Delia Hasch

INFN Frascati

DVCS & hard exclusive meson prod.

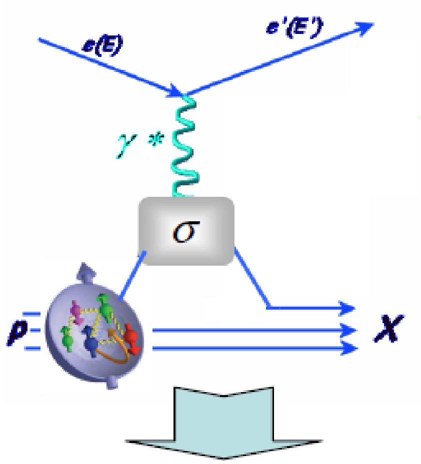
-- experimental review --

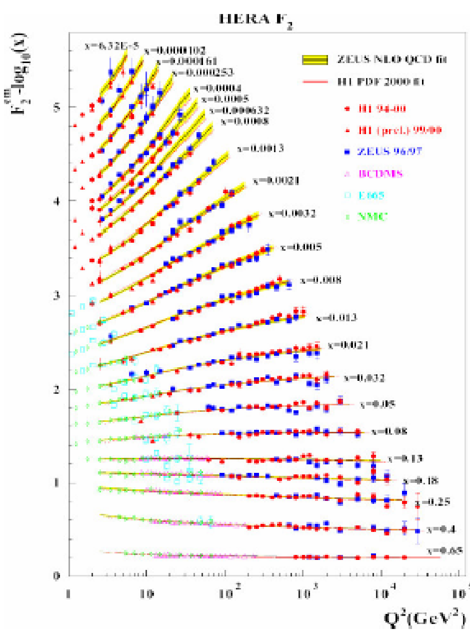
- a very brief introduction
- prerequisites and methods
- from low to high x : selected results
- perspectives

all details tomorrow:
- F. X. Girod
- S. Yaschenko
- N. D’Hose
- V. Burkert

[slide by L. Pappalardo]

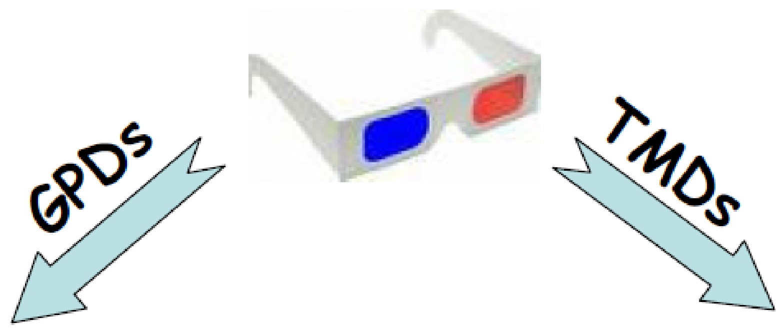
Quantum phase-space tomography of the nucleon

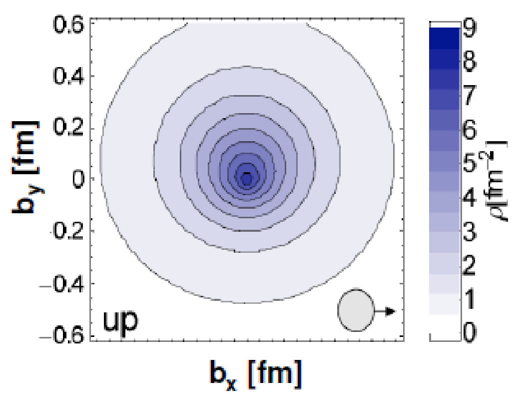




Longitudinal momentum structure of the nucleon

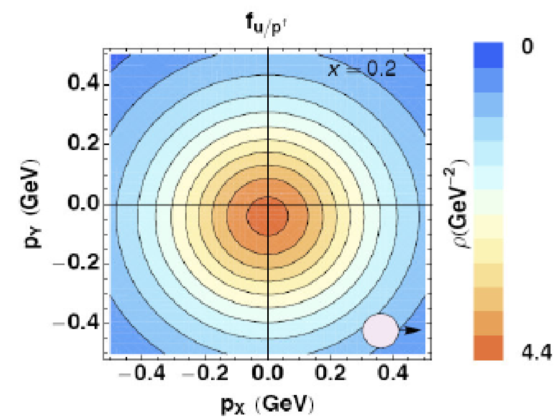
Join the real 3D experience!!





QCDSF/UKQCD, PRL 98 (07)

3D picture in coordinate space



A.B., F. Conti, M. Radici, PRD78 (08)

3D picture in momentum space

3D imaging of the nucleon & OAM

Wigner distribution ('mother function'):

C. Lorce [tomorrow]

$W(x,r,k_T)$

$\int d^3r$

$\int d^2k_T dz$

FT

TMD (x,k_T)
spin-orbit
correlations

GPD(x, ξ, t)
2+1D imaging;
access to OAM

→ (model dependent) relations between TMDs & GPDs:

$$f_{1T}^{\perp(n)}(x) \sim E^{q(n)}(x,0,0)$$

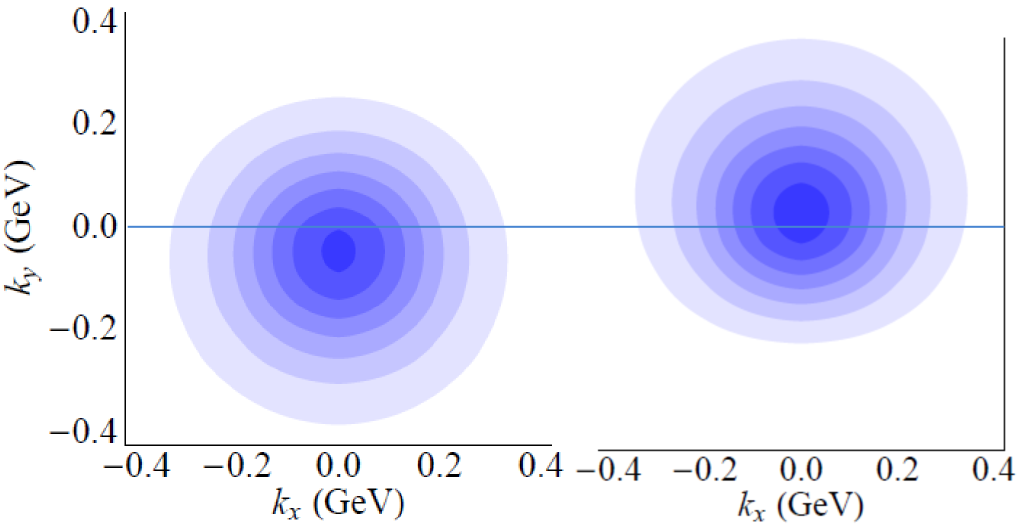
[Burkardt 2002]
[Burkardt, Hwang 2003]
[Diehl, Haegeler 2005]
ecc.

nucleon tomography

[transversely polarised nucleon]

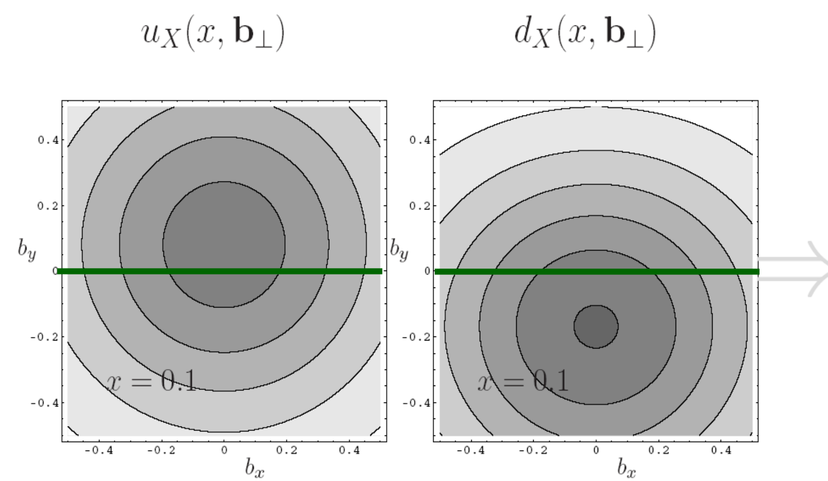
TMDs

[model calculation by B. Pasquini, F. Yuan]



GPDs

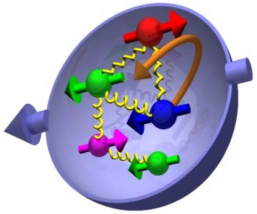
[model calculation by M. Burkardt]



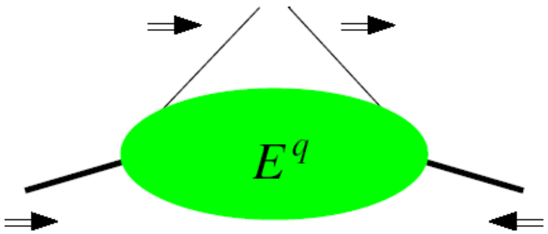
Sivers TMD ← model dependent relation → GPD *E*

--in transverse momentum coordinates-- --in impact parameter coordinates--

relations to OAM



GPDs



proton helicity flipped while
quark helicity is conserved

$E^q \neq 0$ *requires* orbital angular momentum

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

TMDs

[plot: courtesy B. Musch]

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

ΔL=1 ($h_1^\perp$)

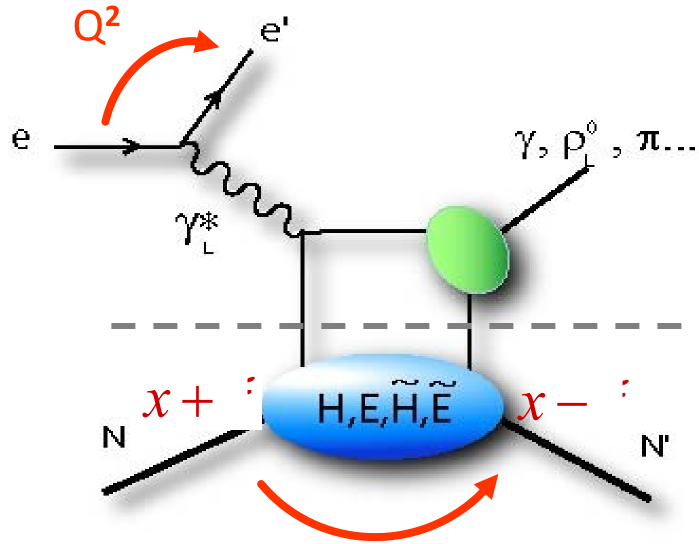
ΔL=1 ($f_{1T}^\perp$)

ΔL=2 ($h_{1T}^\perp$)

require interference of nucleon wave
fct.s with different units OAM

→ spin-orbit correlation

how to measure GPDs ?



$H(x,\xi,t)$

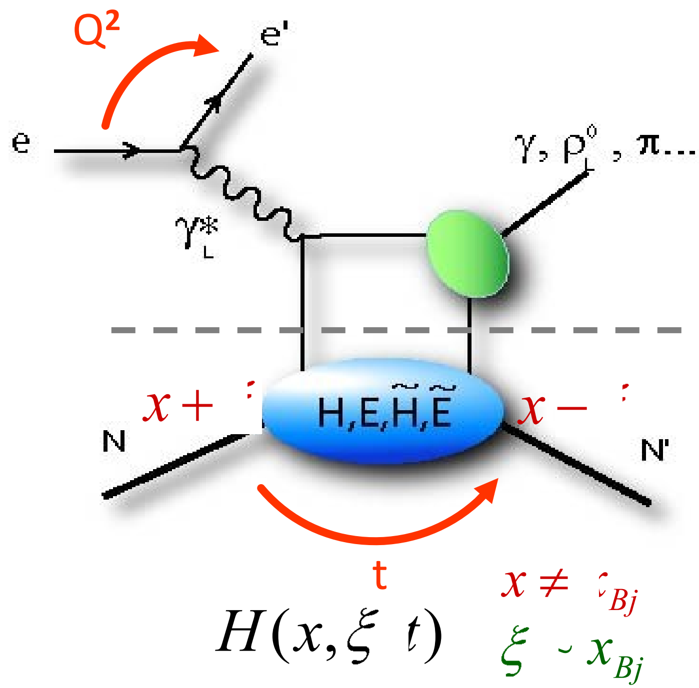
$x \neq x_{Bj}$

$\xi \sim x_{Bj}$

Q²>>, t<<

appear in factorisation theorem for *hard exclusive processes*

how to measure GPDs ?



Q^2>>, t<<

appear in factorisation theorem for *hard exclusive processes*

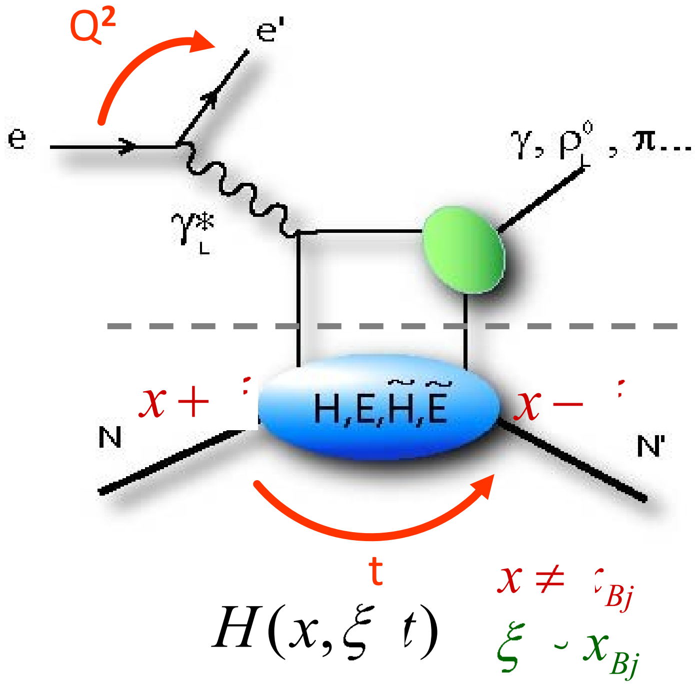
- spin ½ target:

4 leading-tw, chiral even *q* & *g* GPDs: H, H̃ conserve nucleon helicity

E, Ẽ involve nucleon helicity flip

+ 4 chiral odd GPDs → connection to transversity

how to measure GPDs ?



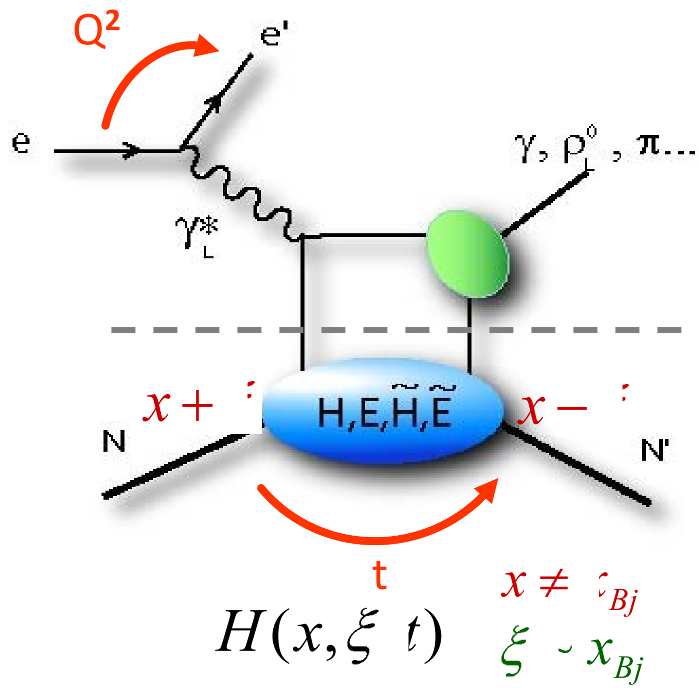
Q^2>>, t<<

appear in factorisation theorem for *hard exclusive processes*

- DVCS: most clean process, (some) flavour dependent info from p & n target

→ H, H̃, E, Ẽ

how to measure GPDs ?



Q²>>, t<<

appear in factorisation theorem for *hard exclusive processes*

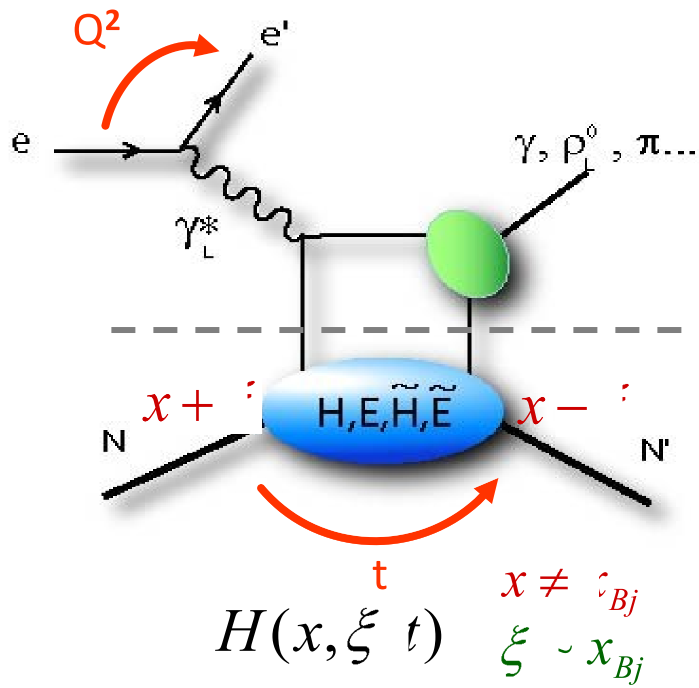
- DVCS: most clean process, (some) flavour dependent info from p & n target
- DVMP: flavour decomposition; gluons:

→ H, H̃, E, Ẽ

VM → H, E

PS → H̃, Ẽ

how to measure GPDs ?



Q²>>, t<<

appear in factorisation theorem for *hard exclusive processes*

- DVCS: most clean process, (some) flavour dependent info from p & n target
- DVMP: flavour decomposition; gluons:

BUT:

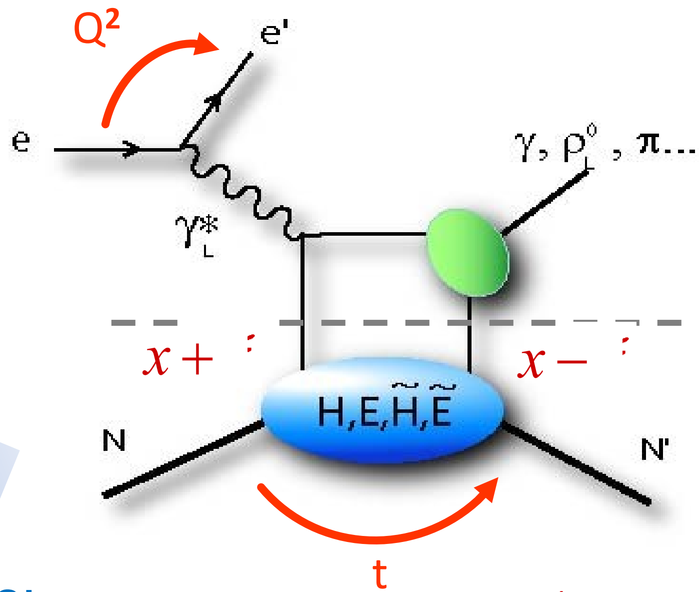
- factorisation only for σ_L
- meson distribution amplitude needed
- large NLO & power corrections

→ H, H̃, E, Ẽ

VM → H, E

PS → H̃, Ẽ

constraints of GPDs



Q²>>, t<<

appear in factorisation theorem for hard exclusive processes

$$H(x,\xi,t)$$

$x \neq x_{Bj}$

$\xi \sim x_{Bj}$

form factors:

$$\sum_q e_q \int dx\, H^q(x,\xi,t) = F_1(t)$$

... ecc.

PDFs :

$$H^{q,g}(x,0,0) = q(x)$$

$$\widetilde{H}^{q,g}(x,0,0) = \Delta q(x)$$

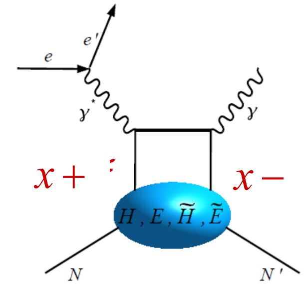
$$H_T^q(x,0,0) = h_1(x)$$

$E, \widetilde{E}$: nucleon helicity flip → don't appear in DIS

+ Lorentz invariance: polynomiality

+ lattice calculations

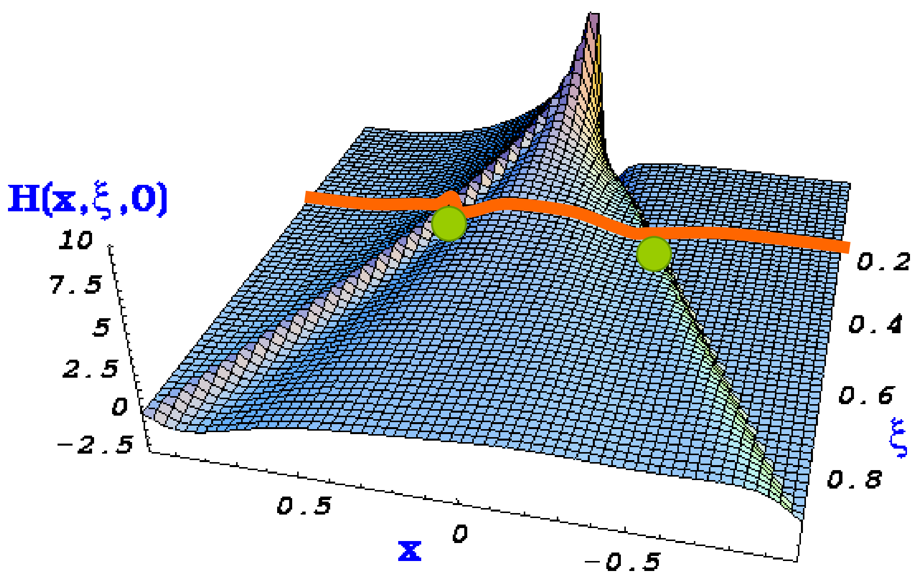
extracting GPDs: caveats



$$T_{\mu\nu} = \left[\mathcal{H},\mathcal{E},\widetilde{\mathcal{H}},\widetilde{\mathcal{E}}\right](\xi,t,Q^2), \qquad \mathcal{F}(\xi,t,Q^2) = \int_{-1}^{1} dx\, C^{-}(\xi,x)\, F(x,\xi,t,Q^2),$$

Compton Form Factor (CFF)

- x is mute variable (integrated over), needs deconvolution
  - → apart from 'cross over' trajectory ($x = \xi$) GPDs not directly accessible
- extrapolation $t \to 0$ model dependent

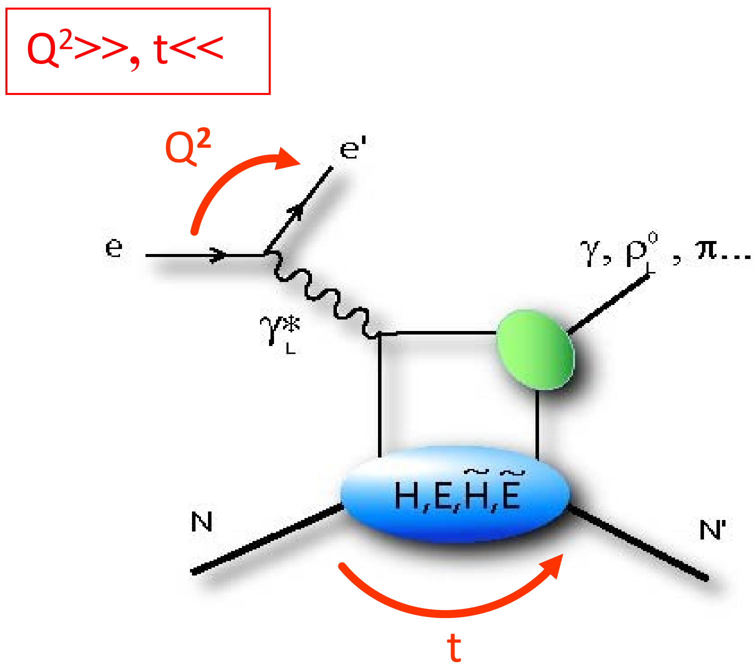


cross section & beam charge asymmetry ~ Re(T^{DVCS})

beam or target spin asymmetries ~ Im(T^{DVCS})

→ x scan of GPDs from Q^2 evolution: *EIC*

the ideal experiment for measuring hard exclusive processes



- high & variable beam energy
  - → ensure hard regime
  - → wide kinematic range
  - → L/T separation for ps meson prod.
- high luminosity
  - → small cross sections
  - → fully differential analysis
- hermetic detectors
  - → ensure exclusivity

… doesn't exist (yet)…

experimental prerequisites

ZEUS

- polarised 27GeV e+/e–
- unpolarised 920GeV p
- ≈full event reconstruction

hermes

- polarised 27GeV e+/e–
- long+transv polarised p, d targets
unpolarised nuclear targets
- missing mass technique
- 2006/7 data taken with recoil det.

experimental prerequisites

- polarised 27GeV e+/e–
- unpolarised 920GeV p
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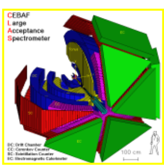
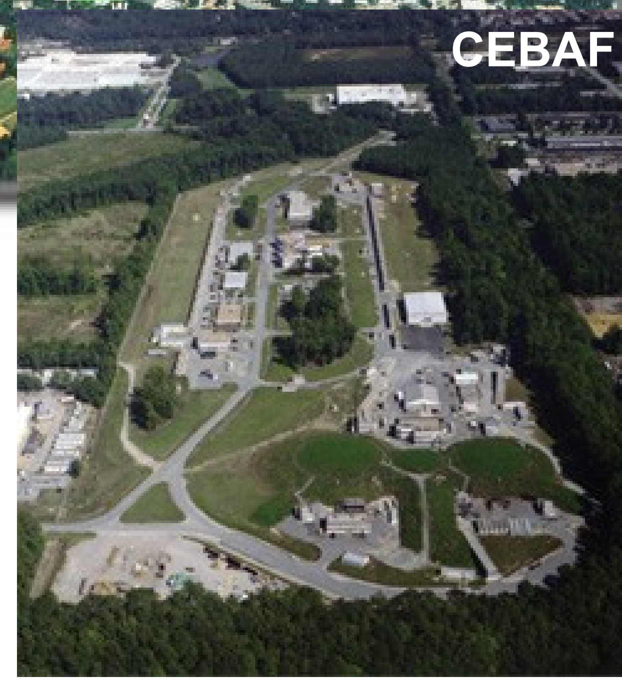
unpolarised nuclear targets

- missing mass/energie technique
- 2006/7 data taken with recoil det.



- highly polarised, high lumi 6GeV e–
- long polarised effective p, n targets
- missing mass/energie technique

Hall-A



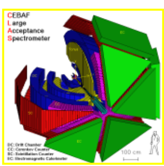
experimental prerequisites

- polarised 27GeV e+/e–
- unpolarised 920GeV p
- ≈full event reconstruction

- polarised 27GeV e+/e–
- long+transv polarised p, d targets

unpolarised nuclear targets

- missing mass/energie technique
- 2006/7 data taken with recoil det.



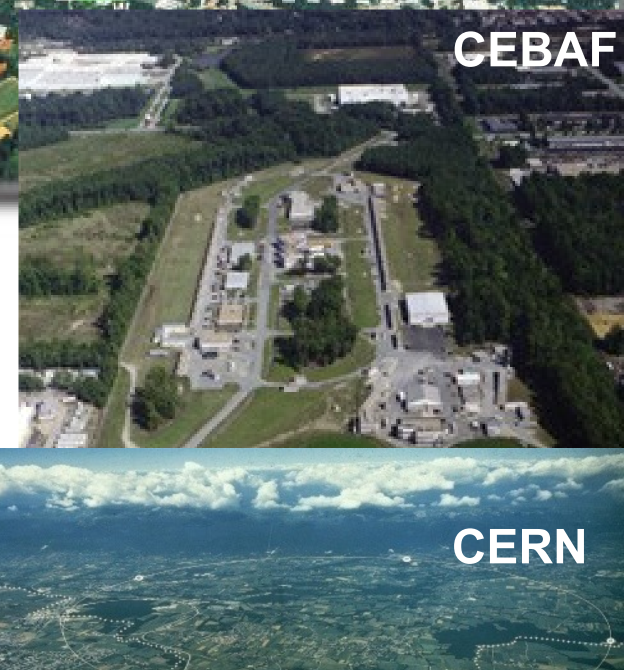
- highly polarised, high lumi 6GeV e–
- long polarised effective p, n targets
- missing mass/energie technique

Hall-A

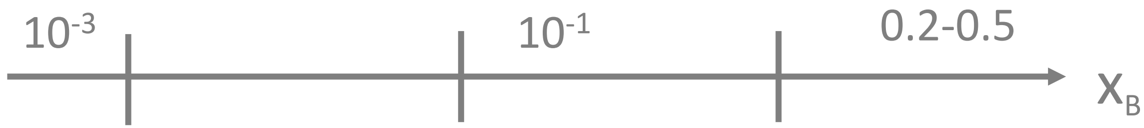
- highly polarised, 160GeV μ
- long+transv polarised effective

p, d targets →

- missing mass/energie technique



low → high x



HERA collider

$10^{-4} < x_B < 0.02$

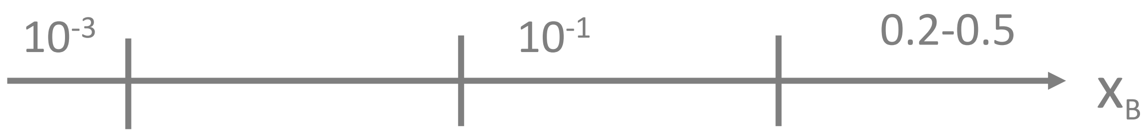
sea quarks & gluons

HERMES / JLab

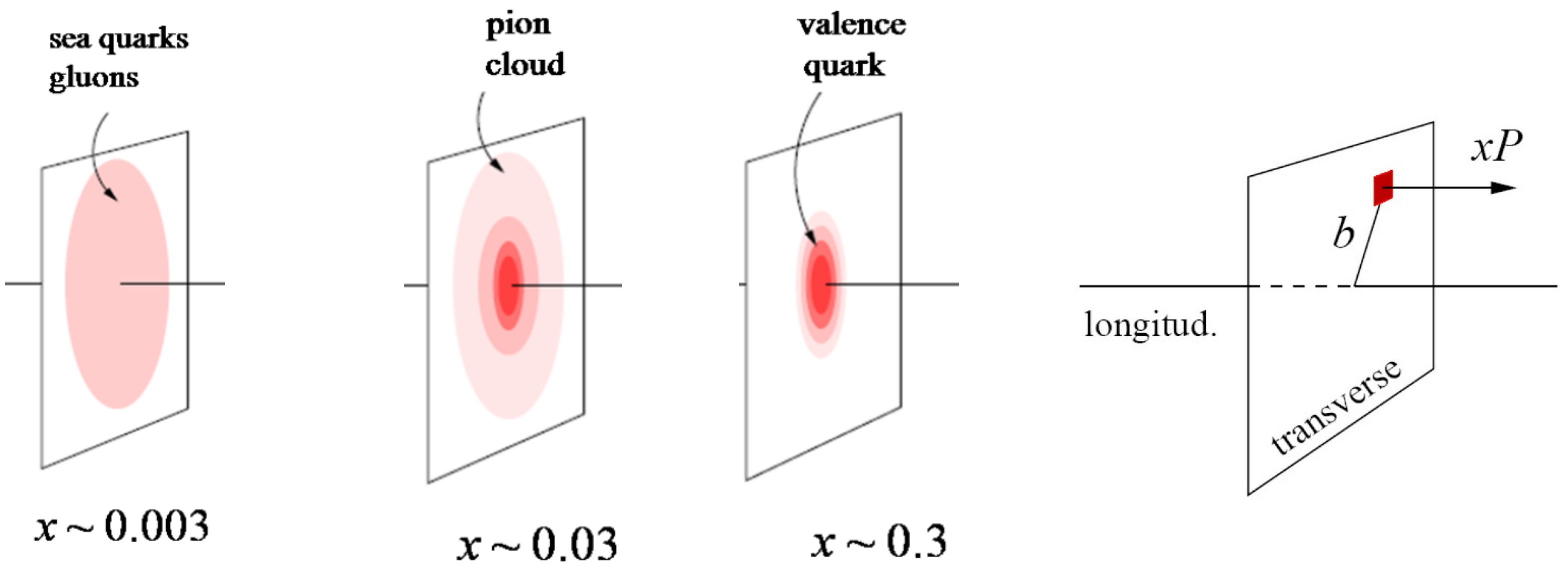
$0.02 < x_B < 0.4$ / $0.1 < x_B < 0.6$

(gluons) (valence) quarks

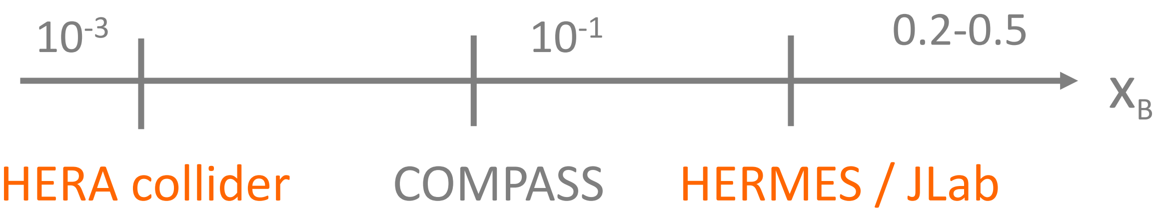
low → high x



HERA collider	COMPASS	HERMES / JLab
$10^{-4} < x_B < 0.02$		$0.02 < x_B < 0.4$ / $0.1 < x_B < 0.6$
sea quarks & gluons		(gluons) (valence) quarks

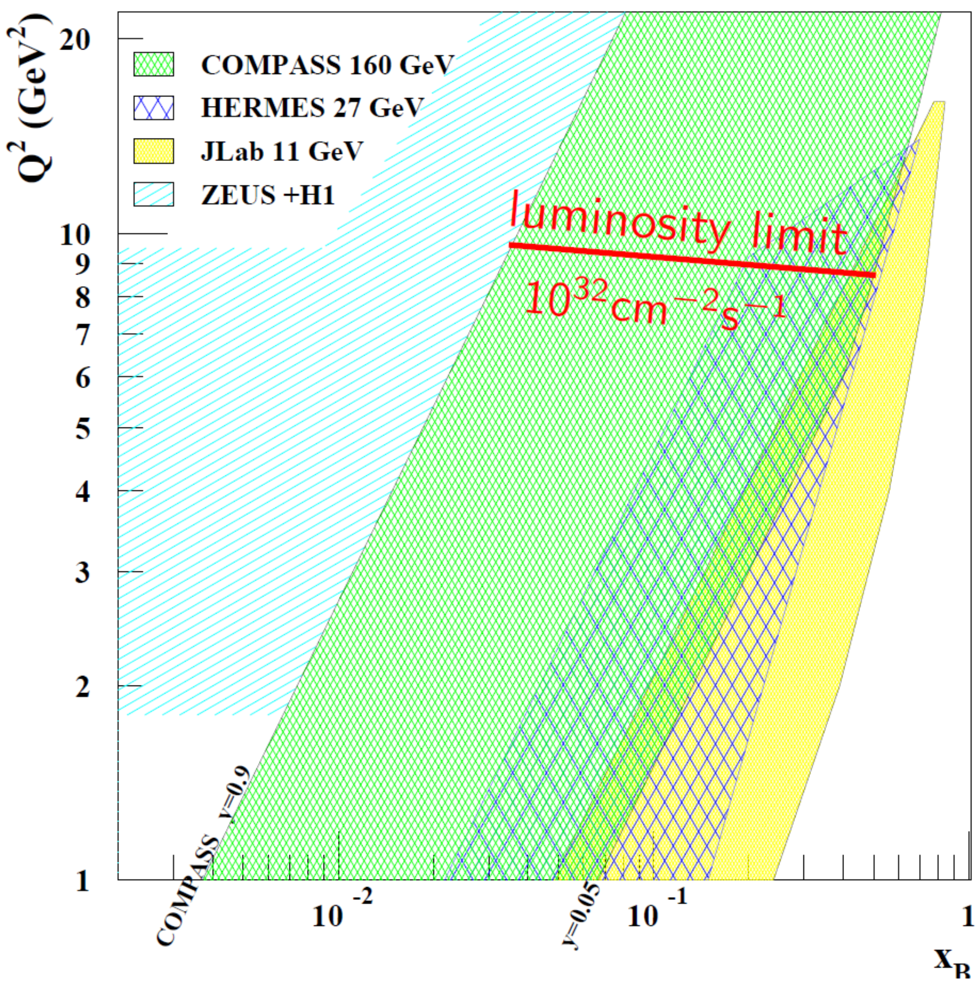


low → high x



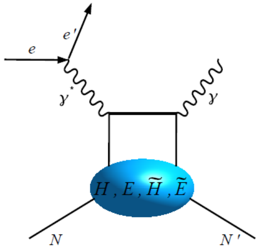
$10^{-4} < x_B < 0.02$

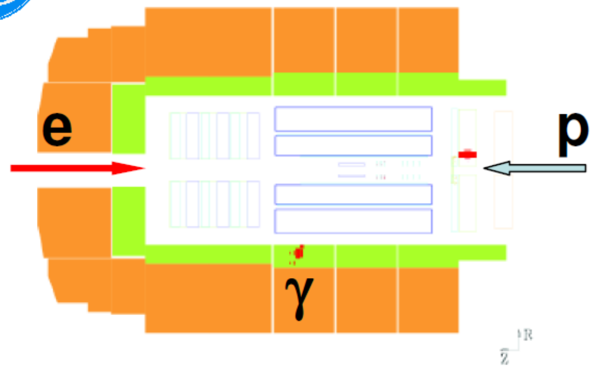
sea quarks & gluons



exclusivity

@ the HERA collider experiments

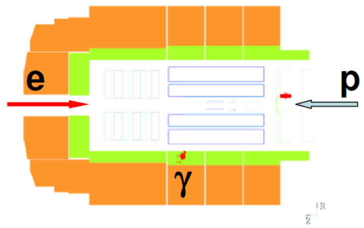




≈ hermetic detector

→ *p* escapes through beam pipe

LPS: *p* tagged control sample



exclusivity

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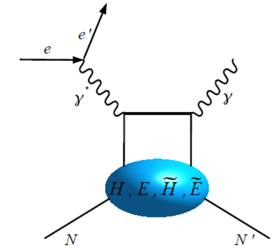
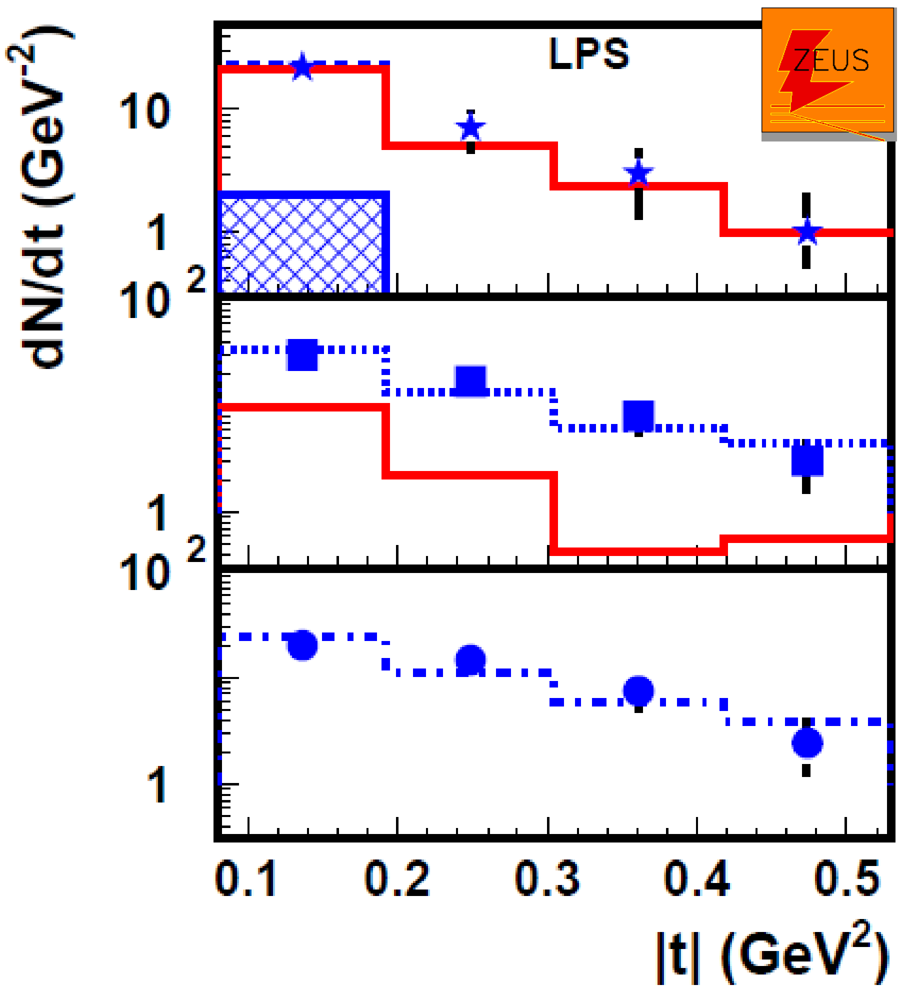


LPS: *p* tagged data sample



★ e-sample: BH control sample

e+e-, J/ψ bg-sample

BH+e^+e^-+J/ψ

BH

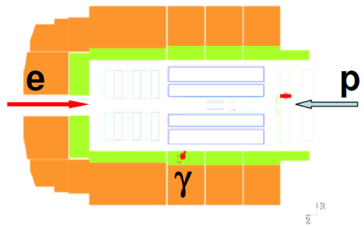
■ γ-sample: BH+DVCS

BH

BH+FFS (DVCS)

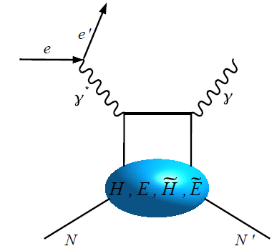
● (BH+DVCS) - BH

FFS (DVCS)

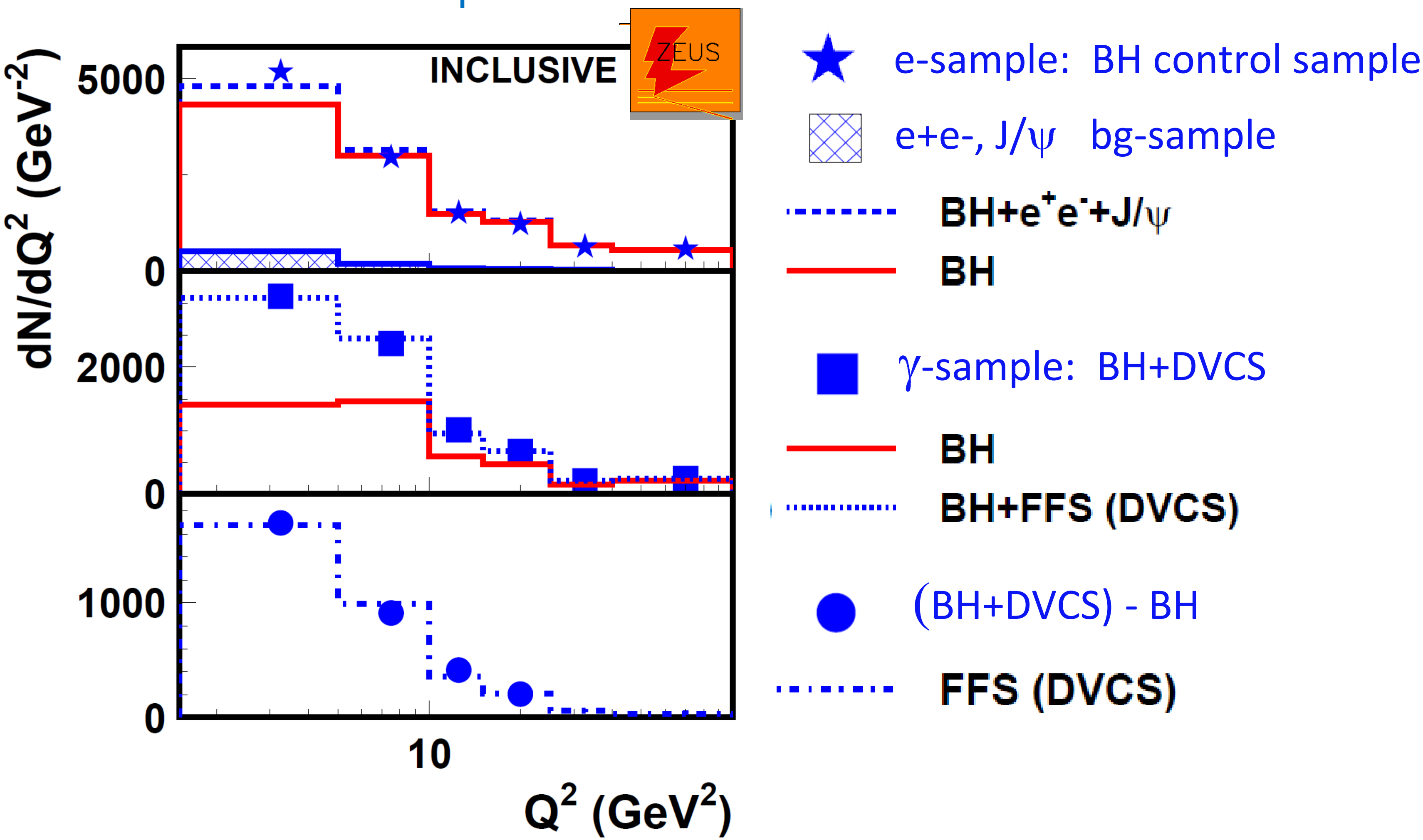


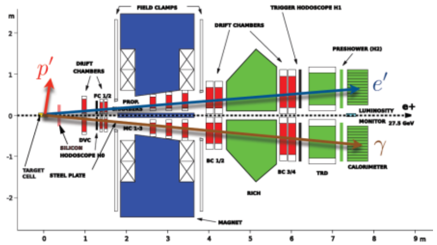
exclusivity

@ the HERA collider experiments



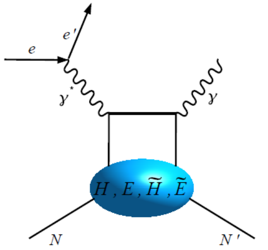
full data sample

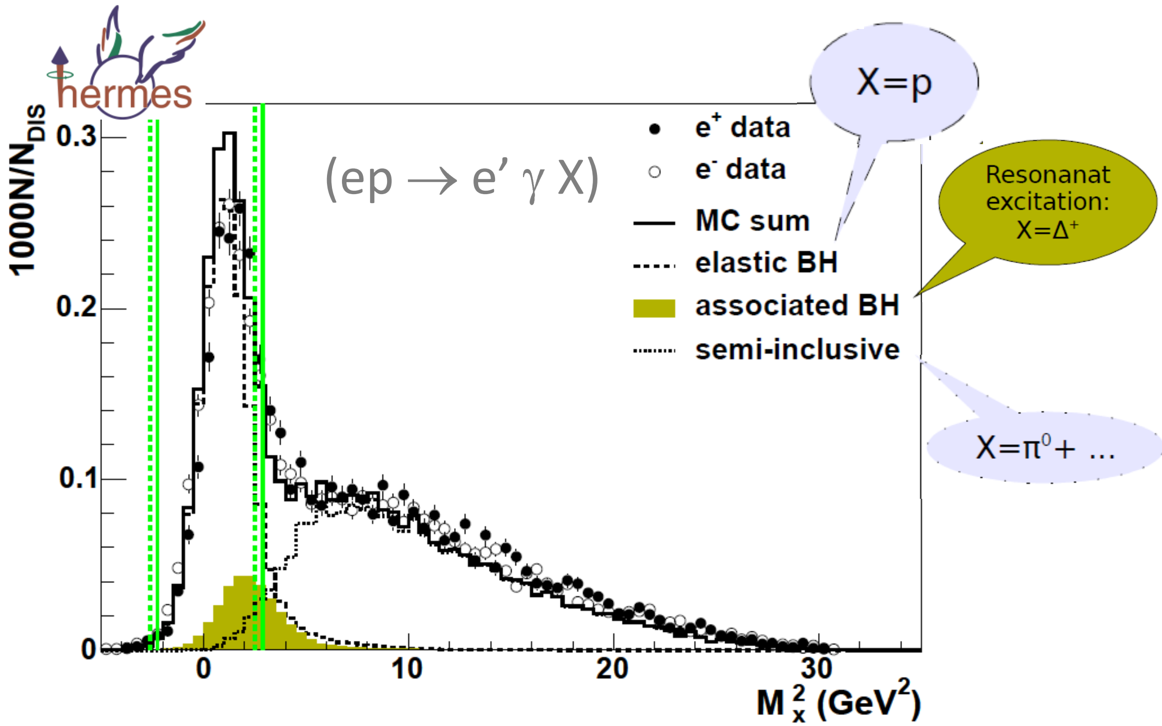




exclusivity

fixed target: via missing mass / energy

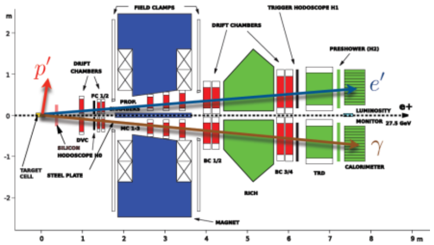




part of the signal

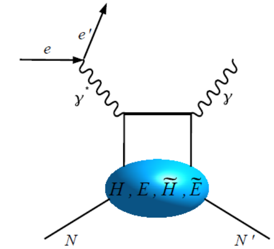
subtracted

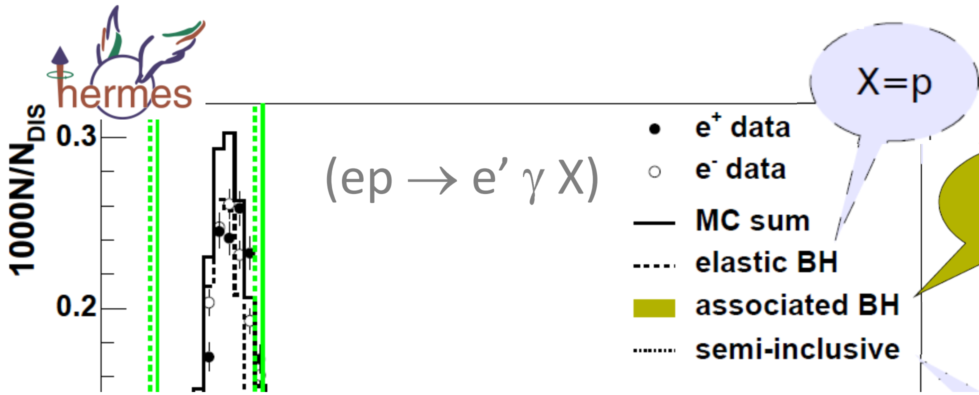
very well understood



exclusivity

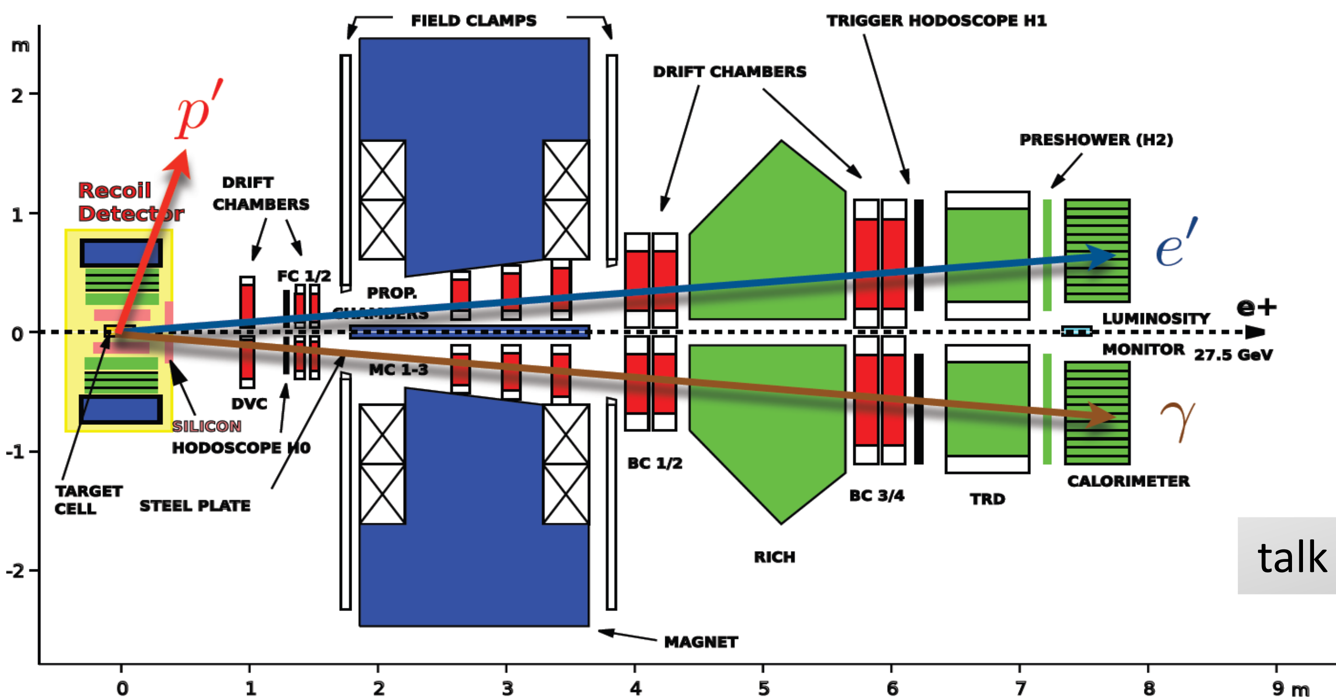
fixed target: via missing mass / energy





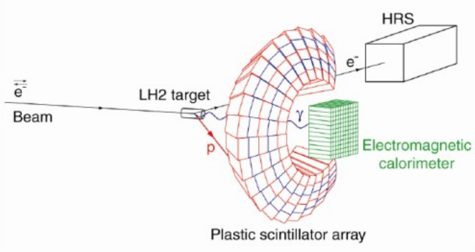
with *p* detection &

Δ$^+$ ID: transition GPDs

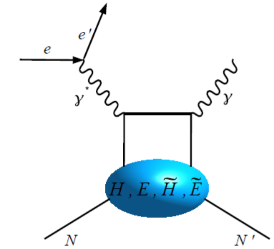


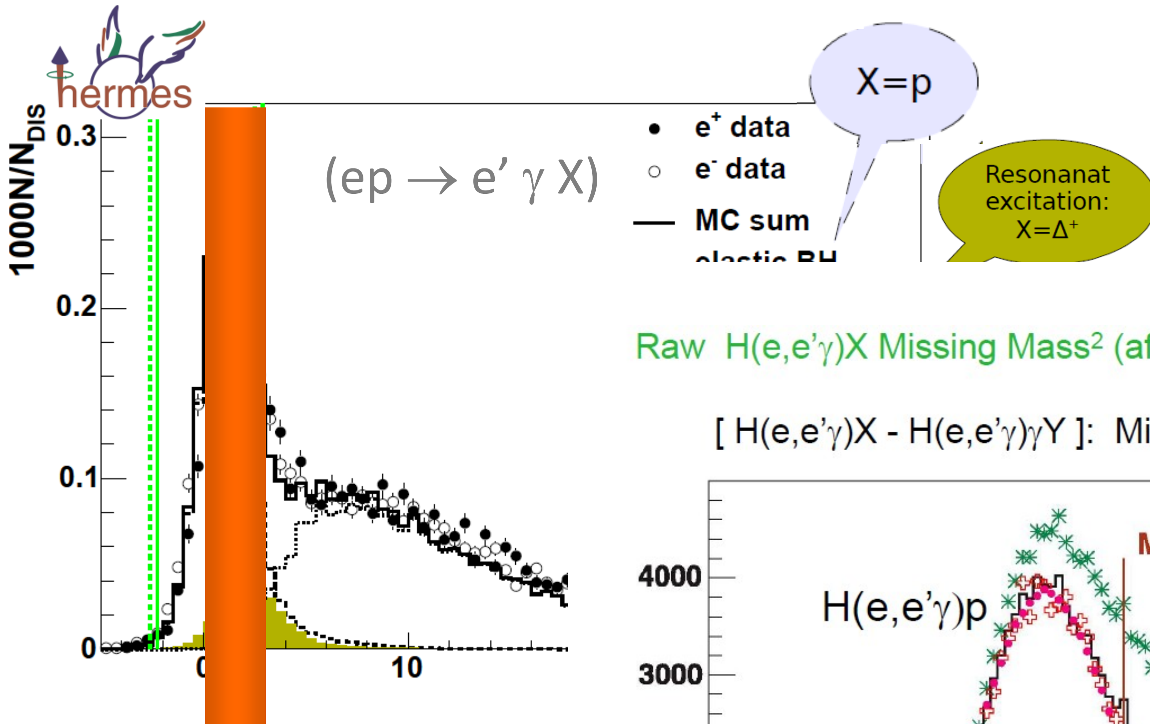
talk by S. Yaschenko

exclusivity

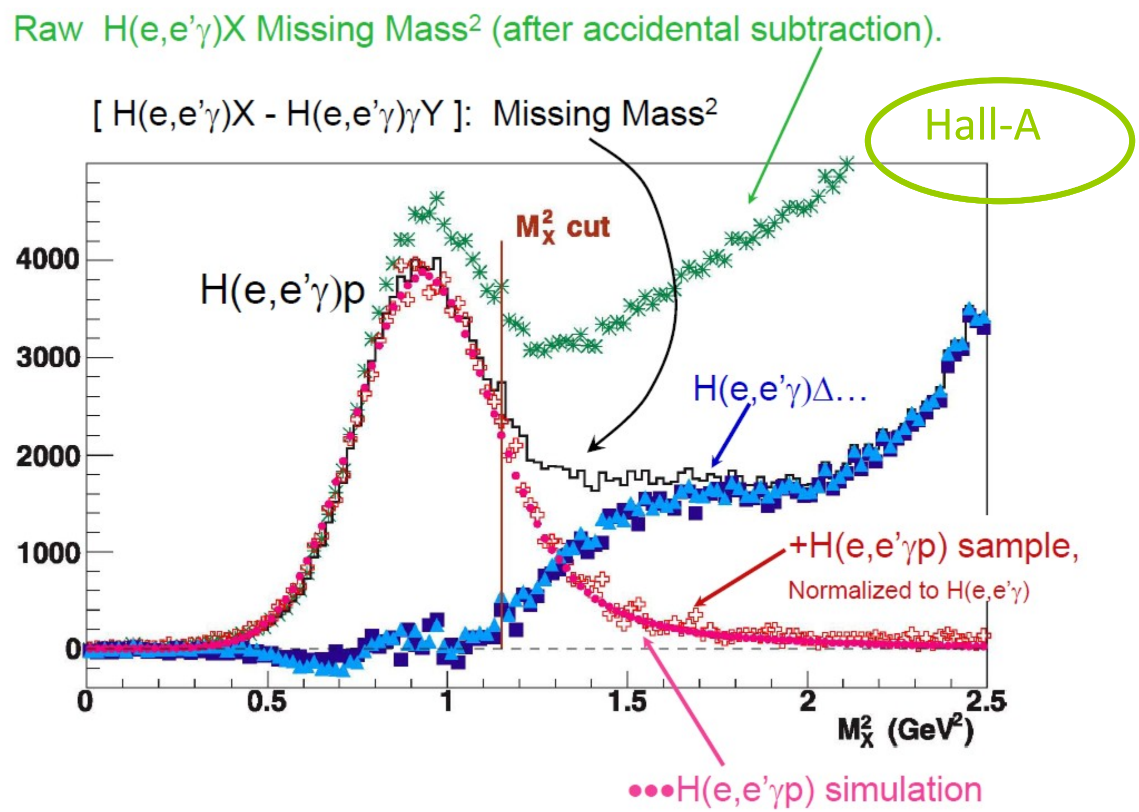


fixed target: via missing mass / energy





part of the signal



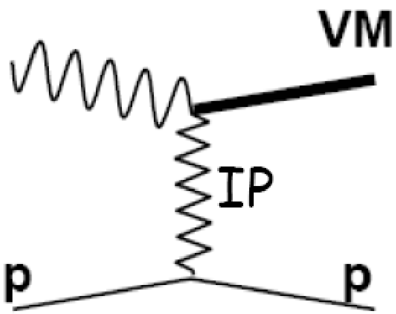
results on (off) the menu

data over wide kinematic range: HERA-collider → COMPASS → HERMES → JLab

- VM production → *H, E*
  - low x: gluon imaging
  - high x: quarks & gluons ; role of NLO & power corrections
  - low W data from Jlab (→ X. Girod, tomorrow)
- ps meson production → $\tilde{H}, \tilde{E}$
  - role of transverse photons: CLAS π^0, π^+ A_{LU}, HERMES π^+ A_{UT}, cross sec.
  - relation to transversity: H_T → h_1 from π^0 A_{UT}
- DVCS → $H, E, \tilde{H}, \tilde{E}$ ... the golden channel & most rich plate
  - nuclear modification of DVCS ampllitudes: HERMES
- models & GPDs
- hunting the OAM

VM production @low x

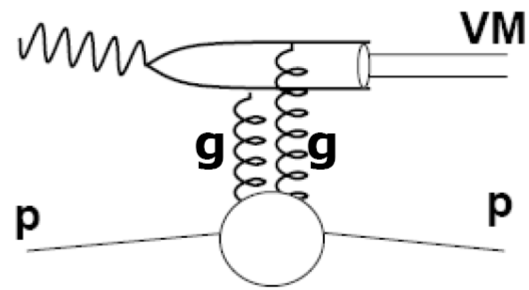
W & *t* dependences: probe transition from soft to hard regime



soft

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

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



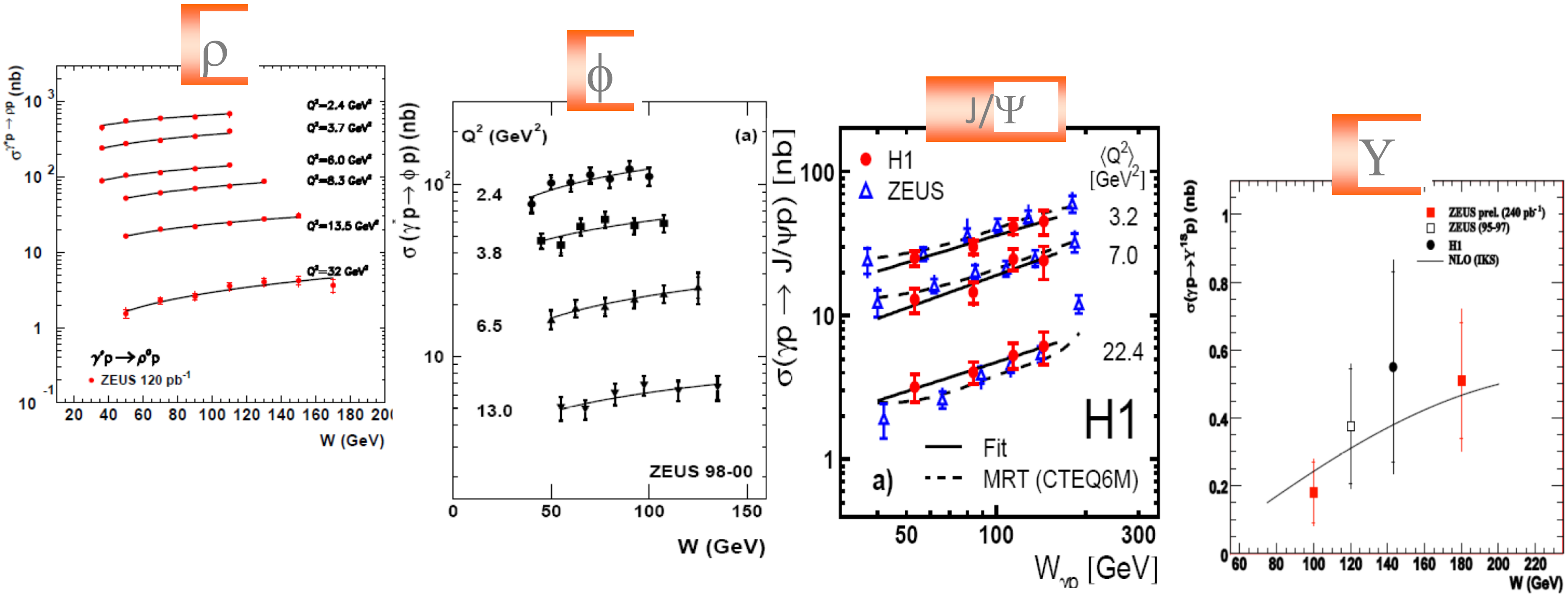
hard

→expect δ to increase from ~0.2 to ~0.8

b to decrease from ~10 to ~4-5 GeV^2

VM production @low x

W dependence: probe transition from soft to hard regime

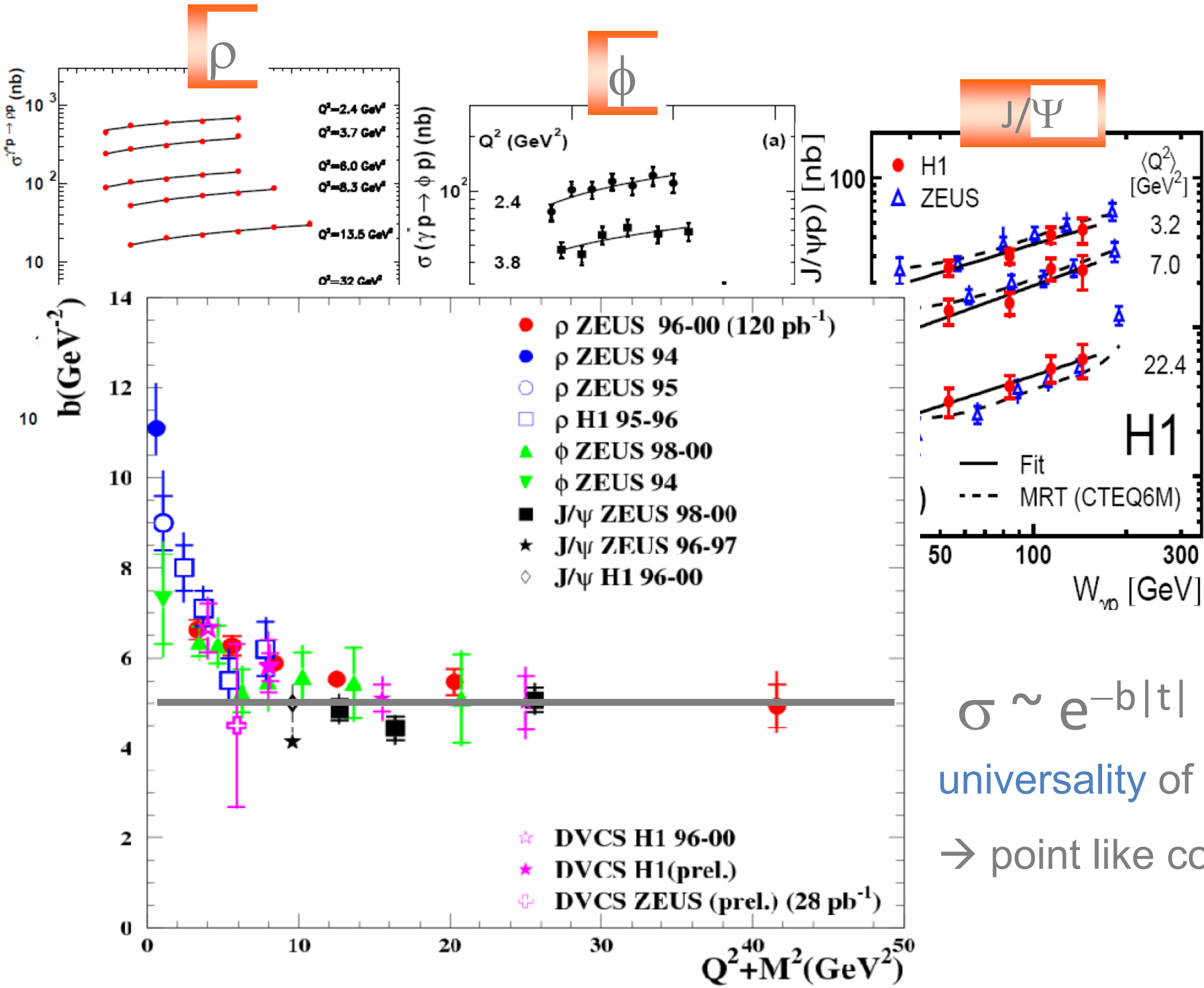


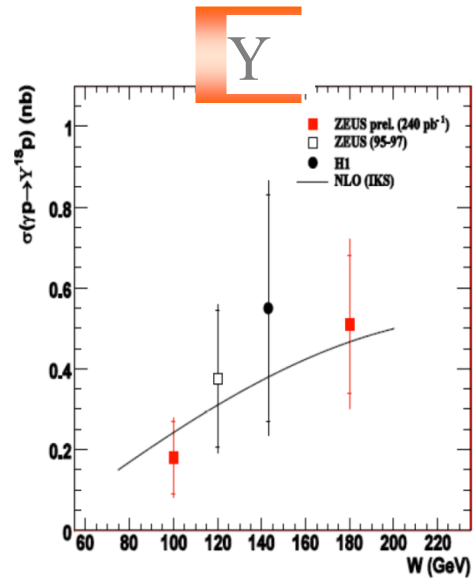
two ways to set a *hard* scale:
- large Q^2
- mass of produced VM

universality: ρ and φ at large Q^2+M^2 similar to J/Ψ , Υ

VM production @low x

t dependence: probe transition from soft to hard regime





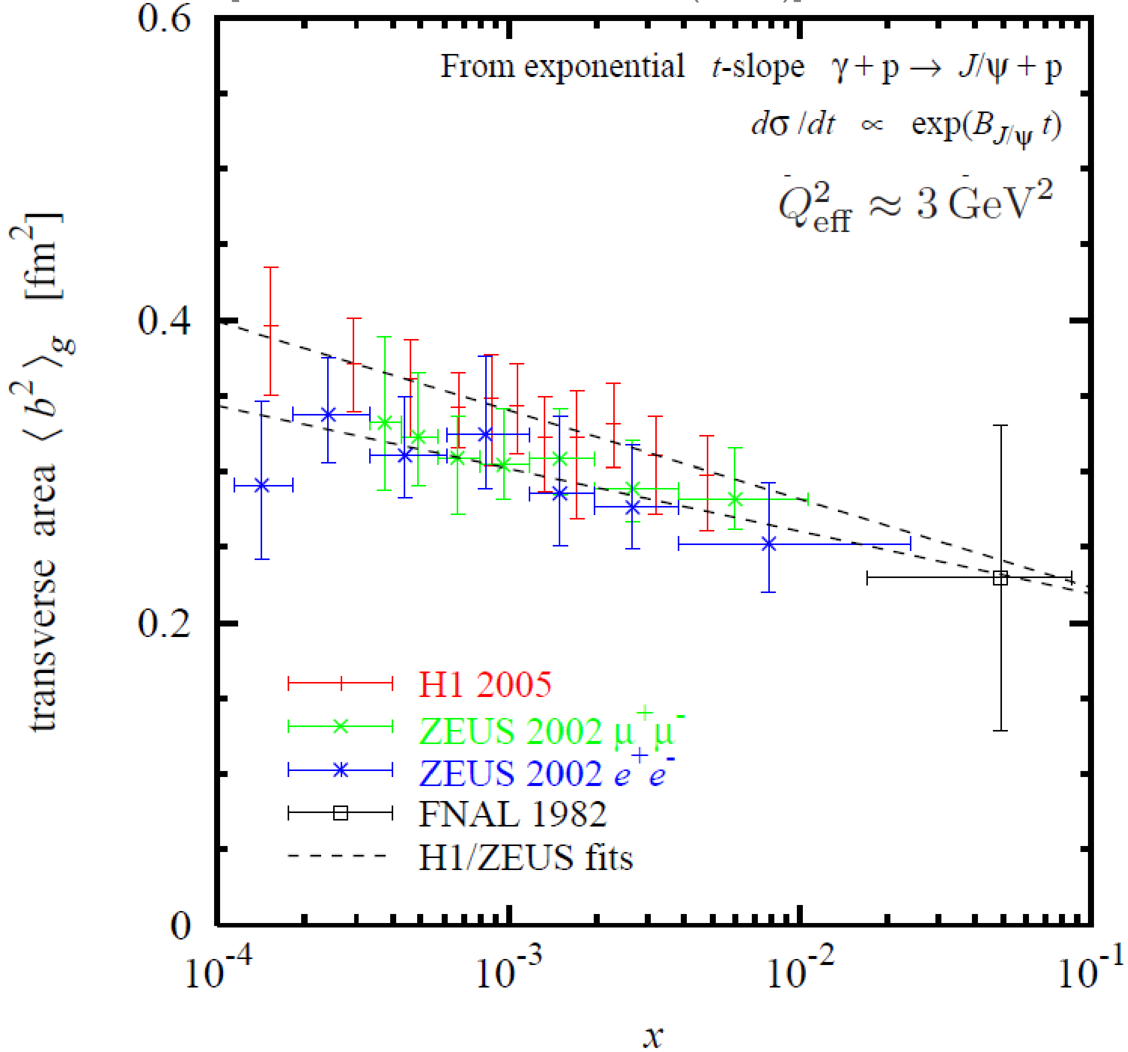
$$\sigma \sim e^{-b|t|}$$

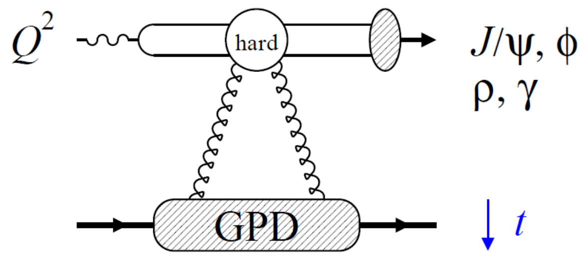
universality of b slope parameter

→ point like configurations dominate

gluon imaging: J/ψ

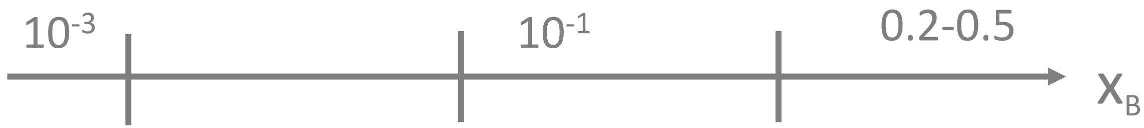
[Frankfurt, Strikman, Weiss (2011)]





- *FT* → average impact parameter

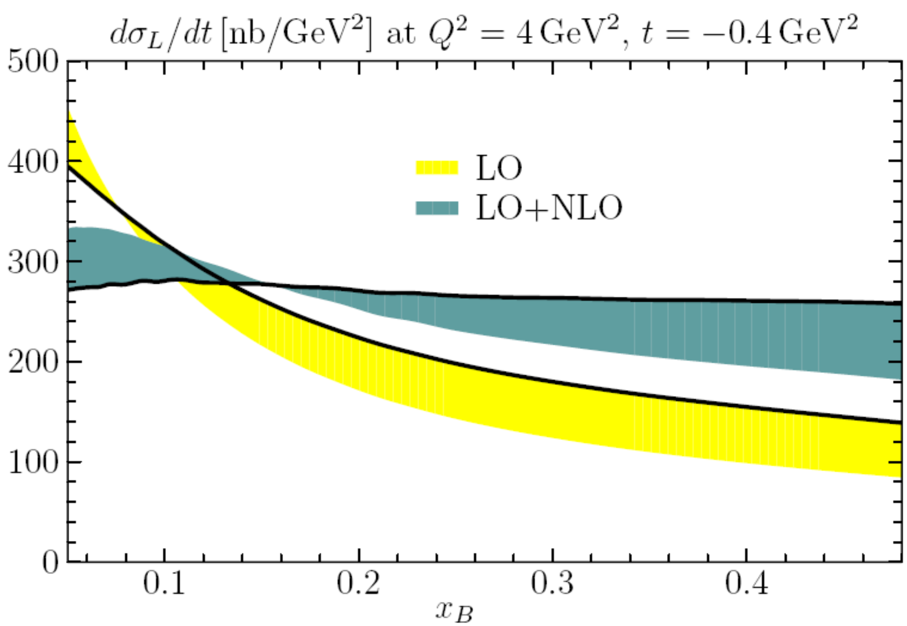
VM production from low → high x



HERA-collider | COMPASS / HERMES / Jlab

g+(sea) | g+(sea)+q_v (ρ,ω) | q_v (ρ,ω)

- NLO corrections to VM production are large: [M. Diehl, W. Kugler (2007)]



ρ^0 cross section @typical kinematics of COMPASS / HERMES / JLab12

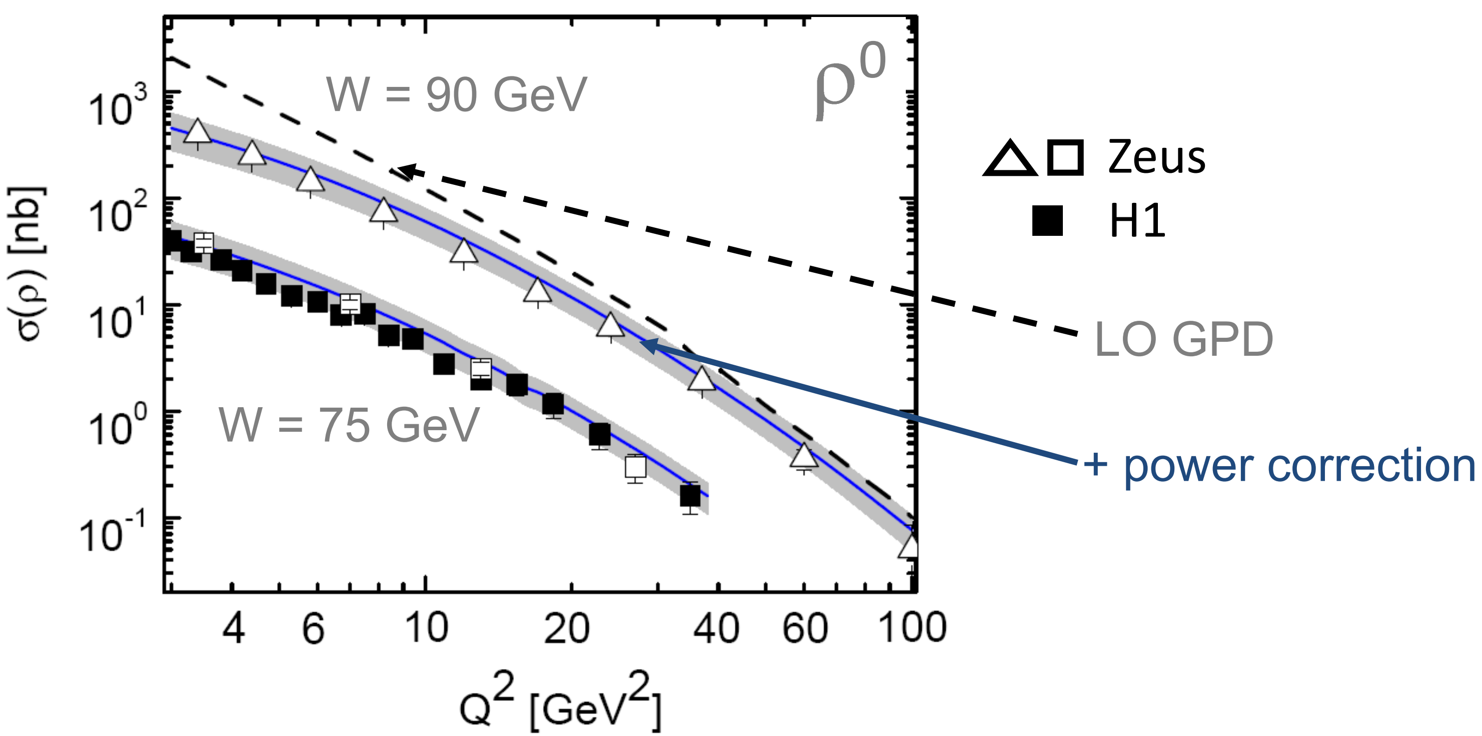
VM production from low → high x

10^{-3} | 10^{-1} | 0.2-0.5 → x_B

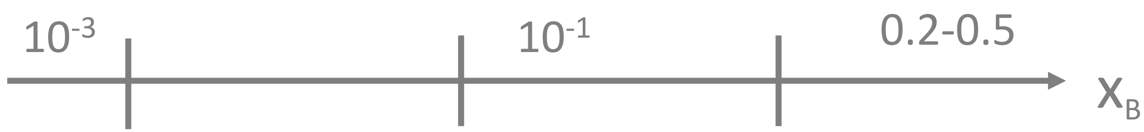
HERA-collider | COMPASS / HERMES / Jlab

g+(sea) | g+(sea)+q_v (ρ,ω) | q_v (ρ,ω)

- ... despite, LO GPD model (handback fact.; DD ansatz): [S. Goloskokov, P. Kroll (2007, 2010)] + power corrections:



VM production from low → high x



HERA-collider — COMPASS / HERMES / Jlab

g+(sea) — g+(sea)+q_v (ρ,ω) — q_v (ρ,ω)

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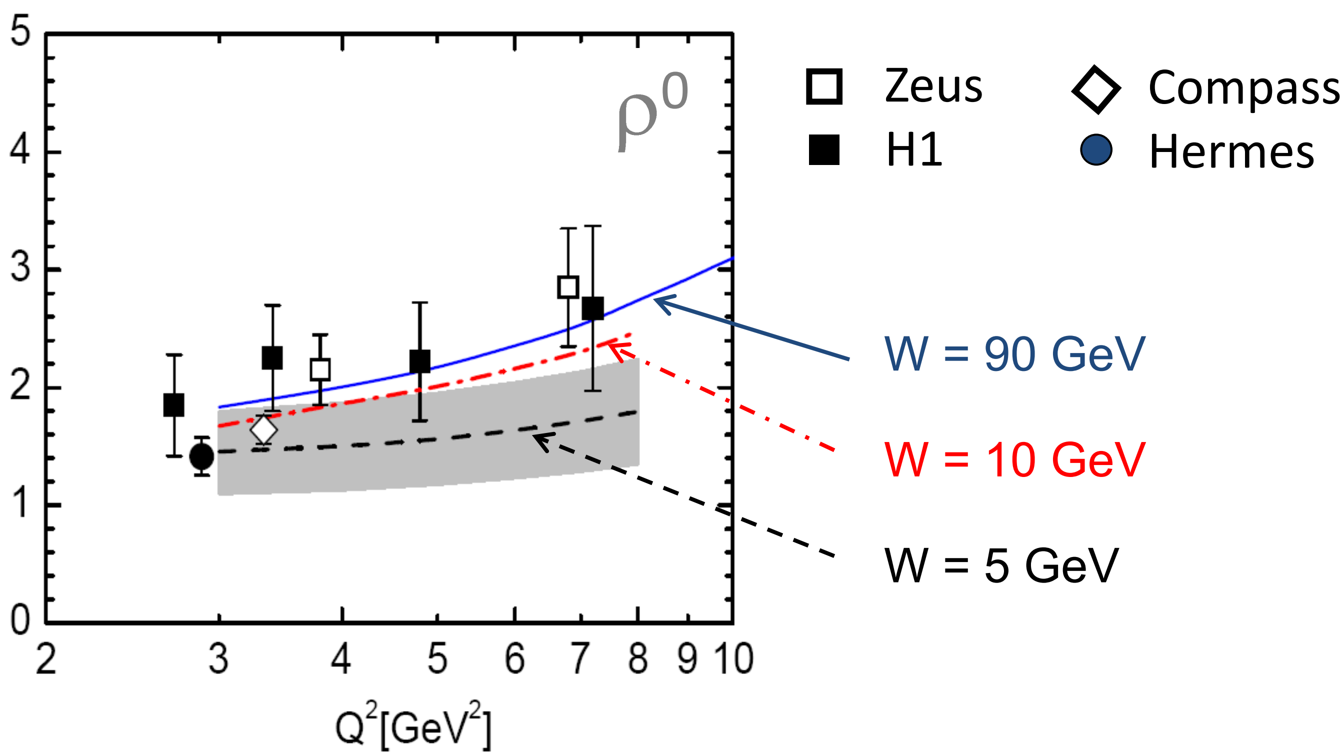
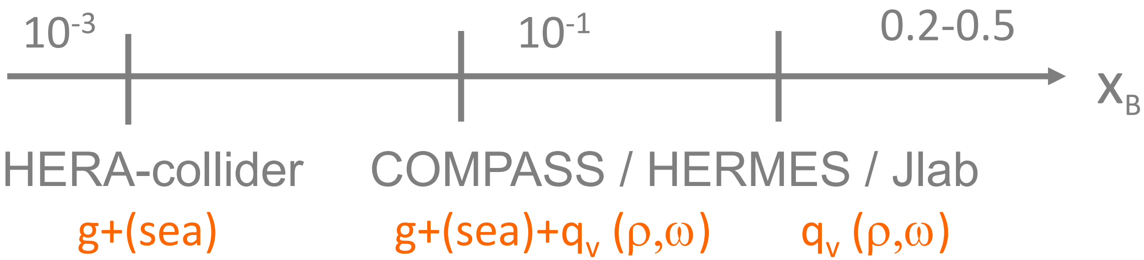


VM production from low → high x



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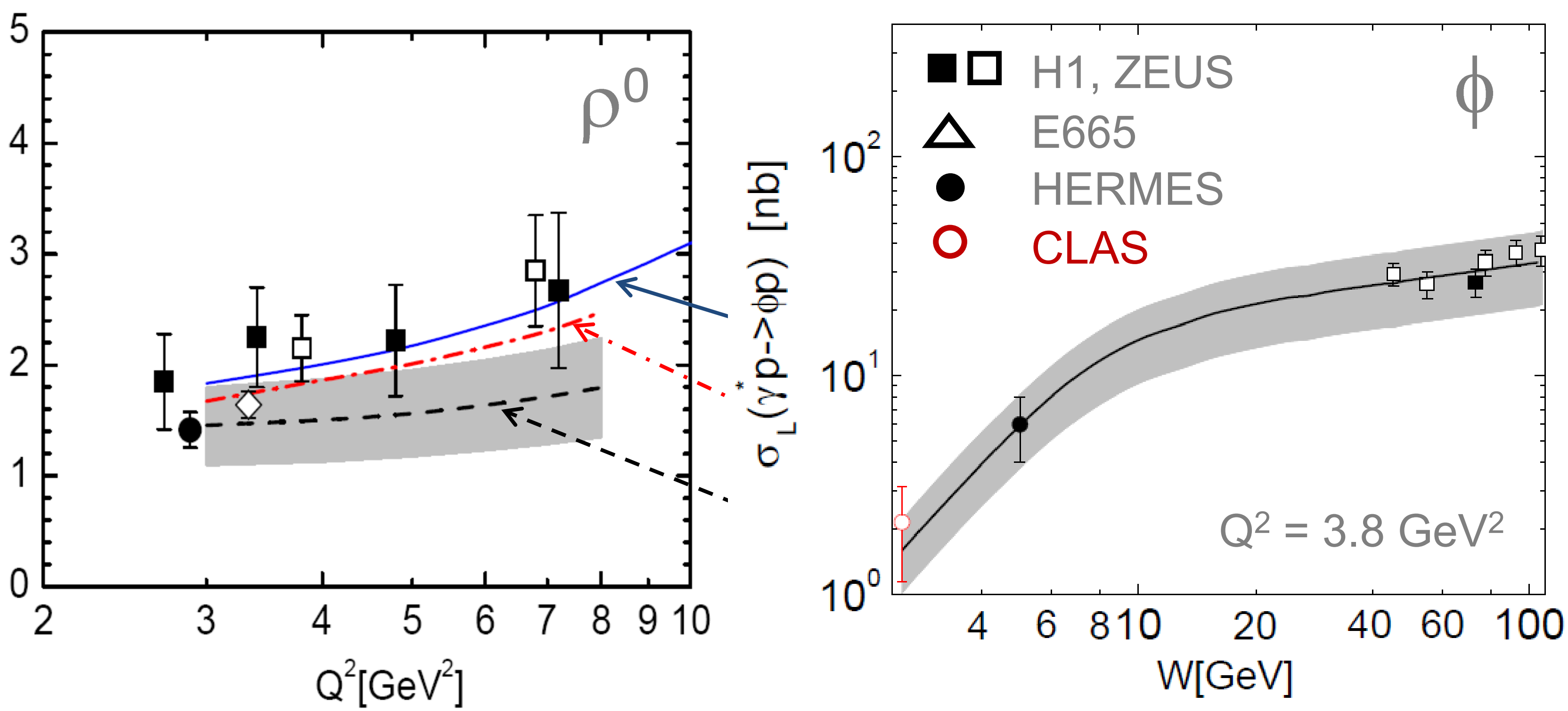
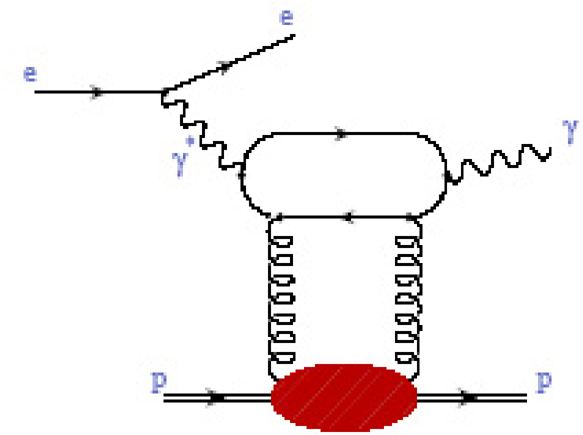


Deeply Virtual Compton Scattering

$\rightarrow H, \widetilde{H}, E, \widetilde{E}$



- DVCS cross sections @ low x

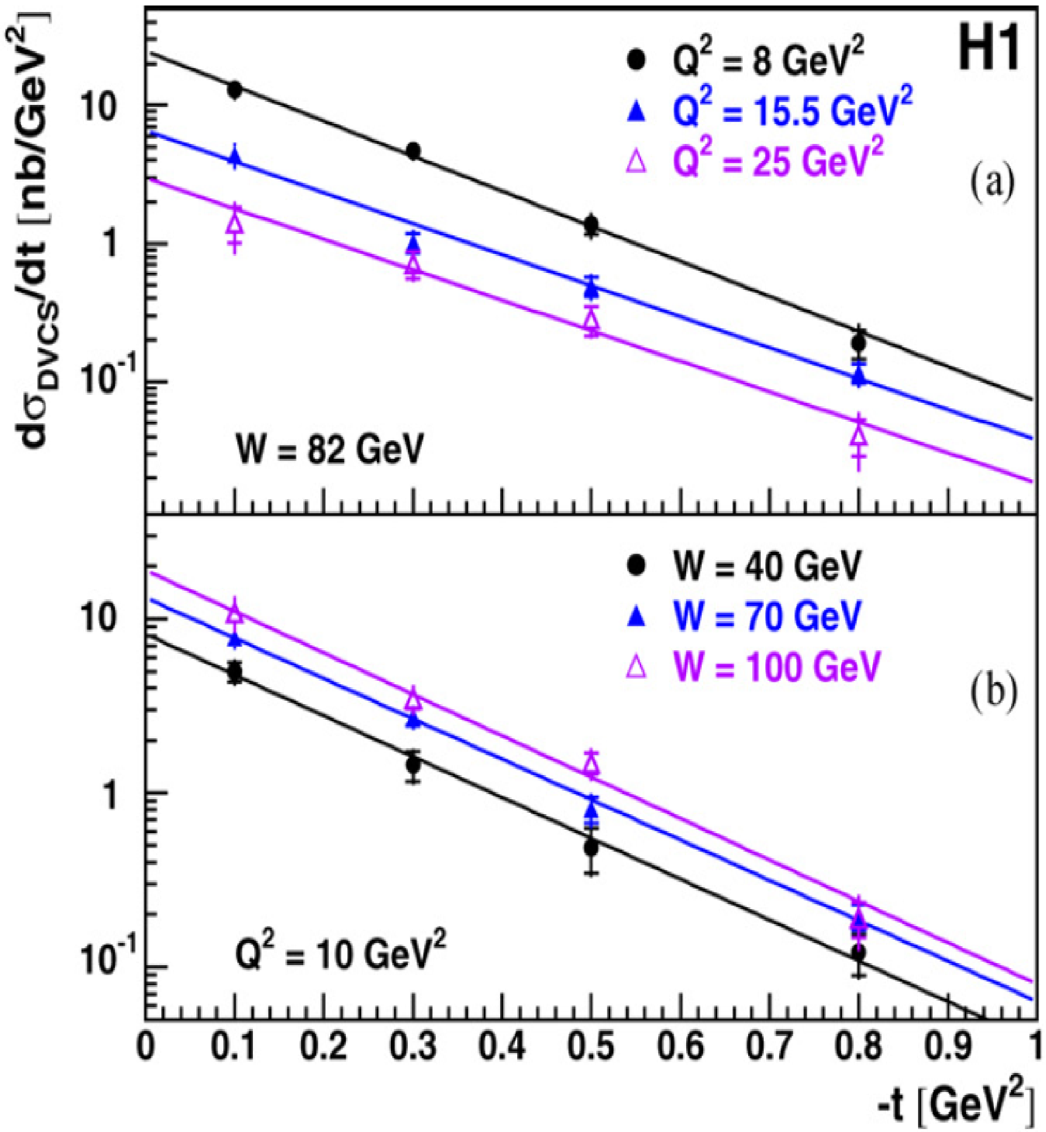
$$d\sigma \propto \tau_{\mathrm{BH}}|^2 + \tau_{\mathrm{DVCS}}|^2$$

$$\frac{d\sigma}{dt} \propto \quad - \; |t|$$

- *t* slope provides absolute normalisation
- *FT* → average impact parameter

DVCS cross section

[PLB659(2008)]

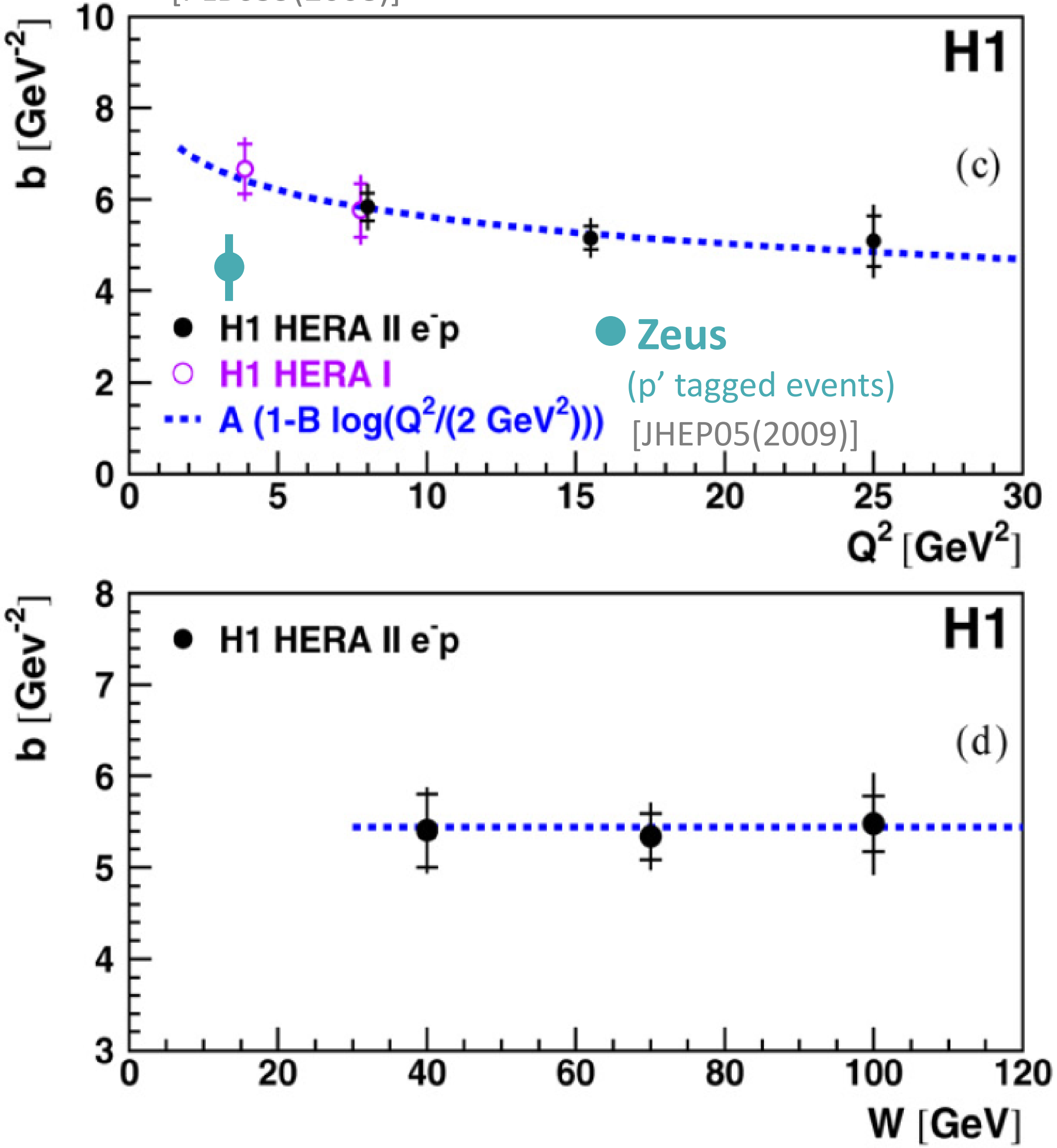


- *t* slope measurement provides absolute normalisation

$$\frac{d\sigma}{dt} \propto \quad - |t|$$

DVCS cross section

[PLB659(2008)]



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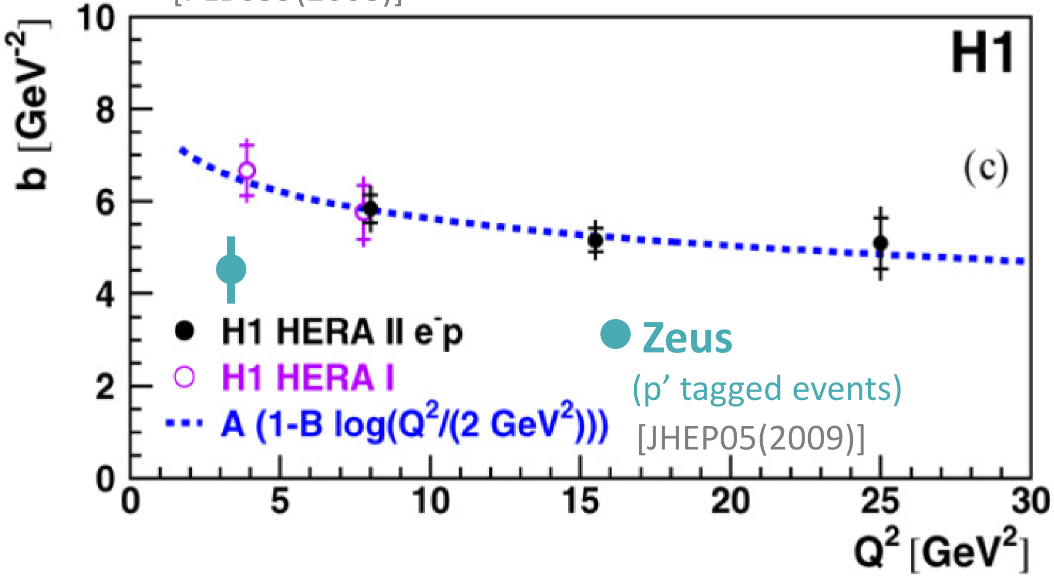
- universality of slope parameter: pointlike configurations dominate

DVCS cross section

[PLB659(2008)]



- *t* slope measurement provides absolute normalisation

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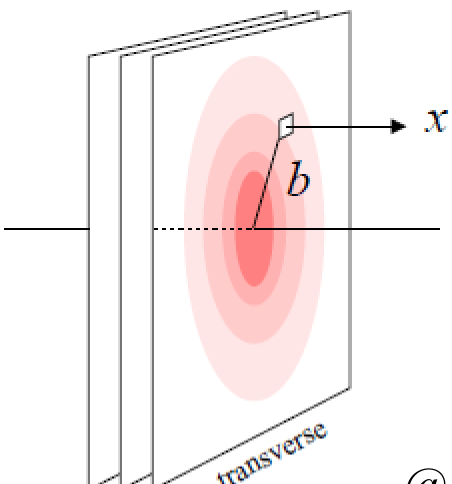
$$\sqrt{\langle b_T^2 \rangle} = (0.65 \pm 0.02)\,\mathrm{fm}$$

@ $x_B = 10^{-3}$

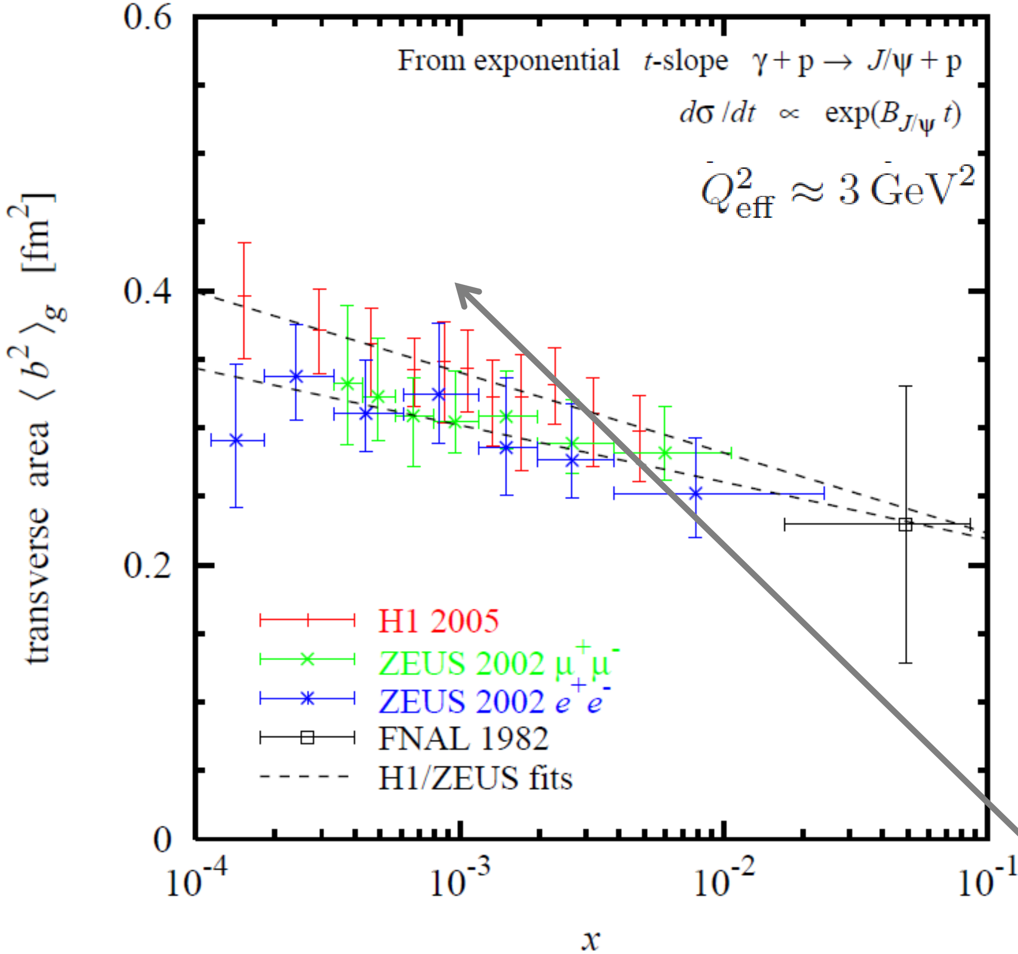
$\langle Q^2 \rangle = 8.0$ GeV^2

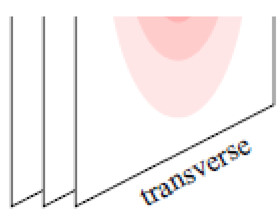


@ $x_B = 10^{-3}$

[courtesy of C. Weiss]

sea quark & gluon imaging





@ $x_B=10^{-3}$

[courtesy of C. Weiss]

→ remember J/ψ

- universality of slope parameter:

pointlike configurations dominate

- *FT* → average impact parameter

$$\sqrt{\langle b_T^2 \rangle} = (0.65 \pm 0.02)\ \mathrm{fm}$$

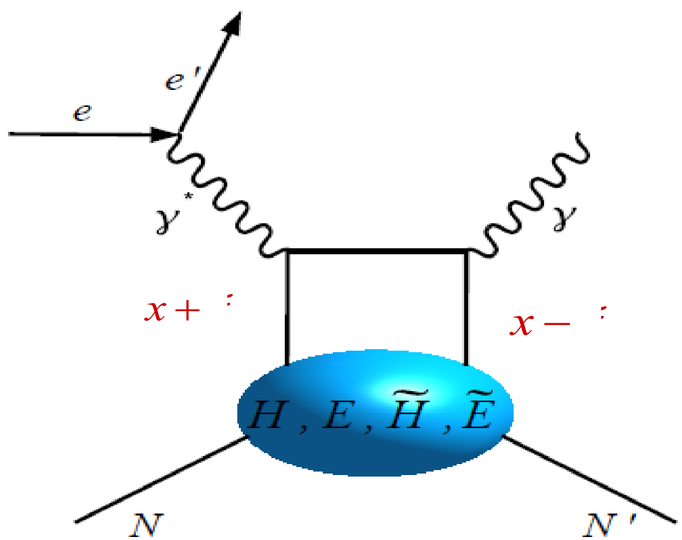
@ $x_B=10^{-3}$

$\langle Q^2 \rangle = 8.0\ \mathrm{GeV}^2$

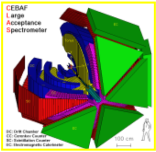
DVCS interference term

$$d\sigma \propto \ {}_{BH}|^2 + \quad + \ \tau^*_{BH}\tau_{DVCS} + \ {}^*_{DVCS}\tau_{BH})$$

→ bilinear in GPDs → *linear* in GPDs



Hall-A



DVCS interference term

hermes

$$d\sigma \propto \quad {}_{BH}|^2 + \qquad + \tau^*_{BH}\,\tau_{DVCS} + {}^*_{DVCS}\,\tau_{BH})$$

→ bilinear in GPDs → *linear* in GPDs

isolate interference term:

- different beam charges: e^+ e^- (only @HERA, upcoming @COMPASS)
- polarisation observables

$\Delta\sigma_{UT}$

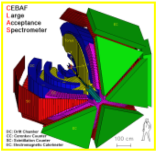
↙ ↘

beam target

U, L U, L, T

Unpolarised, **L**ongitudinally, **T**ransversely polarised

Hall-A



DVCS interference term

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→ bilinear in GPDs → *linear* in GPDs

isolate interference term:

- different beam charges: $e^+ e^-$ (only @HERA, upcoming @COMPASS)
- polarisation observables

$\Delta\sigma_{UT}$

beam: U, L

target: U, L, T

$\Delta\sigma_C$, $\Delta\sigma_{LU}$ → *H*

$\Delta\sigma_{UL}$ → $\tilde{H}$

$\Delta\sigma_{UT}$, $\Delta\sigma_{LU}$ → *H*, *E*

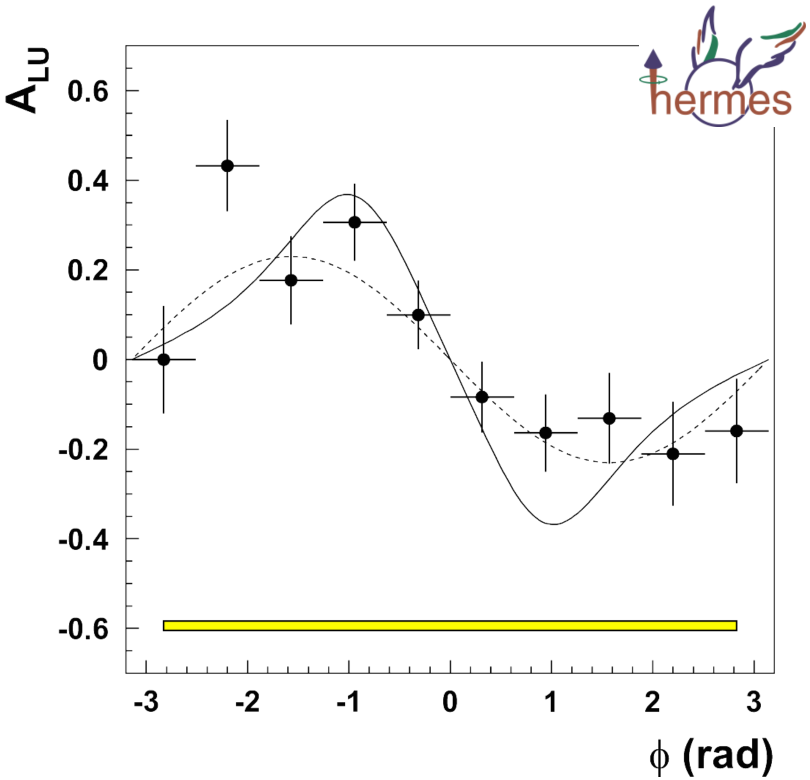
neutron

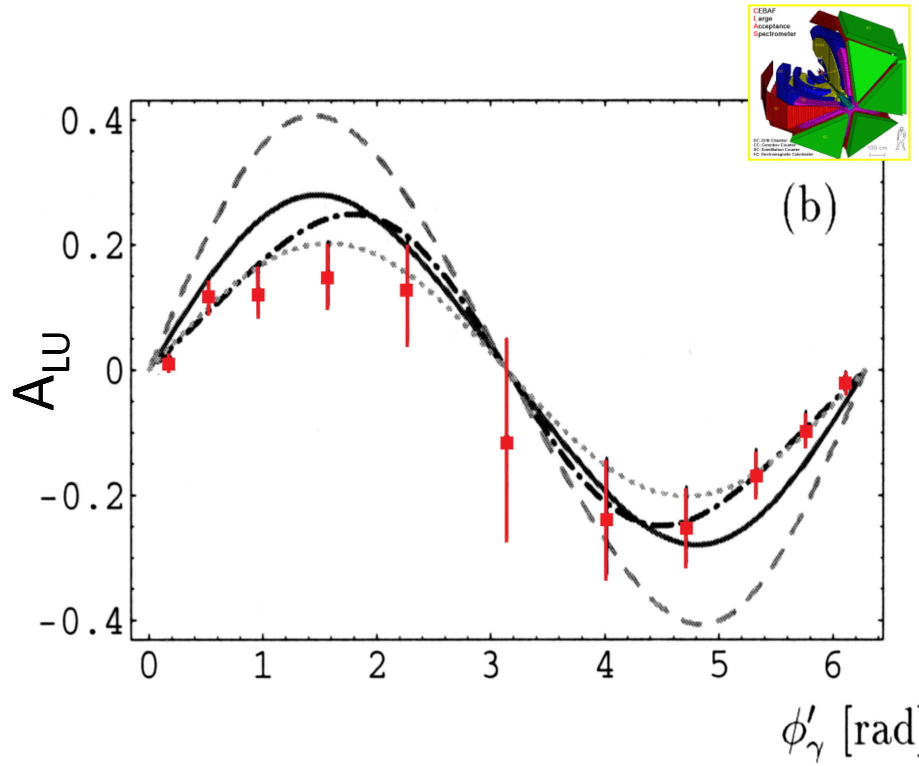
@kinematics of current fixed target exp.

first DVCS signals

-- interference term --

[PRL87(2001)]

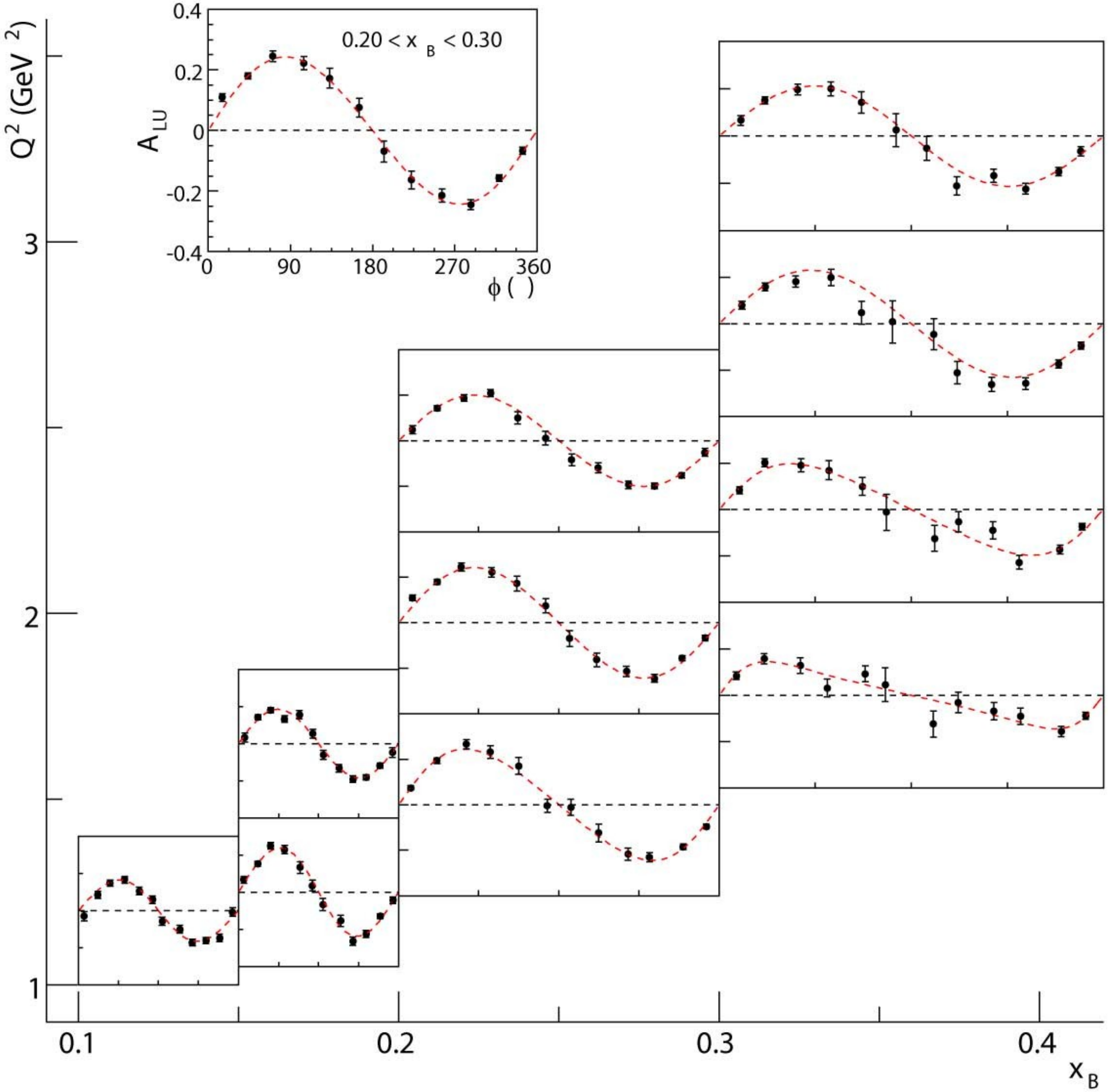




→ sinφ dependence indicates dominance of handback contribution

call for high statistics

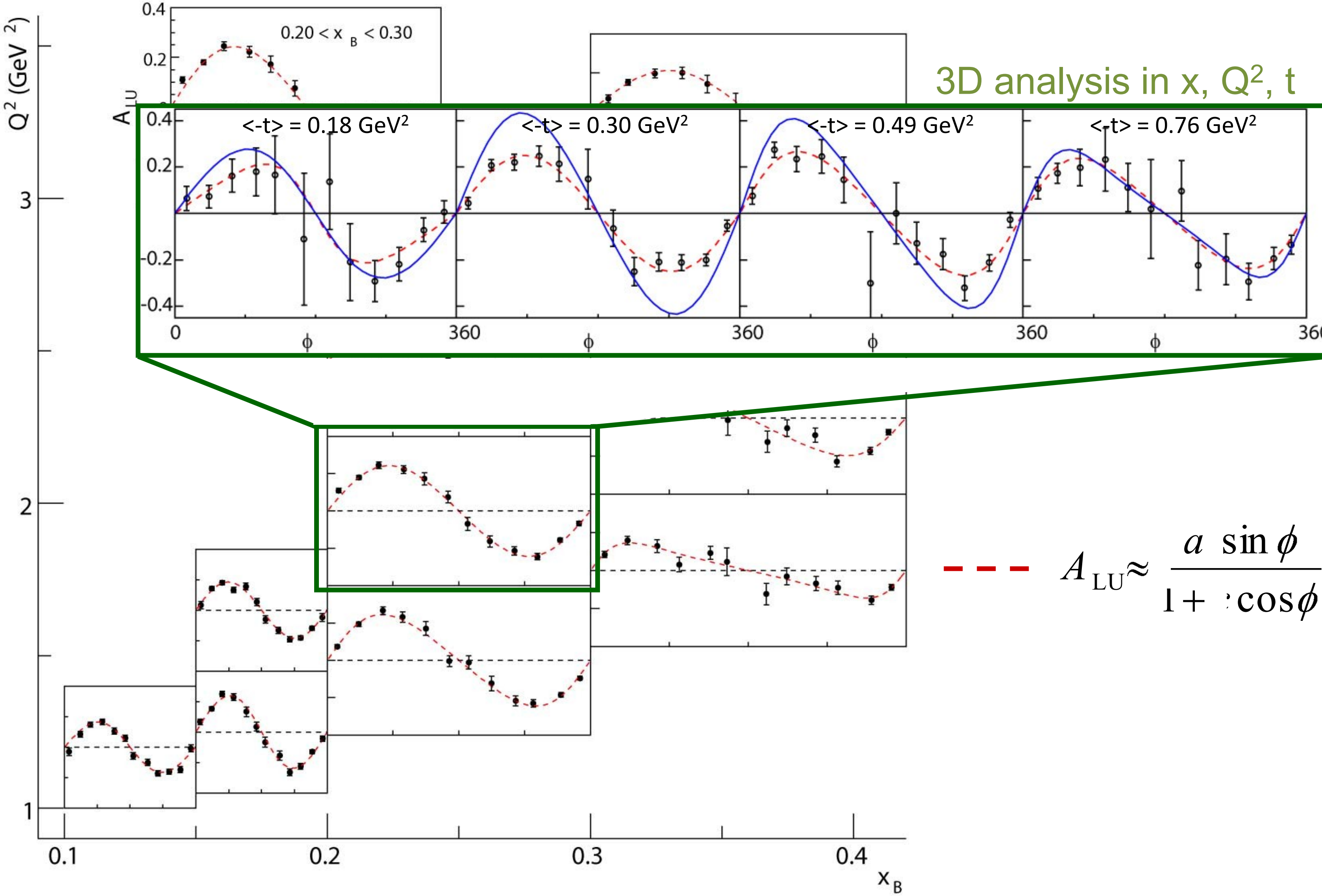
JLab-e1: DVCS beam-spin asymmetry [PRL100(2008)]



$$A_{LU} \approx \frac{a\ \sin\phi}{1+\ \cos\phi}$$

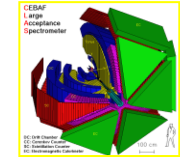
call for high statistics

JLab-e1: DVCS beam-spin asymmetry [PRL100(2008)]

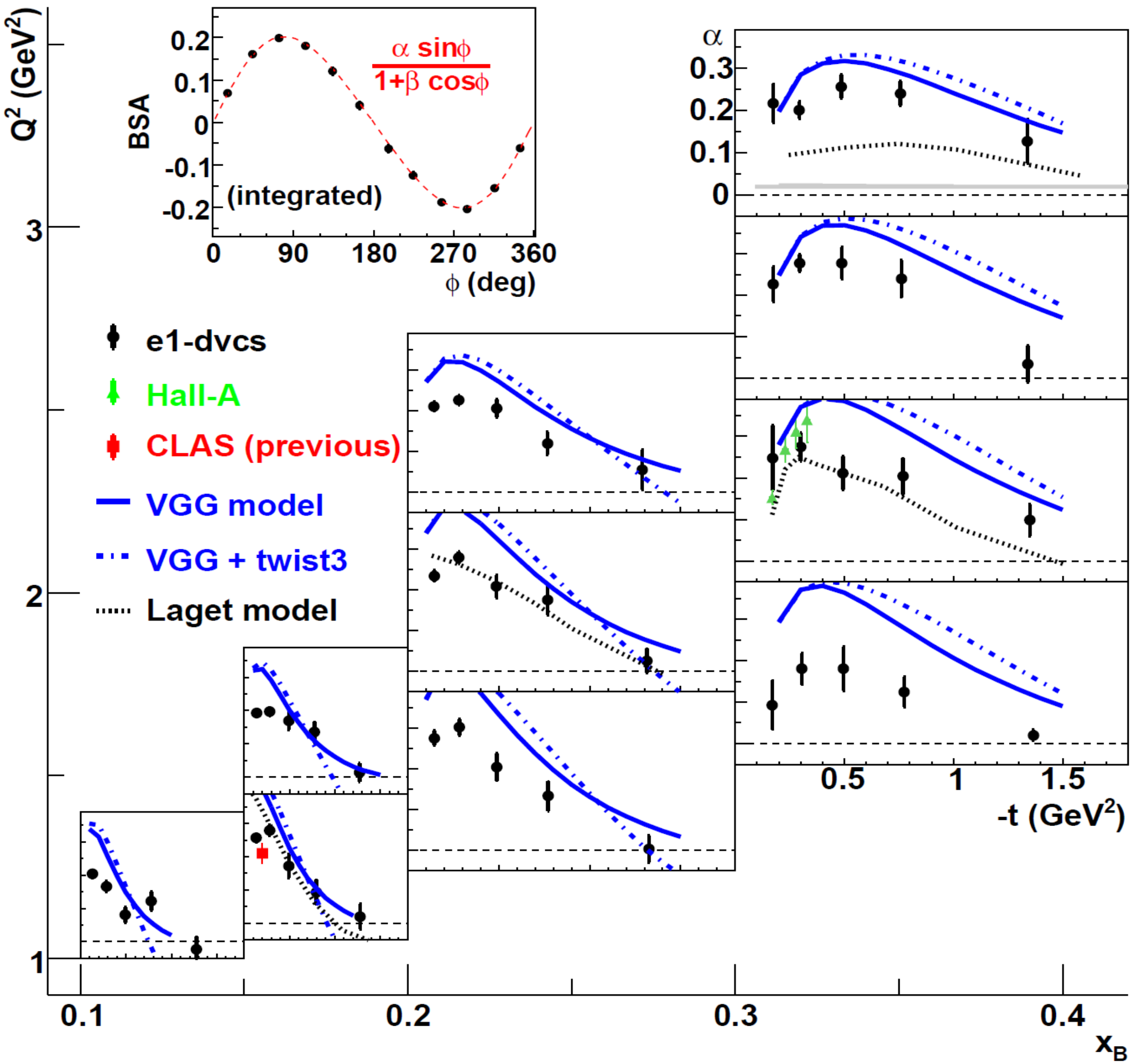


$$A_{LU} \approx \frac{a \sin\phi}{1 + c\cos\phi}$$

call for high statistics



JLab-e1: DVCS beam-spin asymmetry [PRL100(2008)]



$\alpha \propto \mathrm{Im}(F_1 H)$

Hall-A

... cross section from interference term

talk by X. Girod

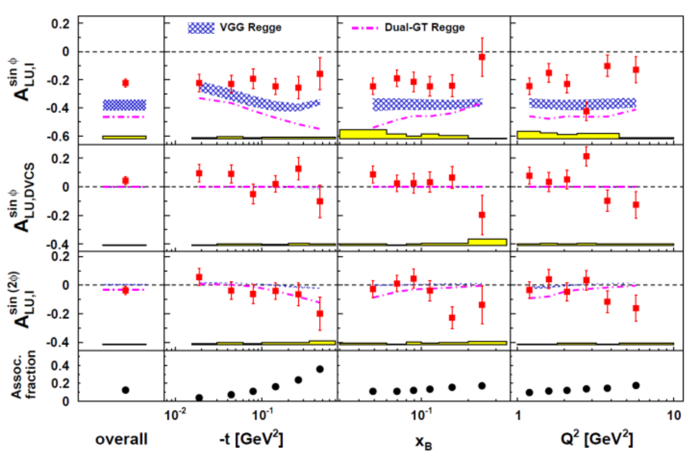
call for new analysis methods

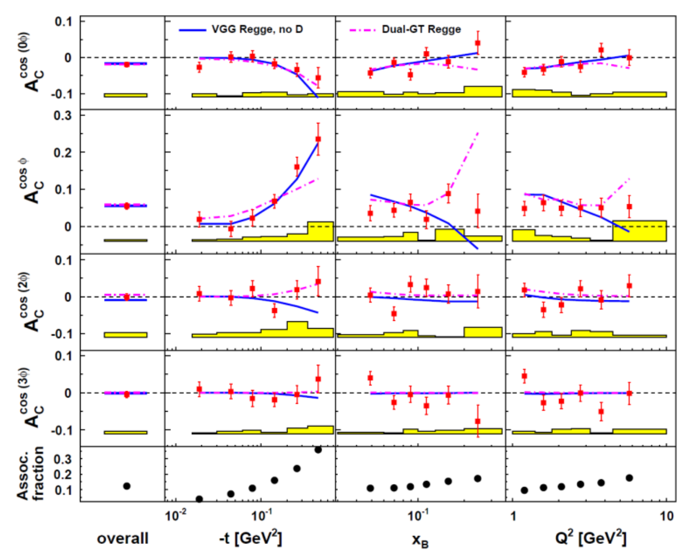
combined analysis of charge & polarisation observables

→ separation of interference & DVCS^2 amplitudes

$$\sigma_{\rm LU}(\phi; P_{\rm l}, e_{\rm l}) = \sigma_{\rm UU}(\phi) \cdot \{1 + P_{\rm l} A_{\rm LU}^{\rm DVCS}(\phi) + e_{\rm l} P_{\rm l} A_{\rm LU}^{\mathcal{I}}(\phi) + e_{\rm l} A_{\rm C}(\phi)\}$$

$$s_1^{\rm DVCS} sin(\phi) \qquad \sum_{n=1}^{2} s_n^{\rm I} sin(n\phi) \qquad \sum_{n=0}^{3} c_n^{I} cos(n\phi)$$





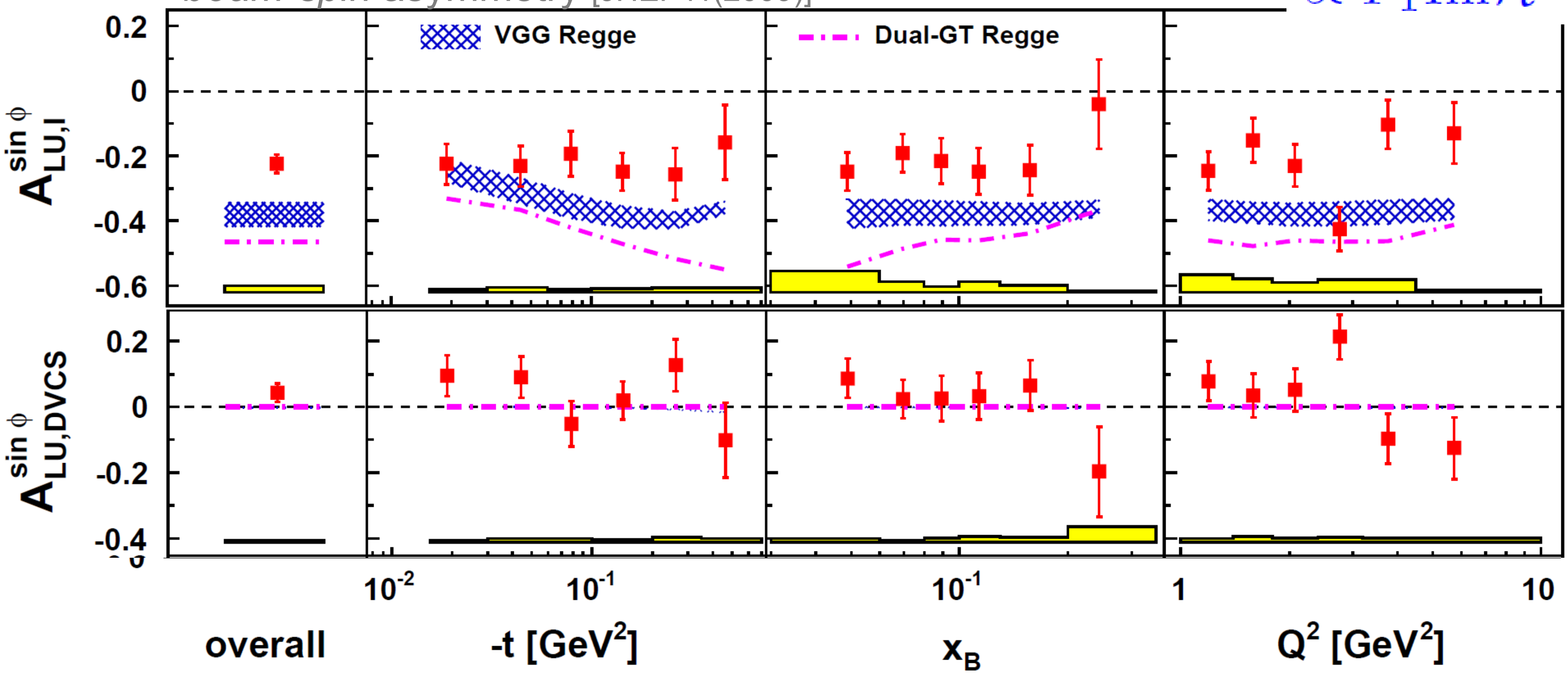
call for new analysis methods

combined analysis of charge & polarisation observables

→ separation of interference & DVCS[2] amplitudes

beam-spin asymmetry [JHEP11(2009)]

$\propto F_1 \mathrm{Im}\mathcal{H}$



GPD models: DD [VGG(1999)]

minimal-dual [GT(2007)]

more, recent results

talk by S. Yaschenko

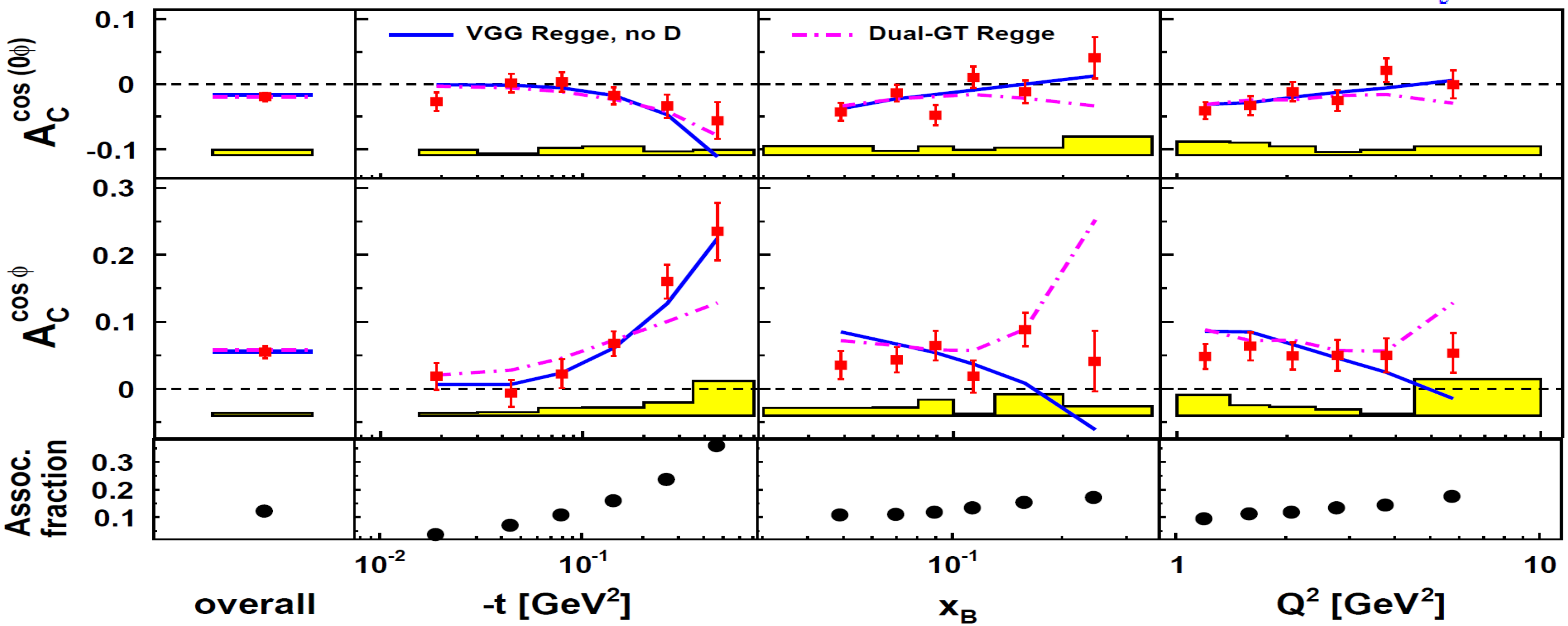
call for new analysis methods

combined analysis of charge & polarisation observables

→ separation of interference & DVCS^2 amplitudes

beam-charge asymmetry [JHEP11(2009)]

$A_C^{\cos\phi} \propto F_1 \mathrm{Re}\mathcal{H}$ $\quad A_C^{\cos 0\phi} \propto -\frac{t}{Q} A_C^{\cos\phi}$



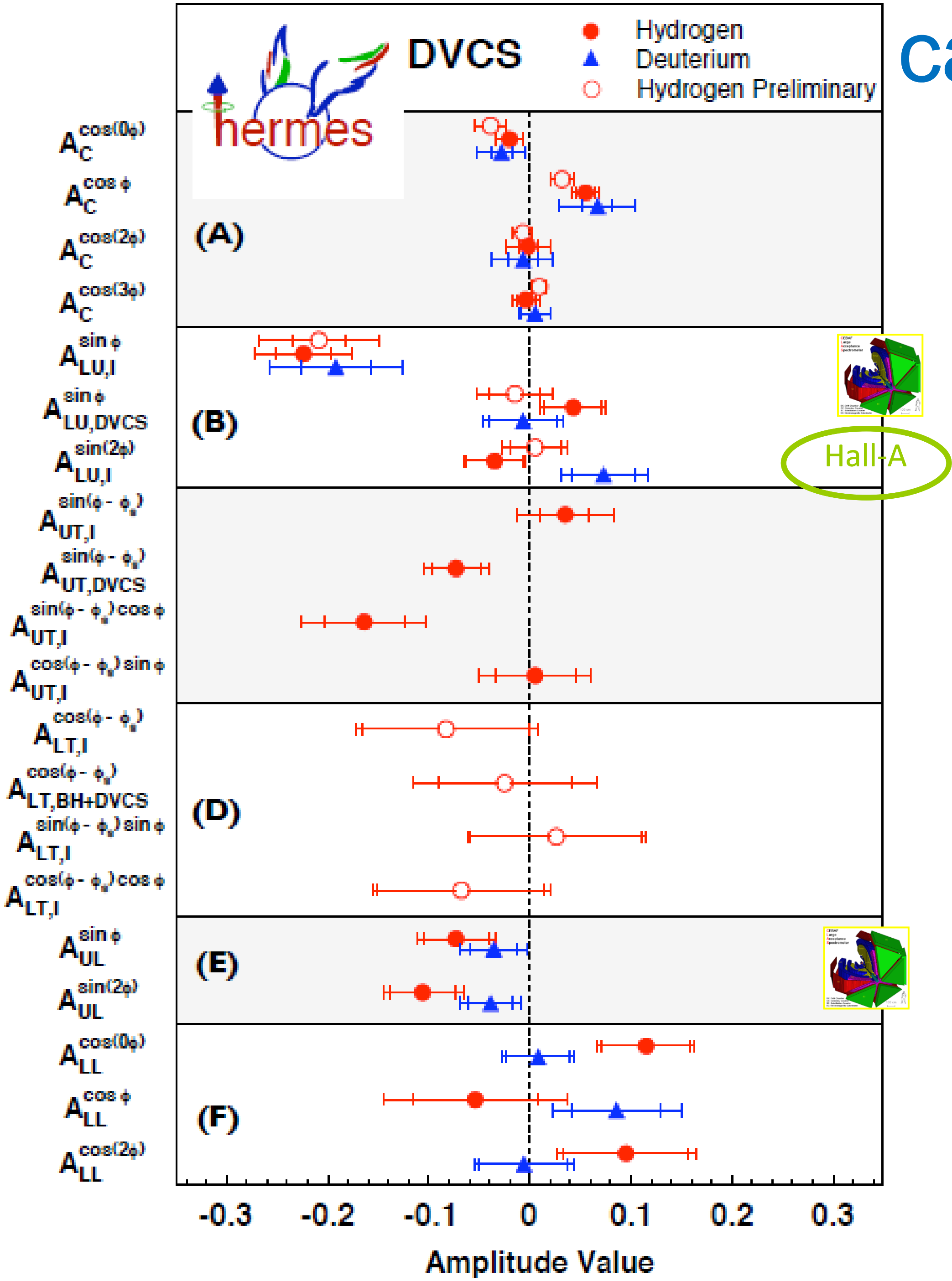
GPD models: DD, no D-term [VGG(1999)]

minimal-dual [GT(2007)]

more, recent results

talk by S. Yaschenko

call for completeness



→charge asymmetry

Re (H)

→beam-spin asymmetry

Im (H)

→ transverse target spin asymmetry

Im (H-E)

→ transverse-target double-spin

Re (H-E)

→ longitudinal target spin asymm.

Im $(\tilde{H})$

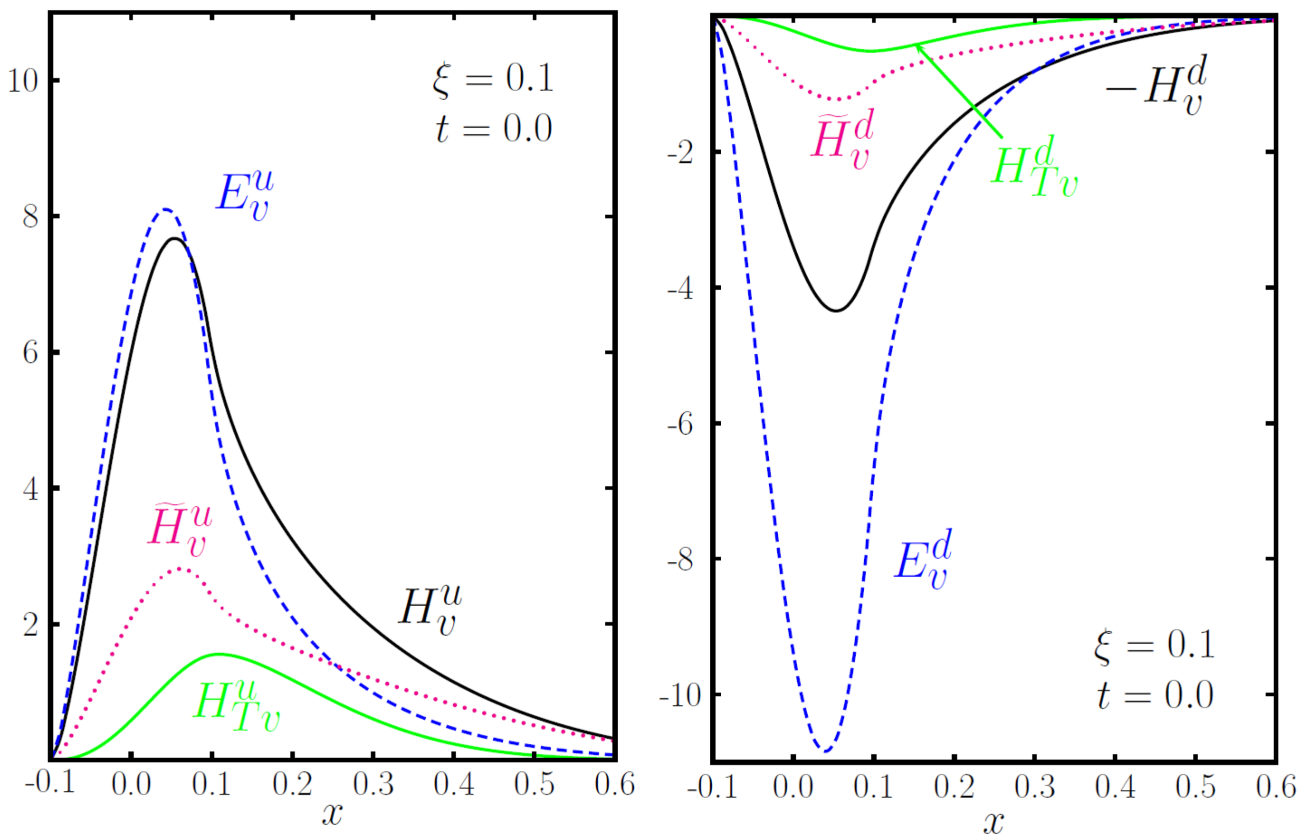
→ longitudinal-target double-spin

Re $(\tilde{H})$

towards GPDs

recent developments (beyond VGG(1999)...)

- Goloskokov, Kroll (2007):
  - → LO GPD model using *DD, regge t dep., power corrections*
  - → fit to exclusive meson production data



towards GPDs

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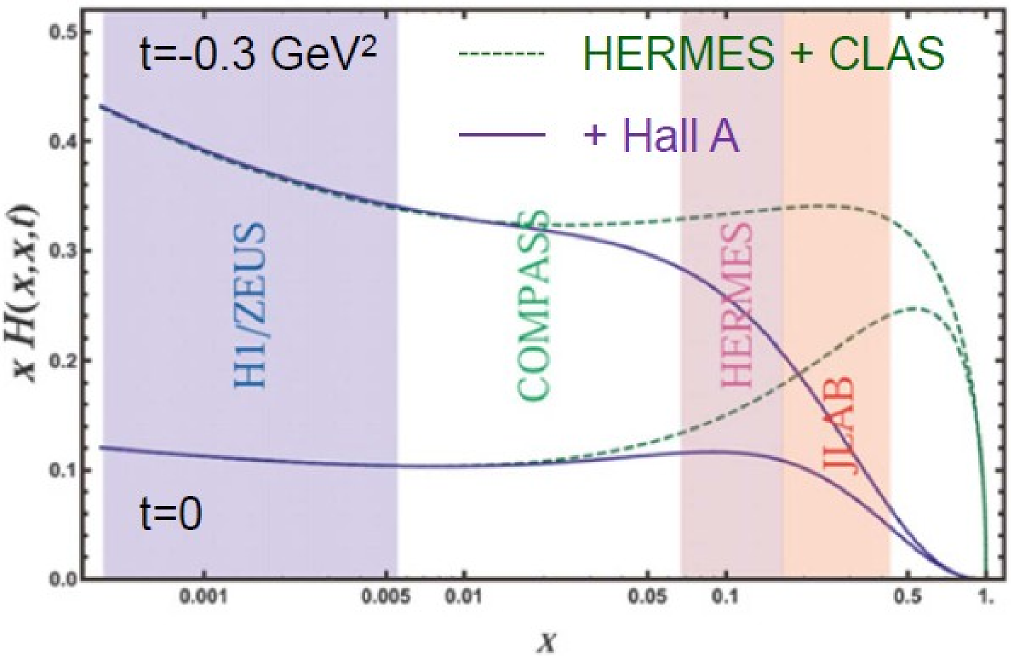
- Kumericki, Müller (2010):
  → partial wave expansion of GPDs*, regge t dep., dispersion relations*
  → fit to DVCS data



towards GPDs

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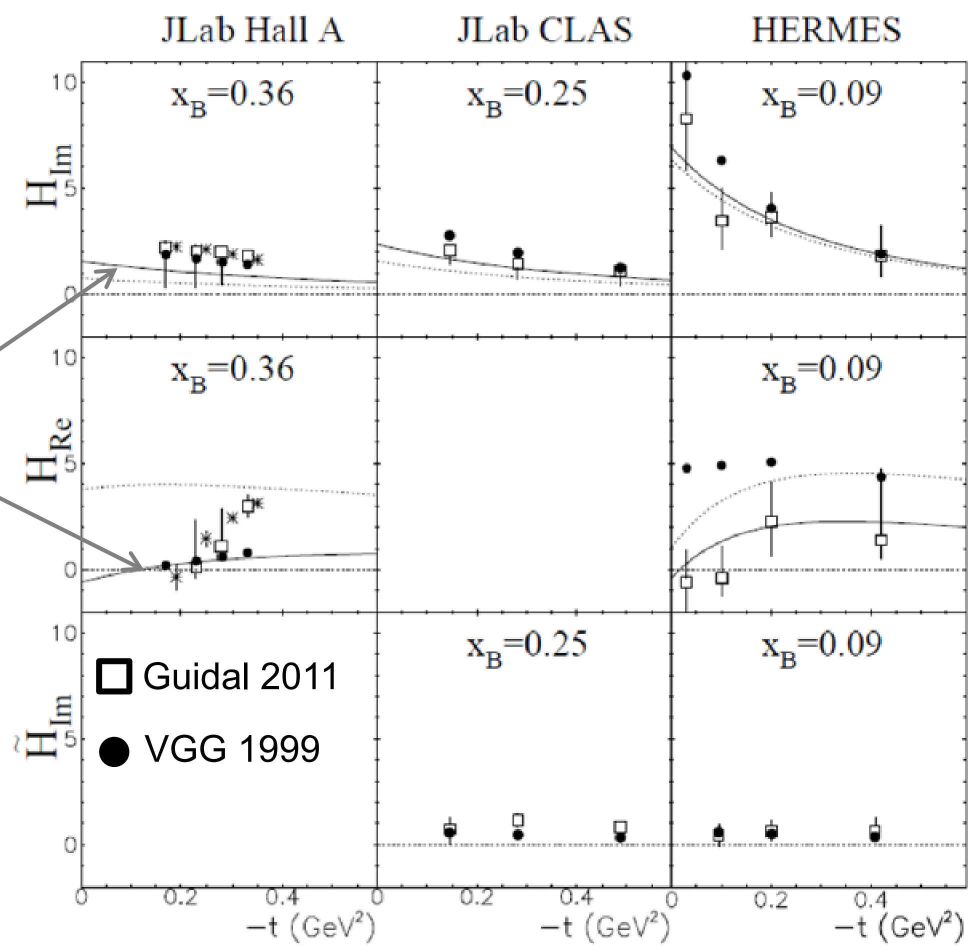
  → fit to DVCS data
- Goldstein, Hernandez,Liuti (2010):
  → quark-diquark model of GPDs*, Regge ansatz for low x region & t dep.*
  → fit to DVCS data

talk by S. Liuti [tomorrow]

towards GPDs

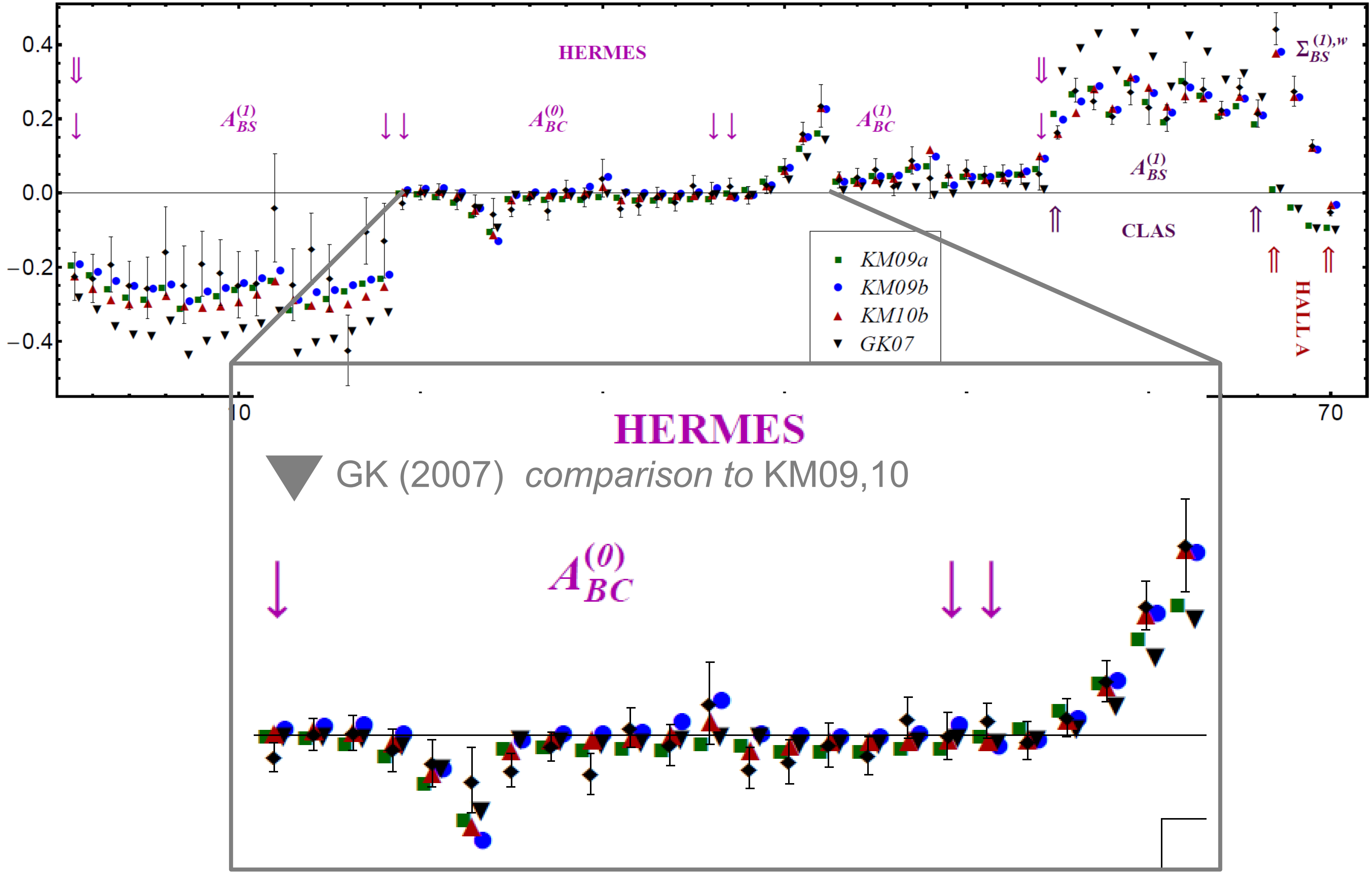
recent developments (beyond VGG(

- Goloskokov, Kroll (2007):
  → LO GPD model using *D*
  → fit to exclusive meson p
- Kumericki, Müller (2010):
  → partial wave expansion c
  → fit to DVCS data
- Goldstein, Hernandez,Liuti (201
  → quark-diquark model of (
  → fit to DVCS data
- Guidal (2011):
  → *model independent* extraction of *CFF* (GPD extr. requires model ansatz)
  → kinematic fitting of DVCS data (per experiment)

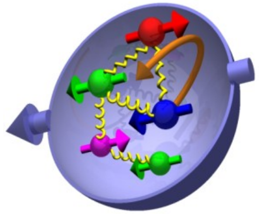


towards global analysis of GPDs

-- employ all available exclusive data (DVCS & meson production) --



hunting the OAM



- attempts to constrain J^q

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

→ GPD models: J^q free parameter in ansatz for E

observables sensitive to E :

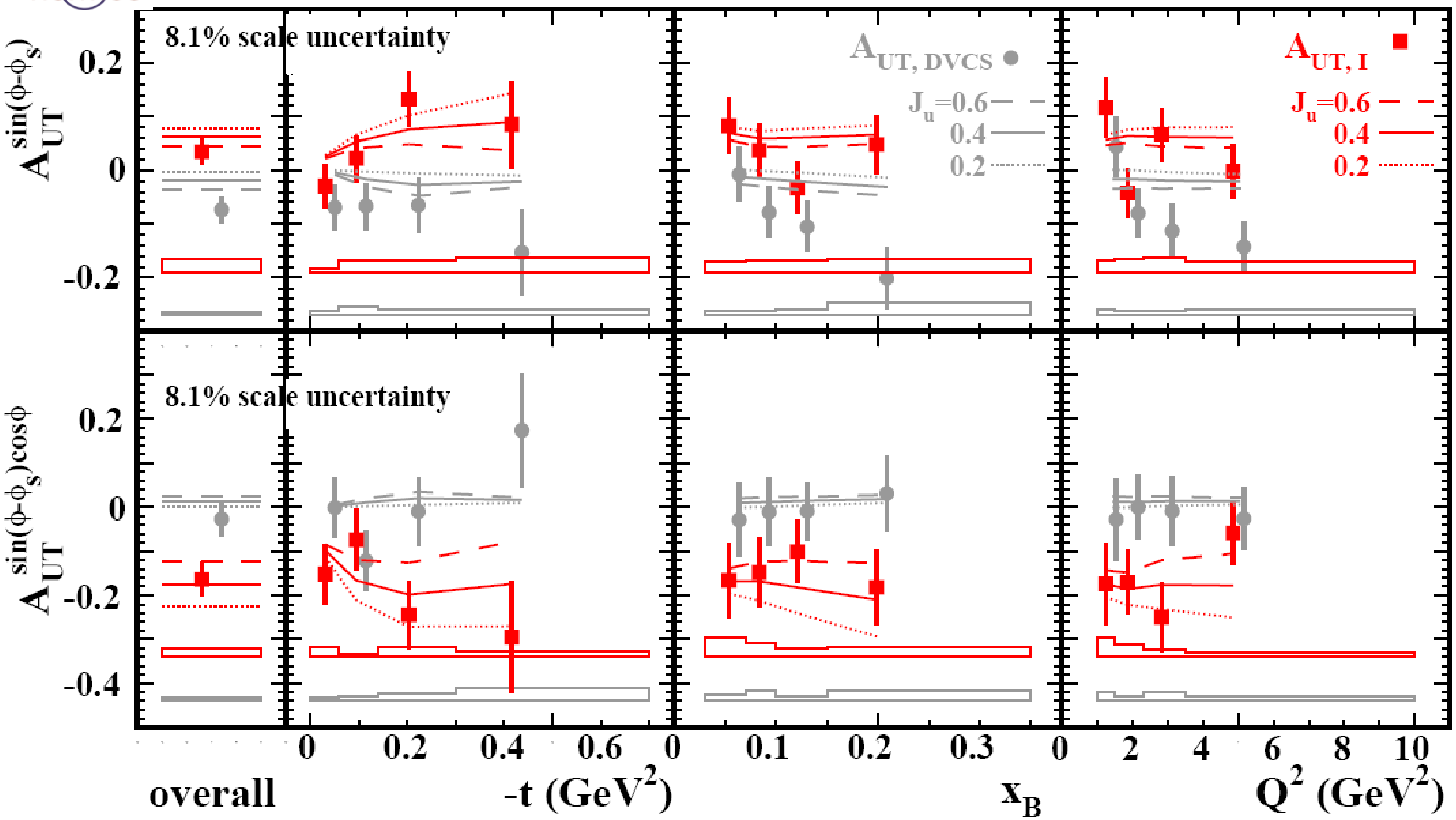
- pDVCS: A_{UT} → HERMES
- nDVCS: A_{LU} → HallA
- meson prod. A_{UT}: ρ^0 → HERMES, COMPASS

...also ω, ϕ, ρ^+, K^{*0}

hunting the OAM

-- pDVCS : transverse target-spin asymmetry --

→ GPD models: J^q free parameter in ansatz for E [JHEP06(2008)]



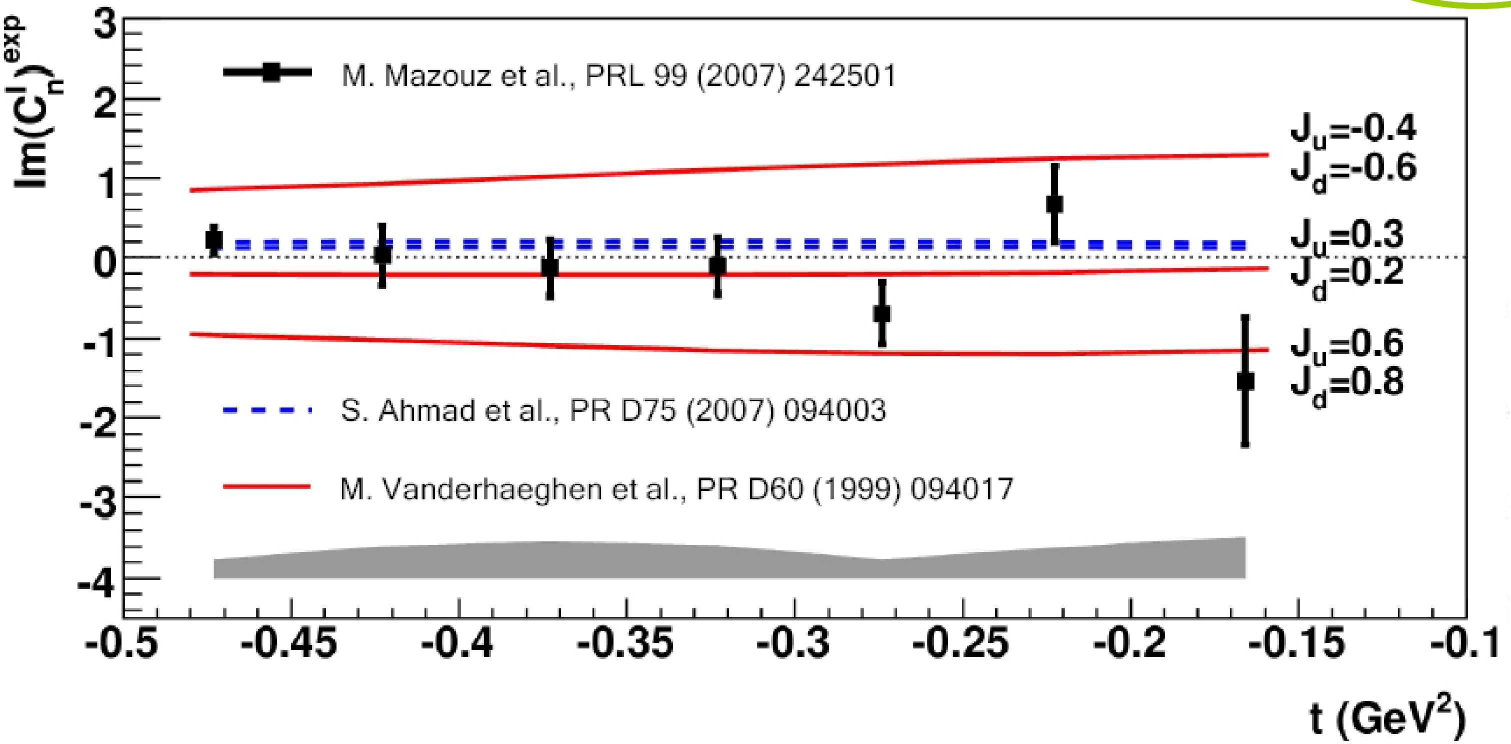
[VGG]

hunting the OAM

-- nDVCS : beam-spin cross section difference --

→ GPD models: J^q free parameter in ansatz for E

Hall-A



hunting the OAM

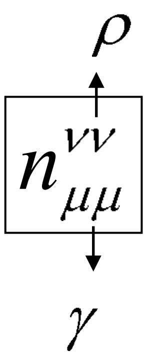
-- ρ^0 : transverse target-spin asymmetry --

after the full glory of SDME extractions

[formalism by M. Diehl (2007)]

$(\gamma_{\_} \rightarrow \quad _{\_}):$

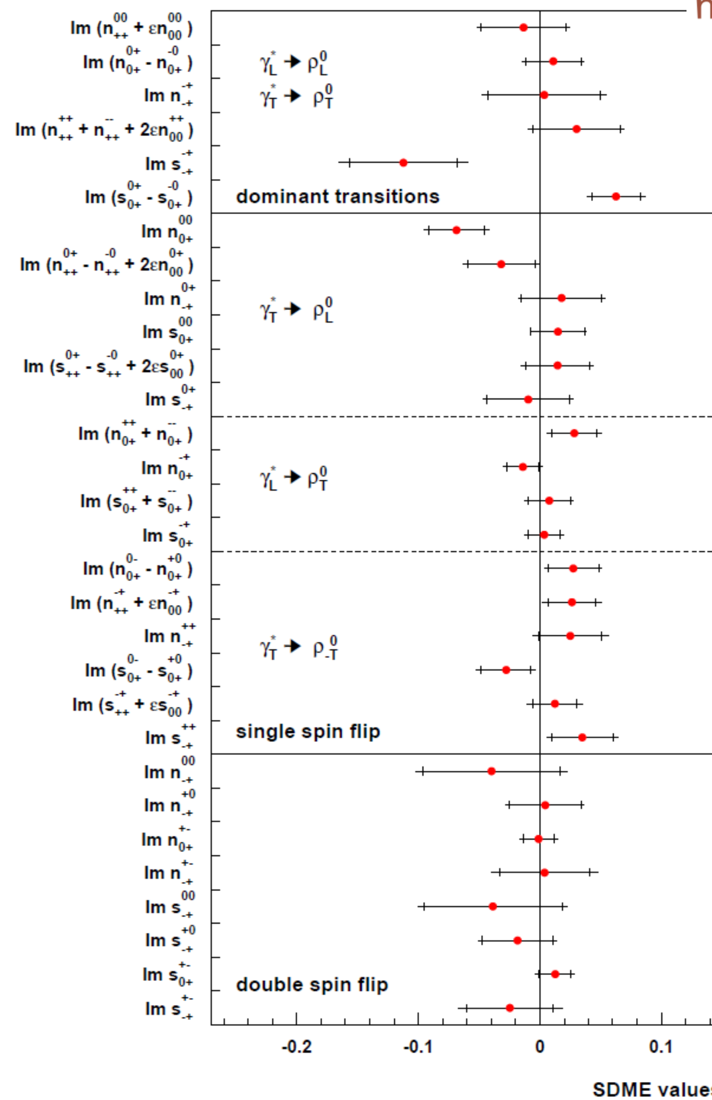
$$A_{UT}^{\gamma^*}(\phi, \phi_s) = \frac{\mathrm{Im}\, n_{00}^{00}}{u_{00}^{00}}$$



$\mu,\nu = \,),\pm$

long.pol: 0

transv.pol: ±1



[PLB679(2009)]

hunting the OAM

-- ρ^0 : transverse target-spin asymmetry --

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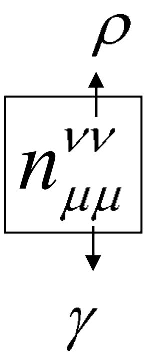
$$A_{UT}^{\gamma^*}(\phi, \phi_s) = \frac{\mathrm{Im}\, n_{00}^{00}}{u_{00}^{00}}$$



$\mu, \nu = \;), \pm$

long.pol: 0

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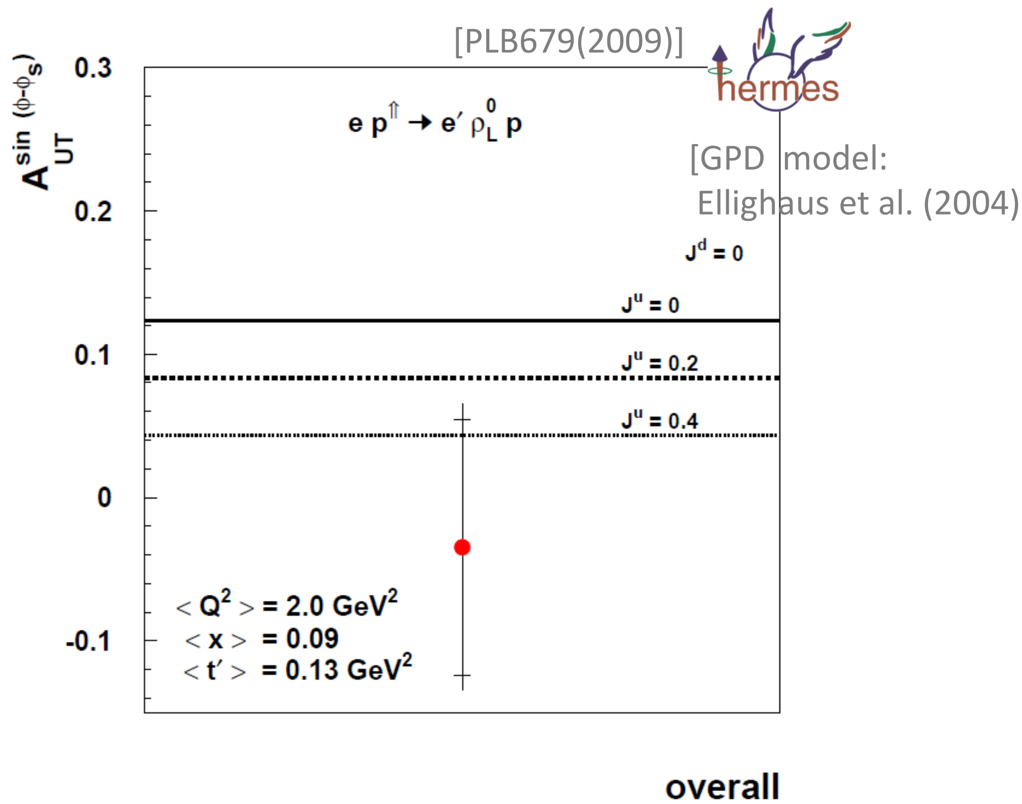
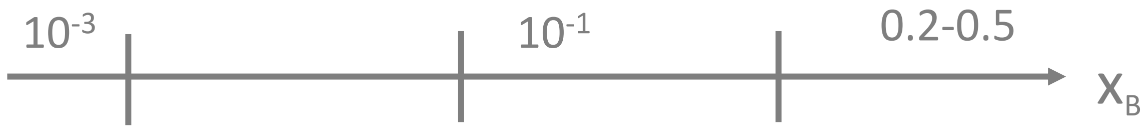


- more data coming: COMPASS, JLab12 with transv. Target
- more models: Goloskokov, Kroll

conclusions & perspectives



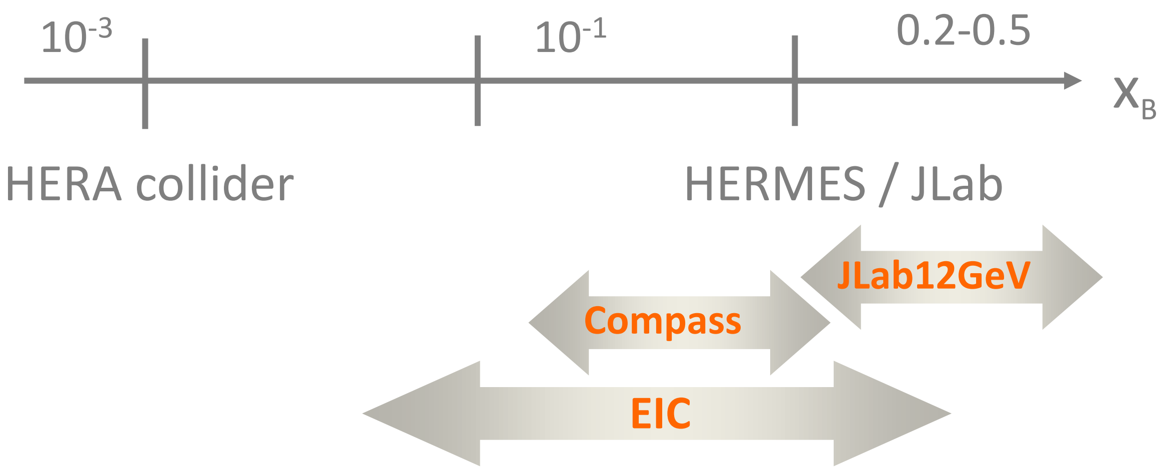
HERA collider — COMPASS — HERMES / JLab

$10^{-4} < x_B < 0.02$ — $0.02 < x_B < 0.4$ / $0.1 < x_B < 0.6$

sea quarks & gluons — (gluons) (valence) quarks

- increasing amount and precision of experimental data
- progress in model calculations, plenty of room for more work...

conclusions & perspectives



- increasing amount and precision of experimental data
- progress in model calculations, plenty of room for more work...
- bright future for GPD studies:

talks by V. Burkert, N. D'Hose, F. Maas

→ JLab12

→ COMPASS-II with recoil

→ EIC/ENC (mapping of GPDs from Q^2 evolution)