Experimental Studies of Exclusive Deep Virtual Processes

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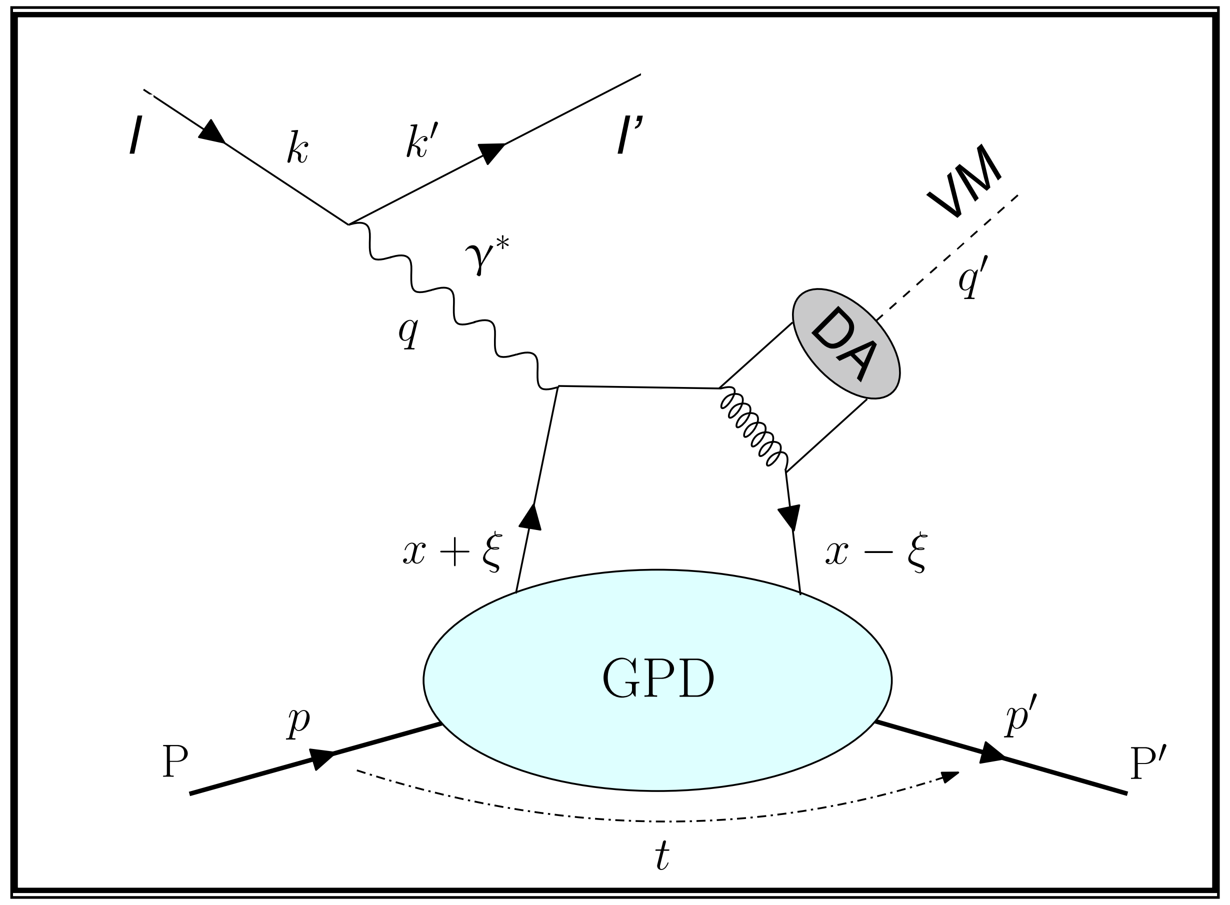
OLD DOMINION UNIVERSITY

Experimental DVES Program

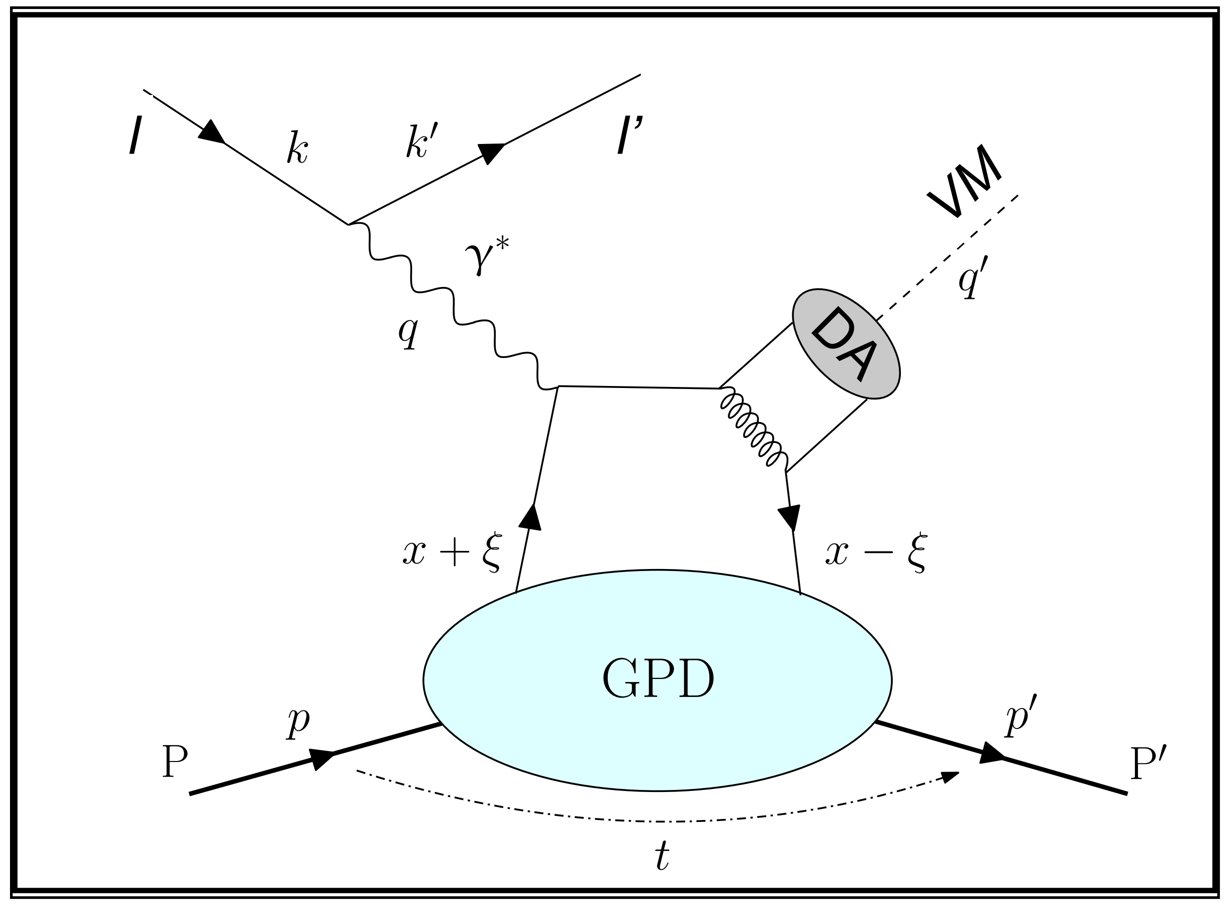
QCD factorization of exclusive processes controversial when first proposed nearly 30 years ago



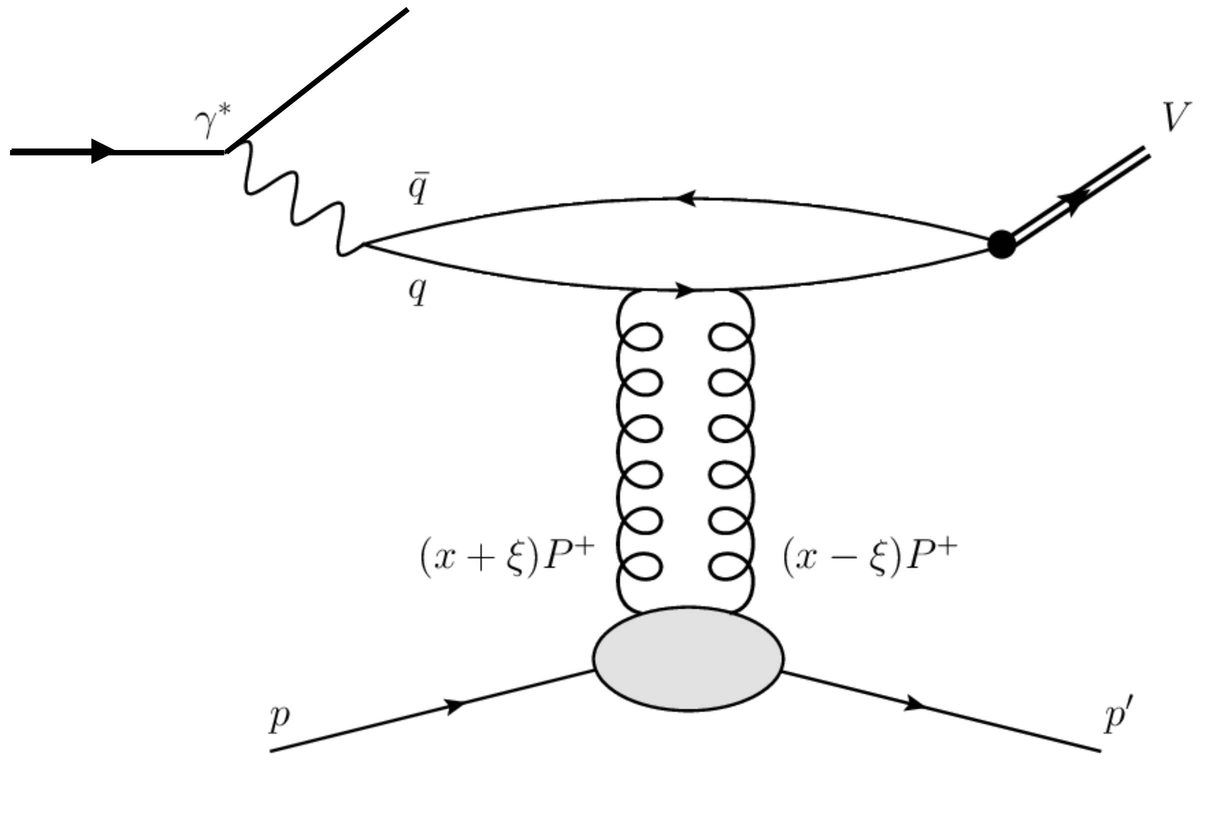
- Basic principle: Meson size (and hadronic content of real photon) parametrically squeezed by $1/(Q^2 + m^2)$
- Validation observables
  - Q^2-dependence of cross sections
  - Spin Density Matrix Elements (SDME)
    - Light vector meson production, prediction $d\sigma_L \gg d\sigma_T$ in contrast to DIS
- Extract novel information about spatial distributions of quarks and gluons in nucleon and nuclei — previously thought impossible

Exclusive Vector-Meson Electroproduction

Introduction and Background



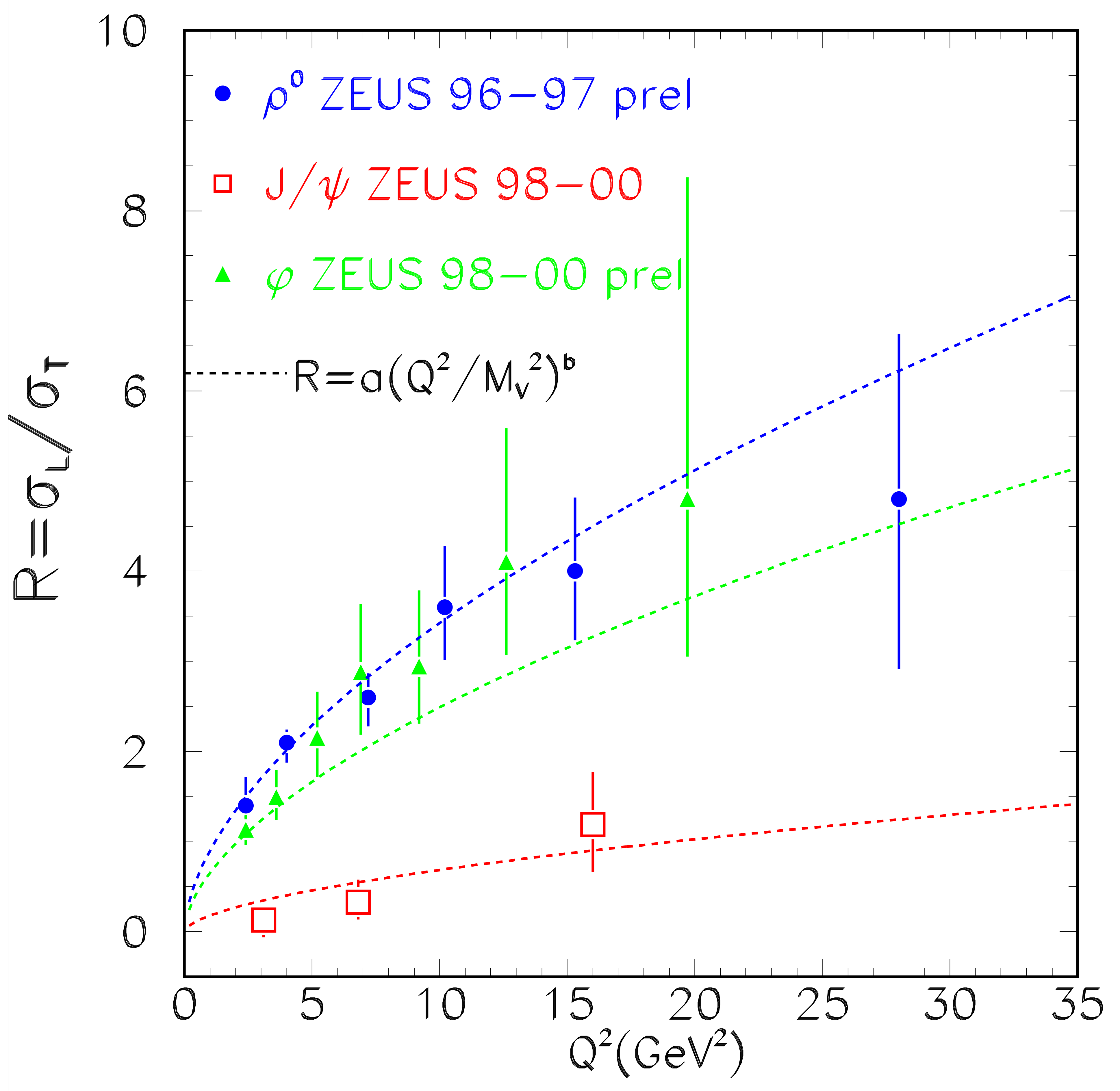
- Leading-twist factorization of $d\sigma_L$
  - Quark/Gluon Helicity conserving:
    - [nucleon GPDs]⨂[meson DAs]
  - SCHC: photon to meson
- Expect $R = d\sigma_L / d\sigma_T \propto Q^2$ in Bjorken regime
  - Factorization of $d\sigma_L$ and $d\sigma_T$ considered separately
    - $d\sigma_T$ suppressed asymptotically, but enhanced by strong chiral symmetry breaking effects in pseudo scalar DAs (and also in light vector mesons) coupled to transversity GPDs



HERA Spin Density Matrix Elements

- **Exclusive $(e, e'\rho)$ production**
- $$R = \frac{1}{\epsilon}\frac{r^{04}_{00}}{1 - r^{04}_{00}}$$
  - Longitudinally polarized virtual photons tagged by observed helicity=0 state of ρ
  - Other SDME values consistent with s-channel helicity conservation (SCHC).
- Approach to $d\sigma_L$ dominance for light vector mesons.
- Anticipating higher statistics at EIC

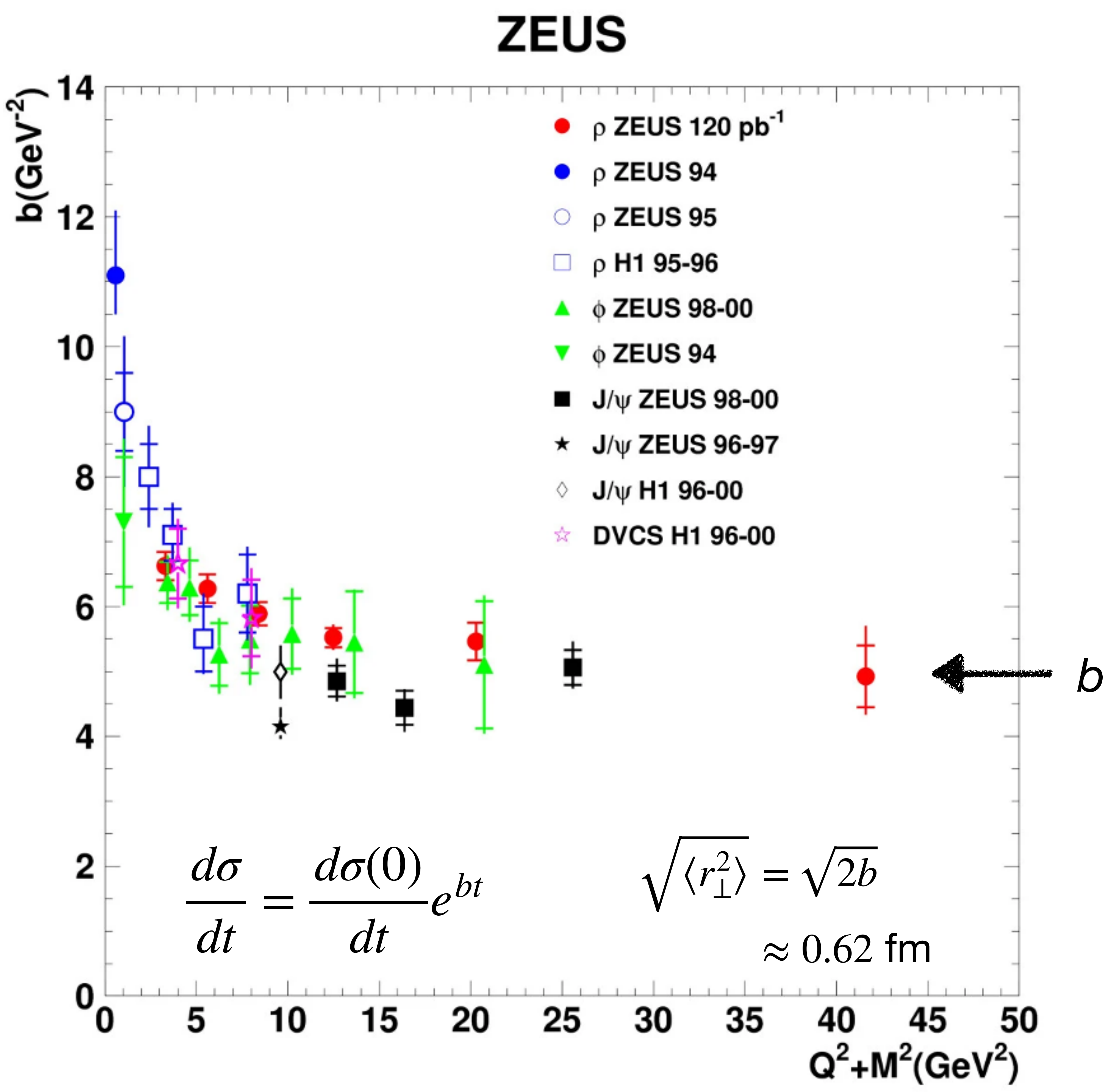
A.Levy PLB **146** (2005) 92–101, arXiv:0501008



HERA VECTOR MESON PRODUCTION

G.Wolf, **https://arxiv.org/abs/0907.1217**

- Slope parameter *b* represents convolution of meson 'size' with intrinsic nucleon size
- Meson 'size' $\sim 1/\sqrt{Q^2 + M_V^2}$
- Meson size ~ point-like for $Q^2 + M_V^2 > 20$ GeV^2
- How will these ~asymptotic *b*-slopes evolve with x_B with higher statistics EIC data?
    - As parton distributions grow at low-x, they also expand transversely by diffusion



HERMES

Exclusive rho

- EPJC 62(2009)659

$$R = \frac{1}{\epsilon}\frac{r^{04}_{00}}{1 - r^{04}_{00}} + \cancel{\text{SCHC}}\text{ terms}$$

From COMPASS, EPJC **83** (2023) 924

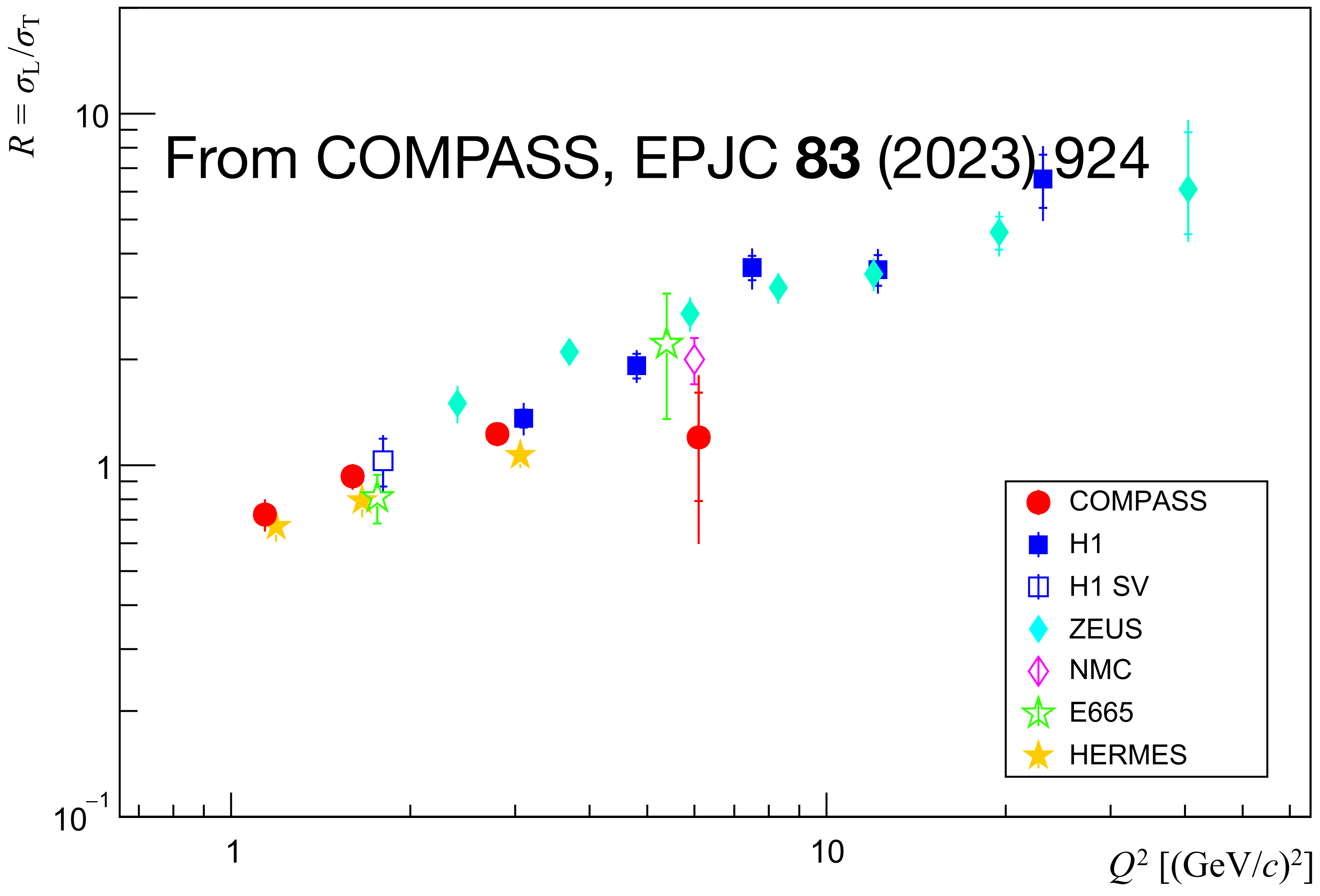
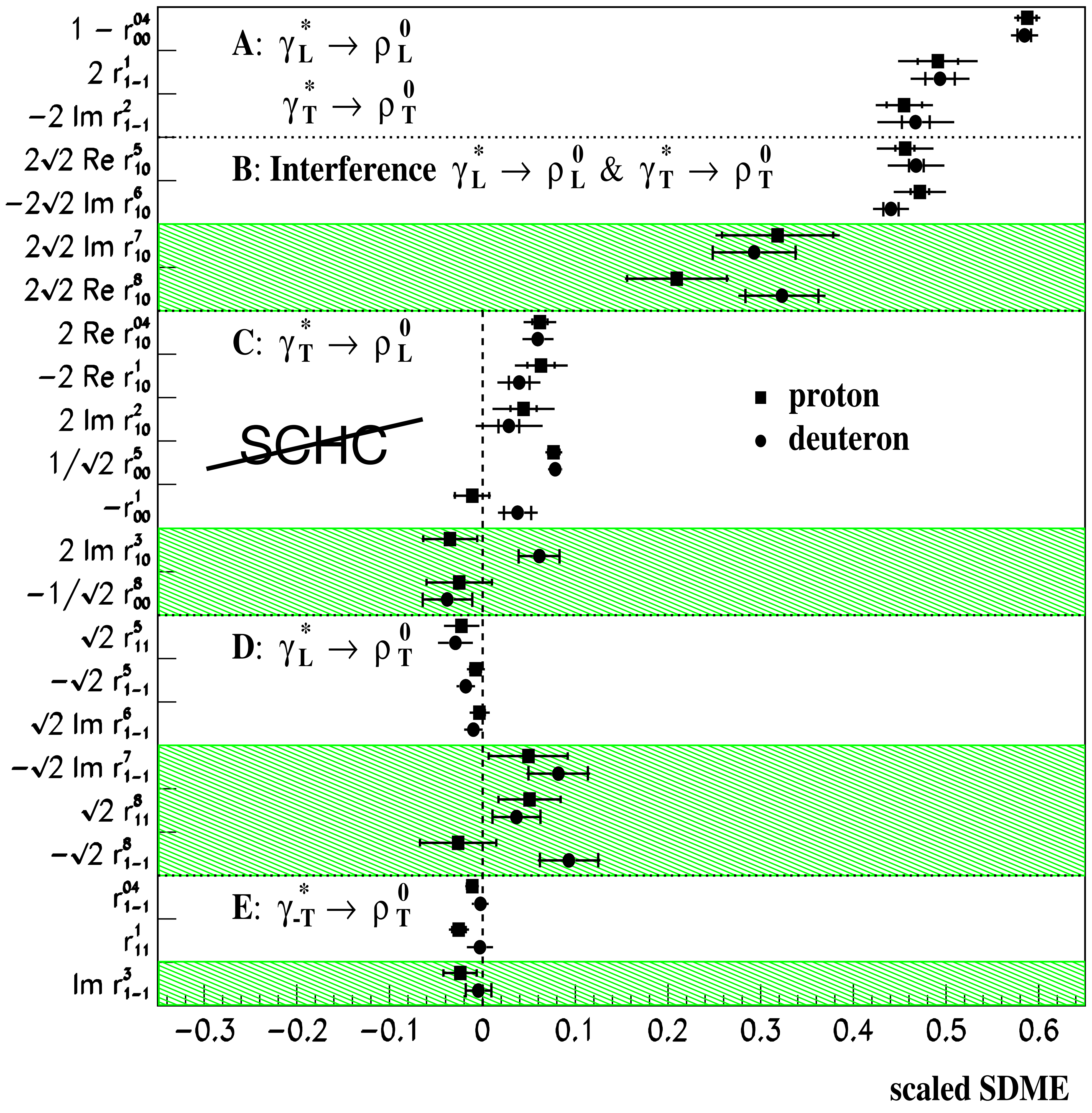


Fig. 9 The 23 SDMEs extracted from ρ^0 data: proton (*squares*) and deuteron (*circles*) in the entire HERMES kinematics with $\langle x\rangle = 0.08$, $\langle Q^2\rangle = 1.95$ GeV^2, $\langle -t'\rangle = 0.13$ GeV^2. The SDMEs are multiplied by prefactors in order to represent the normalized leading contribution of the corresponding amplitude (see (A.1)–(A.23)). The *inner error bars* represent the statistical uncertainties, while the *outer ones* indicate the statistical and systematic uncertainties added in quadrature. SDMEs measured with unpolarized (polarized) beam are displayed in the *unshaded* (*shaded*) *areas*. The *vertical dashed line* at zero is indicated for SDMEs expected to be zero under the hypothesis of SCHC



Also ω-production *Eur.Phys.J.C* 74 (2014) 11, 3110

See next talk for COMPASS results

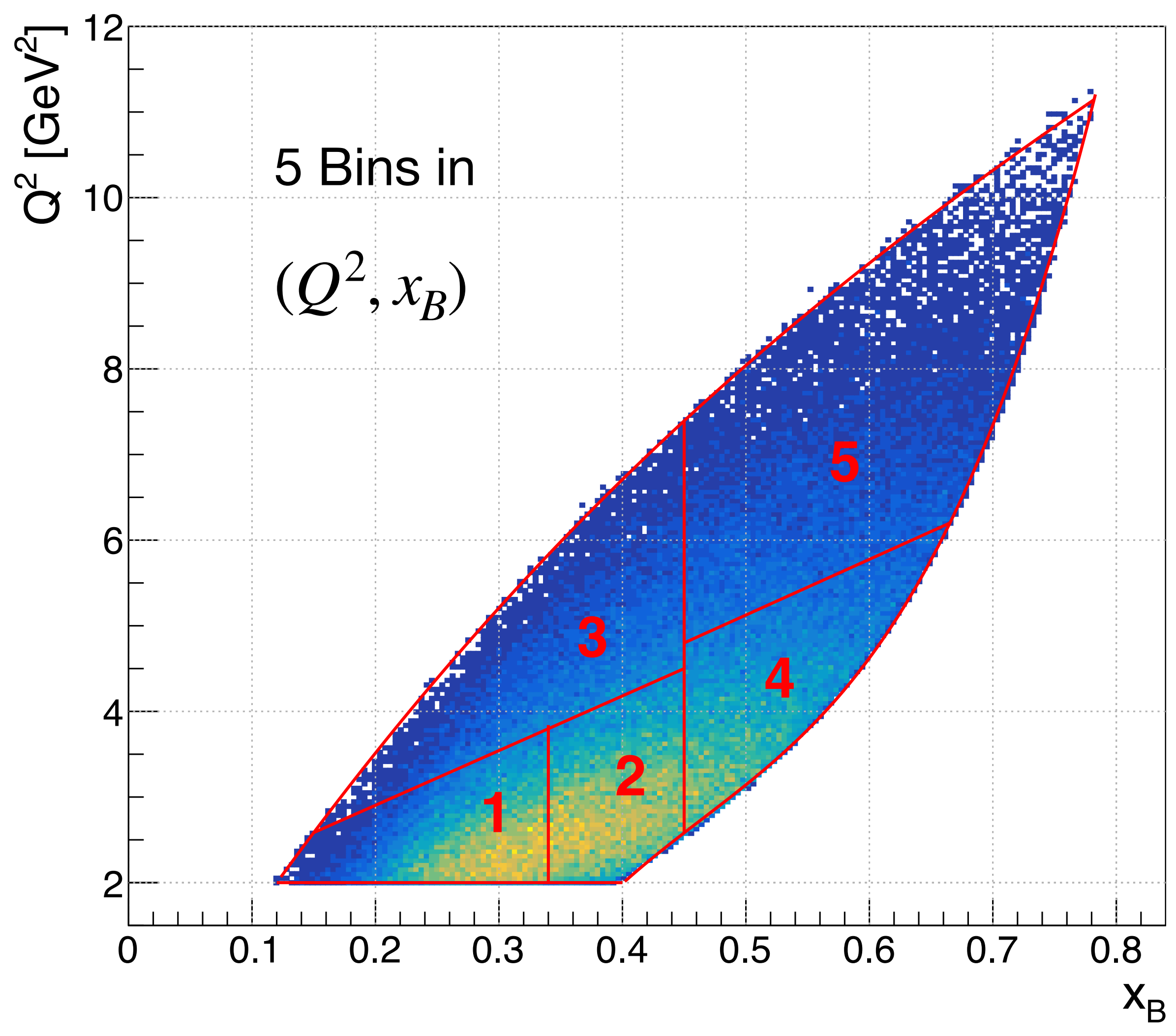
Exclusive Pseudo-Scalar Meson Production

JLab 6 GeV results

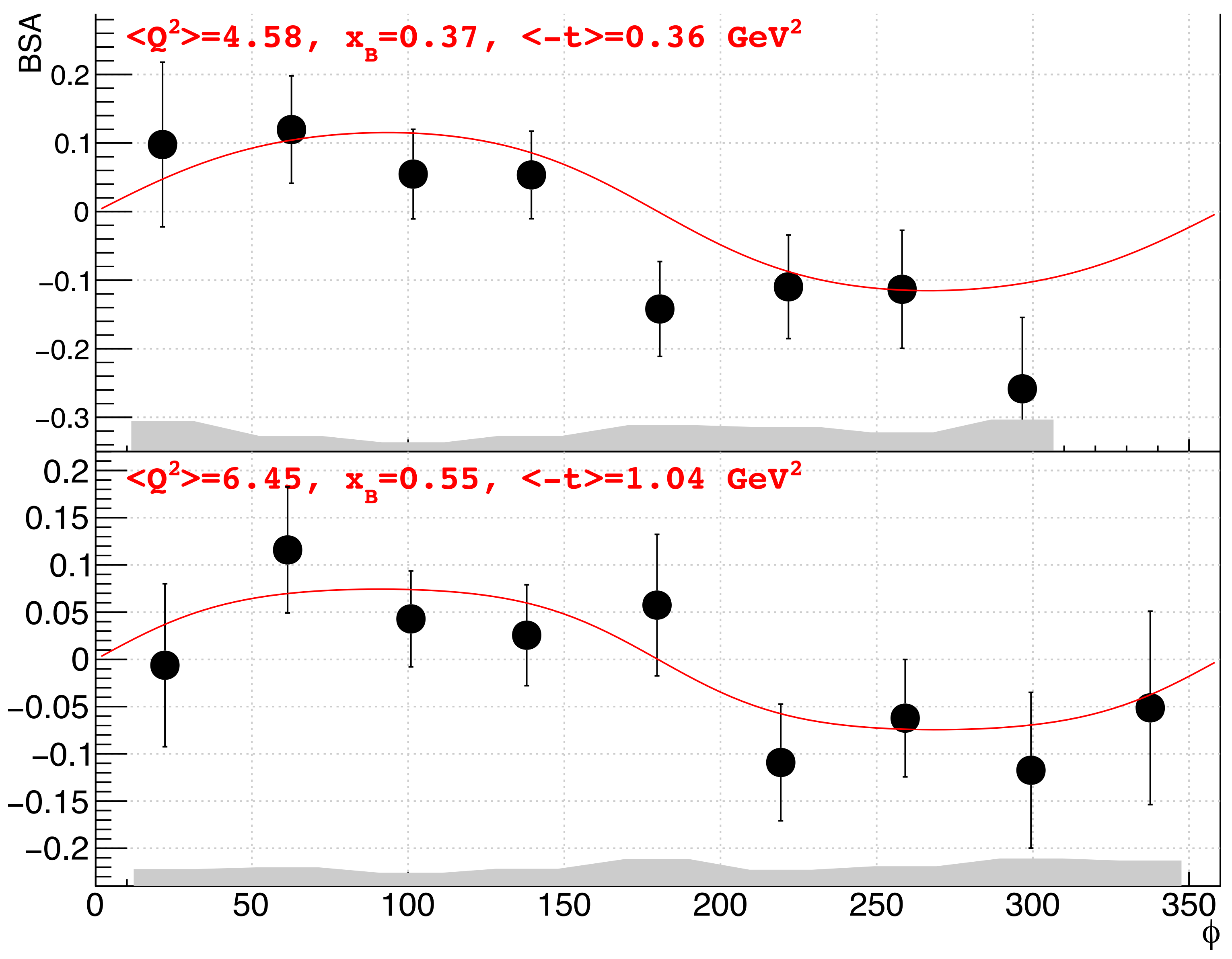
- Hall A Rosenbluth separated $N(e, e'\pi^0)N$ cross sections show $d\sigma_T \gg d\sigma_L$
  - M.Defurne *et al*, *PRL* **117** 262001 (2016) … proton
  - M.Mazouz *et al,* PRL **118**, 222002 (2017) … neutron
- CLAS $d\sigma_U$ on $p(e, e'\pi^0 p)$ and $p(e, e'\eta p)$ also much larger than predictions of $d\sigma_L$ based on GPD models
  - I.Bedlinskiy *et al*, PRL **109**, 112001 (2012), PRC **90**, 025205 (2014)
  - I.Bedlinskiy *et al*, PRC **95**, 035202 (2017)
- S.Ahmad, G.Goldstein, S.Liuti, Phys. Rev. D **79**, 054014 (2009): Pseudo-scalar DAs have helicity flip contributions.
  - Dynamical description in terms of Chiral Symmetry Breaking: S. Goloskokov and P. Kroll, Eur. Phys. J. A 47, 112 (2011).

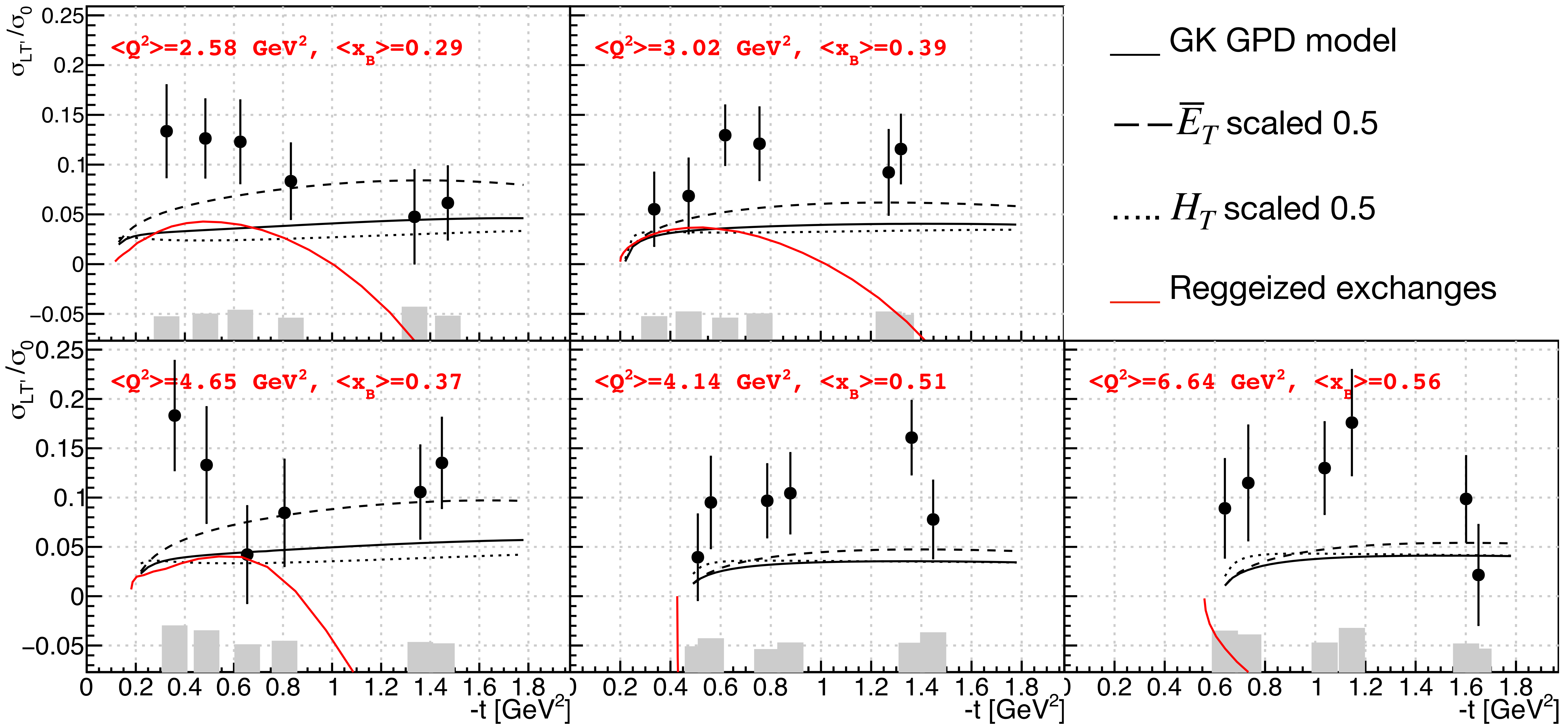
CLAS 12 Results

Deep Exclusive pi0



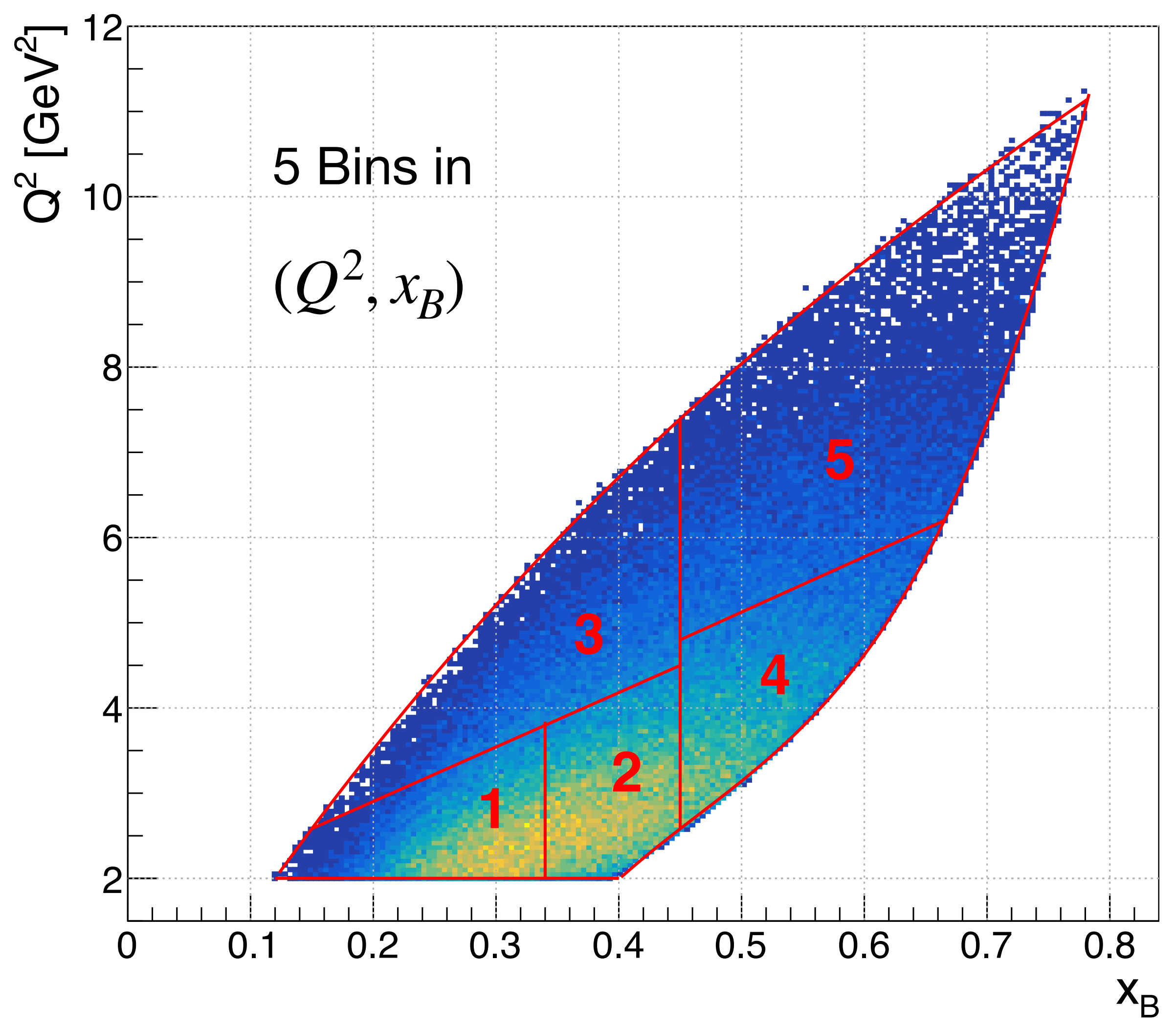
- A.Kim *et al*, *Phys.Lett.B* **849** (2024) 138459
  - $H(e, e'p\gamma\gamma)X$ at 10.6 GeV
  - Exclusivity cuts for $X = 0$ on $|\Delta P_T|$, ΔP_z, $|\Delta\phi_{X\pi}|$, MM^2_{epX}





CLAS 12 Results

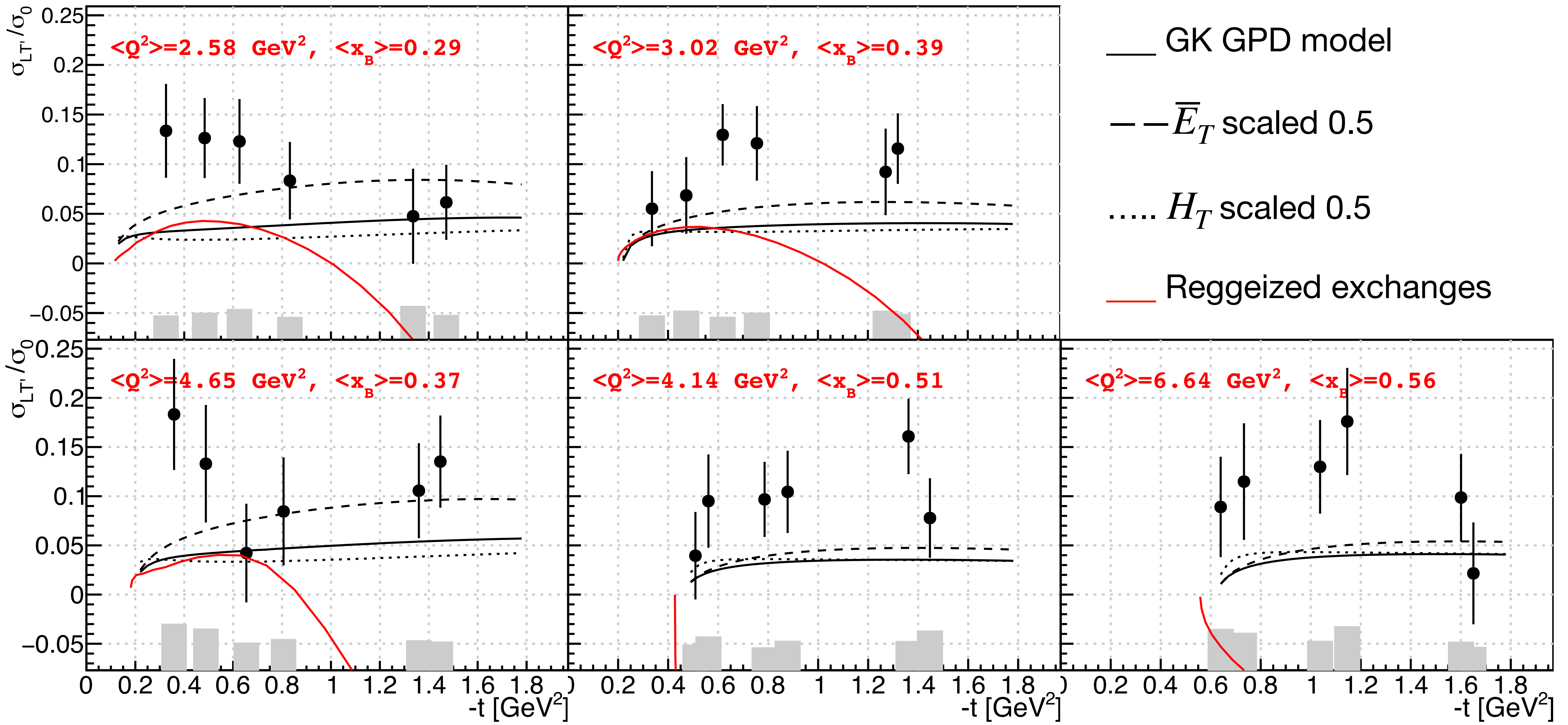
Deep Exclusive pi0



- A.Kim *et al*, *Phys.Lett.B* **849** (2024) 138459
  - H$(e, e'p\gamma\gamma)X$ at 10.6 GeV
  - Exclusivity cuts for $X = 0$ on $|\Delta P_T|$, ΔP_z, $|\Delta\phi_{X\pi}|$, MM^2_{epX}

$$BSA = \frac{\sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}}{\sigma_0}\sin\phi}{1+\sqrt{2\epsilon(1+\epsilon)}\frac{\sigma_{LT}}{\sigma_0}\cos\phi + \epsilon\frac{\sigma_{TT}}{\sigma_0}\cos 2\phi},$$

$$\frac{\sigma_{LT'}}{\sigma_0} \sim \frac{Im[\langle\bar{E}_T\rangle^*\langle\widetilde{H}\rangle + \langle H_T\rangle^*\langle\widetilde{E}\rangle]}{(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2 + \epsilon\sigma_L}.$$



JLab Hall A, 12 GeV

$H(e, e'\pi^0)p$: HRS $\otimes$ 208 PbF_2 Calorimeter

- M.Dlamini *et al*, PRL **127** (2021) 152301

- $d\sigma = \Gamma\left[d\sigma_T + \epsilon d\sigma_L + \sqrt{2\epsilon(1+\epsilon)}d\sigma_{TL}\cos\phi + \epsilon d\sigma_{TT}\cos(2\phi) + h\sqrt{2\epsilon(1-\epsilon)}d\sigma_{TL'}\sin\phi\right]$

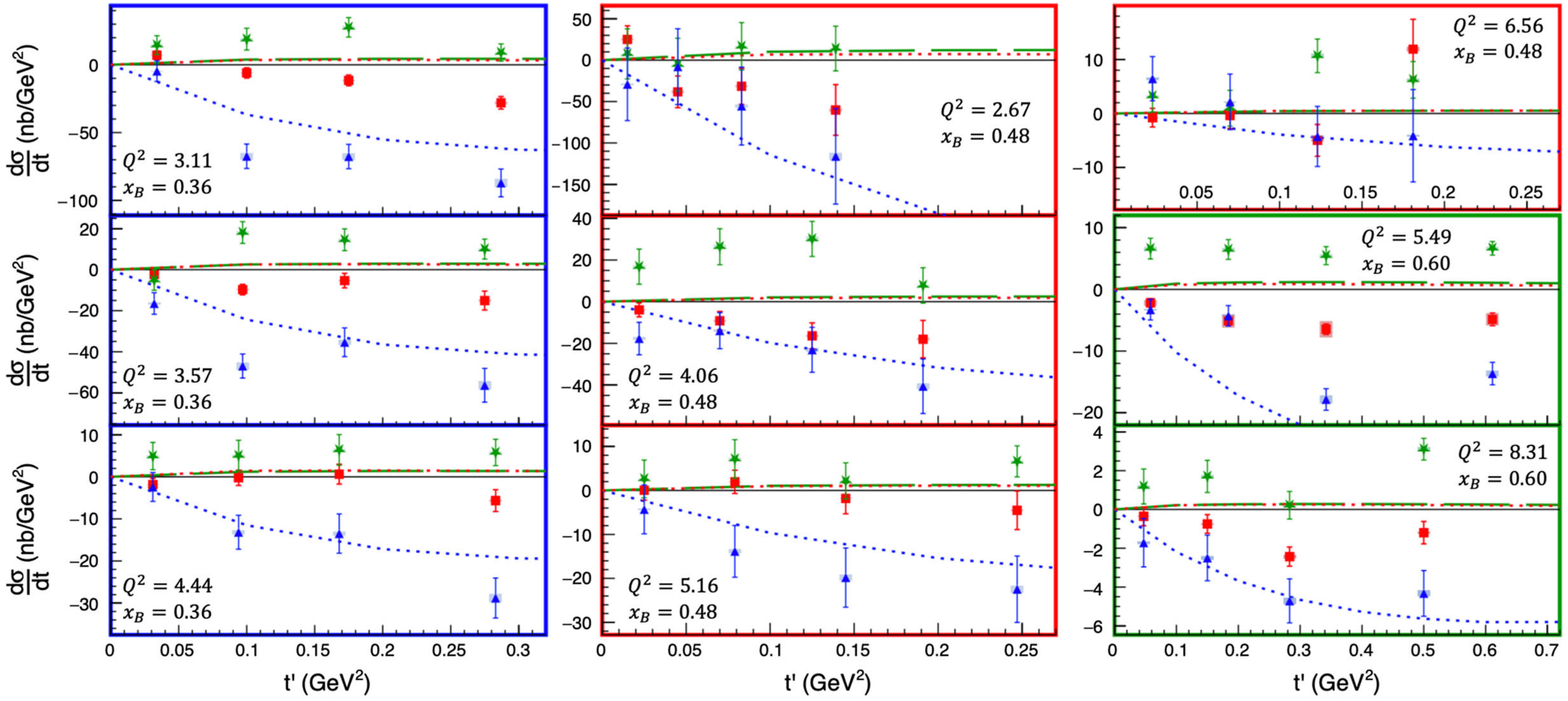
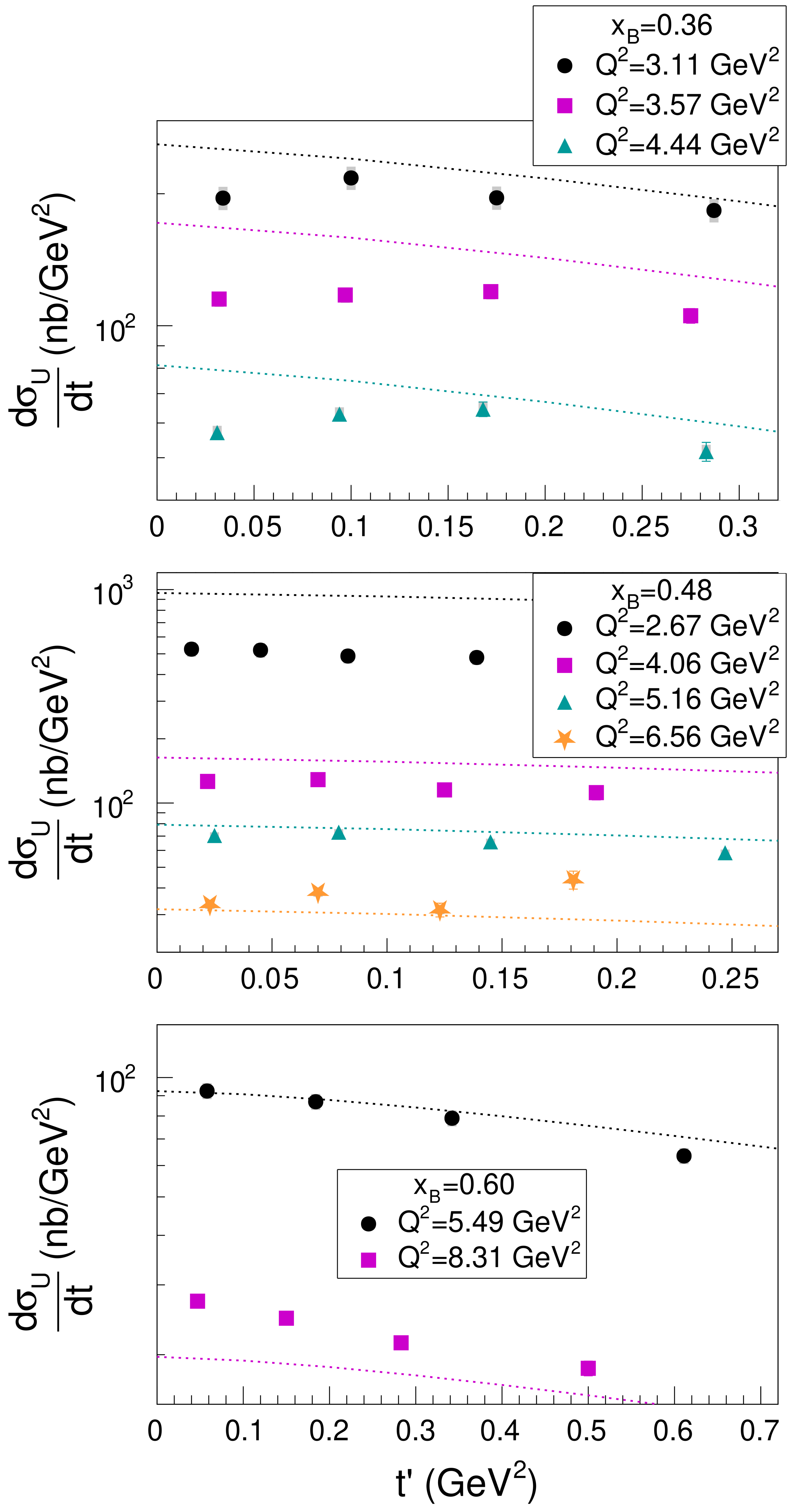


FIG. 2. Structure functions $d\sigma_{TT}$ (blue triangles), $d\sigma_{LT}$ (red squares), and $d\sigma_{LT'}$ (green stars) for all kinematic setting as a function of $t' = t_{\min} - t$. The dashed curves are calculations based on transversity GPDs of the nucleon [15]. The gray boxes surrounding the data points show the systematic uncertainty.



Curves: GK EPJA **47** (2011) 112

DVCS

CLAS12: H$(e, e'\gamma p)$ Single Event Display

•G.Christiaens, PhD Thesis, U.Glasgow Scotland, Feb. 2021: https://theses.gla.ac.uk/82288/

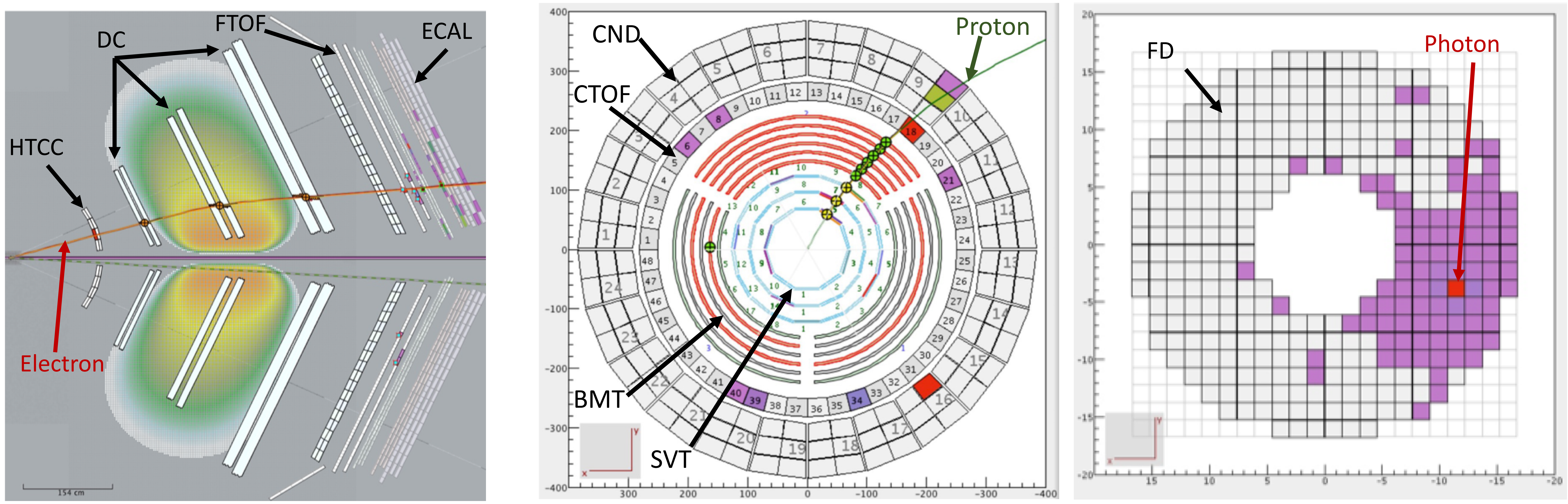


Figure 4.1: Schematic of a typical DVCS event, visualized using the CED tool (CLAS12 event display, see section 2.3.4). Lines (red squares for the FT) represent reconstructed particle tracks and colored shapes represent hits in the detector. The electron is reconstructed in the forward detector (left), the proton in the central detector (middle) and the photon in the forward tagger (right).

G.Christiaens *et al*, PRL 130 (2023) 211902

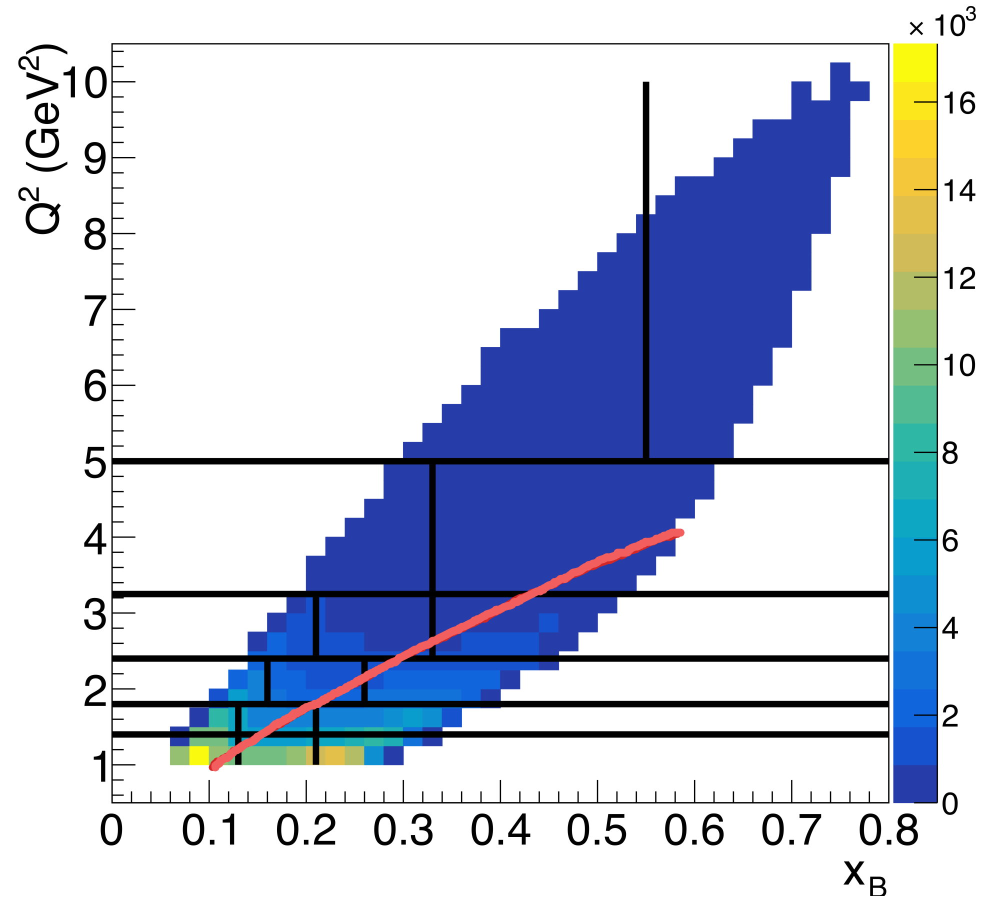
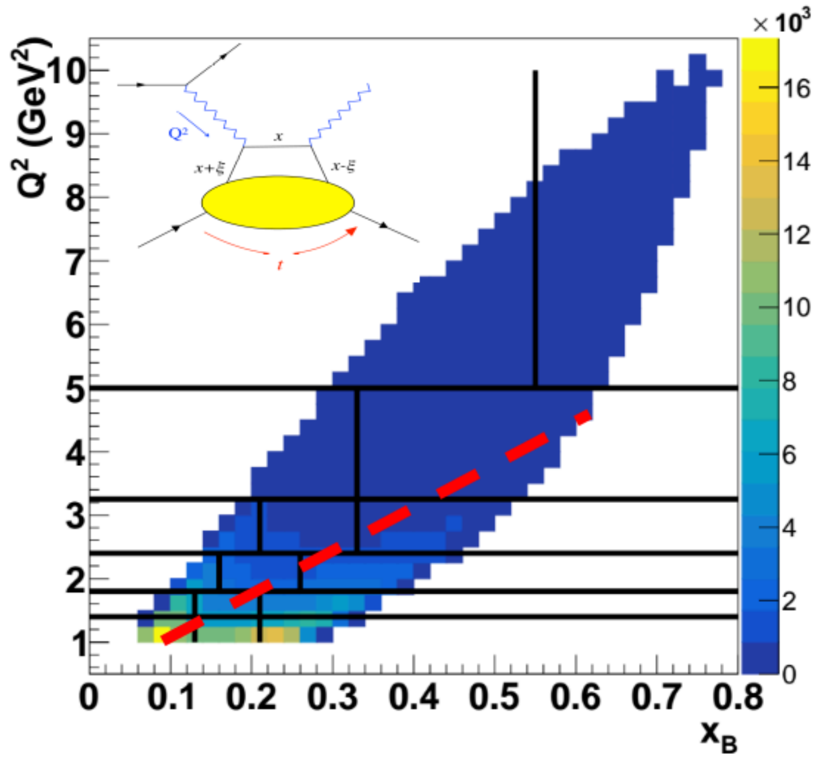
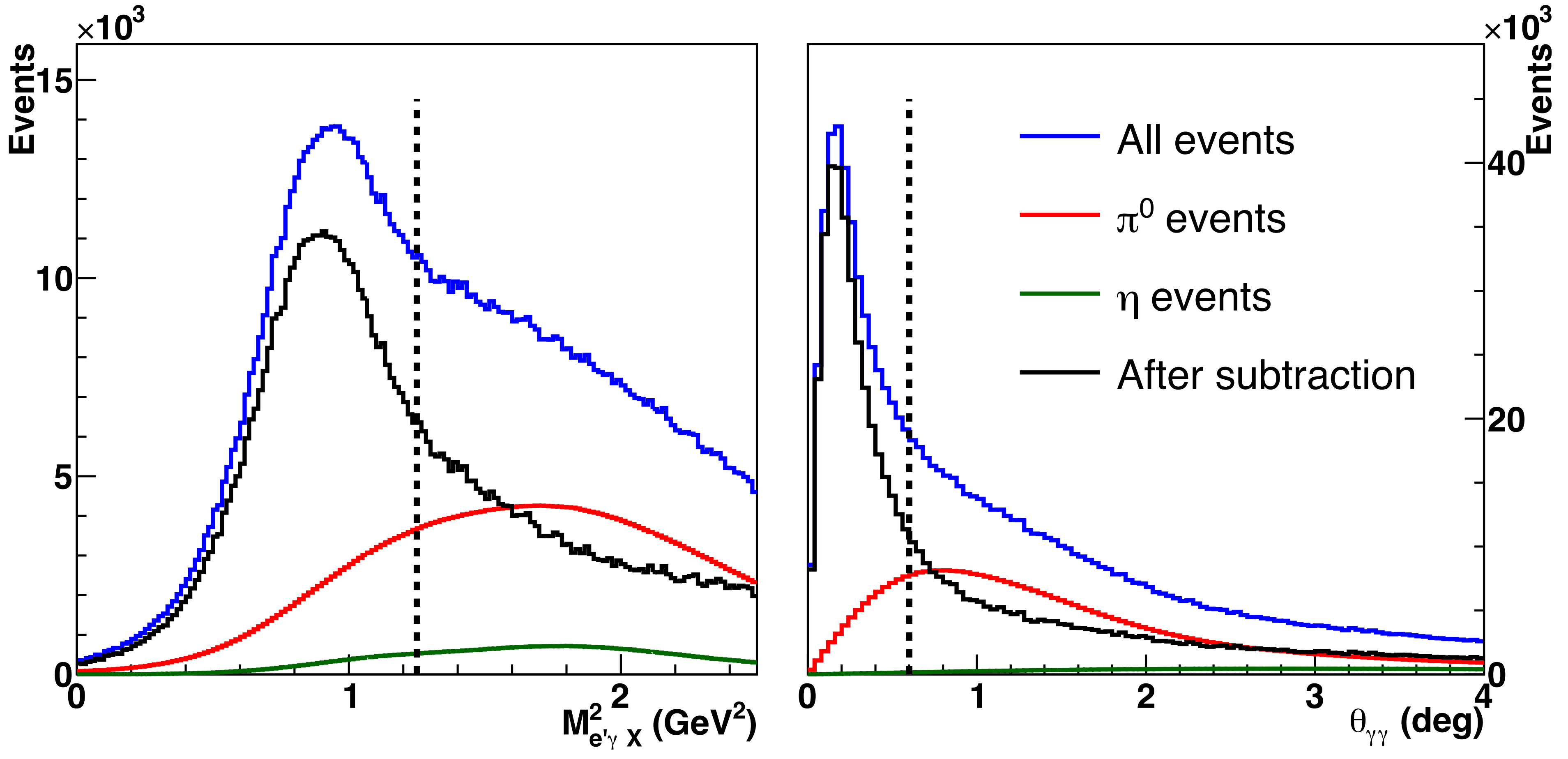


FIG. 3. CLAS12 phase space in Q^2 vs. x_B, showing the division into 16 bins. The red line indicates the approximate upper reach of CLAS data at 6 GeV.

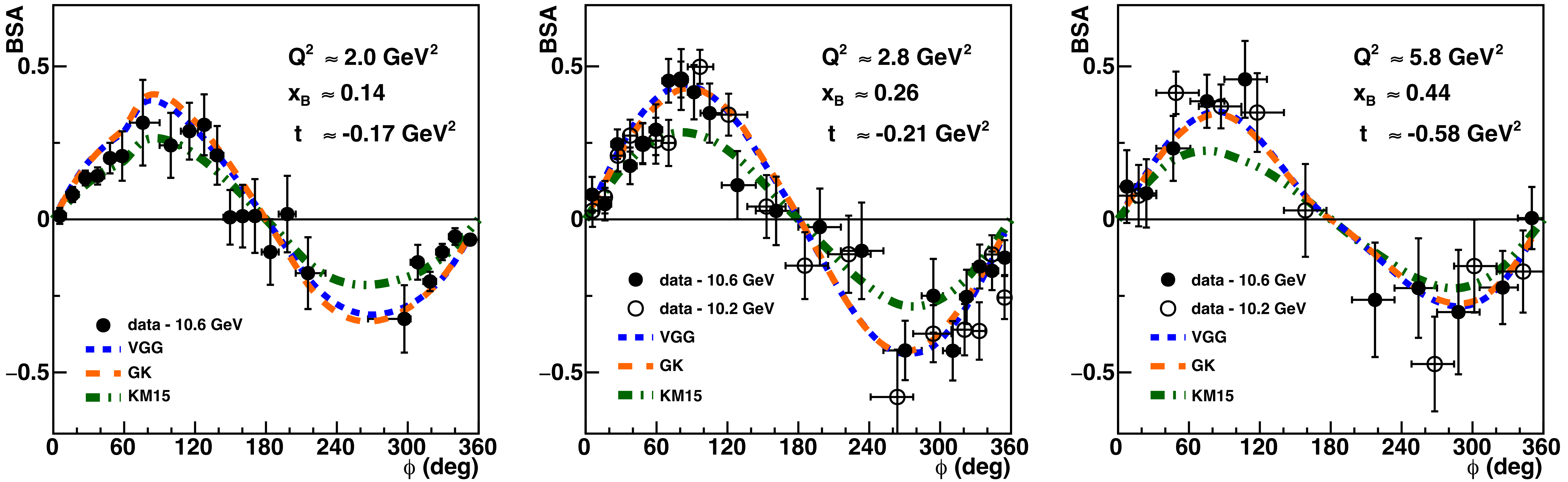
CLAS 12

DVCS First Results I





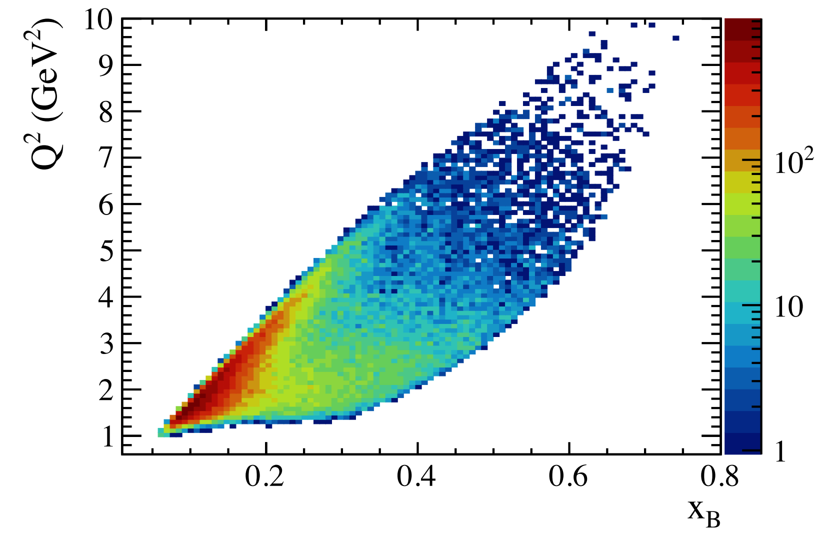
- G.Christiaens et al., PRL **130** (2023) 211902
  - H$(e, e\gamma p)$
  - 2018 data at E=10.6 GeV and 2019 data at E=10.2 GeV
    - 64 (Q^2, x_B, t) bins, each with 10 to 33 $\phi_{\gamma\gamma}$ bins: 1535 distinct A_{LU} values



JLab CLAS12

DVCS First Results: II

- A.Hobart *et al., Phys.Rev.Lett.* **133** (2024) 21, 211903
- $D(e, e'n\gamma)p$ Beam Spin Asymmetry A_{LU}



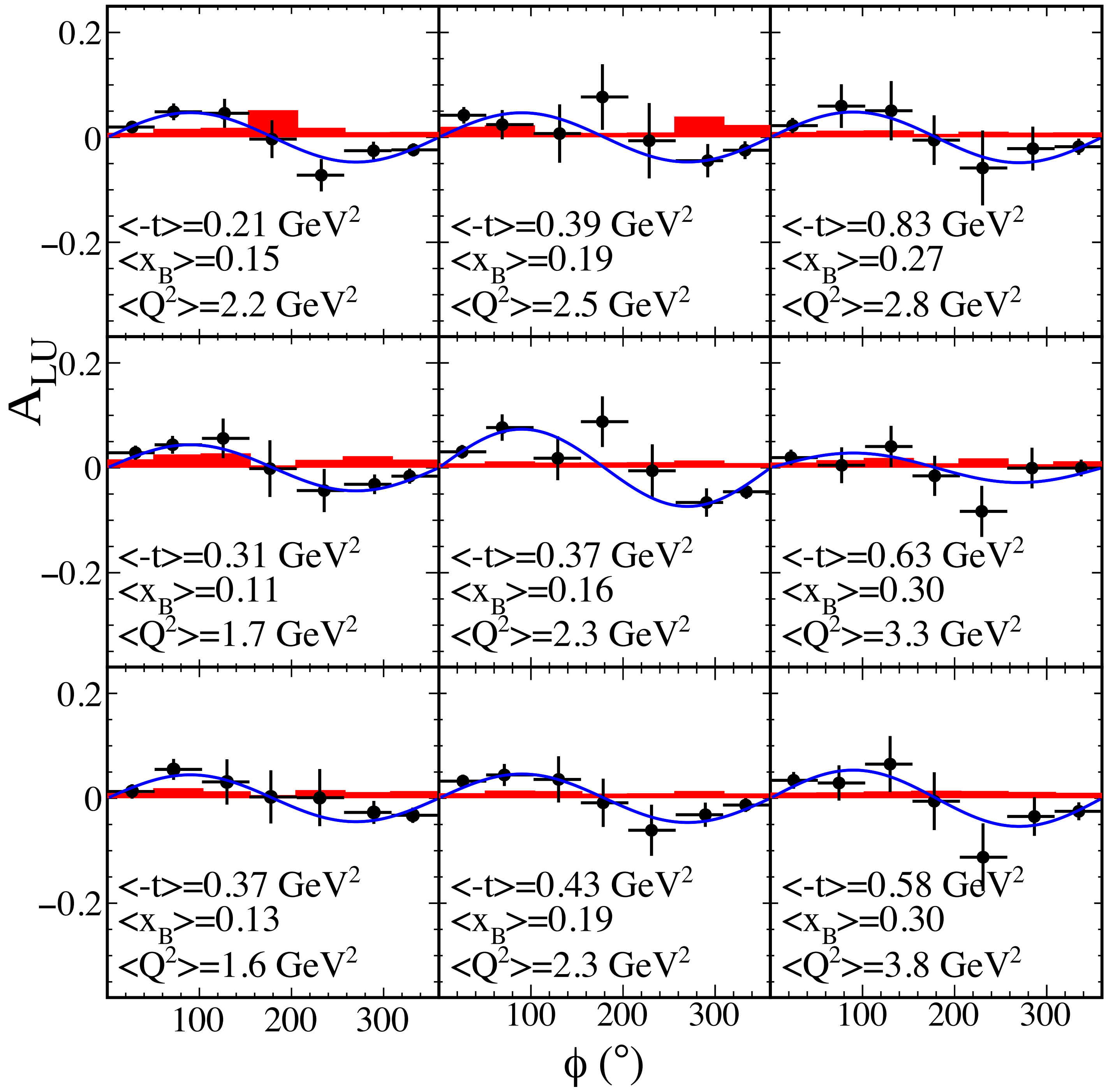


FIG. 4. Beam-spin asymmetry for nDVCS versus ϕ for (top) three bins in $-t$ ([0, 0.3], [0.3, 0.5], and [0.5, 1.1] GeV^2), (middle) three bins in x_B ([0.05, 0.14], [0.14, 0.2], and [0.2, 0.6]), and (bottom) three bins in Q^2 ([1, 1.9], [1.9, 2.9], and [2.9, 6] GeV^2). The error bars are statistical. The data are fit with the function $A_{LU}(90°)\sin\phi$. The histogram shows the total systematic uncertainty.

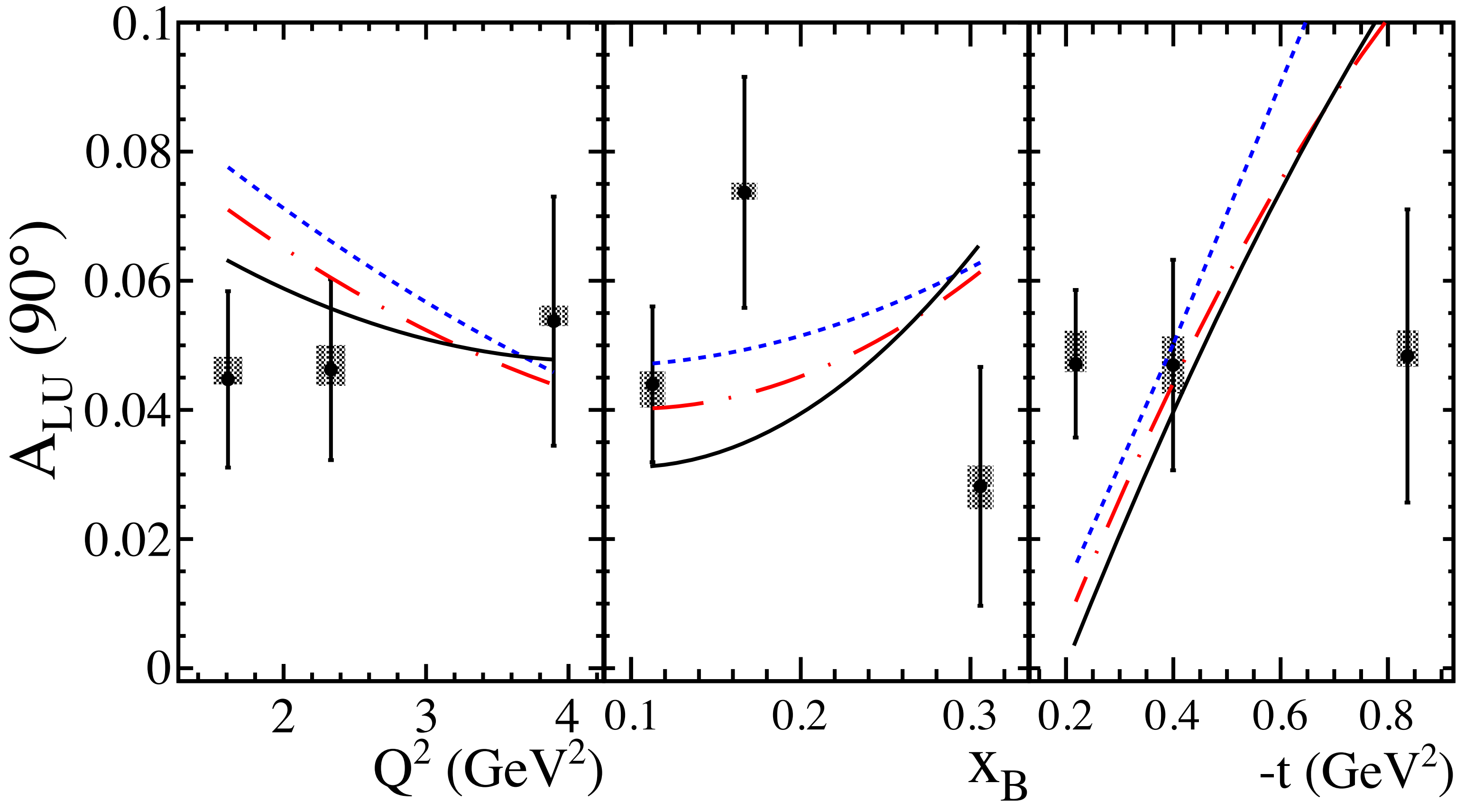
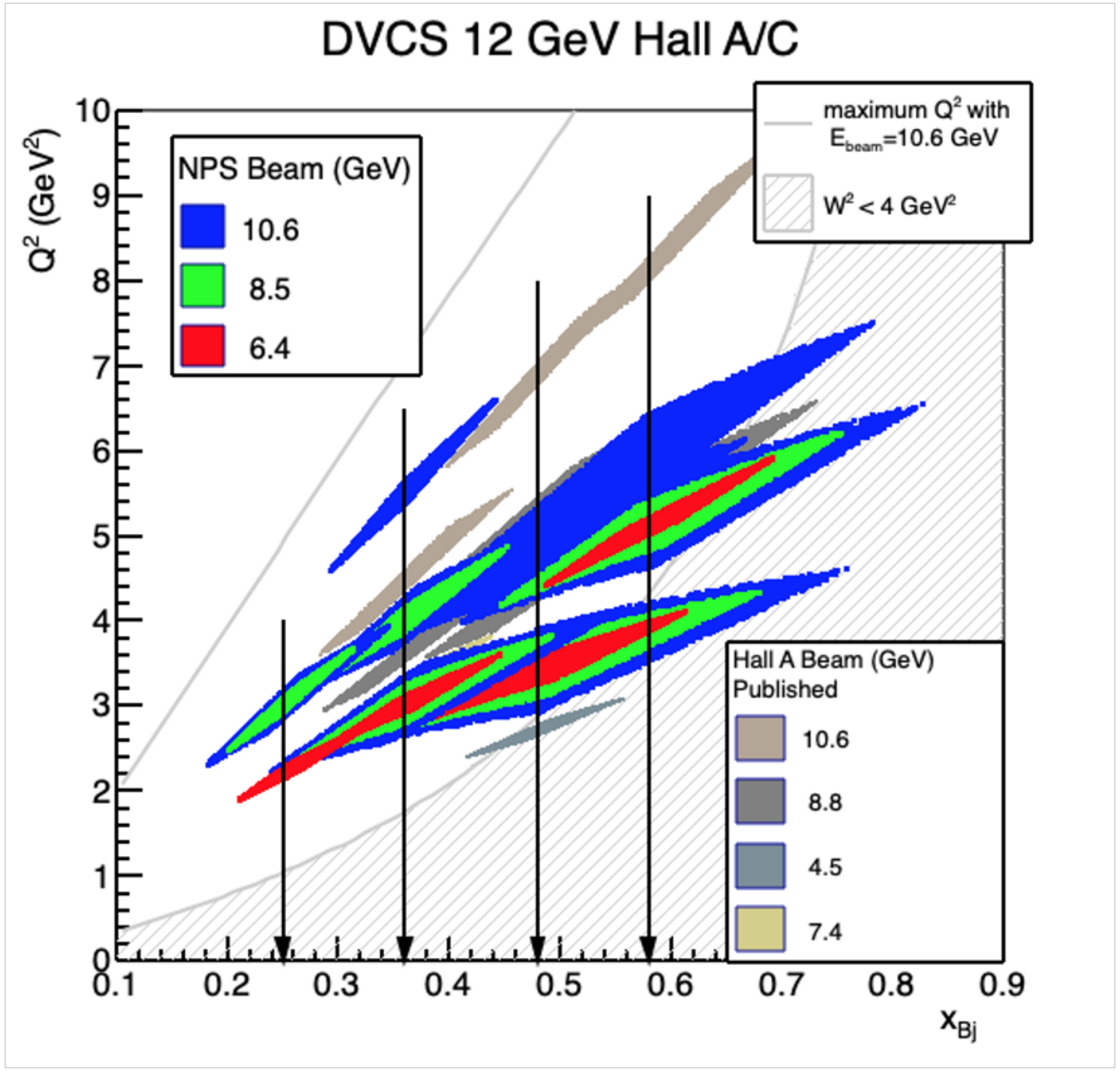


FIG. 5. The $\sin\phi$ amplitude of A_{LU} for nDVCS as a function of Q^2 (left), x_B (middle), and $-t$ (right). The (red online) bands represent the systematic uncertainties. The VGG model [51] predictions for three of the combinations of J_u and J_d yielding the best χ^2 are compared to the data: solid (black online) line for $J_u = 0.35$ $J_d = 0.05$, dashed-dotted (red online) line for $J_u = -0.2$ $J_d = 0.15$, and (blue online) dotted line for $J_u = -0.45$ $J_d = 0.2$.

JLab Hall A / C

12 GeV DVCS ⊕ Deep π^0

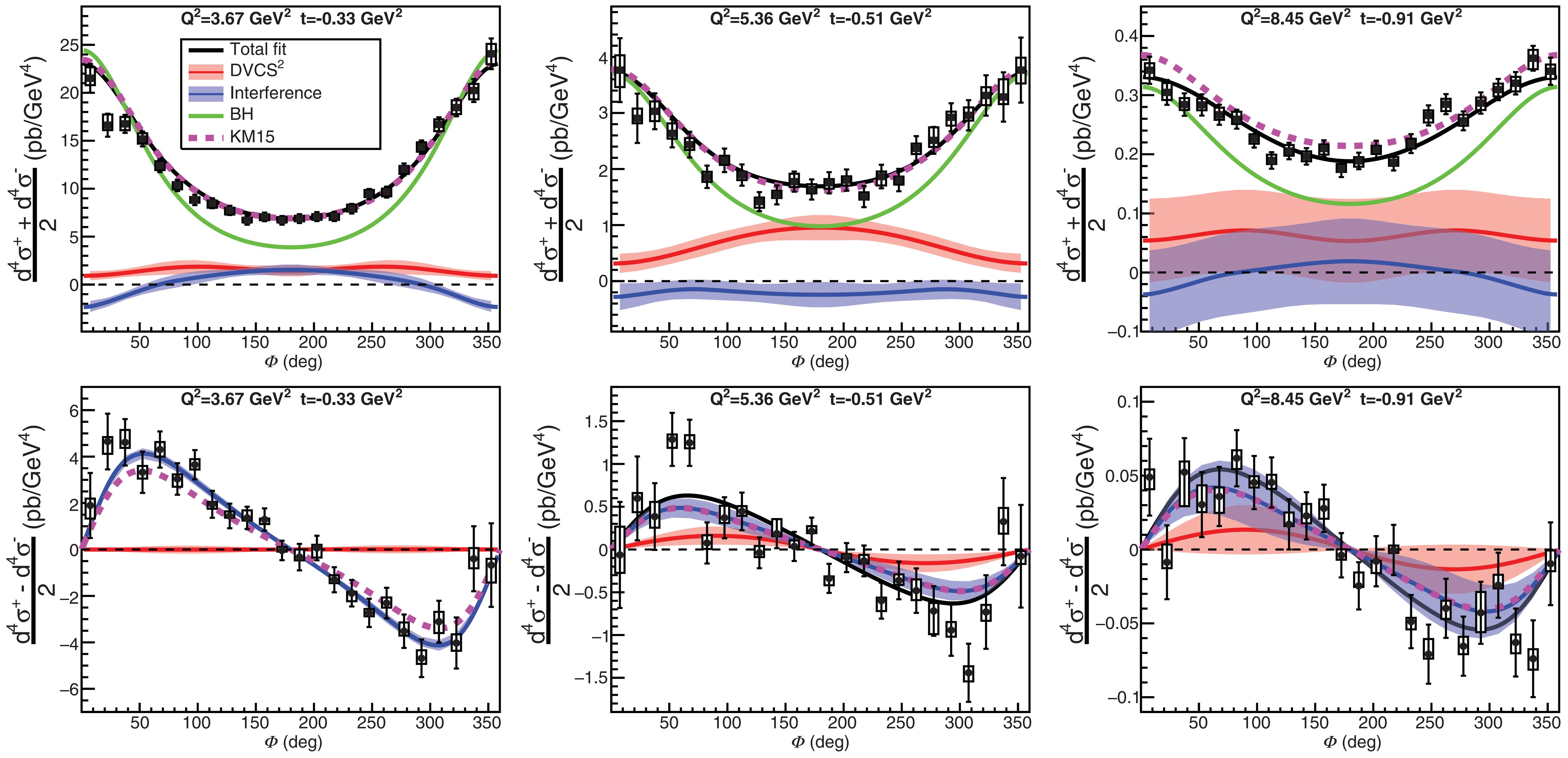
- Hall A published (LH_2)
- Hall C NPS run 2023-2024
  - LH_2 and LD_2 targets
  - Multiple beam energies at each (Q^2, x_B) setting for Rosenbluth separations



JLab Hall A 12 GeV

H$(e, e\gamma)p$

- F.Georges *et al,* PRL **127** (2021) 152301
  - 2064 distinct $(E, Q^2, x_B, t, \phi_{\gamma\gamma})$ cross section data points
- Full Q2, Energy dependence to analyze all 12 Compton amplitudes



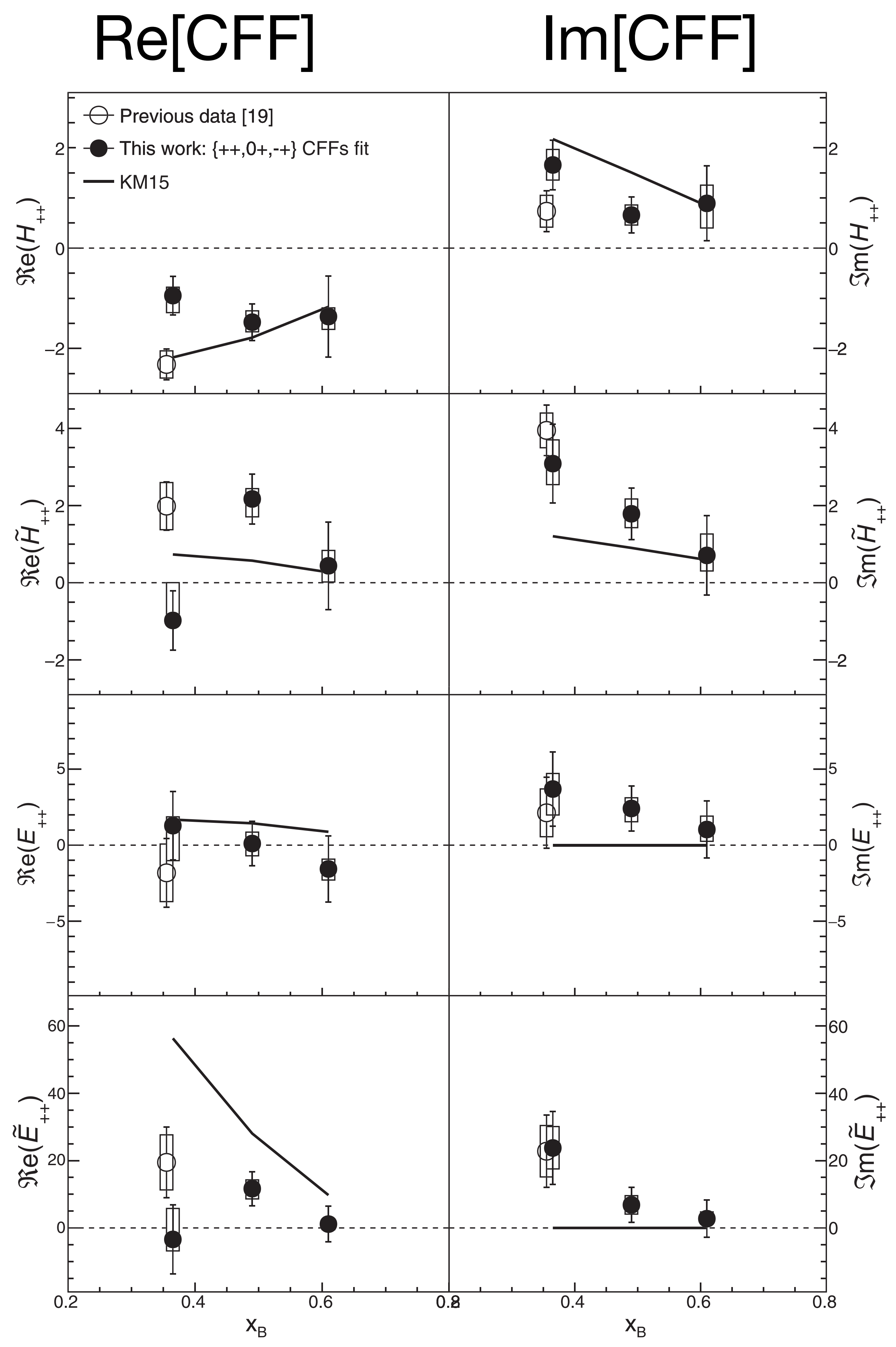
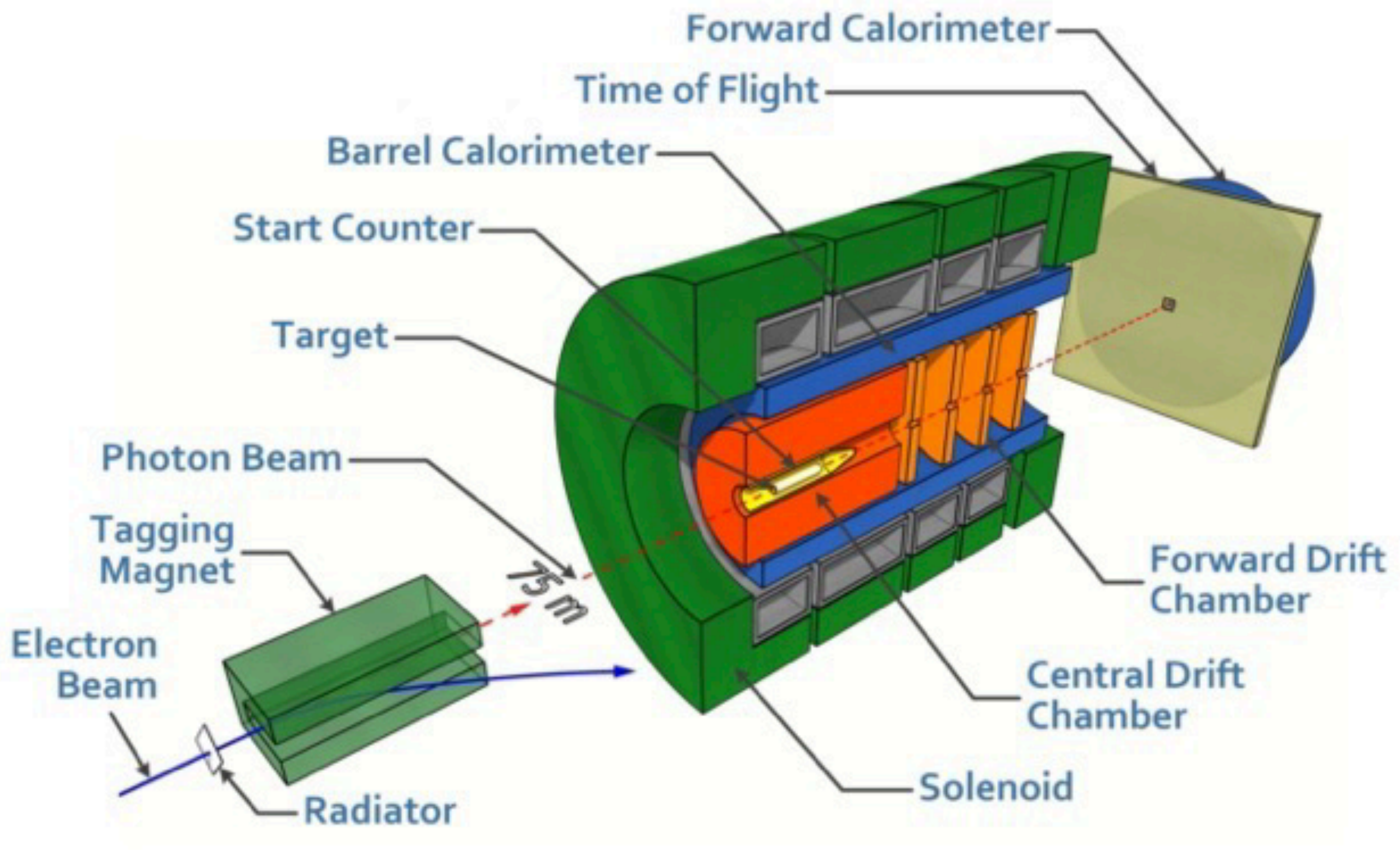


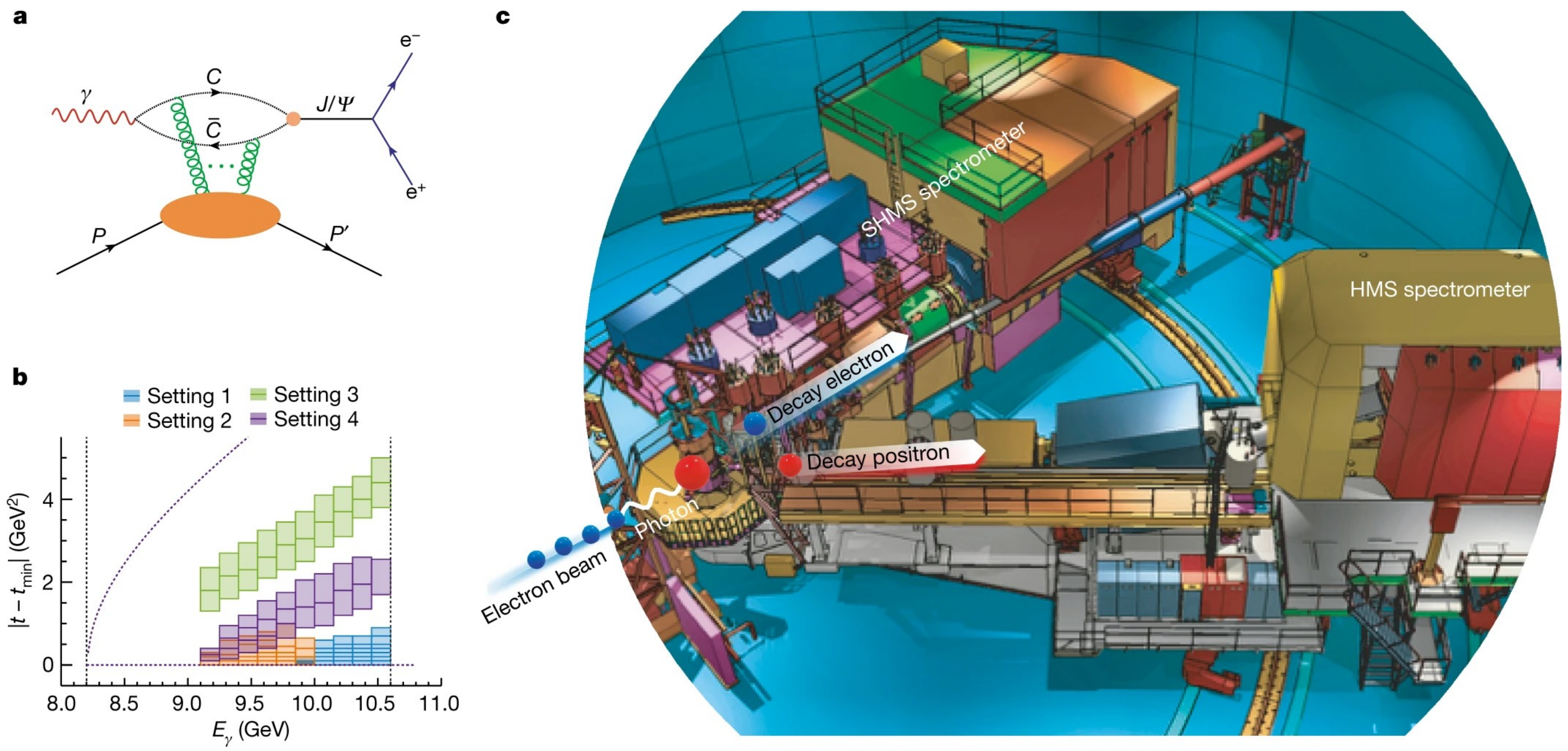
FIG. 4. Values of the helicity-conserving CFFs, averaged over t, as a function of x_B. Bars around the points indicate statistical uncertainty and boxes show the total systematic uncertainty. The fit results of previous data [19] at $x_B = 0.36$ are displayed with the open markers. The average t values are -0.281 GeV^2 [19] and -0.345, -0.702, -1.050 GeV^2 at $x_B = 0.36$, 0.48, 0.60, respectively. The solid lines show the KM15 model [29].

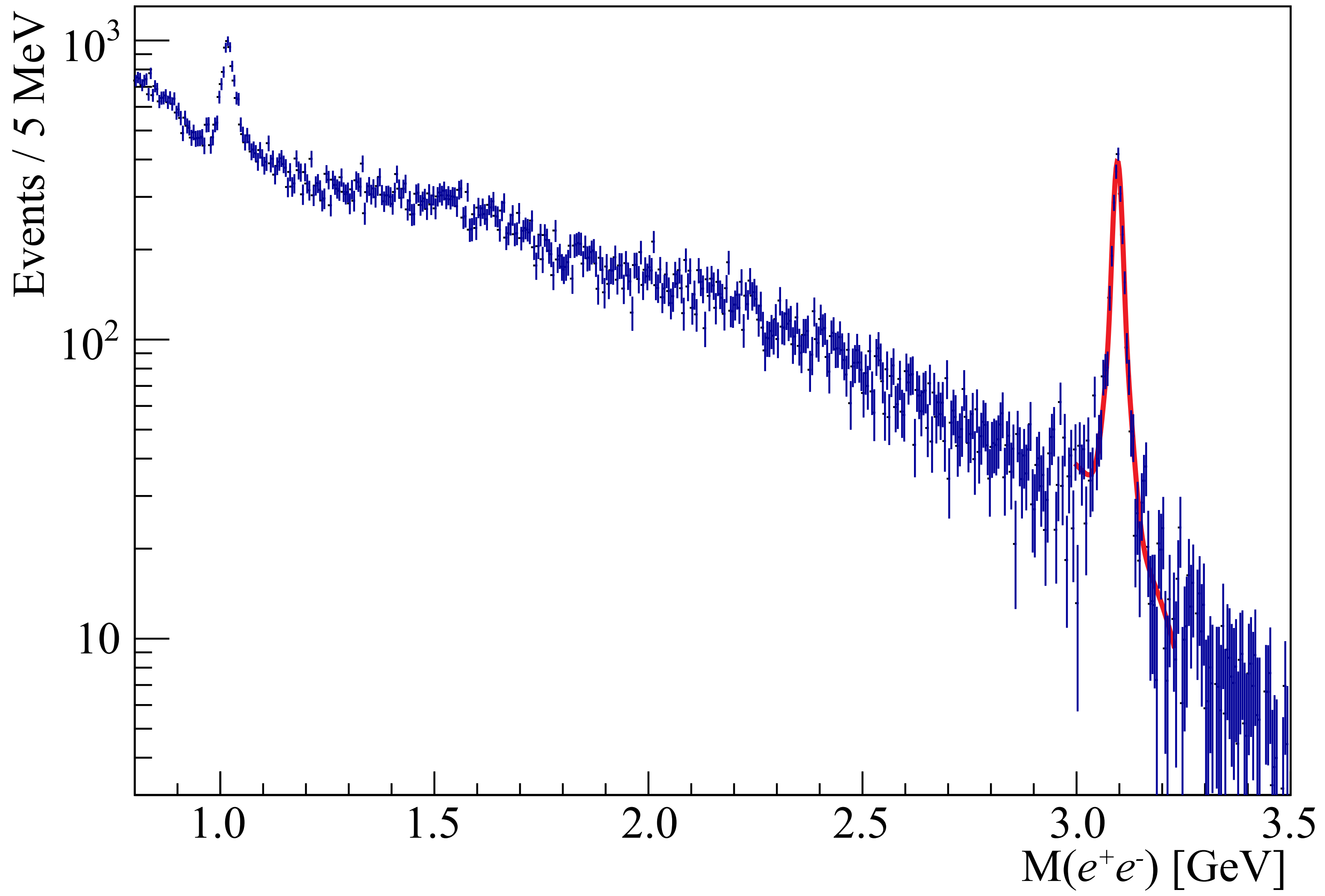
Exclusive J/Ψ

JLab Threshold Photoproduction

- GlueX PRC **108,** 025201 (2023)
- Hall C: Nature **615**, 813 (2023)



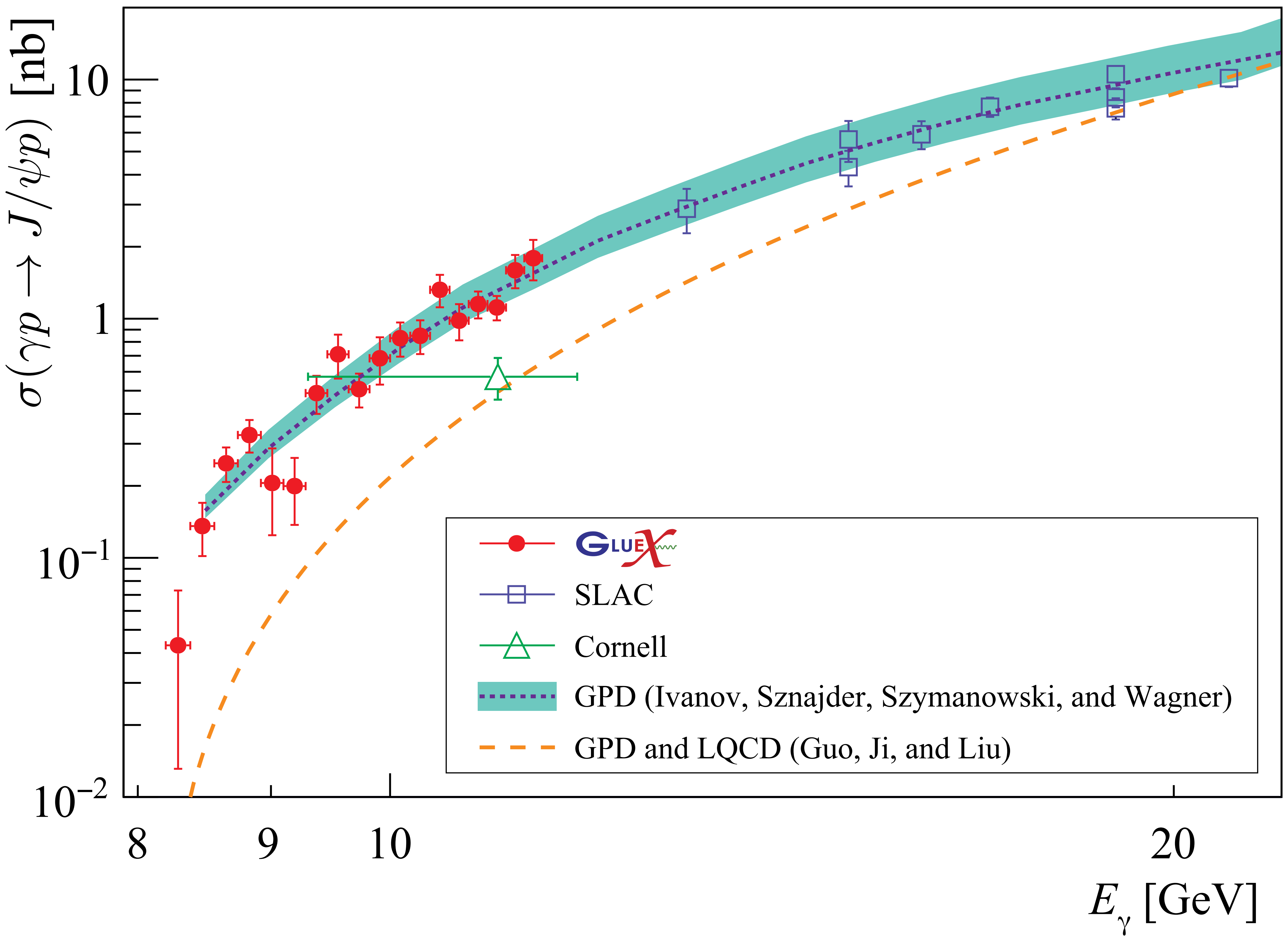


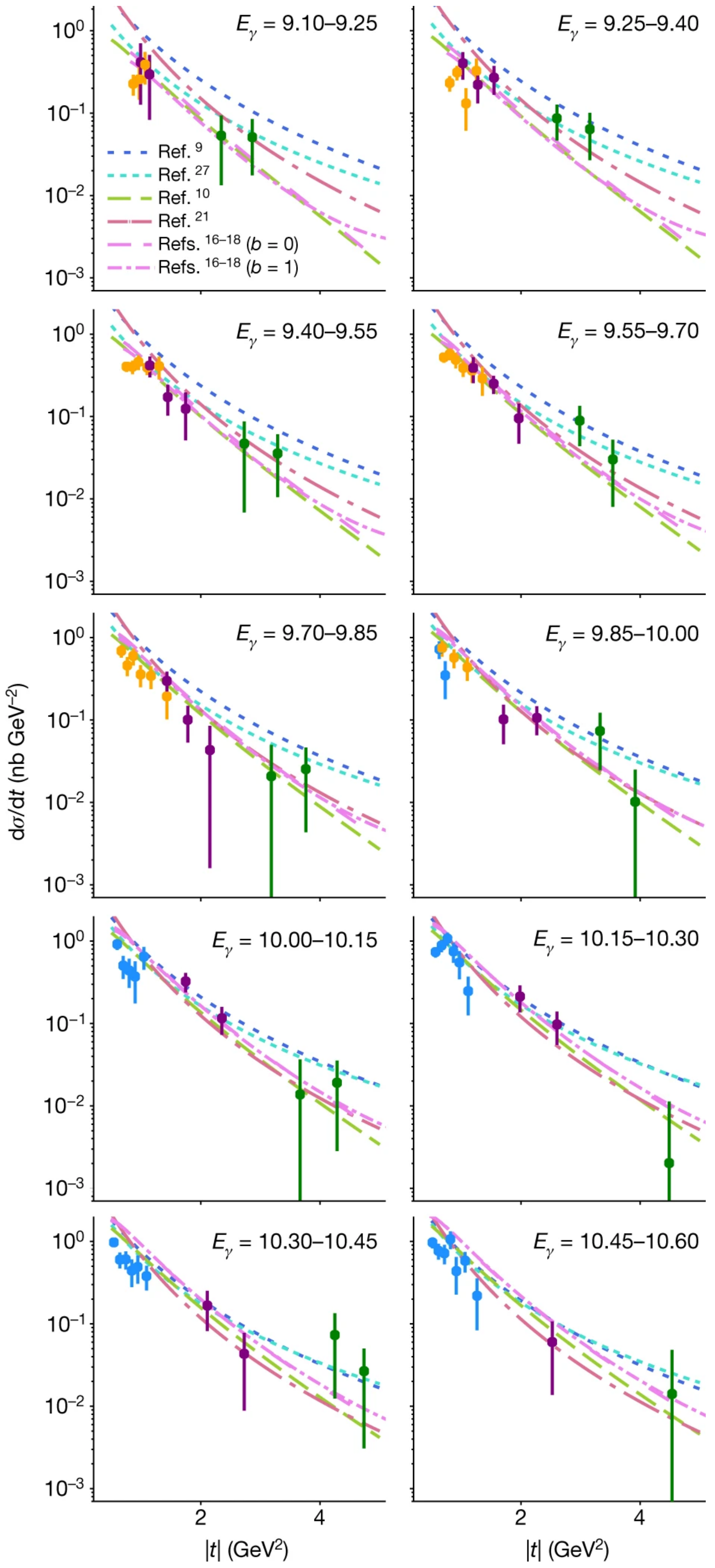


Exclusive J/Ψ

Gluon gravitational form factors —>

- GlueX PRC **108,** 025201 (2023)





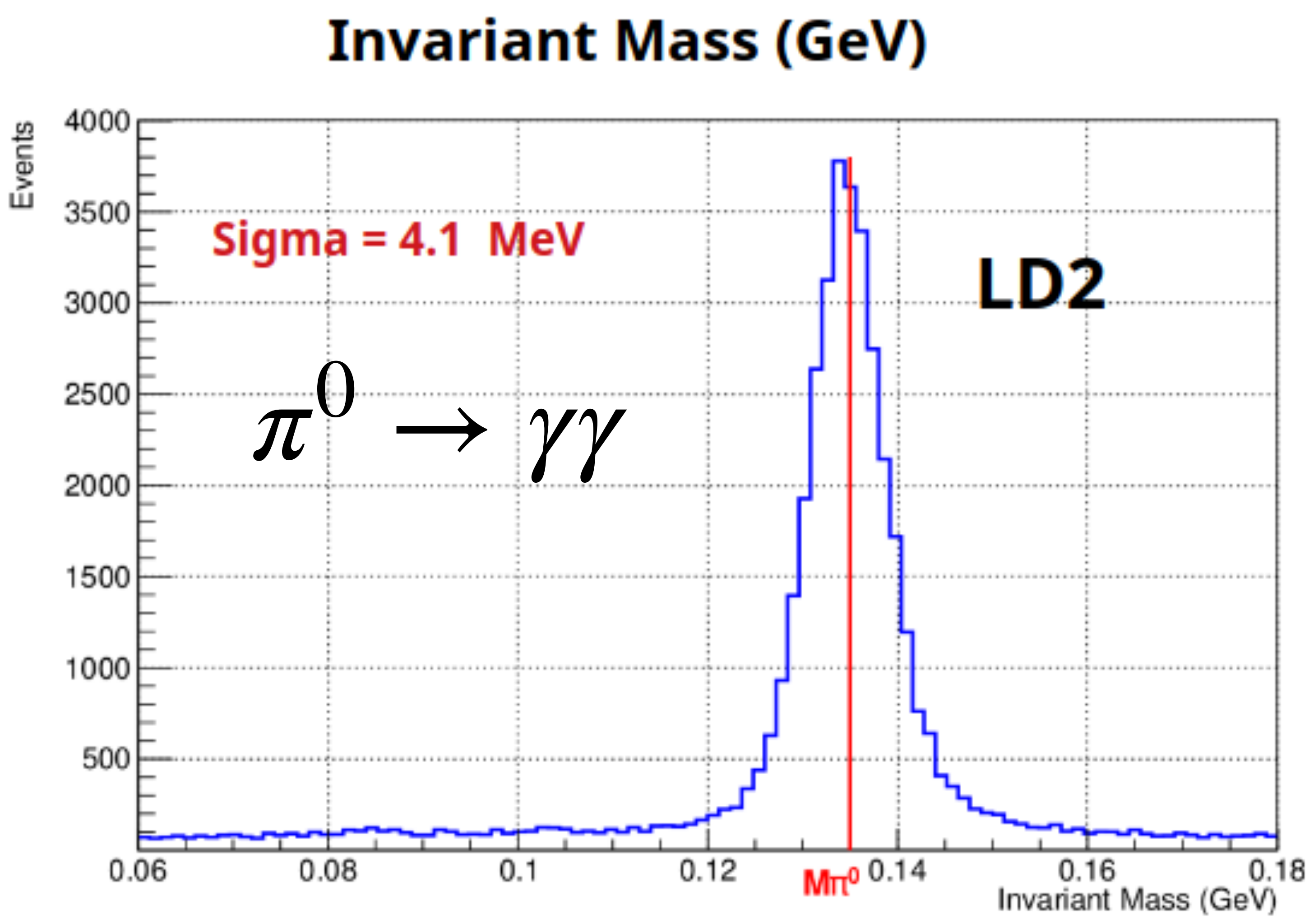
Hall C
007 exp

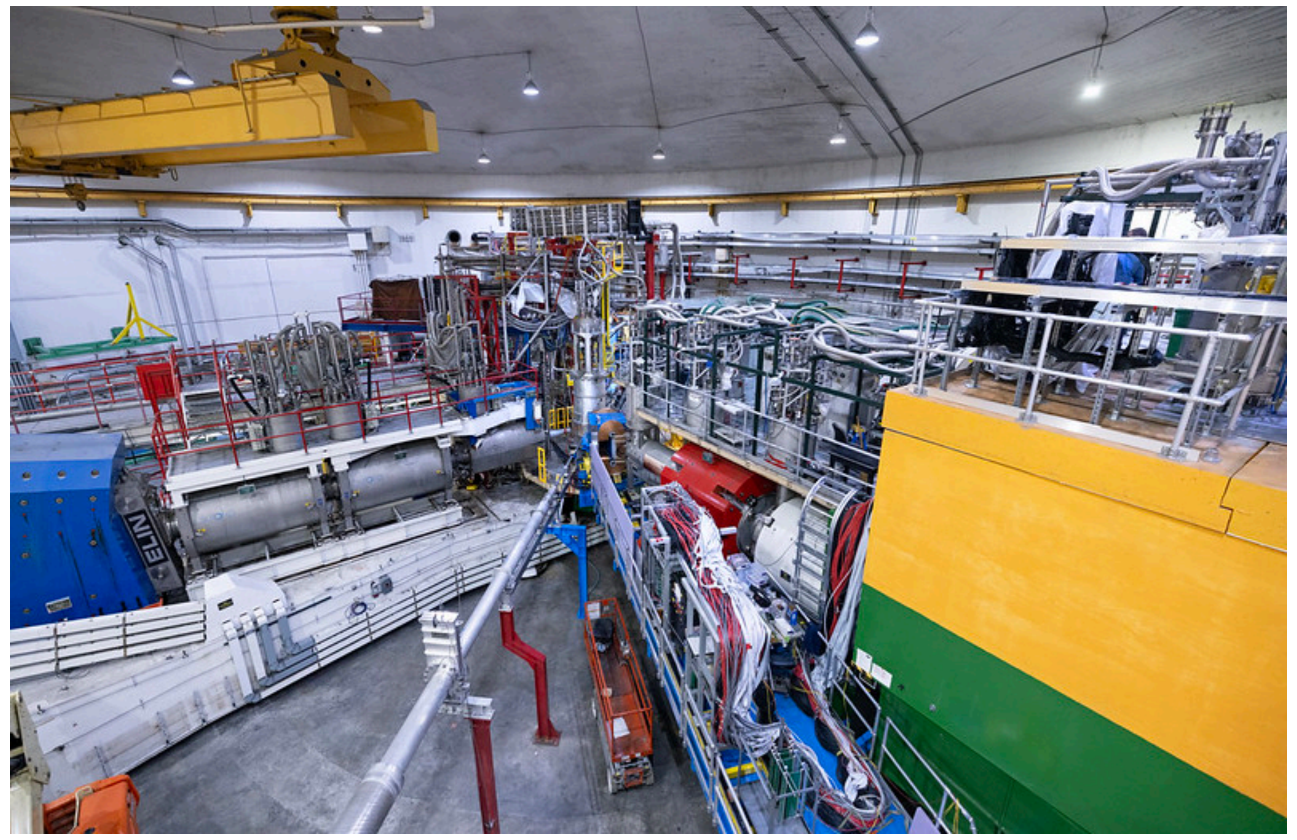
- Nature **615**, 813 (2023)

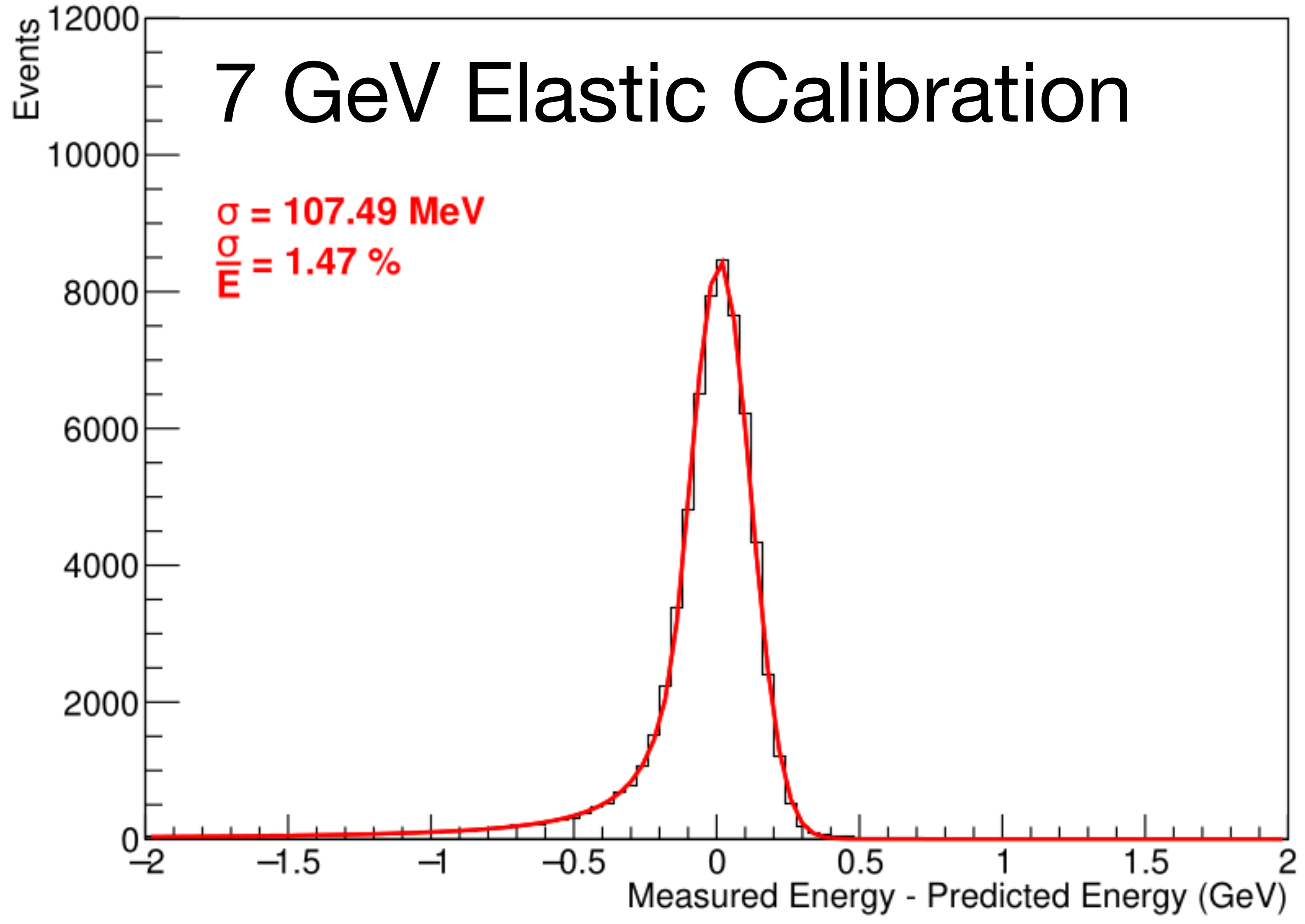
Hall C NPS

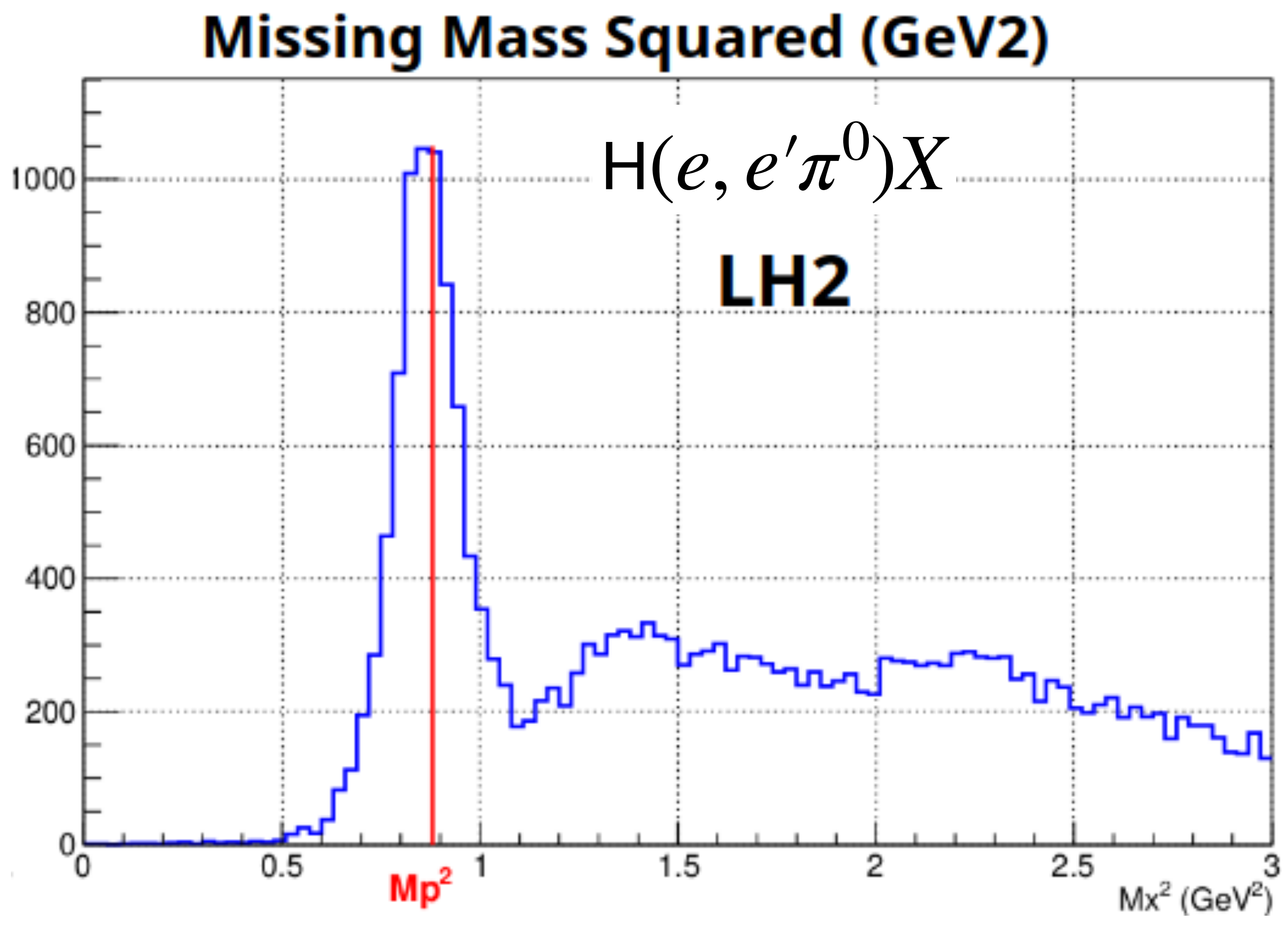
2023-2024

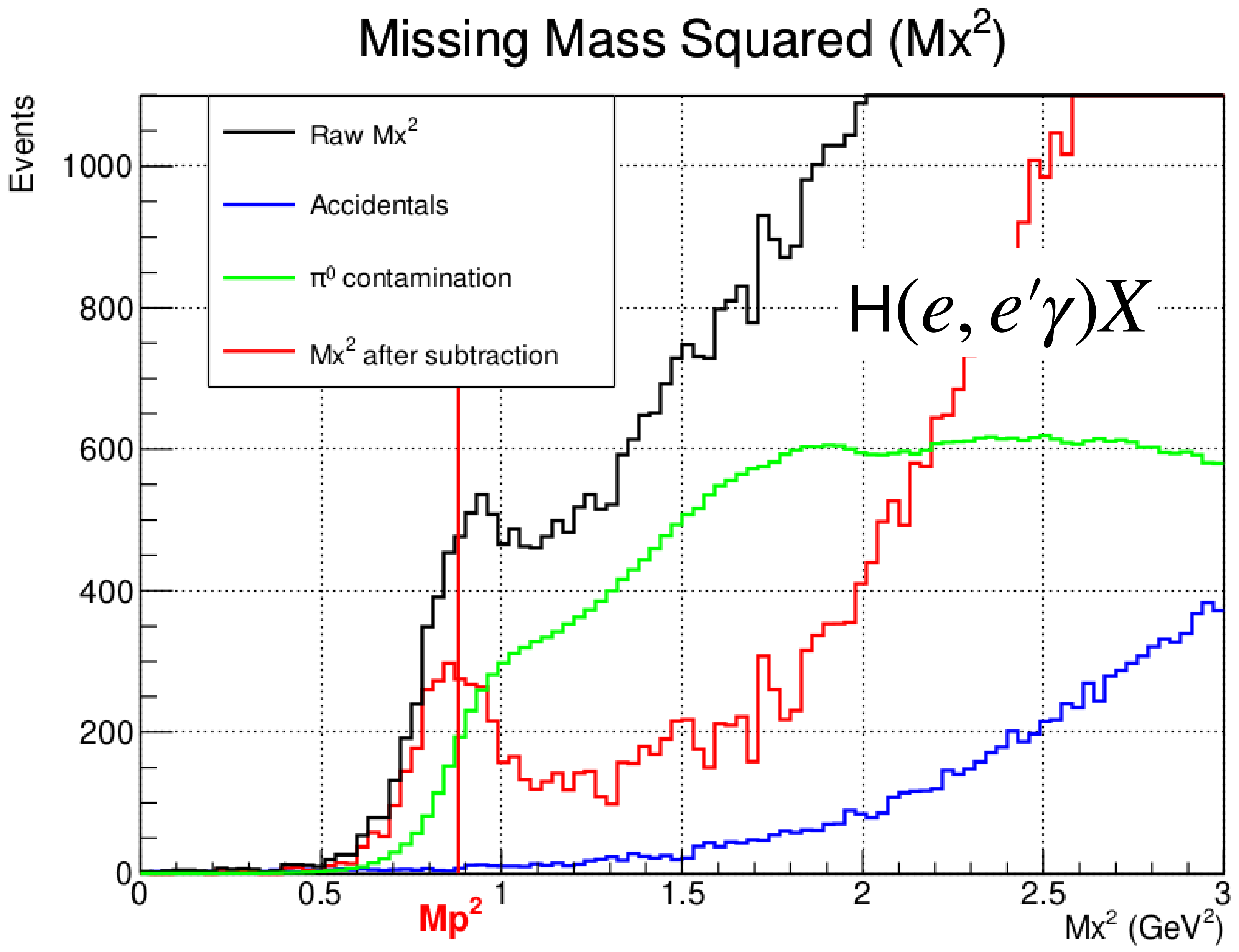
- 1080 $PbWO_4$ array











Jefferson Lab Outlook

- Hall C NPS DVCS, Deep π^0 results soon
  - WACS: H$(\gamma, \gamma p)$ @ 11 GeV in future
- CLAS12
  - Data in analysis
    - H2, D2 data: Exclusive Vector Mesons, DVCS, deep pi0 cross sections
    - Longitudinally polarized NH3, ND3 targets
  - ALERT data taking in progress (He exclusive DVCS)
- GlueX Phase-2 data in analysis, Phase-3 in future
- Active R&D for positron beams
- Active R&D for ~20 GeV

On to the EIC!

- High luminosity
- Forward detection built into integration of detector and accelerator
- Longitudinally and transversely polarized p, ^{3}He beams
- Expect fine kinematic binning to resolve evolution with xB of transverse size of quark and gluon distributions of the proton
- Deep Exclusive processes on nuclei identifiable by breakup veto
- ePIC Diffraction WG producing expectations for first 5 fb^{-1} of data in first year of proton running.

Additional Slides

COMPASS

Exclusive omega

- A.Sandacz, *et al* IJMP(conf) **51** (2023) 2361002
- $$R = \frac{1}{\epsilon}\frac{r^{04}_{00}}{1 - r^{04}_{00}} + \cancel{\text{SCHC}} \text{ terms}$$
- Goloskokov, Kroll (GP) calculations include transversity GPDs

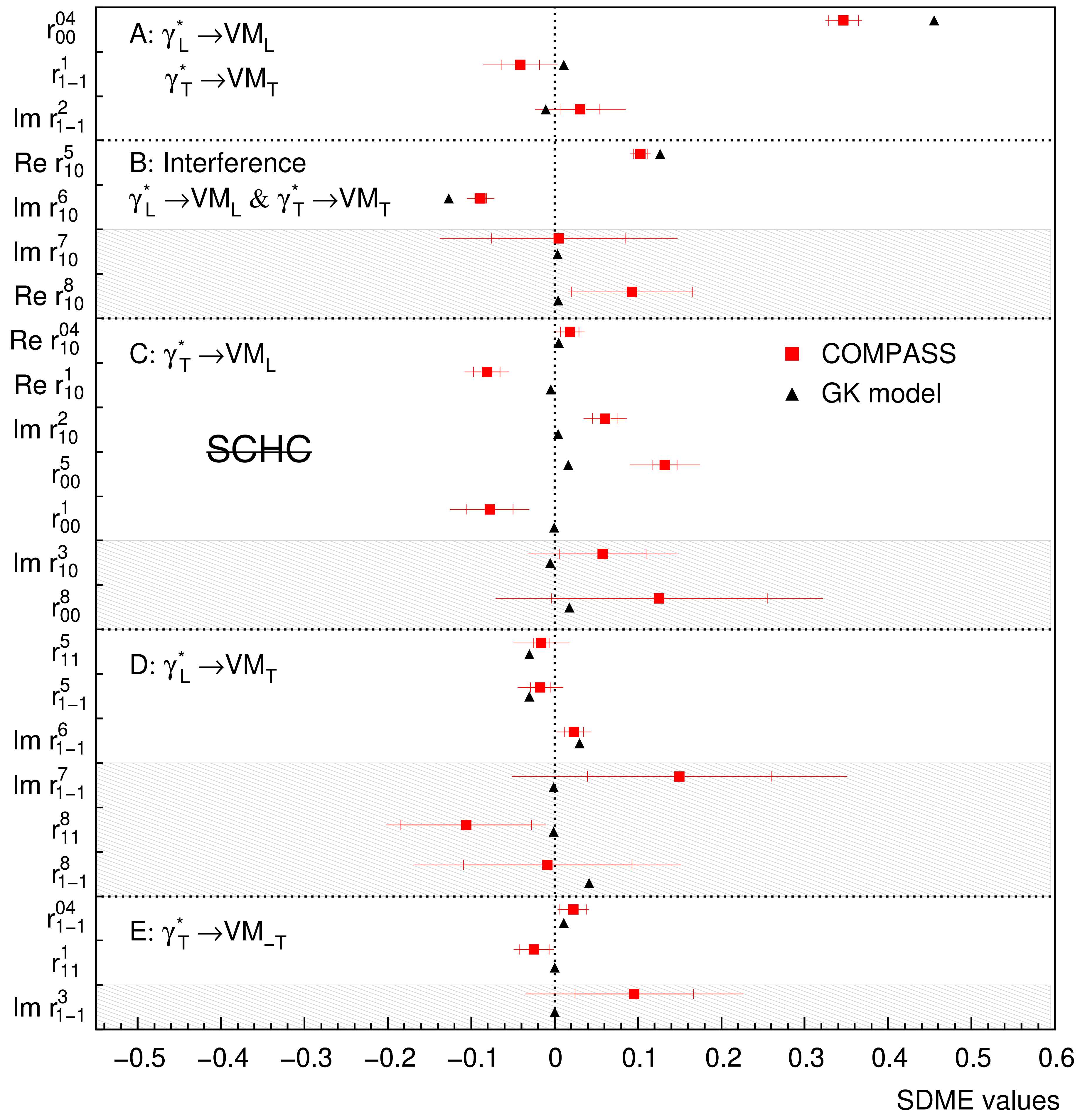


Fig. 4. Comparison of the measured SDMEs for exclusive ω production with predictions of the GPD model of Goloskokov and Kroll.[15] The calculations are obtained for $Q^2 = 2.0\ (\mathrm{GeV}/c)^2$, $W = 7.5\ \mathrm{GeV}/c^2$ and $p_T^2 = 0.14\ (\mathrm{GeV}/c)^2$.

COMPASS SDME

ρ-production

- COMPASS, EPJC **83** (2023) 924

- $$R = \frac{1}{\epsilon}\frac{r^{04}_{00}}{1 - r^{04}_{00}} + \cancel{\text{SCHC}} \text{ corrections}$$

Fig. 13 The ratio $R = \sigma_L/\sigma_T$ as a function of Q^2. For comparison measurements of exclusive ρ^0 leptoproduction by fixed target experiments (HERMES [23], NMC [24], E665 [25]) and by HERA collider experiments (ZEUS [30], H1 [27], H1 SV [26]) are also shown

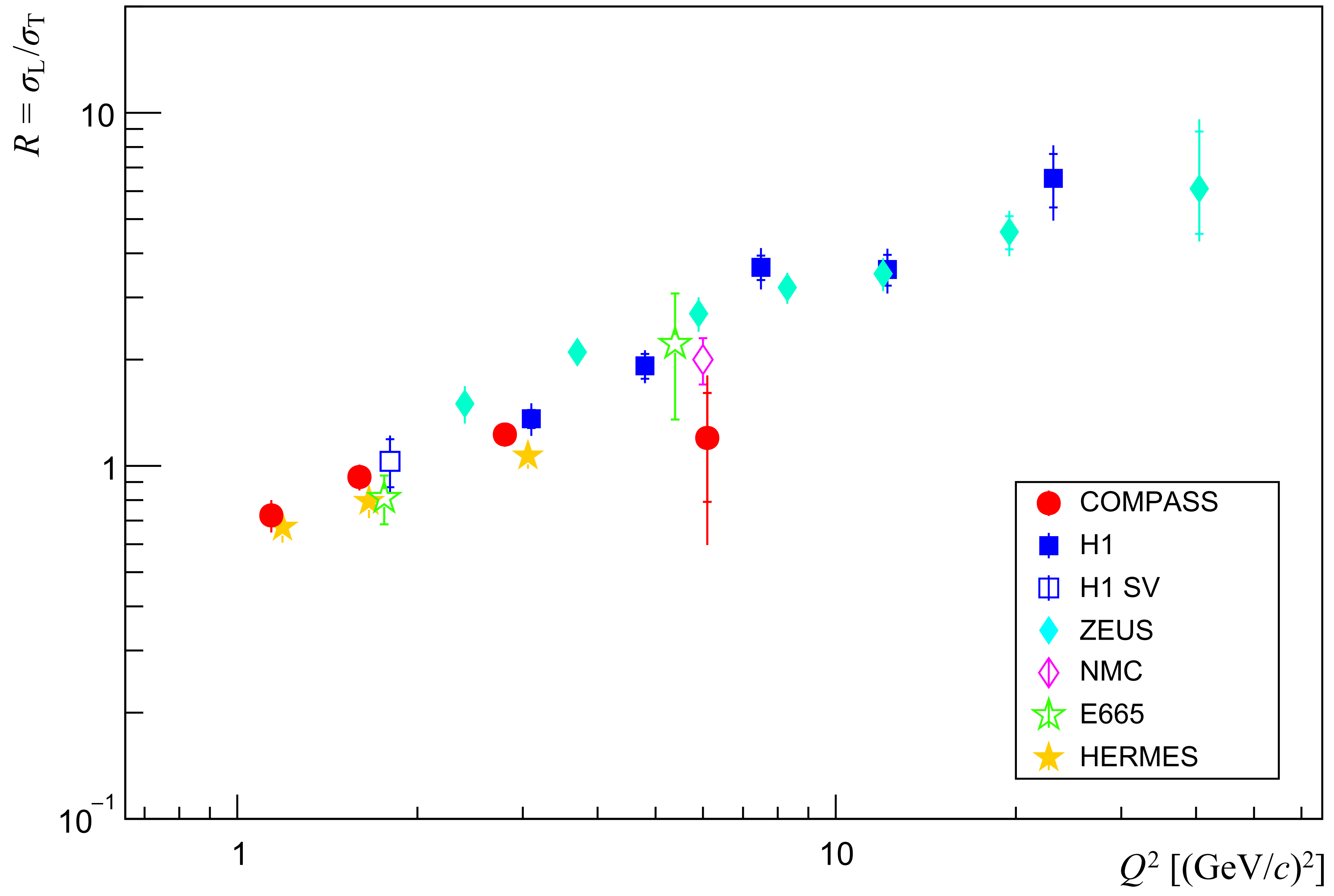
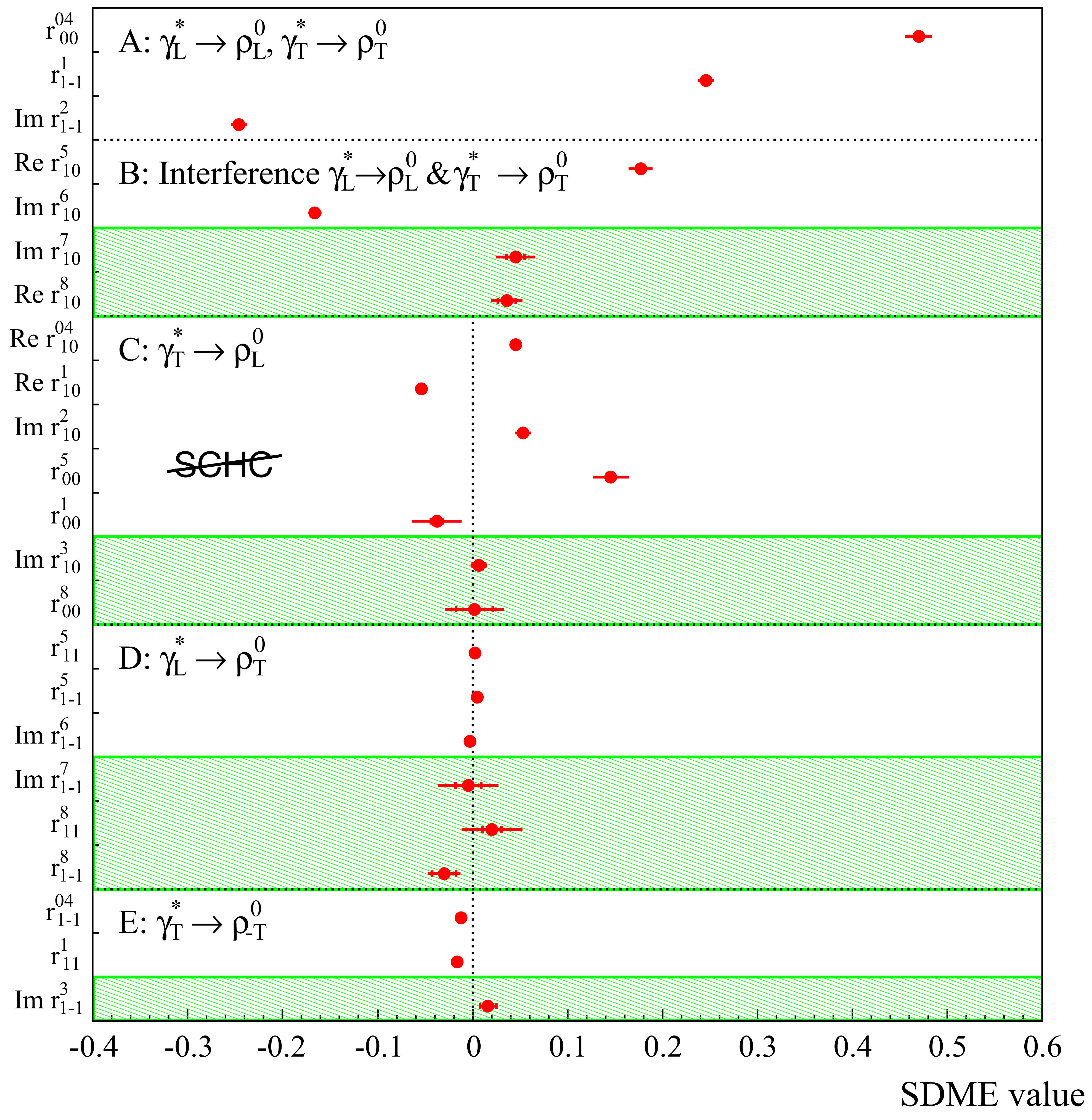


Fig. 4 The 23 SDMEs for exclusive ρ^0 leptoproduction extracted in the entire COMPASS kinematic region with $\langle Q^2\rangle = 2.40$ (GeV/c)^2, $\langle W\rangle = 9.9$ GeV/c^2, $\langle p_T^2\rangle = 0.18$ (GeV/c)^2. Inner error bars represent statistical uncertainties and outer ones statistical and systematic uncertainties added in quadrature. Unpolarised (polarised) SDMEs are displayed in unshaded (shaded) areas



$$\langle Q^2\rangle = 2.4\text{GeV}^2,\ \langle x_B\rangle = 0.024$$

COMPASS:
Deep pi0: arXiV:2412.19923

- 2016 data, 160 GeV $\mu^{\pm}$
  - $\left\langle Q^2 \right\rangle \approx 2.3$ GeV^2
  - $\left\langle x_B \right\rangle \approx 0.14$

- Goloskokov & Kroll

$$\frac{\mathrm{d}\sigma_{\mathrm{T}}}{\mathrm{d}t} \propto \left[(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m_{\mathrm{p}}^2}\left|\langle \overline{E}_{\mathrm{T}}\rangle\right|^2\right],$$

$$\frac{\mathrm{d}\sigma_{\mathrm{TT}}}{\mathrm{d}t} \propto \frac{t'}{16m_{\mathrm{p}}^2}\left|\langle \overline{E}_{\mathrm{T}}\rangle\right|^2,$$

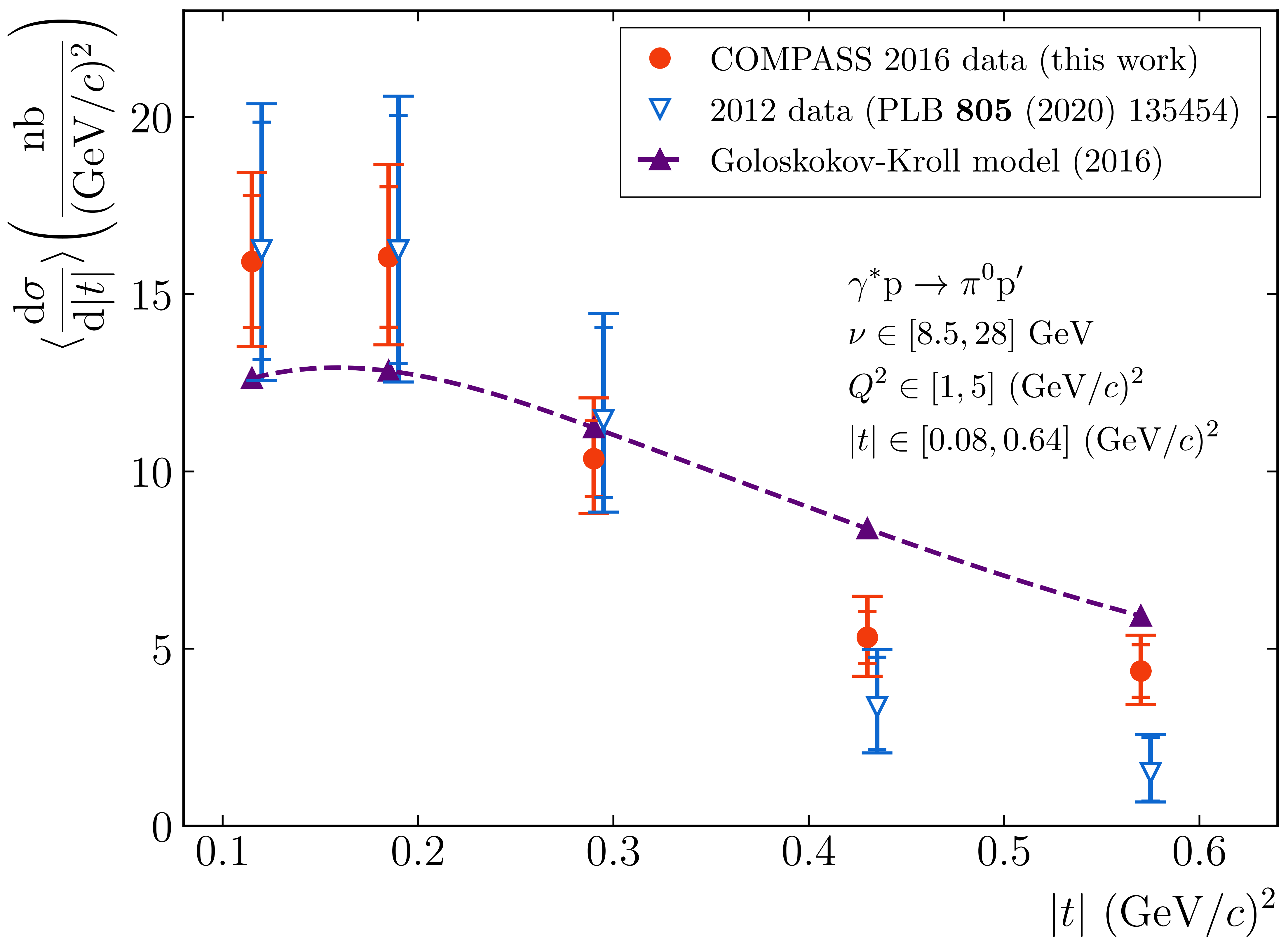


Table 6: The contributions in $\frac{\mathrm{nb}}{(\mathrm{GeV}/c)^2}$ to the spin-independent cross section in the kinematic domain of Ref. [27].

	$\left\langle \frac{\mathrm{d}\sigma_{\mathrm{T}}}{\mathrm{d}\lvert t\rvert} + \varepsilon \frac{\mathrm{d}\sigma_{\mathrm{L}}}{\mathrm{d}\lvert t\rvert} \right\rangle$	$\left\langle \frac{\mathrm{d}\sigma_{\mathrm{TT}}}{\mathrm{d}\lvert t\rvert} \right\rangle$	$\left\langle \frac{\mathrm{d}\sigma_{\mathrm{LT}}}{\mathrm{d}\lvert t\rvert} \right\rangle$
2016 data	$9.0 \pm 0.5_{\mathrm{stat}} {}^{+1.1}_{-1.0}\big\rvert_{\mathrm{sys}}$	$-6.6 \pm 0.8_{\mathrm{stat}} {}^{+0.5}_{-0.5}\big\rvert_{\mathrm{sys}}$	$0.7 \pm 0.3_{\mathrm{stat}} {}^{+0.4}_{-0.4}\big\rvert_{\mathrm{sys}}$
2012 data	$8.1 \pm 0.9_{\mathrm{stat}} {}^{+1.1}_{-1.0}\big\rvert_{\mathrm{sys}}$	$-6.0 \pm 1.3_{\mathrm{stat}} {}^{+0.7}_{-0.7}\big\rvert_{\mathrm{sys}}$	$1.4 \pm 0.5_{\mathrm{stat}} {}^{+0.3}_{-0.2}\big\rvert_{\mathrm{sys}}$

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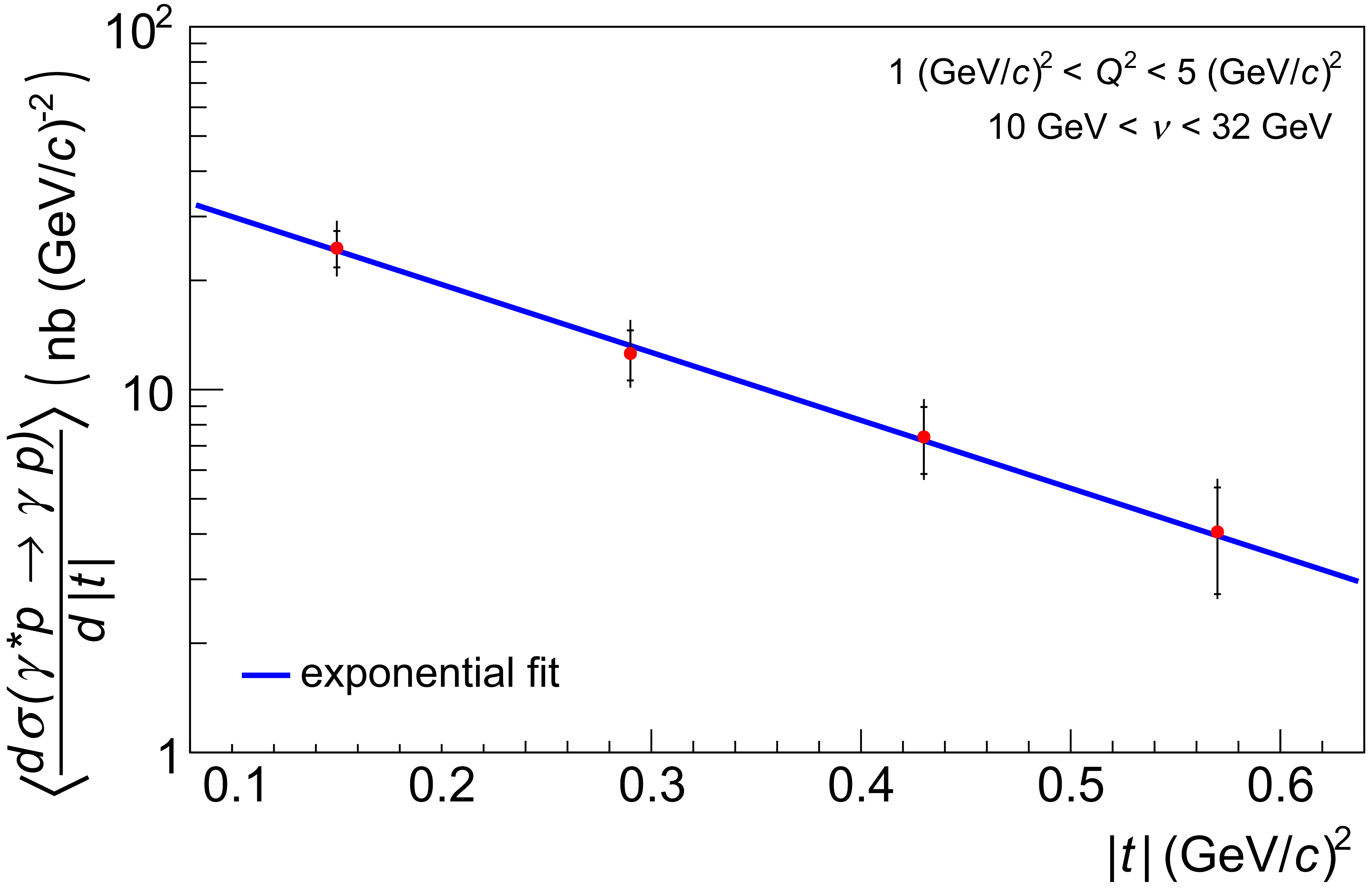
- 2012 data



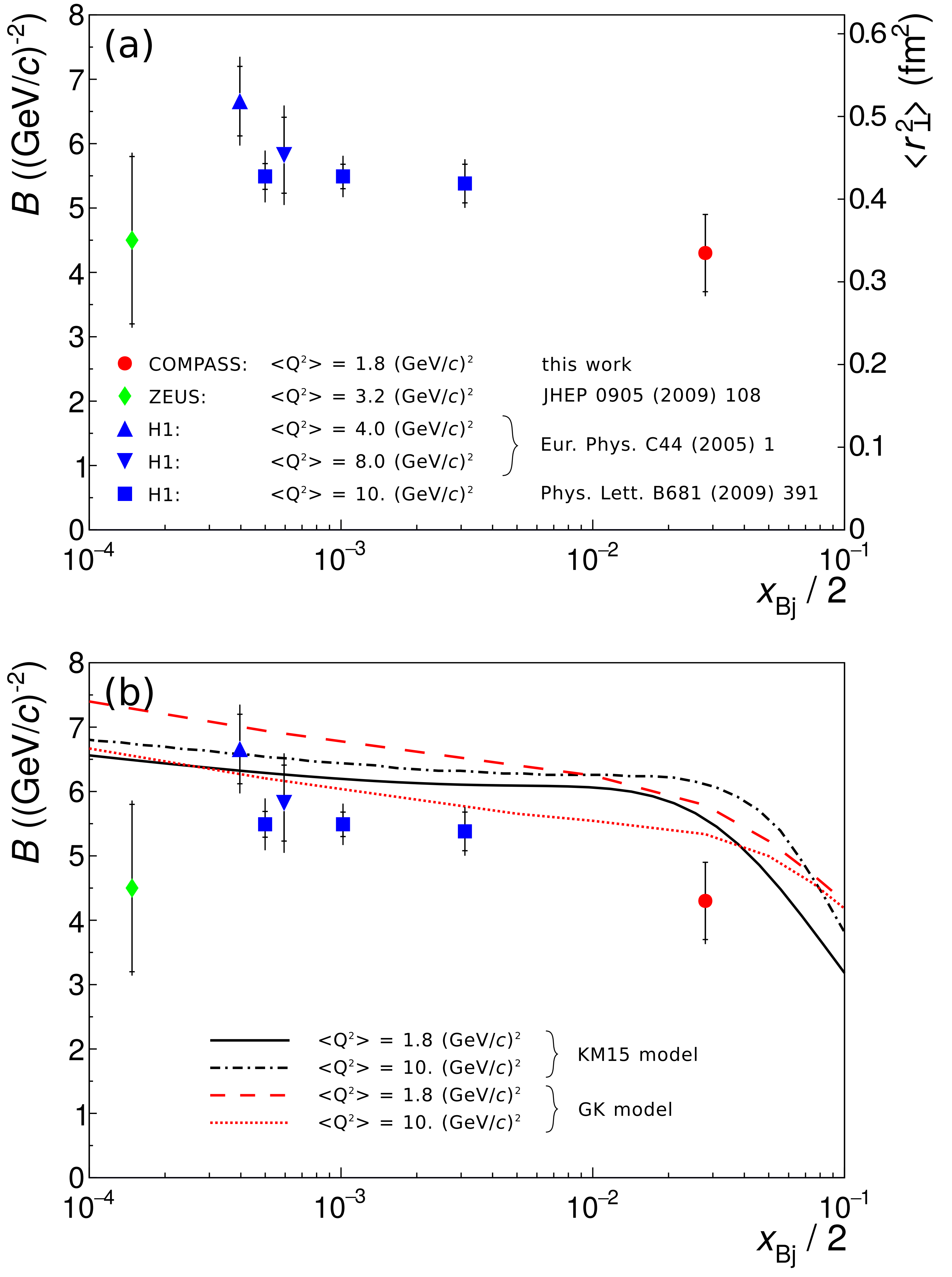


Fig. 1. (a) Results from COMPASS and previous measurements by H1 [2,3] and ZEUS [4] on the t-slope parameter B, or equivalently the average squared transverse extension of partons in the proton, $\langle r_\perp^2 \rangle$, as probed by DVCS at the proton longitudinal momentum fraction $x_{Bj}/2$ (see text [1]). Inner error bars represent statistical and outer ones the quadratic sum of statistical and systematic uncertainties. (b) Same results compared to the predictions of the GK [5–7] and KM15 [8,9] models.

- More data from 2016 still to come