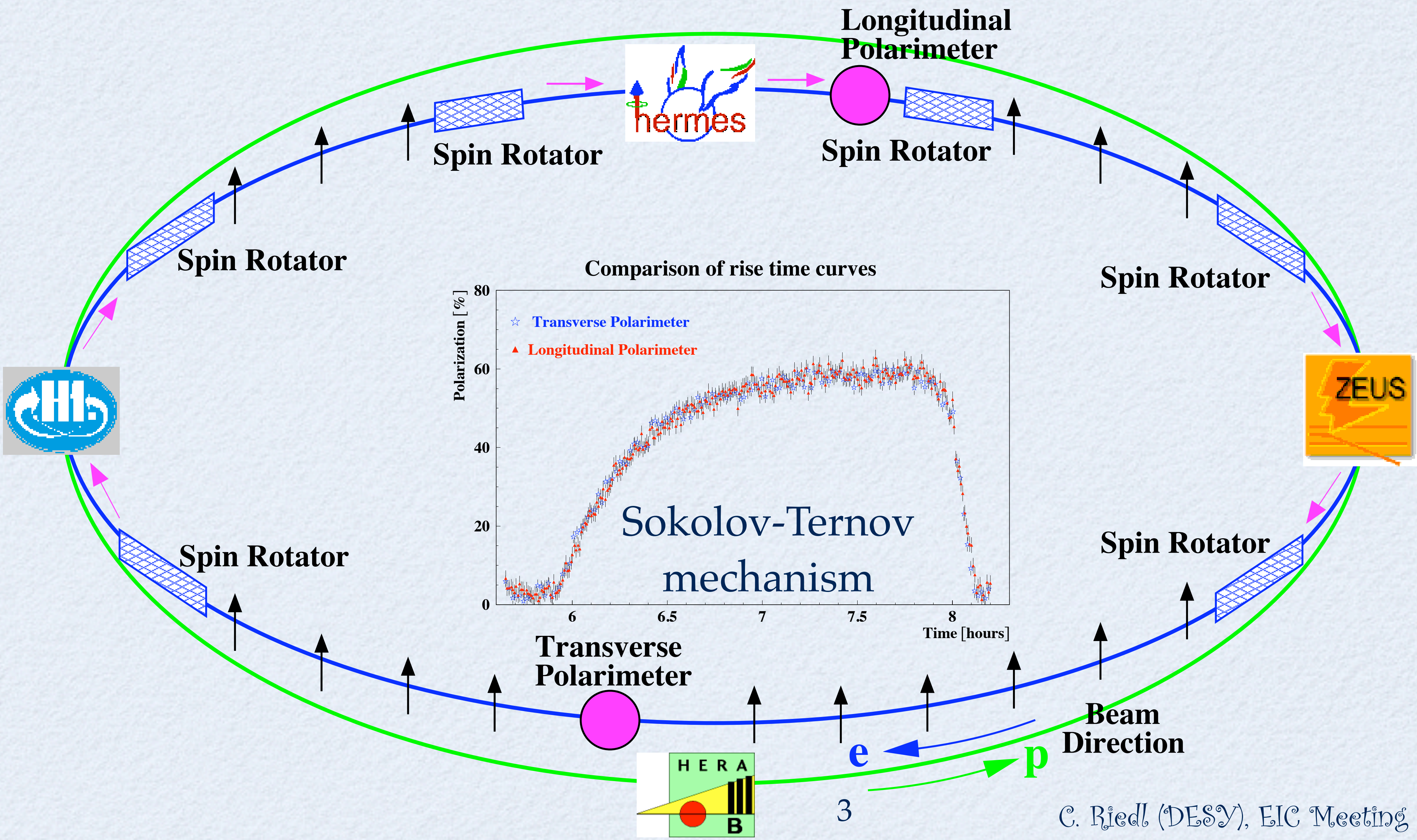
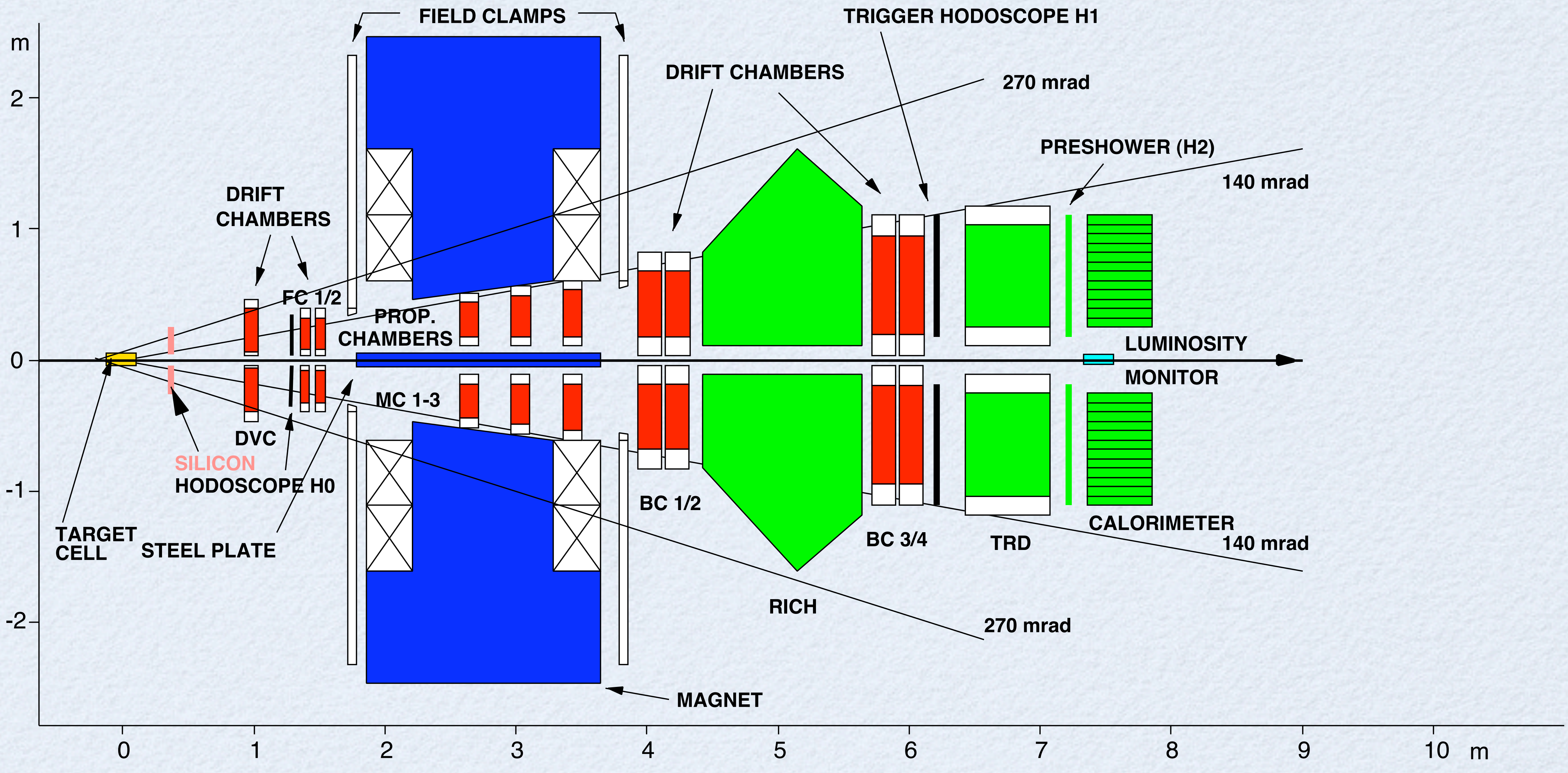


HERMES: HERa MEasurement of Spin



C. Riedl (DESY), EIC Meeting at BNL, August 25, 2009

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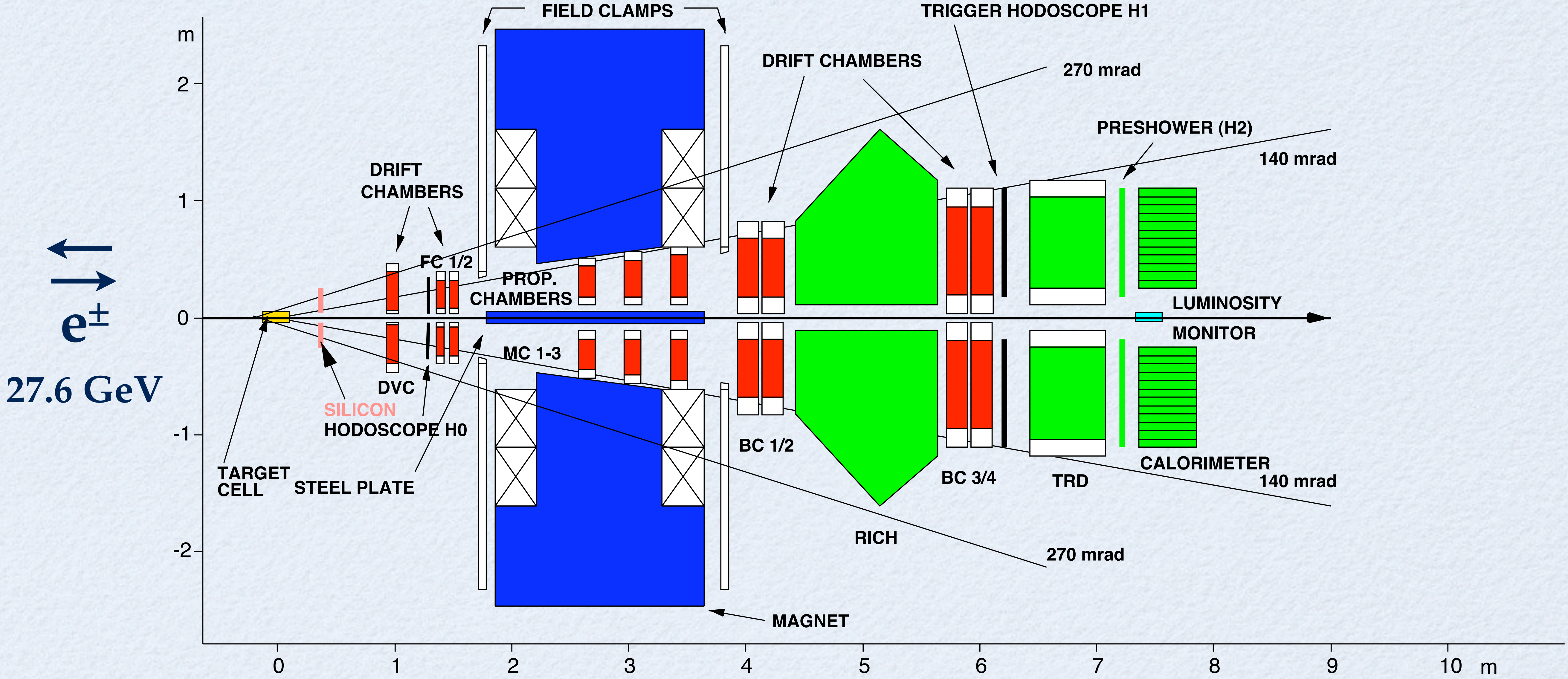

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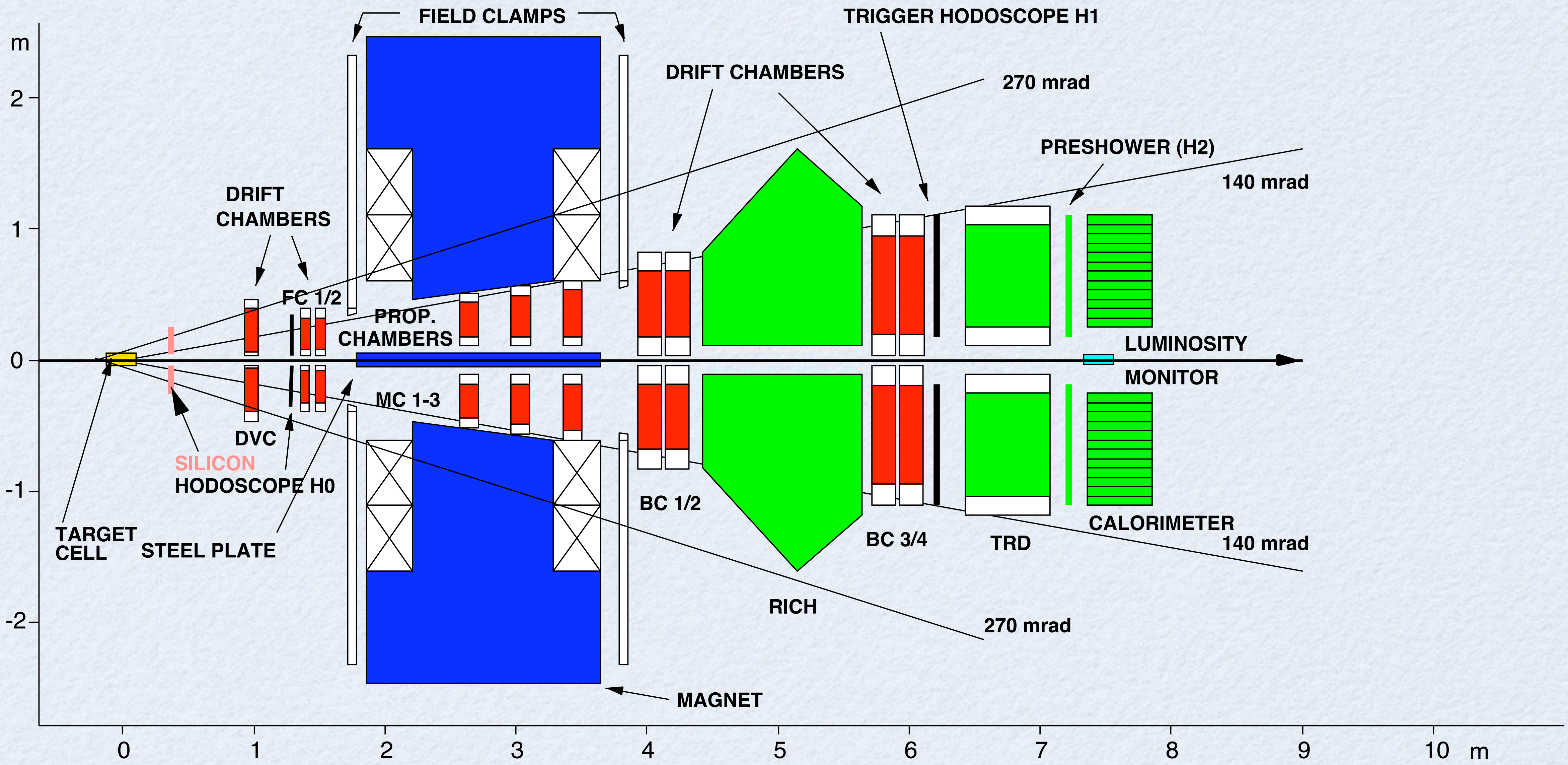
$\overleftarrow{\quad}$ $\overrightarrow{\quad}$

$e^{\pm}$

27.6 GeV



$\vec{H}$, $H^{\uparrow}$, $\vec{D}$

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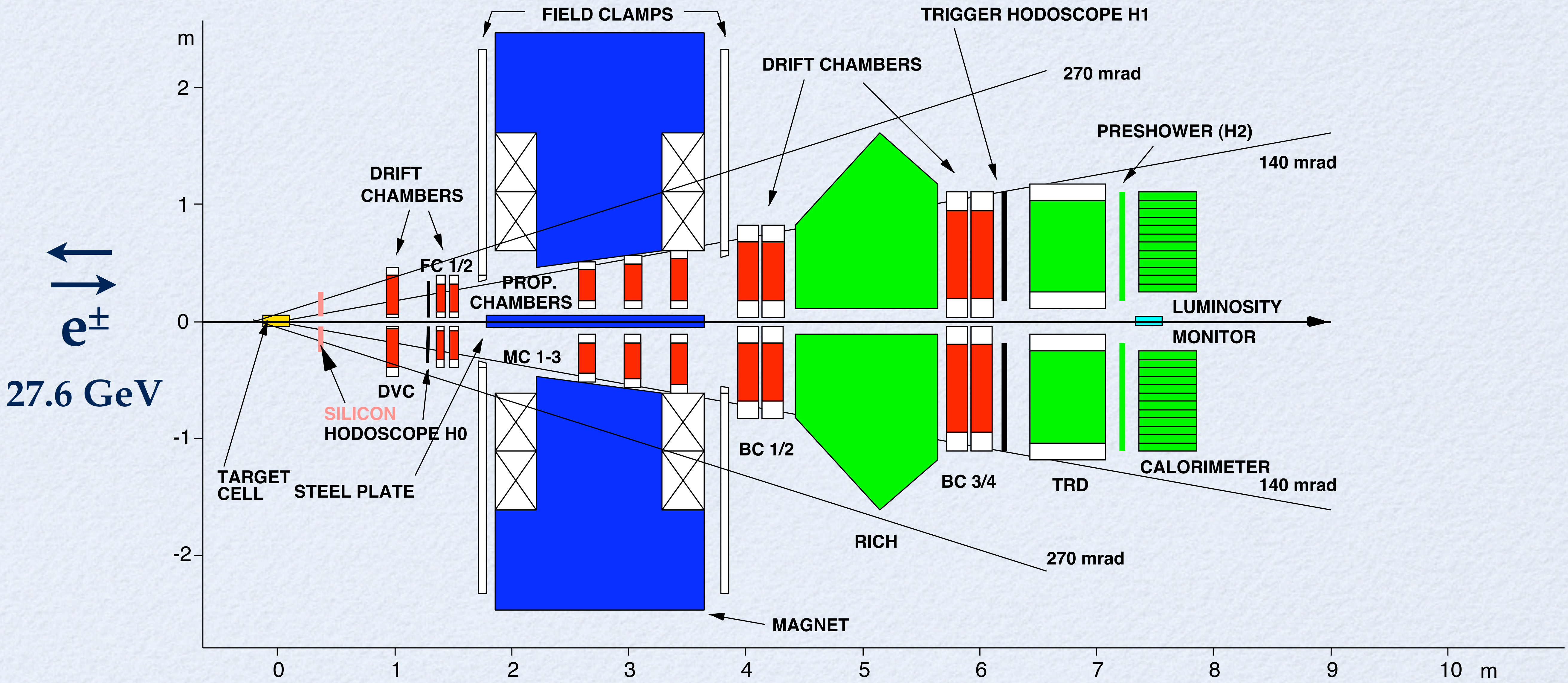

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H, D

He, N, Ne, Kr, Xe

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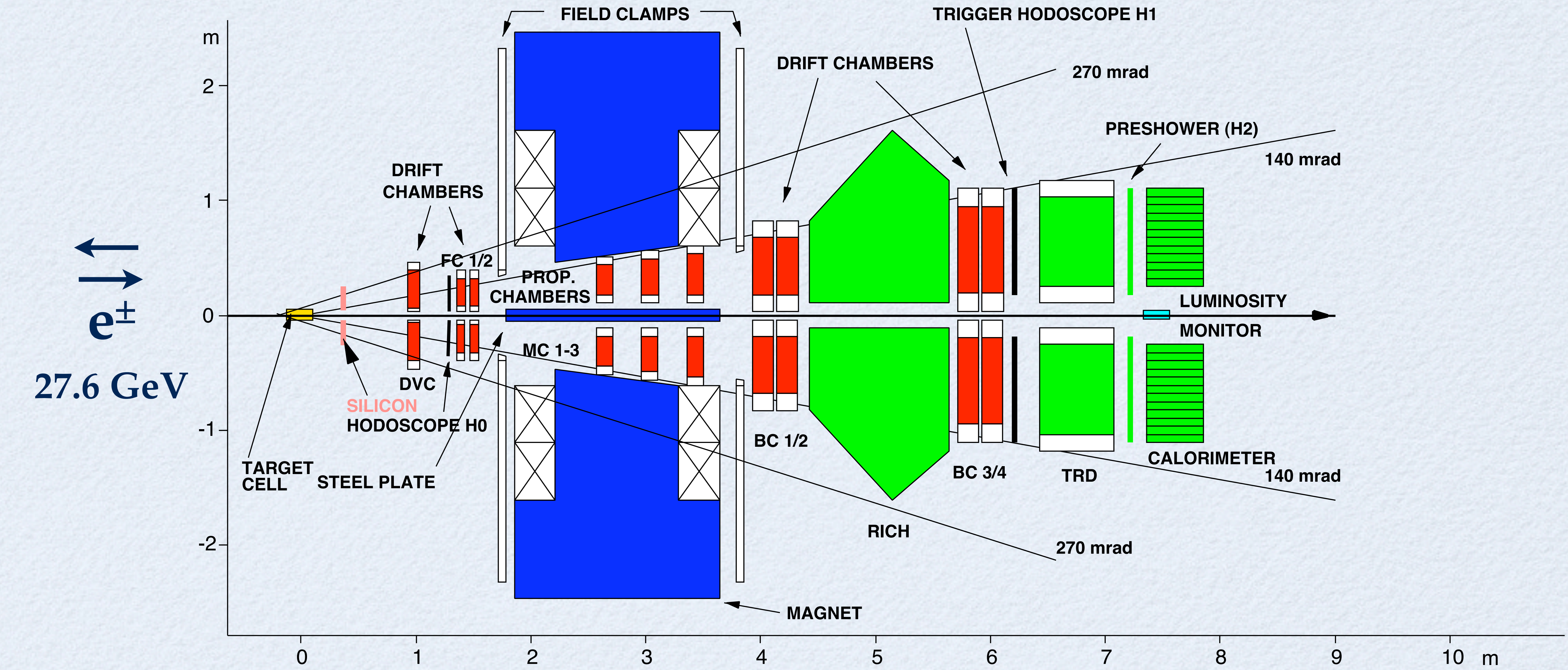

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Tracking
momentum resolution:
$\leq 2\%$
angular resolution:
0.3...0.6 mrad

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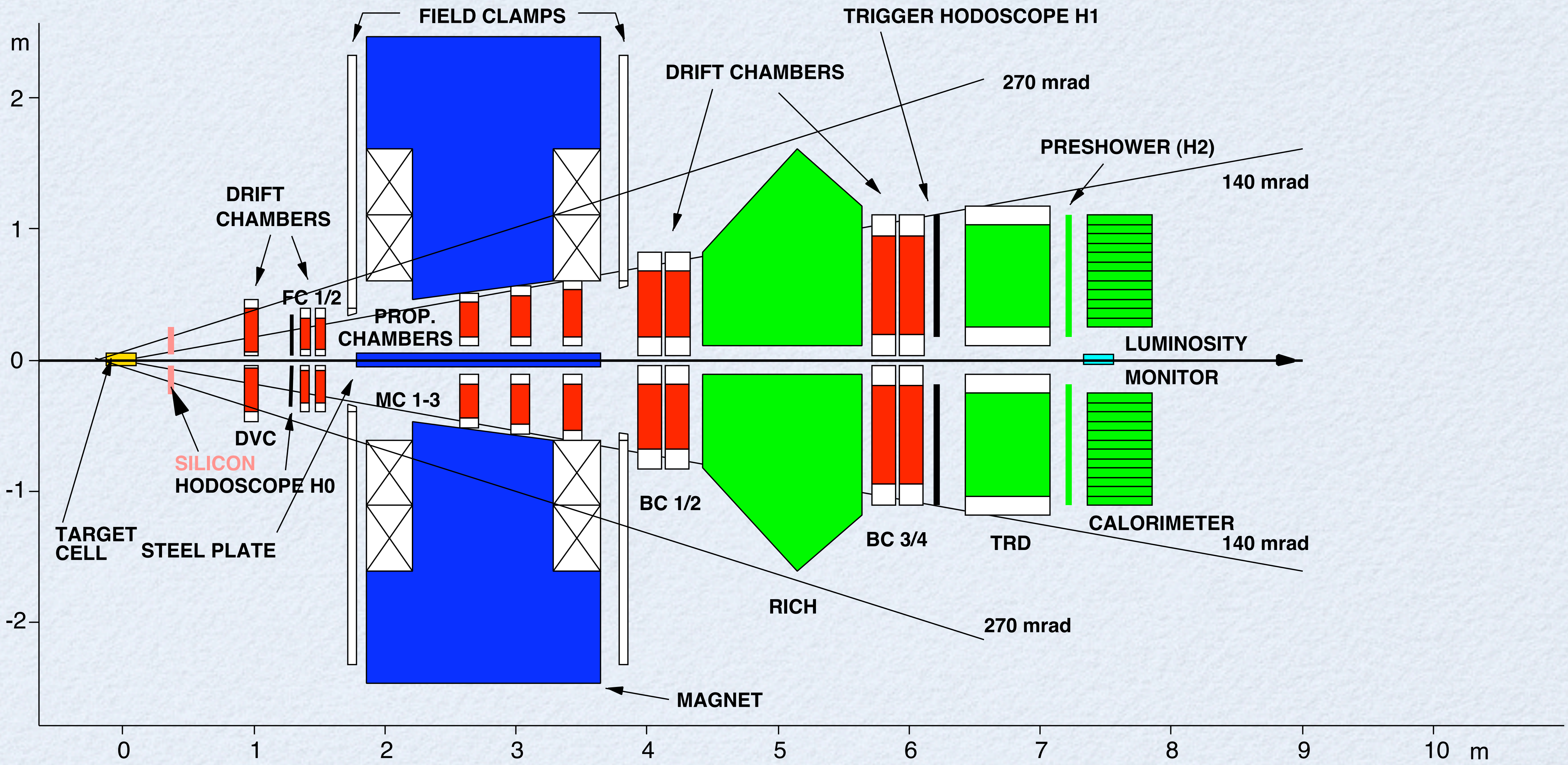

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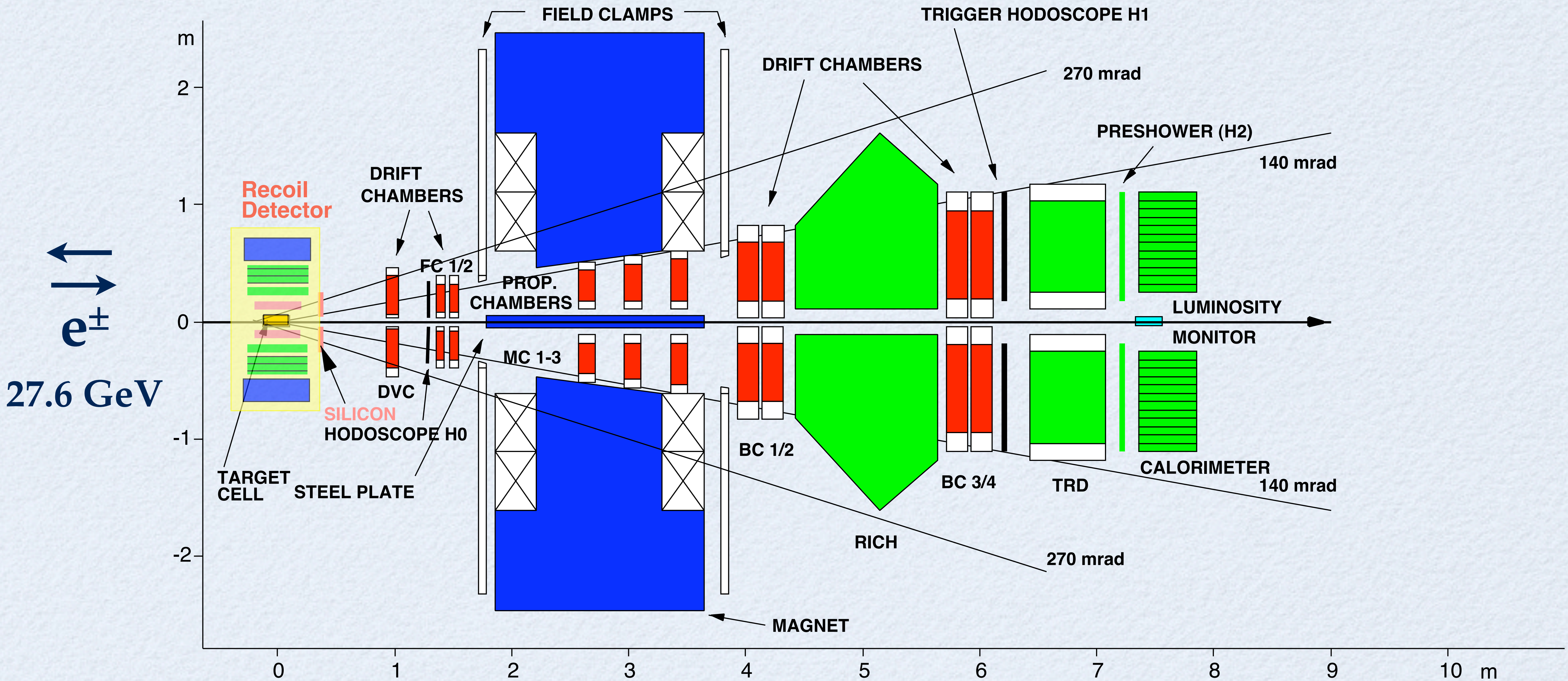

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Deep Inelastic Scattering in ep collisions

Inclusive kinematics

Virtual photon virtuality:

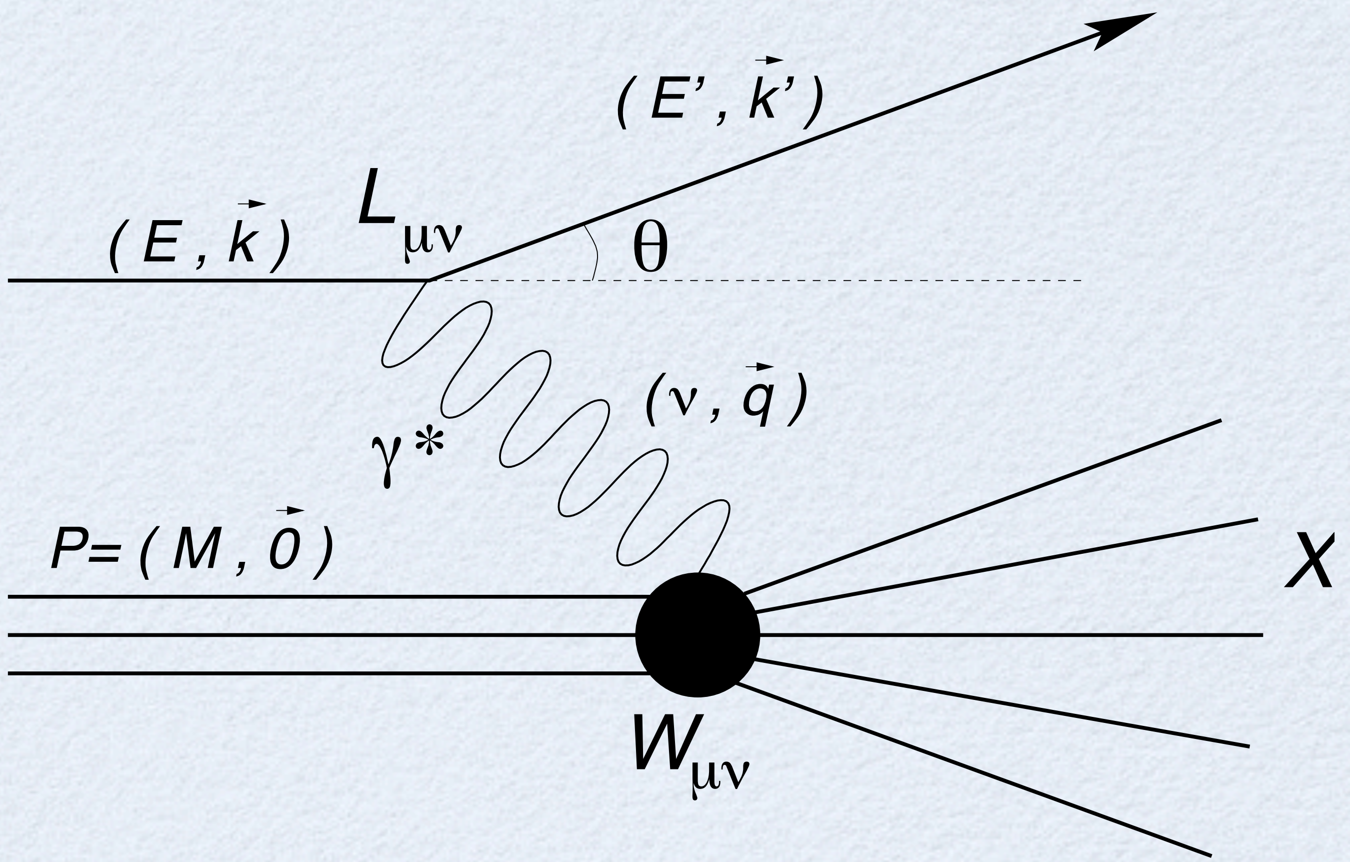
$$Q^2 \equiv -q^2 := (k - k')^2 \overset{\text{lab}}{\approx} 4EE' \sin^2(\theta/2)$$

Bjørken scaling variable:

$$x_\mathrm{B} := \frac{Q^2}{2Pq} \overset{\text{lab}}{=} \frac{Q^2}{2M(E - E')}$$

Invariant mass squared of X:

$$W^2 := (P + q)^2 \overset{\text{lab}}{=} M^2 + 2M(E - E') - Q^2$$



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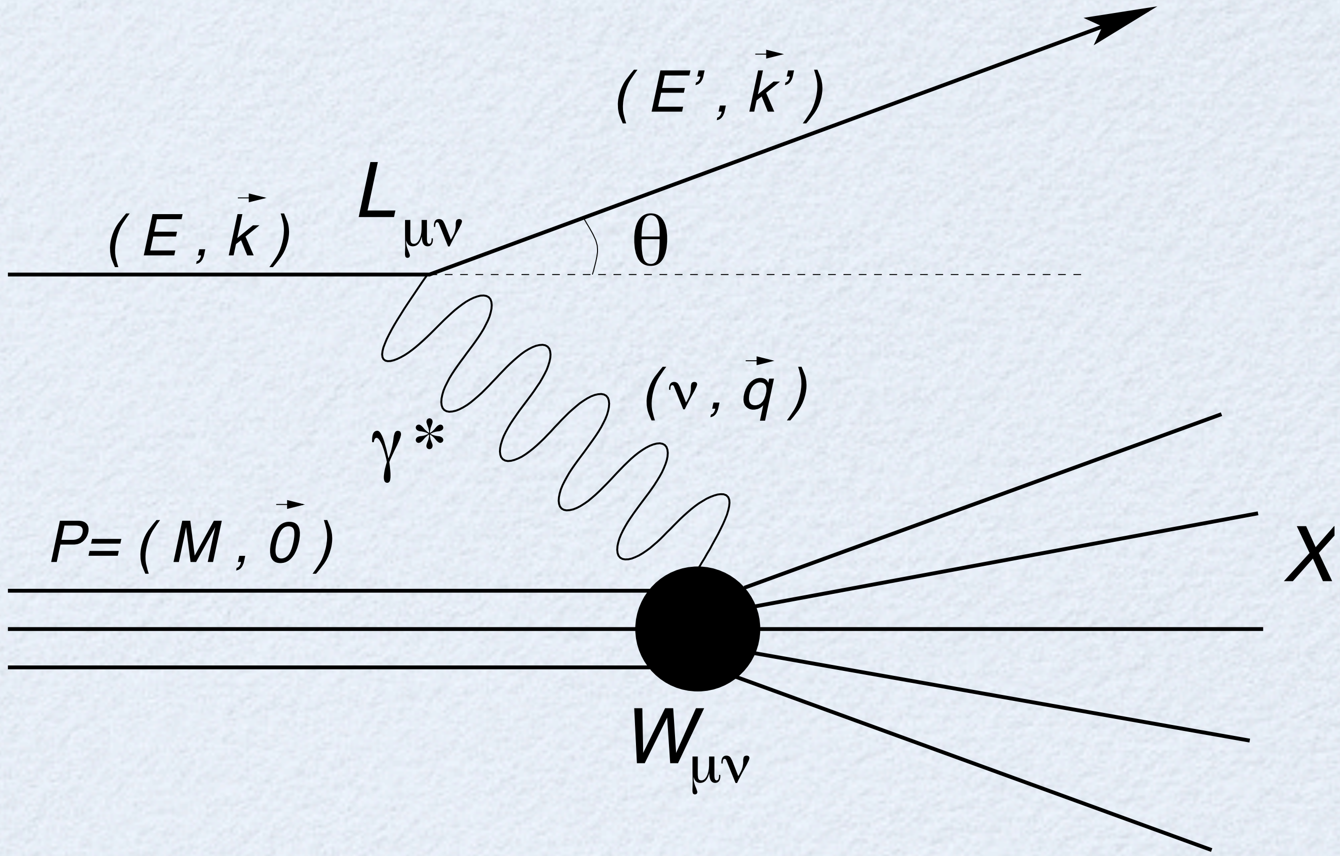
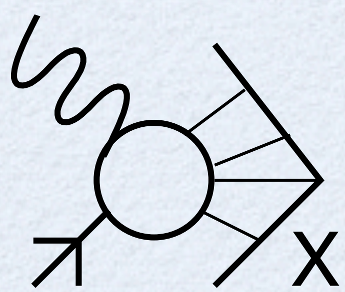


$\sigma_{\rm DIS} \sim \sum_X \Big|$  $\Big|^2$

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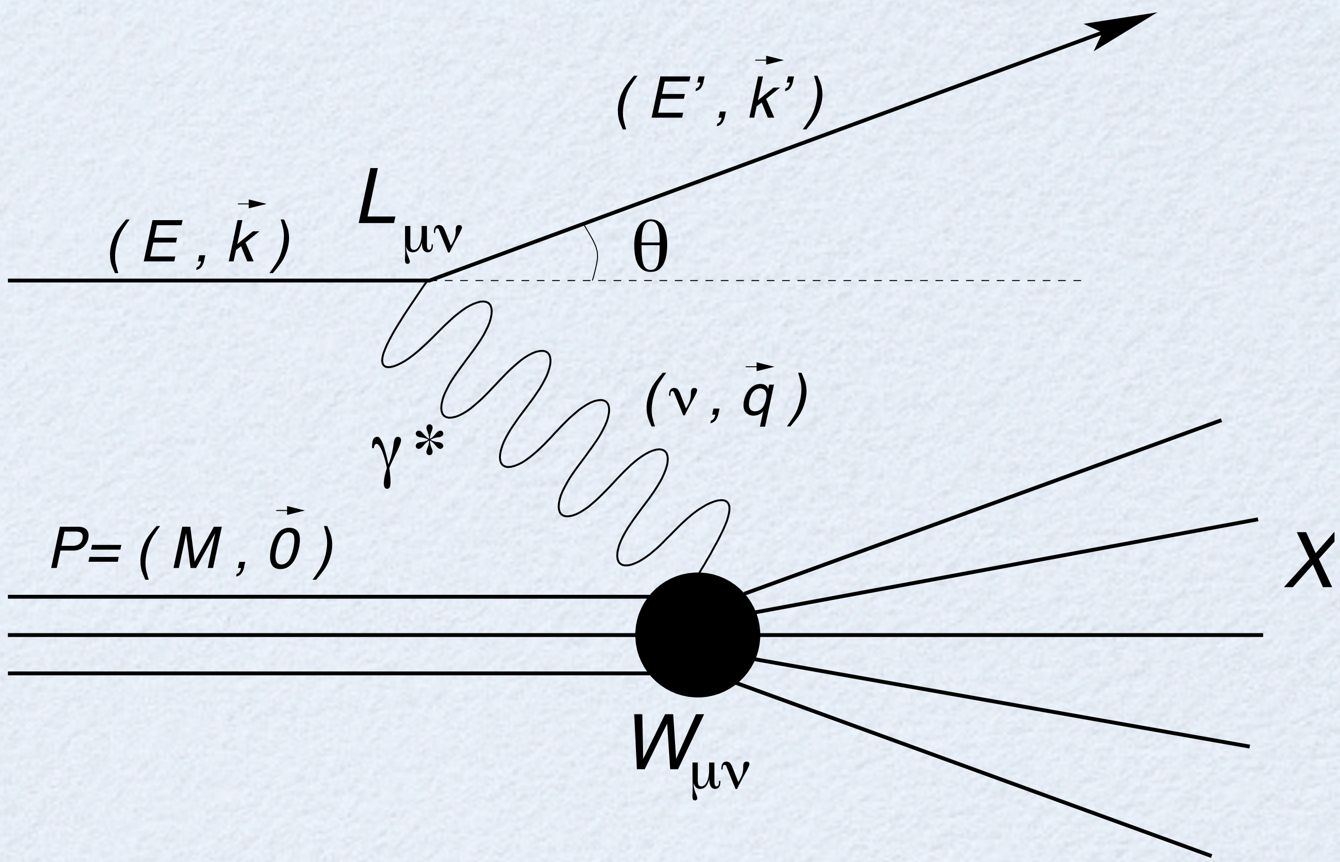
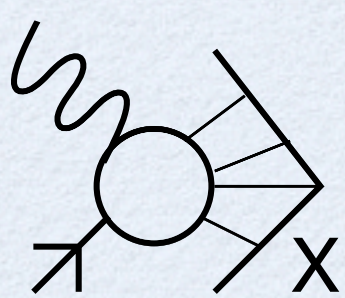


$\sigma_{\text{DIS}} \sim \sum_X$ |  | ^{2}

$$\left.\frac{\mathrm{d}^2\sigma}{\mathrm{d}E'\mathrm{d}\Omega}\right|_{1\gamma^*} = \frac{\alpha^2}{2MQ^4}\frac{E'}{E} L_{\mu\nu} W^{\mu\nu}$$

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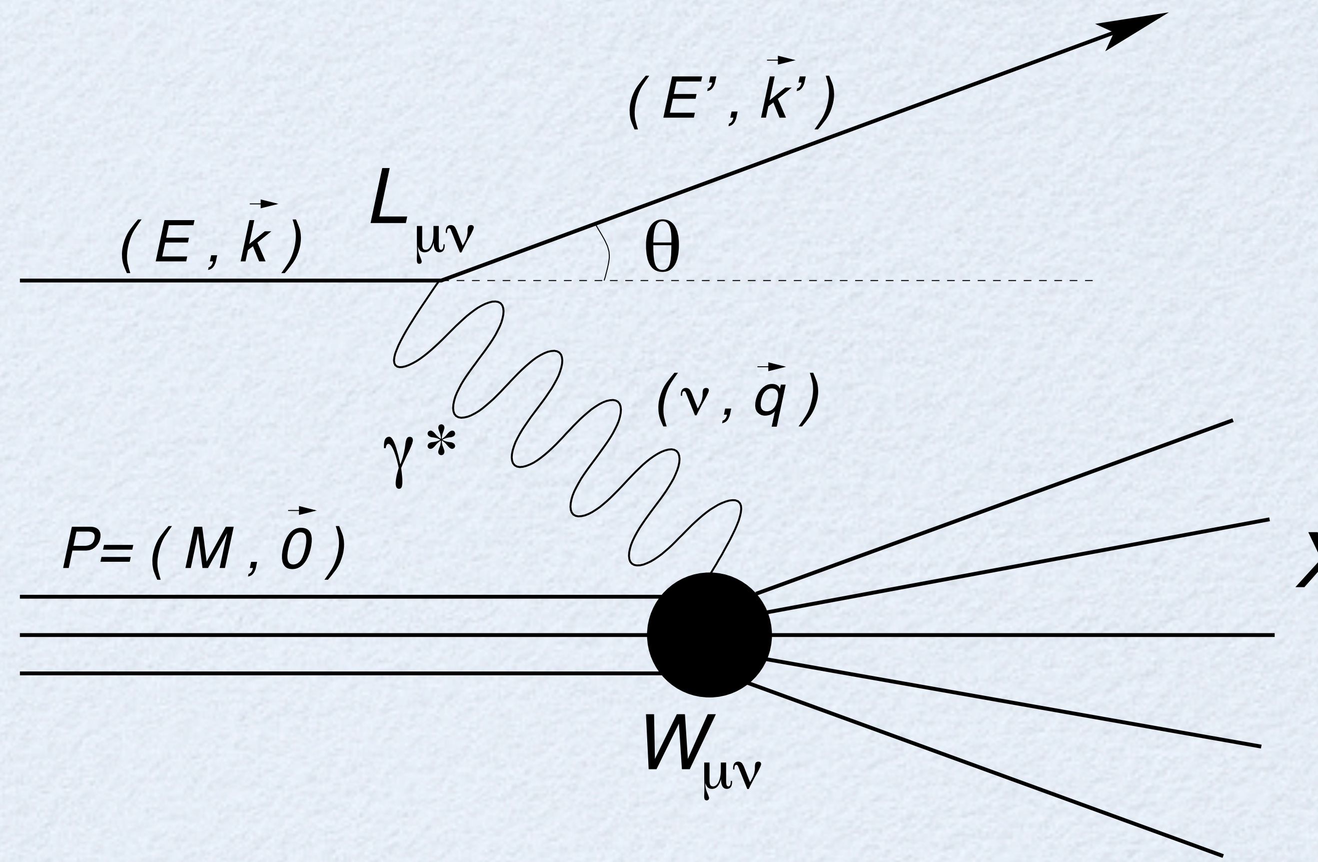
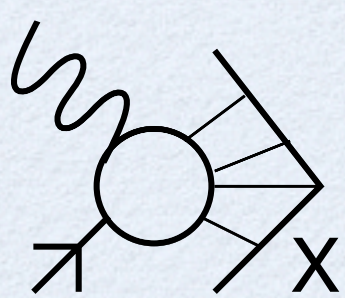


$\sigma_{\mathrm{DIS}} \sim \sum_X \Big|$  $\Big|^2$

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Semi-inclusive kinematics

involve kinematics of produced hadrons

Exclusive kinematics

complete spectrum of X known

The Composition of the Nucleon's Spin

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½ΔΣ + L_q

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- Orbital angular momentum of quarks: L_q?

$$J_q = \frac{1}{2}\lim_{t\to 0}\int_{-1}^{1} \mathrm{d}x\, x\, [H^q(x,\xi,t) + E^q(x,\xi,t)]$$

Ji relation

Ji, PRL **78** (1997) 610

The Composition of the Nucleon's Spin

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$\frac{1}{2}\Delta\Sigma + L_q$

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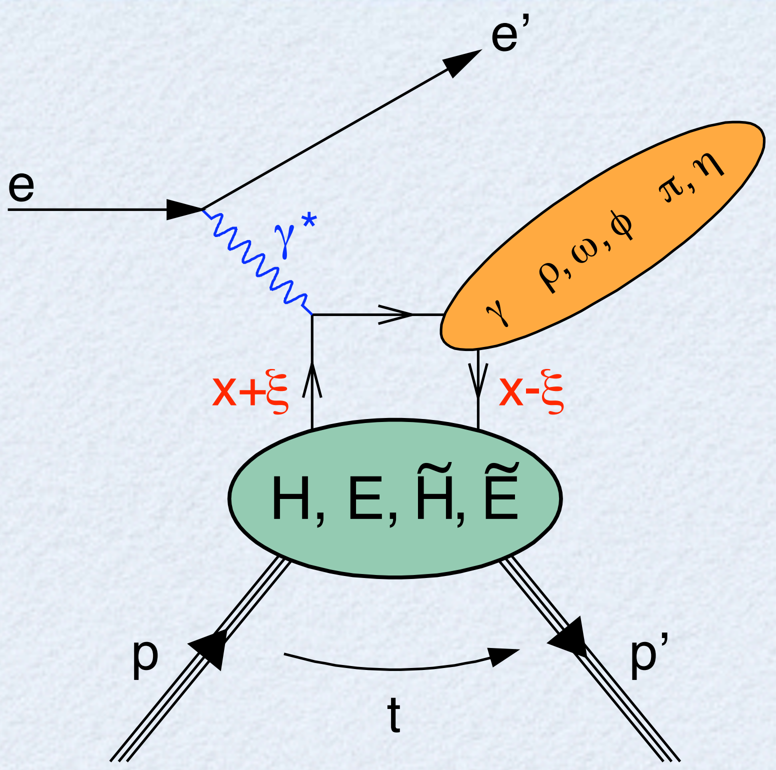
Generalized Parton Distributions (GPDs)

Generalized Parton Distributions



- Access through hard exclusive reactions
  - t: squared momentum transfer to target
  - x: average longitudinal momentum fraction of quark before/after
  - ξ: ½ difference
- GPDs $F^q(x,\xi,t)$ parameterize the non-perturbative nucleon structure
  - ➤ contain info on parton-parton correlations
- 4 GPDs that conserve quark chirality (Spin-1/2 target, leading-twist)

nucleon helicity ↓	quark helicity independent	quark helicity dependent
	photon: $J^P=1^-$ (DVCS)	
conserved	H	$\tilde{H}$
flipped	E	$\tilde{E}$
	$J^P=1^-$ mesons	$J^P=0^-$ mesons

GPDs: A unifying picture of nucleon structure

Parton Distribution Functions: longitudinal momentum

GPDs
$F^q(x,\xi,t)$

Form Factors: transverse position

$$H^q(x,0,0) = q(x)$$

forward limit ξ=0, t=0

$$\int_{-1}^{1} dx H^q(x,\xi,t) = F_1^q(t)$$

moments of GPDs

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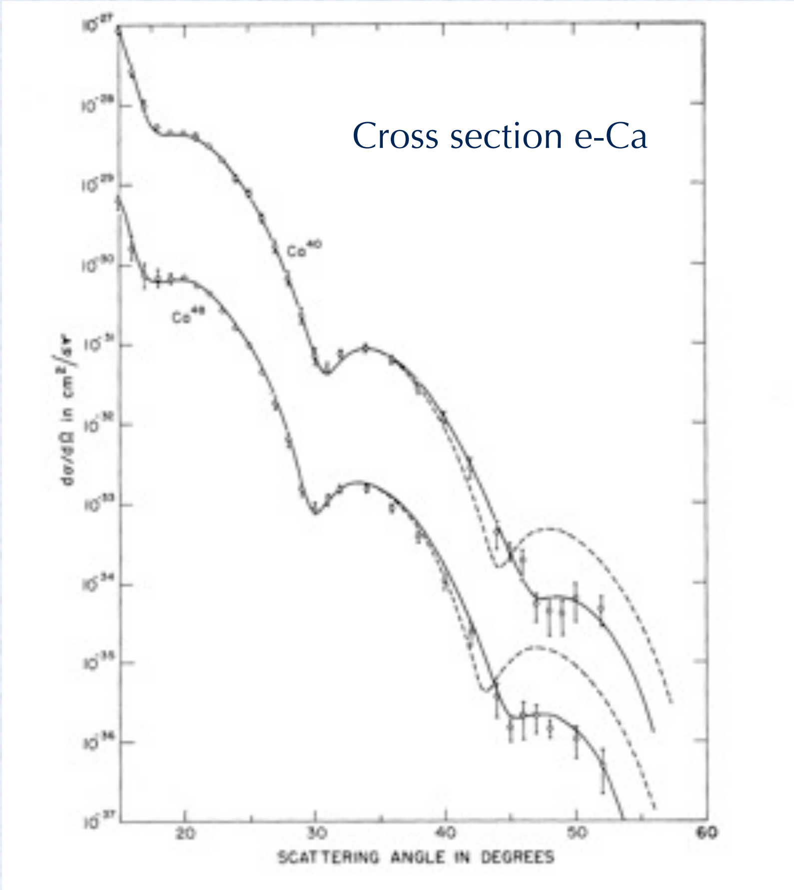

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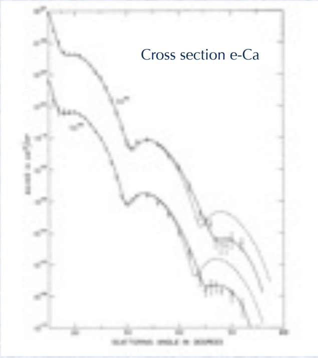

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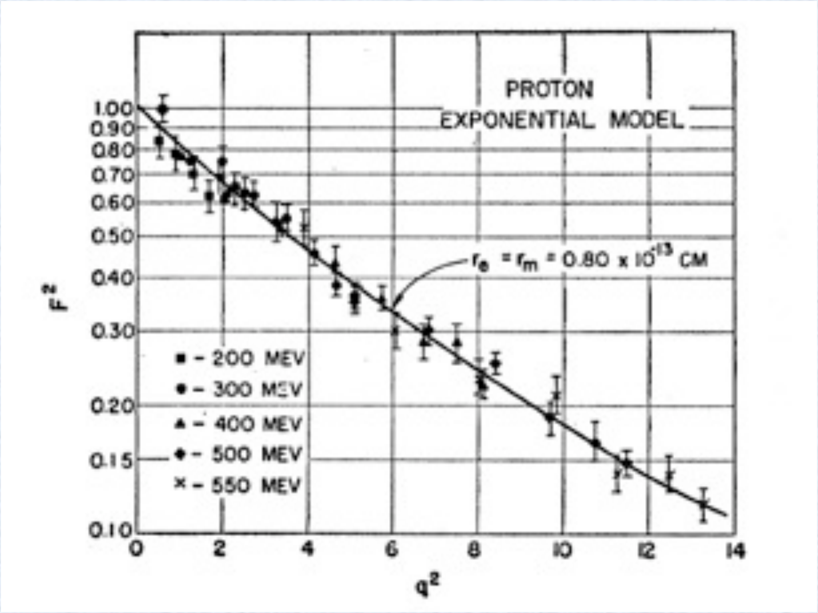

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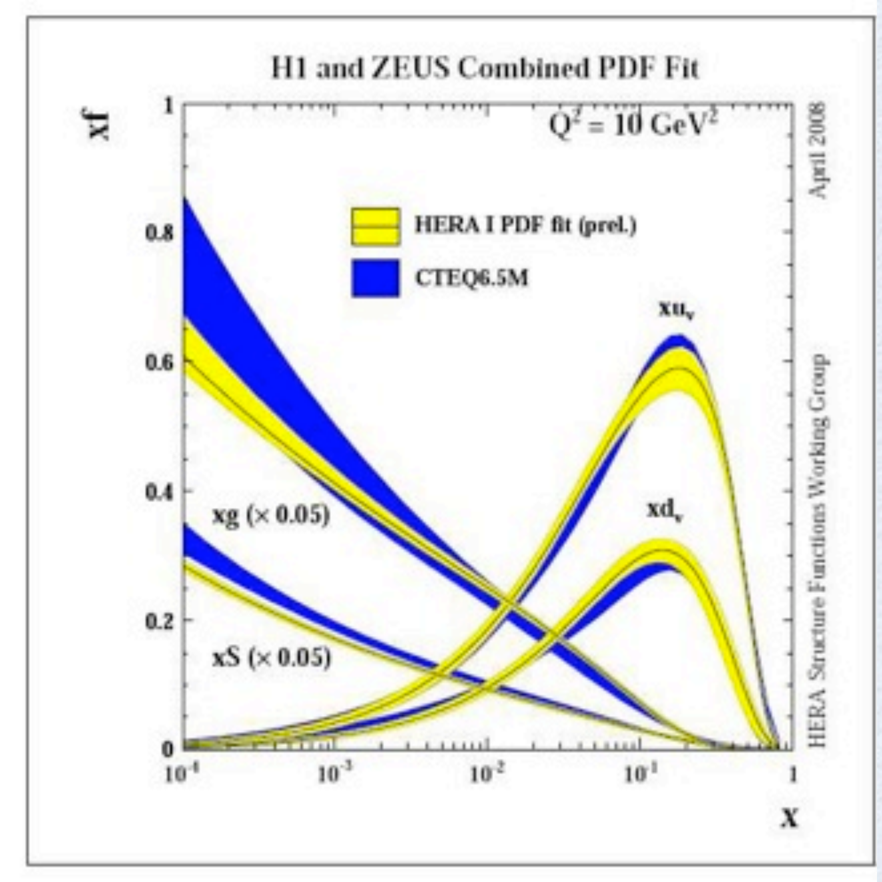

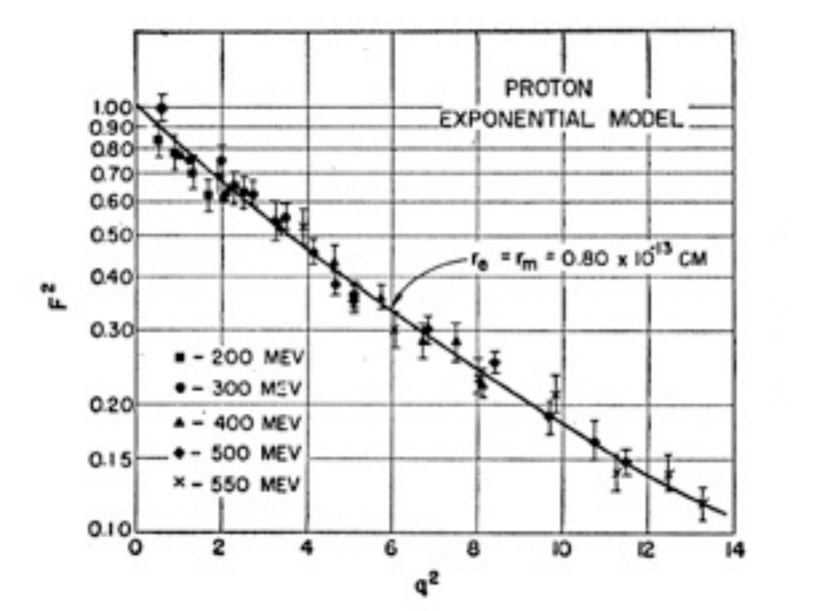

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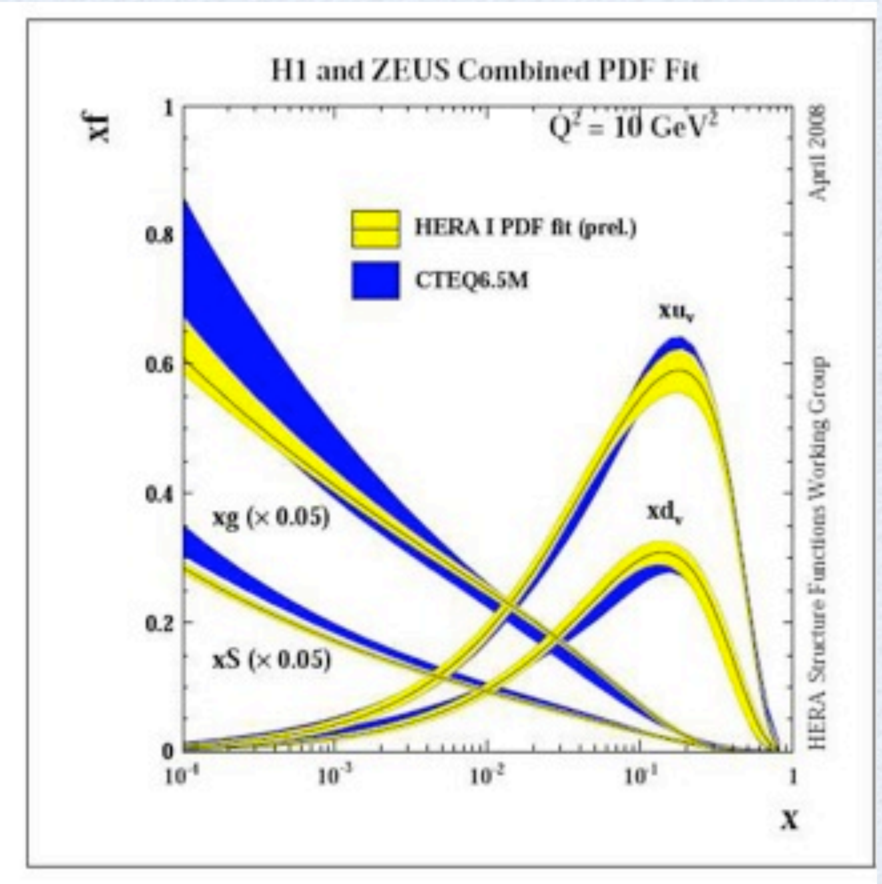

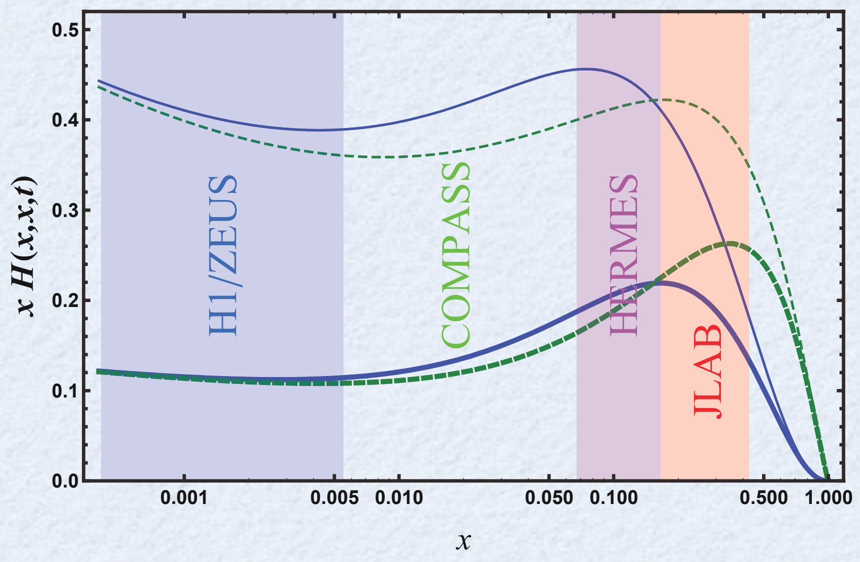

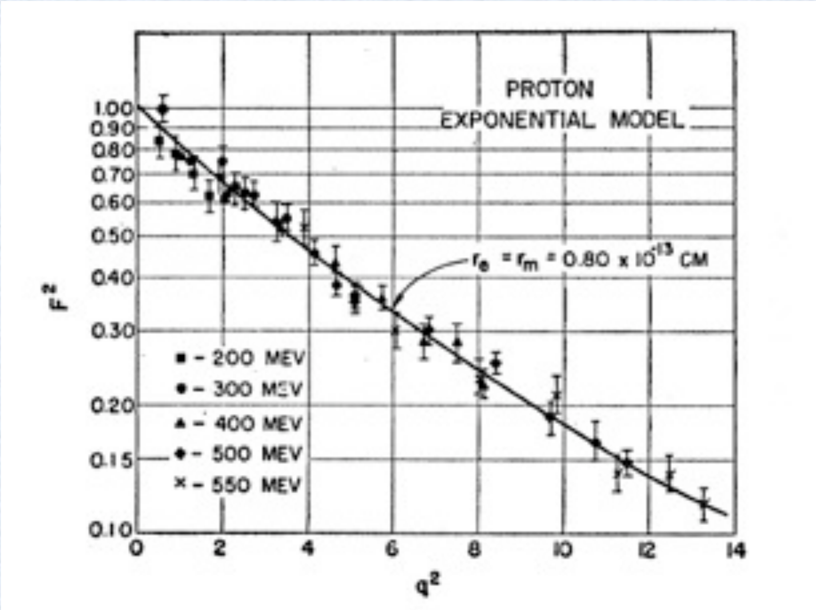

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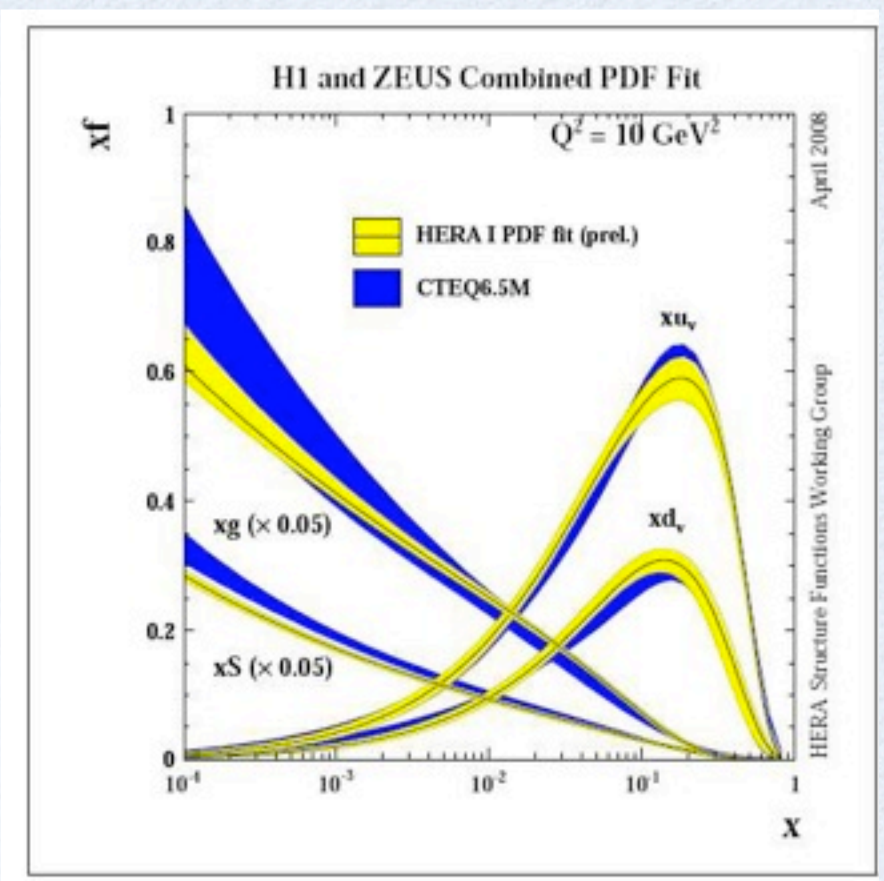

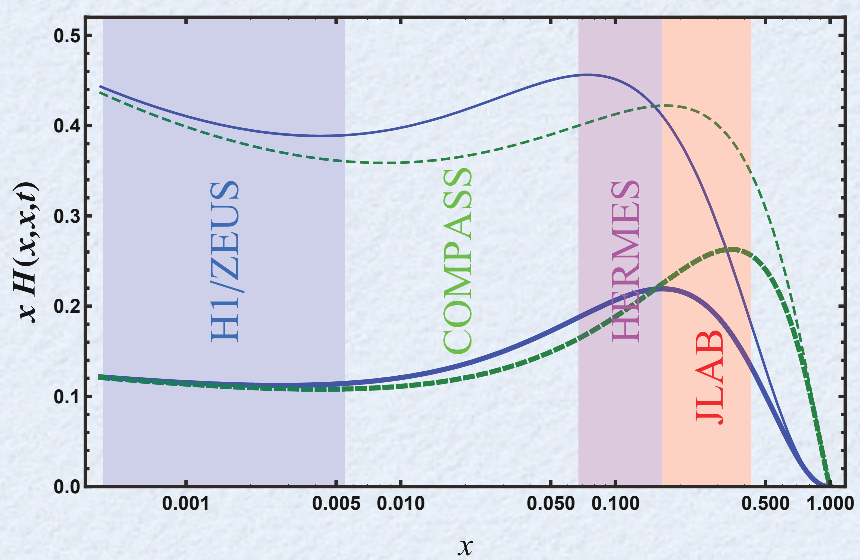

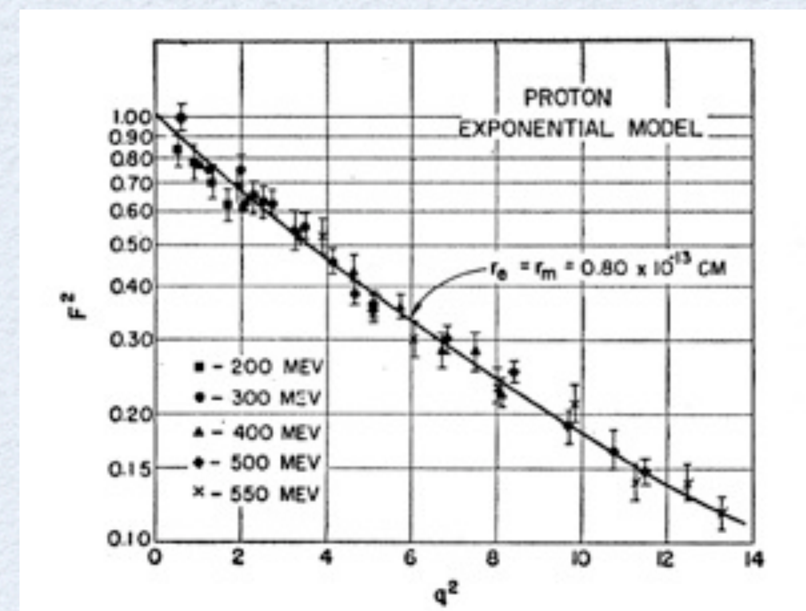

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"Nucleon Tomography"

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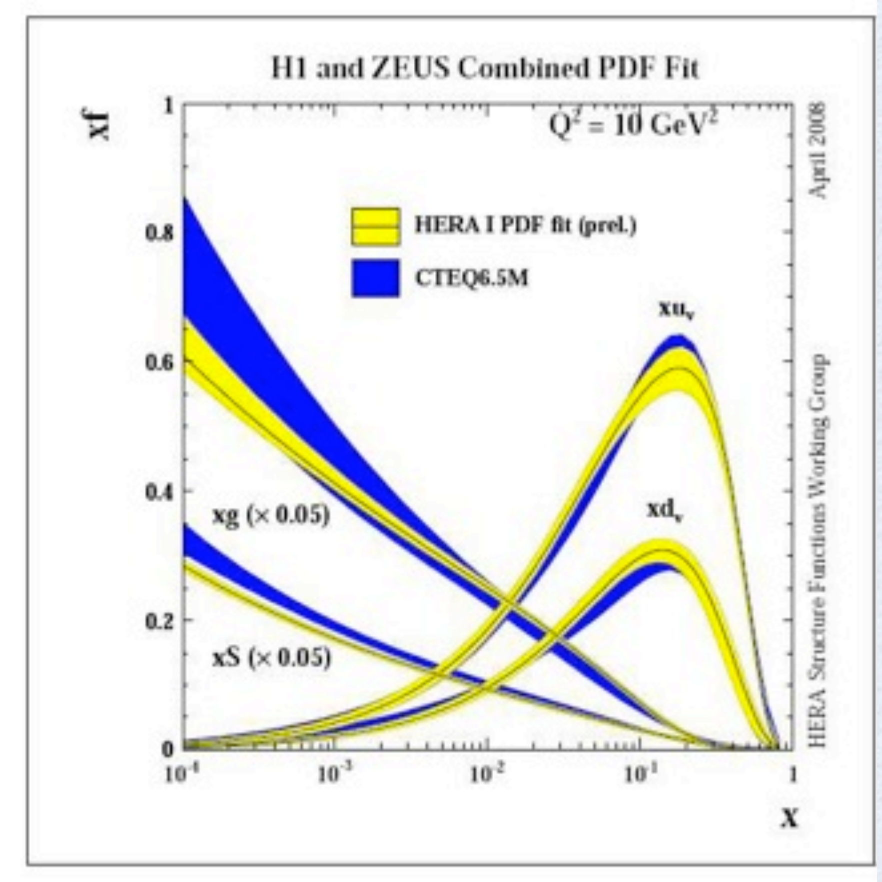

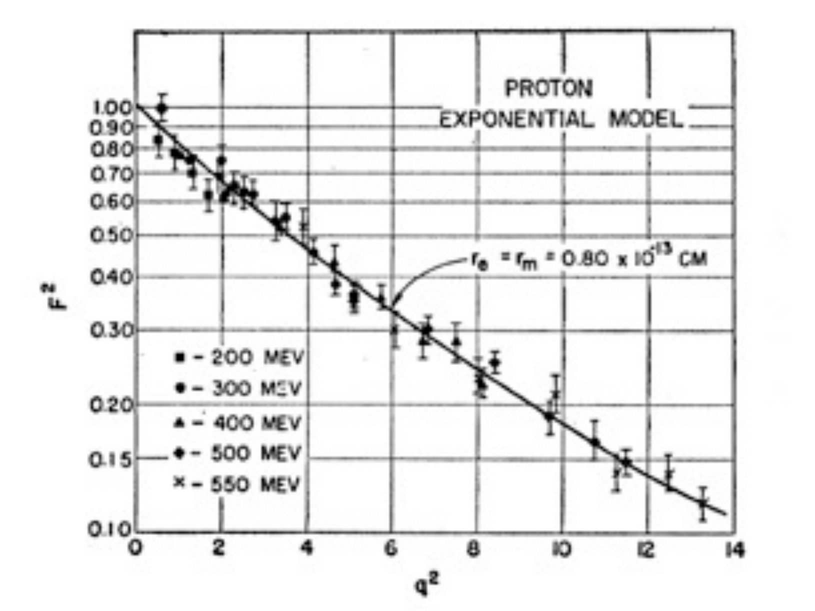

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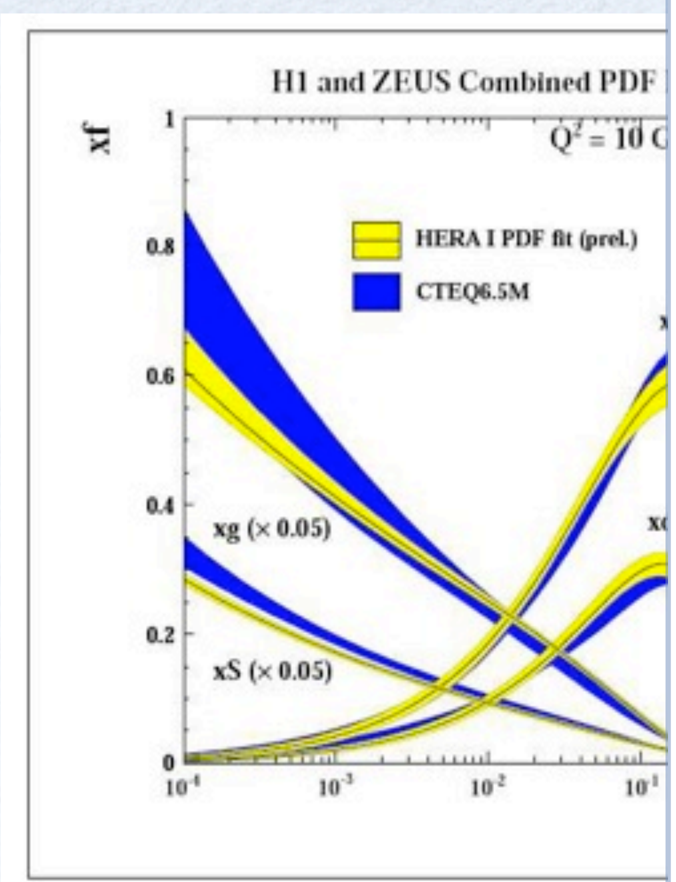

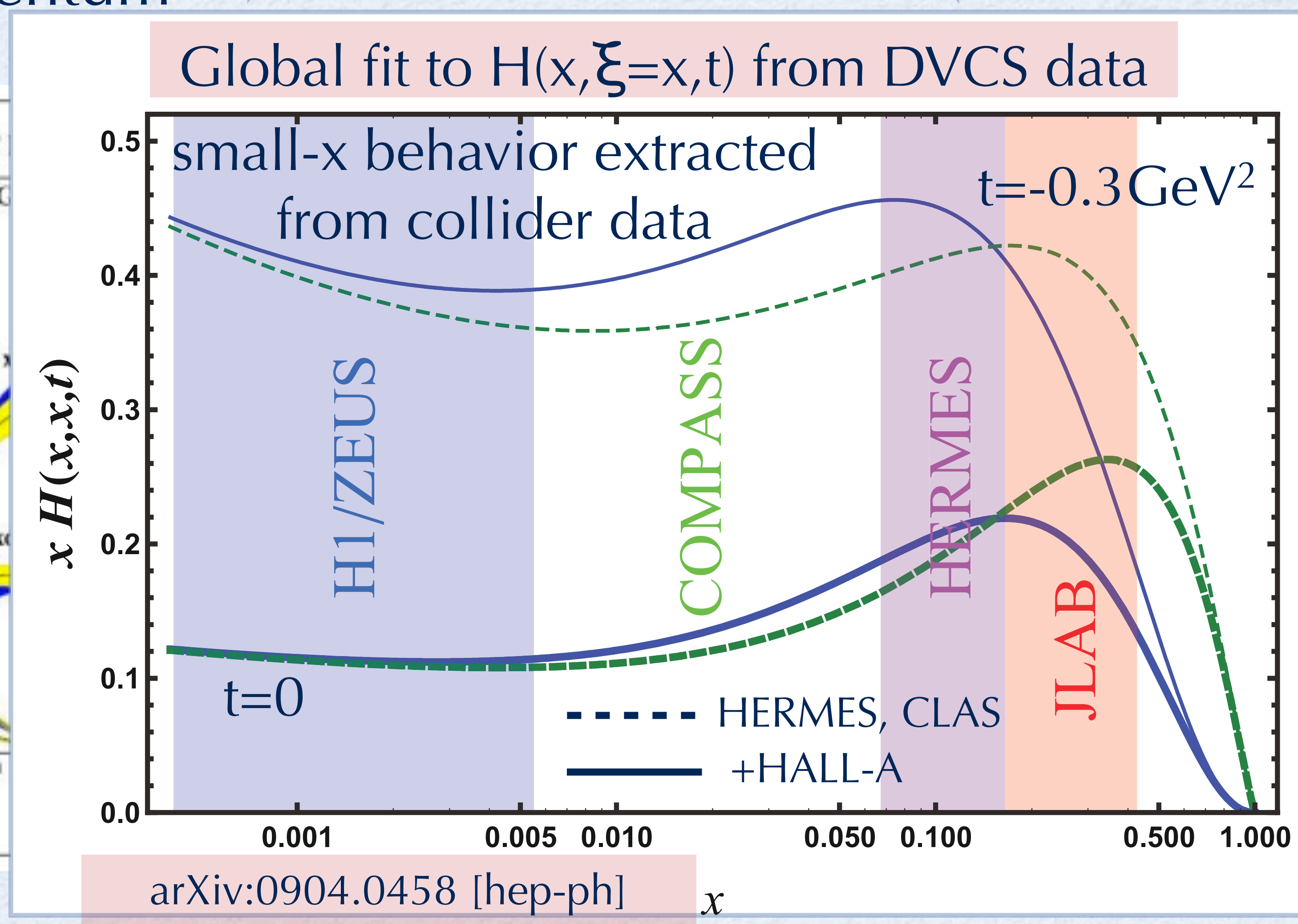

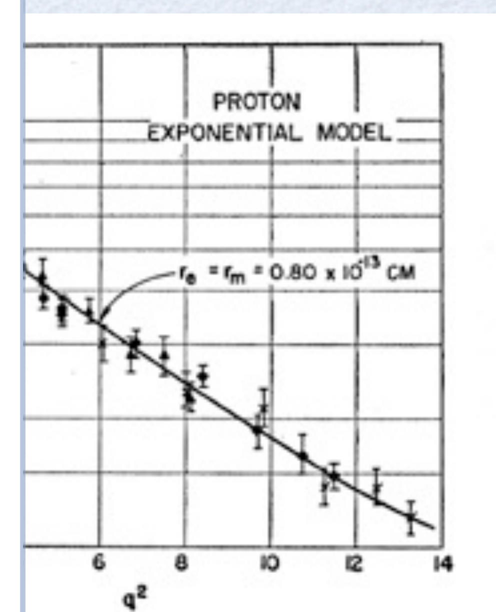

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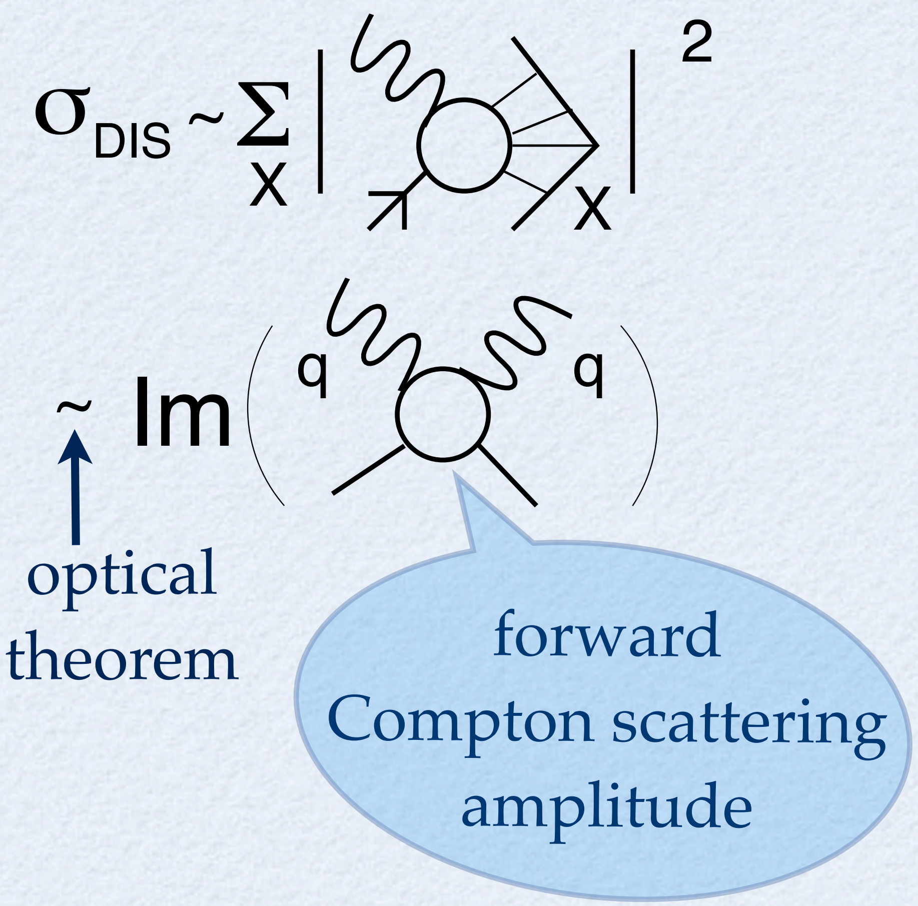

Deeply Virtual Compton Scattering (DVCS)

DVCS = hard electroproduction of a real photon

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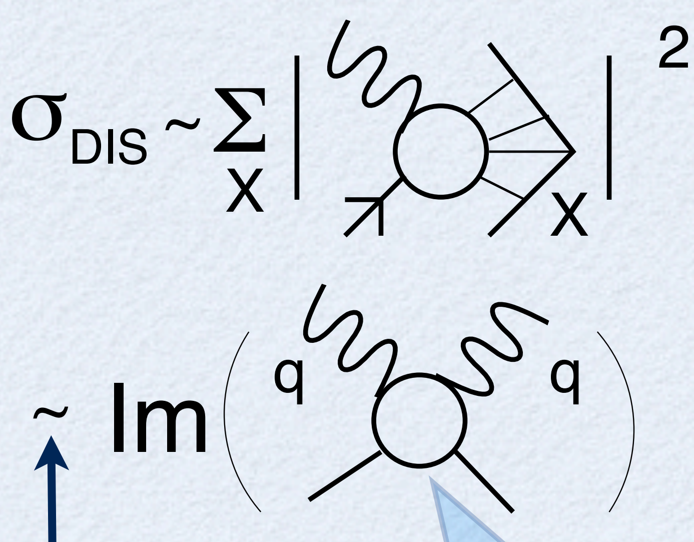
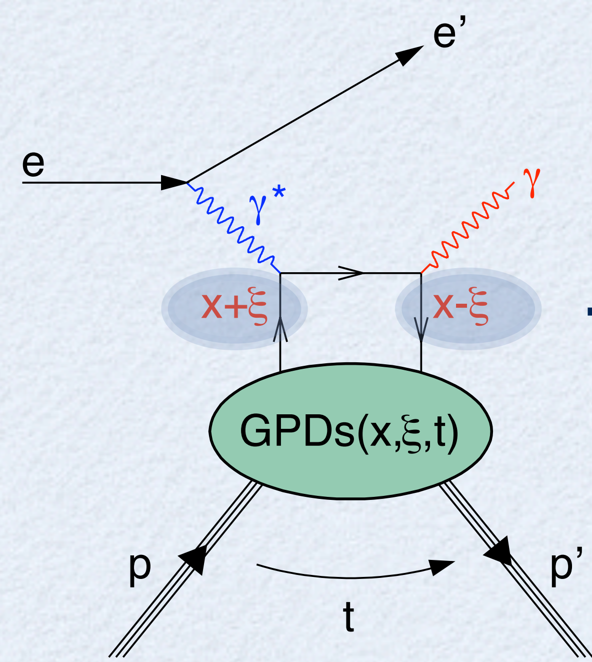


optical theorem

forward Compton scattering amplitude

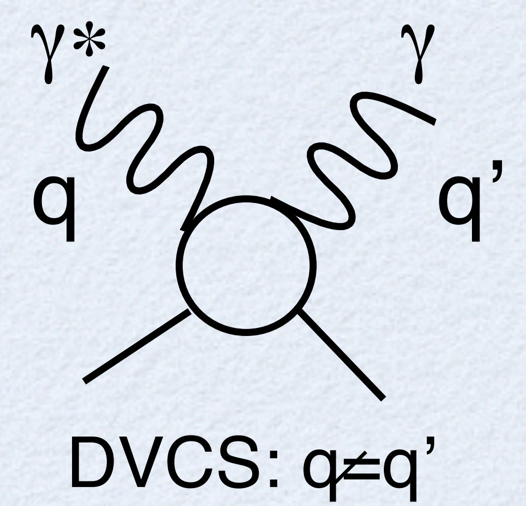


Skewing due to mass difference of photons

the 2 partons have different longitudinal momenta!

Skewness $\xi \neq 0$

Leading order: $\xi \approx x_B/(2-x_B)$



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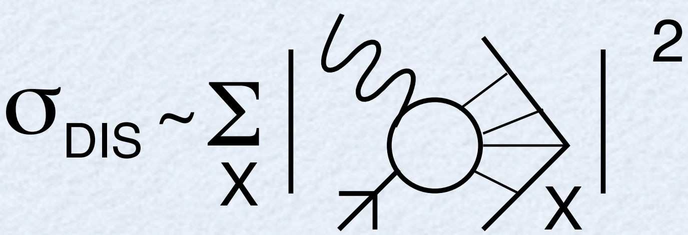

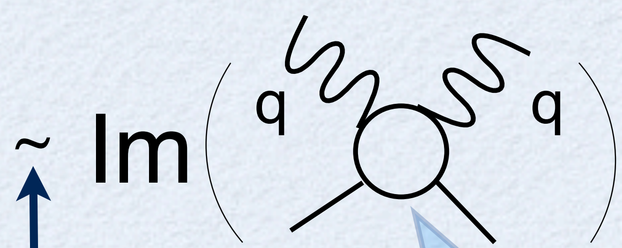

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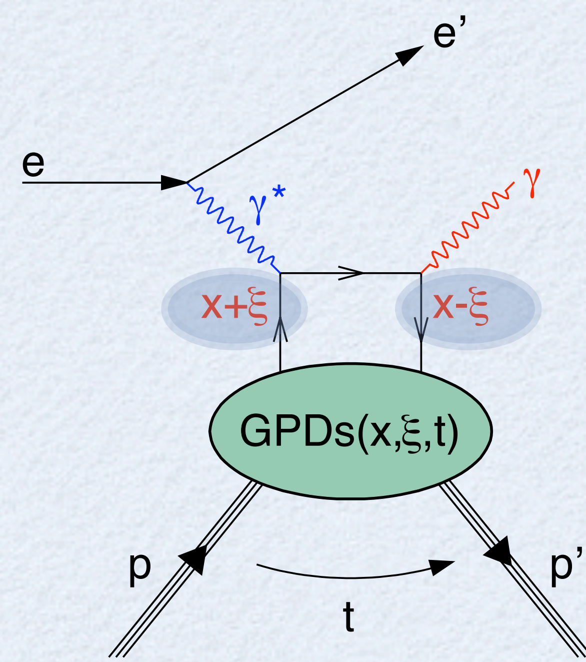

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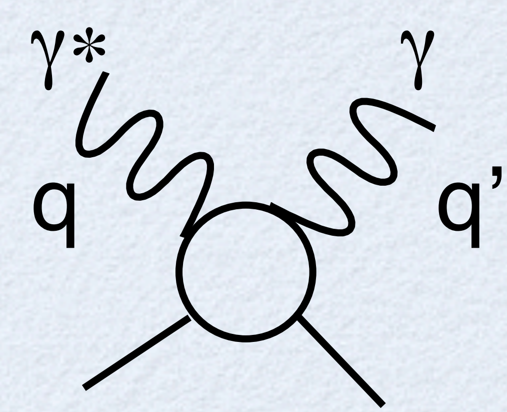
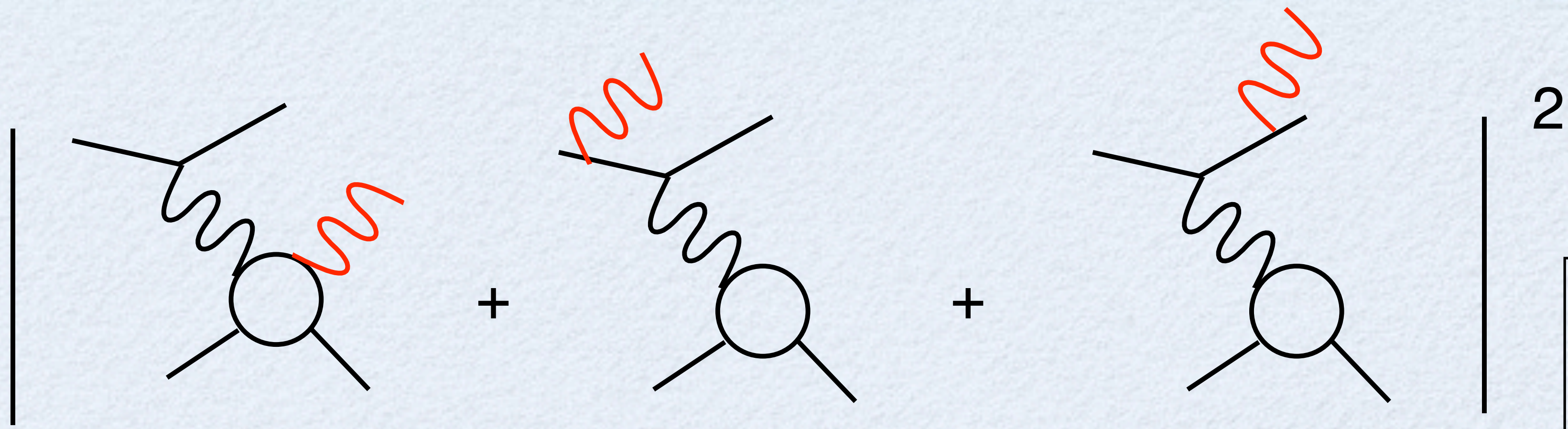


DVCS: $q \neq q'$

Forward limit:
$\xi=0$, $t=0$

The γ*N→γN Cross Section

$\sigma_{\gamma^* \gamma N} =$



DVCS

Bethe–Heitler (BH)

Bjørken limit:
large Q^2 (small distances)
large energy of γ* (small times)
small t, fixed x_B

$$= |\tau_{DVCS}|^2 + |\tau_{BH}|^2 + \tau_{DVCS}\tau_{BH}^* + \tau_{DVCS}^*\tau_{BH}$$

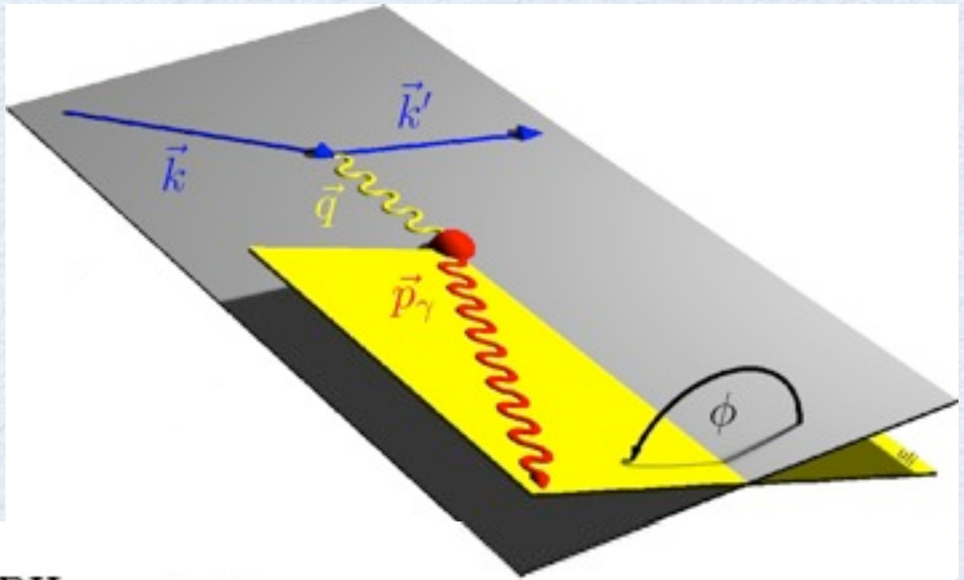
DVCS-BH interference term $\mathcal{I}$

Contribution at colliders.
Fixed target:
$|\tau_{DVCS}|^2 \ll |\tau_{BH}|^2$

exactly calculable in QED given the nucleon elastic form factors F_1 and F_2

Azimuthal Dependences in γ*N→γN

- Unpolarized target
- Lepton beam with charge C_B and polarization P_B



Fourier expansion in azimuthal angle ϕ

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

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

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

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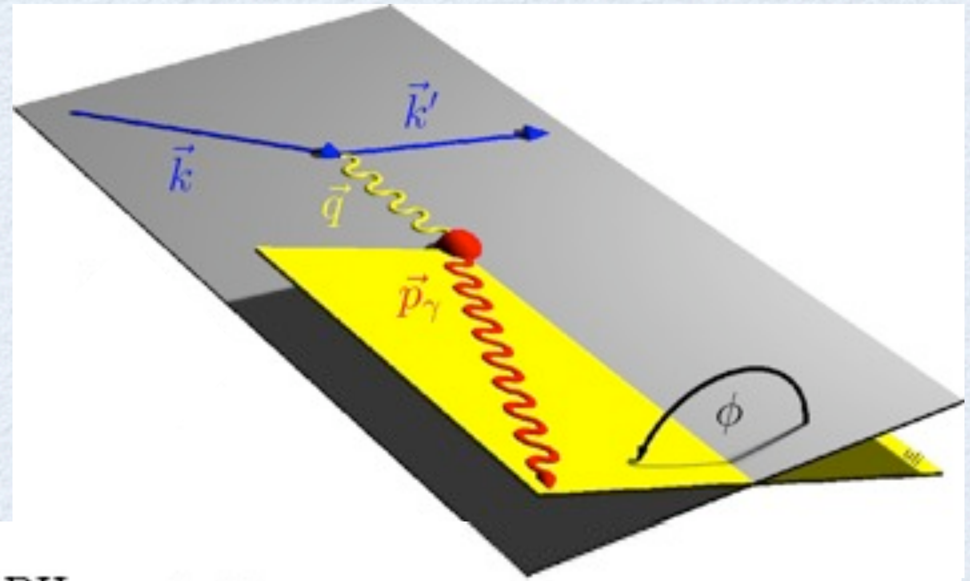

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Bethe-Heitler propagators $\mathcal{P}(\phi)$

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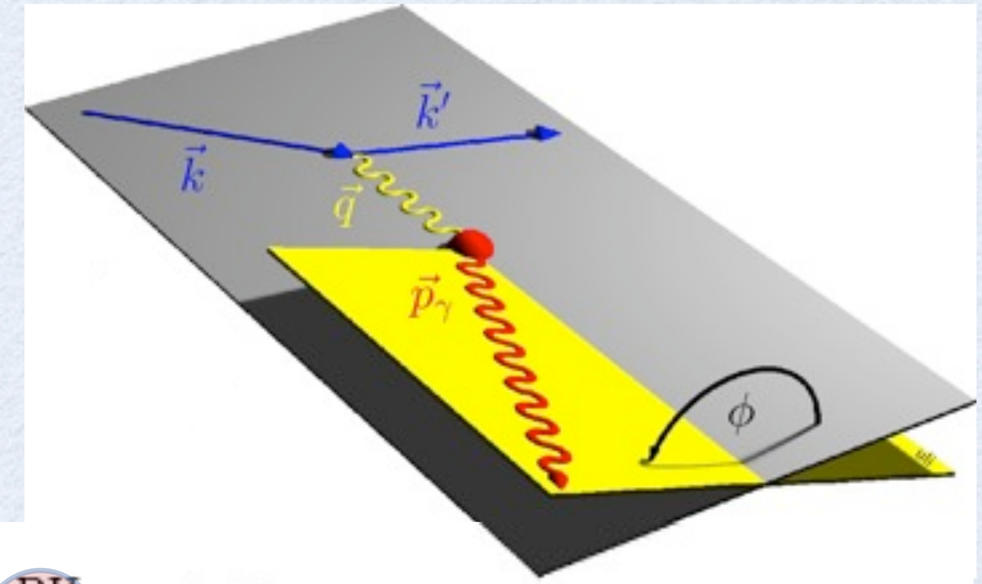

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Bethe-Heitler propagators $\mathcal{P}(\phi)$

Wanted:
Fourier coefficients
s_n and c_n
of BH, DVCS, and $\mathcal{I}$ terms

Measured Azimuthal Asymmetries in DVCS

Born cross-section:

$$\sigma(\phi; P_B, C_B) = \sigma_{UU}(\phi) \cdot [1 + P_B \mathcal{A}_{LU}^{DVCS}(\phi) + C_B P_B \mathcal{A}_{LU}^{\mathcal{I}}(\phi) + C_B \mathcal{A}_C(\phi)]$$

$\mathcal{A}_{LU}$

Beam Target

Beam helicity asymmetries

Beam charge asymmetry

Old approach at HERMES and CLAS: single charge BSA

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

no separate access to $s_1^{\mathcal{I}}$ and s_1^{DVCS}

BSA:
projects out imaginary part of τ_{DVCS}

BCA:
projects out real part of τ_{DVCS}

$$\mathcal{A}_C(\phi) \equiv \frac{d\sigma^{+} - d\sigma^{-}}{d\sigma^{+} + d\sigma^{-}}$$

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no separate access to $s_1^{\mathcal{I}}$ and s_1^{DVCS}

New approach at HERMES: $s_1^{\mathcal{I}}$ and s_1^{DVCS} can be disentangled

Charge difference BSA:

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

Charge average BSA:

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

Relation: asymmetries ↔ Fourier coefficients

Beam helicity asymmetries:

$$\mathcal{A}_{\mathrm{LU}}^{\mathcal{I}}(\phi) = \frac{1}{\mathcal{D}(\phi)} \cdot \frac{x_B}{Q^2} \left[s_1^{\mathcal{I}} \sin(\phi) + s_2^{\mathcal{I}} \sin(2\phi) \right]$$

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

Beam charge asymmetry:

$$\mathcal{A}_{\mathrm{C}}(\phi) = -\frac{1}{\mathcal{D}(\phi)} \cdot \frac{x_B}{y} \left[c_0^{\mathcal{I}} + c_1^{\mathcal{I}} \cos(\phi) + c_2^{\mathcal{I}} \cos(2\phi) + c_3^{\mathcal{I}} \cos(3\phi) \right]$$

Relation: asymmetries ↔ Fourier coefficients

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Additional ϕ dependence in denominator through BH propagators

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

From Azimuthal Asymmetries to GPDs

- To obtain Fourier coefficients = asymmetry amplitudes:
  ➤ Combine data with different beam charges and helicities and **fit all amplitudes simultaneously**

- Compton Form Factors (CFFs) $\mathcal{F}(\xi,t) = \sum_q \int_{-1}^{1} \mathrm{d}x \, C_q^{\mp}(\xi,x) F^q(x,\xi,t)$ — twist-2 GPD
  - Define linear combination of CFFs: $\mathcal{C}^{\mathcal{I}}_{\text{unp}} = F_1 \mathcal{H} + \xi(F_1 + F_2)\widetilde{H} - \frac{t}{4M^2} F_2 \mathcal{E}$
  - $F_1(t)$, $F_2(t)$: Dirac, Pauli nucleonic form factors

- Leading twist level (twist-2):

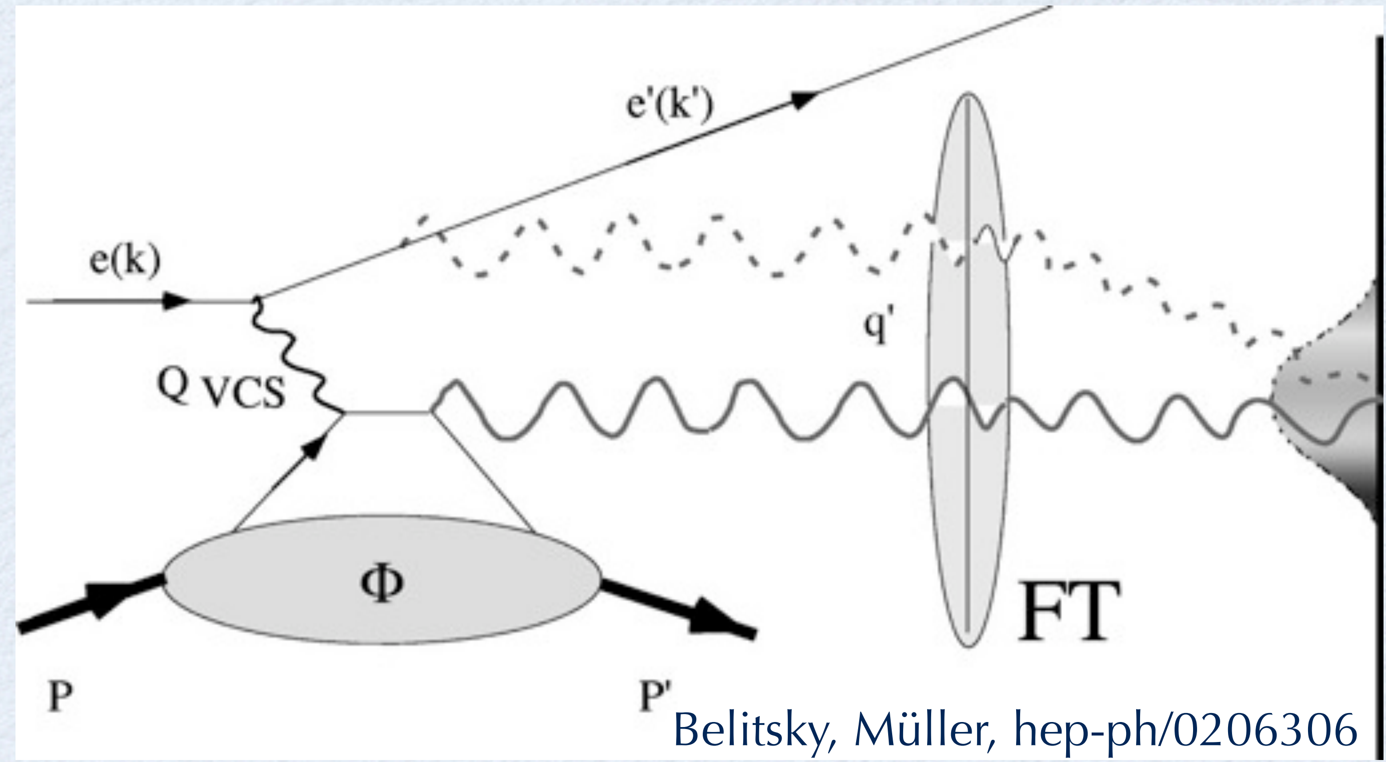
$$c_1^{\mathcal{I}} \propto \frac{\sqrt{-t}}{Q} \Re\left[\mathcal{C}^{\mathcal{I}}_{\text{unp}}\right] \propto -\frac{Q}{\sqrt{-t}} c_0^{\mathcal{I}} \qquad s_1^{\mathcal{I}} \propto \frac{\sqrt{-t}}{Q} \Im\left[\mathcal{C}^{\mathcal{I}}_{\text{unp}}\right]$$

BCA (Re part) — **constant term** ($c_0^{\mathcal{I}}$) — **BSA** (Im part)

Holographic Principle / Femtophotography

➤ Wanted: 3-dim spatial picture

- ➢ $(FT)^{-1}$ of diffraction pattern, given amplitude $\tau = Ae^{i\varphi}$
- ➢ Need both magnitude A & phase φ
- ➢ Usually $|\tau|^2$ is measured, phase is lost (e.g. PDFs)



Belitsky, Müller, hep-ph/0206306

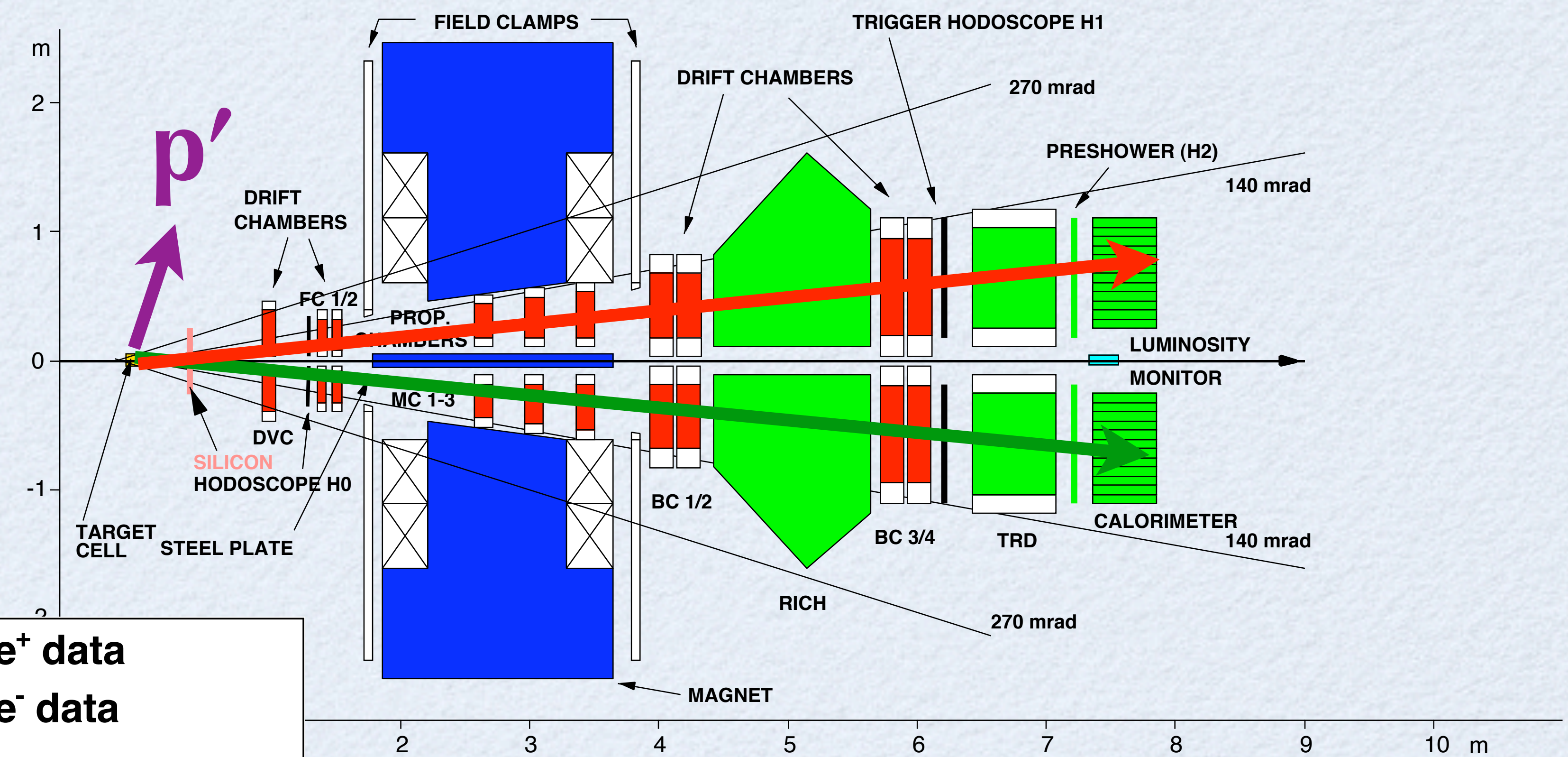
➤ Holography technique:

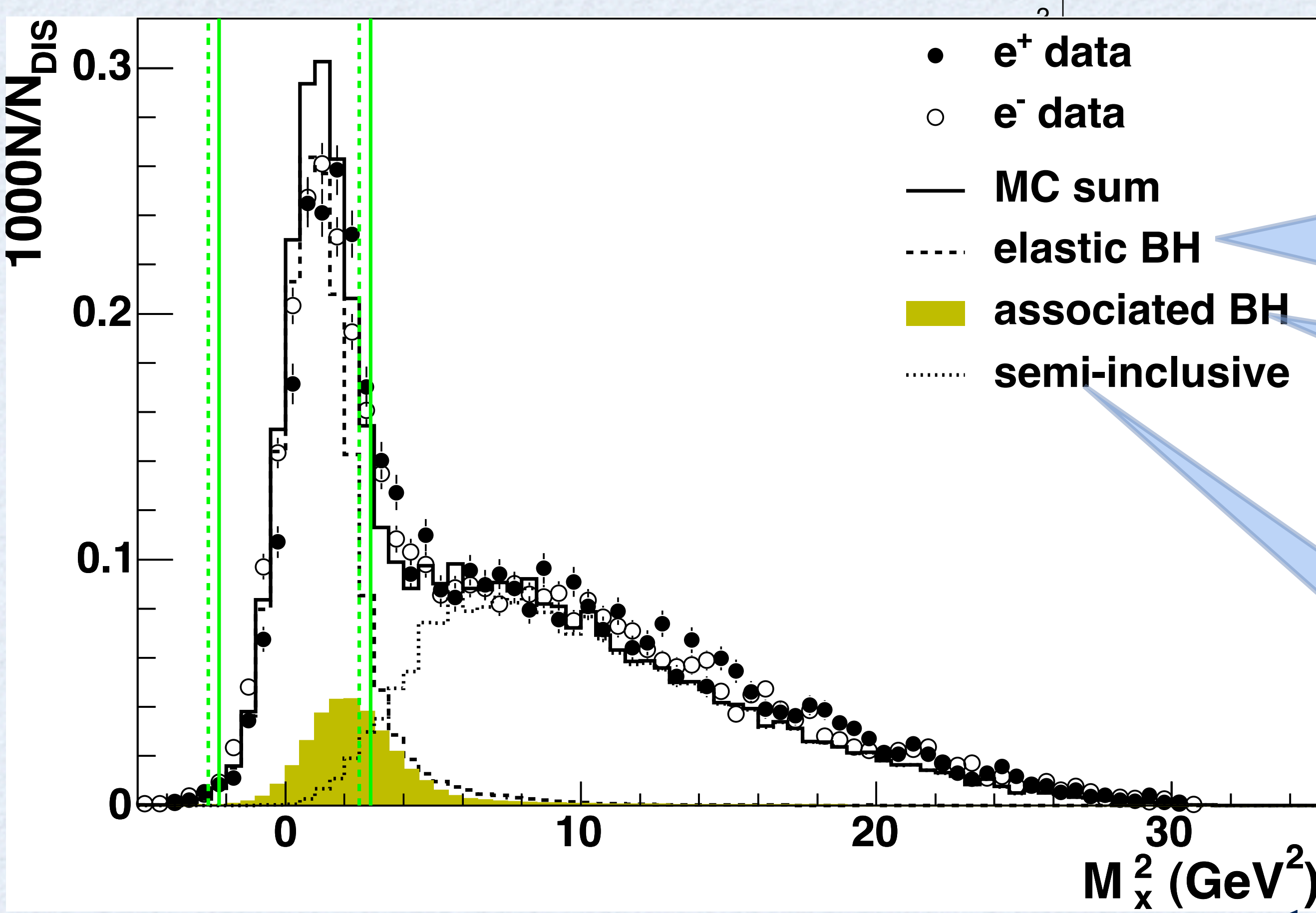
- ➢ Known BH process as reference amplitude that magnifies DVCS effect
- ➢ Measure phase of DVCS through its interference with BH

DVCS at HERMES 1996-2005 (w/o Recoil)

Detected particles:
electron and photon

Missing mass technique for
ep→eXγ
$M_X^2=(p+q-p_\gamma)^2$





X=p

resonant excitation: X=Δ^+

$p\pi^0$

$n\pi^+$

X=π^0+...

hydrogen target:
25k events
(400 pb^{-1})

unpolarized deuterium:
15k events
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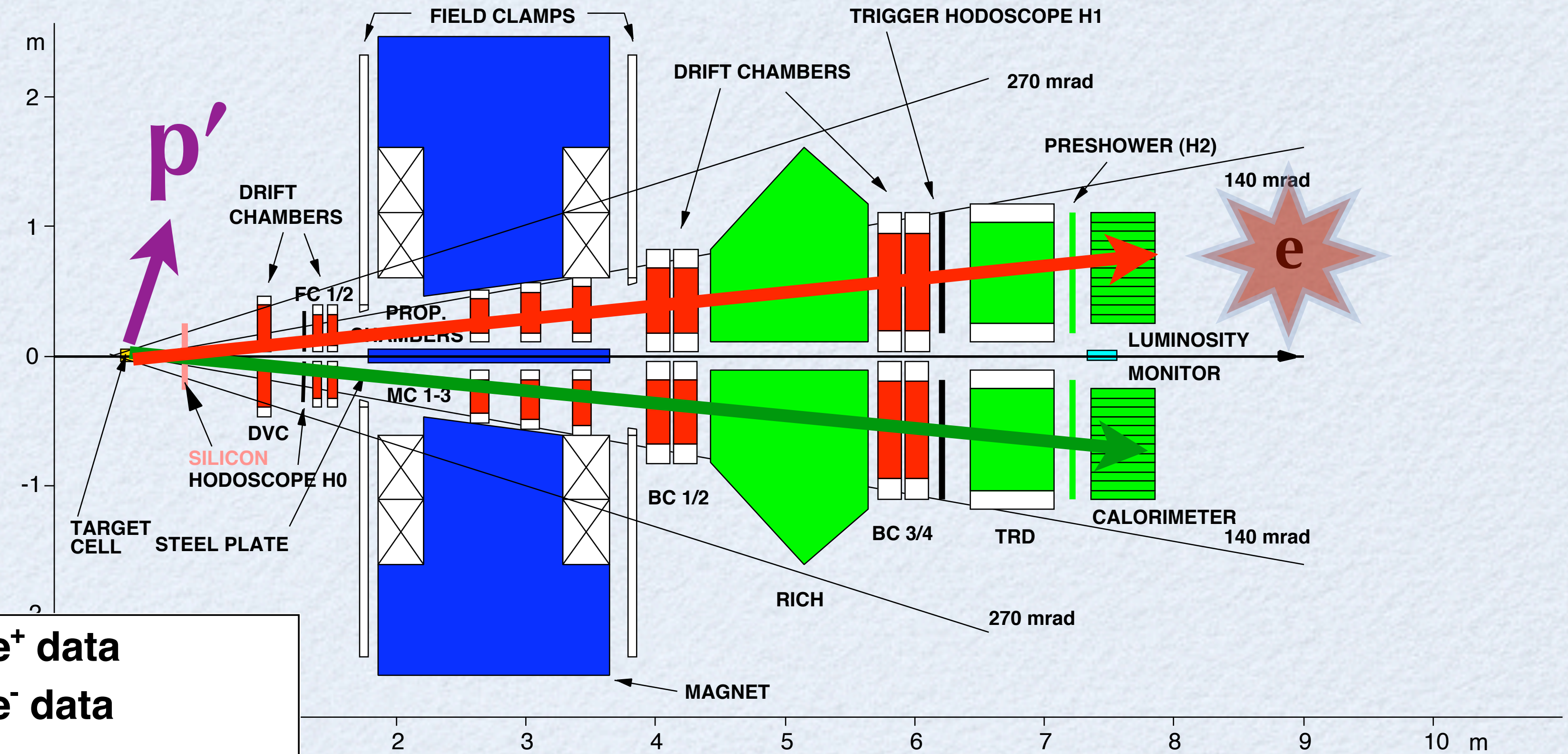

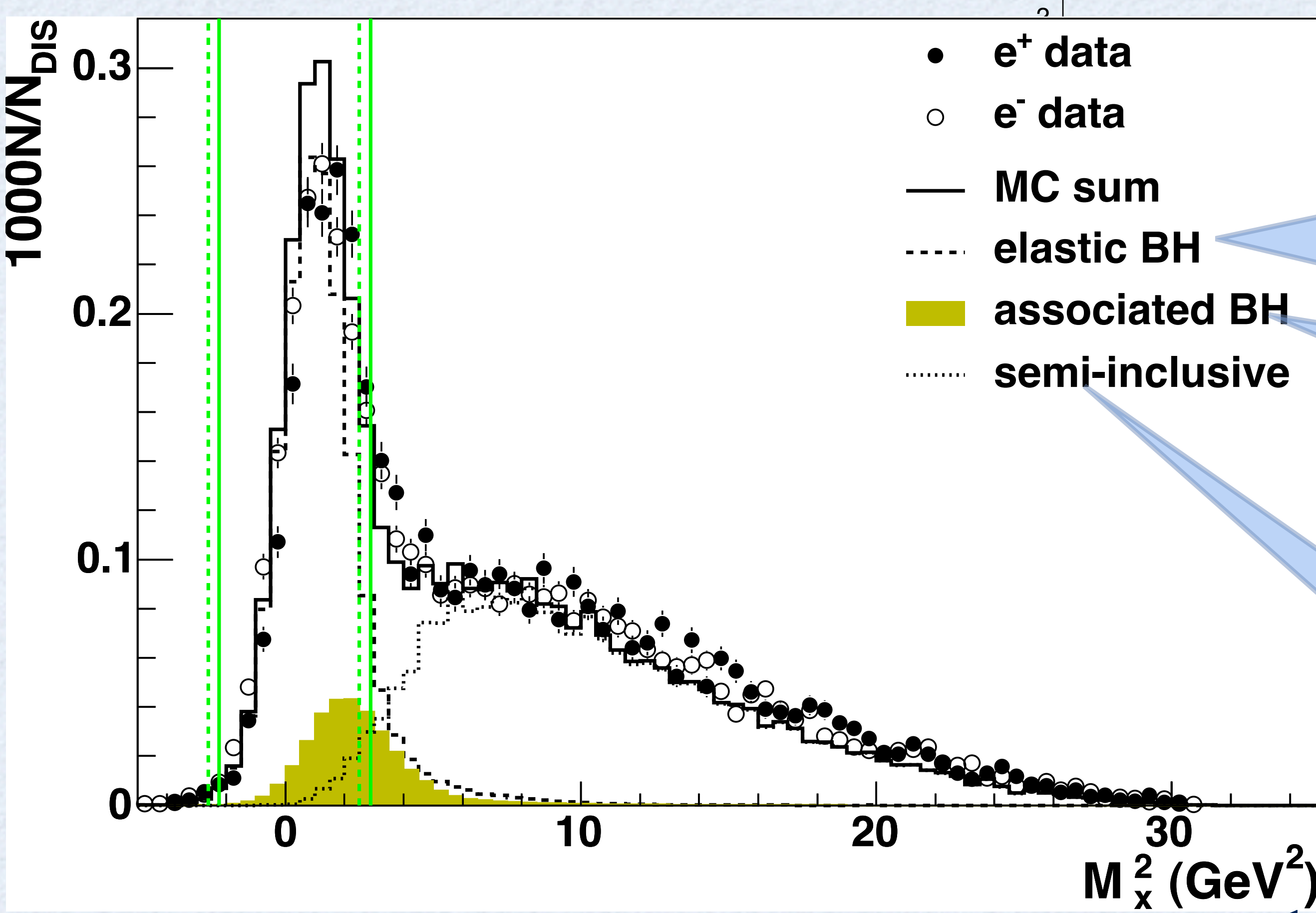

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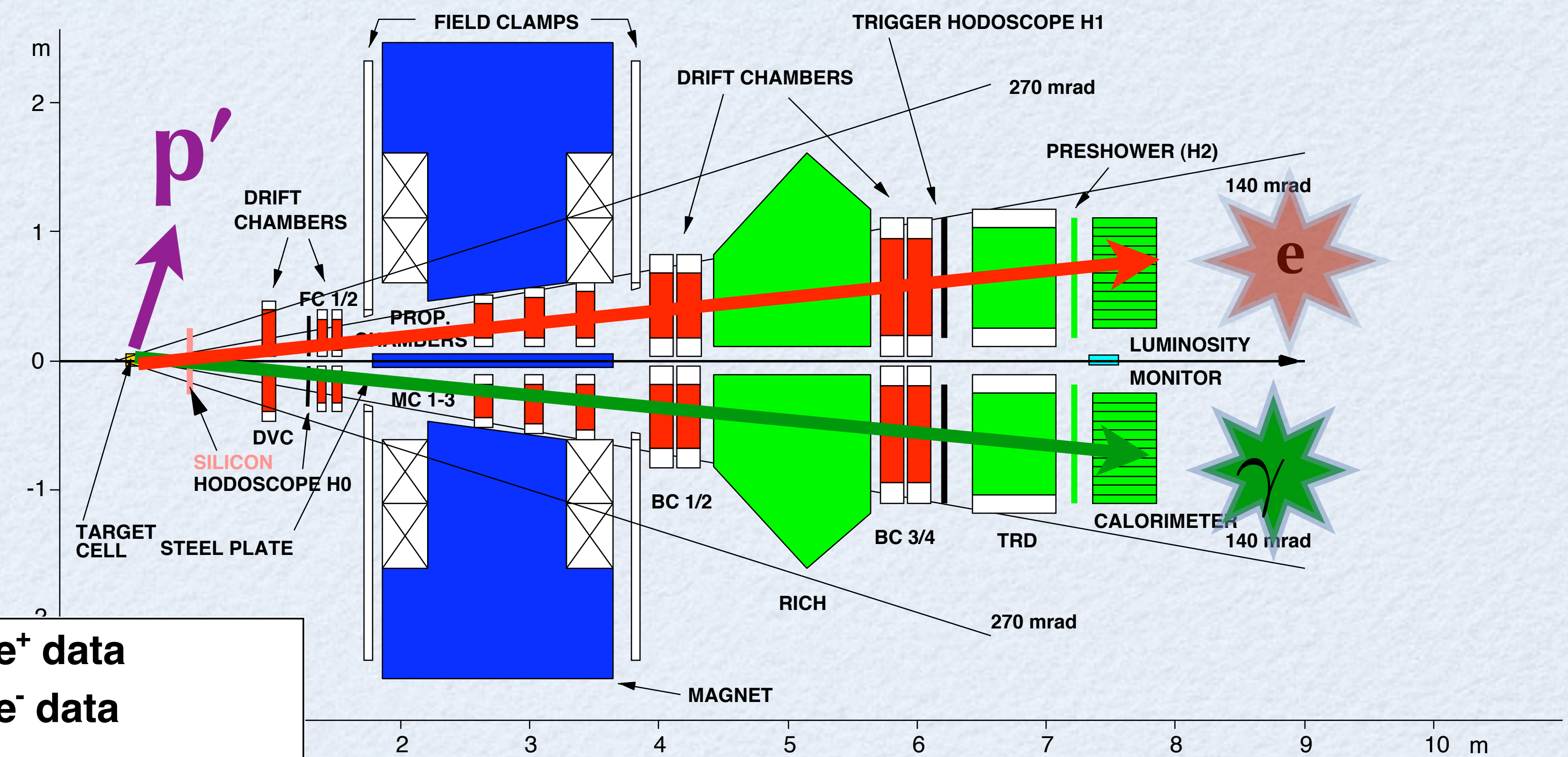

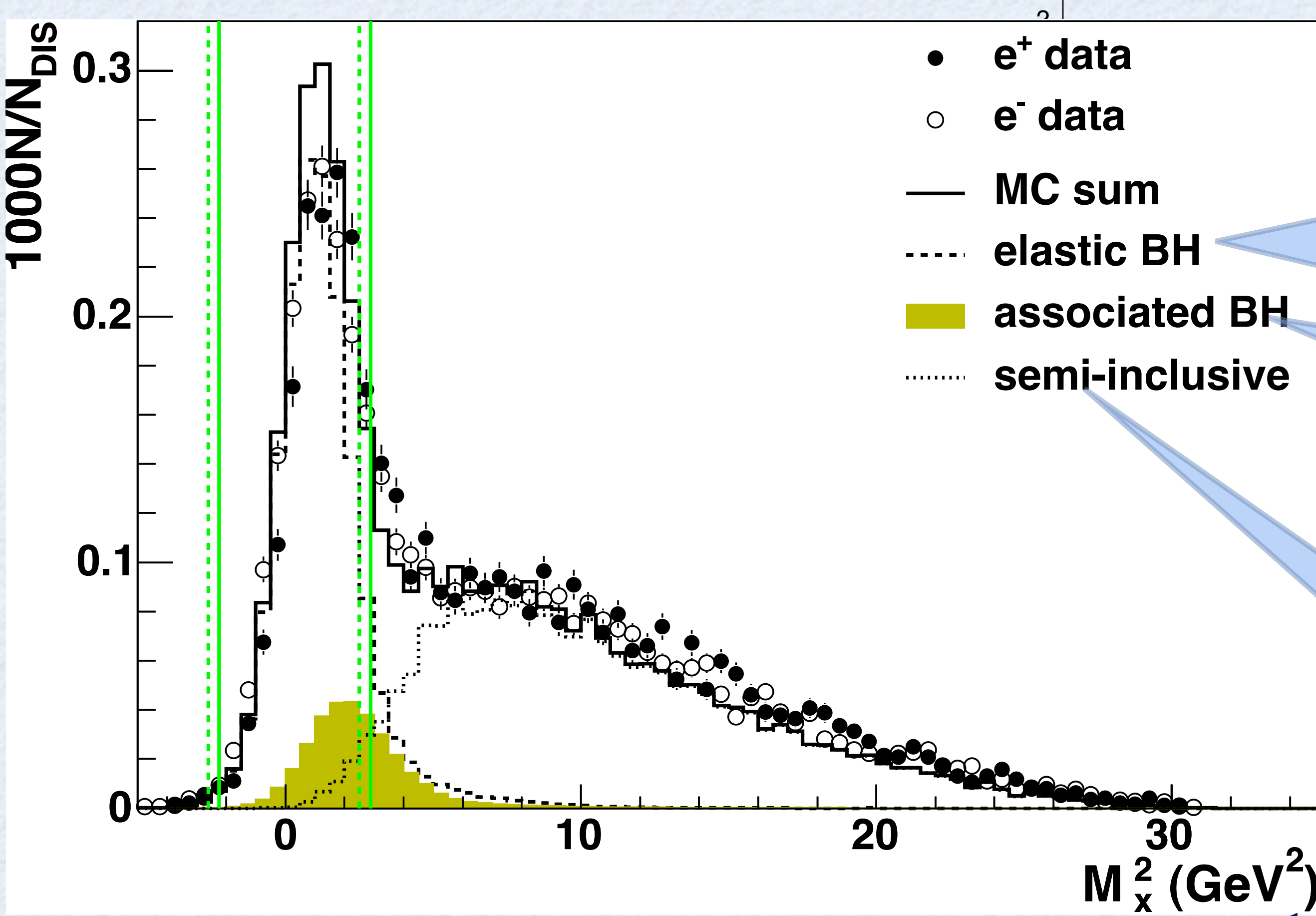

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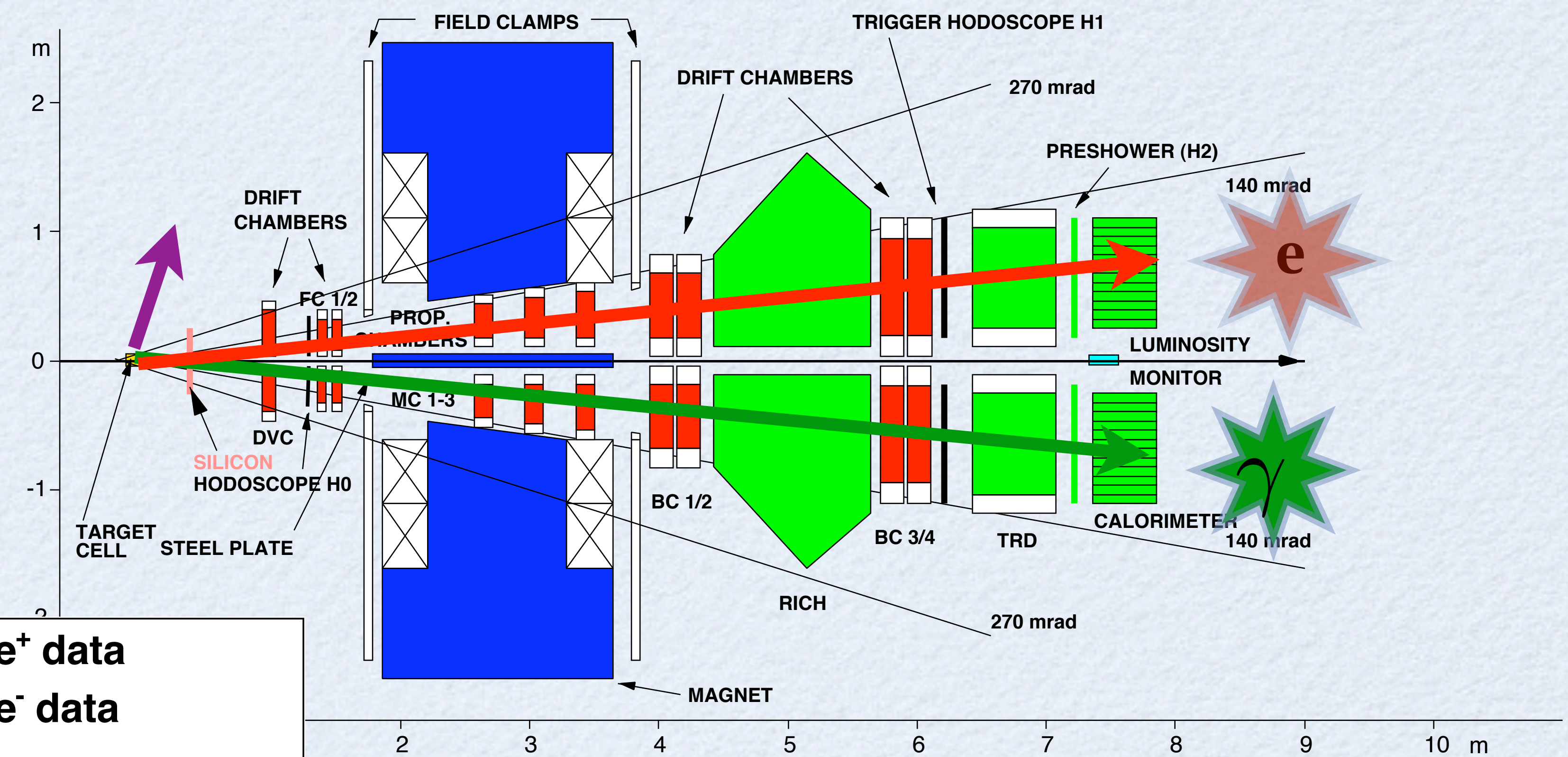

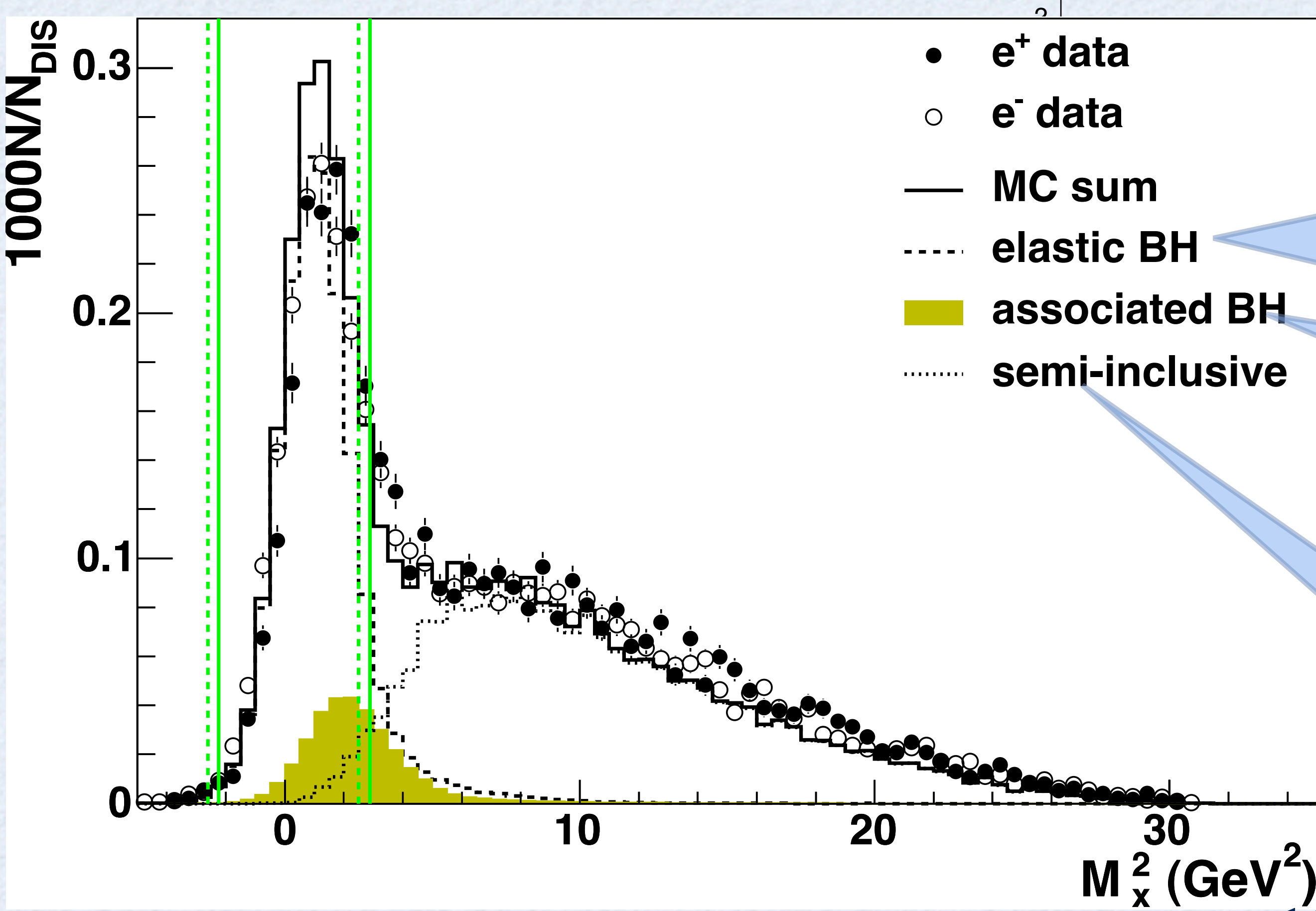

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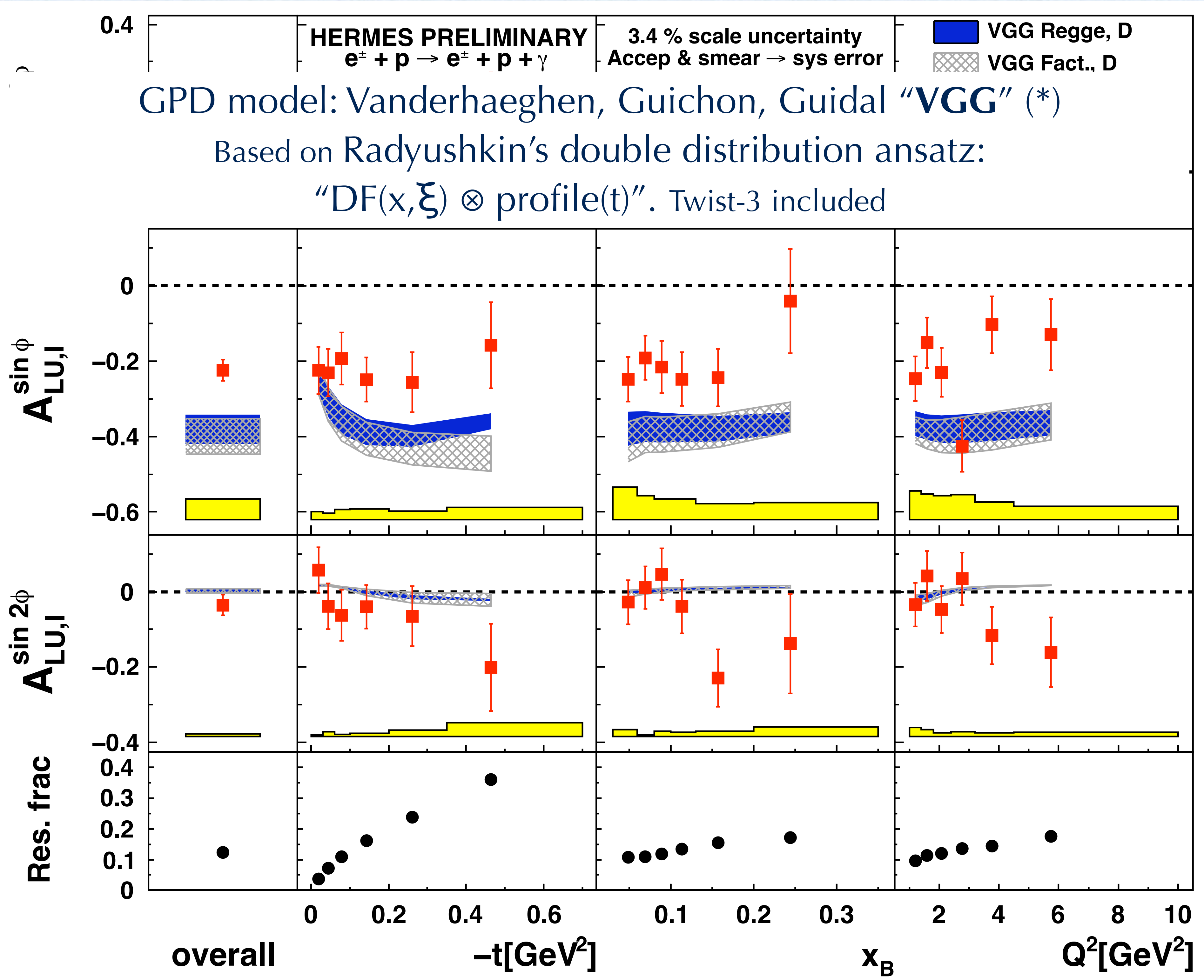
HERMES: BSA from $\mathcal{I}$ on hydrogen



GPD model: Vanderhaeghen, Guichon, Guidal "**VGG**" (*)

Based on Radyushkin's double distribution ansatz:

"DF(x,ξ) ⊗ profile(t)". Twist-3 included

$\propto \Im\,[F_1 \mathcal{H}]$

← Higher twist (twist-3)

← Fraction of resonant excitation

(*) Phys.Rev. **D60** (1999) and Prog.Nucl.Phys. **47** (2001) 401

HERMES: BSA from $\mathcal{I}$ on hydrogen

D-term to restore polynomiality

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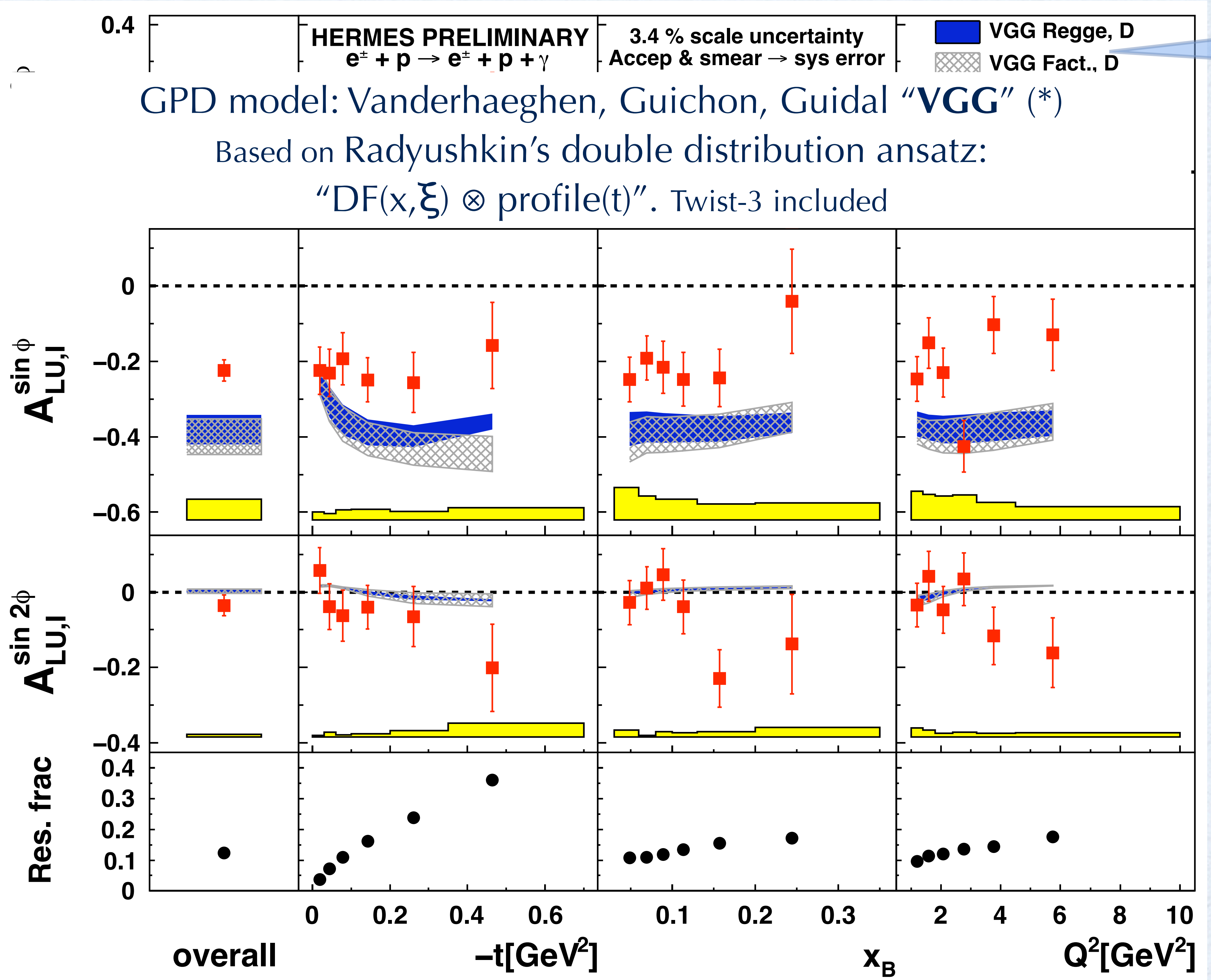

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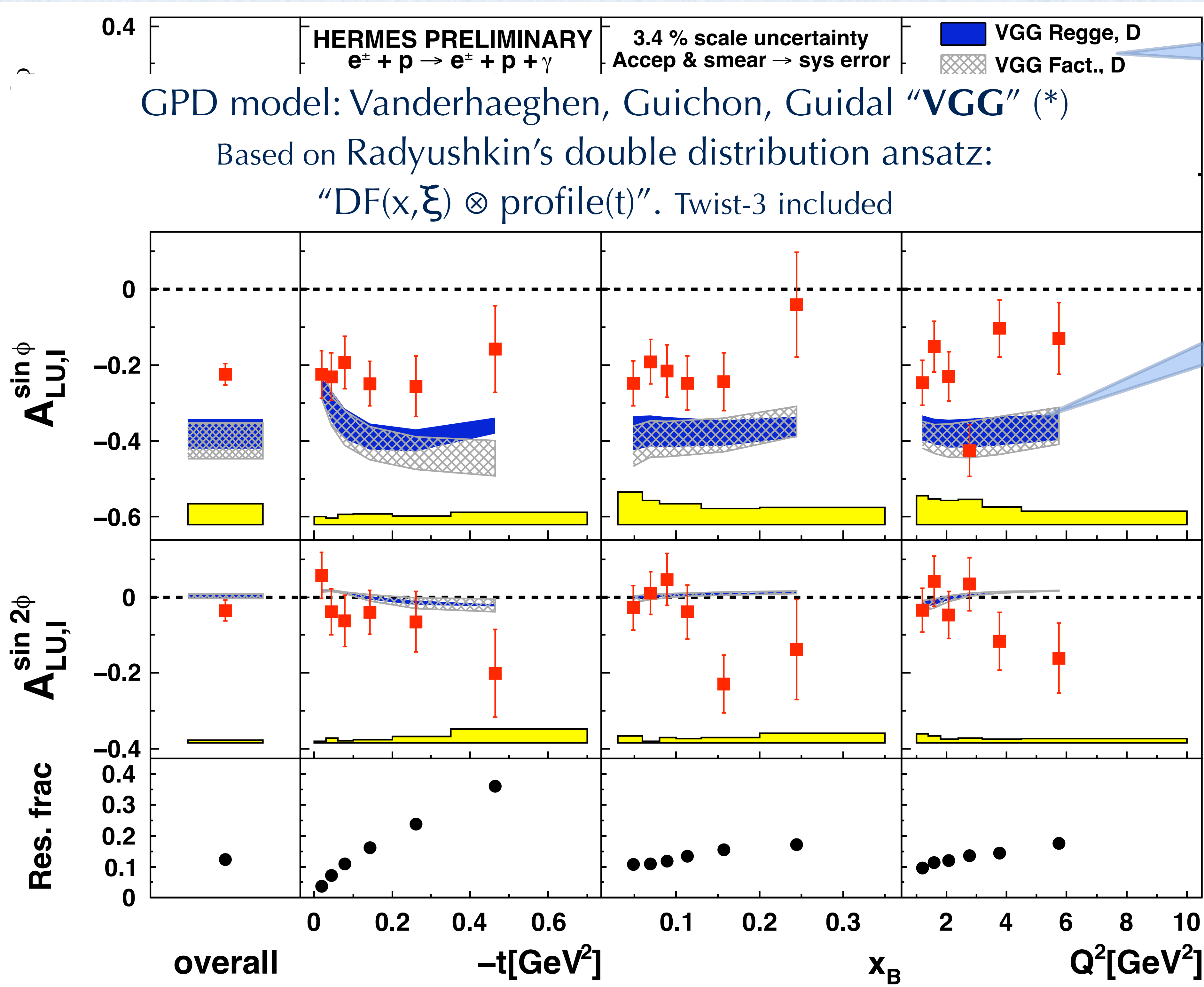

D-term to restore polynomiality

Bands by variation of skewness parameters

$\propto \Im\,[F_1 \mathcal{H}]$

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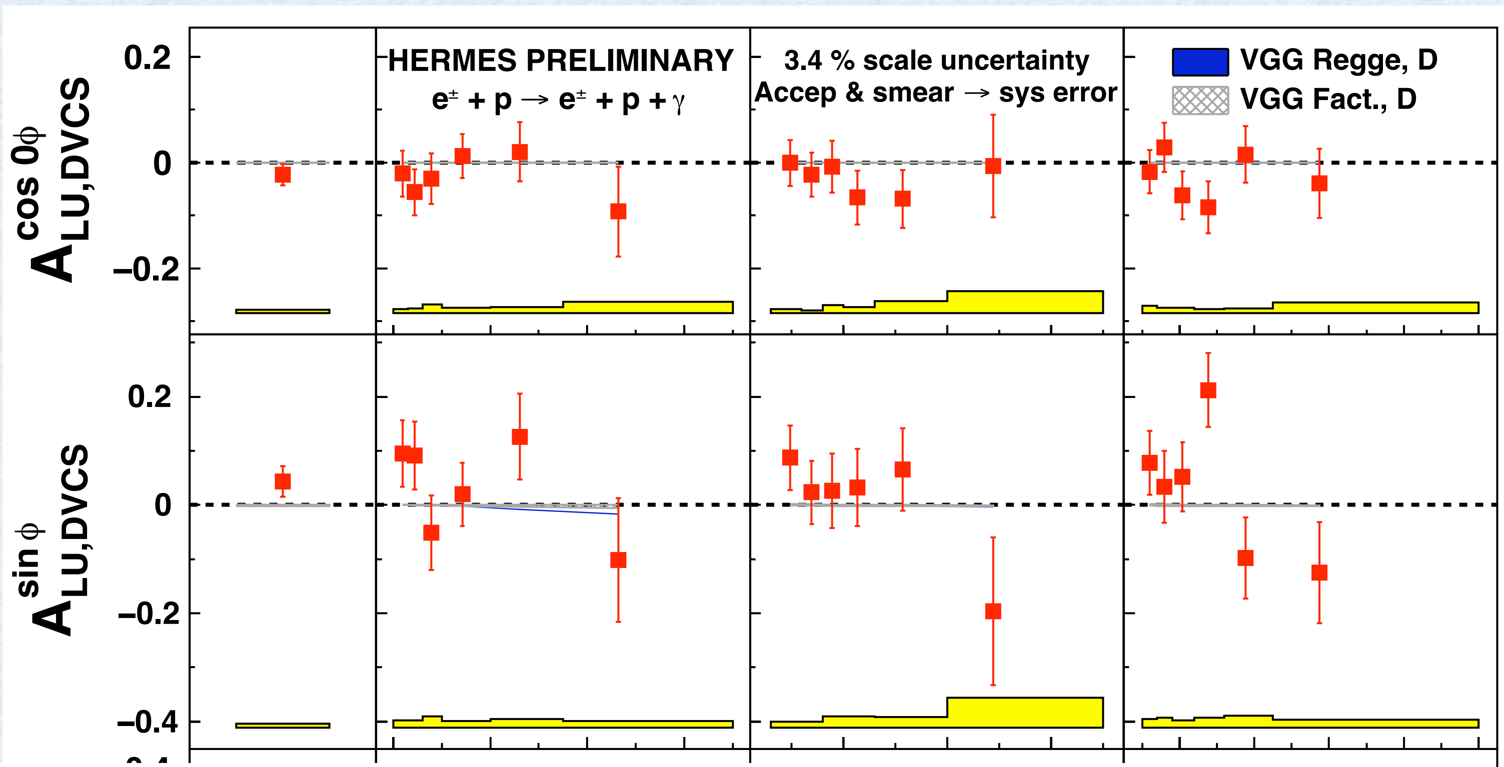
HERMES: BSA from $|\tau_{DVCS}|^2$ on hydrogen



$$\propto \left[\mathcal{H}\mathcal{H}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^*\right]$$

bilinear combination of CFFs

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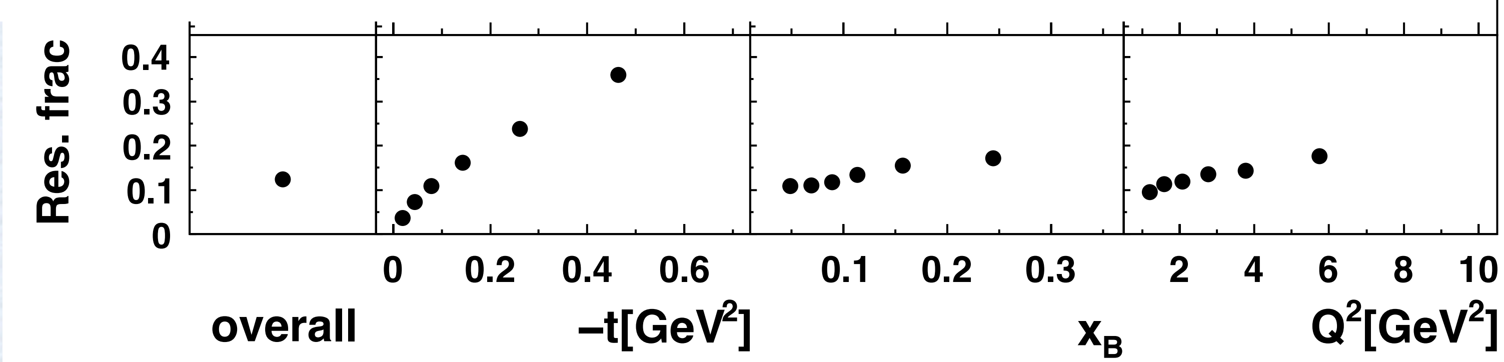
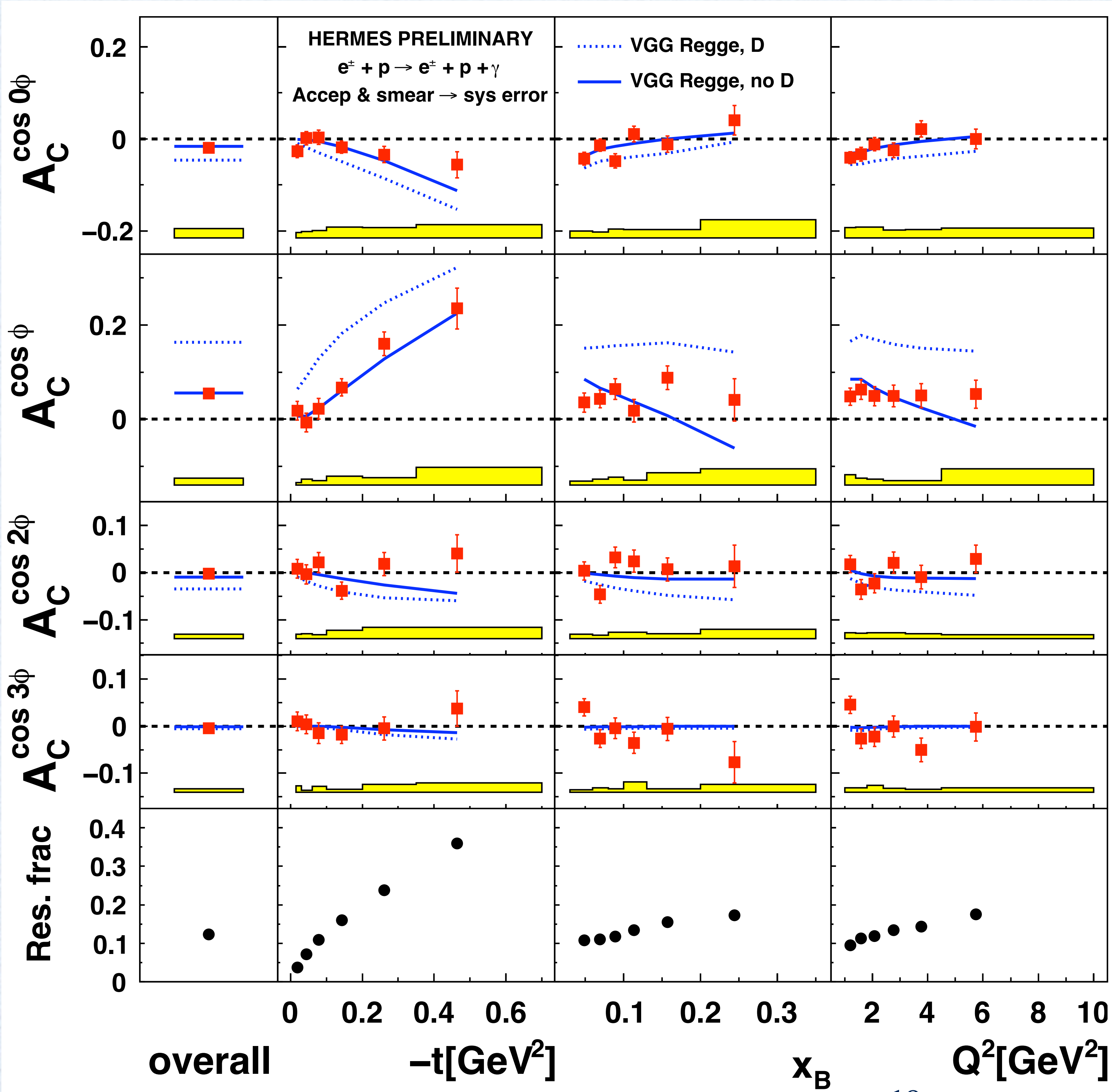
Twist-3 included



HERMES: BCA on hydrogen



constant term:

$$\propto -A_C^{\cos\phi}$$

$$\propto \Re\left[F_1 \mathcal{H}\right]$$

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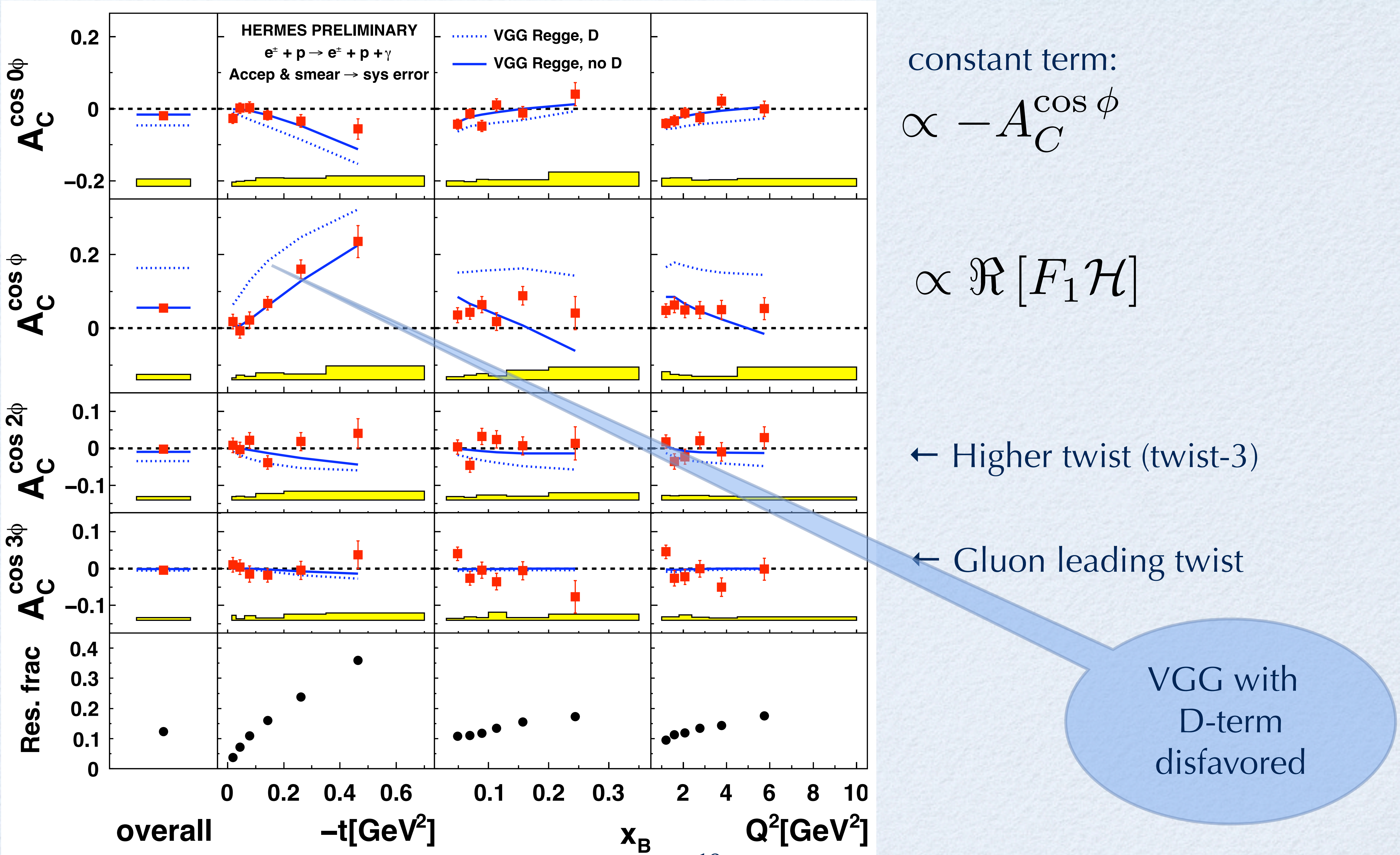

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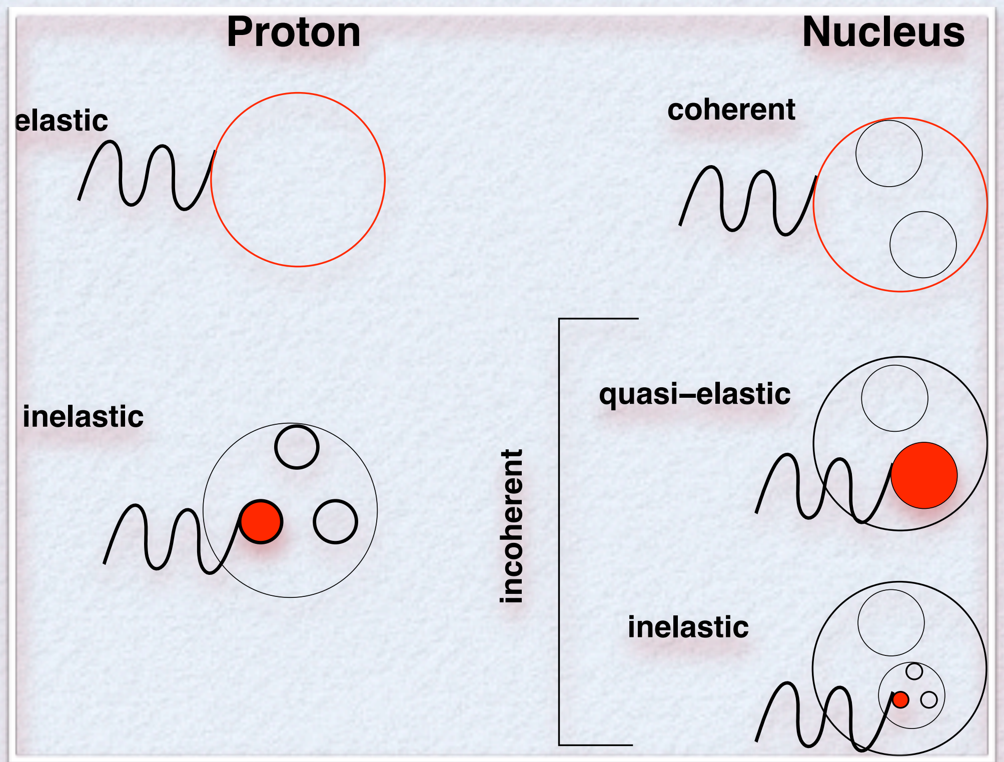
DVCS on Nuclear Targets

- How does the nuclear environment modify parton-parton correlations?
- How do nucleon properties change in the nuclear medium?



(Bethe-Heitler)

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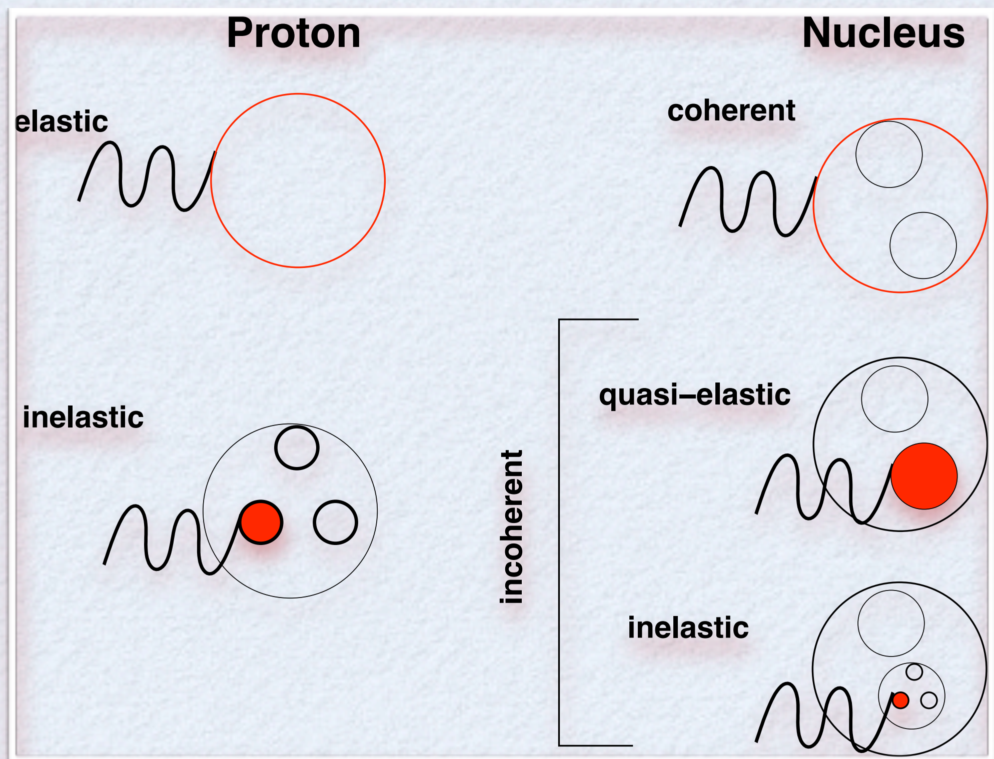
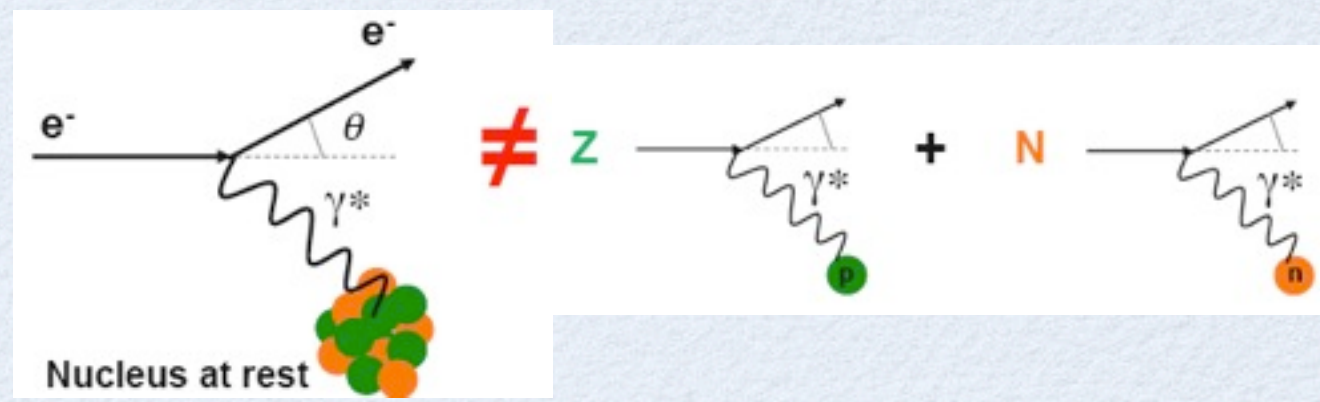


(Bethe-Heitler)

- DVCS in coherent region:
new insights into 'generalized EMC effect'?



- ➤ Nuclear GPDs ≠ GPDs of free nucleon
- ➤ Enhancement of effect when leaving forward limit?
  - ➢ caused by transverse motion of partons in nuclei?
  - ➢ important role of mesonic degrees of freedom?
  - ➢ manifest in strong increase of real part of τ_{DVCS} with atomic mass number A?

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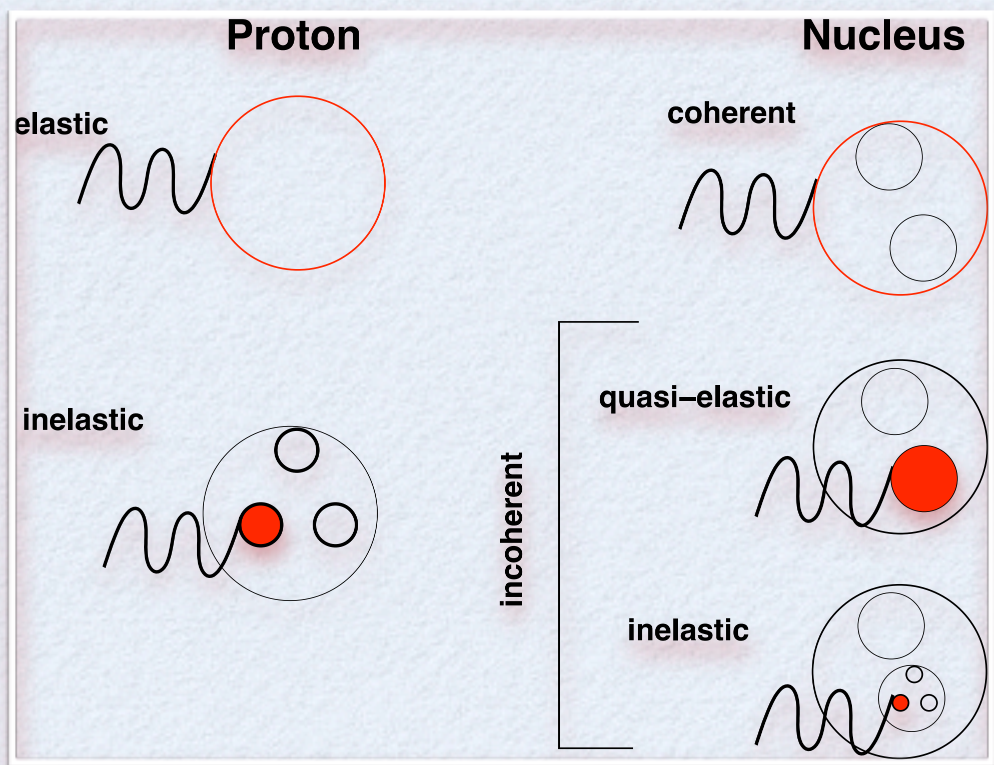

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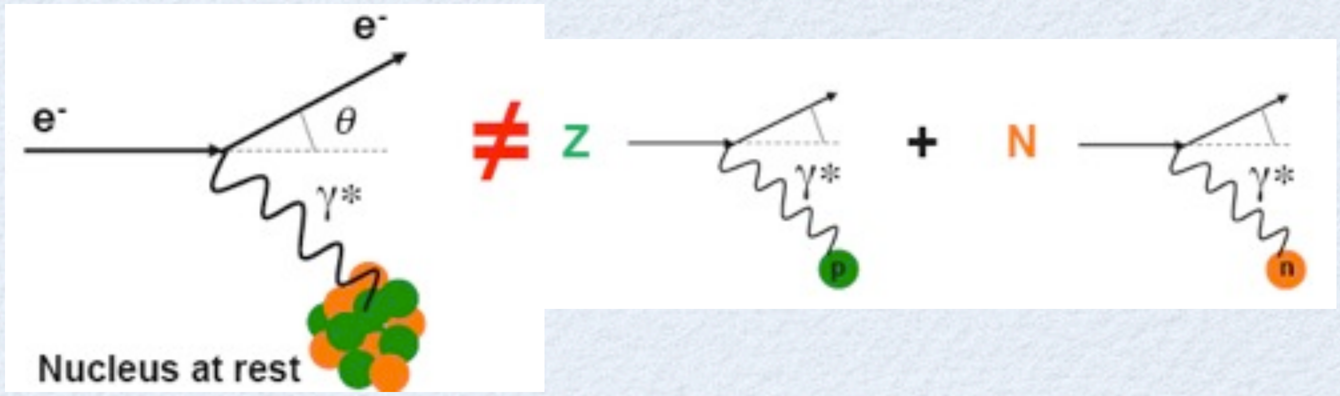

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HERMES measurements on nuclear targets

Target	spin	L (pb^{-1})
H	1/2	227
He	0	32
N	1	51
Ne	0	86
Kr	0	77
Xe	0, 1/2, 3/2	47

DVCS on Nuclear Targets

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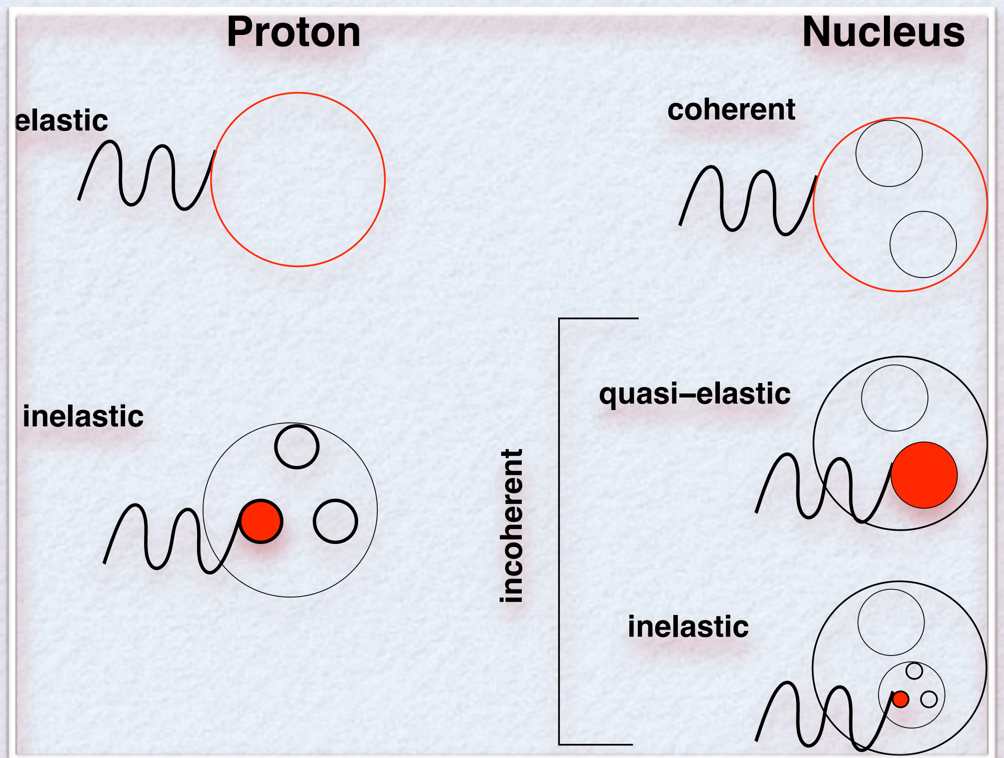

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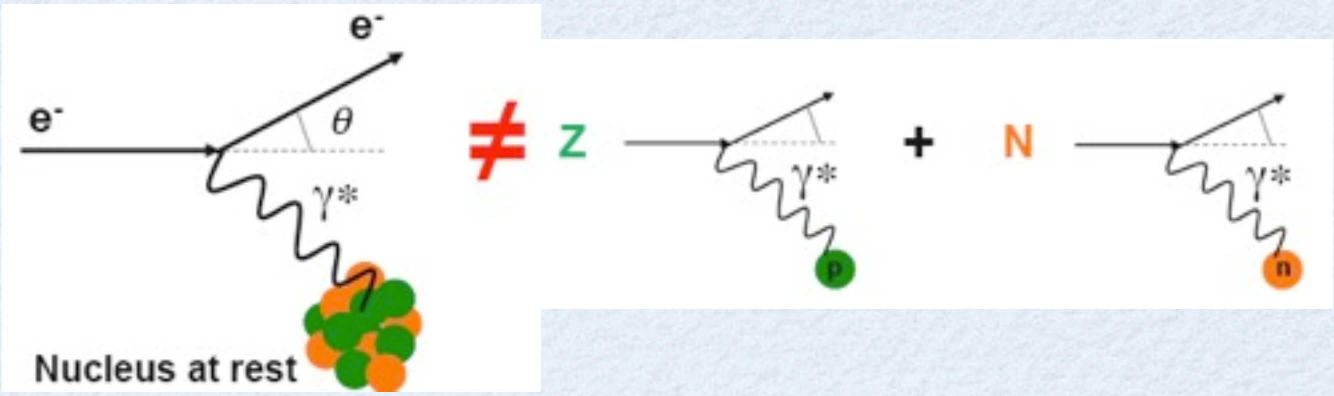

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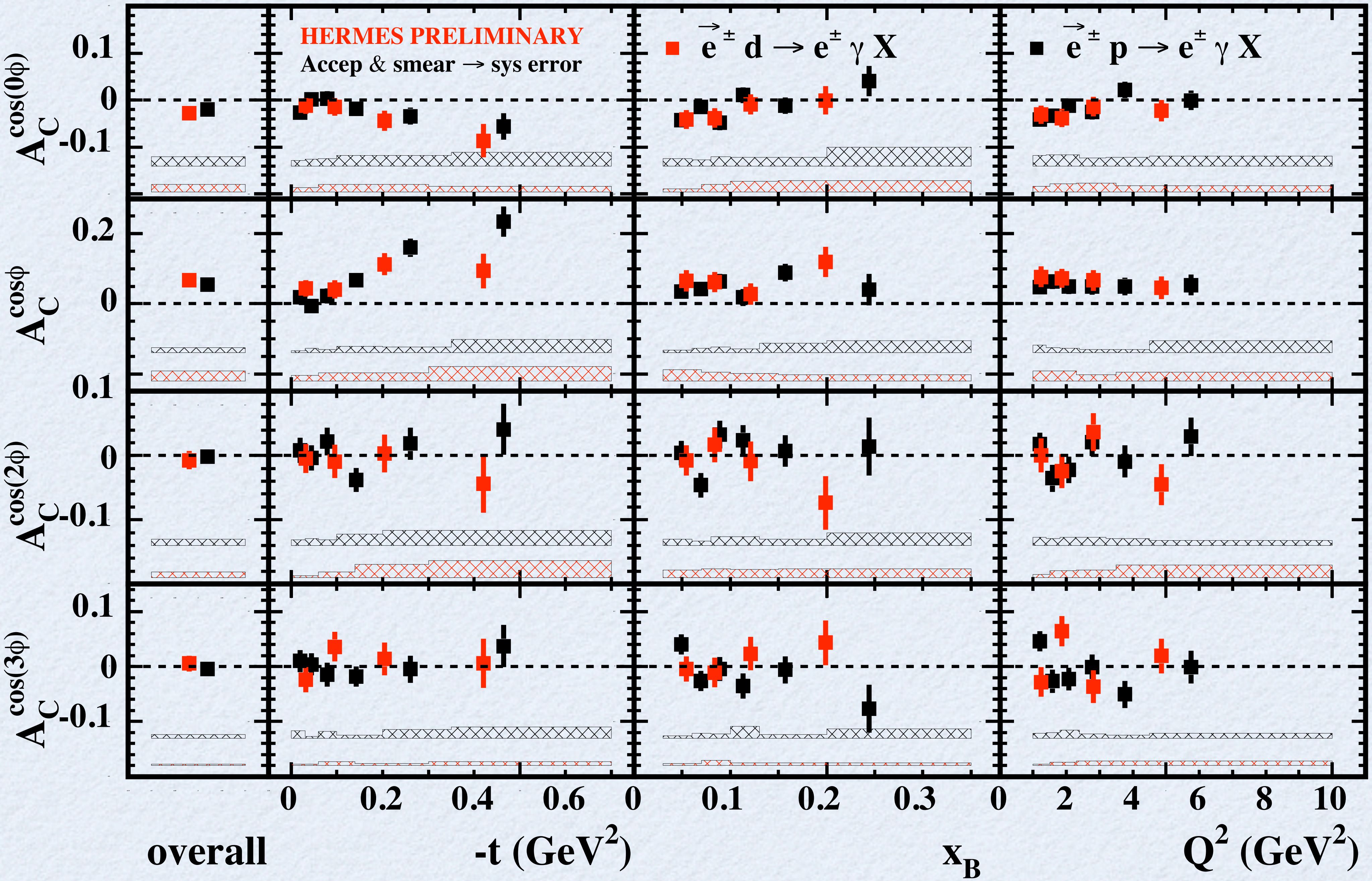
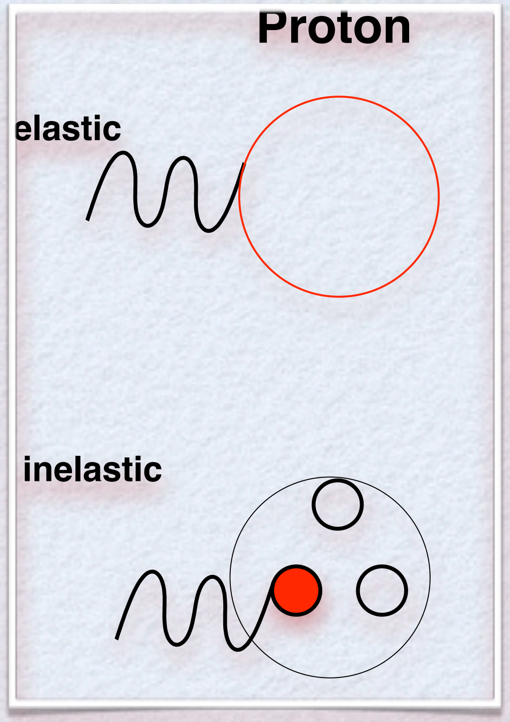
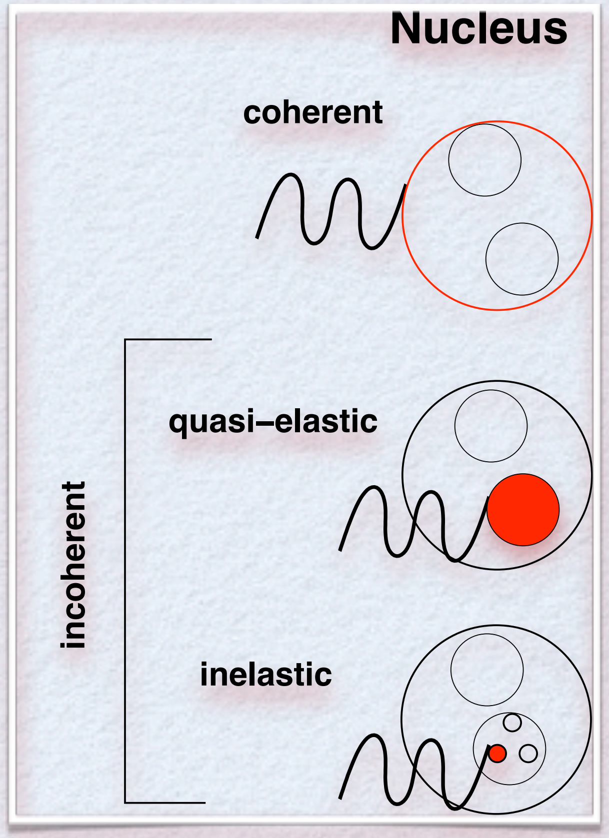
+ deuterium, spin-1, 300 pb^{-1}

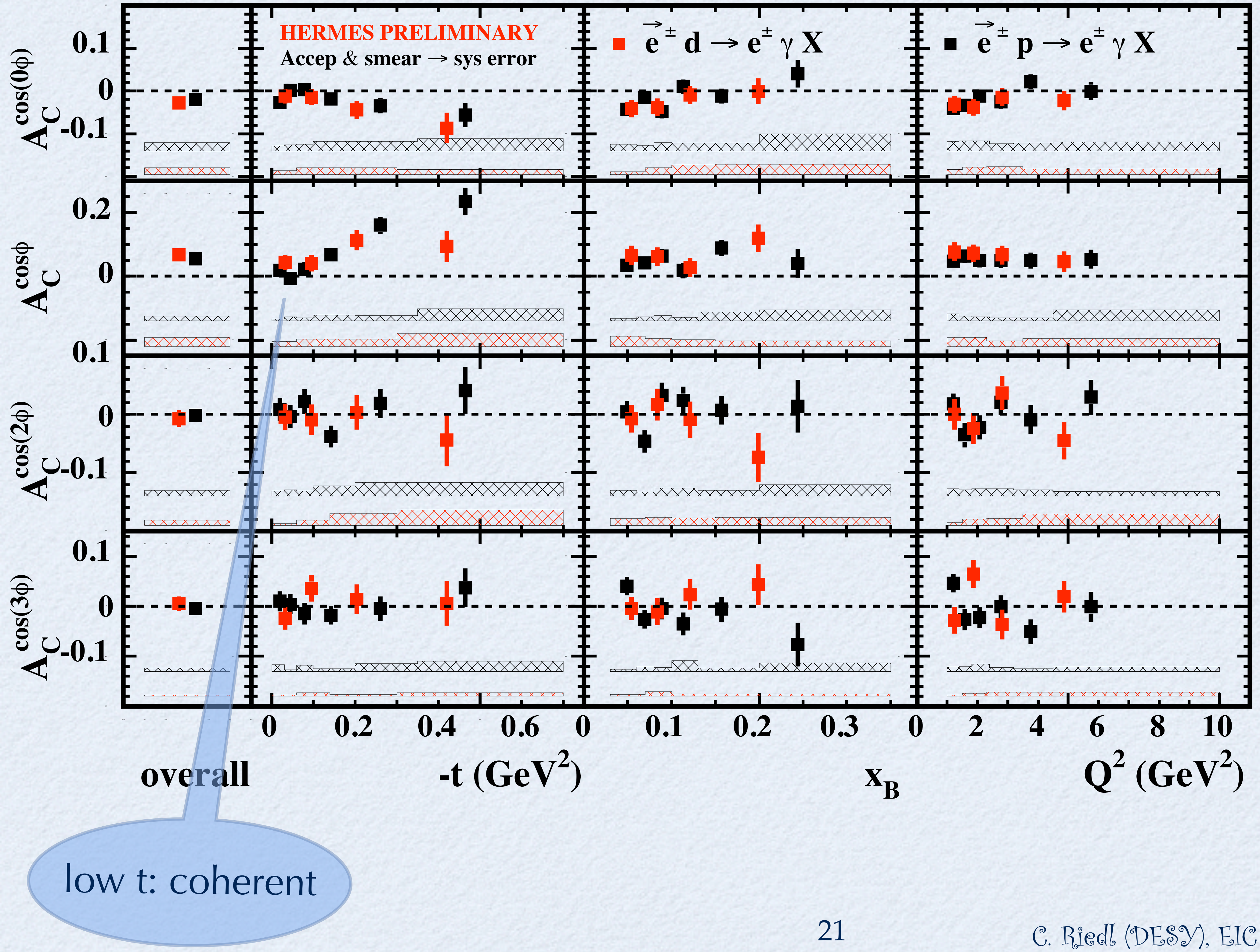
HERMES: BCAs on hydrogen and deuterium

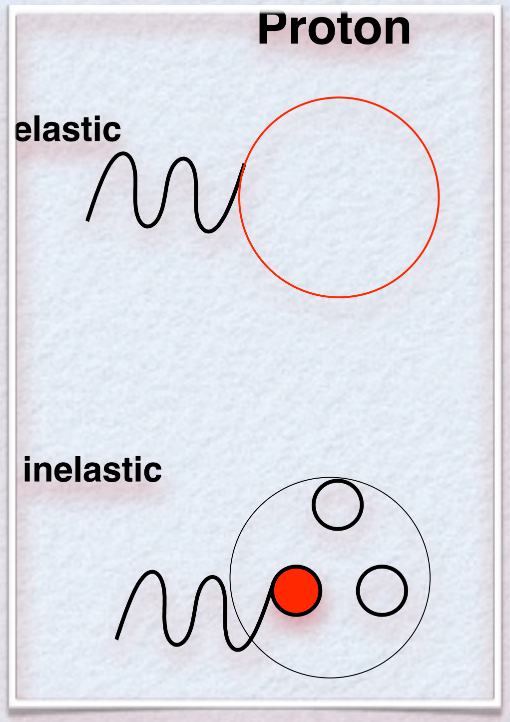


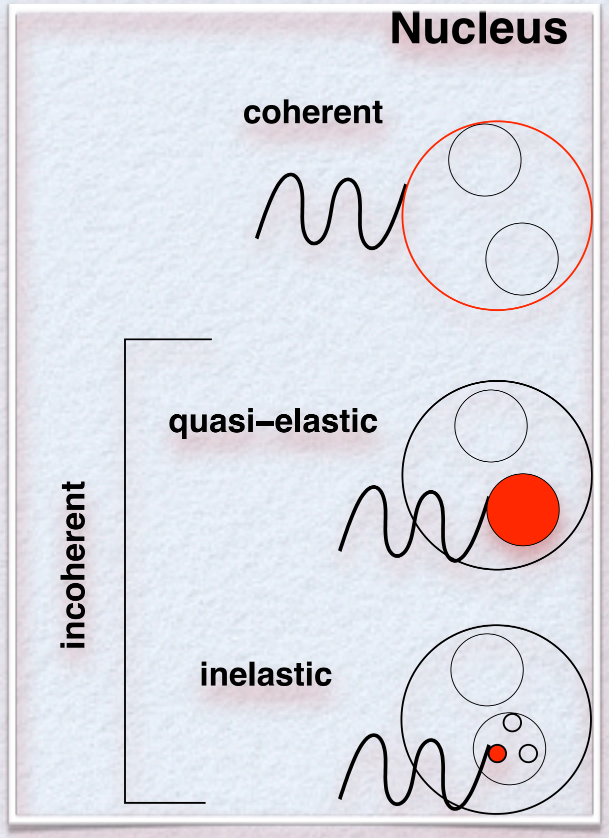




HERMES: BCAs on hydrogen and deuterium







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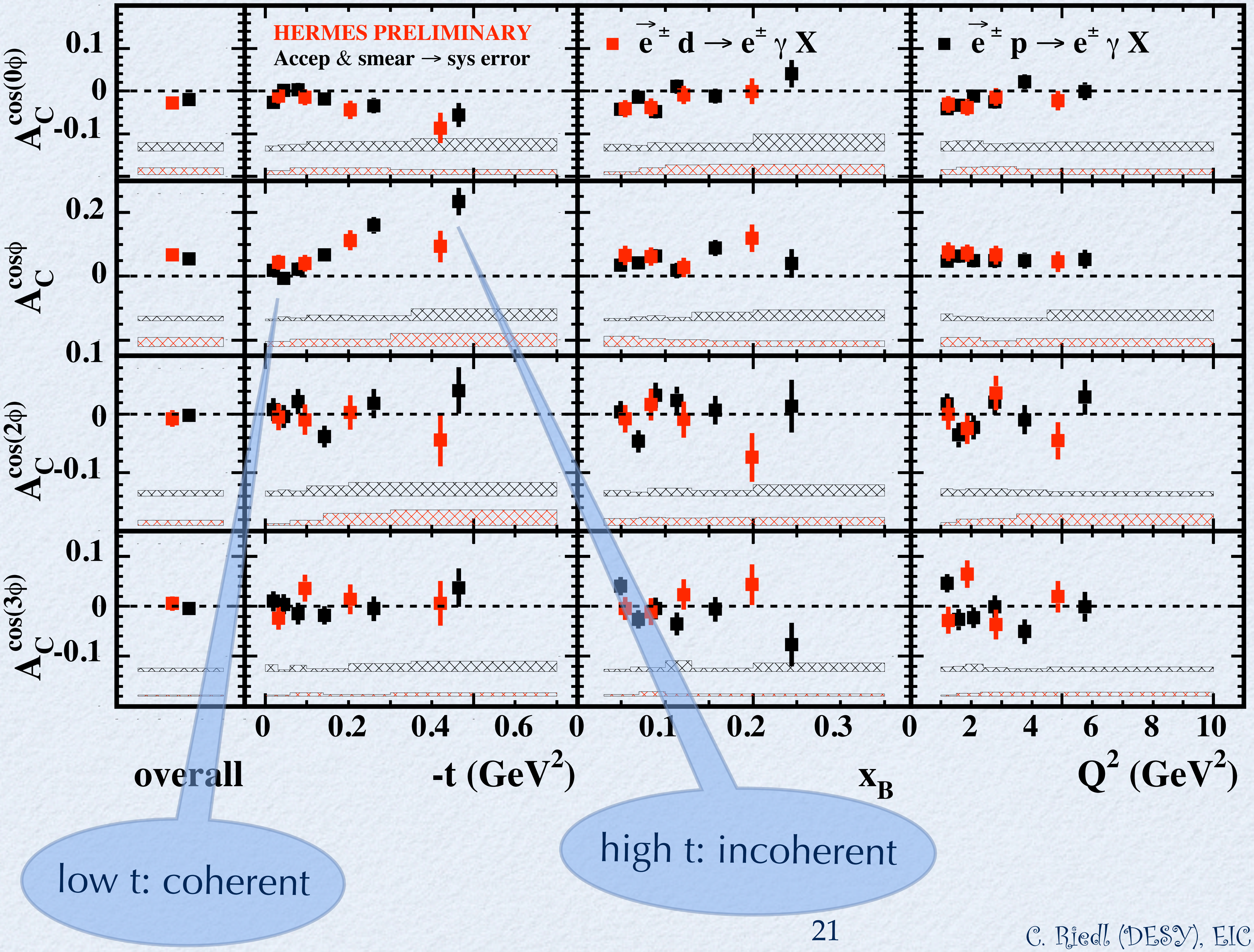
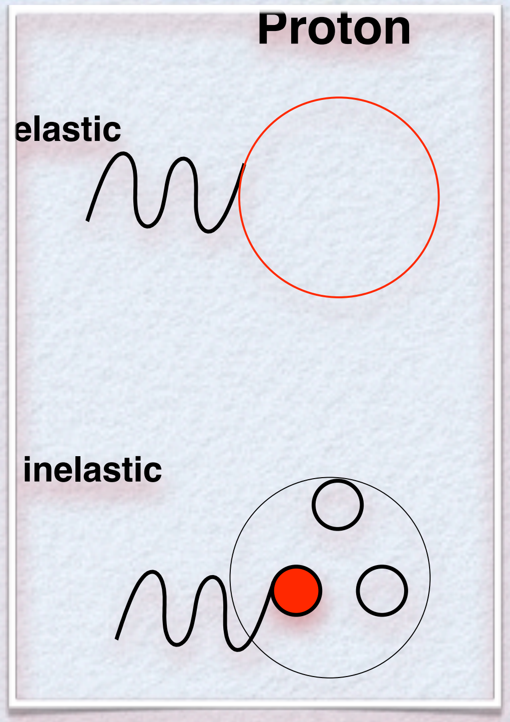
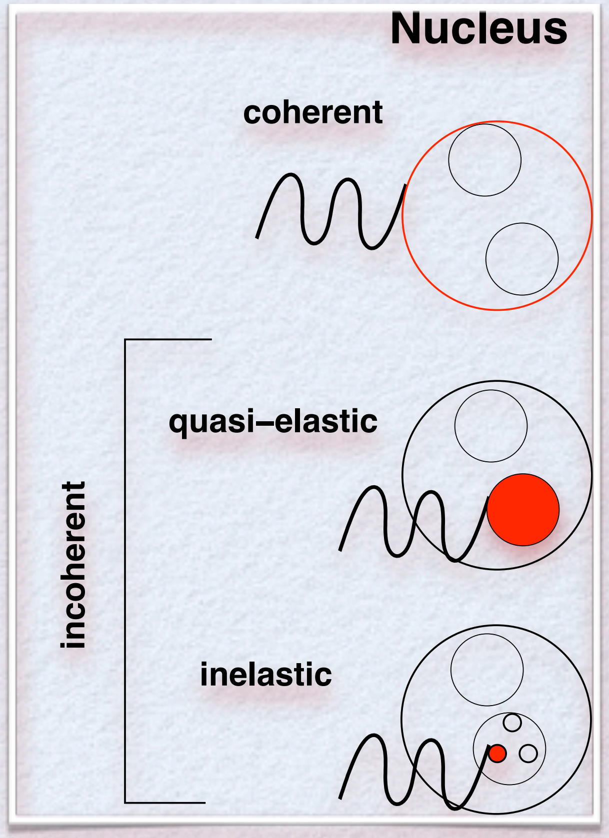
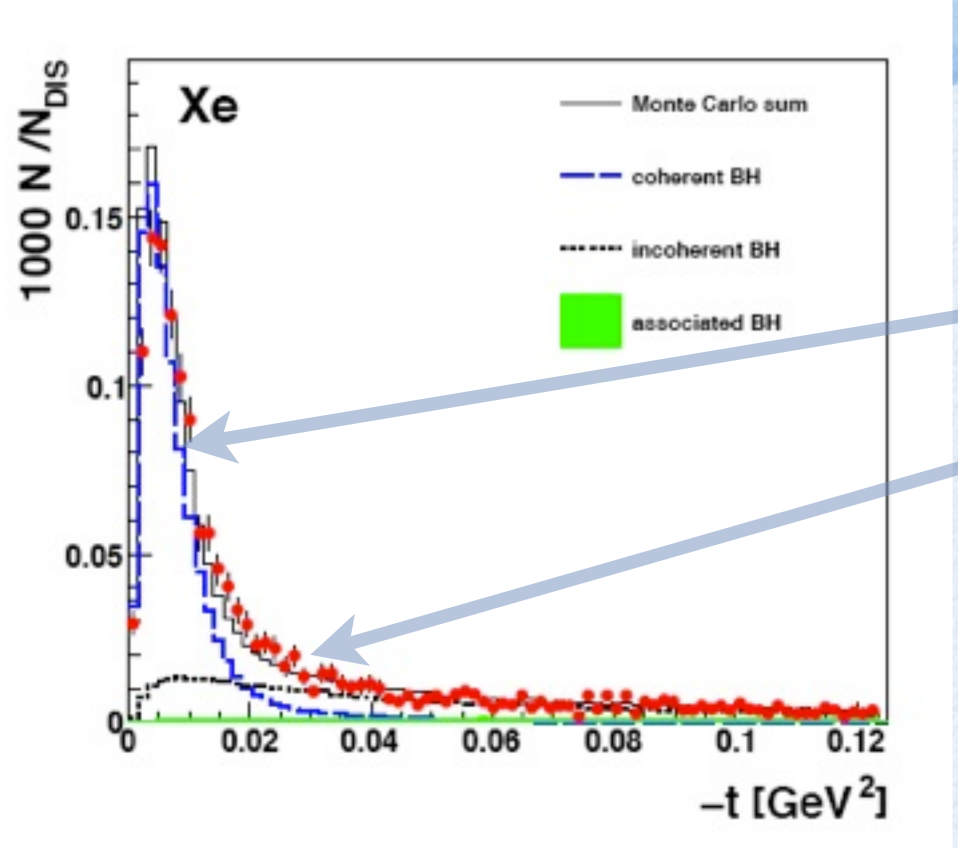






DVCS at HERMES: Nuclear mass dependence



Select for each target two samples (t-cutoffs):

➢ **coherent enriched**

(≈ 65% coherent fraction)

➢ **incoherent enriched**

(≈ 60% incoherent fraction)

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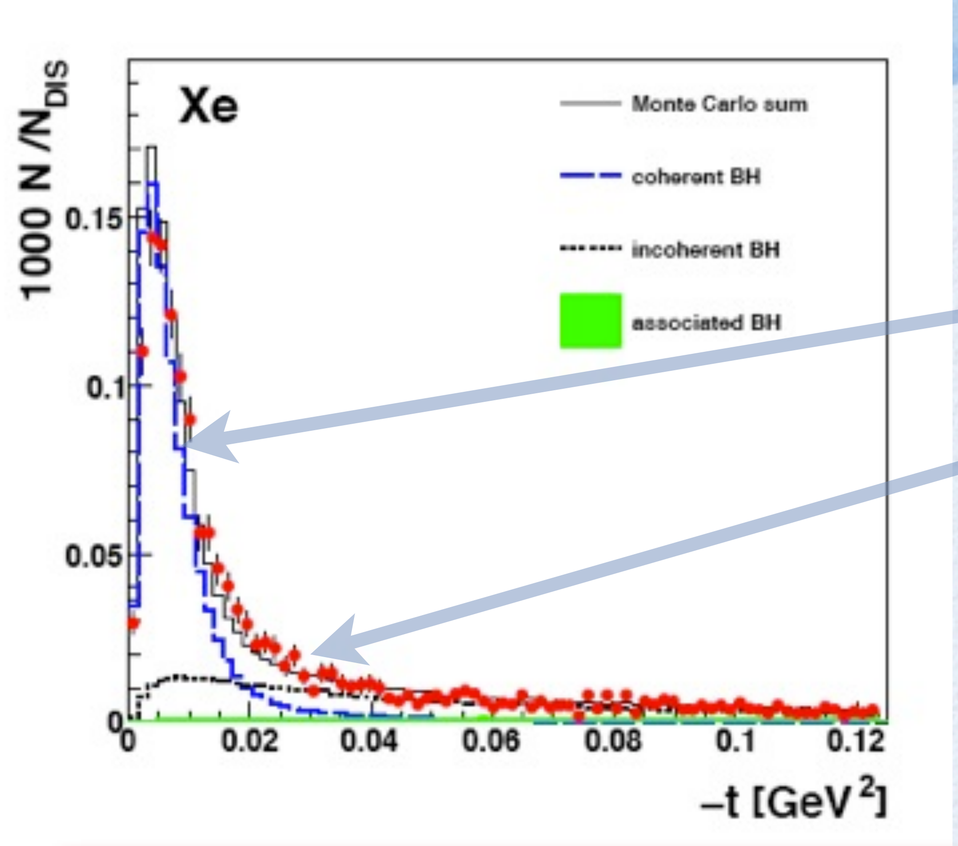

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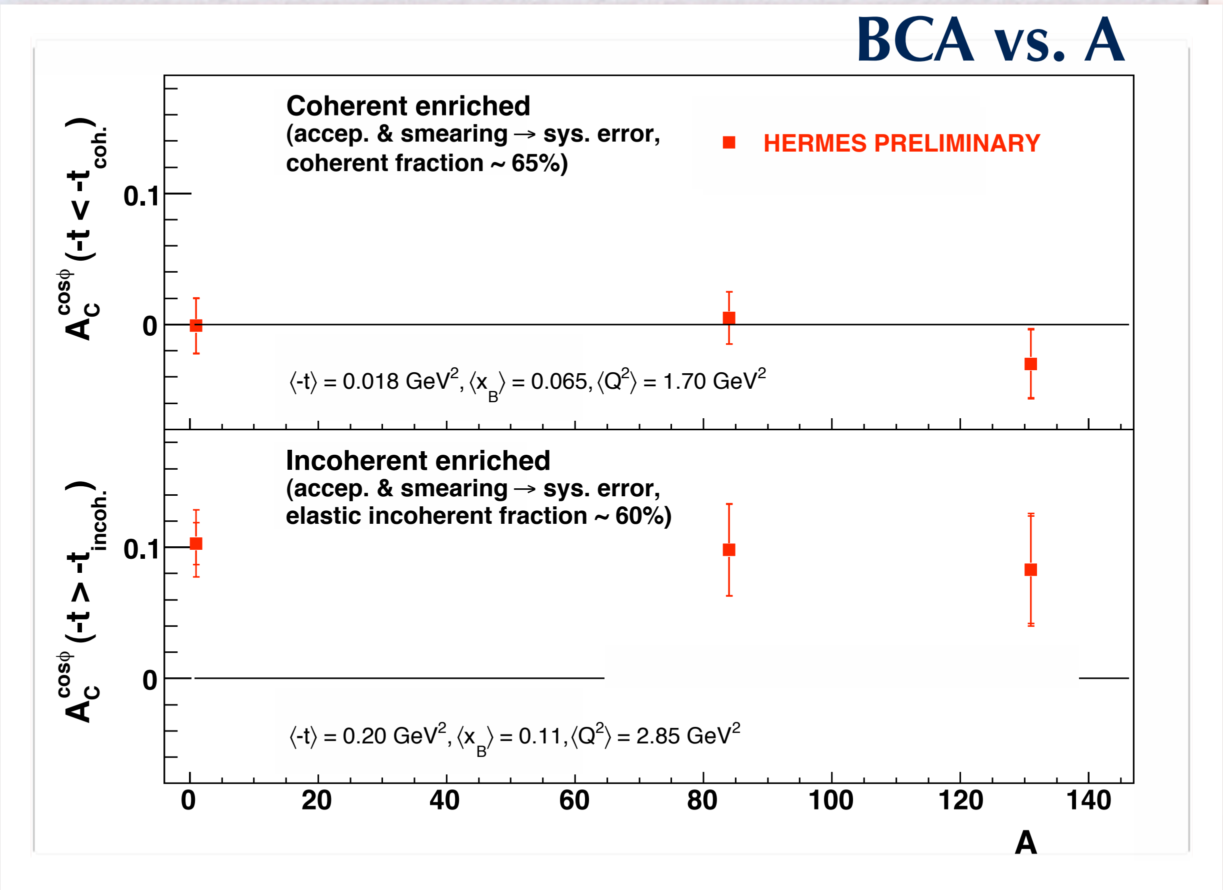
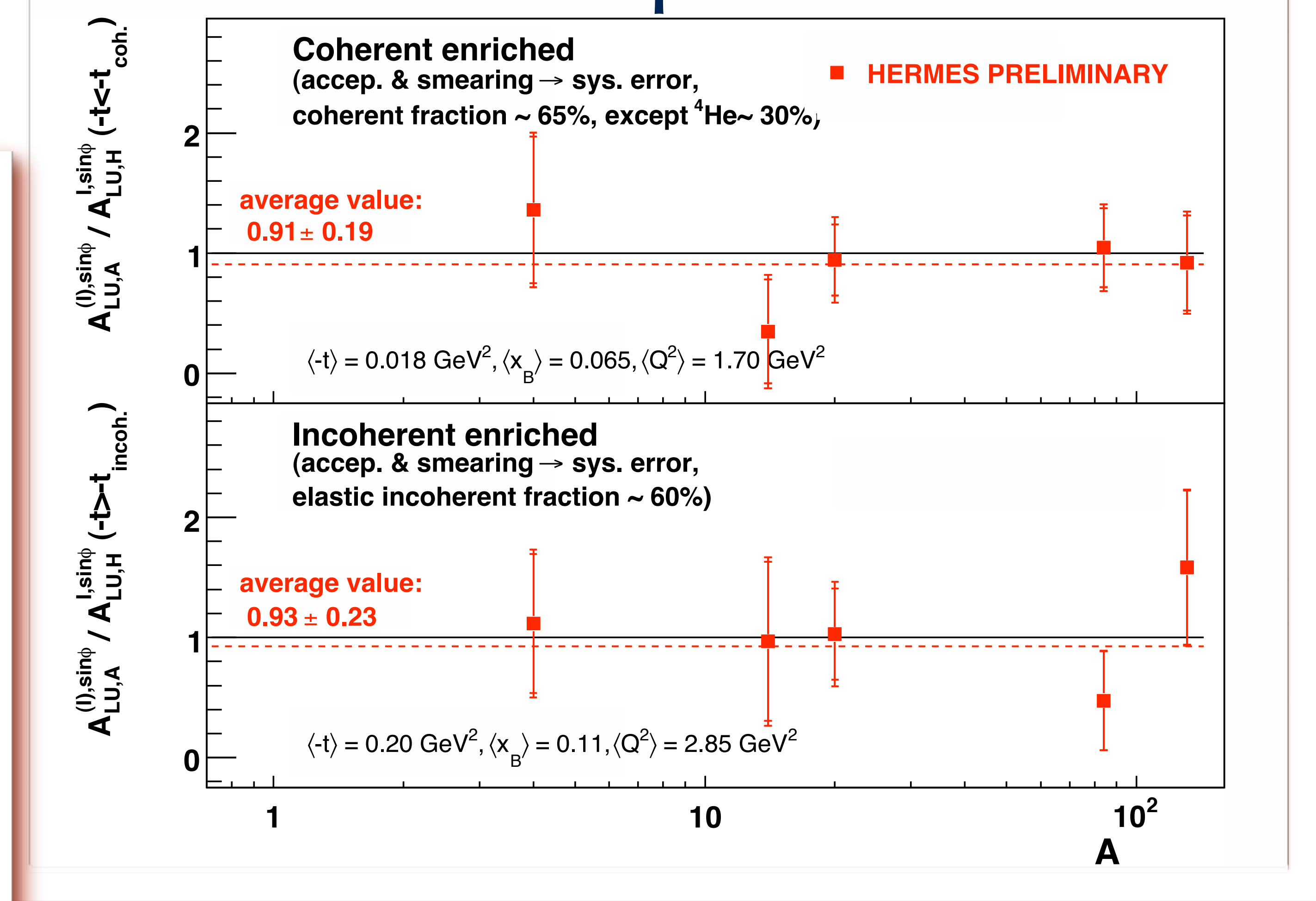
BCA vs. A



BSA ratio: nuclear / free proton vs. A



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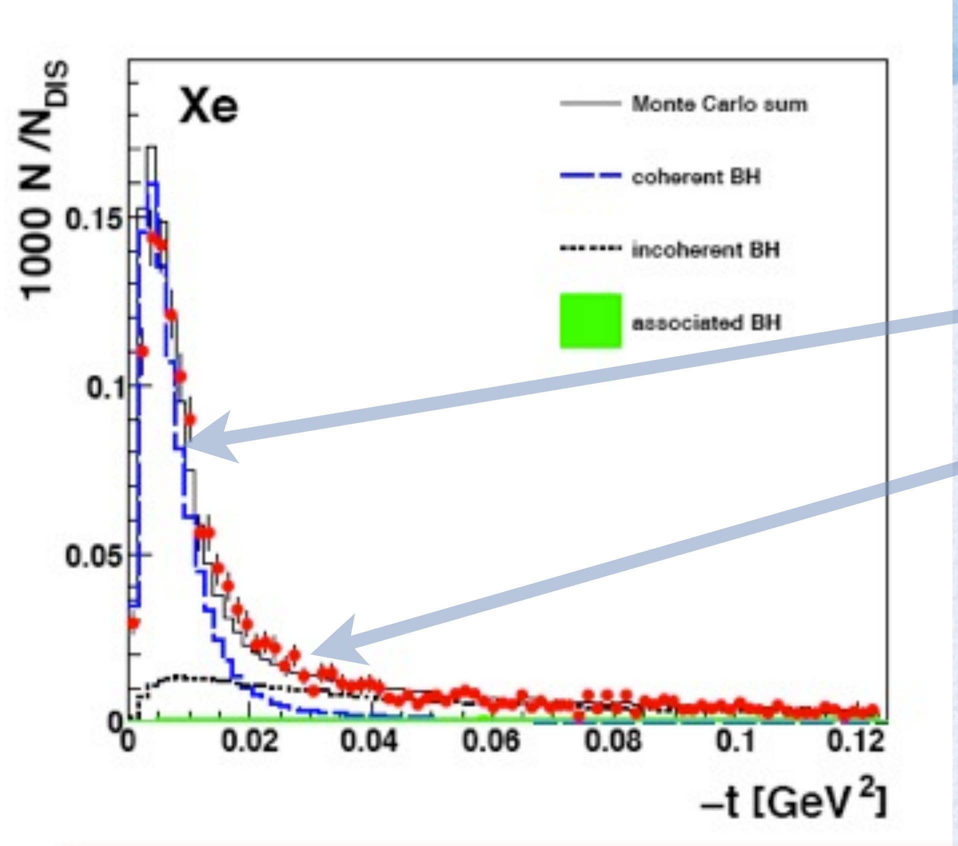

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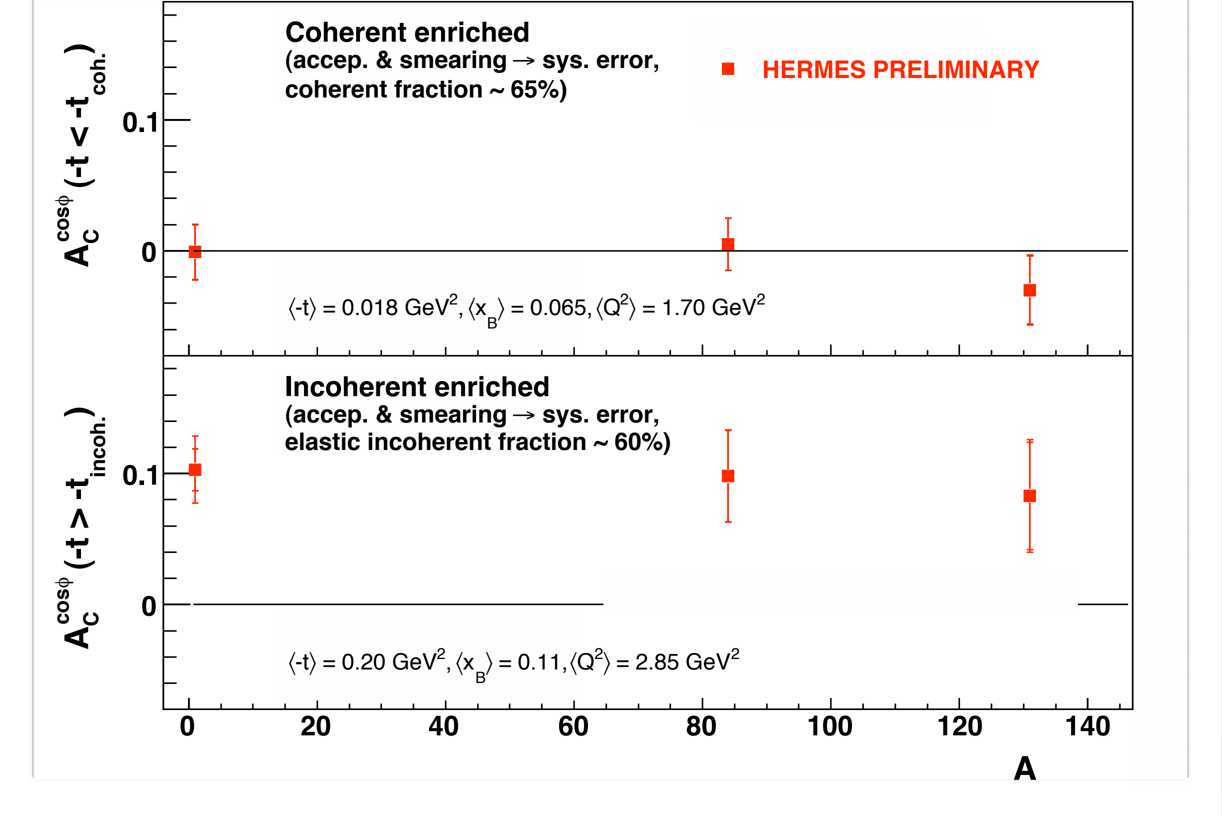
No nuclear mass dependence of BCA and BSA observed within uncertainties

⇒ no enhancement of τ_{DVCS}

BCA vs. A



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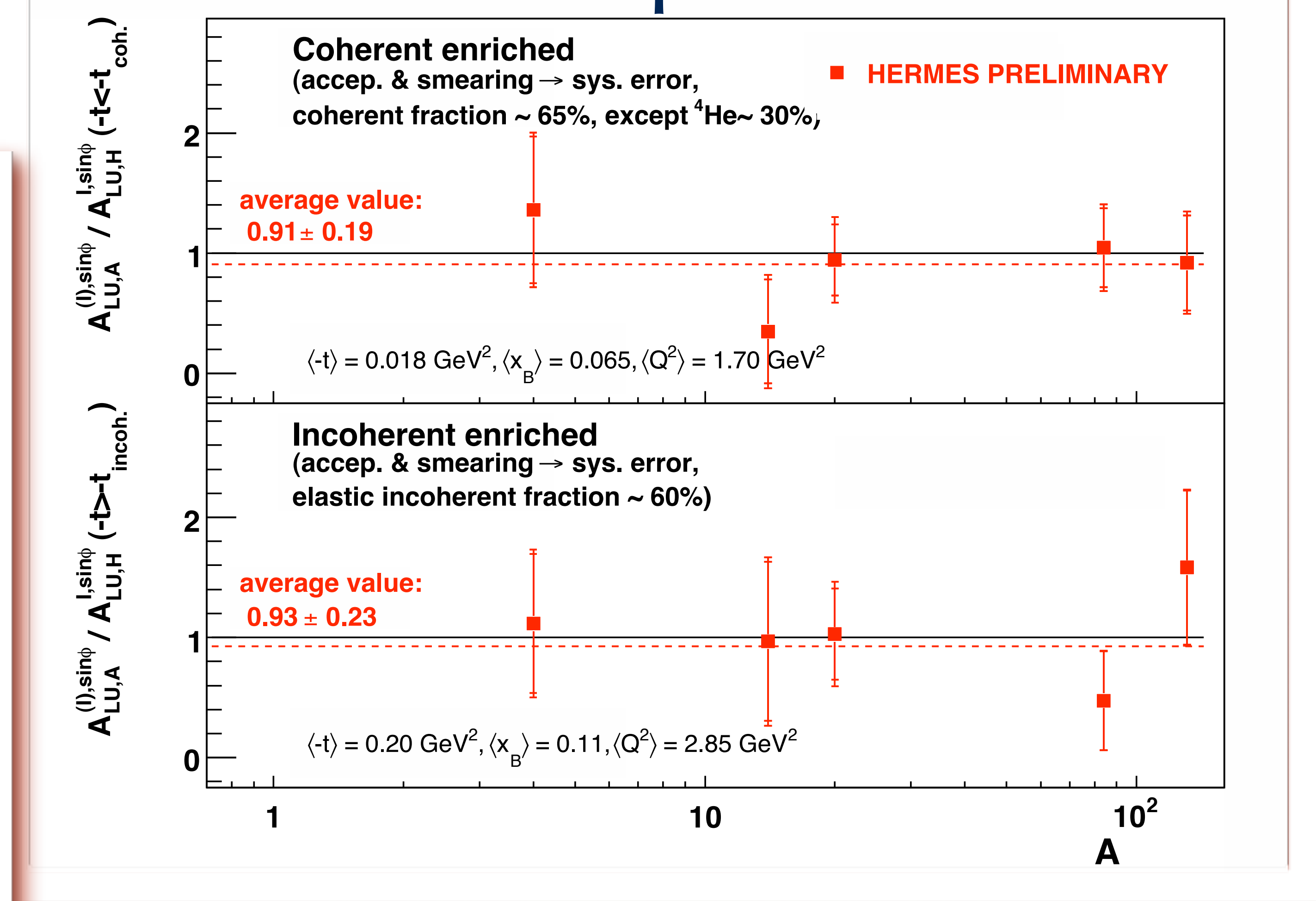
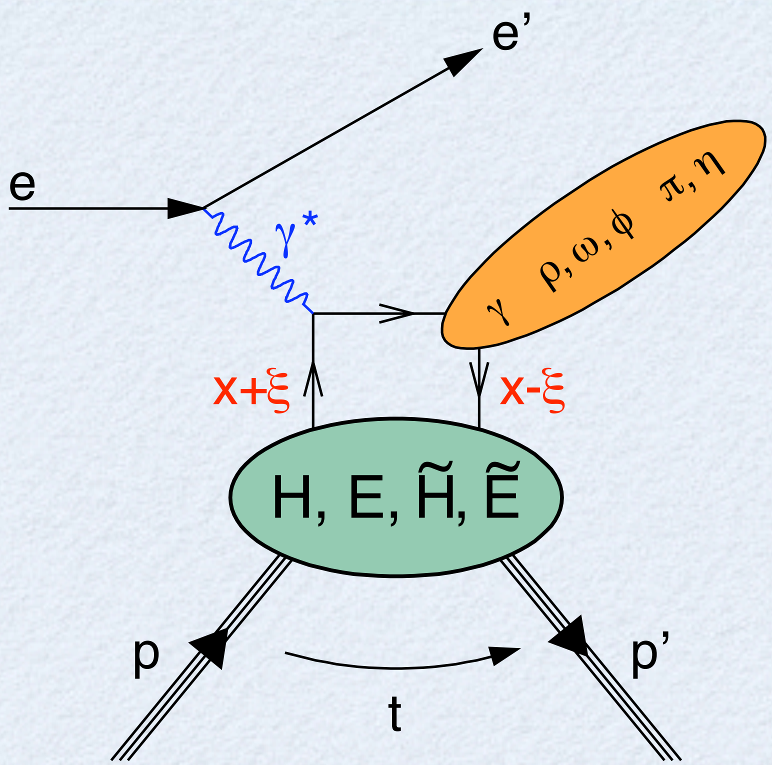


Exclusivity at HERMES in a Nutshell



GPD access at HERMES:

nucleon helicity	quark helicity independent	quark helicity dependent
	photon: $J^P=1^-$ (DVCS)	
conserved	**H**: A_C, A_{LU}, A_{UT}	$\widetilde{\mathbf{H}}$: A_{UL}, [A_{UT}]
flipped	**E**: A_{UT}	$\widetilde{\mathbf{E}}$: [A_{UT}]
	$J^P=1^-$ mesons	$J^P=0^-$ mesons

$$J_q = \frac{1}{2} \lim_{t\to 0} \int_{-1}^{1} dx\, x \left[H^q(x,\xi,t) + E^q(x,\xi,t)\right]$$

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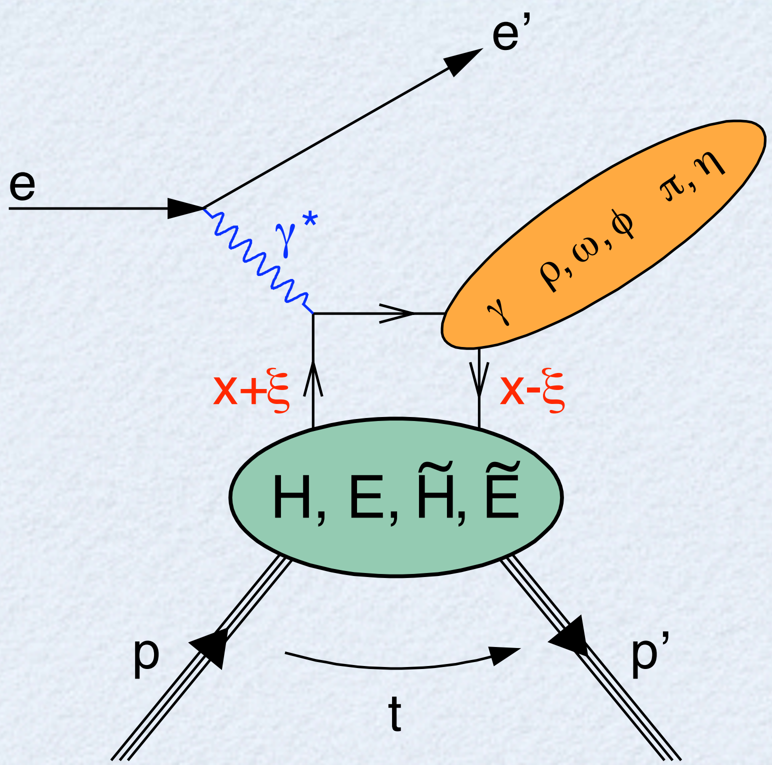

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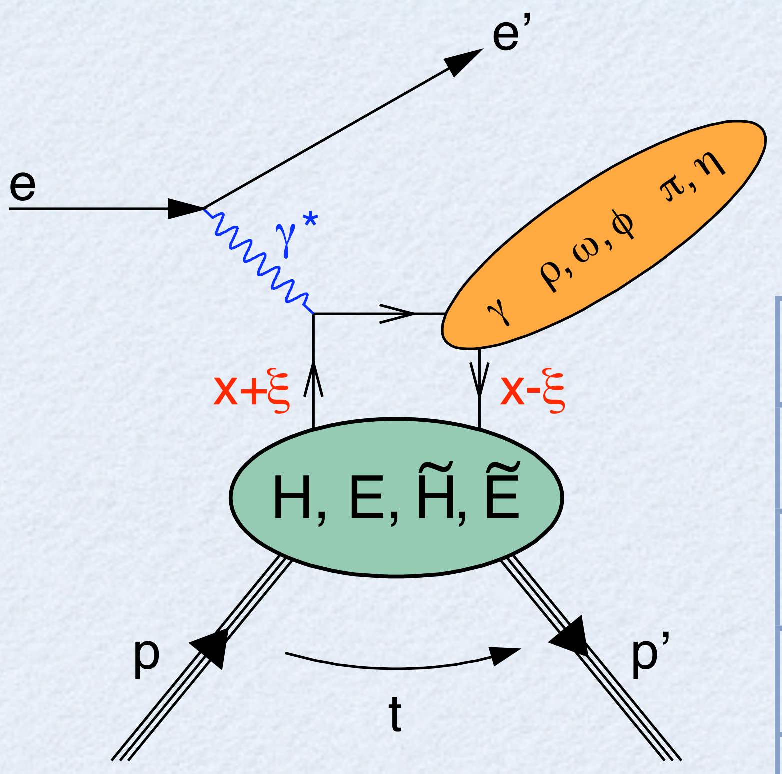

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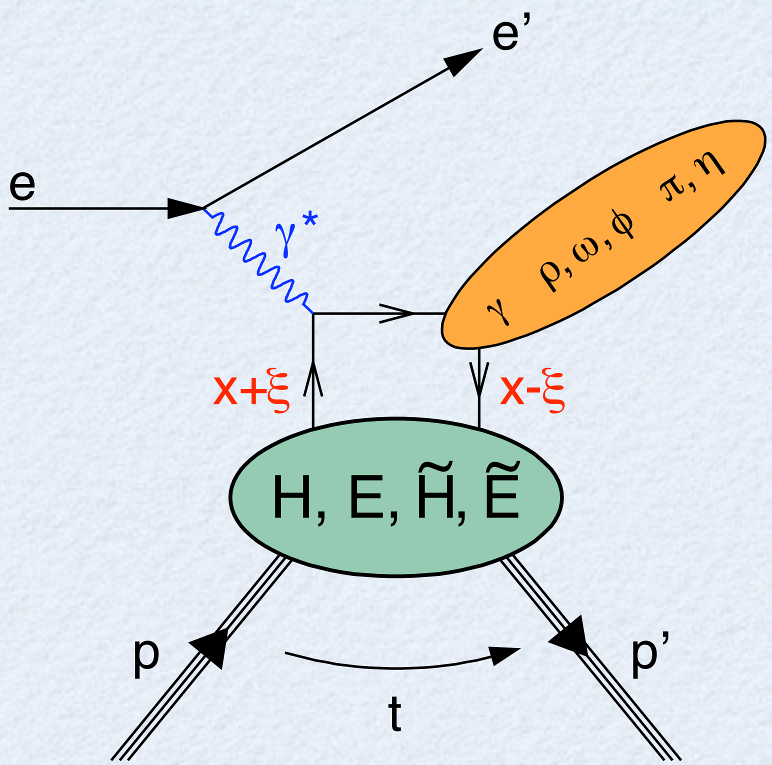

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vector mesons
ρ^0, ω, φ

pseudoscalar mesons
π^+, η

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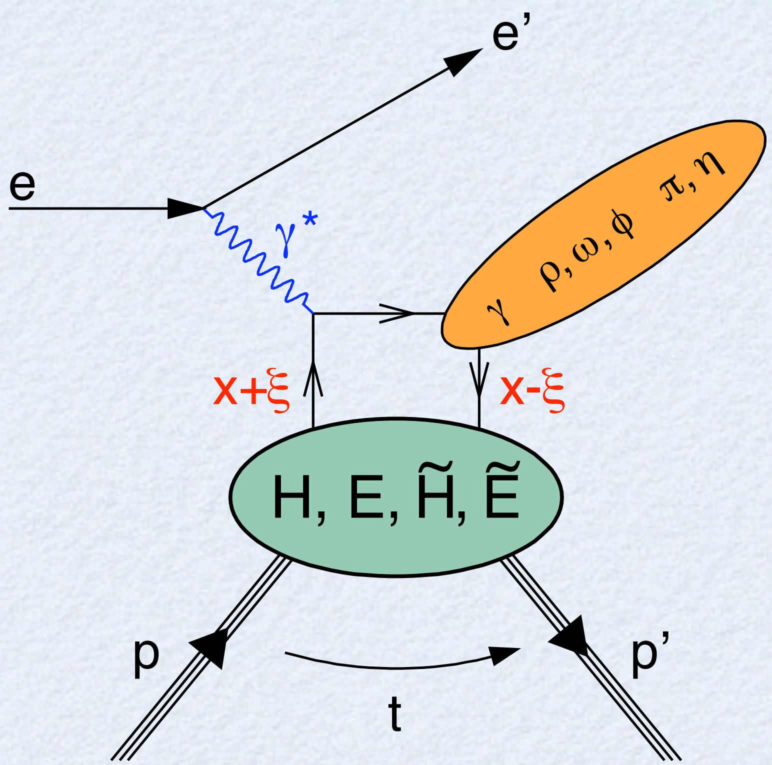

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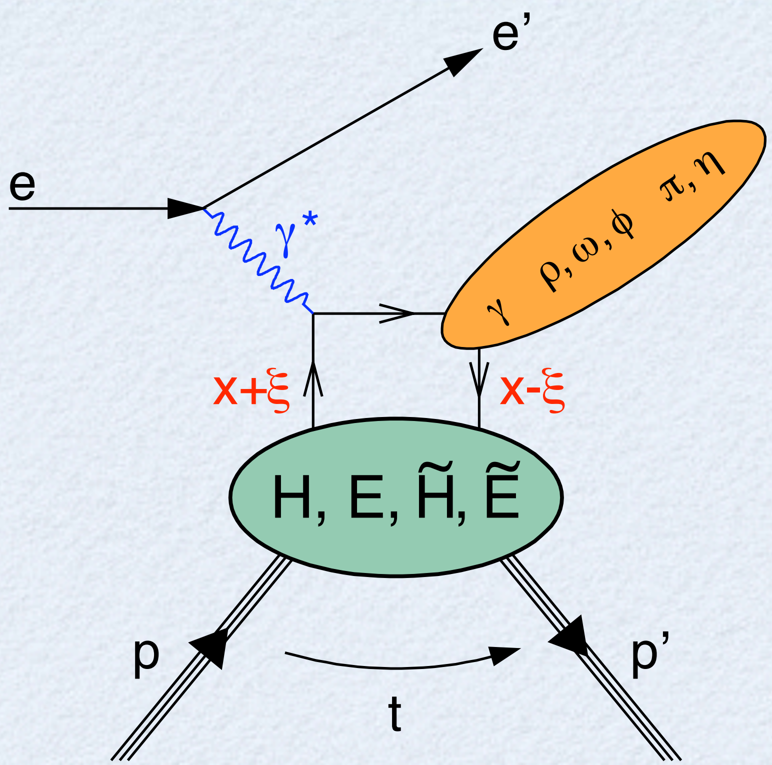

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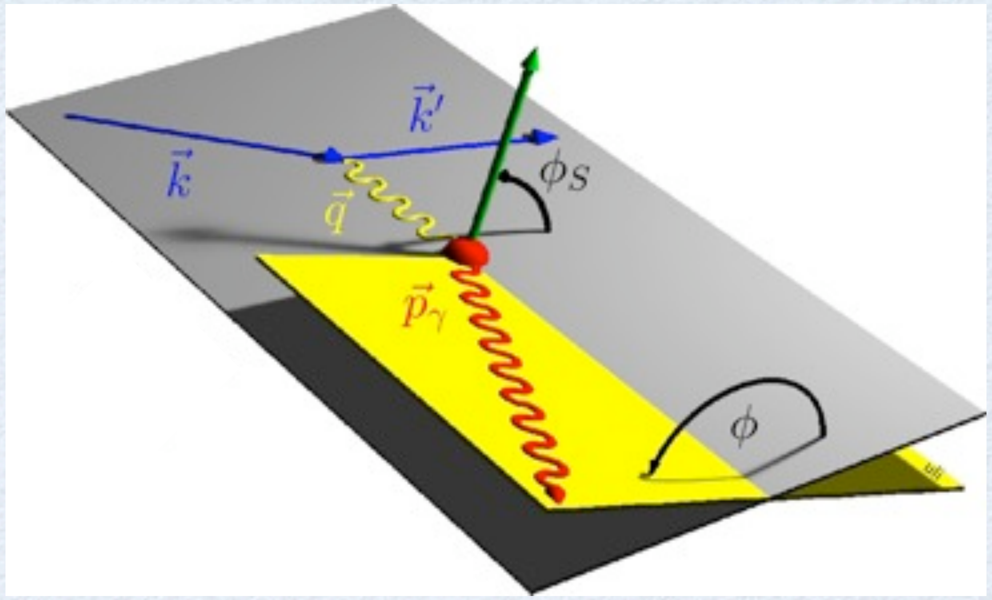
DVCS Transverse Target Spin Asymmetry $\mathcal{A}_{UT}(\phi,\phi_S)$



- $\mathcal{A}_{UT}$: the only DVCS asymmetry on the proton for which **GPD E is not suppressed**
  (Hall-A: BSA on neutron)

- **HERMES:** transversely polarized hydrogen, 170 pb^{-1}, 2 beam charges
  ➢ Separation of DVCS and interference terms possible

$$A^{\mathcal{I}}_{\mathrm{UT}}(\phi,\phi_s) \propto \left[\mathrm{d}\sigma^{+}(\phi,\phi_s) - \mathrm{d}\sigma^{-}(\phi,\phi_s)\right] - \left[\mathrm{d}\sigma^{+}(\phi,\phi_s+\pi) - \mathrm{d}\sigma^{-}(\phi,\phi_s+\pi)\right]$$

$$\begin{aligned} A^{\mathcal{I}}_{\mathrm{UT}}(\phi,\phi_s) \quad \propto \quad & \mathrm{Im}\,(F_2\mathcal{H} - F_1\mathcal{E})\,\sin(\phi-\phi_s)\cos\phi \\ + \quad & \mathrm{Im}\left(F_2\widetilde{\mathcal{H}} - (F_1+\xi F_2)\widetilde{\mathcal{E}}\right)\cos(\phi-\phi_s)\sin\phi \end{aligned}$$

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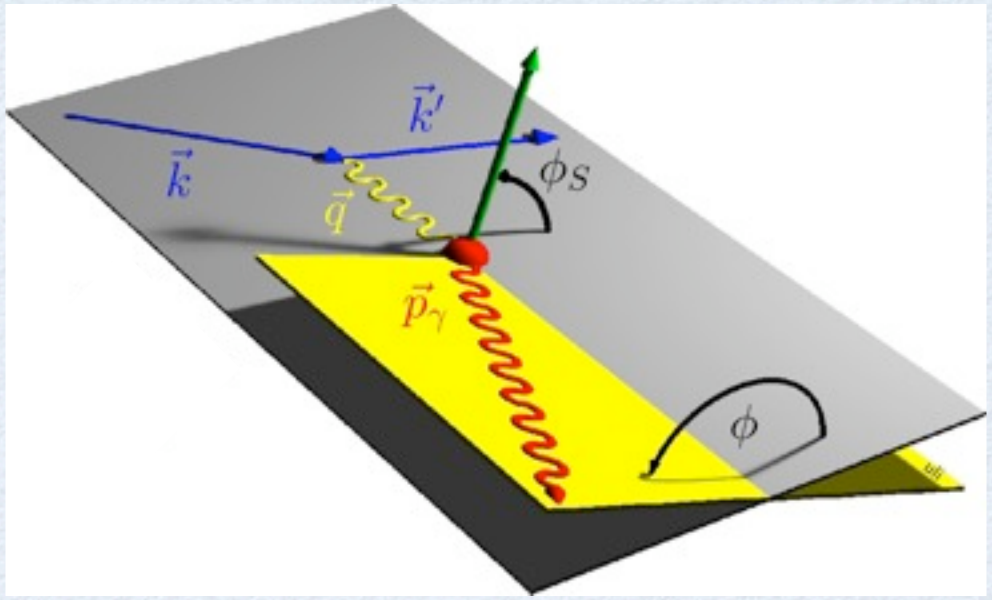

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- **HERMES:** transversely polarized hydrogen, 170 pb^{-1}, 2 beam charges
  ➢ Separation of DVCS and interference terms possible

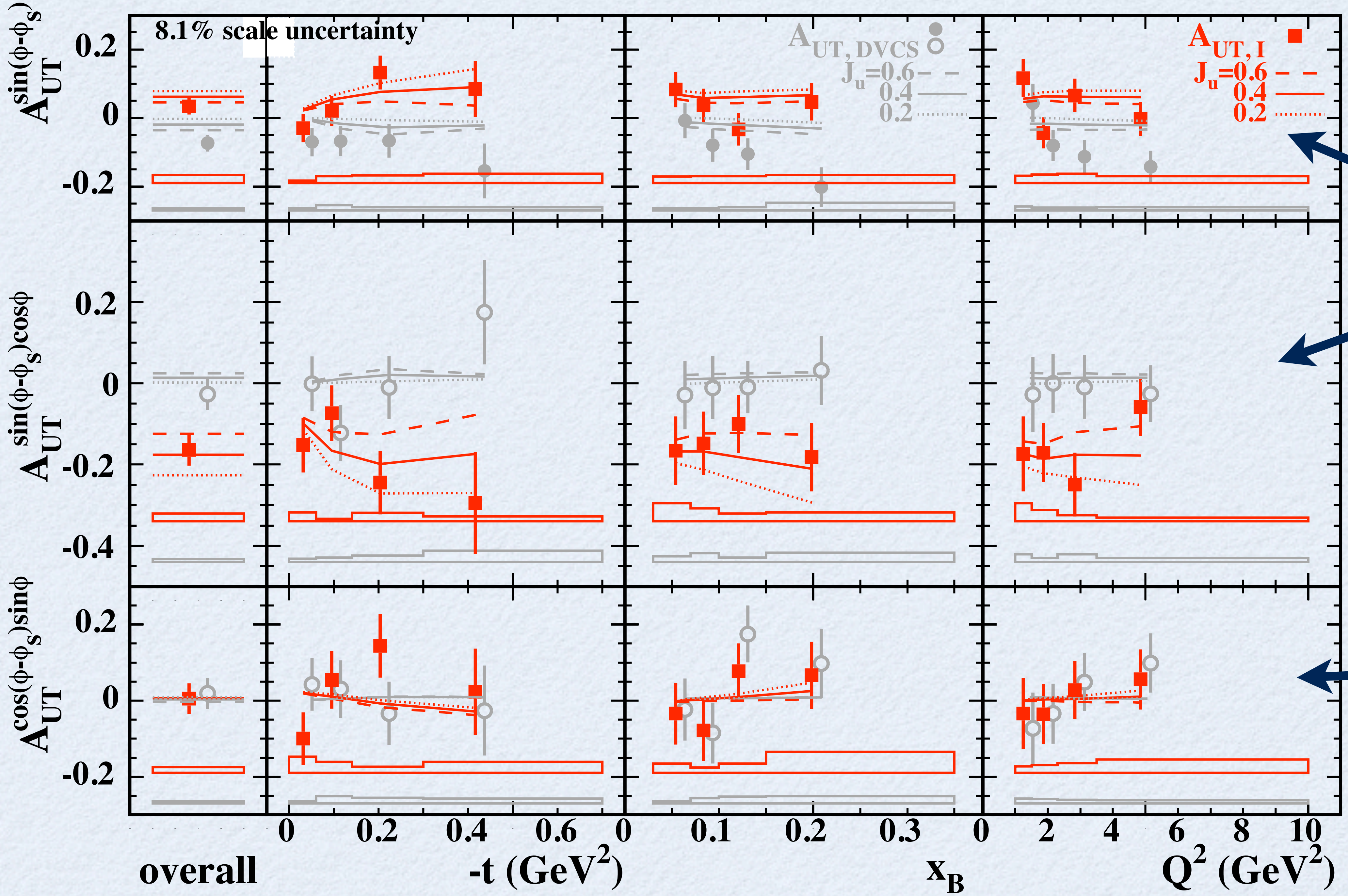
also sensitive to GPD E (bilinear combination)

$A_{UT}^{DVCS}(\phi,\phi_S)$

$$A^{\mathcal{I}}_{\mathrm{UT}}(\phi,\phi_s) \propto [\mathrm{d}\sigma^+(\phi,\phi_s) - \mathrm{d}\sigma^-(\phi,\phi_s)] \pm [\mathrm{d}\sigma^+(\phi,\phi_s+\pi) - \mathrm{d}\sigma^-(\phi,\phi_s+\pi)]$$

$$\begin{aligned} A^{\mathcal{I}}_{\mathrm{UT}}(\phi,\phi_s) \quad &\propto \quad \mathrm{Im}\,(F_2\mathcal{H} - F_1\mathcal{E})\sin(\phi-\phi_s)\cos\phi \\ &+ \quad \mathrm{Im}\left(F_2\widetilde{\mathcal{H}} - (F_1+\xi F_2)\widetilde{\mathcal{E}}\right)\cos(\phi-\phi_s)\sin\phi \end{aligned}$$

HERMES DVCS $\mathcal{A}_{UT}$ Amplitudes



sensitive to J_u:

$\mathrm{Im}(F_2\mathcal{H} - F_1\mathcal{E}) \cdot$

$\sin(\phi-\phi_s)\cos(n\phi)$

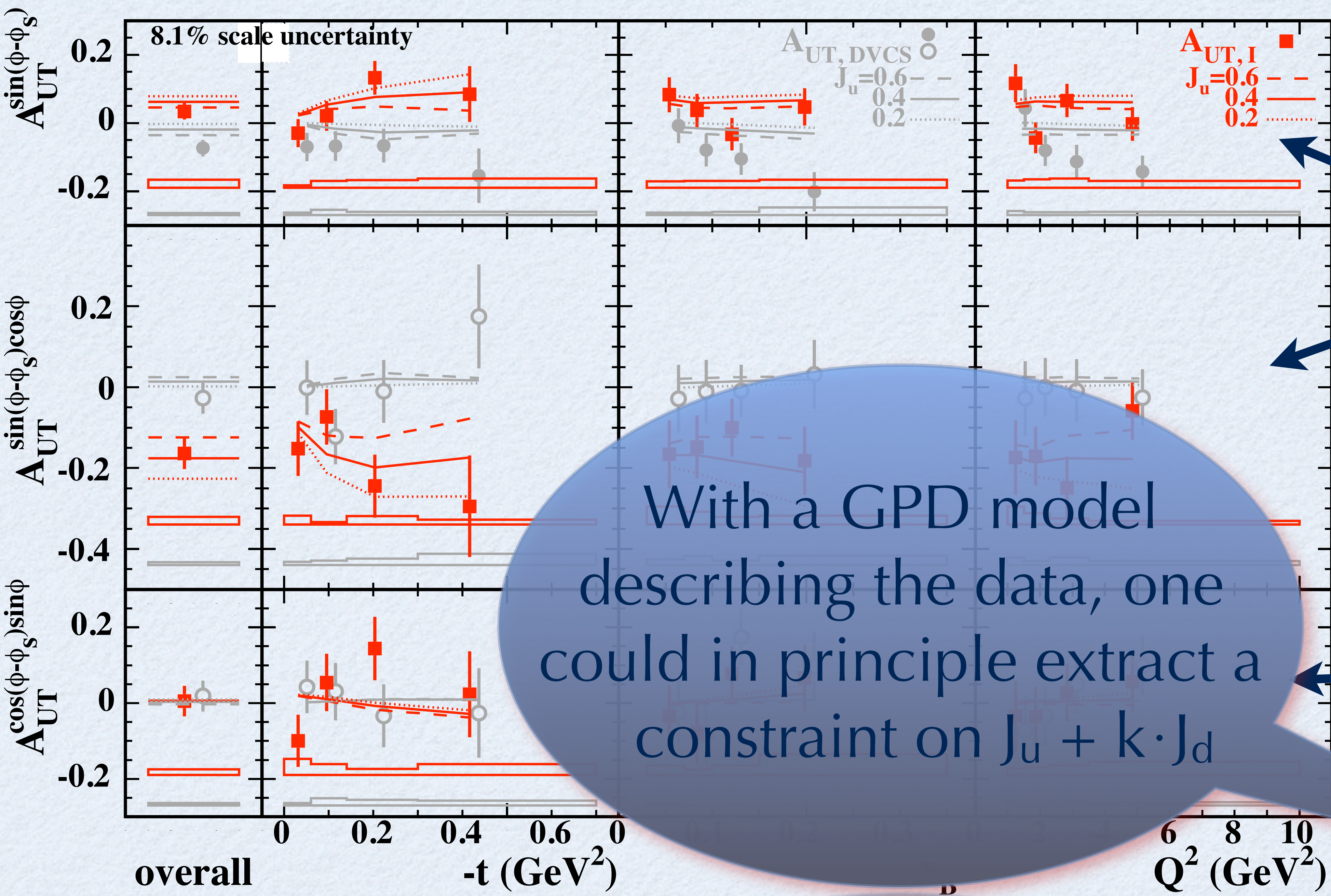
NOT sensitive to J_u:

$\mathrm{Im}\left(F_2\widetilde{\mathcal{H}} - (F_1+\xi F_2)\widetilde{\mathcal{E}}\right) \cdot$

$\cos(\phi-\phi_s)\sin\phi$

Model: VGG with variation of J_u, while J_d=0

HERMES DVCS $\mathcal{A}_{UT}$ Amplitudes



sensitive to J_u:

$\mathrm{Im}(F_2\mathcal{H} - F_1\mathcal{E})\cdot$
$\sin(\phi - \phi_s)\cos(n\phi)$

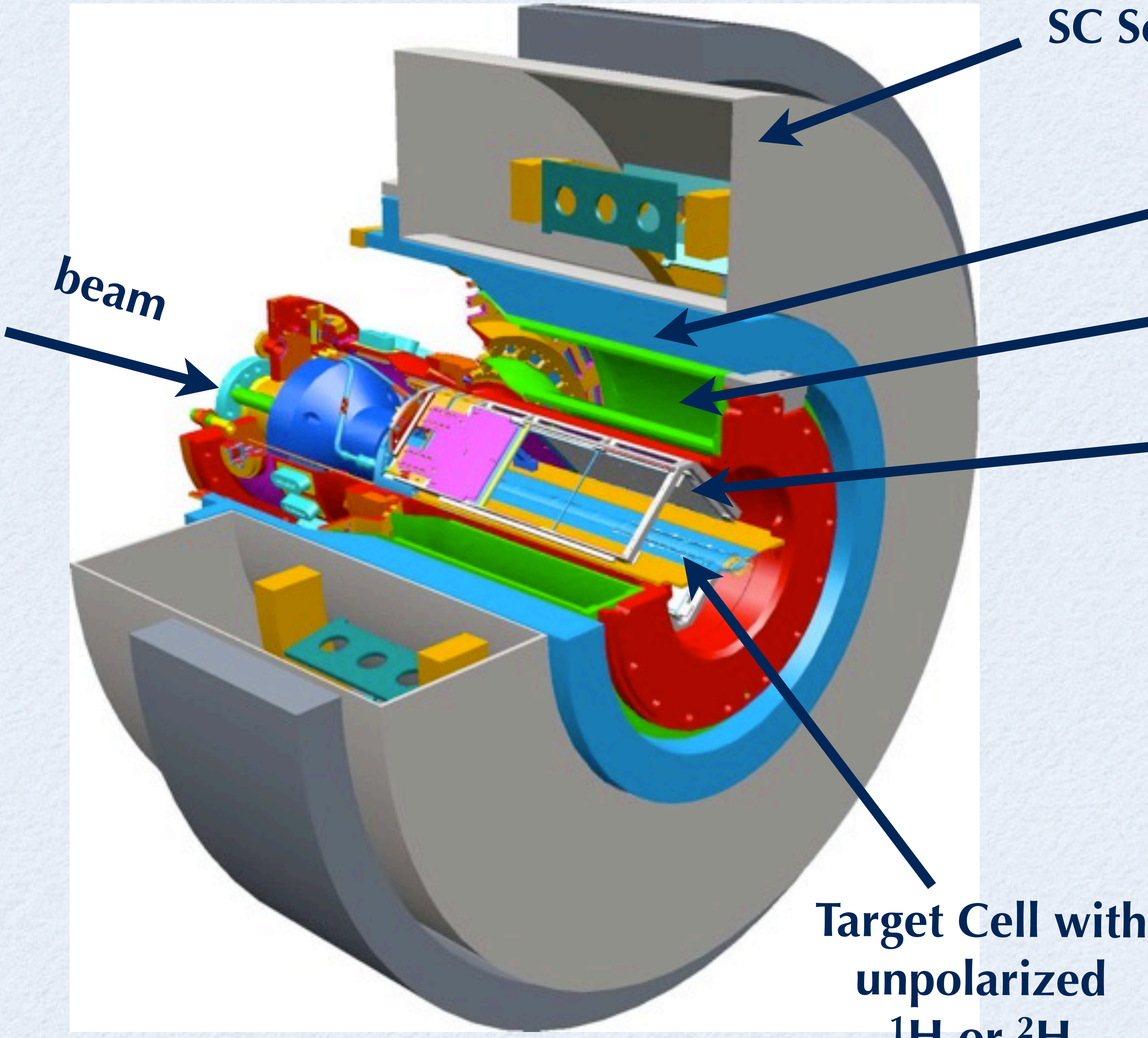
NOT sensitive to J_u:

$\mathrm{Im}\left(F_2\widetilde{\mathcal{H}} - (F_1 + \xi F_2)\widetilde{\mathcal{E}}\right)\cdot$
$\cos(\phi - \phi_s)\sin\phi$

With a GPD model describing the data, one could in principle extract a constraint on $J_u + k\cdot J_d$

Model: VGG with variation of J_u, while J_d=0

HERMES 2006-2007: Recoil Detector



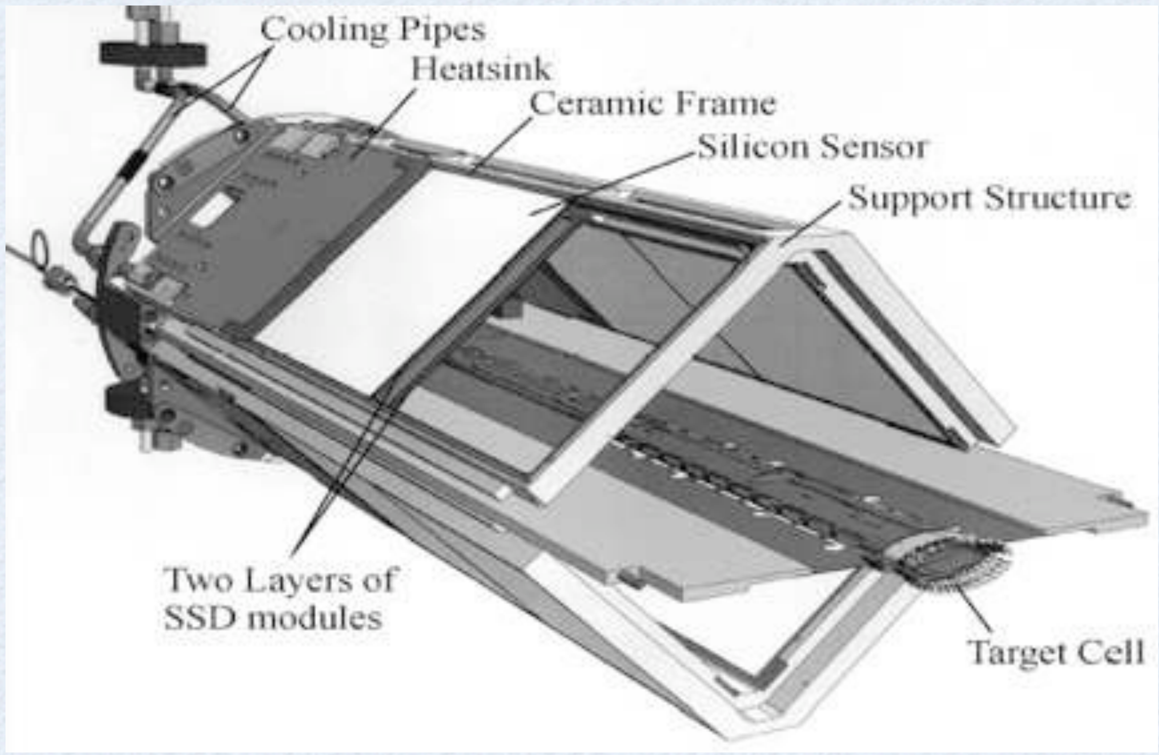
Purpose:

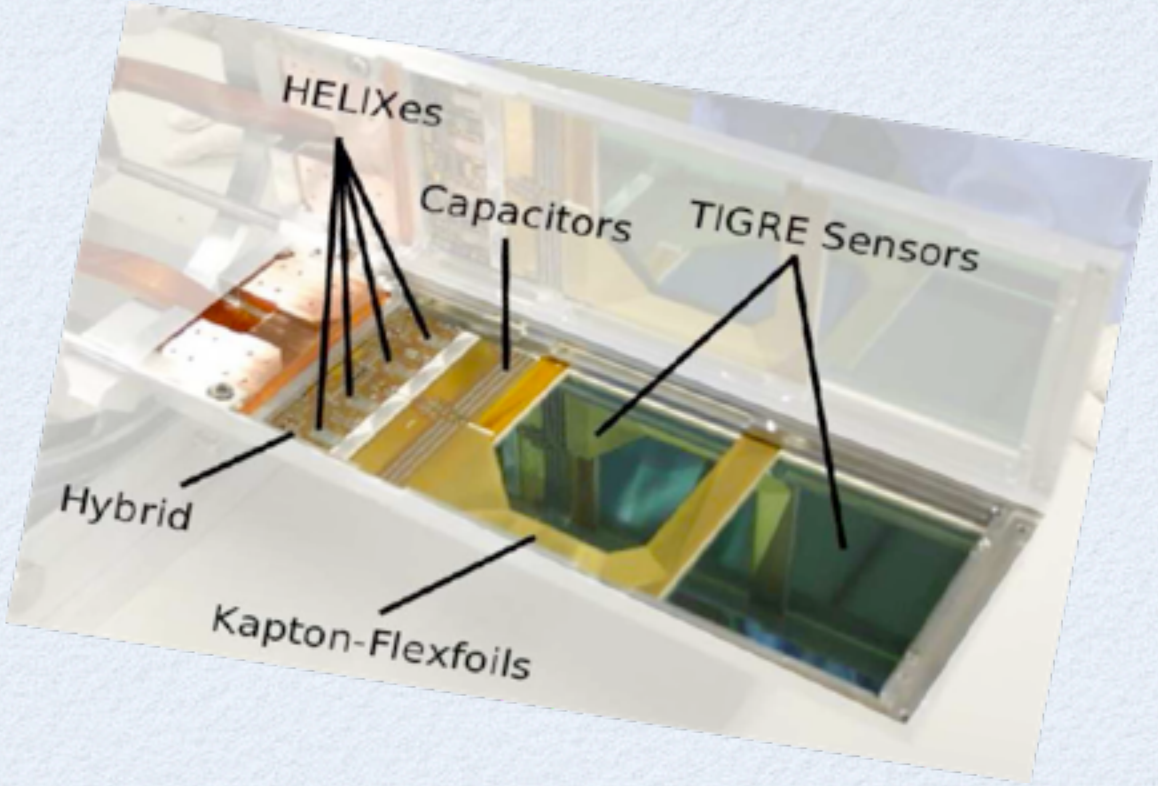
★ **To tag exclusive events**

- ➢ Identify recoiling target proton
- ➢ Identify particles from background processes

^1H (^2H): factor of 1.6 (0.5) more than 1996-2005

The Silicon Strip Detector (SSD)



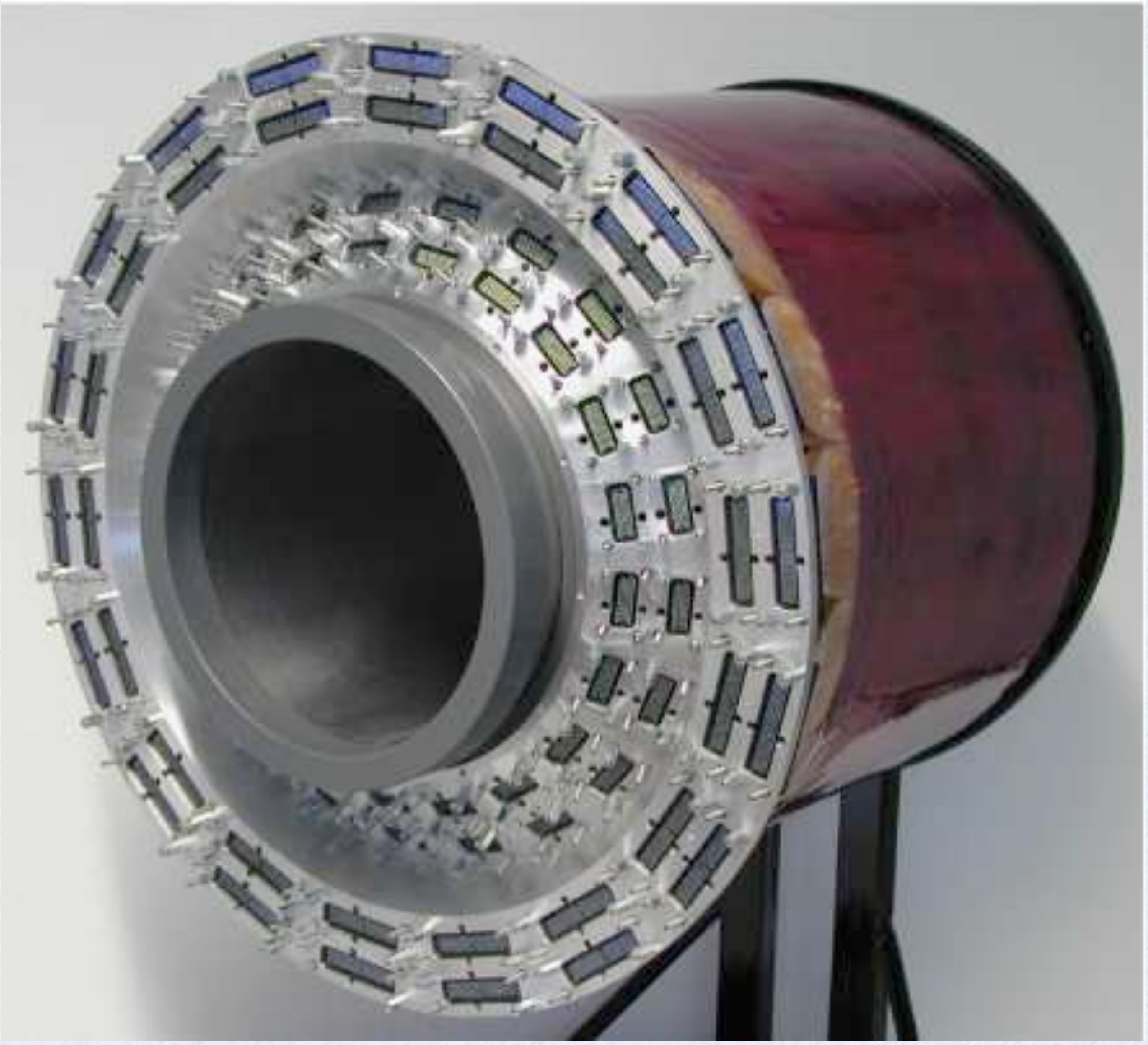


$E_{kin} \approx 8$ MeV
for protons

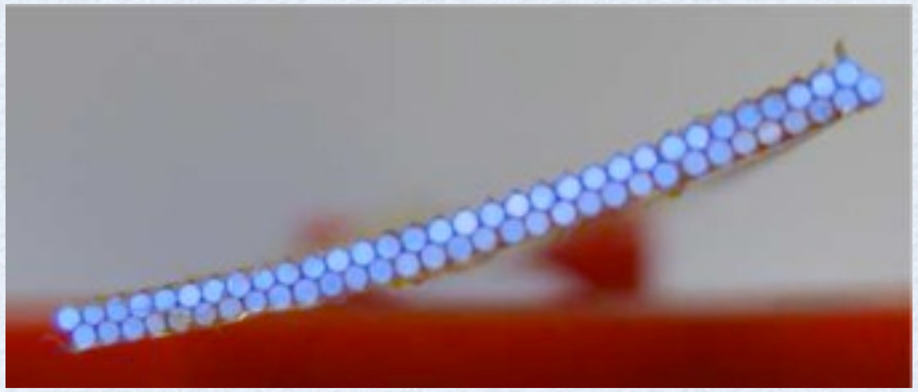
- Purpose:
  - Track reconstruction
  - Momenta: > 125 MeV/c
  - PID for low and medium momenta
- 2 layers of 16 double-sided sensors
  - (10 cm $\times$ 10 cm) active area
  - 300 μm thickness
- Inside accelerator vacuum, 5 cm close to electron beam

to reach as low t as possible

The Scintillating Fiber Tracker (SFT)



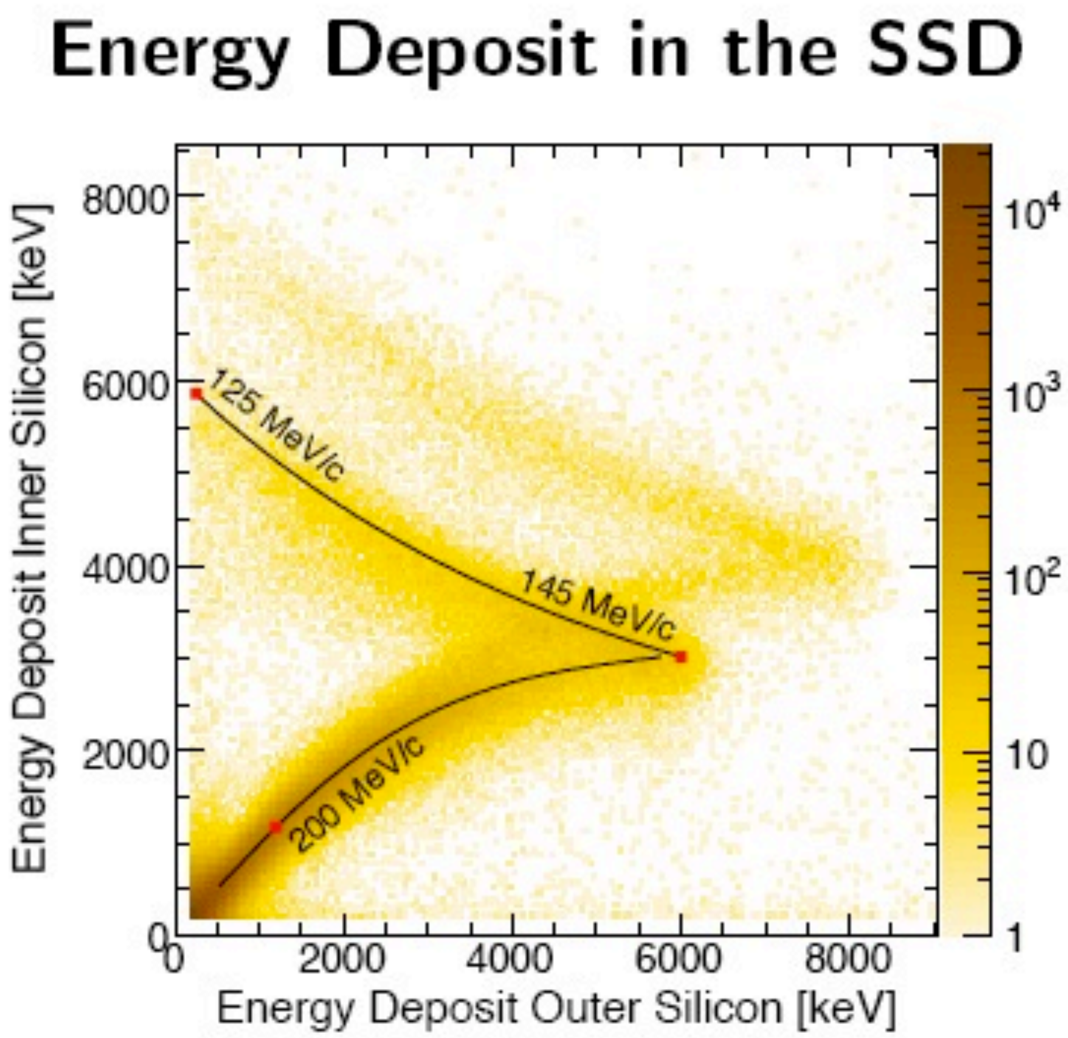
- Purpose:
  - Track reconstruction
  - Momenta: 250-1400 MeV/c (protons)
  - PID for medium and high momenta
- 2 Barrels with each 4 layers of scintillating fibers
- Per Barrel:
  - 2 parallel layers
  - 2 stereo-layers
  - Stereo angle: 10°

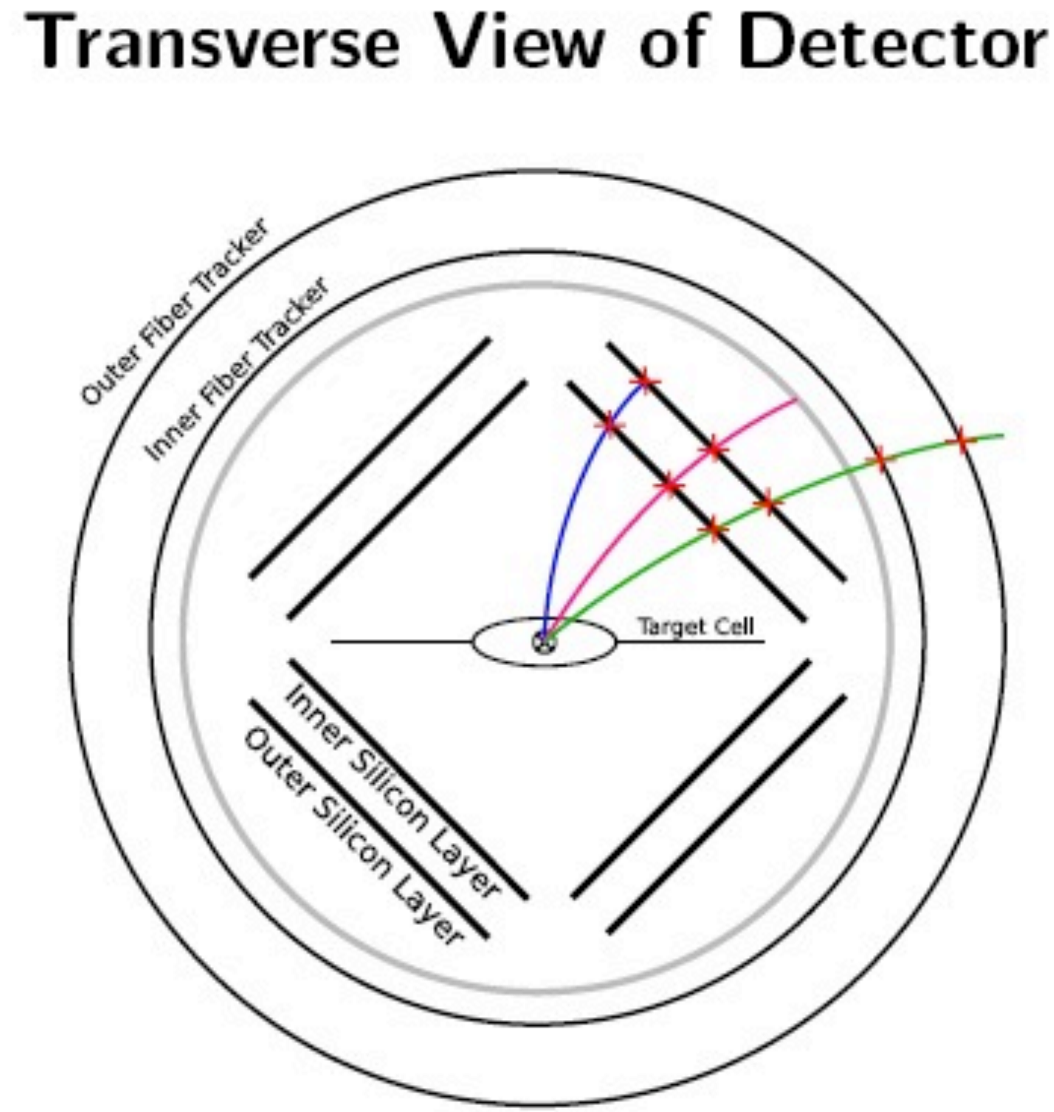


The Photon Detector (PD)

- Purpose:
  - Detection of photons from resonance decay $\Delta^+ \rightarrow p\pi^0$
  - PID for $p > 600$ MeV/c
- 3 layers of tungsten/scintillator sandwich
  - 1 layer parallel to beam axis
  - 2 layers under +45°/-45° angles

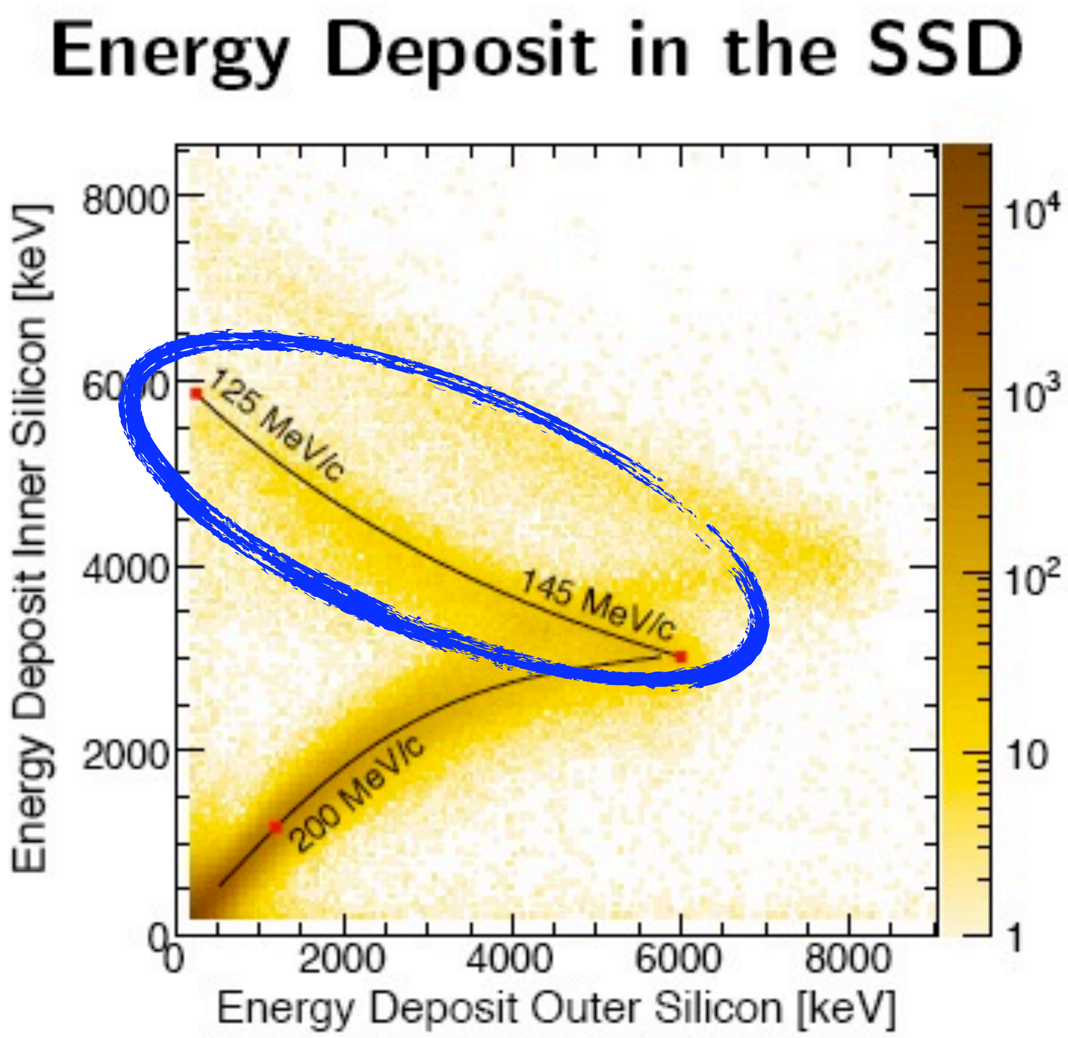
Tracking with the Recoil Detector

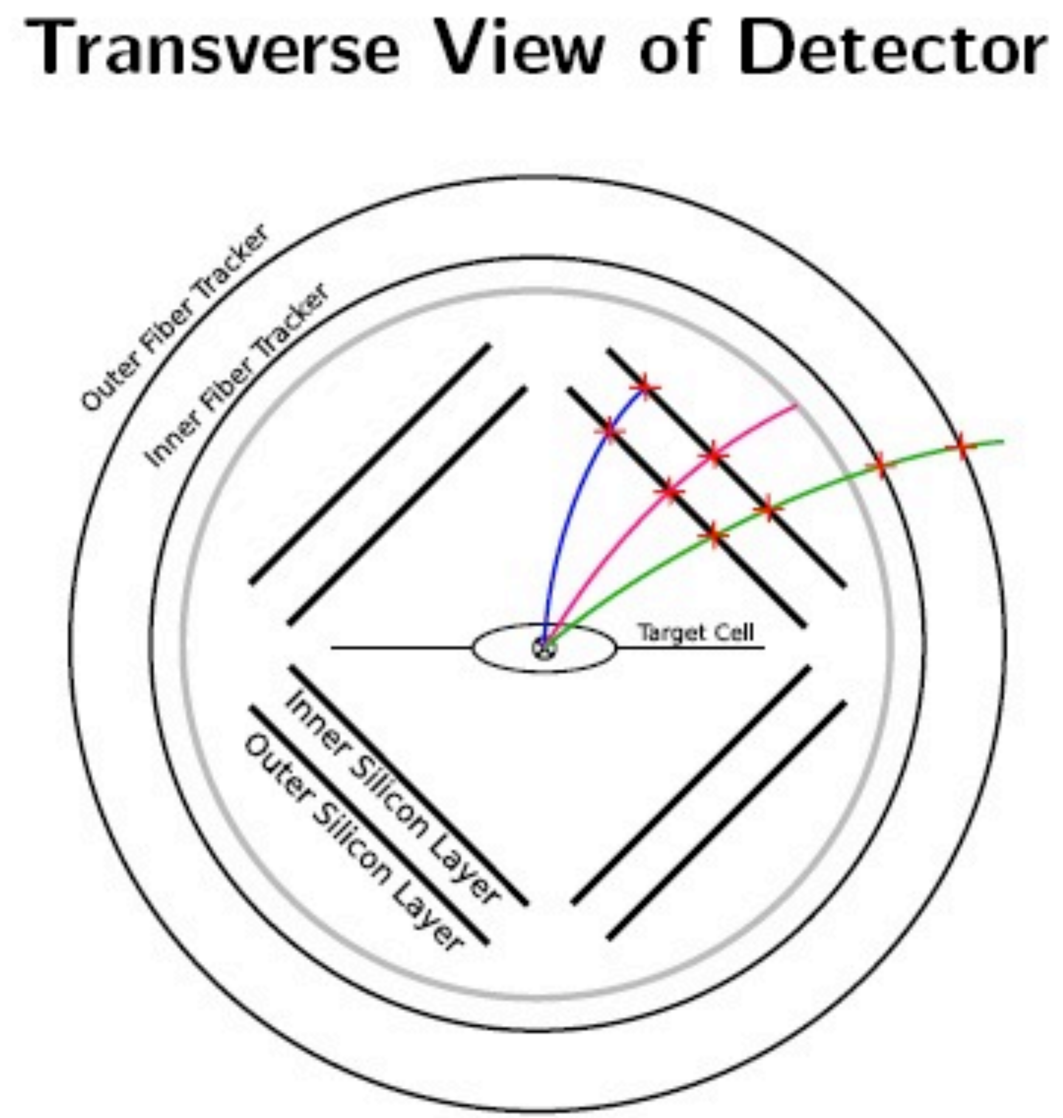




- **Low-energy protons**: momentum $\propto (\sum_i \Delta E_i)^{-1}$
- **Medium-energy protons**: momentum $\propto (\frac{dE}{dx})^{-1}$ (Bethe-Bloch)
- **Higher-energy particles (protons/pions)**: momentum $\propto eB\rho$

Tracking with the Recoil Detector





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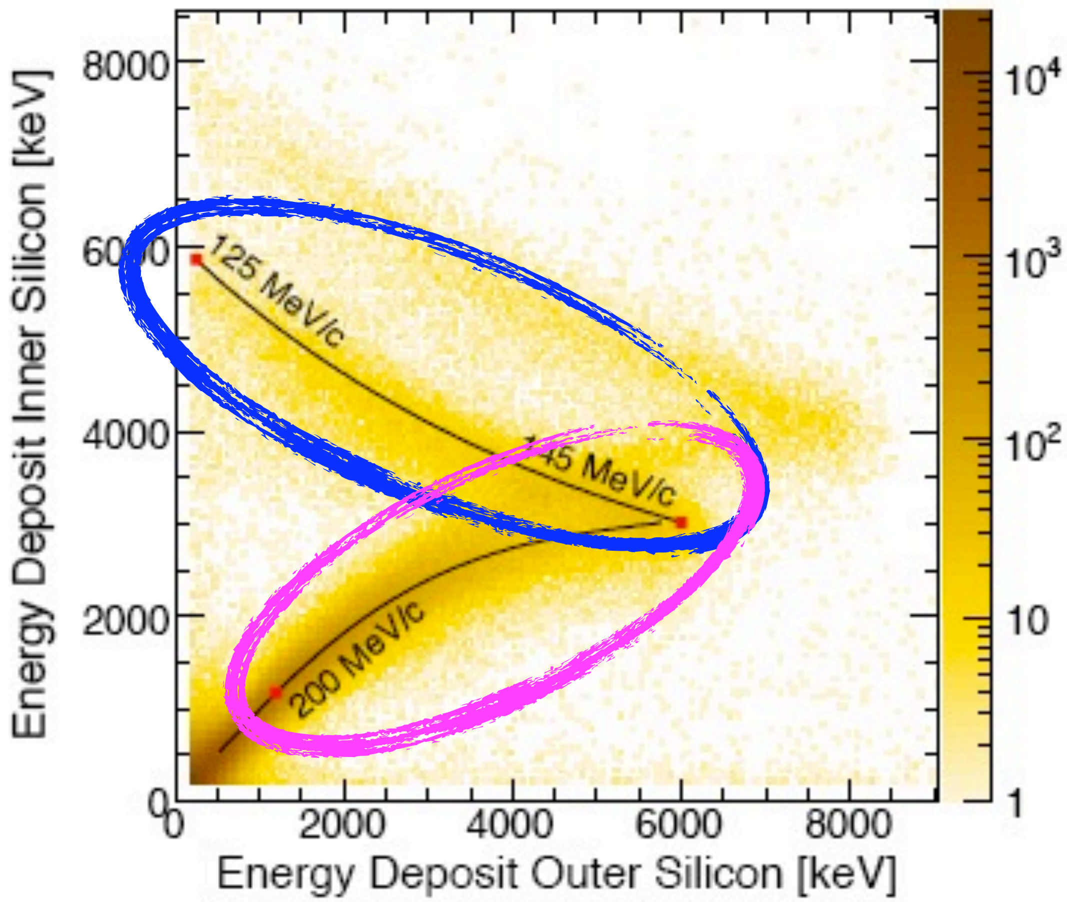
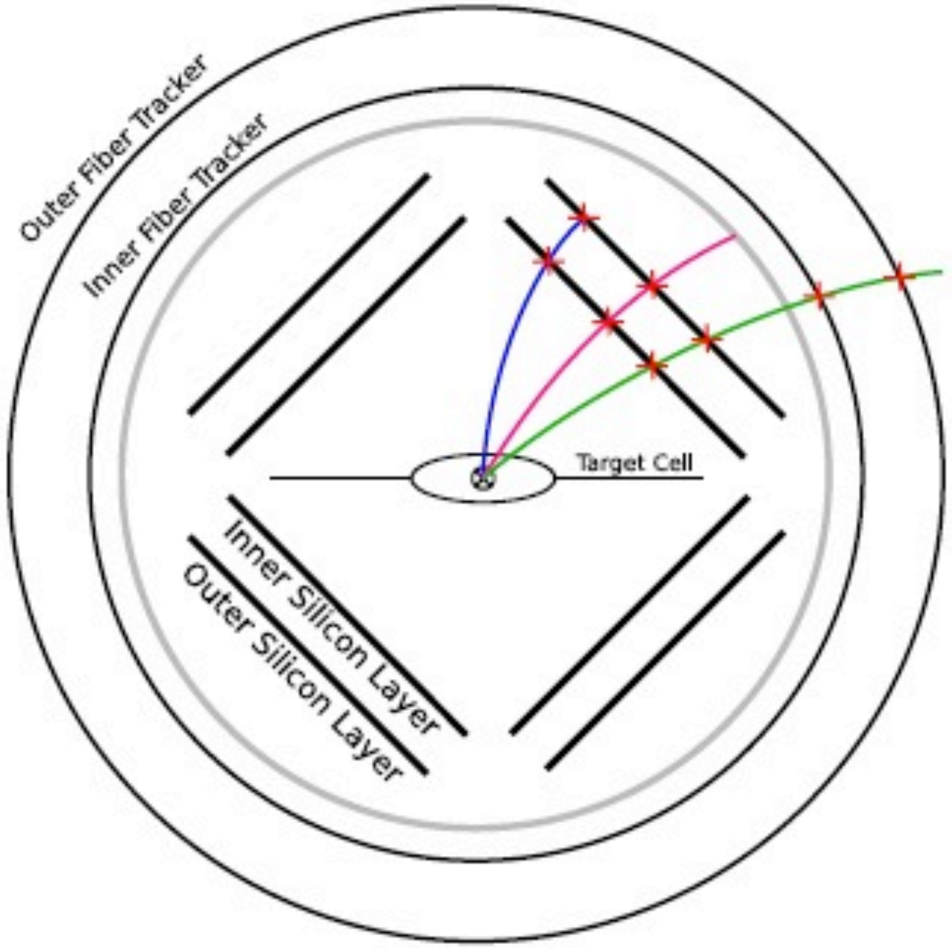
Tracking with the Recoil Detector

Energy Deposit in the SSD



Transverse View of Detector



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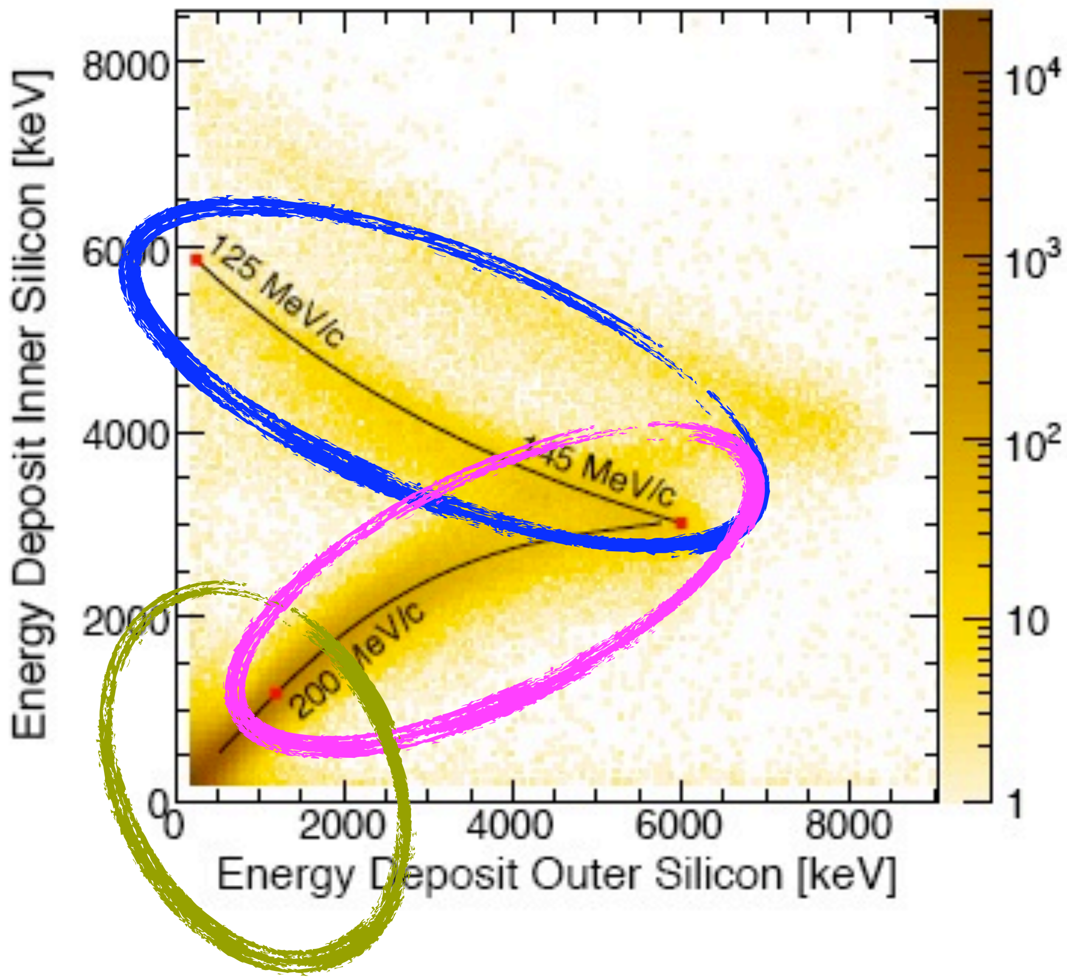

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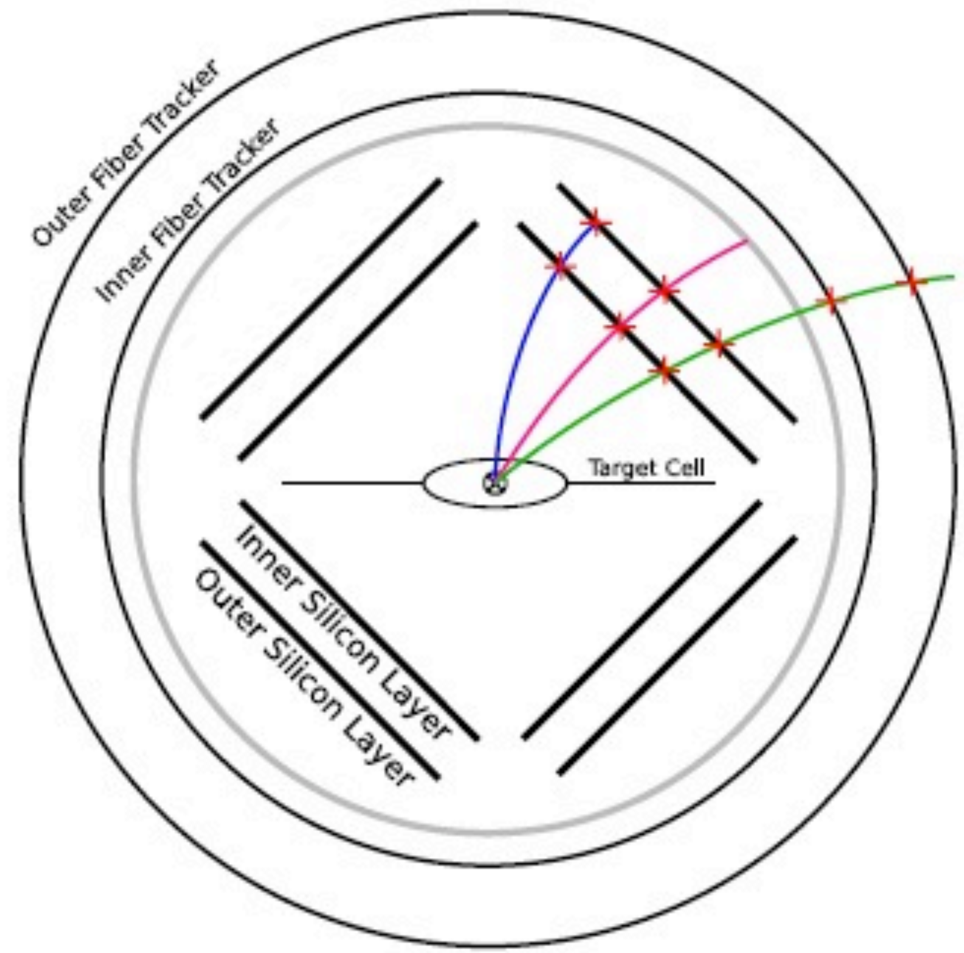

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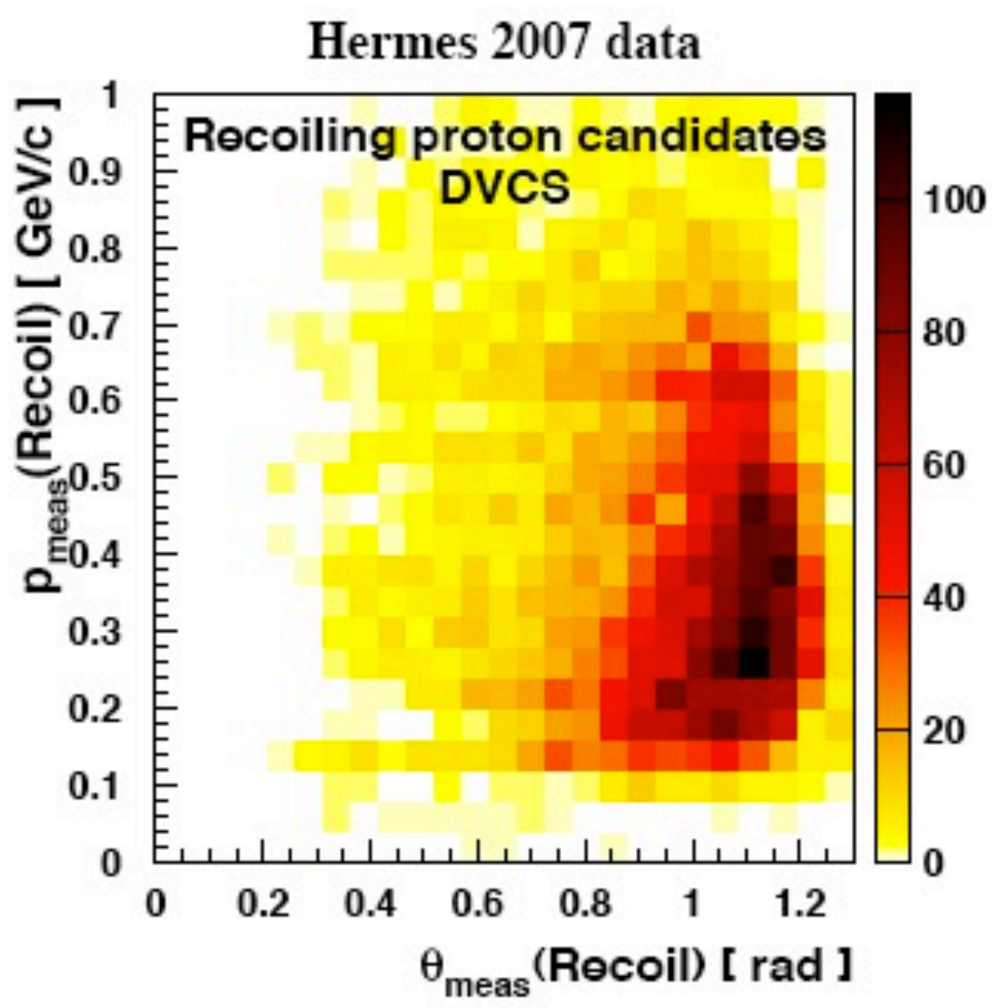
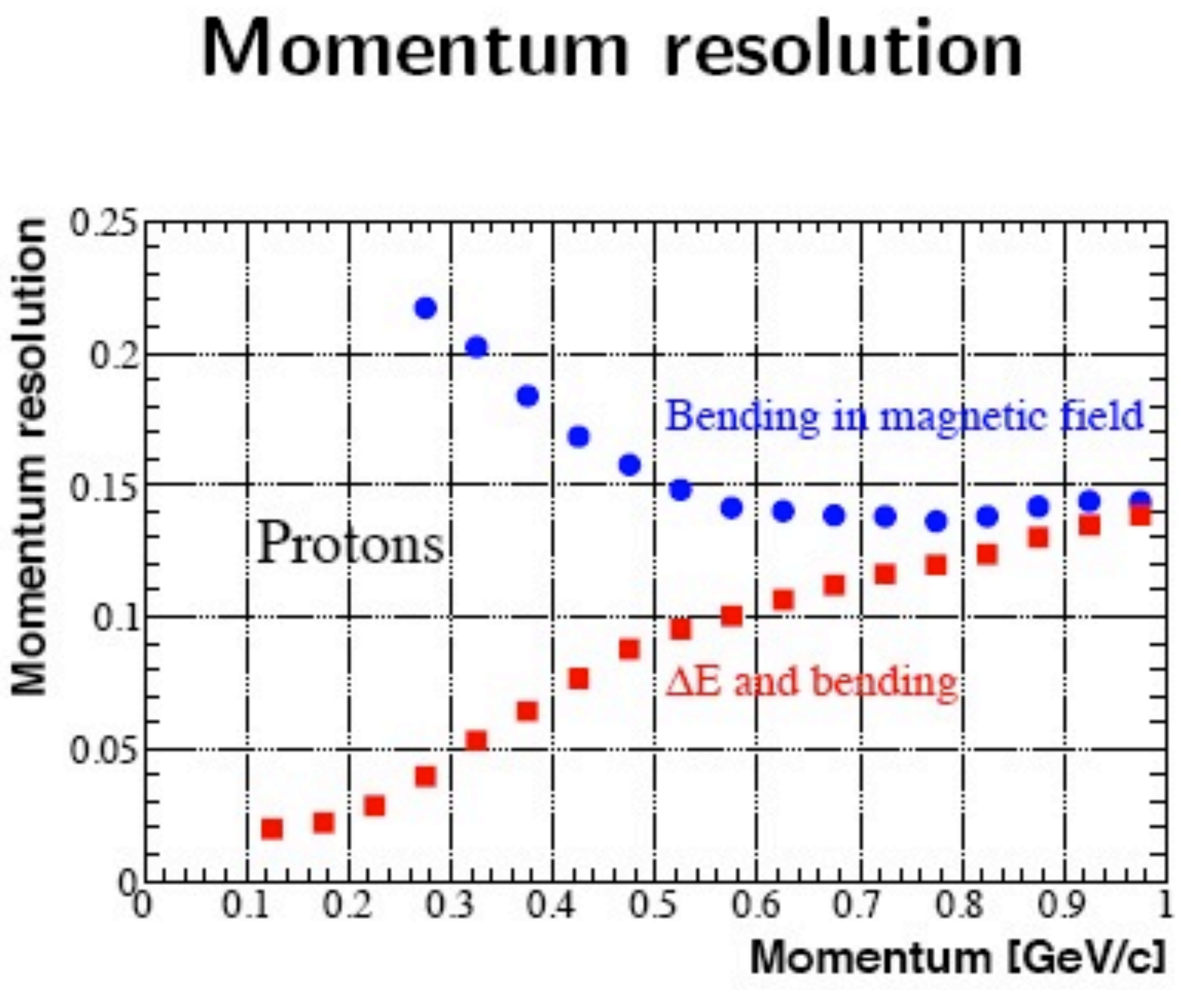
Reconstructed Momenta and Angles





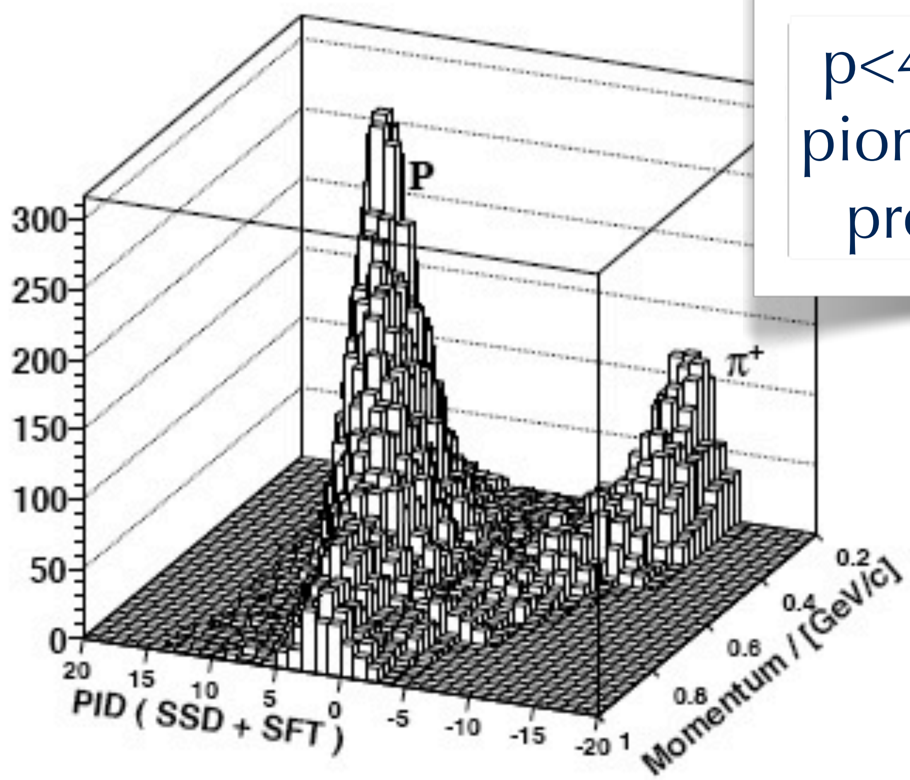
- Recoiling target protons
  - Large θ-angles $\lesssim 90°$
  - Small momenta < 1 GeV/c
- Azimuthal ϕ coverage: 76%

■ ΔE accounted for in track fitting
$\Rightarrow \Delta p/p$ improvement

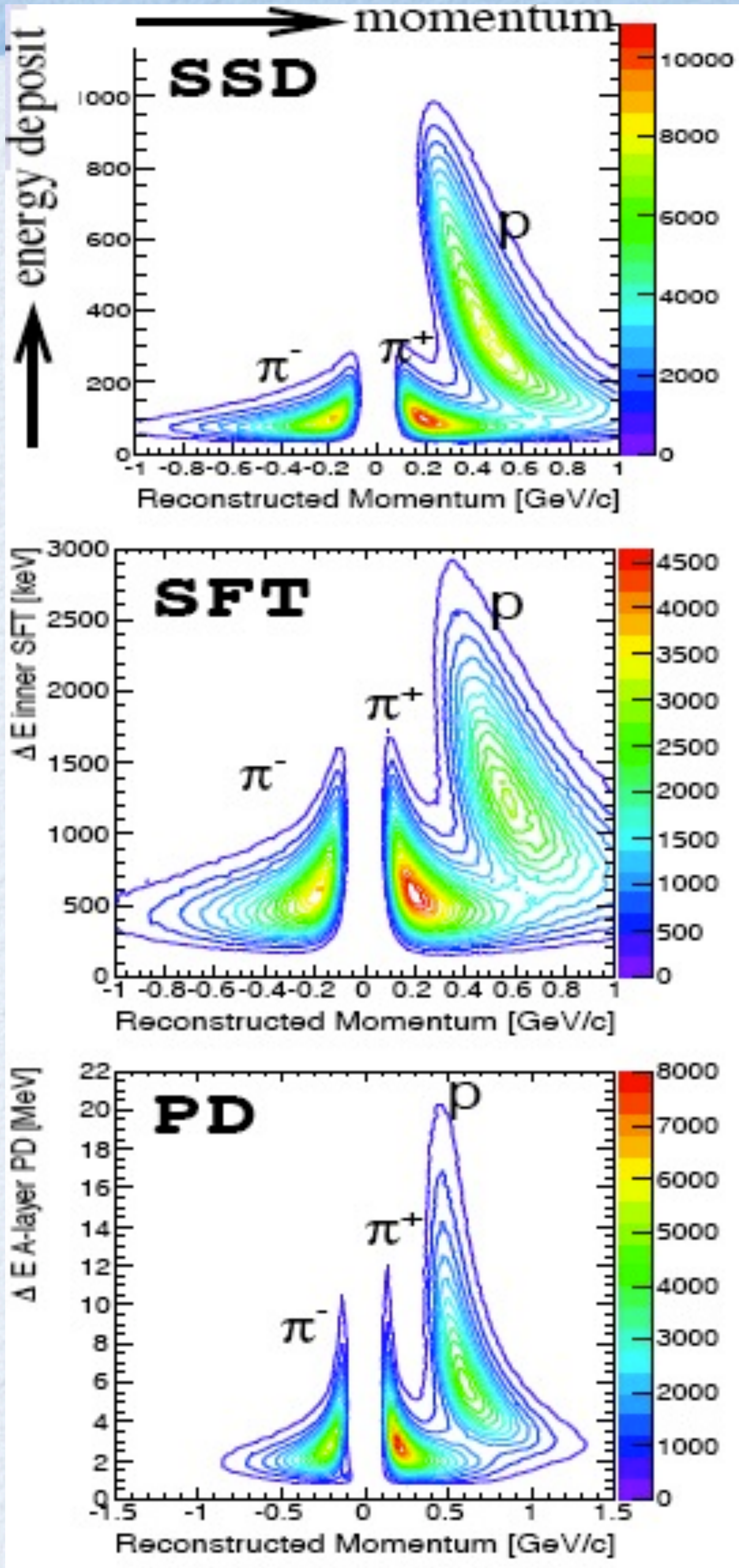
Proton / Pion Separation with the Recoil

- $p < 600$ MeV/c: SSD + SFT (6 layers)
- $p > 600$ MeV/c: include PD
- Log-likelihood formalism:

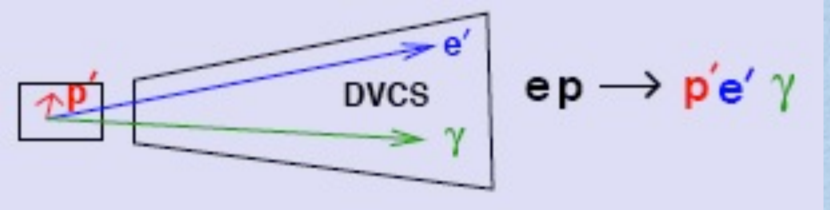
$$\mathrm{PID} \equiv \log \frac{\mathcal{P}(\Delta E|\text{proton}, p)}{\mathcal{P}(\Delta E|\text{pion}, p)}$$



p<450 MeV/c, PIDcut=0:
pion contamination ≈0.1%
proton efficiency >99%



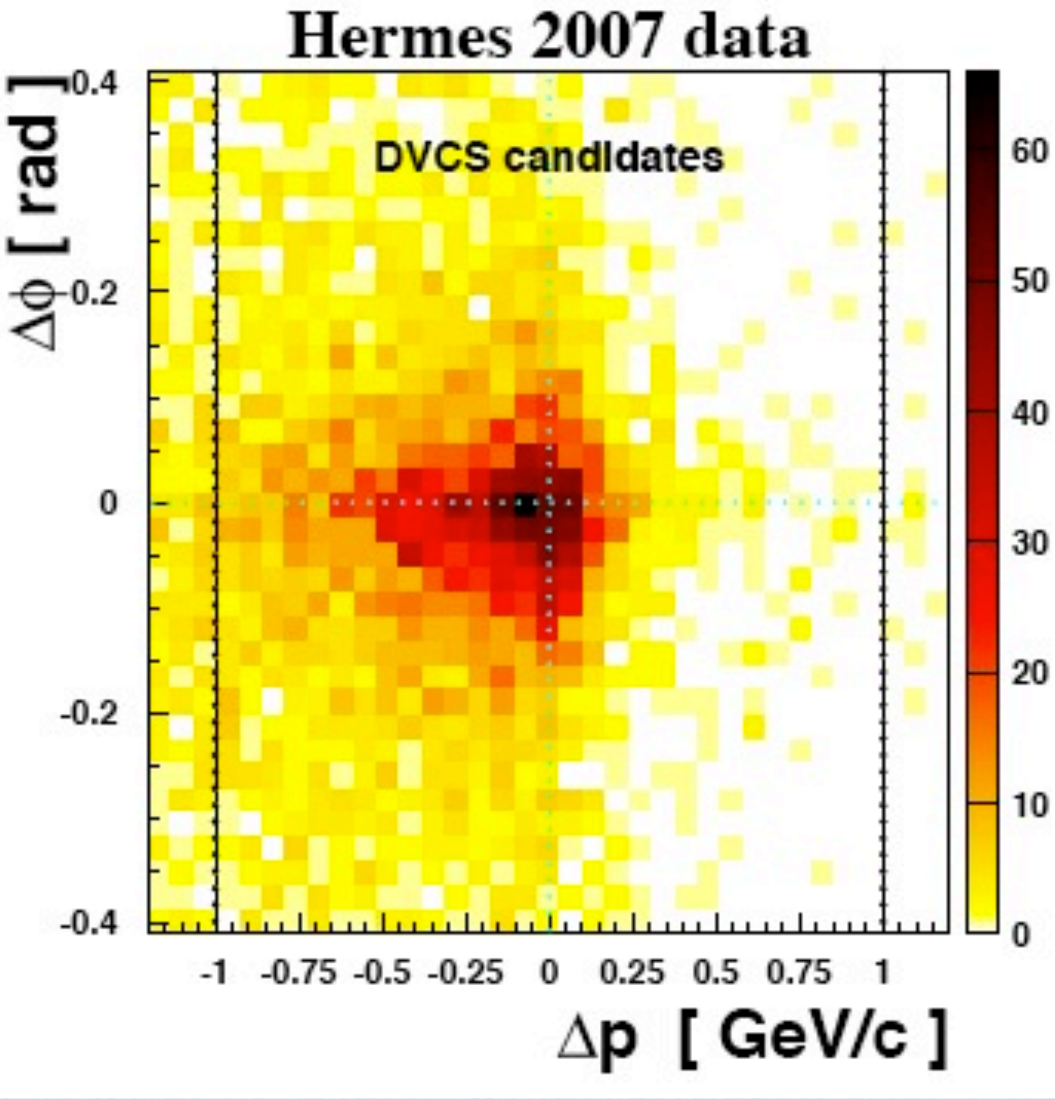
DVCS and the Recoil

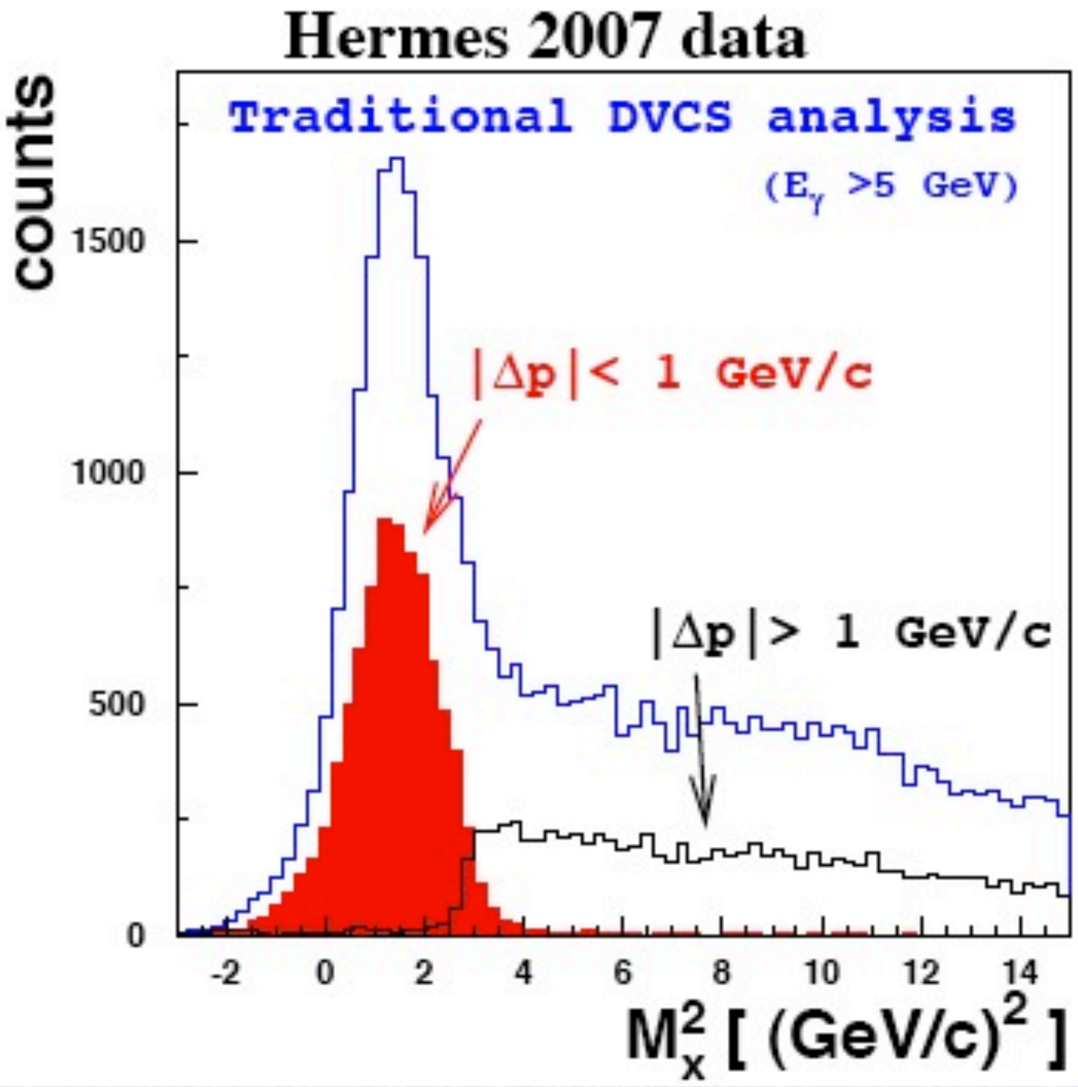


- **Missing ϕ:** $\Delta\phi = \phi_{\mathrm{meas}} - \phi_{\mathrm{calc}}$
- **Missing p:** $\Delta p = p_{\mathrm{meas}} - p_{\mathrm{calc}}$

Missing Mass ($\approx M_P^2$):

$$M_X^2 = (p + p_{\gamma^*} - p_\gamma)^2$$





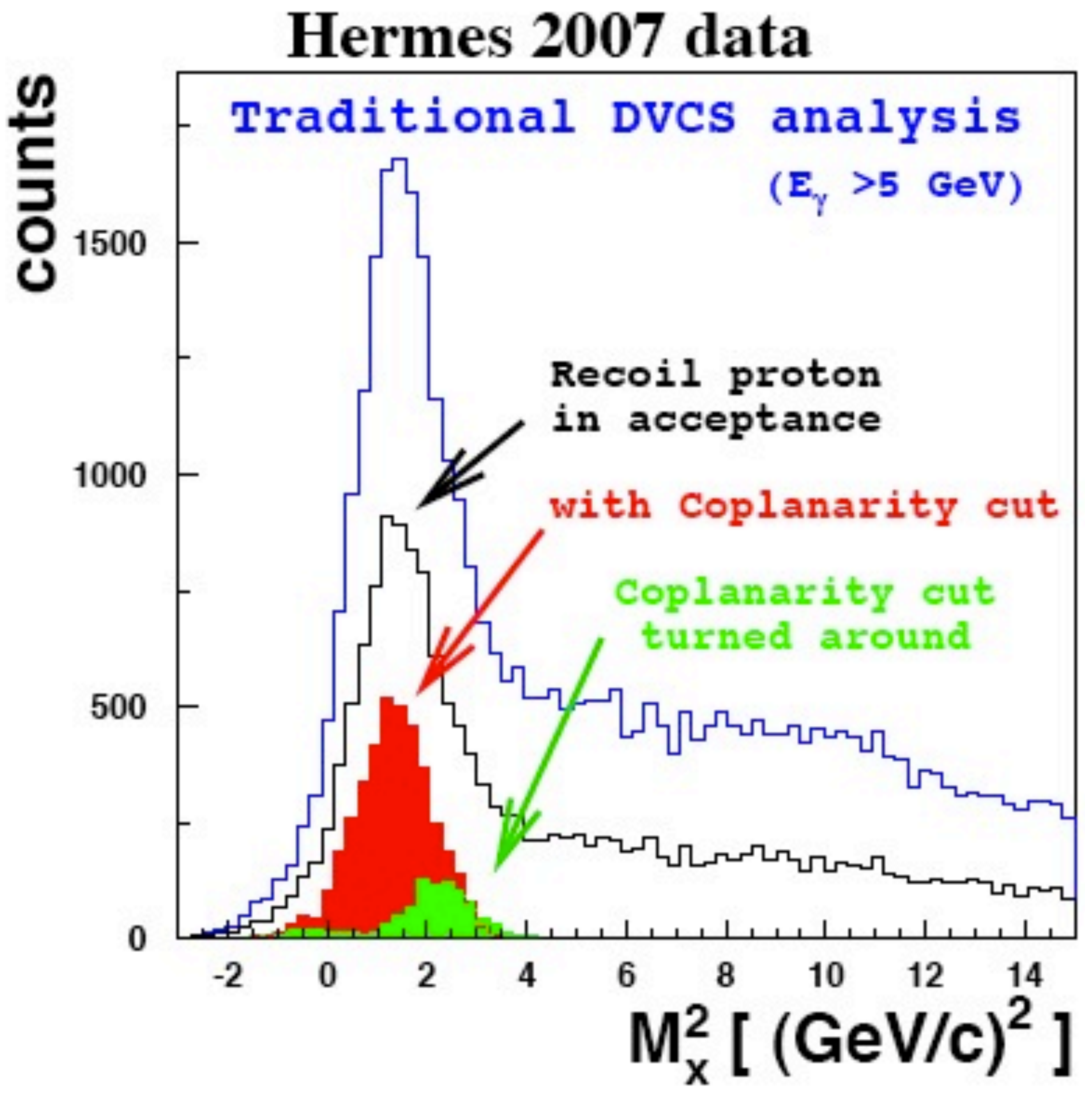
Separation of Resonant States in DVCS

DVCS / Bethe Heitler

- Elastic:
  - $ep \to ep\gamma$
- Resonant ('associated'):
  - $ep \to e\Delta^+\gamma$

$$\Delta^+ \to \left\{ \begin{array}{l} n\pi^+,\ 1/3 \\ p\pi^0,\ 2/3 \end{array} \right.$$

  - 12% of signal
- Presence of $\pi^0 \Rightarrow$ proton fails coplanarity cut
  - Select elastic:
    - ★ $|\Delta\phi| < 0.1$ rad
    - ★ $|p_T^{\text{calc}}|/|p_T^{\text{meas}}| = 0.5 \div 1.5$
  - Select resonant:
    - ★ $|\Delta\phi| > 0.35$ rad



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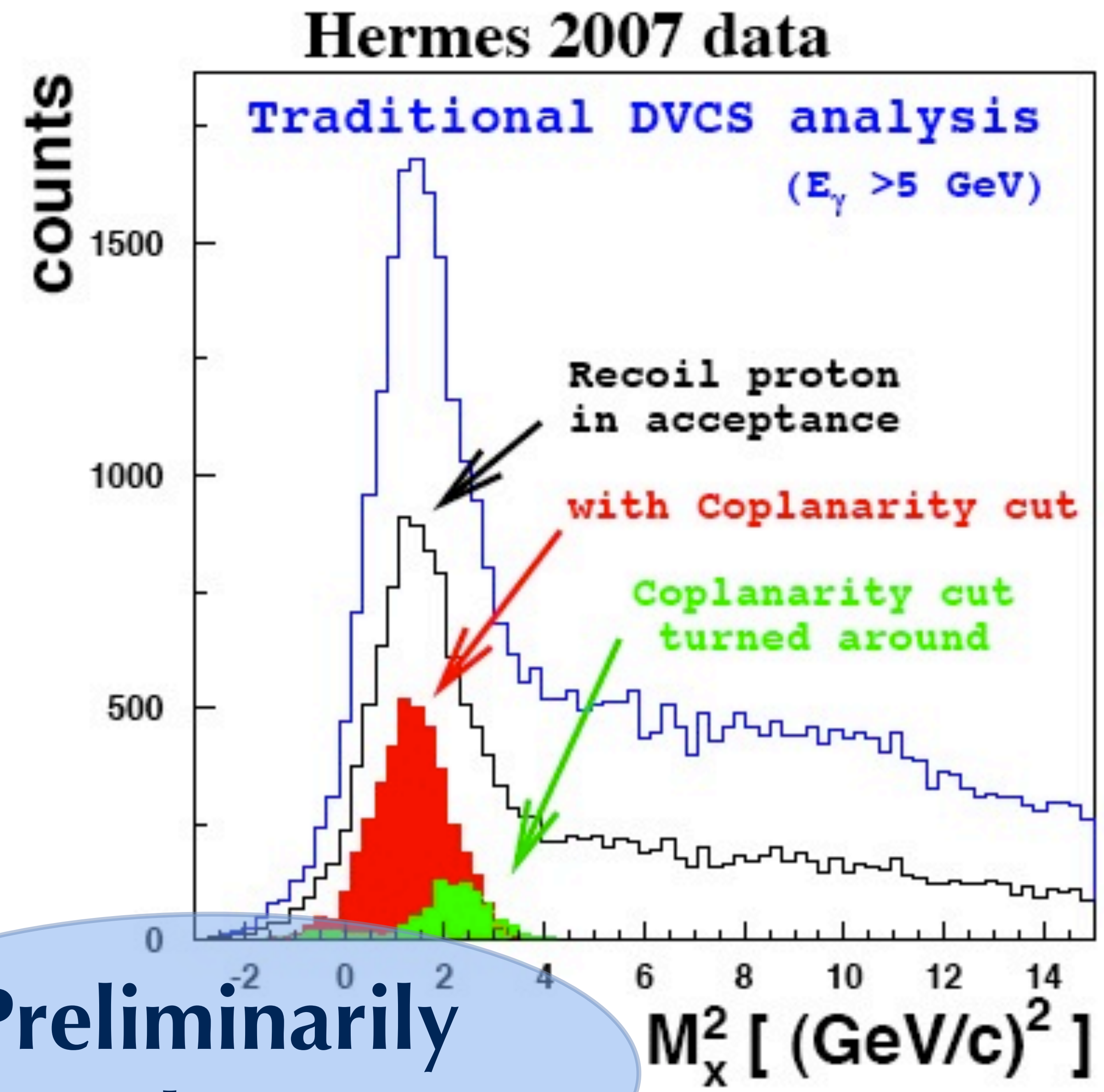
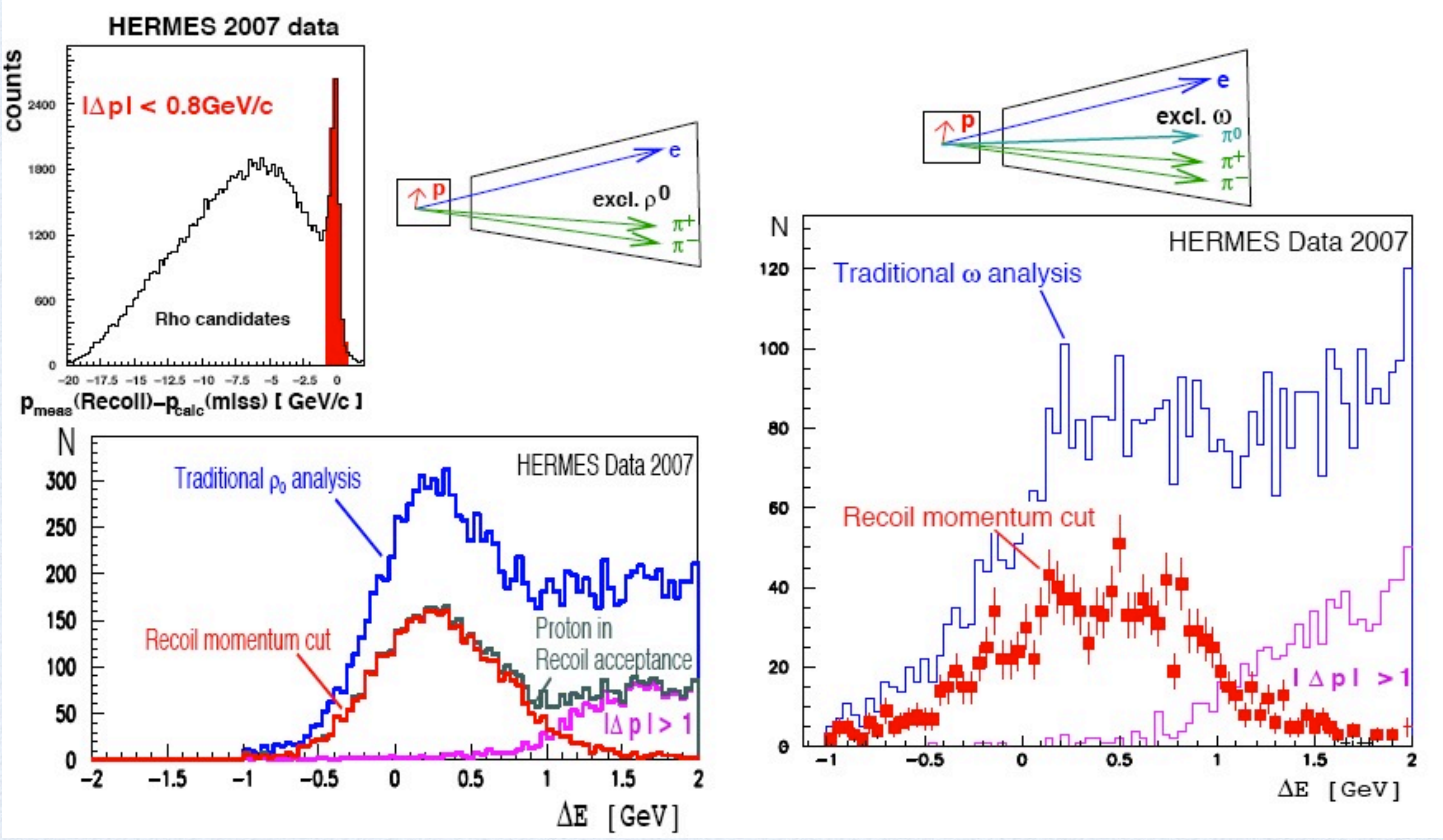
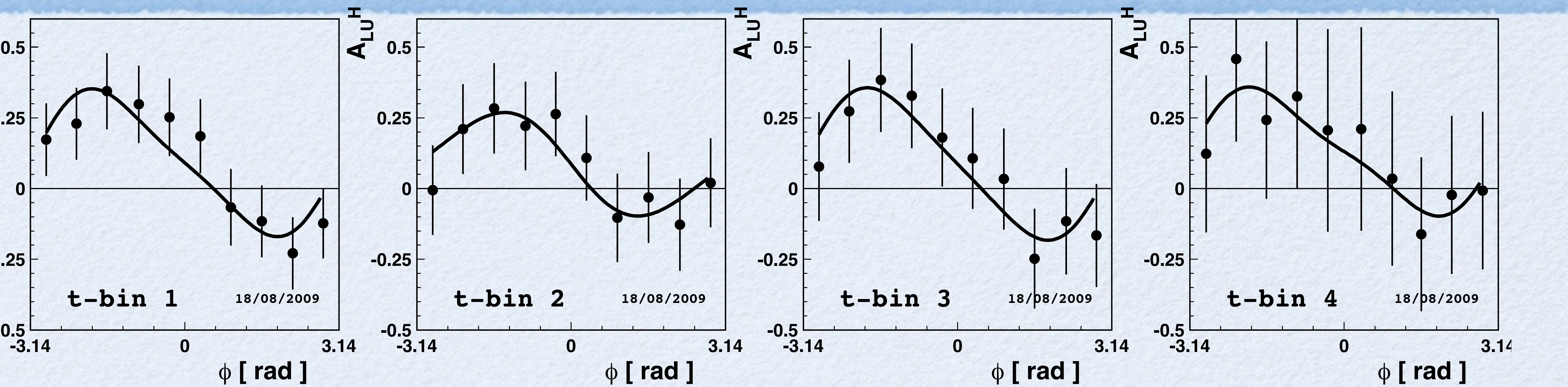


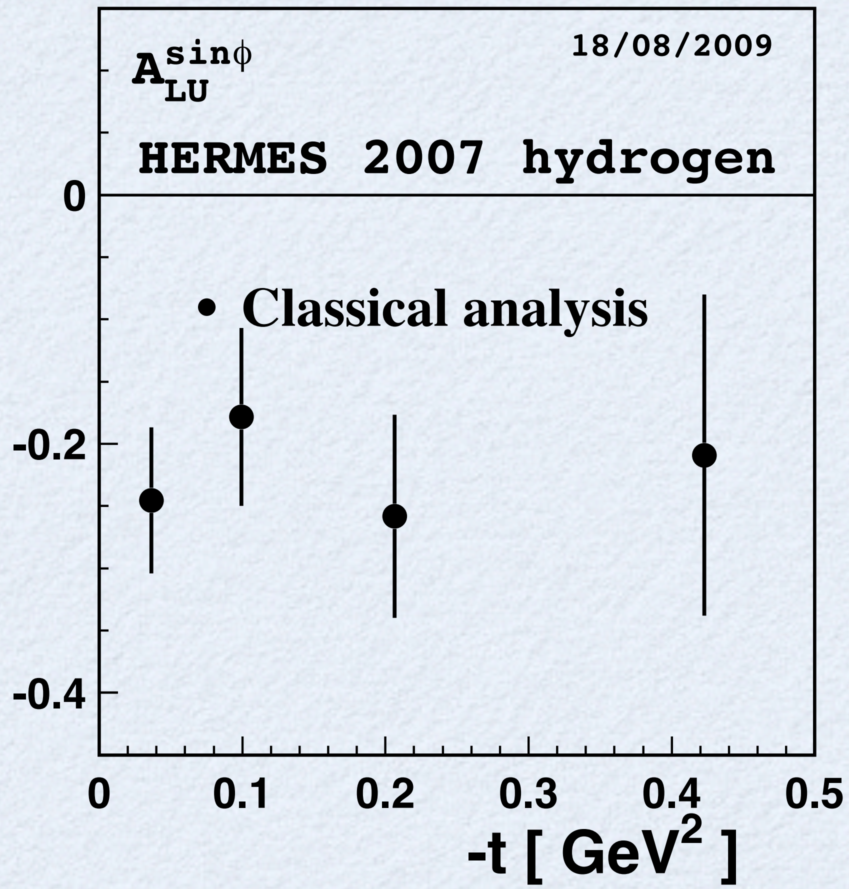
Preliminarily tuned on MC

Exclusive Mesons and the Recoil



DVCS Beam Helicity Asymmetry with Recoil



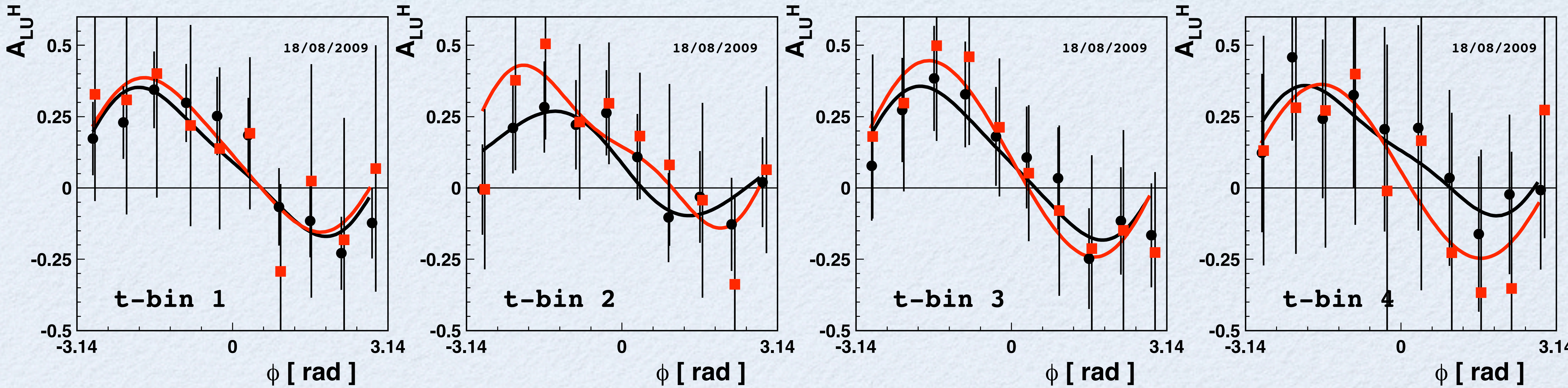


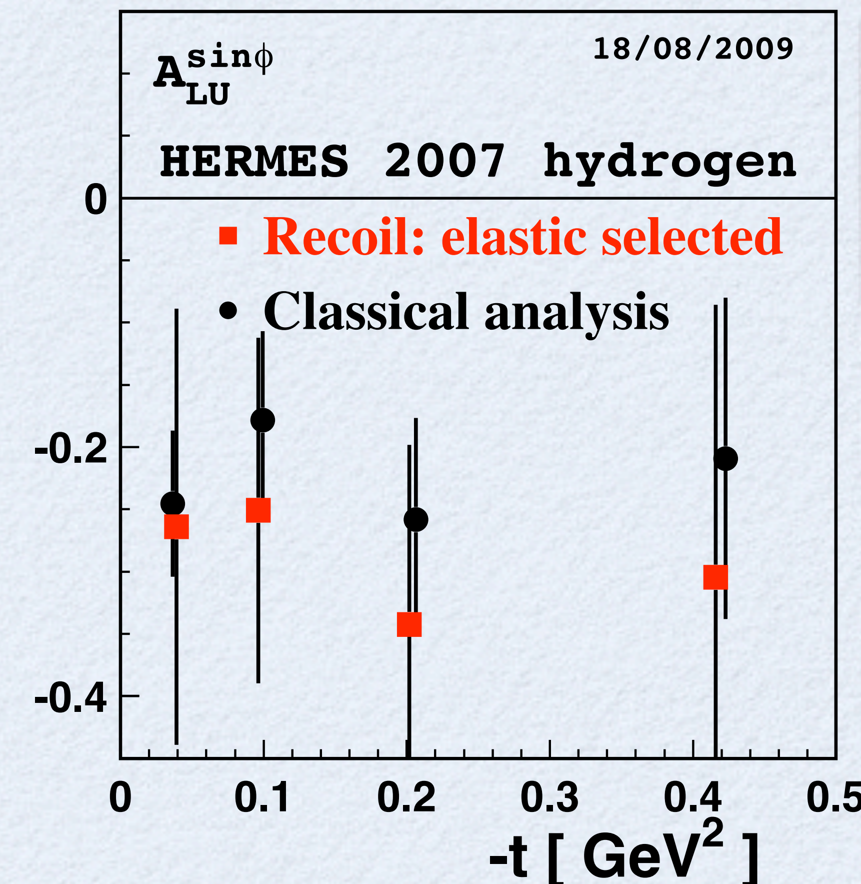
Pre-preliminary, private analysis

DVCS Beam Helicity Asymmetry with Recoil

Pre-preliminary, private analysis

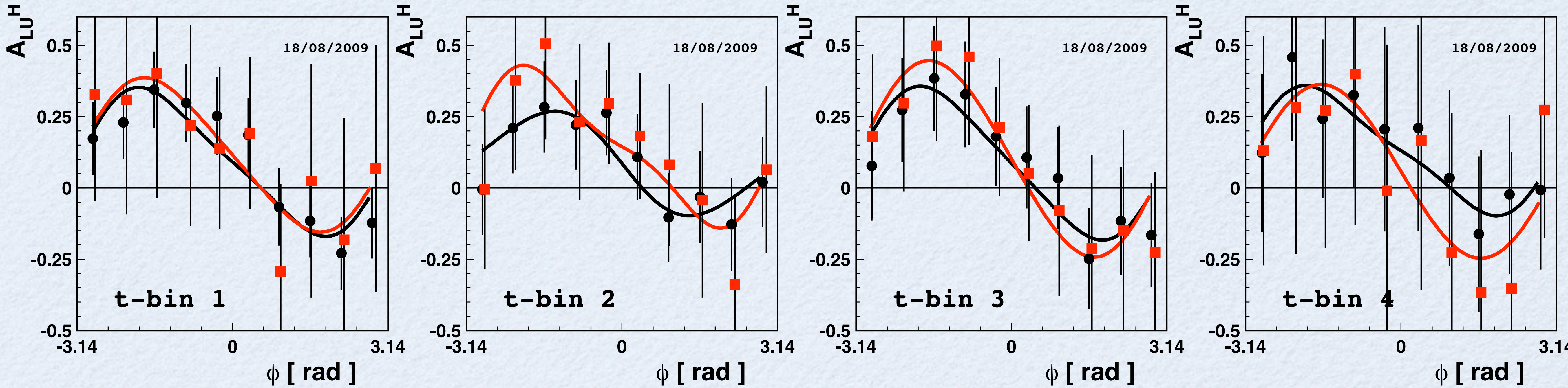
DVCS Beam Helicity Asymmetry with Recoil

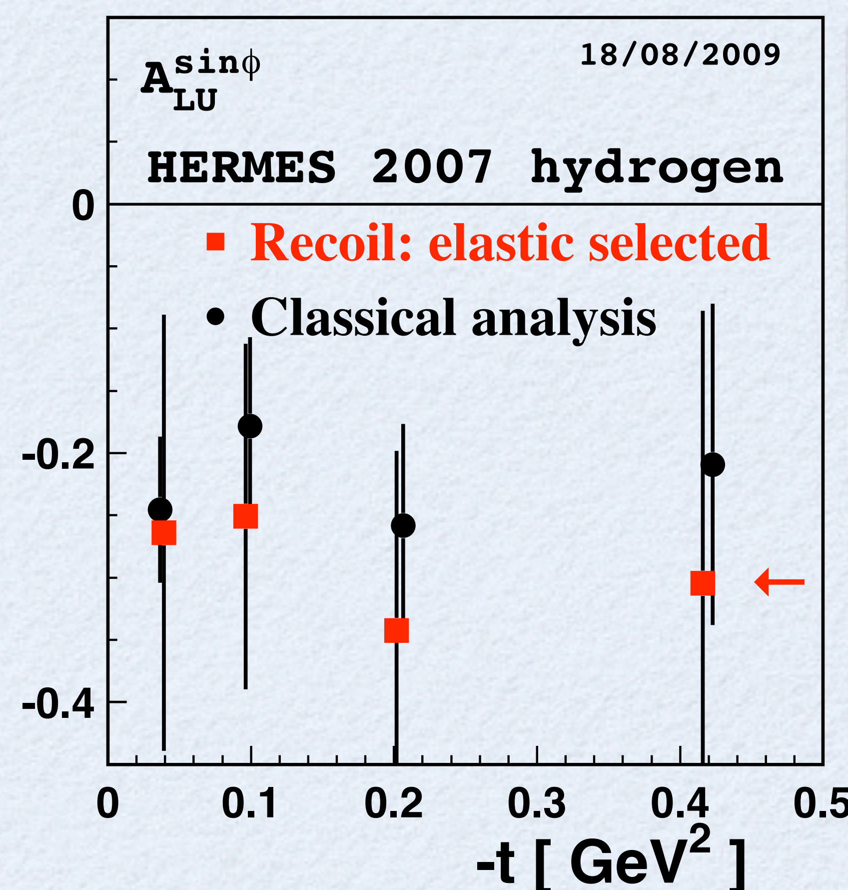




Pre-preliminary, private analysis

DVCS Beam Helicity Asymmetry with Recoil





Pre-preliminary, private analysis

← Elastic fraction: >95%

Summary

* Generalized Parton Distributions
  * Give glimpse of three-dimensional structure of nucleons
  * Allow to access total angular momentum carried by quarks

* Deeply Virtual Compton Scattering:
  the golden channel to study GPDs
  * Measurements of cross sections and asymmetries as input to GPD constraints and fits
  * Measurement of various azimuthal asymmetries at HERMES and other fixed target experiments

* HERMES high lumi run 2006/2007 with Recoil detector
  * Exclusive event tagging
  * First time: separation of elastic and resonant BSA in DVCS