The Generalised Parton Distributions - Experiment

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- Generalised Parton Distributions
- Selected results on DVCS
- Selected results on HEMP
- Perspectives for GPDs prior to next e-h colliders
- GPDs at EIC

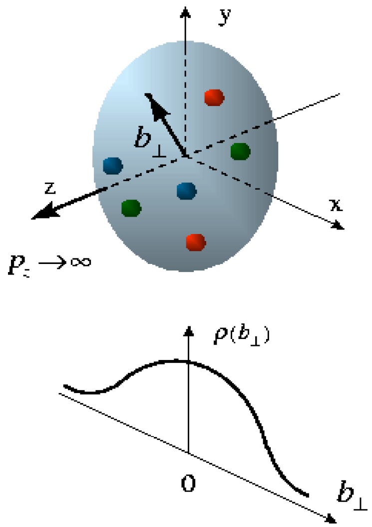
Structure of the Nucleon

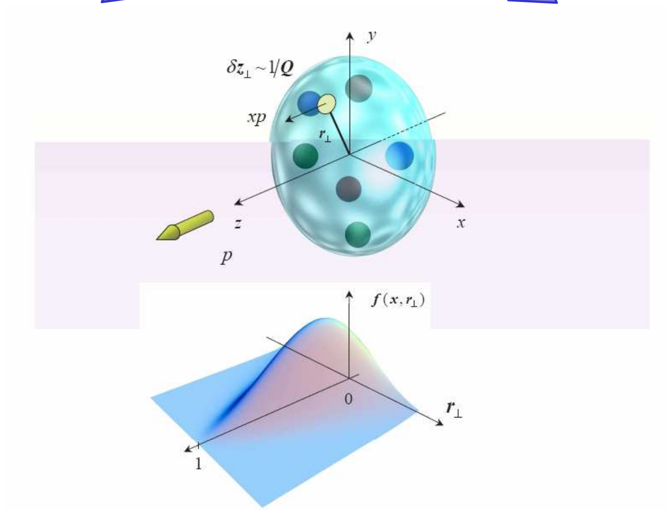
form factors

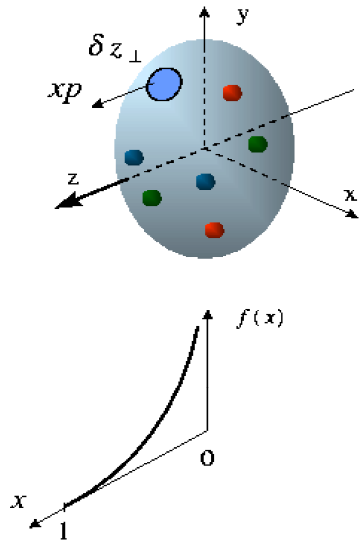
location of partons in nucleon

parton distributions

longitudinal momentum fraction x





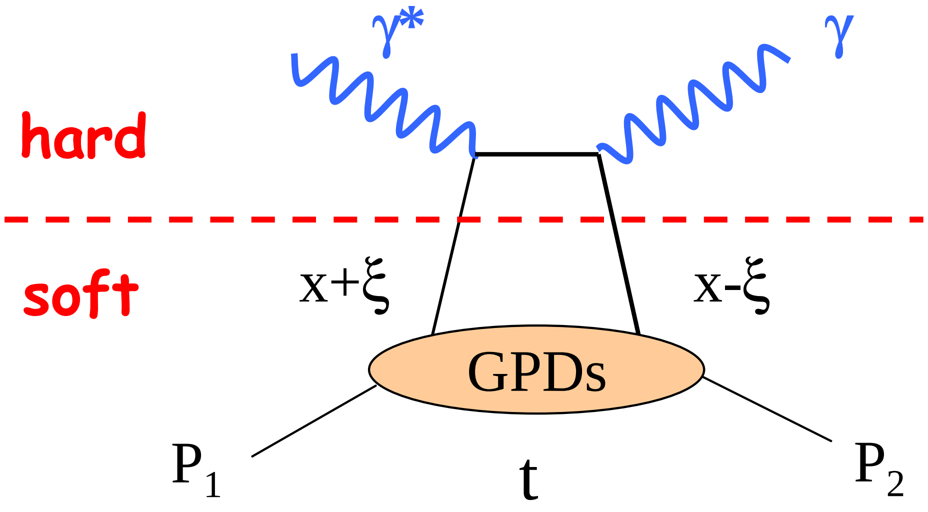


generalised parton distributions (GPDs)

transverse location $b_\perp$ and longitudinal momentum fraction x

embody 3D picture of hadrons

Generalized Parton Distributions and DVCS



Factorisation:

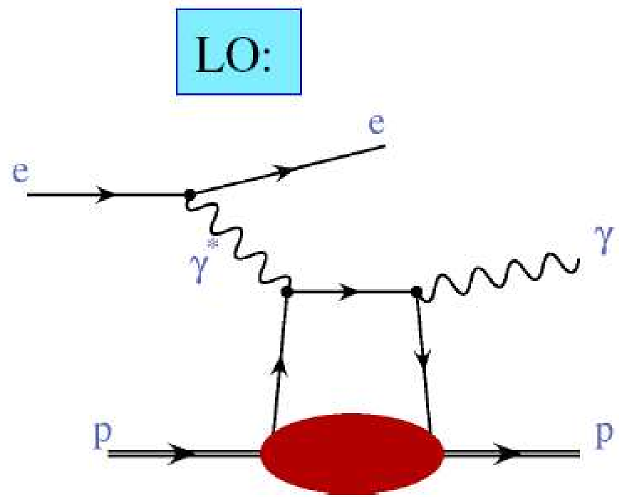
Q^2 large, $-t < 1$ GeV^2

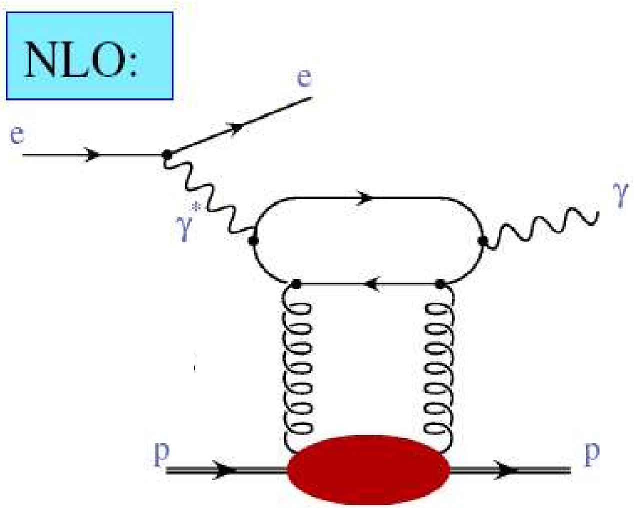
$$\xi = \frac{x_B}{2 - x_B}$$

4 Generalised Parton Distributions : $H, E, \tilde{H}, \tilde{E}$ depending on 3 variables: x, ξ, t

for each quark flavour and for gluons

for DVCS gluons contribute at higher orders in α_s



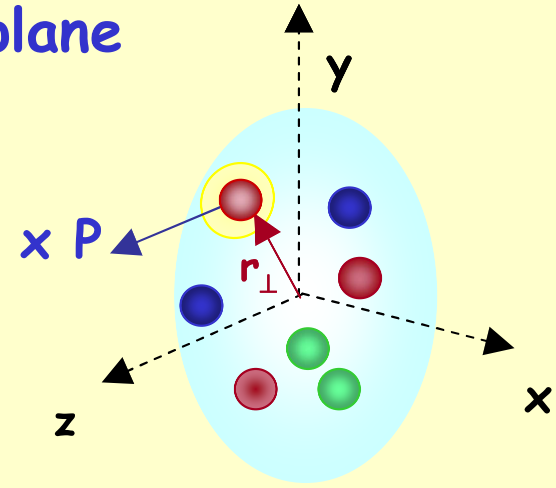


'Holy Grails' of the GPD quest

- GPD= a 3-dimensional picture of the partonic nucleon structure or spatial parton distribution in the transverse plane

$$H(x,\ \xi=0,\ t) \rightarrow H(x,\ r_{x,y})$$

probability interpretation
Burkardt

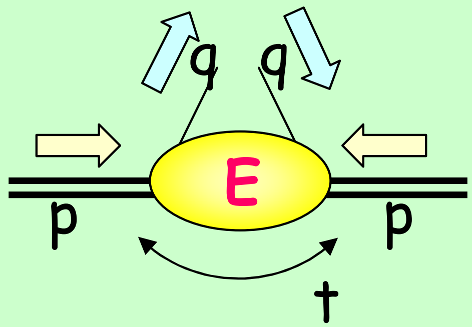


- Contribution to the nucleon spin puzzle

E related to the angular momentum

$$2J_q = \int x\,(H^q\,(x,\xi,0) + E^q\,(x,\xi,0))\,dx$$

$$\tfrac{1}{2} = \tfrac{1}{2}\,\Delta\Sigma + \Delta G + \langle L_z^q \rangle + \langle L_z^g \rangle$$



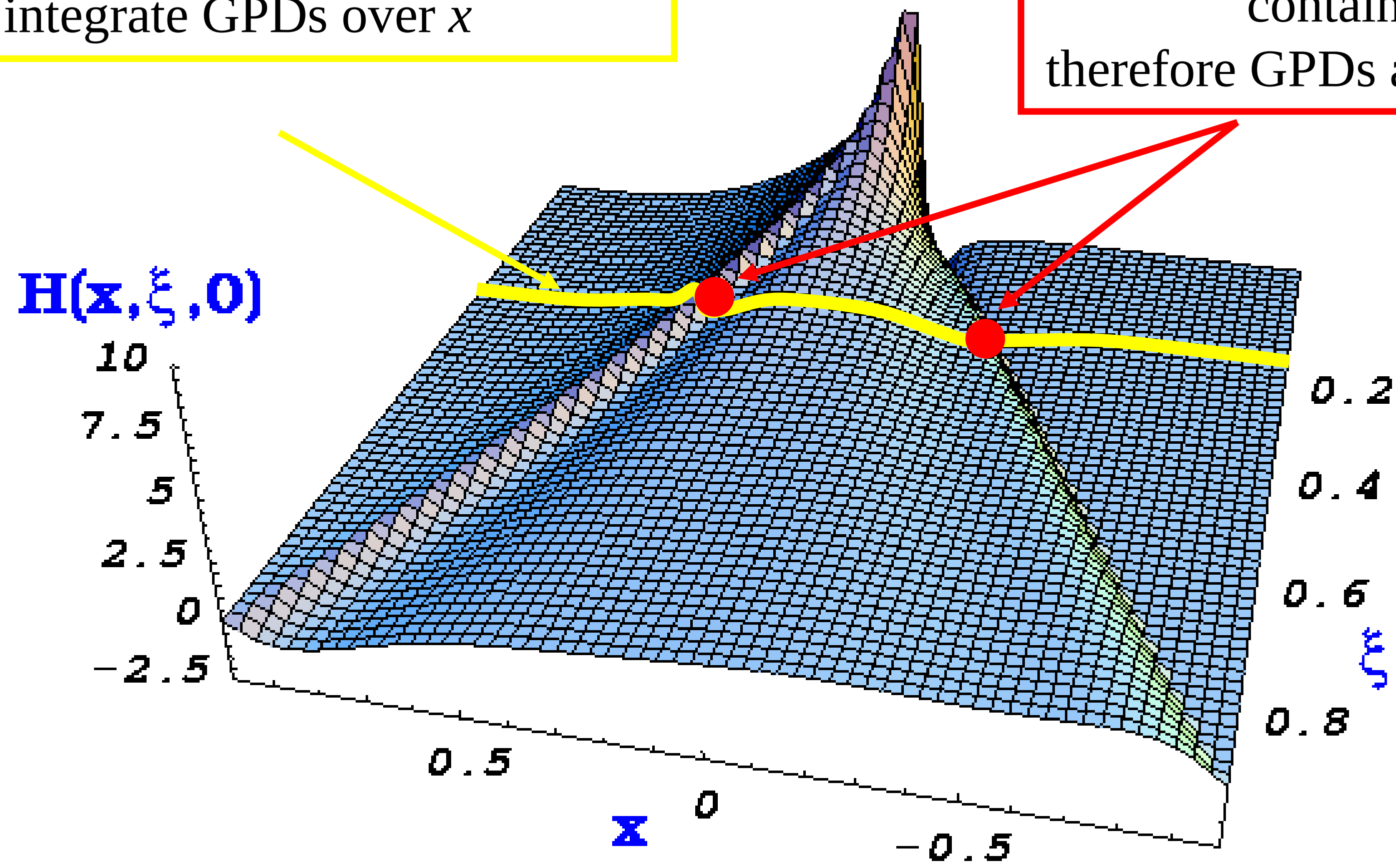
Observables and their relationship to GPDs

(at leading order:)

$$T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi + i\varepsilon} dx + \ldots \sim \quad P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi} dx - i\pi H(\pm\xi,\xi,t) + \ldots$$

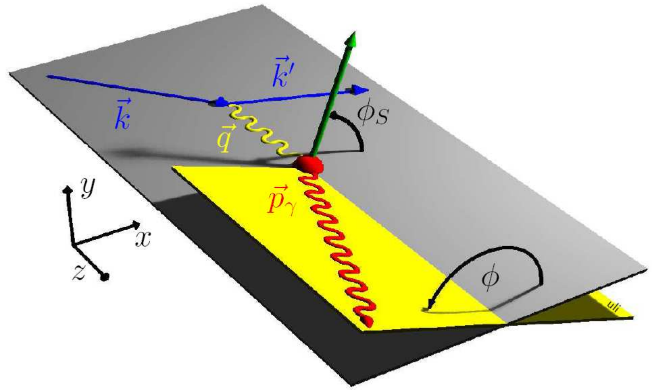
Beam charge asymmetry contain ReT, integrate GPDs over x

Beam or target spin asymmetry contain ImT, therefore GPDs at $x = \xi$ and $-\xi$



DVCS Asymmetries measured up to now

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



→ different charges: e^+ e^- *(only @HERA!)*:

$$\Delta\sigma_C \sim \cos\phi \cdot \mathrm{Re}\{\, \mathbf{H} + \cancel{\xi \tilde{\mathbf{H}}} + \ldots \} \Rightarrow H$$

→ polarization observables:

$$\Delta\sigma_{LU} \sim \sin\phi \cdot \mathrm{Im}\{\mathbf{H} + \cancel{\xi \tilde{\mathbf{H}}} + \cancel{k\mathbf{E}}\} \Rightarrow H$$

$$\Delta\sigma_{UL} \sim \sin\phi \cdot \mathrm{Im}\{\tilde{\mathbf{H}} + \cancel{\xi \mathbf{H}} + \ldots\} \Rightarrow \tilde{H}$$

$$\Delta\sigma_{UT} \sim \sin(\phi - \phi_s)\cos\phi \cdot \mathrm{Im}\{k(\mathbf{H} - \mathbf{E}) + \cancel{\ldots}\} \Rightarrow H, E$$

$\xi = x_B/(2-x_B)$, $k = t/4M^2$ **kinematically suppressed**

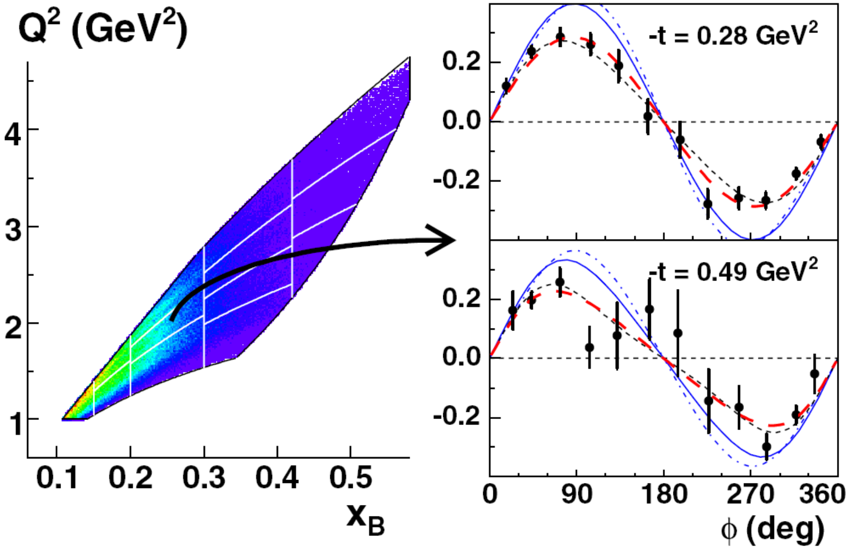
Highlight 1

DVCS – BSA from CLAS

[PRL 100, 162002 (2008)]

The most extensive set of DVCS data up to date

2 out of 65 bins in (Q^2, x, t)



BSA at leading twist $A = \dfrac{a \sin\phi}{1 + c\cos\phi + d\cos 2\phi}$

with $a \sim \mathrm{Im}\,\mathcal{H}$

fits of A (with d=0)

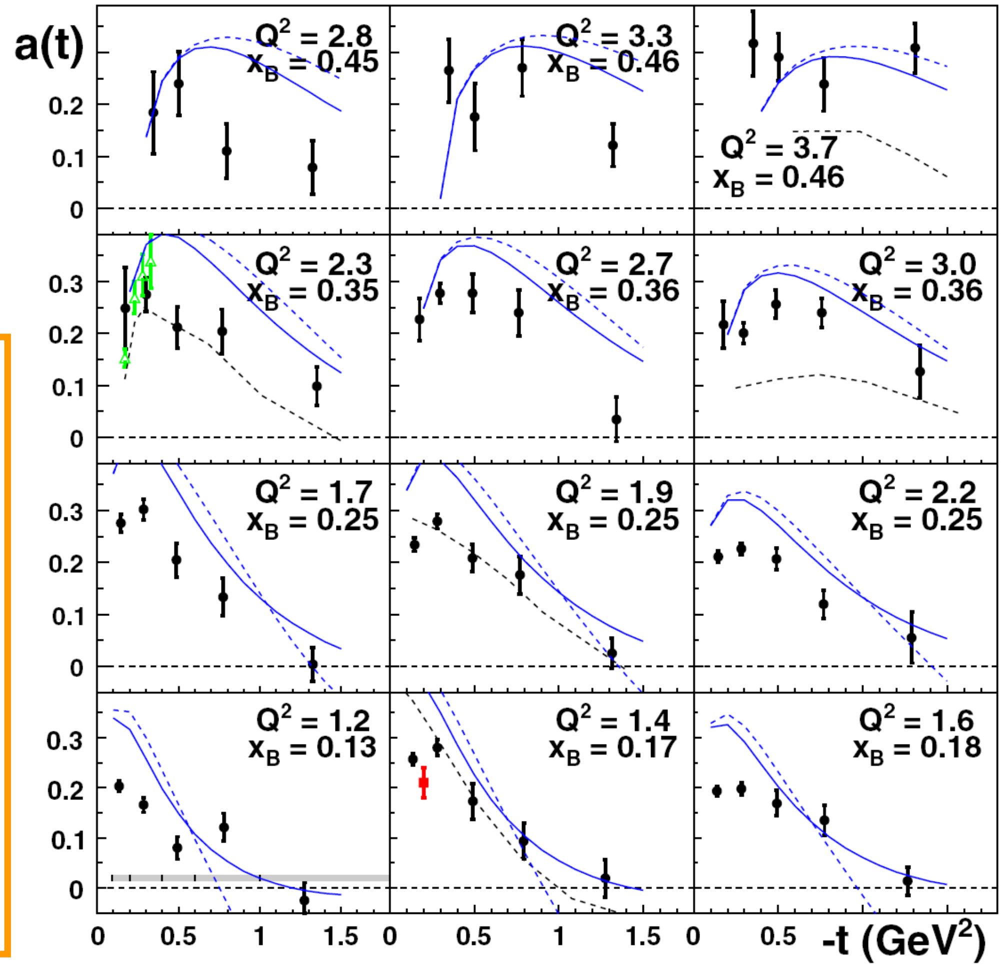
Regge calculation, Laget 2007

GPD model (twist2/twist2+3)

Guidal, Polyakov, Radyushkin, Vanderhaegen, 2005

BSA at leading twist

$Q^2 = 1.95$ GeV^2
$x_B = 0.25$



- Calculations based on **hadronic degrees of freedom**, within a Regge approach, are in fair agreement with data up to 2.3 GeV^2.
- **GPD** based calculation qualitatively reproduce the main features of the data. Data provide stringent constraints on GPD models
- The angular dependence of BSA asymmetries is compatible with expectations from leading-twist dominance

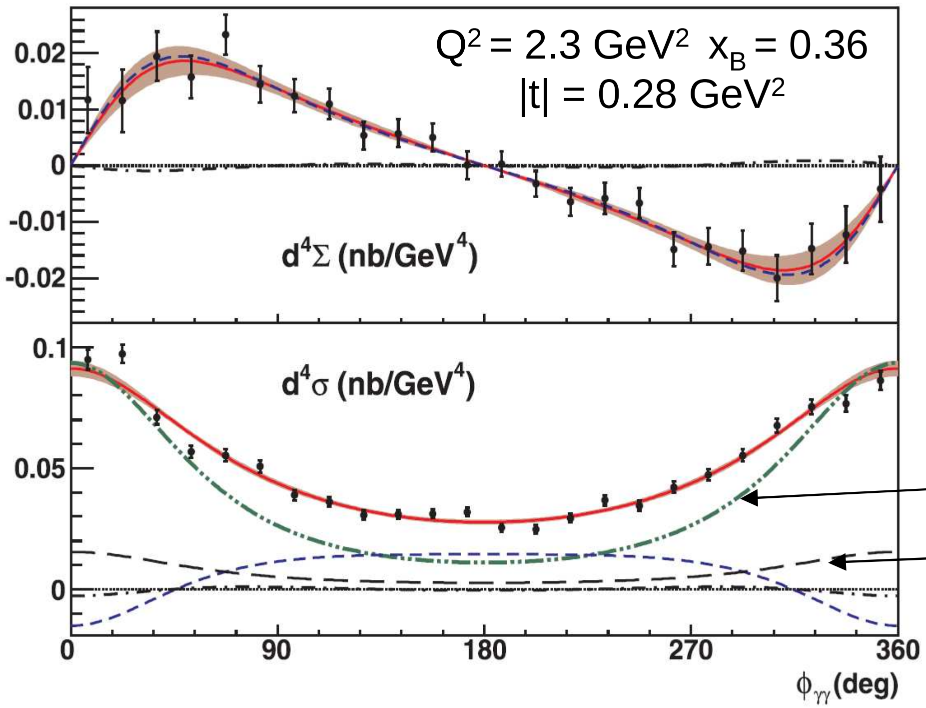
Highlight 2

Results from JLAB Hall A E00-100

[PRL97, 262002 (2006)]

Measured polarised and unpolarised cross sections

1 out of 12 bins in (Q^2, x, t)

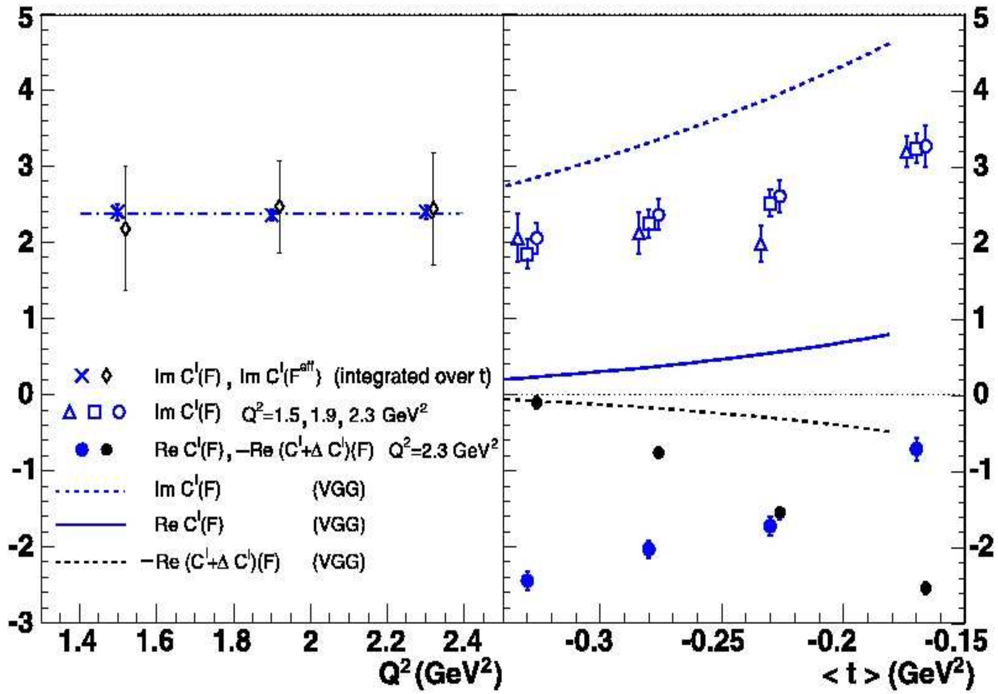


Complete up to twist-3 decomposition in terms of harmonics sin(nφ), cos(nφ) (n=0,1,2)

coefficients $C^I(F)$ and $[C^I+\Delta C^I](F)$ related to twist-2 CFF's (integral of GPD')s, and $C^I(F_{eff})$ to twist-3 CFF's

e.g. $$C^I(\mathcal{F}) = F_1(t)\,\mathcal{H} + \xi\left(F_1(t)+F_2(t)\right)\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2(t)\,\mathcal{E}$$

Fit
1 σ
Im C^I(F)
Re C^I(F)
Im $C^I(F_{eff})$
Re $C^I(F_{eff})$
BH
Re $[C^I + \Delta C^I]$(F)



- **Twist-two** contributions **dominate** the DVCS cross section and are **Q^2 independent** in the measured kinematic range.

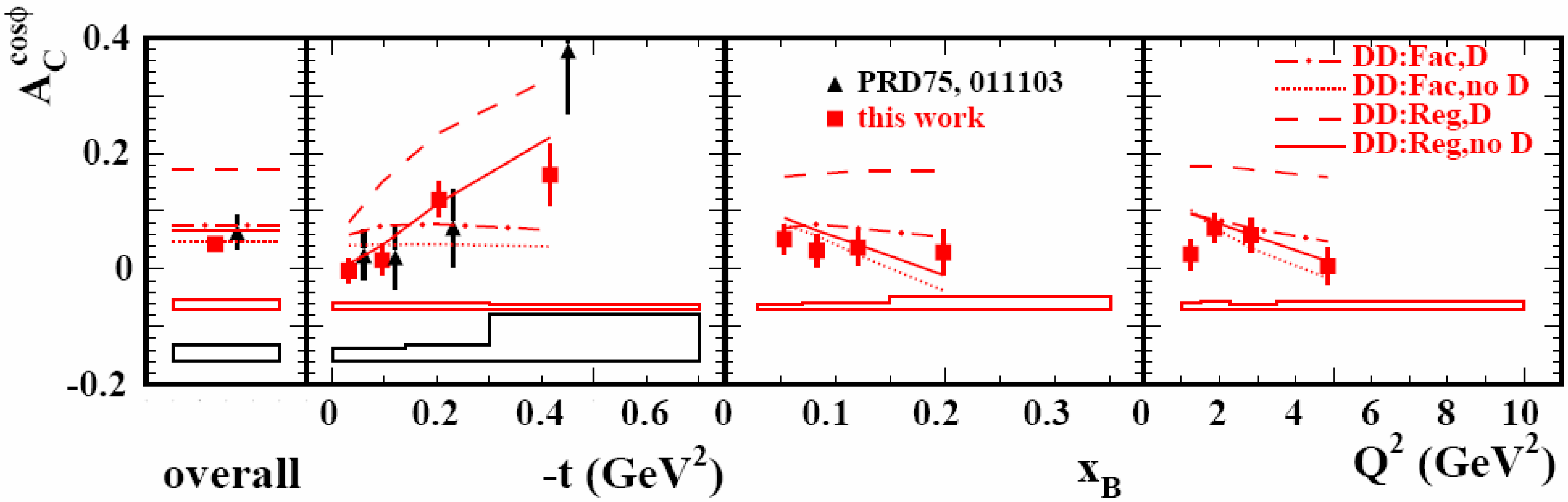
- **Twist-three** contributions to the cross section are **small** and are **Q^2 independent** within error bars.

Highlight 3

Combined analysis of BC and TTS asymmetries from HERMES transversly polarised p target

A_C: Beam Charge Asymmetry

$$A_c(\phi) = \frac{d\sigma(e^+,\phi) - d\sigma(e^-,\phi)}{d\sigma(e^+,\phi) + d\sigma(e^-,\phi)} \propto \mathrm{Re}[F_1\mathcal{H}] \cdot \cos\phi$$



- **DD** model for proton from M.Vanderhaeghen et al (PRD 60 (1999) 094017)
- data taking years 2002-2005 with transverse target

HERMES, JHEP 06 (2008) 066

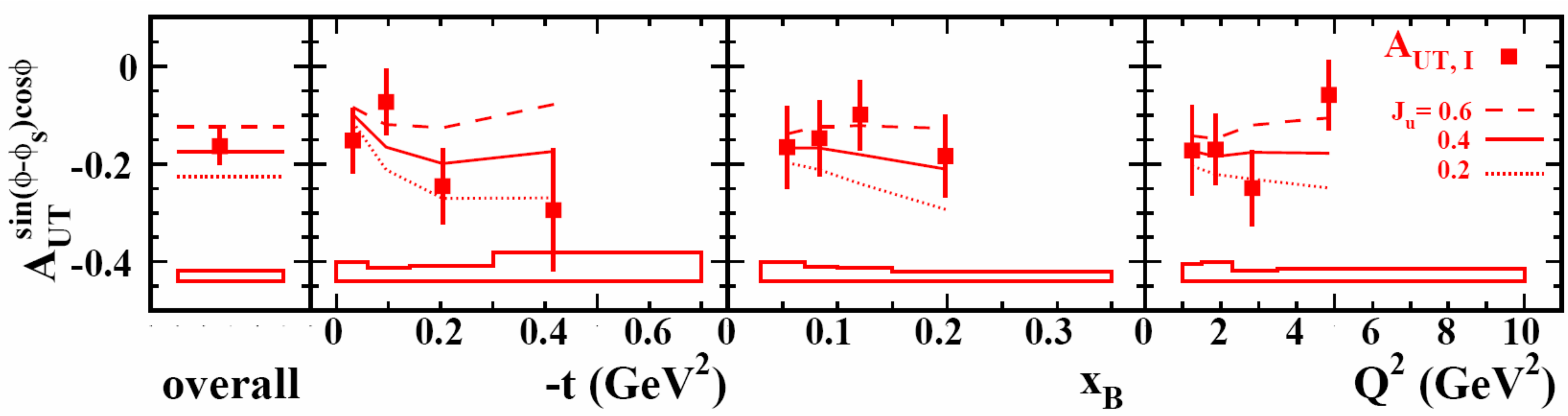
Regge model without D-term favoured by the t-dependence of the BCA

Transverse Target Spin Asymmetry A_{UT}

$$A_{UT}(\phi,\phi_S) = \frac{1}{P_T}\cdot\frac{d\sigma(P^{\Uparrow},\phi,\phi_S)-d\sigma(P^{\Downarrow},\phi,\phi_S)}{d\sigma(P^{\Uparrow},\phi,\phi_S)+d\sigma(P^{\Downarrow},\phi,\phi_S)}$$

$$\propto \mathrm{Im}[F_2\mathcal{H}-F_1\mathcal{E}]\sin(\phi-\phi_S)\cos\phi+\mathrm{Im}[F_2\mathcal{H}-F_1\mathcal{E}]\sin(\phi-\phi_S)$$

$$+ \mathrm{Im}[\mathcal{H}\mathcal{E}^*-\mathcal{E}\mathcal{H}^*+\xi\widetilde{\mathcal{E}}\widetilde{\mathcal{H}}^*-\widetilde{\mathcal{H}}\xi\widetilde{\mathcal{E}}^*]\sin(\phi-\phi_S)+\ldots$$



$A_{UT}^{\sin(\phi-\phi_S)\cos\phi}$

for proton sensitive to J_u (not to J_d) => allows model dependent constraints

Highlight 4

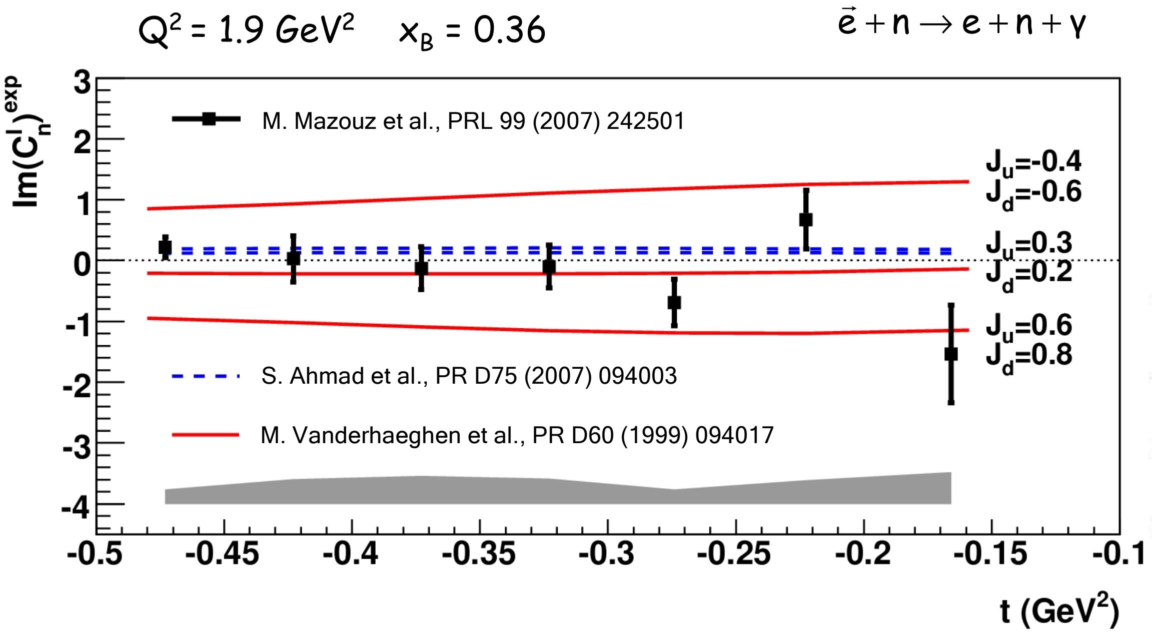
e n → e n γ

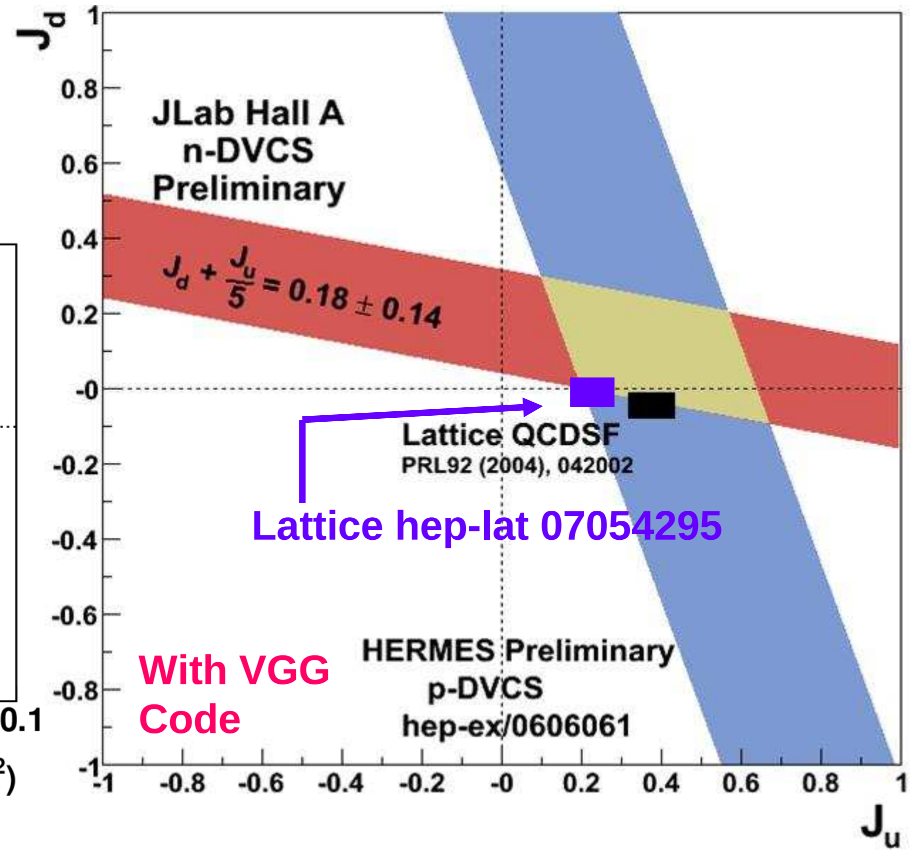
$$C_n^I(\mathcal{F}) = F_1(t)\,\mathcal{H} + \xi\big(F_1(t)+F_2(t)\big)\,\tilde{\mathcal{H}} - \boxed{\frac{t}{4M^2}F_2(t)\,\mathcal{E}}$$

0 because $F_1(t)$ is small

0 because of cancelation of u and d quarks

n-DVCS gives access to the least known and constrained GPD, E



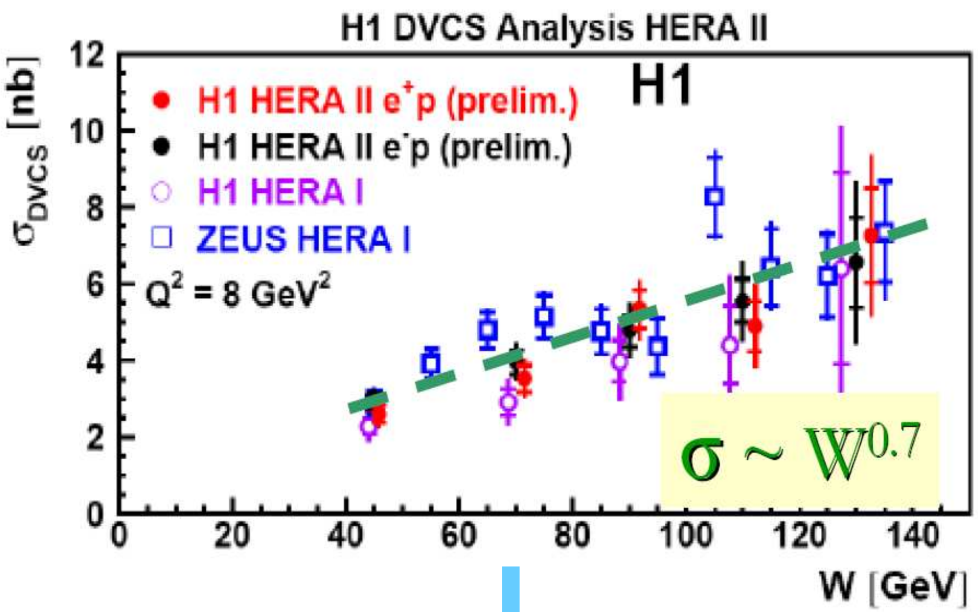


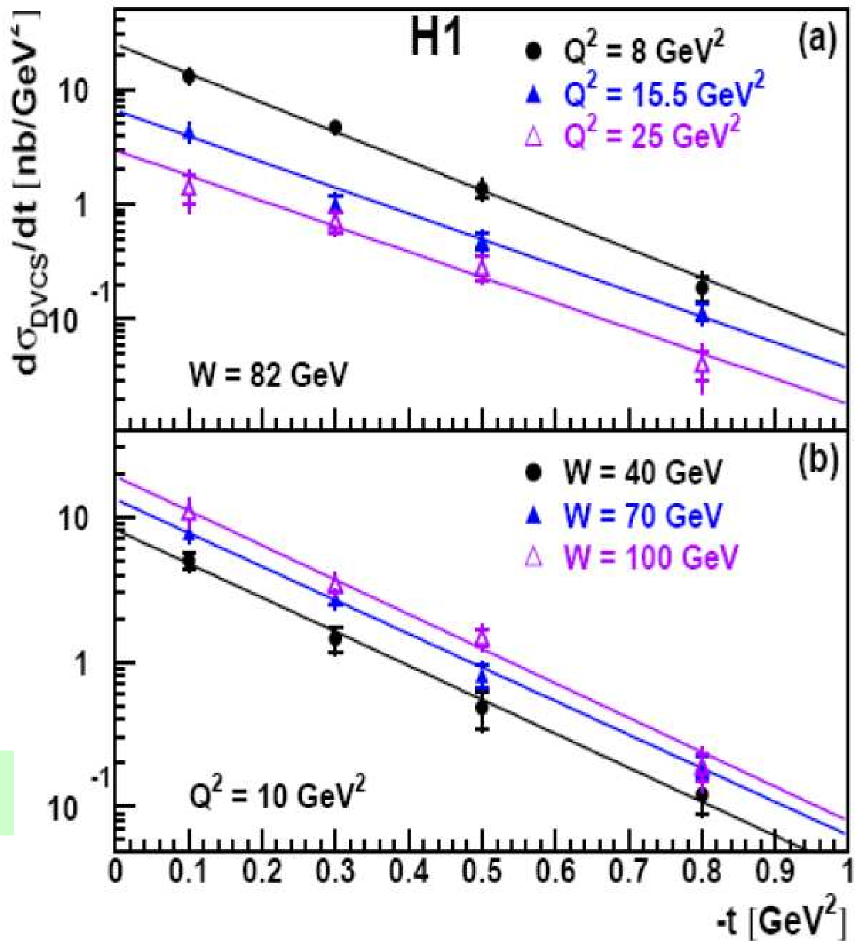
The GPDs at small x

unpolarised cross section σ_{DVCS} on protons averaged over φ H1 and ZEUS

at small x_B (< 0.01) $\sigma_{DVCS}^{unp} \propto 4(\mathcal{H}\mathcal{H}^* + \tilde{\mathcal{H}}\tilde{\mathcal{H}}^*) - 2\frac{t}{4M^2}\mathcal{E}\mathcal{E}^*$ $\rightarrow$ $\boxed{H^{sea}, H^{g}}$

GPDs H related to the 3D picture of the unpolarised proton





DVCS at HERA is a hard process

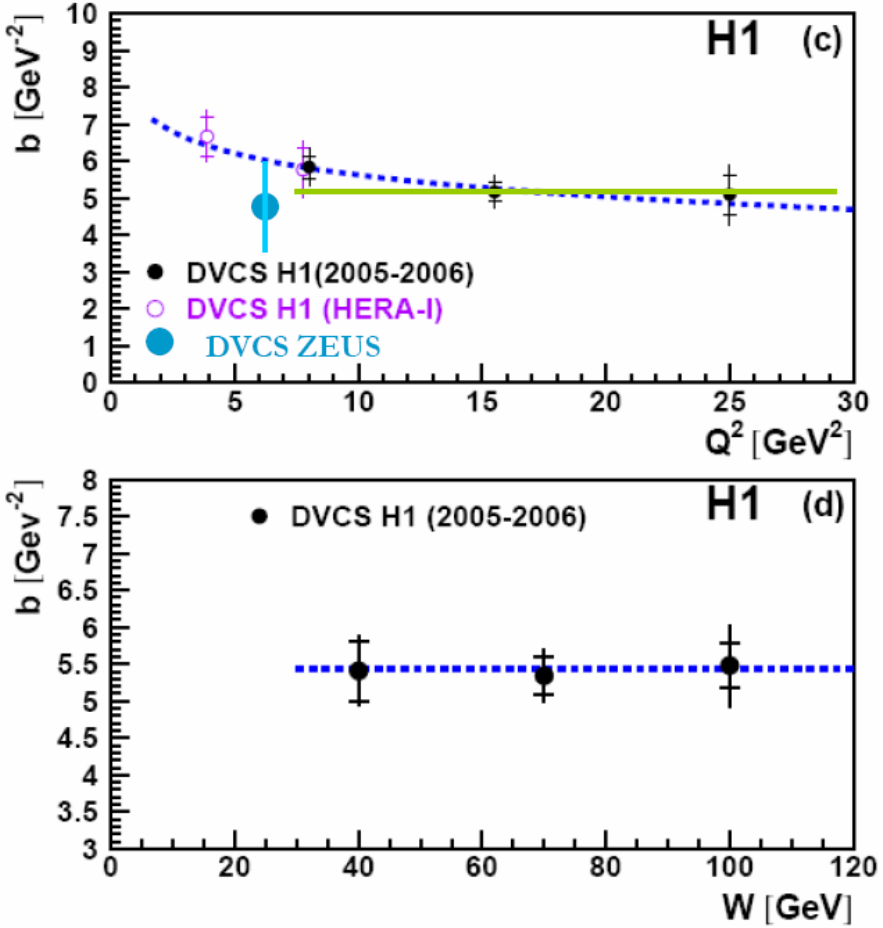
$d\sigma/dt \sim \exp(-b|t|)$: **$b = 5.45 \pm 0.19 \pm 0.34$ GeV^{-2}**

@ $x=10^{-3}$ & $Q^2=10$ GeV^2

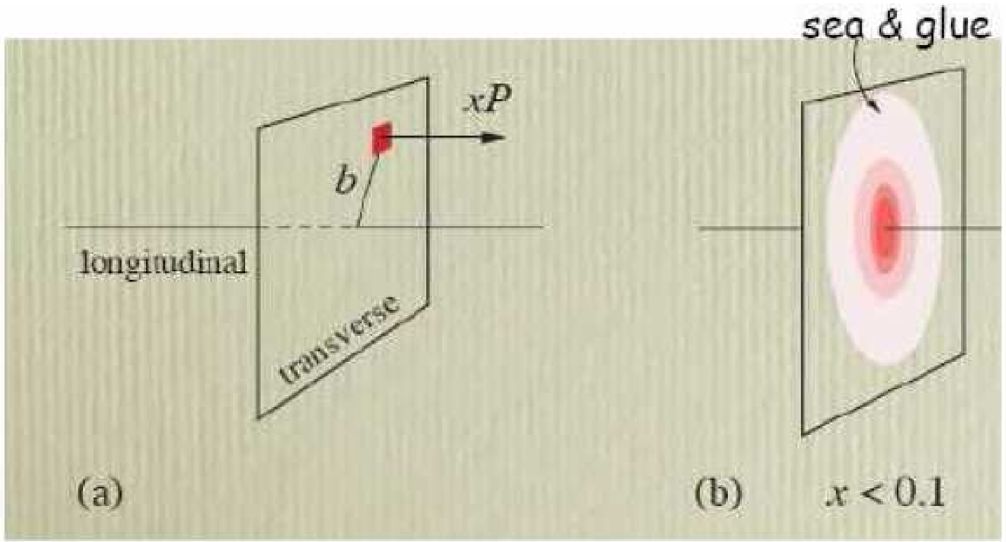
t-distributions for DVCS at HERA

Measurement of dσ/dt [DVCS] => spatial distribution of sea and gluons

$$q(x,\mathbf{r}_\perp,Q^2) = \int \frac{d^2\Delta_\perp}{(2\pi)^2}\, e^{-i\mathbf{r}_\perp\cdot\Delta_\perp}\, GPD_q(x,Q^2,t=-\Delta_\perp^2)$$



$$\langle r_T^2 \rangle = 4\, d/dt[GPD(x,t)] / GPD(x,0)$$
$$= 2\, d/dt[\sigma(t)] / \sigma(t=0)$$



$$\boxed{[\langle r_T^2 \rangle]^{1/2} = 0.65 \pm 0.02 \text{ fm}}$$

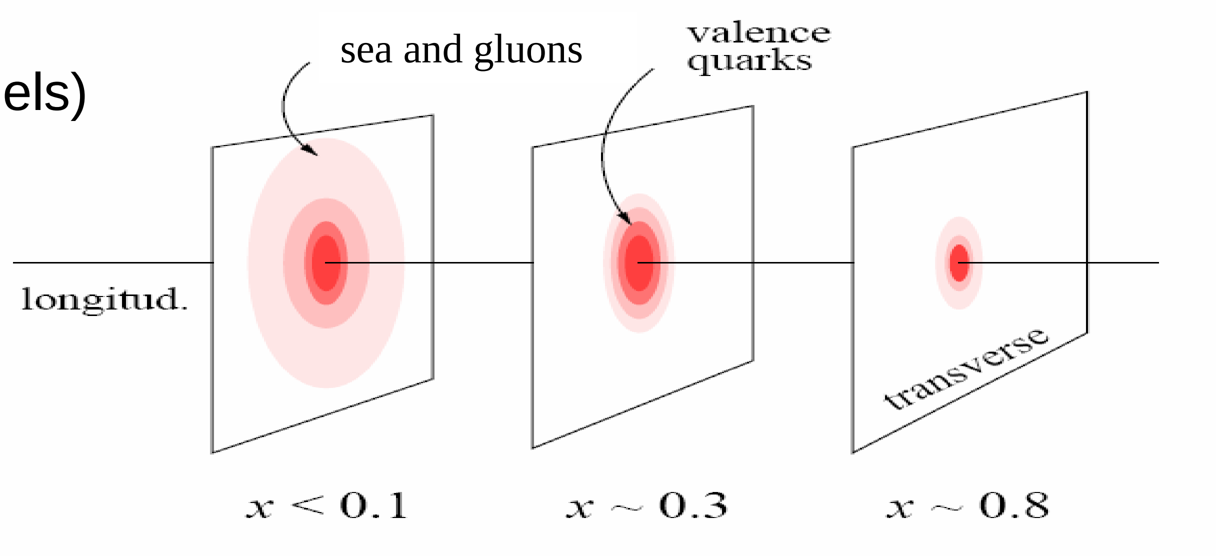
@ $x=10^{-3}$ & $Q^2=10$ GeV^2

- higher twist effects @ small Q^2
- scaling in Q^2 at large Q^2
- no W-dependence for singlet part at low x

Probing x-t correlation

Expected (QCD Lattice and models)
x-t correlation

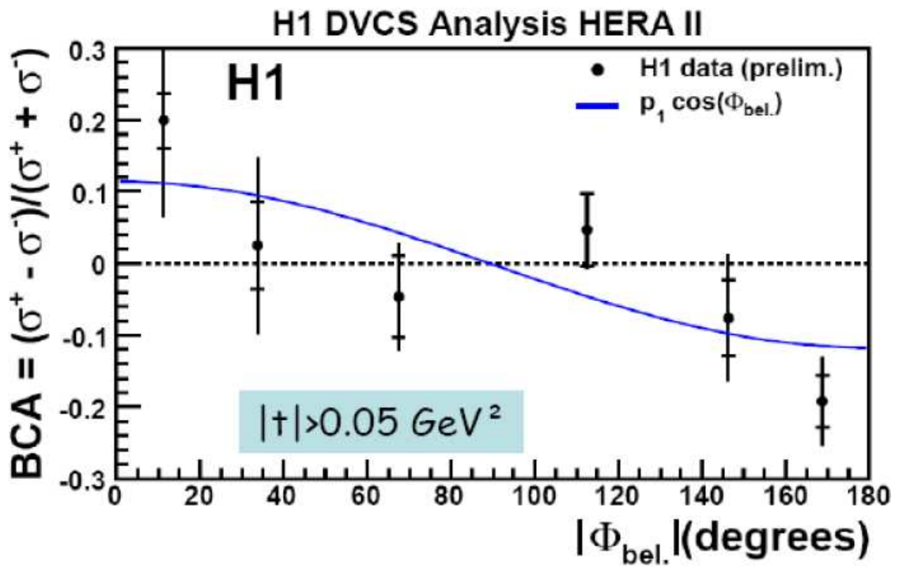
Fast partons ⇔ core => small r_T
Slow partons ⇔ perifery



Promissing observable: Beam Charge Asymmetry

BCA ~ Re A_{DVCS} ~ integral of GPDs over whole range of x

➡ sensitivity to x-t correlations cf. HERMES results



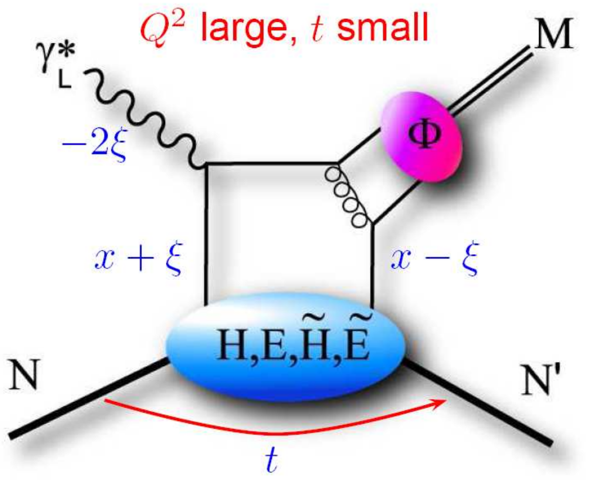
preliminary H1 result

$(0.17 \pm 0.06) \cos \varphi$

@ x=0.005 & Q^2 = 10 GeV^2

Non factorisable x vs.t GPD models favoured

GPDs and Hard Exclusive Meson Production



- 4 Generalised Parton Distributions (GPDs)
  for each quark flavour and for gluons
- factorisation proven only for σ_L
  σ_T suppressed of by $1/Q^2$
  necessary to extract longitudinal contribution to observables (σ_L , …)
- allows separation $(H,E) \leftrightarrow (\tilde{H},\tilde{E})$ and wrt quark flavours

$\left.\begin{matrix} H \\ \tilde{H} \end{matrix}\right\}$ $\left.\begin{matrix} E \\ \tilde{E} \end{matrix}\right\}$ Vector mesons (ρ, ω, φ)
Pseudoscalar mesons (π, η)

conserve flip nucleon helicity

Flavour sensitivity of HEMP on the proton

π^0	$2\Delta u+\Delta d$
η	$2\Delta u-\Delta d$
ρ^0	2u+d, 9g/4
ω	2u–d, 3g/4
ϕ	s, g
ρ^+	u–d
J/ψ	g

- quarks and gluons enter at the same order of α_s
- at $Q^2 \approx$ few GeV² power corrections/higher order pQCD terms are essential
- wave function of meson (DA Φ)
  additional input

Highlight 6

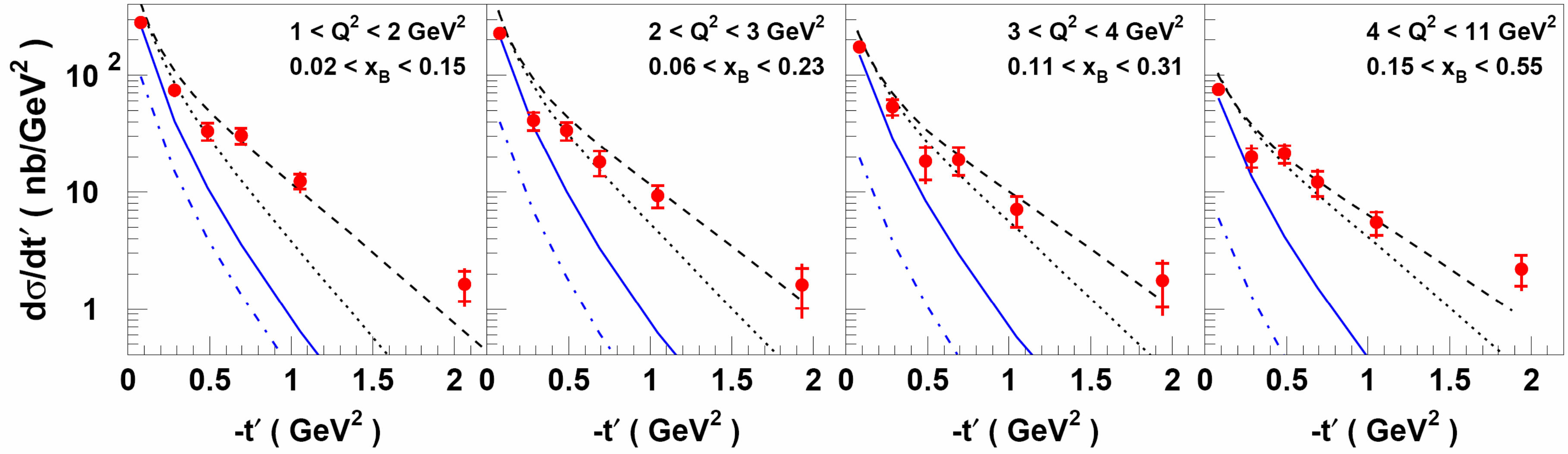
Exclusive π^+ production from HERMES

$e\,p \rightarrow e\,n\,\pi^+$

- L/T separation at HERMES not possible
- σ_T expected to be supressed as $1/Q^2$

  dominance of σ_L at large Q^2 supported by Regge model (Laget 2005)
- at leading twist σ_L sensitive to GPDs $\tilde{H}$ and $\tilde{E}$
- at small $|t'|$ $\tilde{E}$ dominates as it contains t-channel pion-pole

[PLB659(2008)]



σ_L VGG LO

σ_L VGG LO+power corrections

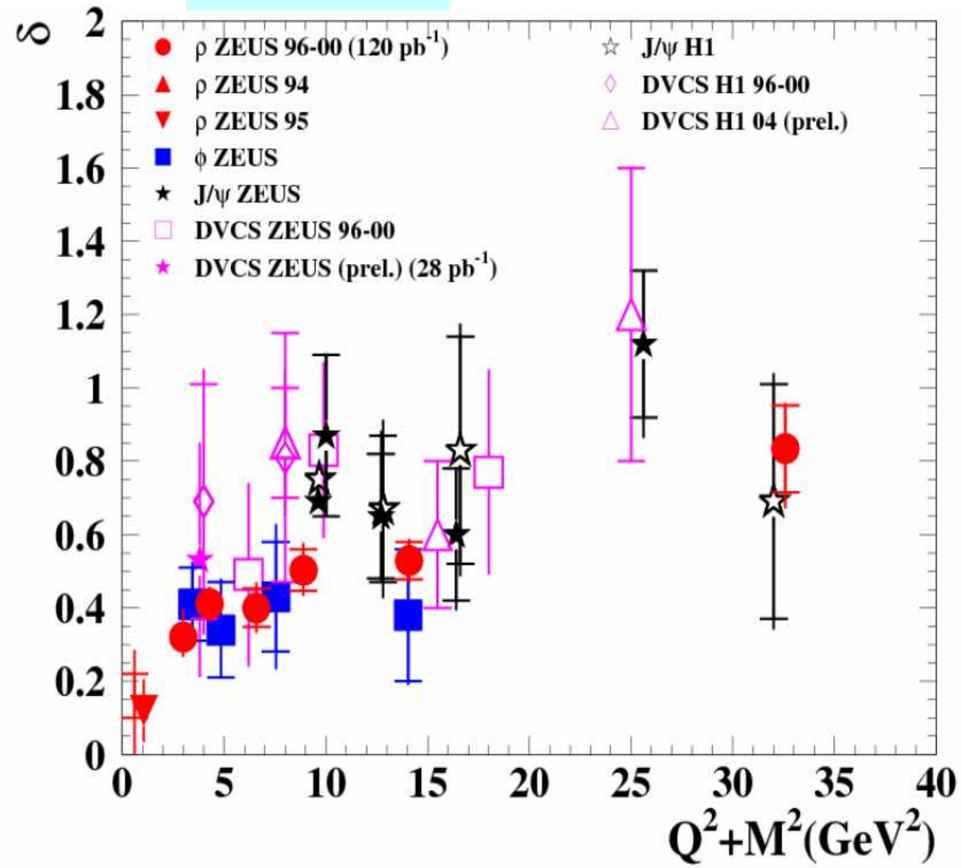
σ_L Regge model (Laget)

$\sigma_T + \varepsilon\,\sigma_L$ Regge model (Laget)

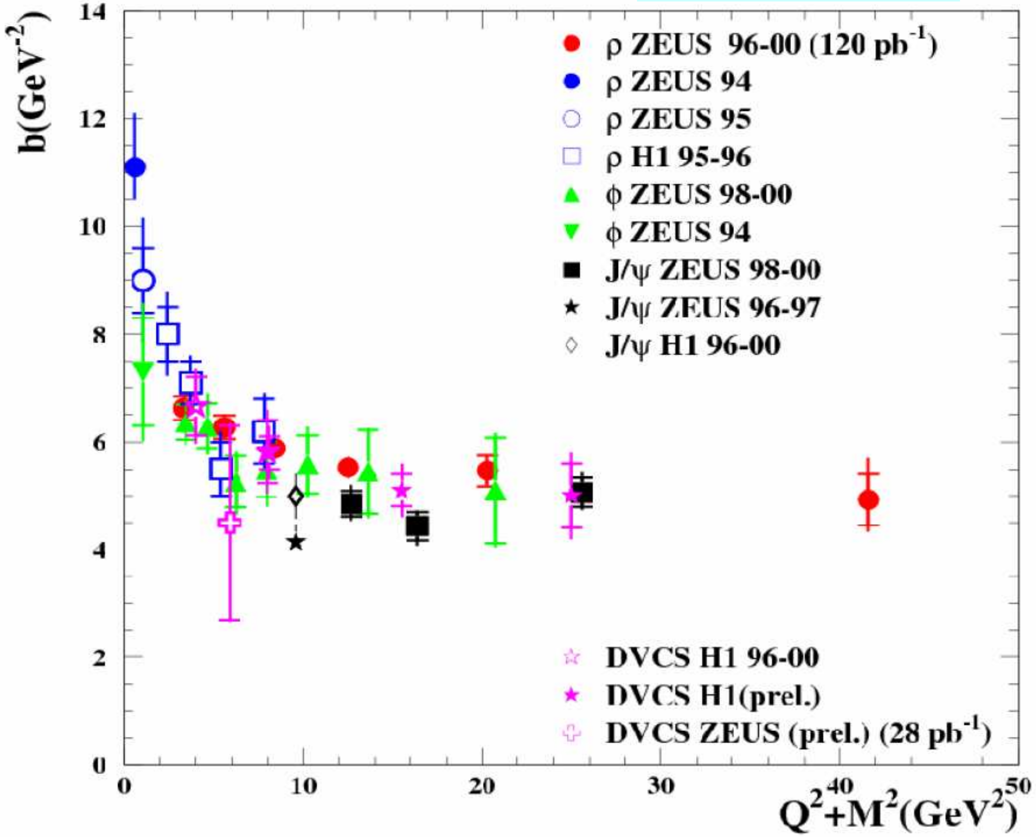
- LO calculations underestimate the data
- data support magnitude of the power corrections (k_t and soft overlap)
- Regge calculations provides good description of the magnitude of σ_{tot} and of t' and Q^2 dependences

Diffractive channels at small x

$\sigma \propto W^{\delta}$



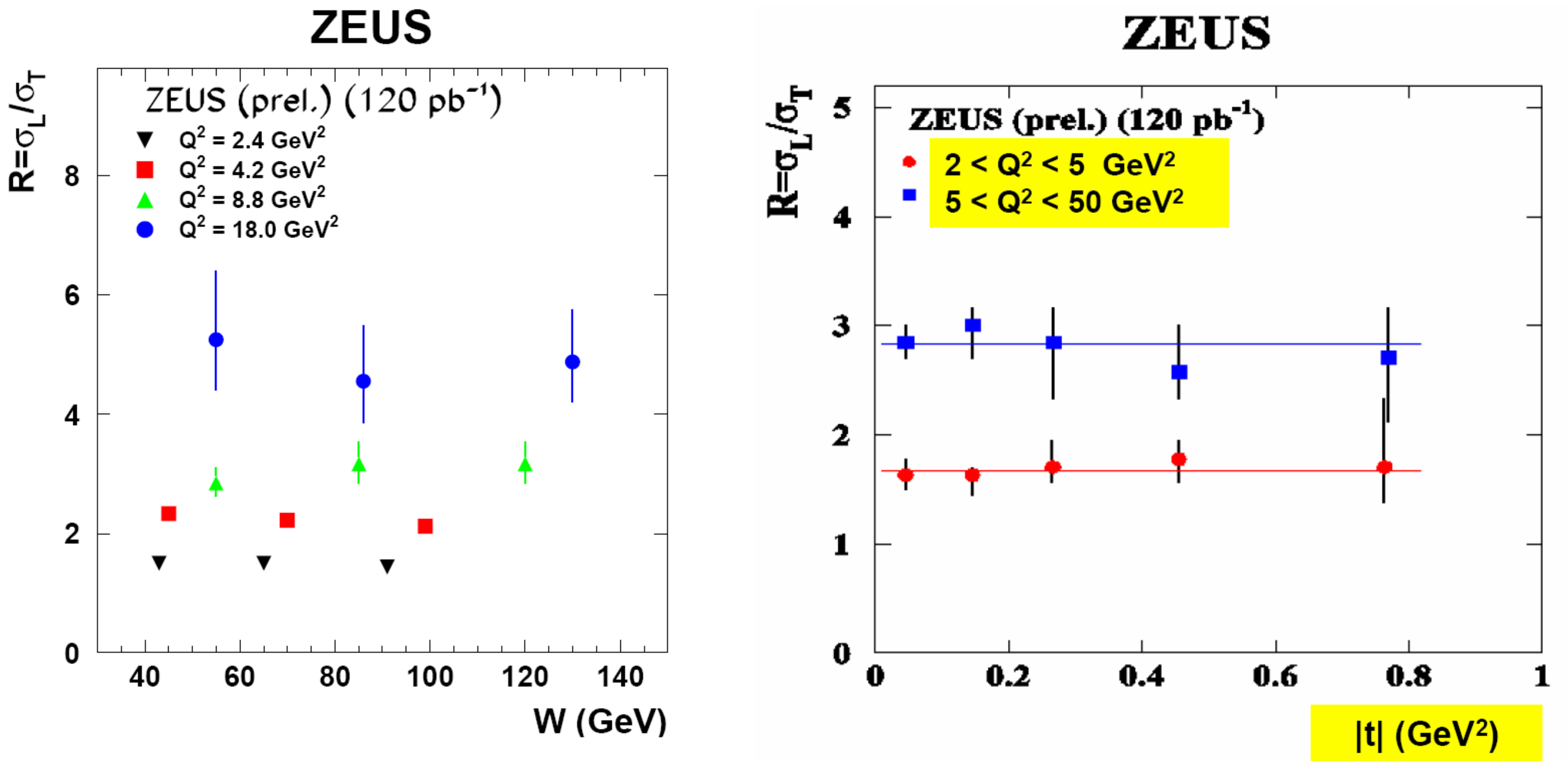
$d\sigma / dt \propto e^{-b|t|}$



- steep energy dependence in presence of hard scale Q^2 and/or M^2
- b-slopes decrease with increasing scale approaching a limit ≈ 5 GeV^{-2} at large scales
- approximate 'universality' of energy dependence and b-slopes at small *x*

Highlight 7

Results on $R = \sigma_L/\sigma_T$ for ρ^0 production



the same W- and t-dependence for σ_L and σ_T

$\delta_L \approx \delta_T$ $\qquad$ $b_L \approx b_T$

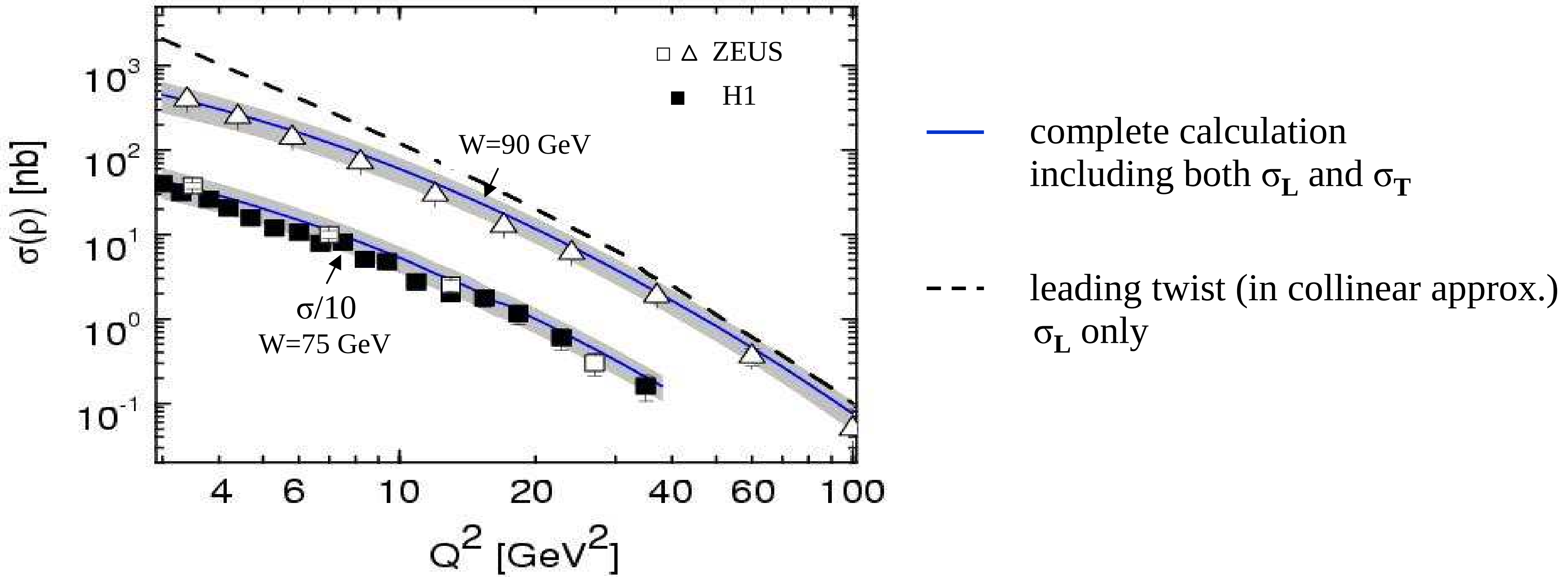
the same size of the longitudinal and transverse γ^* involved in hard ρ^0 production

i.e. contribution of large qqbar fluctuations of transverse γ^* suppressed

Comparison to a GPD model

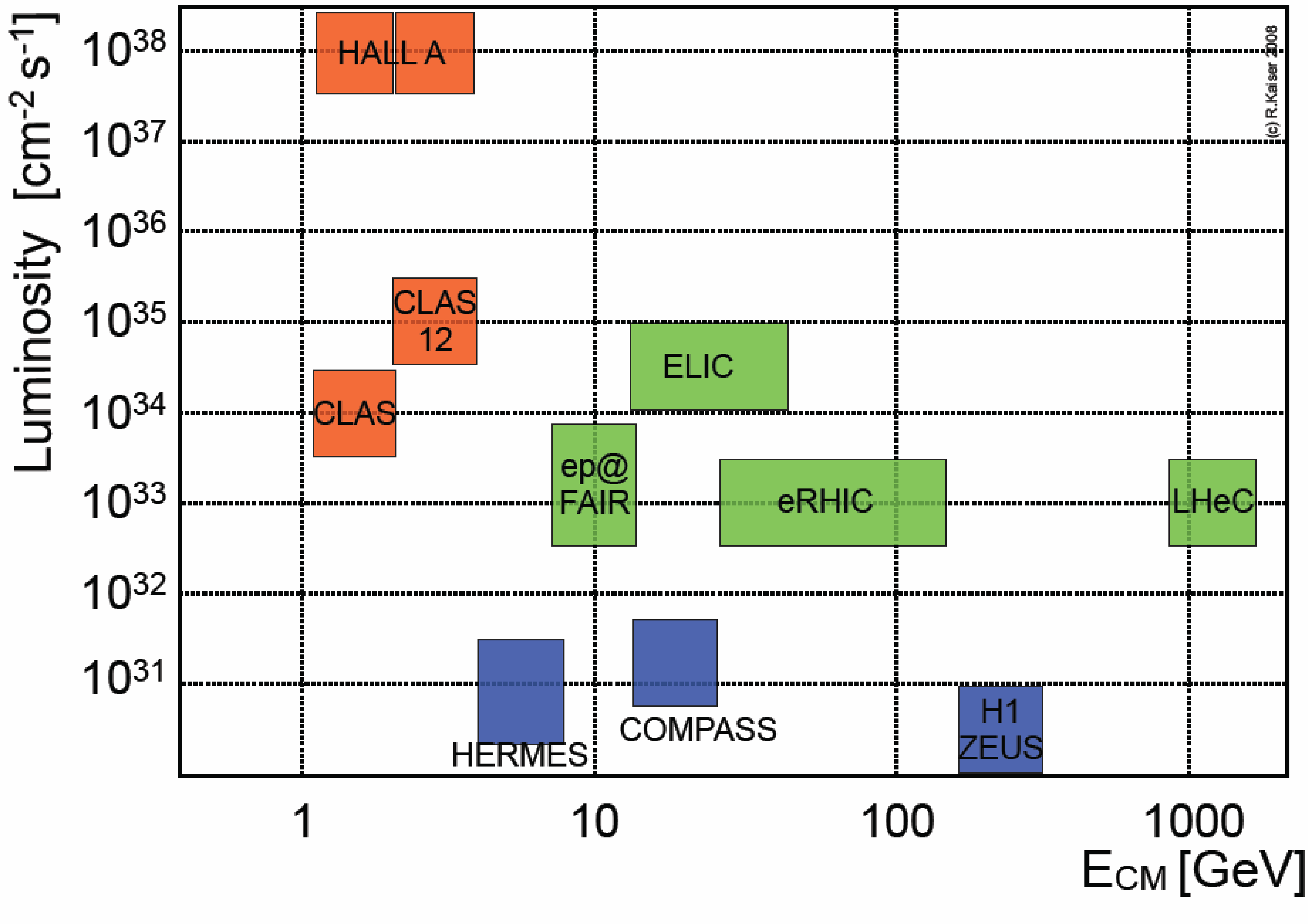
- Goloskokov-Kroll
  [EPJ C53 (2008) 367]

'Hand-bag model'; GPDs from DD using CTEQ6
power corrections due to k_t of quarks included
both contributions of γ^*_L and γ^*_T calculable



- leading twist prediction above full calculation, even at Q^2 = 100 GeV^2
  ≈ 20%
- contribution of σ_T decreases with Q^2, but does not vanish even at Q^2 = 100 GeV^2
  ≈ 10%
- sea quark contribution, including interference with gluons, non-negligible
  25% at Q^2 = 4 GeV^2

Present and future of GPD experiments

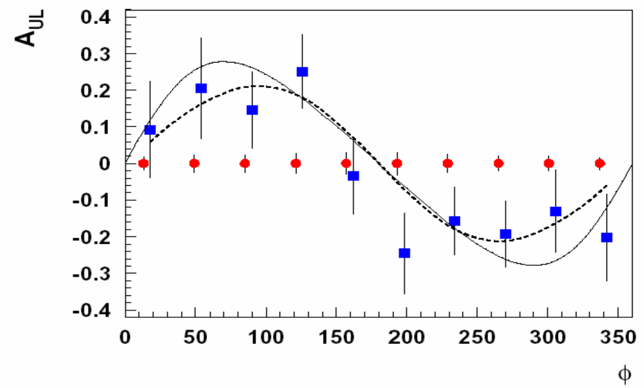


Perspectives for GPDs @ JLAB

- DVCS with longitudinally polarized target $\vec{p}(\vec{e},e'p\gamma)$

  Target spin asymmetry

  Double target-beam spin asymmetry

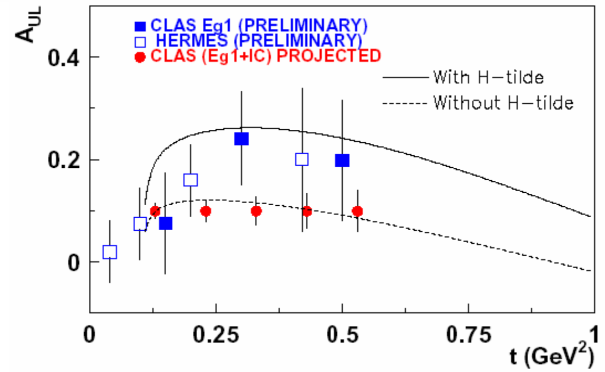


- DVCS with unpolarized target $p(\vec{e},e'p\gamma)$

  Doubling present statistics (CLAS)

  @ Various beam energies

  --> separation of DVCS² and BH DVCS (Hall A)



proton x=0.25,Q^2=2.0

- DVCS on a neutron target $n(\vec{e},e'\gamma)n$

  Sensitivity to E GPD

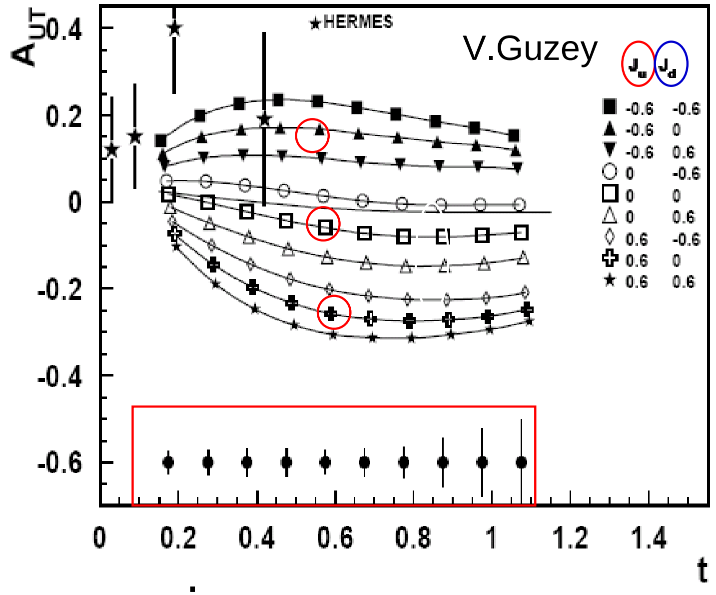
- Meson production (π^0, η, ω, ρ...)

- Double DVCS $ep \to ep\gamma^* \to ep\mu^+\mu^-$

- DVCS on a transversaly polarised proton target

  High sensitivity to J_u

  Relies on success of R&D of HDice target



- Development of neutron detection capabilities in the central detector (Hall B)

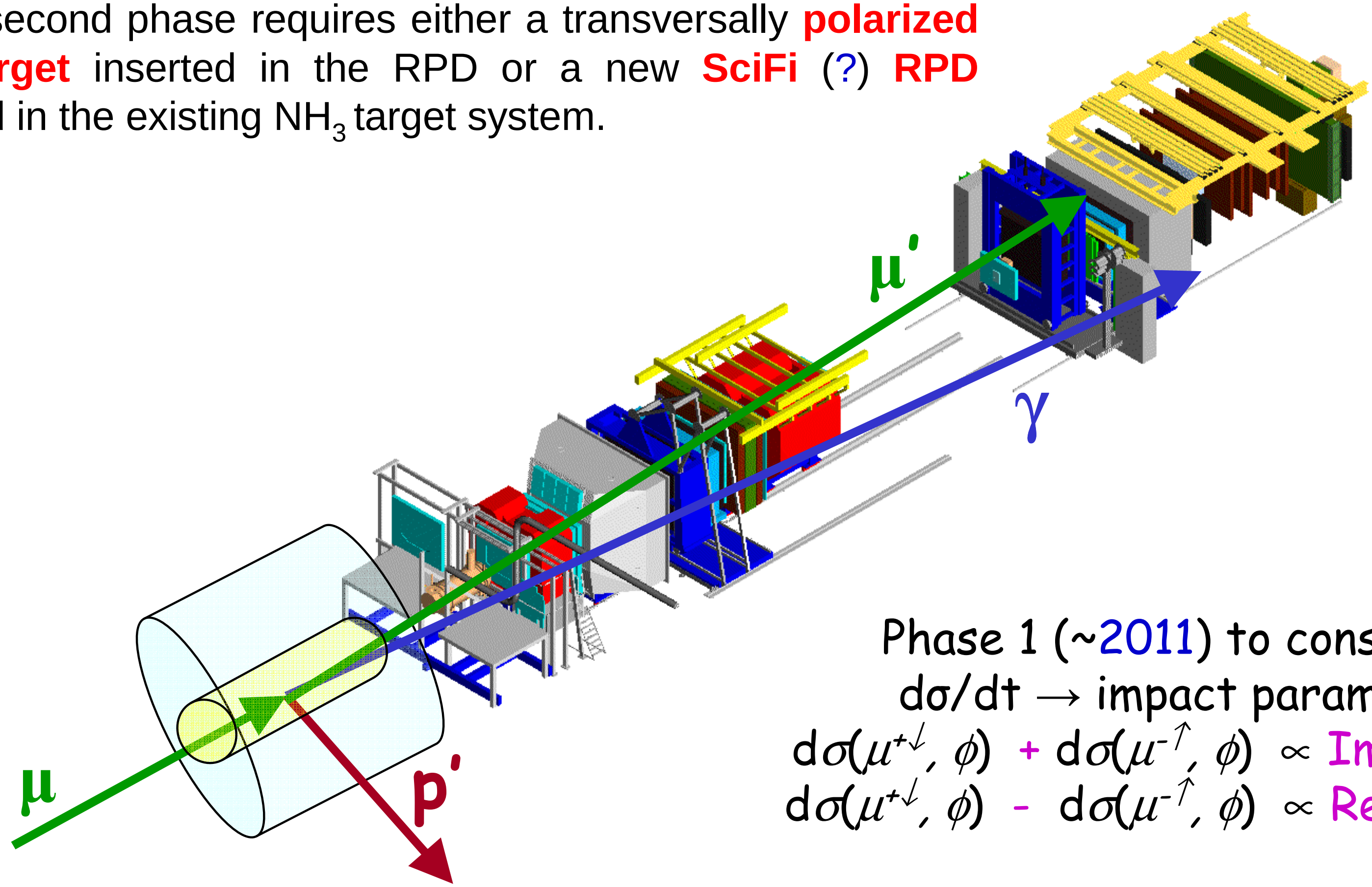
  and polarized neutron targets sustaining high beam currents (Hall A)

GPDs @ COMPASS

- The GPDs program is part of the **COMPASS Phase II** (2010-2015) proposal to be submitted to CERN in 2009.

- The first phase of this program requires a 4 m long recoil proton detector (**RPD**) together with a 2.5 m long **LH_2 target**. An additional electromagnetic calorimeter will enlarge the kinematical coverage at large x_B.

- The second phase requires either a transversally **polarized NH_3 target** inserted in the RPD or a new **SciFi** (?) **RPD** inserted in the existing NH_3 target system.



Phase 1 (~2011) to constrain **H**

$d\sigma/dt \rightarrow$ impact parameter b

$$d\sigma(\mu^{+\downarrow}, \phi) + d\sigma(\mu^{-\uparrow}, \phi) \propto \mathrm{Im}(F_1 H) \sin\phi$$

$$d\sigma(\mu^{+\downarrow}, \phi) - d\sigma(\mu^{-\uparrow}, \phi) \propto \mathrm{Re}(F_1 H) \cos\phi$$

Phase 2 (~2013) to constrain **E**

$$d\sigma(\phi, \phi_S) - d\sigma(\phi, \phi_S+\pi) \propto \mathrm{Im}(F_2 H - F_1 E) \sin(\phi-\phi_S) \cos\phi$$

100 – 190 GeV $\mu^{+\downarrow,-\uparrow}$ 80 %

The GPDs prior to birth of new electron-hadron colliders

- **H1, ZEUS, HERMES, JLab 6 GeV** are providing the first results
  significant increase of statistics expected after
  full data sets analysed

- The **energy upgrade** of the **CEBAF** accelerator will allow access
  to the **high x_B** region which requires **large luminosity**.

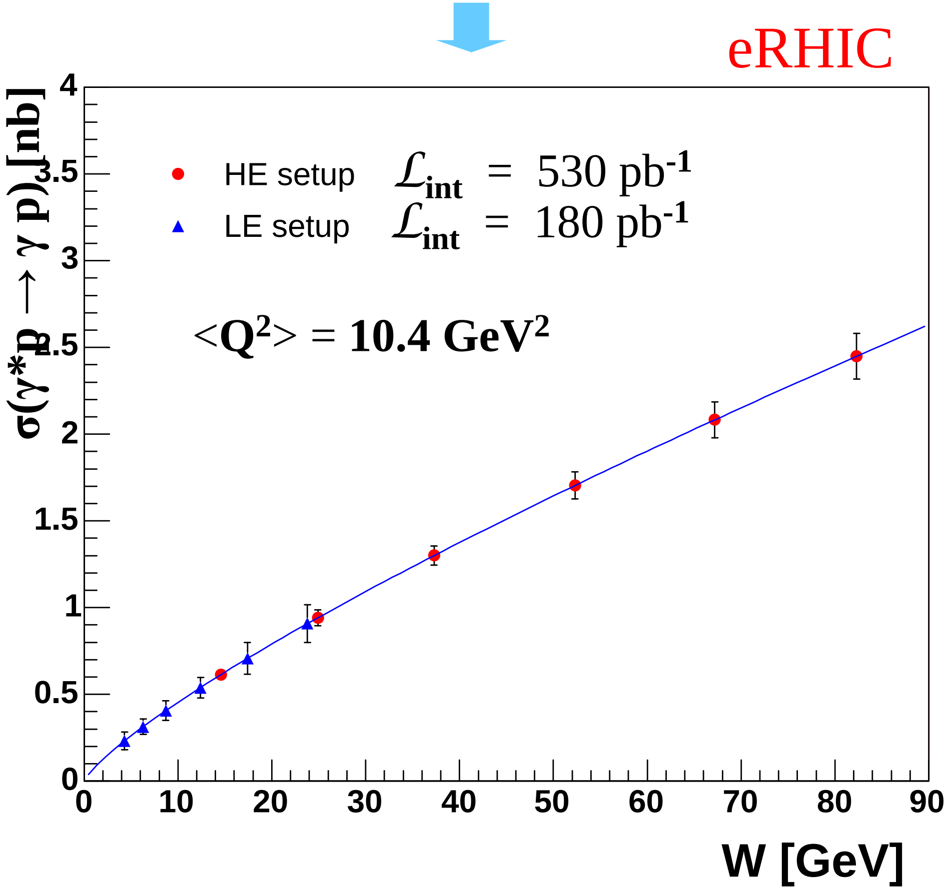
- The **DVCS** project at **COMPASS** will explore **intermediate x_B**
  (0.01-0.10) with a reasonable overlap with the **JLab**
  kinematic domain.

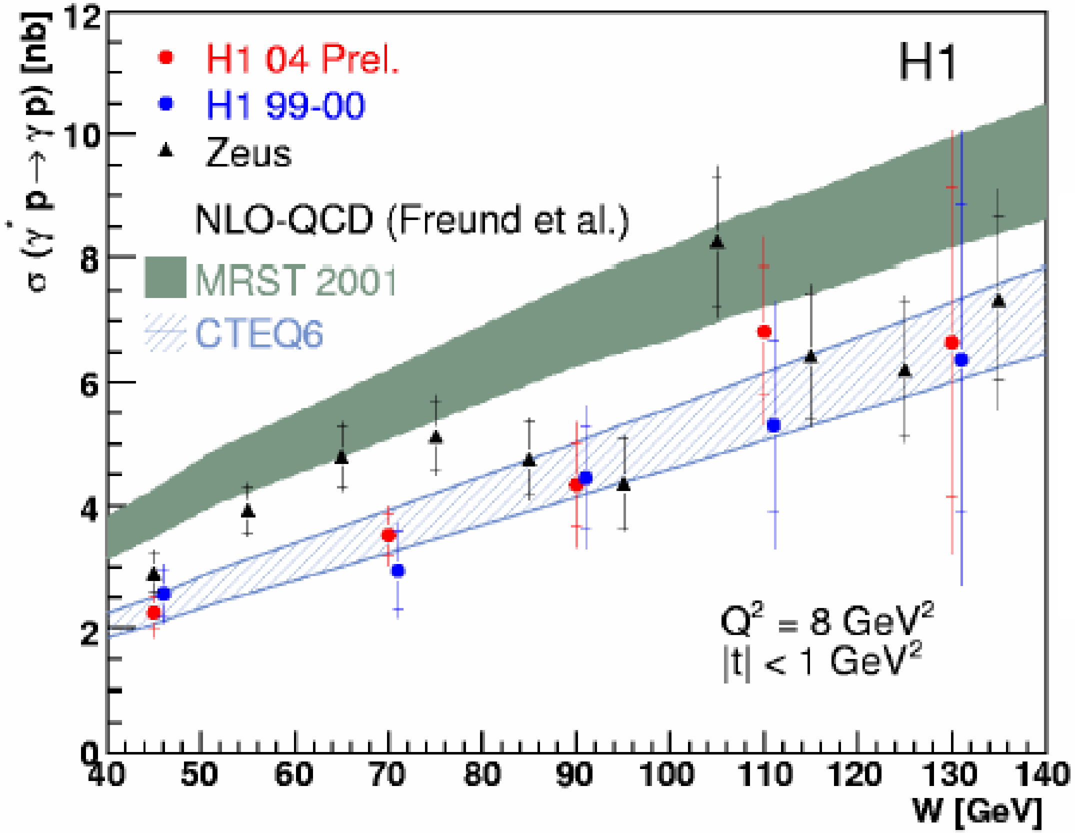
Precision of DVCS unpolarized cross sections at eRHIC

HE setup: $e^{+/-}$ (10 GeV) + p (250 GeV) $\mathcal{L} = 4.4 \cdot 10^{32}\ cm^{-2}s^{-1}$ 38 pb^{-1}/day

LE setup: $e^{+/-}$ (5 GeV) + p (50 GeV) $\mathcal{L} = 1.5 \cdot 10^{32}\ cm^{-2}s^{-1}$ 13 pb^{-1}/day

For one out of 6 Q^2 intervals ($8 < Q^2 < 15\ GeV^2$)



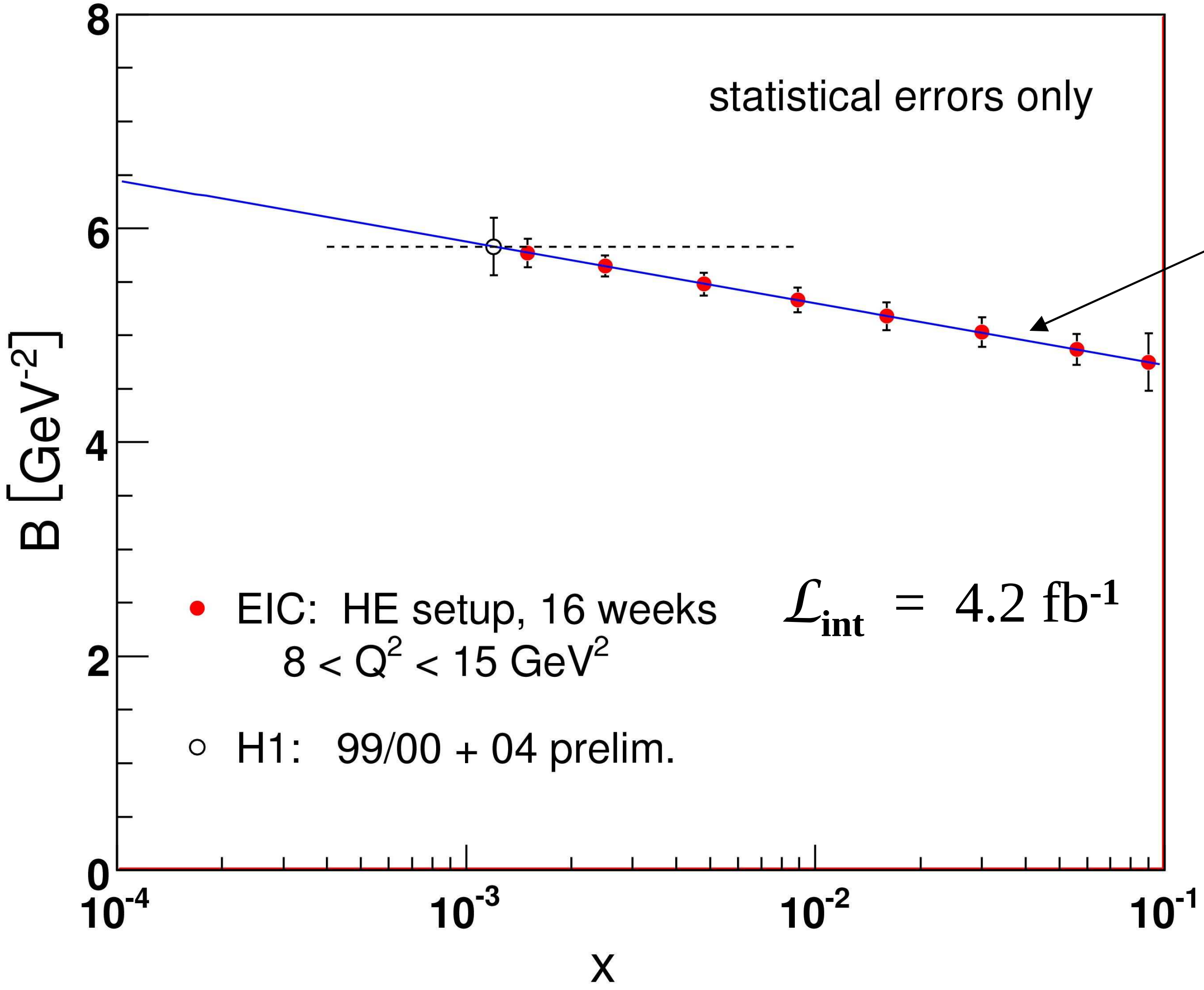


[A.S. @ Workshop on Hard Exclusive Processes, Univ. of Maryland, October 2006]

❖ EIC measurements of cross section will provide stronger constraints on GPD models

Towards 3D mapping of parton structure of the nucleon at EIC

$$d\sigma / dt(\gamma^* p \to \gamma\, p) \propto \exp(-B\,|\,t\,|)$$



(assumed for illustration)

$$B(x) = B(x_o) + 2\alpha' \ln(x_0 / x)$$

$$\alpha' = 0.125\ \mathrm{GeV}^{-2}$$

[A.S. @ EIC Collaboration Meeting, Stony Brook, December 2007]

simultaneous data in several (6) Q^2 bins

Sufficient luminosity to do triple-differential measurements in x, Q^2, t at EIC!

Hard Exclusive Meson Production at EIC

- 'diffractive' channels $J/\psi, \rho^{0}, \varphi\ldots$ sensitivity to gluons

  → transverse gluon (and sea quarks) imaging

- 'non-diffractive' channels $\pi, \eta, K, \rho^{+}\ldots$

  → probe spin/flavour/charge non-singlet GPD's

  by model-independent comparison of channels

π^0/η	$\Delta u/\Delta d$, meson wave functions
ρ^+/K^*	SU(3) symmetry of quark GPD's
π^0/π^+	role of the pion pole in GPD

  experimentally more challenging than 'diffractive' channels

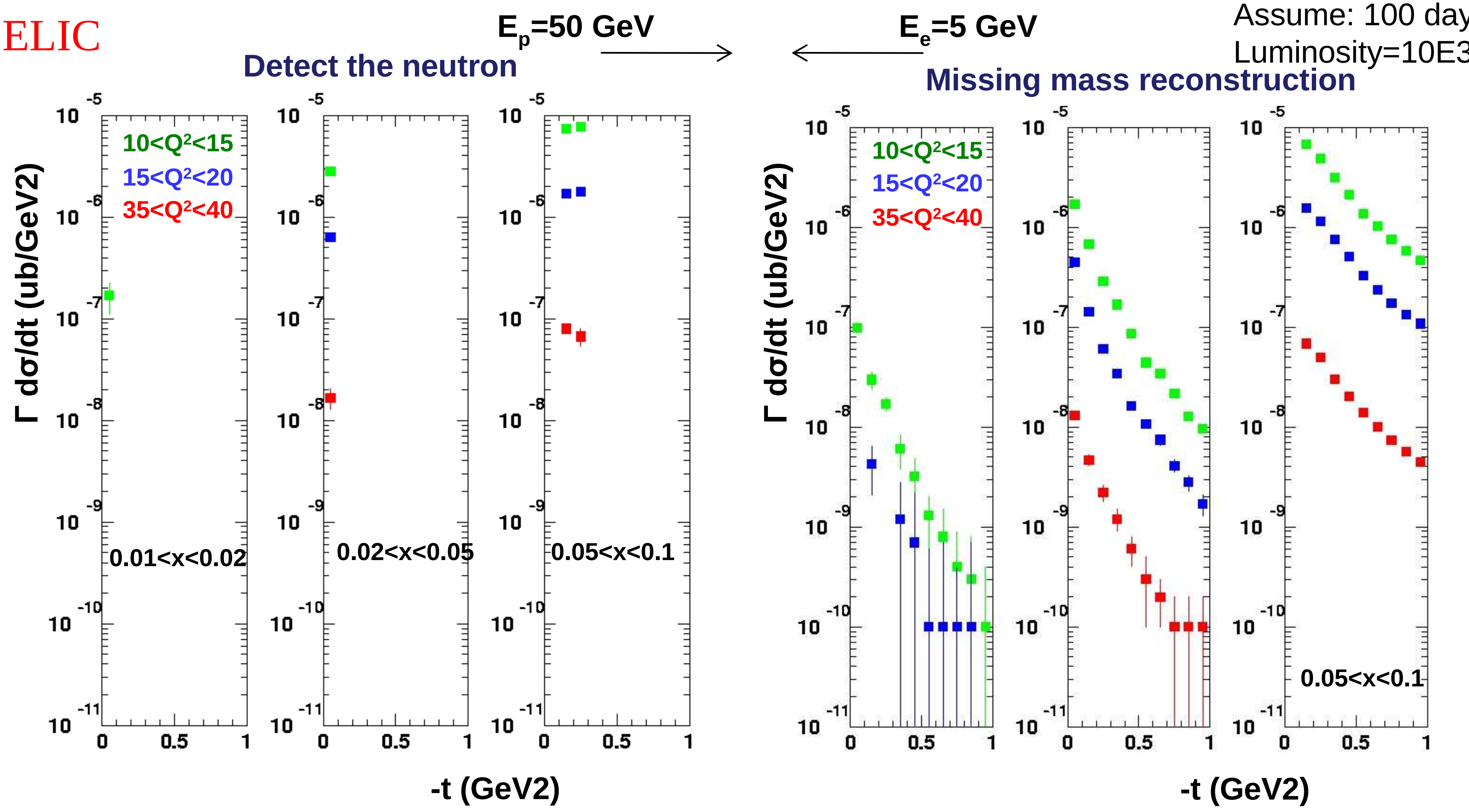
  smaller cross sections, L/T separation for pseudo-scalar mesons

- advantage of EIC - high Q^2 ; power corrections less important

Rates and coverage in different Event Topologies for $e\,p \rightarrow e\,n\,\pi^+$ at ELIC

ELIC

Assume: 100 days, Luminosity=10E34



- Neutron acceptance limits the t-coverage
- The missing mass method gives full t-coverage for x<0.2

Assume dp/p=1% (p_π<5 GeV)

[T. Horn, A. Bruell, G. Hubner, C. Weiss @ EIC Collaboration Meeting, Hampton, May 2008]

Requirements for exclusive processes at an EIC

small cross sections
a challenge →
- large luminosity
- effective suppression of non-exclusive background

- **Hermeticity :** wide kinematical range and suppression of non-exclusive bkg.
  - angular acceptance of Central Detector strongly affects small x region
    $2^{o} \div 178^{o}$ ('improved eRHIC ZDR')
  - importance of coverage of low E_γ region (both π^0 bkg. and accept. at small W)
    E_γ > 0.5 GeV (?)
  - Leading Proton Detector - suppression of bkg. from proton diff. dissociation

    acceptance and t-range strongly dependent on

    beam-line design and beam tune (β*)

- **Particle Identification :** required - e/μ/h separation

  with Calorimetry and Muon Detection

Summary for DVCS and HEPM at EIC

- Wide kinematical range, overlap with HERA and COMPASS

  $1.5 \cdot 10^{-4} < x_B < 0.15$ - sensitivity to gluons and sea quarks

  $1 < Q^2 < 50\ GeV^2$ - sensitivity to QCD evolution

- Significant improvement of precision wrt HERA

- Sufficient luminosity to do tripple-differential measurements in x_B, Q^2, t

- Variable beam energy settings

  will provide kinematical overlap with existing data

  separation of $|DVCS|^2$ and BH·DVCS terms

  and L/T separation for pseudoscalar meson production

- Full exploratory potential for DVCS at amplitude level

  with e^+ and e^- polarised beams as well as with

  longitudinaly and transversely polarized protons