Delia Hasch

INFN Frascati

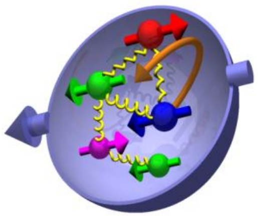
GPDs

-- status of measurements --

- a very brief introduction
- prerequisites and methods
- DVCS & DVMP: *selected* results
- on the way to an *EIC*

→ see additional slides for results not covered

POETIC 2012, Bloomington, Indiana-USA, 20 - 22 Aug, 2012

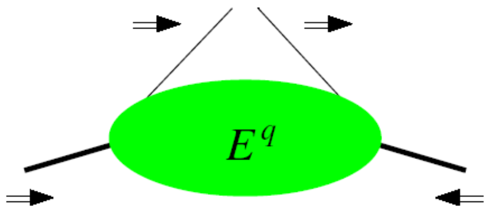


why GPDs ?

'spin puzzle'

$$s_z = \frac{1}{2} = J^q + J^g = \frac{1}{2}\sum_q \Delta q + L_z^q + \Delta g + L_z^g$$

≈30% ≈zero

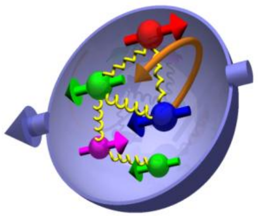


proton helicity flipped while
quark helicity is conserved

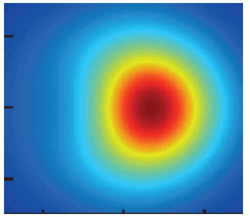
$E^q \neq 0$ *requires* orbital angular momentum

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

[X. Ji (1996)]



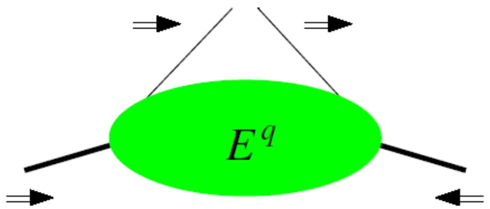
why GPDs ?



'spin puzzle'

$$s_z = \frac{1}{2} = J^q + J^g = \frac{1}{2}\sum_q \Delta q + L_z^q + \Delta g + L_z^g$$

≈30% ≈zero



proton helicity flipped while quark helicity is conserved

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

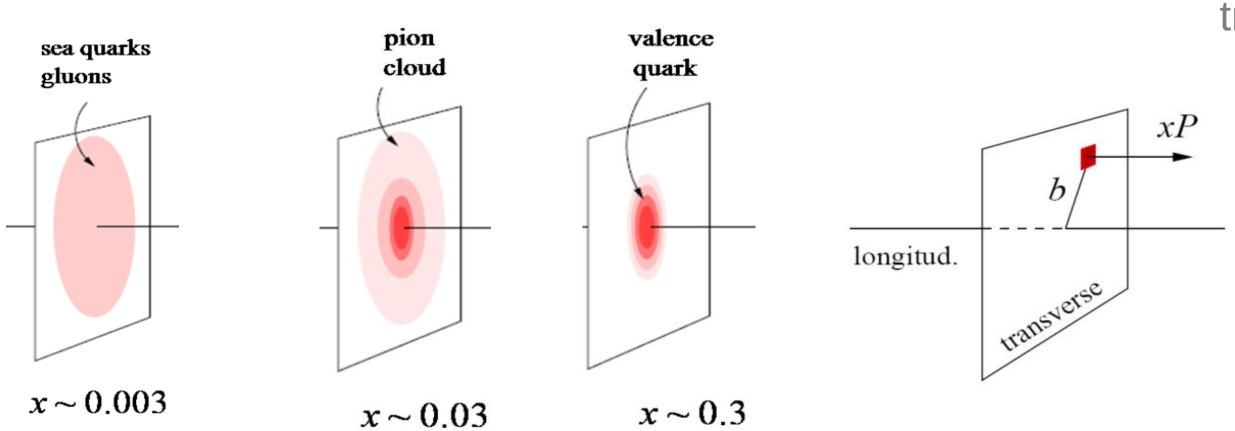
$$J^q = \frac{1}{2}\int_{-1}^{1} x dx \left[H^q(x,\xi,t) + E^q(x,\xi,t)\right]_{t=0}$$

[X. Ji (1996)]

nucleon imaging: *FT* (GPD) → impact parameter space $b_\perp$: spatial distribution in transverse plane

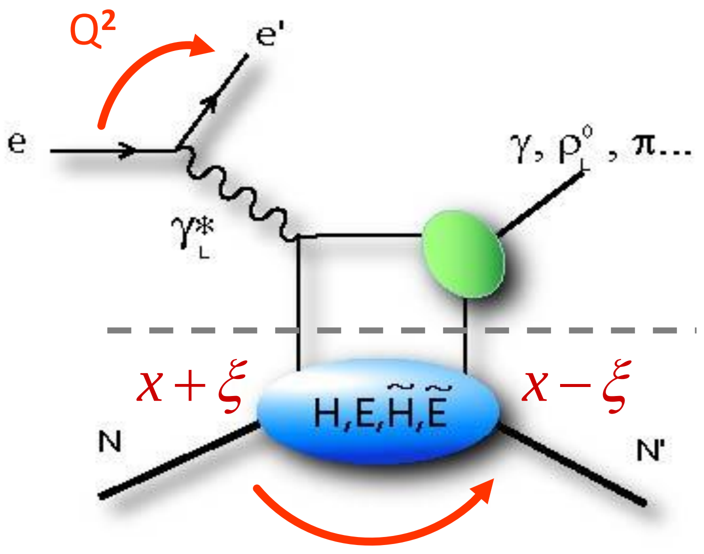
(transverse distance from proton center of momentum)

[M. Burkardt(2001), M. Diehl(2002)]



[fig: courtesy C. Weiss]

how to constrain GPDs ?



$H(x,\xi,t)$

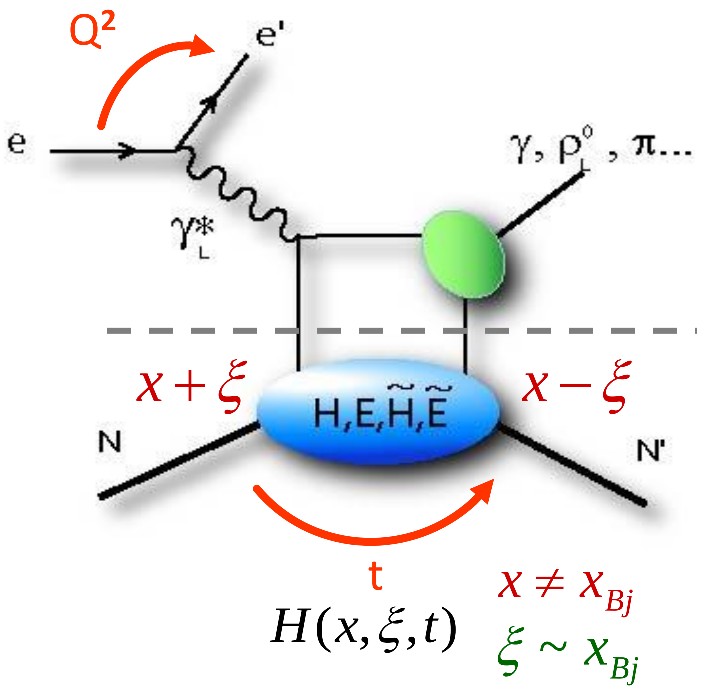
$x \neq x_{Bj}$

$\xi \sim x_{Bj}$

Q^2>>, t<<

appear in factorisation theorem for *hard exclusive* processes

how to constrain GPDs ?



Q^2>>, t<<

appear in factorisation theorem for *hard exclusive* processes

- spin ½ target:

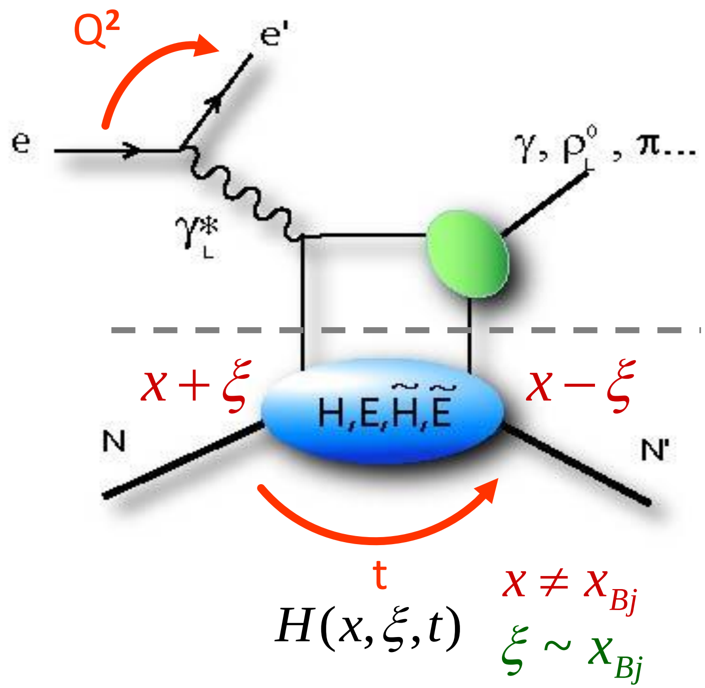
  4 leading-tw, chiral even *q* & *g* GPDs: H, $\tilde{H}$ conserve nucleon helicity

  E, $\tilde{E}$ involve nucleon helicity flip

  + 4 chiral odd ('transversity') GPDs, which flip the parton helicity

  H_T → related to transversity

how to constrain GPDs ?



Q^2>>, t<<

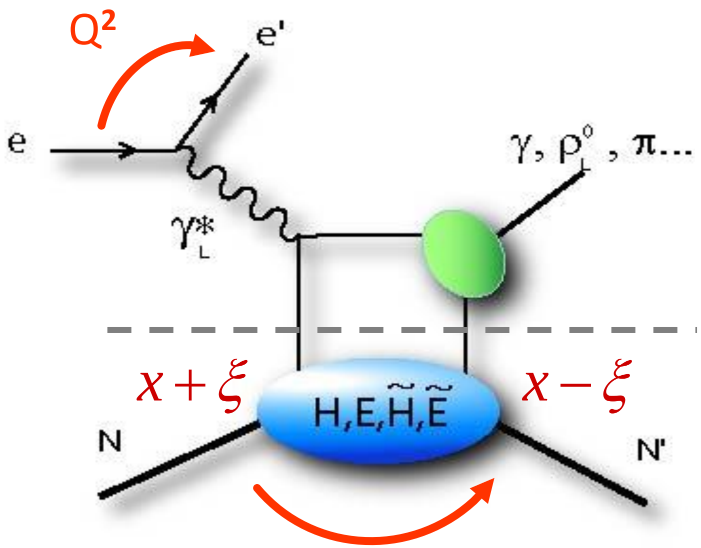
appear in factorisation theorem for *hard exclusive* processes

- **DVCS**: most clean process, (some) flavour dependent

information from p & n target OR: *evolution*

→ H, $\tilde{H}$, E, $\tilde{E}$

how to constrain GPDs ?



$H(x,\xi,t)$ $x \neq x_{Bj}$ $\xi \sim x_{Bj}$

Q^2>>, t<<

appear in factorisation theorem for *hard exclusive* processes

- **DVCS**: most clean process, (some) flavour dependent information from p & n target OR: *evolution*

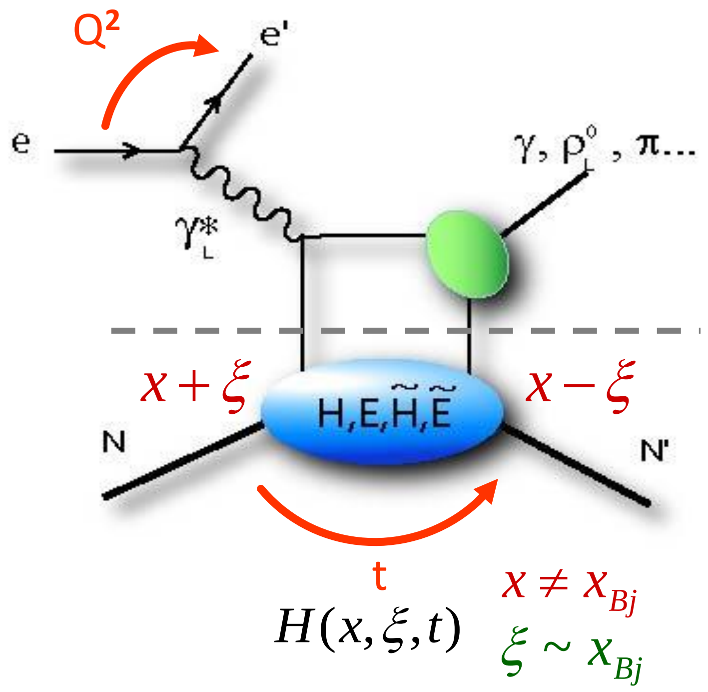
- **DVMP**: flavour decomposition & gluons

→ H, H̃, E, Ẽ

VM → H, E

PS → H̃, Ẽ, $\tilde{H}_T$, $\tilde{E}_T$

how to constrain GPDs ?



Q^2>>, t<<

appear in factorisation theorem for *hard exclusive* processes

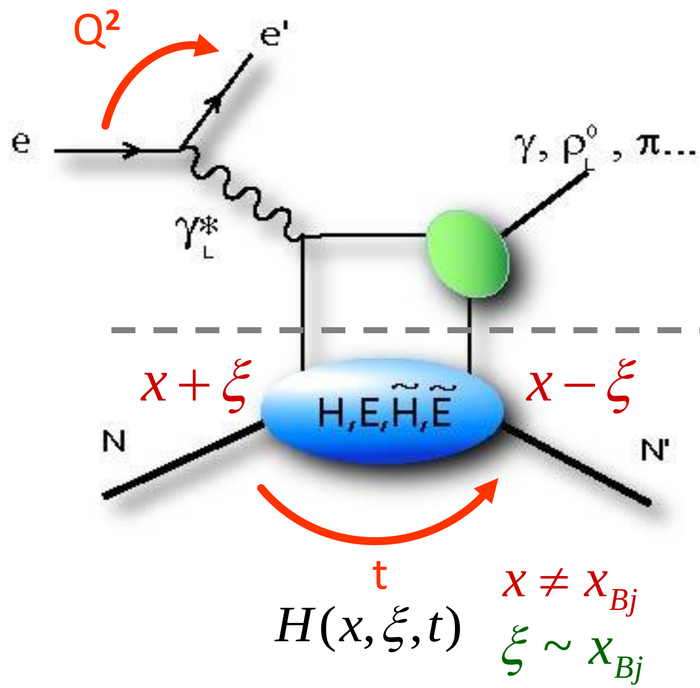
- **DVCS**: most clean process, (some) flavour dependent

information from p & n target OR: *evolution*

- **DVMP**: flavour decomposition & gluons

ρ^0	2u+d, 9g/4
ω	2u–d, 3g/4
ϕ	s, g
ρ^+	u–d
J/ψ	g

how to constrain GPDs ?



Q^2>>, t<<

appear in factorisation theorem for *hard exclusive* processes

- **DVCS**: most clean process, (some) flavour dependent

information from p & n target OR: *evolution*

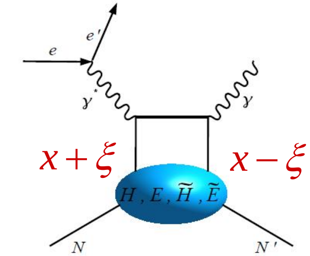
- **DVMP**: flavour decomposition & gluons

ρ^0	2u+d, 9g/4
ω	2u–d, 3g/4
ϕ	s, g
ρ^+	u–d
J/ψ	g

BUT

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

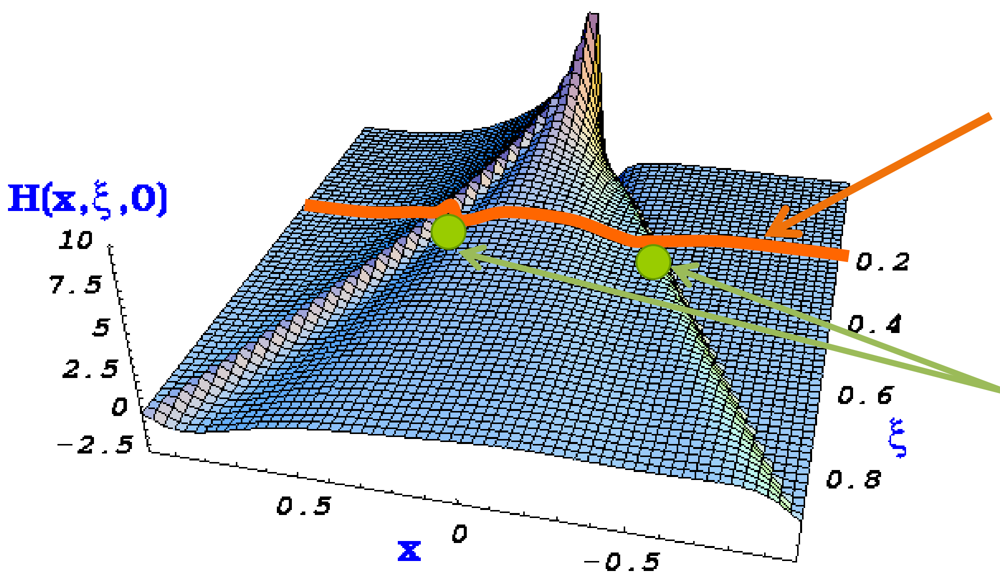
link GPDs & observables



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

complex DVCS amplitude — *Compton Form Factor (CFF)*

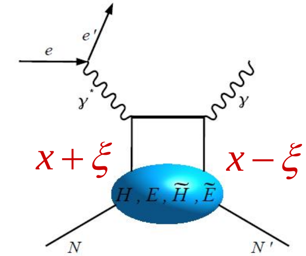
- x is mute variable (integrated over), needs deconvolution
  - → apart from 'cross over' trajectory ($x = \pm\xi$) GPDs not directly accessible
- extrapolation $t \to 0$ model dependent



cross section & beam charge asymmetry
~ Re(T^{DVCS}):
integral of GPDs over x

beam or target spin asymmetries
~ Im(T^{DVCS}),
i.e., *GPDs @ $x = \pm\xi$*

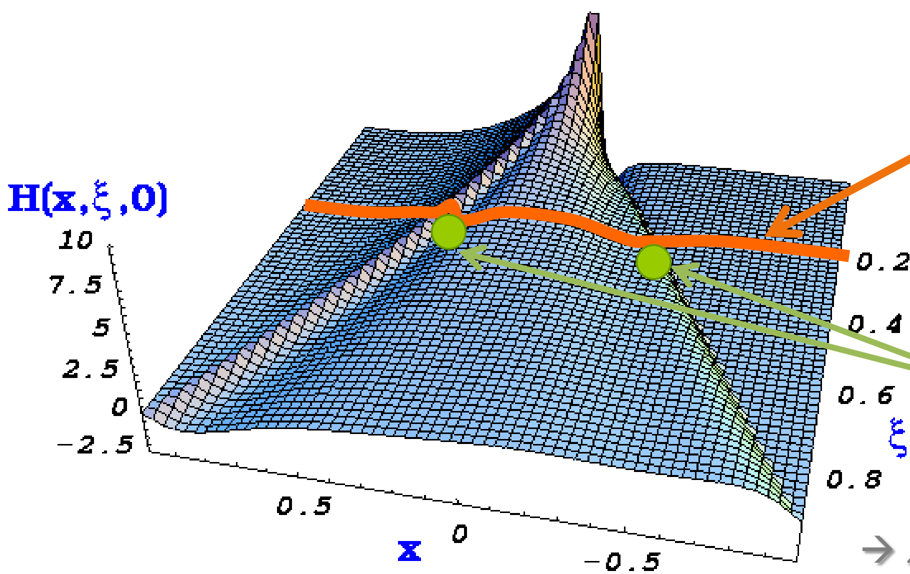
link GPDs & observables



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

complex DVCS amplitude — *Compton Form Factor (CFF)*

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

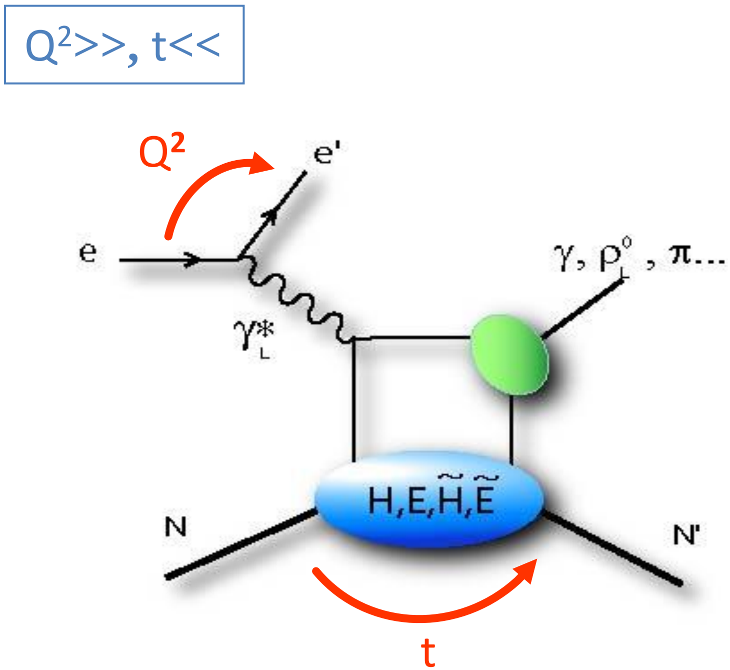


cross section & beam charge asymmetry
~ Re(T^{DVCS}):
integral of GPDs over x

beam or target spin asymmetries
~ Im(T^{DVCS}),
i.e., *GPDs* @ $x = \pm\xi$

→ x scan of GPDs:
- 'double'DVCS: *JLab12* (?)
- Q2 evolution: *EIC*

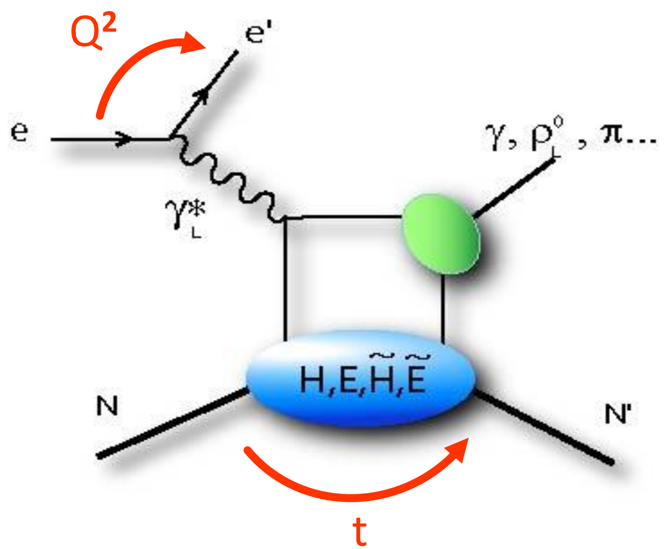
the ideal experiment for measuring hard exclusive processes



- 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

the ideal experiment for measuring hard exclusive processes

Q^2>>, t<<



- 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

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

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

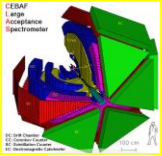
unpolarised nuclear targets

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

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 technique
- 2006/7 data taken with recoil det.



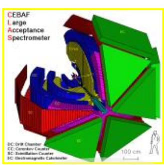
Hall-A

- highly **polarised, high lumi** 6GeV **e–**
- long **polarised** effective **p, n targets**
- **CLAS**: full event reconstruction
- **Hall-A**: missing mass/energy technique

experimental prerequisites

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

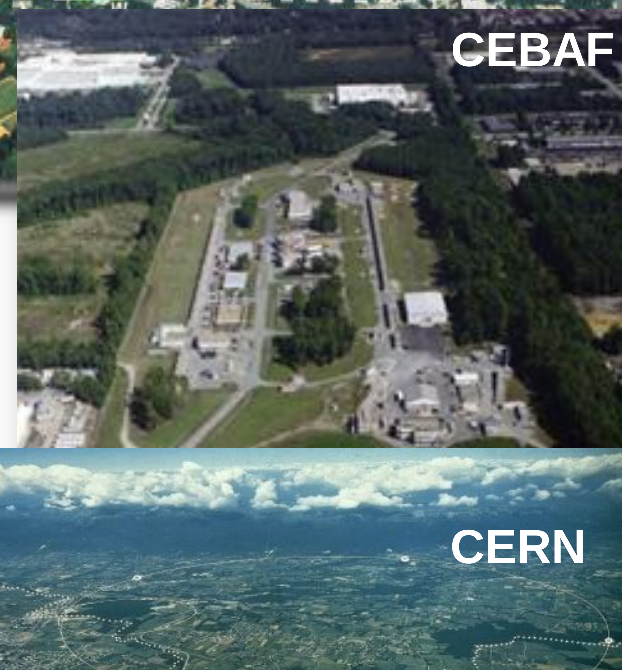
- **polarised** 27GeV **e+/e–**
- long+transv **polarised p, d targets**
unpolarised **nuclear** targets
- missing mass technique
- 2006/7 data taken with recoil det.



Hall-A

- highly **polarised, high lumi** 6GeV **e–**
- long **polarised** effective **p, n targets**
- **CLAS**: full event reconstruction
- **Hall-A**: missing mass/energy technique

- highly **polarised**, 160GeV μ
- long+transv **polarised** effective **p, d targets**
- missing mass/energie technique



results on /off the menu

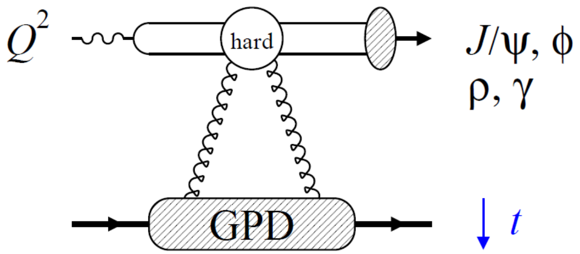
data over wide kinematic range: HERA-collider → (COMPASS) → HERMES → JLab

- VM production → H, E
  - low x: gluon imaging
  - high x: quarks & gluons; role of NLO contributions
  - low W data from Jlab
  - SDMEs / amplitudes
- ps meson production → $\tilde{H}$, $\tilde{E}$, $\tilde{H}_T, \tilde{E}_T$
  - role of transverse photons, power corrections & chiral-odd *GPDs*
- DVCS → H, E, $\tilde{H}$, $\tilde{E}$ ... the golden channel & most rich plate
  - nuclear modification of DVCS amplitudes: HERMES
- hunting the OAM

VM production @low x

energy dependence probes transition from soft to hard regime

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

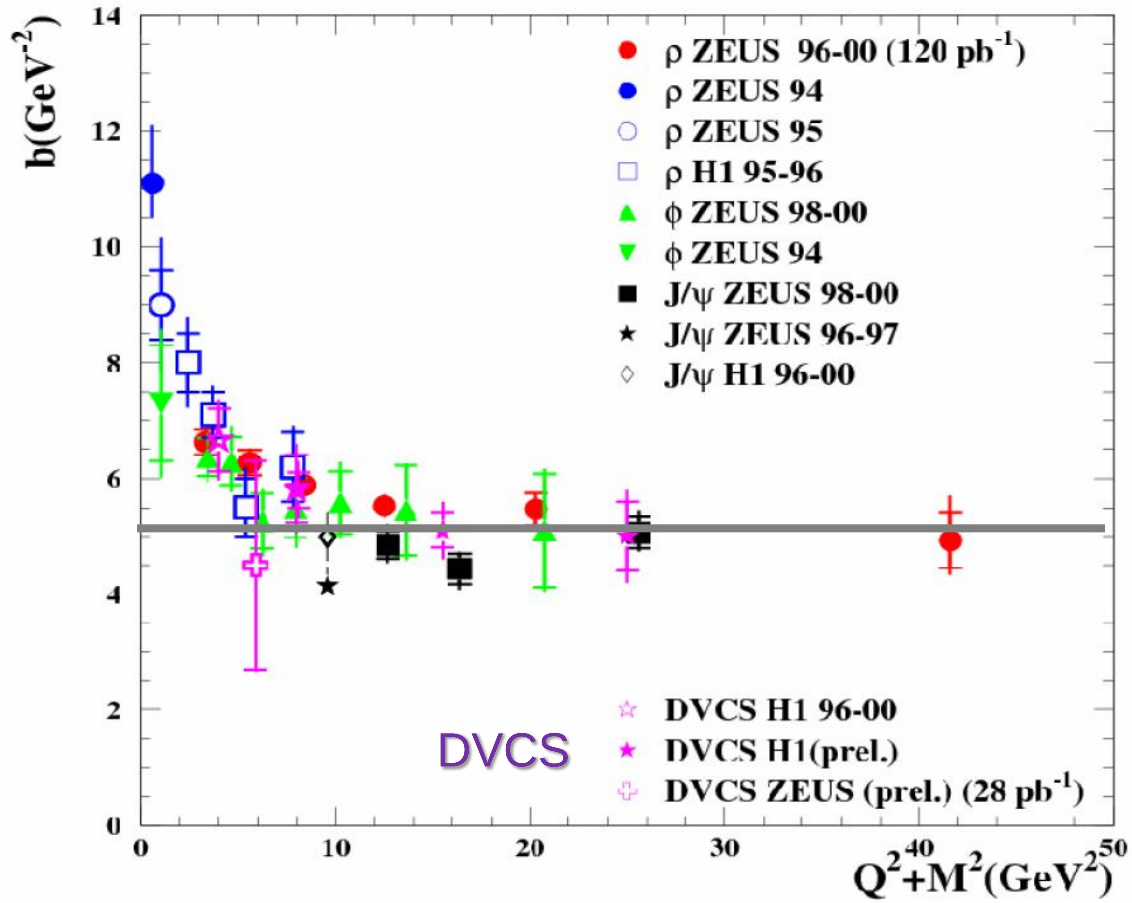


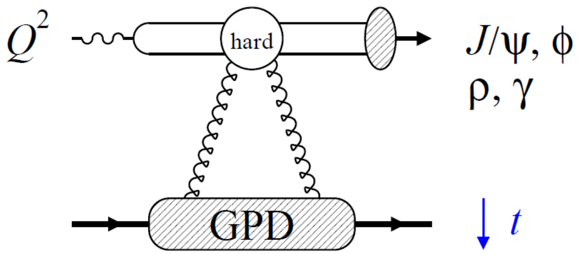
VM production @low x

energy dependence probes transition from soft to hard regime

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

$\rho, \phi, J/\psi$, DVCS





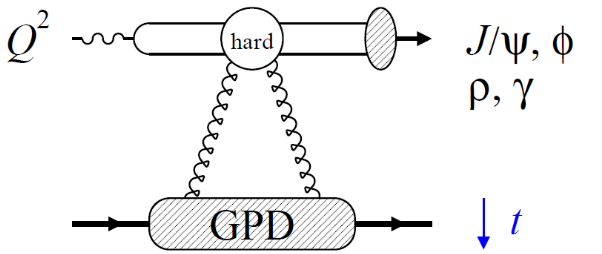
universality of b slope parameter

→ point like configurations dominate

gluon imaging: J/ψ

energy dependence probes hard regime; *FT* → average impact parameter

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

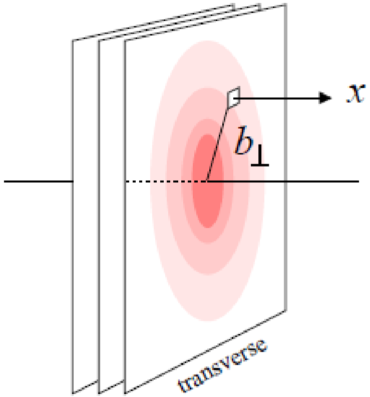


- *FT* → average impact parameter

$$\left\langle b_{\perp}^{2}(x_{Bj})\right\rangle$$

distance between active quark/gluon and proton center of momentum

[M. Burkardt(2001), M. Diehl(2002)]



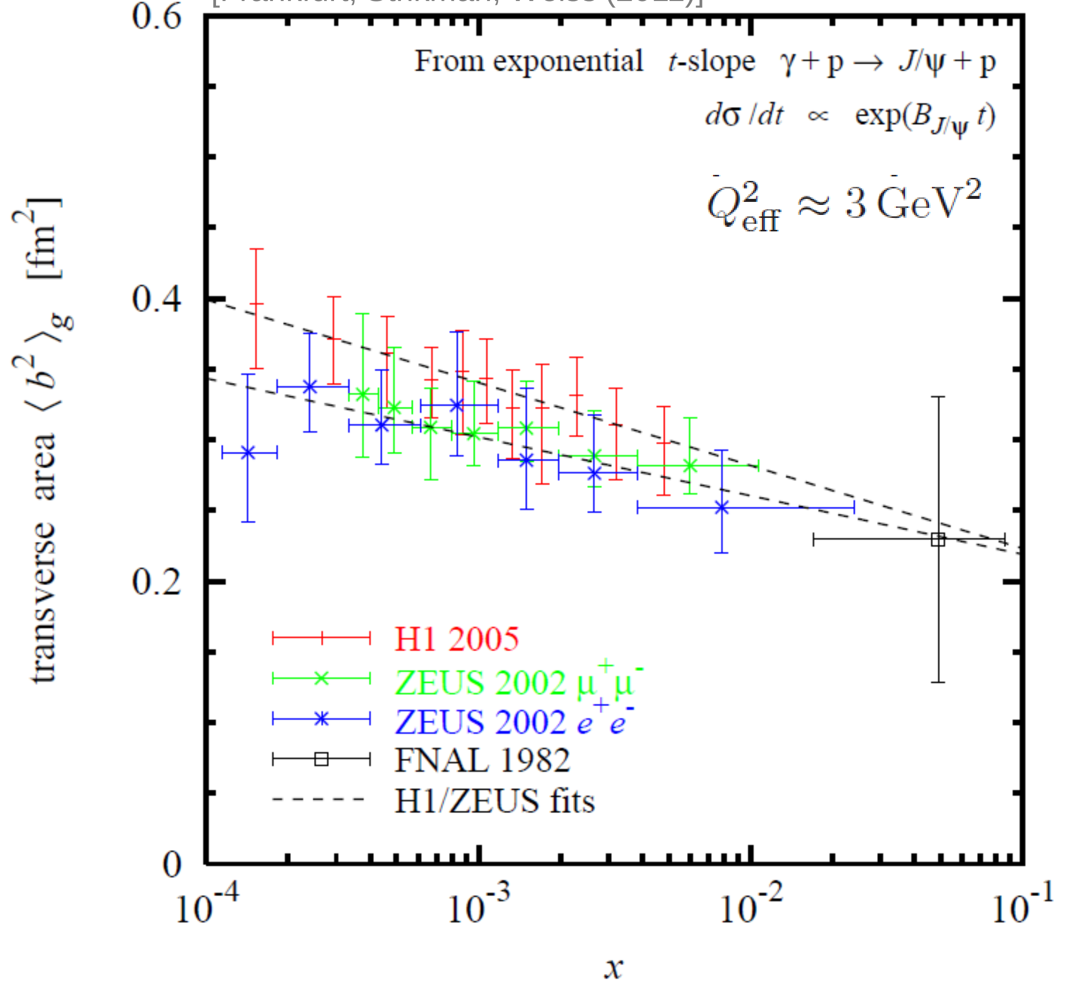
[fig: courtesy C. Weiss]

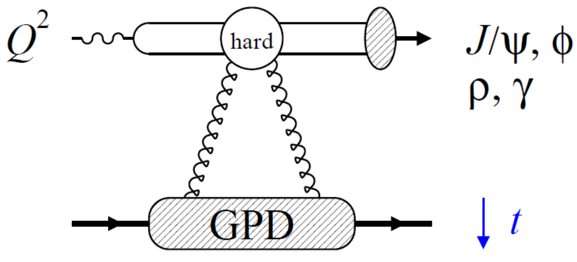
gluon imaging: J/ψ

energy dependence probes hard regime; *FT* → average impact parameter

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

[Frankfurt, Strikman, Weiss (2011)]



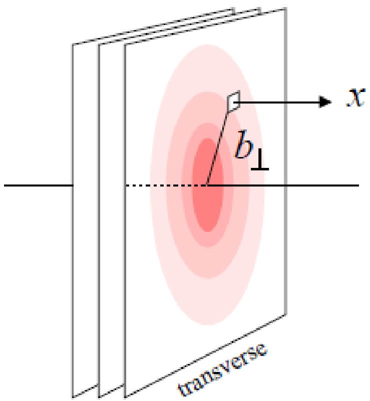


- *FT* → average impact parameter

$$\left\langle b_{\perp}^{2}(x_{Bj})\right\rangle$$

distance between active quark/gluon and proton center of momentum

[M. Burkardt(2001), M. Diehl(2002)]

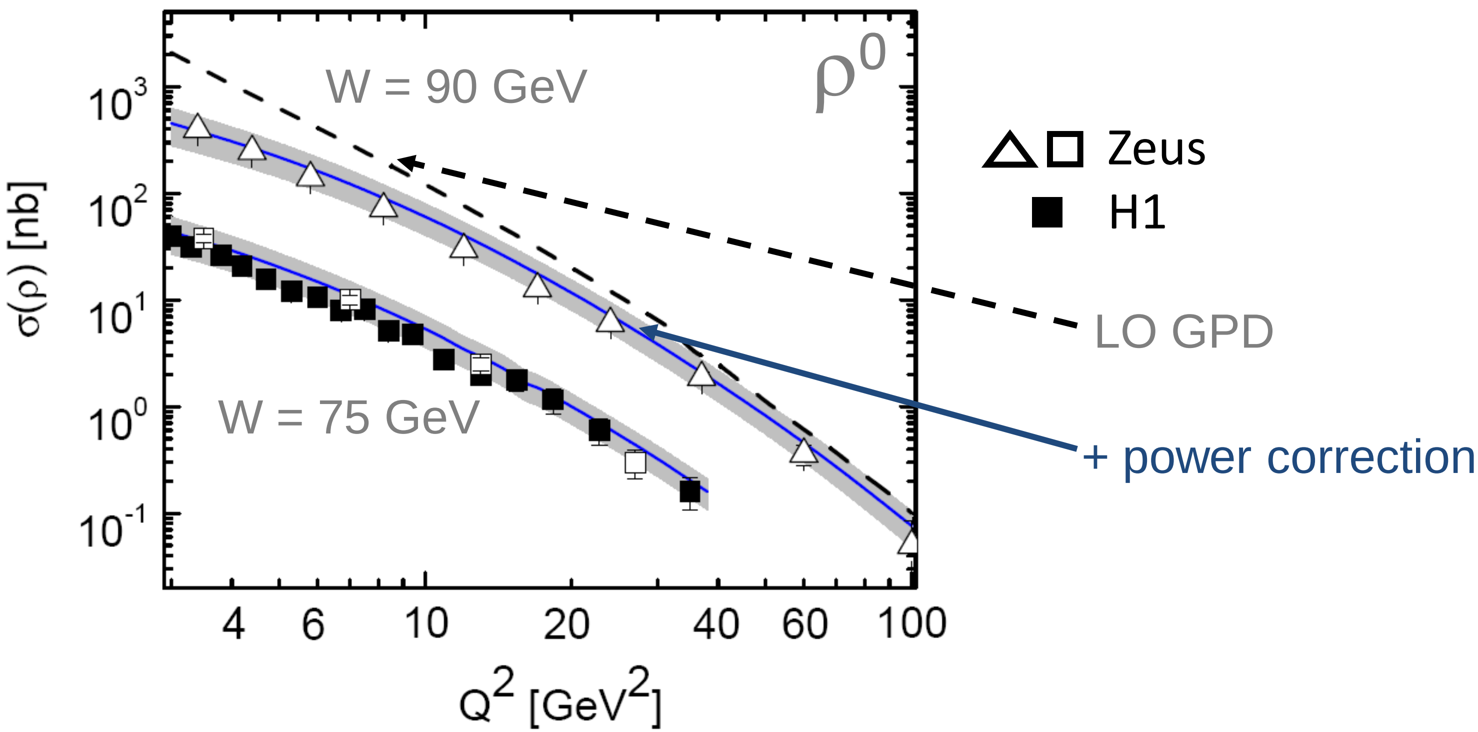


[fig: courtesy C. Weiss]

VM production: from low → high x

- *NLO corrections* to VM production are *large* @typical kinematics of COMPASS/ HERMES/ CLAS12 [M. Diehl, W. Kugler (2007)]
- ... *despite*, LO GPD model (handbag fact.; DD ansatz): [S. Goloskokov, P. Kroll (2007, 2010)]

  + power corrections

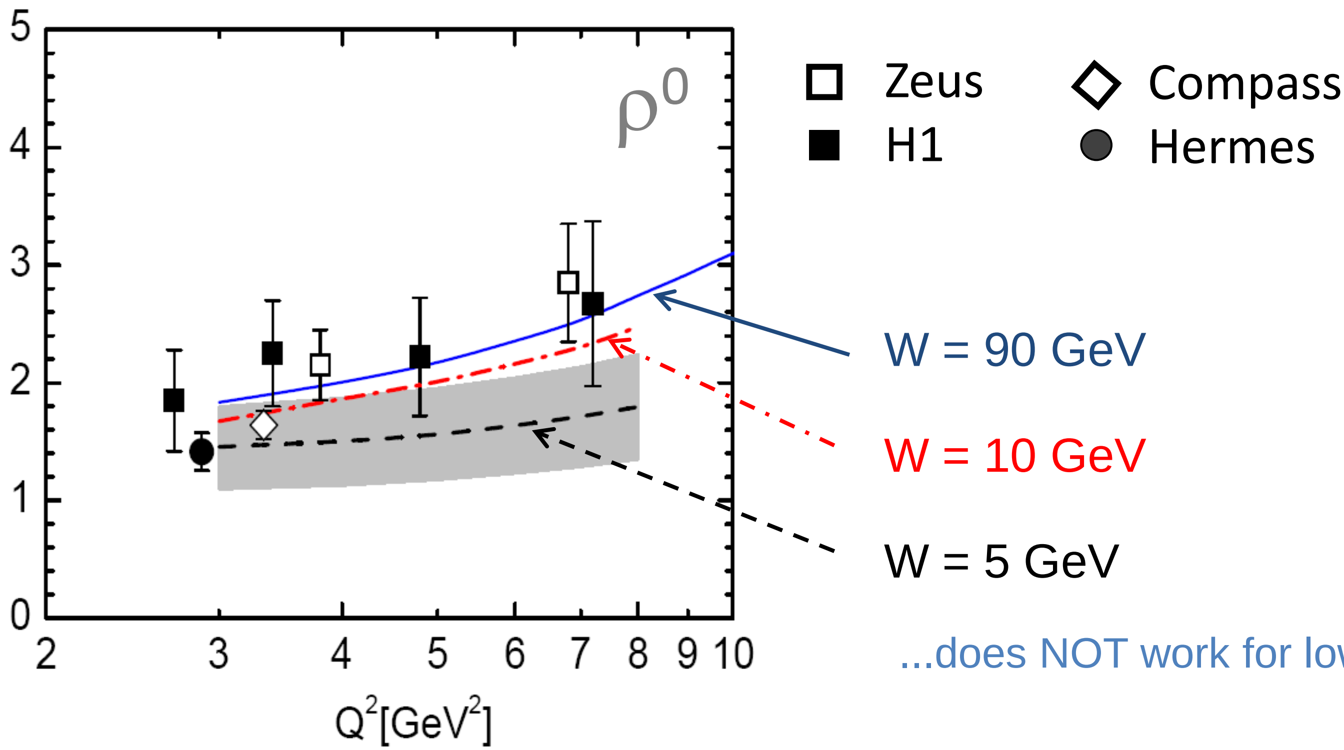


VM production: from low → high x

- *NLO corrections* to VM production are *large* @typical kinematics of COMPASS/ HERMES/ CLAS12 [M. Diehl, W. Kugler (2007)]

- ... *despite*, LO GPD model (handbag fact.; DD ansatz): [S. Goloskokov, P. Kroll (2007, 2010)]

  + power corrections

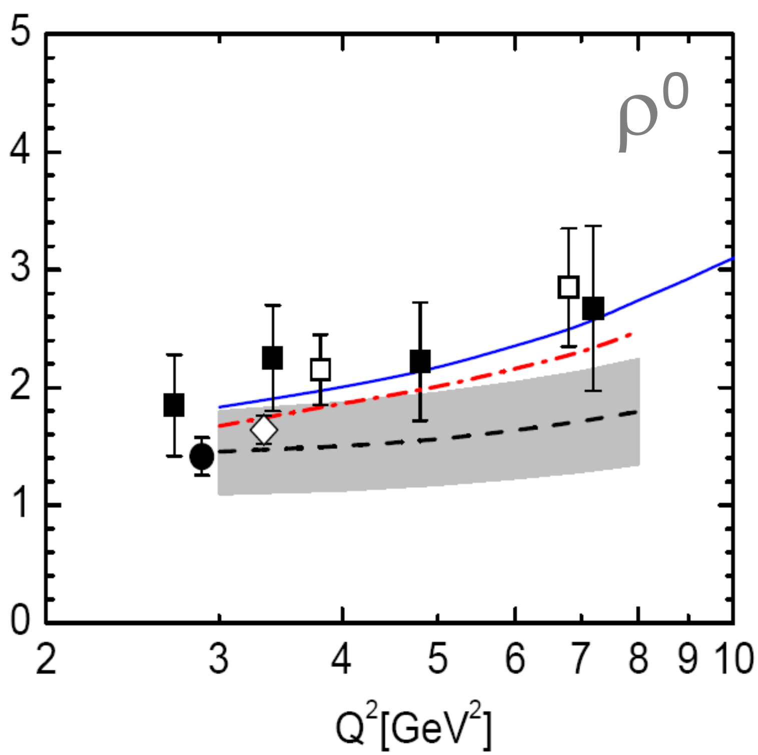


...does NOT work for low W of CLAS

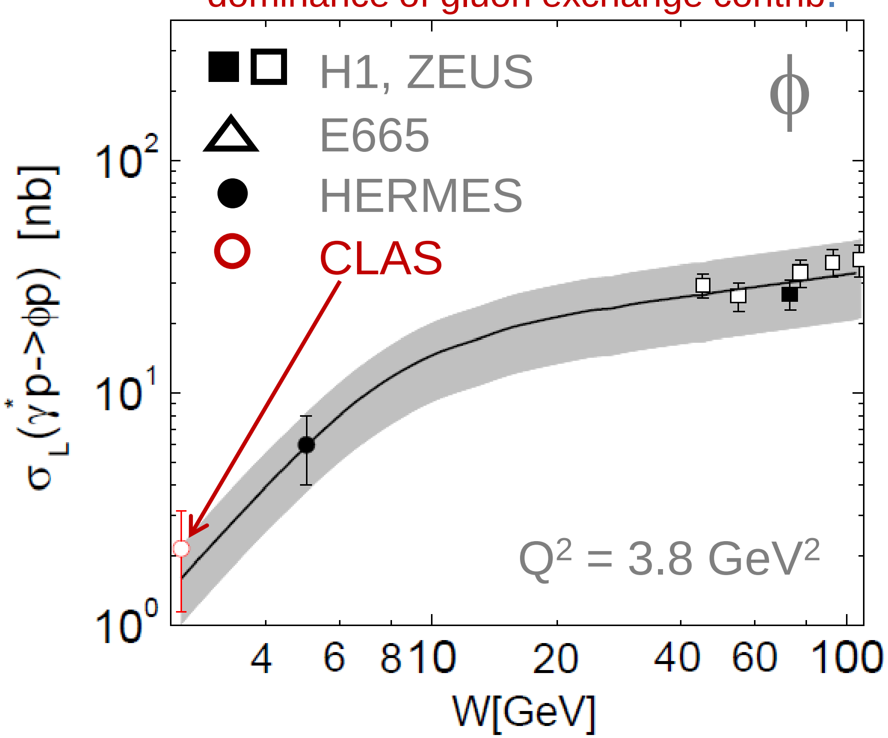
VM production: from low → high x

- *NLO corrections* to VM production are *large* @typical kinematics of COMPASS/ HERMES/ CLAS12 [M. Diehl, W. Kugler (2007)]
- ... *despite*, LO GPD model (handbag fact.; DD ansatz): [S. Goloskokov, P. Kroll (2007, 2010)]

  + power corrections

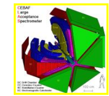


dominance of gluon exchange contrib.



ps meson production

-- role of power corrections & longitudinal-transverse transitions --

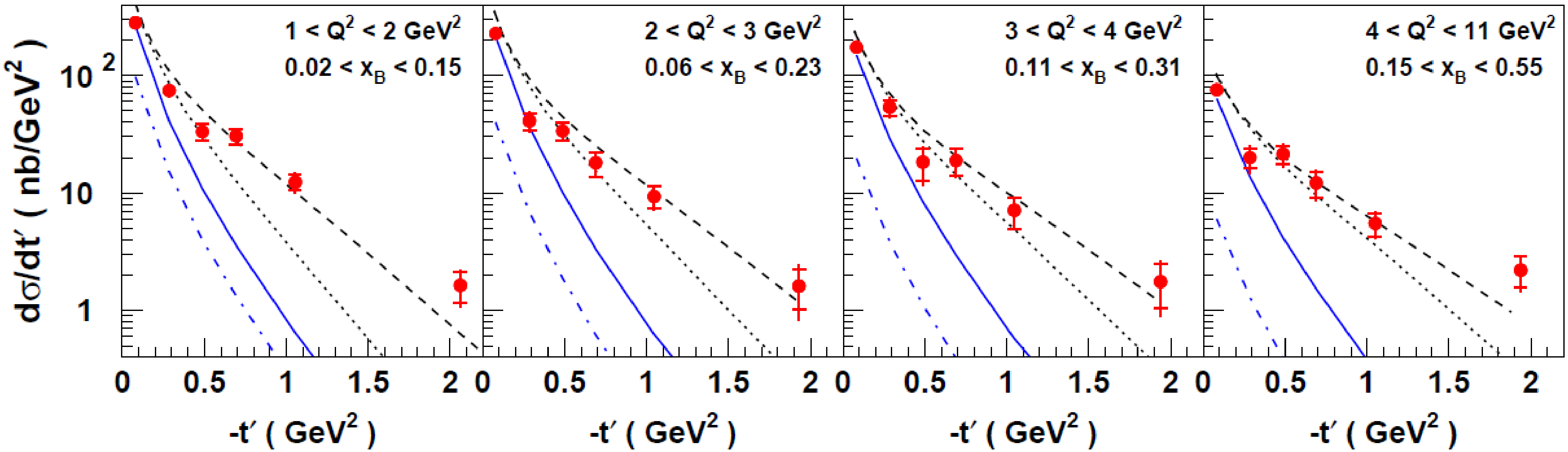
hermes $ep \to n\pi^+$ $ep \to p\pi^0$  Hall-A

ps meson production

-- role of power corrections & longitudinal-transverse transitions --

hermes $\gamma^* p \rightarrow n\pi^+$

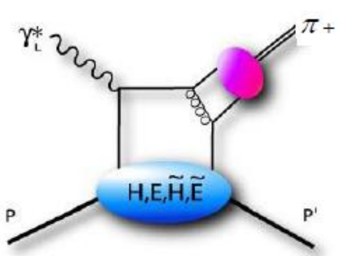
[PLB659(2008)]

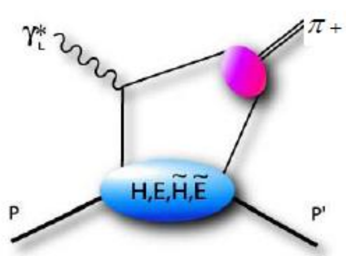


GPD model for $\frac{d\sigma_L}{dt'}$ — · — leading-order calculations

——— with power corrections

Vanderhaeghen, Guichon, Guidal PRD60(1999)094017



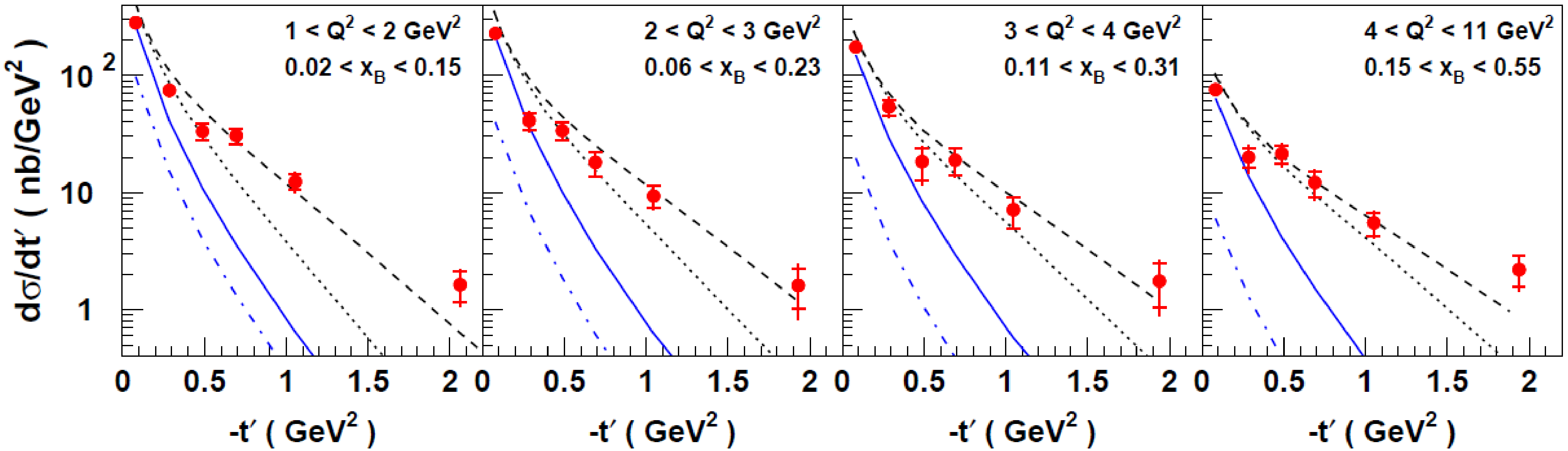


ps meson production

-- role of power corrections & longitudinal-transverse transitions --

$\gamma^* p \rightarrow n \pi^+$

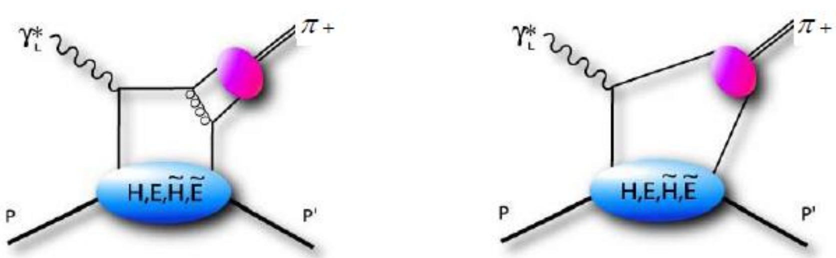
[PLB659(2008)]



GPD model for $\frac{d\sigma_L}{dt'}$ — · — leading-order calculations
——— with power corrections

Vanderhaeghen, Guichon, Guidal PRD60(1999)094017

Regge model ------ σ_{tot}
[Laget(2008)] .... σ_L



→ need of L/T separation, especially for lower Q^2, higher t

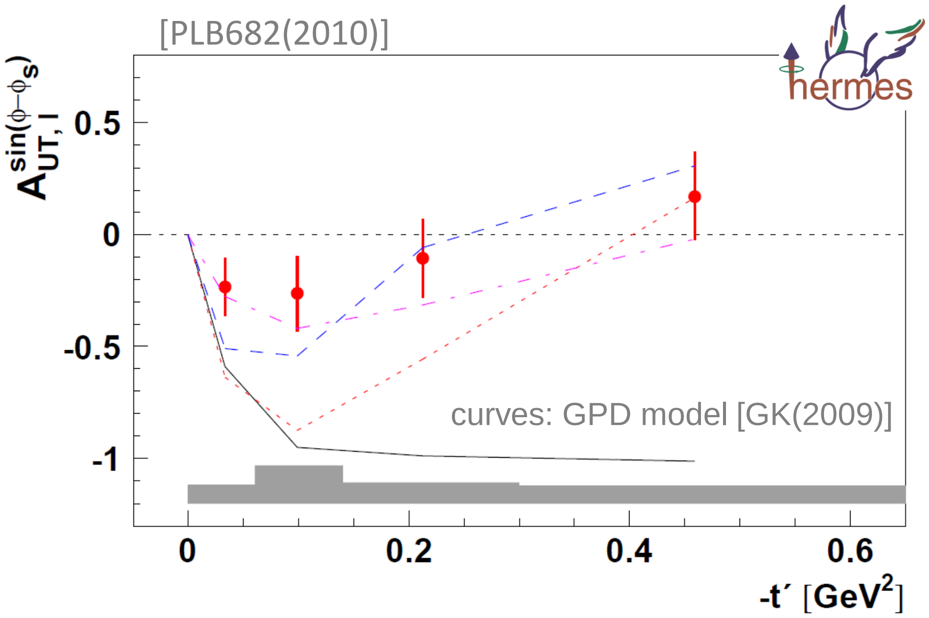
ps meson production

-- role of power corrections & longitudinal-transverse transitions --

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

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

- arises from pure σ_L contribution
- NLO/power corrections cancel to large extend in asymmetry



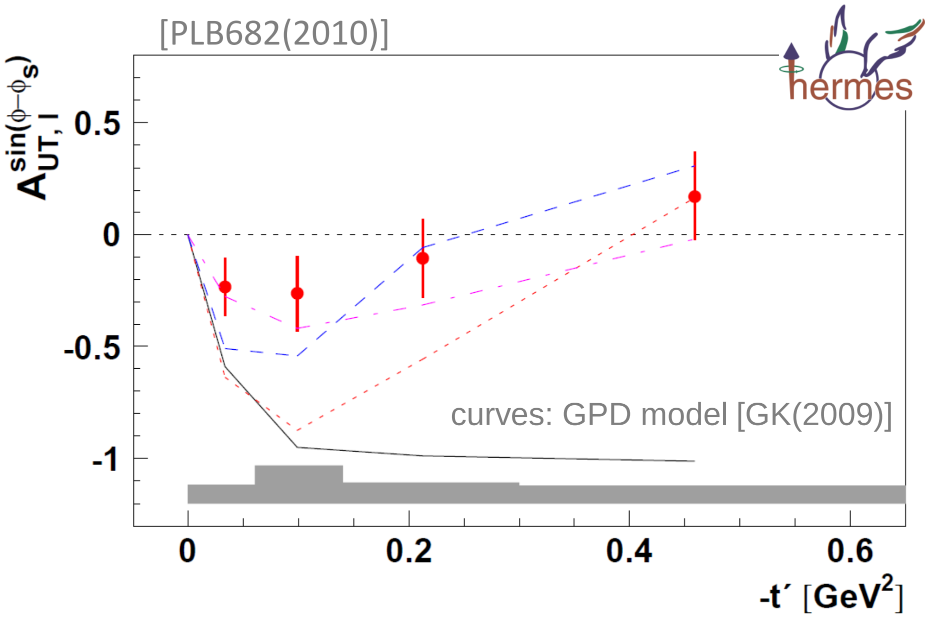
ps meson production

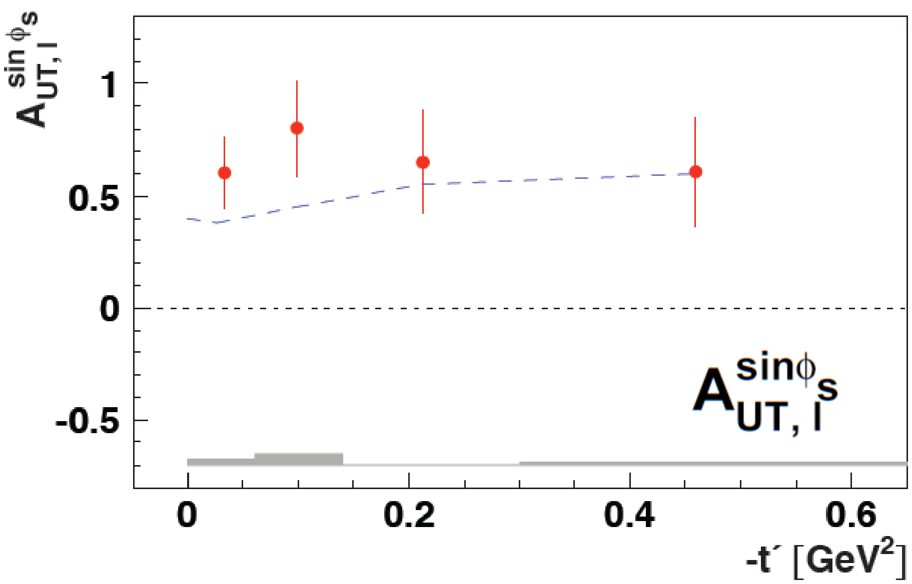
-- role of power corrections & longitudinal-transverse transitions --

$ep \to n\pi^+$

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

- arises from pure σ_L contribution
- NLO/power corrections cancel to large extend in asymmetry





→significant contribution from L/T interference, need to go beyond leading-tw description

ps meson production

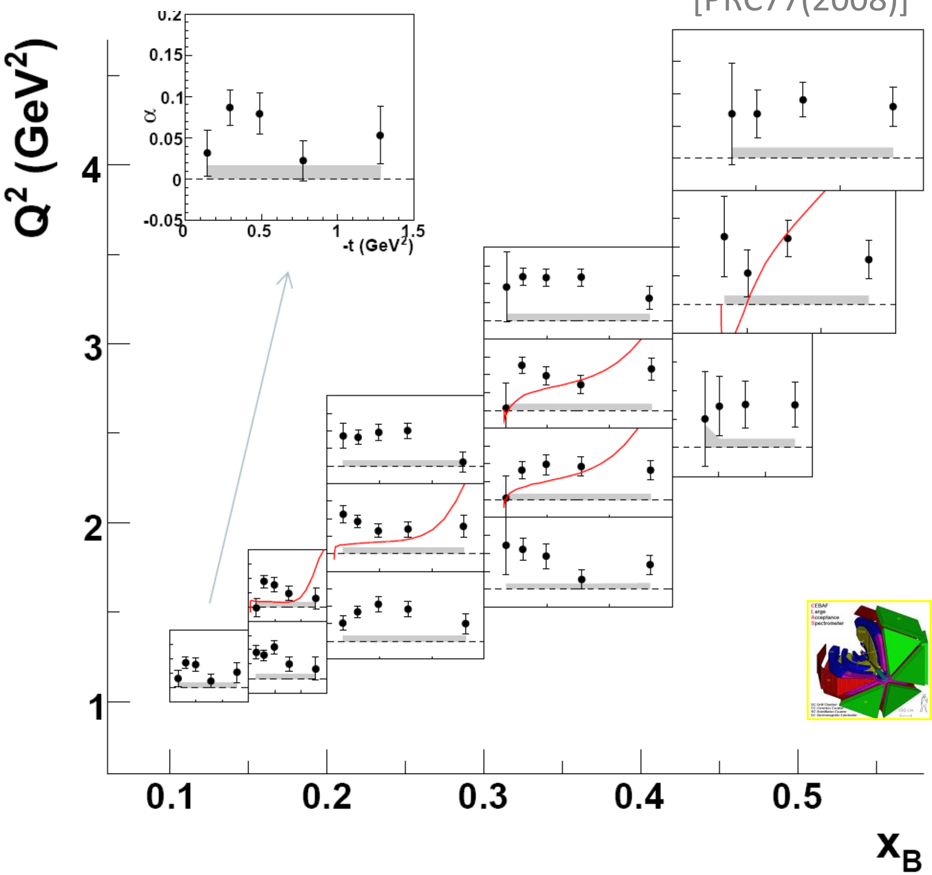
-- role of power corrections & longitudinal-transverse transitions --

$$ep \to p\,\pi^0$$

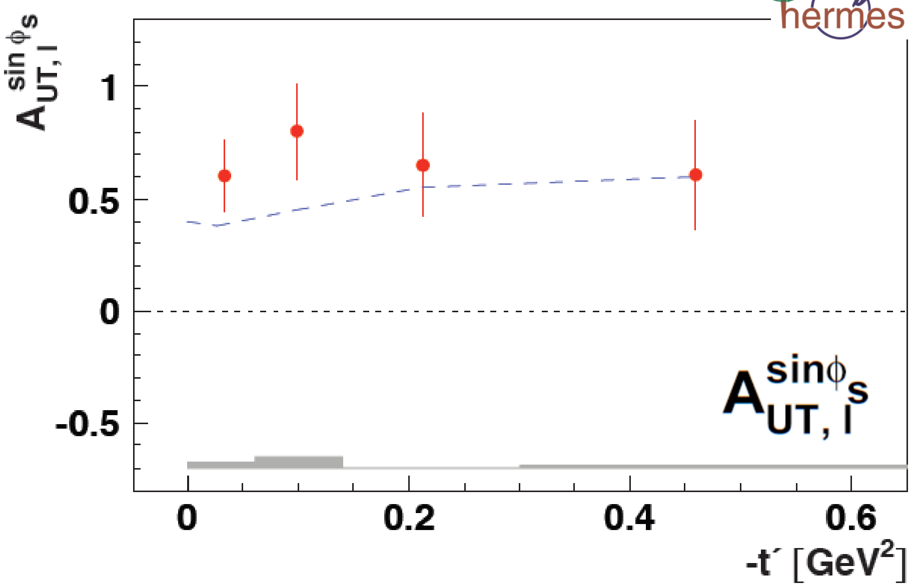
$A_{LU}^{\sin\phi}$

- any non-zero beam-spin asymmetry indicates L-T interference

[PRC77(2008)]



$$ep \to n\,\pi^+$$ [PLB682(2010)]



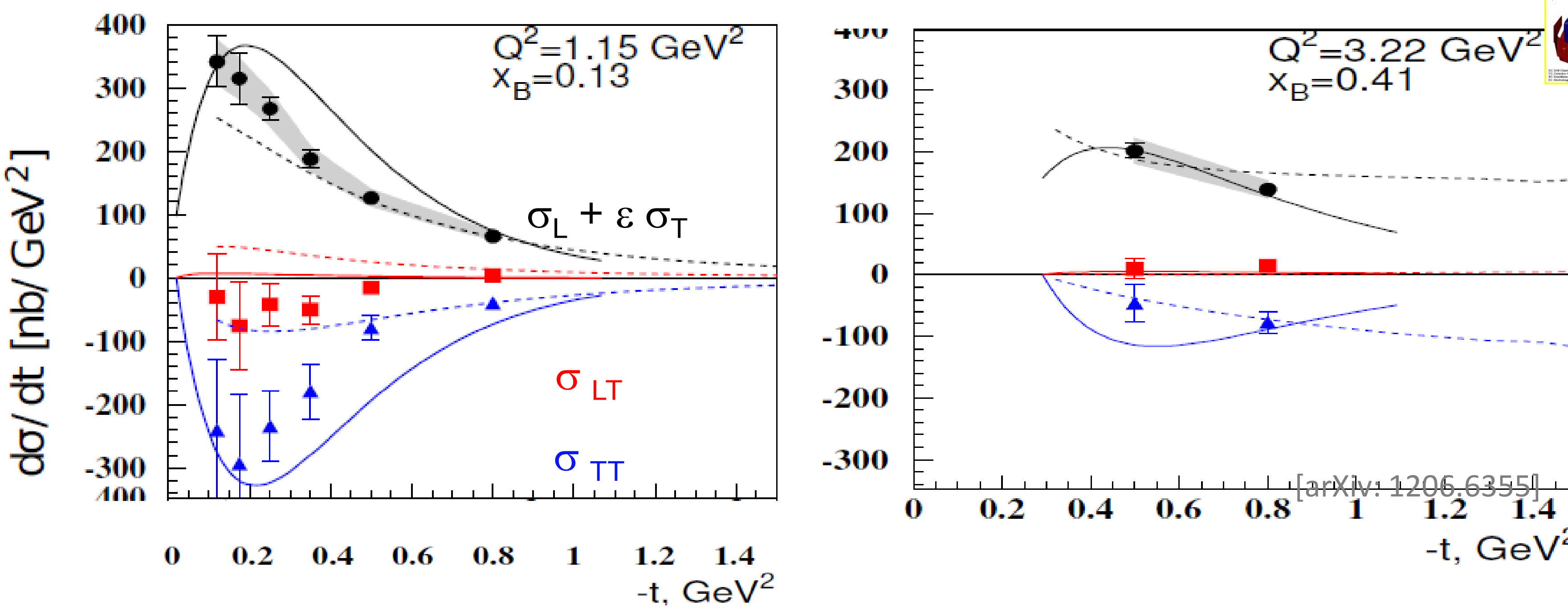
→significant contribution from L/T interference, need to go beyond leading-tw description

ps meson production

-- role of transversity GPDs --

$$ep \to p\,\pi^0$$

- cross sections vs t → σ_T parametrized employing transversity GPDs (and assuming factorization) [Goldstein *etal.*(2011), Goloskokov and Kroll (2011)]



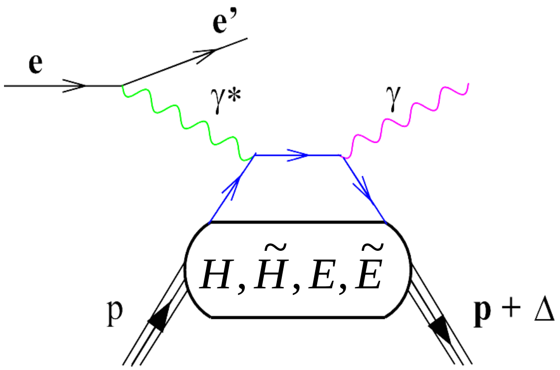
curves: GPD model calc.s with dominant contributions from transversity GPDs

[Goloskokov Kroll(2011)]

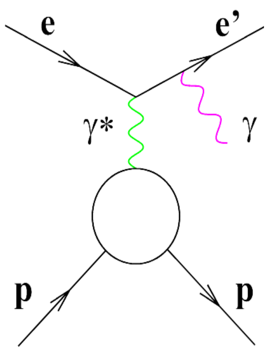
[Goldstein *etal*.(2011)]

Deeply virtual Compton Scattering

DVCS



Bethe-Heitler

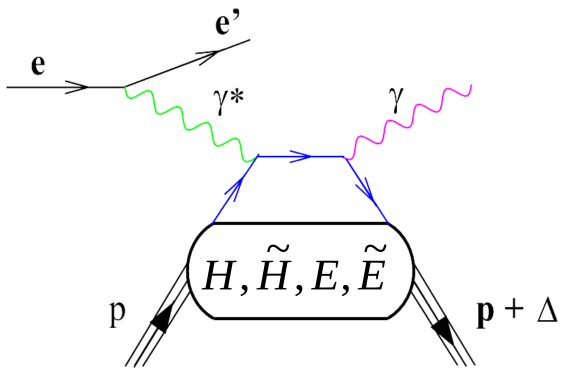


$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + (\tau^*_{BH}\tau_{DVCS} + \tau^*_{DVCS}\tau_{BH})$$

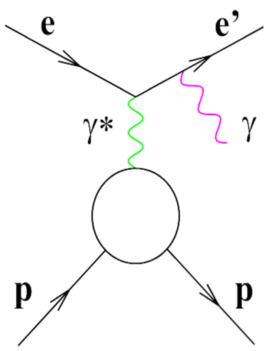
→ bilinear in GPDs → *linear* in GPDs

Deeply virtual Compton Scattering

DVCS

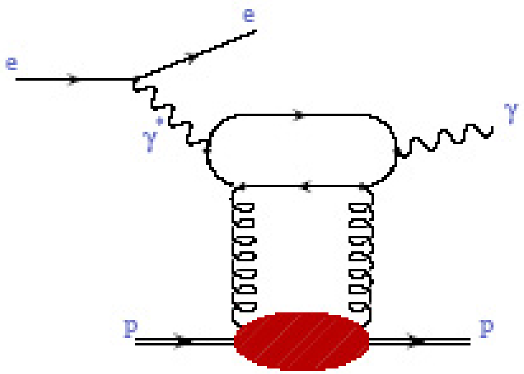


Bethe-Heitler



@H1&Zeus

DVCS ≈ Bethe-Heitler

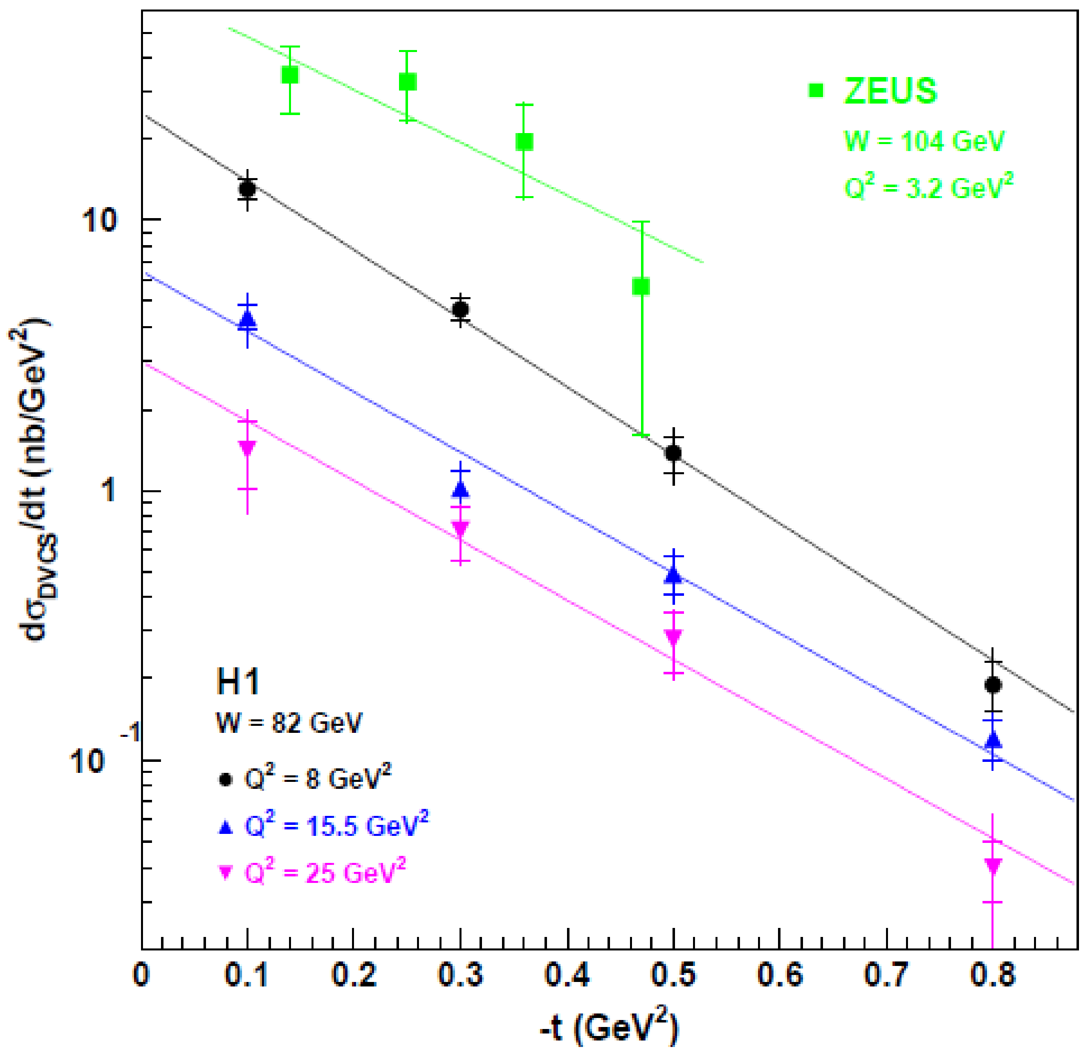


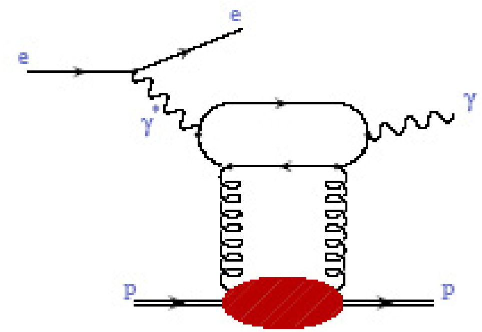
LO sea quarks + NLO gluons

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

→ bilinear in GPDs → *linear* in GPDs

DVCS





extracted transverse size (as before for VM) [H1, PLB659(2008)]

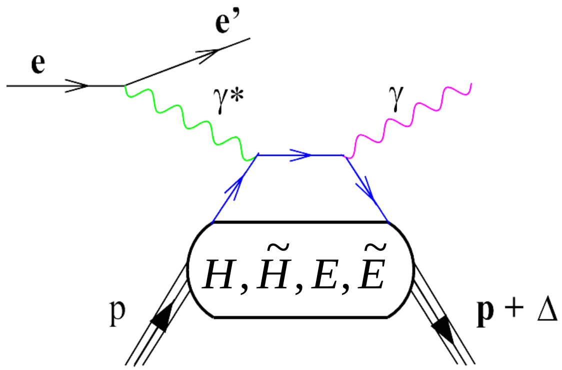
$$\sqrt{\langle b_T^2 \rangle} = (0.65 \pm 0.02)\,\mathrm{fm}$$

@ $x_B = 10^{-3}$

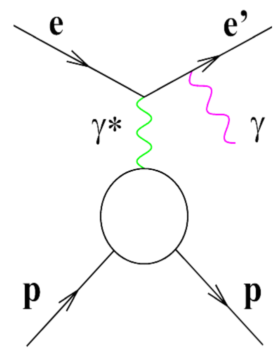
$\langle Q^2 \rangle = 8.0$ GeV^2

DVCS

DVCS



Bethe-Heitler



@H1&ZEUS

DVCS ≈ Bethe-Heitler

@HERMES / JLab

DVCS << Bethe-Heitler

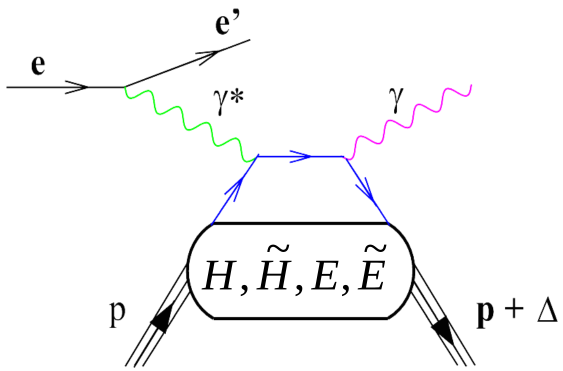
$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + (\tau^*_{BH}\tau_{DVCS} + \tau^*_{DVCS}\tau_{BH})$$

→ bilinear in GPDs → *linear* in GPDs, information about *phase*

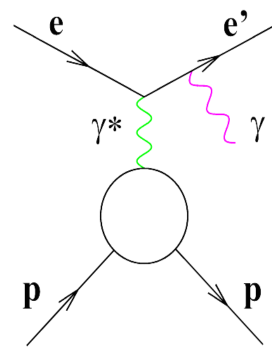
→ access to *Re* and *Im* parts of *CFFs*

DVCS

DVCS



Bethe-Heitler



@H1&ZEUS

DVCS ≈ Bethe-Heitler

@HERMES / JLab

DVCS << Bethe-Heitler

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

→ bilinear in GPDs → *linear* in GPDs, information about *phase*

isolate interference term:

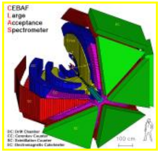
- different beam charges: e^+e^- only @HERA, upcoming @COMPASS
- polarisation observables: $\Delta\sigma_{UT}$

beam — target

U, L — U, L, T

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

DVCS interference term



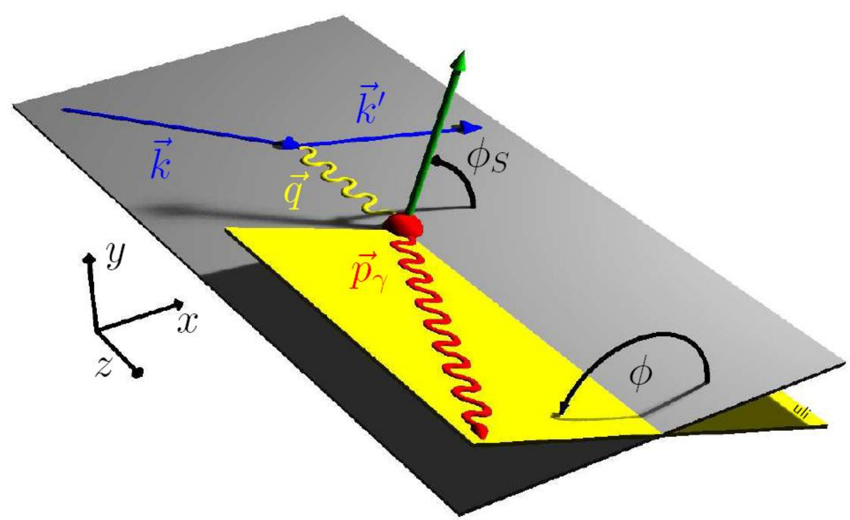
$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + (\tau^*_{BH}\tau_{DVCS} + \tau^*_{DVCS}\tau_{BH})$$

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

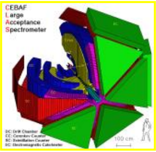
$$\Delta\sigma_{UT}(\phi, \phi_S, \ldots)$$

beam	target
U, L	U, L, T

Unpolarised,
Longitudinally,
Transversely polarised



Hall-A



DVCS interference term

hermes

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

DVCS cross section in full glory: [M. Diehl]

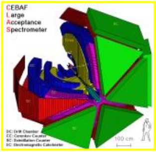
$$
\begin{aligned}
d\sigma(\ell p \to \ell \gamma p) \sim \\
& d\sigma^{BH}_{UU} && + e_\ell \, d\sigma^{I}_{UU} && + d\sigma^{DVCS}_{UU} \\
& + P_\ell S_L \, d\sigma^{BH}_{LL} && + e_\ell P_\ell S_L \, d\sigma^{I}_{LL} && + P_\ell S_L \, d\sigma^{DVCS}_{LL} \\
& + P_\ell S_T \, d\sigma^{BH}_{LT} && + e_\ell P_\ell S_T \, d\sigma^{I}_{LT} && + P_\ell S_T \, d\sigma^{DVCS}_{LT} \\
& && + e_\ell P_\ell \, d\sigma^{I}_{LU} && + P_\ell \, d\sigma^{DVCS}_{LU} \\
& && + e_\ell S_L \, d\sigma^{I}_{UL} && + S_L \, d\sigma^{DVCS}_{UL} \\
& && + e_\ell S_T \, d\sigma^{I}_{UT} && + S_T \, d\sigma^{DVCS}_{UT} .
\end{aligned}
$$

e_ℓ beam charge

P_ℓ longitudinal beam polarisation

S_L S_T Longitudinal or transverse target polarisation

Hall-A



DVCS interference term

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

DVCS cross section in full glory: [M. Diehl]

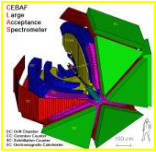
$$
\begin{aligned}
d\sigma(\ell p \to \ell \gamma p) \sim \\
& d\sigma^{BH}_{UU} && + e_\ell\, d\sigma^{I}_{UU} && + d\sigma^{DVCS}_{UU} \\
& + P_\ell S_L\, d\sigma^{BH}_{LL} && + e_\ell P_\ell S_L\, d\sigma^{I}_{LL} && + P_\ell S_L\, d\sigma^{DVCS}_{LL} \\
& + P_\ell S_T\, d\sigma^{BH}_{LT} && + e_\ell P_\ell S_T\, d\sigma^{I}_{LT} && + P_\ell S_T\, d\sigma^{DVCS}_{LT} \\
& && + e_\ell P_\ell\, d\sigma^{I}_{LU} && + P_\ell\, d\sigma^{DVCS}_{LU} \\
& && + e_\ell S_L\, d\sigma^{I}_{UL} && + S_L\, d\sigma^{DVCS}_{UL} \\
& && + e_\ell S_T\, d\sigma^{I}_{UT} && + S_T\, d\sigma^{DVCS}_{UT}.
\end{aligned}
$$

e_ℓ beam charge

P_ℓ longitudinal beam polarisation

$S_L\ S_T$ Longitudinal or transverse target polarisation

DVCS interference term



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

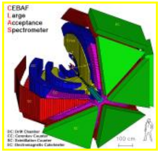
DVCS cross section in full glory: [M. Diehl]

$$\begin{aligned} d\sigma(\ell p \to \ell\gamma p) \sim \\ & d\sigma^{BH}_{UU} && + e_\ell\, d\sigma^{I}_{UU} && + d\sigma^{DVCS}_{UU} \\ & + P_\ell S_L\, d\sigma^{BH}_{LL} && + e_\ell P_\ell S_L\, d\sigma^{I}_{LL} && + P_\ell S_L\, d\sigma^{DVCS}_{LL} \\ & + P_\ell S_T\, d\sigma^{BH}_{LT} && + e_\ell P_\ell S_T\, d\sigma^{I}_{LT} && + P_\ell S_T\, d\sigma^{DVCS}_{LT} \\ & && + e_\ell P_\ell\, d\sigma^{I}_{LU} && + P_\ell\, d\sigma^{DVCS}_{LU} \\ & && + e_\ell S_L\, d\sigma^{I}_{UL} && + S_L\, d\sigma^{DVCS}_{UL} \\ & && + e_\ell S_T\, d\sigma^{I}_{UT} && + S_T\, d\sigma^{DVCS}_{UT}. \end{aligned}$$

fourier coefficients c_n and s_n provide experimenal constrain on *CFFs*

example:

$$d\sigma^{I}_{LU} \propto -e_\ell \left(\sum_{n=0}^{3} c^{I}_{n} \cos(n\phi) + \lambda \sum_{n=1}^{2} s^{I}_{n} \sin(n\phi) \right)$$



DVCS interference term

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

DVCS cross section in full glory: [M. Diehl] $d\sigma(\ell p \to \ell \gamma p) \sim$

$$\begin{aligned}
& d\sigma^{BH}_{UU} && + e_\ell\, d\sigma^{I}_{UU} && + d\sigma^{DVCS}_{UU} \\
+\, & P_\ell S_L\, d\sigma^{BH}_{LL} && + e_\ell P_\ell S_L\, d\sigma^{I}_{LL} && + P_\ell S_L\, d\sigma^{DVCS}_{LL} \\
+\, & P_\ell S_T\, d\sigma^{BH}_{LT} && + e_\ell P_\ell S_T\, d\sigma^{I}_{LT} && + P_\ell S_T\, d\sigma^{DVCS}_{LT} \\
& && + e_\ell P_\ell\, d\sigma^{I}_{LU} && + P_\ell\, d\sigma^{DVCS}_{LU} \\
& && + e_\ell S_L\, d\sigma^{I}_{UL} && + S_L\, d\sigma^{DVCS}_{UL} \\
& && + e_\ell S_T\, d\sigma^{I}_{UT} && + S_T\, d\sigma^{DVCS}_{UT}.
\end{aligned}$$

fourier coefficients c_n and s_n provide experimenal constrain on *CFFs*

example:

$$d\sigma^I_{LU} \propto -e_\ell \left(\sum_{n=0}^{3} c^I_n \cos(n\phi) + \lambda \sum_{n=1}^{2} s^I_n \sin(n\phi) \right)$$

accessible linear combinations of *CFFs*, hence *GPDs :*

$$d\sigma^I_{LU} \propto F_1 H + \frac{x_{Bj}}{2 - x_{Bj}} (F_1 + F_2) \tilde{H} - \frac{t}{4M^2} F_2 E + \ldots$$

F_1, F_2 ... Pauli & Dirac *FF*

dominant contribution for proton

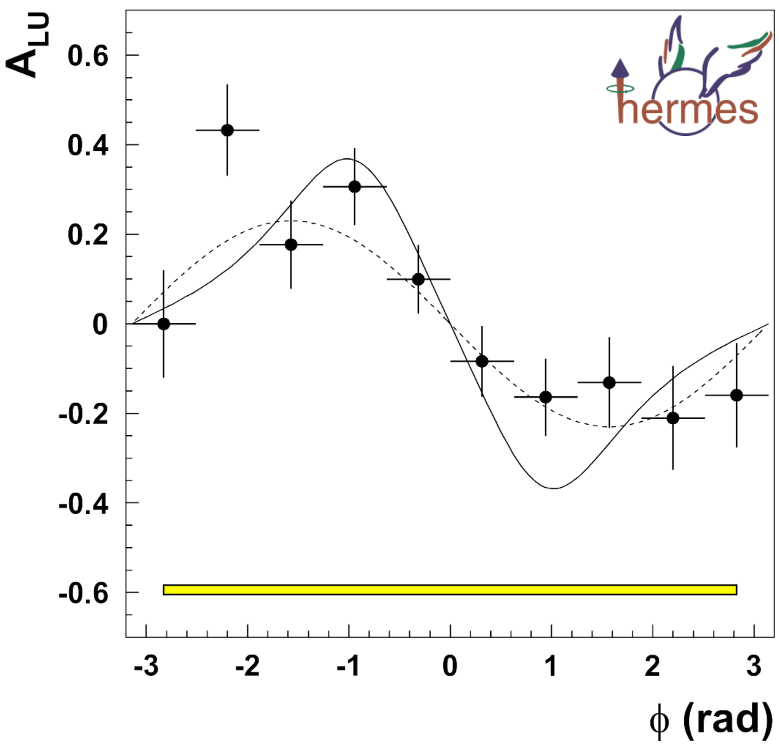
for neutron

first DVCS signals

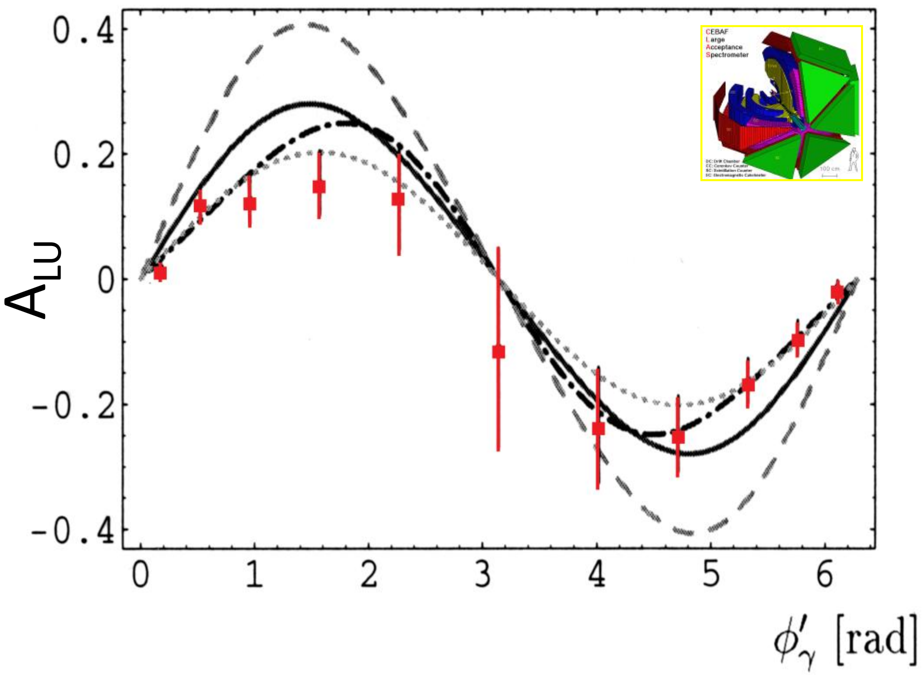
-- interference term --

$$A_{LU} \sim \frac{(BH)*Im(DVCS)*\sin\phi}{(BH^2+DVCS^2)}$$

[PRL87(2001), 182001]



[PRL87(2001), 182002]



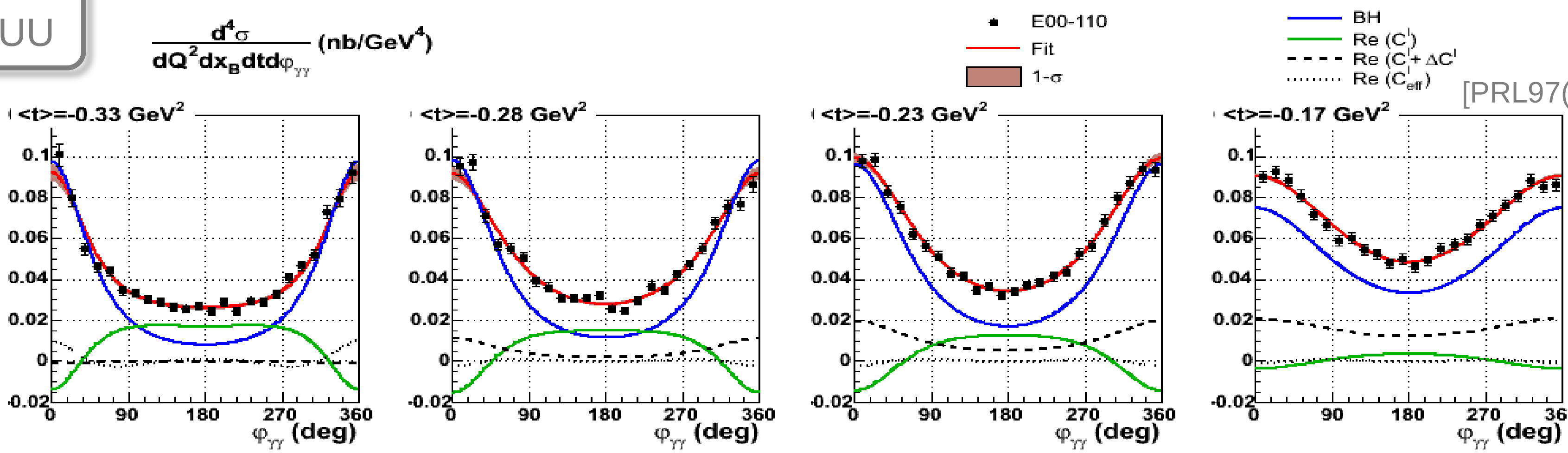
→ sinϕ dependence indicates dominance of handback contribution

Hall-A

call for high statistics

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

σ_{UU}



[PRL97(2006)]

ϕ

BH

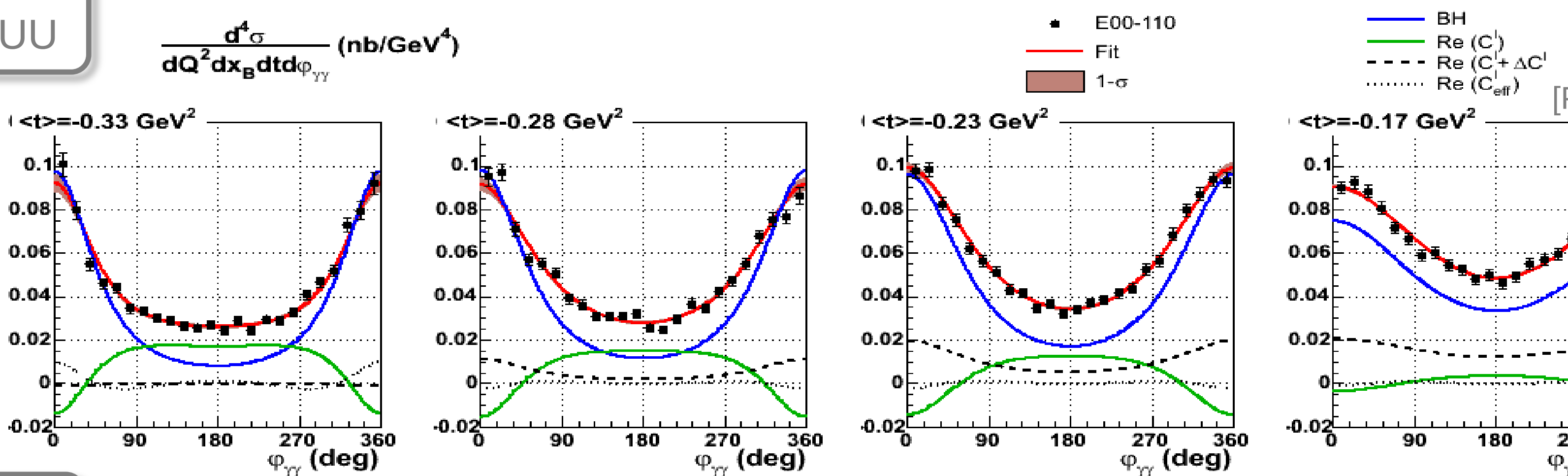
DVCS [GPD model: VGG(1999)]

Hall-A

call for high statistics

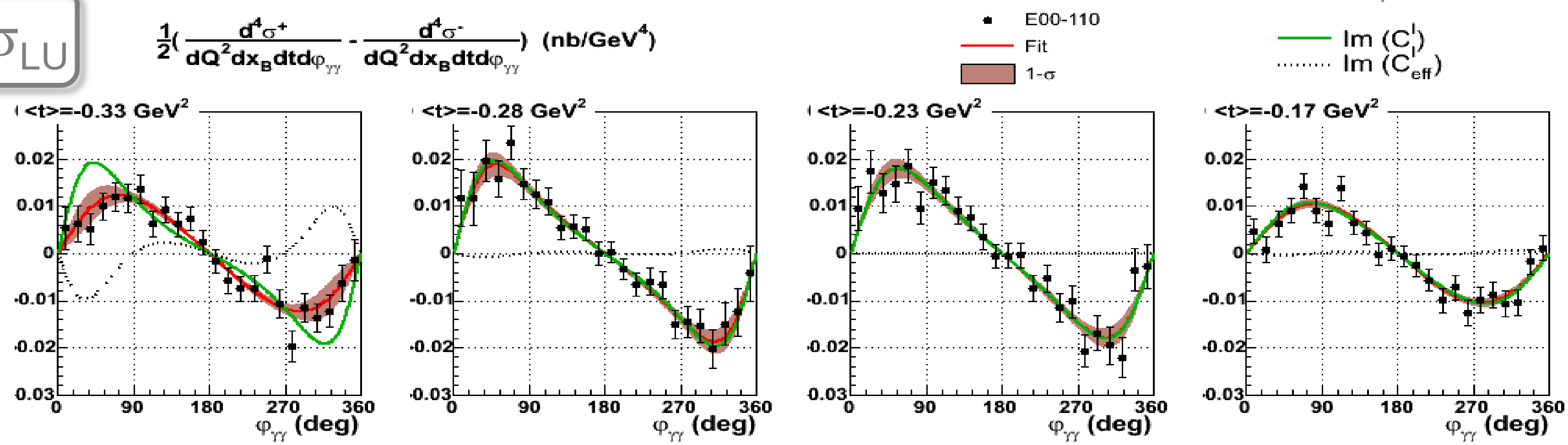
$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + (\tau^*_{BH}\tau_{DVCS} + \tau^*_{DVCS}\tau_{BH})$$

σ_{UU}

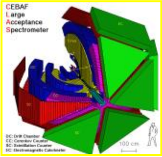


[PRL97(2006)]

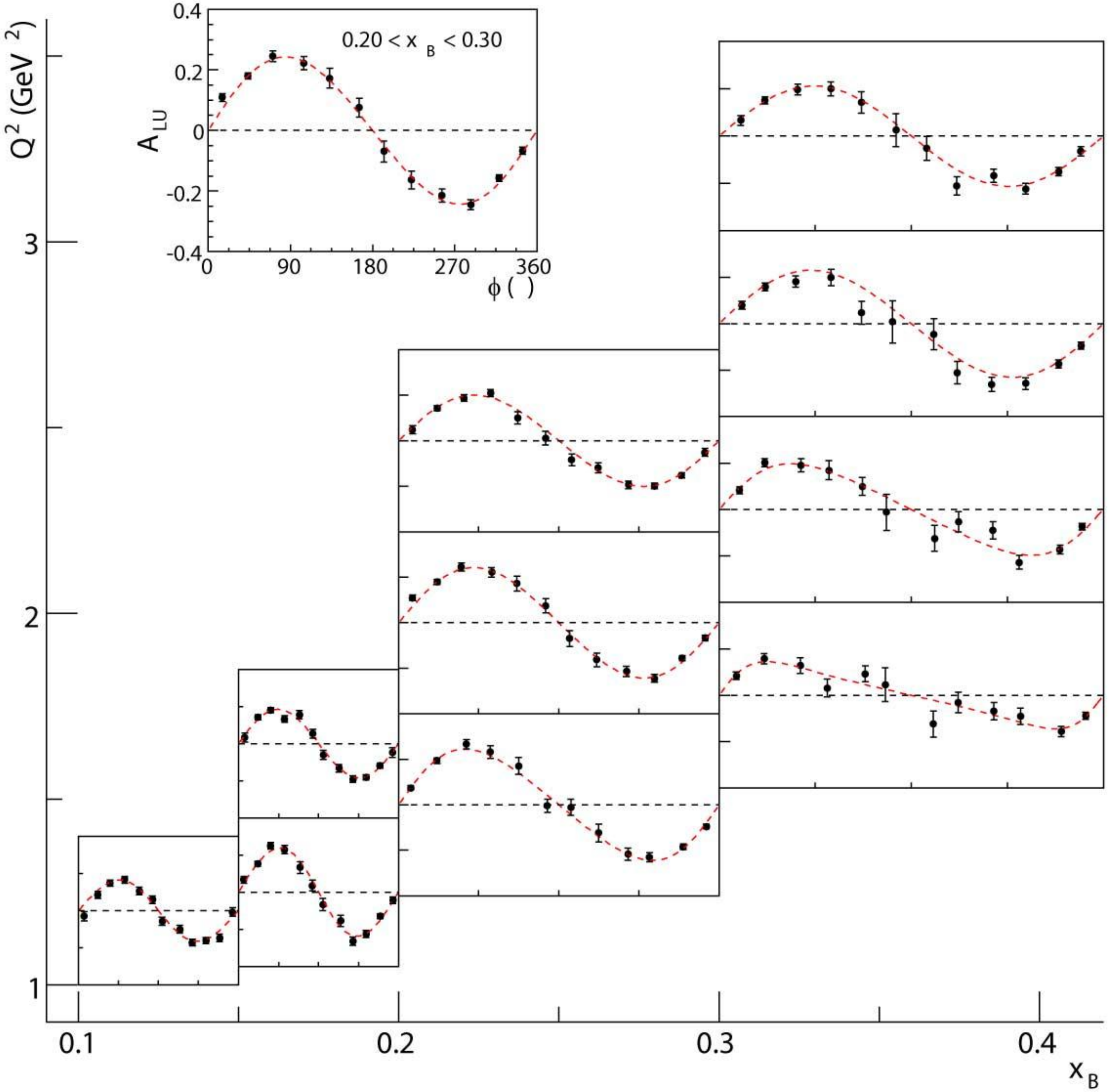
$\Delta\sigma_{LU}$



call for high statistics



DVCS beam-spin asymmetry [PRL100(2008)]

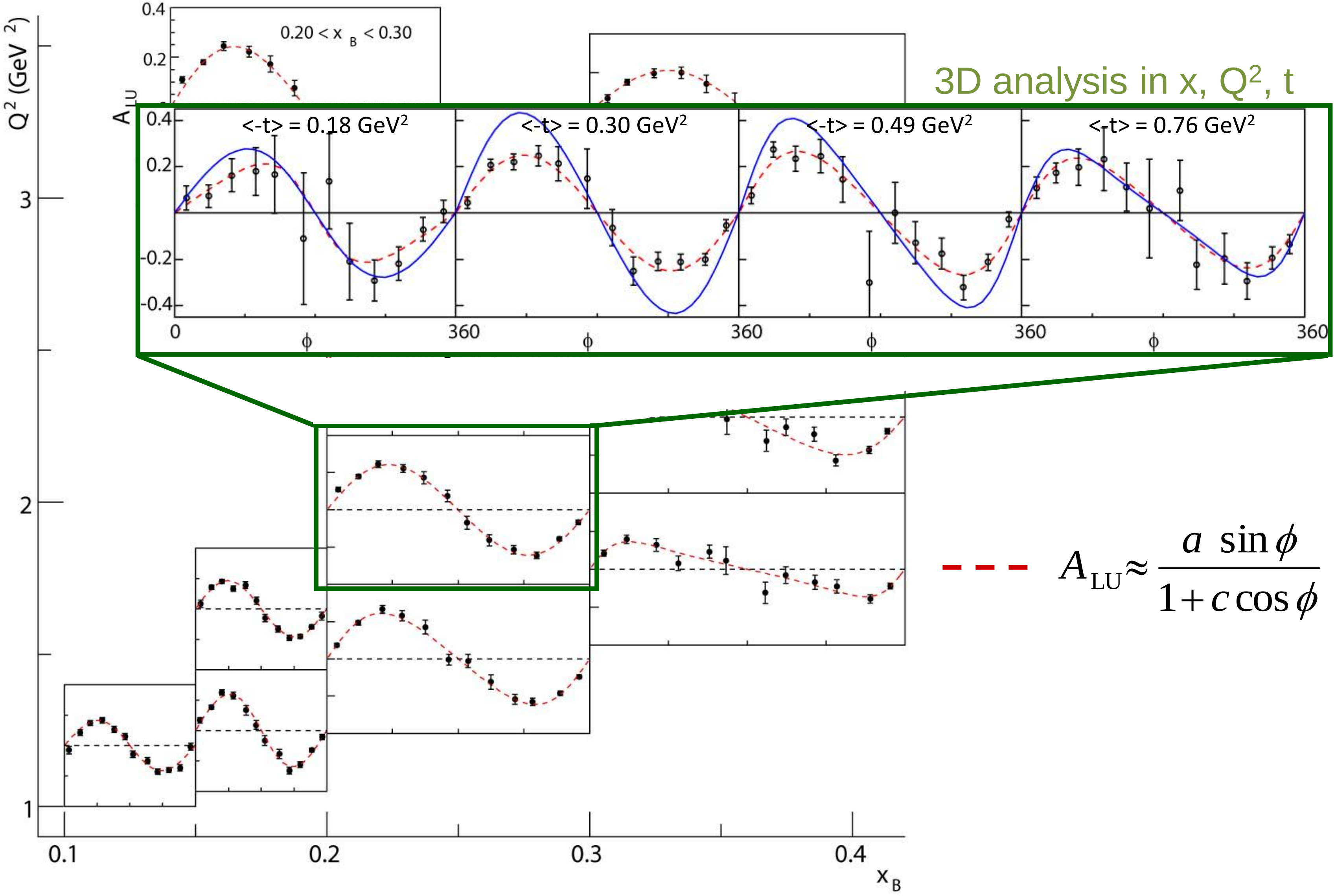


$$A_{LU} \sim \frac{(BH)^* Im(DVCS)^* \sin\phi}{(BH^2+DVCS^2)}$$

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

call for high statistics

DVCS beam-spin asymmetry [PRL100(2008)]



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

call for new analysis methods

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

combined analysis of **charge & polarisation** observables

→ separation of *Interference* & *DVCS*^{2} amplitudes

call for new analysis methods

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

combined analysis of **charge & polarisation** observables

→ separation of *Interference* & *DVCS*^{2} amplitudes

e.g., beam-spin asymmetry:

$$\sigma_{LU}(\phi, P_l, e_l) = \sigma_{UU}(\phi) \cdot \{1 + P_l A_{LU}^{DVCS}(\phi) + e_l P_l A_{LU}^{I}(\phi) + e_l A_C(\phi)\}$$

call for new analysis methods

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

combined analysis of **charge & polarisation** observables

→ separation of *Interference* & *DVCS*^{2} amplitudes

e.g., beam-spin asymmetry:

$$\sigma_{LU}(\phi; P_l, e_l) = \sigma_{UU}(\phi) \cdot \left\{1 + P_l A^{DVCS}_{LU}(\phi) + e_l P_l A^I_{LU}(\phi) + e_l A_C(\phi)\right\}$$

- *charged-averaged* beam-spin asymmetry:

$$A^{DVCS}_{LU}(\phi) = \left(\sigma^{+\rightarrow} - \sigma^{+\leftarrow}\right) + \left(\sigma^{-\rightarrow} - \sigma^{-\leftarrow}\right) / \Sigma \qquad \propto s_1^{DVCS} \sin\phi$$

call for new analysis methods

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

combined analysis of **charge & polarisation** observables

→ separation of *Interference* & *DVCS*^{2} amplitudes

e.g., beam-spin asymmetry:

$$\sigma_{LU}(\phi; P_l, e_l) = \sigma_{UU}(\phi) \cdot \{1 + P_l\, A_{LU}^{DVCS}(\phi) + e_l P_l\, A_{LU}^{I}(\phi) + e_l\, A_C(\phi)\}$$

- *charged-averaged* beam-spin asymmetry:

$$A_{LU}^{DVCS}(\phi) = \left(\sigma^{+\rightarrow} - \sigma^{+\leftarrow}\right) + \left(\sigma^{-\rightarrow} - \sigma^{-\leftarrow}\right) / \Sigma \qquad \propto s_1^{DVCS} \sin\phi$$

- *charge-difference* beam-spin asymmetry:

$$A_{LU}^{DVCS}(\phi) = \left(\sigma^{+\rightarrow} - \sigma^{+\leftarrow}\right) - \left(\sigma^{-\rightarrow} - \sigma^{-\leftarrow}\right) / \Sigma \qquad \propto \sum_{n=1}^{2} s_n^I \sin(n\phi)$$ → *Im(CFF)*

call for new analysis methods

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

combined analysis of **charge & polarisation** observables

→ separation of *Interference* & *DVCS*[2] amplitudes

e.g., beam-spin asymmetry:

$$\sigma_{LU}(\phi; P_l, e_l) = \sigma_{UU}(\phi) \cdot \{1 + P_l\, A_{LU}^{DVCS}(\phi) + e_l P_l\, A_{LU}^{I}(\phi) + e_l\, A_C(\phi)\}$$

- *charged-averaged* beam-spin asymmetry:

$$A_{LU}^{DVCS}(\phi) = \left(\sigma^{+\rightarrow} - \sigma^{+\leftarrow}\right) + \left(\sigma^{-\rightarrow} - \sigma^{-\leftarrow}\right) / \Sigma \qquad \propto s_1^{DVCS} \sin\phi$$

- *charge-difference* beam-spin asymmetry:

$$A_{LU}^{DVCS}(\phi) = \left(\sigma^{+\rightarrow} - \sigma^{+\leftarrow}\right) - \left(\sigma^{-\rightarrow} - \sigma^{-\leftarrow}\right) / \Sigma \qquad \propto \sum_{n=1}^{2} s_n^I \sin(n\phi)$$ → *Im(CFF)*

- beam-spin averaged *charge* asymmetry:

$$A_C(\phi) = \left(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}\right) - \left(\sigma^{-\rightarrow} + \sigma^{-\leftarrow}\right) / \Sigma \qquad \propto \sum_{n=0}^{3} c_n^I \cos(n\phi)$$ → *Re(CFF)*

call for new analysis methods

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

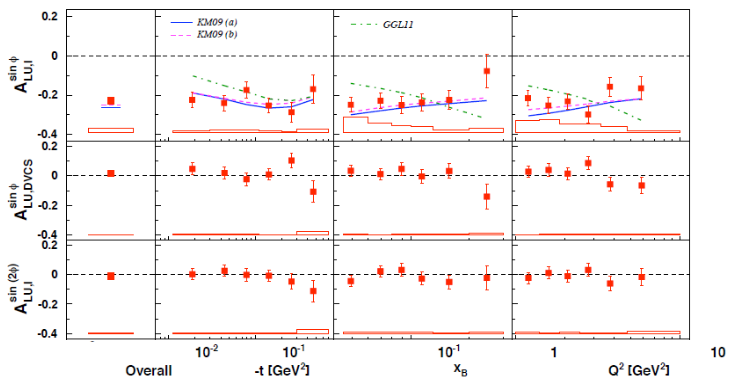
combined analysis of **charge & polarisation** observables

→ separation of *Interference* & *DVCS*² amplitudes

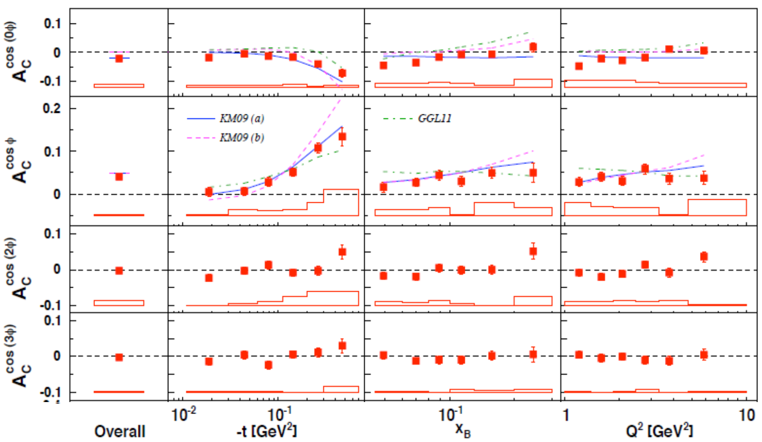
$$\sigma_{LU}(\phi; P_l, e_l) = \sigma_{UU}(\phi) \cdot \{1 + P_l A_{LU}^{DVCS}(\phi) + e_l P_l A_{LU}^{I}(\phi) + e_l A_C(\phi)\}$$

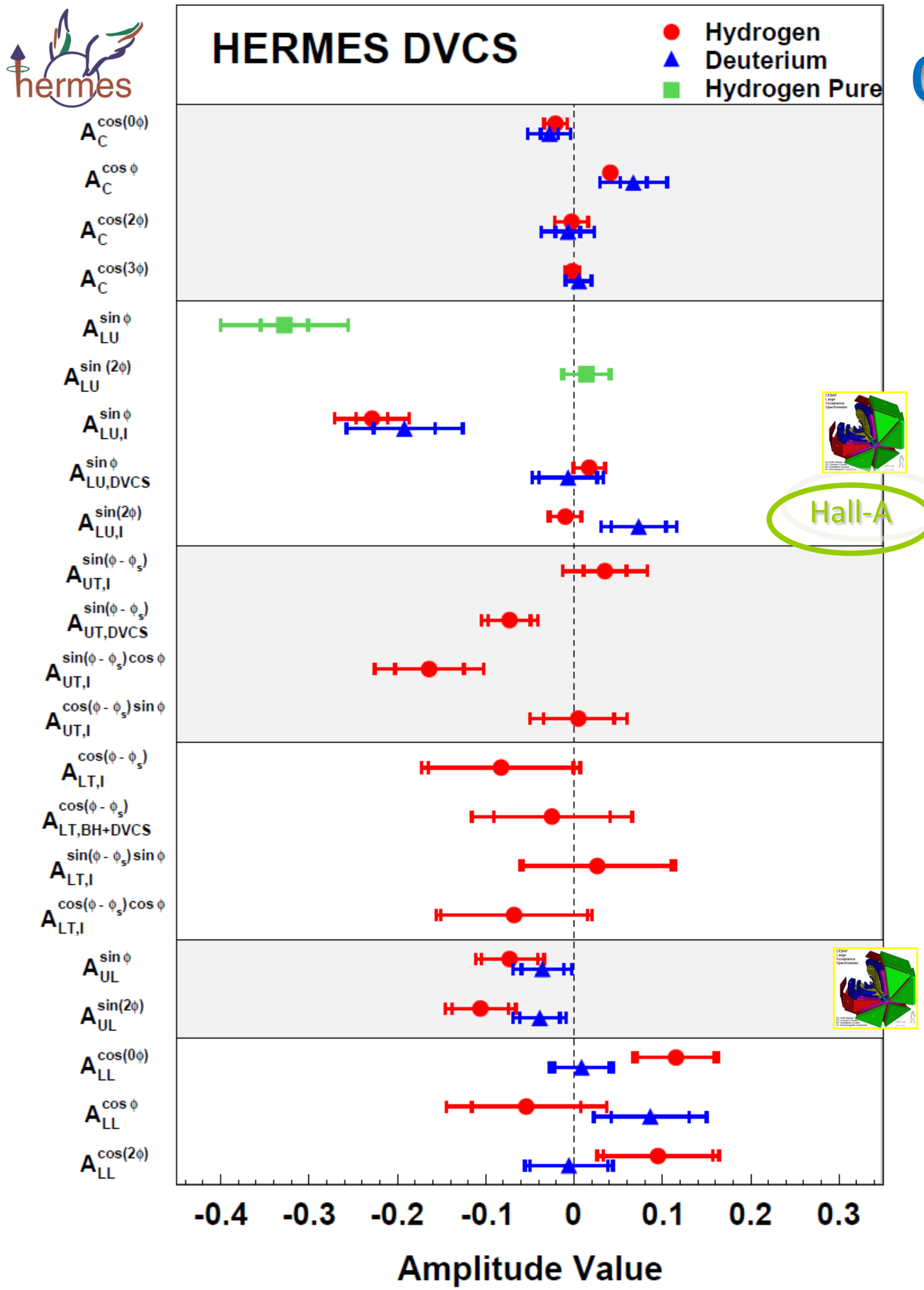
$$s_1^{DVCS} \sin\phi \qquad \sum_{n=1}^{2} s_n^I \sin(n\phi) \qquad \sum_{n=0}^{3} c_n^I \cos(n\phi)$$

[JHEP07(20112]



[JHEP07(20012]





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 $(\widetilde{H})$

→ longitudinal-target double-spin

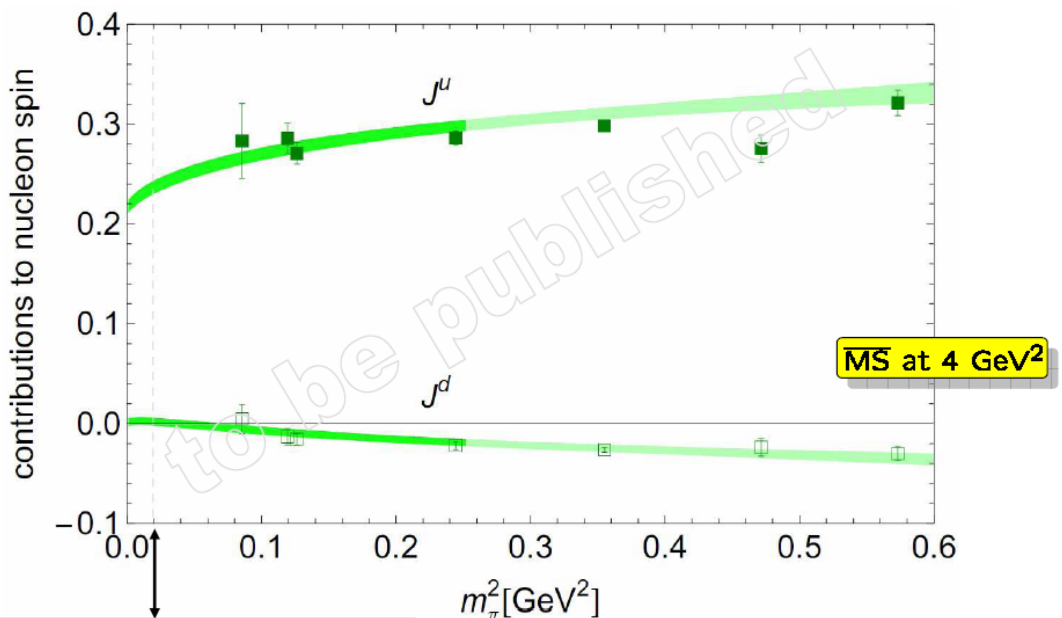
Re $(\widetilde{H})$

hunting the OAM

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

- lattice results:

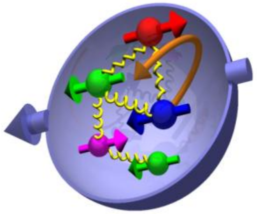
[P. Hägler etal.(2011)]



$J^u = 0.236(6) \approx 47\%$ of $1/2$
$J^d = 0.0018(37) \approx 1\%$ of $1/2$

$J^{u+d} \approx 0.238 \pm 0.008 \approx 48\%$ of $1/2$

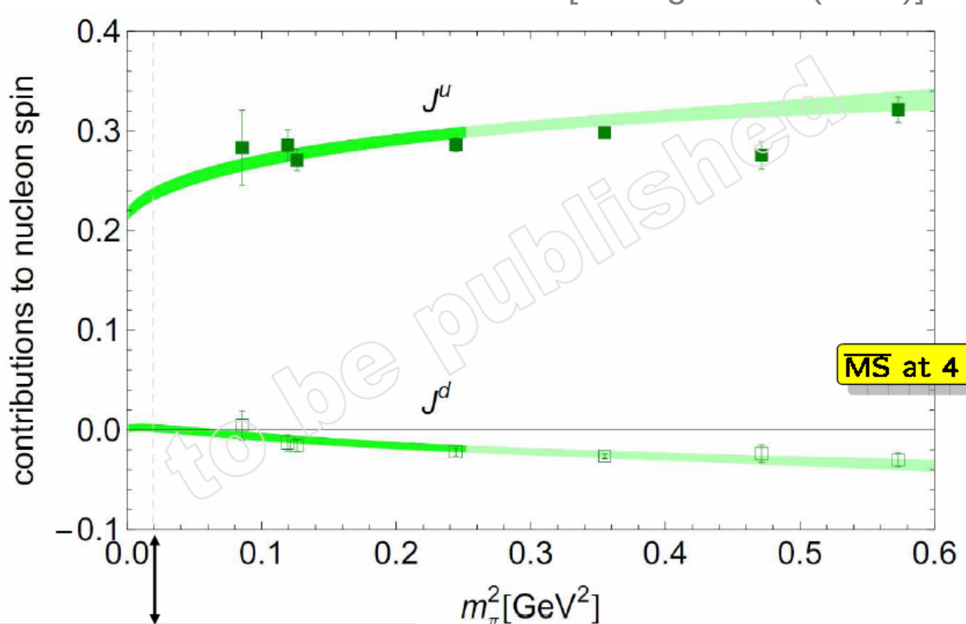
hunting the OAM



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

- lattice results:

[P. Hägler etal.(2011)]



$\overline{\text{MS}}$ at 4 GeV

$J^u = 0.236(6) \approx 47\%$ of $1/2$
$J^d = 0.0018(37) \approx 1\%$ of $1/2$

$J^{u+d} \approx 0.238 \pm 0.008 \approx 48\%$ of 1/2

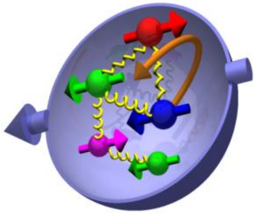
- GPD model tuned to VM:

[Goloskokov, Kroll(2008)]

J^u	J^d	J^s	J^g
0.250	0.020	0.015	0.214
0.276	0.046	0.041	0.132
0.225	-0.005	-0.011	0.286
0.209	0.013	0.015	0.257
0.230	0.024	0.015	0.228
0.234	0.028	0.019	0.214

variants for GPD *E*

hunting the OAM



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

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

- sensitivity to GPD E (@fixed target exp. kinematics)
  - pDVCS: A_{UT} → HERMES
  - nDVCS: A_{LU} → Hall A
  - meson prod. A_{UT}: ρ^0 → HERMES, COMPASS

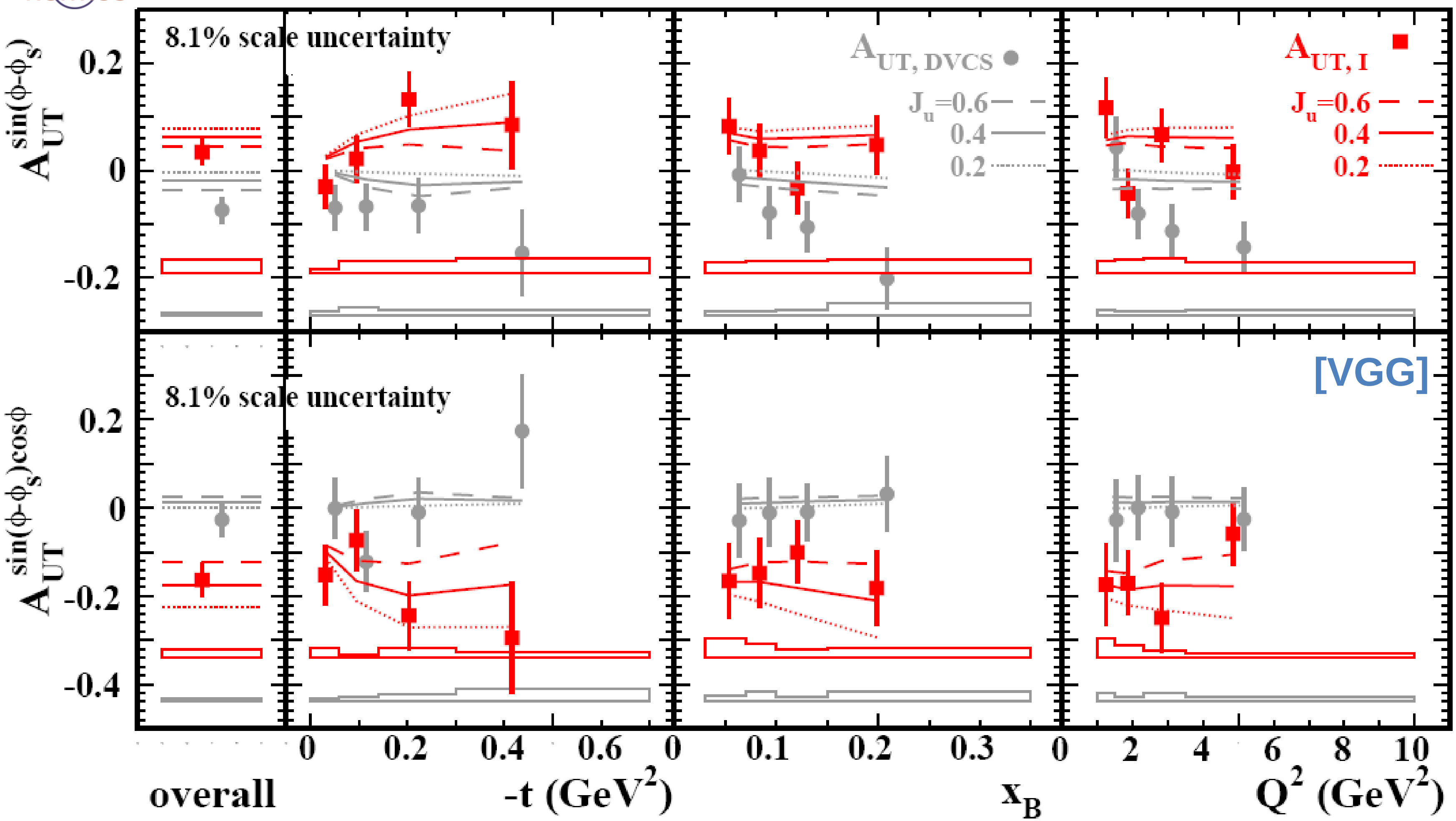
    ...also ω, ϕ, ρ^+, K^{*0}

hunting the OAM

-- pDVCS : transverse target-spin asymmetry --

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

[JHEP06(2008)]



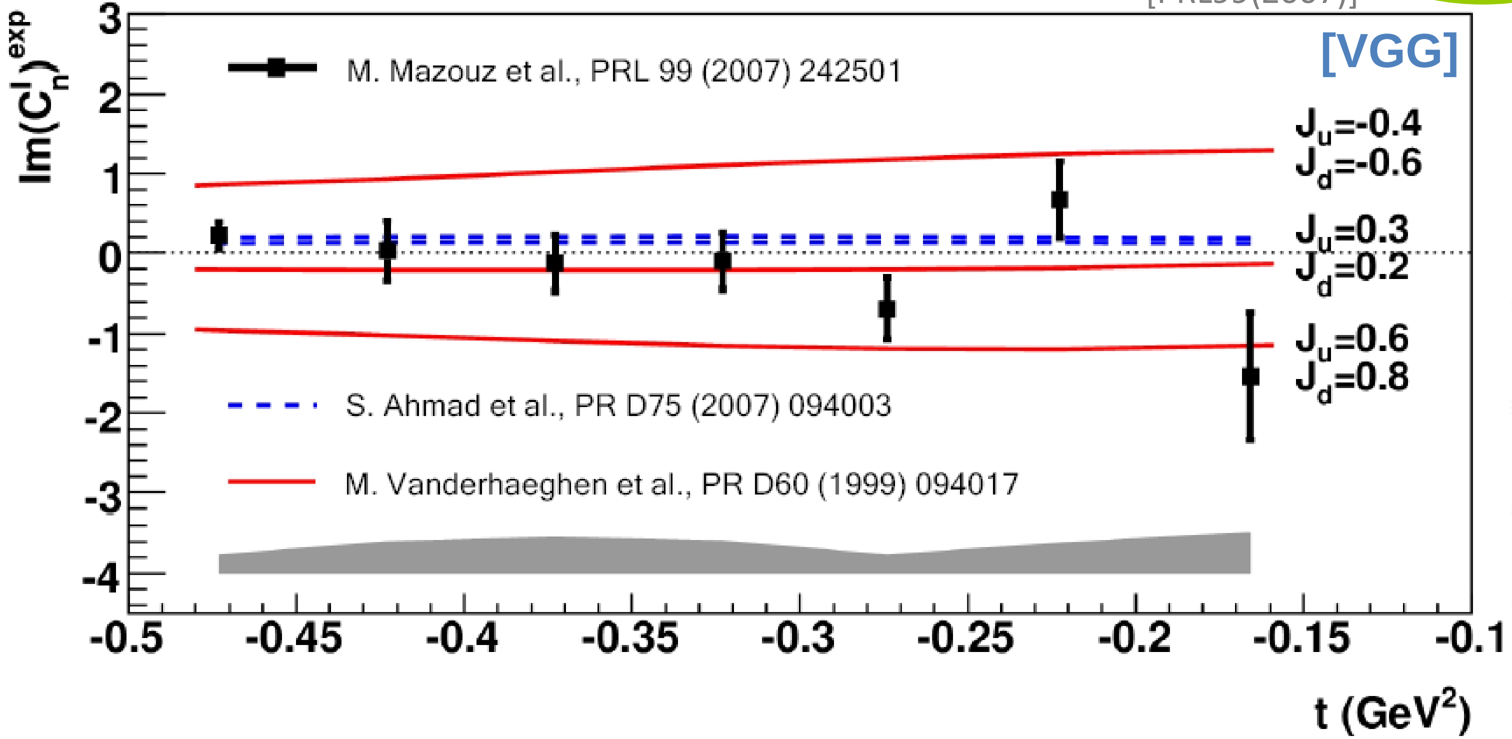
hunting the OAM

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

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

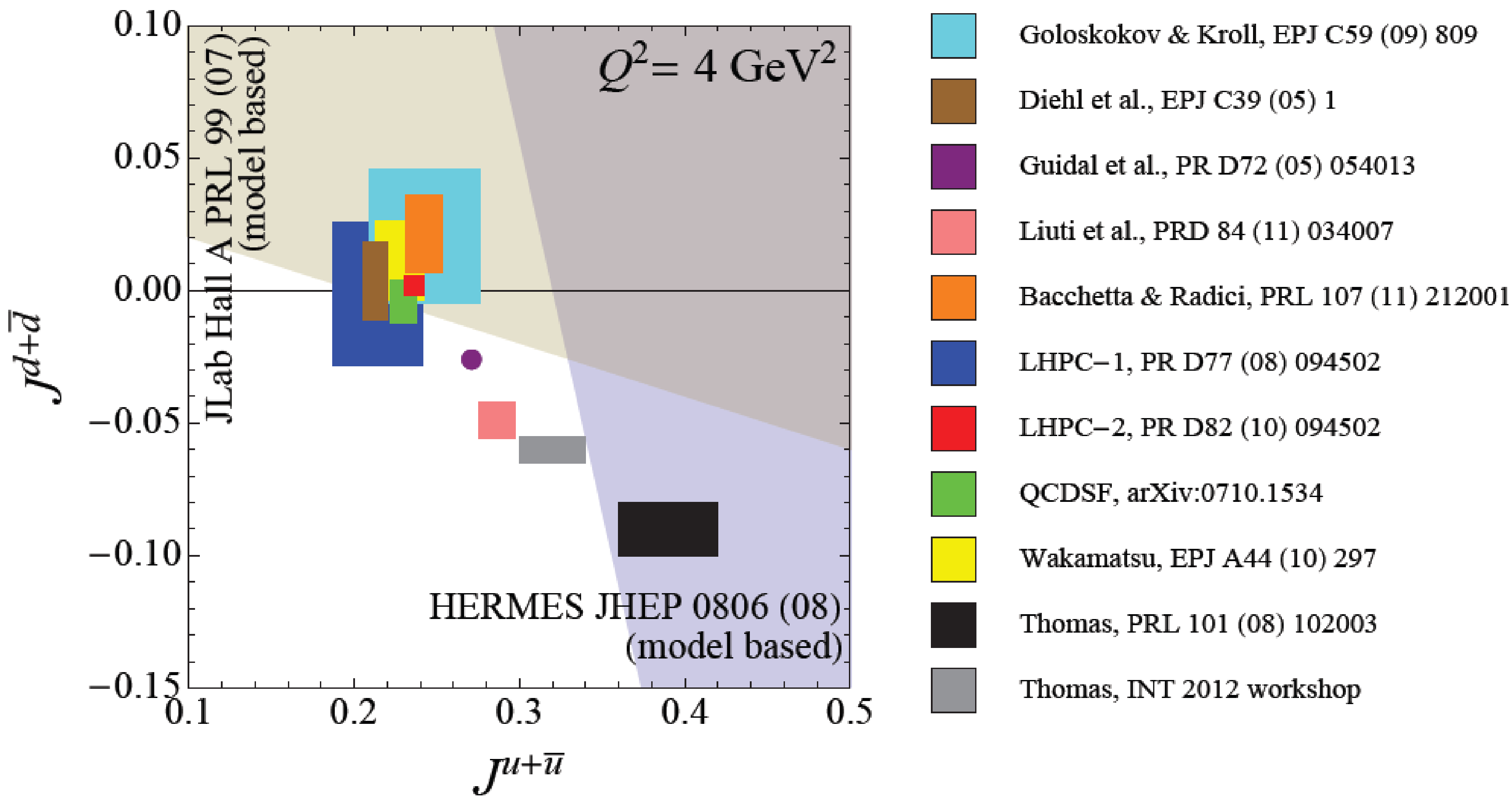
Hall-A

[PRL99(2007)]



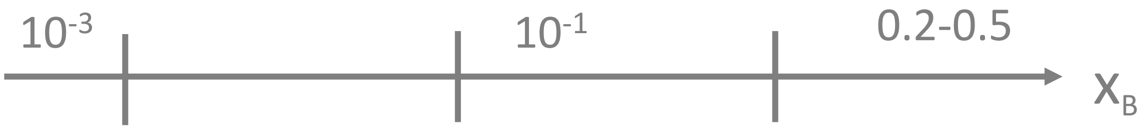
hunting the OAM

- *model dependent* [VGG(1999)] constrain of J_u vs J_d
- lattice
- GPD & TMD models



[figure taken from Bachetta&Radici, PRL107(2011)]

conclusions



HERA collider | COMPASS | HERMES / JLab

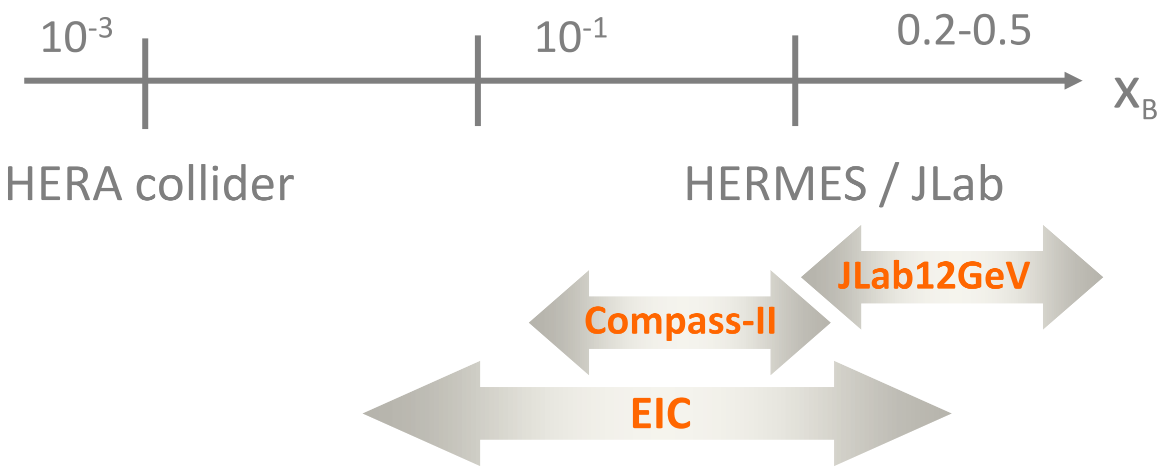
$10^{-4} < x_B < 0.02$ | $0.02 < x_B < 0.4$ / $0.1 < x_B < 0.6$

sea quarks & gluons | (gluons) (valence) quarks

DVCS, VM | DVCS, (mesons)

- increasing amount and precision of experimental data
- large variety of different observables (however, many still with limited precision)
- progress in model calculations, *plenty of room for more work*...

conclusions & perspectives



- increasing amount and precision of experimental data
- large variety of different observables (however, many still with limited precision)
- progress in model calculations, *plenty of room for more work*...
- bright future for GPD studies:

  → JLab12: DVCS in valence kinematic region

  → COMPASS-II with recoil: DVCS & VM in transition kinematic region

[Volker Burkert, 'Enrico Fermi' physics school, Varenna, Italy, July 2011]

12 GeV Approved Experiments by Physics Topics

[http://www.jlab.org/12GeV/]

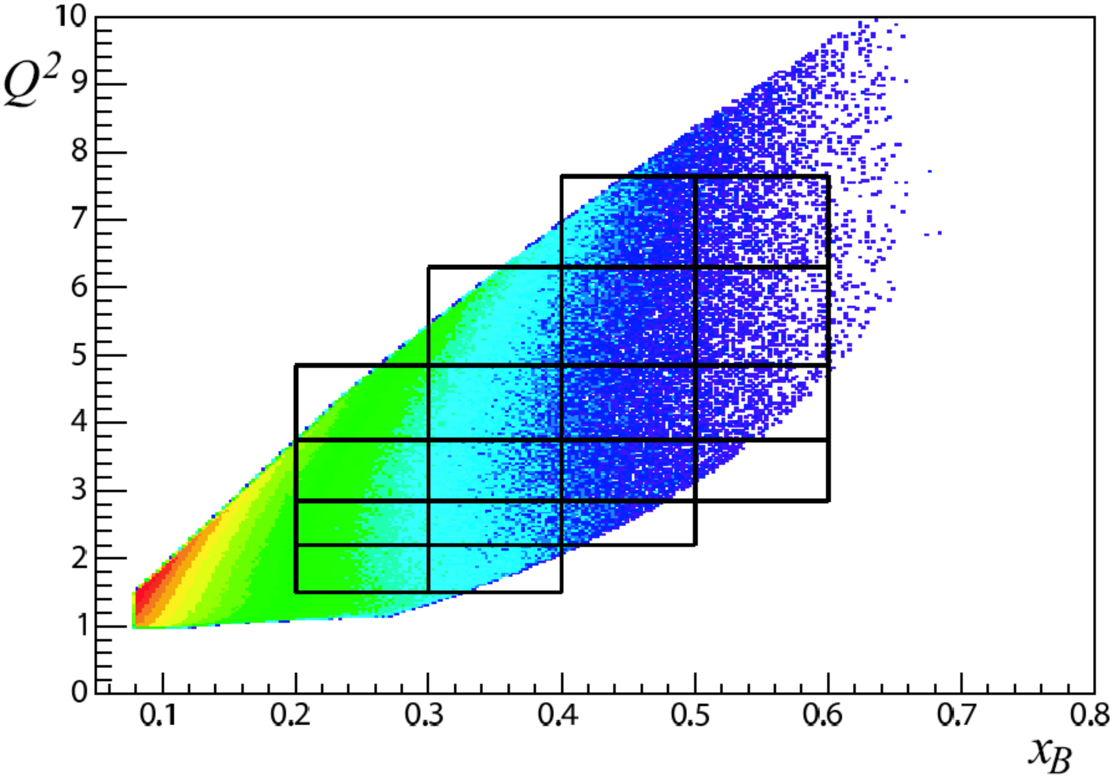
Topic	Hall A	Hall B	Hall C	Hall D	Total
The Hadron spectra as probes of QCD (rated) (GlueX and heavy baryon and meson spectroscopy)		1		1	**2**
The transverse structure of the hadrons (rated) (Elastic and transition Form Factors)	4	2	3		**9**
The longitudinal structure of the hadrons (rated) (Unpolarized and polarized parton distribution functions)	2	2	4		**8**
The 3D structure of the hadrons (unrated) (**Generalized Parton Distributions** and Transverse Momentum Distributions)	3	8 (*)	4		**15**
Hadrons and cold nuclear matter (rated) (Medium modification of the nucleons, quark hadronization, N-N correlations, hypernuclear spectroscopy, few-body experiments)	1	2	5		**8**
Low-energy tests of the Standard Model and Fundamental Symmetries (rated)	2			1	**3**
TOTAL	**12**	**15**	**16**	**2**	**45**

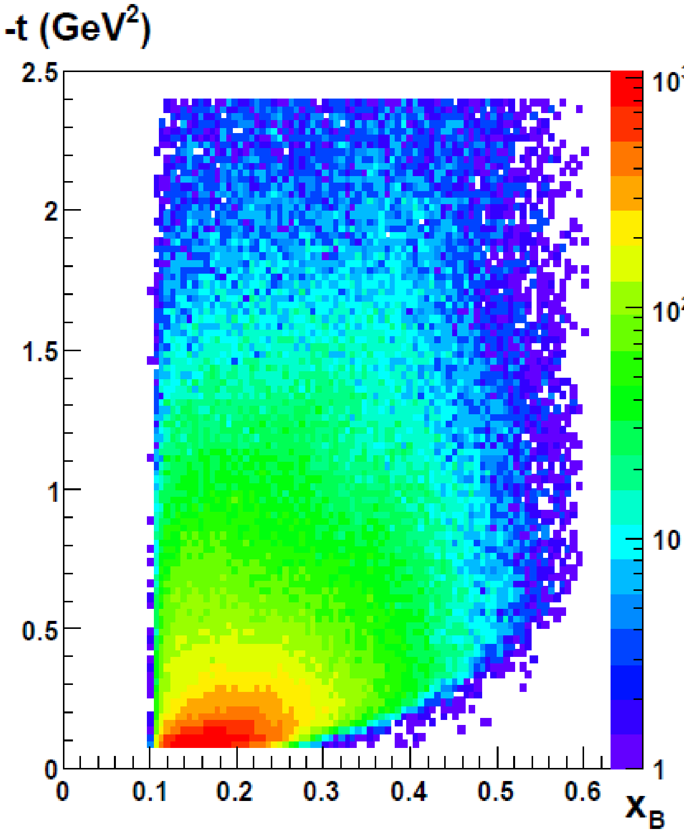
Current PAC approved experiments represent over 6 years of running at 35 weeks/year

(*) 3 new approved proposals on the topic @Hall B since then

DVCS @CLAS12 [2014+]

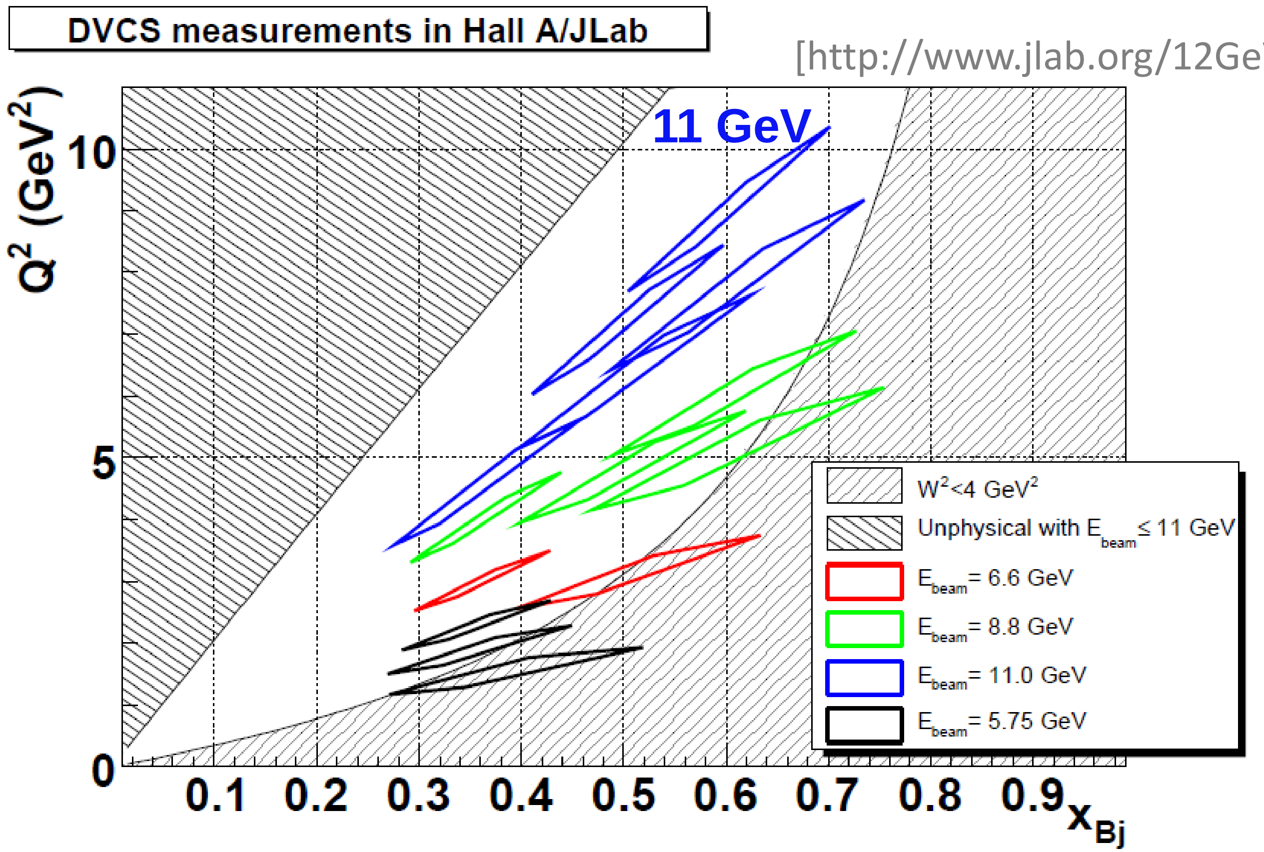
[http://www.jlab.org/12GeV/]





- fully differential analysis
- watch requirement $t << Q^2$

DVCS @Hall A [2014+]

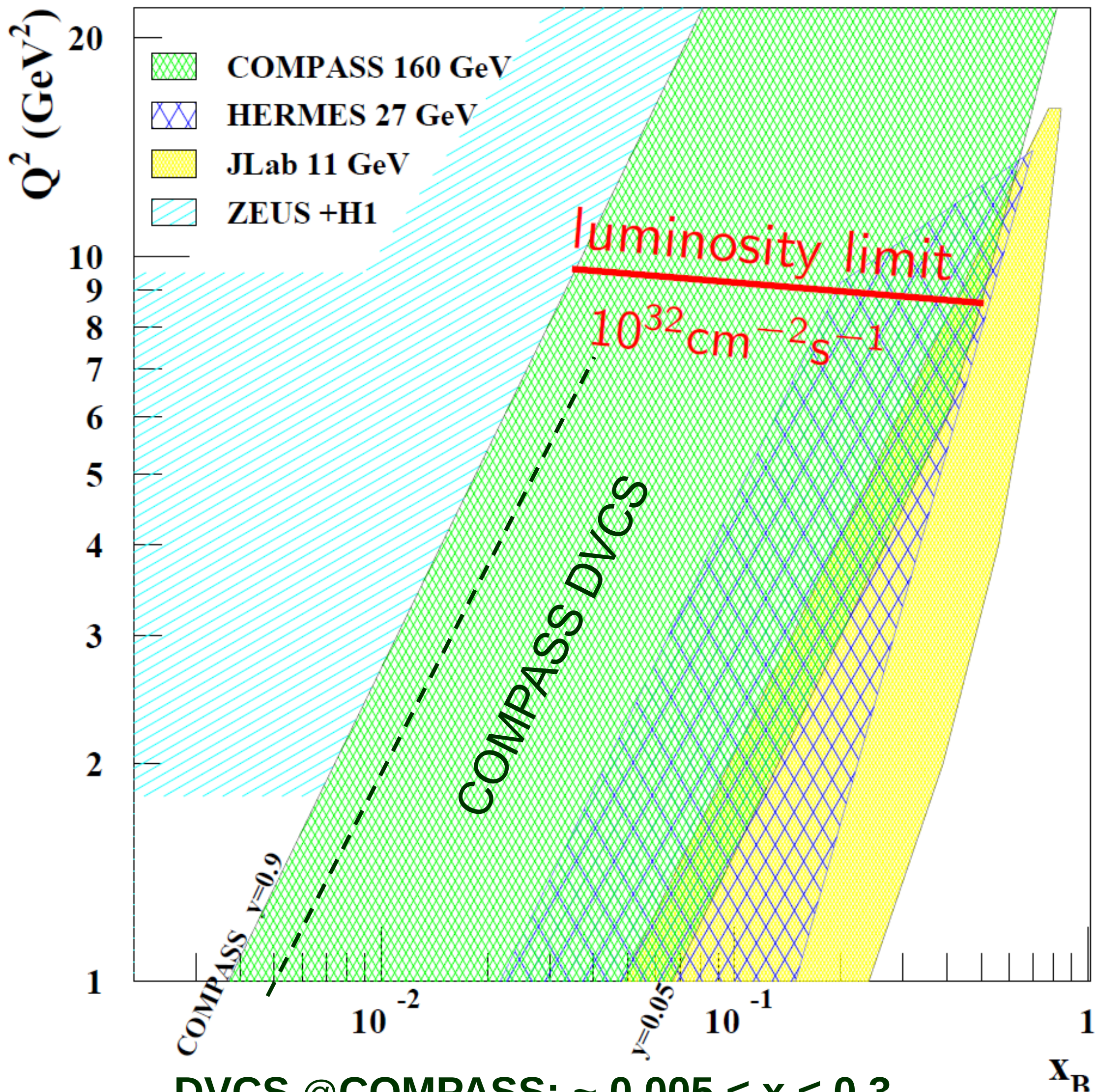


[http://www.jlab.org/12GeV/]

- fully differential analysis
- watch requirement $t << Q^2$

DVCS @COMPASS-II 2014+

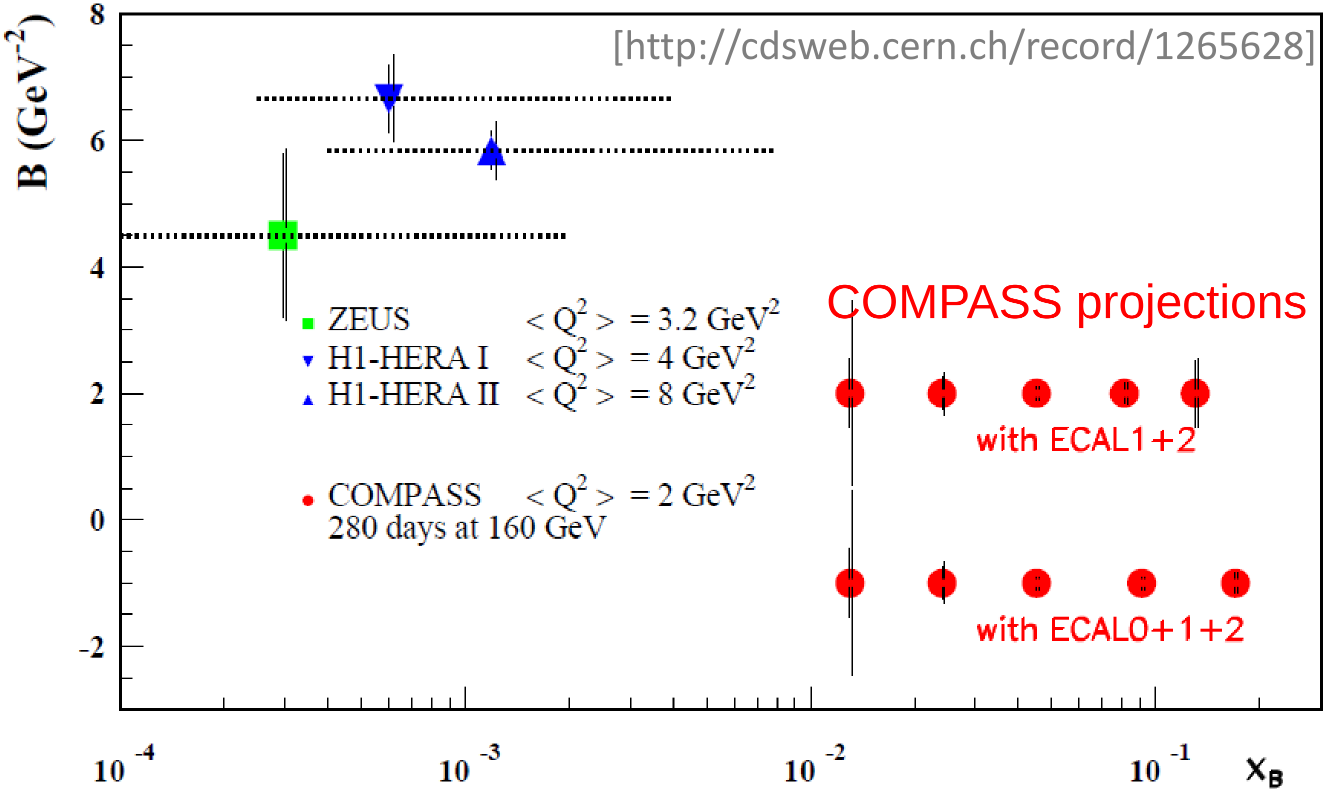
[http://cdsweb.cern.ch/record/1265628]



DVCS @COMPASS: ~ 0.005 < x < 0.3

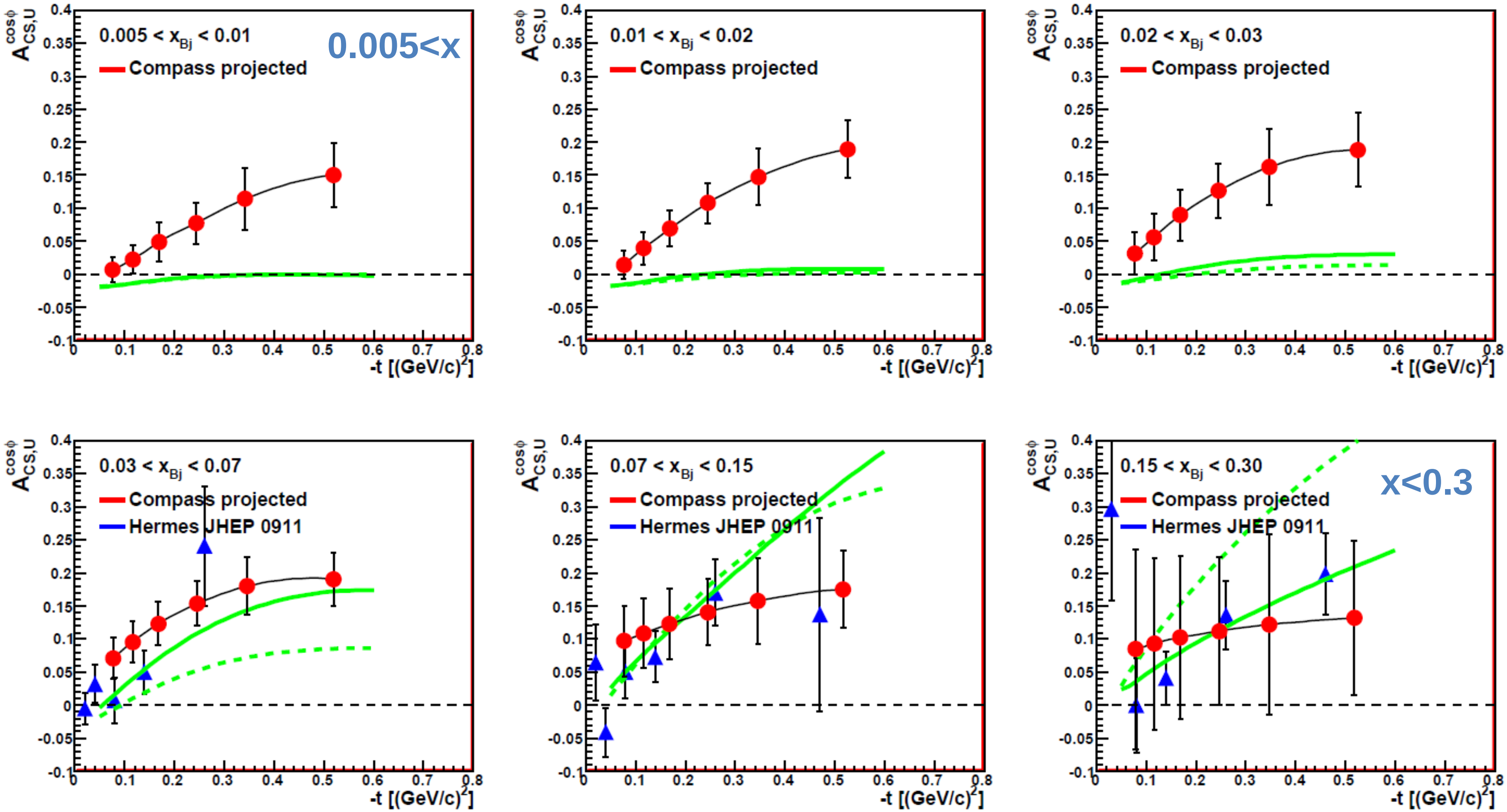
DVCS @COMPASS-II 2014+

- DVCS cross section: slope parameter *b*: $d\sigma/dt \sim e^{-b|t|}$



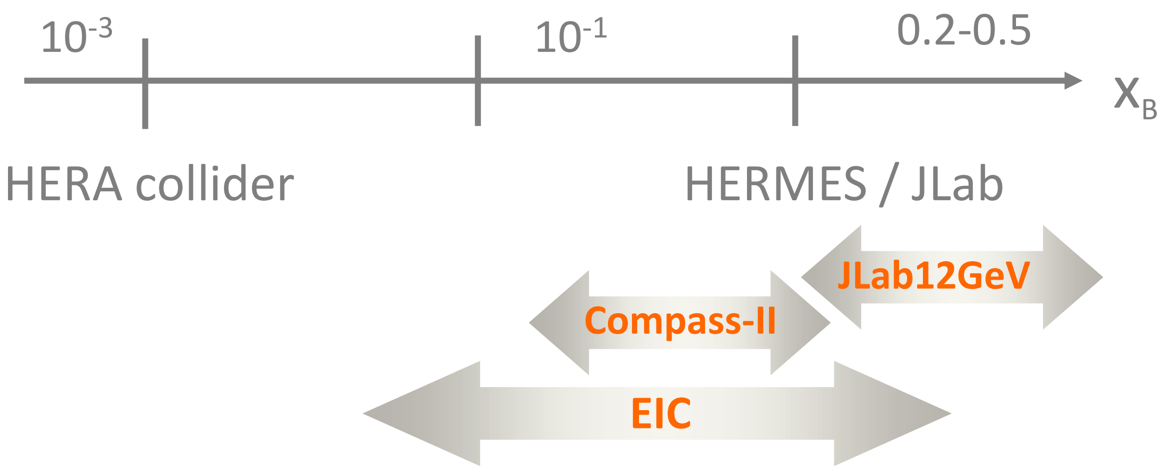
DVCS @COMPASS-II 2014+

- DVCS beam helicity & *charge* asymmetry $A_C^{\cos\phi}(t, x_B)$



[http://cdsweb.cern.ch/record/1265628]

conclusions & perspectives

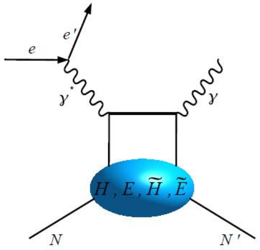


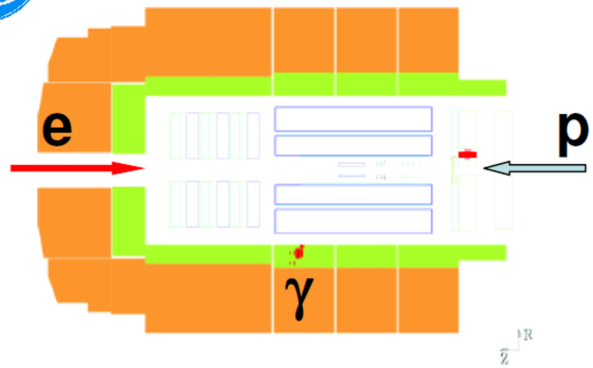
- increasing amount and precision of experimental data
- large variety of different observables (however, many still with limited precision)
- progress in model calculations, *plenty of room for more work*...
- bright future for GPD studies:
  - → JLab12: DVCS in valence kinematic region
  - → COMPASS-II with recoil: DVCS & VM in transition kinematic region
  - → EIC: mapping GPDs from Q^2 evolution of DVCS & from meson production

additional slides

exclusivity

@ the HERA collider experiments

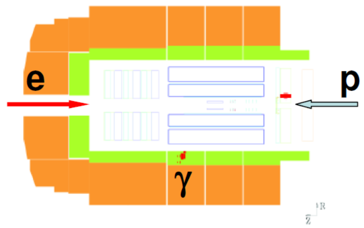




≈ hermetic detector

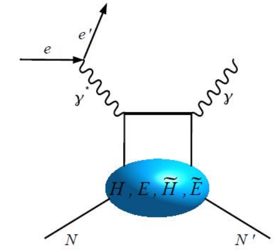
→ *p* escapes through beam pipe

LPS: *p* tagged control sample

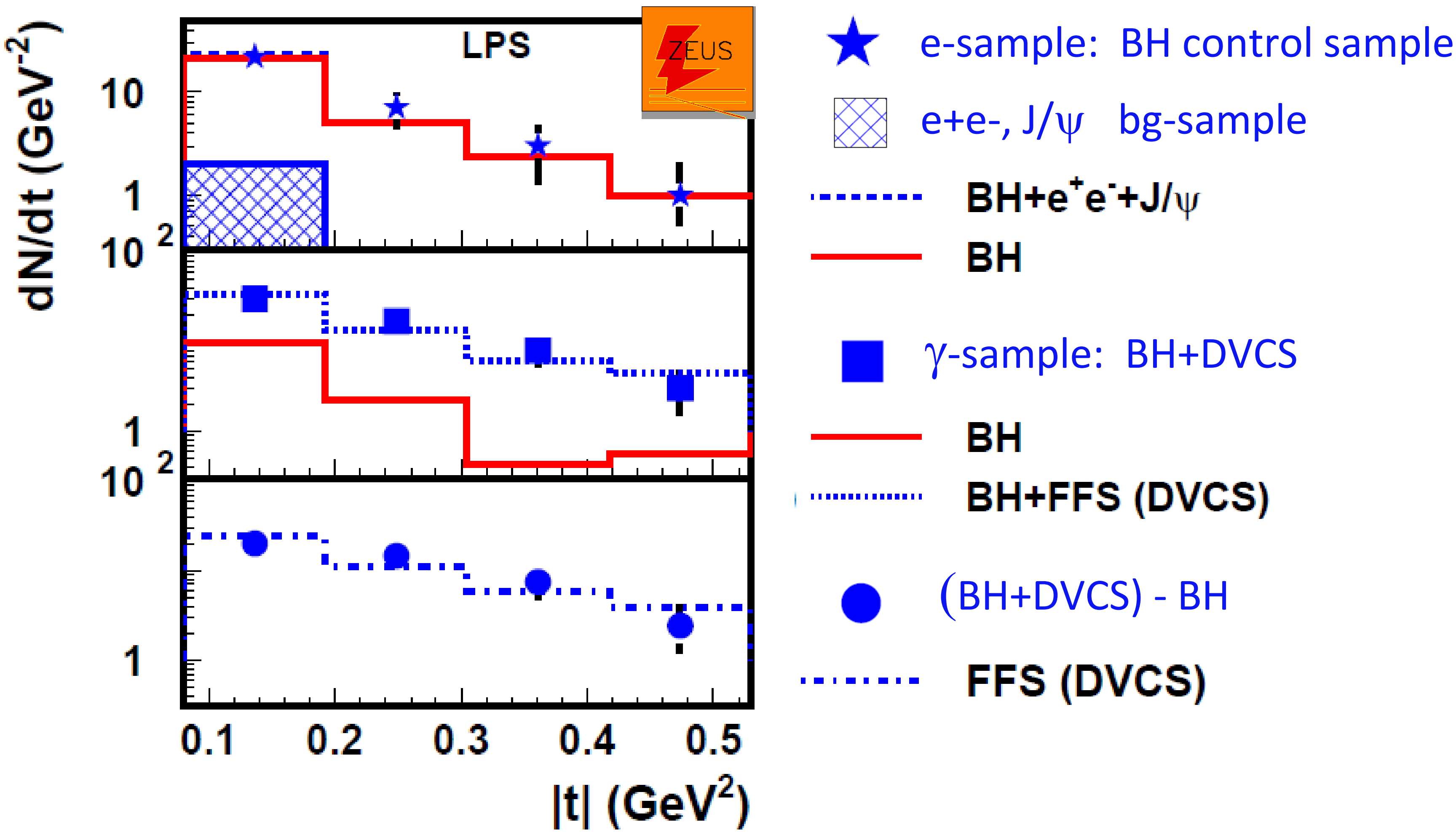


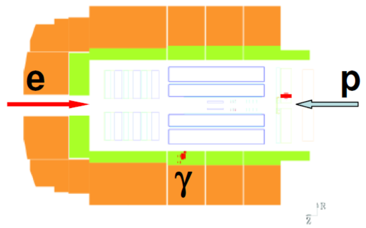
exclusivity

@ the HERA collider experiments



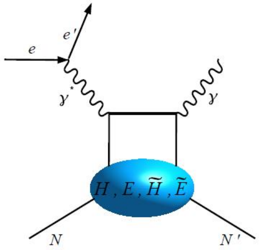
LPS: *p* tagged data sample



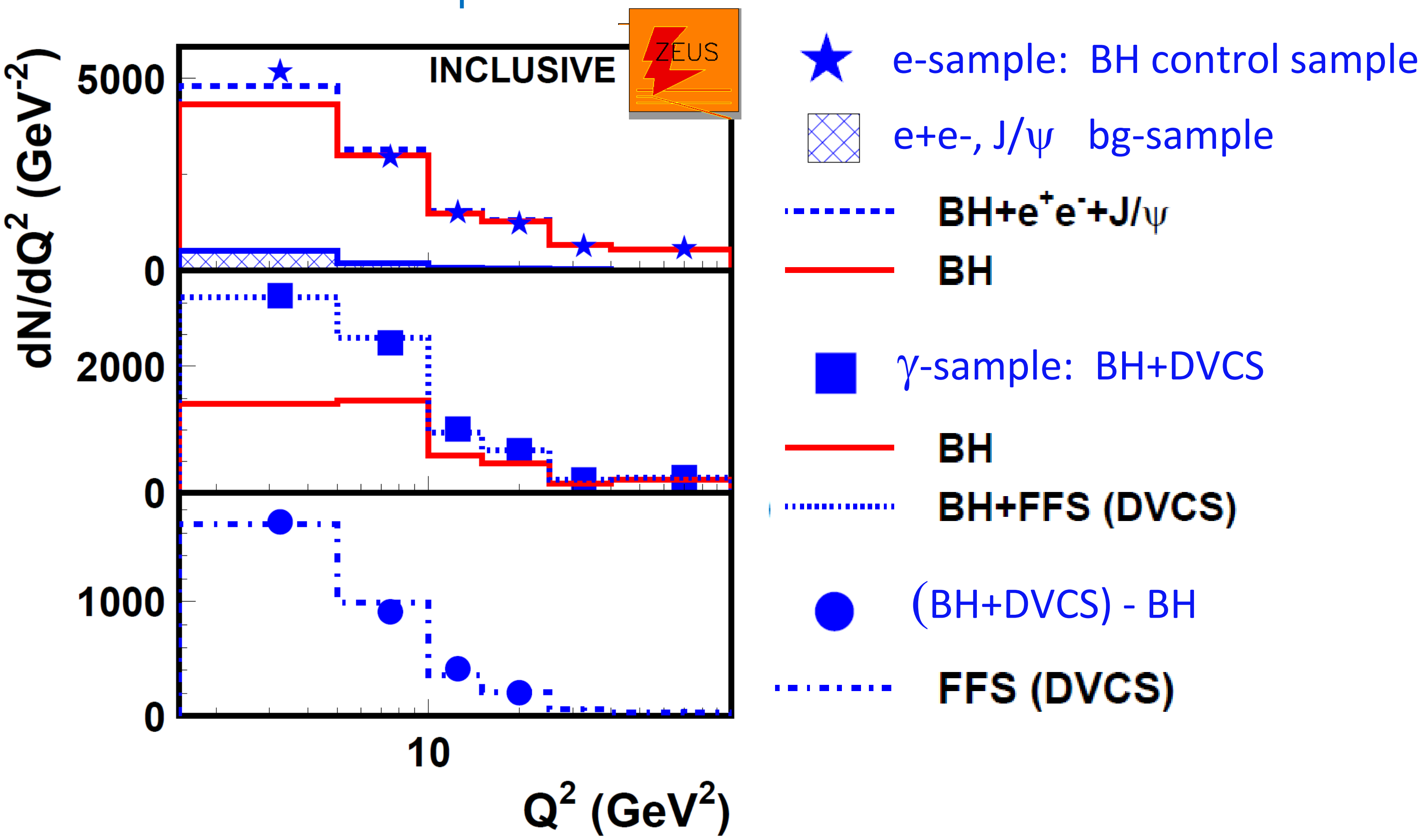


exclusivity

@ the HERA collider experiments

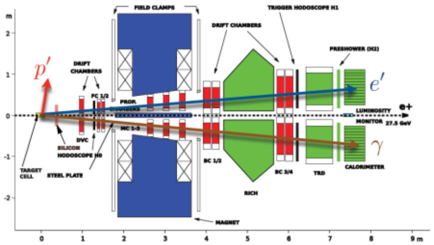


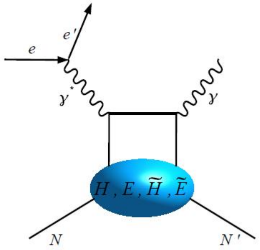
full data sample

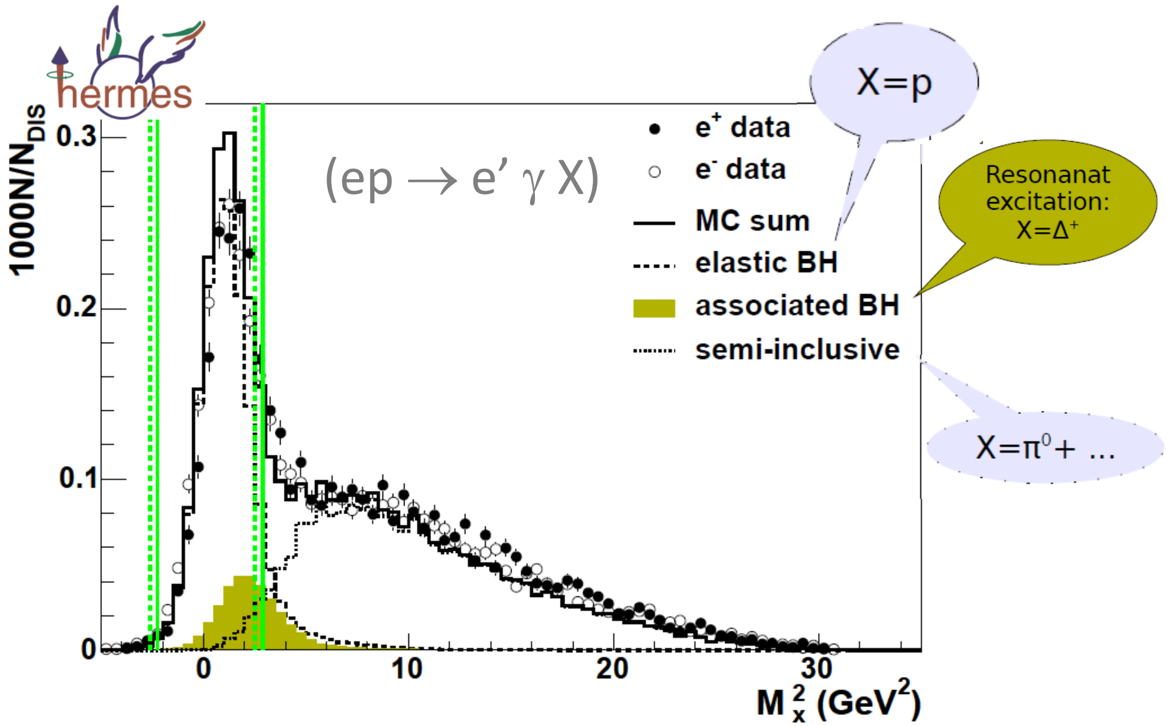


exclusivity

fixed target: via missing mass / energy



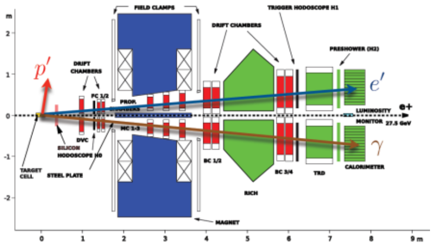




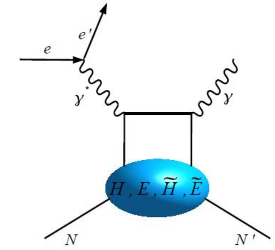
part of the signal

subtracted

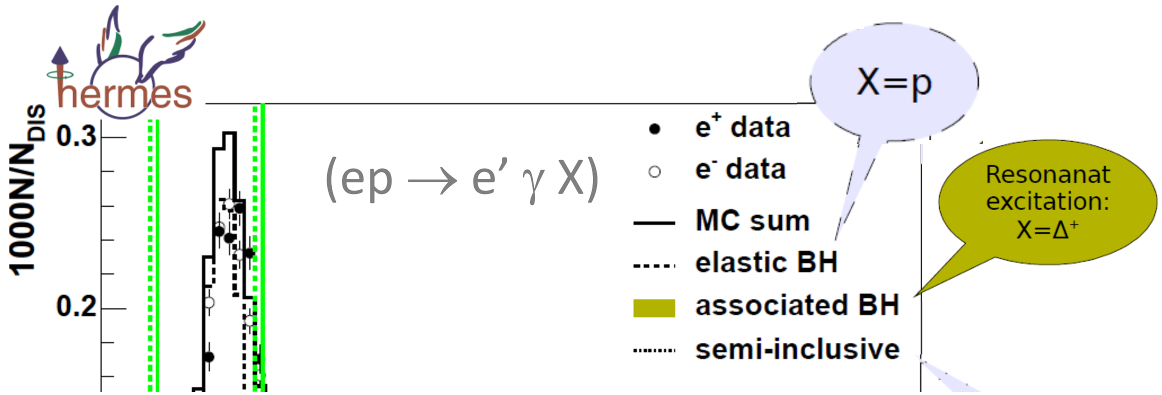
very well understood



exclusivity

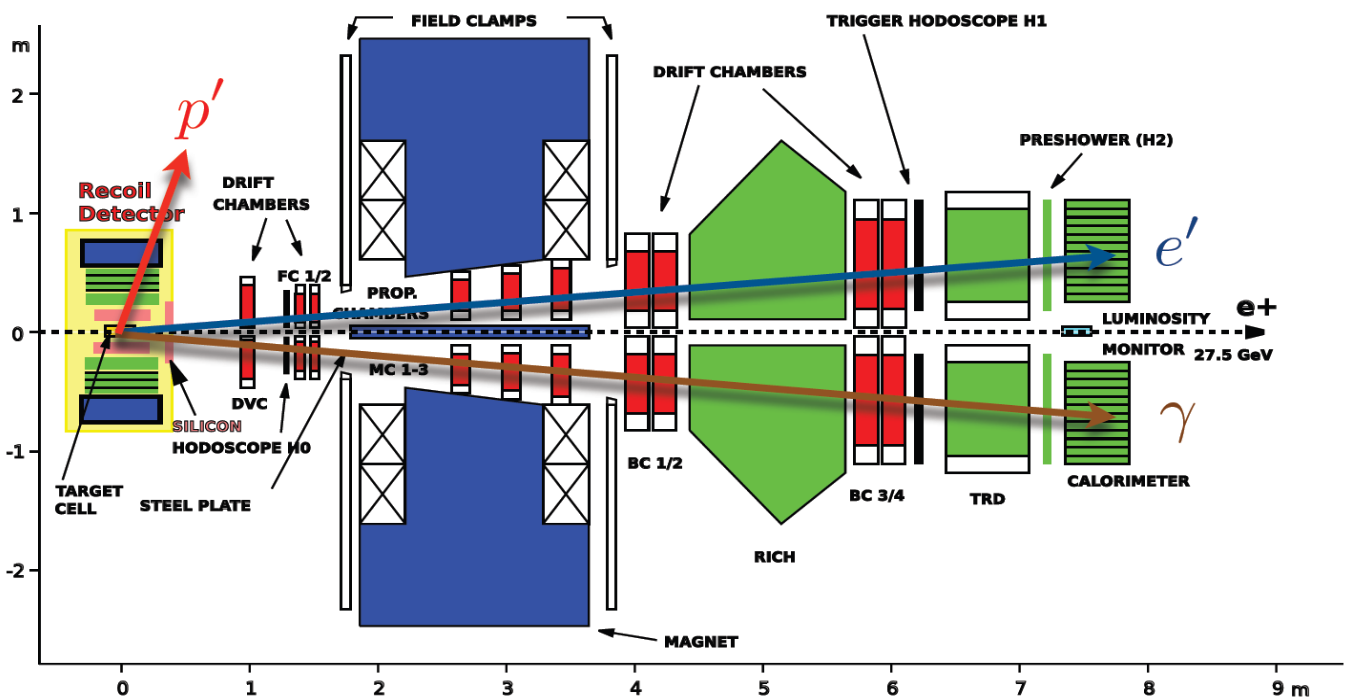


fixed target: via missing mass / energy

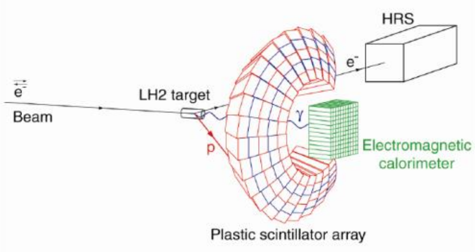


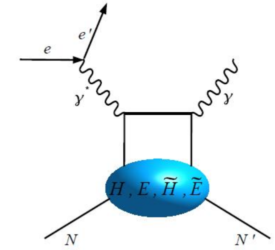
with *p* detection &

Δ^{+} ID: transition GPDs

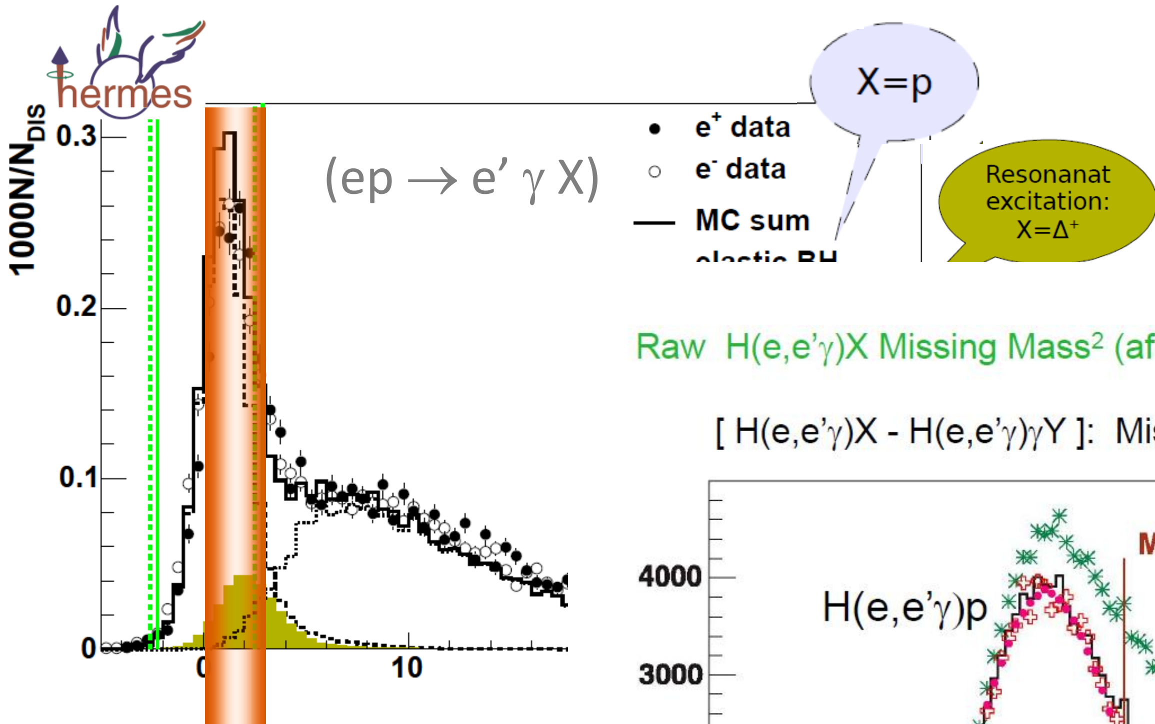


exclusivity

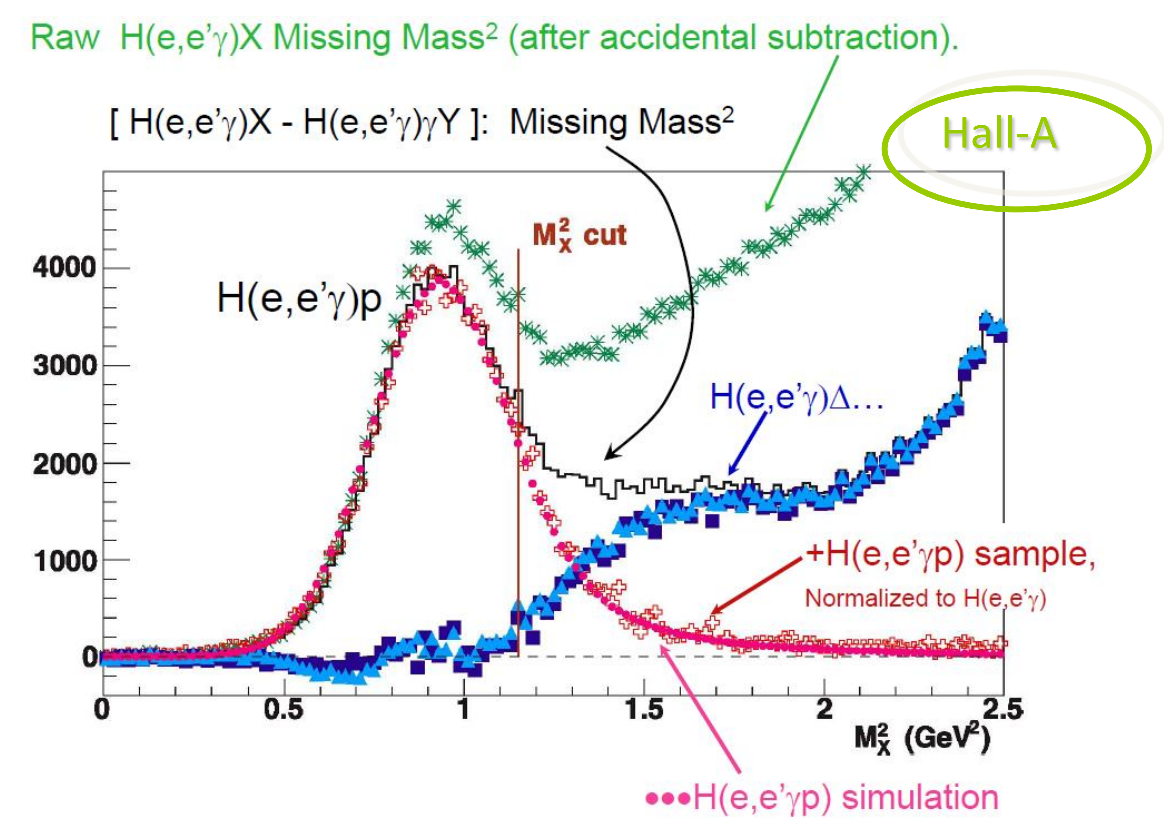




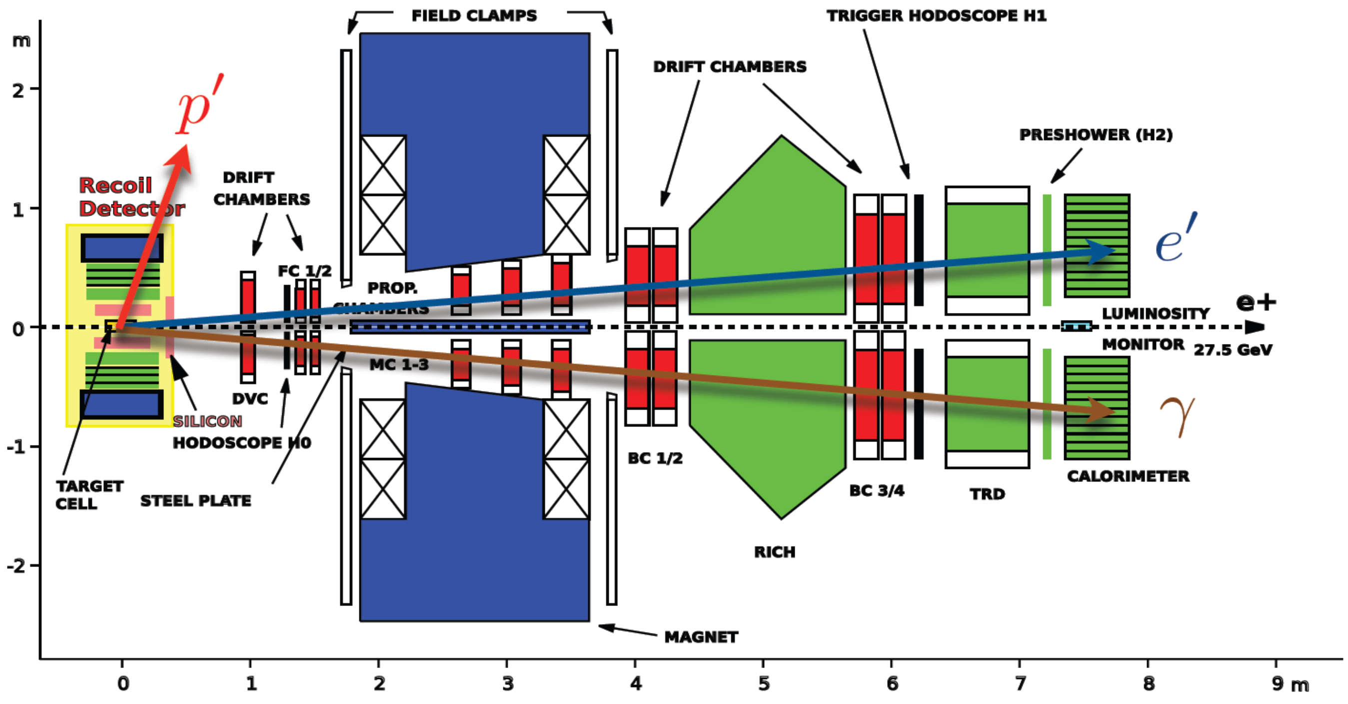
fixed target: via missing mass / energy



part of the signal



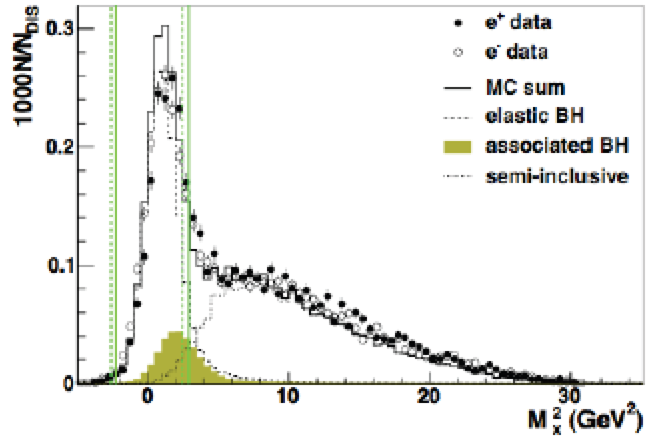
exclusivity: HERMES with recoil



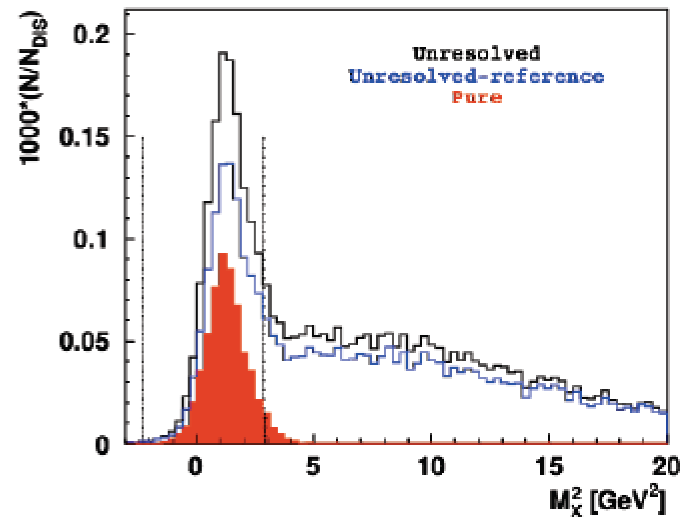
exclusivity: HERMES with recoil

Event Selection with Recoil Detector

- Events with one DIS lepton and one trackless cluster in the calorimeter.
- "***Unresolved***" for associated process $ep \to e\Delta^{+}\gamma$ ≈ 12 %



- "***Unresolved reference***" sample.
- "Hypothetical" proton required in the Recoil Detector acceptance.

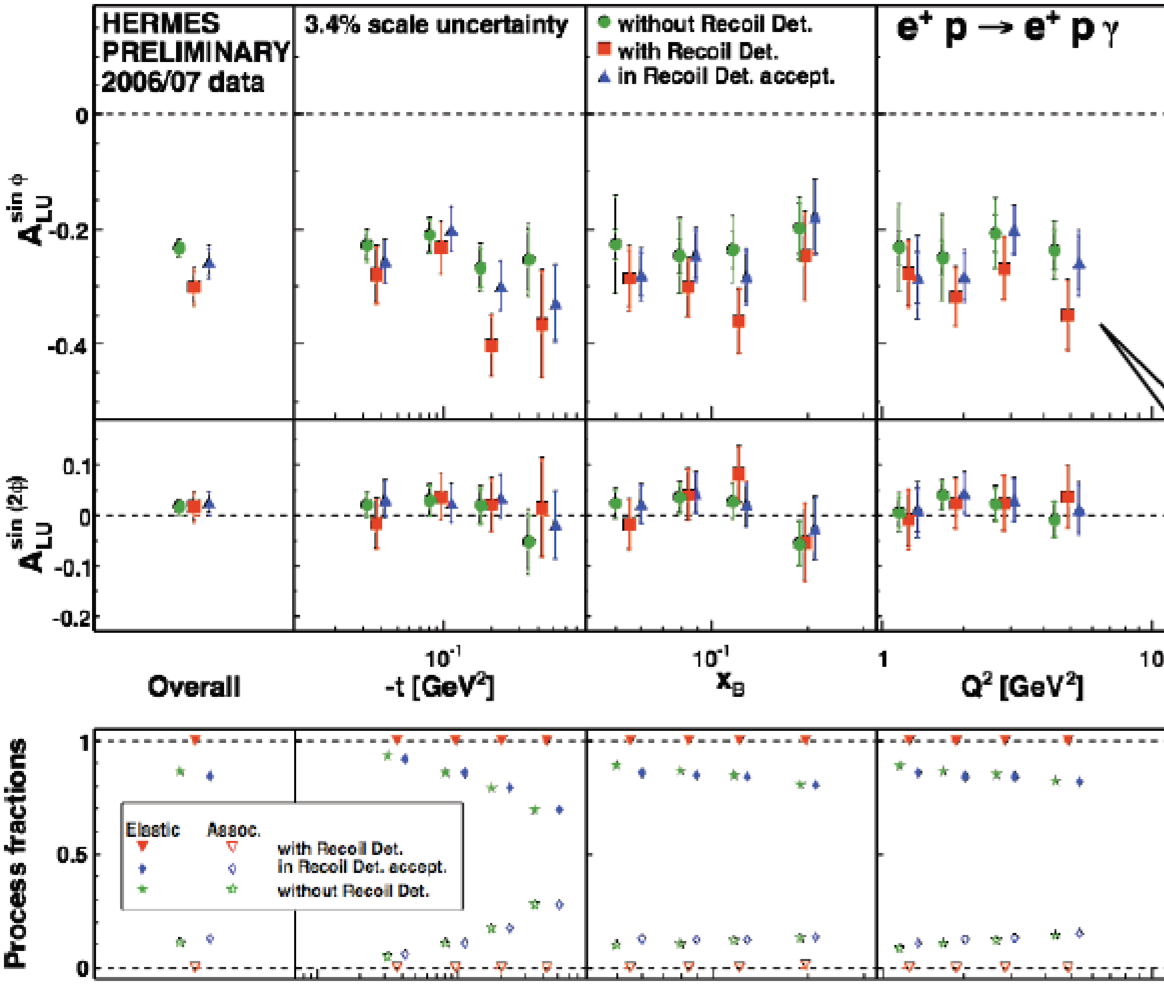


- "***Pure Elastic***" sample.
- Kinematic event fitting technique.

Allows to achieve purity > 99.9 %

exclusivity: HERMES with recoil

Beam-Spin asymmetry with Recoil



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

Indication of slightly larger magnitude of leading amplitude for pure elastic sample compared with reference sample

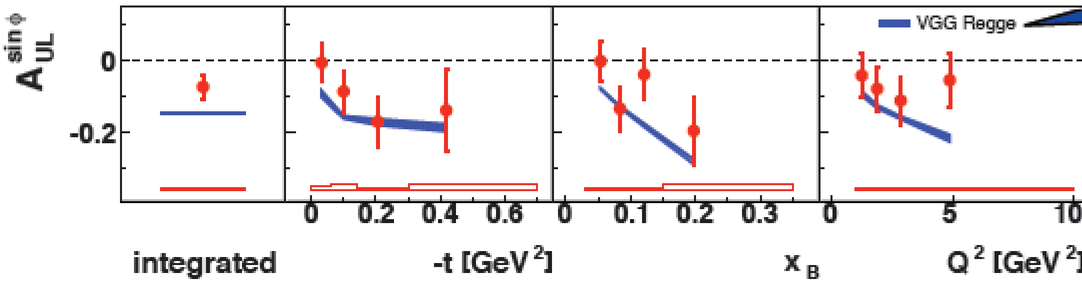
Unresolved
Unresolved Reference
Pure Elastic

Fractional contributions of elastic and associated processes for different samples

HERMES target spin asymmetries

JHEP 06 (2010) 019 — Longitudinal Single Target-Spin and Double-Spin asymmetries

$$\mathcal{A}_{UL}(\phi) = \frac{(\sigma^{\rightarrow\Rightarrow} + \sigma^{\leftarrow\Rightarrow}) - (\sigma^{\rightarrow\Leftarrow} + \sigma^{\leftarrow\Leftarrow})}{(\sigma^{\rightarrow\Rightarrow} + \sigma^{\leftarrow\Rightarrow}) + (\sigma^{\rightarrow\Leftarrow} + \sigma^{\leftarrow\Leftarrow})}$$

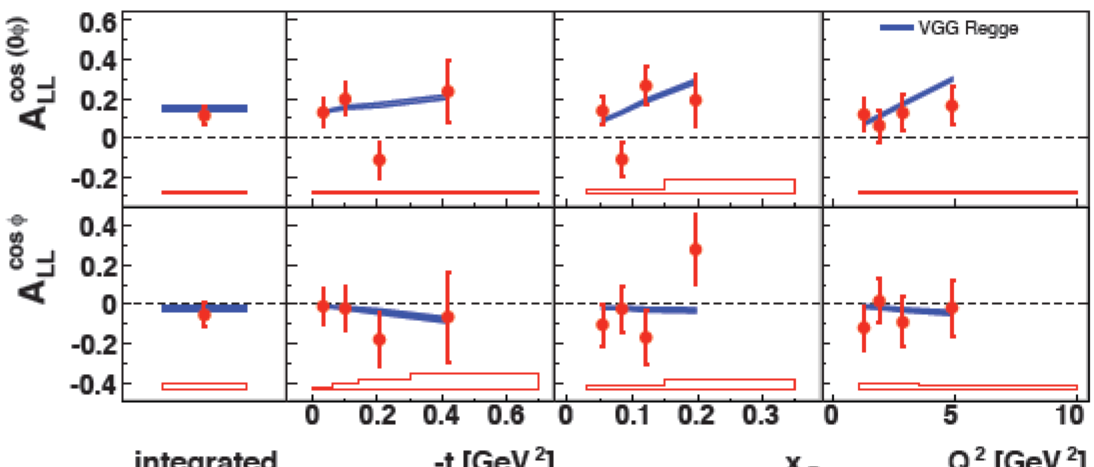


VGG: Model calculation
M. Vanderhaeghen, P. Guichon, M. Guidal
Phys..Rev.D (1999) 094017
Prog. Nucl. Phys, 47 (2001) 401

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

Longitudinal Target Spin Asymmetry
- non-zero negative value of the leading sin(ϕ) amplitude
- mild kinematic dependence

$$\mathcal{A}_{LL}(\phi) = \frac{(\sigma^{\rightarrow\Rightarrow} + \sigma^{\leftarrow\Leftarrow}) - (\sigma^{\rightarrow\Leftarrow} + \sigma^{\leftarrow\Rightarrow})}{(\sigma^{\rightarrow\Rightarrow} + \sigma^{\leftarrow\Leftarrow}) + (\sigma^{\rightarrow\Leftarrow} + \sigma^{\leftarrow\Rightarrow})}$$



Longitudinal Double-Spin Asymmetry
- constant term is positive
- leading cos(ϕ) amplitude is consistent with zero

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

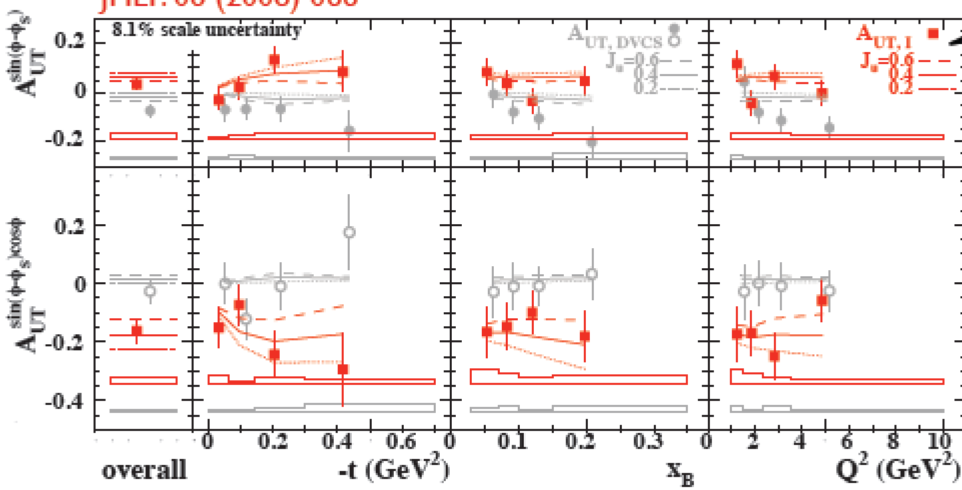
Asymmetry amplitudes are attributed not only to squared DVCS and Interference terms but also to squared BH term

HERMES target spin asymmetries

Transverse Single Target-Spin and Double-Spin asymmetries

$$\mathcal{A}_{UT}^{I,DVCS}(\phi,\phi_S) = \frac{(\sigma^{+\Uparrow}-\sigma^{+\Downarrow}) \pm (\sigma^{-\Uparrow}-\sigma^{-\Downarrow})}{(\sigma^{+\Uparrow}+\sigma^{+\Downarrow})+(\sigma^{-\Uparrow}+\sigma^{-\Downarrow})}$$

JHEP. 06 (2008) 066



VGG: Model calculation
M.Vanderhaeghen, P. Guichon, M. Guidal
Phys..Rev.D (1999) 094017
Prog. Nucl. Phys, 47 (2001) 401

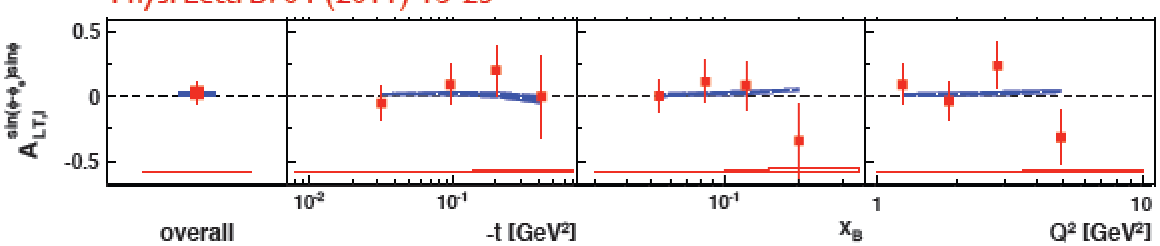
Charge-difference Transverse Target-Spin asymmetry
- Non-zero leading cos(nϕ) amplitudes.

$$\propto \begin{array}{l} \mathcal{I}m[F_2\mathcal{H} - F_1\mathcal{E}] \\ \mathcal{I}m[\mathcal{H}\mathcal{E}^* - \mathcal{E}\mathcal{H}^* - \xi(\widetilde{\mathcal{H}}\widetilde{\mathcal{E}}^* - \widetilde{\mathcal{E}}\widetilde{\mathcal{H}}^*)] \end{array}$$

Leading cos(ϕ) amplitude of charge difference target-spin asymmetry A^I_{UT} is sensitive to CFF $\mathcal{E}$, therefore J_u.

$$\mathcal{A}_{LT}^{I}(\phi,\phi_S) = \frac{(\overrightarrow{\sigma}^{+\Uparrow}+\overleftarrow{\sigma}^{+\Downarrow}-\overrightarrow{\sigma}^{+\Downarrow}-\overleftarrow{\sigma}^{+\Uparrow})-(\overrightarrow{\sigma}^{-\Uparrow}+\overleftarrow{\sigma}^{-\Downarrow}-\overrightarrow{\sigma}^{-\Downarrow}-\overleftarrow{\sigma}^{-\Uparrow})}{(\overrightarrow{\sigma}^{+\Uparrow}+\overleftarrow{\sigma}^{+\Downarrow}+\overrightarrow{\sigma}^{+\Downarrow}+\overleftarrow{\sigma}^{+\Uparrow})+(\overrightarrow{\sigma}^{+\Uparrow}+\overleftarrow{\sigma}^{+\Downarrow}+\overrightarrow{\sigma}^{+\Downarrow}+\overleftarrow{\sigma}^{+\Uparrow})}$$

Phys. Lett. B704 (2011) 15-23



Charge-difference Transverse Double-Spin asymmetry
- leading amplitudes are consistent with zero
- sensitivity to is suppressed J_u is suppressed by kinematic pre-factor

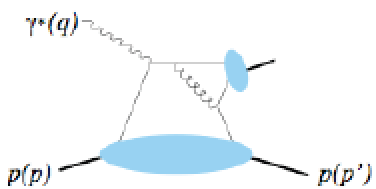
$$\propto \mathcal{R}e[F_2\mathcal{H} - F_1\mathcal{E}]$$

HERMES VM SDMEs

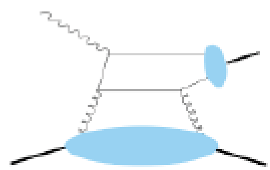
Exclusive Vector Meson Production

pQCD description of the process.

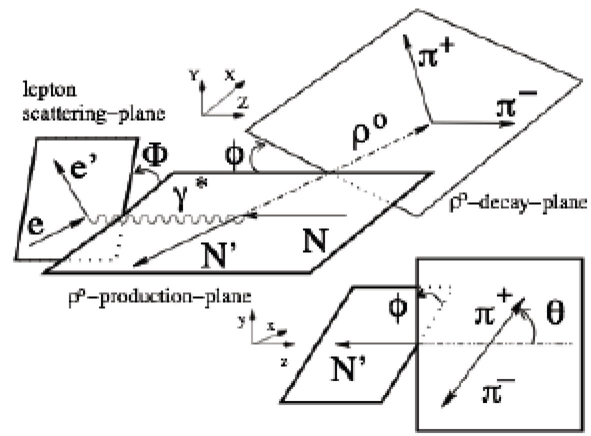
I) dissociation of the virtual photon into quark-antiquark pair
II) scattering of a pair on a nucleon
III) formation of the observed vector meson



UPE
GPDs $\widetilde{H}, \widetilde{E}$



NPE
GPDs H, E

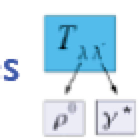
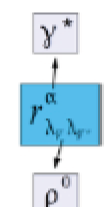


Cross Section

$$\frac{d\sigma}{dx_B dQ^2 dt d\Phi d\cos\theta d\phi} \propto \frac{d\sigma}{dx_B dQ^2 dt} W(x_B, Q^2, t, \Phi, \cos\theta, \phi)$$

production and decay angular distribution: W decomposition

$$W = W_{UU} + P_\ell W_{LU} + S_L W_{UL} + P_\ell S_L W_{LL} + S_T W_{UT} + P_\ell S_T W_{LT}$$

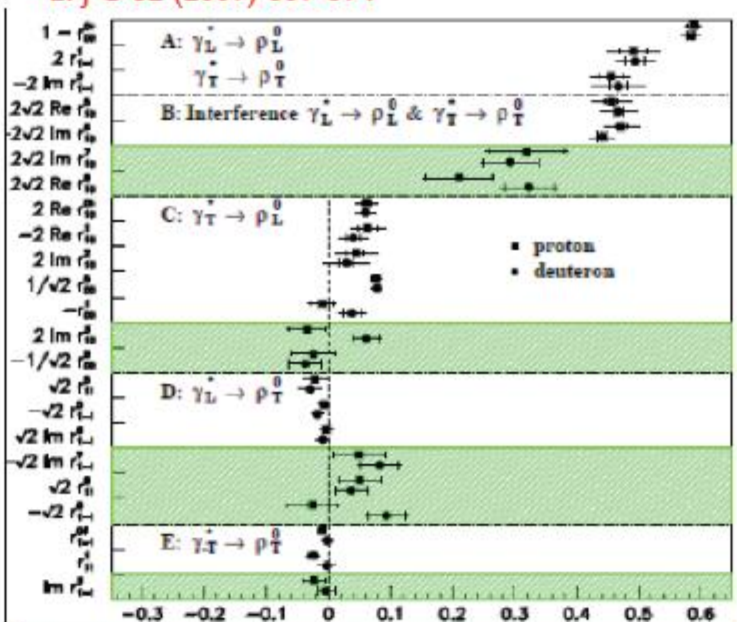
parameterization in terms of helicity amplitudes  or SDMES 

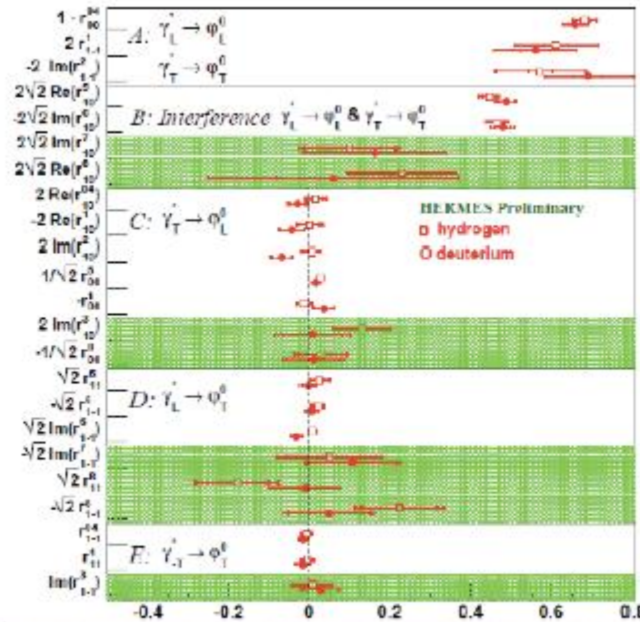
HERMES VM SDMEs

ρ^0 and ϕ SDMEs on an unpolarized target

$$|T_{00}|^2 \sim |T_{11}|^2 \gg |T_{01}|^2 > |T_{10}|^2 \sim |T_{-11}|^2$$

EPJ C 62 (2009) 659-694





$\gamma^*_L \to V_L$ & $\gamma^*_T \to V_T$
- SDMEs are significantly different from zero
- 10-20% difference between ρ and ϕ SDMEs

$\gamma^*_T \to V_L$
- pronounced difference between ρ and ϕ SDMEs
- 2-10 σ level violation from SCHC for ρ

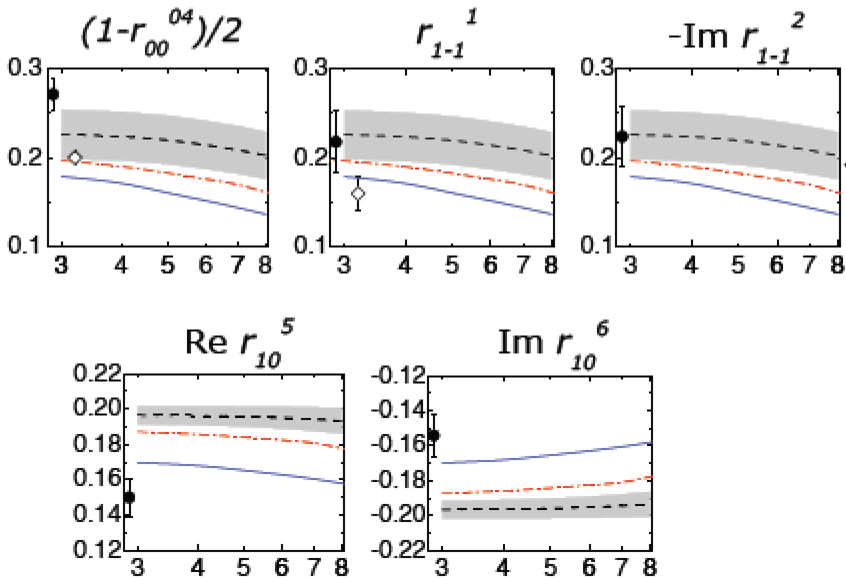
$\gamma^*_L \to V_T$ & $\gamma^*_{-T} \to V_T$
- SDMEs are consistent with zero

- Selected hierarchy is confirmed
- No differences between proton and deuteron

HERMES VM SDMEs

Comparison of ρ^0 SDMEs to GPD model

GPD model: S.Goloskokov, P. Kroll (2007)



W=5 GeV (HERMES)
W=10 GeV (COMPASS)
W=75 GeV (H1,ZEUS)

$\gamma^*_L \rightarrow \rho^0_L$ & $\gamma^*_T \rightarrow \rho^0_T$

$$1 - r^{04}_{00}, r^1_{1-1}, -Imr^2_{1-1} \propto T_{11}$$

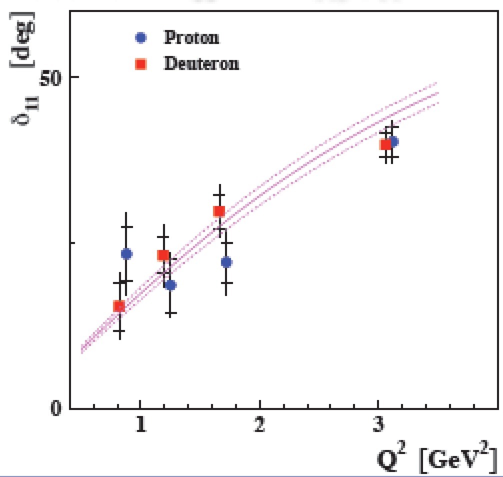
model is in an agreement with data

interference $\gamma^*_L \rightarrow \rho^0_L$ & $\gamma^*_T \rightarrow \rho^0_T$

model dose not describe the data

model predicts phase difference between T_{00} and T_{11}, δ_{11}=3.1 deg.

$$tan\,\delta_{11} = \frac{Im(T_{11}/T_{00})}{Re(T_{11}/T_{00})}$$



HERMES result δ_{11}=31.5 ± 1.4 deg.

Large phase difference was observed also by H1 (δ_{11}=20)

HERMES VM SDMEs

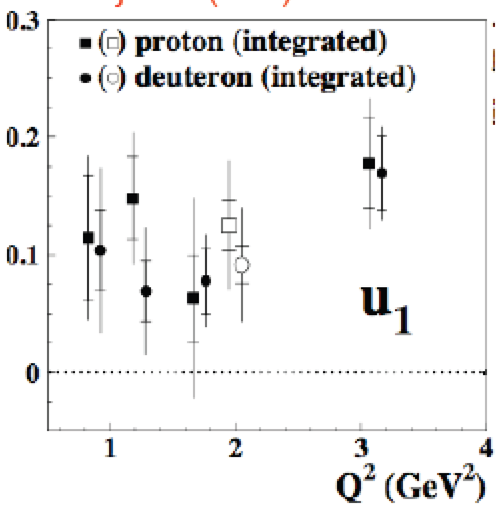
Observation of Unnatural-parity exchange

At large W^2 and Q^2 the transition should be suppressed by M/Q

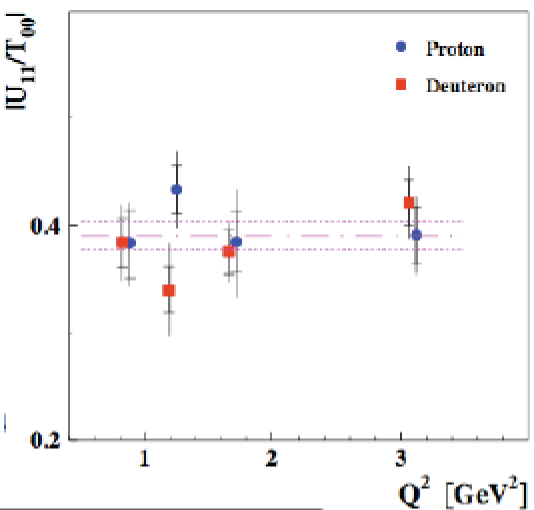
- direct helicity amplitude ratio analysis: U_{11}/T_{00}
- the combination of SDMEs is expected to be zero in case of NPE

$$u_1 = 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^{1}_{11} - 2r^{1}_{1-1} \qquad u_2 = r^{5}_{11} + r^{5}_{1-1} \qquad u_3 = r^{8}_{11} + r^{8}_{1-1}$$

EPJ C 62 (2009) 659-694



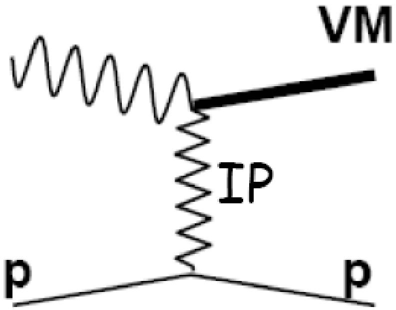
EPJ C 71 (2011) 1609



- Significant UPE contribution for ρ^0
  Sensitivity to GPD $\widetilde{H}$
- No signal of UPE contribution for ϕ

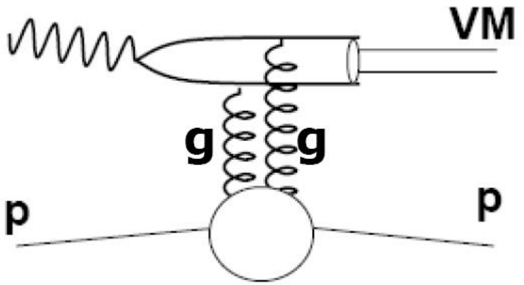
VM production @low x

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



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

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



soft

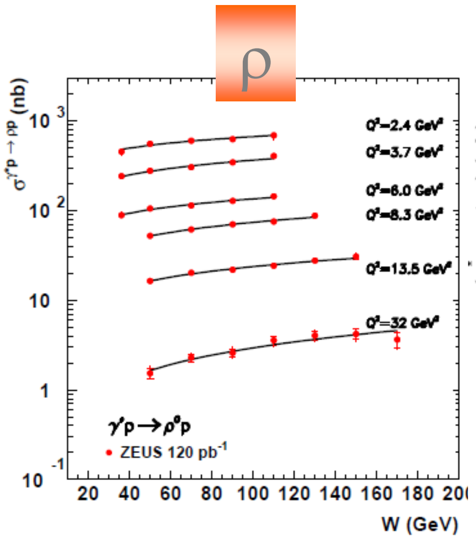
hard

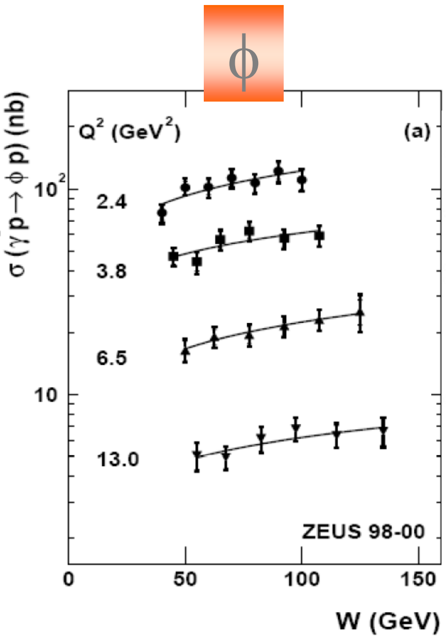
→expect δ to increase from ~0.2 to ~0.8

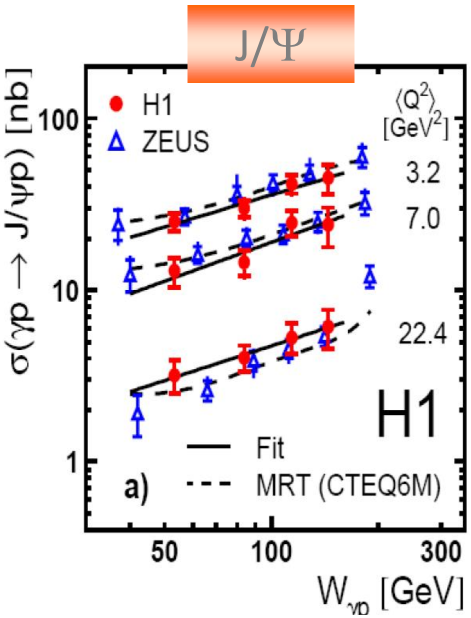
b to decrease from ~10 to ~4-5 GeV^2

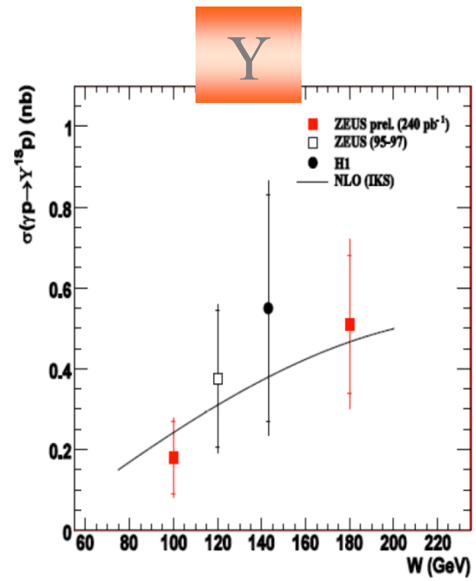
VM production @low x

W dependence: probe transition from soft to hard regime









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

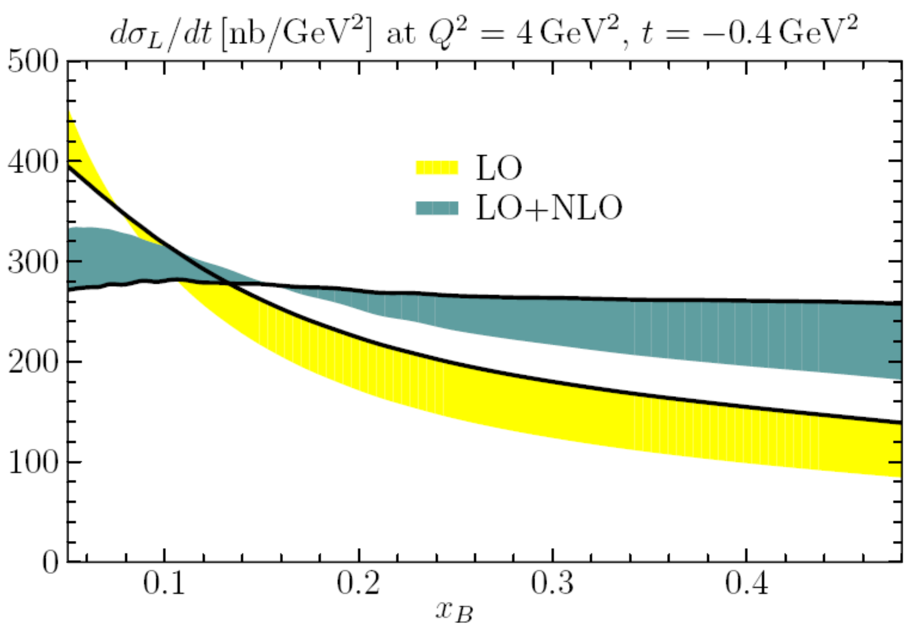
universality: ρ and ϕ at large Q^2+M^2 similar to J/Ψ , Υ

VM production 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)]



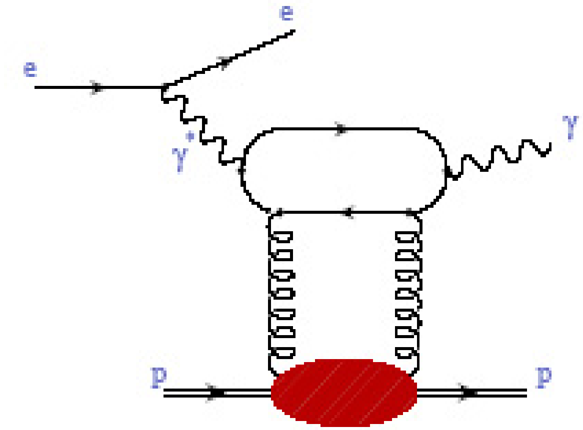
ρ^0 cross section @typical kinematics of COMPASS / HERMES / JLab12

Deeply Virtual Compton Scattering

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

- DVCS cross sections @ low x

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

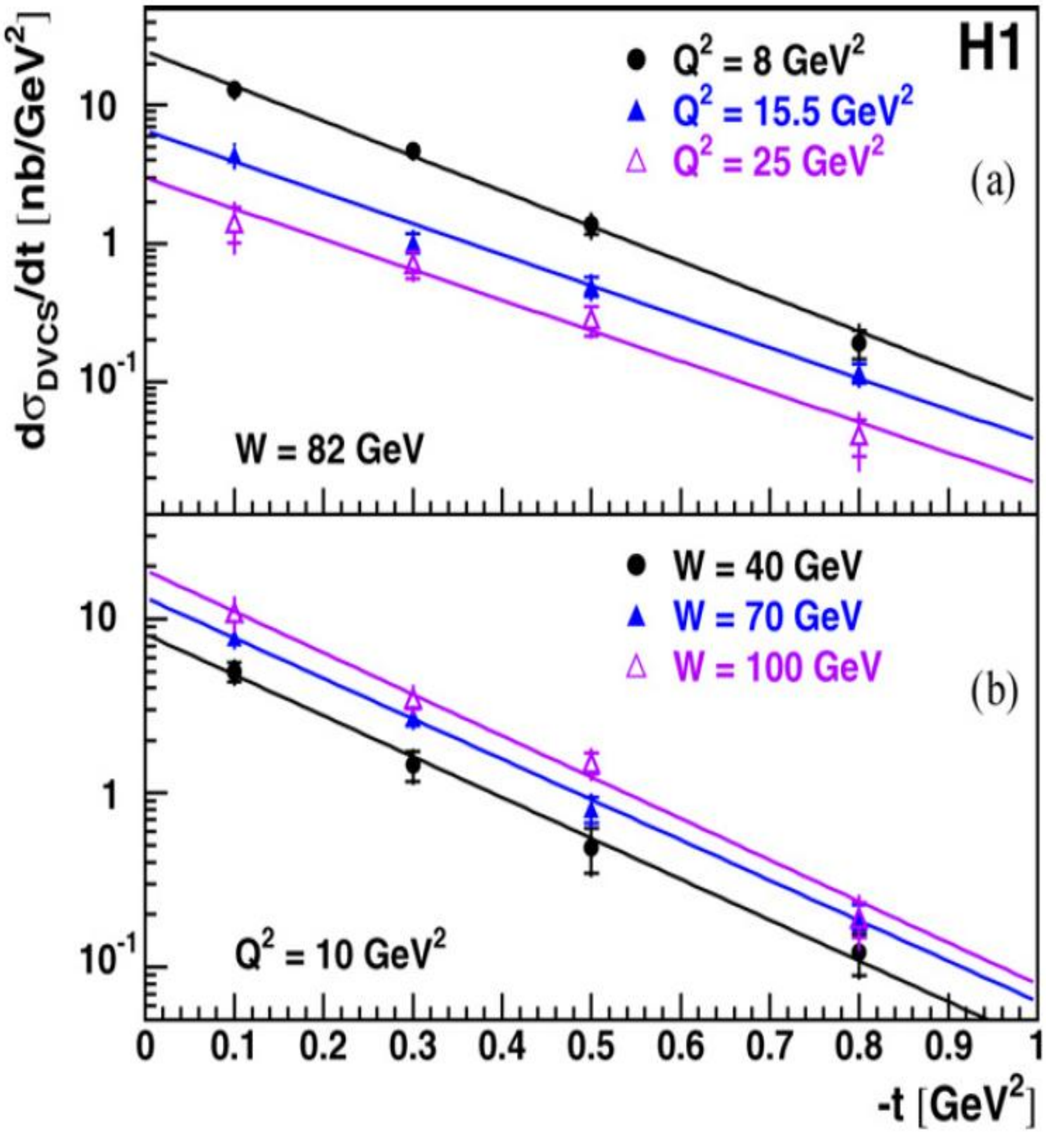


$$\boxed{\frac{d\sigma}{dt} \propto e^{-b|t|}}$$

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

DVCS cross section

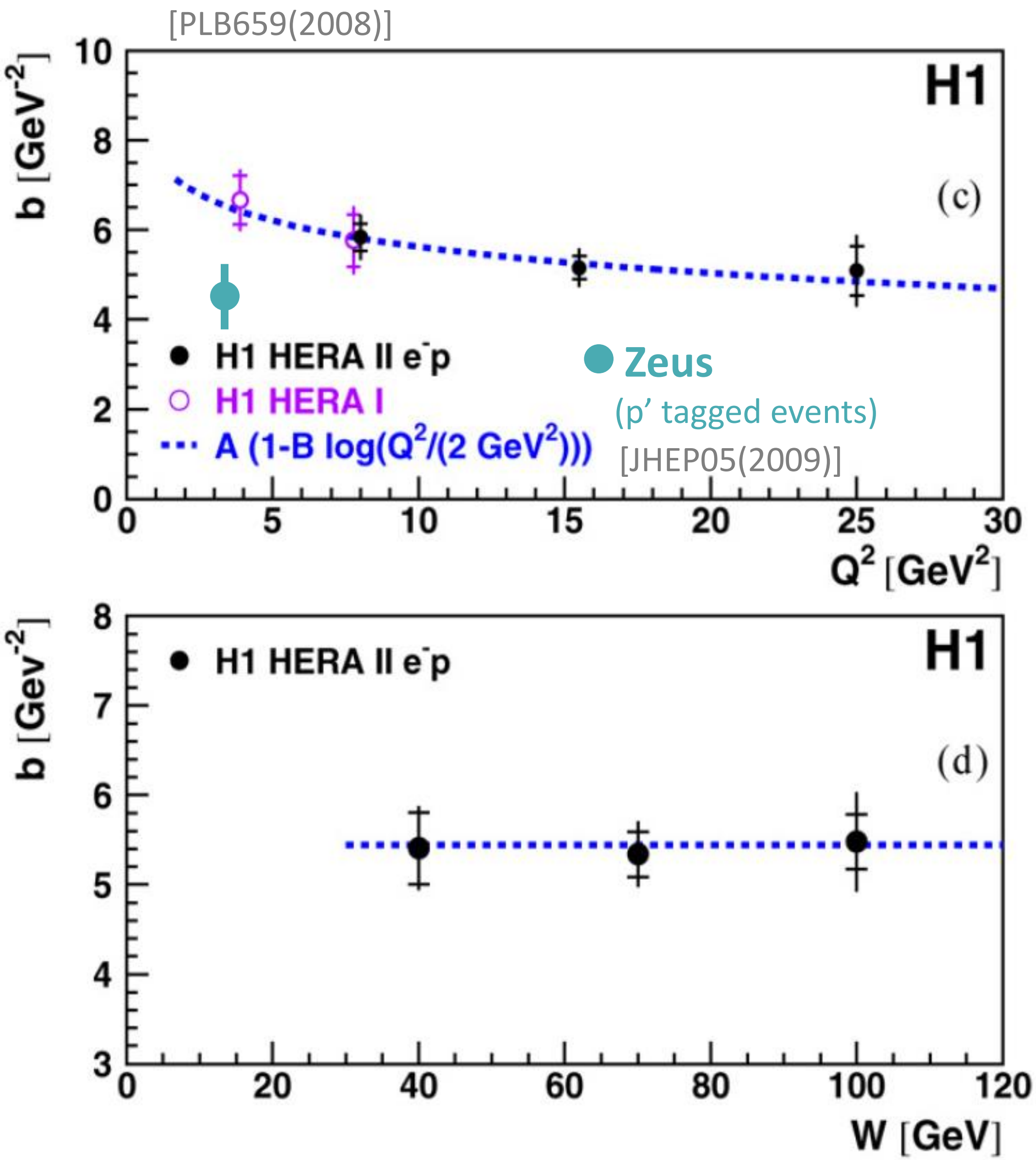
[PLB659(2008)]



- t slope measurement provides absolute normalisation

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

DVCS cross section



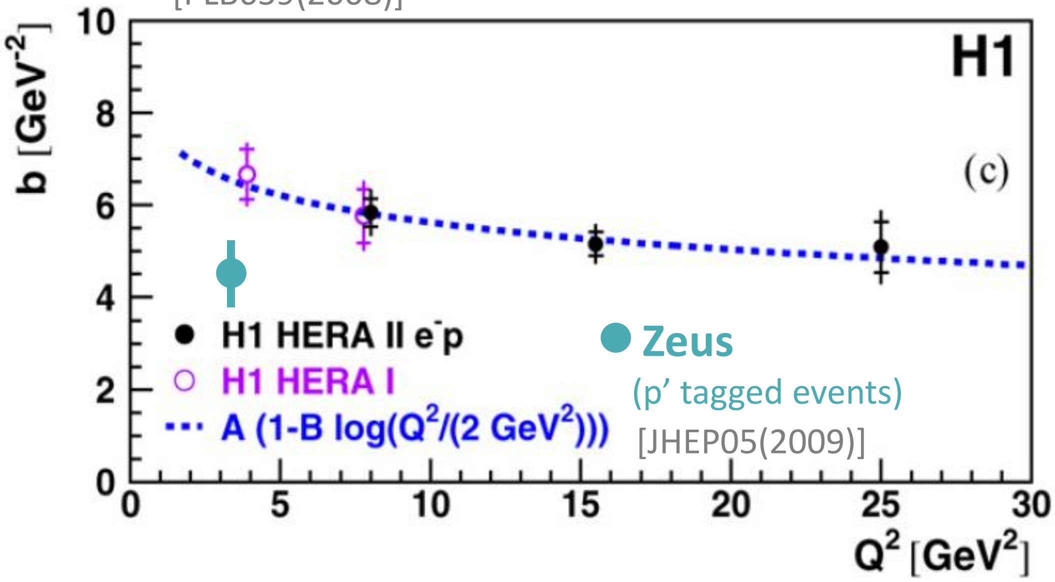
- *t* slope measurement provides absolute normalisation

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

- universality of slope parameter: pointlike configurations dominate

DVCS cross section

[PLB659(2008)]



- *t* slope measurement provides absolute normalisation

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

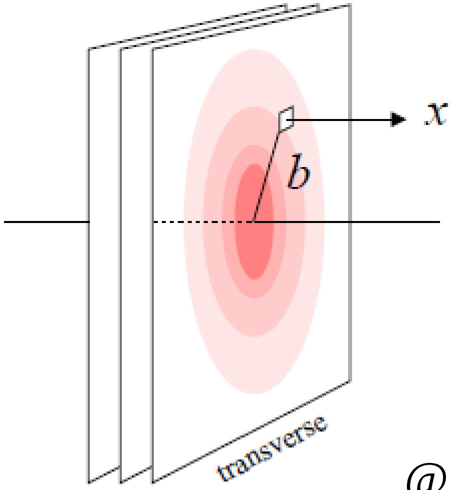
- universality of slope parameter: pointlike configurations dominate

- *FT* → average impact parameter

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

@ $x_B=10^{-3}$

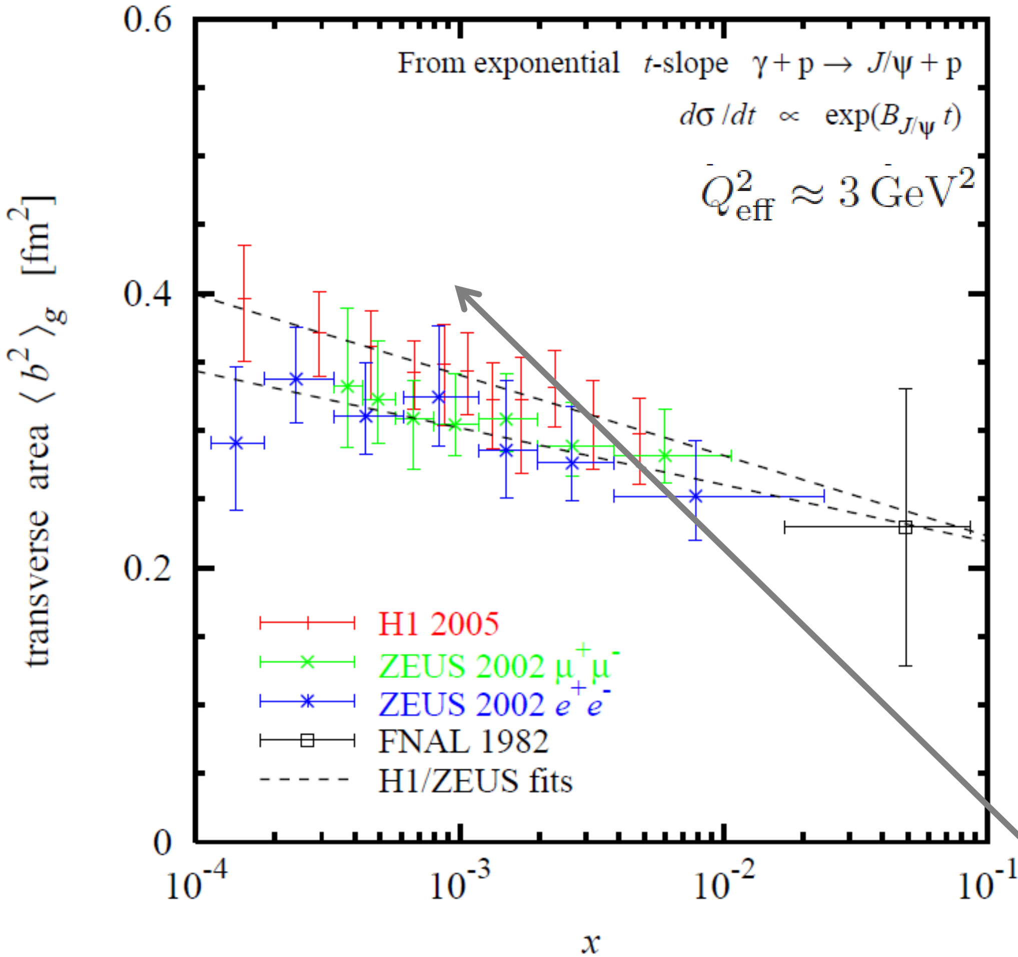
$\langle Q^2 \rangle = 8.0\ \mathrm{GeV}^2$

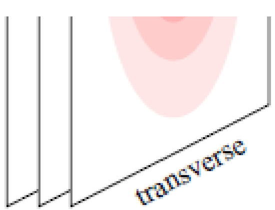


@ $x_B=10^{-3}$

[courtesy of C. Weiss]

sea quark & gluon imaging





@ $x_B=10^{-3}$

[courtesy of C. Weiss]

→ remember J/ψ

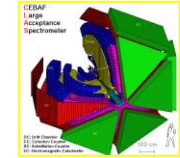
- **universality** of slope parameter: pointlike configurations dominate
- *FT* → average impact parameter

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

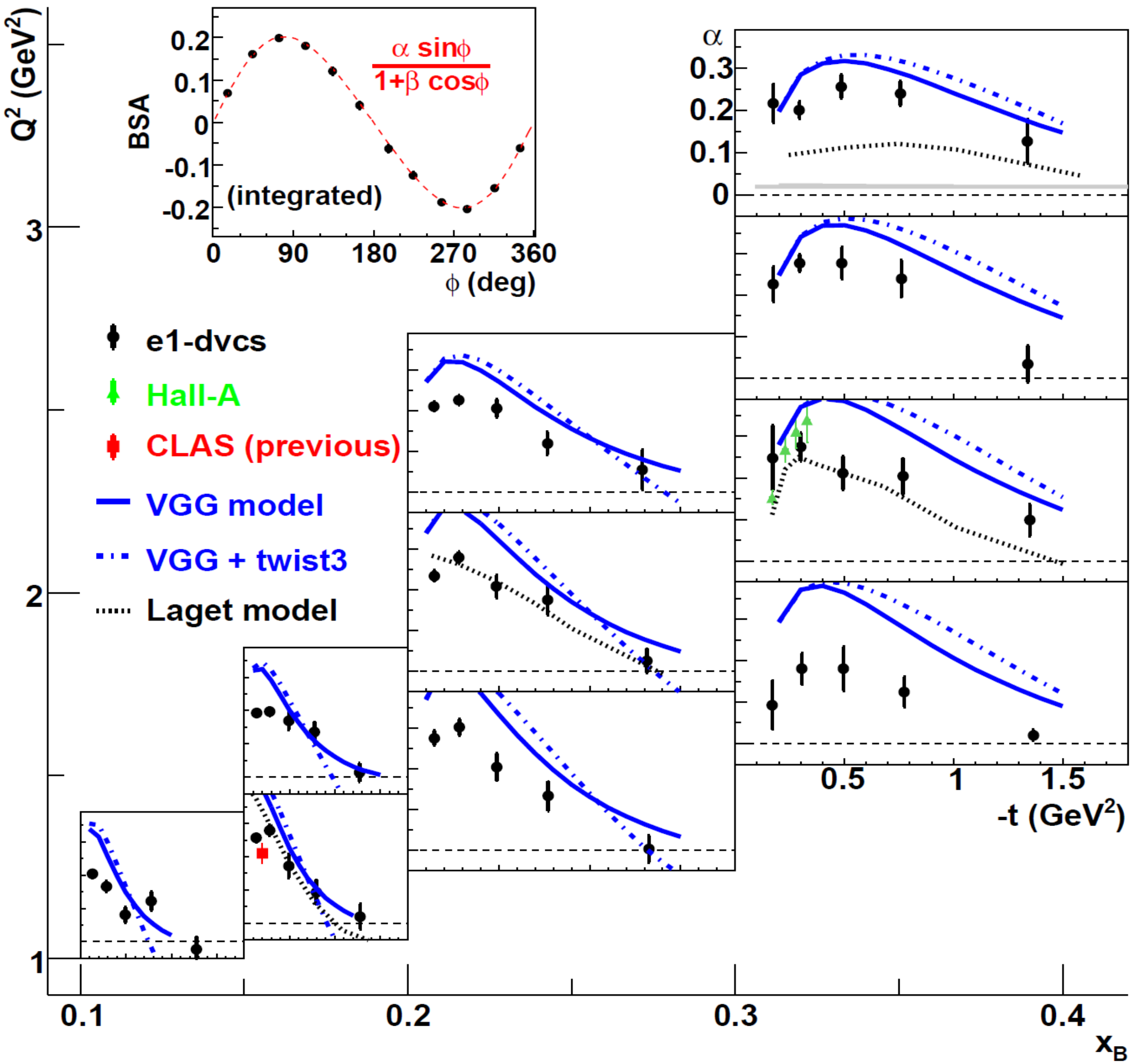
@ $x_B=10^{-3}$

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

call for high statistics



DVCS beam-spin asymmetry [PRL100(2008)]



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

hunting the OAM

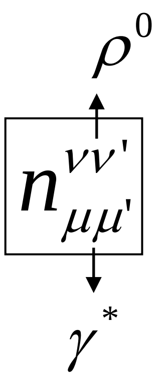
-- ρ^0 : transverse target-spin asymmetry --

after the full glory of SDME extractions

[formalism by M. Diehl (2007)]

$(\gamma_L^* \to \rho_L^0)$:

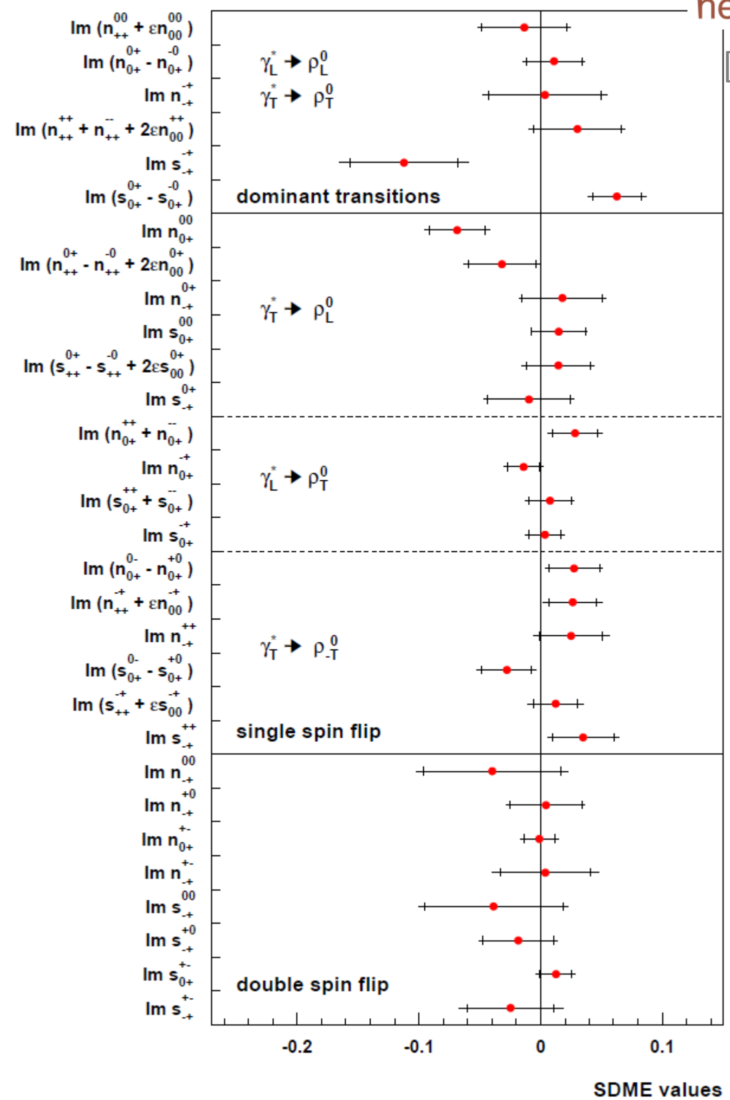
$$A_{UT}^{\gamma^*}(\phi, \phi_s) = \frac{\mathrm{Im}\, n_{00}^{00}}{u_{00}^{00}}$$



$\mu, \nu = 0, \pm 1$

long.pol: 0

transv.pol: ±1



[PLB679(2009)]

hunting the OAM

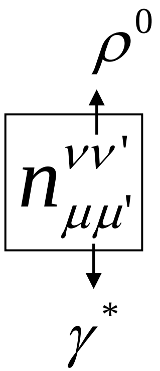
-- ρ^0 : transverse target-spin asymmetry --

after the full glory of SDME extractions

[formalism by M. Diehl (2007)]

$$(\gamma^*_{\mathrm{L}} \to \rho^0_{\mathrm{L}}):$$

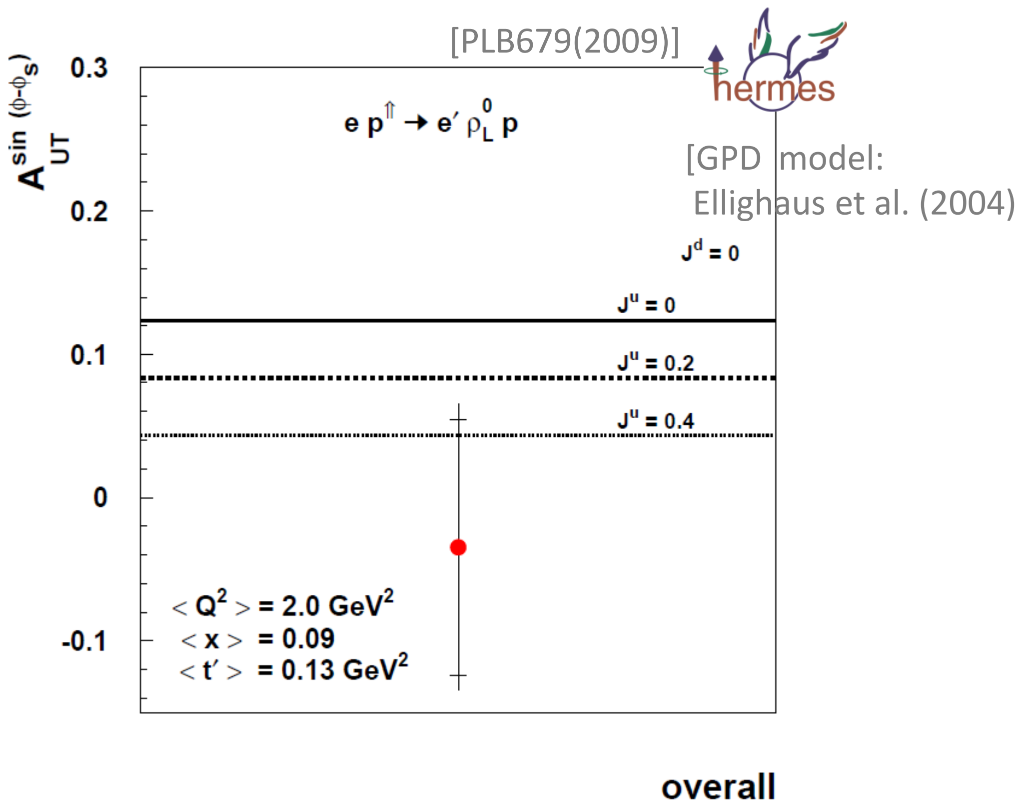
$$A^{\gamma^*}_{UT}(\phi, \phi_s) = \frac{\mathrm{Im}\, n^{00}_{00}}{u^{00}_{00}}$$



$\mu, \nu = 0, \pm 1$

long.pol: 0

transv.pol: ±1

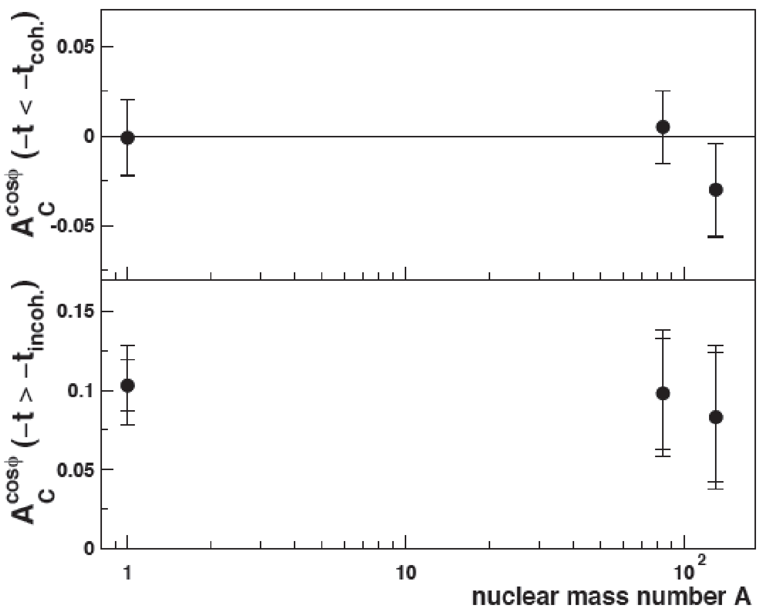


- more data coming: COMPASS, JLab12 with transv. Target
- more models: Goloskokov, Kroll

DVCS nuclear effects

$A_C^{\cos\phi}$ vs. A

Phys. Rev. C 81 (2010) 035202

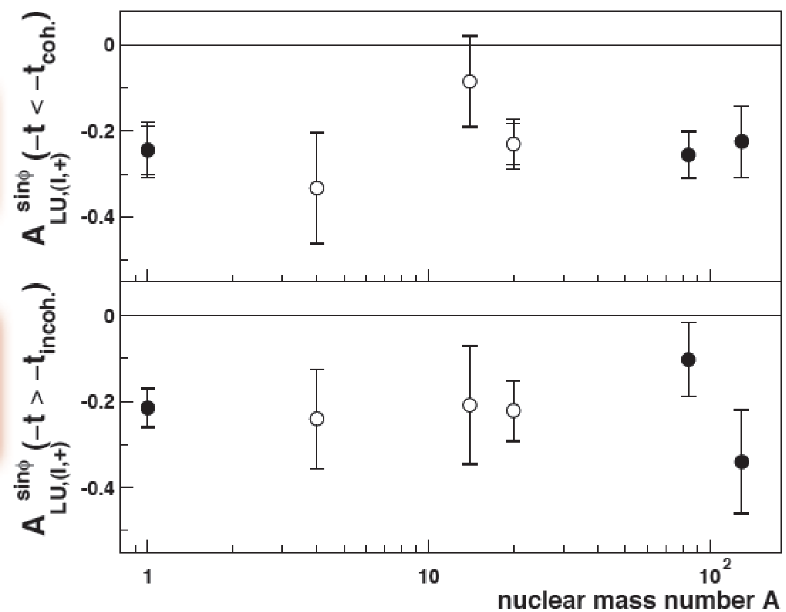


Beam-charge asymmetry

coherent enriched

incoherent enriched

$A_{LU}^{\sin\phi}$ vs. A



Beam-helicity asymmetry

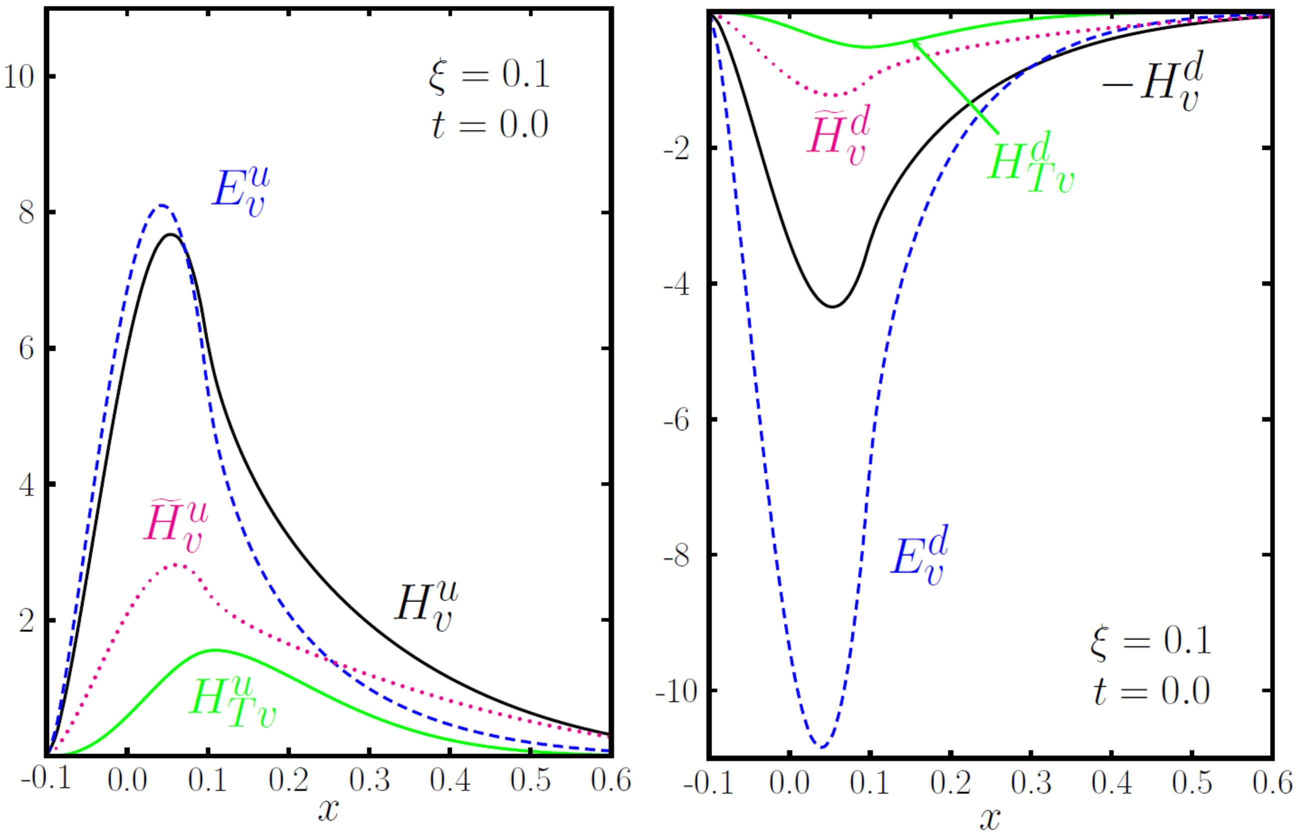
- How does the nuclear medium modify parton-parton correlations?
- How do nucleon properties change in the nuclear medium?
- Enhanced 'generalized EMC effect', rise of T_{DVCS} with A?

Average A_{LU}^A / A_{LU}^H:
0.91±0.19
0.93±0.23

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

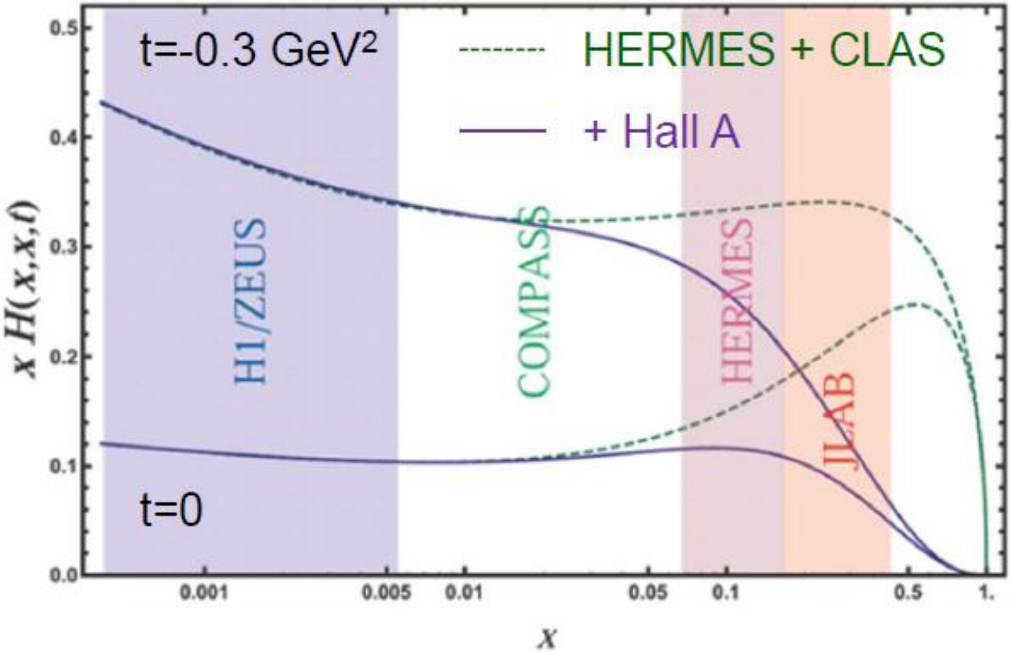


towards GPDs

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

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

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



towards GPDs

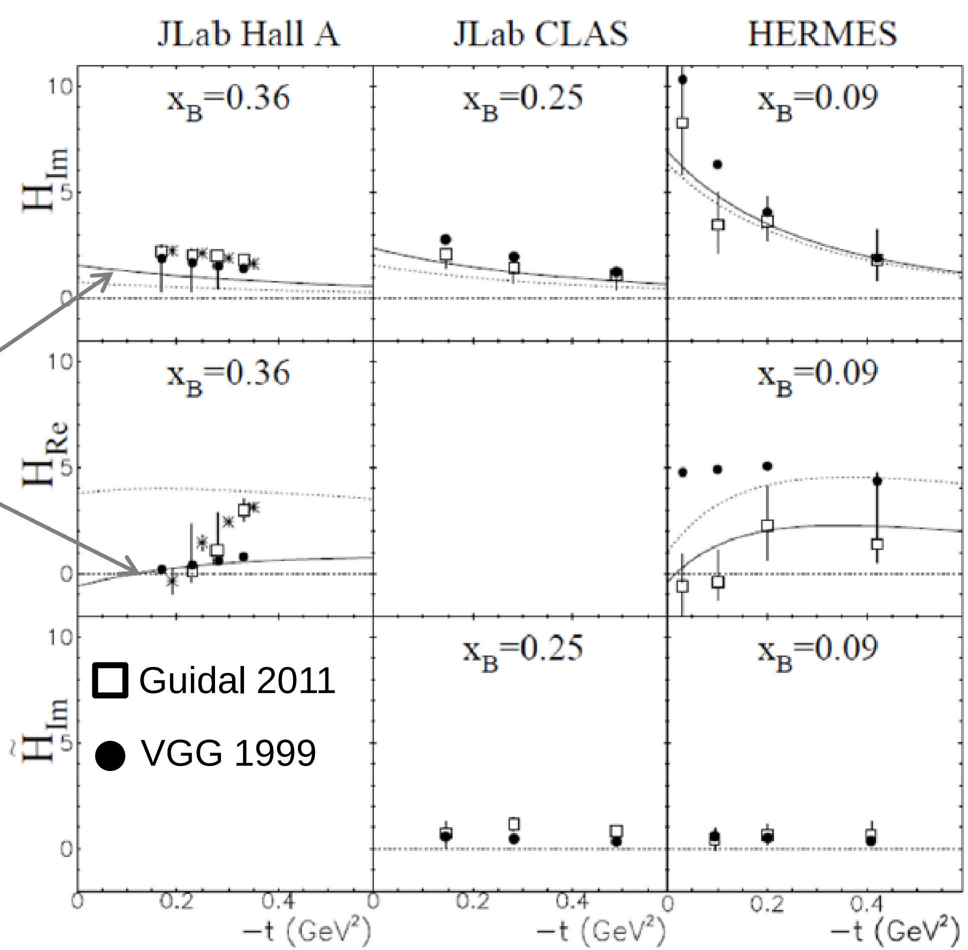
recent developments (beyond VGG(1999)...)

- Goloskokov, Kroll (2007):
  → LO GPD model using *DD, regge t dep., power corrections*
  → fit to exclusive meson production data
- Kumericki, Müller (2010):
  → partial wave expansion of GPDs*, regge t dep., dispersion relations*
  → 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

towards GPDs

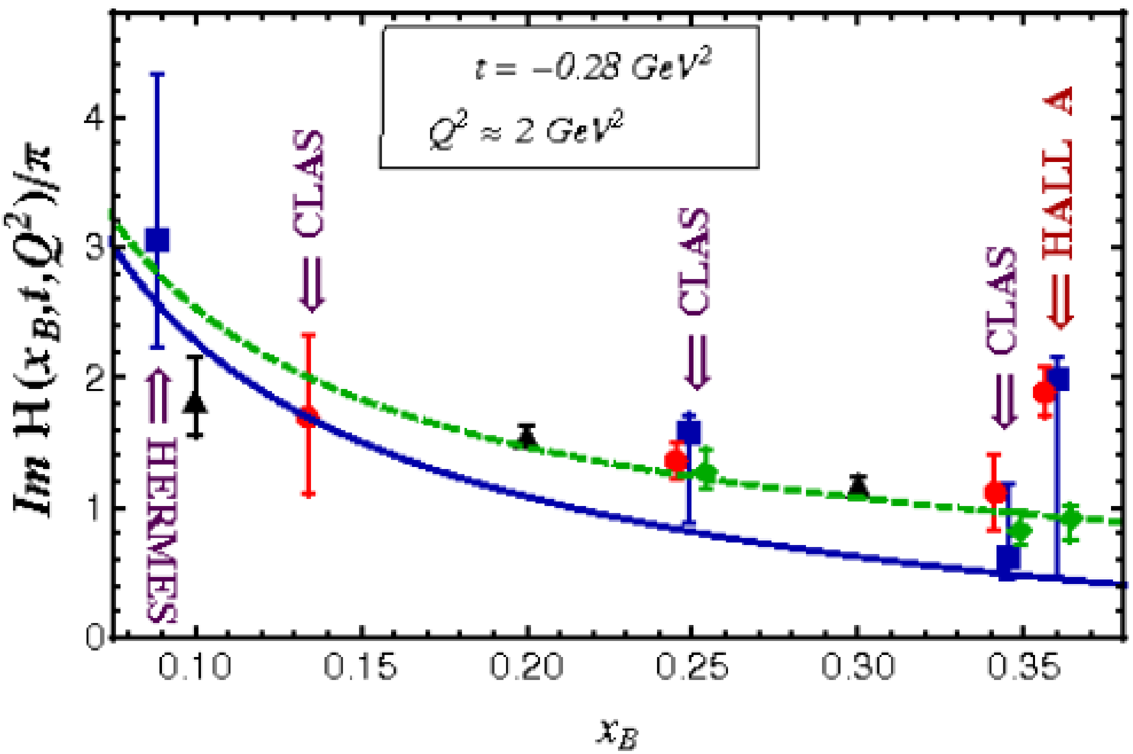
recent developments (beyond VGG(

- 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



[Guidal '08, Guidal and Moutarde '09], seven CFF fit (blue squares), [Guidal '10] $\mathcal{H}$, $\tilde{\mathcal{H}}$ CFF fit (green diamonds), [Moutarde '09] H GPD fit (red circles)

(slide from K. Kumericki, Photons11)

towards global analysis of GPDs

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