# *DVCS analysis status and perspectives*

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- *photon leptoproduction cross section*
- *small $x_B$ fits (H1 and ZEUS)*
- *fixed target (HERMES, JLAB)+ small $x_B$ fits*
- *predictions and studies for future experiments*

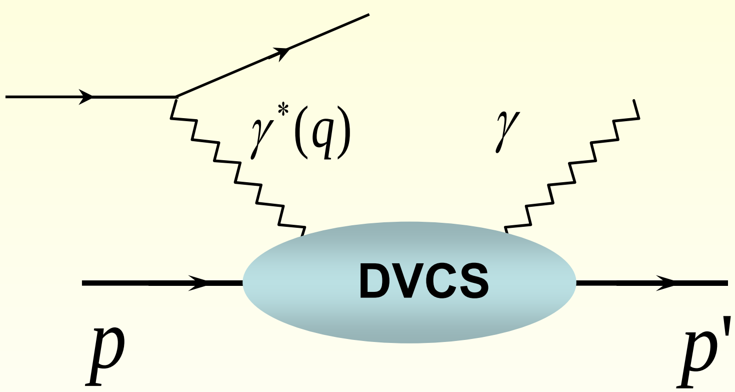
**in collaboration with K. Kumerički**
**E. Aschenauer and S. Fazio (EIC studies)**

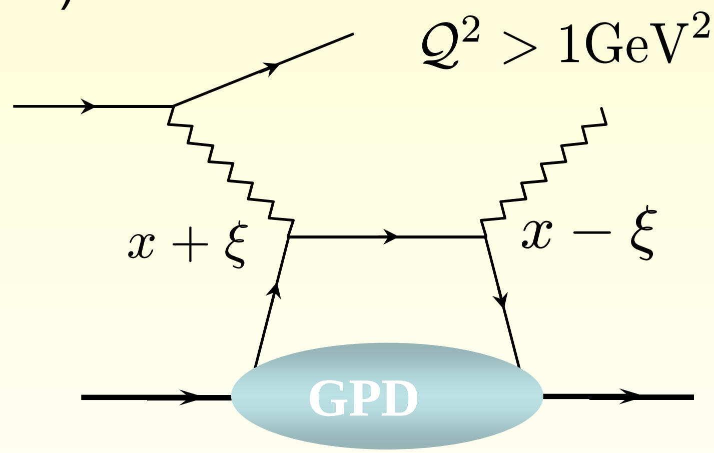
# GPDs embed non-perturbative physics

GPDs appear in various hard exclusive processes,

[DM et. al (90/94)
Radyushkin (96)
Ji (96)]

e.g., hard electroproduction of photons (DVCS)




$t = \Delta^2 \; - \; \text{fix}$

$$\mathcal{F}(\xi, \mathcal{Q}^2, t) = \int_{-1}^{1} dx\, C(x, \xi, \alpha_s(\mu), \mathcal{Q}/\mu) F(x, \xi, t, \mu) + O\left(\frac{1}{\mathcal{Q}^2}\right)$$

**CFF**
Compton form factor
observable

**hard scattering part**
perturbation theory
(our conventions/microscope)

**GPD**
universal
(conventional)

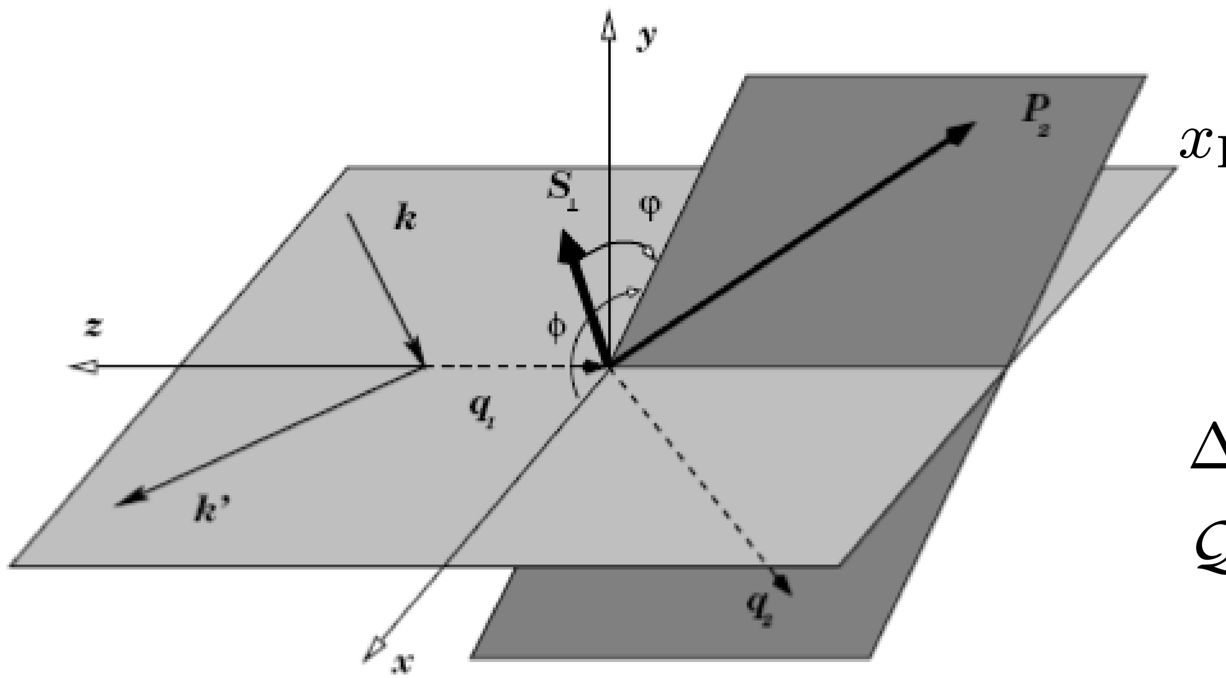
**higher twist**
depends on
approximation

# *Photon leptoproduction* $e^{\pm}N \to e^{\pm}N\gamma$

measured by ***H1, ZEUS, HERMES, CLAS, HALL A*** collaborations

planed at ***COMPASS, JLAB@12GeV***, perhaps at ?? EIC,

$$\frac{d\sigma}{dx_{\rm Bj}dyd|\Delta^2|d\phi d\varphi} = \frac{\alpha^3 x_{\rm Bj} y}{16\,\pi^2\,\mathcal{Q}^2}\left(1+\frac{4M^2x_{Bj}^2}{\mathcal{Q}^2}\right)^{-1/2}\left|\frac{\mathcal{T}}{e^3}\right|^2,$$



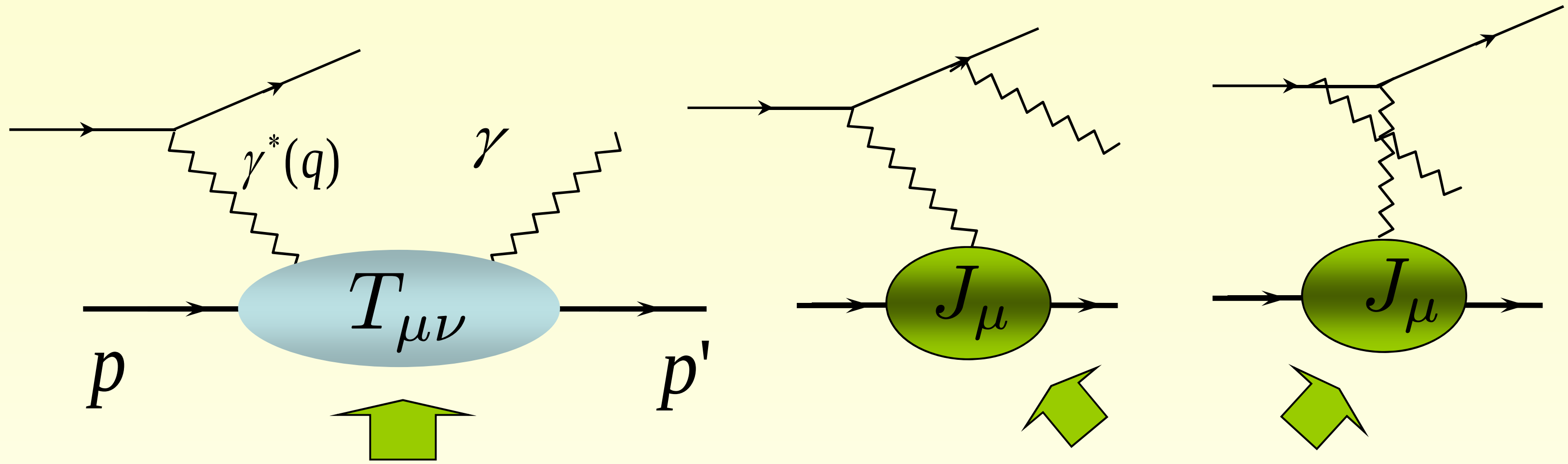

$$x_{\rm Bj} = \frac{\mathcal{Q}^2}{2P_1\cdot q_1} \approx \frac{2\xi}{1+\xi},$$

$$y = \frac{P_1\cdot q_1}{P_1\cdot k},$$

$$\Delta^2 = t \quad (\text{fixed, small}),$$

$$\mathcal{Q}^2 = -q_1^2 \quad (> 1\text{GeV}^2),$$

# interference of *DVCS* and *Bethe-Heitler* processes




12 Compton form factors (helicity amplitudes) $\mathcal{H}, \mathcal{E}, \widetilde{\mathcal{H}} \ldots$ elastic form factors $F_1, F_2$

$$|\mathcal{T}_{\rm BH}|^2 = \frac{e^6(1+\epsilon^2)^{-2}}{x_{\rm Bj}^2 y^2 \Delta^2\, \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{\rm BH} + \sum_{n=1}^{2} c_n^{\rm BH} \cos(n\phi) \right\},$$

**exactly known** (LO, QED)

$$|\mathcal{T}_{\rm DVCS}|^2 = \frac{e^6}{y^2 \mathcal{Q}^2} \left\{ c_0^{\rm DVCS} + \sum_{n=1}^{2} \left[ c_n^{\rm DVCS} \cos(n\phi) + s_n^{\rm DVCS} \sin(n\phi) \right] \right\},$$

harmonics ⇕ **1:1** helicity ampl.

$$\mathcal{I} = \frac{\pm e^6}{x_{\rm Bj} y^3 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{\mathcal{I}} + \sum_{n=1}^{3} \left[ c_n^{\mathcal{I}} \cos(n\phi) + s_n^{\mathcal{I}} \sin(n\phi) \right] \right\}.$$

harmonics ⇕ helicity ampl.

## *access of CFFs from measurements:*

| sector | | harmonics in $\mathcal{I}$ | | | | extraction | $P$ of | $\Delta_\perp^l$ behavior | |
|---|---|---|---|---|---|---|---|---|---|
| twist | $\mathcal{C}$'s | unp | LP | $\mathrm{TP}_x$ | $\mathrm{TP}_y$ | of CFFs | $Q^{-P}$ | unp, LP | TP |
| two | $\Re\mathrm{e}\mathcal{C}(\mathcal{F}),\ \Delta\mathcal{C}(\mathcal{F})$ | $c_1$, $c_0$ | $c_1$, $c_0$ | $c_1$, $c_0$ | $s_1$, - | over compl. | 1,2 | 1,0 | 0,1 |
| | $\Im\mathrm{m}\mathcal{C}(\mathcal{F}),\ \Delta\mathcal{C}(\mathcal{F})$ | $s_1$, - | $s_1$, - | $s_1$, - | $c_1$, $c_0$ | over compl. | 1,2 | 1,0 | 0,1 |
| three | $\Re\mathrm{e}\mathcal{C}(\mathcal{F}^{\mathrm{eff}})$ | $c_2$ | $c_2$ | $c_2$ | $s_2$ | complete | 2 | 2 | 1 |
| | $\Im\mathrm{m}\mathcal{C}(\mathcal{F}^{\mathrm{eff}})$ | $s_2$ | $s_2$ | $s_2$ | $c_2$ | complete | 2 | 2 | 1 |
| two | $\Re\mathrm{e}\mathcal{C}_T(\mathcal{F}_T)$ | $c_3$ | - | - | - | $1 \times \Re\mathrm{e}$ of 4 | 1 | 3 | 2 |
| | $\Im\mathrm{m}\mathcal{C}_T(\mathcal{F}_T)$ | - | $s_3$ | $s_3$ | $c_3$ | $3 \times \Im\mathrm{m}$ of 4 | 1 | 3 | 2 |

three possible nucleon polarization + electron/positron beam + neglecting transversity allows to access imaginary and real part of

$$\mathcal{F} = \{\mathcal{H}, \mathcal{E}, \widetilde{\mathcal{H}}, \widetilde{\mathcal{E}}\}$$

$$\mathcal{F}^3 = \{\mathcal{H}^3, \mathcal{E}^3, \widetilde{\mathcal{H}}^3, \widetilde{\mathcal{E}}^3\}$$

twist-three offers access to quark-gluon-quark correlations
transversity arises at NLO from gluons at twist-two or at LO as a twist-four effect

$$\mathcal{F}_T = \mathcal{O}(\alpha_s, 1/\mathcal{Q}^2)$$

relations among **harmonics** and **GPDs** are based on $1/\mathcal{Q}$ expansion:
(all harmonics are expressed by twist-2 and -3 GPDs) **[Diehl et. al (97) Belitsky, DM, Kirchner (01)]**

$$\begin{Bmatrix} c_1 \\ s_1 \end{Bmatrix}^{\mathcal{I}} \propto \frac{\Delta}{\mathcal{Q}} \,\text{tw-2(GPDs)} + O(1/\mathcal{Q}^3), \qquad c_0^{\mathcal{I}} \propto \frac{\Delta^2}{\mathcal{Q}^2} \,\text{tw-2(GPDs)} + O(1/\mathcal{Q}^4),$$

$$\begin{Bmatrix} c_2 \\ s_2 \end{Bmatrix}^{\mathcal{I}} \propto \frac{\Delta^2}{\mathcal{Q}^2} \,\text{tw-3(GPDs)} + O(1/\mathcal{Q}^4), \qquad \begin{Bmatrix} c_3 \\ s_3 \end{Bmatrix}^{\mathcal{I}} \propto \frac{\Delta\alpha_s}{\mathcal{Q}} (\text{tw-2})^{\mathrm{T}} + O(1/\mathcal{Q}^3),$$

$$c_0^{\mathrm{CS}} \propto (\text{tw-2})^2, \qquad \begin{Bmatrix} c_1 \\ s_1 \end{Bmatrix}^{\mathrm{CS}} \propto \frac{\Delta}{Q} (\text{tw-2})\,(\text{tw-3}), \qquad \begin{Bmatrix} c_2 \\ s_2 \end{Bmatrix}^{\mathrm{CS}} \propto \alpha_s (\text{tw-2})(\text{tw-2})^{\mathrm{GT}}$$

setting up the **perturbative framework:** **[Belitsky, DM (97); Mankiewicz et. al (97);Ji, Osborne (98); Pire et. al (11)]**

- ✓ ***twist-two*** coefficient functions at ***next-to-leading*** order
- ✓ evolution kernels at ***next-to-leading*** order **[Belitsky, DM, Freund (01)]**
- ✓ ***next-to-next-to-leading*** order in a specific conformal subtraction scheme **[KMP-K & Schaefer 06]**
- ✓ ***twist-three*** including quark-gluon-quark correlation at LO **[Anikin,Teryaev, Pire (00); Belitsky DM (00); Kivel et. al]**
- ✓ partially, ***twist-three*** sector at ***next-to-leading*** order **[Kivel, Mankiewicz (03)]**
- ✓ \`target mass corrections' (not well understood) **[Belitsky DM (01)]**
- ✓ ***twist-four*** sector **[Braun, Manashov (11)]**

# Can one `measure' GPDs?

- ***CFF*** given as ***GPD*** **convolution**:

$$\mathcal{H}(\xi,t,\mathcal{Q}^2) \stackrel{\rm LO}{=} \int_{-1}^{1} dx \left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right) H(x,\eta=\xi,t,\mathcal{Q}^2)$$

$$\stackrel{\rm LO}{=} i\pi H^-(x=\xi,\eta=\xi,t,\mathcal{Q}^2) + {\rm PV}\int_0^1 dx \frac{2x}{\xi^2 - x^2} H^-(x,\eta=\xi,t,\mathcal{Q}^2)$$

- $H(x,x,t,\mathcal{Q}^2)$ viewed as **"spectral function"** (*s*-channel cut):

$$H^-(x,x,t,Q^2) \equiv H(x,x,t,Q^2) - H(-x,x,t,Q^2) \stackrel{\rm LO}{=} \frac{1}{\pi}\Im{\rm m}\mathcal{F}(\xi=x,t,Q^2)$$

- ***CFFs*** satisfy `**dispersion relations'**
  **(not the physical ones, threshold $\xi_0$ set to 0)**

**[Frankfurt et al (97)**
**Chen (97)**
**Terayev (05)**
**KMP-K (07)**
**Diehl, Ivanov (07)]**

⇨ $$\Re{\rm e}\mathcal{F}(\xi,t,Q^2) = \frac{1}{\pi}{\rm PV}\int_0^1 d\xi' \left(\frac{1}{\xi - \xi'} \mp \frac{1}{\xi + \xi'}\right) \Im{\rm m}\mathcal{F}(\xi',t,Q^2) + \mathcal{C}(t,Q^2)$$

**[Terayev (05)]**

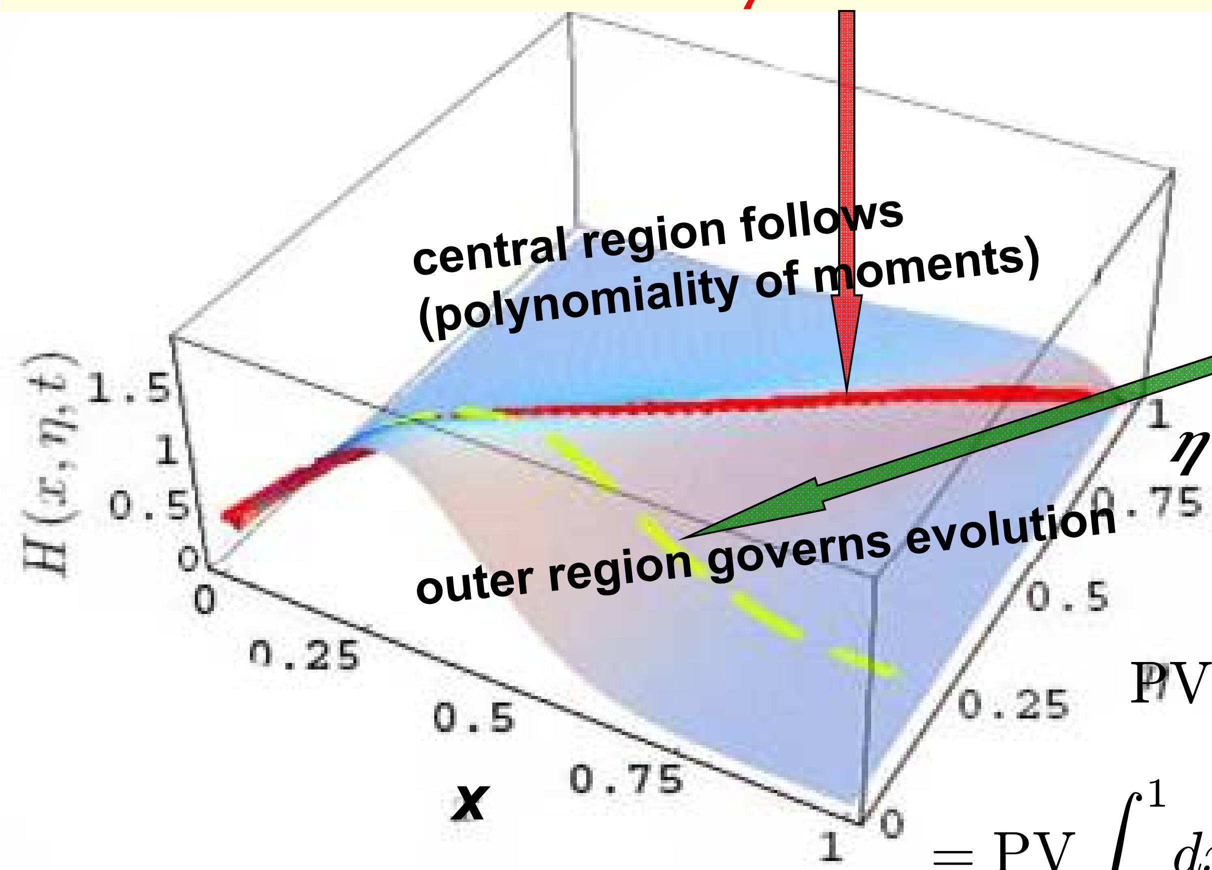
⇨ ***access*** to the ***GPD*** on the **cross-over line** $\eta = x$ (at LO )

# *Modeling & Evolution*

*outer region governs the evolution at the cross-over trajectory*

$$\mu^2 \frac{d}{d\mu^2} H(x,x,t,\mu^2) = \int_x^1 \frac{dy}{x} V(1, x/y, \alpha_s(\mu)) H(y,x,\mu^2)$$

**GPD at $\eta = x$ is `measurable' (LO)**




**net contribution of outer + central region is governed by a sum rule:**

$$\mathrm{PV} \int_0^1 dx \, \frac{2x}{\eta^2 - x^2} H^-(x,\eta,t)$$

$$= \mathrm{PV} \int_0^1 dx \, \frac{2x}{\eta^2 - x^2} H^-(x,x,t) +_8 C(t)$$

# Strategies to analyze DVCS data

**(ad hoc) modeling:** **VGG** code [**Goeke et. al (01)** based on **Radyuskin's** DDA]
**(first decade)** BKM model [**Belitsky, Kirchner, DM (01)** based on RDDA]
`aligned jet' model [**Freund, McDermott, Strikman (02)**]
**Goloskokov/Kroll (05)** based on RDDA (pinned down by DVMP)
`dual' model [**Polyakov,Shuvaev 02;Guzey,Teckentrup 06;Polyakov 07**]
" -- " [**KMP-K (07)** in MBs-representation]
polynomials **[Belitski et al. (98), Liuti et. al (07), Moutarde (09)]**

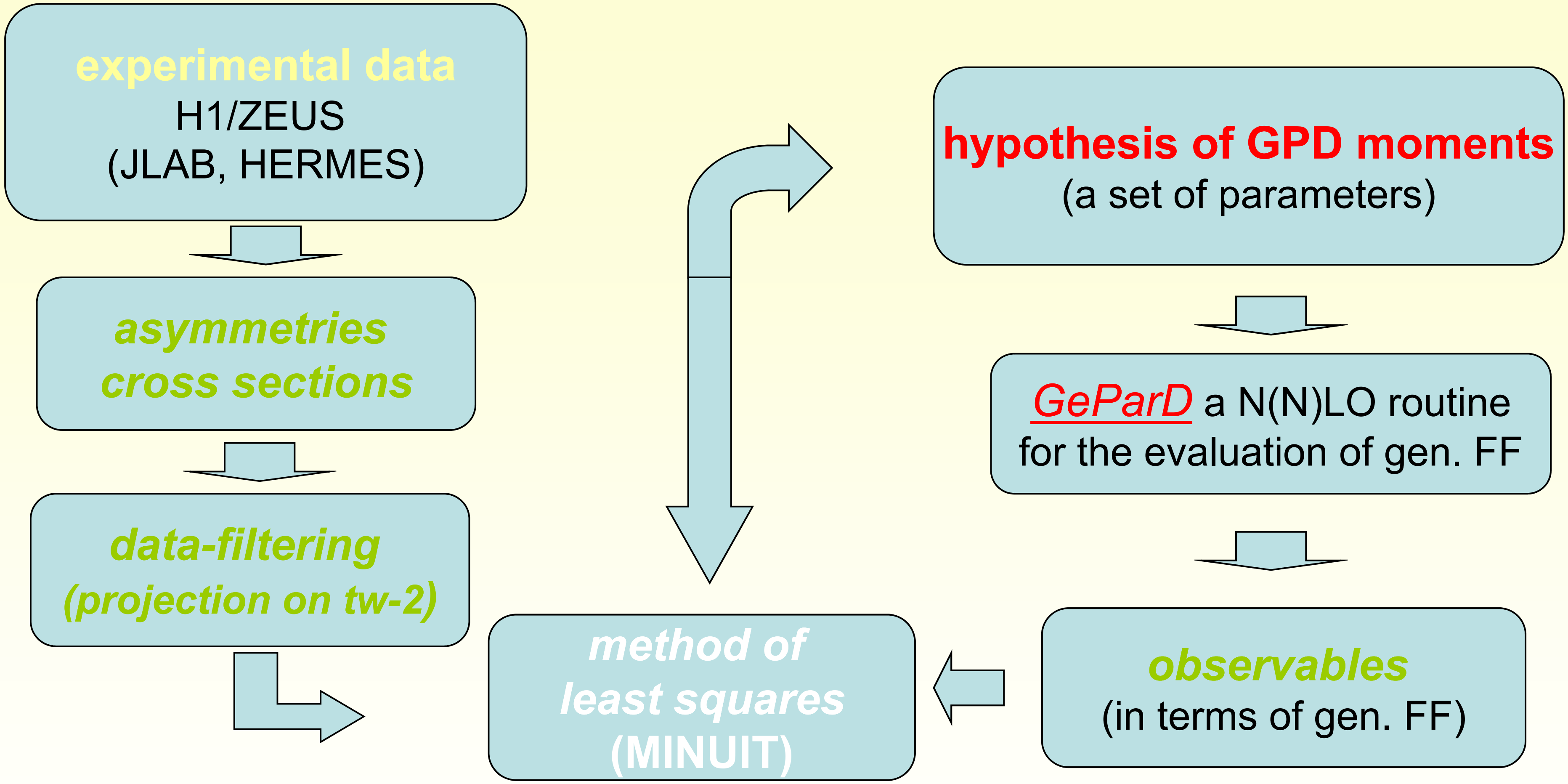
**dynamical models:** not applied **[Radyuskin et.al (02); Tiburzi et.al (04); Hwang DM (07)]…**
(respecting Lorentz symmetry)

**flexible models:** any representation by including ***unconstrained*** degrees of freedom
(for fits) **KMP-K (07/08)** for H1/ZEUS in MBs-integral-representation

## *Extracting CFFs from data: real and imaginary part*

i. CFF extraction with formulae **[BMK (01), HALL-A (06)]**
fits **[Guidal, Moutarde (08...)]**
neural networks **[KMS (11) neural networks]**
ii. `dispersion integral' fits **[KMP-K (08),KM (08...)]**
iii. flexible GPD modeling **[KM (08...)]**
vi. model comparisons **Goldstein et al. (11)** (no sea, giving up polynomiality)
**Goloskokov/Kroll (07) model** based on RDDA

# Ready for flexible GPD model fits?




***YES*** for small x and ***we don`t use it*** for fixed target kinematics

- reasonable well motivated hypotheses of GPDs (moment) must be known first
- many parameters – Is a least square fit an appropriate strategy?
- some code writing is left

# DVCS fits to H1 and ZEUS data

DVCS cross section measured at small $x_{\rm Bj} \approx 2\xi = \frac{2\mathcal{Q}^2}{2W^2+\mathcal{Q}^2}$

predicted by

$$\frac{d\sigma}{dt}(W,t,\mathcal{Q}^2) \approx \frac{4\pi\alpha^2}{\mathcal{Q}^4}\frac{W^2\xi^2}{W^2+\mathcal{Q}^2}\left[|\mathcal{H}|^2 - \frac{\Delta^2}{4M_{\rm p}^2}|\mathcal{E}|^2 + \left|\widetilde{\mathcal{H}}\right|^2\right](\xi,t,\mathcal{Q}^2)\Big|_{\xi=\frac{\mathcal{Q}^2}{2W^2+\mathcal{Q}^2}}$$

suppressed contributions *<<0.05>>* relative *O(ξ)*

- LO data could not be described before **2008**
- NLO works with ad hoc GPD models **[Freund, McDermott (02)]**

  results strongly depend on employed PDF parameterization

➡ ***do a simultaneous fit to DIS and DVCS*** **[KMP-K (07)]**

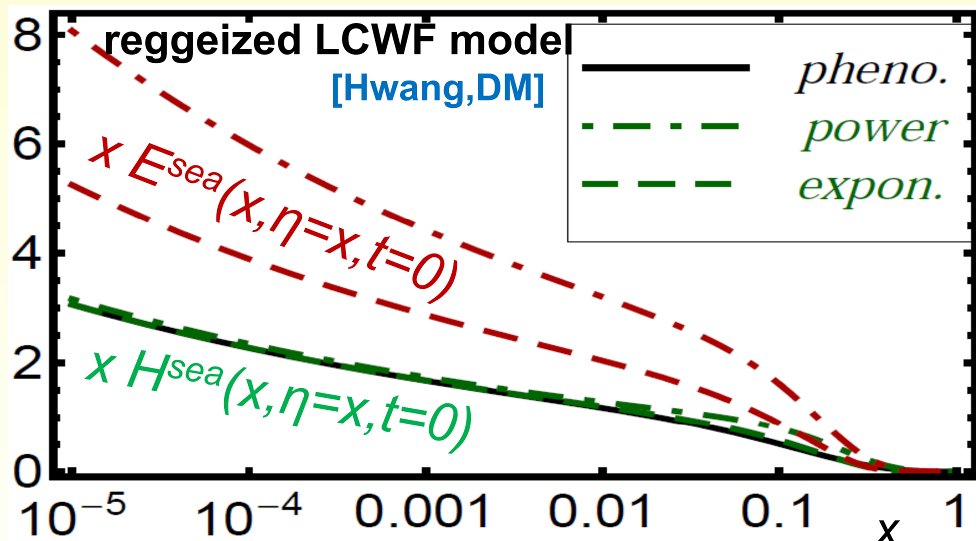
➡ ***use flexible GPD models in a two-step fit*** **[KM (09)]** effective functional form at small *x*:

PDFs: $$q^{\rm sea}(\xi,\mathcal{Q}) = n(\mathcal{Q})\xi^{-\alpha(\mathcal{Q})}, \quad \alpha \gtrsim 1, \quad F^{\rm sea}(0)=1$$

GPDs: $$H^{\rm sea} = r(\eta/x=1,\mathcal{Q})F^{\rm sea}(t)\xi^{\alpha'(t,\mathcal{Q})}q^{\rm sea}(\xi,\mathcal{Q})$$

**?** $E(\xi,\xi,t,\mathcal{Q})$ ***skewness***

***transverse distribution***

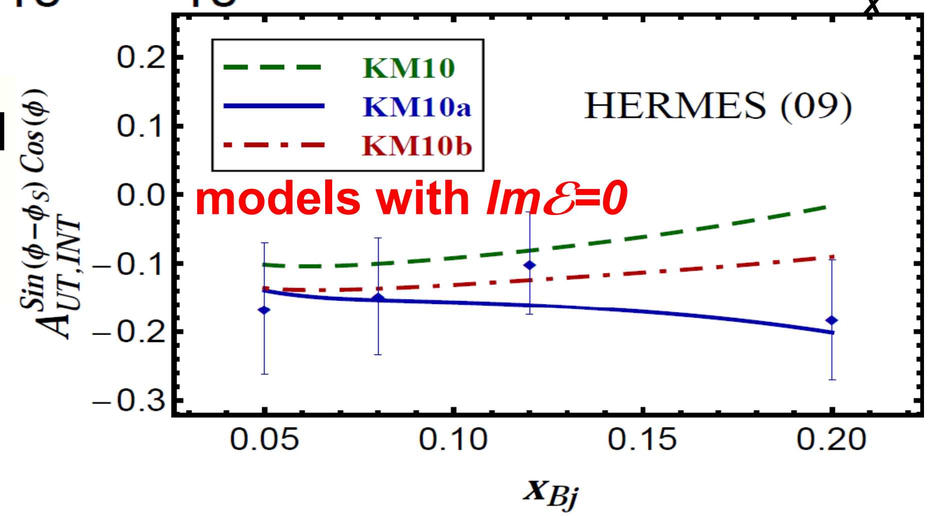



- not seen in Regge phenomenology
- might be sizeable in instanton models
- reggeized spectator quark models
- pQCD suggests `pomeron' intercept
- however, *B* vanishes asymptotically
- so far *E* is "not seen" in DVCS

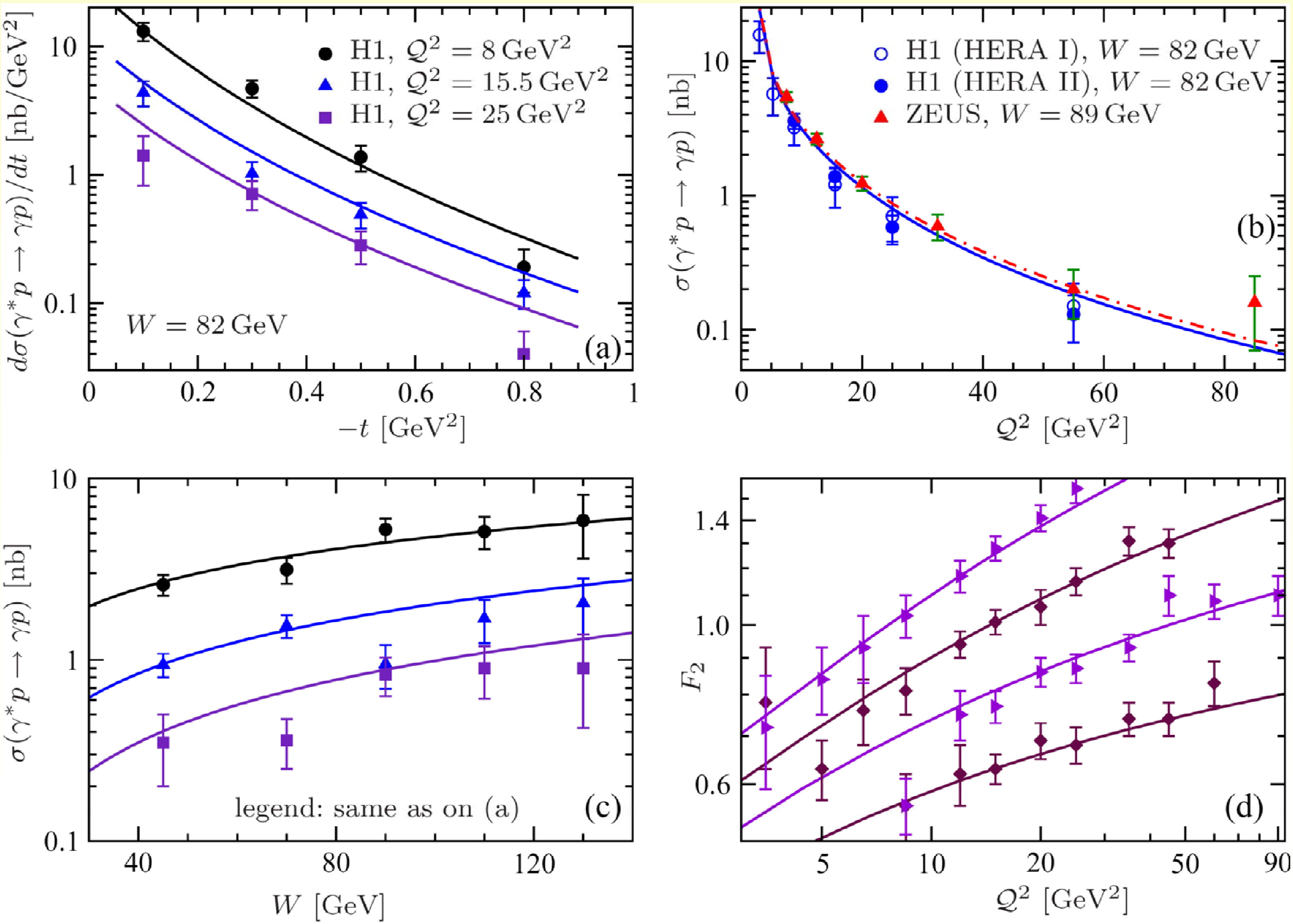
qualitative understanding of *E* is needed
(not only forJi`s spin sum rule)

$$B = \int_0^1 dx\, x E(x,\eta,t,\mathcal{Q})$$

transverse target spin asymmetry
is **sensitive to *E* and sizeable at EIC**



# good DVCS fits at LO, NLO, and NNLO with flexible GPD ansatz



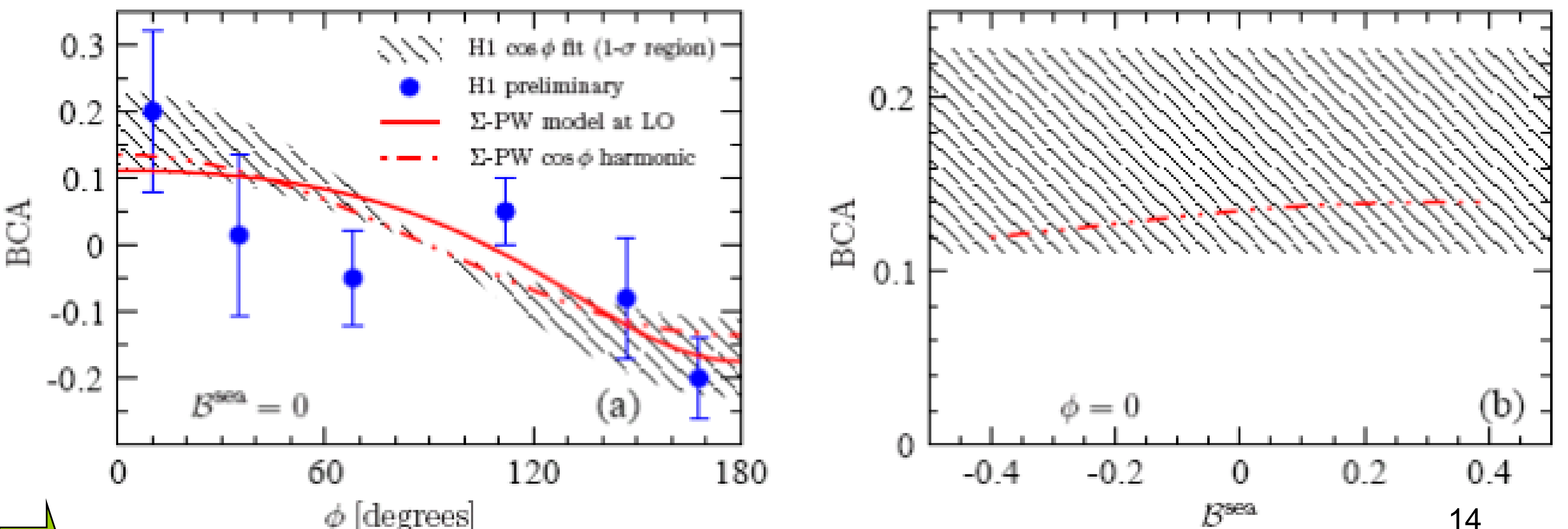
# Beam charge asymmetry

$$BCA = \frac{d\sigma_{e^+} - d\sigma_{e^-}}{d\sigma_{e^+} + d\sigma_{e^-}} = \frac{\mathcal{T}_{\rm Interference}}{|\mathcal{T}_{\rm BH}|^2 + |\mathcal{T}_{\rm DVCS}|^2}$$

$$\propto F_1(t)\Re\mathrm{e}\mathcal{H} + \frac{|t|}{4M^2} F_2(t)\Re\mathrm{e}\mathcal{E}$$

**the unknown in Ji's nucleon spin sum rule**

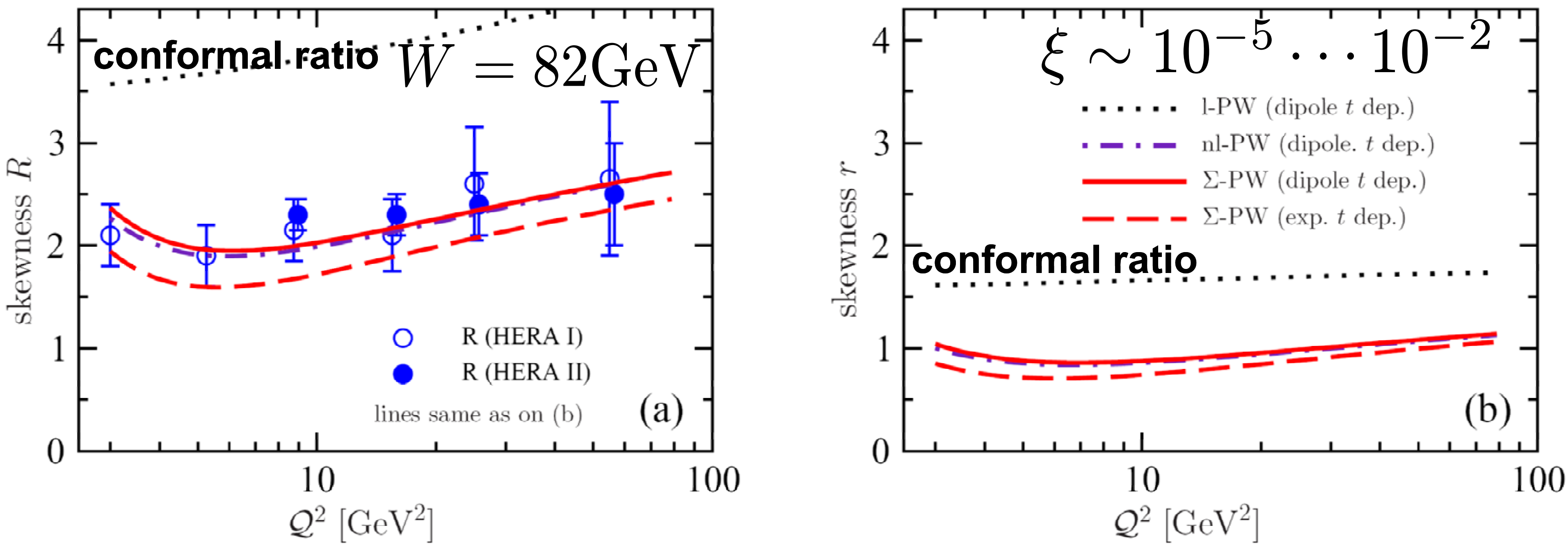
- set $E_{\rm sea} \propto H_{\rm sea}$ use *anomalous gravitomagnetic moment* $B_{\rm sea} = \int_0^1 dx\, x E_{\rm sea}$ as parameter




➡ unfortunately, H1 data do not allow to access $B_{\rm sea}$

# quark skewness ratio from DVCS fits @ LO

$$R = \frac{\Im\mathrm{m} A_{\mathrm{DVCS}}}{\Im\mathrm{m} A_{\mathrm{DIS}}} \stackrel{LO}{=} \frac{H(\xi,\xi)}{H(2\xi,0)} \approx 2^{\alpha} r \qquad r = \frac{H(\xi,\xi)}{H(\xi,0)}$$



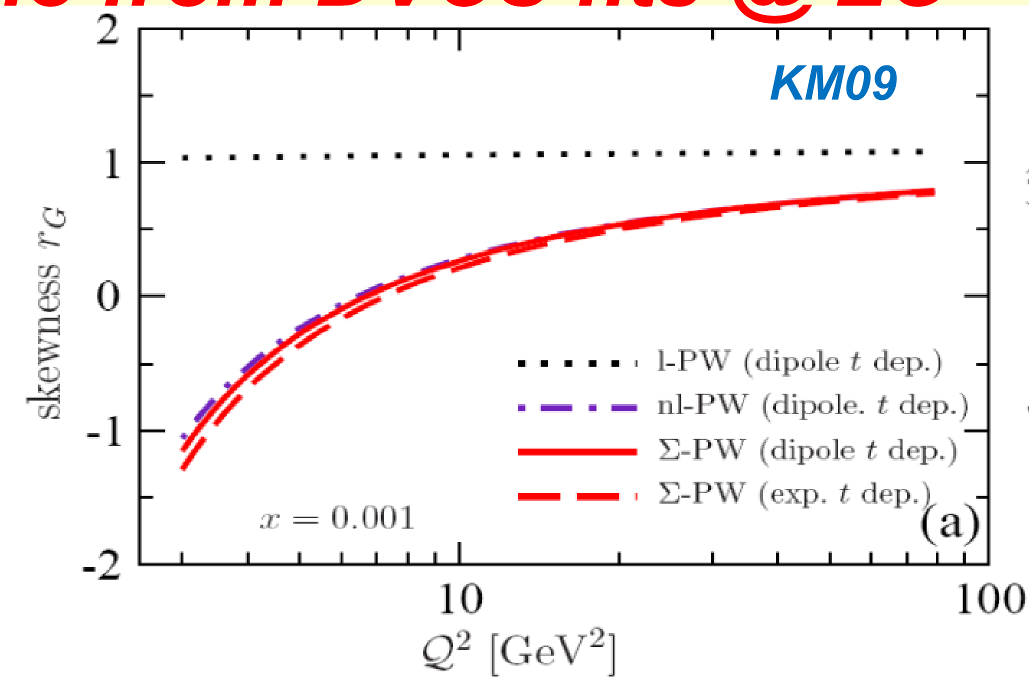

- @LO the conformal ratio $r_{\mathrm{con}} = \frac{2^{\alpha}\Gamma(3/2+\alpha)}{\Gamma(3/2)\Gamma(2+\alpha)}$ is ruled out for sea quark GPD
- a generically zero-skewness effect over a large $Q^2$ lever arm
- scaling violation consistent with pQCD prediction
- this zero-skewness effect is non-trivial to realize in conformal space (SO(3) sibling poles are required)

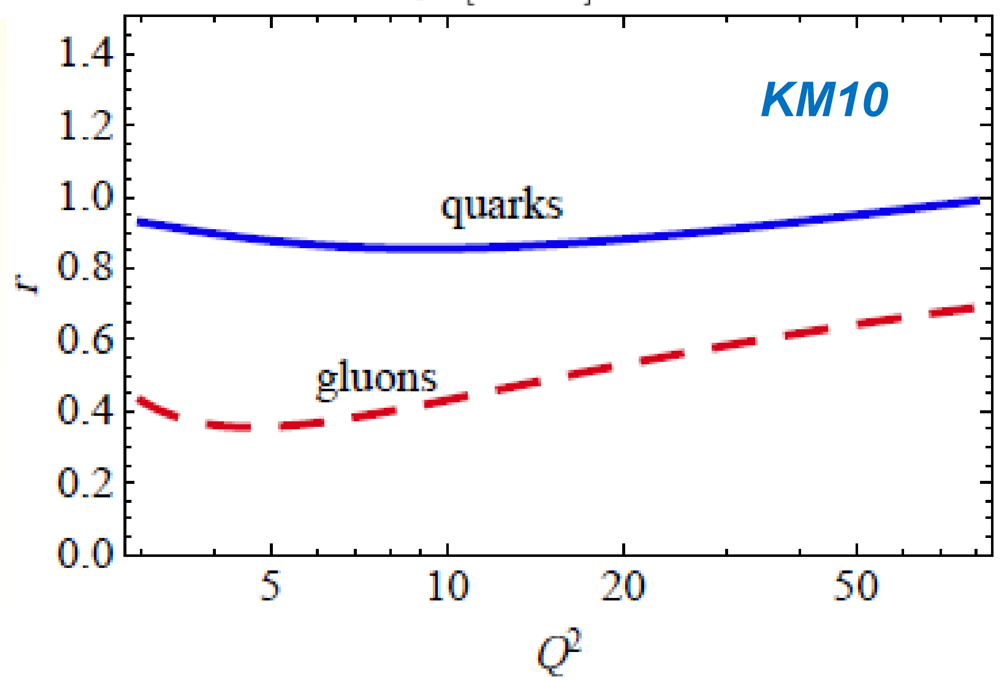
# Gluon skewness ratio from DVCS fits @ LO

**conformal ratio**

$$r^G_{\rm con} = \frac{2^{1+\alpha}\Gamma(3/2+\alpha)}{\Gamma(3/2)\Gamma(3+\alpha)} \approx 1$$

- imposed in all popular models
- accessible due to evolution
- @LO the gluonic *r*-ratio is smaller than the conformal one
- negative value is an artifact (still a to rigid model)
- gluonic r-ratio @LO from *ρ* electroproduction is 0.1…0.5
- qualitatively consistent with DVCS findings



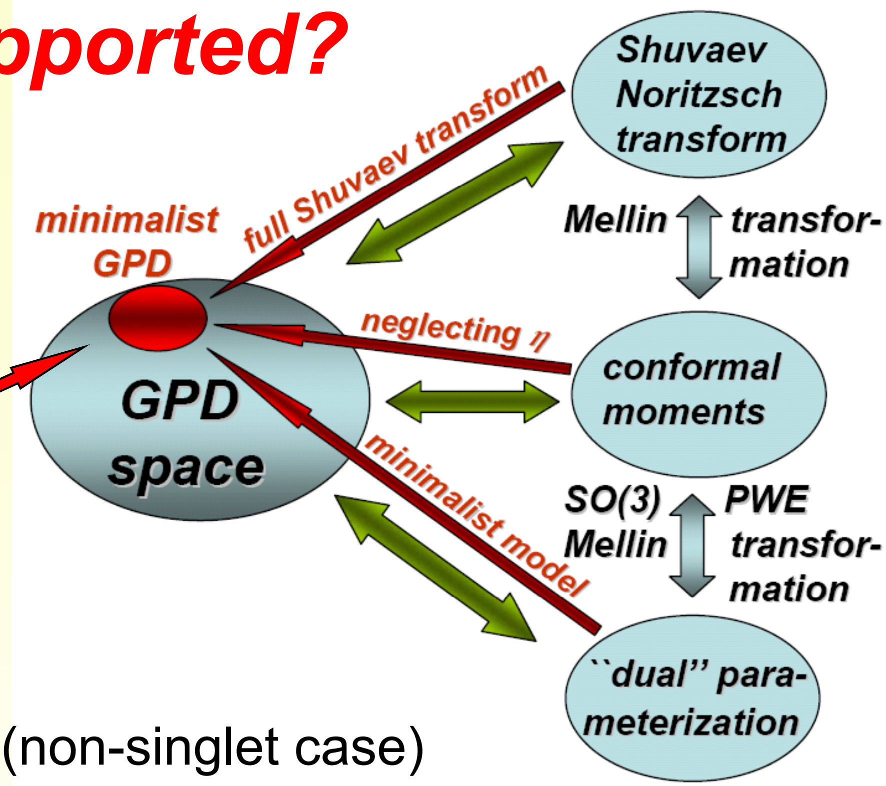



# Is the conformal ratio supported?

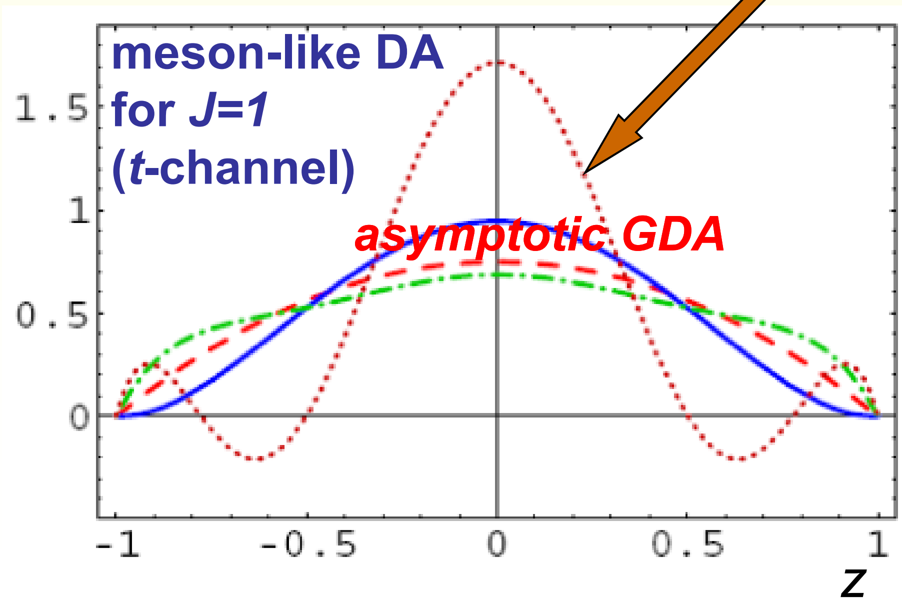
$$r = \frac{H(x,x,t=0,Q^2)}{q(x,Q^2)}$$

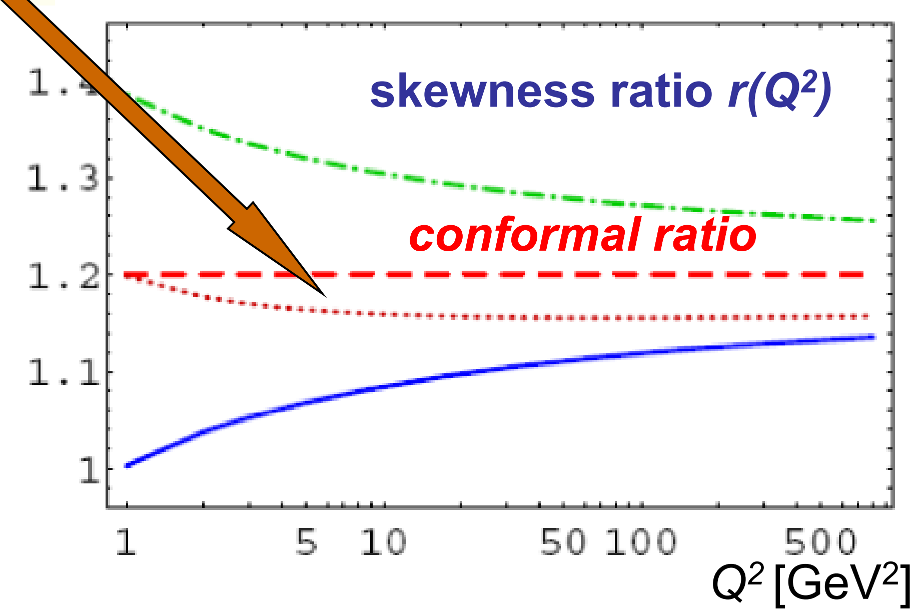
``erroneous small *x*-claim''

$$r_{\text{con}} = \frac{2^{\alpha}\Gamma(3/2+\alpha)}{\Gamma(3/2)\Gamma(2+\alpha)}$$




a **counter example** (non-singlet case)

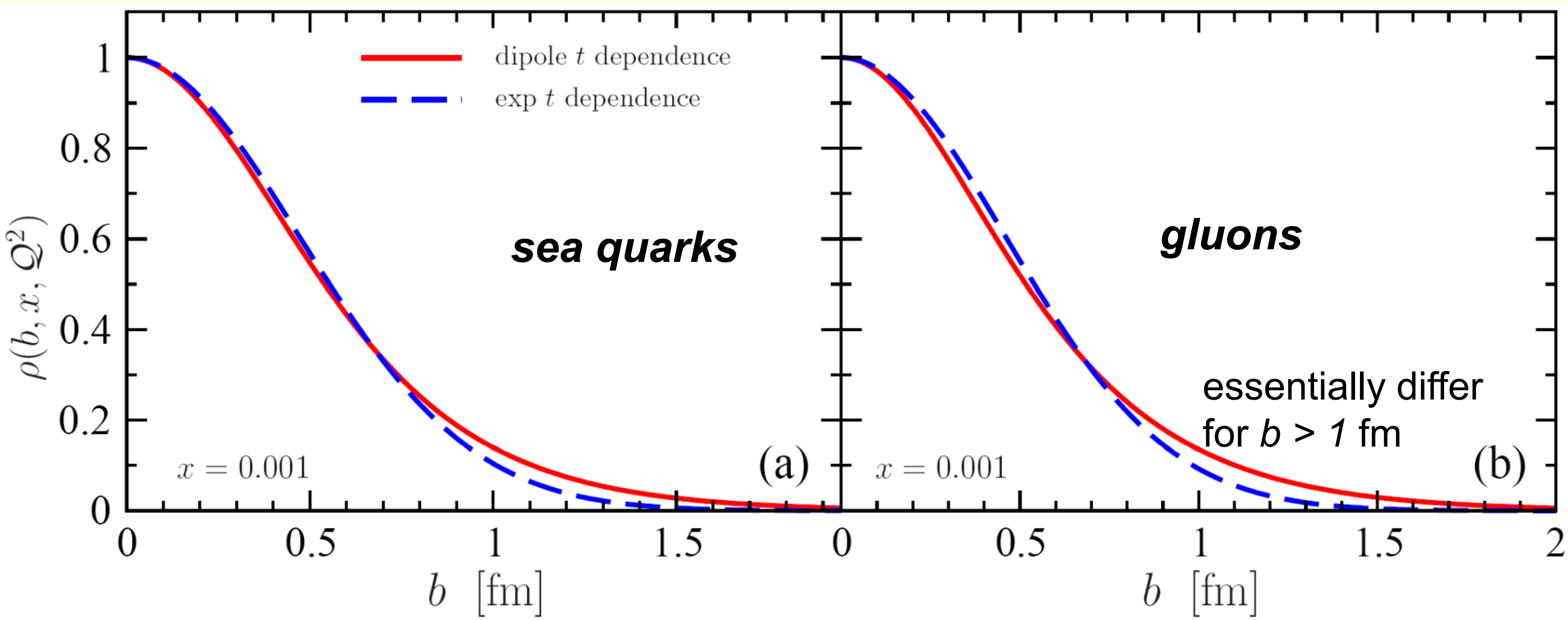


- CFF *H* posses ``pomeron behavior'' $\xi^{-\alpha(Q) - \alpha'(Q)t}$
  - ✓ ***α* increases with growing** $Q^2$
  - ✓ ***α'* decreases growing** $Q^2$
- *t*-dependence: exponential shrinkage is disfavored ($\alpha' \approx 0$)

  dipole shrinkage is visible ($\alpha' \approx 0.15$ at $Q^2=4$ $GeV^2$)
- (normalized) profile functions

$$\rho \propto \int d^2\vec{\Delta}_\perp \, e^{i\vec{b}\cdot\vec{\Delta}_\perp} H(x,0,t=-\vec{\Delta}_\perp^2)$$



## *data set for unpolarized proton target used for KM09/10 fits*

- H1/ZEUS 98 [$\sigma$, $d\sigma/dt$] +1x6 [BCA($\varphi$)] $\langle\langle x\rangle\rangle \approx 10^{-3}$, $\langle|t|\rangle \leq 0.8$ GeV$^2$
  $\langle\langle Q^2\rangle\rangle \approx 8$ GeV$^2$
- HERMES(02) 12+3 [BSA, $\sin(\varphi)$]
- HERMES(08) 12x2 [BCA, $\cos(0\,\varphi)$, $\cos(\varphi)$] $0.05 \leq \langle x\rangle \leq 0.2$, $\langle|t|\rangle \leq 0.4$ GeV$^2$
  12x2 [$\cos(2\,\varphi)$, $\cos(3\,\varphi)$] $\langle\langle Q^2\rangle\rangle \approx 2.5$ GeV$^2$
- HERMES(09,10) BSA and BCA data (included in KM10 fits)
- CLAS(07) 12x12 [BSA($\varphi$)] $0.14 \leq \langle x\rangle \leq 0.35$, $\langle|t|\rangle \leq 0.3$ GeV$^2$
  40x12 [BSA($\varphi$)] (large |t| or bad sta.) $\langle\langle Q^2\rangle\rangle \approx 1.8$ GeV$^2$
- HALL A(06) 12x24 [$\Delta\sigma(\varphi)$] $\langle x\rangle = 0.36$, $\langle|t|\rangle \leq 0.33$ GeV$^2$
  3x24 [$\sigma(\varphi)$] $\langle\langle Q^2\rangle\rangle \approx 1.8$ GeV$^2$

How to analyze $\varphi$ dependence?

- fit within assumed functional form **[CLAS(07)]**
- likelihood fit with respect to dominant and higher harmonics **[HERMES]**
- utilize Fourier transform (with or without additional weight) **[BMK(01)]**

➡ equivalent results for CLAS data with small stat. errors

# Dispersion relation fits to unpolarized DVCS

- model of GPD *H(x,x,t) within DD motivated ansatz at* $Q^2$=2 $\text{GeV}^2$

***fixed:***
*rules*

*PDF normalization* — *eff. Reage pole* — *large t-counting*

$$H(x,x,t) = \frac{n\, r\, 2^{\alpha}}{1+x}\left(\frac{2x}{1+x}\right)^{-\alpha(t)}\left(\frac{1-x}{1+x}\right)^{b}\frac{1}{\left(1-\frac{1-x}{1+x}\frac{t}{M^2}\right)^{p}}\,.$$

*free:* — *r-ratio at small x* — *large x-behavior* — *p-pole mass*

*sea quarks (taken from LO fits)*

$$n = 0.68, \quad r = 1, \quad \alpha(t) = 1.13 + 0.15t/\text{GeV}^2, \quad m^2 = 0.5\text{GeV}^2, \quad p = 2$$

*valence quarks*

$$n = 1.0, \quad \alpha(t) = 0.43 + 0.85t/\text{GeV}^2, \quad p = 1$$

$$\mathcal{D}(t) = \frac{-C}{(1-t/M_c^2)^2}$$

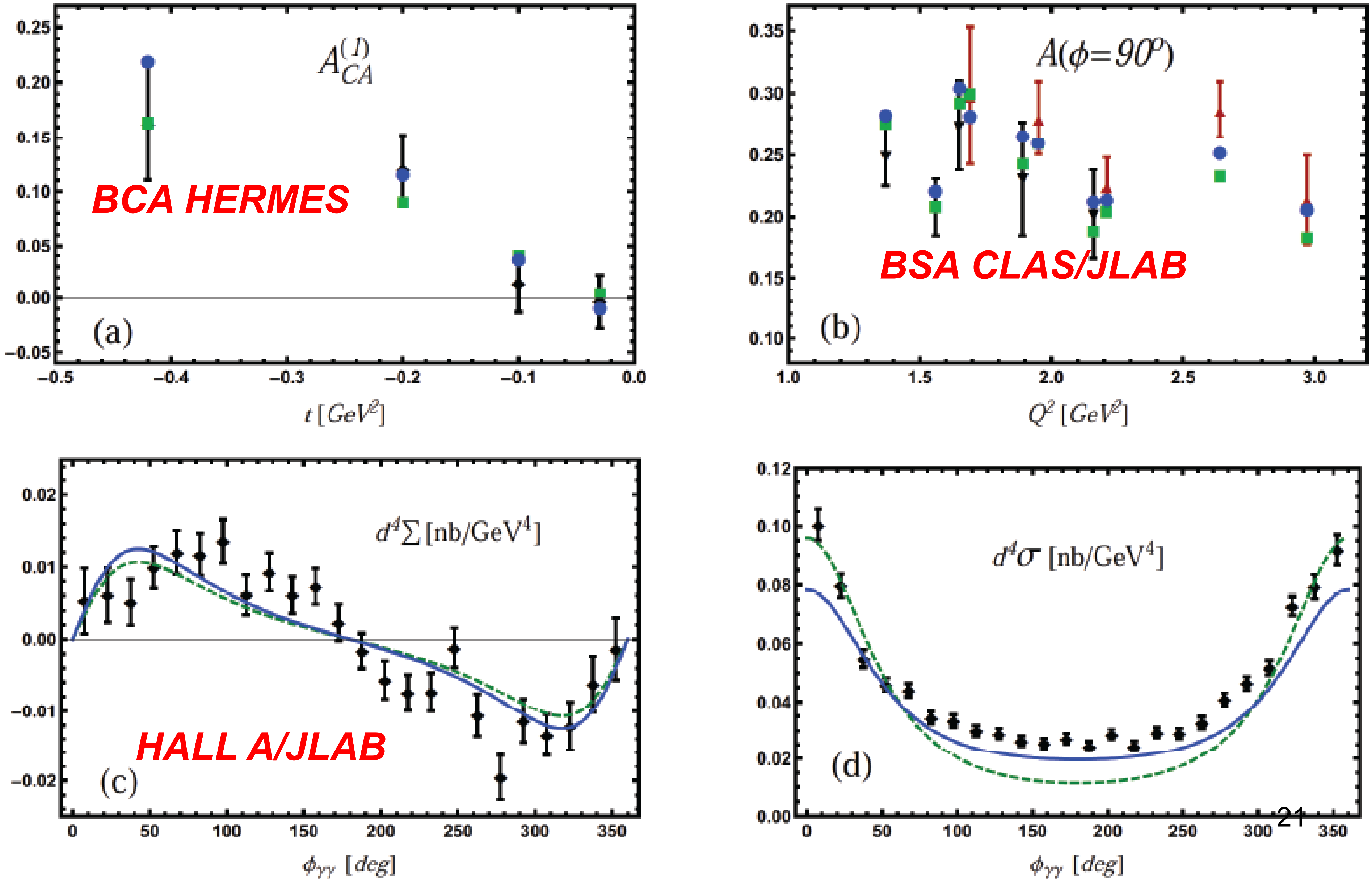
flexible parameterization of subtraction constant

+ pion-pole contribution

36 + 4 data points quality of ***global fit*** is good

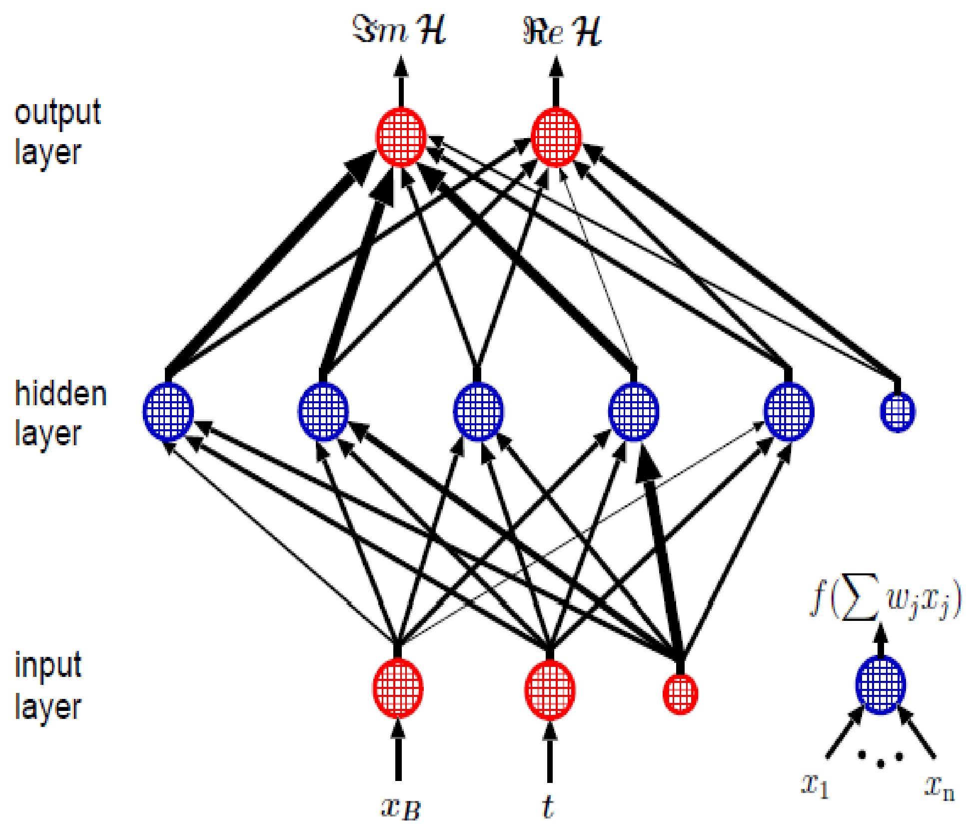
$$\chi^2/\text{d.o.f.} \approx 1$$

# Global GPD fit example: HERMES & JLAB



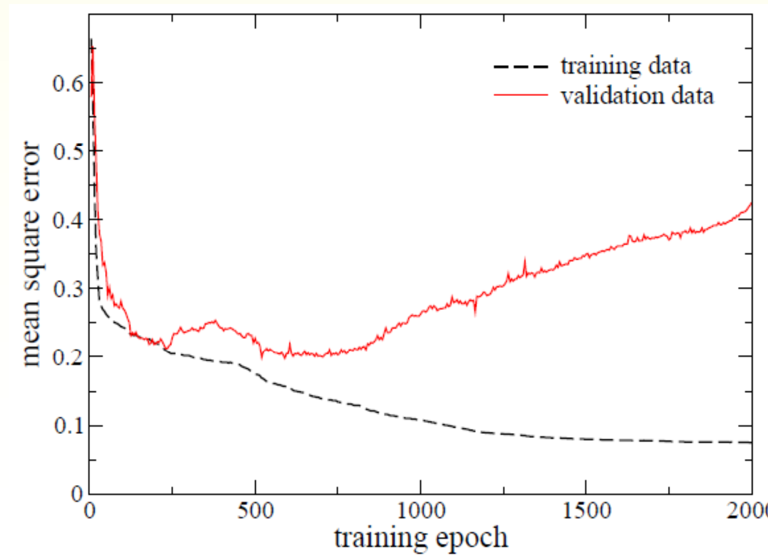
# *Neural Networks*

- kinematical values are represented by the input layer
- propagated trough the network, where weights are set randomly
- random values for $Im\mathcal{H}$ and $Re\mathcal{H}$
- calculation of $\chi^2$
- backwards propagation
- adjusting weights so that error decreases
- repeat procedure
- taking next kinematical point




Monte Carlo procedure to propagate errors, i.e., generating a replica data set

avoiding over fitting (fitting to noise), dividing data set, taking a control example if error increases after decreasing – one stops

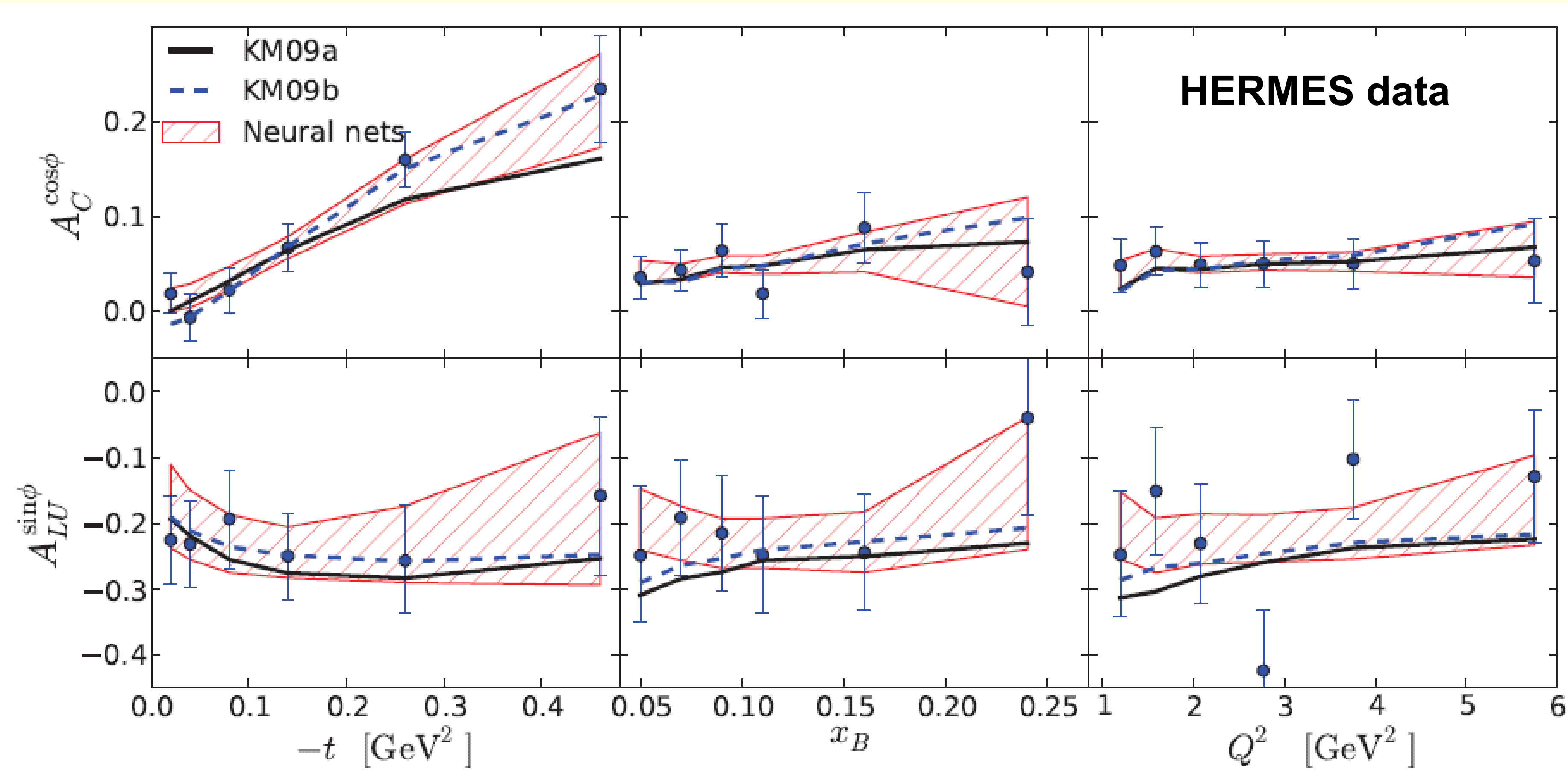


# A first use of neural network fits

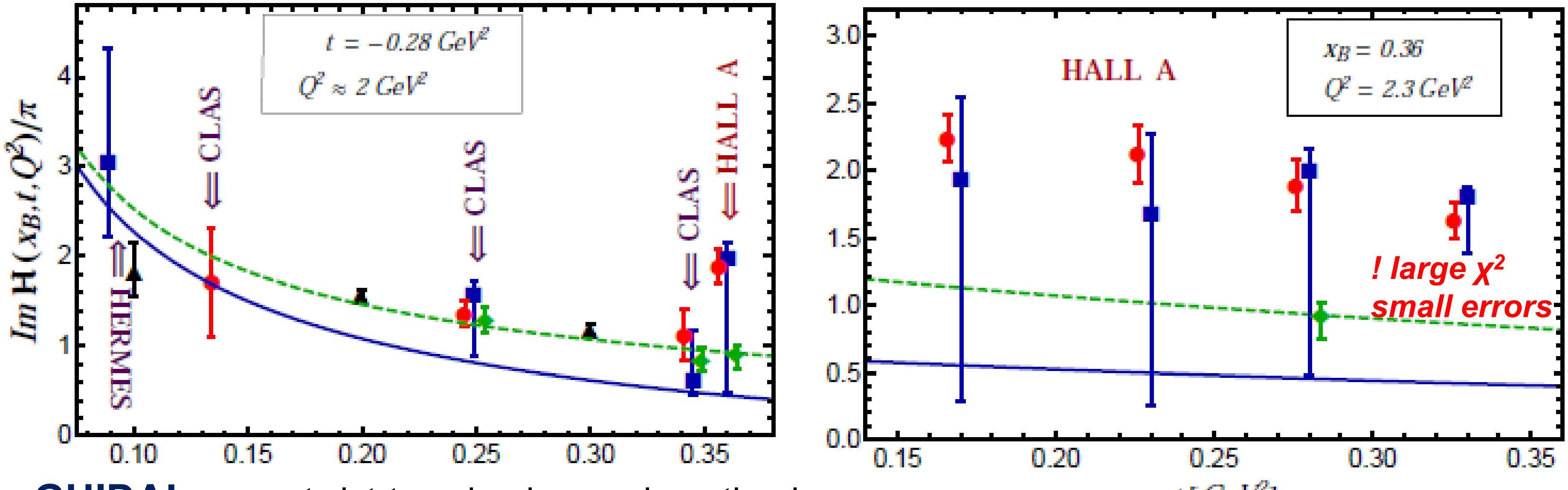
(ideal) tool for error propagation and quantifying model uncertainties

so far it is used to access real and imaginary part of $\mathcal{H}$ CFF

results are compatible to dispersion relation fits



# KM09 versus CFF fits & large-x "model" fit




**GUIDAL** twist-two dominance hypothesis
7 parameter fit to all harmonics of unpolarized cross section
propagated errors + "theoretical" error estimate

**GUIDAL** same + longitudinal TSA

**Moutarde** H dominance hypothesis within a smeared polynomial expansion
propagated errors + "theoretical" error estimate

**KM** neural network within H dominance hypothesis
green (blue) curves (KM09) without (with) HALL A data (ratios)

- reasonable agreement for HERMES and CLAS kinematics
- large *x*-region and real part remains unsettled
- next step: NN within twist-two dominance hypothesis + \`dispersion' integral

# How reliable is the twist-two dominance?

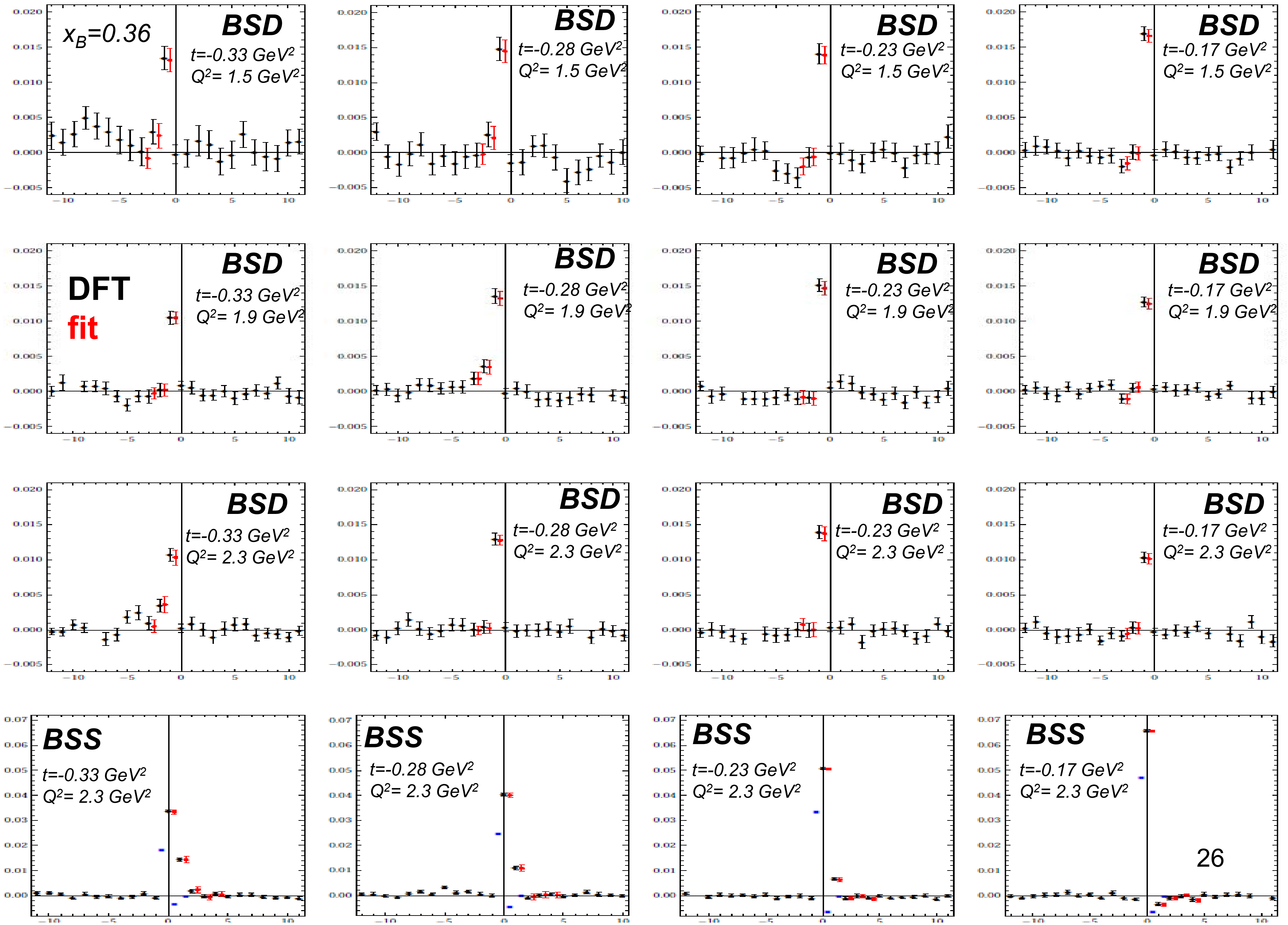
- each interference term harmonic contains twist-2, -3, and transversity (kinematical counting according to BMK + admixture effects **[BM (09,10)])**
- transversity (photon helicity flip by two units) might be neglected (so far not seen in data, kinematical suppressed by *t'/M2* or *t'/Q2*)
- dominant sin/cos($\varphi$) harmonics of the interference term is contaminated by twist-three term from DVCS
- HALL A : twist-3 effects are hardly visible

⇨ ***not conclusive***

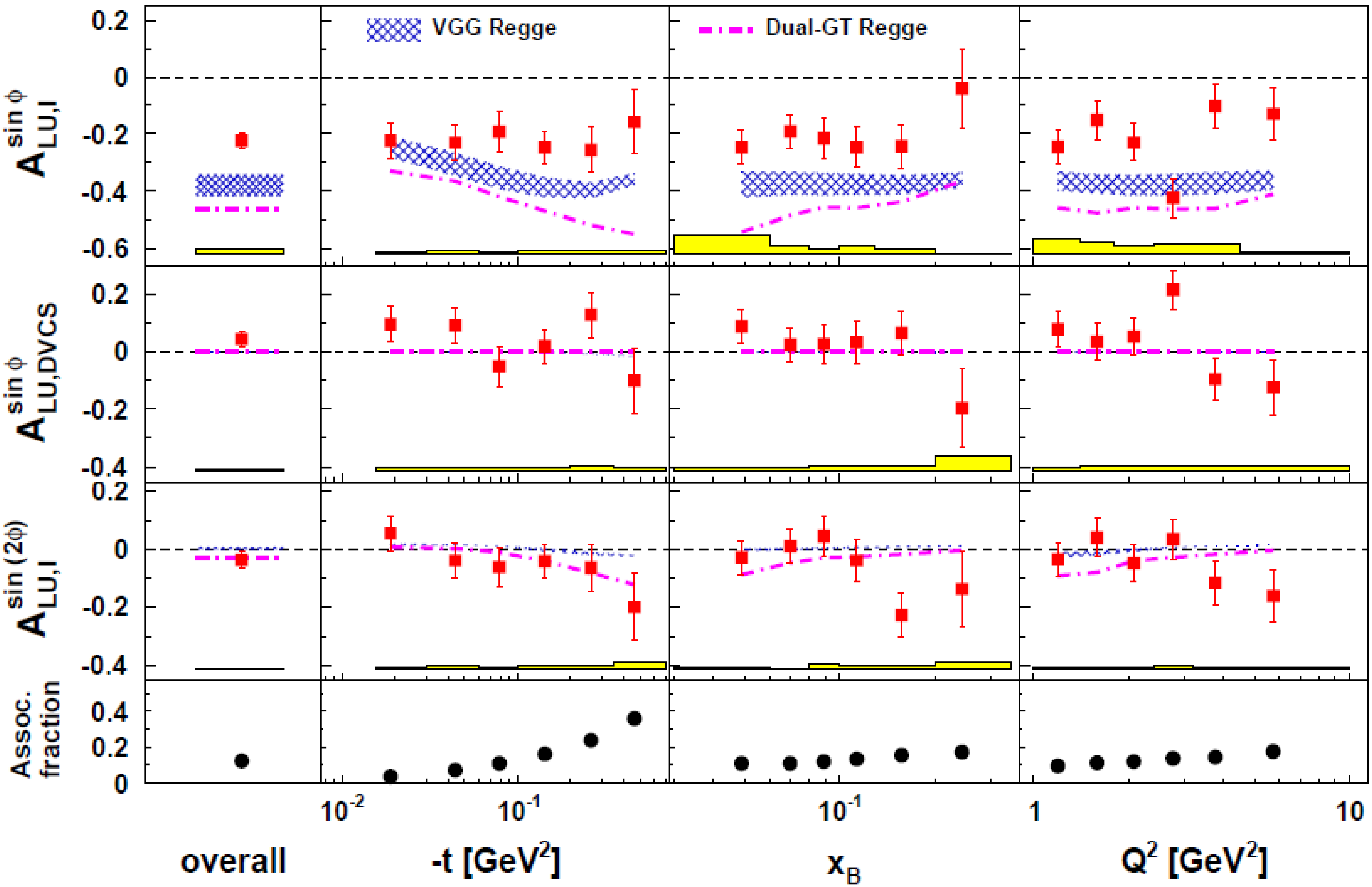
- electron/positron beam is needed for a cleaner separation
- HERMES (09) data might indicate a ~4% overall DVCS twist-3 BSA effect a relative 20% uncertainty for a BSA measurement within electron beam
- HERMES (10) data indicate a zero overall DVCS twist-3 BSA effect

⇨ ***there might be a twist-three contamination on some 10% level***

# Fourier spectra of HALL A data (12 + 4 cross section measurements versus φ)



# *Fourier spectra of HERMES (09) data (1996-2005)*



# *KM10 fits to (unpolarized) DVCS*

- a hybrid model: three effective SO(3) PWs for sea quarks/gluons
  dispersion relations for valence
  flexible pion pole contribution
  still *E* GPD is neglected (only D-term)
- framework

leading order, including evolution for sea quarks/ gluons
twist-two dominance hypothesis within CFF convention **[BM10]**

- data selection (taking moments of azimuthal angle harmonics)

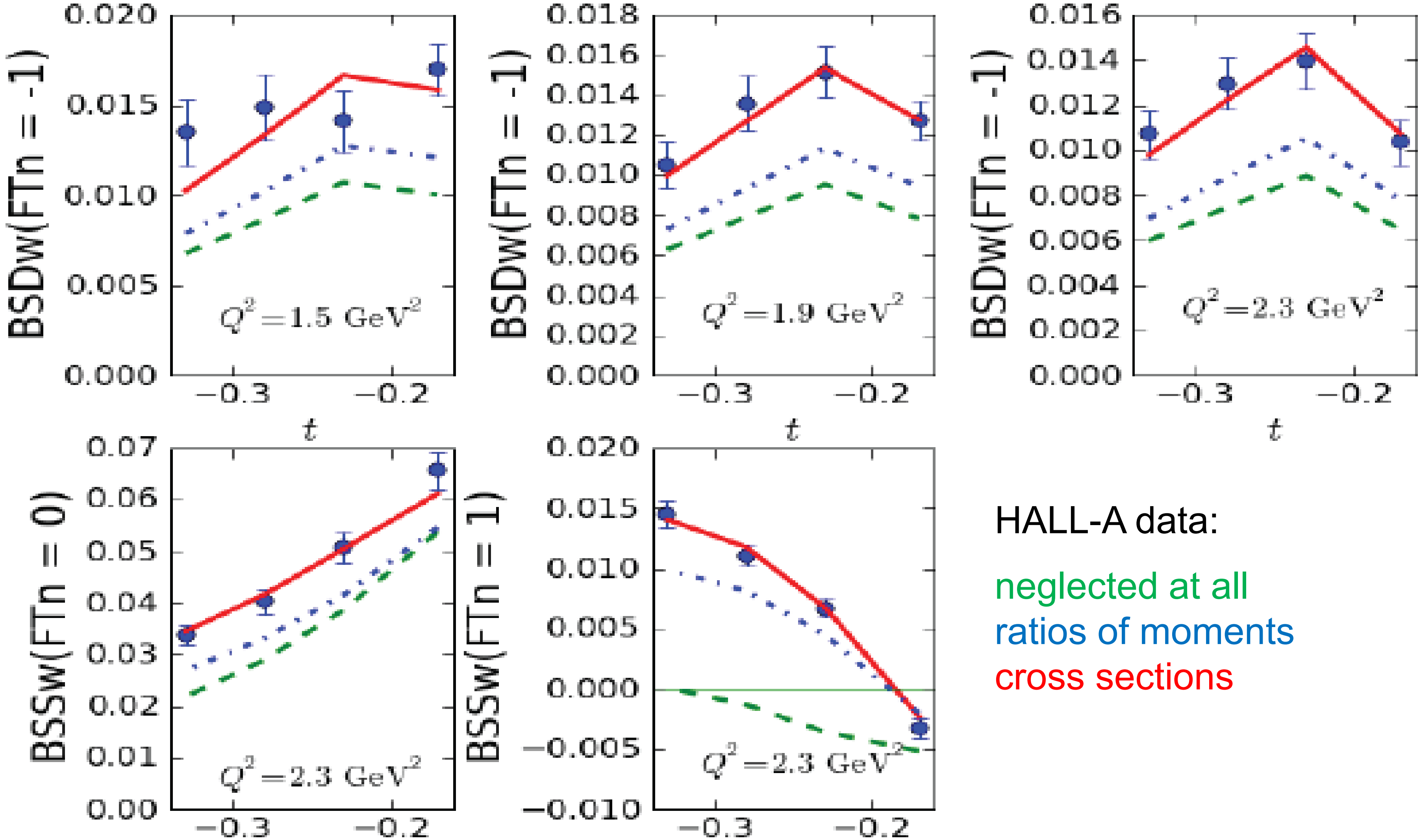
i. neglecting,
ii. ii. forming ratios of moments, or
iii. iii. original HALL-A data
neglecting large $-t$ BSA CLAS data

15 parameter fit, e.g.,
including all HALL-A data

175 data points
$\chi^2/d.o.f. = 132/165$

```
------------------------------
M02S  =  0.51  +-  0.02
SECS  =  0.28  +-  0.02
SECG  = -2.79  +-  0.12
THIS  = -0.13  +-  0.01
THIG  =  0.90  +-  0.05
  Mv  =  4.00  +-  3.33  (edge)
  rv  =  0.62  +-  0.06
  bv  =  0.40  +-  0.67
   C  =  8.78  +-  0.98
  MC  =  0.97  +-  0.11
 tMv  =  0.88  +-  0.24
 trv  =  7.76  +-  1.39
 tbv  =  2.05  +-  0.40
 rpi  =  3.54  +-  1.77
 Mpi  =  0.73  +-  0.37
----------------------------------
```

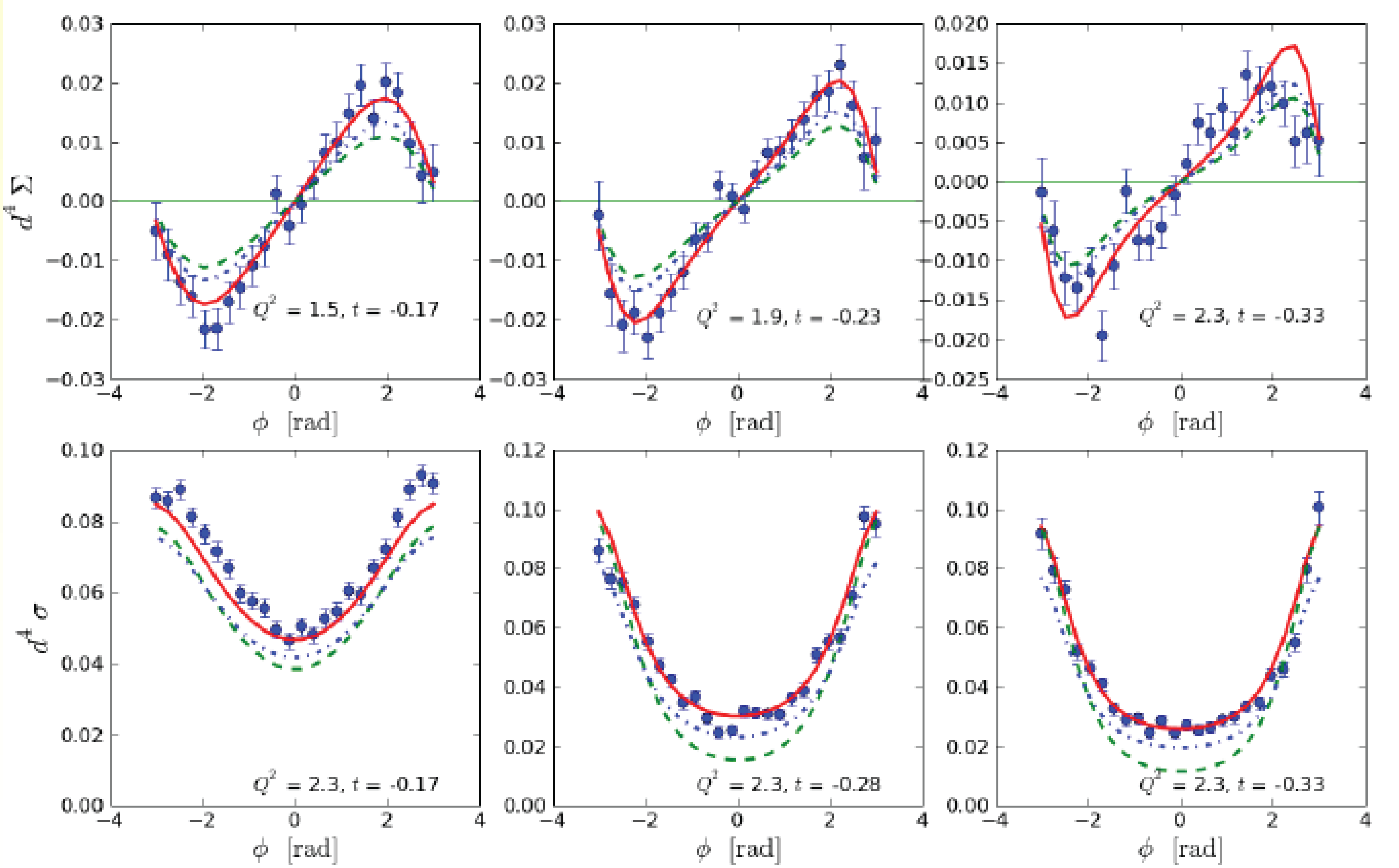
- results are given as **xs.exe** on ***http://calculon.phy.hr/gpd/***




- fits to HALL A harmonics are fine for unexpected large $\hat{H}$ or $\check{E}$ contribution
- large $\hat{H}$ KM09 scenario is excluded from longitudinal TSA (HERMES, CLAS)
- large pion pole scenario might look reasonable (cf. **[Goloskokov and Kroll (10)]** )

# HALL A  φ-dependence

- φ-dependence  is described (if we fit to it)



# DVCS perspectives

**existing data**

including longitudinal and transverse polarized proton data

**new data**

*HERMES*
*(recoil detector data)*

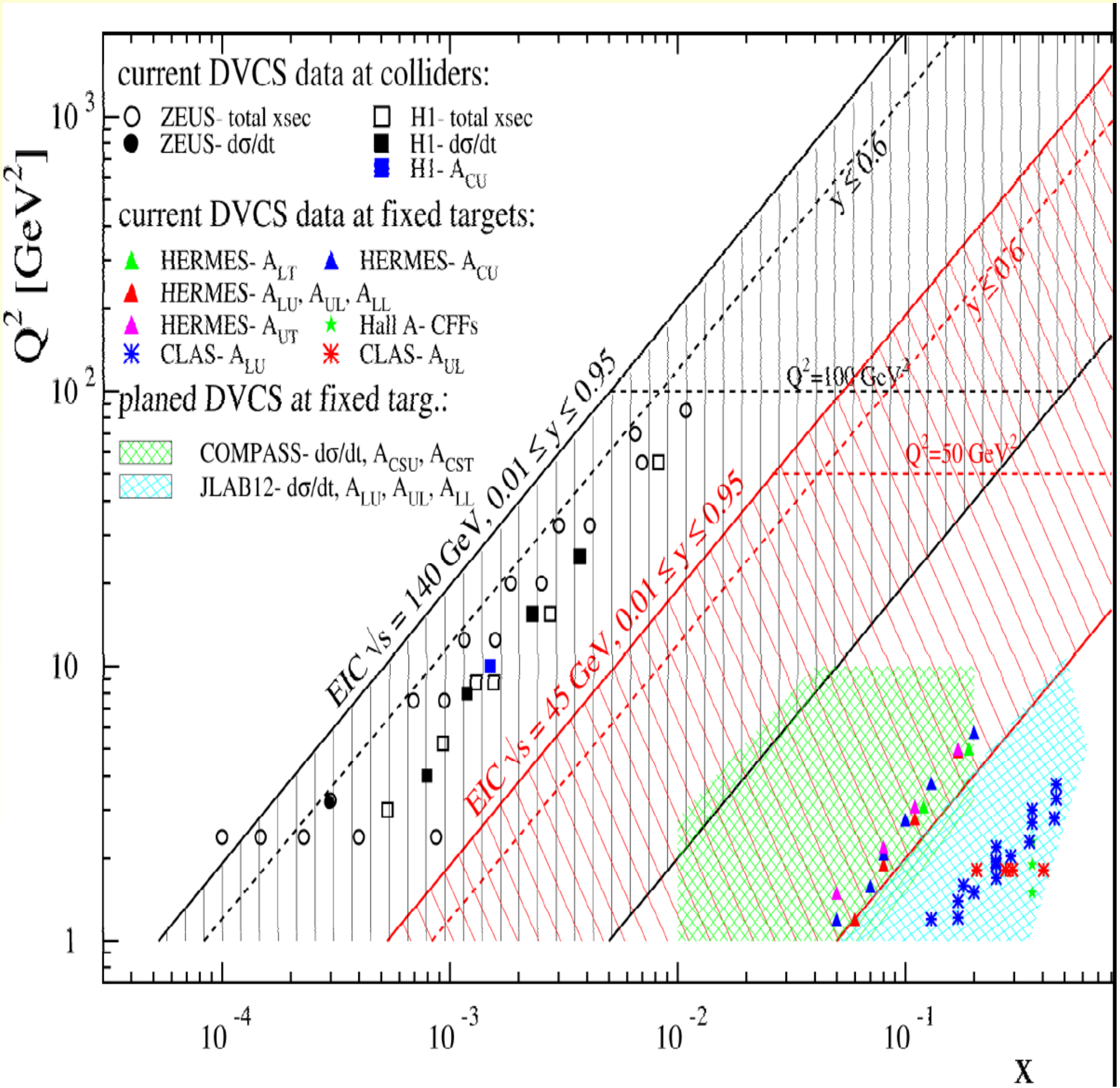
*JLAB*
*(longitudinal TSA, cross sections )*

**planned**

*COMPASS II, JLAB 12*

**proposed**

*EIC*



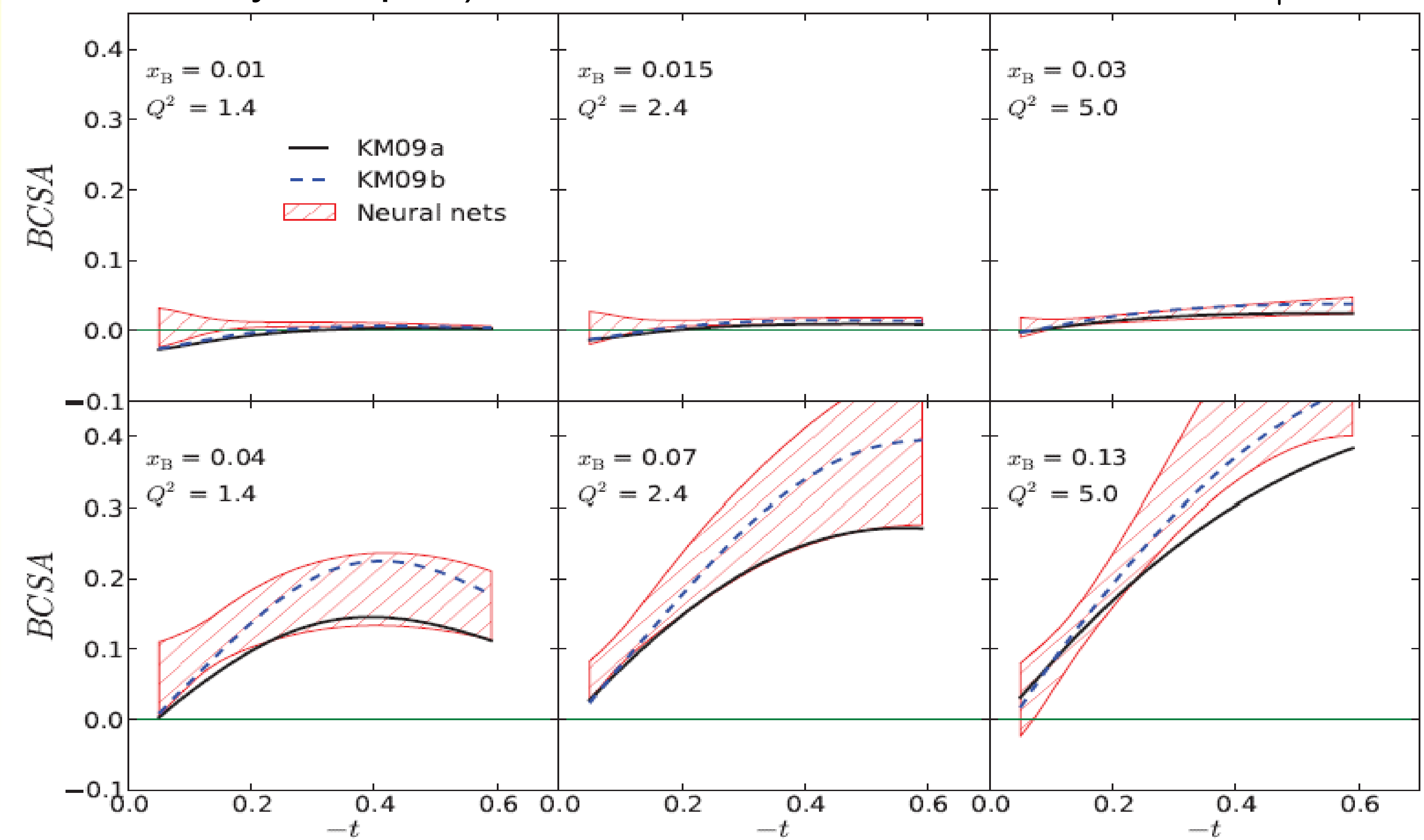
# Predictions for Compass II

fixed target, polarized muon beam (~200 GeV)

cross sections (t-dependence), transverse polarized target (access to E GPD)

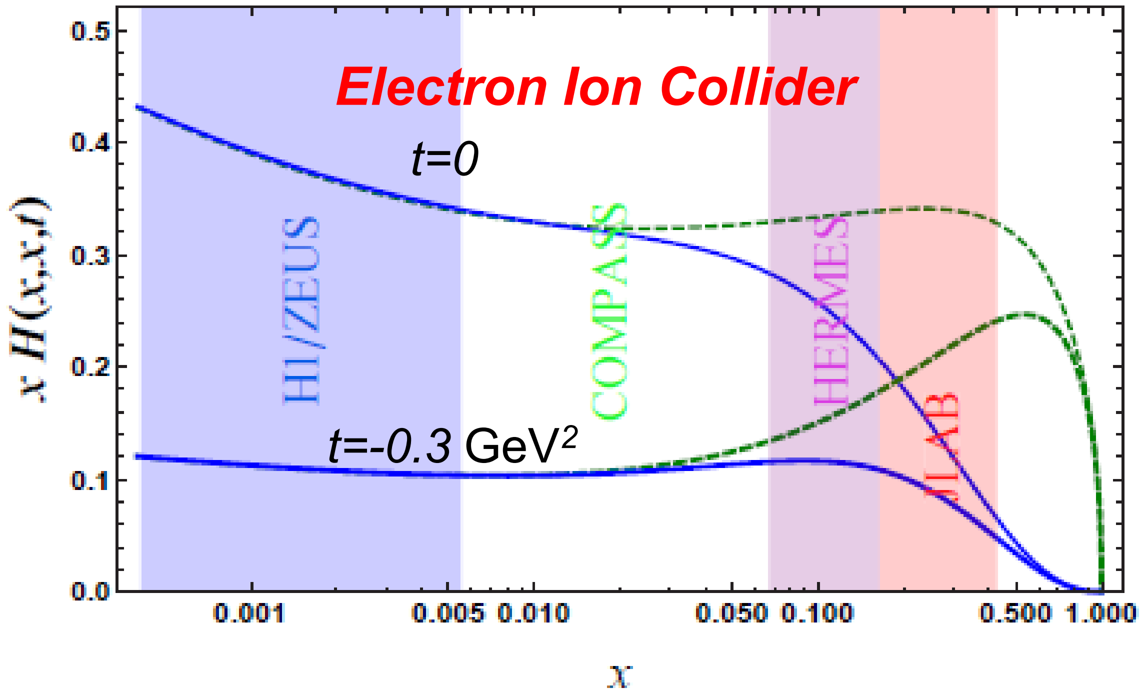
beam charge-spin asymmetry
(dominated by real part)

$$A_{\mathrm{BCSA}} = \frac{d\sigma^{\uparrow +} - d\sigma^{\downarrow -}}{d\sigma^{\uparrow +} + d\sigma^{\downarrow -}}$$



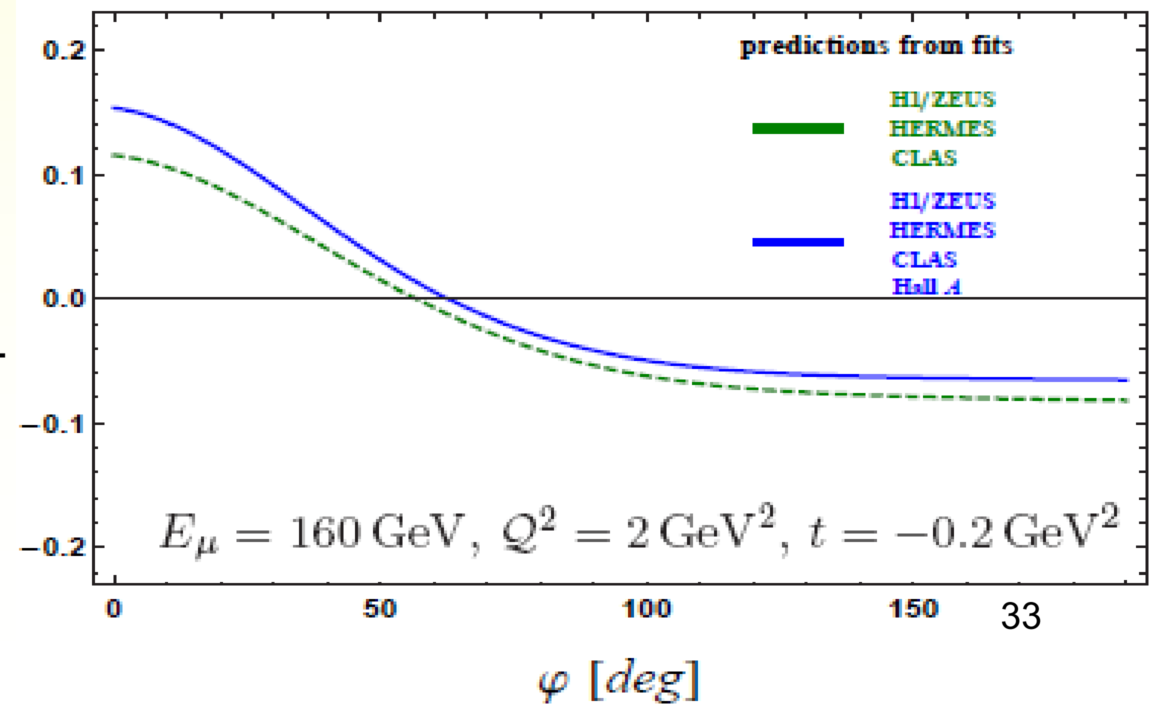
- extracting GPD from present collider and fixed target DVCS data

*H(x,x,t,Q²=2 GeV²)*




- prediction for COMPASS

$$A_{\rm BCSA} = \frac{d\sigma^{\uparrow +} - d\sigma^{\downarrow -}}{d\sigma^{\uparrow +} + d\sigma^{\downarrow -}}$$



# EIC potential for DVCS

to address angular momentum, 3D picture, (effective) nucleon wave function within the GPD framework new DVCS experiments with

*large kinematical coverage, high luminosity, and dedicated detectors are needed to quantify CFFs and GPDs on the cross-over line (and outer region)*

- disentangling CFFs at small(er) *x*
  cross sections
  beam spin, target spin, and double spin flip experiments

$$BSA \propto y\left\{F_1(t)H(\xi,\xi,t,\mathcal{Q}^2) - \frac{t}{4M^2}F_2E(\xi,\xi,t,\mathcal{Q}^2)\right\}$$

$$TSA_T \propto \frac{\sqrt{-t}}{4M^2}\left\{F_1(t)E(\xi,\xi,t,\mathcal{Q}^2) - F_2(t)H(\xi,\xi,t,\mathcal{Q}^2)\right\}$$

$$TSA_L \propto \left\{F_1(t)\widetilde{H}(\xi,\xi,t,\mathcal{Q}^2) + \xi(F_1+F_2)(t)H(\xi,\xi,t,\mathcal{Q}^2)\right\}$$

- off neutron another possibility to access GPD E
- separation of twist-2 and twist-3 induced harmonics requires positron beam
- time-like region (a new field to study)
- off nuclei (has its own interest)

# *Impact of EIC data to extract GPD H*

two simulations from S. Fazio for DVCS cross section ~ 650 data points

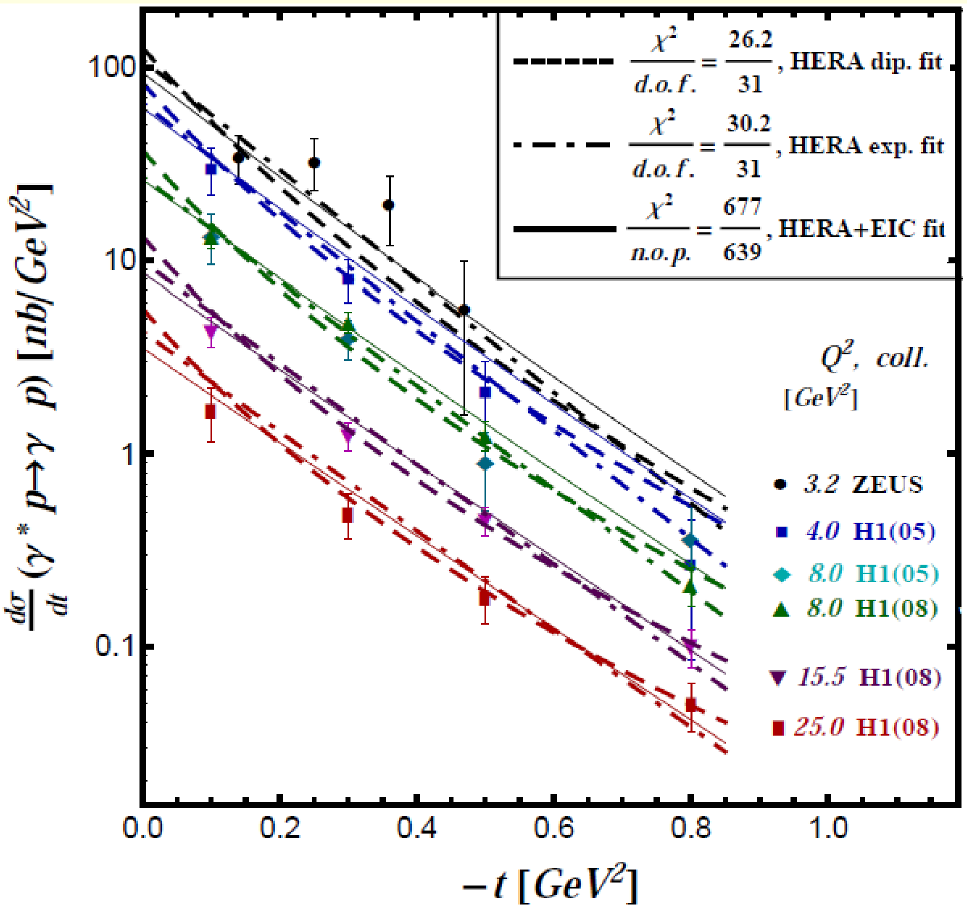
$-t <$ ~$0.8$ GeV$^2$ for ~ 10/fb

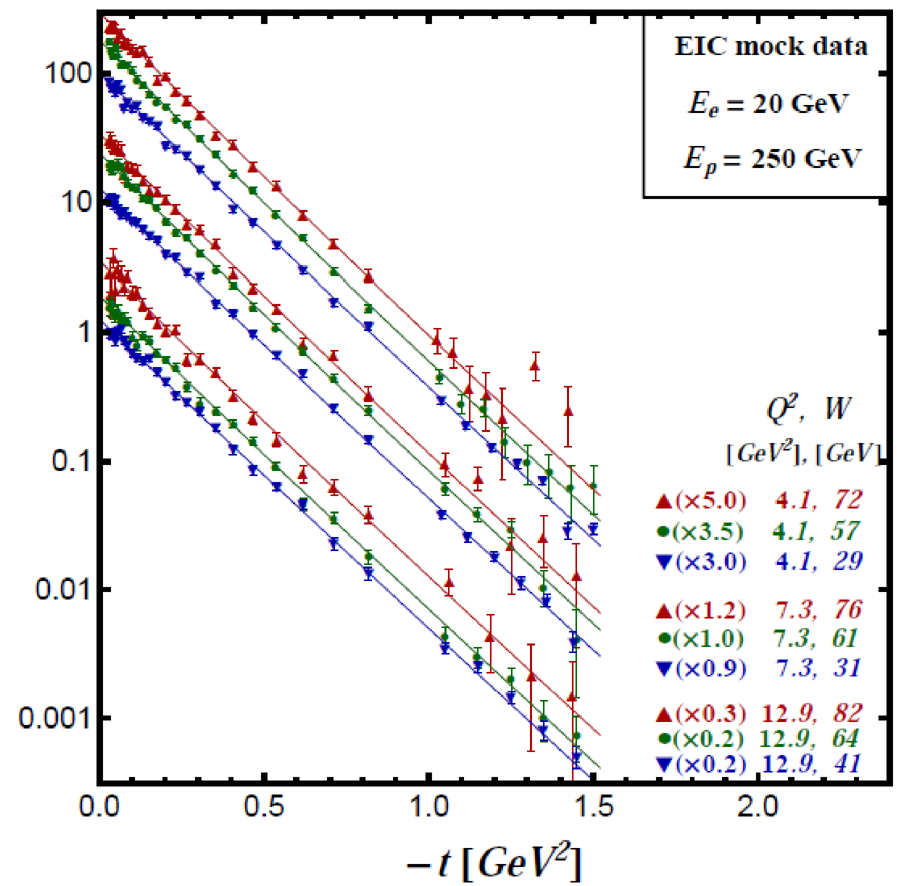
1 GeV$^2$ < $-t$ < $2$ GeV$^2$ for ~ 100/fb (cut: $-t$ < $1.5$ GeV$^2$ , $4$ GeV$^2$ < $Q2$ to ensure $-t < Q^2$)

mock data are re-generated with GeParD

statistical errors rescaled

5% systematical errors added in quadrature, 3% Bethe-Heitler uncertainty



# Imaging (probabilistic interpretation)

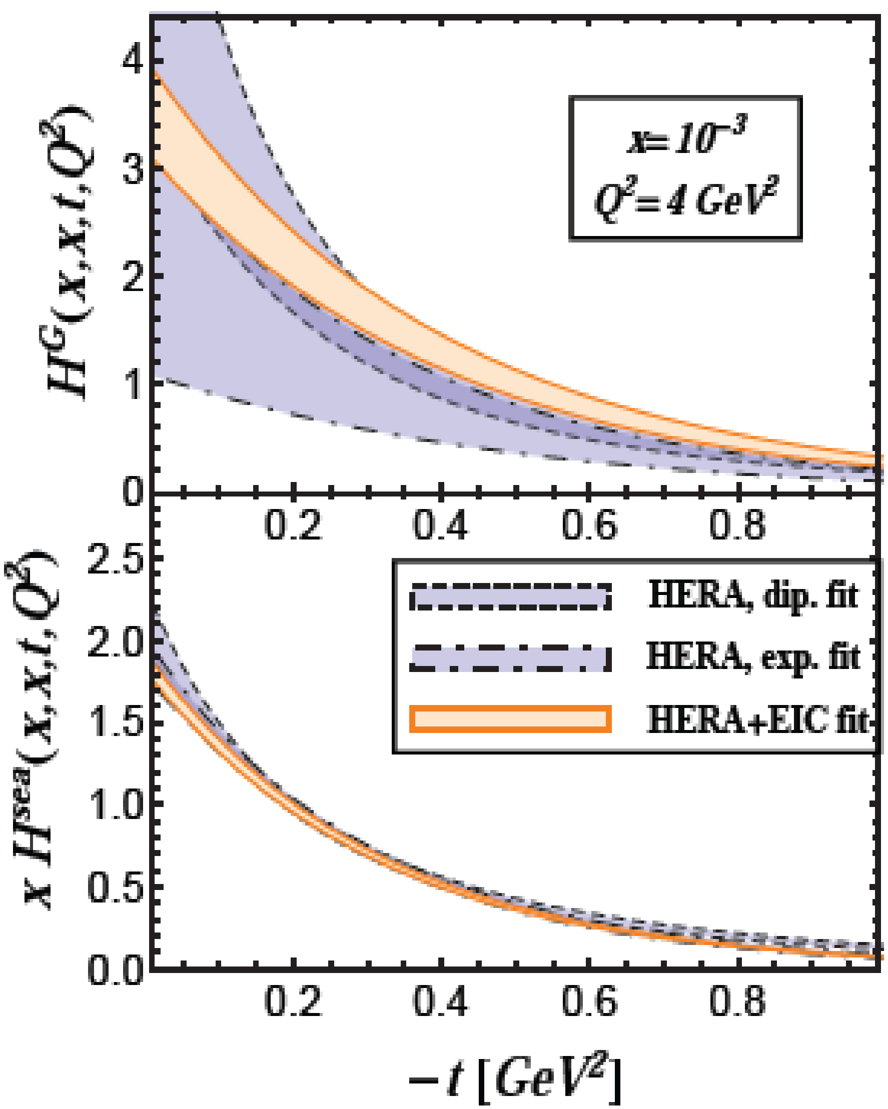
$$q(x,\vec{b},\mu^2) = \frac{1}{4\pi}\int_0^\infty d|t|\, J_0(|\vec{b}|\sqrt{|t|})H(x,\eta=0,t,\mu^2)$$

skewness effect vanishes ($s_2$ , $s_4 \to 0$)

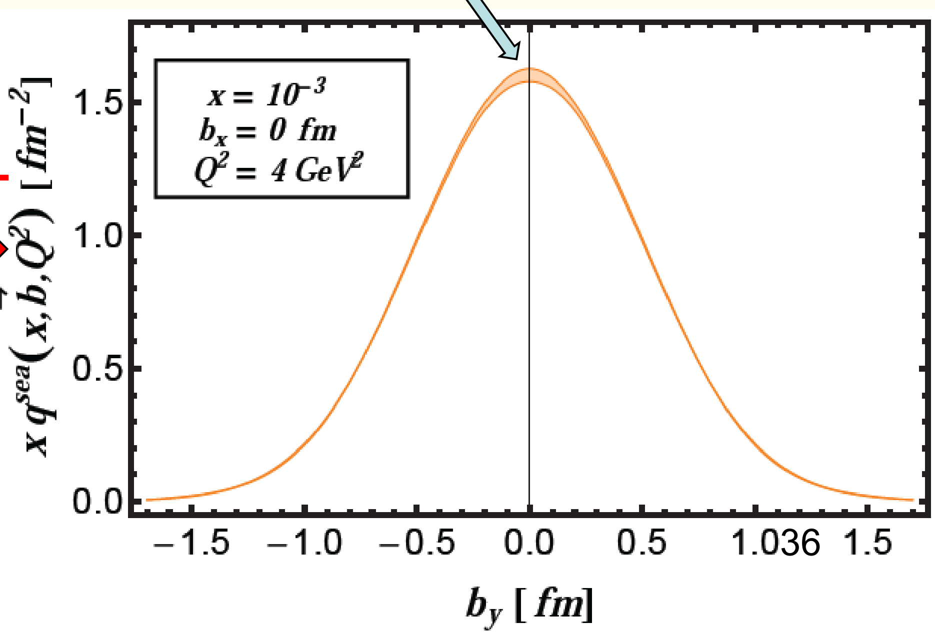
- reduce fit uncertainties
- increase model uncertainties

extrapolation errors for $-t \to 0$
(large b uncertainties – small effect)

extrapolation errors into $-t > 1.5$ GeV$^2$
(small b uncertainties)




FT



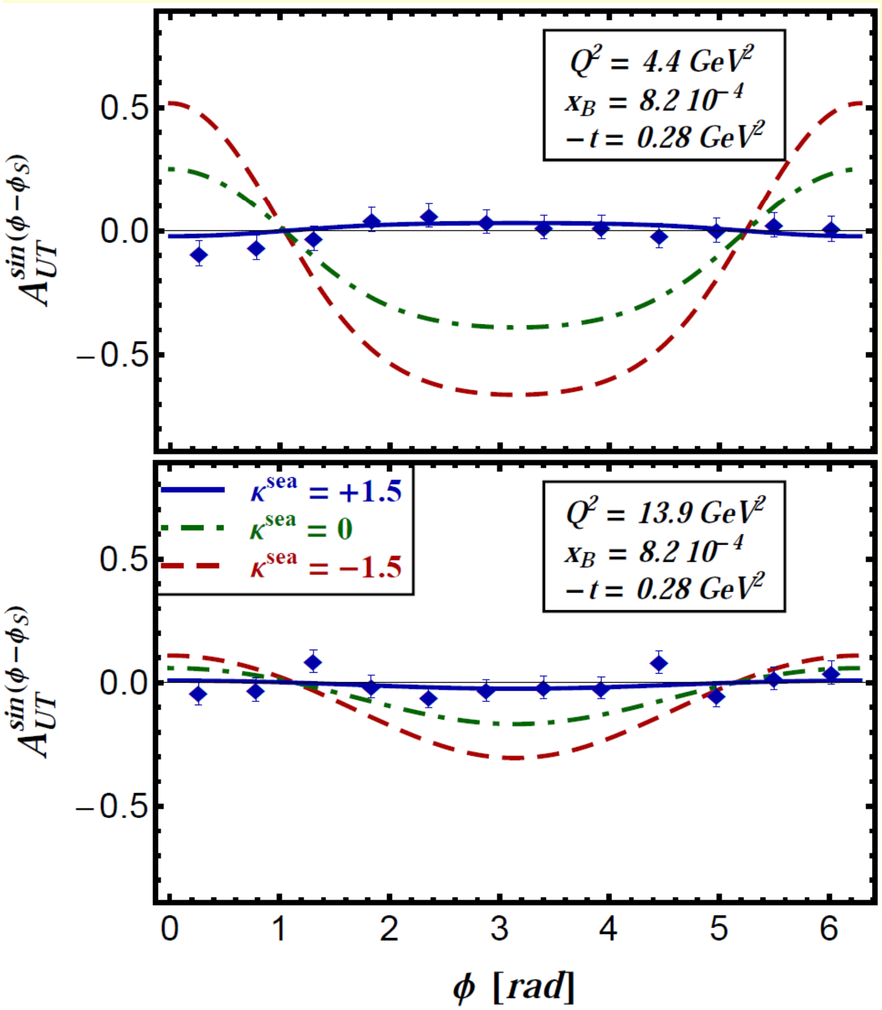
# *Single transverse target spin asymmetry*

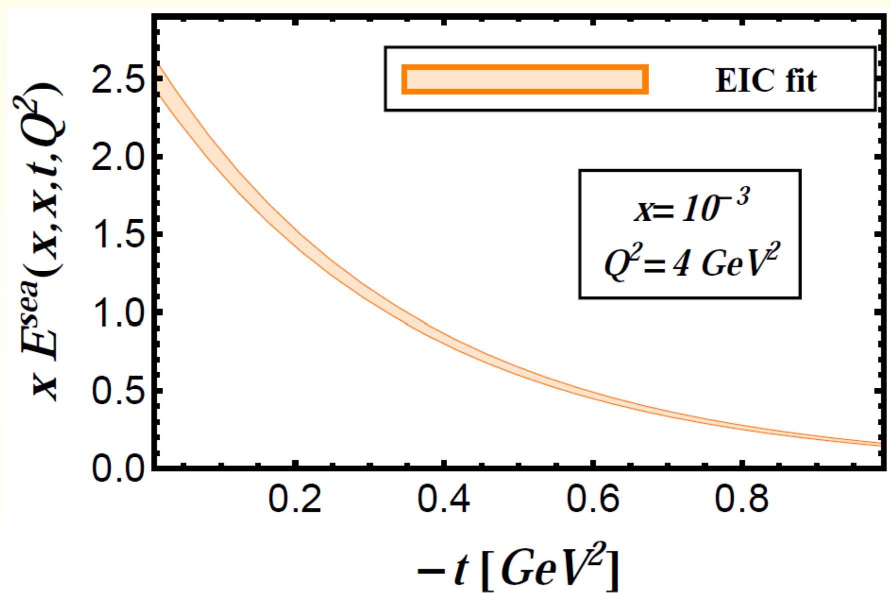
20x250  2x5/fb  mock data
(~1200 data points with statistical errors
+ 5% systematics at cross section level)

flexible GPD model for $E^{sea}$ and $E^{G}$

normalization (and $t$-dependency) of $E^{sea}$ is reasonable constraint

$E^{G}$ is essentially unconstraint




***also imaging of q↑ sea is possible***   **[see Franck`s talk]**

# Summary

## *GPDs are intricate and (thus) a promising tool*

- to reveal the transverse distribution of partons
- to address the spin content of the nucleon
- providing a bridge to LCWFs modeling & non-perturbative methods (lattice)

## *hard exclusive leptoproduction*

- DVCS is widely considered as a theoretical clean process
- it is elaborated in NLO and offers a new insight in QCD
- possesses a rich structure, allowing to access various CFFs/GPDs
- new experiments (high luminosity machines and dedicated detectors) are desired to quantify exclusive (and inclusive) QCD phenomena

## *technology*

software tools for global GPD fits have been developed for demonstration

? global QCD fits (inclusive + exclusive)