GPDs from present and future measurements

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- ***GPDs and perturbative framework***
- ***deeply virtual photon leptoproduction***
- ***GPD modeling and data descriptions***
- ***predictions for COMPASS and EIC***

in collaboration with K. Kumerički (DVCS)
two codes in Phyton (+ Minuit + GeParD) & Mathematica + GeParD
KMPassek-Kumerički hep-ph/0703179 and 0805.0152 [hep-ph]; **KM 0904.0458 [hep-ph]**

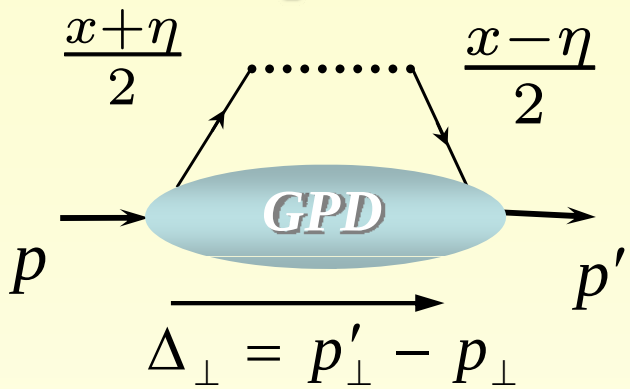
contribution to EIC white paper [M. Diehl, F. Sabatie]
with E. Aschenauer, S. Fazio, K. Kumerički

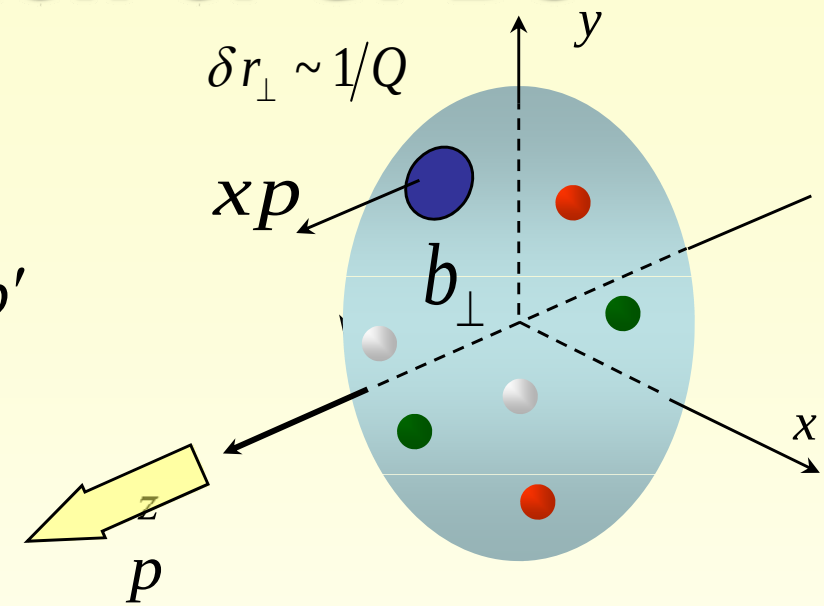
Partonic interpretation of GPDs

$$F(x,\eta,t,Q^2)$$

$$F \in \left\{H, E, \widetilde{H}, \widetilde{E}, \cdots\right\}$$

(intricate distributions)

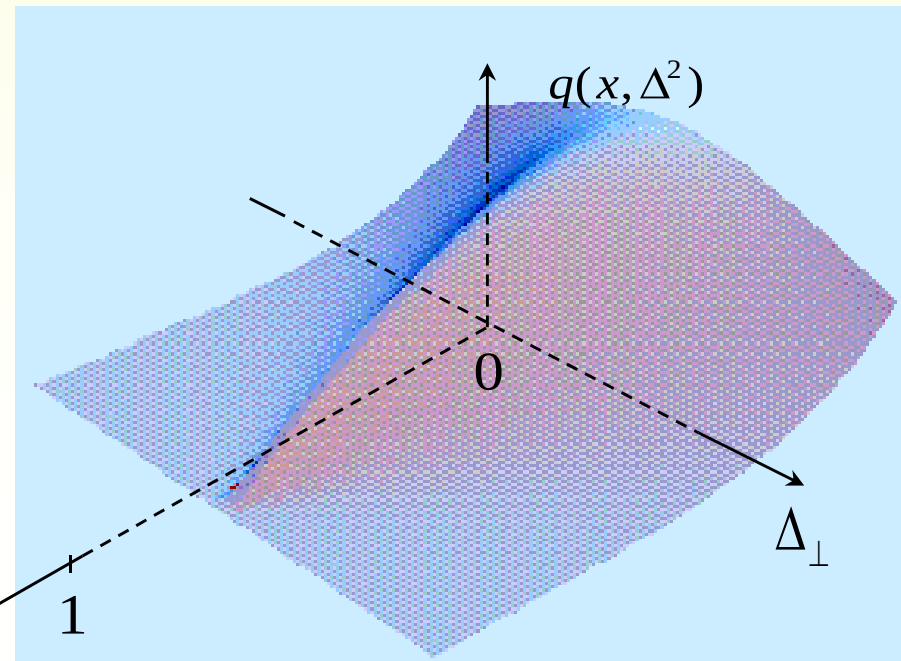




GPDs simultaneously carry information on longitudinal and transverse distributions of partons in a proton

probabilistic interpretation for $\eta=0$
(infinite momentum frame) **[Burkhardt (00)]**

$$b_\perp = \sqrt{4\frac{d}{dt}\ln H(x,0,t)}\Big|_{t=0}$$



GPDs contain also information on partonic angular momentum **[X. Ji (96)]**

$$\frac{1}{2} = \sum_{a=q,G} J_a^z$$

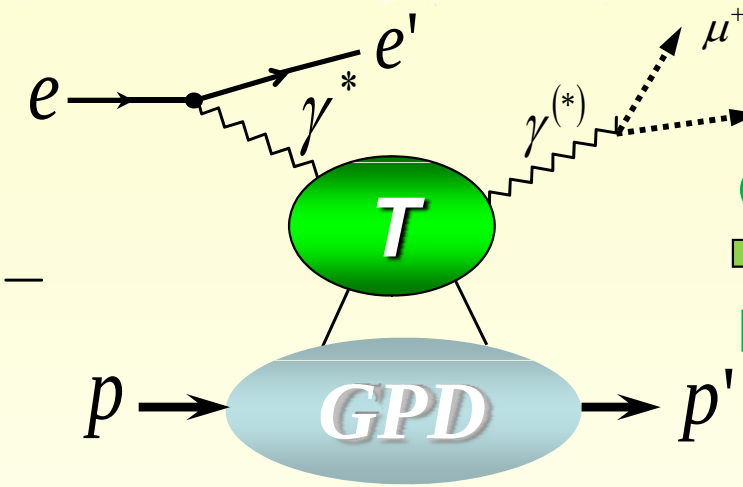
$$J_a^z = \lim_{\Delta\to 0}\frac{1}{2}\int_{-1}^{1} dx\, x\,(H_a + E_a)\,(x,\eta,\Delta^2)$$

GPD phenomenology

- Deeply virtual Compton scattering (clean probe)

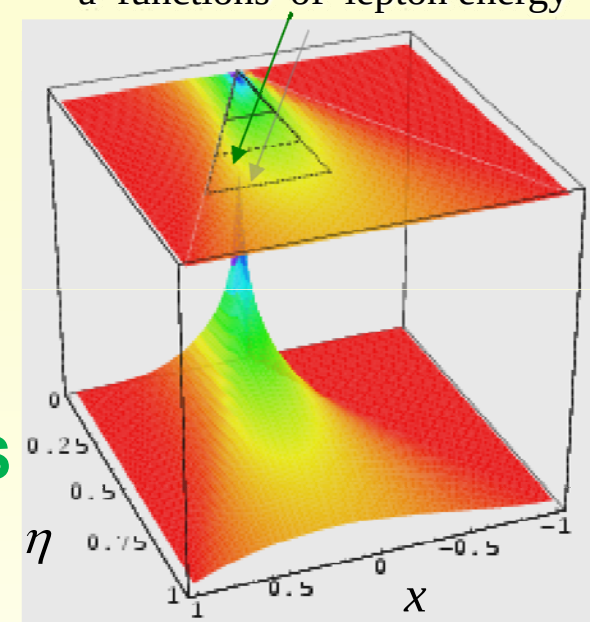
  (factorization holds)

$$ep \to e'p'\gamma$$
$$ep \to e'p'\mu^+\mu^-$$
$$\gamma p \to p'e^-e^+$$



GPD → DDVCS

scanned area of the surface as a functions of lepton energy

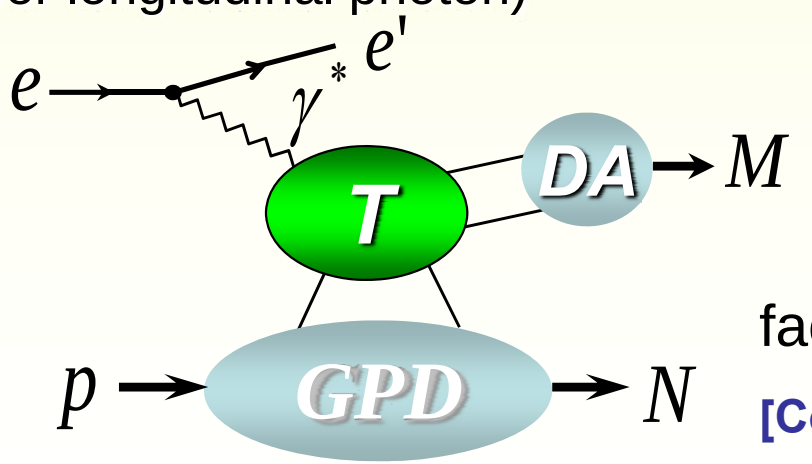


- Deeply virtual meson production (flavor filter)

  (factorization holds for longitudinal photon)

$$ep \to e'p'\rho$$
$$ep \to e'n\rho^+$$
$$ep \to e'p'\pi$$
$$ep \to e'n\pi^+$$

ect.



<u>twist-two observables:</u>

longitudinal cross sections

transverse target spin asymmetries

factorization proof

[Collins, Frankfurt, Strikman (96)]

- hand bag models for exclusive photo- and electro production

  ect.

Status of perturbative framework

The NLO framework has been essentially set up for some time:

[Belitsky, DM (98);
Belitsky, DM, Freund 01]

✓ ***next-to-leading*** order anomalous dimensions and evolution kernels

✓ ***next-to-leading*** order DVCS coefficients (twist-two) [Belitsky, DM (97);
Mankiewicz et. al (97);
Ji, Osborne (98)]

• even for time-like and double DVCS (just use prescription from [Belitsky, DM (03)])
[Wagner et. al (11)]
(talk of J. Wagner)

✓ ***next-to-next-to-leading*** order in a specific conformal subtraction scheme [KMP-K & Schaefer 06]

✓ ***twist-three*** DVCS coefficients at leading order [Anikin,Teryaev, Pire (00);
Belitsky DM (00); Kivel et. al]
(off-forward LO evolution is known)

✓ partial ***twist-three*** DVCS coefficients at ***next-to-leading*** order [Kivel, Mankiewicz (03)]

✓ ***twist-four*** for DVCS [Braun, Manashov (11)] and a previous study [Belitsky, DM (01)]

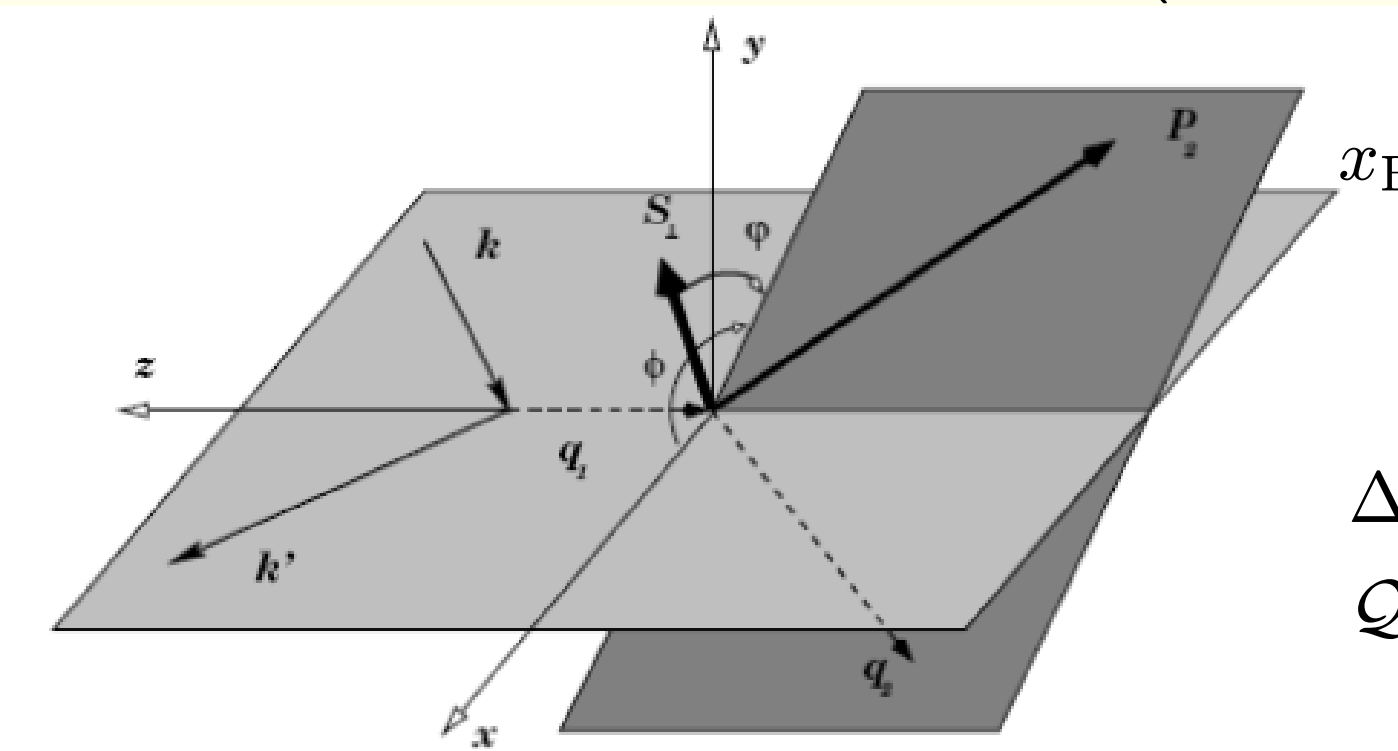
✓ ***next-to-leading*** DVMP coefficients (non-singlet) [Belitsky, DM (01)]
(singlet) [Ivanov, Szymanowski, Krasnikov (04)]

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

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

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

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



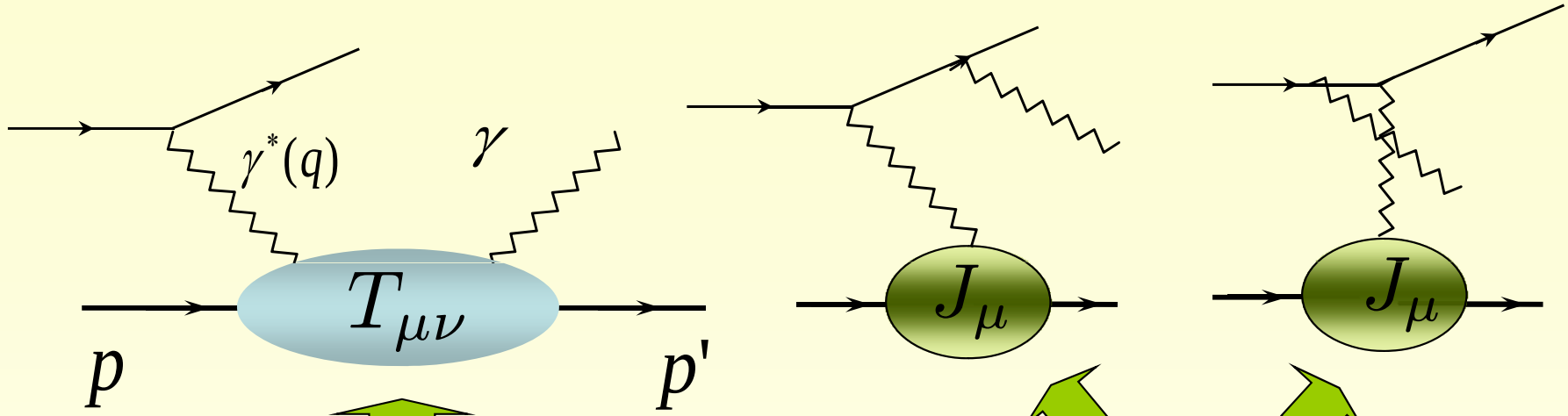
$$x_{\rm Bj} = \frac{\mathcal{Q}^2}{2P_1\cdot q_1} \approx \frac{2\xi}{1+\xi},$$

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

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

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

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



12 Compton form factors $\mathcal{F} \in \left\{\mathcal{H}, \mathcal{E}, \widetilde{\mathcal{H}} \cdots\right\}$ elastic form factors F_1, F_2

or 12 helicity amplitudes

exactly known

$$|\mathcal{T}_{\rm BH}|^2 = \frac{e^6(1+\epsilon^2)^{-2}}{x_{\rm Bj}^2 y^2 t\, \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{\rm BH} + \sum_{n=1}^{2} c_n^{\rm BH} \cos(n\phi) \right\} (F_1, F_2),$$ (LO, QED)

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

$$\mathcal{I} = \frac{\pm e^6}{x_{\rm Bj} y^3 t \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{\mathcal{I}} + \sum_{n=1}^{3} \left[c_n^{\mathcal{I}} \cos(n\phi) + s_n^{\mathcal{I}} \sin(n\phi) \right] \right\} (F_1, F_2, \mathcal{F}).$$

Can one `measure' GPDs?

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

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

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

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

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

- ***CFFs*** satisfy `**dispersion relations**'
  (not the physical ones, threshold ξ_0 set to 1)

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

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

[Terayev (05)]

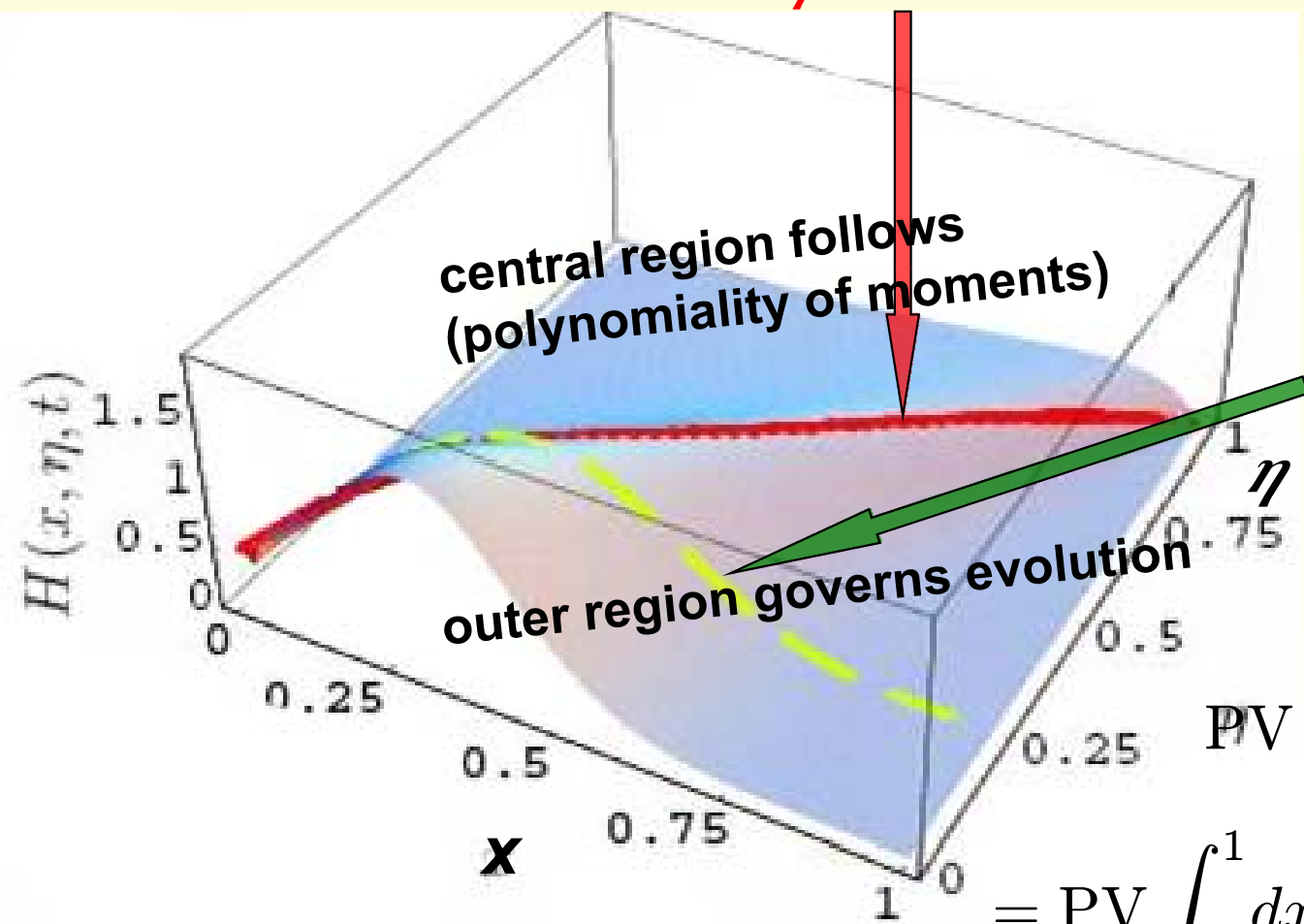
⇒ ***access*** to the ***GPD*** on the **cross-over line** $\eta = x$ (at LO)

GPD 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:

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

$$= \mathrm{PV}\int_0^1 dx\, \frac{2x}{\eta^2 - x^2} H^-(x,x,t) + {}_8C(t)$$

GPD models for valence quarks (using dispersion relation)

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

fixed: *PDF normalization* *eff. Reage trajectory* *large t-counting rules*

$$n = 1.35, \quad \alpha(t) = 0.43 + 0.85t/\mathrm{GeV}^2, \qquad p = 1$$

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

free: *r-ratio at small x* *large x-behavior* *monopole mass*

flexible subtraction constant
(*D*-term content of GPD *H* and *E*)

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

contains pion-pole contribution

Model based on SL(2,R) and SO(3) PWE

- SL(2,R) GPD moments: $F_j(\eta,t) = \sum_{J=J^{\min}}^{j+1} f_j^J(t)\,\eta^{j+1-J}\,\hat{d}_J(\eta)$

  partial wave amplitudes depending on j and J — *reduced Wigner rotation matrices*

- taking 2 better 3 SO(3) PWs:
  (two parameters s_2 and s_4)

$$f_j^{j-1}(t) = s_2 f_j^{j+1}(t)\,,$$
$$f_j^{j-3}(t) = s_4 f_j^{j+1}(t)\,,$$

- resulting CFF easy to handle:

$$\mathcal{F} = \frac{1}{2i}\sum_{\substack{k=0\\ \text{even}}}^{4}\int_{c-i\infty}^{c+i\infty} dj\,\xi^{-j-1}\frac{2^{j+1+k}\Gamma(5/2+j+k)}{\Gamma(3/2)\Gamma(3+j+k)}\left(i-\frac{\cos(\pi j)\mp 1}{\sin(\pi j)}\right)$$
$$\times s_k E_{j+k}(\mathcal{Q}^2) f_j^{j+1}(t)\hat{d}_j(\xi), \quad s_0 = 1$$

- zero-skewness GPD: $h_j^{j+1} = q_j \frac{j+1-\alpha(0)}{j+1-\alpha(0)-\alpha' t}\left(1-\frac{t}{M_j^2}\right)^{-p}$

  PDF — *`pomeron intercept' (biuld in PDF) + Regge slope* — *residual t dependence*

2x(2, 3, or 4) parameters:

***s_2, s_4, M or b*, (perhaps α')**

DVCS measurements & perspectives

existing data

including longitudinal and transverse polarized proton data

new data

HERMES
(recoil detector data)

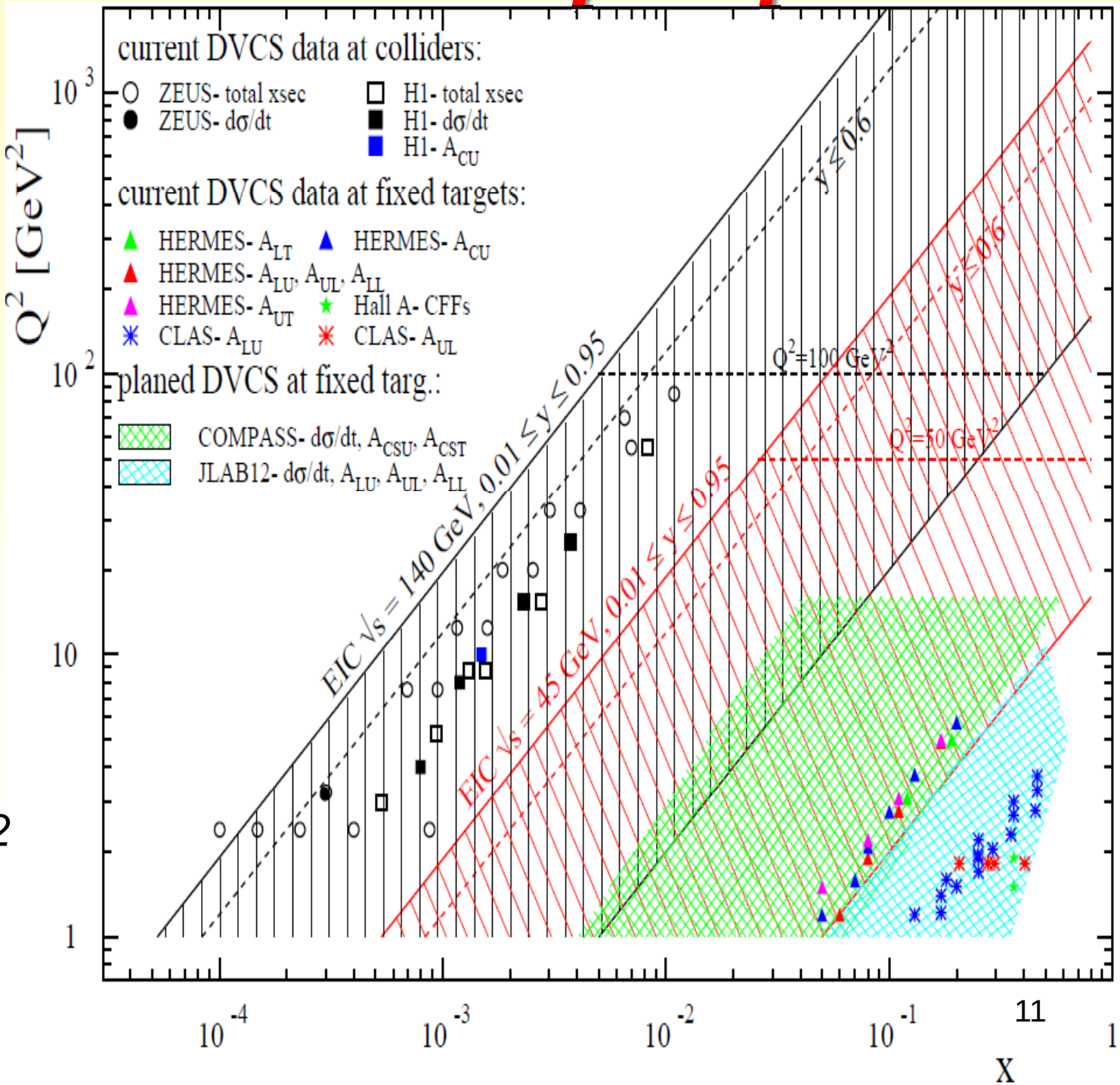
JLAB
(longitudinal TSA, cross sections)

planned

COMPASS II, JLAB 12

proposed

EIC



Strategies to analyze DVCS data

(ad hoc) modeling: **VGG** code [**Goeke et. al (01)** based on **Radyuskin's** DDA]
(first decade) BMK model [**Belitsky, DM, Kirchner, (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)]…**
[Goldstein et. al (10)] (without sea, polynomiality issue)

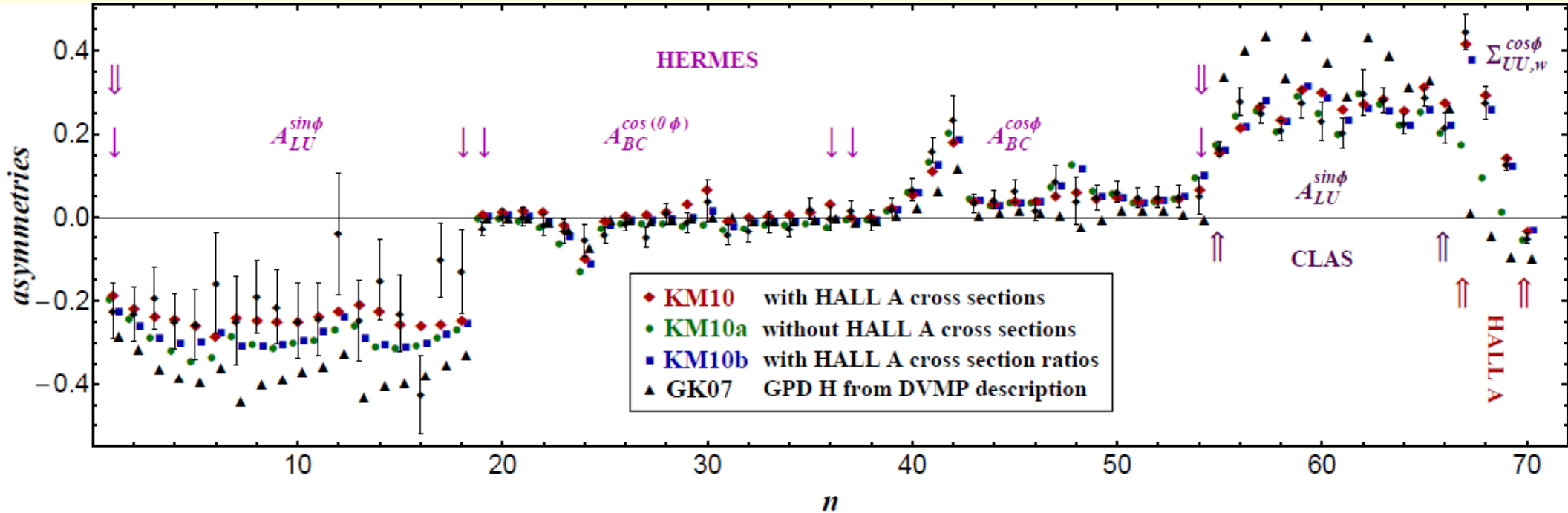
flexible models: any representation by including ***unconstrained*** degrees of freedom
(for fits) **KMP-K (07/08)** for H1/ZEUS in MBs-integral-representation

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)]**
ii. `dispersion integral' fits **[KMP-K (08),KM (08...)]**
iii. flexible GPD modeling **[KM (08...)]**
vi. model comparisons **[KM (11...)]: Goloskokov/Kroll (07) model** based on RDDA

Global fits with hybrid models KM10...

- 150-200 unpolarized proton data from CLAS, HALL A, HERMES, H1 & ZEUS (projected on twist-two dominated observables)
- fitted with hybrid models (`dispersion relation' + flexible sea quark/gluon models) (good fits with χ^2/d.o.f. $\approx$ 1)



- good description of small x_B data from H1 and ZEUS

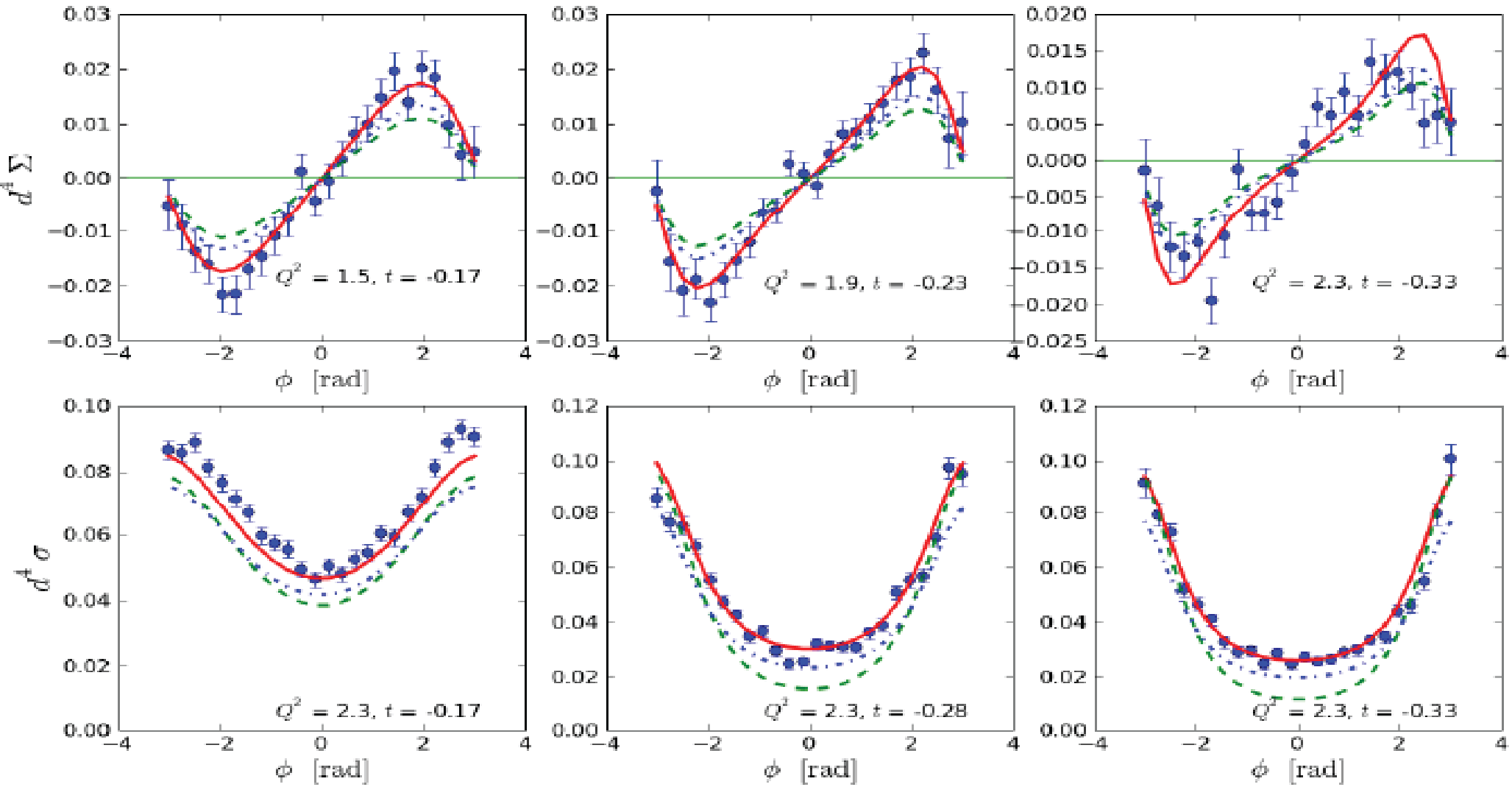
see talk of M. Murray

- KM10... cross sections are published as code ***http://calculon.phy.hr/gpd/***
- GK07 model from DVMP hand-bag description overshoots A_{LU} **[Goloskokov, Kroll (07)]** (typical for RDDA prediction like VGG of BMK01 models)

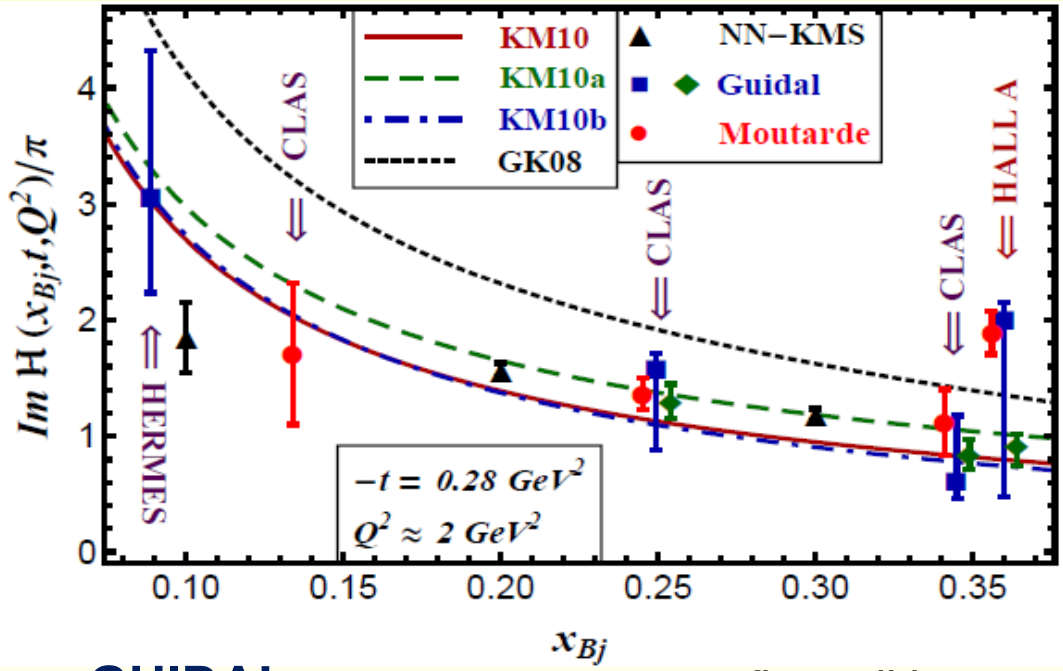
HALL A electroproduction cross sections

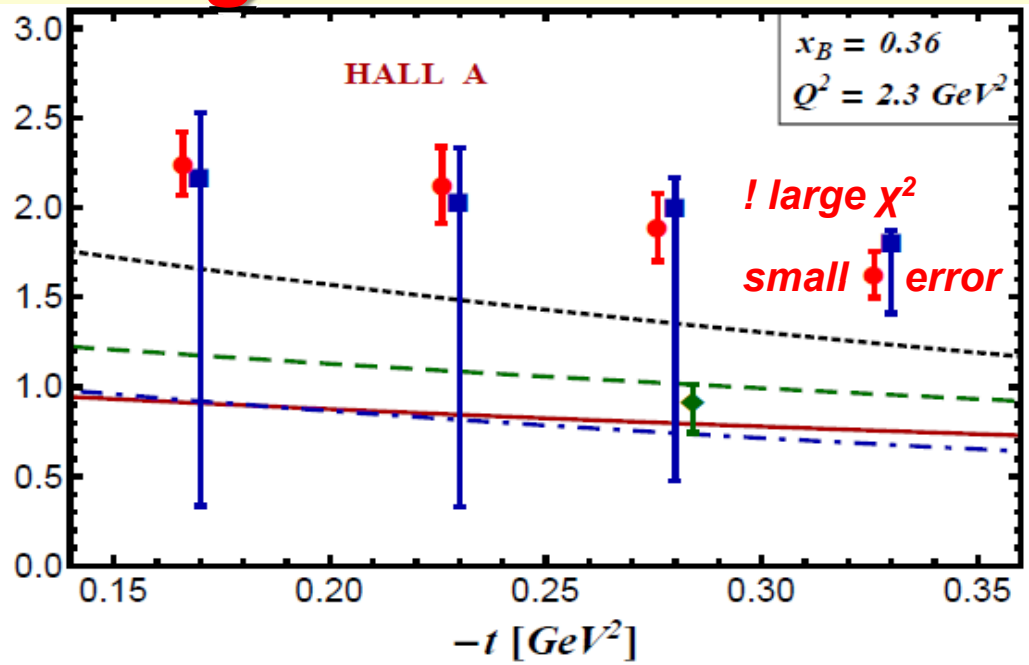
Φ description of unpolarized cross section @ x_B=*0.36* requires:

- large DVCS amplitude (model independent statement)
- KM10 model with large $\hat{H}$ and/or $\hat{E}$ (pion pole) induce a large DVCS amplitude (poor man approach: an effective parameterization which has not to be taken literally)



KM10... versus CFF fits & large-x "model" fit





GUIDAL 7 parameter CFF fit to all harmonics with twist-two dominance hypothesis
propagated errors + "theoretical" error estimate

GUIDAL same + longitudinal TSA

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

KMS neural network within H dominance hypothesis

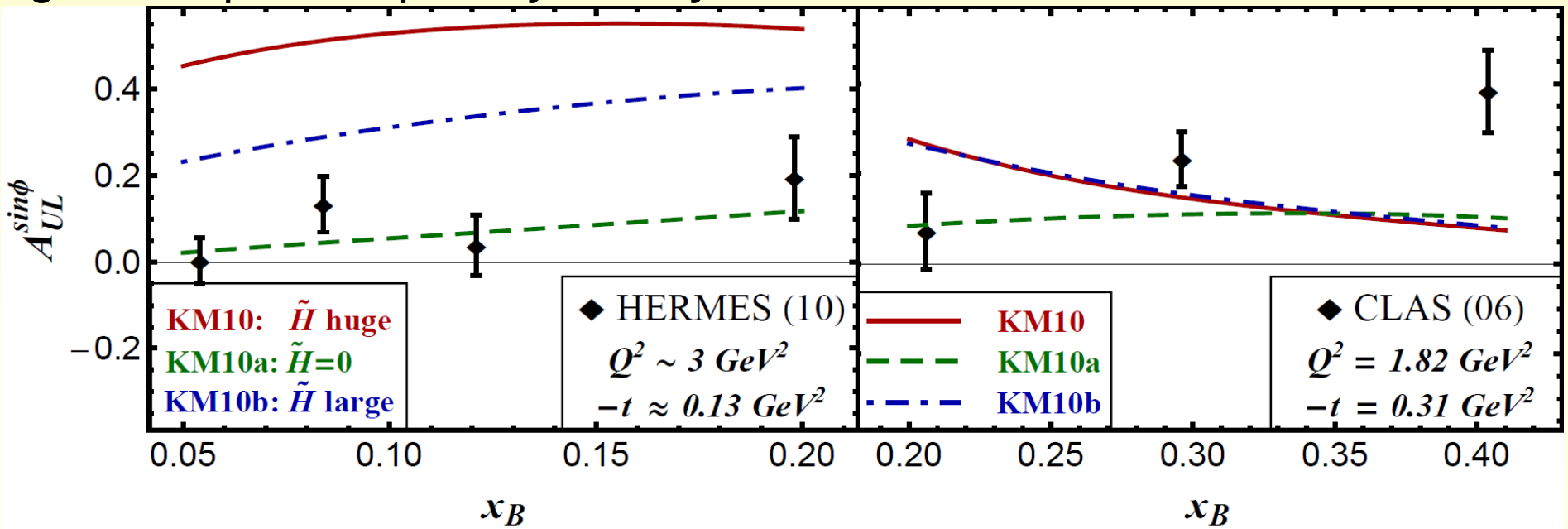
KM10 (KM10a) [KM10b] curves with (without) [ratios of] HALL A data

GK07 model based on RDDA pinned down by DVMP data via handbag approach

- reasonable agreement for HERMES and CLAS kinematics
- large x_B-region and real part remains unsettled

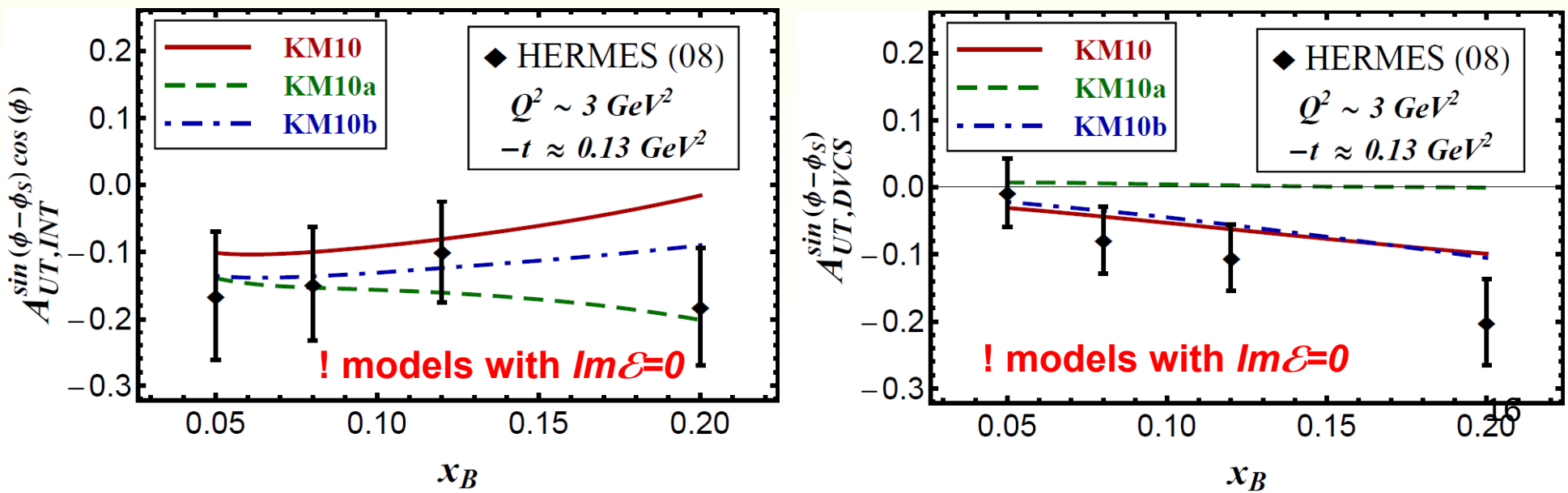
What about other CFFs (from fixed target)?

longitudinal proton spin asymmetry is sensitive to GPD $\hat{H}$



transverse proton spin asymmetry is sensitive to GPD E, however:

(beam charge flip allows to disentangles interference and DVCS terms)



Predictions for COMPASS II

[K. Kumerički,DM, A. Schäfer (11)]

fixed target, polarized muon beam (~200 GeV)

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

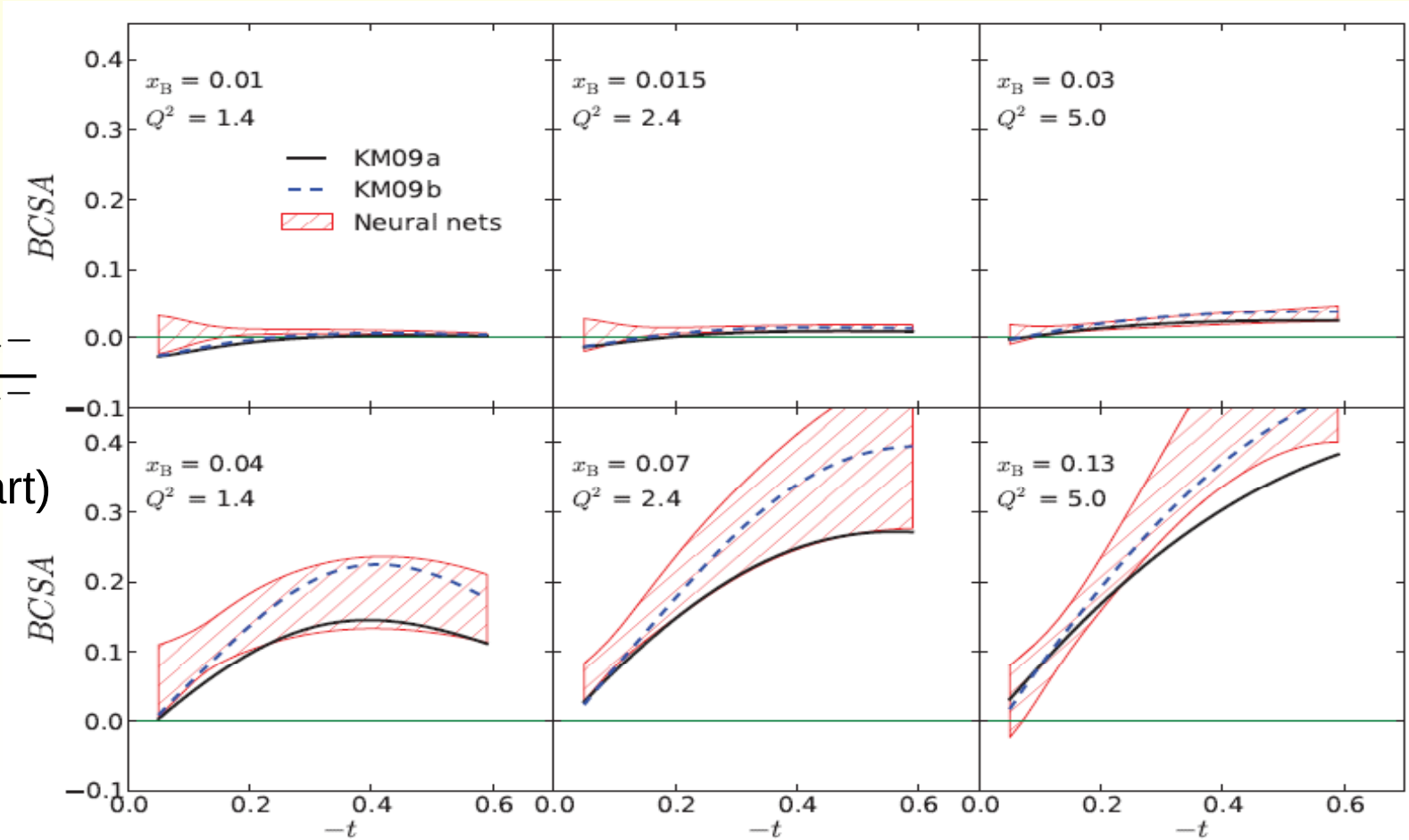
NN (ideal) tool for error propagation and quantifying model uncertainties

- used to access real and imaginary part of $\mathcal{H}$ CFF from HERMES
- results are compatible with dispersion relation fits

Beam Charge-Spin Asymmetry @ COMPASS II

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

(dominated by real part)



DVCS+DVMP fits to H1/ZEUS data

[M. Meškauskas, DM arXiv:1112.2597]

strategies: pure DVCS fit χ^2/d.o.f. = 130/(126-3)

DVCS + H1 DVMP fit χ^2/d.o.f. = 342/(230-6)

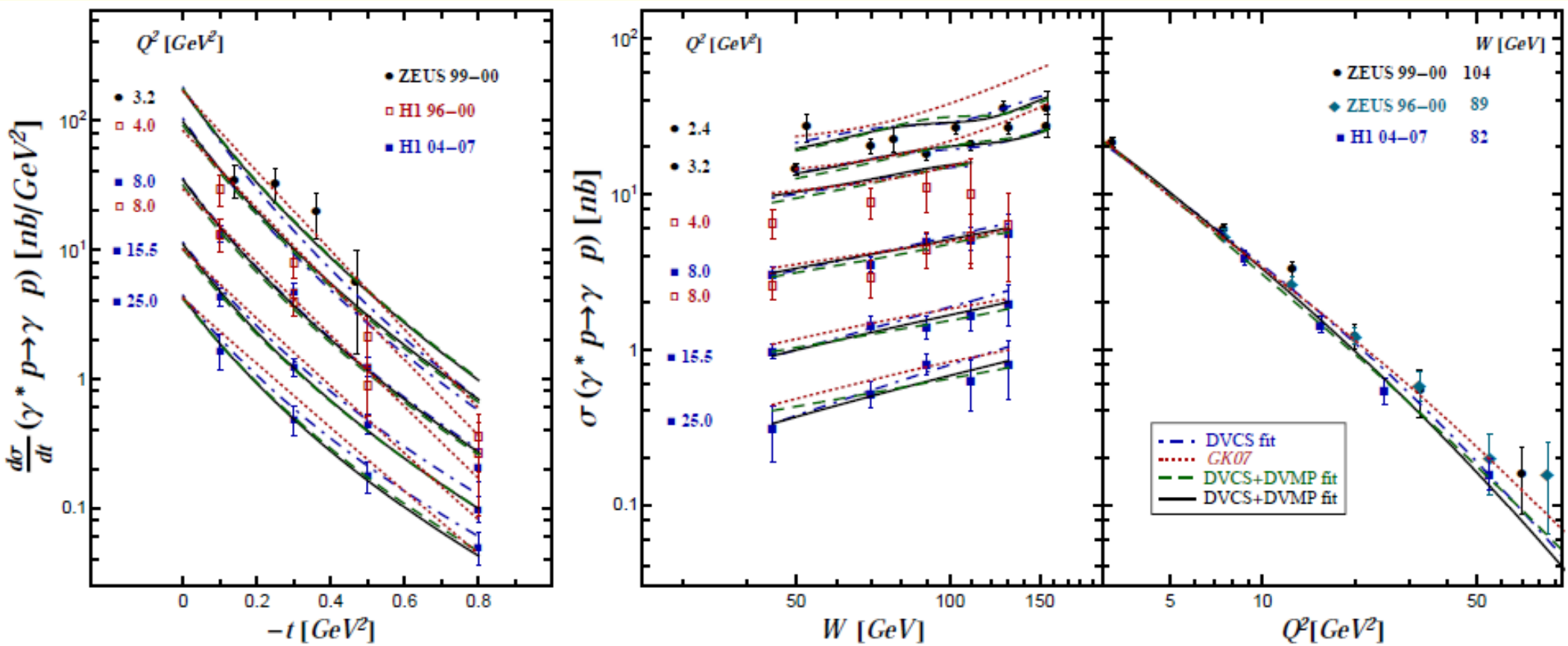
DVCS + H1/ZEUS DVMP fit -very soft gluon χ^2/d.o.f. = 618/(304-7)

confronting GK07 model with DVCS (χ^2/n.o.p. = 226/126)

R and normalization errors are not taken into account, cut $Q^2 > 4$ GeV^2 for DVMP data

DVCS data dominated by quark GPD

gluon GPD is to some extend not pinned down

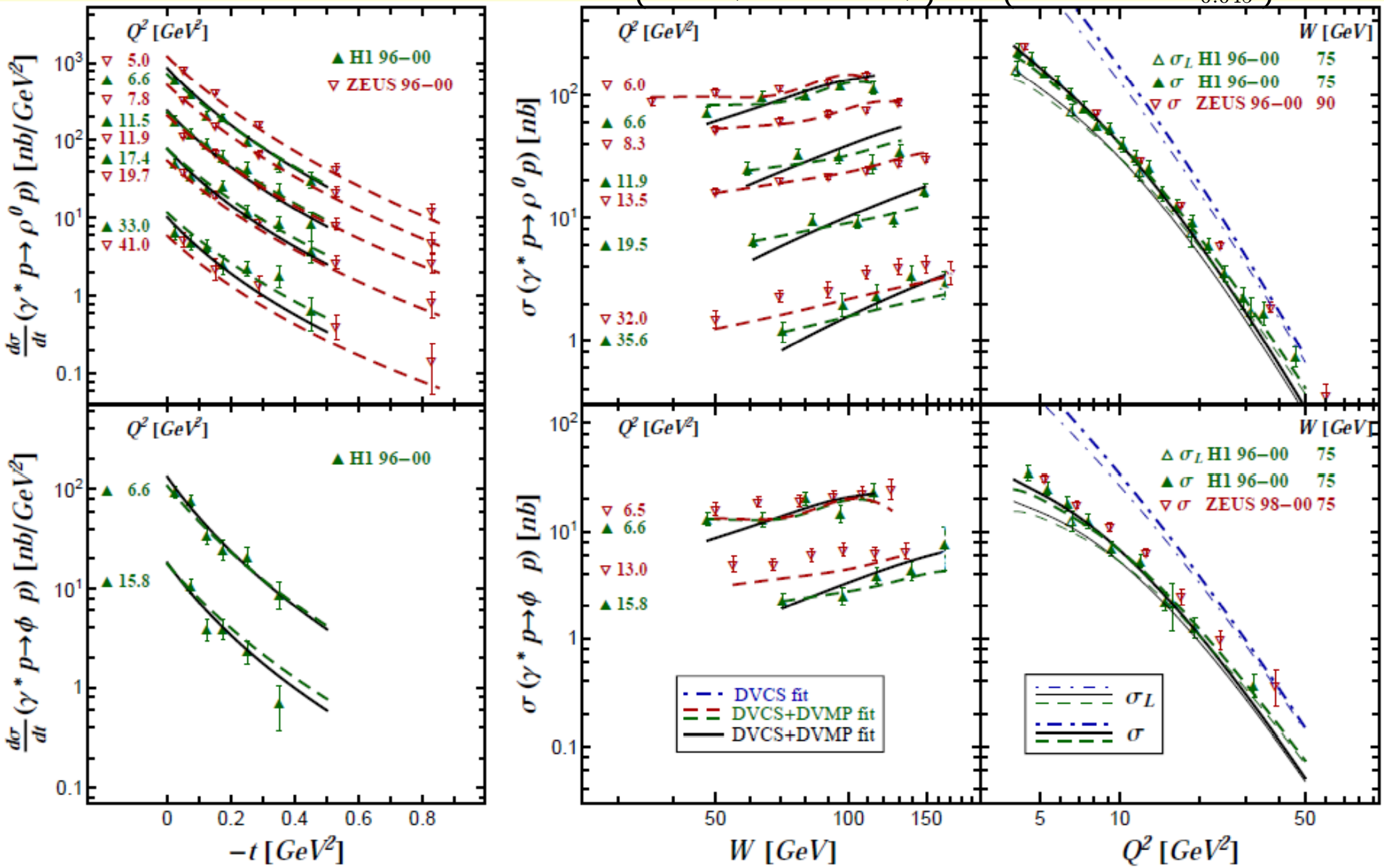


H1 and ZEUS DVMP data

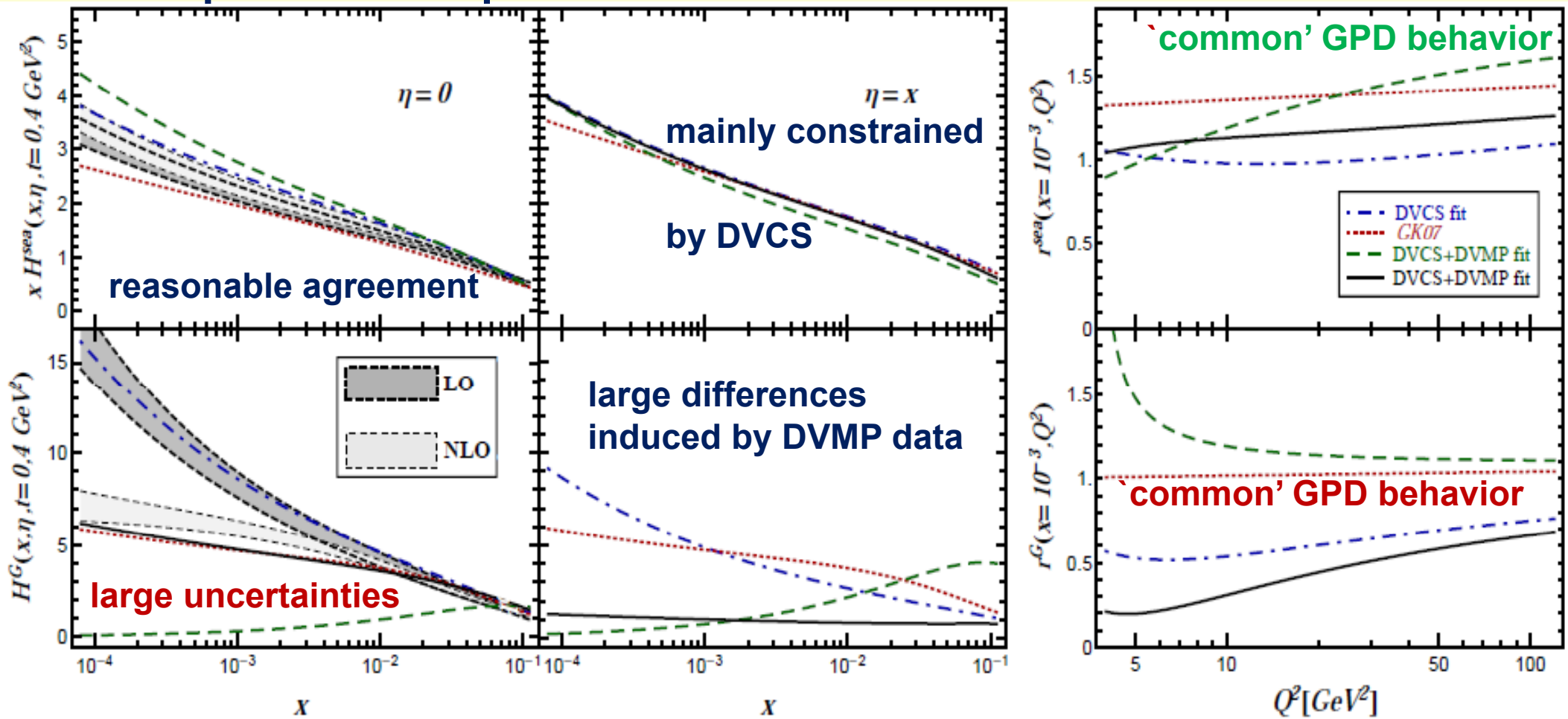
are compatible
however, there are differences

$$\left\{\begin{array}{l} b^{\rm H1}(\mathcal{Q}^2=11.5\,{\rm GeV}^2) \\ b^{\rm ZEUS}(\mathcal{Q}^2=11\,{\rm GeV}^2) \end{array}\right\} = \left\{\begin{array}{l} 6.72 \pm 0.53 \;^{+0.23}_{-0.25} \\ 5.7 \;\; \pm 0.5 \;\; ^{+0.2}_{-0.2} \end{array}\right\} /{\rm GeV}^2 \,,$$

$$\left\{\begin{array}{l} \delta^{\rm H1}(\mathcal{Q}^2=6.6\,{\rm GeV}^2) \\ \delta^{\rm ZEUS}(\mathcal{Q}^2=6\,{\rm GeV}^2) \end{array}\right\} = \left\{\begin{array}{l} 0.57 \pm 0.10 \;^{+0.05}_{-0.07} \\ 0.4 \;\; \pm 0.052 \;^{+0.048}_{-0.045} \end{array}\right\} ,$$



different partonic interpretations



- $r^{sea} \sim 1$ (small skewness effect at LO) of sea quarks are driven by DVCS data
- $r^{G} < 1$ gluon GPD is suppressed at LO
- very soft gluon GPD is disfavored by DIS fit
- GK07 model is based on NLO PDFs [(very) good small x_B DVCS description at LO]

interchange of skewing and evolution provides a very desired GPD behavior

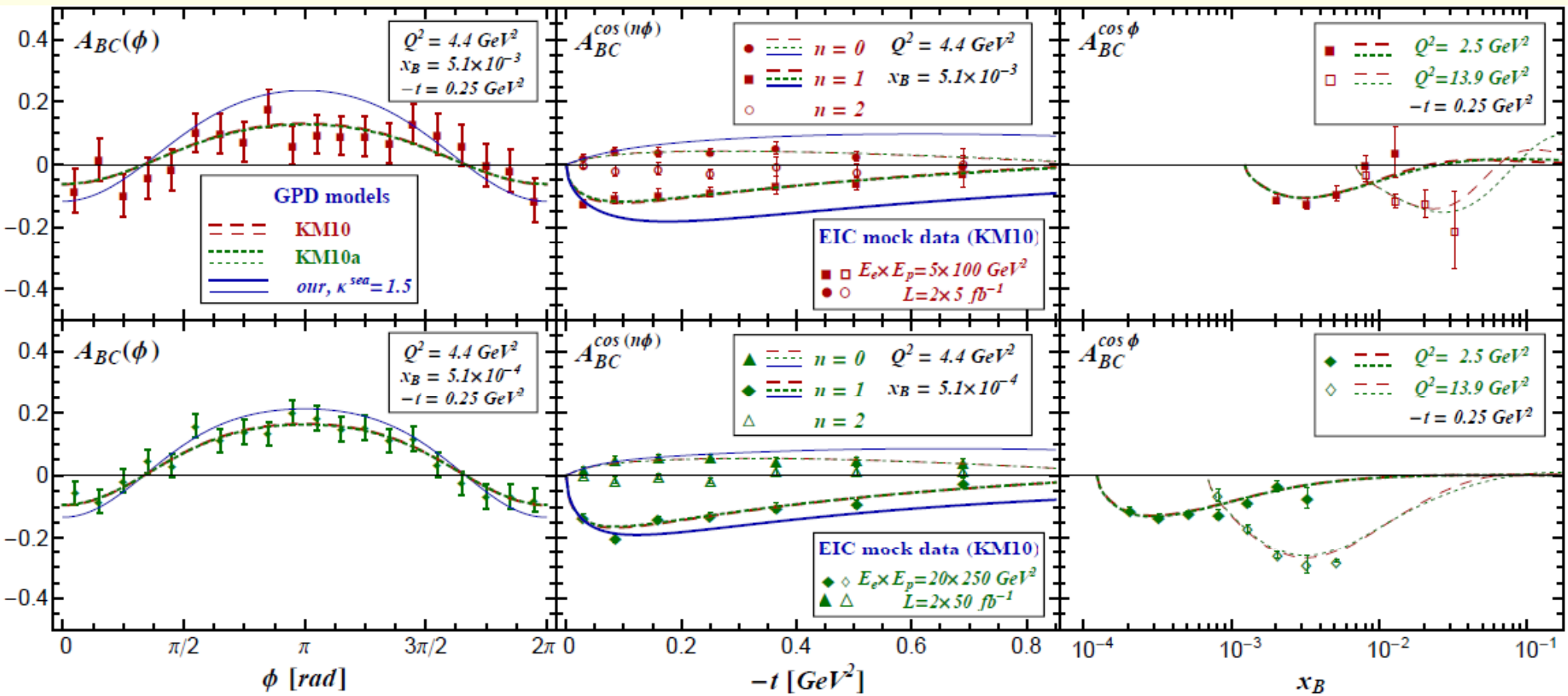
remember Freund/McDermott could not reach DVCS description @LO with similar model

EIC I and II predictions from hybrid models

- various asymmetries might be sizeable (there might be sensitivity even to $\hat{H}$ and $\hat{E}$)
- predictions from **KM10...** models and **our** one (sea quark+gluons, e^{-bt} dependence) (statistical errors from MILOU + 5% $d\sigma$ systematic errors in quadrature) **(see talk of S. Fazio)**
- beam charge asymmetry (even unpolarized beam) would be necessary

➢ to clarify the status of twist-3 admictures

➢ to disentangle interference and DVCS contributions for single spin flip experiments



Impact of EIC II data to extract GPD H

two simulations from S. Fazio (see his talk) for DVCS cross section (~ 650 data)

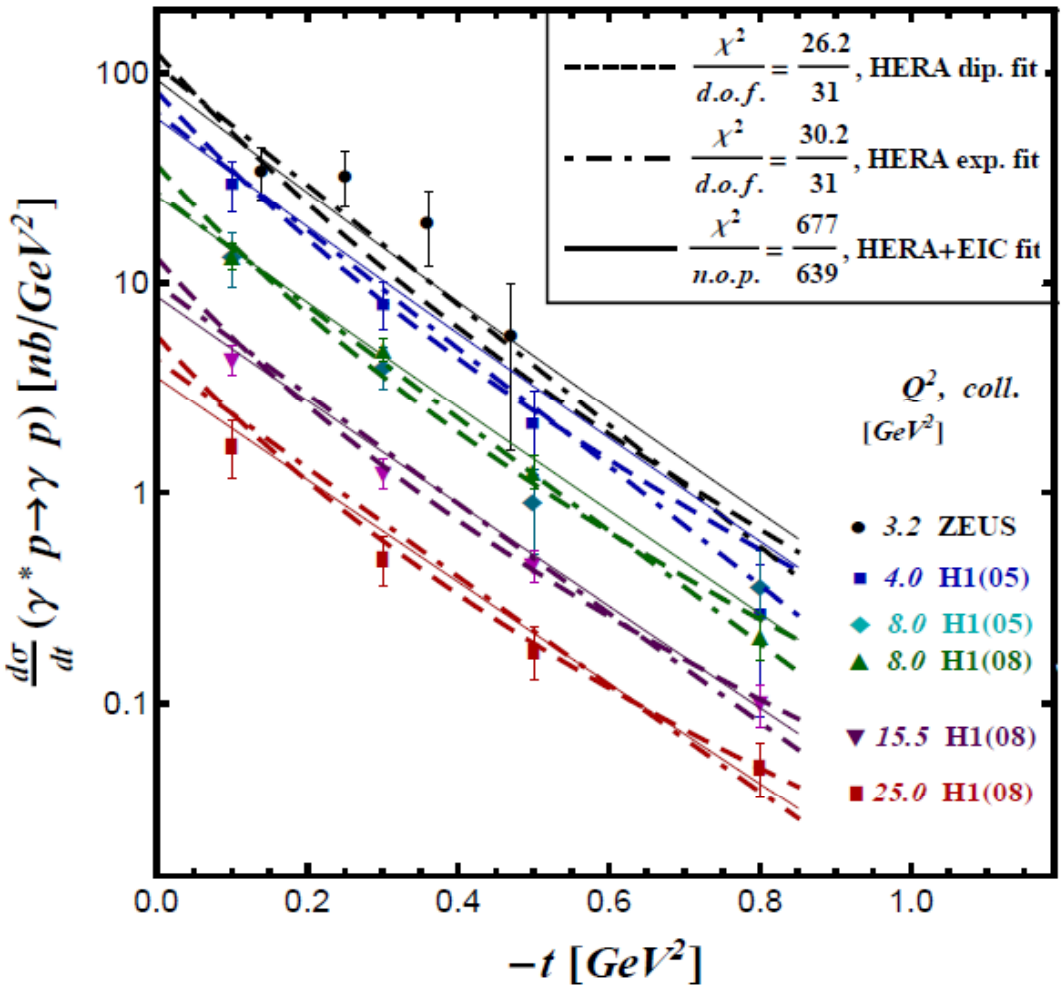
$-t <$ ~*0.8* GeV^2 for ~ 10/fb for $E_e \times E_p$ = 20 x 250 GeV^2

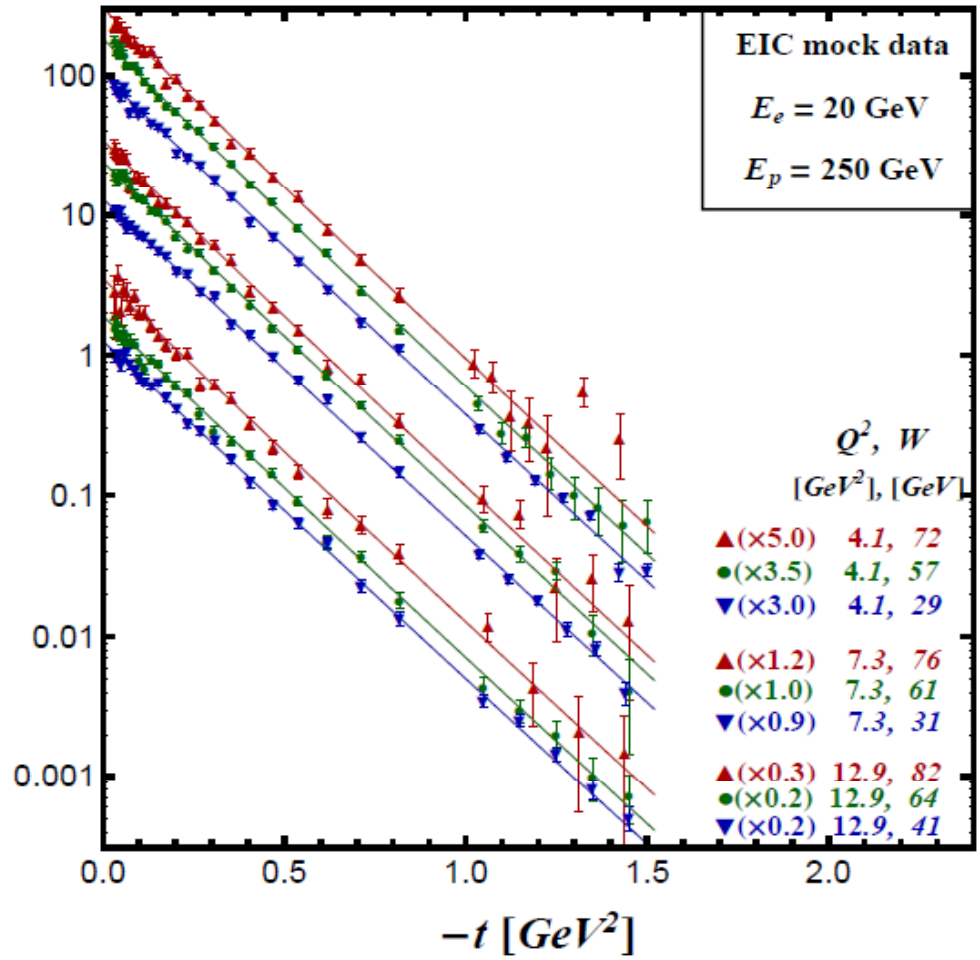
1 GeV^2 < $-t$ < *2* GeV^2 for ~ 100/fb (cut: $-t$ < *1.5* GeV^2 , *4* GeV^2 < *Q2* to ensure $-t < Q^2$)

mock data are regenerated with GeParD

(rescaled) statistical errors from MILOU + 5% systematical errors +

3% Bethe-Heitler cross section uncertainties, added in quadrature

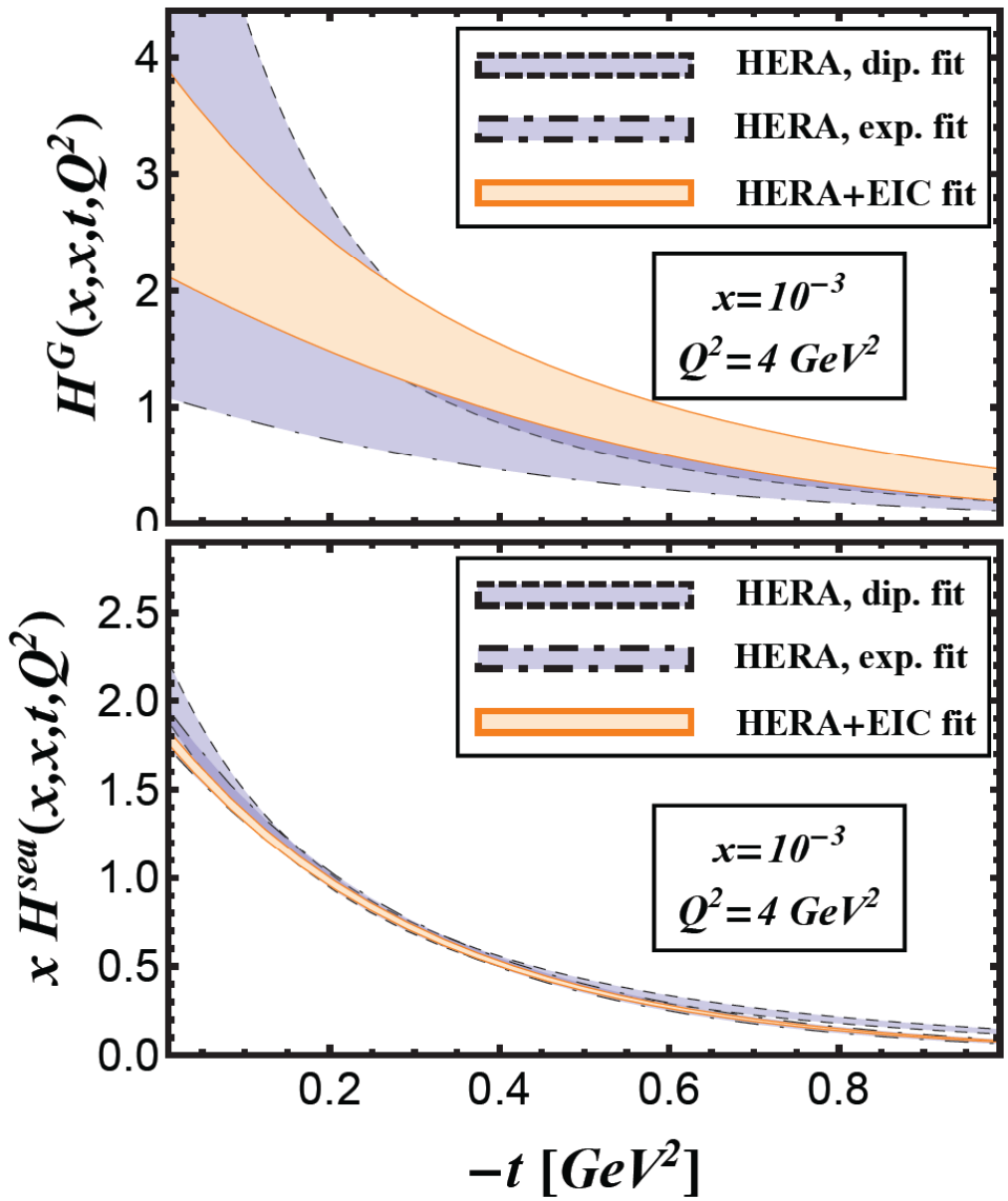




Imaging (probabilistic interpretation)

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

A_{UT} study to get *E*
see talk of M. Diehl



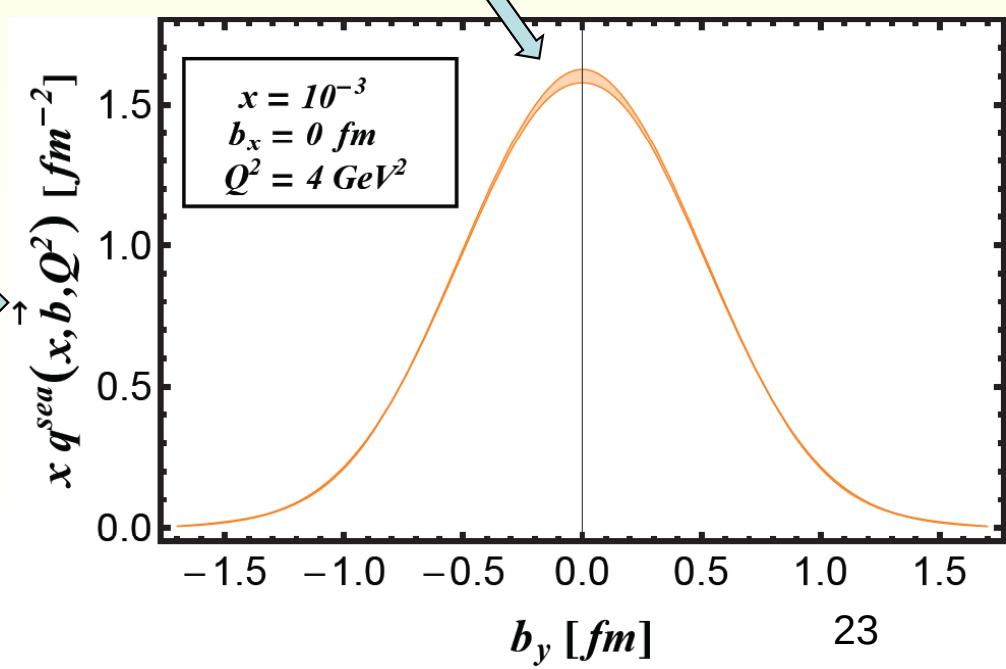
skewness effect vanishes (s_2 , $s_4 \rightarrow 0$)

- reduce fit uncertainties
- increase model uncertainties

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

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

FT



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 (NNLO) 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)

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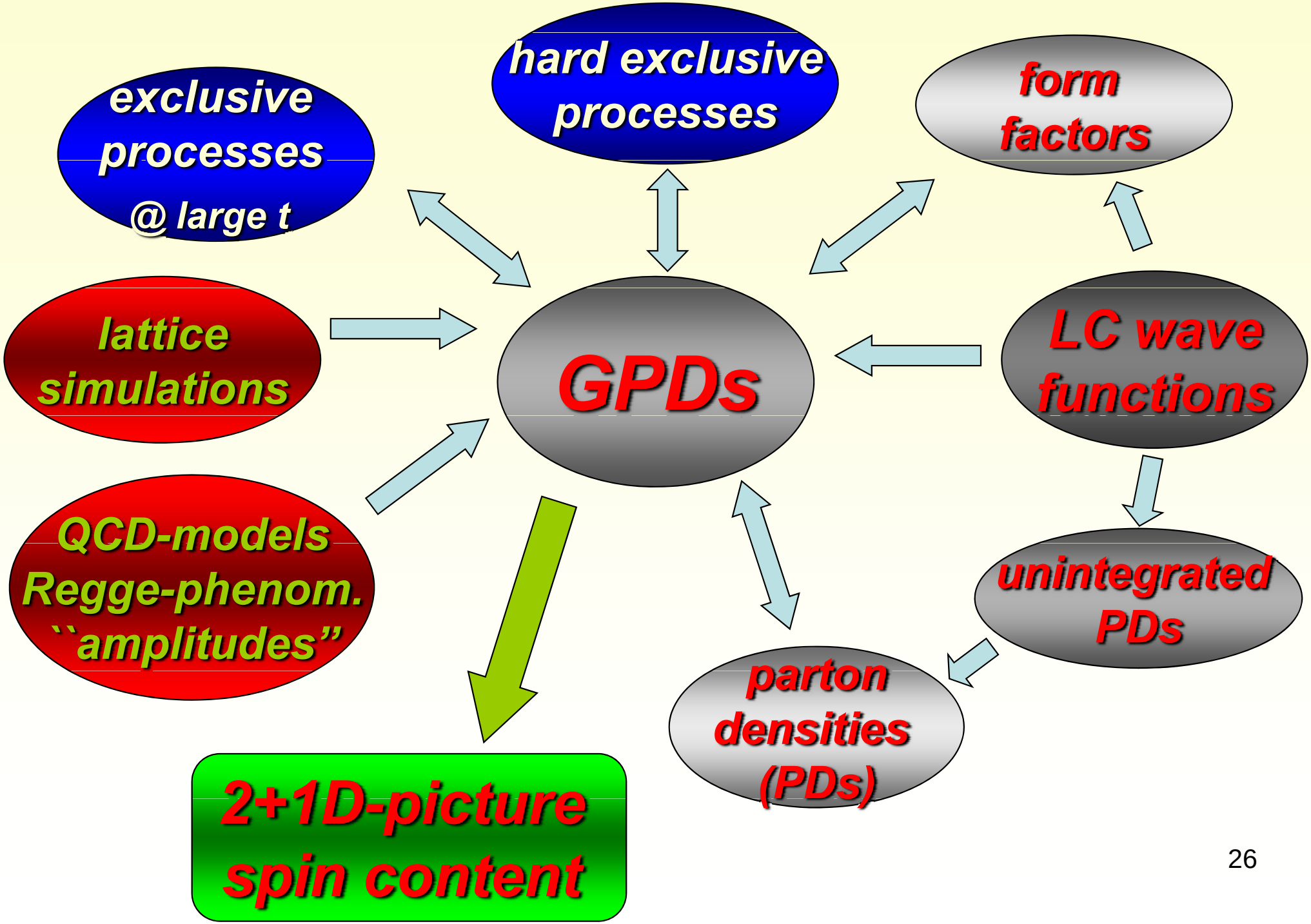
Why are GPDs needed?



access of CFFs from measurements:

sector		harmonics in $\mathcal{I}$				extraction	P of	$\Delta_\perp^l$ behavior	
twist	$\mathcal{C}$'s	unp	LP	TP_x	TP_y	of CFFs	$\mathcal{Q}^{-P}$	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

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

effective model parameterization (small x)

PDF: $$q^{\rm sea}(\xi, \mathcal{Q}_0) = n\xi^{-\alpha}, \quad \alpha \gtrsim 1, \quad F_1^{\rm sea}(0) = 1$$

GPD *H*: $$H^{\rm sea}(\xi, \xi, t, \mathcal{Q}_0) = r(\eta/x = 1|s_2, s_4) F_1^{\rm sea}(t) \xi^{\alpha'(t)} q^{\rm sea}(\xi)$$

- PDF is assumed to be known (from some fit with to old HERA data)
- *t*-dependence of residue is taken to be exponential with slope *B*
- free parameters: two sets $\{\alpha', B, s_2, s_4\}$ for sea quarks and gluons
- momentum sum rule is implemented

GPD *E*:

$$E^{\rm sea}(\xi, \mathcal{Q}_0) = nF_2^{\rm sea}(0)\xi^{-\alpha}, \quad \alpha \gtrsim 1, \quad F_2^{\rm sea}(0) = \kappa^{\rm sea}$$

$$E^{\rm sea}(\xi, \xi, t, \mathcal{Q}_0) = r(\eta/x = 1|s_2, s_4) F_2^{\rm sea}(t) \xi^{\alpha'(t)} E^{\rm sea}(\xi, \eta = 0)$$

- PDF analog is unknown
- *t*-dependence of residue is taken to be exponential with slope *B*
- free parameters: κ^{sea} + two sets $\{\alpha, \alpha', B, s_2, s_4\}$ for sea quarks and gluons
- κ^G *is constrained by Ji`s* sum rule

real part of Compton form factors is determined by their imaginary parts

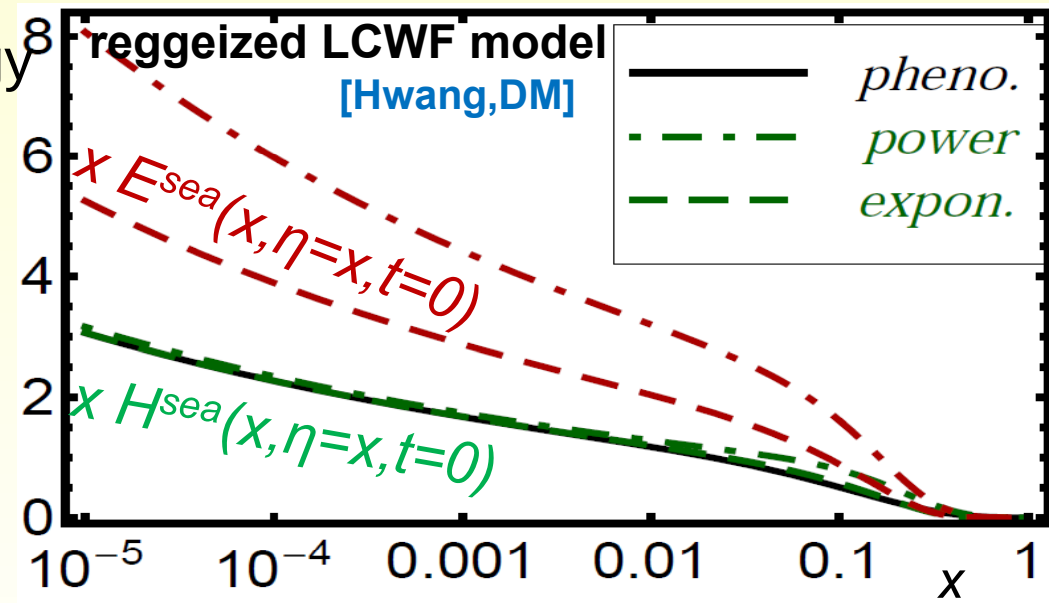
PDF analog: $E^{\rm sea}(\xi,\eta=0,\mathcal{Q}_0)=nF_2^{\rm sea}(0)\xi^{-\alpha},\quad \alpha\gtrsim 1,\quad F_2^{\rm sea}(0)=\kappa^{\rm sea}$

GPDs: $E^{\rm sea}(\xi,\xi,t,\mathcal{Q}_0)=r(\eta/x=1|s_2,s_4)F_2^{\rm sea}(t)\xi^{\alpha'(t)}E^{\rm sea}(\xi,\eta=0)$

? $\kappa^{\rm sea}$ or $J^{\rm sea}$ ***skewness***

transverse distribution

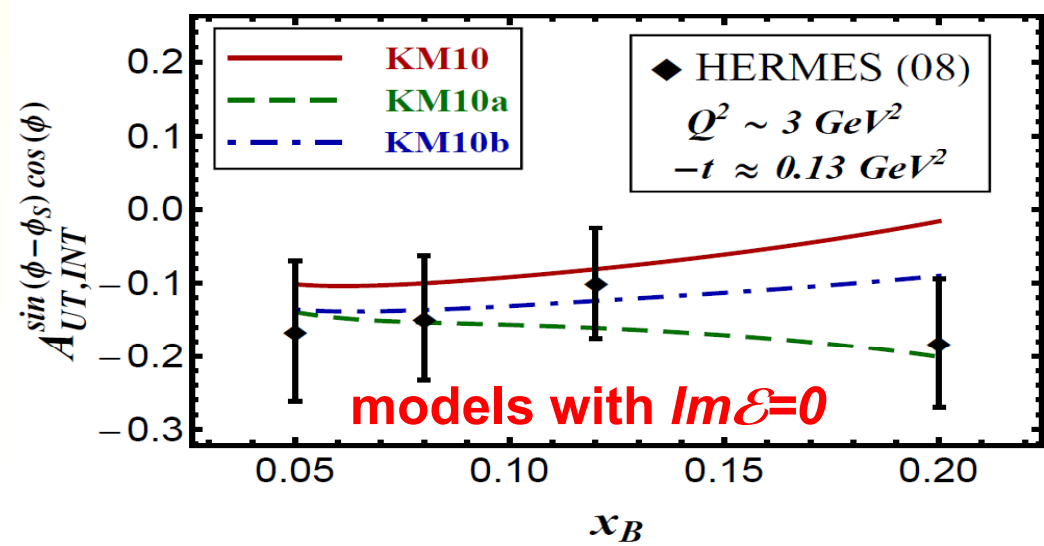
- mostly not seen in Regge phenomenology
- might be sizeable in instanton models
- reggeized spectator quark models
- pQCD suggests `pomeron' intercept
- however, *B* vanishes asymptotically
- so far *E* is "not clearly seen" in DVCS



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

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

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



Observables for $e^- p \to e^- p \gamma$ at small x_B

DVCS cross section (dominated by *H* and slightly dependent on *E*)

$$\frac{d\sigma^{\rm DVCS}}{dt}(W,t,\mathcal{Q}^2) \approx \frac{\pi\alpha^2 x_{\rm Bj}^2}{\mathcal{Q}^4}\left[|\mathcal{H}|^2 - \frac{t}{4M_p^2}|\mathcal{E}|^2\right](x_{\rm Bj},t,\mathcal{Q}^2)\Big|_{x_{\rm Bj}\approx\frac{\mathcal{Q}^2}{W^2+\mathcal{Q}^2}}$$

(electron) beam spin asymmetry (dominated by ***H*** and slightly dependent on *E*)

$$A_{\rm BS}^{(1)} \propto y\left[F_1(t)H(\xi,\xi,t,\mathcal{Q}^2) - \frac{t}{4M^2}F_2(t)E(\xi,\xi,t,\mathcal{Q}^2)+\cdots\right]$$

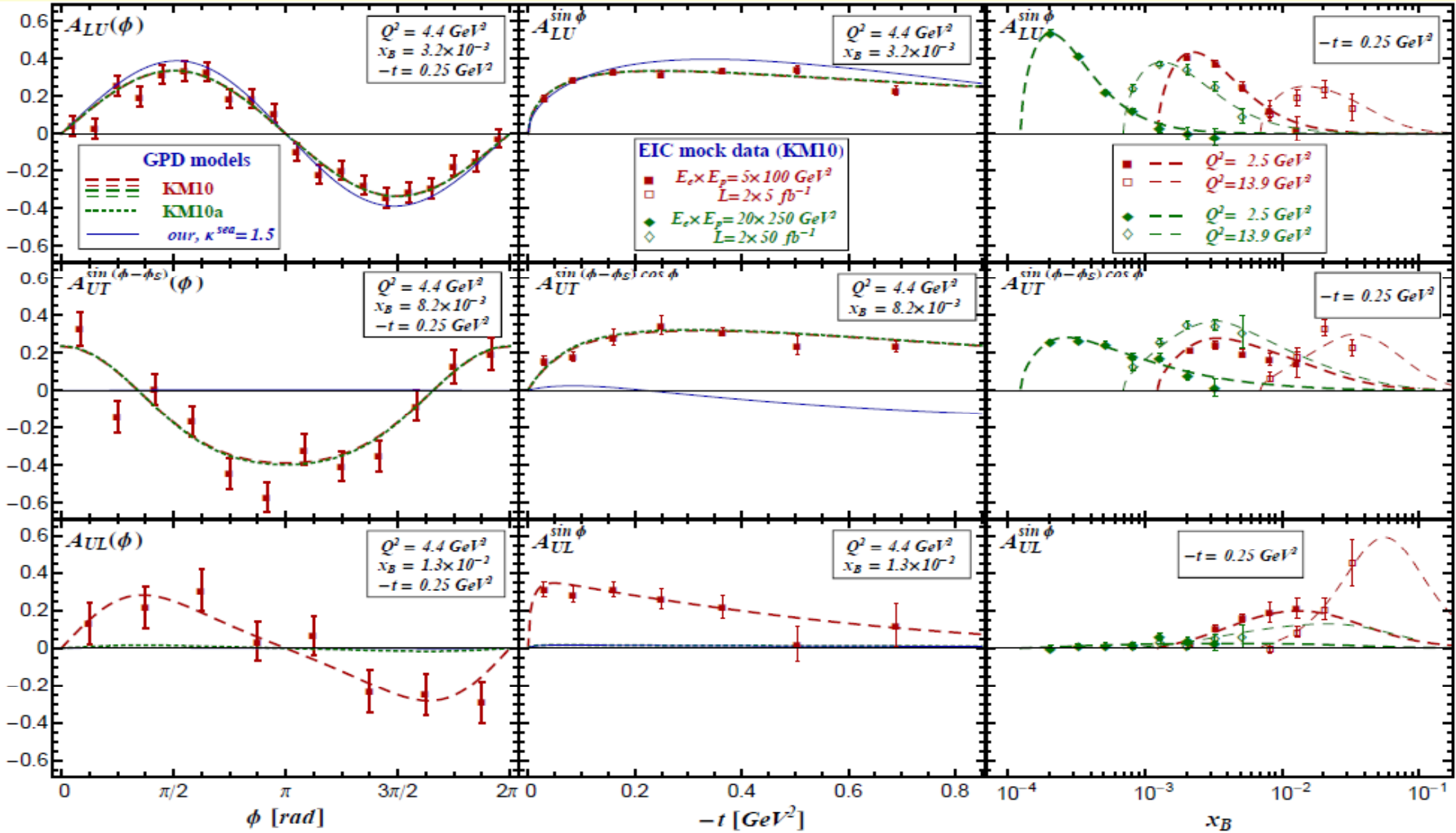
sin(ψ) transverse target spin asymmetry (governed by ***E*** and ***H***)

$$A_{\rm TS}^{\Uparrow(1)} \propto \sqrt{\frac{-t}{4M^2}}\left[F_2(t)H(\xi,\xi,t,\mathcal{Q}^2) - F_1(t)E(\xi,\xi,t,\mathcal{Q}^2)+\cdots\right]$$

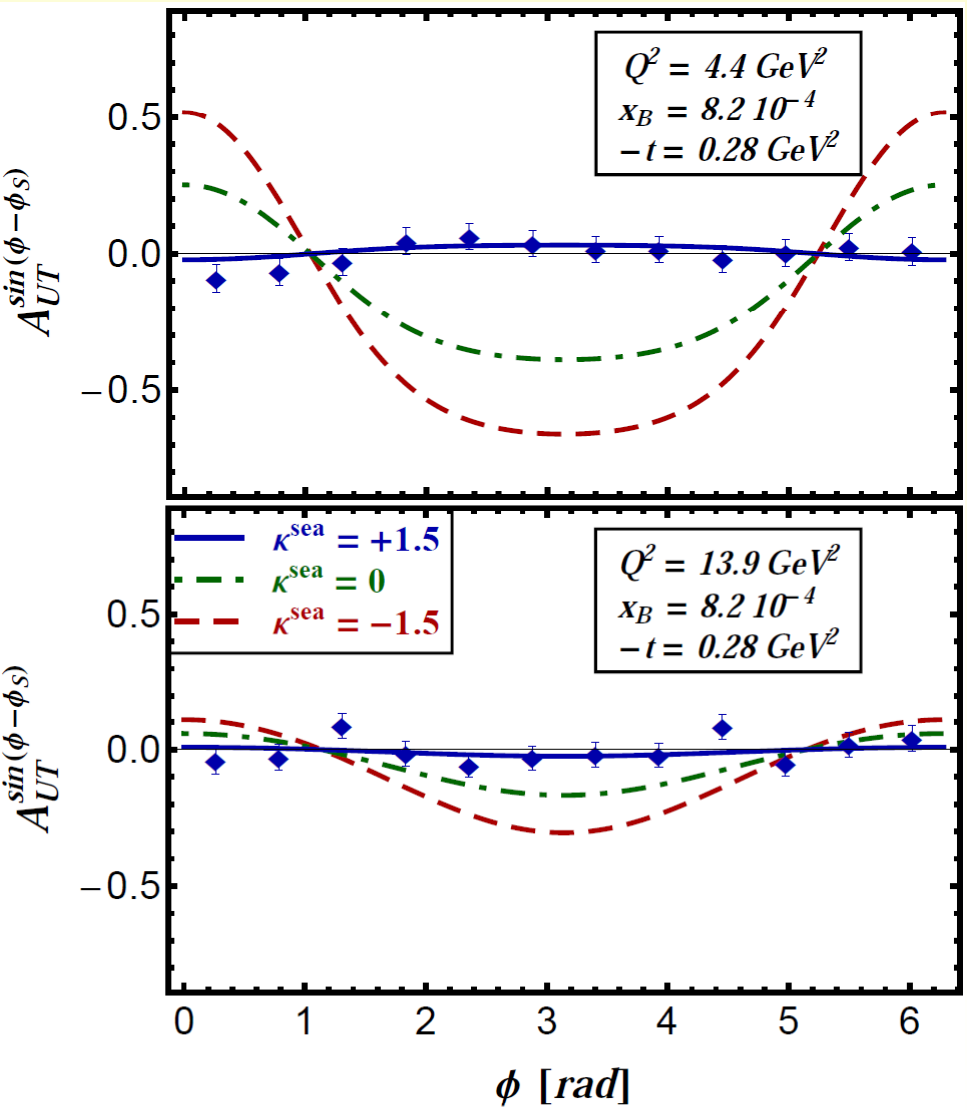
cos(ψ) transverse and longitudinal target spin asymmetries are sensitive to parity odd GPDs $\hat{H}$ and $\hat{E}$ – expected to be suppressed at small x_B

$$A_{\rm TS}^{\Downarrow(1)} \propto \sqrt{\frac{-t}{4M^2}}\left[F_2(t)\widetilde{H}(\xi,\xi,t,\mathcal{Q}^2) - F_1(t)\xi\widetilde{E}(\xi,\xi,t,\mathcal{Q}^2)+\cdots\right]$$

$$A_{\rm TS}^{\Rightarrow(1)} \propto \left[F_1(t)\widetilde{H}(\xi,\xi,t,\mathcal{Q}^2) - \frac{t}{4M^2}F_2(t)\xi\widetilde{E}(\xi,\xi,t,\mathcal{Q}^2)+\cdots\right]$$


$A_{LU}(\phi)$
$Q^2 = 4.4\ GeV^2$
$x_B = 3.2\times10^{-3}$
$-t = 0.25\ GeV^2$
GPD models
KM10
KM10a
our, $\kappa^{sea}=1.5$
$A_{LU}^{\sin\phi}$
EIC mock data (KM10)
$E_e\times E_p = 5\times100\ GeV^2$
$L = 2\times5\ fb^{-1}$
$E_e\times E_p = 20\times250\ GeV^2$
$L = 2\times50\ fb^{-1}$
$Q^2 = 2.5\ GeV^2$
$Q^2 = 13.9\ GeV^2$
$A_{UT}^{\sin(\phi-\phi_S)}(\phi)$
$x_B = 8.2\times10^{-3}$
$A_{UT}^{\sin(\phi-\phi_S)\cos\phi}$
$A_{UL}(\phi)$
$x_B = 1.3\times10^{-2}$
$A_{UL}^{\sin\phi}$
ϕ [rad]
$-t$ [GeV^2]
x_B

Single transverse proton spin asymmetry

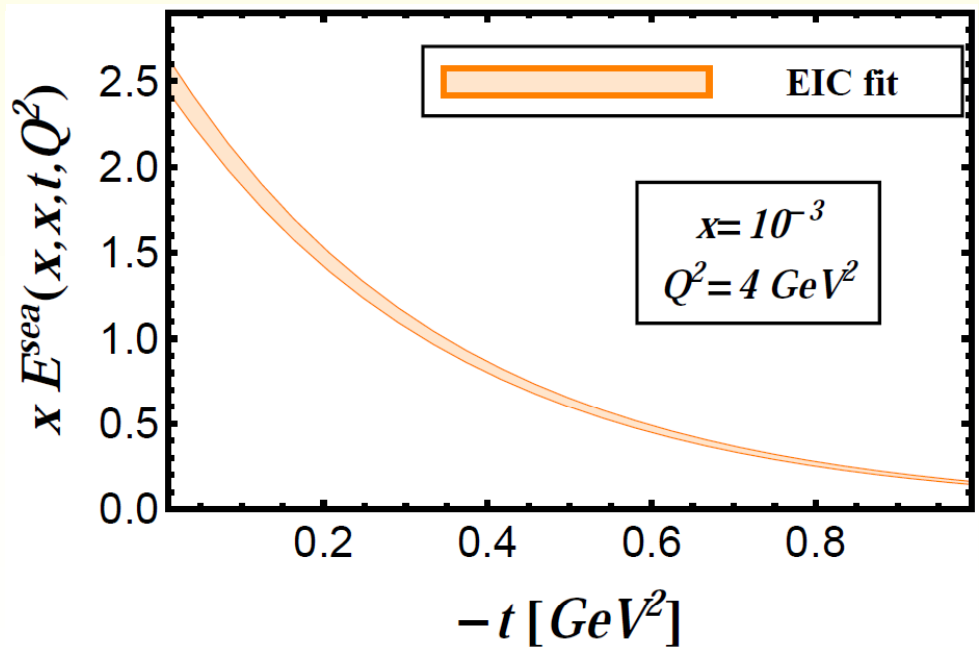


20x250 2x5/fb mock data
(~1200 data points with statistical errors
+ 5% systematics at cross section level)

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

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

E^G is essentially unconstraint



Imaging (probabilistic interpretation)

density for a transverse polarized proton in impact space

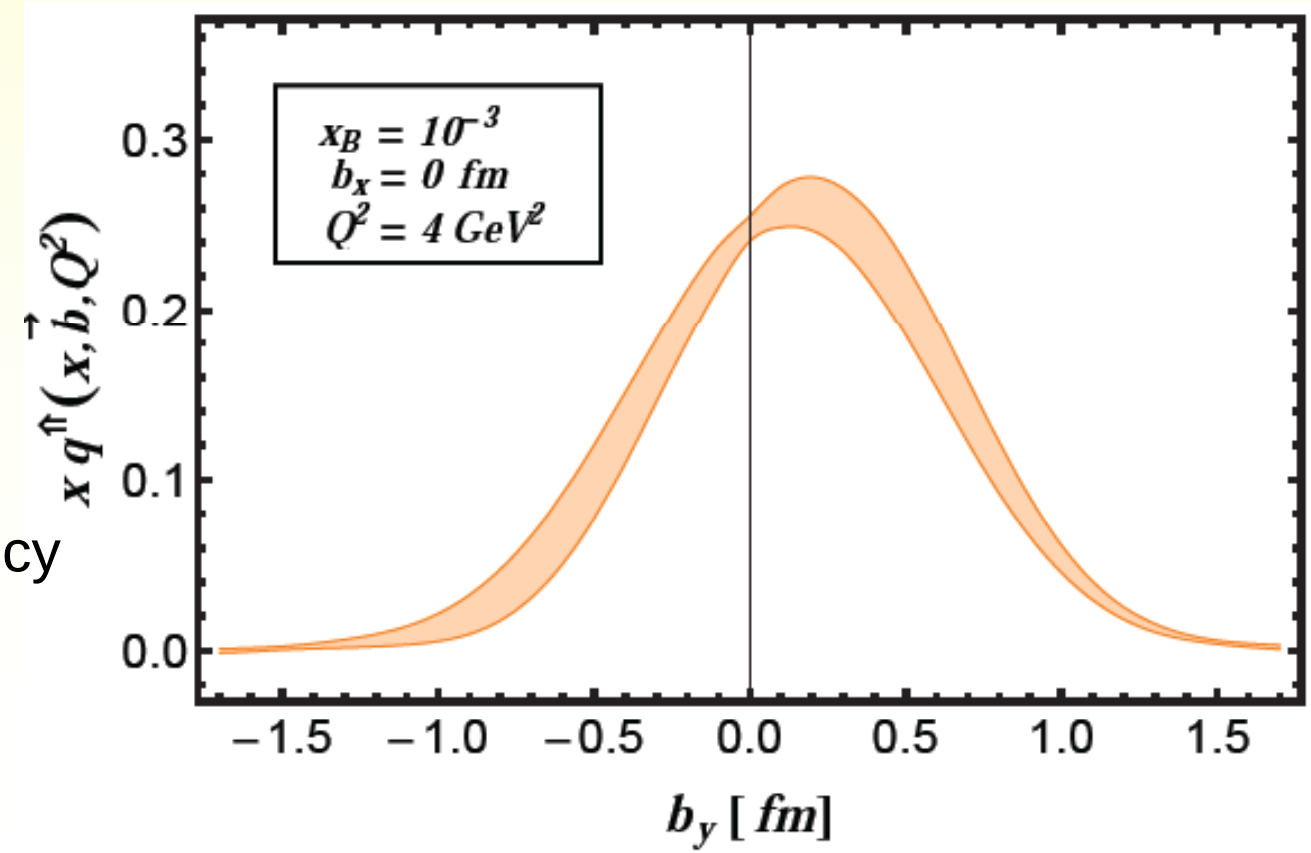
$$q^{\Uparrow}(x,\vec{b},\mu^2) = q(x,\vec{b},\mu^2) - \frac{1}{2M}\frac{\partial}{\partial b_y}E(x,\vec{b},\mu^2)$$

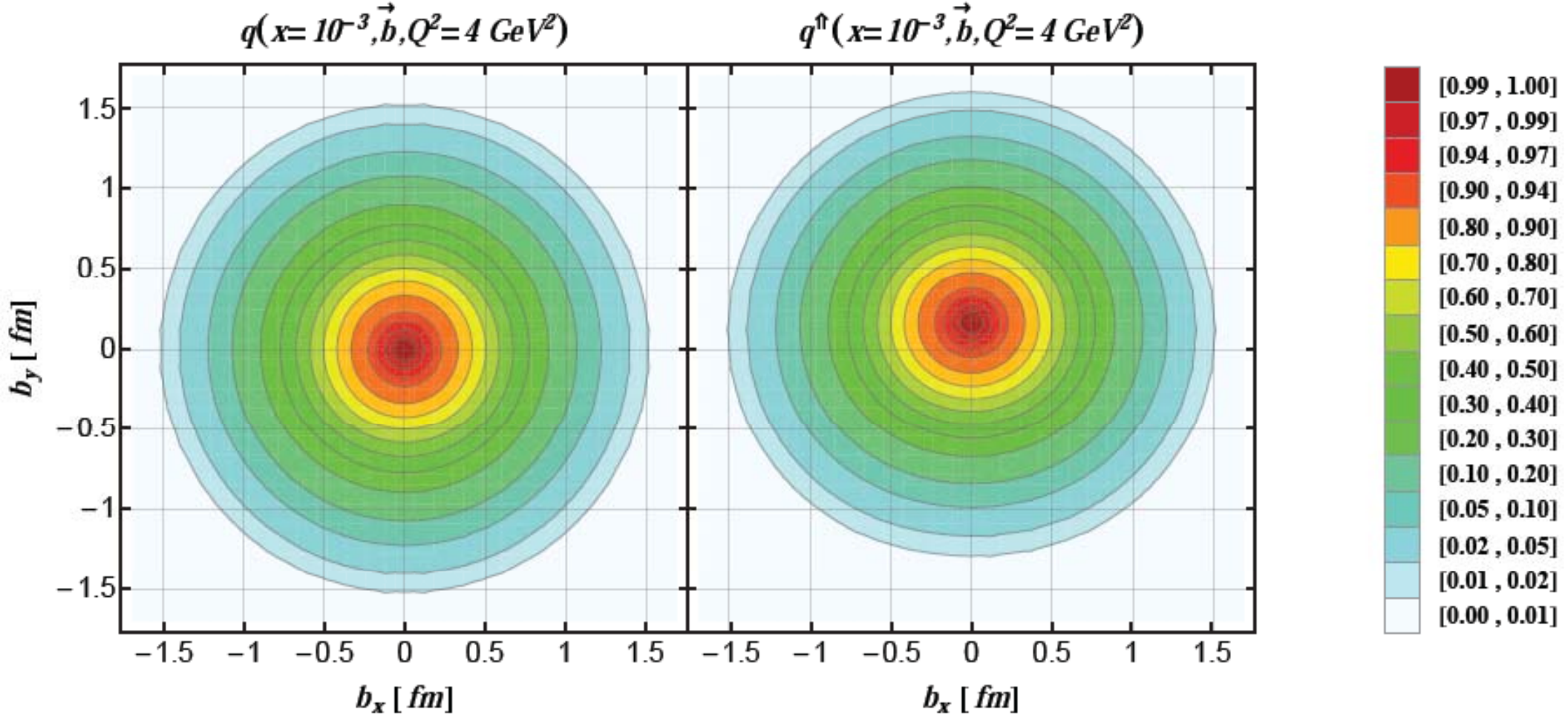
$$= \frac{1}{4\pi}\int_0^\infty d|t|\left[J_0(|\vec{b}|\sqrt{|t|})H + \frac{b_y\sqrt{|t|}}{|\vec{b}|2M}J_1(|\vec{b}|\sqrt{|t|})E\right](x,\eta=0,t,\mu^2$$

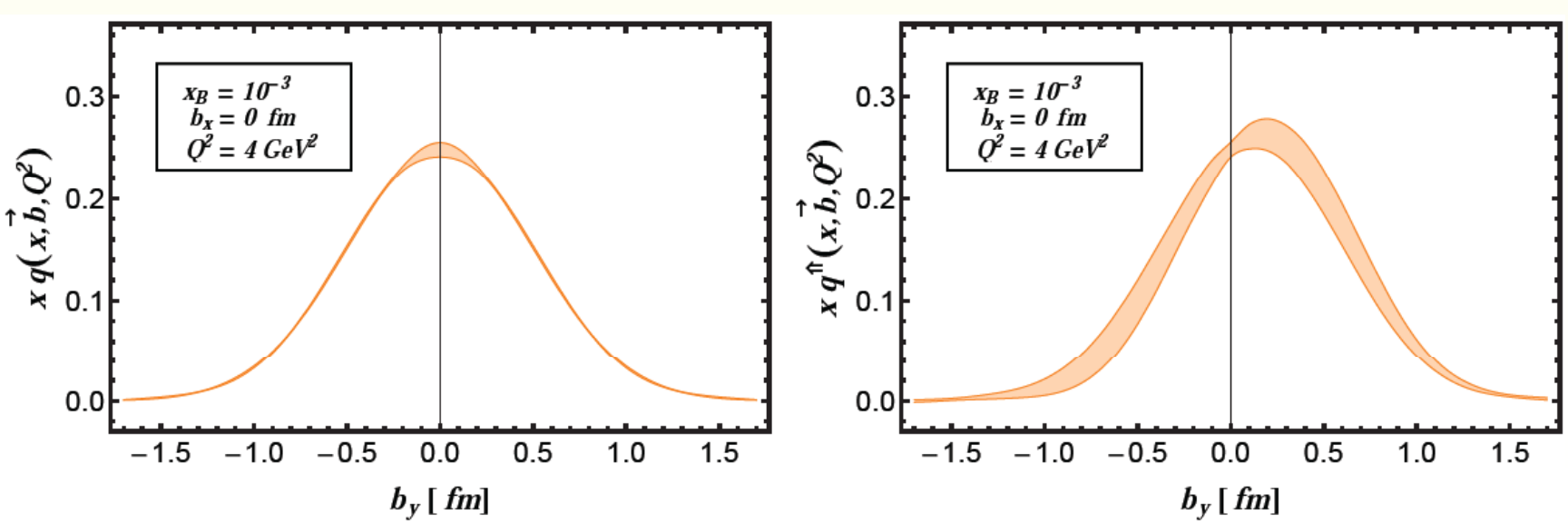
already assumed that E is constrained for -t < 1.5 GeV^2

extrapolation errors into *-t > 1.5* GeV^2 are taken

NOTE:
normalization and t-dependency of E are now extracted while normalization of H is fixed by unpolarized PDF




$q(x=10^{-3},\vec{b},Q^2=4\ GeV^2)$
$q^{\Uparrow}(x=10^{-3},\vec{b},Q^2=4\ GeV^2)$
b_y [fm]
b_x [fm]
[0.99 , 1.00]
[0.97 , 0.99]
[0.94 , 0.97]
[0.90 , 0.94]
[0.80 , 0.90]
[0.70 , 0.80]
[0.60 , 0.70]
[0.50 , 0.60]
[0.40 , 0.50]
[0.30 , 0.40]
[0.20 , 0.30]
[0.10 , 0.20]
[0.05 , 0.10]
[0.02 , 0.05]
[0.01 , 0.02]
[0.00 , 0.01]


$x_B = 10^{-3}$
$b_x = 0$ fm
$Q^2 = 4\ GeV^2$
$x\,q(x,\vec{b},Q^2)$
$x\,q^{\Uparrow}(x,\vec{b},Q^2)$
b_y [fm]