Hard Exclusive Reactions

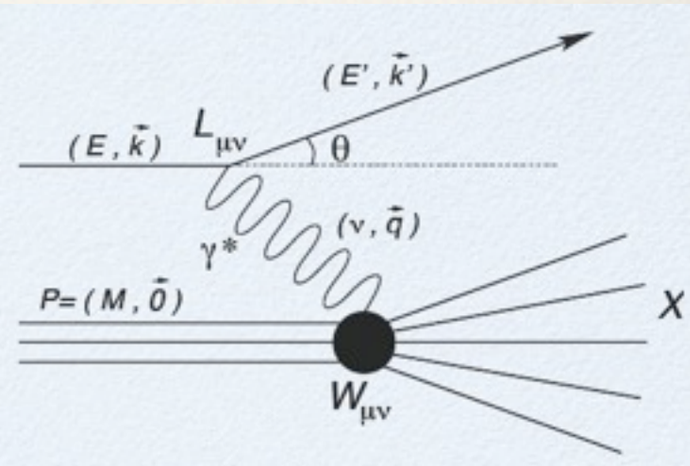
Caroline Riedl

γ ω φ ϱ π η J/Ψ ξ Υ

Milos, Greece, 30.9.2009

EINN09: Electromagnetic Interactions with Nucleons and Nuclei

Outline:
Hard Exclusive Reactions



Hard scale:
Q^2, M, and/or t

Complete spectrum of X known

- Photoproduction ($Q^2 < 1$ GeV^2)
  - Cross sections (Q^2, W, t)

testing ground for QCD

- Electroproduction ($Q^2 > 1$ GeV^2)
  - t slopes
  - Azimuthal asymmetries
  - Spin density matrix elements

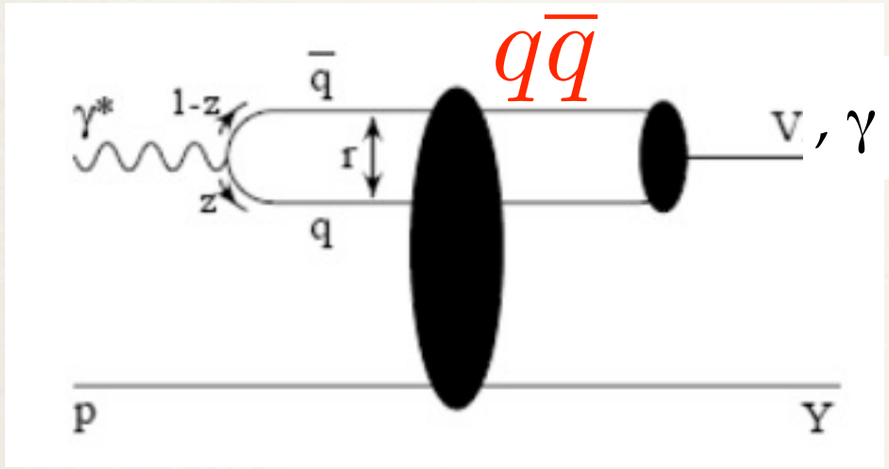
GPDs

total angular momentum of quarks

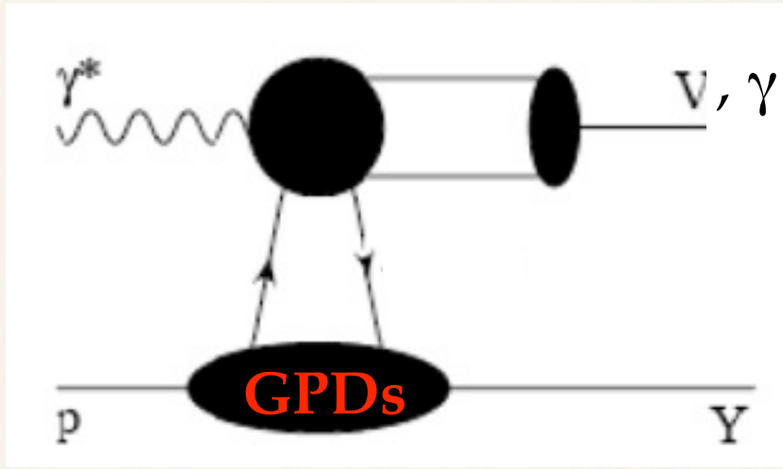
- Future

ep→epV or ep→epγ (DVCS)

High energy factorization



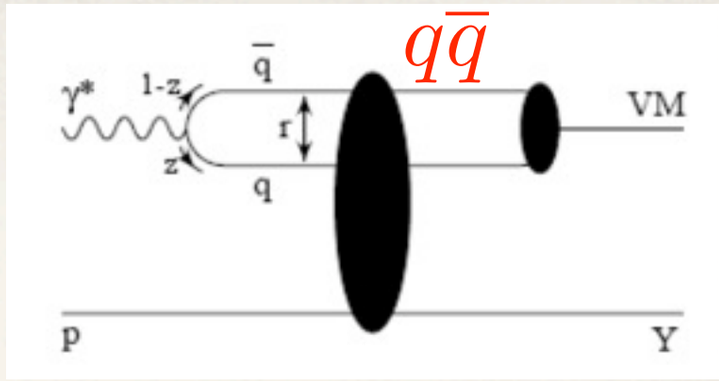
Collinear factorization



- Universal dipole interactions
- Low x ↔ large W
- Scale: $Q^2 + m_V^2$

- Parameterization of non-perturbative nucleonic structure
- Information on parton-parton correlations
- VM: proven only for $\sigma_{Longitudinal}$

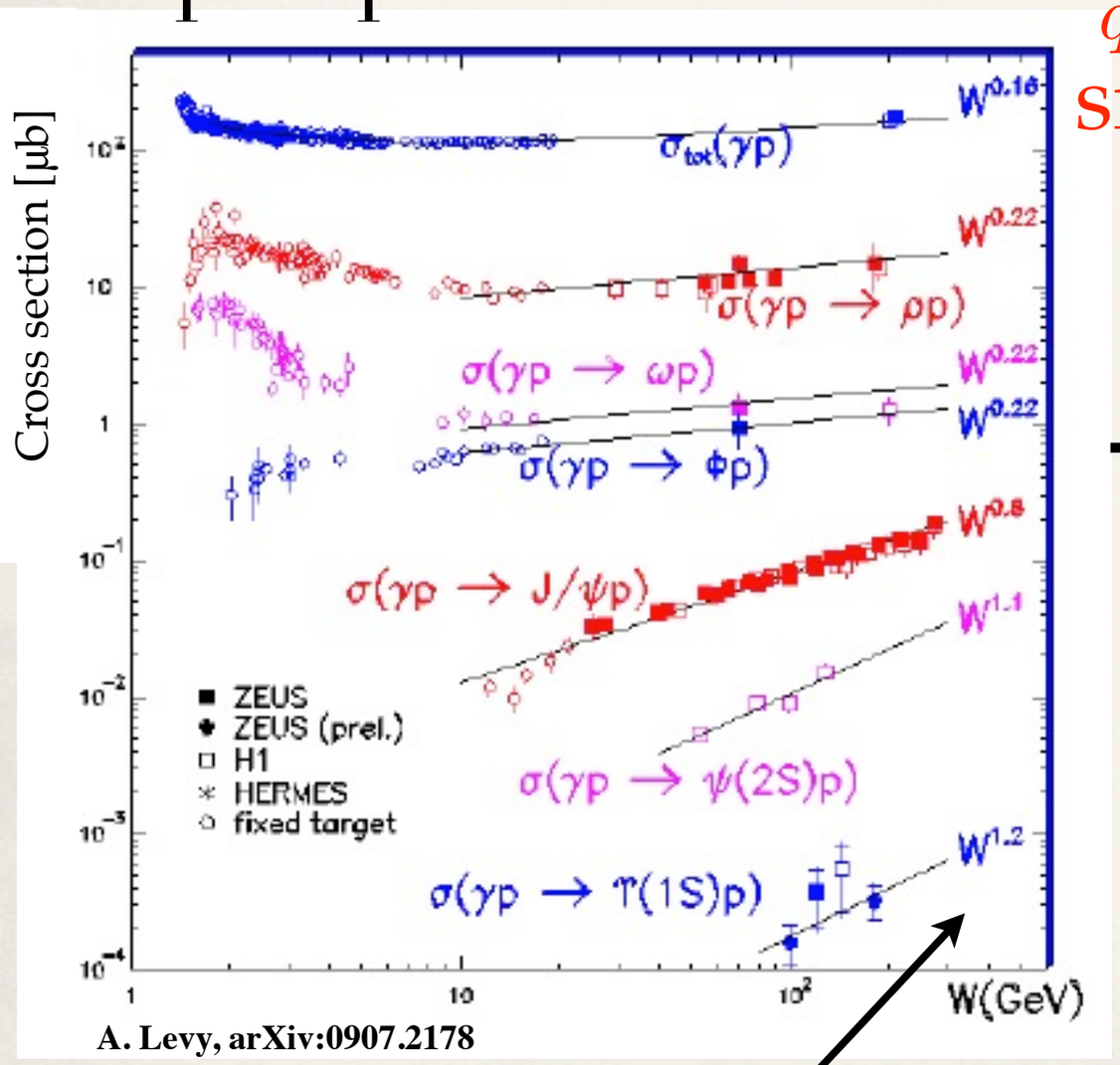
Kinematic Landscape



Photoproduction

ep→epV

σ(W)∝W^δ



A. Levy, arXiv:0907.2178

$d\sigma/dt \propto [xg(x,Q^2)]^2$

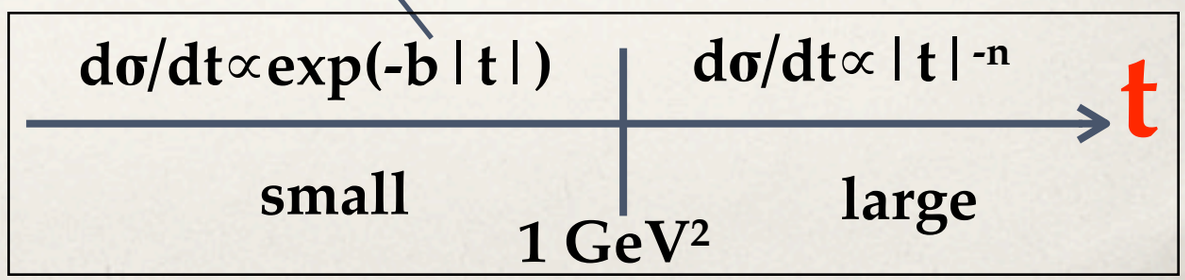
$q\bar{q}$ size

M_V, $\langle W \rangle$

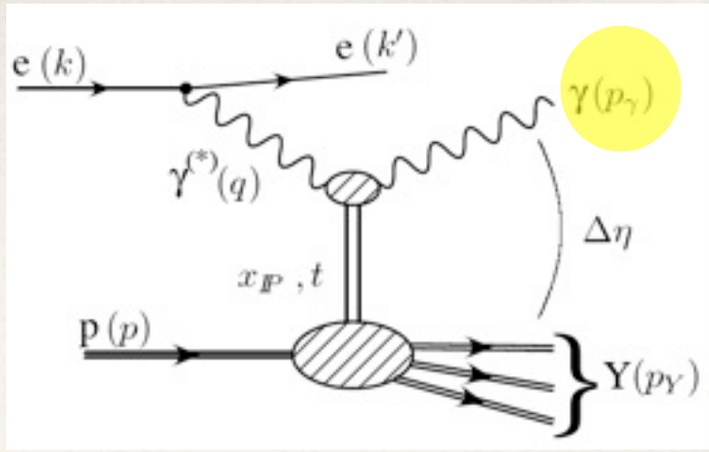
HERA sees interplay between soft and hard

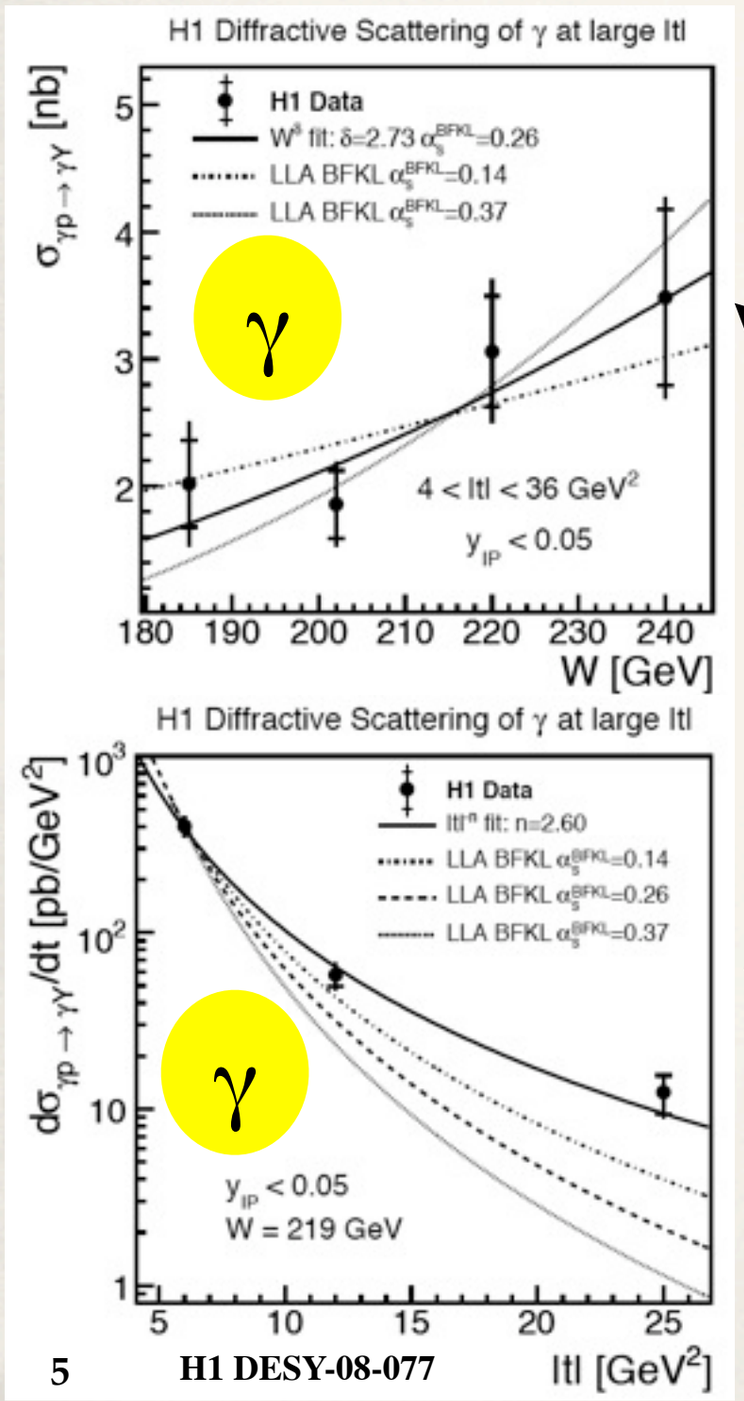
ϱ, ω, ϕ **δ=0.2** **b=10 GeV⁻²** **SOFT Regge,** soft pomeron exchange

J/Ψ, Υ **δ≥0.8** **b=4-5 GeV⁻²** **HARD pQCD,** 2-gluon exchange

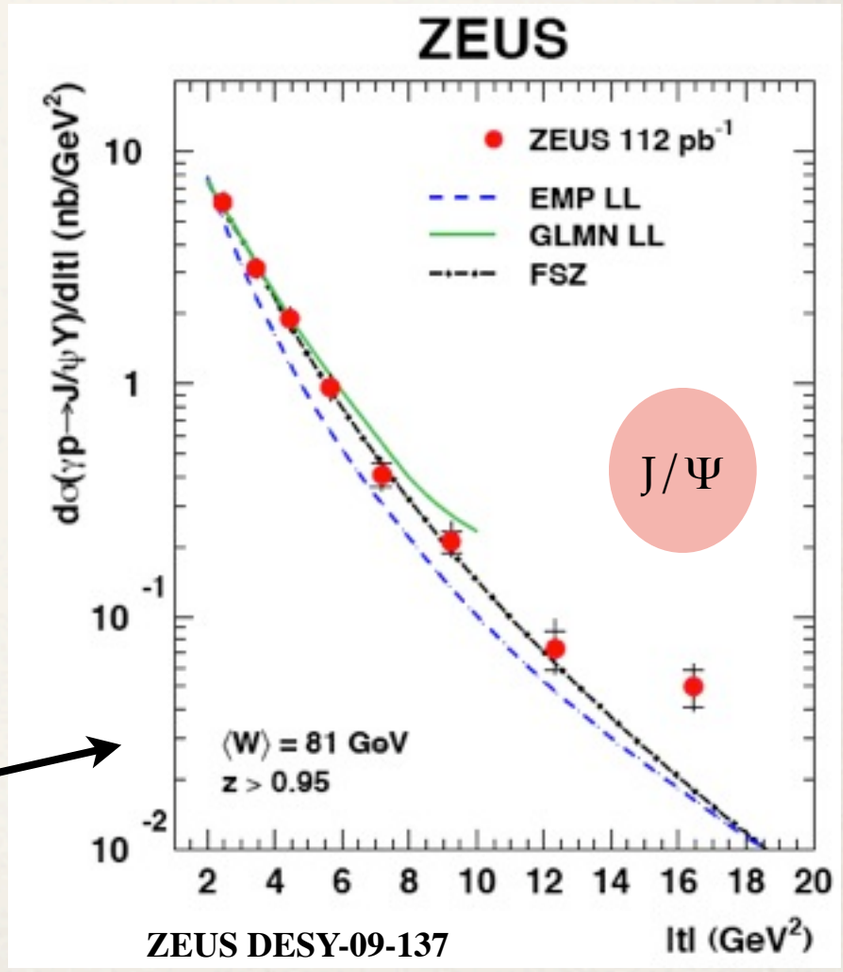


$\gamma^{(*)}p \rightarrow \gamma Y$ Photoproduction





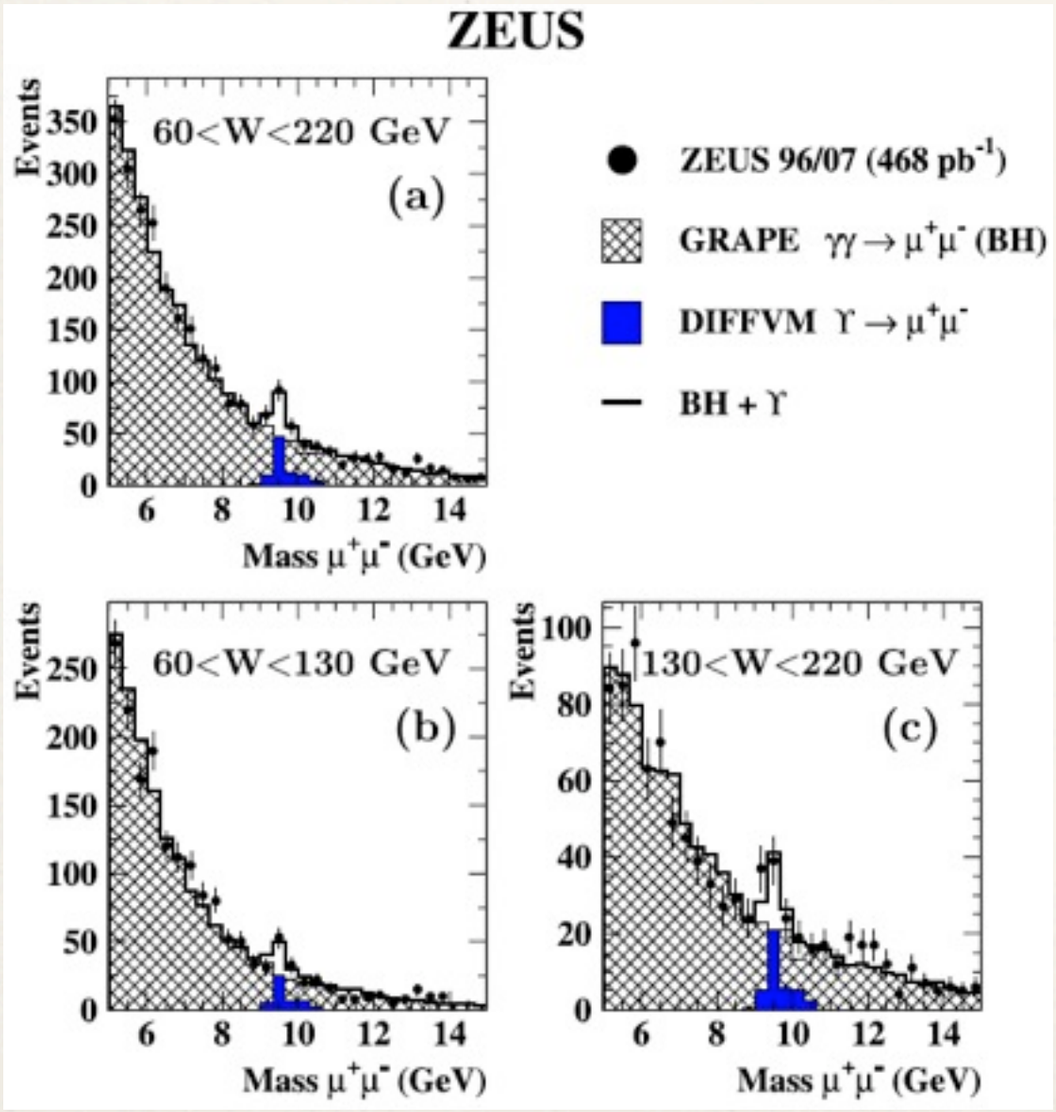
- Large |t|, proton-dissociative
- $\sigma(W) \propto W^{\delta}$
  - pQCD: good description
  - Compatible with J/Ψ
- $d\sigma/dt \propto |t|^{-n}$
  - pQCD: too soft prediction
  - Harder than J/Ψ



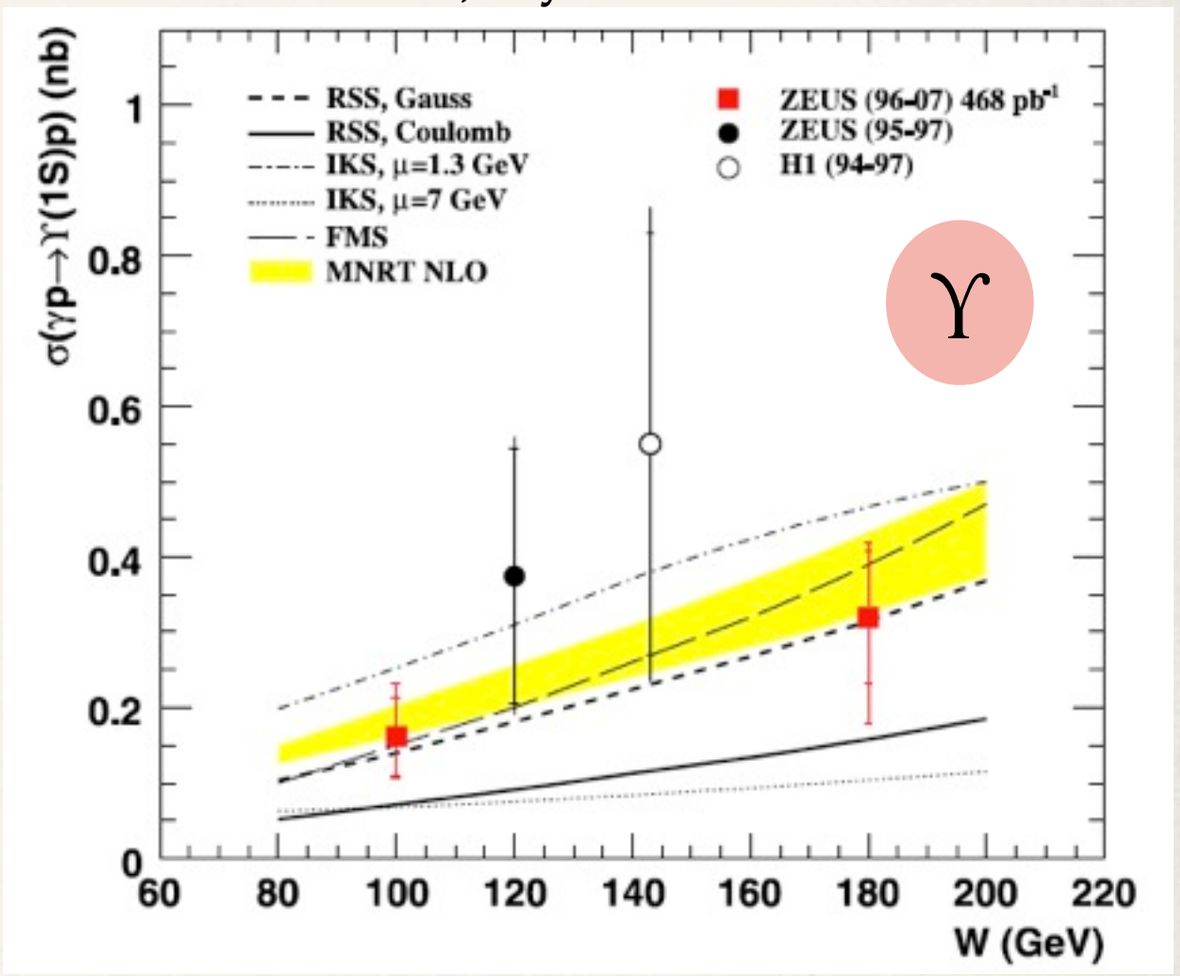
H1 DESY-08-077

ep→epϒ(1S) Photoproduction

Di-muon events, invariant mass:



ZEUS 1996-2007, Phys. Lett. B 680 (2009) 4–12



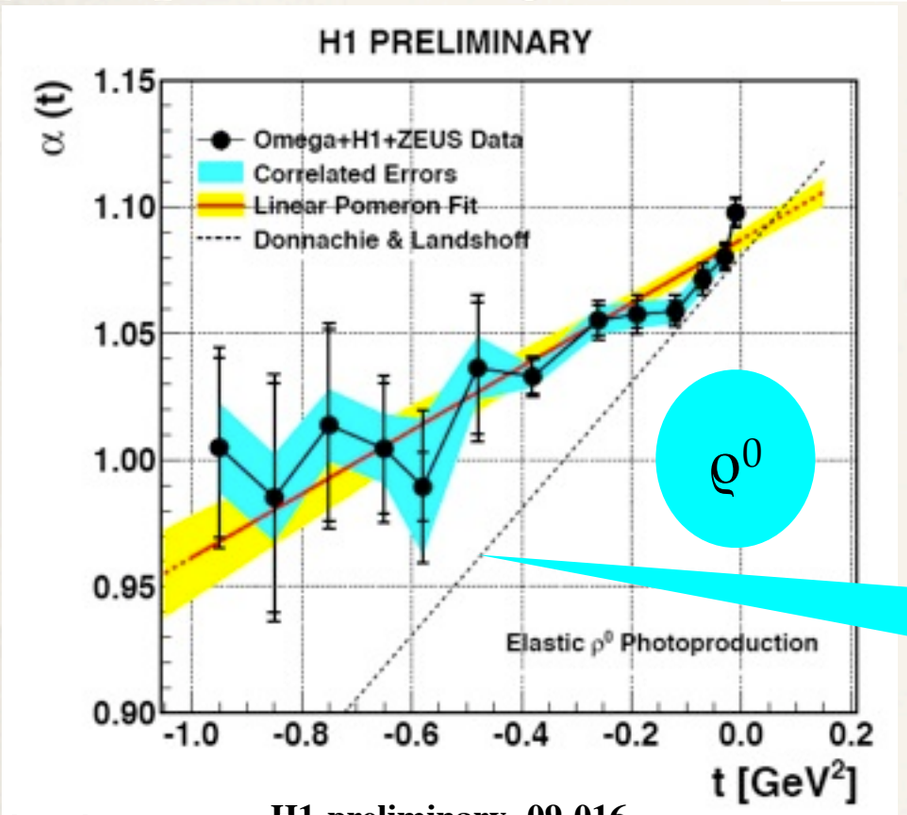
- σ ∝ W^{δ}, δ=1.2±0.8
- ☑ pQCD calculations

ep→epV Pomeron trajectories

$$d\sigma/dt = F(t)W^{4(\alpha_{I\!P}(t)-1)}$$

$$\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P} \cdot t$$

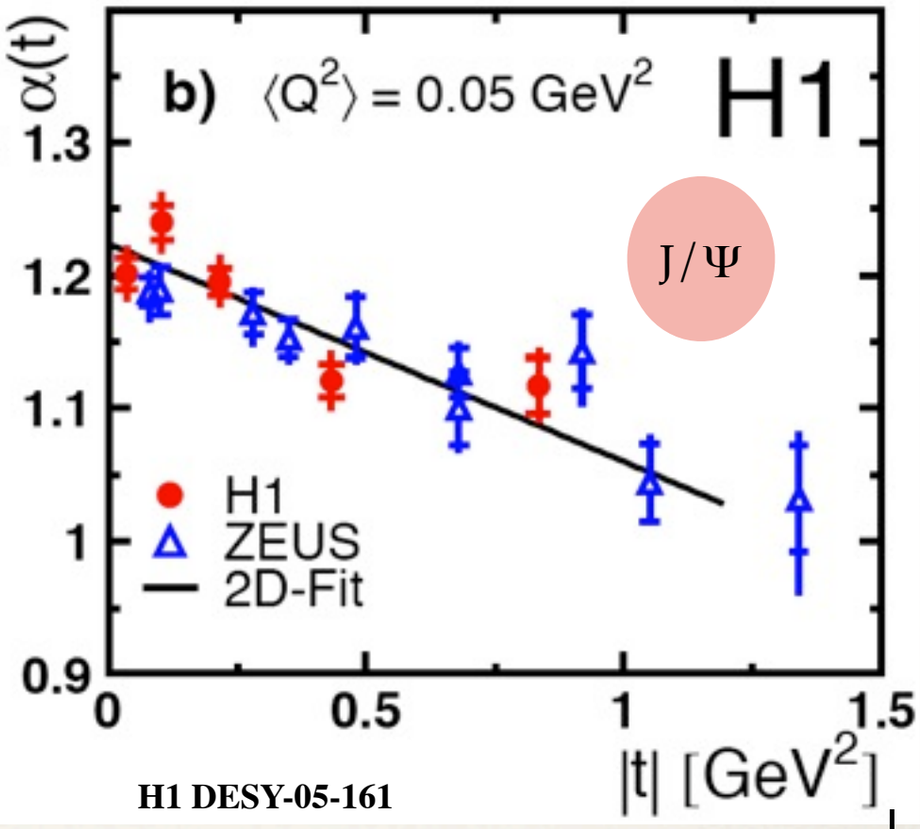
photoproduction light VM



H1-preliminary -09-016

Canonical soft pomeron: $\alpha'_P = 0.25$ GeV^{-2}

photoproduction heavy VM



H1 DESY-05-161

| t | ←

→ | t |

$\alpha'_P = (\underline{0.126} \pm 0.013 \pm 0.012)$ GeV^{-2}

smaller than canonical soft pomeron

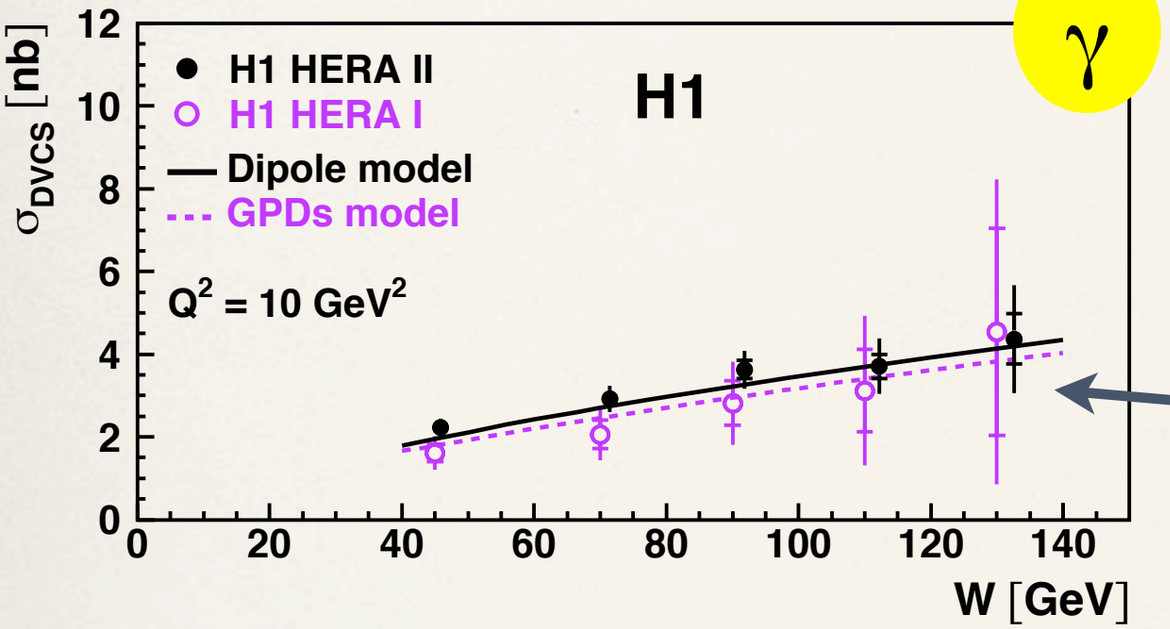
$\alpha'_P = (\underline{0.164} \pm 0.028 \pm 0.030)$ GeV^{-2}

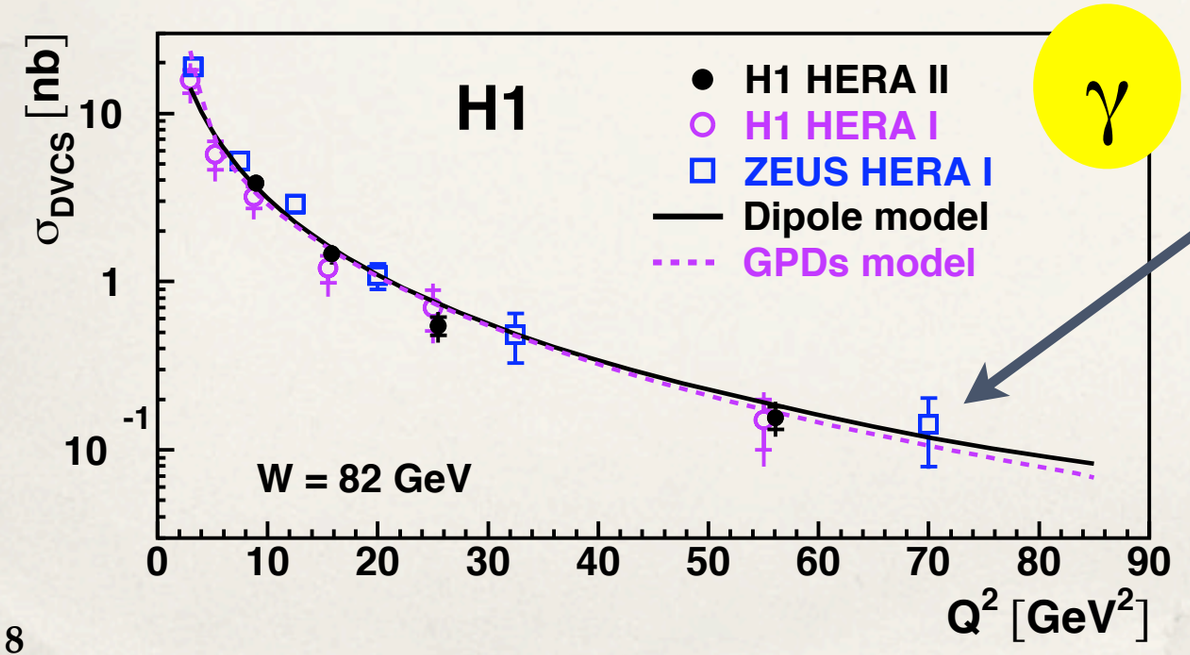
hard pomeron known to be smaller than canonical soft pomeron

ep→epγ cross-section

H1 and ZEUS

H1 arXiv:0907.5289





Hard exclusive <u>electroproduction</u> of a real photon: Deeply Virtual Compton Scattering, DVCS

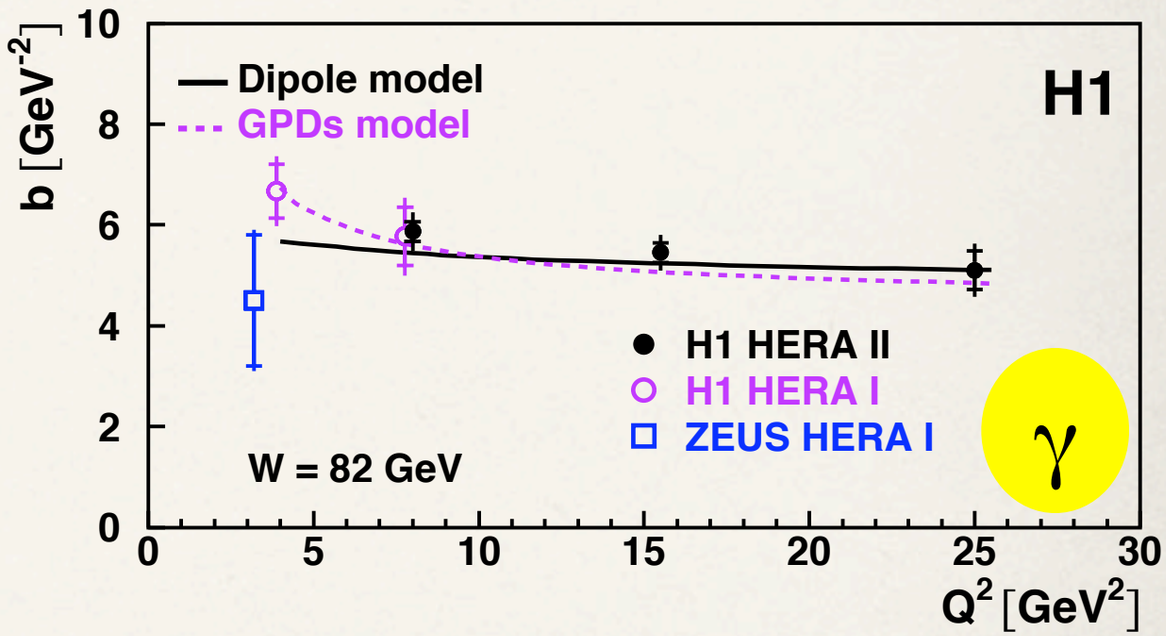
- Steep W^{δ} dependence
  - $\delta \approx 0.7$, independent of Q^2
  - DVCS is a hard process: gluons resolved
- Decrease of σ_{DVCS} with Q^2
  - Q^{2n} dependence, $n \approx 1.5$
  - Slower than for vector mesons

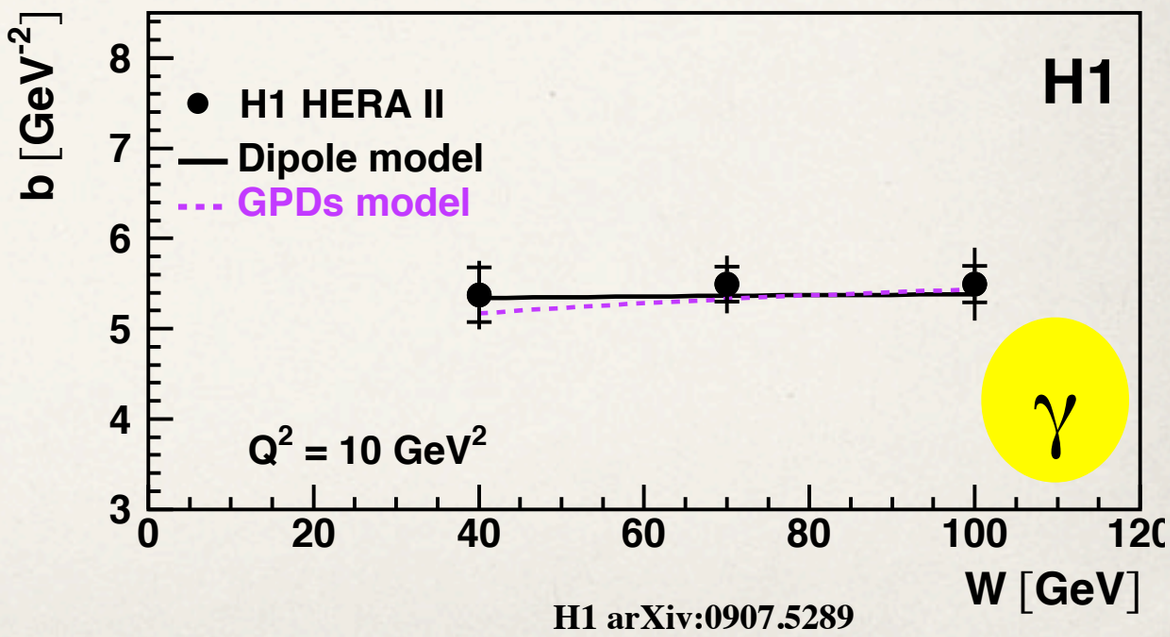
Transverse extension of partons

HERA: DVCS cross section differential in t

- Extract $d\sigma/dt$ in bins of Q^2 and W
- Ansatz $d\sigma/dt \propto \exp(-b|t|)$
- t slope ➡ average impact parameter b
  - Description of transverse extension of partons
  - Size of proton core (w/o soft periphery)

$$\sqrt{\langle r_T^2 \rangle} = (0.65 \pm 0.02)\ \text{fm} \quad \text{at } x_B = 10^{-3}$$



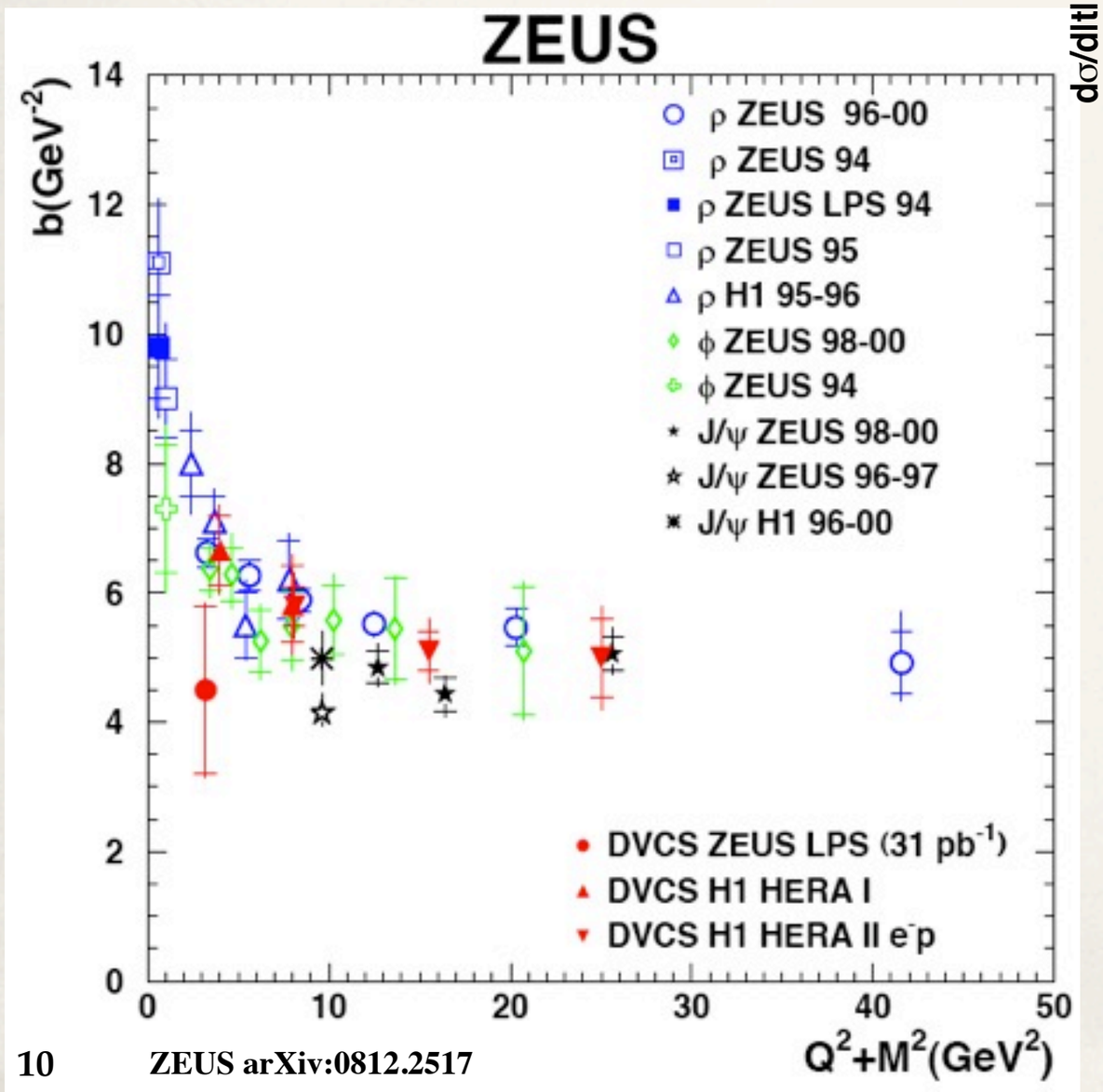


H1 arXiv:0907.5289

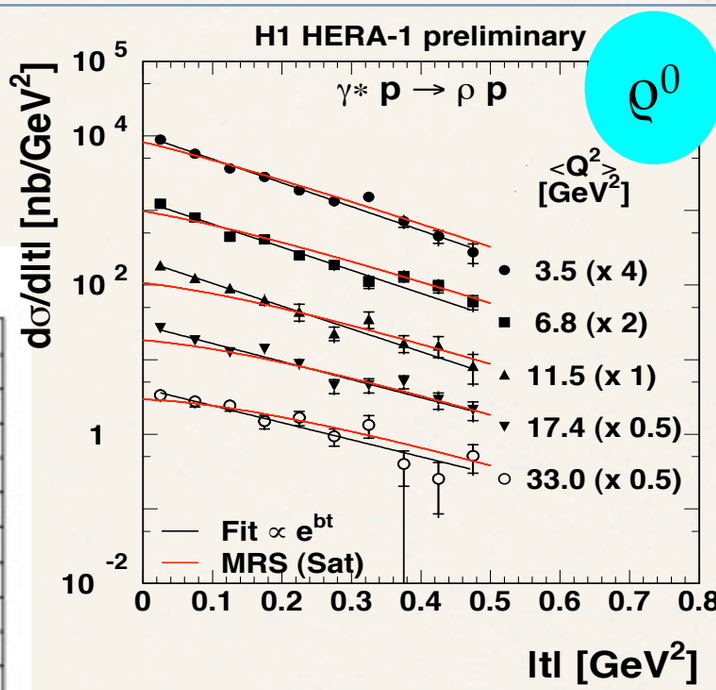
HERA: t slopes

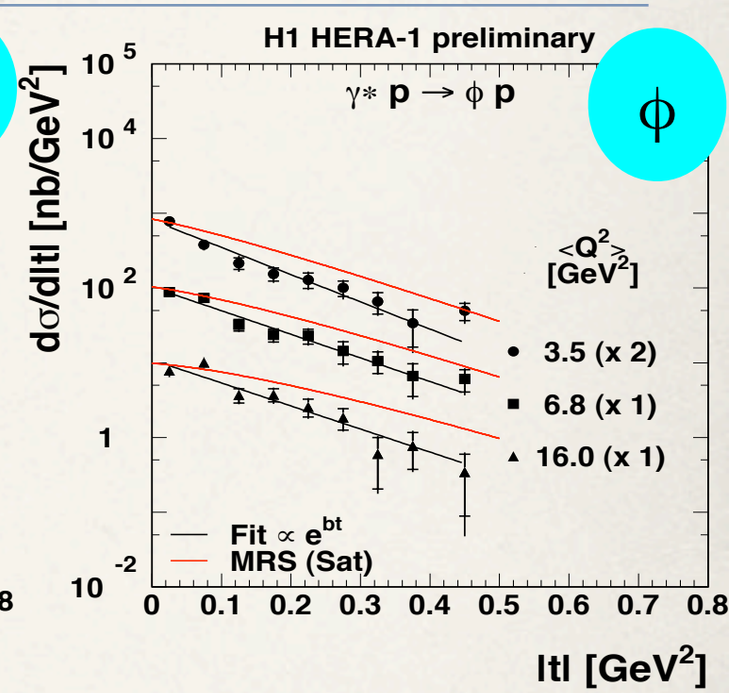
Electroproduction

$ep \to epV$



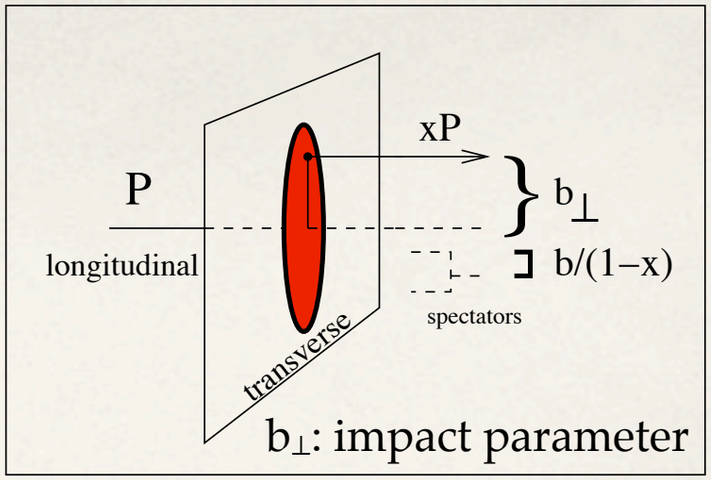
ZEUS arXiv:0812.2517



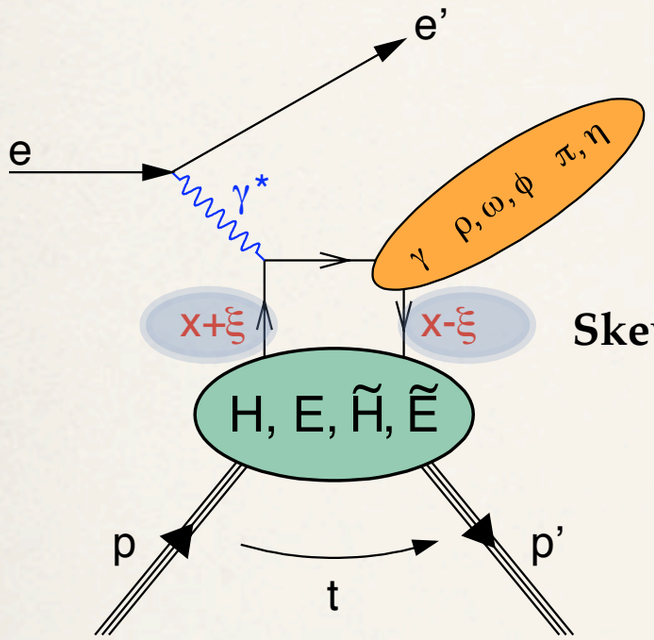


- b measures transverse size of VM ⊕ nucleon
- VM shrinks with increasing photon virtuality
- Universal value of b ≈ 5 GeV^{-2} at large scale

Generalized Parton Distributions



"Nucleon tomography"



Skewing: ξ≠0

leading twist, quark chirality conserving, spin-1/2		
f(quark helicity) ☞	✘	✔
nucleon spin flip ☜	photon: $J^P=1^-$ (DVCS)	
✘	**H**	**$\tilde{H}$**
✔	**E**	**$\tilde{E}$**
	$J^P=1^-$ mesons	$J^P=0^-$ mesons

- PDFs: longitudinal momentum

  forward limit ξ=0, t=0: $H^q(x,0,0) = q(x)$

- Form Factors: transverse position

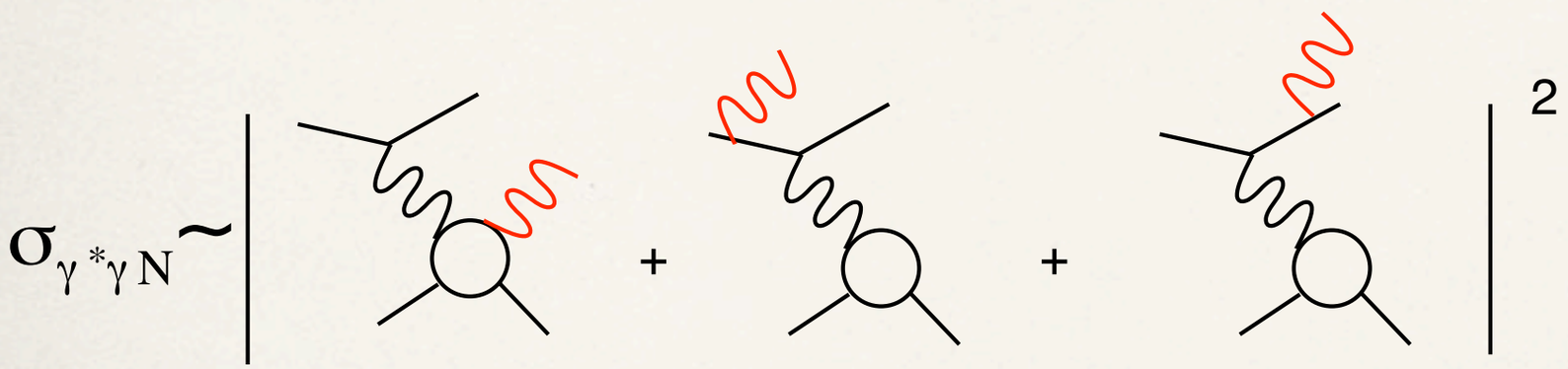
  moments of GPDs: $\int_{-1}^{1} \mathrm{d}x H^q(x,\xi,t) = F_1^q(t)$

- Nucleonic Spin: total angular momentum

  Ji relation:

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

Deeply Virtual Compton Scattering



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

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

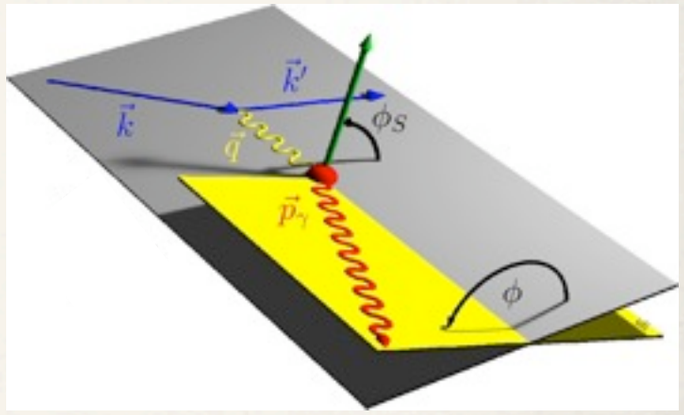
Holographic principle:
- BH reference amplitude magnifies DVCS
- Measure magnitude A **and** phase φ

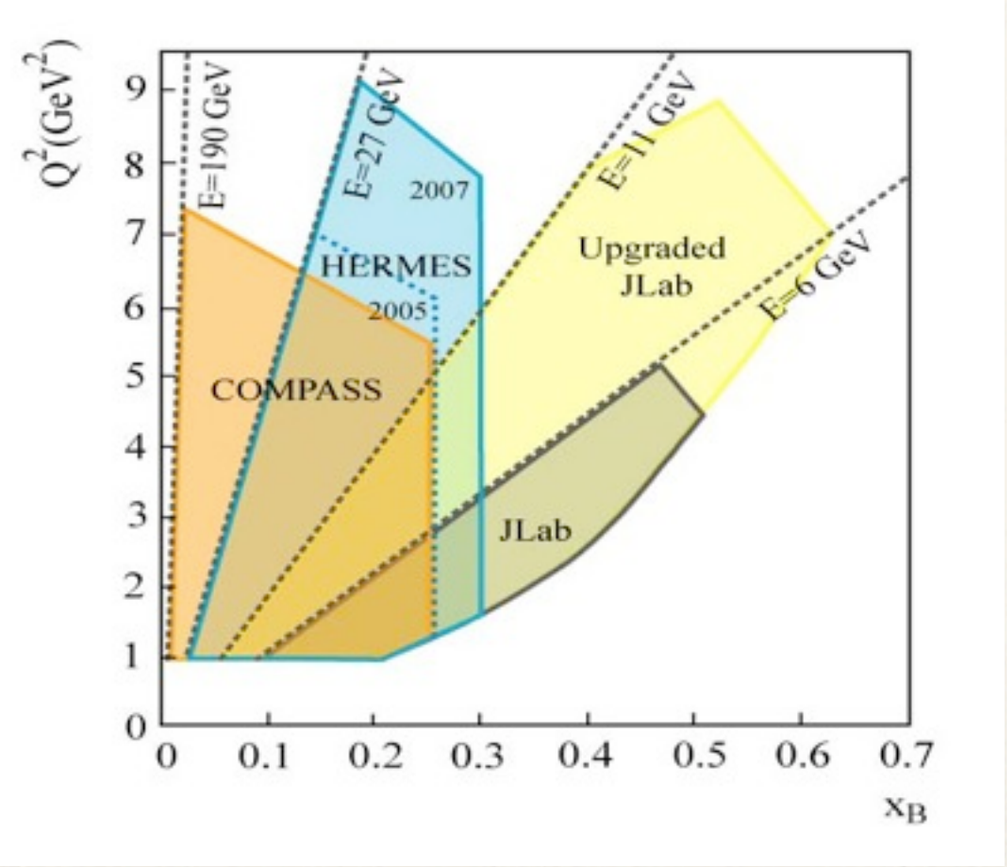
of DVCS amplitude $\tau_{DVCS} = Ae^{i\varphi}$

DVCS @ fixed target experiments

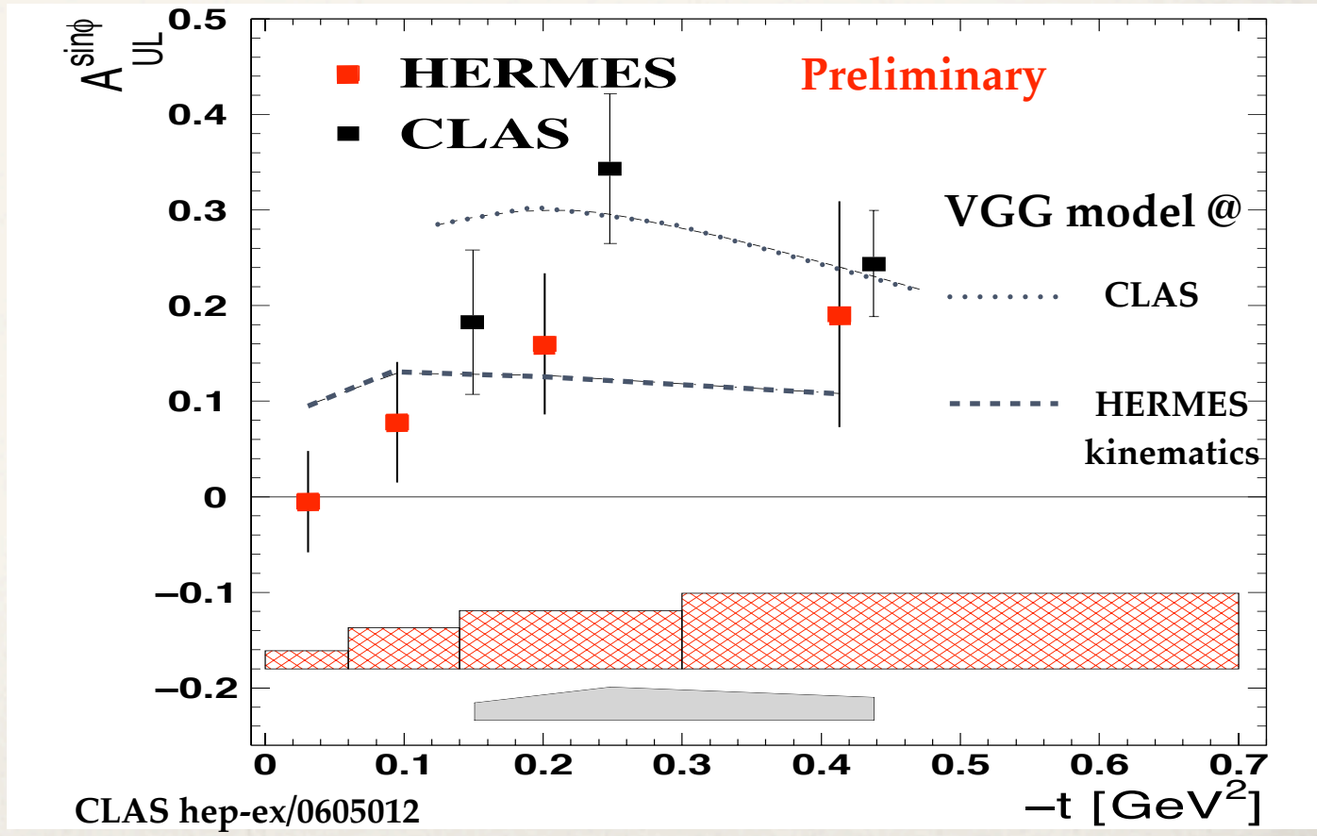
$$\vec{\ell}^{\pm}\ \mathrm{N} \to \ell^{\pm}\ \mathrm{N}\,\gamma \qquad (\to\uparrow)$$

The data are subject to
a harmonic fit w.r.t. the azimuthal
angle(s) ϕ (and ϕ_S)
to obtain **azimuthal asymmetries**





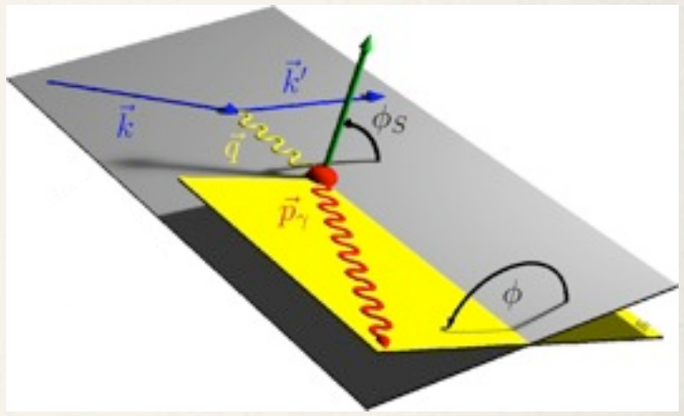
Longitudinal target spin asymmetry in DVCS

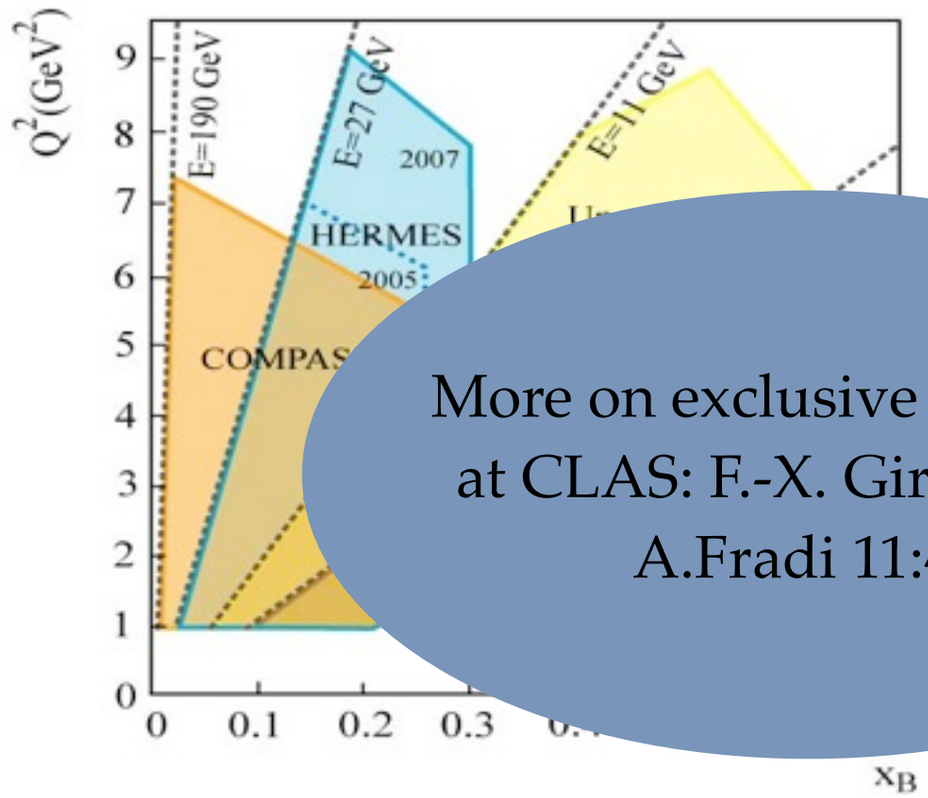


DVCS @ fixed target experiments

$$\vec{\ell}^{\pm}\ \mathrm{N} \to \ell^{\pm}\ \mathrm{N}\,\gamma \qquad (\to\uparrow)$$

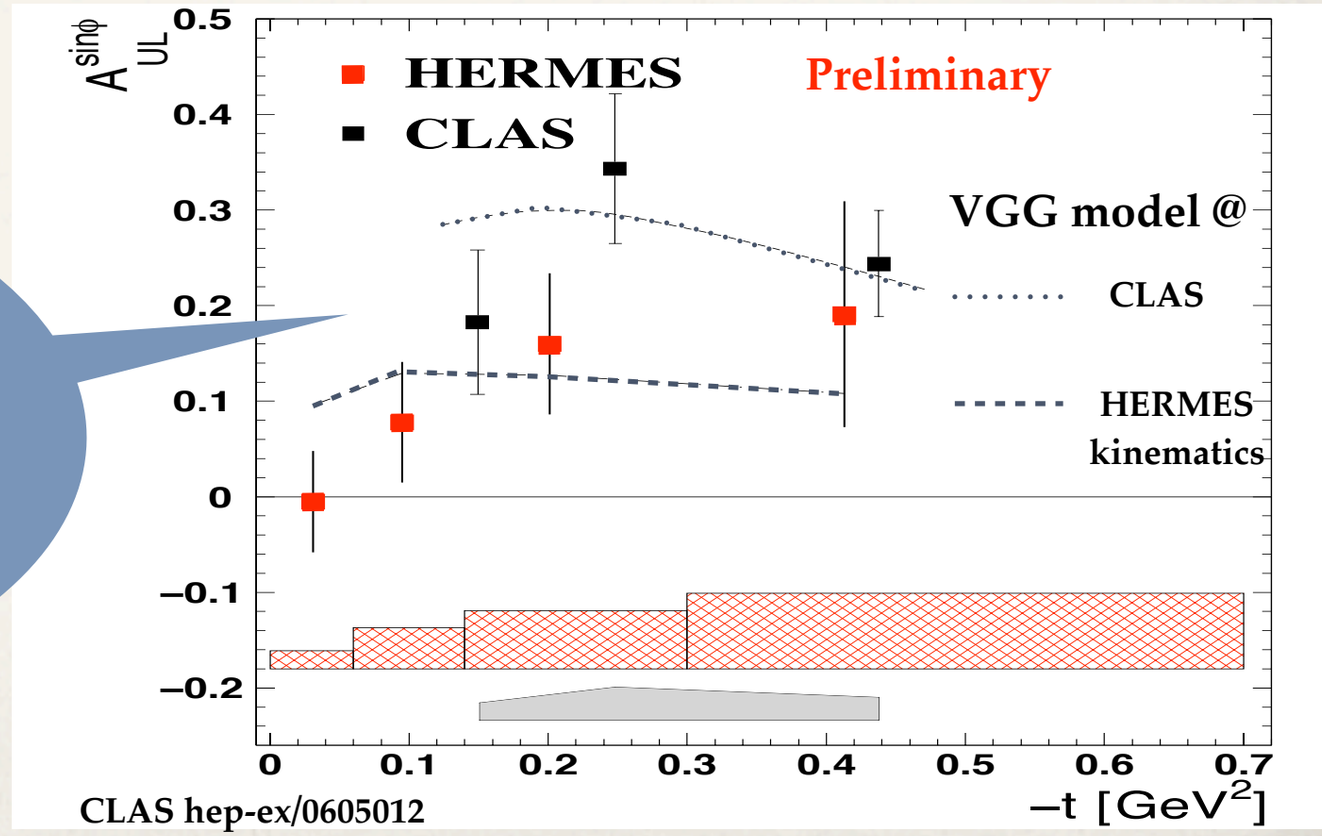
The data are subject to
a harmonic fit w.r.t. the azimuthal
angle(s) ϕ (and ϕ_S)
to obtain **azimuthal asymmetries**





More on exclusive processes
at CLAS: F.-X. Girod 11:00,
A.Fradi 11:40

Longitudinal target spin asymmetry in DVCS



DVCS cross-section
in the valence quark region

- Hall-A at JLab, proton target

Helicity-dependent

$\propto \mathcal{I}m(\mathcal{I})$

GPDs @ $x=\xi$

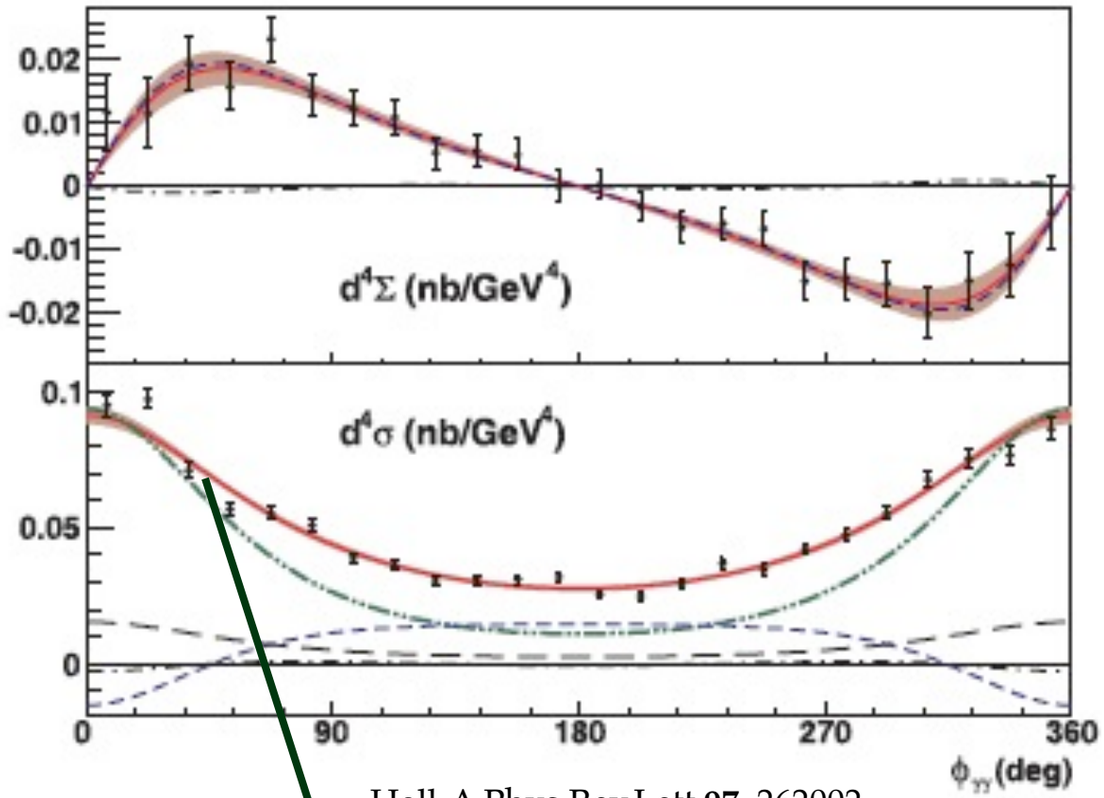
Helicity-independent

$\propto \mathcal{R}e(\mathcal{I})$

integral of GPDs over x

Differential cross section vs. azimuthal angle

Bin: $\langle x_B \rangle = 0.36$, $\langle Q^2 \rangle = 2.3$ GeV^2, $\langle t \rangle = -0.28$ GeV^2



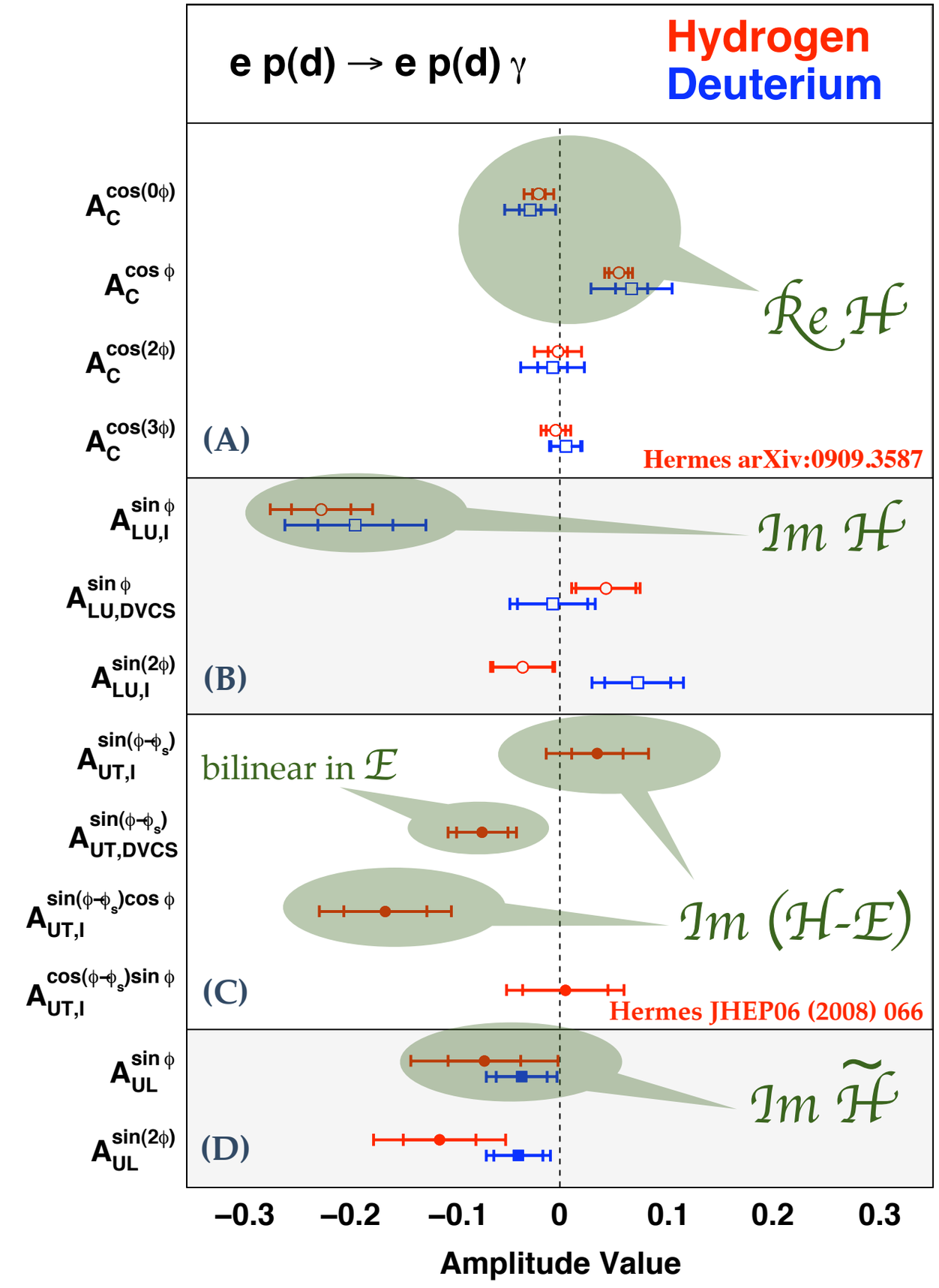
Hall-A Phys.Rev.Lett.**97**, 262002

- No Q^2 dependence of $\mathcal{I}m(\mathcal{I})$
  - Indication of factorization down to $Q^2=2$ GeV^2
  - GPDs accessible at moderate Q^2

Computed BH contribution
< helicity-independent cross section

DVCS azimuthal amplitudes

HERMES (prelim.)



(A) Beam charge asymmetry:
GPD H

(B) Beam helicity asymmetry:
GPD H

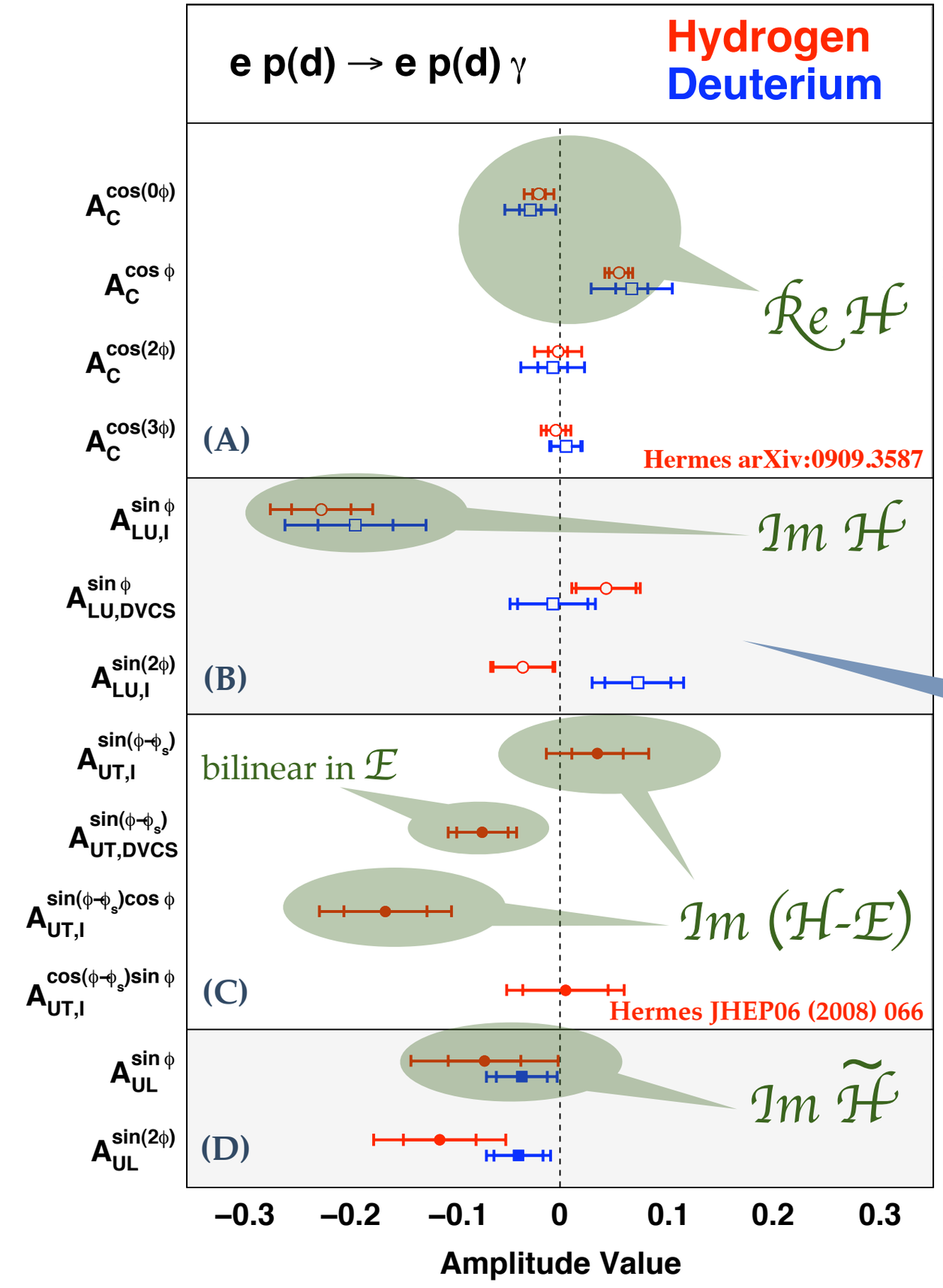
$\mathcal{R}e(\tau_{DVCS})$
↑
Projects out
↓
$\mathcal{I}m(\tau_{DVCS})$

(C) Transverse target spin asymmetry:
GPD E from proton target

(D) Longitudinal target spin asymmetry:
GPD $\tilde{H}$

DVCS azimuthal amplitudes

HERMES (prelim.)



(A) Beam charge asymmetry:
GPD H

(B) Beam helicity asymmetry:
GPD H

(C) Transv… :
GPD E …

(D) Longitudinal target spin asymmetry:
GPD H̃

$\mathcal{R}e(\tau_{DVCS})$

↑

Projects out

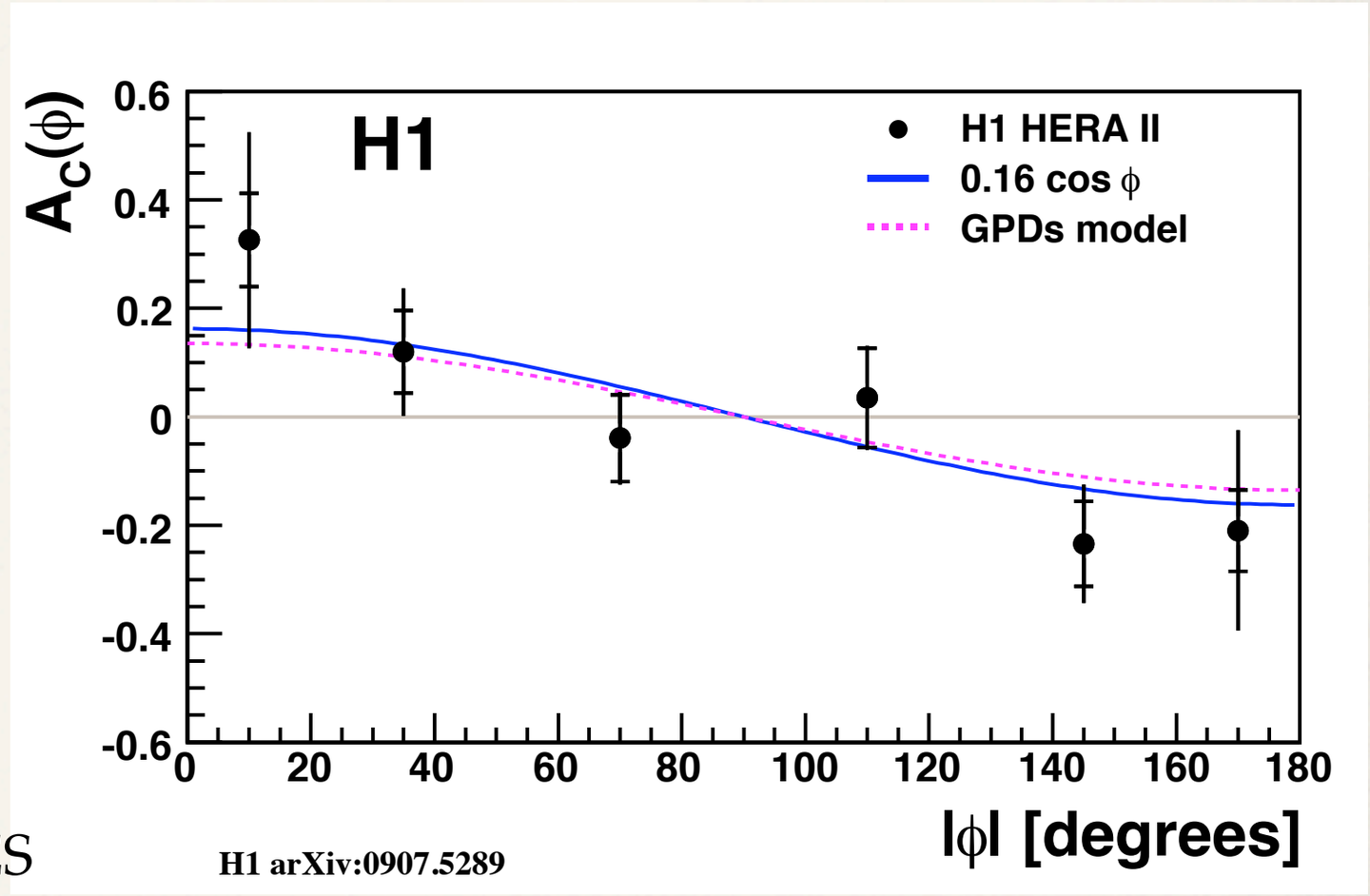
↓

$\mathcal{I}m(\tau_{DVCS})$

Details by
A. Mussgiller 11:20
& HERMES Recoil
detector 2006/07

HERA / H1: Beam Charge Asymmetry in DVCS

- First measurement at collider
  - **low $x_B=10^{-4}...10^{-2}$**
  - $6.5 < Q^2 < 80$ GeV^2
  - $30 < W < 140$ GeV
  - $|t| < 1$ GeV^2



H1 arXiv:0907.5289

- Positive cosϕ amplitude
  - **Re(τ_{DVCS}) > 0**
  - Sign change compared to HERMES

- Ratio ϱ = **Re(τ_{DVCS}) / Im(τ_{DVCS})**
  - $\varrho = 0.20 \pm 0.05(\text{stat}) \pm 0.08(\text{sys})$
  - In good agreement with calculation from dispersion relation

Access to the total angular momentum of quarks

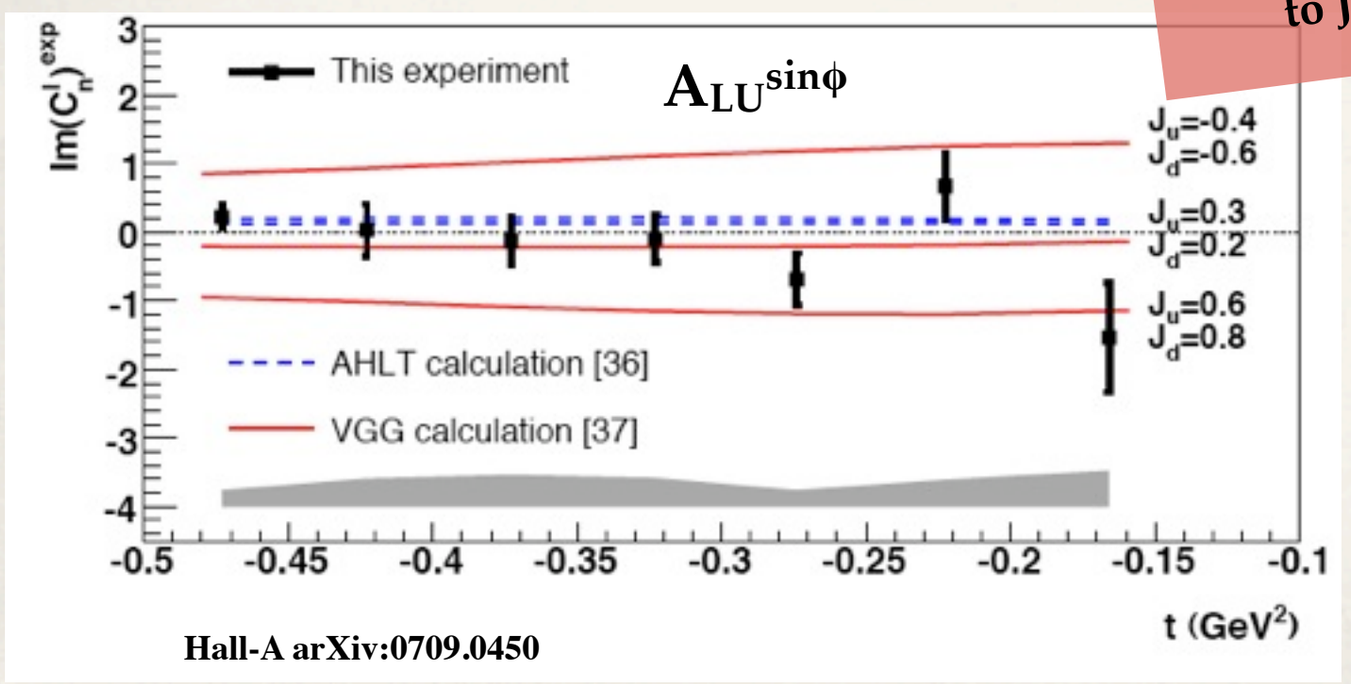
- Hall-A at JLab, deuteron target
- Quasi-elastic proton contribution subtracted from deuteron signal

$\vec{e}\,n \to e\,n\,\gamma$: sensitive to GPD E_q

Total angular momentum of quarks J_q:

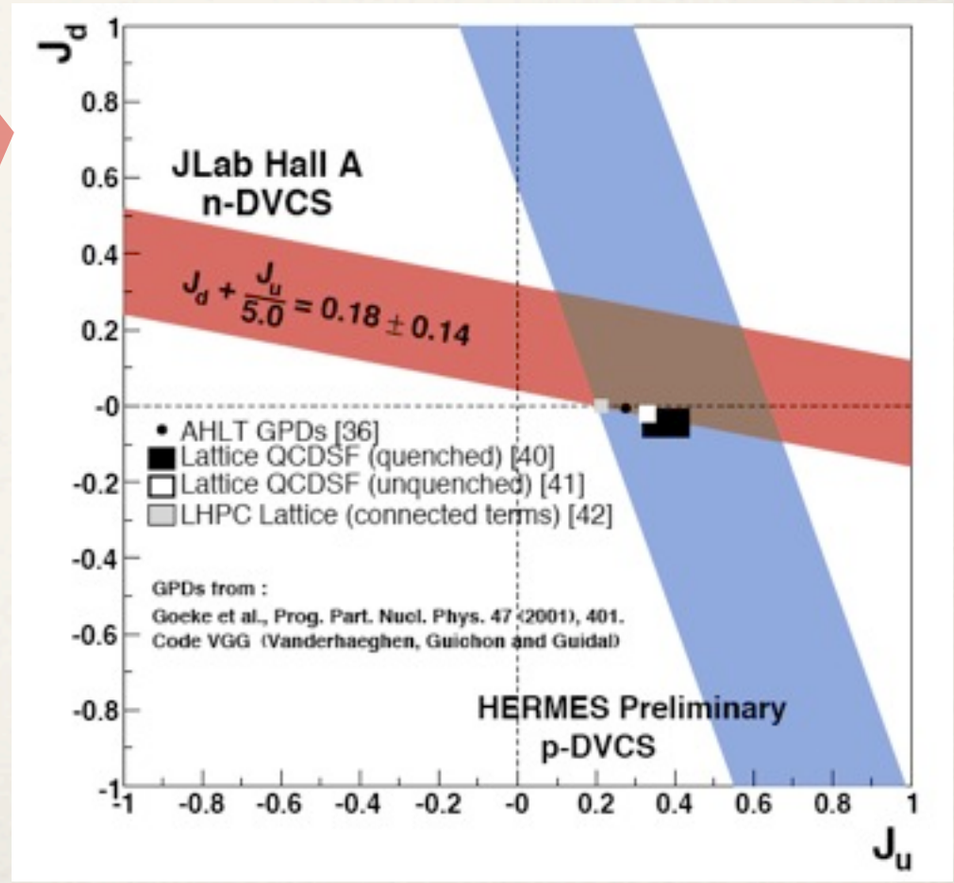
$$J_q = \frac{1}{2}\lim_{t\to 0}\int_{-1}^{1} dx\, x\,[H^q(x,\xi,t) + E^q(x,\xi,t)]$$

- Beam-helicity asymmetry:



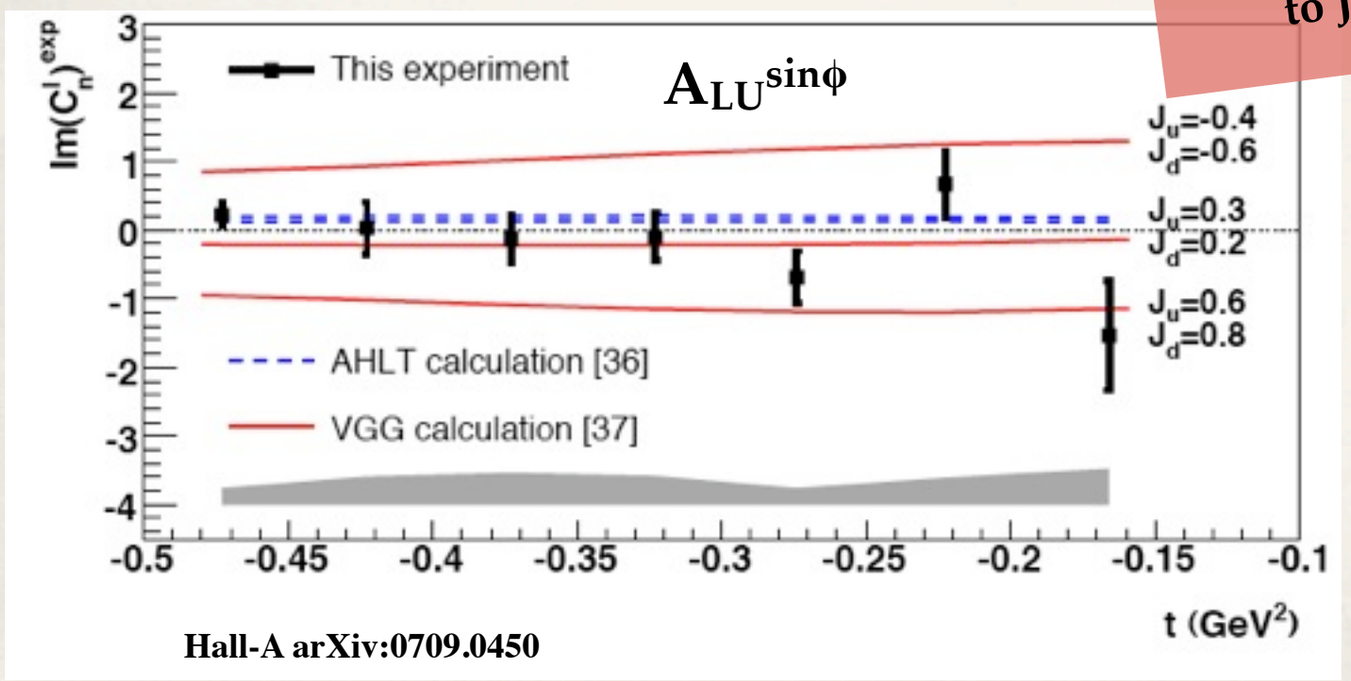
Hall-A arXiv:0709.0450

from sensitivity to J_q:



Access to the total angular momentum of quarks

- Hall-A at JLab, deuteron target
- Quasi-elastic proton contribution subtracted from deuteron signal
- Beam-helicity asymmetry:



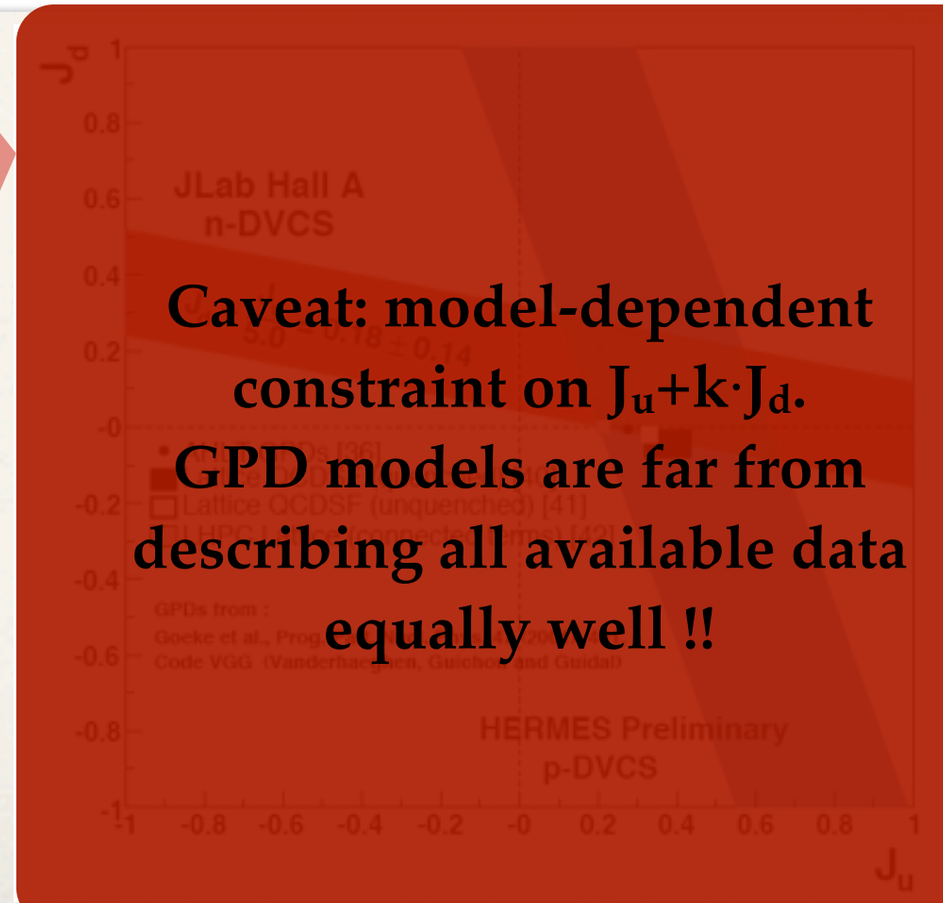
Hall-A arXiv:0709.0450

$\vec{e}\,n \to e\,n\,\gamma$: sensitive to GPD E_q

Total angular momentum of quarks J_q:

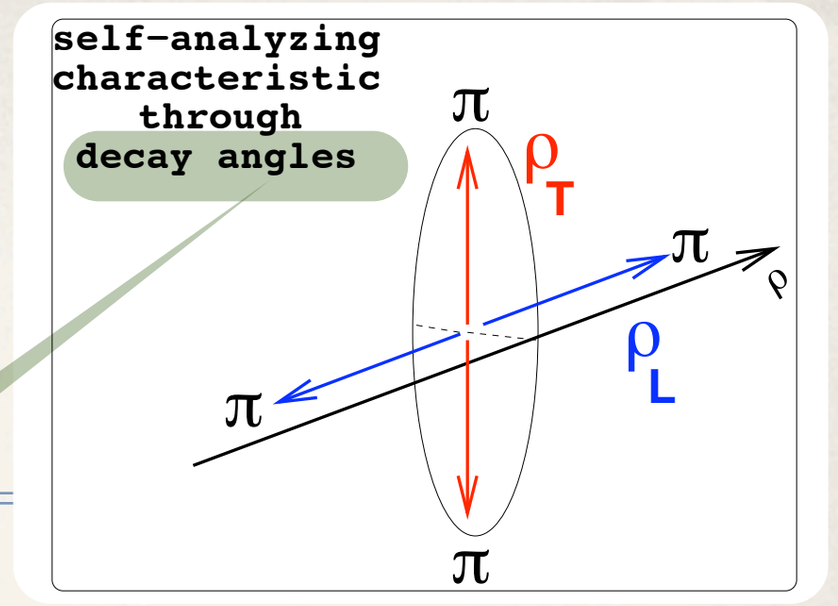
$$J_q = \frac{1}{2}\lim_{t\to 0}\int_{-1}^{1} dx\, x\,[H^q(x,\xi,t) + E^q(x,\xi,t)]$$

from sensitivity to J_q:



Caveat: model-dependent constraint on $J_u + k \cdot J_d$. GPD models are far from describing all available data equally well !!

ϱ^0 Spin Density Matrix Elements



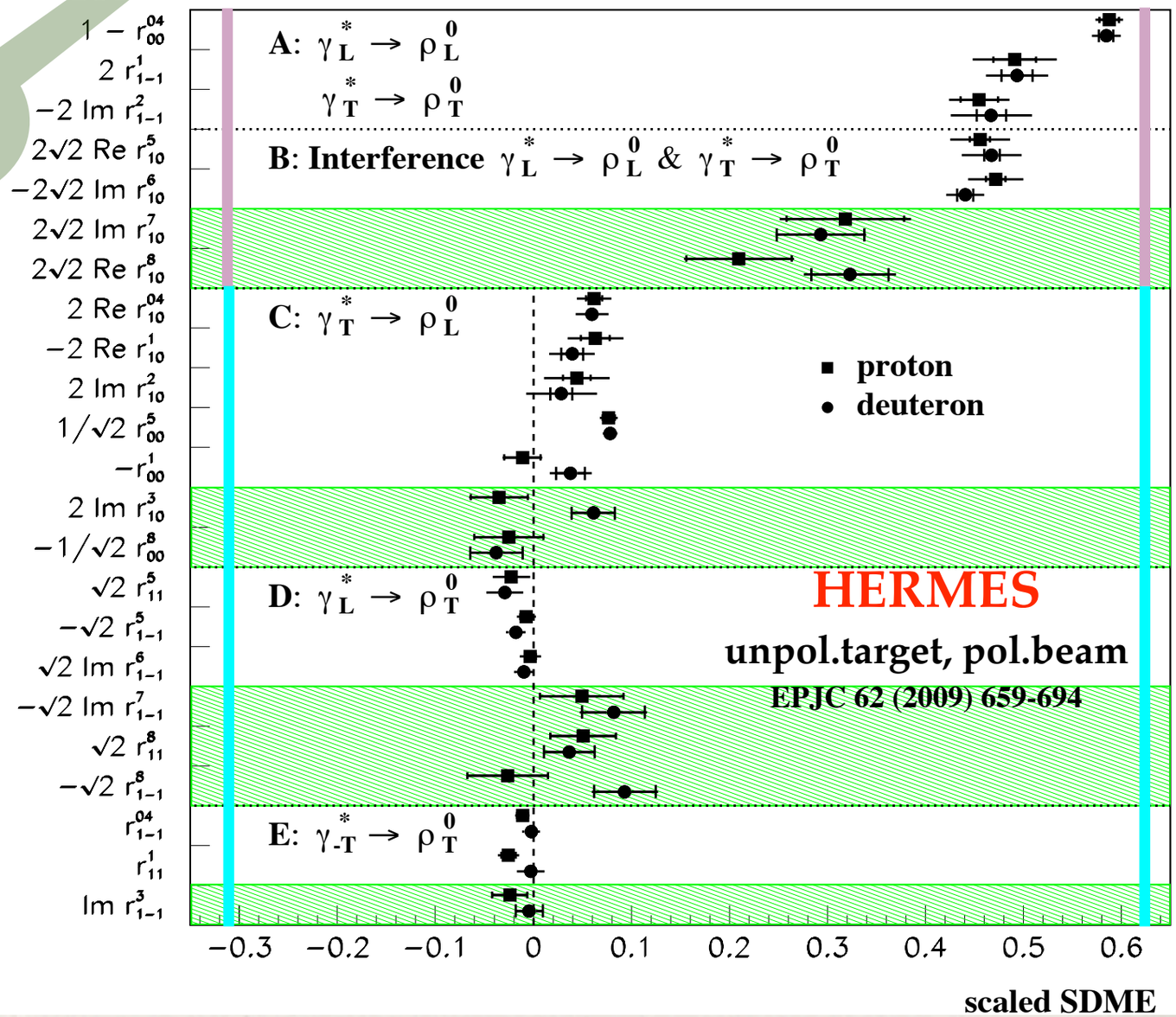
- Cross-section for exclusive ϱ^0 leptoproduction:

$$\frac{d\sigma}{dx_B\, dQ^2\, dt}\, W(x_B, Q^2, t, \phi, \phi_S, \varphi, \vartheta)$$

- **W** parametrized by **Spin Density Matrix Elements** (SDMEs)

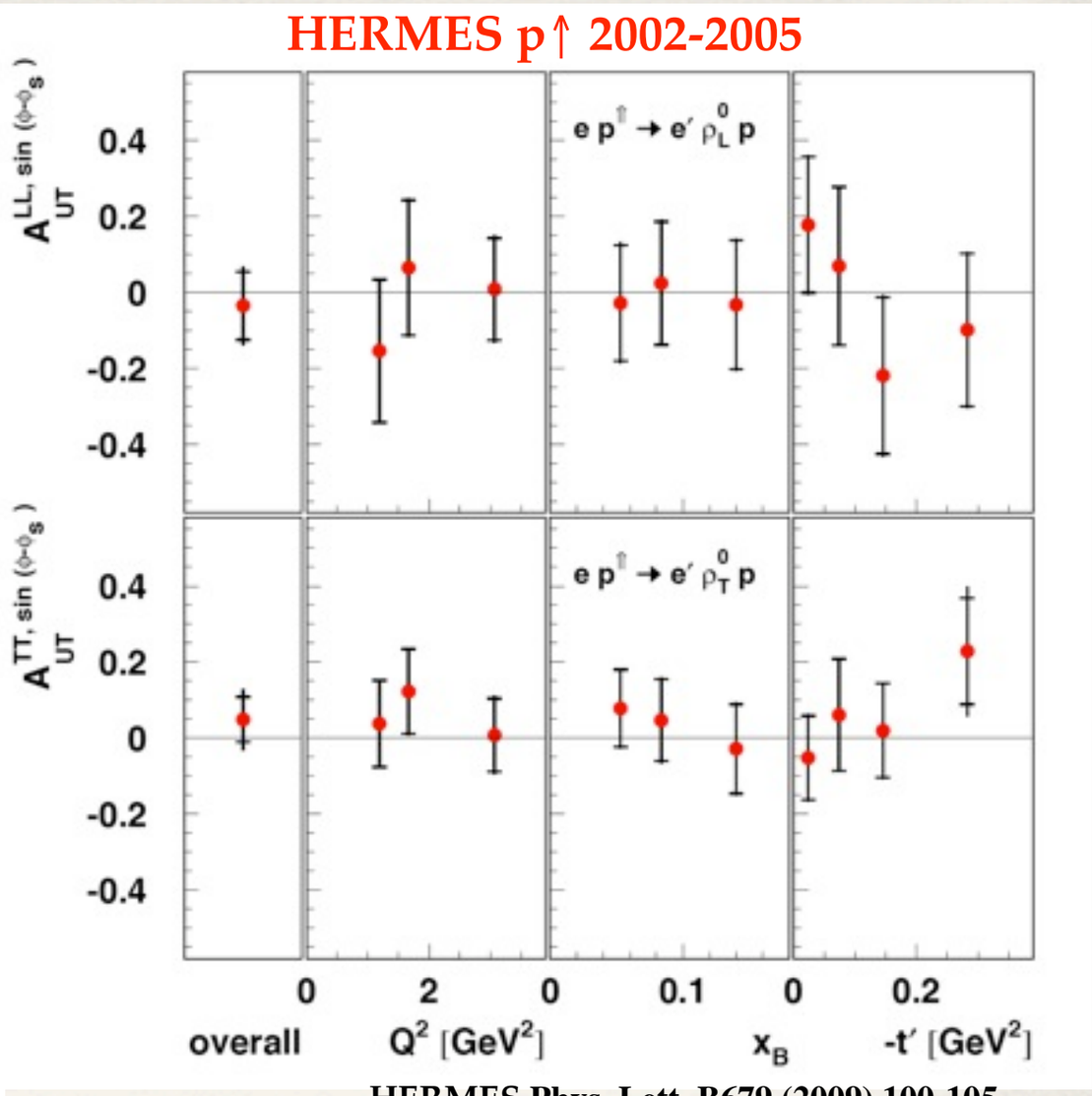
- SDMEs describe **helicity transfer from the γ^* to the ϱ^0:**
  - s-channel helicity conservation (SCHC) L→L, T→T
  - s-channel helicity violation

- More precision data from HERA

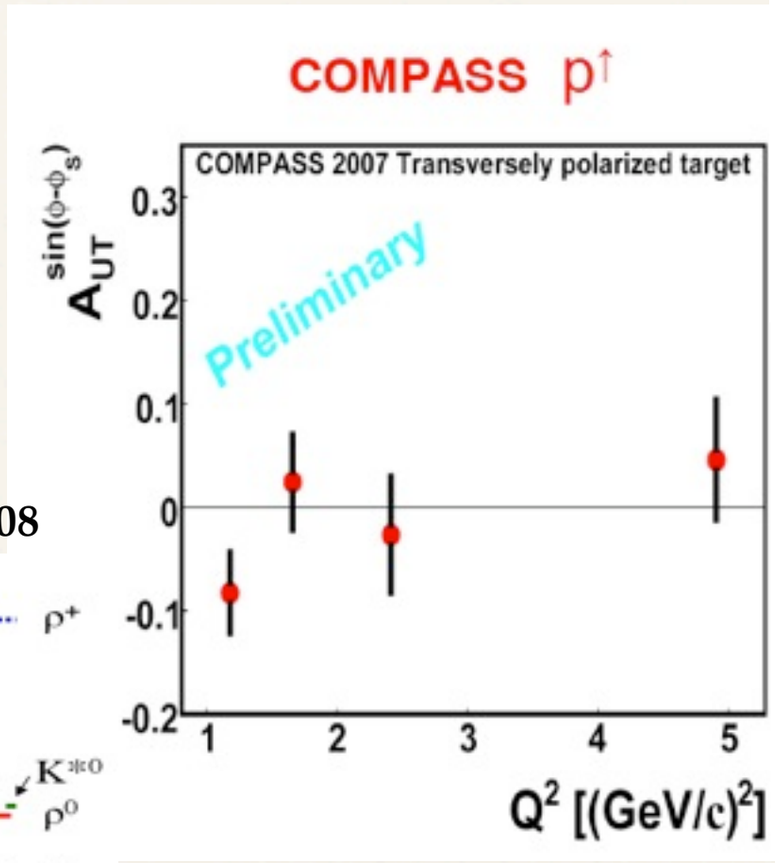


A_{UT} in $ep^{\Uparrow} \rightarrow ep\varrho^0$

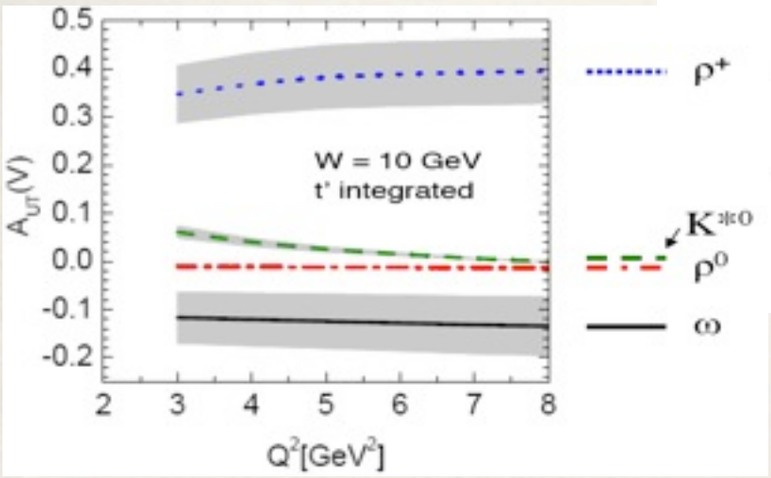
- A_{UT}: depends linearly on GPDs (E_q+E_g), no suppression w.r.t. GPD H



HERMES Phys. Lett. B679 (2009) 100-105



GPDs: Goloskokov, Kroll 2008



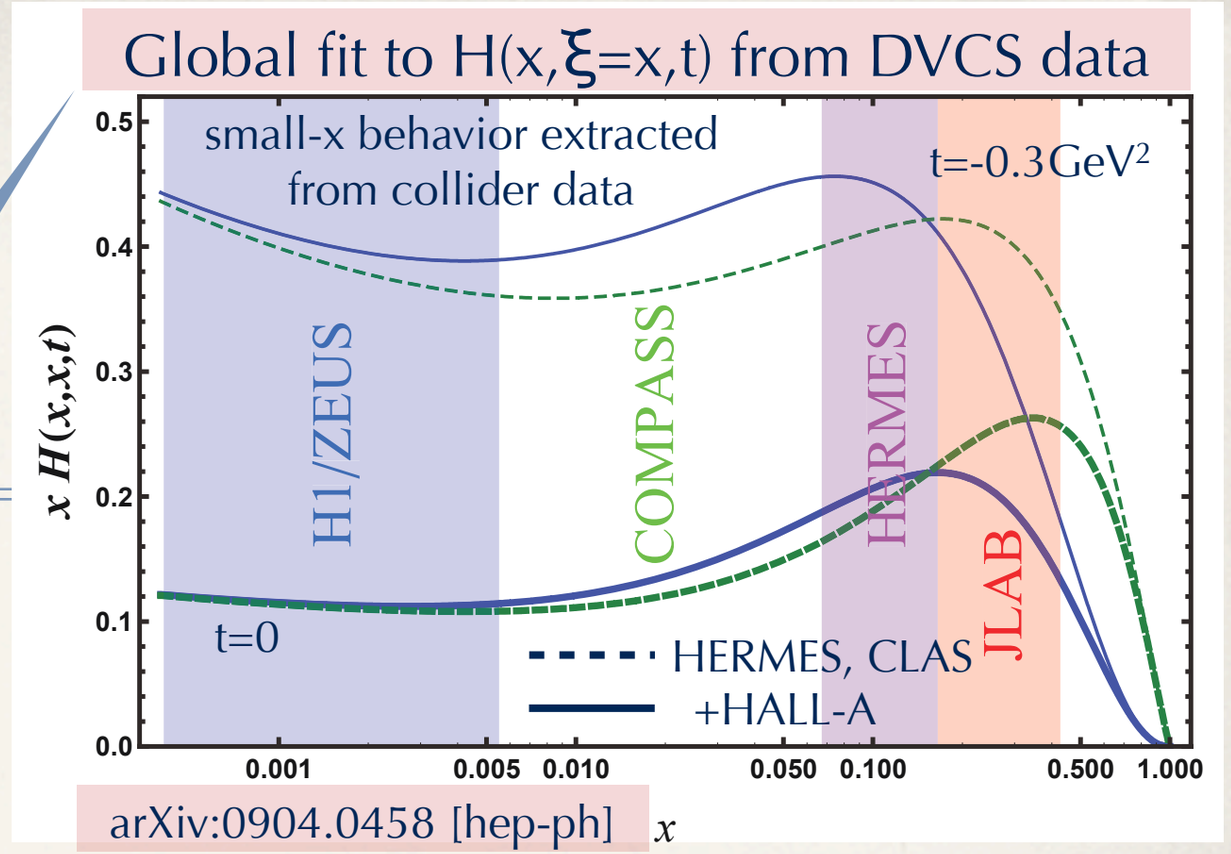
- **Exclusive ω A_{UT}**
  - u- and d-quarks in GPD E do not cancel:
    $A_{UT} \propto \mathcal{I}m\left[\mathbf{(2E^u-E^d)} \,/\, (2H^u-H^d)\right]$
    (≈-0.10 expected)
  - **HERMES: -0.22 ± 0.16 ± 0.11**

The Future

- Global GPD fits

See talk by D. Müller 11:55

- COMPASS 2012-15:
  large Recoil + polarized target
  'DVCS test runs' 08/09, small Recoil



See talk by N. d'Hose Friday afternoon

- JLab 12 GeV upgrade
  - Q^2_{max} = 13...14 GeV², e^+ beam

- Future Electron-Ion Collider ($\vec{e}\vec{p}$ and eA)
  - eRHIC @ BNL: $\sqrt{s}$ = 15-200 GeV (HERMES: 7 GeV),
    ENC @ GSI: $\sqrt{s}$ = 40 GeV, ...

See EIC workshop overview Friday afternoon

Summary: Hard Exclusive Reactions

- Wide spectrum of measurements of cross sections and azimuthal asymmetries
- Hard exclusive reactions as testing ground for QCD
  - Universal t slope
- Access to Generalized Parton Distributions
  - Different quantum numbers of final state select different GPDs
  - GPDs provide 3-dimensional picture of nucleons
  - GPDs allow (in principle) to constrain total angular momentum of quarks

Thanks to everybody who delivered input to this talk!!